Flavour Physics at the LHC

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On behalf of the LHCb collaboration

(showing also some results from ATLAS and CMS)

Outline

- **Exotic states.**
  - **Pentaquarks**
- **Rare decays.**
  - **$B_{(s)} \rightarrow \mu\mu$, $B \rightarrow K^{*}\mu\mu$, $B_s \rightarrow \phi\mu\mu$, $\Lambda_b \rightarrow \Lambda\,\mu\mu$.**
- **Tests of Lepton Universality.**
  - **$B \rightarrow D^{(*)} \tau\, \nu_{\tau}$ / $B \rightarrow D^{(*)}\, l\, \nu_{l}$; $B \rightarrow K^{+} l^{+} l^{-}$.**
- **CP Violation and the CKM unitarity triangle.**
  - **Angles γ, β; B_s mixing phase ϕ_s.**
  - **$|V_{ub}|$ from Λ_b decays.**
  - **B^0 meson mixing.**
  - **CP asym. in D decays.**
- **A few results at 13 TeV.**

(This is a short personal selection of many published results. Emphasis is made on measurements showing tension with SM predictions and recent results. Almost nothing shown on heavy flavour production.)

Introduction

The importance of Flavour Physics

- New Physics might be out of direct reach at the present LHC energy.
- Interference measurements have always been very sensitive to energy scales far away from the one directly accessible (prediction of third flavour generation, observation of gravitational waves….)
- Flavour Physics has a lot to do with measurements of interfering amplitudes and has sensitivity to mass scales well above the direct production scale.
- There is no room in the SM for the amount of CP violation needed to explain this matter-dominated Universe.
- Several measurements in Flavour Physics are coming out showing a significant tension with the Standard Model predictions.

Exotic states

Tetraquark and Pentaquark States

The possible existence of hadrons with more than the minimal quark content ($q\bar{q}$ or qqq) was already proposed by Gell-Mann and Zweig in their 1964 seminal papers.

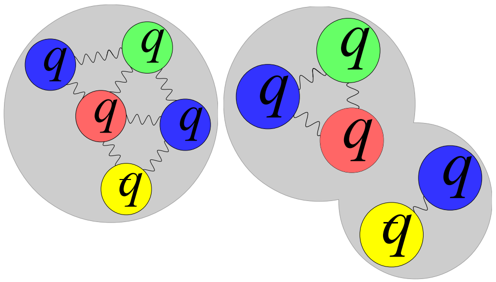
In the past years a number of possible **tetraquark** states have been reported to be found:

- **X states**, e.g. X(3872): neutral, usually seen in J/ψ + pions. $J^{PC} = 0^{++},1^{++},2^{++}$.
- **Y states**, e.g. Y(4260): neutral, seen in e^+e^- annihilation with Initial State Radiation, $J^{PC} = 1^{--}$.
- **Z states**, e.g. Z(4430): charged/neutral, typically positive parity.

Detailed structure still to be understood.

Non-conclusive evidence of **pentaquark** states in the past (see Eur. Phys. J. H 37, 1–31 (2012) for a review).

Several experiments claimed in 2003 evidence of a **$\Theta(1540)^+$** state with quantum numbers compatible with the quark content $uudd\bar{s}$. Evidence not confirmed by subsequent experiments.



five-quark bag

meson-baryon molecule

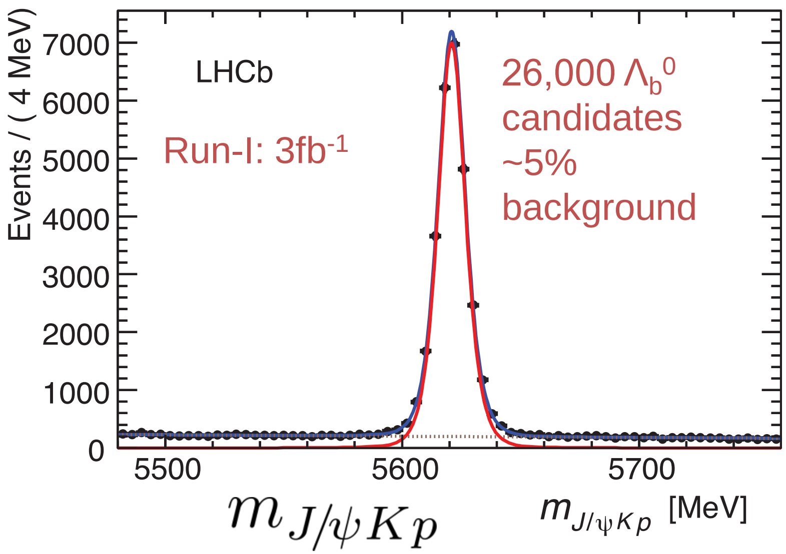
$J/\psi\, p$ resonances

PRL 115, 072001, (2015)

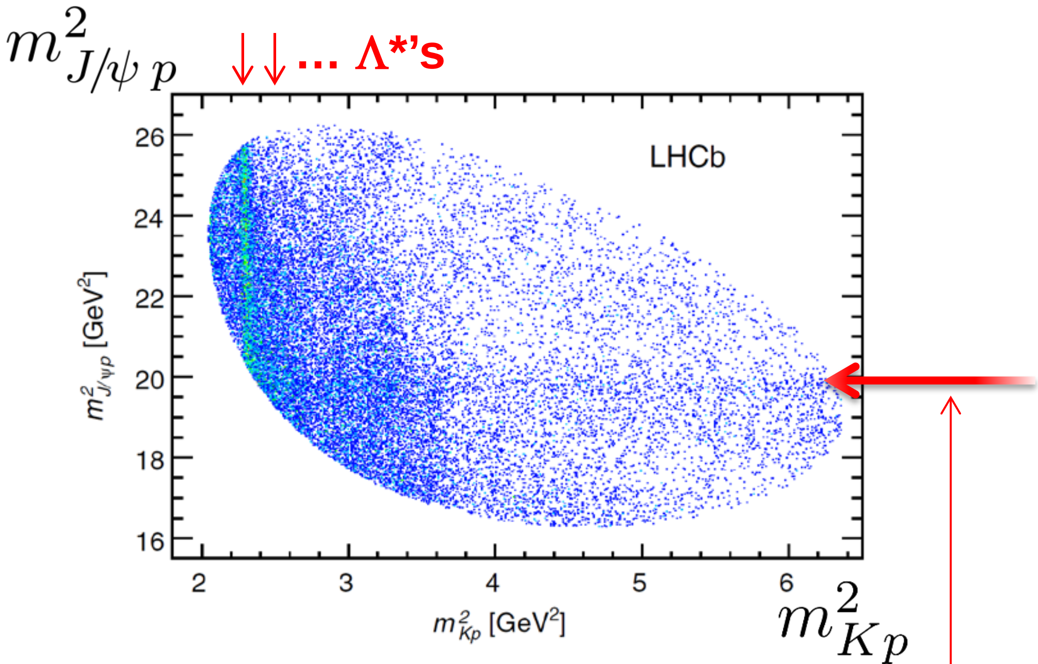
$\int \mathcal{L} = 3\ \mathrm{fb}^{-1}$

Observation of $J/\psi\, p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi\, K^- p$ decays

- Initial goal: precise measurement of the **Λ_b^0 lifetime** (PRL 111 (2013) 102003).
- But, looking closer to the J/ψpK Dalitz plot, **a surprising effect appeared**.



No structure in the **J/ψ Kp** mass spectrum

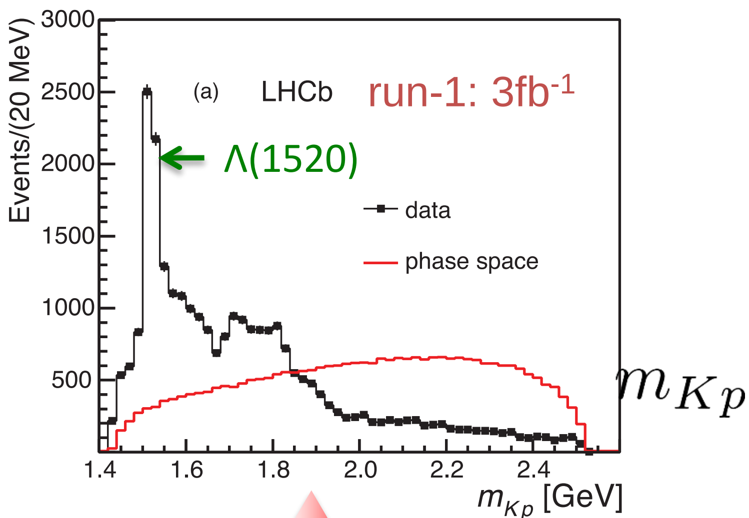


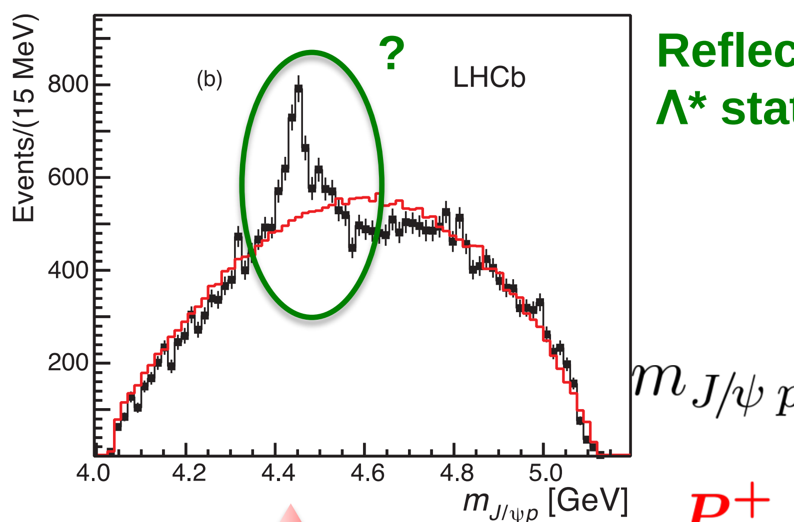
Unusual feature in the Dalitz plot

Projections

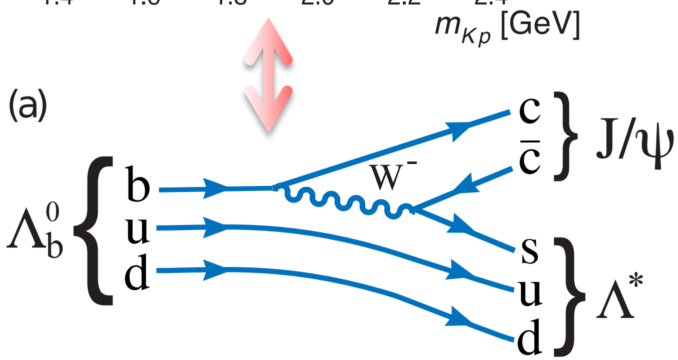
PRL 115, 072001, (2015)

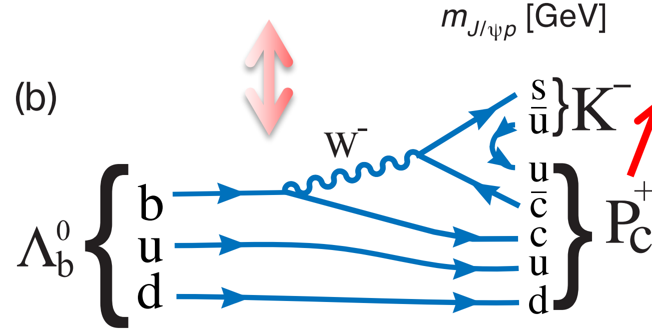
- Projections on Kp and J/ψp:
  - m(Kp): Rich structures due to Λ* states (Λ(1405), Λ(1520) …).
  - m(J/ψp): unexpected structure ~4.5 GeV/c^2.
- Phase space (simulation) shown for comparison.





Reflection from Λ* states?





$P_c^+ = c\bar{c}uud$?

charmonium-pentaquark

Does a qqqq$\bar{q}$ state exist ?

Matrix elements and models

PRL 115, 072001, (2015)

Pentaquarks expected as short-lived (~10^{-23} s) "resonances" whose presence is detected by mass peaks & angular distributions showing the presence of unique J^P quantum numbers.

Two interfering channels in a full amplitude analysis fit.

$$\left.\begin{bmatrix} \Lambda_b^0 \to J/\psi\,\Lambda^*, \quad \Lambda^* \to K^- p \\ \text{and} \\ \Lambda_b^0 \to P_c^+ K^-, \quad P_c^+ \to J/\psi\, p \end{bmatrix}\right\} \boldsymbol{\mu^+\mu^- K^- p}$$

Use m(Kp) and the 5 decay angles as fit parameters.

Resonance mass shapes: Breig-Wigner or Flattè.

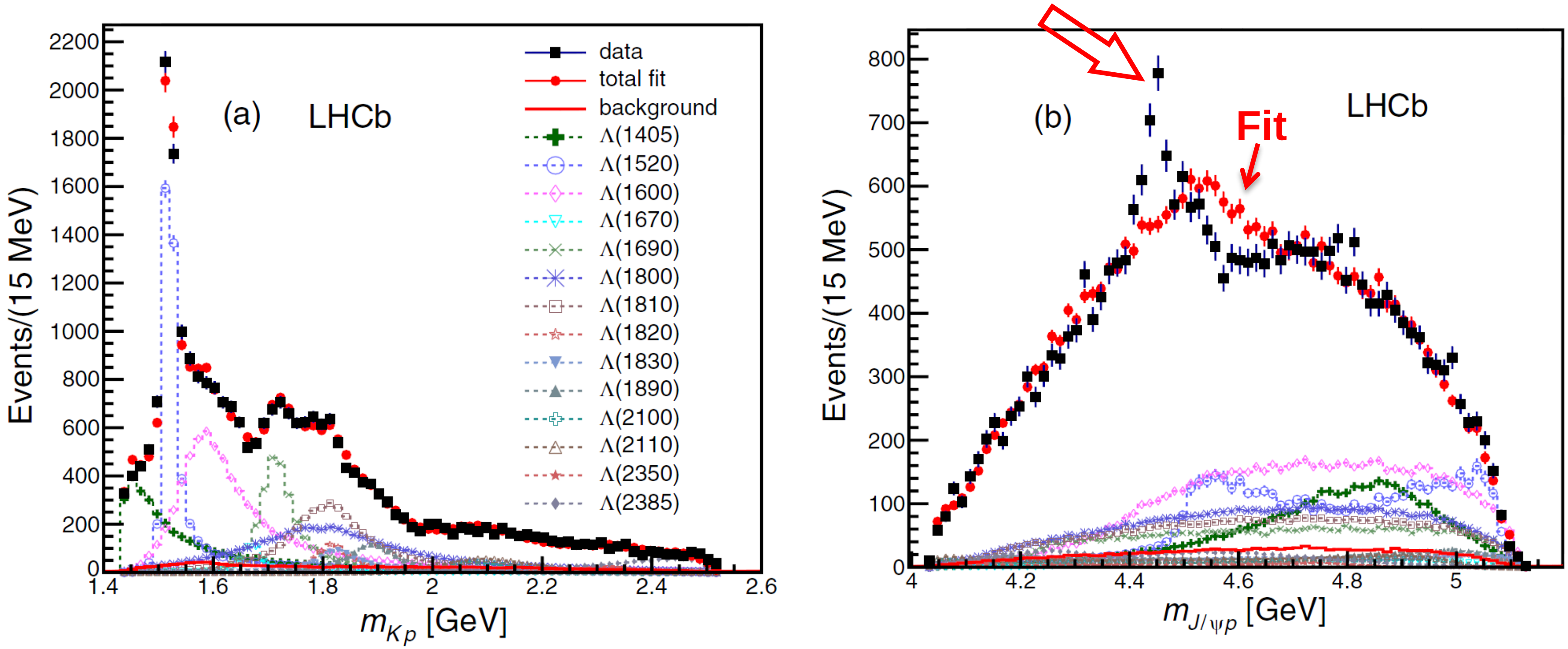
Two models used: **extended** and **reduced.**

State	J^P	M_0 (MeV)	Γ_0 (MeV)
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0
$\Lambda(1600)$	$1/2^+$	1600	150
$\Lambda(1670)$	$1/2^-$	1670	35
$\Lambda(1690)$	$3/2^-$	1690	60
$\Lambda(1800)$	$1/2^-$	1800	300
$\Lambda(1810)$	$1/2^+$	1810	150
$\Lambda(1820)$	$5/2^+$	1820	80
$\Lambda(1830)$	$5/2^-$	1830	95
$\Lambda(1890)$	$3/2^+$	1890	100
$\Lambda(2100)$	$7/2^-$	2100	200
$\Lambda(2110)$	$5/2^+$	2110	200
$\Lambda(2350)$	$9/2^+$	2350	150
$\Lambda(2585)$	?	$\approx$2585	200

Results without P_c states

PRL 115, 072001, (2015)

Model with all known Λ^* amplitudes (extended model).



$\mathbf{m_{Kp}}$ distribution looks fine

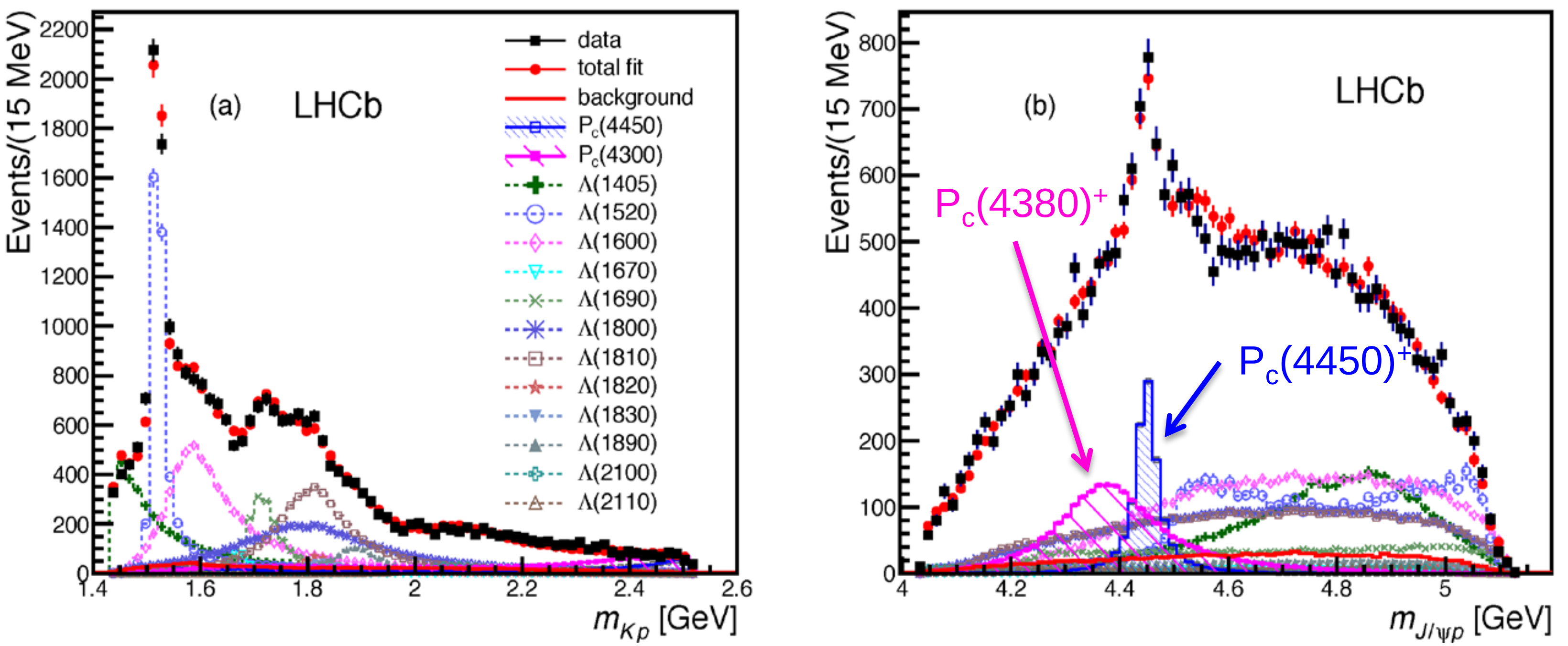
$\mathbf{m_{J/\psi p}}$ does **not** look fine

Additional non-resonant Kp components or extra Λ^* (with floating mass/width) does not improve the fit.

Results with 2 P_c states

PRL 115, 072001, (2015)

Model including **2 J/ψ p** resonances (floating mass and width).

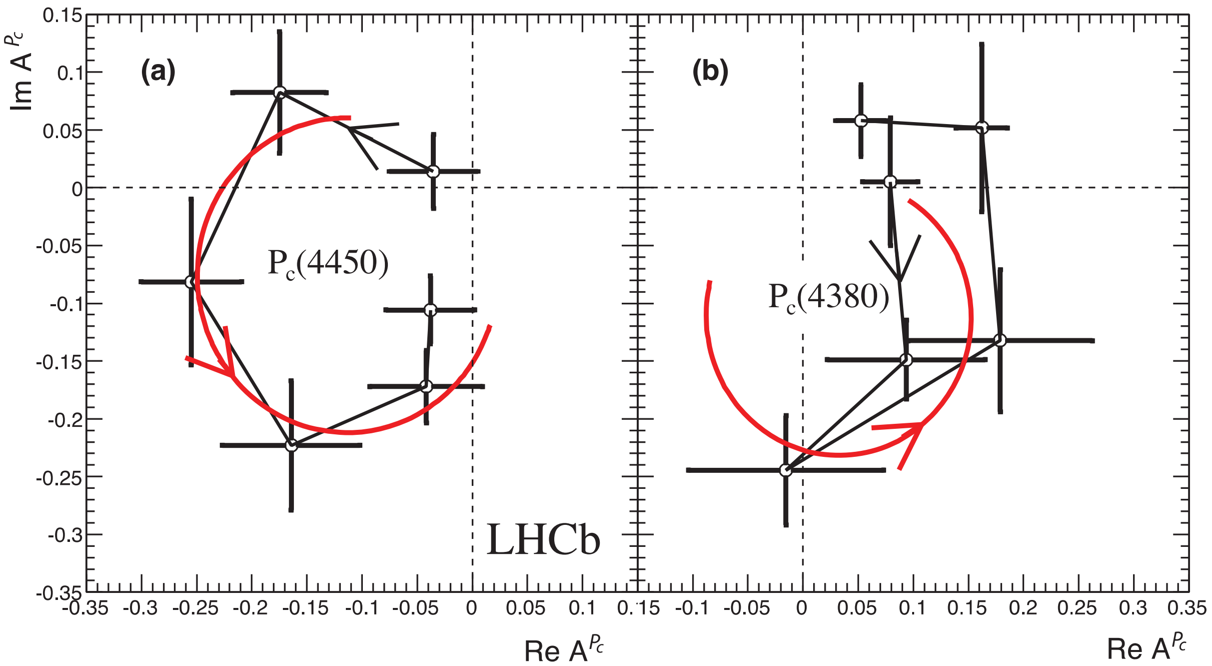


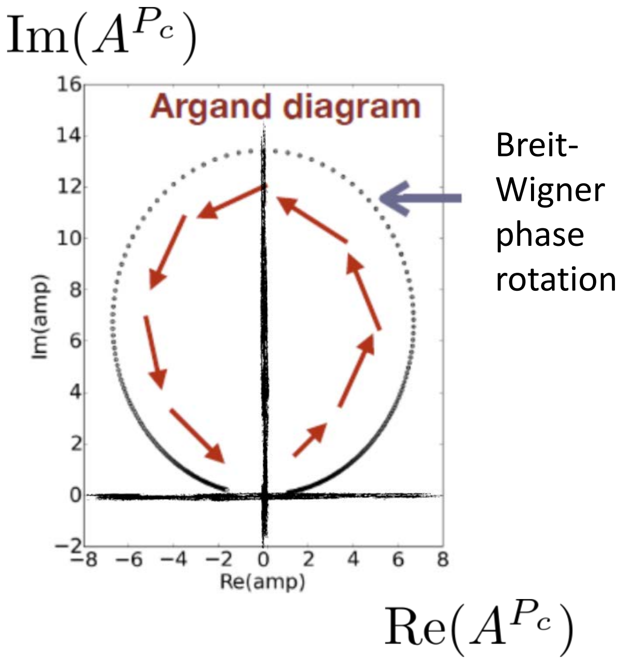
- Fit improves w.r.t fit with only one P_c by $\sqrt{\Delta 2 \ln \mathcal{L}} = 11.6\,\sigma$ (18.7σ w.r.t no P_c)
- Adding further states (also in J/ψK) does not improve the fit significantly.
- **Fit prefers two opposite-parity states**.
  - $P_c(4380)^+$: M = 4380 ± 8 ± 29 MeV/c^2, Γ = 205 ± 18 ± 86 MeV/c^2, $J^P = 3/2^-$. (8.4%)
  - $P_c(4450)^+$: M = 4449.8 ± 1.7 ± 2.5 MeV/c^2, Γ = 39 ± 5 ± 19 MeV/c^2, $J^P = 5/2^+$. (4.1%)

Argand diagrams

PRL 115, 072001, (2015)

The phase should vary with $m_{J/\psi\, p}$ according to a circle in the complex plane





- Significances evaluated through simulation: $S(P_c(4380)^+) = 9\sigma$, $S(P_c(4450)^+) = 12\sigma$.
- Many cross-checks done (particle misidentification, acceptance effects …)
- Spin-parity not conclusive: ($3/2^-$, $5/2^+$), ($3/2^+$, $5/2^-$), ($5/2^+$, $3/2^-$) all possible.

Important confirmation by other experiments

Model-indep. analysis of $\Lambda_b^0 \to J/\psi\, pK^-$

LHCb-PAPER-2016-009

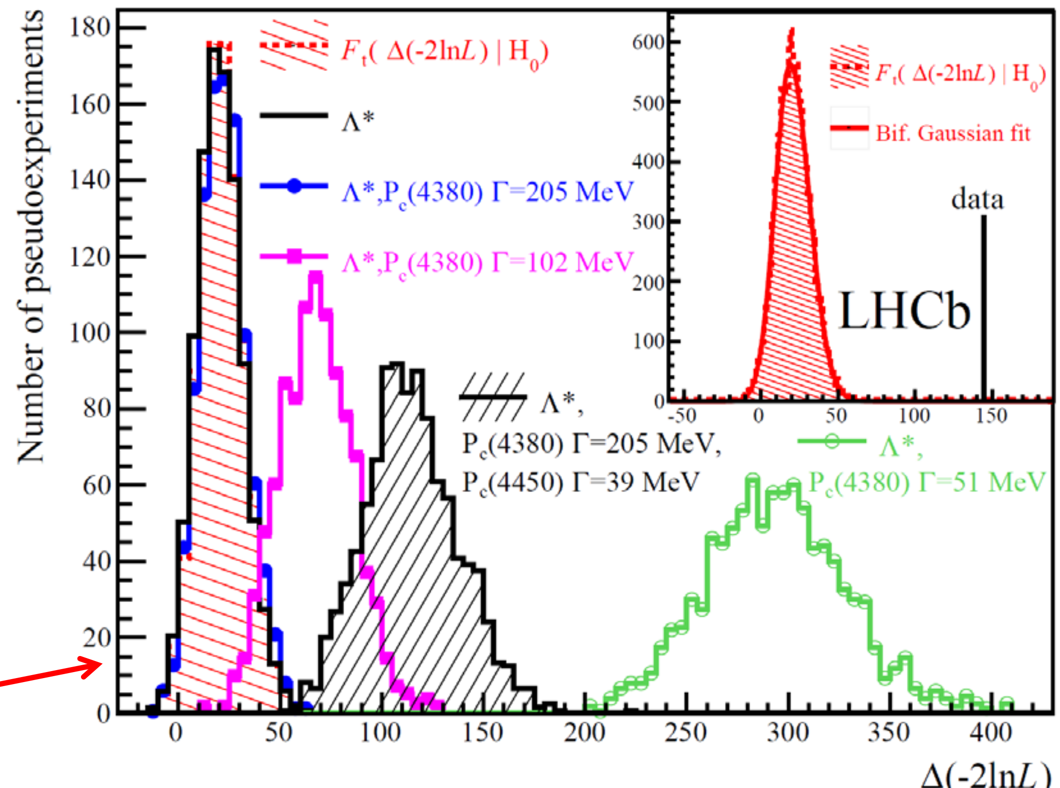
Assess the consistency of the data with the hypothesis that all $\Lambda_b \to J/\psi\, pK^-$ decays proceed via $\Lambda_b \to J/\psi\, \Lambda^*$, $\Lambda^* \to K^- p$ decays **(null (H_0) hypothesis)**

Minimal assumptions about the spin and mass structure of Λ^* contributions.

2D analysis based in the Dalitz variables $\mathbf{m_{Kp}}$ and $\mathbf{cos\theta_\Lambda}$ in a rectangular plane.

Expand the $\mathbf{cos\theta_\Lambda}$ angular distribution in terms of Legendre polinomials.

Generate high-stat toy data sets to simulate contributions from Λ^* and **Pc** states.



Distributions of Δ(-2ln L) in the H_0 model-independent pseudo-experiments (red hatched) compared to the distributions generated from various amplitude models. In the inset the vertical bar marks the value obtained for the data

Null (H_0) hypothesis) rejected with a significance of more than 9 σ.

$X(5568) \to B_s^0 \pi^\pm$?

arXiv:1602.07588

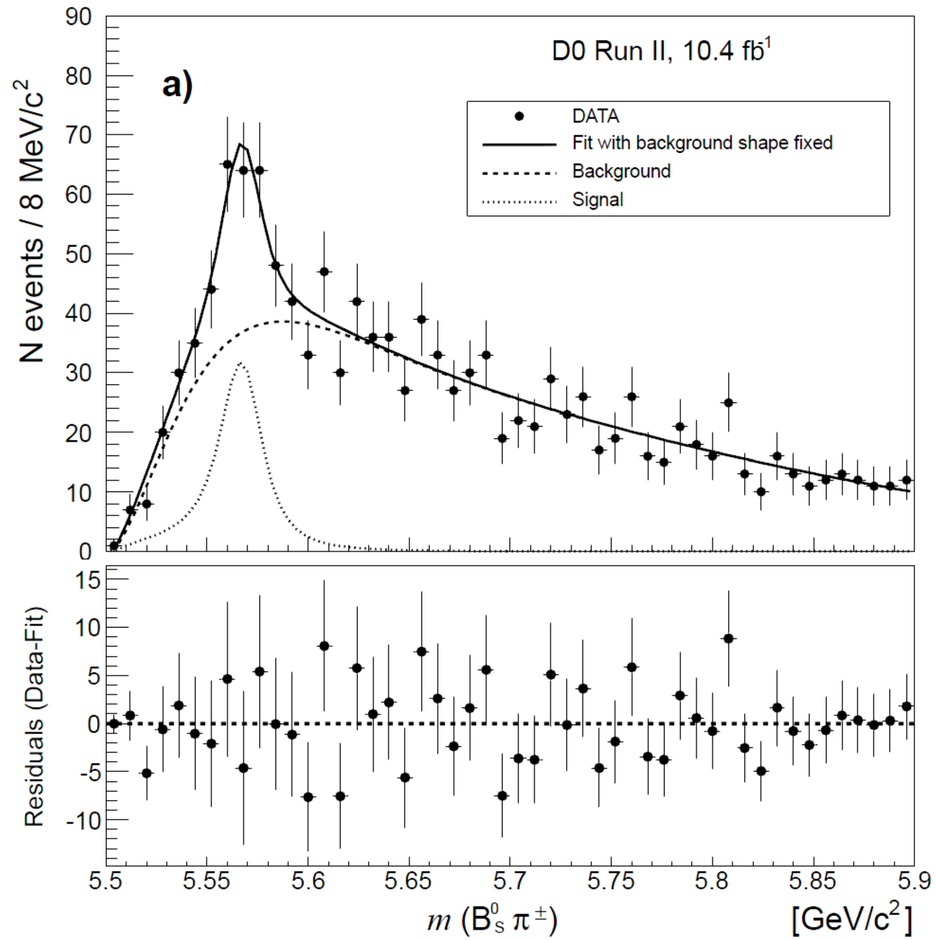
D0 reported on Feb 25, 2016, the observation (5.1 σ) of a narrow structure, possibly made up of a diquark-antidiquark pair.

$$m = 5678.8 \pm 2.9^{+0.9}_{-2.5}\ \mathrm{MeV}/c^2, \quad \Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}\ \mathrm{MeV}/c^2$$

The X(5568), if confirmed, would be of a different type of exotic hadron.

Constituent quarks with four different flavours (b, s, u , d) ?

Mass dominated by one constituent quark ?

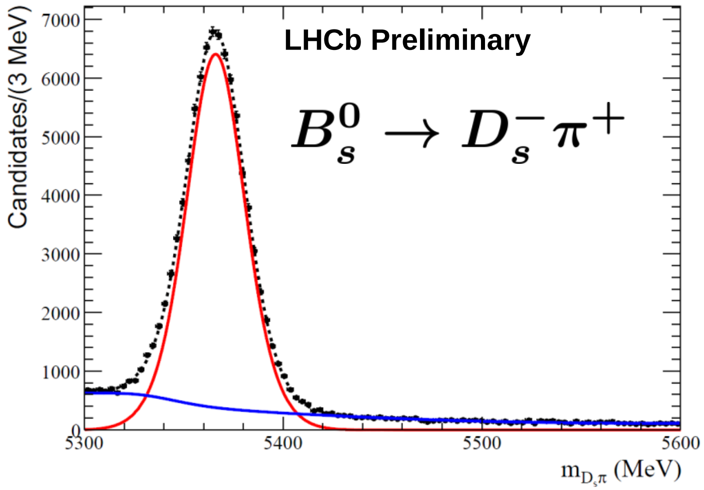


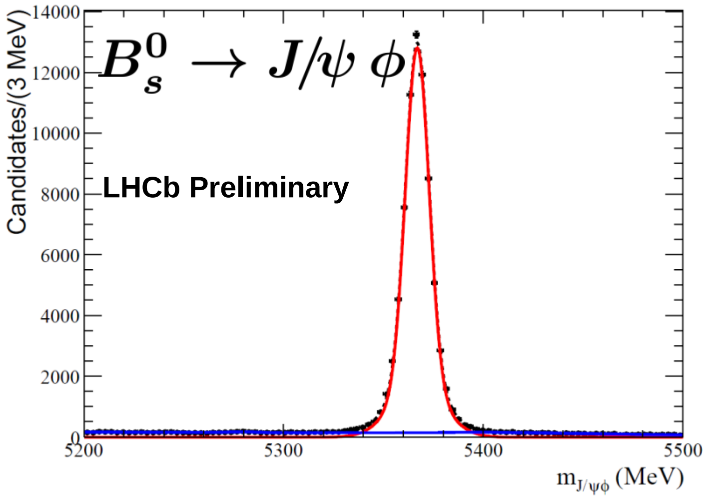
$X(5568) \to B_s^0\pi^\pm$?

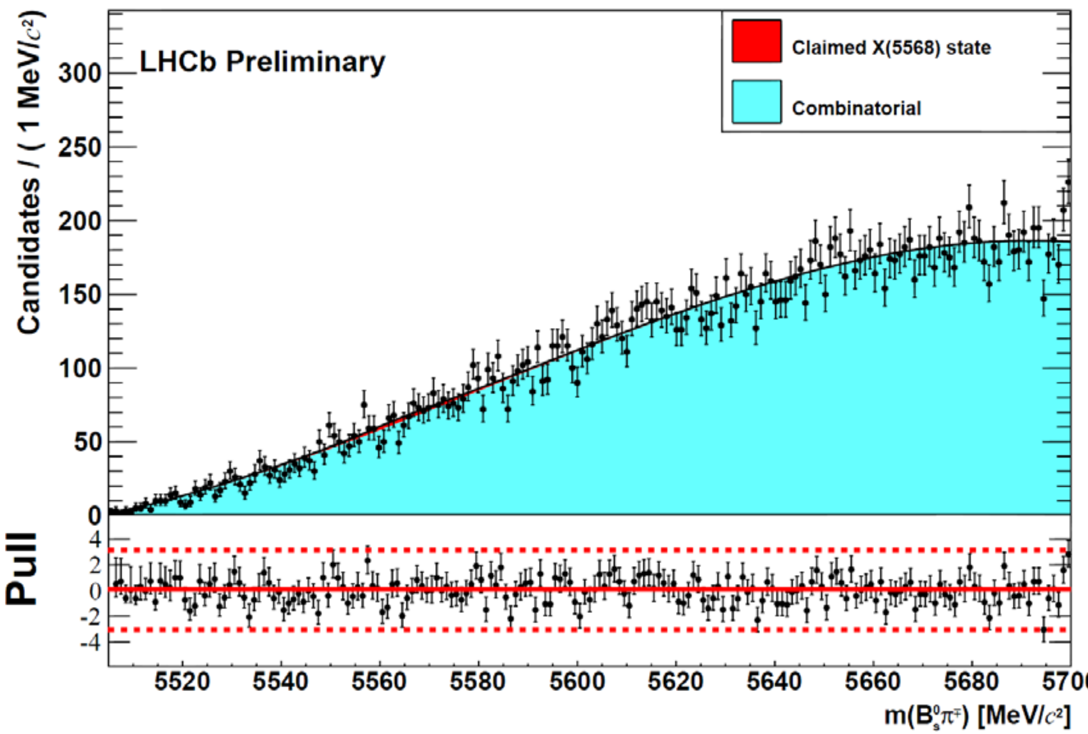
LHCb-CONF-2016-004

$\int \mathcal{L} = 3\ \mathrm{fb}^{-1}$

Very large samples of B_s mesons at LHCb (a factor 20 larger than in D0).
Add a pion and study the mass spectrum. Full Run-I statistics used (3 fb^{-1}).







No peak observed at 5568 MeV.

$X(5568) \to B_s^0 \pi^\pm$?

LHCb-CONF-2016-004

Upper limits (preliminary):

Measure the ratio of cross-sections for promptly produced particles within the LHCb acceptance

$$\rho_X^{\mathrm{LHCb}} \equiv \frac{\sigma(pp \to X(5568) + \text{anything}) \times \mathcal{B}(X(5568) \to B_s^0 \pi^\pm)}{\sigma(pp \to B_s^0 + \text{anything})}$$

The upper limits are found to be:

$$\begin{aligned}
\rho_X^{\mathrm{LHCb}}(B_s^0\ p_{\mathrm{T}} > 5\,\mathrm{GeV}/c) &< 0.009\,(0.010)\ @\ 90\,(95)\,\%\ \mathrm{CL} \\
\rho_X^{\mathrm{LHCb}}(B_s^0\ p_{\mathrm{T}} > 10\,\mathrm{GeV}/c) &< 0.016\,(0.018)\ @\ 90\,(95)\,\%\ \mathrm{CL}
\end{aligned}$$

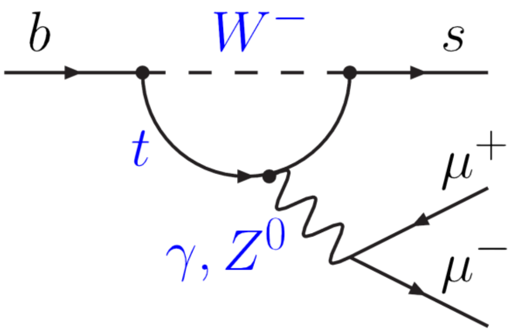
LHCb does not confirm the existence of X(5568)

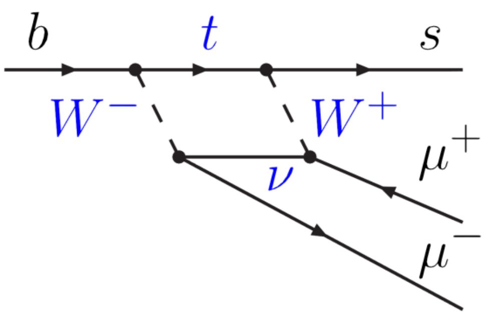
Rare decays

FCNC processes

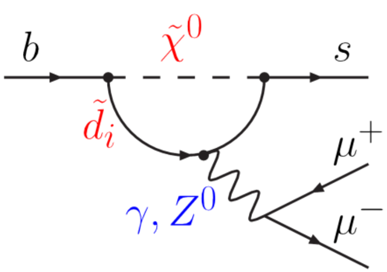
Flavour Changing Neutral Current (FCNC) transitions can only proceed in the SM through loop (and higher order) diagrams.

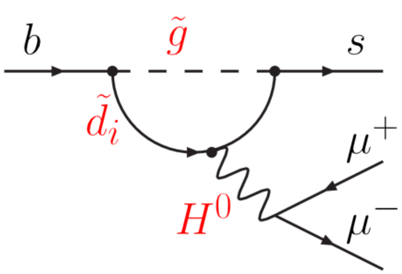
Examples of SM loop diagrams involving charge currents

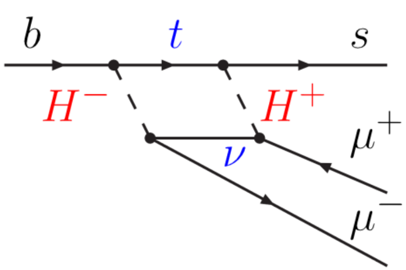


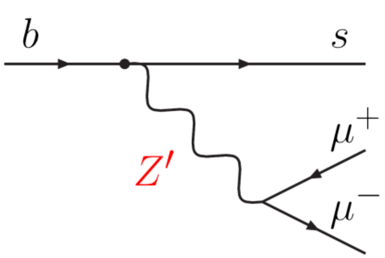


New particles could contribute at tree or loop level, introducing interfering effects and modifying decay rates, angular distributions, CPV observables, etc.









