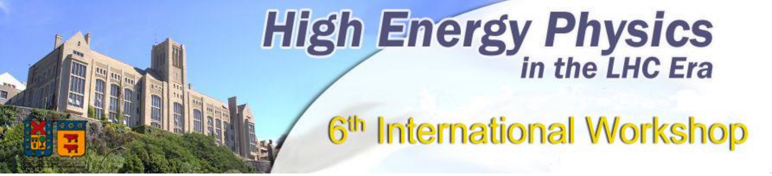


Valparaiso, 6-12 January 2016

Overview of the latest LHCb results

Patrick Robbe, LAL Orsay and CERN, 6 January 2016,

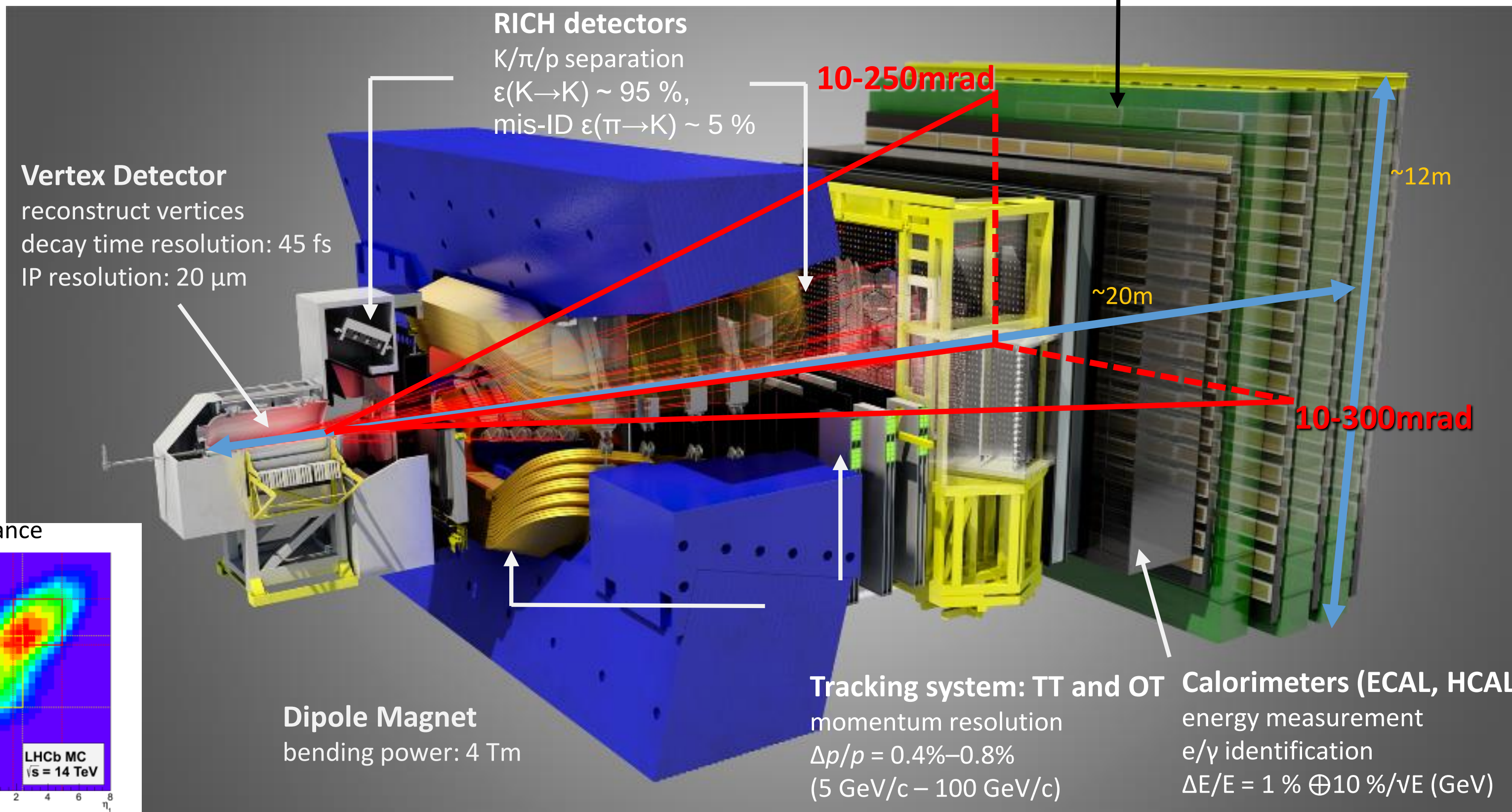
For the LHCb Collaboration

Outline

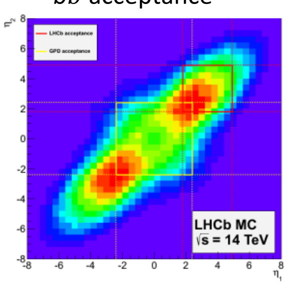
- Run 1 results:
  - Exotic states: observation of pentaquarks
  - Rare *B* decays: $B_{(s)}{}^{0} \rightarrow \mu^{+}\mu^{-}$, $B^{0} \rightarrow K^{*0}\mu^{+}\mu^{-}$
  - CKM matrix elements: $|V_{ub}|/|V_{cb}|$ from $\Lambda_{b}{}^{0} \rightarrow p\mu^{-}\nu_{\mu}$
  - Proton-Lead collisions: $\psi(2S)$ production and two-particle correlations
- Data taking in Run 2:
  - First results: J/ψ and charm cross-sections
  - Heavy ions: PbPb and fixed target physics

The LHCb experiment

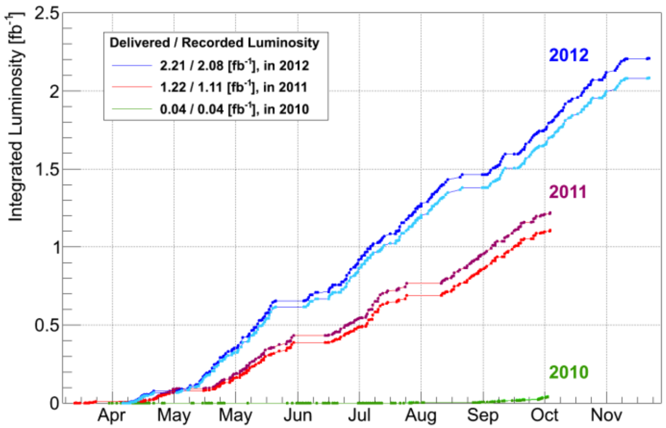
Muon system
μ identification ε(μ→μ) ~ 97 %,
mis-ID ε(π→μ) ~ 1-3 %



