Physics highlights from LHCb

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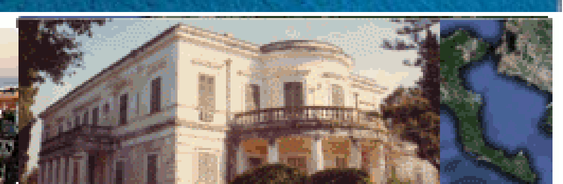


Outline

- The LHCb detector and running conditions
- Selected physics highlights

  Focus on current measurements from LHCb: based on 3 fb^{-1} (2011&12) *pp* collision data at 7 & 8 TeV CM energy.

  - Parameters of the CKM matrix
  - Rare B decays
  - Studies of CPV in the B_s system
  - Mixing and CP violation in charm
  - Other highlights (pentaquarks).

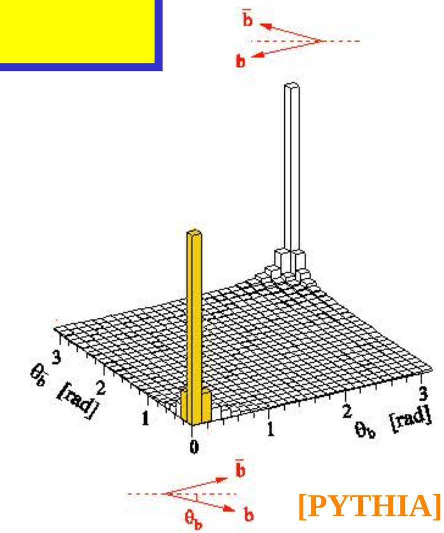
- Summary and Outlook

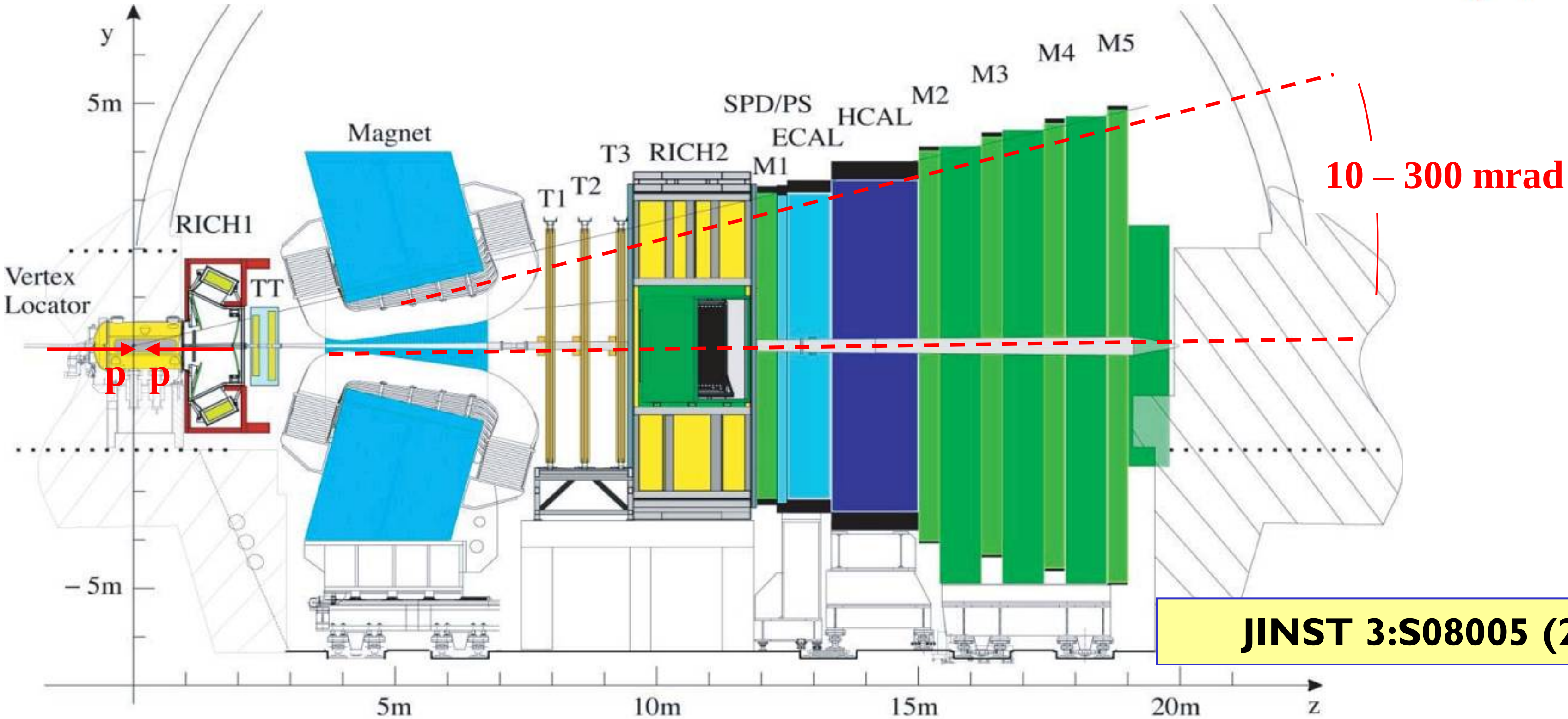

The Large Hadron Collider

LHCb- forward spectrometer

- Forward-peaked production → LHCb is a forward spectrometer (operating in LHC collider mode)
- $b\bar{b}$ cross-section = 284 ± 20 ± 49 μb at $\sqrt{s}$ = 7 TeV
  [Phys. Lett. B694, (2010) 209]
  At $\sqrt{s}$ = 13 TeV : 518 ± 2 ± 53 μb (EPS 2015)

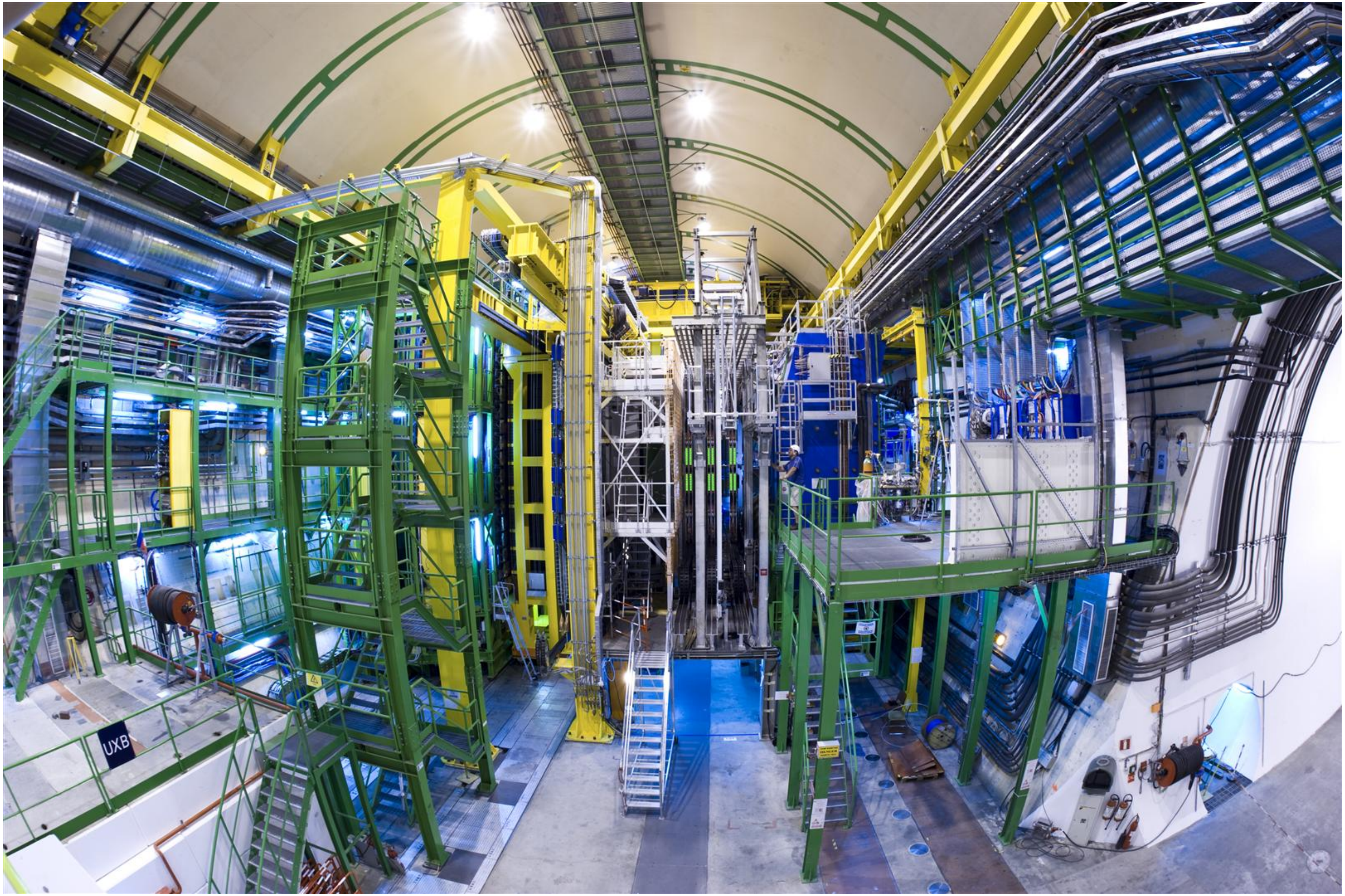
→ ~ 100,000 bb pairs produced/second (10^4 × B factories)





JINST 3:S08005 (2008)

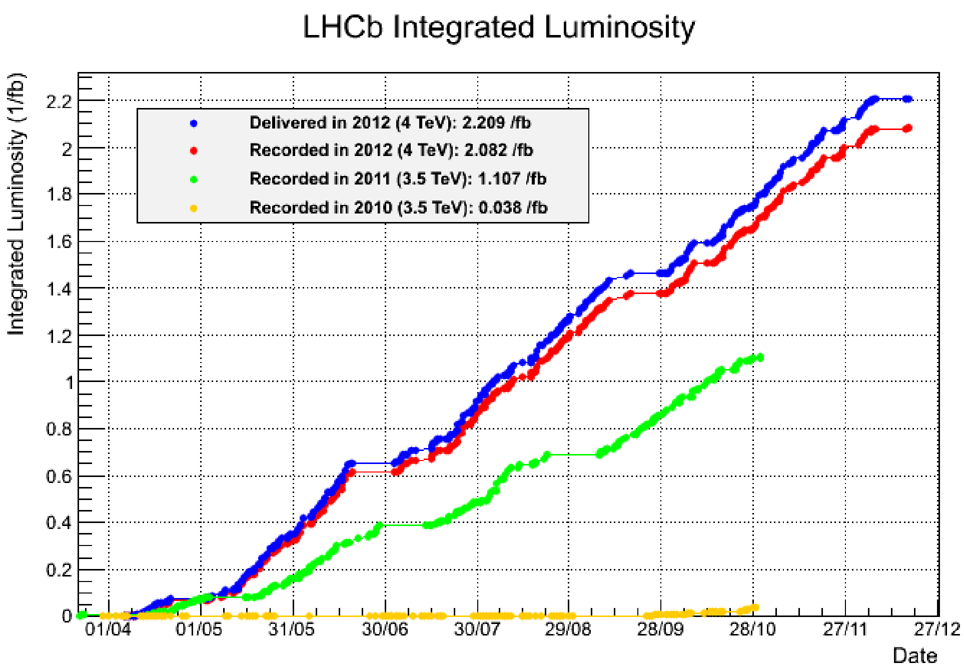
A fish-eye view

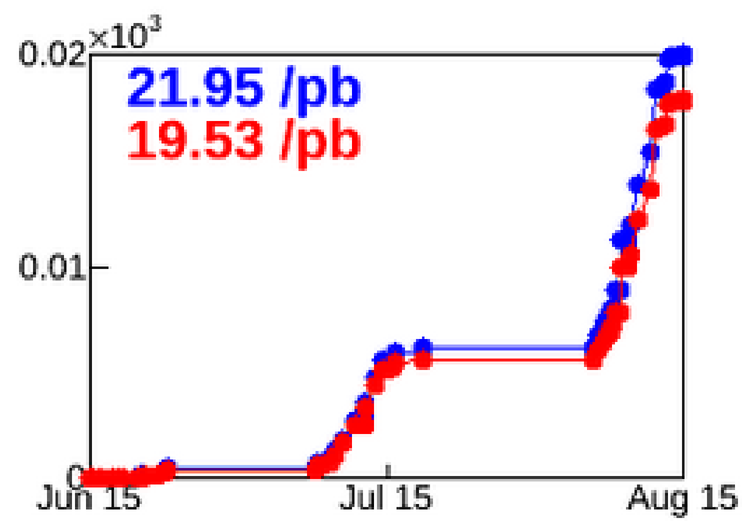


LHCb data taking

- Nominal luminosity = 2×10^{32} cm^{-2} s^{-1} (50 times less than ATLAS/CMS) : however, LHCb has learned to run at >2 times this
  - 37 pb^{-1} @ 7 TeV collected in 2010
  - 1 fb^{-1} @ 7 TeV in 2011
  - 2 fb^{-1} @ 8 TeV recorded in 2012

2015 at 13 TeV !!





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Selected physics highlights

- Parameters of the CKM matrix
- Studies of CPV in the B_s system
- CP violation in charm
- Rare B decays
- Pentaquarks

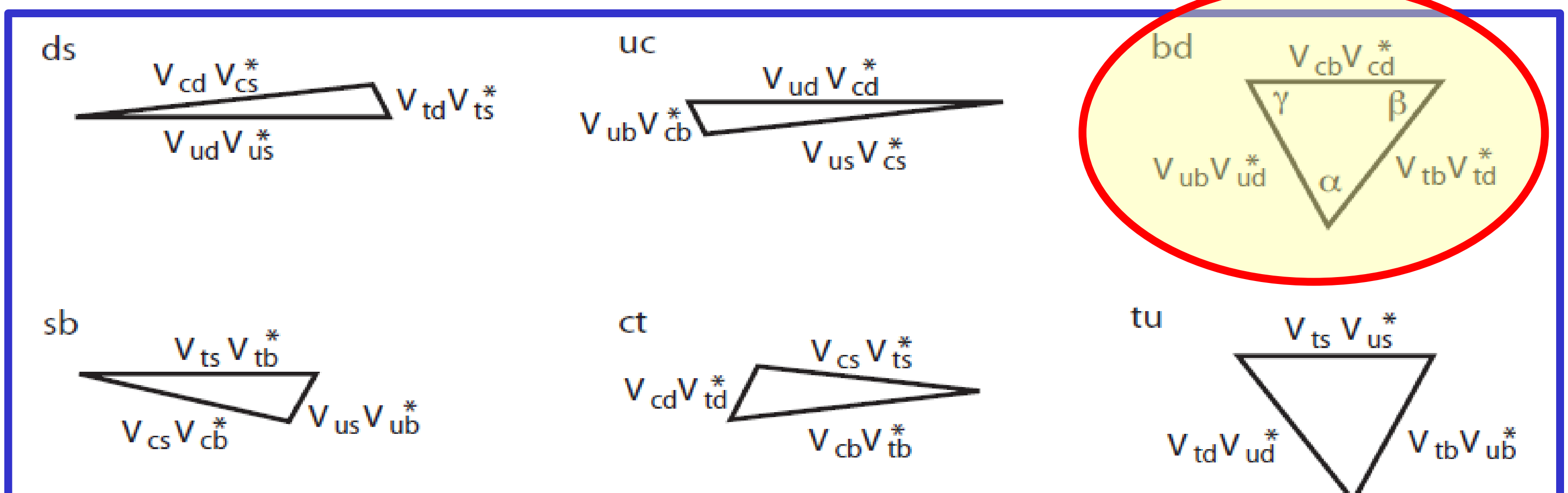
Quark mixing and CKM matrix

- In the SM charge $-1/3$ quarks (d, s, b) are mixed
- Mixing described by CKM matrix

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

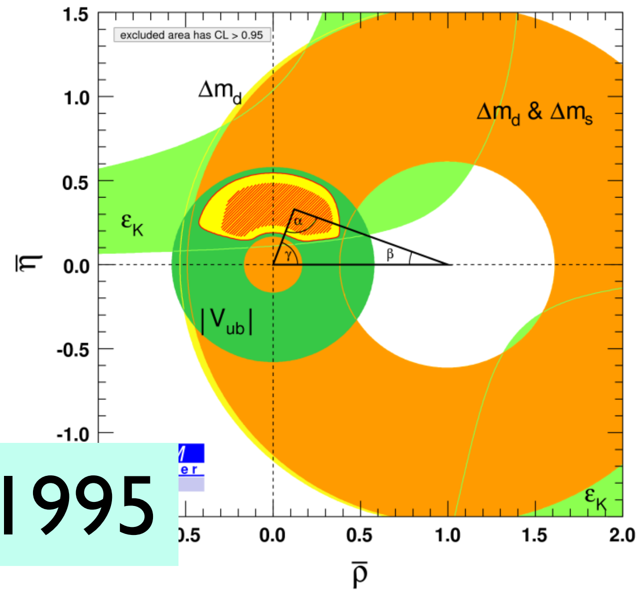
- 6 unitarity conditions of CKM matrix, 2 of which give triangles which do not have a side much shorter than the other two:

$$(V^*_{ub}V_{ud}+V^*_{cb}V_{cd}+V^*_{tb}V_{td}) = 0 \qquad (V^*_{ud}V_{td}+V^*_{us}V_{ts}+V^*_{ub}V_{tb}) = 0$$



THE unitarity triangle

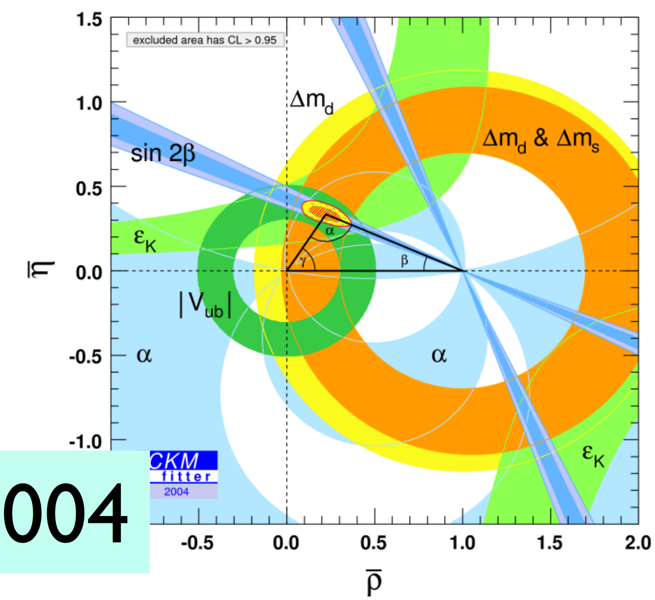
Unitarity triangle history : CKM fitter



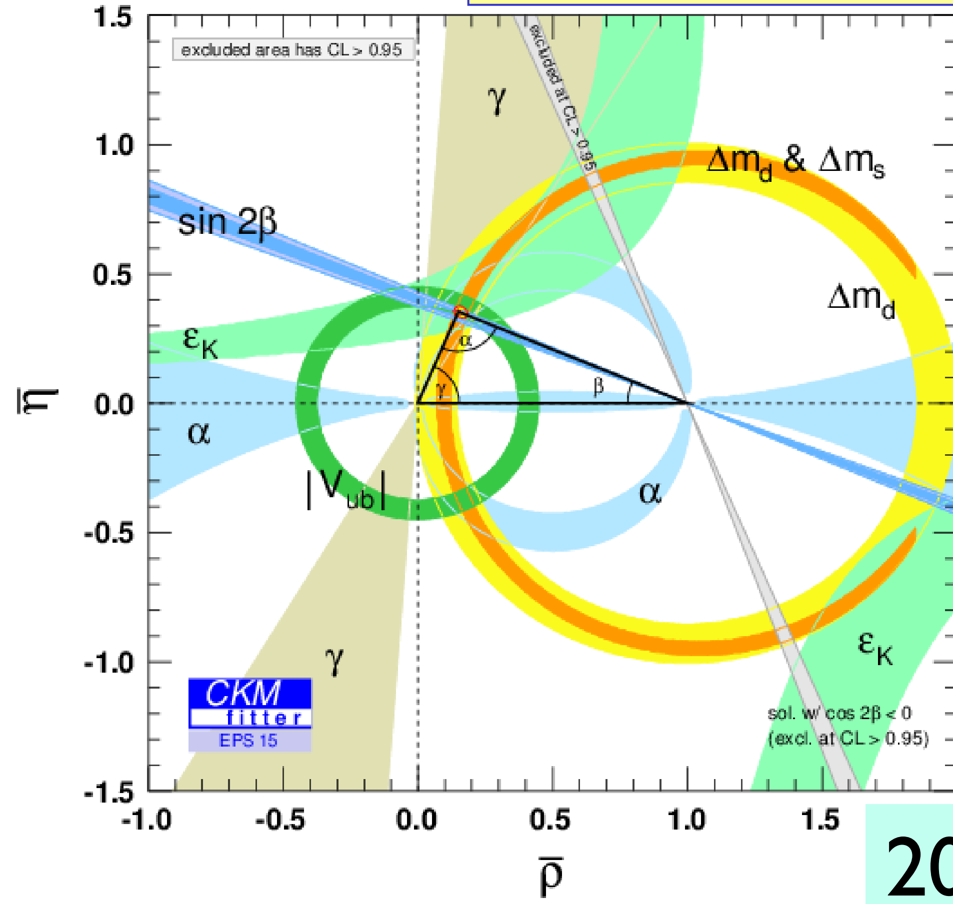
1995

- The CKM describes all the flavour-changing processes in the SM
- Amazing progress in the last 20 years; the SM remains intact, but still a whole lot still to learn

http://ckmfitter.in2p3.fr

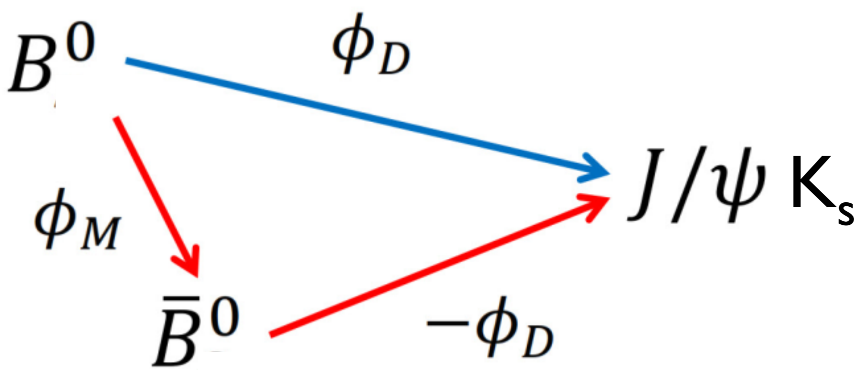


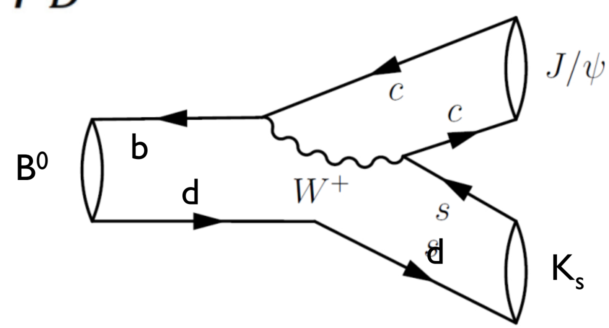
2004

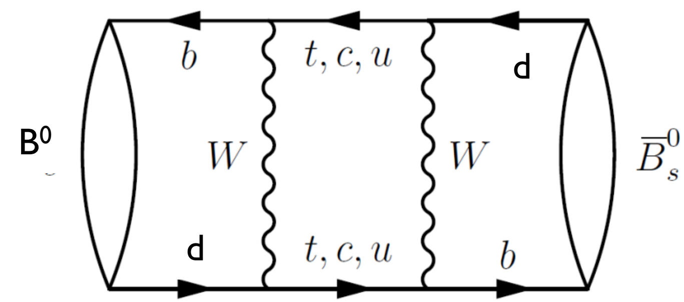


2015

Measurement of angle β







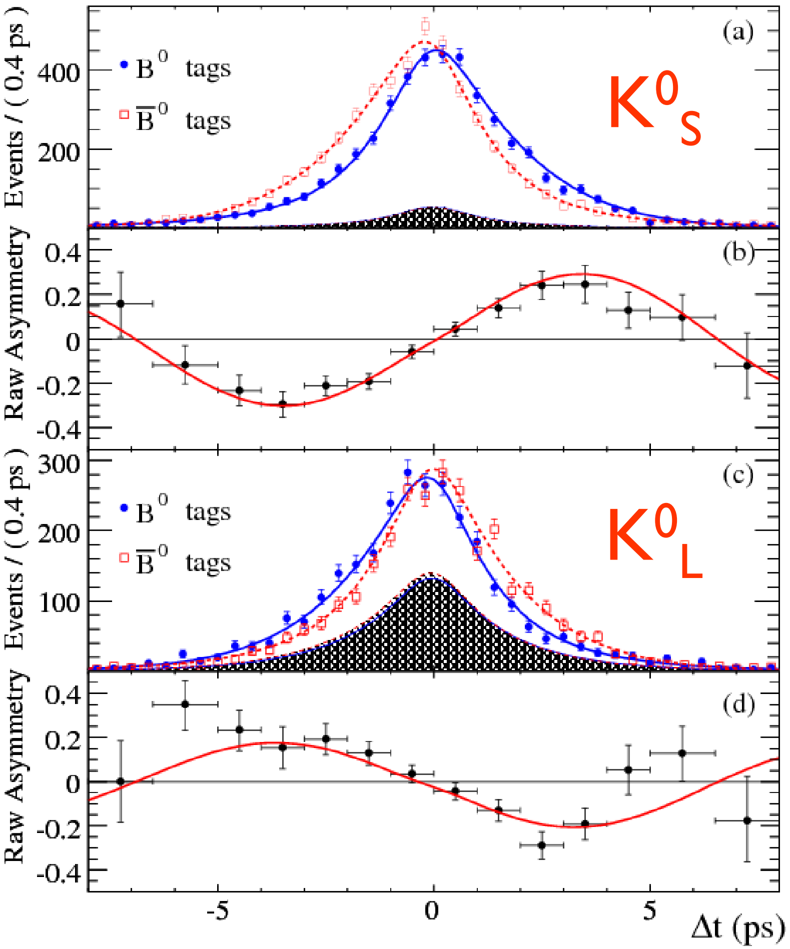
- *Interference* between B^0 decay to $J/\psi K^0_S$ directly and via B^0 $\overline{B^0}$ oscillation gives rise to a CP violating phase

