Selected 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 1 fb^{-1} (2011) and 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

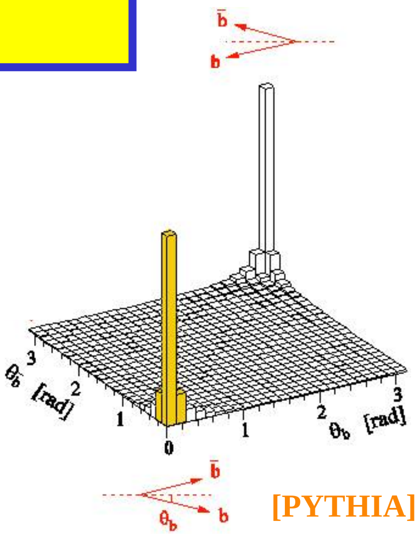
- Summary and Outlook

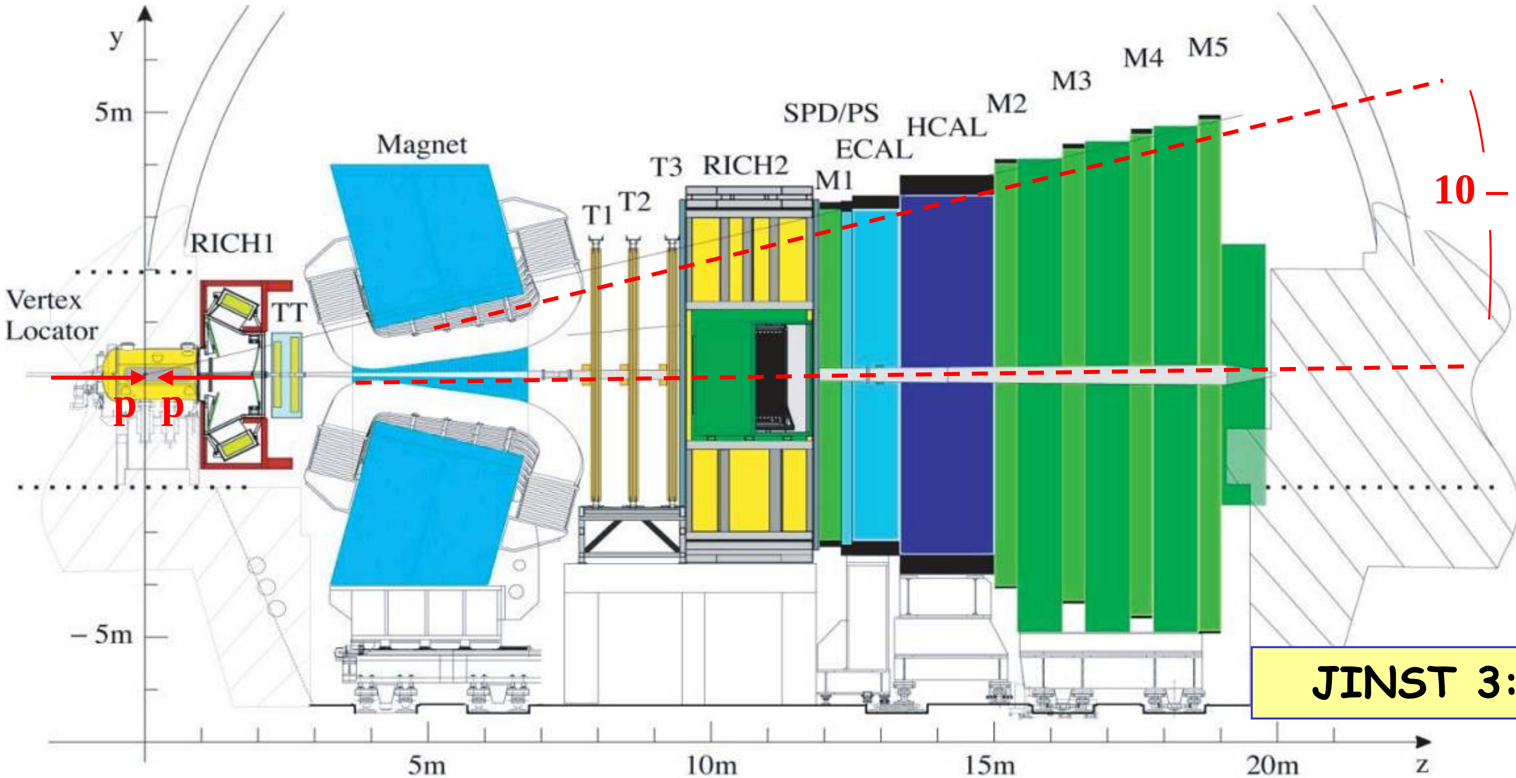

The Large Hadron Collider

LHCb- forward spectrometer

- Forward-peaked production → LHCb is a forward spectrometer (operating in LHC collider mode)
- $b\bar{b}$ cross-section = 284 ± 53 μb at $\sqrt{s}$ = 7 TeV [PLB 694 209]

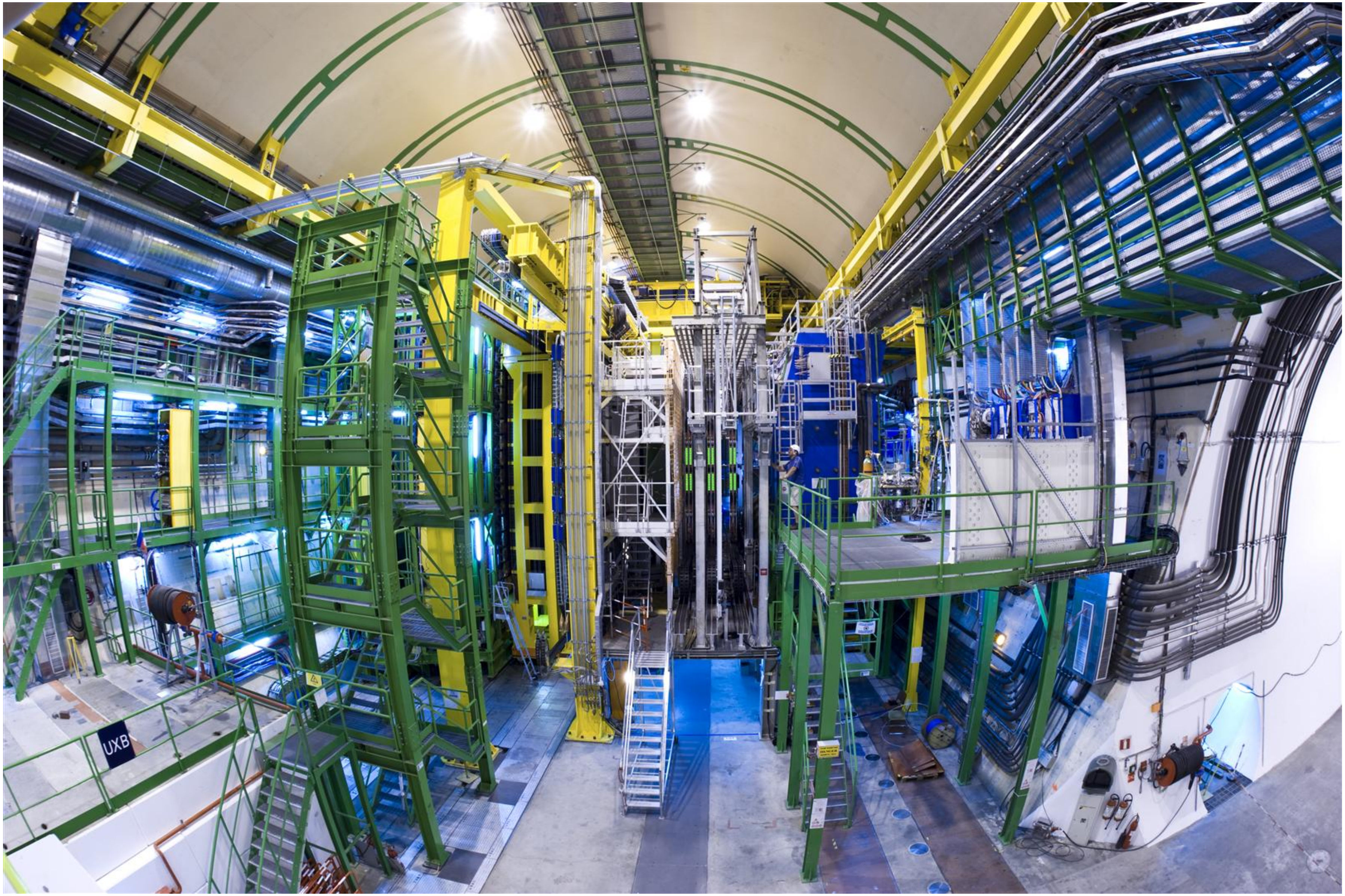
→ ~ 100,000 $b\bar{b}$ pairs produced/second (10^4 × B factories)





JINST 3:S08005 (2008)

A fish-eye view



What the doomsayers said pre-2009

- "Hadron colliders are too dirty an environment for flavour-physics"

- "Impossible to trigger efficiently on non-leptonic final states"

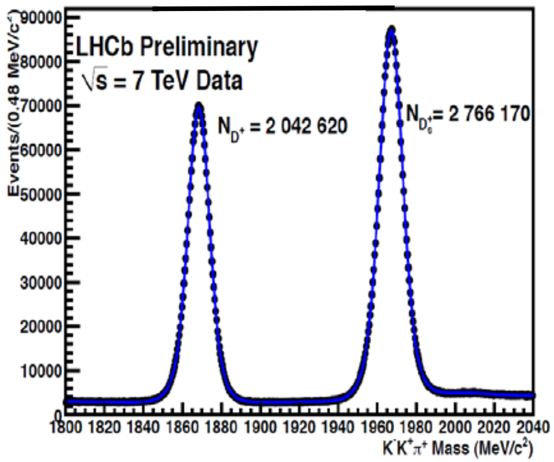
- "It will take a long time to understand detector performance, and so physics output will take years to emerge"

"No, I can't make it next Friday. How about a week Tuesday?"

But if anyone was still left in any doubt…

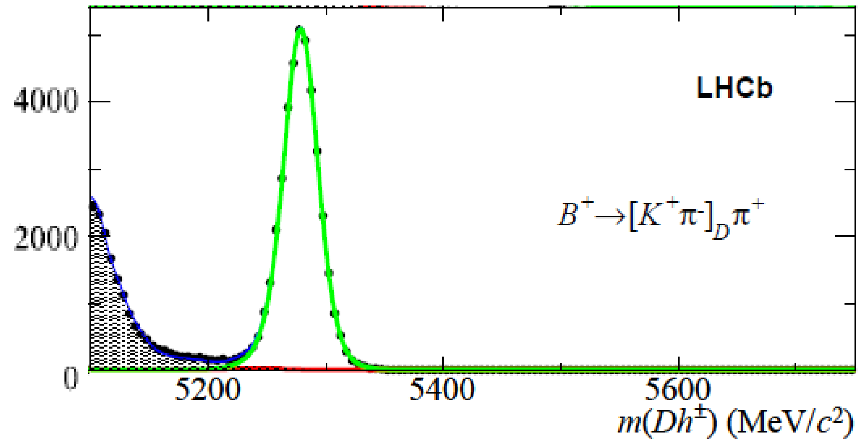
$D^+, D^+_s \to KK\pi$

LHCb-PAPER-2012-026



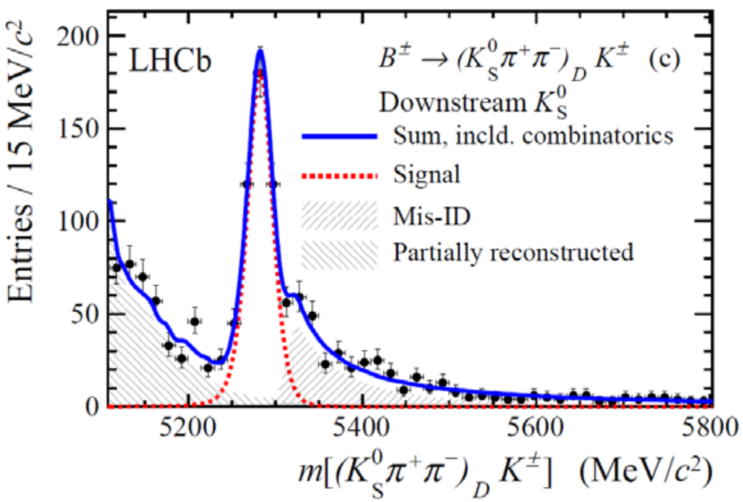
$B^+ \to (K^+\pi^-)_D\pi^+$

Phys Lett B712 (2012) 203



$B^+ \to (K_S\pi\pi)_DK^+$

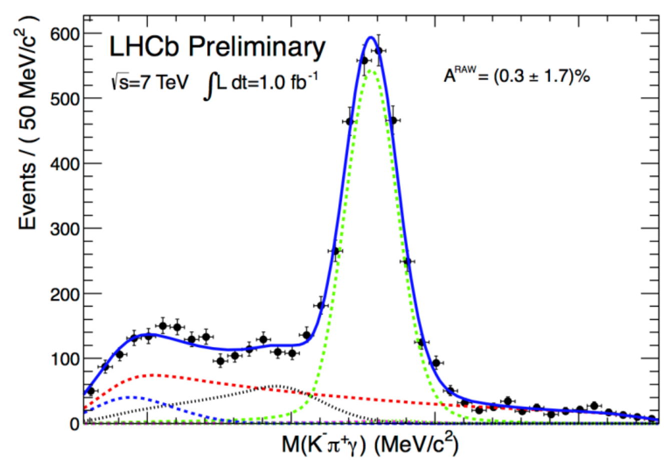
LHCb-PAPER-2012-027



…and even with photons

$B^0 \to K^*\gamma$

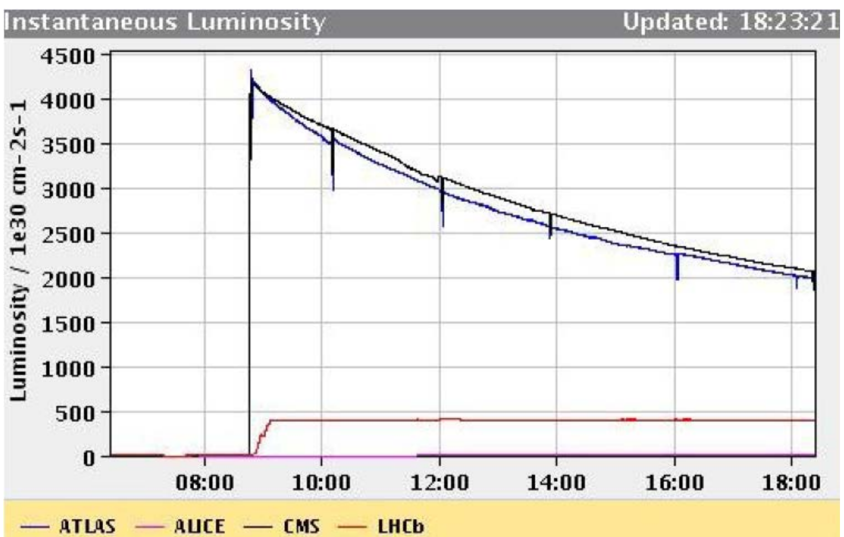
LHCb-CONF-2012-004

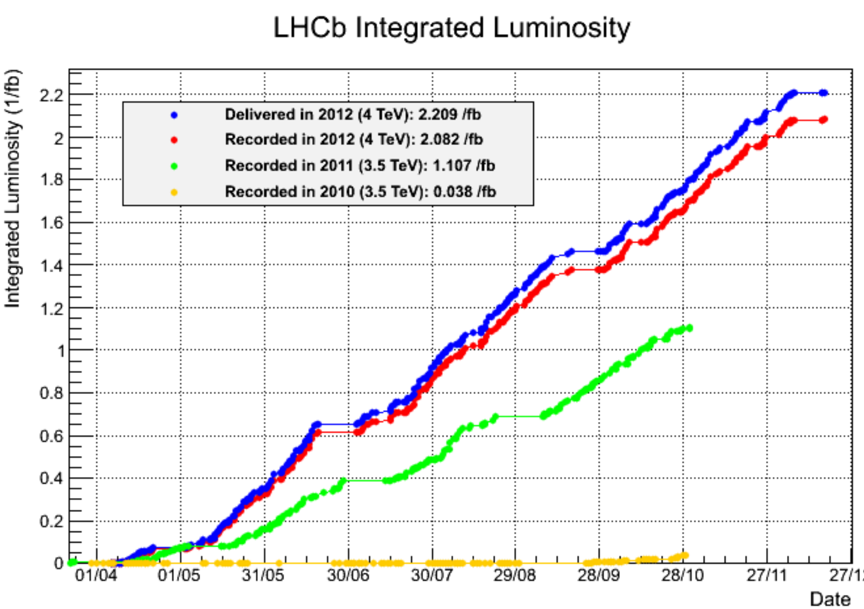


LHCb data taking

- Nominal luminosity = $2 \times 10^{32}\ cm^{-2}\ s^{-1}$: however, LHCb has learned to run at >2 times this.
- Continuous (automatic) adjustment of offset of colliding beams allows luminosity to be *levelled*

    - 37 pb^{-1} collected in 2010
    - 1 fb^{-1} in 2011
    - >2 fb^{-1} recorded in 2012



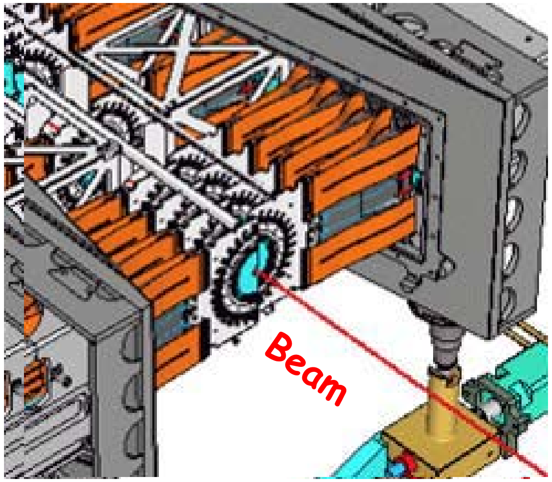


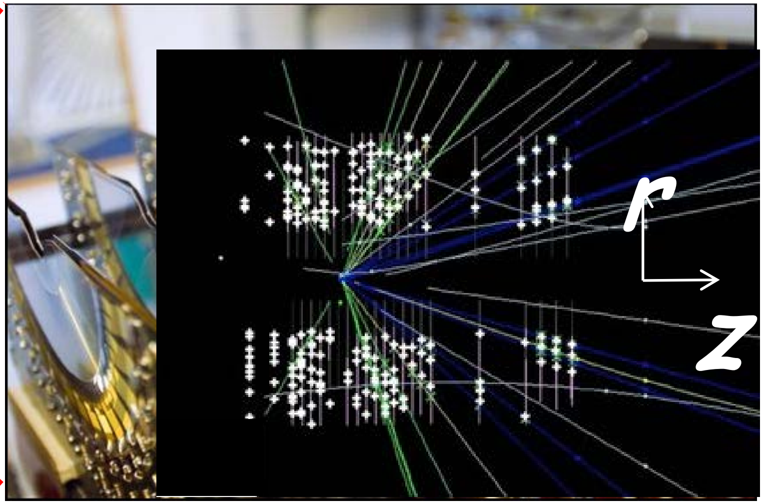
LHCb 2012 data-taking in numbers

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%

Detector performance

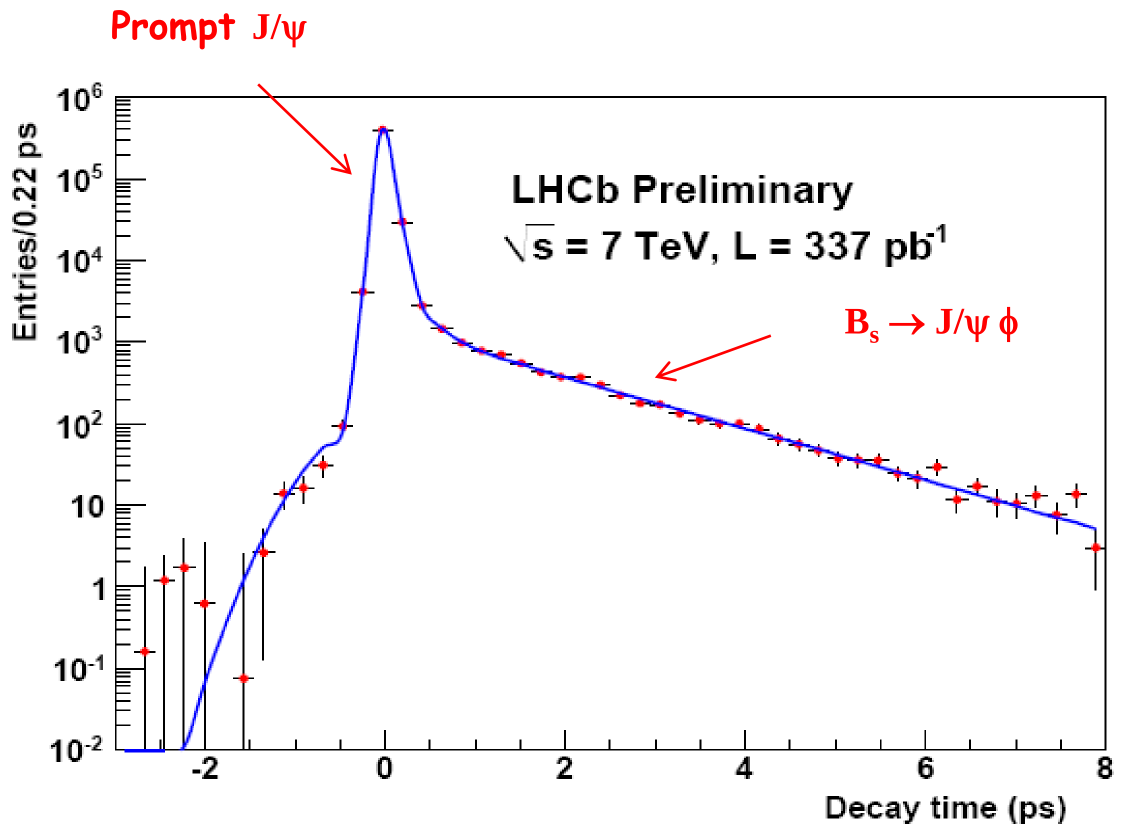
- Vertex Locator (VELO):
  21 modules of back-to-back silicon sensor disks, R-ϕ strip geometry
- Must be retracted for safety during beam injection
- 300 μm-thick silicon
  2048 strips/sensor, 40 μm inner pitch





