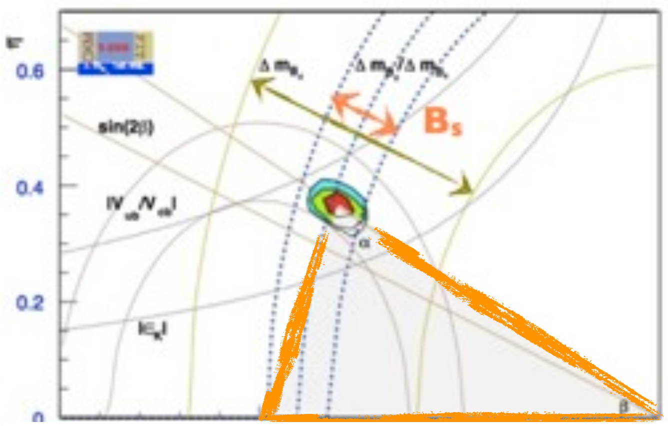
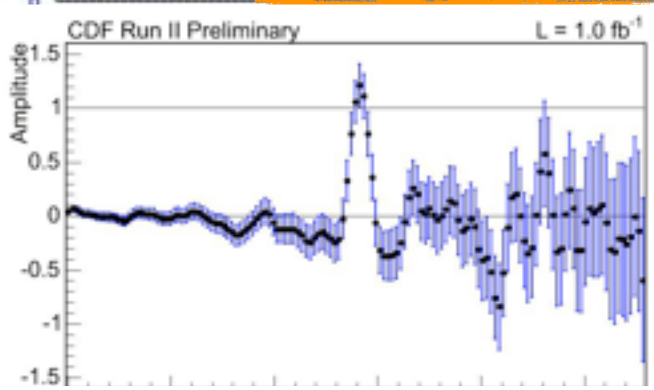
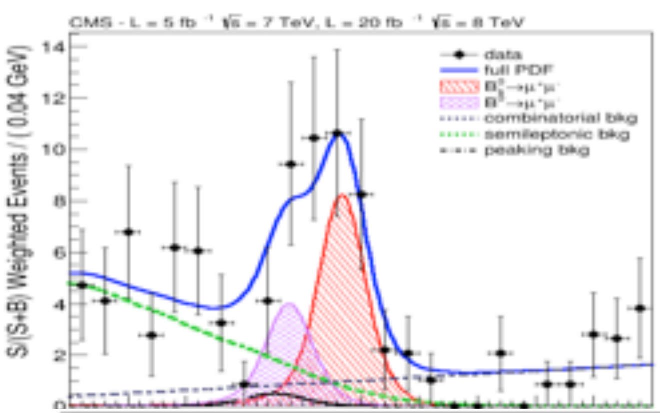
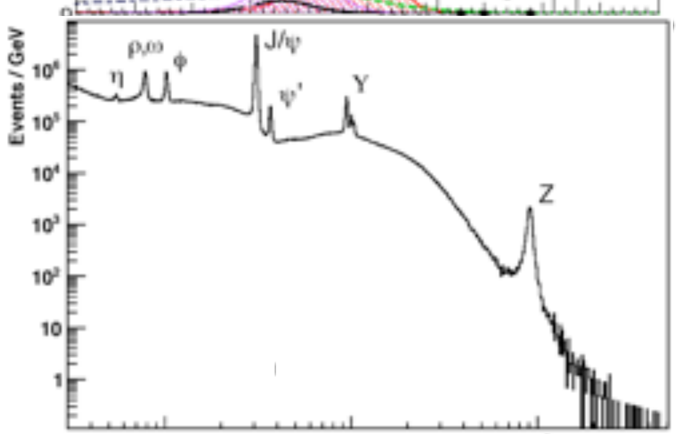








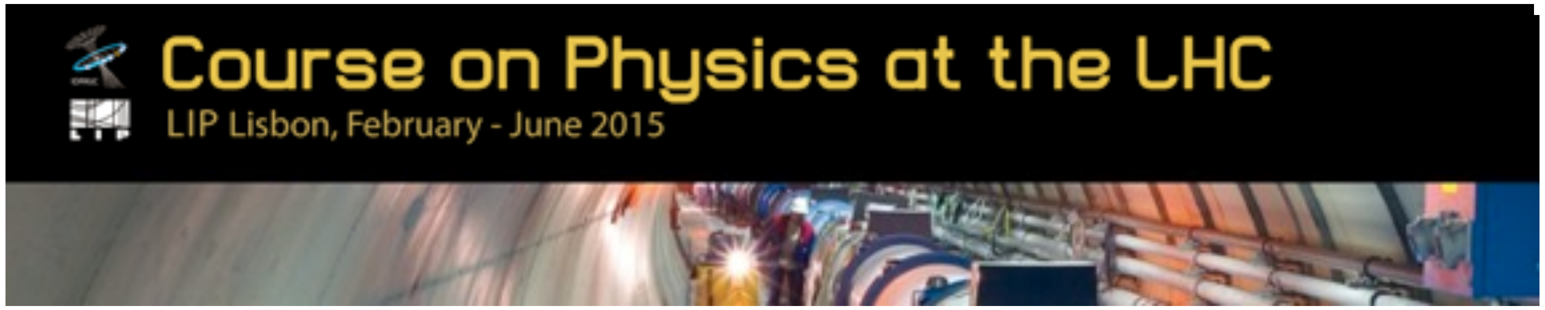
Lecture on

heavy flavor physics

&

rare decay searches

Nuno Leonardo, LIP
CMS B physics convener

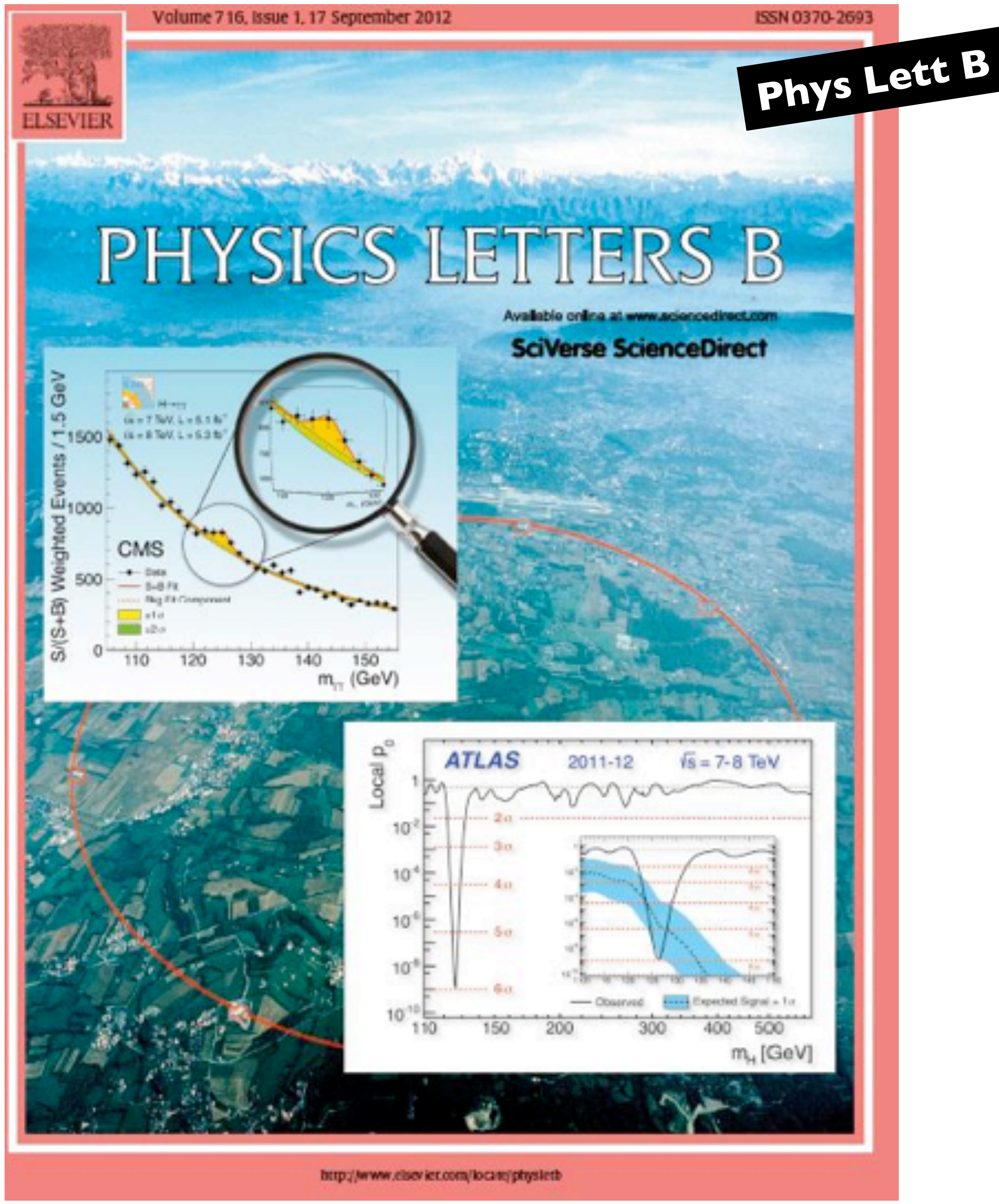


LABORATÓRIO DE INSTRUMENTAÇÃO E
FÍSICA EXPERIMENTAL DE PARTICULAS

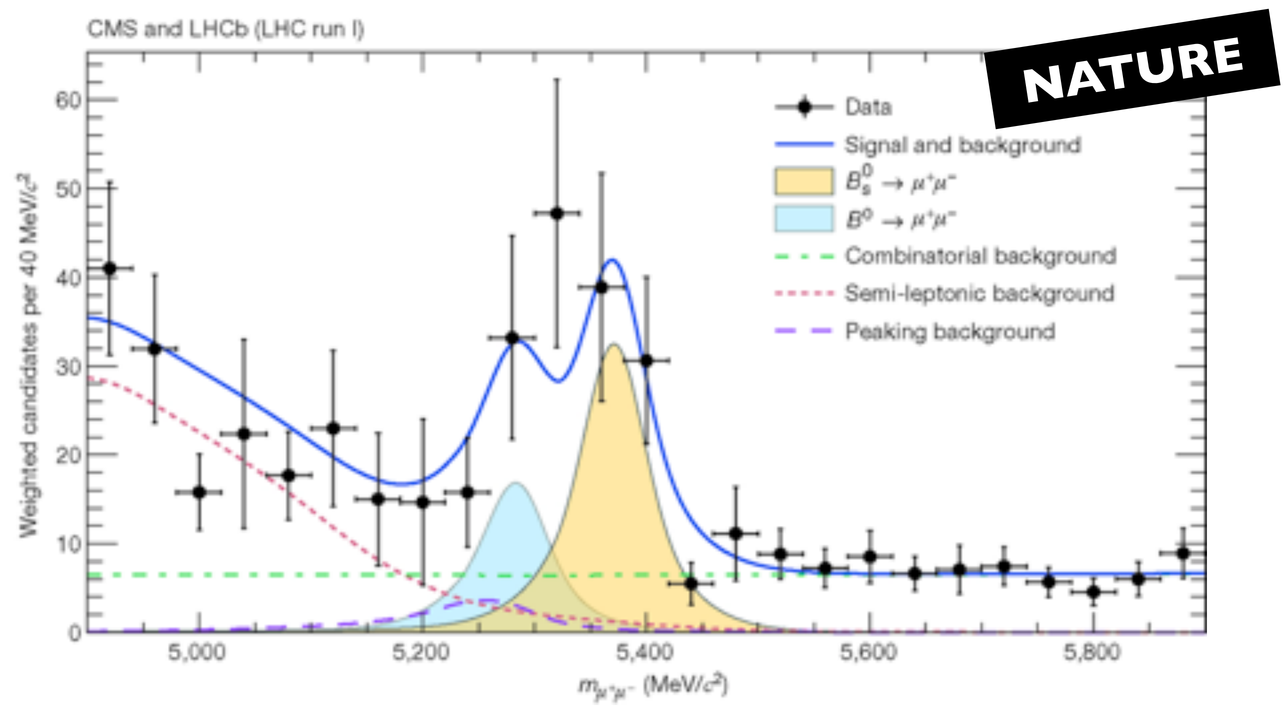
IF INVESTIGADOR FCT

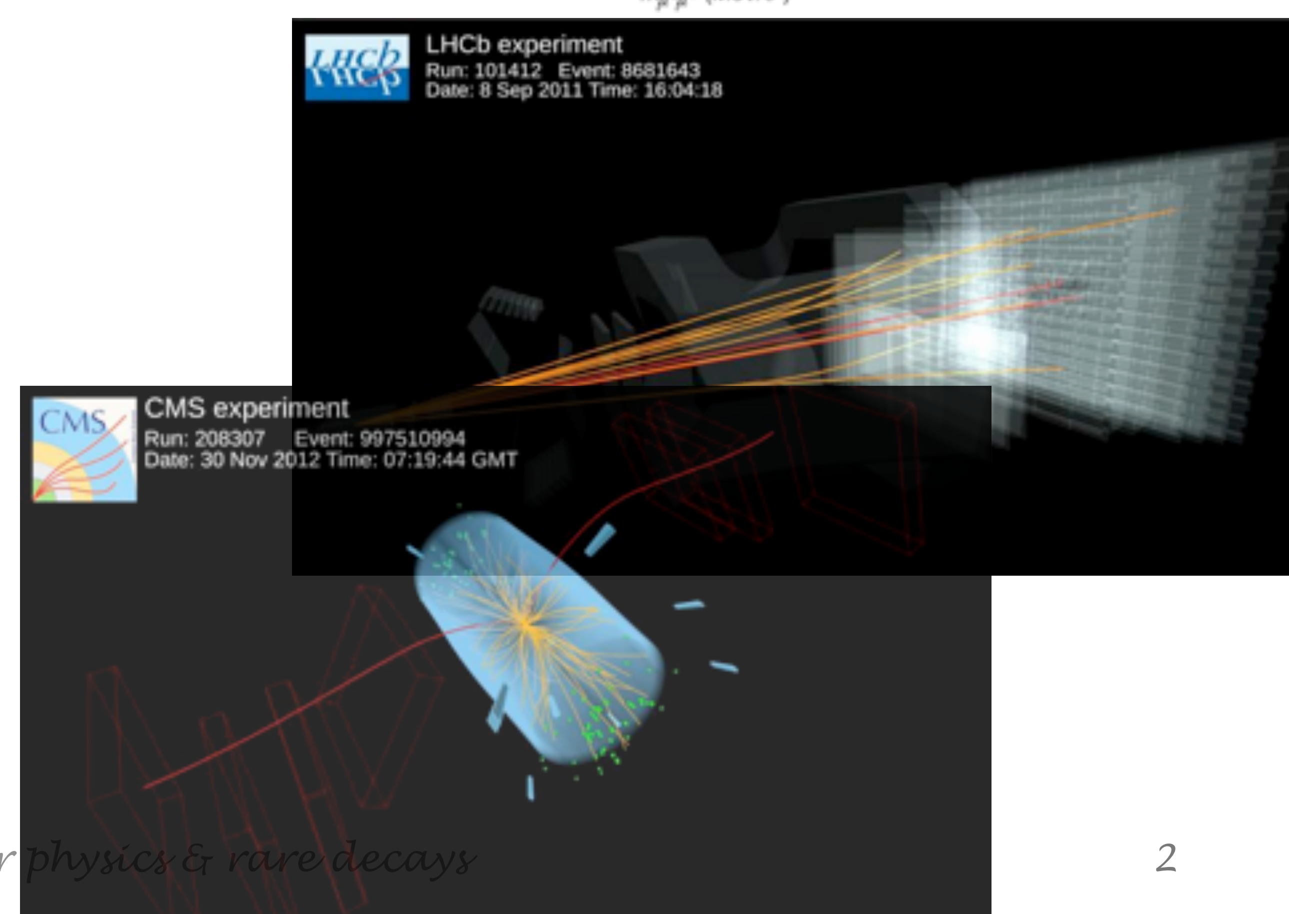
LHC Run I: two flagships

a 4-decade search effort... ended 3 summers ago:
Higgs by ATLAS & CMS



a 3-decade search effort... ended this summer:
$B_s \to \mu\mu$ by CMS & LHCb

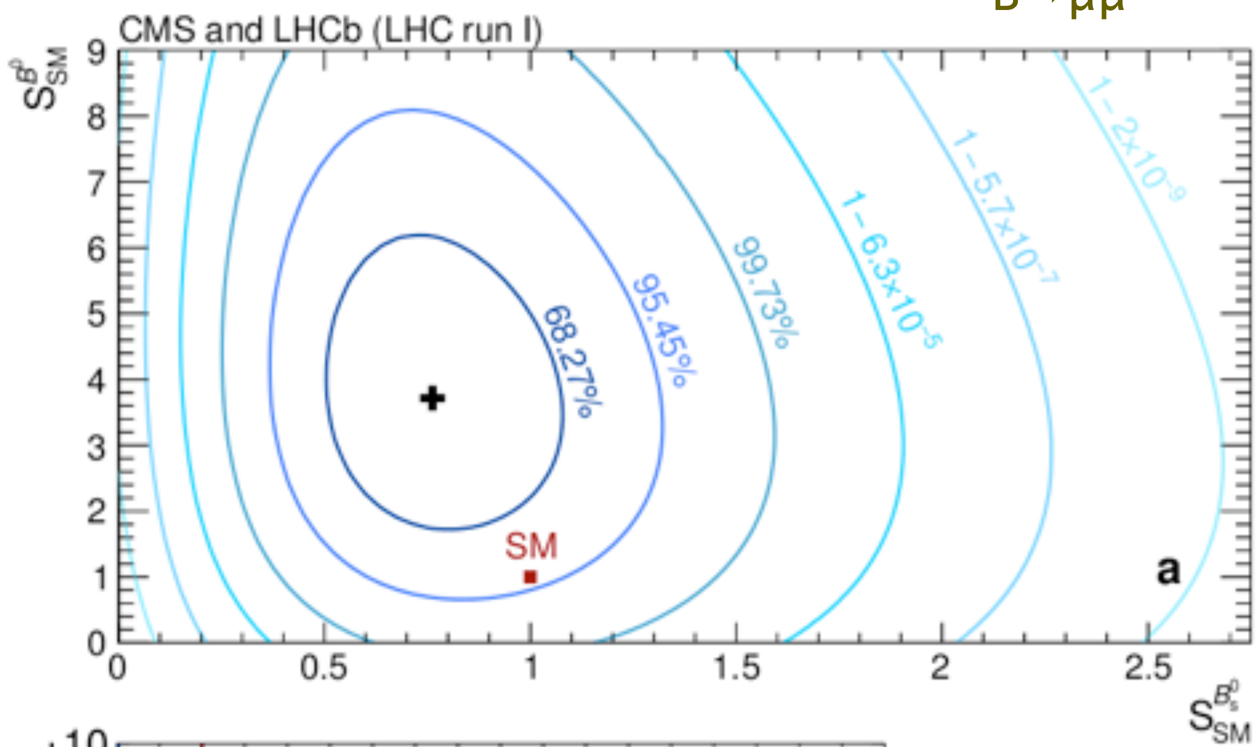


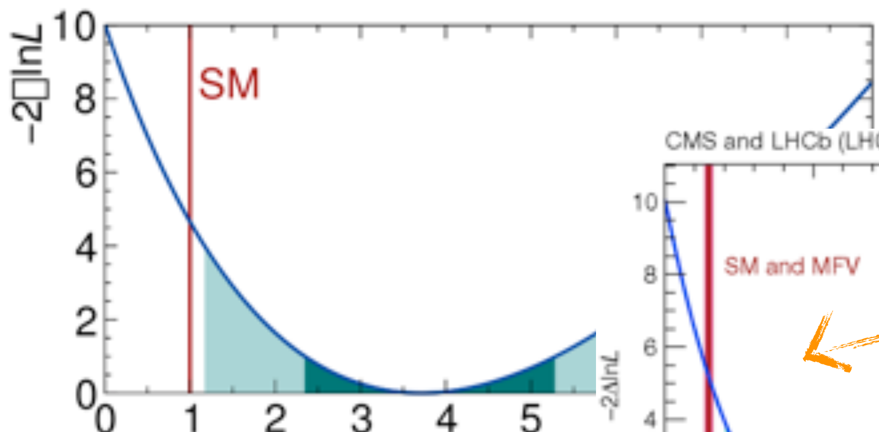


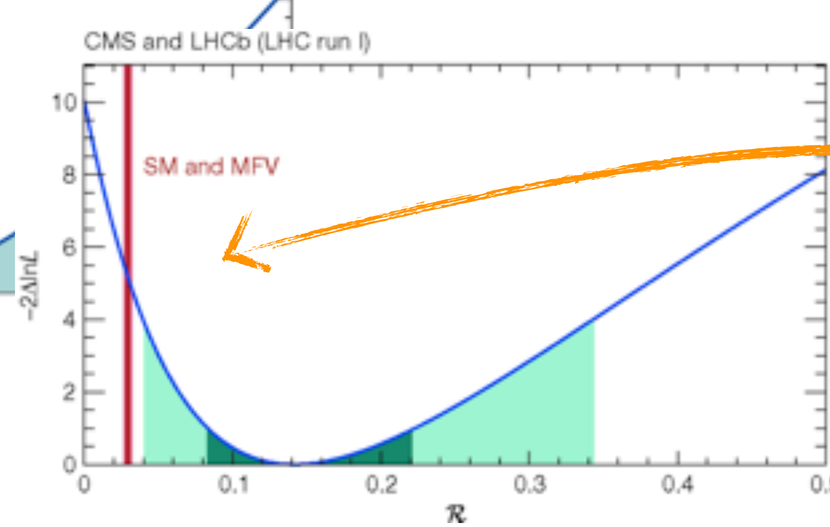
LHC Run I: anything unexpected?

- SM makes precise predictions
- any deviation from SM observed in LHC so far -- in flavor sector?

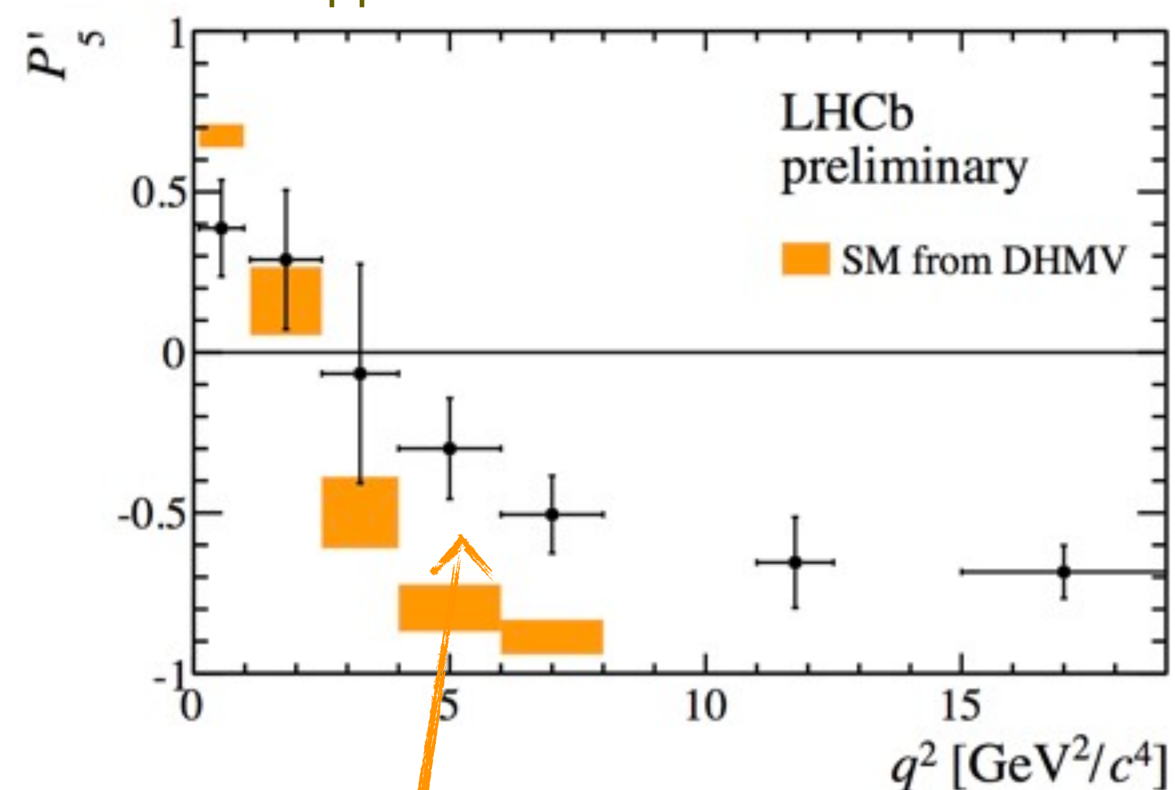
B→μμ







B→Kμμ



3.7σ deviation

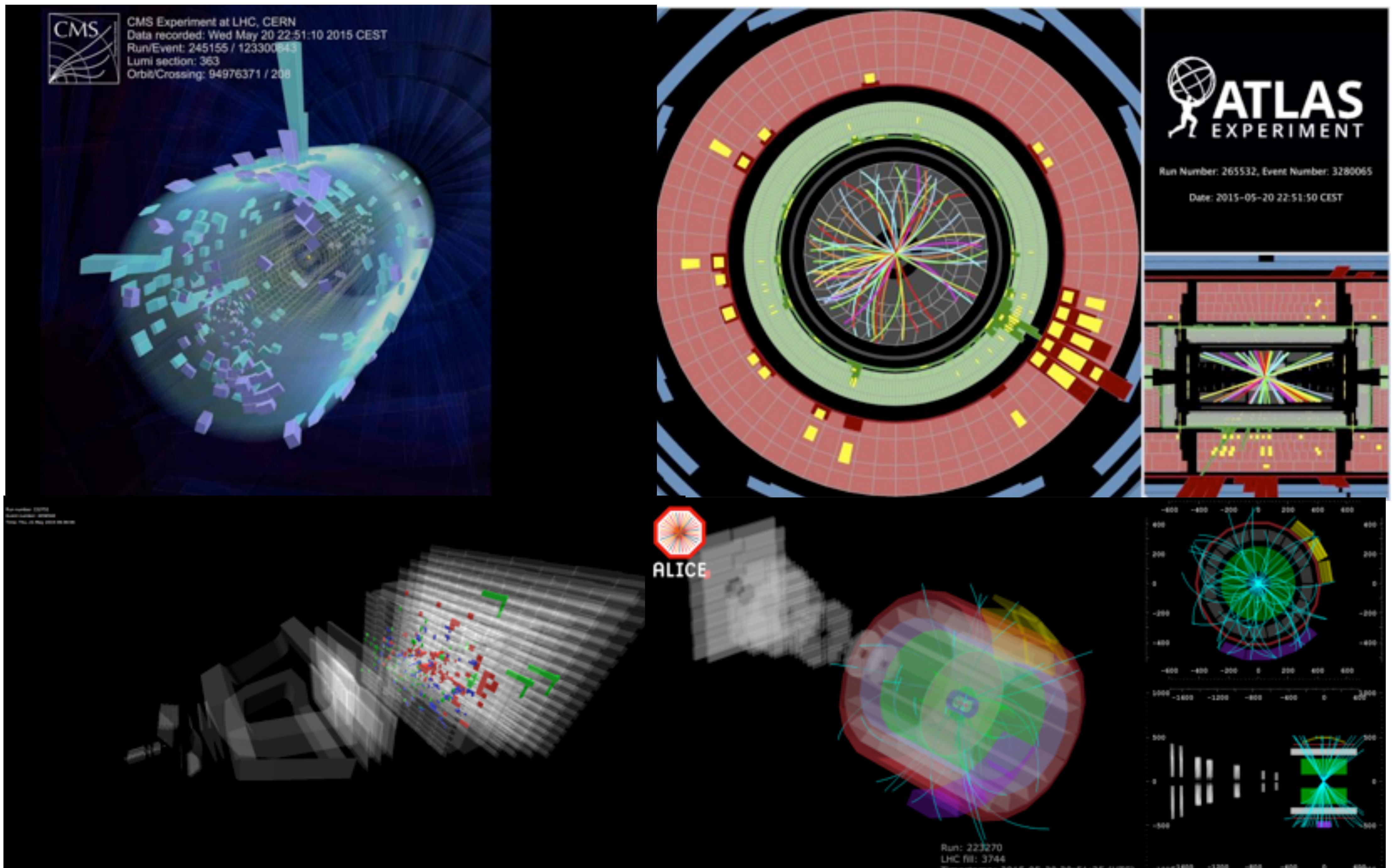
2.3σ deviation

plus a few other hints...

⇝ more **data** needed!

LHC Run II: just starting!

- first record-breaking energy collisions at 13 TeV occurred 10 days ago
- physics run about to start: stable beams aimed within 3 days
- run II of the LHC is starting



Contents

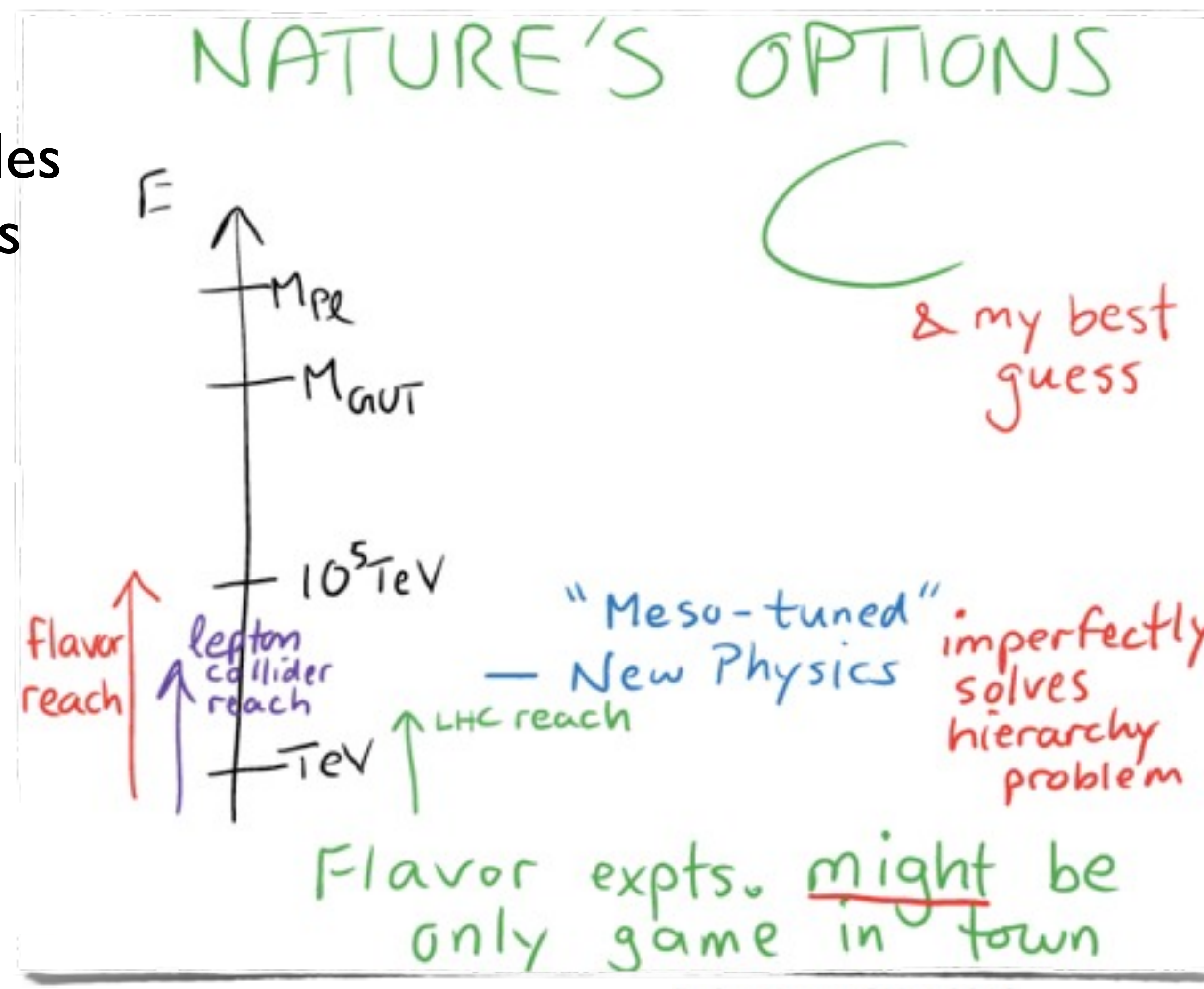
1. LHC: status&highlights — Run I selected highlights. Run II starting now!
2. motivation — NP scale, puzzles, CKM, unitarity, global fits
3. detection — displaced topology, LHC as a HF factory
4. production — cross section, polarization, spectroscopy
5. suppression — melting and energy loss in QGP
6. lifetime — proper time bias and resolution
7. tagging & mixing — flavor tagging techniques, dilution factors, oscillation frequency
8. CP violation — in decay, mixing, and interference
9. rare decays — as New Physics probes, FCNC, LFV

the role of flavor physics

- in searching for **New Physics**
  - discovery potential beyond energy frontier e.g. via searches for rare processes
- in understanding why the **SM** appears so fundamental
  - in that no phenomena beyond the SM has (yet) been detected at LHC Run I
- in learning about standing mysteries of the **flavor structure** of SM (and BSM)
- in connecting **CP violation** to the matter-antimatter asymmetry in the observable universe
- in probing the properties of **deconfined QCD** matter at high temperature and density
- extra: as an experimental tool & probe
  - serve as probe or a **dominant background** in SM measurements and BSM searches
  - used for **detector calibration** (e.g. material budget, magnetic field, detector performance)

probing beyond (the SM)

- central goal of LHC physics program:
  - discover new physics (NP) aka BSM
- complementary approaches
  - direct searches for new heavy particles produced (on-shell) in LHC collisions
  - indirect searches via virtual NP contributions via high-precision measurements of SM processes
  - search for rare decays, highly suppressed (or forbidden) in SM and sensitive to NP
- virtual contributions provide sensitivity to higher mass scales, well beyond the TeV scale



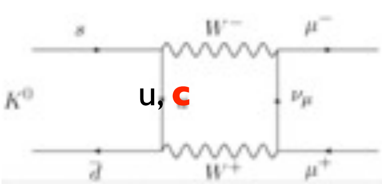
R. Sundrum-CKM 2012

indirect discovery via precision

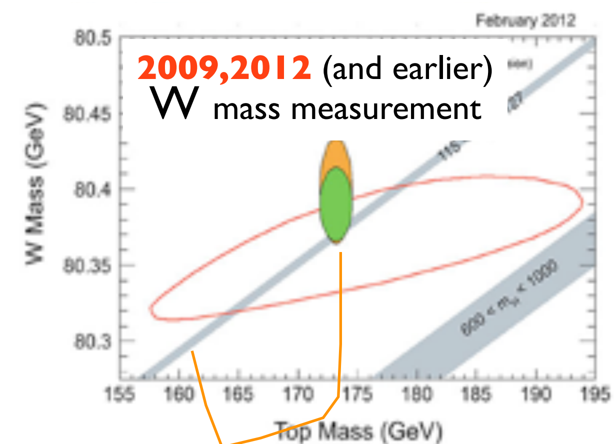
- new physics can show up at precision frontier before energy frontier
  - kaon (1947), Λ^0 (1950) led to discovery of strangeness
  - GIM mechanism (1970) before discovery of charm (1974)
  - CP violation (1964) before discovery of bottom (1977) & top (1995)
  - neutral current (1973) before discovery of Z (1983)
  - precision W and t mass meas. constrained Higgs mass, etc!

(note: quarks postulated 1964 [Gellman&Zweig], based on hadron classification ['eightfold way'], directly confirmed experimentally 1968 [DIS])

1970
GIM mechanism
(Glashow–Iliopoulos–Maiani)
required the fourth quark: **c**harm
e.g. $K^+ \to \mu^+ \nu_\mu$ so why not $K^0 \to \mu^+ \mu^-$?



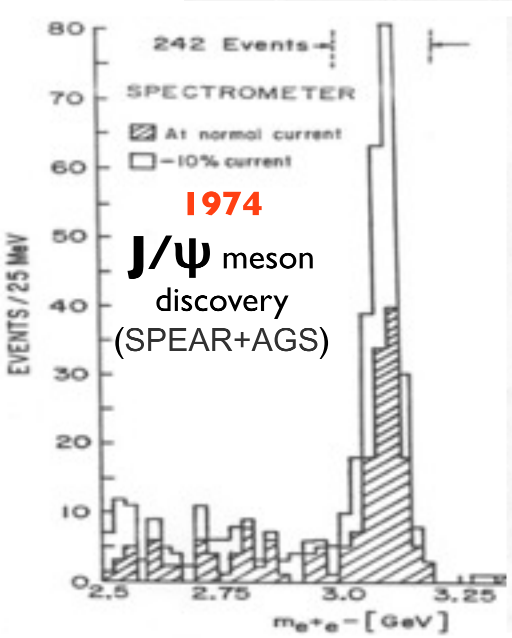
1973
3rd quark generation predicted
bottom and **t**op
by Kobayachi and Maskawa
to explain observed CP violation
(discovered in **1964** in the kaon system)



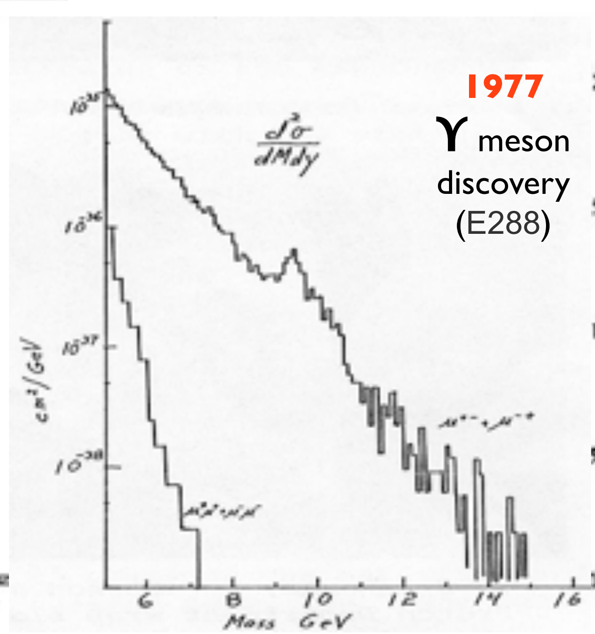
precision m_W and m_t
$\Rightarrow m_H < 145\text{GeV}$

$\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$

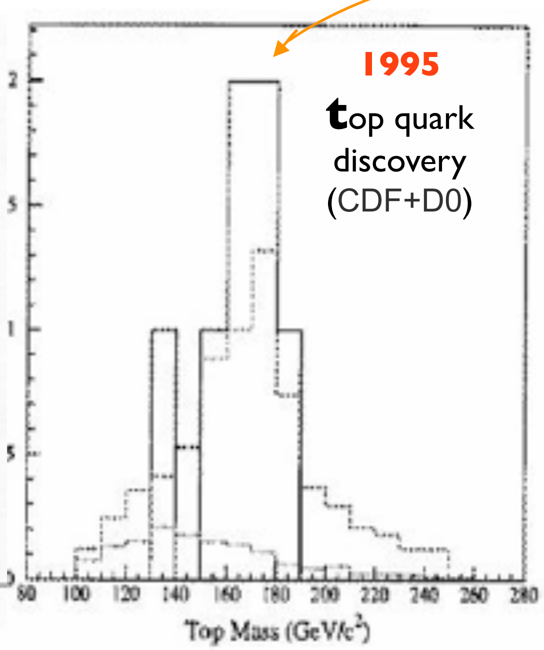
1973
neutral currents observed



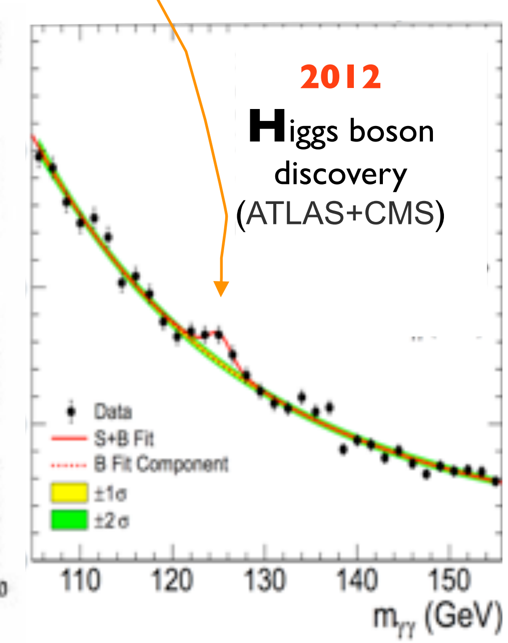
1974
J/ψ meson
discovery
(SPEAR+AGS)



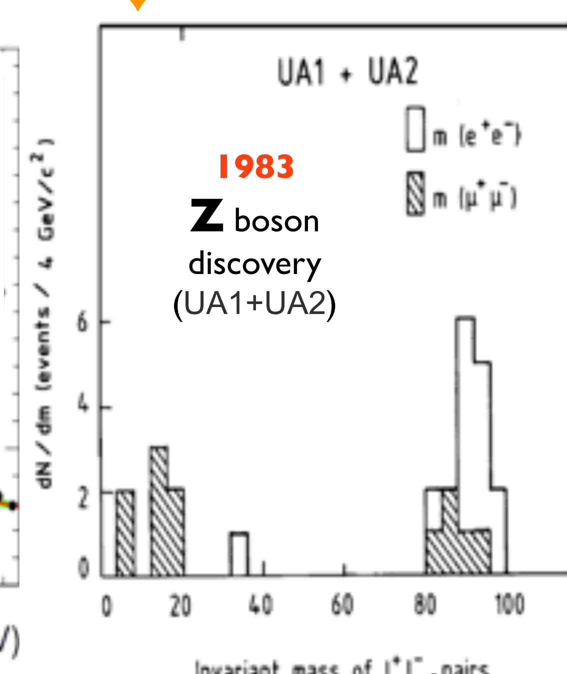
1977
Υ meson
discovery
(E288)



1995
top quark
discovery
(CDF+D0)



2012
Higgs boson
discovery
(ATLAS+CMS)

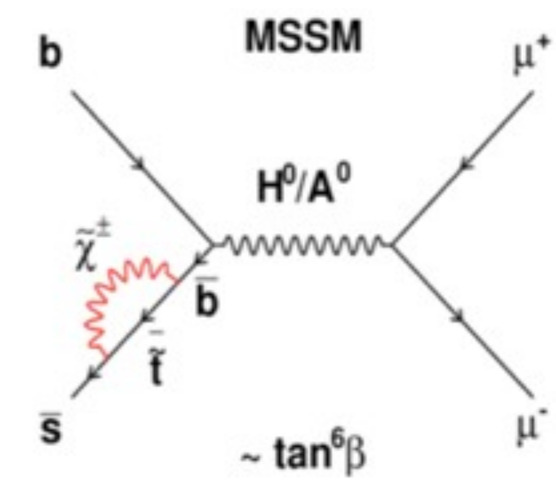


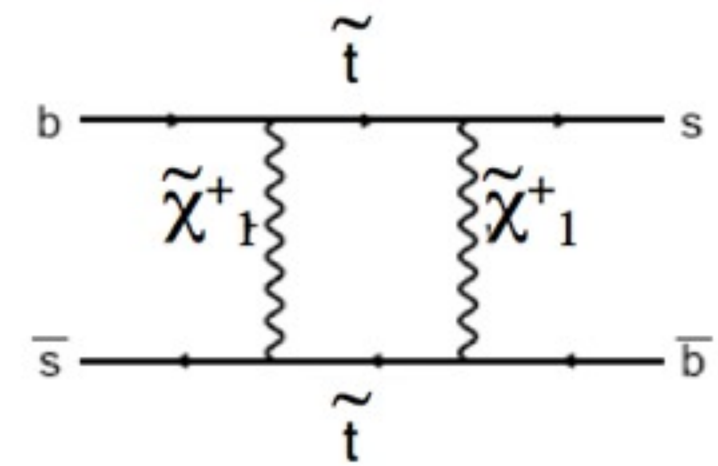
1983
Z boson
discovery
(UA1+UA2)

<u>bottom line</u>: historically, precision measurements at lower energies predicted the existence of new, heavier states

a path to new physics

- the effects of NP can be searched for and revealed indirectly through the virtual exchange of NP particles
  - general quantum effects in flavor loops
  - eg: SUSY particles can contribute in addition to SM; Z' could affect effective couplings
- if NP hides behind SM interactions
  - either NP mass scale is very LARGE
  - or NP couplings mimic Yukawa couplings (minimal flavor violation scenario, MFV)
- in all cases study of flavor observables expected to enlighten or constrain theory





note: flavor-sector constraints at the LHC comparable (or stronger) than direct search limits, e.g. for large regions of the parameter space of minimal supersymmetry models

«flavor» physics?

- the SM flavor sector arises from interplay of fermion-weak–gauge and fermion-Higgs couplings

Electroweak symmetry breaking:
Masses for gauge bosons and fermions [Higgs mechanism]

Three generations of quarks and leptons

T = ½

Left-handed doublets: $\begin{pmatrix}\nu_e \\ e\end{pmatrix}_L, \begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix}_L, \begin{pmatrix}\nu_\tau \\ \tau\end{pmatrix}_L, \quad \begin{pmatrix}u \\ d\end{pmatrix}_L, \begin{pmatrix}c \\ s\end{pmatrix}_L, \begin{pmatrix}t \\ b\end{pmatrix}_L$

Right-handed singlets: $e_R, \quad \mu_R, \quad \tau_R, \quad u_R, d_R, \; c_R, s_R, \; t_R, b_R$

T = 0

Rich flavor phenomenology ...

The parameters of the SM

- 3 gauge couplings
- 2 Higgs parameters
- strong CPV parameter, $\bar{\theta}$
- 6 quark masses
- 3 quark mixing angles + 1 phase (CKM)
- 3 (+3) lepton masses
- (3 lepton mixing angles + 1 phase (PMNS))

Out of the19 parameters of the SM (excluding neutrino masses/mixing), 14 arise from the flavor sector.

flavor parameters

( ) = with Dirac neutrino masses

flavor «puzzle»

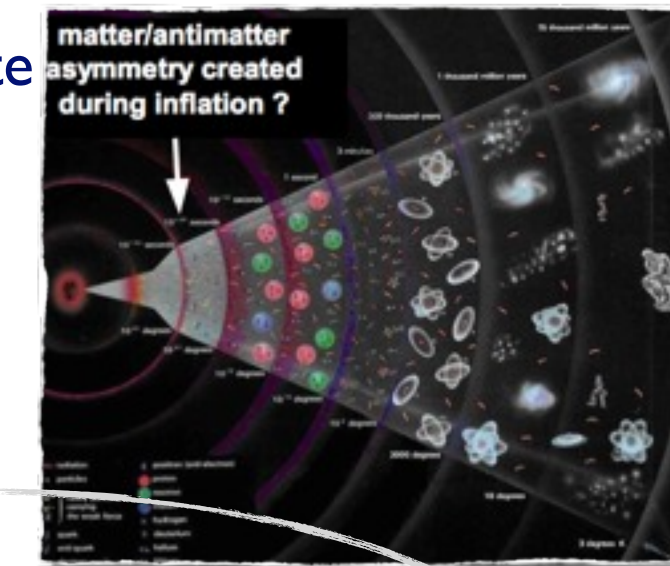
- there are standing mysteries intrinsic to the SM flavor sector
  - why are there so many free parameters
    - why do these parameters exhibit strong hierarchical structure spanning several orders of magnitude
  - why are there so many fermions
  - what is responsible for their organization into generations
    - and why are there 3 such generations each of leptons and quarks
  - why wide range of fermion couplings and masses
    - for example: $O(10^{-5}) \cdot m_t \sim m_u \sim m_\nu \cdot O(10^{+6})$, $|V_{ub}| \sim O(10^{-3}) \cdot |V_{td}|$
  - why are there flavor symmetries
    - and what breaks them
  - why is $\theta_{QCD} < 10^{-9}$
  - what is the origin of CP violation

- various solutions to this puzzle have been proposed (but not established), inevitably leading to beyond-the-SM scenarios
  - for within the SM these parameters can only be accommodated, not explained

another, related «puzzle»: BAU

(baryon asymmetry in the universe)

- Sakharov conditions (1967), necessary for dynamical evolution of matter dominated universe from symmetric initial state
  1. baryon number violation
  2. C & CP violation
  3. thermal inequilibrium



- no significant amounts of antimatter observed
  - $\Delta N_B/N_\gamma \equiv [N(\text{baryon})-N(\text{antibaryon})] / N_\gamma \sim 10^{-10}$
- amount of CP violation in SM not sufficient to explain BAU
  - CPV in quark sector (CKM) would yield an asymmetry of $O(10^{-17}) \ll 10^{-10}$
- more CPV is needed!
  - to create a larger asymmetry, require: new sources of CP violation ... that occur at higher energies
- where might it be found?
  - lepton sector: CPV in neutrino oscillations
  - quark sector: discrepancies with KM predictions
  - gauge/higgs sector; extra dimensions or other new physics?
  - *precision measurements of flavor observables sensitive to additions to SM*

«heavy» flavor?

light quarks: m≲Λ_{QCD}
u, d: realm of nuclear physics
s: rare kaon decays test SM

$$m_u \approx 3\ MeV$$
$$m_d \approx 5\ MeV$$
$$m_s \approx 100\ MeV$$
$$m_c \approx 1300\ MeV$$
$$m_b \approx 4200\ MeV$$
$$m_t \approx 170000\ MeV$$

top (not that heavy!)
the top quark has its own phenomenology (since it does not hadronize)

$$m_{\nu_1} \lesssim 10^{-6}\ MeV$$
$$m_{\nu_2} \lesssim 10^{-6}\ MeV$$
$$m_{\nu_3} \lesssim 10^{-6}\ MeV$$
$$m_e \approx 0.5\ MeV$$
$$m_\mu \approx 100\ MeV$$
$$m_\tau \approx 1800\ MeV$$

neutrinos
have their own phenomenology, not detected (directly) at LHC

light charged leptons
e.g. electric and magnetic dipole moments test SM

tau
e.g. searches for lepton flavor violation, $\tau \to \mu\mu\mu$

Study Beauty and Charm quarks
- hidden flavor aka quarkonia: ψ ($c\underline{c}$), ϒ($b\underline{b}$), $X_{c,b}$; plus exotic X,Y,Z states
- open charm: D mesons
- open beauty, B mesons (B_u, B_d, B_s, B_c) and b-baryons (Λ_b, Ξ_b, Ω_b, ...)

note:
- «B physics» refers to study of flavor-changing interactions of b-quark mesons
- some extra focus placed today on ϒ and $B_{(s)}$ – particularly interesting at LHC

quark masses [higgs]

Exercise: show this

- a Lagrangian mass term $m\bar{\psi}\psi$ would break chiral gauge symmetry ➠ not allowed
- introducing Yukawa interactions with a scalar field, fermion mass terms get generated

$$-Y\bar{\psi}\psi\phi \xrightarrow[\text{symmetry breaking}]{\text{spontaneous}} -Y\bar{\psi}\psi\,(v+\phi')$$

the Higgs

- the mass terms for up- and down-type quarks have the form

$$\mathcal{L}_M = -\bar{\mathrm{u}}_R^{\circ T}\,\mathbf{m}_\mathrm{u}\,\mathrm{u}_L^\circ - \bar{\mathrm{d}}_R^{\circ T}\,\mathbf{m}_\mathrm{d}\,\mathrm{d}_L^\circ + \text{h.c.}$$

- the mass matrices - m_u, m_d - are not diagonal; may be diagonalized (w/ unitary matrices L,R)

$$L_u\mathbf{m}_\mathrm{u}R_u^\dagger = \hat{\mathbf{m}}_\mathrm{u} \qquad L_d\mathbf{m}_\mathrm{d}R_d^\dagger = \hat{\mathbf{m}}_\mathrm{d} \quad ➠ \quad \hat{\mathbf{m}}_{\mathrm{u(d)}} = \mathrm{diag}\left(m_{u(d)}, m_{c(s)}, m_{t(b)}\right)$$

- flavor changing interactions in the SM (charged currents) through couplings to $W^\pm$ bosons

$$\mathcal{L}_W = \frac{g}{\sqrt{2}}\,\bar{\mathrm{u}}_L^{\circ T}\,\gamma^\mu\,\bar{\mathrm{d}}_L^\circ\,W_\mu^+ + \text{h.c.} = \frac{g}{2\sqrt{2}}\,\bar{\mathrm{u}}^T\,\gamma^\mu(1-\gamma^5)\,\mathbf{V}\,\mathrm{d}\,W_\mu^+ + \text{h.c.}$$

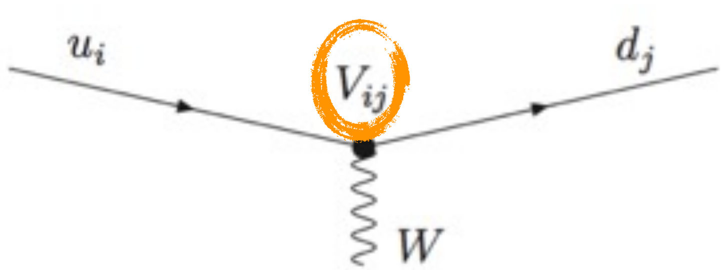
the CKM matrix

- the unitary quark-mixing matrix V is the Cabibbo-Kobayashi-Maskawa matrix

$$\mathbf{V} \equiv L_u L_d^\dagger$$

- describing quark-flavor mixing

$$\mathbf{d}' = \mathbf{V}\,\mathbf{d} \quad \Leftrightarrow \quad \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



quark mixing [CKM]

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- CKM: a unitary 3x3 matrix
  - has 9 parameters: 3 rotation (Euler angles) + 6 phases
  - 5 of these phases can be absorbed by making phase rotations of quark fields
  - we are left with 4 independent parameters: 3 angles & 1 (complex) phase
  - ☛ in a standard parameterization (Wolfenstein) these are: A, λ, ρ & η
- one irreducible phase ➠ the source of CP violation in the SM

Exercise:
* show that in case of N generations, unitarity implies $(N-1)^2$ independent parameters, with $N(N-1)/2$ rotation angles and $(N-1)(N-2)/2$ complex phases
* show that at least three quark generations are required for CP violation

unitarity

- unitarity of the CKM matrix

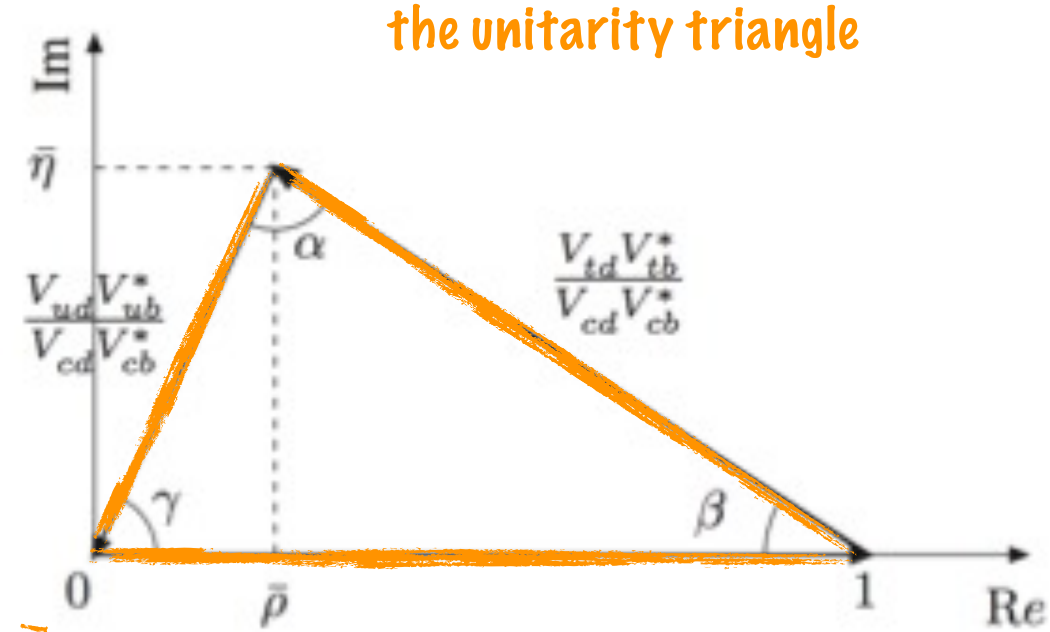
$$\sum_i V_{ij}V^*_{ik} = \delta_{jk} = \sum_i V_{ji}V^*_{ki}$$

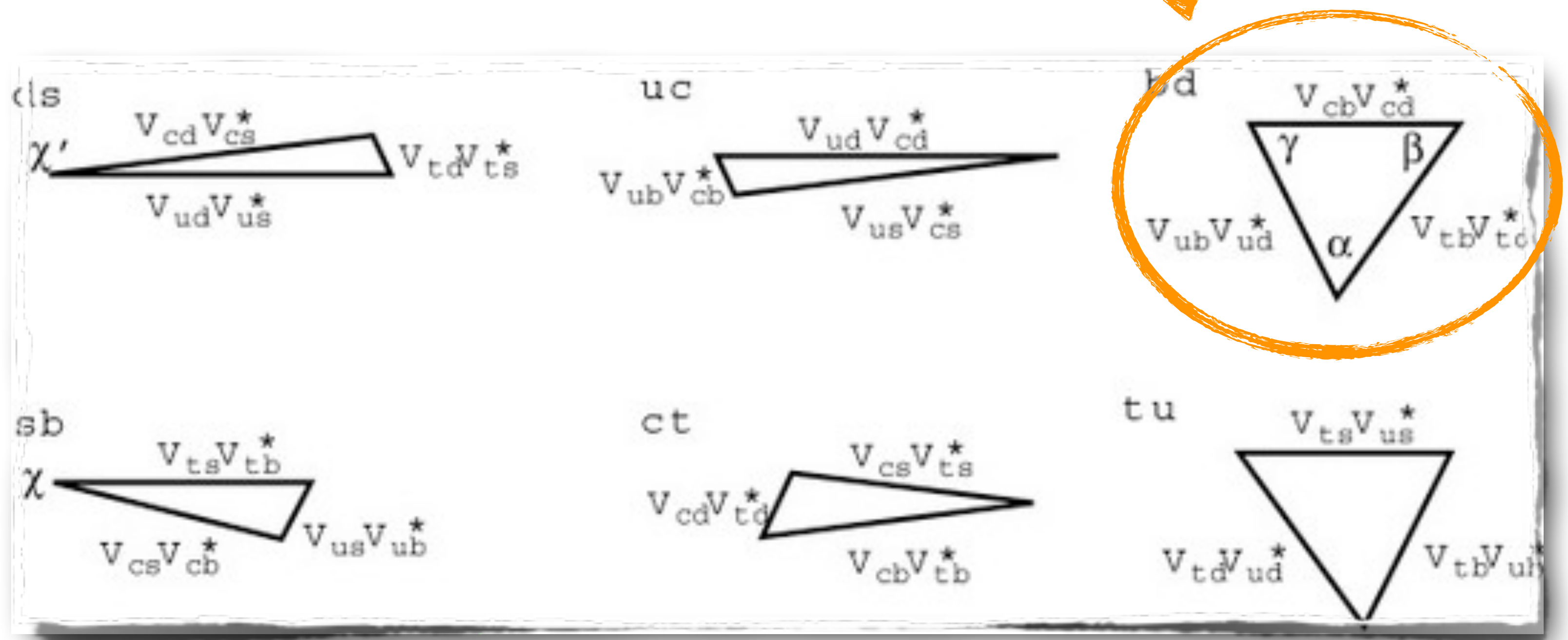
- e.g. multiplying 1st & 3rd columns

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

- may be represented as a triangle in the (ρ,η) plane
- CPV is proportional to triangles' area

the unitarity triangle

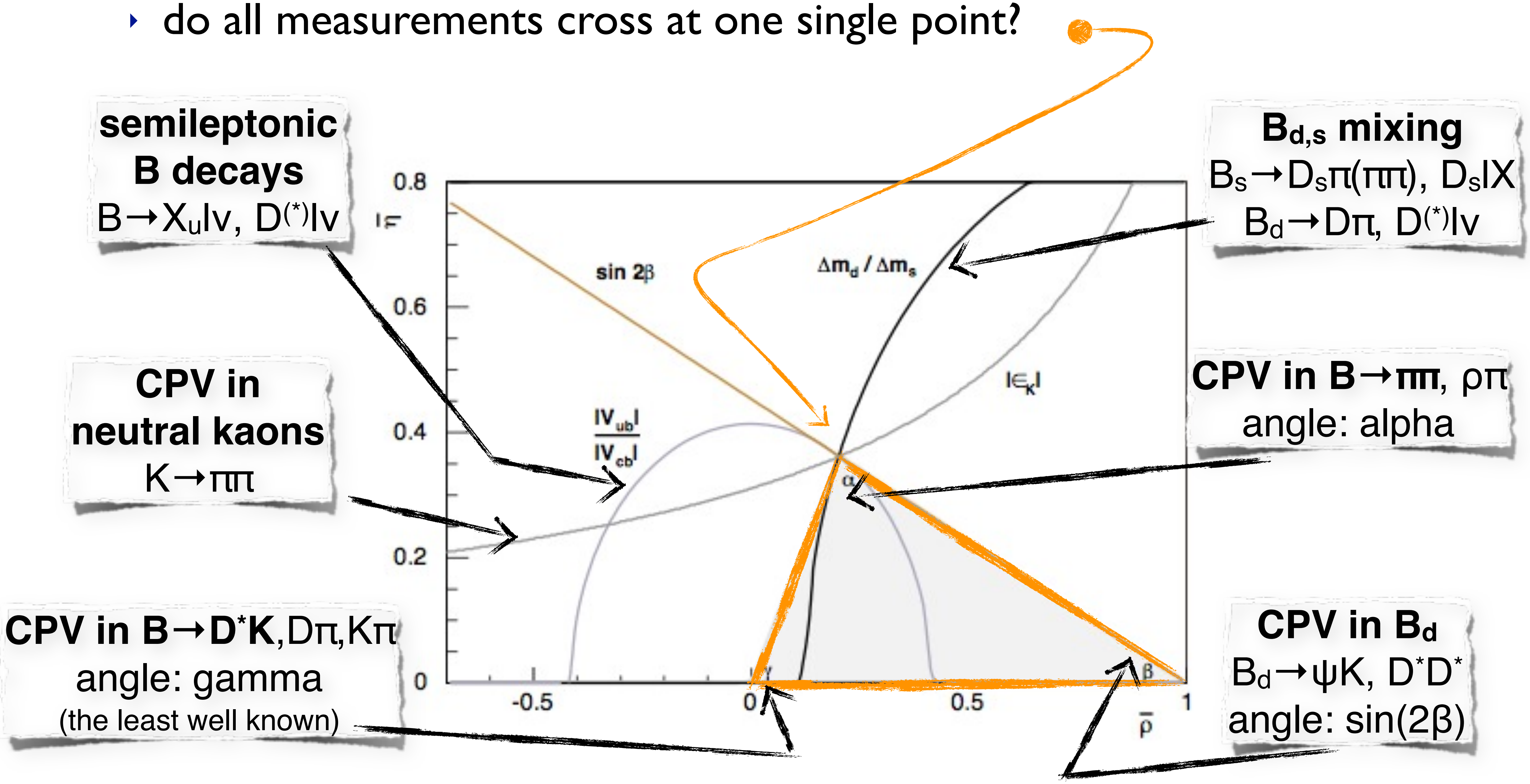




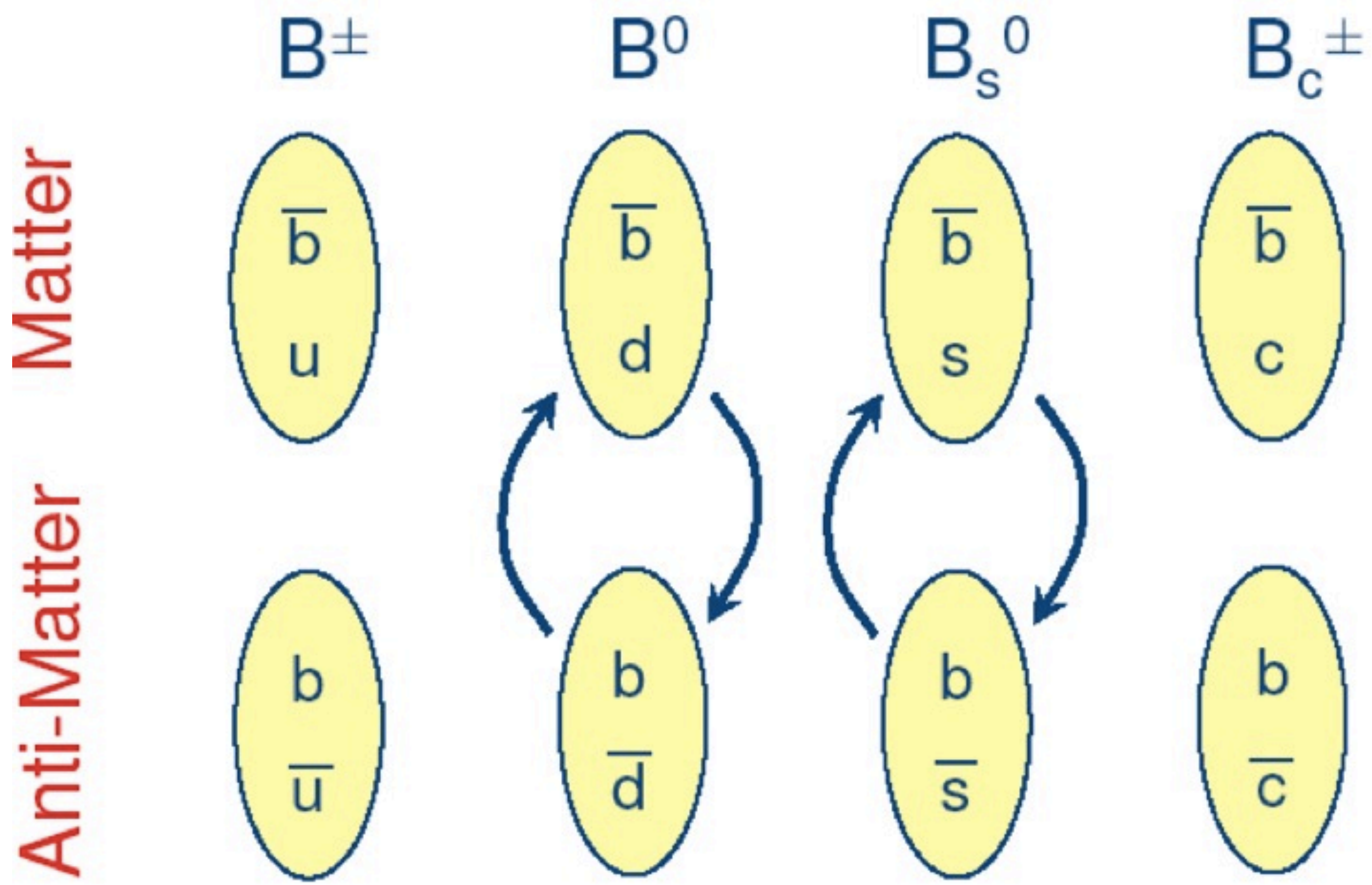
Exercise: show that CKM unitarity yields six triangles
(note: the bs triangle is much squeezed wrt to the bd one, with small area; a large $\beta_{(bs)}$ angle would indicate BSM contributions)

constraining the unitarity triangle

- is the CKM matrix unitary (as expected in the SM)?
  - 4th generation of quarks? New forces? E.g. SUSY?
- over-constrain the UT: measure each side and each angle
  - do all measurements cross at one single point?

