Hadron Spectroscopy and Heavy Ion Results at LHCb

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On behalf of the LHCb collaboration

55th International Winter Meeting on Nuclear Physics

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Outline

- LHCb has a wide hadronic physics program: QCD, EW, spectroscopy, heavy ions
- Spectroscopy of exotic states
  - ★ Observation of pentaquarks in $\Lambda_b \rightarrow J/\psi pK$
  - ★ Observation of exotic states in $B^+ \rightarrow J/\psi\phi K^+$
- Heavy ions
  - ★ Results from pPb collisions
  - ★ Fixet target program
  - ★ First look at pPb run in 2016
- Conclusions

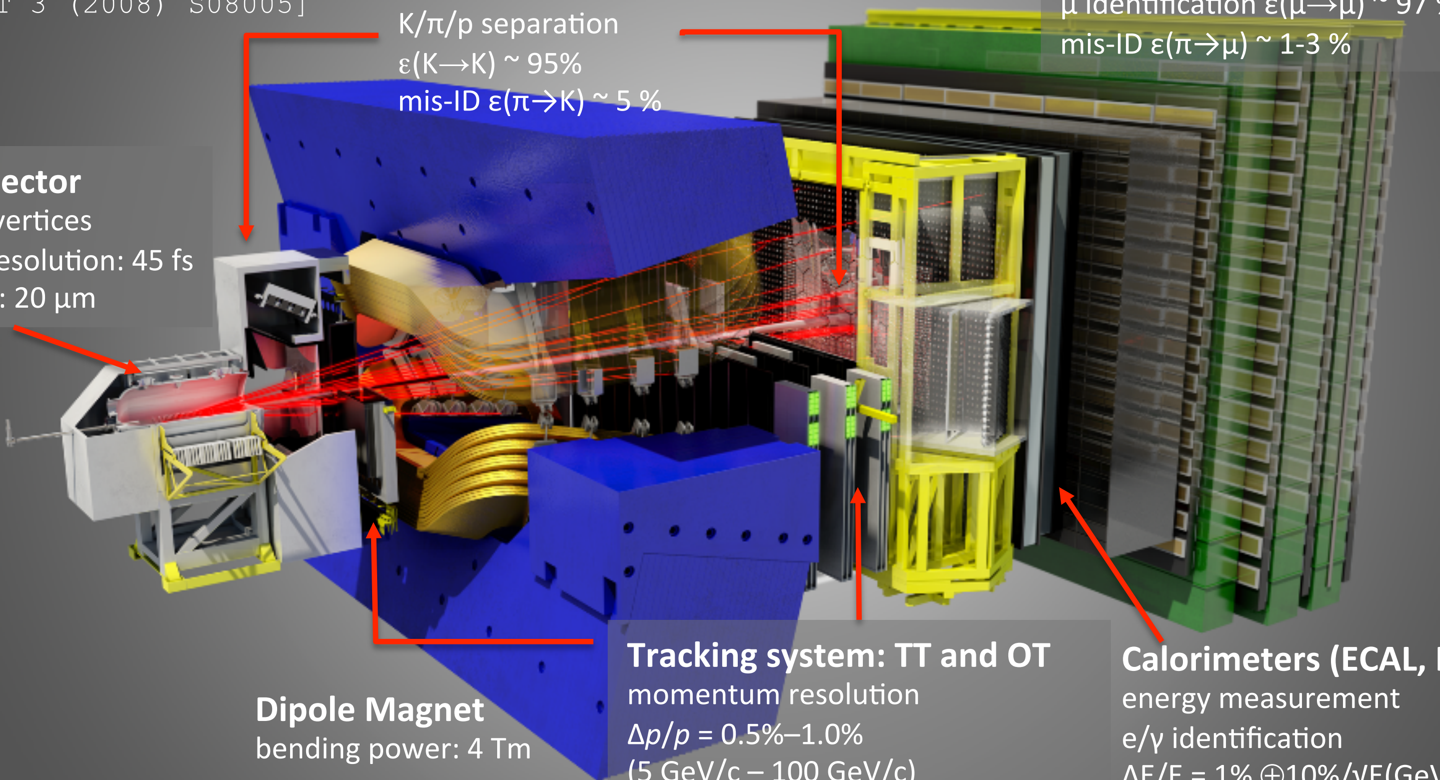
LHCb

[IJMPA 30 (2015) 1530022]
[JINST 3 (2008) S08005]

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 %

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



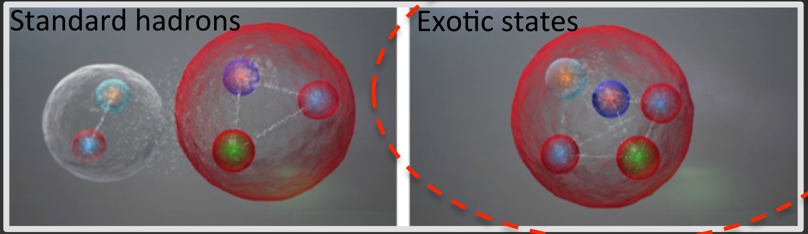
Dipole Magnet
bending power: 4 Tm

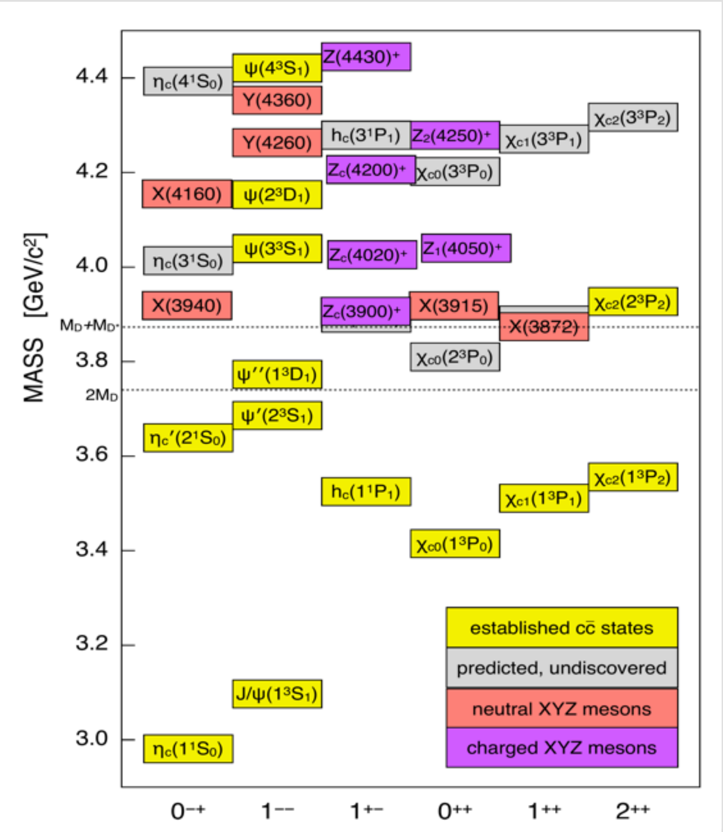
Tracking system: TT and OT
momentum resolution
$\Delta p/p$ = 0.5%–1.0%
(5 GeV/c – 100 GeV/c)

Calorimeters (ECAL, HCAL)
energy measurement
e/γ identification
$\Delta E/E = 1\% \oplus 10\%/\sqrt{E(\mathrm{GeV})}$

Spectroscopy at LHCb

- LHCb particularly suitable for hadron spectroscopy:
  - ★ Large production cross section
  - ★ Excellent mass resolution
  - ★ Excellent vertexing and PID (→ low background)
- Many new states have been observed in heavy flavor spectroscopy: see for example the charmonium spectrum
- Many of them can be interpreted as "standard" hadronic states while others require an "exotic" interpretation

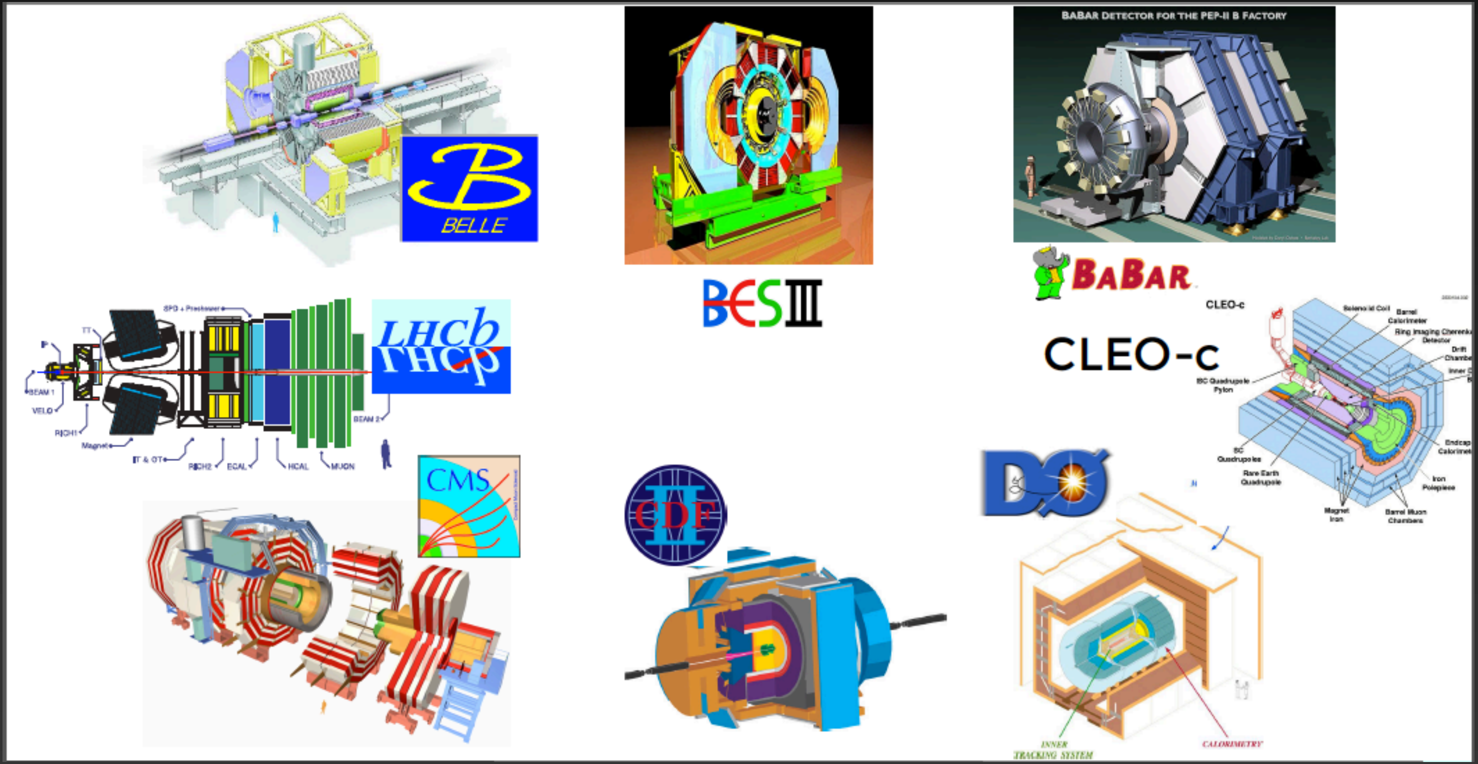




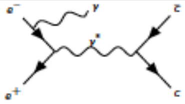
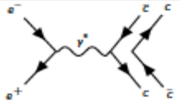
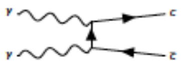
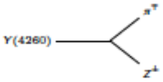
[PoS Bormio 050(2015) arXiv:1511.01589]

Experimental efforts on charmonium-like exotics

- Spectroscopy studies in LHCb are part of a worldwide experimental effort (see also the talk by S.L. Olsen)



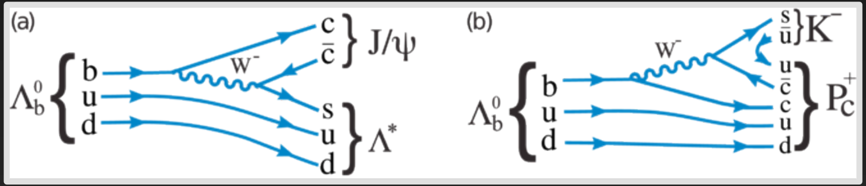
Experimental efforts on charmonium-like exotics

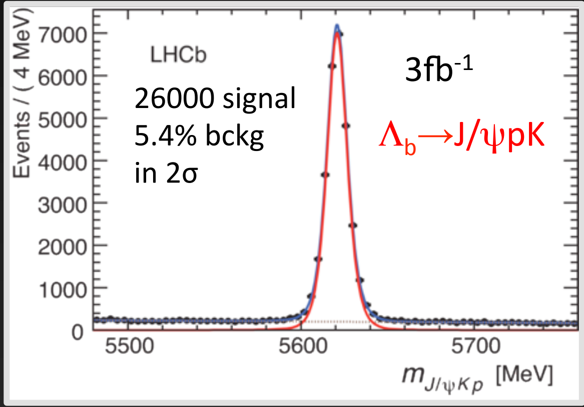
						$p\bar{p}$ incl.	pp incl.
$J/\psi\pi^+\pi^-$	X(3872)	Y(4260) Y(4008)				X(3872)	X(3872)
$\psi(2S)\pi^+\pi^-$		Y(4360) Y(4660)					
$\Lambda_c\bar{\Lambda}_c$		Y(4630)					
$\psi\gamma$	X(3872)						
$\chi_{c1}(1P)\gamma$	X(3832)						
$\chi_{c1}(1P)\omega$				Y(4220)			
$J/\psi\omega$	X(3872) Y(3940)			X(3915)			
$J/\psi\phi$	X(4140) X(4274) X(4500) X(4700)			X(4350)			
$J/\psi\pi$	Z(4430) Z(4200) Z(4240)				Z(3900)		
$\psi(2S)\pi$	Z(4430)						
$\chi_{c1}(1P)\pi$	Z(4051) Z(4248)						
$h_c(1P)\pi$					Z(4020)		
$D\bar{D}$				Z(3930)			
$D\bar{D}^*$	X(3872)		X(3940)		Z(3885)		
$D^*\bar{D}^*$			X(4160)		Z(4025)		
$J/\psi p$	$P_c(4380)$ $P_c(4430)$						
$B_s^0\pi$						X(5568)	-

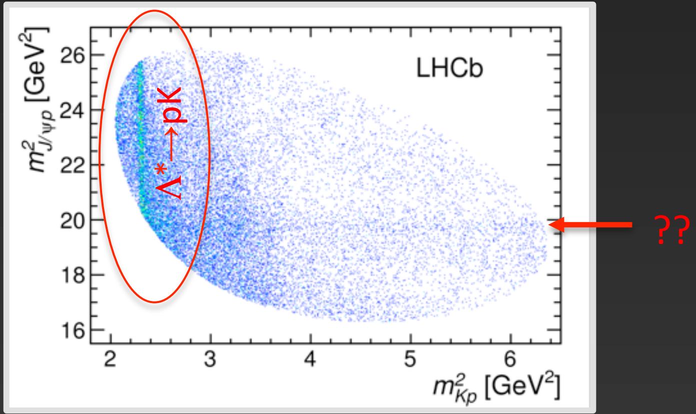
Observation of pentaquarks in $\Lambda_b \rightarrow J/\psi pK$

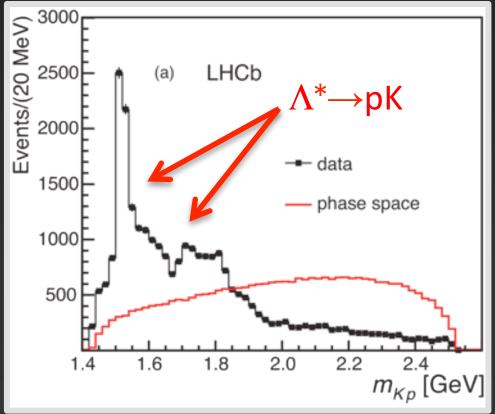
[PRL 115 (2015) 072001]

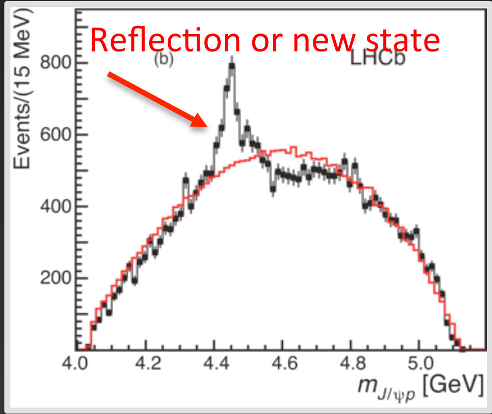
- The decay proceeds through diagram a) dominated by decays into Λ^* resonances
- It can also proceed through exotic states decaying to $J/\psi p$ (diagram b)





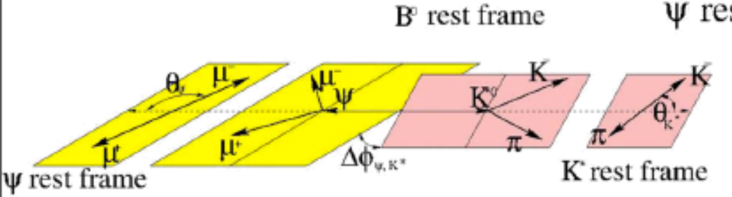


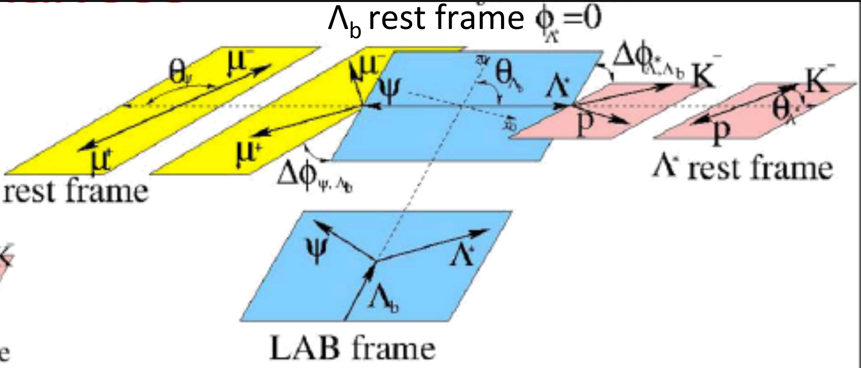




Full amplitude analysis

For the best sensitivity and to avoid dependence of efficiency on fit model, use all degrees of freedom in the decay





4D maximum likelihood fit

$$\Omega \equiv (\theta_{K^*}, \theta_{\psi}, \Delta\phi_{\psi,K^*})$$

6D maximum likelihood fit

$$\Omega \equiv (\theta_{\Lambda_b}, \theta_{\Lambda^*}, \Delta\phi_{\Lambda^*,\Lambda_b}, \theta_{\psi}, \Delta\phi_{\psi,\Lambda_b})$$

$$\mathrm{PDF}(\mathrm{m}_{K\pi/Kp}, \Omega) = \left| MatrixEle(\mathrm{m}_{K\pi/Kp}, \Omega \,|\, J_R^P, M_R, \Gamma_R, H_R) \right|^2 \times \mathrm{eff}(\mathrm{m}_{K\pi/Kp}, \Omega) + \mathrm{PDF}_{\mathrm{bkg}}(\mathrm{m}_{K\pi/Kp}, \Omega)$$

Fixed to known values.
M_R, Γ_R varied within errors for systematics.