Effective Field Theory

QCD effects in B decays very difficult to compute.

Effective Hamiltonians parametrize the low-energy effects of "any" full theory. Very suitable for the inclusion of possible NP effects.

Describe B decays with an effective Hamiltonian, $\langle F|\mathcal{H}_{\text{eff}}|B\rangle$.

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{tq}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

Wilson coefficients, $\mathcal{C}_i$, computed perturbatively in terms of fundamental couplings (SM and beyond). They describe the short-distance contributions.

Matrix elements, $\langle F|\mathcal{O}_i|B\rangle$, contain long-distance (non-perturbative) contributions. Use lattice calculations, QCD sum rules, $1/N$ expansion, chiral perturbation theory, etc. They are the source of the dominant theoretical uncertainties.

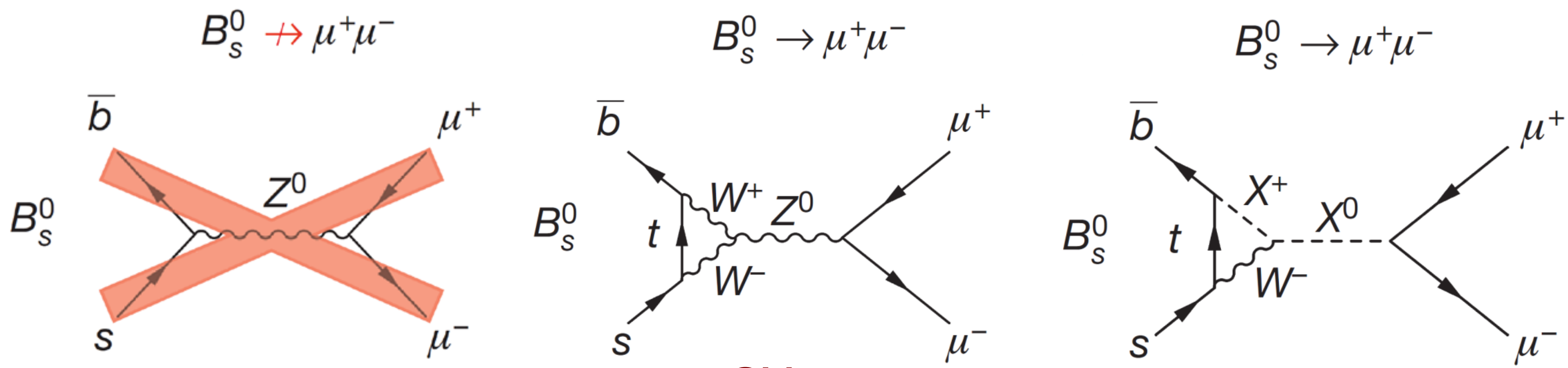
Relevant coefficients for rare decays:

Electromagnetic $\mathcal{C}_7$; Semileptonic $\mathcal{C}_{9,10}$; Scalar/Pseudoscalar $\mathcal{C}_{S,P}$ and their chirally-flipped counterparts: $\mathcal{C}_{7',9',10',S',P'}$

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

Nature 522 (2015) 68

- $B_{(s)}^0 \rightarrow \mu^+\mu^-$: very rare decays (→ very small branching ratio).
  - Flavour changing neutral current (FCNC) process forbidden in the Standard Model.
  - It can proceed through loops. Helicity suppressed. CKM suppressed.



SM

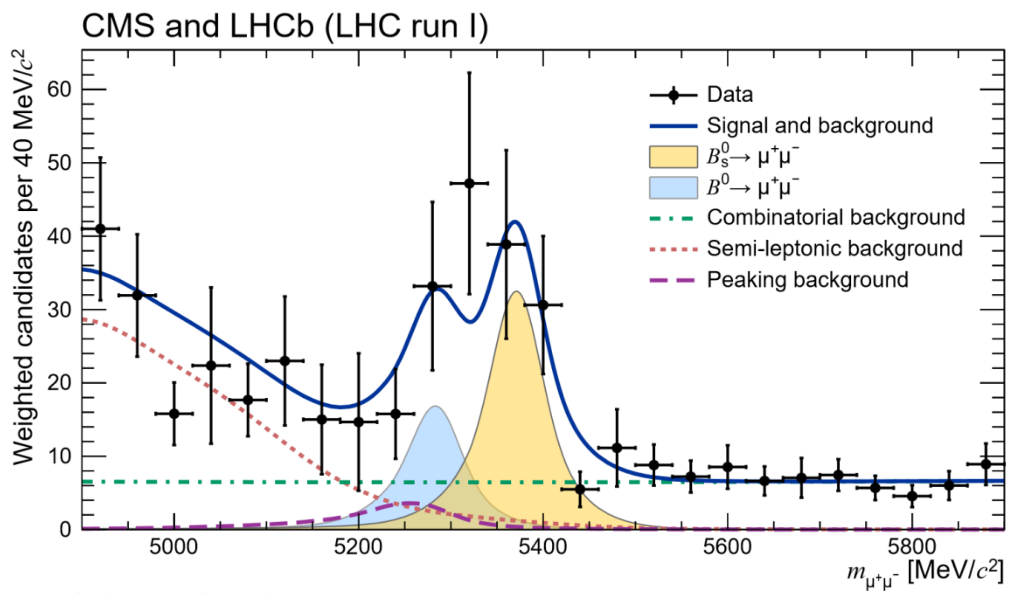
New physics

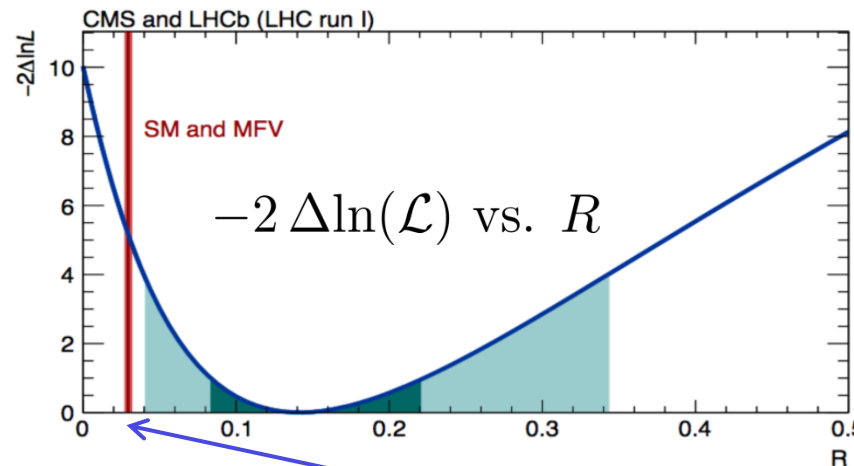
- Branching ratios predicted with high accuracy:
  - $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)^{SM} = (3.66 \pm 0.23) \times 10^{-9}$
  - $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)^{SM} = (1.06 \pm 0.09) \times 10^{-10}$
  - $\mathcal{B}(B_{(s)}^0 \rightarrow \mu^+\mu^-)^{MSSM} \sim \tan^6\beta/M^4$ (tan(β) is the ratio of neutral Higgs vev)

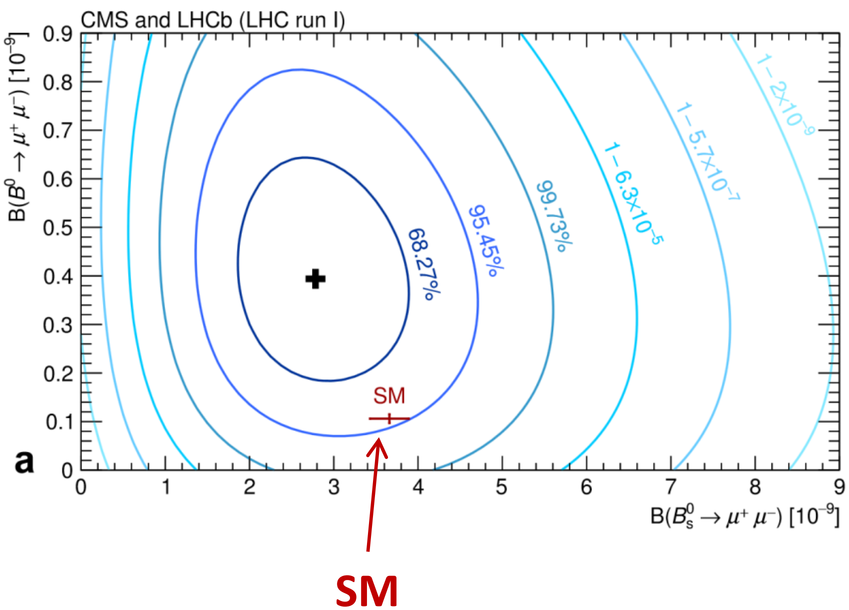
- Measurement of those branching ratios probe different new physics scenarios.

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

Nature 522 (2015) 68







$$\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B^0_s\to\mu^+\mu^-)} = 0.14^{+0.08}_{-0.06}\ (2.3\sigma)\ \text{from SM}$$

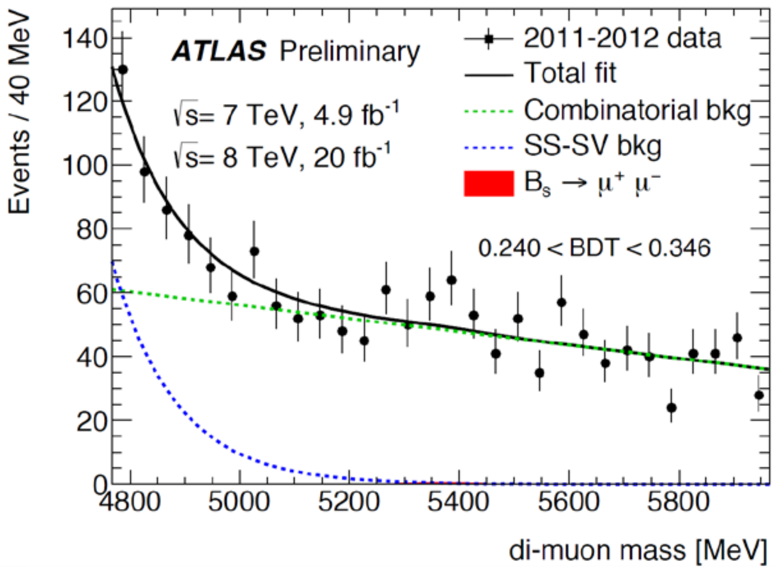
First observation (stat)

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

First evidence (stat)

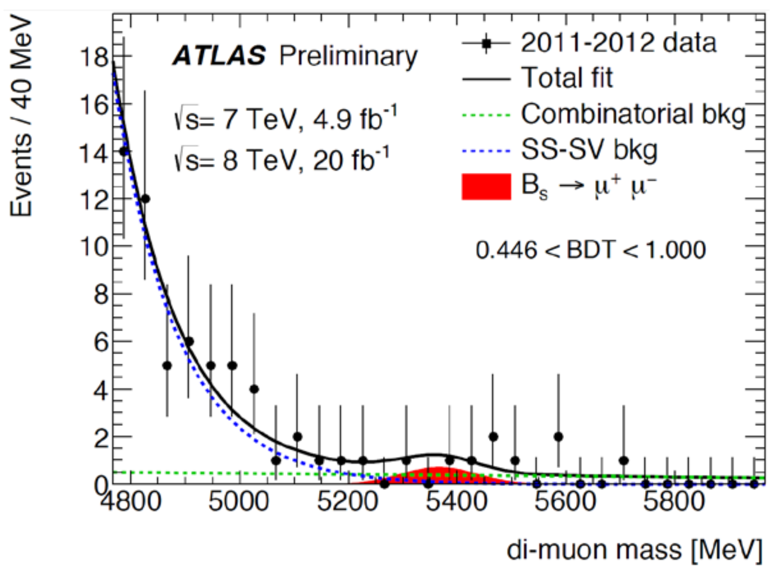
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10},\ (3.2\sigma)$$

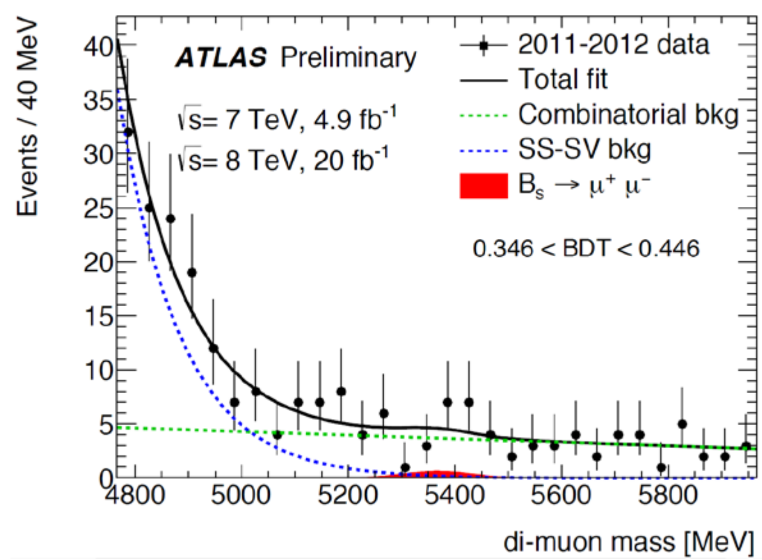
$B^0_{(s)} \to \mu^+\mu^-$

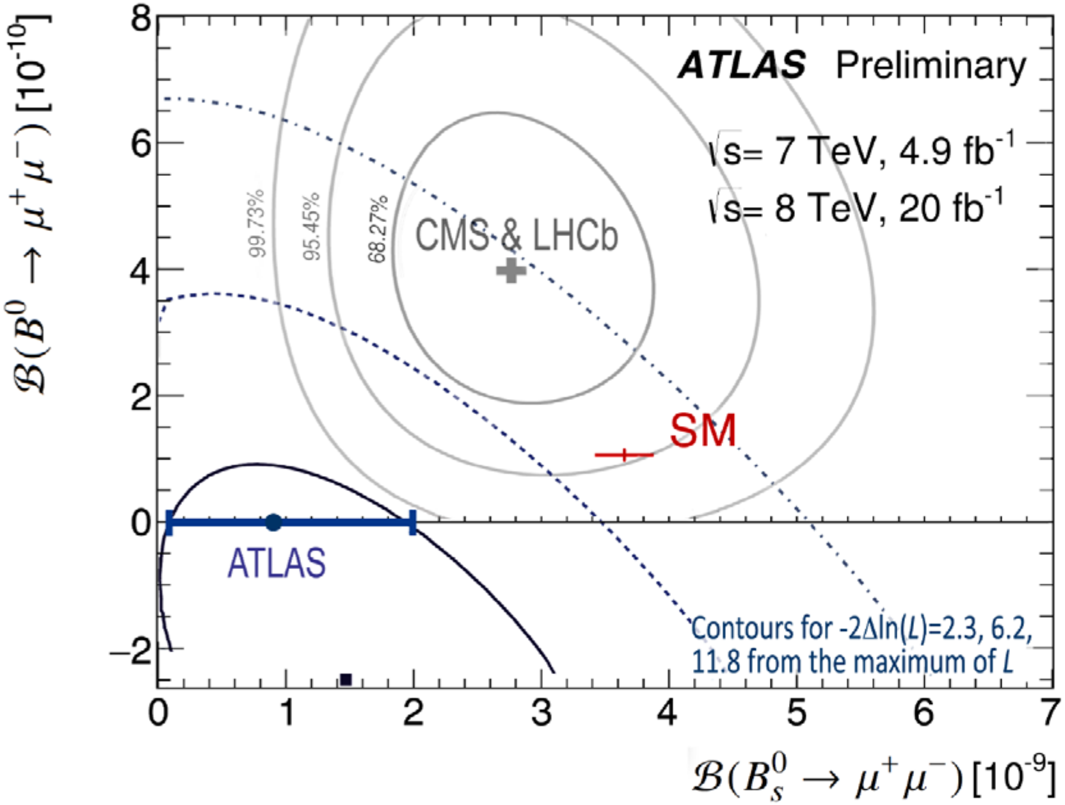


ATLAS new results shown by S. Palestini in Moriond EW 2016, from RUN-I data

Fewer B_s events than expected and no B^0 event







$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 0.9^{+1.1}_{-0.8} \times 10^{-9}$
$< 3.0 \times 10^{-9}$ at 95% CL

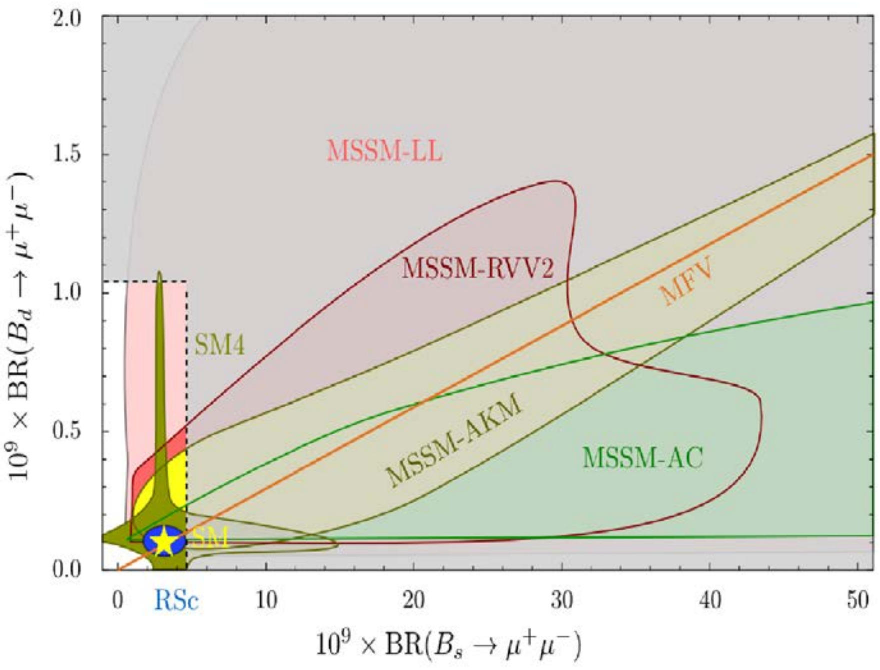
Lower than the SM prediction and also lower than the CMS-LHCb combination.

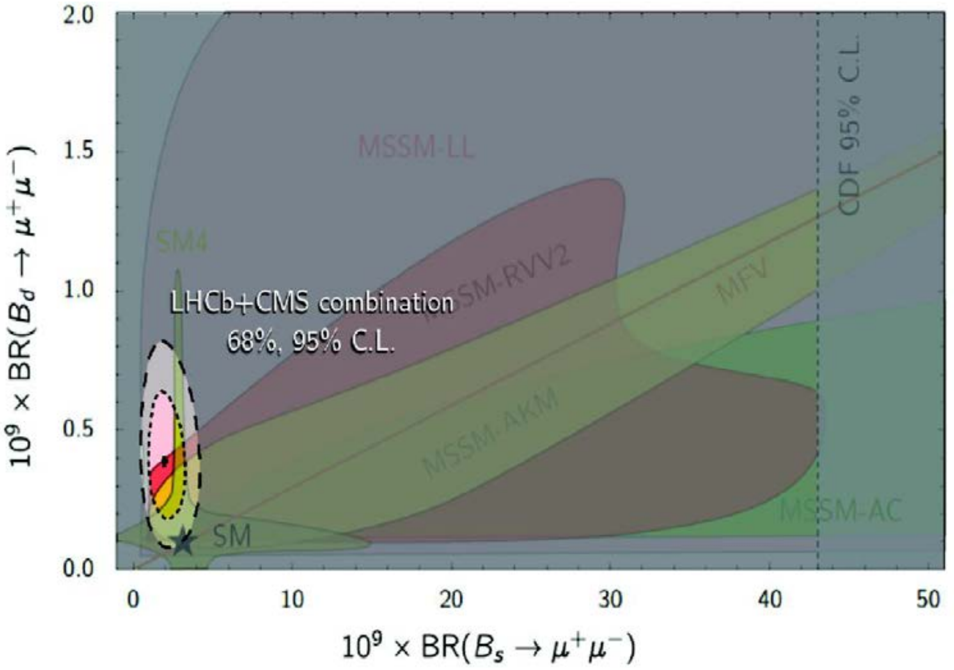
$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10}$
at 95% CL

Limit above the SM prediction and reaches the central value of the CMS-LHCb combination

The compatibility with the SM, for the simultaneous fit, is **2.0 σ**.

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





SM4: SM with sequential fourth generation.
MSSM with left-handed currents only (**MSSM-LL**)
Ross, Velasco, Sevilla and Vives (**MSSM-RVV2**)
Antusch, King and Malinksy (**MSSM-AKM**)
RSc: Randall-Sundrum with custodial protection
Agashe and Carone (**MSSM-AC**)

Figures taken from O. Leroy and modified from D. Straub, arXive:1205.6094

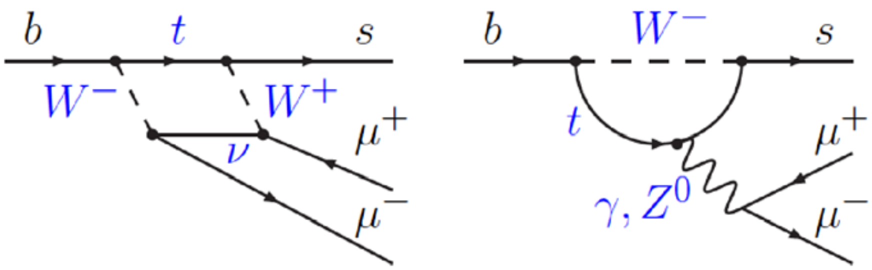
$B^0 \to K^{*0}\mu^+\mu^-$

JHEP 02 (2016) 104

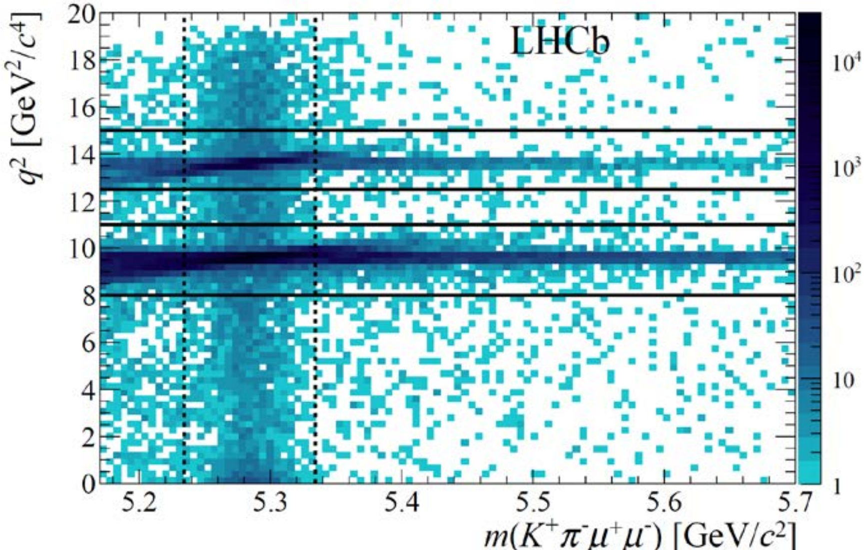
$\int \mathcal{L} = 3\ \mathrm{fb}^{-1}$

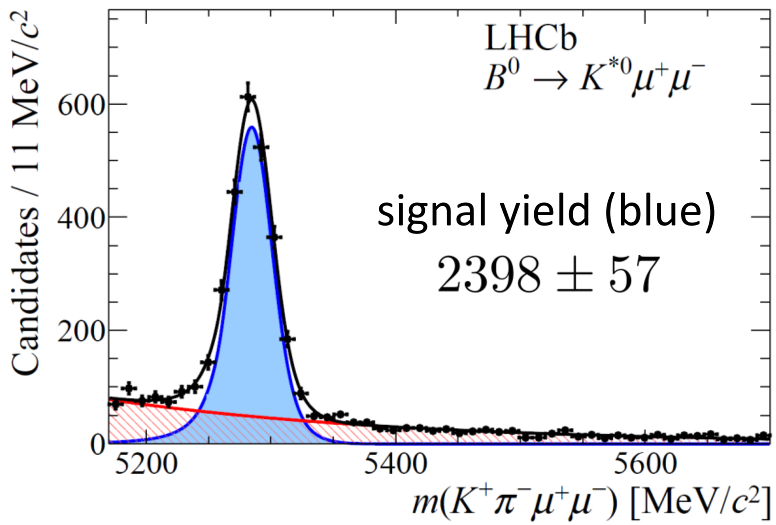
$$B^0 \to K^{*0}\mu^+\mu^-, \quad K^* \to K^+\pi^-$$

Only possible in the SM at loop level



Angular analysis of the Kπμμ final state offers a large number of observables.





$$q^2 = m^2_{\mu\mu}$$

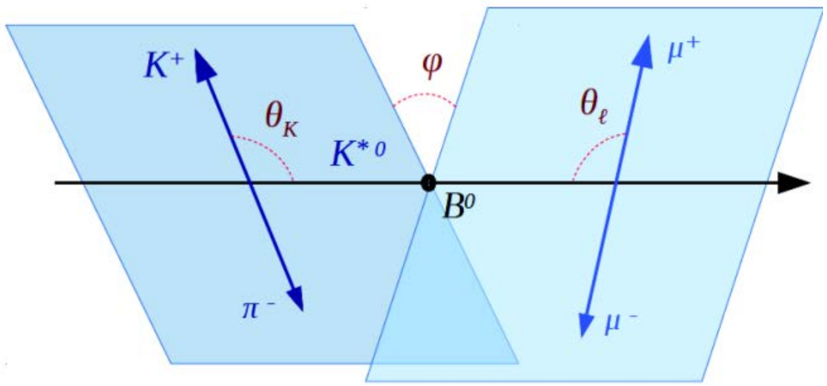
Peaking background from charmonium vetoed with PID (ϕ, Λ, signal swaps…) and q^2 (J/ψ and ψ(2s))

Angular distribution fully described through the coefficients of an expansion in spherical harmonics.

$$\frac{d^4\Gamma\left(\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-\right)}{dq^2 d\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega})$$

$$\frac{d^4\overline{\Gamma}\left(B^0 \to K^{*0}\mu^+\mu^-\right)}{dq^2 d\vec{\Omega}} = \frac{9}{32\pi}\sum_i \overline{I}_i(q^2) f_i(\vec{\Omega})$$

$$\vec{\Omega} = (\cos\theta_l, \cos\theta_K, \phi)$$



Measure full set of q^2-dependent CP-averaged observables, $\mathbf{S_i}$, and CP asymmetries, $\mathbf{A_i}$

$$S_i = (I_i + \overline{I}_i) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\overline{\Gamma}}{dq^2}\right)$$

$$A_i = (I_i - \overline{I}_i) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\overline{\Gamma}}{dq^2}\right)$$

Use an optimized set of observables (F. Krüger, J. Matias, PRD 71 (2005) 094009), where leading form-factor uncertainties cancel, to compare with the SM

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}}$$

$F_L \to$ fraction of longitudinal K^* polarisation.
F_L, S_i depend on Wilson coefficients $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$ $\mathcal{C}_{10}^{(\prime)}$, and form factors.

JHEP 02 (2016) 104

CP-averaged angular distribution showing the q^2-dependent angular observables:

$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + \frac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

Optimised set of observables, for which leading form-factor uncertainties cancel.

$$P_1 = \frac{2S_3}{(1-F_L)} = A_T^{(2)},$$

$$P_2 = \frac{2}{3}\frac{A_{FB}}{(1-F_L)},$$

$$P_3 = \frac{-S_9}{(1-F_L)},$$

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}},$$

$$P'_6 = \frac{S_7}{\sqrt{F_L(1-F_L)}}.$$

The Kπ system can also be in an S-wave configuration. This adds four more terms to the angular distribution (not shown here)

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

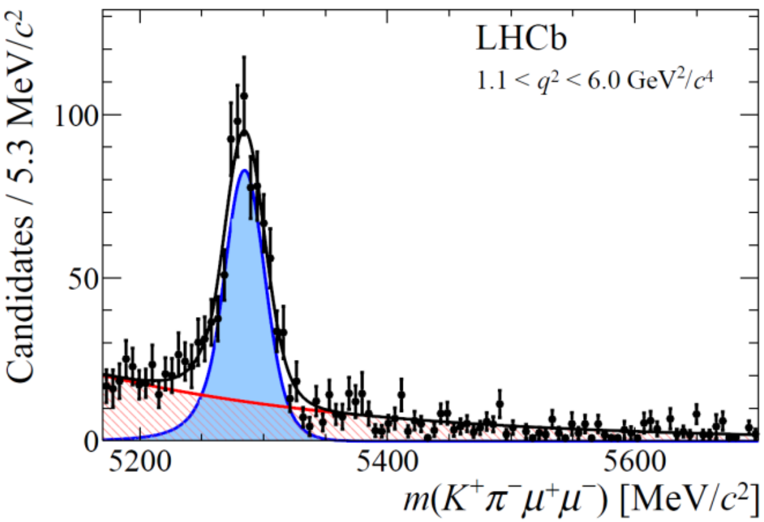
JHEP 02 (2016) 104

Determine angular observables in bins of q^2. Fit simultaneously $m(K\pi)$ and $m(K\pi\mu\mu)$ to constrain backgrounds. Proper treatment of the $K\pi$ S-wave for the first time.

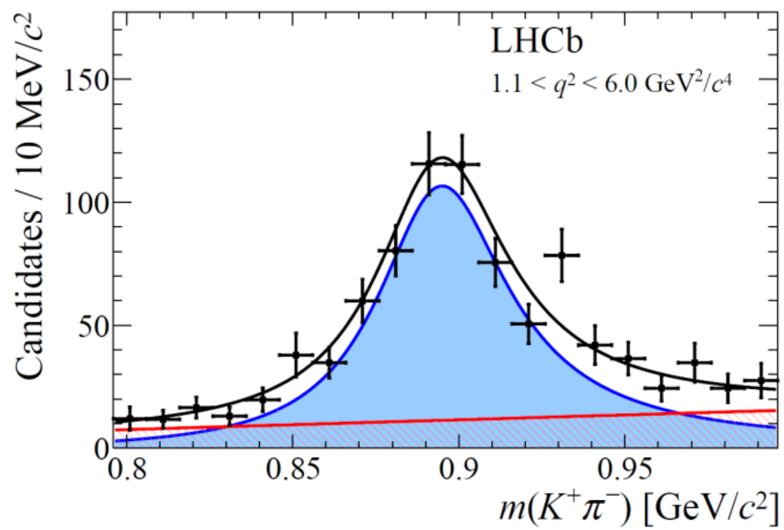
Angular acceptance parameterised in four dimensions $(\cos\theta_\ell, \cos\theta_K, \phi, q^2)$

$\int \mathcal{L} = 3\ \mathrm{fb}^{-1}$

Example of fits in the $1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4$ bin



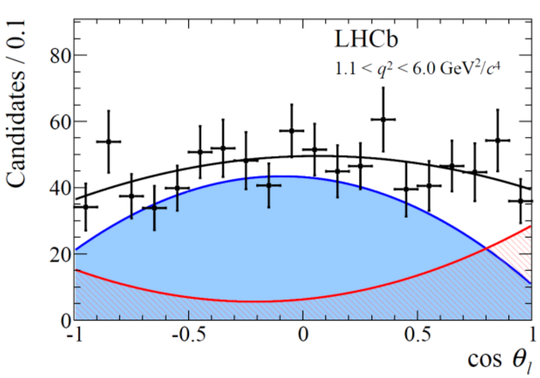
Angles and $m(K\pi)$ projections in a 50 MeV window around the B peak.

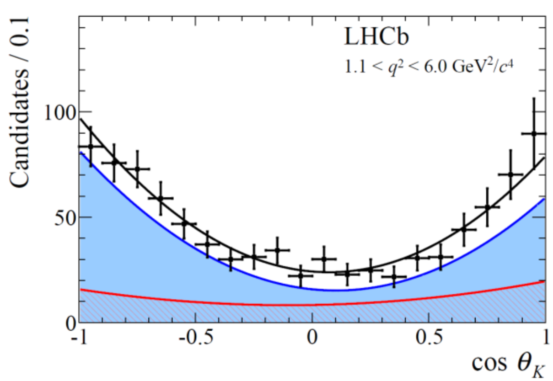


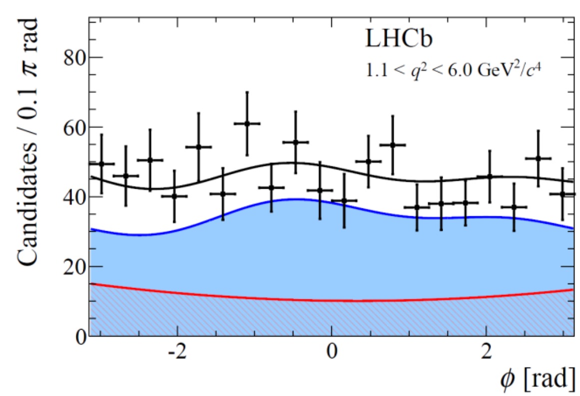
Total fit

Signal

Background





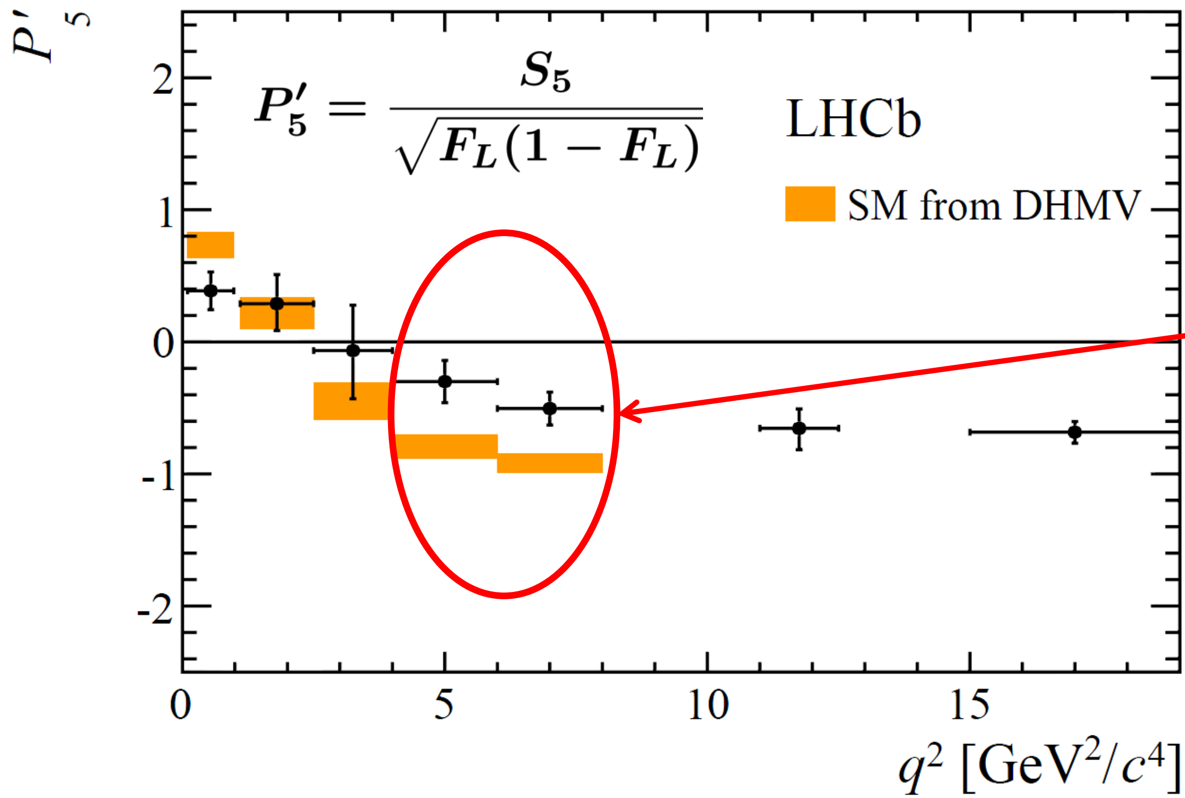


$B^0 \to K^{*0}\mu^+\mu^-$

JHEP 02 (2016) 104

Measure in bins of q^2
a lot of observables

- CP-averaged: $F_L, A_{FB}, S_3, S_4, S_5, S_7, S_8, S_9$
- CP-asymmetric: $A_3, A_4, A_5, A_{6s}, A_7, A_8, A_9$
- Optimised: $P_1, P_2, P_3, P'_4, \boxed{P'_5}, P'_6, P'_8$.



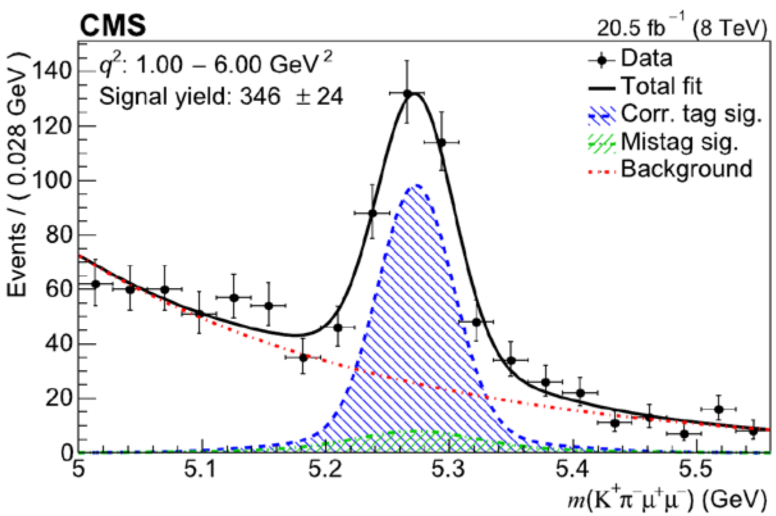
SM predictions by S.Descotes-Genon et al., JHEP 12(2014)125

P'_5 is the only parameter showing some discrepancy (**2.8σ** and **3σ**) with SM prediction.

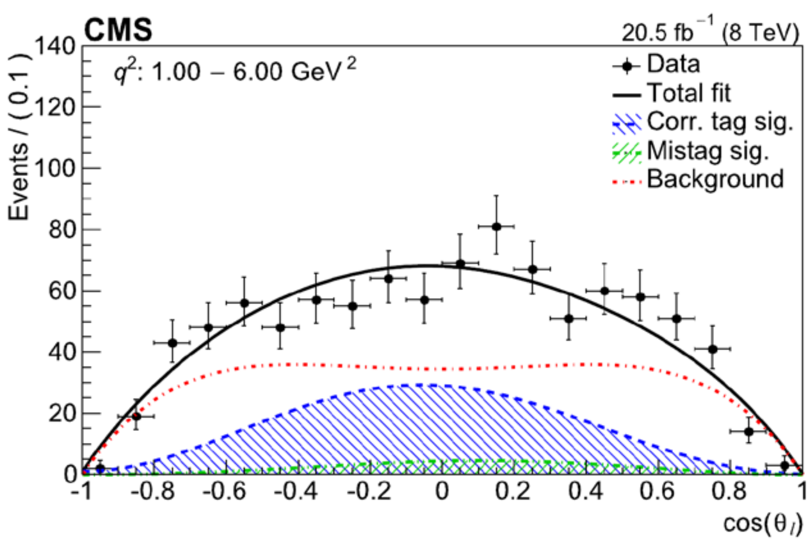
A global analysis of CP-averaged observables indicates differences with the SM at the level of 3.4 σ

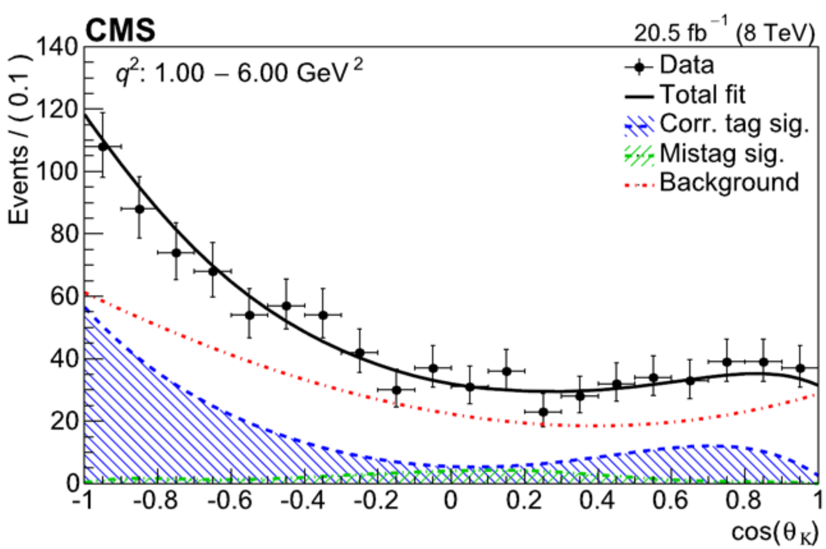
Non-SM particle lurking? Unexpected large hadronic effects? ….

