Flavour Physics at hadron machines

LHCb

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Warning …

If the lectures are going to fast … Do not hesitate to stop me and ask questions !

Thanks to Yasmine Amhis and Mathieu Perrin-Terrin for the slides I have borrowed

Outline of the lectures

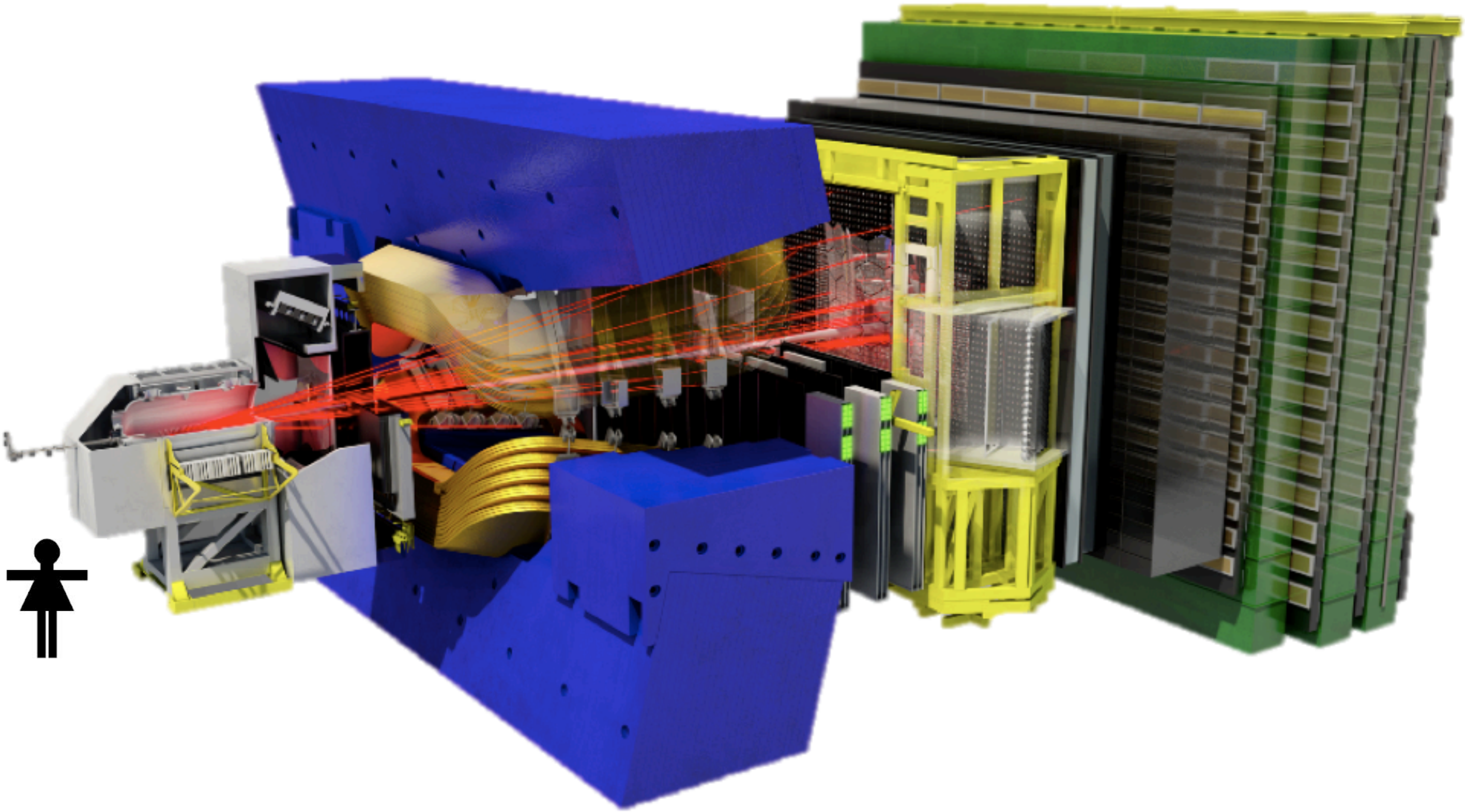
- Experimental setup
  - the LHCb detector and the trigger
  - data taking : specificities wrt ATLAS/CMS

- CP violation
  - an example of direct CP : γ measurement with DK
  - CP violation in mixing : A_{sl}
  - CP violation in the interference between mixing and decay : Φ_s

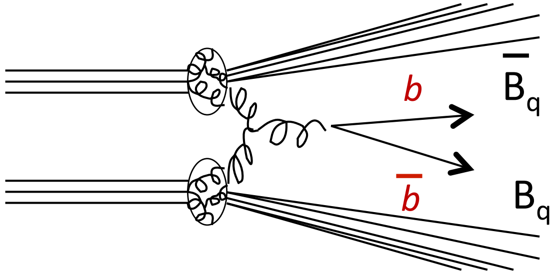
- Rare decays: FCNC
  - $B_s \rightarrow \mu\mu$
  - $B_d \rightarrow K^* \mu\mu$

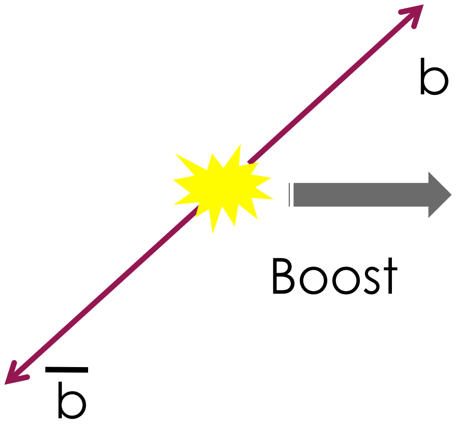
Experimental setup

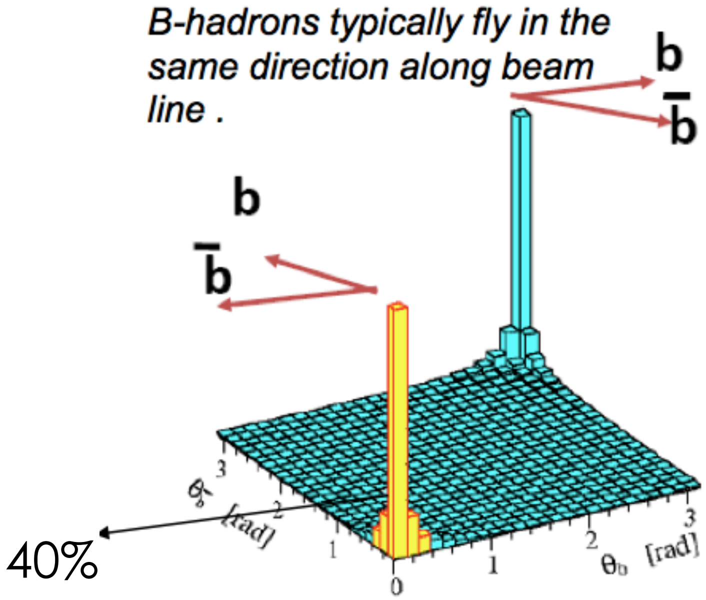
Experimental setup : the LHCb detector

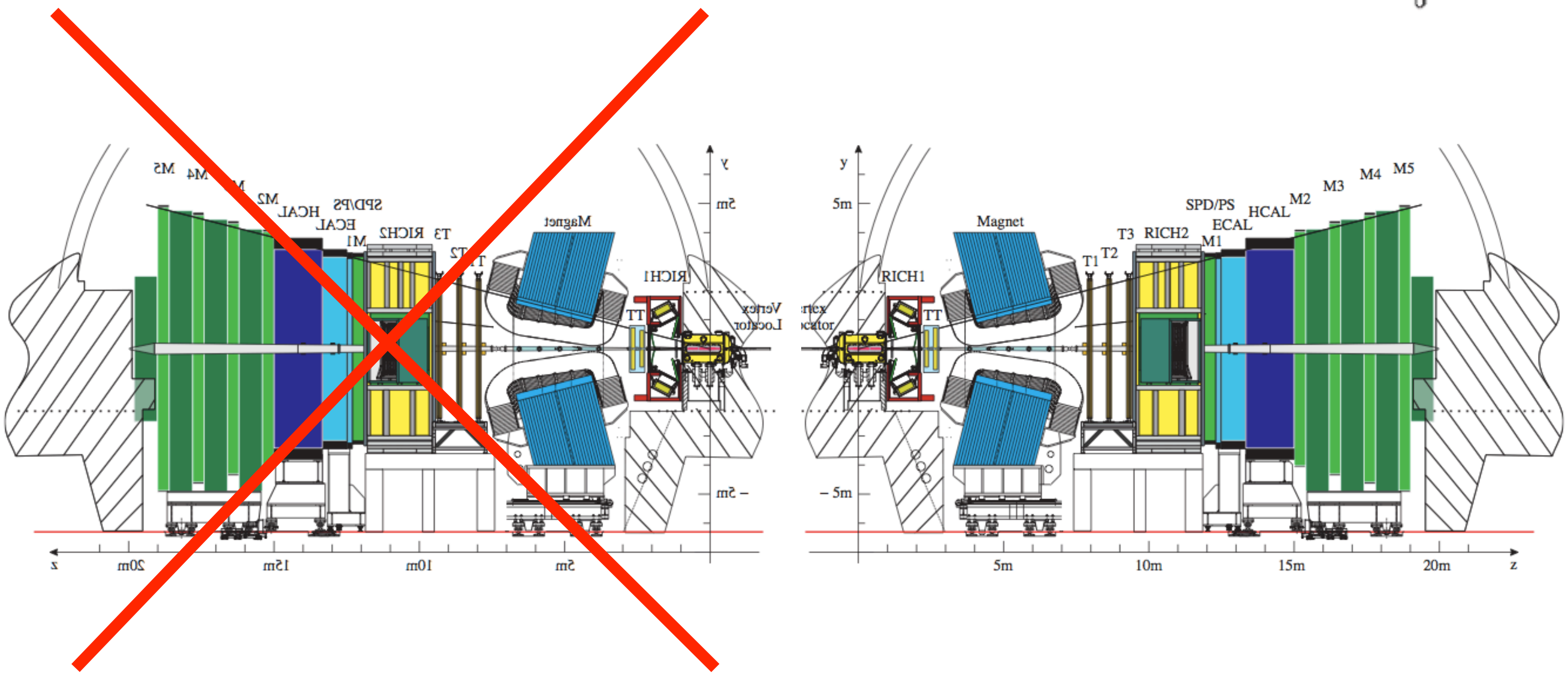


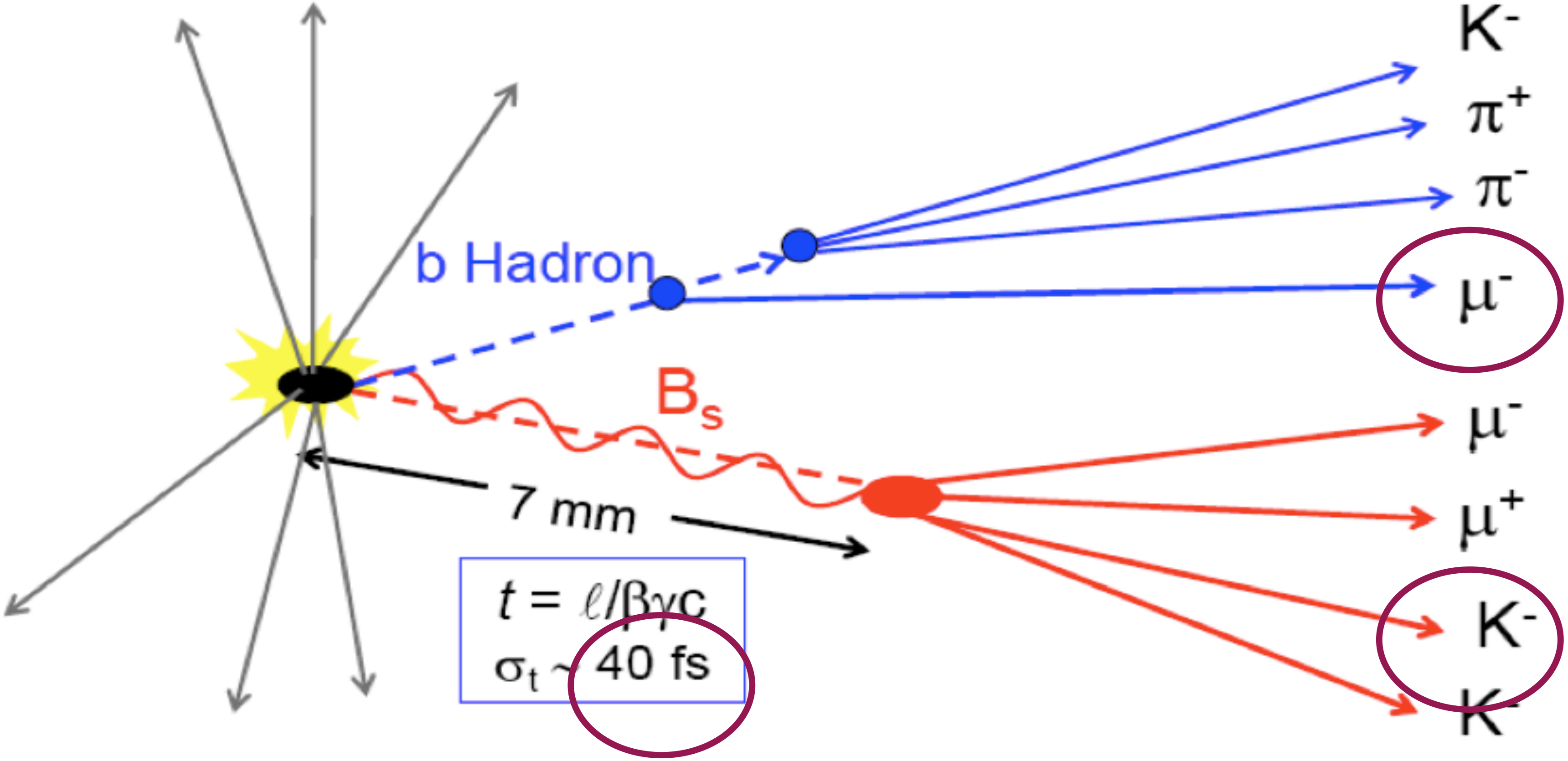
The 2 b-quarks are produced in the same direction along the beam axis











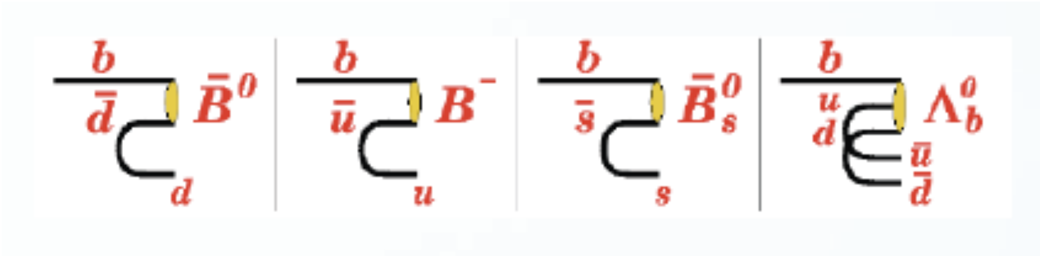
lifetime of a B : 1500 fs

Drives the detector design :

- ability to reconstruct the B vertex and to measure its decay time
- K/π discrimination
- μ identification

All this is similar to (super)B-Factories, but with different kinematic ranges

What is not similar to (super)-B-Factories :



All type of b-hadrons are produced at the LHC

Probability that a b quark hadronize a into a $B_{u,d,s}$ meson or a Λ_b baryon.

Important input for BR measurements since most of the measurements are done relative to another well known BR (B-Factories)

Cross sections at 14 TeV:

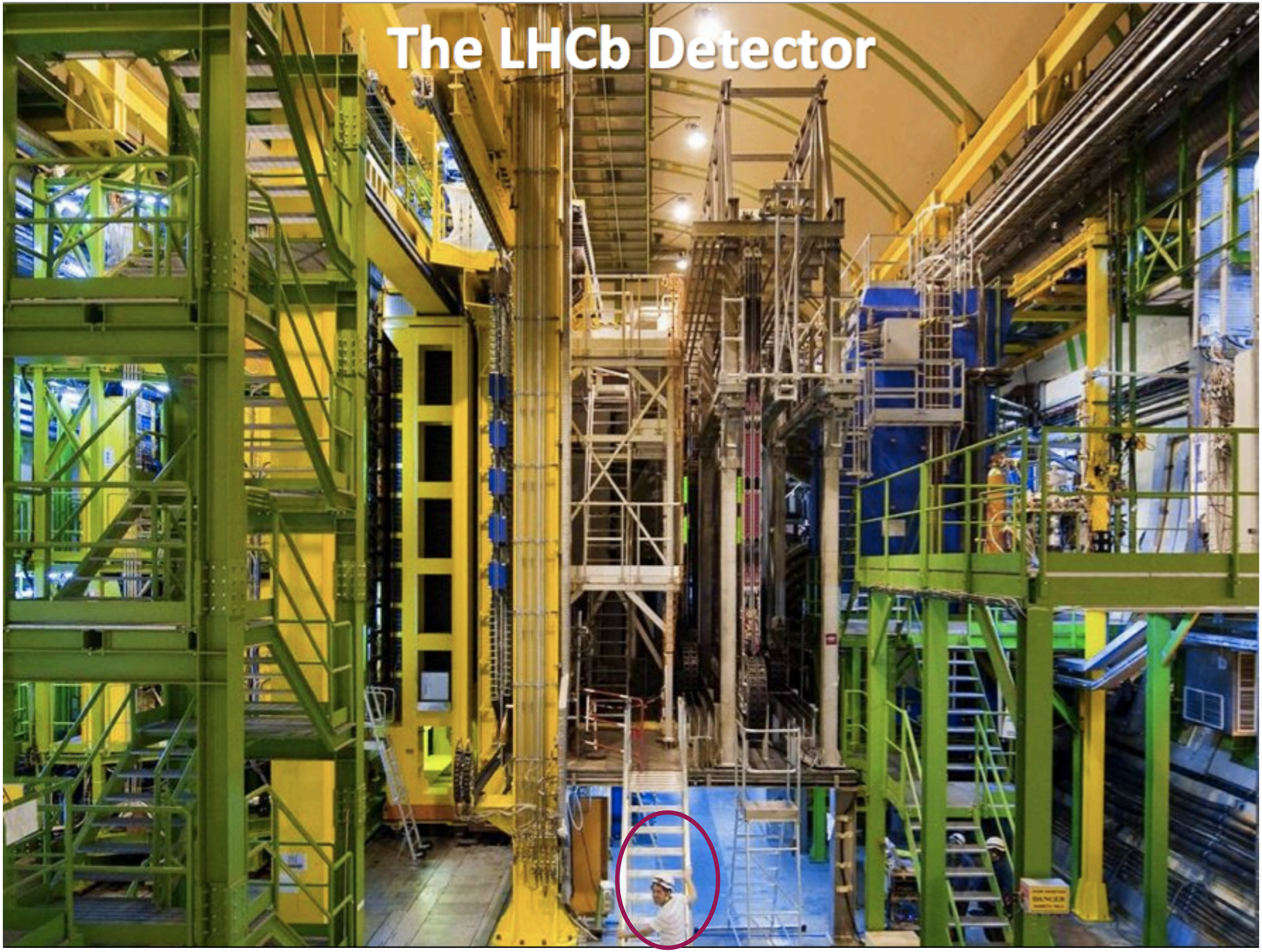
Total	100 mb
Inelastic	80 mb
$c\bar{c}$	3.5 mb
$b\bar{b}$	500 μb

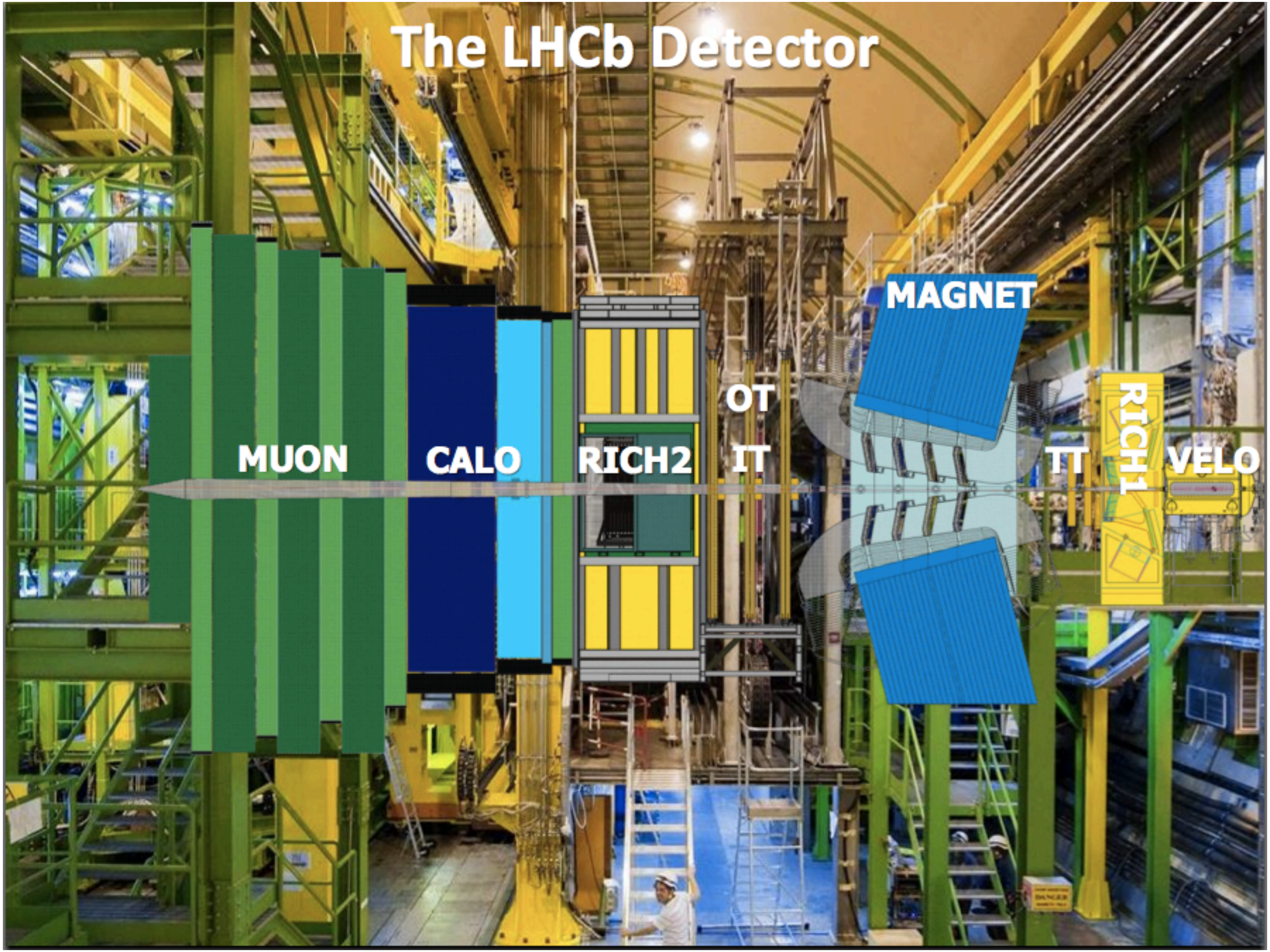
x 160

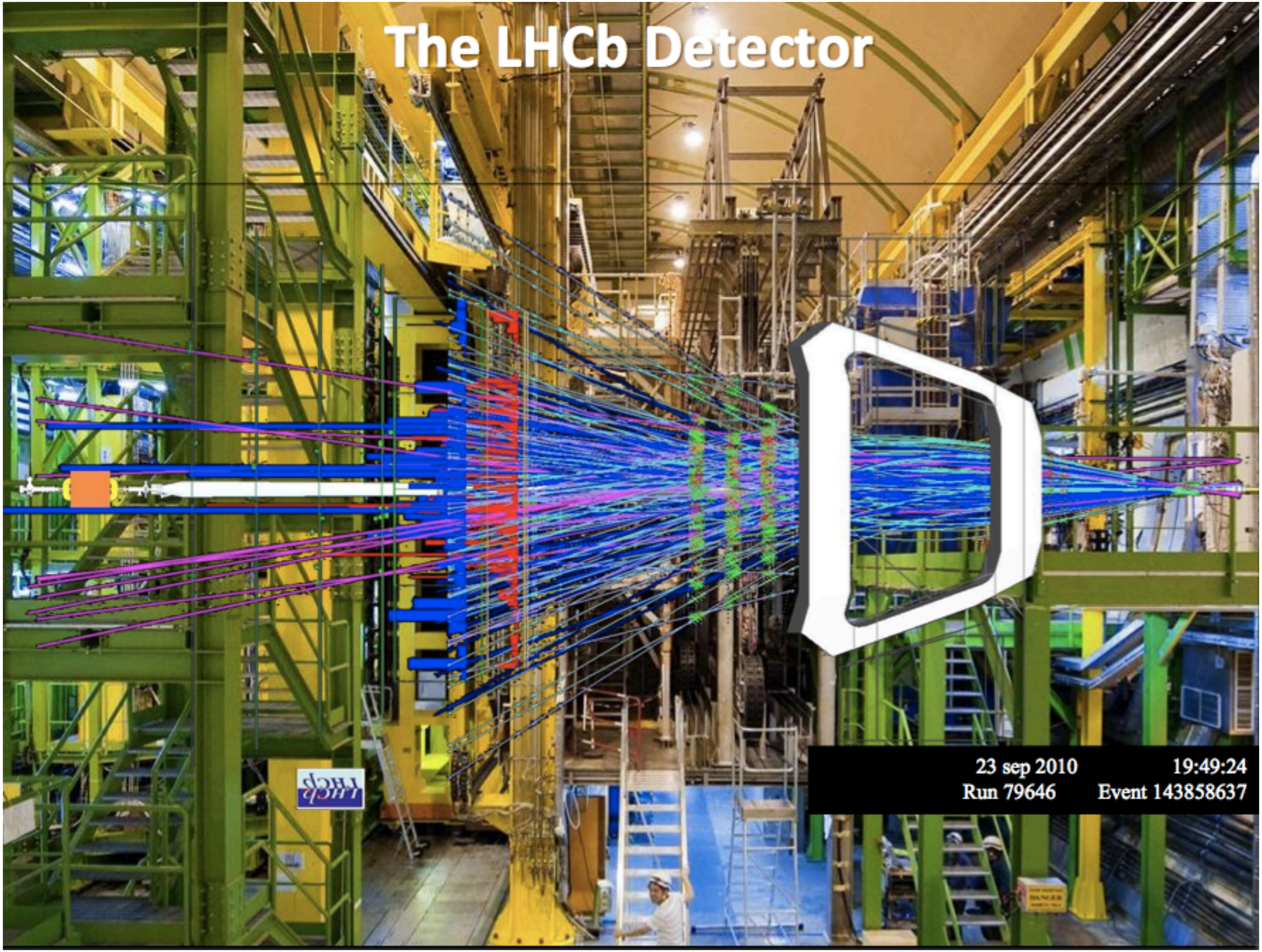
A trigger is needed to:
- reject the light flavours (u,d,s)
- keep only the interesting events

In 1 every 200 collisions a b-bbar pair is produced

The LHCb Detector



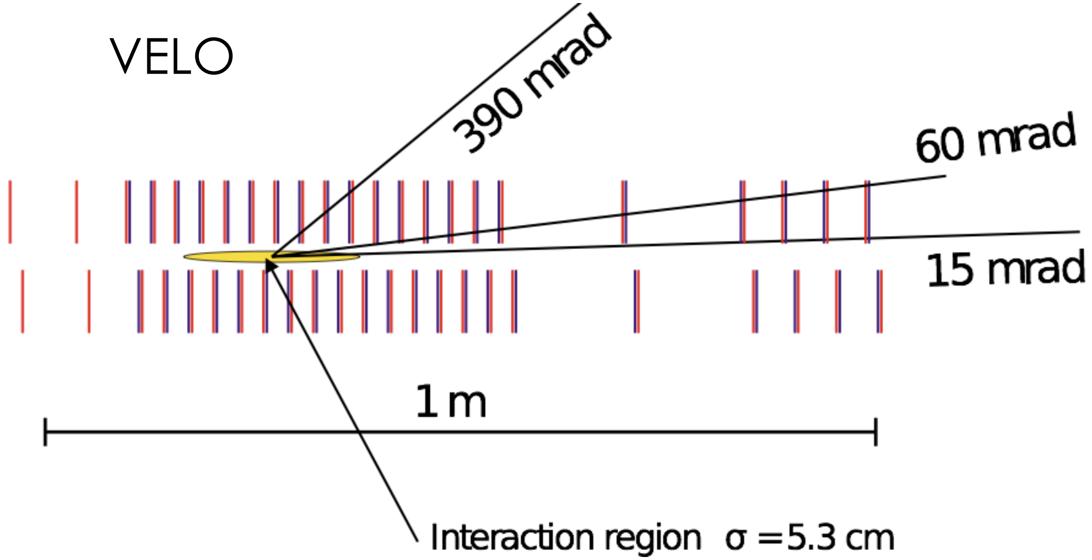

The LHCb Detector
MAGNET
OT
MUON
CALO
RICH2
IT
TT
RICH1
VELO


The LHCb Detector
23 sep 2010
19:49:24
Run 79646
Event 143858637

The tracking :

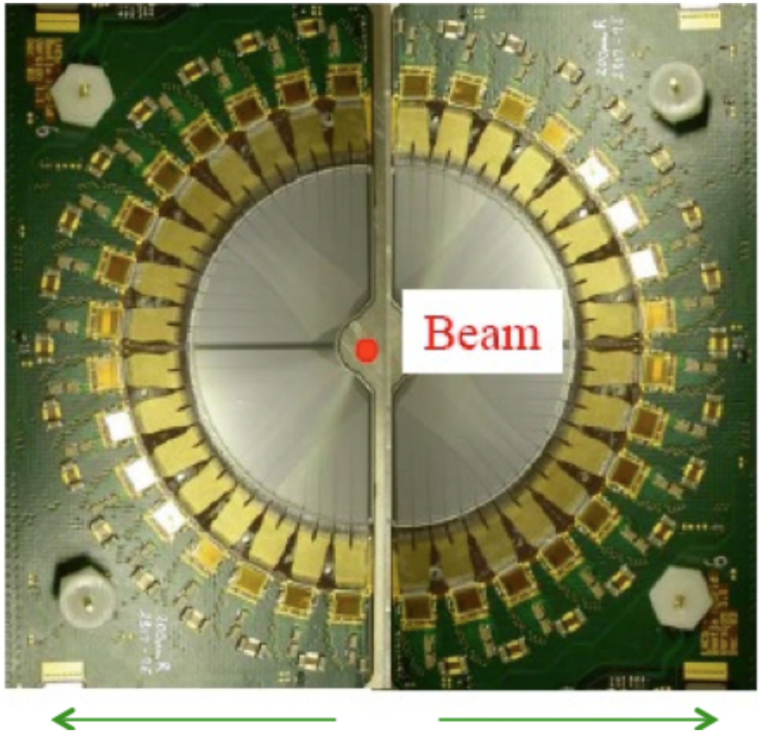
- Proper time measurement :
  - identify b-hadrons ($c\tau$ ~ 450 μm) , also in the trigger
  - perform time dependent analysis

VELO detector is crucial



21 modules r-φ sensors

Impact parameter resolution ~ 20-30 μ m

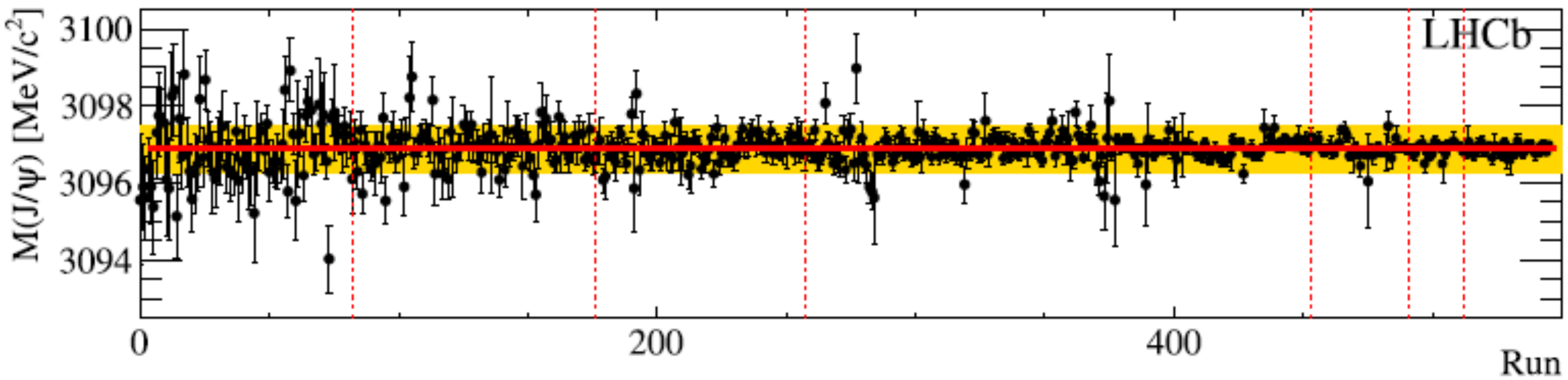


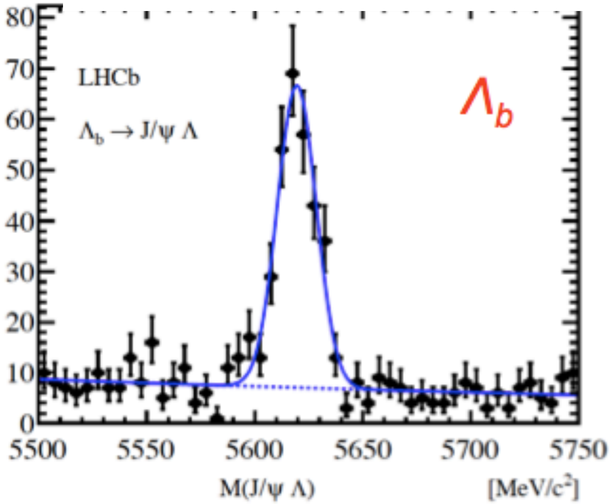
active zone : 8mm from the LHC beam : retractable

