Selected results from LHCb Experiment

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Outline

- LHCb experiment
- Recent results (very selective)
  - charm decays
  - Electroweak measurements
  - Discovery of pentaquark states
  - Heavy ion program at LHCb
  - First physics from RUNII
- Summary

Physics from B decays
(Yuehong Xie's talk)

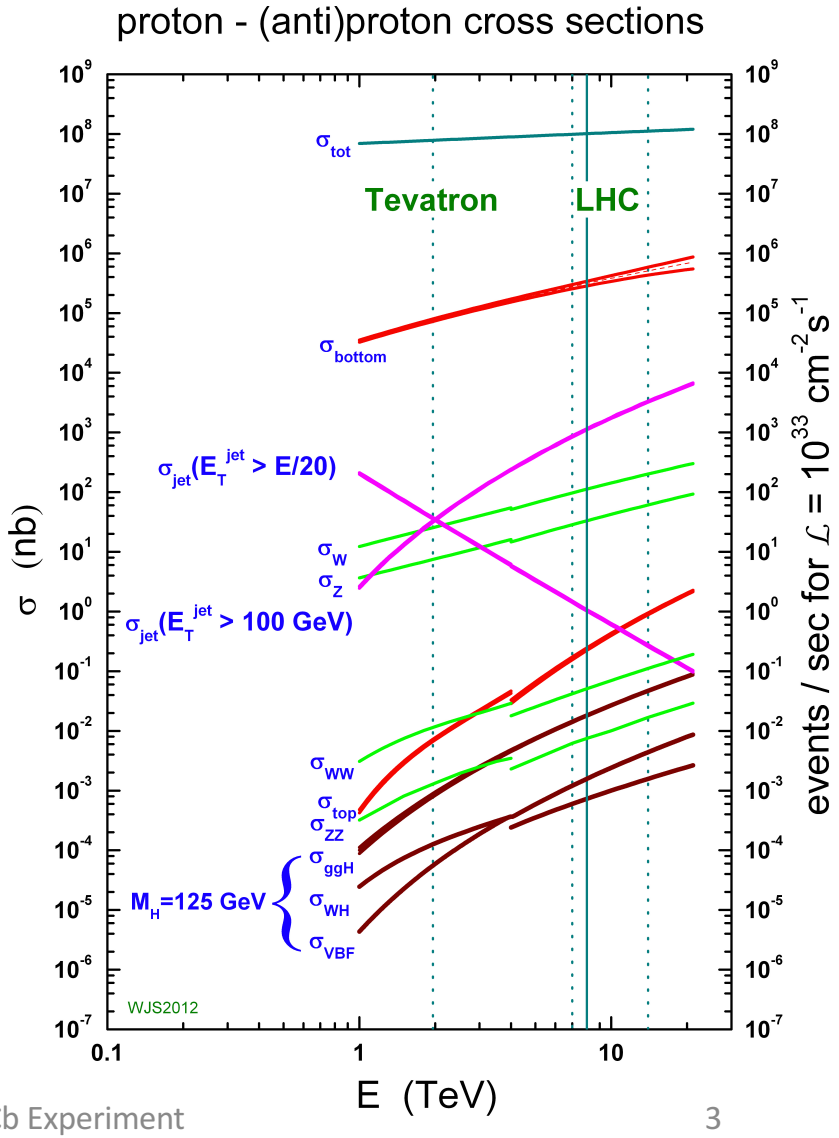
LHC is a *powerful* flavor factory

- Huge numbers of beauty and charm hadrons produced
- All types of b-hadrons

  $B^0, B^{\pm}, B_s, B_c, \Lambda_b^0, \ldots$

  and c-hadrons

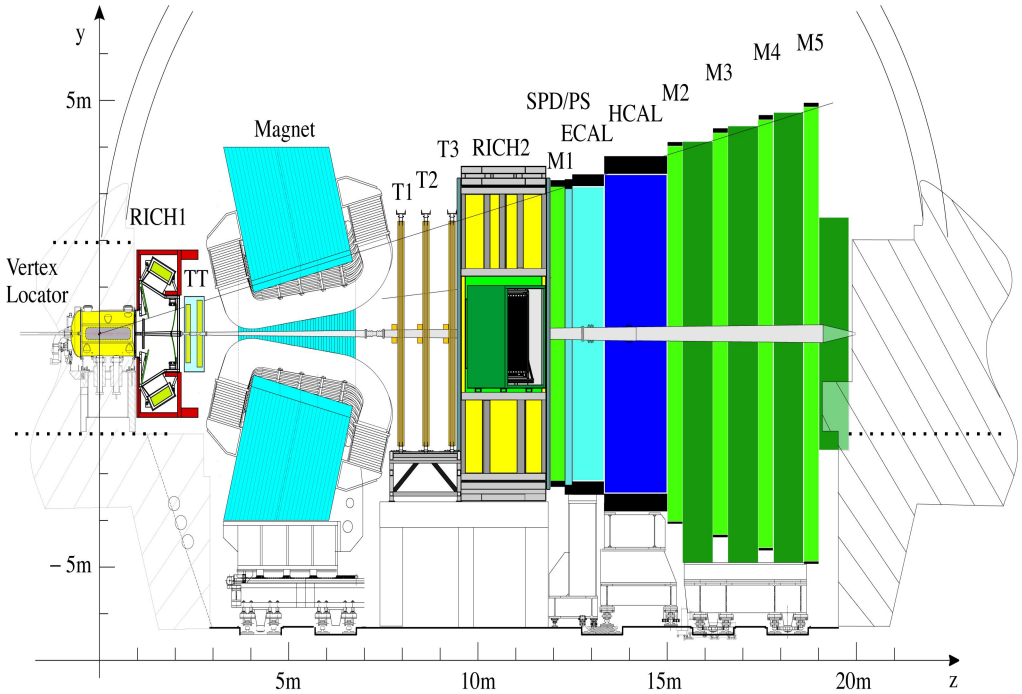
  $D^0, D^{\pm}, D_s, \Lambda_c, \ldots$



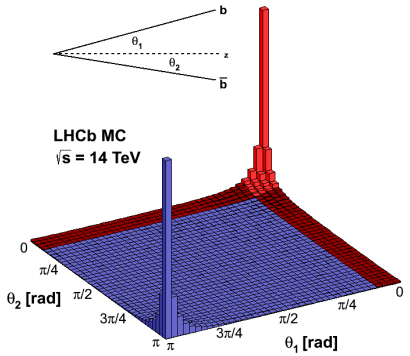
LHCb Detector

LHCb, Int. J. Mod. Phys. A30 (2015) 1530022

Forward spectrometer running in pp collider



- $2 < \eta < 5$ range: $\sim 25\%$ of $b\bar{b}$ pairs inside LHCb acceptance



Excellent vertex and IP, decay time resolution:

- $\sigma(\text{IP}) \approx 20$ μm for high-p_T tracks
- $\sigma(\tau) \approx 45$ fs for $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s^-\pi^+$ decays

Very good momentum resolution:

- $\delta p/p \approx 0.5\% - 1\%$ for $p \in (0{,}200)$ GeV
- $\sigma(m_B) \approx 24$ MeV for two-body decays

Hadron and Muon identification

- $\epsilon_{K\to\text{K}} \approx 95\%$ for $\epsilon_{\pi\to\text{K}} \approx 5\%$ up to 100 GeV
- $\epsilon_{\mu\to\mu} \approx 97\%$ for $\epsilon_{\pi\to\mu} \approx 1 - 3\%$

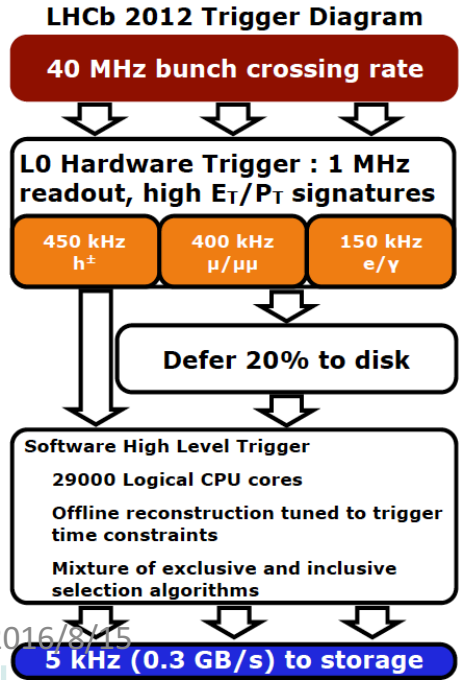
Data good for analyses

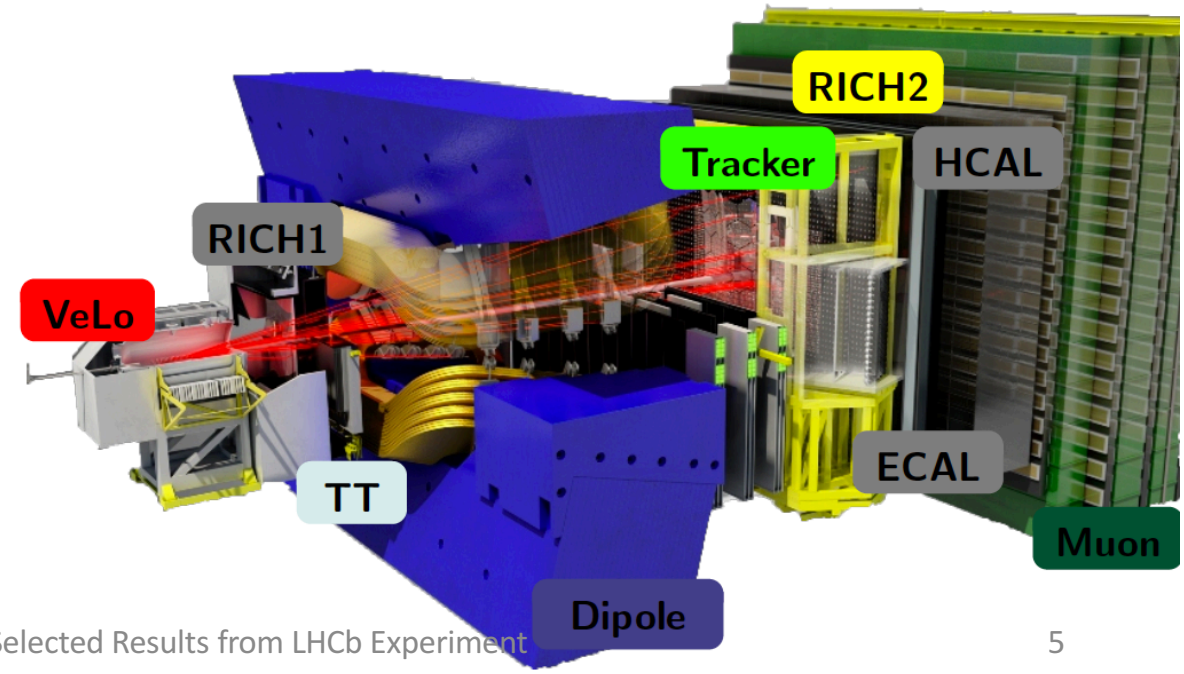
- $> 99\%$

LHCb Trigger at RUNI

Versatile two stage trigger

- Hardware-based L0 trigger: moderate P_T cut
- Software high level trigger: full detector information sent to trigger farm @1.1 MHz
- 3 kHz output rate (2011), 5 kHz (2012)