Measure A_{FB}, F_L and $d\mathcal{B}/dq^2$ as a function of q^2



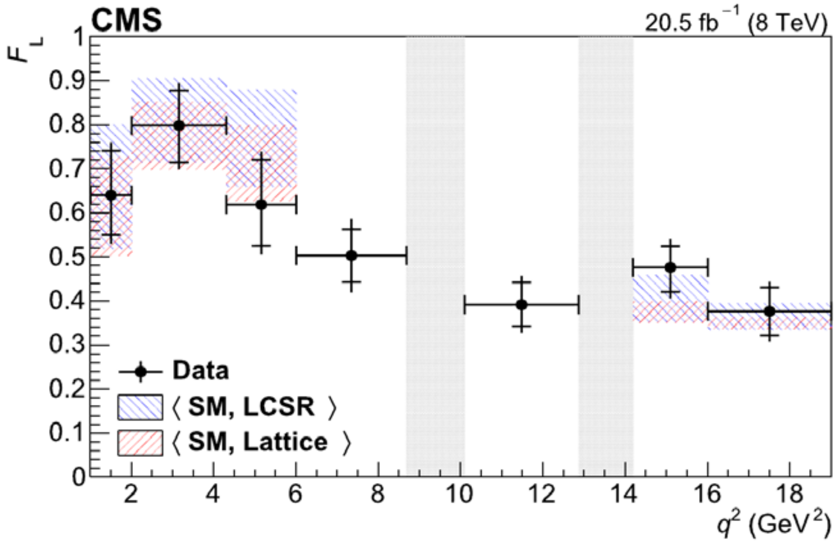
Example of fits in the 1.0 < q^2 < 6.0 GeV^2/c^4 bin

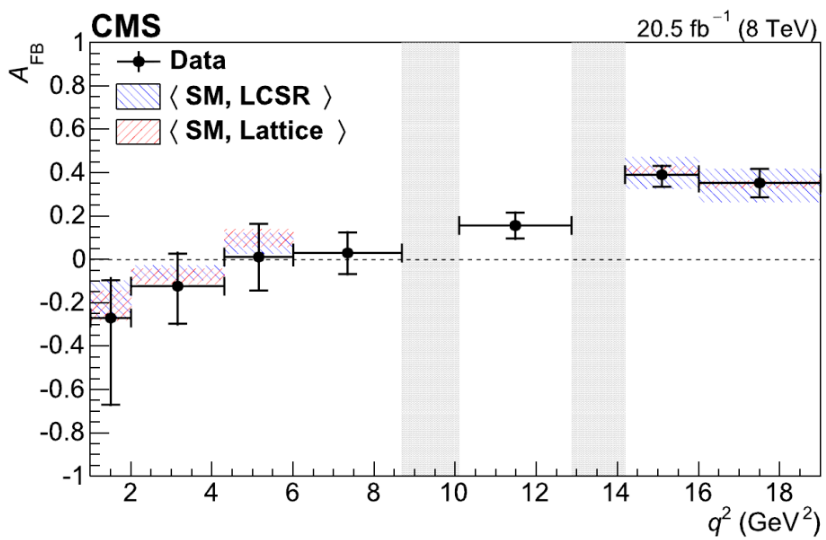




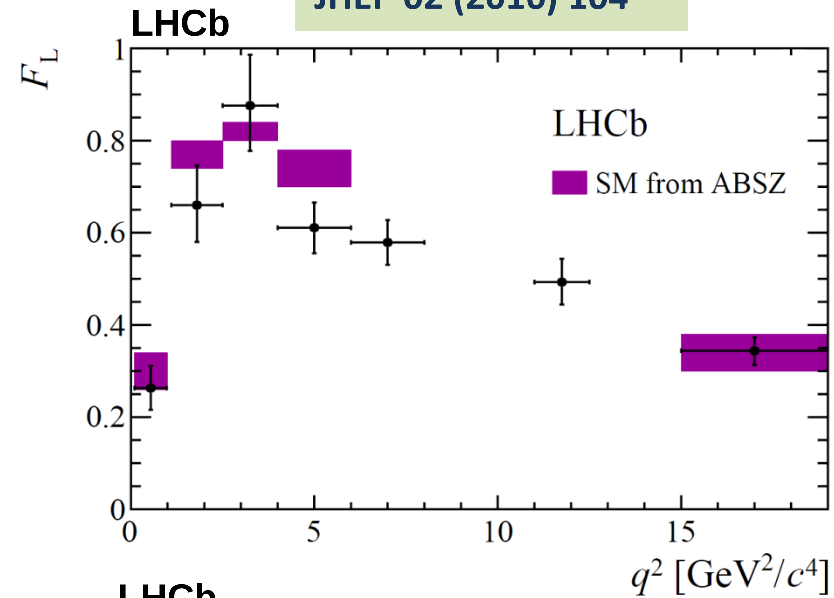
$B^0 \to K^{*0}\mu^+\mu^-$

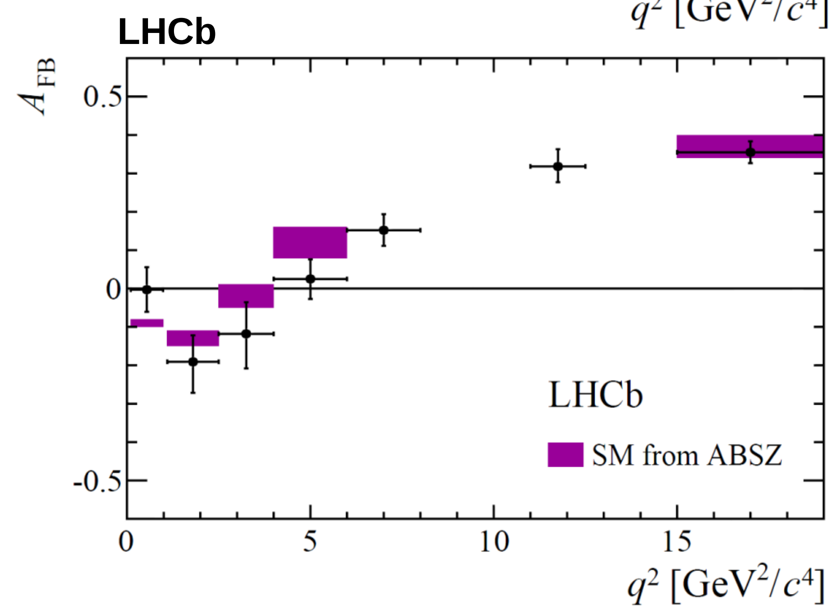
Phys. Lett. B 753 (2016)





JHEP 02 (2016) 104





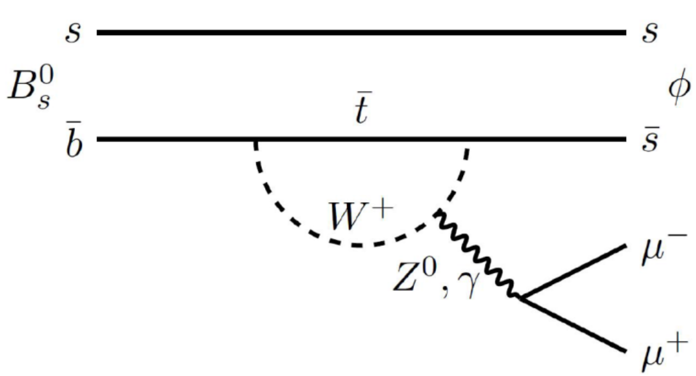
JHEP 09 (2015) 179

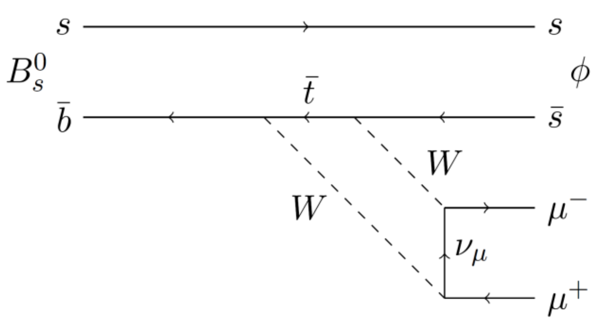
$\int \mathcal{L} = 3 \text{ fb}^{-1}$

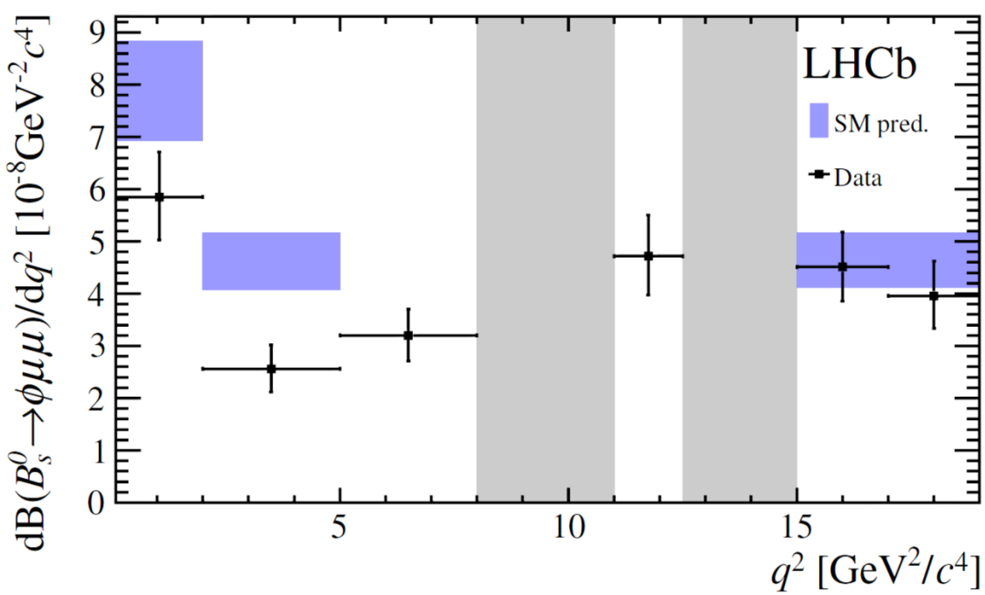
It is similar to B → K*μμ, but not self-tagged (not flavour-specific).

The narrow $\phi(K^+K^-)$ resonance allows to isolate a clean signal.

Full angular analysis performed. Angular observables compatible with SM predictions.







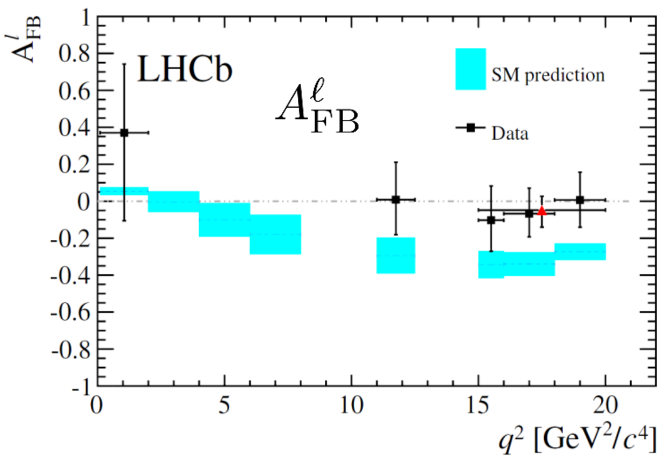
For the q^2 region $1 < q^2 < 6$ GeV$^2/c^2$, the differential BR is more than **3σ** below the SM prediction.

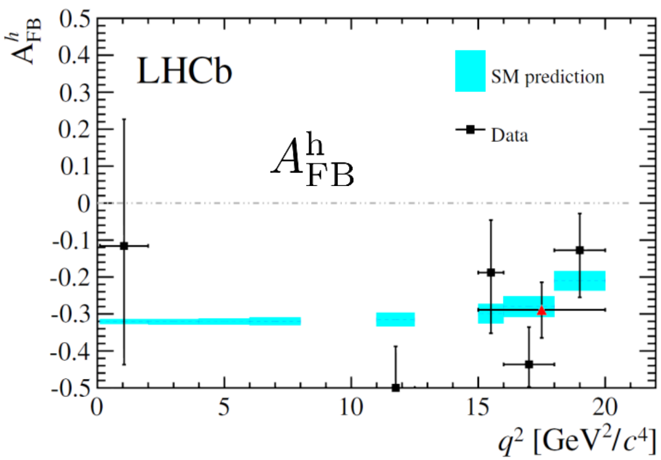
$\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$

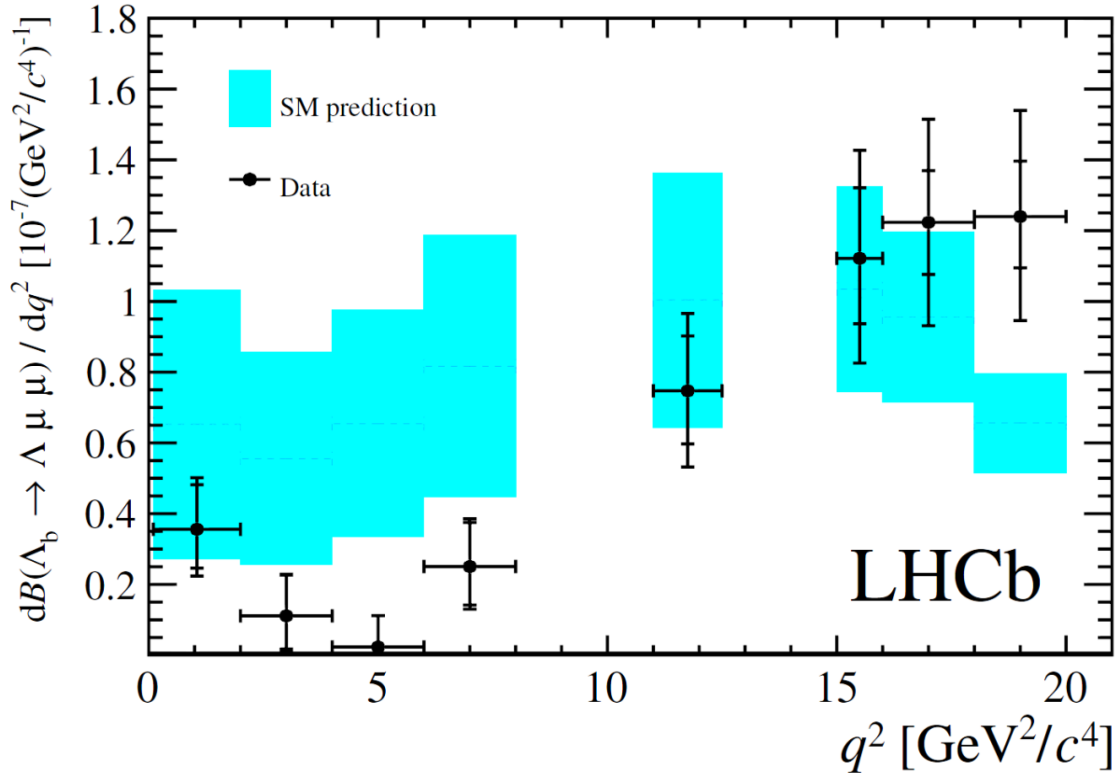
JHEP 06 (2015) 115

$\int \mathcal{L} = 3\ \mathrm{fb}^{-1}$

Also similar to B -> K* μμ. Measure differential BR as a function of q^2.
Baryonic system provides sensitivity to additional observables.
Forward-Backward asymmetries in the dimuon and hadron system: A_{FB}^{ℓ}, $A_{\mathrm{FB}}^{\mathrm{h}}$ $(A_{\mathrm{FB}}^{\mu\mu}, A_{\mathrm{FB}}^{\mathrm{p}\pi})$





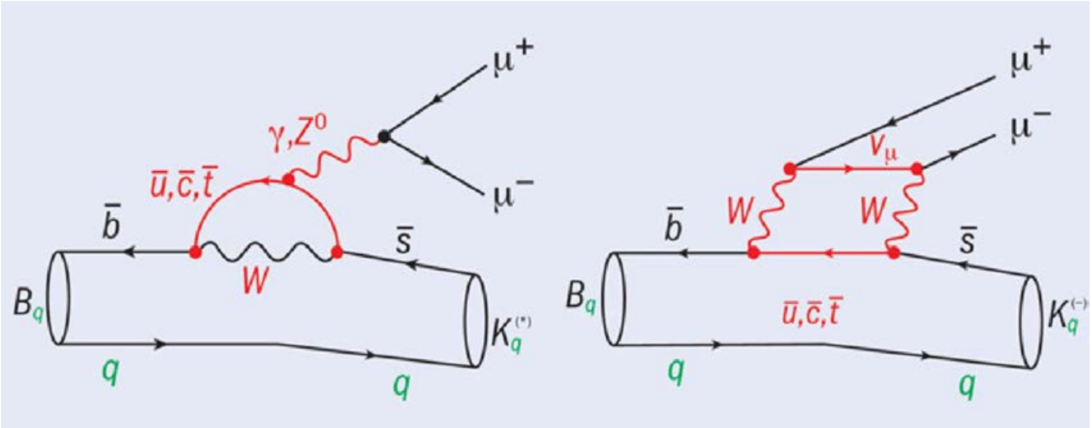


Again, BR a bit lower than SM prediction at low q^2
Deficit of muons ?

Tests of Lepton Universality

$B^+ \to K^+ \ell^+ \ell^-$

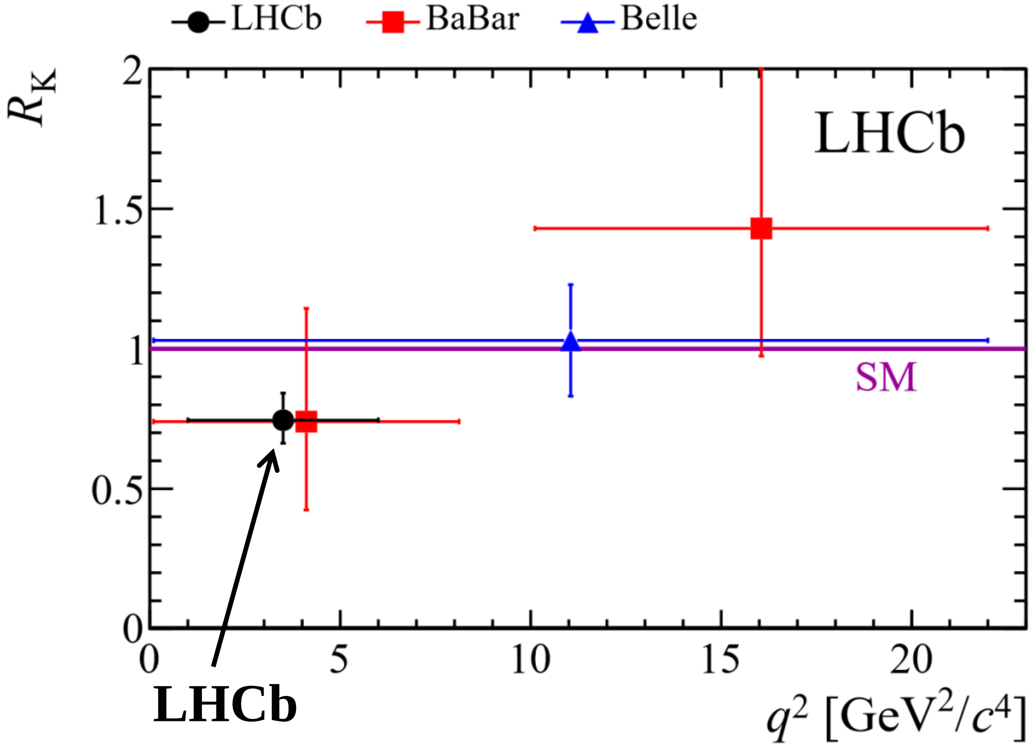
PRL 113, 151601 (2014)



b → s FCNC process

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

$$= 1.003 \pm 0.0001 \quad \text{SM}$$



$$R_K^{\mathrm{LHCb}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

for $1 < q^2 < 6 \ \mathrm{GeV}^2/c^4$

$q^2 = m^2_{\ell\ell}$

LHCb measurement **2.6 σ** away from the **SM** prediction.

More data to clarify situation

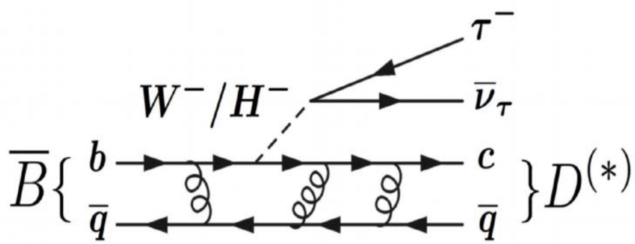
$\mathcal{B}(\overline{B}^0 \to D^{(*)+}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B}^0 \to D^{(*)+}\mu^-\overline{\nu}_\mu)$

PRL 115, 111803 (2015)

$$\mathcal{R}(D) = \frac{\mathcal{B}(\overline{B}^0 \to D^+\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^+\ell^-\overline{\nu}_\ell)} \qquad \mathcal{R}(D^*) = \frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell)} \qquad \ell = \mu,\ e$$

$\int \mathcal{L} = 3\ \mathrm{fb}^{-1}$

Sensitive test to NP at tree level.

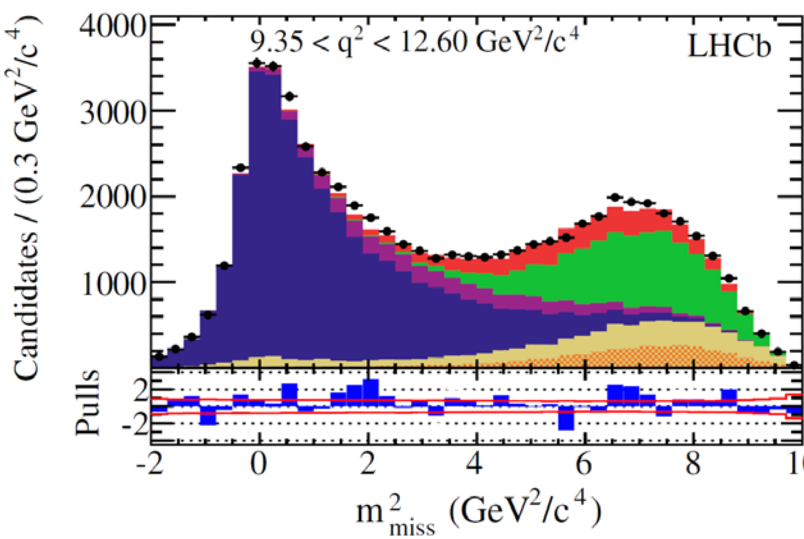


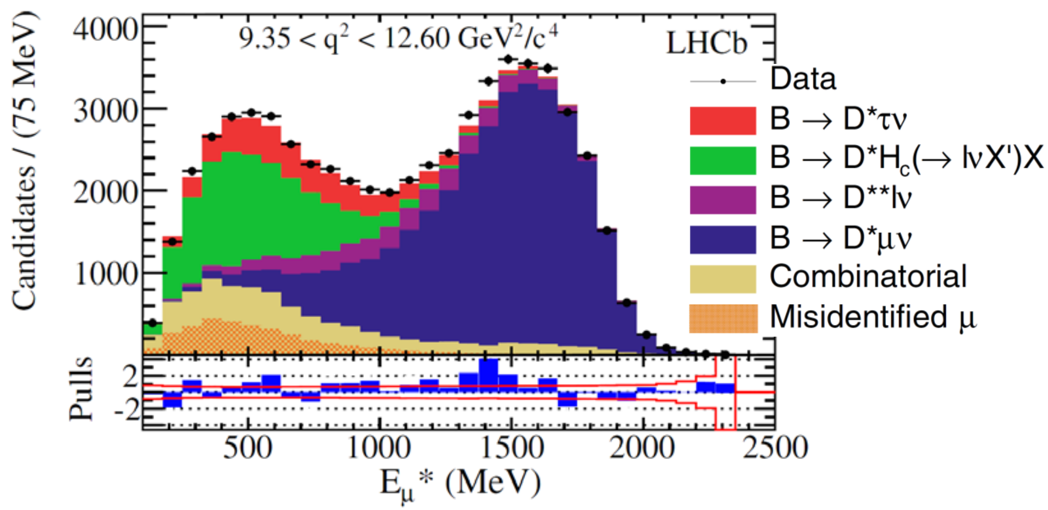
$\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ with $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$ and $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$

visible final-state particles are $K^-\pi^+\pi^+\mu^-$

same for the norm. channel $\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu$

The signal, normalization component and background are statistically disentangled with a multidimensional fit in M_{miss}, E_μ and q^2. $m^2_{miss} = (p_B - p_D - p_\mu)^2$ $\quad q^2 = (p_B - p_D)^2$



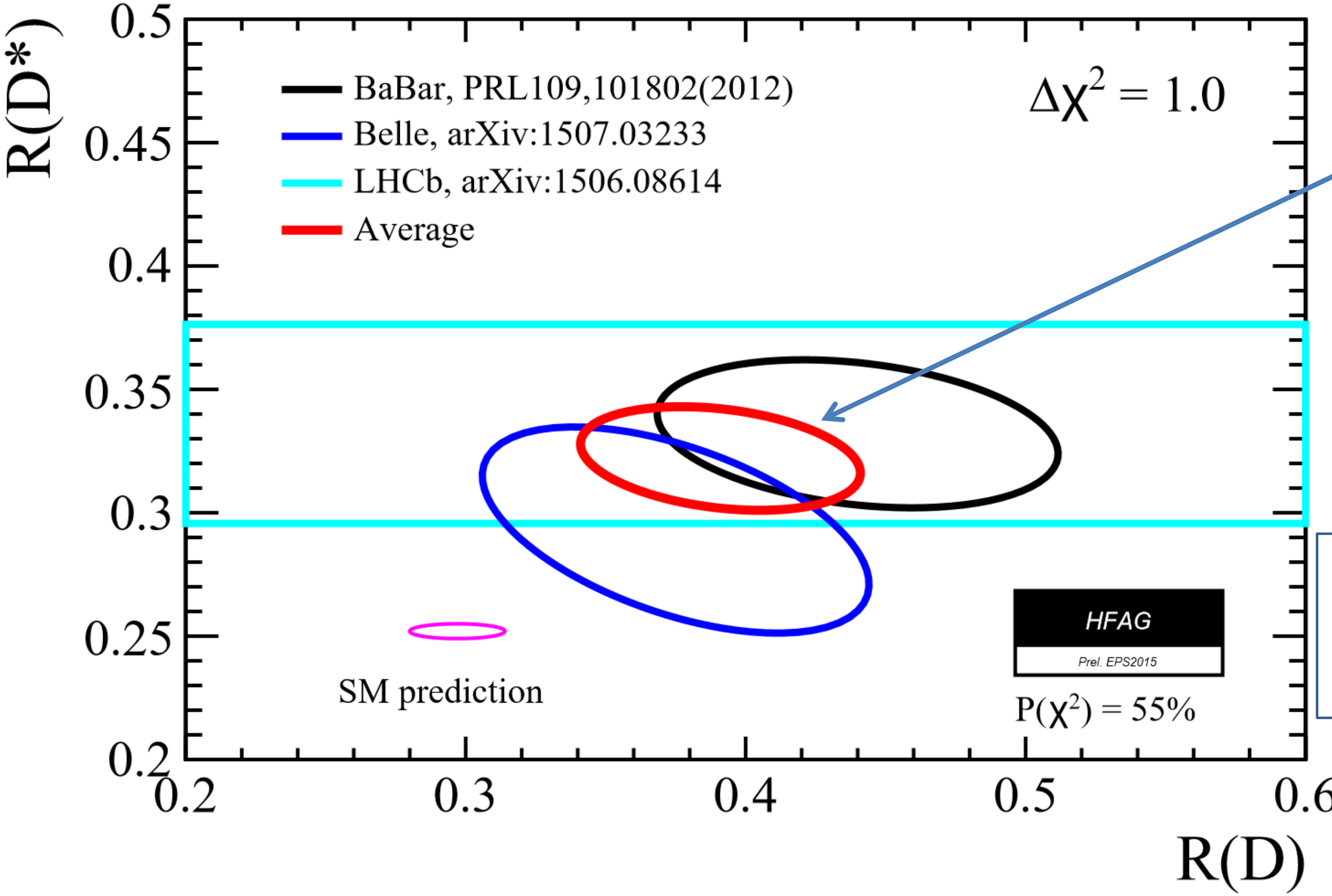


PRL 115, 111803 (2015)

LHCb measures $\mathcal{R}(D^*) = 0.336 \pm 0.027 \pm 0.030$

At **2.1 σ** from **SM** prediction

0.252 ± 0.003 SM



Combination of Babar, Belle and LHCb results at **3.9 σ** from the **SM**

SM prediction from PRD 85 (2012) 094025

(Belle, Moriond EW 2016)

$\mathcal{R}(D^*) = 0.302 \pm 0.030 \pm 0.011$

CP Violation and the CKM unitarity triangle

Introduction

Quark weak eigenstates related to mass eigenstates through the unitary V_{CKM} matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} \boxed{\begin{matrix} V_{ud} \\ V_{cd} \\ V_{td} \end{matrix}} & \begin{matrix} V_{us} \\ V_{cs} \\ V_{ts} \end{matrix} & \boxed{\begin{matrix} V_{ub} \\ V_{cb} \\ V_{tb} \end{matrix}} \end{pmatrix}}_{V_{\text{CKM}}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\boldsymbol{V^\dagger V = VV^\dagger = 1}$$

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

Weak charge currents proportional to CKM matrix elements

$$\mathcal{L}_{\text{int}}^{\text{CC}} = -\frac{g}{\sqrt{2}} \begin{pmatrix} \bar{u}_L & \bar{c}_L & \bar{t}_L \end{pmatrix} \gamma^\mu \boldsymbol{V_{\text{CKM}}} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W_\mu^\dagger + \text{h.c.}$$

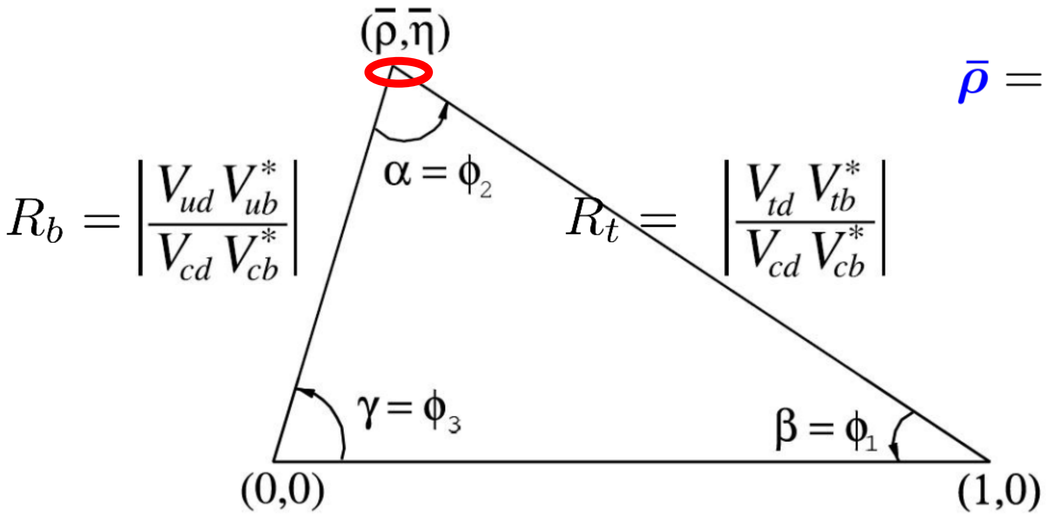
Wolfenstein parameterization using four real parameters: A, ρ, λ, η (**η ≠ 0 => CP Violation**)

$$V_{\text{CKM}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\boldsymbol{\lambda} = \frac{|V_{us}|}{\sqrt{|V_{ud}|^2 + |V_{us}|^2}} \approx 0.22 \qquad \boldsymbol{A} = \frac{1}{\lambda}\left|\frac{V_{cb}}{V_{us}}\right| \qquad V_{ub}^* = A\lambda^3(\boldsymbol{\rho} + i\boldsymbol{\eta})$$

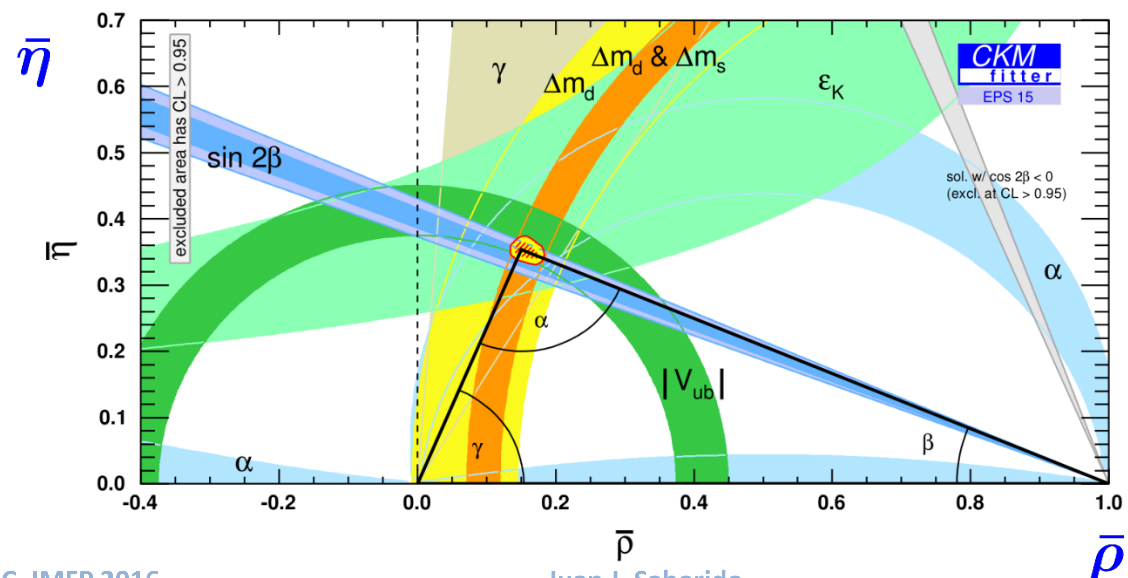
Unitarity triangle

Draw the relation $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ as a triangle in the complex plane:



$$\bar{\rho} = \rho\left(1 - \frac{1}{2}\lambda^2\right), \qquad \bar{\eta} = \eta\left(1 - \frac{1}{2}\lambda^2\right)$$

The measurement of all angles and sides of this triangle using a plethora of decay channels is a stringent test of the SM description of CP violation and quark transitions.



CP Violation

Direct CPV

$$\Gamma\left(B \to f\right) \neq \Gamma\left(\overline{B} \to \overline{f}\right)$$

Best isolated in charged meson decays

$$\mathcal{A}_{\text{CP}}^{\text{dir}} = \frac{\Gamma(B^+ \to f^+) - \Gamma(B^- \to f^-)}{\Gamma(B^+ \to f^+) + \Gamma(B^- \to f^-)}$$

CPV in mixing

$$\Gamma\left(B \to \overline{B}\right) \neq \Gamma\left(\overline{B} \to B\right)$$

Best isolated in semi-leptonic decays of neutral mesons

$$\frac{\Gamma(\overline{B}^0(t) \to \ell^+ \nu X) - \Gamma(B^0(t) \to \ell^- \overline{\nu} X)}{\Gamma(\overline{B}^0(t) \to \ell^+ \nu X) + \Gamma(B^0(t) \to \ell^- \overline{\nu} X)}$$

CPV in mixing-decay

$$\Gamma\left(B \to f_{CP}\right) \neq \Gamma\left(\overline{B} \to f_{CP}\right)$$

f_{CP}, is a CP eigenstate

Direct CPV

$$\mathcal{A}(t) = \frac{\boldsymbol{S_f} \sin(\Delta m_{d(s)} t) - \boldsymbol{C_f} \cos(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) - \boldsymbol{A_f^{\Delta\Gamma}} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)}$$

Mixing-induced CPV

$\Delta\Gamma$ is negligible for B_d, so in that case $\mathcal{A}(t) \approx \boldsymbol{S_f} \sin(\Delta m_d t) - \boldsymbol{C_f} \cos(\Delta m_d t)$

$\sin(2\beta)$

$\beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$ is one of the angles of the CKM triangle (also called ϕ_1)

$B^0 \to J/\psi K_S^0$ Golden decay mode to measure **sin(2β)** through time-dependent CP Asy.

$$\mathcal{A}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to J/\psi K_S^0) - \Gamma(B^0(t) \to J/\psi K_S^0)}{\Gamma(\overline{B}^0(t) \to J/\psi K_S^0) + \Gamma(B^0(t) \to J/\psi K_S^0)} \approx S\sin(\Delta m t) - C\cos(\Delta m t)$$

Direct CP violation expected to be very small ($C \approx 0$), $S \approx \sin(2\beta)$

PRD 91 073007 (2015)

Other measurements that constrain the CKM triangle predict $\sin(2\beta) = 0.771^{+0.017}_{-0.041}$

Small discrepancy with the average of direct measurements: $\sin(2\beta) = 0.682 \pm 0.019$

HFAG arXiv:1412.7515

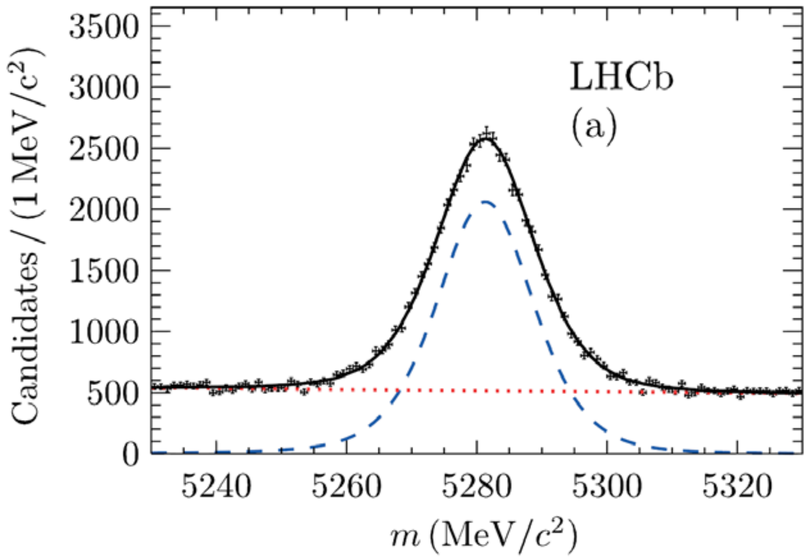
Better experimental precision and understanding of higher-order contributions needed to clarify the CKM picture.

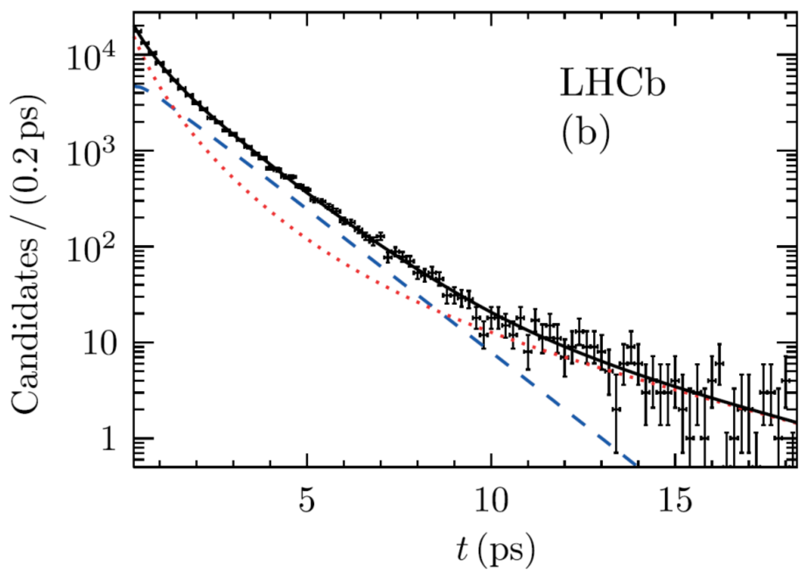
$\sin(2\beta)$

PRL 115, 072001, (2015)

Now LHCb becomes competitive with B-factories measurements.