  $\phi = \phi_{Mixing} - 2\,\phi_{Decay} = 2\beta$

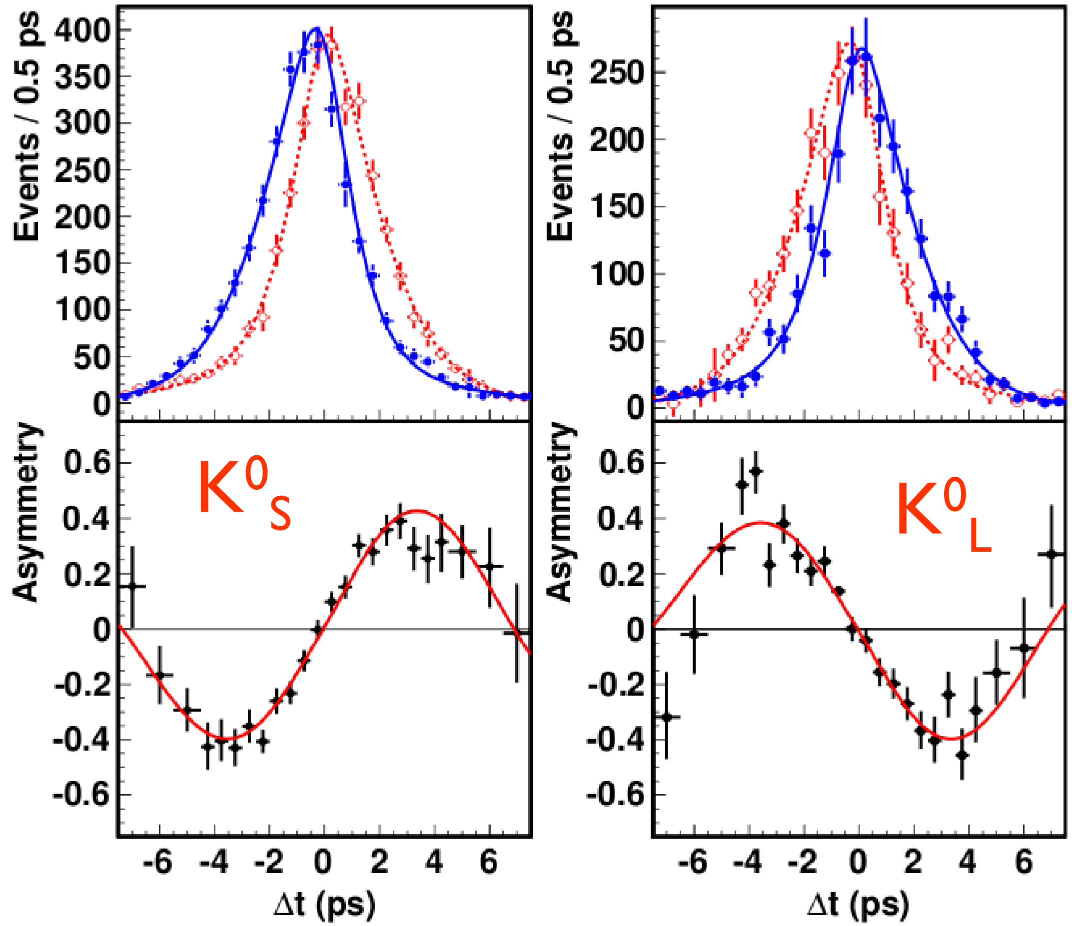
Spectacular results from e^+e^- B factories on CP violation

Large CP violation effects : $\sin(2\beta)$ from $B^0 \rightarrow J/\psi K^0_{S/L}$

Babar PRD 79 (2009) 072009



Belle PRL 108 (2012) 171802



LHCb now well into the game …

$\sin(2\beta)$ from $B^0 \to J/\psi K^0_S$

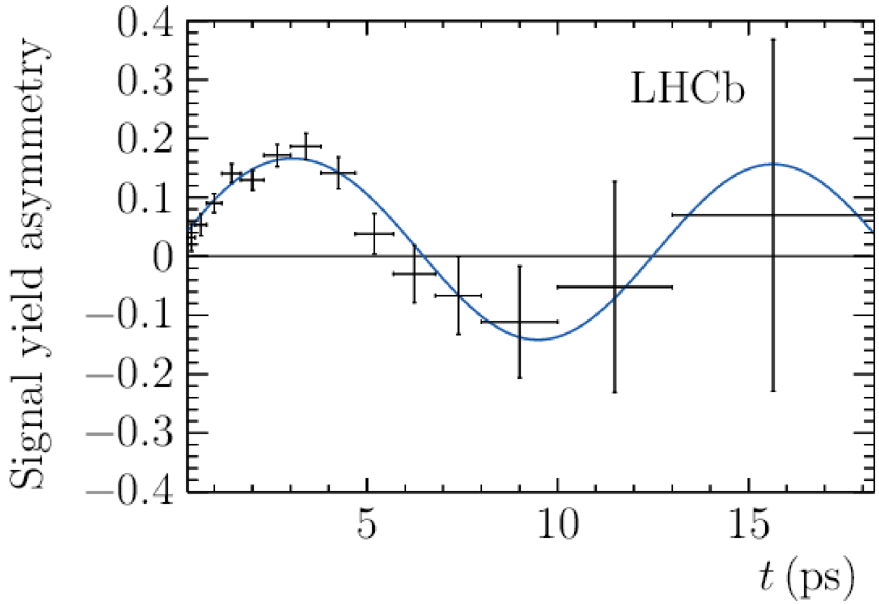
Phys.Rev. Lett 115,031601 (2015)

$$\mathcal{A}_{J/\psi K^0_S}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to J/\psi\, K^0_S) - \Gamma(B^0(t) \to J/\psi\, K^0_S)}{\Gamma(\overline{B}^0(t) \to J/\psi\, K^0_S) + \Gamma(B^0(t) \to J/\psi\, K^0_S)}$$
$$= S_{J/\psi K^0_S} \sin(\Delta m_d t) - C_{J/\psi K^0_S} \cos(\Delta m_d t).$$

$S_{J/\psi Ks}$ = 0.731 ± 0.035 (stat) ± 0.020 (syst)

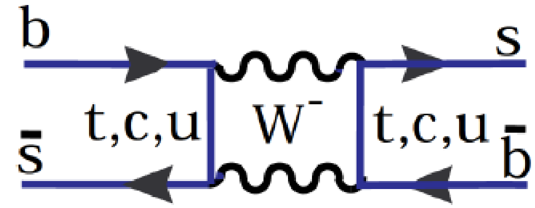
$C_{J/\psi Ks}$ = 0.0308 ± 0.032 (stat) ± 0.005 (syst)

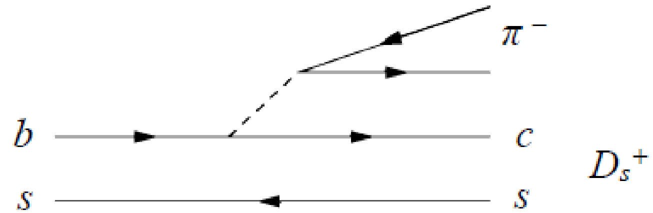
World average from (HFAG) all modes :
$\sin(2\beta)$ = 0.691 ± 0.0170



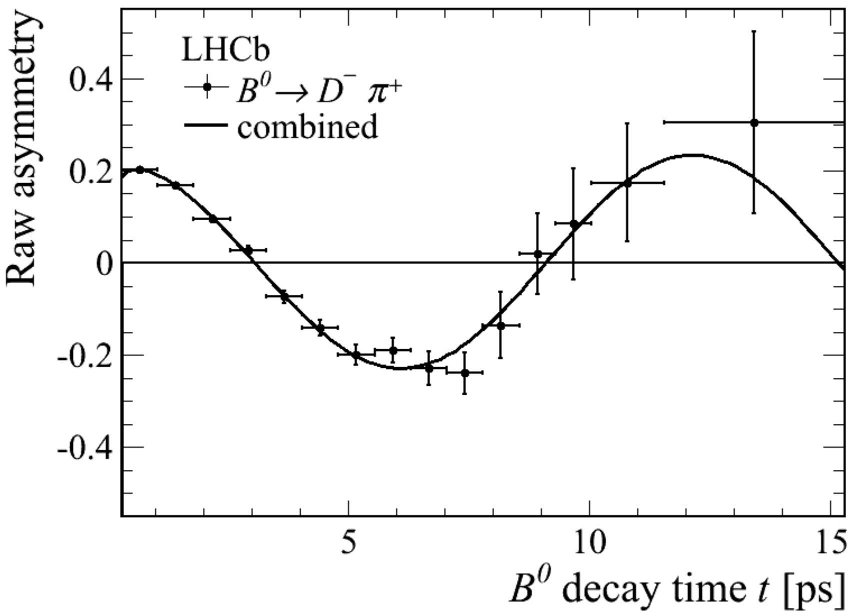
World average from $B^0 \to J/\psi\ K^0_S$(EPS 2015) : $\sin(2\beta) = 0.748\ ^{+0.030}_{-0.032}$

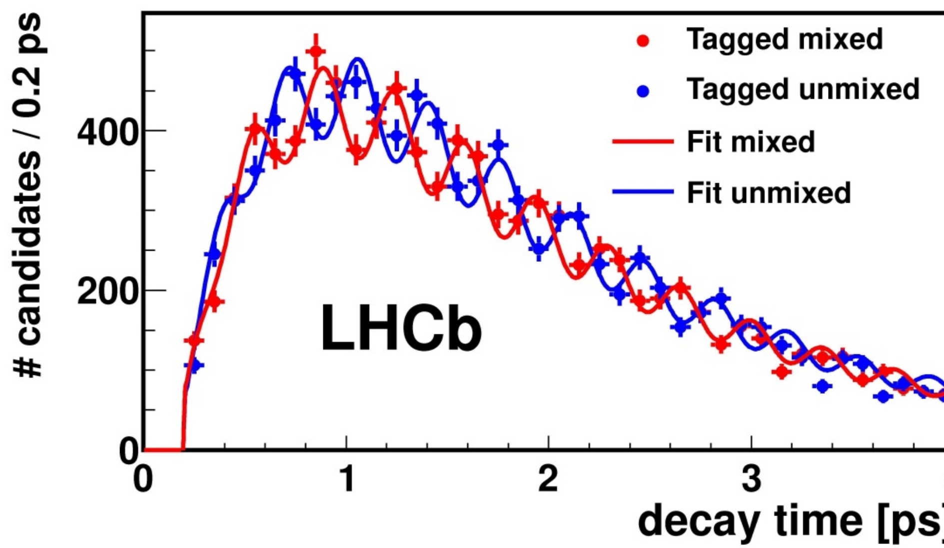
… and $B_{(s)}$ mixing





$$\frac{N(B^0 \to B^0) - N(B^0 \to \overline{B^0})}{N(B^0 \to B^0) + N(B^0 \to \overline{B^0})}$$





$\Delta m_d = 0.5156 \pm 0.0051 \pm 0.0033\ \mathrm{ps}^{-1}$

$\Delta m_s = 17.768 \pm 0.023 \pm 0.006\ \mathrm{ps}^{-1}$

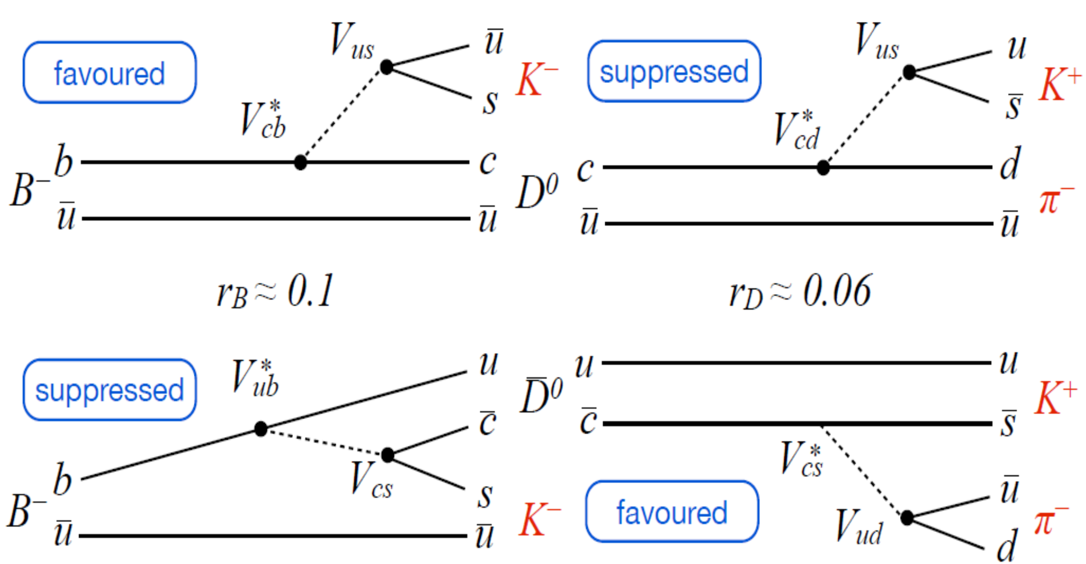
Phys.Lett B721 (2013) 24-31

J. Phys. 15 (2013) 053021

A measurement of γ from $B^{\pm} \to DK^{\pm}$ and $D\pi^{\pm}$

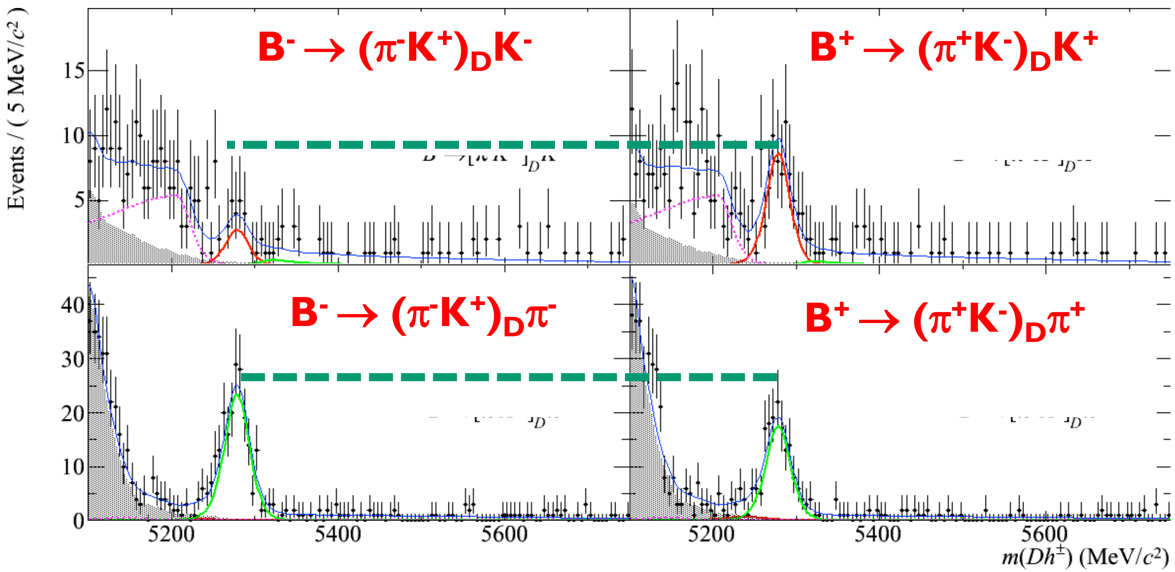
- Four methods, comprising 14 $B^{\pm}$ decays included in a combined fit

$B^{\pm} \to DK^{\pm}$, $D \to K_S^0 \pi^{\pm} \pi^{\mp}$ and $D \to K_S^0 K^{\pm} K^{\mp}$	"GGSZ"	JHEP 10 (2014) 097
$B^{\pm} \to Dh^{\pm}$, $D \to \pi^{\pm} K^{\mp} \pi^{\pm} \pi^{\mp}$ and $D \to K^{\pm} \pi^{\mp} \pi^{\pm} \pi^{\mp}$	"K3π" :	PLB 712 (2012) 203
$B^{\pm} \to Dh^{\pm}$, $D \to \pi^{\pm} K^{\mp}$ and $D \to K^{\pm} \pi^{\mp}$	"ADS"	Phys Lett B712 (2012) 203
$B^{\pm} \to Dh^{\pm}$, $D \to K^{\pm} K^{\mp}$ and $D \to \pi^{\pm} \pi^{\mp}$	"GLW"	Phys Lett B712 (2012) 203



- Two paths to the same final state via D^0 and $\bar{D}^0$ $\to$ interference sensitive to gamma

$B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D\pi^{\pm}$ ADS & GLW modes



Phys Lett B712 (2012) 203

ADS modes

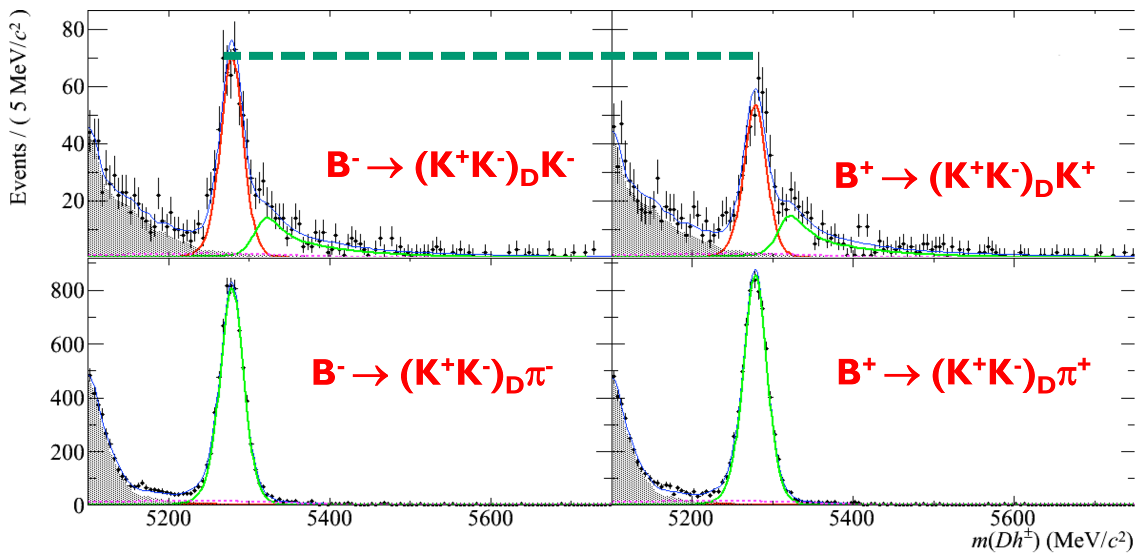
$A_{ADS}(K) = (-52 \pm 15 \pm 2)\%$

$A_{ADS}(\pi) = (14.3 \pm 6.2 \pm 1.1)\%$

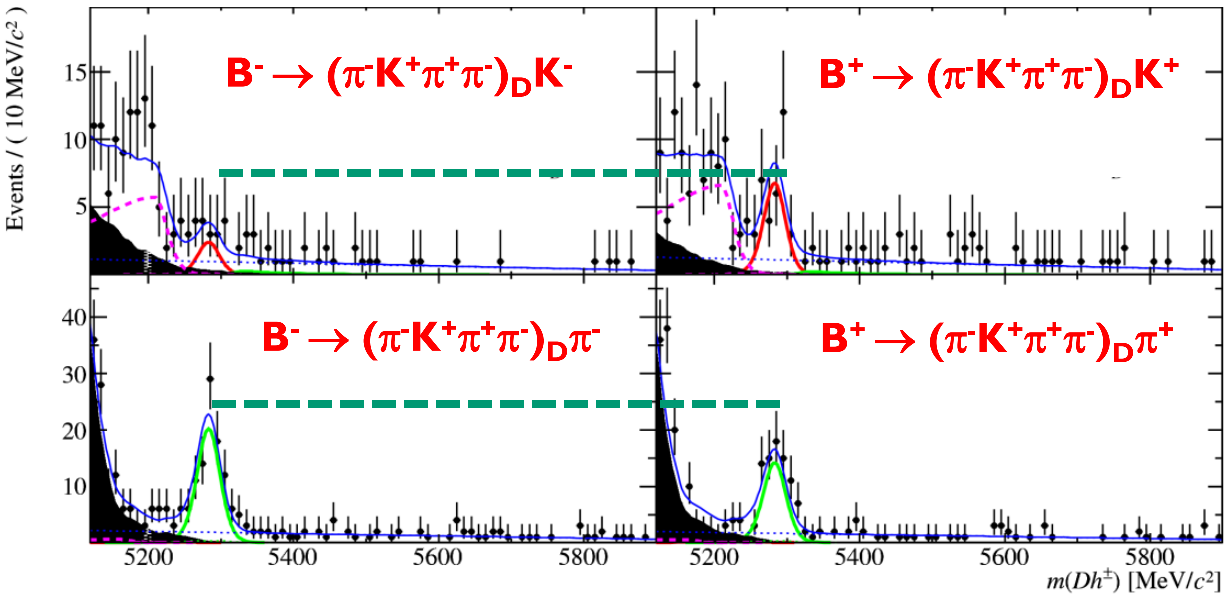
1 fb^{-1}, 7 TeV data

GLW modes

$A_{GLW} = (14.5 \pm 3.2 \pm 1.0)\%$



$B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D\pi^{\pm}$ GGSZ & K(3π) modes



K(3π) modes

1 fb^{-1}

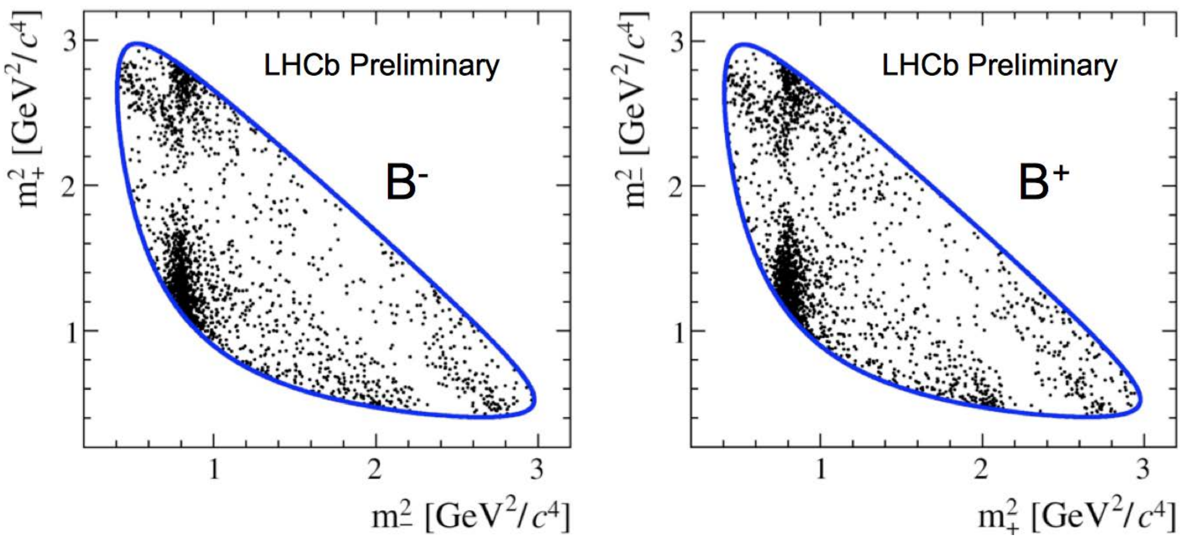
PLB 712 (2012) 203

JHEP 10 (2014) 097

GGSZ mode

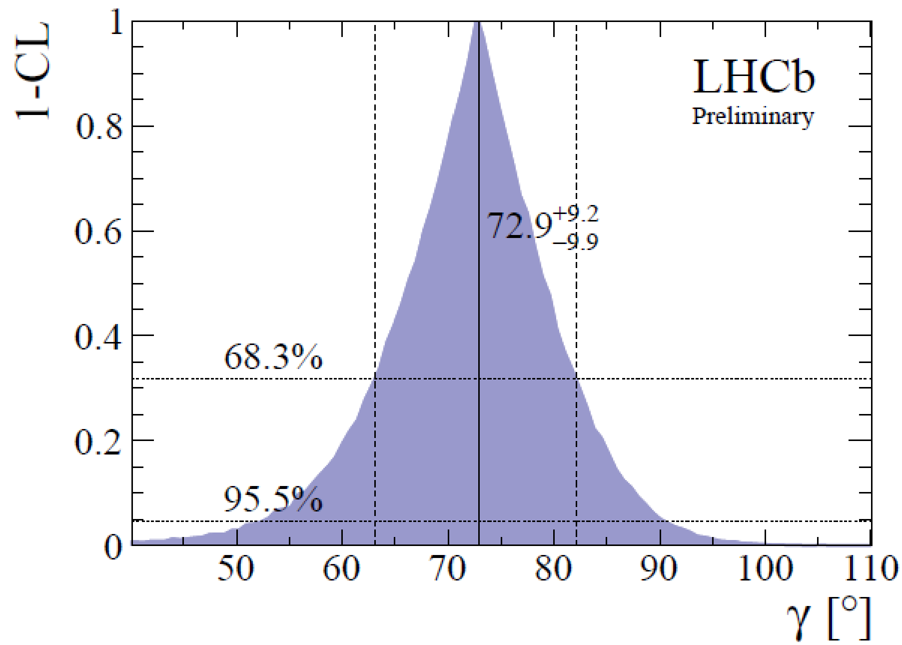
$(K_S\pi^+\pi^-)_D$

3 fb^{-1}



$B^{\pm} \to DK^{\pm}$ γ measurement

LHCb-CONF-2014-004



LHCb combined

GLW($D^0 \to \pi^+ \pi^-$, $K^+ K^-$) $1 fb^{-1}$

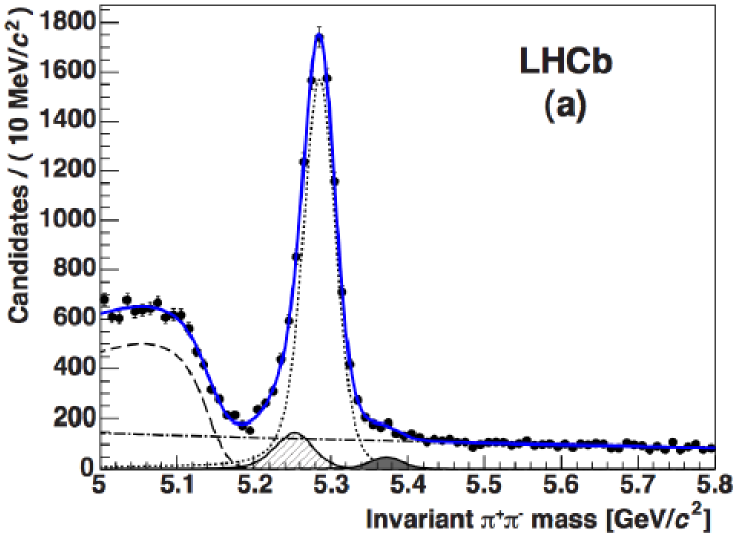
ADS ($D^0 \to K^+ \pi^-$, $K^+ \pi^- \pi^+ \pi^-$) $1 fb^{-1}$

GGSZ($D^0 \to K_S \pi^+ \pi^-$, $K_S K^+ K^-$) $3 fb^{-1}$

Combined: $\gamma = (72.9^{+9.2}_{-9.9})^{\circ}$

- Compare :
  - Belle $(69^{+17}_{-16})^{\circ}$
  - BaBar $(68^{+15}_{-14})^{\circ}$
- Indirect γ value from global CKM fit: $\gamma = (66.5^{+1.3}_{-2.5})^{\circ}$

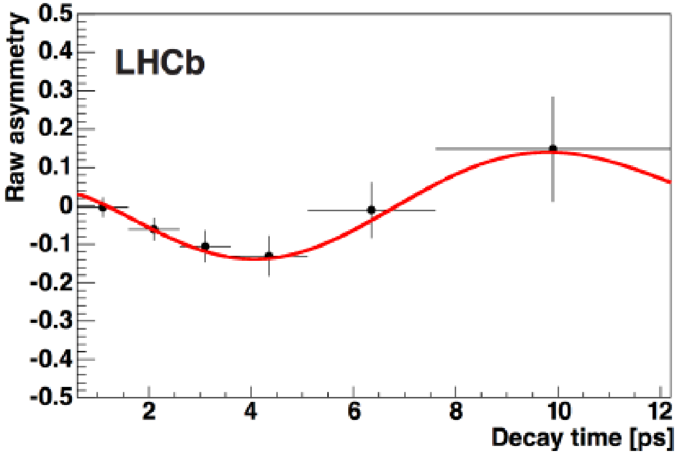
CP violation in $B \to \pi^+\pi^-$ & $B_s \to K^+K^-$ (angle α/γ)