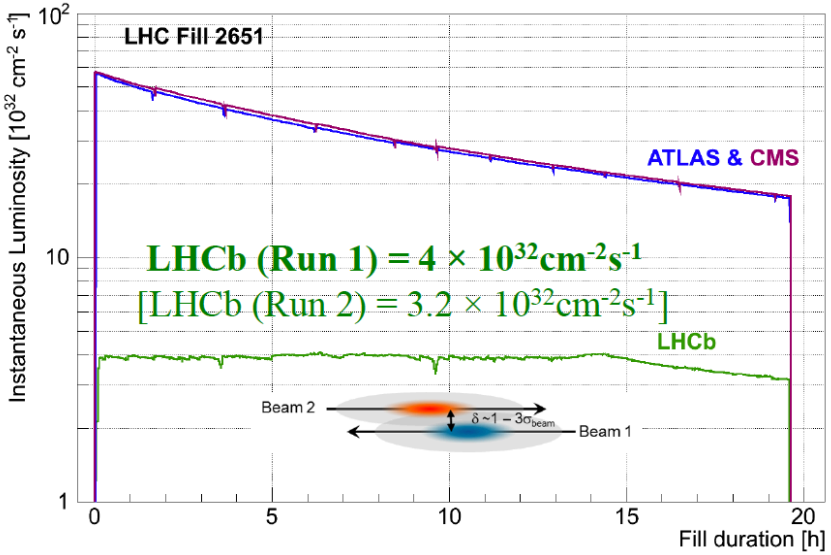




Physics program at LHCb

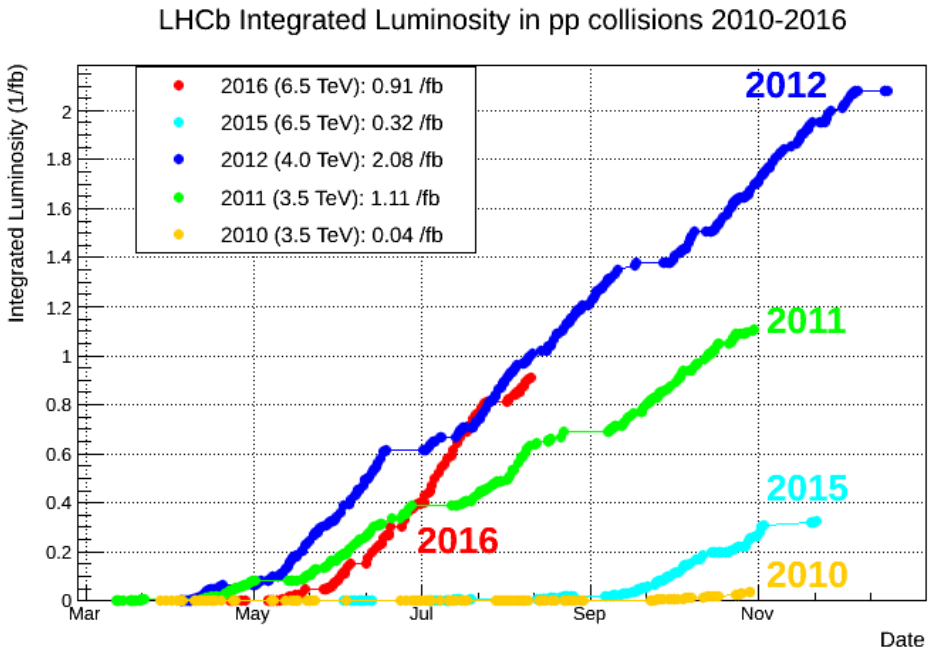
- Not only precision measurements in *b, c* sectors
  - CKM and CP-violation parameters
  - rare decays
  - testing lepton universality
  - …
- But also a general purpose experiment
  - electroweak measurements: $\sin\theta_W$, W/Z, top quark, ..
  - spectroscopy, exotic hadrons
  - soft QCD
  - heavy ions
  - …

LHCb data taking



- **Luminosity leveling: constant at**
  - **~4x10^{32} cm^{-2}s^{-1} (RUNI)**
  - **~3x10^{32} cm^{-2}s^{-1} (RUNII)**
  - **cf. 2x10^{32} cm^{-2}s^{-1} (design)**

- **1 fb^{-1} in 2011 at 7 TeV**
- **2 fb^{-1} in 2012 at 8 TeV**
- **0.3 fb^{-1} in 2015 at 13 TeV**
- **0.9 fb^{-1} in 2016 at 13 TeV**



Recent results from B decays

- Measurements of CKM matrix elements
- CP violation
- Rare decays and tests of lepton universality

→ **Yuehong Xie's talk on Tuesday morning**

Recent results

- Measurement of *CP* asymmetry in $D^0 \to K^-K^+$ decays
  LHCb-PAPER-2016-035 (in preparation)

- Search for mixing and CP violation with
  Wrong-Sign $D^0 \to K\pi$ from $\bar{B} \to \mu D^* X$
  LHCb-PAPER-2016-033 (in preparation)

- Search for $D^0 \to e^+\mu^-$ decay
  LHCb-PAPER-2016-035 (in preparation)

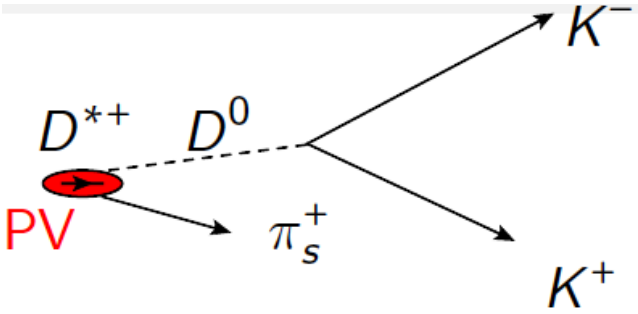
$A_{CP}(D^0 \to KK)$

LHCb-PAPER-2016-035 (in preparation)

- Experimental method

  — raw asymmetry

$$A_{\text{raw}}(D^0 \to KK) = \frac{N(D^0 \to KK) - N(\bar{D}^0 \to KK)}{N(D^0 \to KK) + N(\bar{D}^0 \to KK)}$$



  — measure the CP asymmetry

$$A_{CP}(D^0 \to KK) = A_{\text{raw}}(D^0 \to KK) - A_P(D^{*+}) - A_D(\pi_s^+) + O(A^3)$$

— detection/production asymmetries eliminated by control processes

$$D^{*+} \to D^0(\to K^-\pi^+)\pi_s^+, D^+ \to K^-\pi^+\pi^+, D^+ \to \bar{K}^0\pi^+$$

$A_{CP}(D^0 \to KK)$

LHCb-PAPER-2016-035 (in preparation)

- Use 3fb^{-1} data collected at RUNI

$$A_{CP}(KK) = (0.14 \pm 0.15 \pm 0.10)\%$$

consistent with *CP* conservation

- Previous measurements
  - $\boldsymbol{\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi) = (-0.10 \pm 0.08 \pm 0.03)\%}$

    (now agrees with SM, PRL 116 (2016) 191601)

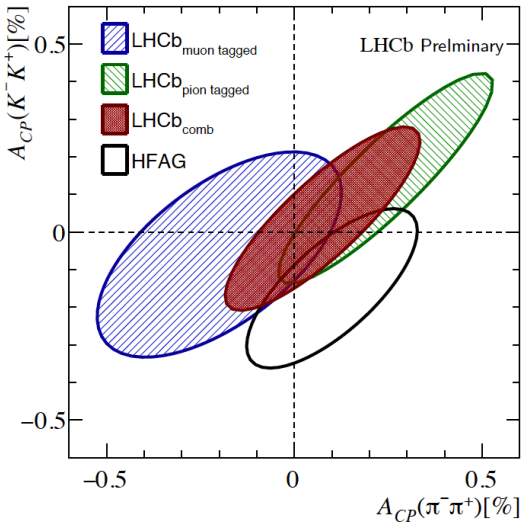
  → $\boldsymbol{A_{CP}(\pi\pi) = (0.24 \pm 0.15 \pm 0.11)\%}$

  — combine muon tagged results (JHEP 07 (2014) 041)

    with full correlations

$$\boldsymbol{A_{CP}^{\mathrm{comb}}(KK) = (0.04 \pm 0.12 \pm 0.10)\%}$$

$$\boldsymbol{A_{CP}^{\mathrm{comb}}(\pi\pi) = (0.07 \pm 0.14 \pm 0.11)\%}$$



Mixing & CP violation with $D^0 \to K\pi$ from $\overline{B} \to \mu D^*$

LHCb-PAPER-2016-033 (in preparation)

- D^0-$\overline{D}^0$ mixing
  - mxing → mass eigenstates ≠ flavor eigenstate
  - mass eigenstates $|D_{1,2}\rangle = p|D^0\rangle + q|\overline{D}^0\rangle$

$$|p|^2 + |q|^2 = 1, x = \frac{m_2 - m_1}{\Gamma}, y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}, \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

- CP violation

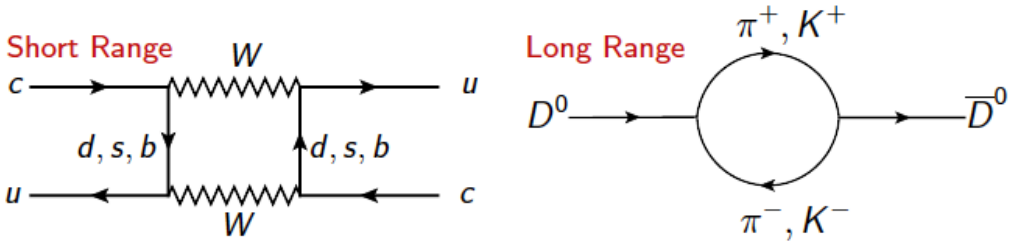
$$\mathcal{A}_f = \langle f|\mathcal{H}|D\rangle, \overline{\mathcal{A}}_{\bar{f}} = \langle \bar{f}|\mathcal{H}|\overline{D}\rangle$$

  - Direct CP violation: $\left|\frac{\overline{\mathcal{A}}_{\bar{f}}}{\mathcal{A}_f}\right| \neq 1$
  - CP violation in Mixing: $\left|\frac{q}{p}\right| \neq 1$, weak phase $\phi = \arg\left(\frac{q}{p}\right) \neq 0$
  - CP violation in Interference between Mixing & Decay: $\arg\left(\frac{q}{p}\frac{\overline{\mathcal{A}}_{\bar{f}}}{\mathcal{A}_f}\right) \neq 0$

Mixing & CP violation with $D^0 \to K\pi$ from $\overline{B} \to \mu D^*$

LHCb-PAPER-2016-033 (in preparation)

- D^0-$\overline{D}^0$ mixing in SM



— Mixing enters at 1 loop level in SM, GIM and CKM suppressed

— Non-perturbative long-range effects may dominate short-range interactions, difficult to calculate

— x, y expected to be $\leq 0.5\%$

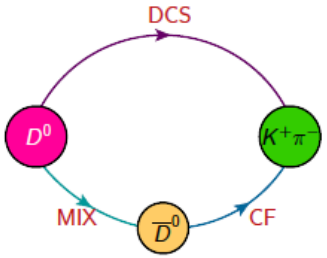
— CP violation expected to be $\mathcal{O}(10^{-3})$ in SM. If enhancement seen, could be the signal for new physics

Mixing & CP violation with $D^0 \to K\pi$ from $\bar{B} \to \mu D^*$

LHCb-PAPER-2016-033 (in preparation)

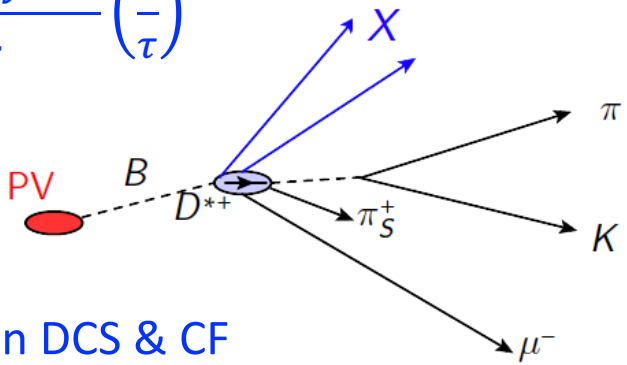
- Time dependent wrong-sign/right-sign ratio

$$R(t)^{\pm} = \frac{WS(t)^{\pm}}{RS(t)^{\pm}} \approx R_D^{\pm} + \sqrt{R_D^{\pm}} y'^{\pm} \frac{t}{\tau} + \frac{x'^{\pm 2} + y'^{\pm 2}}{4} \left(\frac{t}{\tau}\right)^2$$

