Heavy Quark Production at LHCb

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Heavy Flavor Production in High-Energy Collisions

&

Forty Years of Quark-Gluon Plasma

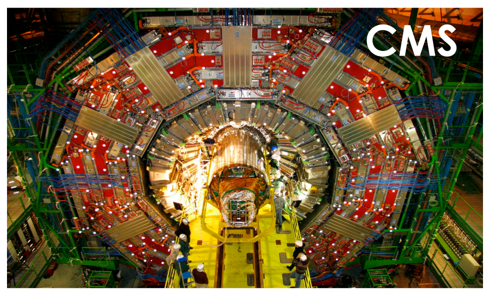
CCNU, Oct.8-11,2018


Mont Blanc
欧洲核子研究中心（CERN）
大型强子对撞机（LHC）
1250 members
18 countries
79 institutes
(September 2018)
Geneva airport
LHCb
CERN
ATLAS
CMS
ALICE
LHC tunnel

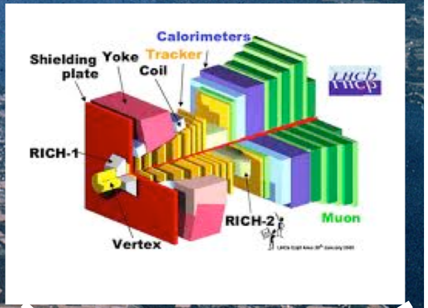
China Participation to LHC

From Z.G. Zhao

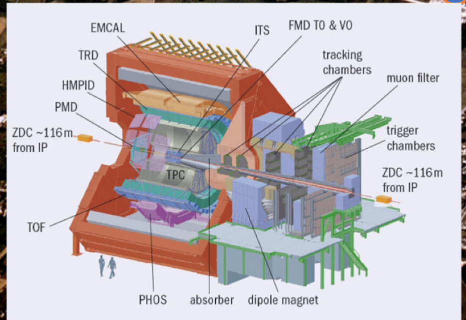
IHEP, PKU, THU,
BUAA, SYSU
5 institutions
24(author)/31(participants)



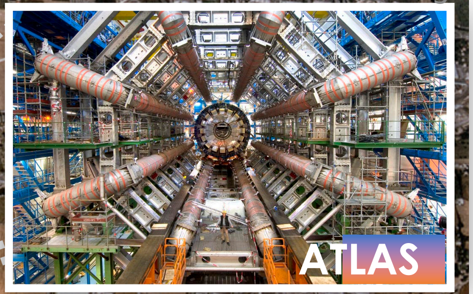
CCNU, IHEP, SCNU,THU,
WHU, UCAS
6 institutions
22/42



USTC, SJTU, SDU
IHEP, NJU, THU
6 institutions
11/18



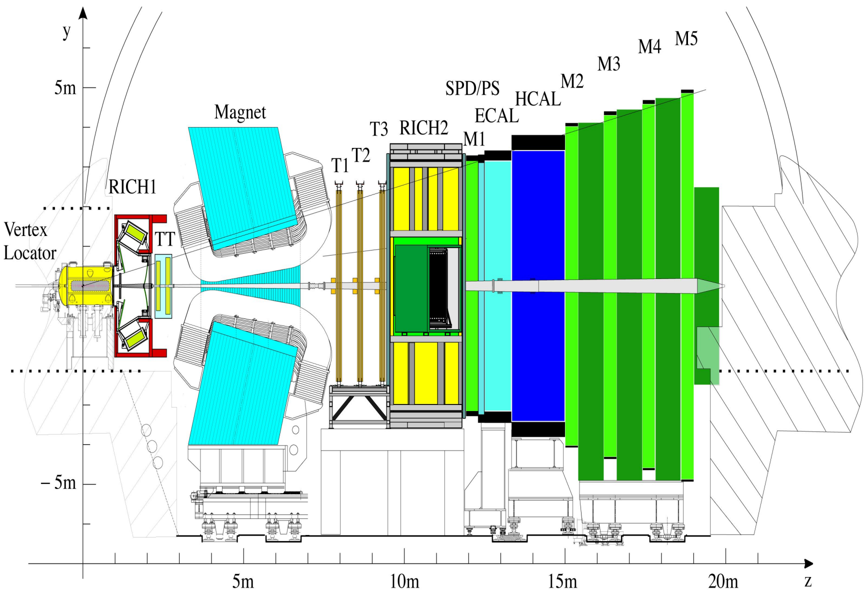
USTC, SJTU, SDU
IHEP, NJU, THU
6 institutions
48/84



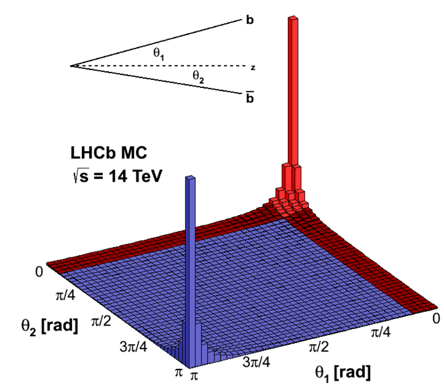
LHCb Detector

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

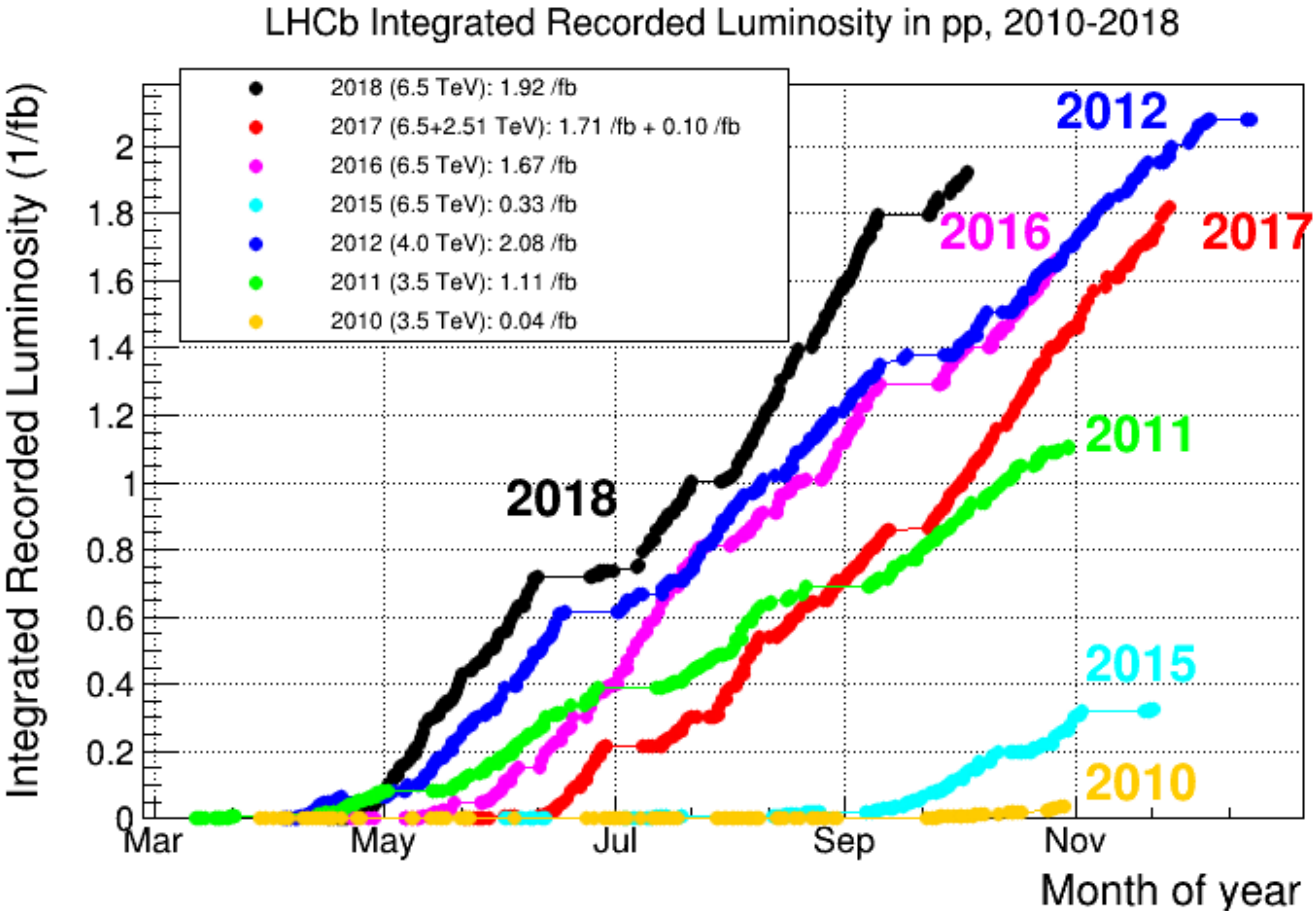


Excellent vertex and IP, decay time resolution:
- $\sigma(\mathrm{IP}) \approx 20$ μm for high-p_{T} tracks
- $\sigma(\tau) \approx 45$ fs for $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s^- \pi^+$ decays

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

Data good for analyses
- $> 99\%$


LHCb Integrated Recorded Luminosity in pp, 2010-2018
2018 (6.5 TeV): 1.92 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
Integrated Recorded Luminosity (1/fb)
Month of year
Mar
May
Jul
Sep
Nov
2018
2012
2016
2017
2011
2015
2010