- 1 fb^{-1} : ~9000 $B^0 \to \pi^+\pi^-$ events
- First time-dependent CP asymmetry plot of $B^0 \to \pi^+\pi^-$ at a hadron collider

$$C_{\pi\pi} = -0.38 \pm 0.15 \pm 0.02$$ cos term (direct)

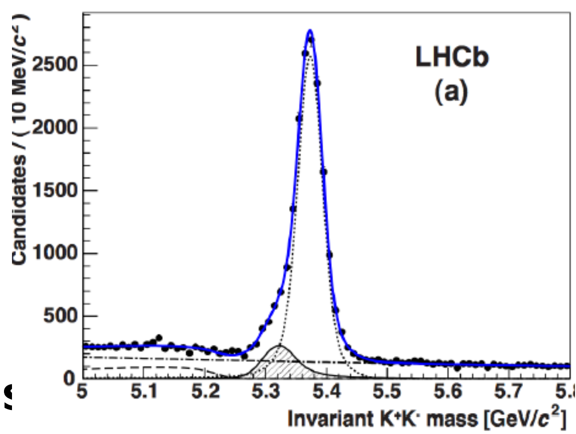
$$S_{\pi\pi} = -0.71 \pm 0.13 \pm 0.02$$ sine term (indirect)

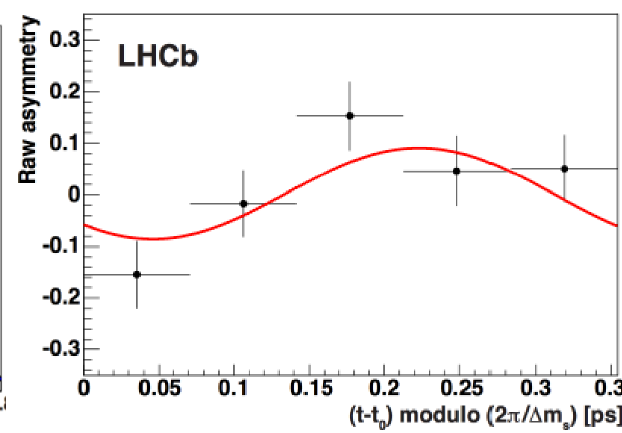


- Also first ever time-dependent asymmetry seen in $B_s \to K^+K^-$

$$C_{KK} = 0.14 \pm 0.11 \pm 0.03$$

$$S_{KK} = 0.30 \pm 0.12 \pm 0.04$$

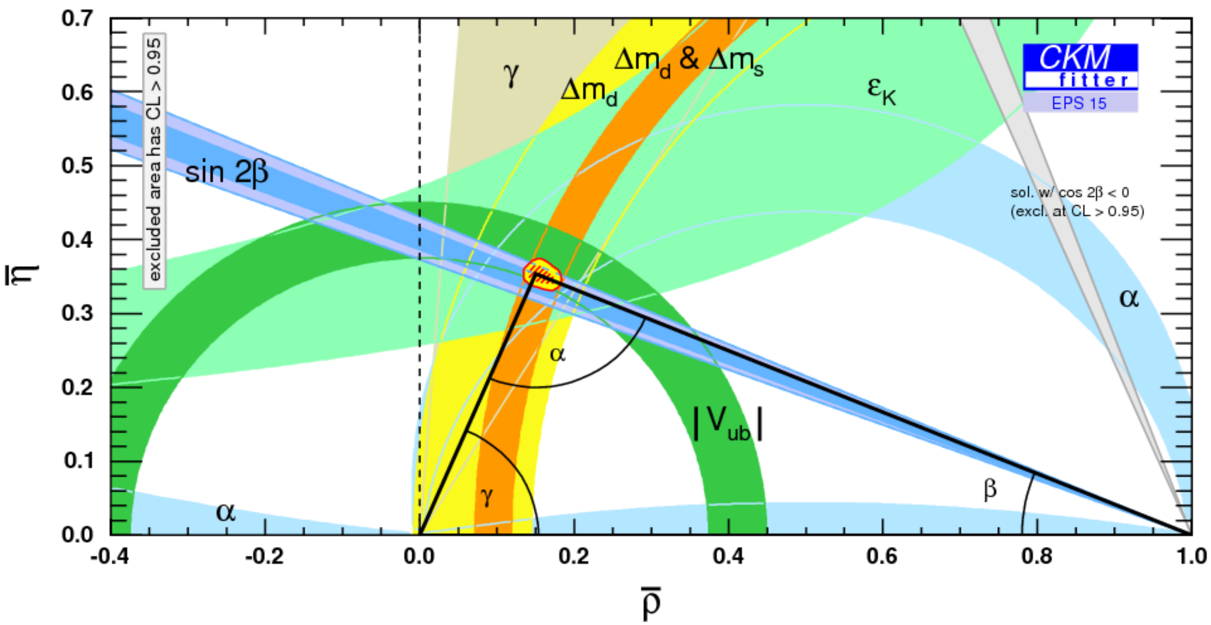


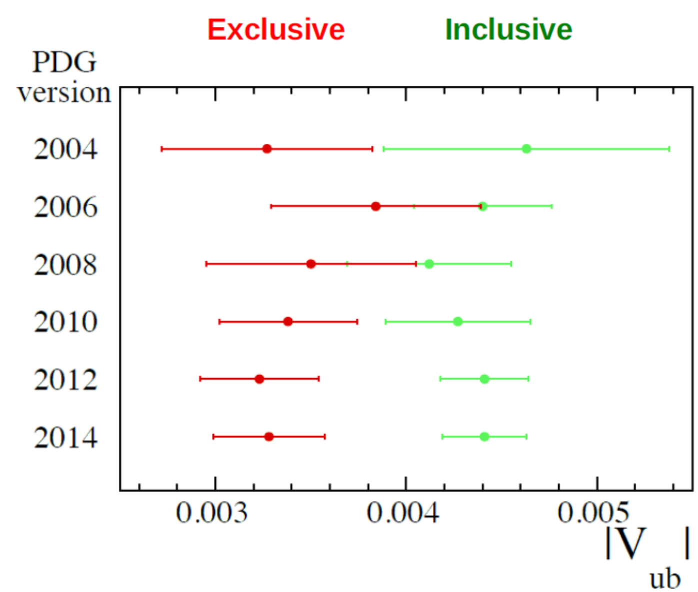


JHEP 10 (2013) 183

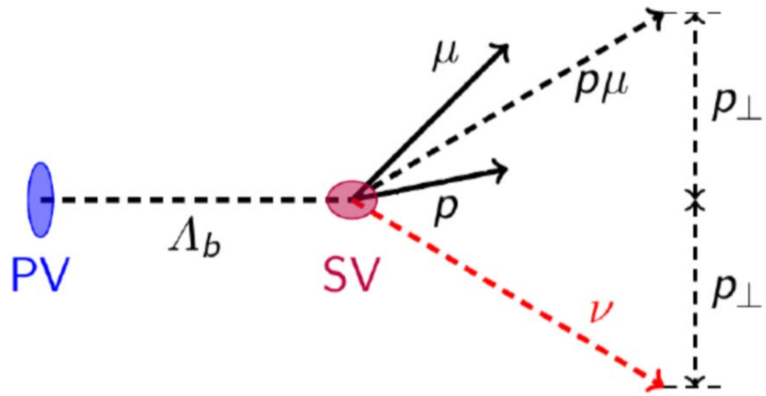
LHCb measurement of $|V_{ub}|$

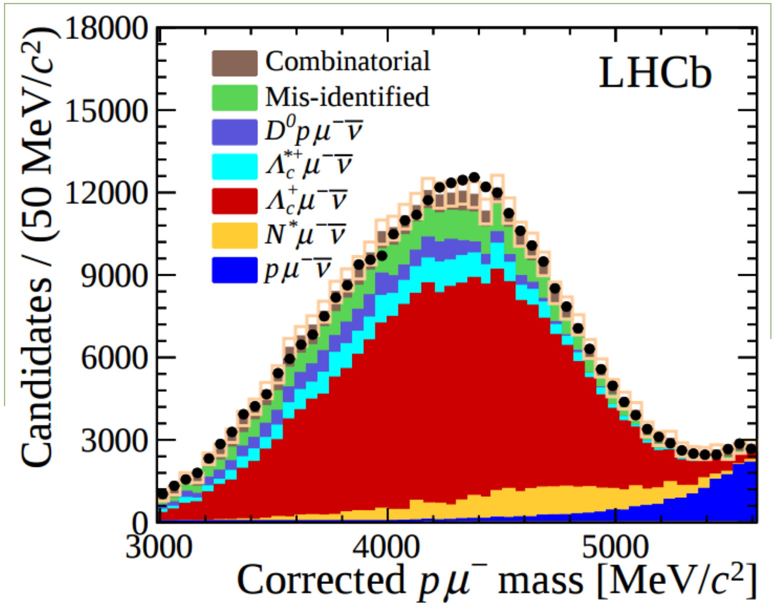
- Side opposite to β proportional to $|V_{ub}|$ / $|V_{cb}|$. Both β and $|V_{cb}|$ known better than 3%.
- Closure test of UT mainly limited by $|V_{ub}|$
- The measurement of $|V_{ub}|$ has an internal inconsistency between
  - Exclusive measurement: $B^0 \rightarrow \pi^- \mu^+ \nu$
  - Inclusive measurement : $B^0/B^+ \rightarrow X_u \mu^+ \nu$





- $|V_{ub}|/|V_{cb}|$ long thought to be impossible at a hadron colliders due to neutrinos
- NEW : LHCb measures $\Lambda_b \rightarrow p\,\mu^-\,\nu$





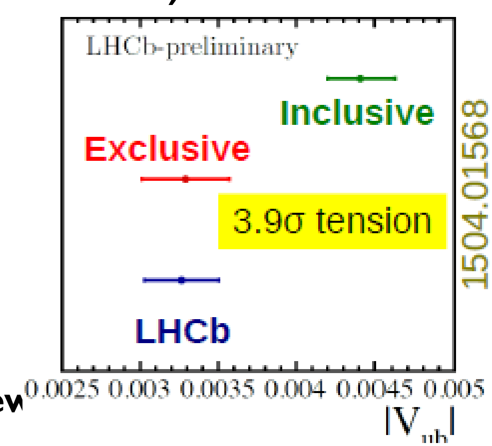
- LHCb measures

$|V_{ub}| = (3.27 \pm 0.15(\text{exp}) \pm 0.17(\text{theory}) \pm 0.06\ (|V_{cb}|) \times 10^{-3}$

(relies on new $\Lambda_b \rightarrow p$ form factors from the lattice)

(Nature Physics 10 (2015) 1038)

Tension between inclusive and exclusive $|V_{ub}|$ persists



Selected physics highlights

- Parameters of the CKM matrix
- Rare B decays
- Studies of CPV in the B_s system
- CP violation in charm
- Pentaquarks

Rare decay $B^0_{(s)} \to \mu^+\mu^-$

- Decays strongly suppressed in SM

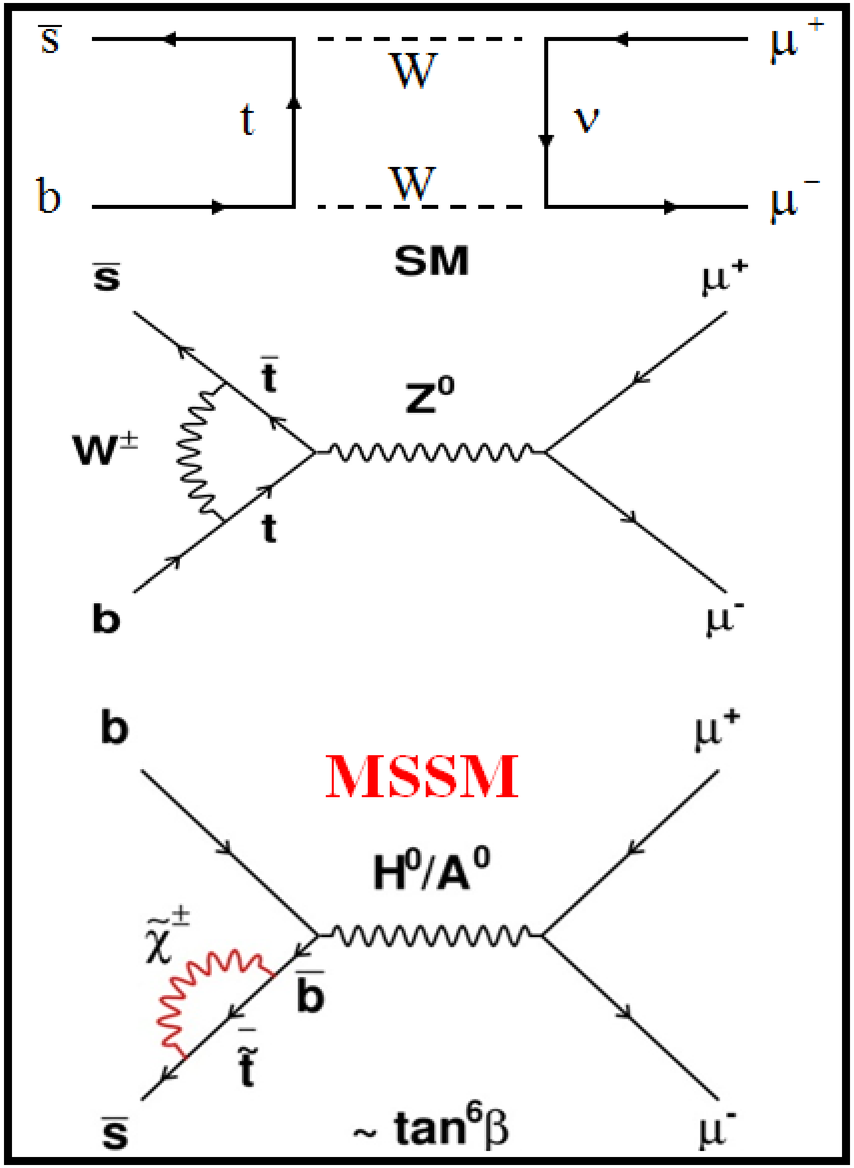
- Predicted BRs

  $B^0_s \to \mu^+\mu^- = (3.66 \pm 0.23) \times 10^{-9}$

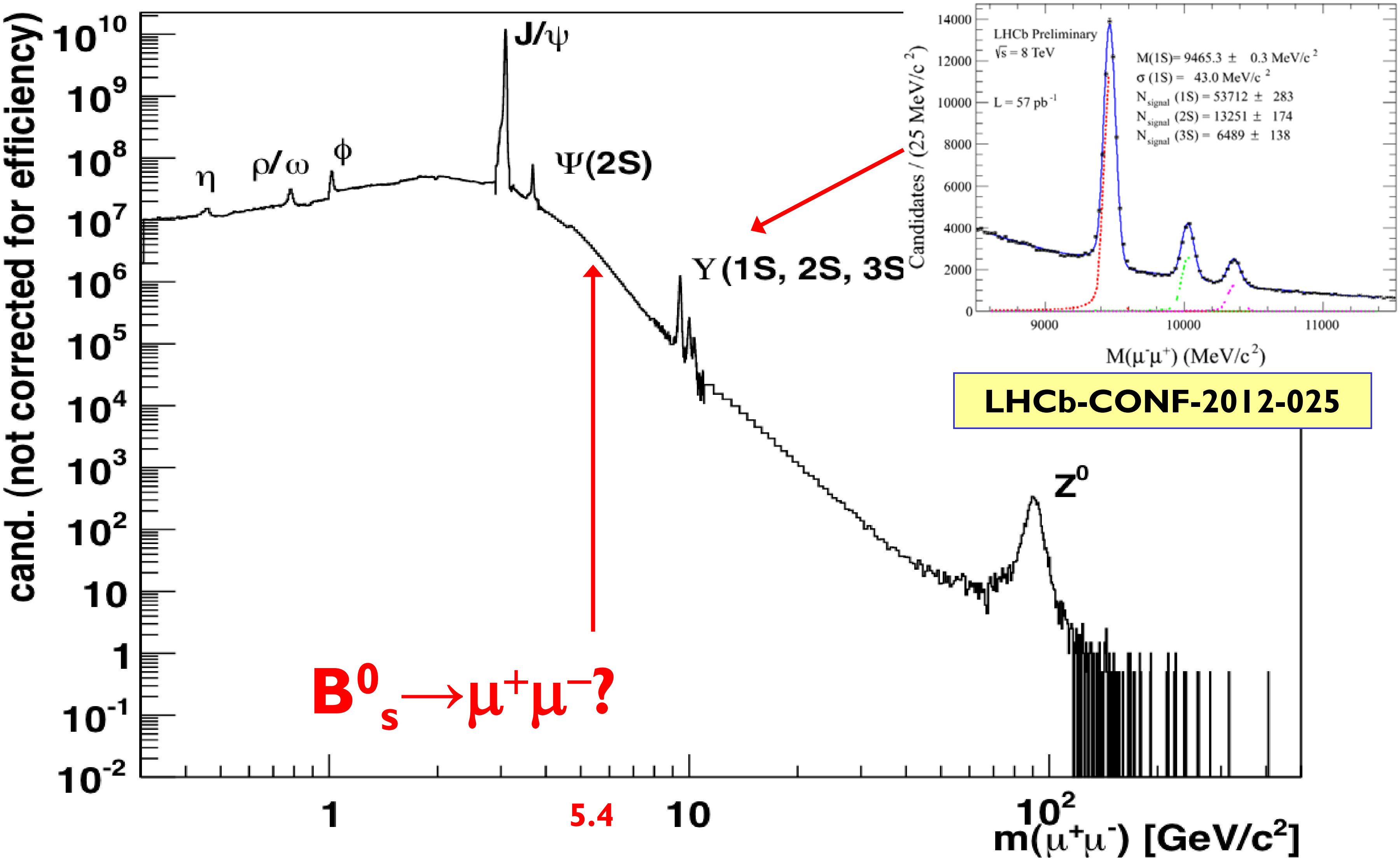
  $B^0 \to \mu^+\mu^- = (1.06 \pm 0.09) \times 10^{-10}$

  arXiv:1208:0934 & PRL 109 041801 (2012)

- Very sensitive to new physics - e.g. MSSM
- But it's a bit like looking for a needle in a haystack



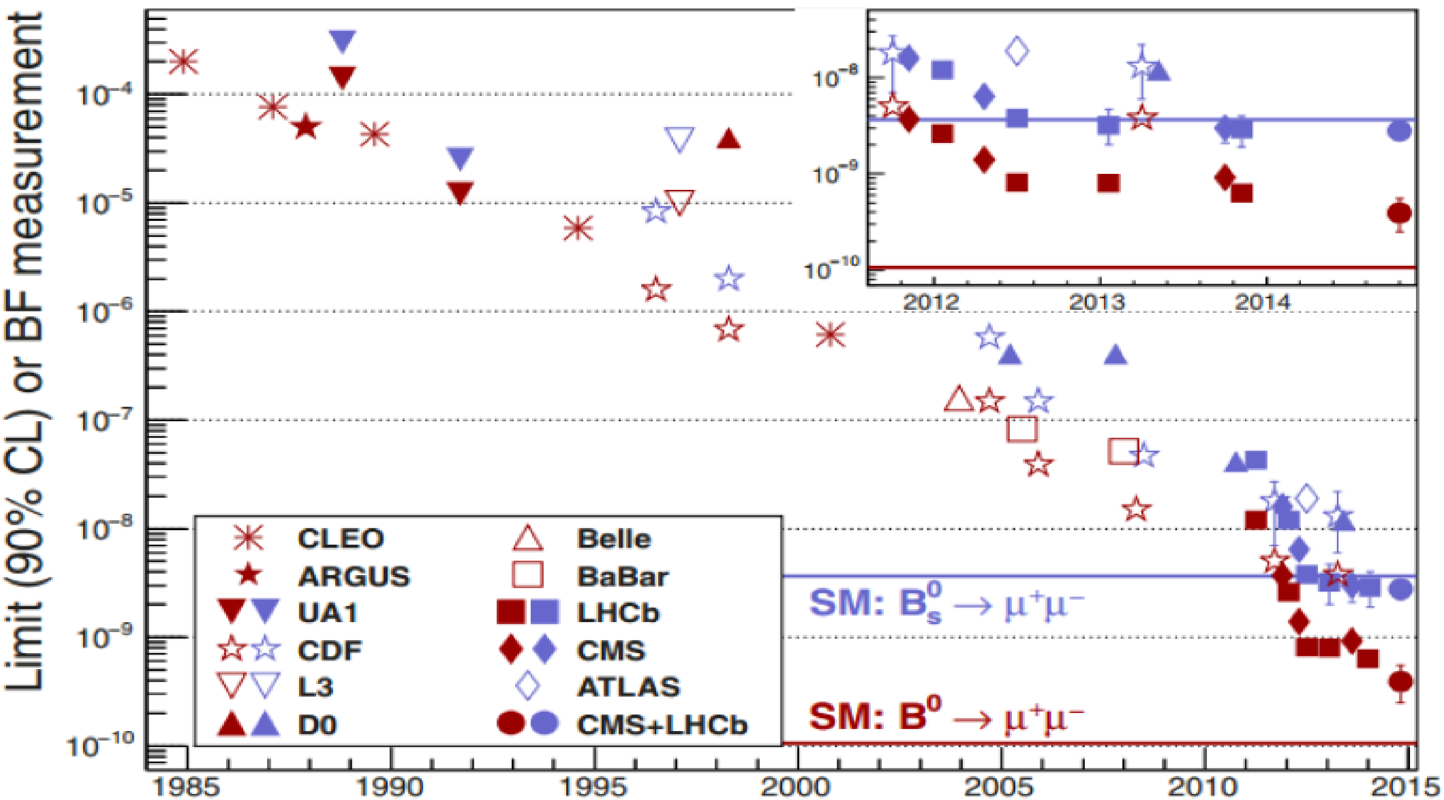
LHCb μ+μ– mass spectrum



History

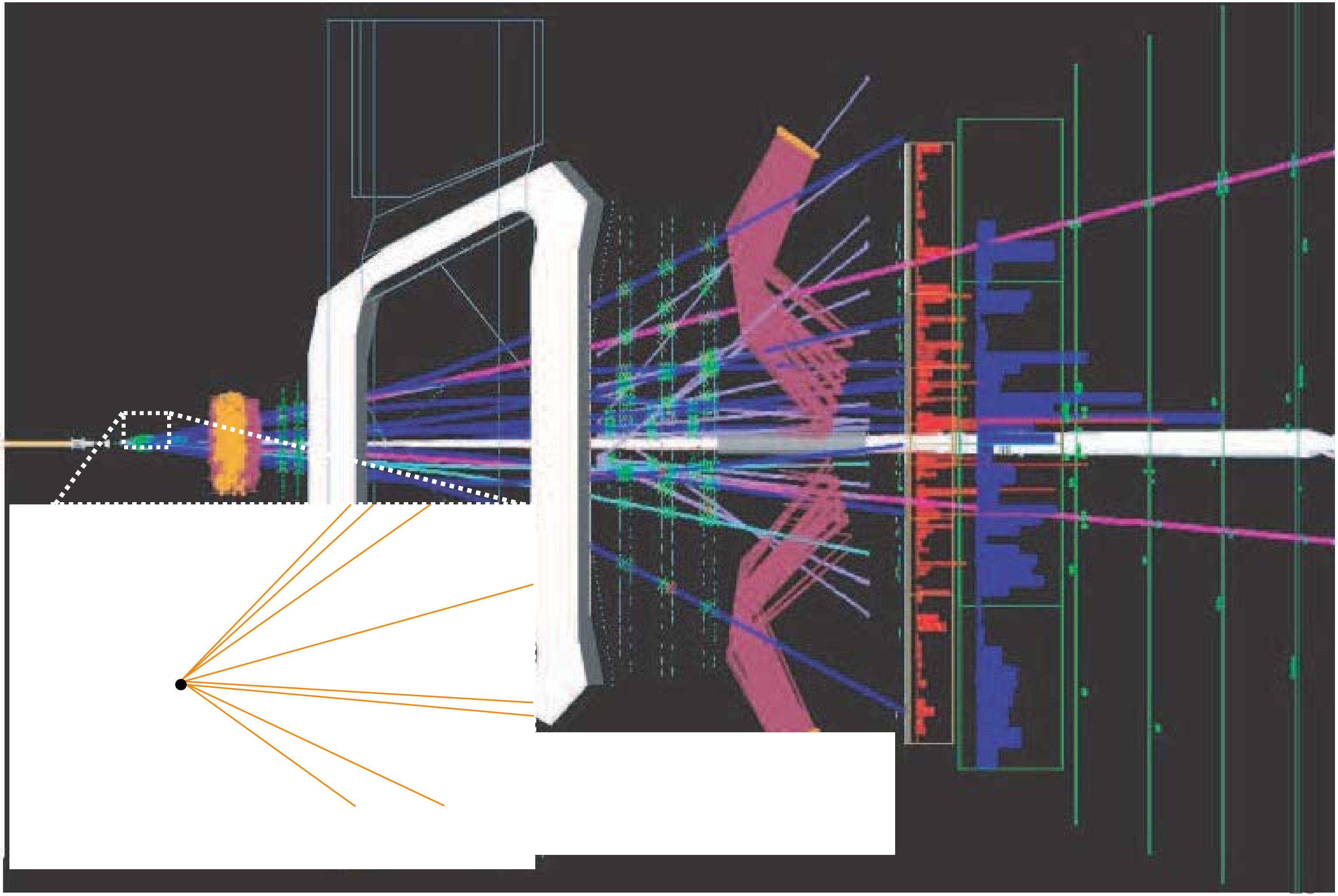
LHCb: Phys. Rev. Lett. 108 (2012) 231801

- $B^0_{(s)} \to \mu^+\mu^-$ sensitivity to NP has motivated searches since 1984 …
- $BR(B^0_s \to \mu^+\mu^-)$ has now surpassed the SM prediction