$\int \mathcal{L} = 3\ \mathrm{fb}^{-1}$

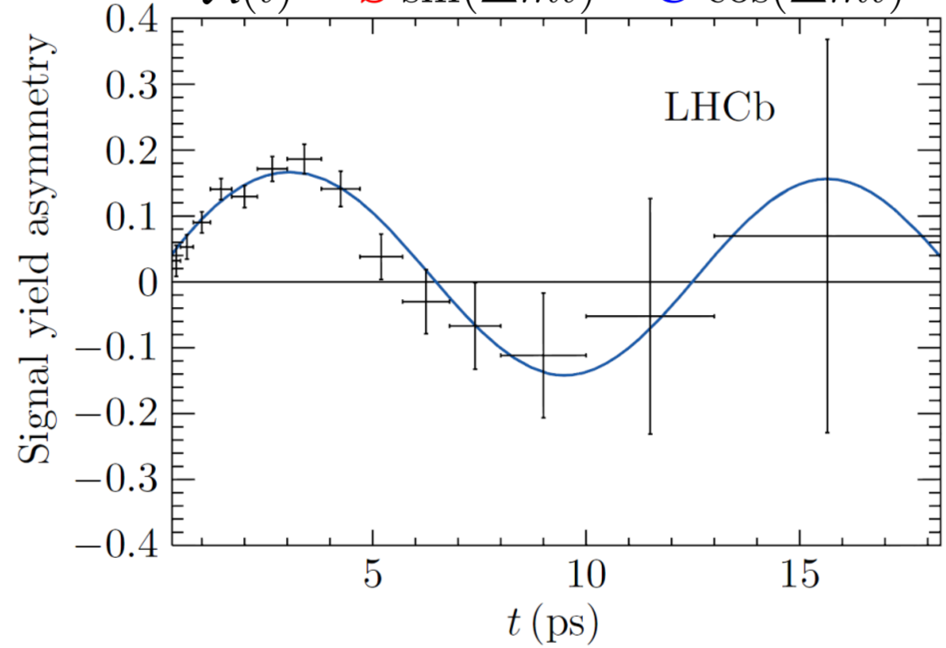




41560 ± 270 tagged $B^0 \to J/\psi\, K_S$ decays

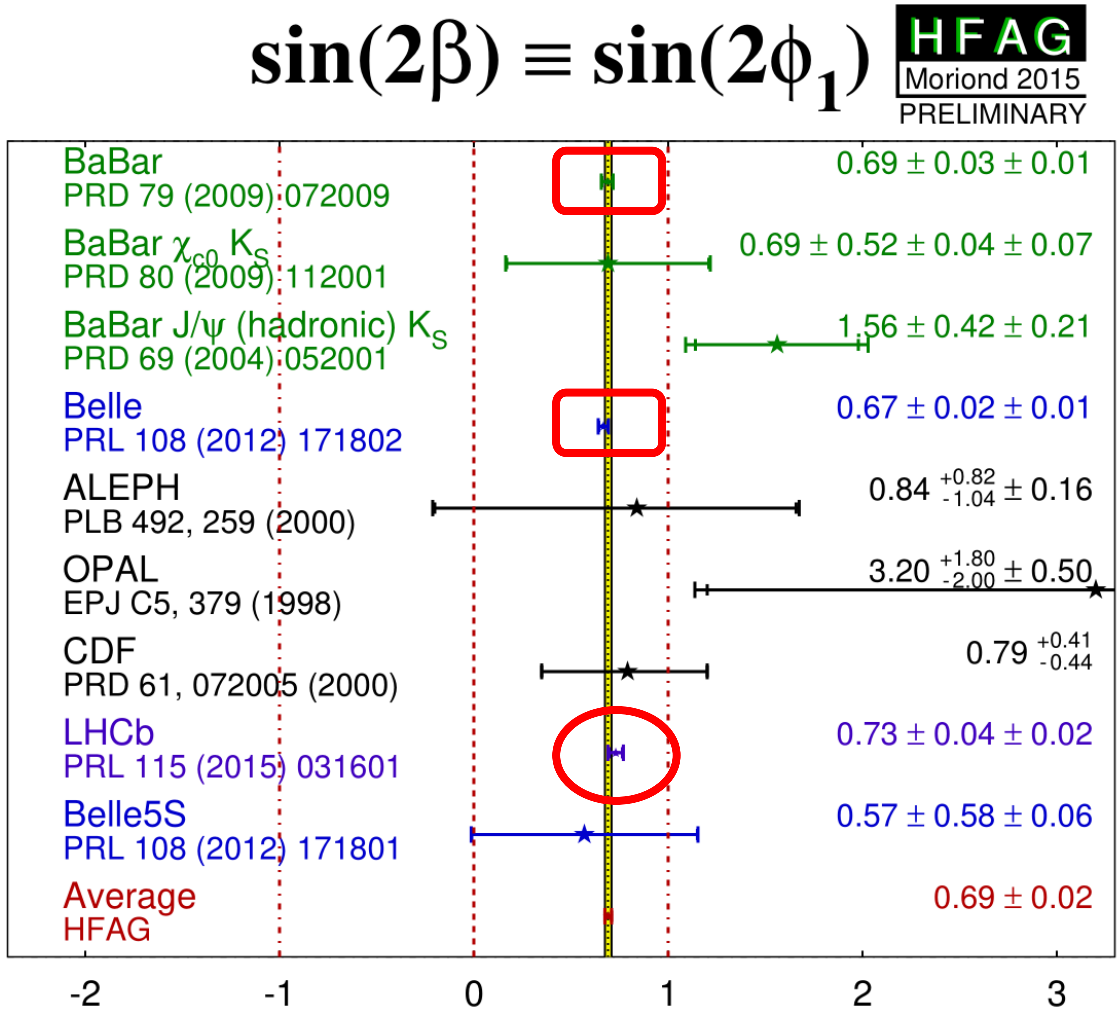
Effective tagging efficiency: (3.02 ± 0.05) %

$$\mathcal{A}(t) = \boldsymbol{S} \sin(\Delta m t) - \boldsymbol{C} \cos(\Delta m t)$$



$$\boldsymbol{S} = +0.731 \pm 0.035 \pm 0.020$$
$$\boldsymbol{C} = -0.038 \pm 0.032 \pm 0.005$$

$\sin(2\beta)$



$$\text{World average } \sin(2\beta) = 0.691 \pm 0.017$$

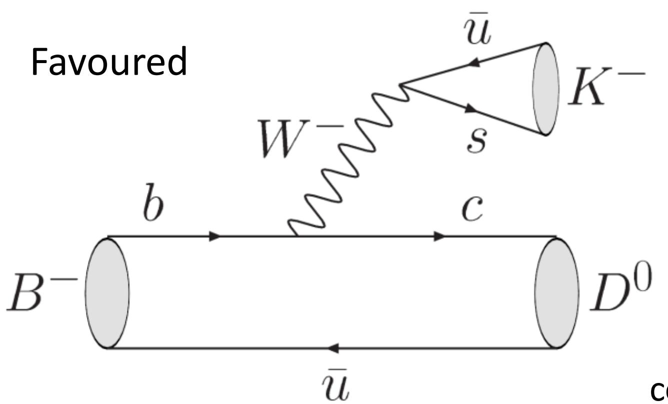
The CKM unitarity angle γ

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

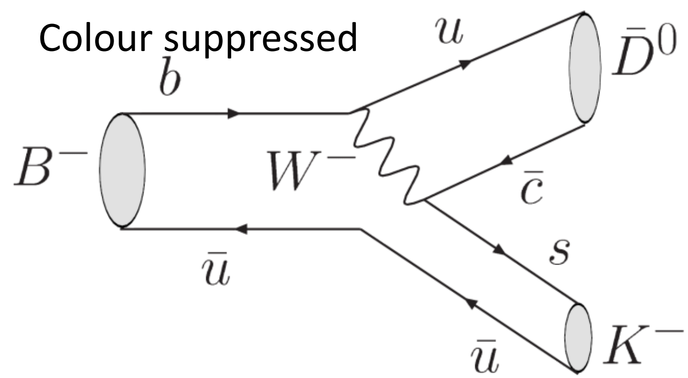
(also called ϕ_3) still the least-well known of the CKM unitarity angles (precision about 7°, compared to 3° and <1° for α and β).

Best measured in the interference of tree-level b→u and b→ c transitions. For example:

Favoured

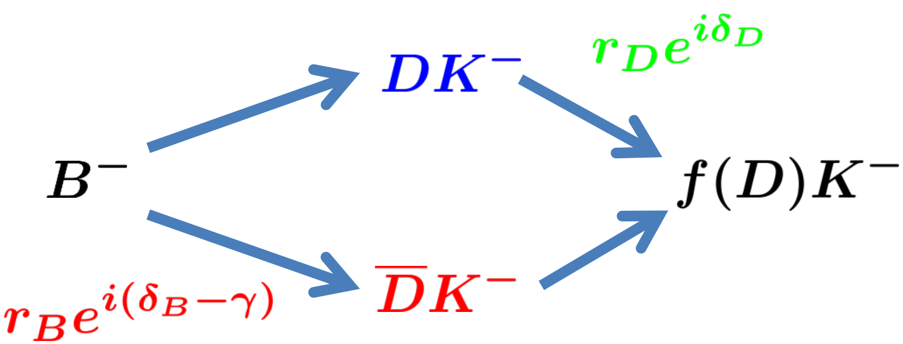


Colour suppressed



coherence factor

$$\Gamma(B^\pm \to [f]_D K^\pm) = r_D^2 + r_B^2 + 2\kappa r_D r_B \cos(\delta_B + \delta_D \pm \gamma)$$ (example of decay rate)



weak phase

$$\frac{A(B^- \to \overline{D}^0 K^-)}{A(B^- \to D^0 K^-)} = r_B e^{i(\delta_B - \gamma)}$$

CP conserving phases

$$\frac{A(D^0 \to K^+\pi^-)}{A(D^0 \to K^-\pi^+)} = r_D e^{i\delta_D}$$

CP observables in $B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$

$\int \mathcal{L} = 3\ \mathrm{fb}^{-1}$

arXiv:1603.08993

D meson final states: $K^\pm\pi^\mp,\ \pi^\pm K^\mp,\ K^+K^-,\ \pi^+\pi^-,\ K^\pm\pi^\mp\pi^+\pi^-,\ \boxed{\pi^+\pi^-\pi^+\pi^-}$

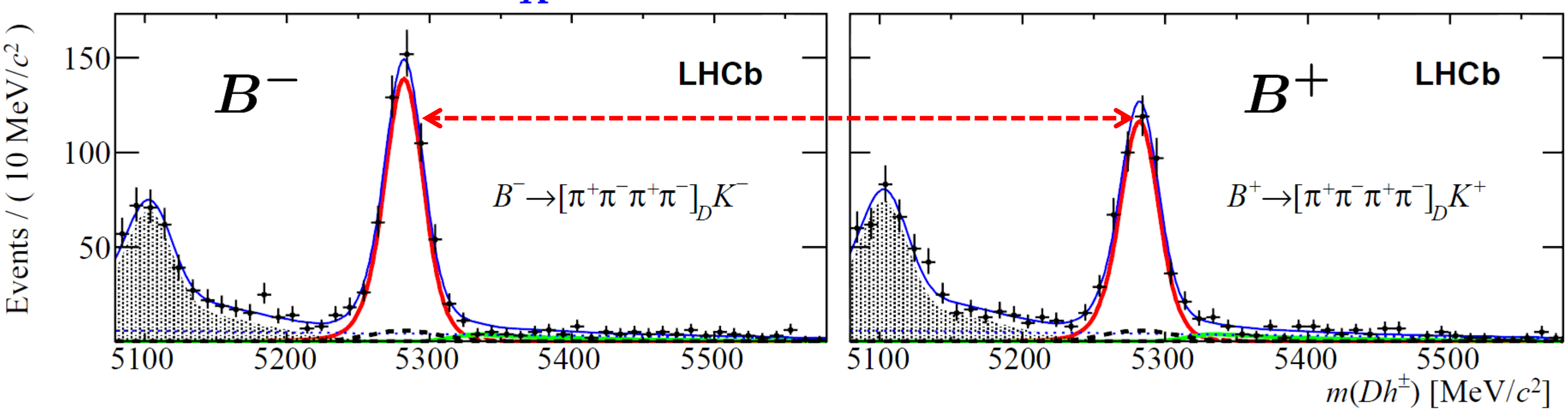
First of its kind

Measure 21 CP observables, providing important input for the determination of the angle γ.

Show now only a few representative charge asymmetries

$$A_h^f = \frac{\Gamma(B^- \to [f]_D h^-) - \Gamma(B^+ \to [\bar{f}]_D h^+)}{\Gamma(B^- \to [f]_D h^-) + \Gamma(B^+ \to [\bar{f}]_D h^+)}$$

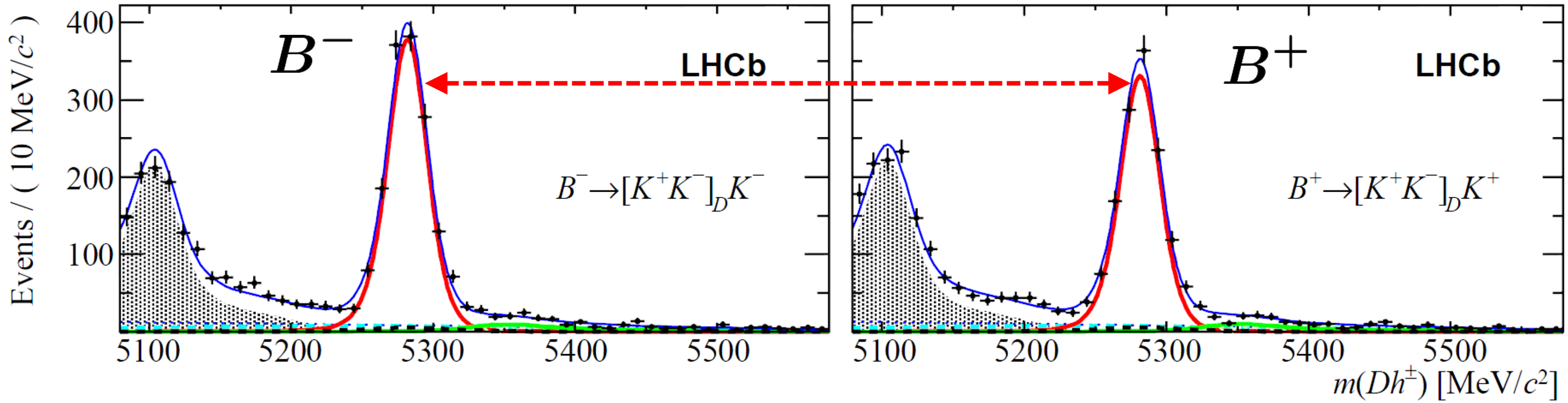
$$A_K^{\pi\pi\pi\pi} = -0.100 \pm 0.034 \pm 0.018$$



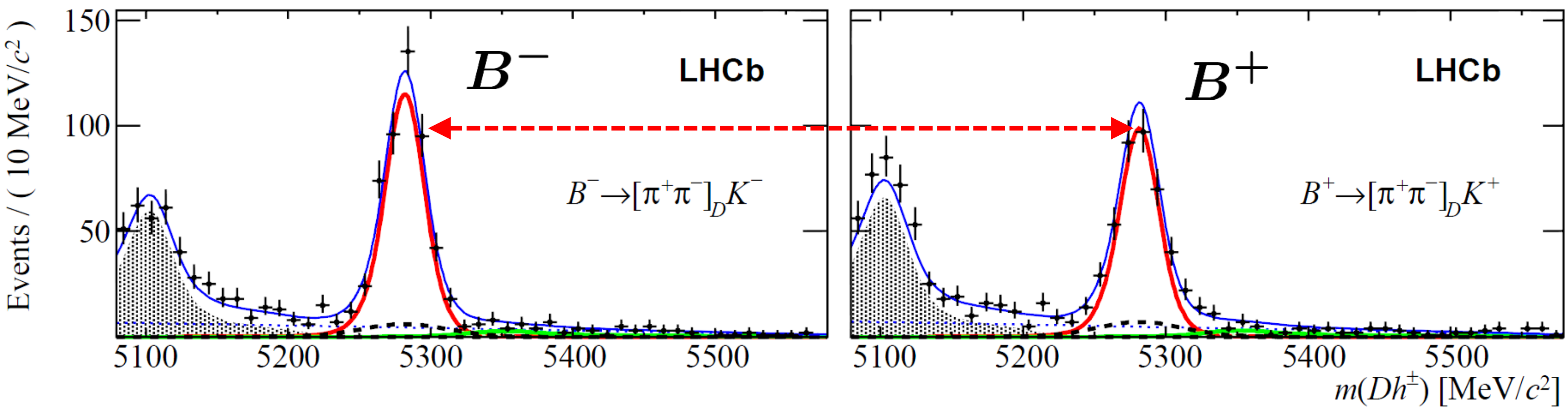
CP observables in $B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D\pi^{\pm}$

arXiv:1603.08993

$$A_K^{KK} = -0.087 \pm 0.020 \pm 0.008$$



$$A_K^{\pi\pi} = -0.128 \pm 0.037 \pm 0.012$$



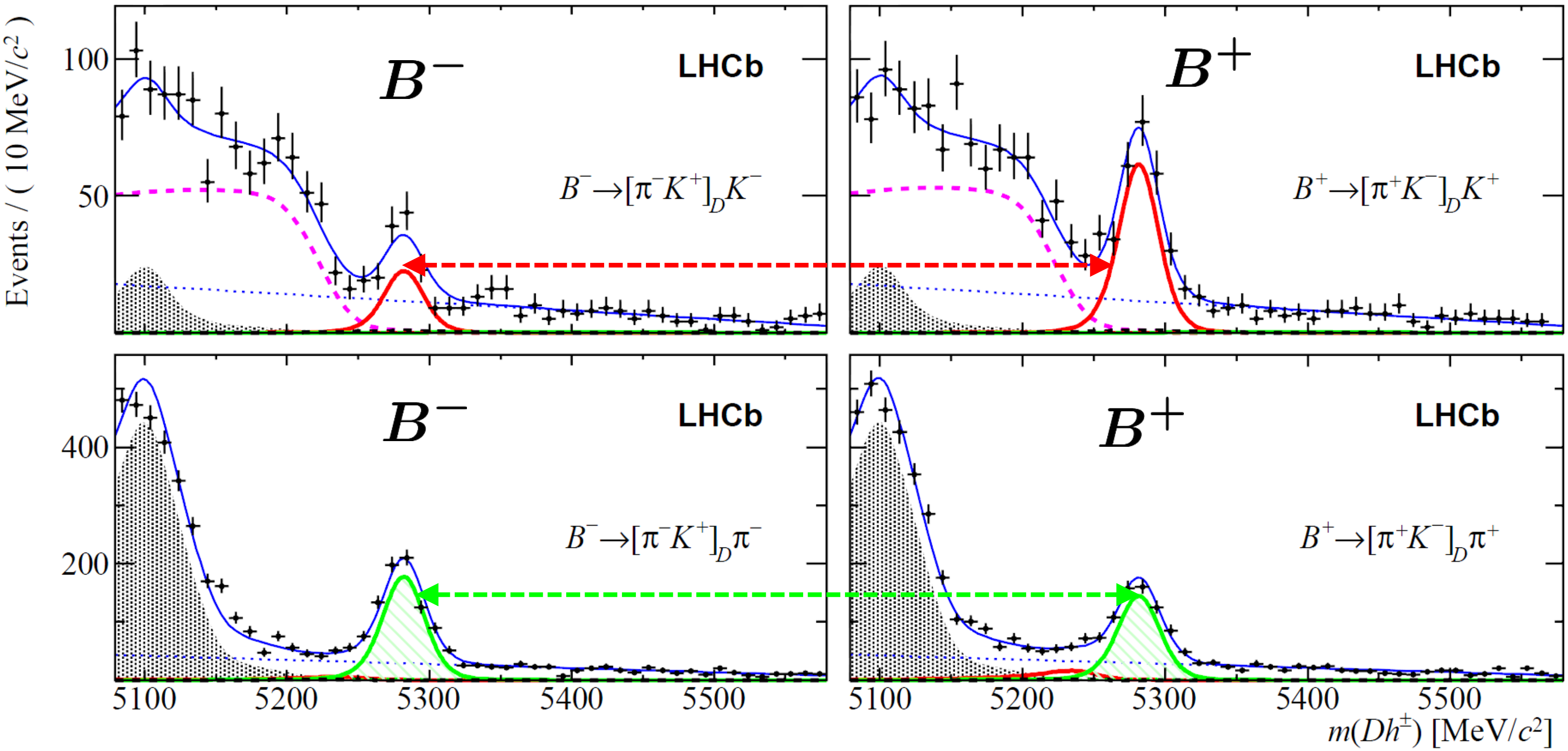
CP observables in $B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D\pi^{\pm}$

arXiv:1603.08993

(ADS mode: D-> quasi flavour-specific state)

$$A^{\overline{f}}_{\mathrm{ADS}(h)} = \frac{\Gamma(B^- \to [\overline{f}]_D h^-) - \Gamma(B^+ \to [f]_D h^+)}{\Gamma(B^- \to [\overline{f}]_D h^-) + \Gamma(B^+ \to [f]_D h^+)}$$

$$A^{\pi K}_{\mathrm{ADS}(K)} = -0.403 \pm 0.056 \pm 0.011$$



$$A^{\pi K}_{\mathrm{ADS}(\pi)} = -0.100 \pm 0.031 \pm 0.009$$

Angle γ from tree-level processes

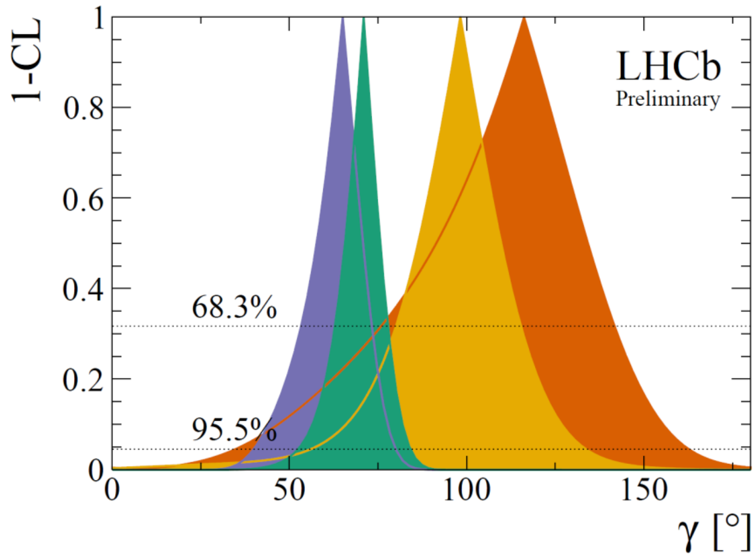
$\int \mathcal{L} = 3\ \mathrm{fb}^{-1}$

LHCb-CONF-2016-001

Time integrated analysis of $B^+ \to DK^+$, $B^0 \to DK^{*0}$ and $B^+ \to DK^+\pi^+\pi^-$ decays, where the D meson decays to a large variety of final states: (hh, $hh\pi^0$, $K^0_S hh$, $h\pi\pi\pi$, where $h = \pi^\pm, K^\pm$).

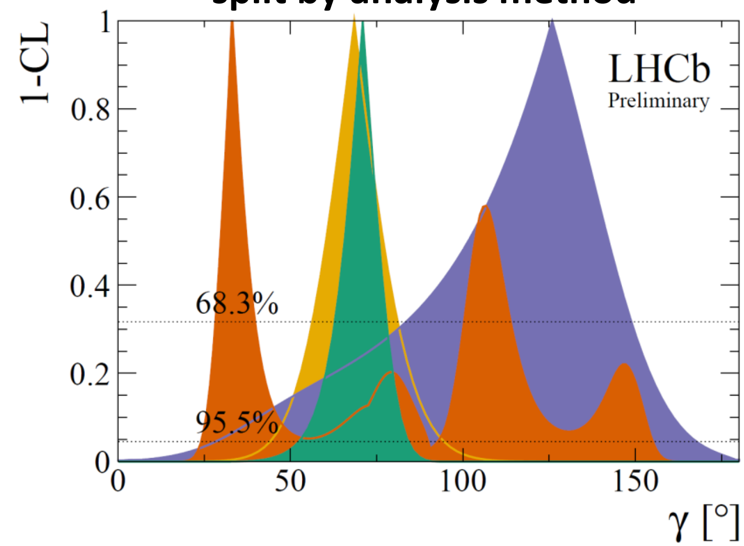
Resulting confidence intervals for different B flavours and analysis method

split by initial B flavour



B_s decays
B^0 decays
B^+ decays
Combination

split by analysis method



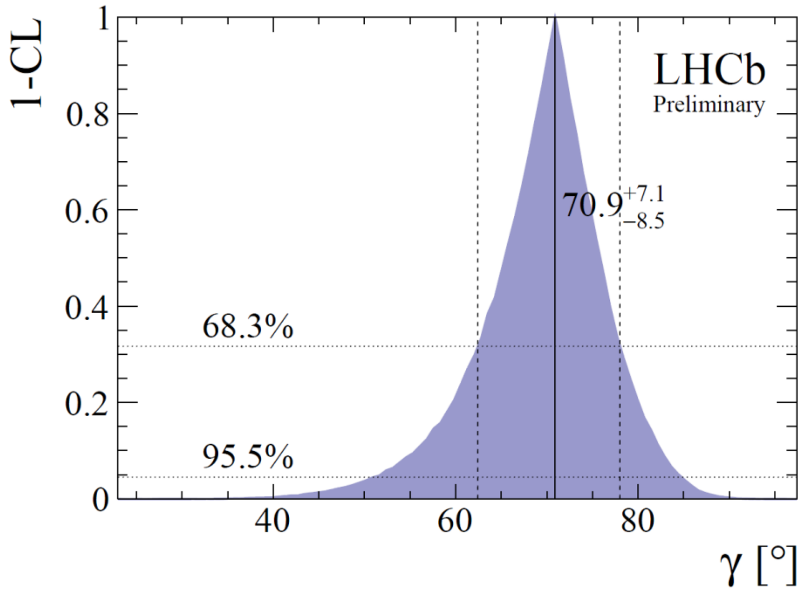
GGSZ
GLW/ADS
Others
Combination

Angle γ from tree-level processes

LHCb-CONF-2016-001

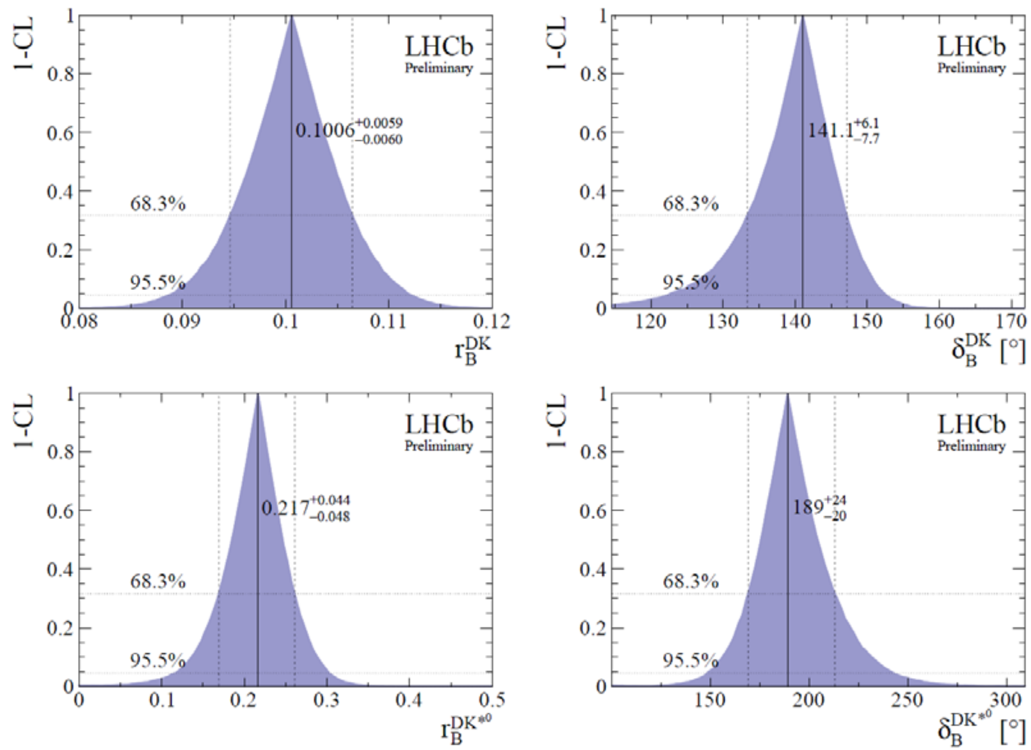
Combination of all LHCb γ measurements from tree-level processes.

Using the best fit value and the 68% CL interval, γ is measured to be

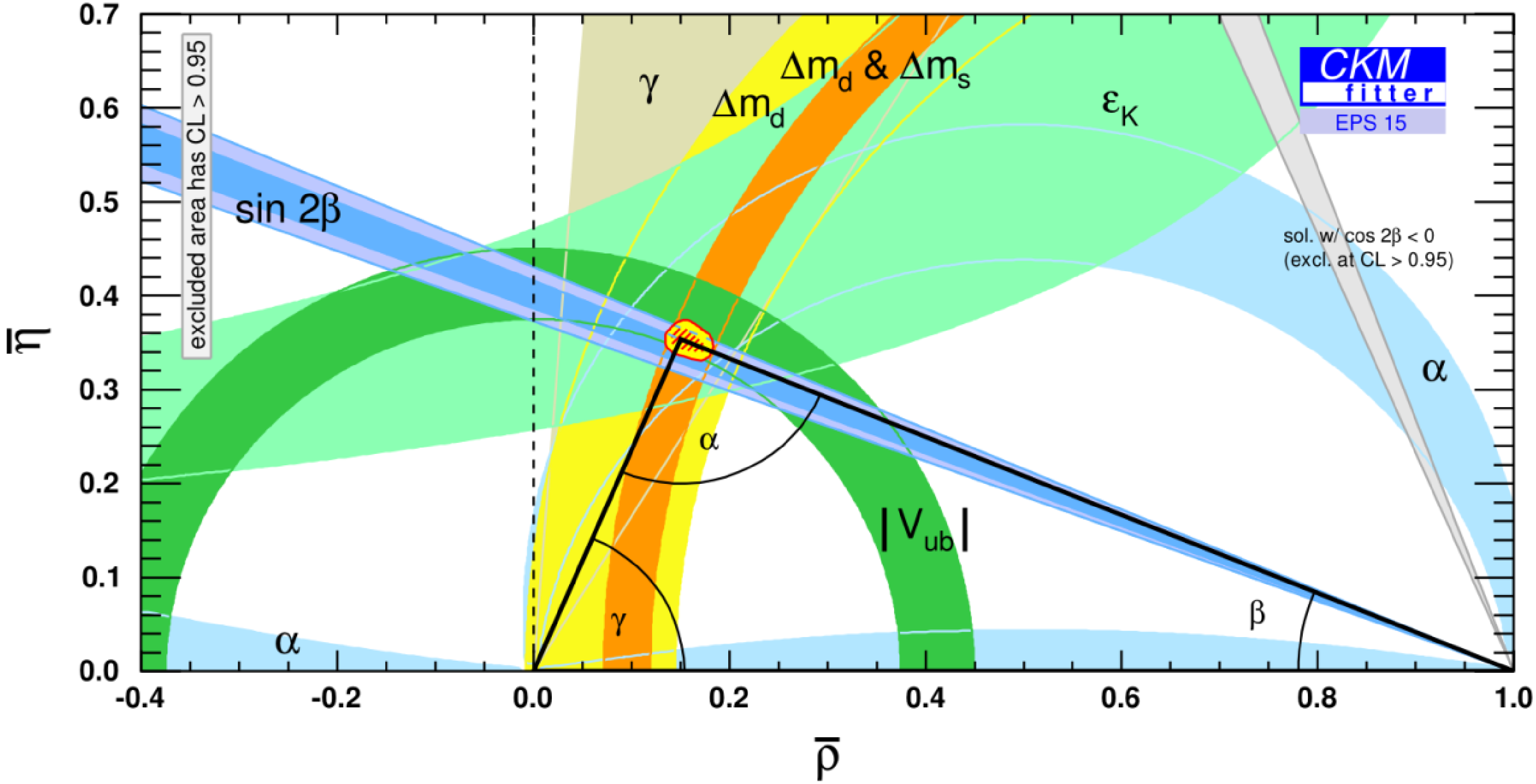


$$\gamma = \left(70.9^{+7.1}_{-8.5}\right)^\circ$$

Uncertainty better than combined B factories



Unitarity triangle

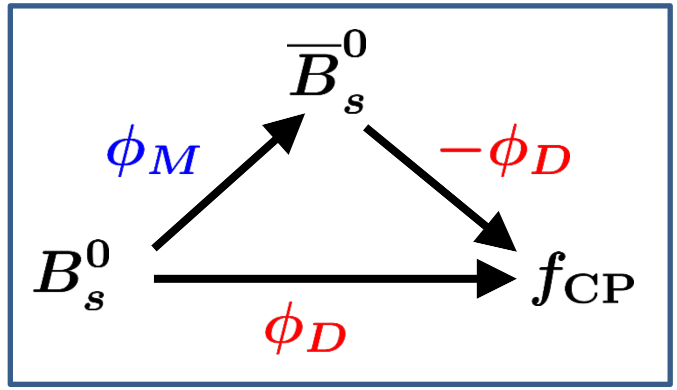


CPV through the interference between mixing and decay

The inteference between two "decay paths" of a B_s meson to a CP eigenstate gives rise to a (final state dependent) weak phase $\phi_s = \phi_M - 2\phi_D$

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

$$= -\eta_f \sin(\phi_s)\sin(\Delta m_s t)$$



$\phi_D \approx 0$

in the SM

NP might add larges phases to the SM prediction: $\phi_s = \phi_s^{\mathrm{SM}} + \phi_s^{\mathrm{NP}}$

For $b \to c\bar{c}s$ $(B_s^0 \to J/\psi K^+K^-)$ indirect determination in the SM via global fits gives (neglecting penguin contributions):

$$\phi_s^{\mathrm{SM}} = -2\arg\left(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = 0.0363 \pm 0.0013 \text{ rad}$$

CKMfitter
PRD 84 (2011) 033005

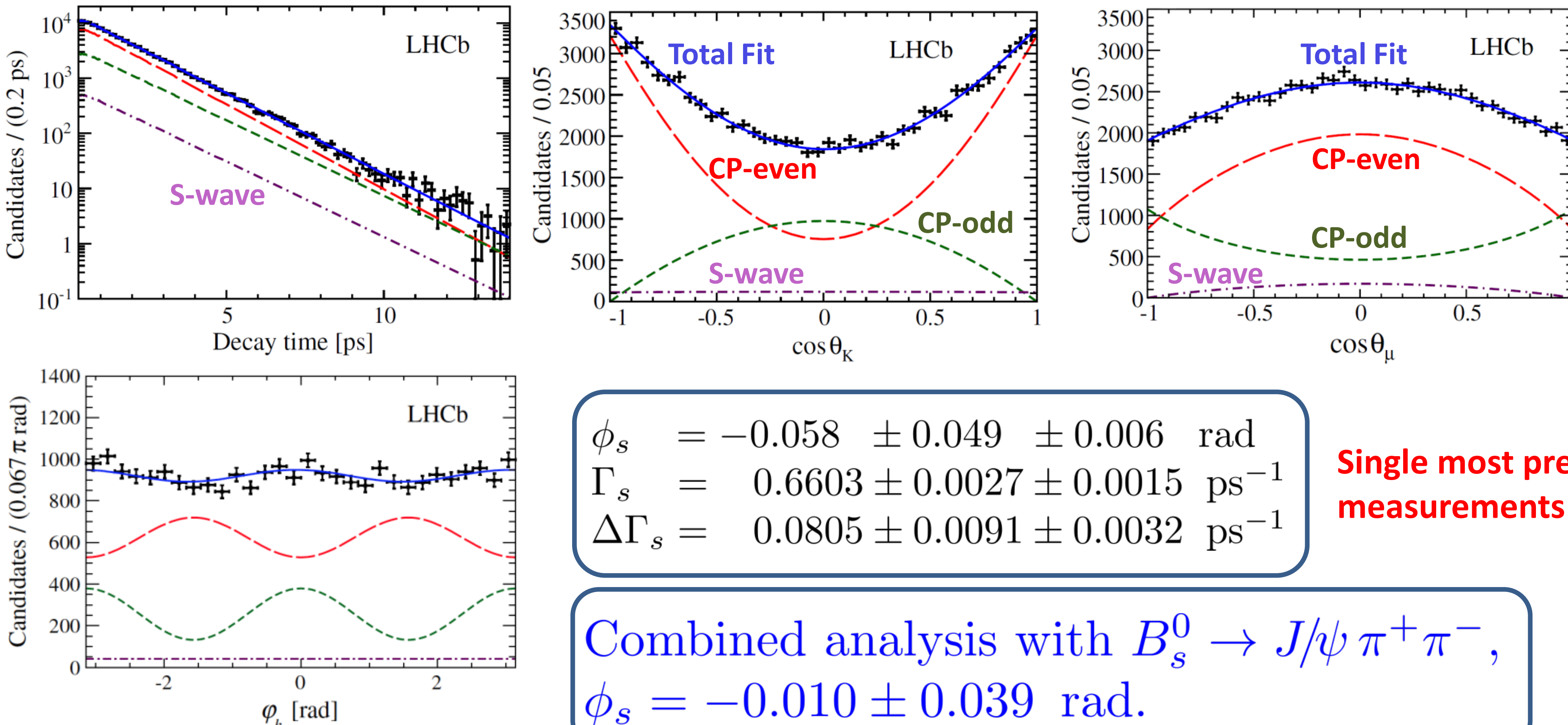
A precise determination of ϕ_s is as a sensitive test of NP in the B_s sector.

ϕ_s from $B_s^0 \to J/\psi K^+ K^-$

$\int \mathcal{L} = 3\ \mathrm{fb}^{-1}$

PRL 114, 041801 (2015)

- Final state with CP-even and CP-odd components. KK system dominated by ϕ reson.
- Fit invariant mass, decay time and angular distributions of flavour-tagged events.
- $3\mathrm{fb}^{-1}$ of data at √s=7 TeV and 8 TeV. (96000 events). Tagging power (3.73 ± 0.15)%



$$\begin{aligned}\phi_s &= -0.058 \pm 0.049 \pm 0.006 \ \ \mathrm{rad}\\ \Gamma_s &= \ \ 0.6603 \pm 0.0027 \pm 0.0015 \ \ \mathrm{ps}^{-1}\\ \Delta\Gamma_s &= \ \ 0.0805 \pm 0.0091 \pm 0.0032 \ \ \mathrm{ps}^{-1}\end{aligned}$$

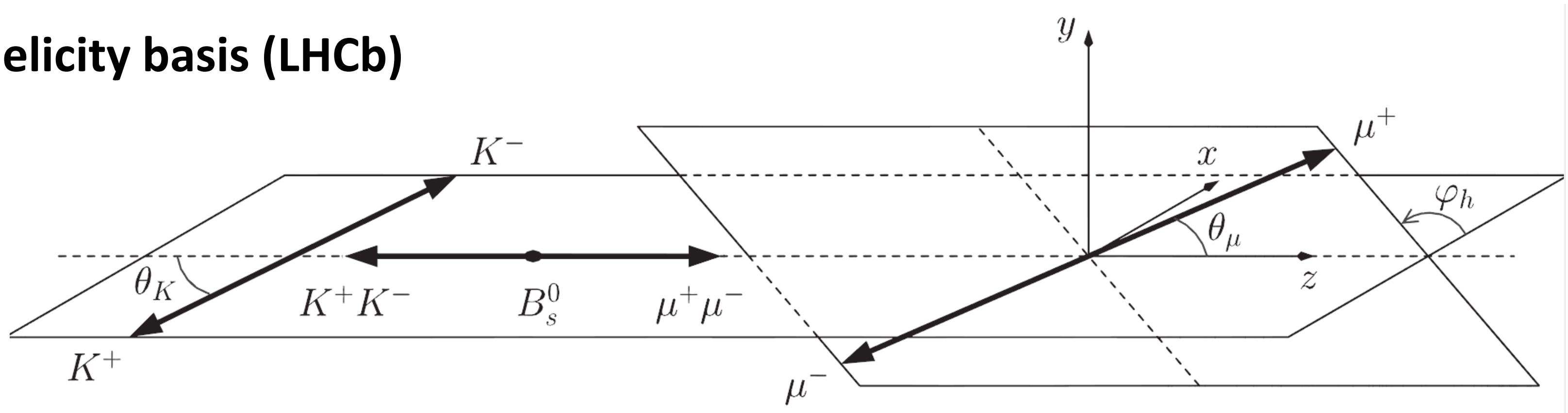
Single most precise measurements

Combined analysis with $B_s^0 \to J/\psi\, \pi^+\pi^-$,
$\phi_s = -0.010 \pm 0.039$ rad.

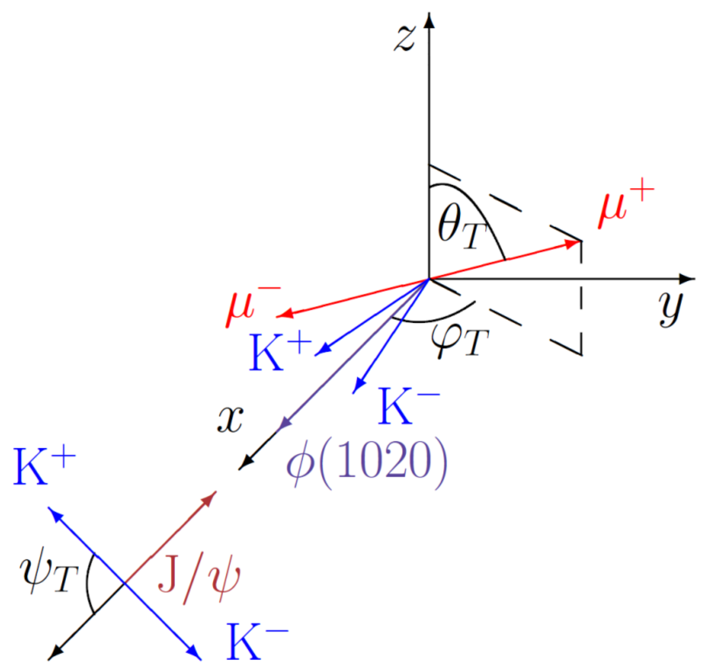
Angles expressed in the helicity basis (see next slide).