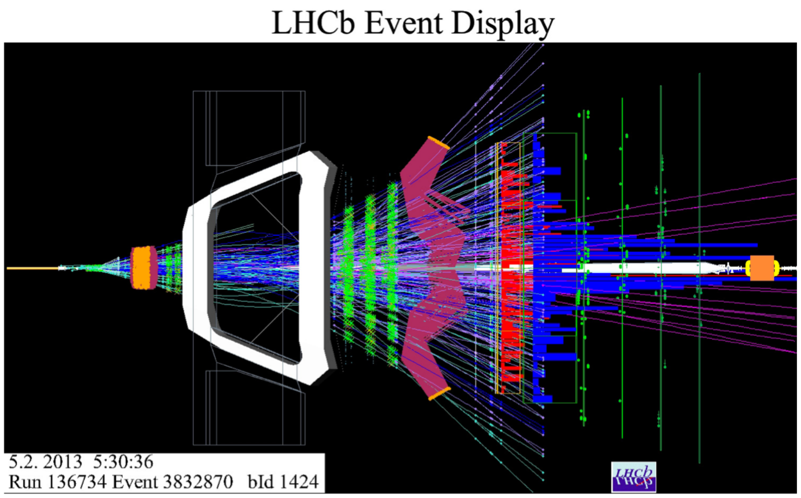
Physics program at LHCb

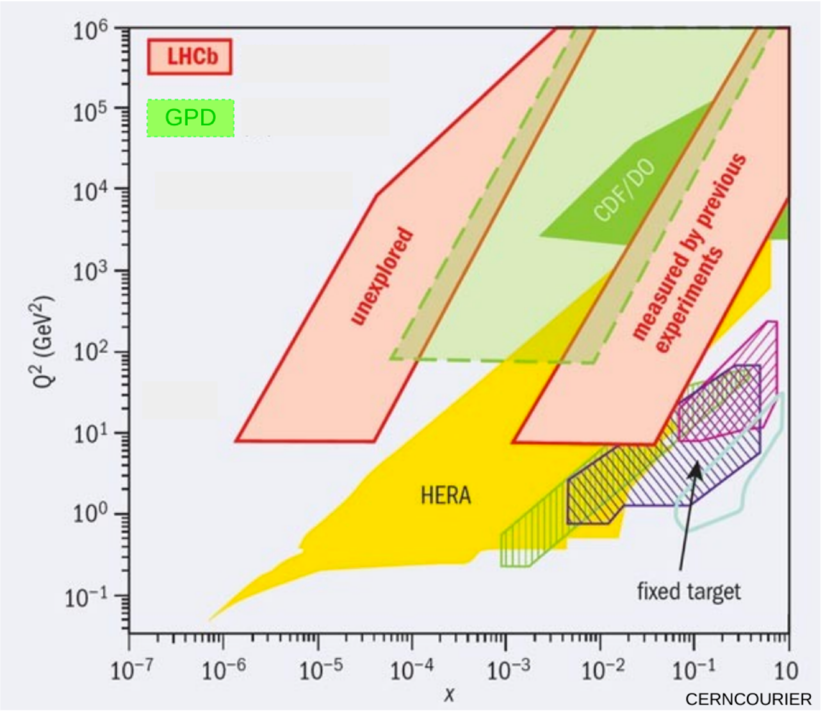
- Not only precision measurements in *b, c* sectors
  - CKM and CP-violation parameters
  - rare decays
  - testing lepton universality
  - …
- But also a general purpose detector
  - electroweak measurements: $\sin\theta_W$, W/Z, top quark, ..
  - QCD studies: production, spectroscopy, exotic hadrons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

Heavy flavor production at LHCb

- Unique rapidity coverage

  → access to small Bjorken x region
- Exceptional coverage at small p_T





Studies of H-F productions at LHCb

	Collision	$\sqrt{s}/\sqrt{s_{NN}}$	Year published
Central exclusive production of J/ψ and $\psi(2S)$ mesons	pp	13 TeV	2018
Measurement of $D_s^{\pm}$ production asymmetry	pp	7 + 8 TeV	2018
Measurement of Υ production	pp	13 TeV	2018
Study of coherent J/ψ production (CONF)	PbPb	5 TeV	2018
Measurement of the $B^{\pm}$ production cross-section	pp	7 + 13 TeV	2017
Measurement of the Υ polarizations	pp	7 + 8 TeV	2017
Study of $b\bar{b}$ correlations in high energy proton-proton collisions	pp	7 + 8 TeV	2017
Study of prompt D^0 meson production	pPb	5 TeV	2017
Prompt and nonprompt J/ψ production and nuclear modification	pPb	8.16 TeV	2017
Measurement of B^0, B_s^0, B^+ and Λ_b^0 production asymmetries	pp	7 + 8 TeV	2017
Measurement of the $B^{\pm}$ production asymmetry	pp	7 + 8 TeV	2017
Study of J/ψ production in jets	pp	13 TeV	2017
Measurement of the J/ψ pair production cross-section	pp	13 TeV	2017
Measurement of the b-quark production cross-section	pp	7 + 13 TeV	2017
Measurement of forward $t\bar{t}$, $W + b\bar{b}$ and $W^+c\bar{c}$ production	pp	8 TeV	2017
Measurements of prompt charm production cross-sections	pp	5 TeV	2017
Prompt Λ_c^+ production (CONF)	pPb	5.02	2017
Measurement of J/ψ and D^0 production (CONF)	pAr	110 GeV	2017
Study of $\psi(2S)$ production and cold nuclear matter effects	pPb	5 TeV	2016
Production of associated Υ and open charm hadrons	pp	7 + 8 TeV	2015
Measurements of prompt charm production cross-sections	pp	13 TeV	2015
Forward production Υ mesons	pp	7+ 8 TeV	2015
Measurement of forward J/ψ production cross-sections	pp	13 TeV	2015
Study of the production of Λ_b^0 and $\bar{B}^0$ hadrons	pp	7 + 8 TeV	2015
Measurement of the exclusive Υ production cross-section	pp	7 + 8 TeV	2015
Identification of beauty and charm quark jets at LHCb	pp	7 + 8 TeV	2015
Measurement of B_c^+ production	pp	8 TeV	2015

Studies of H-F productions at LHCb

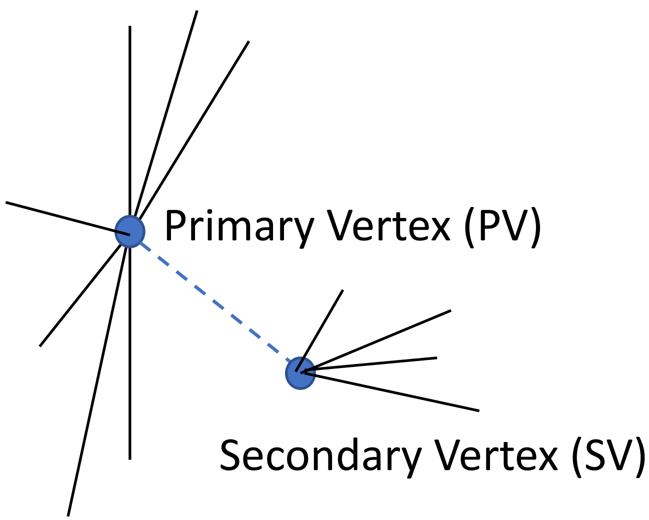
	Collision	$\sqrt{s}/\sqrt{s_{NN}}$	Year published
Study of χ_b meson production	pp	7 + 8 TeV	2014
Observation of charmonium pairs produced exclusively	pp	7 + 8 TeV	2014
First measurement of the charge asymmetry in beauty-quark pair production	pp	7 TeV	2014
Study of Υ production and cold nuclear matter effects	pPb	5 TeV	2014
Measurement of $\psi(2S)$ polarisation	pp	7 TeV	2014
Measurement of the $\eta_c(1S)$ production cross-section	pp	7 + 8 TeV	2014
Measurement of Υ production	pp	2.76	2014
Updated measurements of exclusive J/ψ and $\psi(2S)$ production	pp	7 TeV	2014
Study of J/ψ production and cold nuclear matter effects	pPb	5 TeV	2014
Reference cross-sections for $\Upsilon(1S)$ studies (CONF)	pp	5.02 TeV	2014
Measurement of J/ψ polarization	pp	7 TeV	2013
Measurement of the relative rate of prompt χ_{c0}, χ_{c1} and χ_{c2} production	pp	7 TeV	2013
Measurement of B meson production cross-sections	pp	7 TeV	2013
Production of J/ψ and Υ mesons	pp	8 TeV	2013
Measurements of the Λ_b^0 polarisation	pp	7 TeV	2013
Prompt charm production	pp	7 TeV	2013
Exclusive J/ψ and $\psi(2S)$ production	pp	7 TeV	2013
Measurement of J/ψ production	pp	2.76	2013
Measurement of the $D^{\pm}$ production asymmetry	pp	7 TeV	2013
Measurements of the B_c^+ production	pp	7 TeV	2013
Reference cross-sections for J/ψ studies (CONF)	pp	5.02	2013
Measurement of $\sigma(b\bar{b})$ with inclusive final states (CONF)	pp	7 TeV	2013
Measurement of prompt hadron production ratios	pp	0.9 + 7 TeV	2012
Measurement of the ratio of prompt χ_c to J/ψ production	pp	7 TeV	2012
Measurement of $\psi(2S)$ production	pp	7 TeV	2012
Measurement of Υ production	pp	7 TeV	2012
Measurement of the $B^{\pm}$ cross-section	pp	7 TeV	2012
Measurement of the cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ for prompt χ_c	pp	7 TeV	2012
Measurement of b hadron production fractions	pp	7 TeV	2012
Measurement of J/ψ production	pp	7 TeV	2011
Measurement of $\sigma(pp \to b\bar{b}X)$ in forward region	pp	7 TeV	2010