Vertex reconstruction performance

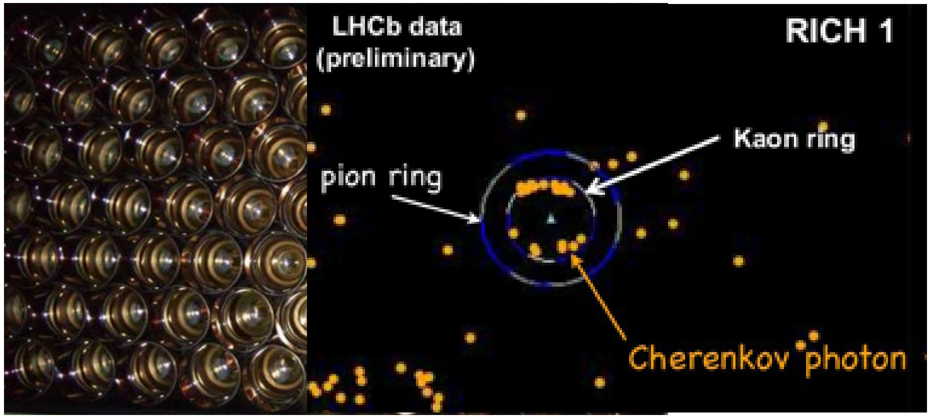
- Impact parameter resolution = 12 μm for high p_T tracks from VELO detector.
- Proper-time resolution: σ_t = 45 fs



LHCb-CONF-2011-49

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)

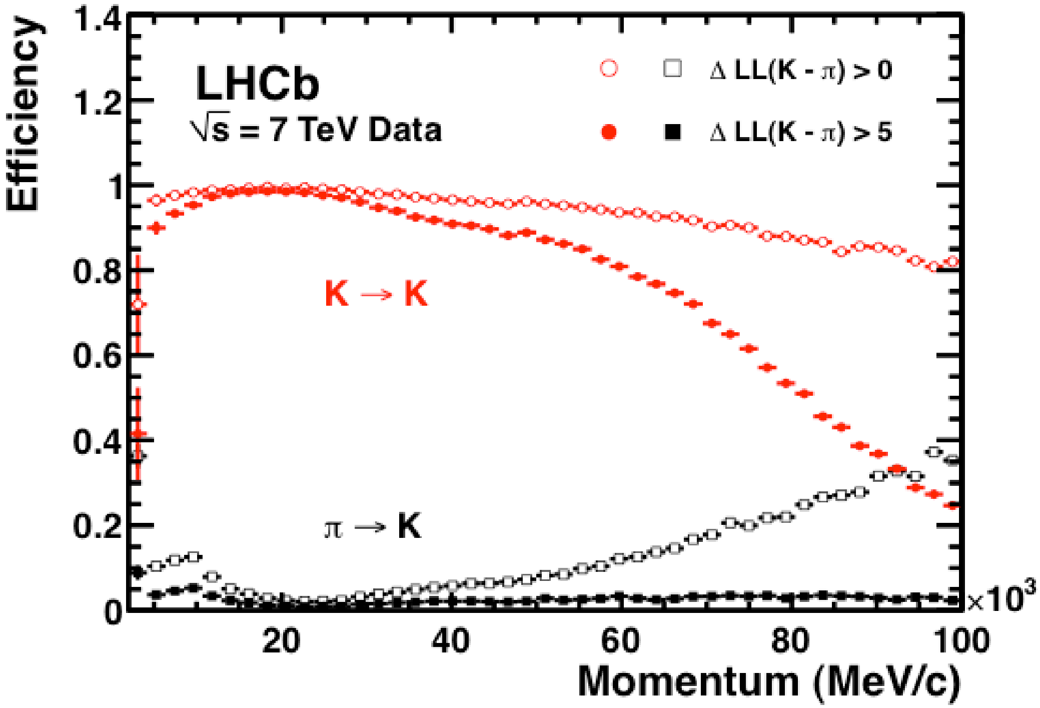


PID performance

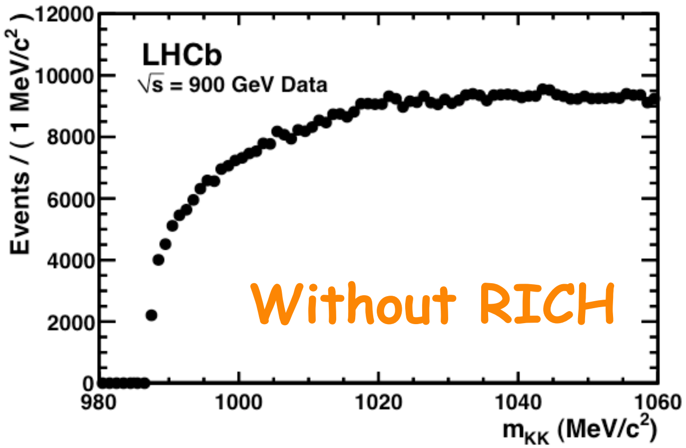
arXiv:1211.6759

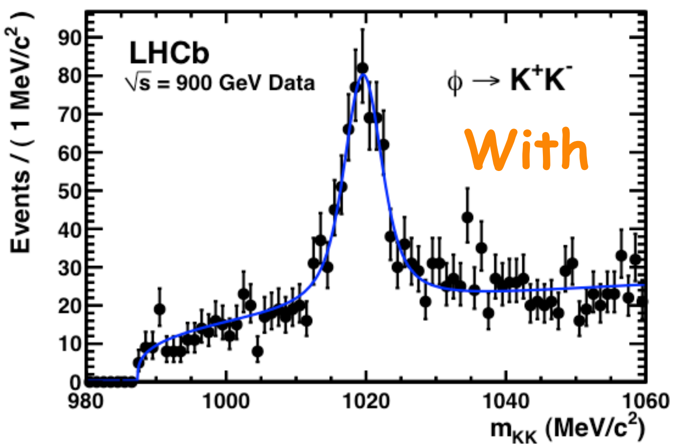
- Kaon identification efficiency > 90% for pion misidentification < 5% over a large momentum range ($2 < p < 100$ GeV/c)

Calibration data



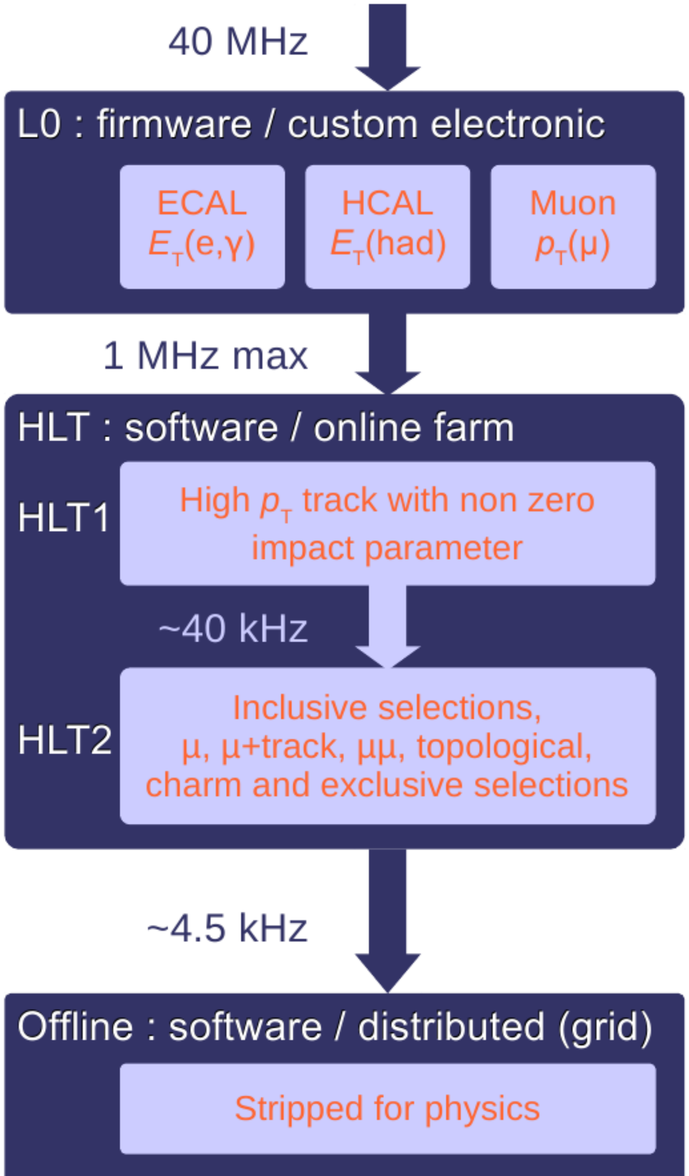
- Allows strong suppression of combinatorial background *eg* for $\phi \to K^+K^-$





The LHCb trigger performance

arXiv:1211.3055



Hardware level (L0):

- 4 μs latency @ 40MHz
- high-p_T μ, e, γ, hadron candidates, typically $p_T(\mu)>1.4$; $E_T(e/\gamma)>2.7$; $E_T(\text{hadron})>3.6$ [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 O(10^7) events for analyses

Selected physics highlights

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

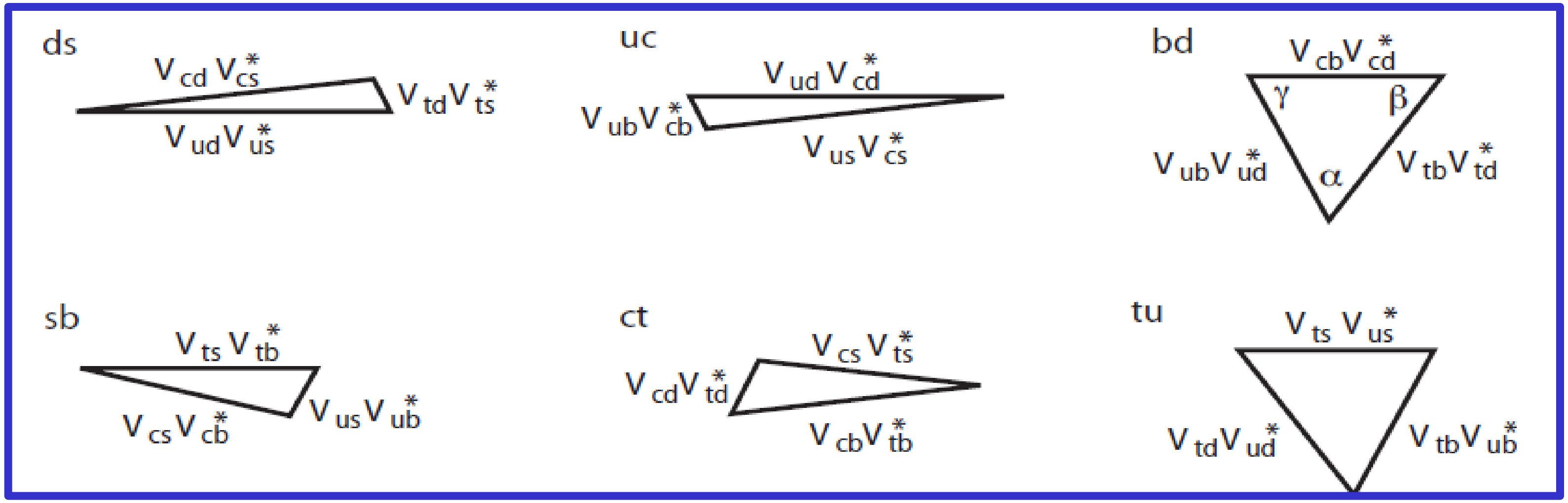
Quark mixing and CKM matrix

- In 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:

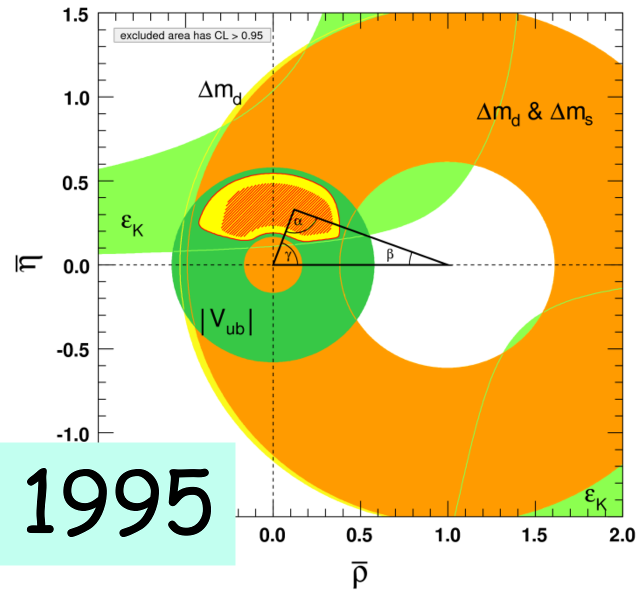
$$(V^*_{ub}V_{ud}+V^*_{cb}V_{cd}+V^*_{tb}V_{td}) = 0 \qquad (V^*_{ud}V_{td}+V^*_{us}V_{ts}+V^*_{ub}V_{tb}) = 0$$

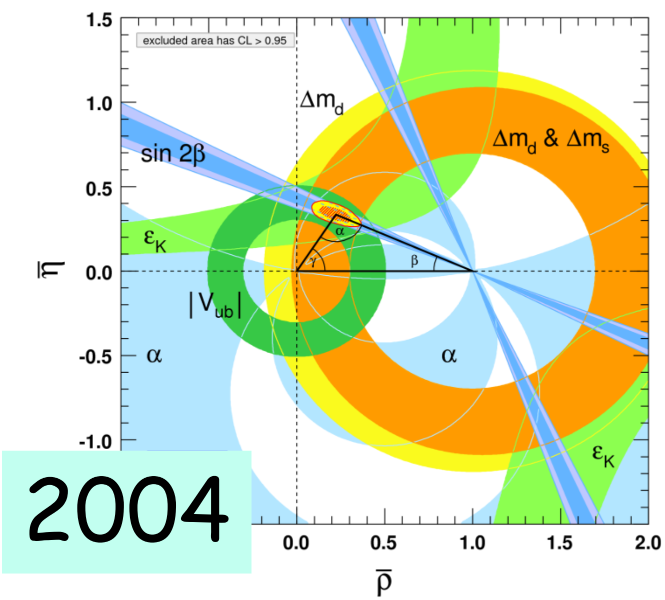


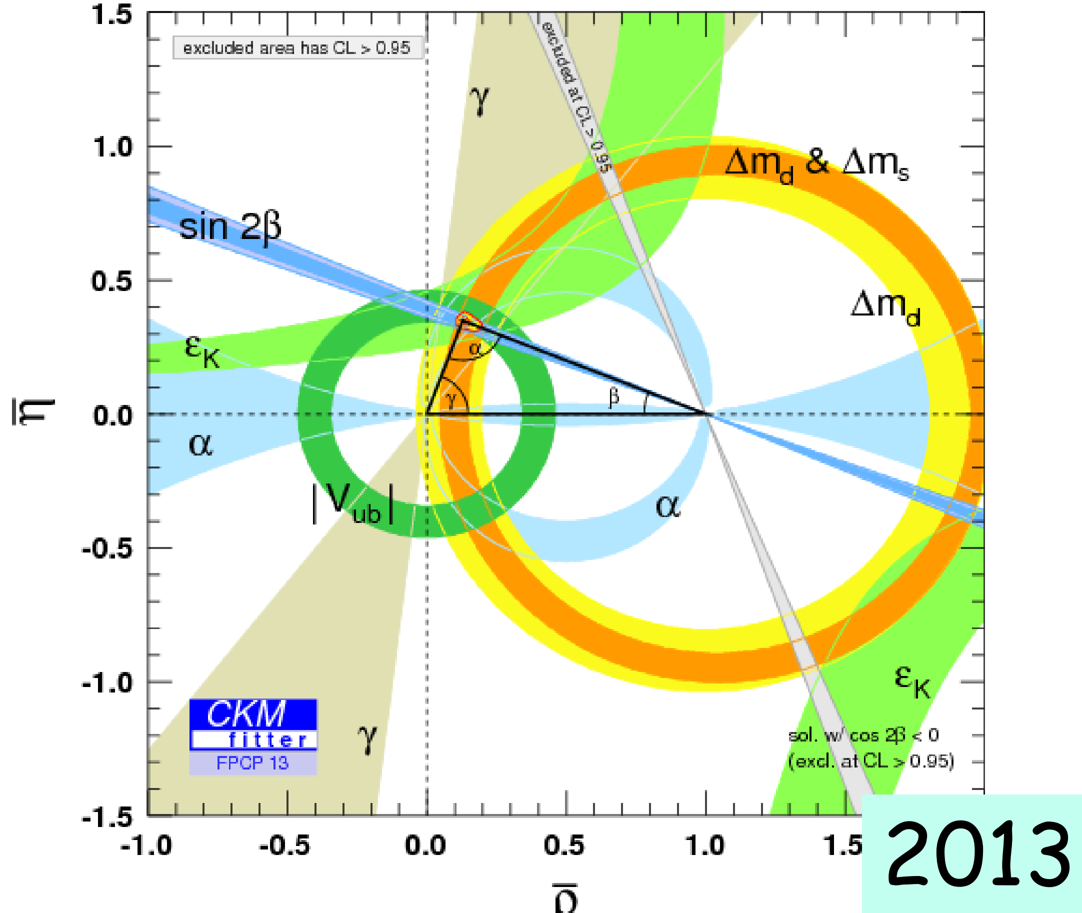
Unitarity triangle : CKM fitter

- 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

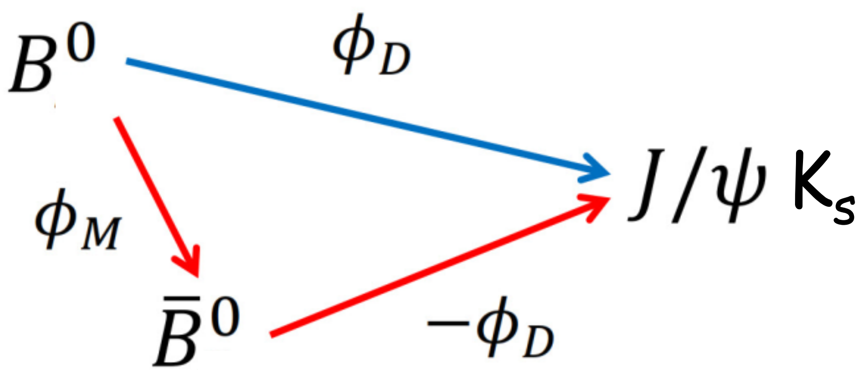
http://ckmfitter.in2p3.fr

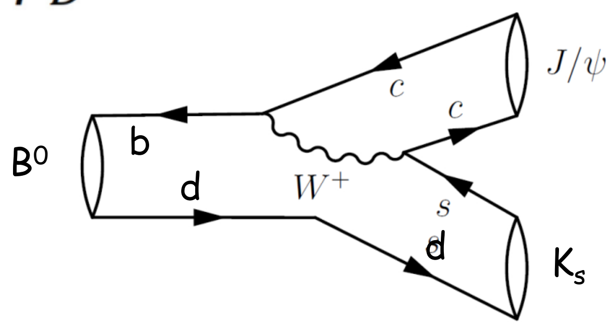


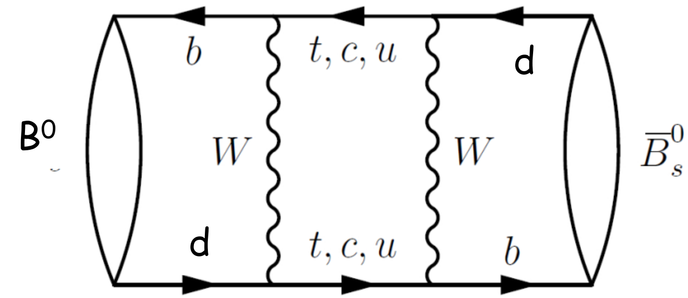




Measurement of angle β







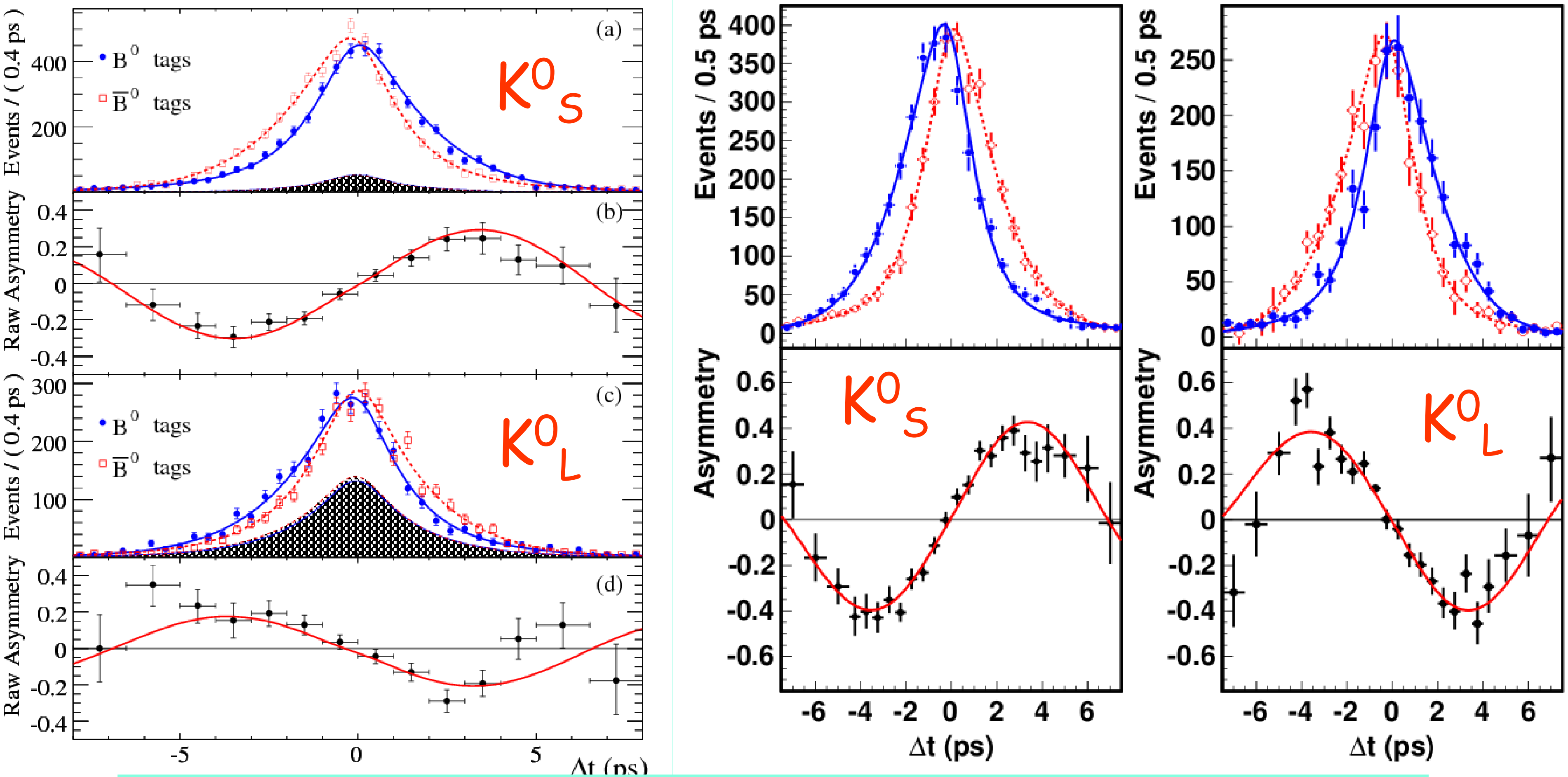
- *Interference* between B^0 decay to $J/\psi K^0{}_S$ directly and via B^0 $\overline{B^0}$ oscillation gives rise to a CP violating phase

