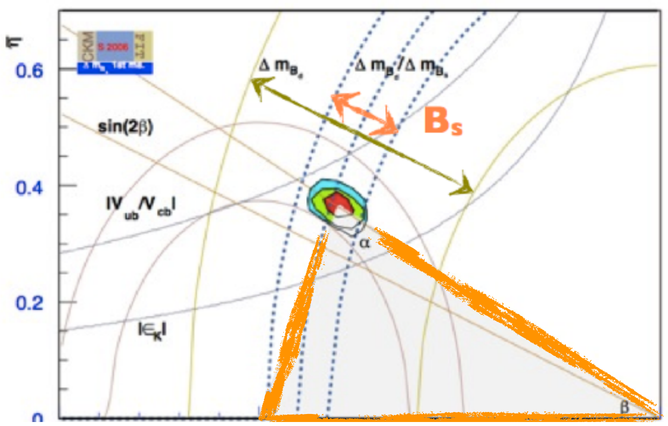
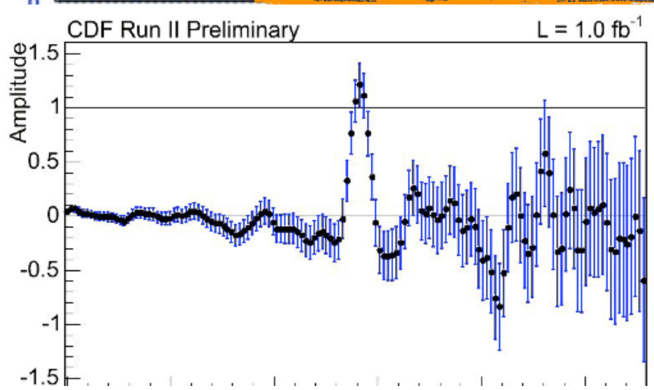
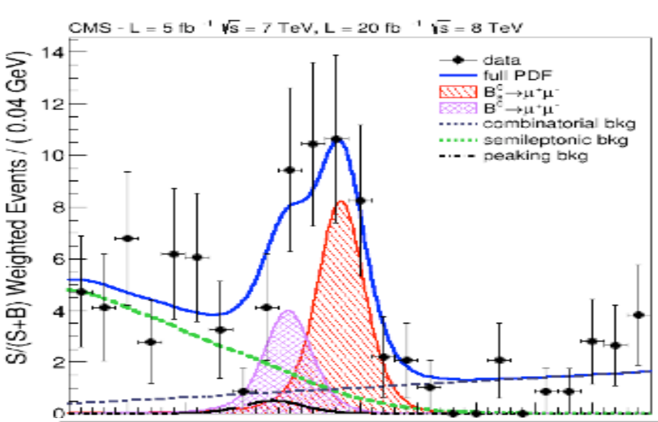
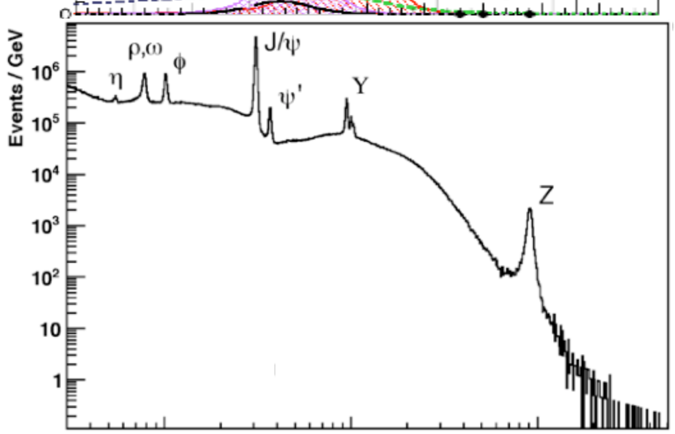








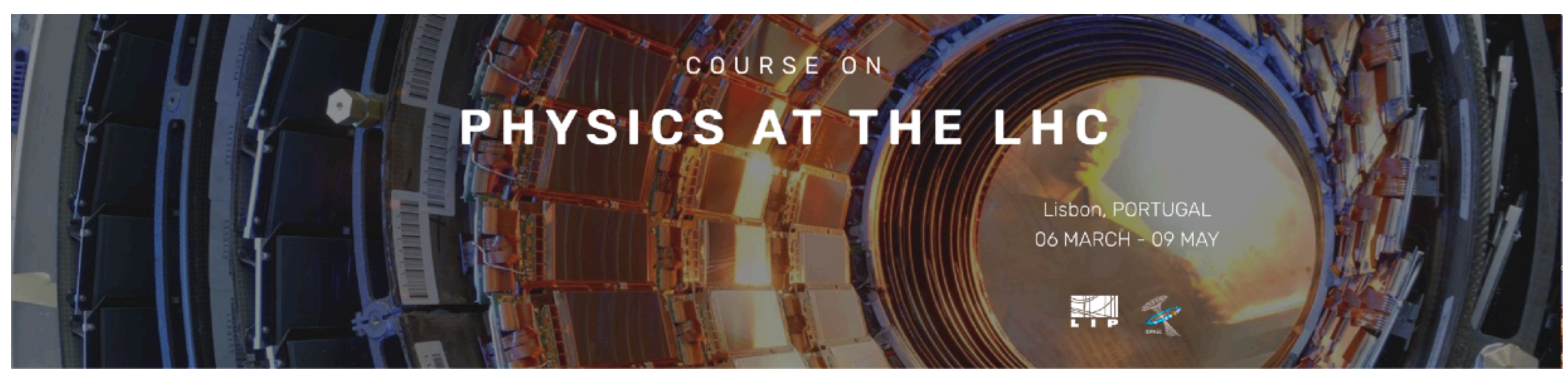
Lecture on

heavy flavor physics

&

rare decay searches

Nuno Leonardo, nuno@cern.ch



LABORATÓRIO DE INSTRUMENTAÇÃO E
FÍSICA EXPERIMENTAL DE PARTICULAS

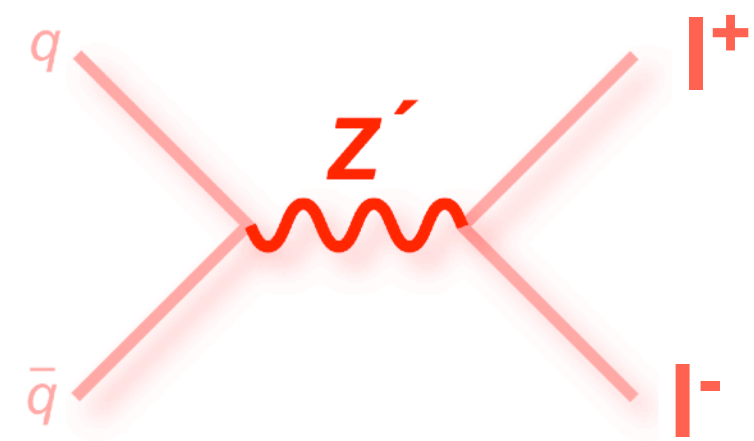
IF INVESTIGADOR FCT

N.Leonardo's introduction

- Under-graduate: LEFT/IST
- Graduate: MSc Cambridge, PhD MIT
  - CDF experiment @ Fermilab's Tevatron
    ➠ the most powerful collider then
  - discovery of B_s particle-antiparticle oscillations (doctoral thesis)
- Post-graduate: CERN, Purdue
  - CMS experiment @ CERN's LHC
    ➠ the most powerful collider now (and next decades')
  - discovery of sequential meson melting in QGP
    discovery of $B_s \to \mu\mu$ rare decay
  - CMS Trigger Performance and Validation coordinator
- PI Researcher, LIP
  - CMS heavy Flavor physics group coordinator

LHC goal: find New Physics beyond the SM

PATH A



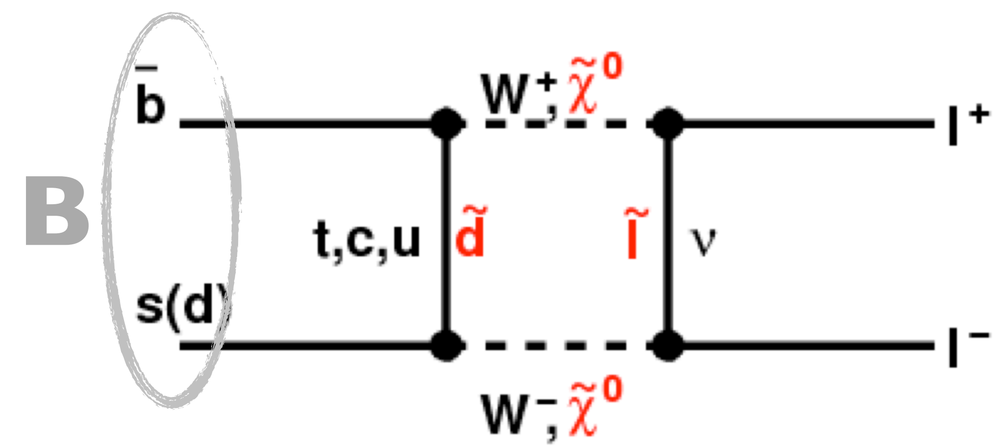
BSM particles directly produced in collision
(provided NP scale ~ few TeV)

the direct way

Energy frontier!

search for
SUSY, extra dimensions,
Z', other "exotic" objects

PATH B



BSM particles modify SM processes
via Quantum mechanical effects

the indirect way

Luminosity frontier!

measure H, W, Z, top,
b hadron properties,
search for rare decays

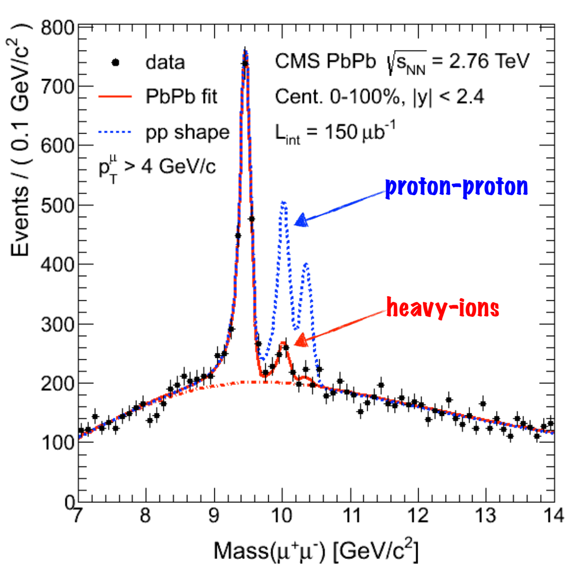
flavor!

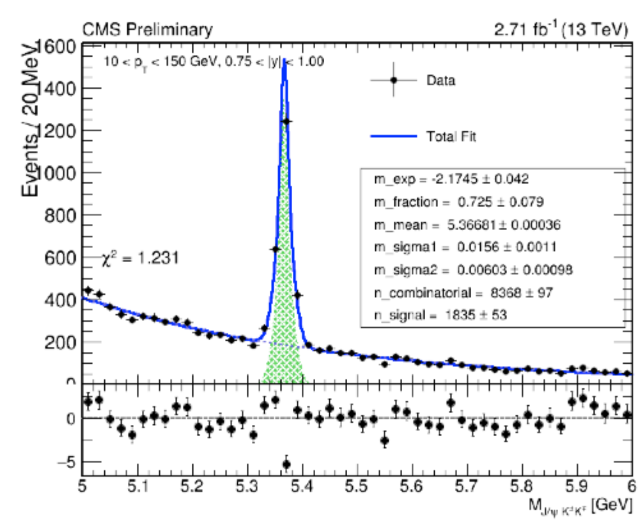
flavor: constraining the theory

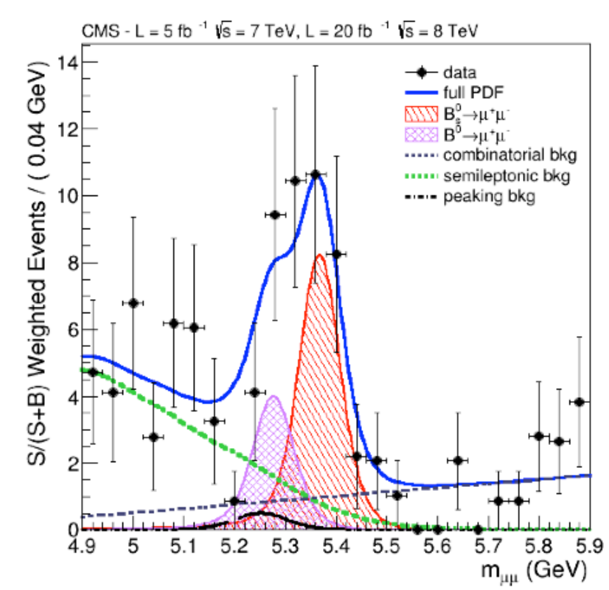
STANDARD MODEL & BEYOND

SU(3) ⊗ SU(2) ⊗ U(1) ⊗ ...

strong sector	electroweak sector	new sector
HF production & suppression	HF decay (mixing, cpv, ...)	rare decays

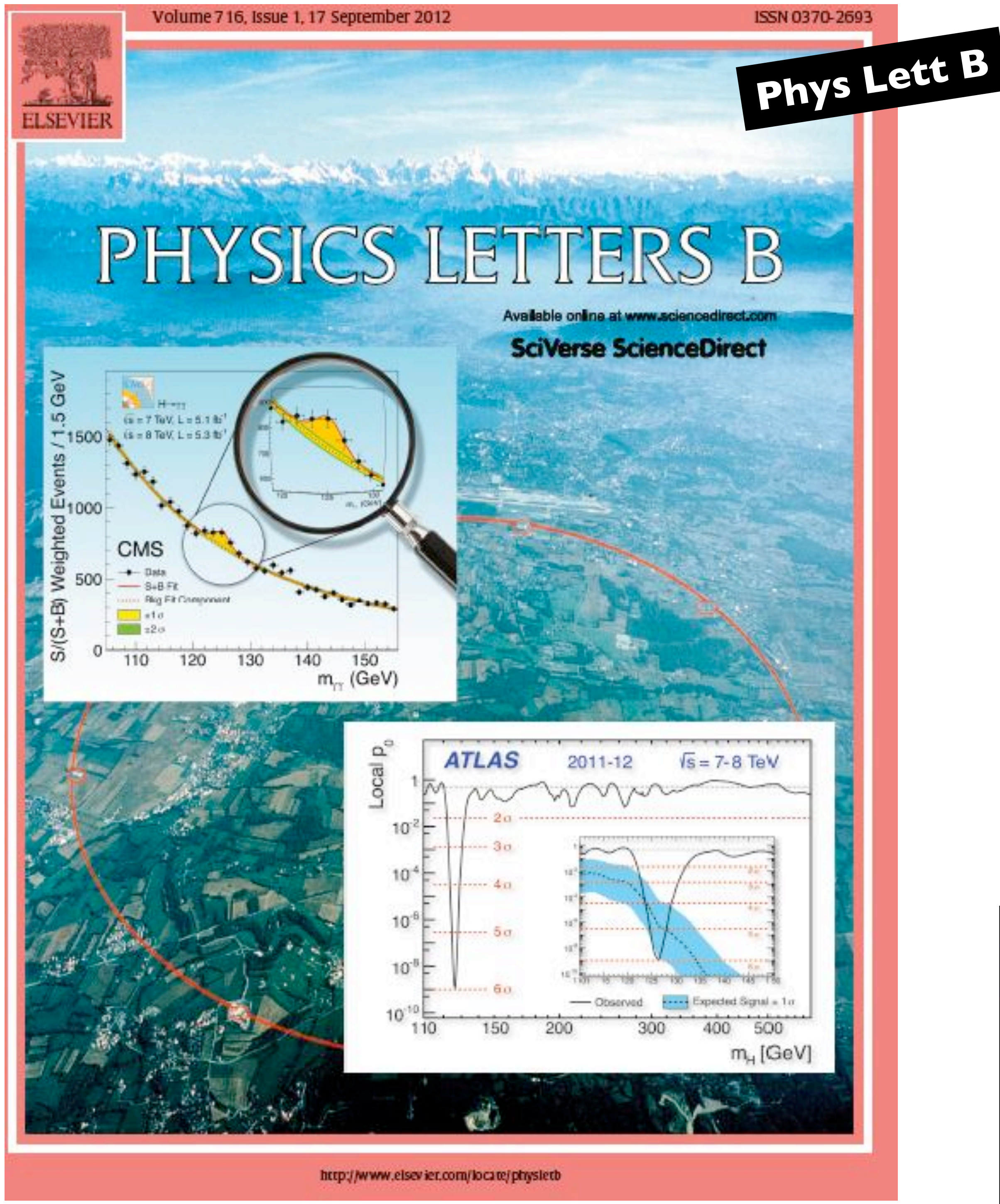




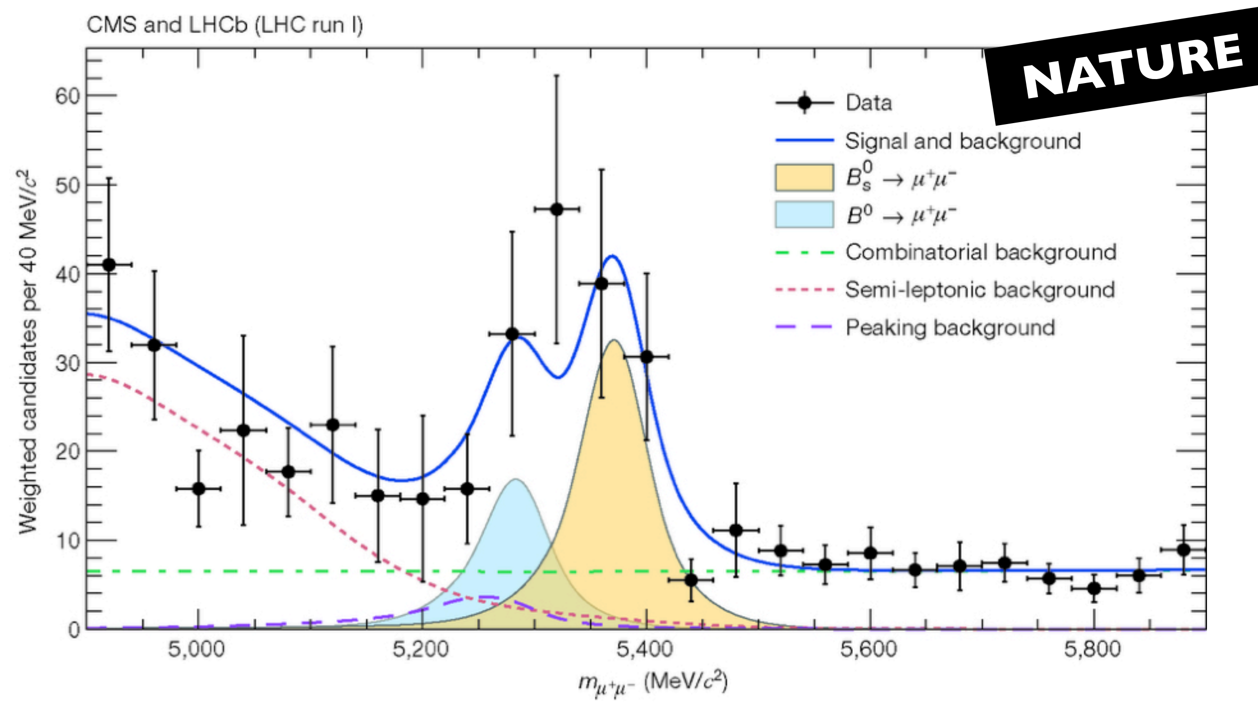


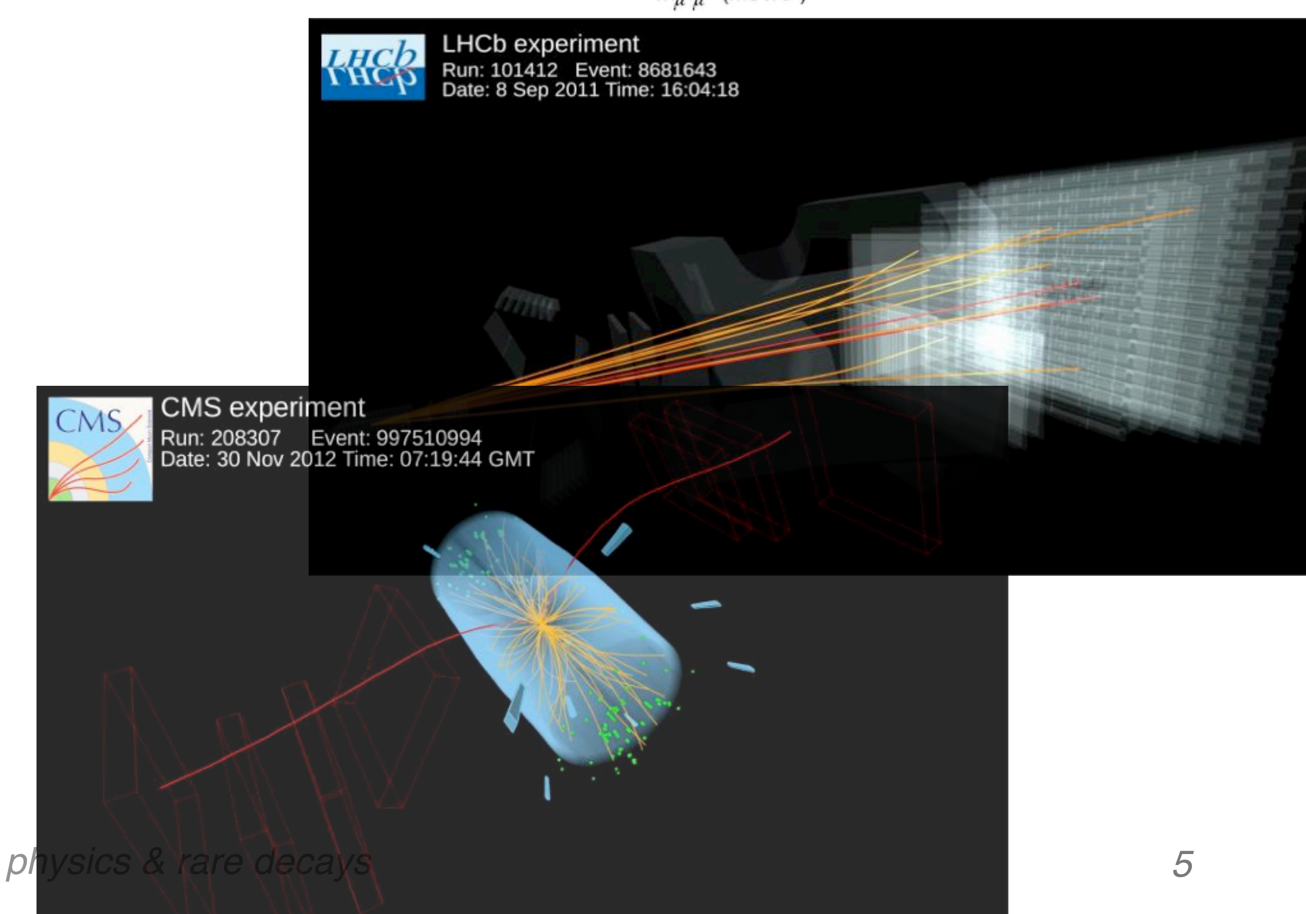
LHC discovery flagships

a 4-decade search effort... ended in 2012:
Higgs by ATLAS & CMS



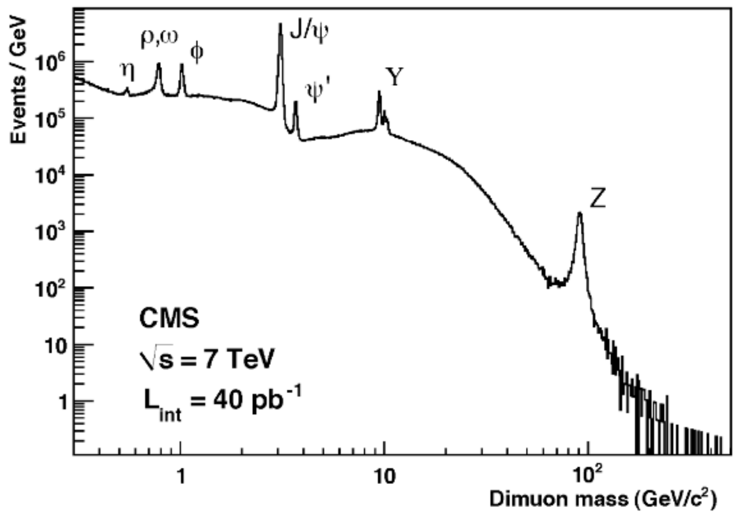
a 3-decade search effort... ended in 2015:
$B_s \rightarrow \mu\mu$ by CMS & LHCb

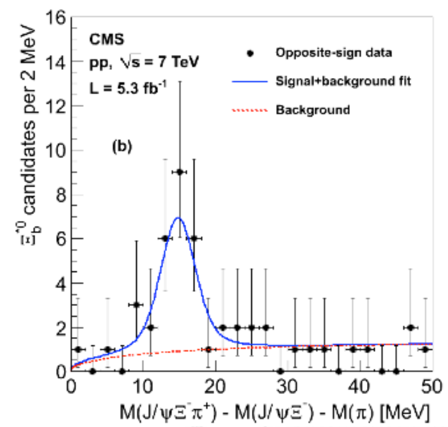


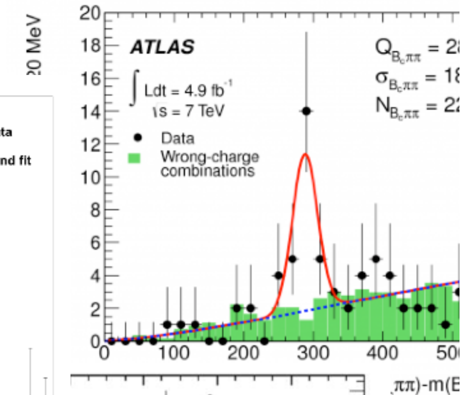


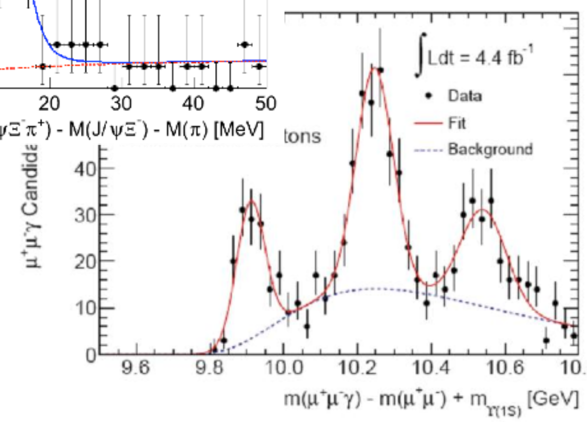
LHC: measurements & searches

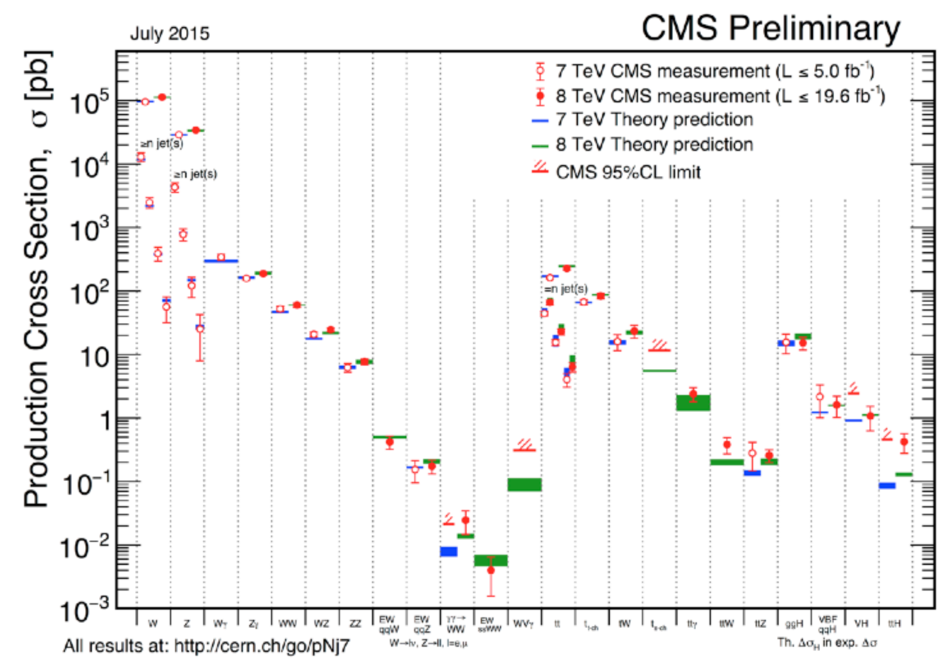
Impressive amount of sophisticated measurements
exploring fantastic and unique data

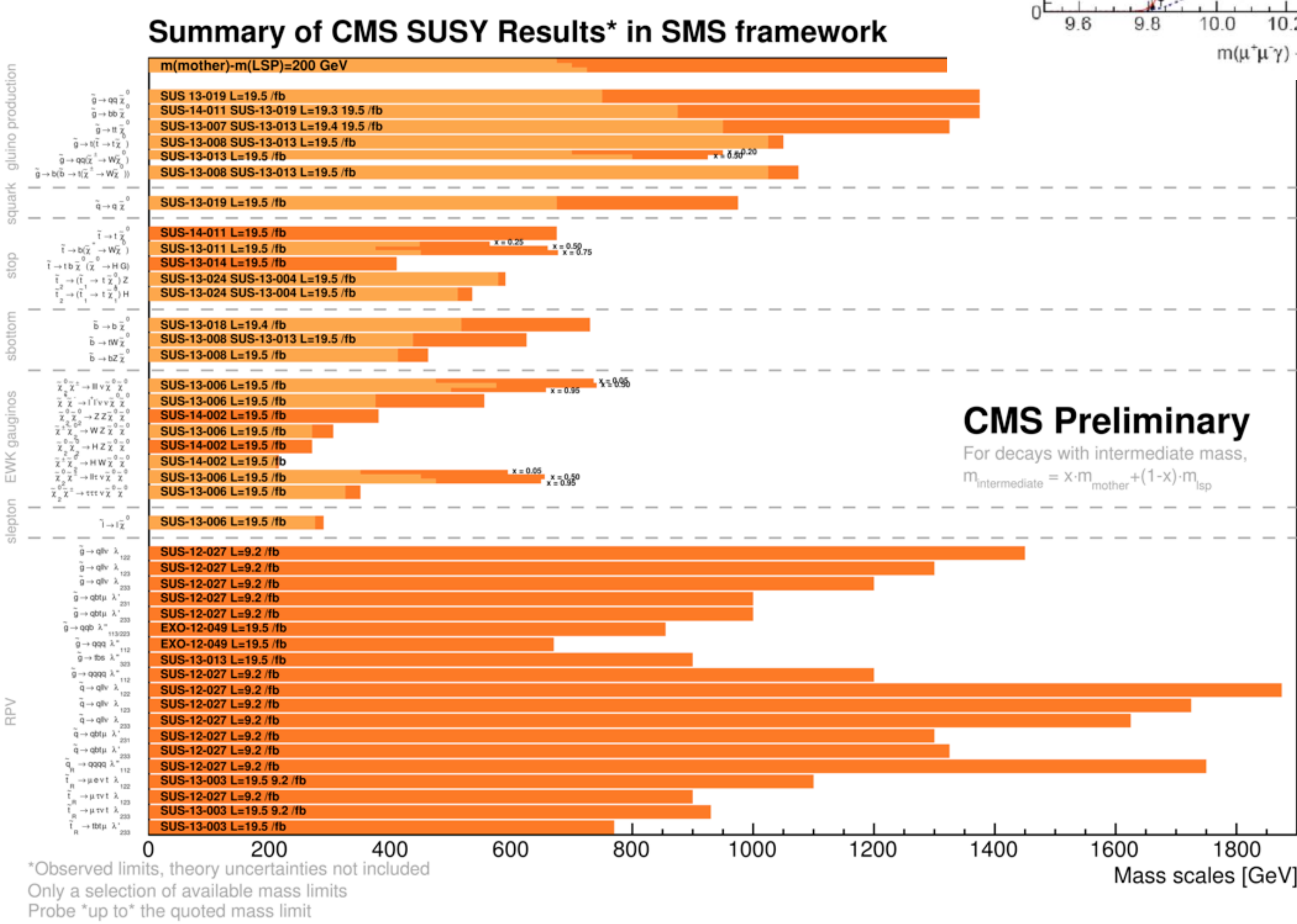


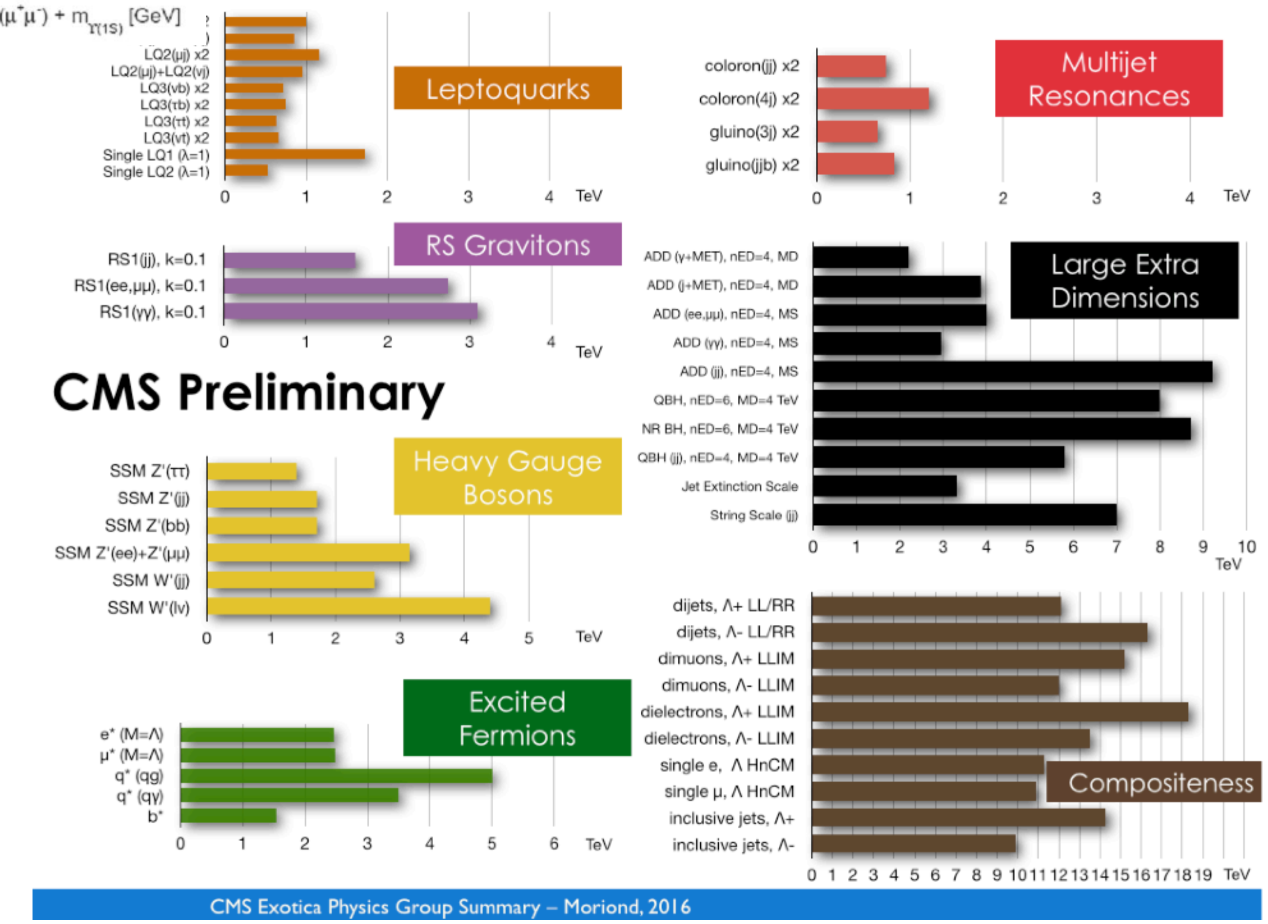








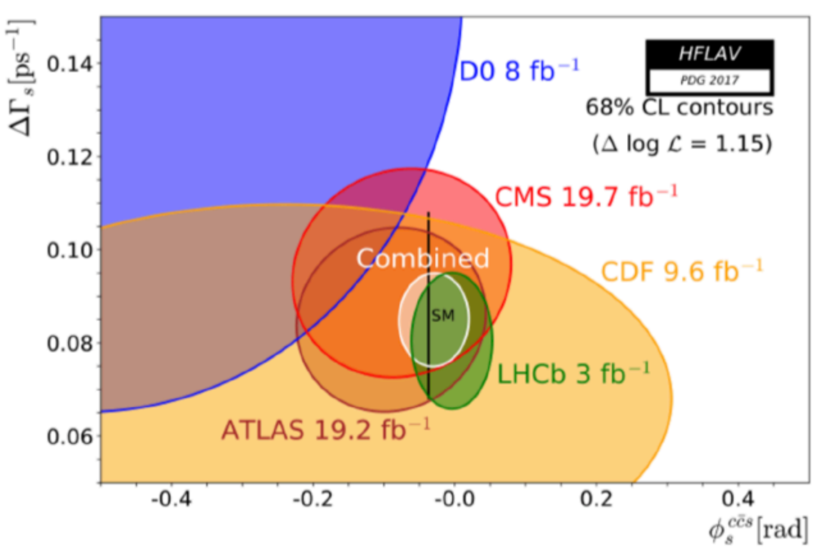


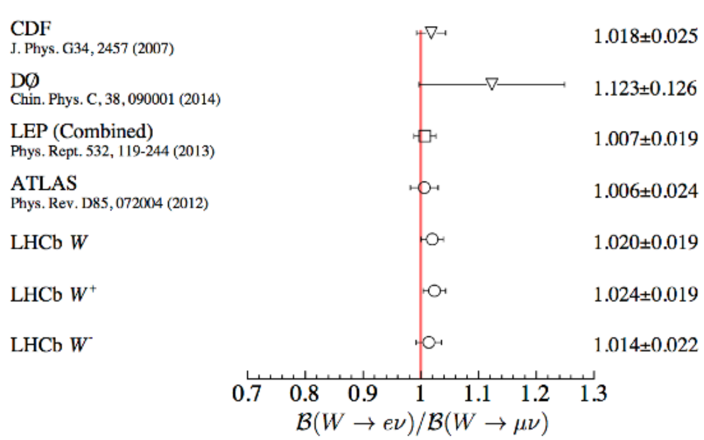


flavor anomalies

Are these the first indications of Physics Beyond the Standard Model?

This is how theory - data **agreement** (aka no-anomaly) looks like:



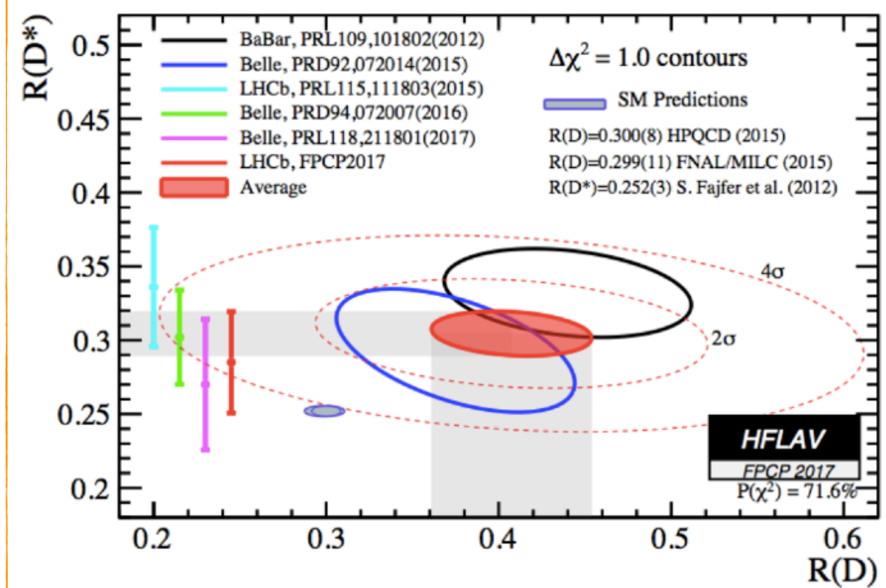


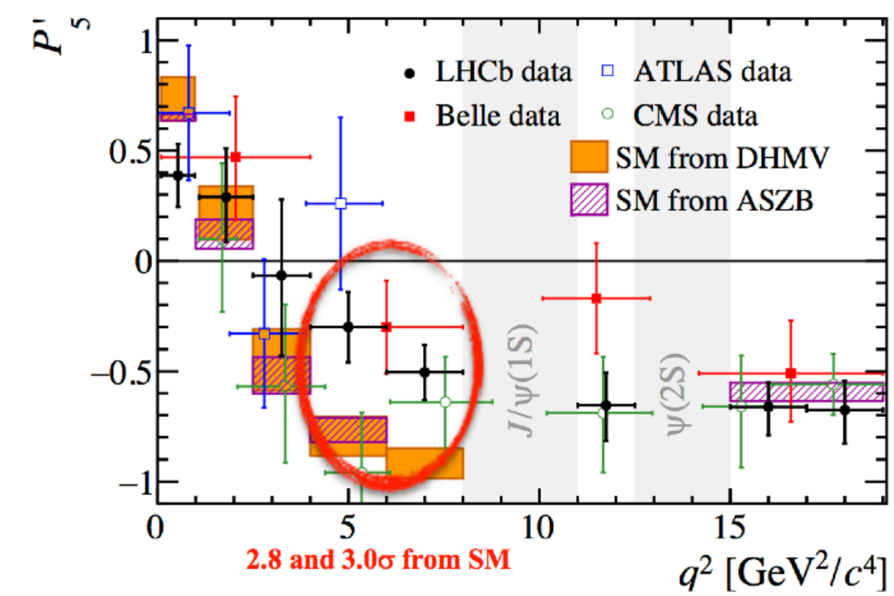
$$\frac{\Gamma_{\mu\mu}}{\Gamma_{ee}} = \frac{B(Z \to \mu^+\mu^-)}{B(Z \to e^+e^-)} = 1.0009 \pm 0.0028$$

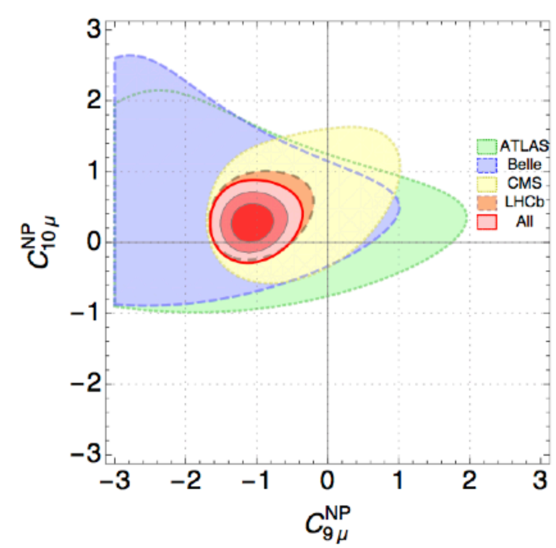
$$\frac{\Gamma_{\tau\tau}}{\Gamma_{ee}} = \frac{B(Z \to \tau^+\tau^-)}{B(Z \to e^+e^-)} = 1.0019 \pm 0.0032$$

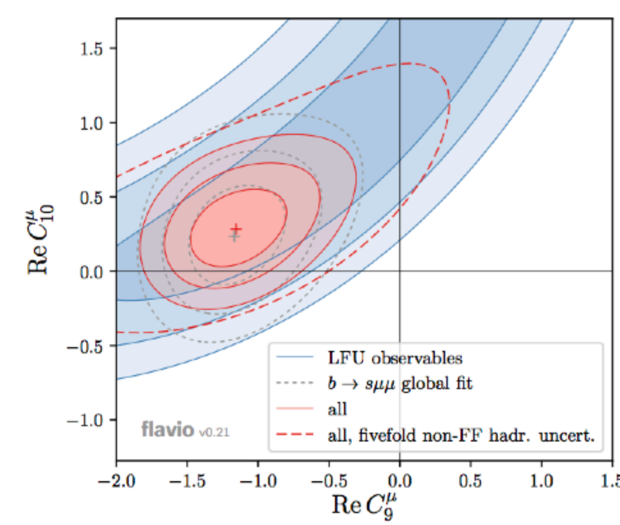
Test **lepton flavour universality**
(electroweak couplings of leptons to gauge bosons are independent of their flavours)

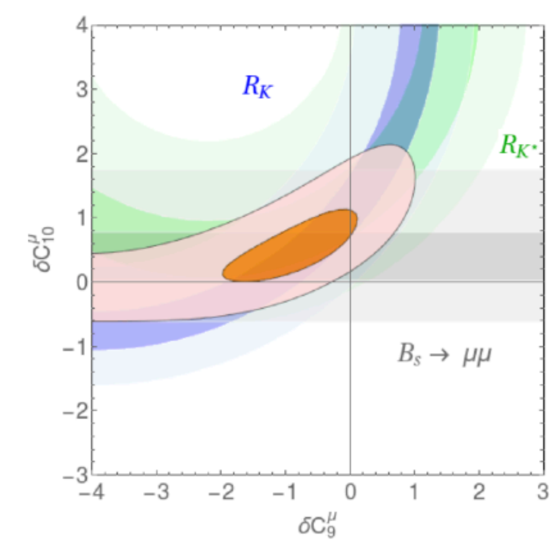
$$R_H = \frac{\int \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B\to He^+e^-)}{dq^2}\, dq^2}$$











Global fit: take into account O(100) observables from different experiments
Coherent pattern that requires (2-3σ) BSM contributions to accommodate data
Largest "coherent" set of BSM effects in present data

Contents

the role of flavor physics

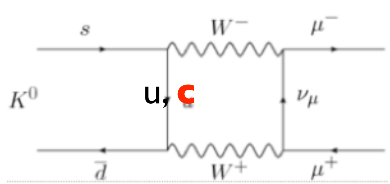
- in searching for **New Physics**
  - discovery potential beyond energy frontier e.g. via searches for rare processes
- in understanding why the **SM** appears so fundamental
  - in that no phenomena beyond the SM has (yet) been detected at LHC
- in learning about standing mysteries of the **flavor structure** of SM (and BSM)
- in connecting **CP violation** to the matter-antimatter asymmetry in the observable universe
- in understanding **QCD**, and probing the properties of **deconfined** 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)

indirect discovery via precision

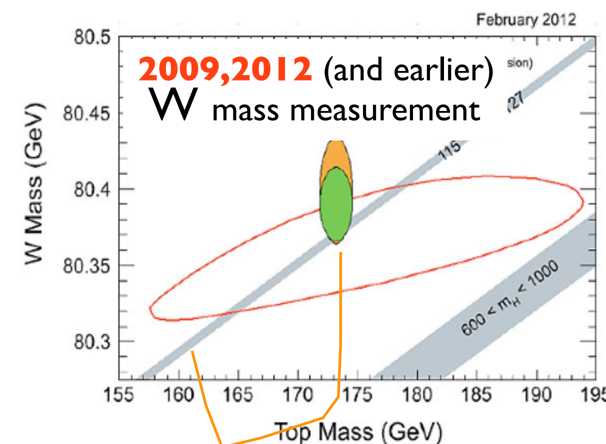
- new physics can show up at precision frontier before energy frontier
  - kaon (1947), Λ^0 (1950) led to discovery of strangeness
  - GIM mechanism (1970) before discovery of charm (1974)
  - CP violation (1964) before discovery of bottom (1977) & top (1995)
  - neutral current (1973) before discovery 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])

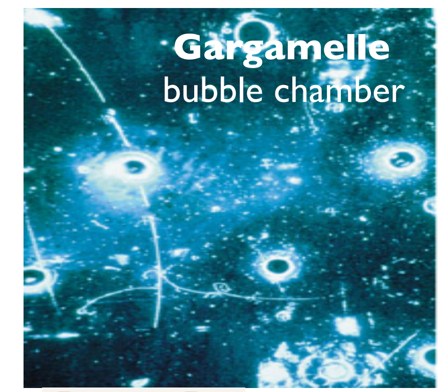
1970
GIM mechanism
(Glashow–Iliopoulos–Maiani)
required the fourth quark: **c**harm
e.g. $K^+ \to \mu^+ \nu_\mu$ so why not $K^0 \to \mu^+ \mu^-$?