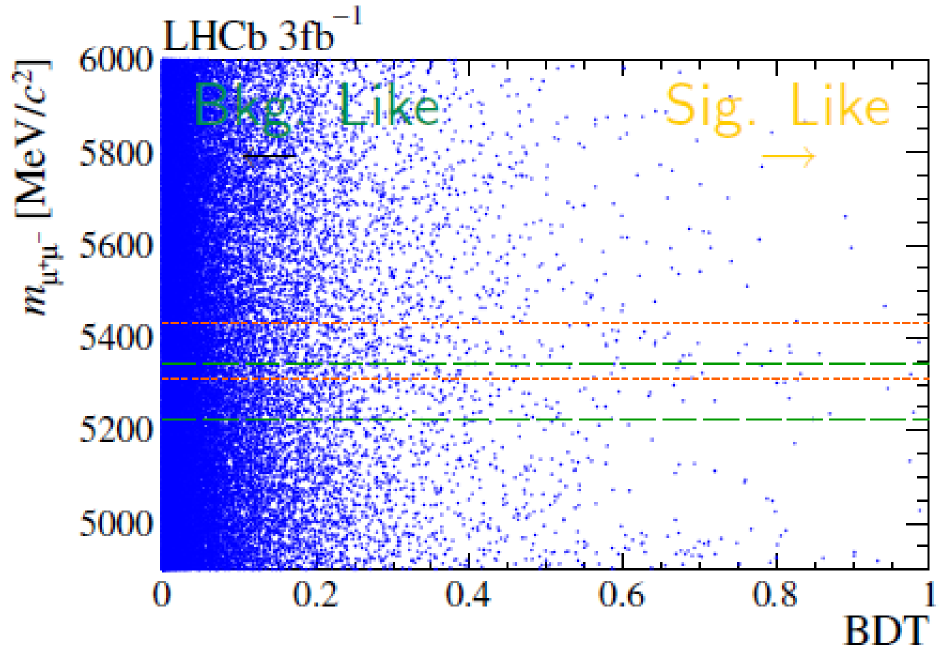


Long story with increasing precision

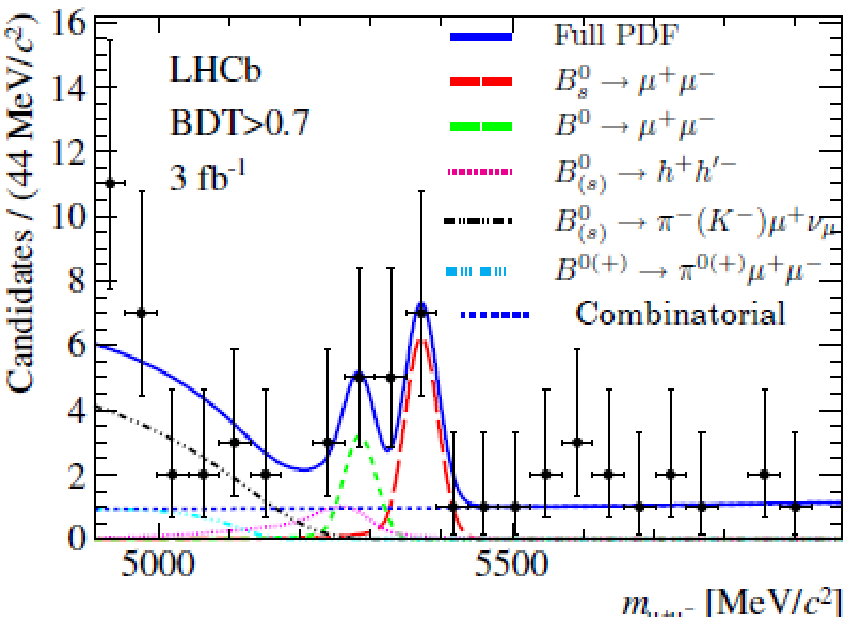
LHCb $B_s \to \mu^+\mu^-$ candidate



- Results based on 2011/12 data: 3 fb^{-1} blinded analysis
- Selection based on multivariate estimator (BDT) combining vertex and topological information
- Cut on BDT>0.5
- The known B masses and widths are fixed in the fit



PRL 111 (2013) 101805



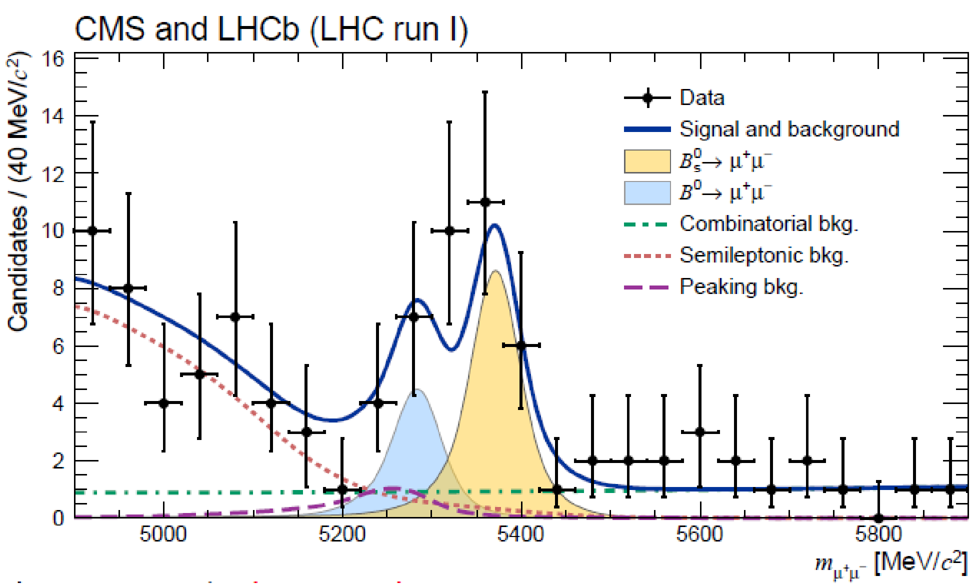
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0} st \ ^{+0.3}_{-0.1} sy) \times 10^{-9}$$

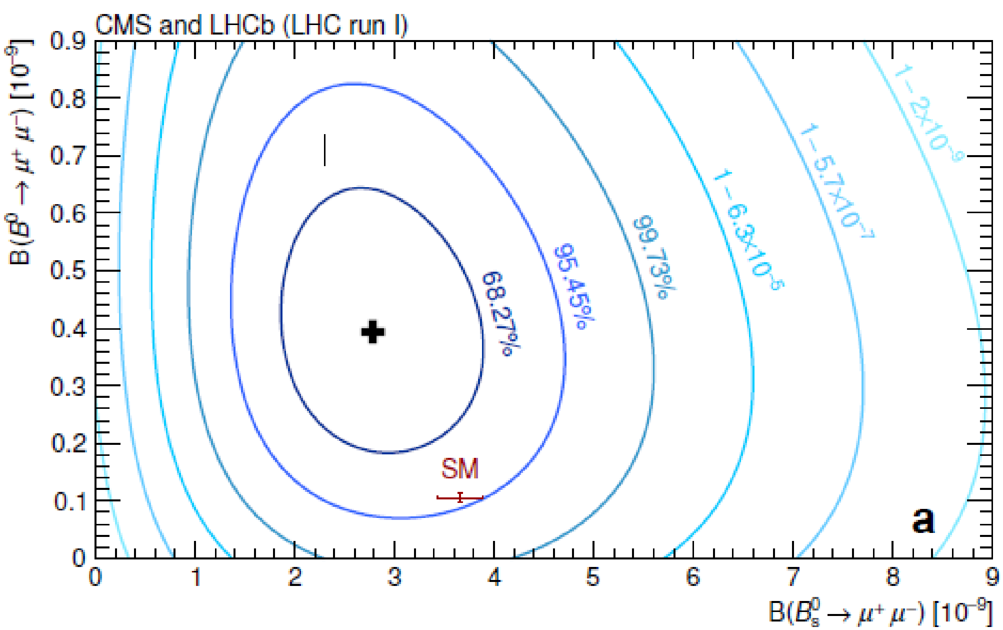
Significance : 4.0 (*Expected* 5.0)

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1} st \ ^{+0.6}_{-0.4} sy) \times 10^{-10}$$

Significance : 2.0

Combining with CMS results





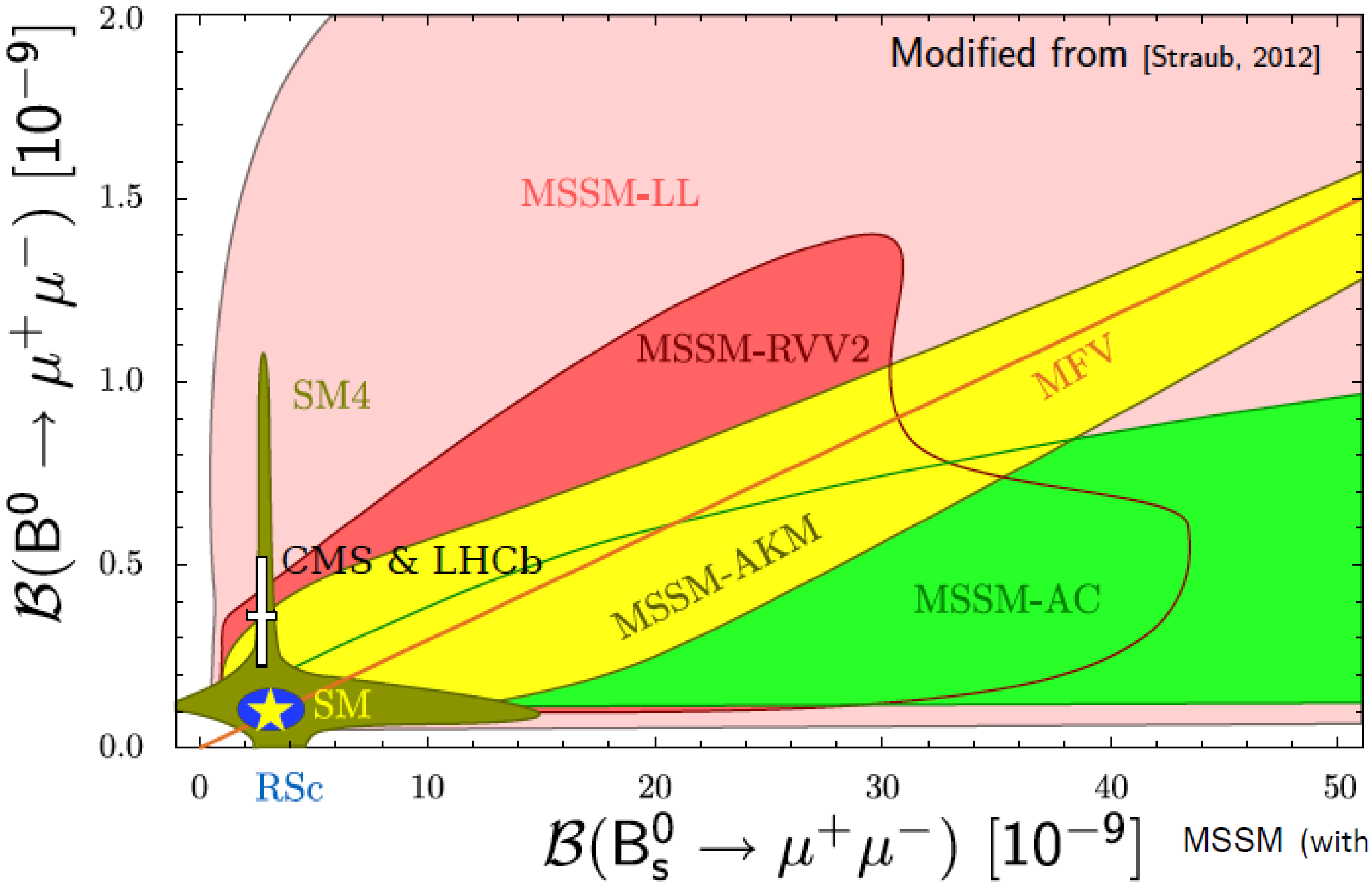
Nature 522, 68–72 (June 2015)

$B_d \to \mu^+\mu^-$:
$BR = (3.9^{+1.6}_{-1.4})\times 10^{-10}$
3.0σ significance

$B_s \to \mu^+\mu^-$:
$BR = (2.8^{+0.7}_{-0.6})\times 10^{-9}$
6.2σ significance
First observation!

B^0 compatible at 2.2σ with SM, B_s at 1.2σ

Constraints on new physics models

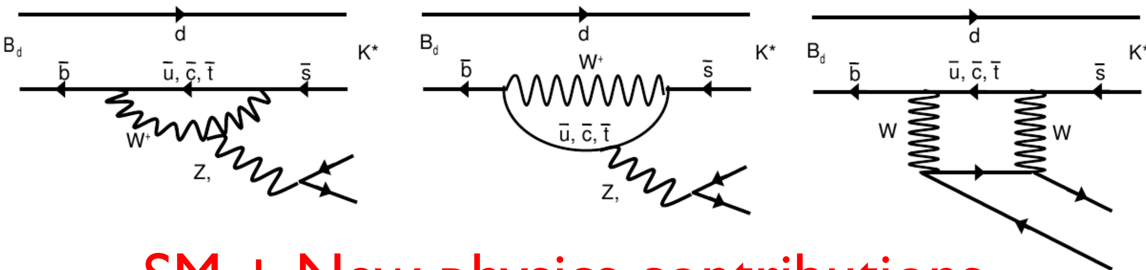


MSSM (with R-Parity conservation)

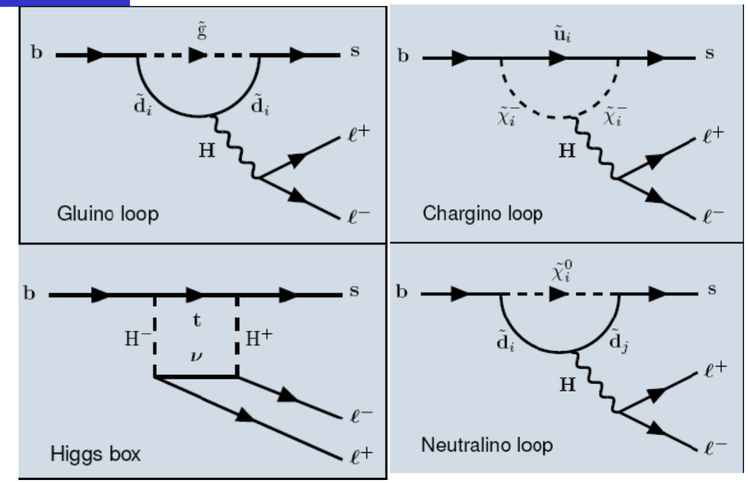
$$B(B_s \to \mu^+\mu^-)\ \alpha\ \frac{\tan^6\beta}{m_A^4}$$

Straub Moriond 2012
(http://phys.davidstraub.de/files/dstraub-moriond12.pdf)

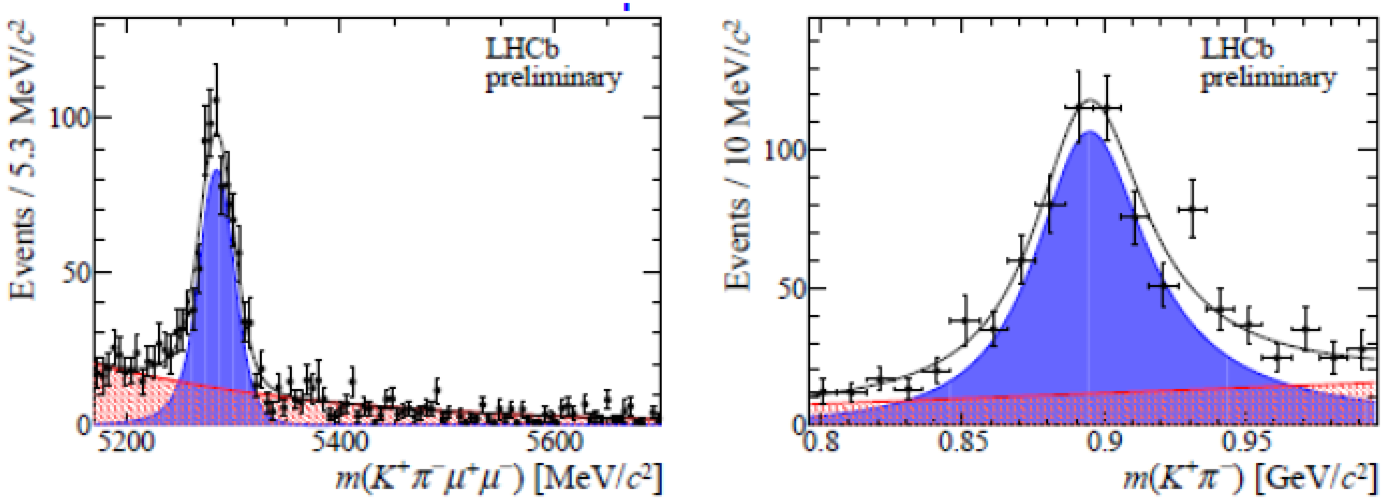
FCNC decay $B^0 \to K^{*0}\mu^+\mu^-$



SM + New physics contributions



- LHCb has largest sample in world, as clean as the B Factories!
- Interesting anomoly seen in 1 fb^{-1} dataset **JHEP 08 (2013) 131**
- New 3fb^{-1} sample now analysed, 7/8 TeV dataset **LHCb-CONF-2015-002**

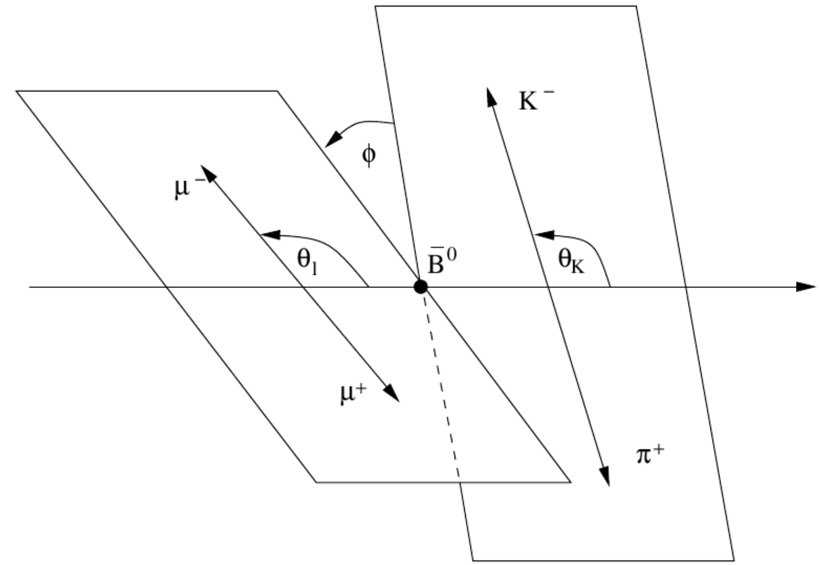


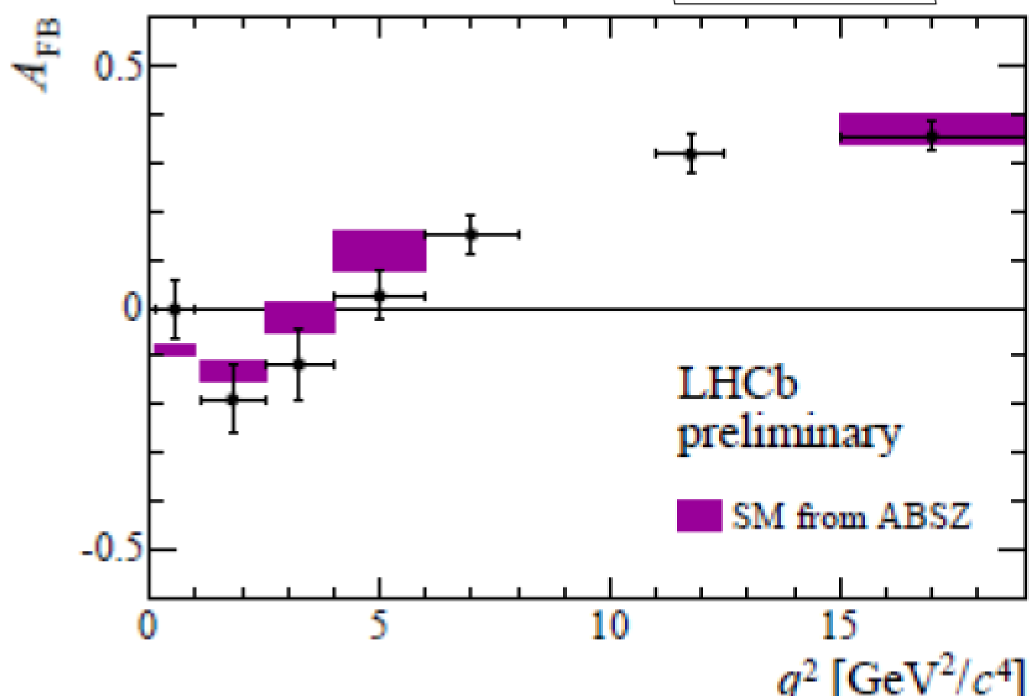
Cor

$B^0 \to K^*\mu^+\mu^-$ continued

JHEP 08 (2013) 131

- But forward-backward asymmetry $A_{FB}(q^2)$ in the $\mu\mu$ rest-frame is a sensitive NP probe ($q^2 = m_{\mu\mu}^2$)
- Measurement of zero crossing point with 3 fb^{-1}: $q^2 = 3.7\ ^{+0.8}_{-1.0}$ GeV^2 [JHEP 01 (2012) 107]
- A_{FB} measured by LHCb consistent with Standard Model





Angular observables in $B^0 \to K^*\mu^+\mu^-$

- Goal: express differential decay rate in terms of parameters that are less sensitive to the hadronic matrix element uncertainty ⇔ prevent NP from hiding under strong interaction effects.
- Same 3 fb^{-1} 7/8 TeV dataset
- Angular differential distribution given by:

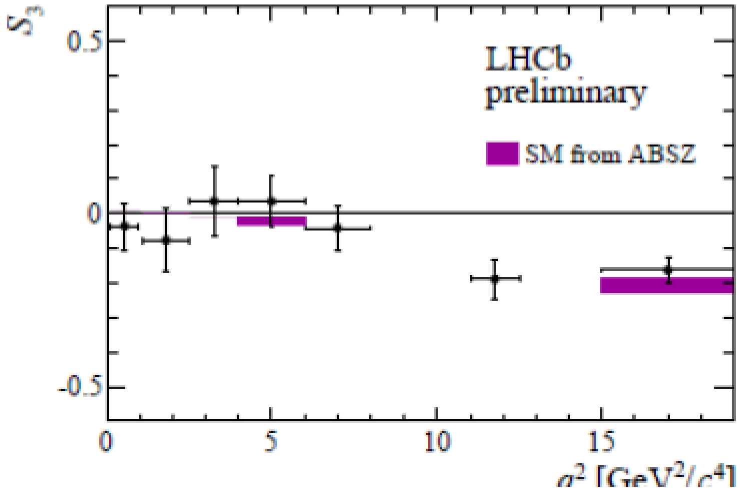
JHEP 08 (2013) 131 : 1 fb^{-1}
LHCb-CONF-2015-002 : 3 fb^{-1}

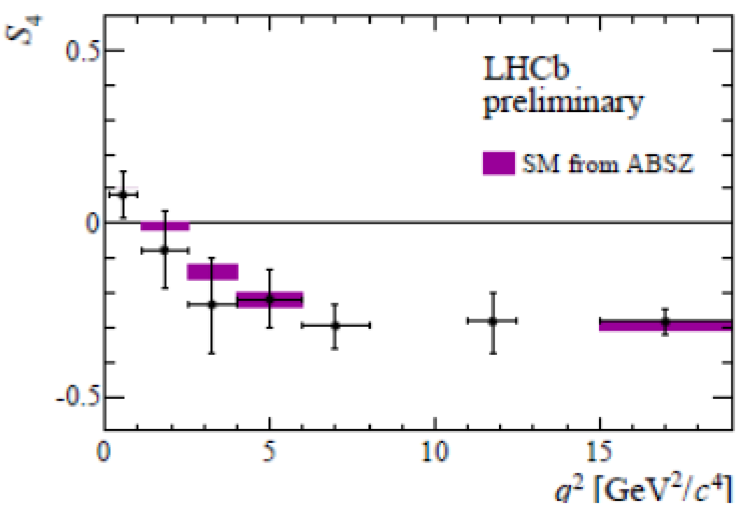
$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi +$$
$$\sqrt{F_L(1-F_L)}P_4'\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_L(1-F_L)}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi +$$
$$(1-F_L)A_{Re}^{T}\sin^2\theta_K\cos\theta_\ell + \sqrt{F_L(1-F_L)}P_6'\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$\sqrt{F_L(1-F_L)}P_8'\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\ \Big]$$

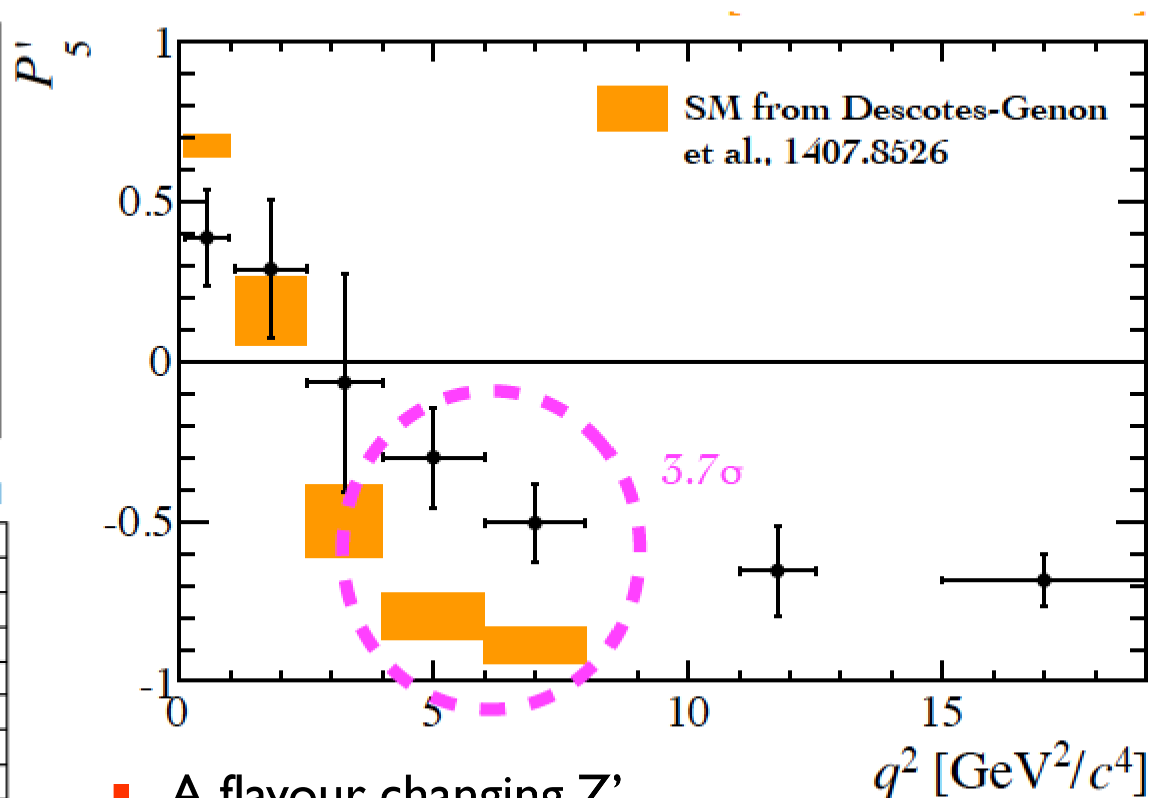
New observables in $B^0 \rightarrow K^*\mu^+\mu^-$ cont'

LHCb-CONF-2015-002

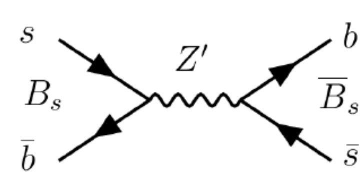
- Local discrepancy of 3.7σ in 2 bins of P_5'
  (SM prediction J.Mathias et al, JHEP 05 (2013) 137)







- A flavour changing Z' boson, QCD effects, or just statistical fluctuation?