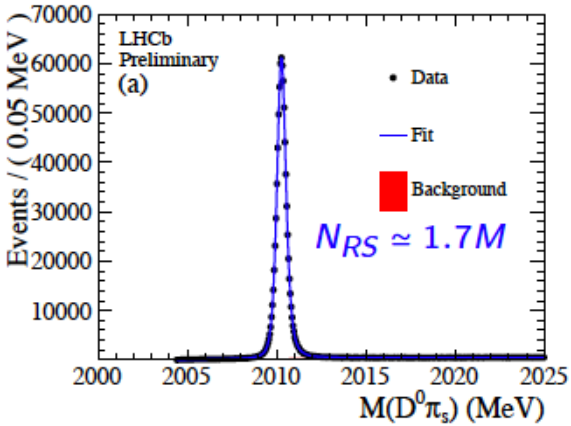


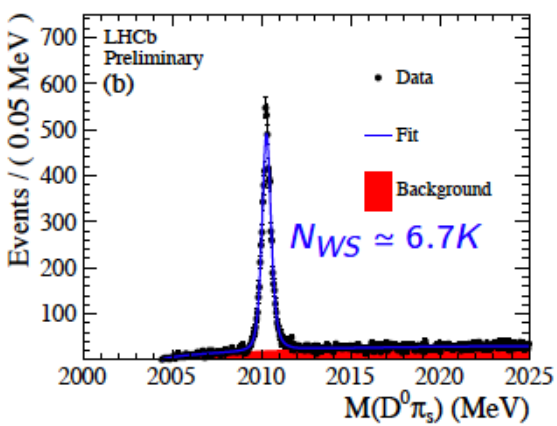
$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

δ: strong phase deference between DCS & CF



- Flavor doubly tagged by μ^-, π_s^+; Extremely clean signal sample



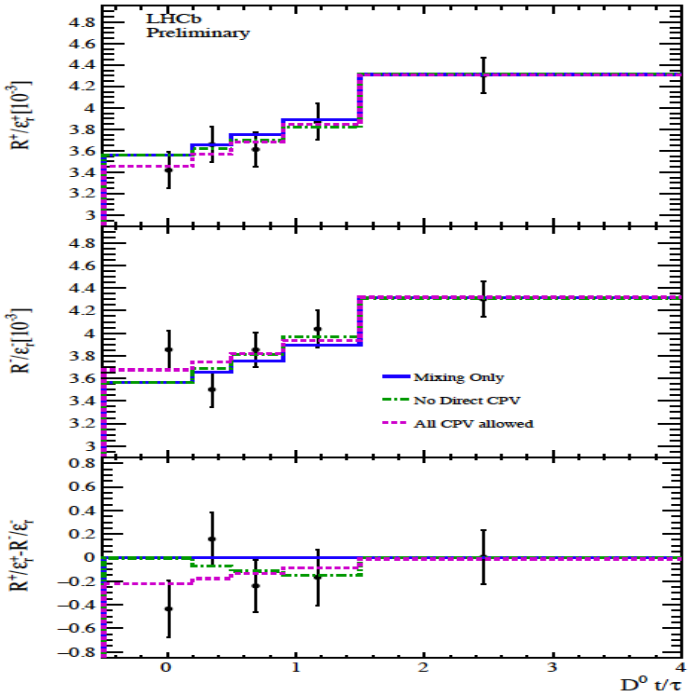


Mixing & CP violation with $D^0 \to K\pi$ from $\overline{B} \to \mu D^*$

LHCb-PAPER-2016-033 (in preparation)

- Three scenarios
  - —mixing only
  - —no direct CP violation
  - — all CP violation allowed

consistent with mixing only



Combined with results from prompt D^* decays

LHCb, PRL 111 (2013) 251801

Parameter	DT+prompt combination	Prompt alone	% Error Improvement
	No CPV		
$R_D[10^{-3}]$	3.533 ± 0.054	3.568 ± 0.067	19
$x'^2[10^{-5}]$	3.6 ± 4.3	5.5 ± 4.9	12
$y'[10^{-3}]$	5.23 ± 0.84	4.80 ± 0.94	11
χ^2/NDF	96.594/111		
	No Direct CPV		
$R_D[10^{-3}]$	3.533 ± 0.054	3.568 ± 0.067	19
$x'^{2+}[10^{-5}]$	4.9 ± 5.0	6.4 ± 5.6	11
$y'^{+}[10^{-3}]$	5.14 ± 0.91	4.80 ± 1.08	16
$x'^{2-}[10^{-5}]$	2.4 ± 5.0	4.6 ± 5.5	9
$y'^{-}[10^{-3}]$	5.32 ± 0.91	4.8 ± 1.08	16
χ^2/NDF	96.147/109		
	All CPV Allowed		
$R_D^+[10^{-3}]$	3.474 ± 0.081	3.545 ± 0.095	15
$x'^{2+}[10^{-5}]$	1.1 ± 6.5	4.9 ± 7.0	7
$y'^{+}[10^{-3}]$	5.97 ± 1.25	5.10 ± 1.38	9
$R_D^-[10^{-3}]$	3.591 ± 0.081	3.591 ± 0.090	10
$x'^{2-}[10^{-5}]$	6.1 ± 6.1	6.0 ± 6.8	10
$y'^{-}[10^{-3}]$	4.50 ± 1.21	4.50 ± 1.39	13
χ^2/NDF	94.960/108		

Search for $D^0 \to e^+\mu^-$

LHCb, PLB 754 (2016) 167

- Predicted to occur in R-parity violating MSSM

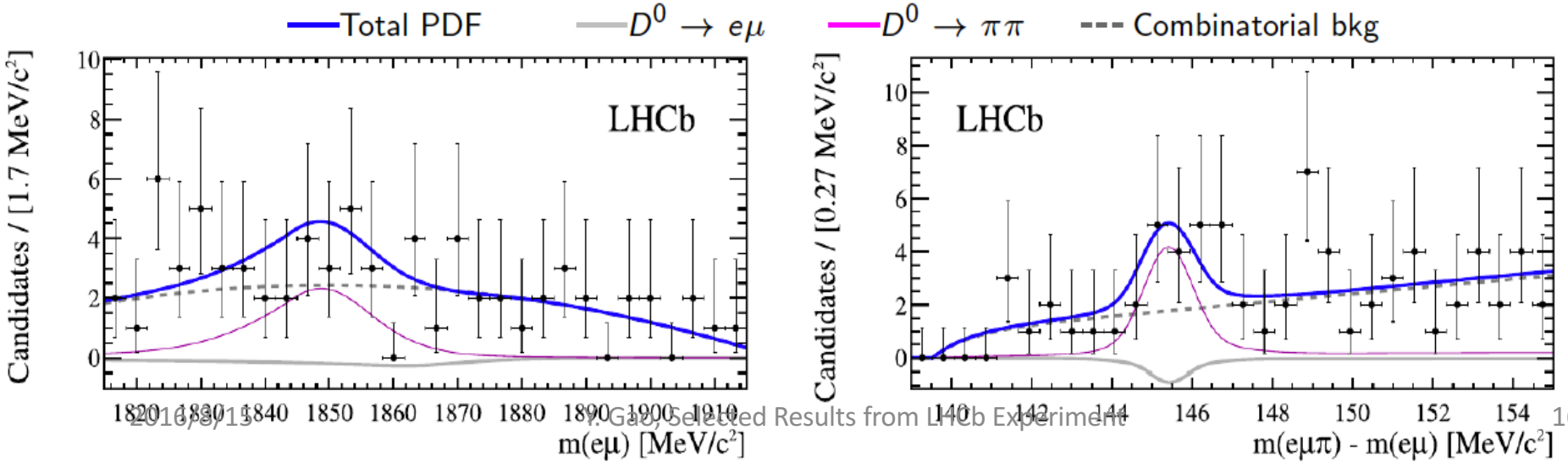
  PRD 66 (2002) 014009, Int. J. Mod. Phys. A29 (2014) 1450169

- Previous 90% CL limits on the branching ratio

  3.3×10^{-7} (BaBar) PRD 86 (2012) 032001, 2.6×10^{-7} (Belle) PRD 81 (2010) 091102R

- Use $D^{*\pm} \to D^0\pi^\pm$ decays at LHCb, new world best limit

$$BF(D^0 \to e^+\mu^-) < 1.3\ (1.6) \times 10^{-8} \text{ @ } 90\ (95)\%\ \text{CL}$$



Recent results

- Measurement of Z forward-backward asymmetry

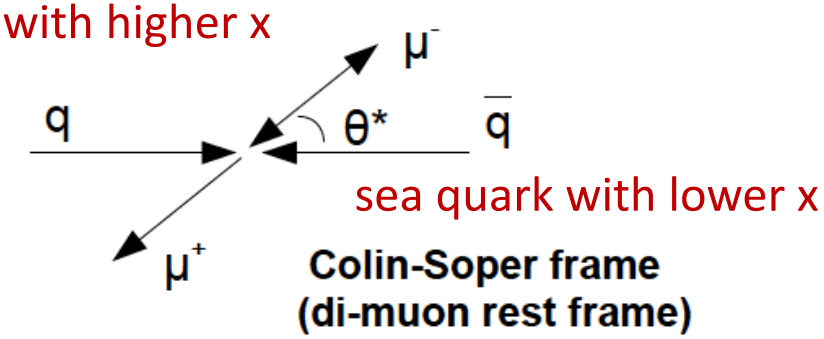
JHEP 11 (2015) 190

Z forward-backward asymmetry at LHC

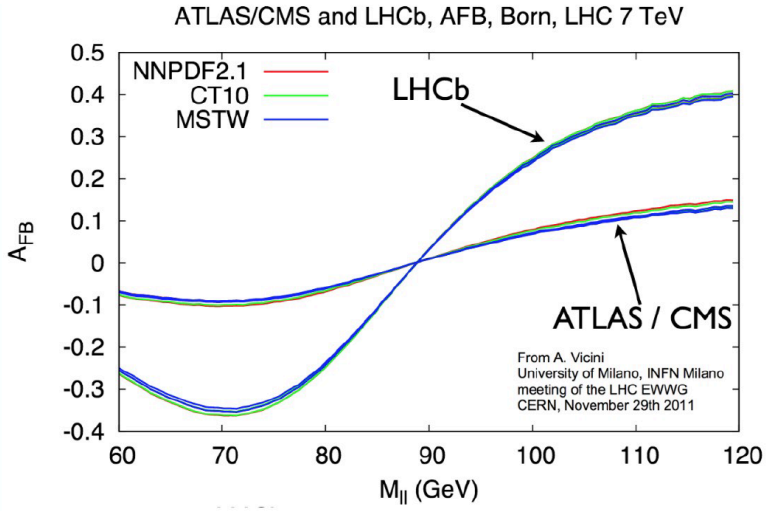
- Define

$$A_{\mathrm{FB}} \equiv \frac{N_{\mathrm{F}} - N_{\mathrm{B}}}{N_{\mathrm{F}} + N_{\mathrm{B}}}$$