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)

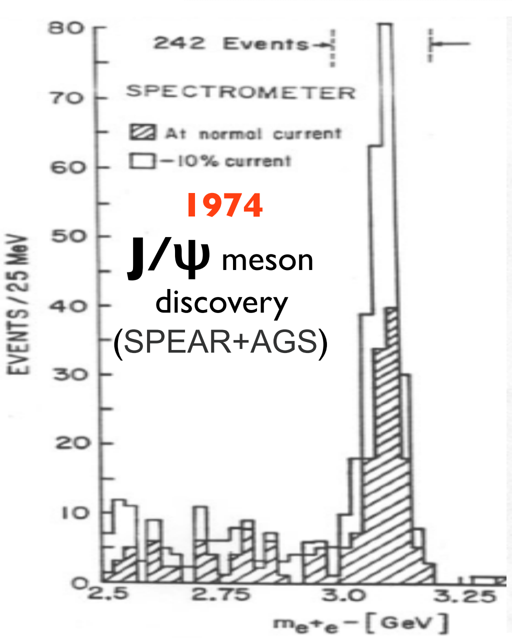


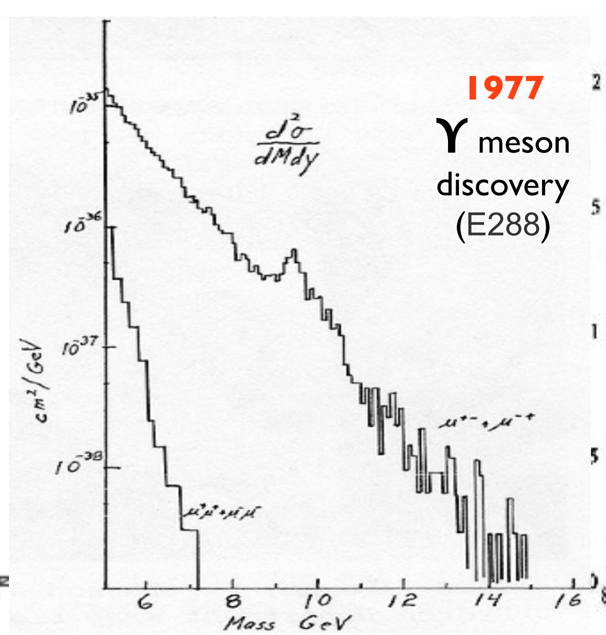
precision m_W and m_t
$\Rightarrow m_H < 145$ GeV

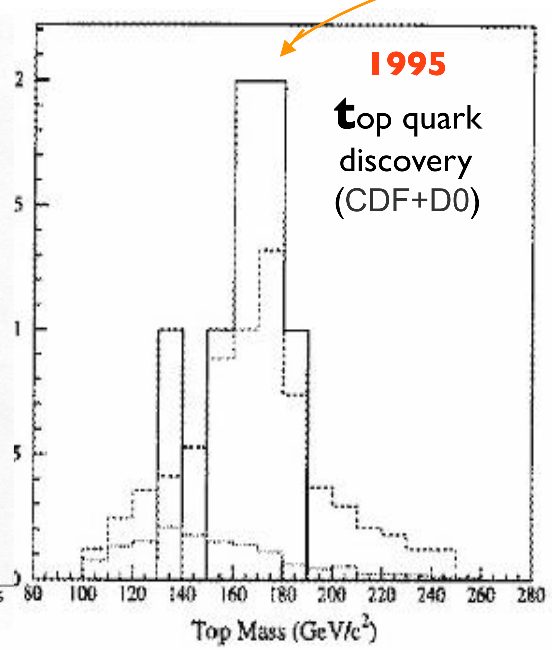


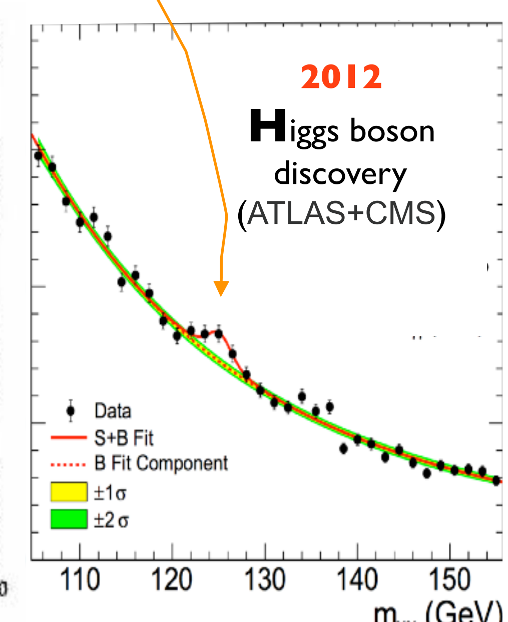
$\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$

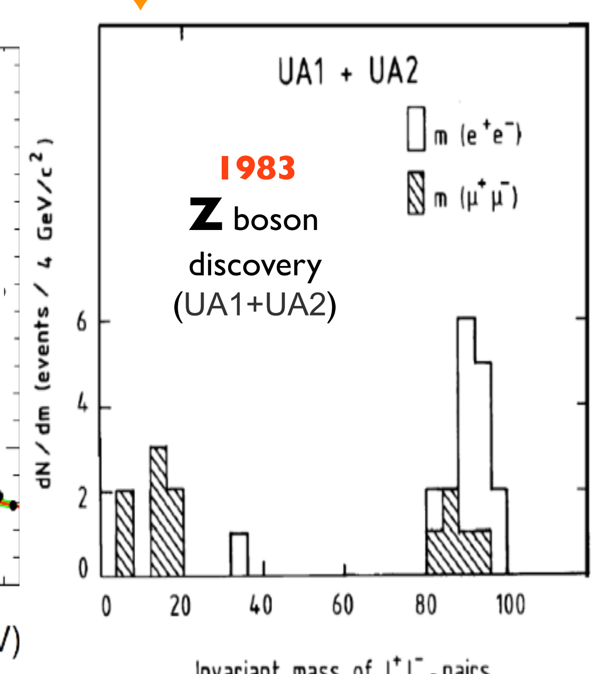
1973
neutral currents observed











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

«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))

( ) = with Dirac neutrino masses

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

flavor parameters

flavor «puzzle»

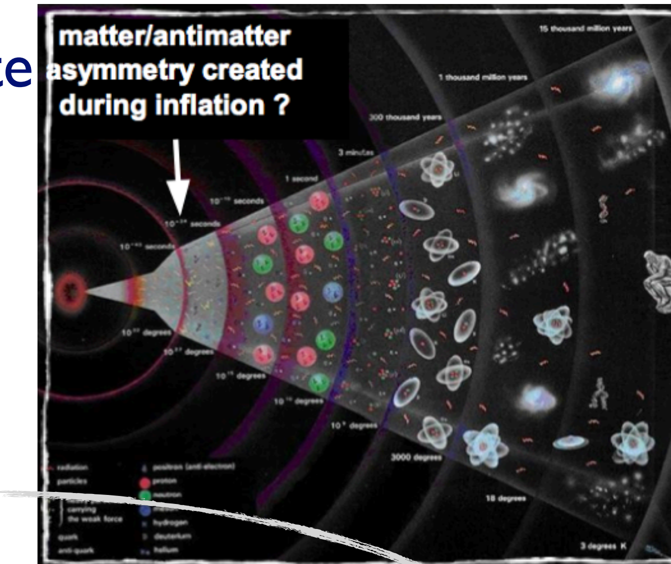
- there are standing mysteries intrinsic to the SM flavor sector
  - why are there so many free parameters
    - why do these parameters exhibit strong hierarchical structure spanning several orders of magnitude
  - why are there so many fermions
  - what is responsible for their organization into generations
    - 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: $m \lesssim \Lambda_{QCD}$
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

the Higgs

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

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

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

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

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

- flavor changing interactions in the SM (charged currents) through couplings to W± bosons

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

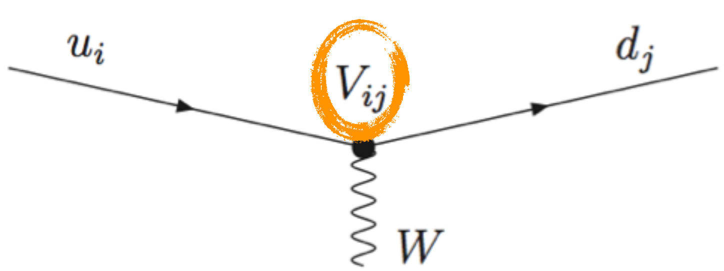
the CKM matrix

- 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]

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

- 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

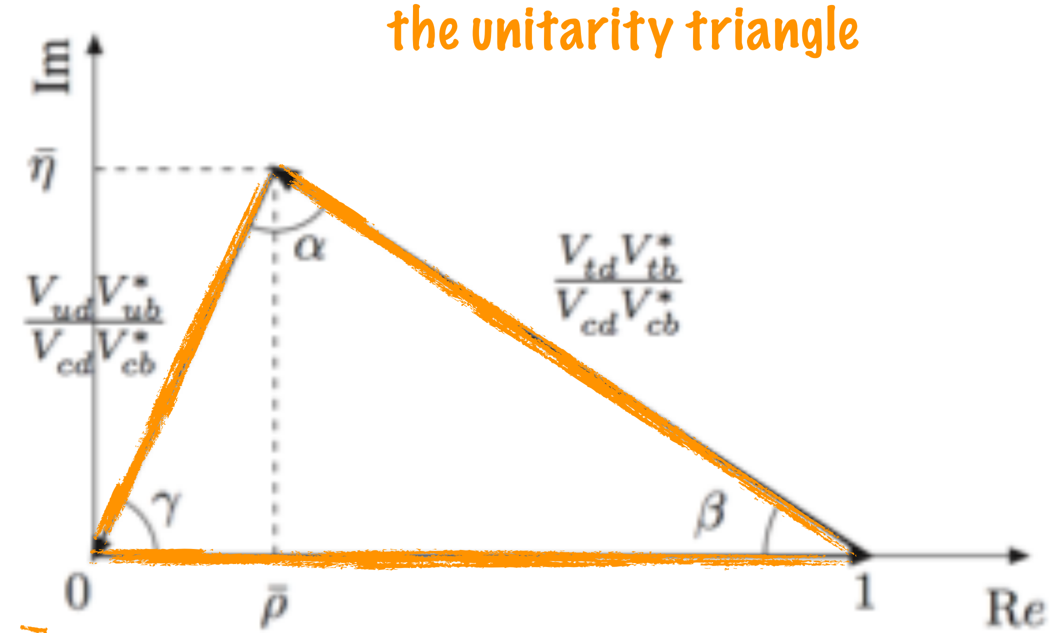
$$\sum_i V_{ij} V_{ik}^* = \delta_{jk} = \sum_i V_{ji} V_{ki}^*$$

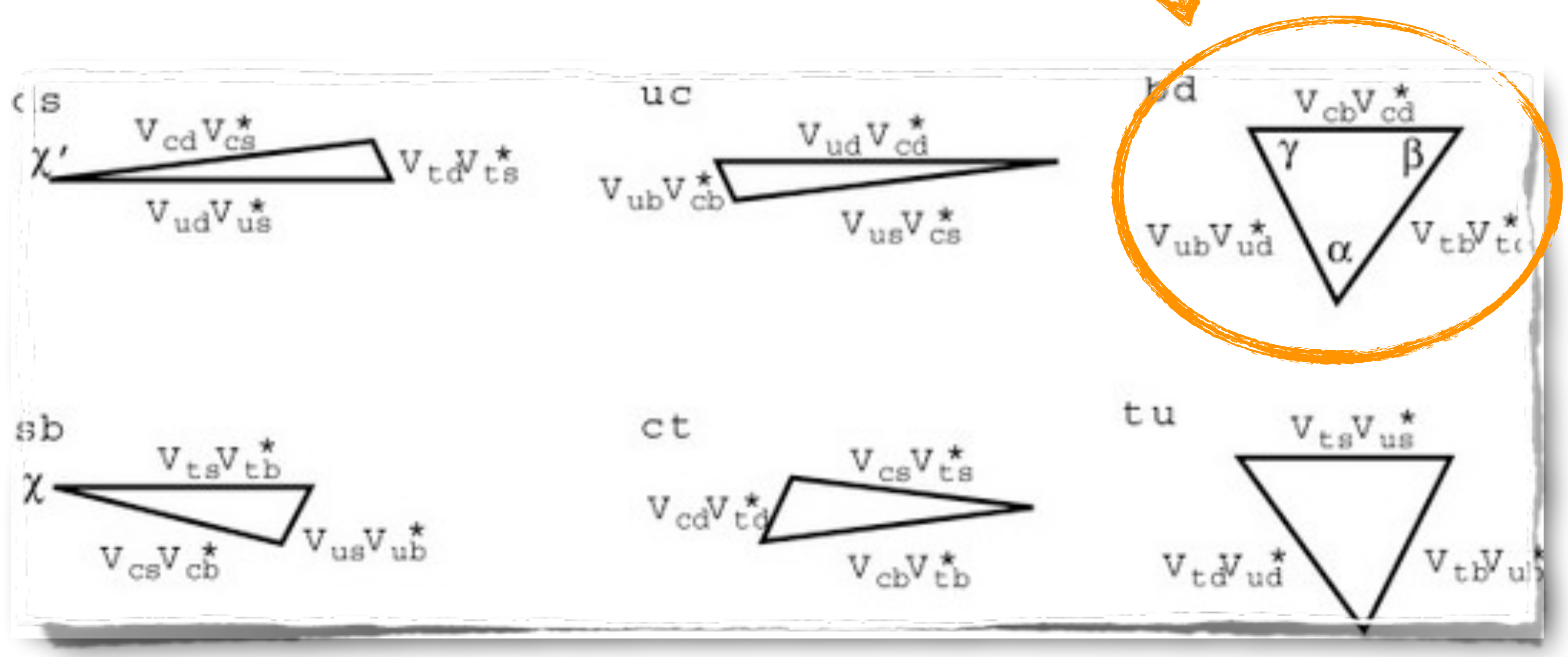
- e.g. multiplying 1st & 3rd columns

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

- 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)

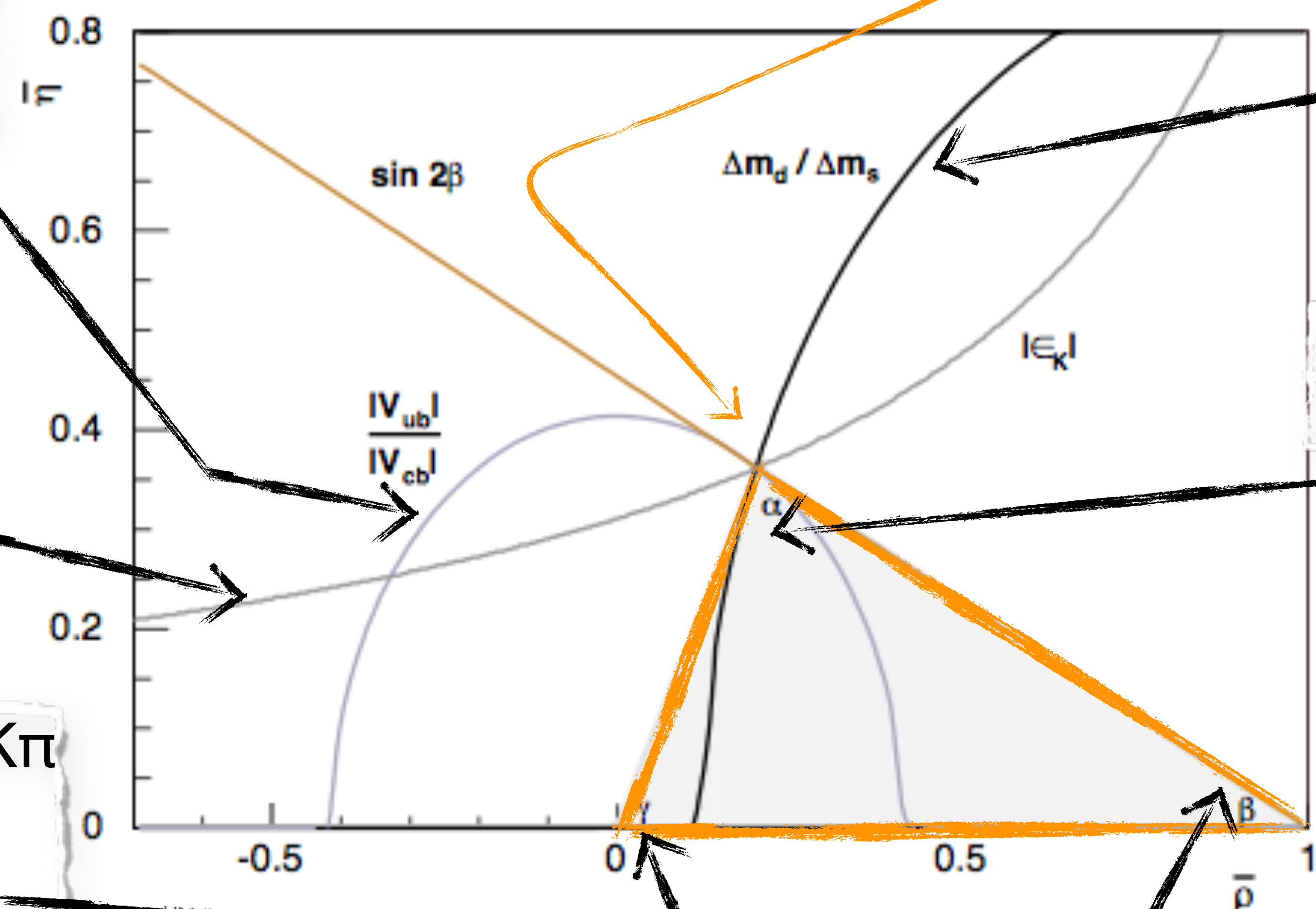
constraining the unitarity triangle

- 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?

semileptonic B decays
$B \to X_u l \nu$, $D^{(*)} l \nu$

CPV in neutral kaons
$K \to \pi\pi$

CPV in $B \to D^* K$, $D\pi$, $K\pi$
angle: gamma
(the least well known)

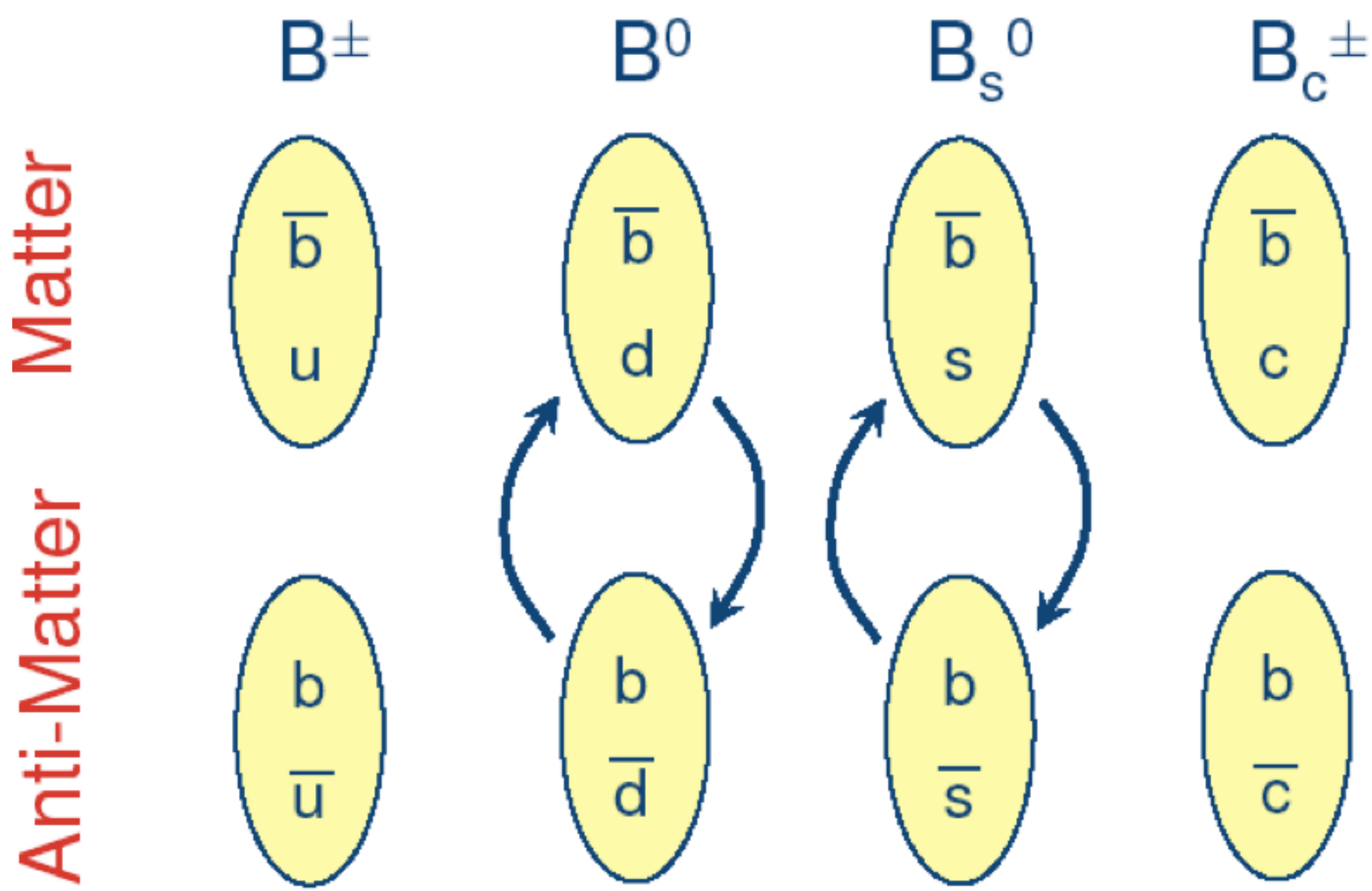


$B_{d,s}$ mixing
$B_s \to D_s \pi(\pi\pi)$, $D_s l X$
$B_d \to D\pi$, $D^{(*)} l \nu$

CPV in $B \to \pi\pi$, $\rho\pi$
angle: alpha

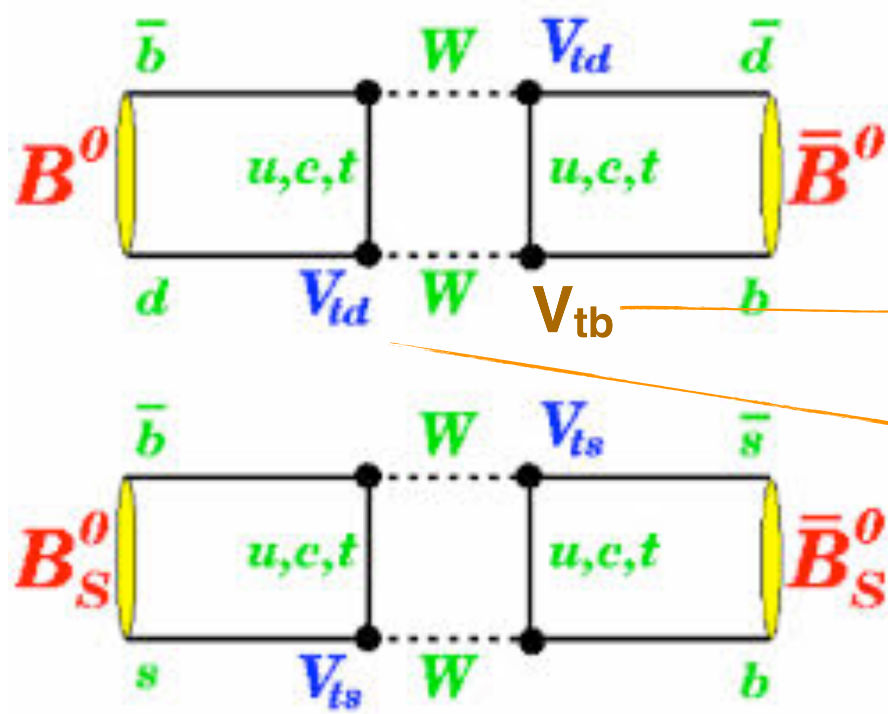
CPV in B_d
$B_d \to \psi K$, $D^* D^*$
angle: sin(2β)

example: B meson mixing



➡ neutral B mesons undergo spontaneous flavor oscillations between particle and

example: B meson mixing



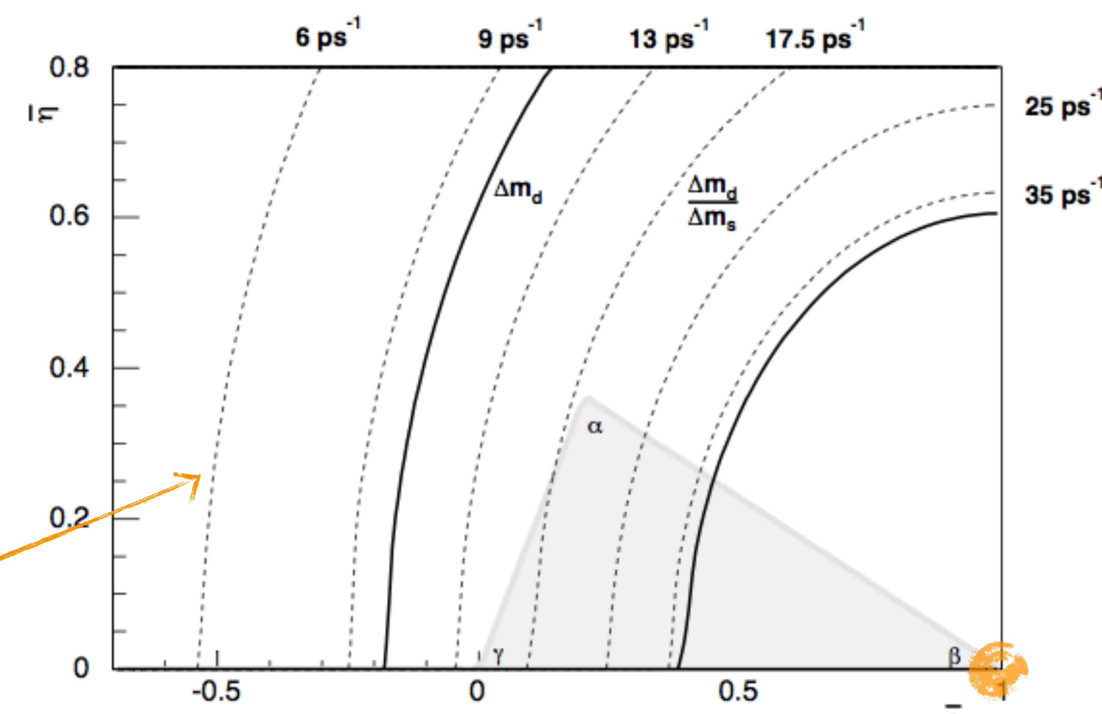
- the mixing process (and oscillation frequency, Δm_q) is proportional to the involved CKM matrix elements

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

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

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

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



- 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

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

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

λ=0.224±0.012

ξ = 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

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

(PDG'14)

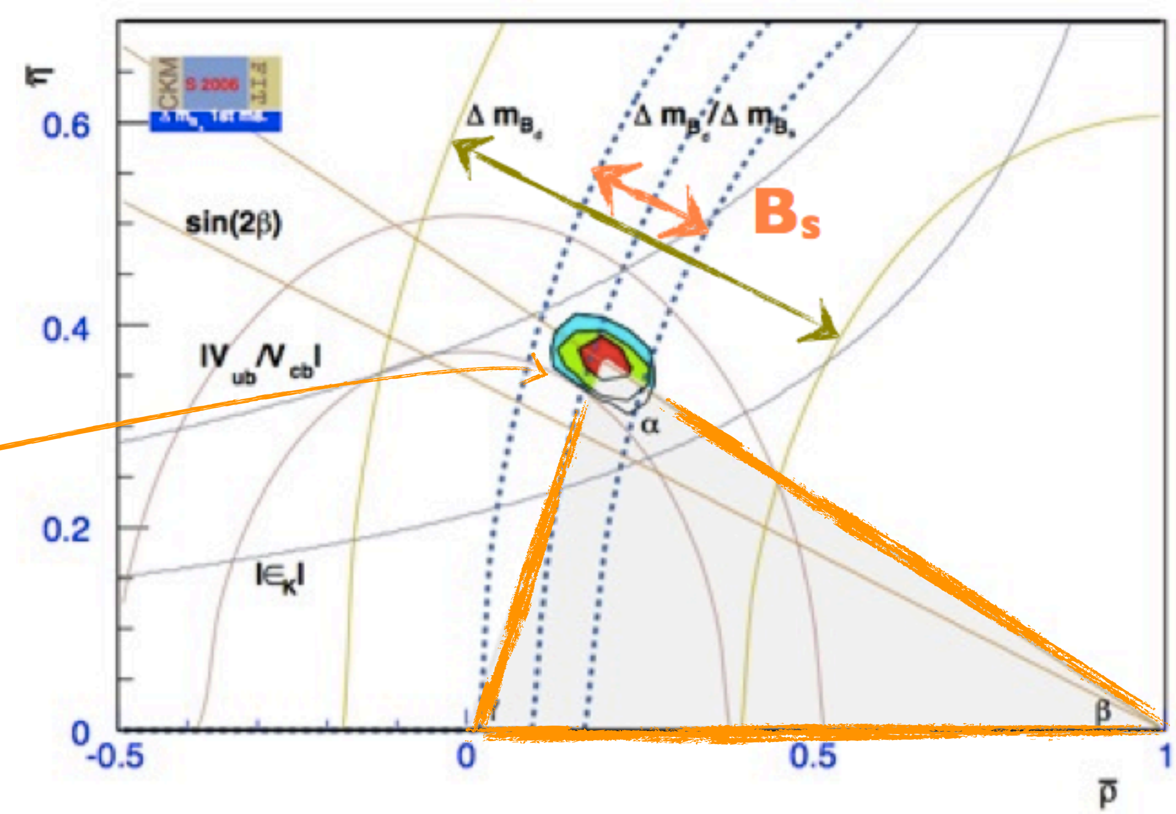
Exercise: which factor limits the CKM-constraining power of B mixing; may it be constrained experimentally

- 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

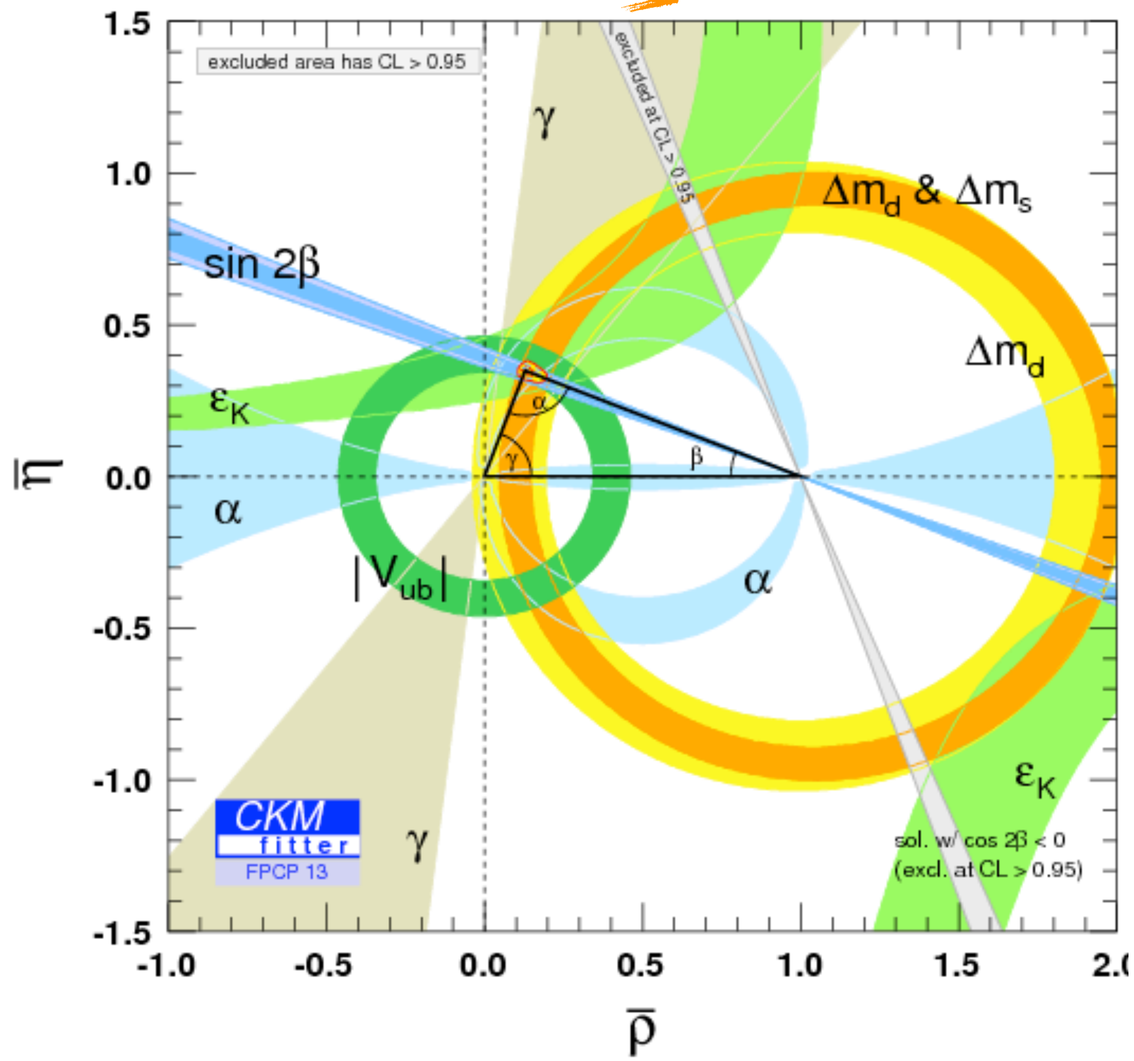
$$\underbrace{\mathcal{L}(\bar{\rho},\bar{\eta},\mathbf{x})}_{\text{posterior PDF}} \;\propto\; \underbrace{\prod_{j=1,M} f(\hat{c}_j|c_j(\bar{\rho},\bar{\eta},\mathbf{x}))}_{\text{constraints}} \times \underbrace{\prod_{i=1,N} f_i(x_i)}_{\text{prior PDF}}$$

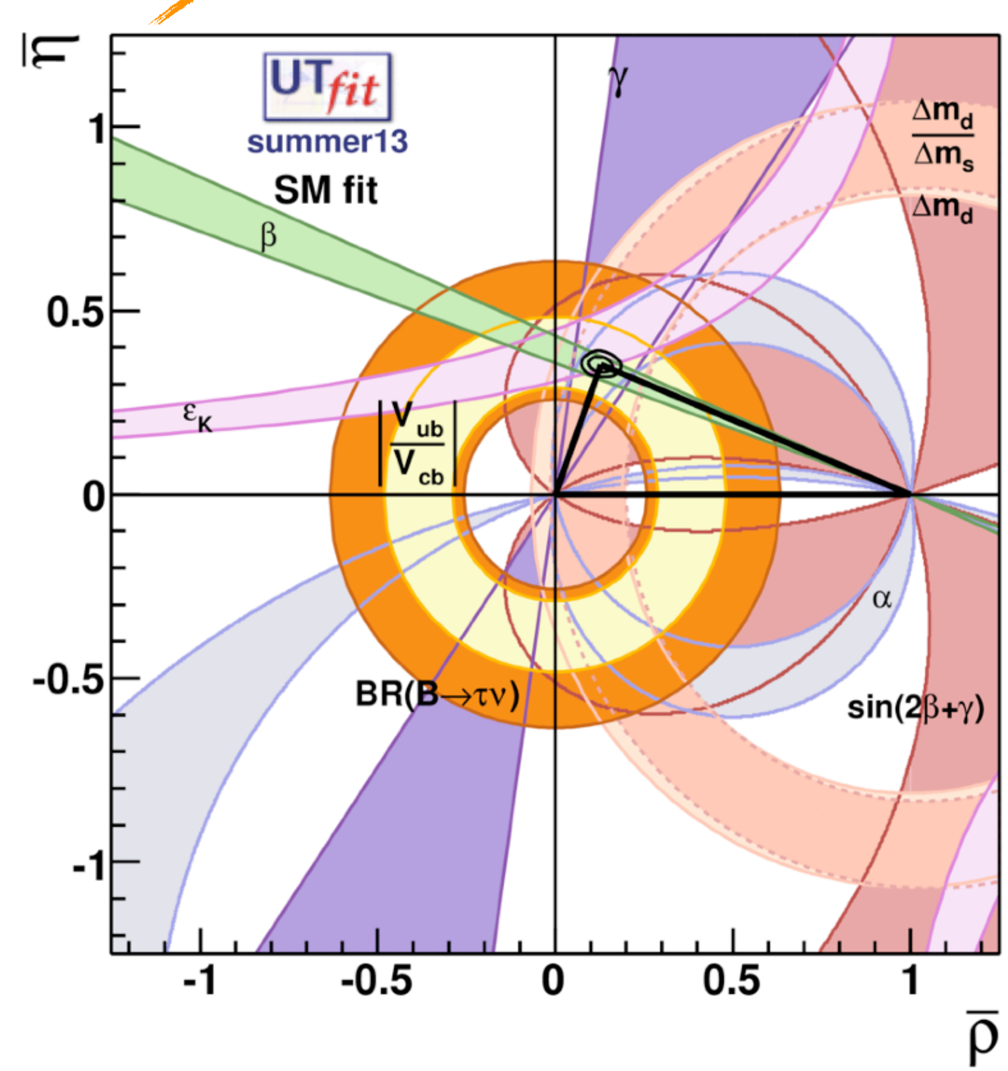


- integration requires use of numerical and statistical sampling techniques, e.g. Monte Carlo

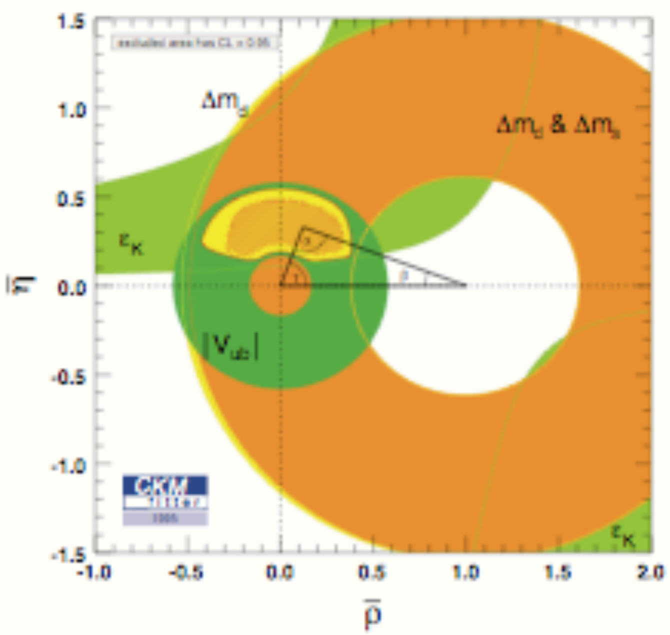
UT fit

- 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.:

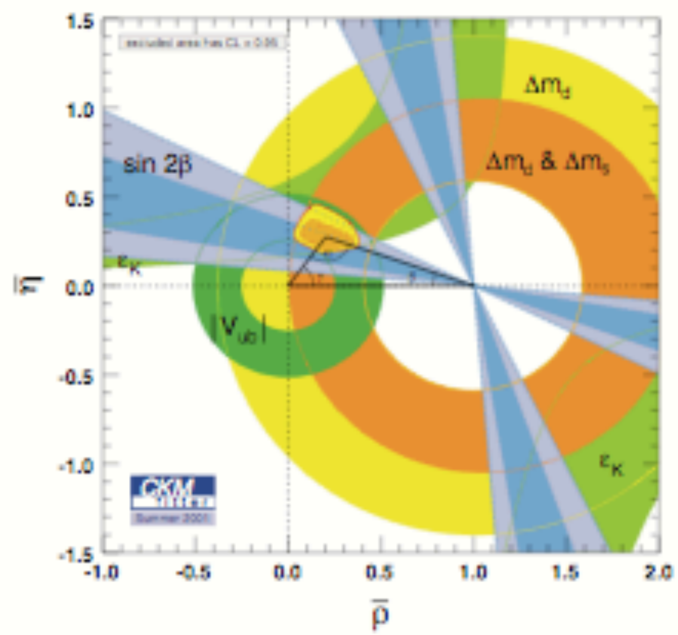




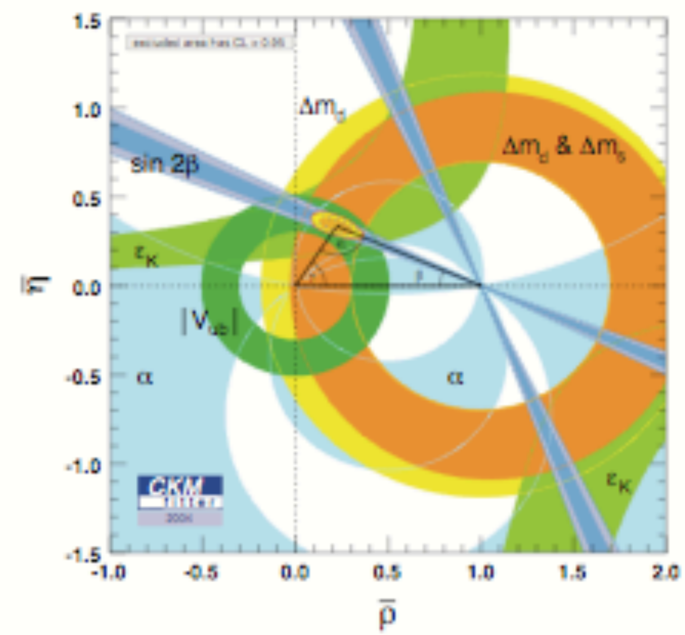
UT fit evolution over 20 years



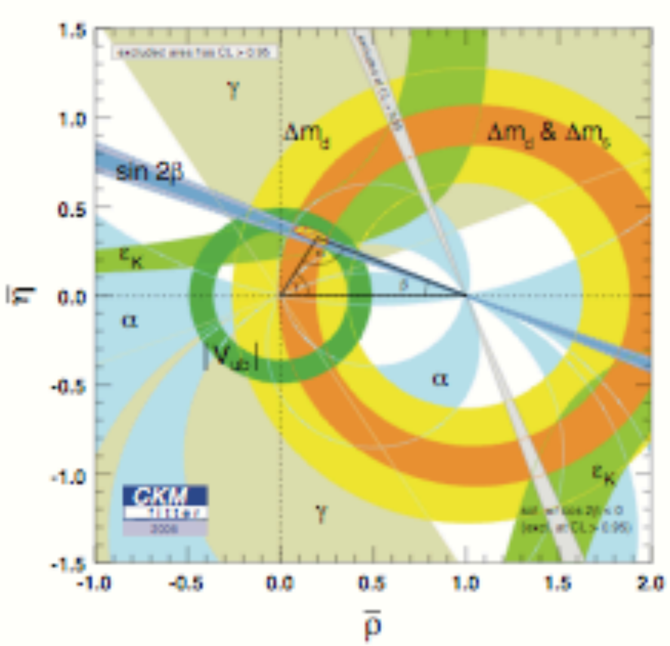
1995



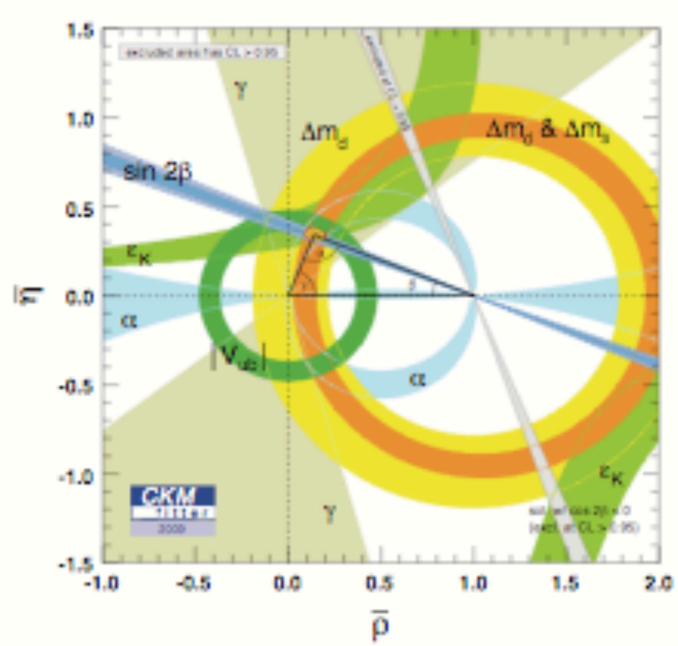
2001



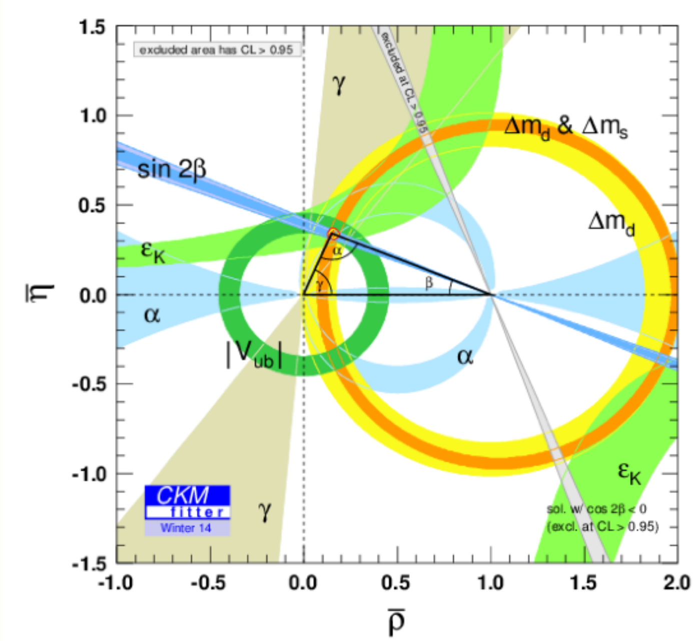
2004



2006



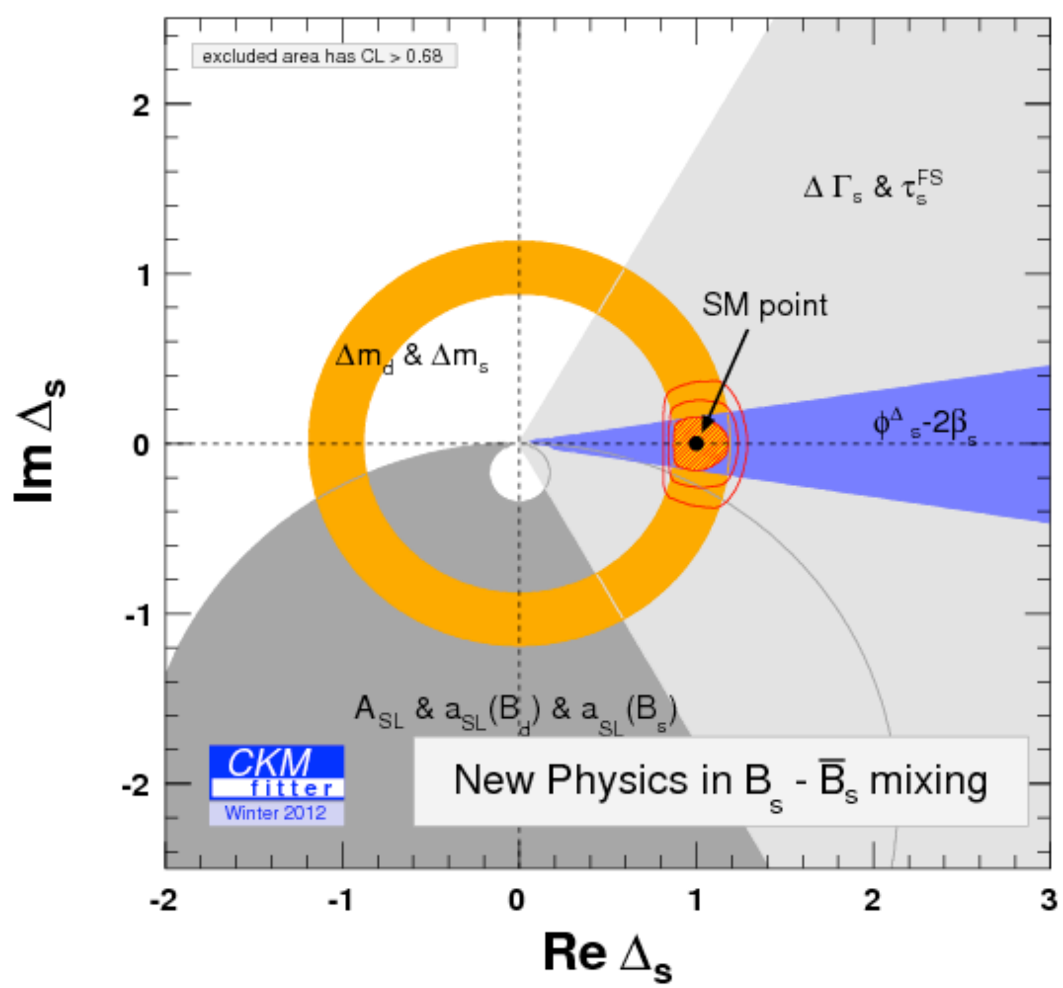
2009

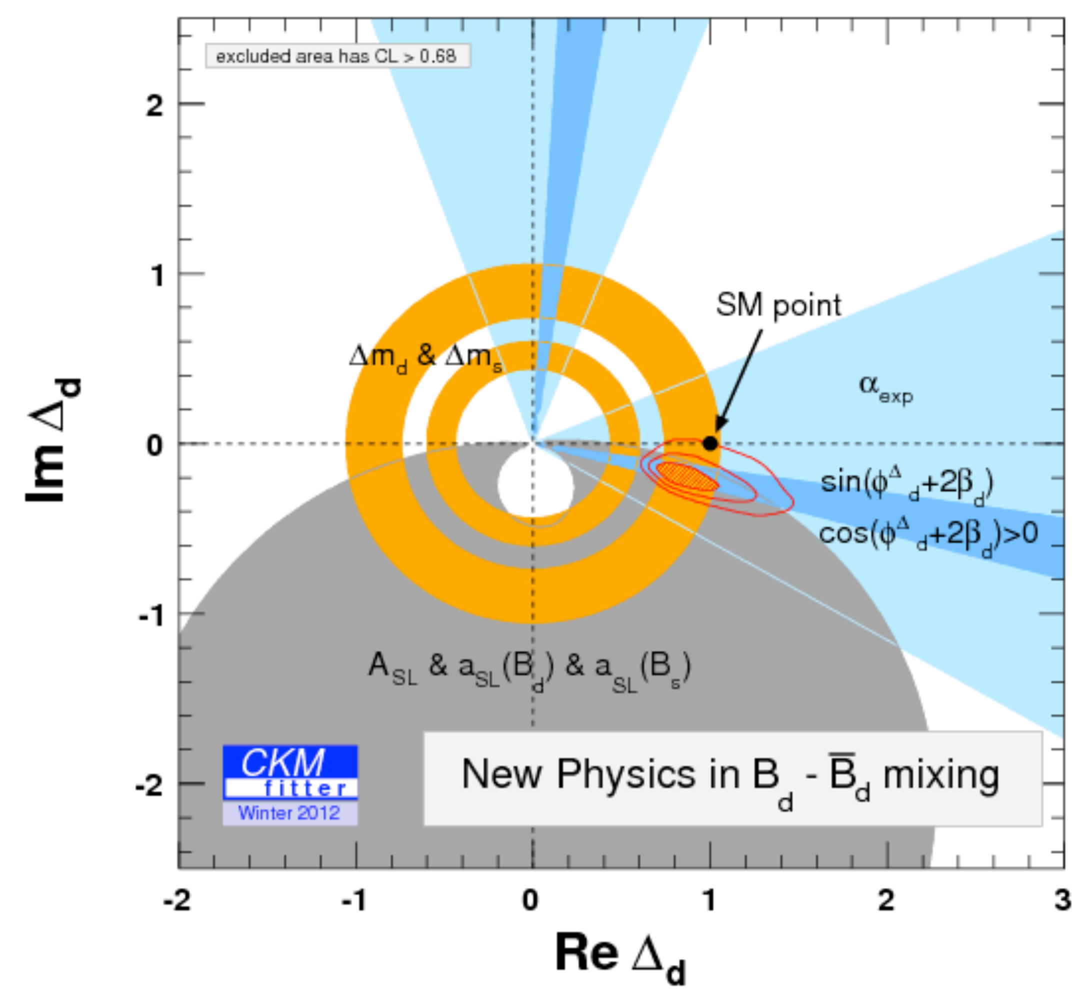


2014

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
  - $2\beta_s \mapsto 2\beta_s - \Phi^{\Delta s}$ ($B_s \to J/\psi\varphi$) and $2\beta_d \mapsto 2\beta_d + \Phi^{\Delta d}$ ($B_d \to J/\psi K$)

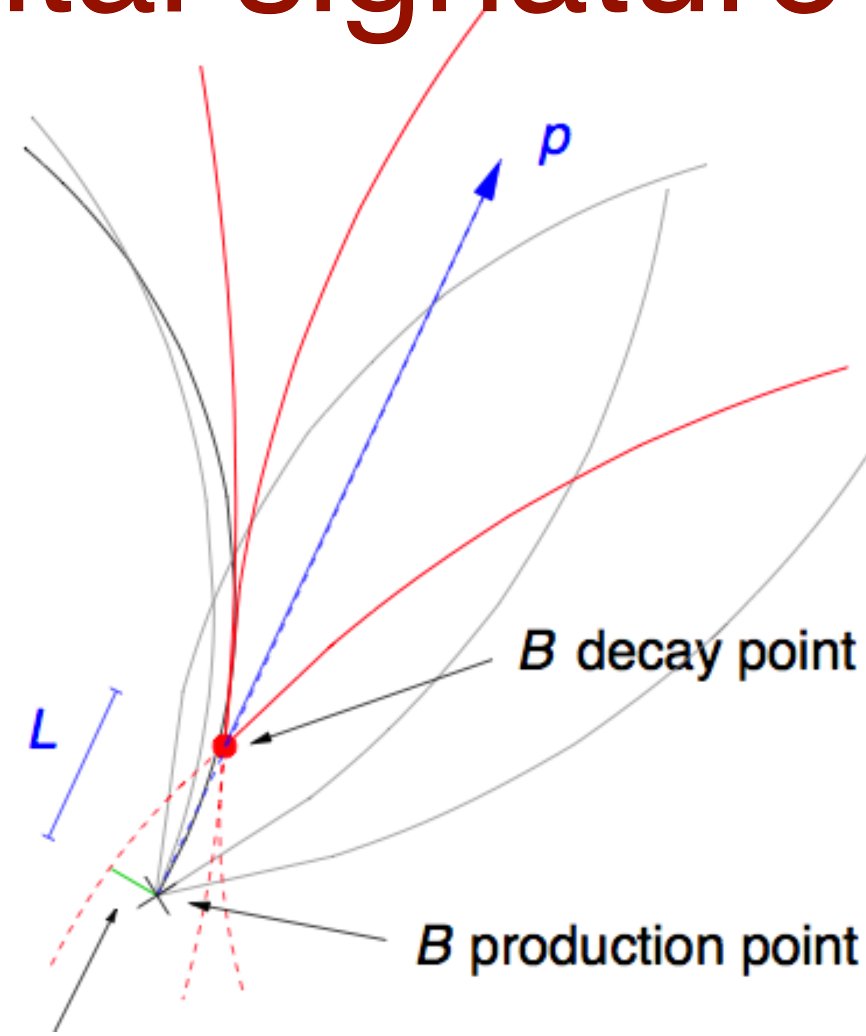




detection

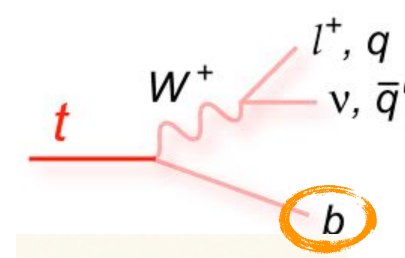
a distinctive experimental signature

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



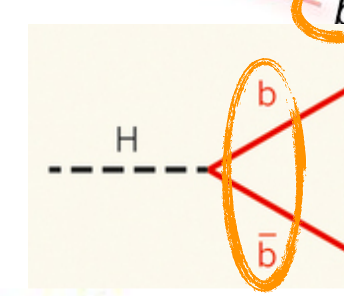
- extensively explored
  - in heavy-flavor analyses themselves
  - b-jet tagging: discriminate b-jets from the lighter quark jets
  - in SM measurements and BSM searches: to detect signal HF components (e.g. $t \to Wb$, $H \to b\underline{b}$,...) or control HF backgrounds (e.g. $b\underline{b}$ dijets,...)

top decays



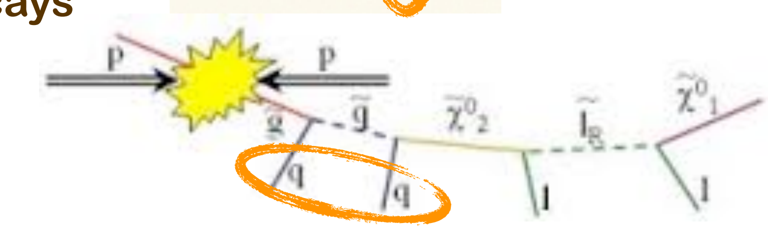
100%

higgs decays



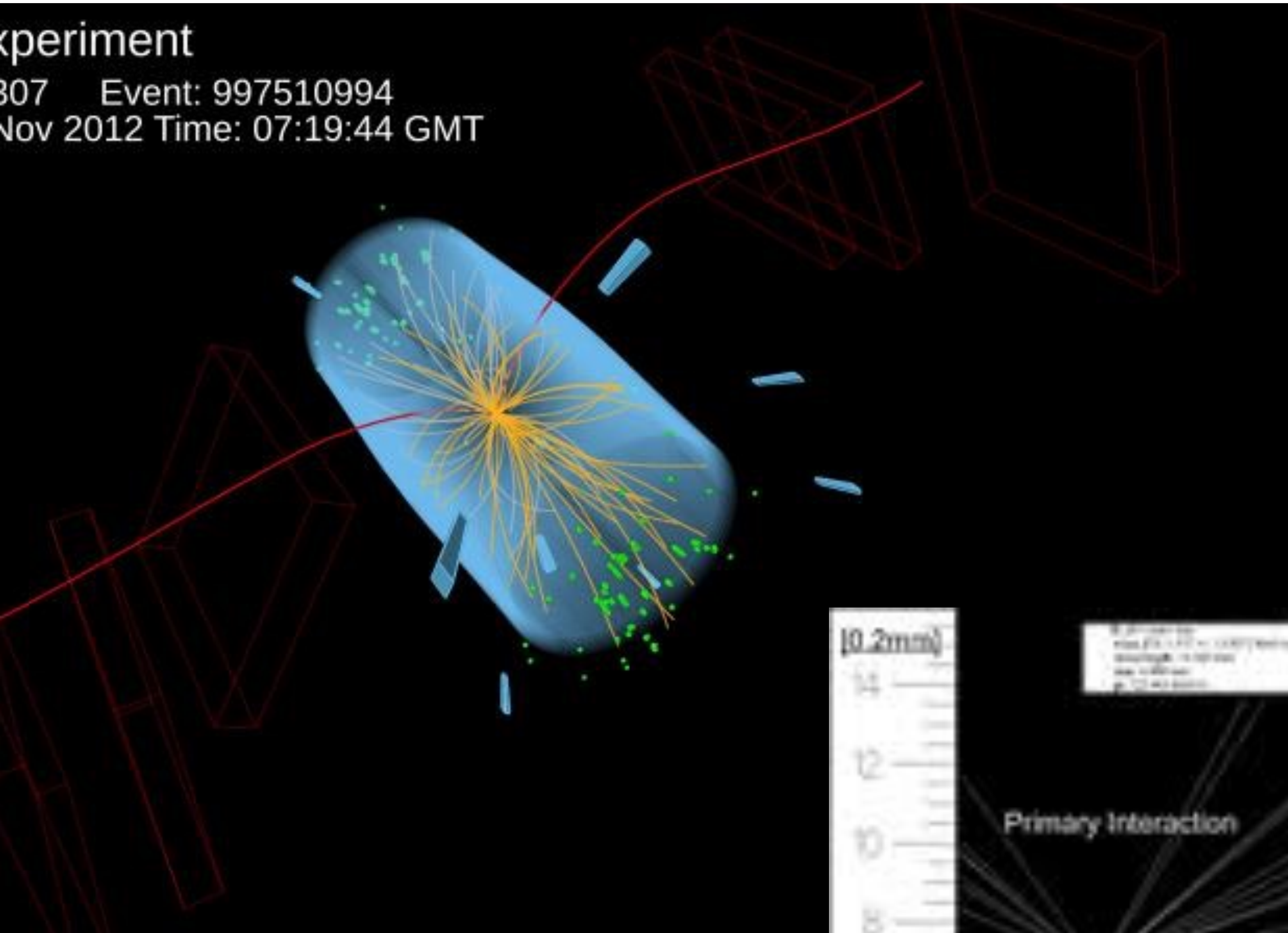
57.7%

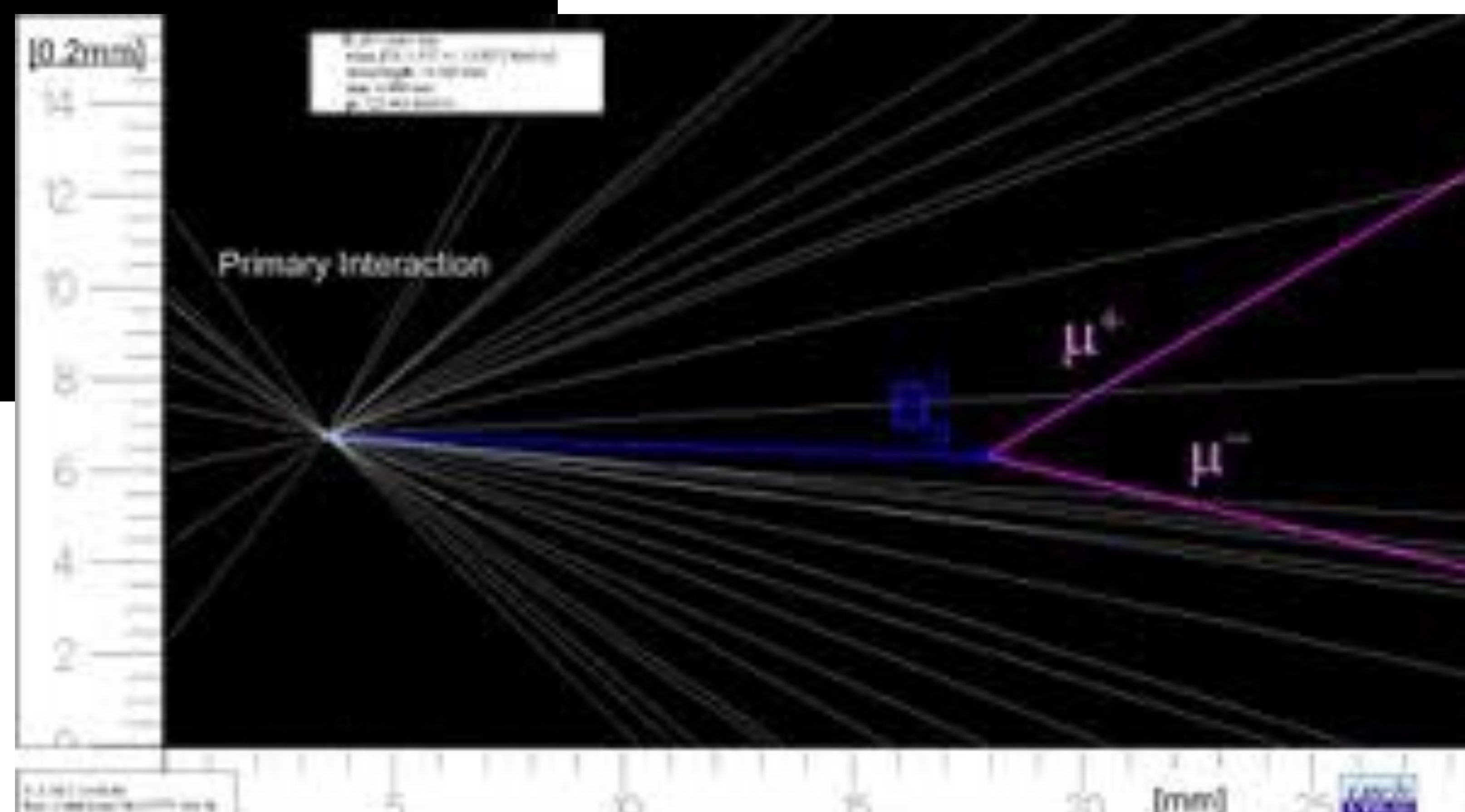
susy decays



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

Event visualisation

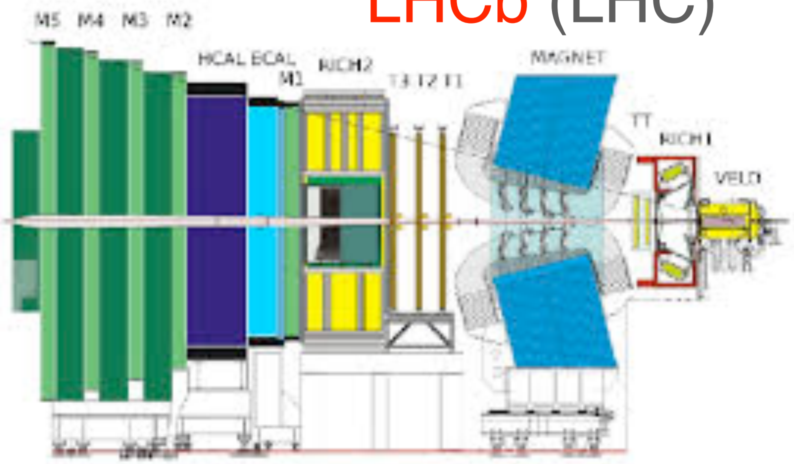




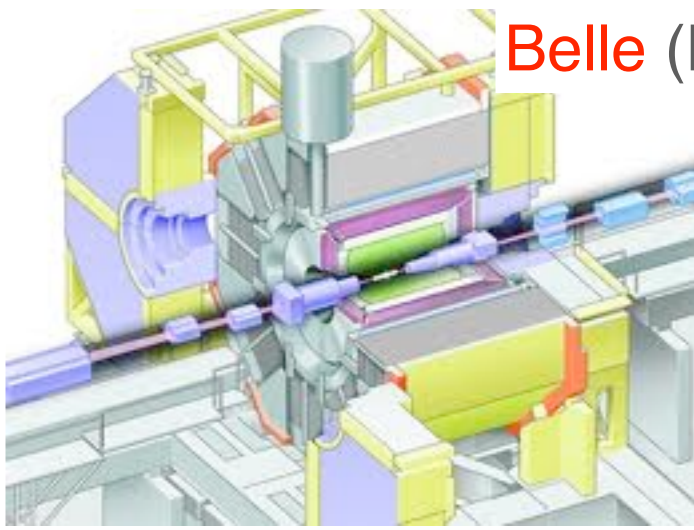
detectors

Specialized

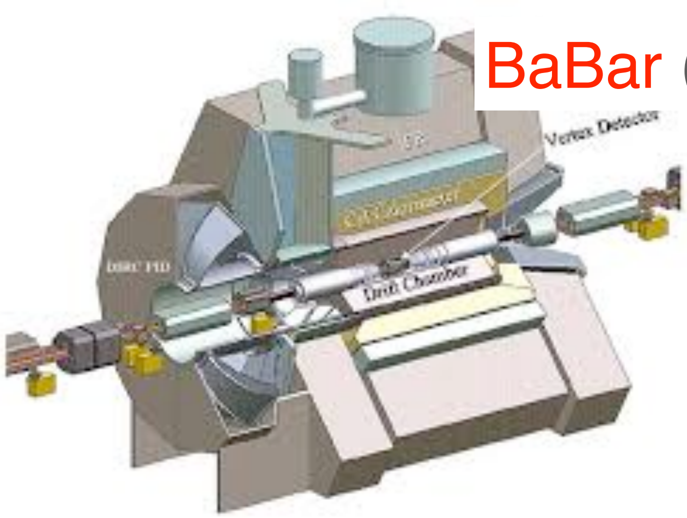
LHCb (LHC)



Belle (KEK)

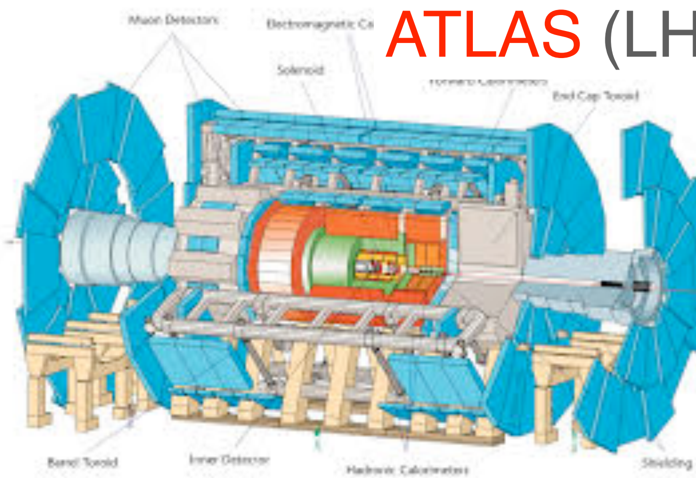


BaBar (PEPII)

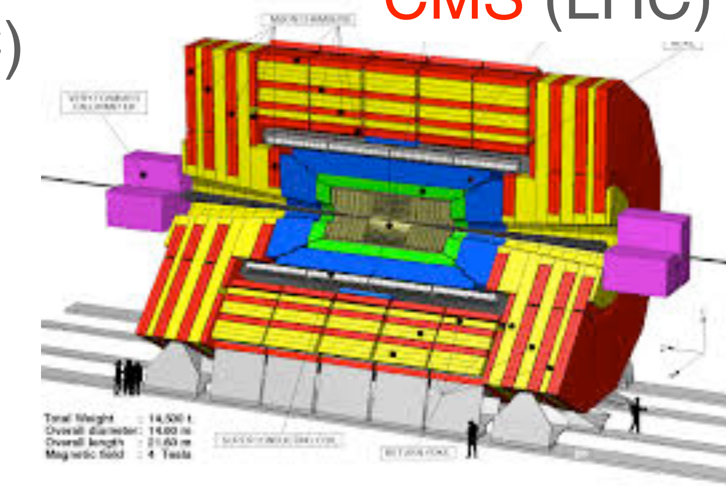


General purpose

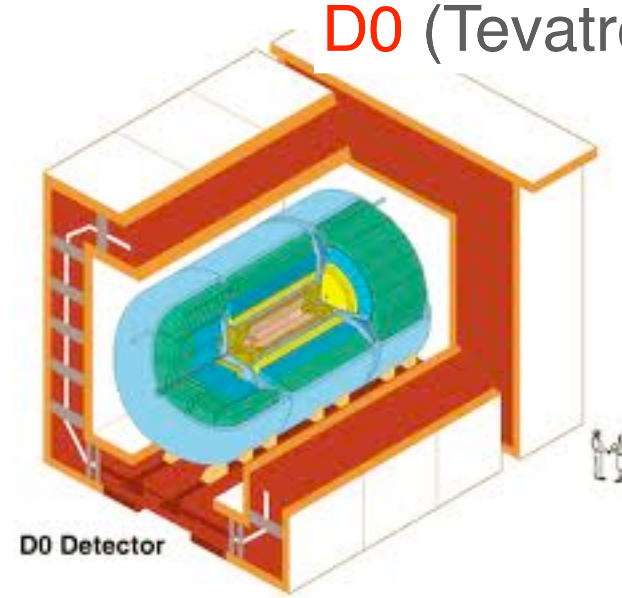
ATLAS (LHC)



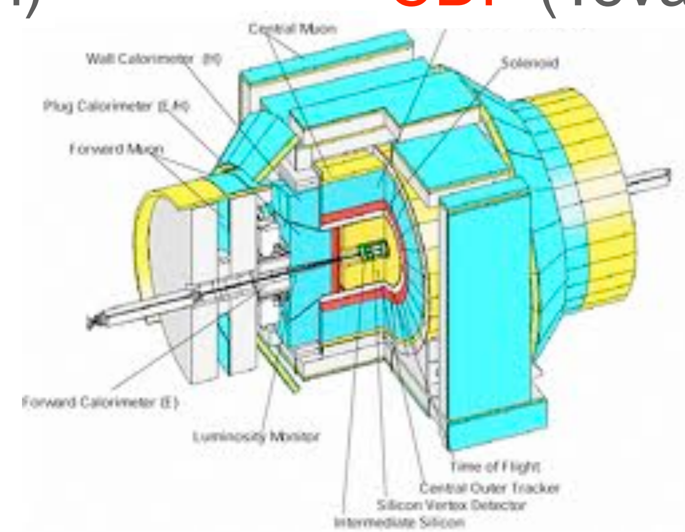
CMS (LHC)



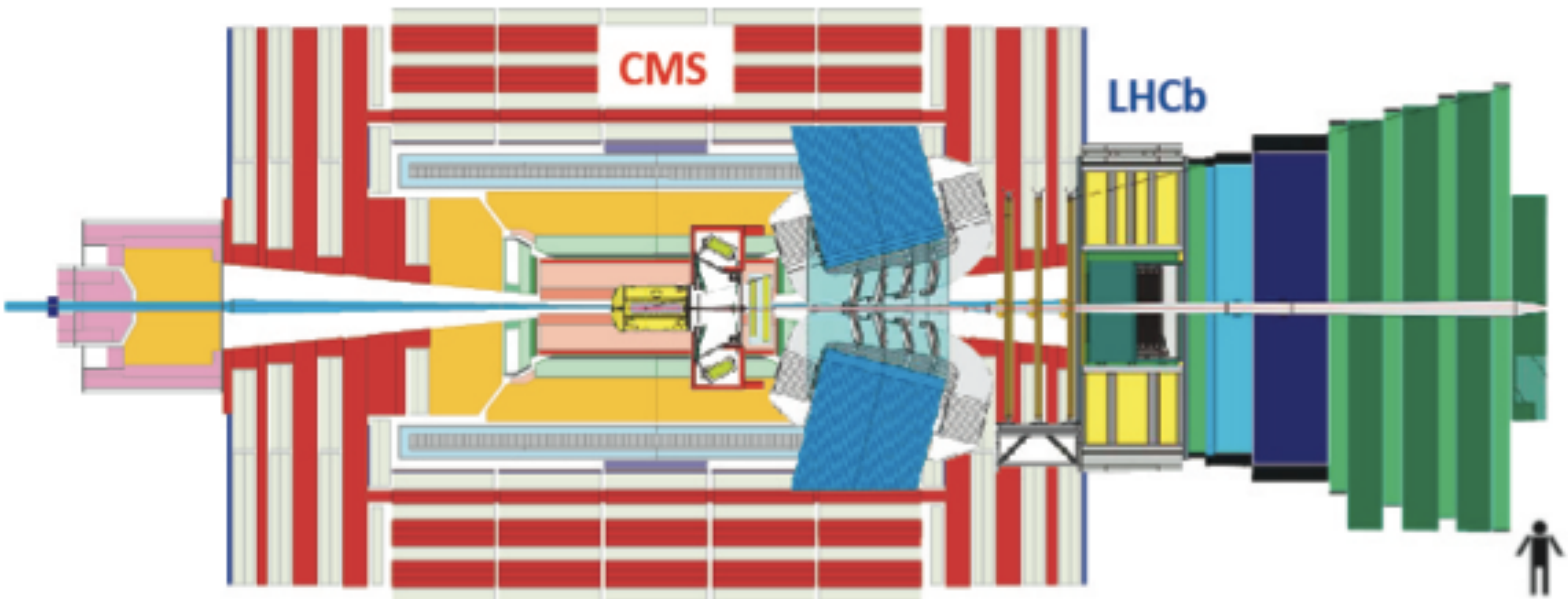
D0 (Tevatron)



CDF (Tevatron)

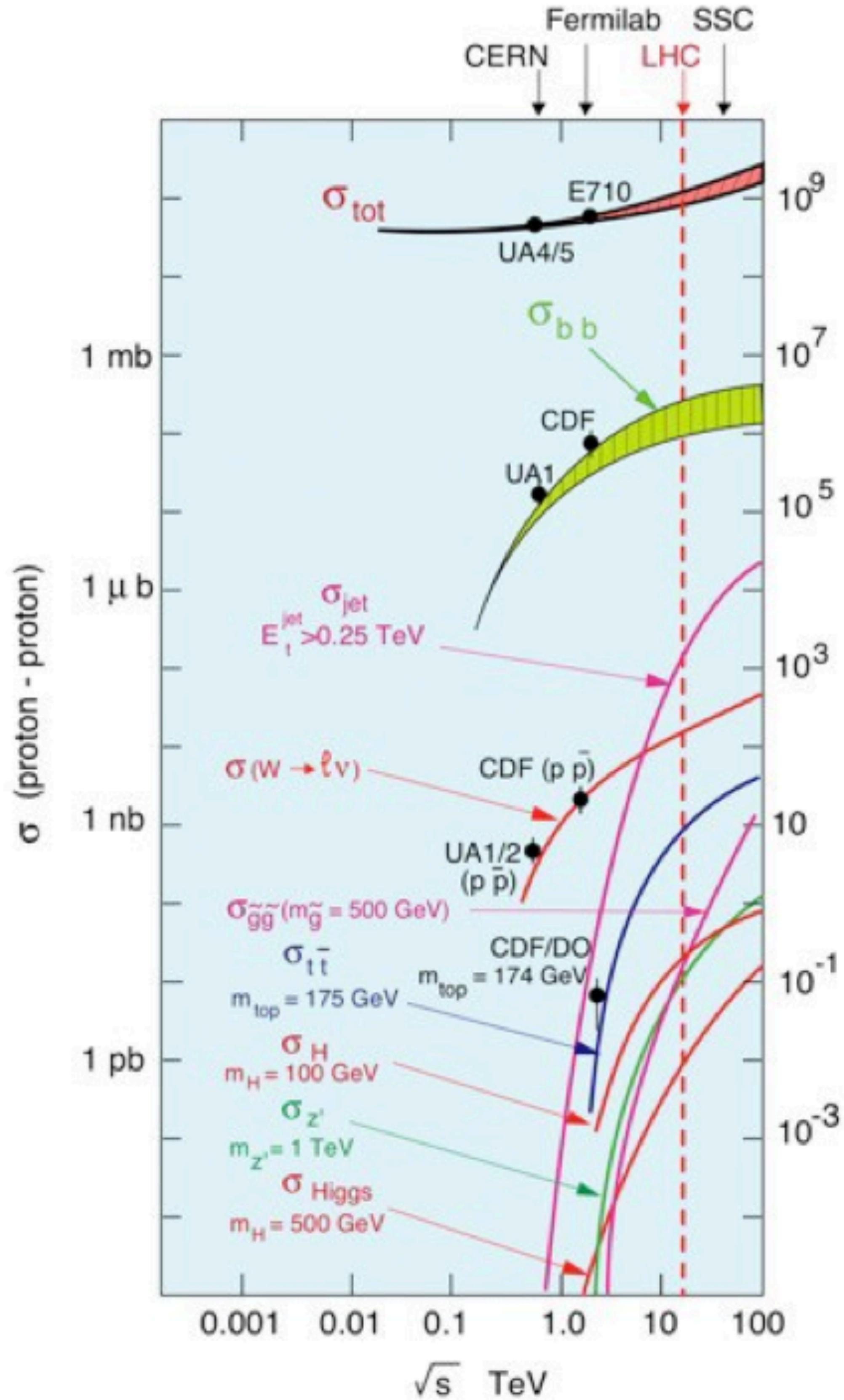


the ideal heavy flavor detector?



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

HF production

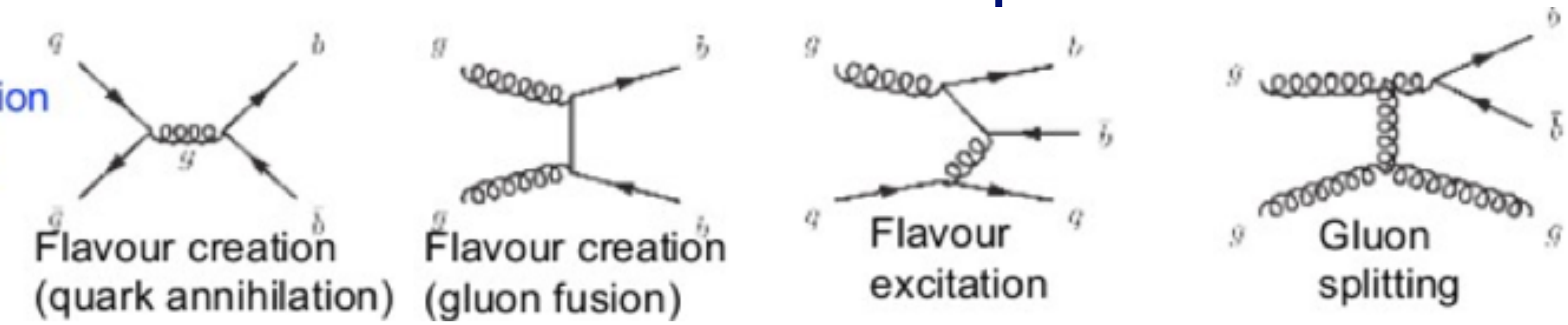


- high HF production rates at the LHC
  - very large production cross section (σ)
  - large accumulated luminosity (L)
- LHC: HF 'factory' (N=L.σ)
  - allow to perform precision measurements, as well as to search for very rare processes
- HF production is ubiquitous
  - forming backgrounds for many physics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

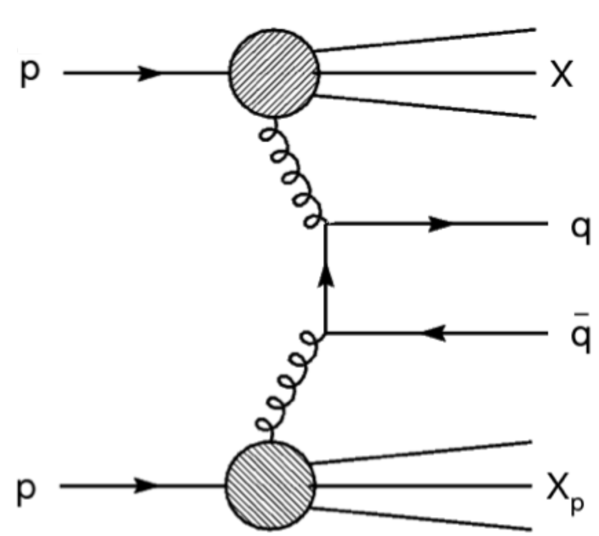
hadron production

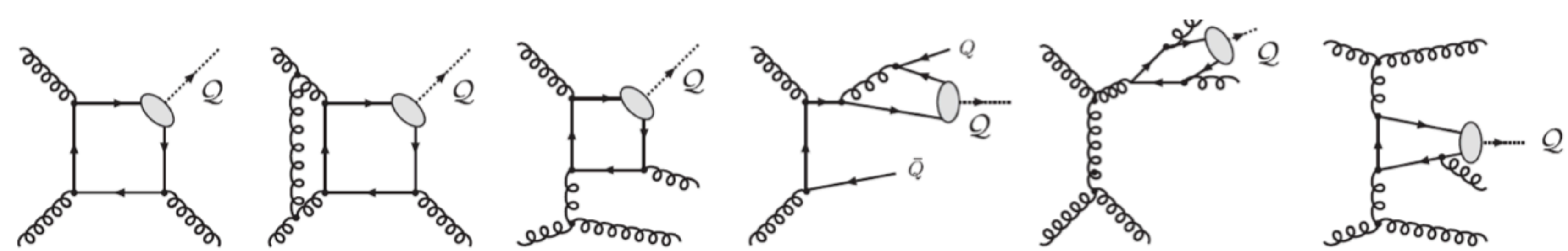
- different mechanisms contribute to HF production

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...)