Helicity basis and transversity basis

Helicity basis (LHCb)

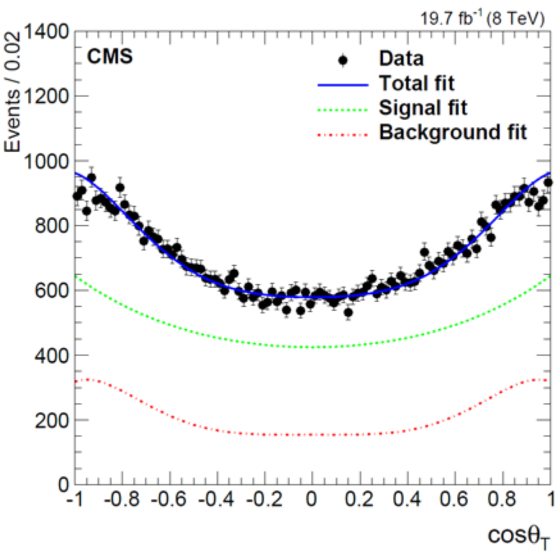


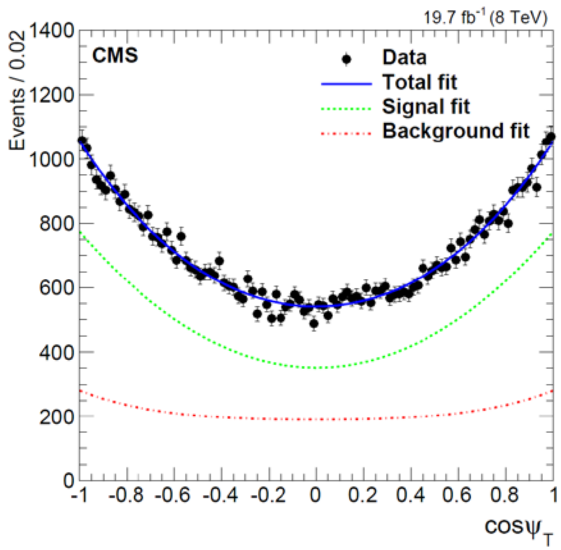
Transversity basis (ATLAS and CMS)

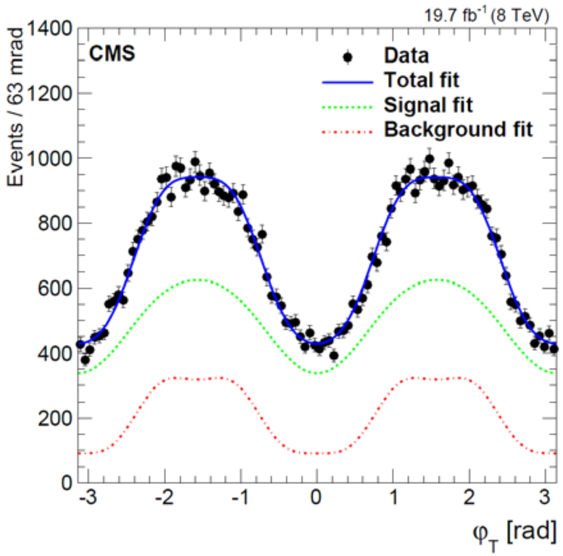


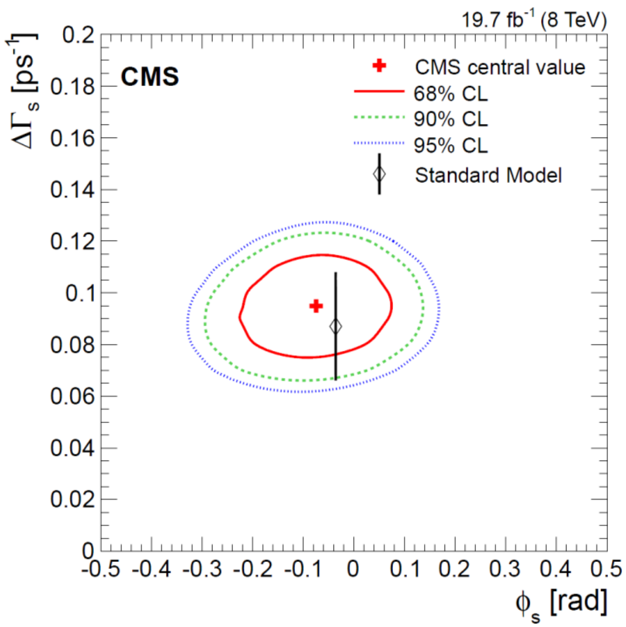
ϕ_s from $B_s^0 \to J/\psi\,\phi$

CMS-BPH-13-012







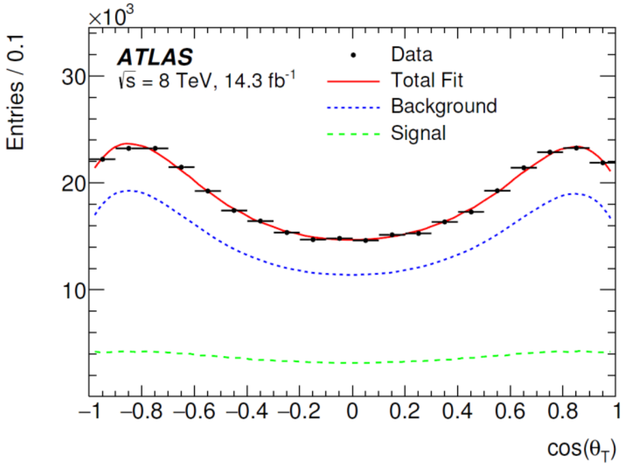


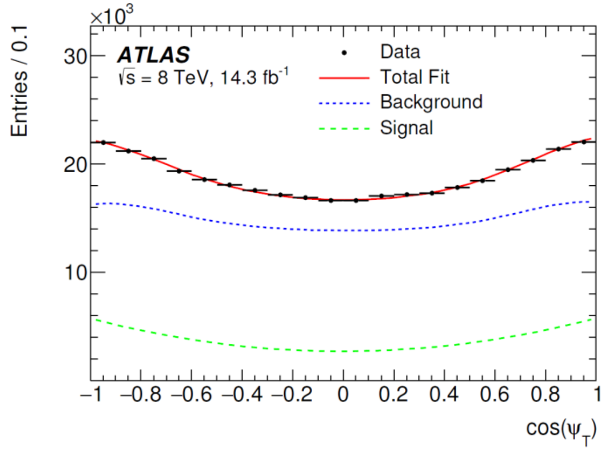
Angles expressed in the transversity basis

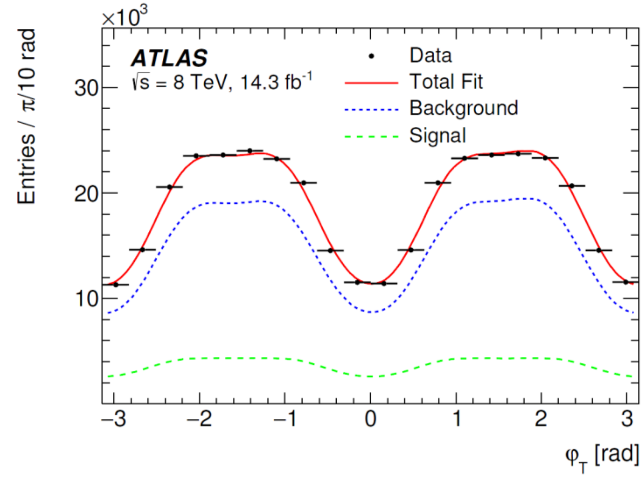
$$\phi_s = -0.075 \pm 0.097\,(\text{stat}) \pm 0.031\,(\text{syst})\,\text{rad}$$
$$\Delta\Gamma_s = 0.095 \pm 0.013\,(\text{stat}) \pm 0.007\,(\text{syst})\,\text{ps}^{-1}.$$

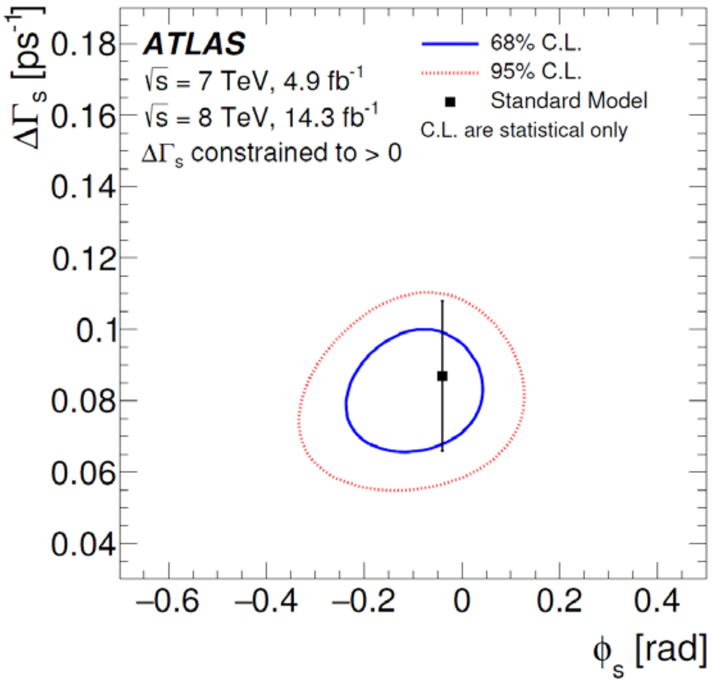
ϕ_s from $B_s^0 \to J/\psi\,\phi$

arXive:1601.03297





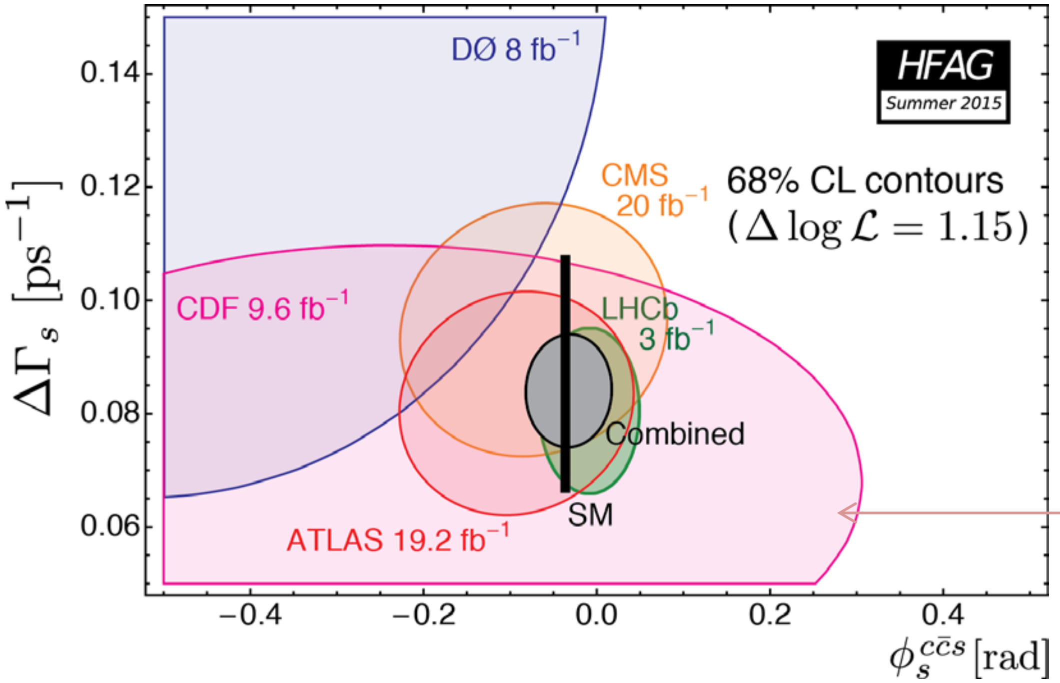




Angles expressed in the transversity basis

$$\begin{aligned}\phi_s &= -0.098 \pm 0.084\ (\text{stat.}) \pm 0.040\ (\text{syst.})\ \text{rad}\\ \Delta\Gamma_s &= 0.083 \pm 0.011\ (\text{stat.}) \pm 0.007\ (\text{syst.})\ \text{ps}^{-1}\\ \Gamma_s &= 0.677 \pm 0.003\ (\text{stat.}) \pm 0.003\ (\text{syst.})\ \text{ps}^{-1}\end{aligned}$$

Combined measurement of ϕ_s



$$\phi_s^{\text{HFAG WA}} = -0.034 \pm 0.033$$

Based on ATLAS preliminary results. Statistically uncertainties only.

World average dominated by LHCb combination. Includes also results from $\overline{B}{}_s^0 \to D_s^+ D_s^-$

The result is compatible with the SM prediction, but still room for NP.

Constraints on penguin pollution using $B_s^0 \to J/\psi\, \bar{K}^*$ and $B^0 \to J/\psi\, \rho^0$

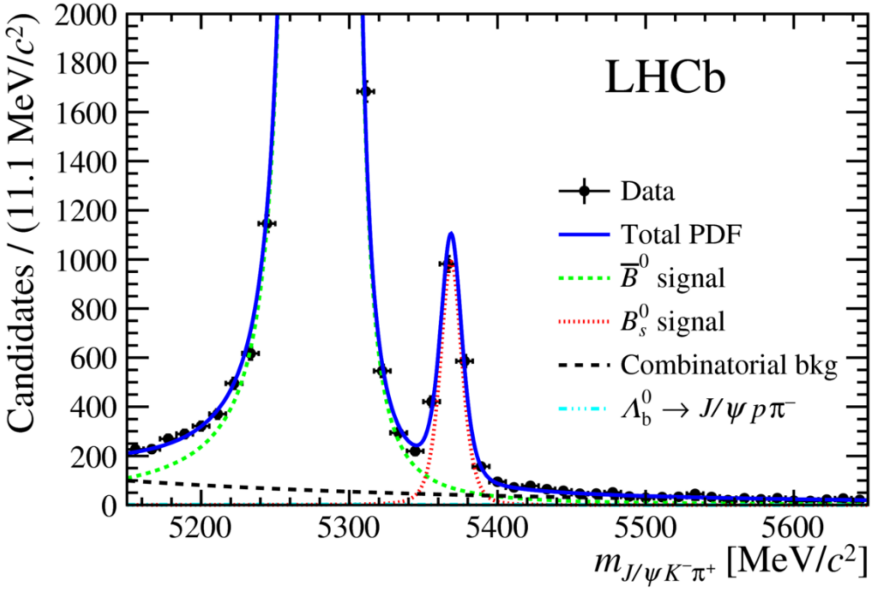
Control of penguin pollution

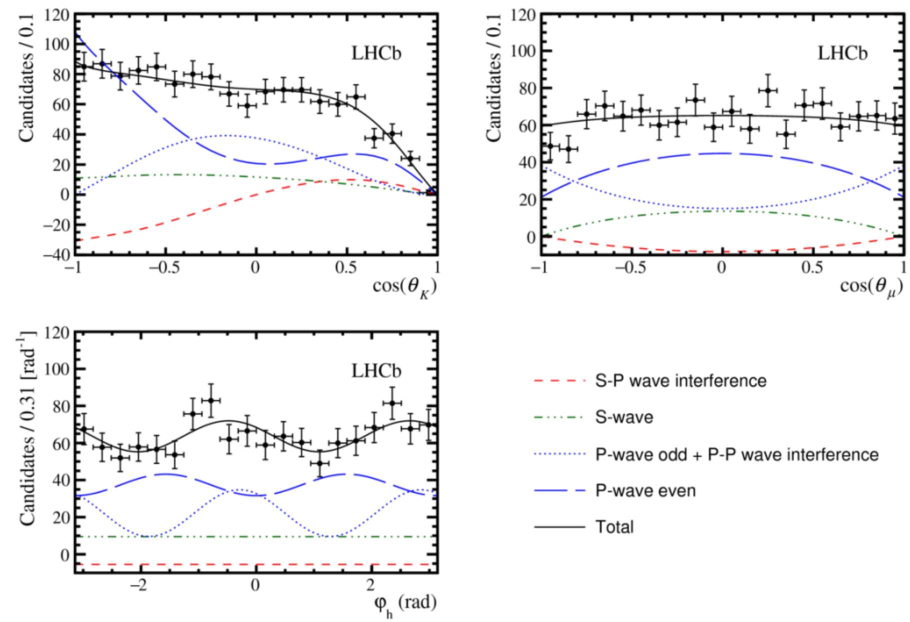
$\int \mathcal{L} = 3\ \mathrm{fb}^{-1}$

JHEP11 (2015) 082

Two main approaches which rely on flavour symmetries:
$B_s^0 \to J/\psi\, \bar{K}^*$ and $B^0 \to J/\psi\, \rho^0$

Phys. Lett. B742 (2015) 38–49





From a combined analysis of both channels:

$$\Delta\phi_{s,0}^{J/\psi\,\phi} = 0.000^{+0.009}_{-0.011}\,(\mathrm{stat})\ ^{+0.004}_{-0.009}\,(\mathrm{syst})\,\mathrm{rad}\,,$$

$$\Delta\phi_{s,\|}^{J/\psi\,\phi} = 0.001^{+0.010}_{-0.014}\,(\mathrm{stat})\ \pm 0.008\,(\mathrm{syst})\,\mathrm{rad}$$

$$\Delta\phi_{s,\perp}^{J/\psi\,\phi} = 0.003^{+0.010}_{-0.014}\,(\mathrm{stat})\ \pm 0.008\,(\mathrm{syst})\,\mathrm{rad}$$

$|V_{ub}|$ from $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$

$\int \mathcal{L} = 2\ \mathrm{fb}^{-1}$ Nature Phys. 11 (2015) 743

Long standing discrepancy (**3σ**) between inclusive and exclusive measurements of V_{ub}:

$|V_{ub}| = (4.41 \pm 0.15^{+0.15}_{-0.17}) \times 10^{-3}$ **inclusive** $(b \to u\ell^-\bar{\nu}_\ell)$ (HFAG arXiv:1412.7515)

$|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}$ **exclusive** $(B \to \pi\ell\bar{\nu}_\ell)$ PDG, Chin. Phys. **C38** (2014) 090001

Measure $|V_{ub}| = (3.27 \pm 0.23) \times 10^{-3}$ through the following ratio (first ever to use a baryonic decay). 2 fb^{-1}.

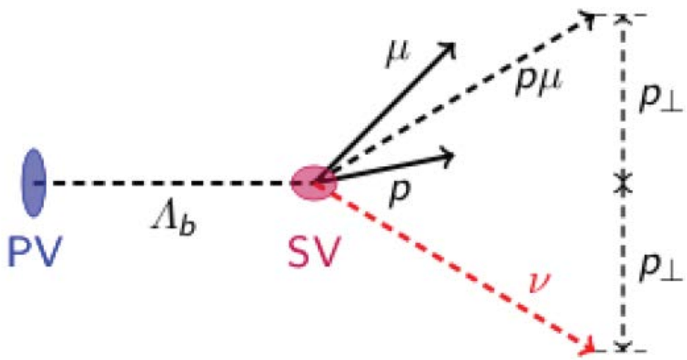
$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)} R_{\mathrm{FF}}$$

$\Lambda_c^+ \to pK^-\pi^+$

R_{FF} ratio of relevant form factors, from lattice QCD.

Experimental method → reconstruct a "corrected" mass:

$$m_{\mathrm{corr}} = \sqrt{m_{h\mu}^2 + p_\perp^2} + p_\perp \qquad h = p, \text{ or } \quad h = \Lambda_c^+$$



$m_{h\mu}$ is the "visible" mass of the hμ pair.

Signal extraction from 1D fit to m_{corr}

$|V_{ub}|$ from $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$

$\int \mathcal{L} = 2\ \mathrm{fb}^{-1}$

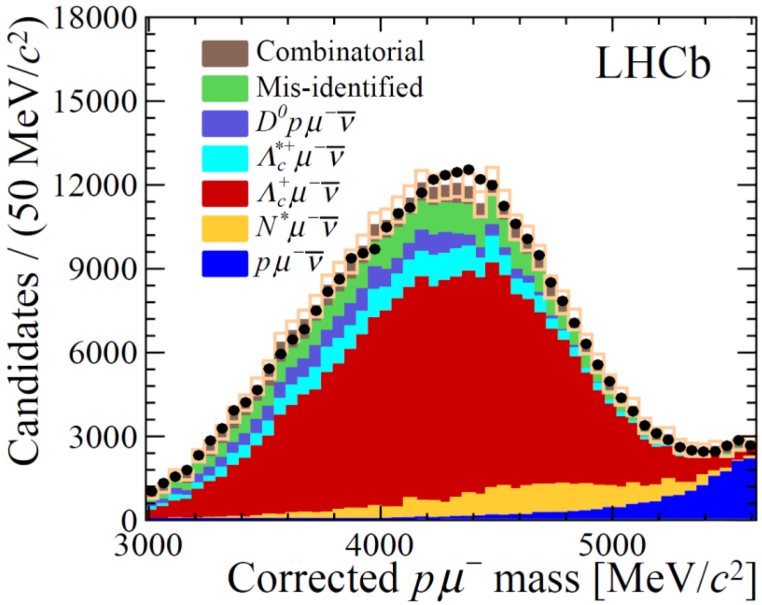
Nature Phys. 11 (2015) 743

Using the Λ_b mass and flight direction, $q^2 = m^2_{\mu\nu} = (p_{\Lambda_b} - p_\mathrm{p})^2$ can be estimated.

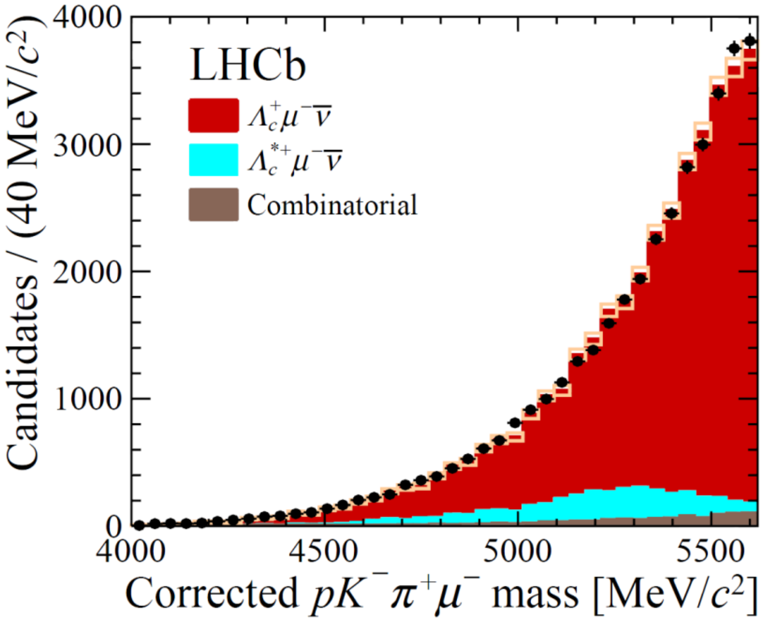
To avoid large corrections from R_{FF}, require

$$q^2 > 15\ \mathrm{GeV}^2/c^2 \text{ for } p\mu\bar{\nu}$$
$$q^2 > 7\ \mathrm{GeV}^2/c^2 \text{ for } \Lambda_c\mu\bar{\nu}$$

Use isolation algorithms to remove background with extra charged tracks.



$$N(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu) = 17687 \pm 733$$



$$N(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu) = 34255 \pm 571$$

$|V_{ub}|$ from $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$

Nature Phys. 11 (2015) 743

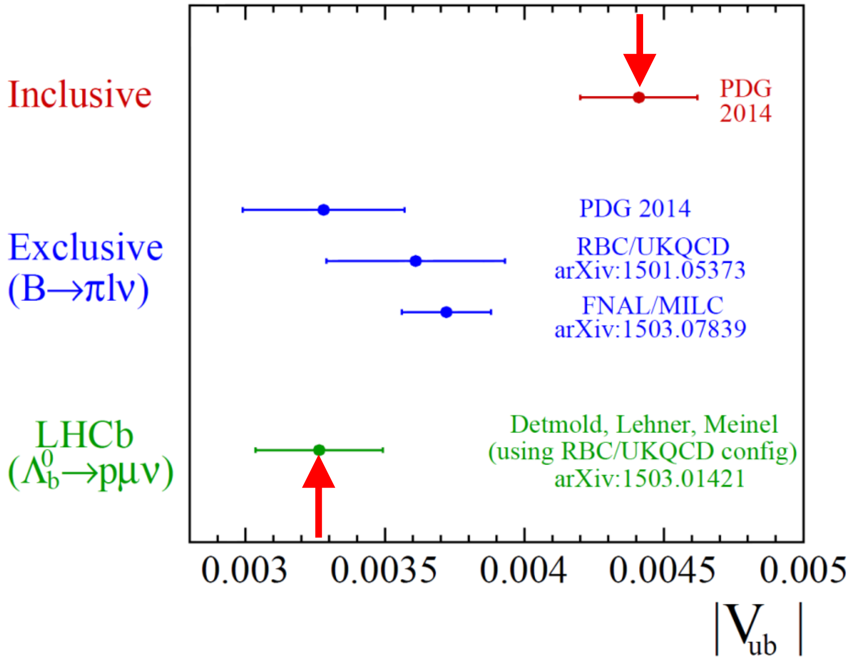
$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu\bar{\nu})_{q^2>15\ \mathrm{GeV}}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu\bar{\nu})_{q^2>7\ \mathrm{GeV}}} = (1.00 \pm 0.04\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst})) \times 10^{-3}$$

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004\,(\mathrm{exp}) \pm 0.004\,(\mathrm{lattice})$$

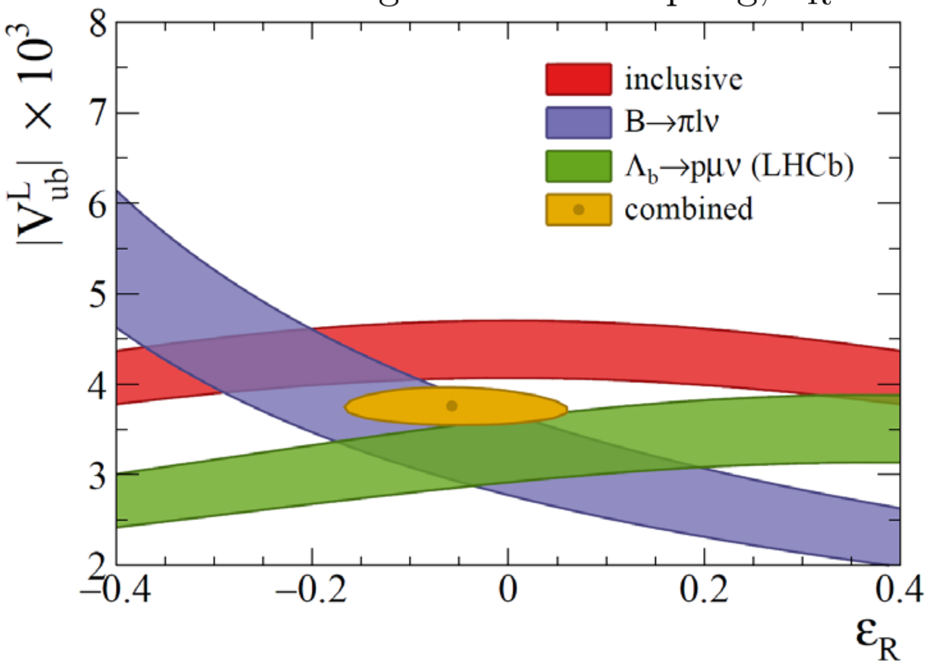
$$\boxed{|V_{ub}| = (3.27 \pm 0.23) \times 10^{-3}}$$

at 3.5 σ from inclusive measur.

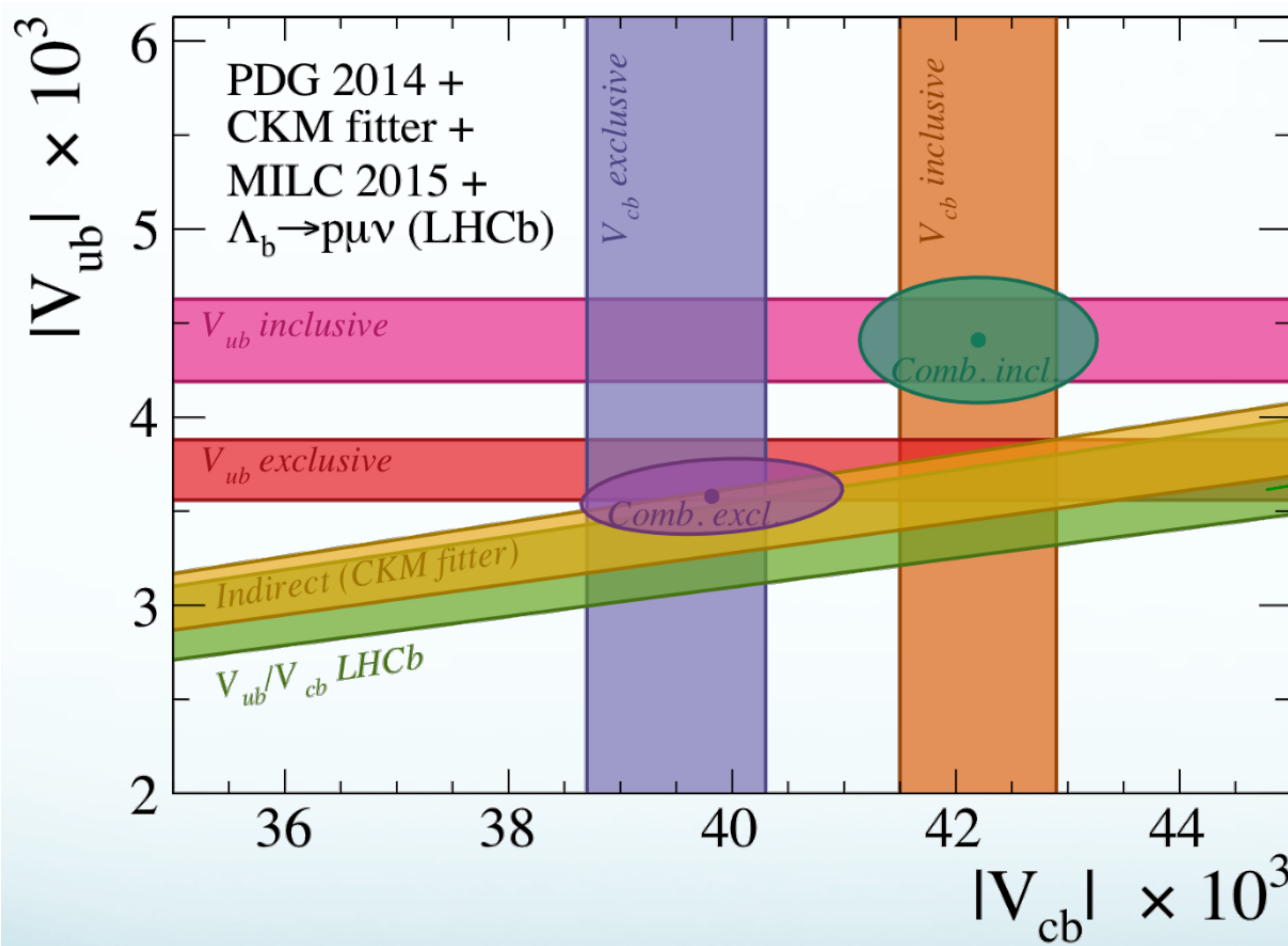
Rules out models with large contributions from right-handed currents



Left-handed coupling, $|V_{ub}^{\mathrm{L}}|$ versus fractional right-handed coupling, ε_{R}



$V_{ub} - V_{cb}$ plane



LHCb

Neutral Meson Mixing

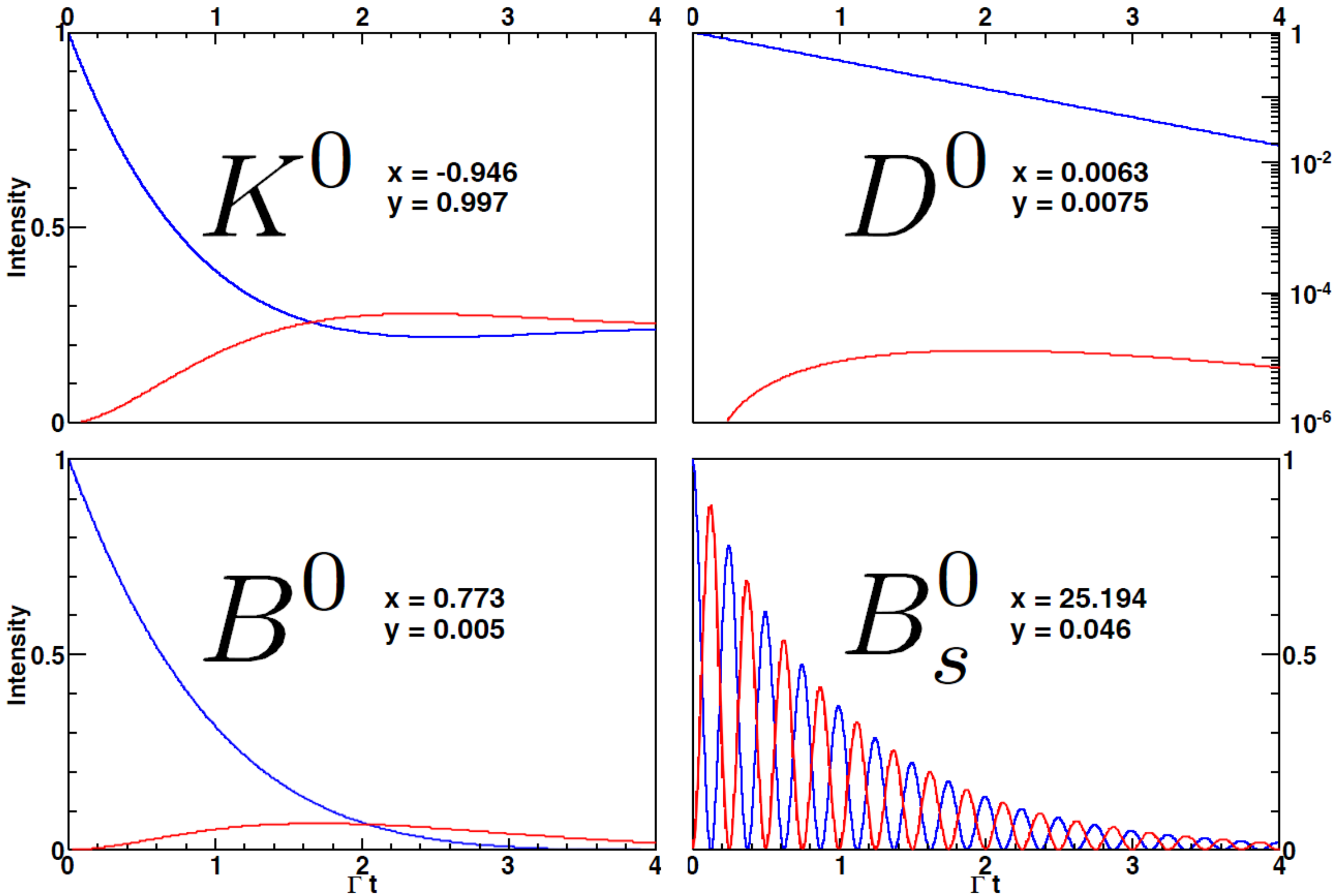
Slide from M. Kenzie
Moriond QCD 2016

$$P\Big(M(0) \to M(t)\Big) \qquad P\Big(M(0) \to \overline{M}(t)\Big)$$

Plots from
arXiv:1209.5806

$$x = \frac{\Delta m}{\Gamma}$$

$$y = \frac{\Delta \Gamma}{2\Gamma}$$



B^0 oscillation frequency

$\int \mathcal{L} = 3\ \mathrm{fb}^{-1}$ LHCb-PAPER-2015-031

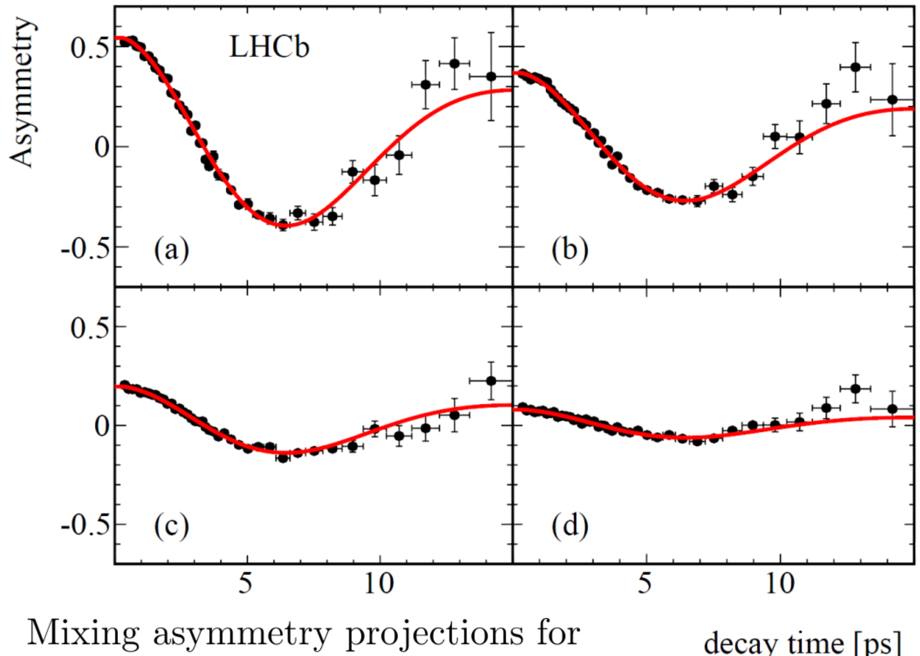
Use $B^0 \to D^{(*)-}\mu^+\nu_\mu X$ decays to make world-leading Δm_d determination.

Assume $\Delta\Gamma_d \approx 0$ and neglect CPV in mixing

$$N^{\mathrm{unmix}}(t) \equiv N(B^0 \to D^{(*)-}\mu^+\nu_\mu X)(t) \propto e^{-\Gamma_d t}[1+\cos(\Delta m_d t)]$$

$$N^{\mathrm{mix}}(t) \equiv N(B^0 \to \overline{B}^0 \to D^{(*)+}\mu^-\overline{\nu}_\mu X)(t) \propto e^{-\Gamma_d t}[1-\cos(\Delta m_d t)]$$

$$\boxed{A(t) = \frac{N^{\mathrm{unmix}}(t) - N^{\mathrm{mix}}(t)}{N^{\mathrm{unmix}}(t) + N^{\mathrm{mix}}(t)} = \cos(\Delta m_d t)}$$



Mixing asymmetry projections for $B^0 \to D^-\mu^+\nu_\mu X$ in four flavour tagging categories.

B^0 flavour at production time and decay time determined using flavour tagging algorithms (effective tagging efficiency close to 2.5%)

Most precise single measurement

$$\Delta m_d = (505.0 \pm 2.1 \pm 1.0)\ \mathrm{ns}^{-1}$$

(stat) (syst)

World average without this measurement

$$\Delta m_d = (510 \pm 3)\ \mathrm{ns}^{-1}$$

B^0 oscillation frequency

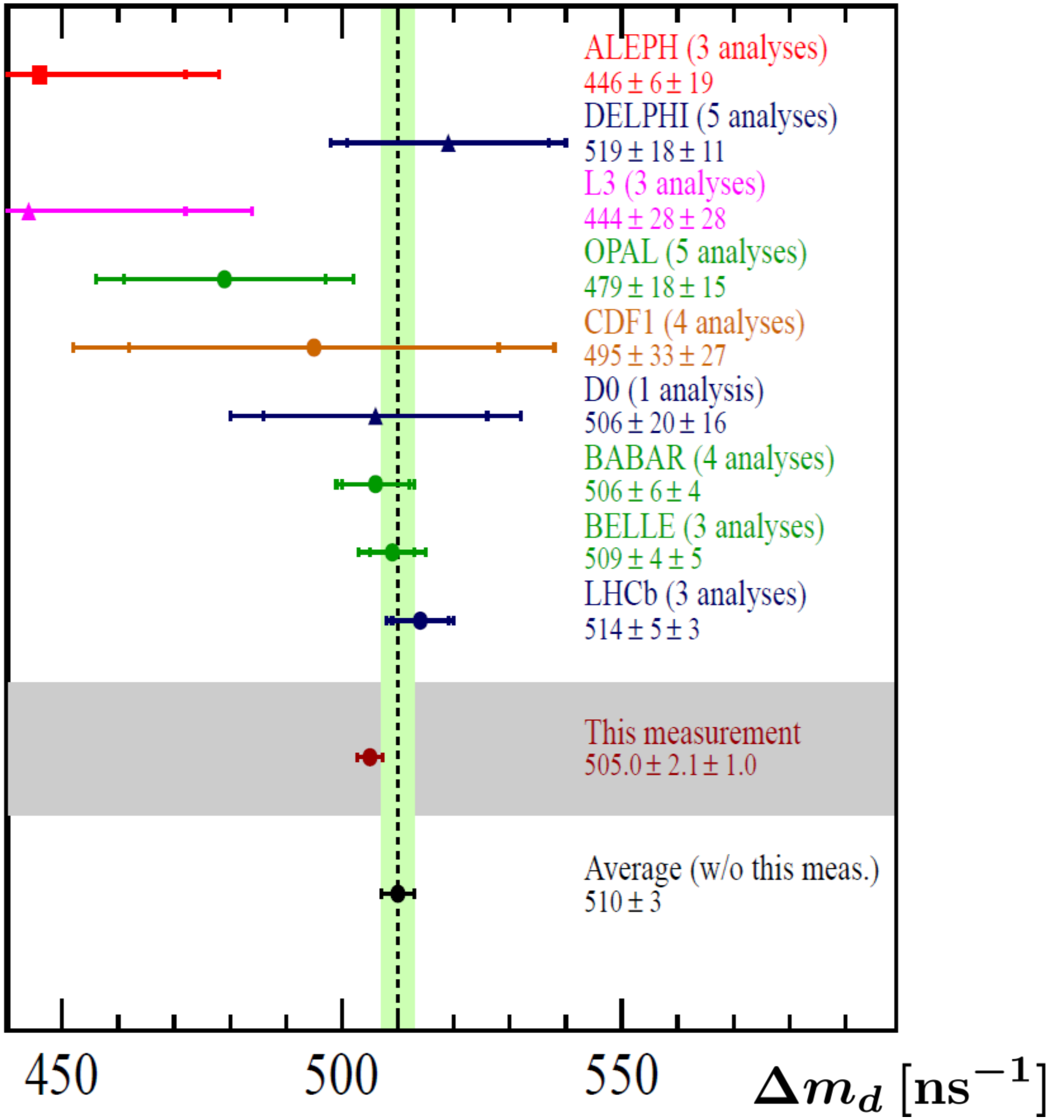
From PDG 2015

$$\Delta m_d = (0.510 \pm 0.003)\ \mathrm{ps}^{-1}$$
$$\Delta m_s = (17.757 \pm 0.021)\ \mathrm{ps}^{-1}$$

Theory prediction (Fermilab Lattice and MILC Collaborations) arXiv:1602.03560

$$\Delta m_d = 0.639(50)(36)(5)(13)\ \mathrm{ps}^{-1}$$
$$\Delta m_d/\Delta m_s = 0.0323(9)(9)(0)(3)$$

Δm_d and $\Delta m_d/\Delta m_s$ measurements are 2.1 σ and 2.9 σ from prediction.