Outline

- In $\boldsymbol{pp}$ collisions
  - ✓ quarkonium production
  - ✓ open heavy flavor production
  - ✓ Bc production
- Beyond $\boldsymbol{pp}$ collisions
- Summary and prospects

Experiment strategies

- Advantage: high production rates
- Challenge: reconstruct an unstable particle from $O(10^2)$ tracks



√ tracking

→ excellent mass resolution

√ particle identification

→ no. of combinations reduced

√ Vertexing

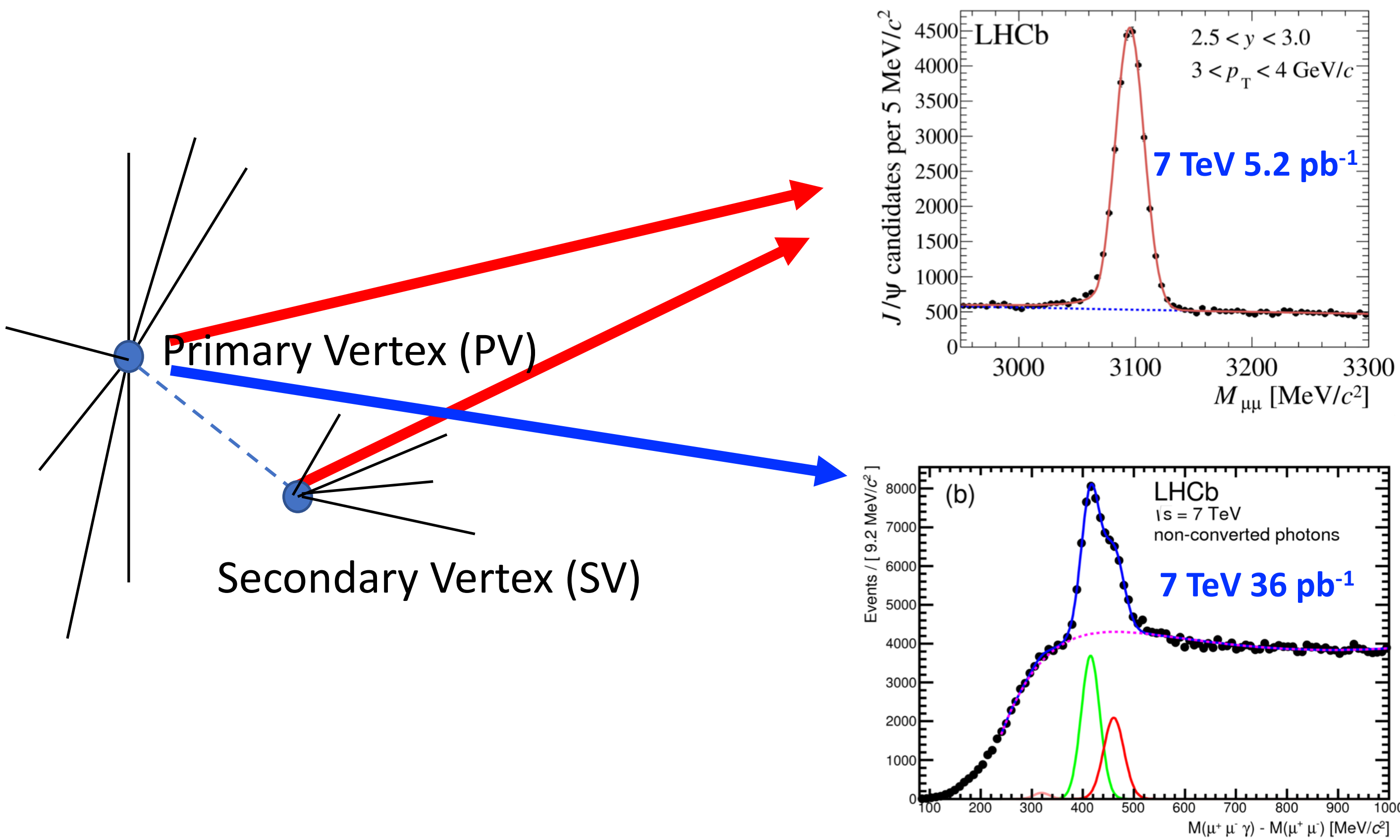
→ weakly decayed particles

→ particles from b/c decays

Charmonia studies at LHCb

- At LHCb charmonia $[c\bar{c}]$ may be accessed by

  - $[c\bar{c}] \to J/\psi(\to \mu^+\mu^-) + X$



$J/\psi \to \mu^+\mu^-$

LHCb, EPJC 71 (2011)1645

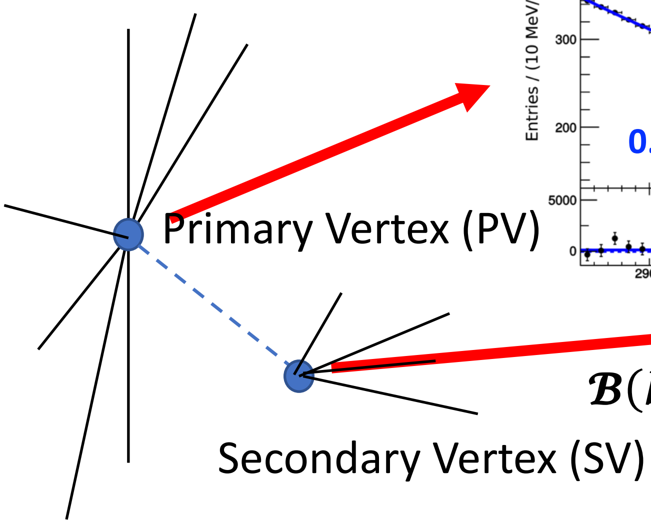
$\chi_{c1,2} \to J/\psi + \gamma$

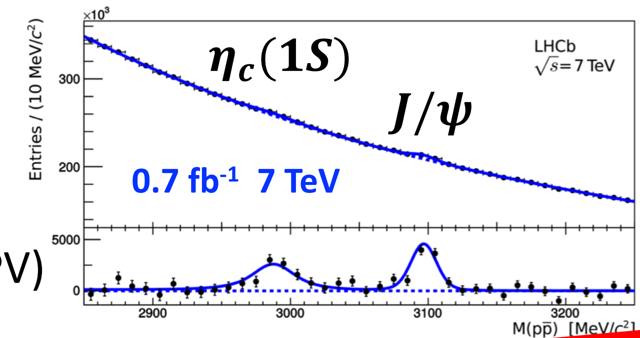
LHCb, PLB 714 (2012) 215

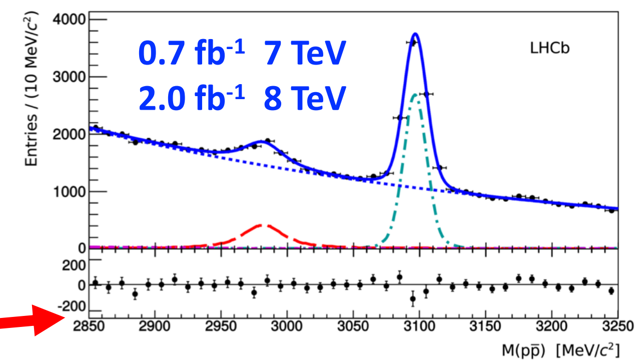
Charmonia studies at LHCb

- At LHCb charmonia $[c\bar{c}]$ may be accessed by
  - $[c\bar{c}] \to J/\psi(\to \mu^+\mu^-) + X$
  - $[c\bar{c}] \to p\bar{p}$

LHCb, EPJC 75 (2015) 311







$$\mathcal{B}(b \to \eta_c(1S)X) = (4.88 \pm 0.64 \pm 0.29 \pm 0.67_{\mathcal{B}})\times 10^{-3}$$

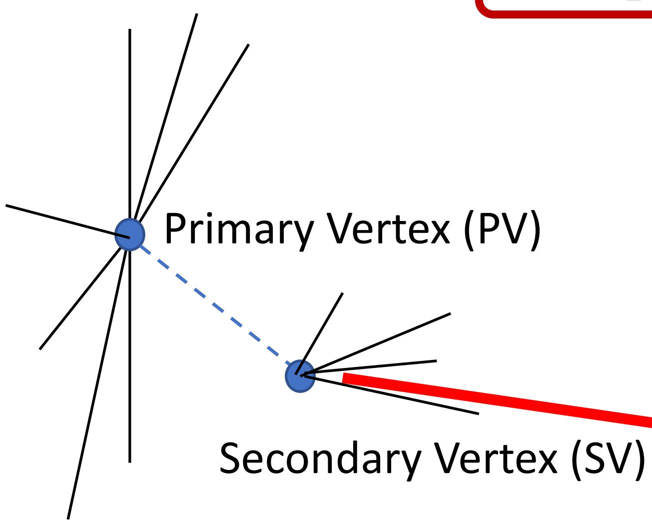
1st Observation

$$\sigma_{\eta_c(1s)} = 0.52 \pm 0.09 \pm 0.08 \pm 0.06_{\sigma_{J/\psi},\mathcal{B}}\,\mu\text{b} \quad \sqrt{s} = 7\text{ TeV}$$
$$= 0.59 \pm 0.11 \pm 0.09 \pm 0.08_{\sigma_{J/\psi},\mathcal{B}}\,\mu\text{b} \quad \sqrt{s} = 8\text{ TeV}$$