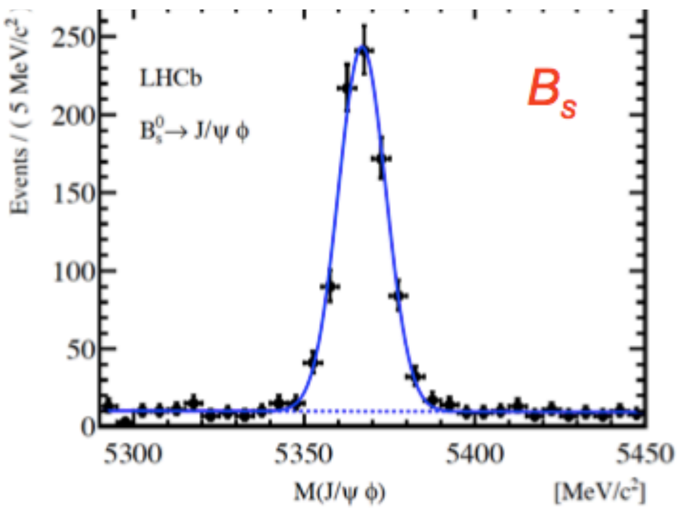
- Invariant mass measurement :
  - identify the signal (B_d and B_s are only 90 MeV apart)
  - separate signal from background

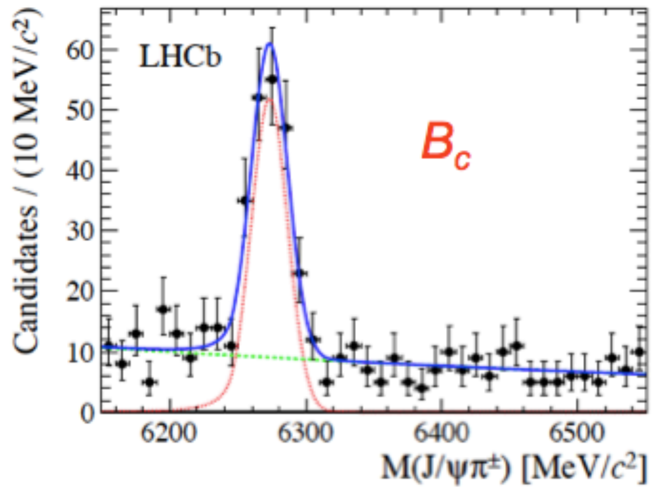
$\Delta p/p$ ~ 0.4 %

tracking performances : resolution + calibration of the mass scale







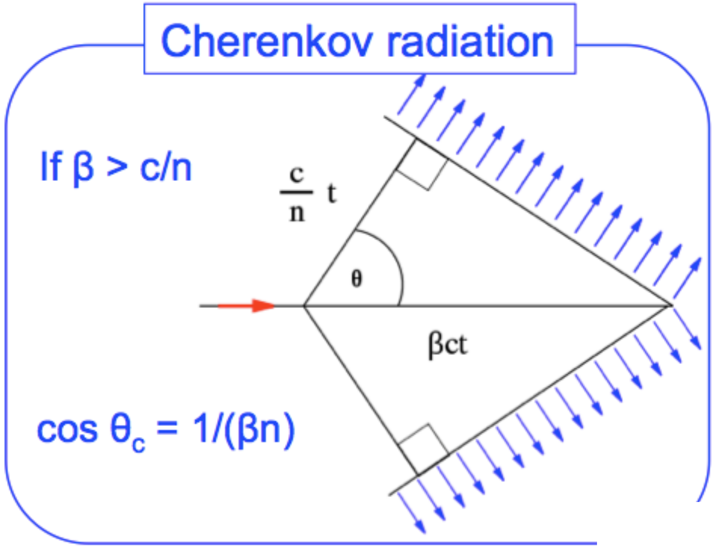


Quantity	LHCb measurement
$M(B^+)$	5279.38 ± 0.35
$M(B^0)$	5279.58 ± 0.32
$M(B^0_s)$	5366.90 ± 0.36
$M(\Lambda^0_b)$	5619.19 ± 0.76
$\boldsymbol{M(B_c^+)}$	$\mathbf{6273.7 \pm 2.1}$

(MeV/c²)

uncertainties ~7 10^{-5}

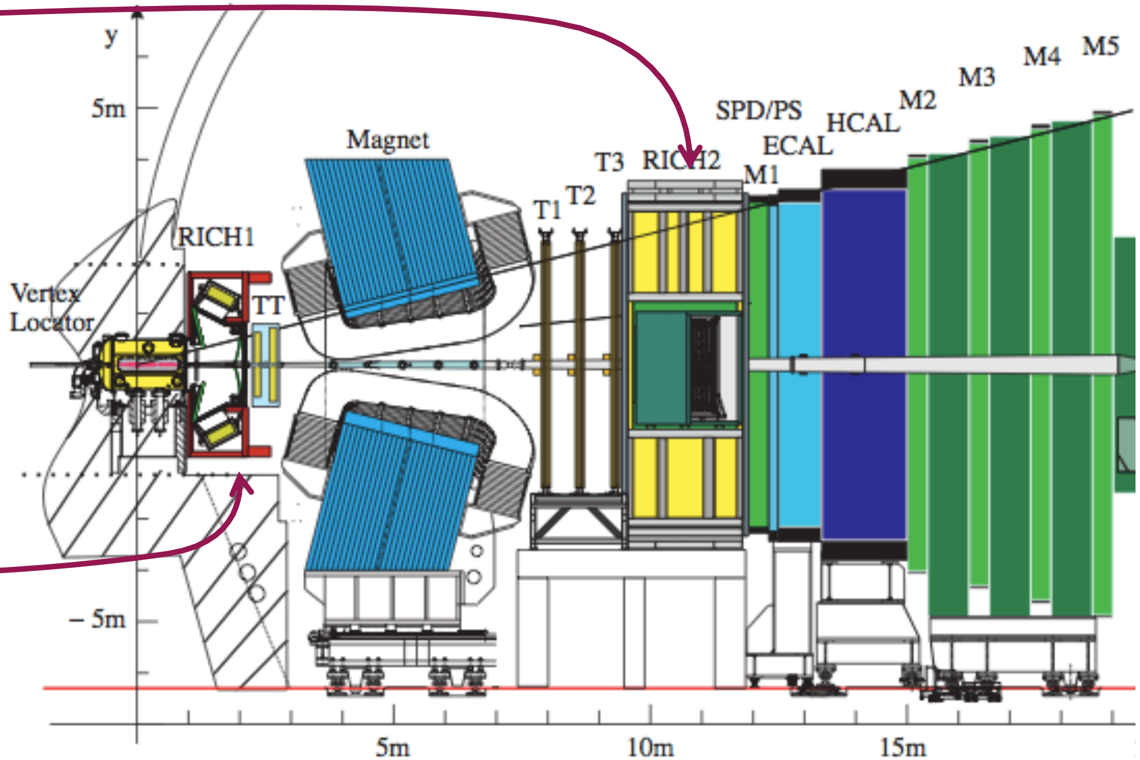
Particle Identification (PID): the RICH detectors



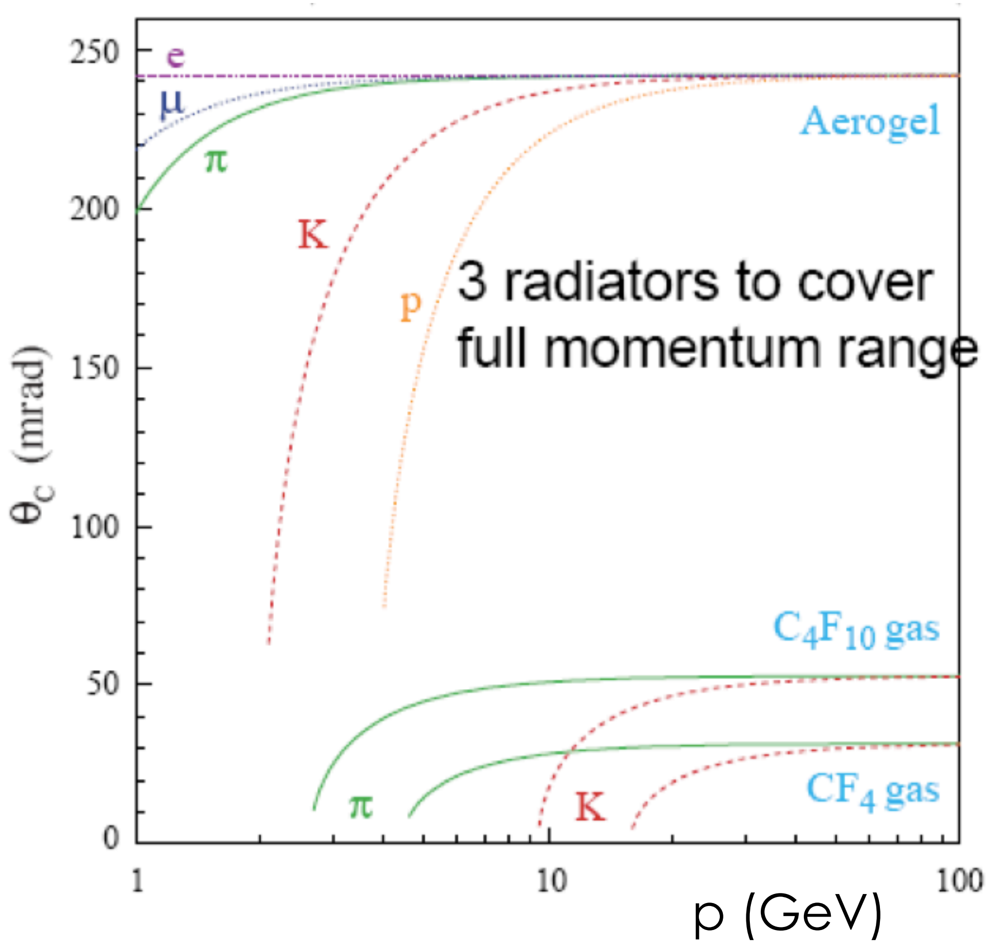
$$\cos\left(\theta_{\mathrm{C}}\right) = \frac{1}{n}\sqrt{1 + \left(\frac{m}{p}\right)^2}$$

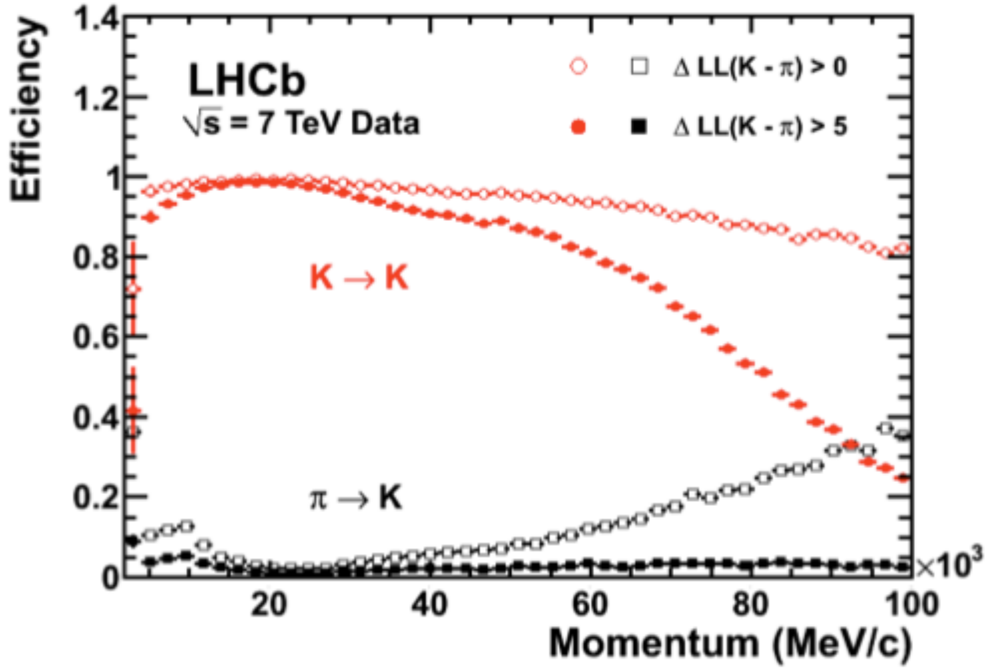
p being measured by the tracking, the particle is identified

3 radiators (different indices) to cover the full momentum range



	RICH1	RICH2
Aerogel	**C_4F_{10}**	**CF_4**
1.03	1.0014	1.0005

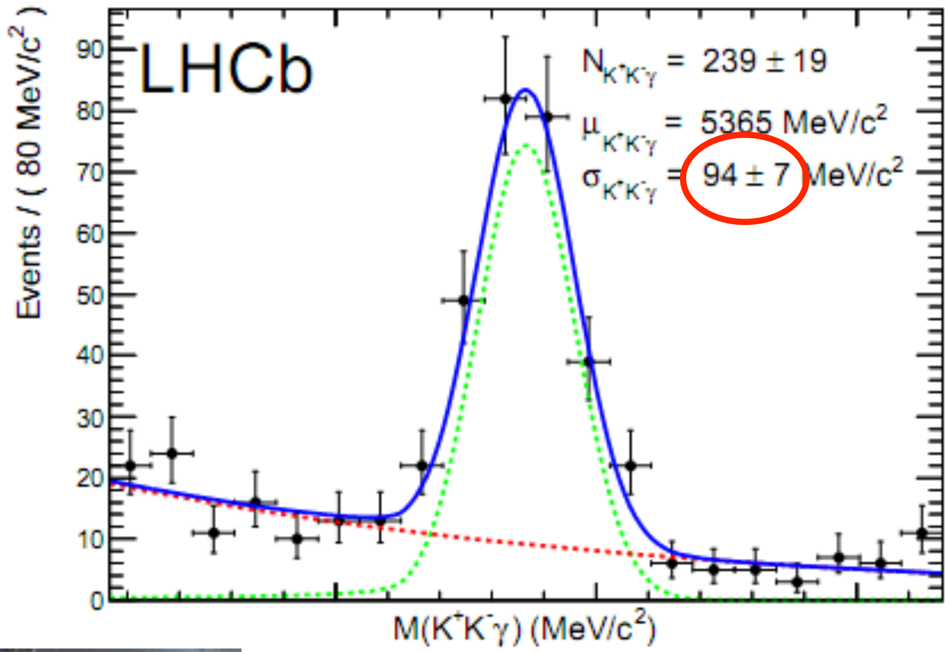


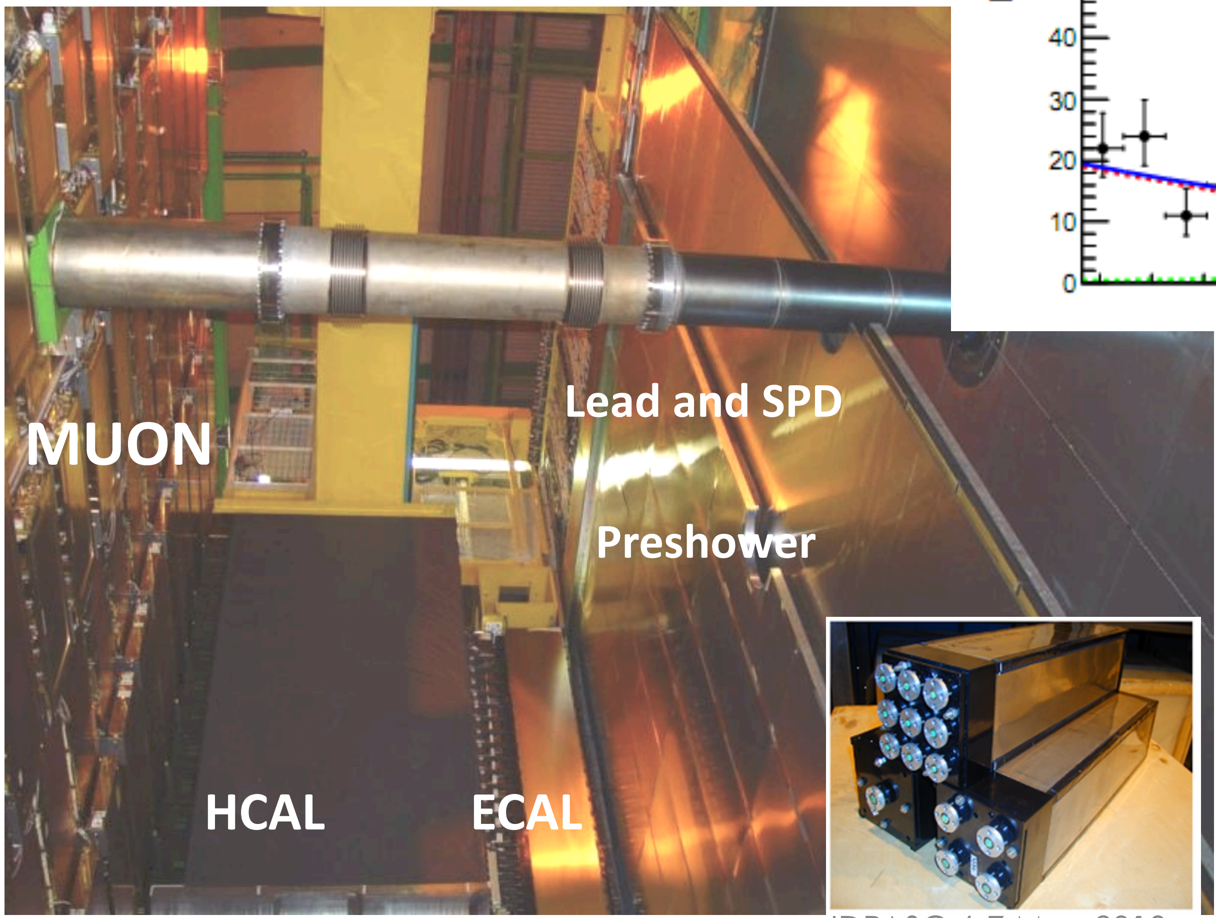


Calorimeters

- ECAL: Shashlik Pb-scintillator
  $\sigma(E)/E = 10\% / \sqrt{E} \oplus 1\%$
- HCAL: Tile Fe-scintillator
  allows triggering on *hadronic* final states

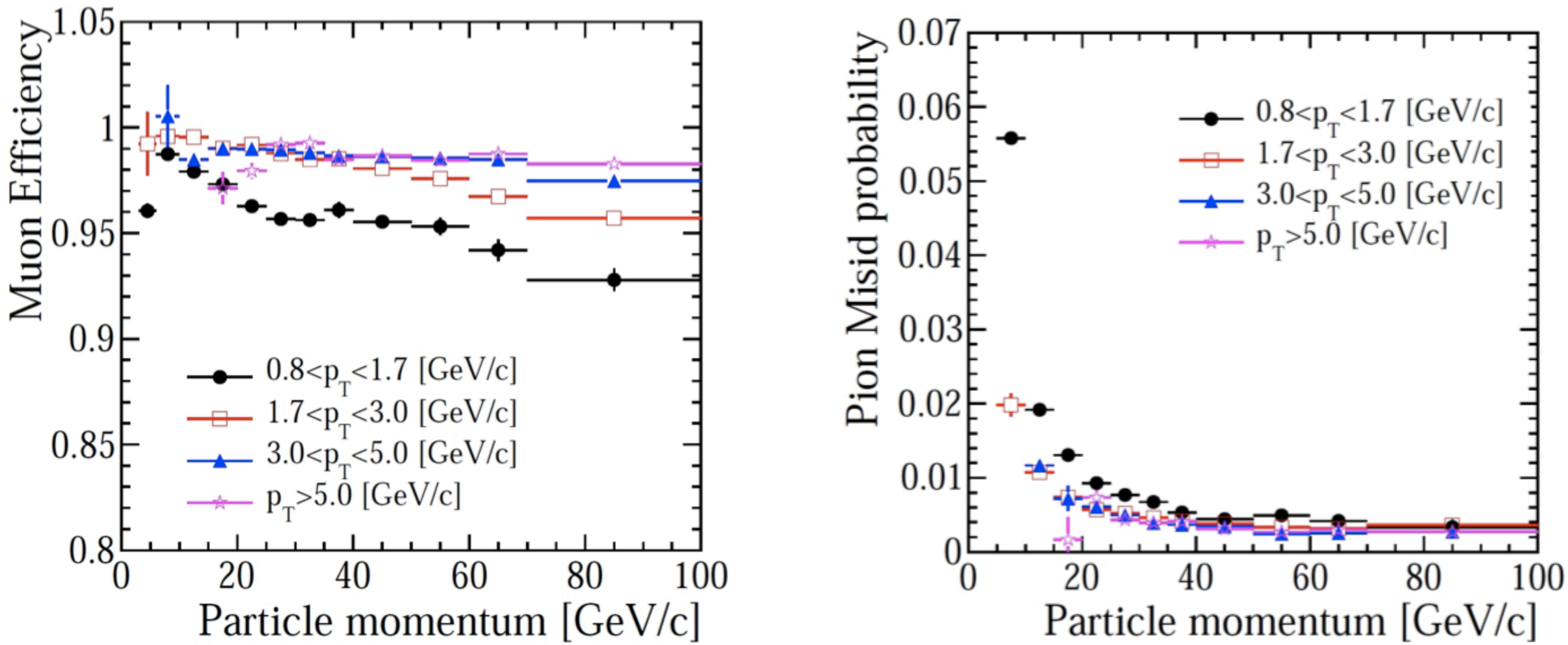
$B_s \rightarrow \Phi\gamma$





Muon chambers

Extremely efficient at triggering and reconstructing muons

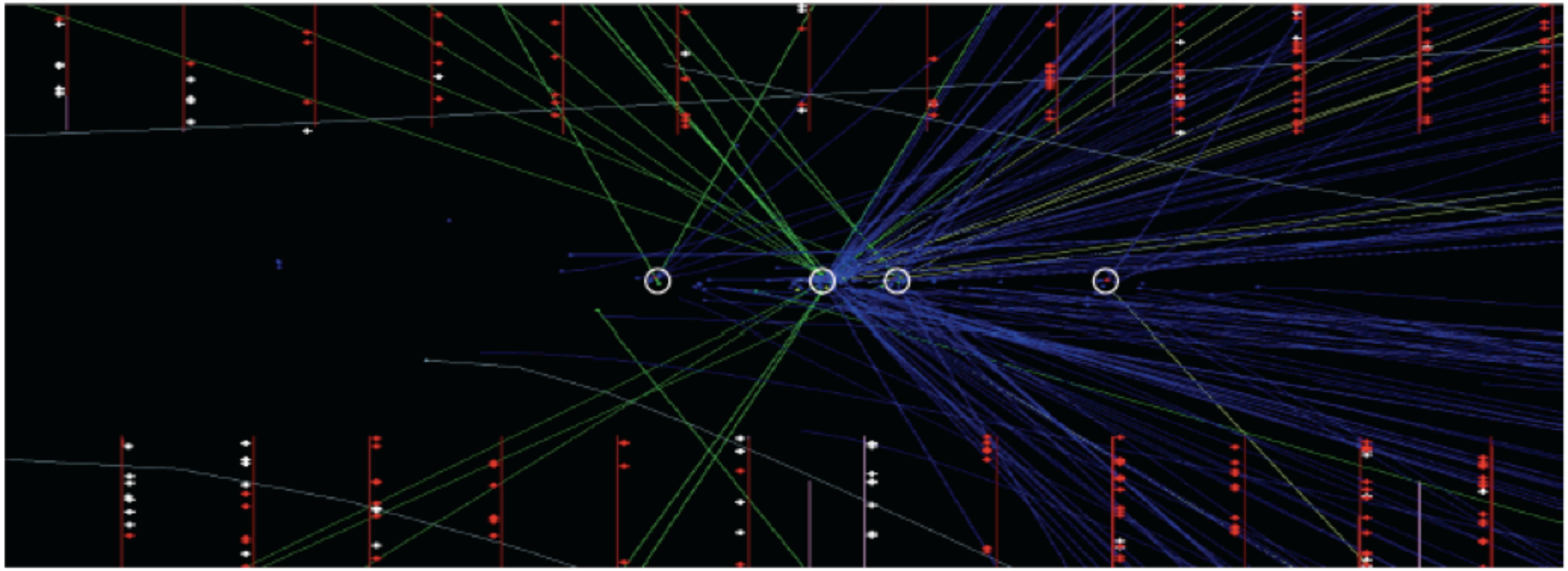


muon ID efficiency: ~ 97% for 1-3% $\pi \rightarrow \mu$ misID probability.

Working with pile up

	Energy	Bunch spacin g	Average number of visible interaction per bunch crossing	Luminosity
Design	14 TeV	25 ns	0.4	$2\ 10^{32}\ cm^{-2}\ s^{-1}$
2011	7 TeV (σ^{14TeV}_{bb} /2)	50 ns	1.4	$3.5\ 10^{32}\ cm^{-2}\ s^{-1}$
2012	8 TeV (σ^{7TeV}_{bb} x 1.15)	50 ns	1.6	$4.\ 10^{32}\ cm^{-2}\ s^{-1}$

VELO rz view



20 MHz of bunch crossing ; about 30 particles produced per interaction
At $\sqrt{s}$=8 TeV 1/200 events contains a b quark ... look for branching fractions < 10^{-8}

the trigger :

40 MHz

Calorimeters, Muon detectors

Level-0
p_T of μ (~1 GeV)
h,e,γ (~3 GeV)

Custom electronics

1MHz limit

All detectors information

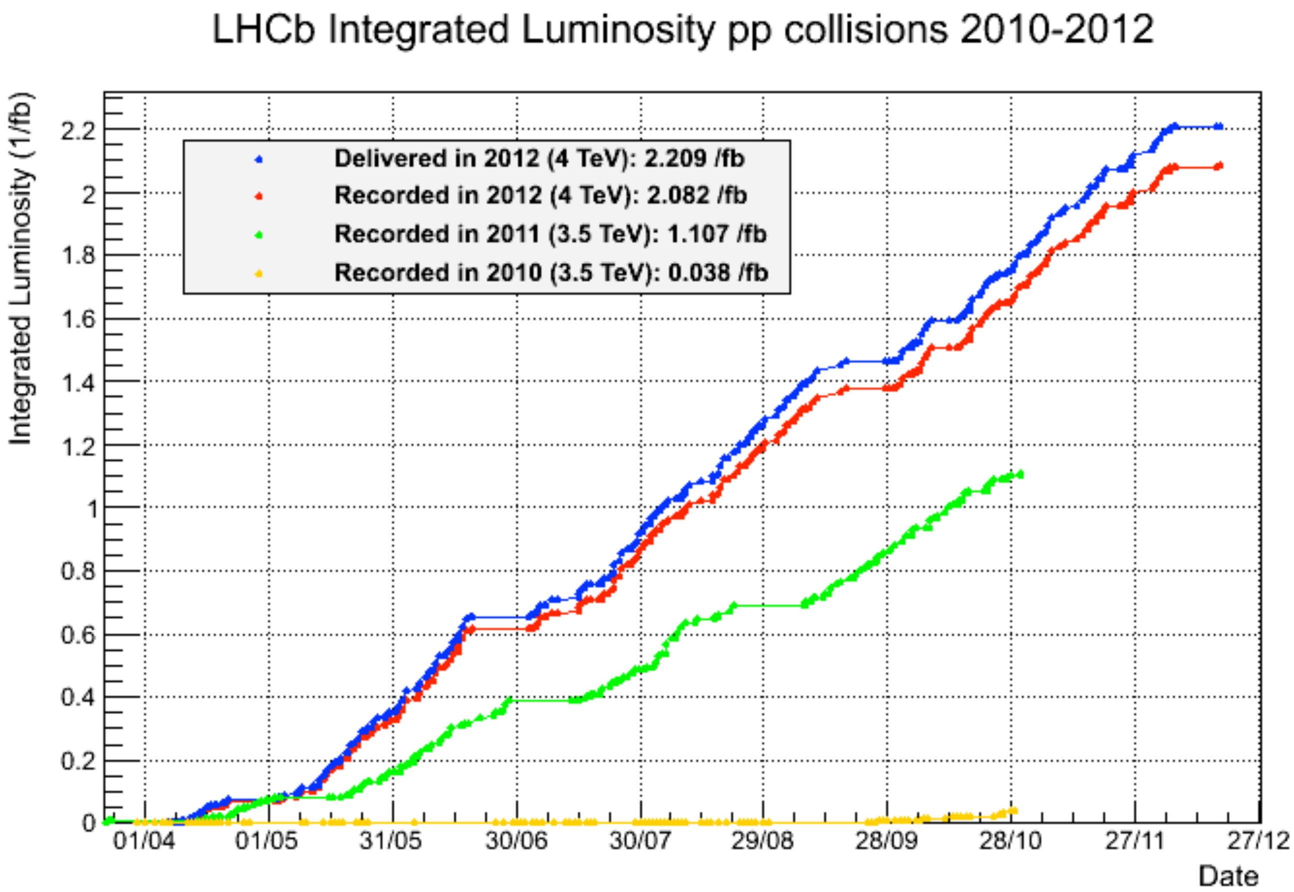
High Level Trigger
Tracking and vertexing
p_T and impact parameter cuts
Inclusive/exclusive selections

CPU farm

3 kHz (2011) – 4.5 kHz (2012)

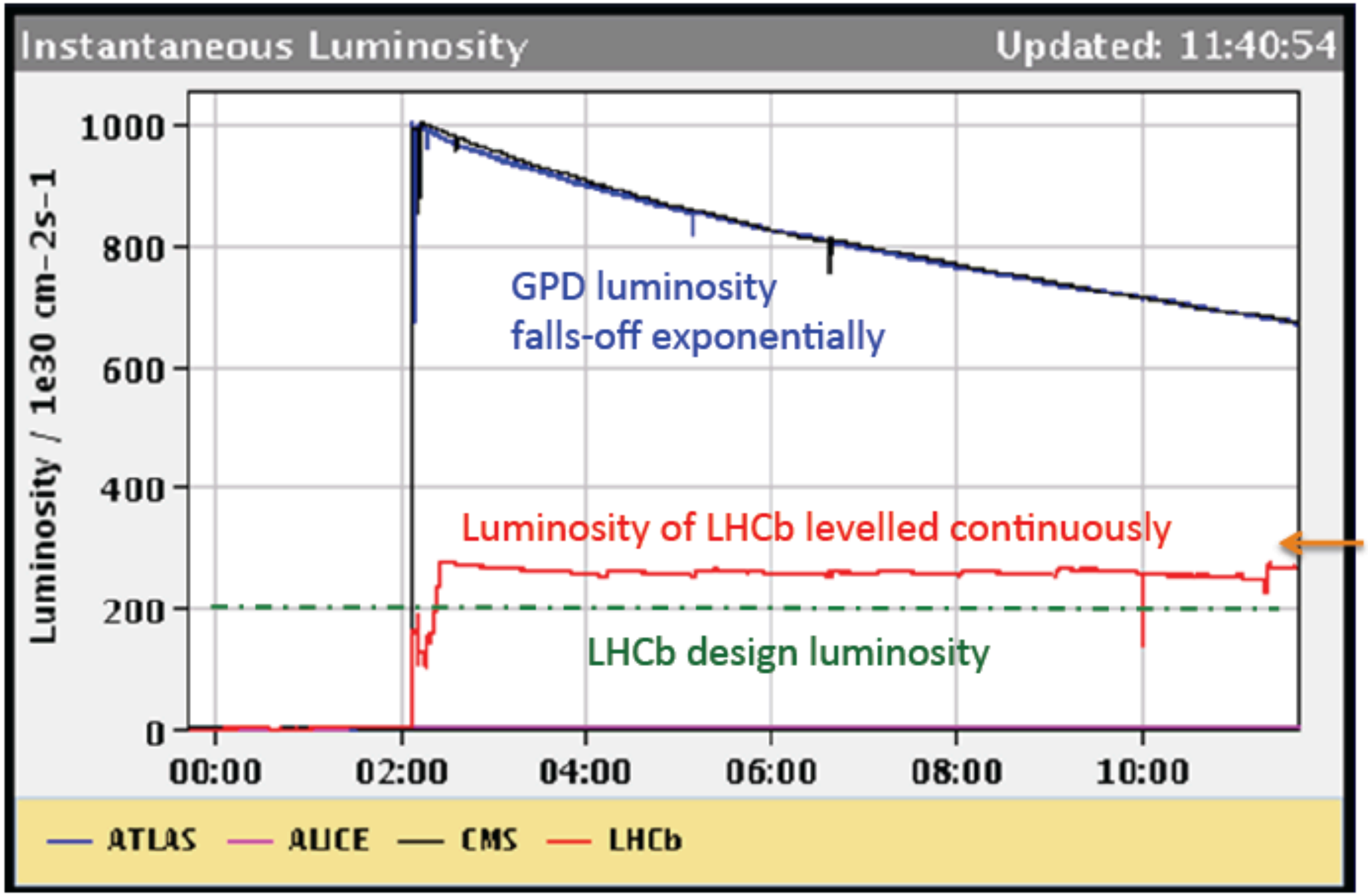
L0xHLT efficiency : ~20-50% on fully hadronic channels and 70-90% on di-muon channels

Experimental setup : the LHCb data-taking characteristics



2011 : 1.1 fb^{-1} at 7 TeV (was 0.038 fb^{-1} in 2010)
2012 : 2.1 fb^{-1} at 8 TeV

luminosity leveling :



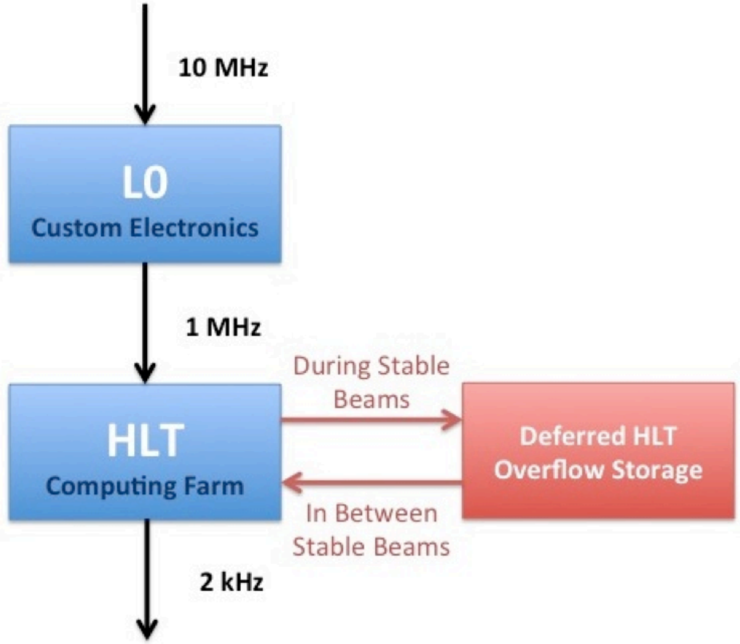
LHCb luminosity is flat for 9h

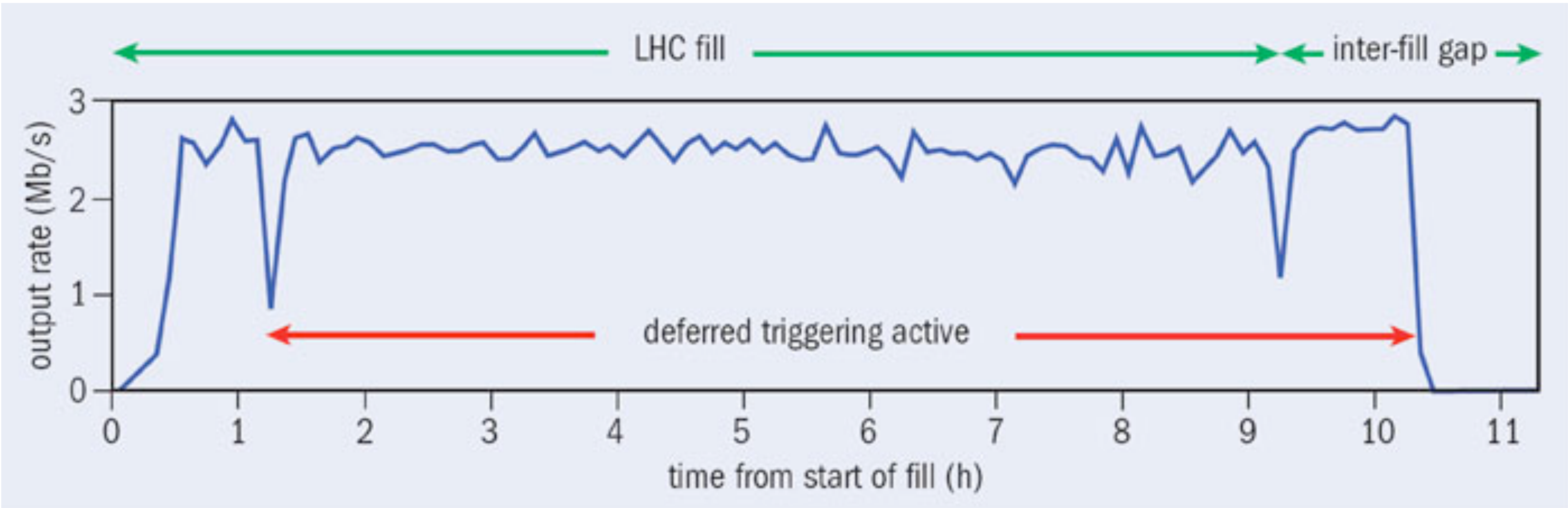
deferred trigger:

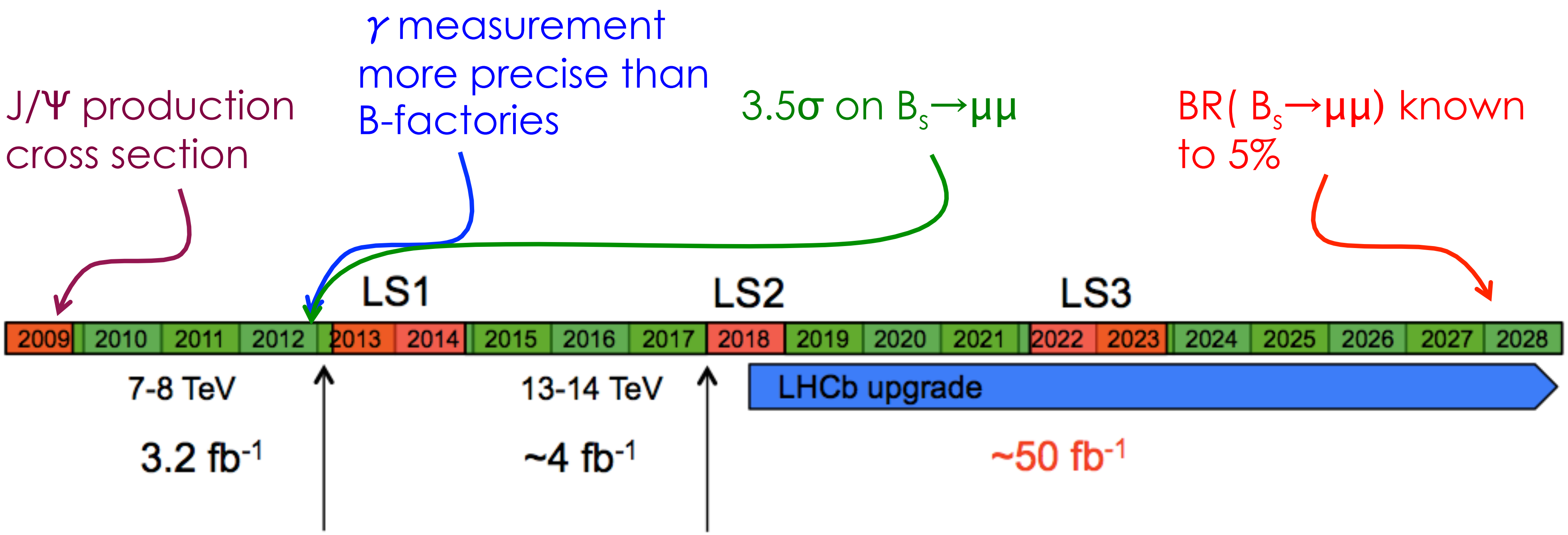
• Due to technical stops and gaps between LHC fills HLT runs only 20% of the time

⇒ Use interfill gaps to process the events collected during the fill :

- Temporarily store about 20% of the L0 triggered events during a fill
- About 200 TB of storage available on CPU farm
- Process them directly after the fill.