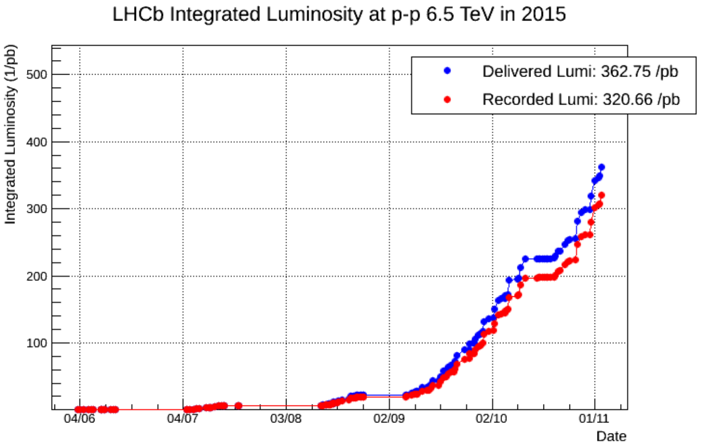
$b\bar{b}$ acceptance



Data Taking



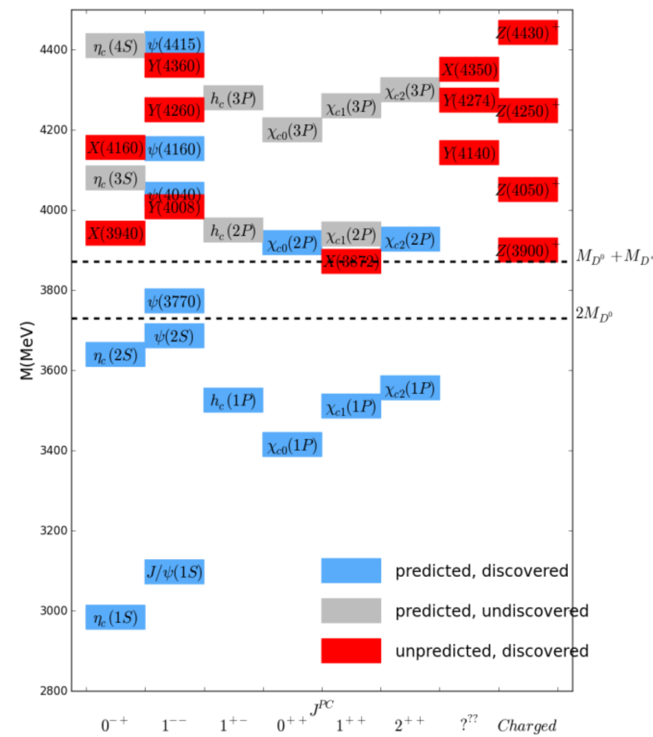
Run 1 (7 and 8 TeV)



Run 2 (13 TeV)

Exotic States

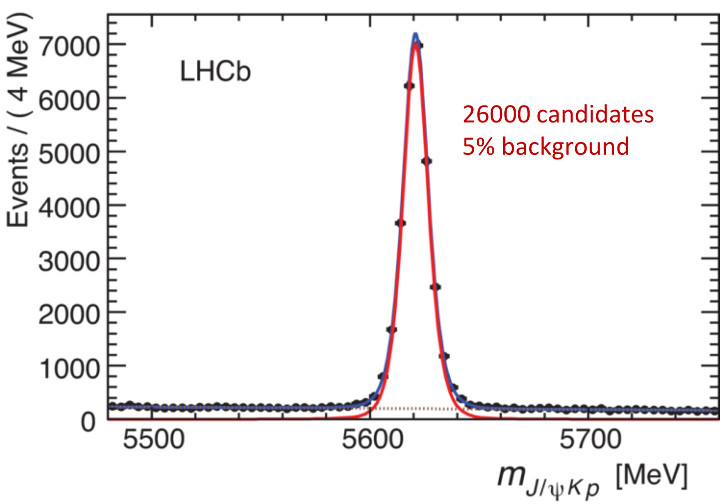
- In the last 10 years, several unexpected quarkonium-like states discovered (BaBar and BELLE): exact nature of them not yet established (hybrids, molecules, tetraquarks)
- LHCb contributed to their studies:
  - Production of X(3872) in *pp* collisions [EPJC 72 (2012) 1972]
  - Determination of X(3872) quantum numbers [PRL 110 (2013) 222001, PRD 92 (2015) 011102]
  - Confirmation of the $Z(4430)^-$ state [PAPER-2015-034, PRL 112 (2014) 222002]
  - $X(3872) \rightarrow \psi(2S)\,\gamma$ decay modes [NPB 886 (2013) 665]

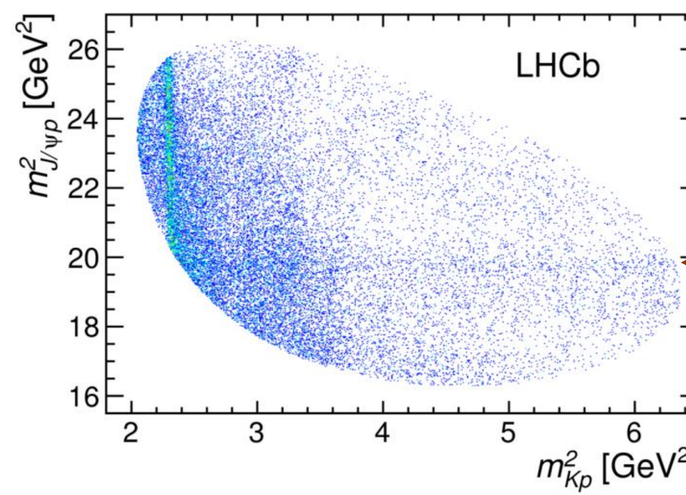


[PRL 115 (2015) 161802]

$\Lambda_b^0 \rightarrow J/\psi K^- p$

- Large samples of the decay reconstructed in Run 1 (3 fb^{-1}, 7 TeV and 8 TeV), e.g. for the measurement of the Λ_b lifetime [PRL 111 (2013) 102003]



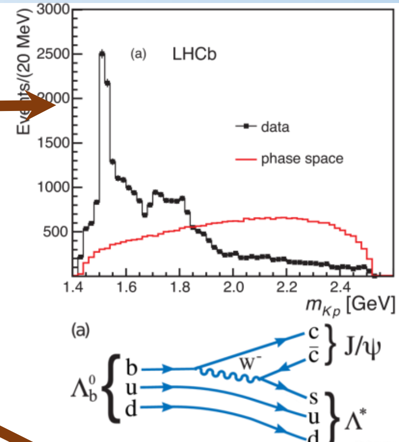


- Clear structure in J/ψ *p* system, studied with a full angular analysis of the decay.

[PRL 115 (2015) 161802]

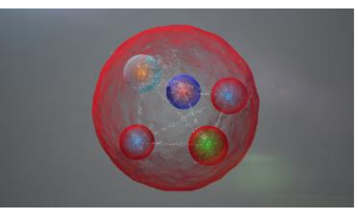
Resonances in $\Lambda_b^0 \rightarrow J/\psi K^- p$

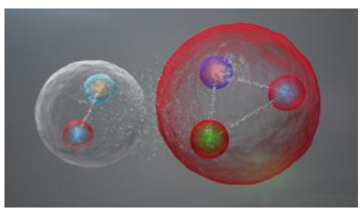
- M(Kp) projection shows known Λ^* contributions

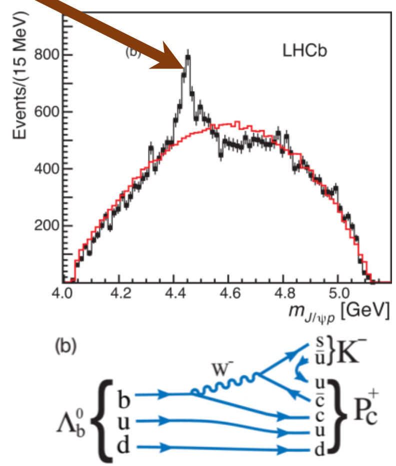


State	J^P	M_0 (MeV)	Γ_0 (MeV)
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0
$\Lambda(1600)$	$1/2^+$	1600	150
$\Lambda(1670)$	$1/2^-$	1670	35
$\Lambda(1690)$	$3/2^-$	1690	60
$\Lambda(1800)$	$1/2^-$	1800	300
$\Lambda(1810)$	$1/2^+$	1810	150
$\Lambda(1820)$	$5/2^+$	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

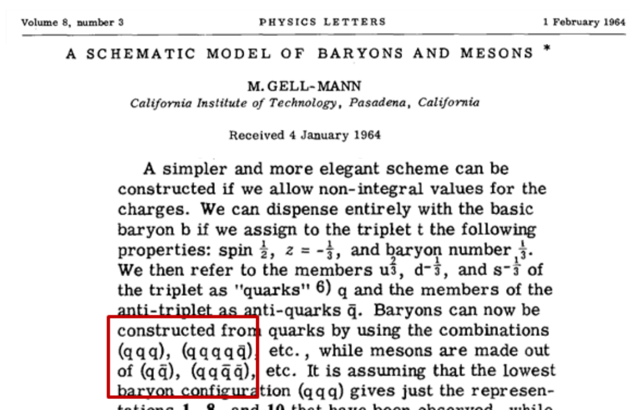
- M($J/\psi p$) projection shows unknown structure around 4.5 GeV:
  - has to contain 5 quarks







  - Could be Λ^* reflection ?


Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

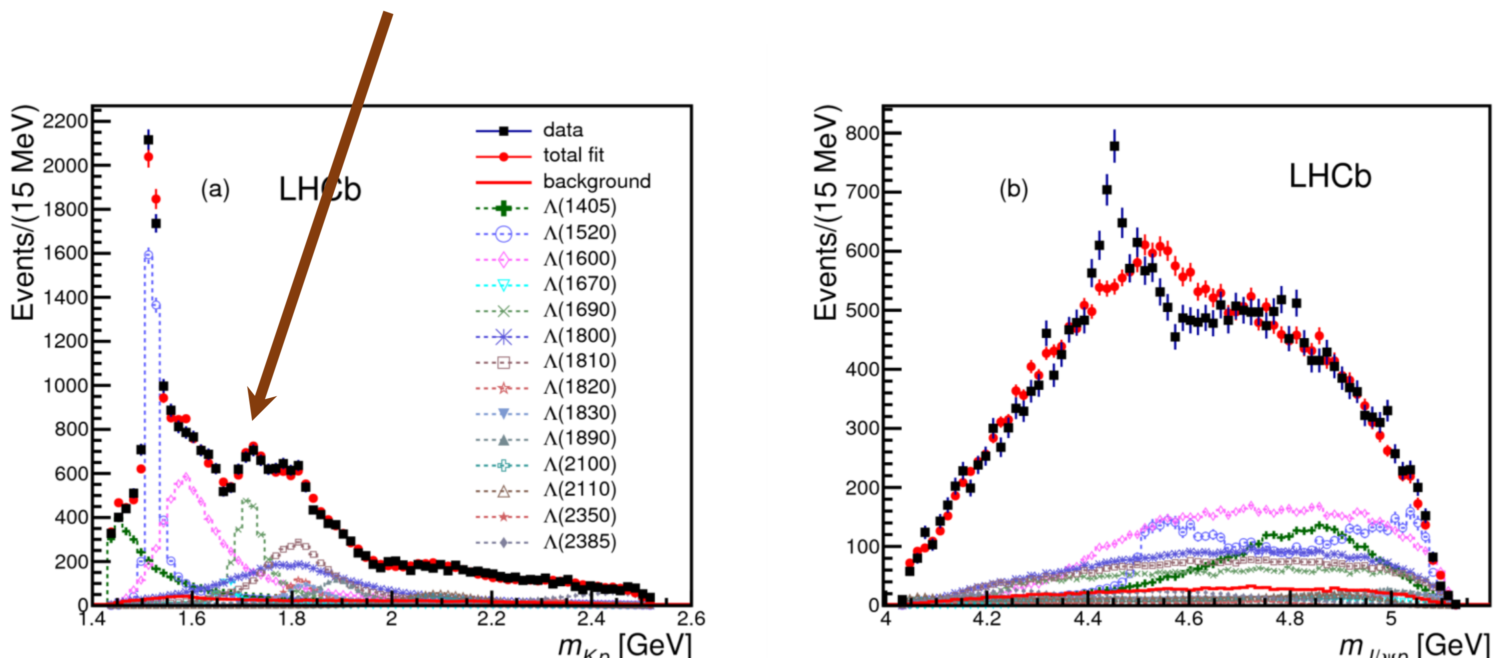
Received 4 January 1964

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while

[PRL 115 (2015) 161802]

Resonances in $\Lambda_b^0 \rightarrow J/\psi K^- p$

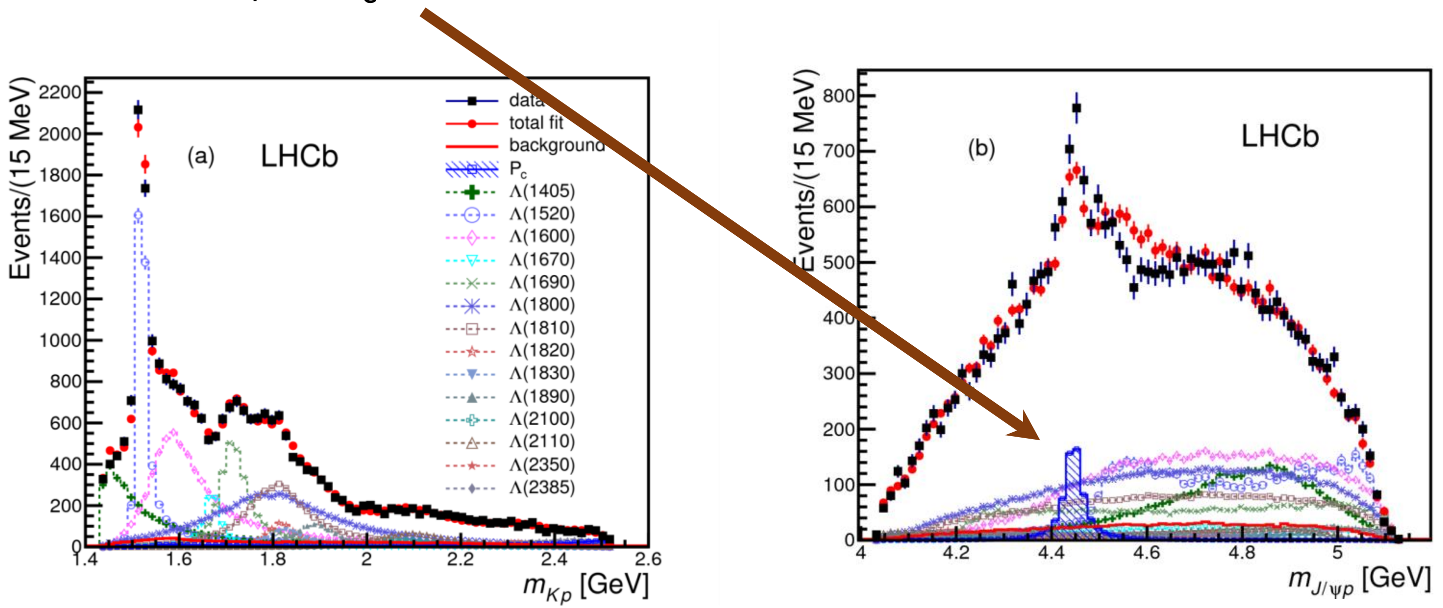
- Considering only Λ^* resonances (fit with 16 known Λ^* resonances)
  - → does not describe the data distributions



Resonances in $\Lambda_b^0 \rightarrow J/\psi K^- p$

[PRL 115 (2015) 161802]

- Adding one $J/\psi p$ (P_c^+) resonance improves the situation but is not enough:

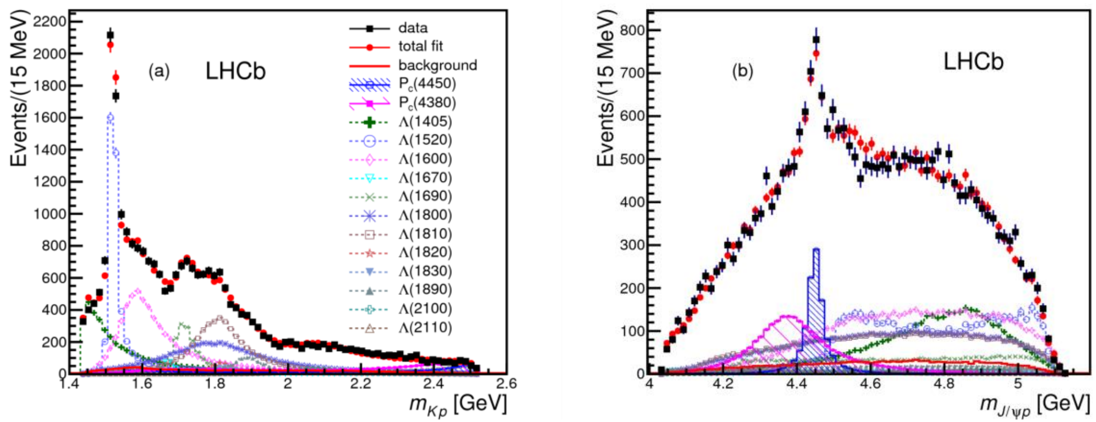


- $\Delta \ln L = 14.7$

[PRL 115 (2015) 161802]

Resonances in $\Lambda_b^0 \rightarrow J/\psi K^- p$

- An extra state is needed to describe correctly the data:



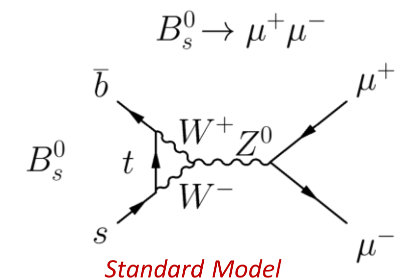
- $\Delta \ln L = 18.7$
- Parameters of the 2 states determined from the fit:

$P_c(4380)^+$: M = 4380 ± 8 ± 29 MeV, Γ = 205 ± 18 ± 86 MeV, $J^P = 3/2^-$
$P_c(4450)^+$: M = 4449.8 ± 1.7 ± 2.5 MeV, Γ = 39 ± 5 ± 19 MeV, $J^P = 5/2^+$

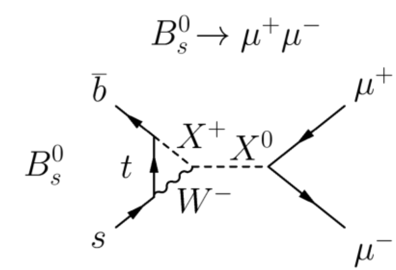
[Nature 522 (2015) 68]

Rare decays: $B_{(s)}^0 \rightarrow \mu^+ \mu^-$

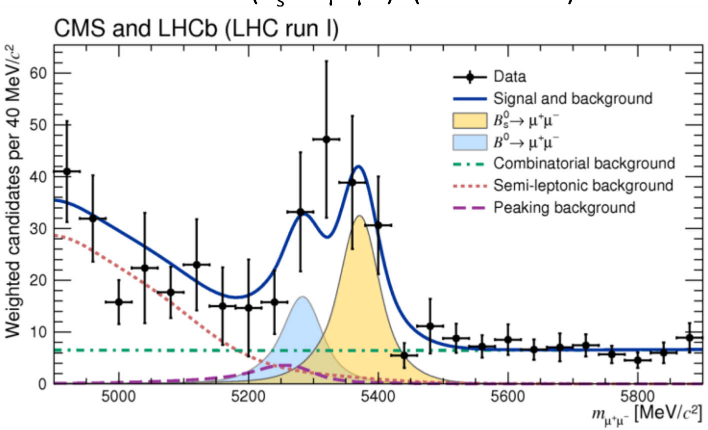
- Very small branching fraction in the standard model:
  - Highly suppressed: flavor changing neutral currents not allowed at tree level in standard model
  - Occur through loops, where new physics presence could enhance significantly branching fraction
  - Standard model predictions [C. Bobeth *et al.*, PRL 112 (2014) 101801]:
    - $BR(B_s^0 \rightarrow \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$
    - $BR(B_s^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$



Standard Model



New Physics



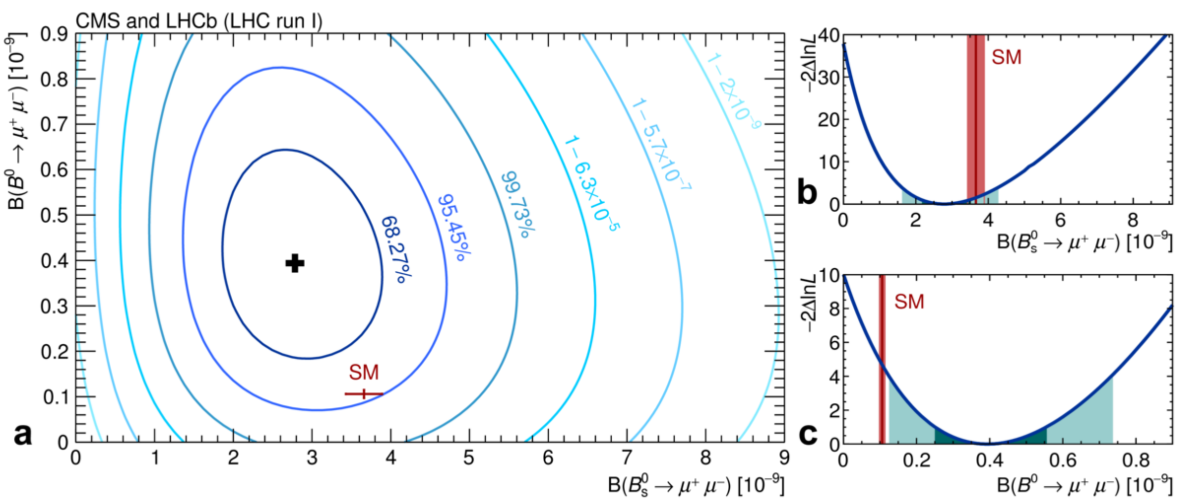
Combination of CMS and LHCb Run 1 datasets:

- First observation of $B_s^0 \rightarrow \mu^+\mu^-$ (6.2σ)
- First evidence of $B^0 \rightarrow \mu^+\mu^-$ (3.0σ)

[Nature 522 (2015) 68]

Rare decays: $B_{(s)}^0 \rightarrow \mu^+ \mu^-$

- Measured values compatible
- Give strong constraints on new physics models with scalar couplings:



$\mathrm{BR}(B_s^0 \rightarrow \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$

$\mathrm{BR}(B^0 \rightarrow \mu^+\mu^-)\ \ (3.9^{+1.6}_{-1.4}) \times 10^{-10}$

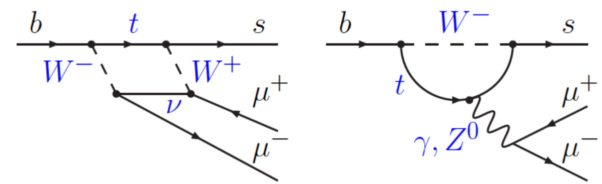
Standard Model

$\mathrm{BR}(B_s^0 \rightarrow \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$

$\mathrm{BR}(B_s^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

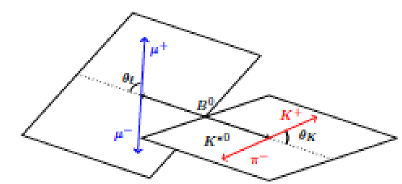
[arXiv: 1512.04442]

Rare decays: $B^0 \rightarrow K^{*0}\,\mu^+\,\mu^-$

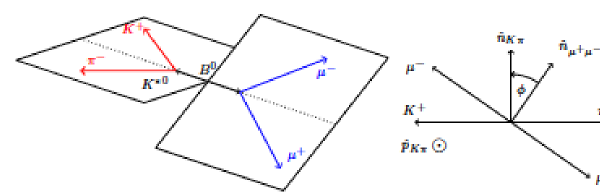


- Also suppressed in the standard model:
  - Only with loops in the SM
  - Can be modified by new physics contributions (at tree or loop level)
- Large set of observables in angular analysis of the $K^+\pi^-\mu^+\mu^-$ final state, sensitive to new physics.