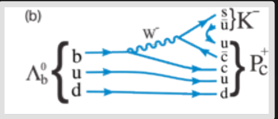
1-3 independent **complex** helicity couplings H_R per K^* resonance

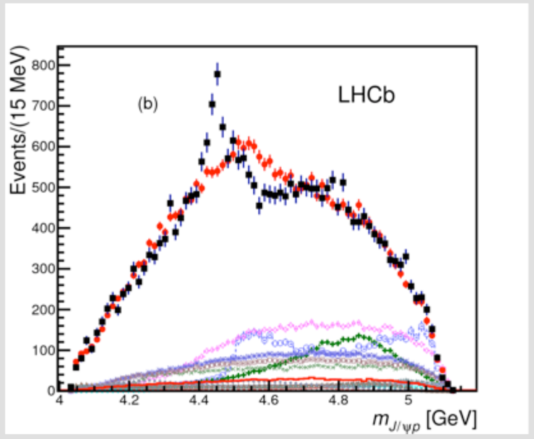
4-6 independent **complex** helicity couplings H_R per Λ^* resonance

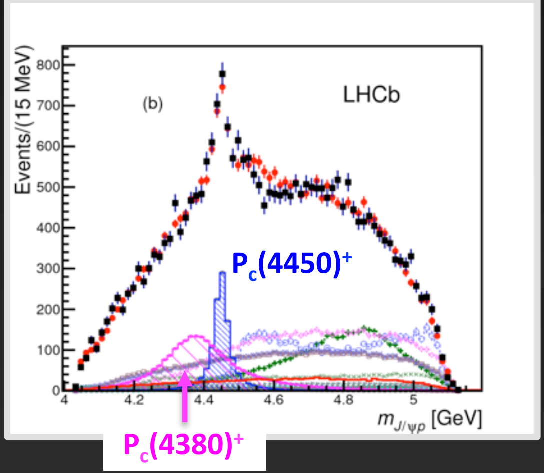
Observation of pentaquarks in $\Lambda_b \rightarrow J/\psi pK$

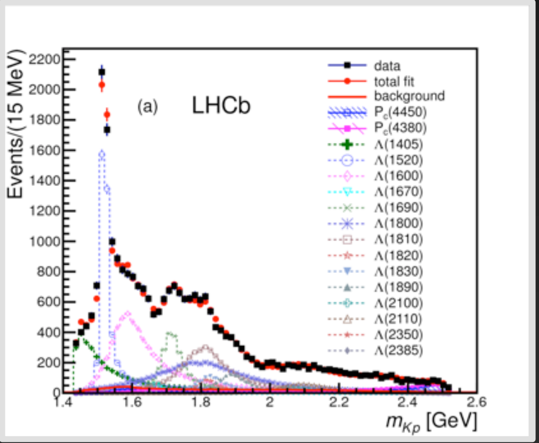
[PRL 115 (2015) 072001]

- Full amplitude analysis needed to correctly interpret the data
- A fit with the full set of Λ resonances not enough to reproduce the data
  ☞ need to include additional resonant states !









	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass [MeV/c^2]	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width [MeV/c^2]	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Fit fraction [%]	$8.4 \pm 0.7 \pm 4.2$	$4.1 \pm 0.5 \pm 1.1$
Significance	9σ	12σ

These states have minimal quark content: $c\bar{c}uud$

Therefore they are considered charmonium pentaquarks

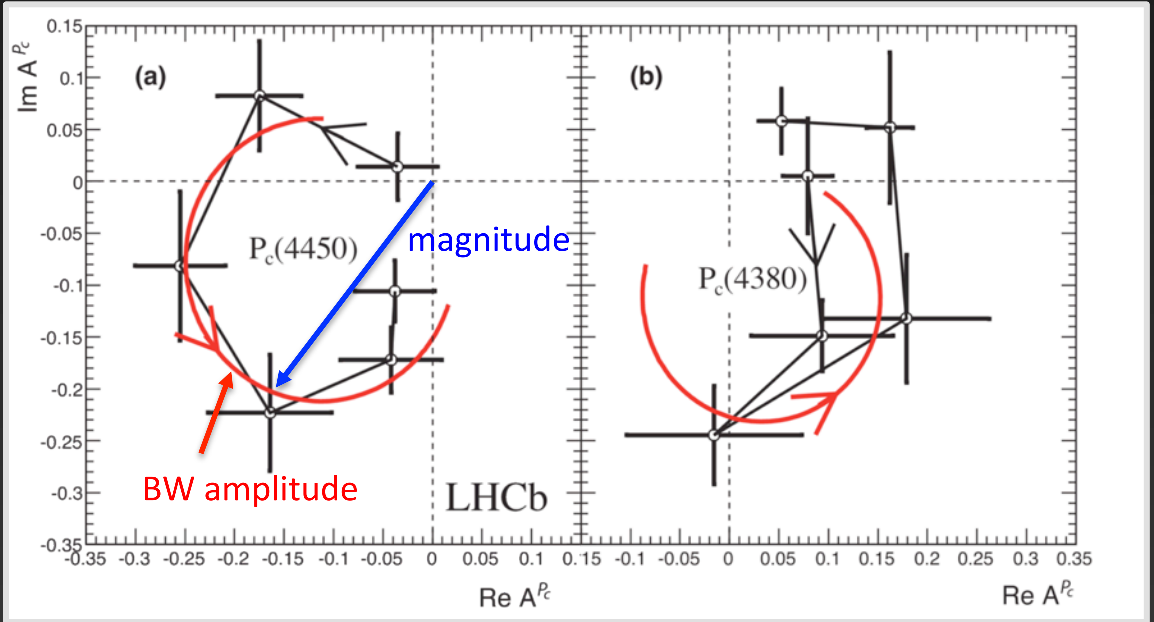
Other J^P combinations: $(3/2^+, 5/2^-)$, $(5/2^+, 3/2^-)$ are possible but slightly disfavoured

Observation of pentaquarks in $\Lambda_b \to J/\psi p K$

[PRL 115 (2015) 072001]

- The resonant character of the new states can be studied by plotting $\mathcal{Im}$(A) vs $\mathcal{Re}$(A) for 6 bins of m(J/ψp) between $-\Gamma$ and Γ, where A is the BW amplitude of the states (Argand diagram)
- P_c(4450) shows the rapid phase shift close to the mass pole typical of a resonant state
- The situation is less clear for P_c(4380), more statistics needed

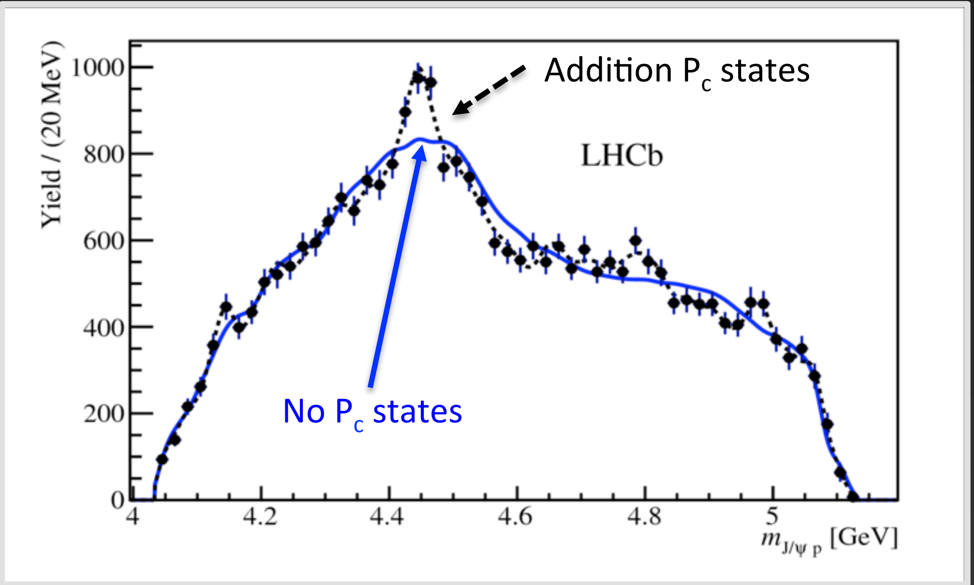
- These results constrain the models of the internal binding mechanism: J^P, mass, width of two states must be explained !
(see e.g. Tim's presentation!)

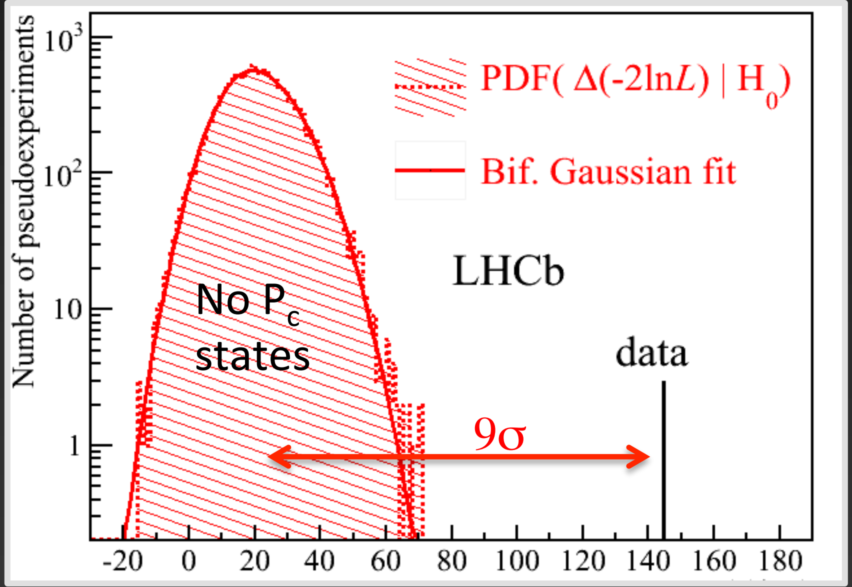


Model independent analysis of $\Lambda_b \rightarrow J/\psi pK$

- A model independent analysis is very important to confirm the P_c states.
- Angular distributions are fitted with a series of Legendre polinomials with mass-dependent upper limits on possible angular momenta
- The null hypothesis (i.e. no P_c states) does not reproduce the data; need to include the new states to describe the peaking structure around 4450 MeV and other features of $m_{J/\psi p}$ spectrum
- The significance of the additional states is $> 9\sigma$

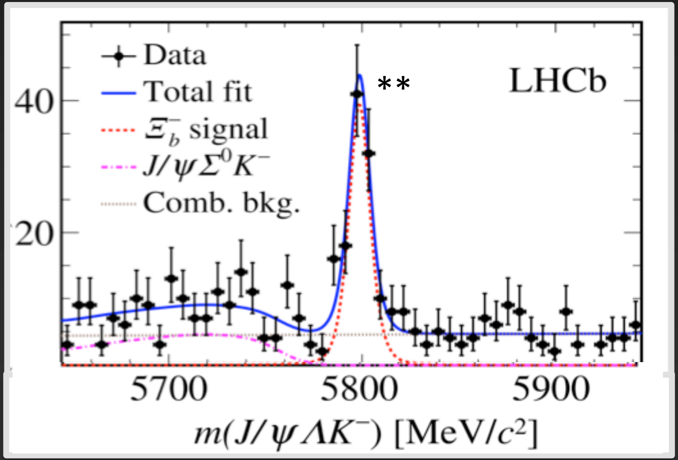
[PRL 115 (2015) 072001]



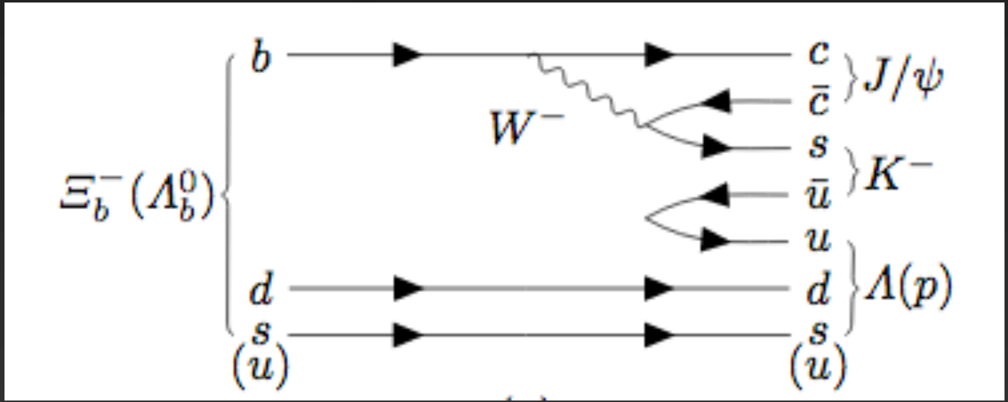


The decay $\Xi^-_b \to J/\psi \Lambda K^-$

- Paper on observation of his decay just released on arXiv:1701.05274, subm. to PLB
- It may proceed through P_c states with open strangeness: $uds c\bar{c}$
- It is the analogous of $\Lambda_b \to J/\psi pK$ with an s spectator quark



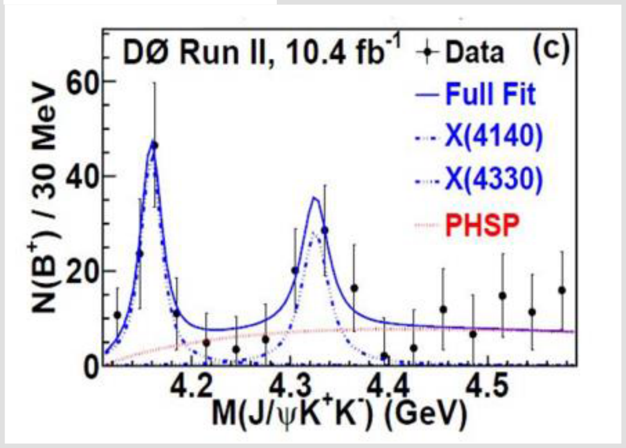
**only L candidates made with 2 long tracks



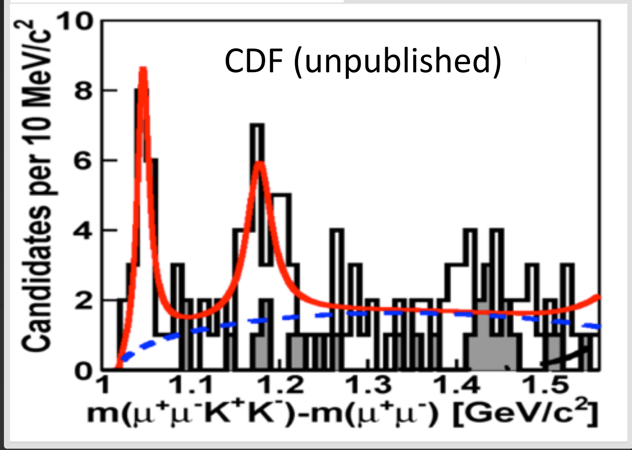
Exotic states in $B^+ \to J/\psi\phi K^+$

- Exotic structures have been observed in the $J/\psi\phi$ mass spectrum in the $B^+ \to J/\psi\phi K$ decays
- Experimental situation confusing: some experiments saw narrow X(4140) [i.e. Y(4140)], some didn't.; possibly a 2nd $J/\psi\phi$ structure in B decays, X(4274), but seen at inconsistent mass. No published claim of its significance.