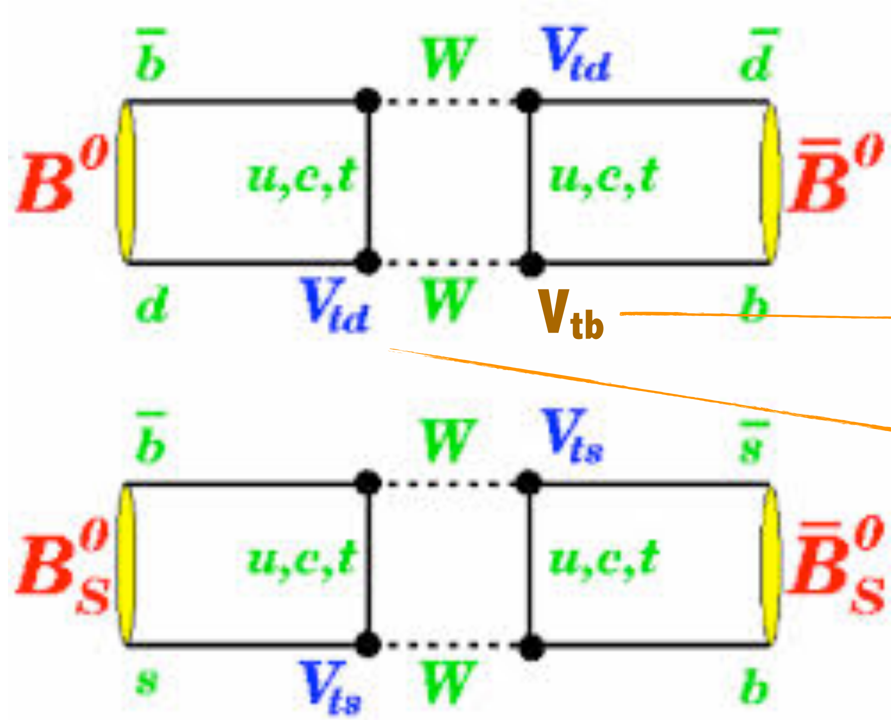


example: B meson mixing



➡ **neutral B mesons undergo spontaneous flavor oscillations between particle and antiparticle!**

example: B meson mixing



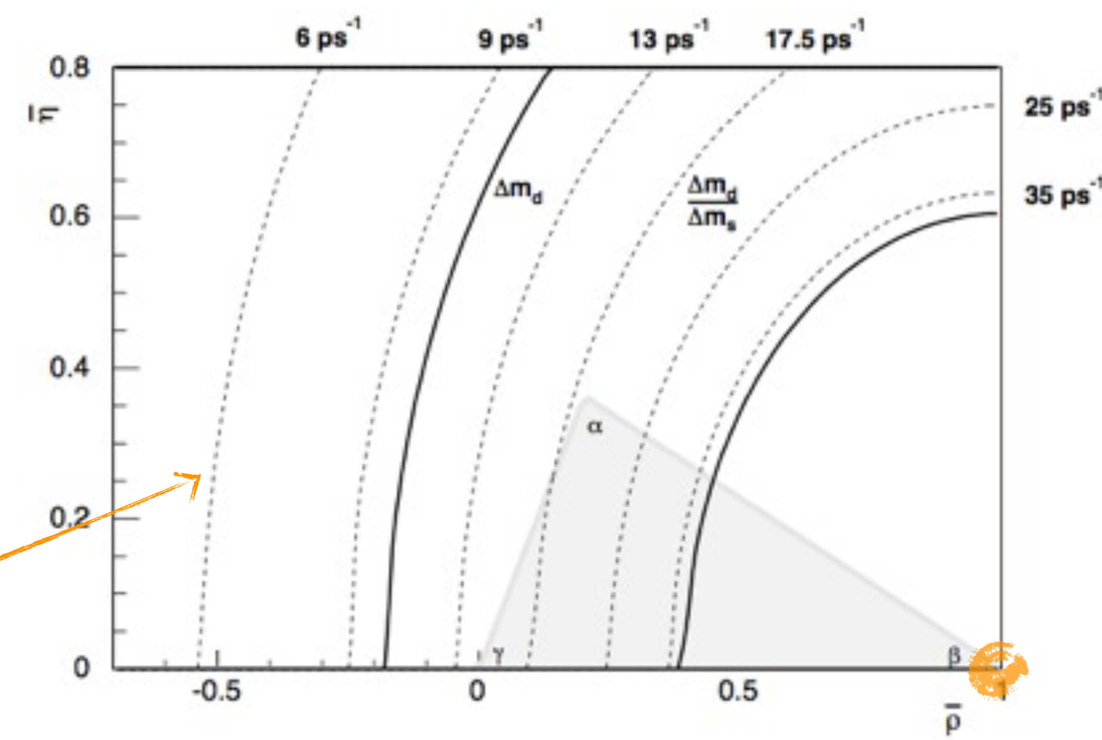
- the mixing process (and oscillation frequency, Δm_q) is proportional to the involved CKM matrix elements

$$\Delta m_q = C_q \left| V_{tb}^* V_{tq} \right|^2 , \qquad (q = d, s)$$

$$\frac{\Delta m_d}{\Delta m_s} = \frac{C_d}{C_s} \frac{|V_{td}|^2}{|V_{ts}|^2} = \frac{m_{B^0}}{m_{B_s}} \xi_\Delta^{-2} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

$$\frac{\Delta m_s}{\Delta m_d} = \xi_\Delta^2 \frac{m_{B_s}}{m_{B^0}} \left(\frac{1 - \frac{1}{2}\lambda^2}{\lambda} \right)^2 \frac{1}{(1-\bar{\rho})^2 + \bar{\eta}^2}$$

$$(1-\bar{\rho})^2 + \bar{\eta}^2 = c$$



- i.e., the ratio of B_d and B_s oscillation frequencies yields a circle centered at the point (ρ=1, η=0)

➡ a measured value of Δm_s away from ~17.5ps^{-1} would have been incompatible with the SM

UT fit

$$(1-\bar\rho)^2 + \bar\eta^2 = c$$

$$c = \frac{\Delta m_d}{\Delta m_s}\,\xi_\Delta^2\,\frac{m_{B_s}}{m_{B^0}}\left(\frac{1-\frac{1}{2}\lambda^2}{\lambda}\right)^2$$

$\lambda = 0.224 \pm 0.012$

$\xi = 1.210\,^{+0.047}_{-0.035}$ from lattice QCD (hep/lat-0510113)

- if c would be exactly known, the constraint would indeed be a circle

$$f(\bar\rho,\bar\eta|c) = \delta((1-\bar\rho)^2 + \bar\eta^2 - c)$$

- but... there are uncertainties, both theoretical and experimental

$$\Delta m_d = (51.0 \pm 0.4) \times 10^{10}\ \hbar\ s^{-1}$$
$$\Delta m_s = (17.69 \pm 0.08) \times 10^{12}\ \hbar\ s^{-1}$$

(PDG'14)

Exercise: which factor limits the CKM-constraining power of B mixing; may it be constrained experimentally

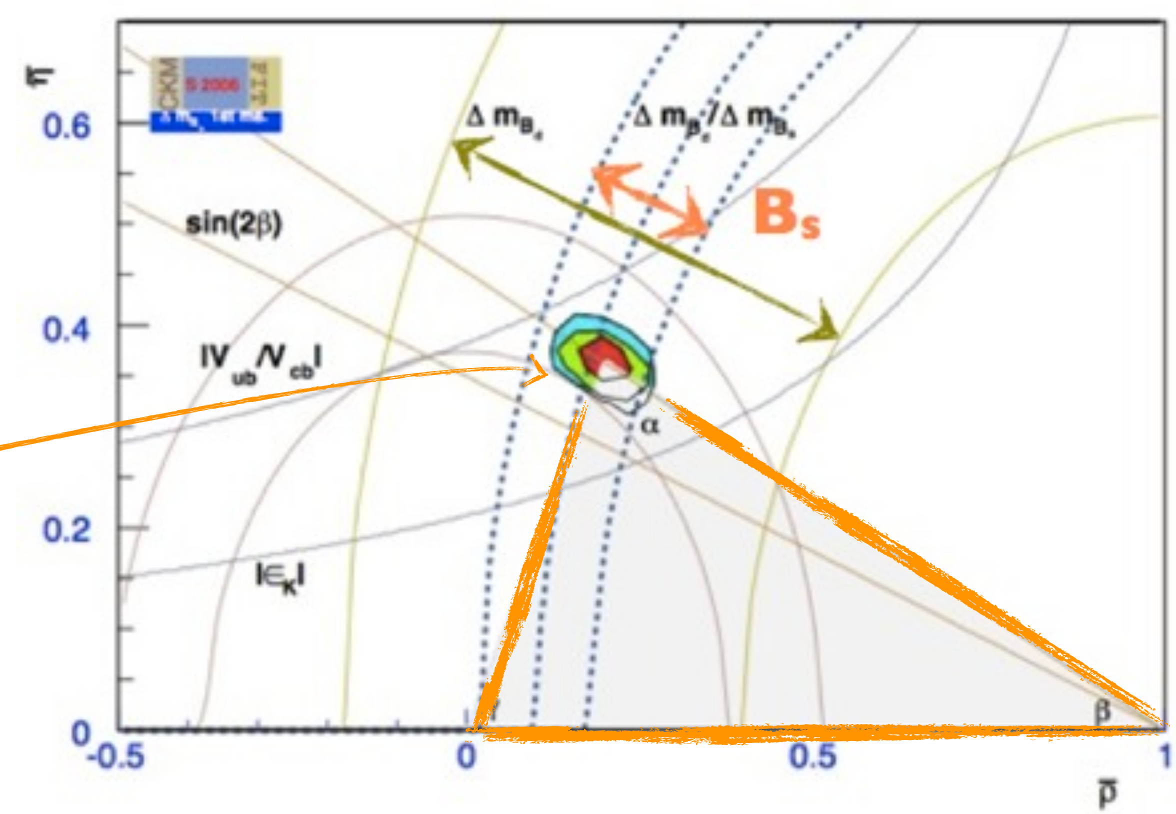
- thus c is described by a probability density function (PDF): f(c)
- upon employing Bayes' theorem

$$\mathcal{L}(\bar\rho,\bar\eta,\mathbf{c},\mathbf{x}|\hat{\mathbf{c}}) \propto f(\hat{\mathbf{c}}|\bar\rho,\bar\eta,\mathbf{c},\mathbf{x})\cdot f(\mathbf{c},\mathbf{x},\bar\rho,\bar\eta)$$

- we obtain the PDF for ρ,η as

$$\mathcal{L}(\bar\rho,\bar\eta,\mathbf{x}) \propto \prod_{j=1,M} f(\hat c_j|c_j(\bar\rho,\bar\eta,\mathbf{x})) \times \prod_{i=1,N} f_i(x_i)$$

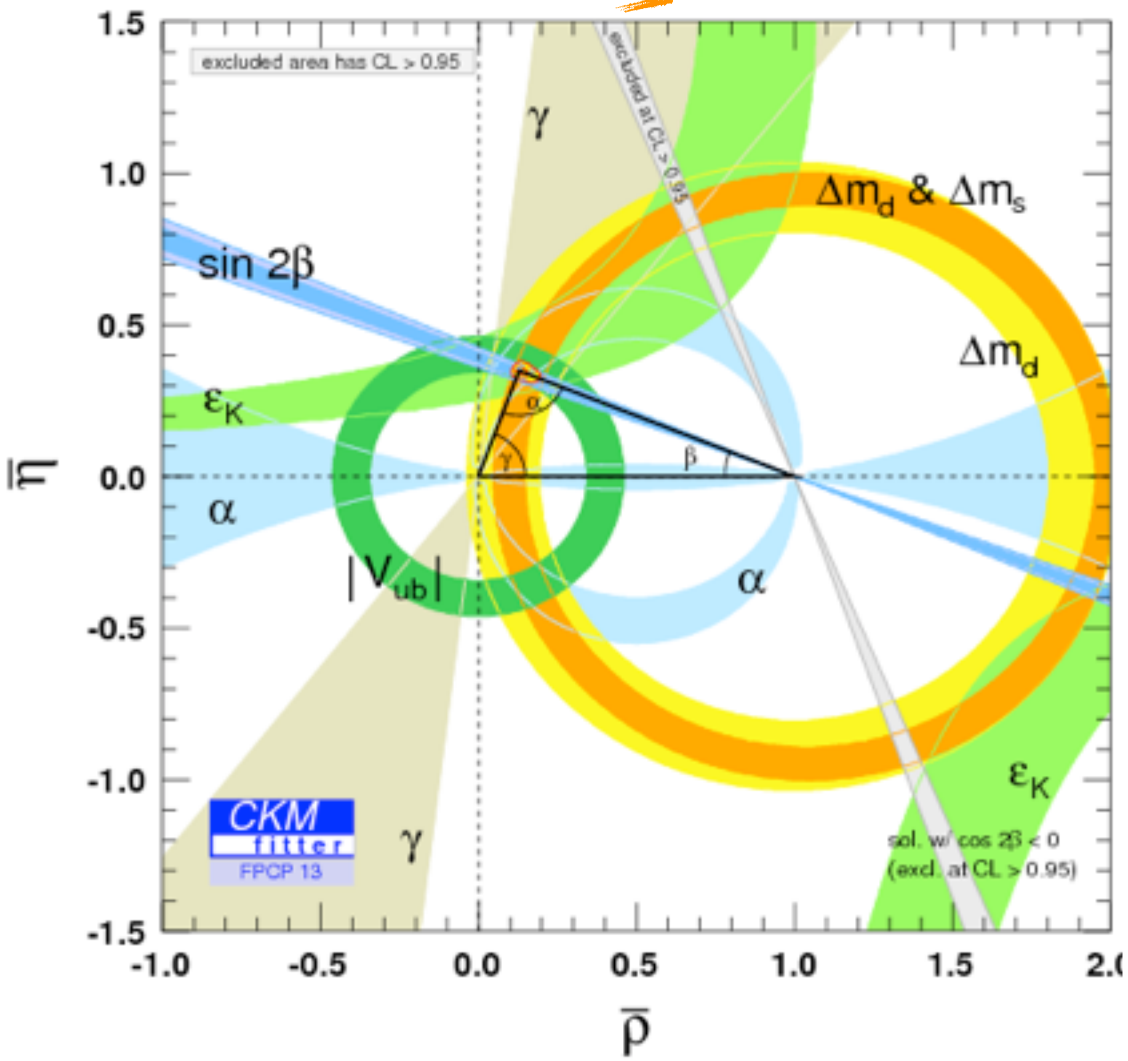
posterior PDF   constraints   prior PDF

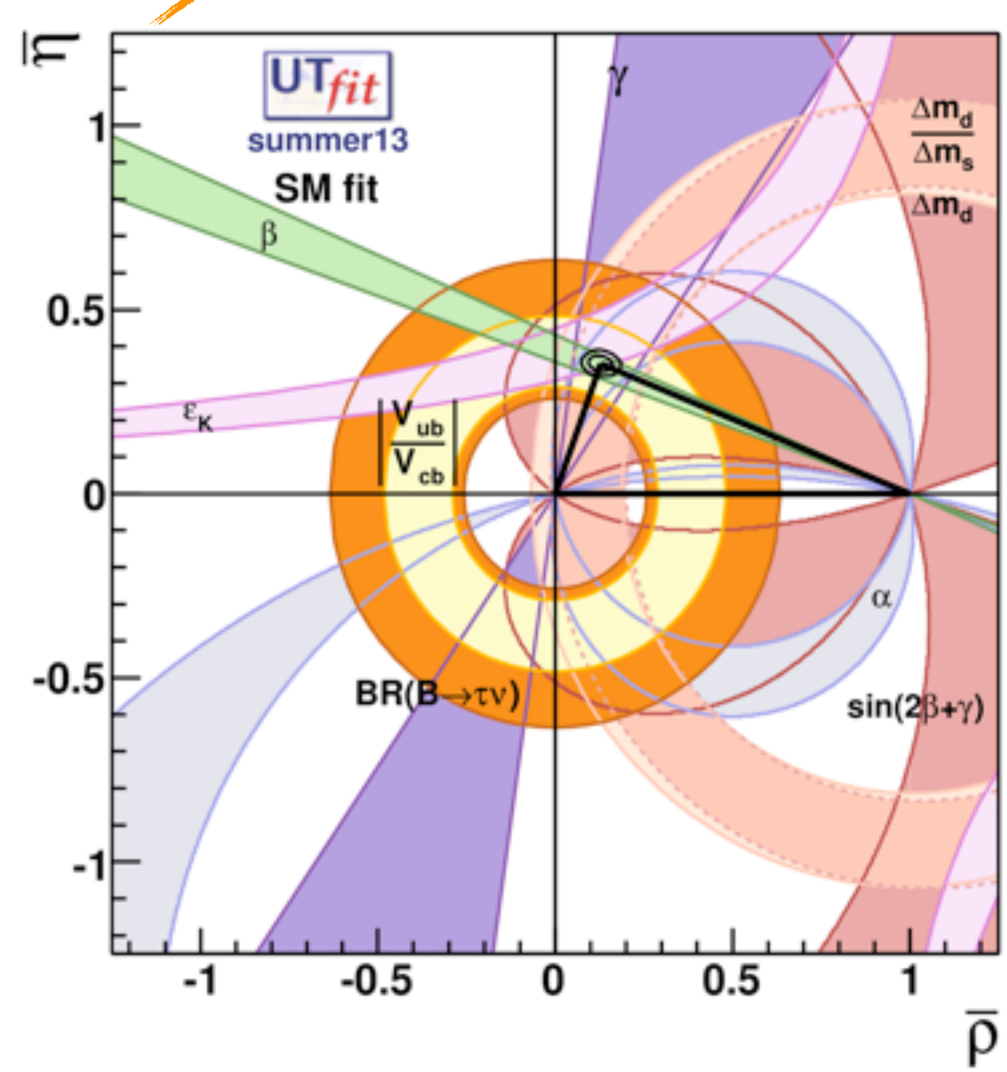


- integration requires use of numerical and statistical sampling techniques, e.g. Monte Carlo

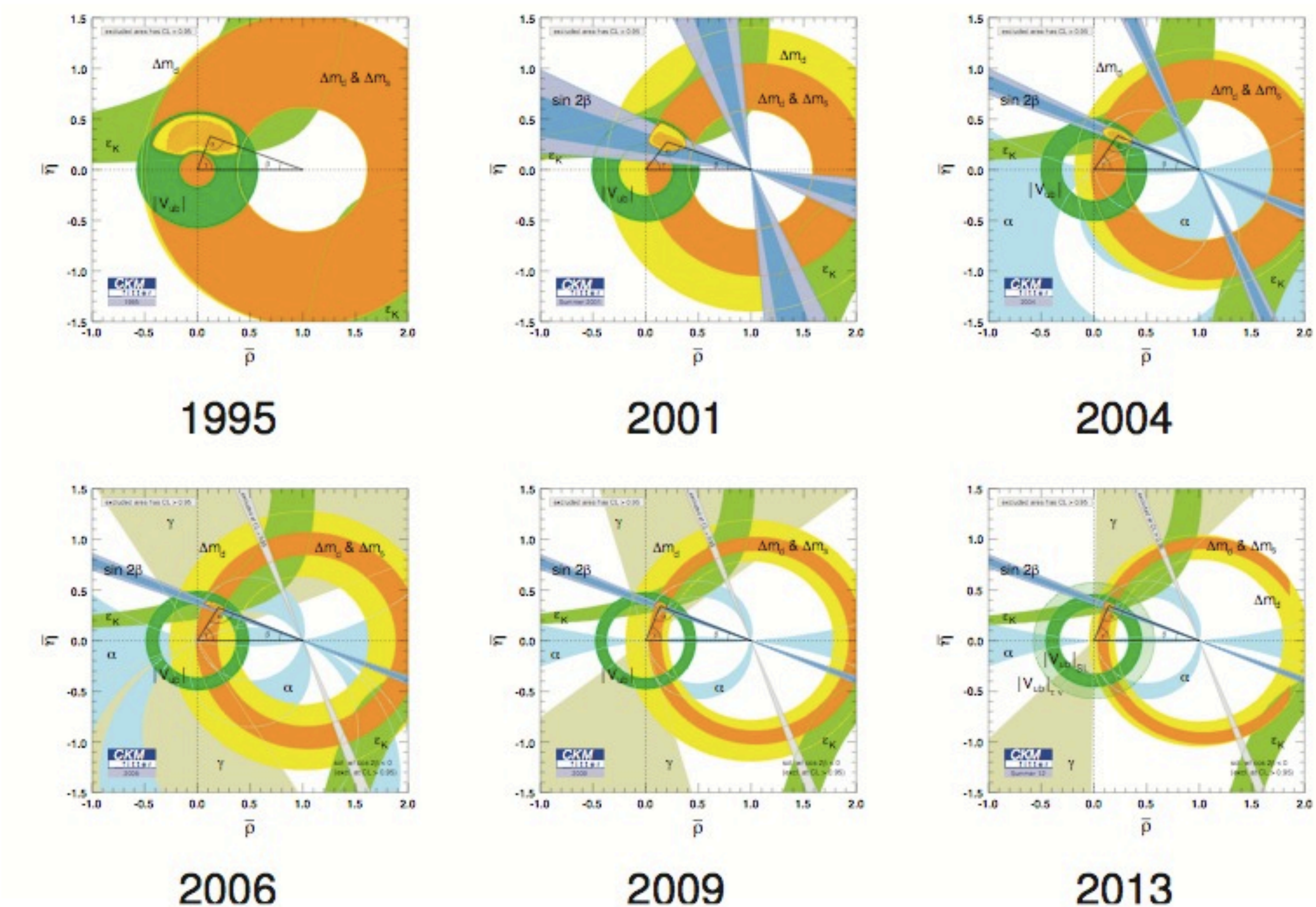
UT fit

- as seen, experimental and theoretical inputs with corresponding uncertainties are combined in global inference frameworks
  - imposing SM relations -- or testing alternative BSM flavor scenarios
  - using frequentist or Bayesian statistical fit approaches, e.g.:



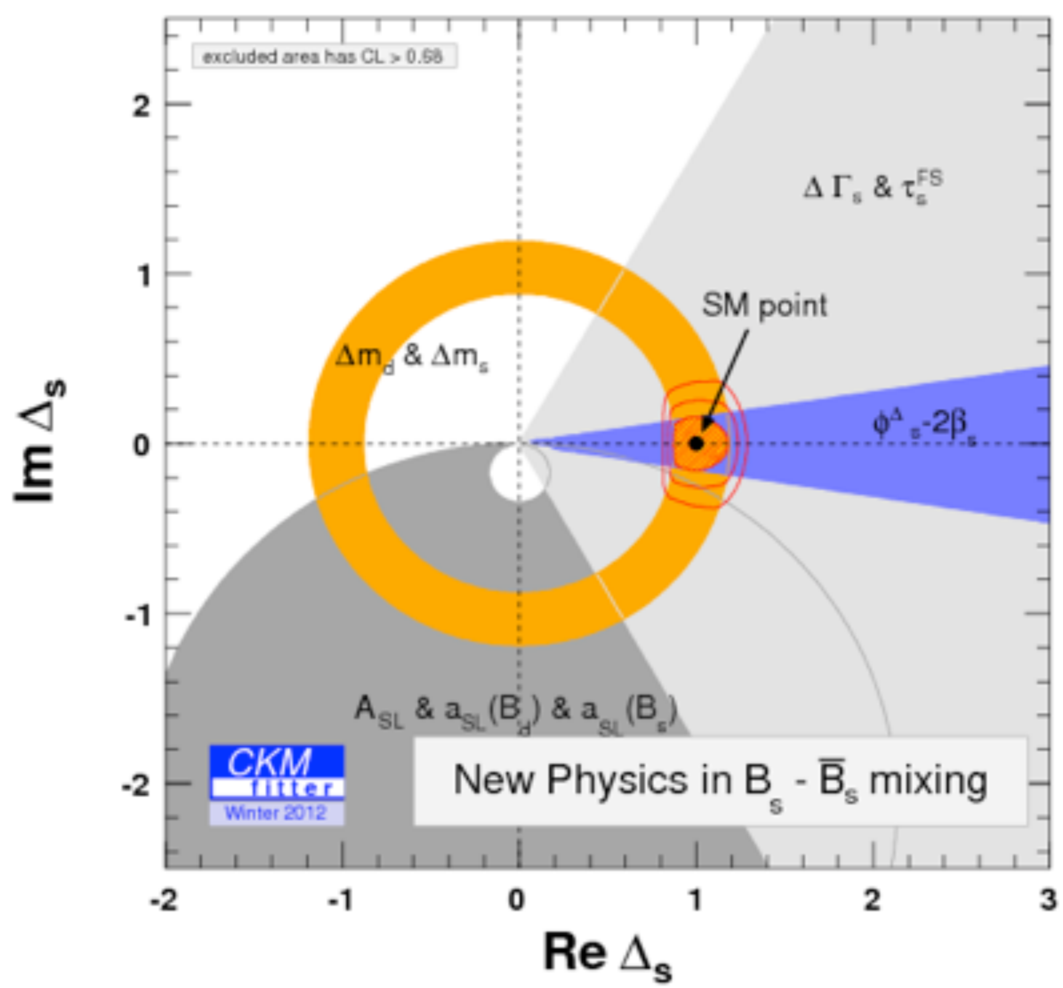


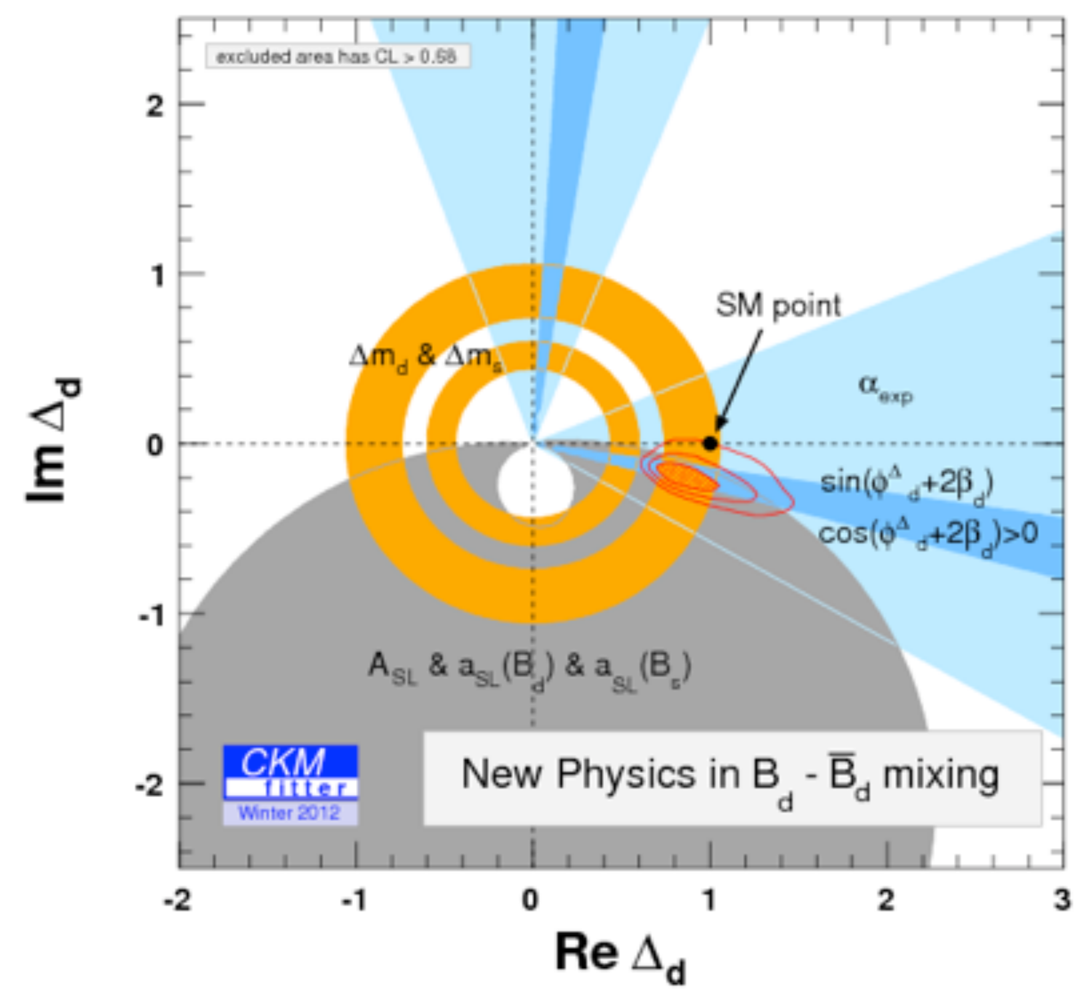
UT fit evolution over 20 years



constraining NP

- allowing for New Physics contributions, via generic parameterizations
- e.g. NP contribution to off-diagonal B mass mixing matrix M_{12} [see mixing section]
  - $M_{12}^{SM,q} = M_{12}^{SM,q} . \ \Delta_q$, with $\Delta_q = |\Delta_q|.\exp(i\Phi^{\Delta q})$ and q=s,d
  - SM point corresponds to: $\Delta_s=1=\Delta_d$
  - NP phases, Φ^{Δ}, shift CP phases from mixing-induced CP asymmetries
  - $2\beta_s \mapsto 2\beta_s - \Phi^{\Delta s}$ ($B_s \rightarrow J/\psi\varphi$) and $2\beta_d \mapsto 2\beta_d + \Phi^{\Delta d}$ ($B_d \rightarrow J/\psi K$)

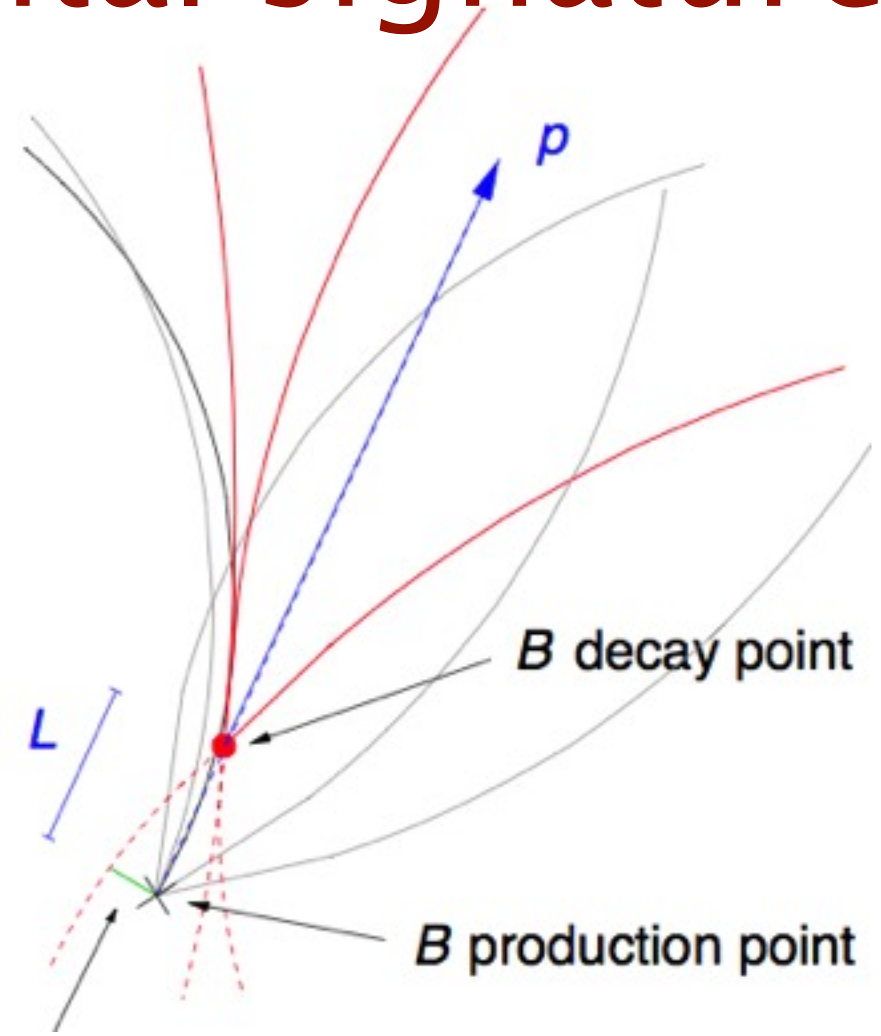




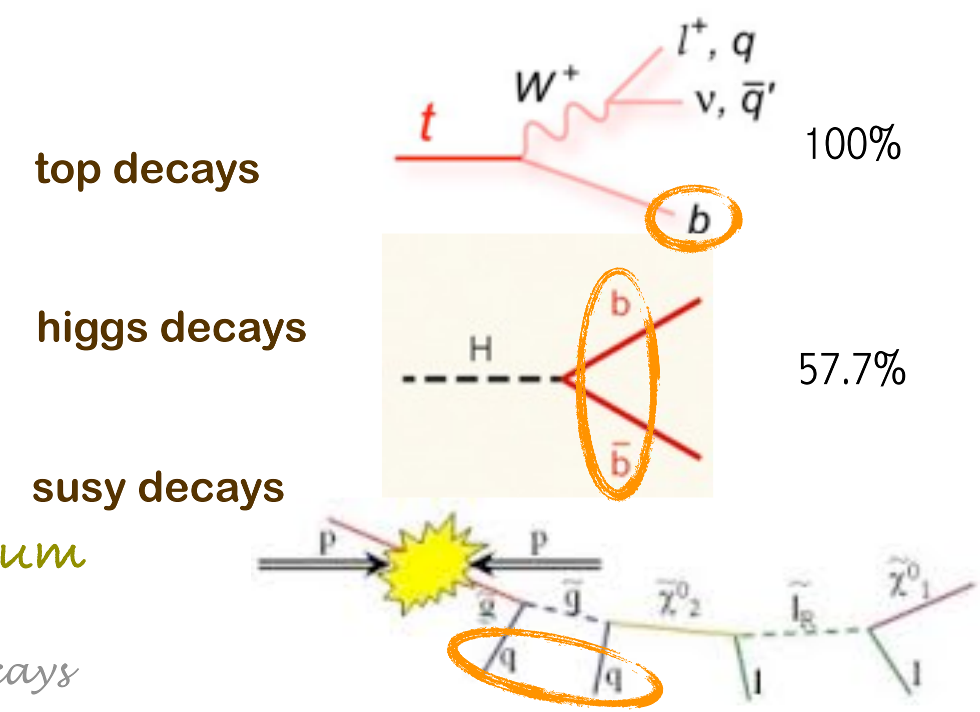
detection

a distinctive experimental signature

- bottom and charm hadrons live longer than the other unstable particles
  - $\tau(D) \sim 0.5$-1ps, $\tau(B) \sim 1.5$ ps
  - they travel macroscopic (i.e. measurable) distances in the detector before decaying, producing a displaced vertex topology



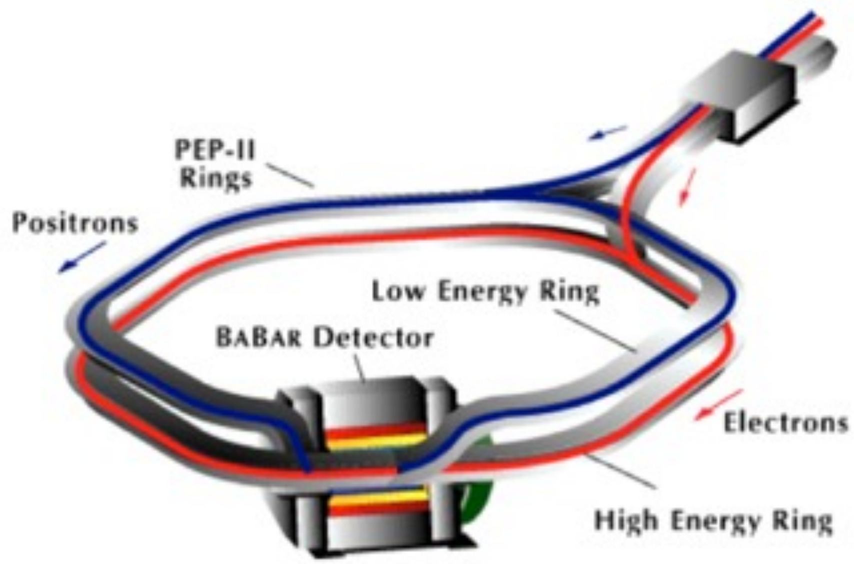
- extensively explored
  - in heavy-flavor analyses themselves
  - b-jet tagging: discriminate b-jets from the lighter quark jets
  - in SM measurements and BSM searches: to detect signal HF components (e.g. $t \to Wb$, $H \to b\underline{b}$,...) or control HF backgrounds (e.g. $b\underline{b}$ dijets,...)



Exercise: determine how far a B^0 meson with typical momentum p_{B0}=100GeV is expected to fly at the center of a LHC detector

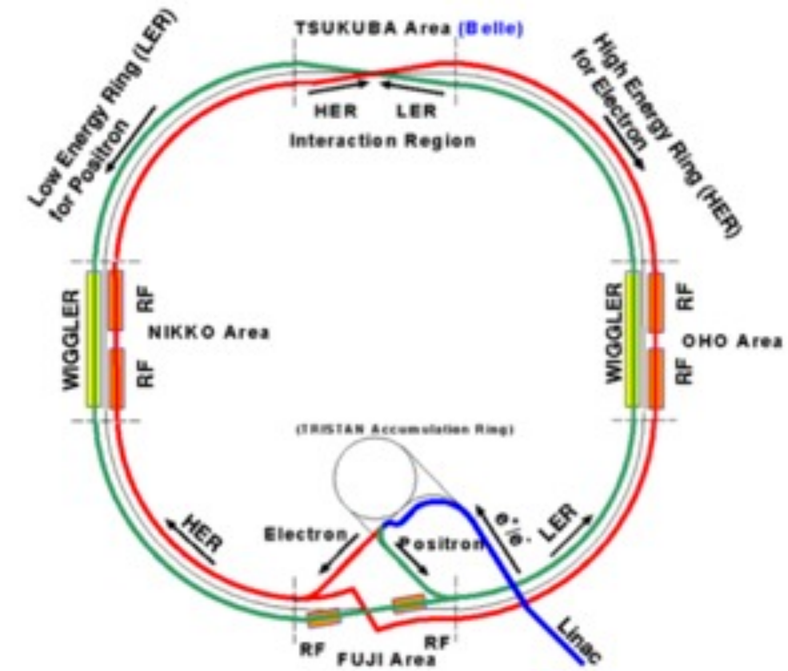
heavy flavor "factories"

PEP II at SLAC (US)
9 GeV e^- on 3.1 GeV e^+

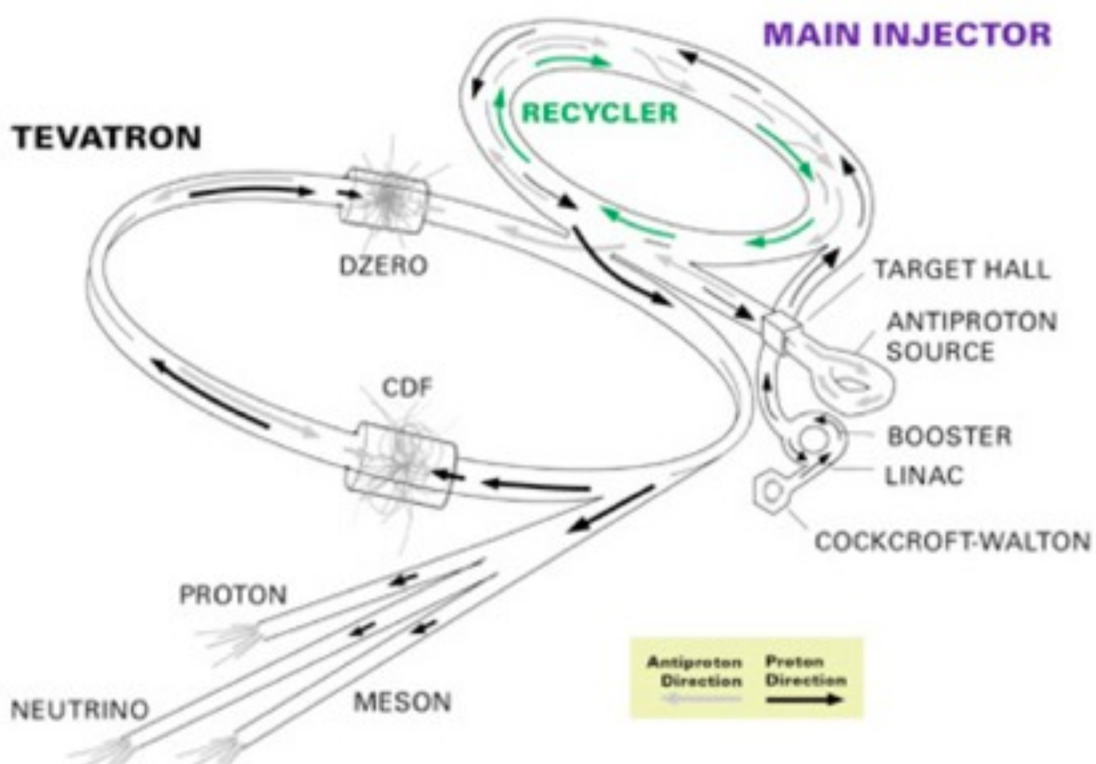


Asymmetric e^+e^- colliders
at $\Upsilon(4S)$ resonance (10.58GeV)
aka "B factories"

KEKB at KEK (Japan)
8 GeV e^- on 3.5 GeV e^+

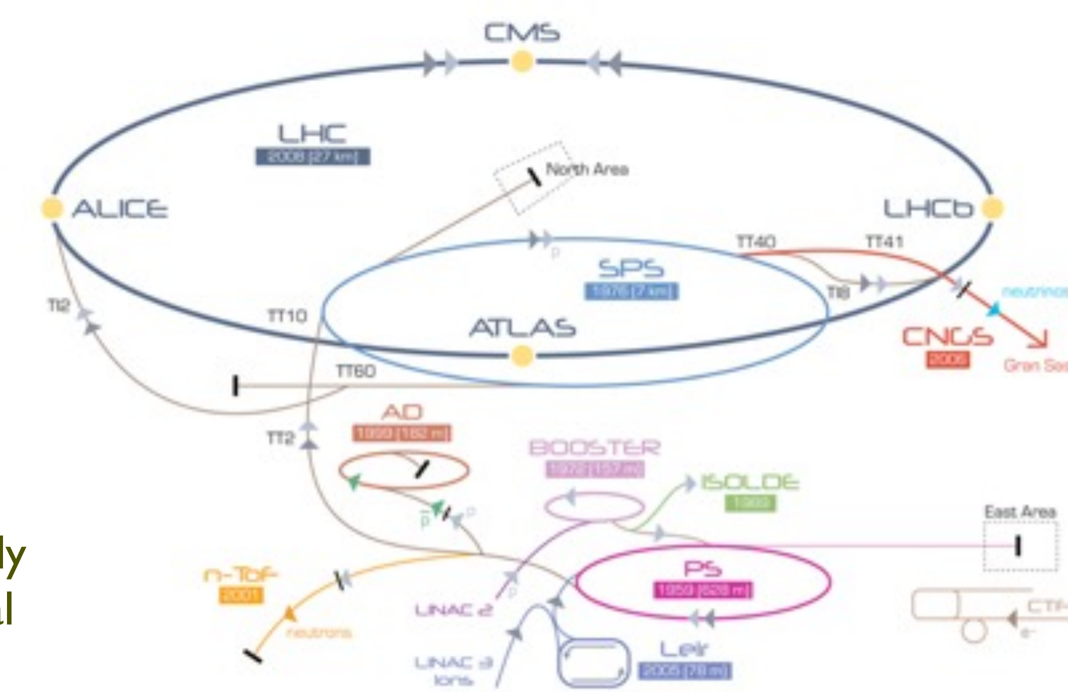


Tevatron at FNAL (US)
$p\bar{p}$ at 2 TeV



General purpose
hadron colliders

LHC at CERN
pp at 14 TeV



note: currently only
LHC is operational

colliders (comparison)

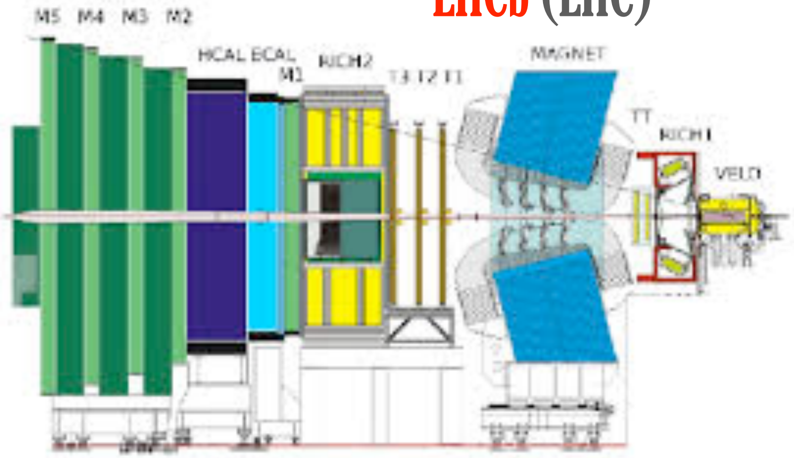
	$e^+e^- \to \Upsilon(4s) \to B\bar{B}$ PEP-II, KEK-B	$p\bar{p} \to b\bar{b}X$ $(\sqrt{s}=2\text{ TeV})$ TeVatron	$pp \to b\bar{b}X$ $(\sqrt{s}=14\text{ TeV})$ LHC
prod	1 nb	~100 μb	~500 μb
typ. $b\bar{b}$ rate	10 Hz	~100 kHz	~500 kHz
purity	~1/4	$\sigma_{b\bar{b}}/\sigma_{inel} \approx 0.2\%$	$\sigma_{b\bar{b}}/\sigma_{inel} \approx 0.6\%$
pile-up	0	1.7	0.5-20
B content	$B^+B^-(50\%), B^0\bar{B}^0(50\%)$	$B^+(40\%), B^0(40\%), B_s(10\%), B_c(<1\%)$, b − baryons(10%)	
B boost	small, βγ~0.56	large, decay vertices are displaced	
event structure	BB pair alone	many particles non-associated to $b\bar{b}$	
prod. vertex	Not reconstructed	reconstructed with many tracks	
$B^0\bar{B}^0$ mixing	coherent	incoherent→ flavour tagging dilution	

- lepton collider (at Υ resonance)
  - pros: clean events, high purity
  - cons: produces only B_u and B_d mesons
- hadron collider
  - pros: high cross sections ($O(10^3)$ larger), all b-hadron species produced
  - contra: trigger, bandwidth, dilution, pileup, ...

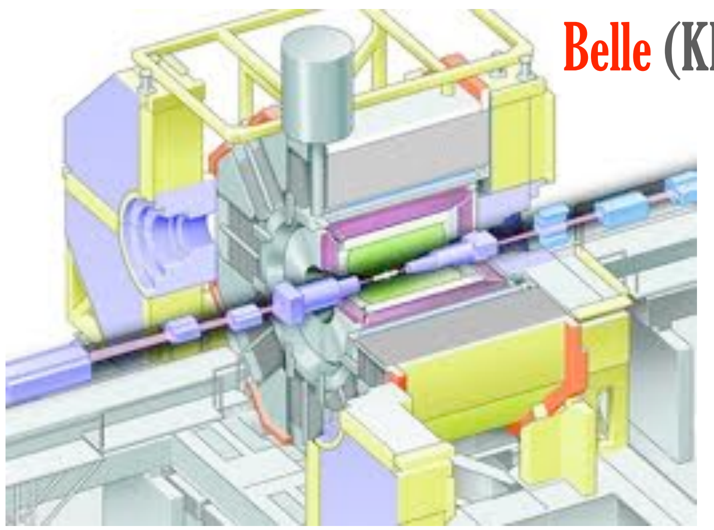
detectors

Specialized

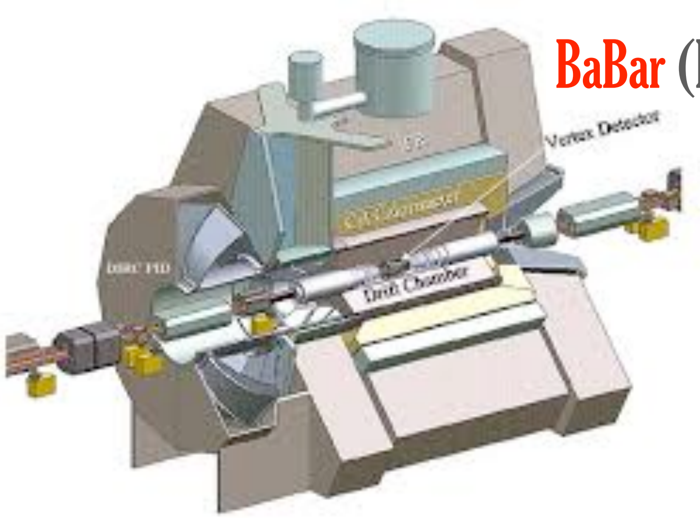
LHCb (LHC)



Belle (KEK)

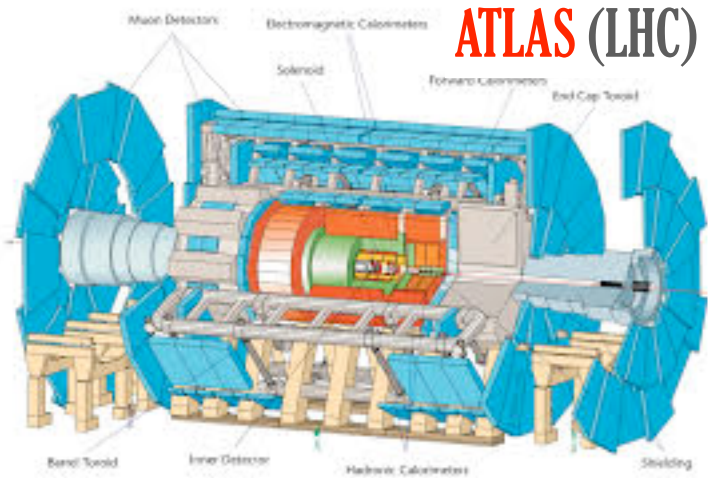


BaBar (PEPII)

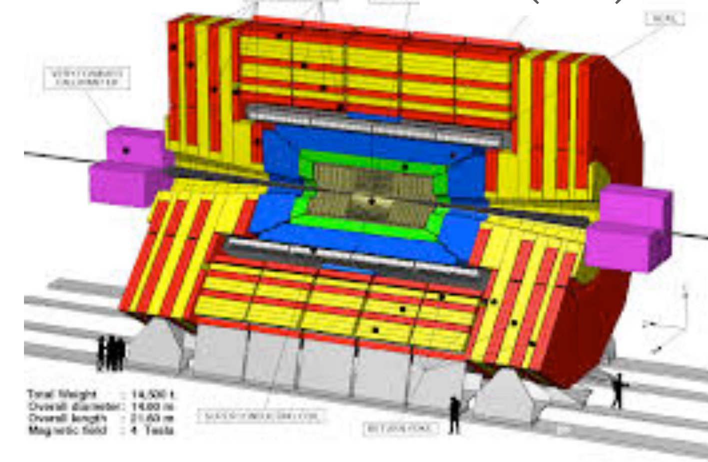


General purpose

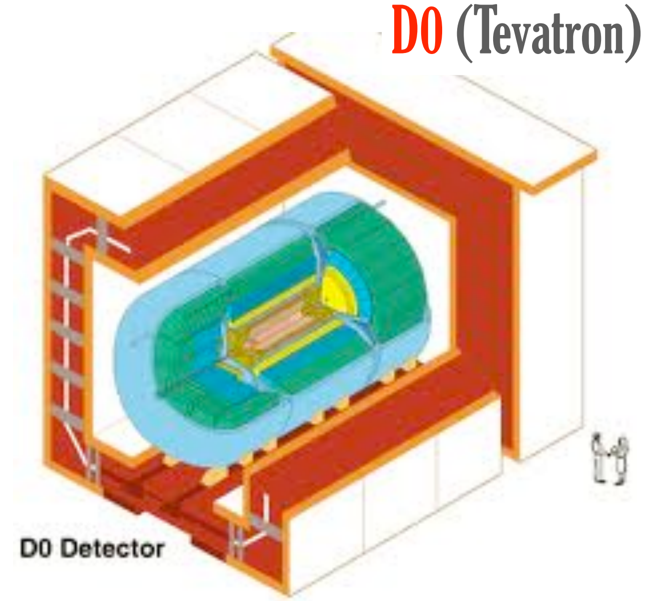
ATLAS (LHC)



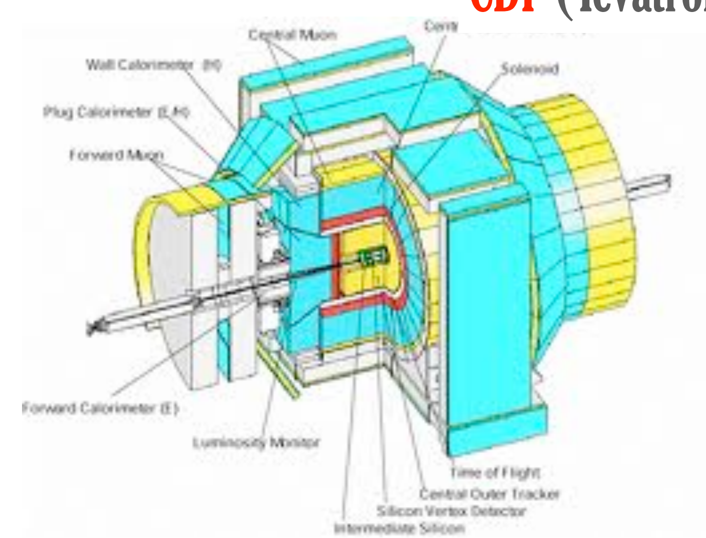
CMS (LHC)



D0 (Tevatron)

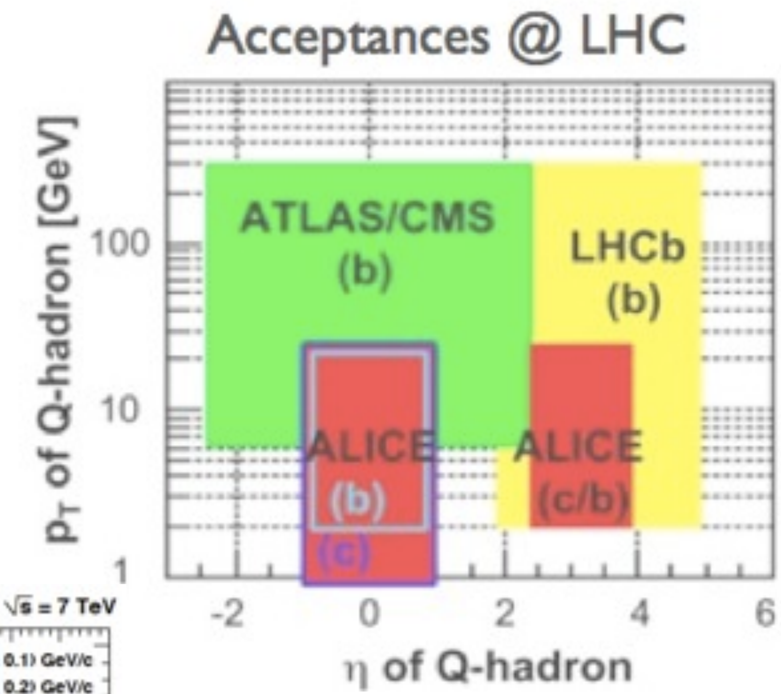


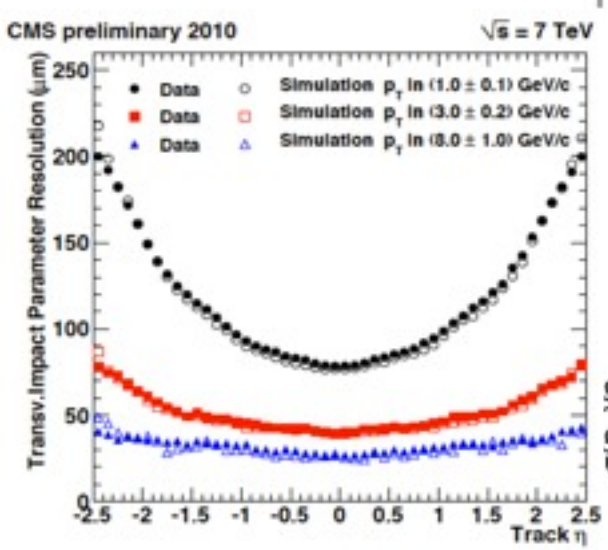
CDF (Tevatron)