valence quark with higher x



- More asymmetries in the forward region

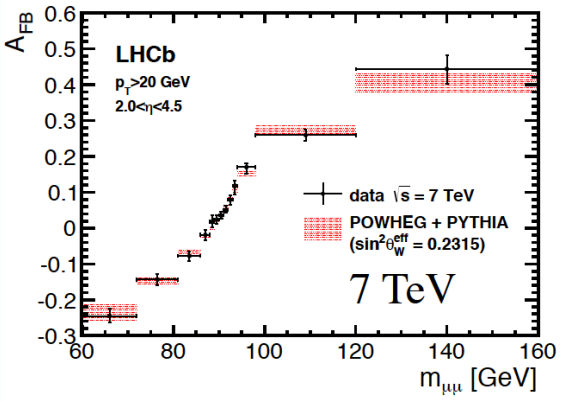


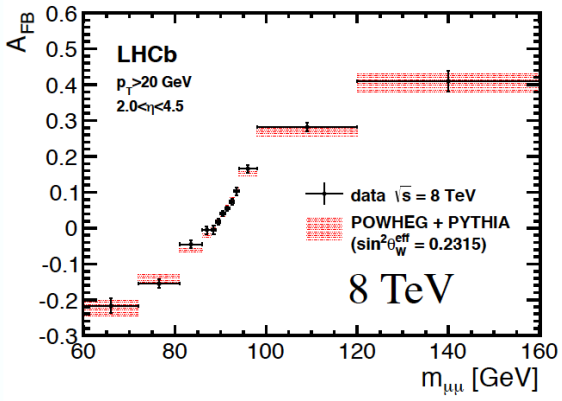
Z forward-backward asymmetry at LHCb

LHCb, JHEP 11 (2015) 190

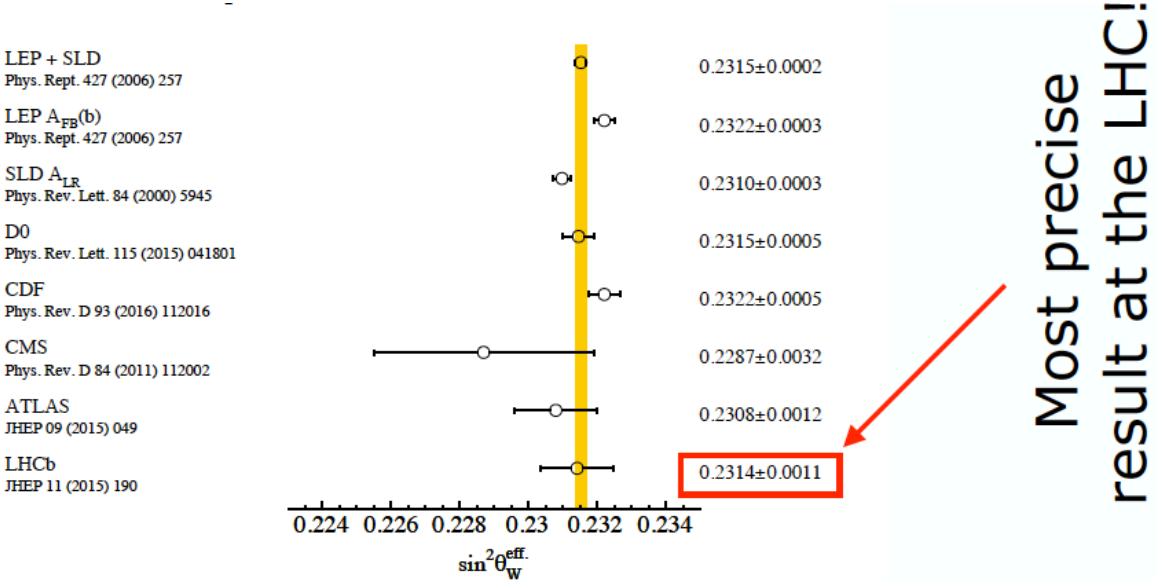
- Use 3.0 fb^{-1} at RUNI

Uncertainty	average $\Delta\lvert A_{FB}^{pred}\rvert$
PDF	0.0062
scale	0.0040
α_s	0.0030
FSR	0.0016





$\sin^2\theta_{W,eff}$= 0.23142 ± 0.00073 (stat.) ± 0.00052 (syst.) ± 0.00056 (th.)



Recent results

- The discovery of pentaquark states

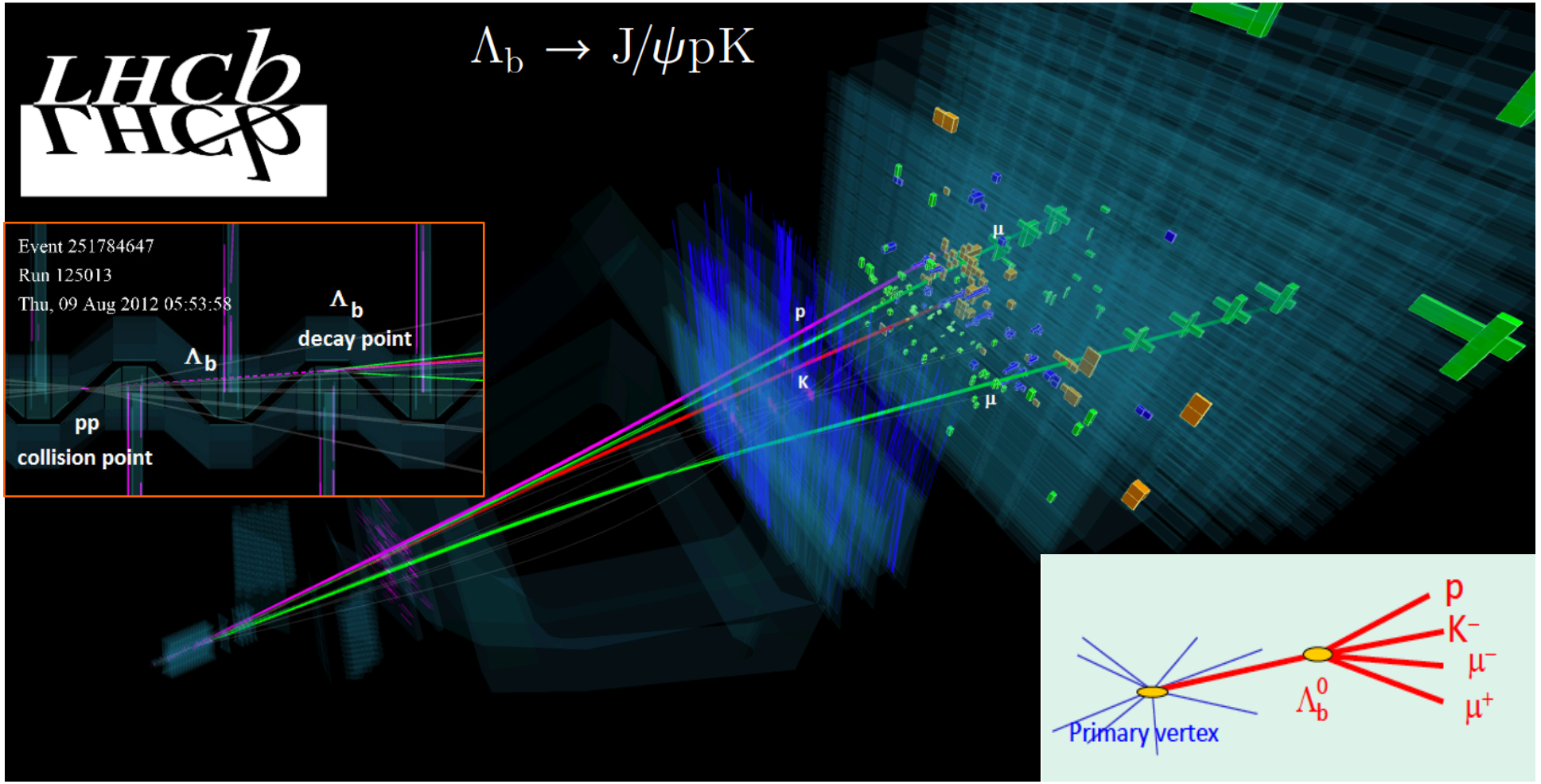
LHCb, PRL 115(2015) 072001

LHCb, Chin. Phys. C 40 (2016) 011001

LHCb-PAPER-2016-009

LHCb-PAPER-2016-015

$\Lambda_b^0 \to J/\psi p K^-$ at LHCb

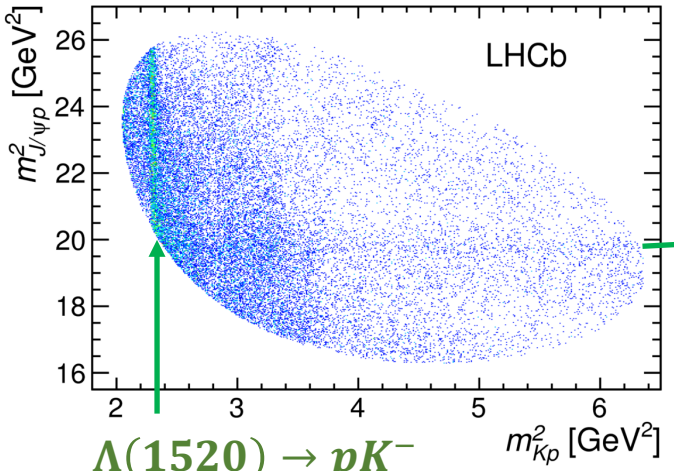


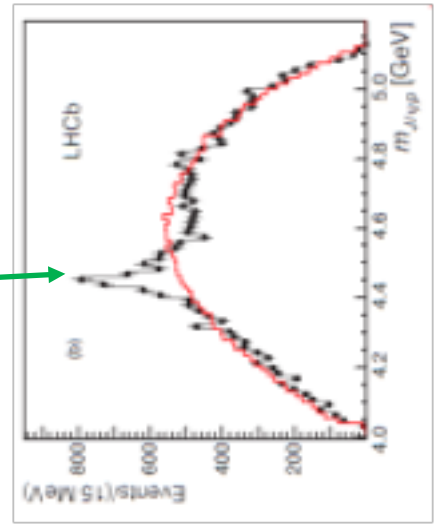
Surprise in $\Lambda_b^0 \to J/\psi p K^-$

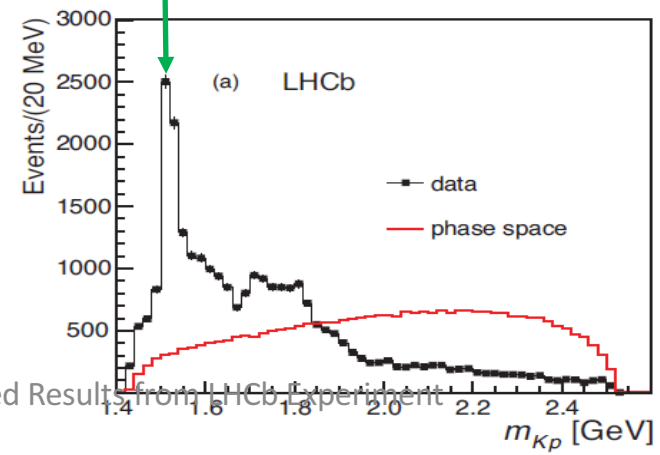
LHCb, PRL 115(2015) 072001

- Unexpected large yield found with 1 fb^{-1} LHCb, PRL 111(2013) 102003
- Used to measure Λ_b^0 lifetime LHCb, PL B734 (2014) 122
- Surprises seen:

  narrow peak in $m_{J/\psi p}$
- Full amplitude analysis to explore the details







Amplitude analysis of $\Lambda_b^0 \to J/\psi p K^-$

LHCb, PRL 115(2015) 072001

- 6D amplitude: m_{pK^-} & 5 decay angles

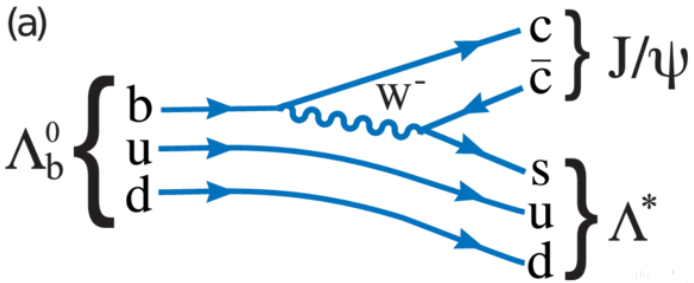
- 2 models for $\Lambda^* \to pK^-$ contributions based on PDG
  - *Extended model* allows all LS couplings of each resonance, and include poorly motivated states
  - *Reduced model* uses only well motivated states
  - *Other possibilities* checked
- Model independent analysis confirmed that conventional pK^- contributions cannot describe the data, with minimal assumptions on their spin, and no assumptions on their number, shapes, masses, widths, and interference patterns