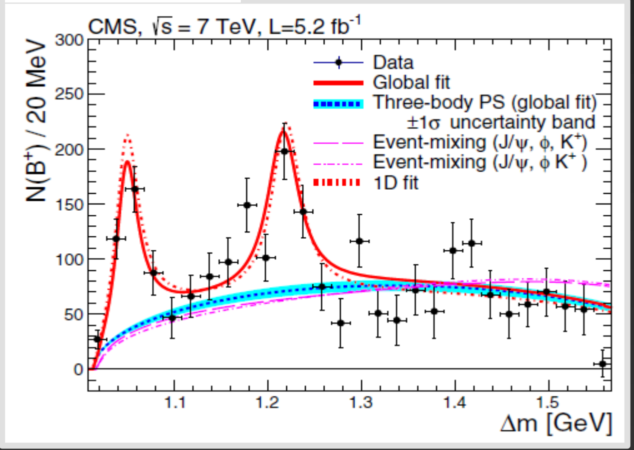
PRD89, 012004



arXiv:1101.6058



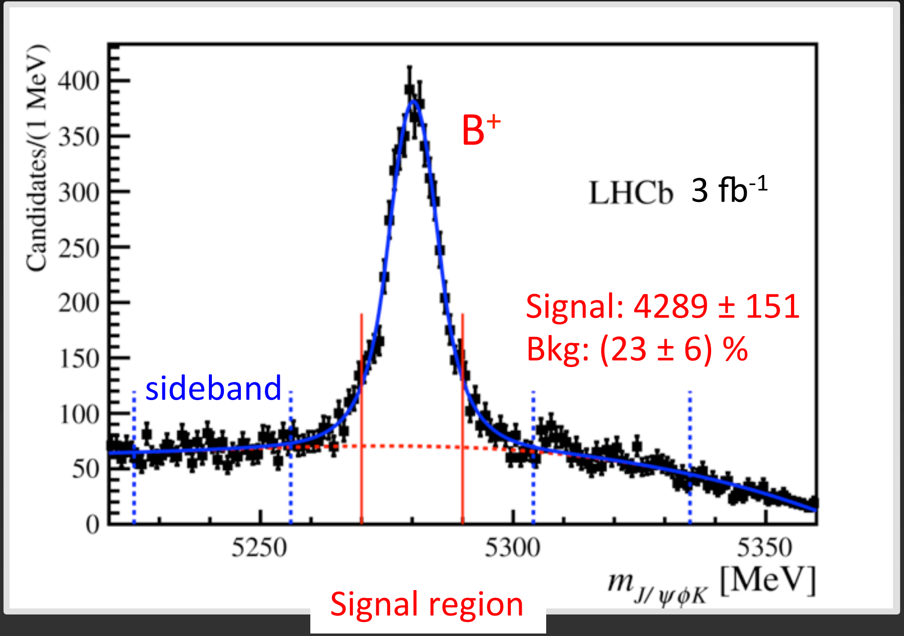
PL B734, 261

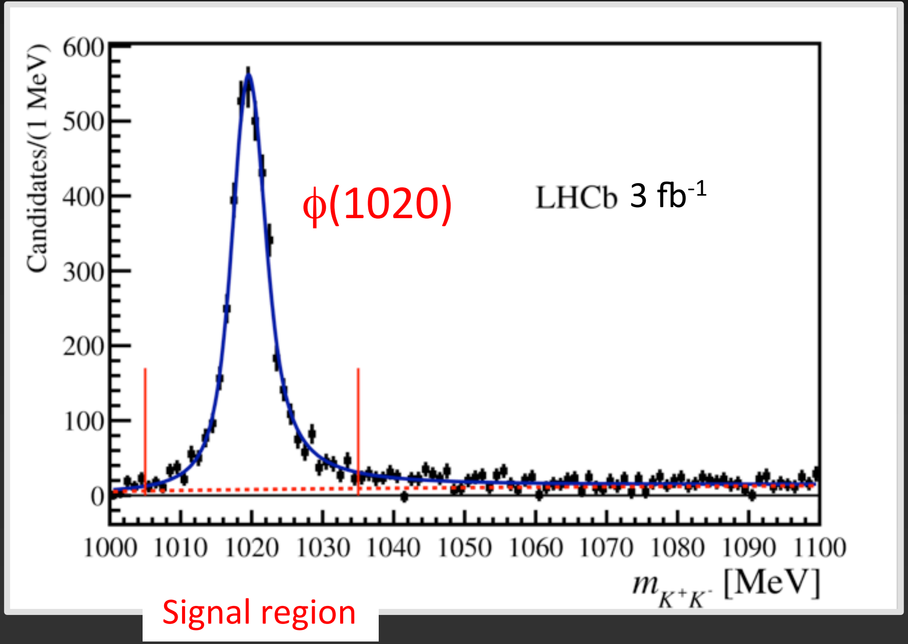


Exotic states in $B^+ \to J/\psi\phi K^+$

Phys. Rev. Lett. 118 (2017) 022003
Phys. Rev. D95 (2017) 012002

- LHCb exploits the largest sample of $B^+ \to J/\psi\phi K^+$ decays so far, trying to shed light on these states.





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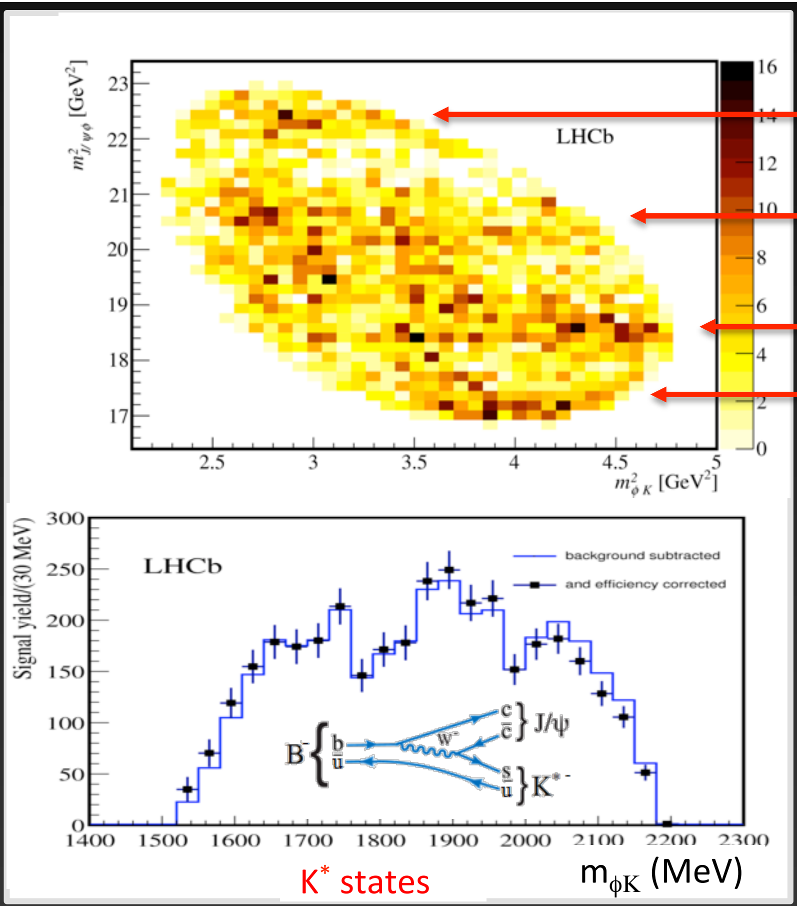


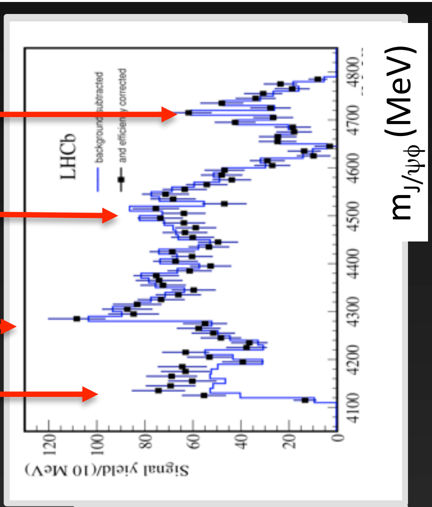
X() ?

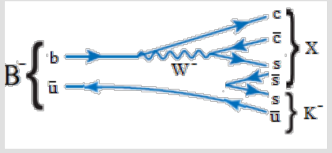
X() ?

X(4274)

X(4140)

→ $J/\psi\phi$





- Are these reflections of interfering $K^* \to \phi K$?
- Proper amplitude analysis needed!

Phys. Rev. Lett. 118 (2017) 022003
Phys. Rev. D95 (2017) 012002

Exotic states in $B^+ \to J/\psi\phi K^+$

Phys. Rev. Lett. 118 (2017) 022003
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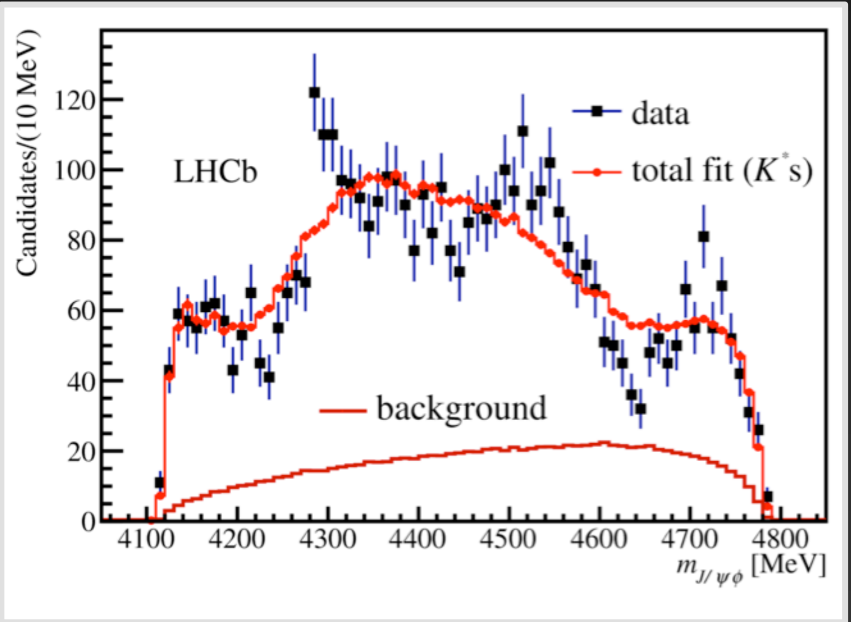
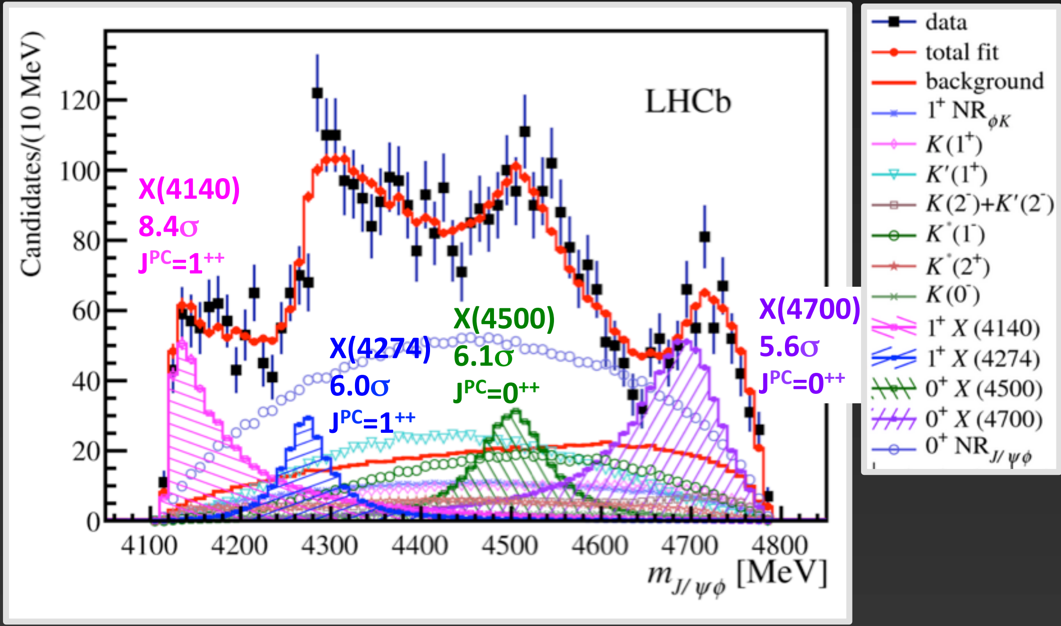
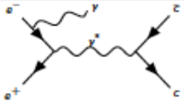
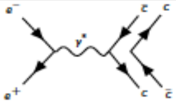
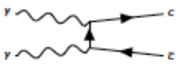
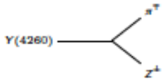
- Try to model the $m_{\phi K}$ spectrum with K^* states.
- Guidance from quark model was used to inform choices for K^* sector
- Try both known and unknown K* states
- Clear evidence that K* states only are not sufficient to reproduce data. Need additional states





Exotic states: summary of LHCb measurements

						$p\bar{p}$ incl.	pp incl.
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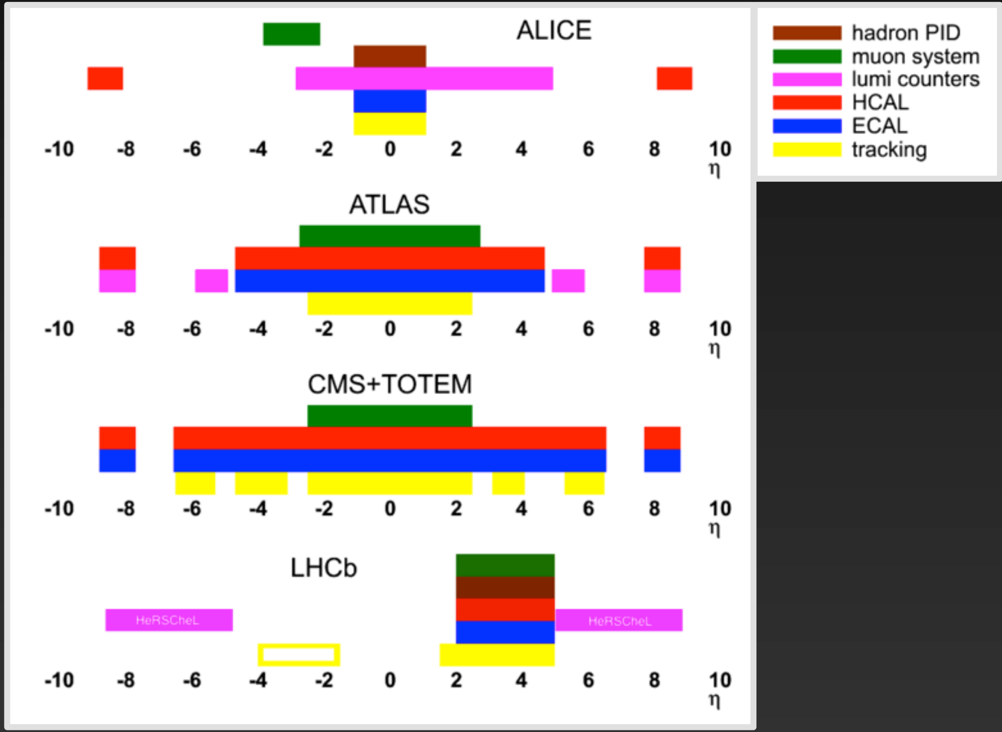
$J/\psi p$	$P_c(4380)$ $P_c(4430)$						
$B_s^0\pi$						X(5568)	-

LHCb

HEAVY ION RESULTS

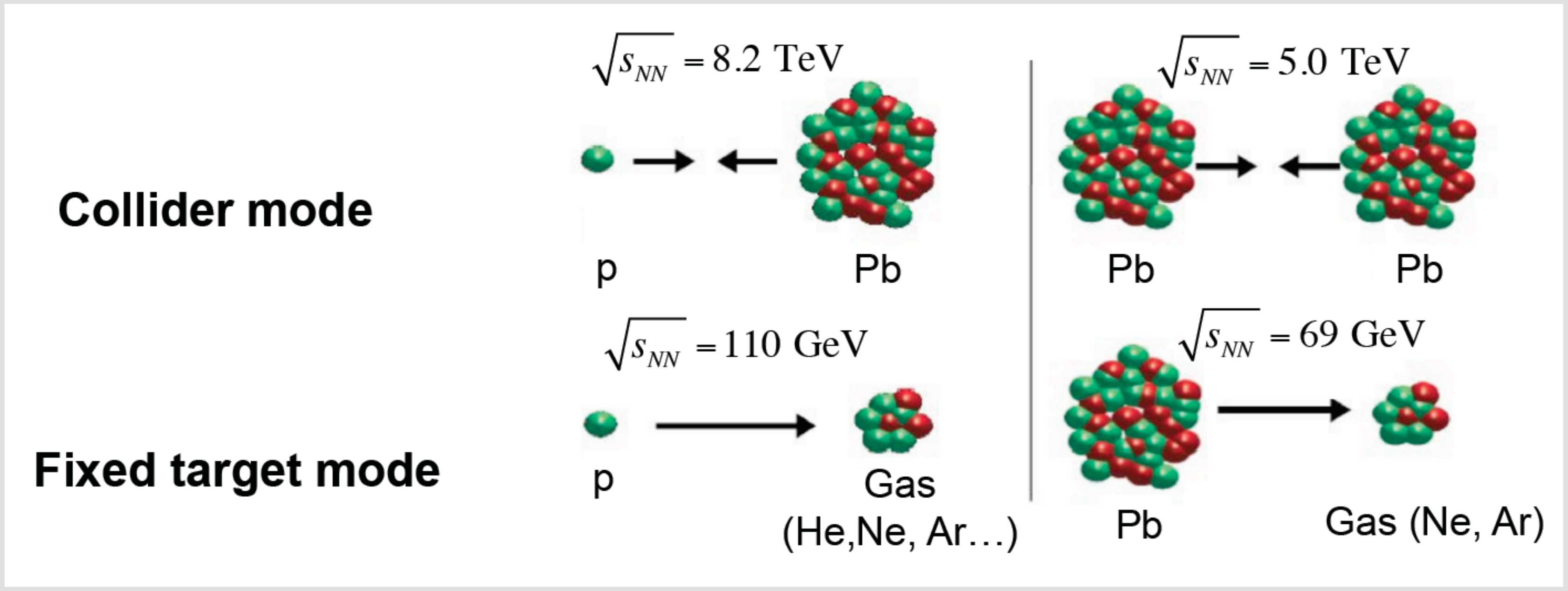
LHCb and Heavy Ions

- LHCb is specialised in heavy flavour precision physics but some characteristics make it attractive for measurements in Heavy ion physics:
  - ★ Detector fully instrumented in the forward region nicely complementary to other LHC experiments
  - ★ Precise vertexing: separation of prompt production from *B* decay products
  - ★ Precise tracking: reconstruction down to $p_T=0$
  - ★ Particle identification: reconstruction of (exclusive) hadronic decays



Heavy ion operation modes

- LHCb can operate in collider mode, fixed target mode or both in parallel!