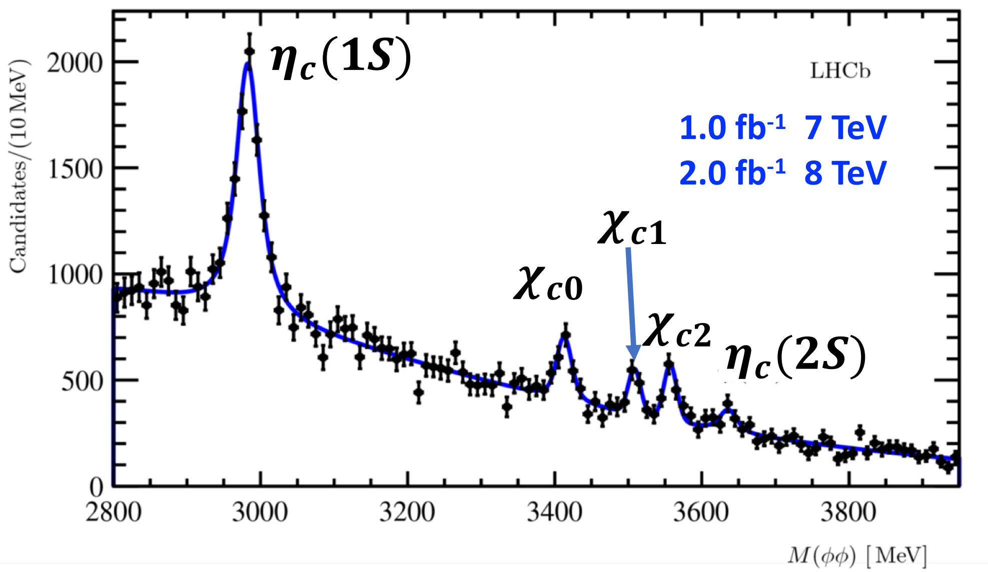
Charmonia studies at LHCb

- At LHCb charmonia $[c\bar{c}]$ may be accessed by
  - $[c\bar{c}] \to J/\psi(\to \mu^+\mu^-) + X$
  - $[c\bar{c}] \to p\bar{p}$
  - $[c\bar{c}] \to \phi\phi$

LHCb, EPJC 77 (2017) 609



$b \to [c\bar{c}](\to \phi\phi) + X$



Quarkonium production

- Two scales of production: hard process of $Q\bar{Q}$ formation

  + hadronization of $Q\bar{Q}$ at softer scales

$$\mathbf{d}\boldsymbol{\sigma}[pp \to \mathcal{Q} + X] = \sum_{i,j,n} \mathbf{d}x_i \mathbf{d}x_j\, f_i(x_i, \mu_F) f_j(x_j, \mu_F) \times \mathbf{d}\boldsymbol{\sigma}_{i+j\to(Q\bar{Q})_n+X}(\mu_R, \mu_F, \mu_\Lambda)\langle \mathcal{O}_{\mathcal{Q}}^n \rangle$$

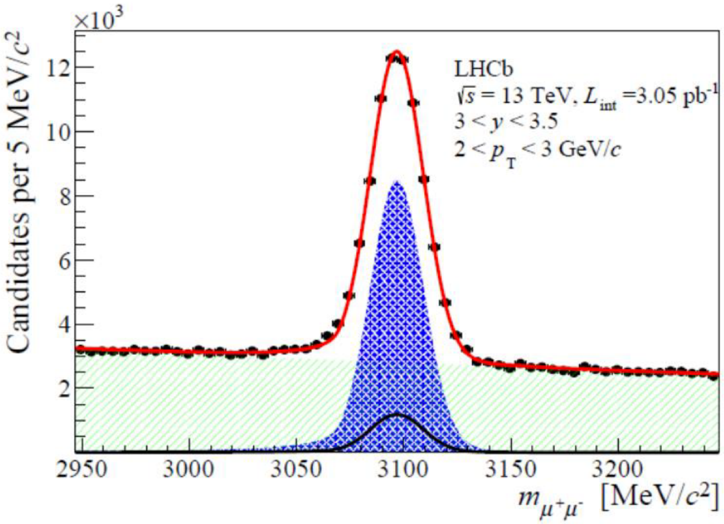
- CSM: intermediate $Q\bar{Q}$ colorless and has same J^{PC} as the final state quarkonium
- NRQCD: all viable colors and J^{PC} allowed for the intermediate $Q\bar{Q}$, Long Distance Matrix Elements, $\langle \mathcal{O}_{\mathcal{Q}}^n \rangle$, from experimental data, same for prompt production and in b decays; color octet mechanism (COM)
- Quarkonium production is test of both perturbative and non-perturbative QCD

J/ψ production

LHCb, JHEP 10 (2015) 172
JHEP 05 (2017) 063

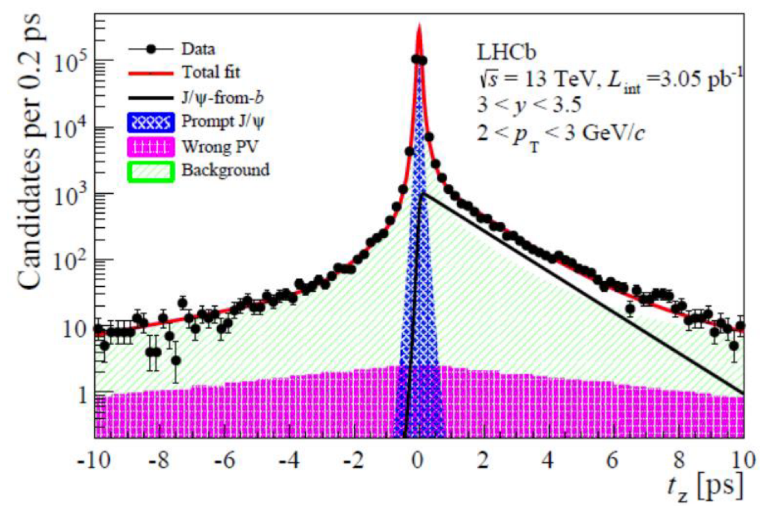
- Lifetime to separate prompt production from b decays

Prompt = direct + feed down from $\psi(2S), \chi_c, \ldots$



$\sqrt{s} = 13$ TeV, $L_{int} = 3.05$ pb^{-1}

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

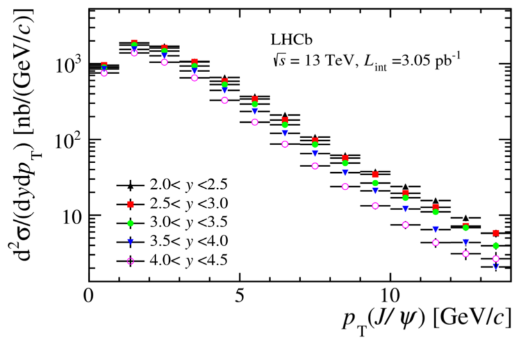


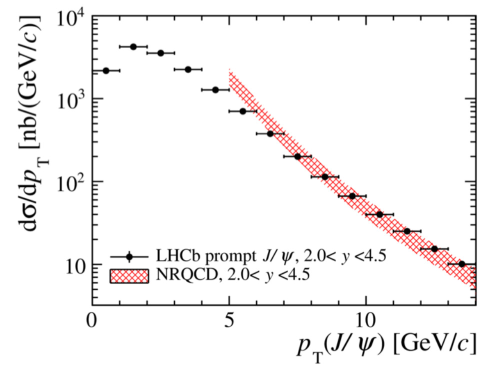
$$\sigma(\text{prompt } J/\psi, p_T < 14\,\text{GeV}/c, 2.0 < y < 4.5) = 15.03 \pm 0.03 \pm 0.94\,\mu\text{b}$$
$$\sigma(J/\psi\text{-from-}b, p_T < 14\,\text{GeV}/c, 2.0 < y < 4.5) = 2.25 \pm 0.01 \pm 0.14\,\mu\text{b}$$

J/ψ production

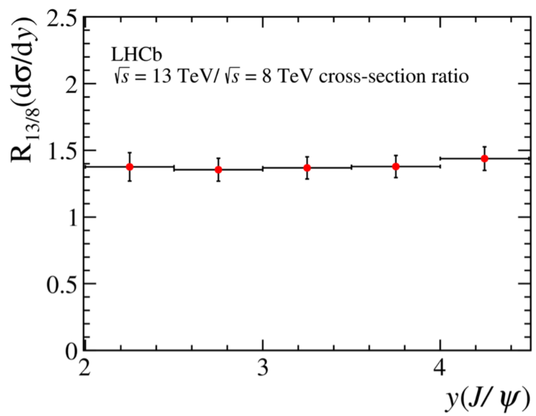
LHCb, JHEP 10 (2015) 172
JHEP 05 (2017) 063

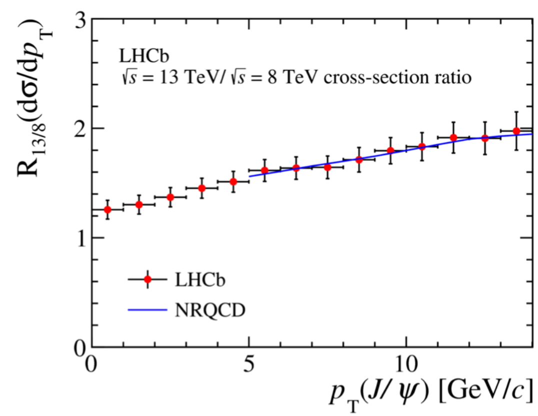
- Double differential cross-sections in bins of p_T and y