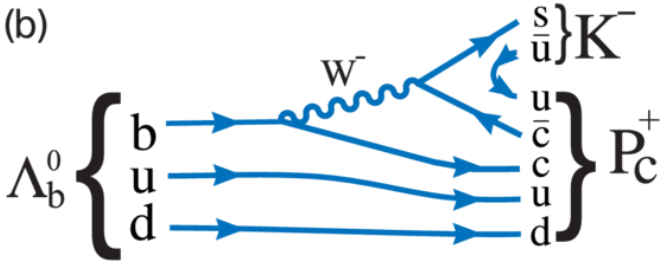
LHCb-PAPER-2016-009

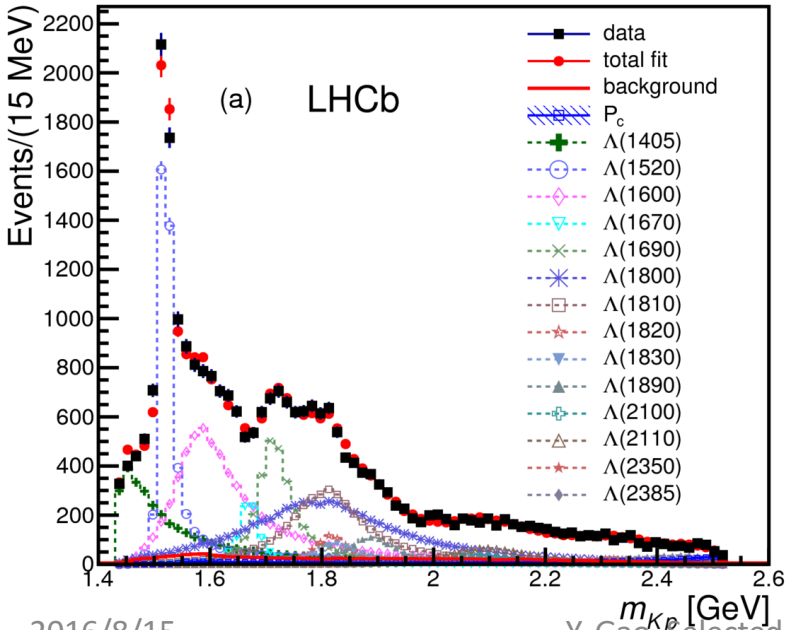
Discovery of pentaquark states

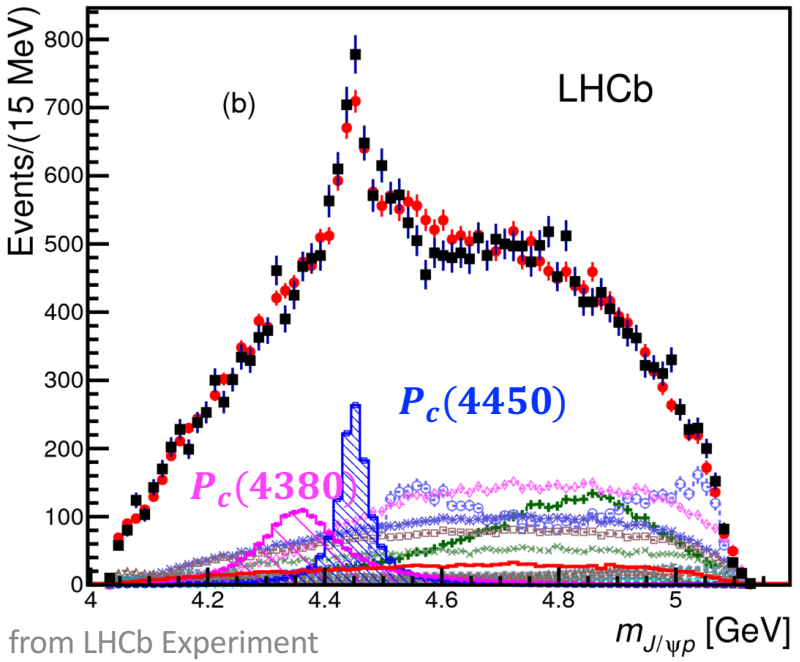
LHCb, PRL 115(2015) 072001

- Need two new states in $J/\psi p$ to fit the data (no $J/\psi K^-$ states!)









Discovery of pentaquark states

LHCb, PRL 115(2015) 072001

- Need two new states in $J/\psi p$ to fit the data (no $J/\psi K^-$ states!)

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

- Best fit has $J^p = \frac{3}{2}^-$ (*lower mass*) and $\frac{5}{2}^+$ (*higher mass*), ($\frac{5}{2}^+$, $\frac{3}{2}^-$) or ($\frac{3}{2}^+$, $\frac{5}{2}^-$) also give good fit, opposite parity is highly significant.
- Branching ratios measured

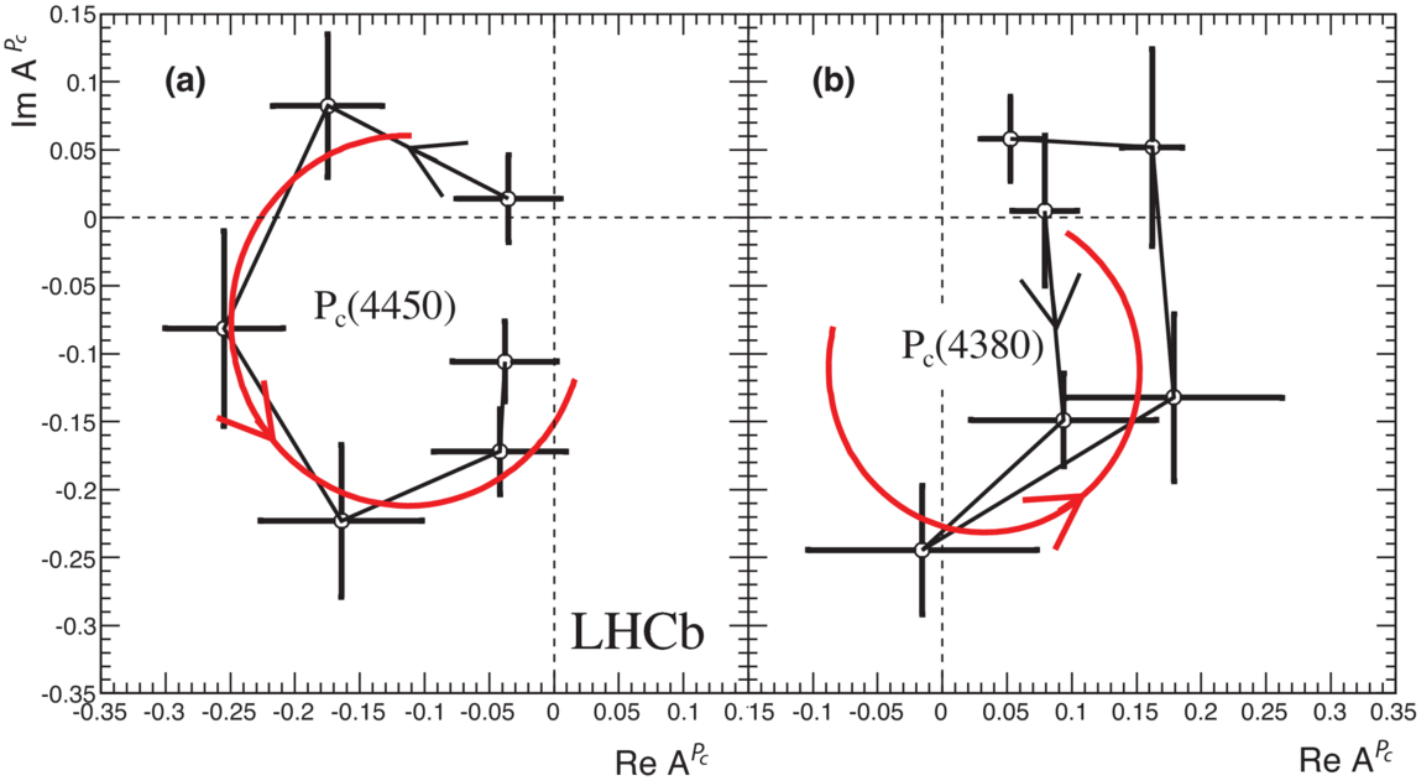
LHCb, Chin. Phys. C 40 (2016) 011001

$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4380)K^-)\mathcal{B}(P_c^+ \to J/\psi\, p) = \left(2.56 \pm 0.22 \pm 1.28\, {}^{+\,0.46}_{-\,0.36}\right) \times 10^{-5}$$
$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4450)K^-)\mathcal{B}(P_c^+ \to J/\psi\, p) = \left(1.25 \pm 0.15 \pm 0.33\, {}^{+\,0.22}_{-\,0.18}\right) \times 10^{-5}$$

Discovery of pentaquark states

LHCb, PRL 115(2015) 072001

- *Argand plots*

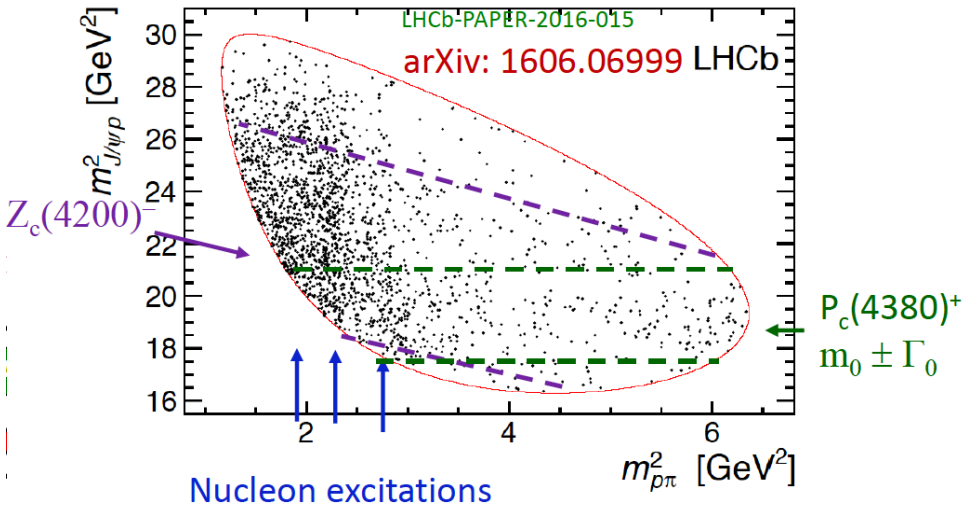


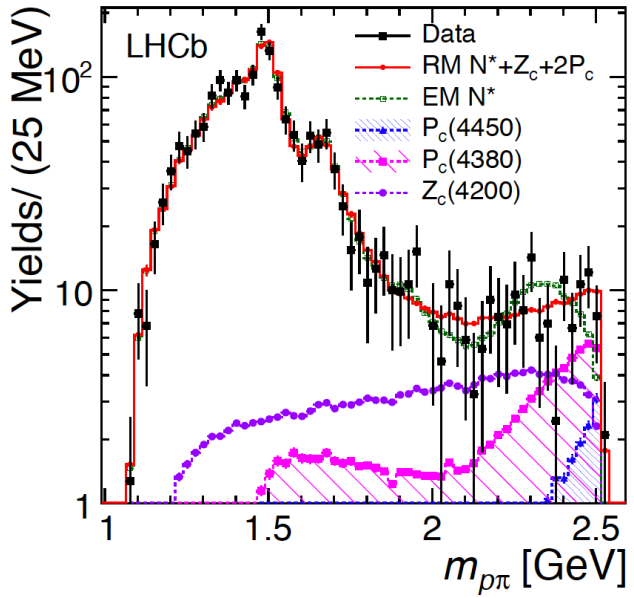
Still large errors, not conclusive!