LHCb has now collected 3.2 fb^{-1}.

- Long Shutdown 1 (LS1) has started

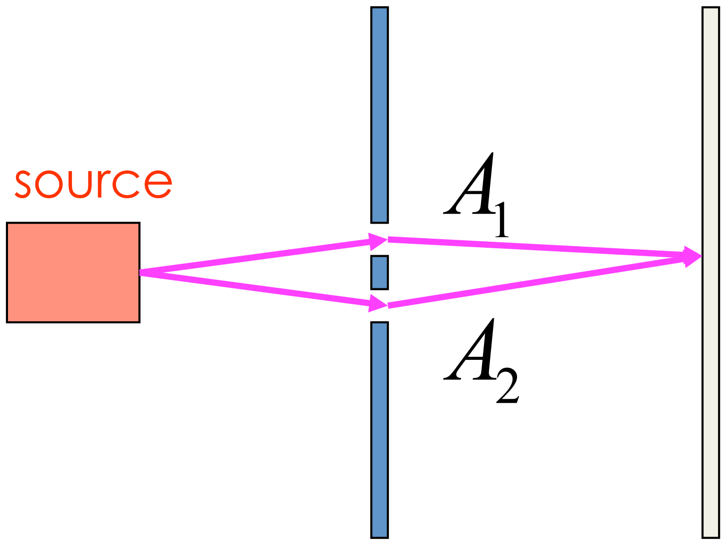
- LHCb will collected another 4 fb^{-1} before LS2

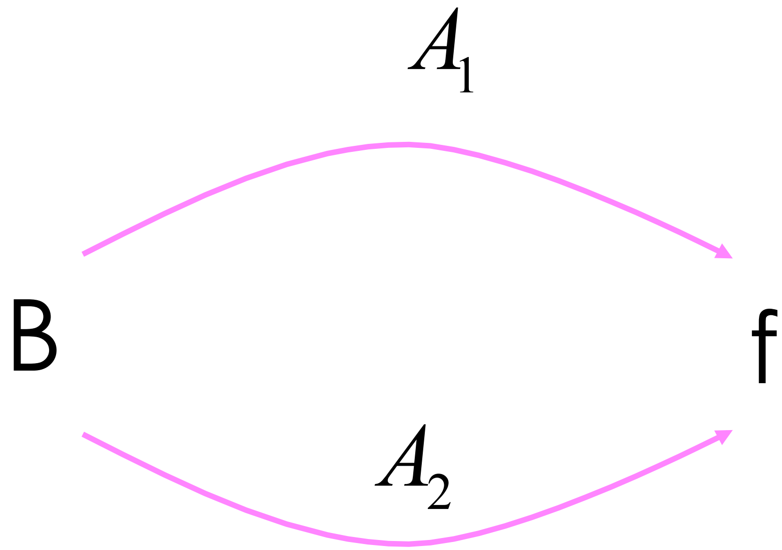
- Then : LHCb upgrade in 2018 to go to higher luminosities.

- Goal: collect 50 fb^{-1} in the following 10 years.

CP violation

Analogy: "Double-Slit" Experiments with Matter and Antimatter





In the double-slit experiment, there are two paths to the same point on the screen.
In the B experiment, we must choose final states which are accessible via at least two different Feynman graphs.

We perform the B experiment twice (starting from B and from $\overline{B}$). We then compare the results.

Three types of CP violation

CP

$$A : B \rightarrow f$$

$$\bar{A} : \bar{B} \rightarrow \bar{f}$$

CP violation if $|A|^2 \neq |\bar{A}|^2$

CP violation in decay (« direct CP») :

$$B \xrightarrow{A} f$$

$$\bar{B} \xrightarrow{\bar{A}} \bar{f}$$

Only one existing for charged B

CP violation in mixing :

$$B^0 \rightarrow \bar{B}^0 \rightarrow \bar{f}$$

$$\bar{B}^0 \rightarrow B^0 \rightarrow f$$

Not yet observed for B mesons.

CP violation in the interference between mixing and decay :

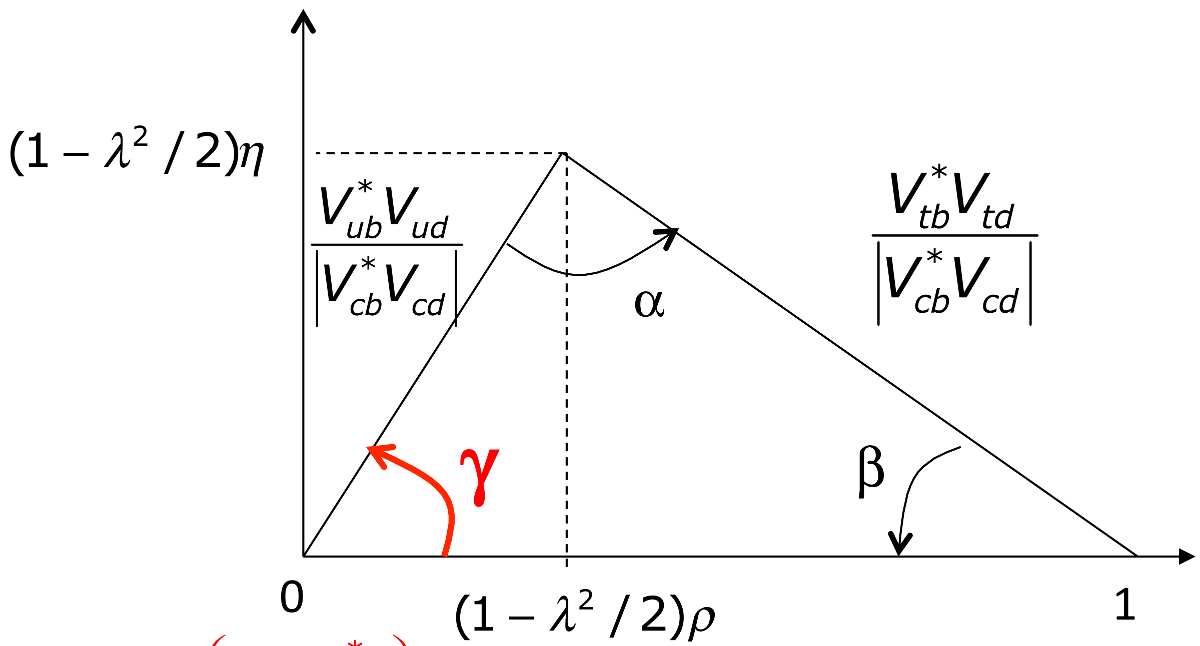
$$B^0 \rightarrow f \qquad B^0 \rightarrow \bar{B}^0 \rightarrow f$$

$$\bar{B}^0 \rightarrow f \qquad \bar{B}^0 \rightarrow B^0 \rightarrow f$$

First observation of CP violation in B decays : sin(2β) measurement.

an example of direct CP : γ measurement with DK

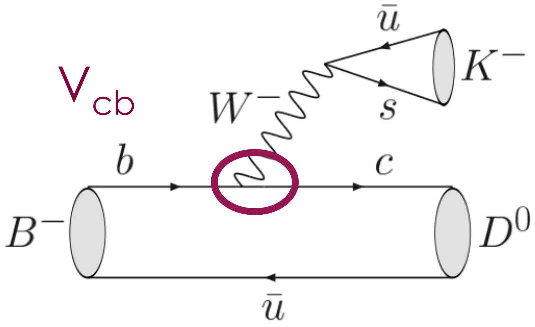
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

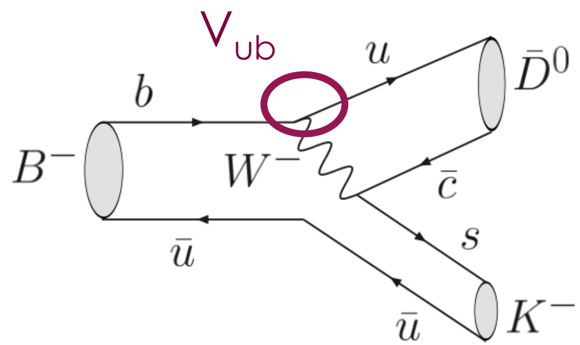


$$\gamma = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Direct CP violation

$$\gamma = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$





Use a D^0 decay mode where D^0 and $\overline{D}^0$ cannot be distinguished : $D^0 \to KK$ or $\pi\pi$

CP

$$A\left(B^- \to D^0\left(\to f_{CP}\right)K^-\right) = A_c \qquad A\left(B^- \to \bar{D}^0\left(\to f_{CP}\right)K^-\right) = A_u e^{i(\delta_B - \gamma)}$$

$$A\left(B^+ \to D^0\left(\to f_{CP}\right)K^+\right) = A_c \qquad A\left(B^+ \to D^0\left(\to f_{CP}\right)K^+\right) = A_u e^{i(\delta_B + \gamma)}$$

γ : weak phase alters sign under CP

δ_B : strong phase : CP invariant

$$r_B = \frac{A_u}{A_c}$$

$$\Gamma\left(B^- \to f_{CP}K^-\right) = \left|A_c + A_u e^{i(\delta_B - \gamma)}\right|^2 = A_c^2 \times \left(1 + r_B^2 + 2r_B\cos\left(\delta_B - \gamma\right)\right)$$

$$\Gamma\left(B^+ \to f_{CP}K^+\right) = \left|A_c + A_u e^{i(\delta_B + \gamma)}\right|^2 = A_c^2 \times \left(1 + r_B^2 + 2r_B\cos\left(\delta_B + \gamma\right)\right)$$

$$A_{CP} = \frac{\Gamma\left(B^- \to f_{CP}K^-\right) - \Gamma\left(B^+ \to f_{CP}K^+\right)}{\Gamma\left(B^- \to f_{CP}K^-\right) + \Gamma\left(B^+ \to f_{CP}K^+\right)} = \frac{2r_B \sin\delta_B \sin\gamma}{1 + r_B^2 + 2r_B \cos\delta_B \cos\gamma}$$

- in order to observe CP violation we need to have at least 2 amplitudes with different weak phase (γ) but also different strong phase (δ_B) !

- sensitivity directly proportional to r_B

- 3 unknows : r_B δ_B and γ

Additional information can be obtained from the Cabibbo-favoured decay : $D^0 \to K^- \pi^+$

$$\Gamma\left(B^- \to D^0 K^-\right) = A_c^2 \simeq \frac{\Gamma\left(B^- \to D^0\left(\to K^-\pi^+\right)K^-\right)}{BF\left(D^0 \to K^-\pi^+\right)}$$

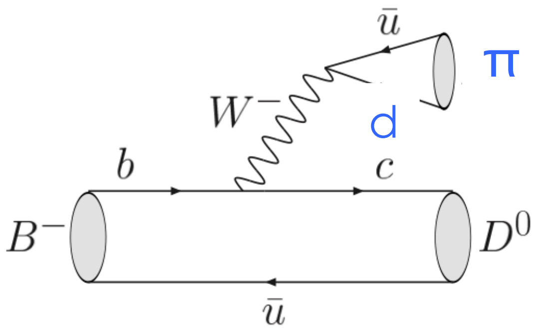
$$R_{CP} = \frac{\Gamma\left(B^- \to f_{CP}K^-\right) + \Gamma\left(B^+ \to f_{CP}K^+\right)}{2\Gamma\left(B^- \to D^0 K^-\right)} = 1 + r_B^2 + 2r_B \cos\delta_B \cos\gamma$$

The analysis (in a nutshell)

- Explicit requirement for the level-0 hadronic trigger to be fired by (at least) one track of the decay or from a track in the event which is not from the $B \to D^0 K$

- Reconstruct $D^0 \to KK$ or $\pi\pi$ or $K\pi$: use of PID to select which is which

- Add a bachelor track the K $B \to D^0 K$ … but here comes the problem



BF larger by $|V_{ud}/V_{us}|^2 \sim 1/\lambda^2 \sim 20$

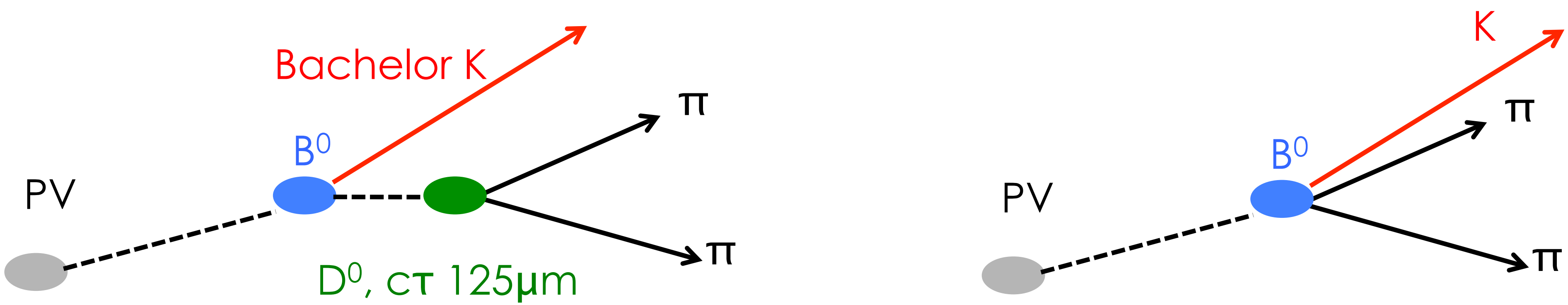
- In principle : small CPV also present but r_B much smaller

- Separate the sample in 2 parts : more K-like or more Pion-like

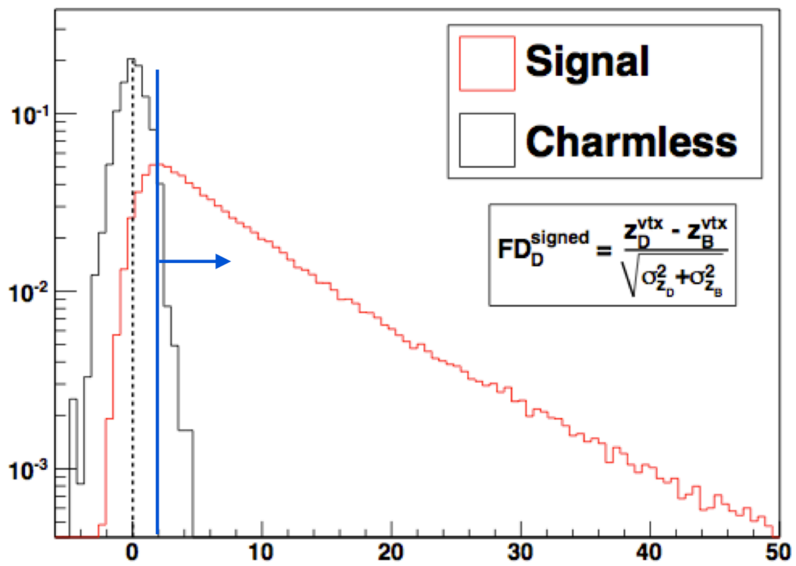
• Remove the non-D^0 background : $B \to KKK$ or $B \to \pi\pi K$ or $B \to K\pi K$

$BR(B^0 \to K\pi\pi) \sim 5.1\ 10^{-5}$
$BR(B^0 \to D^0 K) \times BR(D^0 \to \pi\pi) \sim 5.2\ 10^{-7}$

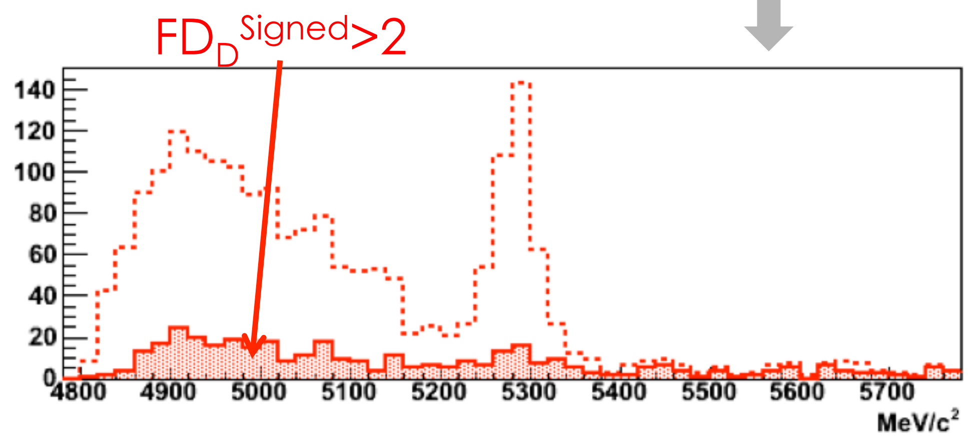
What we want to select: What we want to reject:



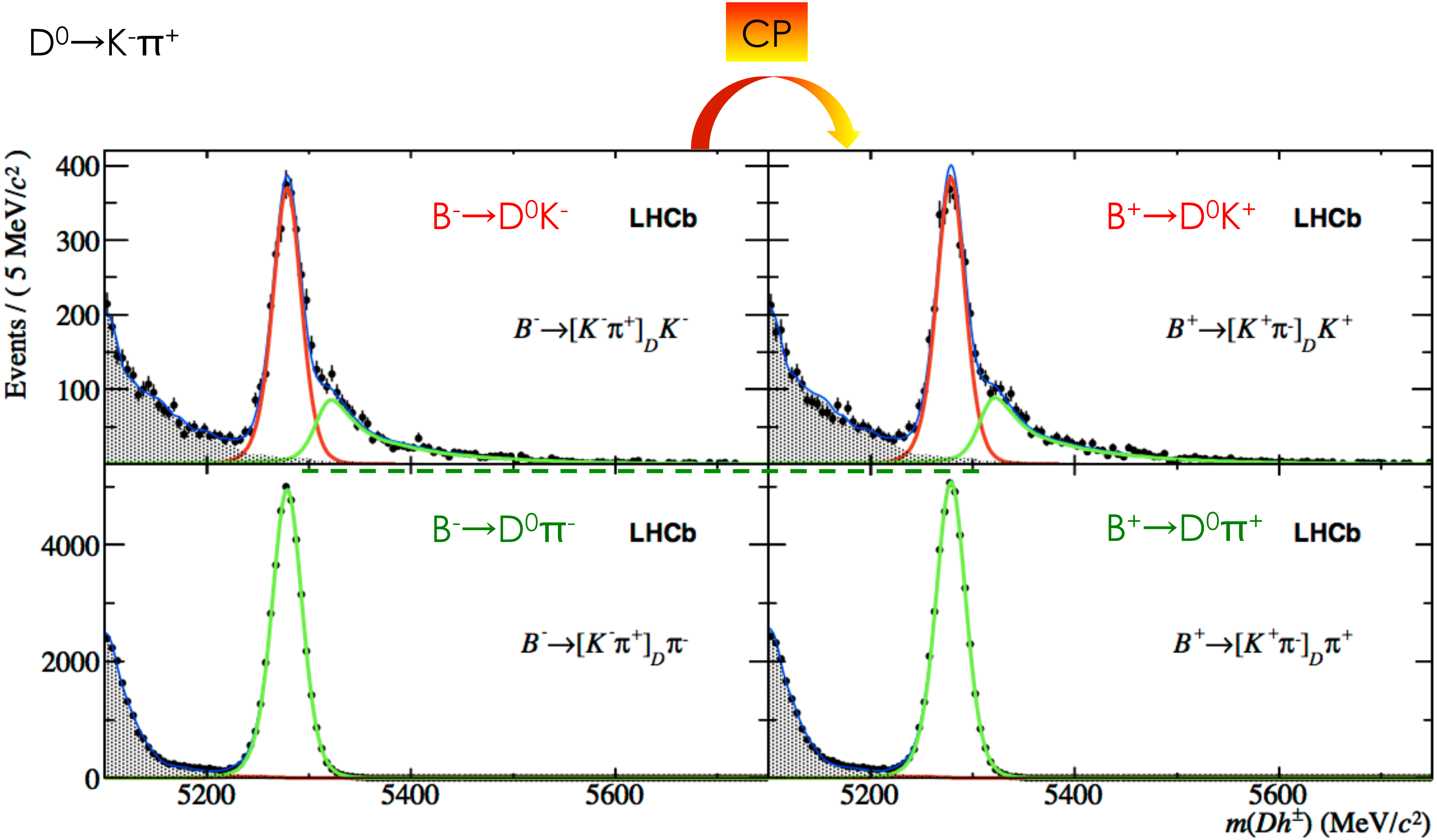
Use the flight distance between the B vertex and the D vertex



Look at the D sidebands, to see whether or not this background exists

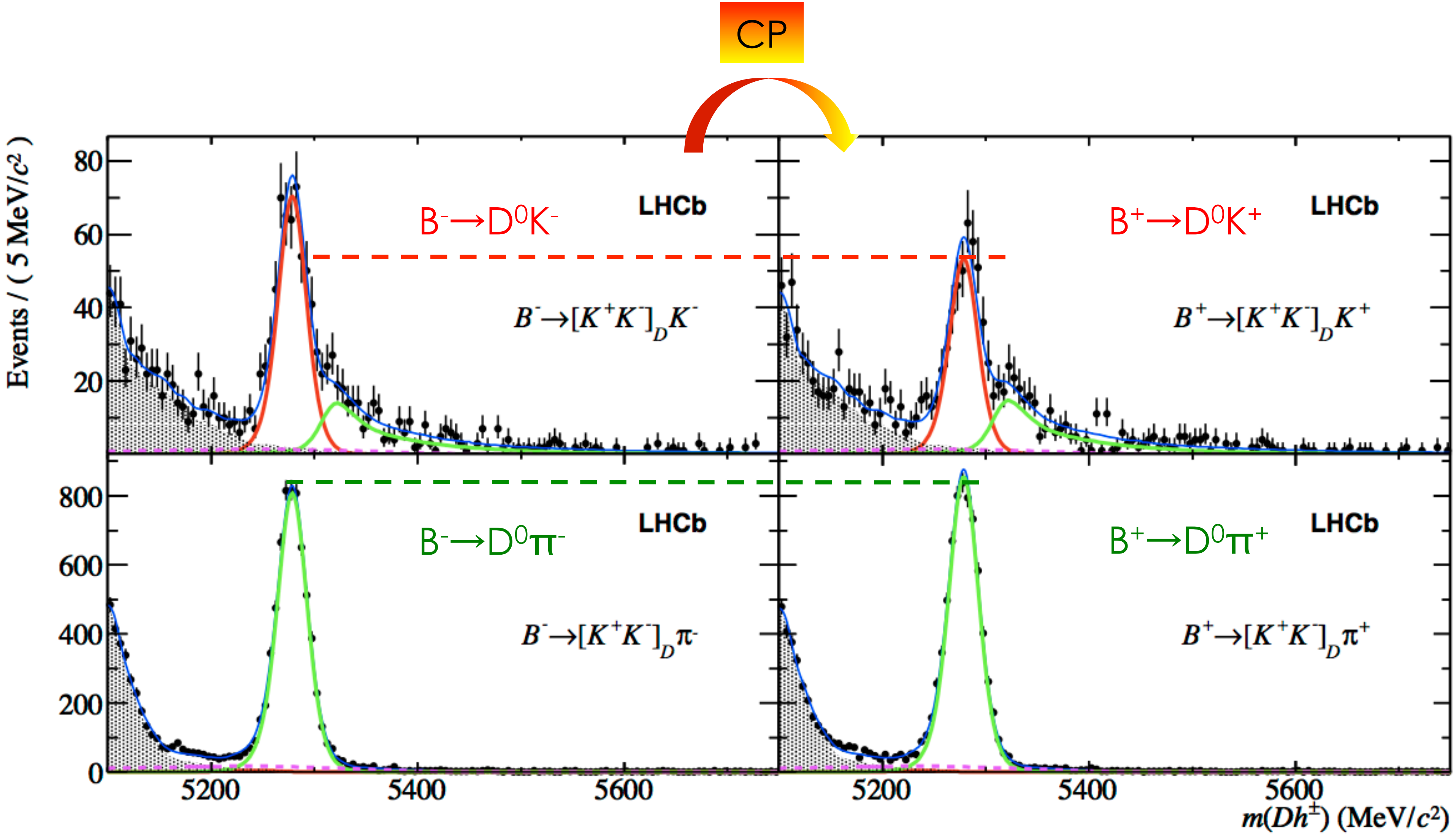


$D^0 \to K^- \pi^+$



Very clean signals

Different behaviours below and above the B^0 mass peak

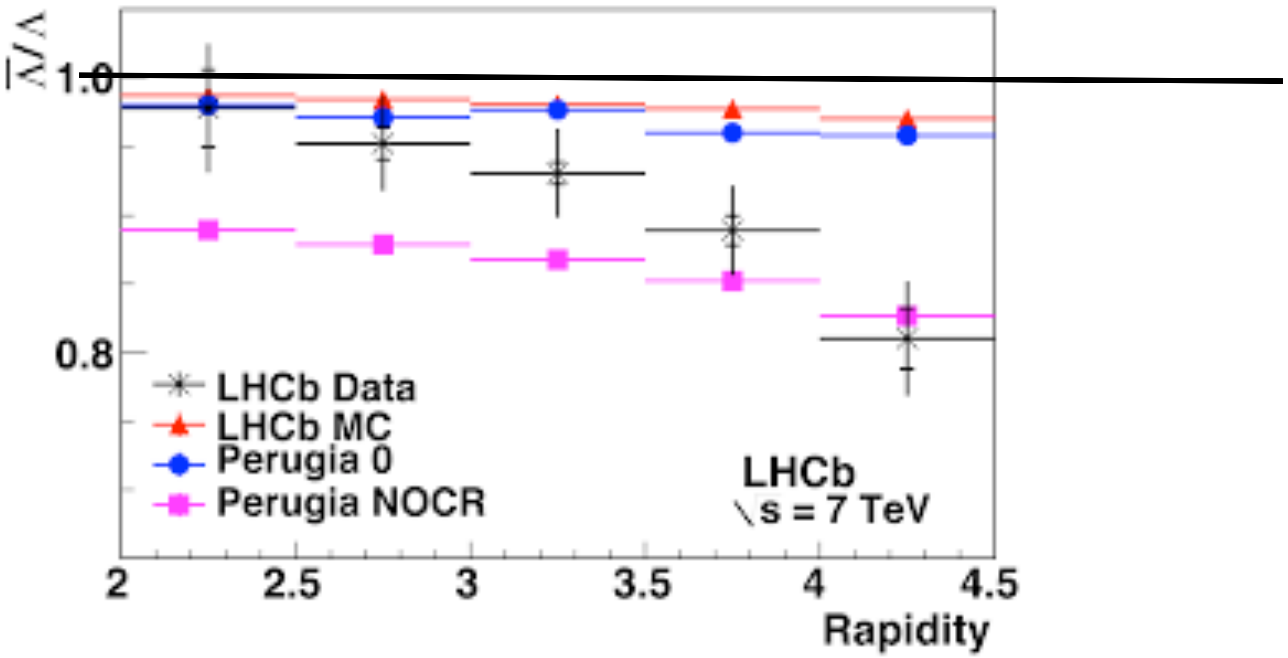


Very clean (and large !) signals

But there are other causes of asymmetries :

• different numbers of B^+ and B^- produced : pp initial state ⇒ slightly less B^- than B^- : (-0.8 ± 0.7)% due to the hadronization asymmetry

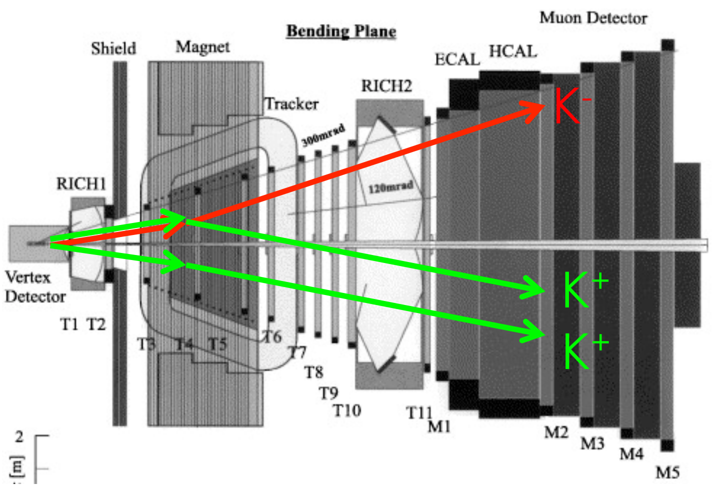
2 protons in the initial state
⇒ higher probability to pick up a diquark than an anti-diquark



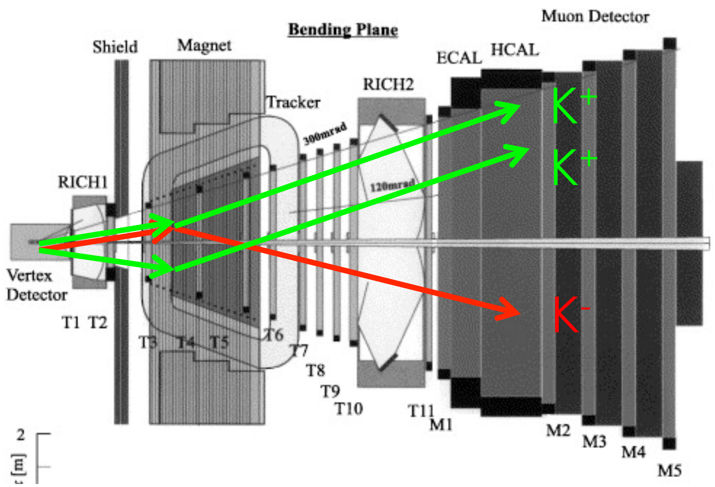
⇒ more b-baryons than anti-b-baryons
since one has the same probability to have a b-quark than anti-b-quark
⇒ less B^-(b anti-u) than B^+ (anti-b u)

- detection asymmetries :
  - K^- and K^+ have different interaction length (negligible for pions)
  - a part of the detector can have a lower efficiency : effect reduced by a flip in magnet polarity