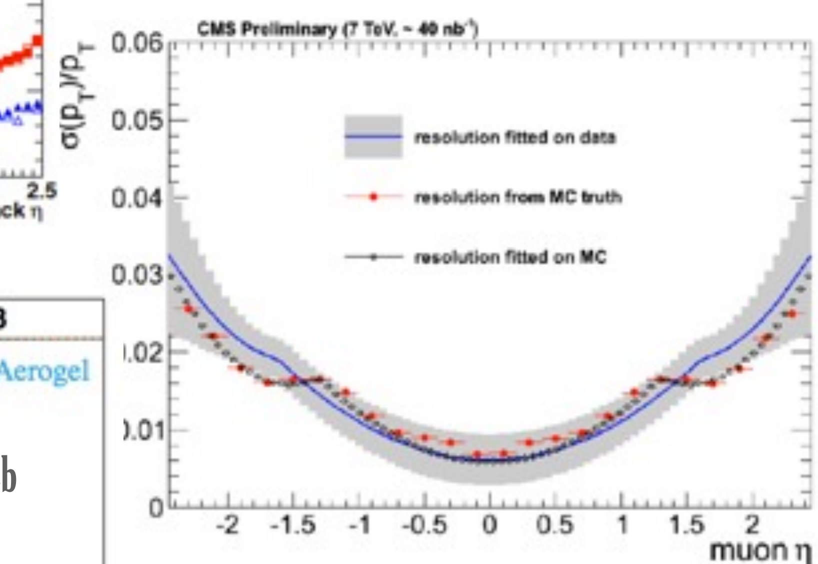


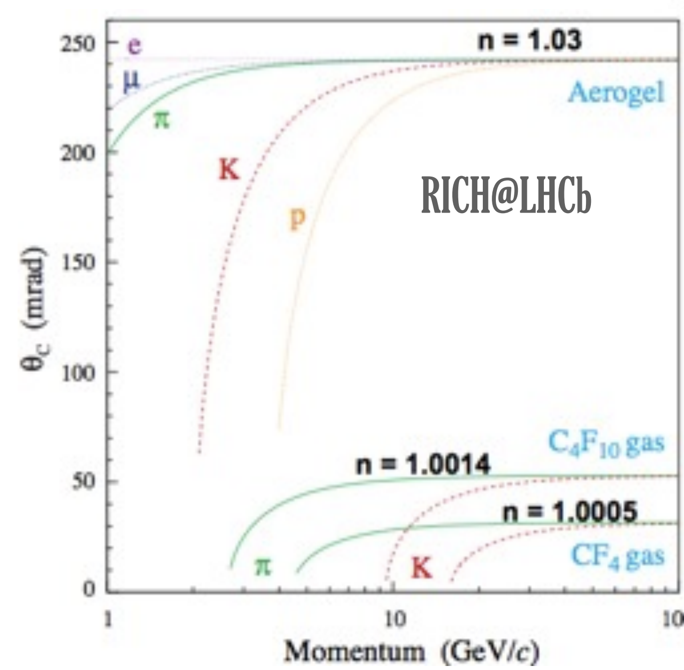
detector capability

- main requirements
  - ability to detect secondary, displaced decay vertices
    ➠ precise silicon tracker
  - ability to select displaced topologies online, in real time
    ➠ flexible trigger system
  - robust and precise event and particle reconstruction
    ➠ momentum resolution
  - particle identification: leptons (distinguish muons from kaons, with low fake rates), hadrons (separate protons from kaons from pions)

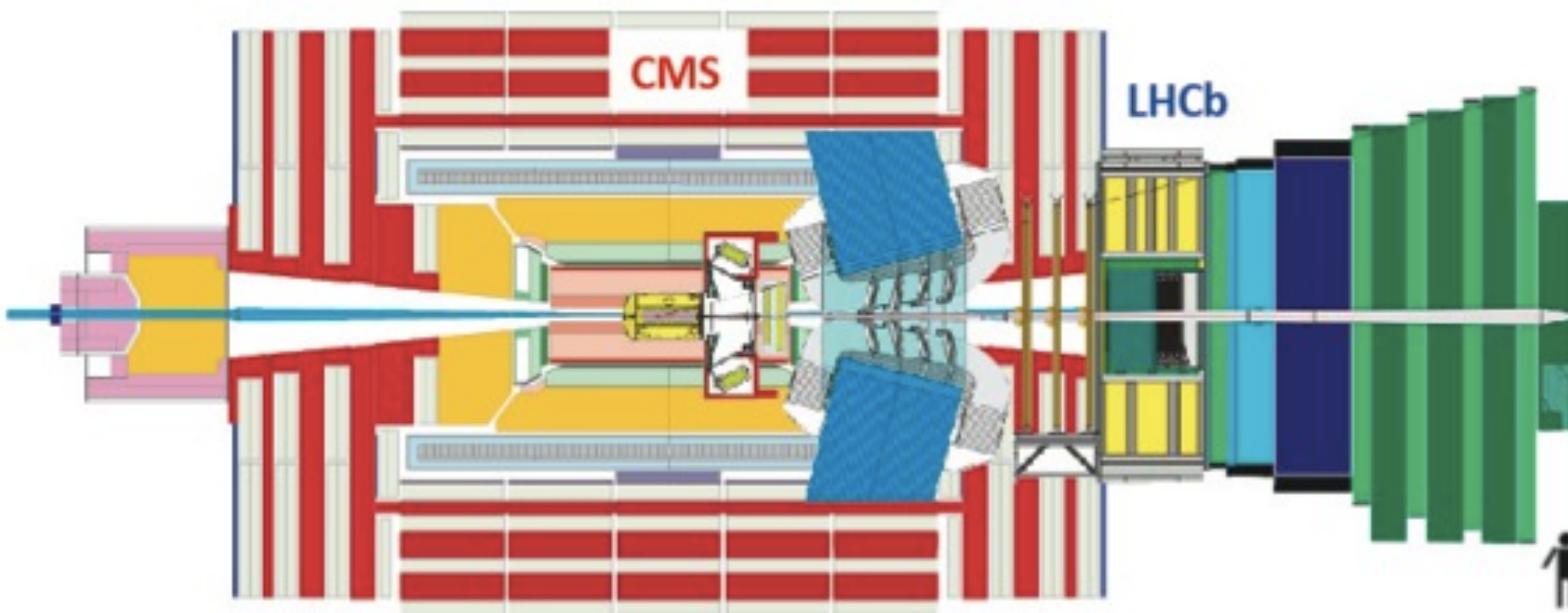






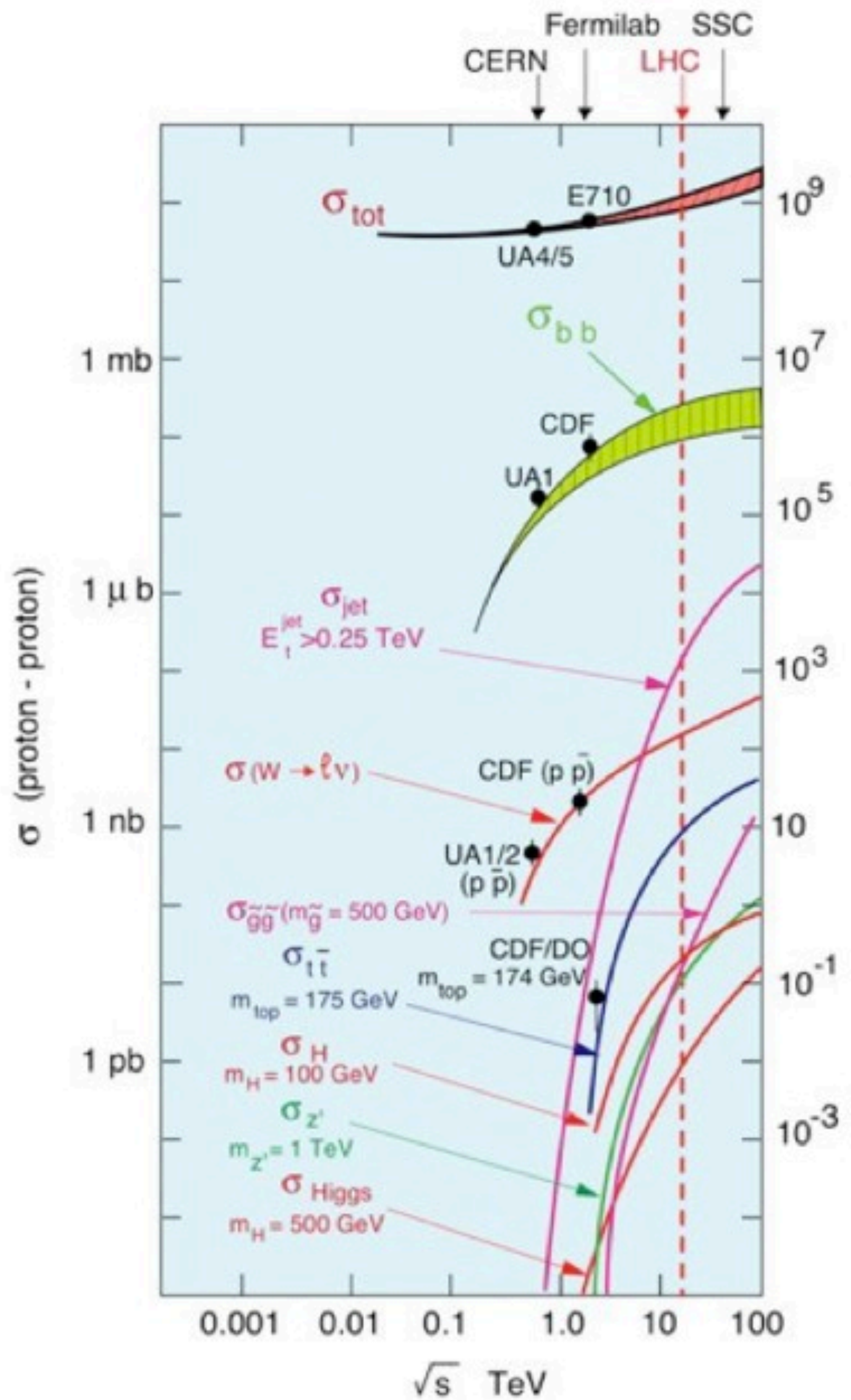


the ideal heavy flavor detector?



Disclaimer: this (combined detector layout) doesn't actually exist production

HF production

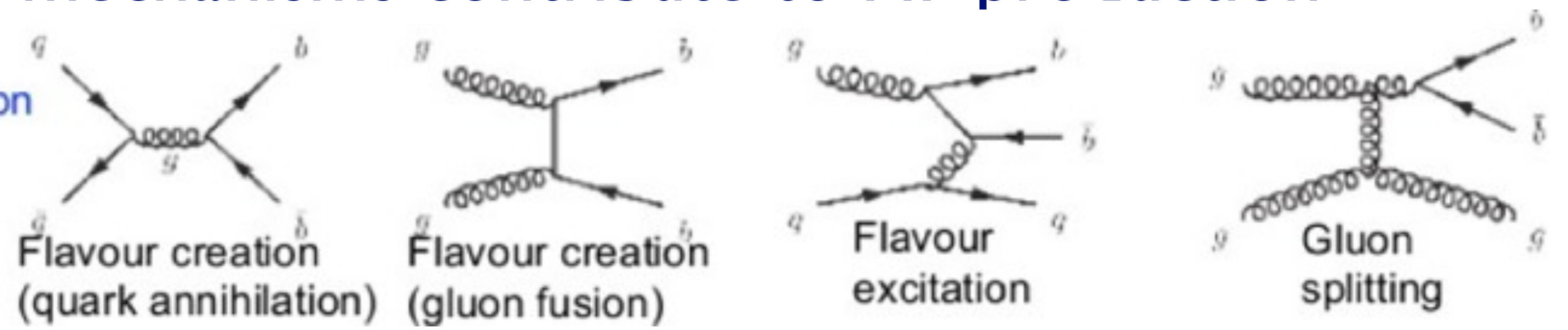


- high HF production rates at the LHC
  - very large production cross section (σ)
  - large accumulated luminosity (L)
- LHC: HF 'factory' (N=L.σ)
  - allow to perform precision measurements, as well as to search for very rare processes
- HF production is ubiquitous
  - forming backgrounds for many physics processes explored at the LHC
  - need to be thoroughly understood

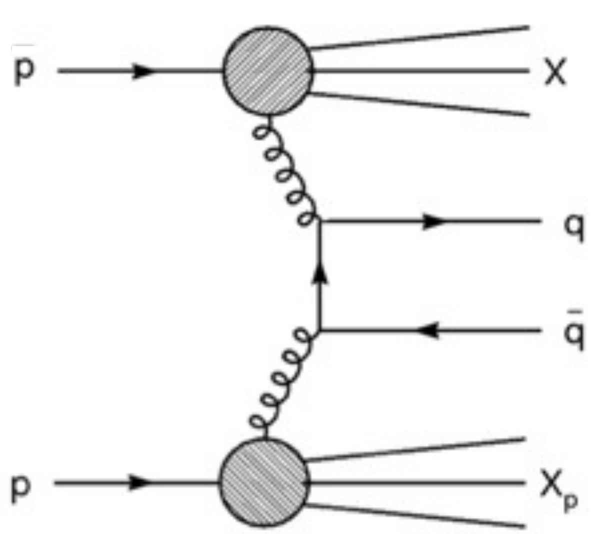
hadron production

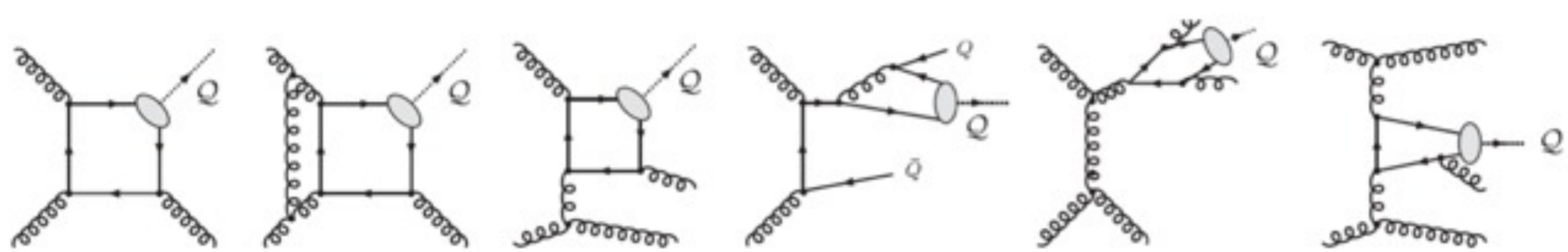
- different mechanisms contribute to HF production

bb production at hadron colliders



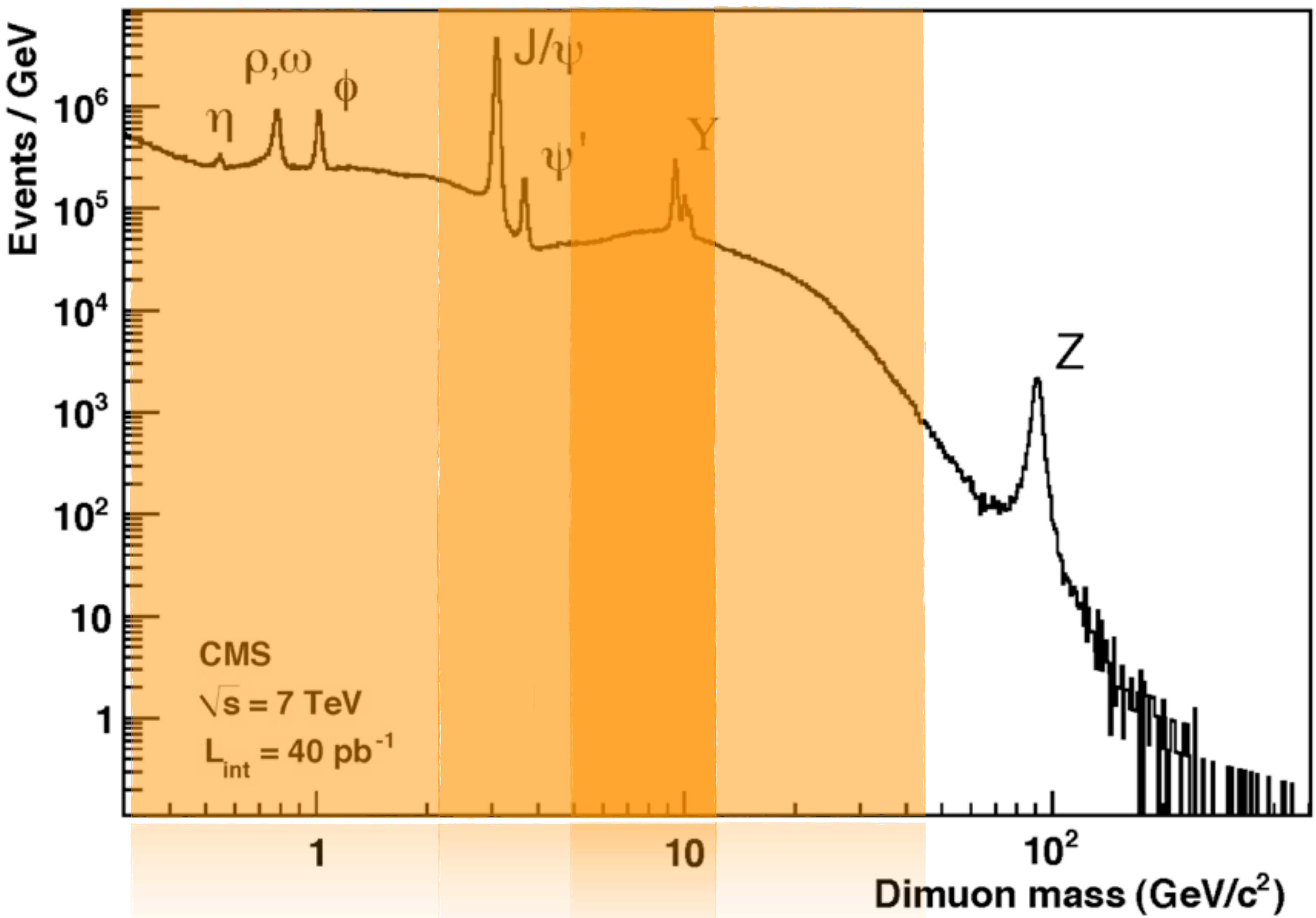
- produced quarks evolve into hadrons: known as fragmentation
  - involving short-distance/perturbative vs long-distance processes
- heavy quarkonia $Q\bar{Q}$=($b\bar{b}$, $c\bar{c}$) are an ideal laboratory in which to study the strong force and the mechanisms of hadron formation
  - non-perturbative evolution of $Q\bar{Q}$ pair into a quarkonium state
  - employ effective theories: e.g. non-relativistic QCD (NRQCD; CSM, CEM...)



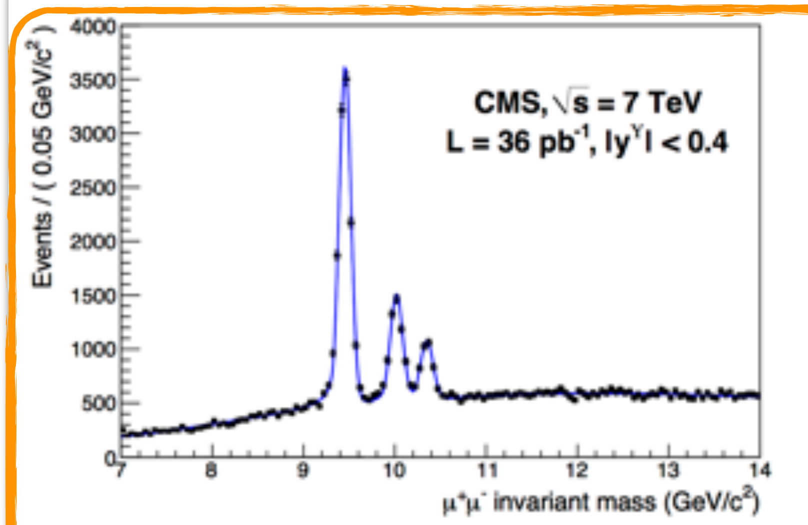


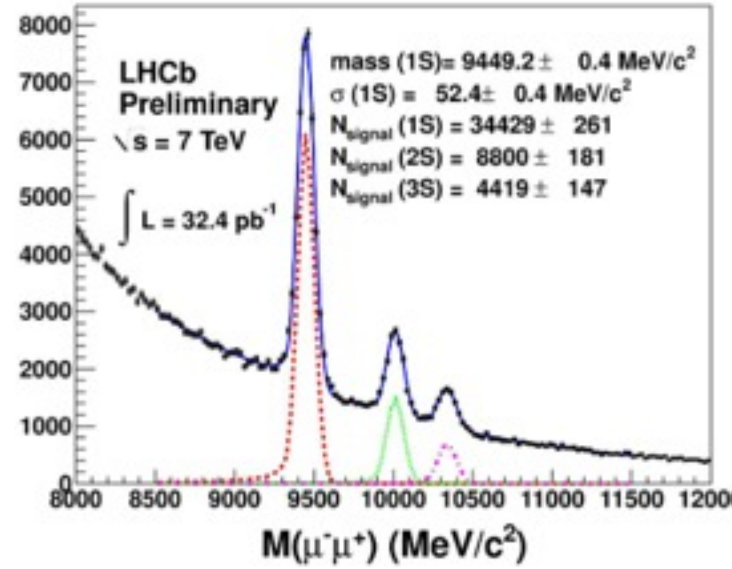
need to carry out detailed of HF production, including cross sections, polarizations, etc

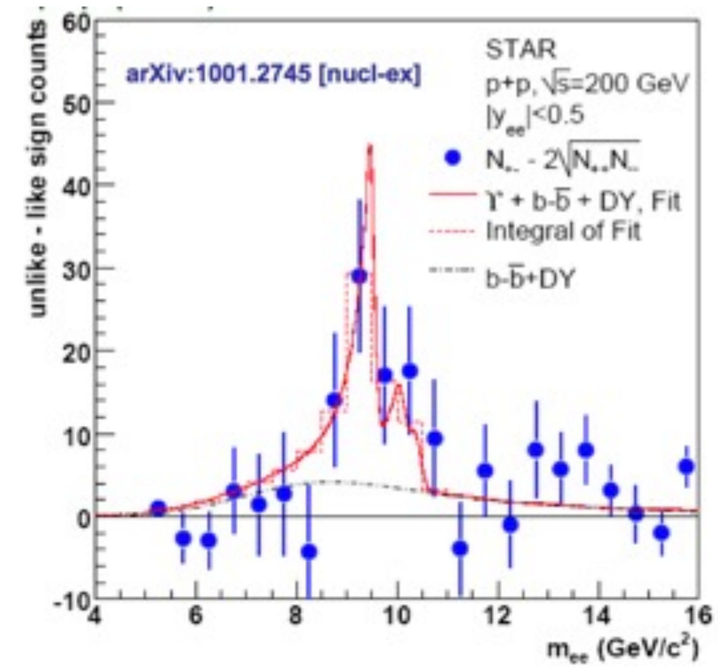
the ‘rediscovery’ of the SM plot

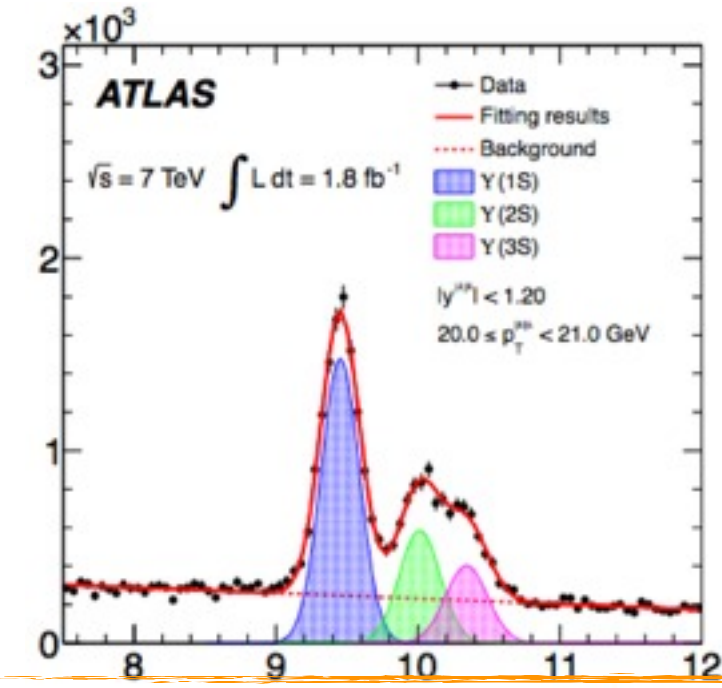


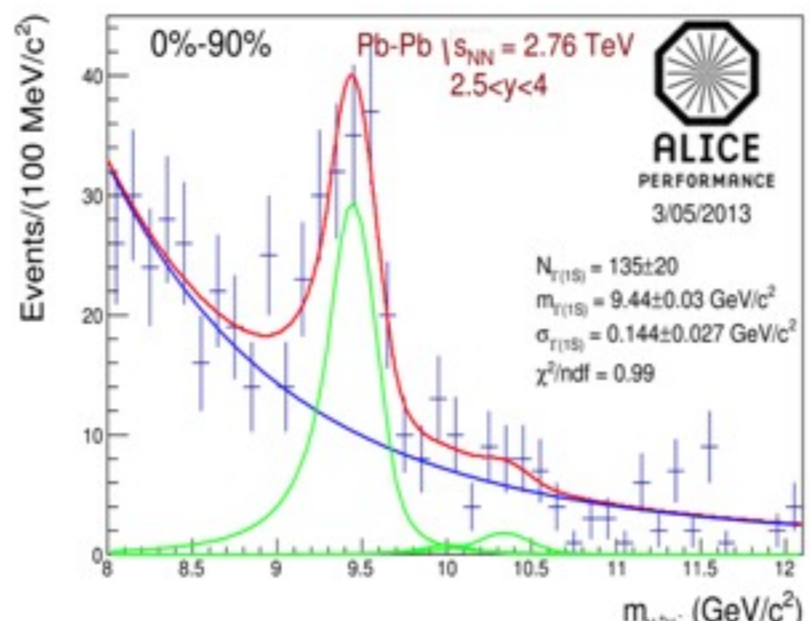
LHC

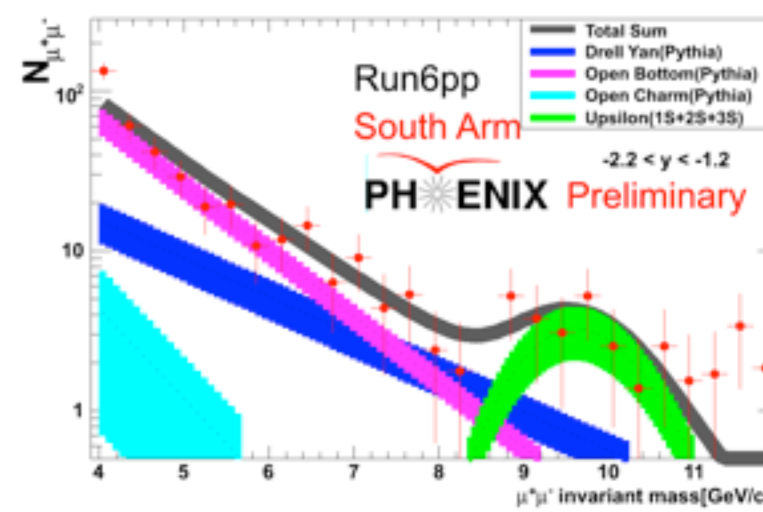

CMS, √s = 7 TeV
L = 36 pb⁻¹, |y^Υ| < 0.4
Events / (0.05 GeV/c²)
μ⁺μ⁻ invariant mass (GeV/c²)

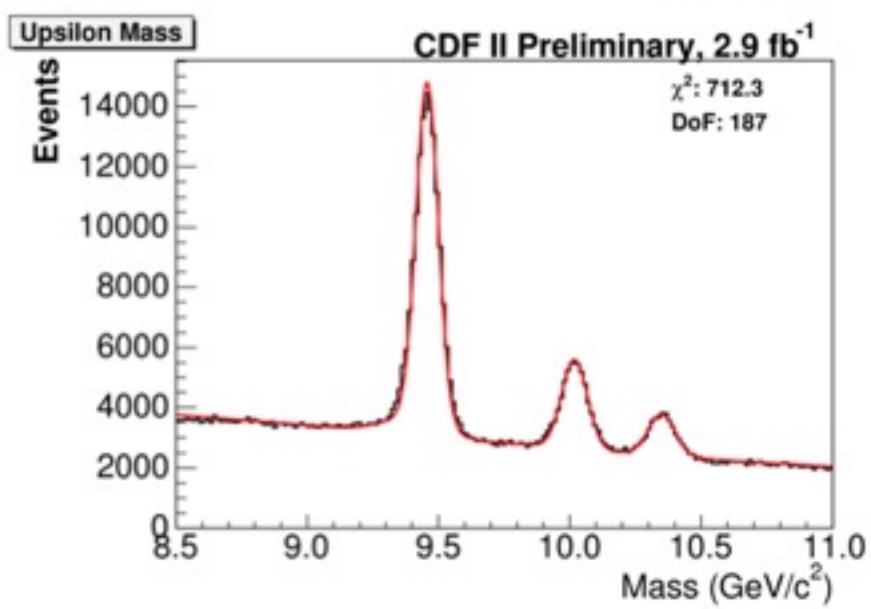

LHCb
Preliminary
√s = 7 TeV
∫ L = 32.4 pb⁻¹
mass (1S) = 9449.2 ± 0.4 MeV/c²
σ (1S) = 52.4 ± 0.4 MeV/c²
N_signal (1S) = 34429 ± 261
N_signal (2S) = 8800 ± 181
N_signal (3S) = 4419 ± 147
M(μ⁻μ⁺) (MeV/c²)

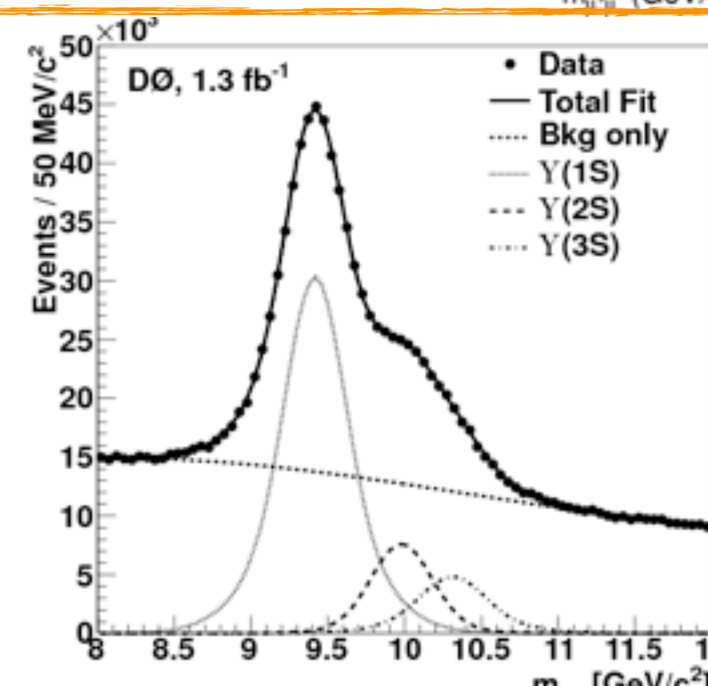

arXiv:1001.2745 [nucl-ex]
STAR
p+p, √s=200 GeV
|y_ee|<0.5
N₊₋ - 2√(N₊₊N₋₋)
Υ + b-b̄ + DY, Fit
Integral of Fit
b-b̄+DY
unlike - like sign counts
m_ee (GeV/c²)

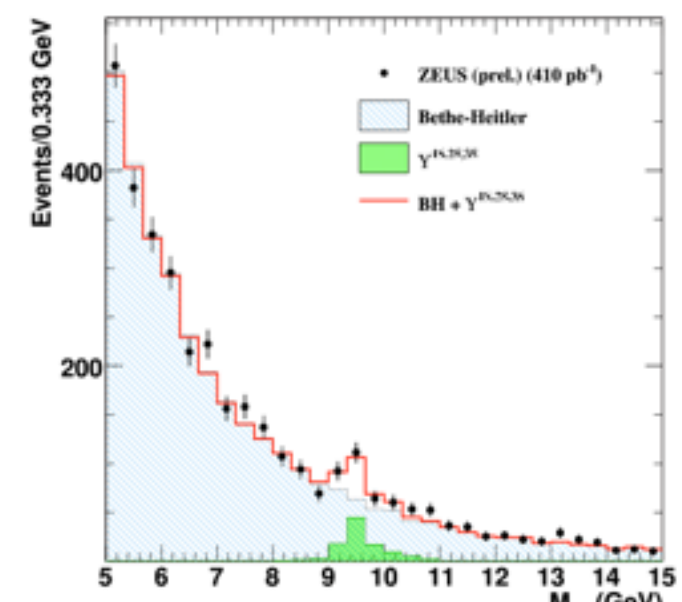

ATLAS
√s = 7 TeV ∫ L dt = 1.8 fb⁻¹
Data
Fitting results
Background
Υ(1S)
Υ(2S)
Υ(3S)
|y^μμ| < 1.20
20.0 ≤ p_T^μμ < 21.0 GeV


0%-90%
Pb-Pb √s_NN = 2.76 TeV
2.5<y<4
ALICE
PERFORMANCE
3/05/2013
N_Υ(1S) = 135±20
m_Υ(1S) = 9.44±0.03 GeV/c²
σ_Υ(1S) = 0.144±0.027 GeV/c²
χ²/ndf = 0.99
Events/(100 MeV/c²)
m_μ⁺μ⁻ (GeV/c²)


Run6pp
South Arm
PHENIX Preliminary
-2.2 < y < -1.2
Total Sum
Drell Yan(Pythia)
Open Bottom(Pythia)
Open Charm(Pythia)
Upsilon(1S+2S+3S)
μ⁺μ⁻ invariant mass[GeV/c²]

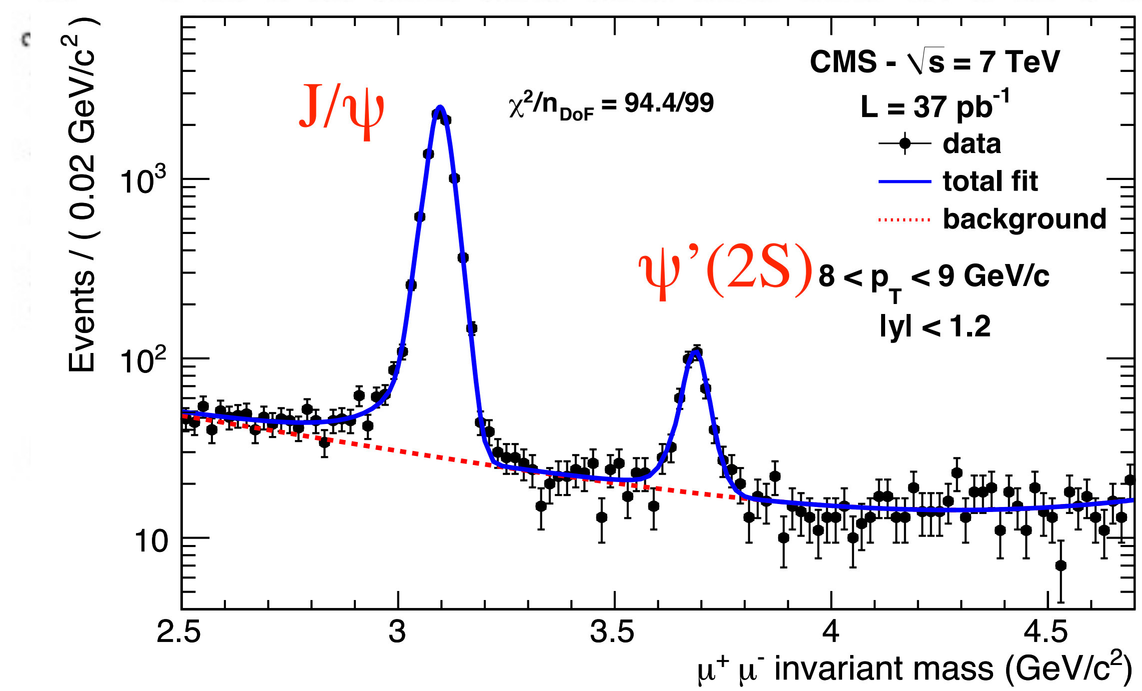

Upsilon Mass
CDF II Preliminary, 2.9 fb⁻¹
χ²: 712.3
DoF: 187
Events
Mass (GeV/c²)


DØ, 1.3 fb⁻¹
Data
Total Fit
Bkg only
Υ(1S)
Υ(2S)
Υ(3S)
Events / 50 MeV/c²
m_μμ [GeV/c²]

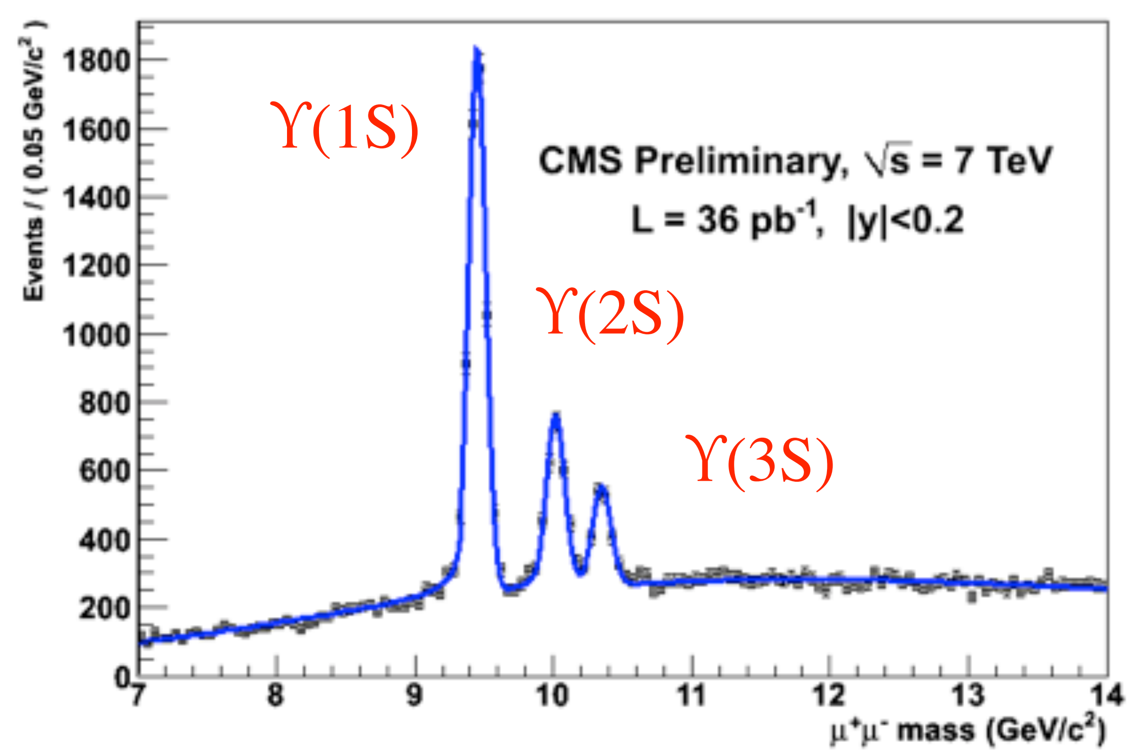

ZEUS (prel.) (410 pb⁻¹)
Bethe-Heitler
BH + Υ
Events/0.333 GeV
M_μμ (GeV)

s–wave quarkonia

charmonia ($c\bar{c}$) ⇨



bottomonia ($b\bar{b}$) ⇨

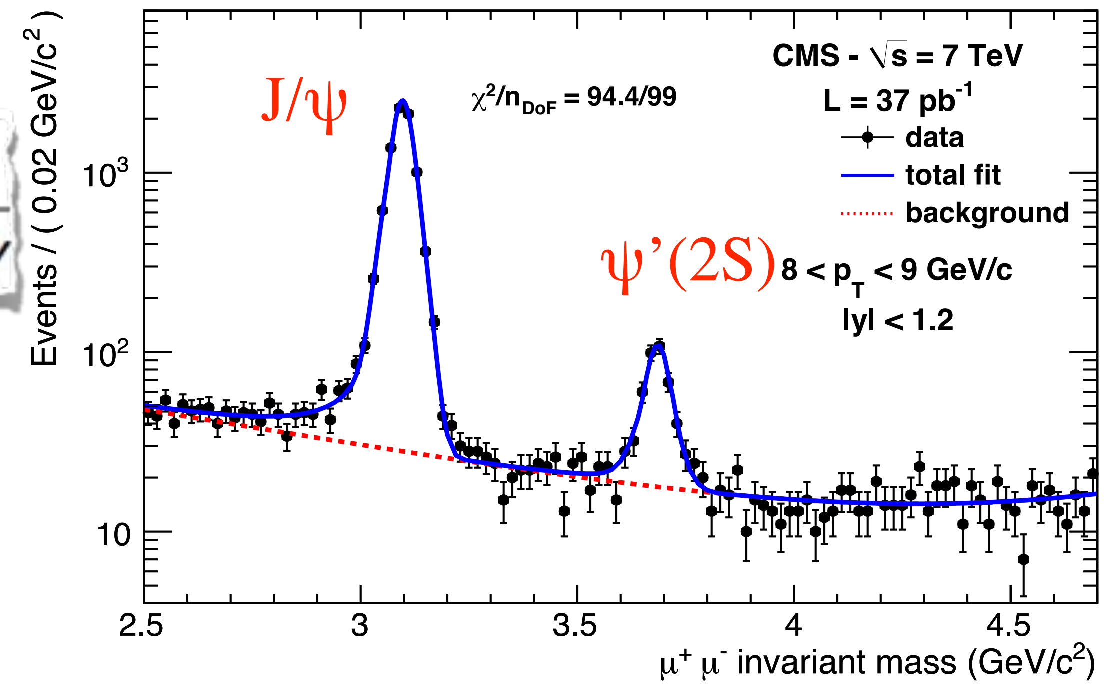


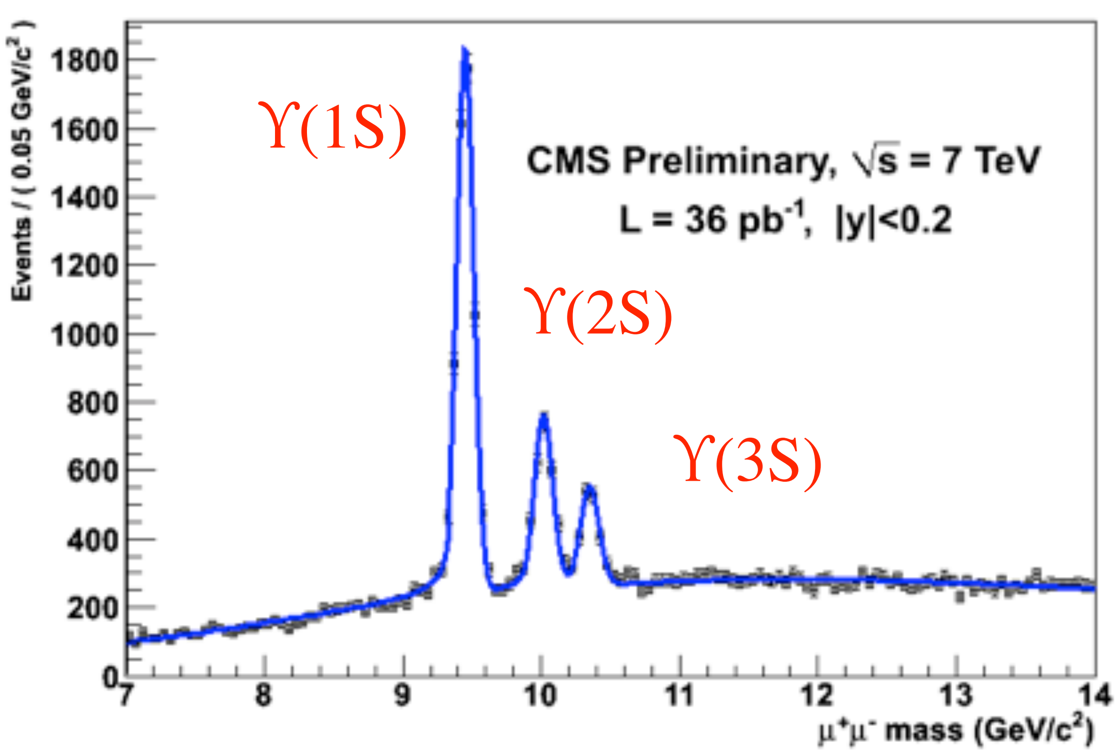
cross section

“N=L.σ ”

$$\frac{d^2\sigma(Q\overline{Q})}{dp_T\,dy}\mathcal{B}\left(Q\overline{Q}\to\mu^+\mu^-\right)=\frac{N_{fit}(Q\overline{Q})}{\mathcal{L}\cdot\mathcal{A}\cdot\epsilon\cdot\Delta p_T\cdot\Delta y}$$

- N: fitted signal yield
- A: detector acceptance from simulation
  - dependent on unknown production polarization
- ε: track, muon reconstruction and trigger efficiencies, from data-driven (T&P) methods
- L: integrated sample luminosity
  - Acceptance and efficiency corrections applied event-per-event or as bin averages 1/< A, ε>

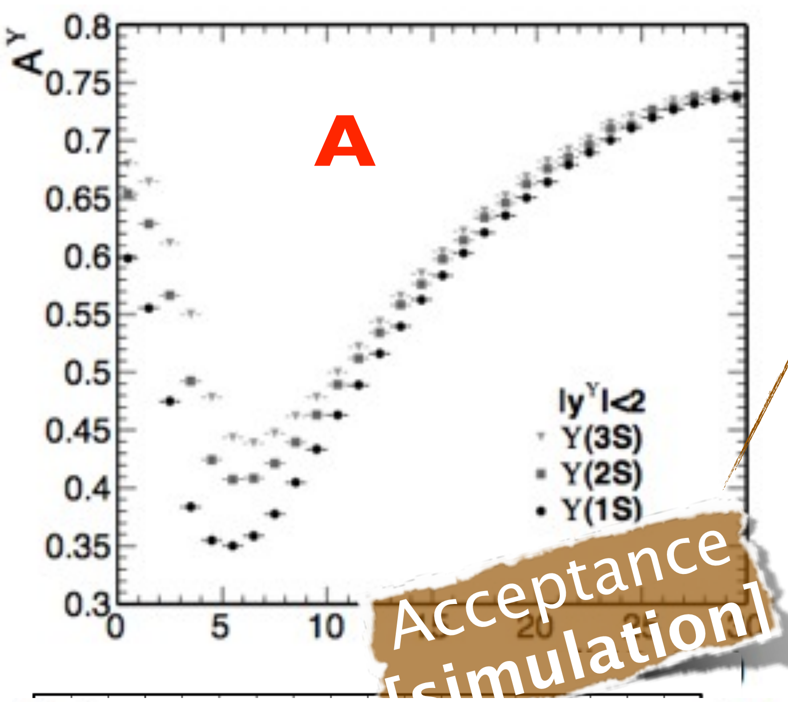


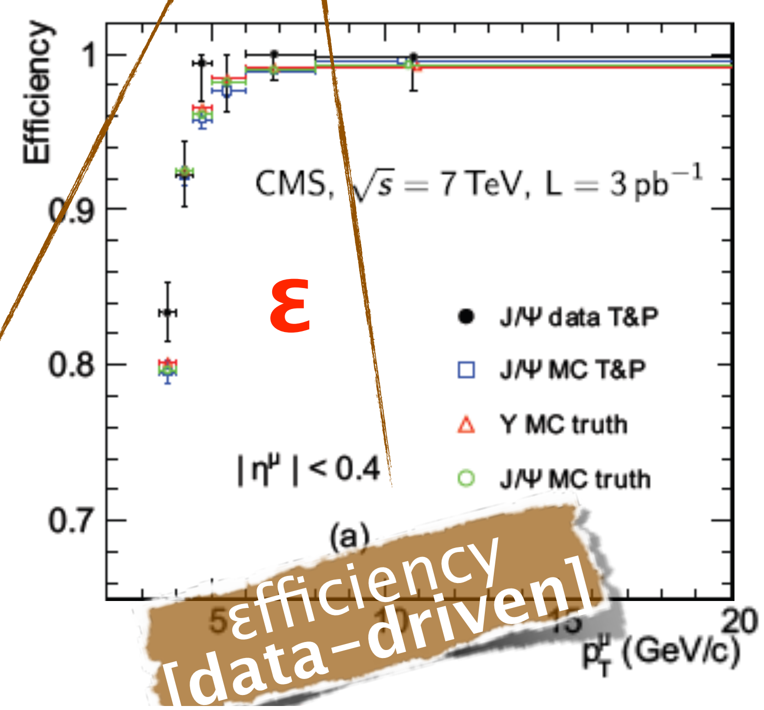


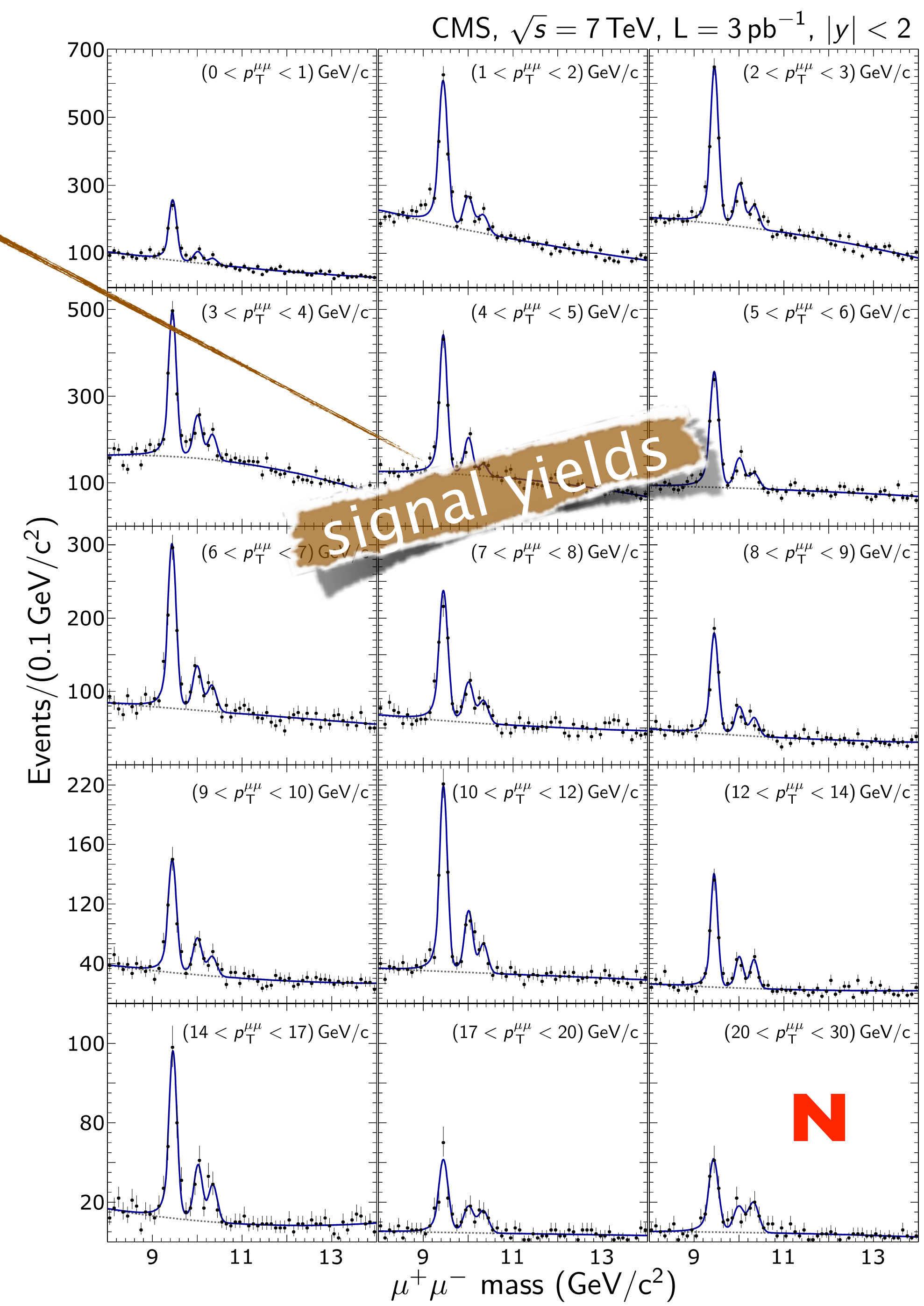
cross section

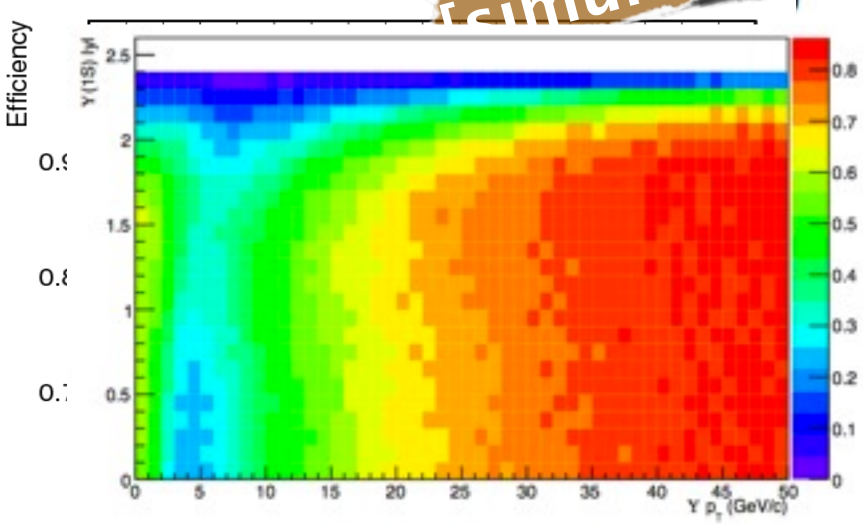
"$N = L.\sigma$"

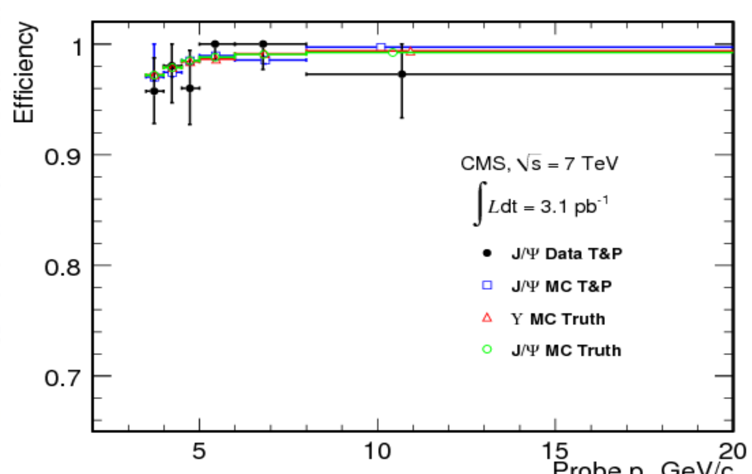
$$\frac{d^2\sigma(Q\overline{Q})}{dp_T dy}\mathcal{B}\left(Q\overline{Q} \to \mu^+\mu^-\right) = \frac{N_{fit}(Q\overline{Q})}{\mathcal{L} \cdot \mathcal{A} \cdot \epsilon \cdot \Delta p_T \cdot \Delta y}$$





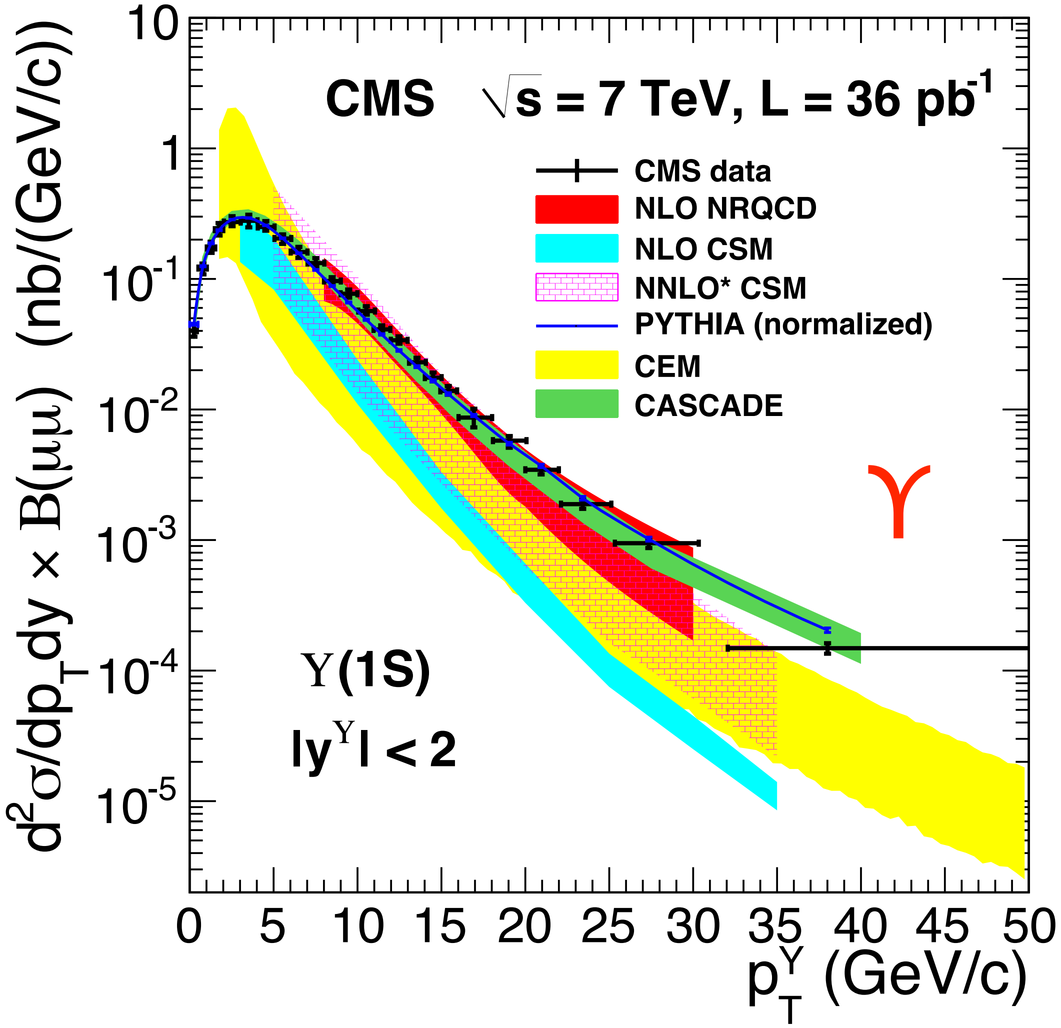


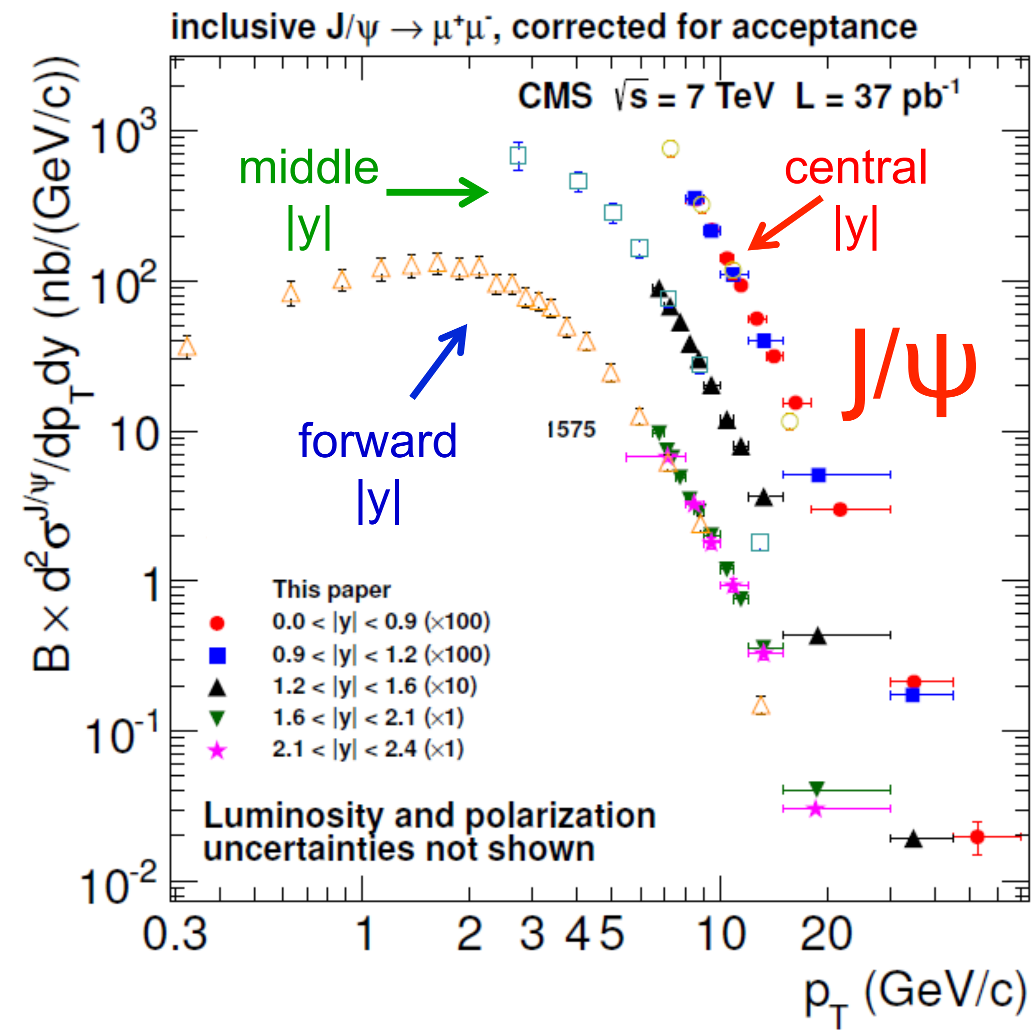




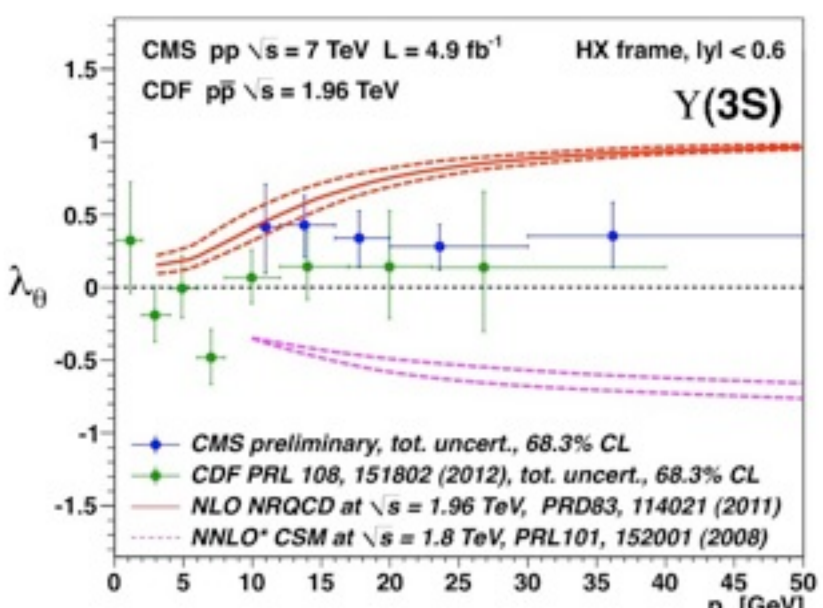
quarkonia production *[in pp]*

cross sections





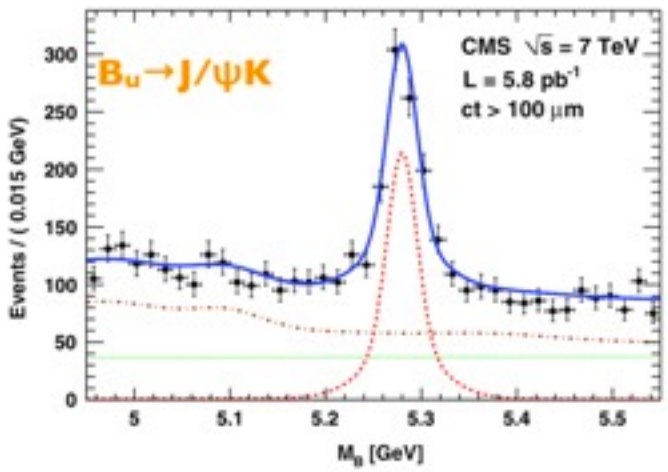
polarizations

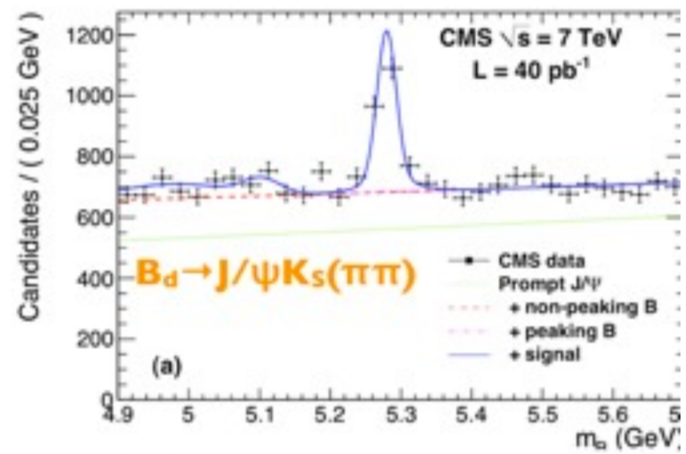


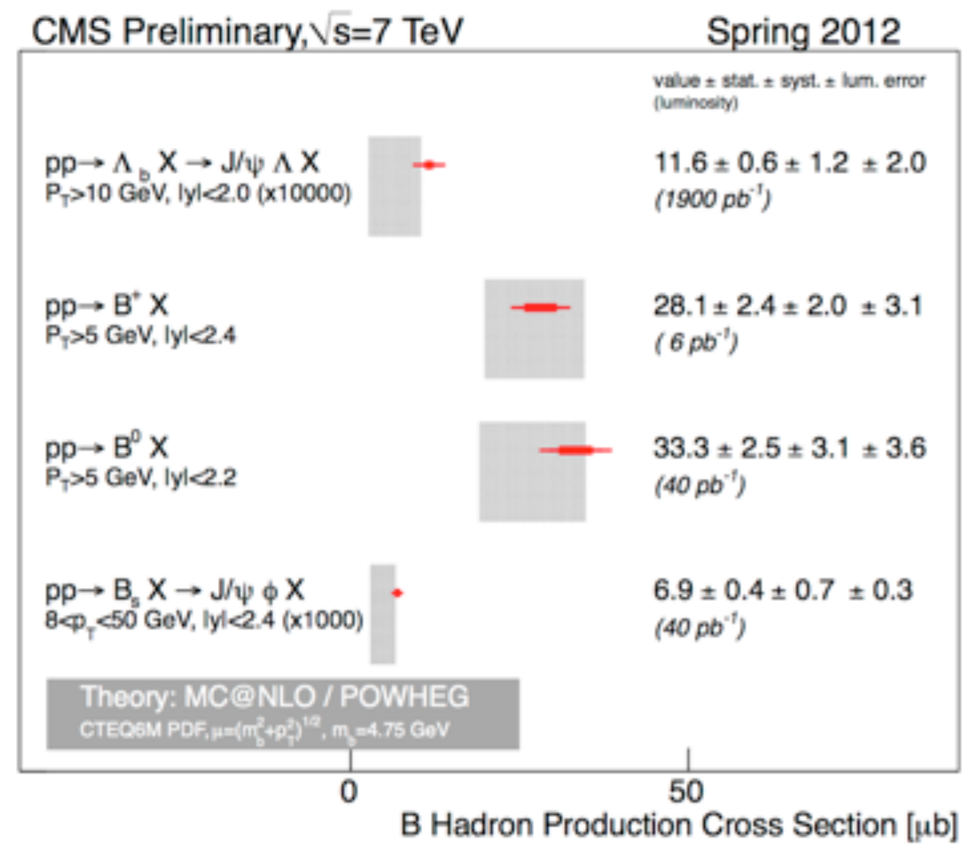
- precision measurements of quarkonium production
- LHC allows to probe higher p_T region for the first time