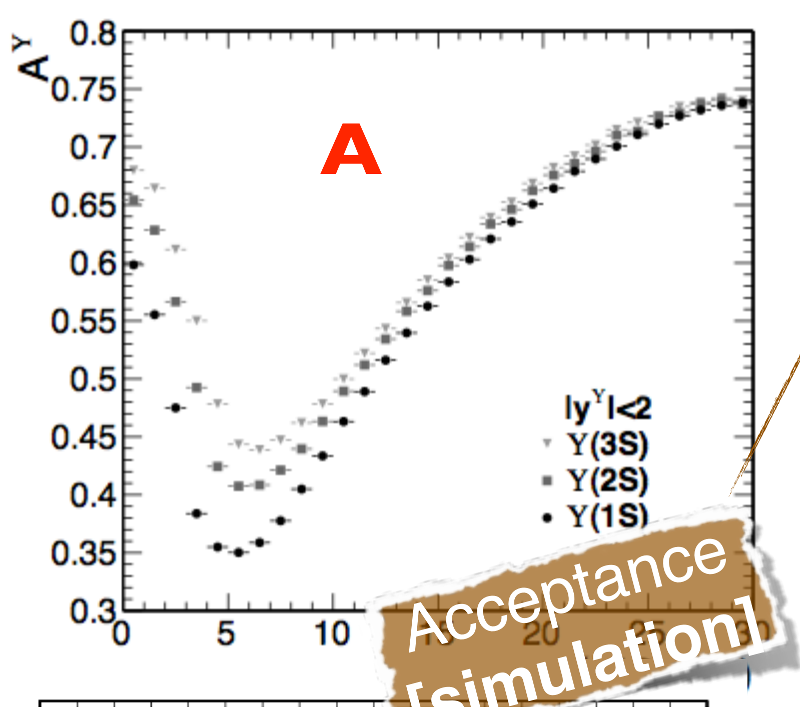


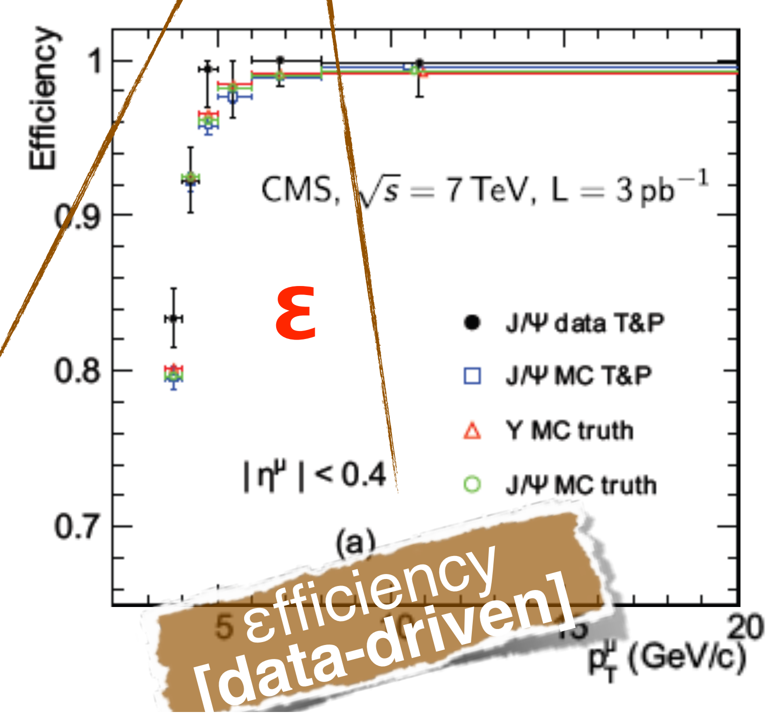
need to carry out detailed of HF production, including cross sections, polarizations, etc

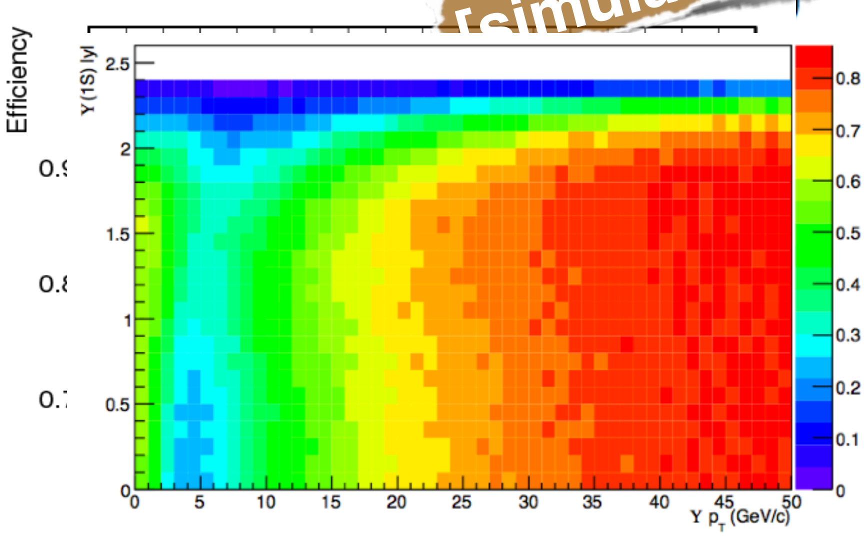
cross section

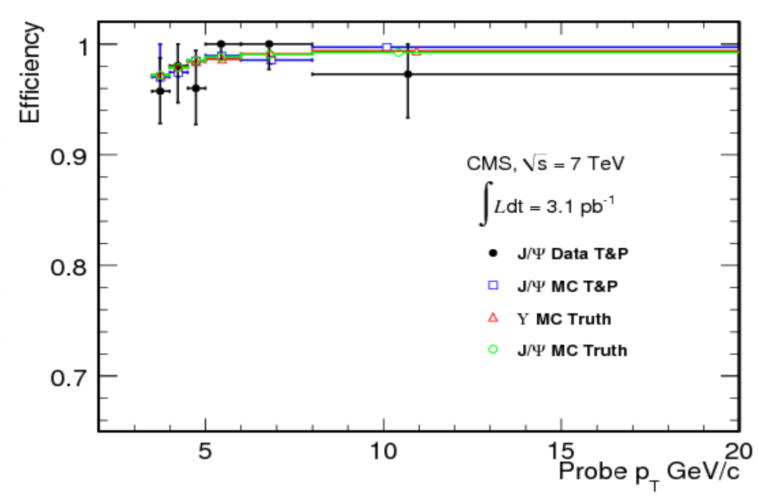
"N=L.σ"

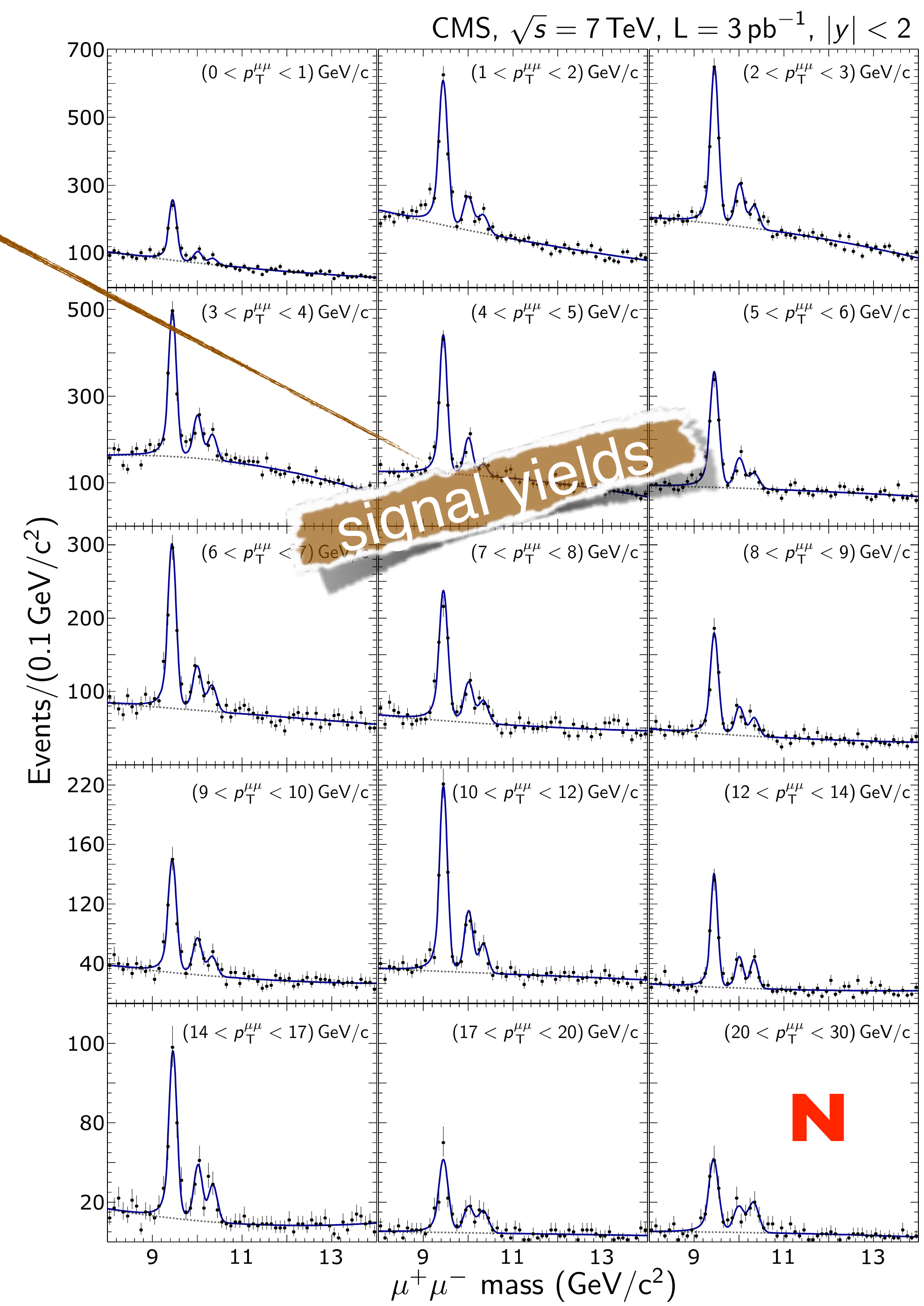
$$\frac{d^2\sigma(Q\overline{Q})}{dp_T\,dy}\mathcal{B}\left(Q\overline{Q}\to\mu^+\mu^-\right)=\frac{N_{fit}(Q\overline{Q})}{\mathcal{L}\;\cdot\mathcal{A}\cdot\epsilon\cdot\Delta p_T\cdot\Delta y}$$





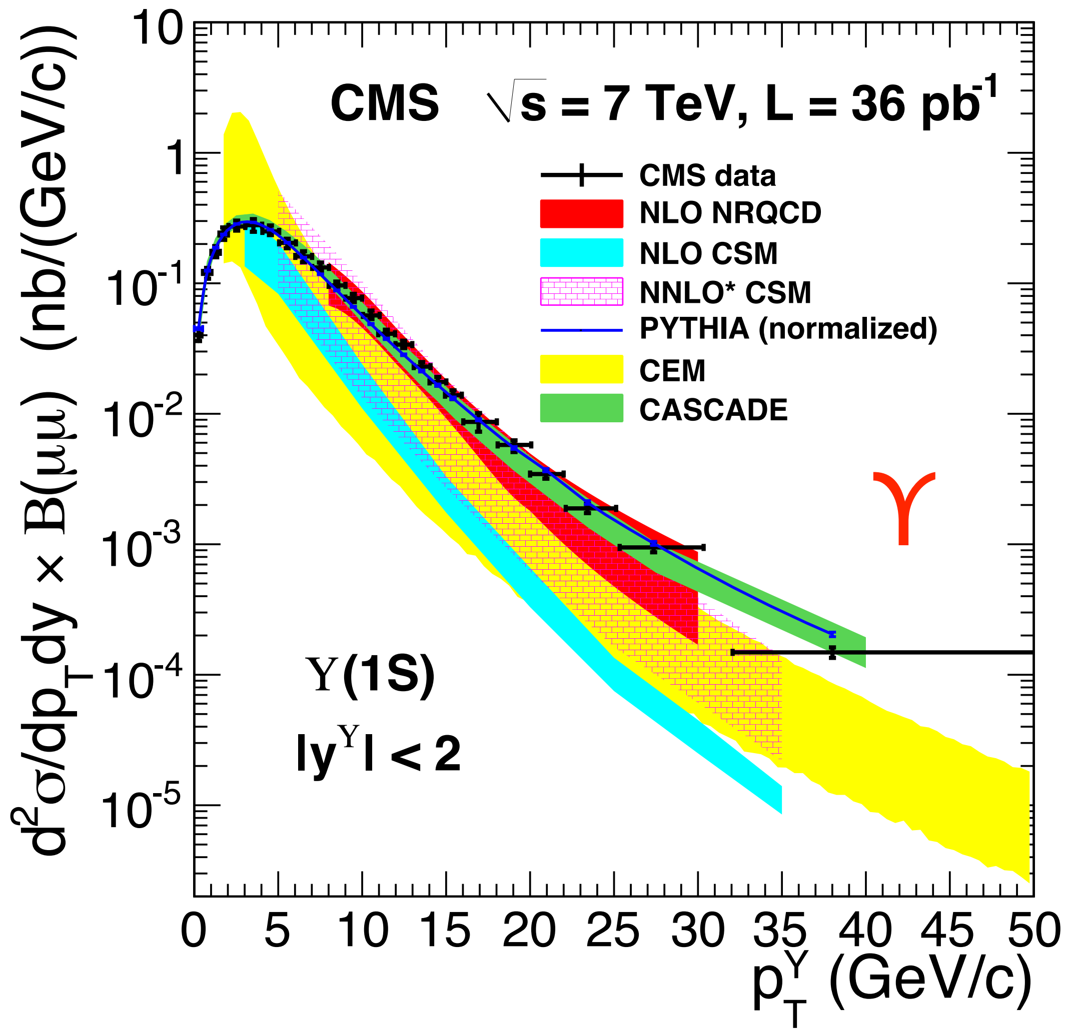


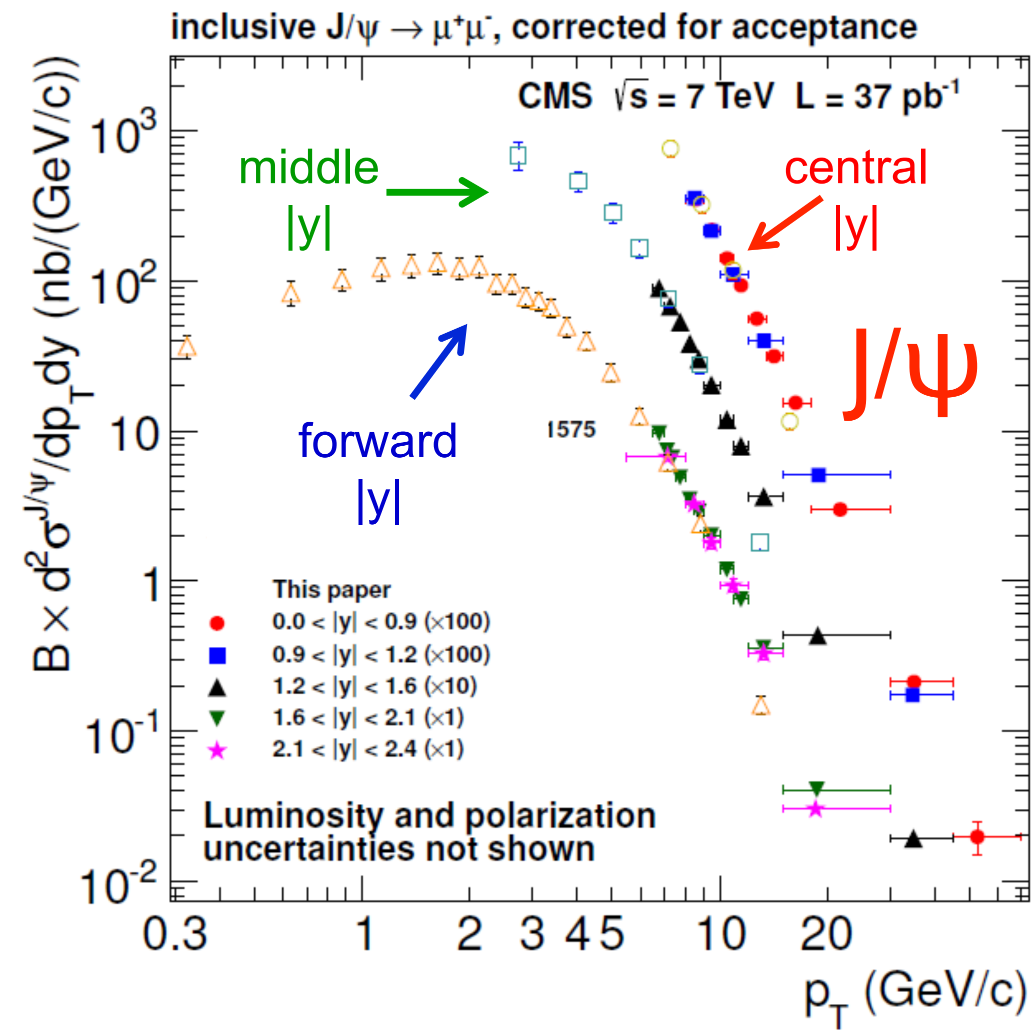




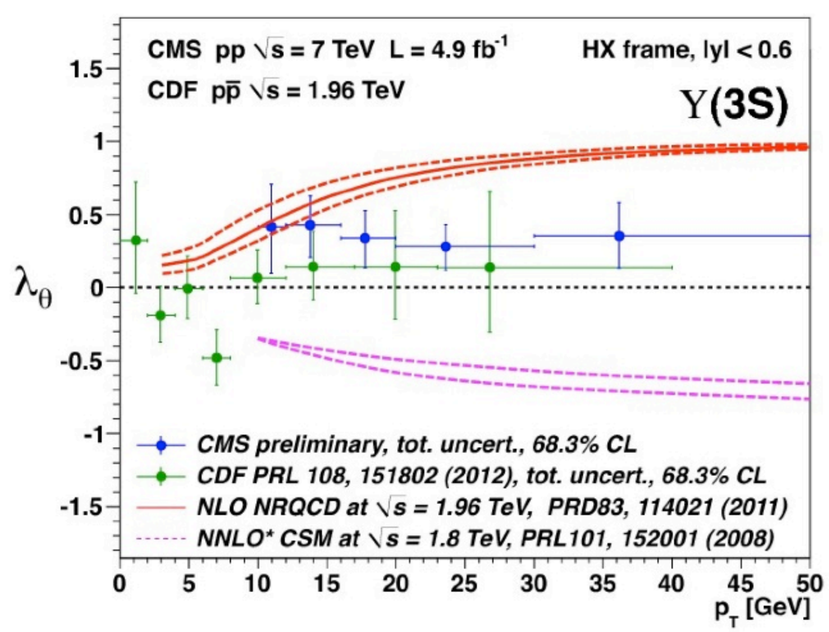
quarkonia production *[in pp]*

cross sections





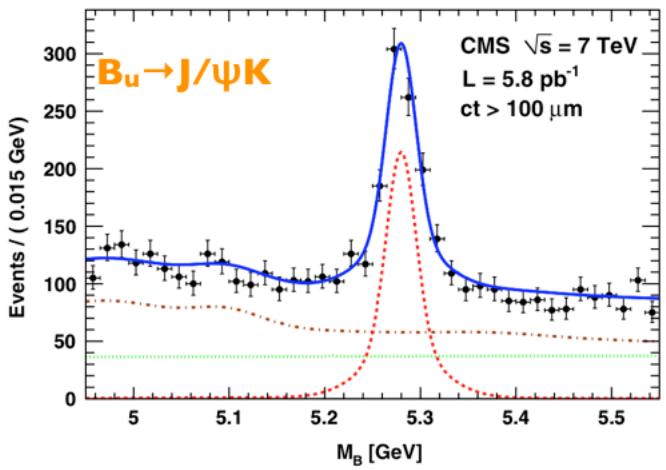
polarizations

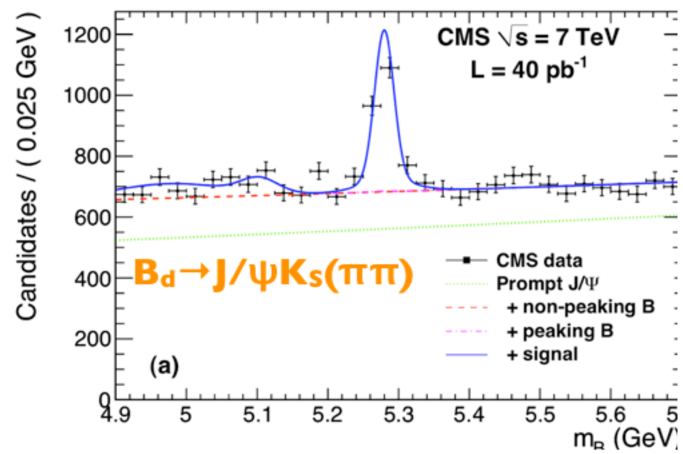


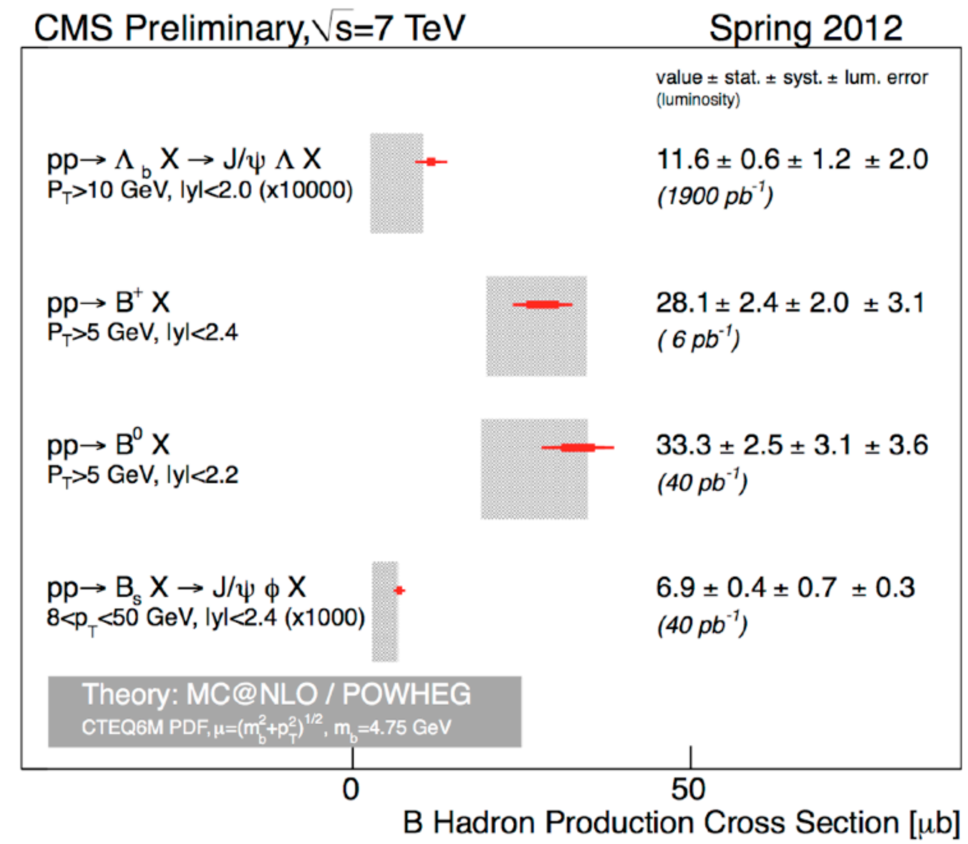
- precision measurements of quarkonium production
- LHC allows to probe higher p_T region for the first time

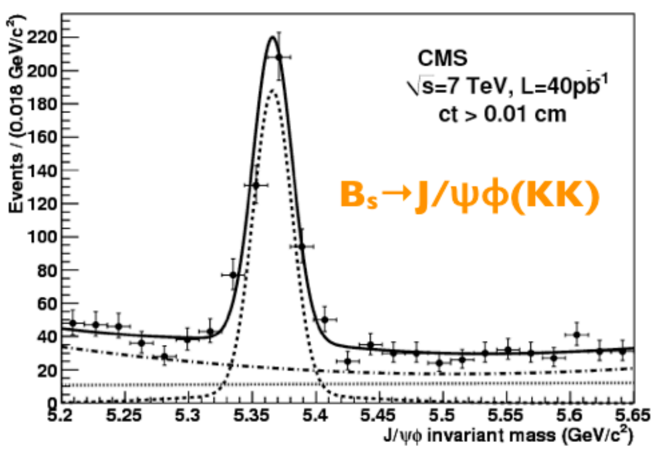
☞ polarization details in dedicated lecture

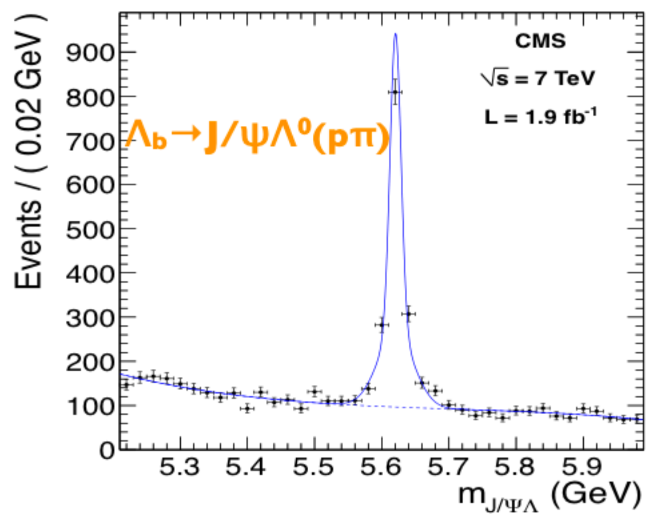
b-hadron production

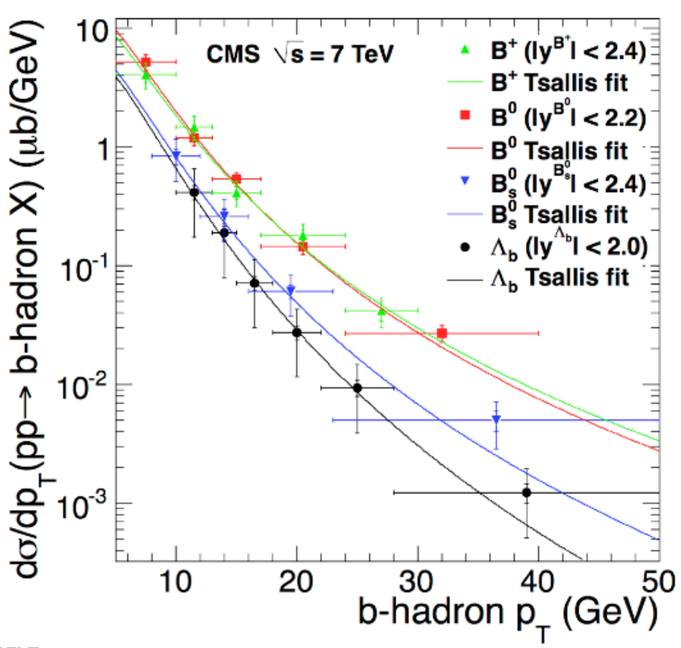








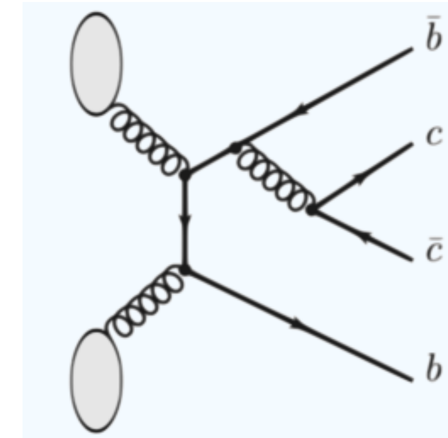




- integrated cross sections and NLO predictions in agreement
- baryon spectrum falls faster than meson spectra
  - analysis of lager datasets will much improve precision of differential measurements

B_c

- 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 b̲+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**

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

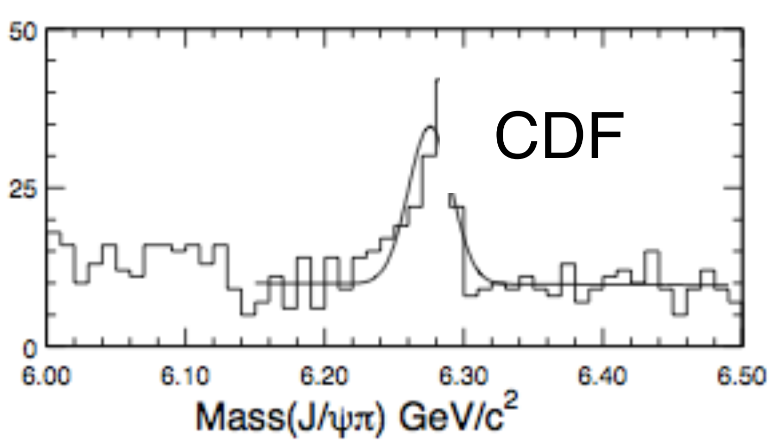
$B_c^+ \to B_s^0\ell^+\nu_\ell$

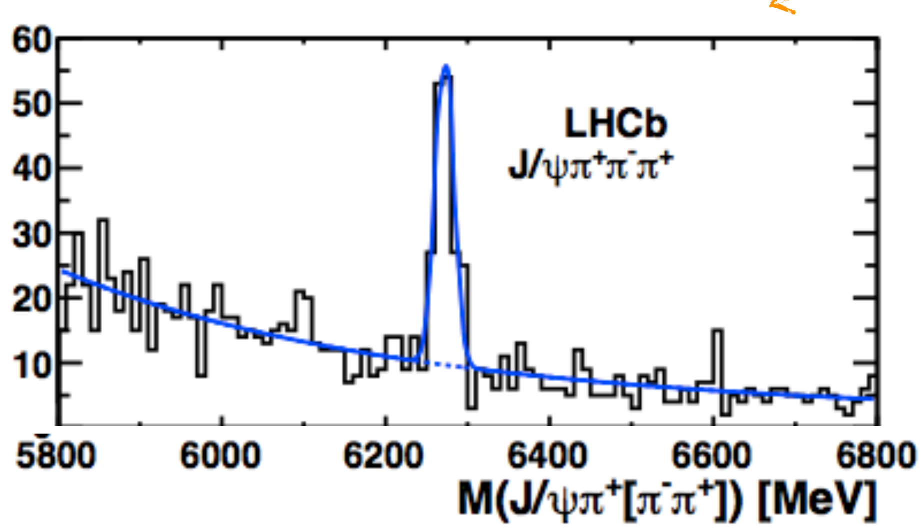
$c\bar{b} \to W^+$ **transition**

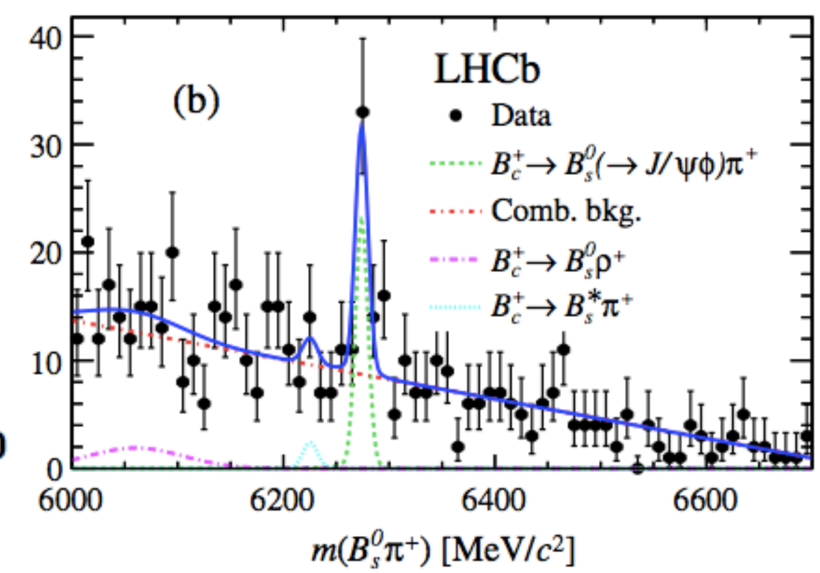
$B_c^+ \to \bar{K}^{*0}K^+$

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

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

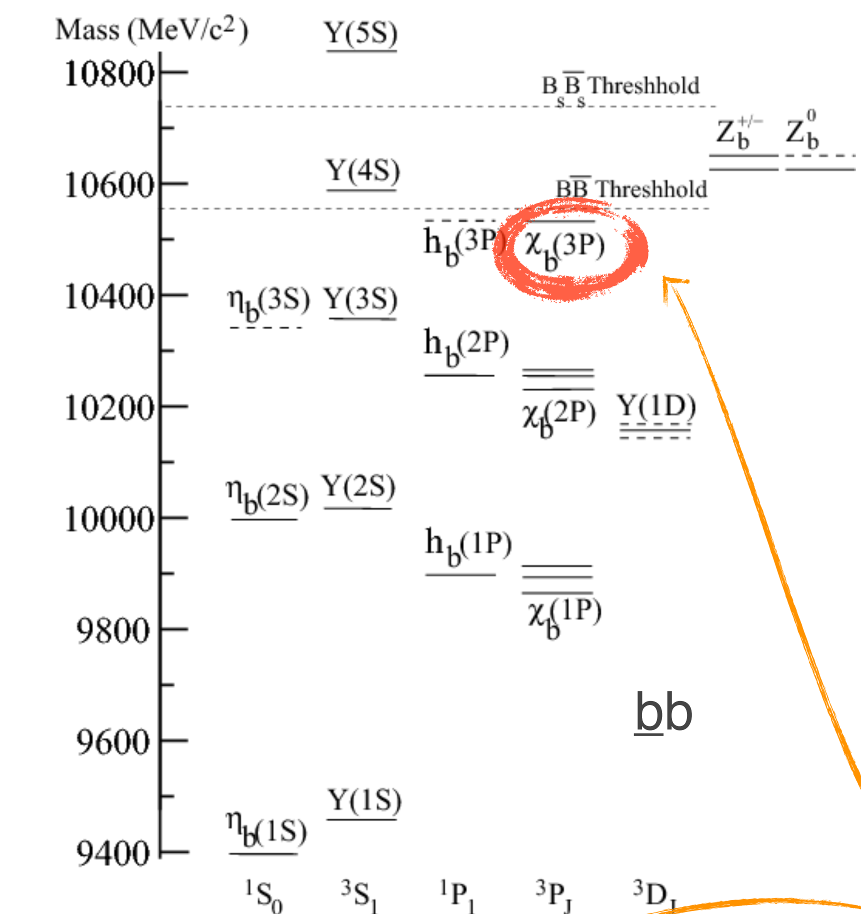


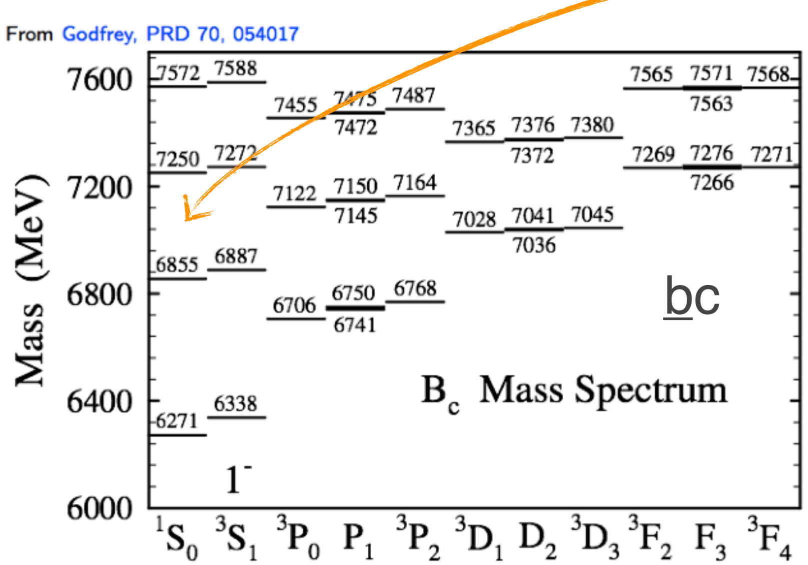




beauty spectroscopy

mesons





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

CDF and D0 contributed several such discoveries:

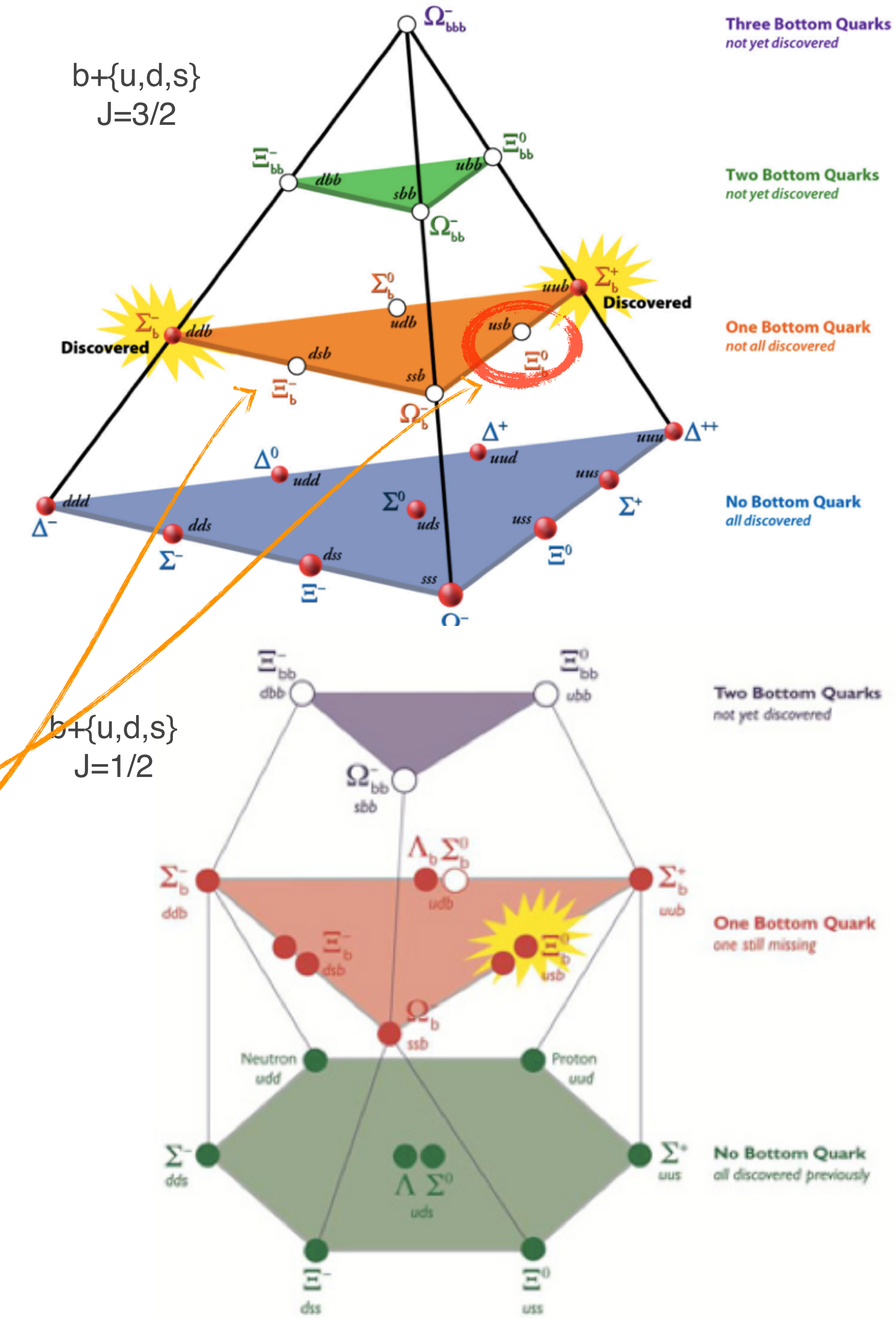
- Σ_b^- (2006)
- Ξ_b- (2007)
- Ω_b (2008)

LHC:

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

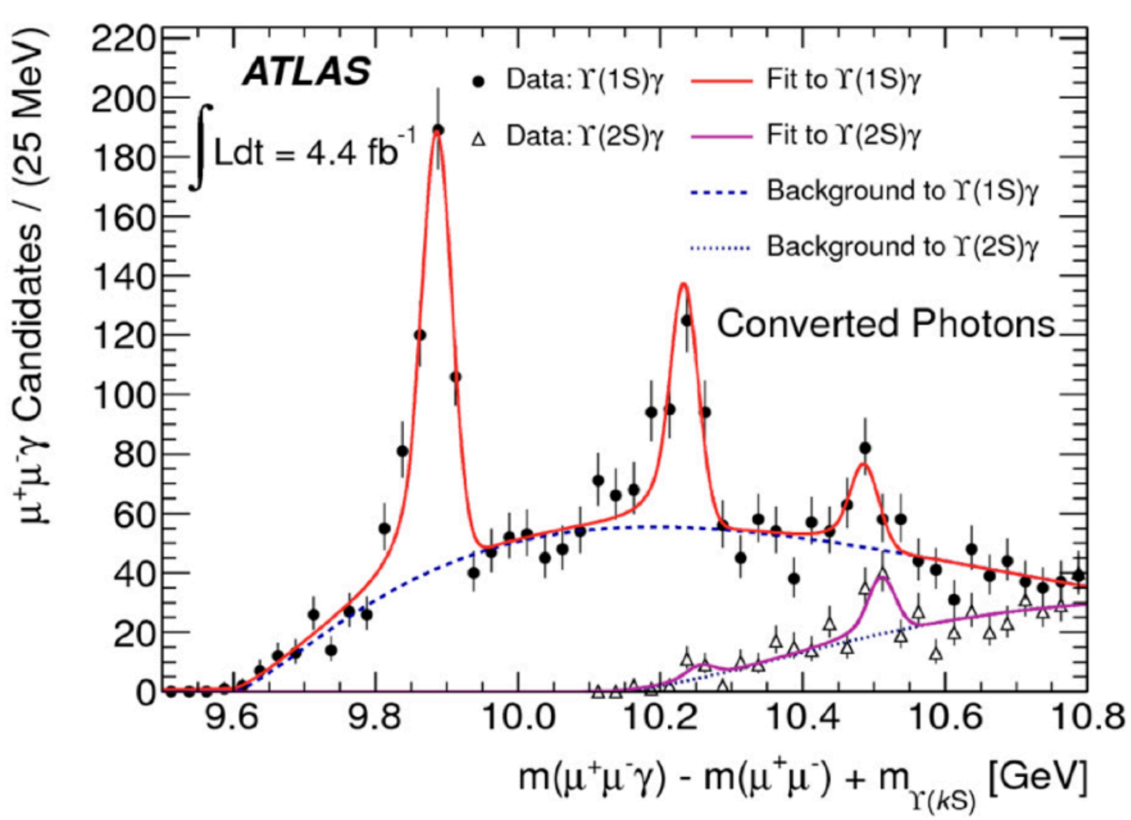
Several other composite particles awaiting to be discovered!...

baryons

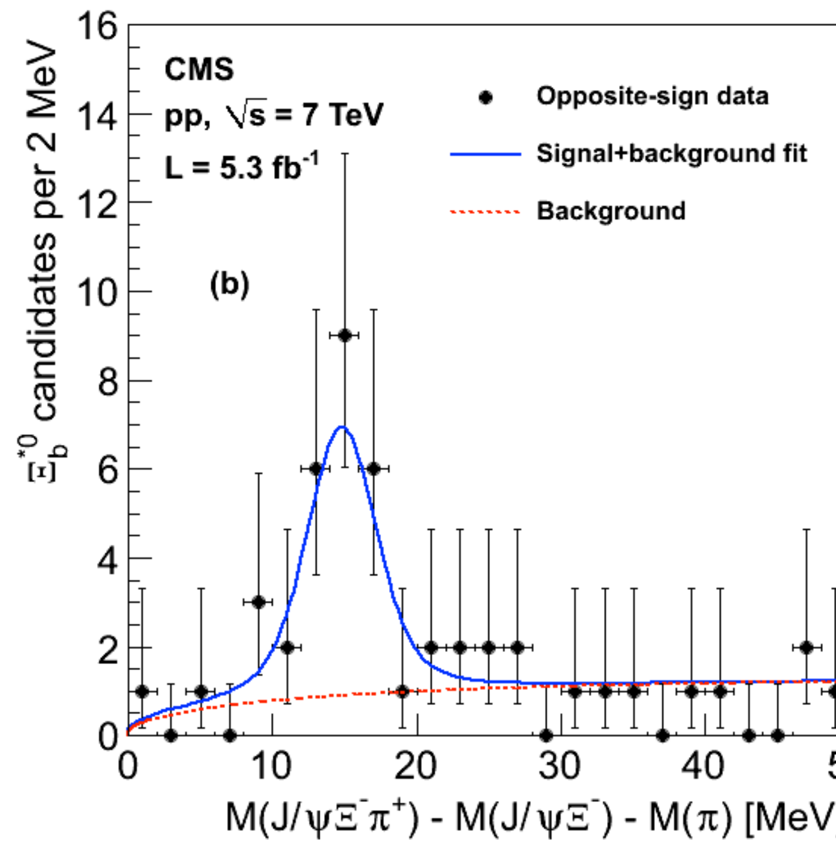


the first new particles found at the LHC

$\chi_b(3P)$ meson



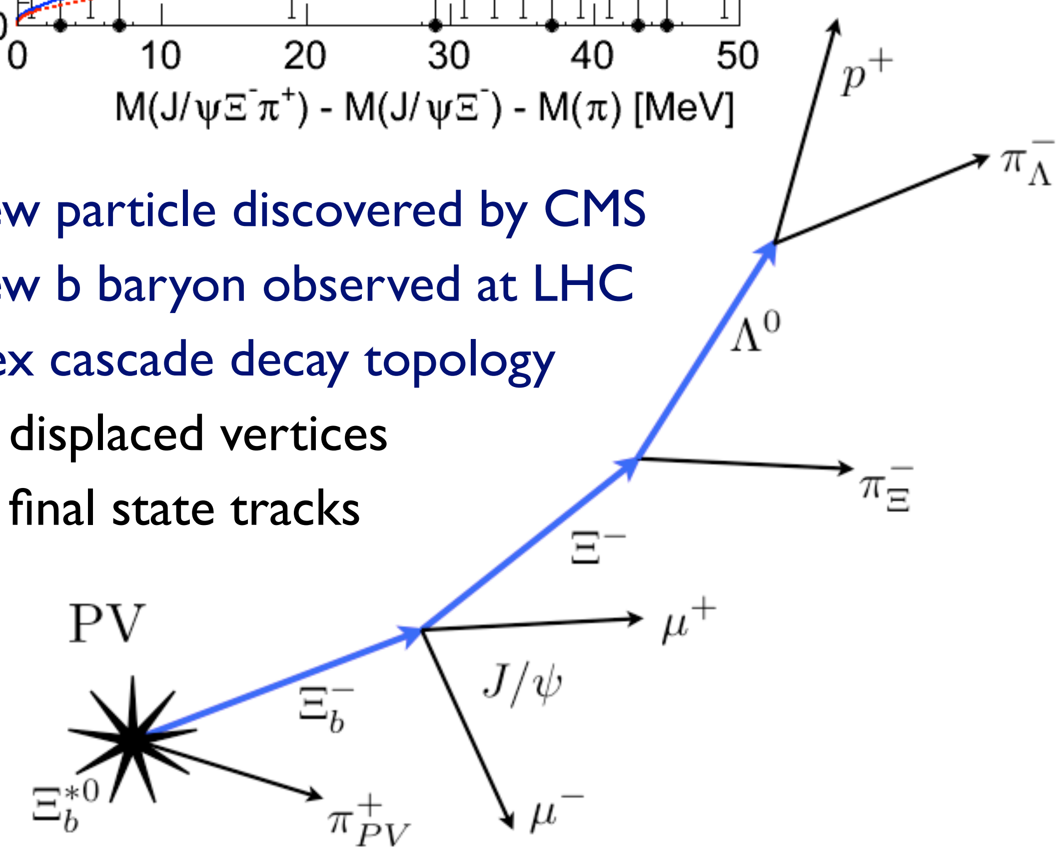
Ξ_b^* baryon



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

$\chi_b \to \Upsilon\gamma$
$\quad\quad\quad\quad \hookrightarrow e^+e^-$
$\quad\quad\quad \hookrightarrow \mu^+\mu^-$

- 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

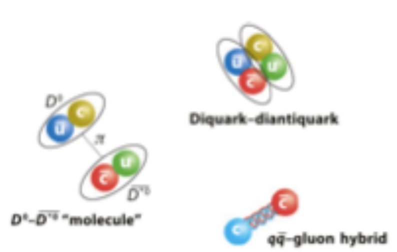
exotic spectroscopy

- 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

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B\to K(\pi^+\pi^-J/\psi)$
		(<2.2)		$p\bar{p}\to(\pi^+\pi^-J/\psi)+\ldots$
				$B\to K(\omega J/\psi)$
				$B\to K(D^{*0}\bar{D}^0)$
				$B\to K(\gamma J/\psi)$
				$B\to K(\gamma\psi(2S))$
$X(3915)$	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}	$?^{?+}$	$e^+e^-\to J/\psi(D\bar{D}^*)$
				$e^+e^-\to J/\psi\ (\ldots)$
$G(3900)$	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]

Many theoretical interpretations in discussion:

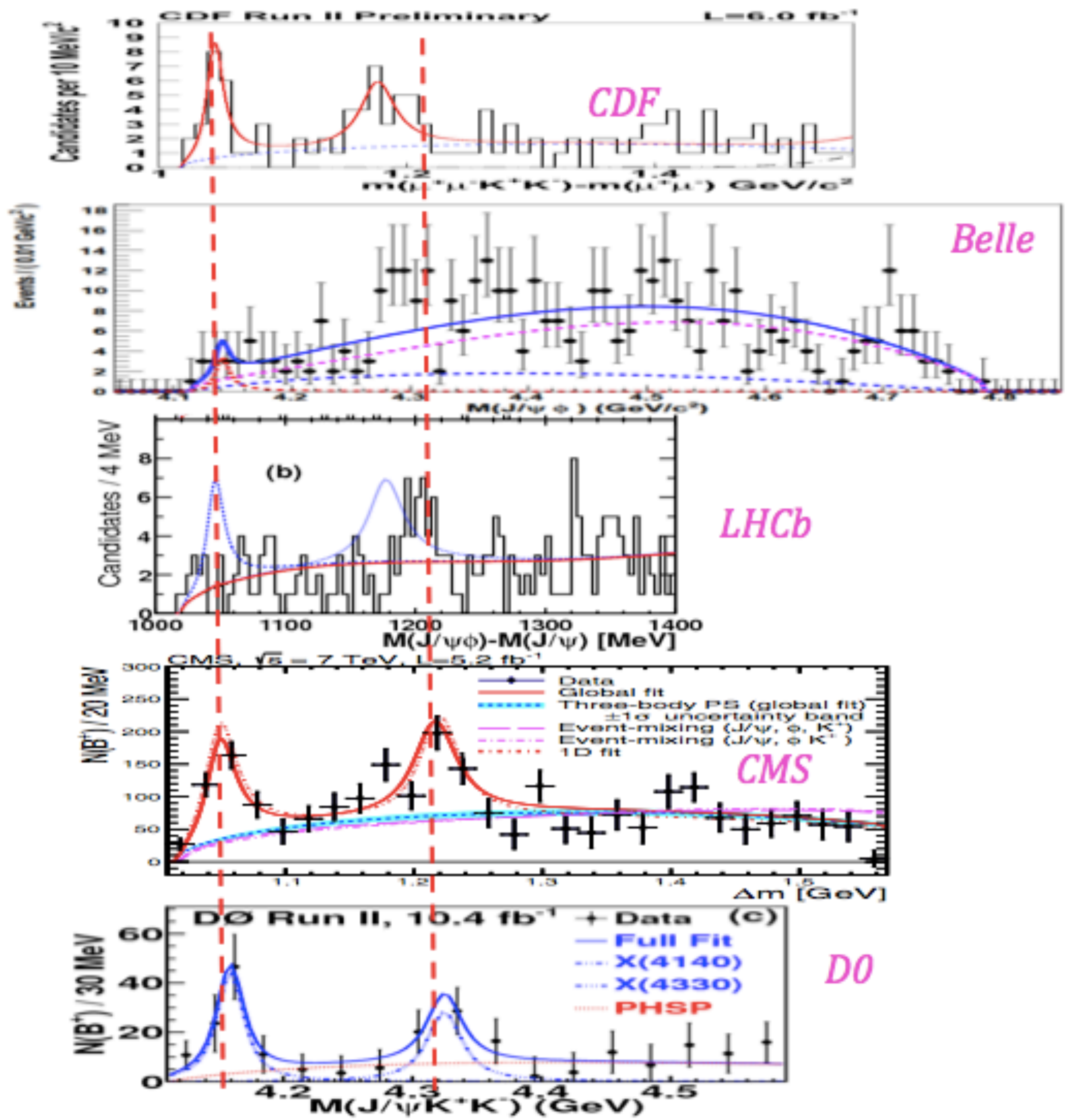


- conventional quarkonia;
- tetra-quarks states;
- meson-molecules;
- hybrid mesons;
- threshold effects;

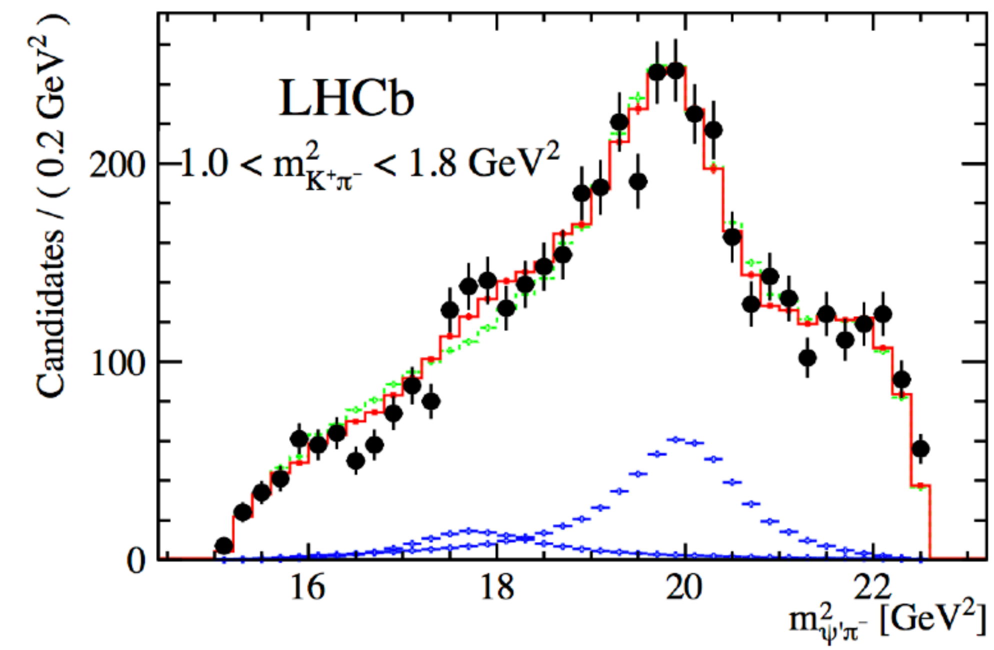
➡ properties do not well fit the quarkonia picture

XYZ states

Y(4140) in $B_u \to X[J/\psi\phi]K$ decays

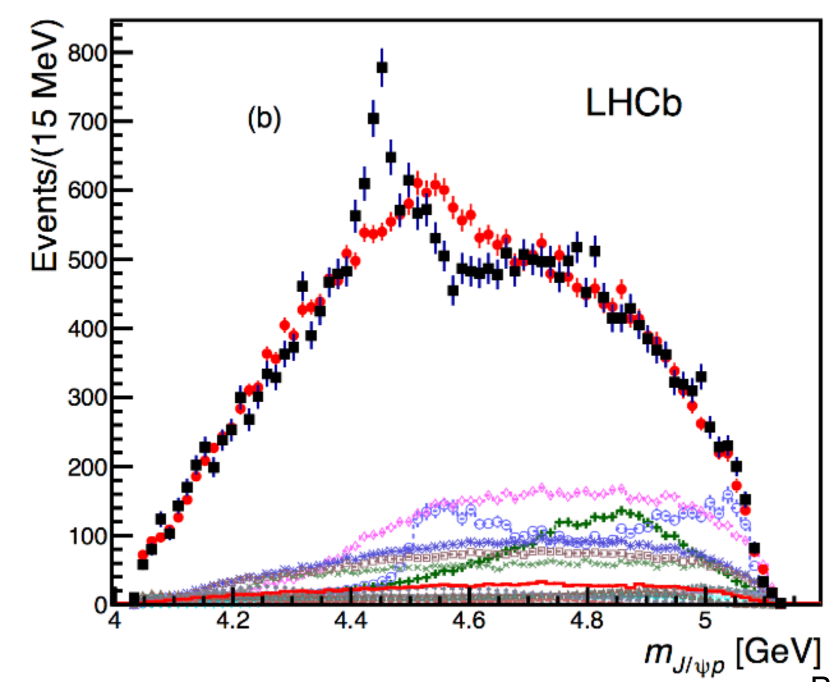


Z(4430)→ψπK



Tetra quark!