Pentaquark states in $\Lambda_b^0 \to J/\psi p \pi^-$

LHCb-PAPER-2016-015

- Cabbibo suppressed decay, more than a factor of 10 lower statistics than in $\Lambda_b^0 \to J/\psi p K^-$.
- More complex because of Z_c^-





- Full amplitude analysis performed: **Significance of 2 P_c states is 3.3σ, if assuming production of $Z_c(4200)$ is negligible**

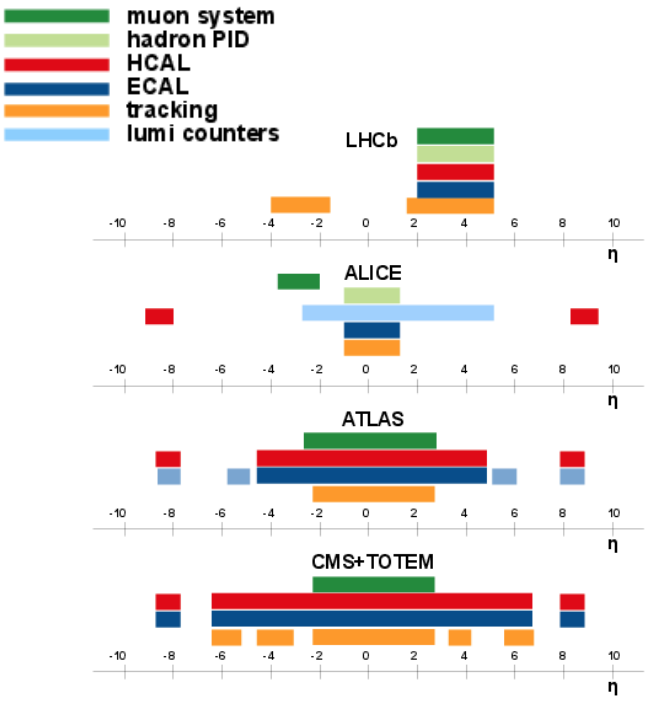
  → Not an independent confirmation of the P_c states

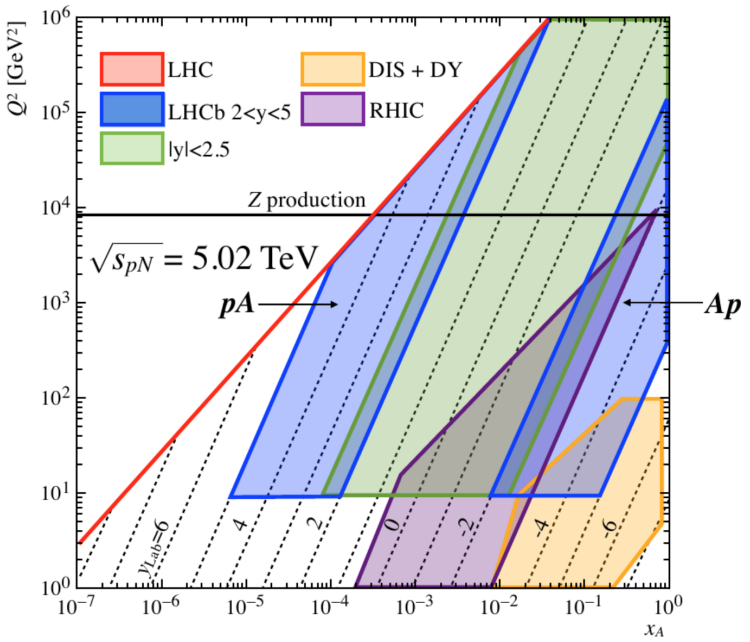
Recent results

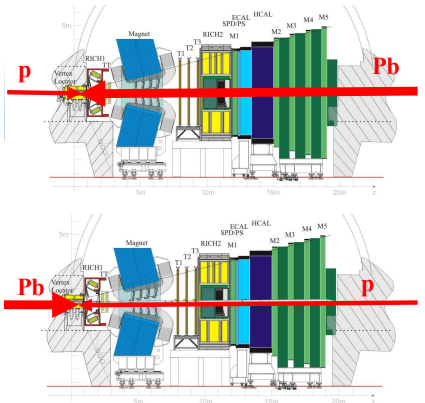
- Heavy ion program at LHCb

Heavy ion run at LHCb

- LHCb fully instrumented in the forward region ($2 < \eta < 5$)
  - heavy ion collisions in a unique kinematic area:
    low p_T, large y, very small or large x

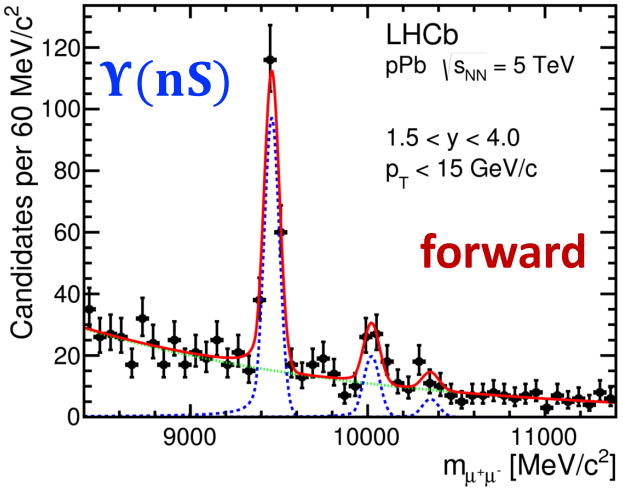


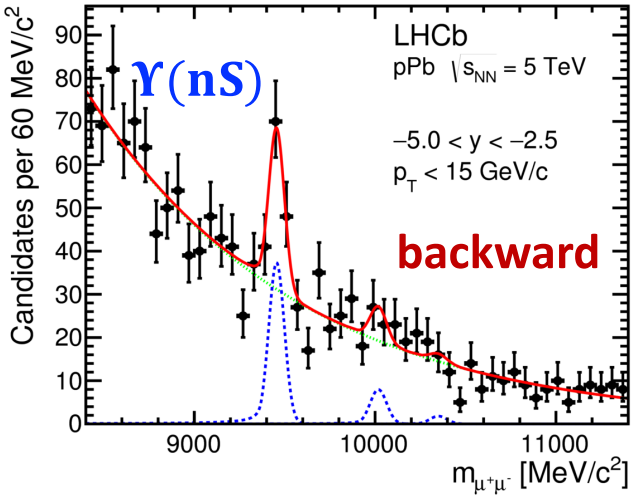




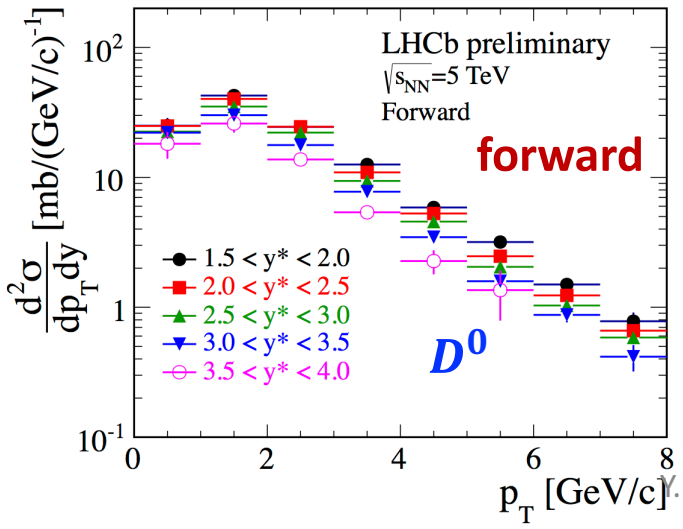
Heavy ion run at LHCb

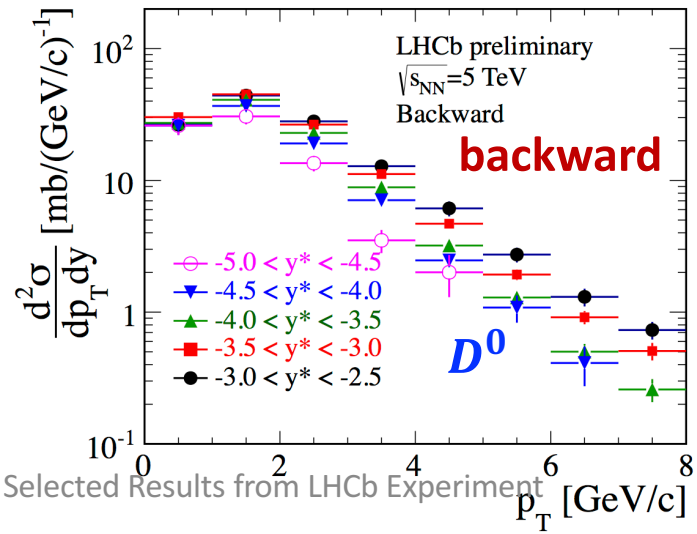
- Heavy flavor productions in $\boldsymbol{p}\mathbf{Pb}$ & $\mathbf{Pb}\boldsymbol{p}$: $\boldsymbol{J/\psi, \psi(2S), \Upsilon(ns), D}$





LHCb, JHEP 02 (2014) 072,
JHEP 07 (2014) 094,
JHEP 03 (2016) 133,
LHCb-CONF-2016-003

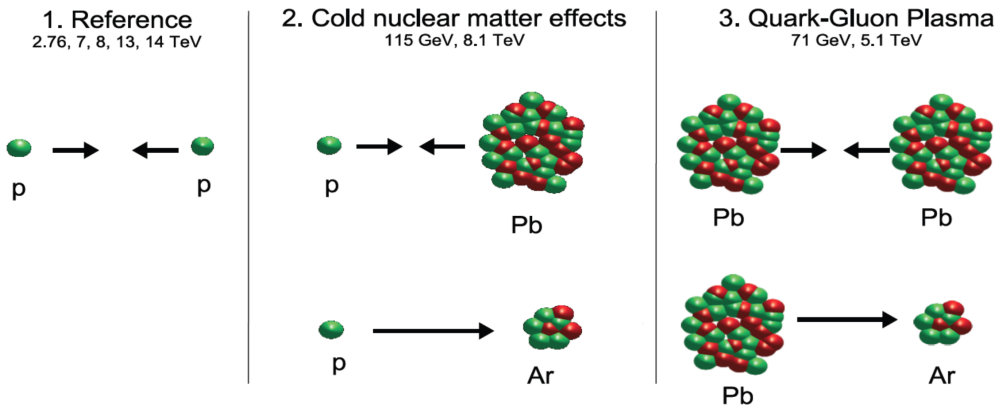




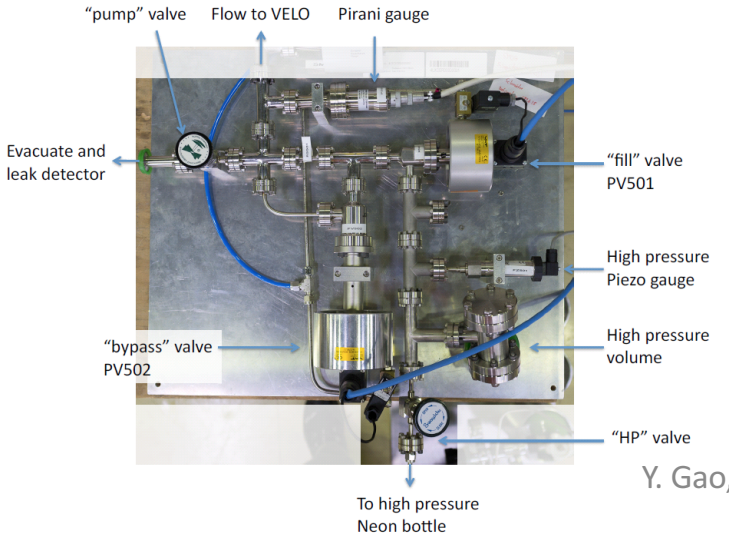
Open heavy flavor & quarkonia as tools to study cold nuclear effect (CNM)