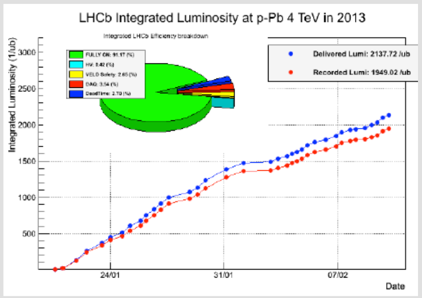


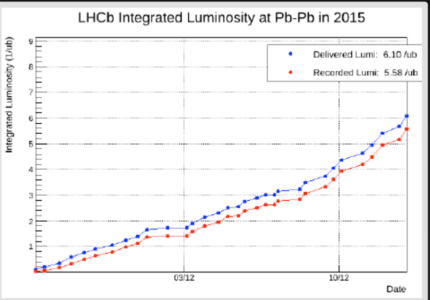
- Collider mode: forward/backward coverage
  Fixed target mode: central and backward coverage with $\sqrt{s_{NN}}$ between SPS and RHIC

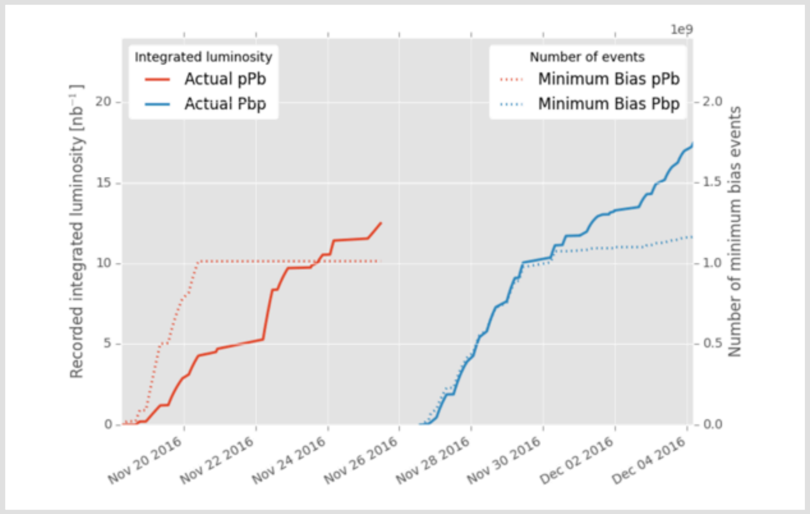
LHCb heavy ion samples

N.B precise luminosity determination in progress

	year	beam1	beam2/target	$\sqrt{s_{NN}}$(GeV)	$\int L$ (nb^{-1})
pA/Ap	2013	p	Pb	5023	1.1
	2013	Pb	p	5023	0.5
	2016	p	Pb	5023	0.6
	2016	p	Pb	8162	12.8
	2016	Pb	p	8162	17.7
Pb-Pb	2015	Pb	Pb	5125	$3\text{-}5\times10^{-3}$
Fixet Target	2012	p	Ne	87	pilot run
	2013	Pb	Ne	54	pilot run
	2015	p	Ne	110	~0.5
	2015	p	He	110	~0.5
	2015	p	Ar	110	~4
	2015	p	Ar	69	n.a.
	2015	Pb	Ar	69	n.a.
	2016	p	He	110	~2
	2016	p	He	87	n.a.



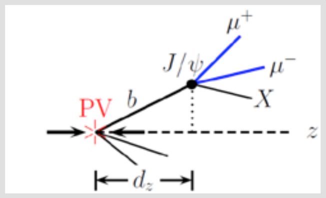




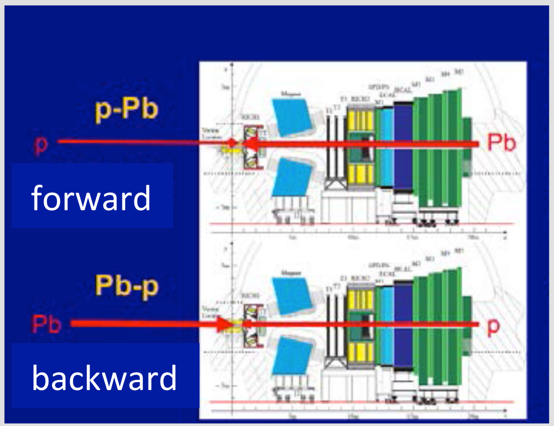
pPb collisions: production of heavy quarkonia

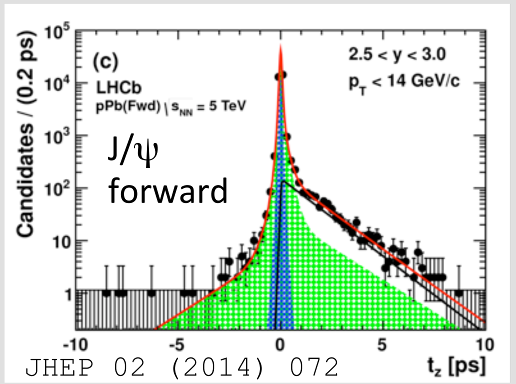
- Candidates fully reconstructed from well identified muons
- Prompt J/ψ, ψ(2S) and ϒ(nS) and those from b decay separated using pseudo-decay time (t_z)

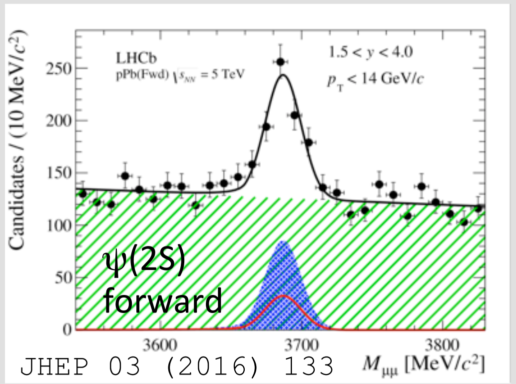
$$t_z(J/\psi) = \frac{d_z \times M_{J/\psi}}{p_z}$$

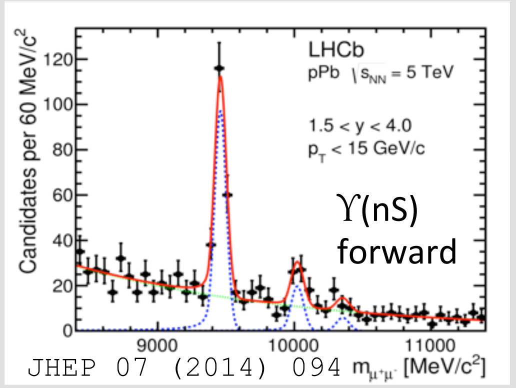


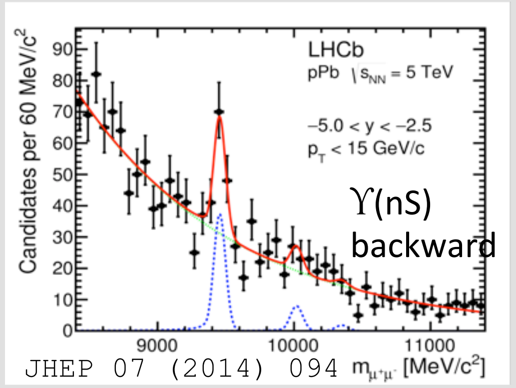
LHCb is unique in separating the two components in the forward acceptance







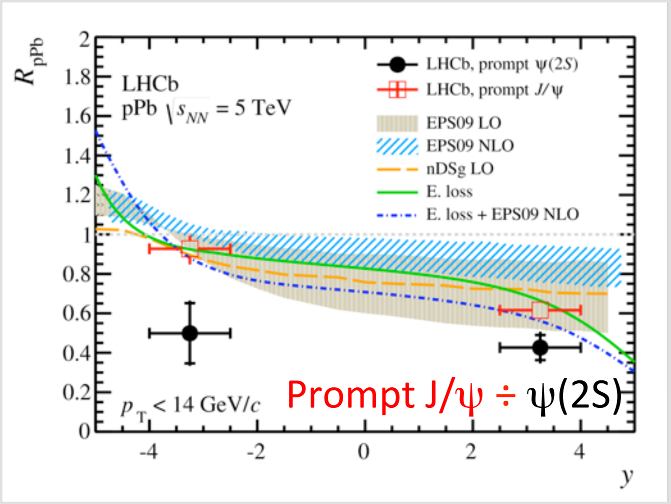


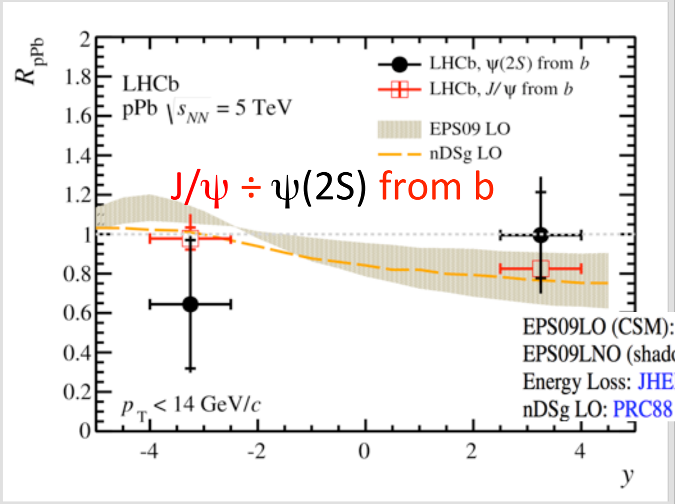


pPb collisions: production of J/ψ and ψ(2S)

- Nuclear modification factor is the key observable

JHEP 02 (2014) 072
JHEP 03 (2016) 133





$$R_{pPb} = \frac{1}{A} \times \frac{d\sigma_{pPb}/dy}{d\sigma_{pp}/dy}$$

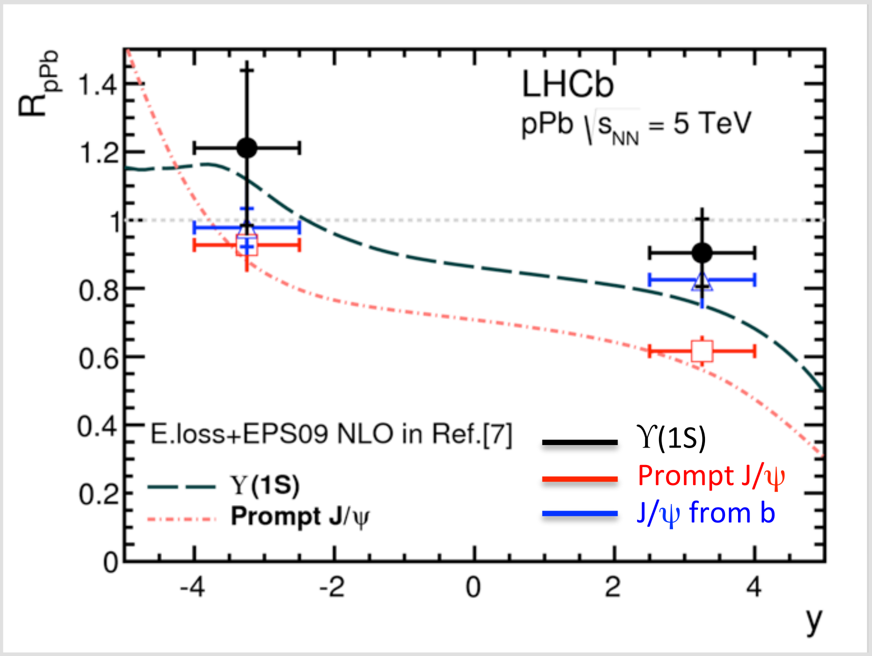
EPS09LO (CSM): PRC88 (2013) 047901, Nuclear Physics A 926 (2014) 236
EPS09LNO (shadowing + CEM): IJMP E 22 (2013) 1330007
Energy Loss: JHEP 03 (2013) 122, JHEP 05 (2013) 155
nDSg LO: PRC88 (2013) 047901

- Prompt J/ψ: strongly suppressed in forward region, significant signs of CNM effects
- J/ψ from b: modest suppression in forward region → Suggests suppression of b-hadron production
- Prompt ψ(2S): more suppressed than J/ψ, intriguing suppression in backward rapidity → energy loss + shadowing don't explain ψ(2S) suppression in backward rapidity, requiring other mechanisms
- ψ(2S) from b: suppression consistent with that of J/ψ from b

Collider mode: production of $\Upsilon(1S)$

JHEP 07 (2014) 094

- Nuclear modification factor is the key observable



EPS09LNO (shadowing + CEM): IJMP E 22 (2013) 1330007
Energy Loss: JHEP 03 (2013) 122, JHEP 05 (2013) 155

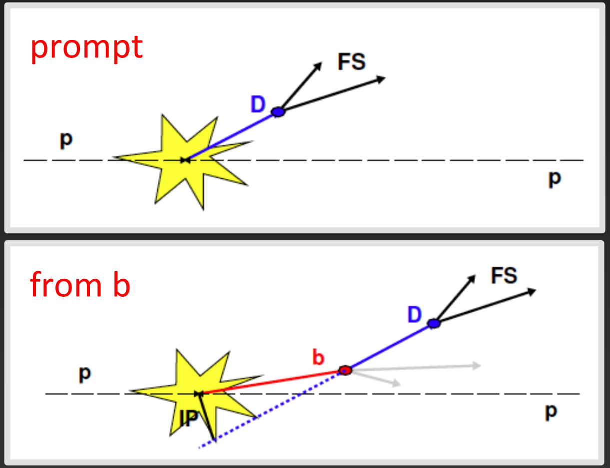
$$R_{pPb} = \frac{1}{A} \times \frac{d\sigma_{pPb}/dy}{d\sigma_{pp}/dy}$$

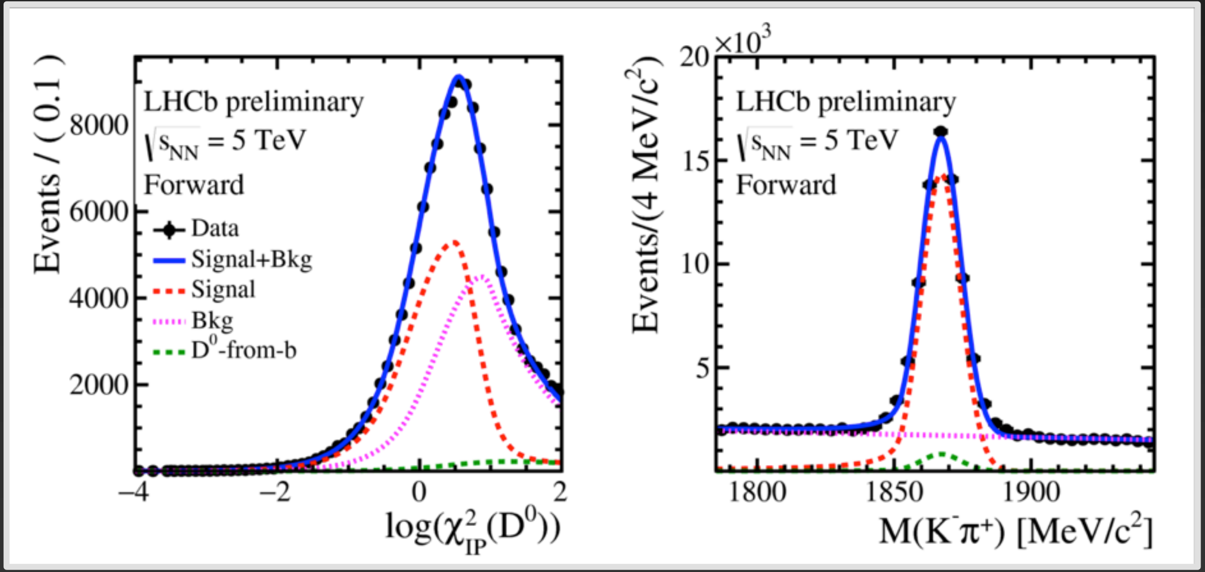
- Suppression in forward region is smaller than for J/ψ, but close to that of J/ψ from b → CNM effects on open b hadrons and bottomonia are not very different
- Hint of enhancement in the backward region → could be effect of anti-shadowing
- Data agree with prediction of energy loss + shadowing

Prompt D^0 production in pPb collisions

LHCb-CONF-2016-003

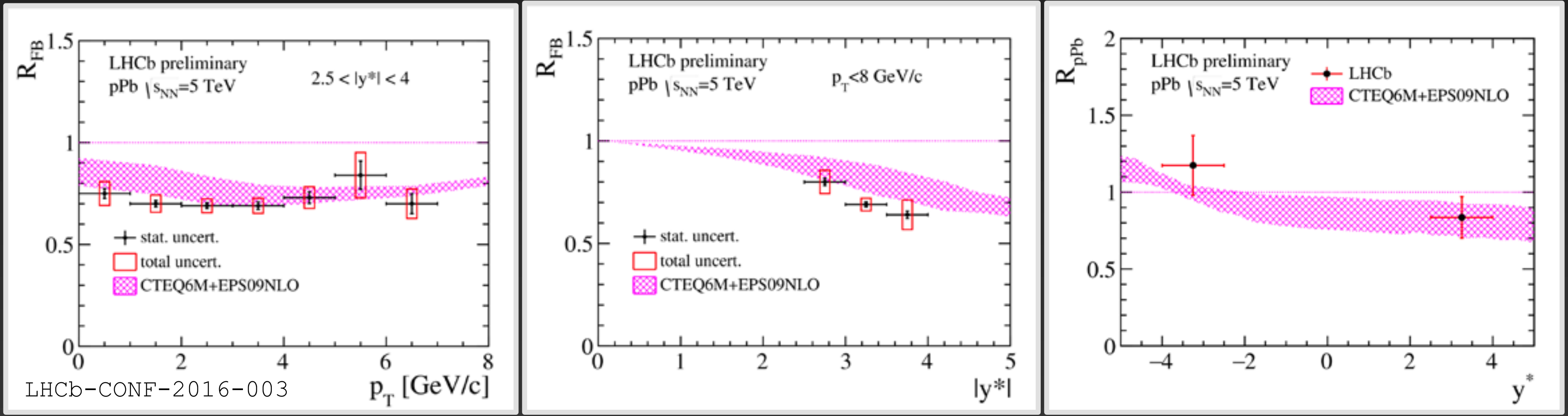
- D^0 reconstruction in the hadronic decay mode $D^0 \rightarrow K^- \pi^+$ down to $p_T = 0$
- Particle identification using the RICH Cerenkov detectors
- Vertexing information to select displaced vertices
- Impact parameter to separate prompt production from B decays.