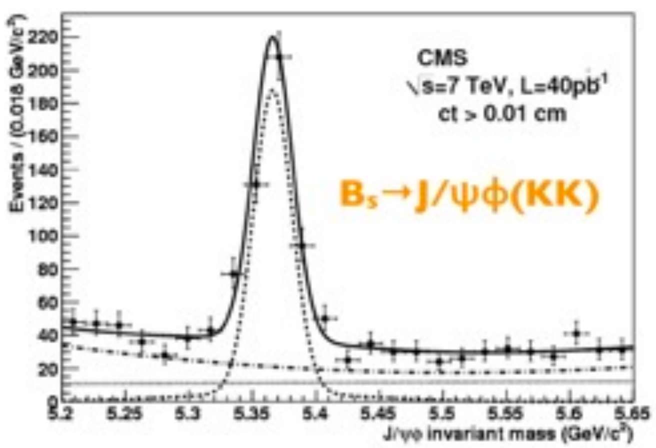
☞ (note: see polarization details in lecture: ‘polarization in LHC physics’)

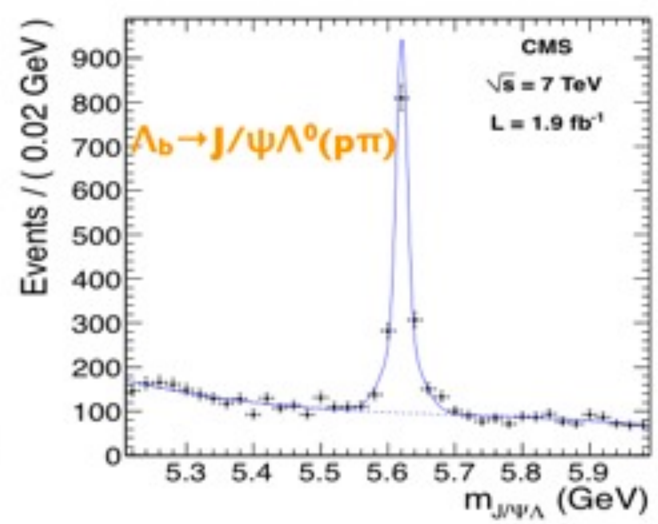
b–hadron production

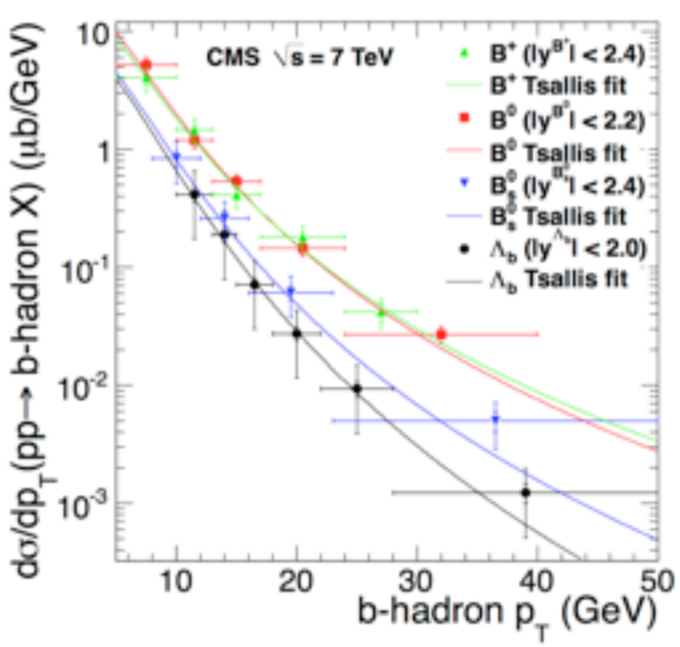






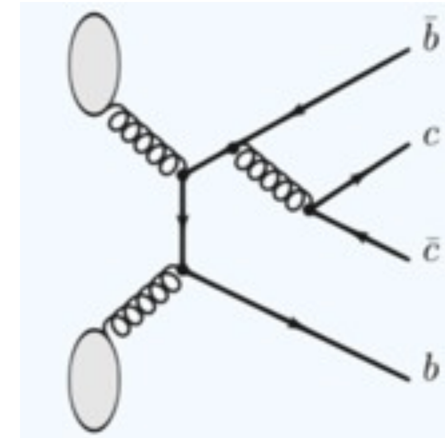






- integrated cross sections and NLO predictions in agreement
- baryon spectrum falls faster than meson spectra
  - analysis of lager datasets will much improve precision of differential measurements

Bc



- meson with different heavy flavors -- unique in SM
  - sometimes also referred to as 'quarkonium': similar non-relativist potential techniques used to predict properties
  - formed of b+c quarks: the heaviest quark flavors expected to form mesons
  - b and c may both decay weakly
    ➠ much shorter lifetime than other B mesons
- state by now observed in several modes
  - no excited states observed yet (many expected)

$\bar{b} \to \bar{c}$ transition

$B_c^+ \to J/\psi\, \ell^+ \nu_\ell$

$B_c^+ \to J/\psi\, \pi^+$

$c \to s$ transition

$B_c^+ \to B_s^0 \pi^+$

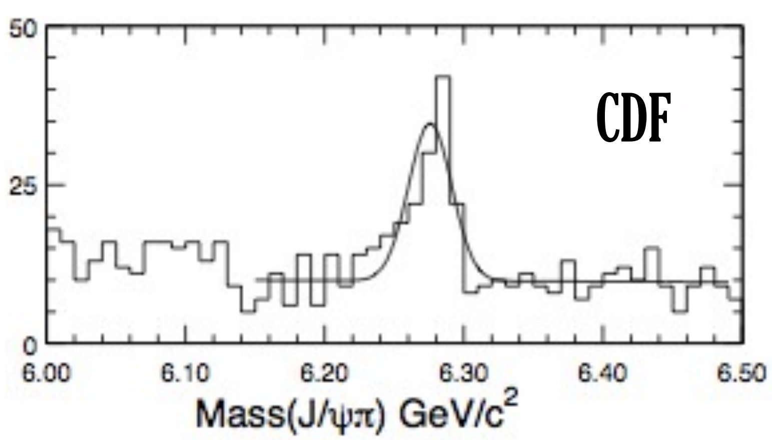
$B_c^+ \to B_s^0 \ell^+ \nu_\ell$

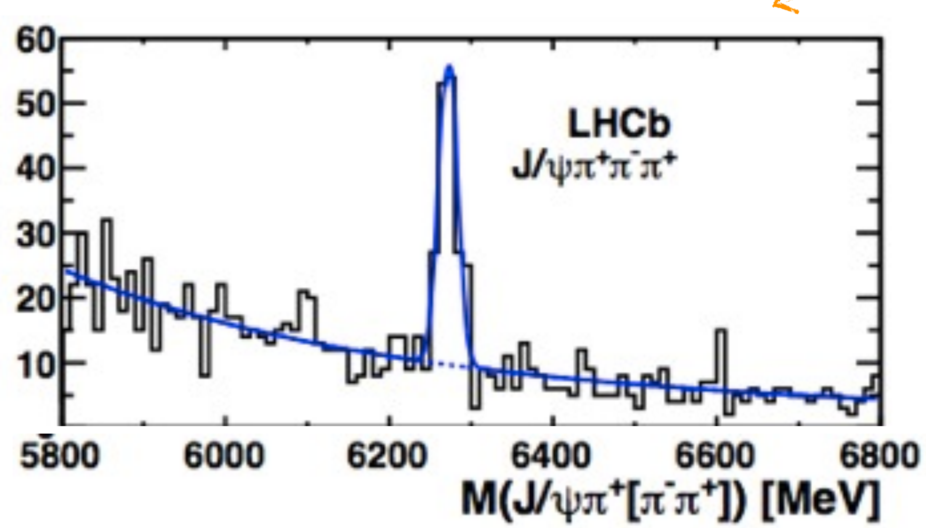
$c\bar{b} \to W^+$ transition

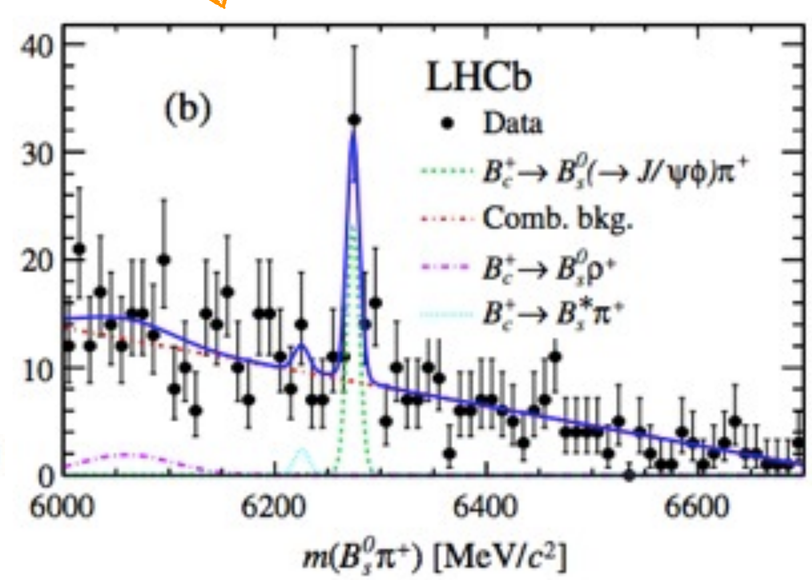
$B_c^+ \to \bar{K}^{*0} K^+$

$B_c^+ \to \phi K^+$

$B_c^+ \to \tau^+ \nu_\tau$

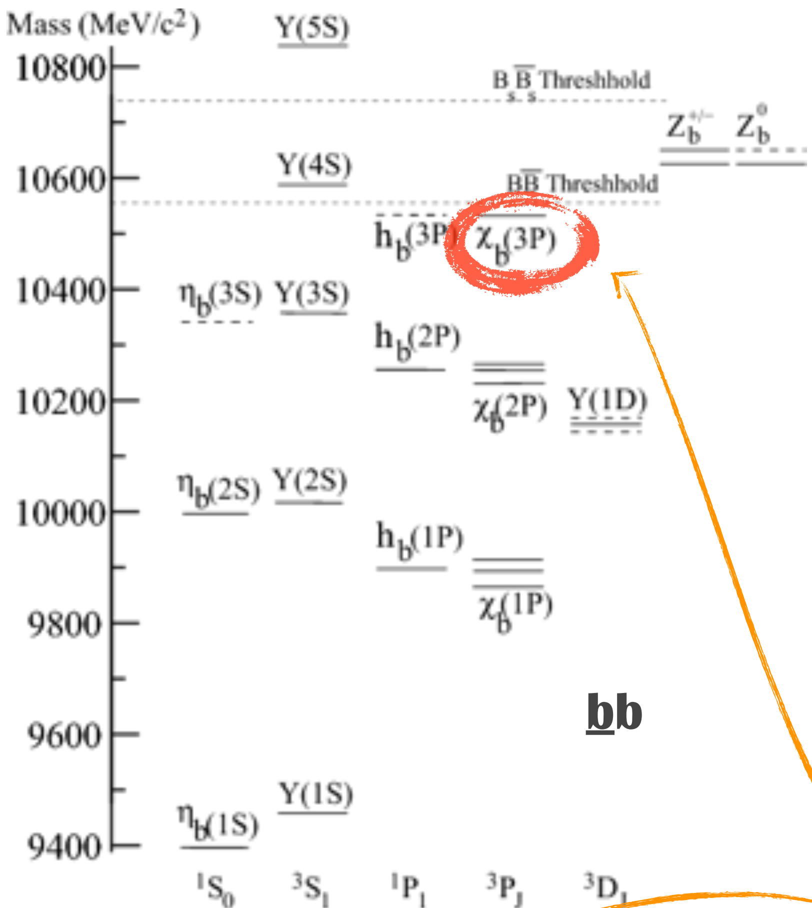


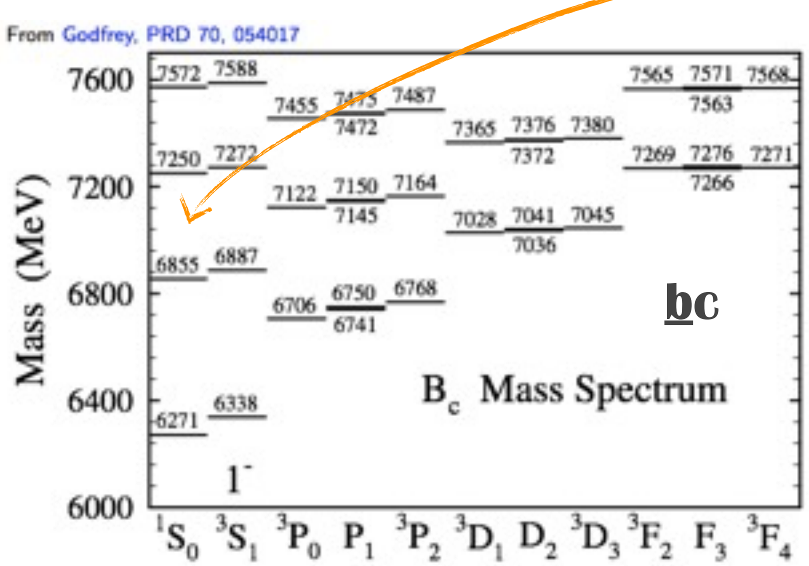




beauty spectroscopy

mesons





Before 2006, only one b baryon had been seen: Λ_b

CDF and D0 contributed several such discoveries:

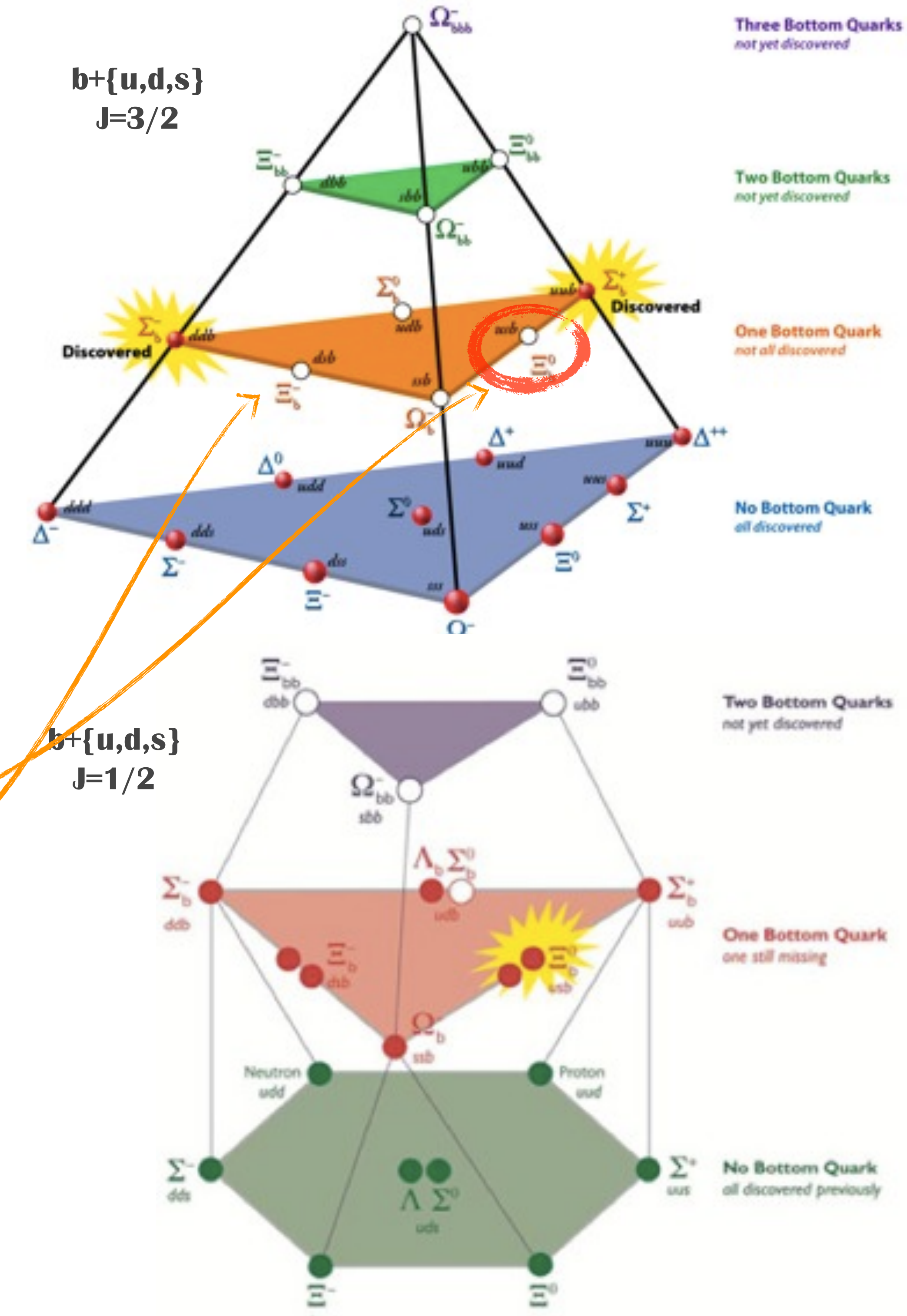
- Σ_b^- (2006)
- Ξ_b- (2007)
- Ω_b (2008)

LHC:

- χ_b(3P) (ATLAS' 2011)
- Ξ_b^{*0} (CMS'2012)
- B_c(2S) (ATLAS'2014)
- Ξ_b^{*-} $\Xi_b'^-$ (LHCb'2014)

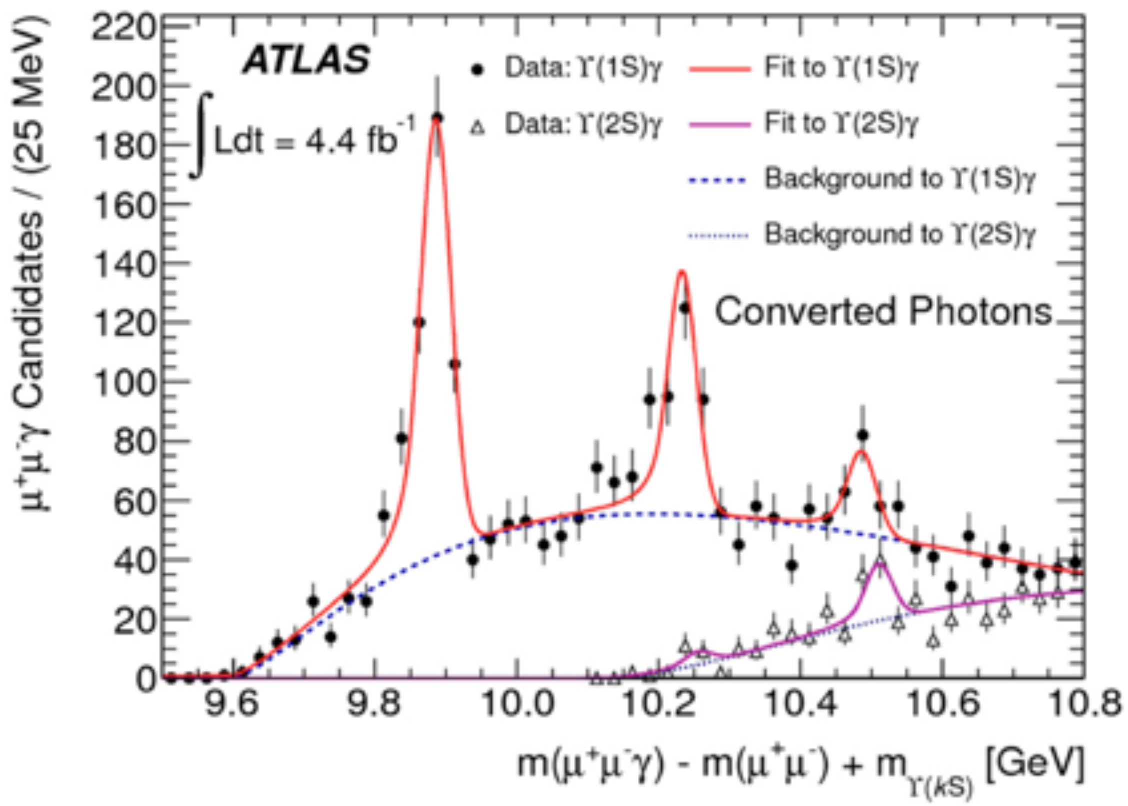
Several other composite particles awaiting to be discovered!...

baryons



the first new particles found at the LHC

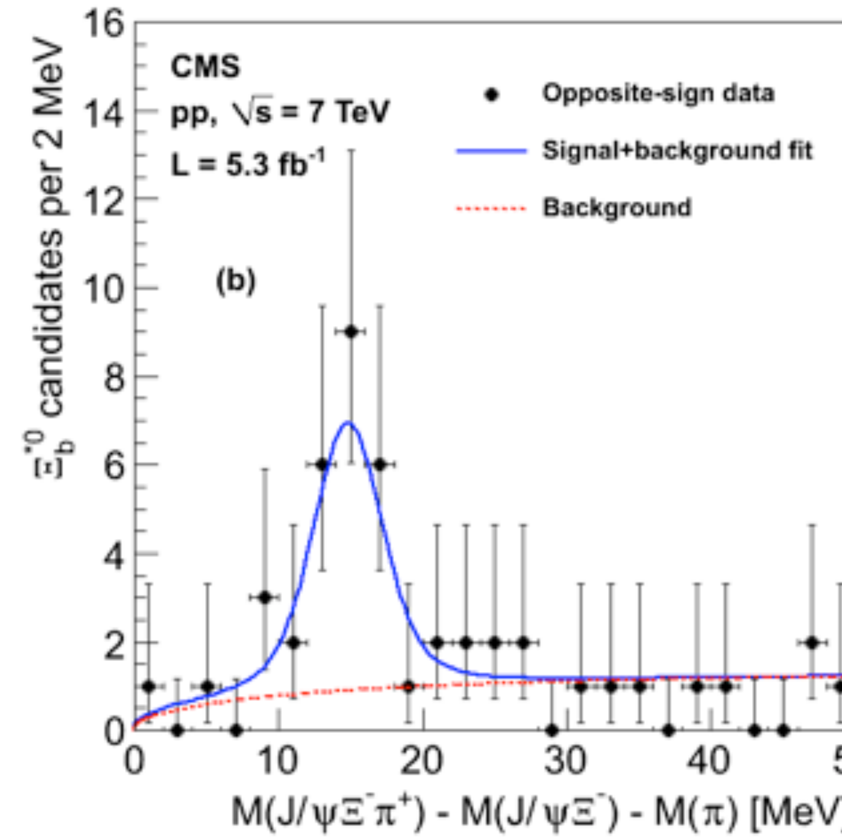
$\chi_b(3P)$ meson



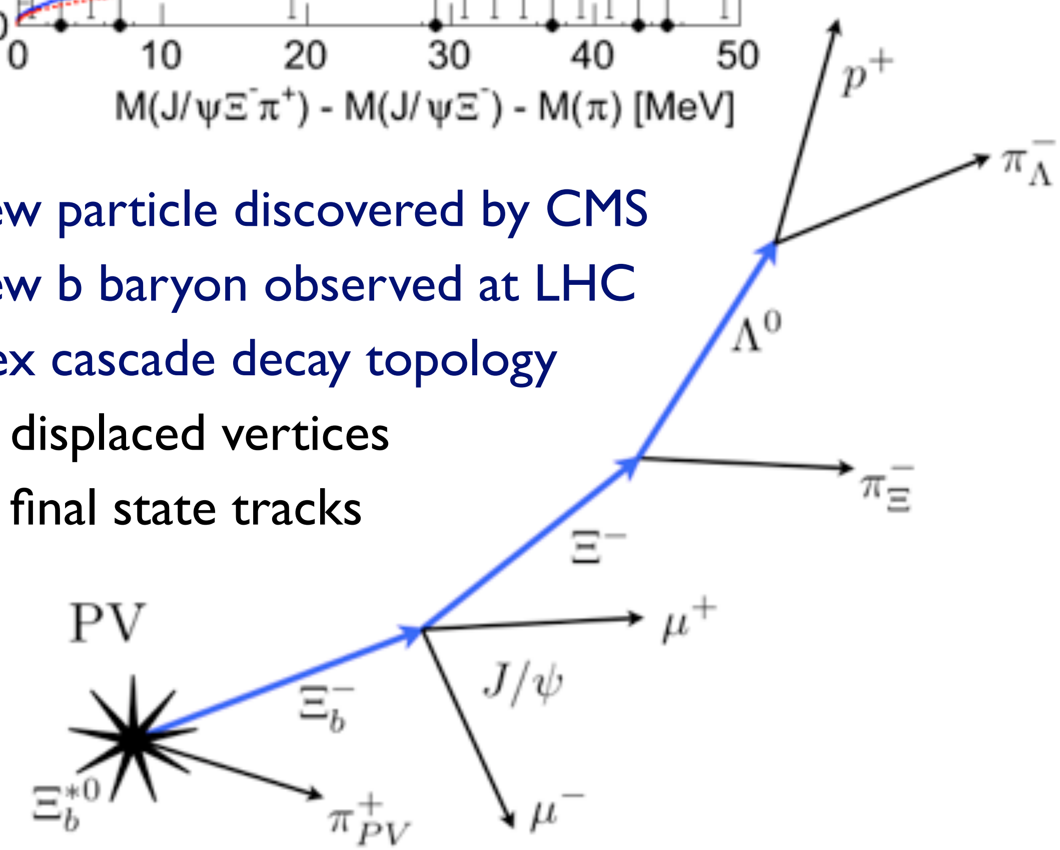
- first new particle discovered by ATLAS
- reconstruct the radiative bottomonium decay by exploring photon conversions in tracker material

$$\chi_b \rightarrow \Upsilon\ \gamma$$
$\gamma \rightarrow e^+e^-$
$\Upsilon \rightarrow \mu^+\mu^-$

Ξ_b^* baryon



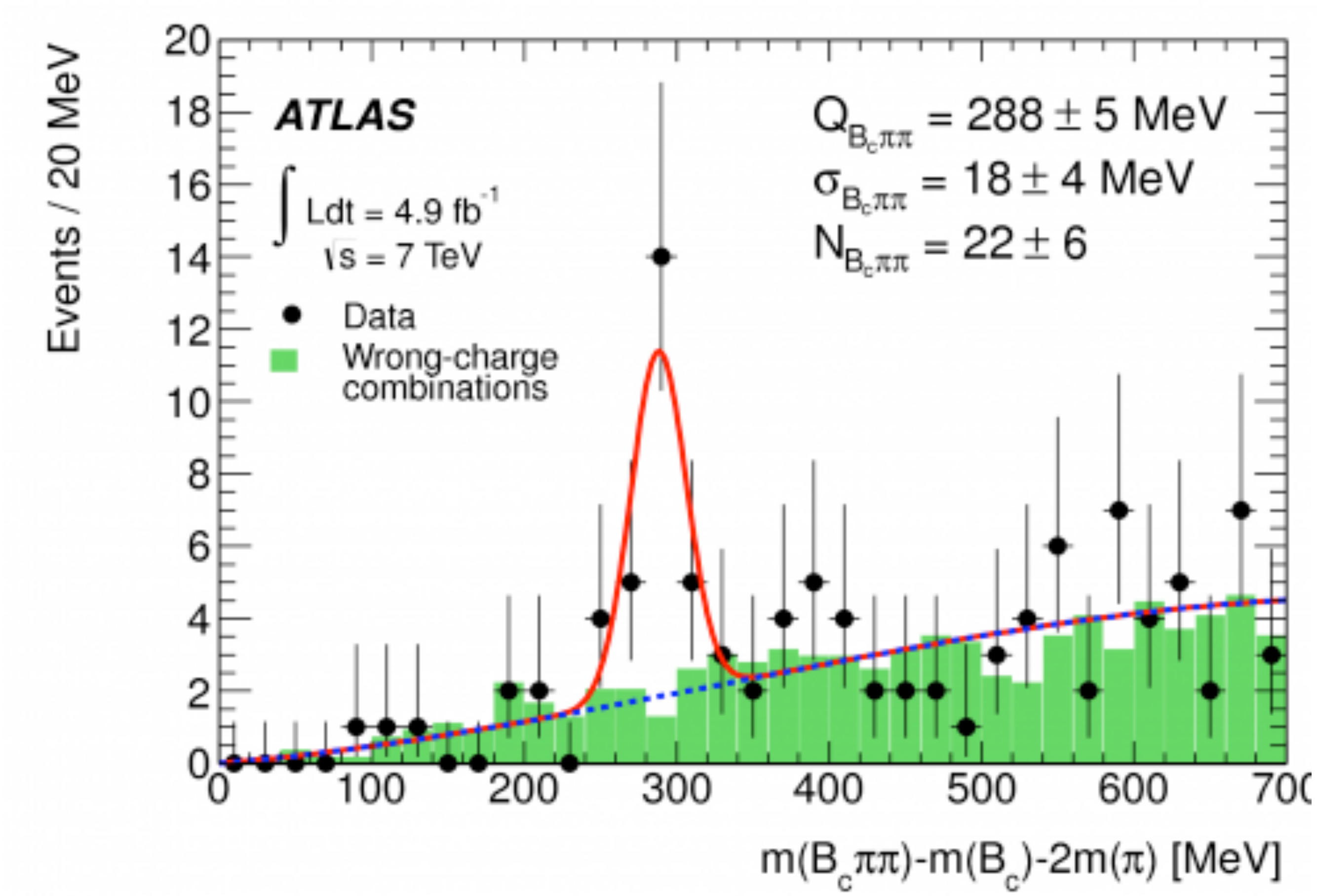
- first new particle discovered by CMS
- first new b baryon observed at LHC
- complex cascade decay topology
    - 4 displaced vertices
    - 6 final state tracks



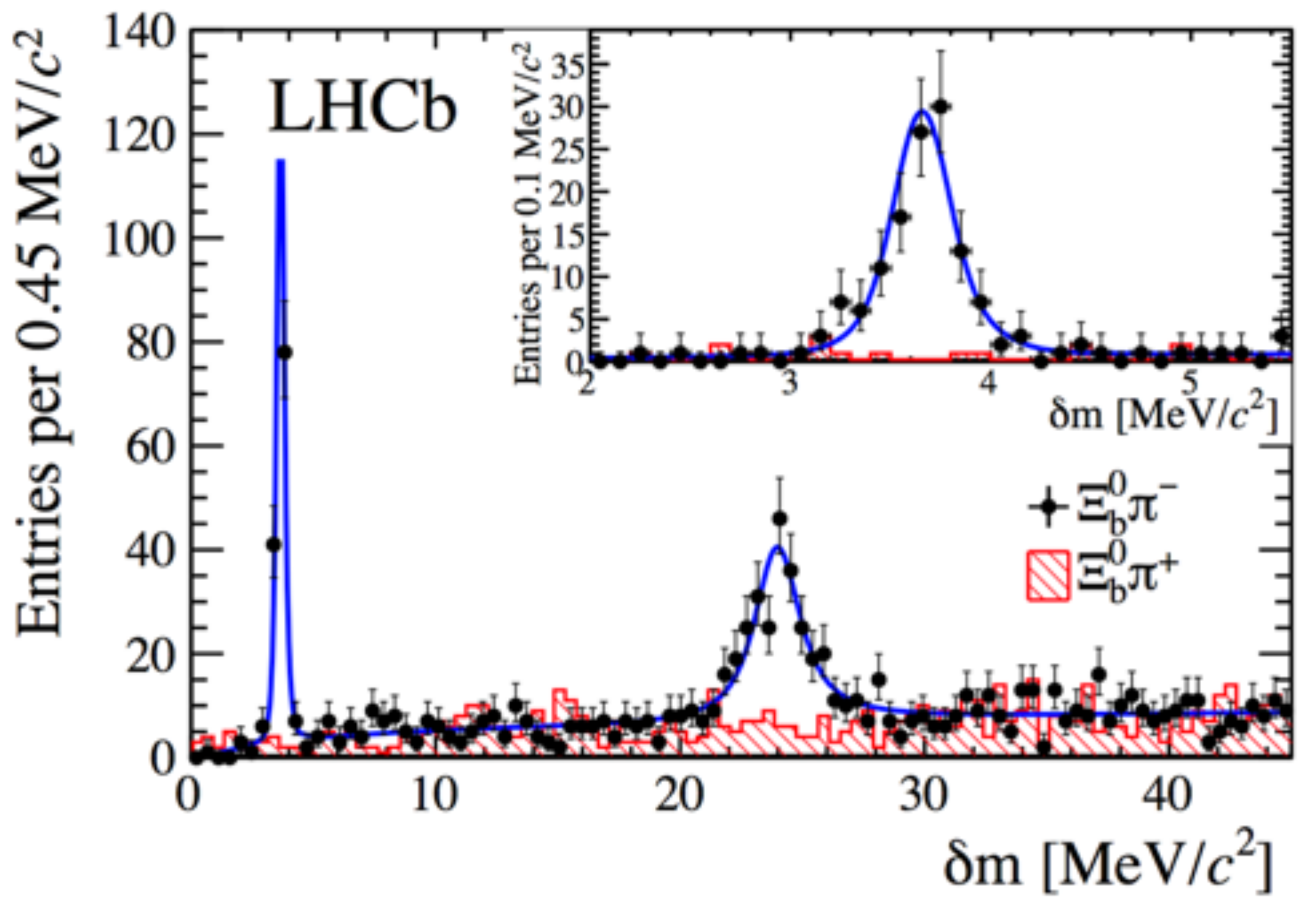
➡ note: these (orthogonal capabilities) further illustrate the ability of general purpose detectors to make flavor discoveries

and couple more recent discoveries

[ATLAS'2014]
Bc(2S)→μμπ ππ



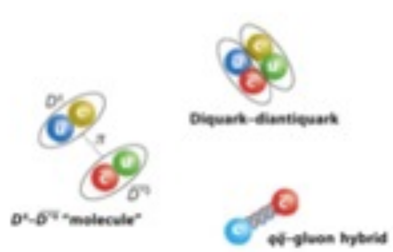
[LHCb'2014]
$\Xi_b'^-, \Xi_b^{*-} \to pK\pi\pi\pi$



exotic spectroscopy

- while not all of the predicted states have been observed yet... many unexpected ones already have
- referred to as XYZ states
- all started with the discovery of the X(3872) state by Belle in 2003
  - quickly confirmed by Babar, CDF, D0
  - other unconventional states popped up

Many theoretical interpretations in discussion:



- conventional quarkonia;
- tetra-quarks states;
- meson-molecules;
- hybrid mesons;
- threshold effects;

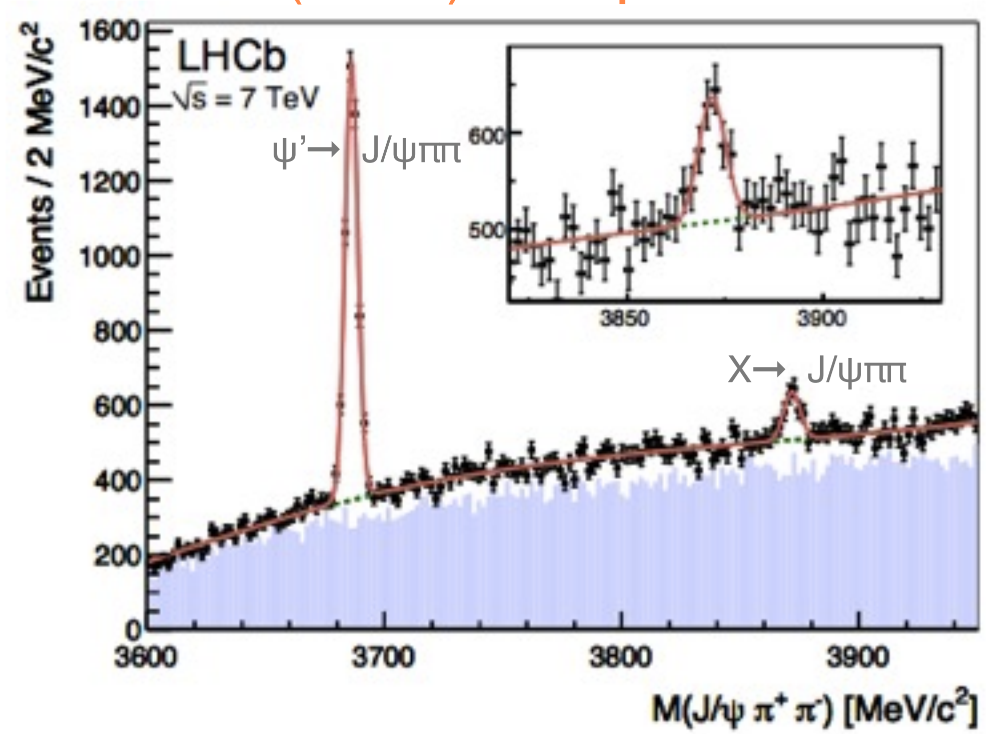
➡ properties do not well fit the quarkonia picture

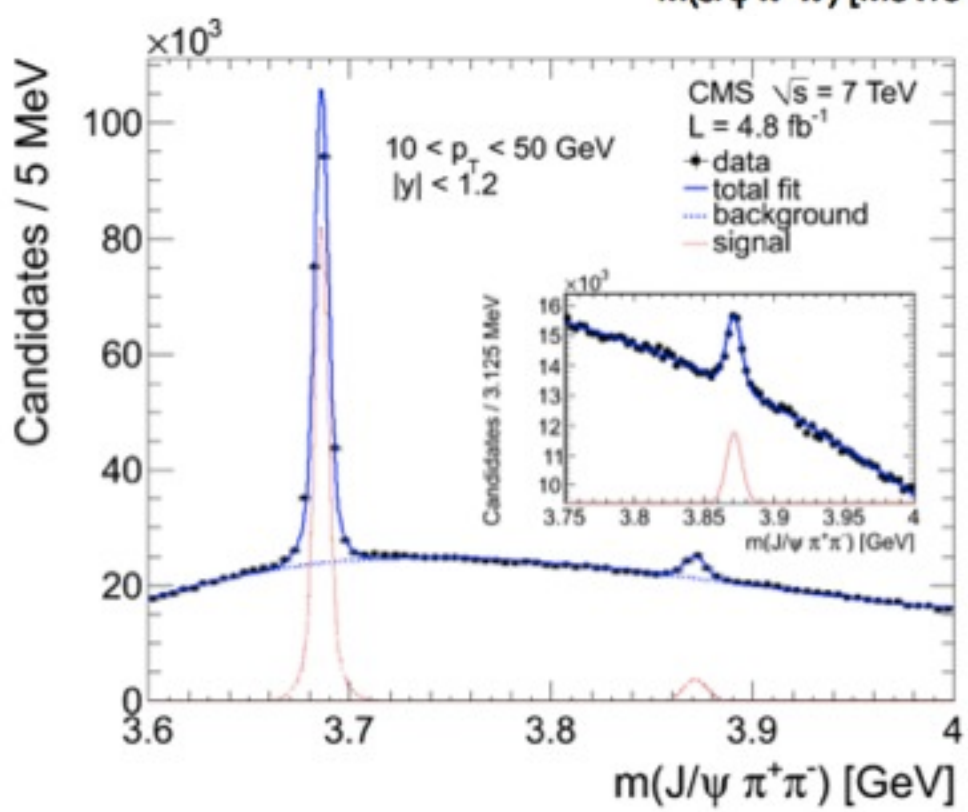
State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6 (<2.2)	$1^{++}/2^{-+}$	$B\to K(\pi^+\pi^-J/\psi)$ $p\bar{p}\to(\pi^+\pi^-J/\psi)+...$ $B\to K(\omega J/\psi)$ $B\to K(D^{*0}\bar{D}^0)$ $B\to K(\gamma J/\psi)$ $B\to K(\gamma\psi(2S))$
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B\to K(\omega J/\psi)$ $e^+e^-\to e^+e^-(\omega J/\psi)$
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^-\to J/\psi(D\bar{D}^*)$ $e^+e^-\to J/\psi\ (...)$
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^-\to\gamma(D\bar{D})$
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^-J/\psi)$
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B\to K(\pi^+\chi_{c1}(1P))$
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B\to K(\phi J/\psi)$
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^-\to J/\psi(D\bar{D}^*)$
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B\to K(\pi^+\chi_{c1}(1P))$
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^-J/\psi)$
				$e^+e^-\to(\pi^+\pi^-J/\psi)$ $e^+e^-\to(\pi^0\pi^0J/\psi)$
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B\to K(\phi J/\psi)$
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^-\to e^+e^-(\phi J/\psi)$
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^-\psi(2S))$
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B\to K(\pi^+\psi(2S))$
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^-\to\gamma(\Lambda_c^+\Lambda_c^-)$
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^-\psi(2S))$
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^-\to(\pi^+\pi^-\Upsilon(nS))$

[Eur.Phys.J.C71:1534,2011]

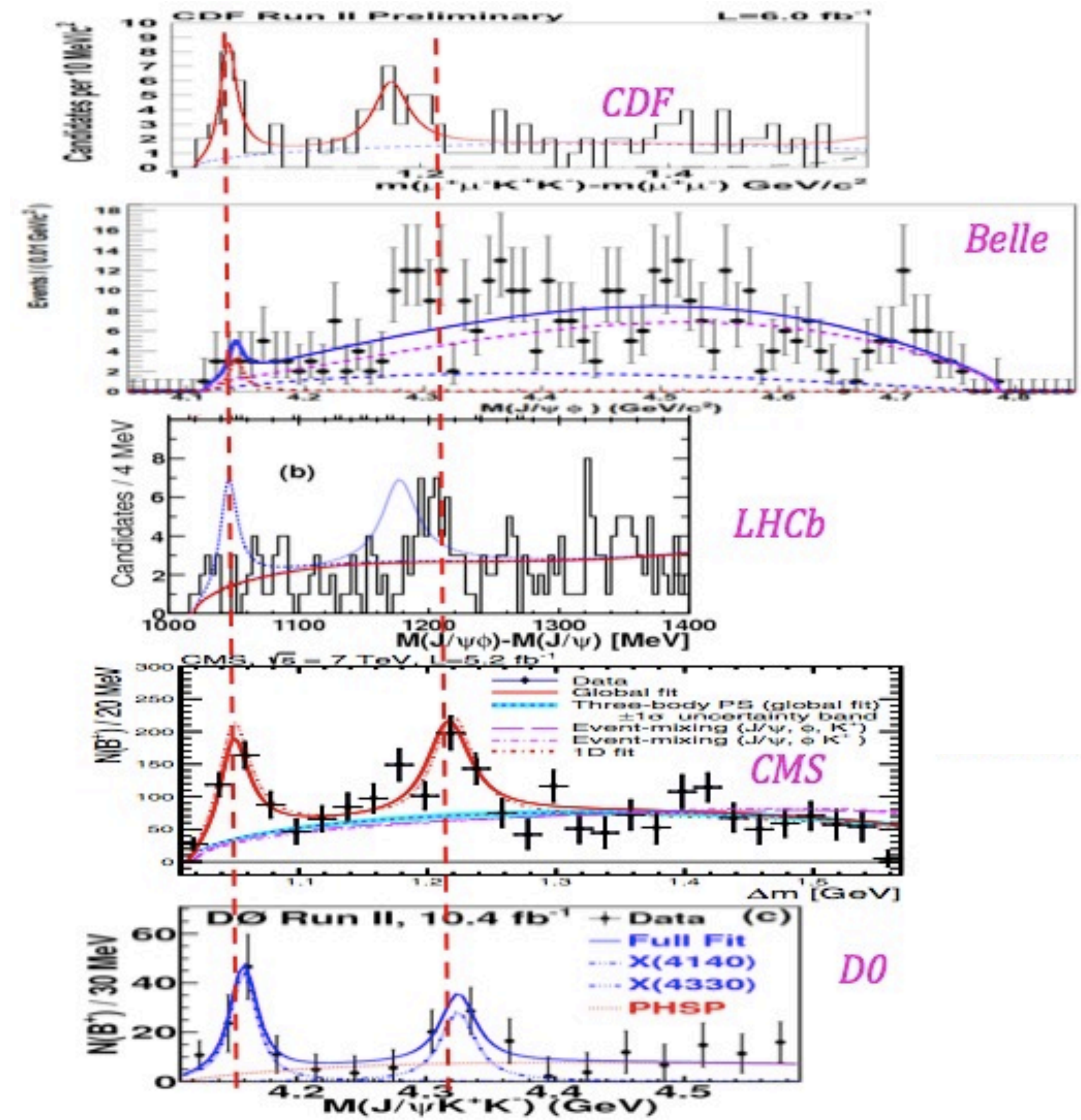
XYZ states

X(3872) →J/ψππ





Y(4140) in B_u→X[J/ψϕ]K decays



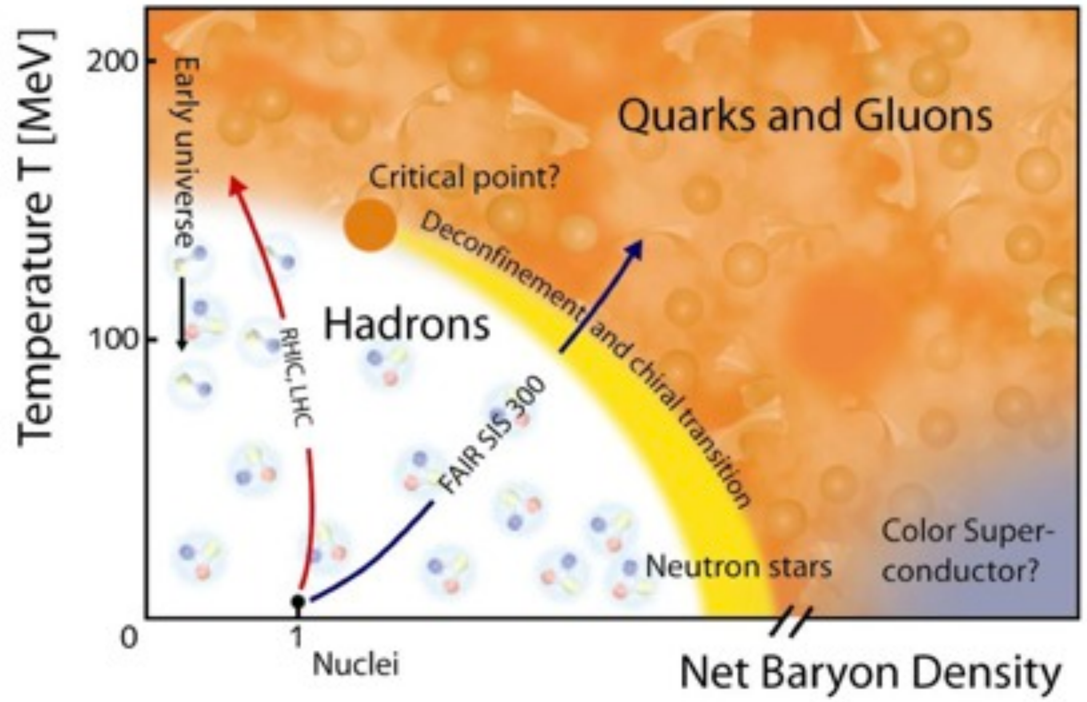
heavy flavor (suppression)

in

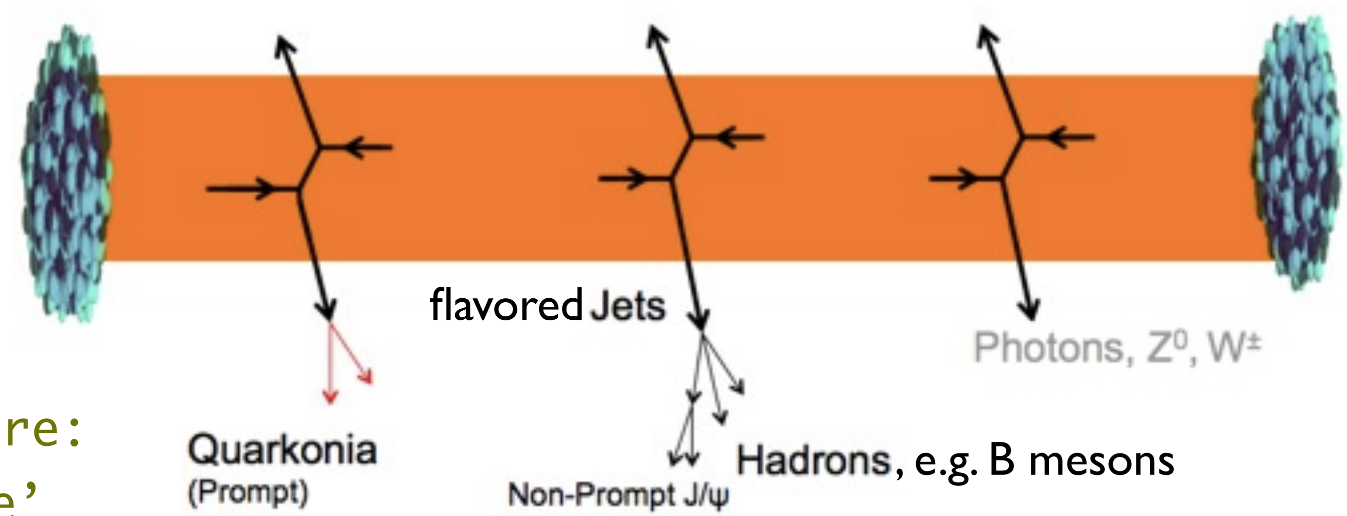
heavy ion collisions

➡ at large energy densities, QCD predicts the existence of a deconfined state of quarks and gluons -- the quark gluon plasma (QGP)

- studied in heavy ion collisions
- the goal is to characterize and quantify the properties of the dense and hot medium produced at the unprecedented LHC energies

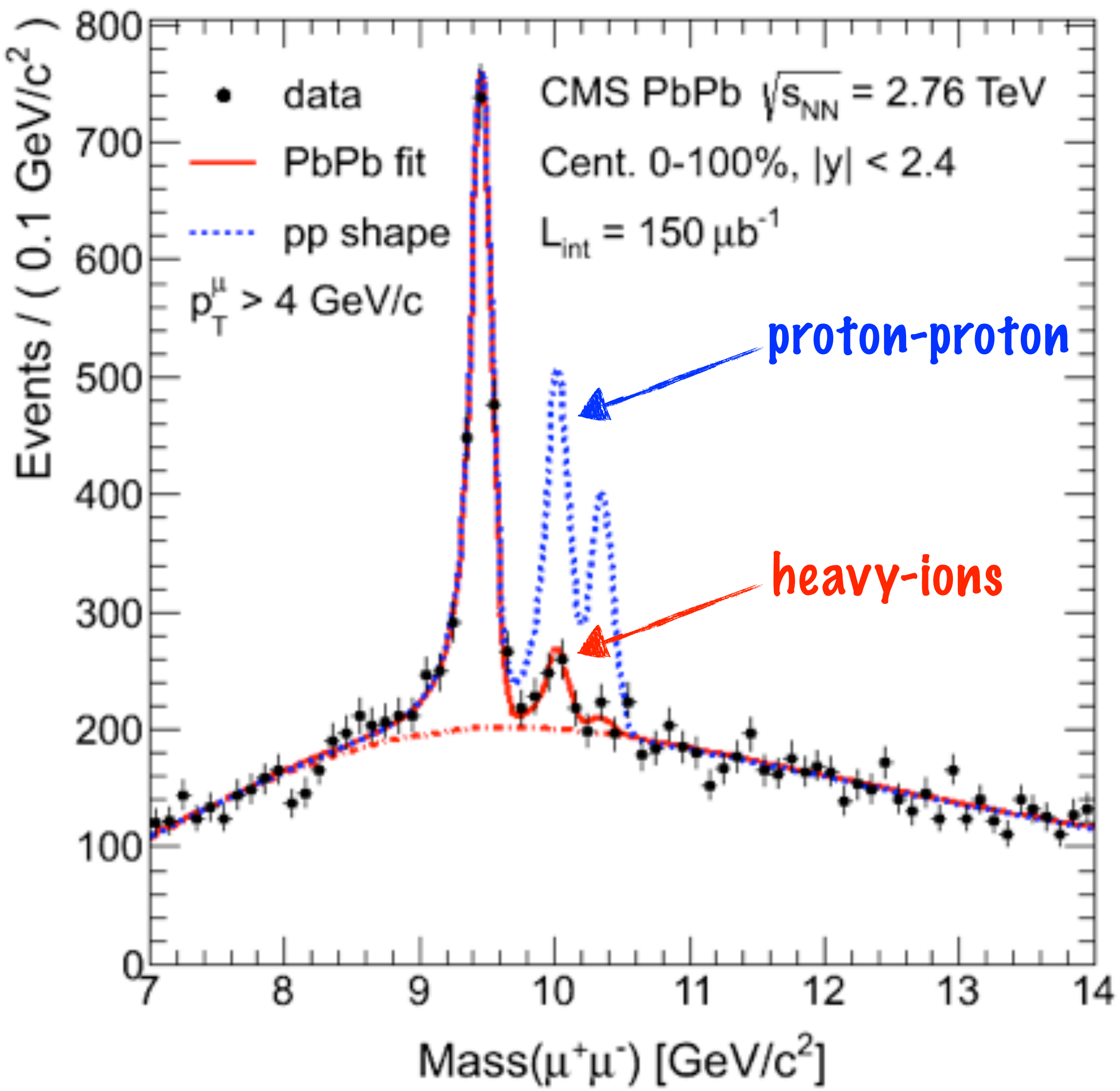


- heavy-flavor states are ideal "hard probes" for studying the properties of the created medium



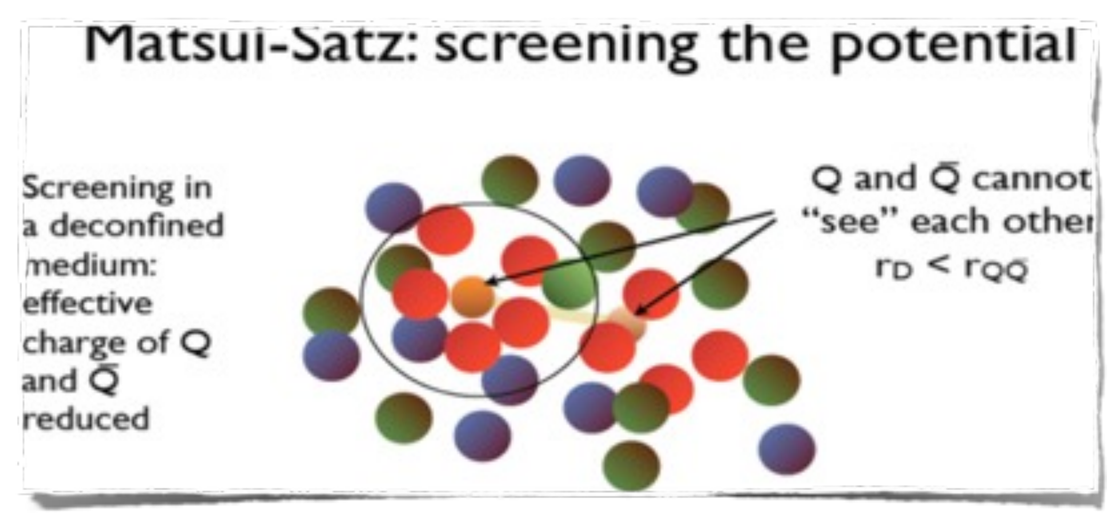
note: topic presented in dedicated lecture: 'matter at high density and temperature'

quarkonium suppression *[Pb-Pb]*



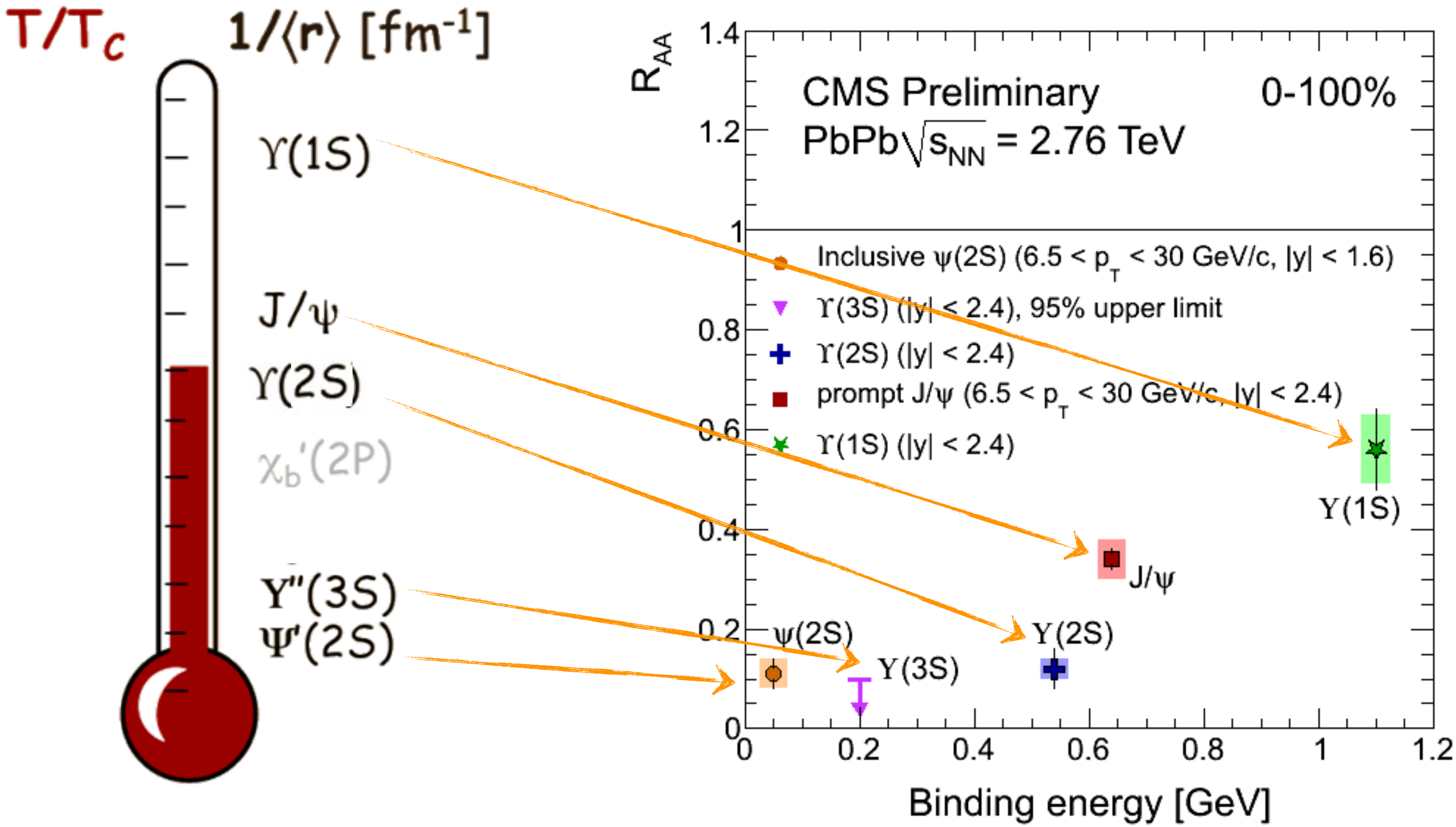
- first (quantitative) measurements of the Υ(nS) states in HI collisions
- unprecedented resolutions, allowing to separate the three states
  - experimentally and theoretically robust
- excited states observed (>5σ) to be more suppressed than ground state
- spectacular indication of formation of **Q**uark **G**luon **P**lasma in heavy ion coll.