$$
\begin{aligned}
\frac{1}{\mathrm{d}\,\Gamma+\bar{\Gamma}/\,\mathrm{d}\,q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}^3\vec{\Omega}} = \frac{9}{32\pi}\Big(&\frac{3}{4}(1-F_L)\sin^{\theta}_{K}+F_L\cos^2\theta_K \\
&+\frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell \\
&-F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\
&+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi \\
&+\frac{3}{4}A_{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\cos\phi \\
&+S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin\theta_\ell\sin 2\phi\Big)
\end{aligned}
$$



(a) θ_K and θ_ℓ definitions for the B^0 decay

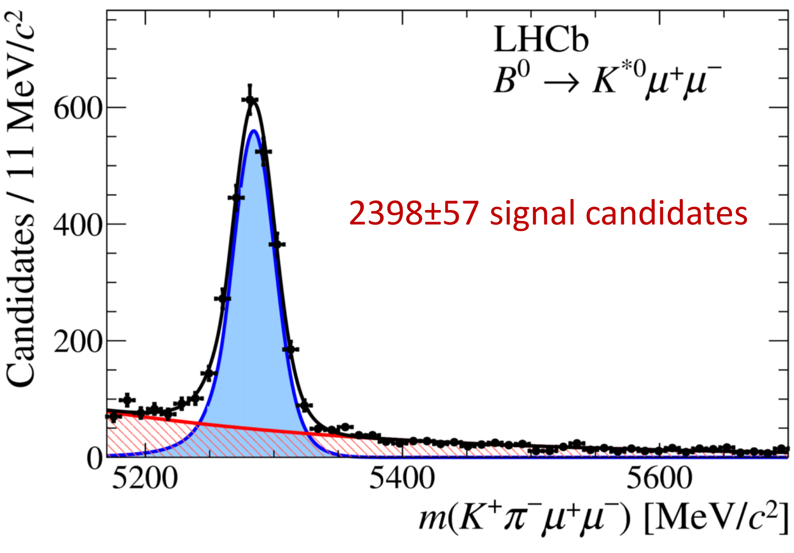


(b) ϕ definition for the B^0 decay

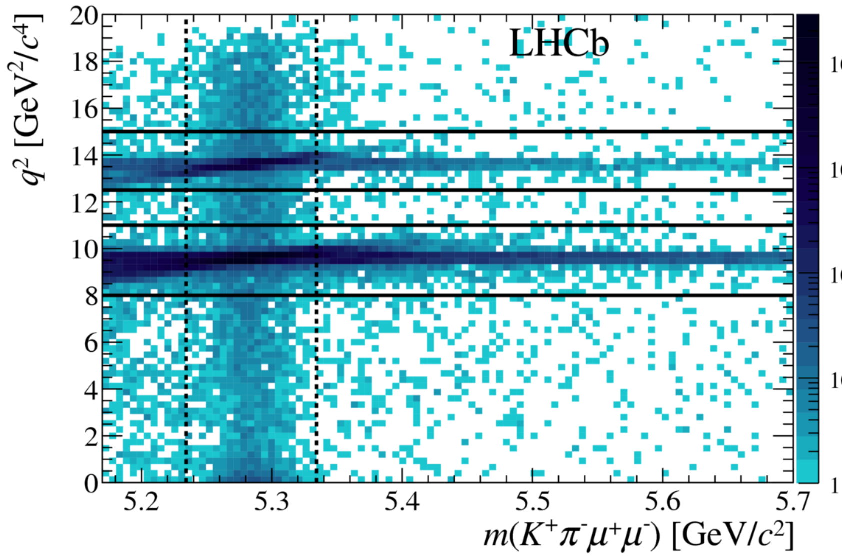
Rare decays: $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

[arXiv: 1512.04442]

- Contributions from J/ψ and ψ(2S) vetoed.
- Analysis done in bins of $q^2 = M(\mu^+\mu^-)^2$ with 3fb^{-1} of Run 1 data



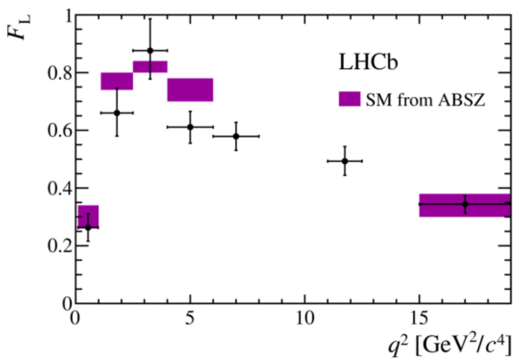
Full q² range with J/ψ and ψ(2S) veto

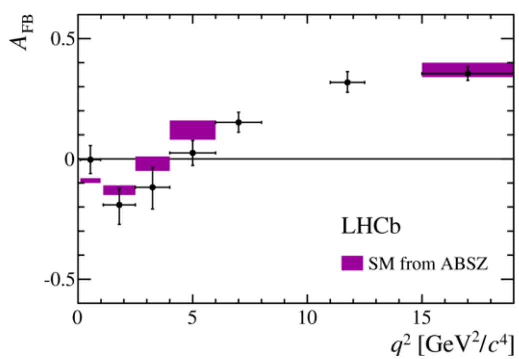


[arXiv: 1512.04442]

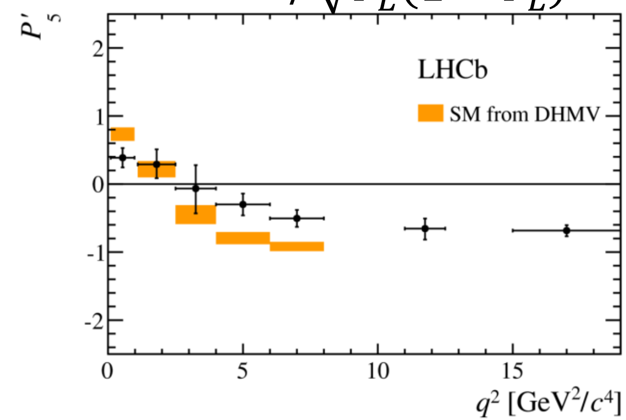
Rare decays: $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

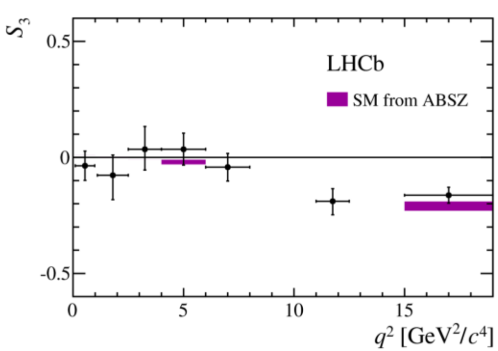
- Distributions compared with standard model predictions:

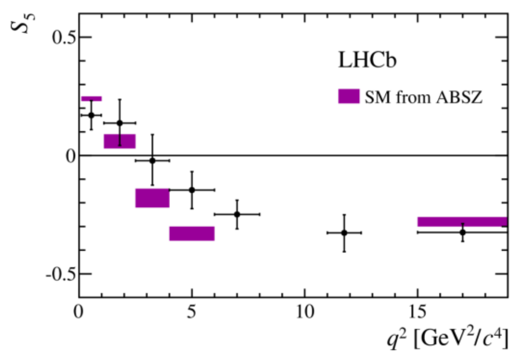




$$P_5' = S_5 \Big/ \sqrt{F_L(1-F_L)}$$





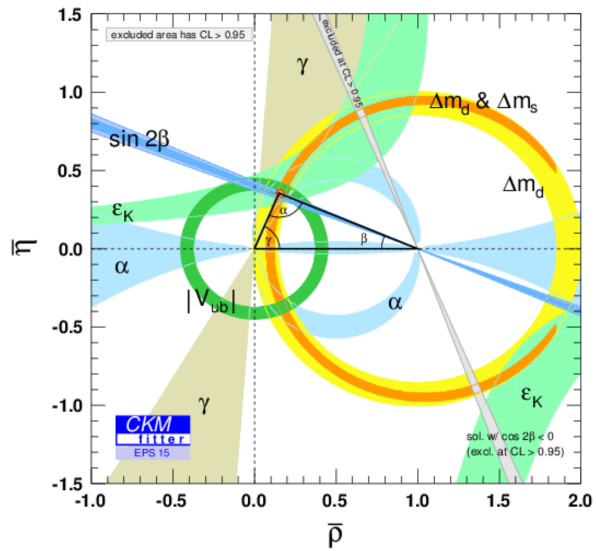


ABSZ: [W. Altmannshofera, D. M. Straubb, EPJC 75 (2015) 382]

DHMV: [S. Descotes-Genon, L. Hofer, J. Matias, J. Virto, JHEP 12 (2014) 125]

CP Violation

- Precise measurements of phases of the CKM matrix is one of the main goal of the experiment
- LHCb contributions:
  - $\gamma = 73^{+10}_{-9}{}^{\circ}$ [LHCb-CONF-2014-004]
  - $\sin(2\beta) = 0.73 \pm 0.04 \pm 0.02$ [PRL 114 (2015) 041801]
  - ϕ_s = -0.034 ± 0.033 [PRL 114 (2015) 041801]

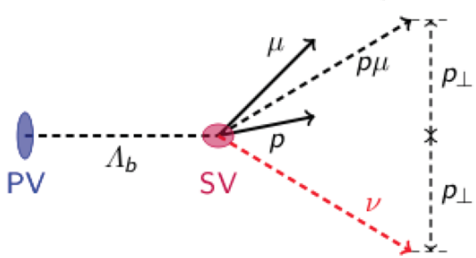


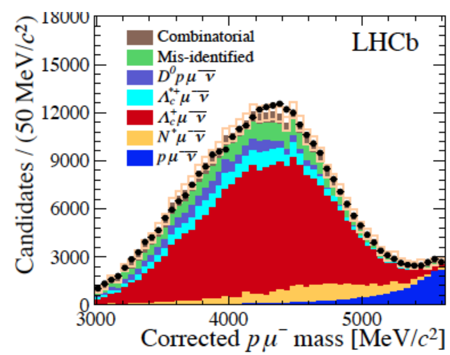
[Nature Physics 11 (2015) 743]

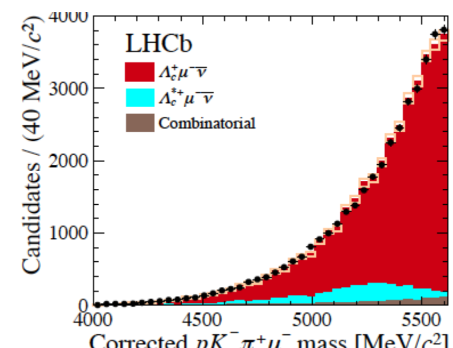
$|V_{ub}|/|V_{cb}|$ from $\Lambda_b^0 \to p\mu^-\nu_\mu$

- Measured with the branching ratios of *b*-baryons: $\Lambda_b^0 \to p\mu^-\nu_\mu$ and $\Lambda_b^0 \to \Lambda_c^+\mu^-\nu_\mu$
  - $|V_{ub}|^2/|V_{cb}|^2 = \mathrm{BR}(\Lambda_b^0 \to p\mu^-\nu_\mu)/\mathrm{BR}(\Lambda_b^0 \to \Lambda_c^+\mu^-\nu_\mu) \times F$
  - F = ratio of form factors, from lattice QCD computations
- Semi-leptonic decay modes, challenging in hadronic environments
- From Λ_b direction and mass constraints and detected decay products, compute a corrected mass

$$M_{corr} = \sqrt{M_{p\mu}^2 + p_\perp^2} + p_\perp$$







$N(\Lambda_b^0 \to p\mu\nu_\mu) = 17687 \pm 733$ $N(\Lambda_b^0 \to \Lambda_c^+\mu\nu_\mu) = 34255 \pm 571$

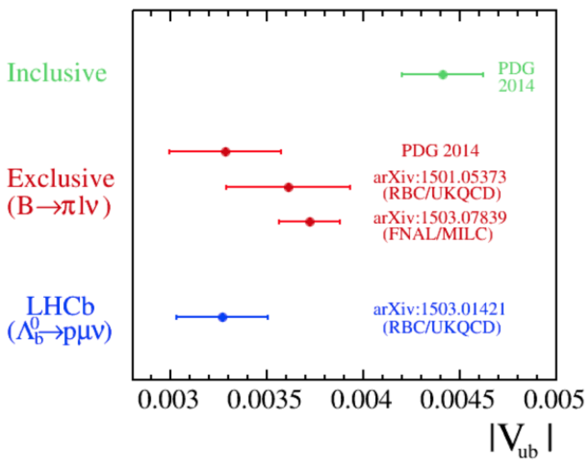
$|V_{ub}|/|V_{cb}|$ from $\Lambda_b^0 \to p\mu\nu_\mu$

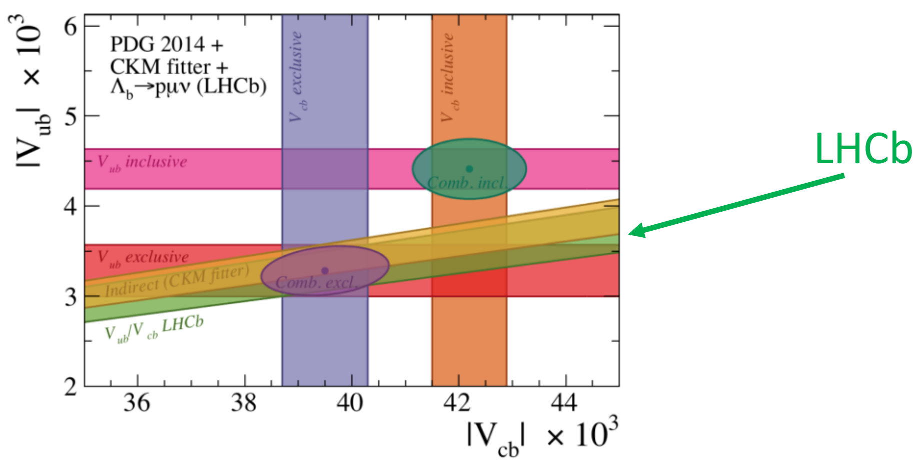
[Nature Physics 11 (2015) 743]

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

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

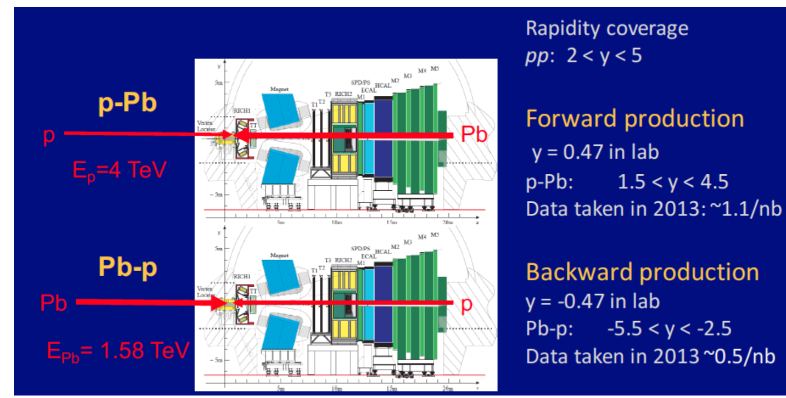
- Discrepancy between exclusive and inclusive measurements, not solved by LHCb measurement



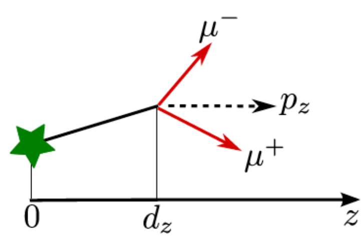


ψ(2S) production in *p*A collisions

- LHCb took part to the pA LHC run in 2013, with 2 configurations:
  - *p*Pb: 1.1 nb^{-1}
  - Pb*p*: 0.5 nb^{-1}
- Published measurements of J/ψ, Υ(1S) and *Z* production, providing input to study of cold nuclear matter effects and constrain nuclear parton density functions (nPDF), at low x.
- Measurement of production cross-section in bins of p_T and *y*
- Separating prompt ψ(2S) from the ones from b decay with the pseudo propertime
  - Effects on ψ(2S) from *b* are in fact effects on b hadrons.