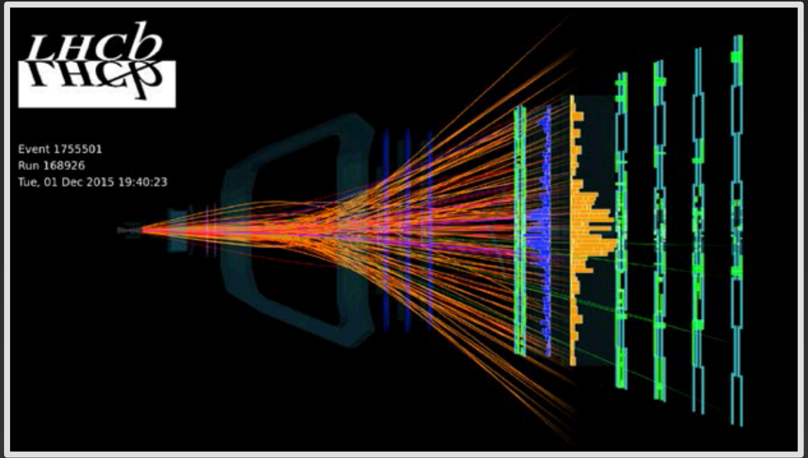
Prompt D^0 production in pPb collisions

- In addition to R_{pPb} consider also the forward-backward ratio $$R_{FB}(p_T, |y^*|) = \frac{\sigma_{pPb}(p_T, y^*)}{\sigma_{Pbp}(p_T, y^*)}$$
- Measure it in a common rapidity range 2.5 < |y| < 4
- No input from pp cross-section and cancelation of experimental systematic uncertainties
- Good agreement with models based on pQCD and nuclear PDF EPS09NLO Nucl.Phys. B373 (1992) 295

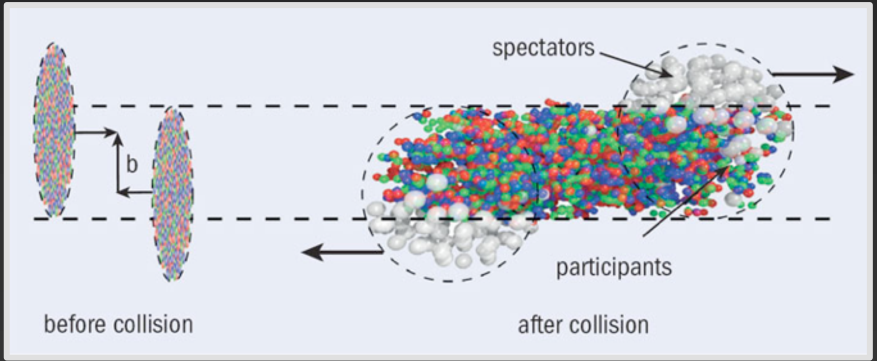


PbPb collisions in LHCb

- LHCb is optimised for low multiplicity events (flavour physics). Nevertheless…
- …LHCb took part for the first time to a LHC PbPb run in 2015, with emphasis on low multiplicity events.
- All sub-detectors running in nominal configuration
- 3-5 μb^{-1} integrated luminosity
- Basic quantity in heavy ion collisions: centrality
- Related to overlap of colliding nuclei; determines the number of nucleons taking part in the collision
  ☞ related to the multiplicity in the event !

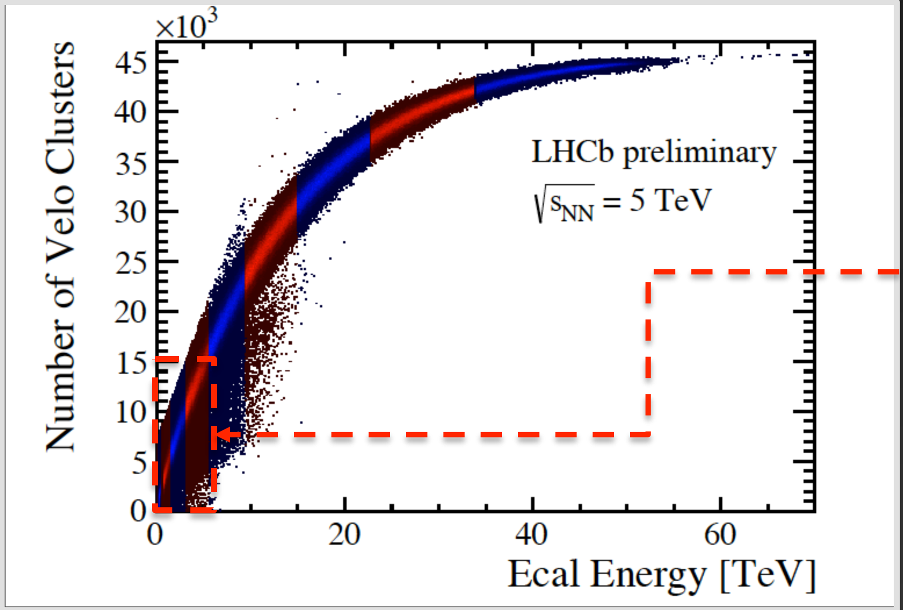


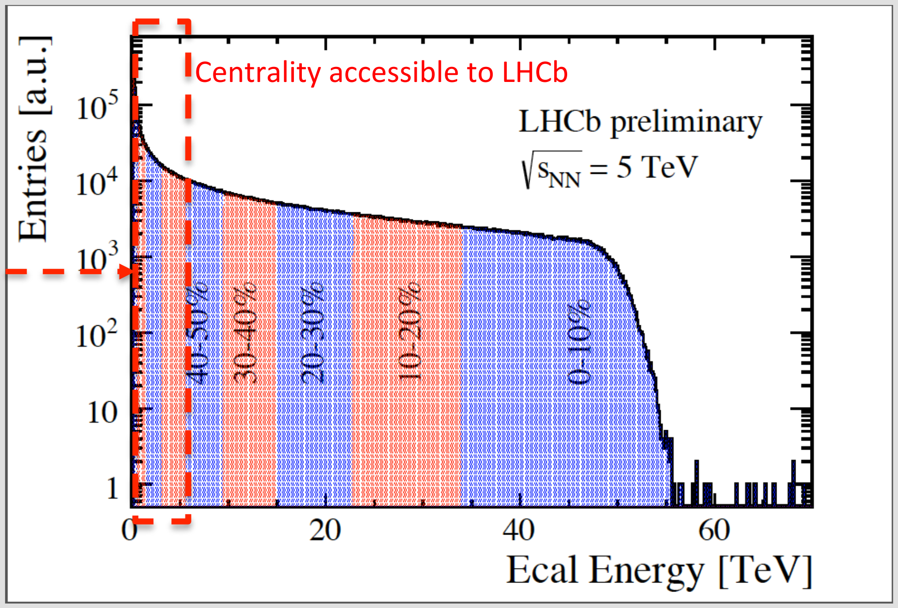
- How to define it in LHCb ?
- What is the LHCb centrality reach ?



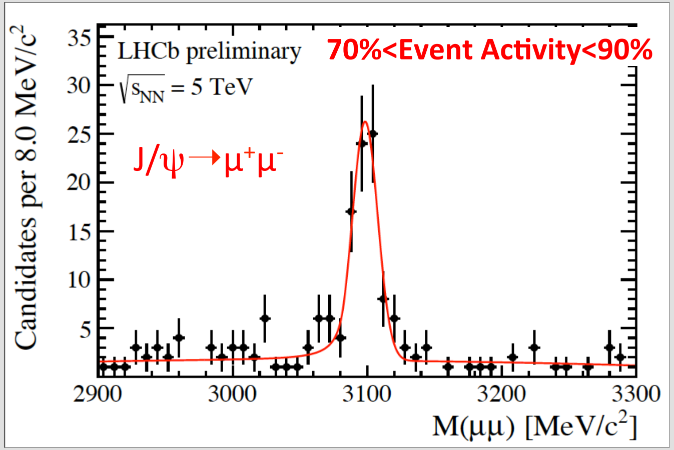
PbPb collisions in LHCb: centrality reach

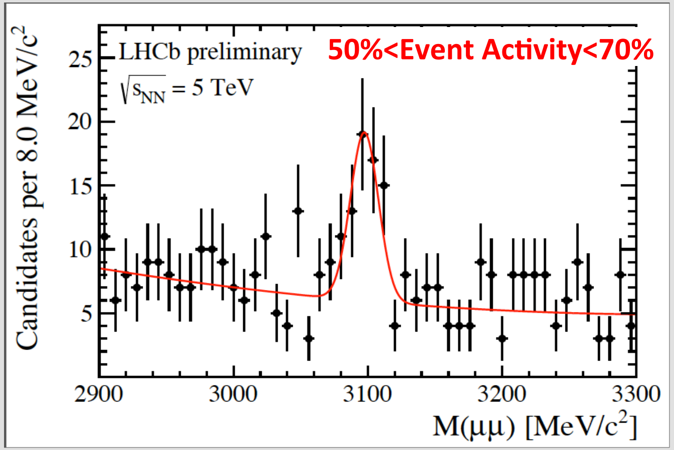
- Observable to measure event activity: energy E_{CAL} deposited in the calorimeters, which is not saturated even at large multiplicities. Tracking variables saturate at high multiplicity !
- Track reconstruction possible only up to 15000 VELO hits (using standard pp reconstruction algorithms: this corresponds to the 50-100% event activity region (based on E_{CAL} energy)

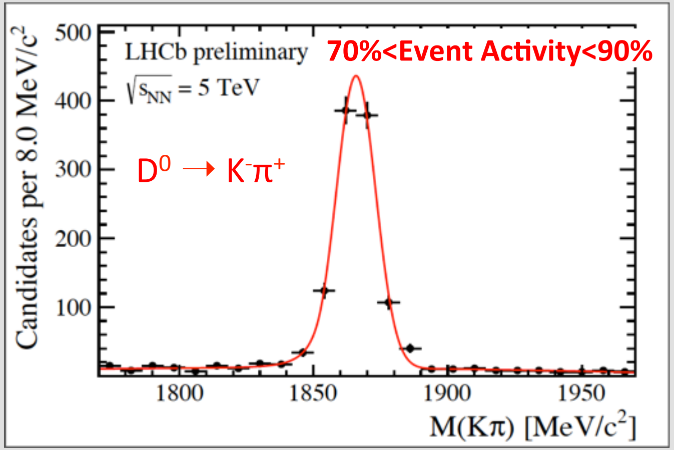


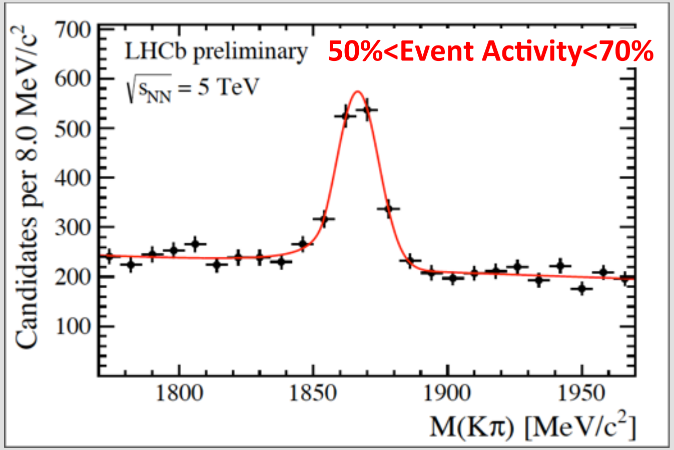


J/ψ and D^0 signals in PbPb collisions

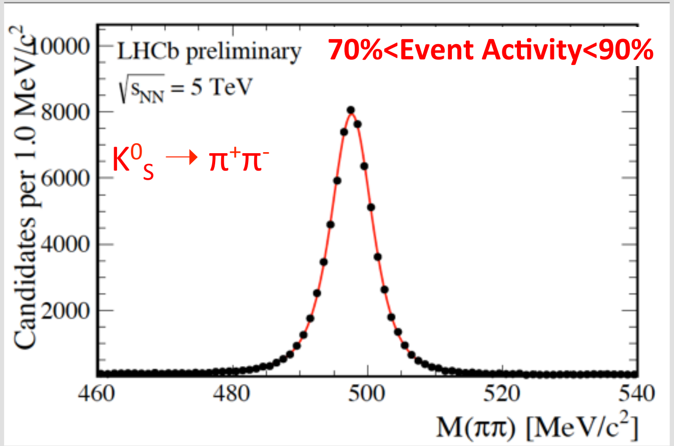


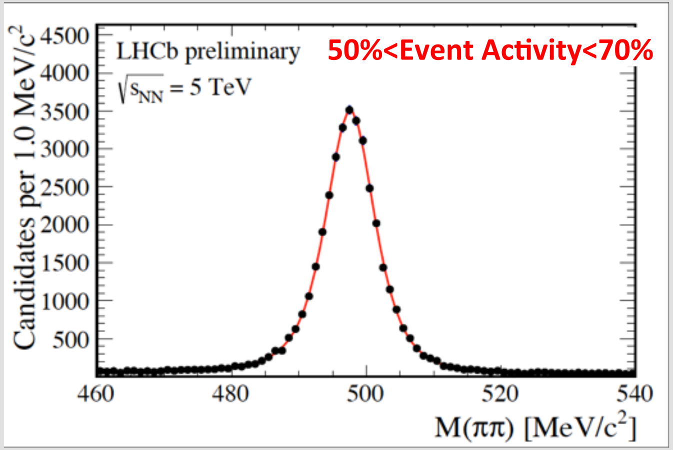


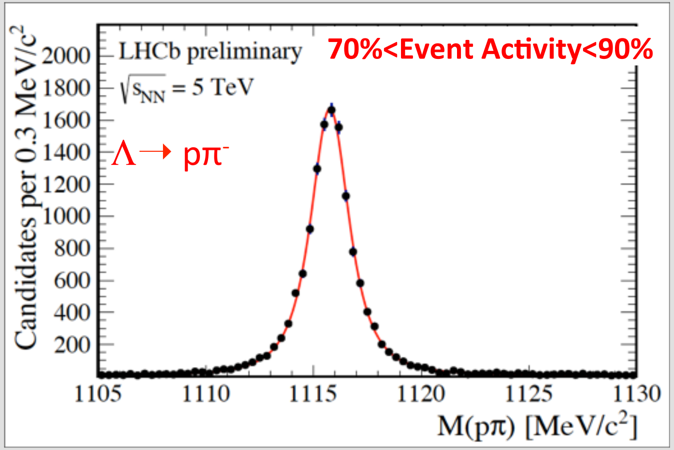


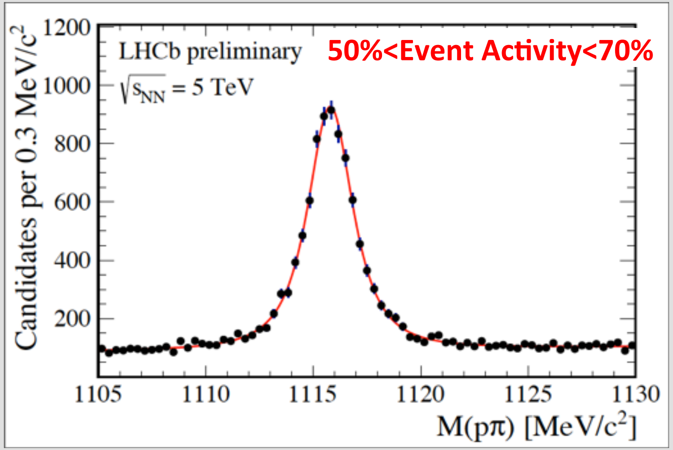


K^0_s and Λ signals in PbPb collisions



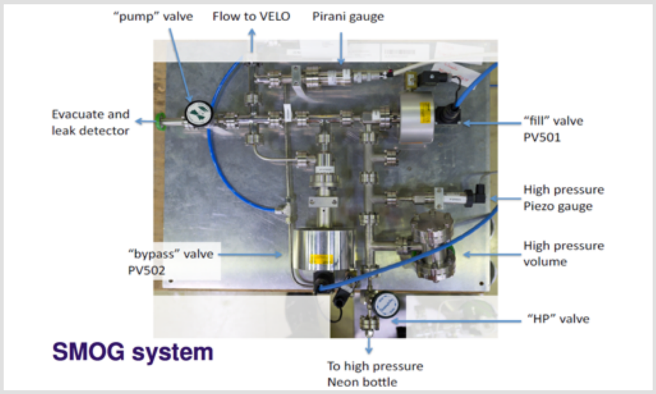




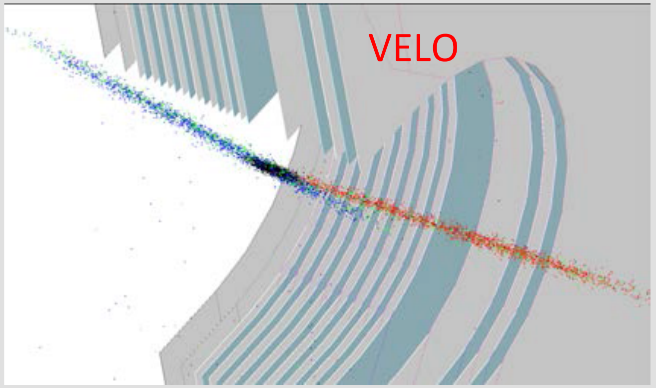


Fixed target physics with LHCb

- Gas can be injected inside the LHC vacuum, in the VELO volume (SMOG device)
- Used to determine the luminosity but since 2015 is used to collect physics data. JINST 7 (2012) P01010
- The pressure in the LHC when the gas is injected is ~2×10^{-7} mbar (instead of 10^{-9} mbar with no injection)
- Several data samples taken with He, Ne, Ar, at different $\sqrt{s_{NN}}$