Polarity Up



Polarity Down



This can be measured using both the $B \to D^0 K$ and the $B \to D^0 \pi$ for the CP modes but also for the (very useful) Cabibbo-favoured decay : $D^0 \to K^- \pi^+$

$$A_{meas}\left(\left(K\pi\right)_D \pi\right) = \underbrace{\cancel{A_{CP}\left(\left(K\pi\right)_D \pi\right)}}_{=0} + A_{\mathrm{Prod}} + A_{K\ \mathrm{Det}}$$

$$A_{meas}\left(\left(K\pi\right)_D K\right) = A_{CP}\left(\left(K\pi\right)_D K\right) + A_{\mathrm{Prod}} + 2 \times A_{K\ \mathrm{Det}}$$

$$A_{meas}\left(\left(KK\right)_D K\right) = A_{CP}\left(\left(KK\right)_D K\right) + A_{\mathrm{Prod}} + A_{K\ \mathrm{Det}}$$

$\vdots$

$B^{\pm}$ mode	D mode	B^-	B^+
$DK^{\pm}$	$K^{\pm}\pi^{\mp}$	3170 ± 83	3142 ± 83
	$K^{\pm}K^{\mp}$	592 ± 40	439 ± 30
	$\pi^{\pm}\pi^{\mp}$	180 ± 22	137 ± 16
$D\pi^{\pm}$	$K^{\pm}\pi^{\mp}$	40767 ± 310	40774 ± 310
	$K^{\pm}K^{\mp}$	6539 ± 129	6804 ± 135
	$\pi^{\pm}\pi^{\mp}$	1969 ± 69	1973 ± 69

From these numbers, the CP parameters can be computed

$$\boxed{\begin{aligned} A_K^{KK} &= 0.148 \pm 0.037 \pm 0.010 \\ A_K^{\pi\pi} &= 0.135 \pm 0.066 \pm 0.010 \end{aligned}}$$

Several techniques to reach the same final state :

1) Use a CP mode for the D^0

GLW (Gronau, London, Wyler)
CP+ and CP- modes

$(K^+K^-, \pi^+\pi^-)$ ← → $(K_S\pi^0, \phi K_S, \eta K_S, \rho K_S, \omega K_S)$

(Very) small Branching Ratios

CP- probably not accessible at LHC

2) Use CA($K^-\pi^+$) mode for the V_{ub} decay and DCS($K^-\pi^+$) for the V_{cb} decay

ADS (Atwood, Dunietz, Soni)

$$\left\{ \begin{array}{l} D^0 \to K^-\pi^+ \\ D^0 \to K^-\pi^+\pi^0 \\ D^0 \to K^-\pi^+\pi^-\pi^+ \end{array} \right.$$

(Very) small Branching Ratios

Strong phase between the D^0 decays

3) Use the $D^0 \to K_S\, \pi\, \pi$ decay

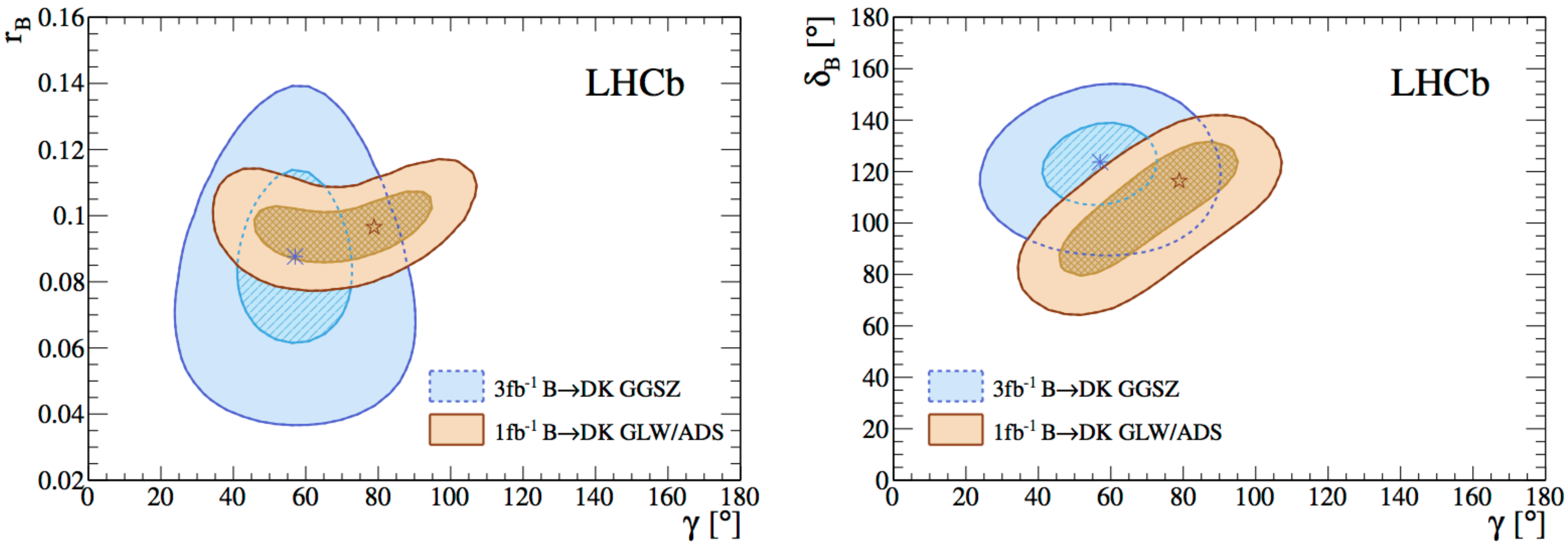
Dalitz GGSZ (Giri, Grossman, Soffer, Zupan)

3 body decay : 2D plane (Dalitz plot) analysis

Dalitz plot description

Only analysis giving information on γ

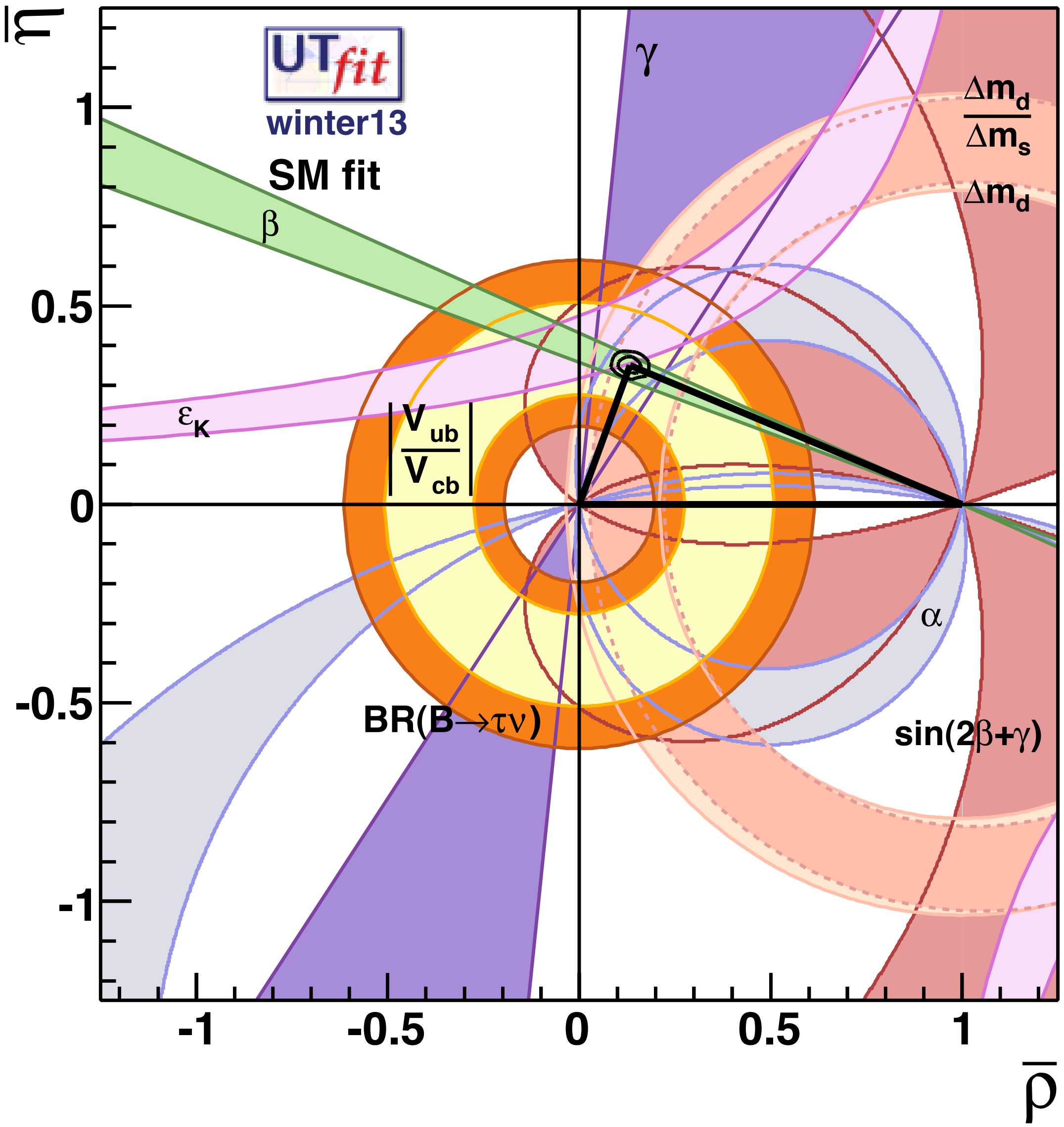
LHCb results : 2D projections of the 3 parameters r_B δ_B and γ



[LHCb-CONF-2013-006, in prep., prelim.]

$$\gamma = (67.2 \pm 12.0)^\circ$$

But still a long way to go …



CP violation in mixing : A_{sl}

They are flavour eigenstates with definite quark content $|B^0\rangle, |\overline{B}^0\rangle$

- useful to understand particle production and decay

Apart from the flavour eigenstates there are mass eigenstates: $|B_L\rangle, |B_H\rangle$

- eigenstates of the Hamiltonian
- states of definite mass and lifetime

$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle$$

$$|B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle$$

$|B_L\rangle, |B_H\rangle$: mass eigenstates

$|B^0\rangle, |\overline{B}^0\rangle$: flavour eigenstates

Since flavour eigenstates are not mass eigenstates, the flavour eigenstates are mixed with one another as they propagate through space and time

$|B^0(t)\rangle$ $(|\bar{B}^0(t)\rangle)$: the flavour state of a B meson that was a $\bar{B}^0$ (B^0) at $t=0$.

Schrödinger equation governs time evolution of the B^0-$\bar{B}^0$ System:

$$i\frac{d}{dt}\begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix} = \underbrace{\left(\begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}\right)}_{H \text{ (effective Hamiltonian)}}\begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix}$$

CPT conservation

➡ $M_{11} = M_{22} = m_B$, $\Gamma_{11} = \Gamma_{22} = 1/\tau_B$

H (effective Hamiltonian)

Mass states are eigenvectors of ***H***

$$H|B_L^0\rangle = \boxed{(M_L - i/2\Gamma_L)}|B_L^0\rangle$$
$$H|B_H^0\rangle = \boxed{(M_H - i/2\Gamma_H)}|B_H^0\rangle$$

eigenvalues

$$\Delta m_B \equiv M_H - M_L = 2|M_{12}|$$
$$\Delta\Gamma_B \equiv \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos\phi_{12}$$
$$m_B \equiv \frac{M_H + M_L}{2}$$
$$\Gamma_B \equiv \frac{\Gamma_H + \Gamma_L}{2}$$

$$\phi_{12} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

The time evolution of the mass eigenstates is governed by their eigenvalues :

$$|B_{H,L}(t)\rangle = e^{-i\left(M_{H,L} - i\frac{\Gamma_{H,L}}{2}\right)t}|B_{H,L}(t=0)\rangle \quad + \quad \begin{aligned} |B_L\rangle &= p|B^0\rangle + q|\bar{B}^0\rangle \\ |B_H\rangle &= p|B^0\rangle - q|\bar{B}^0\rangle \end{aligned}$$

Time evolution

Solving the Schrödinger equation :

$$\frac{q}{p} = -\sqrt{\frac{M_{12}^{*} - i\Gamma_{12}^{*}/2}{M_{12} - i\Gamma_{12}/2}}$$

Time evolution of a $B^0(t=0)$: $|B^0(t)\rangle$ and of a $B^0(t=\bar{0})$: $|\bar{B}^0(t)\rangle$

$$|B^0(t)\rangle = g_+(t)|B^0\rangle + \frac{q}{p} g_-(t)|\bar{B}^0\rangle$$

$$|\bar{B}^0(t)\rangle = \frac{p}{q} g_-(t)|B^0\rangle + g_+(t)|\bar{B}^0\rangle$$

$$g_+(t) = e^{-i(m_B - i\frac{\Gamma_B}{2})t}\left[\cosh\frac{\Delta\Gamma_B t}{4}\cos\frac{\Delta m_B t}{2} - i\,\sinh\frac{\Delta\Gamma_B t}{4}\sin\frac{\Delta m_B t}{2}\right],$$

$$g_-(t) = e^{-i(m_B - i\frac{\Gamma_B}{2})t}\left[-\sinh\frac{\Delta\Gamma_B t}{4}\cos\frac{\Delta m_B t}{2} + i\,\cosh\frac{\Delta\Gamma_B t}{4}\sin\frac{\Delta m_B t}{2}\right]$$

More general formulae

CP

$$P\left(B^0(0) \to \bar{B}^0(t)\right) = \left|\frac{q}{p}\right|^2 |g_-(t)|^2$$

$$P\left(\bar{B}^0(0) \to B^0(t)\right) = \left|\frac{p}{q}\right|^2 |g_-(t)|^2$$

CP violation is present if $|q/p| \neq 1$

Experimentally, one builds :

$$a_{sl} = \frac{P\left(\bar{B}^0(0) \to B^0(t)\right) - P\left(B^0(0) \to \bar{B}^0(t)\right)}{P\left(\bar{B}^0(0) \to B^0(t)\right) + P\left(B^0(0) \to \bar{B}^0(t)\right)} = \frac{1 - \left|\frac{q}{p}\right|^4}{1 + \left|\frac{q}{p}\right|^4}$$

Standard Model for B

$a_{sl}^{s} = (1.9 \pm 0.3) \times 10^{-5}$

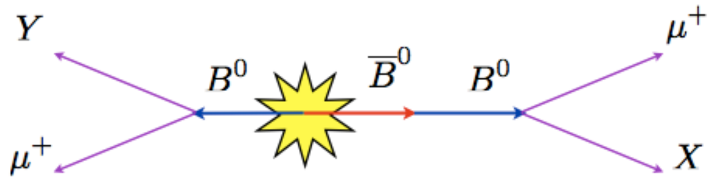
$a_{sl}^{d} = (-4.1 \pm 0.6) \times 10^{-4}$

- Can be done for B_d and B_s
- Does not depend on the time anymore !

Possible measurements :

- dimuon analysis

$$A_{sl} = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)} = C_d a_{sl}^d + C_s a_{sl}^s$$ (for hadron colliders)



- Untagged analysis

$$A = \frac{\Gamma(D_{(s)}^- \mu^+ \nu_u) - \Gamma(D_{(s)}^+ \mu^- \overline{\nu}_u)}{\Gamma(D_{(s)}^- \mu^+ \nu_u) + \Gamma(D_{(s)}^+ \mu^- \overline{\nu}_u)} \approx \frac{a_{sl}^{d,s}}{2}$$

Dilutes sensitivity by 50% (compared to 3% from flavour tagging)
→ need to measure production asymmetry and detection asymmetry

dimuon analysis from D0 (magnet polarity flip possible, symmetric initial state)

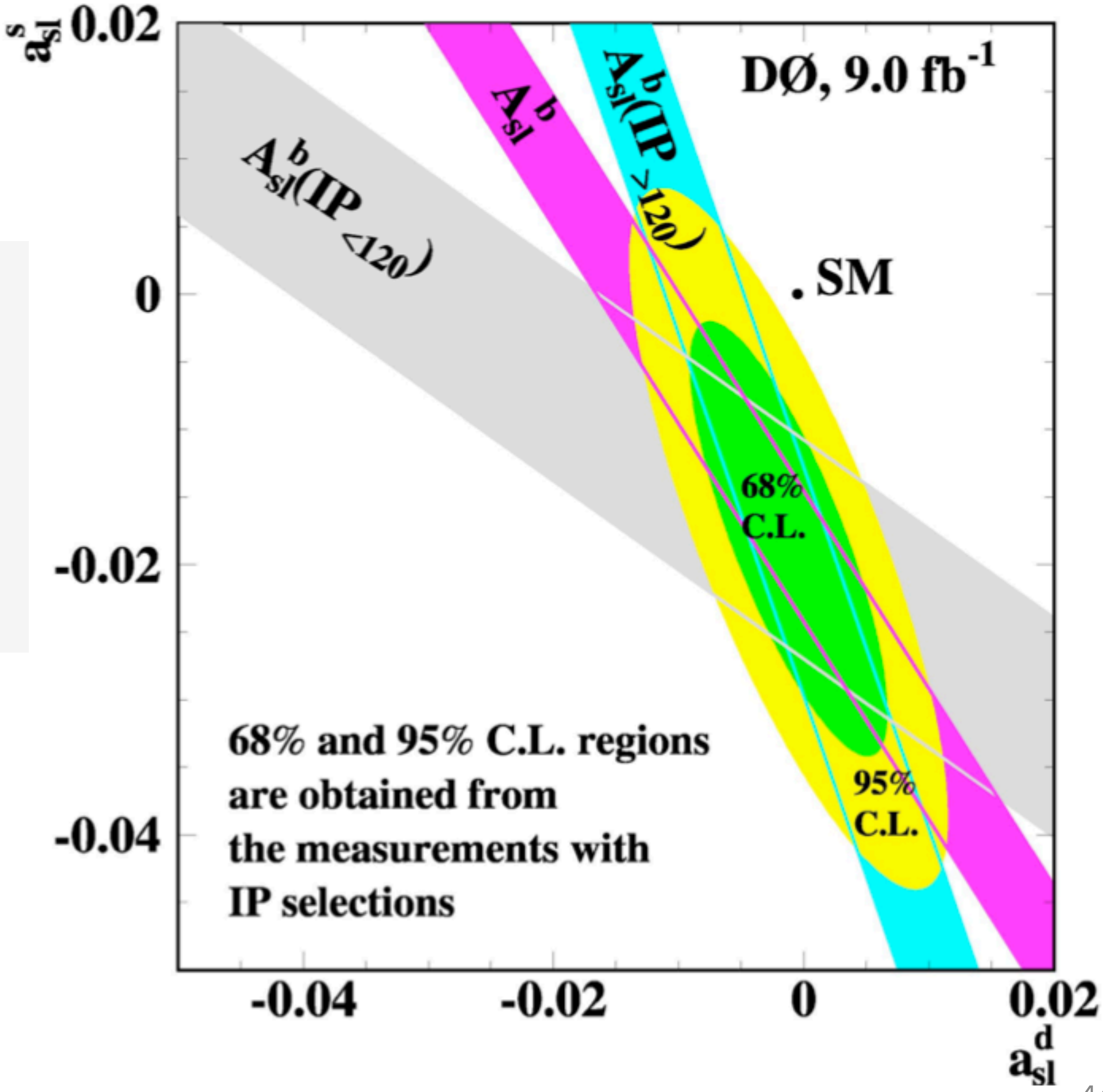
$$A^b_{sl} = (-0.787 \pm 0.172(\mathrm{stat}) \pm 0.093(\mathrm{syst}))\,\%$$

$$A_{sl} = C_d a^d_{sl} + C_s a^s_{sl}$$

-3.9 σ from SM predictions

changing the impact parameter cut changes the composition of the sample

Extraction of a_{sl}^d and a_{sl}^s



$$\begin{aligned} a^d_{\rm sl} &= (-0.12 \pm 0.52)\%, \\ a^s_{\rm sl} &= (-1.81 \pm 1.06)\%. \end{aligned}$$

LHCb untagged analysis $B_s \to D_s^+ (\to \Phi\pi^+)\mu^-$:

$$A_{\text{meas}} = \frac{\Gamma[D_s^- \mu^+] - \Gamma[D_s^+ \mu^-]}{\Gamma[D_s^- \mu^+] + \Gamma[D_s^+ \mu^-]} = \frac{a_{\text{sl}}^s}{2} + \left[a_{\text{p}} - \frac{a_{\text{sl}}^s}{2}\right] \underbrace{\frac{\int_{t=0}^{\infty} e^{-\Gamma_s t} \cos(\Delta M_s\, t)\epsilon(t)dt}{\int_{t=0}^{\infty} e^{-\Gamma_s t} \cosh \frac{\Delta\Gamma_s\, t}{2} \epsilon(t)dt}}_{\text{very small (0.2 \%) due to the large mixing frequency}}$$

production asymmetry

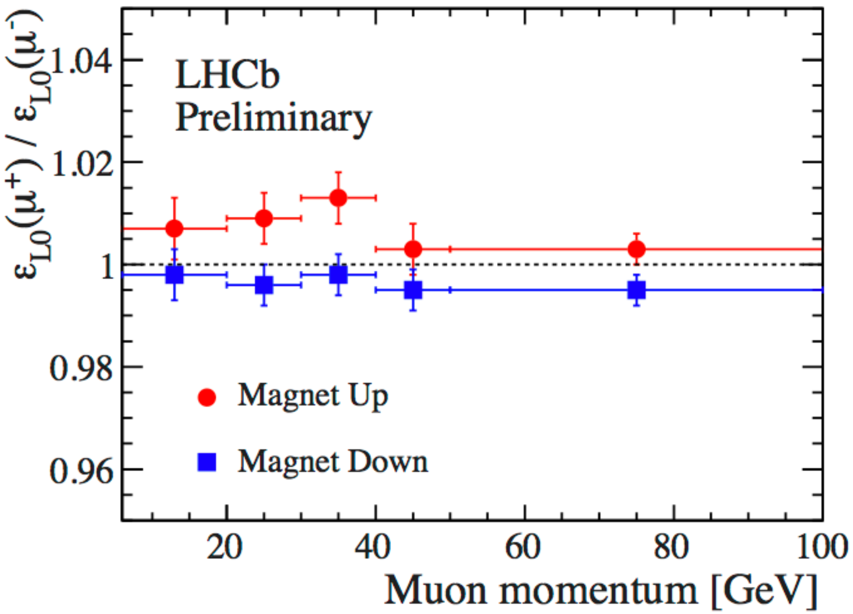
very small (0.2 %) due to the large mixing frequency

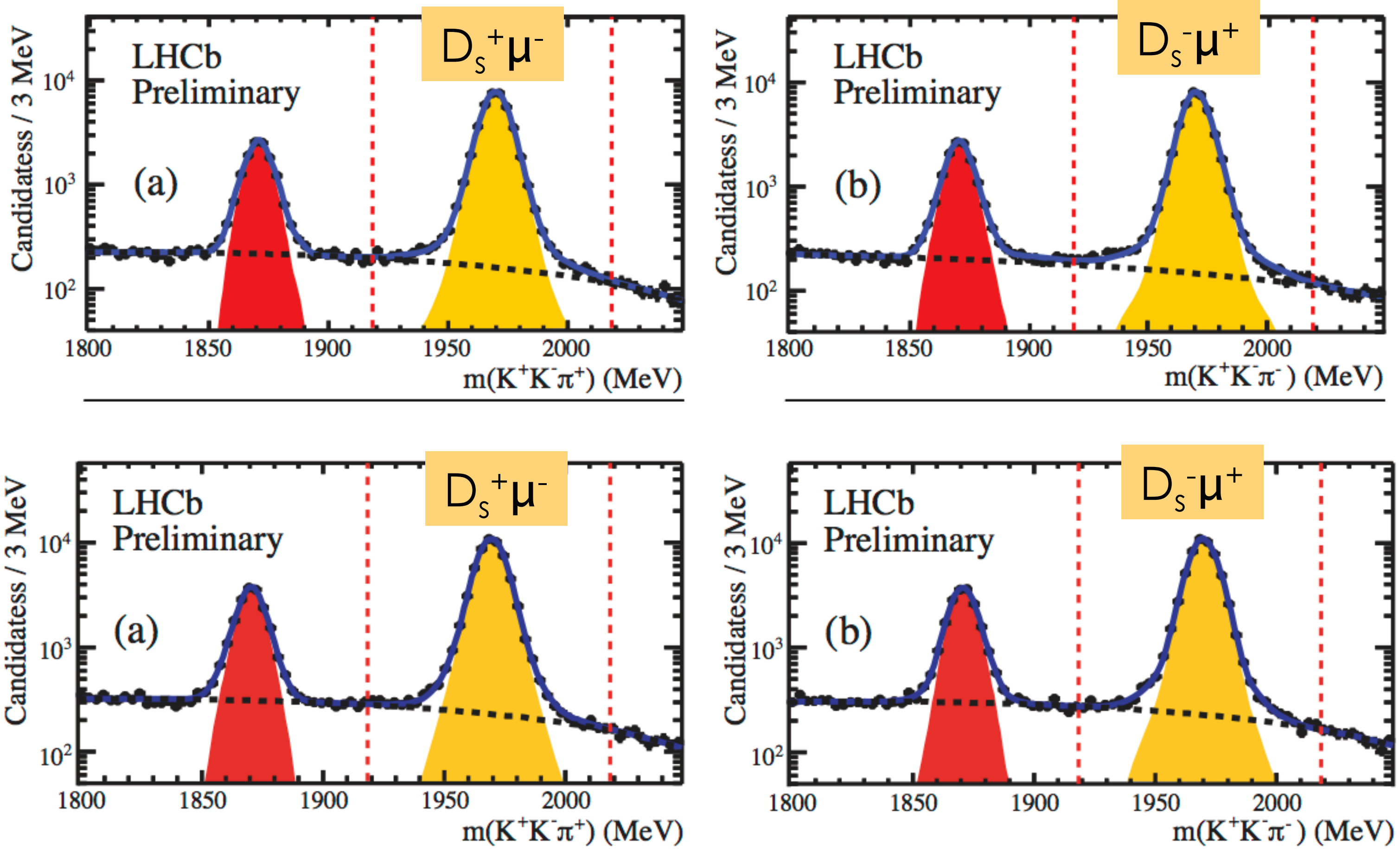
$$A_{\text{meas}} = \frac{N(D_s^- \mu^+) - N(D_s^+ \mu^-) \times \frac{\epsilon(D_s^- \mu^+)}{\epsilon(D_s^+ \mu^-)}}{N(D_s^- \mu^+) + N(D_s^+ \mu^-) \times \frac{\epsilon(D_s^- \mu^+)}{\epsilon(D_s^+ \mu^-)}}$$

$$\epsilon(D_s^- \mu^+) = \epsilon_{\text{id}}(\mu^+) \times \epsilon_{\text{trigger}}(D_s^- \mu^+)$$

- detector, trigger , track and muon ID efficiencies as a function of the charges are measured on data control samples (J/Ψ,$D^{*\pm}$)

- events analyzed separately for magnet UP and DOWN and averaged (cancellation of potential residual effects)





Magnet UP

Magnet DOWN

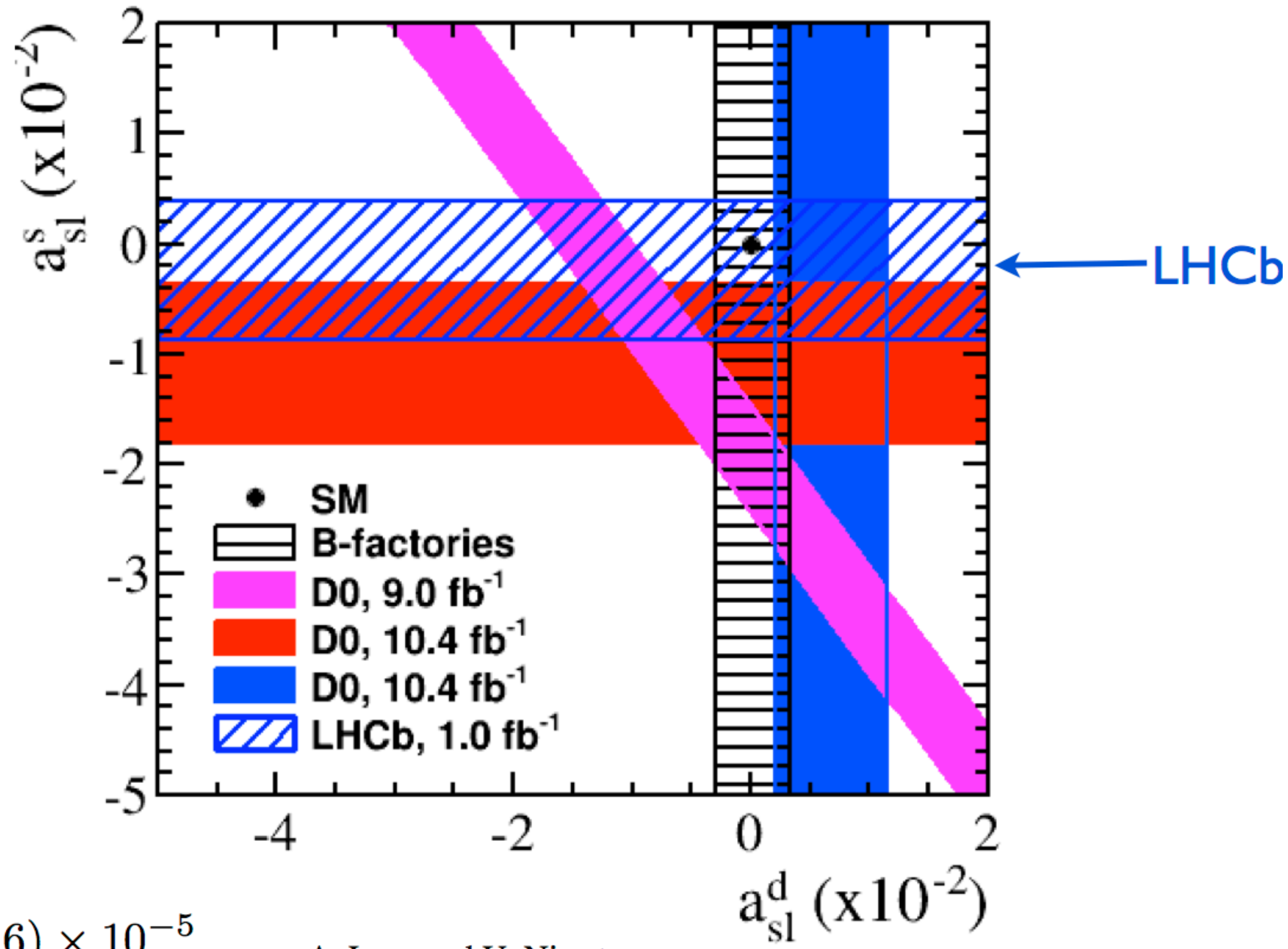
Raw yields (not corrected for detection asymmetries).

	Up	Down
$D_s^-\mu^+$	40945 ± 285	55755 ± 278
$D_s^+\mu^-$	39849 ± 239	56447 ± 294

$$\boxed{a_{sl}^{s} = (-0.24 \pm 0.54 \pm 0.33)\%}$$

systematics dominated by the statistical uncertainties on the efficiencies ratios

$$a_{sl}^{s} = (-0.24 \pm 0.54_{stat} \pm 0.33_{syst})\%$$



SM :

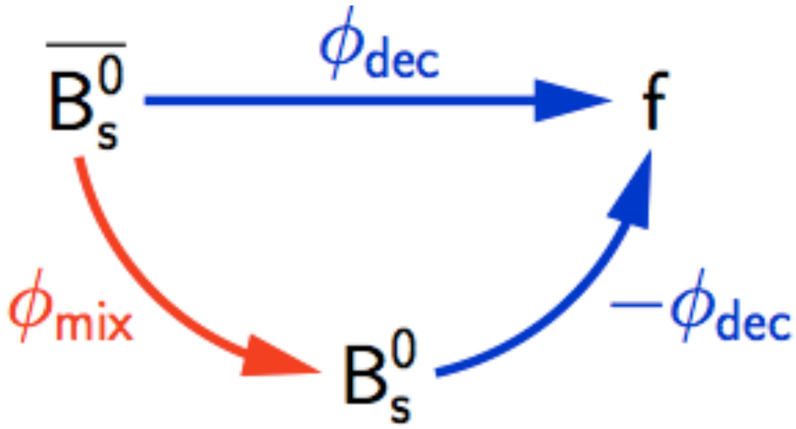
$$a_{\rm sl}^s = (2.0 \pm 0.6) \times 10^{-5}$$

$$a_{\rm sl}^d = (-4.8 \pm 1.1) \times 10^{-4}$$

A. Lenz and U. Nierste, JHEP06(2007)072

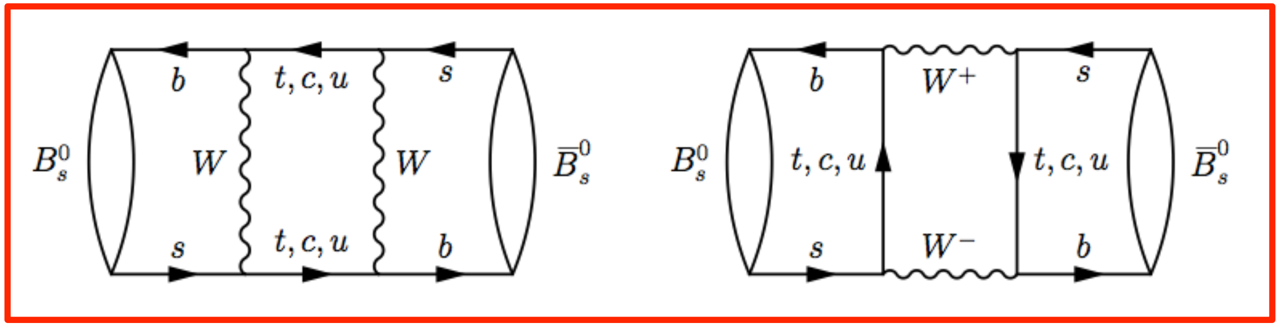
CP violation in the interference between mixing and decay : Φ_s

This is very similar to the sin2β measurement at B-Factories

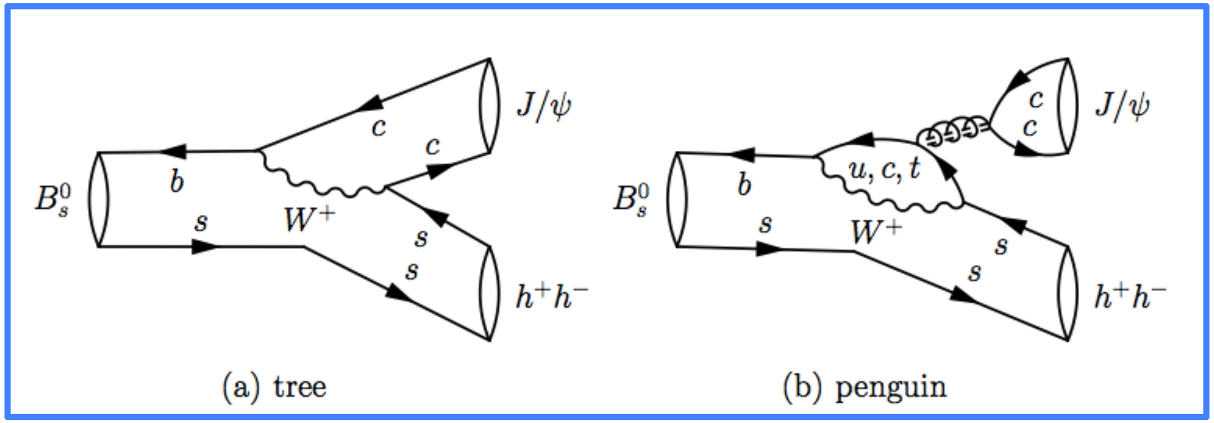


$$\phi_s = \phi_{mix} - 2\,\phi_{dec}$$

Φ_s is the equivalent to 2β

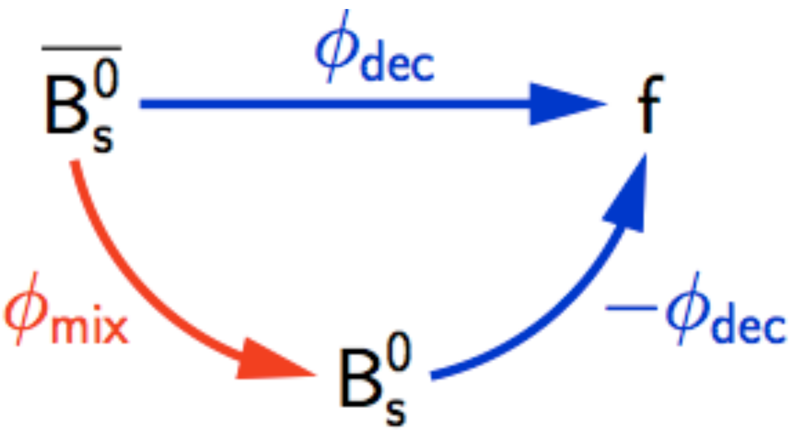


Mixing



(a) tree (b) penguin

Decay



$$\phi_s = \phi_{mix} - 2\,\phi_{dec}$$

Decay dominated by tree-level amplitude ⇒ nearly all CPV induced by mixing

In the SM and ignoring penguins Φ_{dec}=0 :

$$\phi_s^{SM} \simeq -2\beta_s, \text{ where } \beta_s = \arg\left(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*\right)$$

$$V_{CKM} \approx \begin{pmatrix} V_{ud} & V_{us} & |V_{ub}|e^{-i\gamma} \\ V_{cd} & V_{cs} & V_{cb} \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & V_{tb} \end{pmatrix}$$

Fit to experimental data (excluding CPV in the B_s sector !)

$$\boxed{2\beta_s = 0.036 \pm 0.002\,\text{rad}}$$

Theoretically :

- b→ccs tree dominance leads to precise prediction of ϕ_s in SM.
- PS → VV, admixture of CP-odd and CP-even states, measure also $\Delta\Gamma_s$.