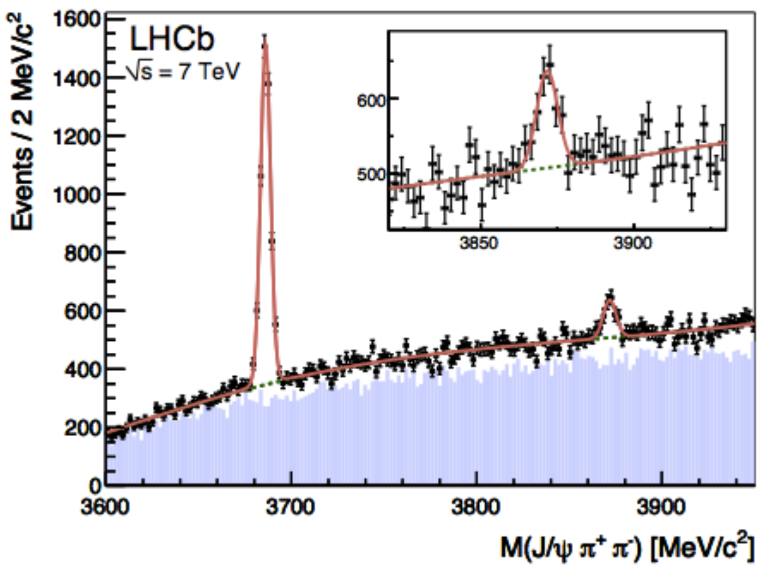
x(4380)→ψp

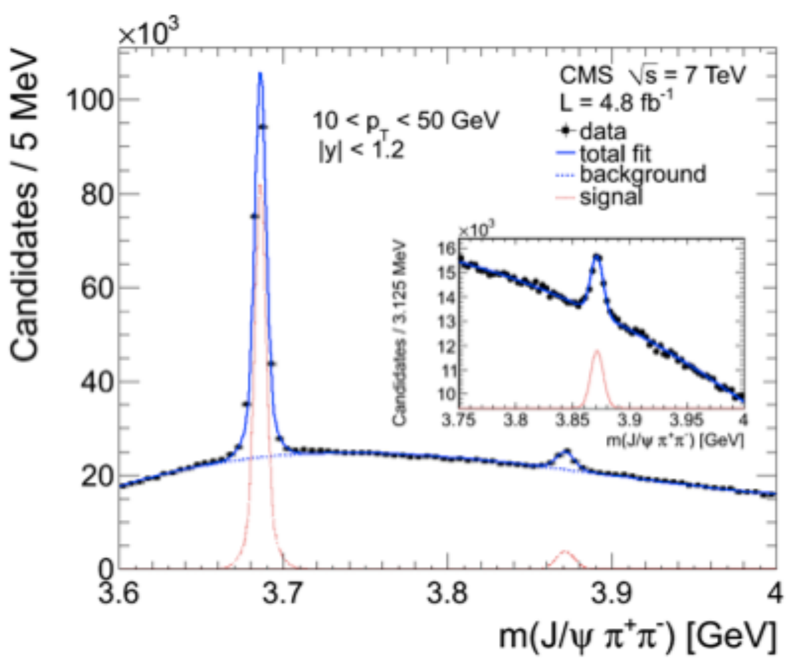


Penta quark!

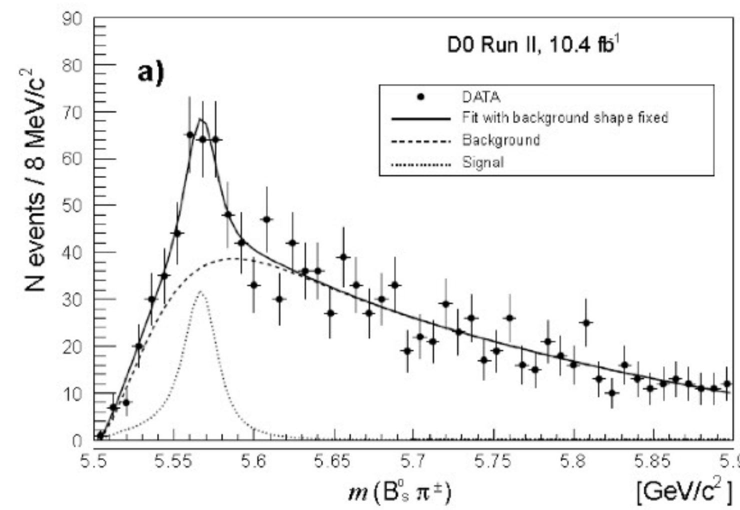
importance of independent experimental confirmation

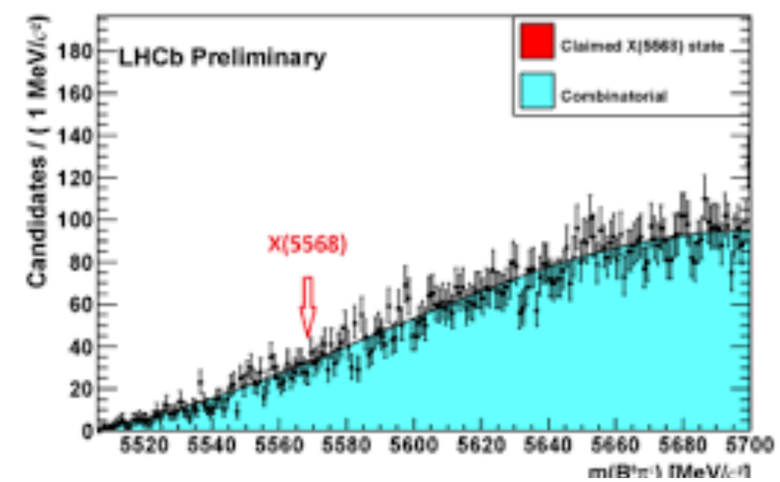
X(3872) →J/ψππ

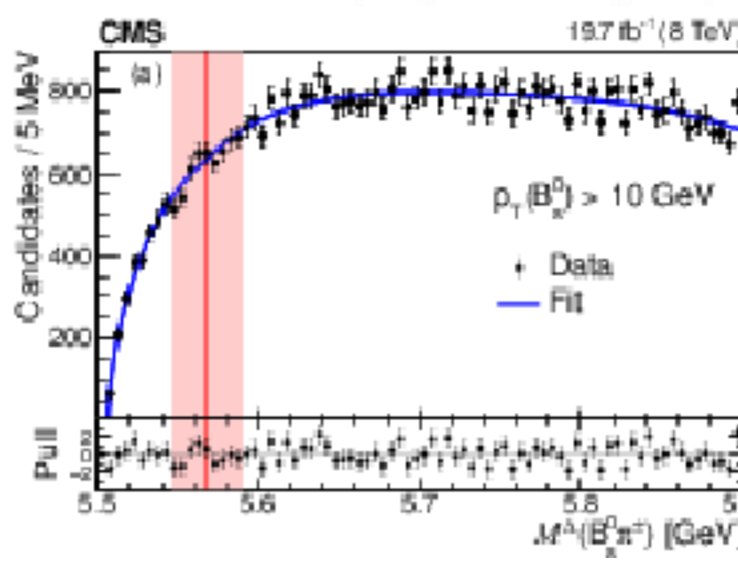


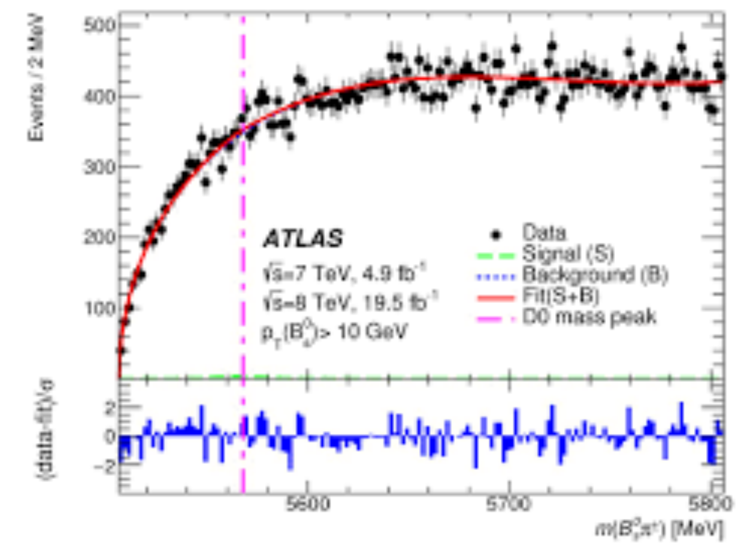


X(5568) → Bsπ ?

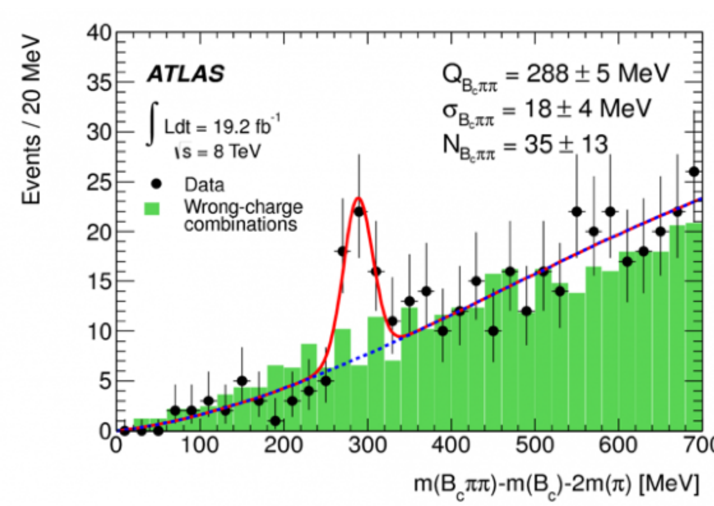


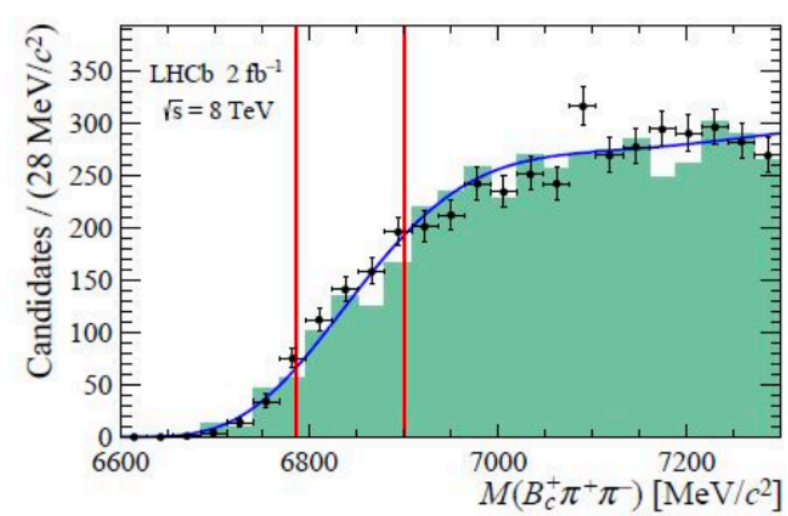






Bc(2S) → Bcπ ?





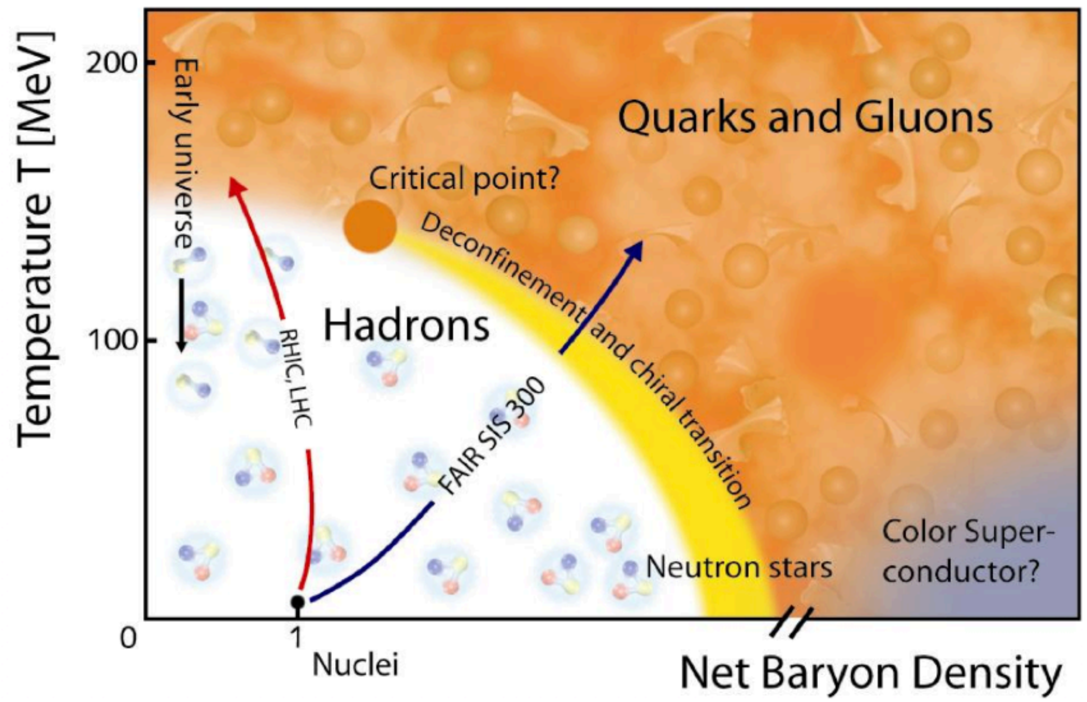
heavy flavor (suppression)

in

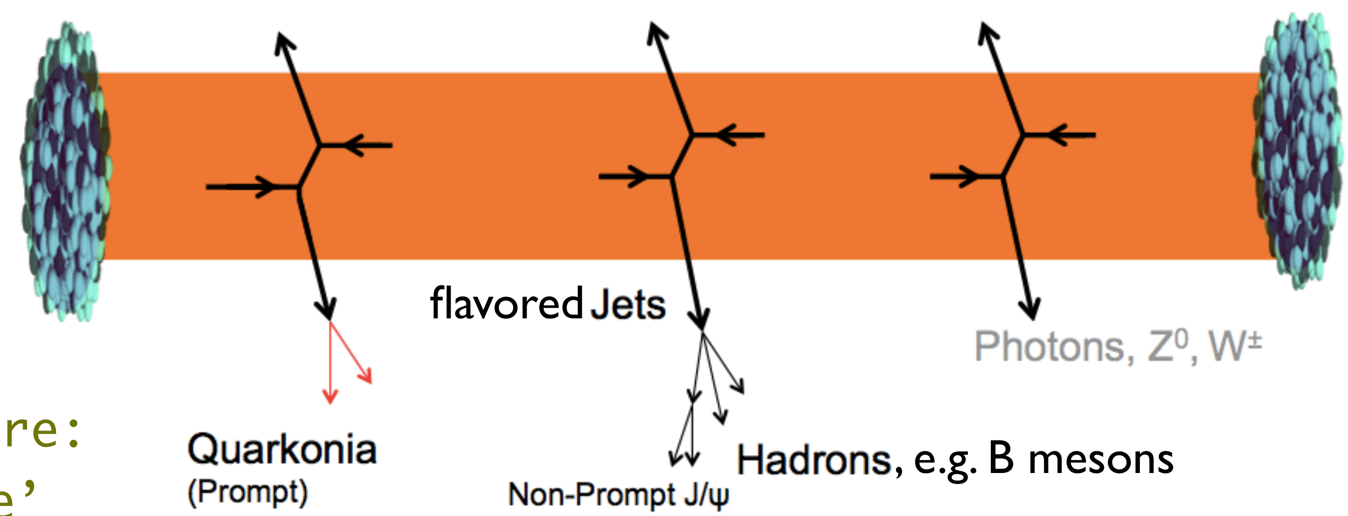
heavy ion collisions

➡ 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

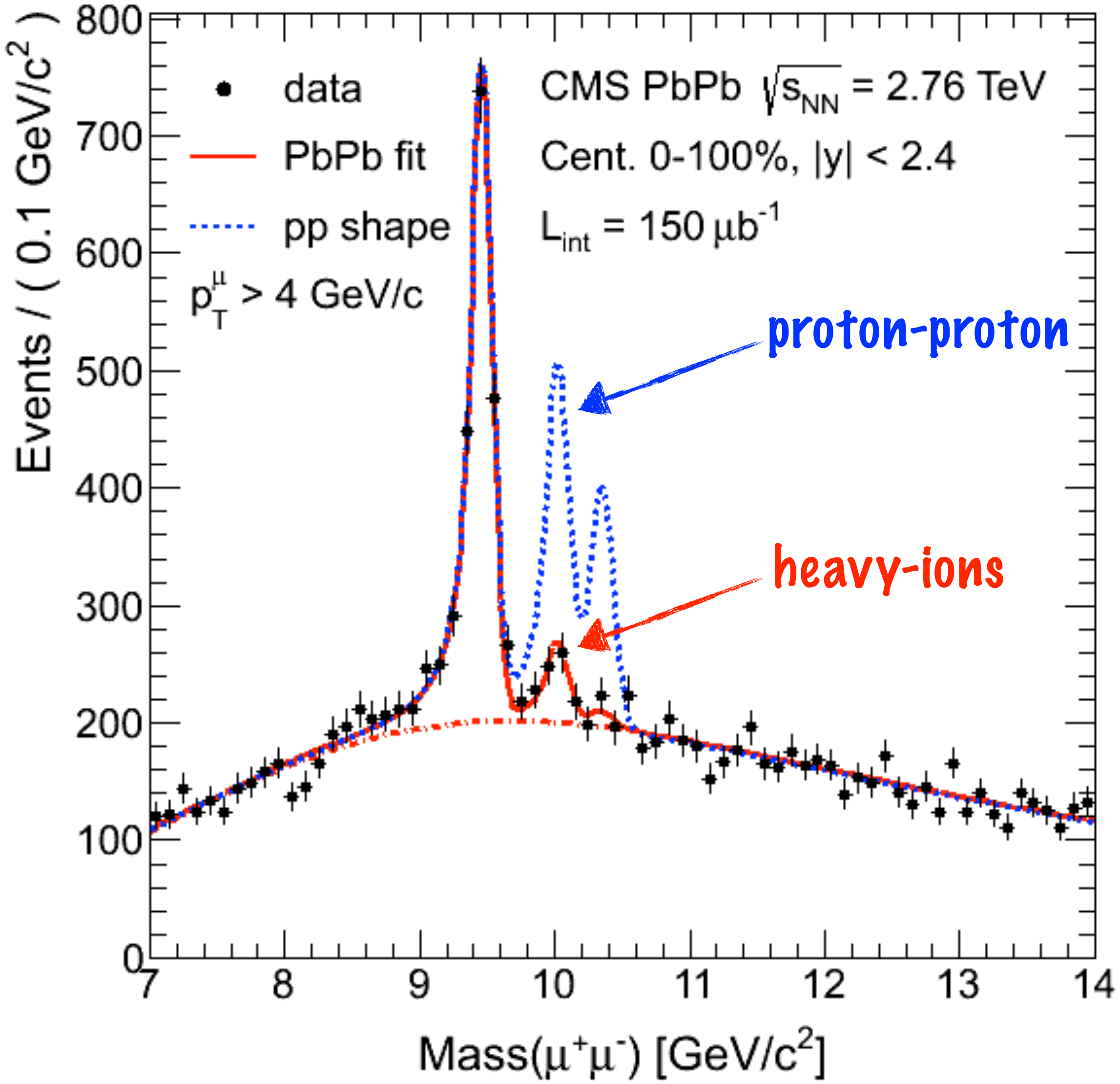


- heavy-flavor states are ideal "hard probes" for studying the properties of the created medium



note: topic presented in dedicated lecture: '<u>matter at high density and temperature</u>'

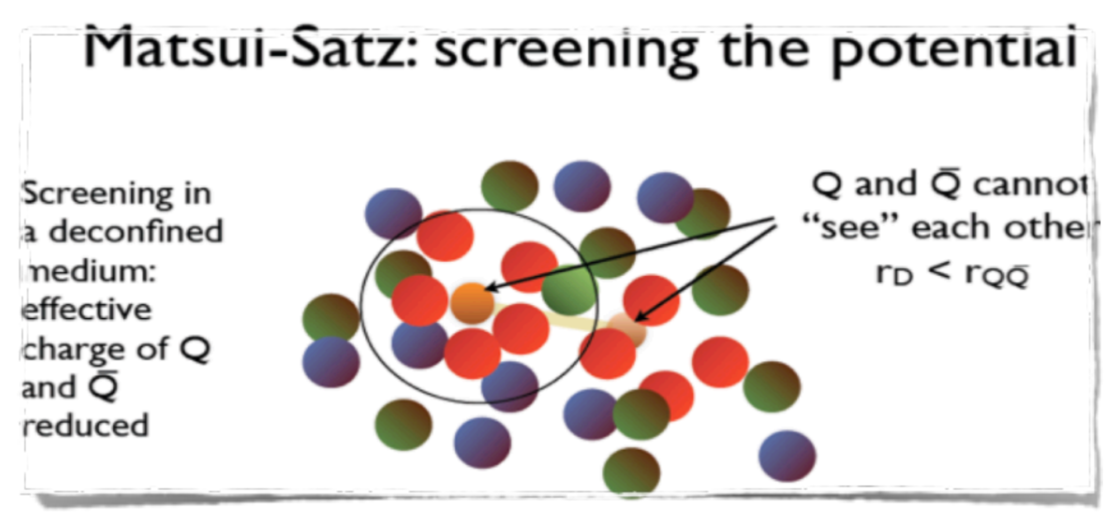
quarkonium suppression *[Pb-Pb]*



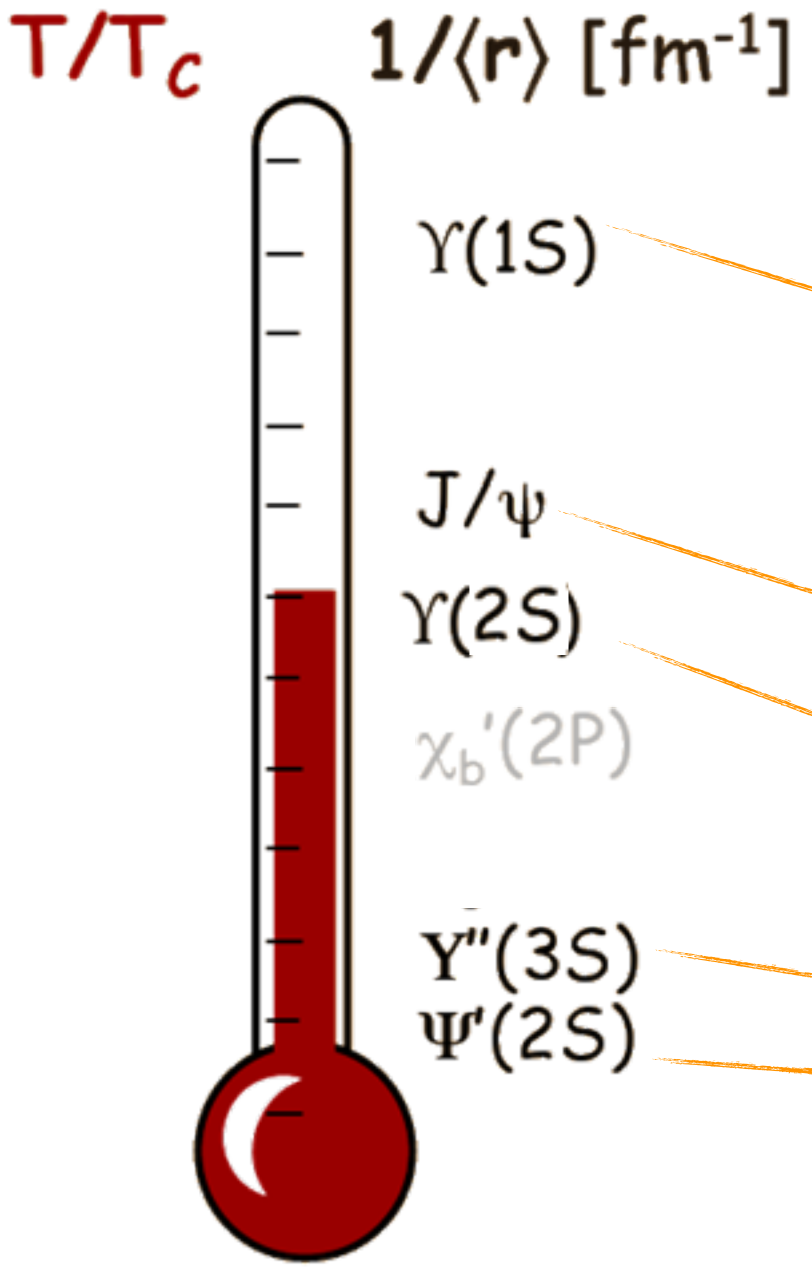
"the LHC heavy-ion **text book** result"

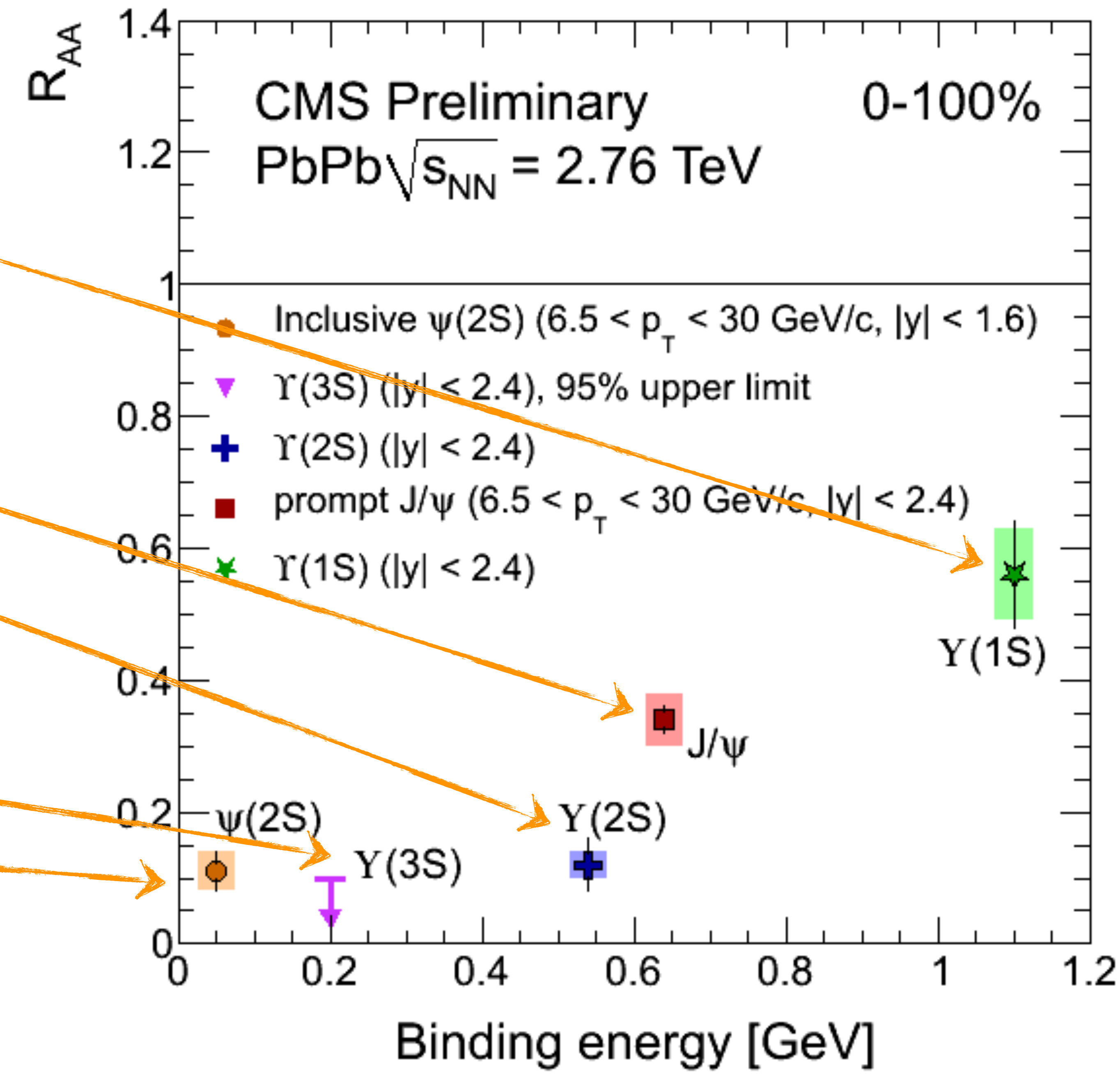
Exercise: the excited states being suppressed, what may be expected also of the observed ground state (hint: nS→1S feed-down)

- 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.



quarkonium sequential suppression

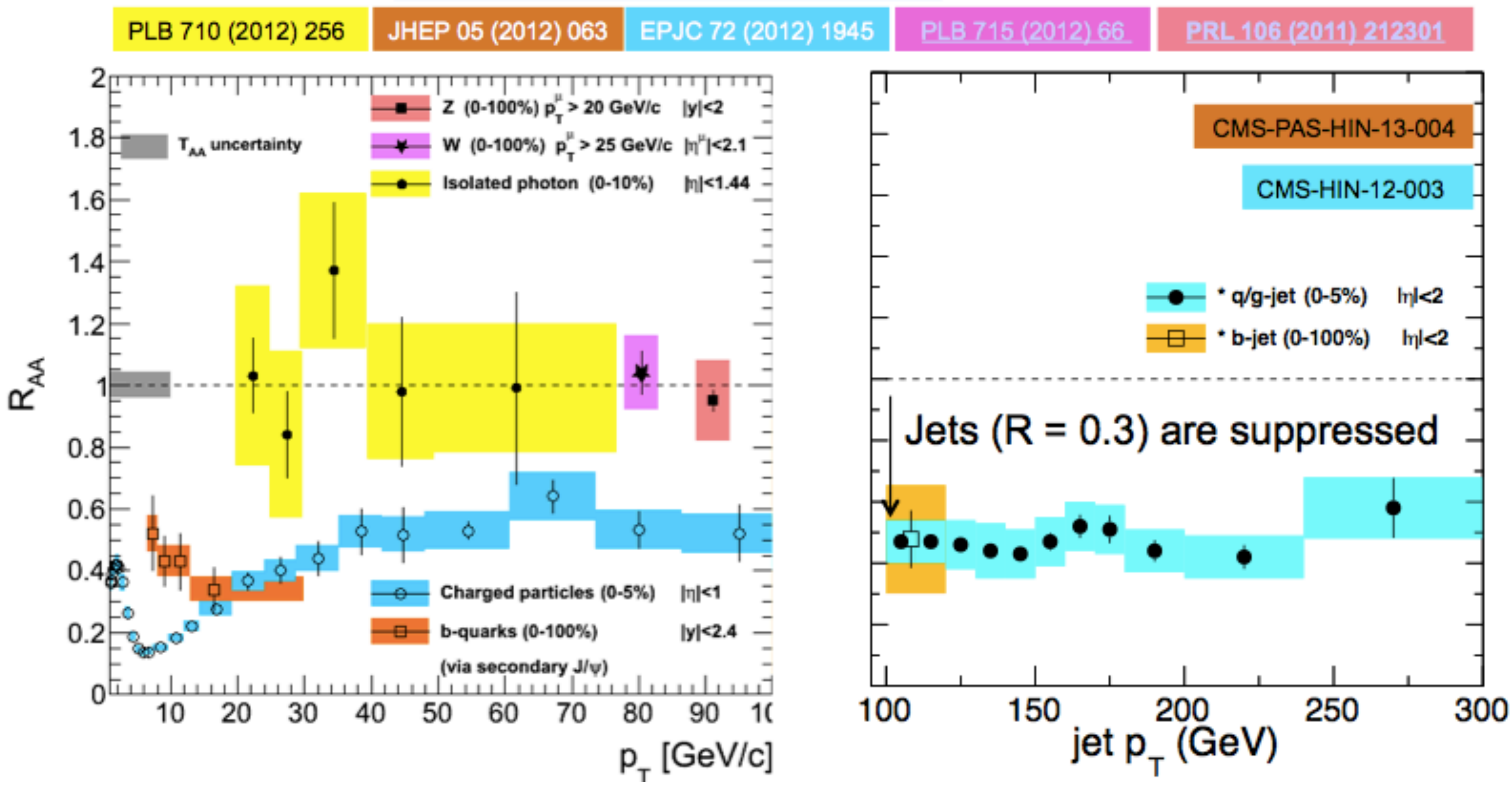




quarkonia suppression pattern experimentally established:

less tightly bound states are more suppressed in the medium

in medium hadron suppression

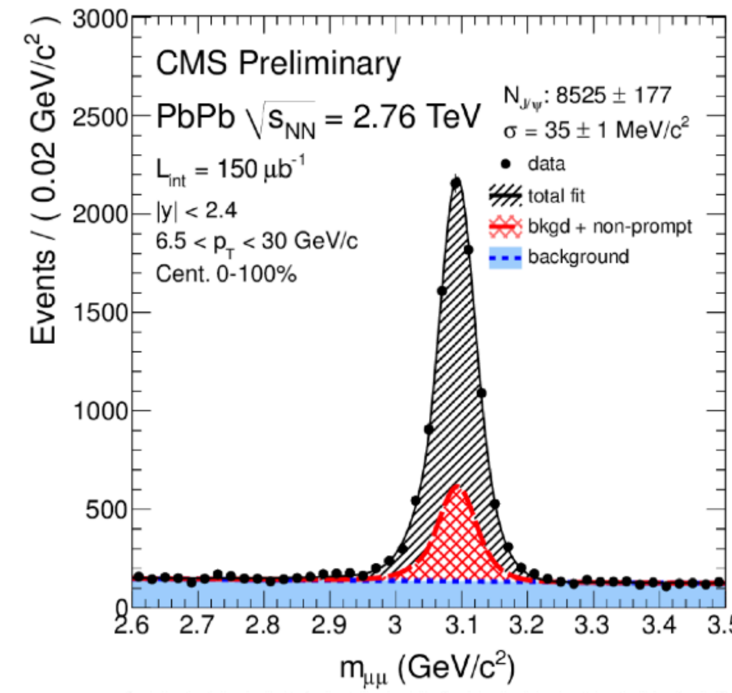


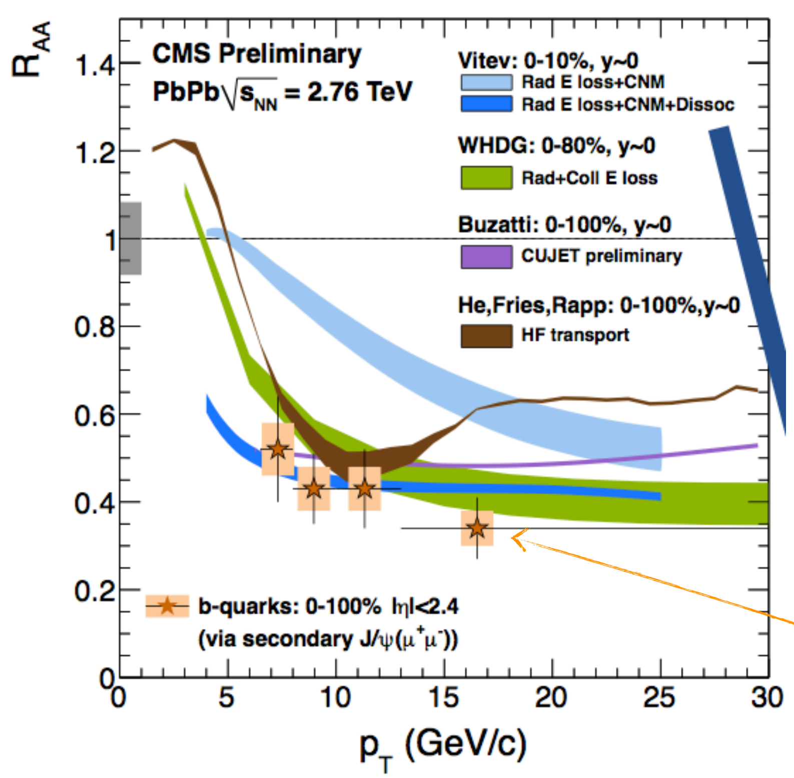
- measure of suppression, R_{AA} (nuclear modification factor)
  - cross section ration in PbPb vs pp, scaled by number of binary collisions
- different particle species undergo different energy loss in the medium
  - colorless probes (W,Z,γ) are not suppressed (R_{AA} ~ 1)

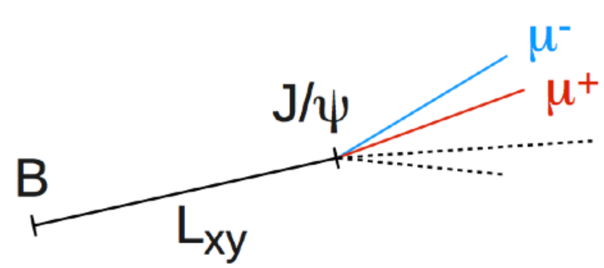
➡study flavor dependence of energy loss

b-hadron detection

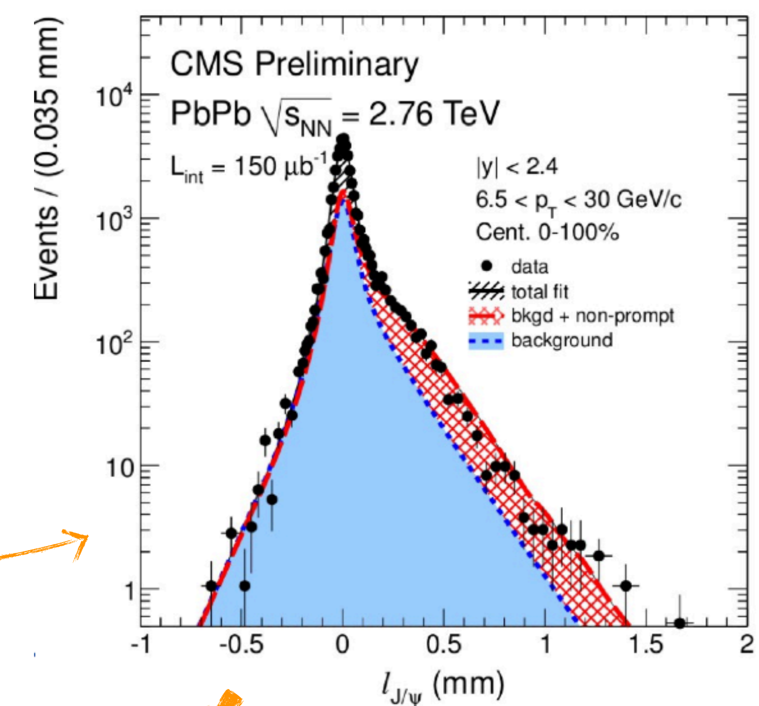
- prior to LHC, b-hadron detection was pursued mostly through inclusive-lepton (B→lX) and inclusive-charmonia (B→J/ψX) studies
- with LHC, moved to a new class of more reliable and precise new measurements
  - through non-prompt charmonia: remove prompt contribution through lifetime analysis [see next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