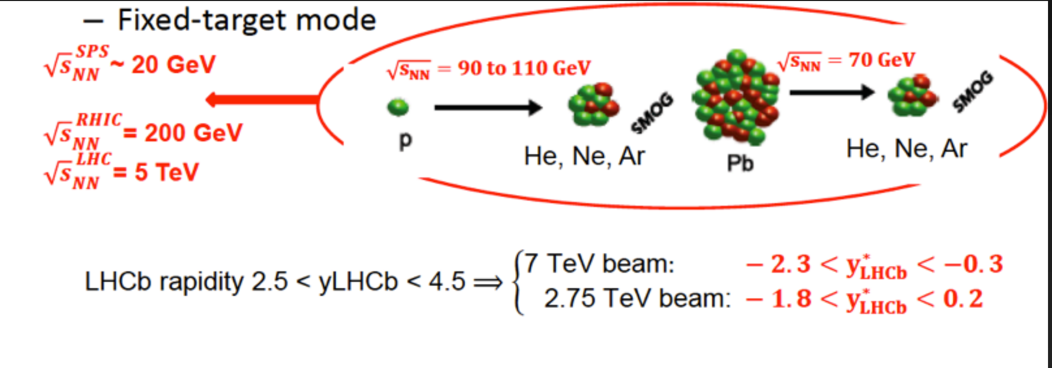


Imaging of beams with gas collisions



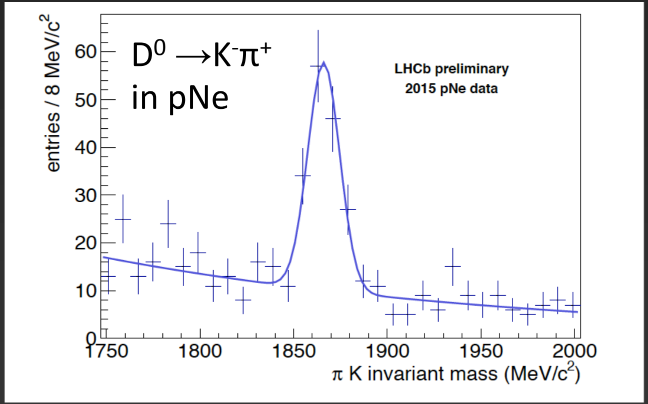
	year	beam1	beam2/target	$\sqrt{s_{NN}}$(GeV)	∫L (nb^{-1})
Fixet Target	2012	p	Ne	87	pilot run
	2013	Pb	Ne	54	pilot run
	2015	p	Ne	110	~0.5
	2015	p	He	110	~0.5
	2015	p	Ar	110	~4
	2015	p	Ar	69	n.a.
	2015	Pb	Ar	69	n.a.
	2016	p	He	110	~2
	2016	p	He	87	n.a.

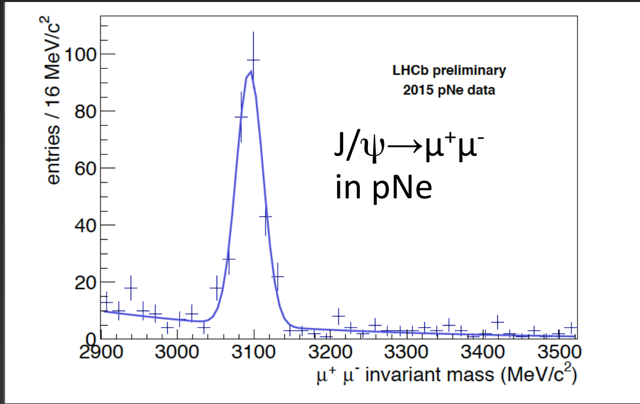
Fixed target physics with LHCb



- Collisions at energies unique to LHCb
- Energies between SPS and RHIC
- Probes the negative rapidity region

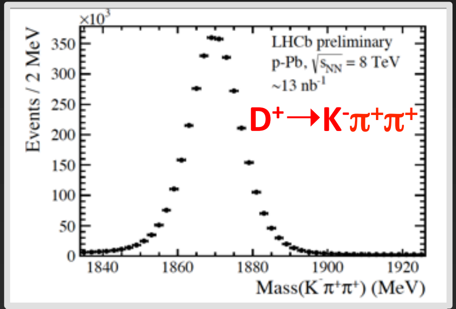
- COSMIC RAY PHYSICS @ LHCb:
  pHe collisions will provide $\sigma(pHe \rightarrow \bar{p}\, X)$ crucial for the interpretation of major cosmic ray physics results
- Analysis ongoing

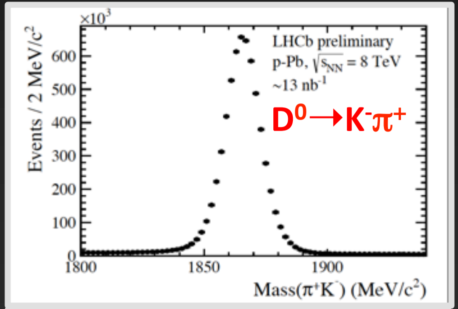


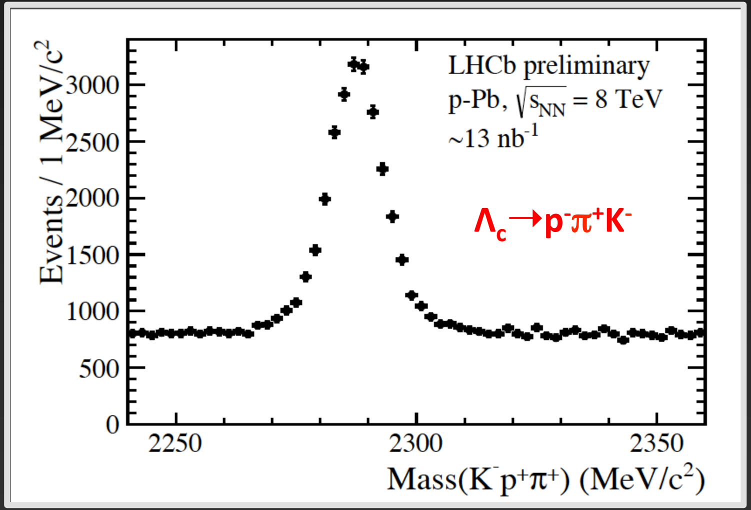


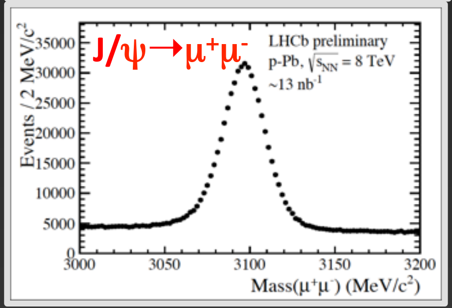
2016 pPb run

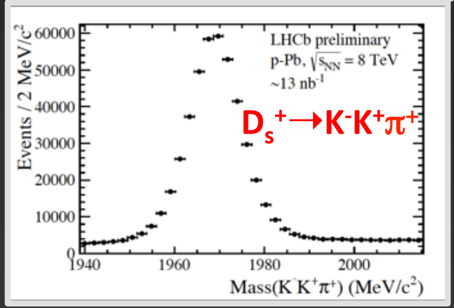
- pPb @ 5 TeV: LHCb injected Helium for the fixed target program with the 4 TeV proton beam, and collected heavy flavour pPb triggers in parallel
- pPb + Pbp @ 8 TeV: collected 10^9 minimum bias events and heavy flavour triggers for each configuration
- Thanks to excellent performances of LHC, LHCb collected much more data than anticipated: 0.3 nb^{-1} in pPb at 5 TeV and 30 nb^{-1} in pPb+Pbp at 8 TeV











Conclusions

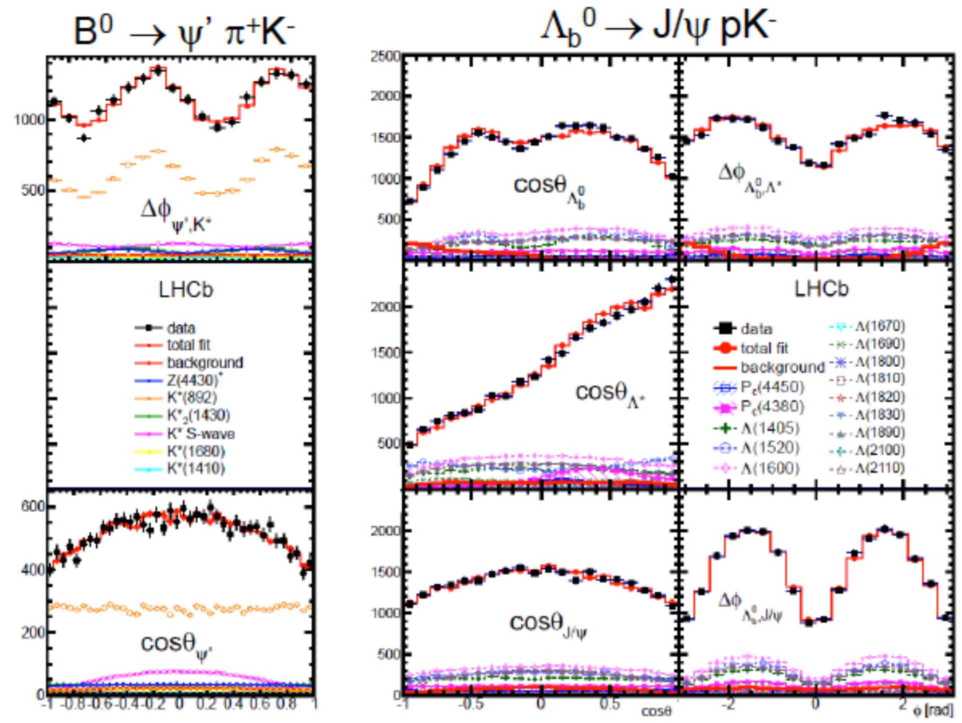
- LHCb is providing a wealth of results on hadron physics both from pp and from heavy ion collisions
- I have reviewed a few selected recent results on spectroscopy of exotic states
  - ★ Observation of penta-quarks
  - ★ Observation of (new) exotic X states
  - ★ Many results also in standard hadron spectroscopy

- LHCb has also a solid heavy ion physics program featuring also a unique fixed target mode
  - ★ Many data taking run at different c.o.m energies and different beam/target combinations
  - ★ Unique opportunity to measure pA cross sections useful also for astroparticle physics
  - ★ First results coming out
  - ★ Many more to come !

THANK YOU!

BACKUP

Fit of angular distributions

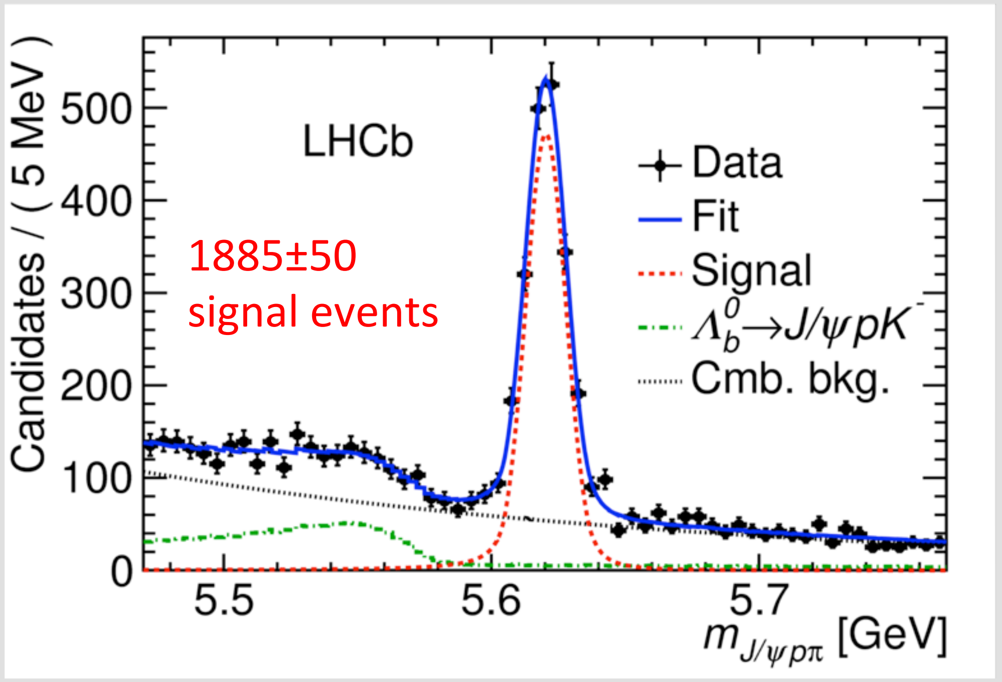


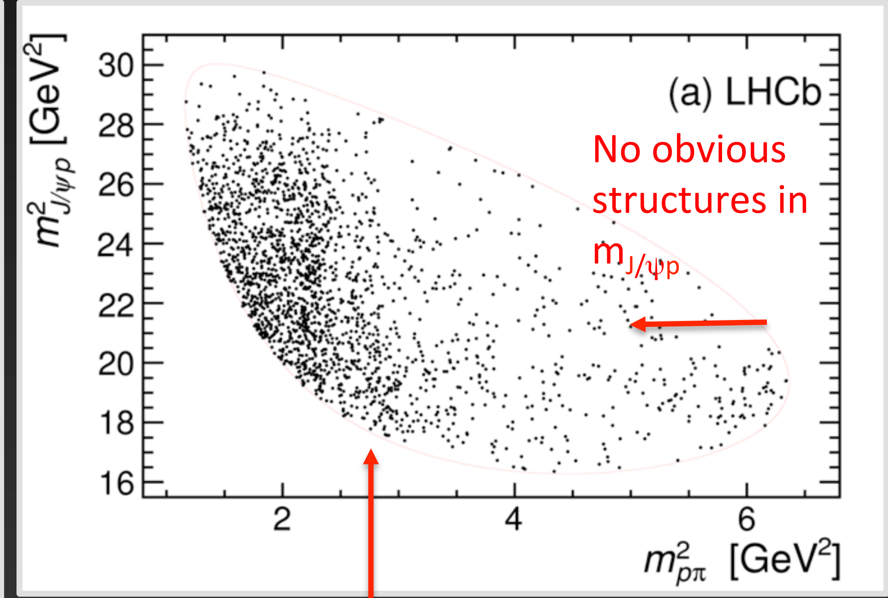
- They greatly increase discrimination power between resonances of different J^P
- Without using full decay phase-space difficult to do efficiency correction correctly

Cabibbo suppressed decays: $\Lambda_b \rightarrow J/\psi p \pi$

- Evidence for exotic states searched for also in Cabibbo-suppressed decays $\Lambda_b \rightarrow J/\psi p \pi$
- Much lower statistics !
- Full amplitude analysis performed, including $P_c(4380)^+$,$P_c(4450)^+$, $Z_c(4200)^-$ states

[PRL 117 (2016) 082003]



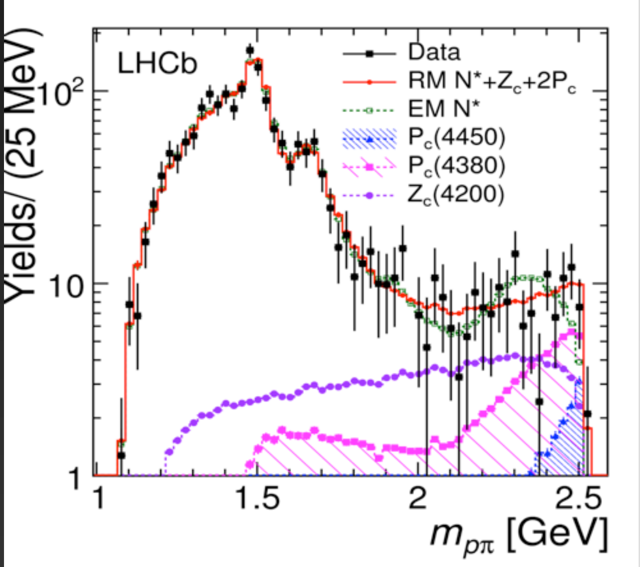


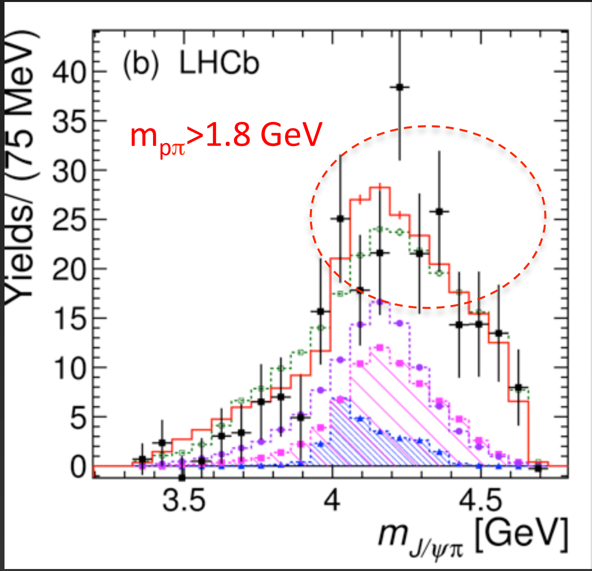
N(1535) and other N*'s→ p π

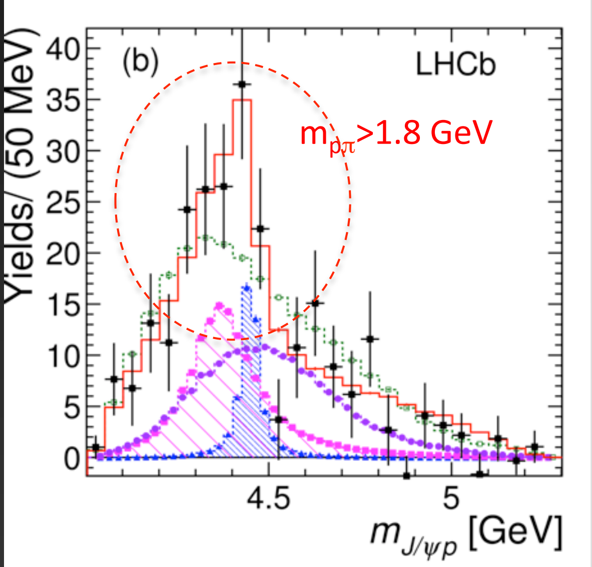
Cabibbo suppressed decays: $\Lambda_b \rightarrow J/\psi p\pi$