CP asym. in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

$\int \mathcal{L} = 3\ \mathrm{fb}^{-1}$ arXiv:1602.03160

World's most precise measurement of a time-integrated CP asymmetry in the charm sector.

Tag $\boldsymbol{D^0}$ $(\overline{\boldsymbol{D}}^{\boldsymbol{0}})$ from $\boldsymbol{D^{*+} \to D^0\pi^+}$ $(\boldsymbol{D^{*-} \to \overline{D}^0\pi^-})$ decays and measure
$\boldsymbol{\Delta A_{\mathrm{CP}} = A_{\mathrm{CP}}(K^+K^-) - A_{\mathrm{CP}}(\pi^+\pi^-)}$

Time-dependent
$$A_{CP}(f;t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)}$$

Time-integrated
$$A_{CP}(f) \approx a_{CP}^{\mathrm{dir}}(f)\left(1 + \frac{\langle t(f)\rangle}{\tau}y_{CP}\right) + \frac{\langle t(f)\rangle}{\tau}a_{CP}^{\mathrm{ind}}$$

$\langle t(f)\rangle$ is the mean decay time of $D^0 \to f$ decays in the reconstructed sample.

y_{CP} is the deviation from unity of the ratio of the effective lifetimes of decays to flavour specific and CP-even final states.

$$\begin{aligned}\Delta A_{CP} &\equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)\\ &\approx \Delta a_{CP}^{\mathrm{dir}}\left(1 + \frac{\overline{\langle t\rangle}}{\tau}y_{CP}\right) + \frac{\Delta\langle t\rangle}{\tau}a_{CP}^{\mathrm{ind}}\end{aligned}$$

CP asym. in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

arXiv:1602.03160

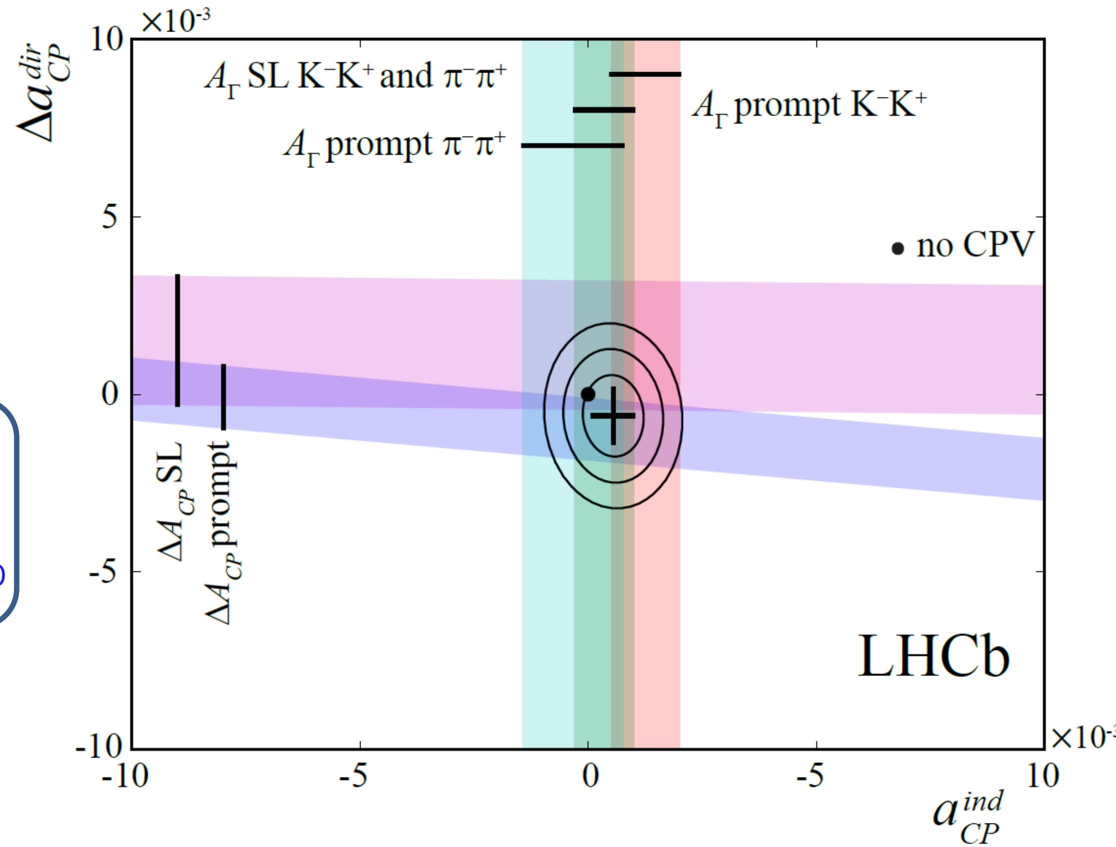
World's most precise measurement of a time-integrated CP asymmetry in the charm sector.

$$\Delta A_{\mathrm{CP}} = (-0.10 \pm 0.08 \pm 0.03)\%$$

Consistent with no Direct CP violation

Supersedes the value $\Delta A_{CP} = -0.82 \pm 0.21 \pm 0.11$ published in PRL 108, 111602 (2012), based only on an integrated luminosity of 0.6 fb^{-1}.

Direct versus Indirect A_{CP}



Combination of LHCb measurements

JHEP 07 (2014) 041, JHEP 04 (2012) 129
JHEP 04 (2015) 043, arXiv:1602.03160

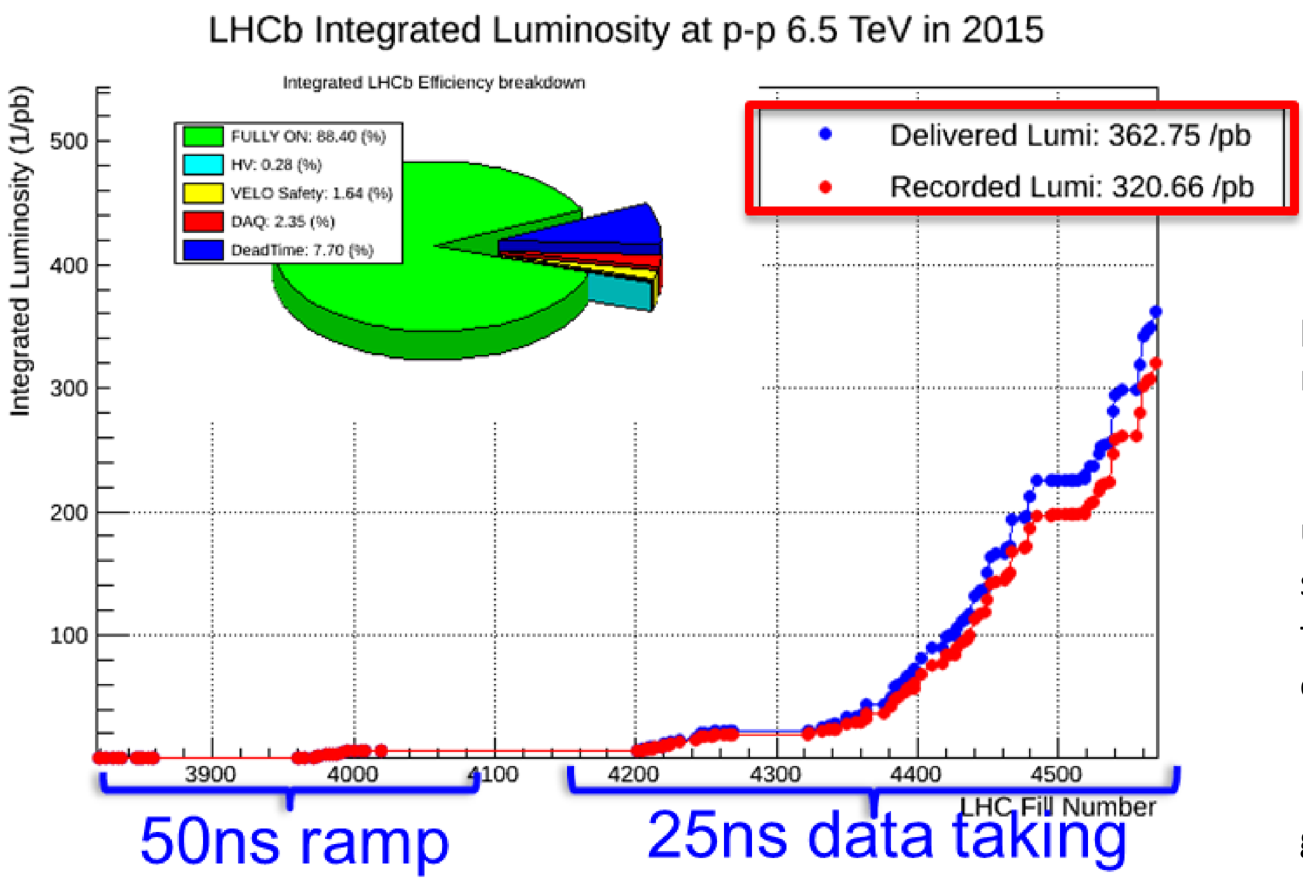
$$a^{\mathrm{ind}}_{\mathrm{CP}} = +(0.058 \pm 0.044)\%$$
$$\Delta a^{\mathrm{dir}}_{\mathrm{CP}} = -(0.061 \pm 0.076)\%$$

pp collisions @ 13 TeV

2015 pp collisions @ 13 TeV

321 pb^{-1} (0.3 fb^{-1}) of recorded luminosity in 2015

1 fb^{-1} in 2011 @ 7 TeV
3 fb^{-1} in 2012 @ 8 TeV



First open charm and J/Ψ production measurements made at 13 TeV.

Interesting to better understand QCD (cross sections, fragmentation functions, structure functions of the proton,…).

Unique LHCb acceptance: gluon PDF at small Bjorken x

Measurement of $\sin^2\theta_W$

2015 pp collisions @ 13 TeV

Measurement of forward J/ψ production cross-sections in pp collisions at 13 TeV

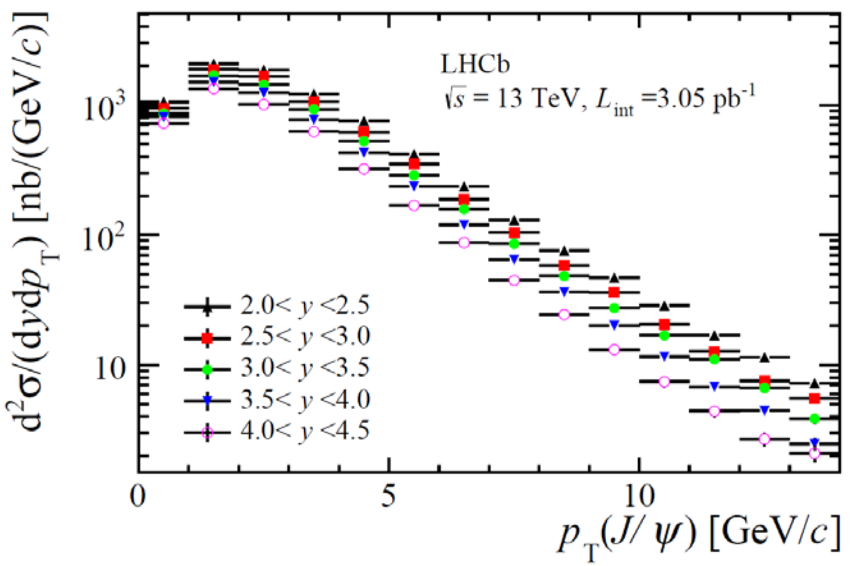
JHEP 10 (2015) 172

$\int \mathcal{L} = 3.05\ \mathrm{pb}^{-1}$

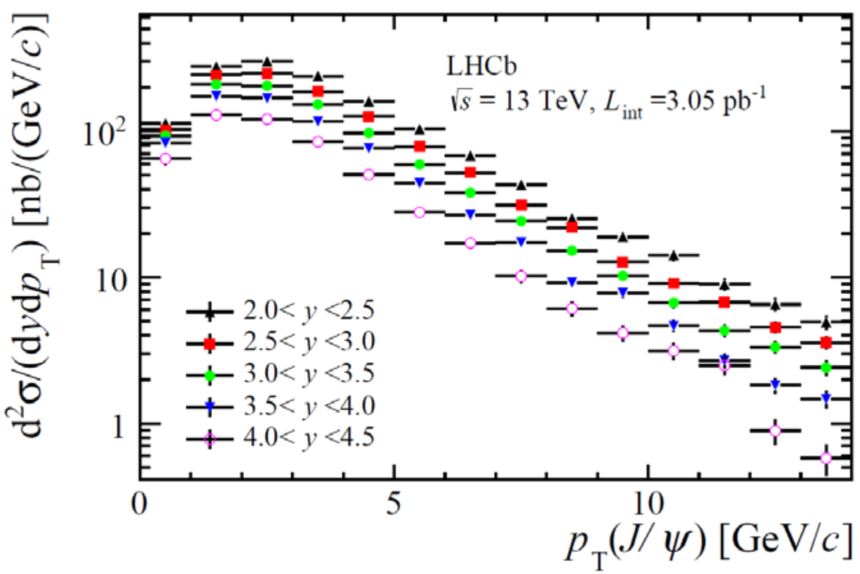
Double differential cross-sections as a function of p_T for different y bins.

$$p_T < 14\,\mathrm{GeV}/c \quad \text{and} \quad 2.0 < y < 4.5$$

Prompt J/ψ



J/ψ from B decays



Integrated $\sigma(\text{prompt } J/\psi) = 15.30 \pm 0.03 \pm 0.86\ \mu\mathrm{b}$

Integrated $\sigma(J/\psi \text{ from-}b) = 2.34 \pm 0.01 \pm 0.13\ \mu\mathrm{b}$

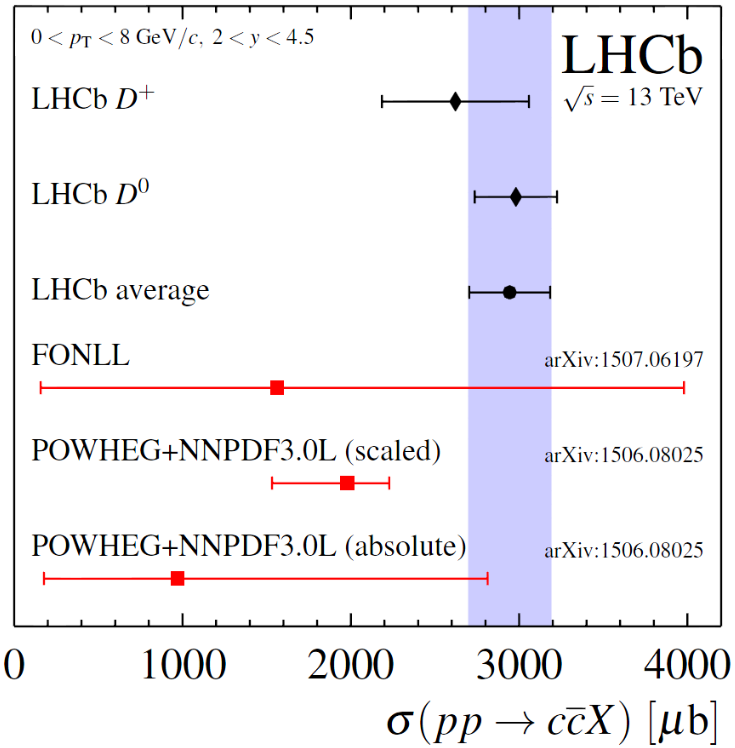
2015 pp collisions @ 13 TeV

JHEP03 (2016) 159

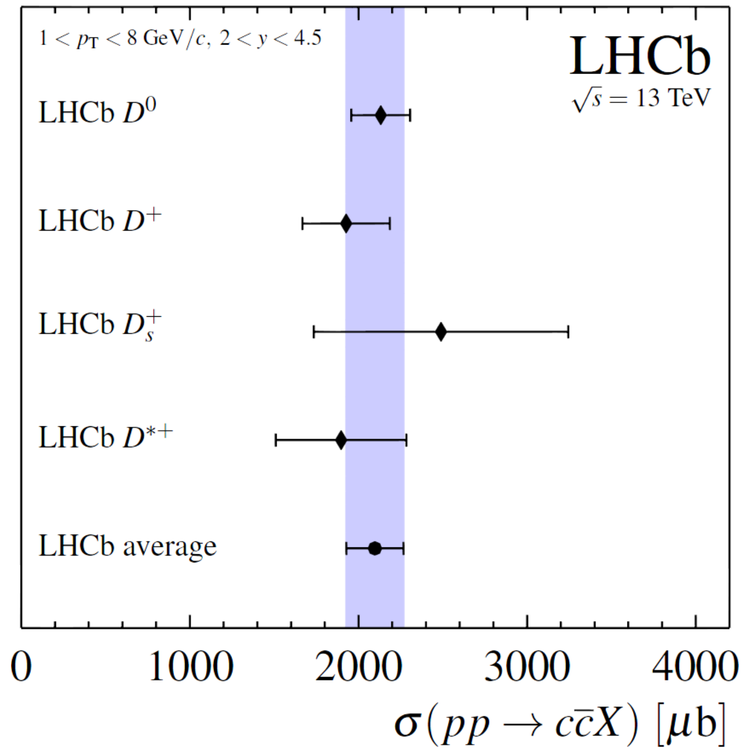
$\int \mathcal{L} = 4.98\ \mathrm{pb}^{-1}$

Measurements of prompt charm production cross-sections in pp collisions at 13 TeV

$0 < p_T < 8$ GeV$/c$

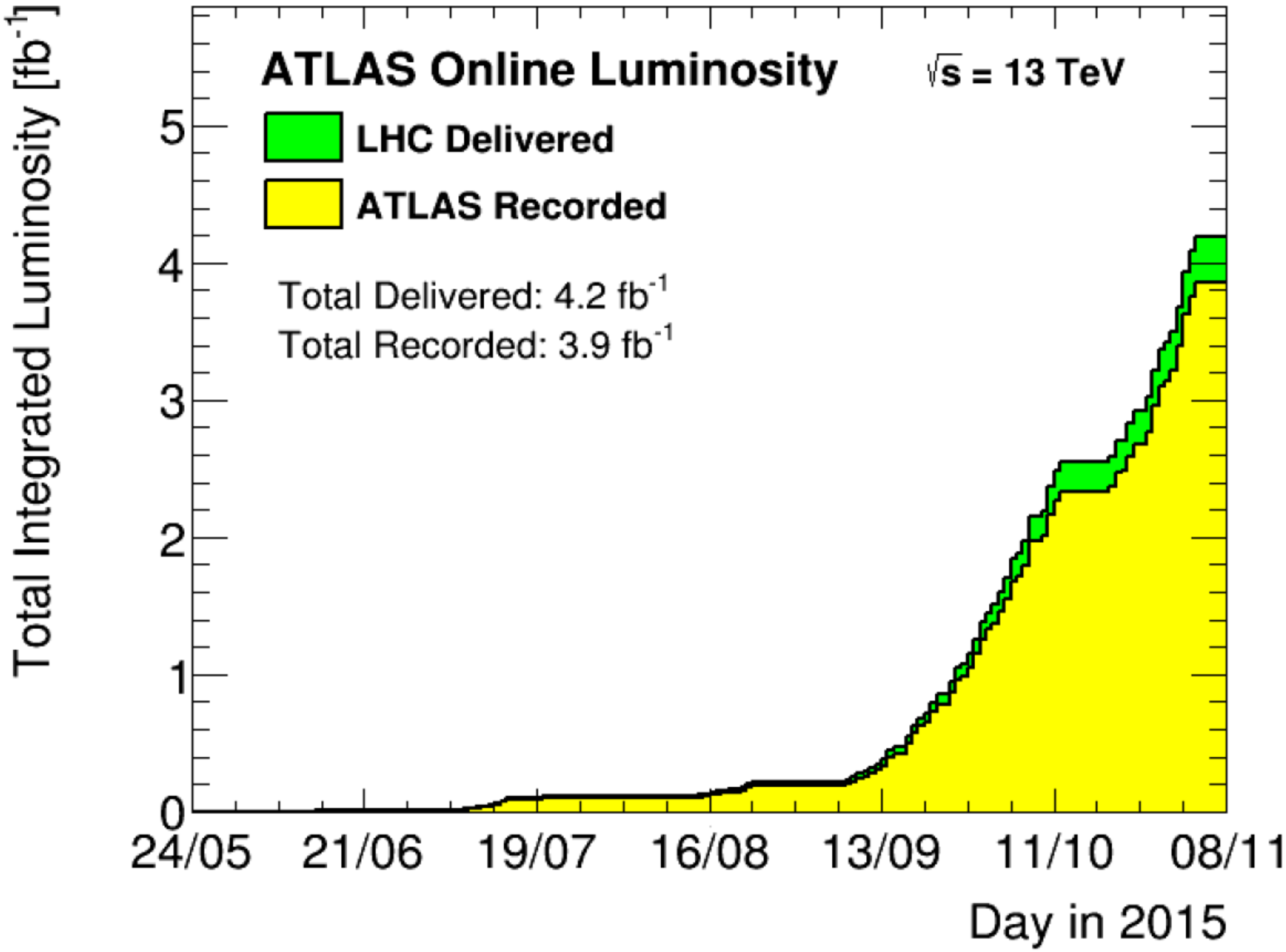


$1 < p_T < 8$ GeV$/c$

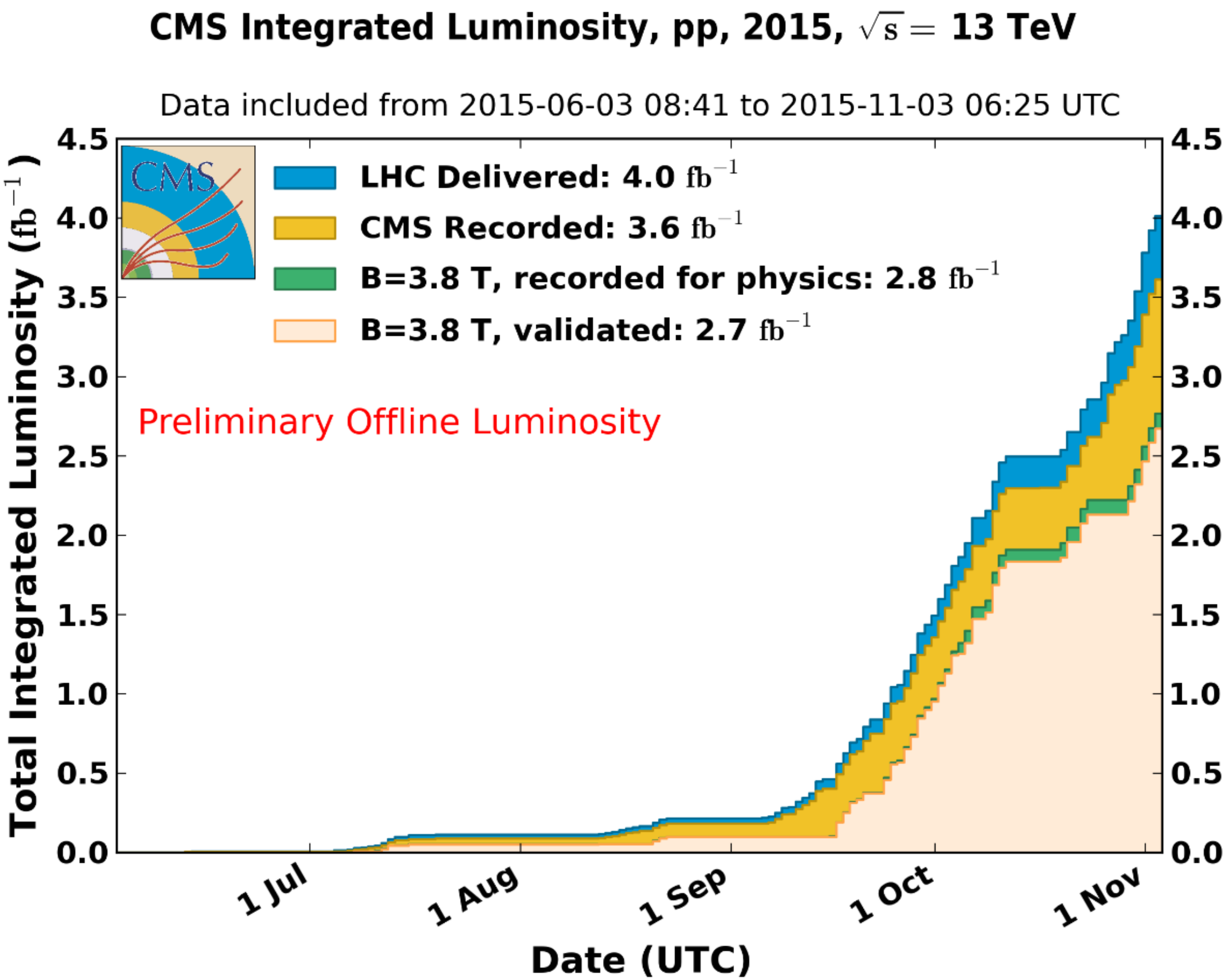


Integrated production cross-sections for several D mesons (diamonds) and the average (blue band). Red squares: theory predictions.

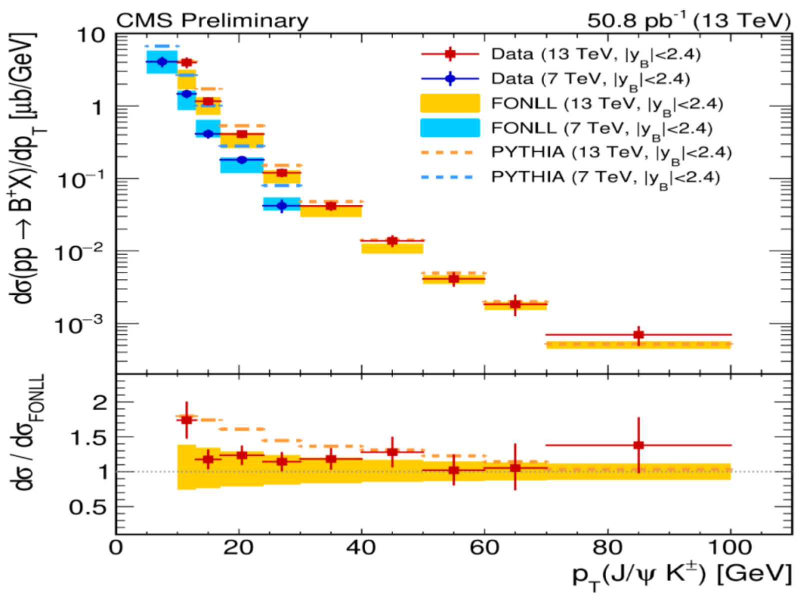
pp collisions @ 13 TeV

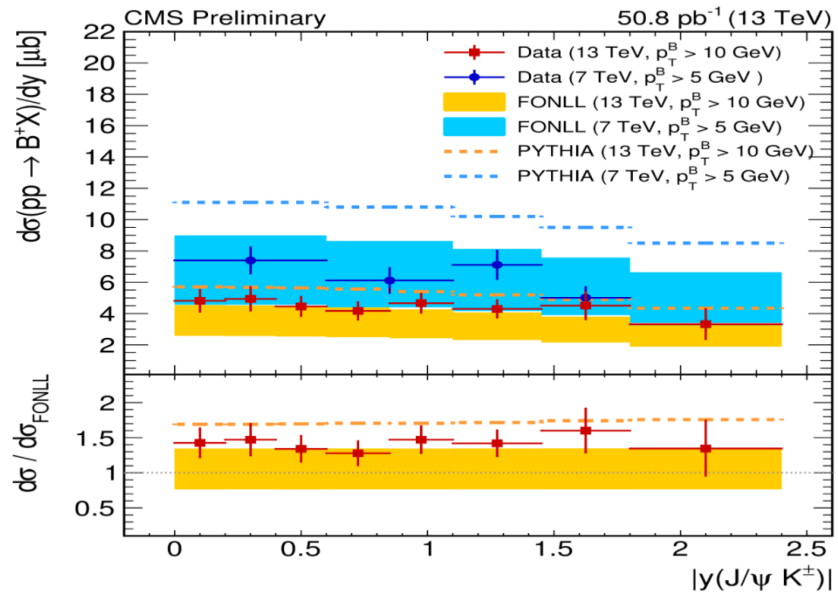


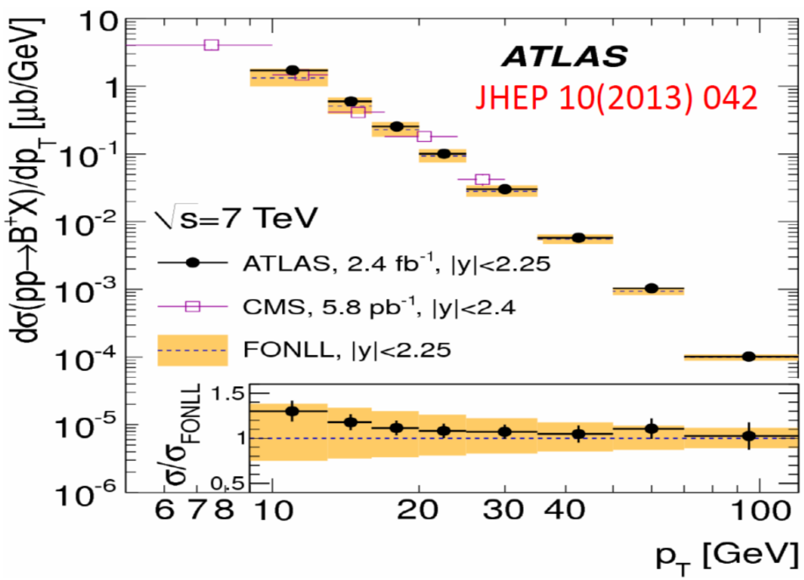
pp collisions @ 13 TeV

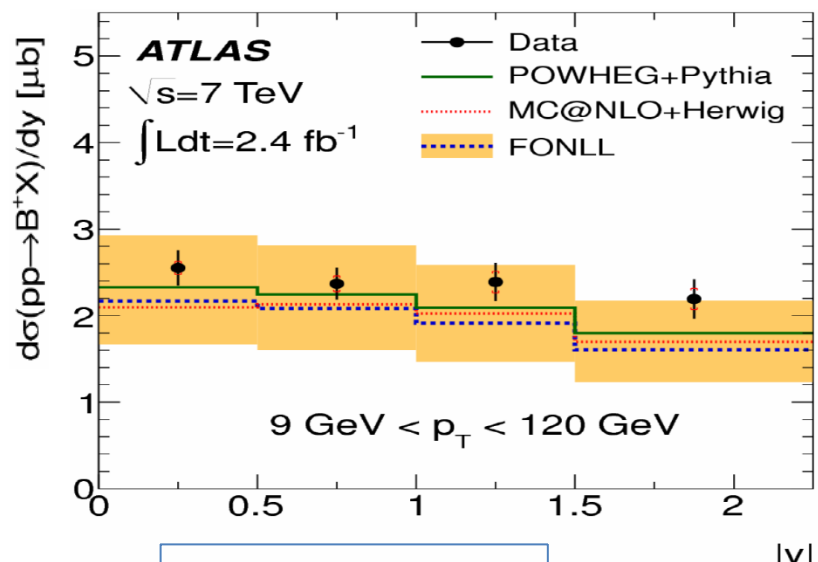


B⁺ prod. cross section @ 13 TeV from CMS and ATLAS









Modified from S. K. Swain Moriond EW 2016

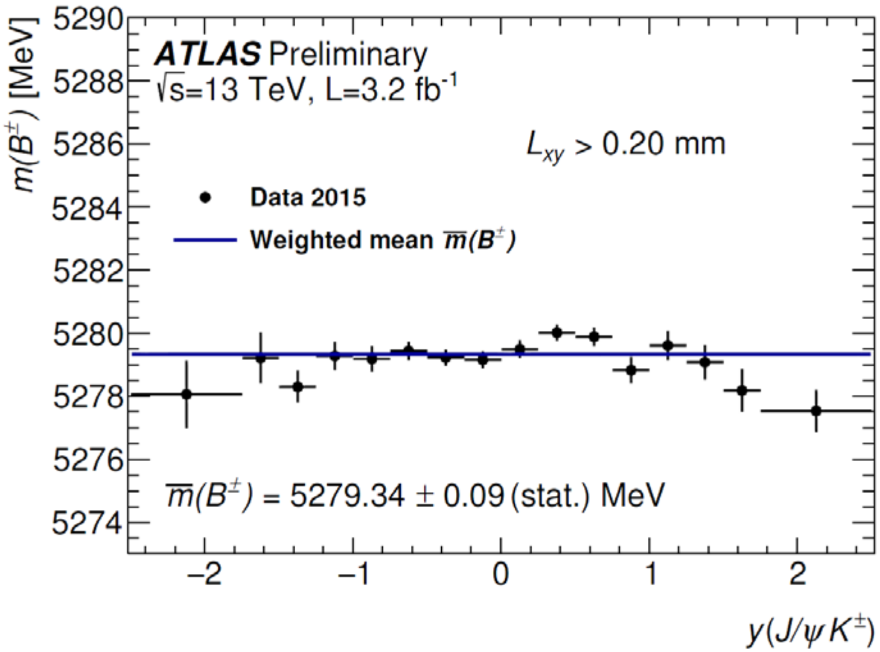
M(B^+) measurement @ 13 TeV from ATLAS

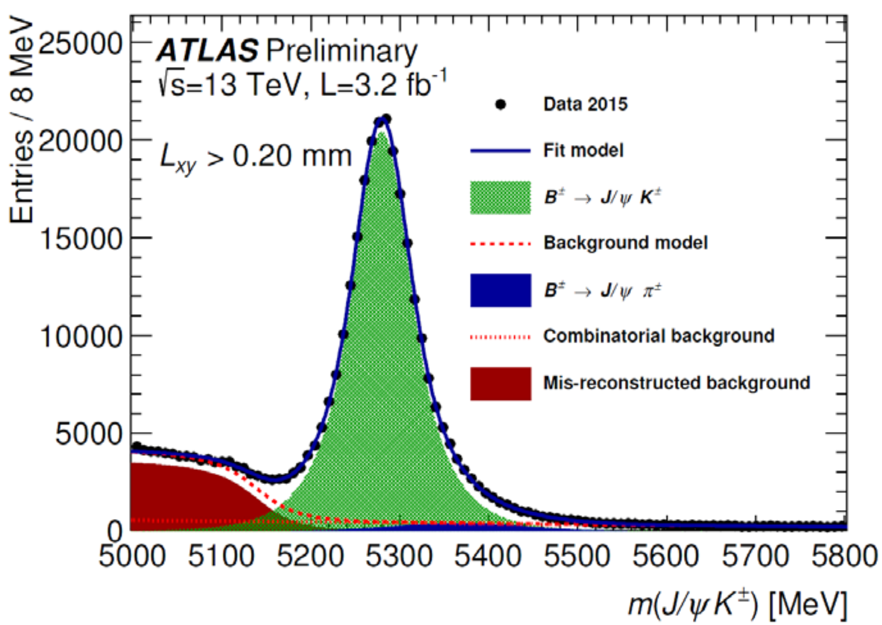
ATLAS-CONF-2015-064

Test ATLAS detector performance by looking at M(B^+) vs rapidity.

B^+ reconstructed in the $J/\psi\ (\mu^+\mu^-)K^+$ decay mode.

Use 3.2 fb^{-1} of data collected at 13 TeV.





$$M(B^+) = 5279.31 \pm 0.11\ \mathrm{MeV}$$ **(preliminary)**

$$(\mathrm{PDG\ 2014:}\ M(B^+) = 5279.29 \pm 0.15\ \mathrm{MeV})$$

Conclusions and Prospects

- Many more results not shown here.
- LHCb has performed in Run I better than expected, and it is improving in Run 2.
- Several measurements in heavy flavour physics start to show tensions with SM prediction. More data are needed to clarify the situation.
- Good progress in the first year of Run 2. Important improvements in the trigger for LHCb.
- LHCb expects to collect about 5 fb^{-1} of integrated luminosity in the full Run 2.
- Beyond Run 2 LHCb will be operating with an upgraded detector.
- ATLAS and CMS also performing very well, as shown in detail in other talks at this conference.