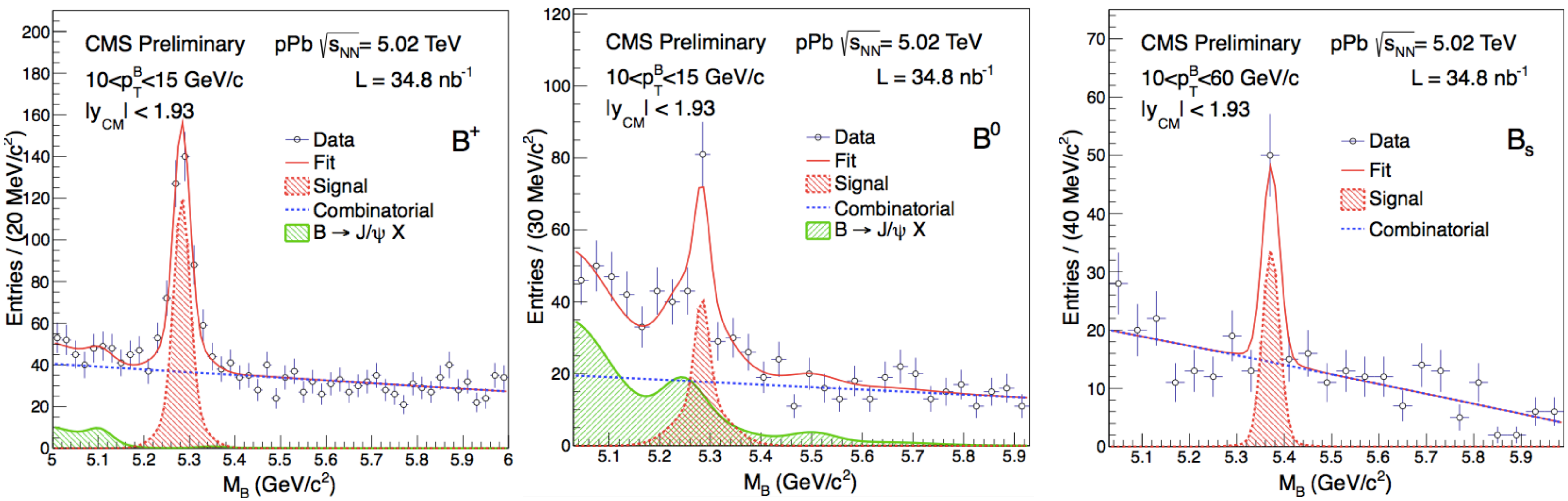


$$l_{J/\psi} = L_{xy}\,\frac{m_{J/\psi}}{p_T}$$



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	0.2 TeV RHIC	2.76 TeV LHC Run I	5.5 TeV LHC Run II

x7 x27 energy

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

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

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)

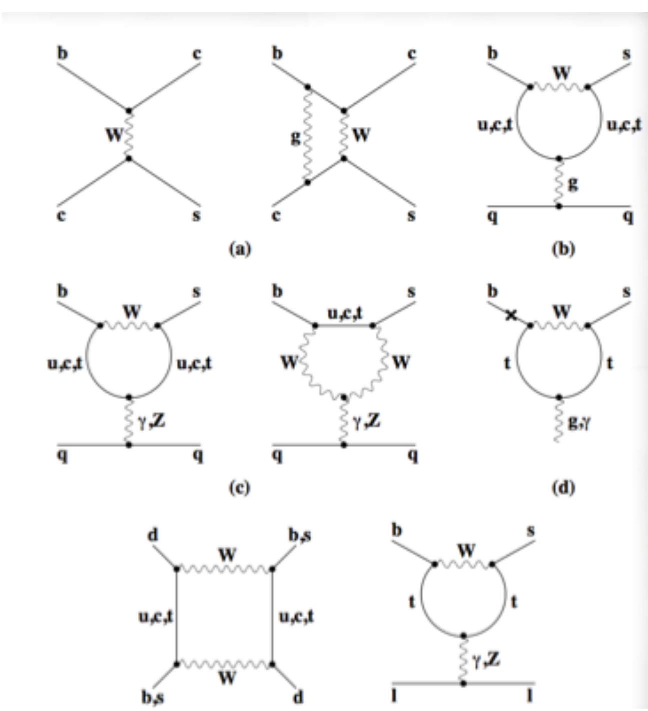
Fermi constant — CKM matrix element

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

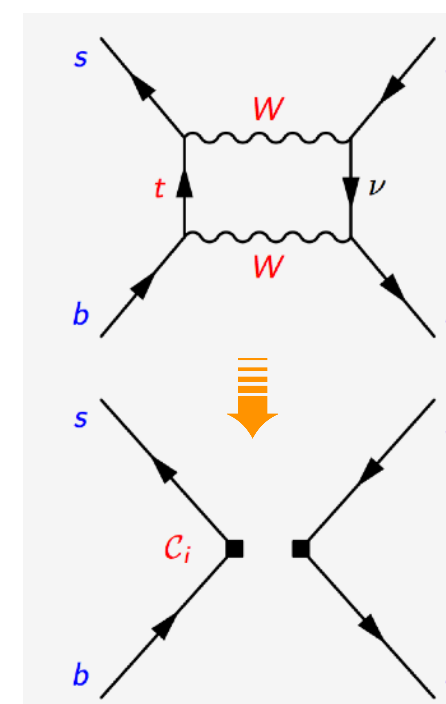
Wilson coefficient
short distance coupling (perturbative)

hadronic matrix element
long distance/non-perturbative

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

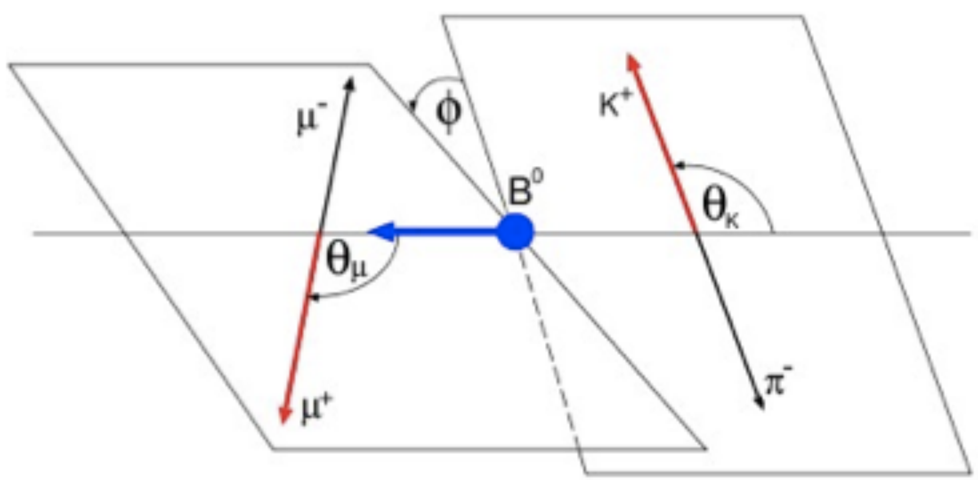


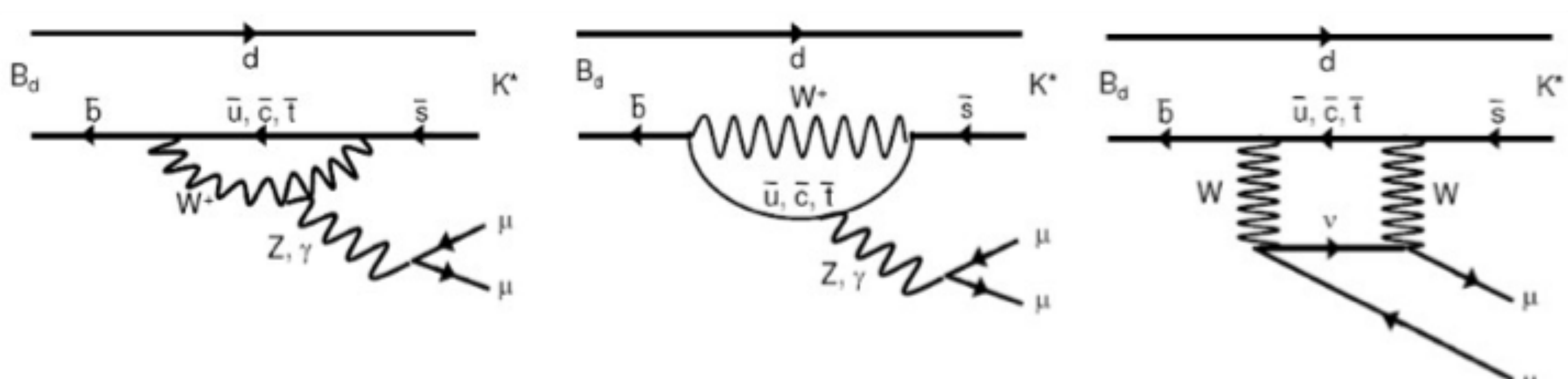
operator O_i	$B\to K\mu\mu$	$B\to\mu\mu$
$\mathcal{O}_7 \sim m_b(\bar{s}_L\sigma_{\mu\nu}b_R)F_{\mu\nu}$	✔	
$\mathcal{O}_9 \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_V$	✔	
$\mathcal{O}_{10} \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_A$	✔	✔
$\mathcal{O}_{S,P} \sim (\bar{s}b)_{S+P}(\bar{\ell}\ell)_{S,P}$		✔



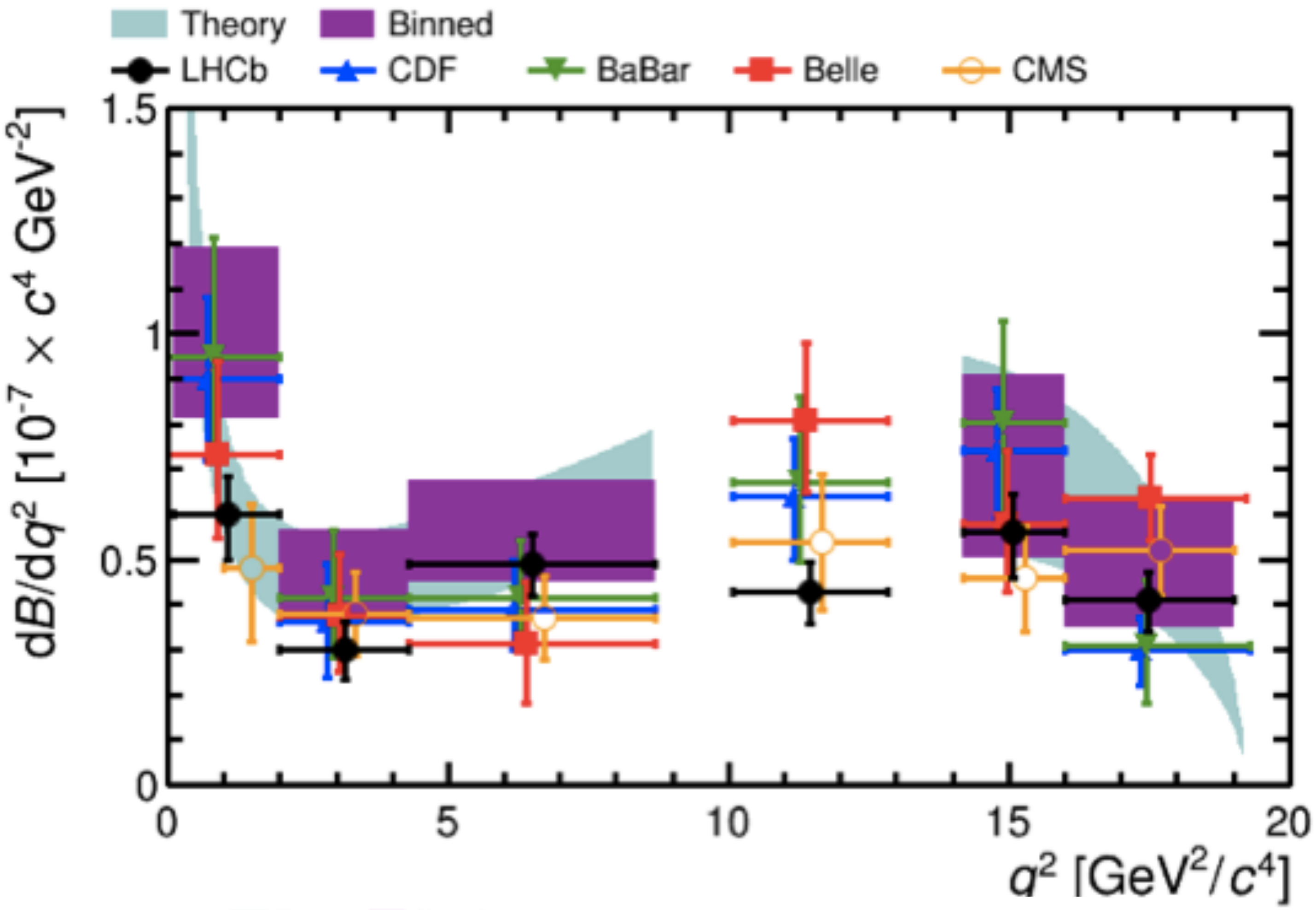
$B^0 \to K^{*0}\mu\mu$

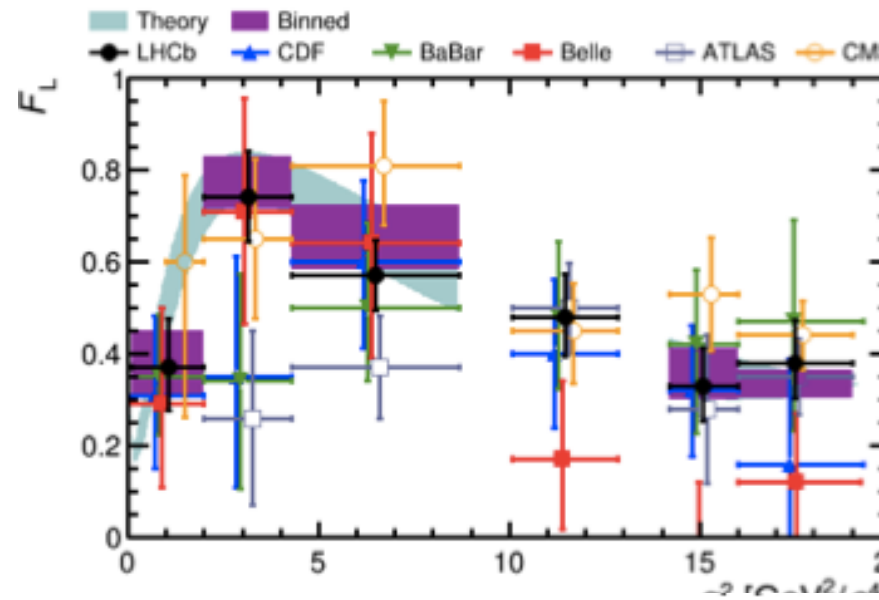
- $b \to sll$ transitions, governed by FCNCs
- experimentally clean signature ➠ superb laboratory for NP tests
- with clean theoretical predictions (at least at low $q^2 := m_{\mu\mu}^2$)
- and not so rare ➠ allow measurements of many sensitive kinematic variables and asymmetries
- measure differential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

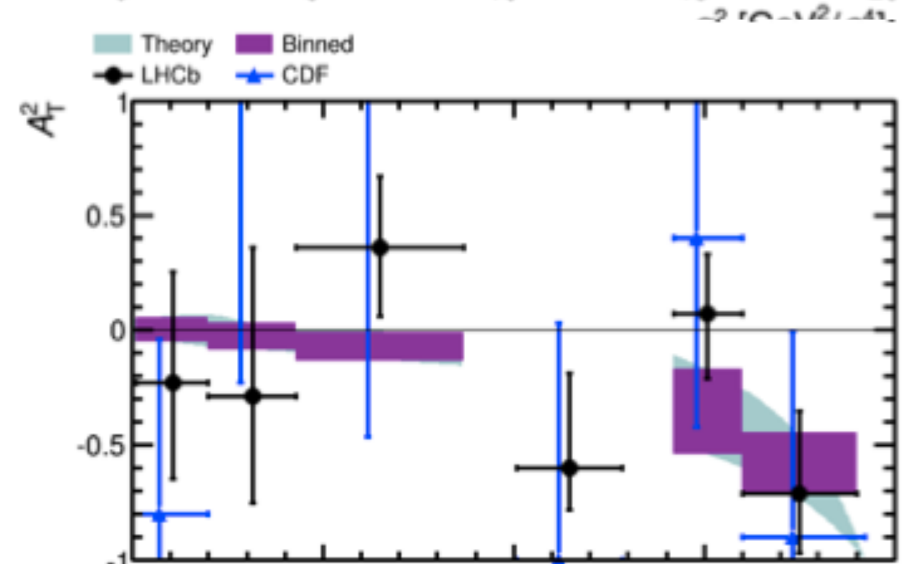


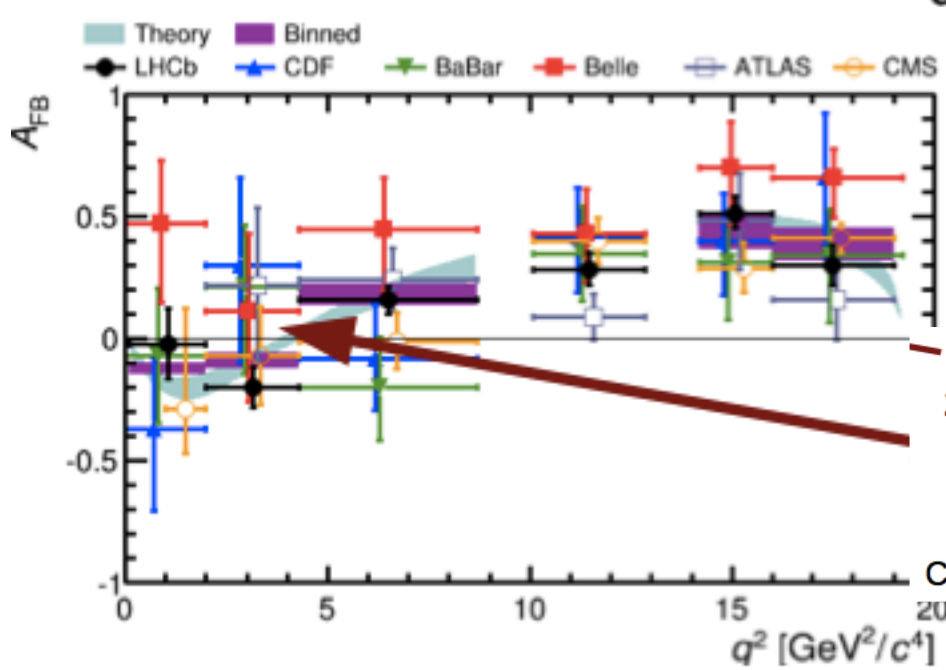


$B^0 \to K^{*0}\mu\mu$





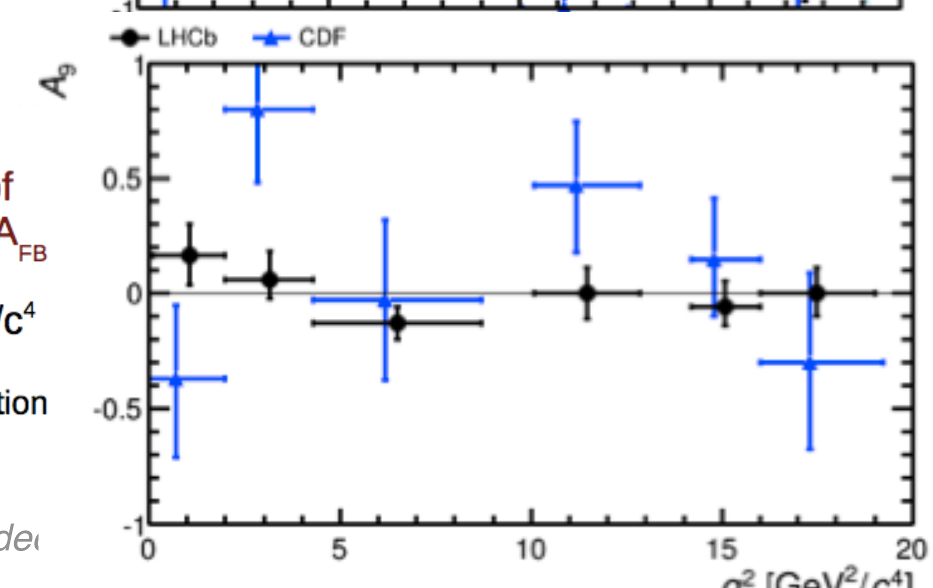




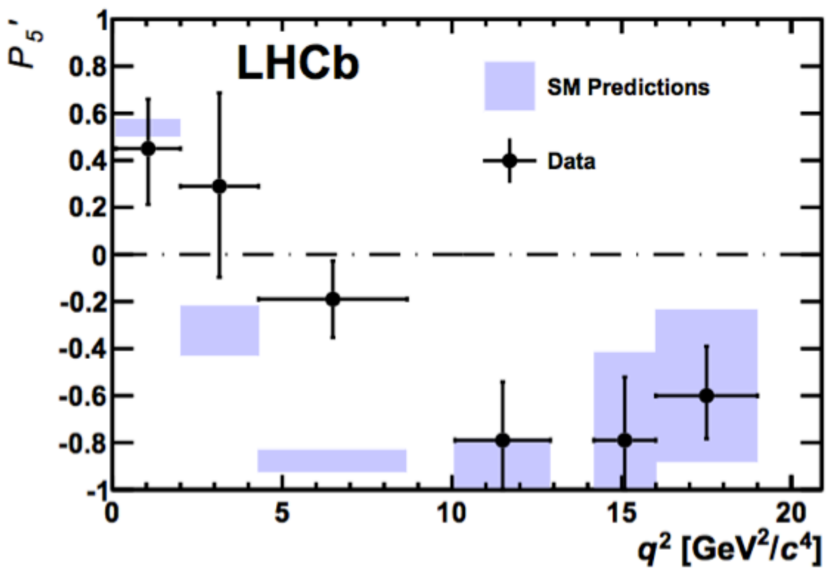
First measurement of zero-crossing point of A_{FB}

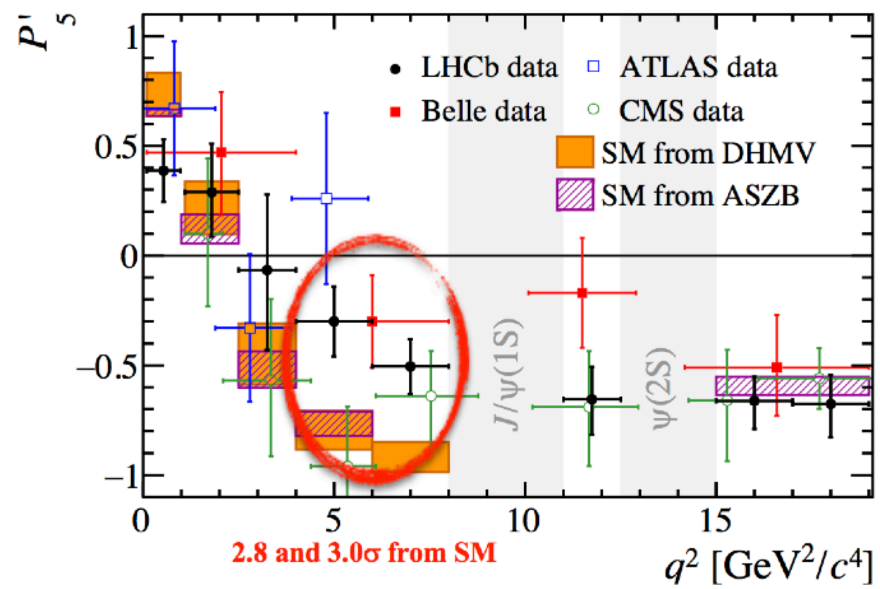
$q^2_0 = (4.9 \pm 0.9)\ \mathrm{GeV}^2/c^4$

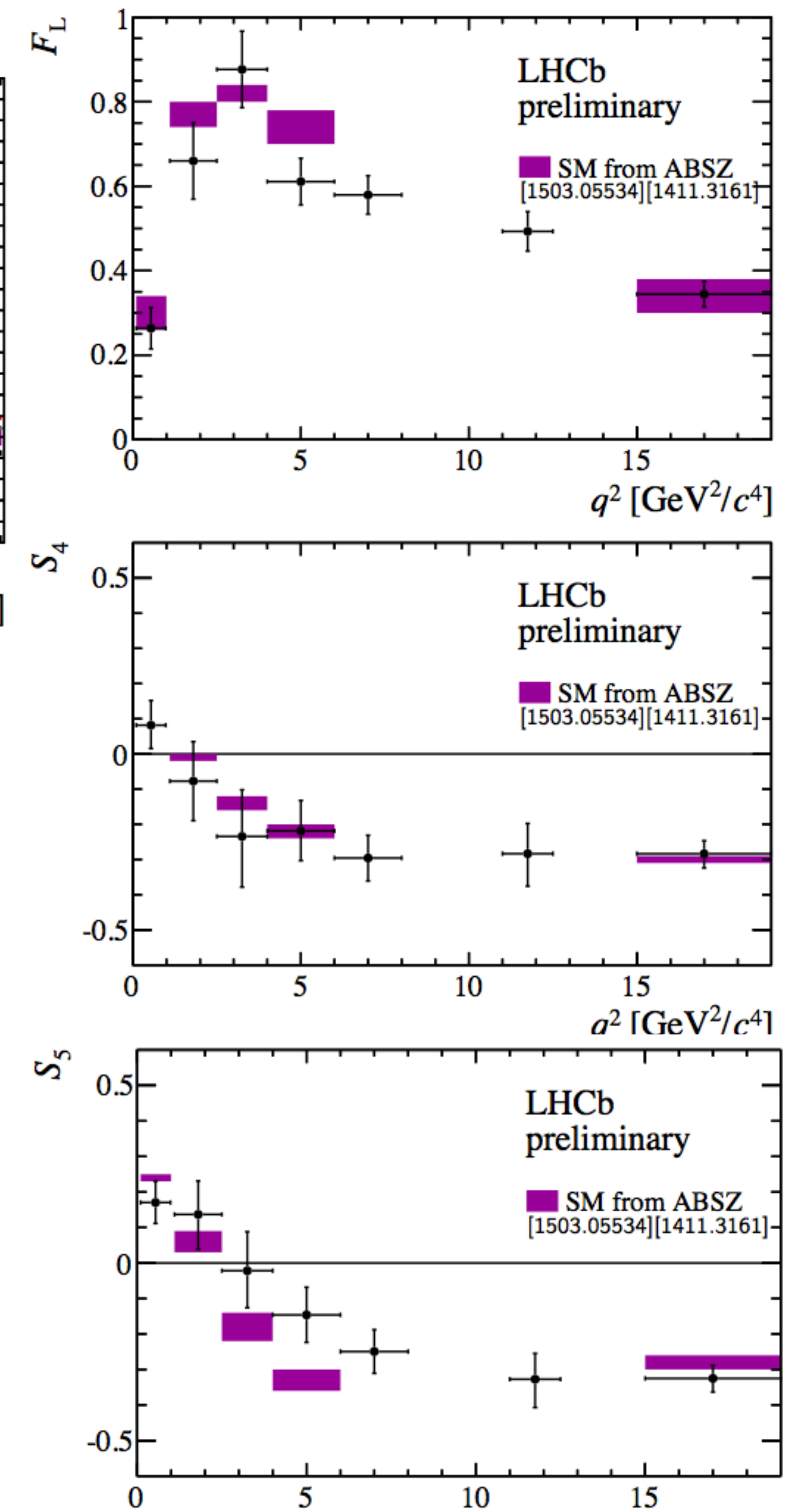
Consistent with SM expectation



B→Kμμ



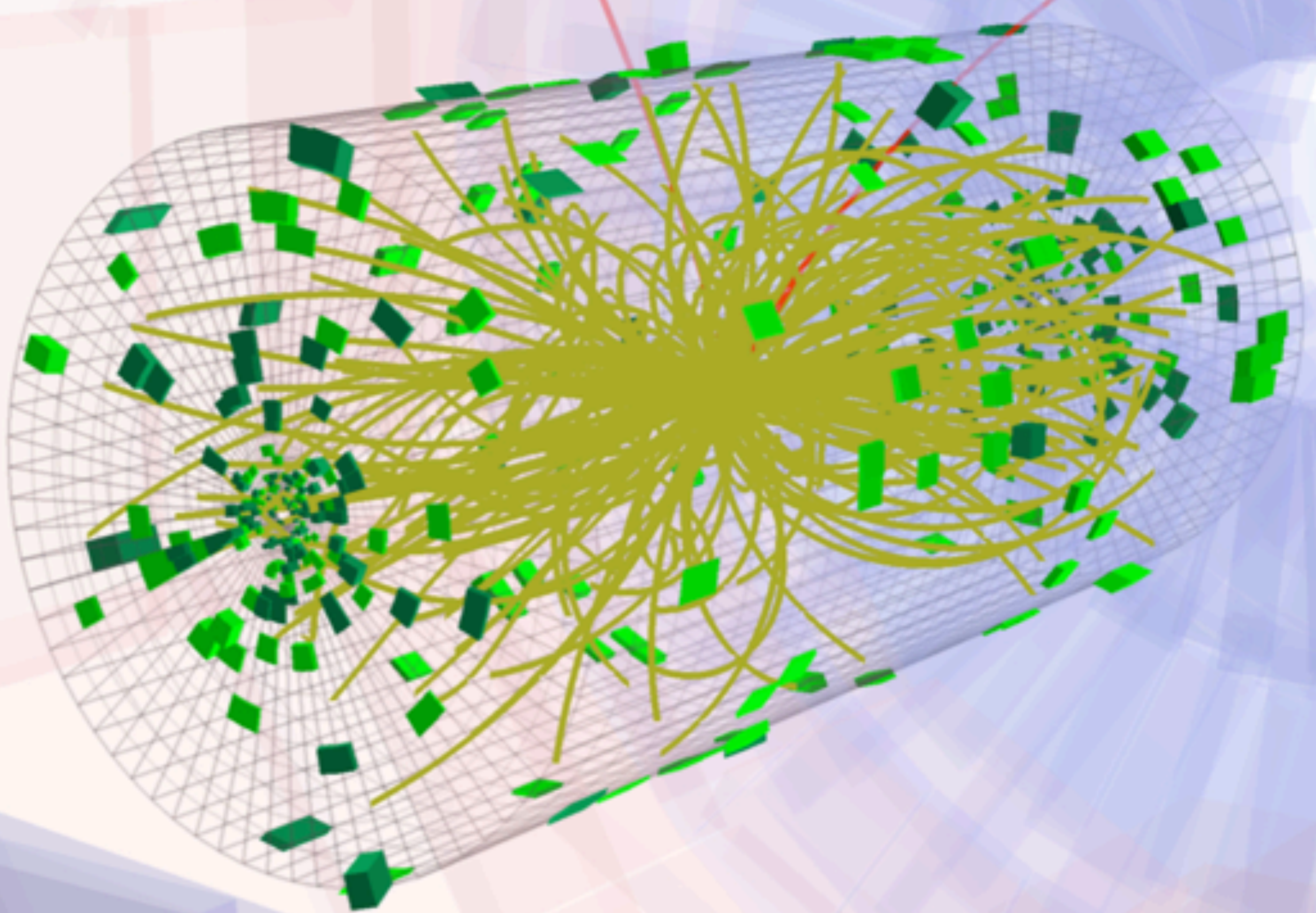




- new set of variables proposed ➠ less sensitive to hadronic form factors
- P_5': LHCb measures 4 new observables in 6 bins of q^2; one of the 24 measurements deviates from SM by ~3.7σ
- possible interpretation as a NP contribution to Wilson coefficient C_9
- interesting (correlated?) tensions with SM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

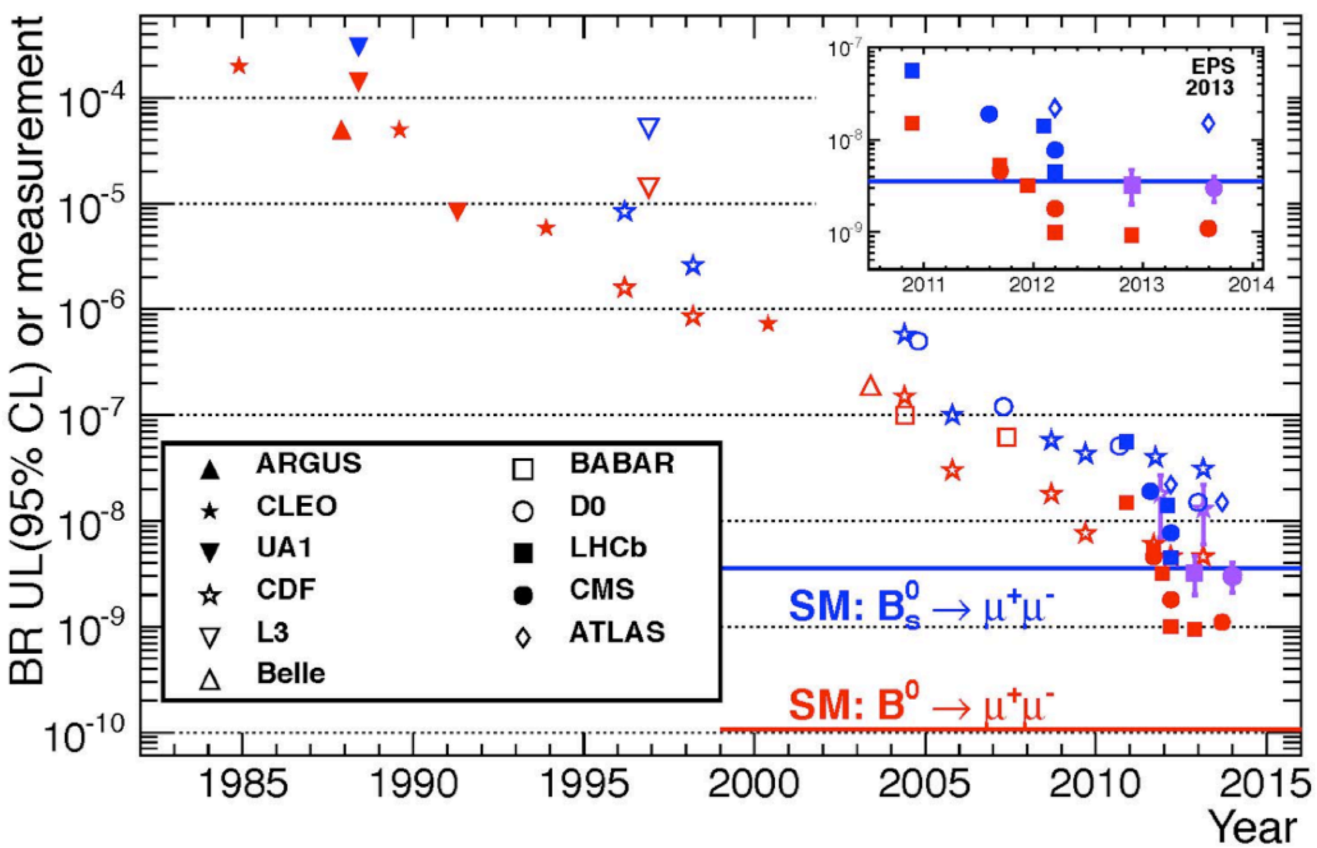
$B_s \rightarrow \mu\mu$

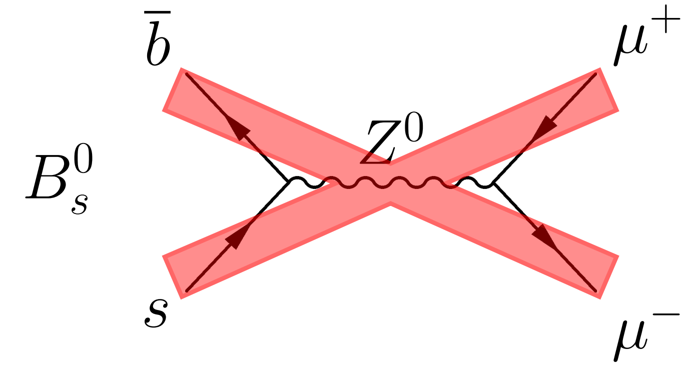
the ‘golden’ rare decay

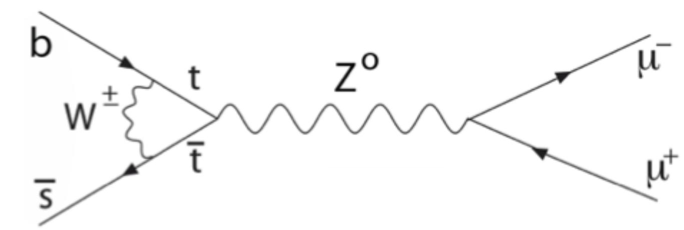


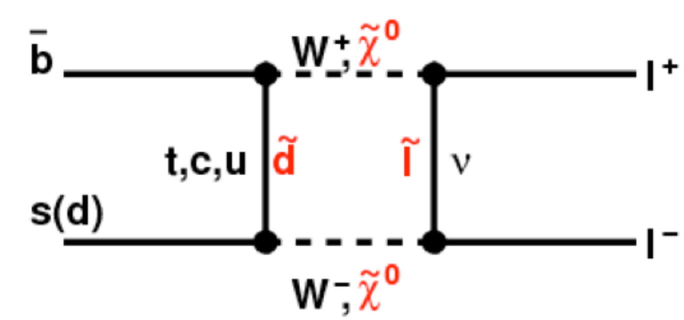
searching for an ultra-rare decay: B→μμ

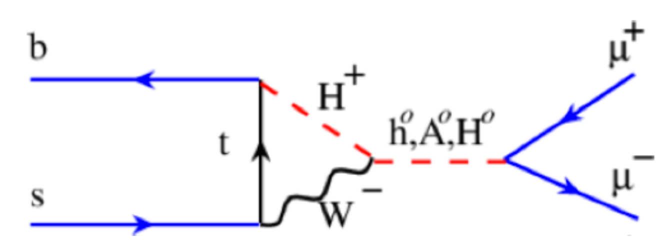
- the decay $B_s \to \mu\mu$ is very suppressed in SM, O (10^{-9})
- it can be sizeably enhanced by various BSM models
- search has been pursued for 3 decades

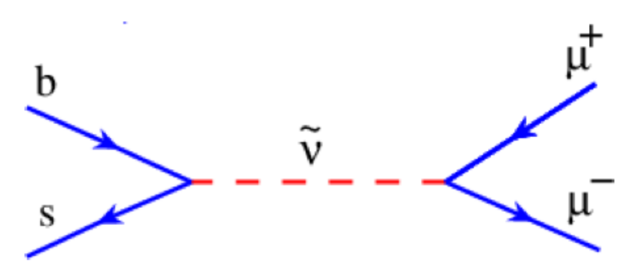






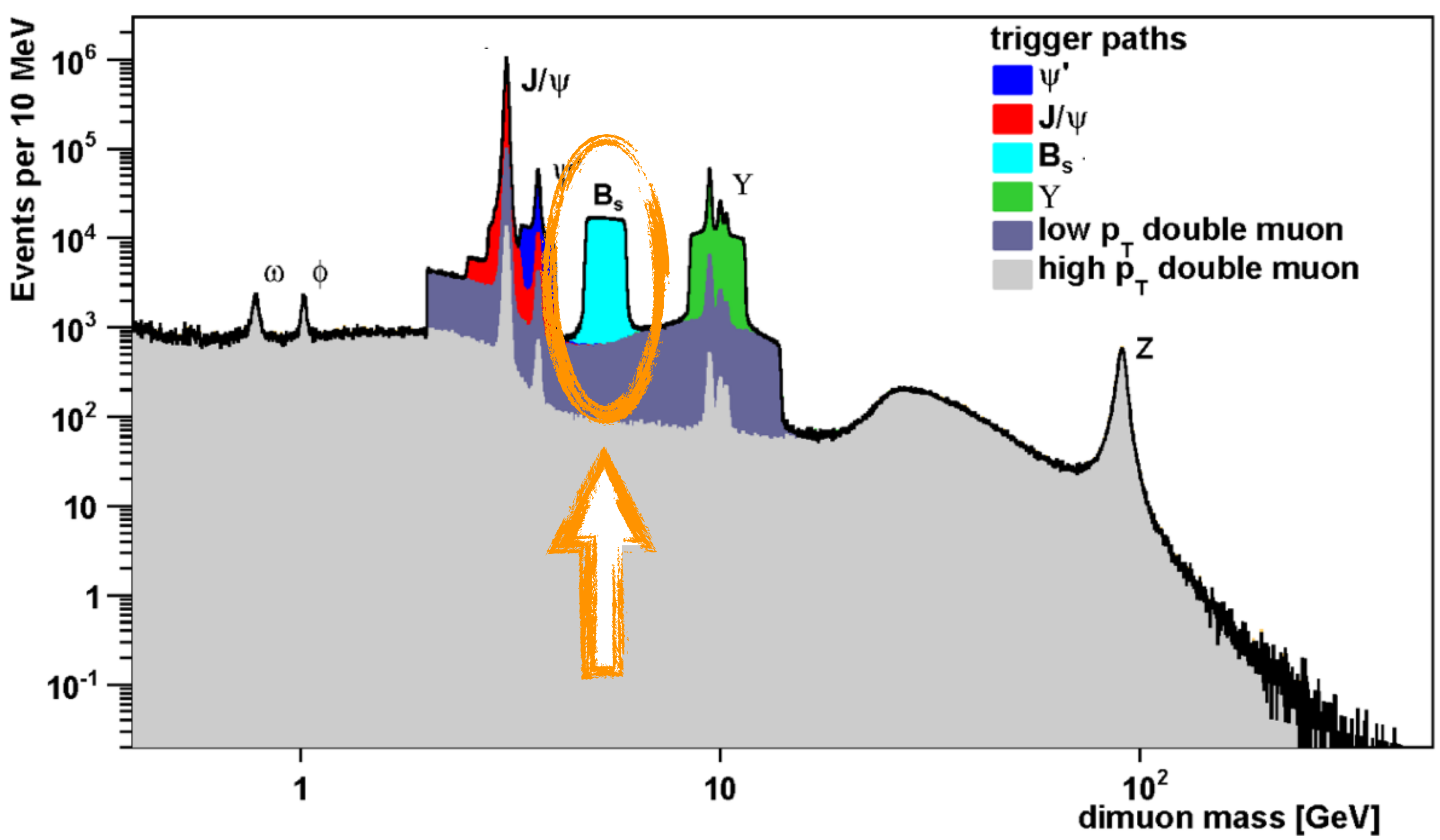






searching for an *ultra-rare* decay: B→μμ

1. ONLINE SELECTION (TRIGGER)



Dimuon Trigger

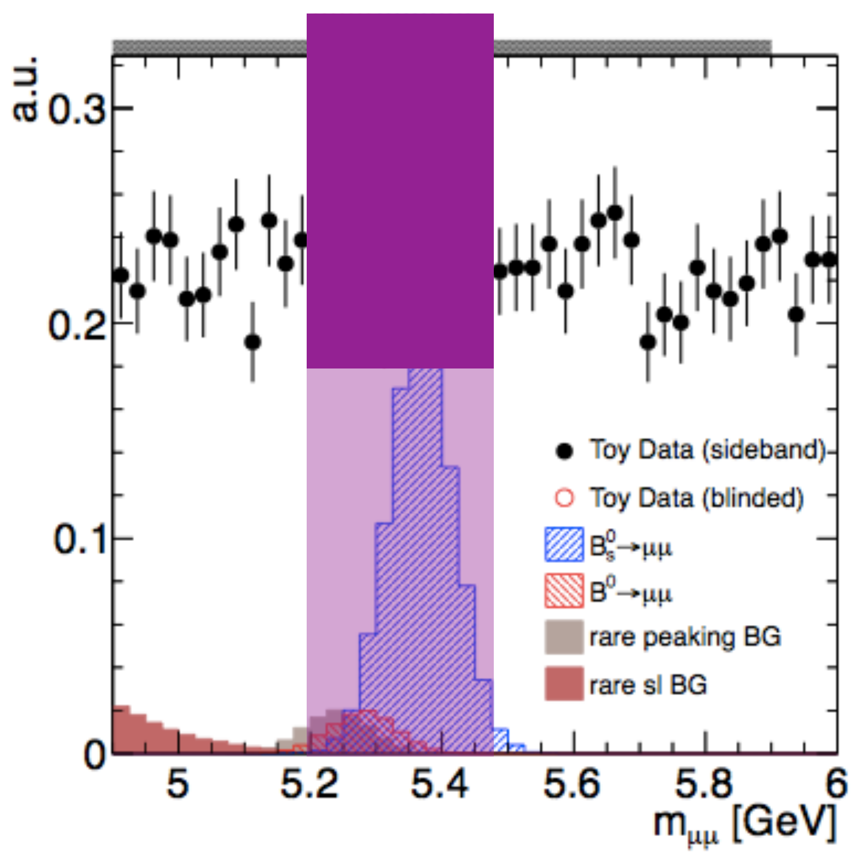
- L1 Hardware Trigger
  - p_T>3 GeV (few kHz)
- HLT Full tracking and vertexing
- HLT B_s→μμ
  - Leading and sub-leading μ p_T>3,4 (4,4) GeV $|\eta_{\mu\mu}|$<1.8 (1.8<$|\eta_{\mu\mu}|$<2.2)
  - p_T (μμ)>5 (4.8-6) GeV
  - 4.8 <m(μμ)< 6.0 GeV
  - $P(\chi^2/dof)$ >0.5%

searching for an *ultra-rare* decay: $B \to \mu\mu$

1. ONLINE SELECTION (TRIGGER)

2. BLIND THE DATA (AVOID BIAS)

SIGNAL
REGION
BLINDED

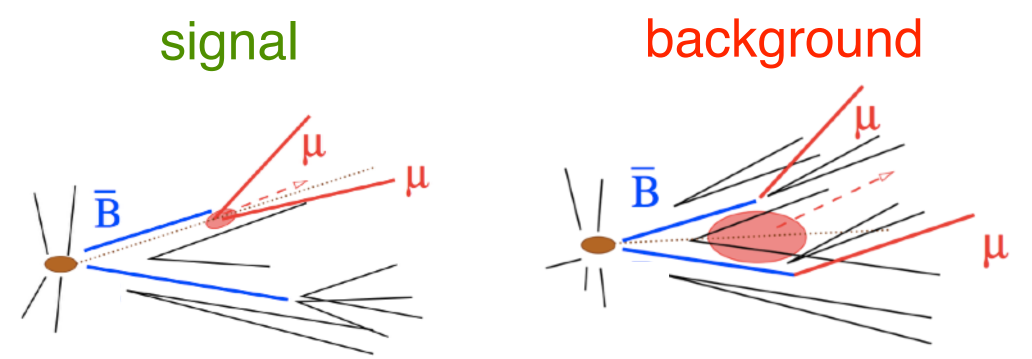


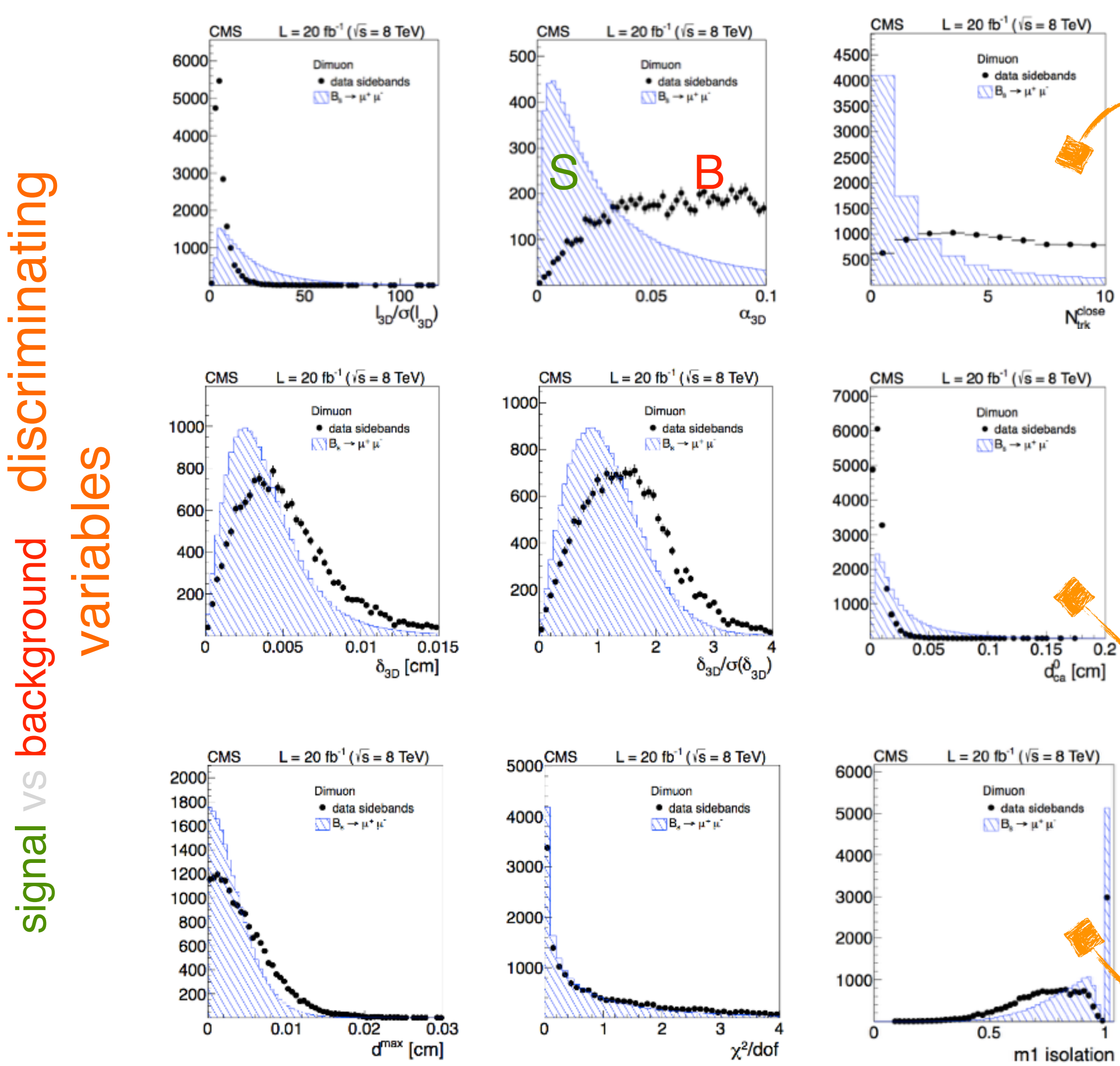
analysis procedure and event selection developed without inspecting the data in region where signal is expected