“the LHC heavy-ion **text book** result”



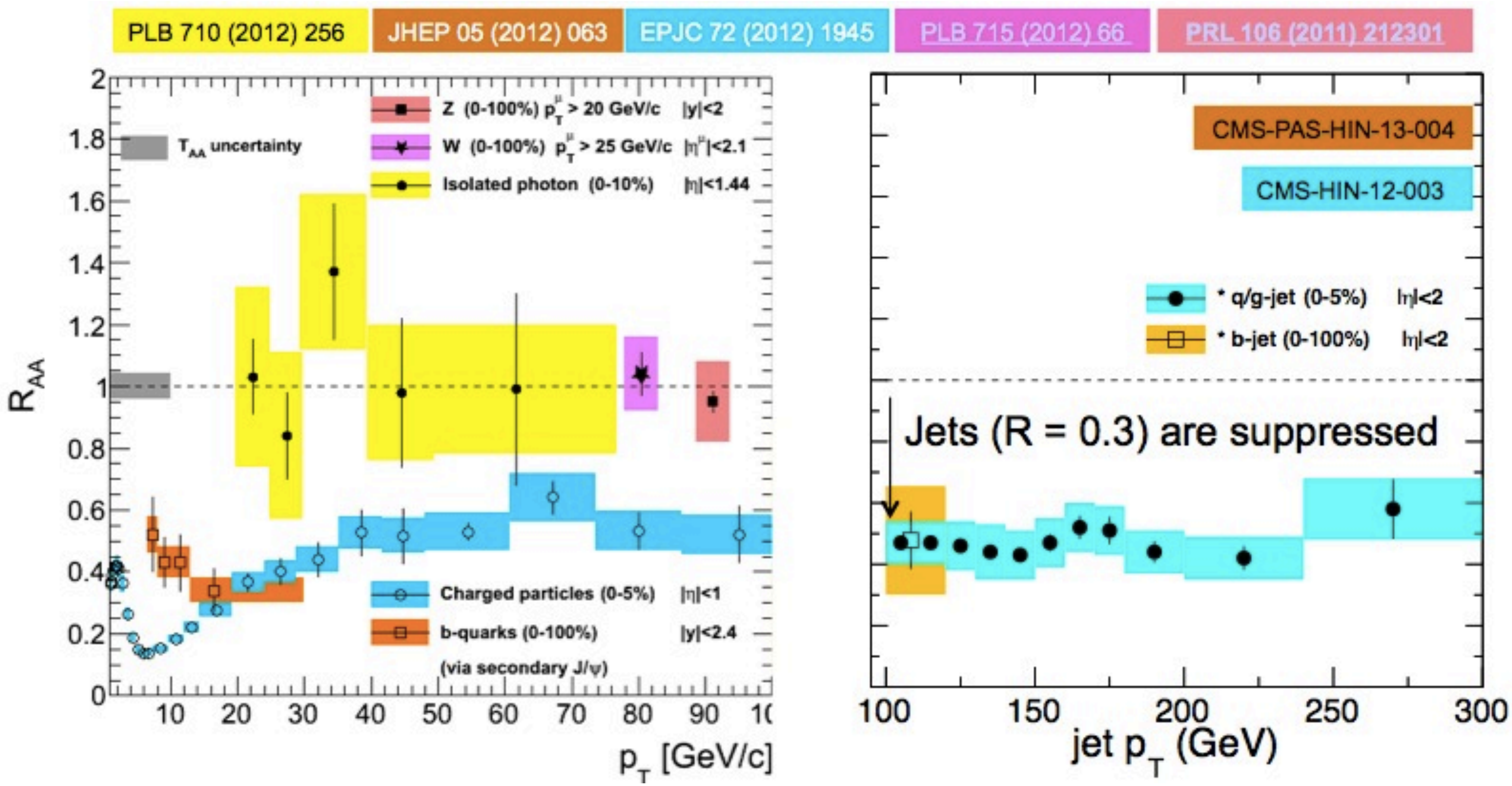
Exercise: the excited states being suppressed, what may be expected also of the observed ground state (hint: nS→1S feed-down)

quarkonium sequential suppression



quarkonia suppression pattern experimentally established:
less tightly bound states are more suppressed in the medium

in medium hadron suppression

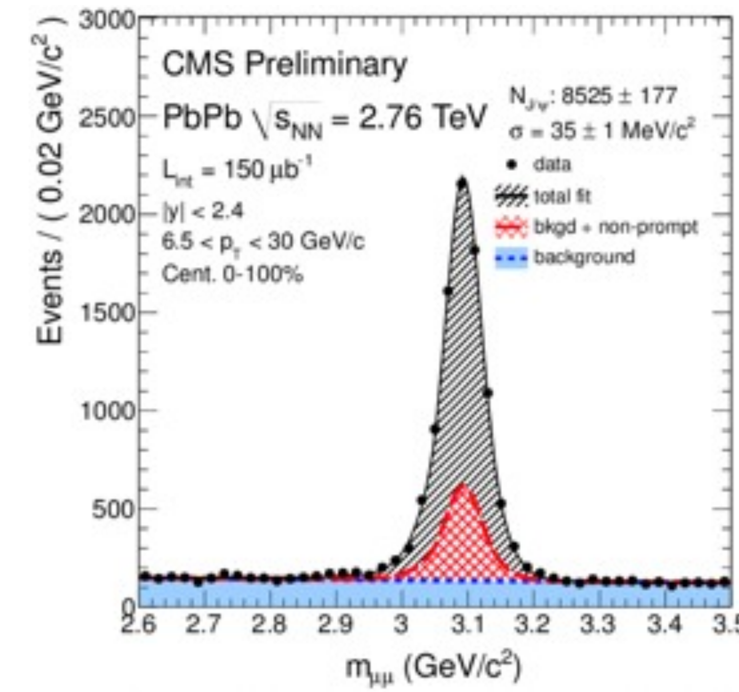


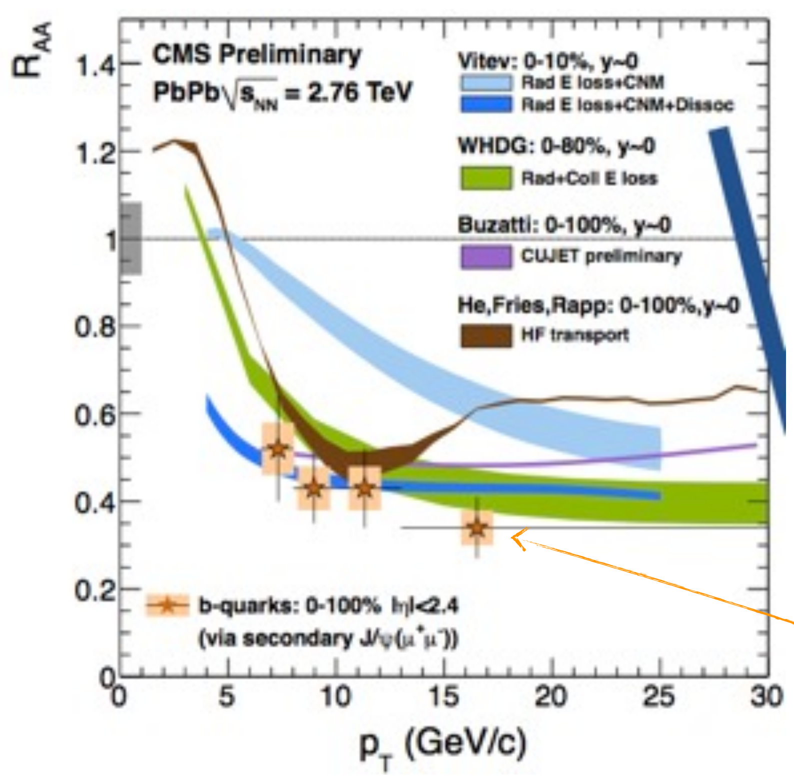
- measure of suppression, R_{AA} (nuclear modification factor)
  - cross section ration in PbPb vs pp, scaled by number of binary collisions
- different particle species undergo different energy loss in the medium
  - colorless probes (W,Z,γ) are not suppressed (R_{AA} ~ 1)

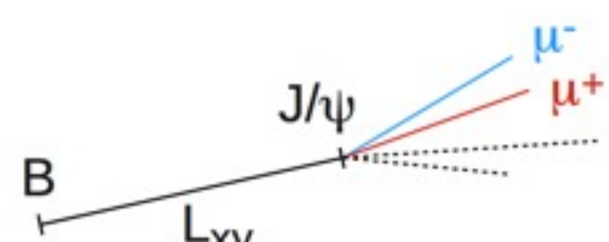
➡ study flavor dependence of energy loss

b–hadron detection

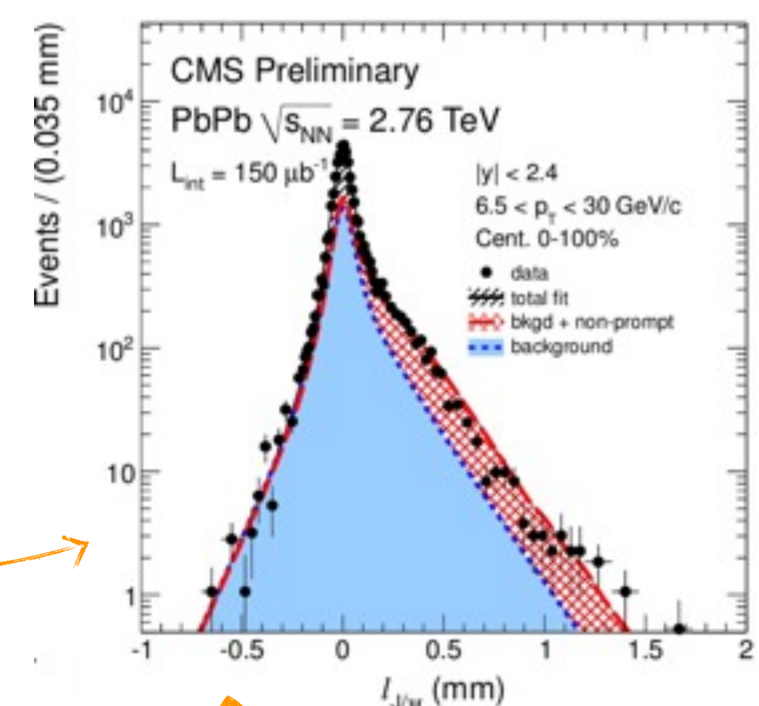
- prior to LHC, b-hadron detection was pursued mostly through inclusive-lepton (B→lX) and inclusive-charmonia (B→J/ψX) studies
- with LHC, moved to a new class of more reliable and precise new measurements
  - through non-prompt charmonia: remove prompt contribution through lifetime analysis [see next section]
  - through exclusive state reconstruction [see next slide]
  - ➡ both achieved for the first time at the LHC





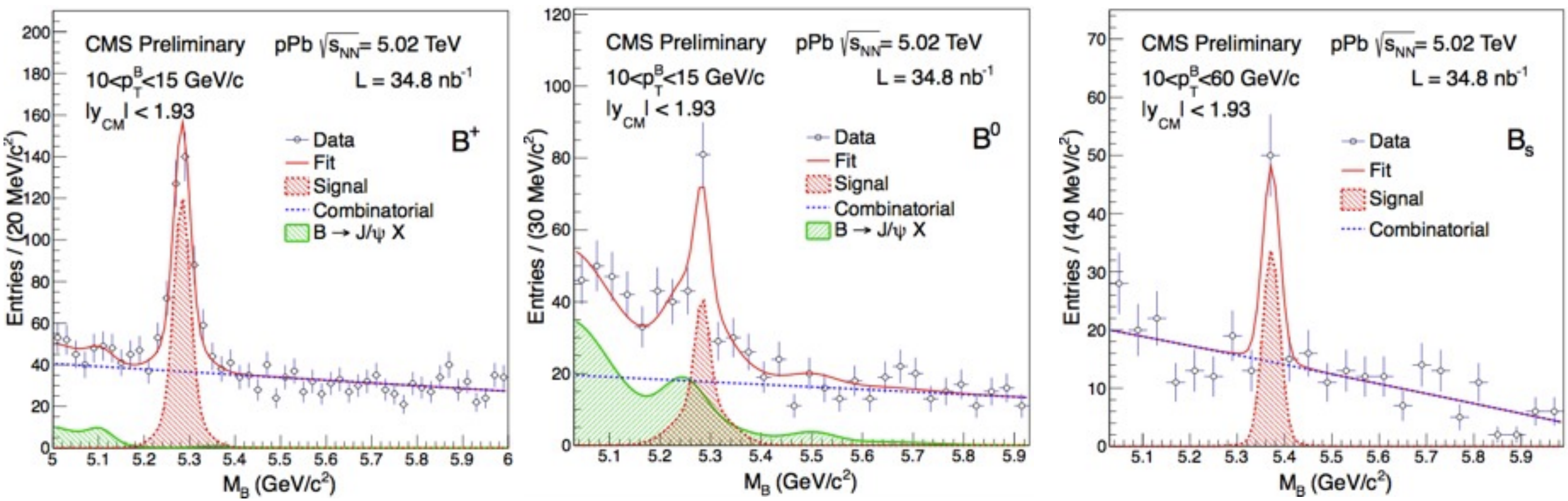


$$l_{J/\psi} = L_{xy} \frac{m_{J/\psi}}{p_T}$$



Bu, Bd, Bs *[in p-Pb]*

- first B meson peaks reconstructed in collisions involving heavy ions (2014/5)



these systems constitute precise handles that will facilitate a much improved understanding of the mechanisms of energy loss of hadrons in the deconfined ('hot') and nuclear ('cold') media -- and of its flavor dependence

➡ heavy flavor studies at the LHC are opening up new research lines in nuclear physics, benefitting from the exquisite capability of the detectors and unprecedented collision energies at the LHC

- ➡ several ground-breaking results already delivered, many more to come

proton-proton | **heavy-ion**

$\sqrt{s_{NN}}$

1.96 TeV (Tevatron (Run II)) ➠ $7_{(8)}$ TeV (LHC Run I) ➠ $13_{(14)}$ TeV (LHC Run II) — **x7**

0.2 TeV (RHIC) ➠ 2.76 TeV (LHC Run I) ➠ 5.5 TeV (LHC Run II) — **x27**

energy

$\mathcal{L}$ very large datasets are being accumulated at the LHC

intensity

- ➡ large HF production cross section + precision HF detection capability lifetime

quantum mechanics (i)

- an unstable particle may be described by an effective hamiltonian
- through the non-relativistic Schrodinger equation
- the solution reproduces the law of radioactive decay

$$\mathcal{P}(t) \sim \frac{1}{\tau} e^{-t/\tau}$$

τ is the lifetime

- t is the proper decay time, experimentally it is measured from the decay length L and momentum p
  (or their projections on the transverse plane)

$$t = \frac{L}{\beta\gamma} = L\frac{M}{p} = L_{xy}\frac{M}{p_T}$$

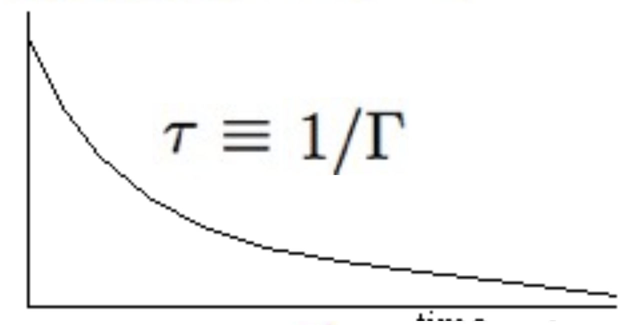
↳ Lorentz boost factor

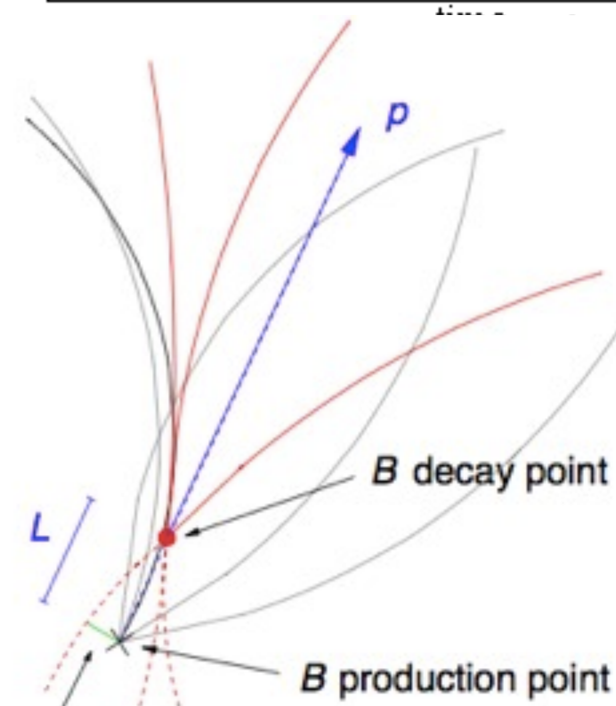
$$\mathcal{H} = m - \frac{i}{2}\Gamma$$

$$i\partial_t \psi = \mathcal{H}\psi$$

$$|\psi\rangle_t = e^{-imt} e^{-\frac{1}{2}\Gamma t} |\psi_0\rangle$$

$$|\langle\psi_0|\psi\rangle_t|^2 = e^{-\Gamma t};$$





lifetime modeling

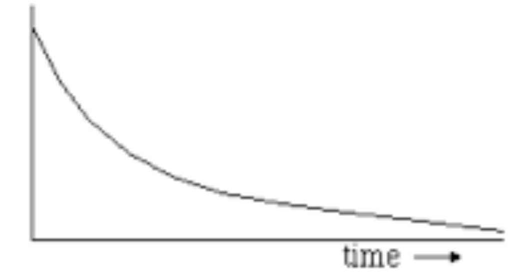
signal model → $$L(t|\sigma_t,\tau) = \frac{1}{\mathcal{N}} \cdot \left[\frac{1}{\tau} e^{-\frac{t}{\tau}} \theta(t) \otimes G(t;\sigma_t) \right] \cdot \mathcal{E}(t)$$

PDF normalization | theory model | t-resolution function | t-acceptance function

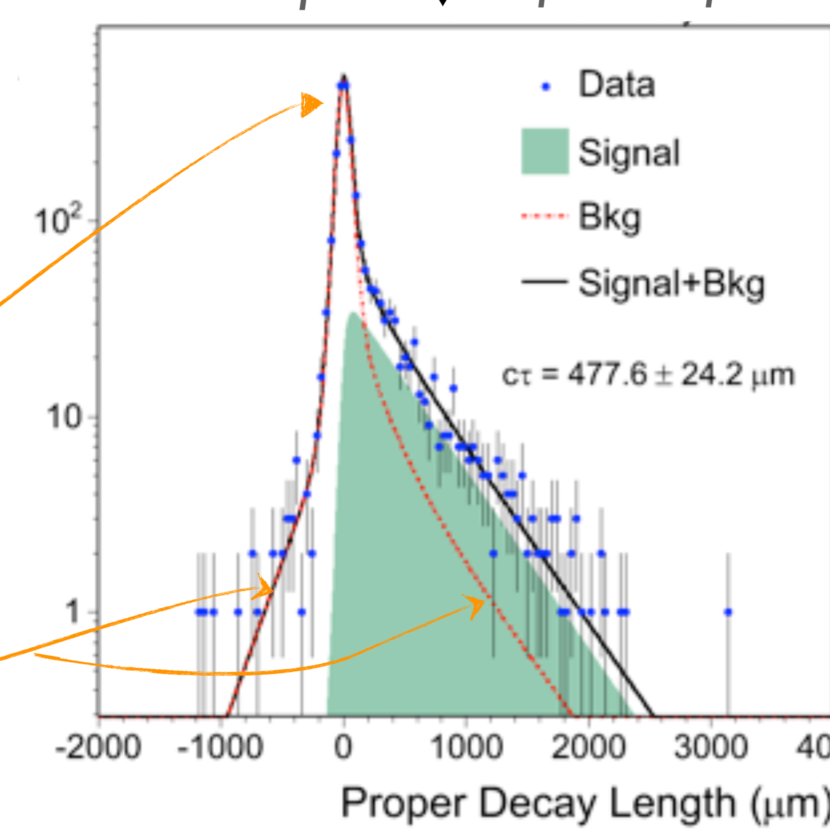
- t-resolution
  - use per-event uncertainties σ_t (more precisely reco'd B's get larger weight)
  - calibrate using data (high stat. modes)

$$\sigma_t \mapsto S_t \cdot \sigma_t$$

- trigger/selection bias
  - vertex detachment requirements used in selection bias t-distribution, requires acceptance correction, $\varepsilon(t)$
- backgrounds
  - prompt, $\delta(t)$ (→ resolution)
  - long-lived (from decay products of other b-hadrons)

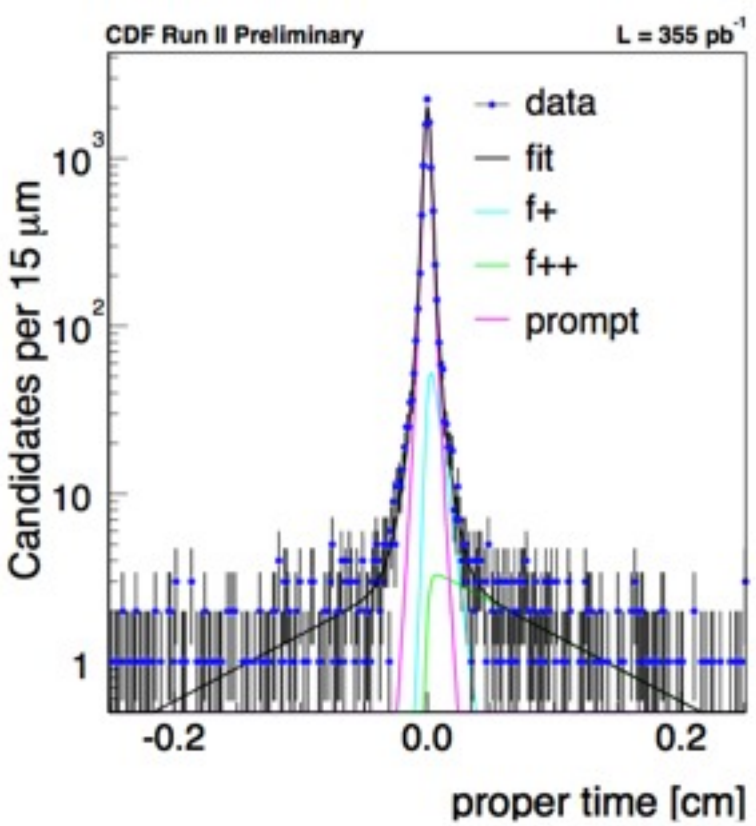


example ⇓ *lifetime fit*



[t-resolution, σ_t]

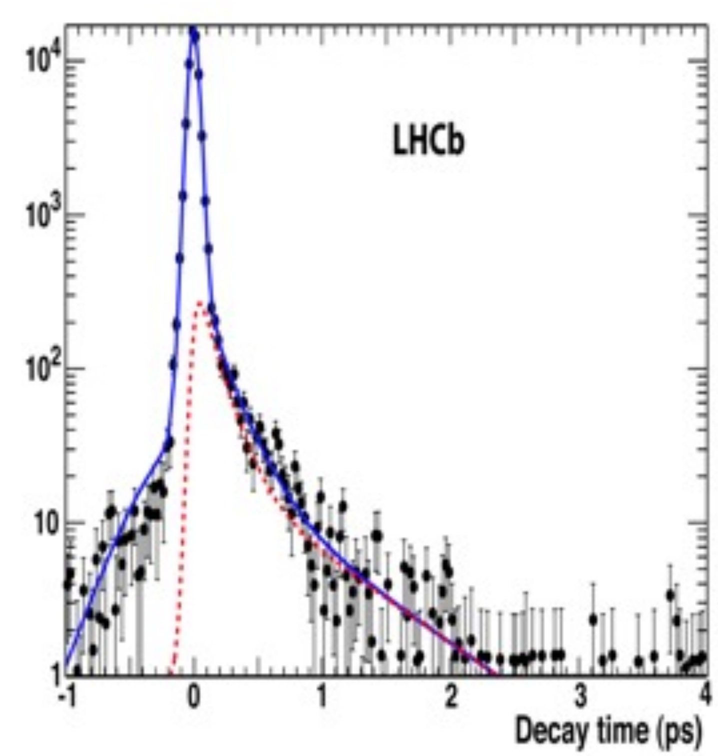
- σ_t may be taken per-event from the vertex kinematic fit
- should be calibrated, using data
- a possible strategy (CDF, also used for example by LHCb)
  - *if* dataset is t-*un*biased: fit prompt peak with scale factor, $e^{-\Gamma \cdot t} \otimes R(t, S_t . \sigma_t)$; *else*:
  - construct a prompt sample of B-like vertices, closely mimicking kinematics and topology of the signal; fit this sample as above, allowing for scale factor
  - to further facilitate transfer to signal sample, parameterize $S_t(\Delta R, l, \eta, z, X^2)$



CDF

signals:
B→Dπ,DlX
triggered by SVT

calibration sample:
SVT-displaced D +
prompt tracks



(PLB 713 (2012) 378)

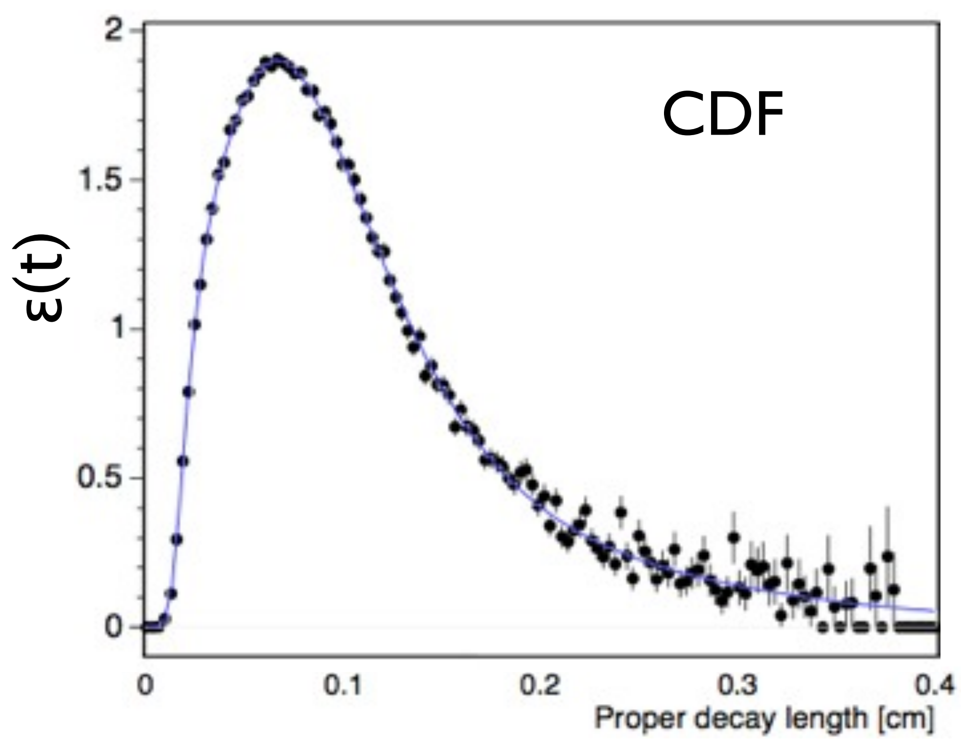
LHCb

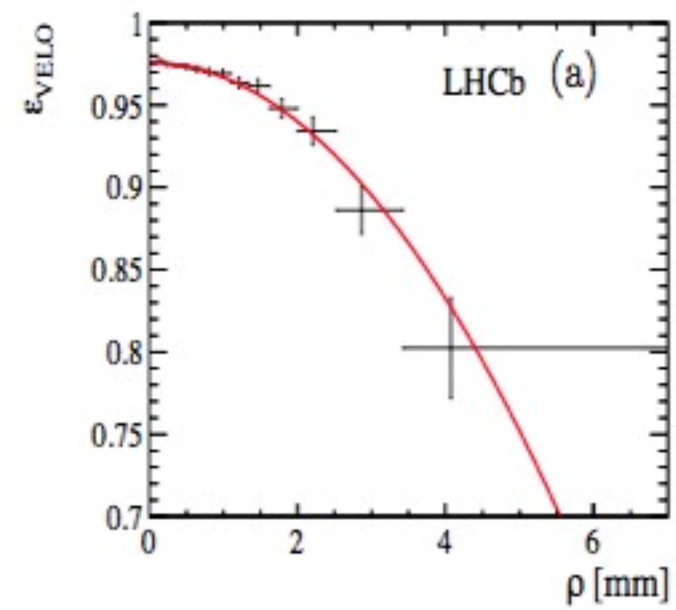
signal:
B→J/ψππ
displaced

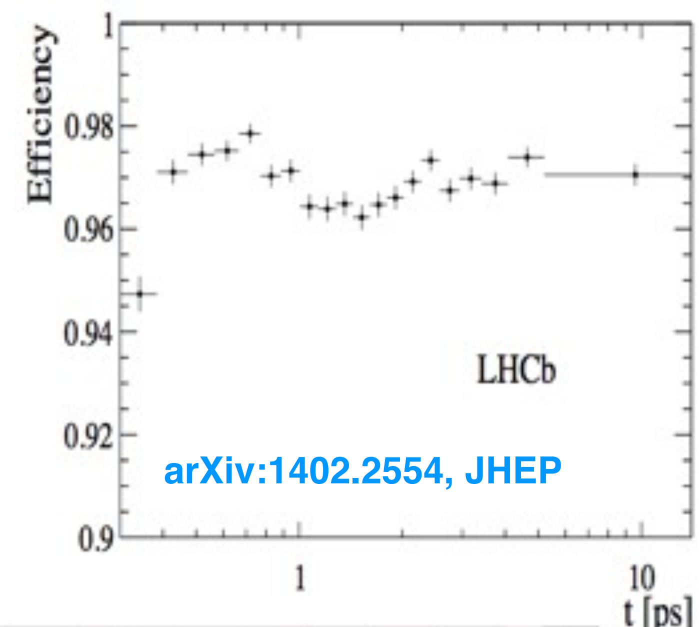
calibration sample:
prompt J/ψ +
prompt pion pair

[t–acceptance, ε(t)]

- *if* dataset is not biased, $\varepsilon(t)=1$
- *if* bias corresponds to a threshold (global or per-event) on L_{xy} or t, then the efficiency is given by a threshold function $\varepsilon(t)=\theta(t-t_0)$
- *if* a more general bias, $\varepsilon(t)$ can be estimated from MC or data



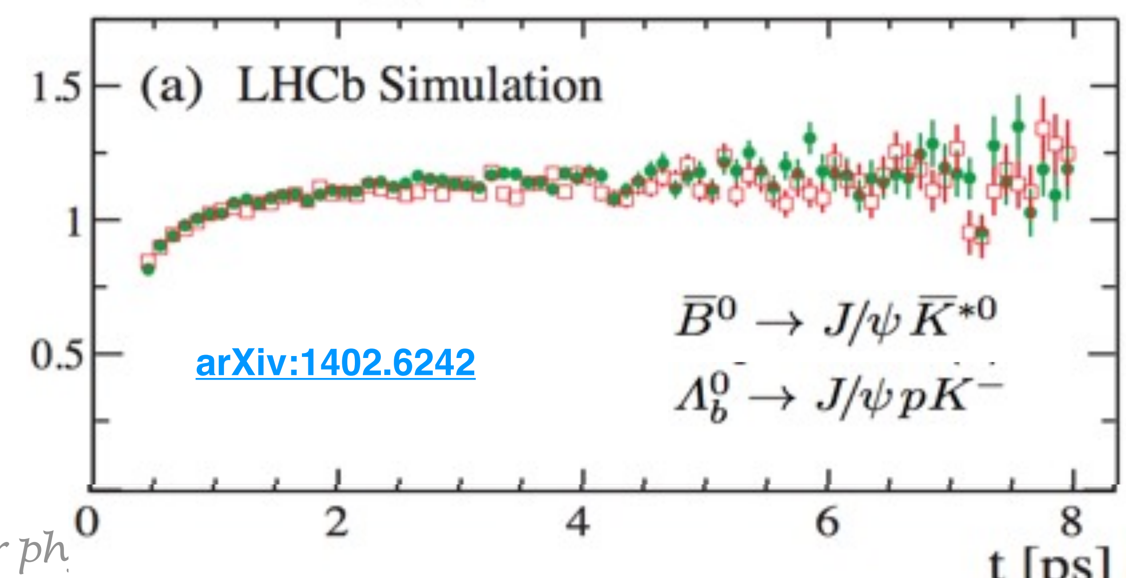




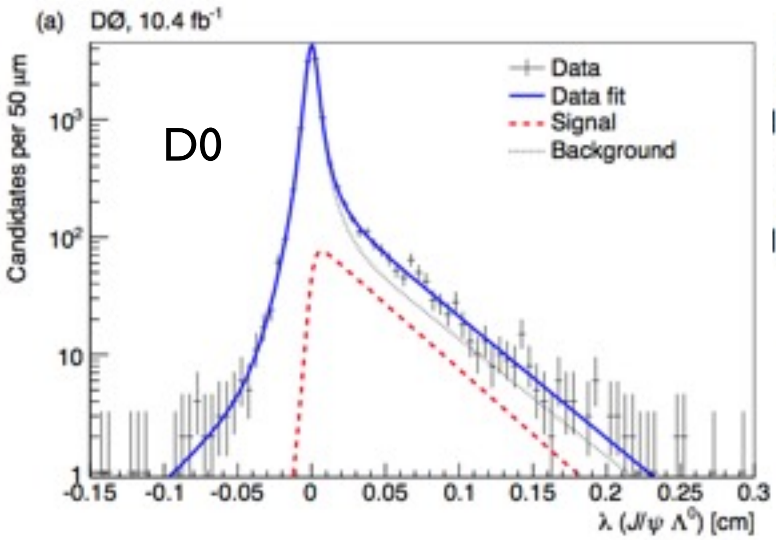
MC driven:

$$\mathcal{E}(t) = \frac{t\text{–distribution after selection}}{\sum_{\{\sigma_t\}} \frac{1}{\tau} e^{-t/\tau} \otimes G(t;\sigma_t)}$$

Data driven: PRD 83 (2011) 032008



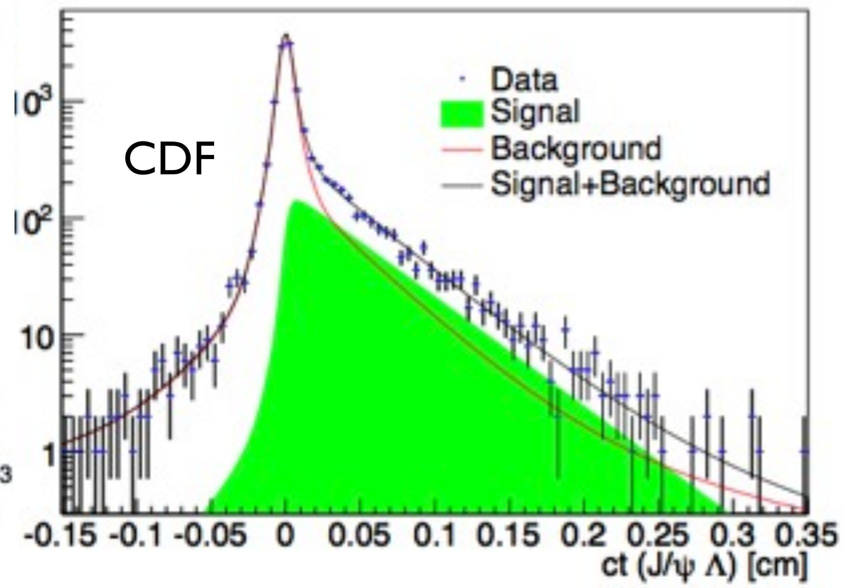
b-hadron lifetimes



PRD 85 (2012) 112003

τ(B^0) = 1.508 ± 0.025 ± 0.043 ps

τ(Λ_b) = 1.303 ± 0.075 ± 0.035 ps



PRL 106 (2011) 121804

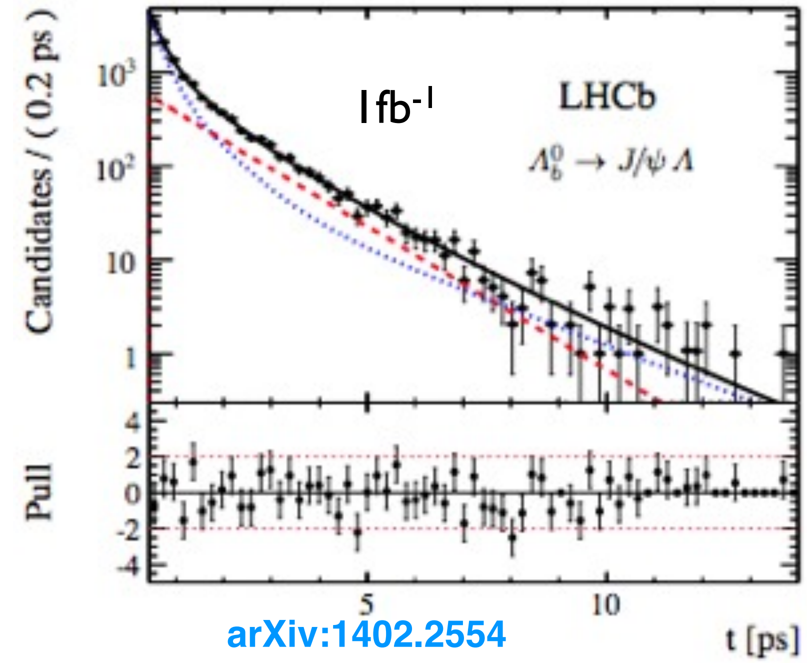
τ(B^+)=1.639 ± 0.009 ± 0.009 ps

τ(B^0)=1.507 ± 0.010 ± 0.008 ps

τ(Λ_b)=1.537 ± 0.045 ± 0.014 ps

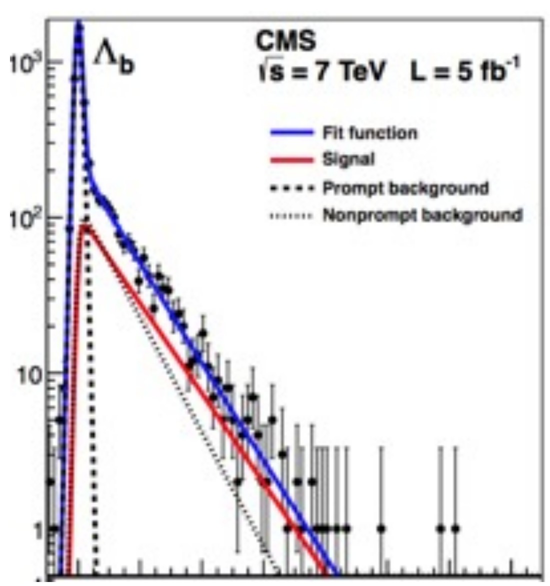
τ(B^+)/τ(B^0)=1.088 ± 0.009 ± 0.004

τ(Λ_b)/τ(B^0)=1.020 ± 0.030 ± 0.008



arXiv:1402.2554

$$\tau_{B^+\to J/\psi K^+} = 1.637 \pm 0.004 \pm 0.003 \text{ ps}$$
$$\tau_{B^0\to J/\psi K^{*0}} = 1.524 \pm 0.006 \pm 0.004 \text{ ps}$$
$$\tau_{B^0\to J/\psi K^0_S} = 1.499 \pm 0.013 \pm 0.005 \text{ ps}$$
$$\tau_{\Lambda_b^0\to J/\psi \Lambda} = 1.415 \pm 0.027 \pm 0.006 \text{ ps}$$
$$\tau_{B_s^0\to J/\psi \phi} = 1.480 \pm 0.011 \pm 0.005 \text{ ps}$$

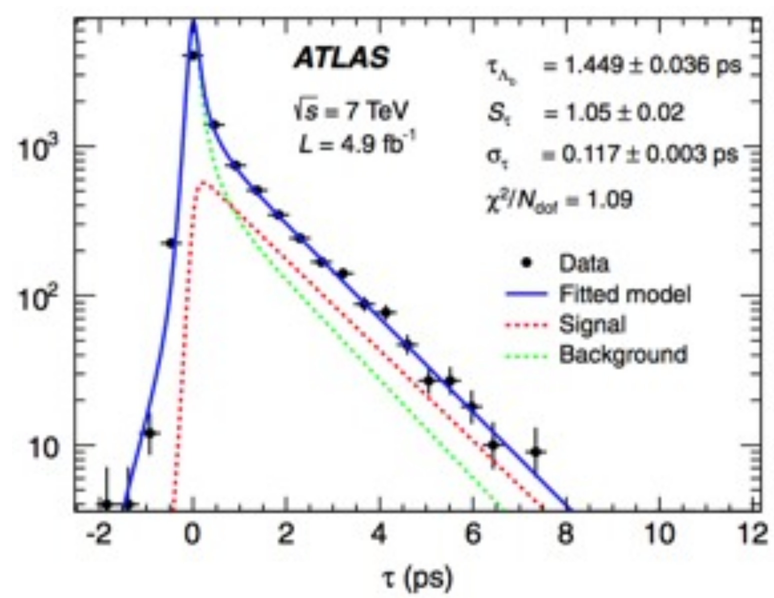


JHEP 07 (2013) 163

τ(Λ_b) =
1.503 ± 0.052 ± 0.031 ps

PRD 87 (2013) 032002

τ(Λ_b) =
1.449 ± 0.036 ± 0.017 ps



PDG 2013
B^0 1.519 ± 0.007 ps
B^+ 1.641 ± 0.008 ps
B_s 1.516 ± 0.011 ps
B_c 0.452 ± 0.033 ps
Λ_b 1.429 ± 0.024 ps

flavor oscillations

&

flavor tagging

quantum mechanics (ii)

- allowing for a flavor-changing perturbation (ΔF) in the hamiltonian

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{\Delta F} \qquad i\,\frac{d}{dt}\psi = \mathcal{H}\,\psi \qquad i\,\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} m - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & m - \frac{i}{2}\Gamma \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix}$$

$$|\psi\rangle = a\,|P^0\rangle + b\,|\bar{P}^0\rangle$$

- a pure flavor eigenstate at t=0 will evolve to an admixture
  - non-diagonal elements in H ⇒ flavor eigenstates differ from mass eigenstates
- flavor eigenstates

$$|P_L\rangle = p\,|P^0\rangle + q\,|\bar{P}^0\rangle$$
$$|P_H\rangle = p\,|P^0\rangle - q\,|\bar{P}^0\rangle$$

with $|p|^2 + |q|^2 = 1$

- time evolution of flavor eigenstates (after finding H eigenvalues $\lambda_{H,L}$)

$$|P_{L,H}\rangle_t = e^{-i\,\lambda_{L,H}\,t}\,|P_{L,H}\rangle = e^{-i\,m_{L,H}\,t - \frac{1}{2}\Gamma_{L,H}\,t}\,|P_{L,H}\rangle$$

- probability for particle-antiparticle transition

$$|\langle P^0|\mathcal{H}|\bar{P}^0\rangle|^2 = \left|\frac{p}{q}\right|^4 |\langle \bar{P}^0|\mathcal{H}|P^0\rangle|^2 = \left|\frac{p}{q}\right|^2 \frac{1}{2}e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma}{2}\,t\right) - \cos\left(\Delta m\,t\right)\right]$$

  - with $\Delta\Gamma \equiv \Gamma_L - \Gamma_H$ and $\Delta m \equiv m_H - m_L$

- neglecting CPV in mixing (i.e. p/q=1) and ΔΓ, the mixing probability is:

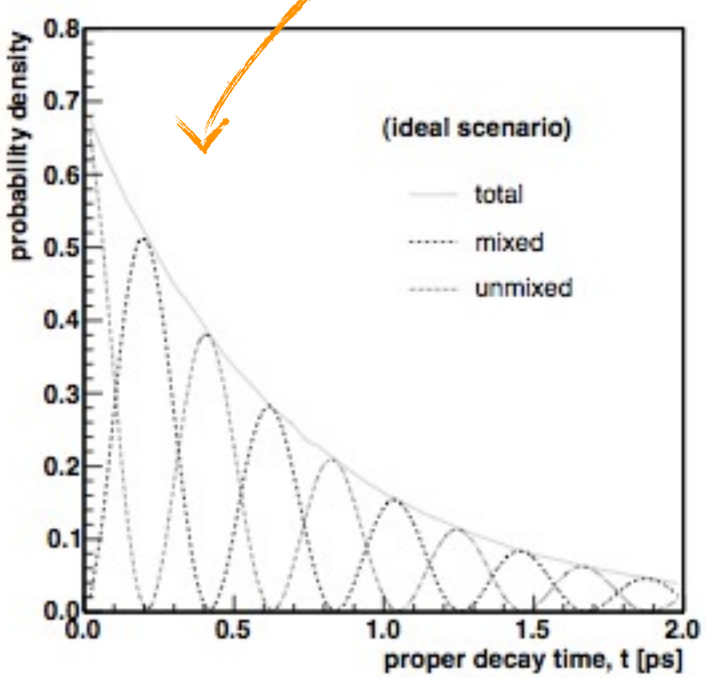
$$\mathcal{P}_{B_q^0 \to \bar{B}_q^0}(t) = \mathcal{P}_{\bar{B}_q^0 \to B_q^0}(t) = \frac{\Gamma}{2}e^{-\Gamma\,t}\left[1 - \cos\left(\Delta m\,t\right)\right]$$

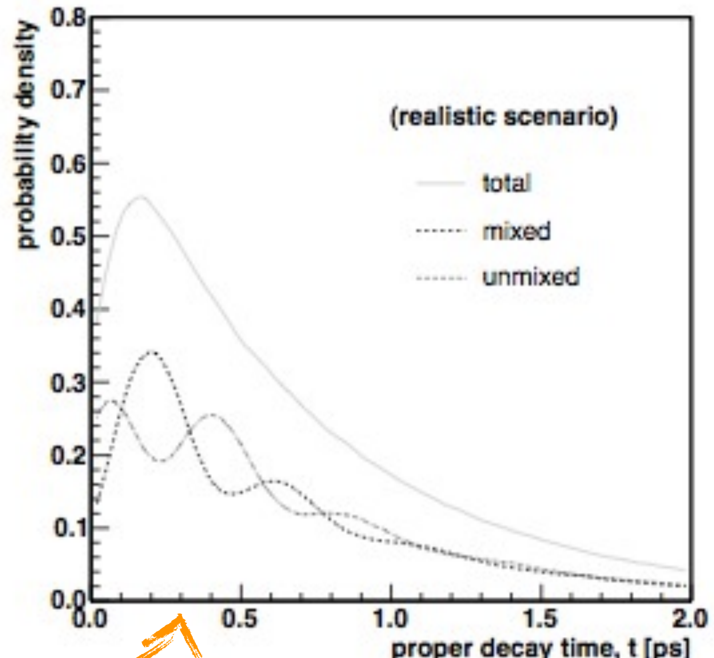
flavor oscillations

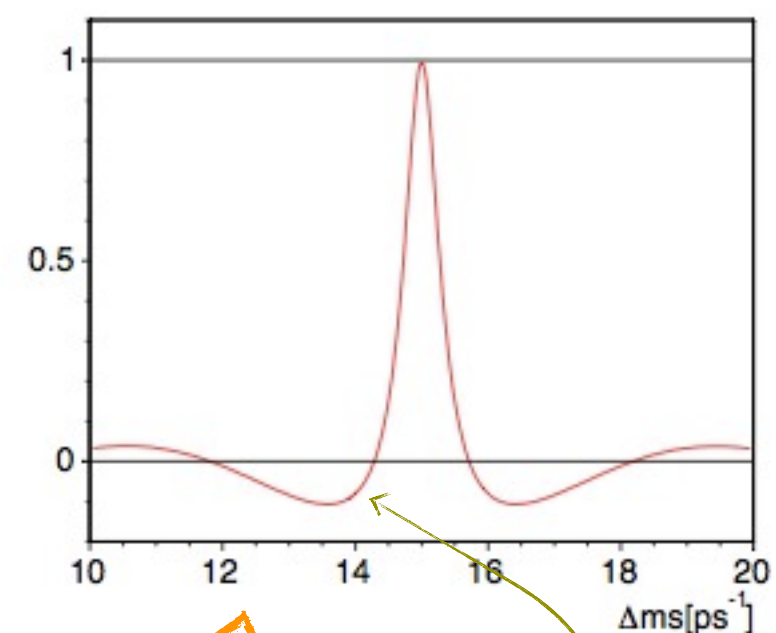
$$p(B \to B) = \frac{e^{-t/\tau}}{2\tau}(1 + \cos \Delta m t)$$

$$p(B \to \overline{B}) = \frac{e^{-t/\tau}}{2\tau}(1 - \cos \Delta m t)$$

oscillation frequency given by mass difference between heavy and light H eigenstates







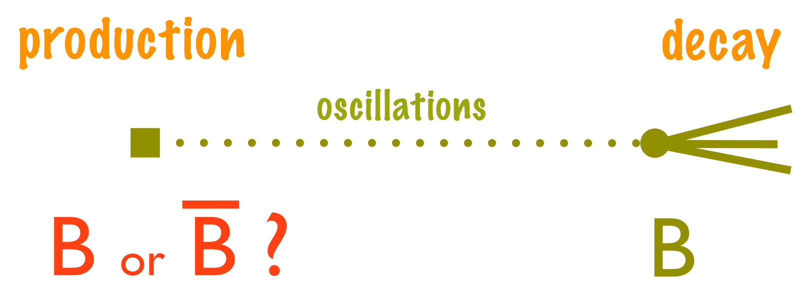
t-resolution, t-bias, dilution

Fourier transform

Exercise: show that a proper time cut $t>t_0$ induces undershootings besides the peak in the Fourier transform of the oscillation signal

- but... one critical ingredient still missing: need to known whether or not a given B candidate in the data has mixed ➠ flavor tagging

particle or antiparticle



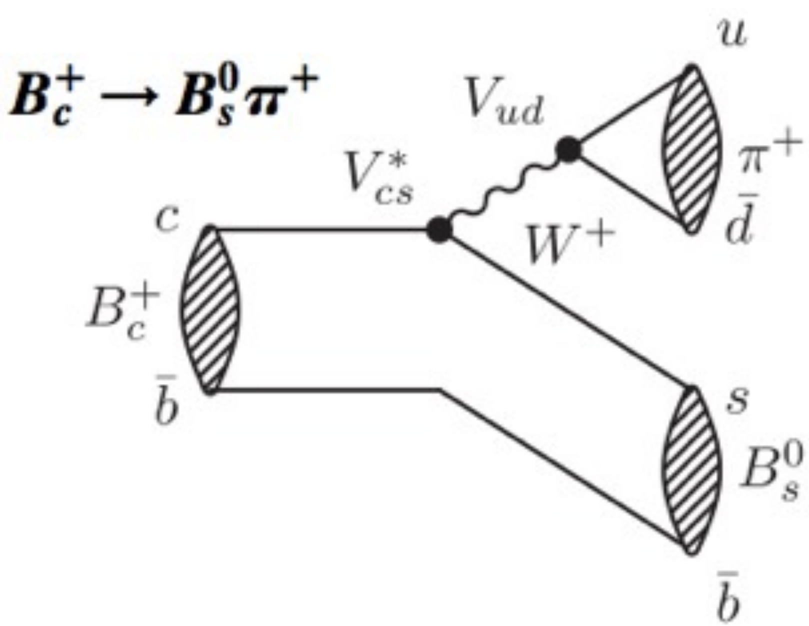
- (let ‘flavor’ here refer to the particle and antiparticle state)
- flavor at decay time:
  - trivially given by the charge of the decay products, if using flavor specific final states
  - (e.g. final flavor given by pion charge in $B_s \rightarrow D_s^- \pi^+$ *vs* $\underline{B_s} \rightarrow D_s^+ \pi^-$
- flavor at production time: ...

how may it be determined ??

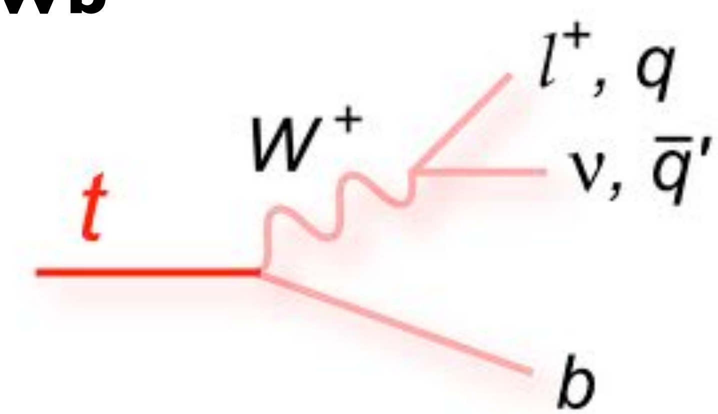
Exercise: think about it before resuming discussion in next 2 slides

how to tag?

- attempt #1: use B_s mesons from the decay of heavier particles



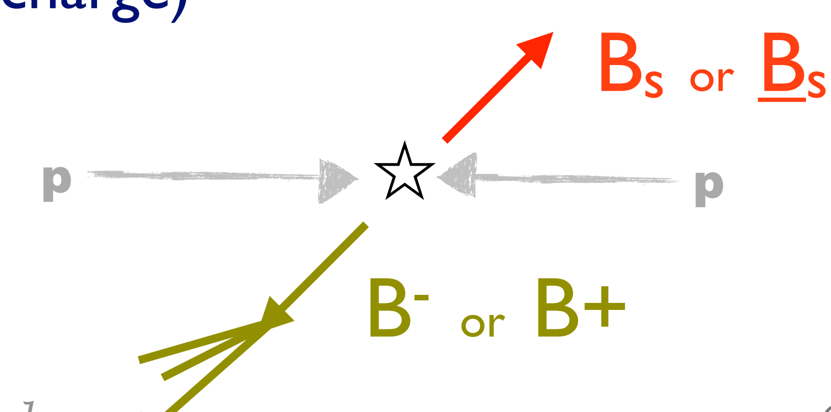
t→Wb



  - the initial B flavor (b or $\bar{b}$) could be inferred from the decay products of the heavier, parent state, eg from the charge of the pion in the examples

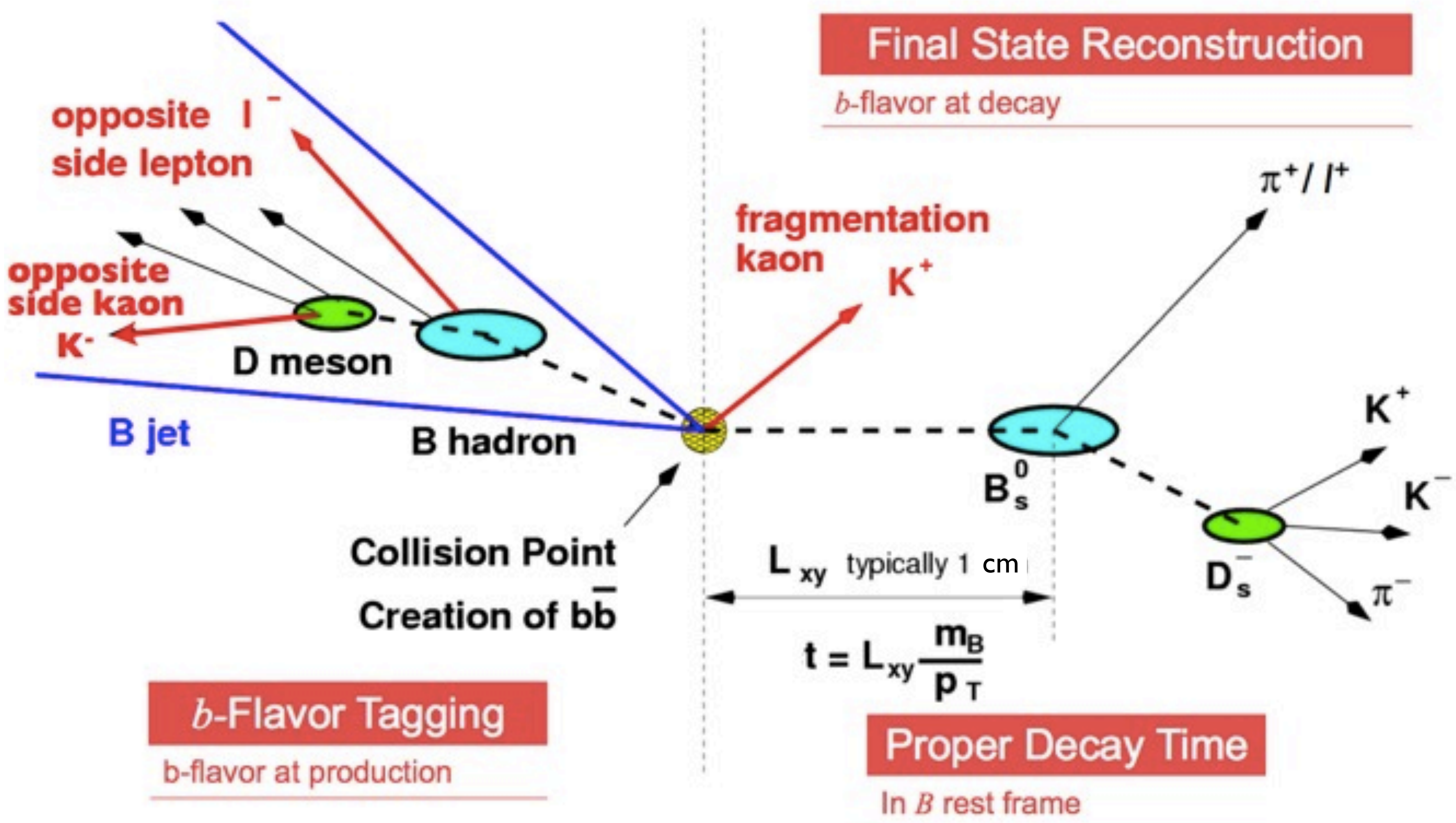
- attempt #2 : make use of the other b quark (from the originally produced $b\bar{b}$ pair), by reconstructing the other b-hadron in the event, say $B^\pm \to J/\psi K^\pm$ (flavor given by the kaon charge)

  - these possibilities are quite interesting! but given reconstruction inefficiencies (of parent or other B), very high signal statistics would/will be required...