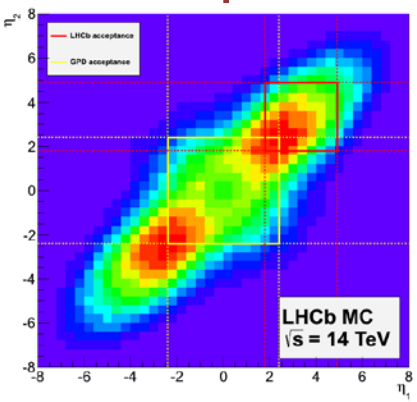
Thanks for your attention

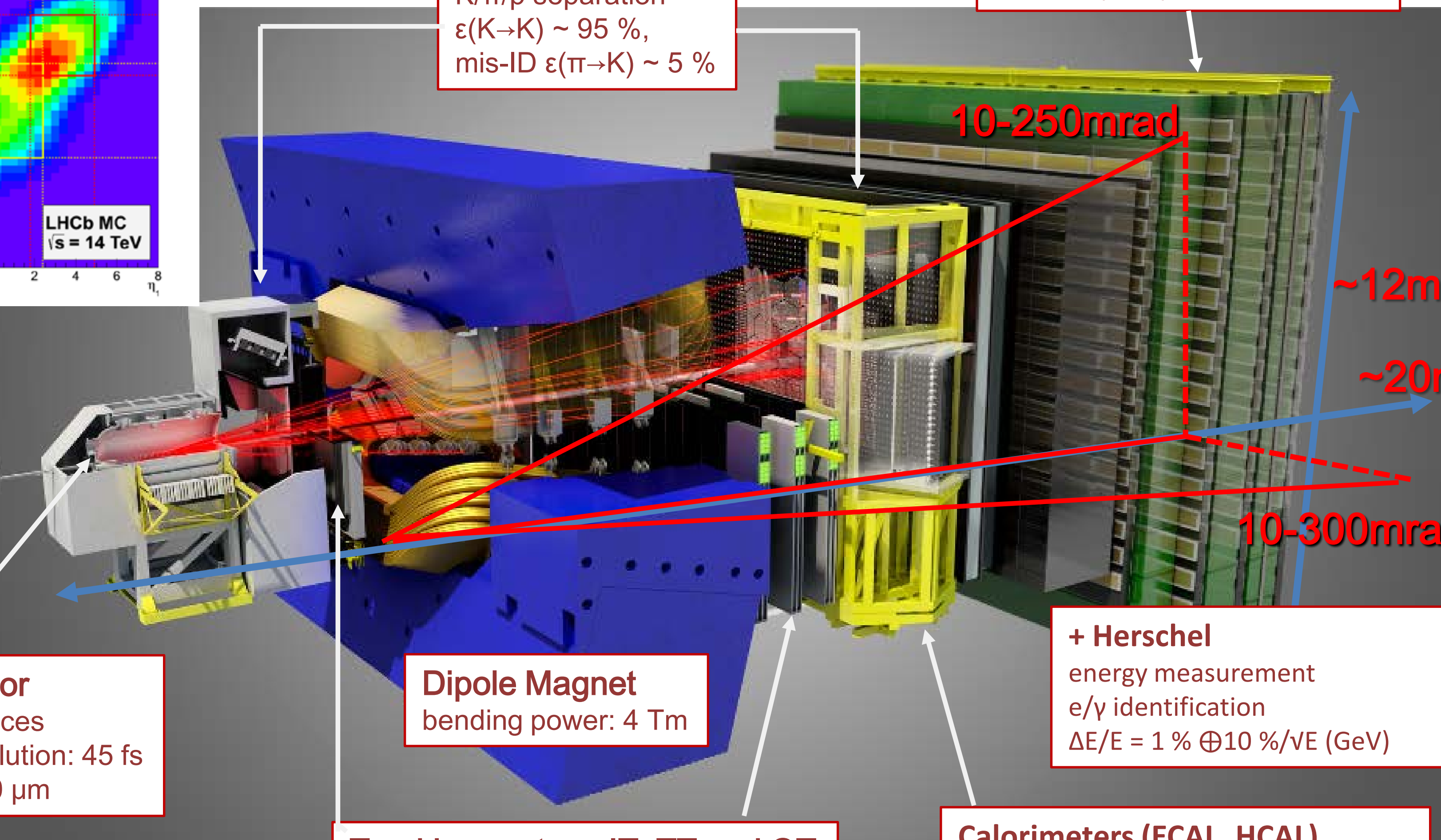
Backup

The LHCb detector

JINST 3 (2008) S08005

$b\bar{b}$ acceptance





RICH detectors
K/π/p separation
ε(K→K) ~ 95 %,
mis-ID ε(π→K) ~ 5 %

Muon system
μ identification ε(μ→μ) ~ 97 %,
mis-ID ε(π→μ) ~ 1-3 %

+ Herschel
energy measurement
e/γ identification
ΔE/E = 1 % ⊕10 %/√E (GeV)

Vertex Detector
reconstruct vertices
decay time resolution: 45 fs
IP resolution: 20 μm

Dipole Magnet
bending power: 4 Tm

Tracking system: IT, TT and OT
momentum resolution
$\Delta p/p$ = 0.4%–0.8%
(5 GeV/c – 100 GeV/c)

Calorimeters (ECAL, HCAL)
energy measurement
e/γ identification
ΔE/E = 1 % ⊕10 %/√E (GeV)

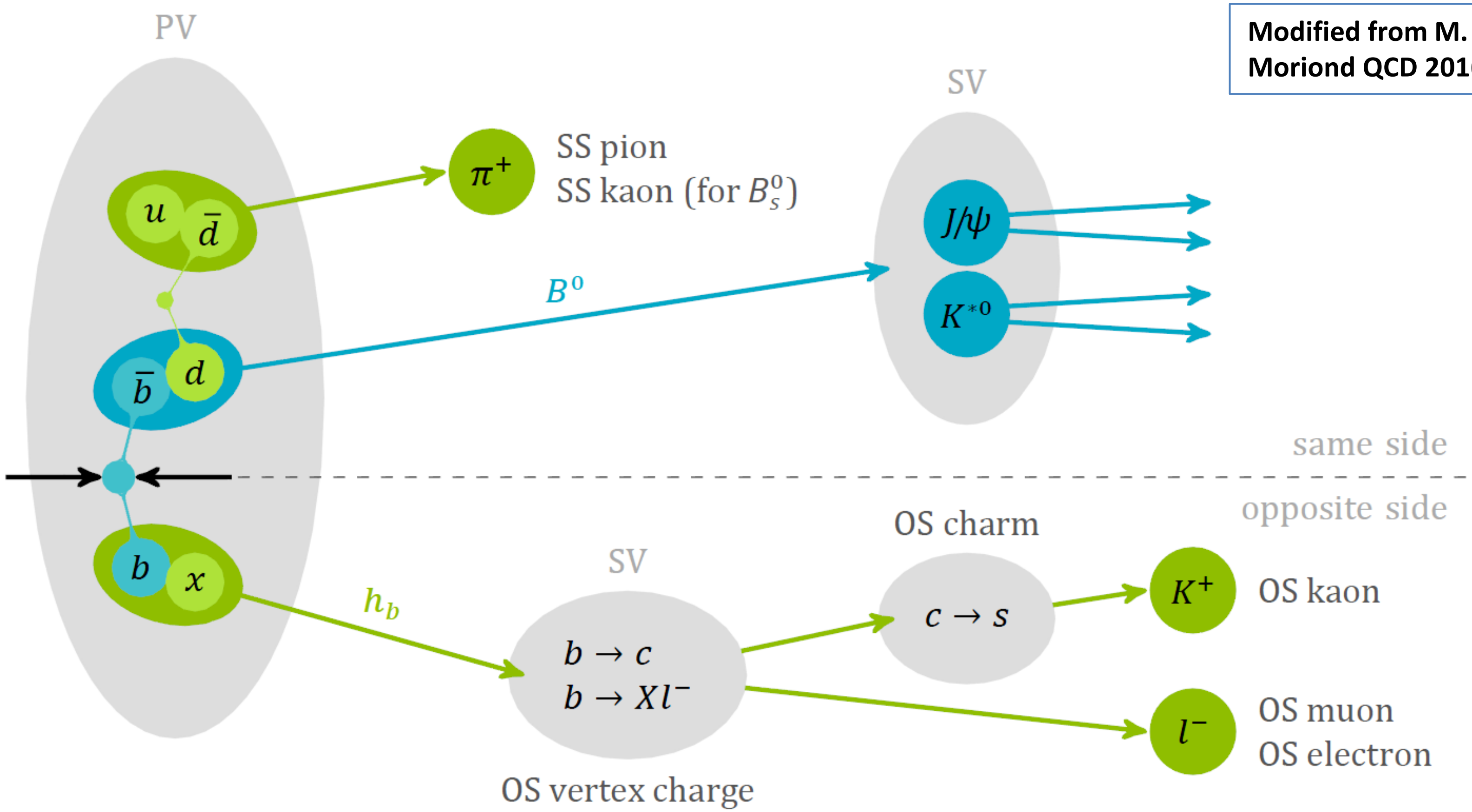
Flavour tagging in LHCb

Charm decays: tag initial flavour using $D^{*+} \to D^0\pi^+$ or $B^- \to D^0\mu^- X$.

The bachelor π^+ or μ^- unambiguosly tags the D^0 $\left(\overline{D}^0\right)$ flavour.

***B* decays:** a more complex process. In the $B^0 \to J/\psi\, K^{*0}$ analysis, for example:

Modified from M. Kenzie Moriond QCD 2016



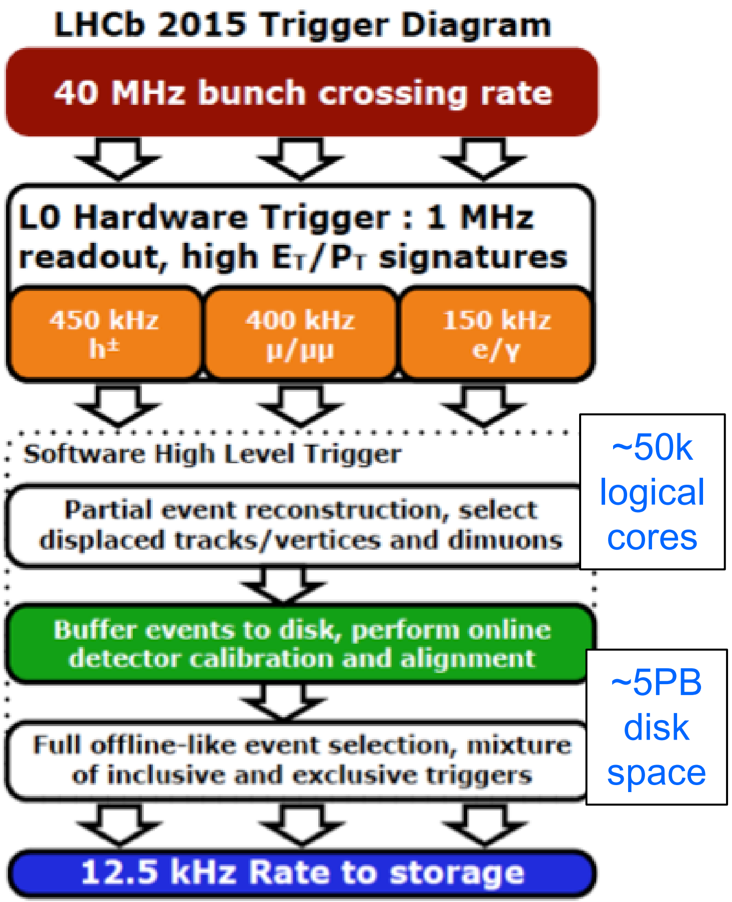
The tagging output is a tag decision and a tag (or mistag) probability.

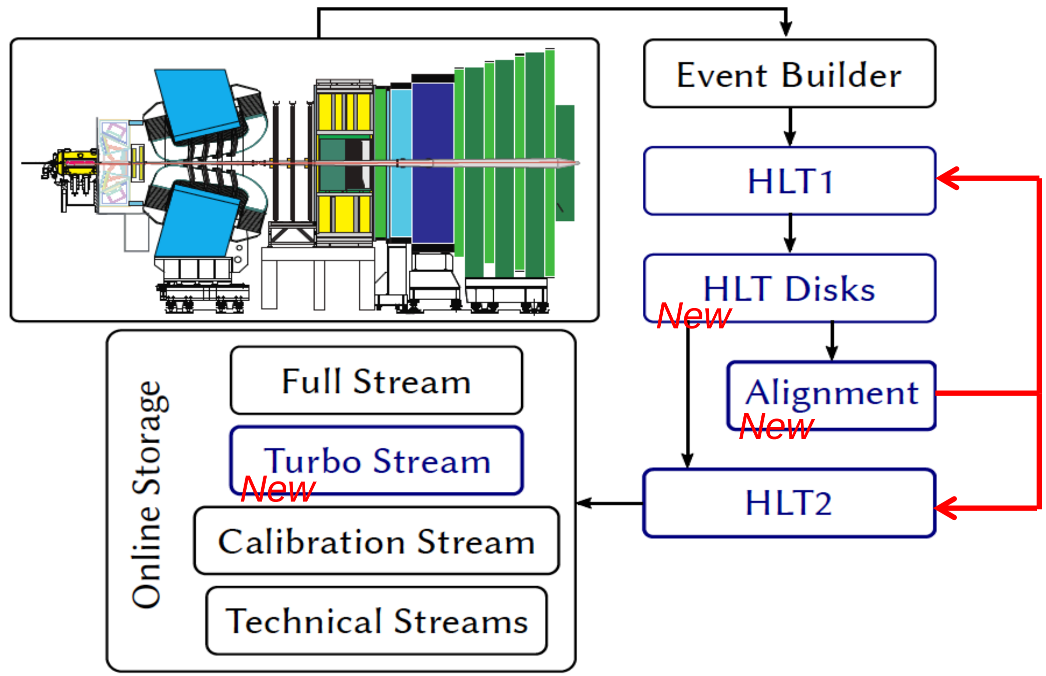
New software trigger architecture

Slide from F. Alessio
Moriond QCD 2016

Real time calibration and alignment

New trigger system





Same online and offline reconstruction and PID!

- prompt alignment and calibration
- completely automatic and in real-time

Physics out of the trigger with Turbo Stream

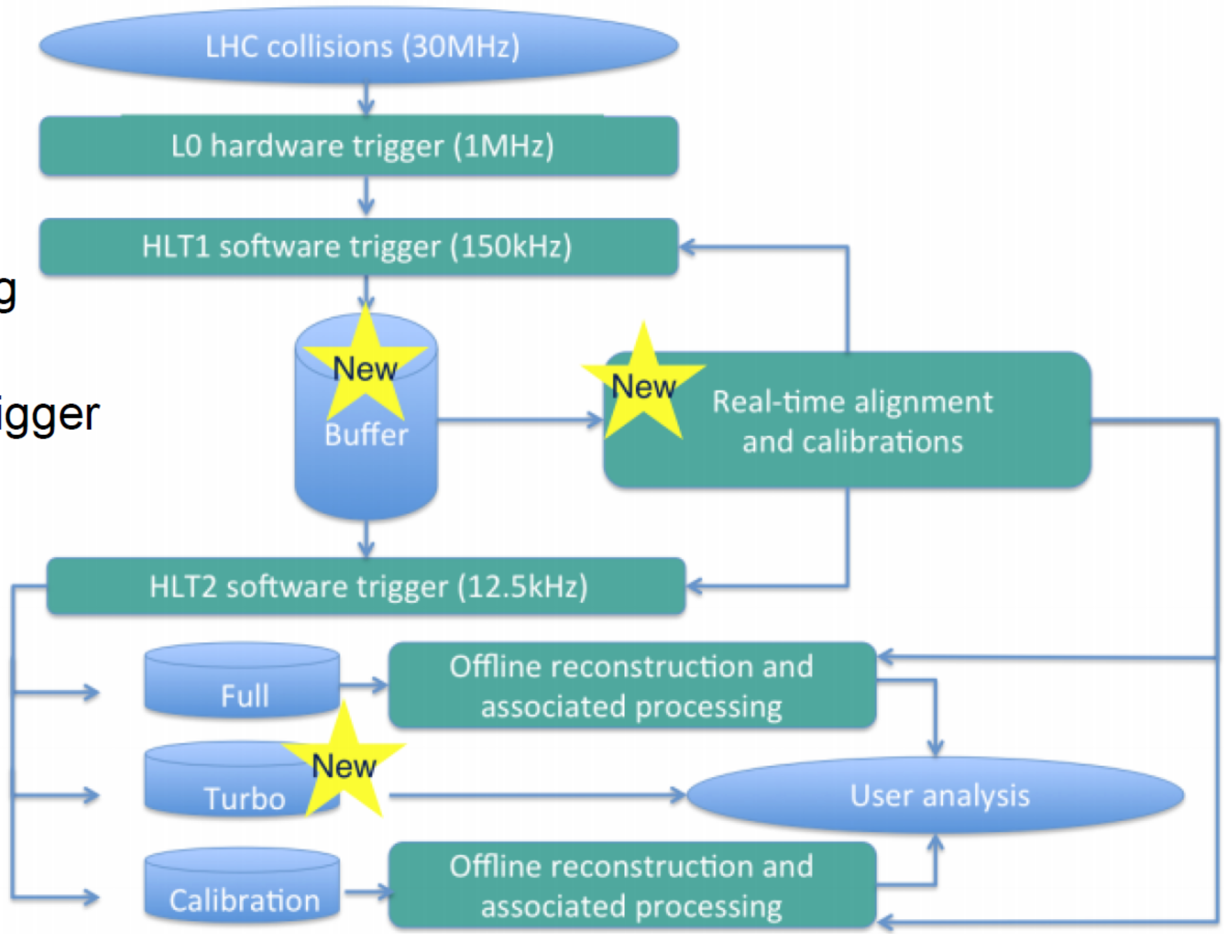
- Raw info discarded, candidates direclty available 24h after being recorded

New software trigger architecture

Slide from S. Borghi
LHCC, Dec 2015.

- Buffer all events to disk before running 2nd software level trigger (HLT2)
- Perform calibration and alignment of the full tracking sub-detectors in real-time

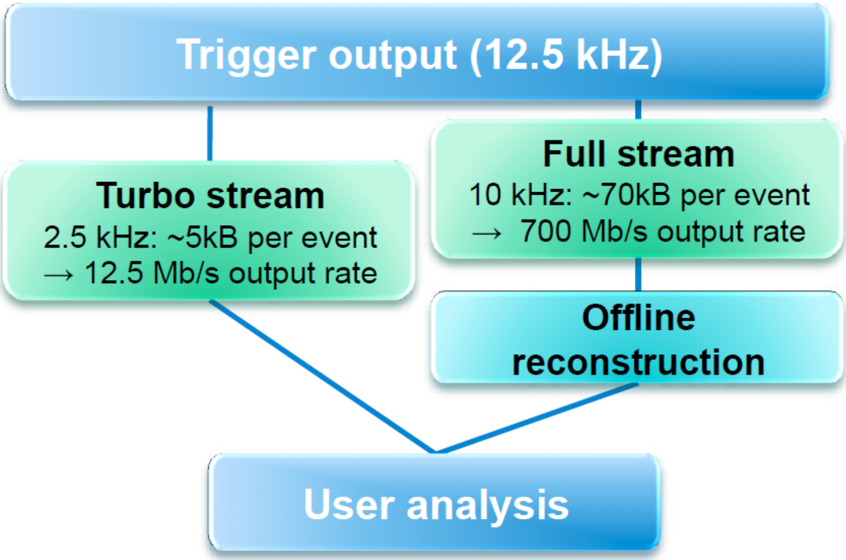
  ➔ same constants in the trigger and offline reconstruction
- Last trigger level runs the same offline reconstruction
- Some analyses performed directly on the trigger output
  - Storing only selected candidates to reduce event size



Turbo Stream

Slide from S. Borghi
LHCC, Dec 2015.

- Some analyses performed directly on the trigger output
- Storing only selected candidates to reduce event size ➔ Save ~90% of space
- Analysis with large yields: possible to reduce the pre-scaling of all the channels that were trigger output rate constrained



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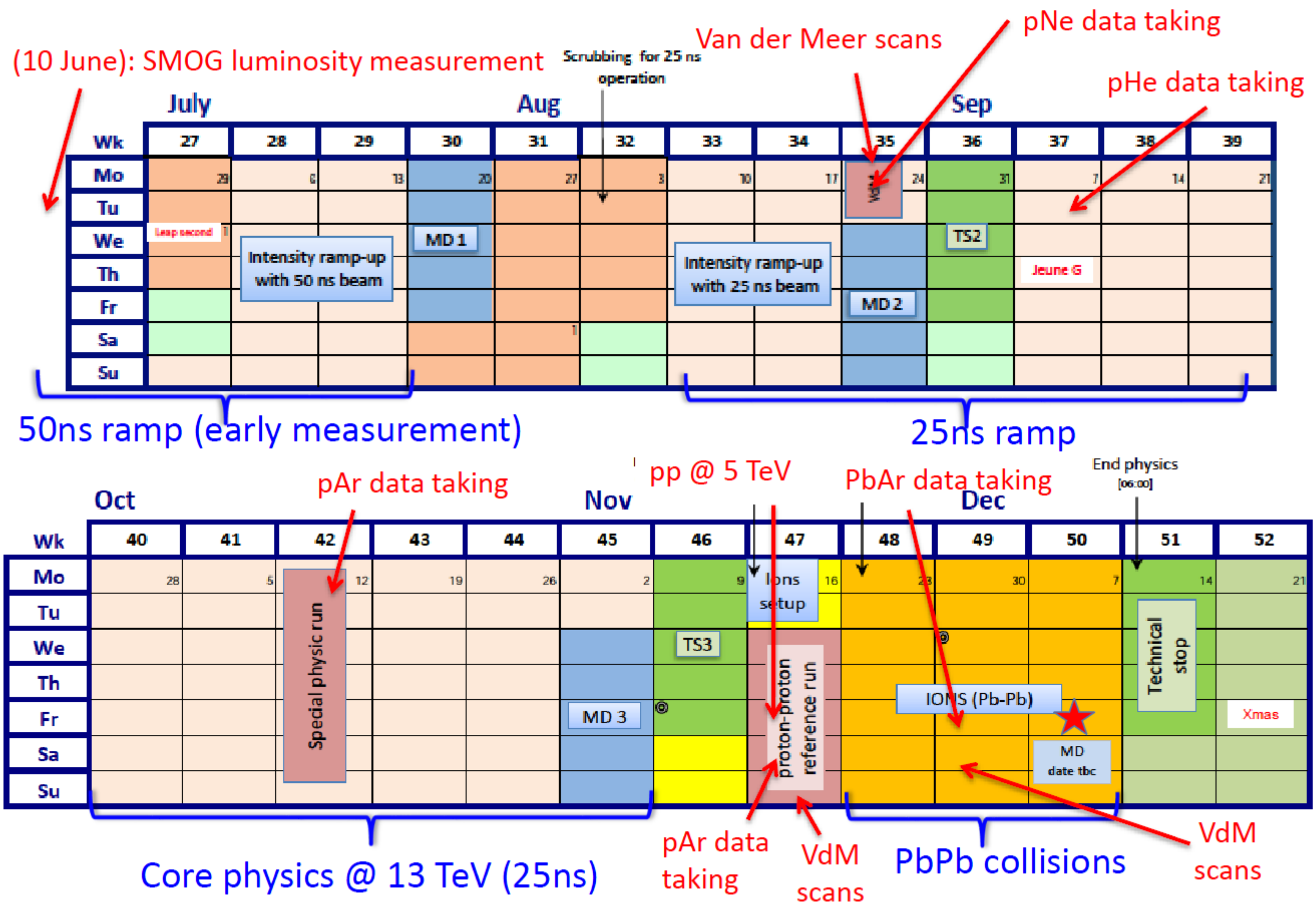
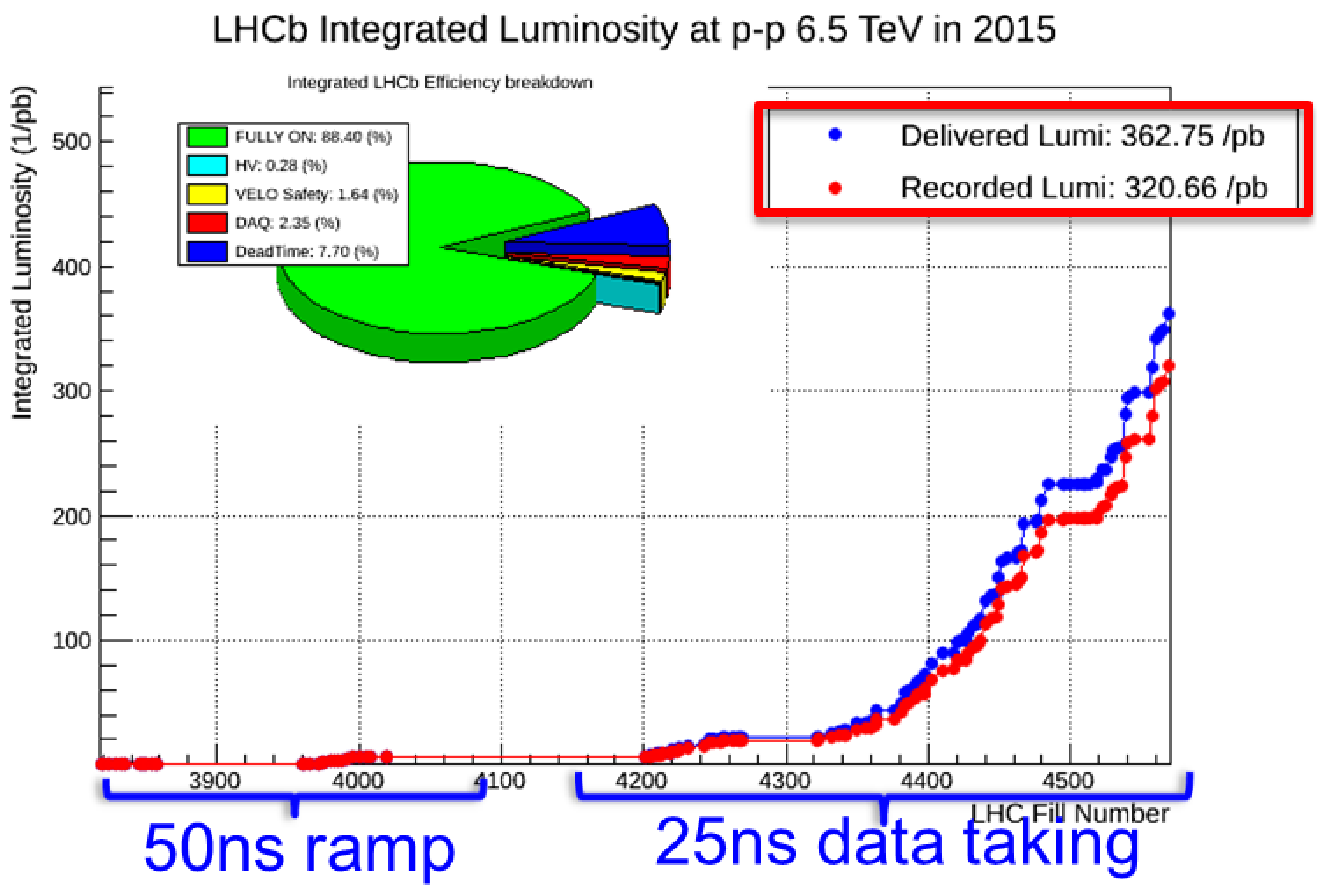
LHCb Run2 start-up



pp collisions @ 13 TeV



$1\ \mathrm{fb}^{-1}$ in 2011 @ 7 TeV

$3\ \mathrm{fb}^{-1}$ in 2012 @ 8 TeV

The ATLAS detector

General purpose detector

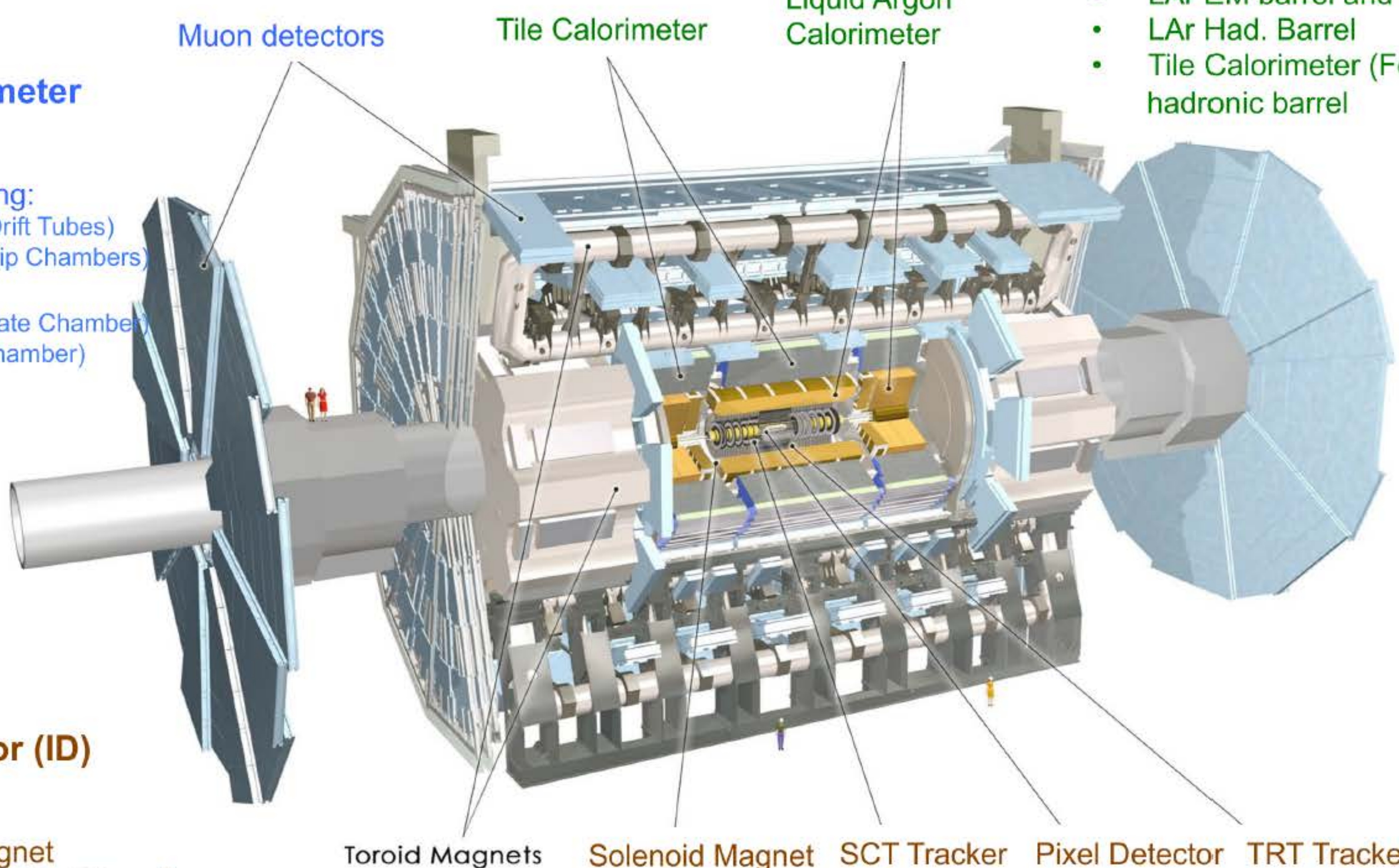
Muon Specrometer

Toroid Magnets
Precision μ tracking:
- MDT (Monitored Drift Tubes)
- CSC (Cathode Strip Chambers)

Trigger:
- RPC (Resistive Plate Chamber)
- TGC (Thin Gas Chamber)

Calorimeter System

EM and Hadronic energy
- LAr EM barrel and EC
- LAr Had. Barrel
- Tile Calorimeter (Fe-Scin.) hadronic barrel

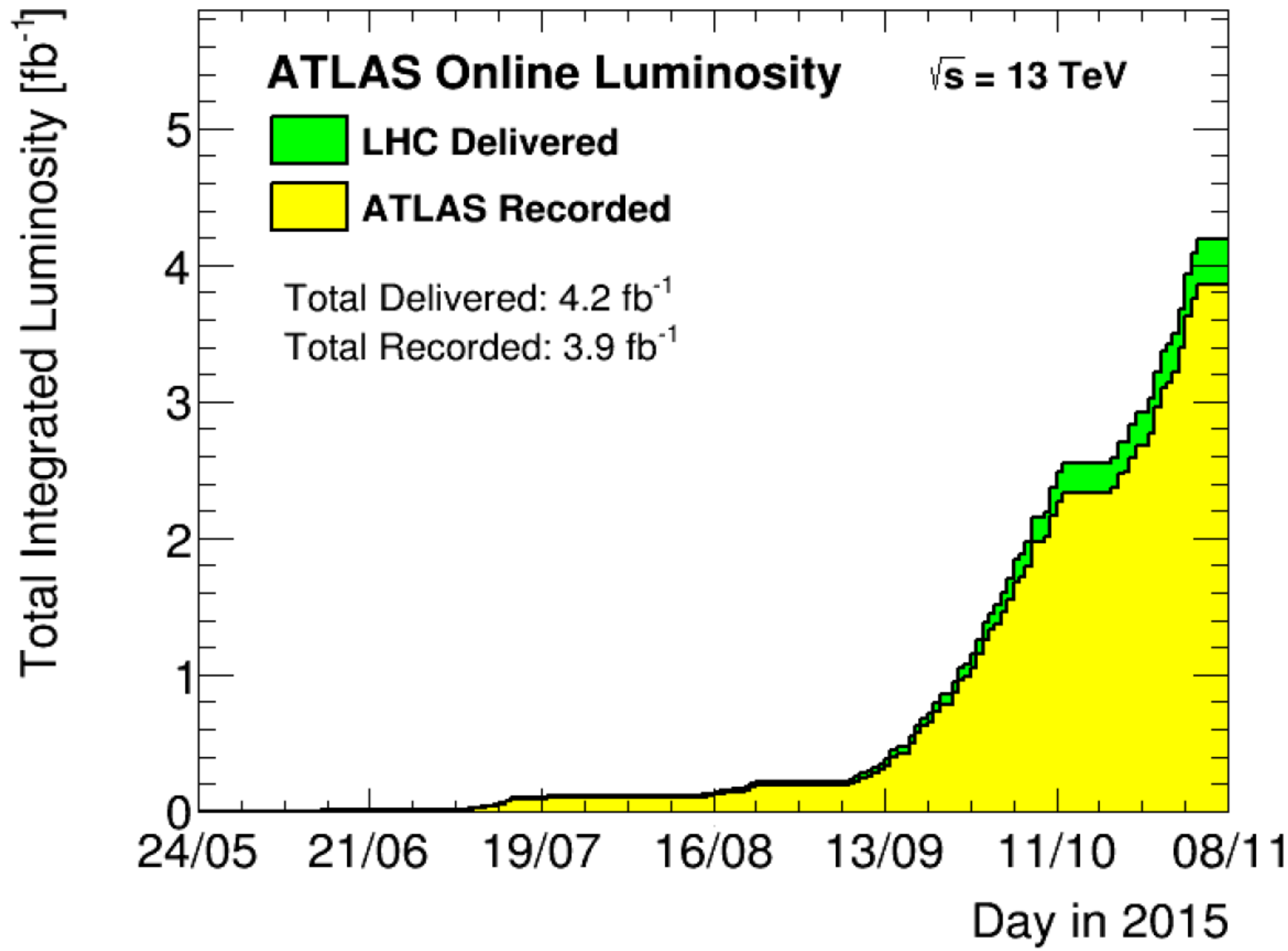


Inner Detector (ID)

Tracking
2T Solenoid Magnet
- Silicon Pixels, 50x400 μm^2
- Silicon Strips (SCT), 80 μm stereo
- Transition Ratiation Tracker (TRT) 36 points/track

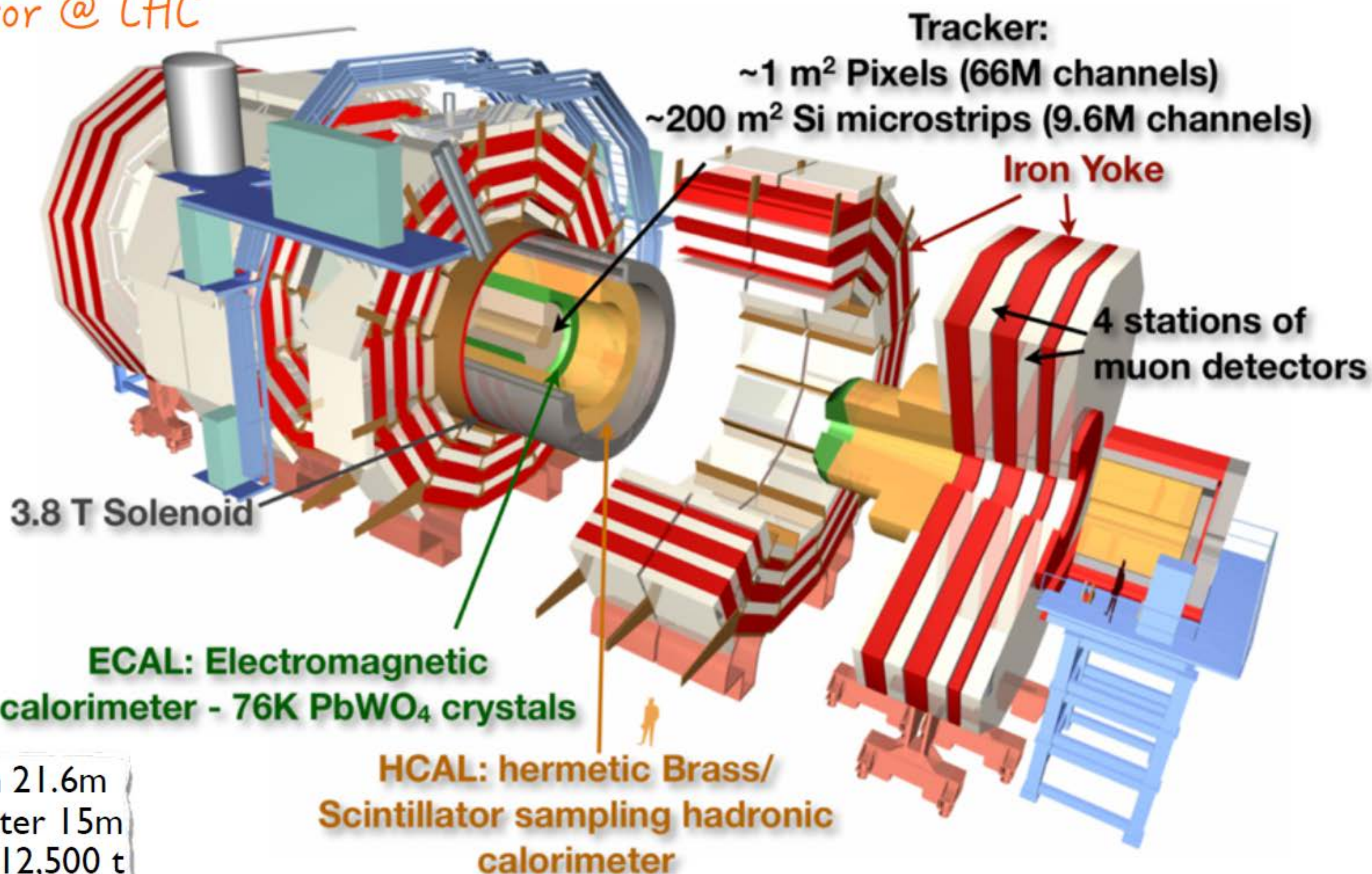
Slide from P. Reznicek La Thuile 2016

pp collisions @ 13 TeV



The CMS detector

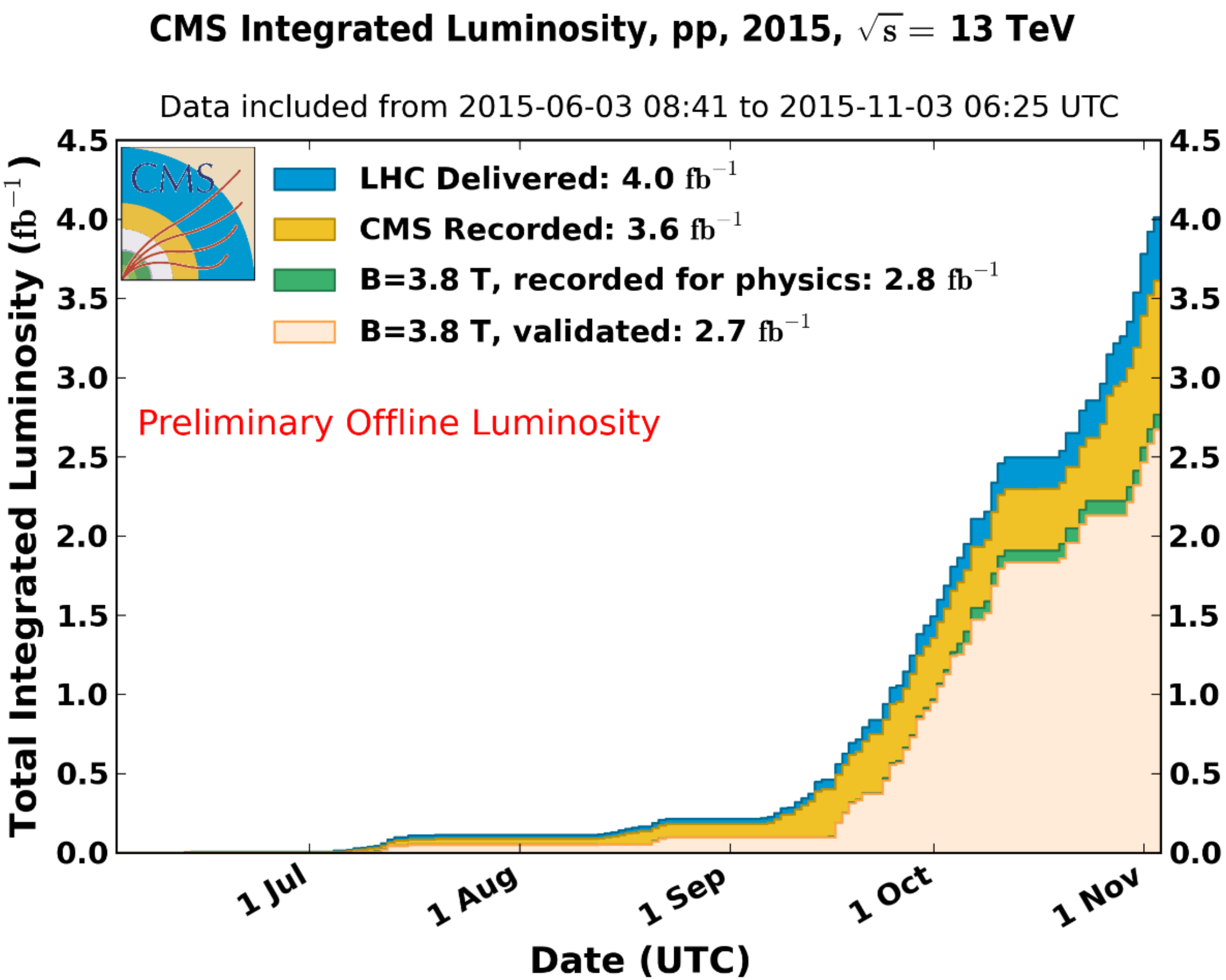
a multi-purpose detector @ LHC



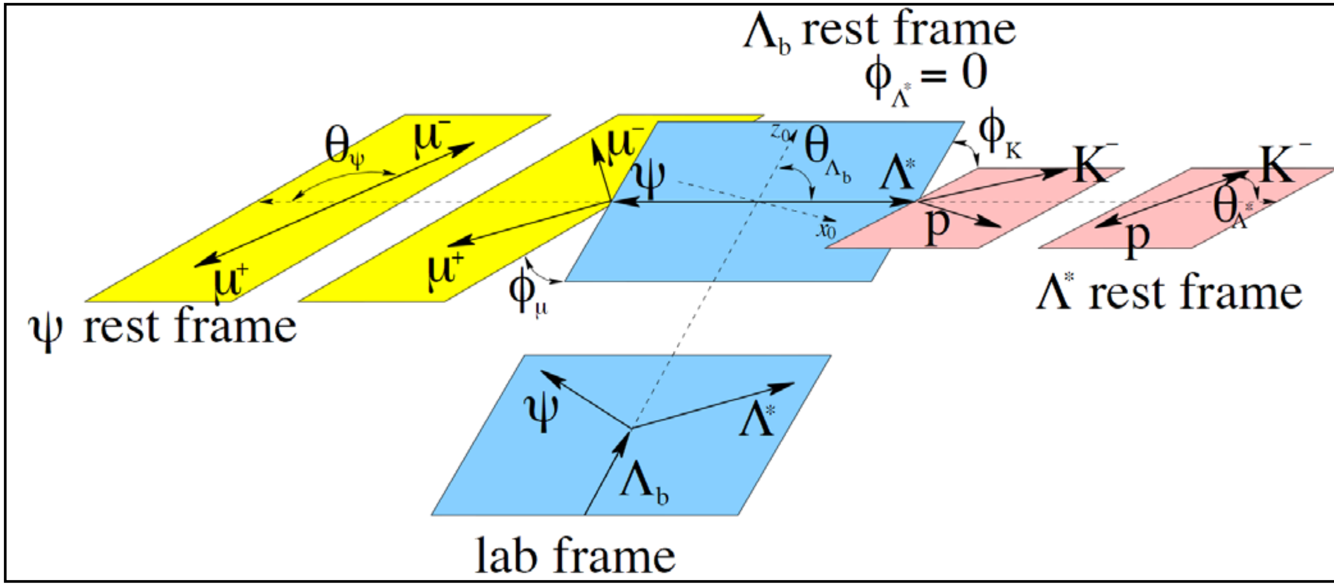
length 21.6m
diameter 15m
weigh 12,500 t
B 3.8T