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

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

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

Babar PRD 79 (2009) 072009 Belle PRL 108 (2012) 171802



World average (Aug 2013) : $\sin(2\beta) = 0.689 \pm 0.019$

And now LHCb in the game …

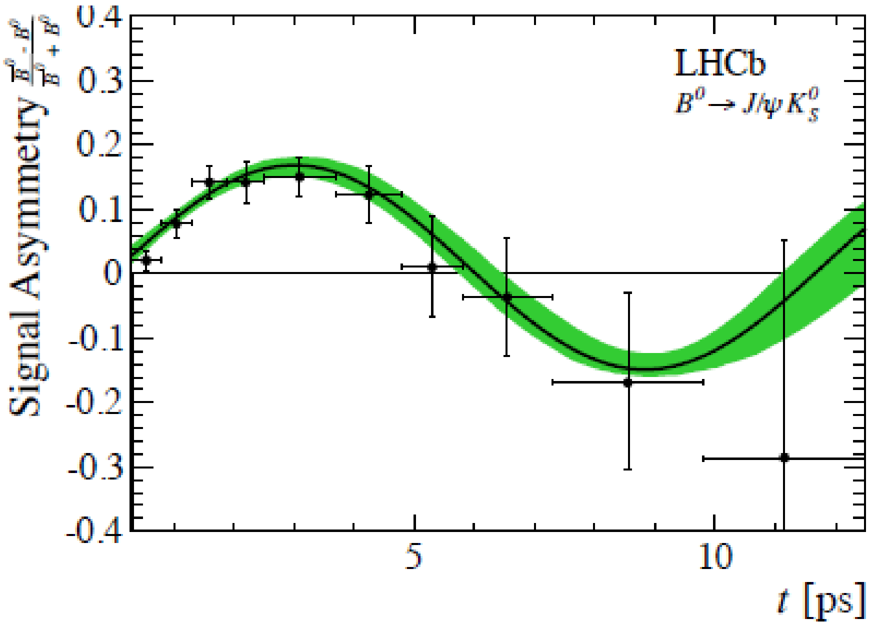
sin(2β) from $B^0 \to J/\psi K^0_S$

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

$S_{J/\psi Ks}$ = 0.73 ± 0.07 (stat) ± 0.04 (syst)

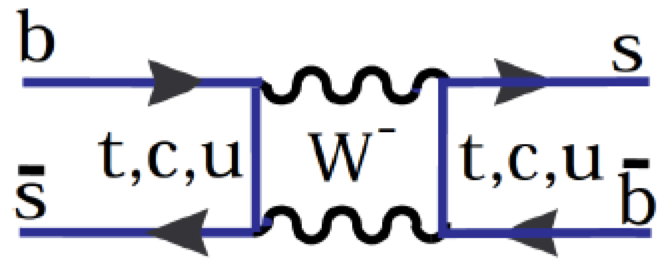
$C_{J/\psi Ks} = 0.030 \pm {}^{0.089}_{0.091}$ (stat) ± 0.012 (syst)

Phys.Lett B721 (2013) 24-31

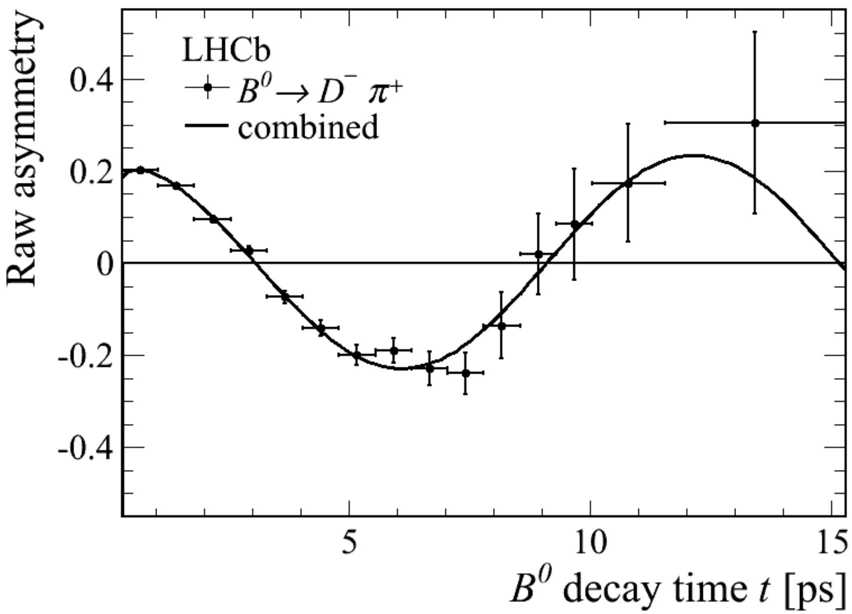


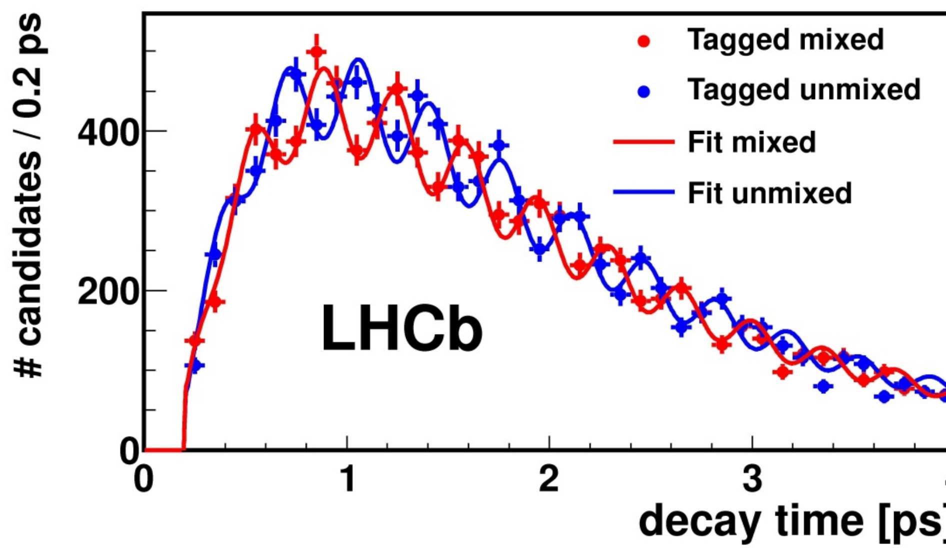
World average (Aug 2013) : sin(2β) = 0.689 ± 0.019

… and B mixing



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





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

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

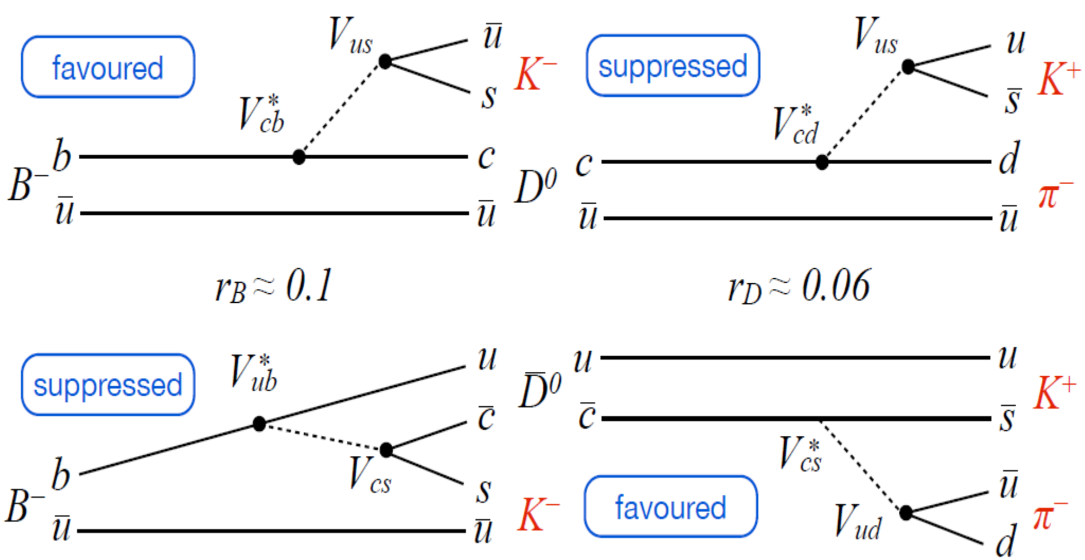
Phys.Lett B721 (2013) 24-31

New J. Phys. 15 (2013) 053021

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

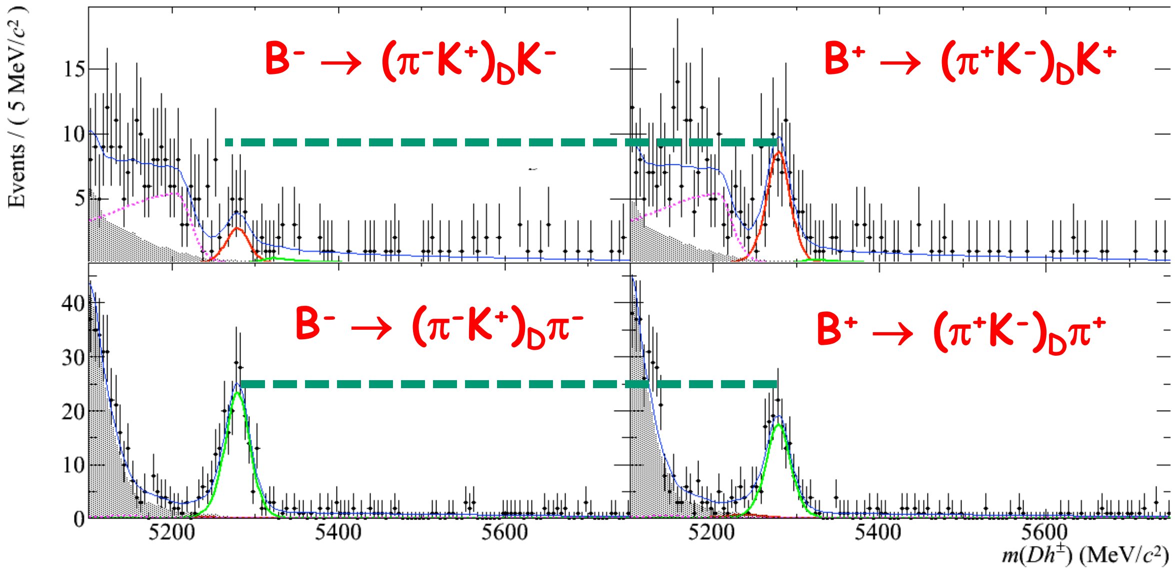
- Four methods, comprising 14 $B^\pm$ decays included in a combined fit

  - $B^\mp \to DK^\mp$, $D \to K_S{}^0\pi^\pm\pi^\mp$ and $D \to K_S{}^0K^\pm K^\mp$ — "GGSZ" — Phys Lett B718 (2012) 43
  - $B^\mp \to Dh^\mp$, $D \to \pi^\mp K^\pm\pi^\mp\pi^\pm$ and $D \to K^\mp\pi^\pm\pi^\mp\pi^\pm$ — "K3π" : — LHCb-CONF-2012-030
  - $B^\mp \to Dh^\mp$, $D \to \pi^\mp K^\pm$ and $D \to K^\mp\pi^\pm$ — "ADS" — Phys Lett B712 (2012) 203
  - $B^\mp \to Dh^\mp$, $D \to K^\pm K^\mp$, $D \to \pi^\pm\pi^\mp$ — "GLW" — Phys Lett B712 (2012) 203



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

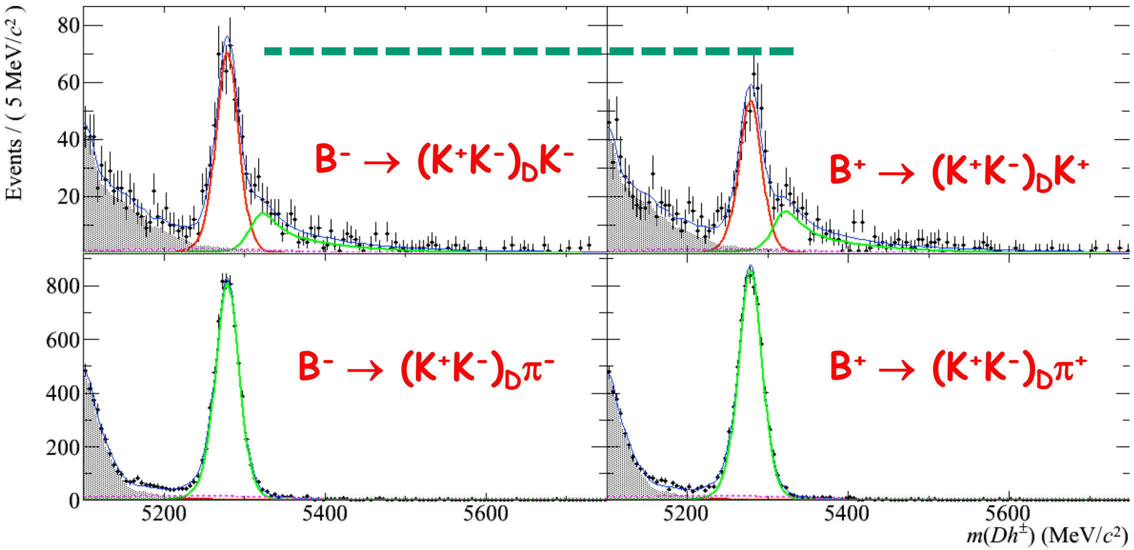
$B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$ ADS & GLW modes



ADS modes

1 fb⁻¹, 7 TeV data

GLW modes



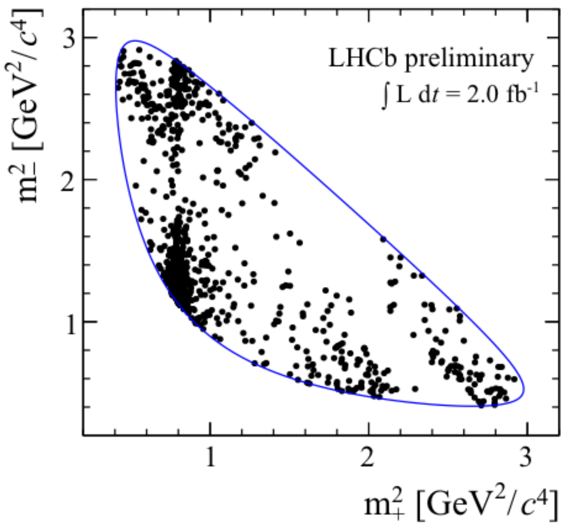
$B^{\pm} \rightarrow DK^{\pm}$ and $B^{\pm} \rightarrow D\pi^{\pm}$ GGSZ & $K(3\pi)$ modes

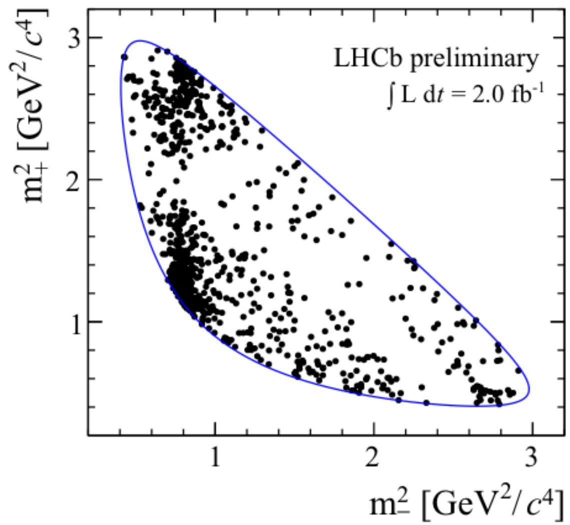
LHCb-CONF-2013-004

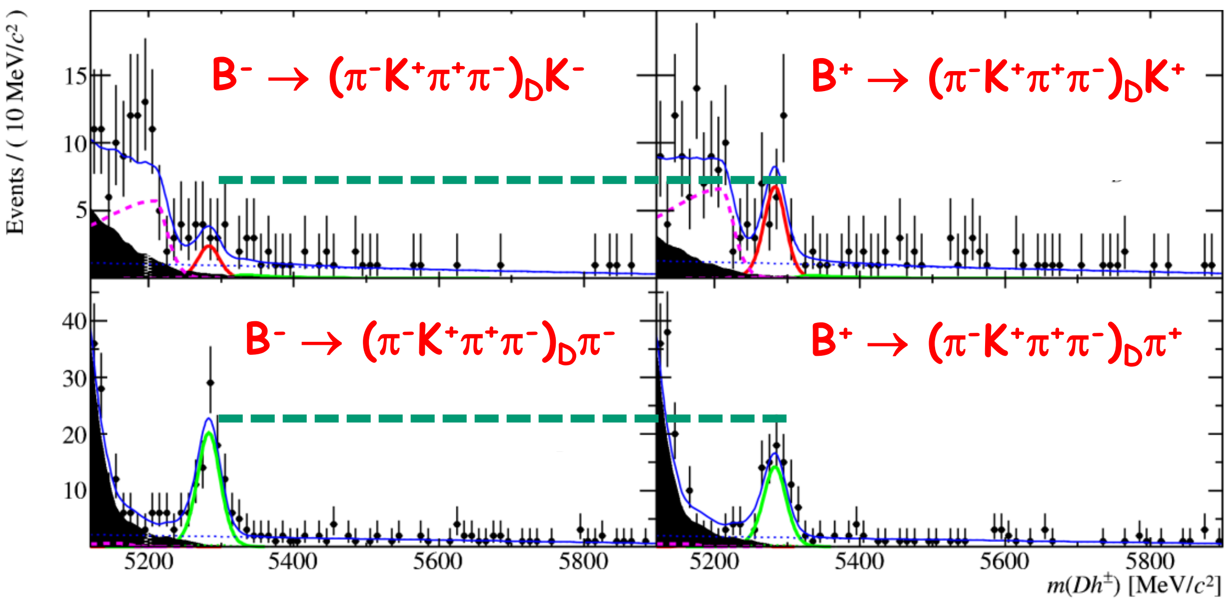
GGSZ mode

$(K_S\pi\pi)_D$

3 fb^{-1}







$K(3\pi)$ modes

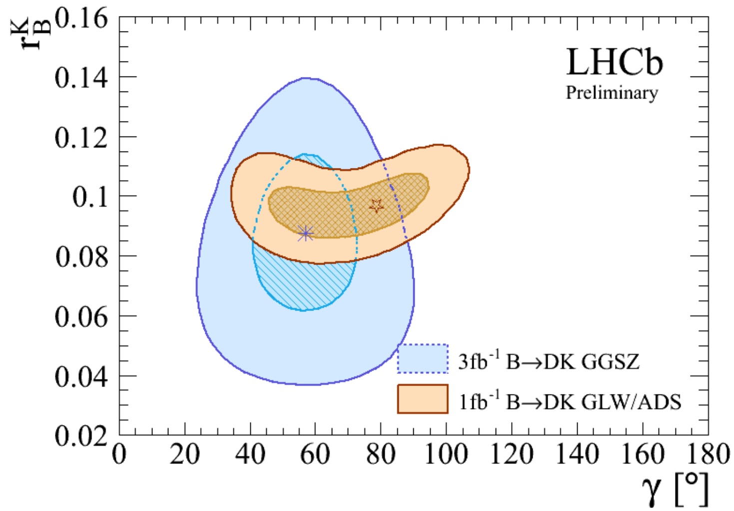
1 fb^{-1}

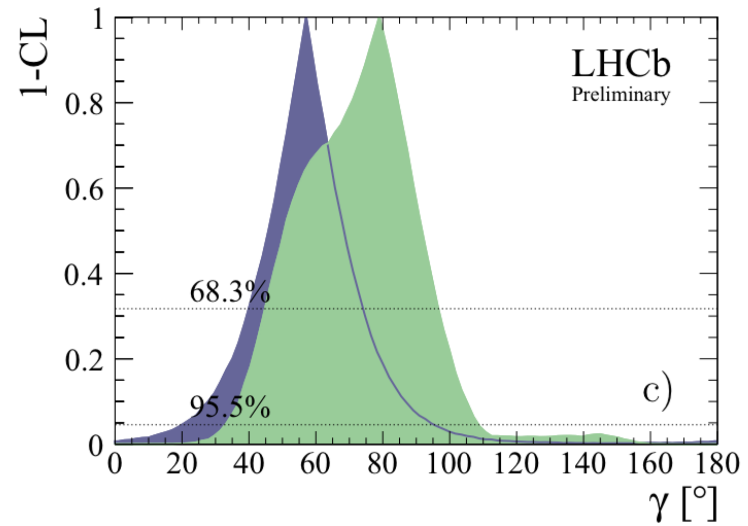
LHCb-CONF-2012-030

$B^\pm \to DK^\pm$ γ measurement

LHCb-CONF-2013-006

GGSZ $3fb^{-1}$





LHCb combined

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

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

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

$$\boxed{\gamma = (67 \pm 12)^\circ}$$

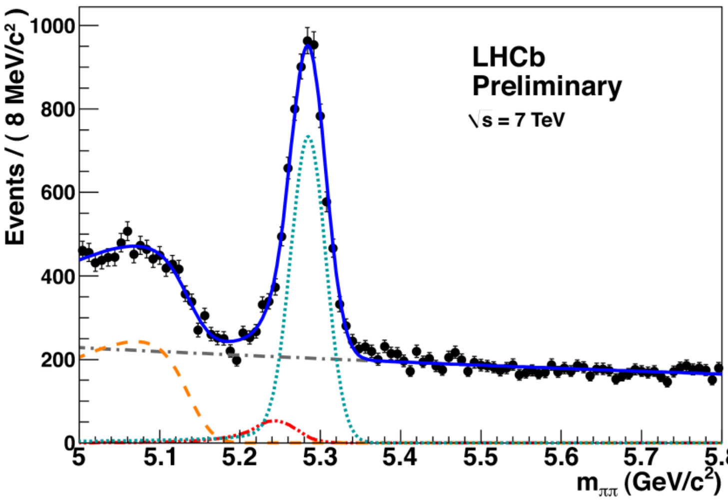
Compare: $Belle: (69^{+17}_{-16})^\circ$