- Ratios 13 TeV / 8 TeV





- NRQCD works very well

Shao, Han, Ma, Meng, Zhang , Chao, JHEP 05 (2015) 103

J/ψ and $\psi(2S)$ polarization

LHCb, EPJC 73 (2013) 2631
EPJC 74 (2014) 2872

- Angular distribution of $\boldsymbol{J/\psi, \psi(2s) \to \mu^+\mu^-}$

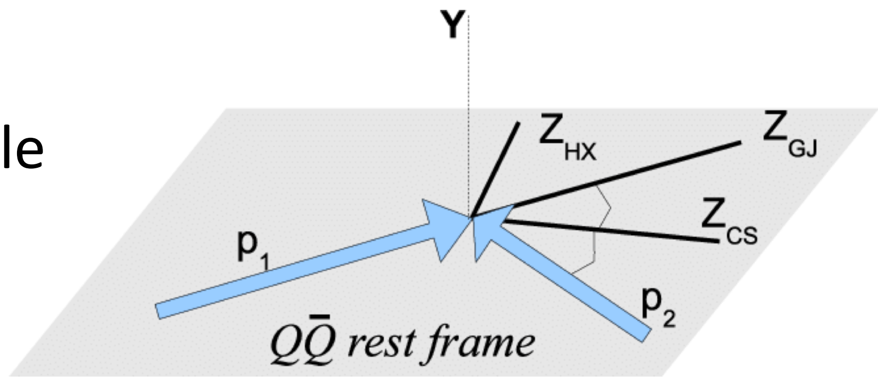
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta \cos^2\theta + \lambda_{\theta\phi}\sin 2\theta \cos\phi + \lambda_\phi \sin^2\theta \cos 2\phi)$$

- Parameters are reference frame dependent

Helicity (HX): z axis is direction of ψ momentum in CM frame of colliding protons

Collins-Soper (CS): z axis bisects angle between $\vec{p}_1$ and $\vec{p}_2$ in ψ rest frame

Gottfried-Jackson (GJ): z axis is Direction of $\vec{p}_1$ in ψ rest frame



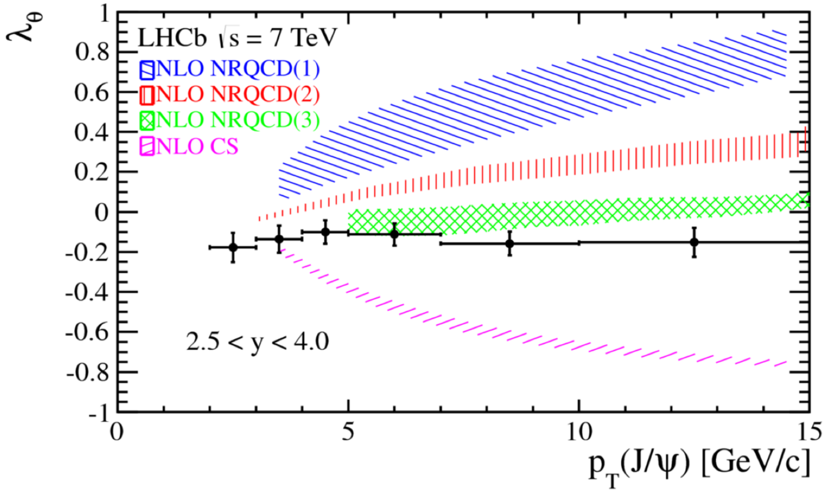
PhysRevD.82.012001

y axes normal to ψ production plane

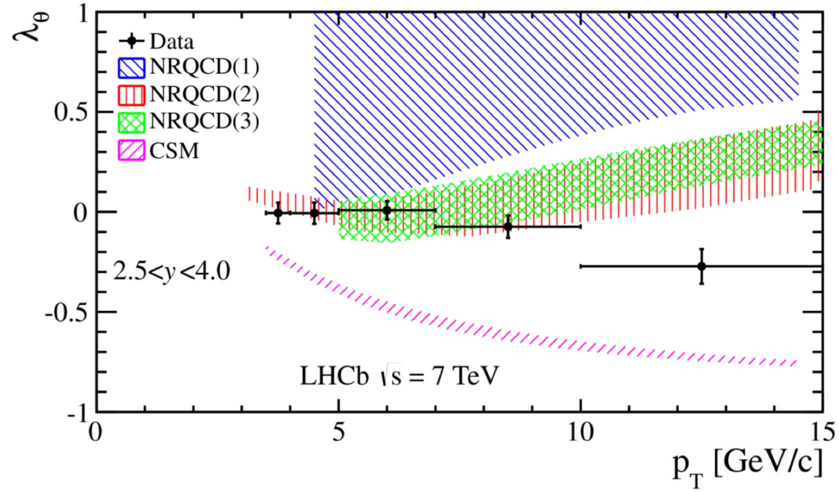
J/ψ and $\psi(2S)$ polarization

LHCb, EPJC 73 (2013) 2631
EPJC 74 (2014) 2872

J/ψ



$\psi(2S)$



- The polarization parameters are generally small
- Disagree with CSM
- Agreements with NRQCD predictions at low p_T, the prediction of increasing polarization with p_T is not supported

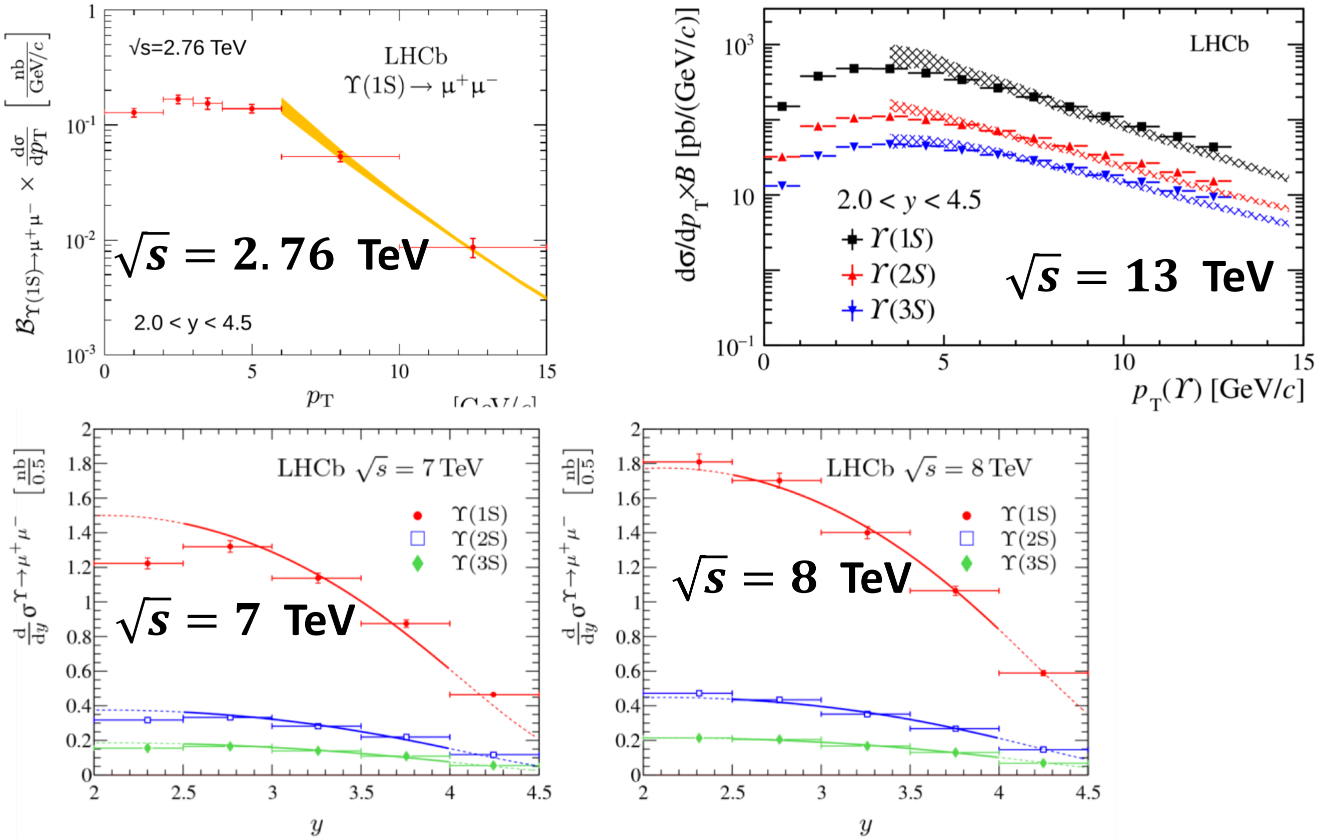
Butenschoen, Kniehl, PRL 108 (2012) 172002; Gong, Wan, Wang, Zhang, PRL 110 (2013) 042002
Chao, Ma, Shao, Wang, Zhang, PRL 108 (2012) 242004; Shao, Chao, PRD 90 (2014) 014002

Υ production

LHCb, EPJC 74 (2014) 2835
JHEP 11 (2015) 103
JHEP 07 (2018) 134

- Perturbative QCD expected to work better; All prompt, but complicated by feed down