[PRL 117 (2016) 082003]

- Significance of $P_c(4380)^+$, $P_c(4450)^+$, $Z_c(4200)^-$ taken together is 3.1σ
- Individual exotic hadron contributions are not significant
- Evidence for exotic hadron contributions to $\Lambda_b \rightarrow J/\psi p\pi$







Model independent analysis of $\Lambda_b \to J/\psi pK$

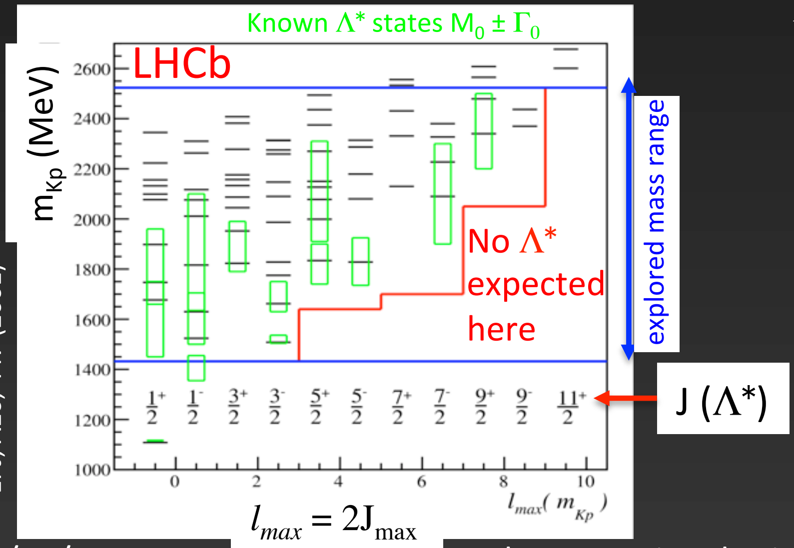
A model independent analysis id very important to confirm the P_c states. [PRL 115 (2015) 072001]

1. The $\cos\theta_{\Lambda*}$ (helicity angle of Kp system) the distribution is expanded in series of Legendre polynomials:

$$dN/d\cos\theta_{\Lambda^*} = \sum_{l=0}^{l_{max}} \langle P_l^U \rangle P_l(\cos\theta_{\Lambda^*})$$

2. A null hypothesis (i.e. no P_c states) H_0 is defined by setting l_{max} as a function of m_{Kp} taking into account only the known and predicted Λ^* states

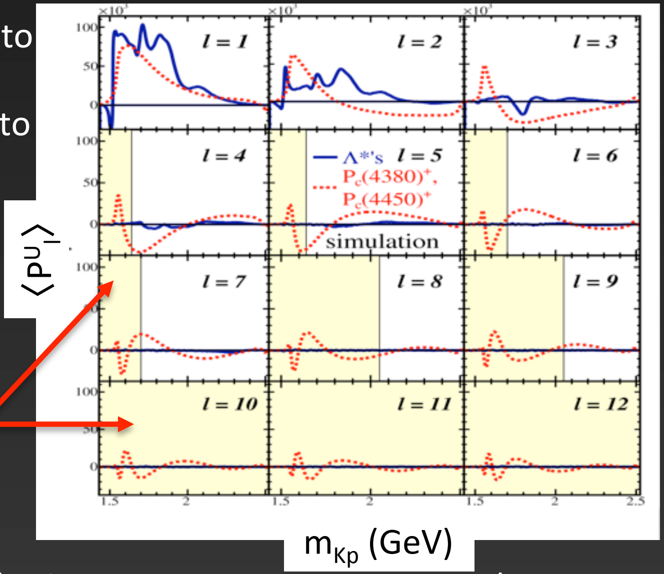
Mass predictions: Loring-Metsch-Petry EPJ, A10, 447 (2001)



Λ^* states contribute only to low l moments

Pc states contribute both to low and high l moments

Yellow areas are excluded by H_0



Model independent analysis of $\Lambda_b \to J/\psi pK$

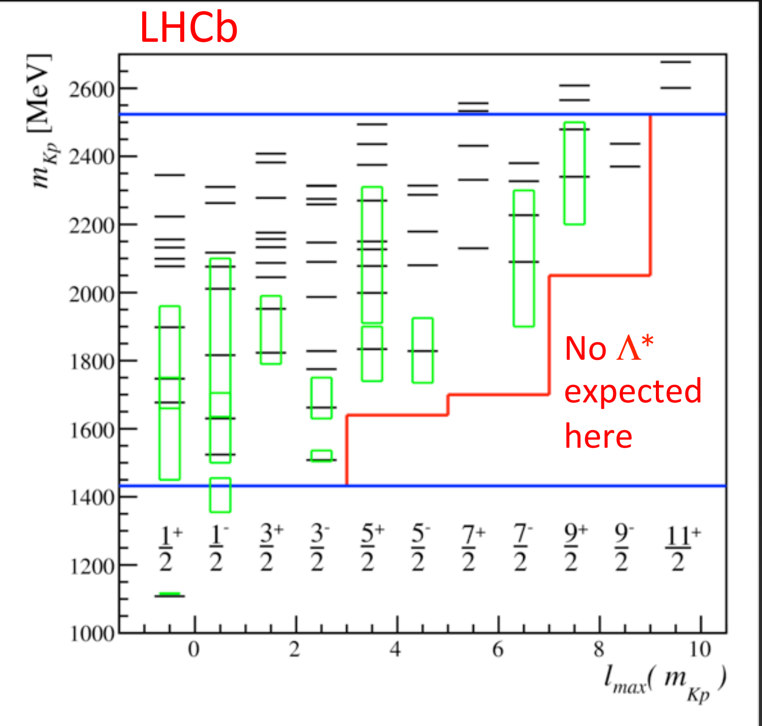
PRL 117 (2016) 082002

- Amplitude analysis of $\Lambda_b \to J/\psi pK$ shows the necessity to include two P_c states in addition to many Λ^* states to explain the data
- Theoretical models predict a much larger number of Λ^* states than is established experimentally
- Non resonant contributions may also be present
- A model independent analysis is therefore very important to confirm the P_c states.

1. The $\cos\theta_{\Lambda^*}$ distribution is expanded in series of Legendere polinomials:

$$dN/d\cos\theta_{\Lambda^*} = \sum_{l=0}^{l_{max}} \langle P_l^U \rangle P_l(\cos\theta_{\Lambda^*})$$

2. A null hypothesis (i.e. no P_c states) H_0 is defined by setting l_{max} as a function of m_{Kp} taking into account only the known and predicted Λ^* states

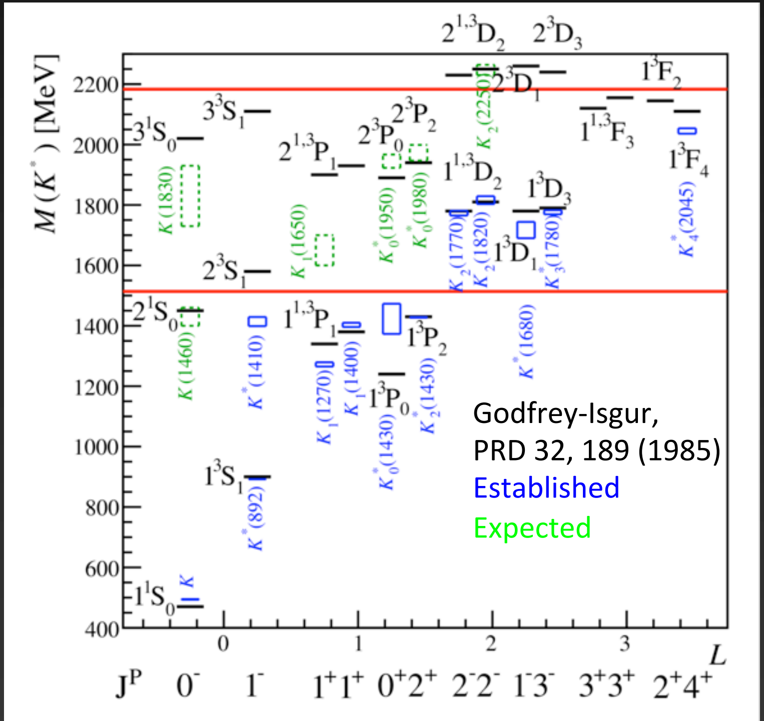


Exotic states in $B^+ \to J/\psi\phi K^+$

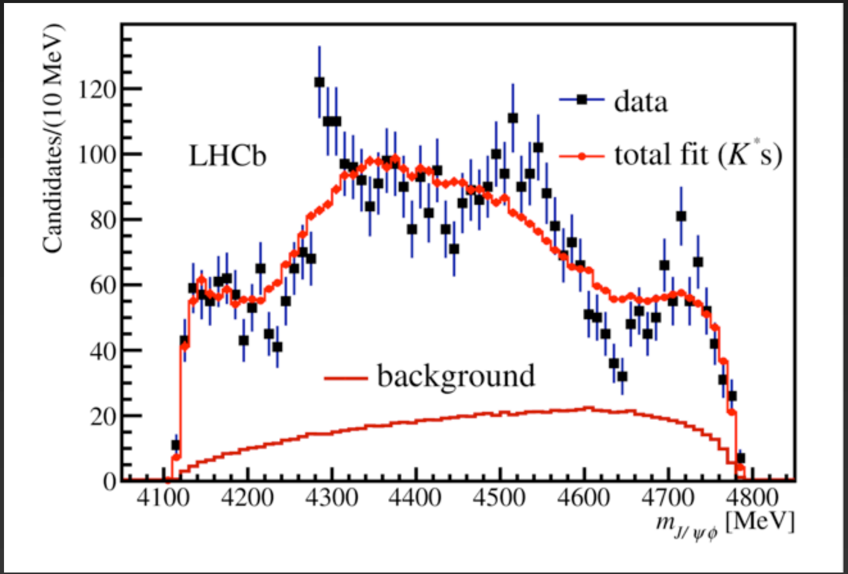
Phys. Rev. Lett. 118 (2017) 022003
Phys. Rev. D95 (2017) 012002

- Try to model the $m_{\phi K}$ spectrum with K^* states.
- Guidance from quark model was used to inform choices for K^* sector
- Try both known and unknown K* states

Mass range in $B^+ \to J/\psi\phi K^+$



Clear evidence that K* states only are not sufficient to reproduce data. Need additional states



Exotic states in $B^+ \to J/\psi\phi K^+$

Phys. Rev. Lett. 118 (2017) 022003
Phys. Rev. D95 (2017) 012002

- Lighter X state masses consistent with previous measurements
- However, X(4140) width substantially larger
- Higher mass states $X(0^+)$ are new !
- J^{PC} combinations are those *preferred* by the fit.

Contri-bution	signif.	Fit results M_0 [MeV]	Γ_0 [MeV]	FF %
All $X(1^+)$				$16\pm3\ ^{+\ 6}_{-\ 2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\ ^{+4.6}_{-2.8}$	$83\pm21\ ^{+21}_{-14}$	$13.0\pm3.2\ ^{+4.8}_{-2.0}$
av. prev. meas		4143.4 ± 1.9	15.7 ± 6.3	
$X(4274)$	6.0σ	$4273.3\pm8.3\ ^{+17.2}_{-\ 3.6}$	$56\pm11\ ^{+\ 8}_{-11}$	$7.1\pm2.5\ ^{+3.5}_{-2.4}$
CDF		$4274.4\ ^{+8.4}_{-6.7}\pm1.9$	$32\ ^{+22}_{-15}\pm8$	
CMS		$4313.8\pm5.3\pm7.3$	$38\ ^{+30}_{-15}\pm16$	
All $X(0^+)$				$28\pm\ 5\pm\ 7$
$X(4500)$	6.1σ	$4506\pm11\ ^{+12}_{-15}$	$92\pm21\ ^{+21}_{-20}$	$6.6\pm2.4\ ^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704\pm10\ ^{+14}_{-24}$	$120\pm31\ ^{+42}_{-33}$	$12\pm\ 5\ ^{+\ 9}_{-\ 5}$

X(4140) summary

Year	Experiment luminosity	Ref	$B \to J/\psi \phi K$ statistics	$X(4140)$ peak mass [MeV]	width [MeV]	sign.	fraction %
2008	CDF 2.7 fb^{-1}	PRL 102,242002	58 ± 10	$4143.0 \pm 2.9 \pm 1.2$	$11.7\,^{+8.3}_{-5.0} \pm 3.7$	3.8σ	
2009	Belle	LP2009 (unpub.)	325 ± 21	4143.0 fixed	11.7 fixed	1.9σ	
2011	CDF 6.0 fb^{-1}	arXiv:1101.6058 (unpub.)	115 ± 12	$4143.4\,^{+2.9}_{-3.0} \pm 0.6$	$15.3\,^{+10.4}_{-6.1} \pm 2.5$	5.0σ	$14.9 \pm 3.9 \pm 2.4$
2011	LHCb 0.37 fb^{-1}	PRD85, 091103	346 ± 20	4143.4 fixed	15.3 fixed	1.4σ	< 7 @ 90%CL
2013	CMS 5.2 fb^{-1}	PL, B734, 261	2480 ± 160	$4148.0 \pm 2.4 \pm 6.3$	$28\,^{+15}_{-11} \pm 19$	5.0σ	10 ± 3 (stat.)
2013	D0 10.4 fb^{-1}	PRD89, 012004	215 ± 37	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6\,^{+1.0}_{-8.0}$	3.1σ	$21 \pm 8 \pm 4$
2014	BaBar 422 fb^{-1}	PRD91, 012003	189 ± 14	4143.4 fixed	15.3 fixed	1.6σ	< 13.3 @ 90%CL
2015	D0 10.4 fb^{-1}	PRL, 115, 232001	$p\bar{p} \to J/\psi \phi ...$	$4152.5 \pm 1.7\,^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$	4.7σ (5.7σ)	
Average				4146.9 ± 2.3	17.8 ± 6.8		

X(4274-4351) summary

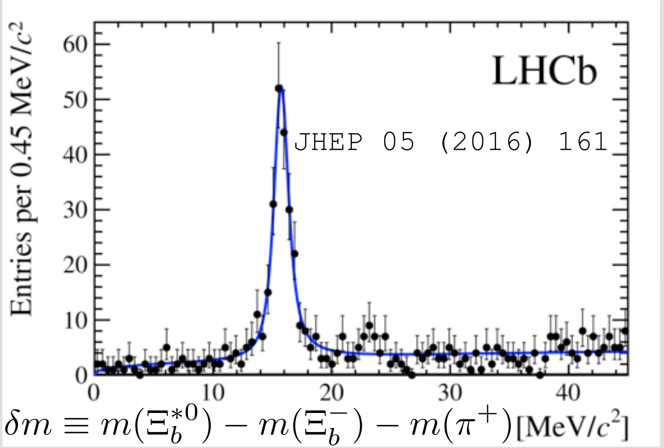
Year	Experiment luminosity	Ref	$B \to J/\psi \phi K$ statistics	$X(4274-4351)$ peaks(s) mass [MeV]	width [MeV]	sign.	fraction [%]
2011	CDF 6.0 fb^{-1}	arXiv:1101.6058 (unpub.)	115 ± 12	$4274.4\,^{+8.4}_{-6.7} \pm 1.9$	$32.3\,^{+21.9}_{-15.3} \pm 7.6$	3.1σ	
2011	LHCb 0.37 fb^{-1}	PRD85, 091103	346 ± 20	4274.4 fixed	32.3 fixed		< 8 @ 90%CL
2013	CMS 5.2 fb^{-1}	PL, B734, 261	2480 ± 160	$4313.8 \pm 5.3 \pm 7.3$	$38\,^{+30}_{-15} \pm 16$		
2013	D0 10.4 fb^{-1}	PRD89, 012004	215 ± 37	4328.5 ± 12.0	30 fixed		
2014	BaBar 422 fb^{-1}	PRD91, 012003	189 ± 14	4274.4 fixed	32.3 fixed	1.2σ	< 18.1 @ 90%CL
2010	Belle 825 fb^{-1}	PRL 104, 112004	$\gamma\gamma \to J/\psi \phi$	$4350.6\,^{+4.6}_{-5.1} \pm 0.7$	$13\,^{+18}_{-9} \pm 4$	3.2σ	

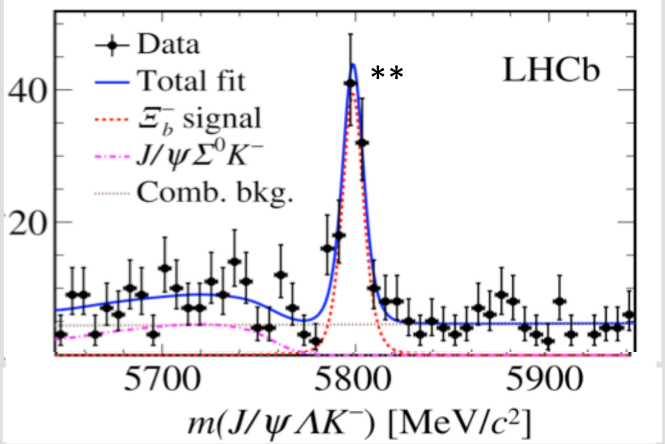
Standard hadron spectroscopy

- LHCb also contributed a lot to standard hadron spectroscopy. Very recent results include:
- Study of $D_{sJ}^{(*)+}$ mesons (prompt production) JHEP 02 (2016) 133
- Amplitude analysis of $B^- \rightarrow D^+\pi^-\pi^-$ decays PRD94 (2016) 072001
- Properties of the Ξ_b^{*0} baryon
  - ★ Confirmation of Ξ_b^{*0}
  - ★ Precise mass and first natural width measurements

$$\delta m = 15.727 \pm 0.068(\text{stat}) \pm 0.023(\text{syst})\ \text{MeV}/c^2$$
$$\Gamma(\Xi_b^{*0}) = 0.90 \pm 0.16(\text{stat}) \pm 0.08(\text{syst})\text{MeV}$$