$BaBar: (68^{+15}_{-14})^\circ$

Prediction: $UTFit: (68.6 \pm 3.6)^\circ$

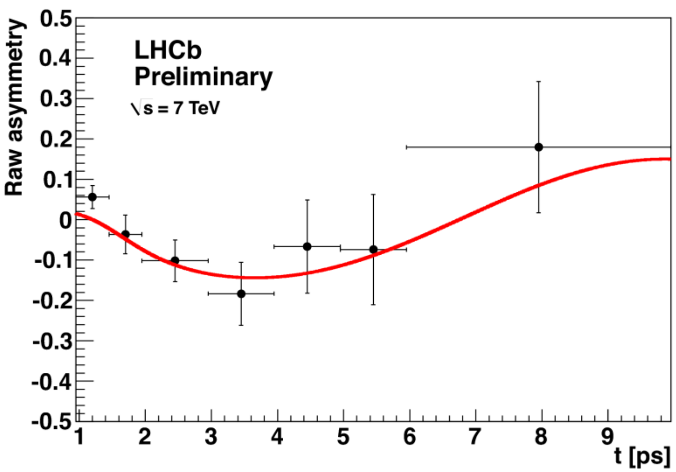
$CKMFitter: (68.0^{+4.1}_{-4.6})^\circ$

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



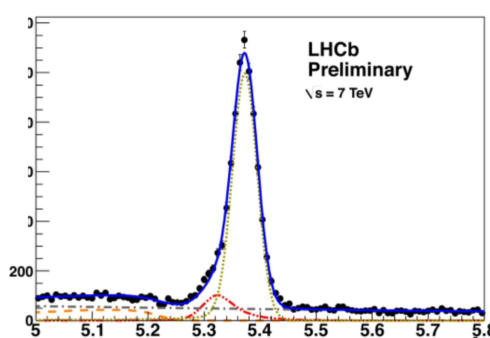
- $0.6\ fb^{-1}$: ~5.4k $B^0 \to \pi^+\pi^-$ events
- First time-dependent CP asymmetry plot of $B^0 \to \pi^+\pi^-$ at a hadron collider

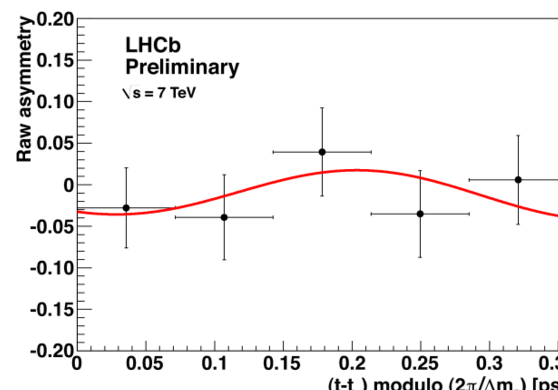
$$A^{dir}_{\pi\pi} = 0.11 \pm 0.21 \pm 0.03$$
$$A^{mix}_{\pi\pi} = -0.56 \pm 0.17 \pm 0.03$$



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

$$A^{dir}_{KK} = 0.02 \pm 0.18 \pm 0.04$$
$$A^{mix}_{KK} = 0.17 \pm 0.18 \pm 0.05$$





LHCb-CONF-2012-007

Selected physics highlights

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

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

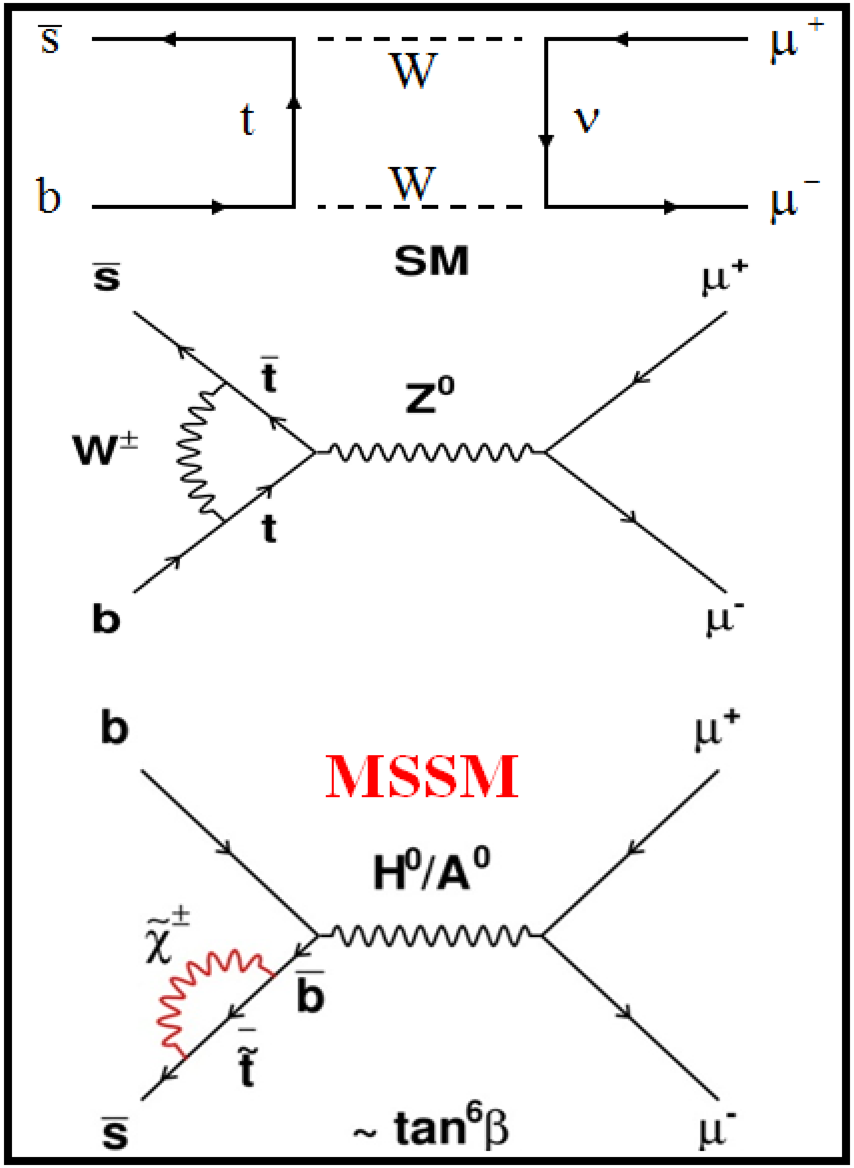
- Decays strongly suppressed in SM
- Predicted BRs

  $B^0_s \rightarrow \mu^+\mu^- = (3.56 \pm 0.30) \times 10^{-9}$

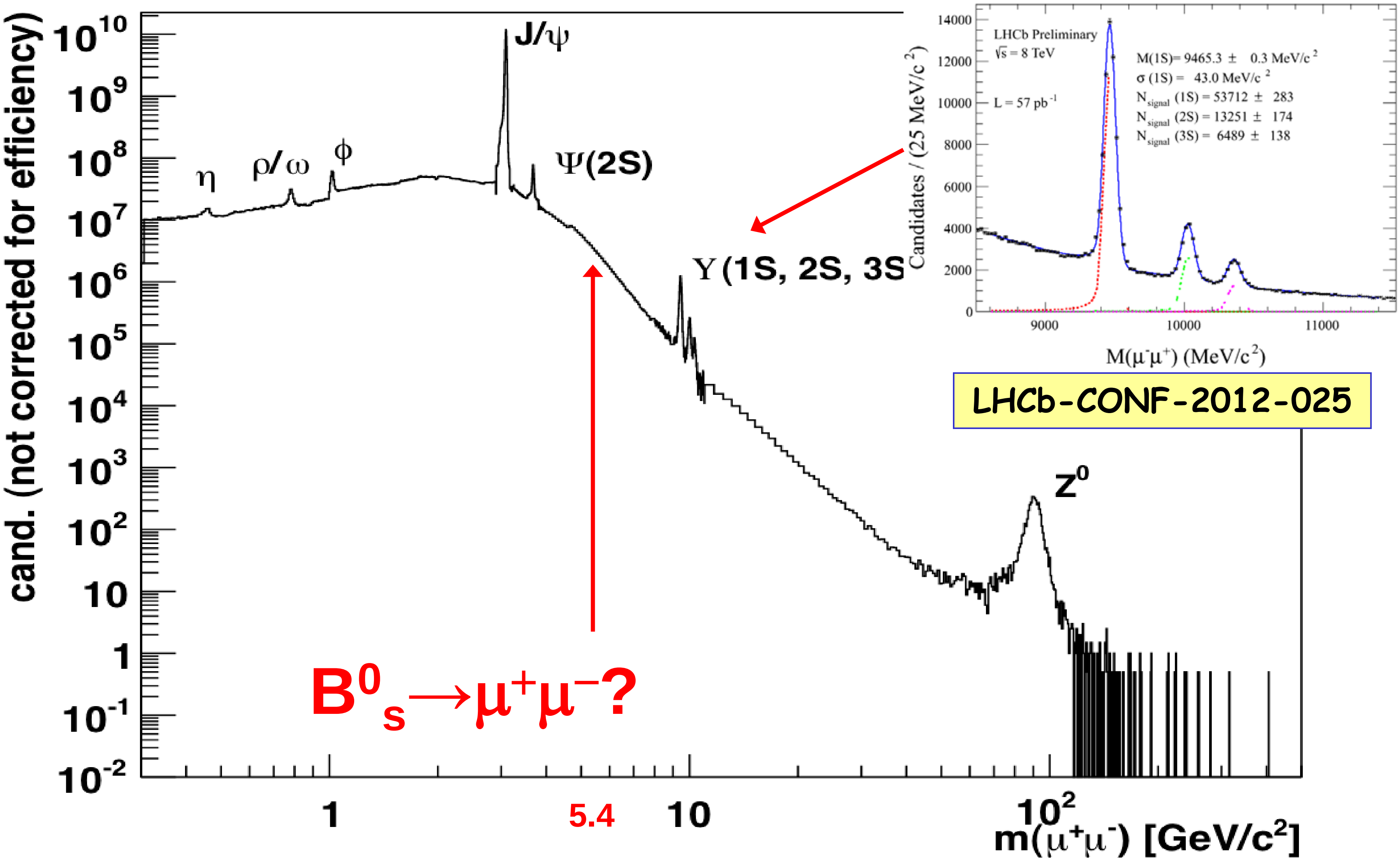
  $B^0 \rightarrow \mu^+\mu^- = (1.07 \pm 0.10) \times 10^{-10}$

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

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



LHCb μ+μ− mass spectrum

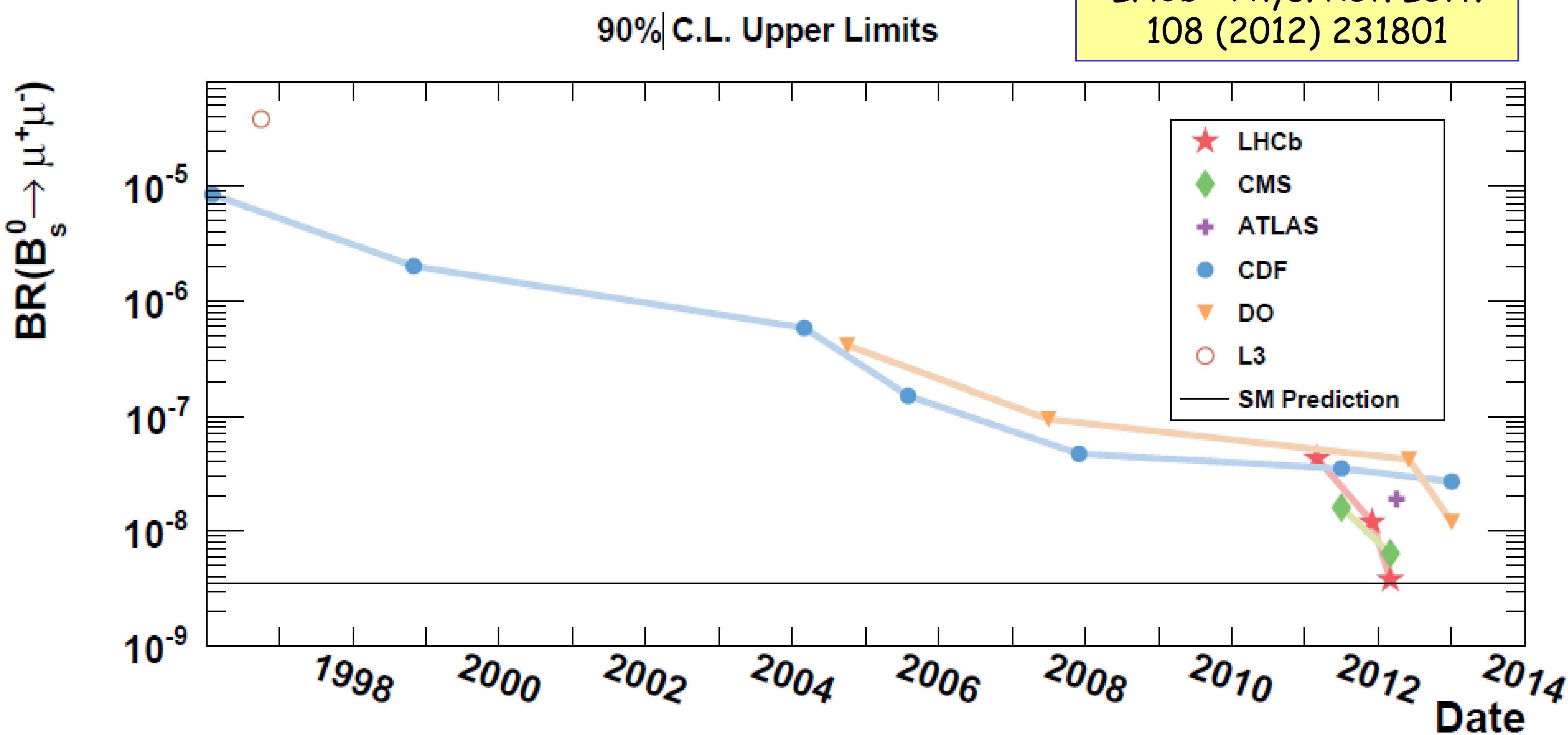


LHCb-CONF-2012-025

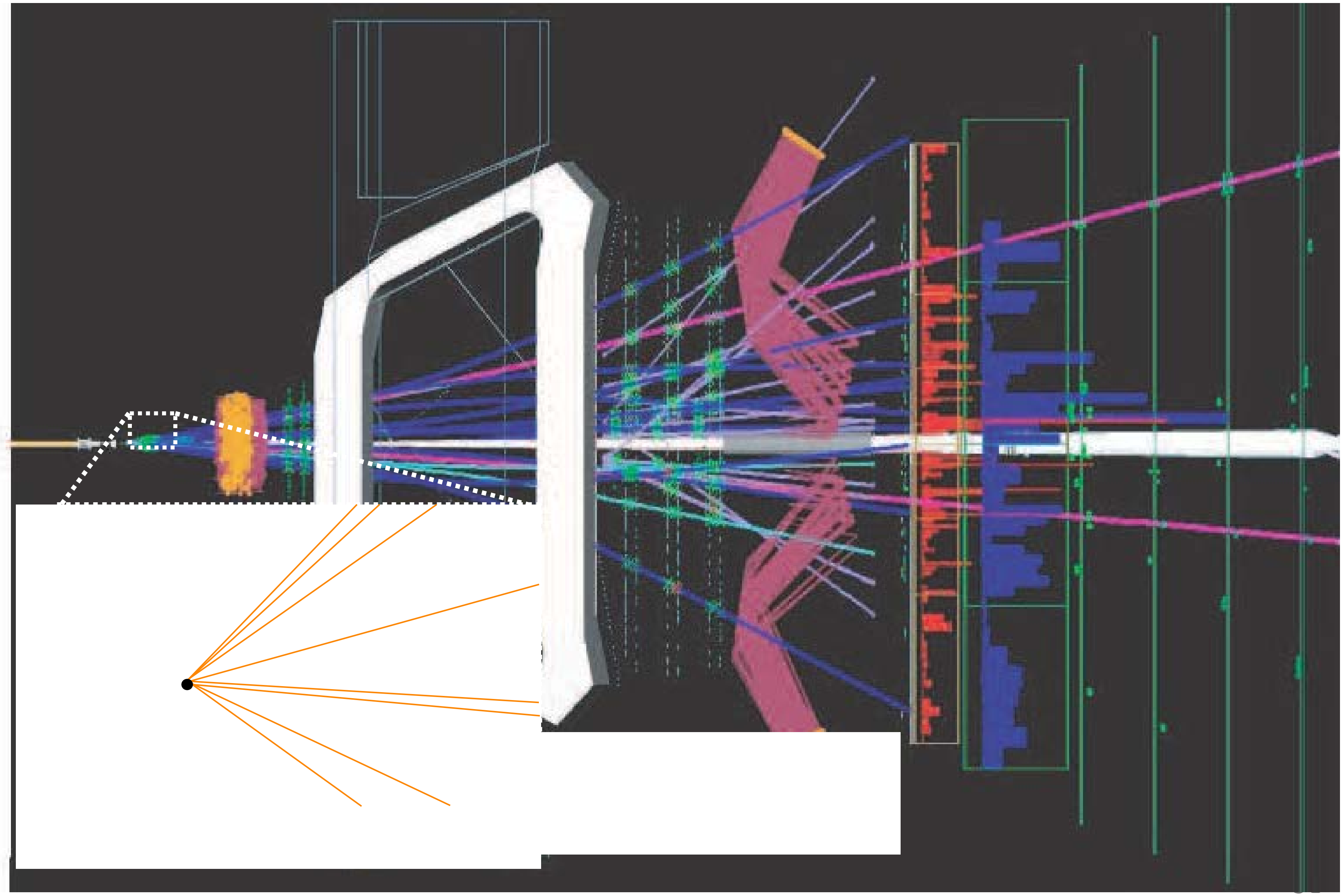
History

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

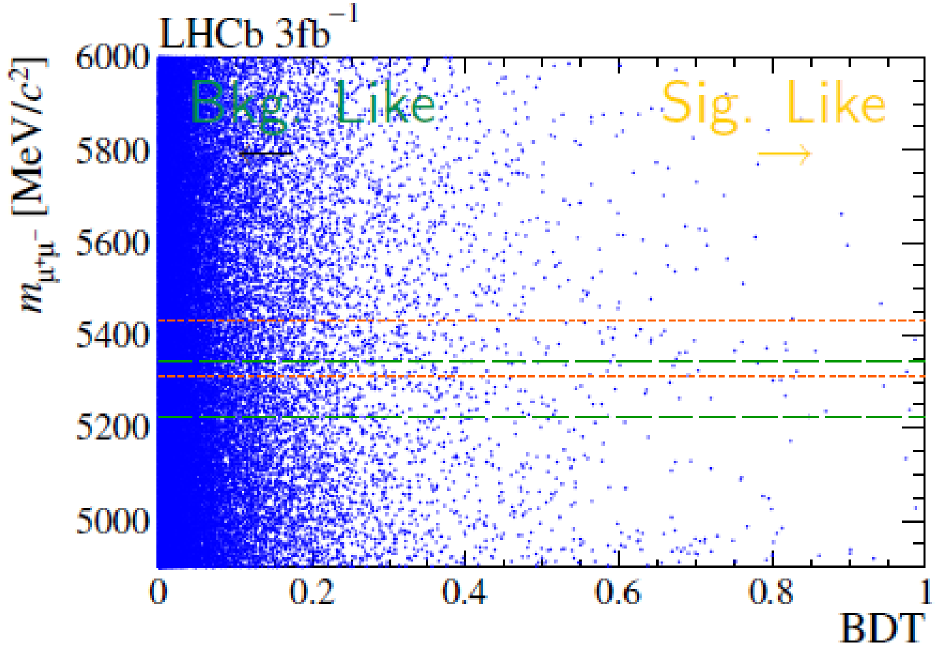
LHCb: Phys. Rev. Lett. 108 (2012) 231801



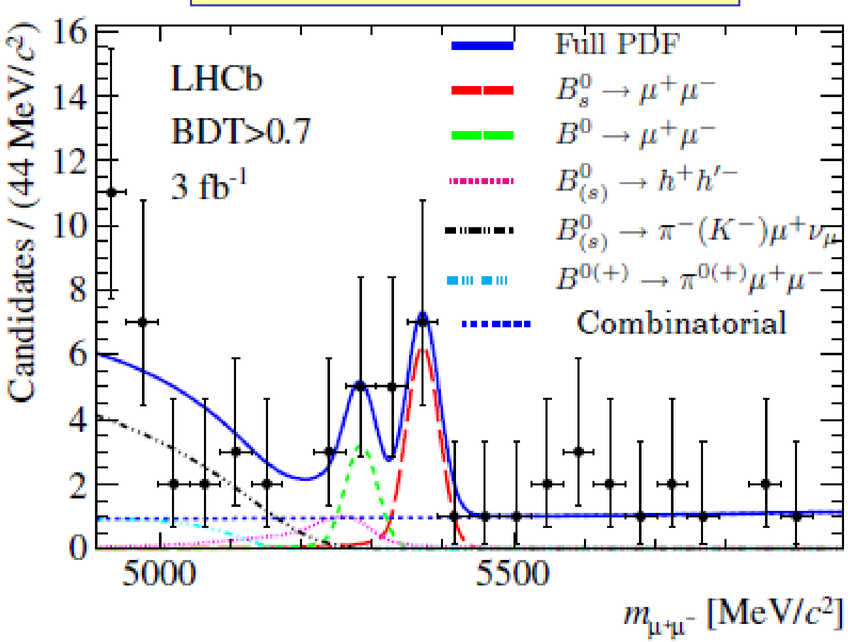
LHCb $B_s \to \mu^+\mu^-$ candidate



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



LHCb-CONF 2013-012



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

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

Upper Limit

No compelling $B^0 \to \mu^+\mu^-$ signal hint

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10}$ at 95%C.L.