- NRQCD can describe cross-section trends with uncertainties

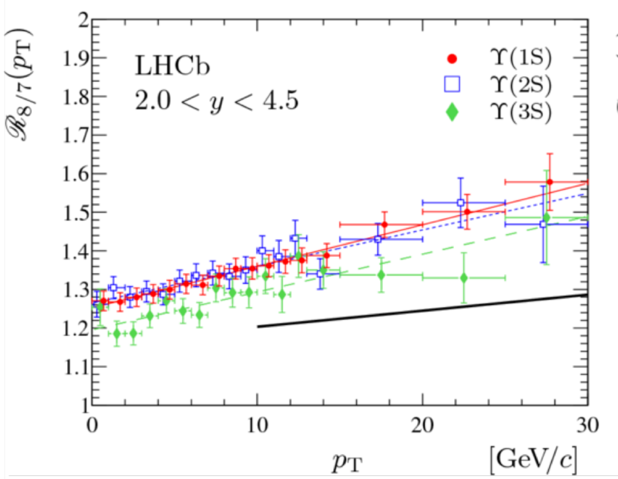


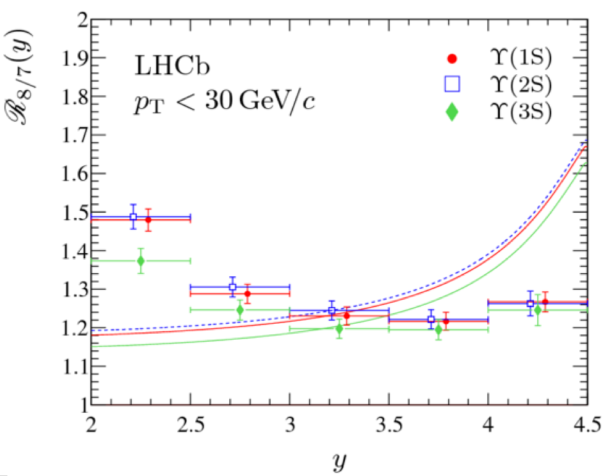
Υ production

LHCb, EPJC 74 (2014) 2835
JHEP 11 (2015) 103
JHEP 07 (2018) 134

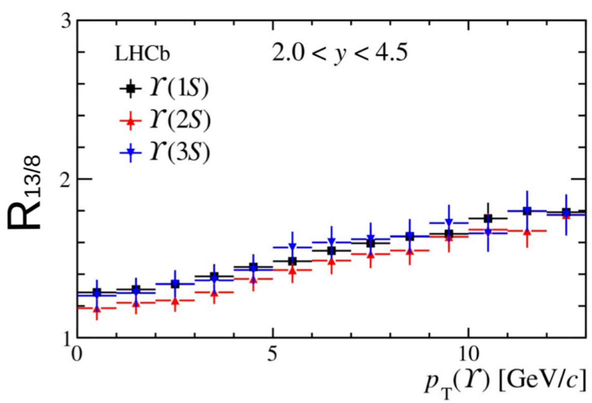
- Cross-section ratios as function of p_T consistently higher than NRQCD predictions, cannot describe trend as function of y

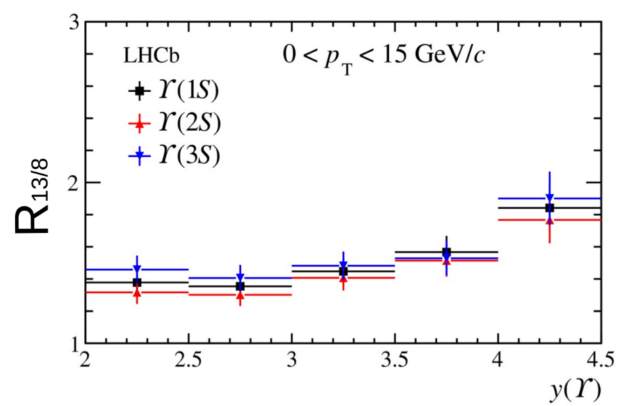
$\frac{\sqrt{s}=8 \text{ TeV}}{\sqrt{s}=7 \text{ TeV}}$





$\frac{\sqrt{s}=13 \text{ TeV}}{\sqrt{s}=8 \text{ TeV}}$





Theoretical predictions for 13/8 not available

Υ polarization

- Experimental results on $\boldsymbol{\Upsilon(nS)}$ polarization not consistent

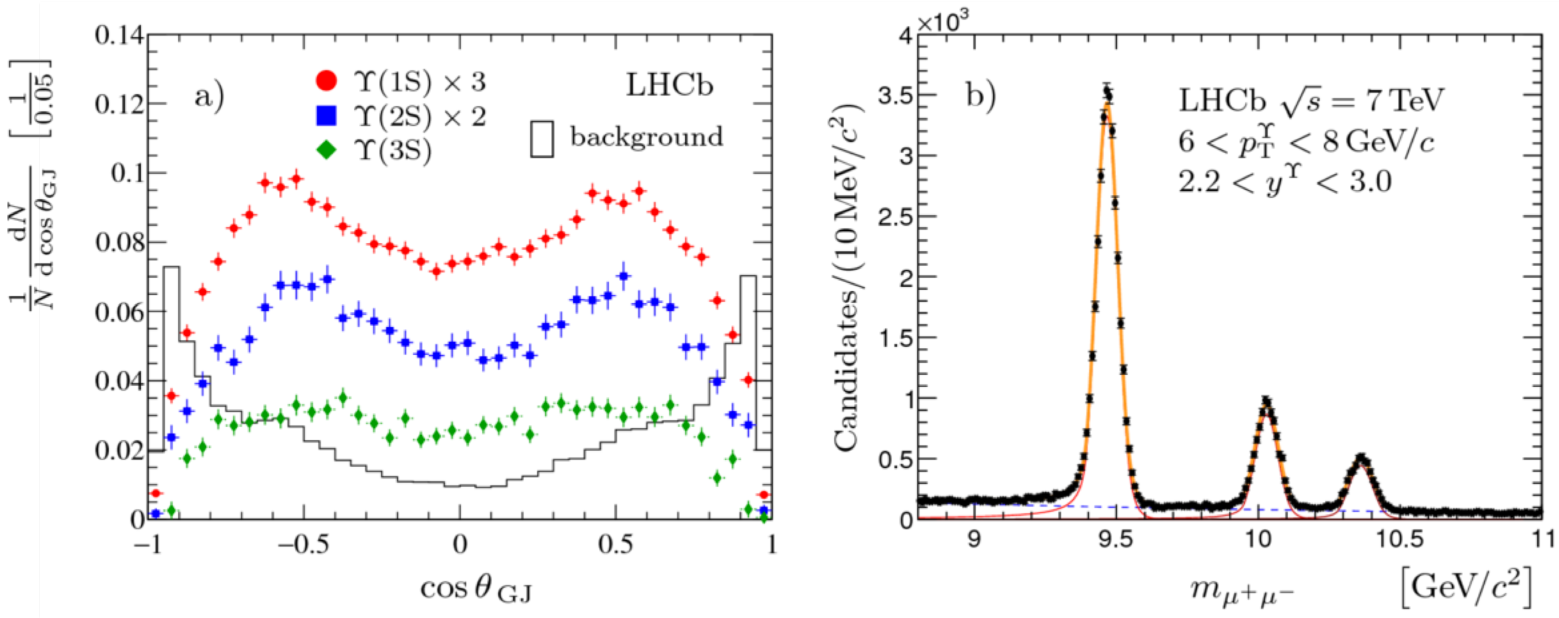
  - CDF No polarization for $\boldsymbol{\Upsilon(nS)}$ in $\boldsymbol{p\bar{p}}$ collisions at $\sqrt{\boldsymbol{s}}$ =1.8 and 1.96 TeV PRL 108 (2012) 151802
  - D0 Significant p_T dependent longitudinal polarizations for $\boldsymbol{\Upsilon(1S)}$ in $\boldsymbol{p\bar{p}}$ collisions at $\sqrt{\boldsymbol{s}}$ =1.96 TeV PRL 101 (2008) 182004
  - CMS No polarization for $\boldsymbol{\Upsilon(nS)}$ in $\boldsymbol{pp}$ collisions at $\sqrt{\boldsymbol{s}}$ =7 TeV PRL 110 (2013) 081802

- NLO NRQCD calculations predict $\boldsymbol{\Upsilon(1S)}$ and $\boldsymbol{\Upsilon(2S)}$ have small transverse polarization across p_T