➡ catch: infer flavor without full decay reconstruction

flavor tagging methods

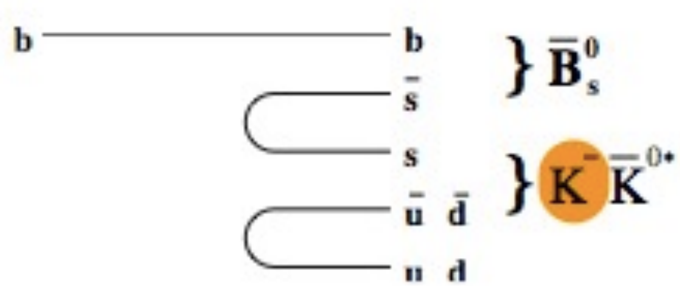


opposite-side tagging

- lepton (e,μ)
- jet-charge
- kaon

Exercise:
1.explain how B flavor oscillations cause an intrinsic dilution of the OST methods performance
2. show how the lepton tagger, based on semileptonic B decays ($B \to l$) is affected by sequential decays such as $B \to D \to l$

same-side tagging



Exercise: explain why the performance of SST (OST) should (not) depend on the species of B meson being tagged

dilution factors

- various effects decrease the amplitude of an oscillation signal

$$\left(\begin{matrix}\text{mixing}\\ \text{significance}\end{matrix}\right)^2 \sim \frac{\epsilon D^2 S}{2}\cdot\frac{S}{S+B}\cdot e^{-\sigma_t^2 w^2}$$

flavor tagging | signal yield | signal purity | proper time resolution

oscillation frequency w

Exercise: explain why the t-resolution is even more determining for B_s than B_d mixing

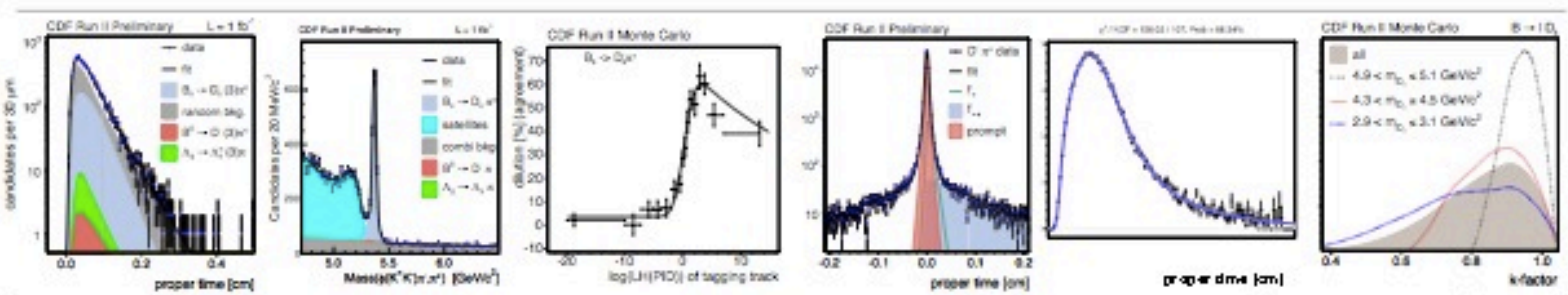
- tagging power εD^2 is given by the algorithm efficiency ε and dilution $D=(1-2w)^2$ where w is the wrong-tag fraction (i.e. probability algorithm gives wrong decision)
- it determines the effective statistical reduction of the sample size: S ➠ S . $\varepsilon_{tag}D^2$

tagger \ εD^2	CDF	D0	ATLAS	CMS	LHCb
for decay $B_s \to J/\psi\Phi$	1.39±0.05% [OST] 3.5±1.4% [SST] **~4.9%**	[OST+SST] 4.68±0.54% **~4.7%**	[OST] 1.45±0.05% **~1.5%**	[OST] **~1%**	2.43±0.08±0.26% [OST] 0.89±0.06% [SST] **~3.3%**

mixing model

$$\mathcal{L} = \mathcal{L}_{mass} \cdot \mathcal{L}_t \cdot \mathcal{L}_{\sigma_t} \cdot \mathcal{L}_D$$

[for each sample component & event]



$$\mathcal{L}_t = \frac{1}{N}\kappa \frac{e^{-\frac{\kappa t'}{\tau}}}{\tau} \frac{1 \pm A\, S_D\, D \cos(\Delta m_s\, \kappa\, t')}{2} \otimes R(t-t'; S_{\sigma_t}\sigma_t) \cdot \mathcal{E}(t) \otimes F(\kappa)$$

analytical computation (if need be)

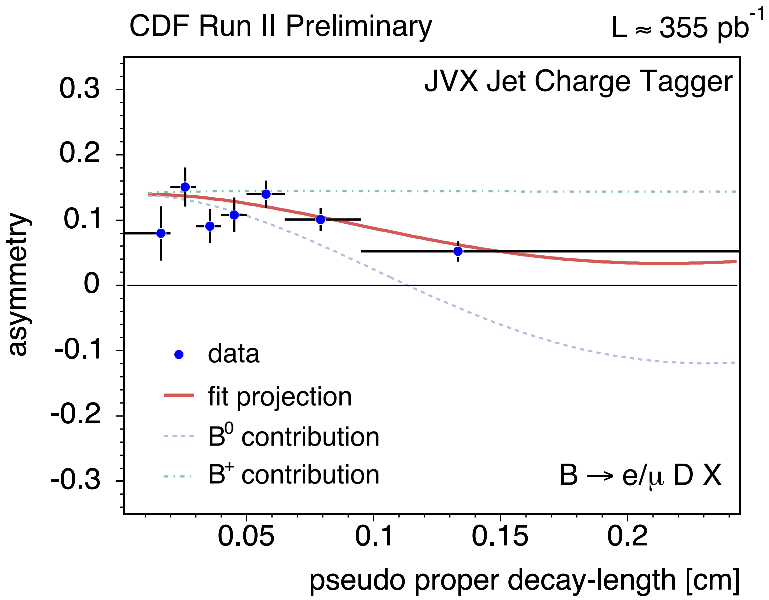
Frequency Δm_s

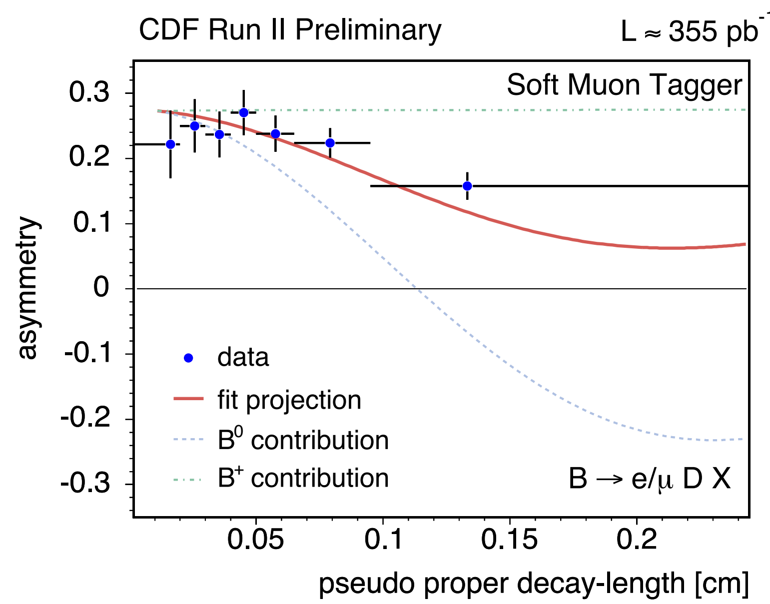
or

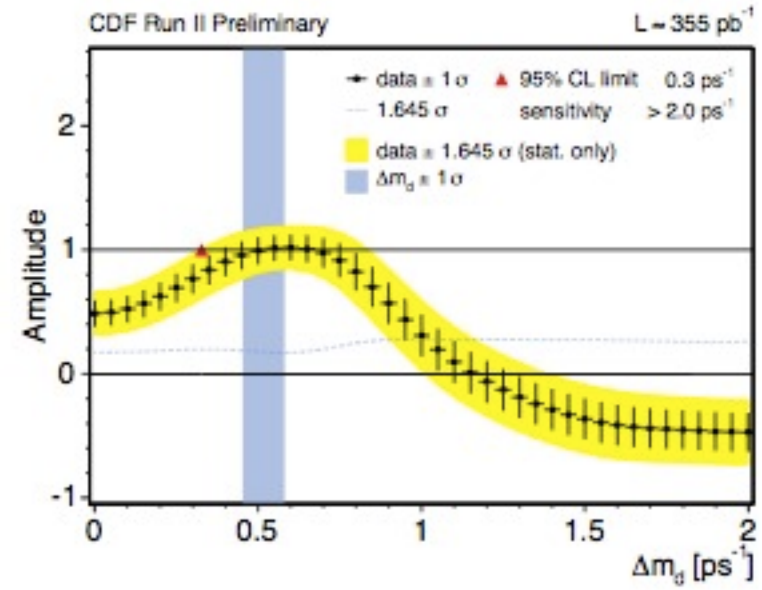
Amplitude (A, σ_A) for fixed Δm_s

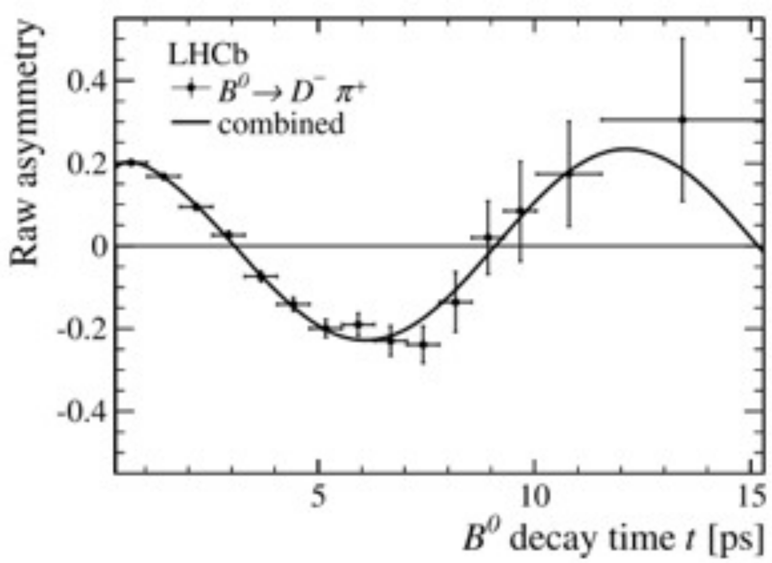
- ingredients: mass, proper time, proper time resolution, t-acceptance function, kinematic factor (for partially reco'd decays), and... flavor tagging

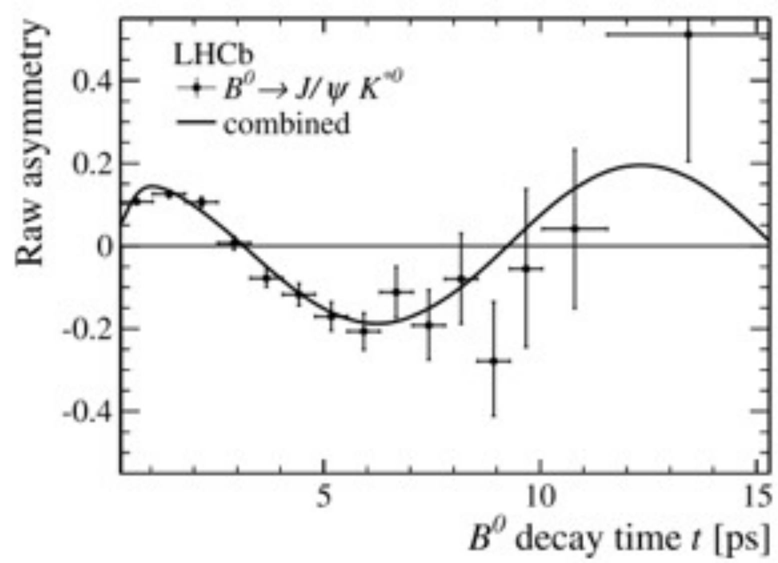
B_d mixing

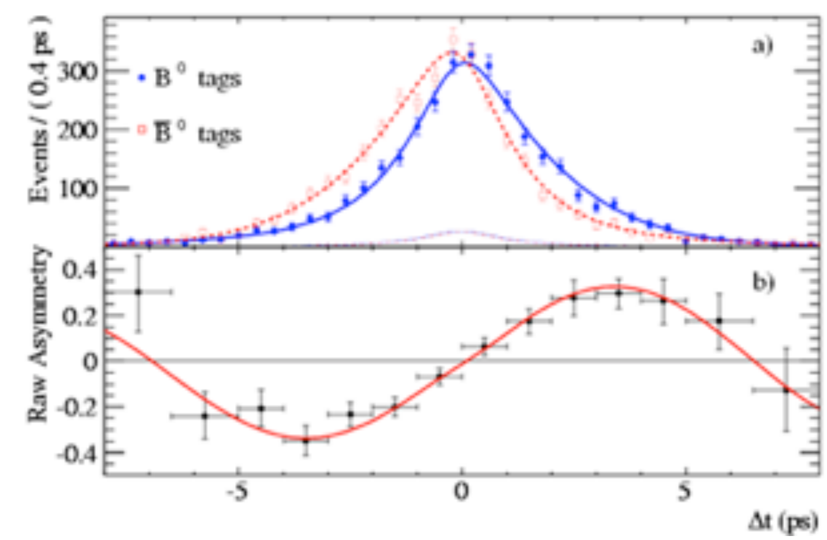






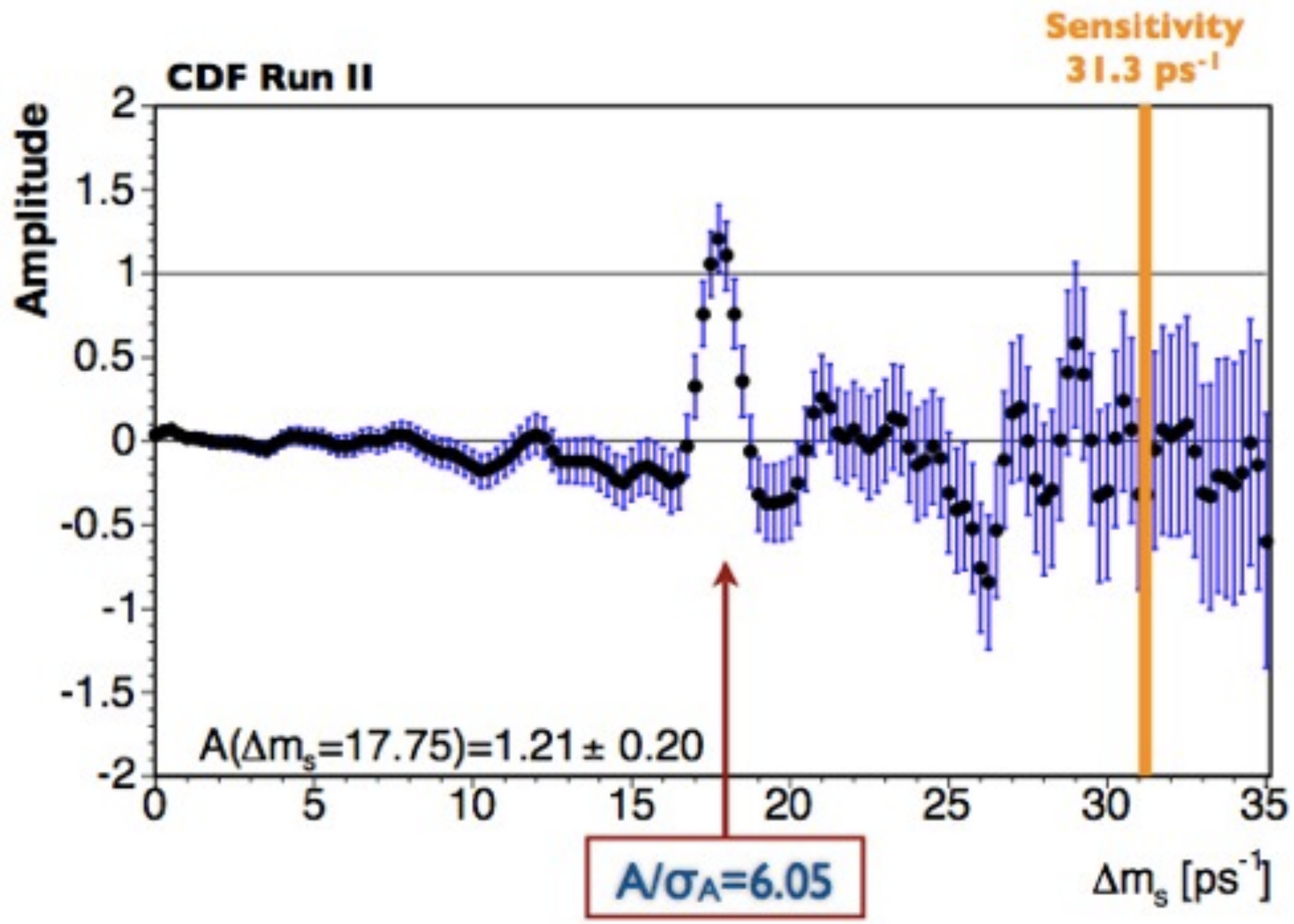


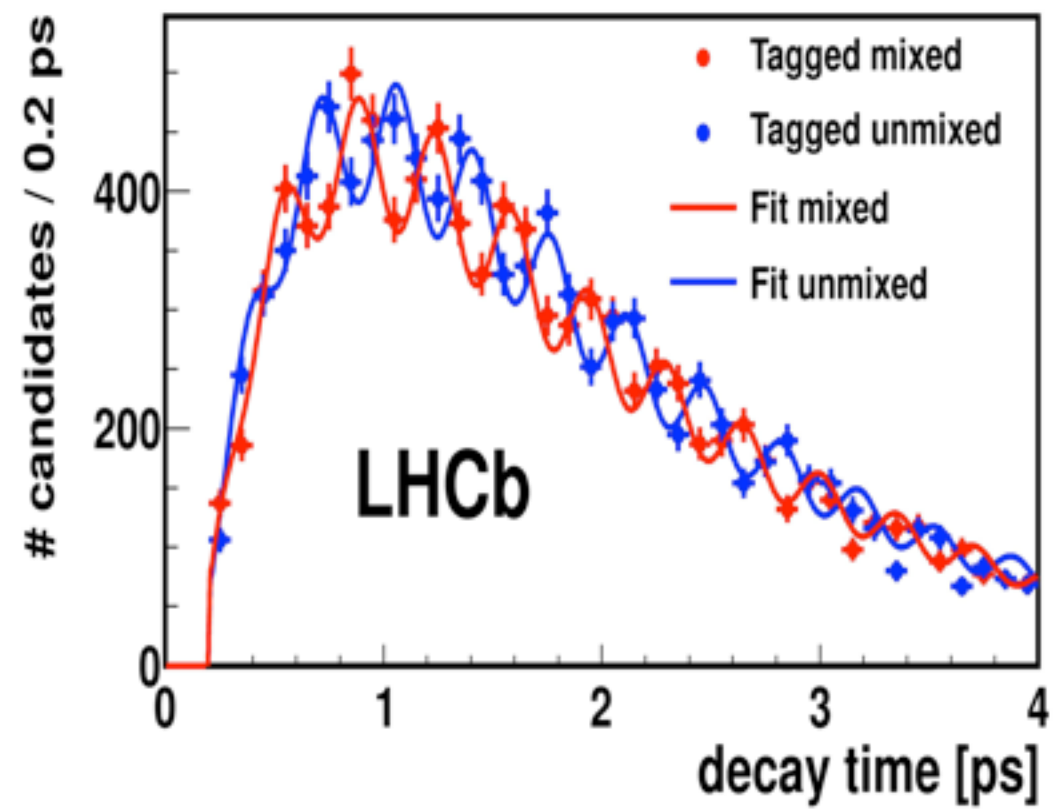




$\Delta m_d = 0.5156 \pm 0.0051\ (\text{stat.}) \pm 0.0033\ (\text{syst.})\ \text{ps}^{-1}$ (most precise measurement)

B_s mixing





frequency space ⇔ time space

observation by CDF (2006)

p-value = 8×10^{-8} corresponding to 5.4σ

$\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})$ ps-1

LHCb confirmed (improved precision)

$\Delta m_s = 17.768 \pm 0.023$ (stat) ± 0.006 (syst) ps^{-1}

In agreement with SM expectation $\Delta m_s = 17.3 \pm 2.6\ ps^{-1}$ [arXiv: 1102.4274]

note: experimental precision $O(10^2)$ times better than theory calculation

CP violation

quantum mechanics (iii)

- discrete symmetries
  - **C**harge conjugation: particle→ antiparticle
  - **P**arity: x→-x
  - **T**ime reversal: t →-t
- C and P are maximally violated in weak interactions
  - no right handed neutrinos, no left-handed antineutrinos)
- CPT is conserved in any Lorentz invariant gauge field theory; thus, CP⇔T

- under CP, an operator O(**x**,t) transforms as $O(\vec{x},t) \to O^{\dagger}(-\vec{x},t)$
- the effective Lagrangian (L=L†) has the structure $\mathcal{L} = aO + a^{*}O^{\dagger} \overset{CP}{\to} aO^{\dagger} + a^{*}O = \mathcal{L}$
  - CP violation thus requires $a^{*} \neq a$, i.e. a complex phase

- Yuakawa term $-\mathcal{L}_{Yukawa} = Y_{ij}\overline{\psi_{Li}}\,\phi\,\psi_{Rj} + Y_{ij}^{*}\overline{\psi_{Rj}}\,\phi^{\dagger}\,\psi_{Li}$
- Charged current term $\mathcal{L}_W = \frac{g}{\sqrt{2}}\overline{u_{iL}}V_{ij}\gamma_\mu W^{-\mu}d_{iL} + \frac{g}{\sqrt{2}}\overline{d_{iL}}V_{ij}^{*}\gamma_\mu W^{+\mu}u_{iL}$

Exercise: verify that CP invariance applied to Yukawa and W currents would imply $Y_{ij}=Y_{ij}^{*}$ and $V_{ij}=V_{ij}^{*}$ using CP transformations recalled in tables below

Field		P	C
Scalar field	$\phi(\vec{x},t)$	$\phi(-\vec{x},t)$	$\phi^{\dagger}(\vec{x},t)$
Dirac spinor	$\psi(\vec{x},t)$	$\gamma^0\psi(-\vec{x},t)$	$i\gamma^2\gamma^0\overline{\psi}^T(\vec{x},t)$
	$\overline{\psi}(\vec{x},t)$	$\overline{\psi}(-\vec{x},t)\gamma^0$	$-\psi^T(\vec{x},t)C^{-1}$
Axial vector field	$A_\mu(\vec{x},t)$	$-A^\mu(-\vec{x},t)$	$A_\mu^{\dagger}(\vec{x},t)$

	Bilinear	P	C	T	CP	CPT
scalar	$\overline{\psi}_1\psi_2$	$\overline{\psi}_1\psi_2$	$\overline{\psi}_2\psi_1$	$\overline{\psi}_1\psi_2$	$\overline{\psi}_2\psi_1$	$\overline{\psi}_2\psi_1$
pseudo scalar	$\overline{\psi}_1\gamma_5\psi_2$	$-\overline{\psi}_1\gamma_5\psi_2$	$\overline{\psi}_2\gamma_5\psi_1$	$-\overline{\psi}_1\gamma_5\psi_2$	$-\overline{\psi}_2\gamma_5\psi_1$	$\overline{\psi}_2\gamma_5\psi_1$
vector	$\overline{\psi}_1\gamma_\mu\psi_2$	$\overline{\psi}_1\gamma^\mu\psi_2$	$-\overline{\psi}_2\gamma_\mu\psi_1$	$\overline{\psi}_1\gamma^\mu\psi_2$	$-\overline{\psi}_2\gamma^\mu\psi_1$	$-\overline{\psi}_2\gamma_\mu\psi_1$
axial vector	$\overline{\psi}_1\gamma_\mu\gamma_5\psi_2$	$-\overline{\psi}_1\gamma^\mu\gamma_5\psi_2$	$\overline{\psi}_2\gamma_\mu\gamma_5\psi_1$	$\overline{\psi}_1\gamma^\mu\gamma_5\psi_2$	$-\overline{\psi}_2\gamma^\mu\gamma_5\psi_1$	$-\overline{\psi}_2\gamma_\mu\gamma_5\psi_1$
tensor	$\overline{\psi}_1\sigma_{\mu\nu}\psi_2$	$\overline{\psi}_1\sigma^{\mu\nu}\psi_2$	$-\overline{\psi}_2\sigma_{\mu\nu}\psi_1$	$-\overline{\psi}_1\sigma^{\mu\nu}\psi_2$	$-\overline{\psi}_2\sigma^{\mu\nu}\psi_1$	$\overline{\psi}_2\sigma_{\mu\nu}\psi_1$

quantum mechanics (iv)

- consider neutral meson P^0 decays to a final state f
- the time dependent decay rates may be expressed as

$$\bar{A}(f) = \langle f|T|\bar{P}^0\rangle$$
$$A(f) = \langle f|T|P^0\rangle$$

$$\Gamma_{P^0\to f}(t) = |A_f|^2 (1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t + D_f \sinh\frac{1}{2}\Delta\Gamma t + C_f\cos\Delta m t - S_f \sin\Delta m t\right)$$

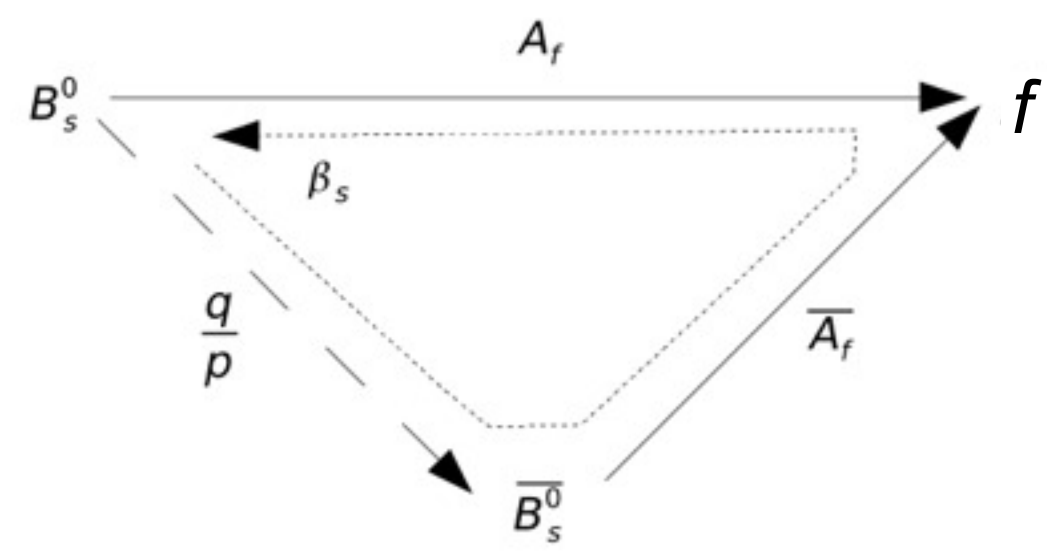
$$\Gamma_{\bar{P}^0\to f}(t) = |A_f|^2 \left|\frac{p}{q}\right|^2 (1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t + D_f \sinh\frac{1}{2}\Delta\Gamma t - C_f\cos\Delta m t + S_f \sin\Delta m t\right)$$

- with $\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$ $\quad D_f = \frac{2\Re\lambda_f}{1+|\lambda_f|^2}$ $\quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$ $\quad S_f = \frac{2\Im\lambda_f}{1+|\lambda_f|^2}$
  - sin and sinh terms are associated to interference of decays with and without oscillation
- CP violation classification
  - CPV in decay $\quad \Gamma(P^0\to f) \neq \Gamma(\bar{P}^0\to\bar{f})$ $\quad \left|\frac{\bar{A}_f}{A_f}\right| \neq 1$
  - CPV in mixing $\quad \mathrm{Prob}(P^0\to\bar{P}^0) \neq \mathrm{Prob}(\bar{P}^0\to P^0)$ $\quad \left|\frac{q}{p}\right| \neq 1$
  - CPV in interference between decay with and without mixing $\quad \Gamma(P^0(\rightsquigarrow\bar{P}^0)\to f)(t) \neq \Gamma(\bar{P}^0(\rightsquigarrow P^0)\to f)(t)$ $\quad \Im\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$

$$A_{CP}(t) = \frac{\Gamma_{P^0(t)\to f} - \Gamma_{\bar{P}^0(t)\to f}}{\Gamma_{P^0(t)\to f} + \Gamma_{\bar{P}^0(t)\to f}} = \frac{2C_f\cos\Delta m t - 2S_f\sin\Delta m t}{2\cosh\frac{1}{2}\Delta\Gamma t + 2D_f\sinh\frac{1}{2}\Delta\Gamma t}$$

CPV in interference w/or w/o mixing

- defined by Im $\lambda_f \neq 0$
- available to modes in which both B and B decay to a same final state f
- example: $B_s \to J/\psi KK$, $J/\psi\pi\pi$

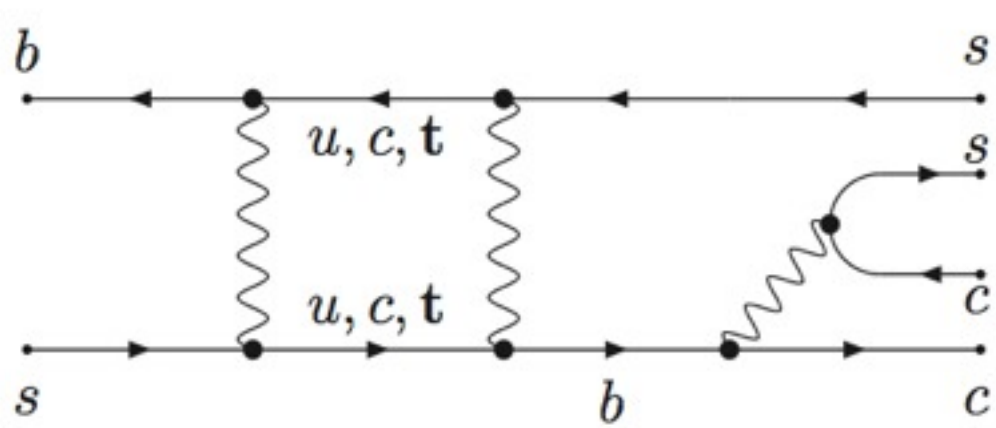


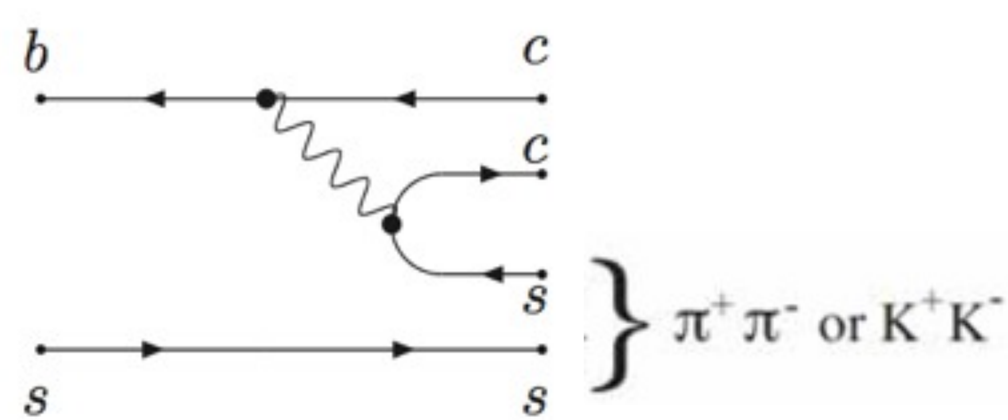
$\phi_s = \phi_s^{SM} + \phi_s^{NP}$

$\phi_{SM} \sim -0.04$
NP can add large phases

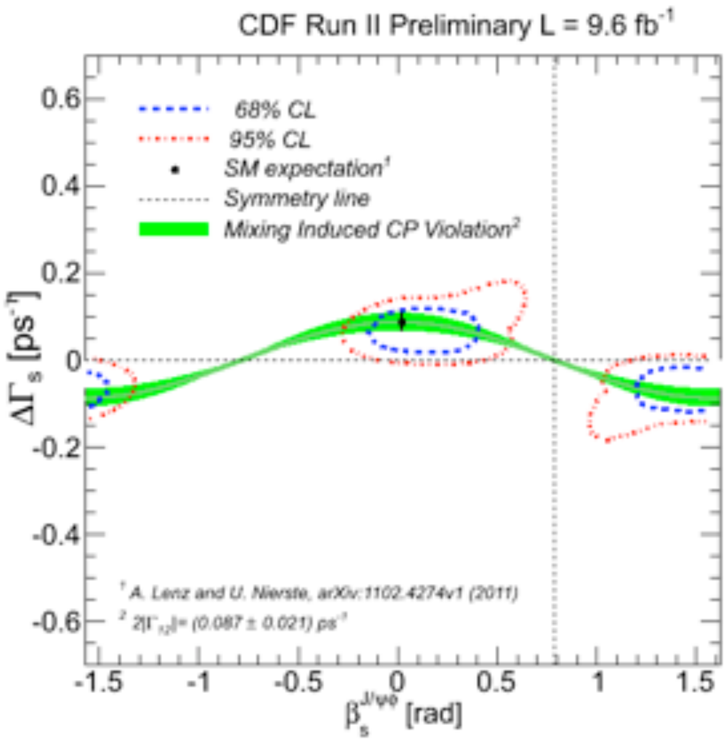
$$\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) = \mathcal{O}(\lambda^2)$$

$$2\beta_s \approx -\phi$$





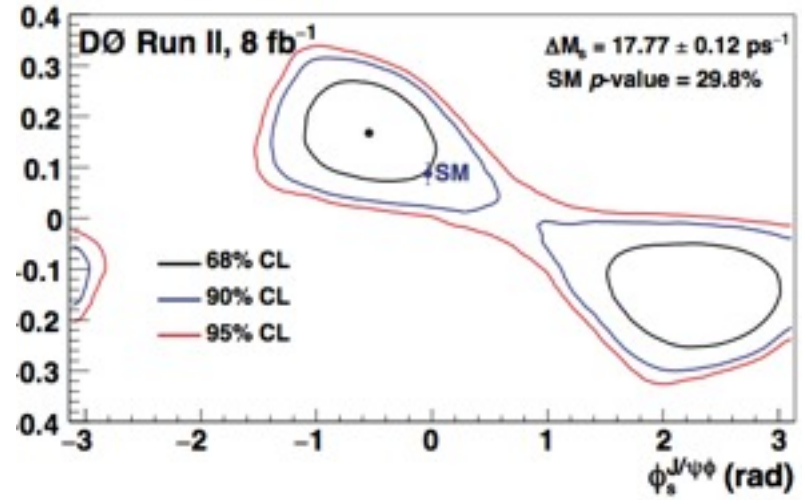
$B_s \to J/\psi\Phi$



PRL 109 (2012) 171802, CDF full Run II

$$\beta_s \in [-\pi/2, -1.51] \cup [-0.06, 0.30] \cup [1.26, \pi/2]$$

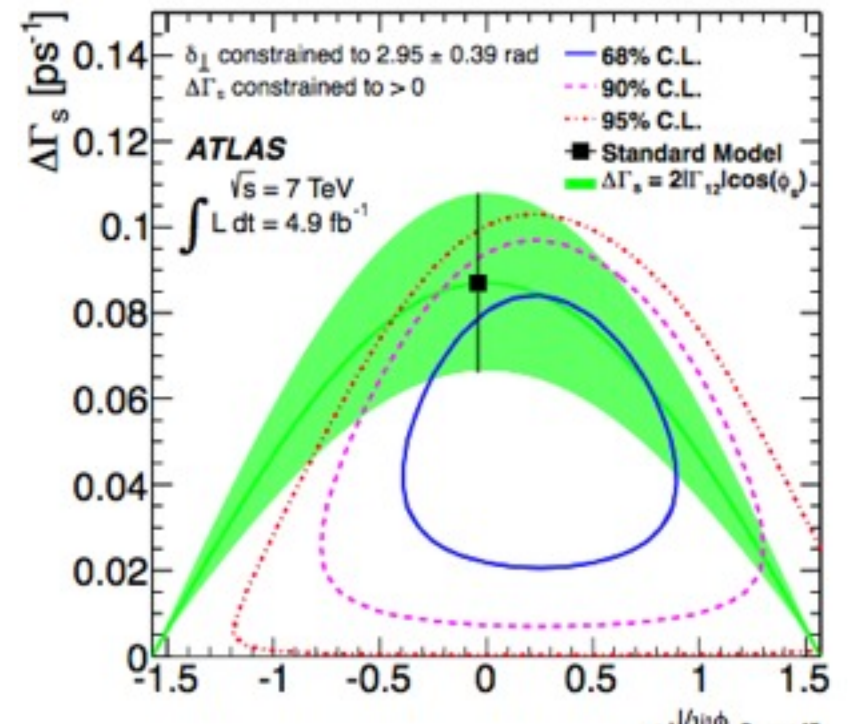
$$\Delta\Gamma_s = 0.068 \pm 0.026(\text{stat}) \pm 0.009(\text{syst})\ \text{ps}^{-1}$$



PRD 85 (2012) 032006, D0 8/fb

$$\phi_s^{J/\psi\phi} = -0.55^{+0.38}_{-0.36}$$

$$\Delta\Gamma_s = 0.163^{+0.065}_{-0.064}\ \text{ps}^{-1}$$

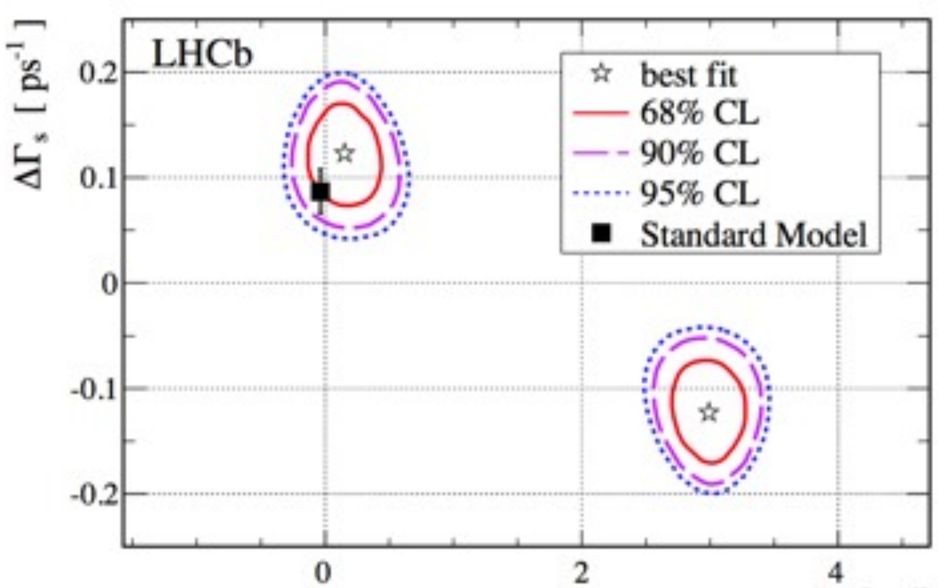


JHEP 1212 (2012) 072

(see also ATLAS-CONF-2013-039)

$$\phi_s = 0.22 \pm 0.41\ (\text{stat.}) \pm 0.10\ (\text{syst.})\ \text{rad}$$

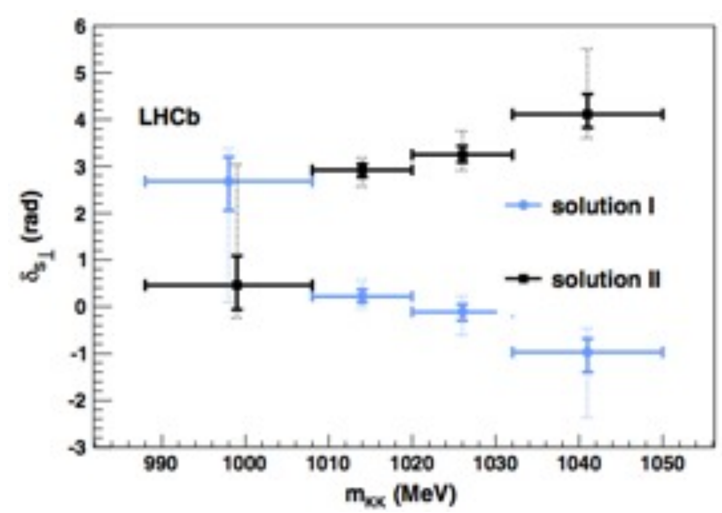
$$\Delta\Gamma_s = 0.053 \pm 0.021\ (\text{stat.}) \pm 0.010\ (\text{syst.})\ \text{ps}^{-1}$$



PRL 108 (2012) 101803

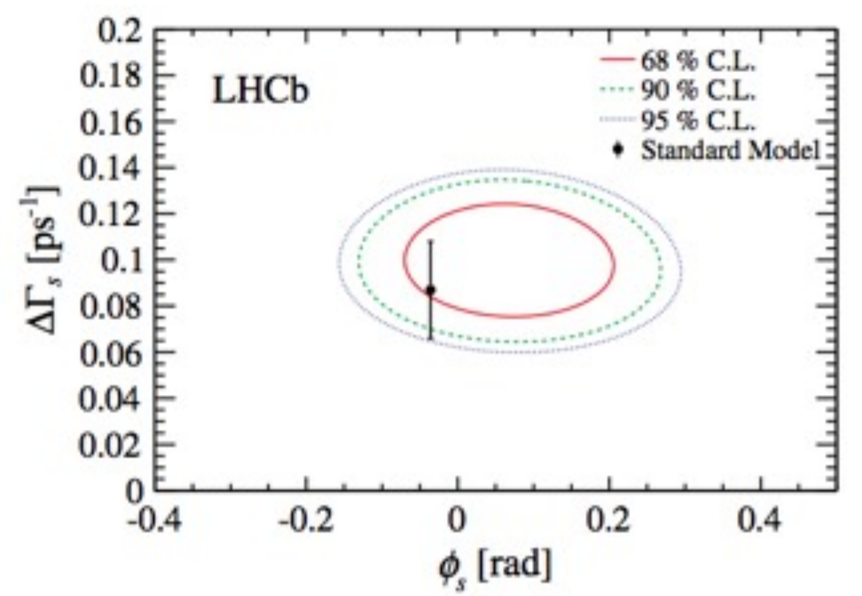
$$\phi_s = 0.15 \pm 0.18\ (\text{stat}) \pm 0.06\ (\text{syst})\ \text{rad}$$

$$\Delta\Gamma_s = 0.123 \pm 0.029\ (\text{stat}) \pm 0.011\ (\text{syst})\ \text{ps}^{-1}$$



PRL 108 (2012) 241801

Removal of sign ambiguity:
physical solution $\Delta\Gamma_s > 0$

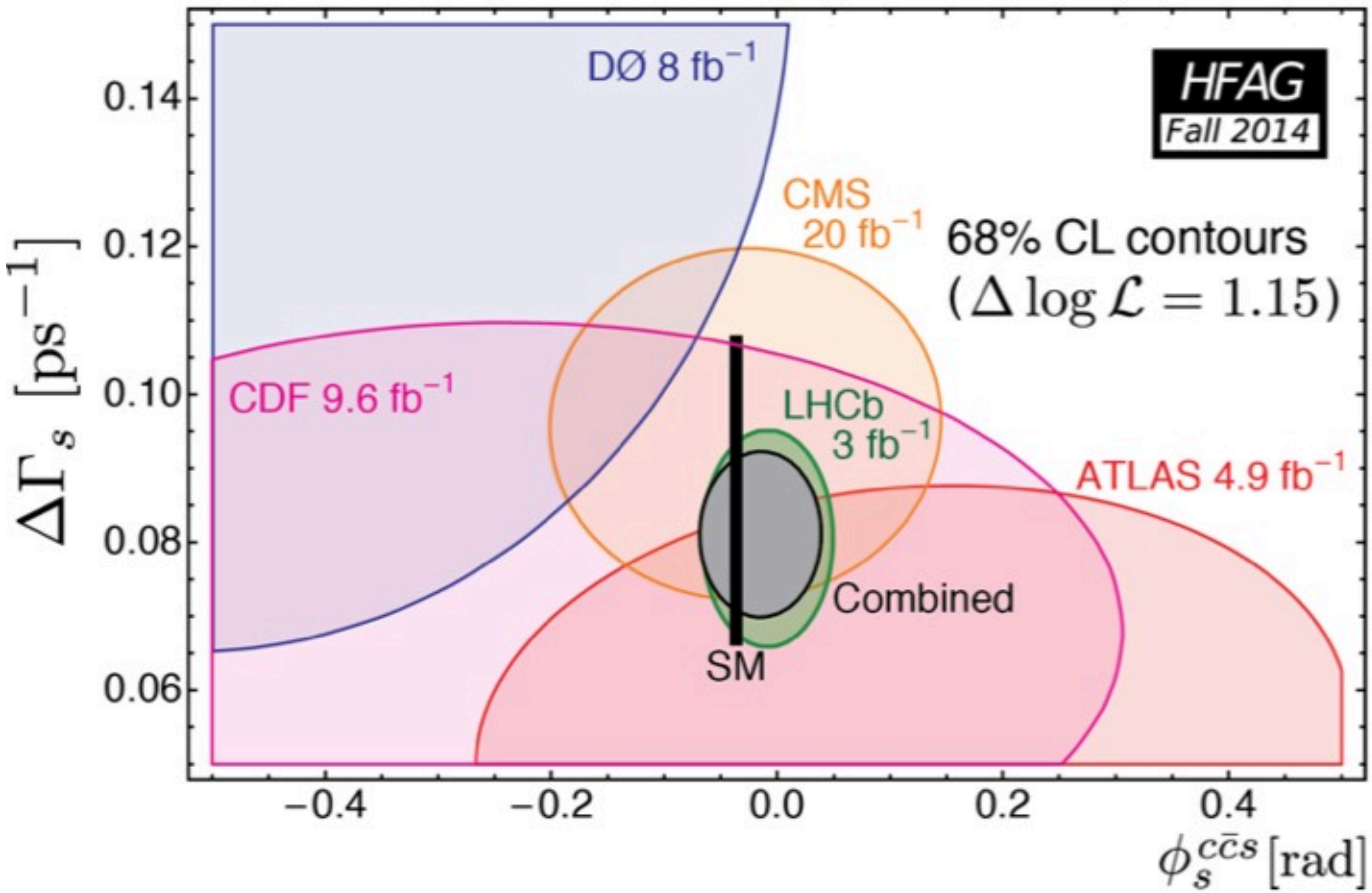


PRD 87 (2013) 112010

$$\phi_s = 0.07 \pm 0.09(\text{stat}) \pm 0.01(\text{syst})\ \text{rad},$$

$$\Delta\Gamma_s = 0.100 \pm 0.016(\text{stat}) \pm 0.003(\text{syst})\ \text{ps}^{-1}$$

ϕ_s & $\Delta\Gamma_s$ [world summary]



Experiment	$\Delta\Gamma_s$ (ps^{-1})	ϕ_s (rad)
ATLAS (4.9/fb)	0.053±0.021±0.010	0.12±0.25±0.05
CMS (20/fb)	0.096±0.014±0.007	−0.03±0.11±0.03
LHCb (3/fb)	0.0805±0.0091±0.0032	−0.058±0.049±0.006

← ← $B_s \to J/\psi \Phi$ (ATLAS, CMS)

← $B_s \to J/\psi KK$, $J/\psi \pi\pi$, $\Phi\Phi$ (LHCb)

rare decays

rare NP probes

- search for virtual contributions of new heavy particles in loops
- most interesting processes are those highly suppressed in SM
  - flavor-changing neutral current (FCNC), forbidden at tree level in SM
  - lepton flavor violation (LFV)
  - CKM suppressed
  - helicity suppressed
  - dominance of short distance effects, SM uncertainties under control
- experimental probes with precise theory prediction
  - uncertainty typically dominated by QCD; e.g. prefer leptonic to hadronic final states
- processes that may be modified (enhanced or suppressed) by orders of magnitude by NP
  - SUSY, 2HDM, LHT, Z', RS models ....

$$A(b \to \underset{s}{d})_{\mathrm{FCNC}} \sim c_{\mathrm{SM}} \frac{y_t^2 V_{td}^* V_{tb}}{16\pi^2 M_W^2} + c_{\mathrm{NP}} \frac{\delta_{3d}}{16\pi^2 \Lambda_{NP}^2}$$

quantum mechanics (v)

- Effective Hamiltonian (describing weak decay of hadron M into final state F)
  - expressed by means of an operator product expansion (OPE)

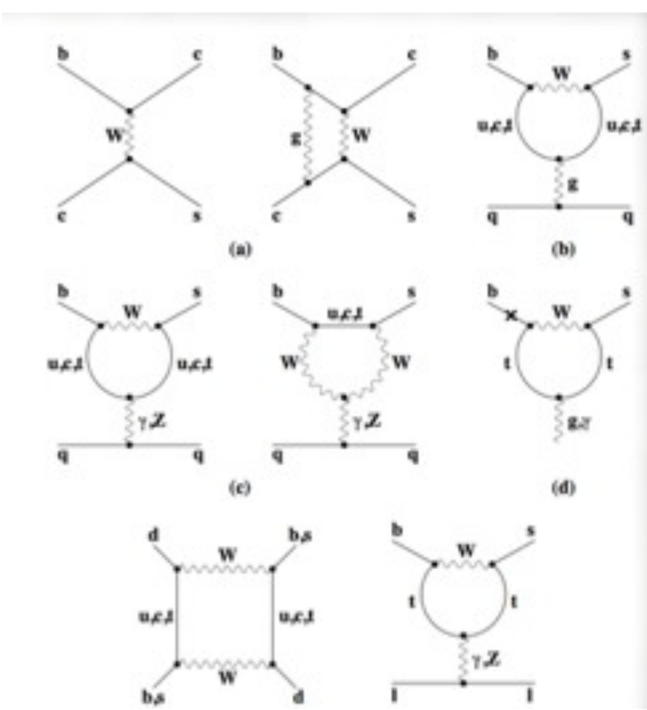
Fermi constant CKM matrix element

$$A(M \to F) = \langle F|\mathcal{H}_{eff}|M\rangle = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\mu) \langle F|Q_i(\mu)|M\rangle$$

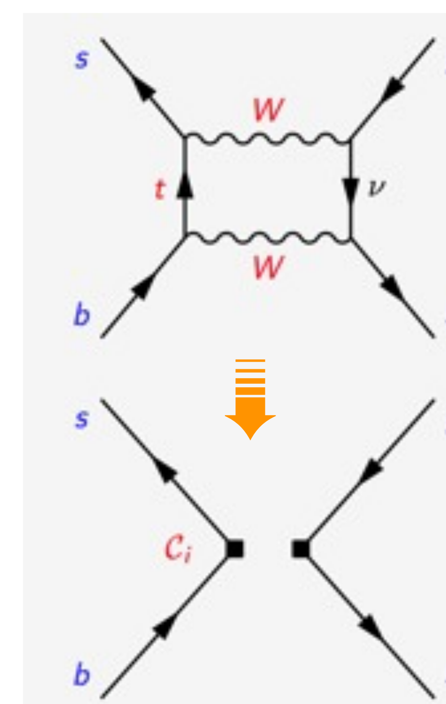
Wilson coefficient
short distance coupling (perturbative)

hadronic matrix element
long distance/non-perturbative

- new physics can modify C_i couplings and/or add new operators Q_i
- EFT for $b \to s l^+ l^-$ FCNC transitions

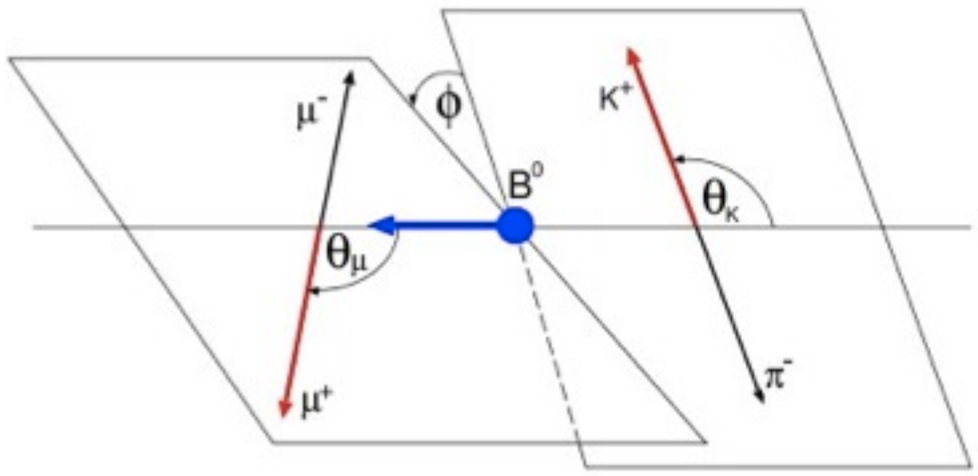


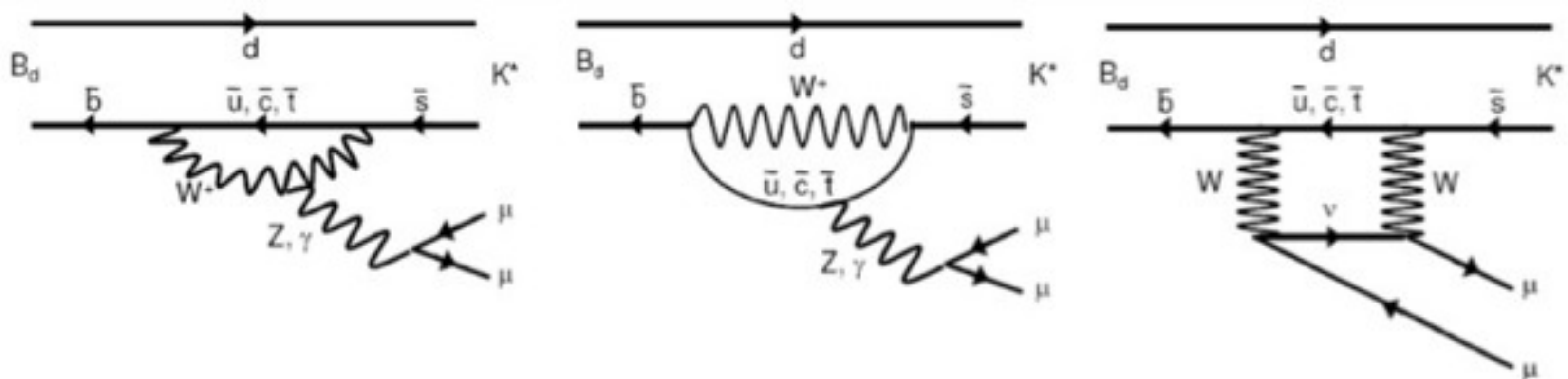
operator Q_i	$B \to K\mu\mu$	$B \to \mu\mu$
$\mathcal{O}_7 \sim m_b(\bar{s}_L \sigma_{\mu\nu} b_R) F_{\mu\nu}$	✔	
$\mathcal{O}_9 \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_V$	✔	
$\mathcal{O}_{10} \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_A$	✔	✔
$\mathcal{O}_{S,P} \sim (\bar{s}b)_{S+P}(\bar{\ell}\ell)_{S,P}$		✔



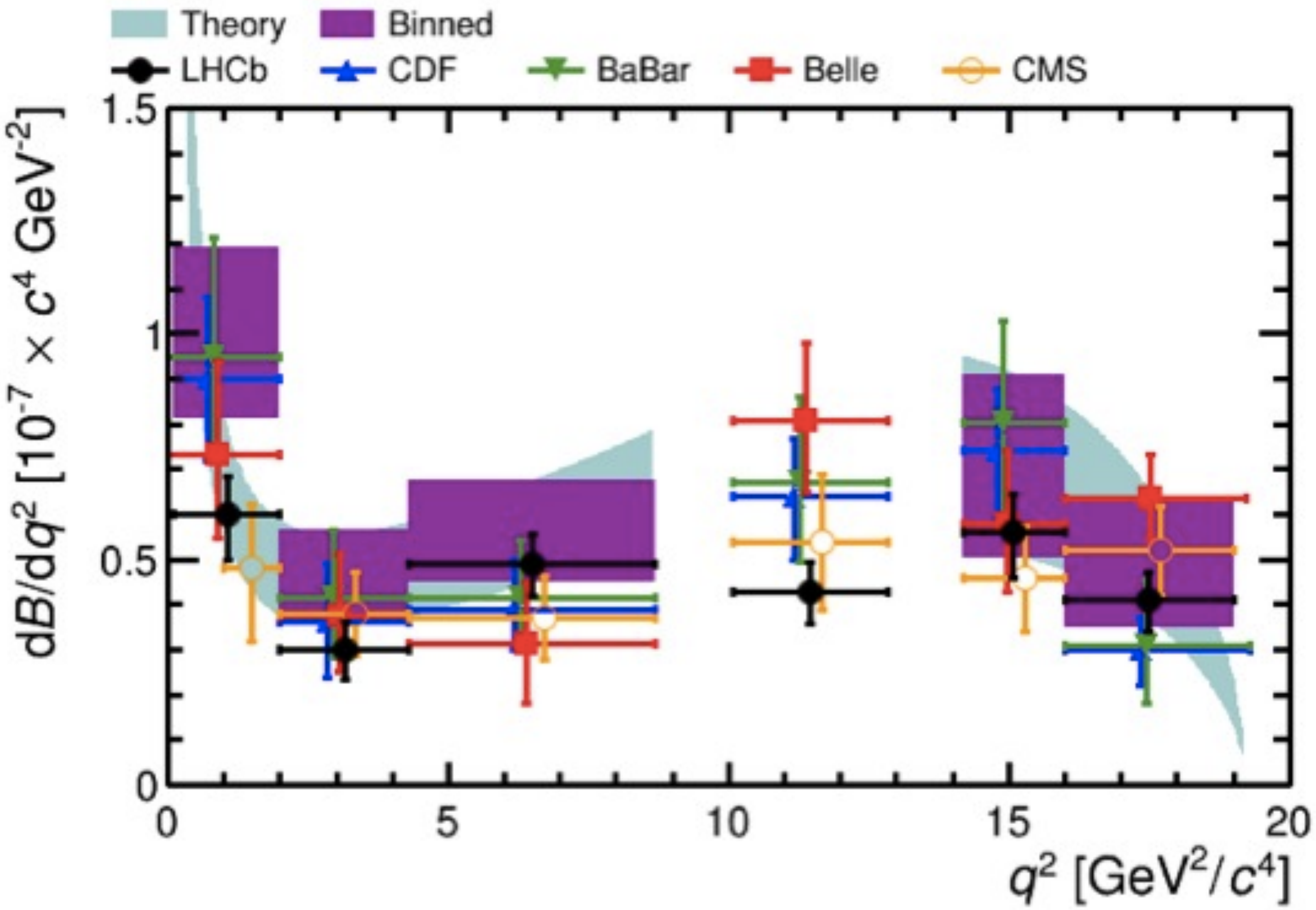
$B^0 \rightarrow K^{*0}\mu\mu$

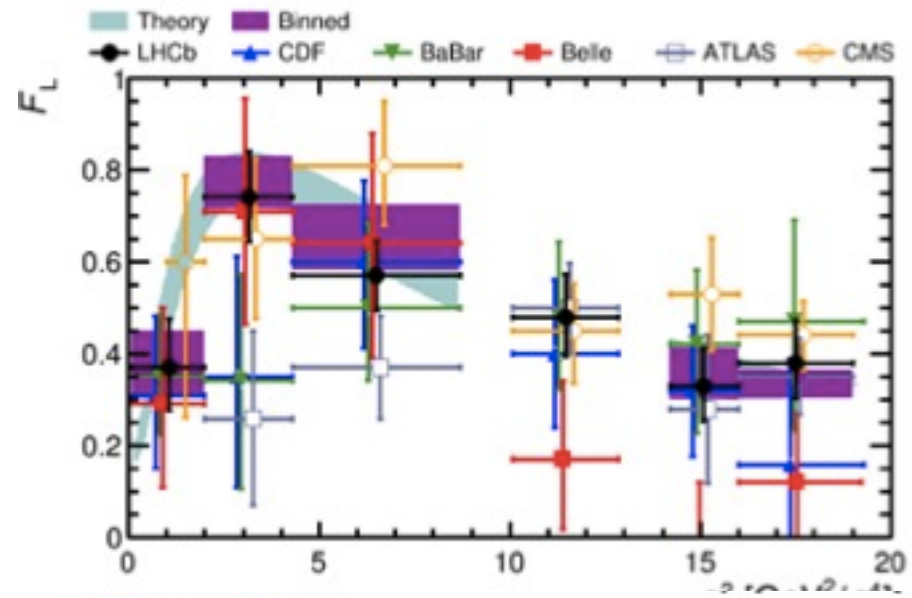
- $b \rightarrow sll$ transitions, governed by FCNCs
- experimentally clean signature ➟ superb laboratory for NP tests
- with clean theoretical predictions (at least at low $q^2 := m_{\mu\mu}^2$)
- and not so rare ➟ allow measurements of many sensitive kinematic variables and asymmetries
- measure differential decay distributions
  - multivariate analysis in mass, proper time
  - and angular distributions