Combining with CMS results

- $25\,\mathrm{fb}^{-1}$ of integrated luminosity
- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$ Significance $= 4.3\sigma$ (4.8 Expected)
- $\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10}$ Significance $= 2.0\sigma$

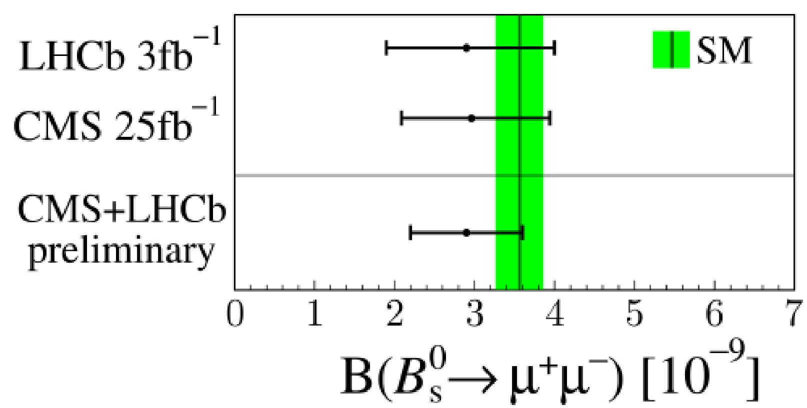
Weighed $\mathcal{B}$ **Average (not Likelihood Combination)**

Significance

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \stackrel{\mathrm{LHC}}{=} (2.9 \pm 0.7) \times 10^{-9} \qquad > 5\sigma$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) \stackrel{\mathrm{LHC}}{=} (3.6^{+1.6}_{-1.4}) \times 10^{-10} \qquad > 3\sigma$$

CMS-PAS-BPH-13-007
LHCb-CONF-2013-012



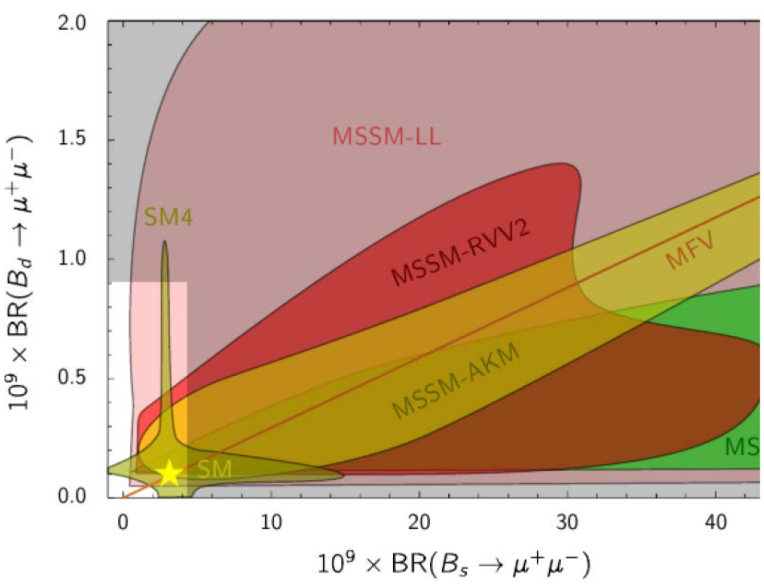
Constraints on new physics models

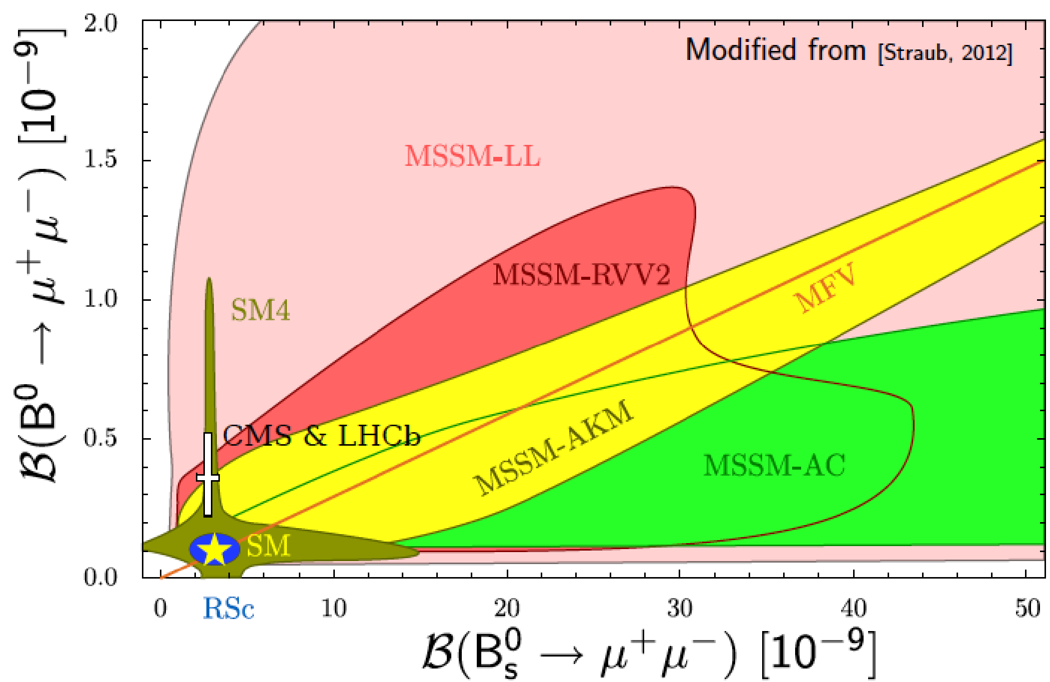
Status in June 2012 (LCC combination)

$\mathcal{B}r\ (B_s^0 \to \mu^+\mu^-) < 4.2\cdot10^{-9}$ at 95% C.L.
$\mathcal{B}r\ (B^0 \to \mu^+\mu^-) < 8.1\cdot10^{-10}$ at 95% C.L.

Status now

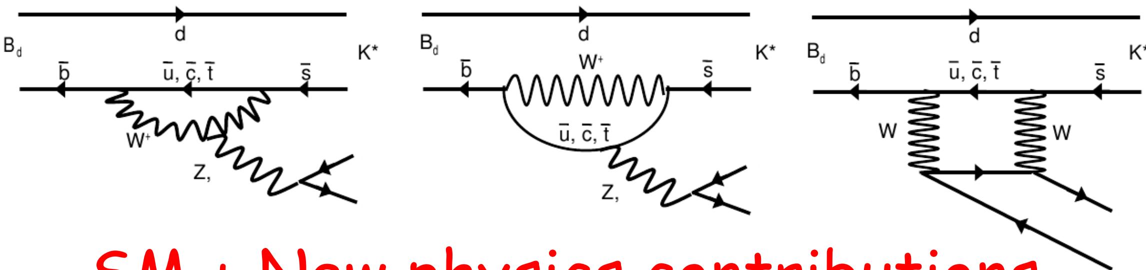
$\mathcal{B}r\ (B_s^0 \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2})\cdot10^{-9}$
$\mathcal{B}r\ (B^0 \to \mu^+\mu^-) < 9.4\cdot10^{-10}$ at 95% C.L.

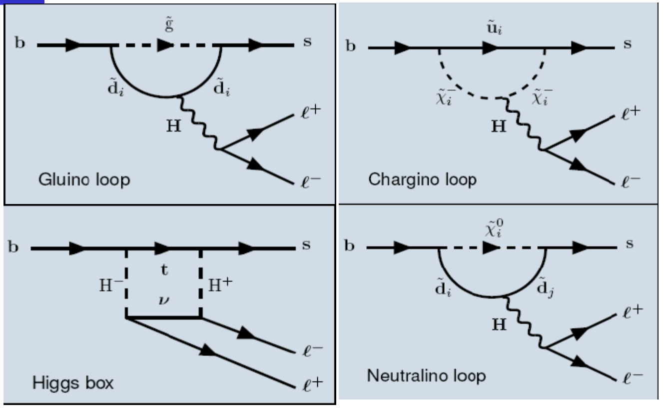




Straub Moriond 2012 (http://phys.davidstraub.de/files/dstraub-moriond12.pdf)

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



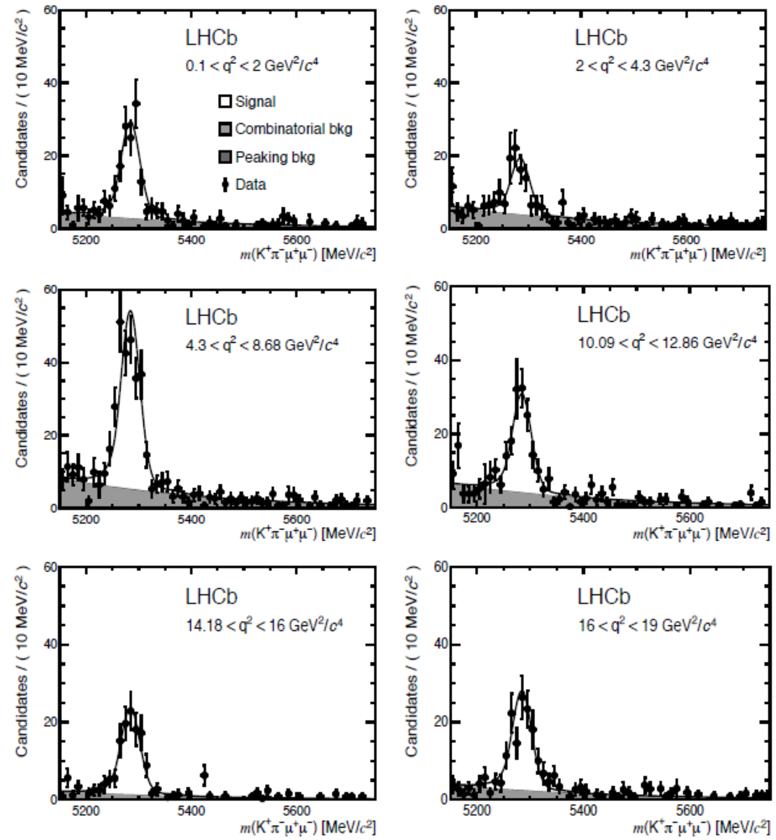


SM + New physics contributions

- LHCb has largest sample in world, as clean as the B Factories!
- LHCb BR = $(1.22^{+0.38}_{-0.32}) \times 10^{-6}$ agrees to within ~30% of SM

arXiv:1210.4492

- Latest analysis : 883 ± 34 events (1fb^{-1} at 7 TeV)

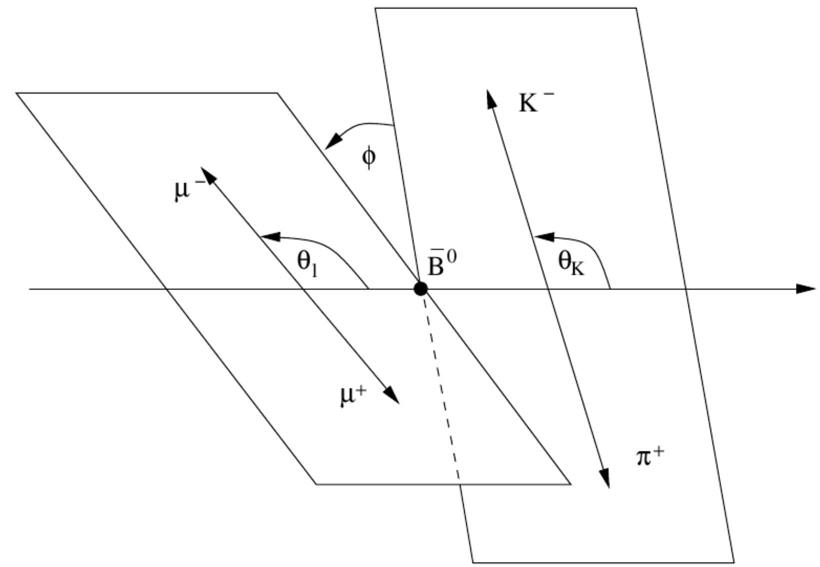


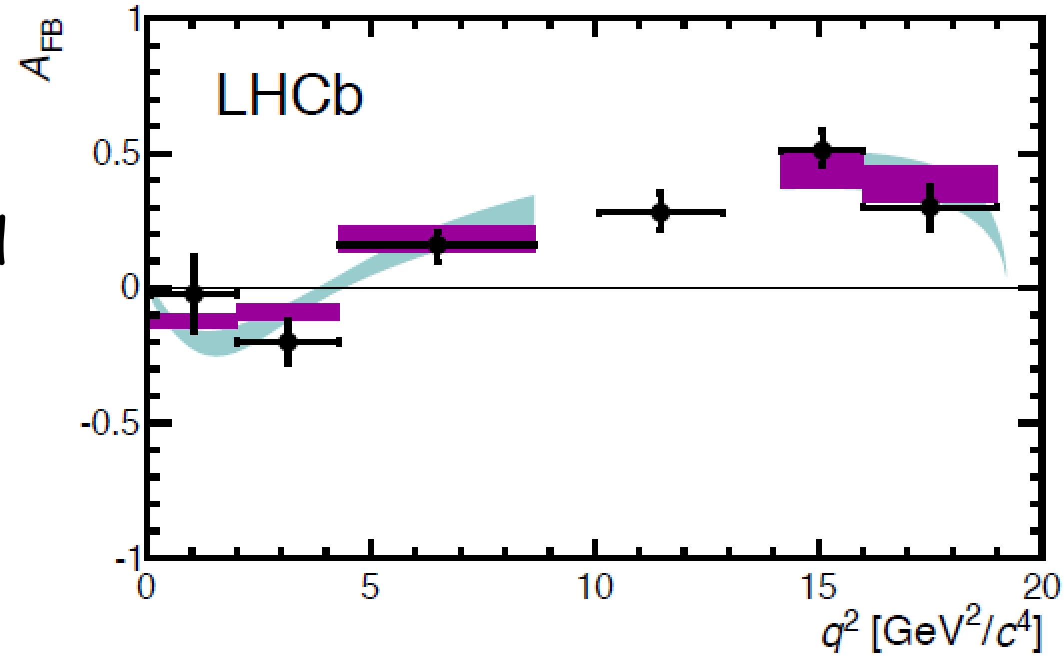
arXiv:1304.6325

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

arXiv:1304.6325

- But forward-backward asymmetry $A_{FB}(q^2)$ in the $\mu\mu$ rest-frame is a sensitive NP probe ($q^2 = m_{\mu\mu}{}^2$)
- First measurement of zero crossing point:
  $q^2 = 4.9 \pm 0.9$ GeV^2
- A_{FB} measured by LHCb consistent with Standard Model





New 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.

arXiv:1308.1707

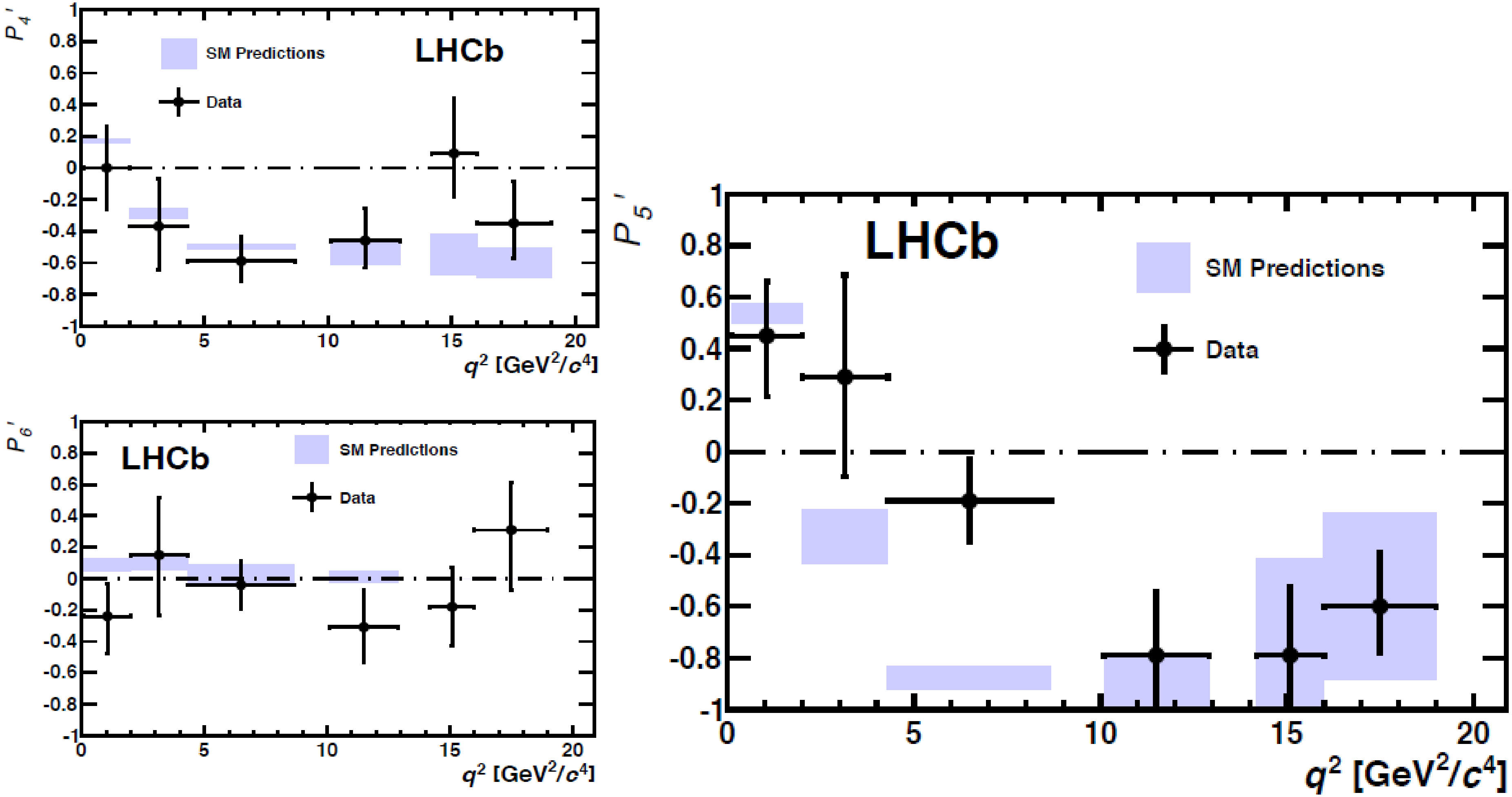
- Same 1 fb^{-1} 7 TeV dataset
- Angular differential distribution given by:

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

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

arXiv:1308.1707

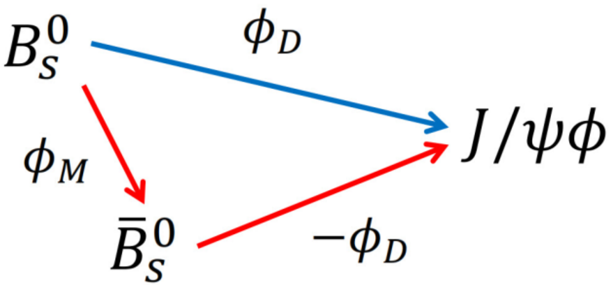
- Local discrepancy of 3.7σ in 3rd bin of P_5' (SM prediction J.Mathias et al, JHEP 05 (2013) 137)

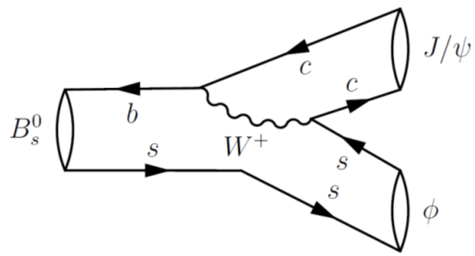


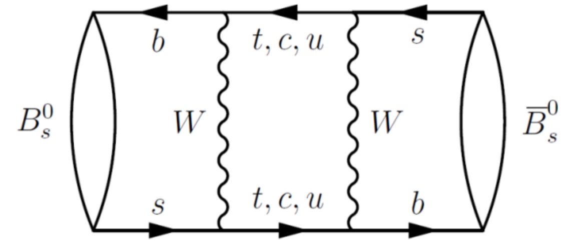
Selected physics highlights

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

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







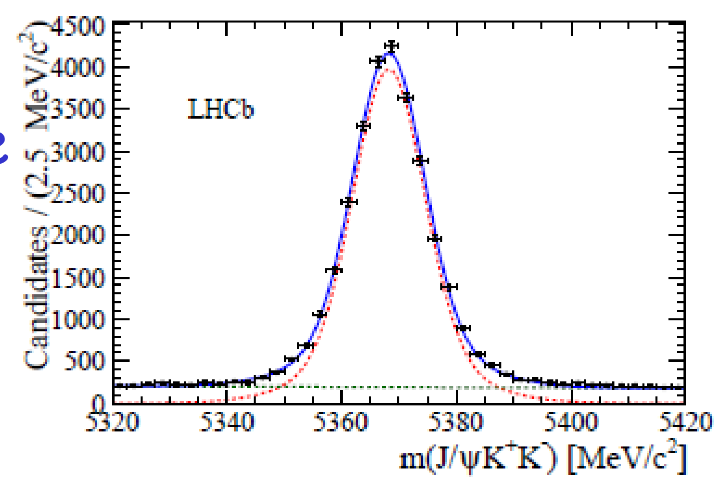
- Golden mode for this study is $B_s \to J/\psi\ \phi$
- Analogue of 2β (phase of B^0 mixing) in the B_s system
- *Interference* between B^0 decay to $J/\psi K^0_S$ directly and via B^0 - $\bar{B}^0$ oscillation gives rise to a CP violating phase