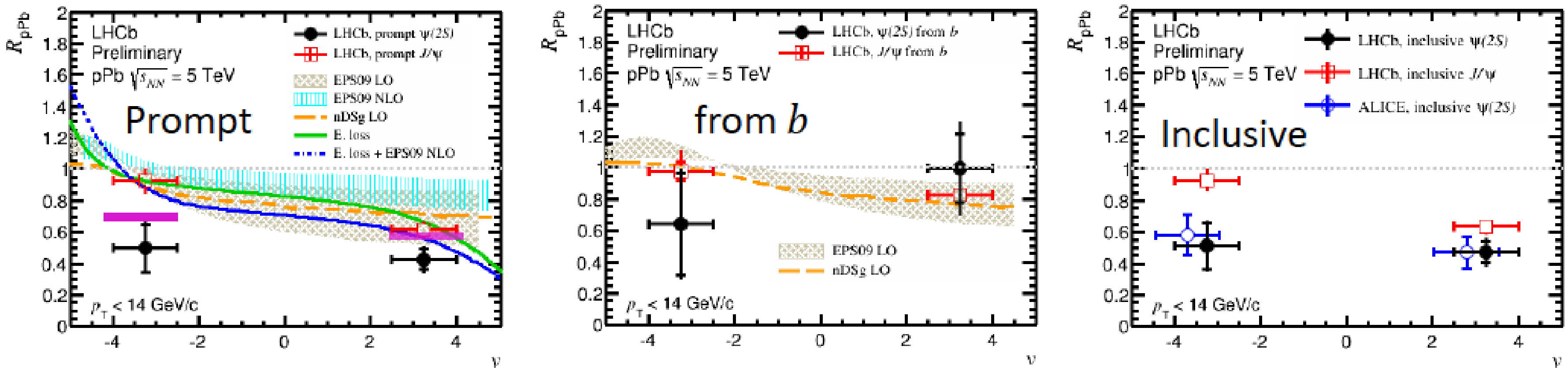


$$t_z(J/\psi) = \frac{d_z \times M_{J/\psi}}{p_z}$$



[LHCb-CONF-2015-005]

ψ(2S) production in *p*A collisions



EPS09 LO — Phys. Rev. C88 (2013) 047901

EPS09 NLO — Int. J. Mod. Phys. E22 (2013) 1330007

nDSg LO — Phys. Rev. C88 (2013) 047901

E. loss — JHEP 03 (2013) 122

E. loss + EPS09 NLO — JHEP 03 (2013) 122

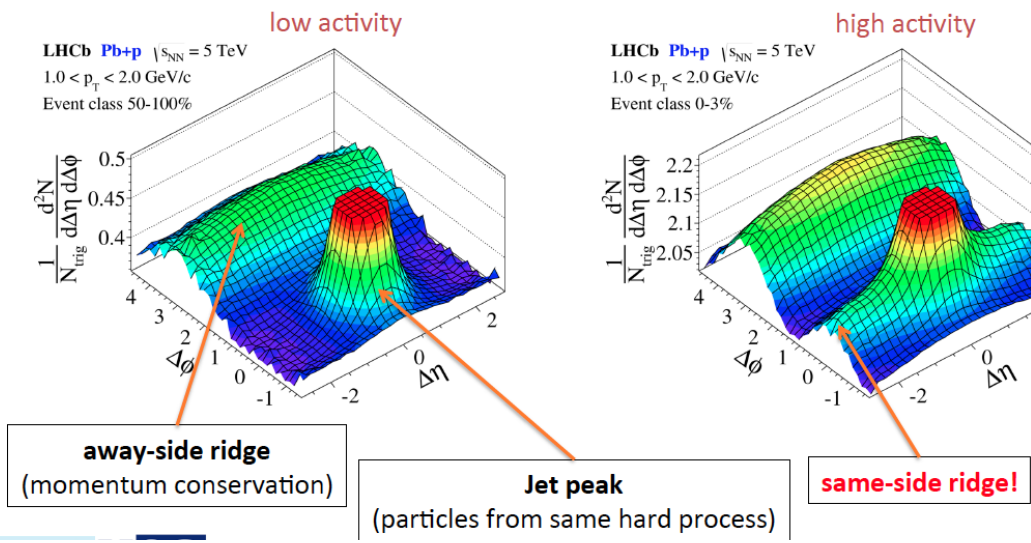
EPS09 LO, nDSg LO — Nucl.Phys.A926 (2014) 236

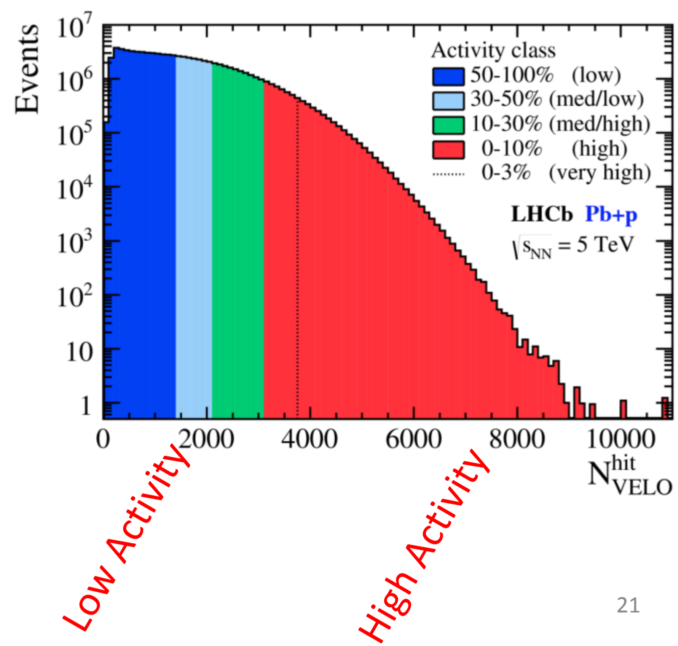
Comover — Phys. Lett. B749 (2015) 98

[arXiv:1512.00239]

Two-particle correlations in pPb collisions

- Measurement of two-particle correlations ($\Delta\phi$, $\Delta\eta$) , as a function of the event activity (estimated with number of tracks in the VELO)