- Observation of $\Xi^-_b \rightarrow J/\psi \Lambda K^-$ decay
  just released on arXiv:1701.05274, subm. to PLB
  May decay through P_c states with strangeness





**only L candidates made with 2 long tracks

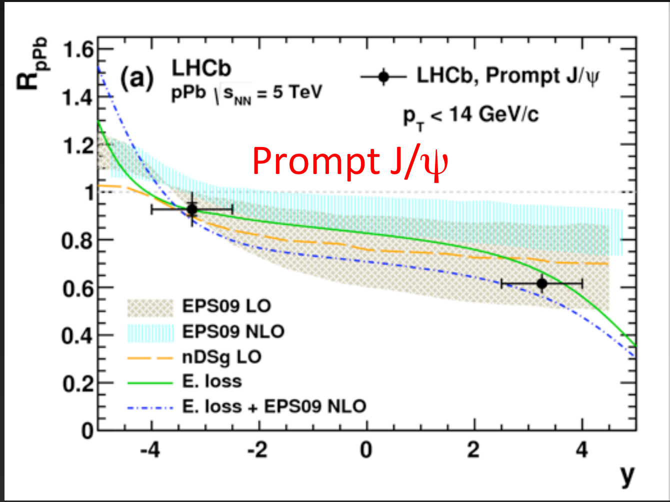
LHCb: heavy flavours and heavy ions

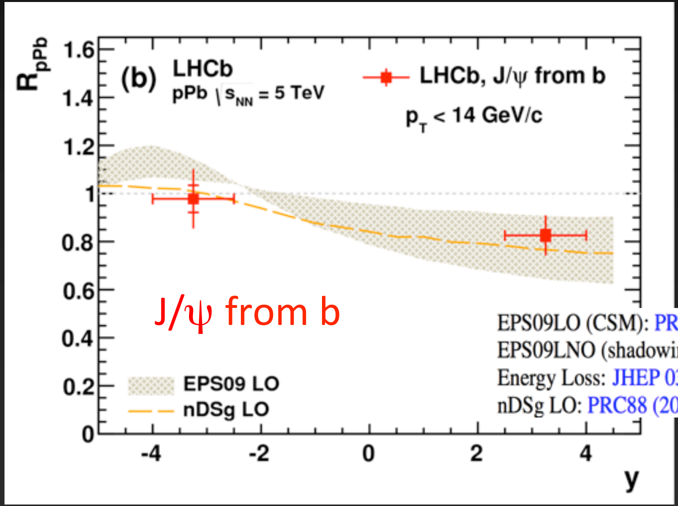
- Most of the analyses (for heavy flavour) consist in measuring the ratio of production in pPb collisions to pp collisions: R_{pPb}.
- pp collisions: hard process cross-section
- pPb collisions: hard process + “cold” nuclear matter (CNM) effects
  - ★ Shadowing and anti-shadowing: parton density functions of protons and neutrons are modified when they are in a Pb nucleus compared to a single proton
  - ★ Energy loss: quarks loose energy in the medium of the collision before forming hadrons
- pPb collisions allow to understand the “background” mechanisms to the ones due to QGP in PbPb collisions and are also interestingin theirown rights.
- PbPb collisions: hard process + “cold” nuclear matter effects+ “hot” nuclear matter effects (due to Quark Gluon Plasma, free quarks during a short time after the collision):
  - ★ Recombination: a lot of other heavy quarks are present in the medium and enhance the production of quarkonium (heavy quark bound states)
  - ★ Dissociation: quarkonium melt in the medium

pPb collisions: production of heavy quarkonia

JHEP 02 (2014) 072

- Nuclear modification factor is the key observable





$$R_{pPb} = \frac{1}{A} \times \frac{d\sigma_{pPb}/dy}{d\sigma_{pp}/dy}$$

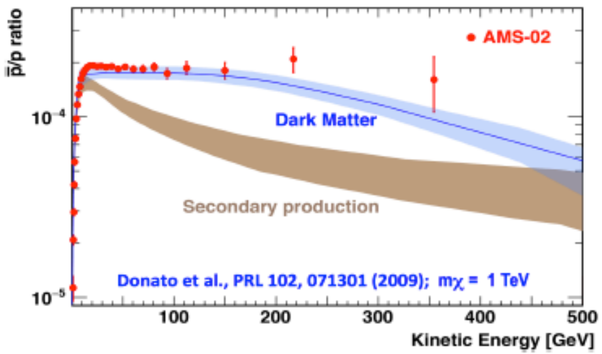
EPS09LO (CSM): PRC88 (2013) 047901, Nuclear Physics A 926 (2014) 236
EPS09LNO (shadowing + CEM): IJMP E 22 (2013) 1330007
Energy Loss: JHEP 03 (2013) 122, JHEP 05 (2013) 155
nDSg LO: PRC88 (2013) 047901

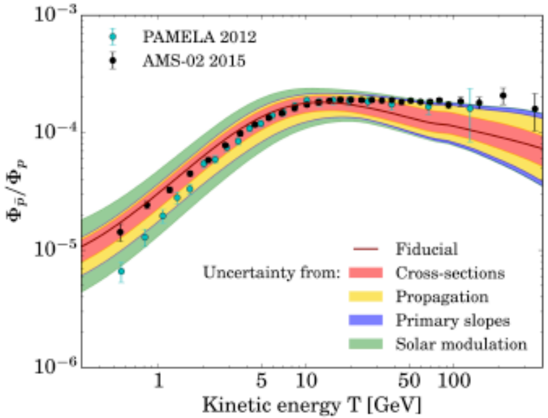
- Prompt J/ψ: strongly suppressed in forward region, significant signs of CNM effects
  ⟶ data well described by energy loss models w/ and w/o shadowing
- J/ψ from b: modest suppression in forward region ⟶ Suggests suppression of b-hadron production
- Backward rapidity: compatible with no suppression

Cosmic ray physics at LHCb

- Recent results from AMS-02 exhibit an antiproton excess with respect to expectations from secondary production (p+p → $\bar{p}$X and p+He → $\bar{p}$X) in the interstellar medium, in the O(100 GeV) region
- Possible evidence for Dark Matter Contribution

AMS Coll., Cern 15.04.2015





arXiv:1504.04276

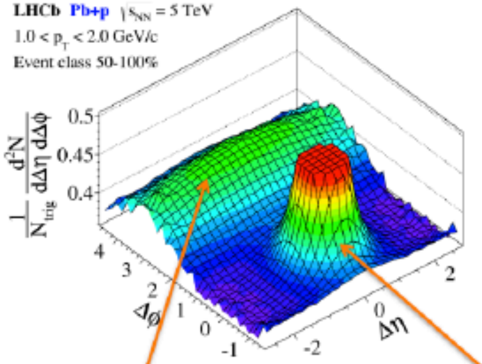
- More conservative estimates on the related uncertainties show that the results could still fit with secondary production
- Largest uncertainty comes from σ(pHe→ $\bar{p}$X)

➡ **In fixed target mode, proton beam (6.5 TeV) on He at rest suits well the physics case**

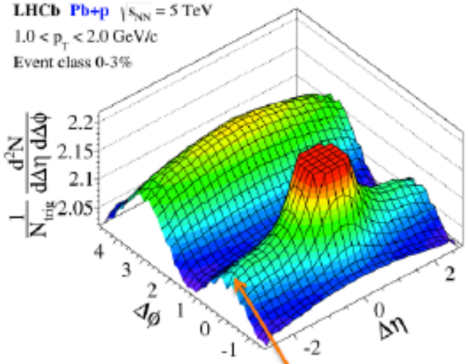
➡ Also possibility to investigate **intrinsic charm at large x**: important for backgrounds in high energy neutrino astrophysics (for IceCube experiment)

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

low activity



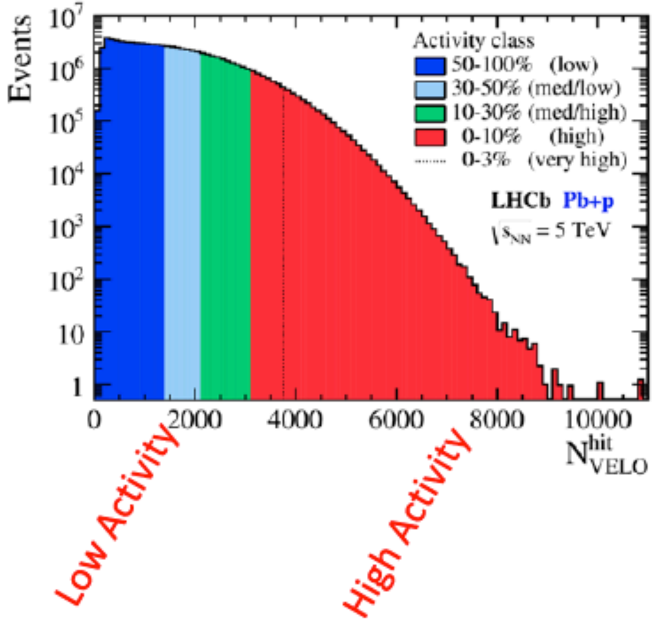
high activity



away-side ridge
(momentum conservation)

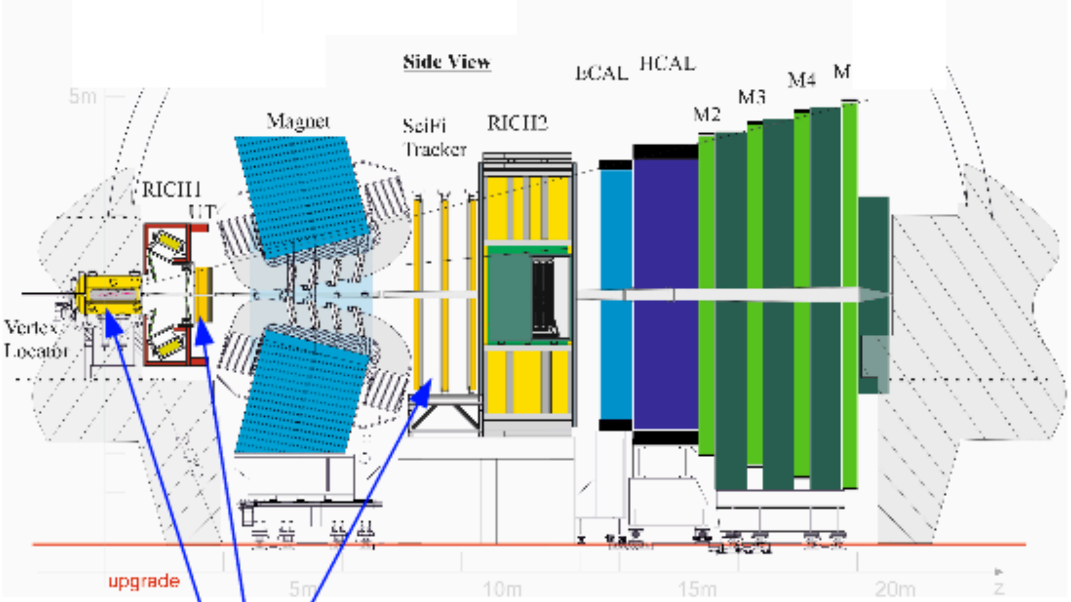
Jet peak
(particles from same hard process)

same-side ridge!



PLB 762C (2016) 473

LHCb detector upgrade

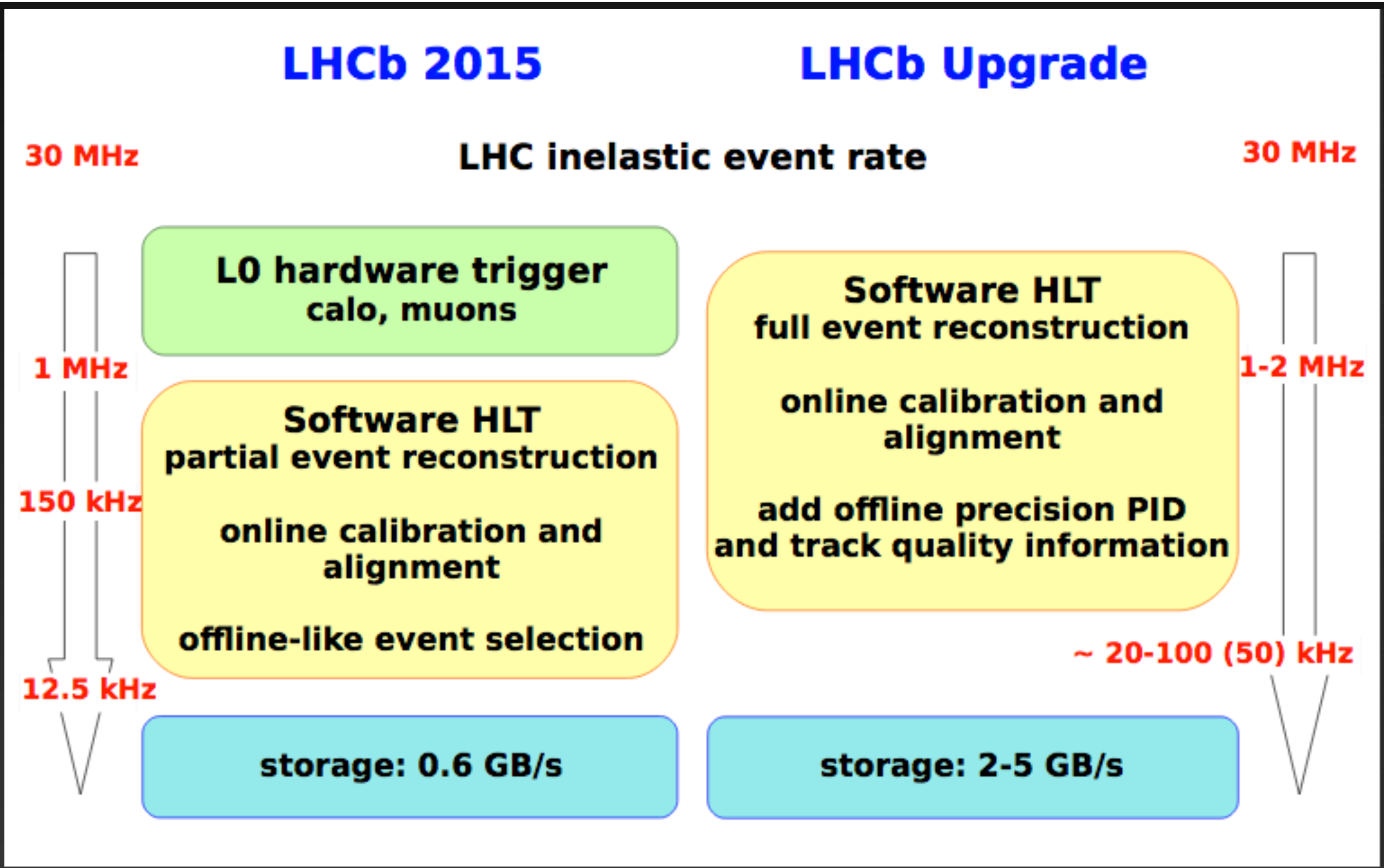


new trackers

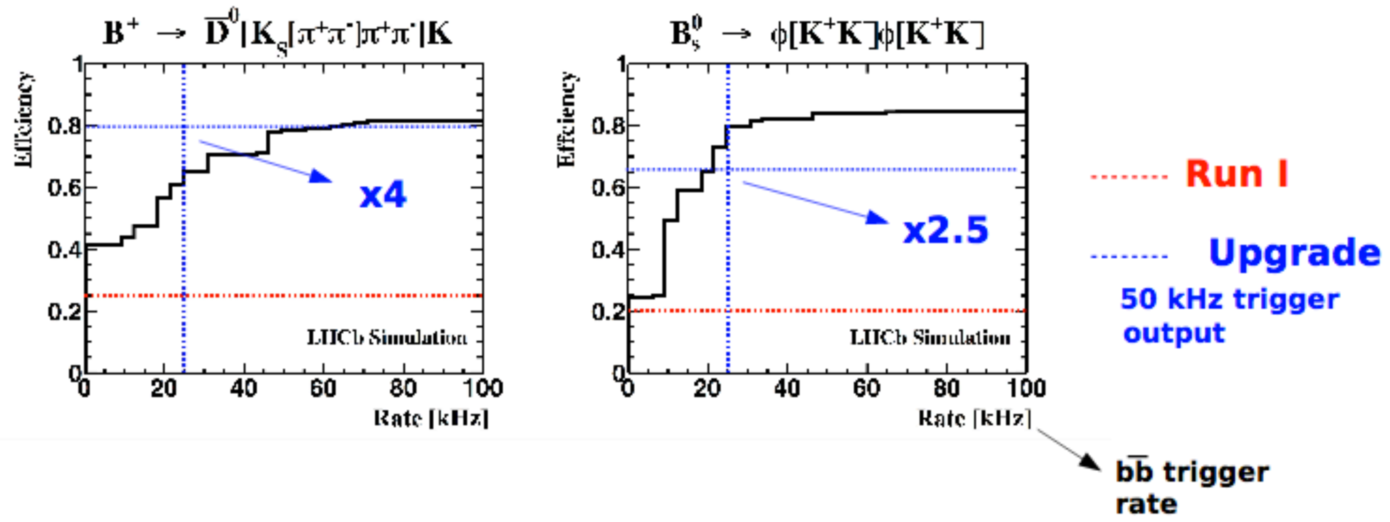
upgrades of RICHs, calorimeters, muon chambers

- higher granularity and radiation tolerance

LHCb trigger upgrade



LHCb trigger upgrade performance on hadrons



Hadronic yields > 10-20x Run I

(~lumi * $\varepsilon_{trigger}$)

LHCC 2014-016