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

- 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)

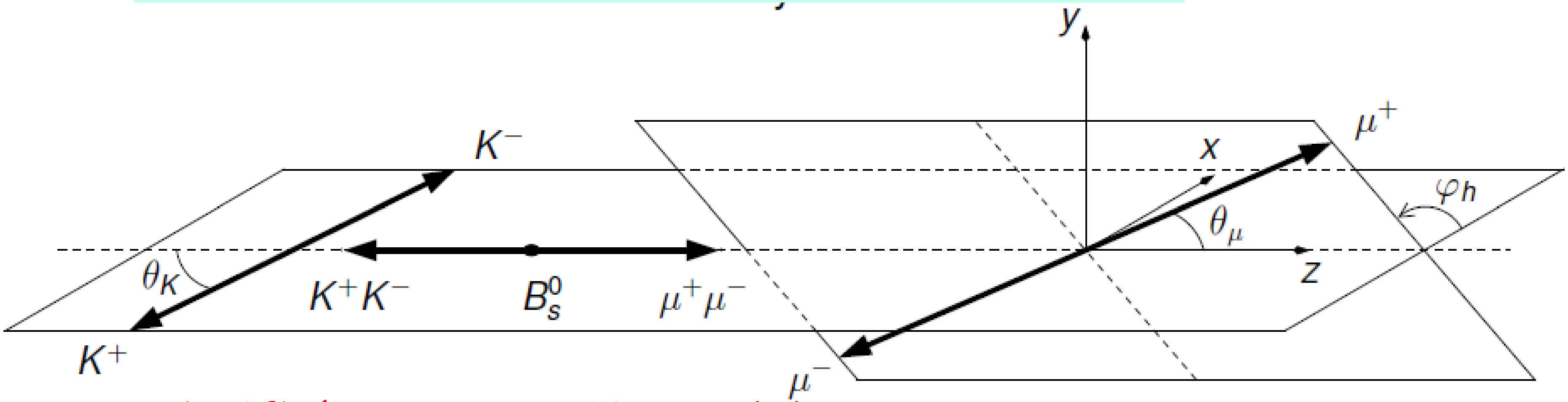


1fb^{-1}, 7 TeV PRD 87 112010 (2013)

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

- But 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

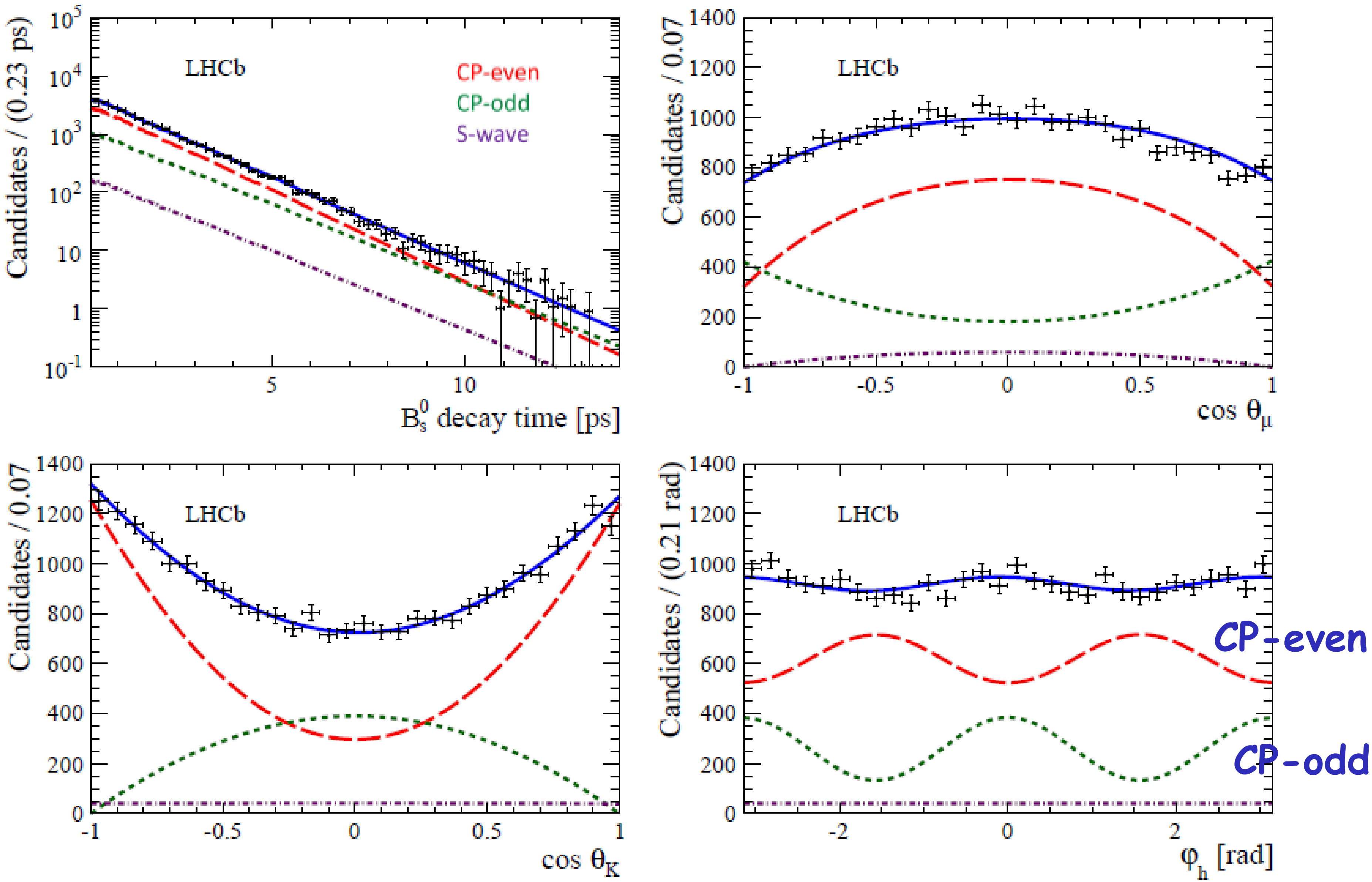


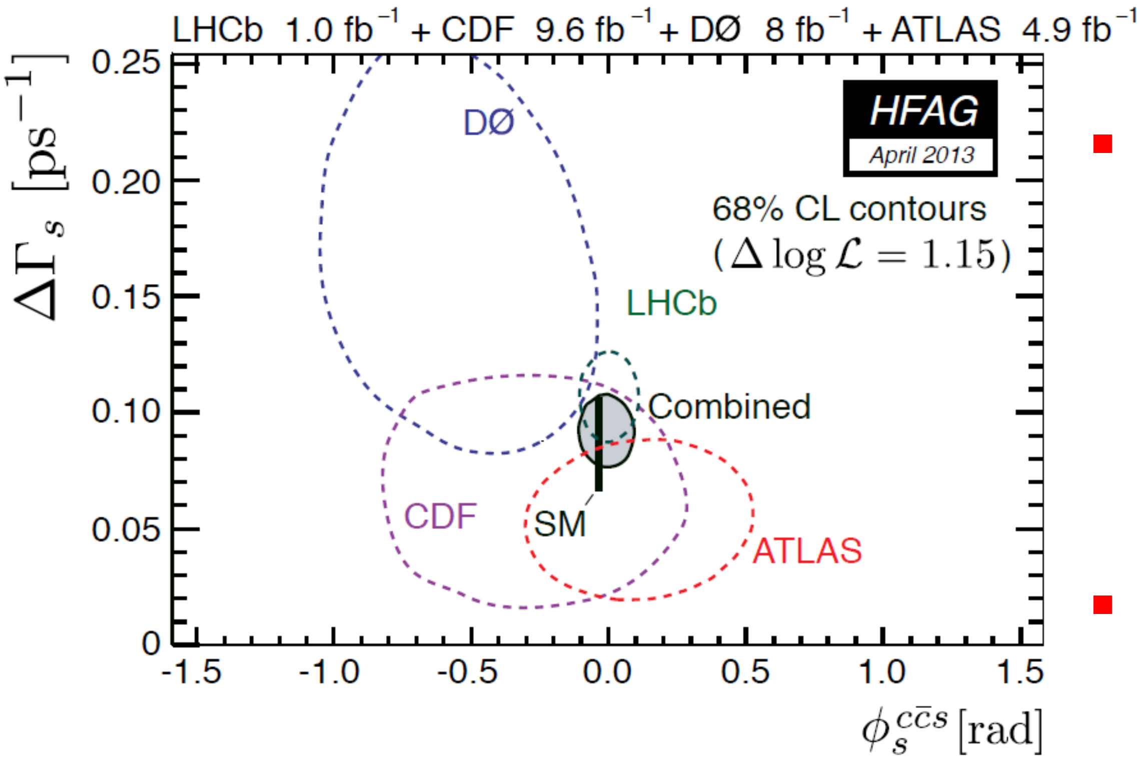
LHCb: $1 fb^{-1}$, 7 TeV, 27617 candidates

Use opposite side tag: Power = $(2.29 \pm 0.07 \pm 0.26)\%$

- First measurements from the Tevatron indicated large values for ϕ_s discrepancy with SM reaching $\sim 3\sigma$

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





- Results correlated with $\Delta\Gamma_s$ = width diff. of the B_s mass eigenstates → plot as contours in (ϕ_s *vs* $\Delta\Gamma_s$) plane
- Also add in $B_s \to J/\psi\ \pi\pi$

World's most significant direct measurement of ϕ_s & $\Delta\Gamma_s$ $\Delta\Gamma_s$

$$\phi_s = 0.01 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (syst) rad,}$$
$$\Gamma_s = 0.661 \pm 0.004 \text{ (stat)} \pm 0.006 \text{ (syst) } \mathrm{ps}^{-1}$$
$$\Delta\Gamma_s = 0.106 \pm 0.011 \text{ (stat)} \pm 0.007 \text{ (syst) } \mathrm{ps}^{-1}$$

Still much room for new physics in ϕ_s, will continue to improve precision

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.

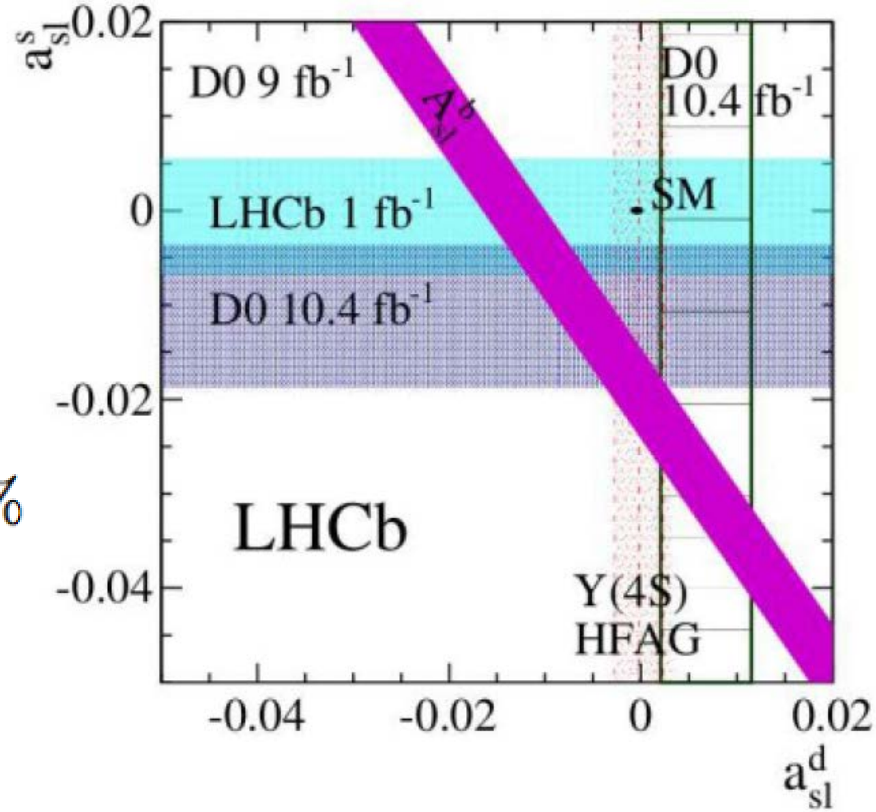
Phys. Rev. D 84, 052007 (2011), Phys. Rev. D 86, 072009 (2012)

- 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

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

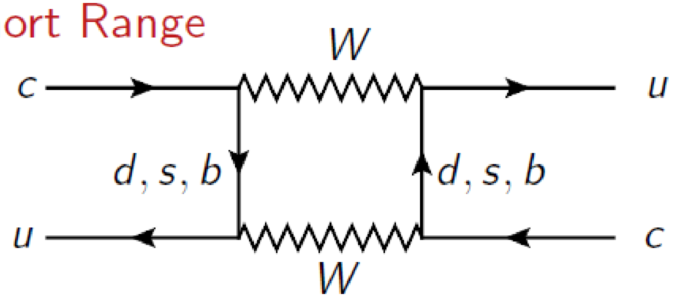
A.Lenz
arXiv:1205.1444

Selected physics highlights

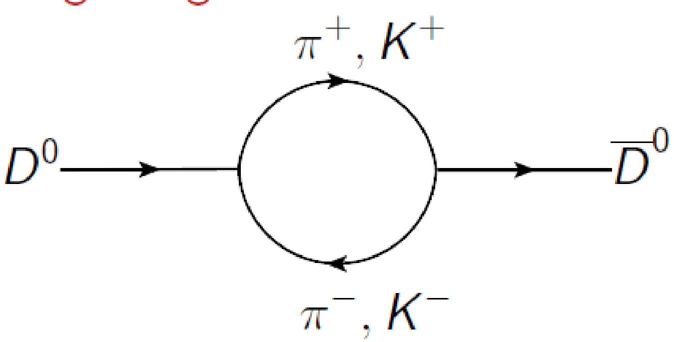
- Parameters of the CKM matrix
- Rare B decays
- Studies of CPV in the B_s system
- CP violation in charm

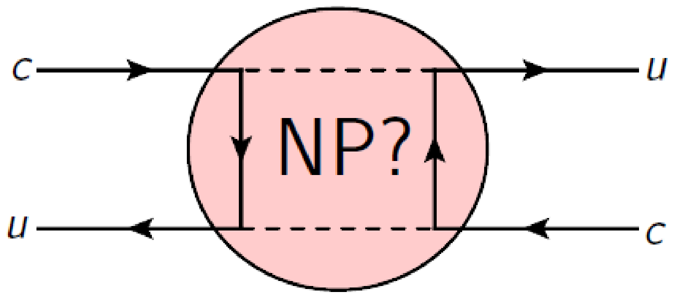
Mixing (and CP-violation) in charm decays

Short Range



Long Range





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15 November 2011 Last updated at 12:18 GMT

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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.

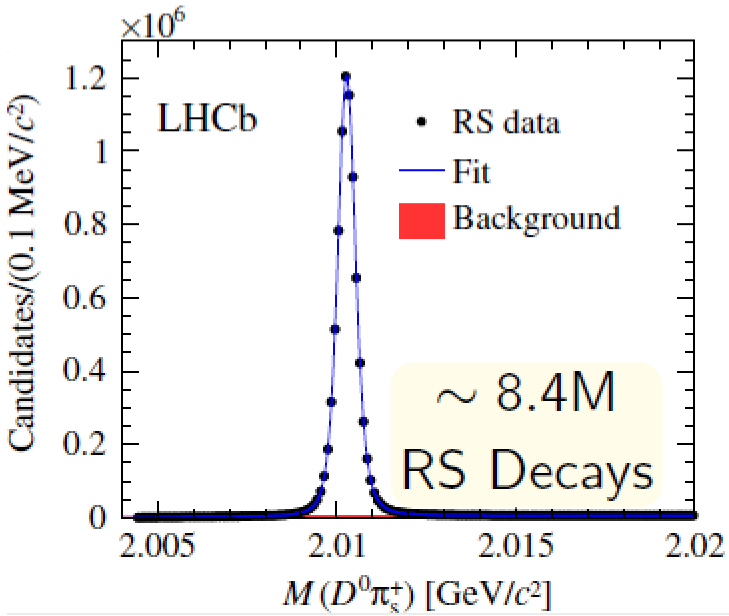
The result may help explain why we see so much more matter than antimatter.

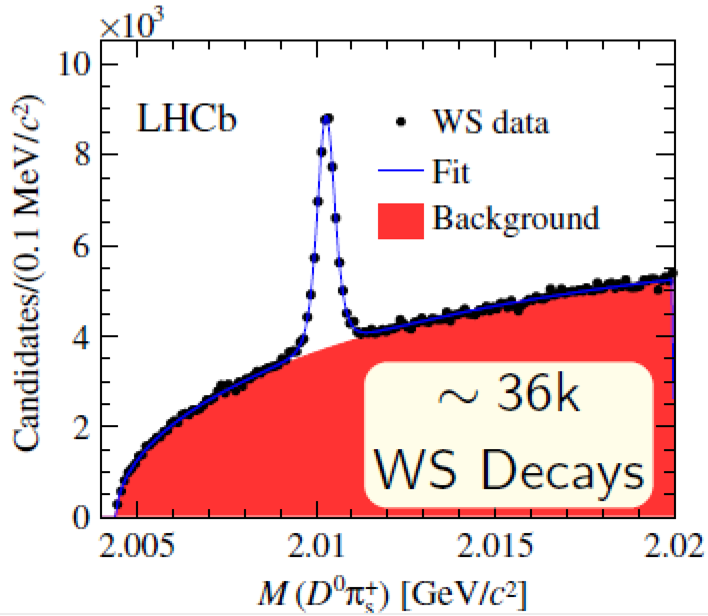
Charm mixing measurement

- Charm mixing has been confirmed by BaBar, Belle & CDF, but LHCb now show clear observation in a single experiment.
- LHCb measure the time-dependent ratio of D^0 decays to Wrong Sign to Right Sign

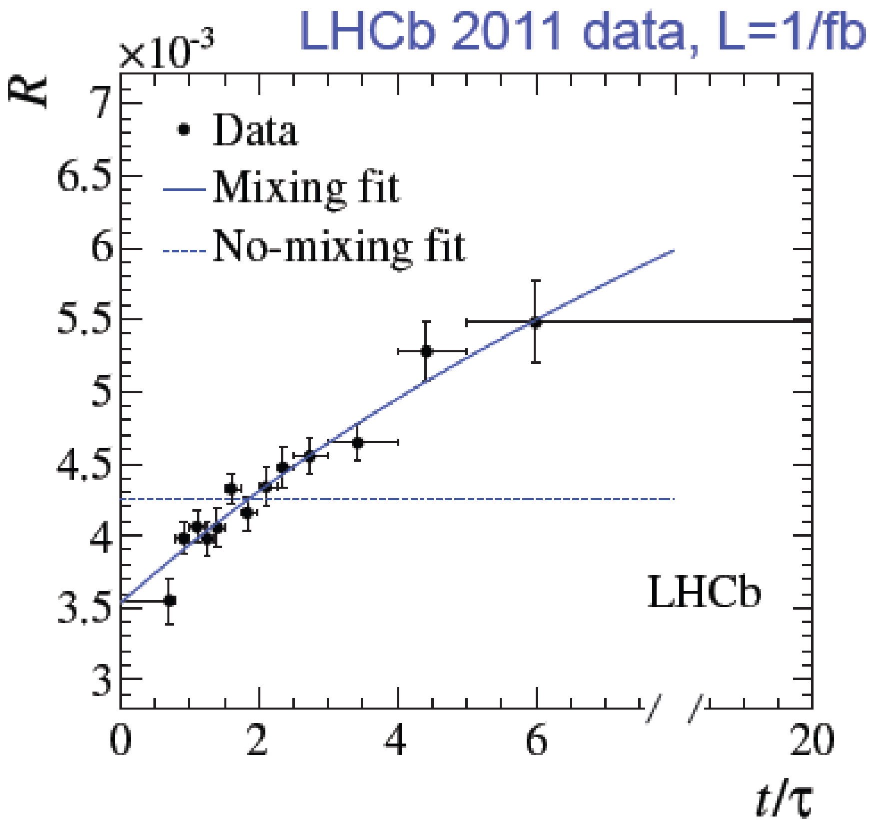
$$R(t) = \frac{N(D^0 \to K^+\pi^-)}{N(D^0 \to K^-\pi^+)}$$