Experimentally :

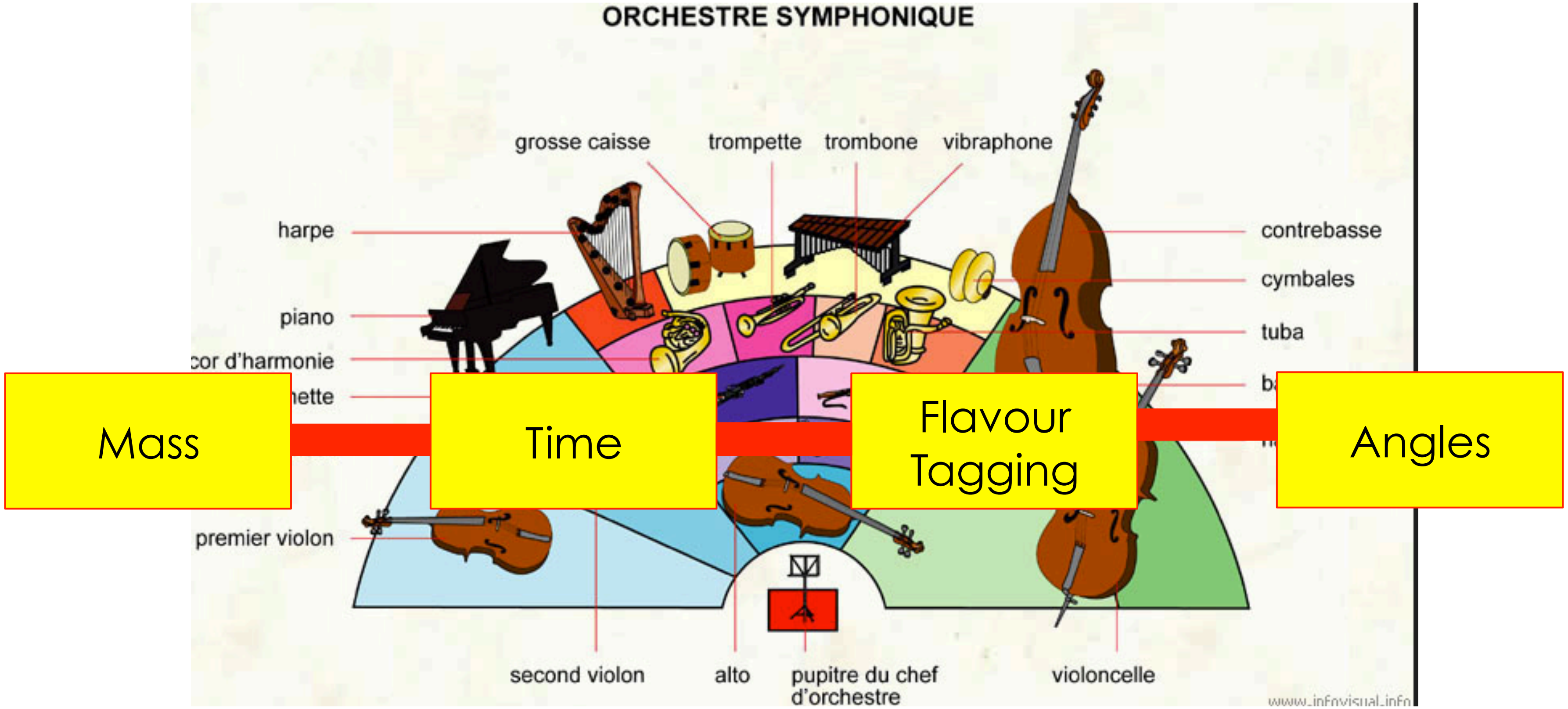
- Relatively large branching ratio.
- Easy to trigger on muons from $J/\psi \rightarrow \mu^+\mu^-$.

The Observables

- the tagging decision (answer the question is it a B_s or a $\overline{B}_s$ which was produced ?)
- the B_s proper time
- the decay angles

The physics parameters

- 3 "P-wave" amplitudes of KK system (A_0, A_{perp}, A_{para})
- 1 "S-wave" amplitude (A_s)
- 10 terms with all the interferences (see the next slide)
- ϕ_s , $\Delta\Gamma_s$, , Γ_s


ORCHESTRE SYMPHONIQUE
grosse caisse
trompette
trombone
vibraphone
harpe
contrebasse
cymbales
piano
tuba
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second violon
alto
pupitre du chef d'orchestre
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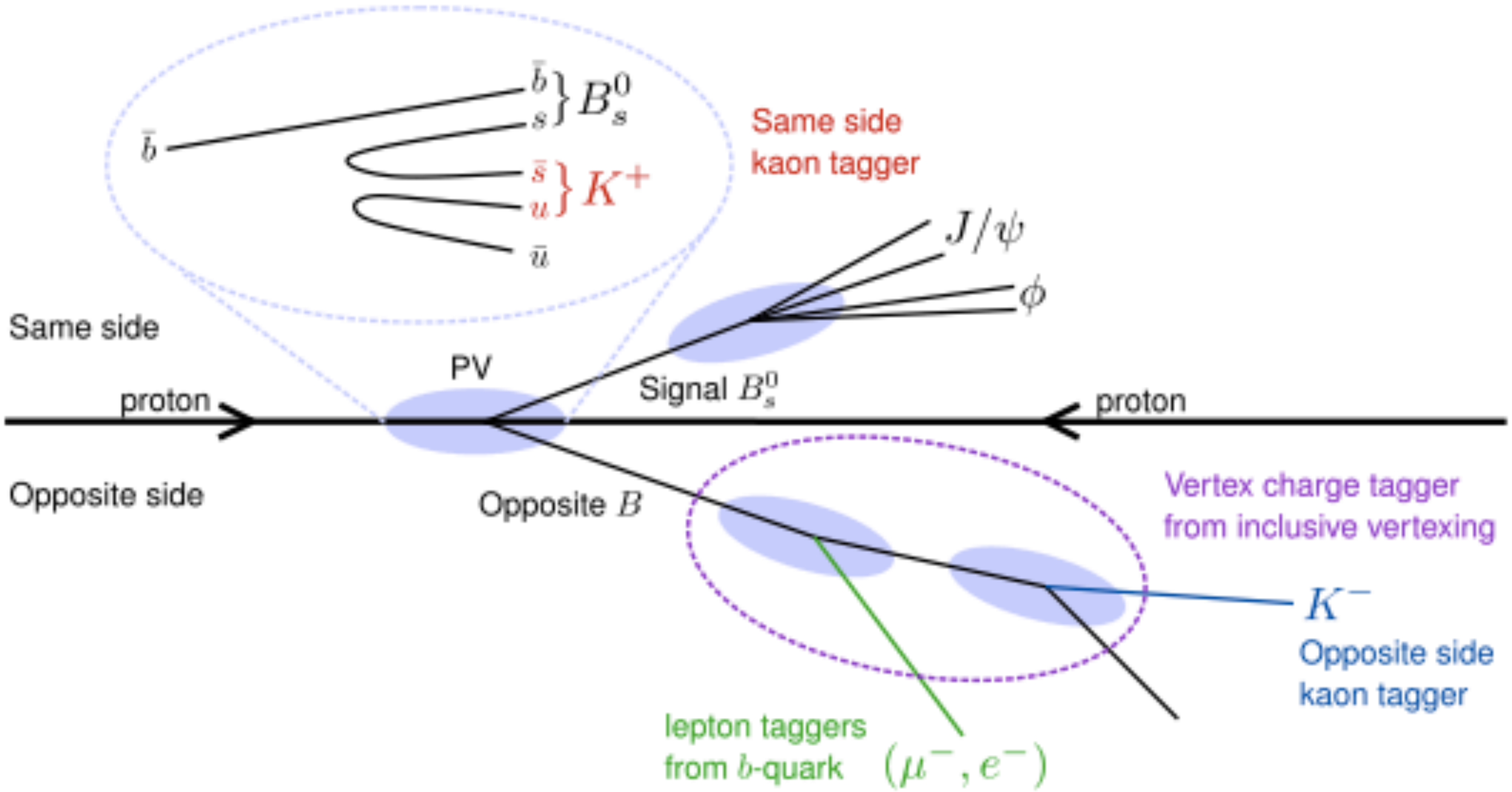
Mass
Time
Flavour Tagging
Angles

measure if a B_s or a $\overline{B}_s$ was produced (tagging)



Main differences wrt B-Factories :

- all the tracks from the hadronisation process (coud also be used for the SameSide tagging)
- the 'other' B can be of any flavour (if it is a B_s the information is lost …)
- several interactions in the same bunch crossing

The performances of the tagging algorithm are given by its efficiency and the mistag fraction

$$\varepsilon_{tag} = \frac{N_{tag}}{N_{tag} + N_{untag}} \text{ and } \omega = \frac{N_{rigth\ tag}}{N_{right\ tag} + N_{wrong\ tag}}$$

$$\varepsilon_{eff} = \varepsilon_{tag}(1-2\omega)^2$$ what really enters in the equations

If ε_{eff} = 10% , it is equivalent to have 10% of the signal events perfectly tagged ...

Opposite Side tagging requires the combination of several information :
- is there a lepton ? Is it from $b \to \ell$ or $c \to \ell$?
- is there a K ?
- what is the charge of the charm vertex ?

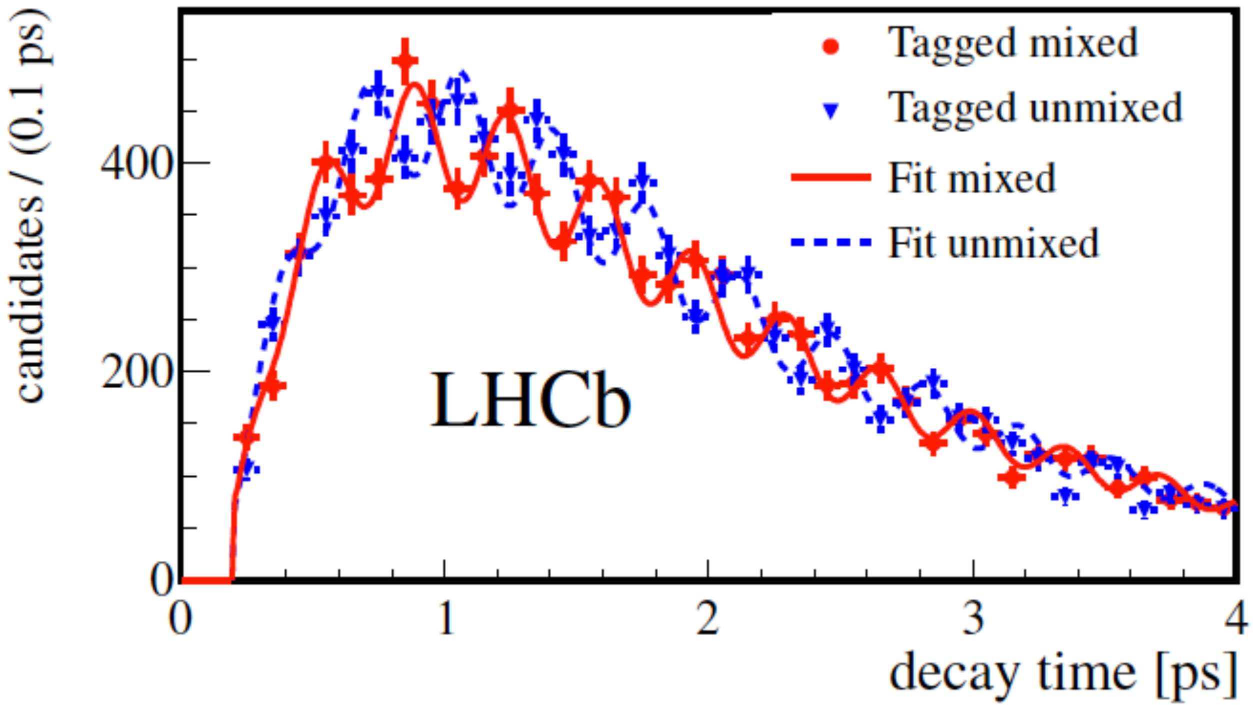
Same Side tagging :
- look for the closest hadronization track
- more difficult to calibrate

The tagging performances have to be calibrated on data

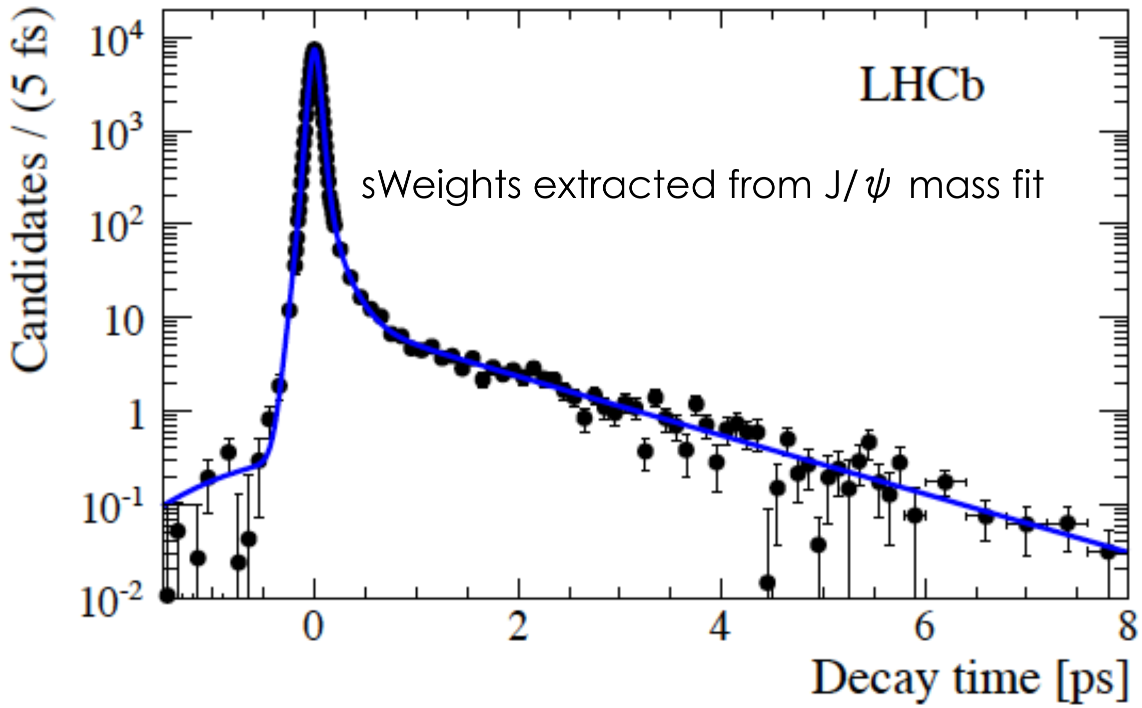
- Opposite side tagging : can use the $B^+ \to J/\Psi\ K^+$ to calibrate
- Same Side tagging has to be calibrated using $B_s \to D_s\ \pi$
- they have to be combined :

	ε_{tag} (%)	ω (%)	$\varepsilon_{tag}(1-2\omega)^2$ (%)
OS	33.00	36.83	2.29
SSK	10.26	35.27	0.89
Combined	39.36	35.90	3.13

OS tagging :a factor 10 smaller than at B-Factories !

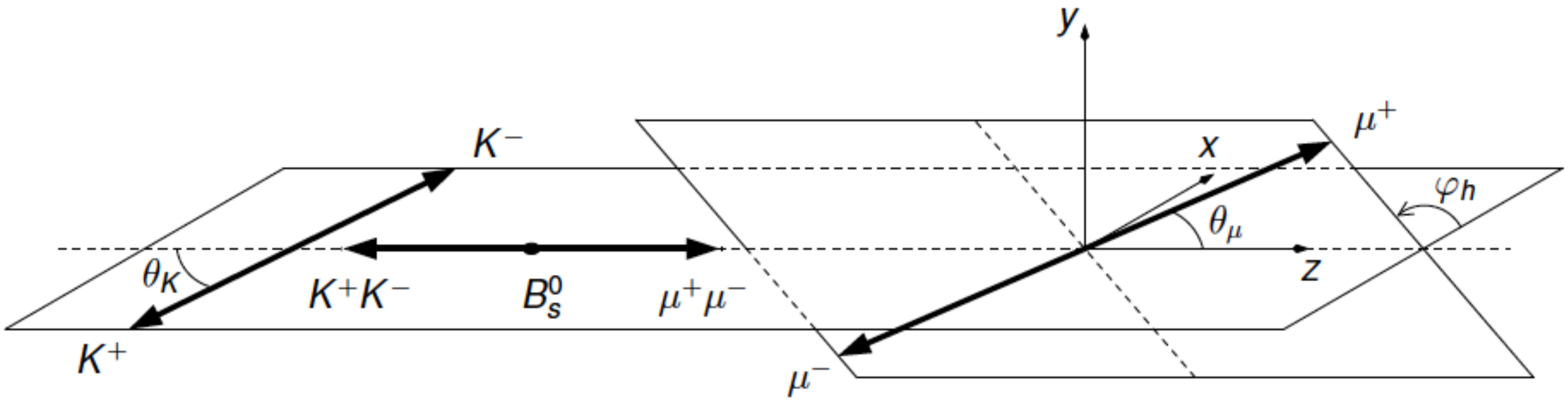


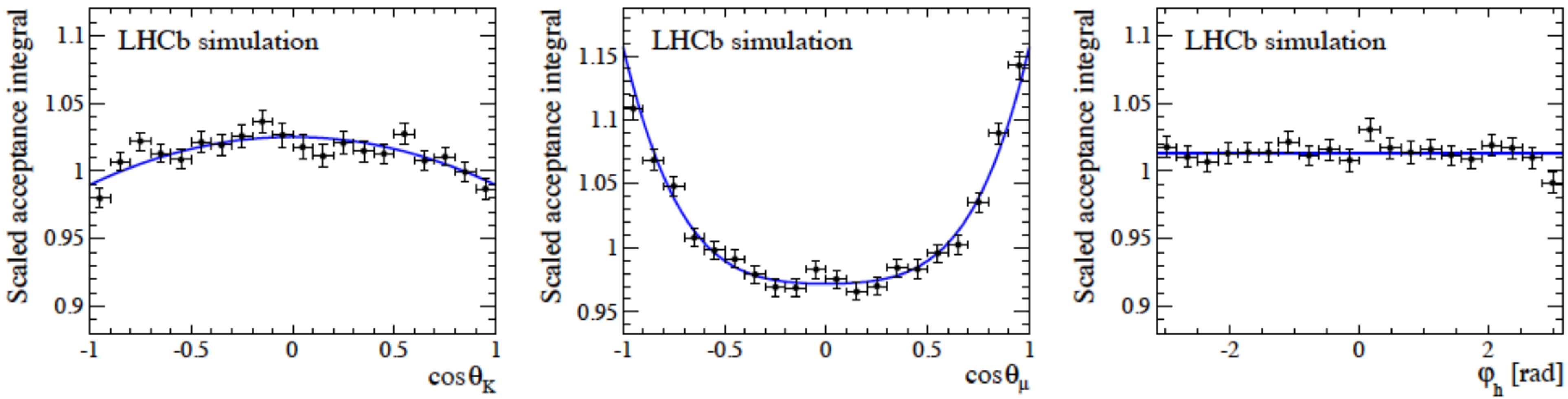
The B_s proper time



- Time measured from data using prompt J/ψ which decay at t = 0 ps triggered with unbiased triggers.
- Modeled with a triple Gaussian ⇒resolution 45 fs
- oscillation period : $2\pi/\Delta m_s \sim 350$ fs

But things are complicated wrt to sin2β measurement because J/Ψ Φ is a vector-vector final state and thus a mixture of CP-even and CP-odd final state :

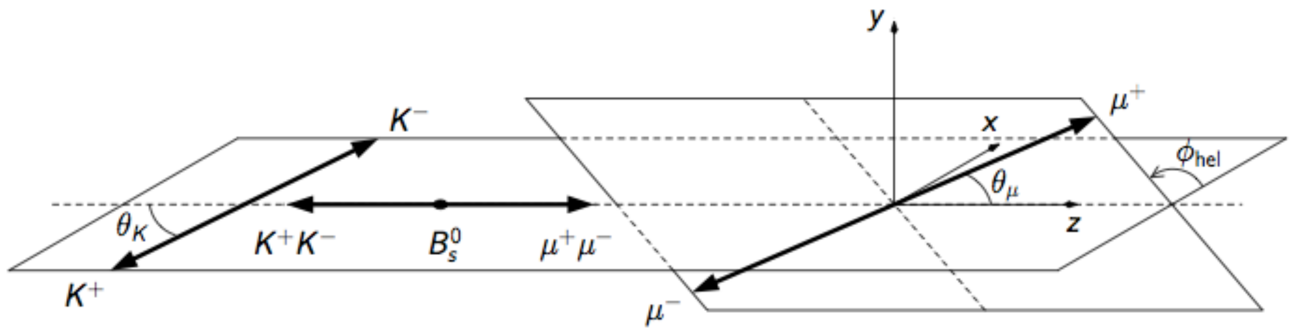




Forward geometry of LHCb + selections cuts : distorted angular acceptance
Determined using MC

57

Three amplitudes: A_0, $A_{||}$ (CP-even) and $A_\perp$ (CP-odd)



Complicated fit function ....

the 3 angles

$$\frac{d^4\Gamma(B_s^0 \to J/\psi\,\phi)}{dt\, d\Omega} \propto \sum_{k=1}^{10} h_k(t)\, f_k(\Omega)$$

the proper time

$$h_k(t) = N_k e^{-\Gamma_s t}\left[c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t) + a_k \cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right)\right].$$

in the a_k,b_k,c_k,d_k : Φ_s, 4 amplitudes (A_i) , 4 phases (δ_i) (1 overall normalisation , 1 overall phase)

$$\frac{\mathrm{d}^4\Gamma(B_s^0 \to J/\psi\,\phi)}{\mathrm{d}t\;\mathrm{d}\Omega} \propto \sum_{k=1}^{10} h_k(t)\, f_k(\Omega)$$

$$h_k(t) = N_k e^{-\Gamma_s t}\left[a_k \cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right],$$

k	$f_k(\theta_\mu, \theta_K, \varphi_h)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\theta_K \sin^2\theta_\mu$	$\lvert A_0\rvert^2$	1	D	C	$-S$
2	$\sin^2\theta_K\left(1-\sin^2\theta_\mu\cos^2\varphi_h\right)$	$\lvert A_\parallel\rvert^2$	1	D	C	$-S$
3	$\sin^2\theta_K\left(1-\sin^2\theta_\mu\sin^2\varphi_h\right)$	$\lvert A_\perp\rvert^2$	1	$-D$	C	S
4	$\sin^2\theta_K\sin^2\theta_\mu\sin 2\varphi_h$	$\lvert A_\parallel A_\perp\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{2}\sqrt{2}\sin 2\theta_K\sin 2\theta_\mu\cos\varphi_h$	$\lvert A_0 A_\parallel\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$-\frac{1}{2}\sqrt{2}\sin 2\theta_K\sin 2\theta_\mu\sin\varphi_h$	$\lvert A_0 A_\perp\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}\sin^2\theta_\mu$	$\lvert A_S\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\theta_K\sin 2\theta_\mu\cos\varphi_h$	$\lvert A_S A_\parallel\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$-\frac{1}{3}\sqrt{6}\sin\theta_K\sin 2\theta_\mu\sin\varphi_h$	$\lvert A_S A_\perp\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\theta_K\sin^2\theta_\mu$	$\lvert A_S A_0\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

$$C \equiv \frac{1-|\lambda|^2}{1+|\lambda|^2} \qquad S \equiv -\frac{2|\lambda|\sin\phi_s}{1+|\lambda|^2} \qquad D \equiv -\frac{2|\lambda|\cos\phi_s}{1+|\lambda|^2} \qquad \lambda_i \equiv \frac{q}{p}\frac{\bar{A}_i}{A_i}$$

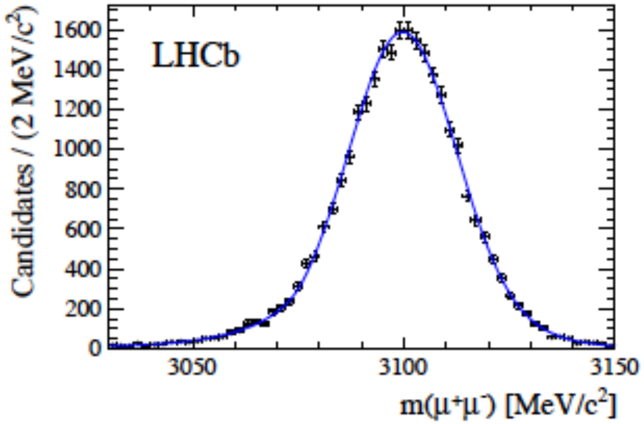
two-fold ambiguity in solution: fit function invariant under transformation

$$(\phi_s, \Delta\Gamma_s, \delta_\parallel, \delta_\perp) \leftrightarrow (\pi-\phi_s, -\Delta\Gamma_s, 2\pi-\delta_\parallel, -\delta_\perp)$$

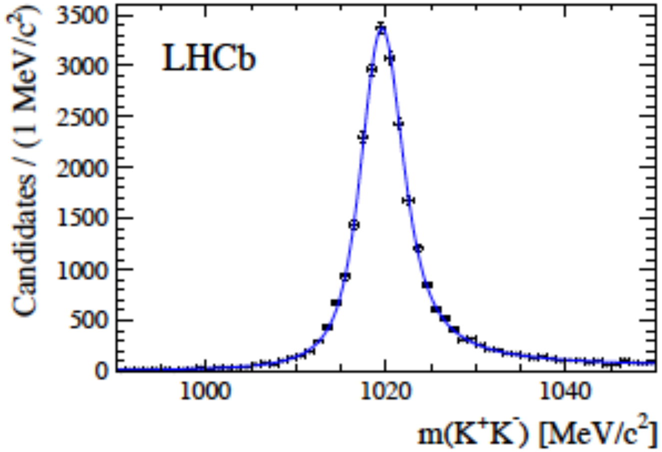
British poster (1939)

A simple selection (cut based)

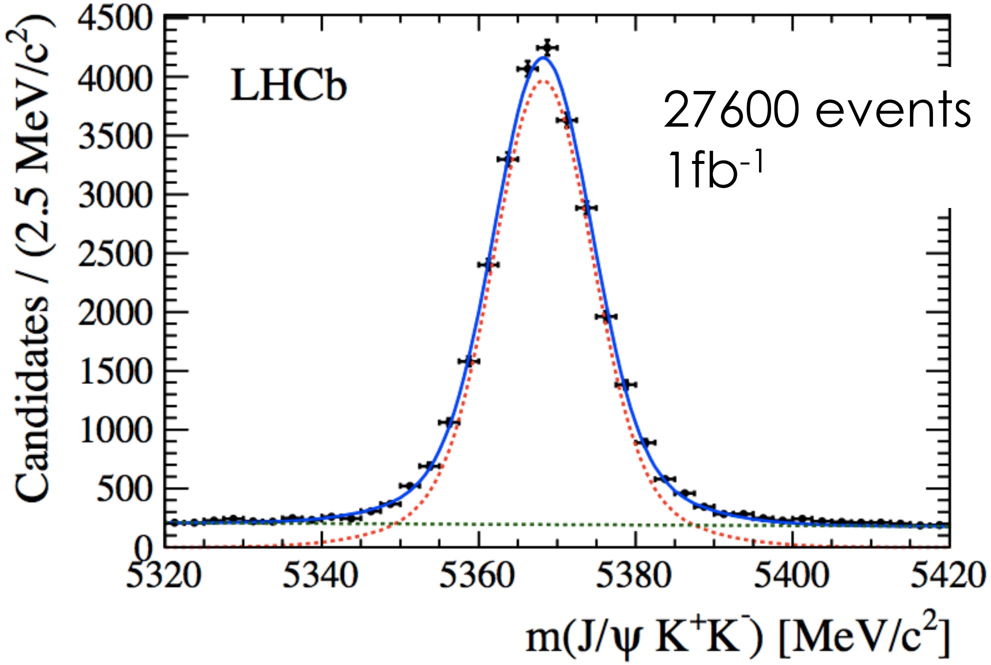
$J/\psi \to \mu^+\mu^-$



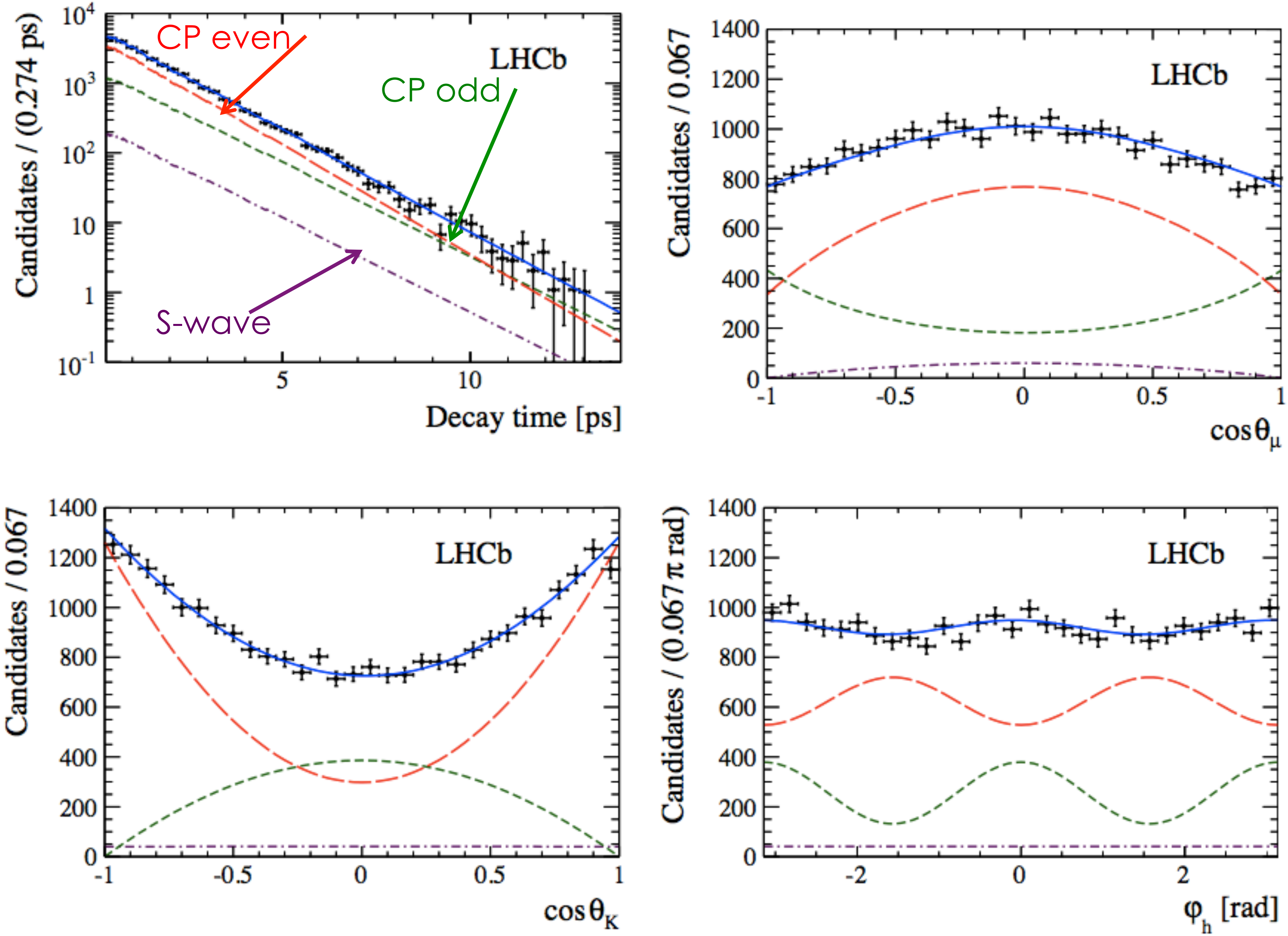
$\phi \to K^+K^-$



very large sample of selected events :

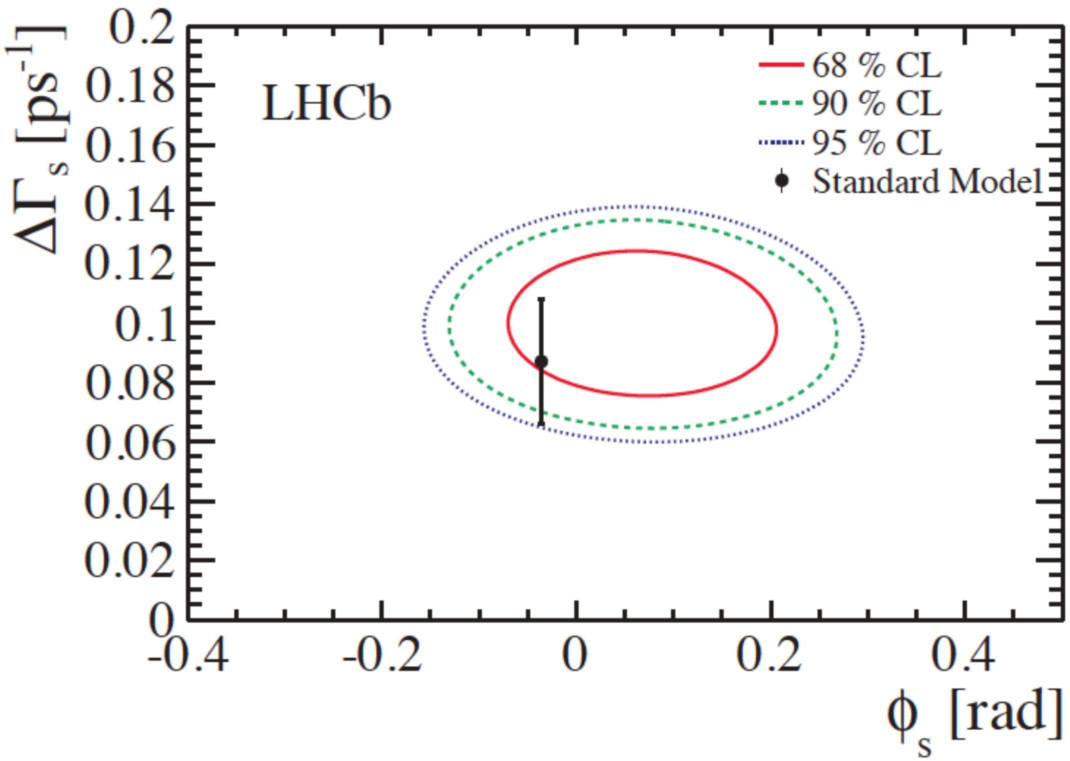


27600 events
$1 fb^{-1}$


CP even
CP odd
S-wave
LHCb
Candidates / (0.274 ps)
Decay time [ps]
Candidates / 0.067
$\cos\theta_\mu$
$\cos\theta_K$
Candidates / (0.067 π rad)
φ_h [rad]

But two-fold ambiguity in solution: fit function invariant under transformation

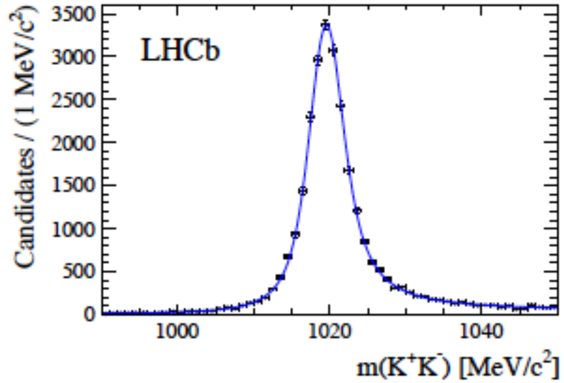
$$(\phi_s, \Delta\Gamma_s, \delta_\parallel, \delta_\perp) \leftrightarrow (\pi-\phi_s, -\Delta\Gamma_s, 2\pi-\delta_\parallel, -\delta_\perp)$$



where is the $(\pi\text{-}\Phi_s, -\Delta\Gamma_s)$ solution ?