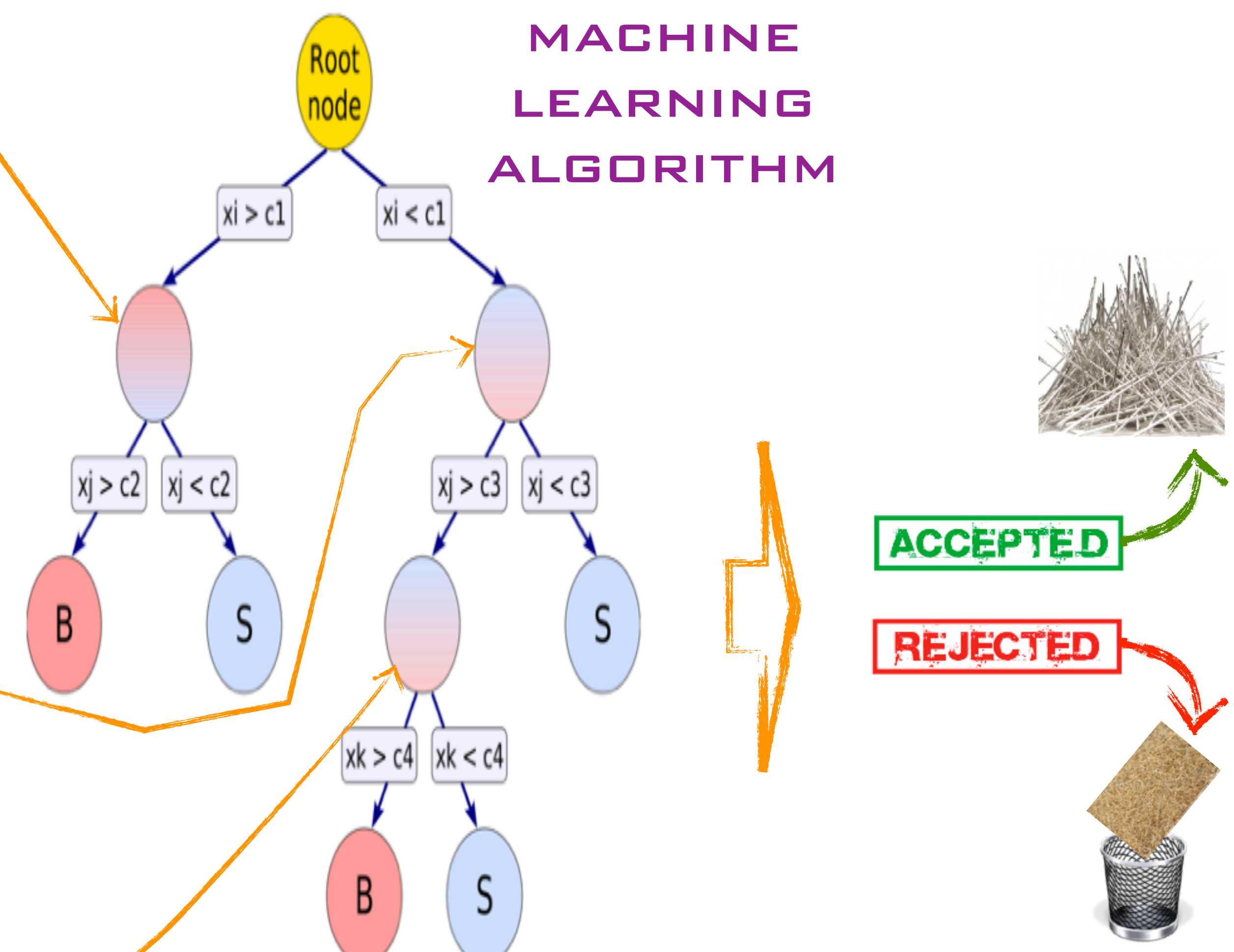
"box opening" only later, at final analysis stages

searching for an ultra-rare decay: B→μμ

1. ONLINE SELECTION (TRIGGER)
2. BLIND THE DATA (AVOID BIAS)
3. MULTIVARIATE SELECTION



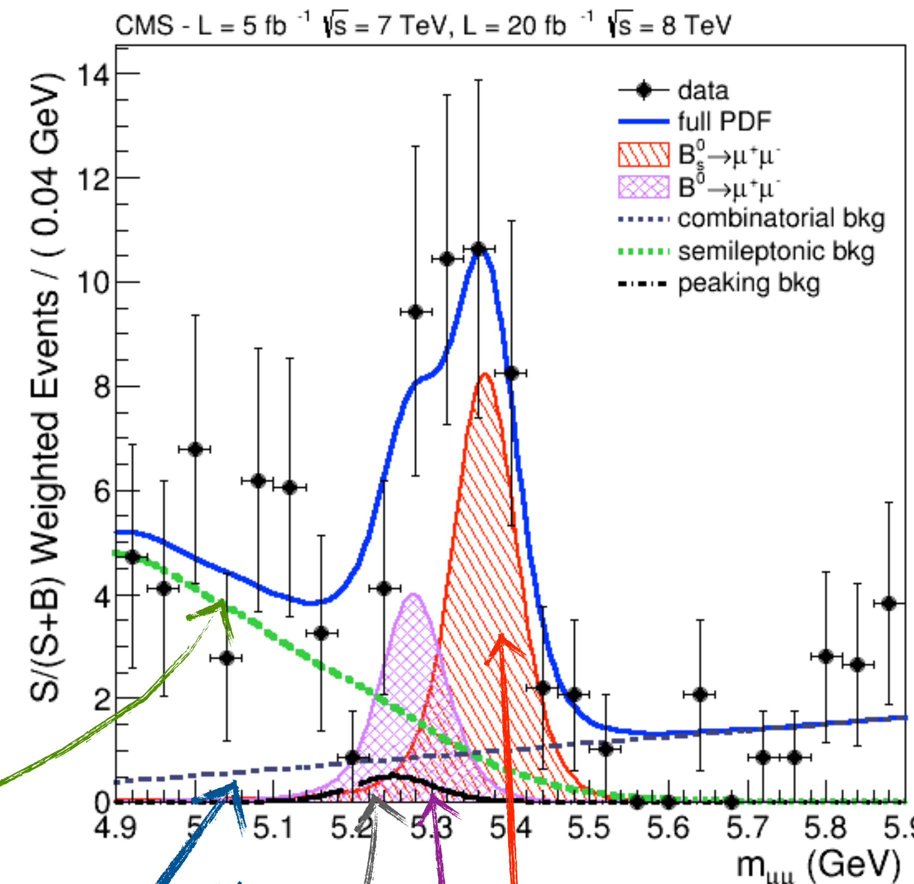




searching for an *ultra-rare* decay: $B \to \mu\mu$

1. ONLINE SELECTION (TRIGGER)
2. BLIND THE DATA (AVOID BIAS)
3. MULTIVARIATE SELECTION
4. **FIT THE DATA (LIKELIHOOD)**

Fit the data accounting for the various signal and background components



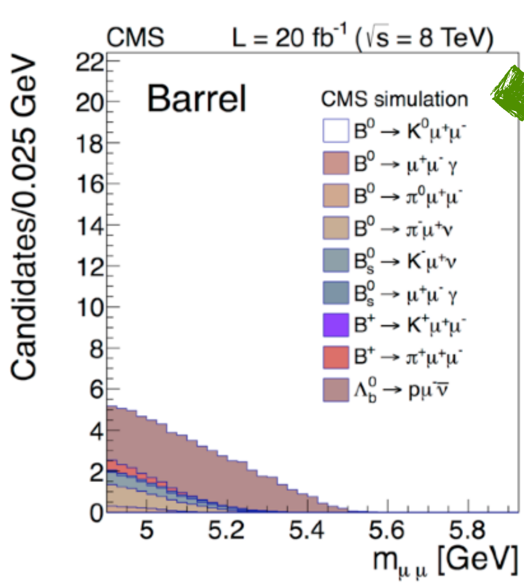
SEMILEPTONIC BKG

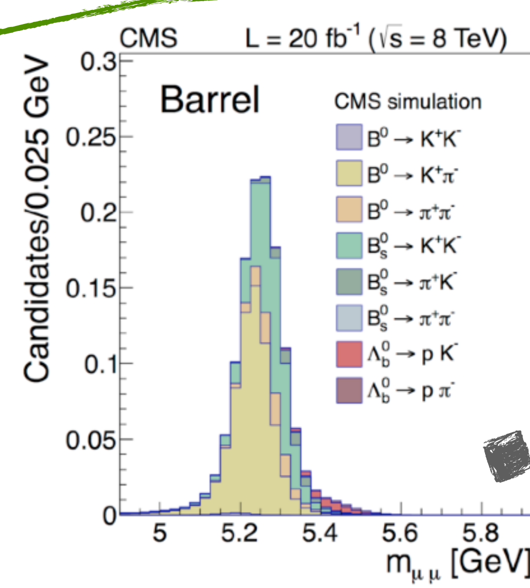
COMBINATORIAL BKG

PEAKING BKG

SIGNAL 1: $B_s \to \mu\mu$

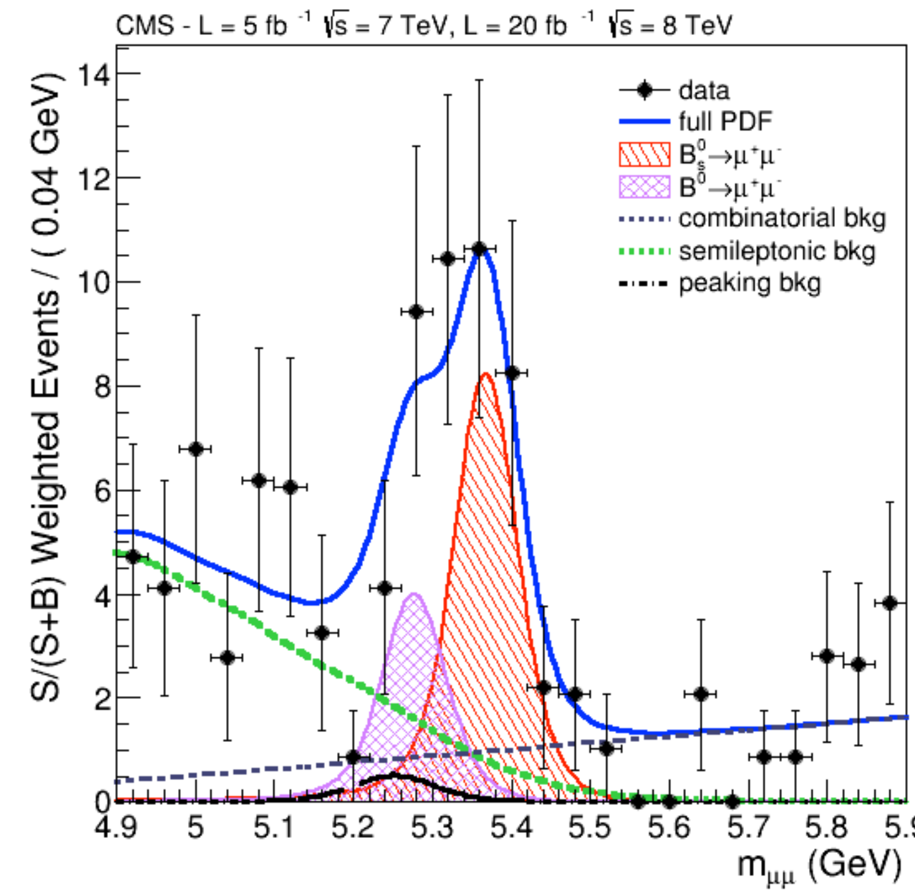
SIGNAL 2: $B^0 \to \mu\mu$



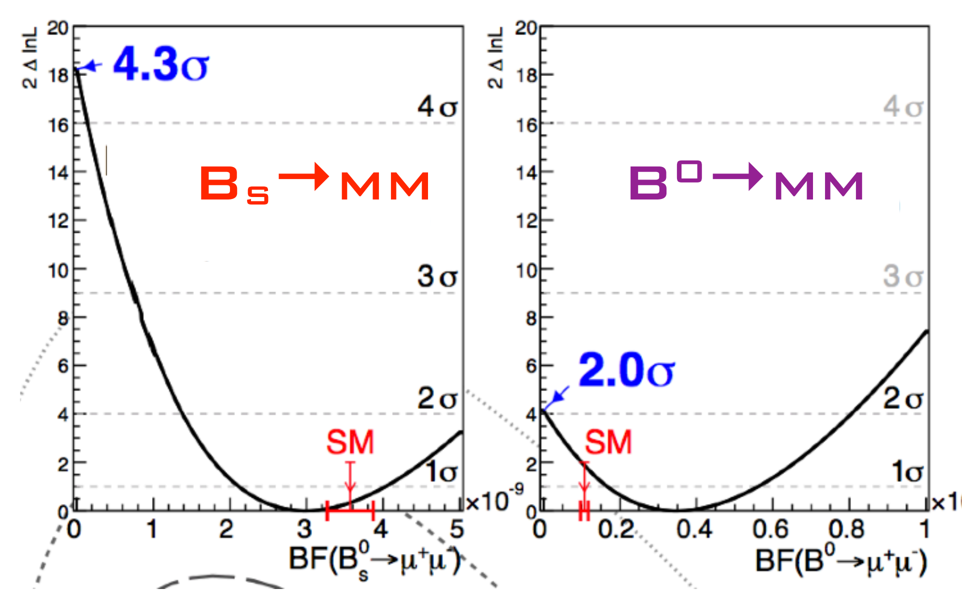


searching for an ultra-rare decay: B→μμ

1. ONLINE SELECTION (TRIGGER)
2. BLIND THE DATA (AVOID BIAS)
3. MULTIVARIATE SELECTION
4. FIT THE DATA (LIKELIHOOD)
5. **STATISTICAL SIGNIFICANCE**

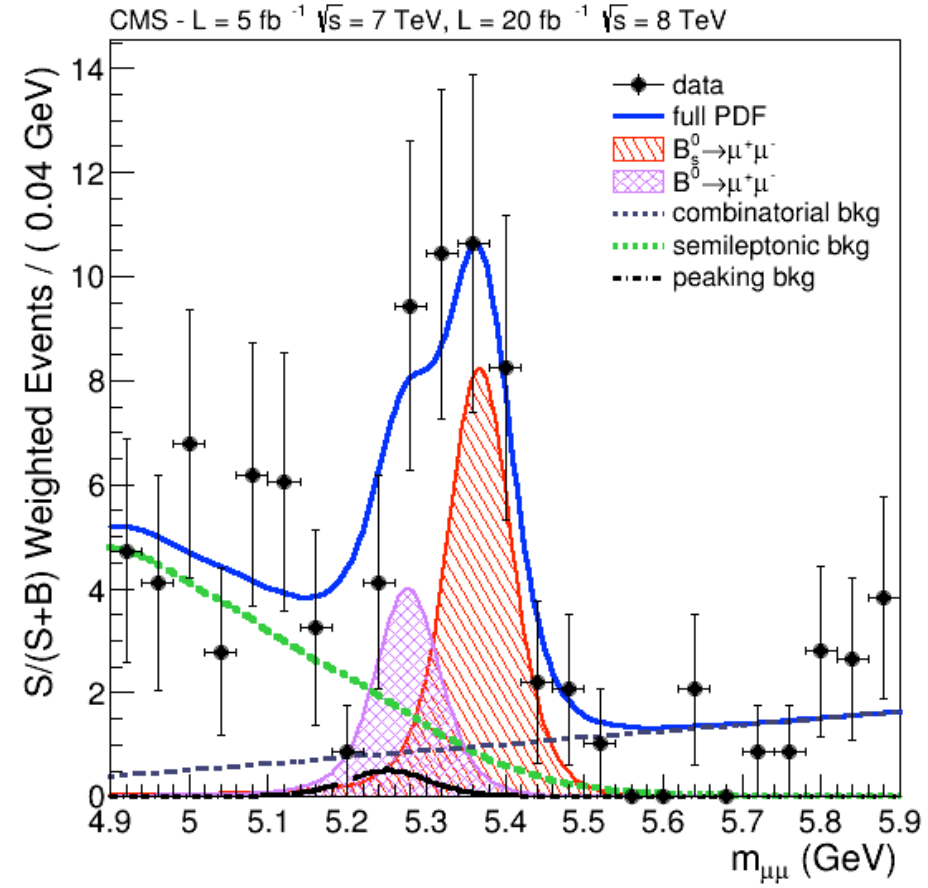


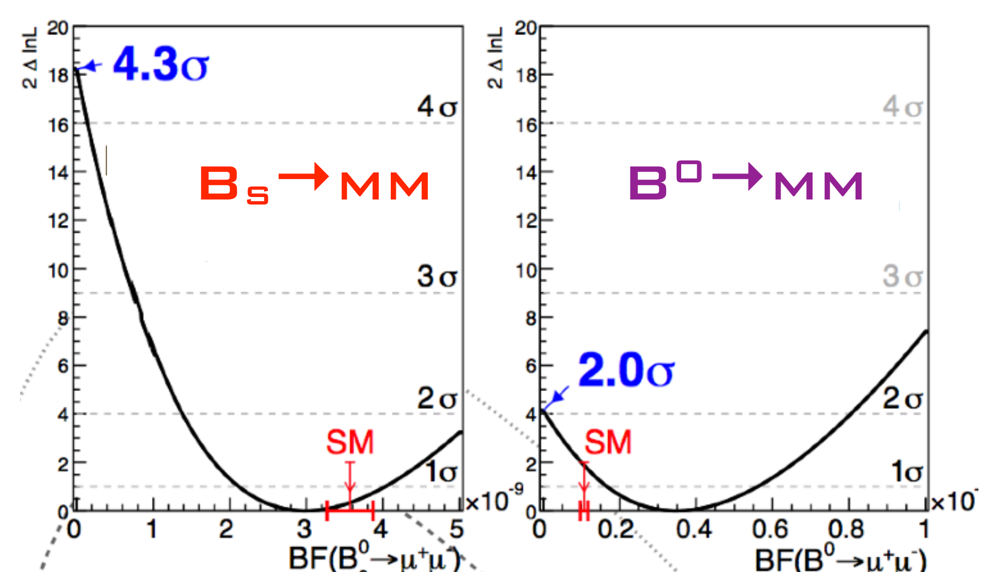
is the observed excess a genuine signal, or just a fluctuation of the background?



searching for an *ultra-rare* decay: B→μμ

1. ONLINE SELECTION (TRIGGER)
2. BLIND THE DATA (AVOID BIAS)
3. MULTIVARIATE SELECTION
4. FIT THE DATA (LIKELIHOOD)
5. STATISTICAL SIGNIFICANCE
6. EXTRACT MEASUREMENT

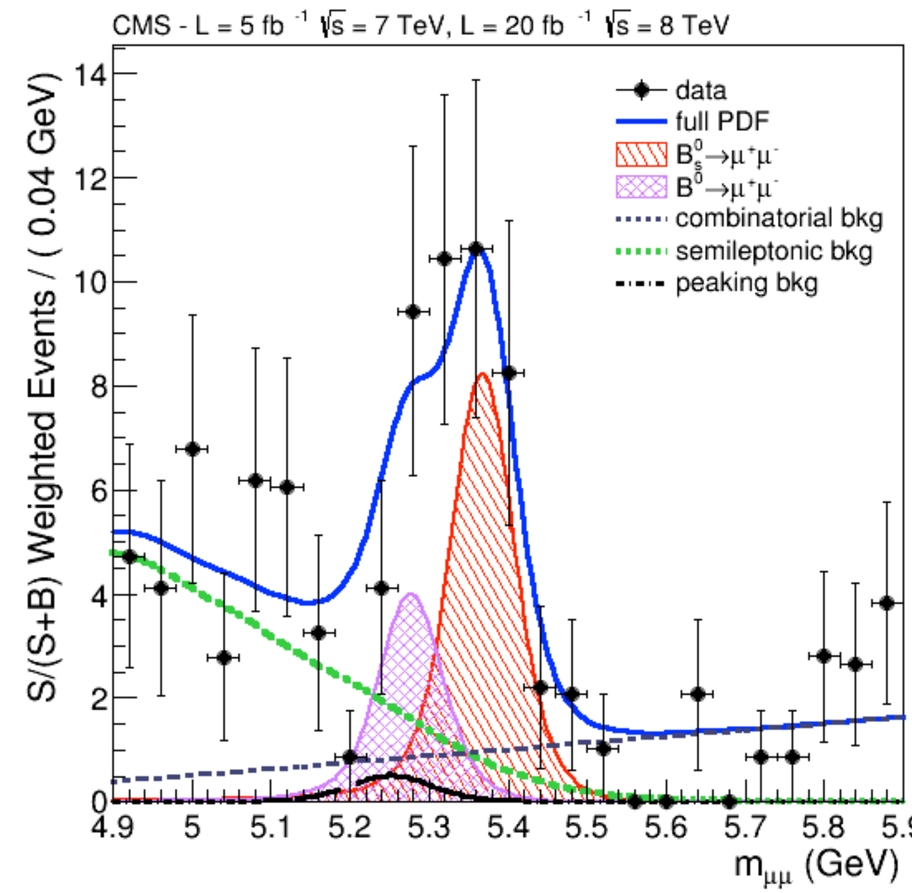




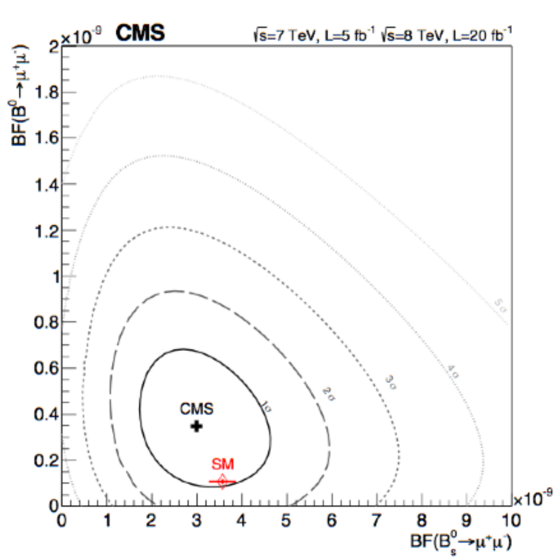
$$BR(B_s \to \mu\mu) = \left(3.0^{+0.9}_{-0.8}\ (\text{stat})^{+0.6}_{-0.4}\ (\text{syst})\right) \times 10^{-9}$$

searching for an *ultra-rare* decay: B→μμ

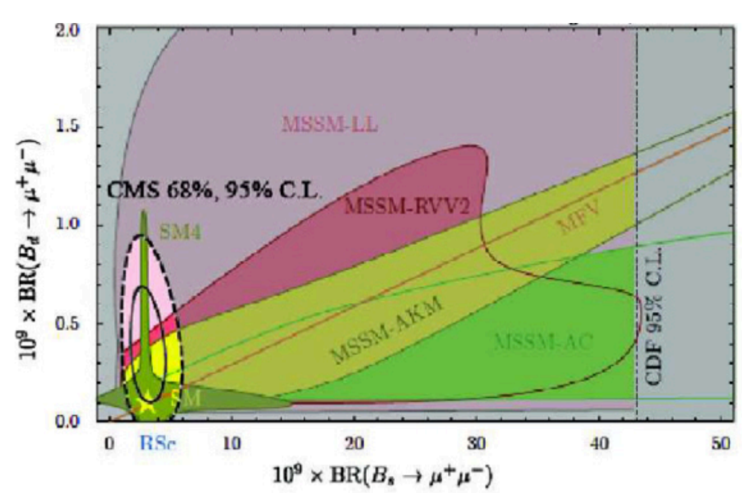
1. ONLINE SELECTION (TRIGGER)
2. BLIND THE DATA (AVOID BIAS)
3. MULTIVARIATE SELECTION
4. FIT THE DATA (LIKELIHOOD)
5. STATISTICAL SIGNIFICANCE
6. EXTRACT MEASUREMENT
7. **COMPARE TO THEORY**

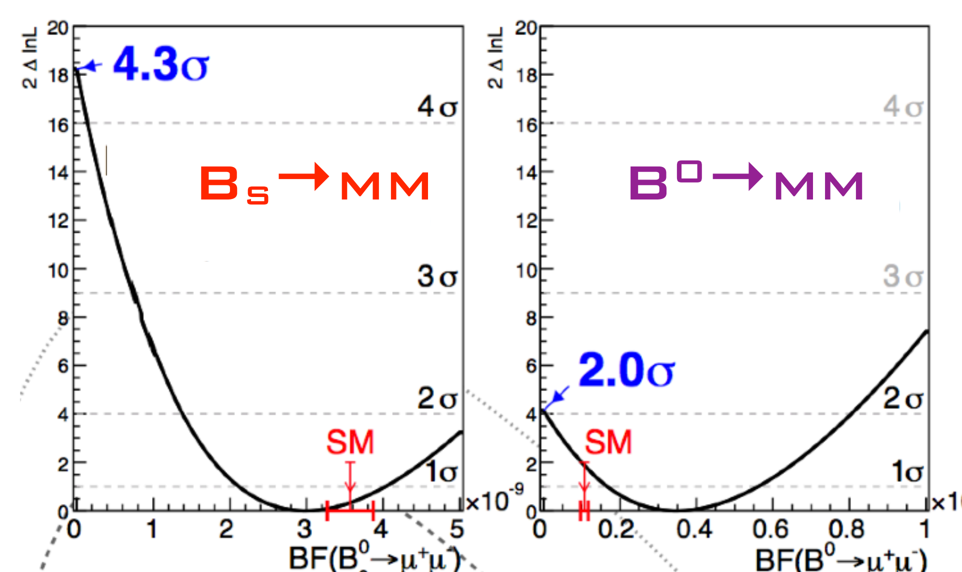


THE SM...



AND BEYOND





$$BR(B_S \to \mu\mu) = \left(3.0^{+0.9}_{-0.8}\ (\text{stat})^{+0.6}_{-0.4}\ (\text{syst})\right) \times 10^{-9}$$

summary

- broad and successful flavor physics programme at the LHC
- advancements and breakthroughs in the different subject areas
  - rare decays, CP violation, production, spectroscopy, QGP hard probes
- no definitive individual discrepancies wrt the Standard Model found, yet
  - several ~3σ level tensions will be pursued and clarified in next LHC runs
- Largest "coherent" set hinting (3-5σ) BSM effects in present data
  - Provided in tests of lepton flavor universality and other flavor anomalies
- flavor physics program complementary to direct searches
  - into the high luminosity LHC era (HL-LHC) into next decade
  - in the quest for finding evidence of New Physics and setting its scale
  - to differentiate amongst NP models and characterize their flavor structure

[extra]

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)

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

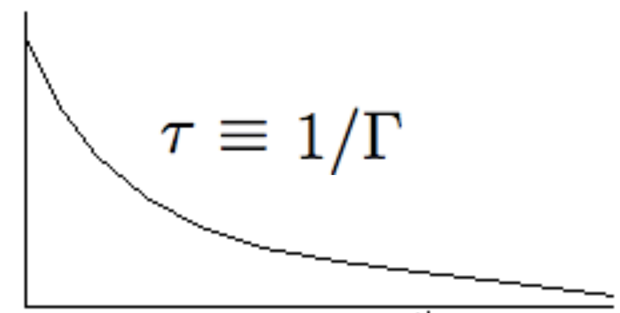
Lorentz boost factor

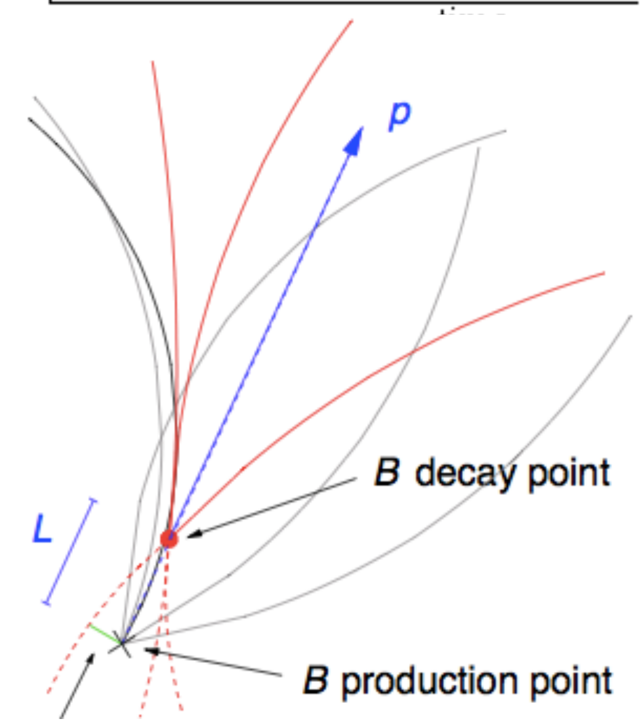
$$\mathcal{H} = m - \frac{i}{2}\Gamma$$

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

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

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





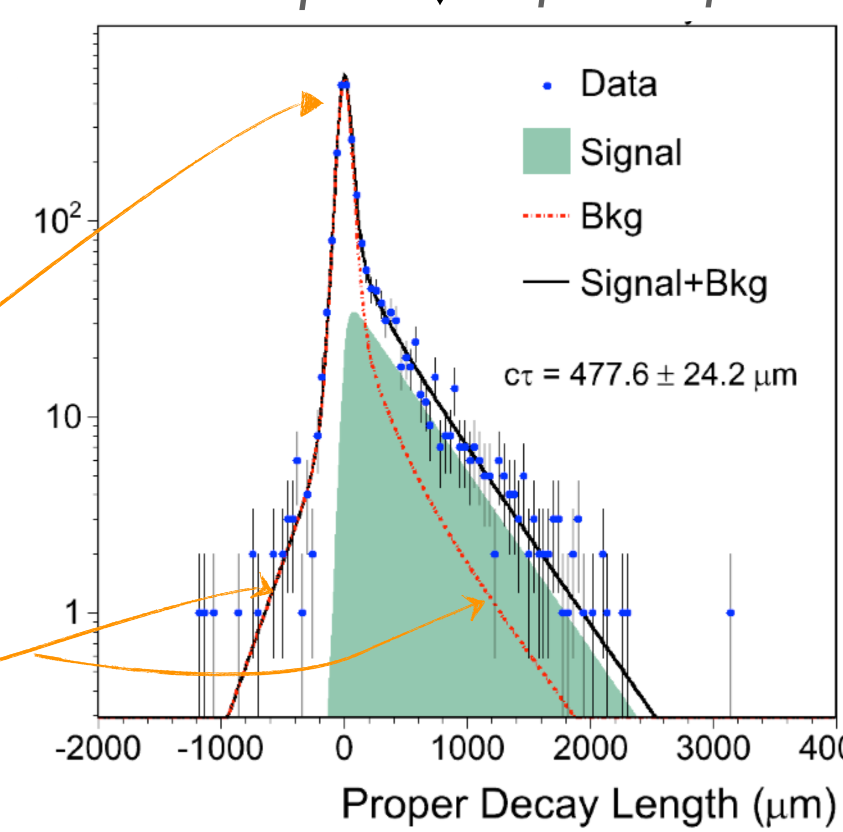
lifetime modeling

signal model $\rightarrow$ $$L(t|\sigma_t,\tau) = \underbrace{\frac{1}{\mathcal{N}}}_{\text{PDF normalization}} \cdot \left[\underbrace{\frac{1}{\tau} e^{-\frac{t}{\tau}} \theta(t)}_{\text{theory model}} \otimes \underbrace{G(t;\sigma_t)}_{\text{t-resolution function}} \right] \cdot \underbrace{\mathcal{E}(t)}_{\text{t-acceptance function}}$$

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

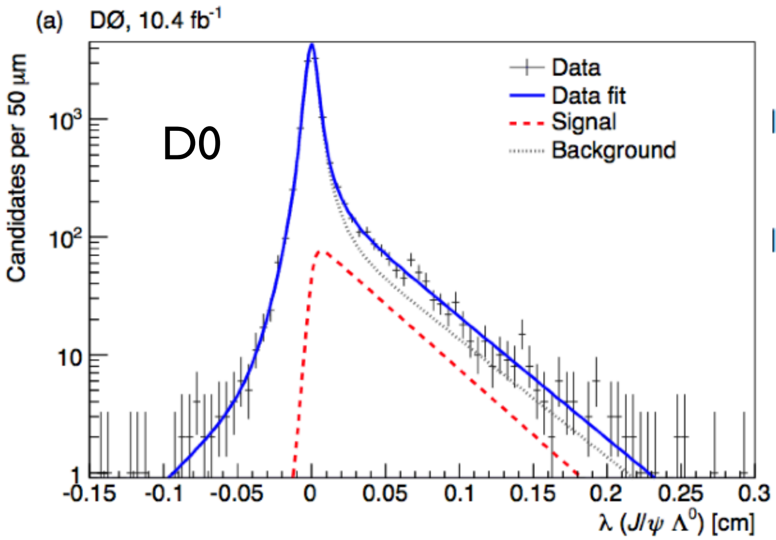
$$\sigma_t \mapsto S_t \cdot \sigma_t$$

example ⇓ *lifetime fit*



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

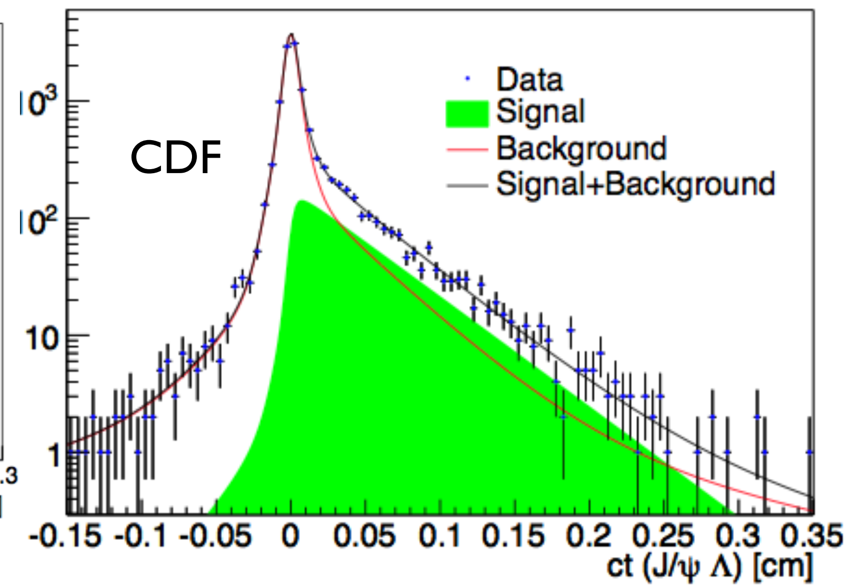
b-hadron lifetimes



PRD 85 (2012) 112003

$\tau(B^0)$ = 1.508 ± 0.025 ± 0.043 ps

$\tau(\Lambda_b)$ = 1.303 ± 0.075 ± 0.035 ps



PRL 106 (2011) 121804

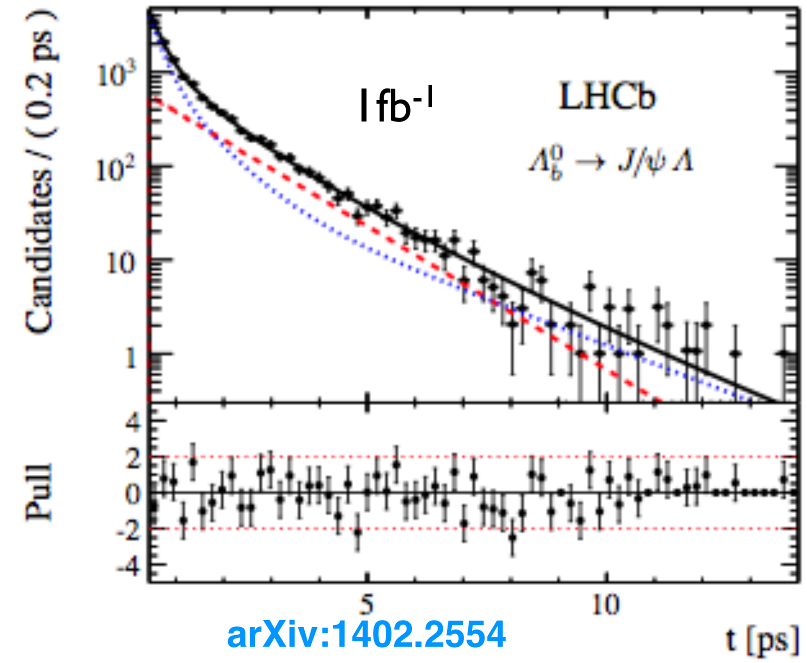
$\tau(B^+)$=1.639 ± 0.009 ± 0.009 ps

$\tau(B^0)$=1.507 ± 0.010 ± 0.008 ps

$\tau(\Lambda_b)$=1.537 ± 0.045 ± 0.014 ps

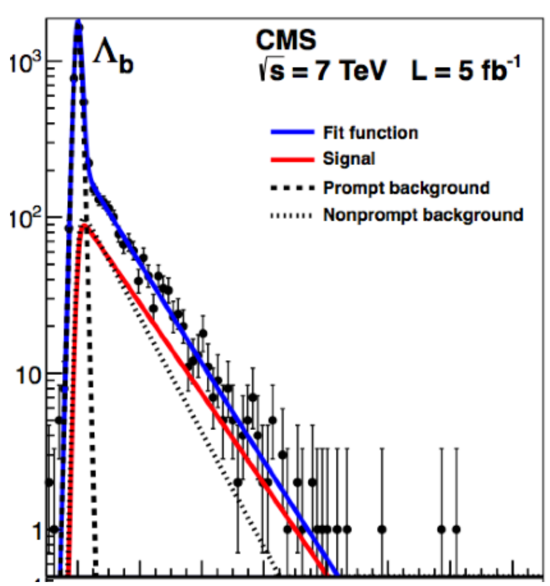
$\tau(B^+)/\tau(B^0)$=1.088 ± 0.009 ± 0.004

$\tau(\Lambda_b)/\tau(B^0)$=1.020 ± 0.030 ± 0.008



arXiv:1402.2554

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

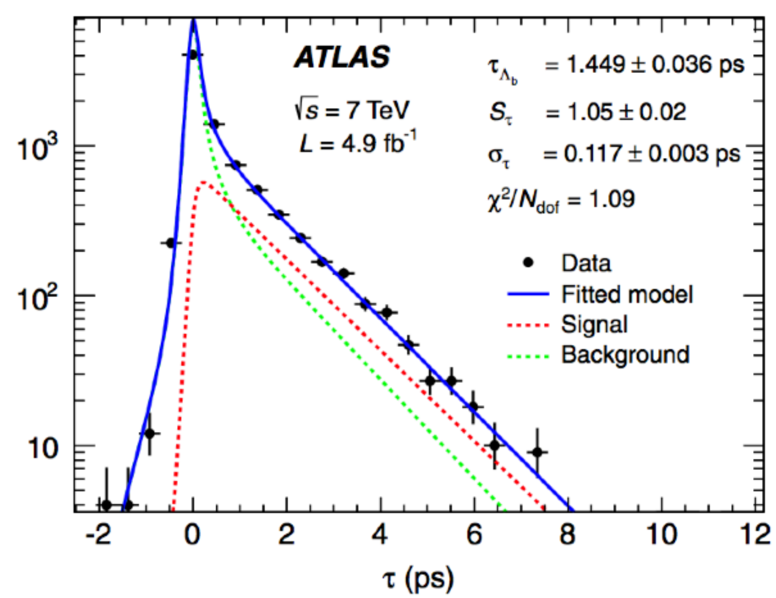


JHEP 07 (2013) 163

$\tau(\Lambda_b)$ =
1.503 ± 0.052 ± 0.031 ps

PRD 87 (2013) 032002

$\tau(\Lambda_b)$ =
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

[extra]

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

$$\begin{aligned} |P_L\rangle &= p\,|P^0\rangle + q\,|\bar{P}^0\rangle \\ |P_H\rangle &= p\,|P^0\rangle - q\,|\bar{P}^0\rangle \end{aligned} \qquad \text{with} \quad |p|^2 + |q|^2 = 1$$

- 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

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

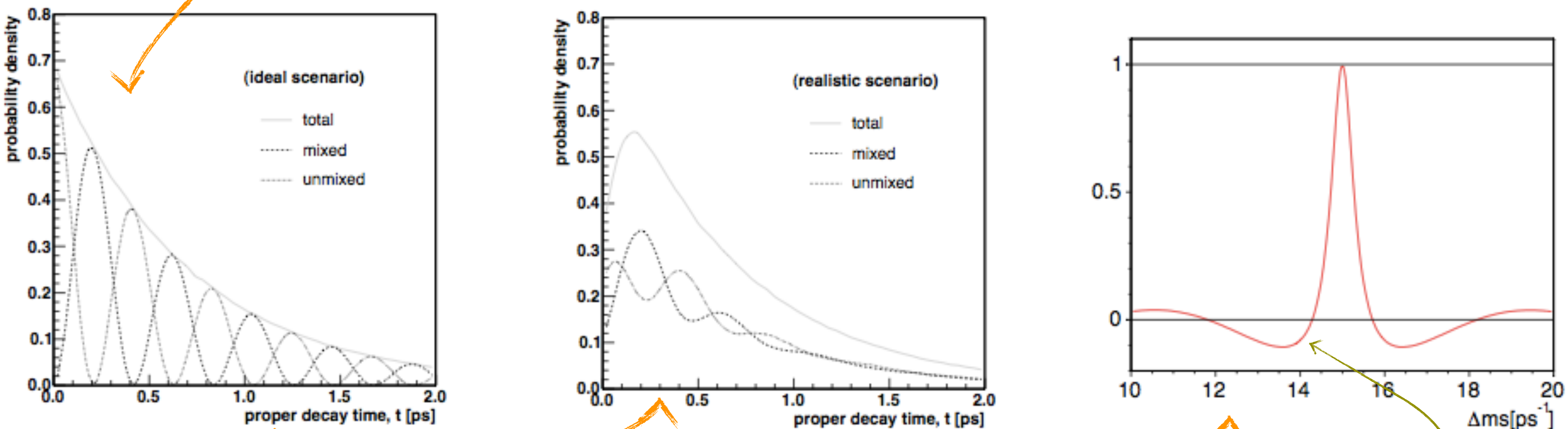
  - with $\Delta\Gamma \equiv \Gamma_L - \Gamma_H$ and $\Delta m \equiv m_H - m_L$
- neglecting CPV in mixing (i.e. p/q=1) and $\Delta\Gamma$, the mixing probability is:

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

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



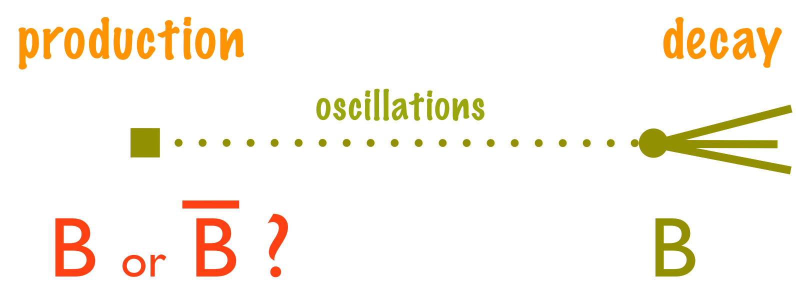
t-resolution, t-bias, dilution

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



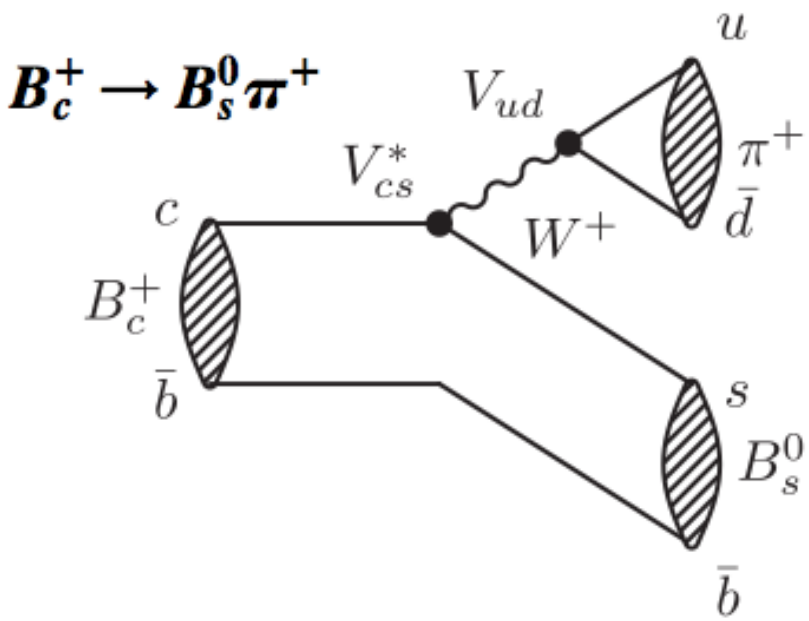
- (let ‘flavor’ here refer to the particle and antiparticle state)
- flavor at decay time:
  - trivially given by the charge of the decay products, if using flavor specific final states
  - (e.g. final flavor given by pion charge in $B_s \rightarrow D_s^- \pi^+$ *vs* $\underline{B_s} \rightarrow D_s^+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

how may it be determined ??