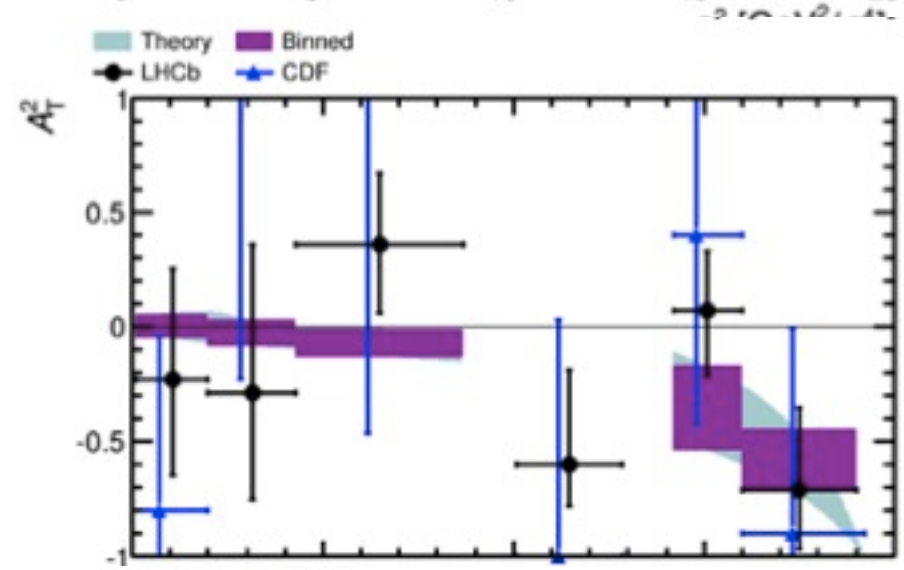


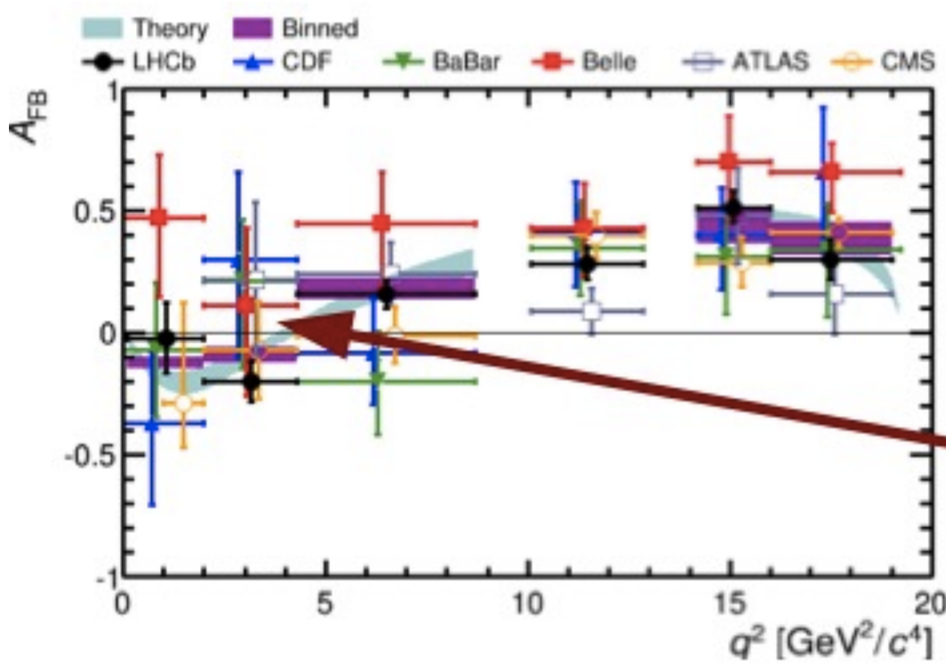


$B^0 \to K^{*0}\mu\mu$





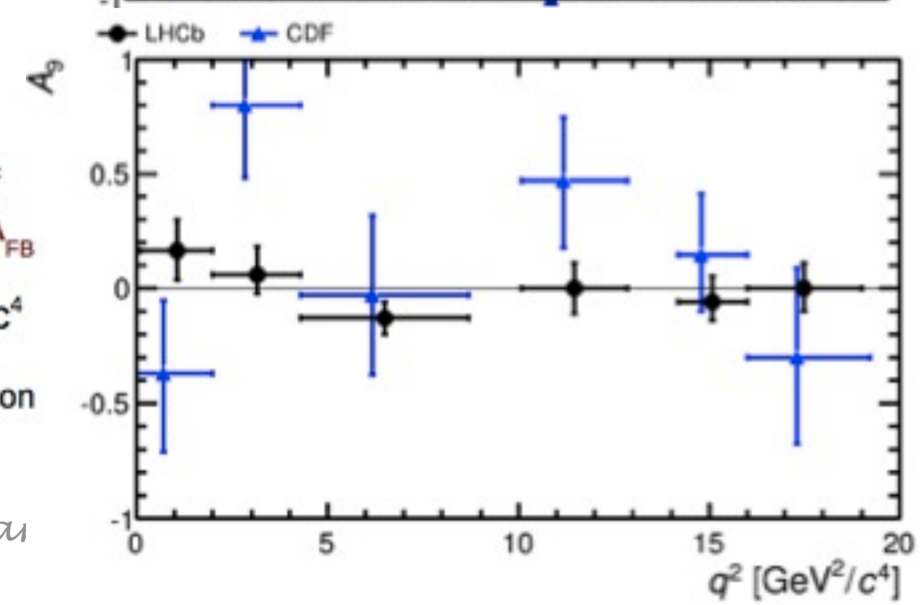




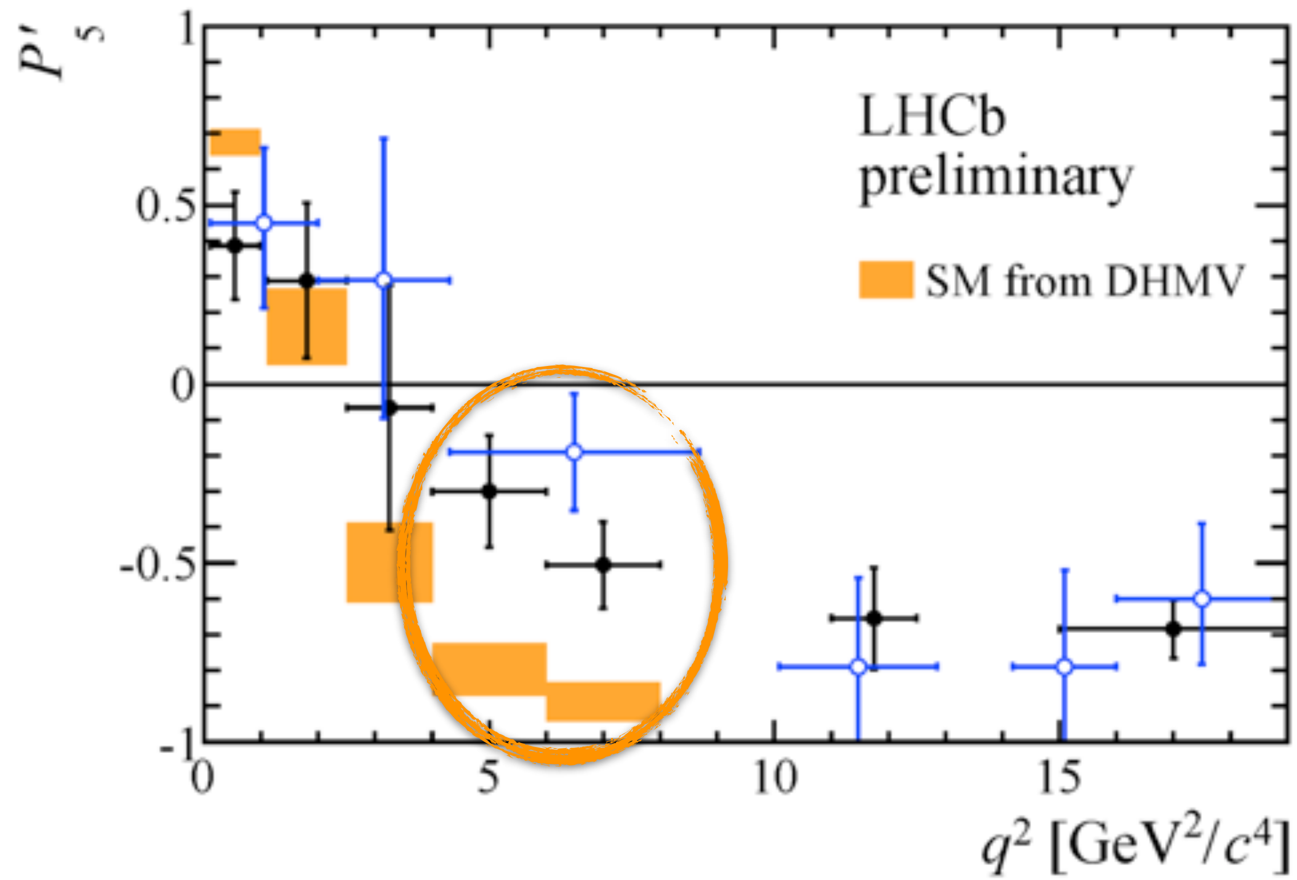
First measurement of zero-crossing point of A_{FB}

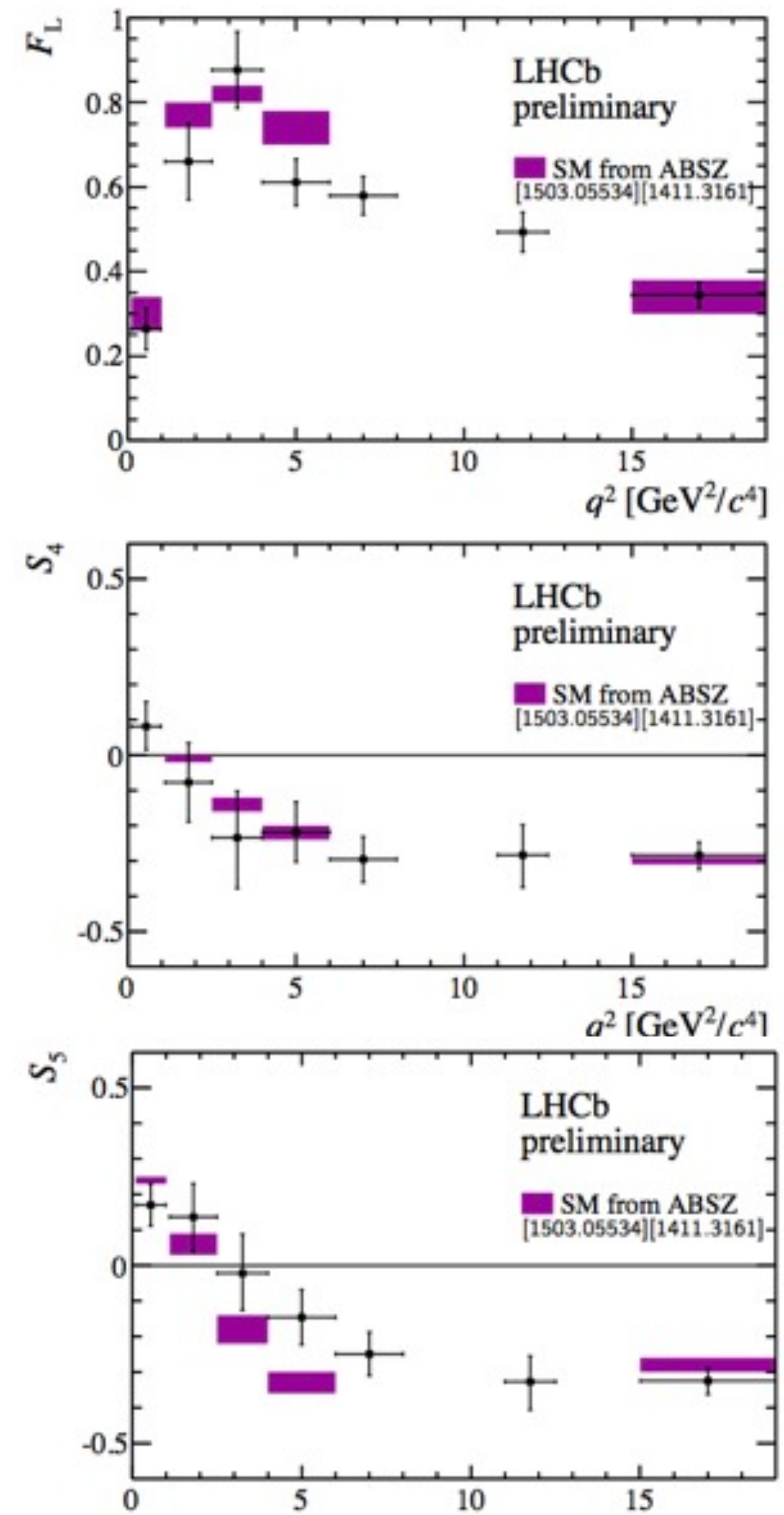
$q^2_0 = (4.9 \pm 0.9)\ \mathrm{GeV}^2/c^4$

Consistent with SM expectation



B→Kμμ

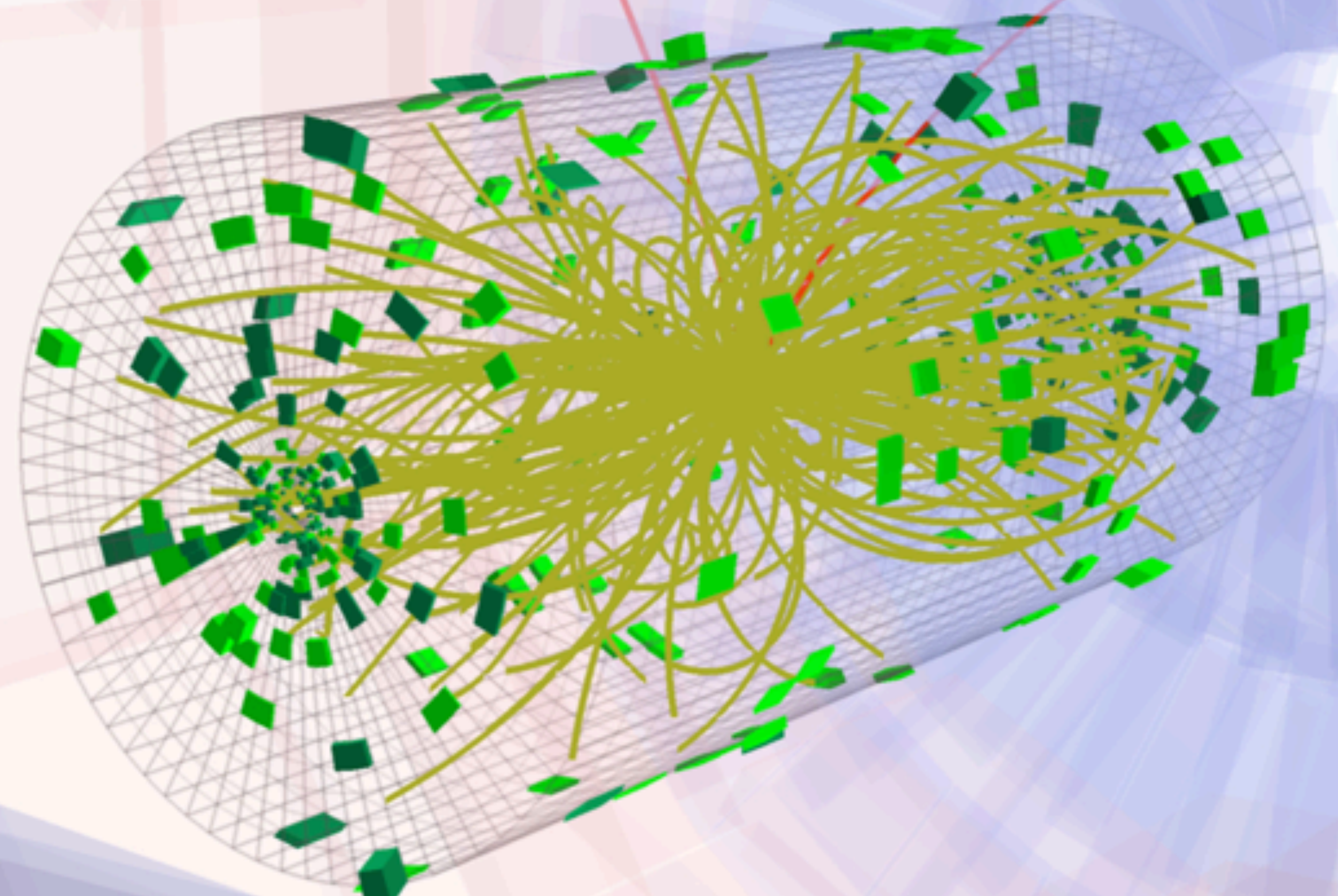




- new set of variables proposed ➟ less sensitive to hadronic form factors
- P_5': LHCb measures 4 new observables in 6 bins of q^2; one of the 24 measurements deviates from SM by ~3.7σ
- possible interpretation as a NP contribution to Wilson coefficient C_9
- interesting (correlated?) tensions with SM prediction
- ➟ to be explored with priority with more data and additional decays

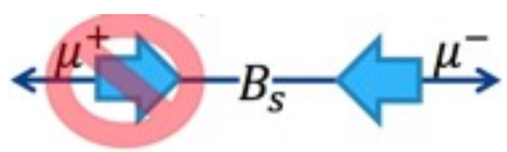
$B_s \rightarrow \mu\mu$

the ‘golden’ rare decay



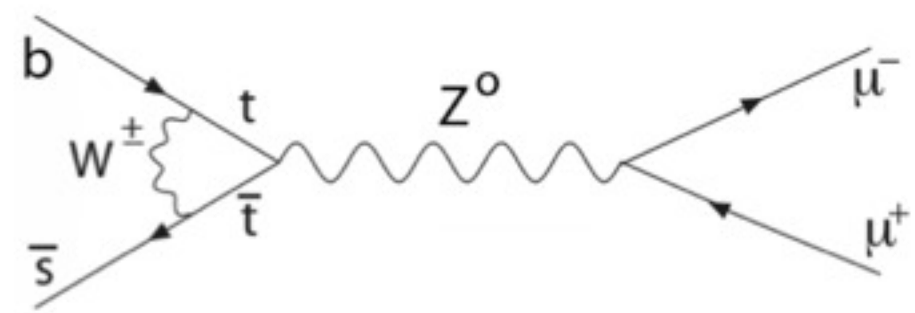
motivation

- in the Standard Model $B_{d/s} \to \mu\mu$ decays are highly suppressed
  - helicity suppressed, by factor of $(m_\mu/m_B)^2$

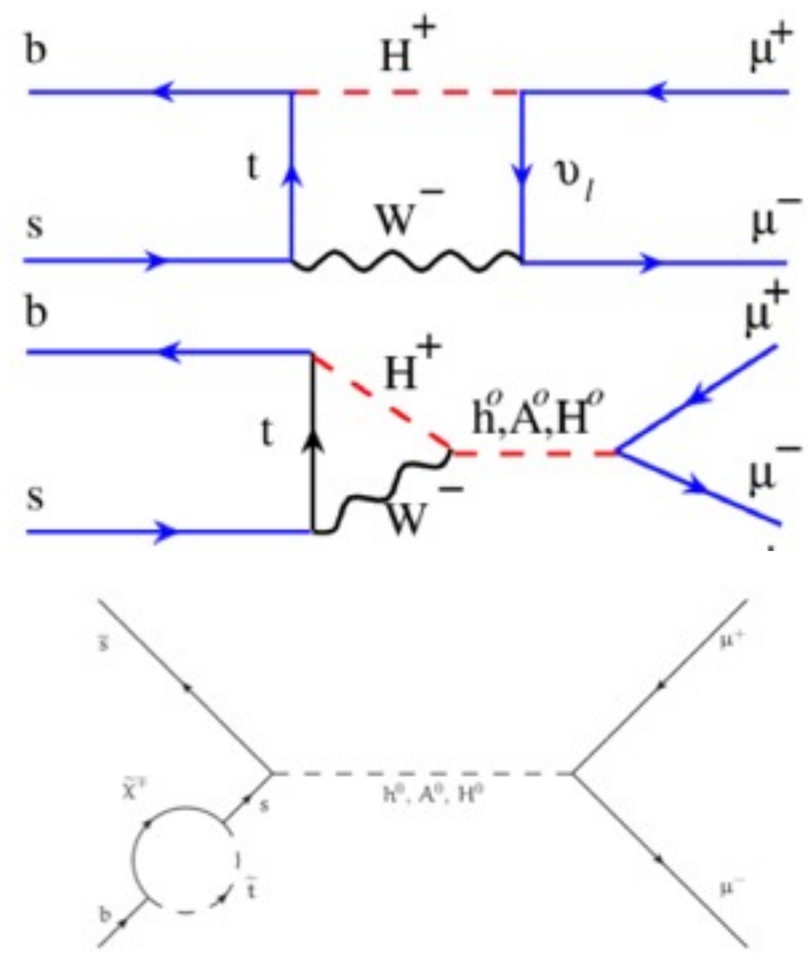


  - in the limit of massless muons, the process would be forbidden by spin conservation
  - FCNC, forbidden at tree level, in SM, can only proceed through higher-order loop diagrams
  - Cabibbo suppressed $|V_{ts(td)}|^2$
- Possible new particles in the loops!
  - may enhance *or* suppress the decay rates

Standard Model

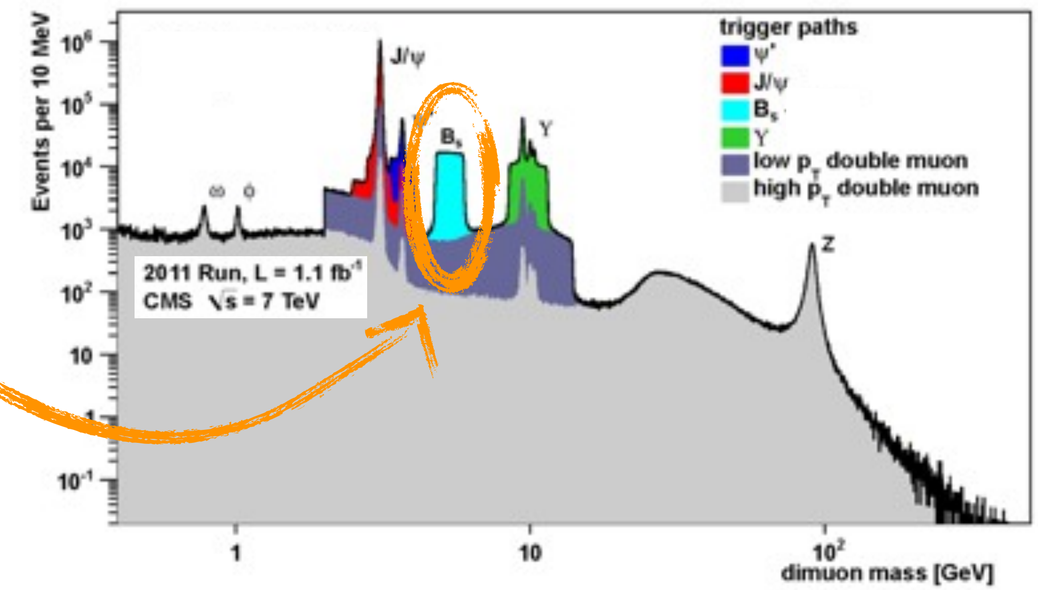


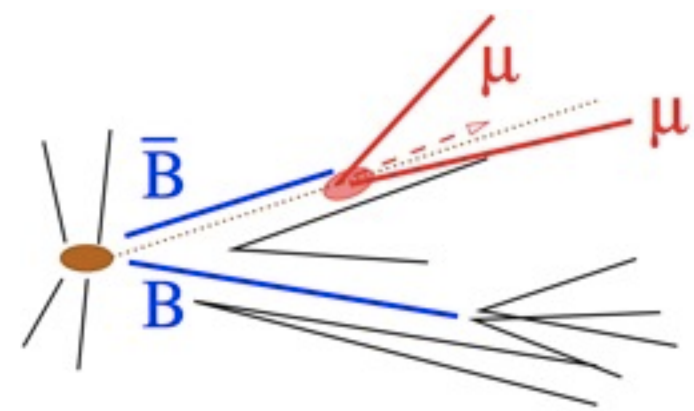
New Physics
(extended scalar sector, eg SUSY)



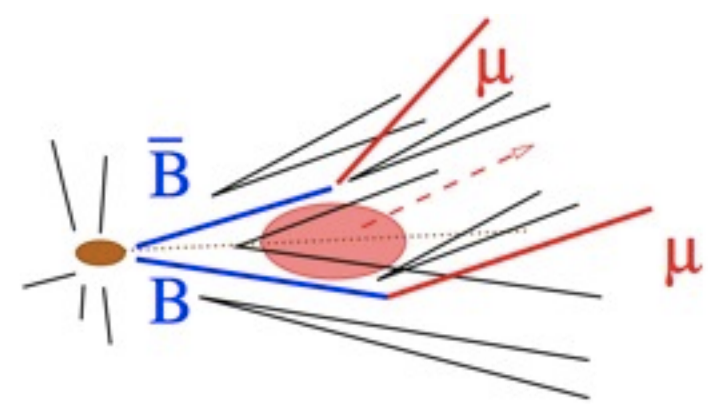
analysis steps

- collect the data
  - dedicated algorithm deployed online for selection in real time
- optimize selection criteria
  - while keeping signal-region data blind
  - use multivariate discriminators to reject backgrounds from signals
- likelihood fit to the dimuon mass
  - fit simultaneously $B_s \to \mu\mu$ and $B_d \to \mu\mu$
- evaluate statistical significance
  - if excess is observed: is it a fluctuation?
  - if no excess: place exclusion limit
- measure branching fraction





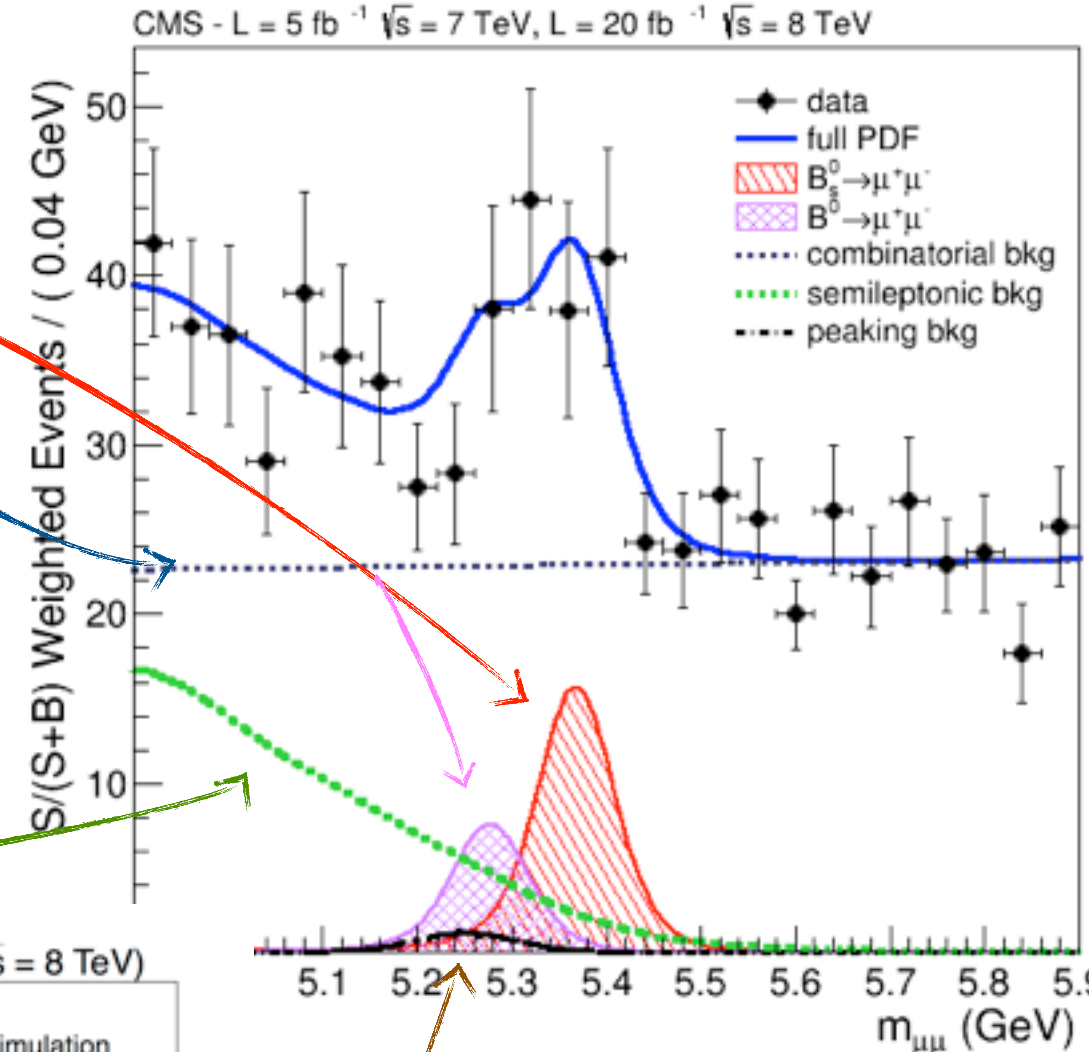
signal

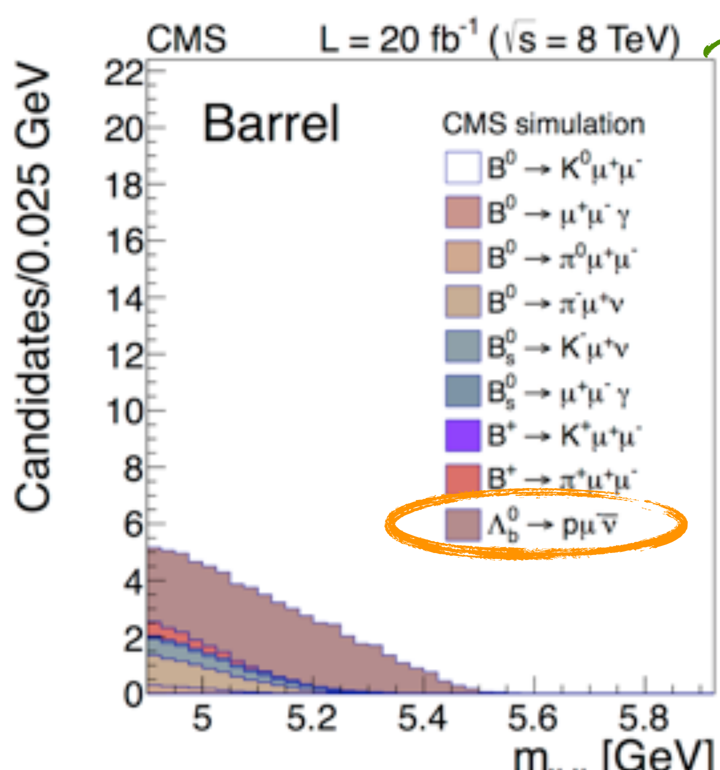


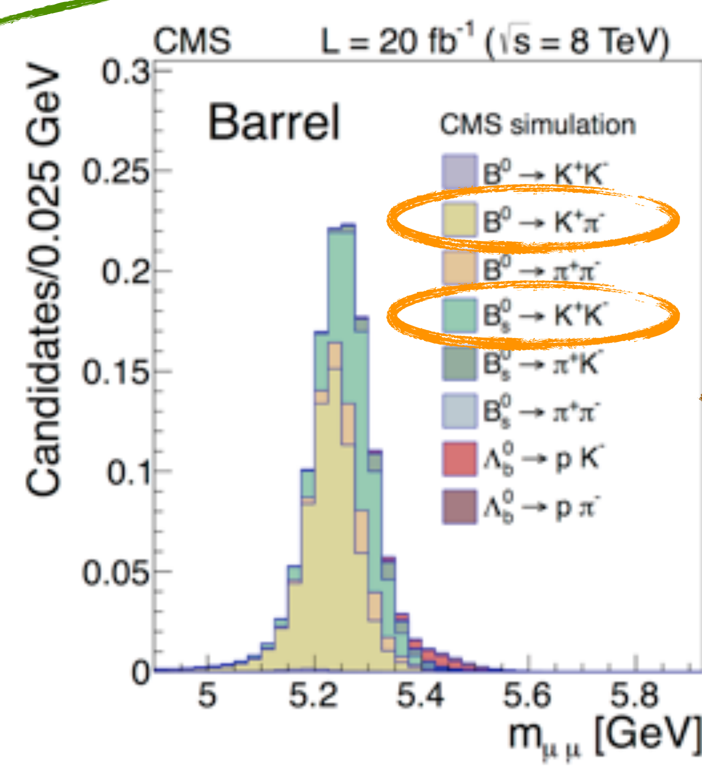
noise

physics backgrounds

- B_d and B_s signals
  - Crystal Ball, fixed shape,
  - normalization floating
- combinatorial background
  - first-degree polynomial
- rare semileptonic background ($b \rightarrow q\mu\nu$)
  - fixed shape, constrained normalization
- rare peaking background
  - constrained to expectation

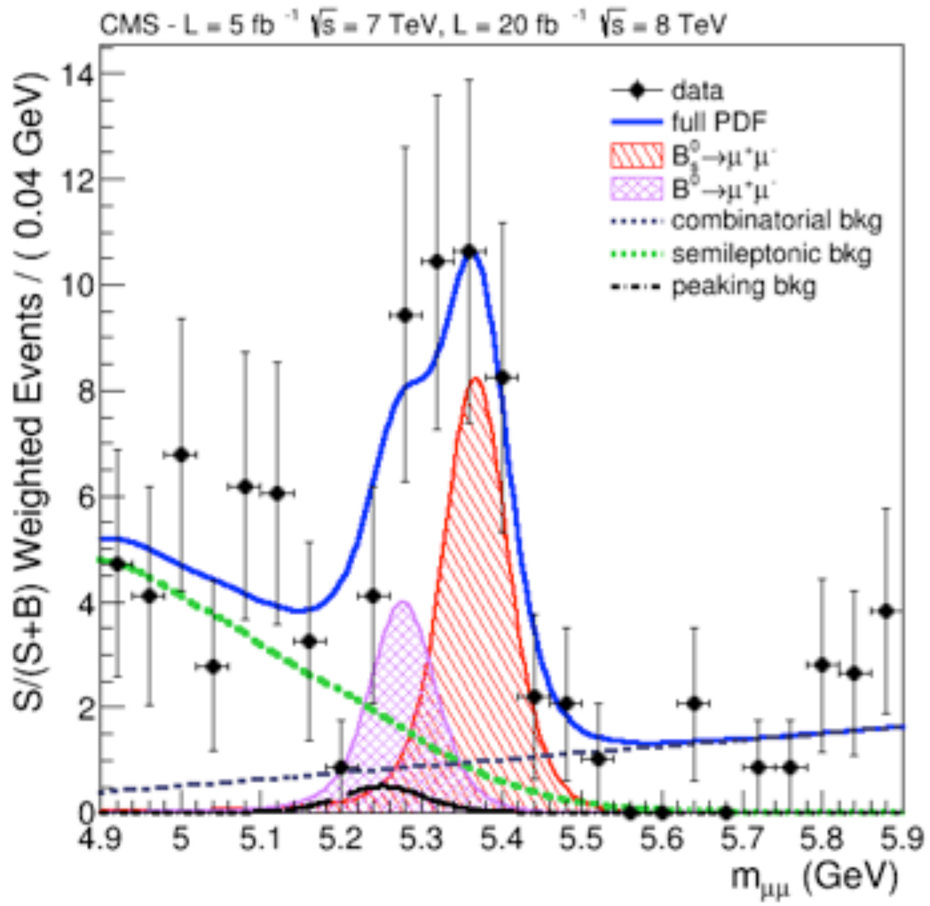






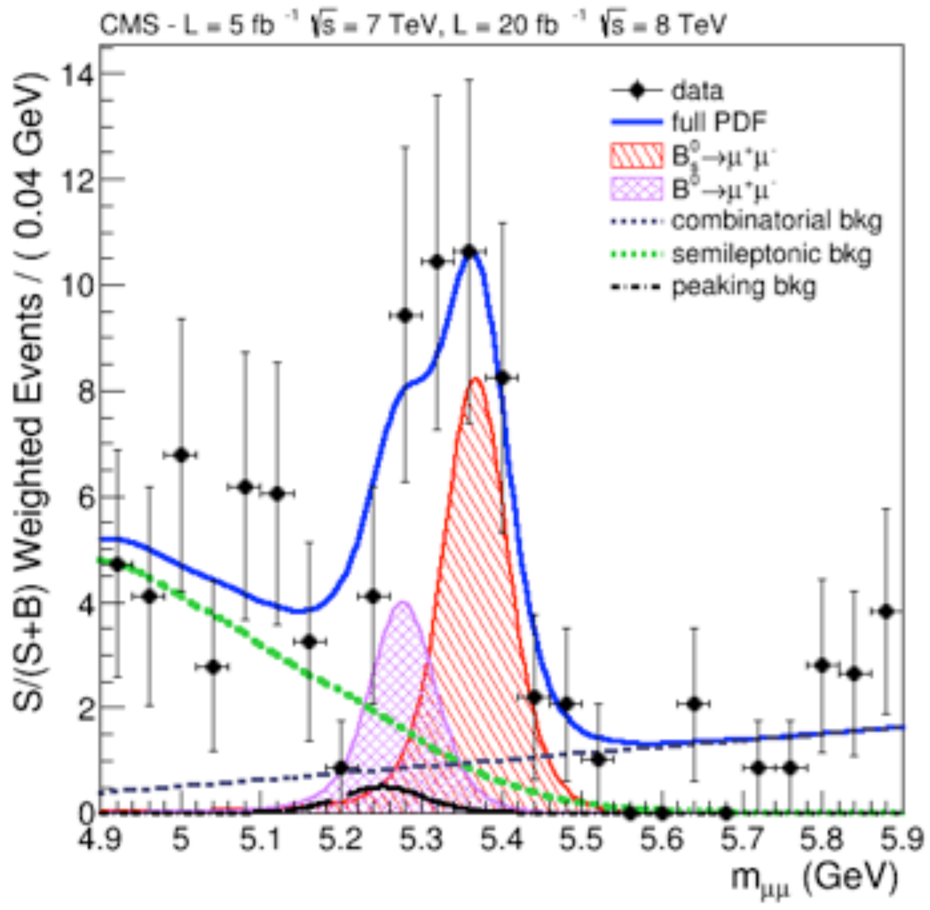
- rare physics backgrounds normalized to B^+ yields in data, for each analysis channel

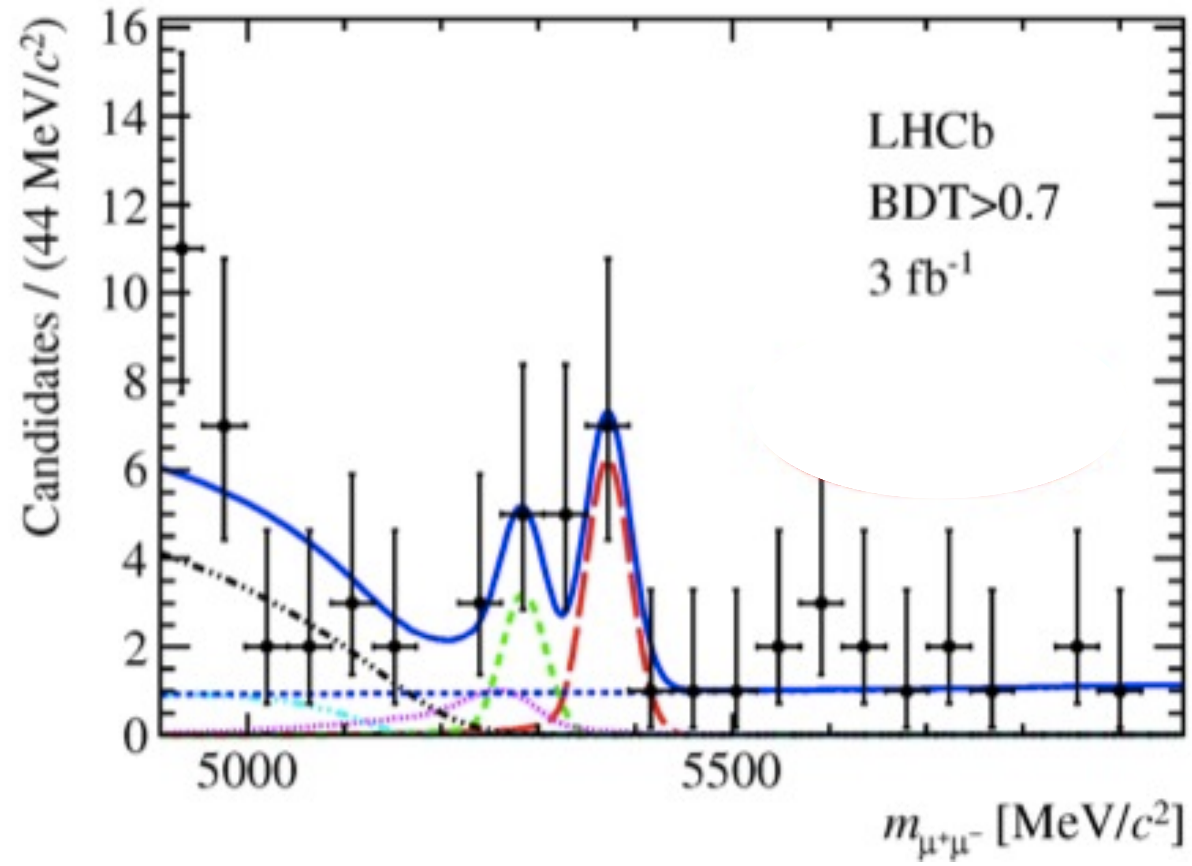
opening the box



- CMS observes an excess!
- but is it statistical significant?
  - $B_s \to \mu\mu$: 4.3σ [yes...]
  - $B_d \to \mu\mu$: 2.0σ [no...]

opening the box

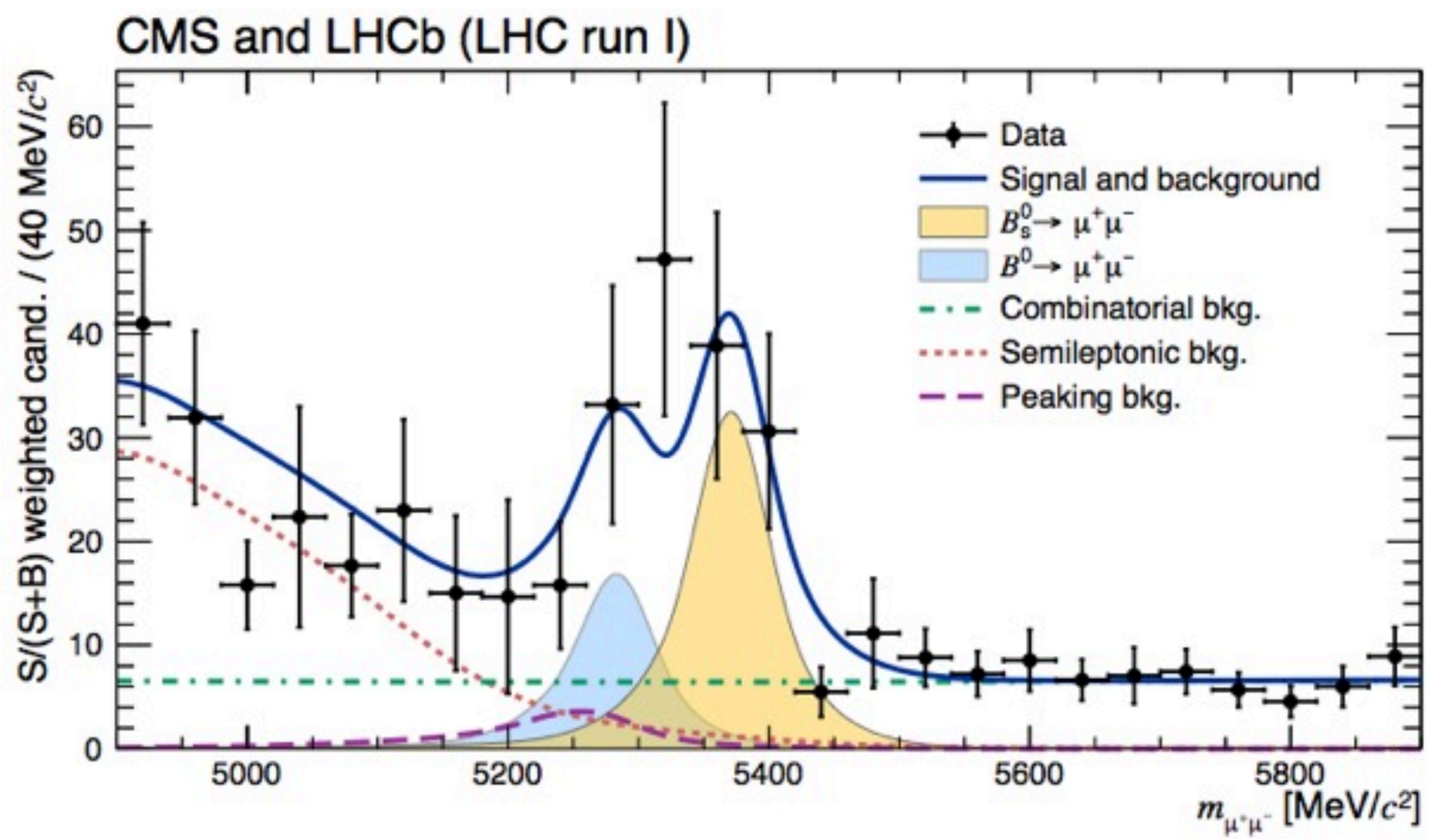




- CMS observes an excess!
- but is it statistical significant?
  - $B_s\to\mu\mu$: 4.3σ [yes...]
  - $B_d\to\mu\mu$: 2.0σ [no...]

- LHCb observes an excess, too!
  - $B_s\to\mu\mu$: 4.0σ
  - $B_d\to\mu\mu$: 2.0σ

CMS + LHCb



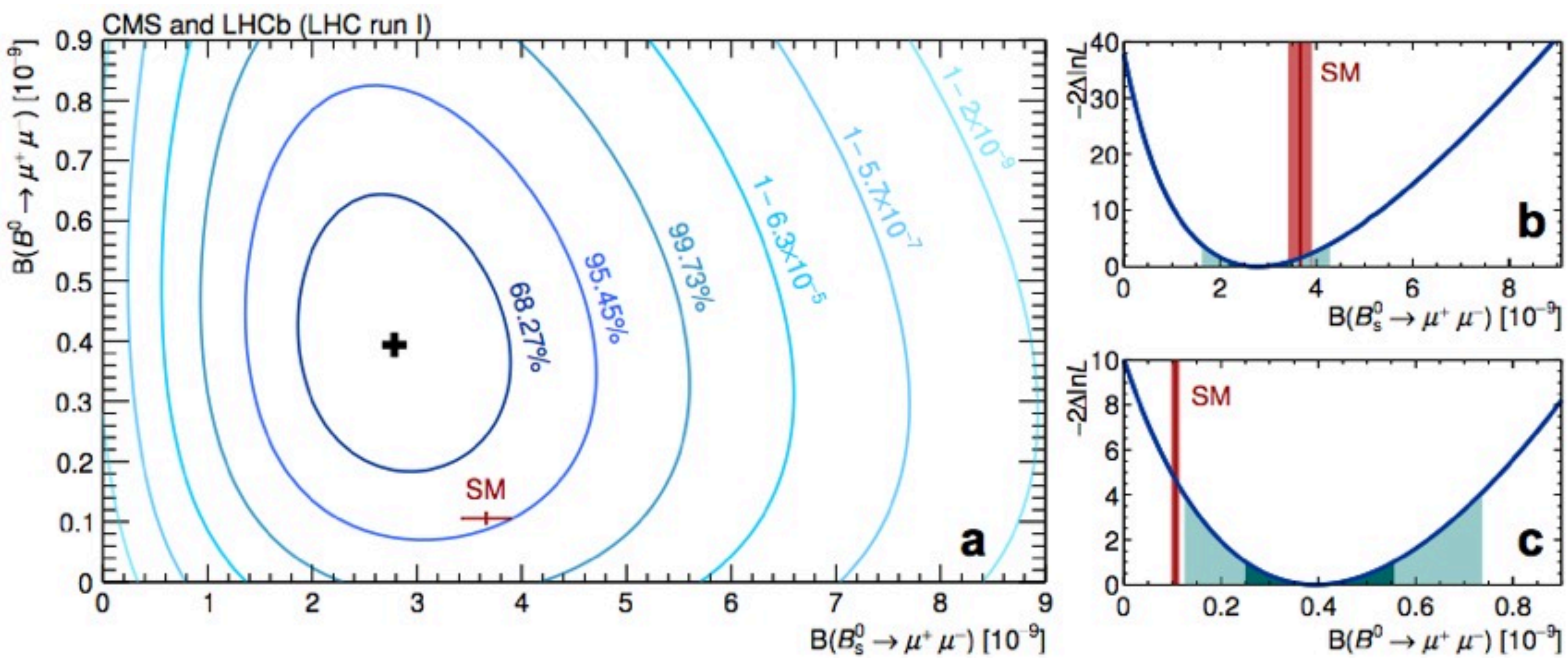
- CMS and LHCb have performed a combined analysis of their full Run 1 datasets, and delivered a definitive observation of $B_s \to \mu\mu$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9} \quad (6.2\sigma)$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10} \quad (3.0\sigma)$$

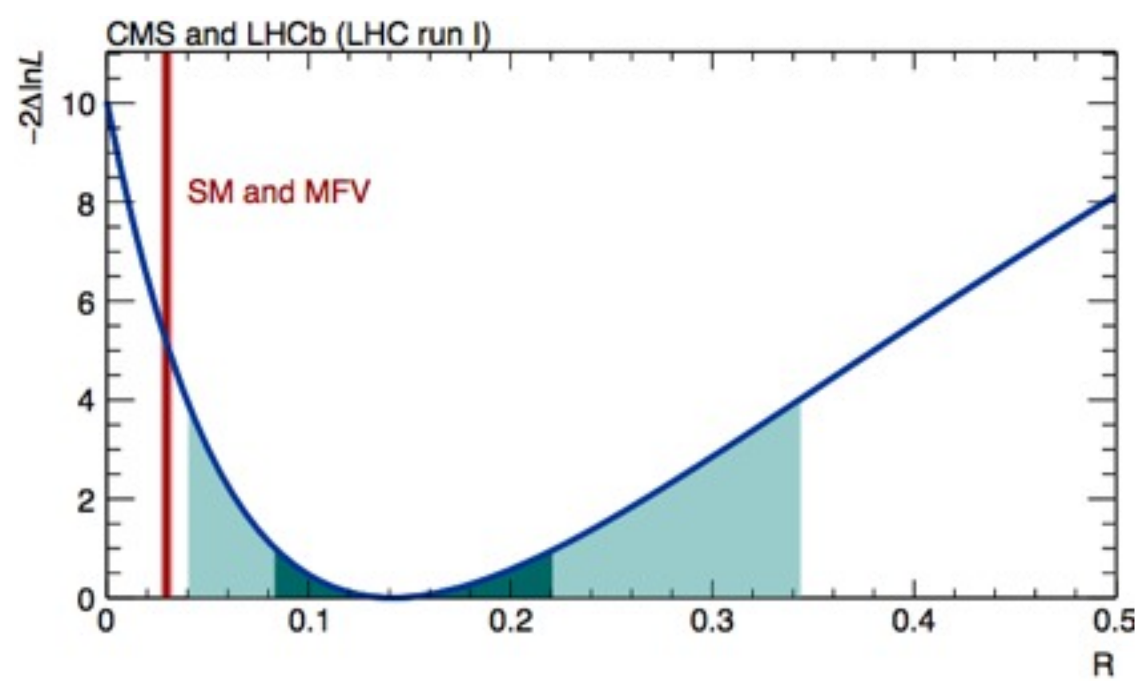
to appear in Nature, arXiv:1411.4413

comparison to SM expectation



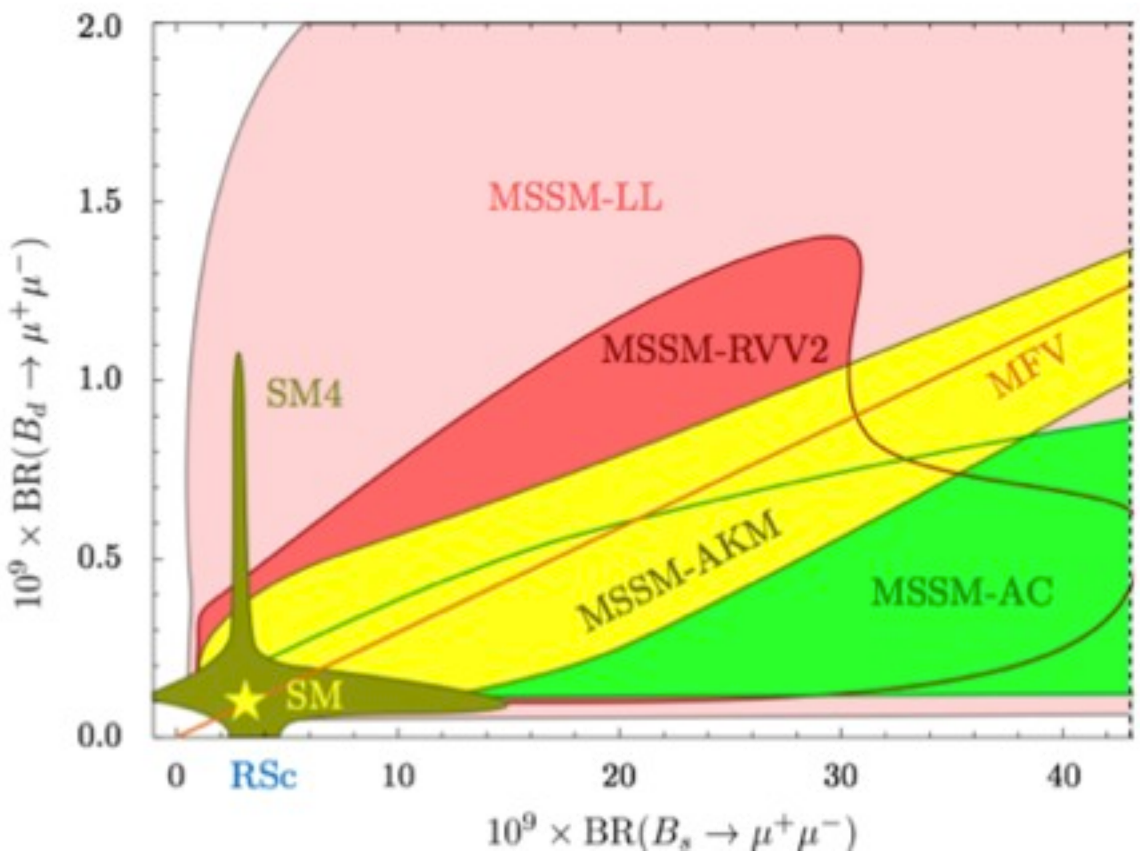
SM compatibility:
B_s: 1.2σ
B_d: 2.2σ

B_s/B_d: 2.3σ



new–physics constraints

➠ Measurement results in strong constraints to the parameter space of certain classes of NP models; some specific examples:



D. Straub et al, arXiv:1012.3893

Constraints on MSSM (incl. models with abelian/non-abelian flavor symmetries), 4^{th} generation, RS, and MFV models

JHEP 0903 (2009) 108, JHEP 1009 (2010) 106
JHEP 06 (2008) 068 , Nucl.Phys.B831 (2010) 26

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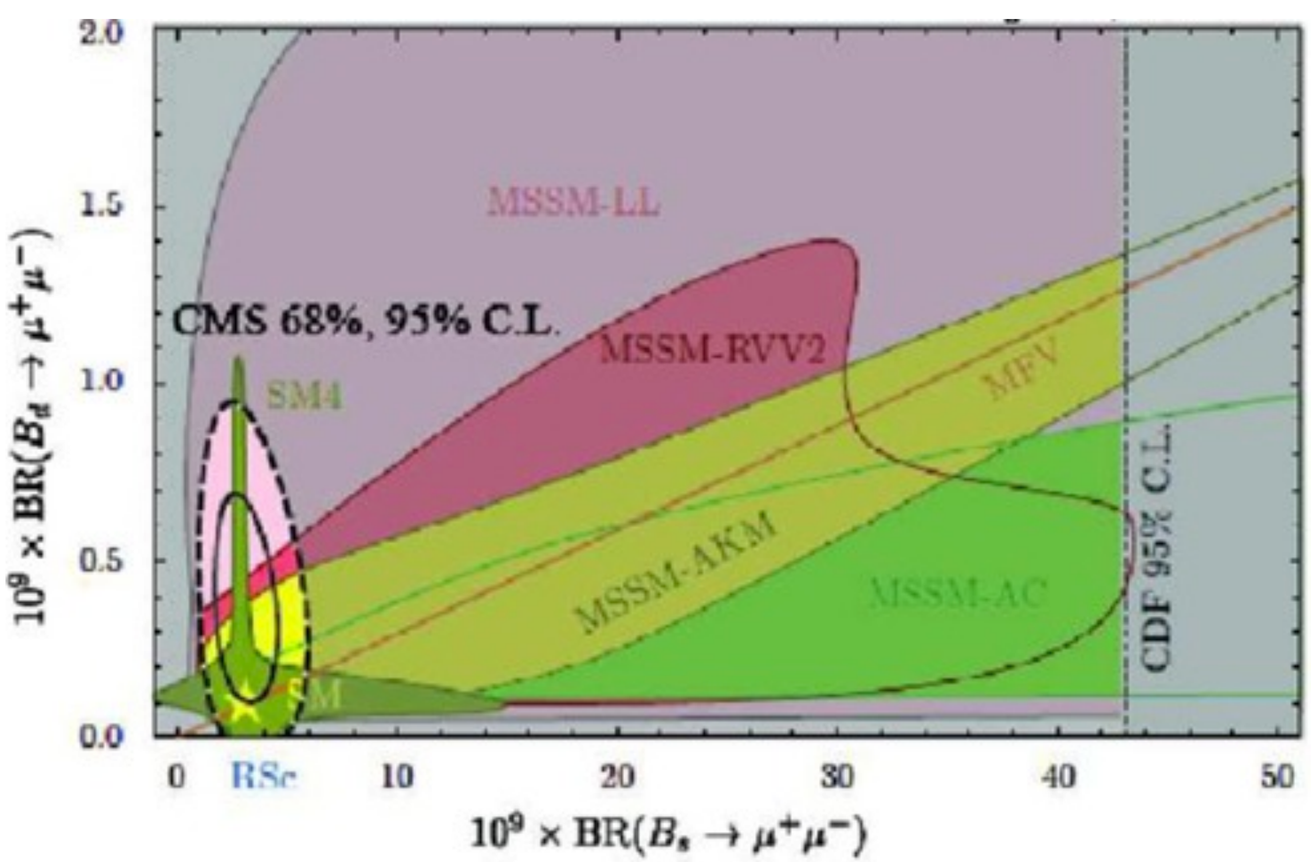

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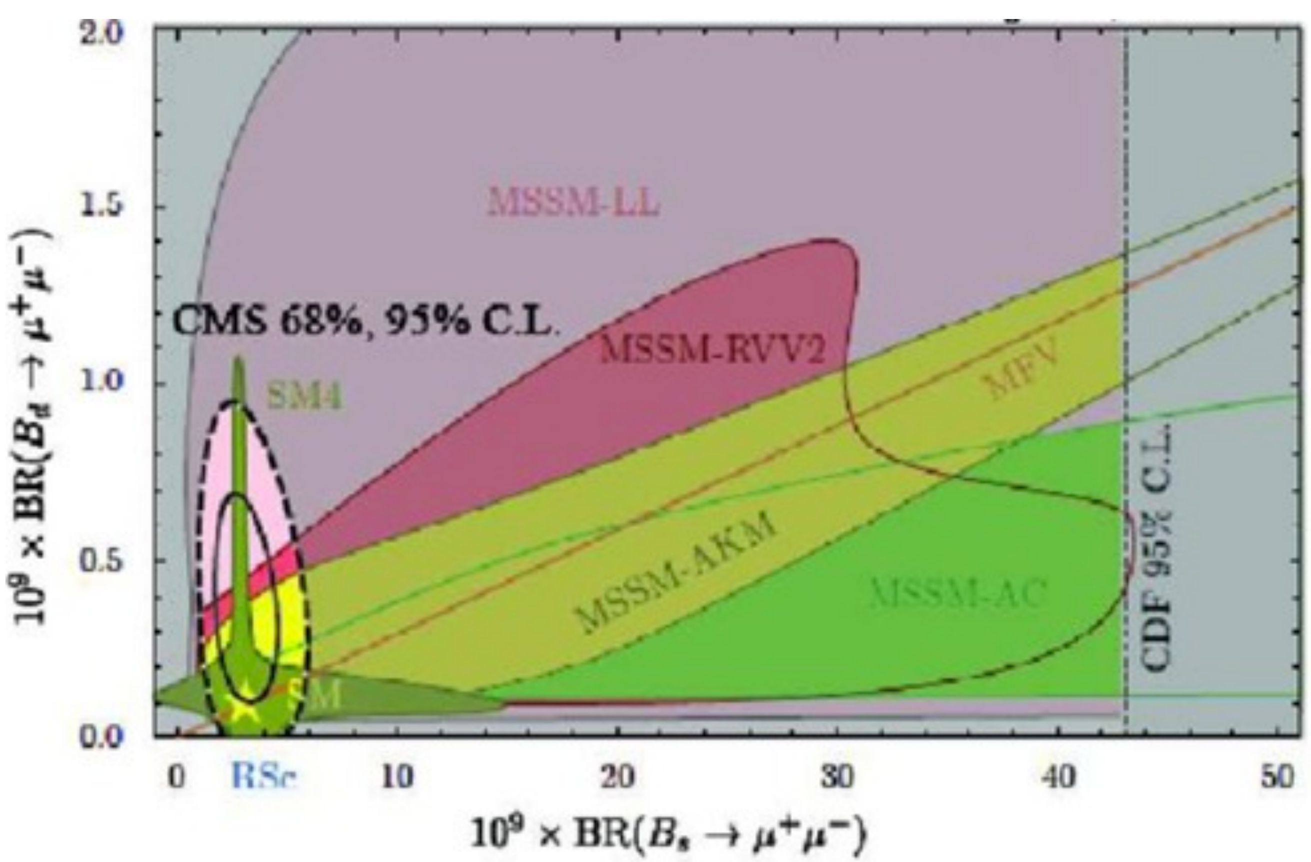