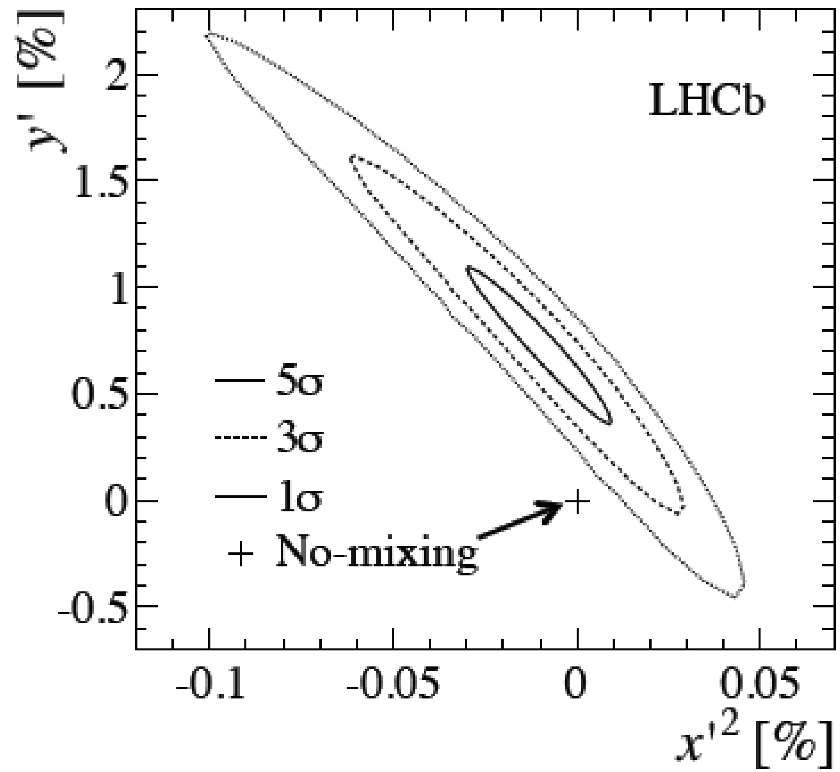
- Use the sign of the slow pion from $D^{*+} \to D^0\pi^+_s$ and $D^{*-} \to \bar{D}^0\pi^-_s$ to tag the initial D^0 flavour





Charm mixing measurement





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

PRL 110, 101802 (2013)

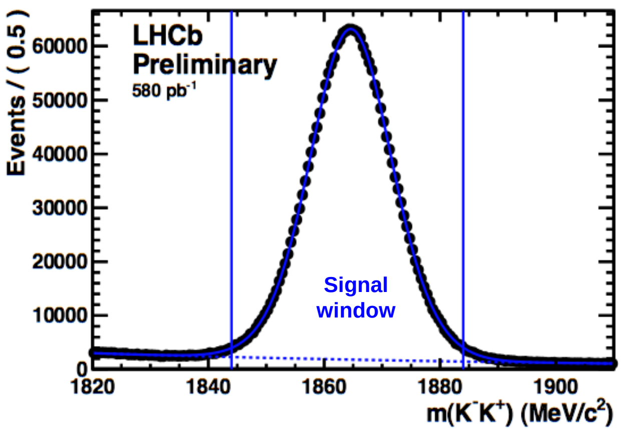
CP violation in charm

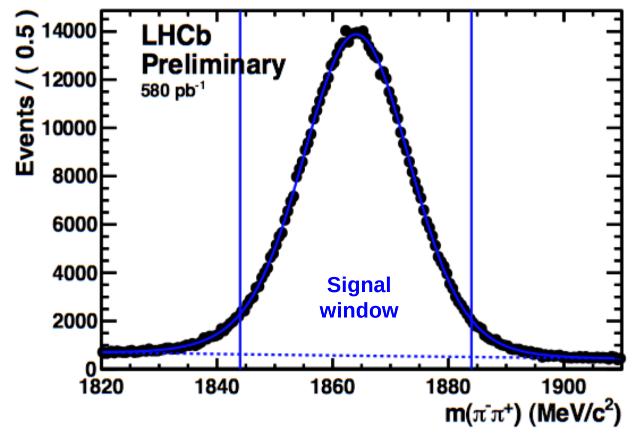
Phys. Rev. Lett. 108 (2012) 111602

Measure $D^0/\overline{D^0}$ decay asymmetries - charge of π from D* determines production state of the D^0

$$A_K = \frac{N(D^0 \to K^+K^-) - N(\overline{D^0} \to K^+K^-)}{N(D^0 \to K^+K^-) + N(\overline{D^0} \to K^+K^-)} \qquad A_\pi = \frac{N(D^0 \to \pi^+\pi^-) - N(\overline{D^0} \to \pi^+\pi^-)}{N(D^0 \to \pi^+\pi^-) + N(\overline{D^0} \to \pi^+\pi^-)}$$

In the Standard Model these asymmetries should be close to zero





The quantity $\Delta A_{CP} = A_K - A_\pi$ is measured (since systematics largely cancel)

Based on 0.62 fb^{-1} (2011 data)

ΔA_{CP}=[-0.82±0.21(stat)±0.11(sys)]%

3.5σ different from zero

CP violation in charm - now with more data - 1 fb^{-1}

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

LHCb ΔA_{CP}= -0.34 ± 0.15 ± 0.10%

2240k $D^0 \to K^+K^-$, 690k $D^0 \to \pi^+\pi^-$ in 1fb^{-1} LHCb-CONF-2013-003

Previous: ΔA_{CP}= -0.82 ± 0.21 ± 0.11%

1440k $D^0 \to K^+K^-$, 380k $D^0 \to \pi^+\pi^-$ in 0.62fb^{-1} PRL108(2012)111602

- Add muon tag data

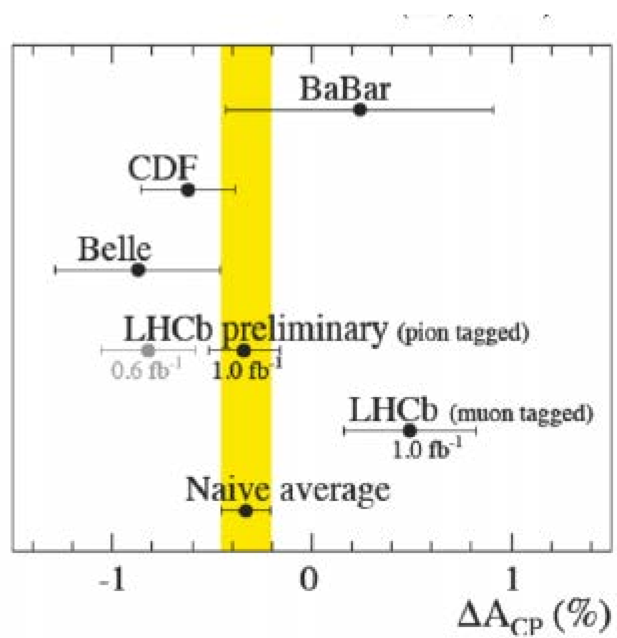
Tag from $\bar{B} \to D^0\mu^-$:

560k $D^0 \to K^+K^-$, 220k $D^0 \to \pi^+\pi^-$ in 1fb^{-1} PLB723(2013)33

Dedicated calibration of muon trigger charge asymmetry

ΔA_{CP} = +0.49 ± 0.30 ± 0.14%

LHCb D*+SL comb: ΔA_{CP} = -0.15 ± 0.16%



- Combination now consistent with zero CP violation

Summary and Outlook

- The LHCb experiment works spectacularly well

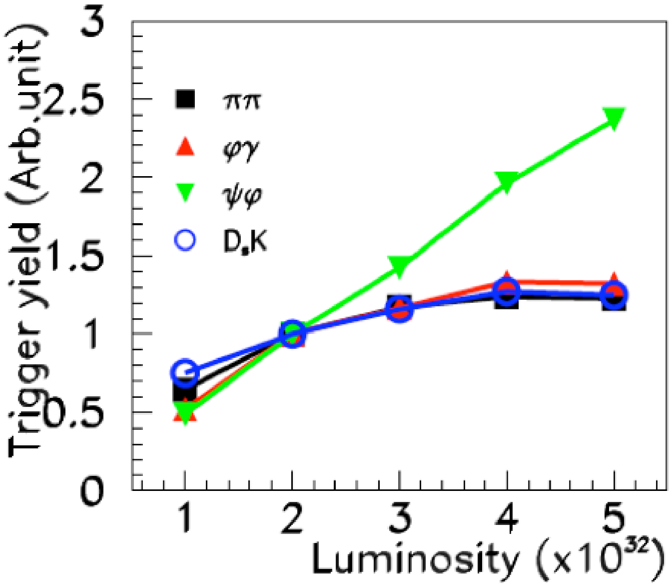
- So far all in good agreement with the Standard Model
  → New physics is becoming constrained in the flavour sector
  → Hints of new physics await more data.

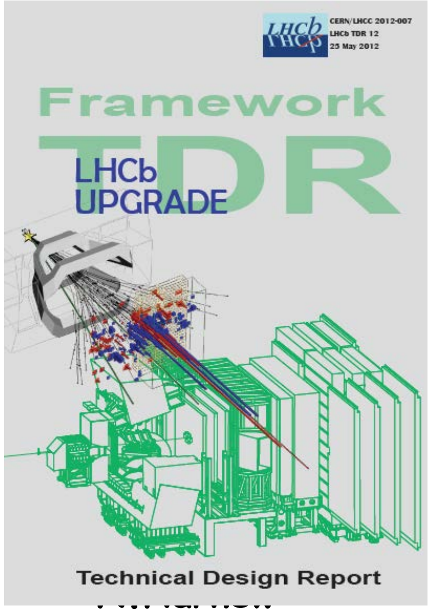
- Up to 2017 we expect 7-8 fb^{-1} of data in total, and much of this at ~double the current heavy-flavour production cross-section (since $\sqrt{s}$: 8→14 TeV)

- Still much room for new physics, higher precision required …

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}
- Framework TDR submitted to the LHCC: 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 %	~ 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}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [28, 29]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_sK)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	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}	–

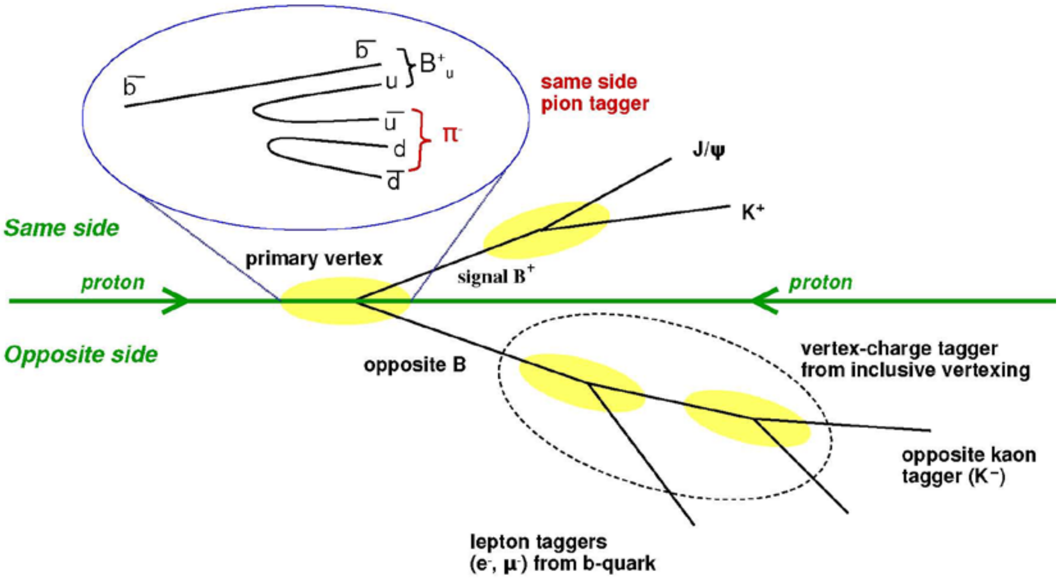
Spare slides from here on

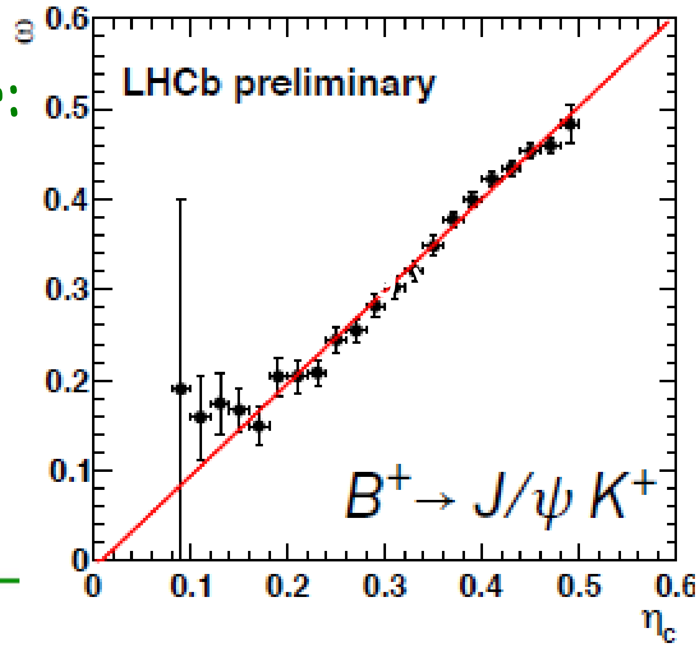
Flavour tagging

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

$$\varepsilon\,(1-w)^2 = (2.29 \pm 0.06 \pm 0.22)\%$$

LHCb-CONF-2012-026





The sign of $\Delta\Gamma_s$

PRL 108 (2012) 241801

- To resolve ambiguity
  $(\phi_s, \Delta\Gamma_s, \delta_{||}, \delta_\perp) \leftrightarrow (\pi-\phi_s, -\Delta\Gamma_s, 2\pi-\delta_{||}, -\delta_\perp)$
  study strong phase difference $\delta_{s\perp} = \delta_s - \delta_\perp$
  between K^+K^- P-wave and S-wave amplitudes
  as a function of $m(K^+K^-)$ around the $\phi(1020)$

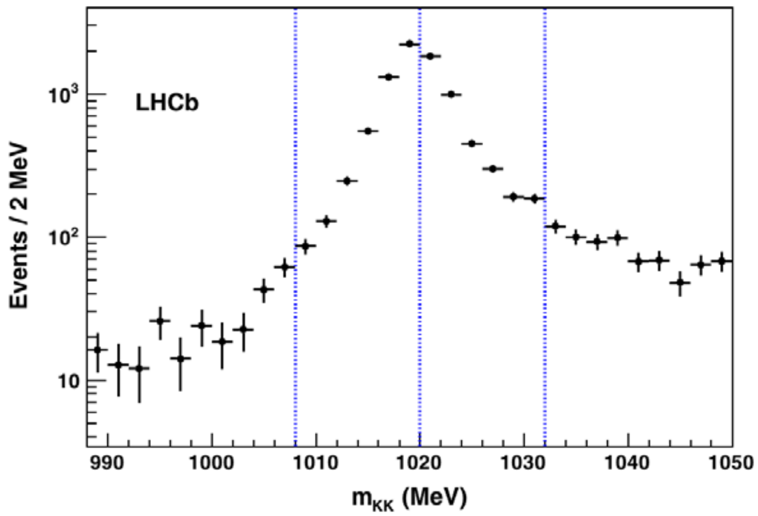
- P-wave: $\phi(1020)$, going through resonance
  $\rightarrow$ expect rapid positive phase shift

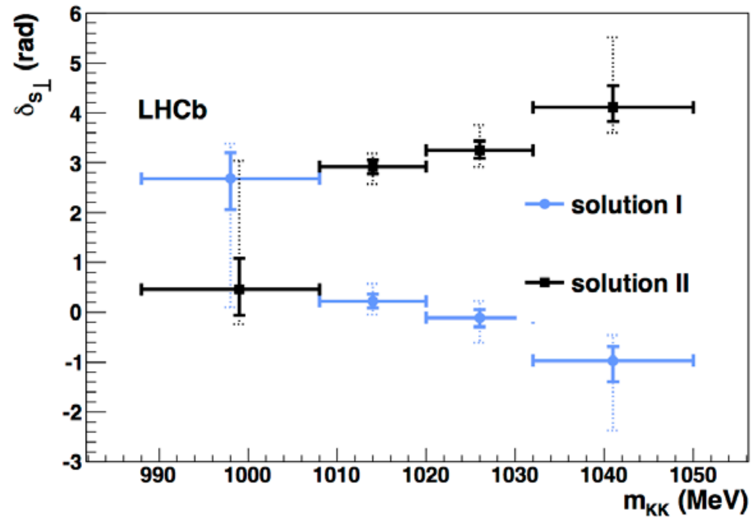
  - S-wave: non-resonant and tail from $f_0(980)$
    $\rightarrow$ expect no fast variation of phase

- Analysis based on 0.37 fb^{-1}

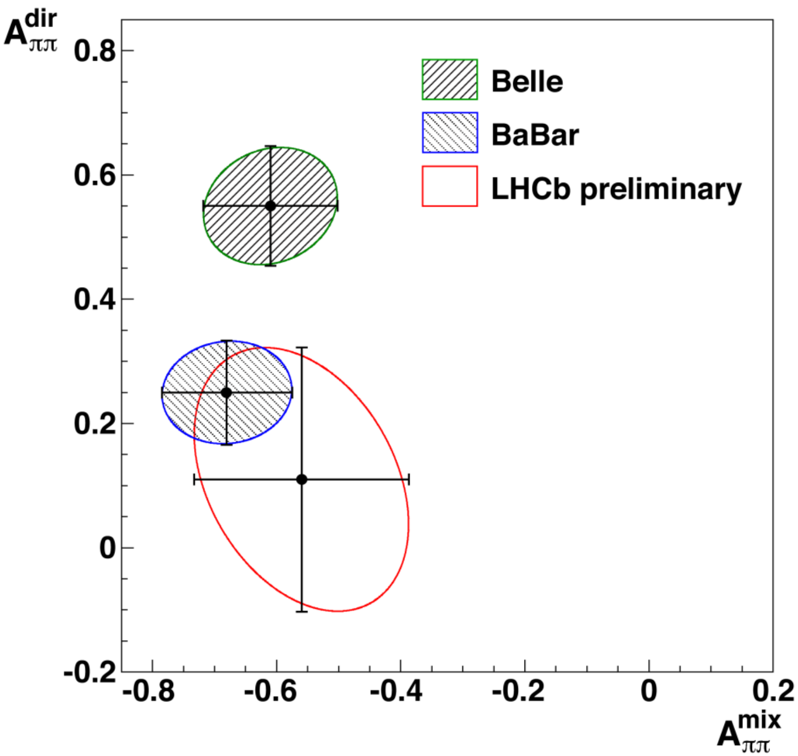
  - Determine $\delta_{s\perp}$ in four K^+K^- mass bins

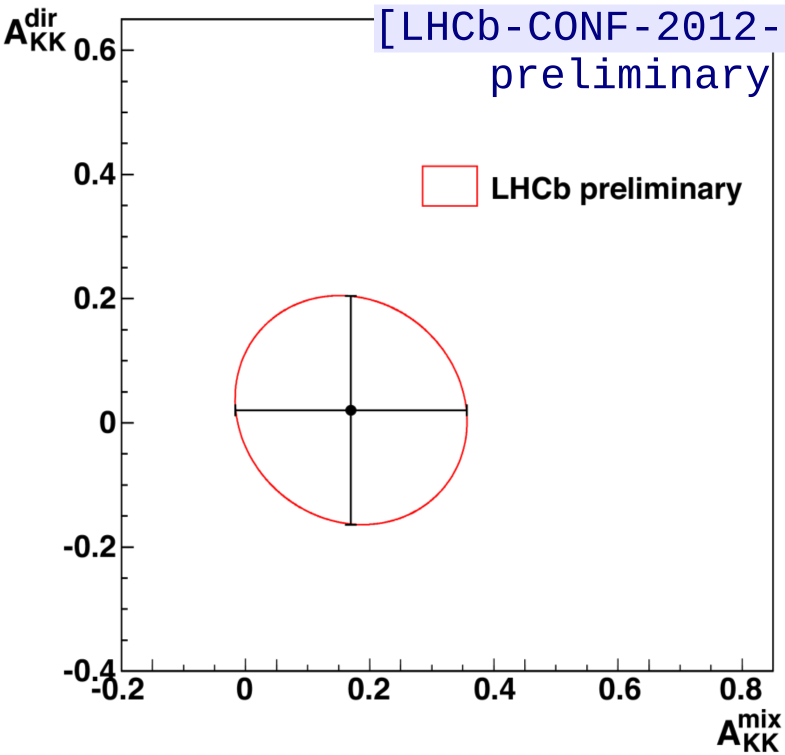
Solution corresponding to $\Delta\Gamma_s > 0$
preferred with 4.7σ significance





Time-dependent CPV in $B^0_{(s)} \to h^+h^-$





[LHCb-CONF-2012-007]
preliminary

$$A_{CP}(t) = \frac{\Gamma(\bar{B} \to f_{CP}) - \Gamma(B \to f_{CP})}{\Gamma(\bar{B} \to f_{CP}) + \Gamma(B \to f_{CP})}$$

$$A_{CP}(t) = \frac{A_{\rm dir}\cos(\Delta m t) + A_{\rm mix}\sin(\Delta m t)}{\cosh(\frac{\Delta\Gamma}{2}t) - A_{\Delta}\sinh(\frac{\Delta\Gamma}{2}t)}$$