Slide from N. Leonardo
La Thuile 2016

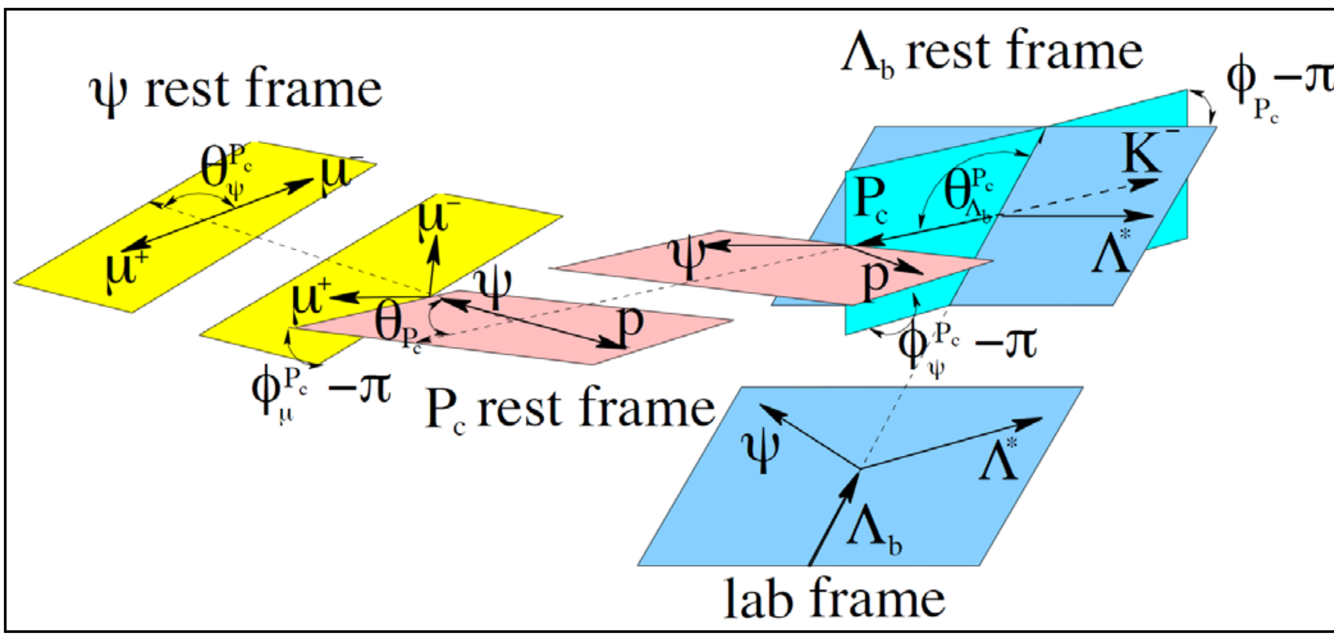
pp collisions @ 13 TeV



Definition of the decay angles in the Λ^* decay chain



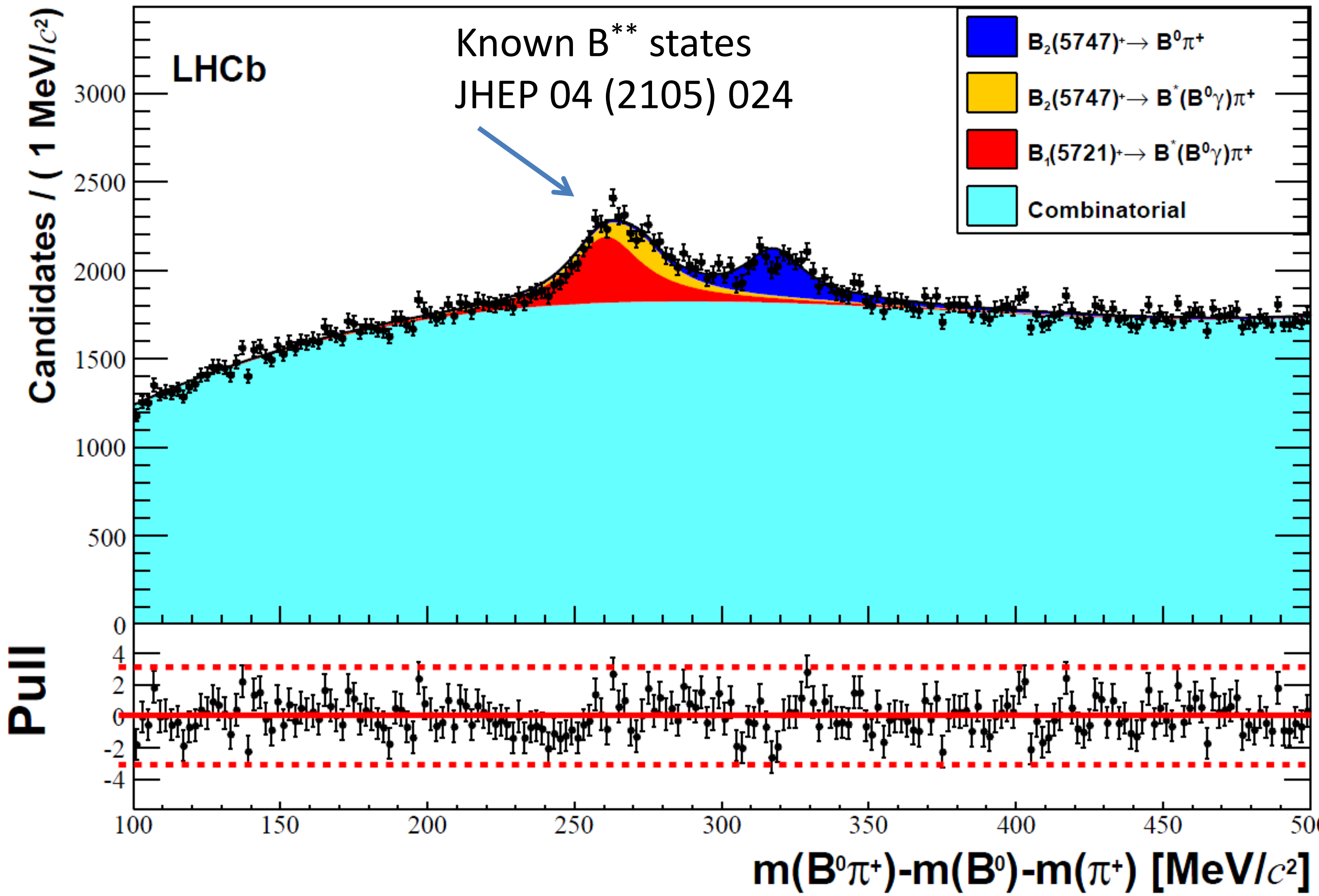
Definition of the decay angles in the **P_c** decay chain



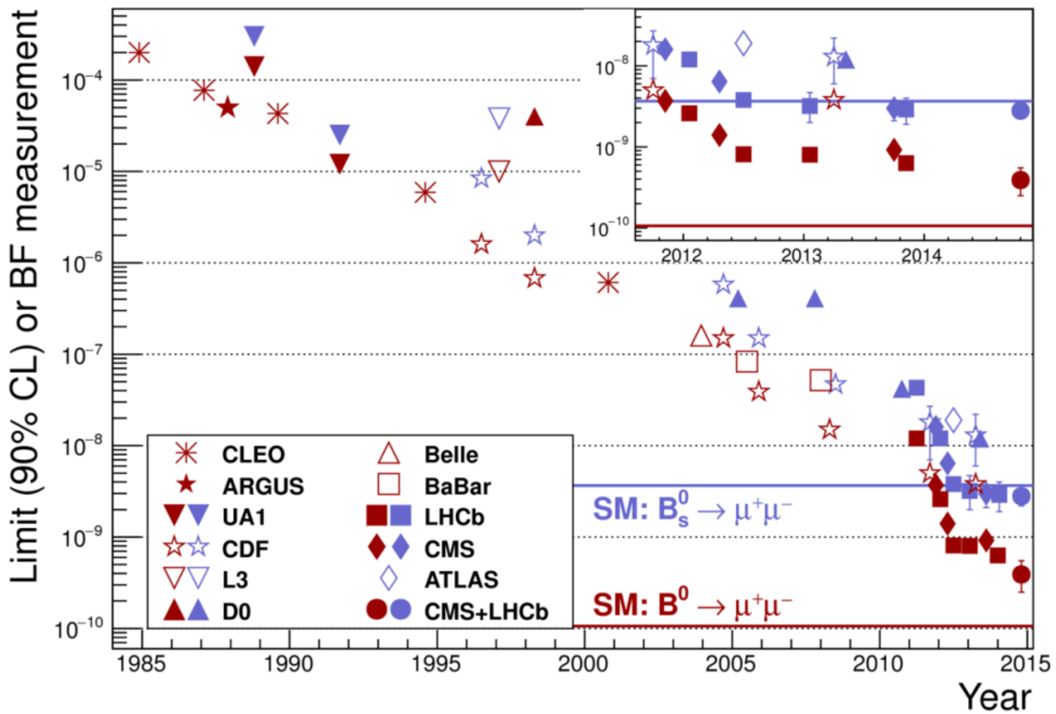
$X(5568) \to B_s^0\pi^\pm$?

LHCb-CONF-2016-004

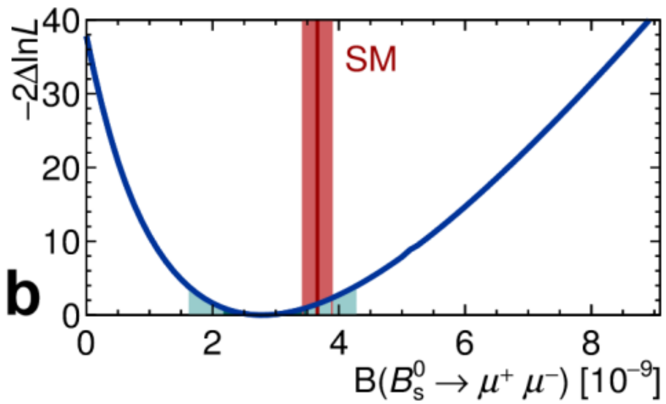
Cross-check with the $B^0\pi$ spectrum



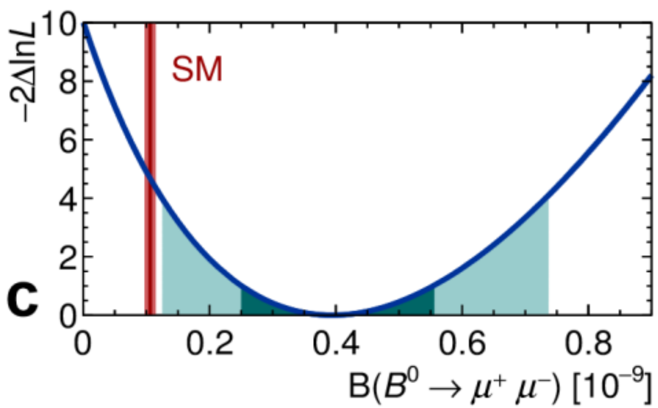
$B^0_{(s)} \to \mu^+\mu^-$



Limit (90% CL) or BF measurement
Year
CLEO
ARGUS
UA1
CDF
L3
D0
Belle
BaBar
LHCb
CMS
ATLAS
CMS+LHCb
SM: $B^0_s \to \mu^+\mu^-$
SM: $B^0 \to \mu^+\mu^-$



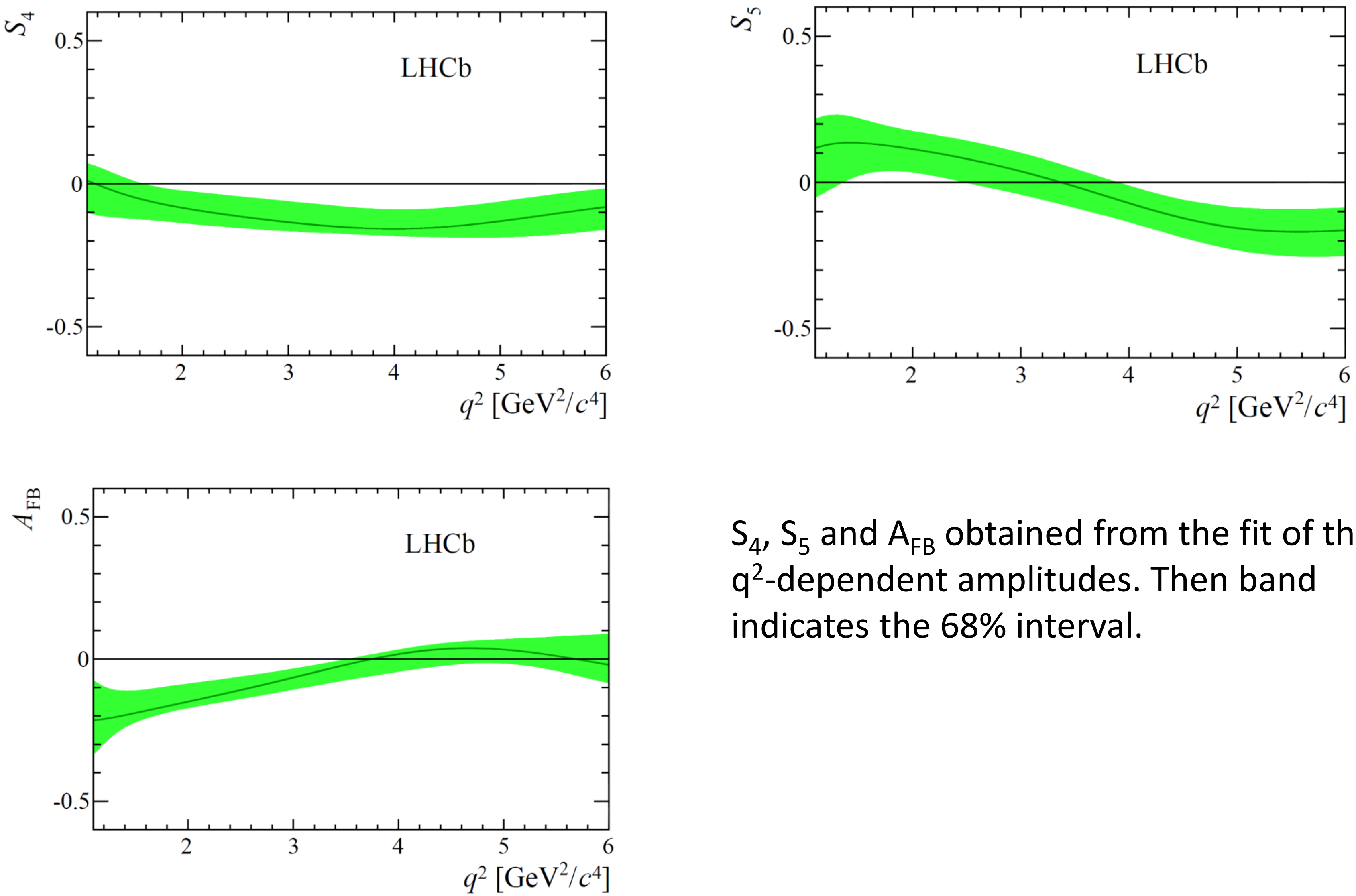
b
SM
$-2\Delta\ln L$
$B(B^0_s \to \mu^+\mu^-)$ [10^{-9}]



c
SM
$-2\Delta\ln L$
$B(B^0 \to \mu^+\mu^-)$ [10^{-9}]

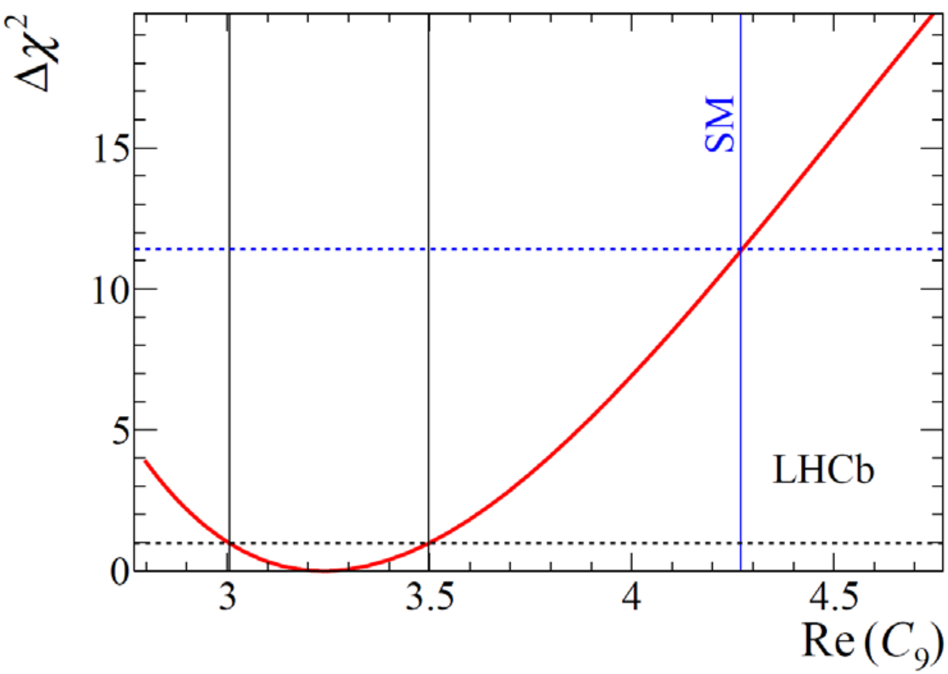
$B^0 \to K^{*0}\mu^+\mu^-$

JHEP 02 (2016) 104



S_4, S_5 and A_{FB} obtained from the fit of the q^2-dependent amplitudes. Then band indicates the 68% interval.

Use EOS software package to determine the level of compatibility of the data with the SM. Perform a χ^2 fit to the CP-averaged observables F_L, $A_{\rm FB}$, and S_3-S_9. Measurements can be accounted for by modifying only the real part of the vector coupling strength of the decays, $\mathrm{Re}(\mathcal{C}_9)$. Modifying just the axial-vector coupling, $\mathcal{C}_{10}$, would contradict the measured value of $\mathcal{B}(B^0_s \to \mu^+\mu^-)$.



$\Delta\chi^2$ distribution for the real part of the generalised vector-coupling strength, $\mathcal{C}_9$.

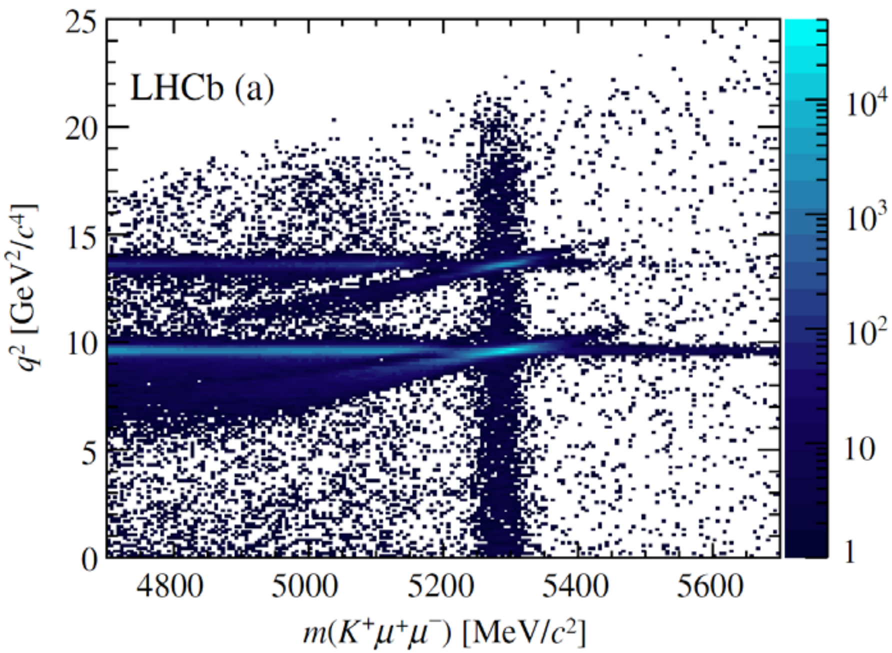
The SM central value is $\mathrm{Re}(\mathcal{C}_9^{\rm SM}) = 4.27$

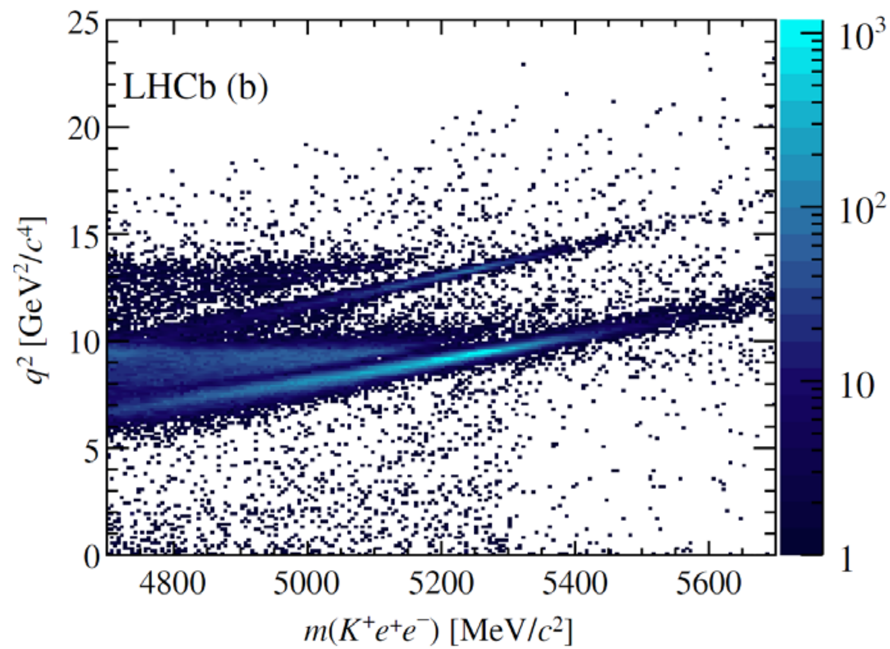
The best fit point is found to be at $\Delta\mathrm{Re}(\mathcal{C}_9) = 1.04 \pm 0.25$

$B^+ \to K^+\ell^+\ell^-$

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

Determine R_K using the ratio of the relative branching fractions of the decays $B^+ \to K^+\ell^+\ell^-$ and $B^+ \to J/\psi(\ell^+\ell^-)\,K^+$, with $\ell = e, \mu$. The well known large $\mathcal{B}(B^+ \to J/\psi\,K^+)$ helps to reduce systematic uncertainties.





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$B^+ \to K^+ \ell^+ \ell^-$

PRL 113, 151601 (2014)

$$R_K = \left(\frac{\mathcal{N}_{K^+\mu^+\mu^-}}{\mathcal{N}_{K^+e^+e^-}}\right)\left(\frac{\mathcal{N}_{J/\psi(e^+e^-)K^+}}{\mathcal{N}_{J/\psi(\mu^+\mu^-)K^+}}\right) \times \left(\frac{\epsilon_{K^+e^+e^-}}{\epsilon_{K^+\mu^+\mu^-}}\right)\left(\frac{\epsilon_{J/\psi(\mu^+\mu^-)K^+}}{\epsilon_{J/\psi(e^+e^-)K^+}}\right)$$

Parametrization of mass distribution dominates the syst. uncertainty.

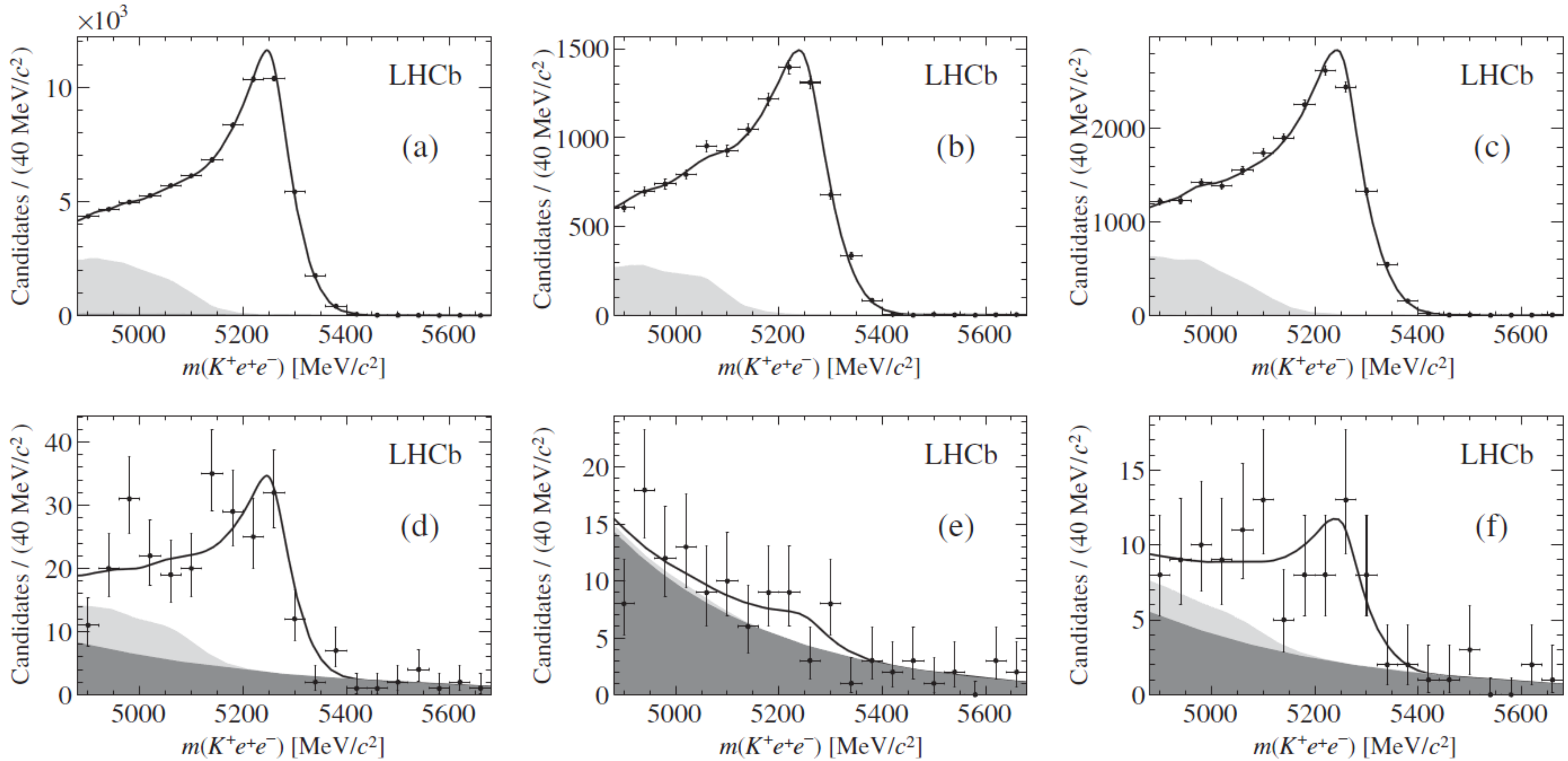


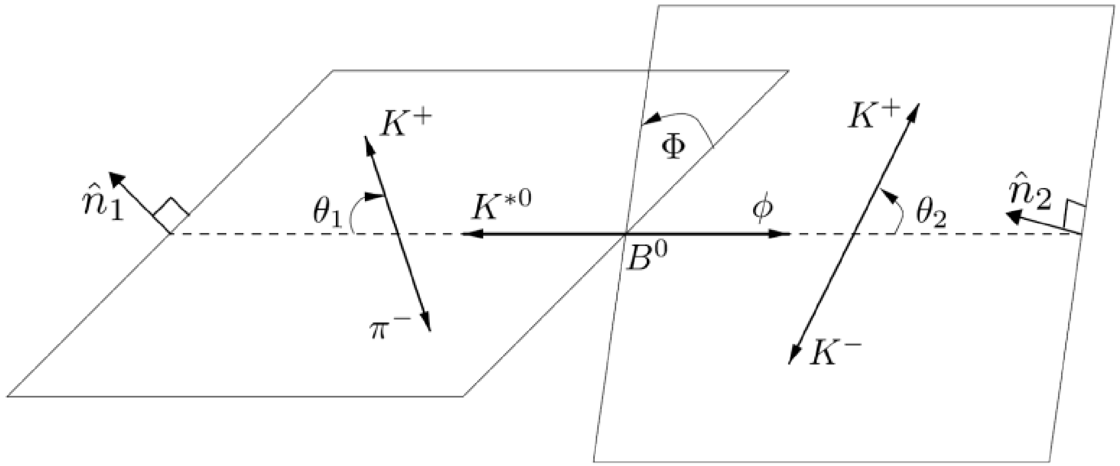
FIG. 2. Mass distributions with fit projections overlaid of selected $B^+ \to J/\psi(\to e^+e^-)K^+$ candidates triggered in the hardware trigger by (a) one of the two electrons, (b) by the K^+, and (c) by other particles in the event. Mass distributions with fit projections overlaid of selected $B^+ \to K^+e^+e^-$ candidates in the same categories, triggered by (d) one of the two electrons, (e) the K^+, and (f) by other particles in the event. The total fit model is shown in black, the combinatorial background component is indicated by the dark shaded region and the background from partially reconstructed b -hadron decays by the light shaded region.

Angle γ from trees

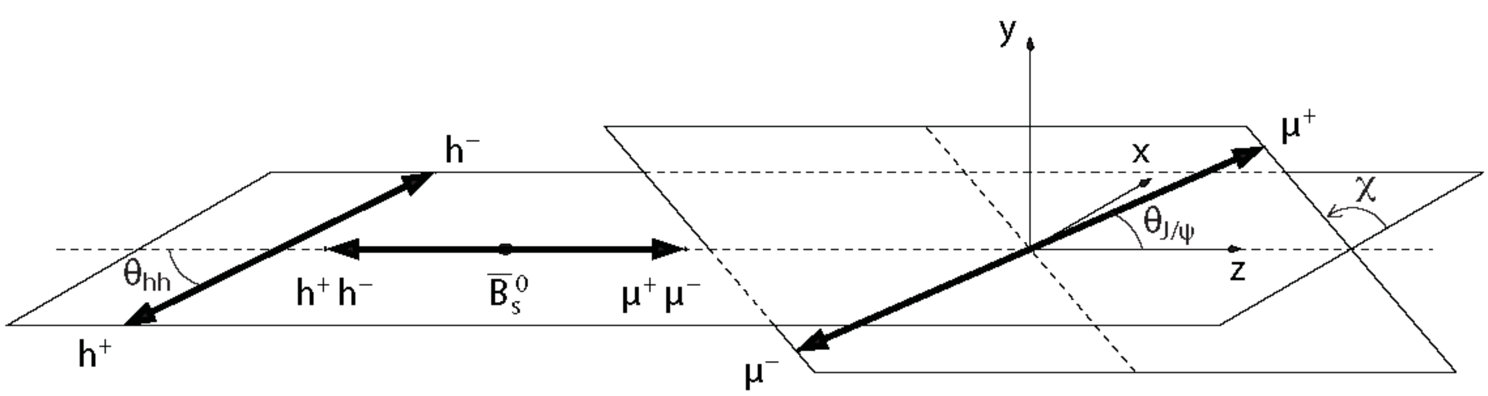
LHCb-CONF-2016-001

Credibility regions and most probable values for the hadronic parameters extracted from the combination. The second part of the table repeats the frequentist results for comparison

Observable	Central value	Intervals	
Bayesian		68%	95%
$\gamma(^\circ)$	68.7	$[58.6, 76.2]$	$[47.0, 82.3]$
r_B^{DK}	0.0989	$[0.0932, 0.1046]$	$[0.0878, 0.1103]$
$\delta_B^{DK}(^\circ)$	139.9	$[130.9, 147.1]$	$[118.4, 152.6]$
$r_B^{DK^{*0}}$	0.201	$[0.145, 0.251]$	$[0.068, 0.297]$
$\delta_B^{DK^{*0}}(^\circ)$	192.3	$[164.5, 224.1]$	$[135.9, 268.6]$
Frequentist		68%	95%
$\gamma(^\circ)$	70.9	$[62.4, 78.0]$	$[51.0, 85.0]$
r_B^{DK}	0.1006	$[0.0946, 0.1065]$	$[0.0890, 0.1120]$
$\delta_B^{DK}(^\circ)$	141.1	$[133.4, 147.2]$	$[122.0, 153.0]$
$r_B^{DK^{*0}}$	0.217	$[0.169, 0.261]$	$[0.115, 0.303]$
$\delta_B^{DK^{*0}}(^\circ)$	189.0	$[169.0, 213.0]$	$[149.0, 243.0]$



K^+
Φ
K^+
$\hat{n}_1$
θ_1
K^{*0}
ϕ
θ_2
$\hat{n}_2$
B^0
π^-
K^-



y
μ^+
h^-
x
χ
$\theta_{J/\psi}$
θ_{hh}
z
h^+h^-
$\overline{B}_s^0$
$\mu^+\mu^-$
h^+
μ^-

Combined measurement of ϕ_s

http://www.slac.stanford.edu/xorg/hfag/osc/summer_2015/#DMS

Table 1: Direct experimental measurements of $\phi_s^{c\bar{c}s}$, $\Delta\Gamma_s$ and Γ_s using $B_s^0 \to J/\psi\,\phi$, $J/\psi\,K^+K^-$, $J/\psi\,\pi^+\pi^-$ and $D_s^+D_s^-$ decays. Only the solution with $\Delta\Gamma_s > 0$ is shown, since the two-fold ambiguity has been resolved in Ref. [1]. The first error is due to statistics, the second one to systematics. The last line gives our average.

Exp.	Mode	Dataset	$\phi_s^{c\bar{c}s}$	$\Delta\Gamma_s$ (ps^{-1})	Ref.
CDF	$J/\psi\,\phi$	$9.6\,\mathrm{fb}^{-1}$	$[-0.60, +0.12]$, 68% CL	$+0.068 \pm 0.026 \pm 0.009$	[2]
D0	$J/\psi\,\phi$	$8.0\,\mathrm{fb}^{-1}$	$-0.55^{+0.38}_{-0.36}$	$+0.163^{+0.065}_{-0.064}$	[3]
ATLAS	$J/\psi\,\phi$	$4.9\,\mathrm{fb}^{-1}$	$+0.12 \pm 0.25 \pm 0.05$	$+0.053 \pm 0.021 \pm 0.010$	[4]
ATLAS	$J/\psi\,\phi$	$14.3\,\mathrm{fb}^{-1}$	$-0.119 \pm 0.088 \pm 0.036$	$+0.096 \pm 0.013 \pm 0.007$	[5]^p
ATLAS	above 2 combined		$-0.094 \pm 0.083 \pm 0.033$	$+0.082 \pm 0.011 \pm 0.007$	[5]^p
CMS	$J/\psi\,\phi$	$20\,\mathrm{fb}^{-1}$	$-0.075 \pm 0.097 \pm 0.031$	$+0.095 \pm 0.013 \pm 0.007$	[6]
LHCb	$J/\psi\,K^+K^-$	$3.0\,\mathrm{fb}^{-1}$	$-0.058 \pm 0.049 \pm 0.006$	$+0.0805 \pm 0.0091 \pm 0.0033$	[7]
LHCb	$J/\psi\,\pi^+\pi^-$	$3.0\,\mathrm{fb}^{-1}$	$+0.070 \pm 0.068 \pm 0.008$	—	[8]
LHCb	above 2 combined		-0.010 ± 0.039(tot)	—	[7]
LHCb	$D_s^+D_s^-$	$3.0\,\mathrm{fb}^{-1}$	$+0.02 \pm 0.17 \pm 0.02$	—	[9]
All combined			-0.034 ± 0.033	$+0.084 \pm 0.007$	

^{p} Preliminary.

CP asym. in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

LHCb-PAPER-2015-055

$$A_{CP}(f;\, t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)}$$

$$A_{CP}(f) \approx a_{CP}^{\rm dir}(f)\left(1 + \frac{\langle t(f)\rangle}{\tau}\, y_{CP}\right) + \frac{\langle t(f)\rangle}{\tau}\, a_{CP}^{\rm ind}$$

where $\langle t(f)\rangle$ denotes the mean decay time of $D^0 \to f$ decays in the reconstructed sample, $a_{CP}^{\rm dir}(f)$ as the direct CP asymmetry, τ the D^0 lifetime, $a_{CP}^{\rm ind}$ the indirect CP asymmetry and y_{CP} is the deviation from unity of the ratio of the effective lifetimes of decays to flavour specific and CP-even final states. To a good approximation, $a_{CP}^{\rm ind}$ is independent of the decay mode

$$\begin{aligned} \Delta A_{CP} &\equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \\ &\approx \Delta a_{CP}^{\rm dir}\left(1 + \frac{\overline{\langle t\rangle}}{\tau}\, y_{CP}\right) + \frac{\Delta\langle t\rangle}{\tau}\, a_{CP}^{\rm ind} \end{aligned}$$

where $\overline{\langle t\rangle}$ is the arithmetic average of $\langle t(K^-K^+)\rangle$ and $\langle t(\pi^-\pi^+)\rangle$

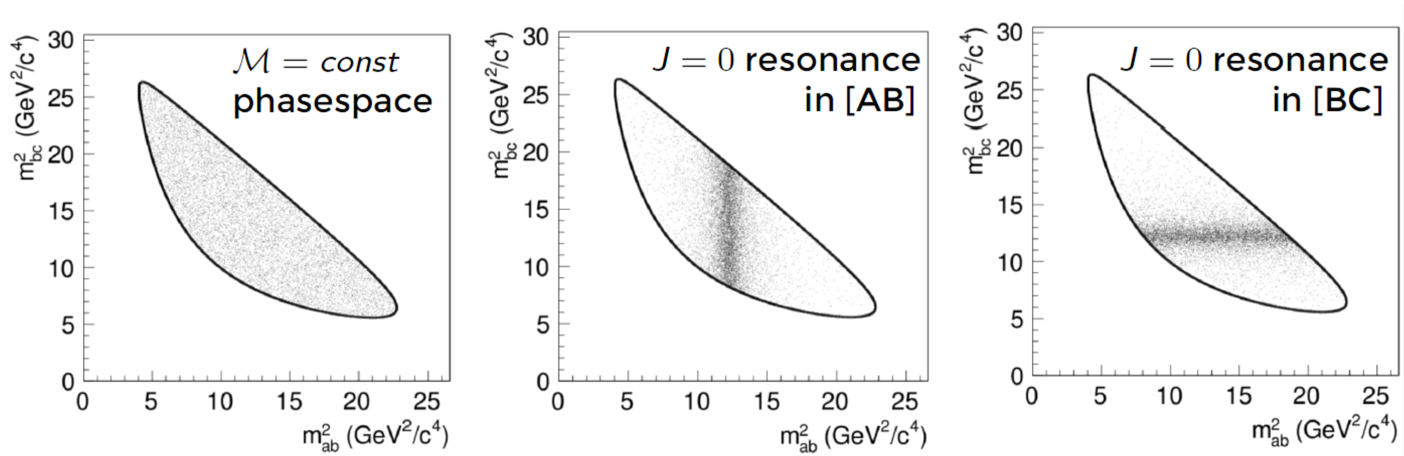
3-body decays and Dalitz-plots

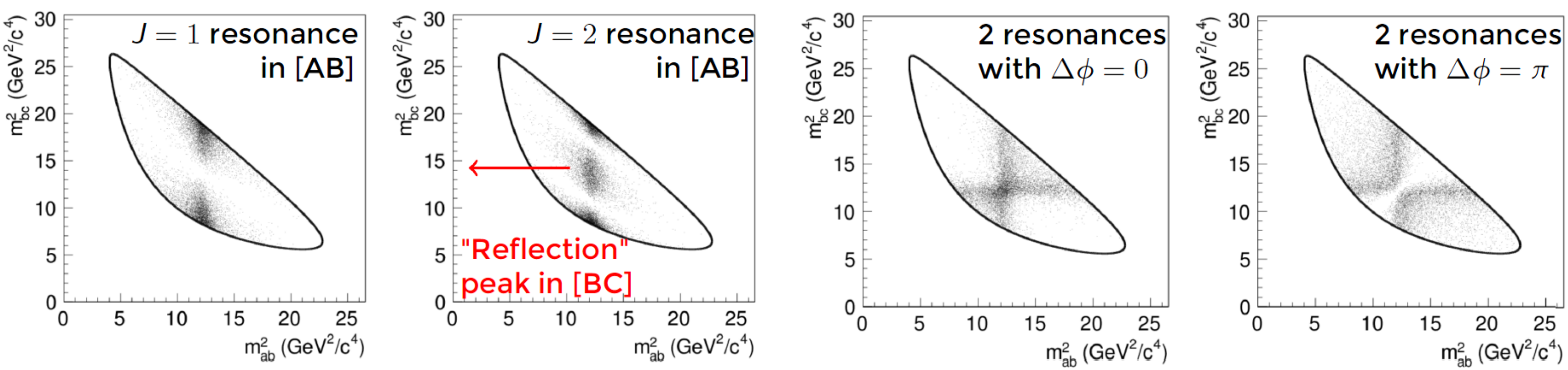
(Slide taken from S. Neubert presentation in *Hadron spectroscpy at LHCb*, Bormio 2016)

all particles spin 0:

$$X \to ABC$$

$$\Gamma \propto |\mathcal{M}|^2 dm^2_{AB} dm^2_{BC}$$





plots by Antimo Palano