$(\phi_s, \Delta\Gamma_s, \delta_\parallel, \delta_\perp) \leftrightarrow (\pi-\phi_s, -\Delta\Gamma_s, 2\pi-\delta_\parallel, -\delta_\perp$

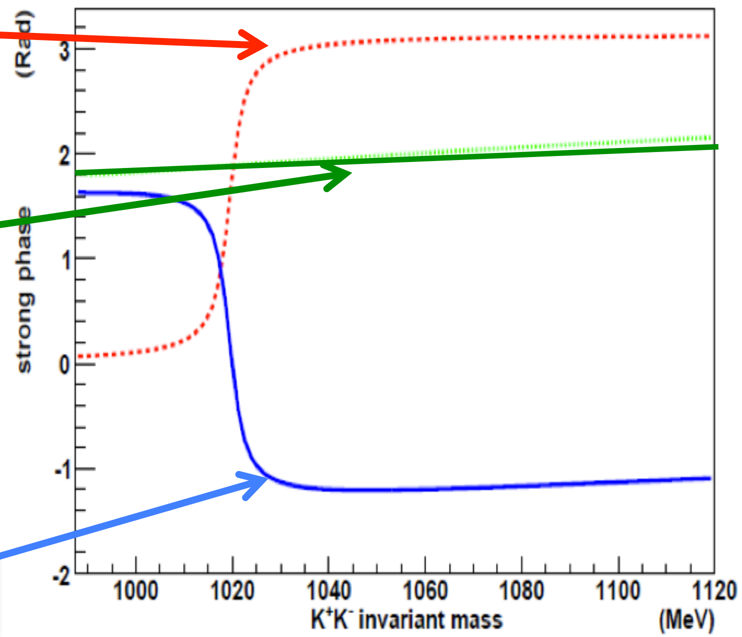
$\phi \to K^+K^-$



K^+K^- P-wave :
Phase of Breit-Wigner amplitude increases rapidly across $\phi(1020)$ mass region

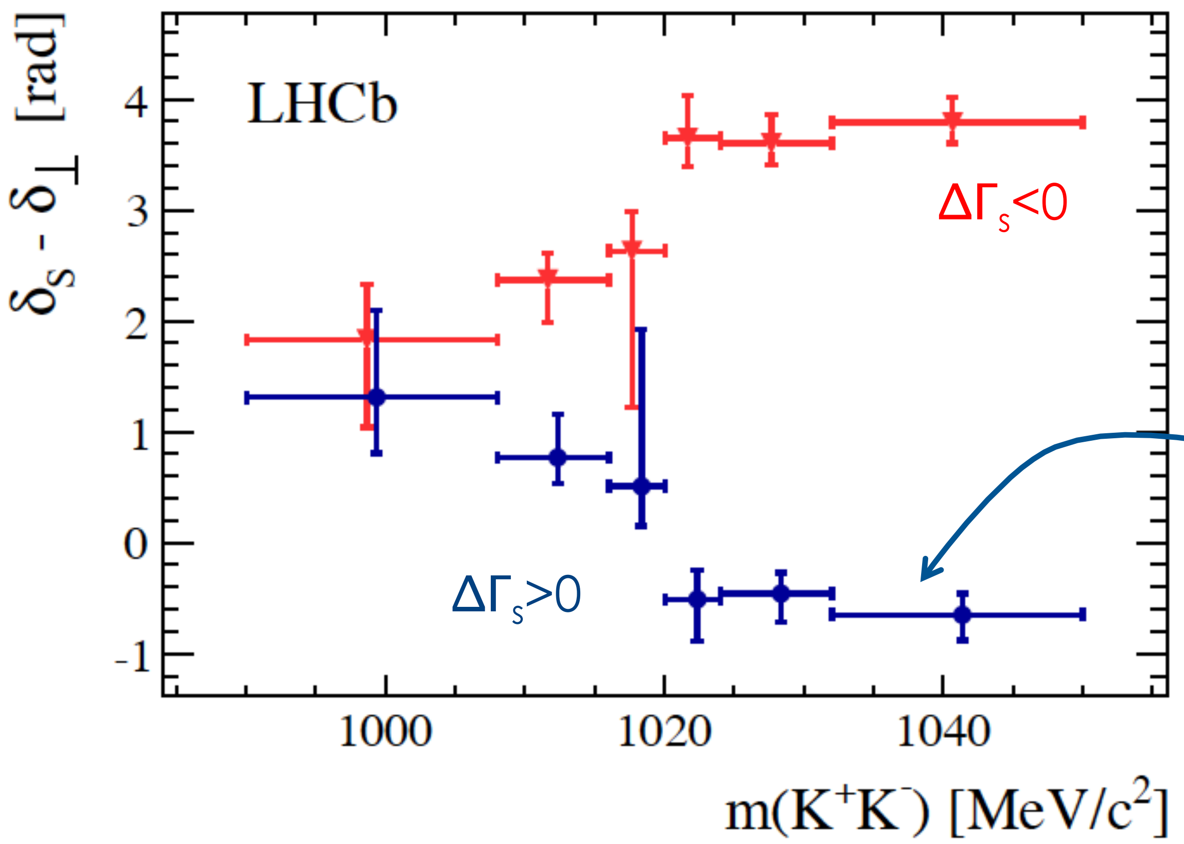
K^+K^- S-wave:
Phase of Flatté amplitude for f0(980) relatively flat (similar for non-resonance)

Phase difference between S- and P-wave amp
$\delta_{S\perp} = \delta_S - \delta_\perp$ decreases rapidly across $\phi(1020)$ mass region



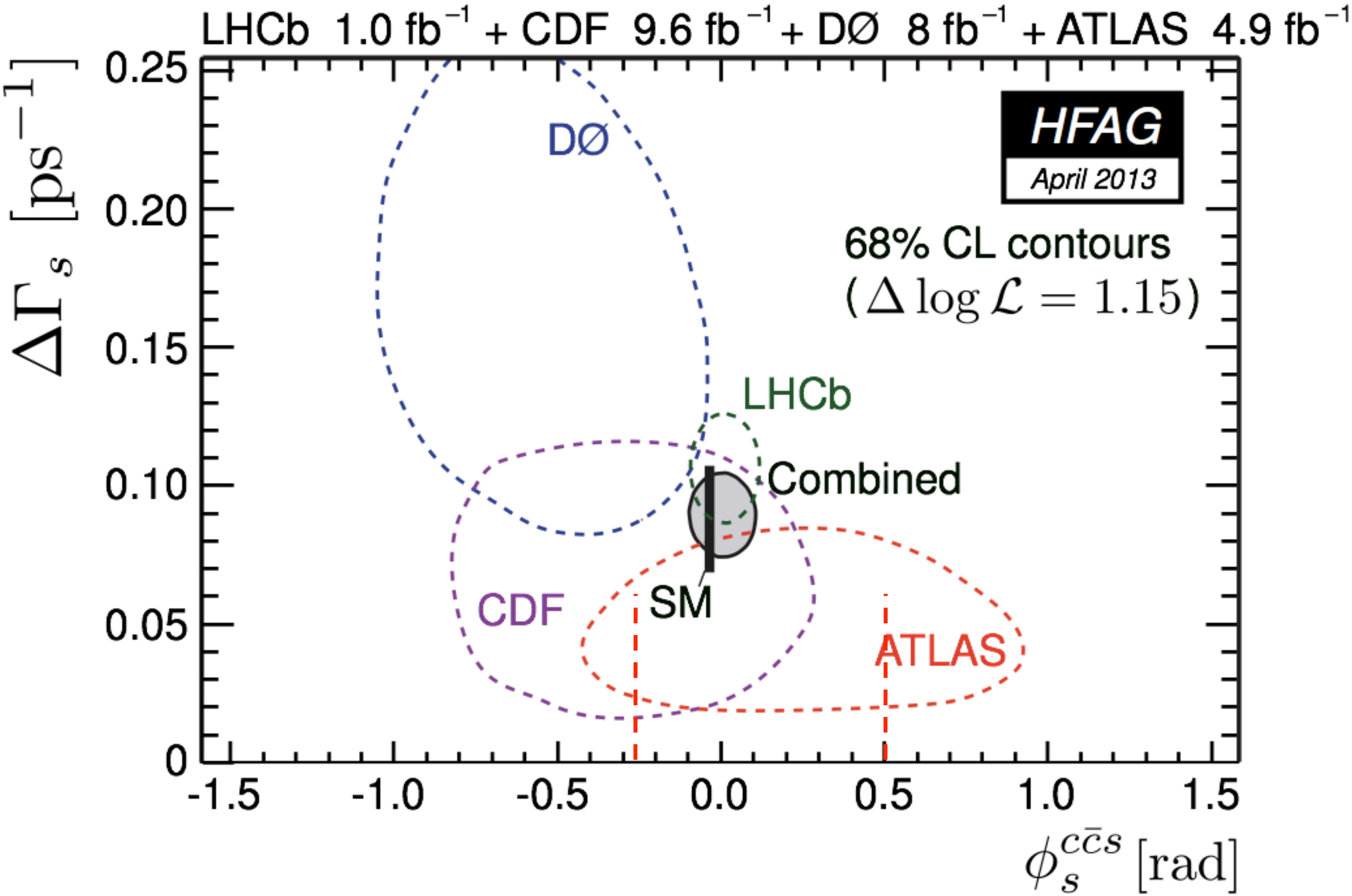
M(KK)

The fit is done in bins of M(KK) :



This is the physical behaviour (decrease of $\delta_{S\perp}$)

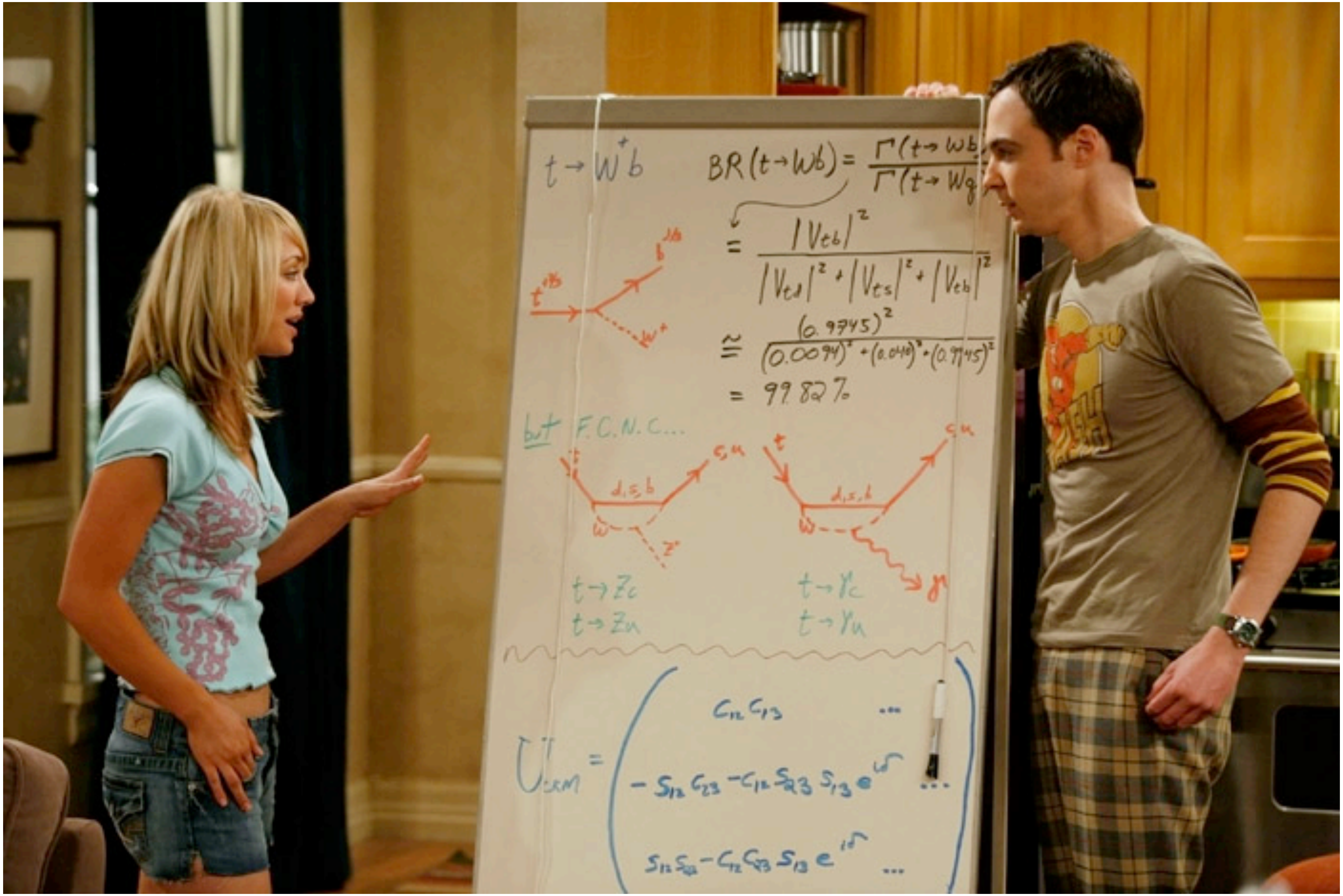
The sign of $\Delta\Gamma_s$ is known !



A very recent result from ATLAS has improved errors on Φ_s

Rare decays : FCNC

FCNC :


t → W⁺b
BR(t→Wb) =
= |Vtb|² / (|Vtd|² + |Vts|² + |Vtb|²)
= 99.82%
but F.C.N.C...
d,s,b
t → Zc
t → Zu
t → γc
t → γu

basics requirements :

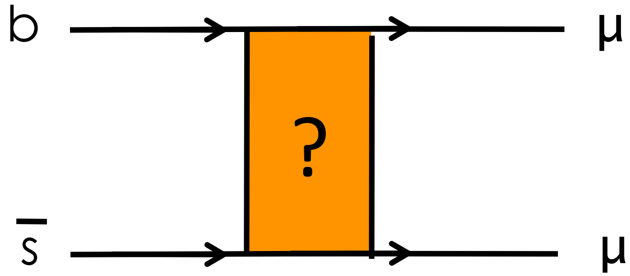
- should not be ruled out by existing measurements

- predictions from SM should be well known

⇒ Flavour Changing Neutral Currents (FCNC) :

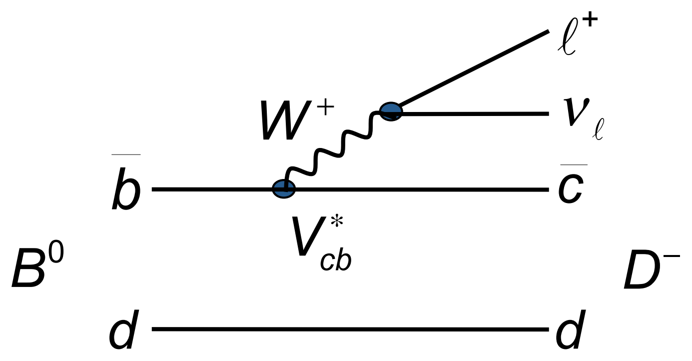
- forbidden in SM at tree level, suppressed at higher-order due to GIM mechanism ⇒ rare decays !

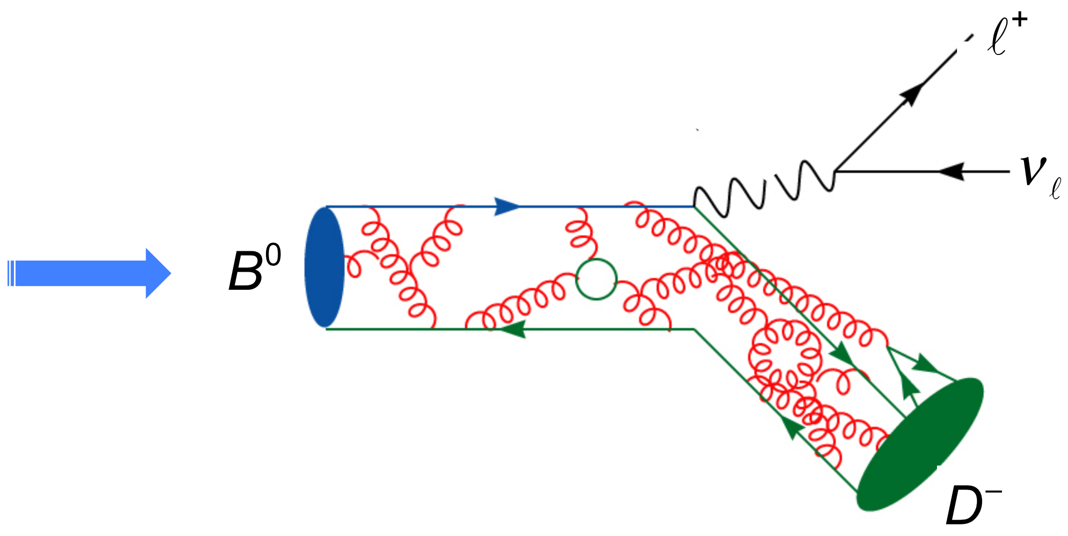
- New virtual particles can appear in box and/or penguins diagrams



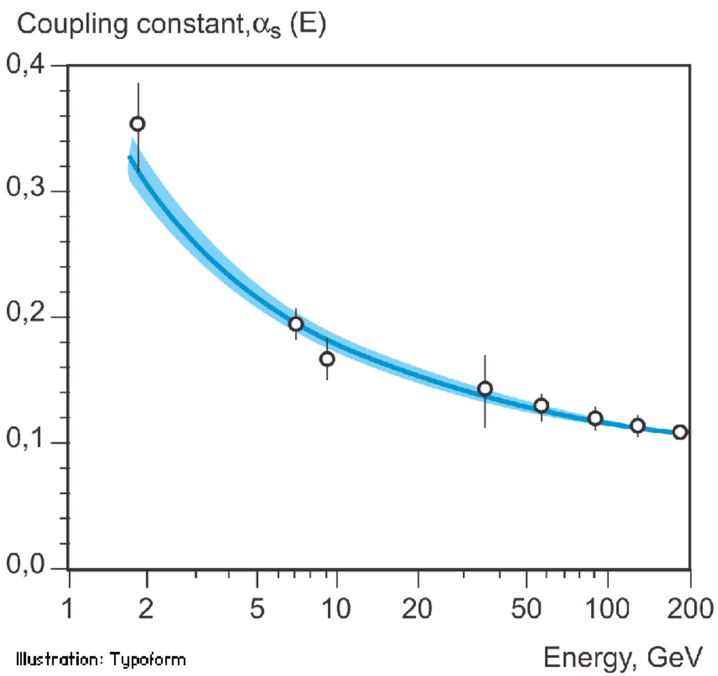
measurements of branching ratios, angular distributions : compare with theoretical predictions from SM ; if deviations are seen : New Physics

Feynman graphs can be computed at quark level but ....





the coupling constant increases
when the energy decreases



⇒ cannot use perturbation theory to calculate the (soft) QCD effects (hadronic effects)

Theoretical approach : Operator Product Expansion (as seen by an experimentalist)

Allows to separate

- the low energy effects (non-perturbative QCD, difficult to calculate), form factors, decay constants …

- the high-energy effects (perturbative QCD + weak interaction+ potential New Physics)

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \Big(\sum_{i=1\cdots 10,S,P} \big(C_i(\mu)\mathcal{O}_i(\mu) + C_i'(\mu)\mathcal{O}_i'(\mu)\big)\Big)$$

μ is the limit between the two regimes (few GeV)

The b→s transition is particularly interesting to search for NP :

- modified Wilson coefficients : $C_i+\Delta C_i$
- new operators : $C^{NP}_j O^{NP}_j$

$B_{d,s} \rightarrow \mu\ \mu$

This is were the non-perturbative QCD is hidden

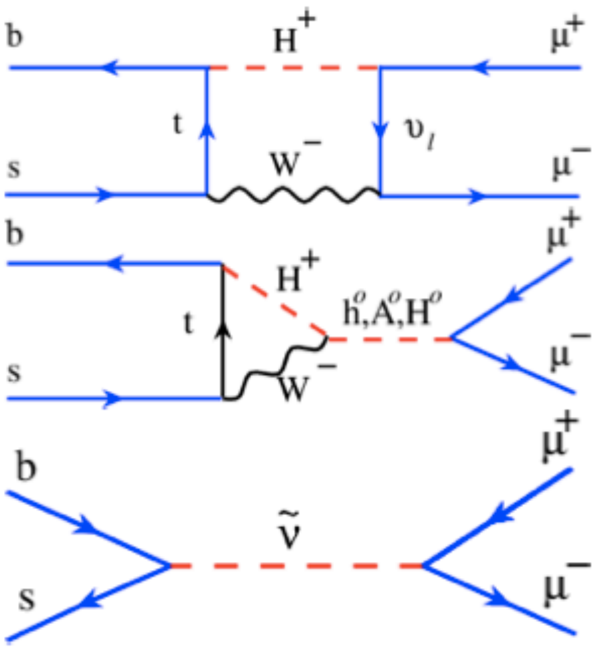
$$\mathrm{BR}(B_s \to \mu^+\mu^-) = \frac{G_F^2\alpha^2}{64\pi^3} f_{B_s}^2 \tau_{B_s} m_{B_s}^3 |V_{tb}V_{ts}^*|^2 \sqrt{1-\frac{4m_\mu^2}{m_{B_s}^2}}$$
$$\times \left\{ \left(1-\frac{4m_\mu^2}{m_{B_s}^2}\right) |C_S - C_S'|^2 + \left|(C_P - C_P') + 2\,(C_{10} - C_{10}')\,\frac{m_\mu}{m_{B_s}}\right|^2 \right\}$$

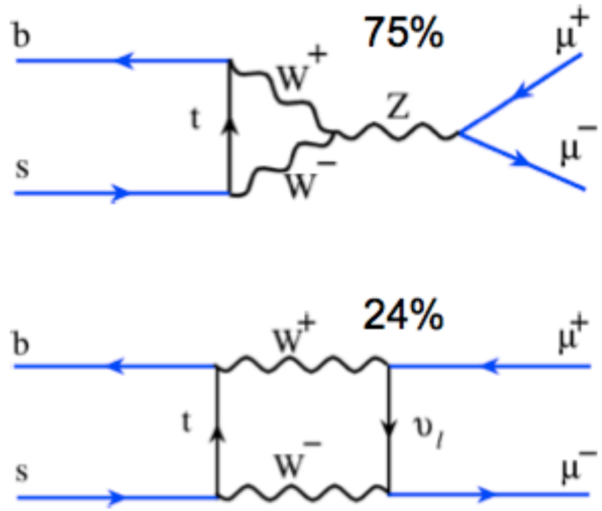
SM

In MSSM: $c_{S,P}^{MSSM\,2} \propto \dfrac{m_b^2 m_\mu^2 \tan^6\beta}{M_A^4}$

2HDM:

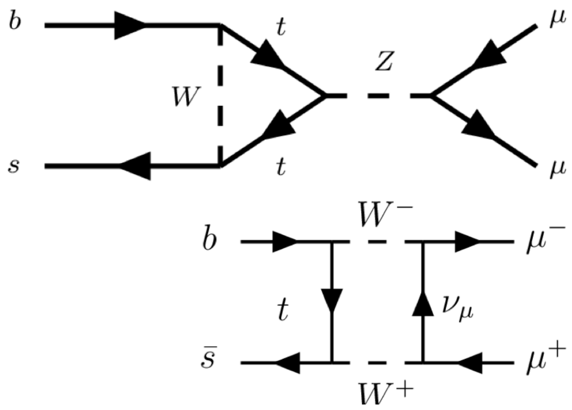
RPV:

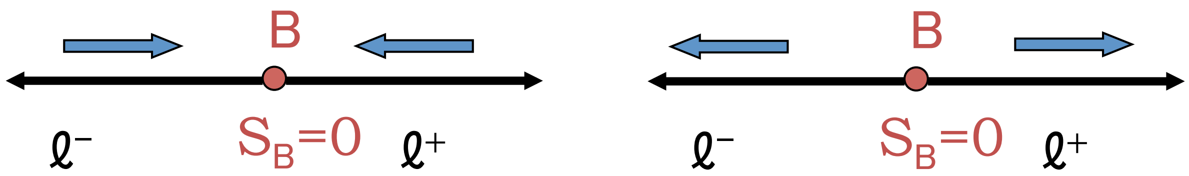




SM Higgs contribution < 1%

Total spin has to be conserved:





left-handed particle
left-handed anti-particle

right-handed particle
right-handed anti-particle

SM : very rare (V_{tq}, helicity suppression)

In the SM, in the massless limit: left-handed anti-particle &right-handed particle are forbidden

	$\mathcal{B}(B_d^0 \to \ell^+\ell^-)$	$\mathcal{B}(B_s^0 \to \ell^+\ell^-)$
$\ell = e$	$(2.40 \pm 0.34) \times 10^{-15}$	$(8.15 \pm 1.29) \times 10^{-14}$
$\ell = \mu$	$(1.00 \pm 0.14) \times 10^{-10}$	$(3.42 \pm 0.54) \times 10^{-9}$
$\ell = \tau$	$(2.90 \pm 0.41) \times 10^{-8}$	$(9.86 \pm 1.55) \times 10^{-7}$

(old numbers)

Latest SM predictions:

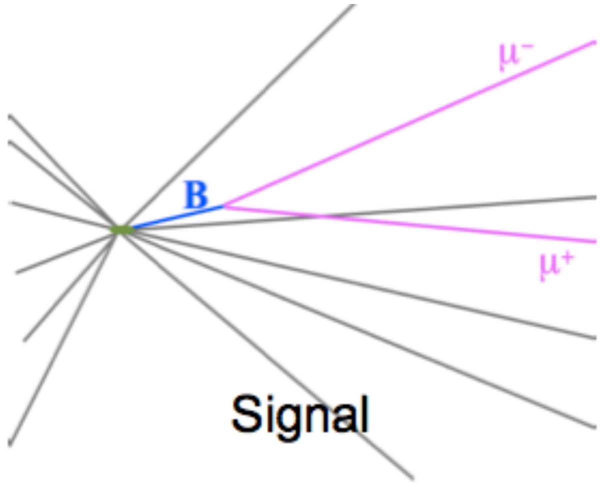
$$B^0\,(B_s^0 \to \mu^+\mu^-)_{SM} = (3.25\ \pm 0.17) \times 10^{-9}$$
$$B\,(B^0 \to \mu^+\mu^-)_{SM} = (1.07 \pm 0.10)\ \times 10^{-10}$$

Time integrated BR: PRD86, 014027

$$\langle B(B_s^0\ \to \mu^+\mu^-)_{SM}\rangle = B^0/(1-y_s)$$
$$= (3.46\ \pm 0.18) \times 10^{-9}$$

Search for B_d and B_s: the branching fractions could be modified differently by New Physics

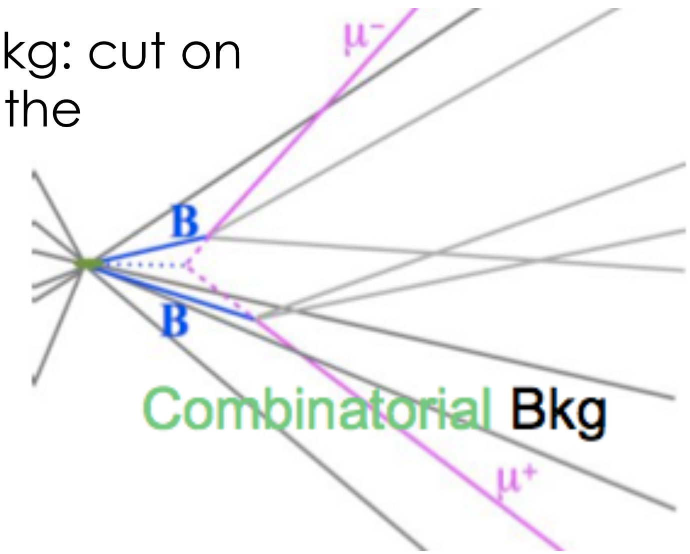
How to select so rare events ?