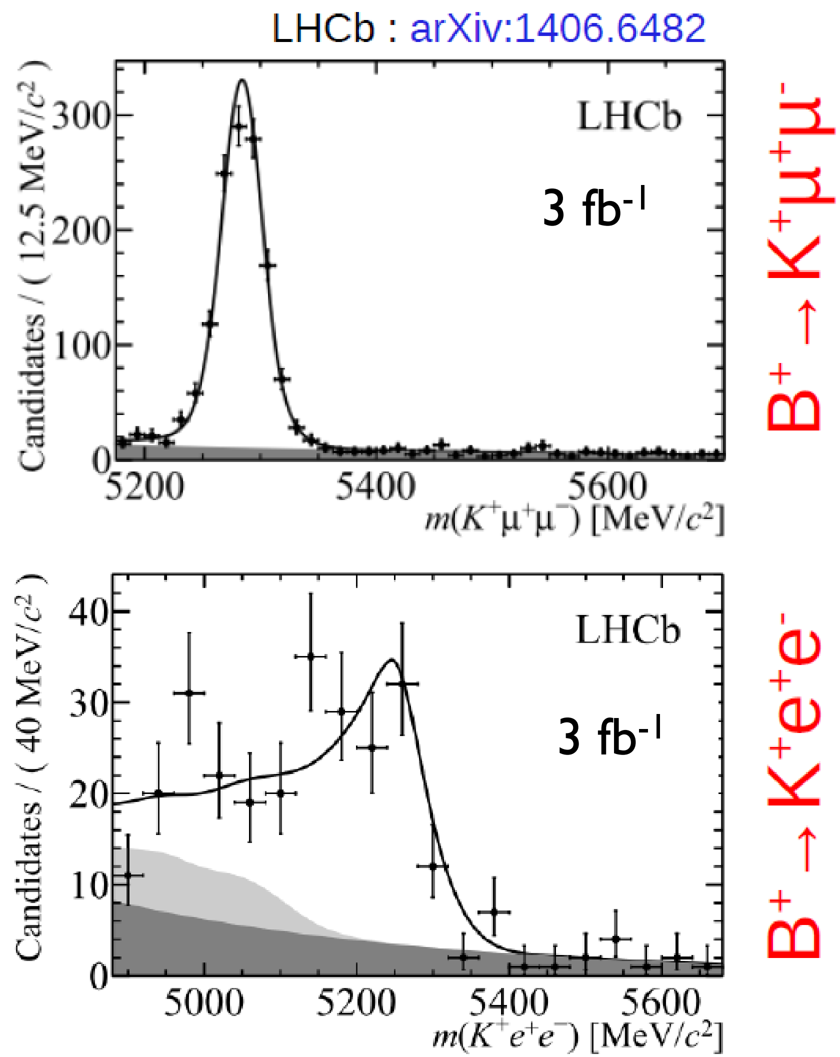
Lepton universality test in $B^+ \to K^+ \ell^+ \ell^-$

- Due to lepton universality, the $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$ decays should have same BF to within a factor 10^{-3}
- The ratio

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

is sensitive to lepton flavour violating NP

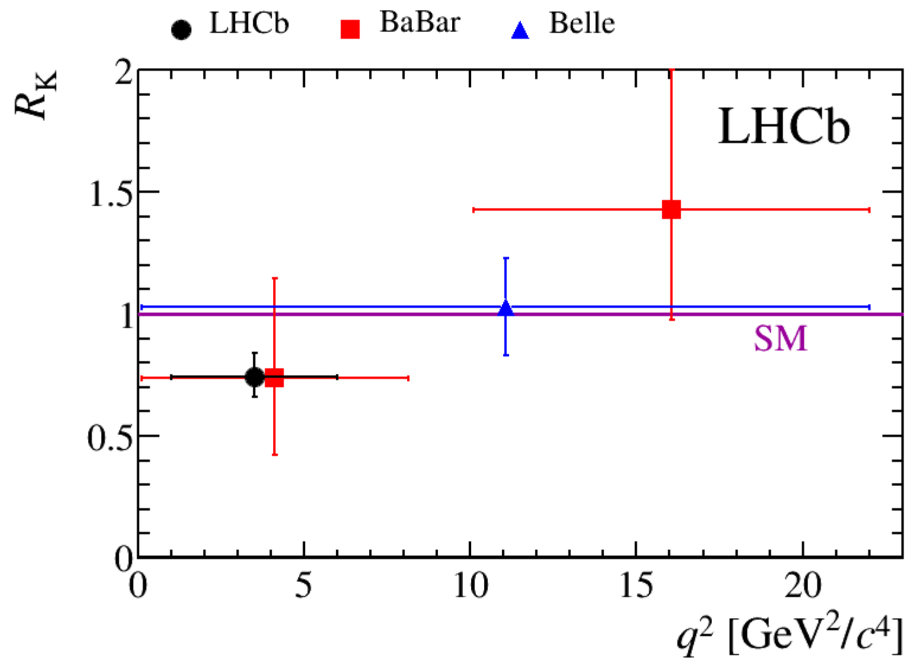
- The electron mode is a challenge for LHCb



Lepton universality test in $B^+ \to K^+ \ell^+ \ell^-$

- Define R_K as: $R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} = 1 \pm \mathcal{O}(10^{-3})$ in SM

- To cancel systematics, form double ratios with
  $B^+ \to K^+ J/\psi(\to \ell^+ \ell^-)$
  (assuming lepton universality for $J/\psi \to \ell^+ \ell^-$)
- The result for R_K differs from SM at 2.6 sigma level. This is using the 3 fb^{-1} of data.
- This is the most precise measurement of R_K to date.

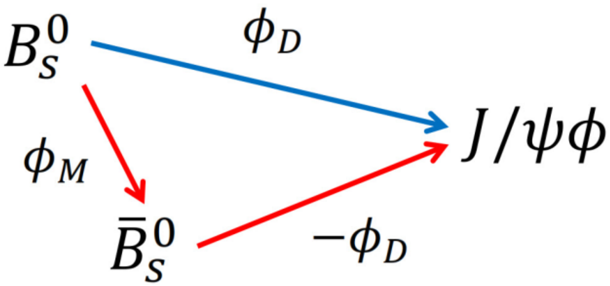


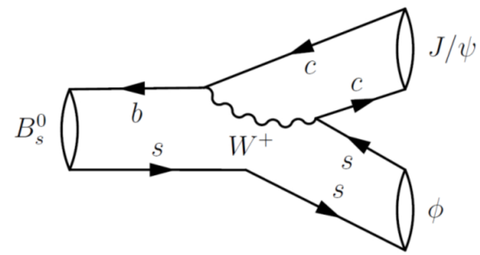
$$R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$$

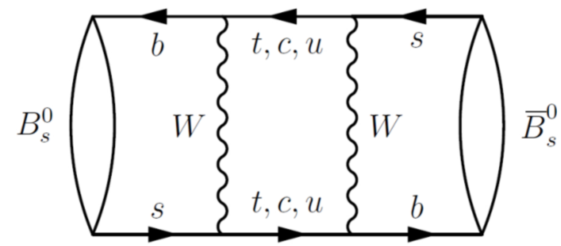
Selected physics highlights

- Parameters of the CKM matrix
- Rare B decays
- Studies of CPV in the B_s system
- CP violation in charm
- Pentaquarks

B_s weak mixing phase ϕ_s in $B_s \to J/\psi\ \phi$







- Golden mode for this study is $B_s \to J/\psi\ \phi$

3 fb^{-1} arXiv:1411.3104

- Analogue of 2β (phase of B^0 mixing) but in the B_s system

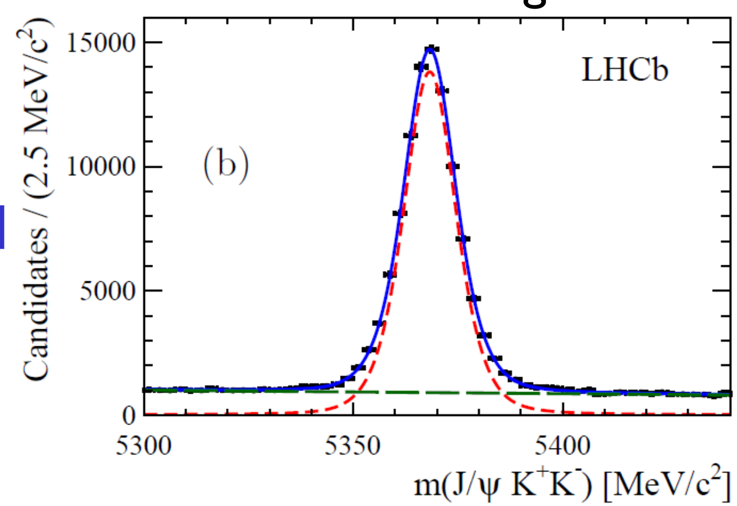
- *Interference* between B^0 decay to $J/\psi\phi$ directly and via B^0 - $\overline{B}^0$ oscillation gives rise to a CP violating phase

  $\phi = \phi_{Mixing} - 2\ \phi_{Decay} = -2\phi_s$

- ϕ_s is expected to be very small in the SM and precisely predicted:

  $\phi_s = -0.036 \pm 0.002$

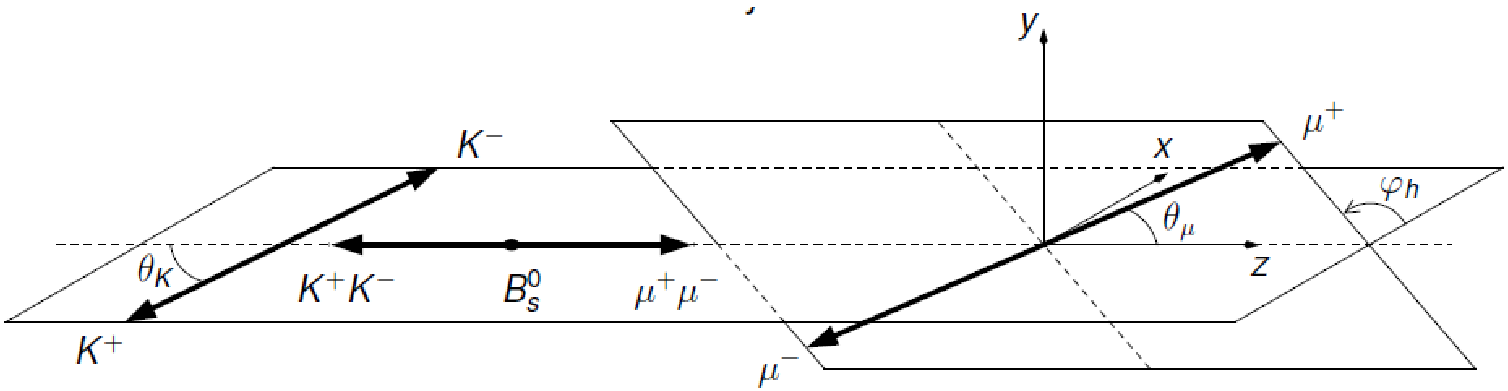
  (see eg Charles et al PRD84 (2011) 033005)



$B_s \to J/\psi\ \phi$ angular analysis

- ϕ is a vector meson (spin 1)
- Vector-vector final state: mixture of CP-odd and CP-even components

Need to perform $B_s \to J/\Psi\ \phi$ angular analysis

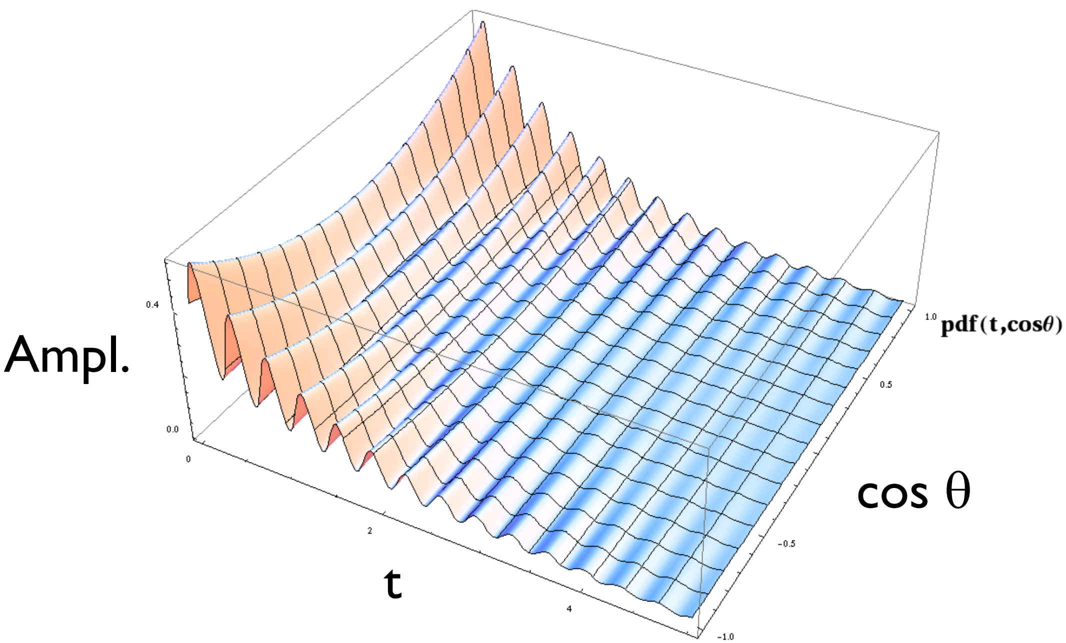


- LHCb 7 & 8TeV, $3fb^{-1}$: 95,690 ± 350 candidates
- Tagging: Opposite side tagging power 2.55% (+15% w.r.t. 2011)

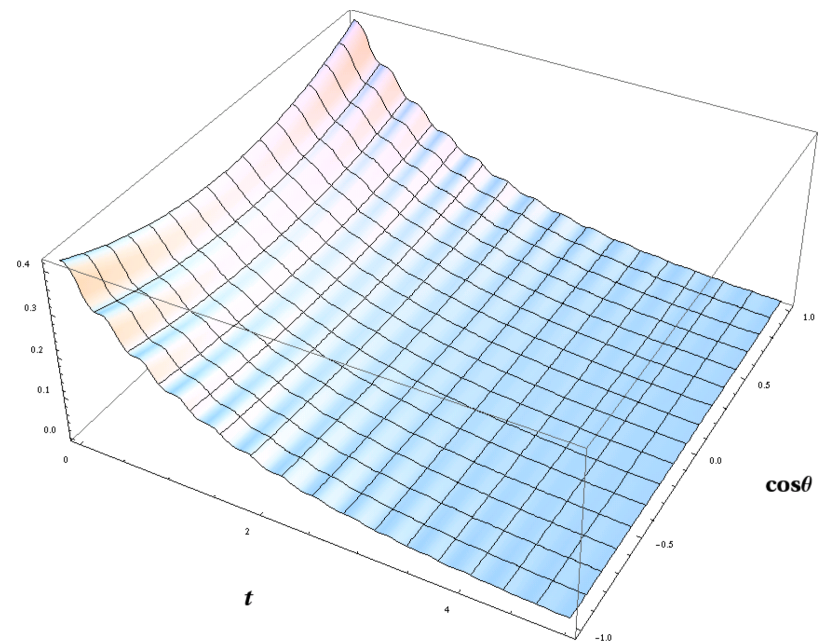
  Same Side Kaon Tagger 1.25% (+40% w.r.t. 2011)

"Visualizing" the effect of ϕ_s in $B_s \to J/\psi\ \phi$

- Amplitude of asymmetry $\propto \sin \phi_s$
- Frequency is the same as in B_s mixing

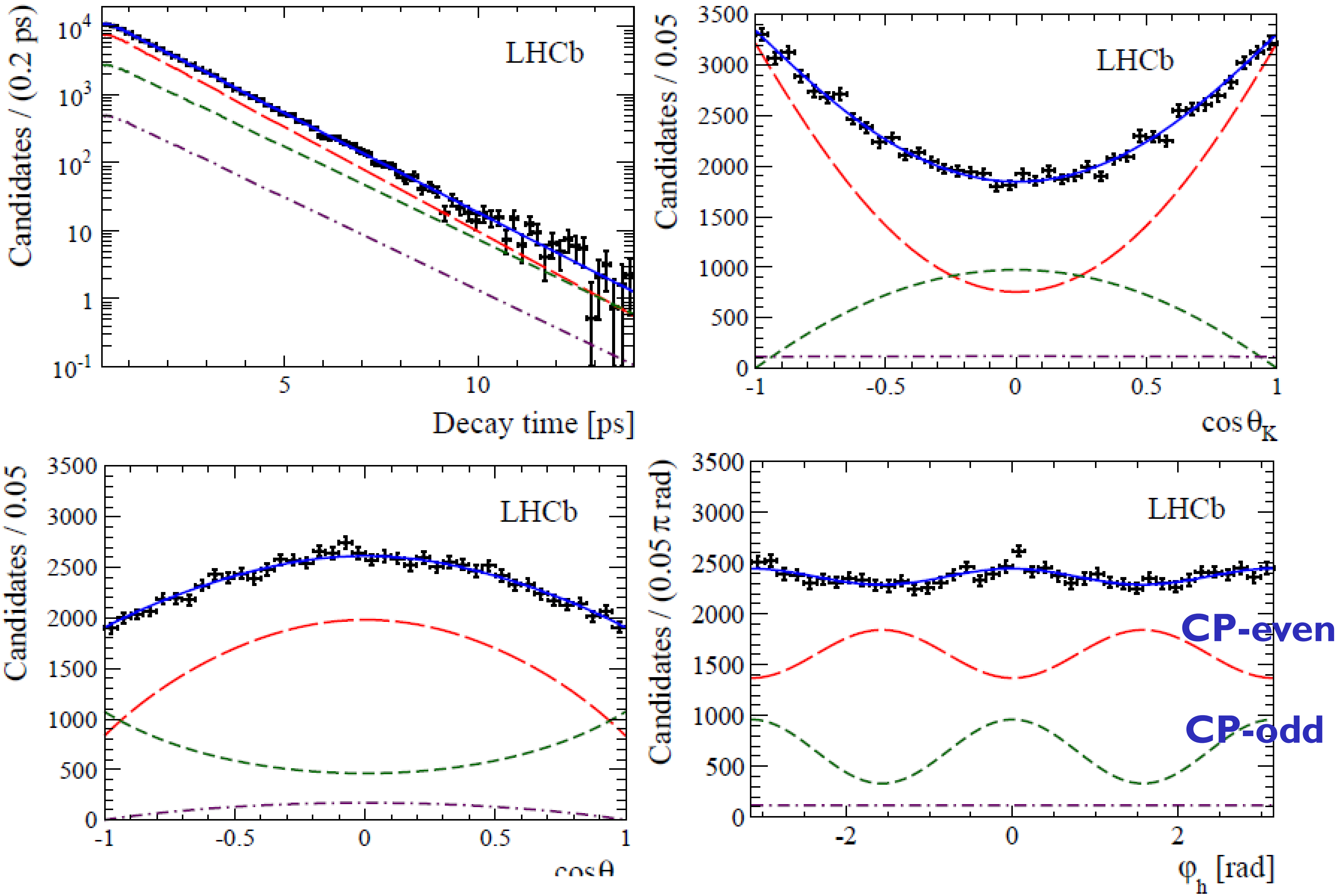


$\phi_s = 0.4$



$\phi_s = 0.04$ (SM)

$B_s \to J/\psi\ \phi$: fit projections



3 fb^{-1} arXiv:1411.3104

- Results correlated with $\Delta\Gamma_s$ = width diff. of the B_s mass eigenstates $\rightarrow$ plot as contours in (ϕ_S *vs* $\Delta\Gamma_S$) plane

- $\Gamma_S = 0.6603 \pm 0.0027 \pm 0.0015$ ps^{-1}
- $\Delta\Gamma_S = 0.0805 \pm 0.0091 \pm 0.0033$ ps^{-1}

CP-violating phase:

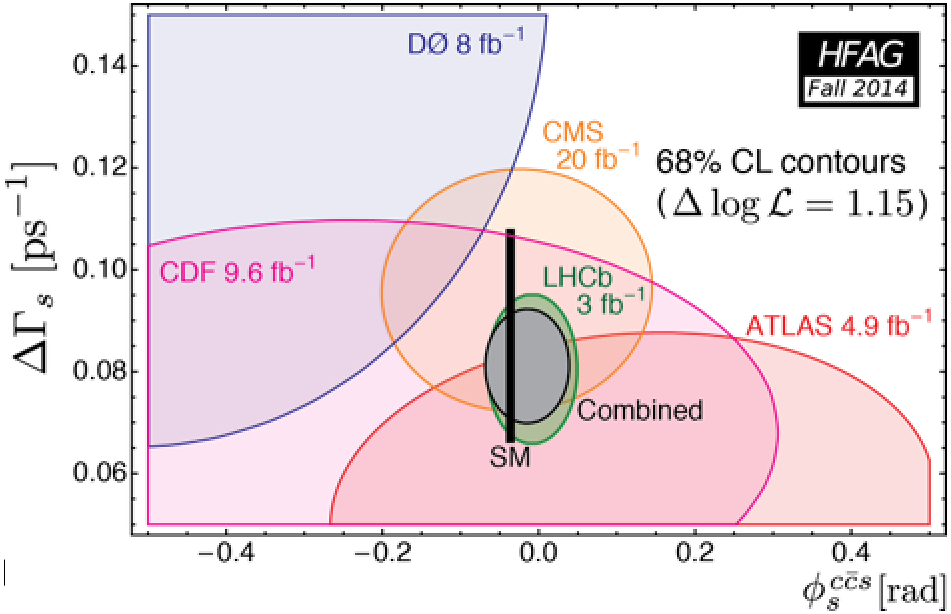
- $\phi_S = -0.058 \pm 0.049 \pm 0.006$ rad

World's most significant direct measurement of ϕ_S & $\Delta\Gamma_S$

- Also add in $B_s \rightarrow J/\psi\ \pi\pi$

$\phi_S = -\ 0.010 \pm 0.039$ rad

PLB 736 (2014) 186

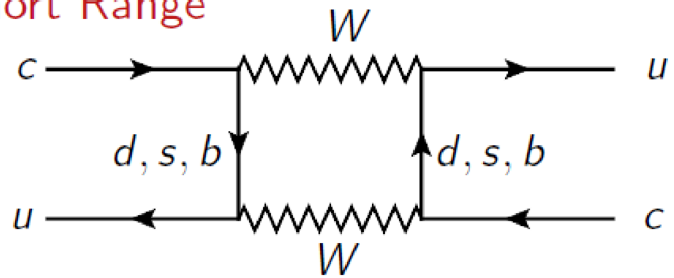


Selected physics highlights

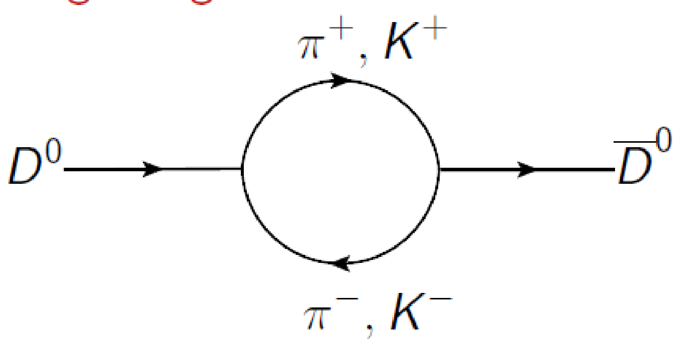
- Parameters of the CKM matrix
- Rare B decays
- Studies of CPV in the B_s system
- CP violation in charm
- Pentaquarks

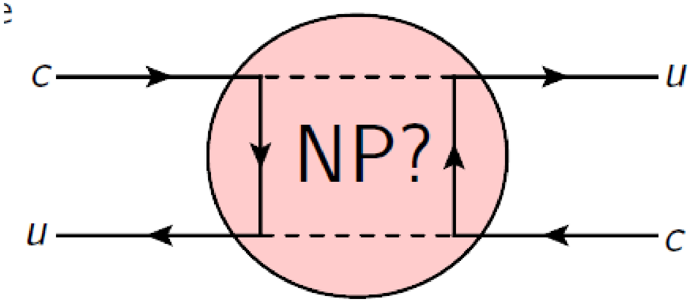
Mixing (and CP-violation) in charm decays

Short Range



Long Range





ptember

15 November 2011 Last updated at 12:18 GMT

Share

LHC reveals hints of 'new physics' in particle decays

By Jason Palmer
Science and technology reporter, BBC News

Large Hadron Collider researchers have shown off what may be the facility's first "new physics" outside our current understanding of the Universe.

Particles called D-mesons seem to decay slightly differently from their antiparticles, LHCb physicist Matthew Charles **told the HCP 2011 meeting** on Monday.

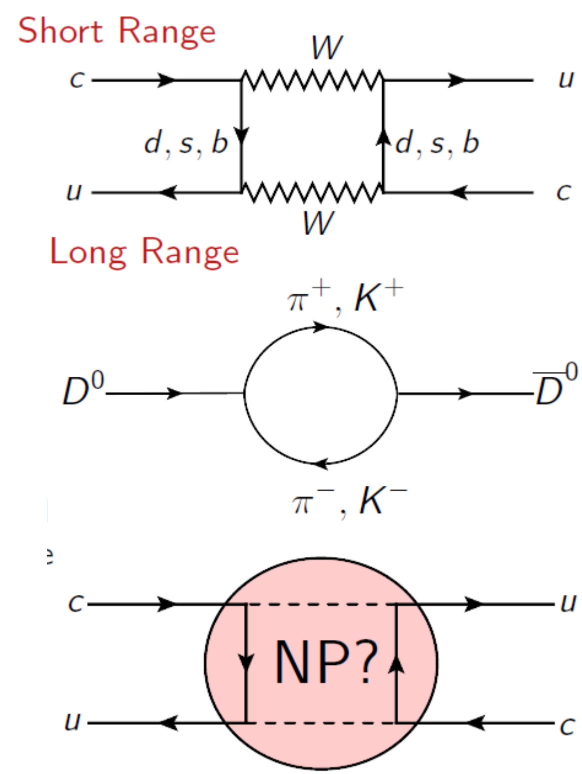
The result may help explain why we see so much more matter than antimatter.

Mixing in charm decays

- Charm mixing was confirmed by BaBar, Belle & CDF, but LHCb shows clear observation in a single experiment.
- LHCb measures the time-dependent ratio of D^0 decays to Wrong Sign over Right Sign (will have contribution from mixing)

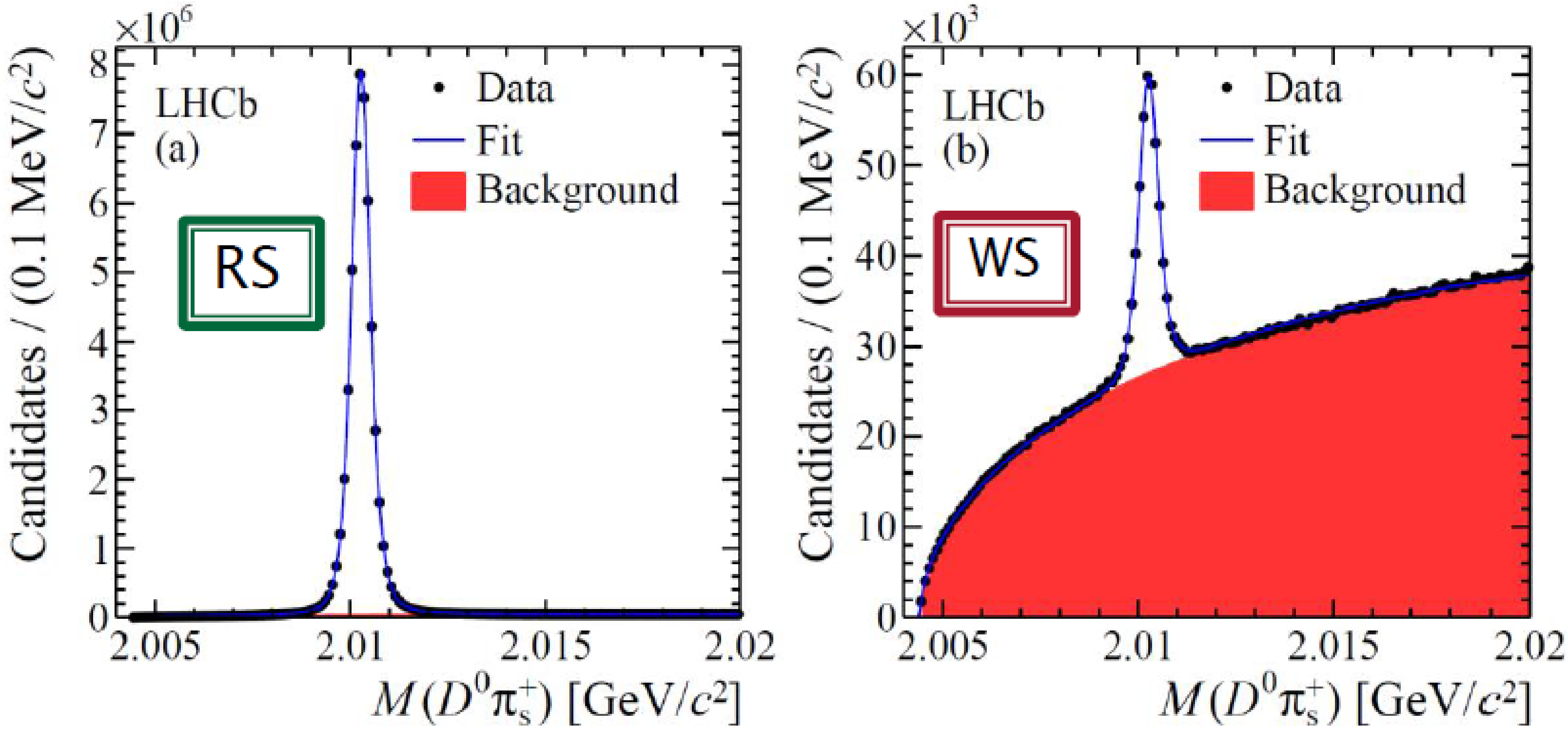
$$R(t) = \frac{N(D^0 \to K^+ \pi^-)}{N(D^0 \to K^- \pi^+)}$$

- Use the sign of the slow pion from $D^{*+} \to D^o \pi^+_s$ and $D^{*-} \to \overline{D}^o \pi^-_s$ to tag the initial D^0 flavour.