Υ polarization at LHCb

LHCb, JHEP 12 (2017) 110

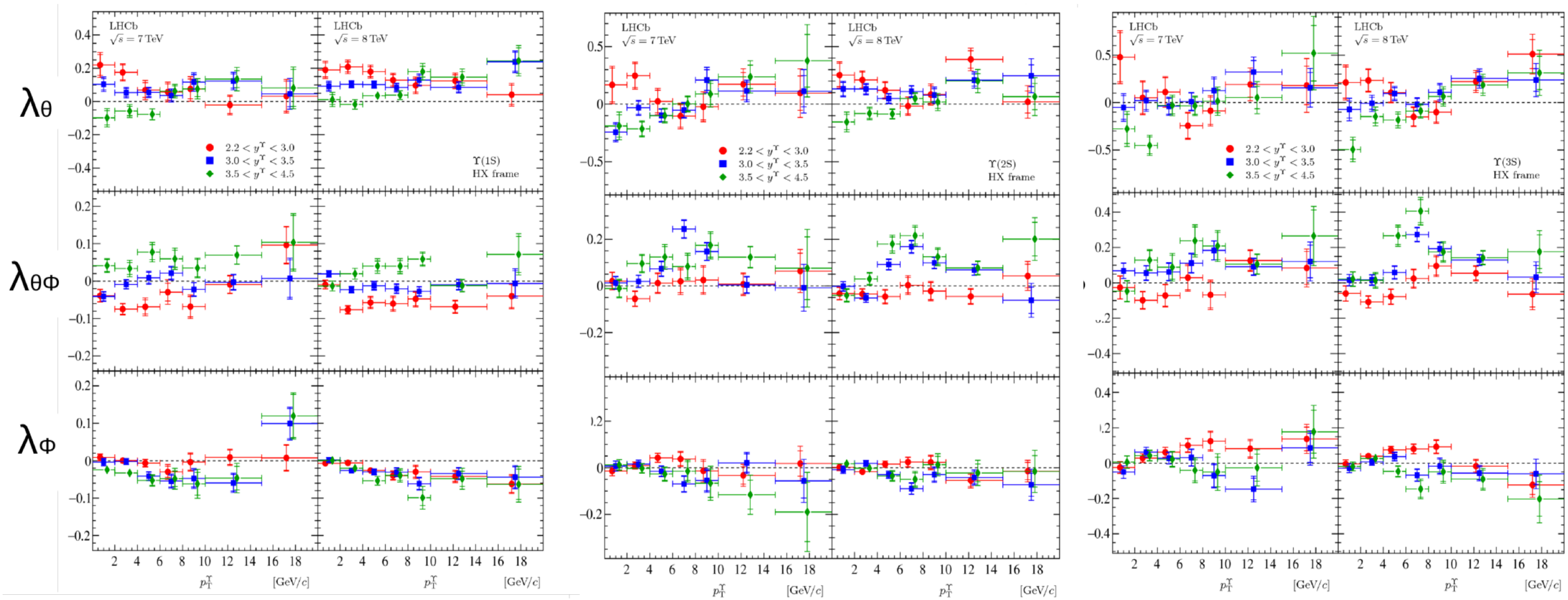
- $\boldsymbol{\Upsilon(nS)}$ polarization measured in pp collisions at $\sqrt{s} = \mathbf{7, 8}$ TeV



Υ polarization at LHCb

LHCb, JHEP 12 (2017) 110

- $\Upsilon(nS)$ polarization measured in pp collisions at $\sqrt{s} = 7, 8$ TeV



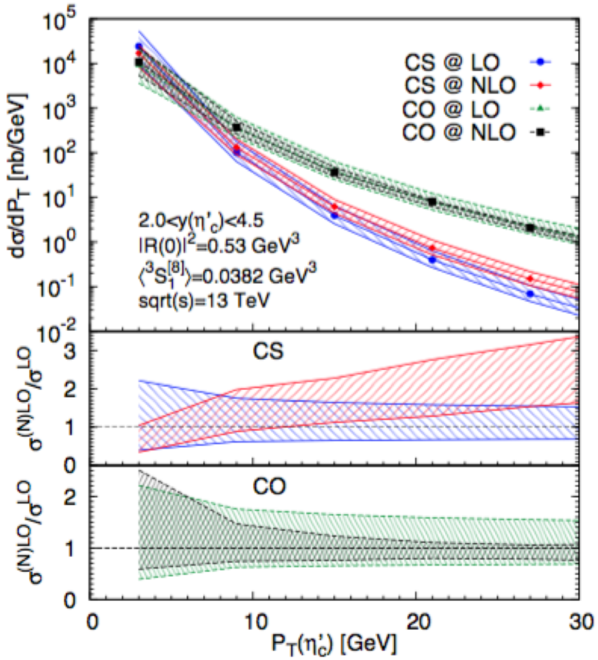
$\Upsilon(1S)$ $\Upsilon(2S)$ $\Upsilon(3S)$

No model as yet can describe both heavy quarkonium production and polarisation

Perspectives: η_c, χ_{cJ}

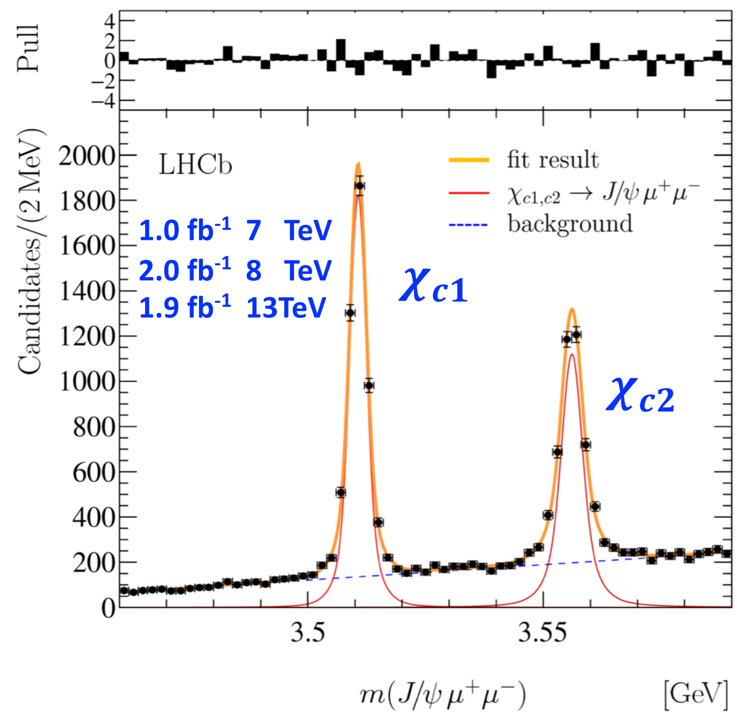
- $\eta_c(1S), \eta_c(2S)$ and χ_{cJ} productions can give more information/constraints

Theory prediction
$\eta_c(2S)$ at $\sqrt{s} = 13$TeV



Lansberg, Shao, Zhang, arXiv:1711.00265

1st observation
$\chi_{c1,2} \to J/\psi\mu^+\mu^-$



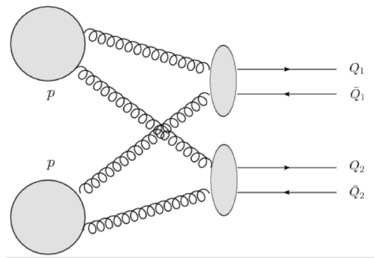
LHCb, PRL 119 (2017) 221801

Double J/ψ production at 13 TeV

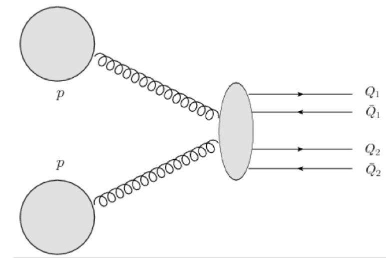
- Double Parton Scattering : two independent hard scatters that are assumed to factorize

  Single Parton Scattering: gluon splitting dominate

DPS



SPS

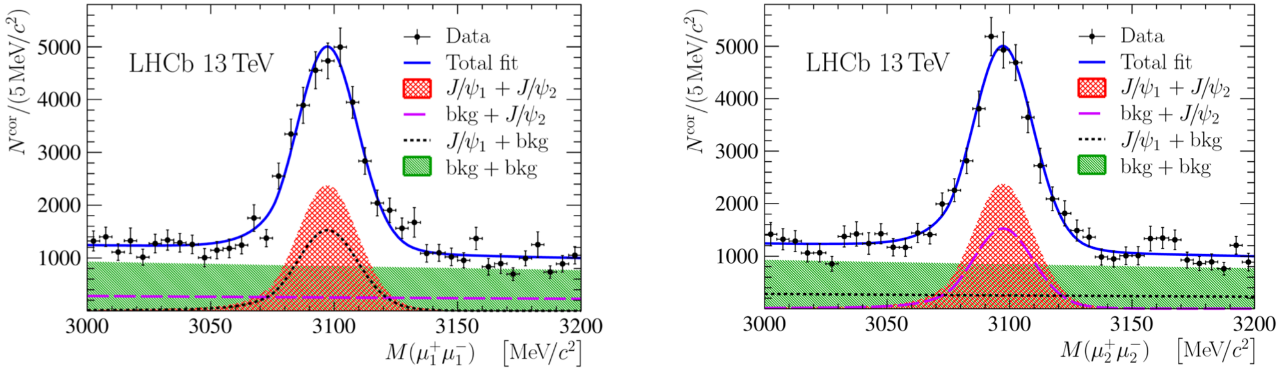


$$\sigma_{\text{DPS}}\left(J/\psi\, J/\psi\right) = \frac{1}{2}\frac{\sigma\left(J/\psi\right)^2}{\sigma_{\text{eff}}}$$

- DPS can provide information on parton transverse momentum and correlations inside proton