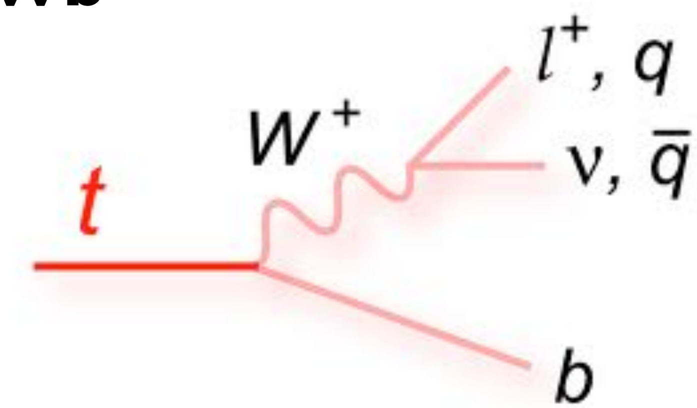
Exercise: think about it before resuming discussion in next 2 slides

how to tag?

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



t→Wb

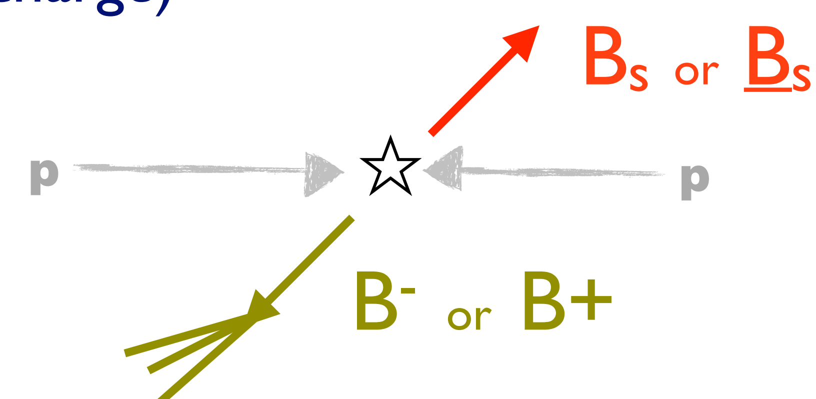


  - the initial B flavor (b or $\underline{b}$) could be inferred from the decay products of the heavier, parent state, eg from the charge of the pion in the examples

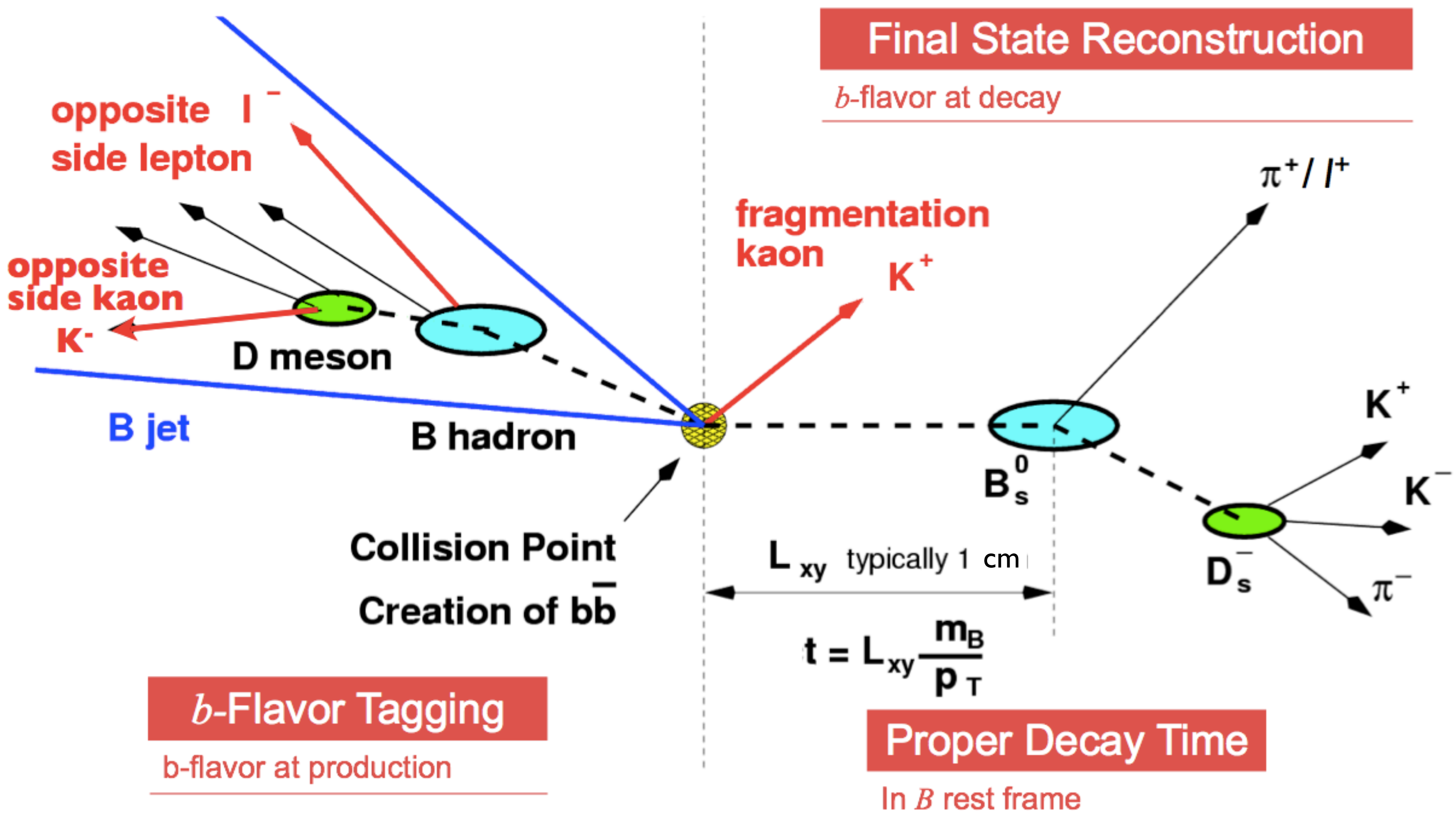
- attempt #2 : make use of the other b quark (from the originally produced b$\underline{b}$ pair), by reconstructing the other b-hadron in the event, say $B^\pm \to J/\psi K^\pm$ (flavor given by the kaon charge)

  - 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

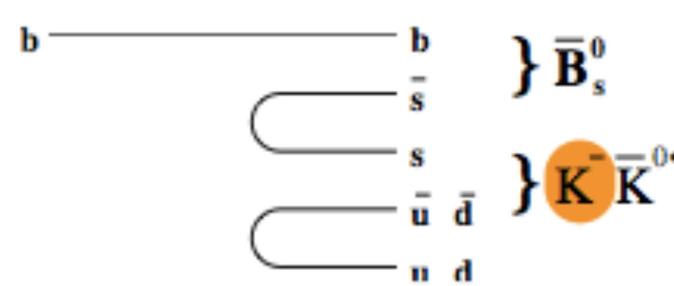


opposite-side tagging

- 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→l) is affected by sequential decays such as B→D→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

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

oscillation frequency w

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

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

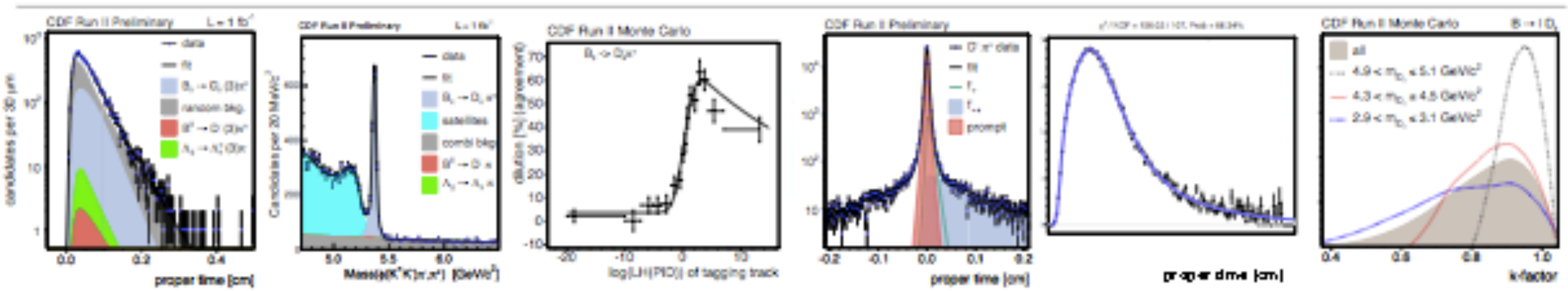
- tagging power εD^2 is given by the algorithm efficiency ε and dilution $D=(1-2w)^2$ where w is the wrong-tag fraction (i.e. probability algorithm gives wrong decision)
- it determines the effective statistical reduction of the sample size: $S \Rightarrow S\ .\ \varepsilon_{tag}D^2$

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)

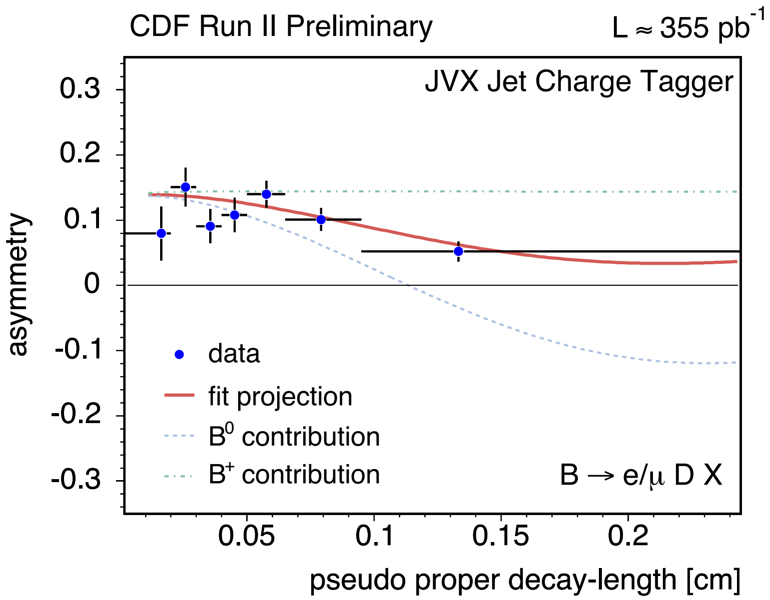
Frequency Δm_s

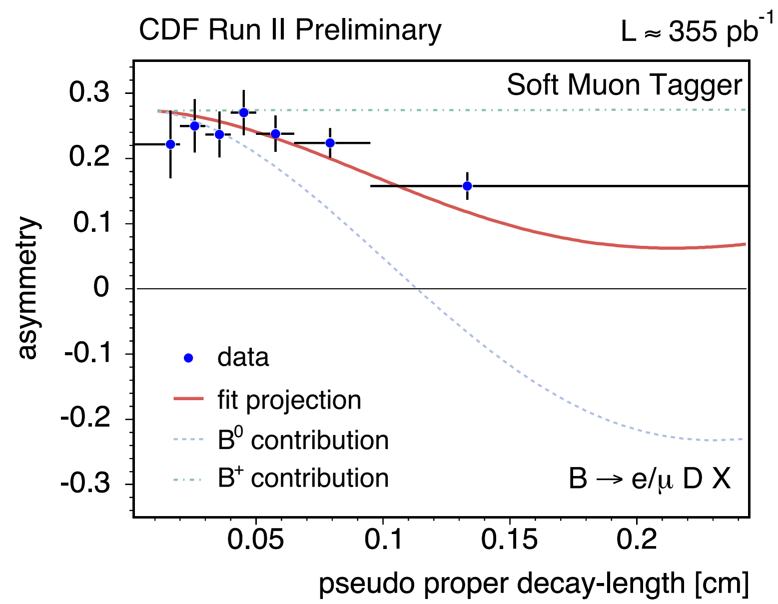
or

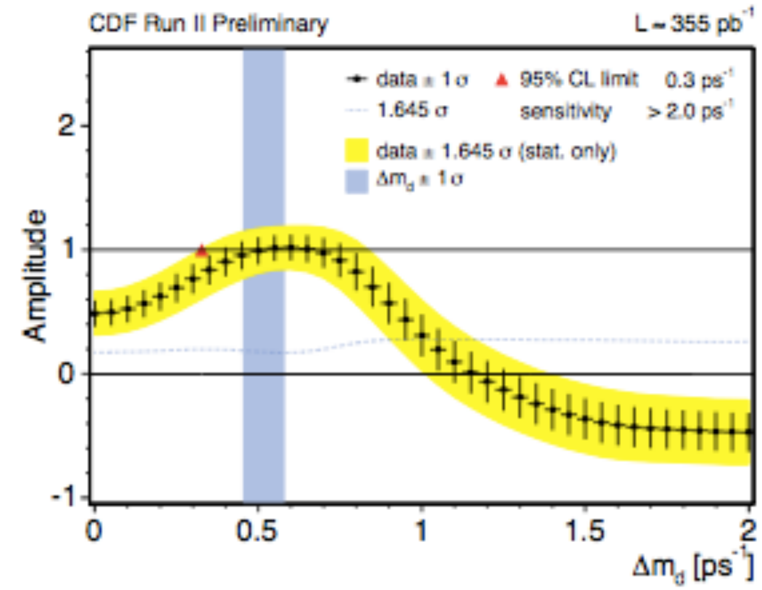
Amplitude (A, σ_A) for fixed Δm_s

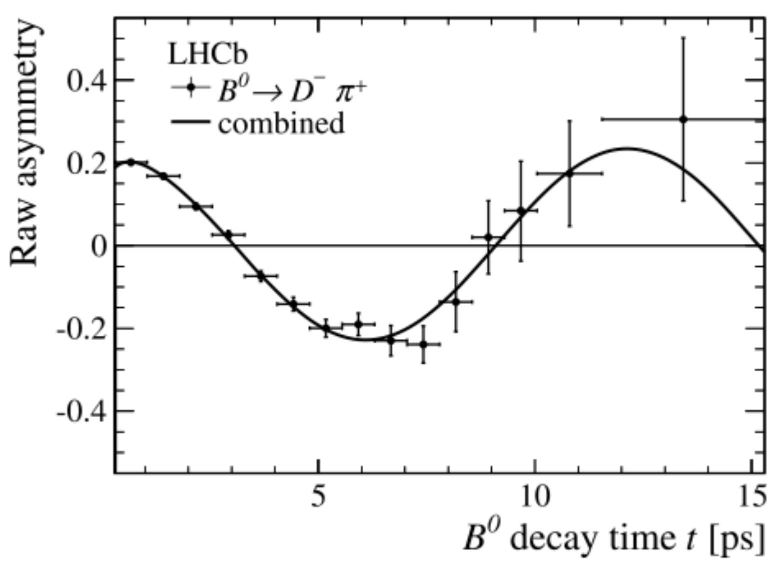
- ingredients: mass, proper time, proper time resolution, t-acceptance function, kinematic factor (for partially reco'd decays), and... flavor tagging

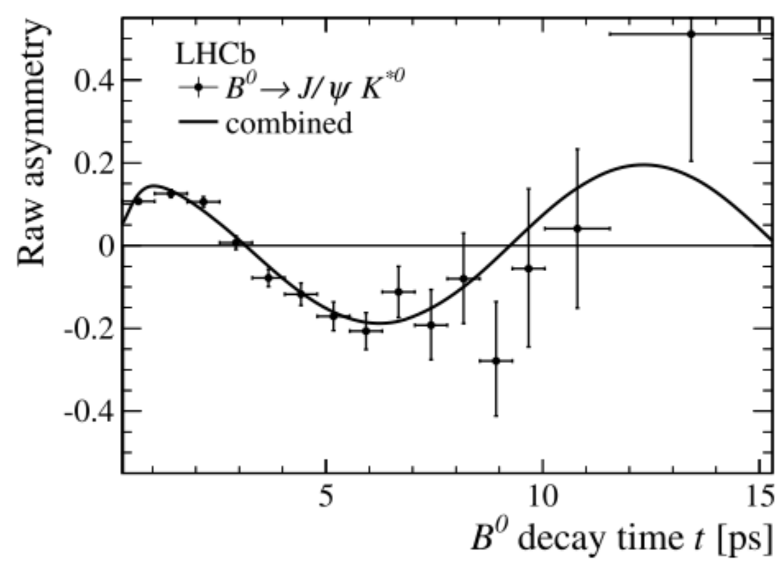
B_d mixing

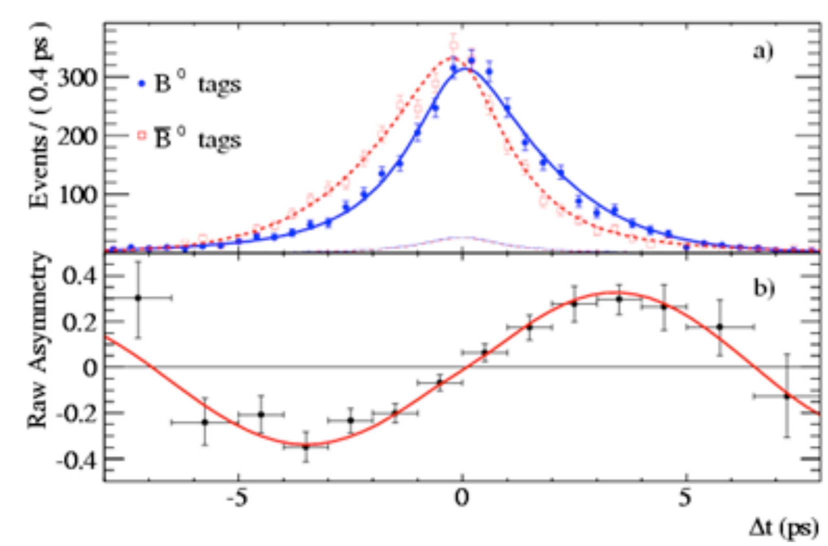






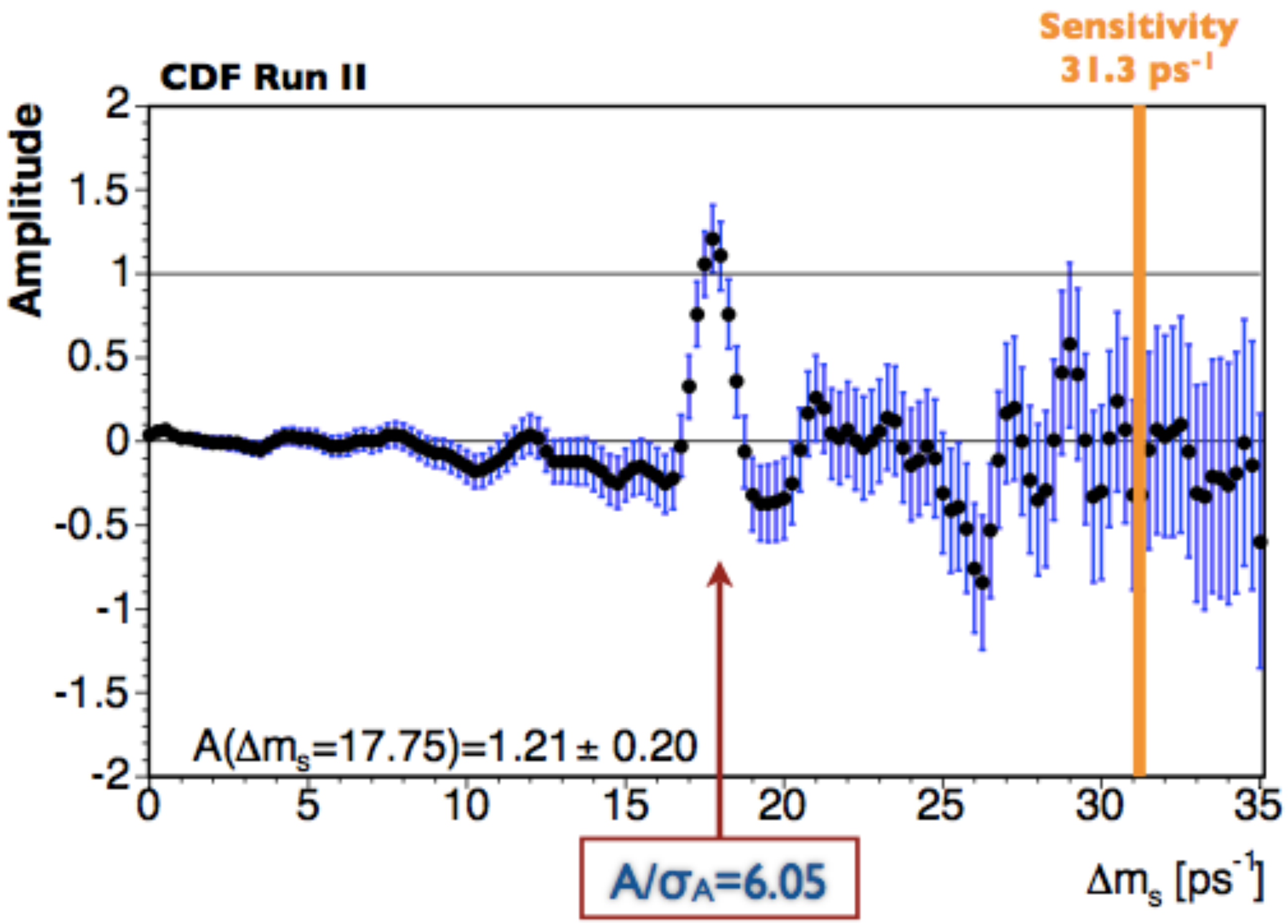


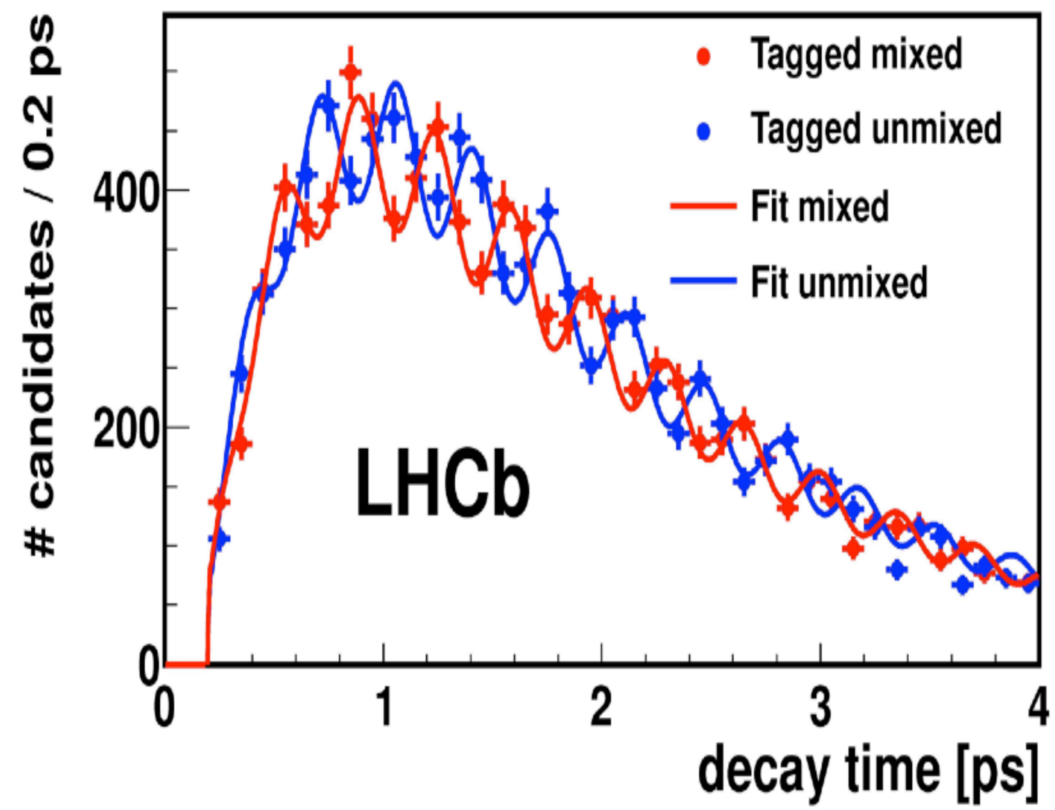




$$\Delta m_d = 0.5156 \pm 0.0051\ (\text{stat.}) \pm 0.0033\ (\text{syst.})\ \text{ps}^{-1}$$ (most precise measurement)

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

[extra]

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*≠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	$A_\mu(\vec{x},t)$	$-A^{\mu}(-\vec{x},t)$	$A^{\dagger}_{\mu}(\vec{x},t)$

	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

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

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

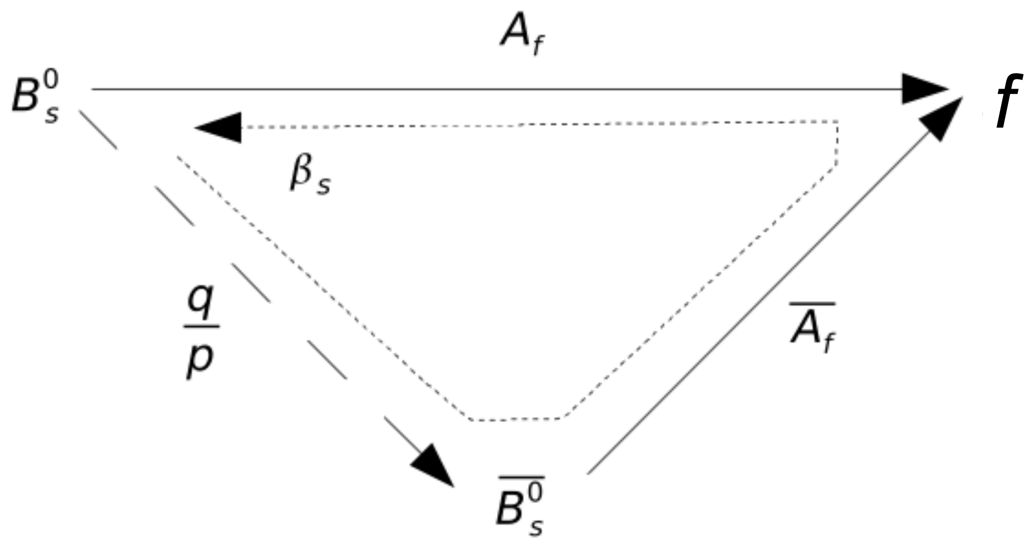
$$\Gamma_{\bar{P}^0\to f}(t) = |A_f|^2\left|\frac{p}{q}\right|^2 (1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t + D_f \sinh\frac{1}{2}\Delta\Gamma t - C_f\cos\Delta m t + S_f \sin\Delta m t\right)$$

- 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 $\quad \Gamma(P^0\to f) \neq \Gamma(\bar{P}^0\to\bar{f})$ $\quad \left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1$
  - 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

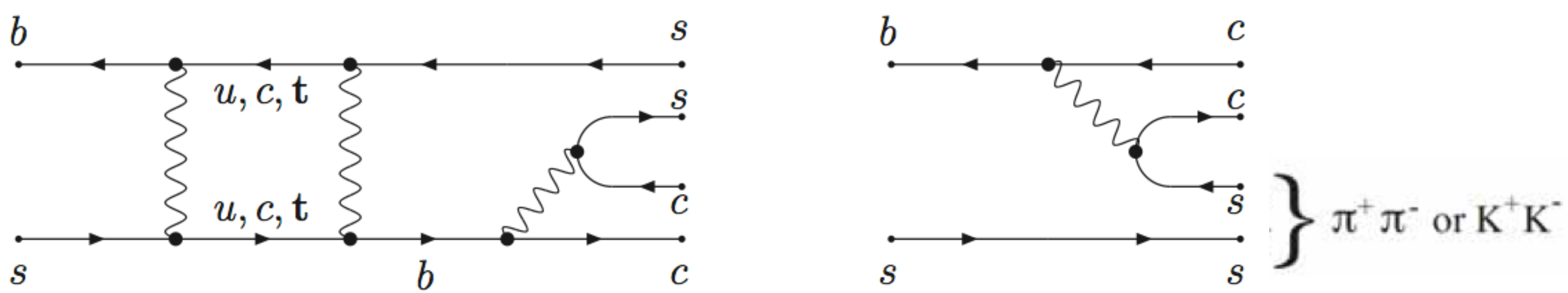
- defined by Im $\lambda_f \neq 0$
- available to modes in which both B and <u>B</u> decay to a same final state f
- example: $B_s \to J/\psi KK$, $J/\psi\pi\pi$



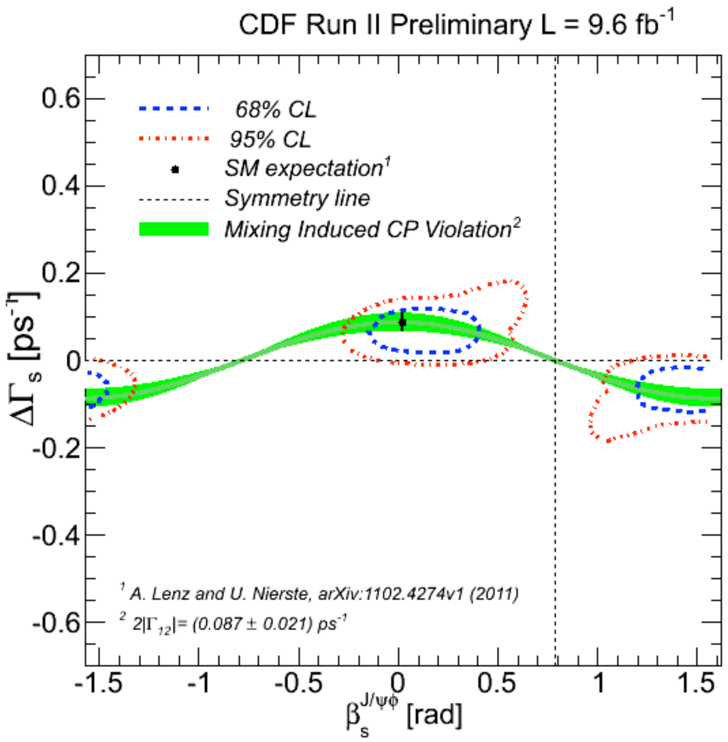
$$\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) = \mathcal{O}(\lambda^2)$$
$$2\beta_s \approx -\phi$$

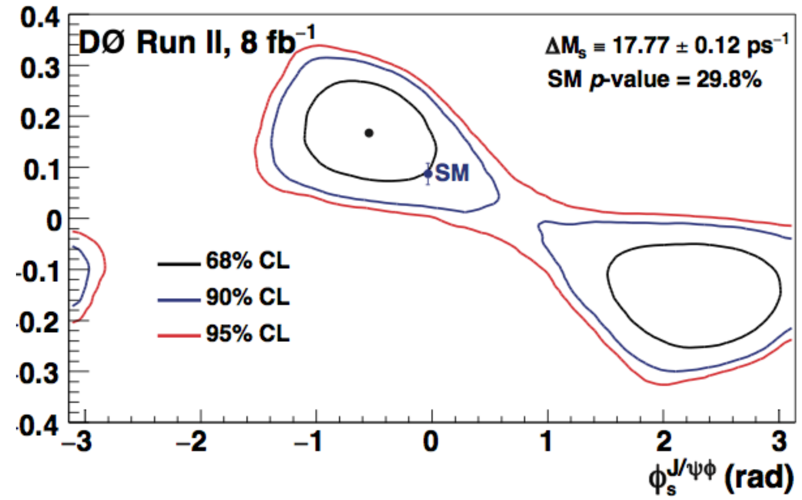
$\phi_s = \phi_s^{SM} + \phi_s^{NP}$

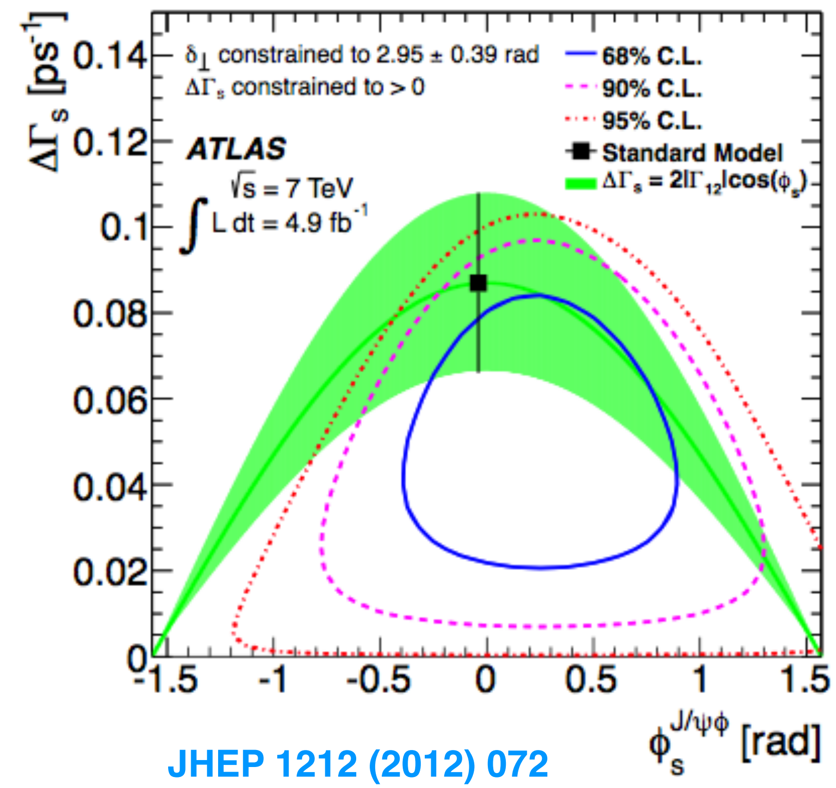
ϕ_{SM} ~ -0.04
NP can add large phases



$B_s \to J/\psi\Phi$







PRL 109 (2012) 171802, CDF full Run II

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

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

PRD 85 (2012) 032006, D0 8/fb

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

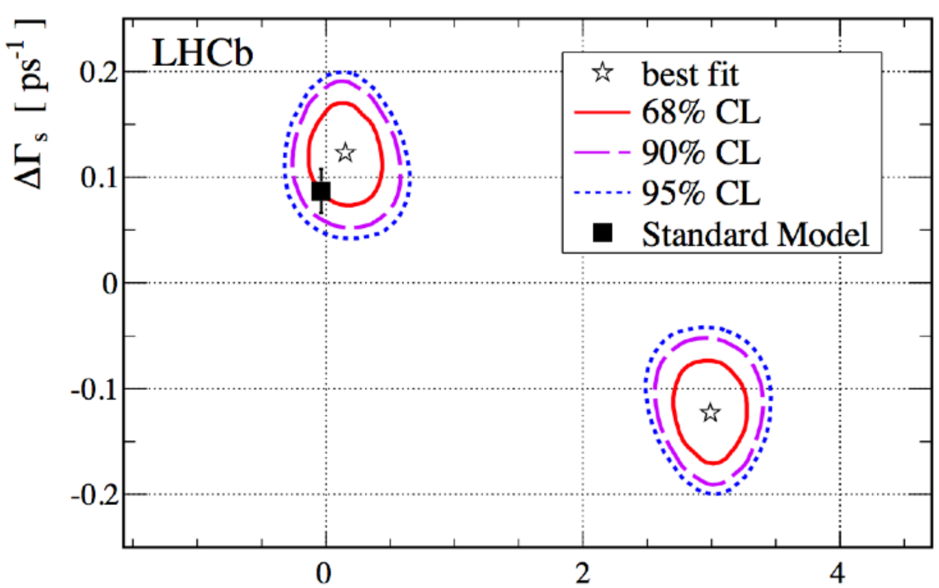
$\Delta\Gamma_s = 0.163^{+0.065}_{-0.064}\ \mathrm{ps}^{-1}$

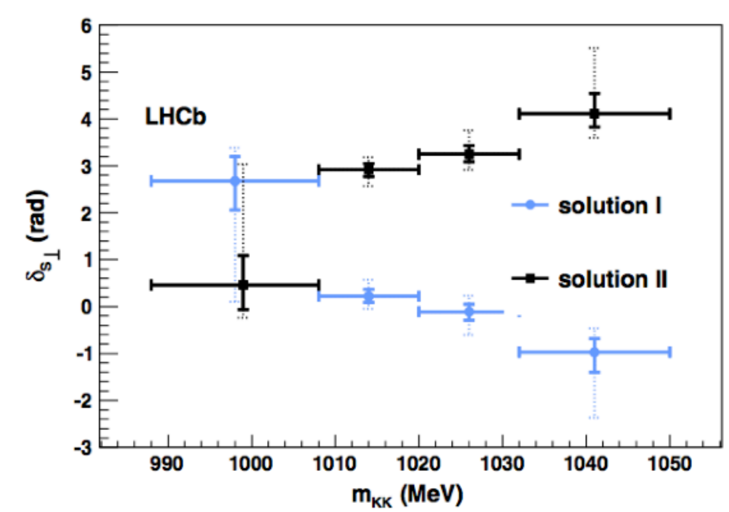
JHEP 1212 (2012) 072

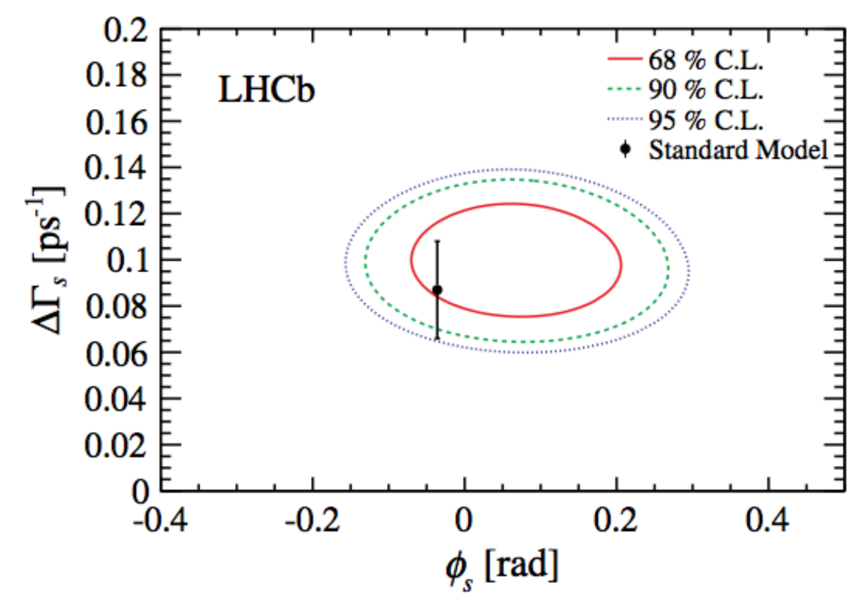
(see also ATLAS-CONF-2013-039)

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

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







PRL 108 (2012) 101803

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

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

PRL 108 (2012) 241801

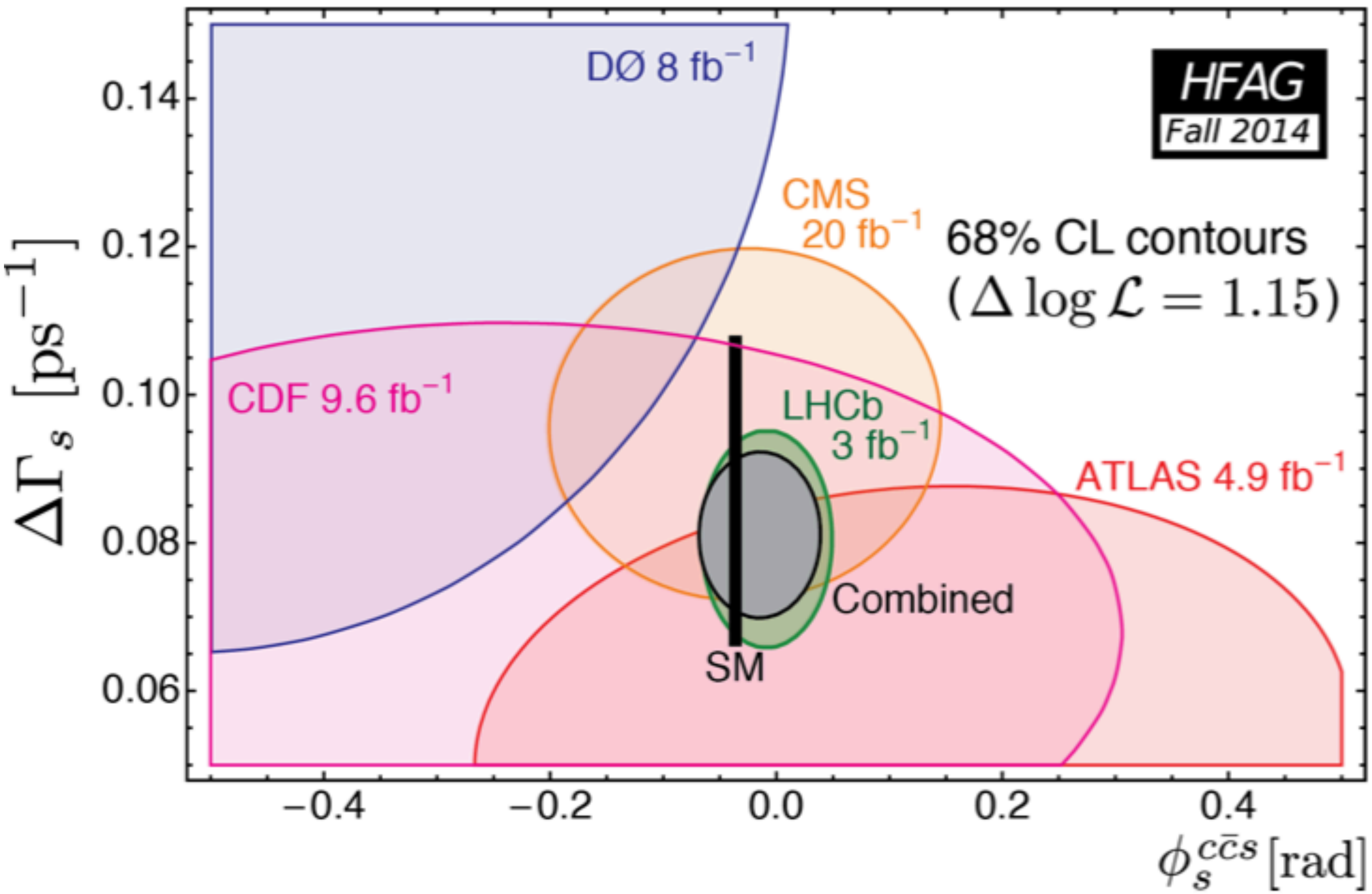
Removal of sign ambiguity: physical solution $\Delta\Gamma_s > 0$

PRD 87 (2013) 112010

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

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

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	$B_s \to J/\psi\phi$
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	$B_s \to J/\psi KK$, $J/\psi\pi\pi$, $\phi\phi$