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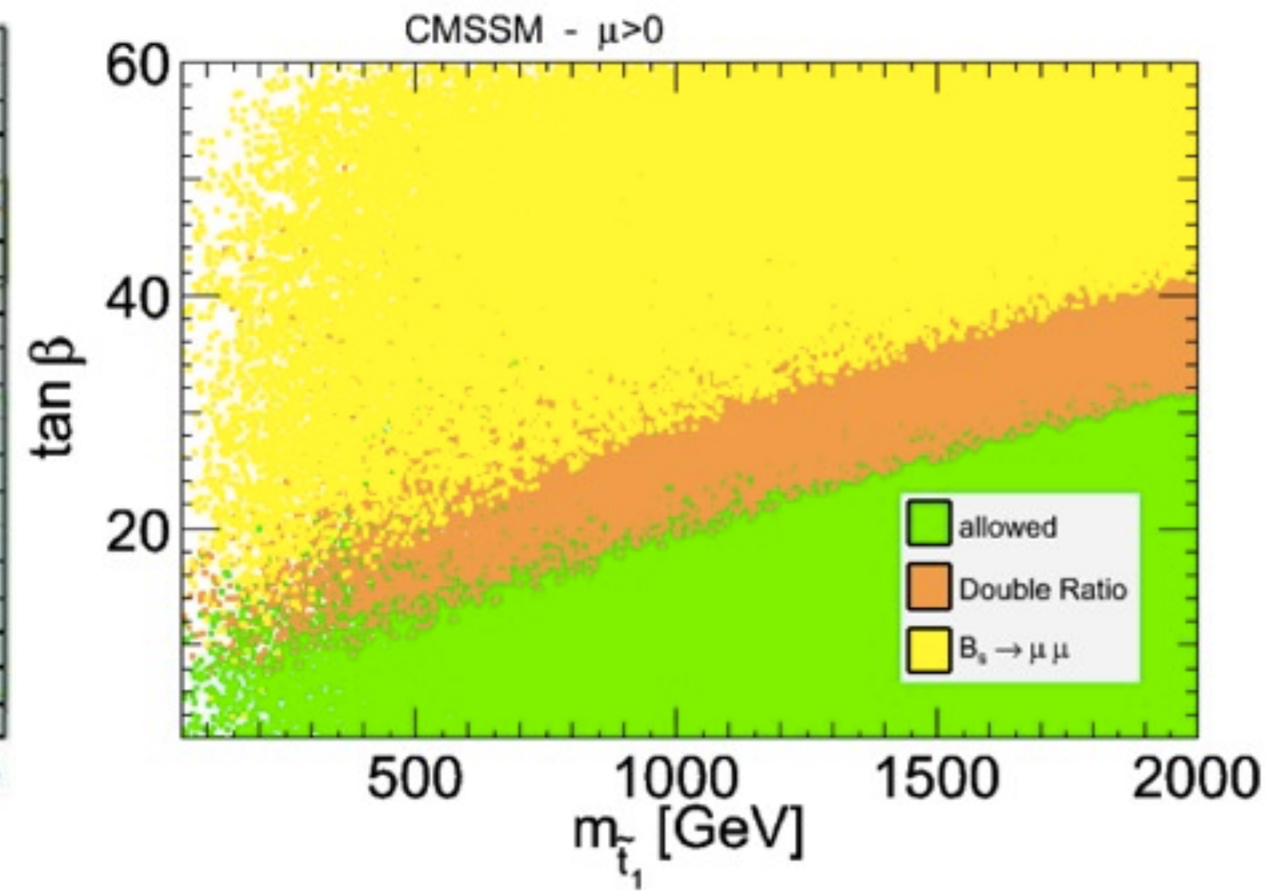

A. Akeroyd et al, JHEP 1112 (2011) 088

Constraints on MSSM (incl. models with abelian/non-abelian flavor symmetries), 4th generation, RS, and MFV models

JHEP 0903 (2009) 108, JHEP 1009 (2010) 106
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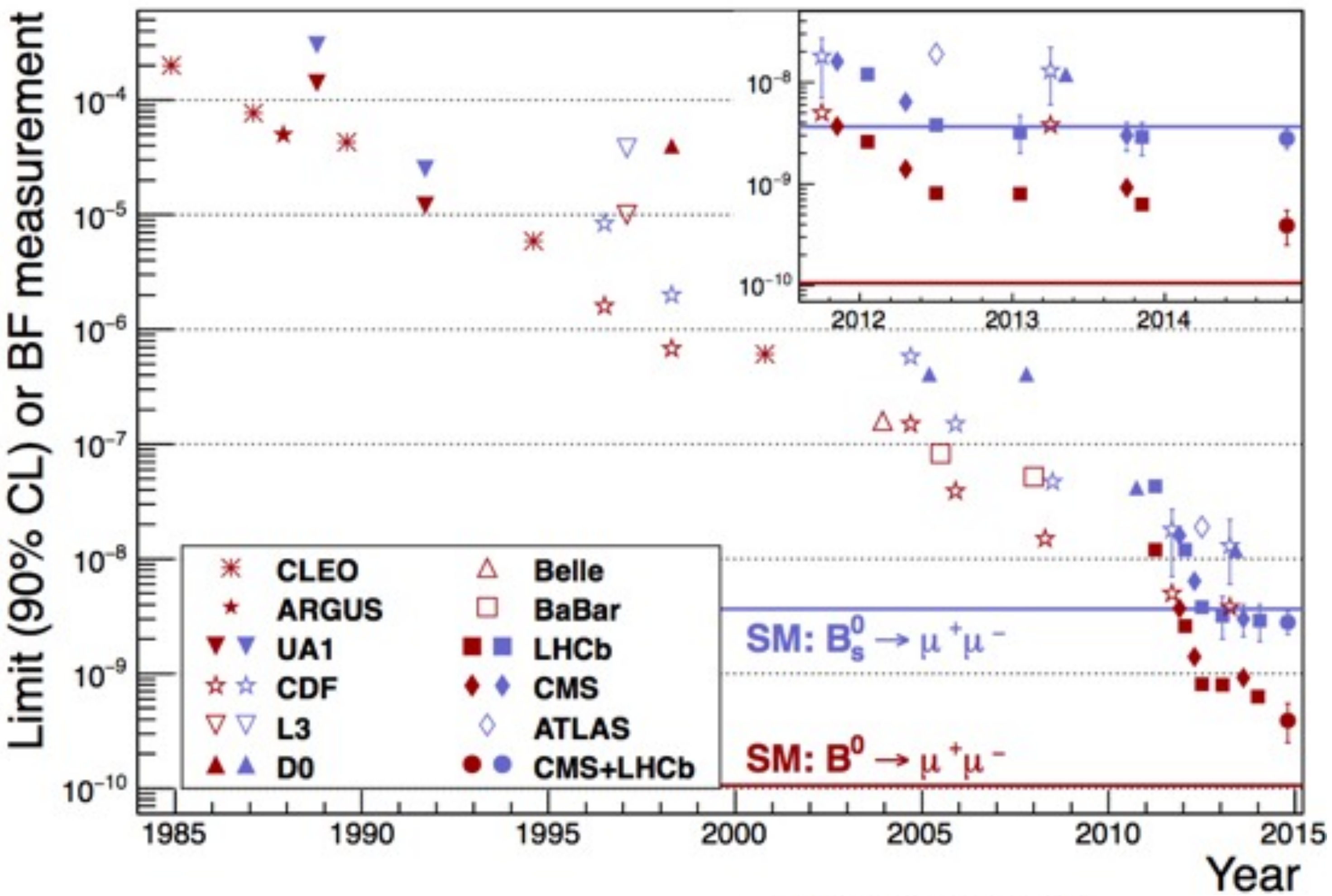
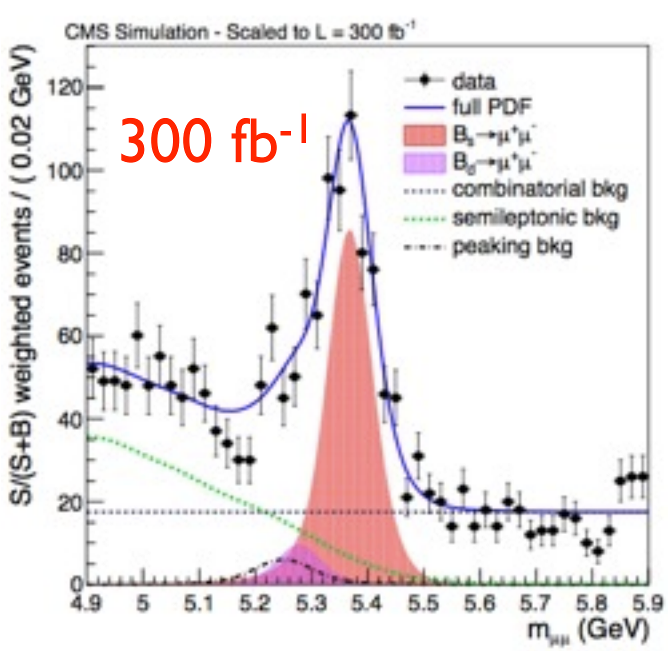
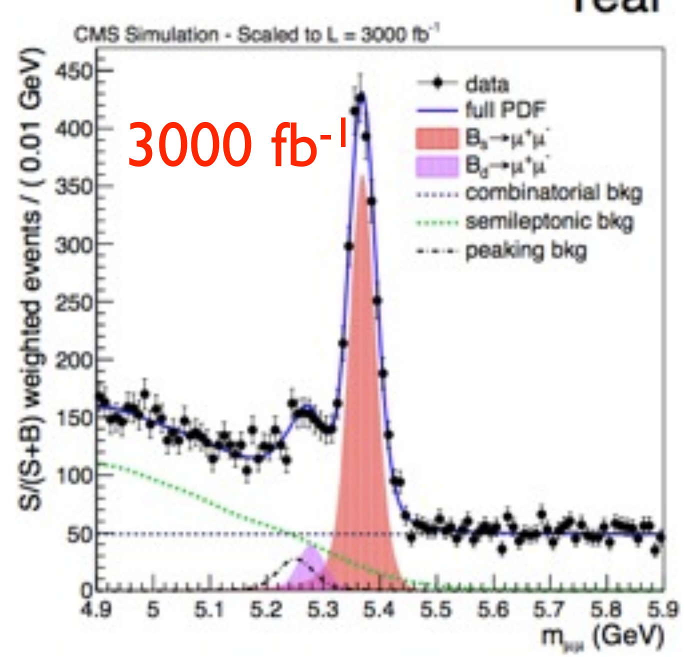
Constraints on CMSSM, in the case of a SM-like $B_s \to \mu\mu$

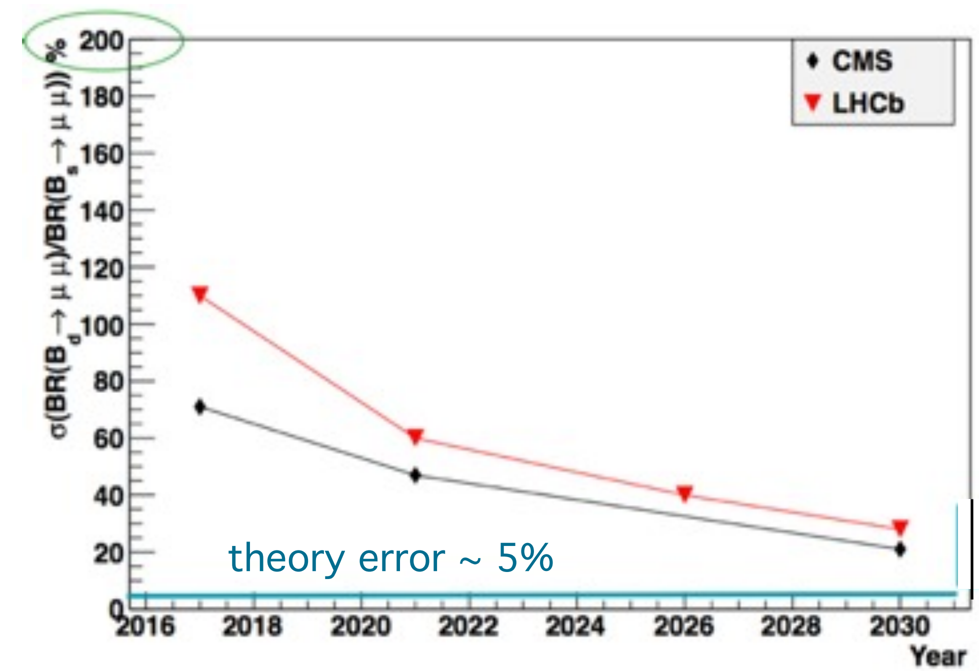
a long journey ends, and new one starts



- following observation of $B_s \to \mu\mu$ in Run, will focus on:
- $B_d \to \mu\mu$: optimize search for Bd, for which the Bs will now be a background!
- explore observables with additional sensitivity to New Physics, e.g. effective lifetimes and CP asymmetries







summary

- broad and successful flavor physics programme at the LHC
- advancements and breakthroughs in the different areas during Run I
  - rare decays, CP violation, production, spectroscopy, QGP hard probes
- no large discrepancies wrt the Standard Model found, yet
  - several ~3σ level tensions will be pursued and clarified in next LHC runs
- exploring highly sensitive phenomena, including
  - fast: B_s oscillations occur at 3 trillion times a second
  - rare: B_s decays to muon pairs 3 times in a billion
  - hot: created medium in ion collisions 5 trillion °C
- continuing flavor physics program complementary to high-p_T searches into the high luminosity LHC runs
  - in the quest of finding evidence of New Physics and setting its scale
  - to differentiate amongst NP models and characterize their flavor structure

References

- experiment: Matter antimatter fluctuations, N.Leonardo, LAP (2011)
  IST lib. 11.10.L.1754, Contents: http://home.fnal.gov/~leonardo/oscillations_book.htm
- theory: CP violation, G.C.Branco, L.Lavoura, J.P.Silva, OUP (1999)

note: references available from LIP/IST/CERN libraries

multiple excellent reviews exist on each of the core topics presented extra material

CPV in decay: B→Kπ

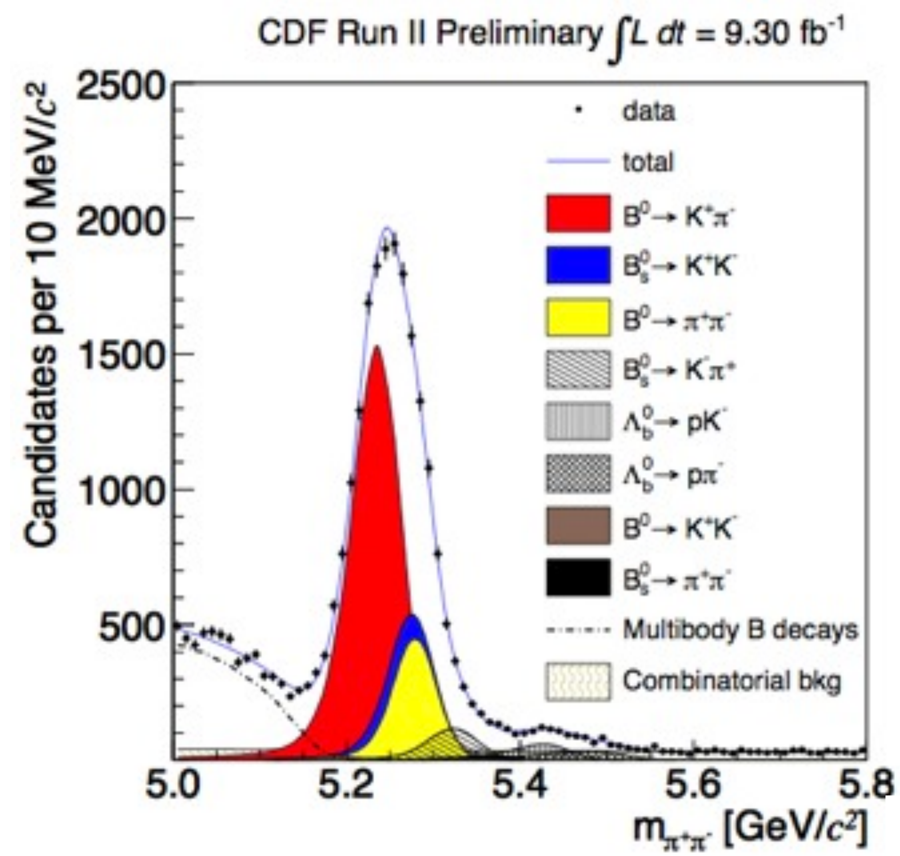
$$A_{dir}^{CP} = \frac{\Gamma(\bar{B}^0 \to \bar{f}) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to \bar{f}) + \Gamma(B^0 \to f)}$$

- B factories: BABAR, BELLE (2004)
  - Babar Collaboration *Phys. Rev. Lett.* **97**, 171805 (2006)
    Belle Collaboration *Phys. Rev.* **D87**, 031103 (2013)

- Tevatron: CDF (2012)

$$A_{CP}(B^0 \to K^+\pi^-) = -0.083 \pm 0.013 \pm 0.003$$

$$A_{CP}(B_s^0 \to K^-\pi^+) = +0.22 \pm 0.07 \pm 0.02$$



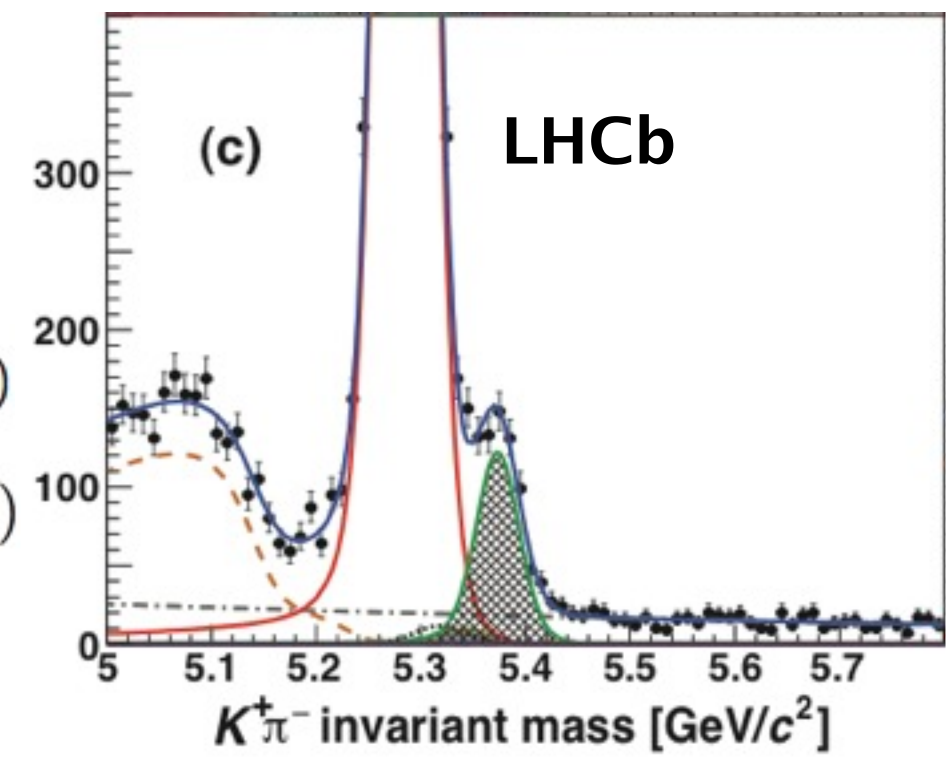
PRL 108 (2012) 211803

- LHC: LHCb (2013)

$$A_{CP}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007\,(\text{stat}) \pm 0.003\,(\text{syst})$$

$$A_{CP}(B_s^0 \to K^-\pi^+) = 0.27 \pm 0.04\,(\text{stat}) \pm 0.01\,(\text{syst})$$

  - first observation (>5σ) of CPV in B_s



PRL 110 (2013) 221601

$B_s \to KK$

- time-dependent asymmetry

direct CPV

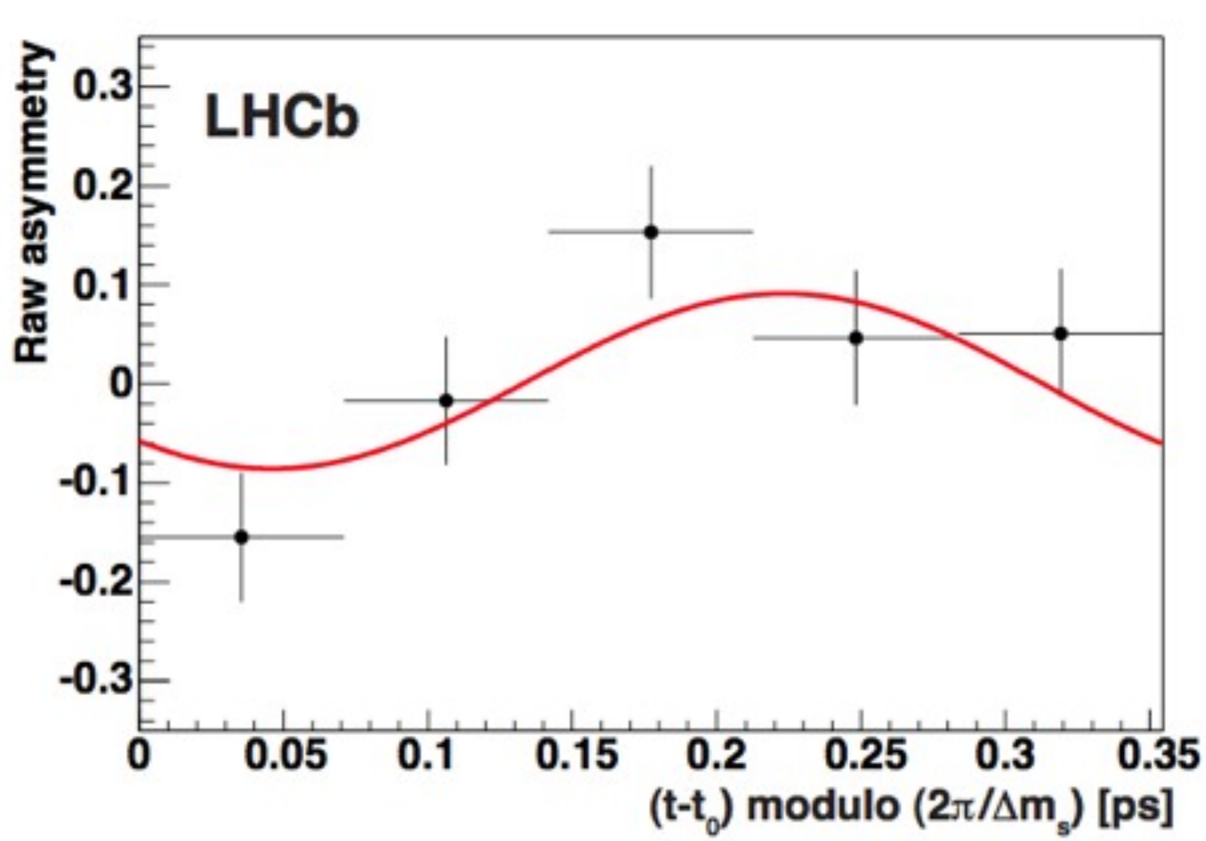
CPV in decay-mixing interference

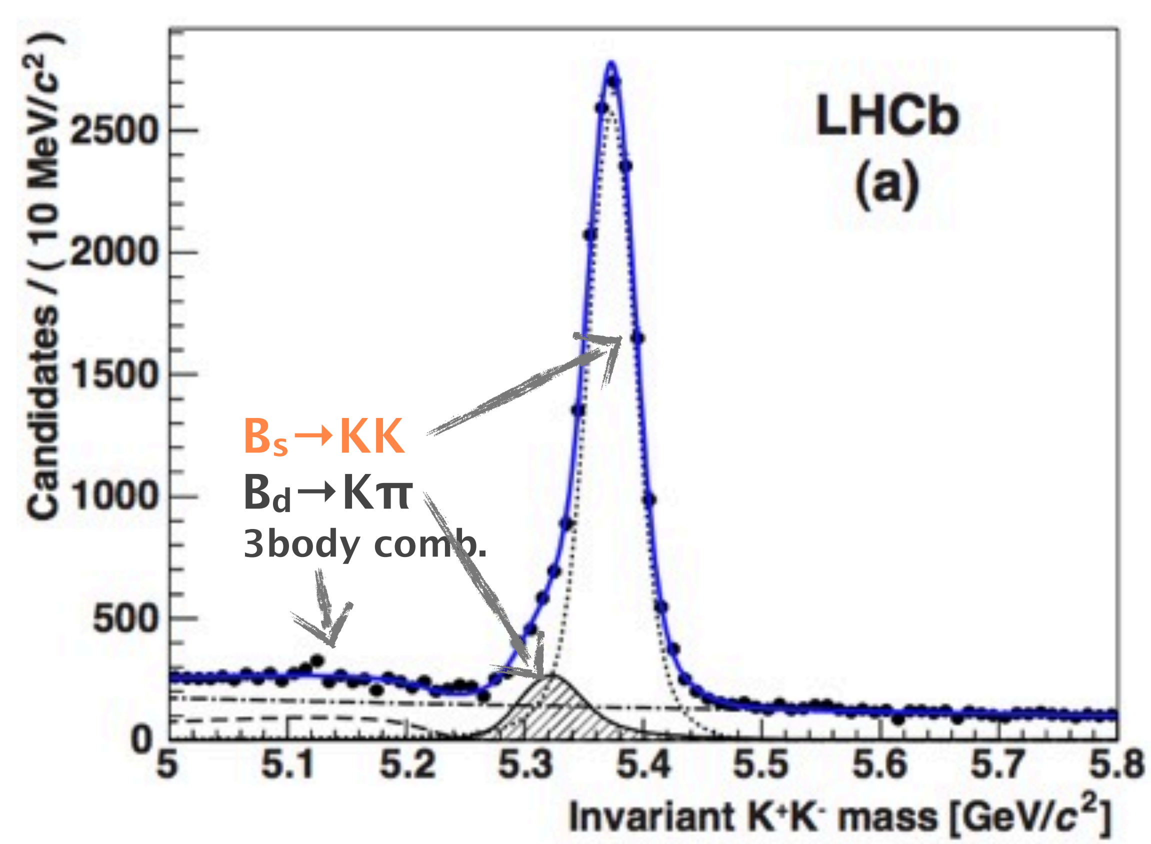
$$\mathcal{A}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f \cos(\Delta m_{d(s)} t) + S_f \sin(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) - A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)}$$

$$C_{KK} = 0.14 \pm 0.11\,(\text{stat}) \pm 0.03\,(\text{syst})$$
$$S_{KK} = 0.30 \pm 0.12\,(\text{stat}) \pm 0.04\,(\text{syst})$$

- first time-dependent CPV measurement in $B_s \to KK$ decays

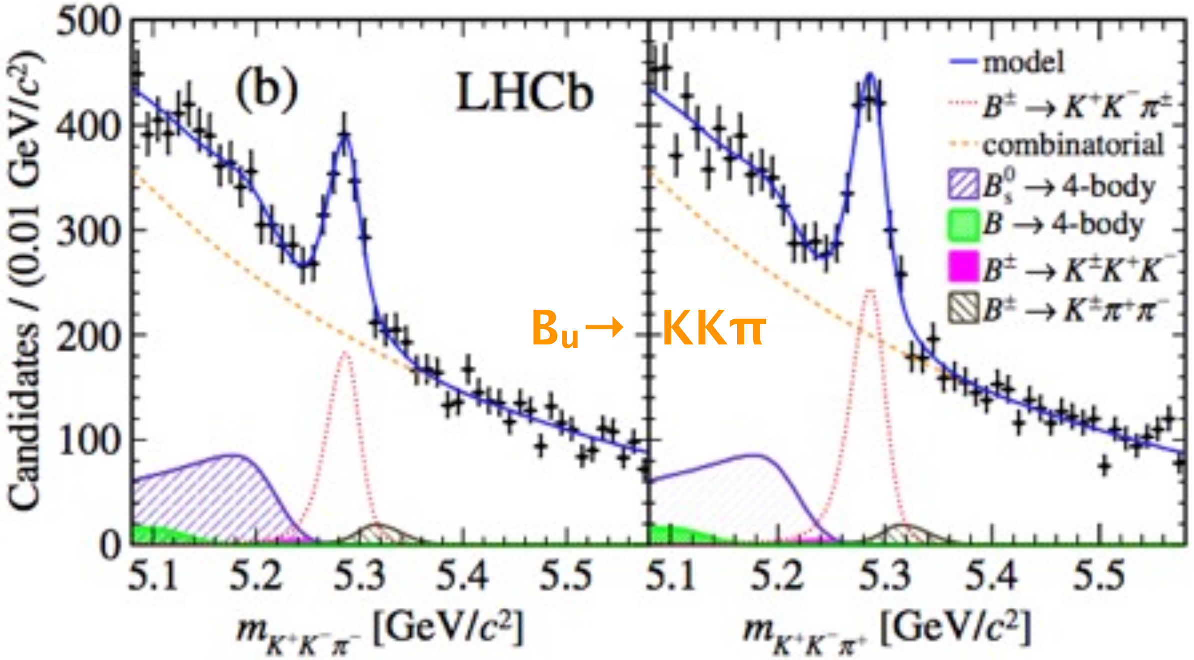
JHEP 10 (2013) 183



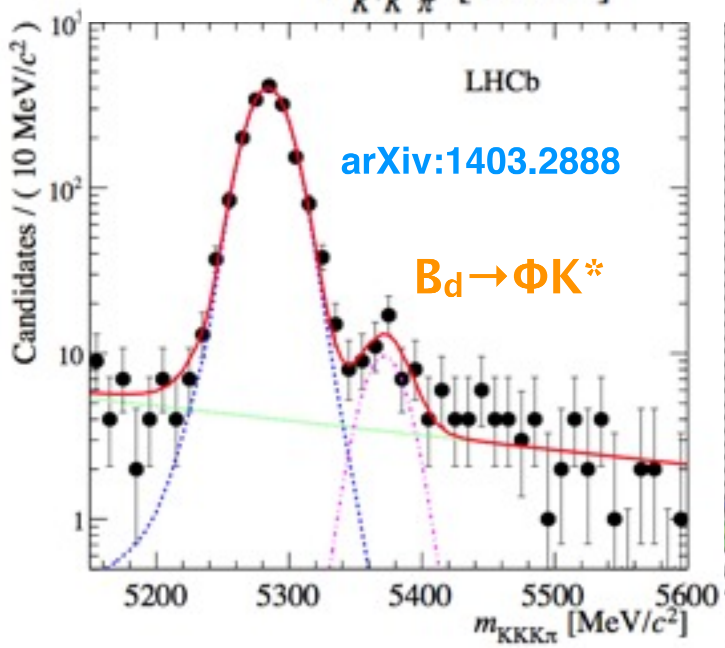


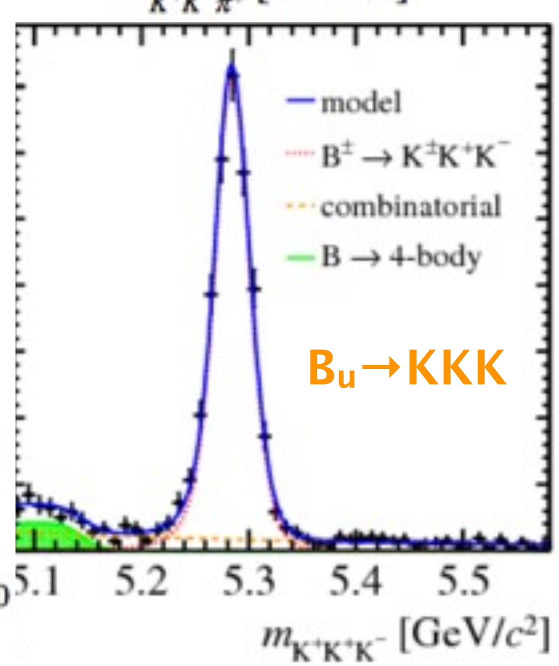
A_{CP}

- extensive set of measurements of CPV in charmless B decays
- example, B→hhh(h) from LHCb

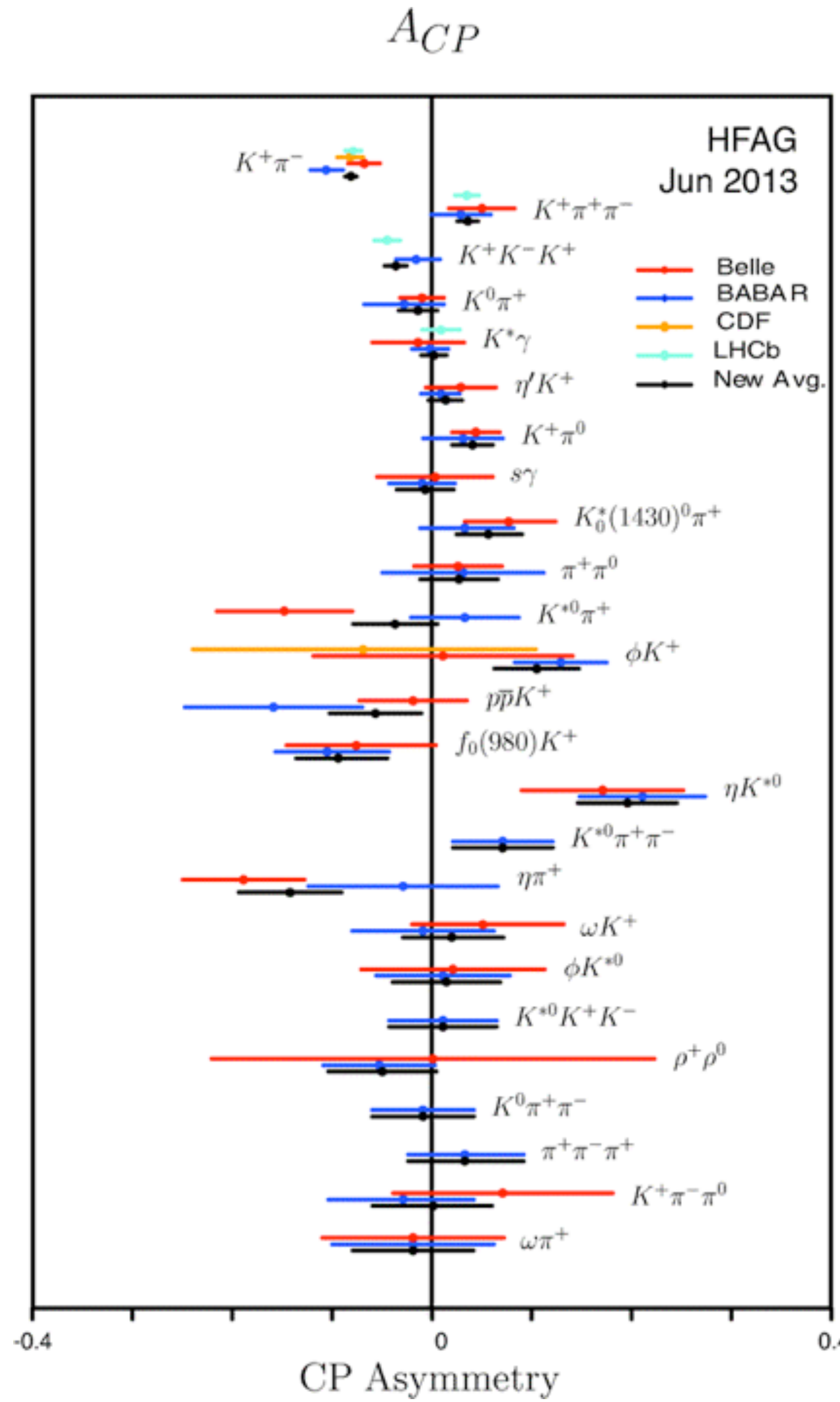


PRL 112 (2014) 011801





PRL 111 (2013) 101801



$B_u \to \psi h$, Dh

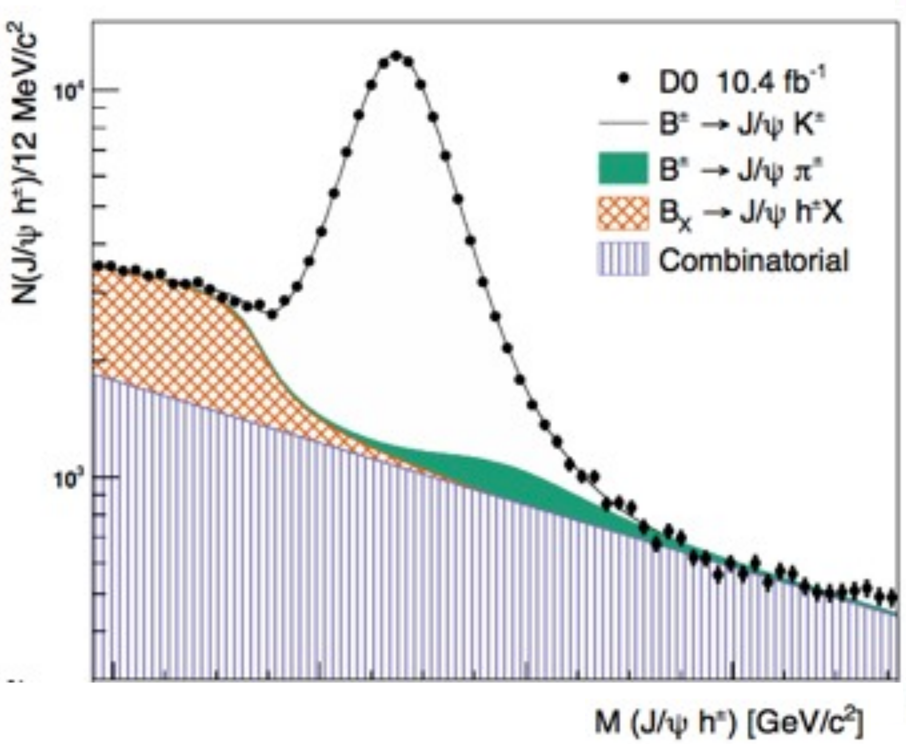
- direct CPV is *only* type possible for charged B
- hidden charm
  - no direct CPV expected for the Cabbibo-favored decay $B \to J/\psi K$
  - Cabbibo-suppressed decays $B^+ \to J/\psi\pi^+$, $\psi'\pi^+$, $\psi' K^+$, with $\psi \to \mu\mu$:
  - tree and penguin contribute different phases ⇒ possible CPV
- open charm
  - $B \to DK$ with $D \to KK, \pi\pi, \pi K$, w/ first observation of $B^\pm \to [\pi^\pm K]_D K^\pm$
  - interference through D final state accessible to both D^0 and $\underline{D}^0$

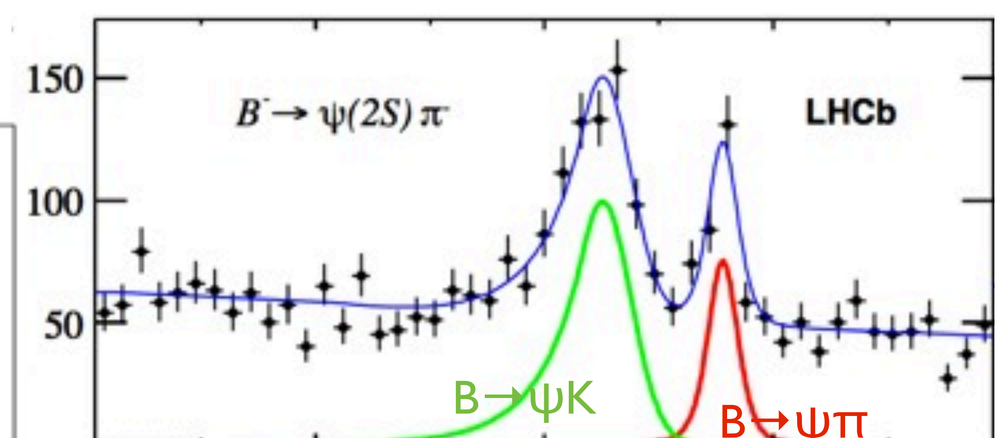
time-integrated asymmetry:

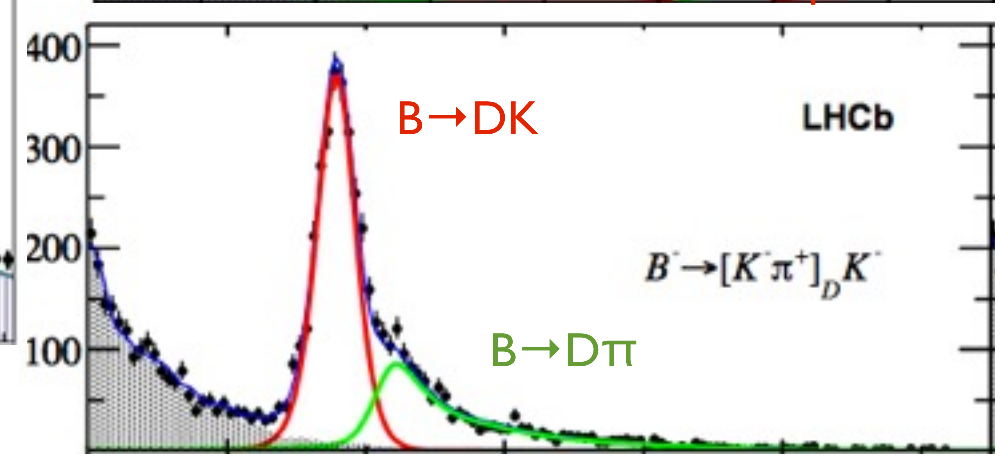
$$A^{\psi\pi} = \frac{\mathcal{B}(B^- \to \psi\pi^-) - \mathcal{B}(B^+ \to \psi\pi^+)}{\mathcal{B}(B^- \to \psi\pi^-) + \mathcal{B}(B^+ \to \psi\pi^+)}$$

$$A_{CP}^{J/\psi\,\pi} = 0.005 \pm 0.027 \pm 0.011$$
$$A_{CP}^{\psi(2S)\pi} = 0.048 \pm 0.090 \pm 0.011$$
$$A_{CP}^{\psi(2S)K} = 0.024 \pm 0.014 \pm 0.008$$

$$A^{J/\psi K} = [0.59 \pm 0.36\,(\text{stat}) \pm 0.07\,(\text{syst})]\,\%,$$
$$A^{J/\psi\pi} = [-4.2 \pm 4.4\,(\text{stat}) \pm 0.9\,(\text{syst})]\,\%.$$







No evidence of direct CPV in $B^+ \to \psi h$

D0

PRL 110 (2012) 241801

LHCb:

PRD 85 (2012) 091105

Measurement (5.8σ) of direct CPV in $B^+ \to DK$

PLB 712 (2012)

also study decay $B^+ \to [K_S K\pi]_D\, h$

arXiv:1402.2982

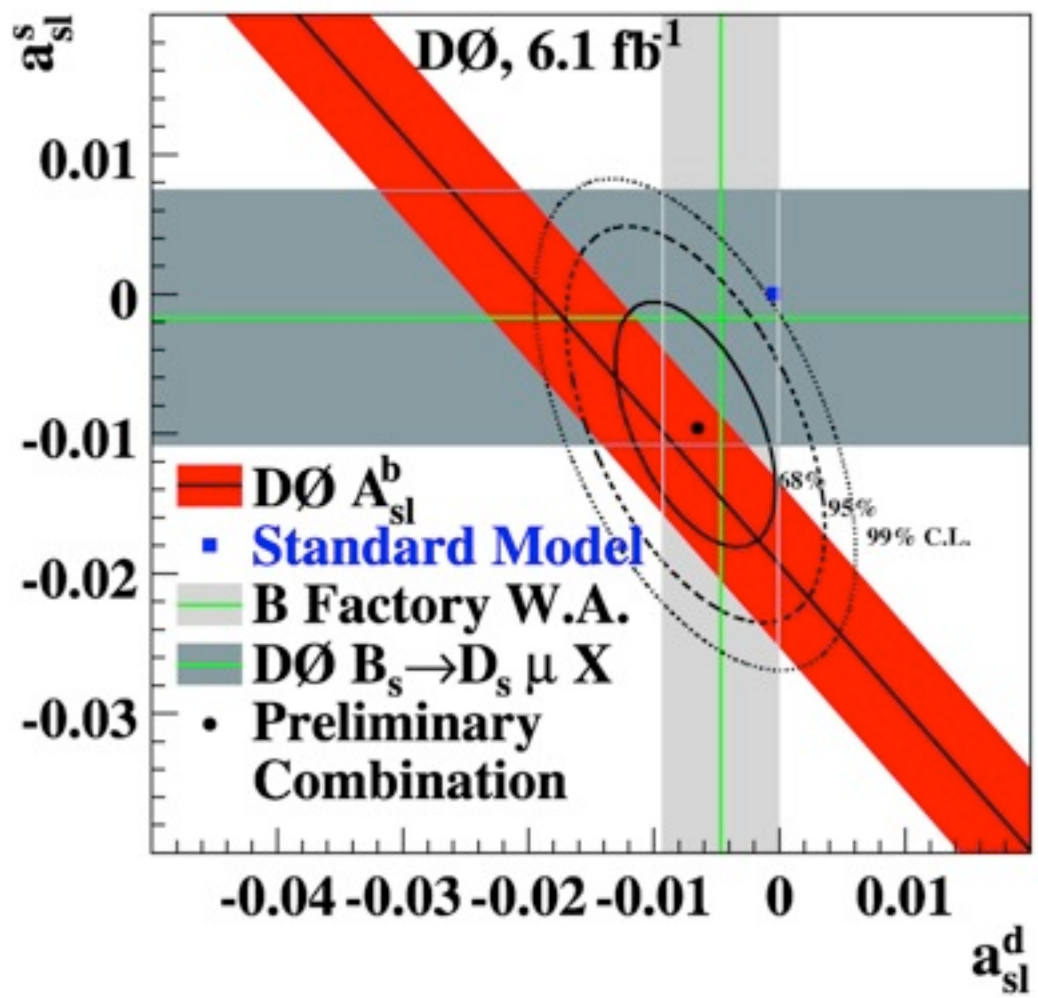
CPV in mixing

- defined by condition $|q/p| \neq 1$
- induces charge asymmetry in semileptonic B decays
  - eg, $B_s \to \mu^+ D_s \nu X$
- dilepton asymmetry

$$A_{\rm SL}(t) = \frac{\Gamma[\overline{B}^0(t) \to \ell^+ X] - \Gamma[B^0(t) \to \ell^- X]}{\Gamma[\overline{B}^0(t) \to \ell^+ X] + \Gamma[B^0(t) \to \ell^- X]} = \frac{1 - |q/p|^4}{1 + |q/p|^4} \approx 2(1 - |q/p|),$$

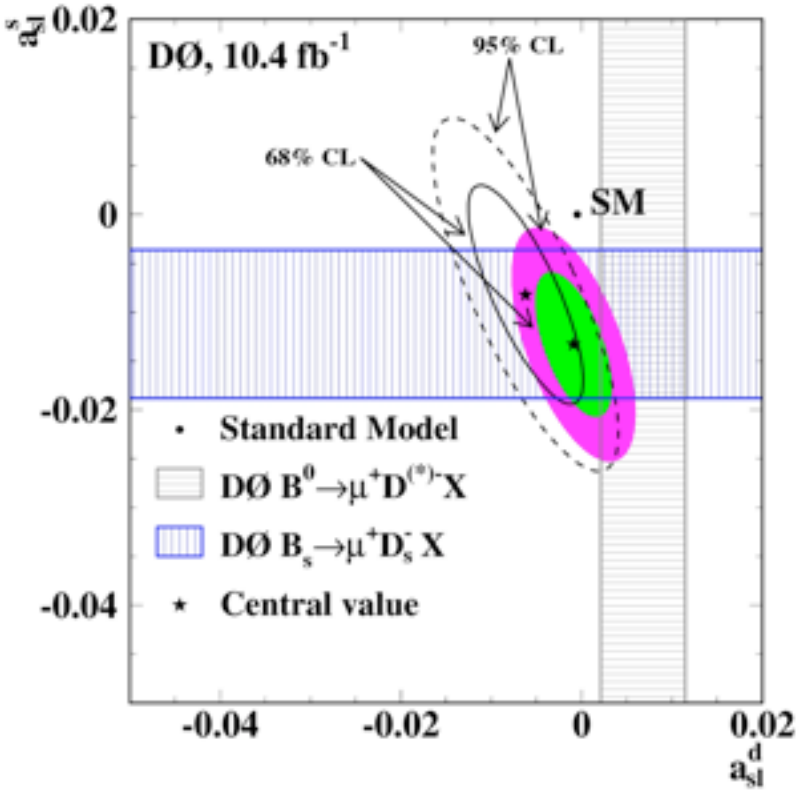
  - A_{SL} is, actually, time-independent
  - sensitive to deviations of |q/p| from 1

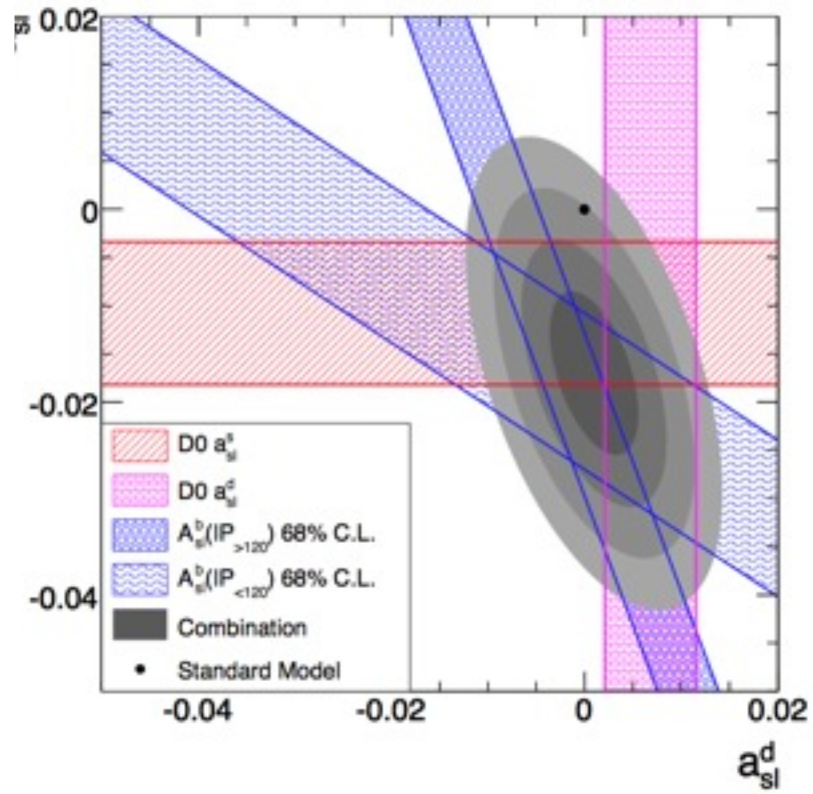
D0, PRD 82, 032001 (2010)

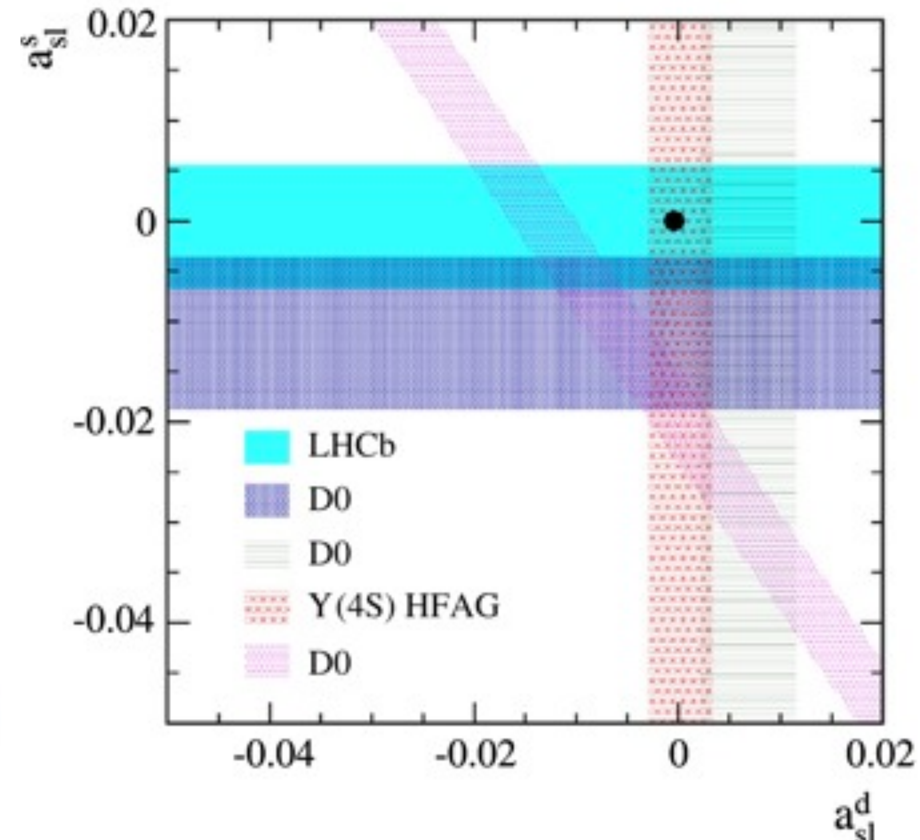


D0 reported 3.9σ discrepancy with SM
both Bs and Bd contribute to the asymmetry
➩ evidence for anomalous CPV in the mixing of B mesons

a_{sl} asymmetry







inclusive measurements:

single and like-sign dimuon charge asymmetries

PRD 89 (2014) 012002

$$a_{sl}^d = (-0.62 \pm 0.43) \times 10^{-2}$$
$$a_{sl}^s = (-0.82 \pm 0.99) \times 10^{-2}$$

assuming $\Delta\Gamma_d/\Gamma_d$ SM value:

$$a_{sl}^d = (-0.62 \pm 0.42) \times 10^{-2},$$
$$a_{sl}^s = (-0.86 \pm 0.74) \times 10^{-2}.$$

semileptonic decays:

PRD 86 (2012) 072009: a_{sl_d} from $B_d \to \mu D_s^{(*)} X$

$$a_{sl}^d = (0.51 \pm 0.86)\% \ (\mu D \text{ channel}),$$
$$a_{sl}^d = (1.25 \pm 0.87)\% \ (\mu D^* \text{ channel})$$

PRL 110 (2013) 011801: a_{sl_s} from $B_s \to \mu D_s X$

$$a_{sl}^s = [-1.12 \pm 0.74\,(\text{stat}) \pm 0.17\,(\text{syst})]\,\%$$

$$a_{sl}^d(\text{comb.}) = (0.07 \pm 0.27)\%,$$
$$a_{sl}^s(\text{comb.}) = (-1.67 \pm 0.54)\%$$

semileptonic decays:

PLB 728 (2014) 607

a_{sl_s} from $B_s \to \mu D_s X$

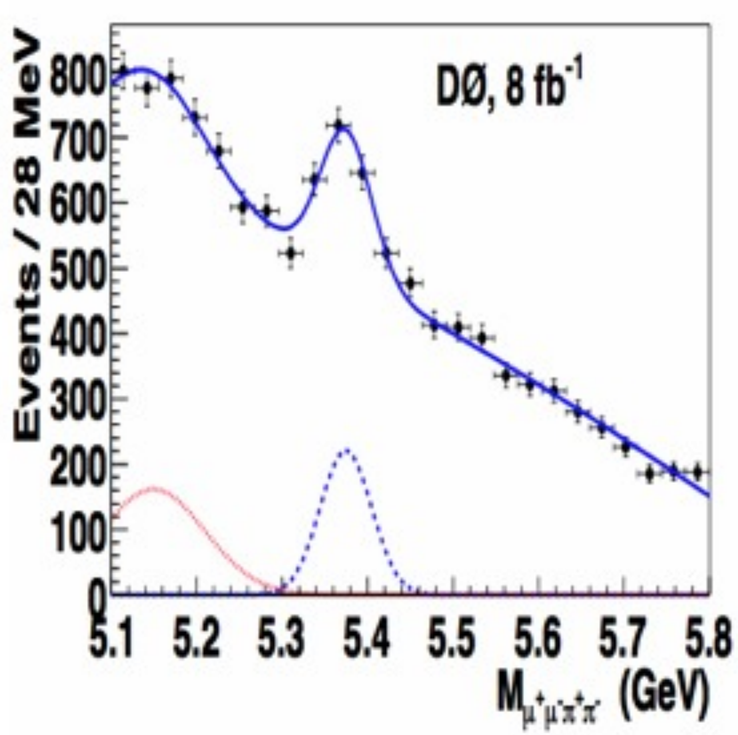
most precise measurement

$$a_{sl}^s = (-0.06 \pm 0.50 \pm 0.36)\%$$

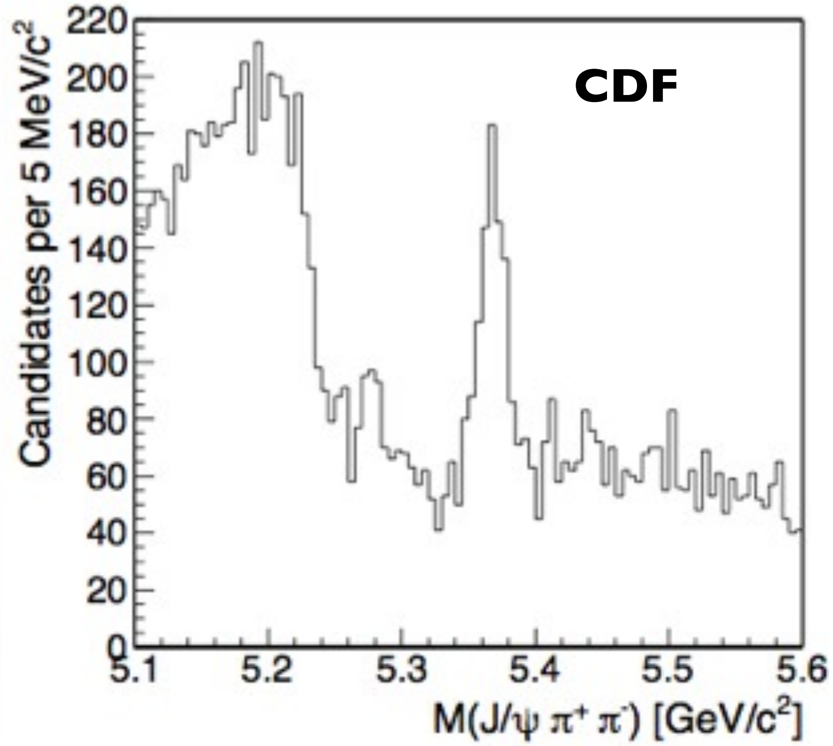
D0 final Run II results yield 3σ discrepancy with SM

LHCb + Υ(4S) results appear consistent with SM expectation

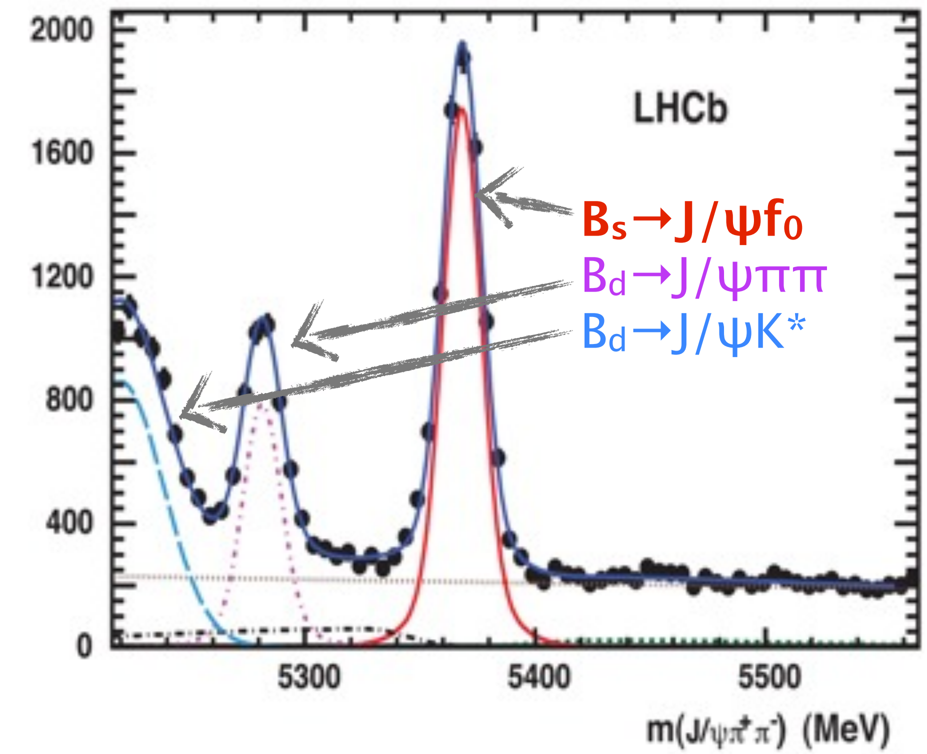
$B_s \to J/\psi f_0$



PRD 85 (2012) 011103



PRD 84 (2011) 052012



PLB 698 (2011) 11, first observation

➠ CP-odd final state: no need for angular analysis!

PLB 713 (2012) 378, Φ_s measurement:

$$\phi_s = -0.019^{+0.173+0.004}_{-0.174-0.003}$$

untagged:

$$\Gamma(B_s^0 \to f_-) + \Gamma(\bar{B}_s^0 \to f_-)$$
$$= \mathcal{N}e^{-\Gamma_s t}\{e^{\Delta\Gamma_s t/2}(1+\cos\phi_s) + e^{-\Delta\Gamma_s t/2}(1-\cos\phi_s)\}$$

☞ lifetime-like measurement!

tagged:

$$\Gamma(\overset{(-)}{B}{}_s^0 \to f_-)$$
$$= \mathcal{N}e^{-\Gamma_s t}\left\{\frac{e^{\Delta\Gamma_s t/2}}{2}(1+\cos\phi_s) + \frac{e^{-\Delta\Gamma_s t/2}}{2}(1-\cos\phi_s) \pm \sin\phi_s \sin(\Delta m_s t)\right\}$$

☞ mixing-like measurement!

$D^0 \rightarrow \mu\mu$

- FCNC search in up-type quark sector
  - complement B and K searches
- decay $D^0 \rightarrow \mu^+\mu^-$ highly suppressed in SM ($\sim 10^{-13}$), but enhanced by NP scenarios
- use normalization channel; e.g. at CMS $D^{*+} \rightarrow D^0(K^-\mu^+\nu)\pi^+$
  - no excess observed, place upper limit (@90% CL)

➡ exclusion limits

- CDF < 2.1×10^{-7} PRD 82 (2010) 091195
- BABAR: $[0.6, 8.1] \times 10^{-7}$ PRD 86 (2012)032001
- BELLE < 1.4×10^{-7} PRD 81 (2010) 091102
- LHCb < 1.3×10^{-8} LHCb-CONF-2012-005
- CMS < 5.4×10^{-7} CMS-PAS-BPH-11-017