$A^{dir}_{\pi\pi} = 0.11 \pm 0.21 \pm 0.03$

$A^{mix}_{\pi\pi} = -0.56 \pm 0.17 \pm 0.03$

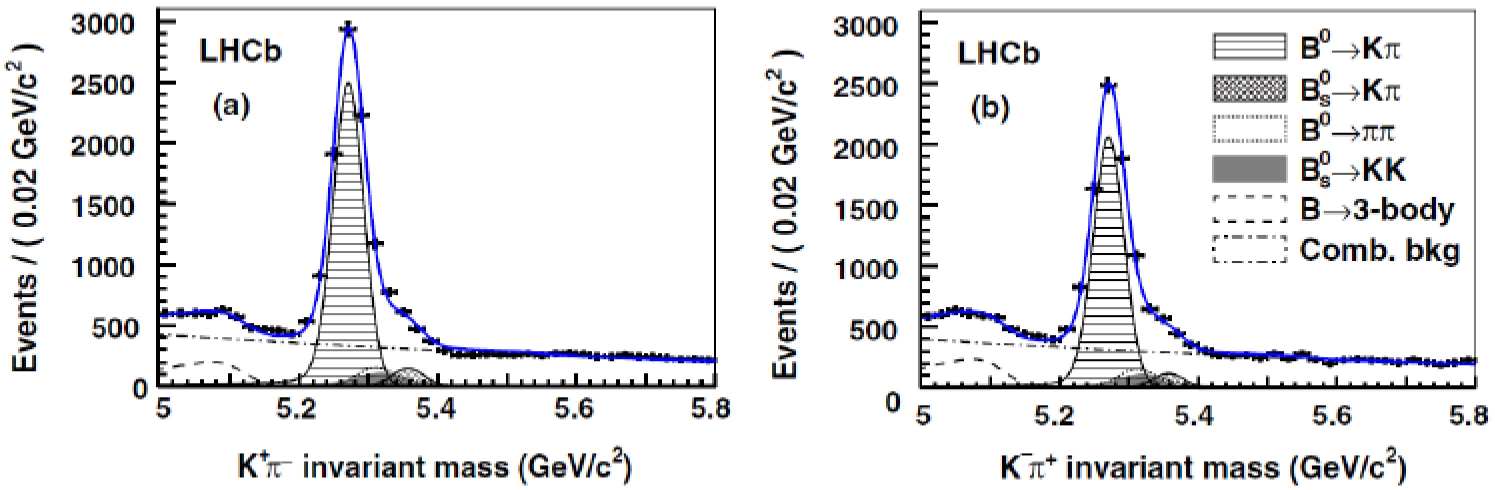
$A^{dir}_{KK} = 0.02 \pm 0.18 \pm 0.04$

$A^{mix}_{KK} = 0.17 \pm 0.18 \pm 0.05$

CP violation in B→Kπ and B_s→Kπ

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

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



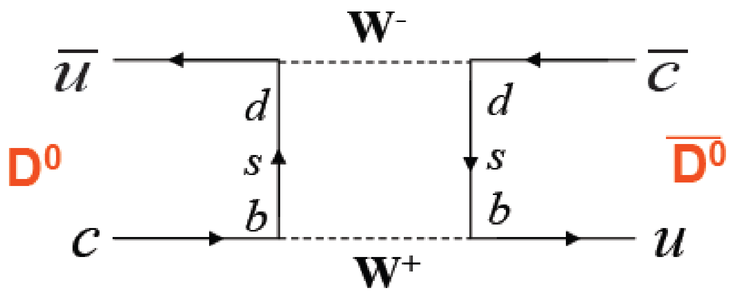
$$A_{CP}(B^0 \to K\pi) = -0.088 \pm 0.011(\text{stat}) \pm 0.008(\text{syst})$$

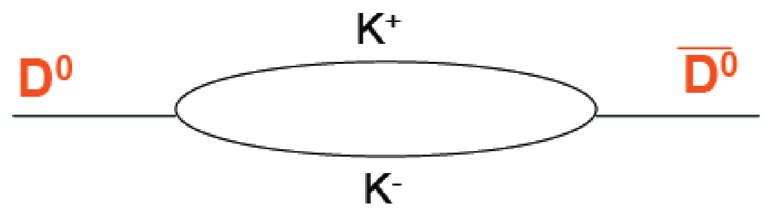
$$A_{CP}(B_s^0 \to K\pi) = 0.27 \pm 0.08(\text{stat}) \pm 0.02(\text{syst}).$$

most precise >6σ

first evidence 3.3σ

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:

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

the ratio of DCS to CF decay rates

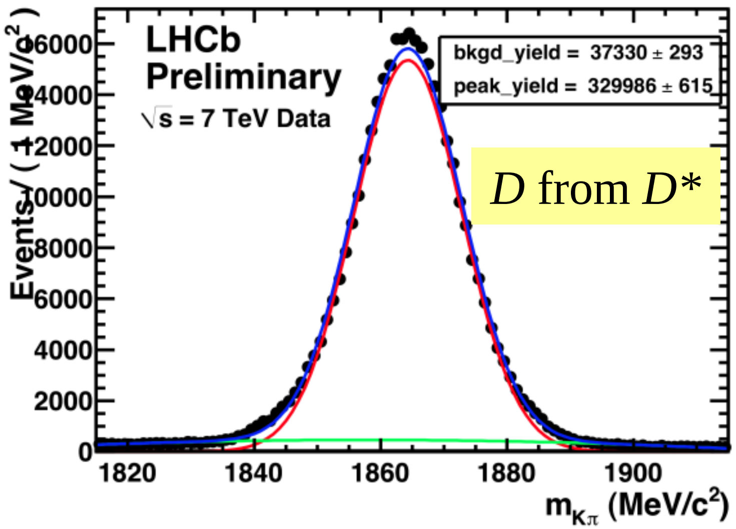
the interference of the DCS and mixed decays

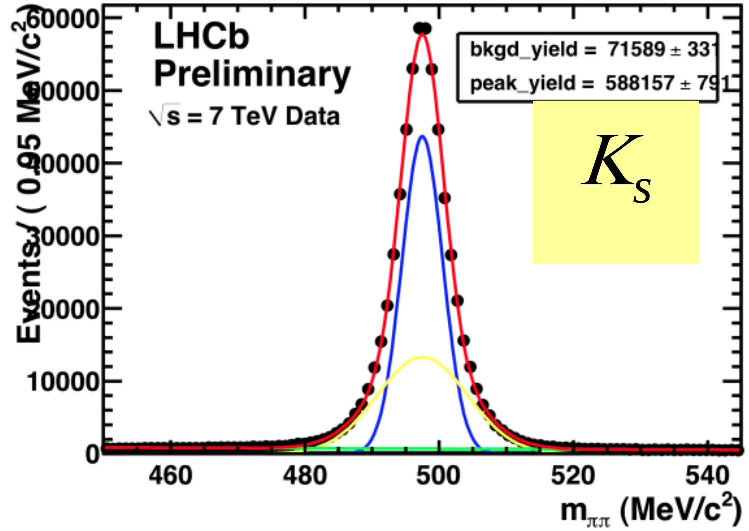
mixing parameters

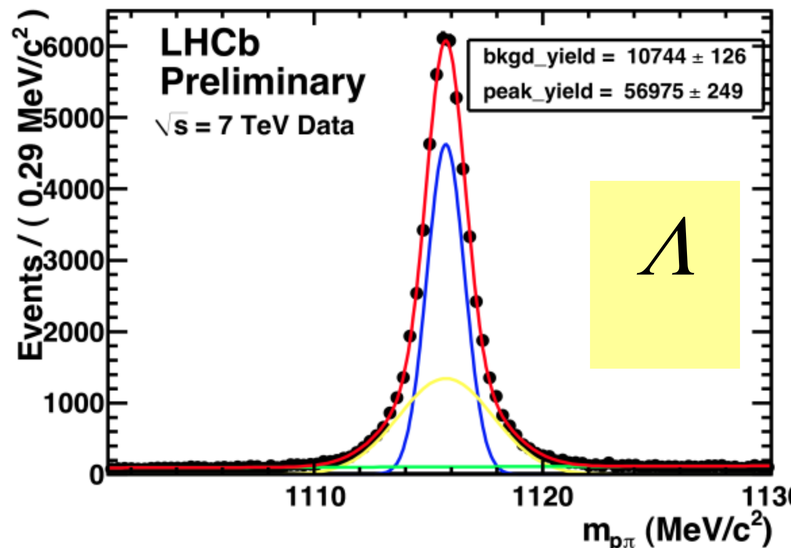
$$x' = x\cos\delta + y\sin\delta \qquad y' = y\cos\delta - x\sin\delta$$

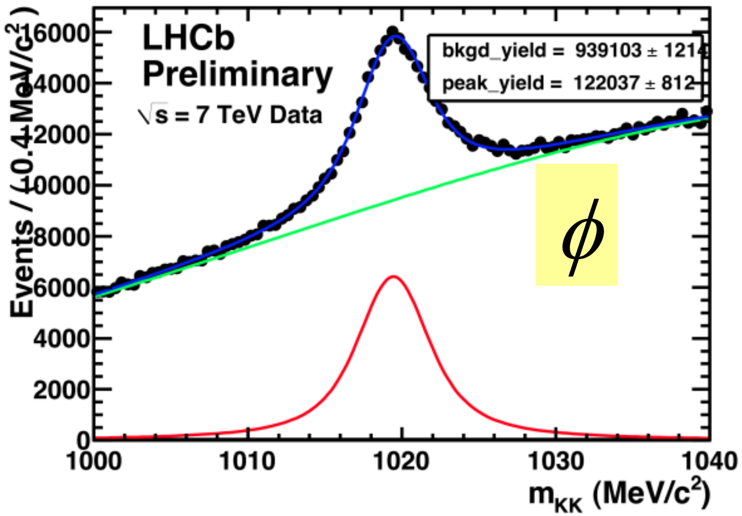
δ is a strong phase difference between DCS and CF amplitudes

PID calibration samples







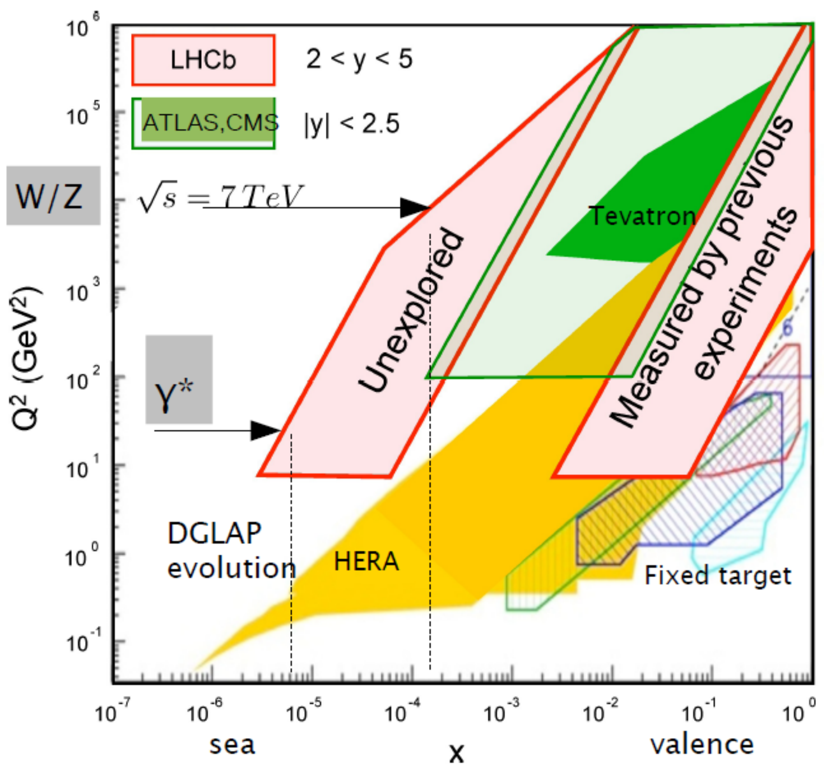


- Impressive calibration purity → samples allow PID calibrations in efficiency and purity to be evaluated with data

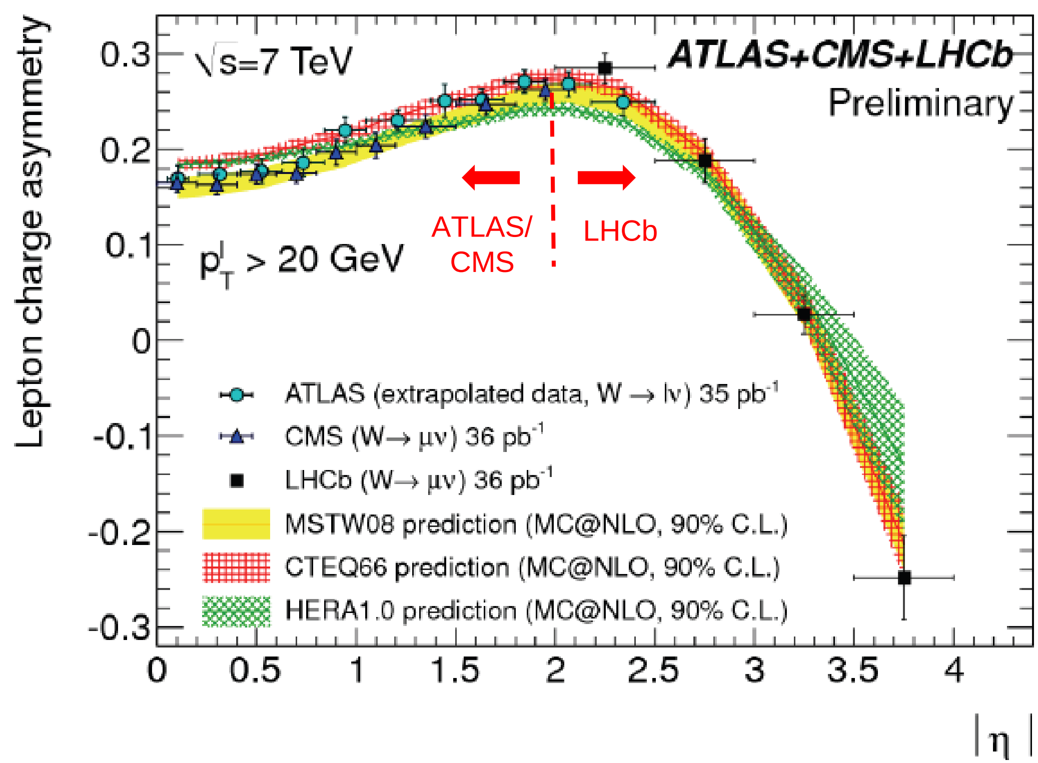
Away from flavour: W/Z production

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

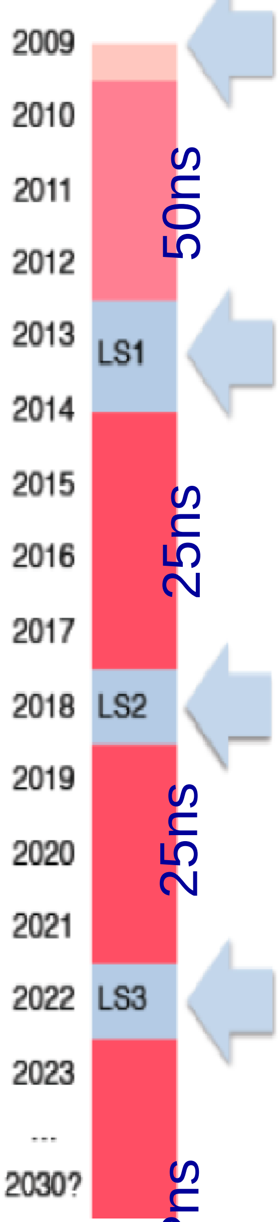
Unique kinematical acceptance



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



LHC(b) Long Term Plan



✧ LHC startup, √ s = 900 GeV

√ $\sqrt{s}$=7/8TeV; L_{LHCb}= 3-4x10^{32} $cm^{-2}s^{-1}$
→ ~1.5fb^{-1}/year

Go LHCb first infrastructure for Upgrade

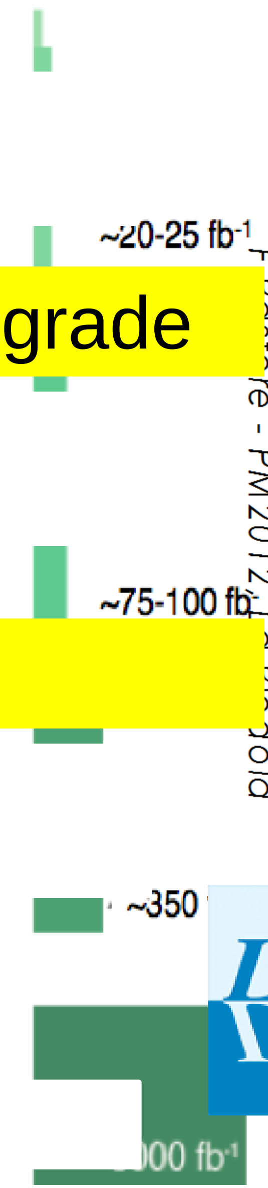
$\sqrt{s}$=13/14TeV; L_{LHCb}= 4x10^{32} $cm^{-2}s^{-1}$
√s → 1.5-2fb^{-1}/year

Inj LHCb Upgrade Installation

√ $\sqrt{s}$=14TeV; L_{LHCb}= 1-2x10^{33} $cm^{-2}s^{-1}$
→ >5fb^{-1}/year

HL-LHC Phase-2 upgrade, IR, crab cavities?

√ $\sqrt{s}$=14TeV; L_{LHCb}= ~2x10^{33} $cm^{-2}s^{-1}$



$\int L\,dt$

3/fb

5-7/fb

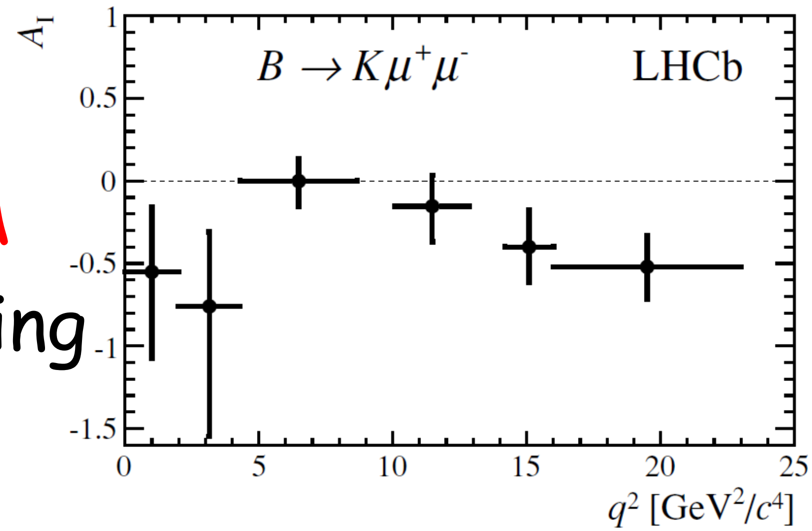
50/fb

Isospin asymmetry in $B^0 \rightarrow K^0\mu^+\mu^-$

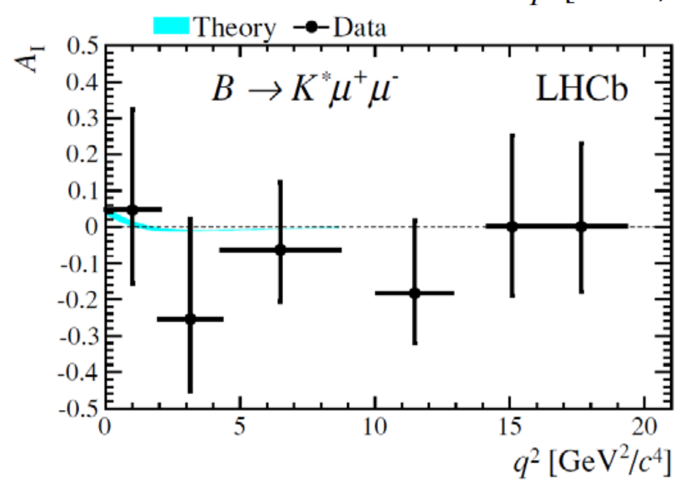
JHEP 7 (2012) 133

- 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 deviation emerging (4.6σ from zero). Requires further studies and better theoretical understanding
- No similar effects seen in $B\rightarrow K^*\mu^+\mu^-$



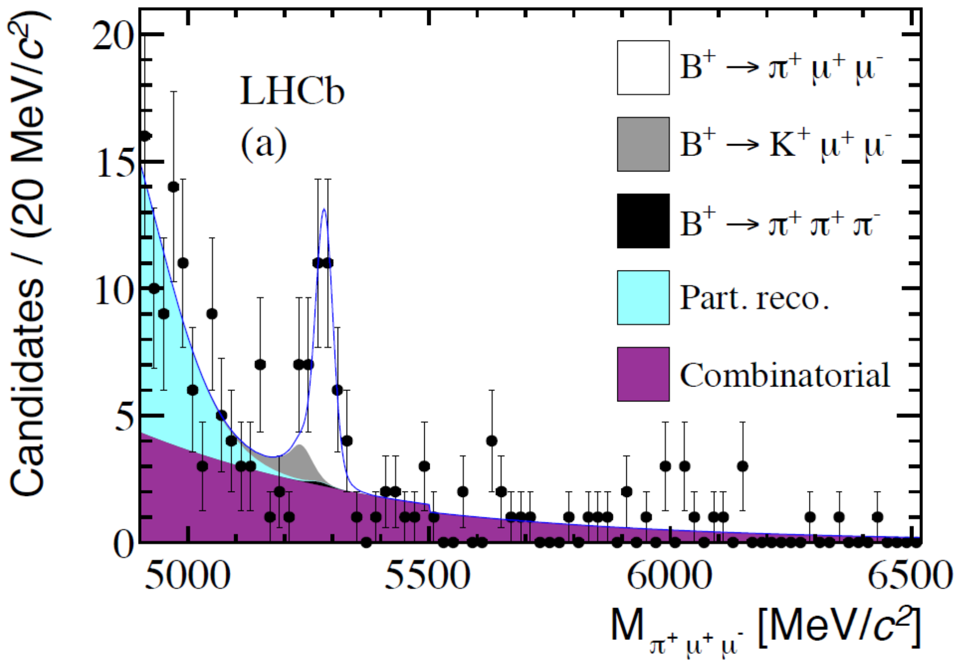
$B^+ \rightarrow \pi^+\mu^+\mu^-$ rare penguin decay

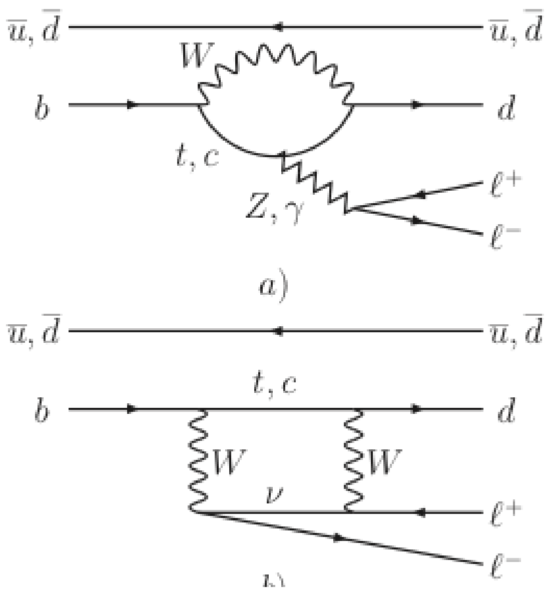
- $B^+ \rightarrow \pi^+\mu^+\mu^-$

  First observation – (rarest B decay ever observed that has >5σ significance)

arXiv: 1210.2645

25±6 events
5.2 σ significance





- SM prediction: $(2.0 \pm 0.2)\times10^{-8}$

  PRD77 (2008) 014017

- BR measured

  $(2.4\pm0.6\pm0.2)\ 10^{-8}$