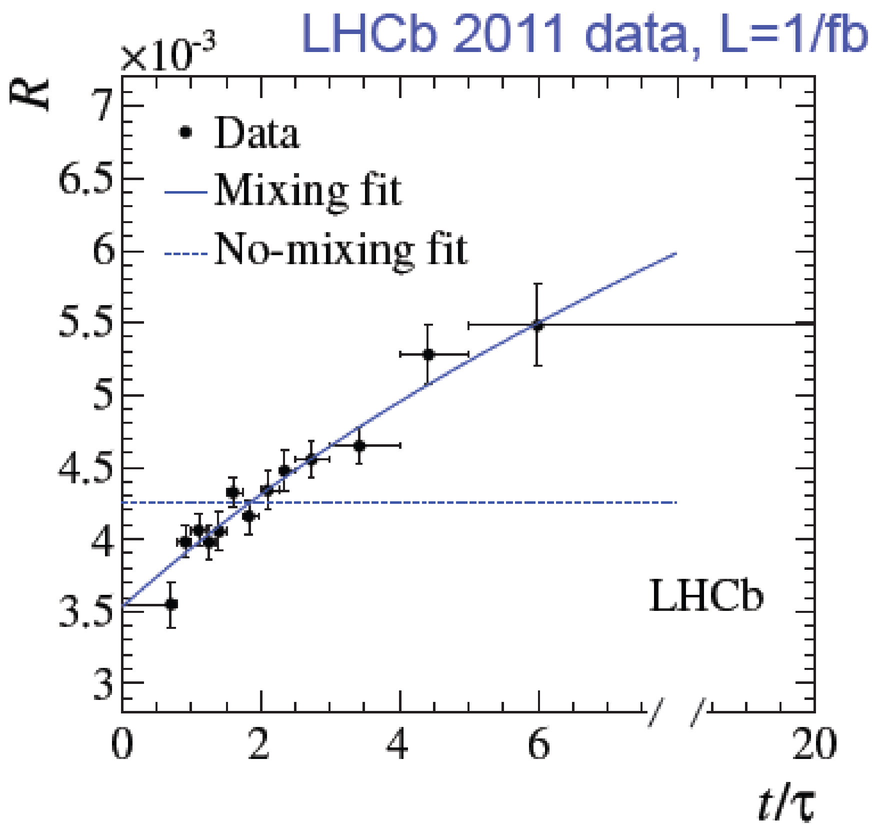
Charm mixing measurement

$$R(t) = \frac{N(D^0 \to K^+\pi^-)}{N(D^0 \to K^-\pi^+)}$$



- New analysis uses 3 fb^{-1} of data (results coming soon)
- Huge samples of D candidates: 230k WS and 54M RS

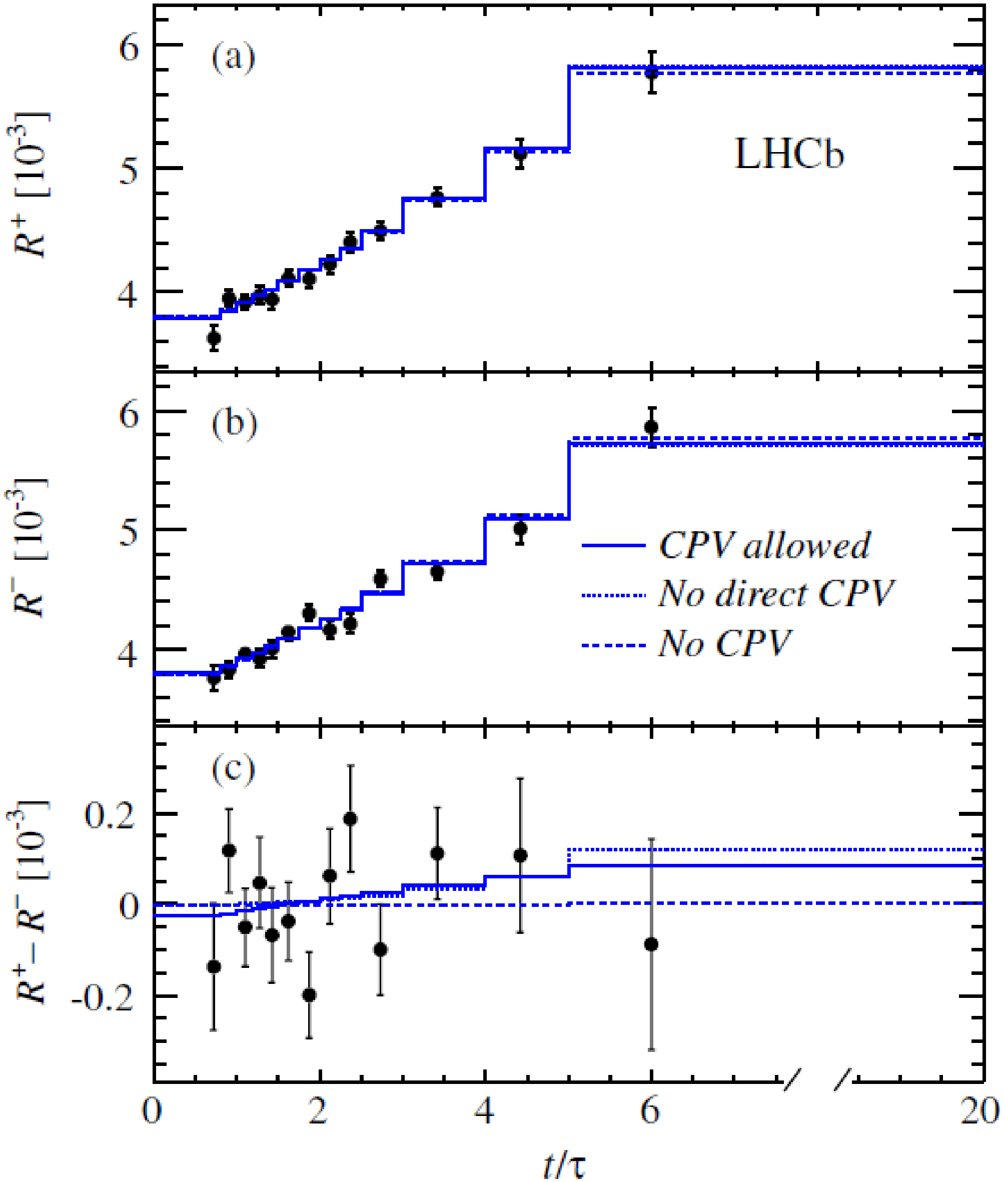
Charm mixing measurement (2011 data)



The no mixing hypothesis is excluded at the 9.1σ level in a single experiment

PRL 110, 101802 (2013)

CP violation in charm



Consistent with no CP violation in charm sector

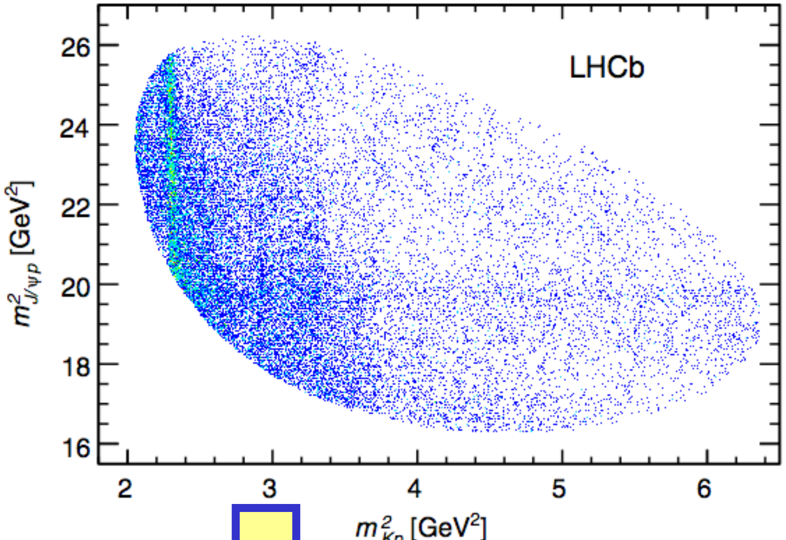
New J.Phys. 15 (2013) 053021

Selected physics highlights

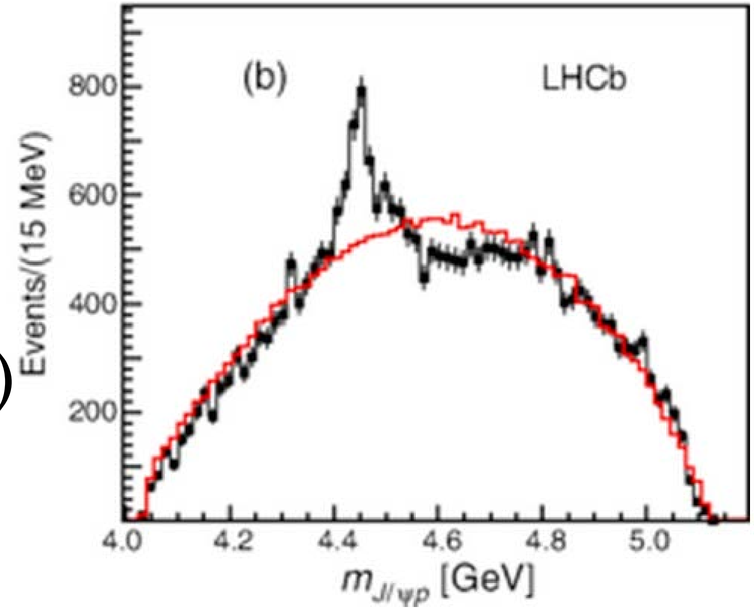
- Parameters of the CKM matrix
- Rare B decays
- Studies of CPV in the B_s system
- CP violation in charm
- Pentaquarks

NEW … pentaquarks !

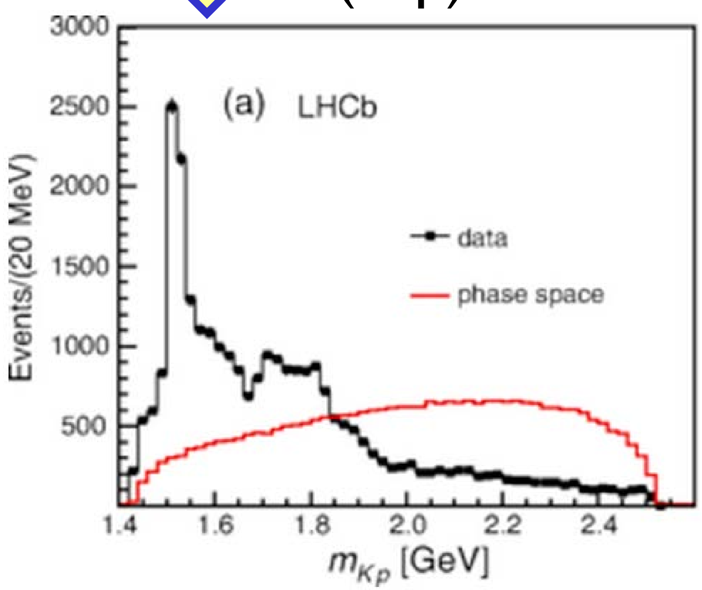
PRL 115 (2015) 072001



m(J/ψ p)

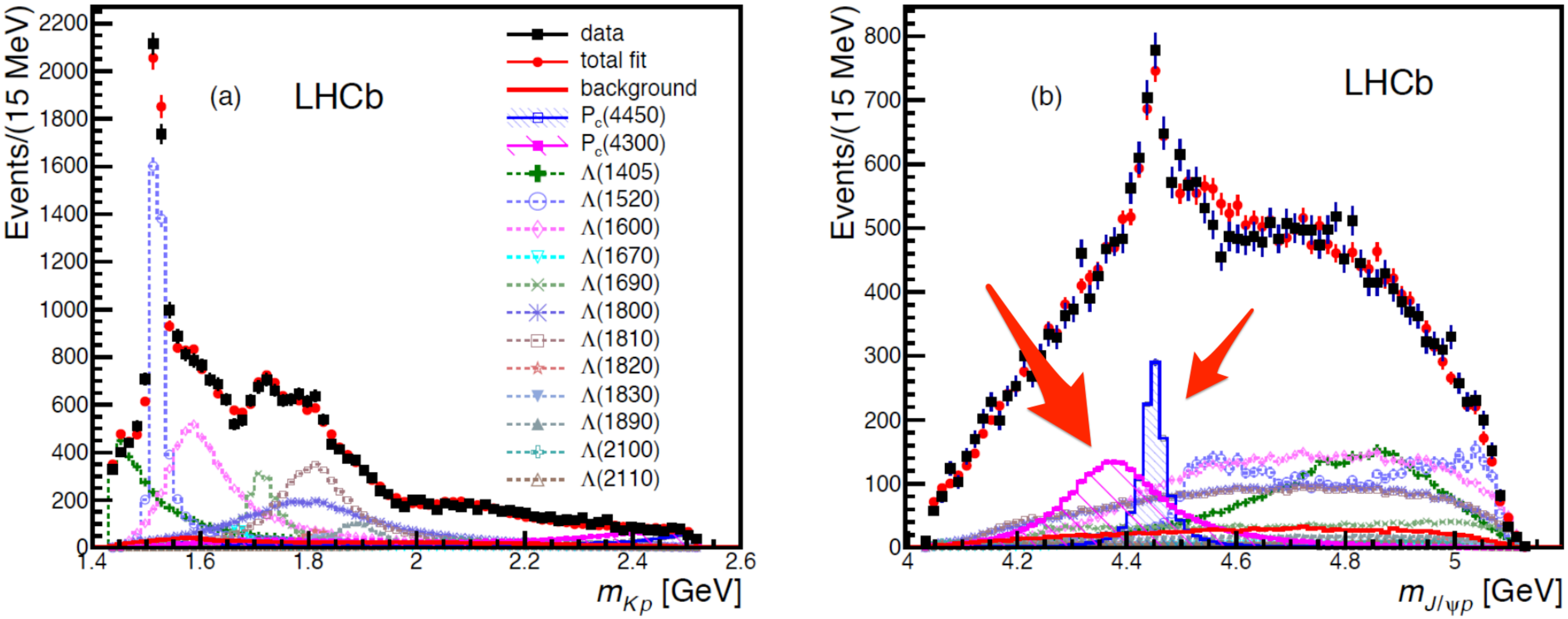


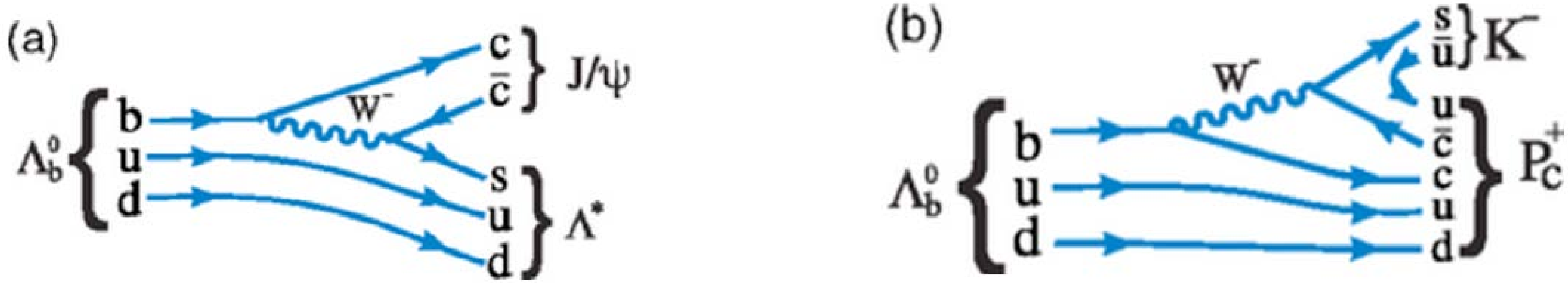
m(K p)



- Unexpected narrow resonance in m(J/ψ p) where $\Lambda_b \rightarrow$ (J/ψ p) K$^-$
- Consistent with pentaquarks: allowed by QCD, but not seen for 50 years.

Pentaquarks – full amplitude analysis





$P_c^+(4380)$: M = 4380±8±29 MeV , Γ = 205±18±86 MeV

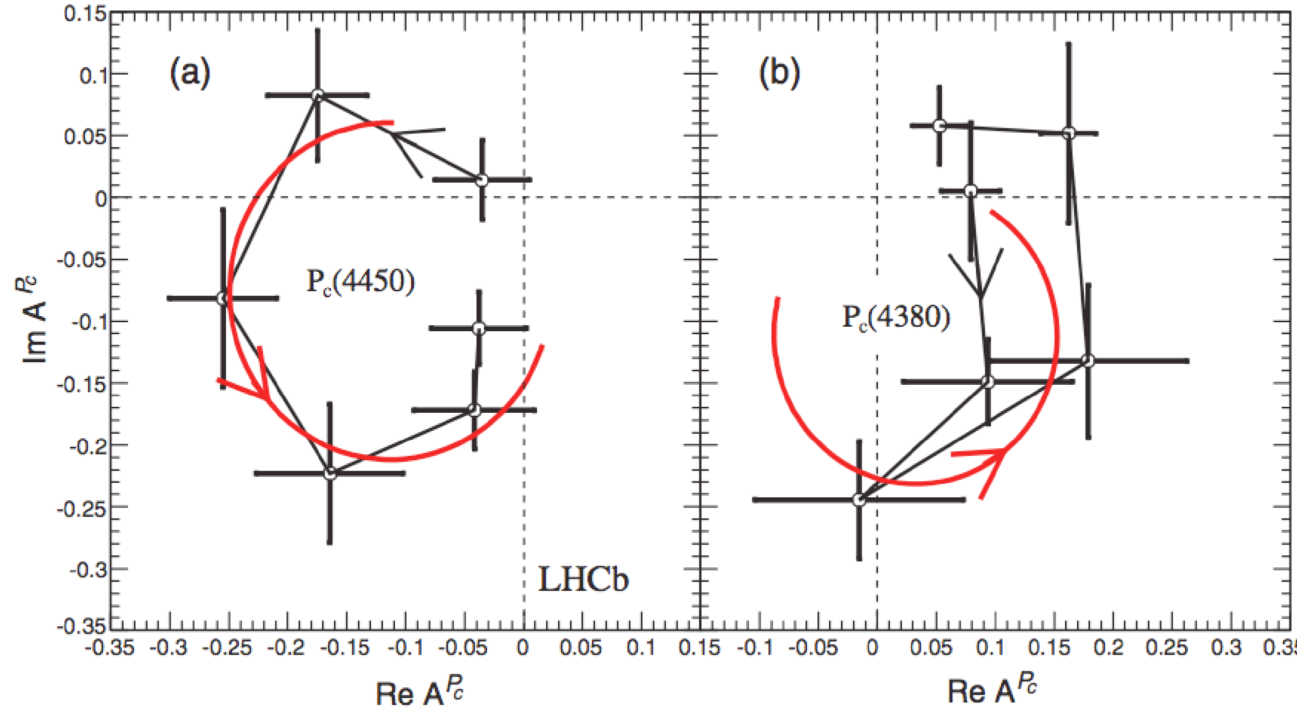
$P_c^+(4450)$: M = 4449.8±1.7±2.5 MeV , Γ = 39±5±19 MeV

9 sigma

12 sigma

Pentaquarks J^P assignments

Argand diagram



- The preferred J^P assignments are of opposite parity, with $P_c^+(4380)$ having $3/2^-$ and the $P_c^+(4450)$ having $5/2^+$
- Good evidence for the resonant character of $P_c^+(4450)$ Too large errors for $P_c^+(4380)$: hard to make a definitive conclusion

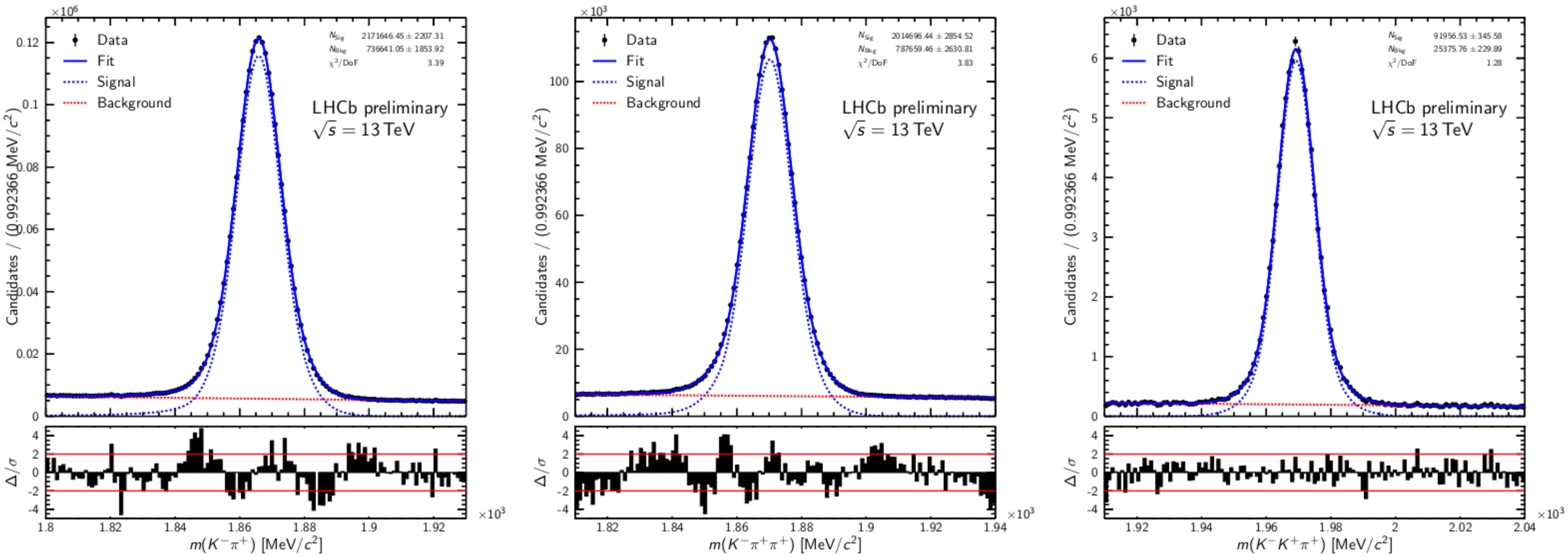
PRL 115 (2015) 072001

Summary and Outlook

- The LHCb experiment is performing spectacularly well
- So far all is in good agreement with the Standard Model
  $\rightarrow$ New physics is becoming constrained in the flavour sector
  $\rightarrow$ Hints of new physics await more data
- Up to 2017 we expect 7-8 fb^{-1} of data in total, much of this at nearly double the beam energy (now $\sqrt{s}$ =13 TeV) giving ~twice the 8 TeV heavy-flavour production cross-section
- Still much room for new physics, higher precision required …
  $\rightarrow$ preparing for LHCb Upgrade beyond 2020 !