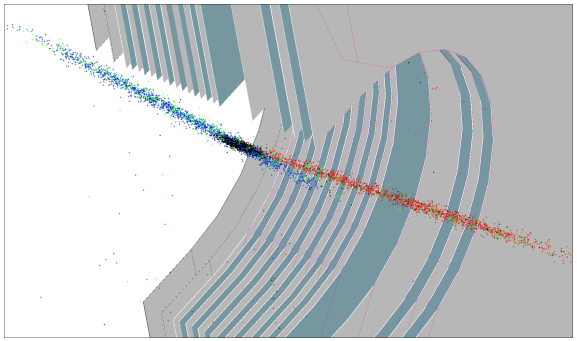
Heavy ion program in fixed target mode

- LHCb collects data from colliding beams & fixed targets



SMOG: System for Measuring the Overlap with Gas





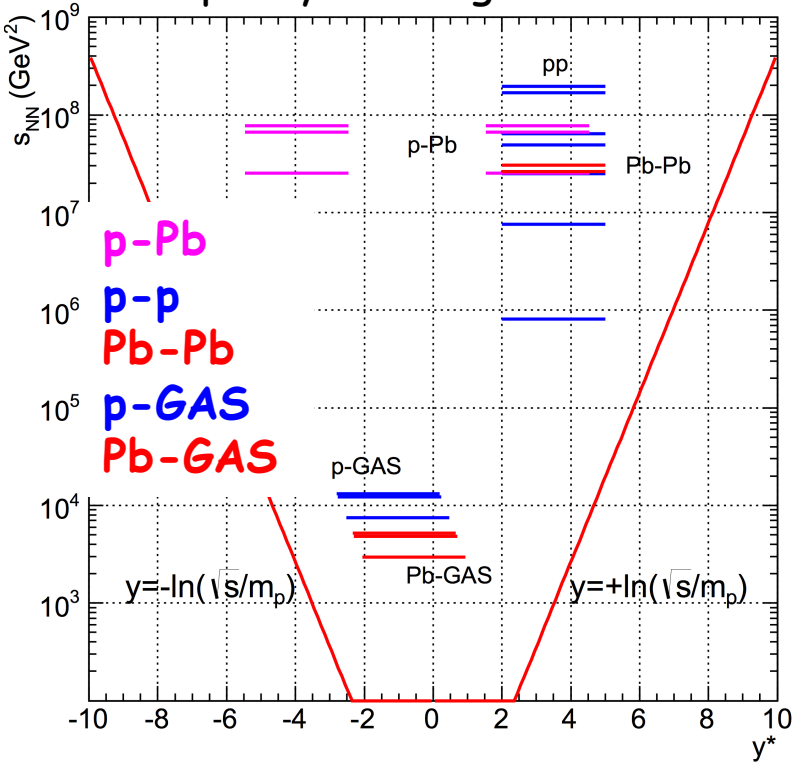
- Injection of noble gas into interaction region
- Simple and robust system
- Used for a precise luminosity determination: 1.1% accuracy at RUNI

LHCb, JINST 9 (2014) P12005

Heavy ion program in fixed target mode

- Data taking, more in 2016

LHCb rapidity coverage in rest frame



E_{beam}	pp	p-GAS	p-Pb	Pb-GAS	Pb-Pb
450 GeV	0.9 TeV				
1.38 TeV	2.76 TeV				
2.5 TeV	5 TeV	69 GeV			
3.5 TeV	7 TeV				
4.0 TeV	8 TeV	87 GeV	5 TeV	54 GeV	
6.5 TeV	13 TeV	110 GeV	8.2 TeV	69 GeV	5.1 TeV
7.0 TeV	14 TeV	115 GeV	8.8 TeV	72 GeV	5.5 TeV

Already collected

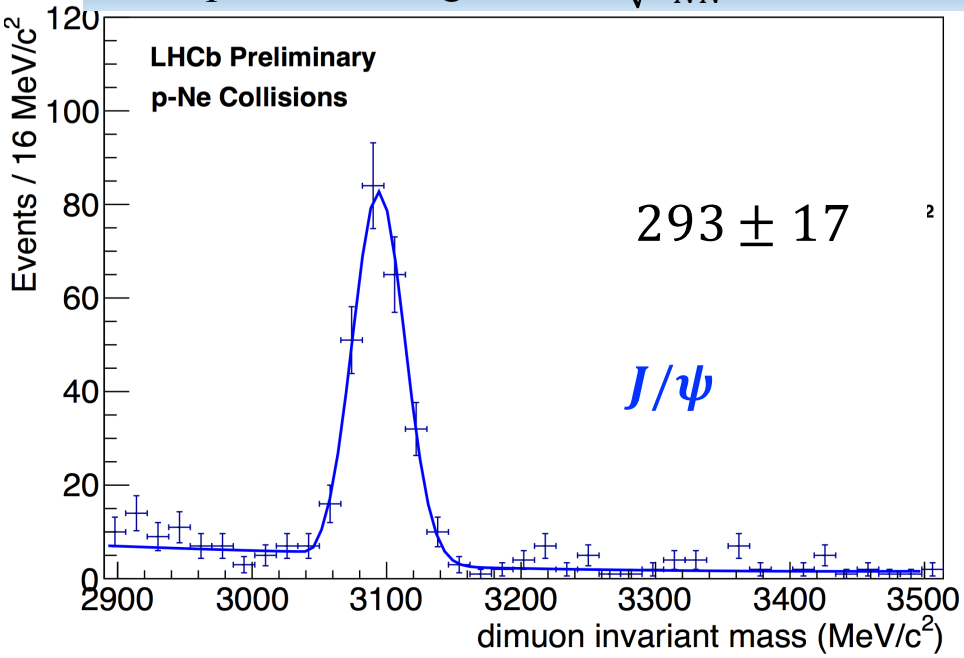
GAS targets: He, Ne, Ar, Kr, Xe

→ Different sizes of colliding system

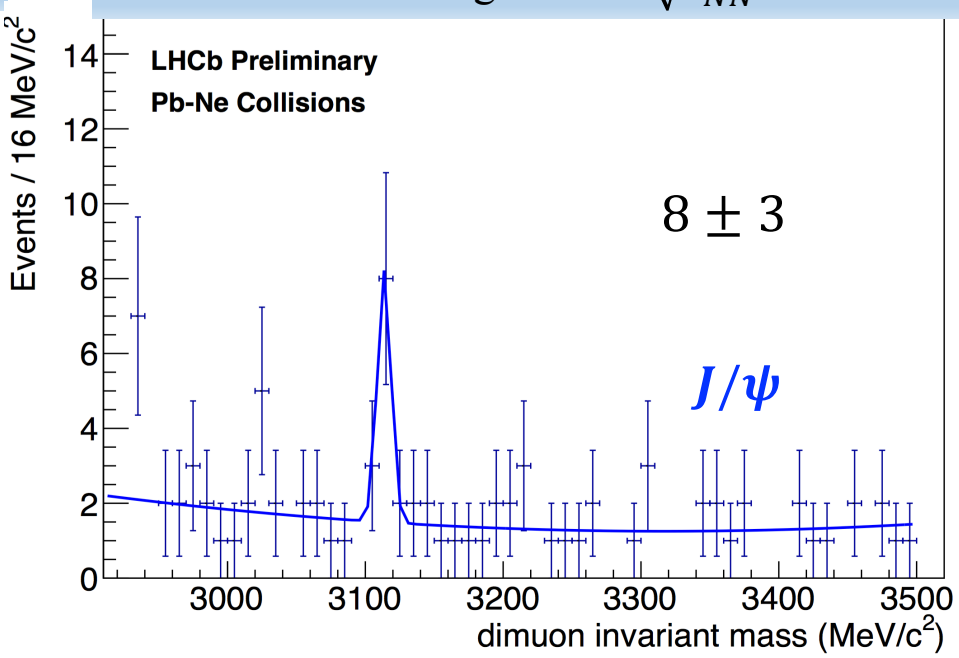
Heavy ion program at LHCb

- Fixed target runs

2015 pNe fixed target run at $\sqrt{s_{NN}} = 110$ GeV



2013 PbNe fixed target run at $\sqrt{s_{NN}} = 54$ GeV



- *Expect more results in 2016*

Bridge the gap from SPS to LHC with a single experiment

Recent results

- J/ψ Production at 13 TeV **JHEP 10 (2015) 172**
- $b\bar{b}$ cross-section at 13 TeV from $b \to X_c \mu \nu X$

LHCb-PAPER-2016-031 (in preparation)

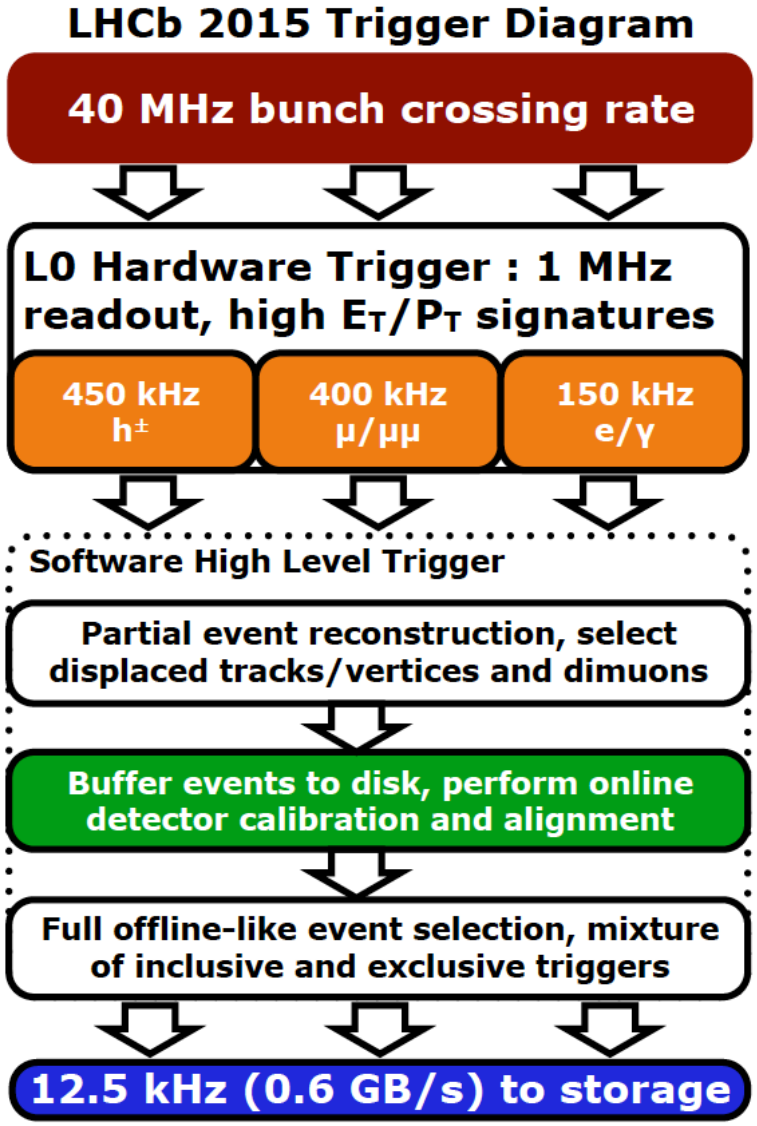
LHCb Trigger in RUN II

TURBO stream introduced in 2015

- 5 kHz of 12 kHz go to TURBO
- Only trigger information saved

  → smaller event, faster analysis

  → Used for high yield exclusive trigger lines: $J/\psi, D^0, D^+, \ldots$



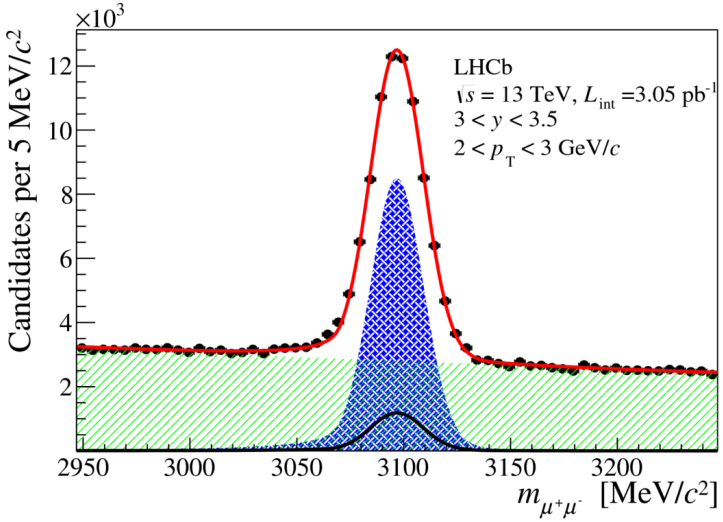
First QUICK results at 13 TeV:

- J/ψ production JHEP 10 (2015) 172
- charm production JHEP 03 (2016) 159
- Z production LHCb-PAPER-2016-021

J/ψ cross section at $\sqrt{s} = 13$ TeV

LHCb, JHEP 10 (2015) 172

- A quick measurement of J/ψ cross-section at $\sqrt{s} = 13$ TeV based on $3.02 \pm 0.12\ \mathrm{pb}^{-1}$ of data



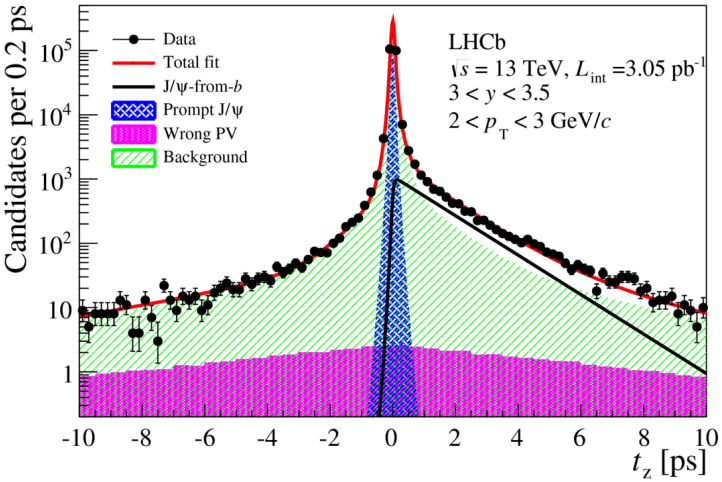
$$\sigma_{J/\psi}(\mathrm{LHCb}) = 15.30 \pm 0.03 \pm 0.86\ \mu\mathrm{b}$$

$$\sigma_{J/\psi/b}(\mathrm{LHCb}) = 2.34 \pm 0.01 \pm 0.13\ \mu\mathrm{b}$$

$$P_T < 14\ \mathrm{GeV}/c, 2 < y < 4.5$$

quasi proper lifetime variable to separate J/ψ from prompt/from b

$$t_z = \frac{(z_{J/\psi} - z_{\mathrm{PV}})M_{J/\psi}}{p_z}$$



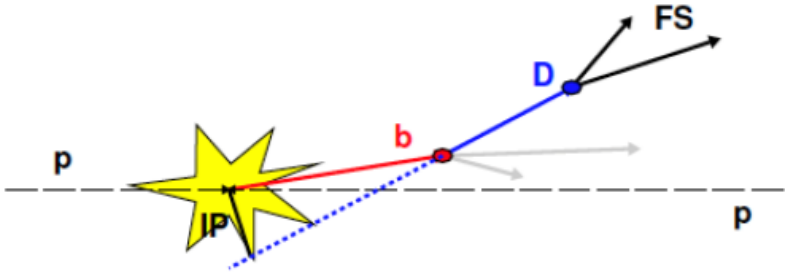
$b\bar{b}$ cross section from $b \to X_c \mu \nu X$

LHCb-PAPER-2016-031 (in preparation)

- Measuring right-sign combination of charmed hadron

  D^0, D^+, D_s, Λ_c

  and μ not pointing at the primary vertex, but forming a good vertex



- Measured cross section $\sigma(pp \to H_b X)$,

  including contributions from

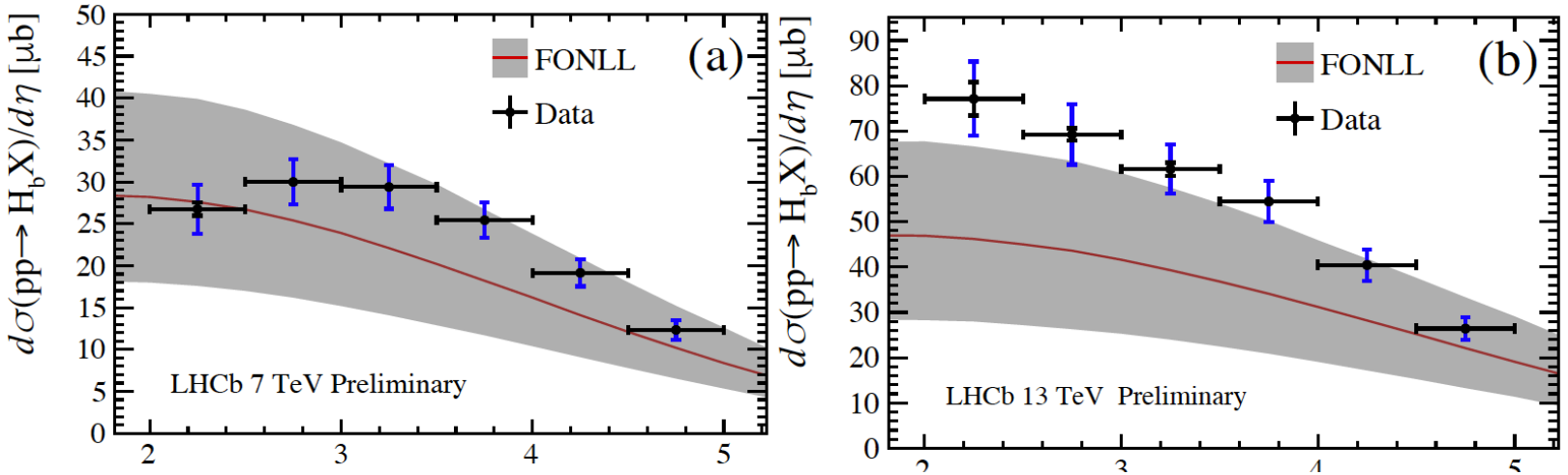
  — $B^0, \bar{B}^0$; B^+, B^-; $B_s^0, \bar{B}_s^0$

  — $\Lambda_b^0, \bar{\Lambda}_b^0$ + other *b* baryons

$b\bar{b}$ cross section at $\sqrt{s} = 7, 13$ TeV

LHCb-PAPER-2016-031 (in preparation)

- Same measurements at 7 TeV & 13 TeV

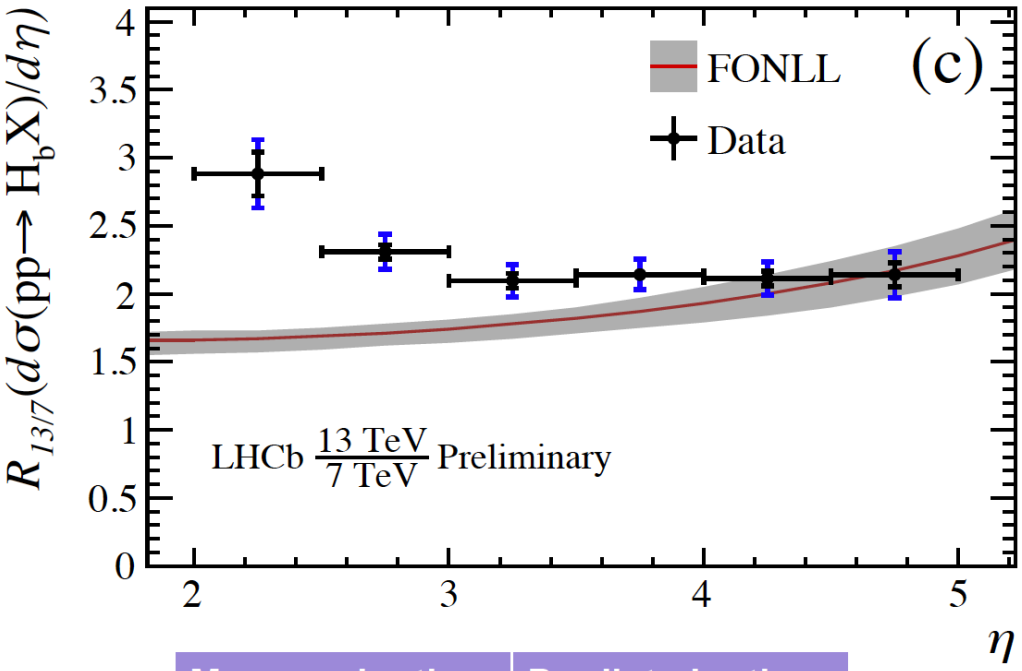


Center-of-mass energy	Cross-section in LHCb acceptance (μb)	Theoretical predications (μb) arXiv:1507.06197
7 TeV	71.7±0.5±6.5	62^{+28}_{-22}
13 TeV	164.9±2.3±14.6	111^{+51}_{-44}

Cross-section ratio

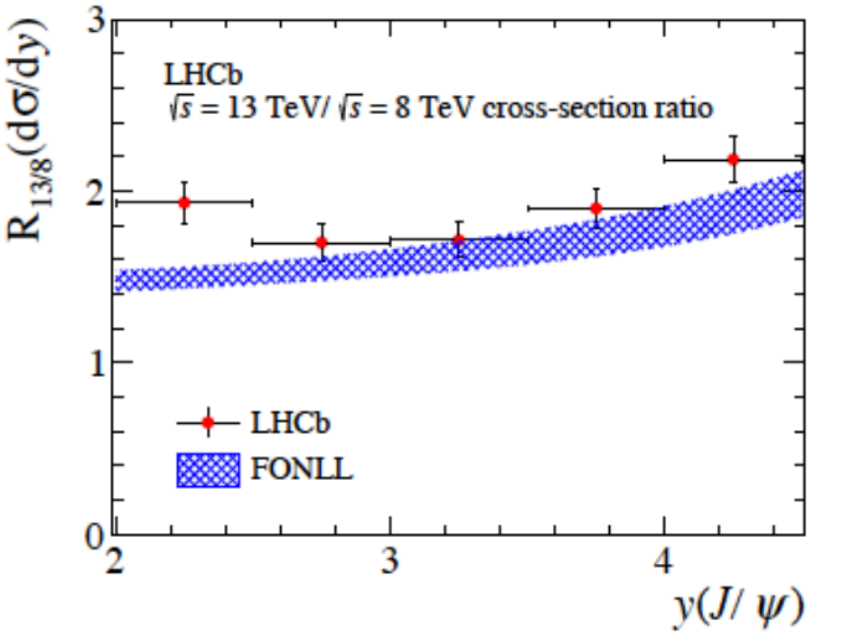
LHCb-PAPER-2016-031 (in preparation)

- Some tensions with theoretical predictions



Measured ratio	Predicted ratio (FONNL)
2.30±0.25±0.19	$1.79^{+0.21}_{-0.15}$

Measured from $pp \to b\bar{b}X, b/\bar{b} \to J/\psi X$



Summary

- LHCb has made great progress with RUNI & RUNII data
  - Precise measurements from b and c decays
  - Electroweak measurements
  - Discovery of two pentaquark states $P_c(4450)$ and $P_c(4380)$, and other exotic states
  - Promising results from the heavy ion program
  - First results from RUNII data
- Aim to collected 6 fb^{-1} in RUNII
- LHCb major upgrade in 2019-2020, 50 fb-1 after upgrade

Stay tuned !