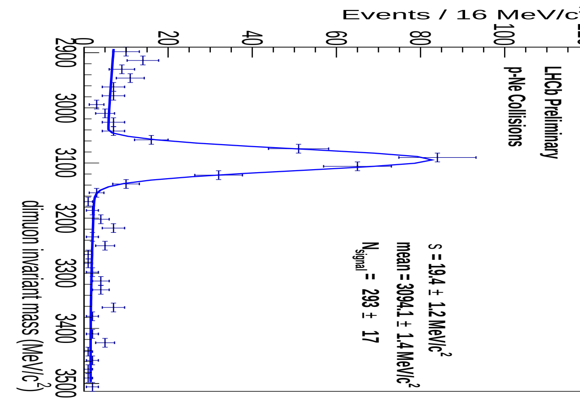


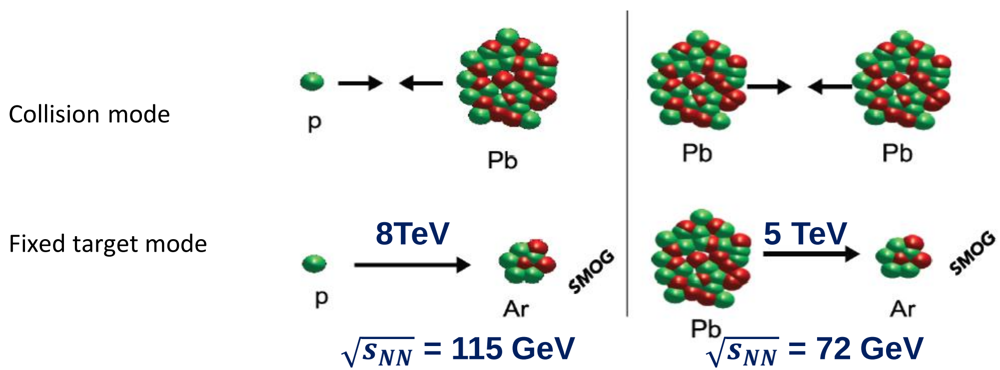


Fixed Target Physics With LHCb

- Done for the first time this year
- Several gases can be injected in the interaction region: Ne (August), He (September), Ar (October)
- Unique energy range reached, used also with Pb beams in december 2015, during PbPb run where LHCb collected data for the first time.

J/ψ signal

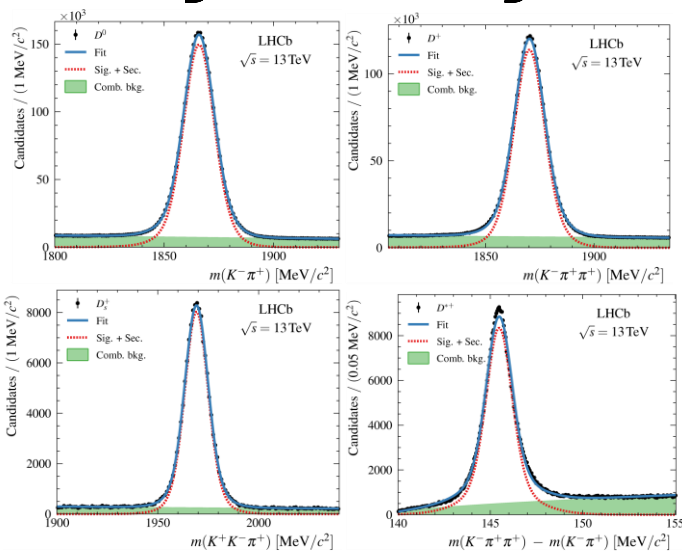




First results at 13 TeV

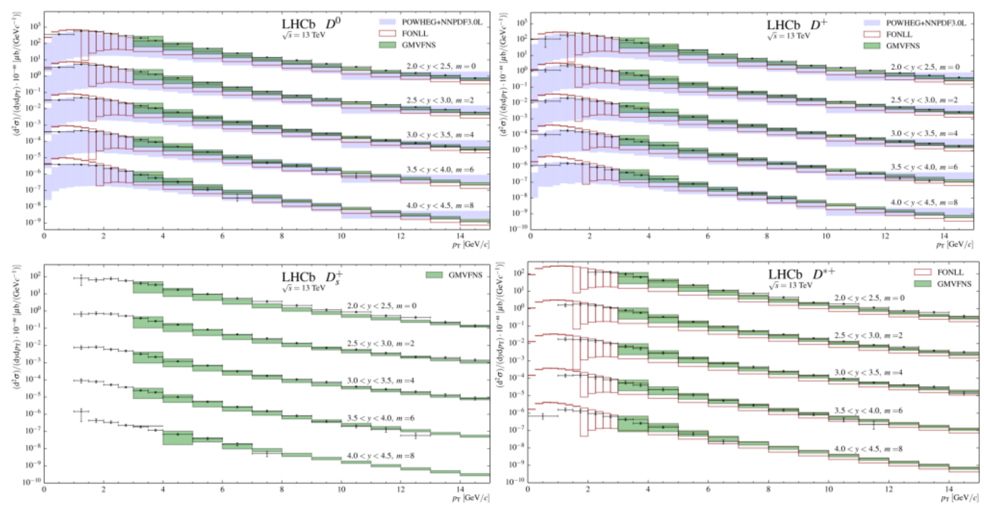
Differential production cross-sections (p_T, y)

D^0 D^+



D_s^+ D^{*+}

D^0 D^+



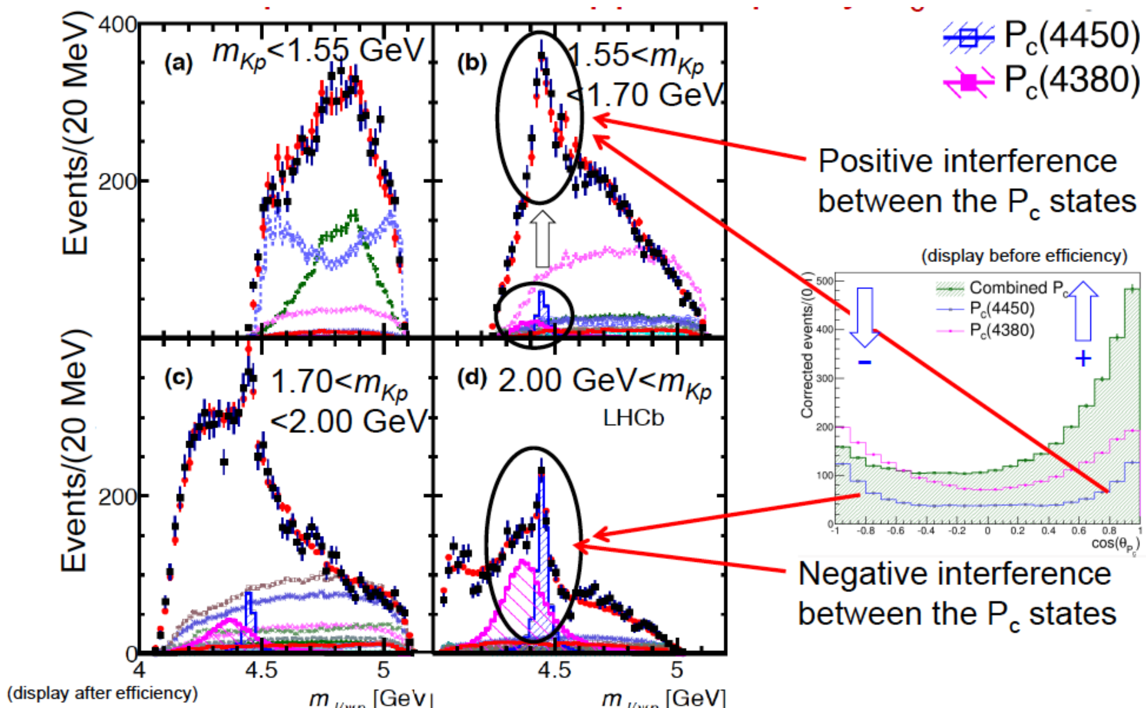
D_s^+ D^{*+}

Conclusions

- Important results obtained recently from Run 1 data
- Run 2 started successfully, a lot of new data will be accumulated in the next years
- LHCb extending its physics program in the area of heavy ions for example

Backup

Opposite Parities



- Two opposite parity states necessary to generate the interference pattern