Selection should be:
- very efficient for the signal
- similar for signal and control channels

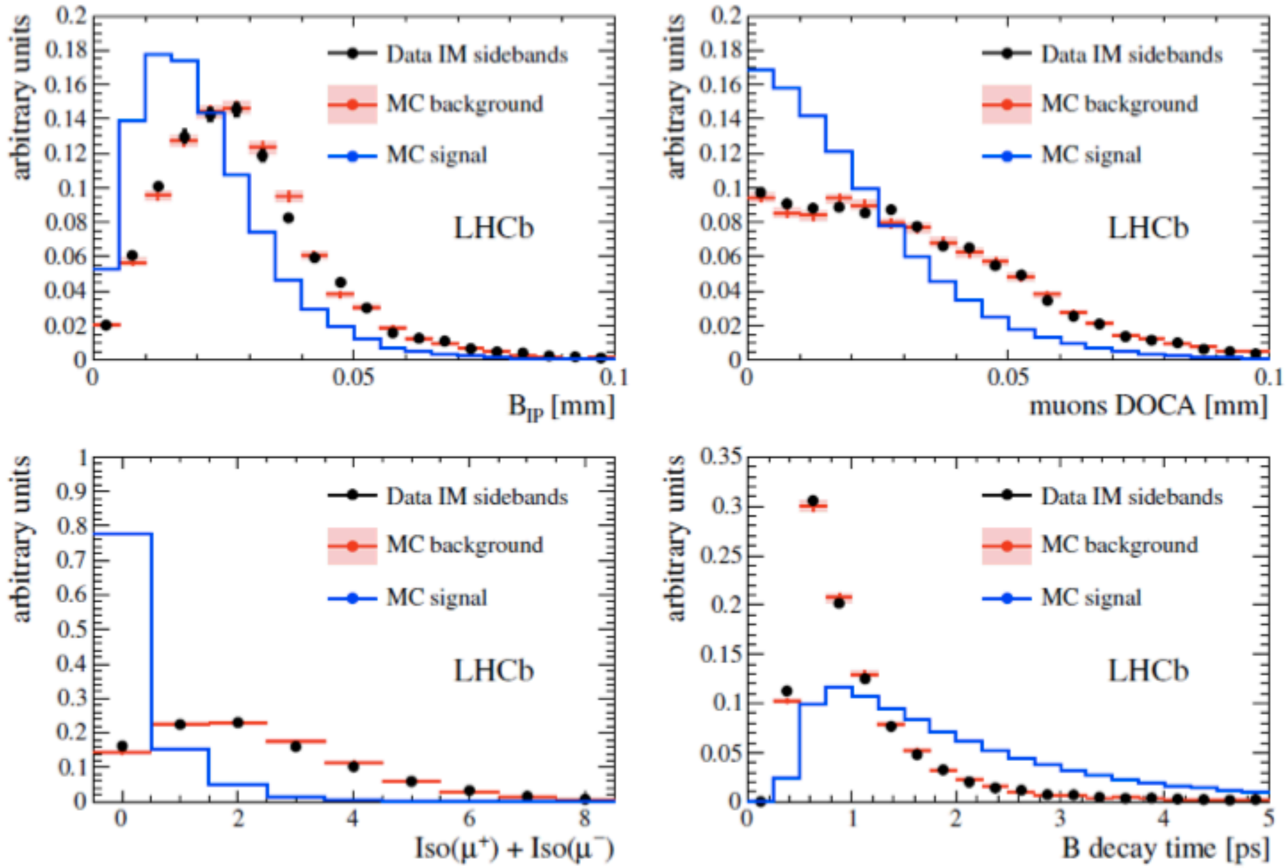
- Initial selection requires:
    - good tracks with a large impact parameter
    - good and displaced secondary vertex pointing to the primary vertex
    - good particle ID to remove $B \rightarrow h^+h^{-\prime}$ $(\mu^+\mu^-)$Signal

- Tighten initial selection to reduce combinatorial bkg: cut on the output of a MVA combining information about the candidate topology



70% bkg rejection
95% signal efficiency

- Boosted Decision Tree
- Inputs : 9 inputs variables uncorrelated with $m_{\mu\mu}$
- Trained and tested on MC signal and $b\bar{b} \to \mu\mu X$

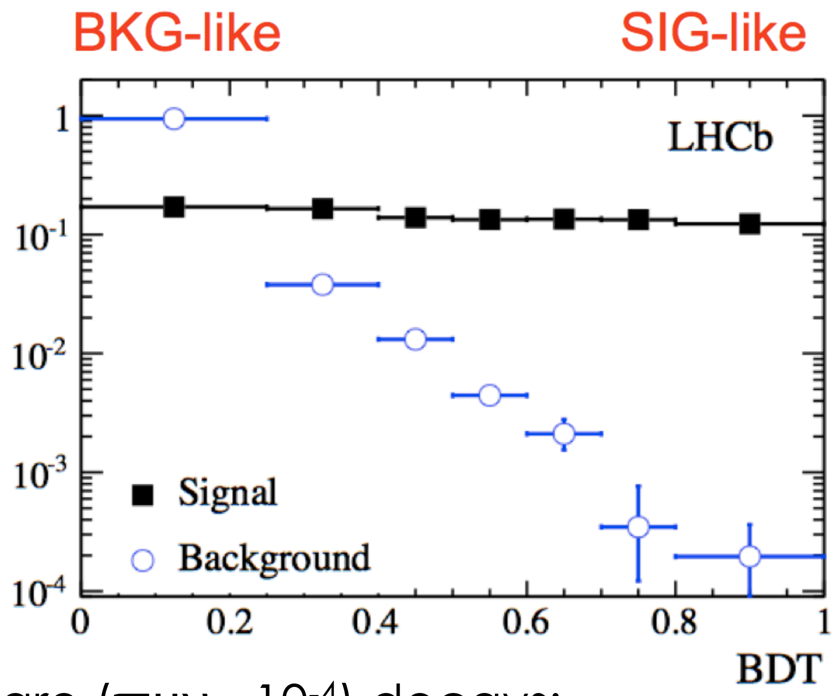


B candidate:
- **proper time**
- impact parameter
- transverse momentum
- B isolation

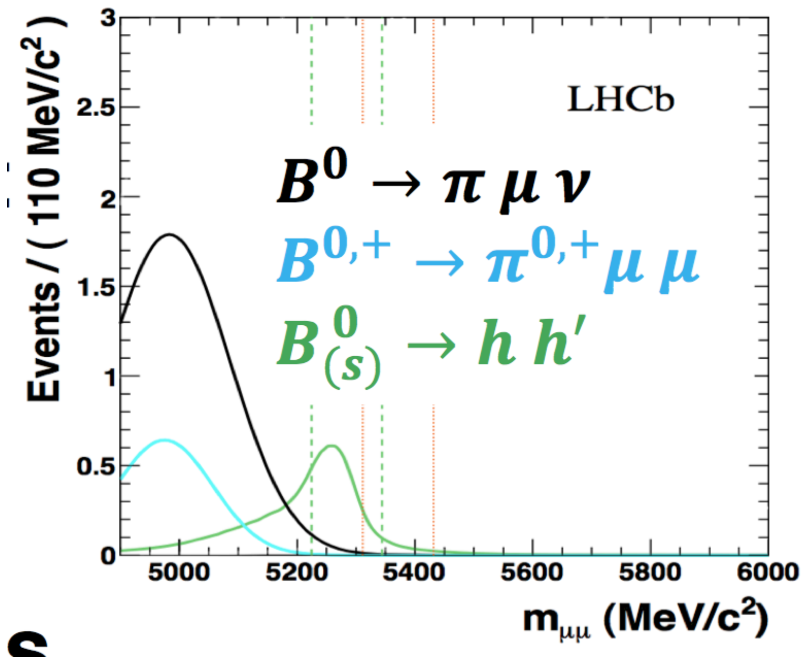
muons:
- min p_T
- **min IP significance**
- dist. of closest approach
- muon isolation,
- polarisation angle

two variables :
- the 2 muons invariant mass
- the BDT output

Flat on signal (by design)



One also has to worry about some rare ($\pi\mu\nu$ ~10^{-4}) decays:



the observed (or not) yield has to be translated into into a BF !

- Number of signal events corresponding to a B :

$$N_{B^0_{(s)}\to\mu^+\mu^-} \propto B(B^0_{(s)} \to \mu^+\mu^-) \times \boldsymbol{N_{B_s}}$$

- $\boldsymbol{N_{B_s}}$ obtained with a channel of known BR:

$$N_{B_s} \propto \frac{N_{B^+\to J/\psi K^+}}{B(B^+ \to J/\psi K^+)} \times \frac{f_s}{f_u} \qquad N_{B_s} \propto \frac{N_{B^0\to K\pi}}{B(B^0 \to K\pi)} \times \frac{f_s}{f_d}$$

- Correcting for efficiencies:

$$\boldsymbol{N(B^0_s \to \mu^+\mu^-) = B(B^0_{(s)} \to \mu^+\mu^-) \times \frac{N_{norm}}{B_{norm}} \frac{\epsilon^{REC}_{sig}\,\epsilon^{SEL,REC}_{sig}}{\epsilon^{REC}_{norm}\,\epsilon^{SEL,REC}_{norm}} \frac{\epsilon^{TRIG,SEL}_{sig}}{\epsilon^{TRIG,SEL}_{norm}} \frac{f_{B^0_{(s)}}}{f_{norm}}}$$

Extracted from Data

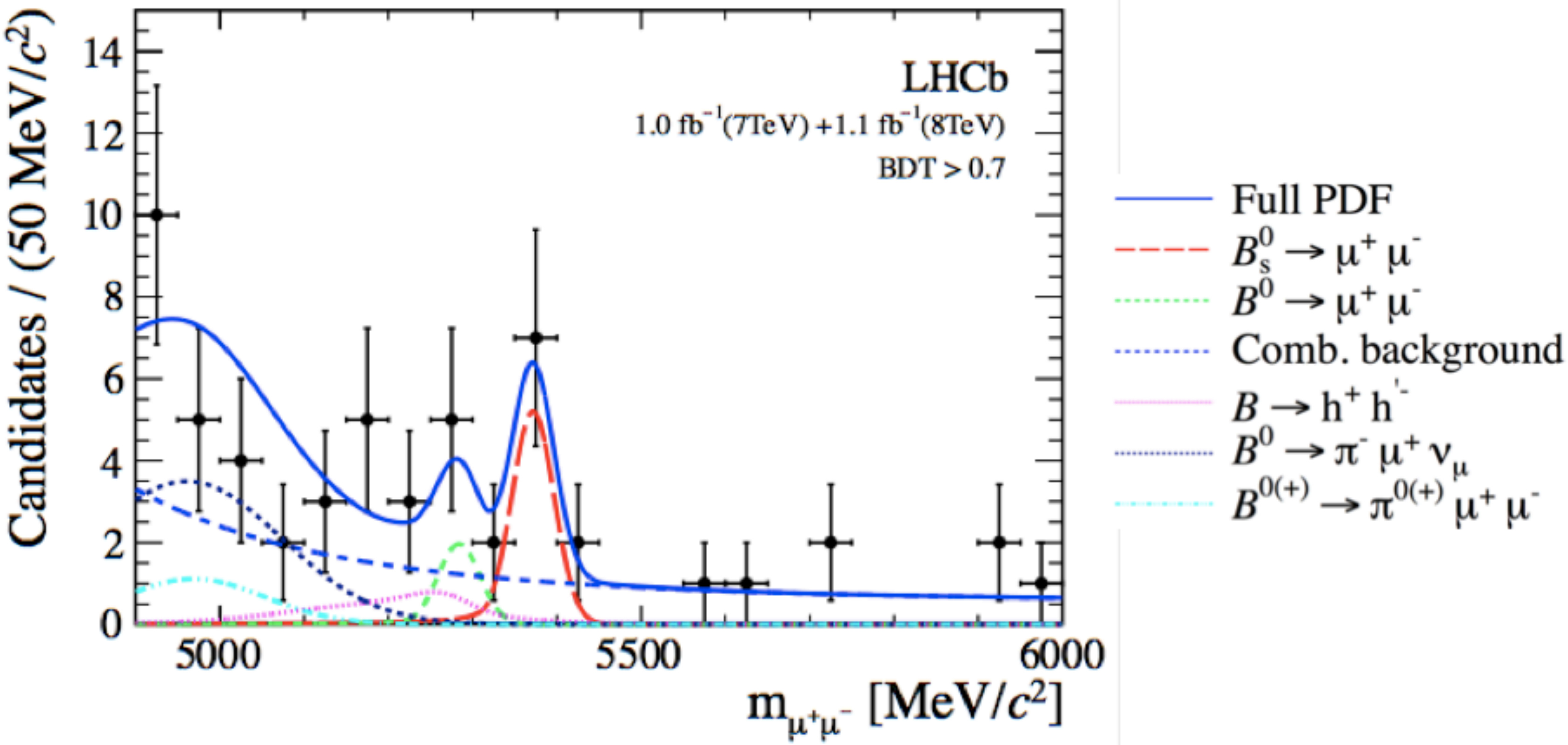
Evaluated from MC, x-checked with data

Measured on data

Ratio of prob for a b quark to hadronise into a $\boldsymbol{B^0_{(s)}}$ or into the norm. init. state

SM expectations 2012+2011 in the mass windows:
13 + 11 $\boldsymbol{B^0_s \to \mu^+\mu^-}$ and **1.5 + 1.3** $\boldsymbol{B^0 \to \mu^+\mu^-}$

Events in the high BDT region:

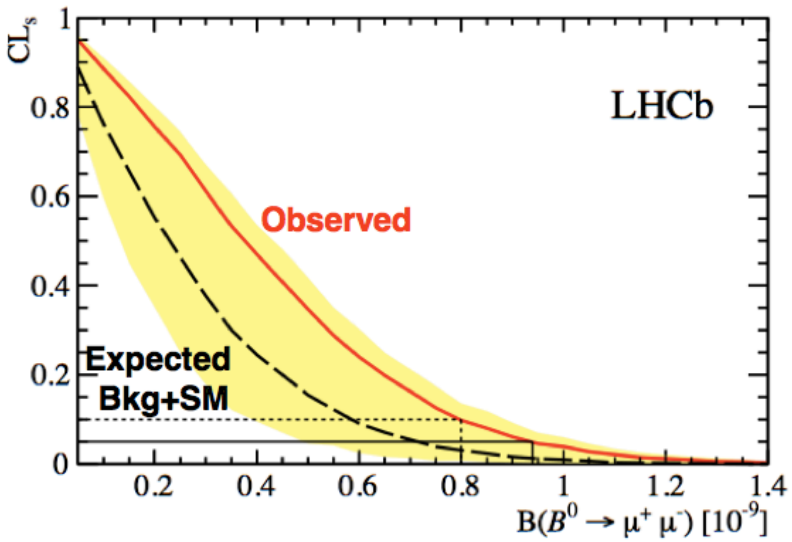


$$B(B_s^0 \to \mu^+\mu^-) = \left(3.2^{+1.5}_{-1.2}\right) \times 10^{-9}$$

Value in agreement with SM time integrated prediction :

$$B(B_s^0 \to \mu^+\mu^-)_{SM} = (3.46 \pm 0.18) \times 10^{-9}$$

What about $B_d \to \mu\mu$?



Compatibility with bkg only hypothesis:

p-value = 11%

Obs. limit: $B(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10}$ at 95% CL

Exp. limit: $B(B^0 \to \mu^+\mu^-) < 7.1 \times 10^{-10}$ at 95% CL

What is the CLs method ?

Idea : compare the observed data with expectations

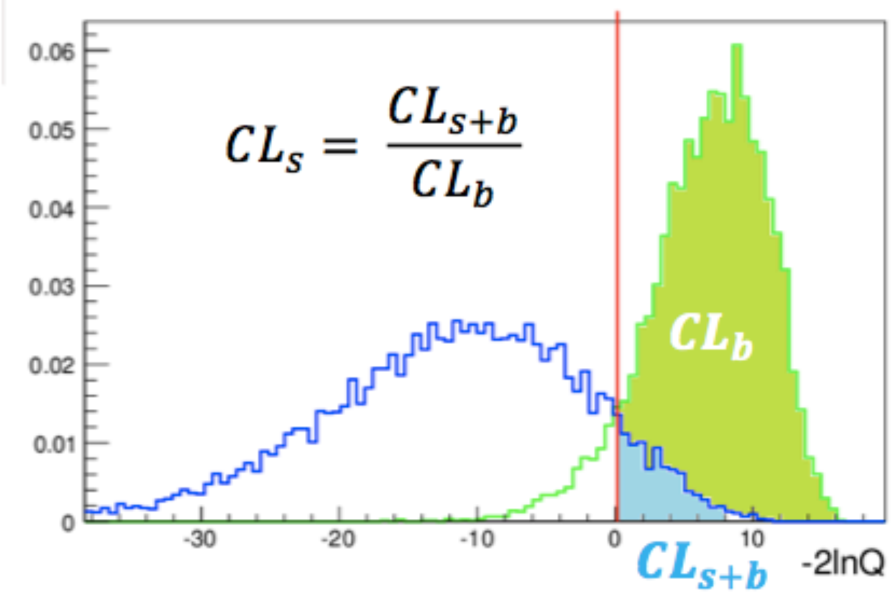
Define a test statistic for this comparison : -2lnQ

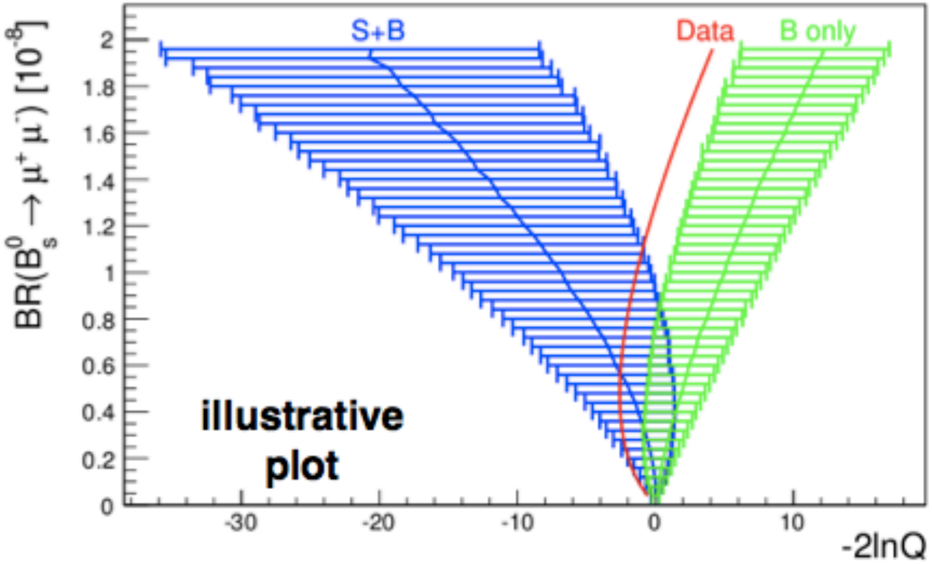
Calibrate -2lnQ with pseudo experiments:
if BR = br then

- -2lnQ would take this value for background only
- -2lnQ would take this value for Signal + background only

Compute -2lnQ for the observed data

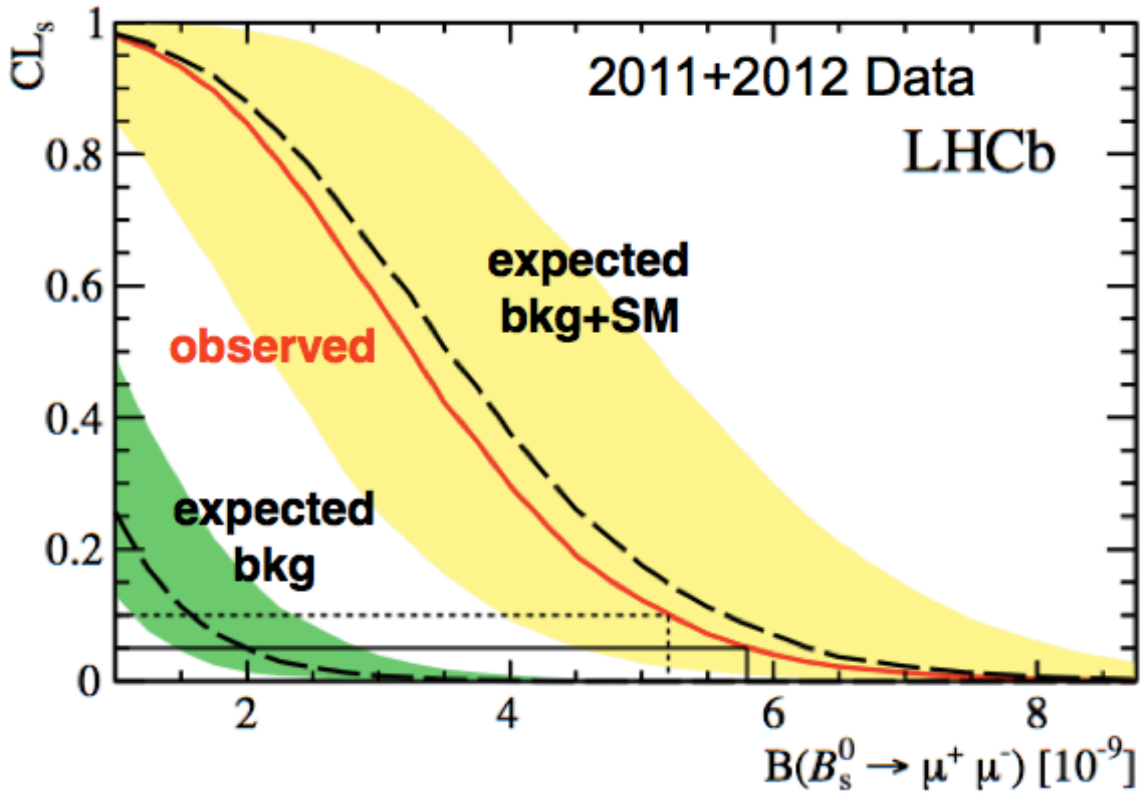
BR = br





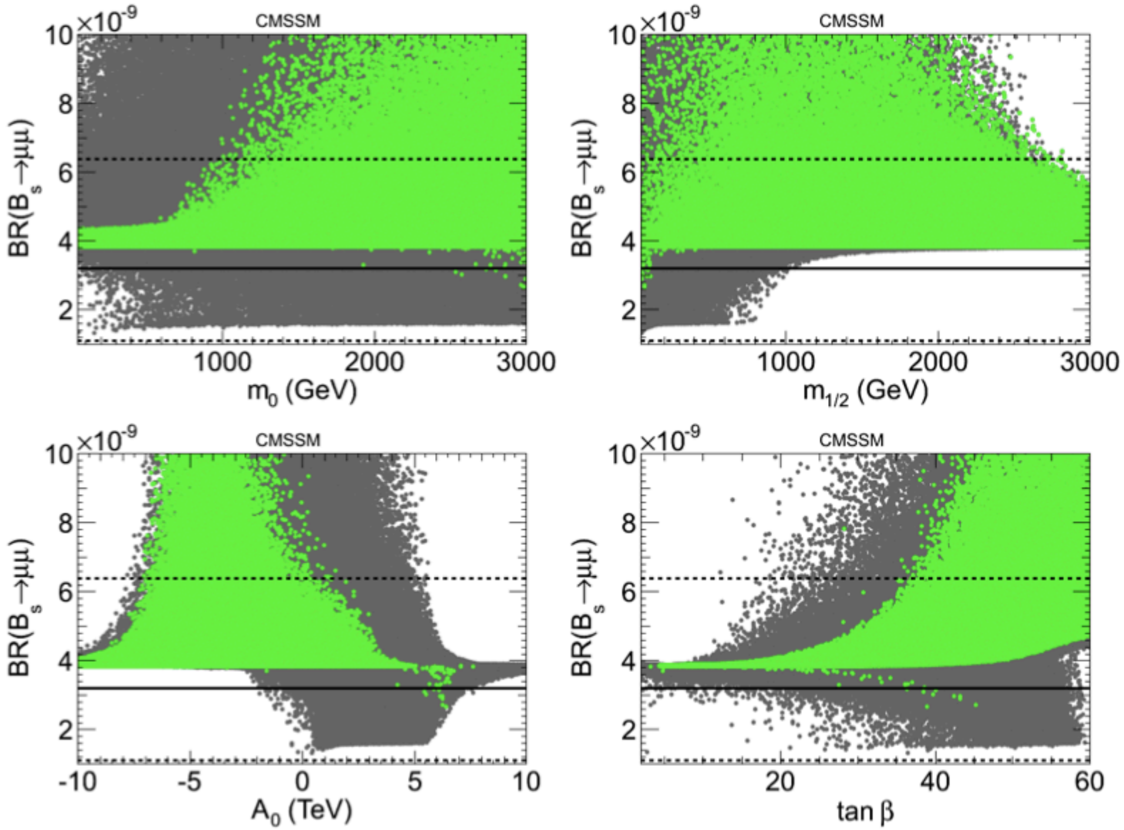
$B_s \to \mu\mu$

good separation between bkg only and bkg+SM expectations



Bkg only p-value: 5.3×10^{-4}

An example of the impact on CMSSM:



A. Arbey, M. Battaglia, FM, D. Martinez Santos, Phys.Rev. D87 (2013) 035026

Solid line: central value of the BR($B_s \to \mu^+\mu^-$) measurement

Dashed lines: 2σ experimental deviations

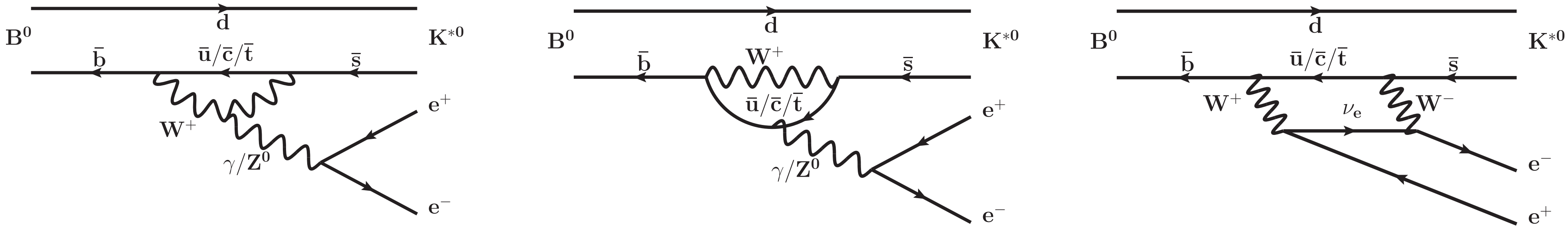
Gray points: all valid points

Green points: points in agreement with the Higgs mass constraint

In this (simple) scenario : the Higgs mass constraint and a BR($B_s \to \mu\,\mu$) smaller than the SM value are not compatible

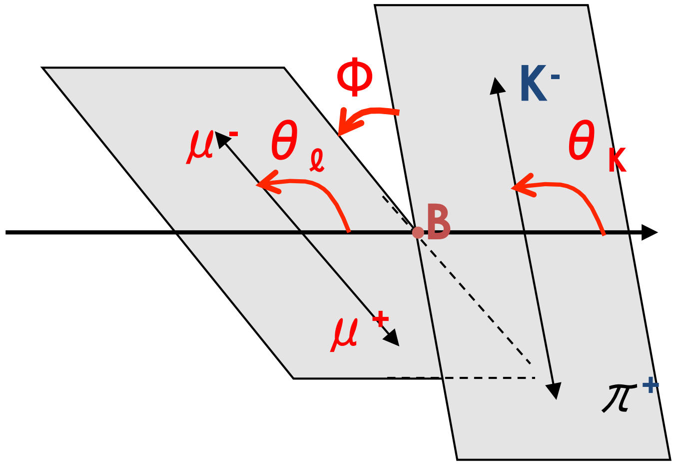
Of course in more realistic/complicated models the constraint gets weaker …

$B_d \to K^* \mu\ \mu$



Interferences between all these diagrams: a large number of observables

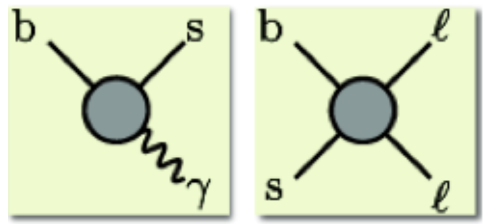
System described by
- $q^2 = M^2(\ell\ell)$
- 3 angles



$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_{i=7,9,10} \left(C_i(\mu) \times O_i(\mu) + \overbrace{C'_i(\mu) \times O'_i(\mu)}^{\text{Right handed part (suppressed in SM)}} \right)$$

C_i : short distance Wilson coefficient (pert.)

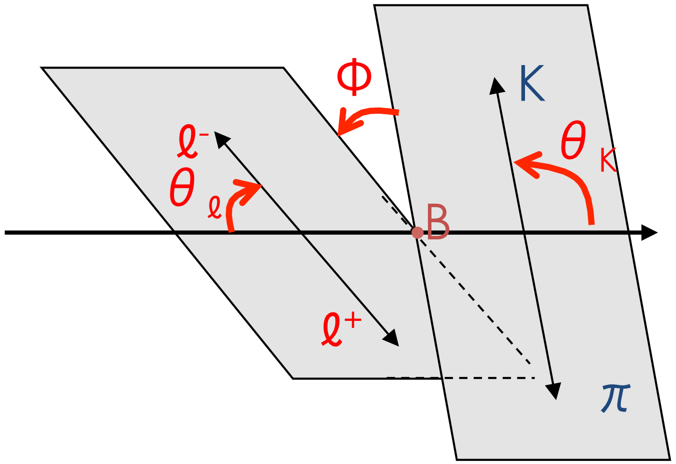
O_i : long distance operator (non-pert.)



$O_{7\gamma}$ $O_{9,10}$

As for the measurement of Φ_s , the full description is complicated :

$$\frac{d\Gamma}{dq^2 d\cos\theta_K d\cos\theta_\ell d\phi} = \frac{9}{32\pi} I\left(q^2, \cos\theta_K, \cos\theta_\ell, \phi\right)$$



The $C^{(\prime)}_{7..10}$ are encoded in the $I_{i=1,..9}$

$$\begin{aligned}
I = {} & I_1\left(q^2,\cos\theta_K\right) + I_2\left(q^2,\cos\theta_K\right)\cos 2\theta_\ell + I_3\left(q^2,\cos\theta_K\right)\sin^2\theta_\ell \cos 2\phi \\
& + I_4\left(q^2,\cos\theta_K\right)\sin 2\theta_\ell \cos\phi + I_5\left(q^2,\cos\theta_K\right)\sin\theta_\ell \cos\phi + \\
& I_6\left(q^2,\cos\theta_K\right)\cos\theta_\ell + I_7\left(q^2,\cos\theta_K\right)\sin\theta_\ell \sin\phi + \\
& I_8\left(q^2,\cos\theta_K\right)\sin 2\theta_\ell \sin\phi + I_9\left(q^2,\cos\theta_K\right)\sin^2\theta_\ell \sin 2\phi
\end{aligned}$$

But

$B_s \to J/\Psi KK$
28000 signal events

$B_d \to K^* \mu\ \mu$
900 signal events

Some tricks have to be found :

Φ transformation:

if $\Phi < 0$ then $\Phi = \Phi + \pi$: keeps cos (2Φ) and sin (2Φ) effects cancels cos(Φ) and sin(Φ) effects (including acceptance effects) !

$$
\begin{aligned}
I = {} & I_1\left(q^2,\cos\theta_K\right) + I_2\left(q^2,\cos\theta_K\right)\cos 2\theta_\ell + I_3\left(q^2,\cos\theta_K\right)\sin^2\theta_\ell \cos 2\phi \\
& + \cancel{I_4\left(q^2,\cos\theta_K\right)\sin 2\theta_\ell \cos\phi} + \cancel{I_5\left(q^2,\cos\theta_K\right)\sin\theta_\ell \cos\phi +} \\
& I_6\left(q^2,\cos\theta_K\right)\cos\theta_\ell + \cancel{I_7\left(q^2,\cos\theta_K\right)\sin\theta_\ell \sin\phi +} \\
& \cancel{I_8\left(q^2,\cos\theta_K\right)\sin 2\theta_\ell \sin\phi} + I_9\left(q^2,\cos\theta_K\right)\sin^2\theta_\ell \sin 2\phi
\end{aligned}
$$

$$\frac{d\Gamma}{dq^2 d\cos\theta_K d\cos\theta_\ell d\phi} \propto$$

$$F_L \cos^2\theta_K + \frac{3}{4}\left(1-F_L\right)\left(1-\cos^2\theta_K\right) + \left(2\cos^2\theta_\ell - 1\right)\left(\frac{1}{4}\left(1-F_L\right)\left(1-\cos^2\theta_K\right) - F_L\cos^2\theta_K\right)$$

$$+\frac{1}{2}\left(1-F_L\right)A_T^2\left(1-\cos^2\theta_K\right)\left(1-\cos^2\theta_\ell\right)\cos 2\phi + \frac{4}{3}A_{FB}\left(1-\cos^2\theta_K\right)\cos\theta_\ell +$$

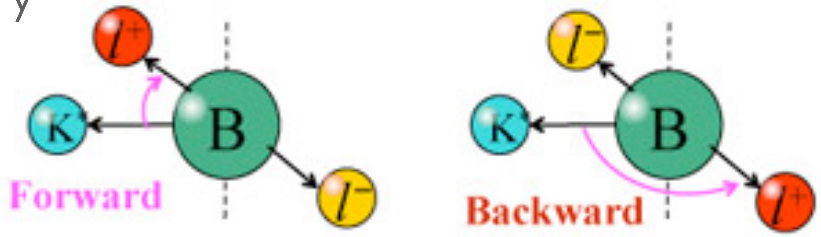
$$\frac{1}{2}\left(1-F_L\right)A_T^{\mathrm{Im}}\left(1-\cos^2\theta_K\right)\left(1-\cos^2\theta_\ell\right)\sin 2\phi$$

Four parameters to fit (F_L, A_{FB}, A_T^2 and A_T^{Im}) in bins of q^2

F_L is the fraction of longitudinal polarization

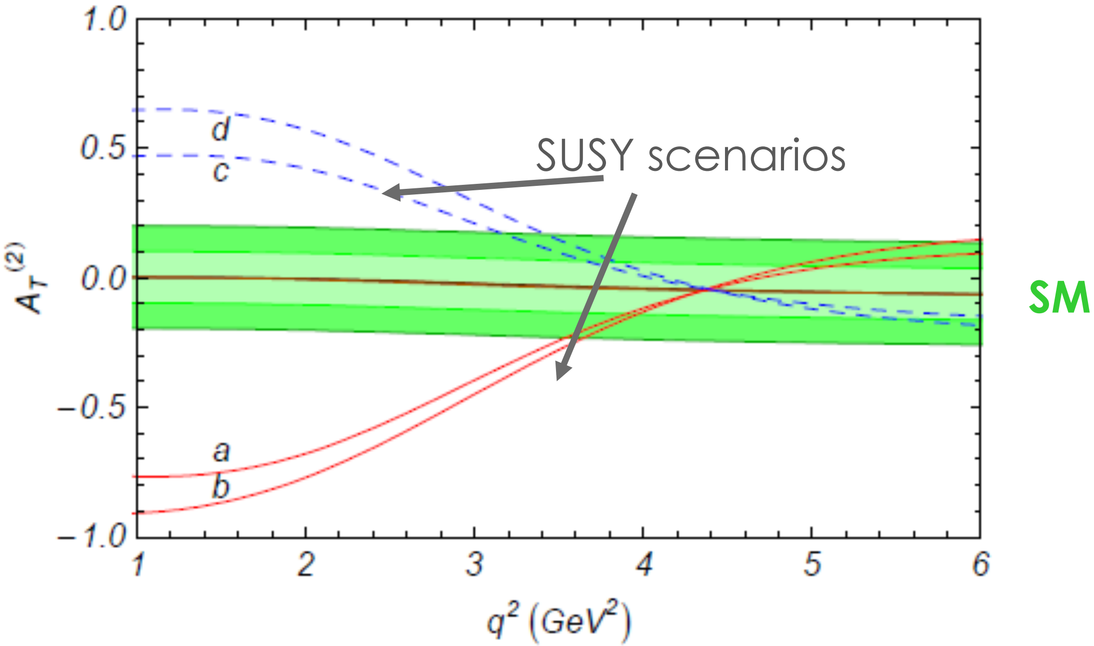
$$F_L = \frac{|A_0|^2}{|A_0|^2 + |A_\perp|^2 + |A_{||}|^2}$$