Looking to the future …

Charm from the first July 2015 run



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

Spare slides from here on

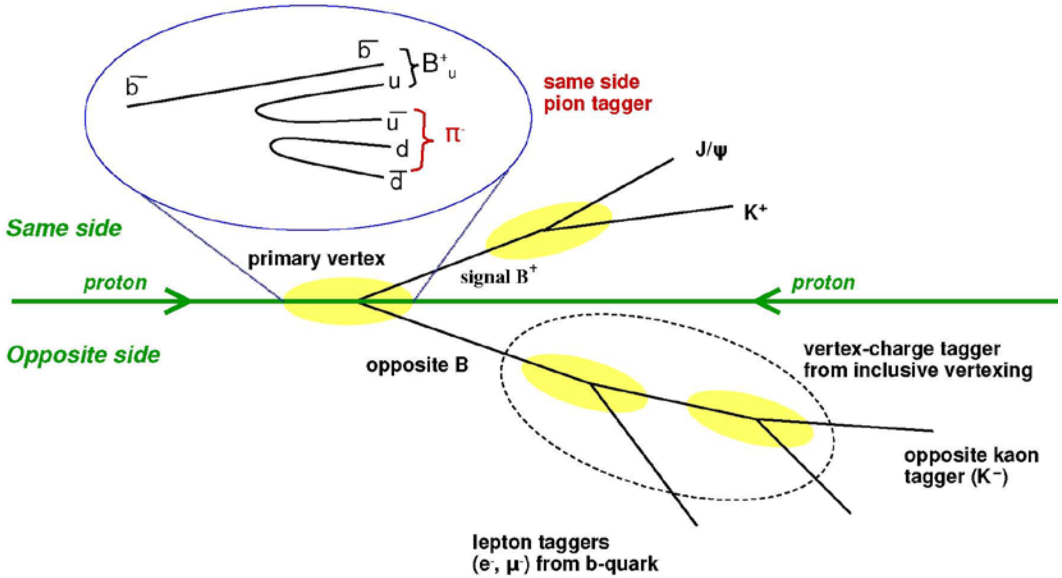
LHCb 2012 data-taking in numbers

Quantity	Unit	TDR	2011	2012	2012/TDR
Peak Luminosity	$\mu b^{-1}/s$	280	400	400	142%
Average Luminosity	$\mu b^{-1}/s$	200	265	390	195%
Seconds of running t	$10^7 s$	1	0.46	0.63	63%
Integrated lumi $\int Ldt$	fb^{-1}	2.0	1.2	2.1	105%
Bunches		2600	1300	1300	50%
CM energy	TeV	14	7	8	57%
Inelastic cross sec σ_{inel}	mb	80	64	67	84%
bb(bar) cross sec $\sigma_{bb(bar)}$	μb	500	284	~330	58%
pp interactions/BeamX		0.55	1.15	1.65	272%
Average min bias rate	MHz	16	17	22	131%
bb(bar) yield: $\sigma_{bb(bar)}\int Ldt$	10^{12}	1	0.35	0.63	63%
HLT rate λ_{HLT}	kHz	2	2.45	4.1	205%
Stored events λ_{HLT} t	10^9	20	11	26	130%

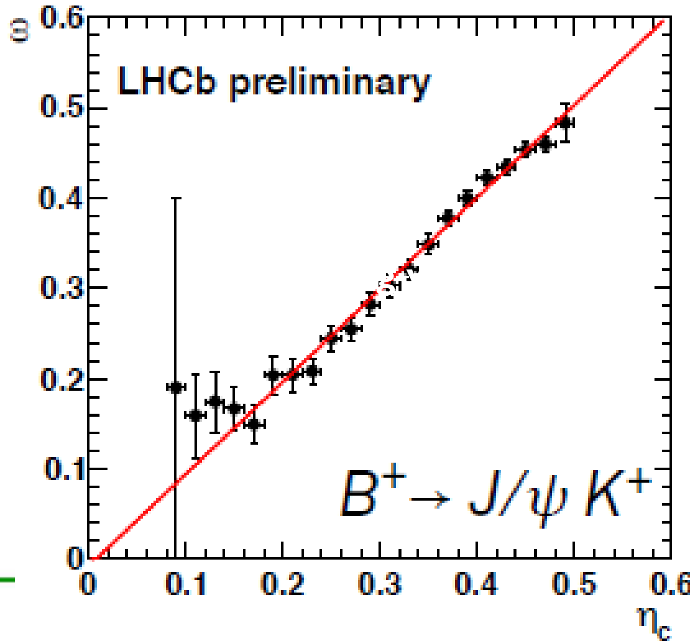
Flavour tagging

- Tagging of production flavour (B or $\overline{B}$) important for mixing and CP analyses. Performance calibrated using control channels such as $B^+ \rightarrow J/\psi\, K^+$
- Current opposite side tagging power:

$$\varepsilon\,(1-w)^2 = (2.10 \pm 0.08 \pm 0.24)\%$$



European Physical Journal C 72 (2012) 1-16

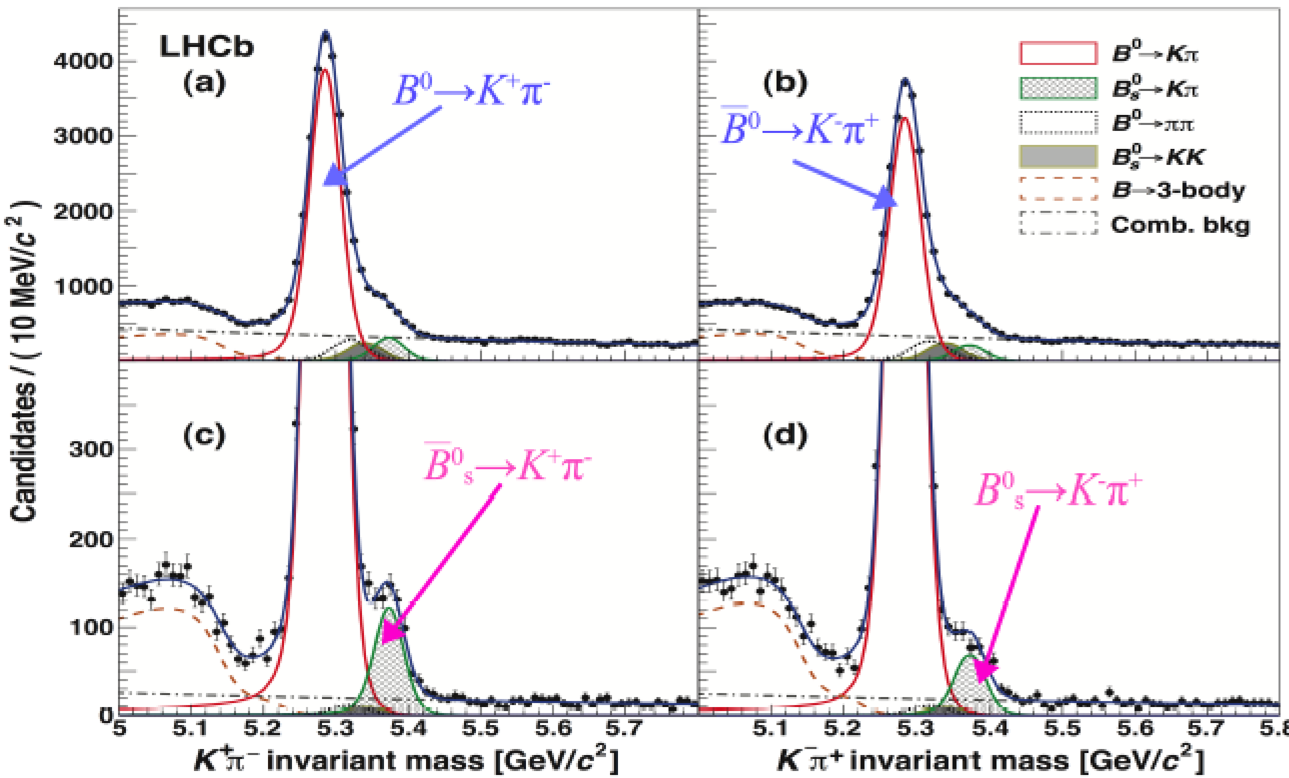


CP violation in B→Kπ and B_s→Kπ

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

$$A_{CP}(B_s^0 \to \pi K) = \frac{\Gamma(\bar{B}_s^0 \to \pi^- K^+) - \Gamma(B_s^0 \to \pi^+ K^-)}{\Gamma(\bar{B}_s^0 \to \pi^- K^+) + \Gamma(B_s^0 \to \pi^+ K^-)}$$

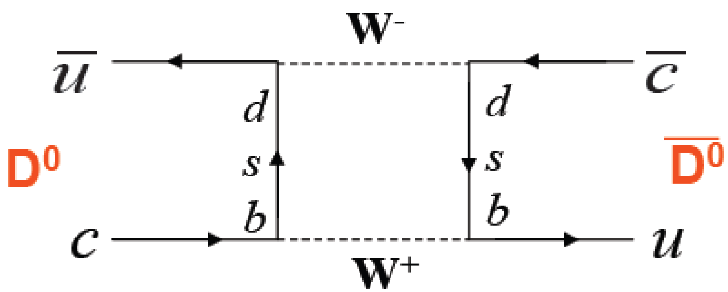
- Using 1/fb (2011) @ $\sqrt{s}$ = 7 TeV.

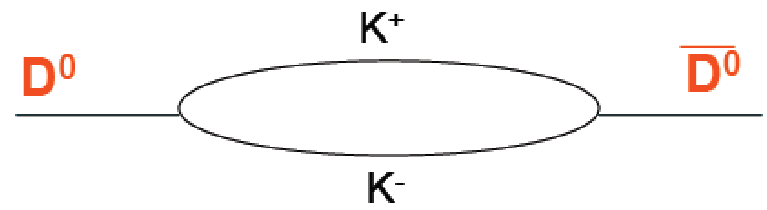


- $\mathcal{A}_{CP}(B^0)$ = -0.080 ± 0.007 ± 0.003 (most precise measurement, 10.5σ)
- $\mathcal{A}_{CP}(B^0_s)$ = -0.27 ± 0.04 ± 0.01 (first observation of CPV in B^0_s decays, 6.5σ)

PRL 110, 221601 (2013)

Charm mixing formulism





mass difference x:

$$x \equiv \frac{m_2 - m_1}{\Gamma} = \frac{\Delta m}{\Gamma}$$

decay width difference y:

$$y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma} = \frac{\Delta\Gamma}{2\Gamma}$$

In the limit of small mixing |x|,|y| << 1 and assuming negligible CPV:

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = \underbrace{R_D} + \underbrace{\sqrt{R_D}\,y' t} + \underbrace{\frac{x'^2 + y'^2}{4} t^2}$$

the ratio of DCS to CF decay rates

the interference of the DCS and mixed decays

mixing parameters

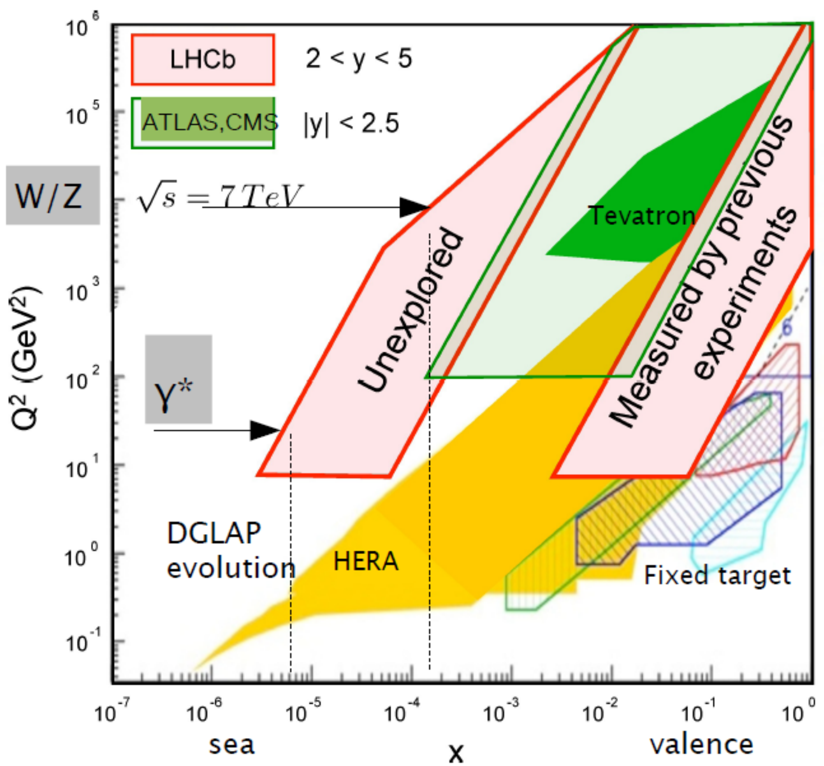
$$x' = x\cos\delta + y\sin\delta \qquad y' = y\cos\delta - x\sin\delta$$

δ is a strong phase difference between DCS and CF amplitudes

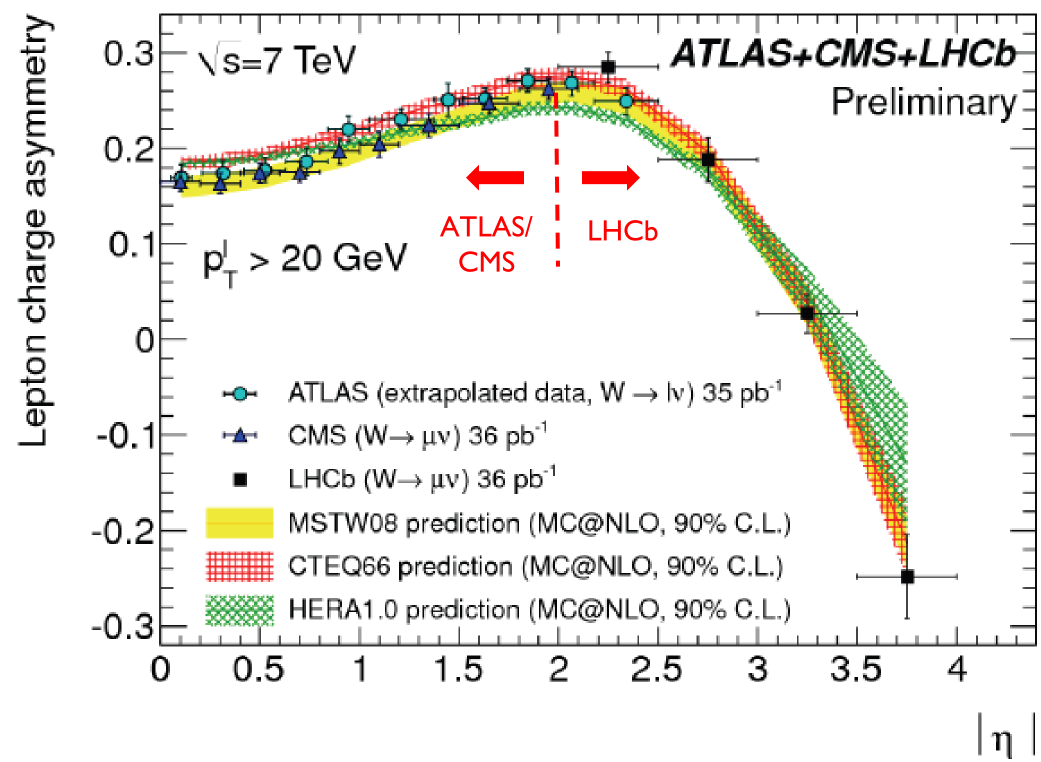
W/Z production

LHCb's unique forward and low p_T acceptance equips it to perform EW / QCD measurements which are highly complementary to those of mid-rapididty GPDs

Unique kinematical acceptance



Studies of W/Z production [JHEP 6 (2012) 58] alongside ATLAS/CMS gives complete picture



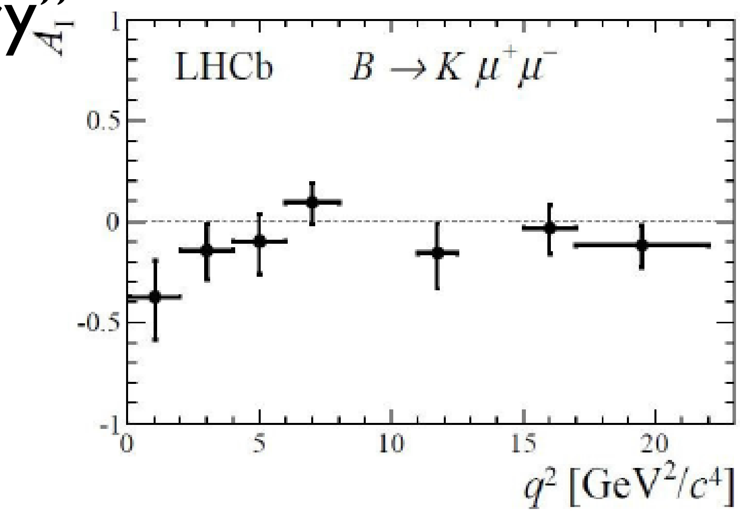
Isospin asymmetry in $B^0 \to K^{0(*)}\mu^+\mu^-$

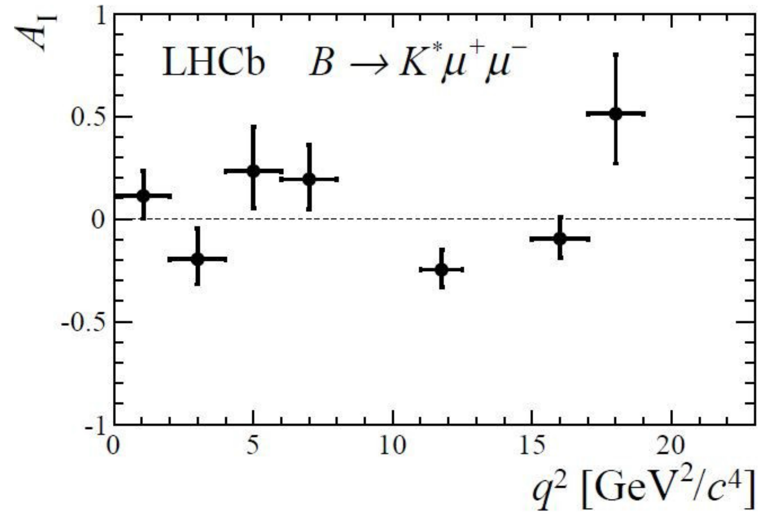
arXiv:1403.8044

- LHCb measure "isospin asymmetry"

$$\frac{\Gamma(B^0 \to K^0\mu^+\mu^-) - \Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^0 \to K^0\mu^+\mu^-) + \Gamma(B^+ \to K^+\mu^+\mu^-)}$$

- Expected to be ~zero in SM
- Significant had emerged (4.6σ from zero) in early K^0 data not in K^*). **JHEP 7 (2012) 133**
- With full 3 fb^{-1} data set the isospin asymmetry is compatible with zero at the 1.5σ level





CP-violating asymmetry a^s_{sl} in B_s decays

- CPV in mixing $P(B \to \bar{B}) \neq P(\bar{B} \to B)$
- First step to resolving the issue of the D0 di-muon asymmetry anomaly.

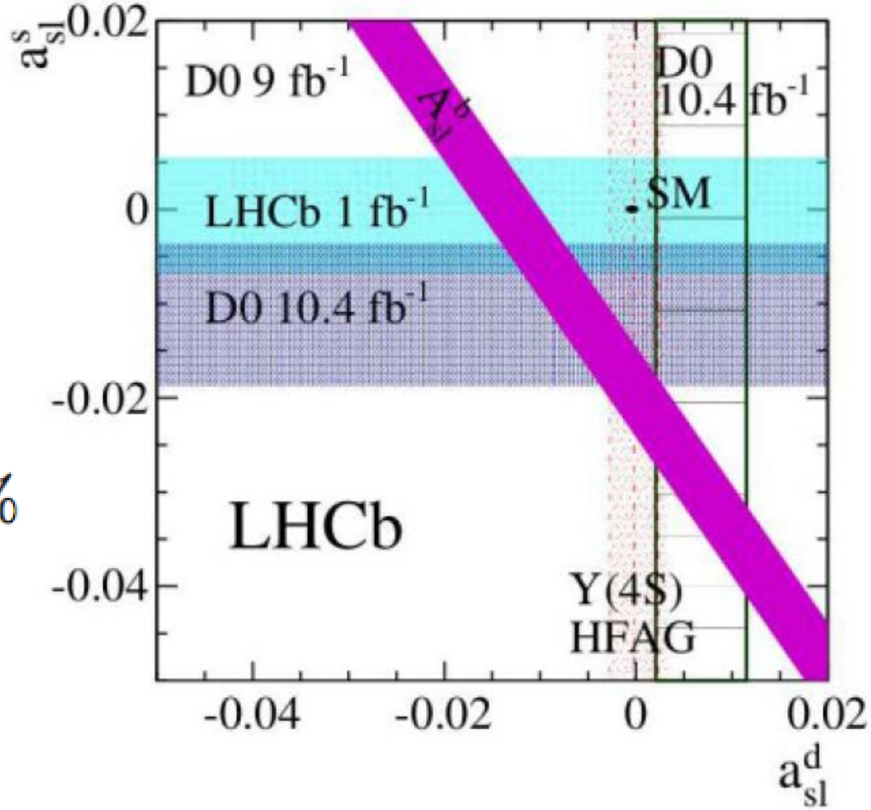
Phys. Rev. D 84, 052007 (2011), Phys. Rev. D 86, 072009 (2012)

- LHCb 1 fb^{-1} result for a^s_{sl}

$$a^s_{sl} \equiv \frac{\Gamma(B^0_s \to D^-_s \mu^+) - \Gamma(\overline{B}^0_s \to D^+_s \mu^-)}{\Gamma(B^0_s \to D^-_s \mu^+) + \Gamma(\overline{B}^0_s \to D^+_s \mu^-)}$$

$$a^s_{sl}[\mathrm{LHCb}] = (-0.06 \pm 0.50 \pm 0.36)\%$$

arxiv: 1308.1048



- D0 result not confirmed nor ruled out.

Standard Model predictions

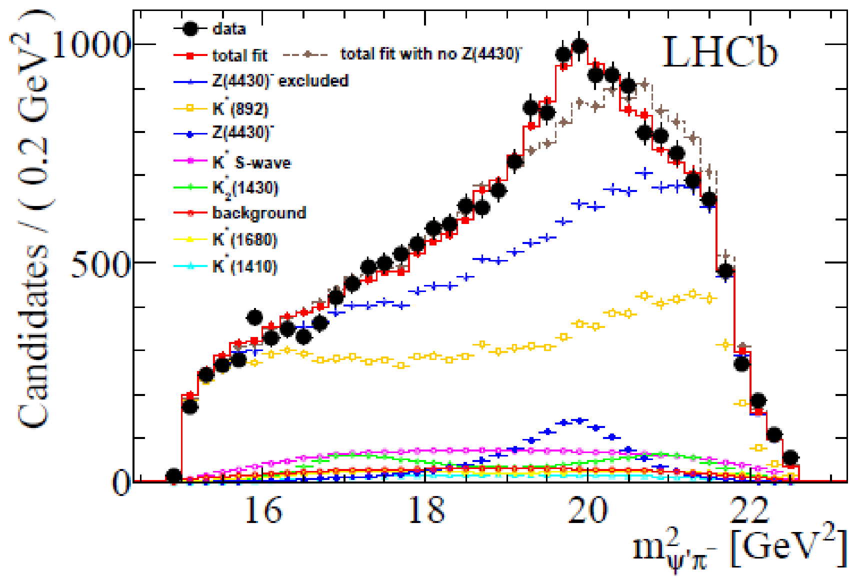
$$\begin{cases} a^s_{sl} = (1.9 \pm 0.3) \times 10^{-5} \\ a^d_{sl} = (-4.1 \pm 0.6) \times 10^{-4} \end{cases}$$

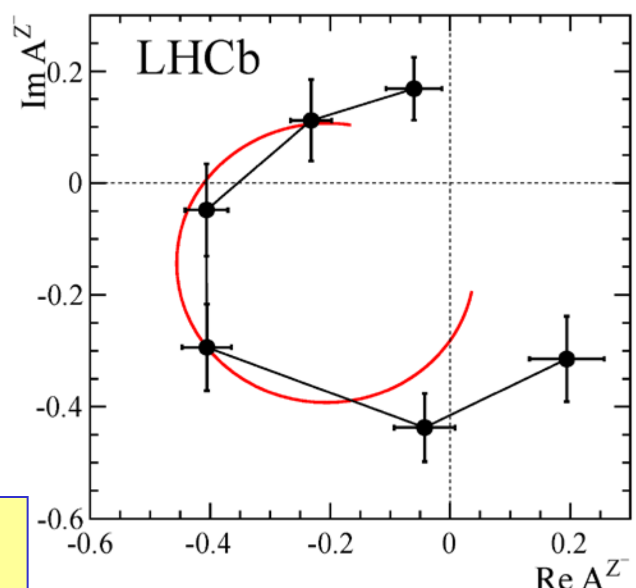
A.Lenz
arXiv:1205.1444

The Z(4430) tetraquark

- First observed by Belle (but not seen by Babar)
- LHCb: use very clean sample of 25,200 $B^0 \rightarrow \psi' K^+\pi^-$, ($\psi' \rightarrow \mu^+\mu^-$) decays observed in 3 fb^{-1} of data (7 and 8 TeV).
- $Z(4430)^-$ peak seen in $\psi' \pi^-$ mass with significance of the signal 13.9σ
- Spin-parity $J^P = 1^+$ at 9.7σ
- Being charged, it cannot be a cc(bar) state. The minimal quark content of the Z(4430) is cc(bar)du(bar). It is therefore a two-quark plus two-antiquark state

$$m = 4475 \pm 7 \,^{+15}_{-25} \text{ MeV}/c^2$$
$$\Gamma = 172 \pm 13 \,^{+37}_{-34} \text{ MeV}/c^2.$$





Phys. Rev. Lett. 112, 222002 (2014)

R(D) and R(D*)

$$R(D^*) = \frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-(\mu^-\bar{\nu}_\mu\nu_\tau)\bar{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}$$

BaBar

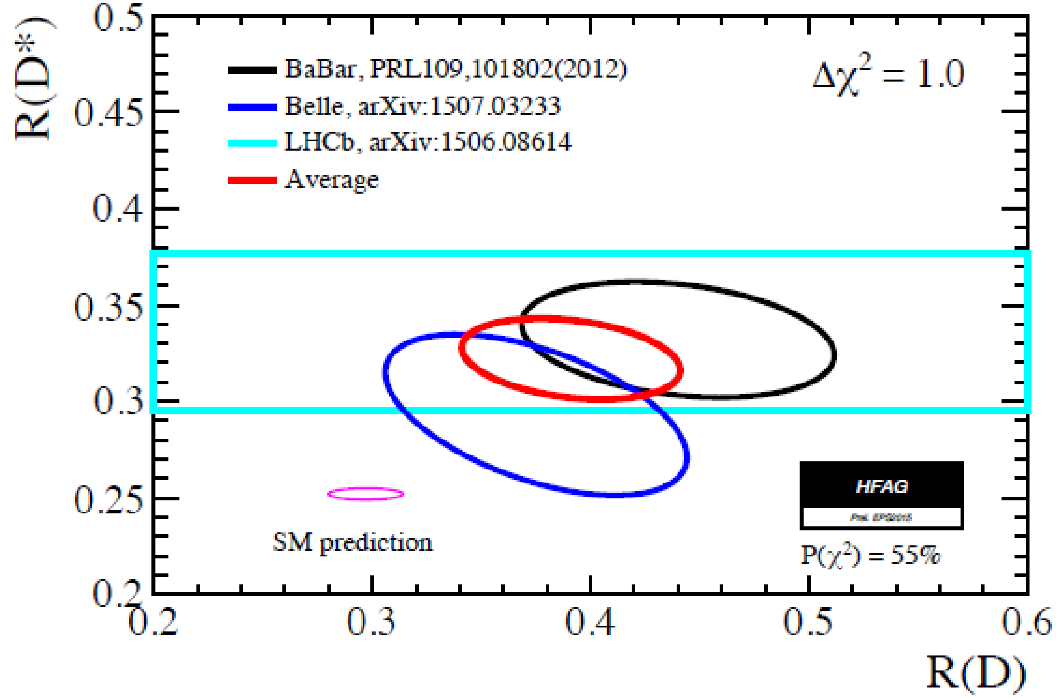
$$R(D) = 0.440 \pm 0.058 \pm 0.042$$
$$R(D^*) = 0.332 \pm 0.024 \pm 0.018$$

Belle

$$R(D) = 0.375 \pm 0.064 \pm 0.026$$
$$R(D^*) = 0.293 \pm 0.038 \pm 0.015$$

LHCb

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$



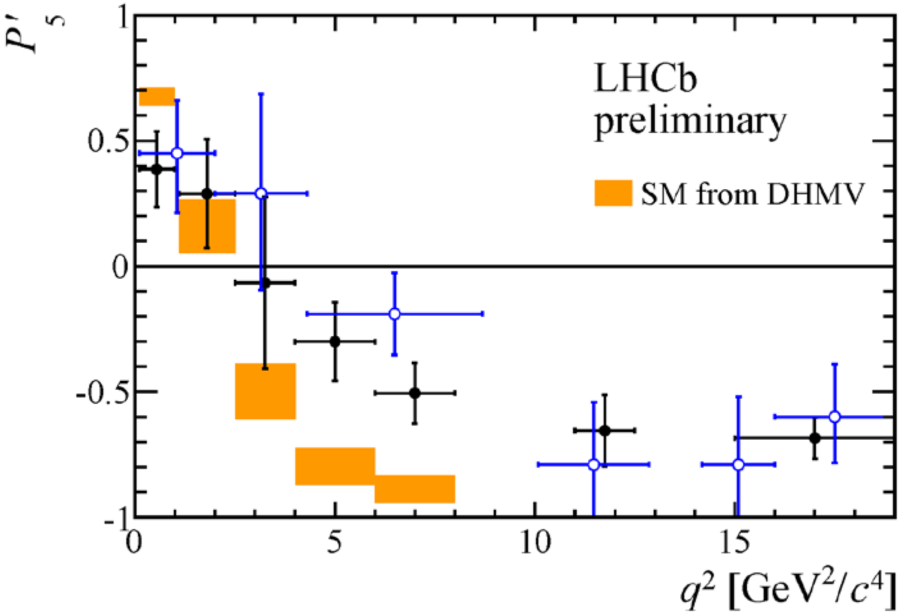
- Combination is **3.9**σ from the SM expectation:

$$R(D) = 0.297 \pm 0.017 \quad , \quad R(D^*) = 0.252 \pm 0.003$$

[Kamenik et al. Phys. Rev. D78 014003 (2008), S. Jajfer et al. Phys. Rev. D85 094025 (2012)]

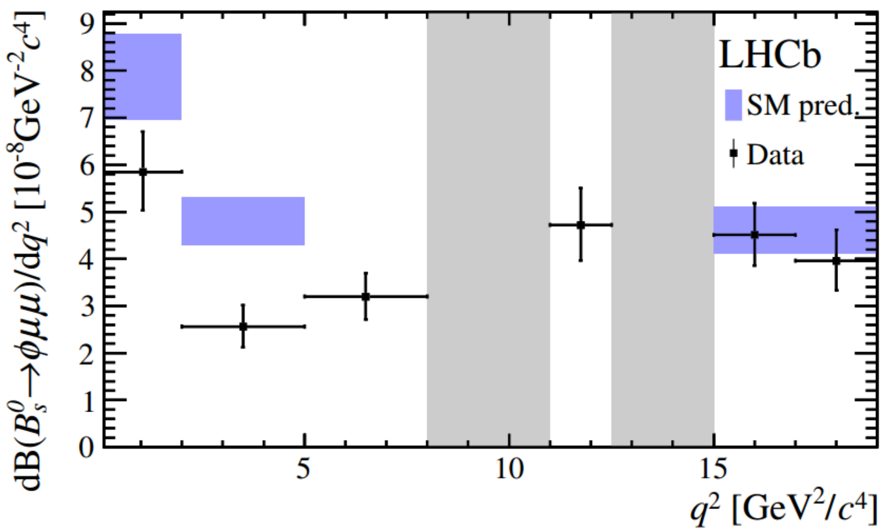
Possible anomaly in $B_s^0 \to \phi\mu^+\mu^-$ decays?

LHCb-CONF-2015-002



$B^0 \to K^{*0}\mu^+\mu^-$ decays

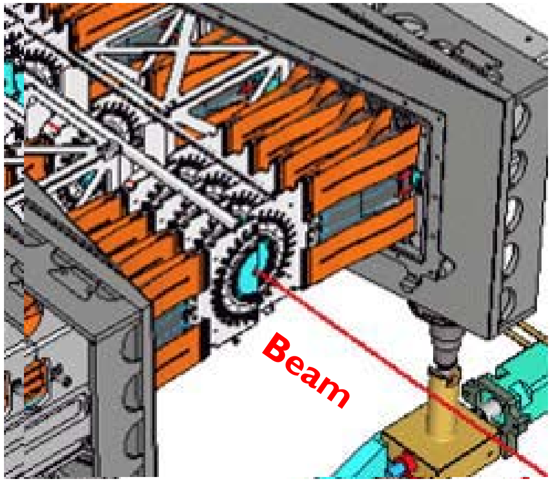
arXiv:1506.08777

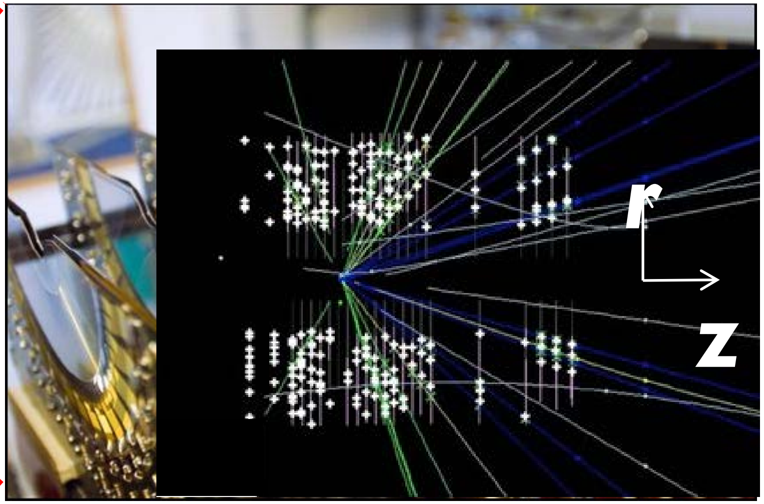


$B_s^0 \to \phi\mu^+\mu^-$ decays

Detector performance – VELO

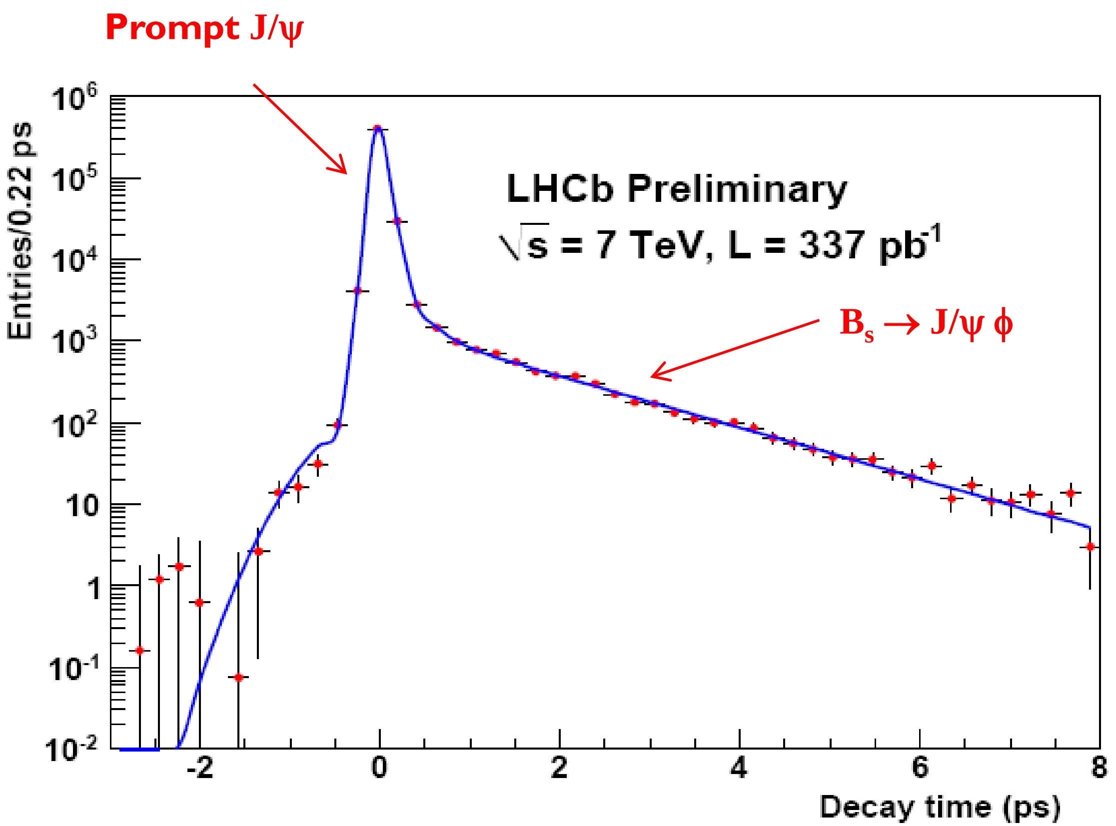
- Vertex Locator (VELO):
  21 modules of back-to-back silicon sensor disks, *R*-ϕ strip geometry
- Silicon is only 8 mm from beams. Must be retracted for safety during beam injection
- 300 μm-thick silicon
  2048 strips/sensor, 40 μm inner pitch





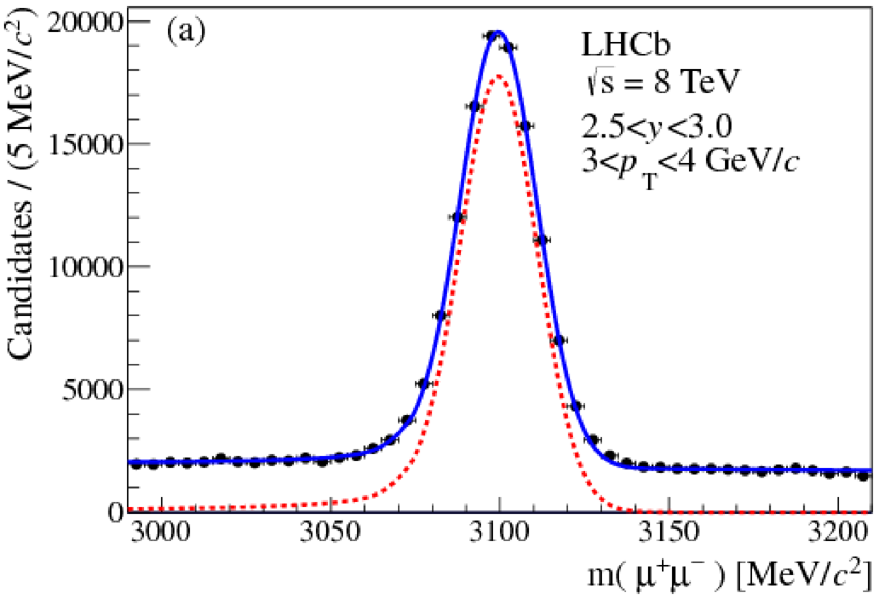
Vertex reconstruction performance

- Impact parameter resolution = 12 μm for high p_T tracks from VELO detector.
- Proper-time resolution: σ_t = 45 fs for eg. $B_s \to J/\psi\phi$



LHCb-CONF-2011-49

Tracking performance



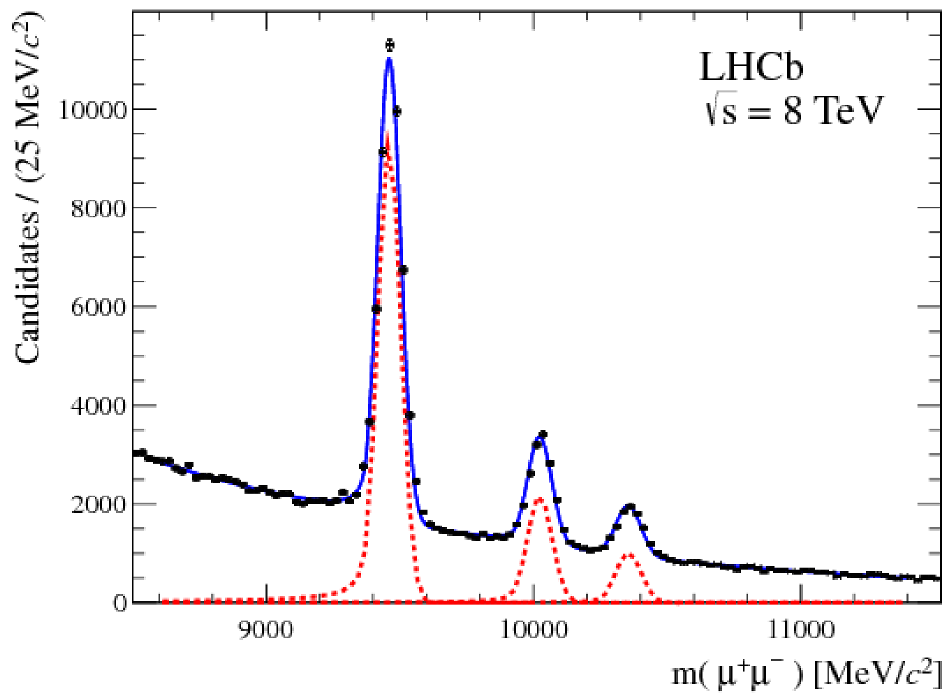
JHEP06 (2013) 064

- Integrated field strength 4 Tm from dipole magnet
- Planes of straw tubes

$\sigma(m_{J/\psi})$=13 MeV/c^2

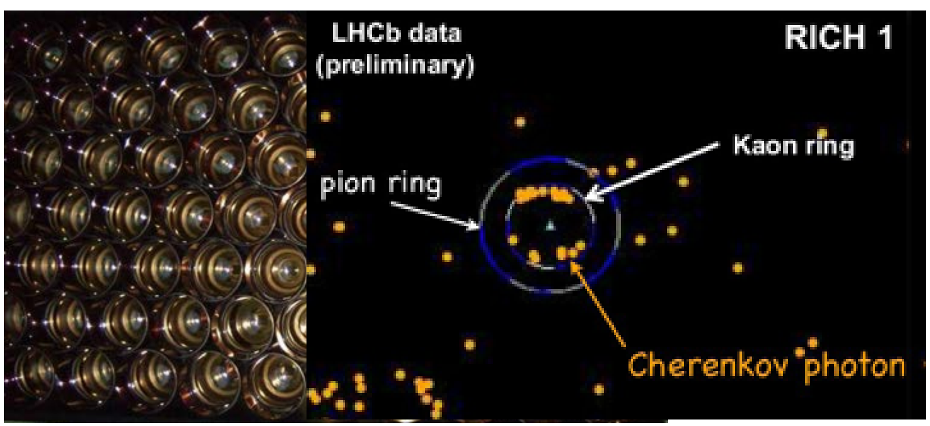
$\sigma(m_{\Upsilon(1S)})$=43 MeV/c^2

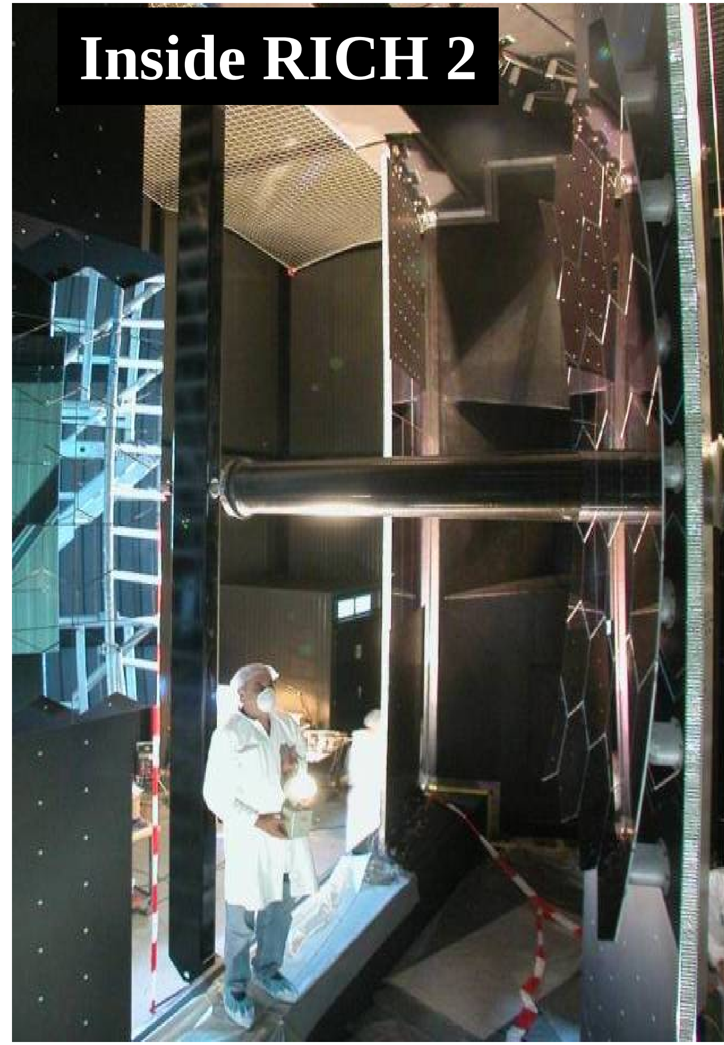
JHEP06 (2013) 064



Particle identification

- Charged particles identified with two Ring-Imaging Cherenkov detectors covering $2 < p < 100$ GeV/c
- Cherenkov angle resolution 0.66 mrad per photon achieved (in RICH 2)



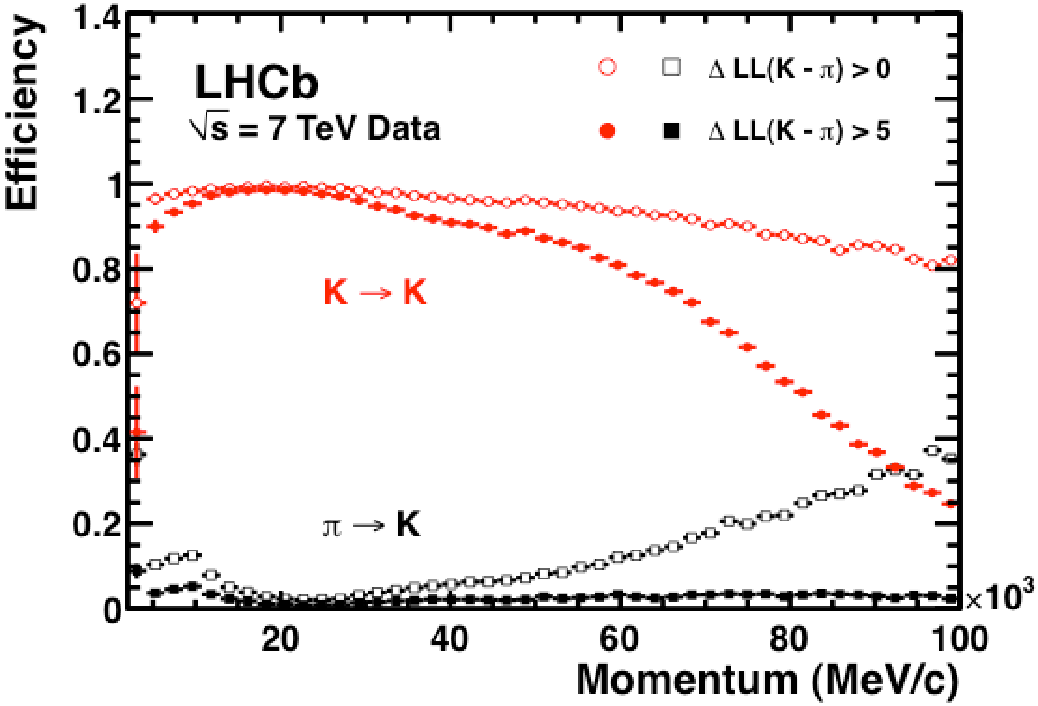


PID performance

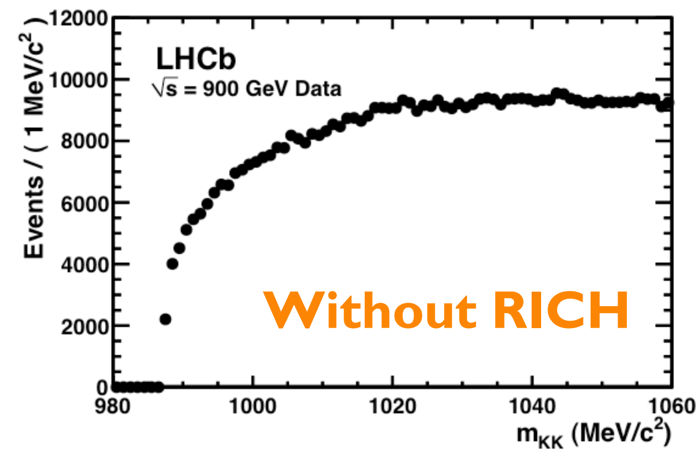
arXiv:1211.6759

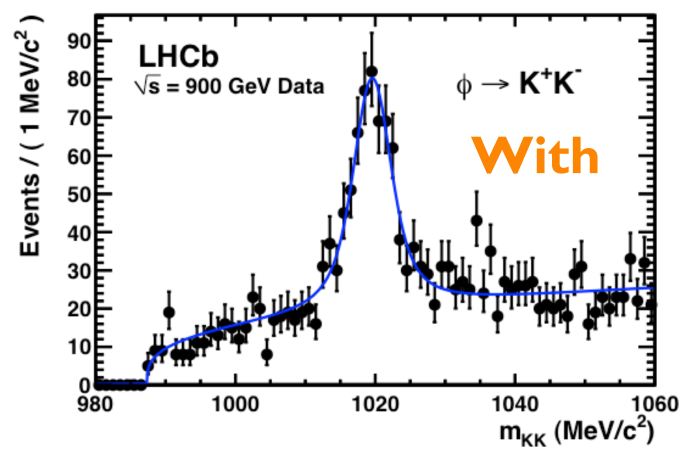
- Kaon identification efficiency > 90% for pion misidentification < 5% over a large momentum range ($2 < p < 100$ GeV/c)

Calibration data



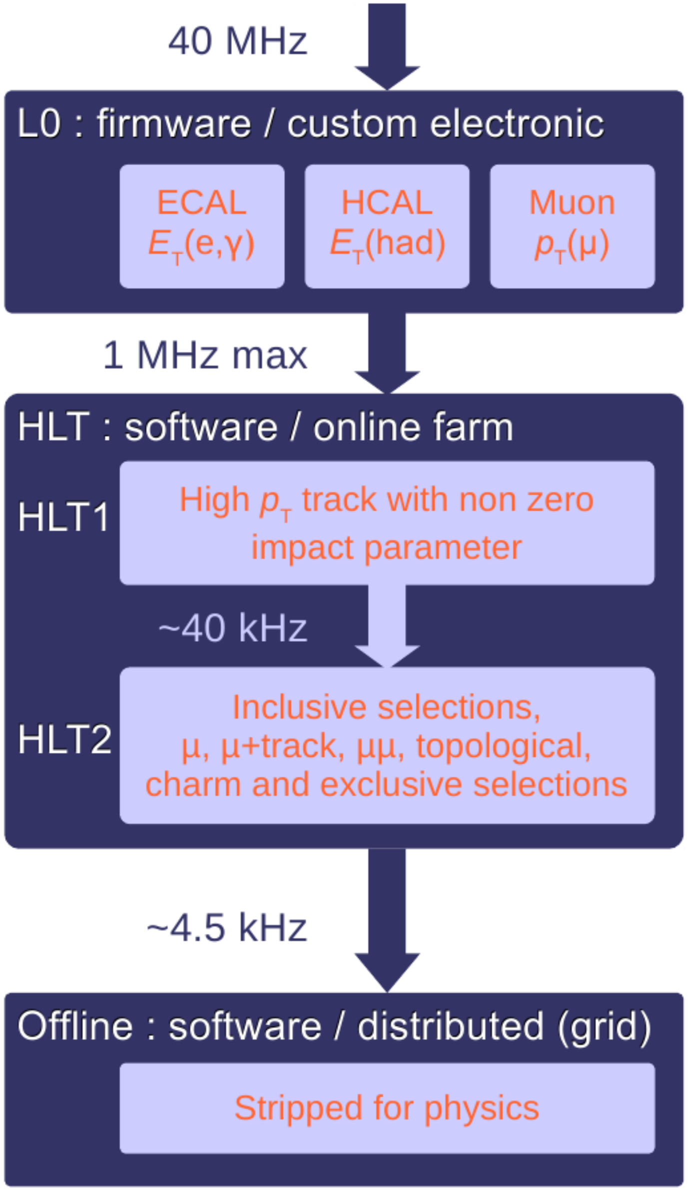
- Allows strong suppression of combinatorial background *eg* for $\phi \to K^+K^-$





The LHCb trigger performance

arXiv:1211.3055



Hardware level (L0):

- 4 μs latency @ 40MHz
  - high-p_T μ, e, γ, hadron candidates, typically $p_T(\mu)>1.4$; $E_T(e/\gamma)>2.7$; $E_T(hadron)>3.6$ [GeV]

Software level (HLT):

- ~30000 tasks in parallel on ~1500 nodes

Combined efficiency (L0+HLT):

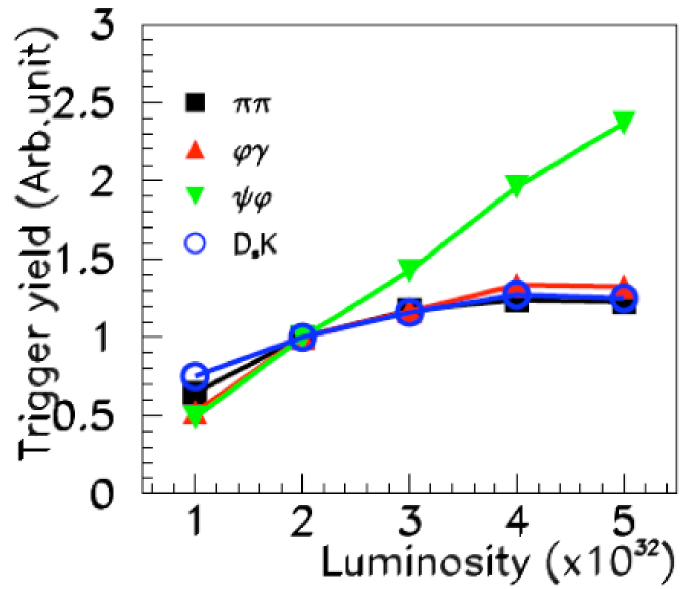
- ~90 % for di-muon channels
- ~30 % for multi-body hadronic final states

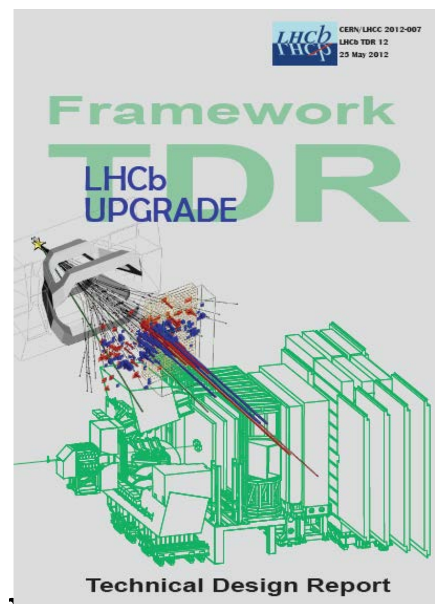
Offline processing:

- ~10^{10} events, 700 TB recorded per year
- ~800 "stripping" selections to reduce to samples with 0(10^7) events for analyses

Outlook: LHCb Upgrade

- Main limitation that prevents exploiting higher luminosity is the Level-0 (hardware) trigger
- To keep output rate < 1 MHz requires raising thresholds → hadronic yields reach plateau
- Proposed upgrade is to *remove* hardware trigger: read out detector at 40 MHz (bunch crossing rate). Trigger fully in software in CPU farm. Requires replacing all front-end electronics
- Will allow to increase luminosity by factor ~ 10 to 1–2 × 10^{33} cm^{-2} s^{-1}
- TDRs being approved by CERN : Physics case enthusiastically endorsed, detector R&D underway





Upgrade of LHCb detector planned for 2019 to take at least
10× more data: 50 fb^{-1}

Upgrade sensitivities 50 fb^{-1}

LHCb-PUB-2012-009

Type	Observable	Current precision	LHCb 2018	Upgrade (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s$ $(B_s^0 \to J/\psi\ \phi)$	0.10 [24]	0.025	0.008	~ 0.003
	$2\beta_s$ $(B_s^0 \to J/\psi\ f_0(980))$	0.17 [26]	0.045	0.014	~ 0.01
	$A_{\rm fs}(B_s^0)$	6.4×10^{-3} [41]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [41]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.08 [42]	0.025	0.008	0.02
	$s_0\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [42]	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.25 [9]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [43]	8 %	2.5 %	$\sim 10\,\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [4]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
Unitarity triangle angles	γ $(B \to D^{(*)}K^{(*)})$	~ 10–$12°$ [28, 29]	4°	0.9°	negligible
	γ $(B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	β $(B^0 \to J/\psi\ K_S^0)$	0.8° [41]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [41]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [8]	0.65×10^{-3}	0.12×10^{-3}	–