A_{FB} is the lepton Forward Backward asymmetry
The q^2 value at which $A_{FB}=0$ is a sensitive probe to New Physics



$$A_T^{(2)} = \frac{|A_\perp|^2 - |A_{||}|^2}{|A_\perp|^2 + |A_{||}|^2}$$

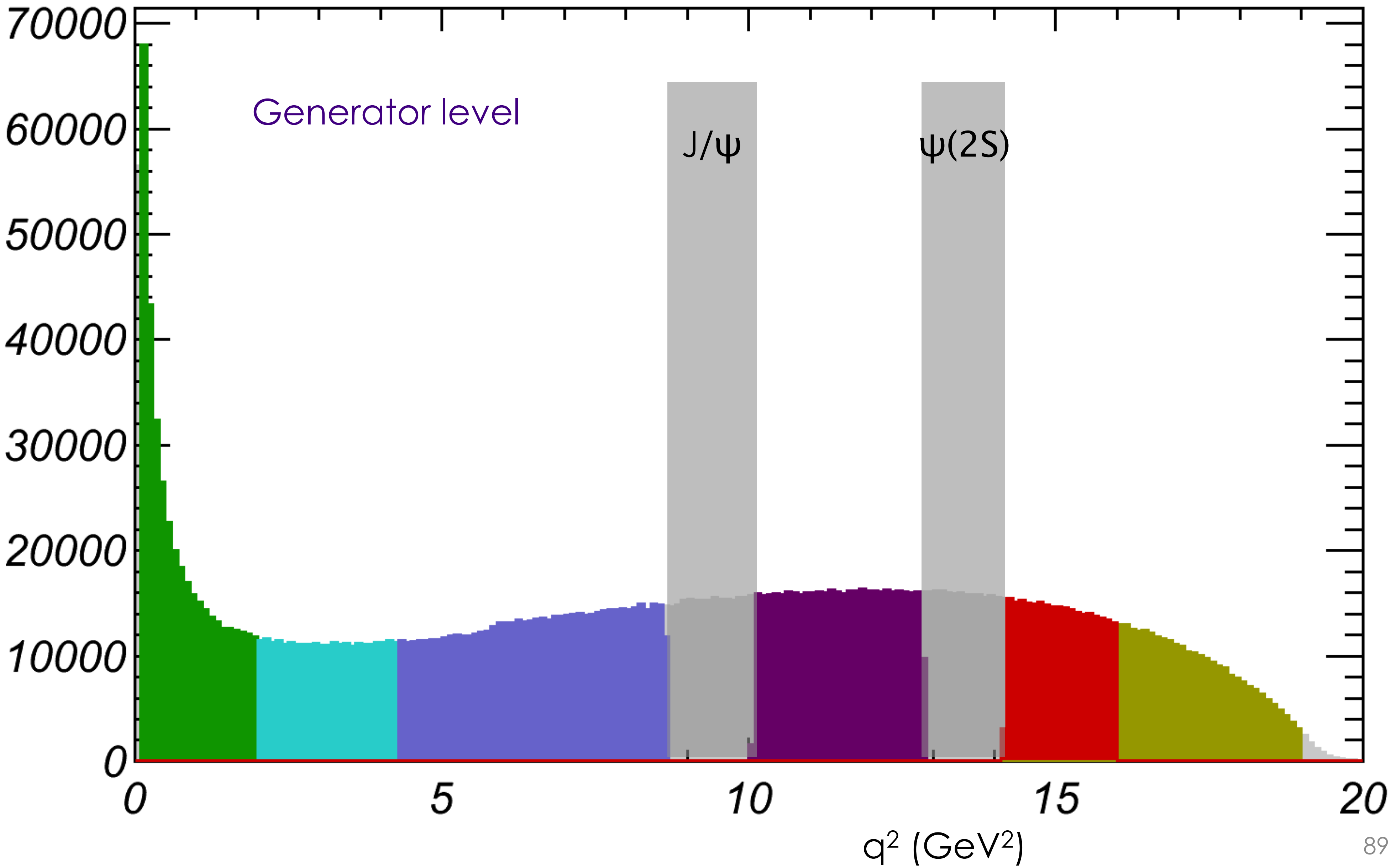
$$A_T^{\mathrm{Im}} = \frac{\mathrm{Im}\left(A^*_{||L} A_{\perp L}\right)}{|A_\perp|^2 + |A_{||}|^2}$$



Egede et al arXiv:0807.2589

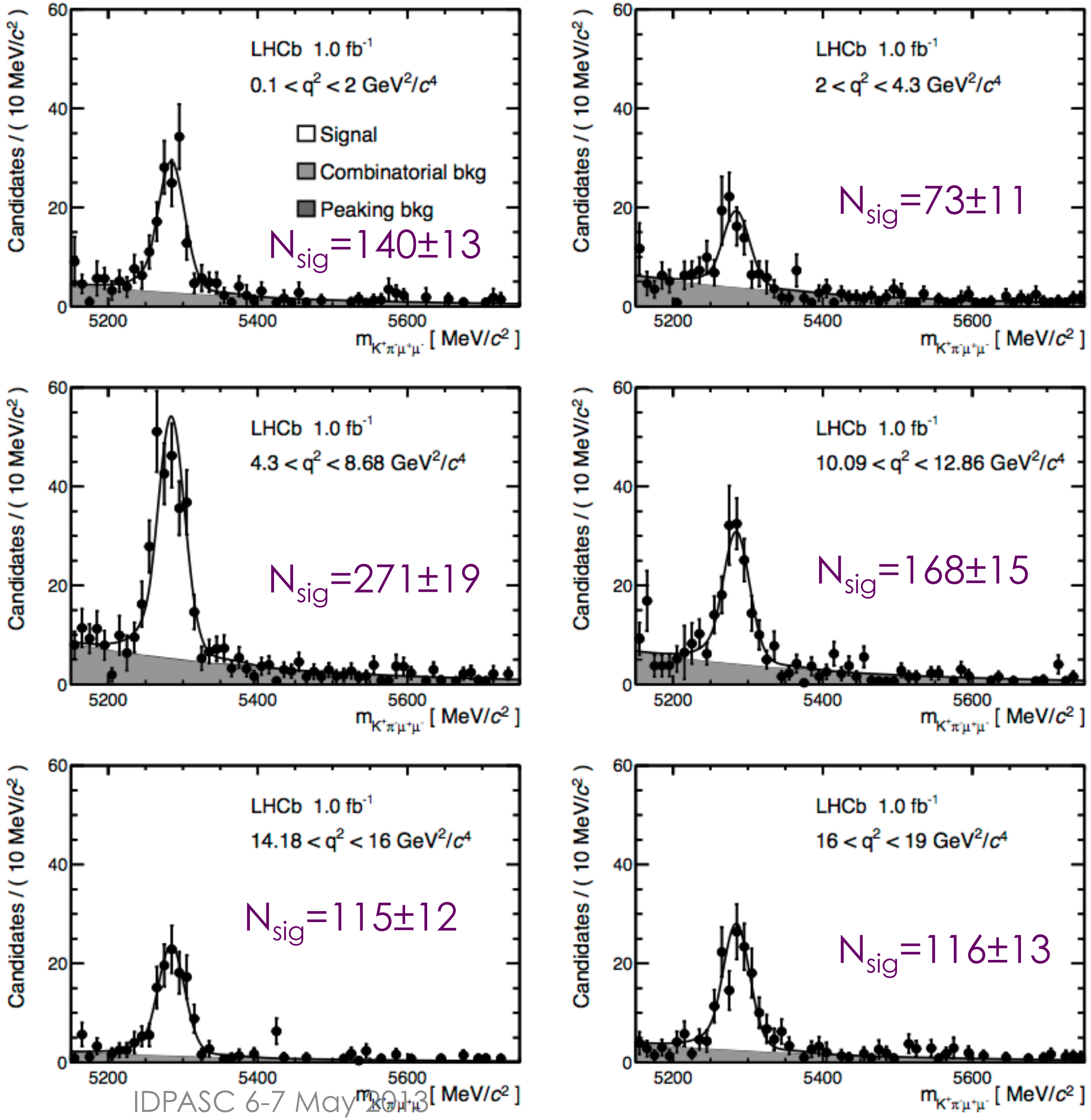
Most of the hadronic uncertainties are put in F_L.

6 q^2 bins

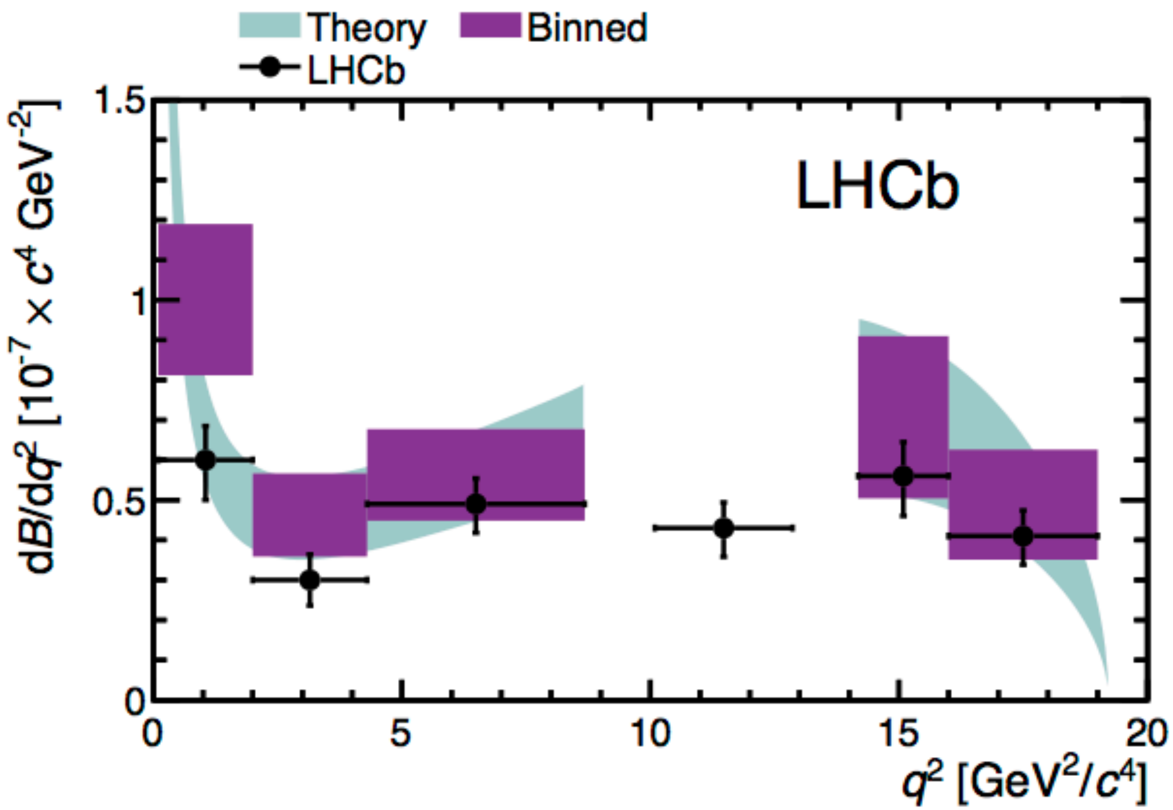

Generator level
J/ψ
ψ(2S)
70000
60000
50000
40000
30000
20000
10000
0
0
5
10
15
20
q² (GeV²)

- In practice:
  - select the events in various q^2 bins
  - fit the yield and compare to the $B \to J/\Psi(\to \mu\mu)\ K^{*0}$ yield :

2011 data (1 fb^{-1})

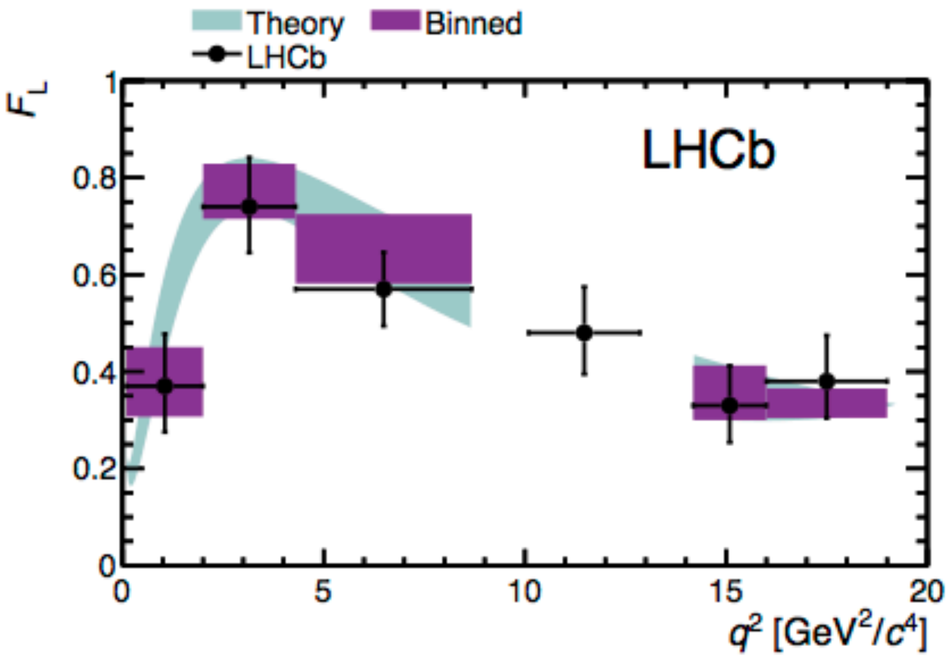


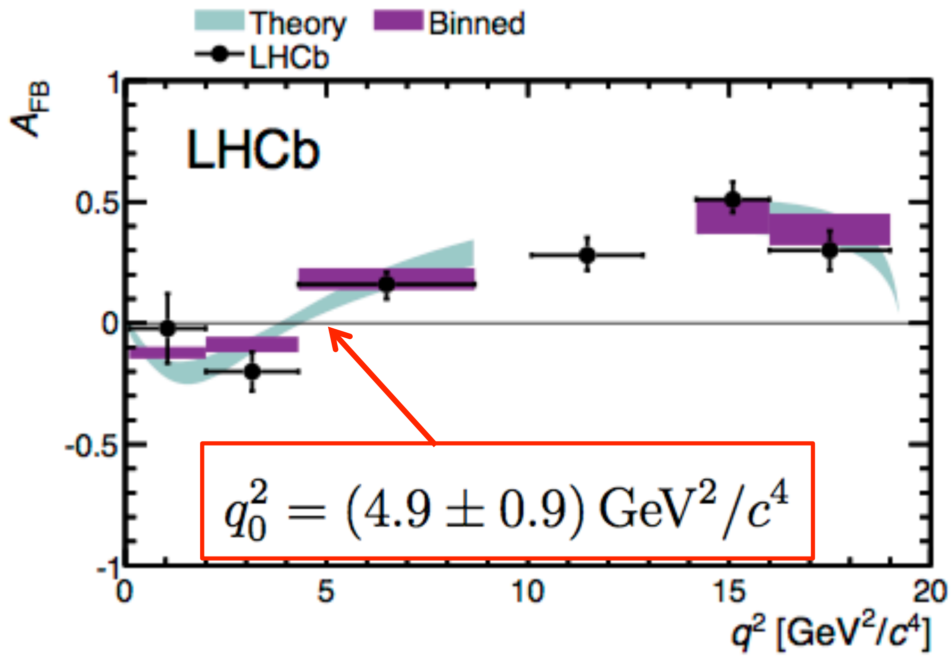
$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2} = \frac{1}{q^2_{\max} - q^2_{\min}} \frac{N_{\text{sig}}}{N_{K^{*0}J/\psi}} \frac{\varepsilon_{K^{*0}J/\psi}}{\varepsilon_{K^{*0}\mu^+\mu^-}} \times \mathcal{B}(B^0 \to K^{*0}J/\psi) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)$$



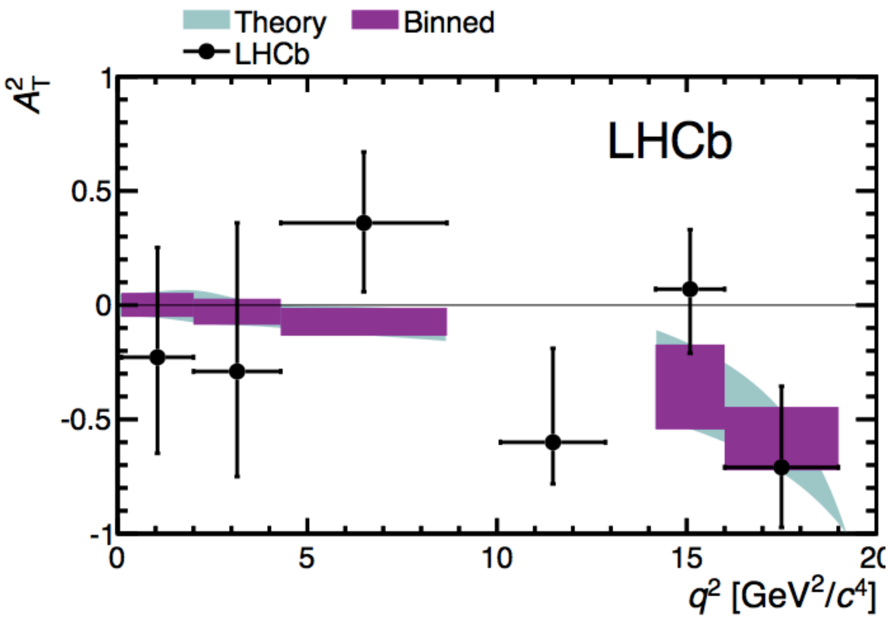
The differential BF has large theoretical uncertainty

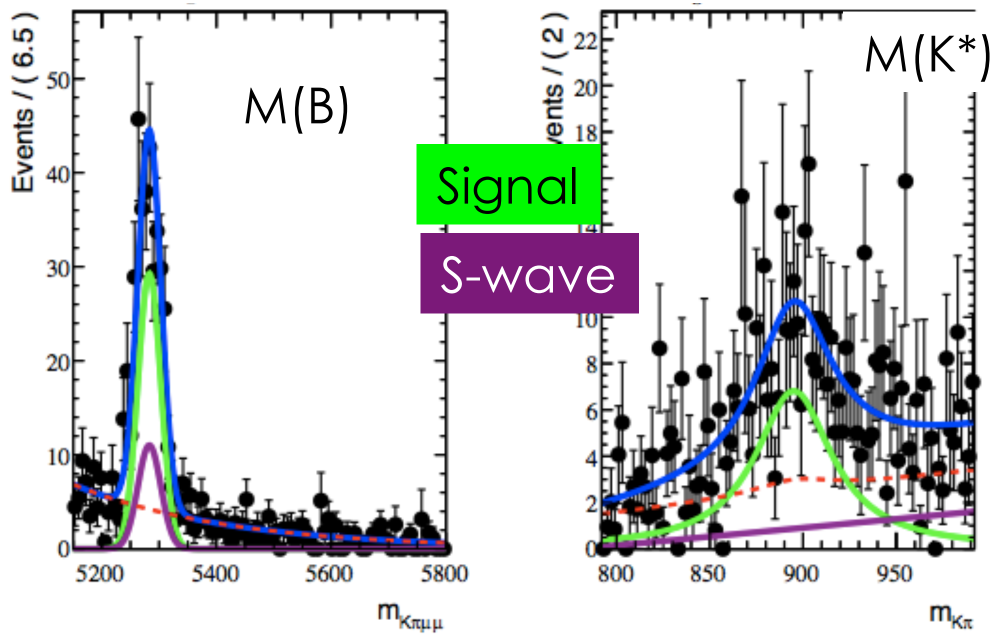
⇒ fit of the angular variables





Improved precision compared to other experiments
Good agreement with the SM … but uncertainties still large.





Many subtleties …

- S-wave under the K^{*0}

$$\left(1-F_S\right)\frac{1}{d\Gamma/dq^2}\frac{d\Gamma}{dq^2 d\cos\theta_K d\cos\theta_\ell d\phi}+\frac{9}{16\pi}\left[\frac{2}{3}F_S\left(1-\cos^2\theta_\ell\right)+\frac{4}{3}A_S\cos\theta_K\left(1-\cos^2\theta_\ell\right)\right]$$

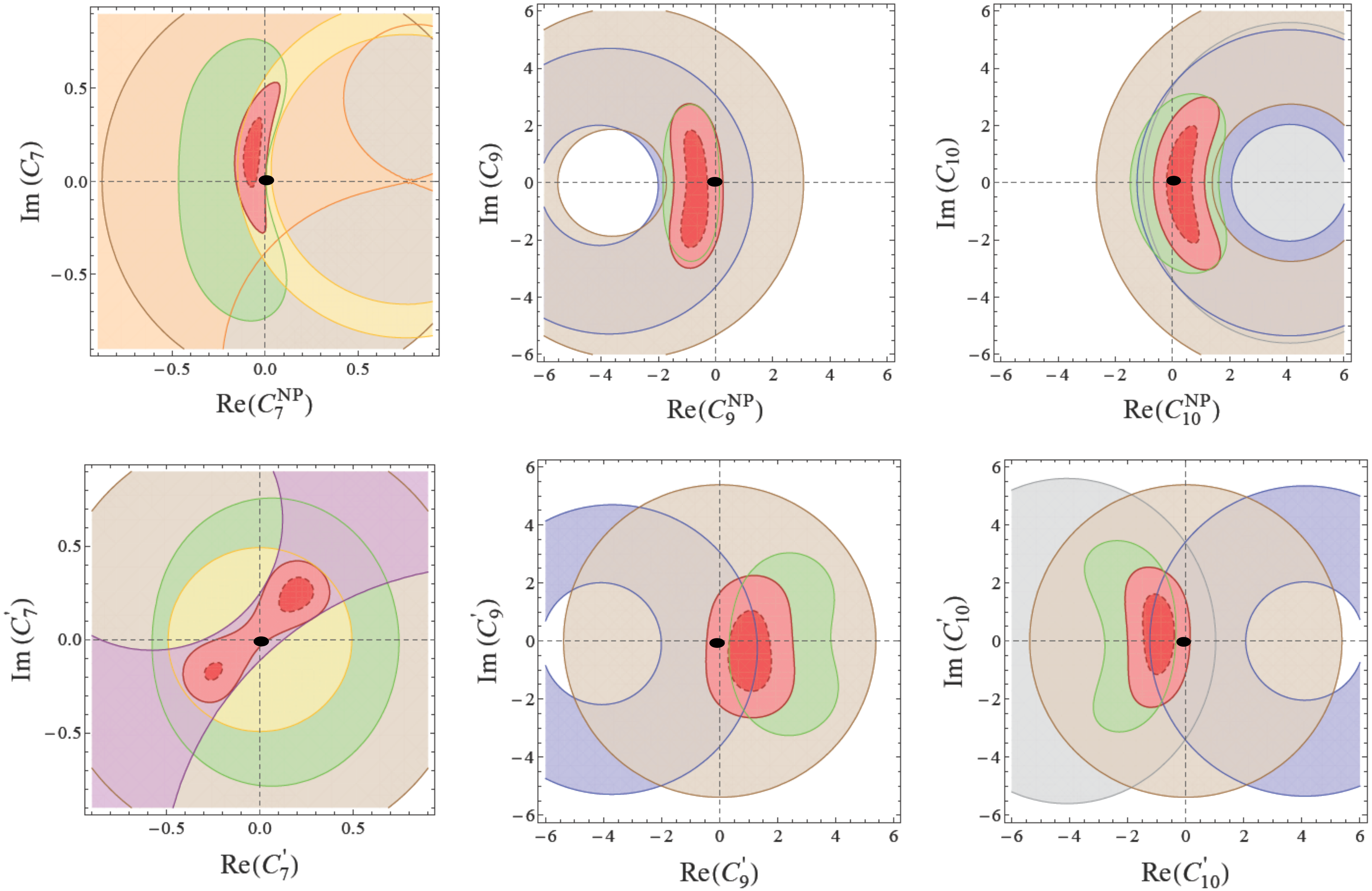
Squared amplitude of the S-wave

interference between the S-wave and the longitudinal amplitude of the K^{*0}

- threshold effects

We are now entering in the era of constraining Wilson's coefficients !
Many preprints out in the last months on this subject (arXiv:1209.0262, arXiv:

$BR(B\to X_s\gamma)$ | $B\to X_s ll$ | $B\to K^*\mu\mu$ | $B_s\to\mu\mu$ | $A_{CP}(b\to s\gamma)$ | $B\to K\mu\mu$ | $A_{CP}(B\to K^*\pi^0\gamma)$



arXiv:1206.0273v2

Combined

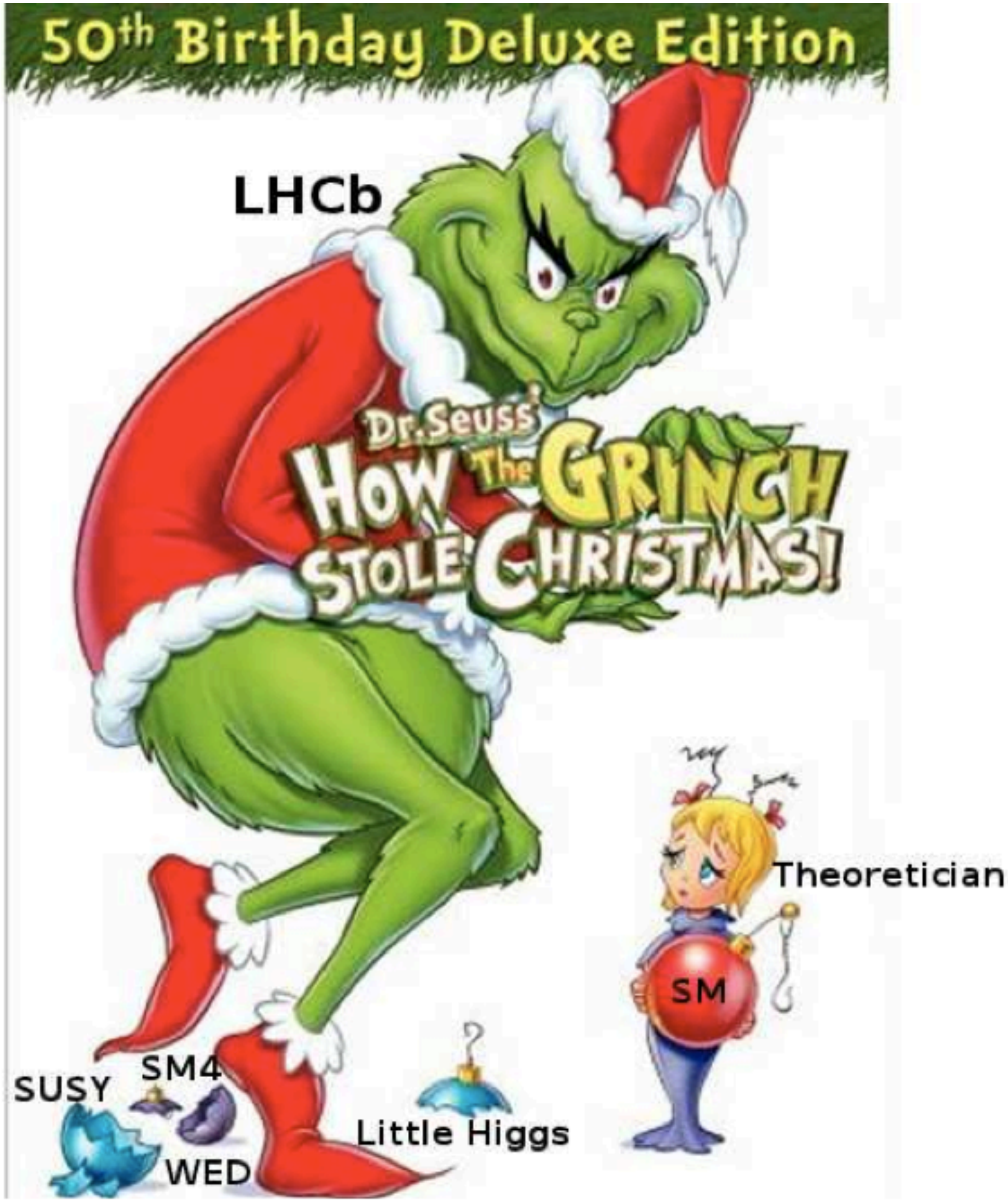
• SM

Large bins in q^2 still used (eg 1-6 GeV^2)
More statistics and finer binning : larger sensitivity

Summary

- Hadronic environment at the LHC
  - hadronisation tracks
  - large multiplicities
  - pile-up
- The LHCb detector is made for it !
- In most of the cases, avoid absolute measurements (ratios of BR, angular analysis)
- Very precise results
  - in the B_s sector
  - B_d and $B^{\pm}$ sectors (competitive with B-factories for modes without neutrals …)
- Now starting more complicated modes : eeK*, modes with neutrals
- Many things were omitted : charm physics (!), spectroscopy, production …

From A. Lenz :



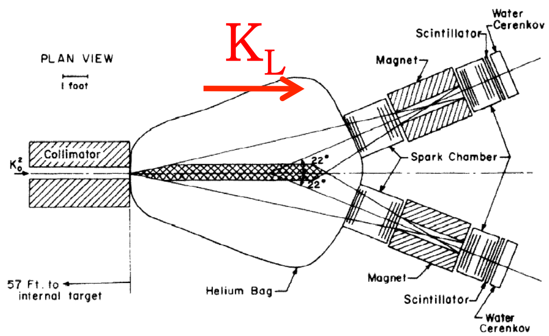
50th Birthday Deluxe Edition
LHCb
Dr. Seuss'
How The Grinch Stole Christmas!
Theoretician
SM
SUSY
SM4
WED
Little Higgs
?

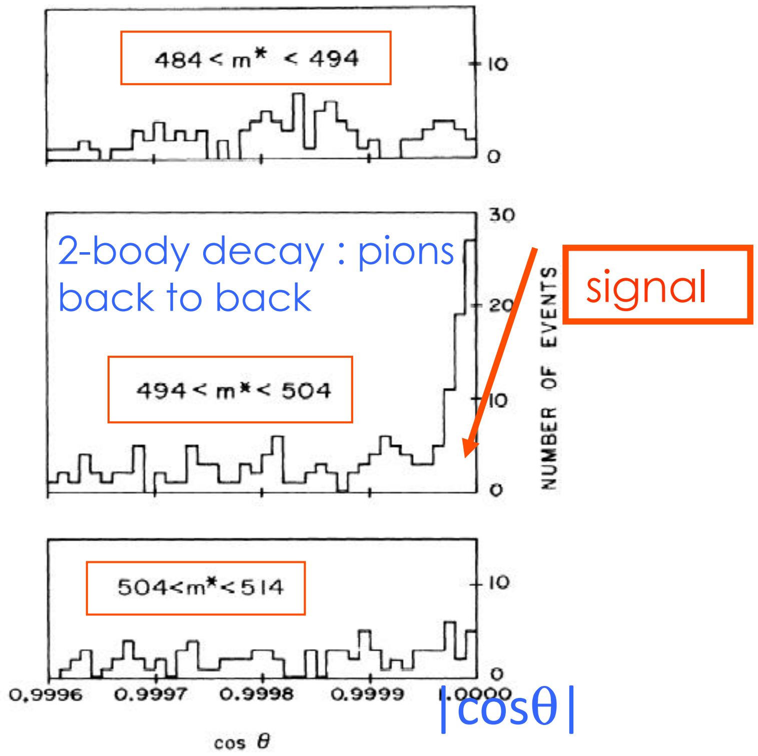
A. Soni at the Opening meeting for the Super-KeKB proto-collaboration (2008)

"Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed"

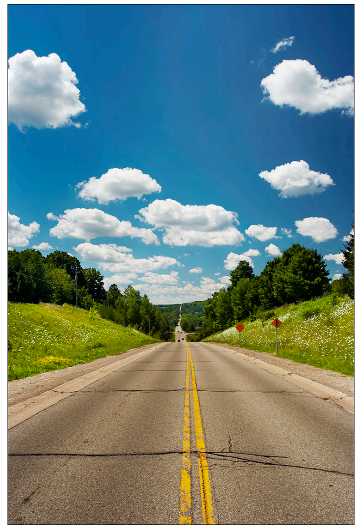
$$\left|K_S^0\right\rangle \to 2\pi \quad CP = +1 \quad \tau \sim 10^{-11} s$$

$$\left|K_L^0\right\rangle \to 3\pi \quad CP = -1 \quad \tau \sim 5\,10^{-8} s$$ large lifetime because of reduced phase space



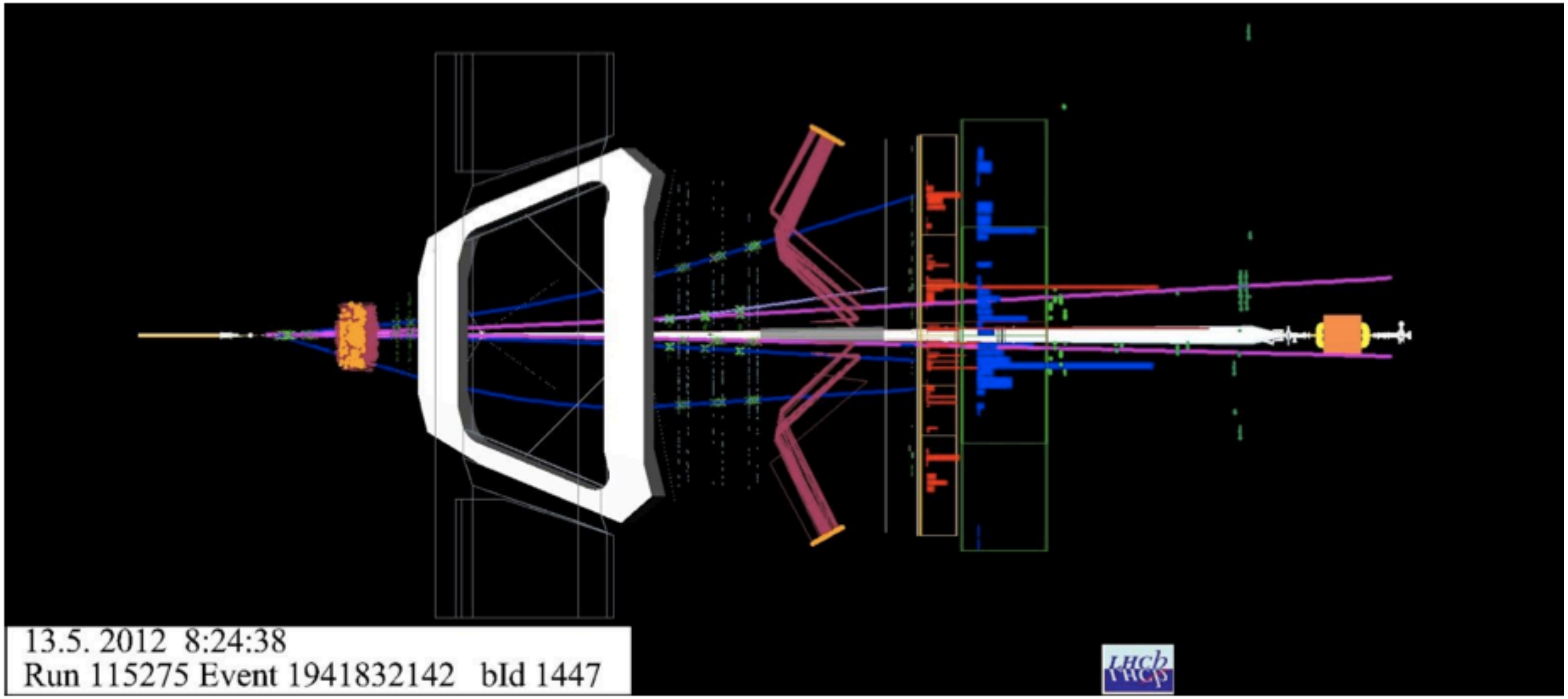


$$\frac{BR\left(\left|K_L^0\right\rangle \to 2\pi\right)}{BR\left(\left|K_L^0\right\rangle \to \text{all ch. modes}\right)} = (2.0 \pm 0.4)10^{-3}$$



Spares

$B_s^0 \to \mu^+\mu^-$ Candidate



B candidate: $m_{\mu\mu}$ = 5353.4 MeV/c² BDT = 0.826

p_T = 4077.4 MeV/c τ = 2.84 ps

muons: $p_{T\mu+}$ = 2329.5 MeV/c $p_{T\mu-}$ = 4179.4 MeV/c

NB : pT>500 MeV and tracks belonging to the same PV are shown