Double J/ψ production at 13 TeV

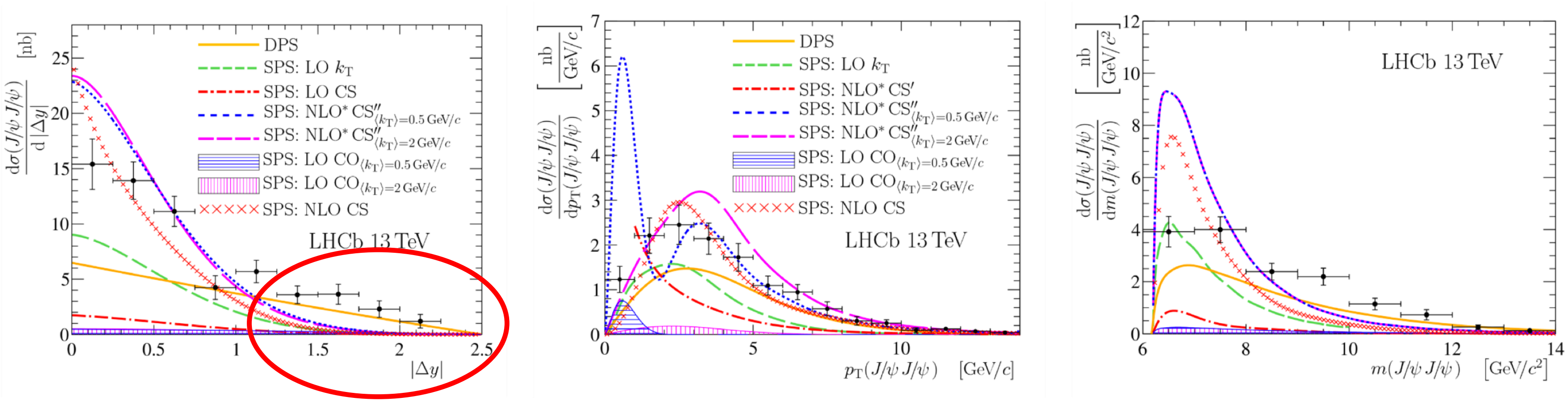
- Require 4 $\boldsymbol{\mu}$-tracks from same primary vertex, 2D fit



	$\sigma(J/\psi\,J/\psi)$ [nb]		
	no $p_{\rm T}$ cut	$p_{\rm T} > 1\,{\rm GeV}/c$	$p_{\rm T} > 3\,{\rm GeV}/c$
LO CS	$1.3 \pm 0.1^{+3.2}_{-0.1}$	—	—
LO CO	$0.45 \pm 0.09^{+1.42+0.25}_{-0.36-0.34}$	—	—
LO $k_{\rm T}$	$6.3^{+3.8+3.8}_{-1.6-2.6}$	$5.7^{+3.4+3.2}_{-1.5-2.1}$	$2.7^{+1.6+1.6}_{-0.7-1.0}$
NLO* CS′	—	$4.3 \pm 0.1^{+9.9}_{-0.9}$	$1.6 \pm 0.1^{+3.3}_{-0.3}$
NLO* CS″	$15.4 \pm 2.2^{+51}_{-12}$	$14.8 \pm 1.7^{+53}_{-12}$	$6.8 \pm 0.6^{+22}_{-5}$
NLO CS	$11.9^{+4.6}_{-3.2}$	—	—
DPS	$8.1 \pm 0.9^{+1.6}_{-1.3}$	$7.5 \pm 0.8^{+1.5}_{-1.2}$	$4.9 \pm 0.5^{+1.0}_{-0.8}$
Data	$15.2 \pm 1.0 \pm 0.9$	$13.5 \pm 0.9 \pm 0.9$	$8.3 \pm 0.6 \pm 0.5$

Double J/ψ production at 13 TeV

- Differential cross-sections



- Evidence for DPS at high $|\boldsymbol{\Delta y}|$ region
- Fit of kinematical distribution to extract DPS fraction & $\boldsymbol{\sigma_{\mathrm{eff}}}$

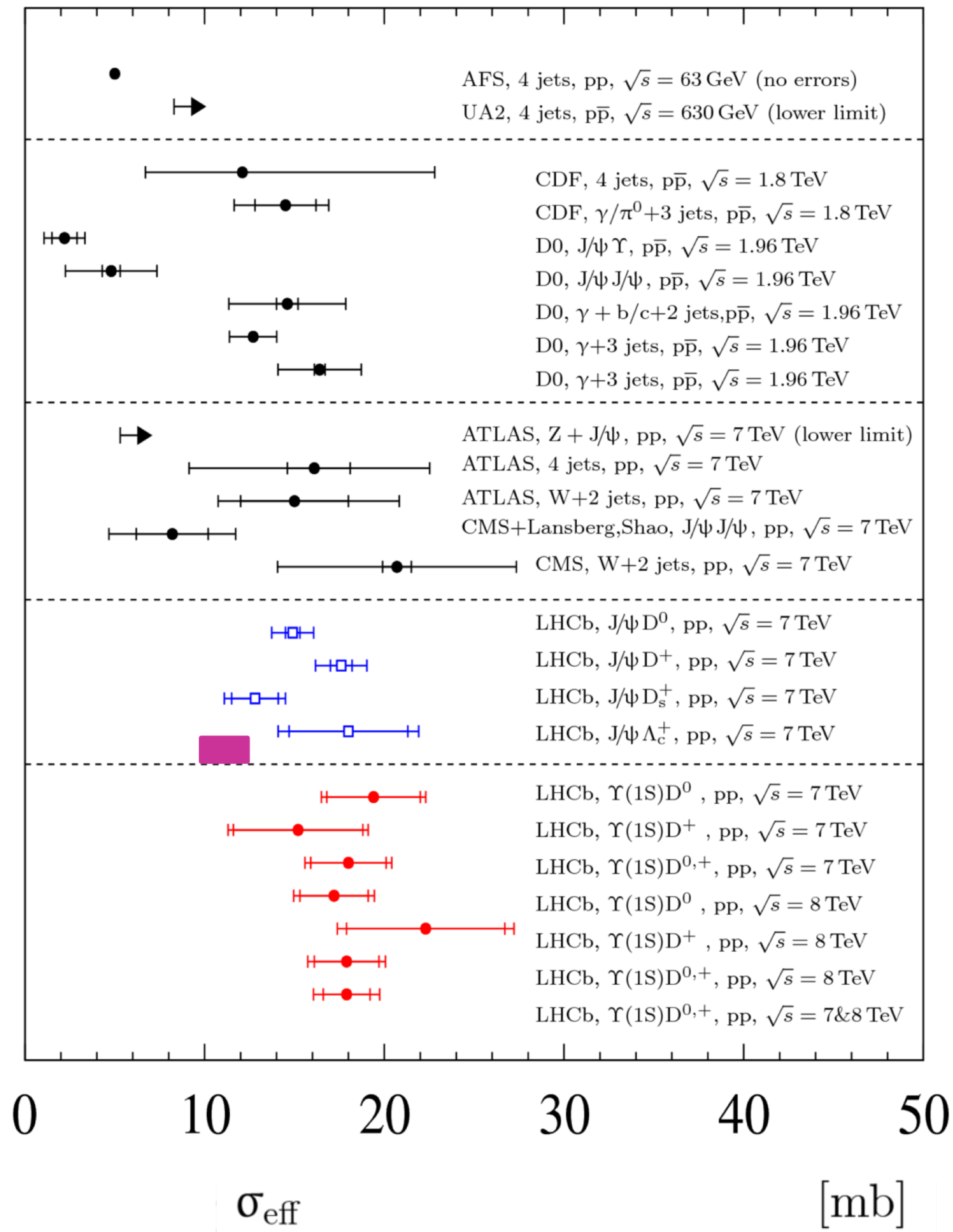
$$\sigma_{\mathrm{eff}} \sim 10 - 12 \text{ mb}$$

using various SPS descriptions

Double J/ψ production at $\sqrt{s}$=13 TeV

- Compilation of results on σ_{eff}

LHCb, $J/\psi J/\psi$, pp, $\sqrt{s}$=13 TeV
JHEP 1706 (2017) 047

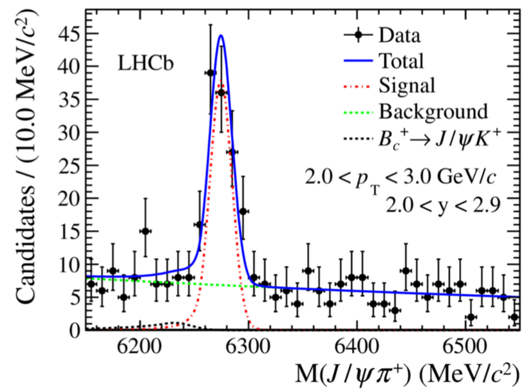


B_c production at 8 TeV

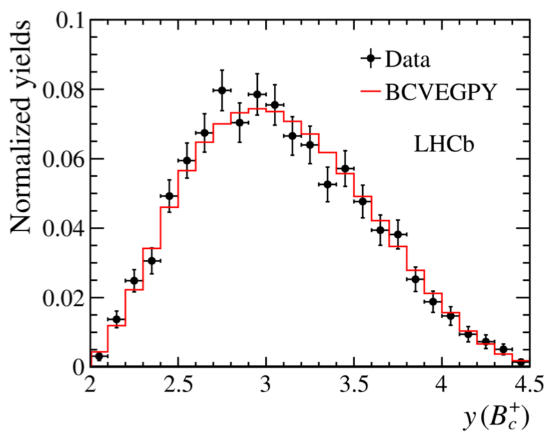
LHCb, PRL 114 (2015) 132001

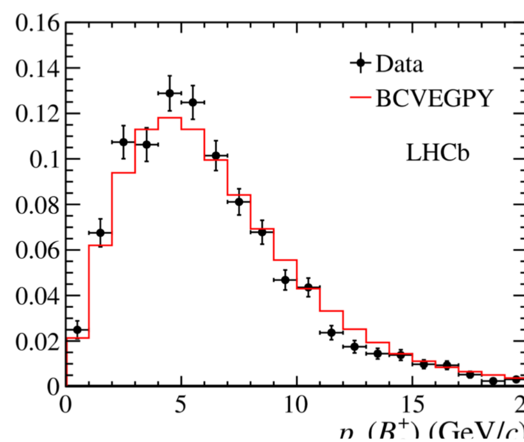
- Use $B_c \to J/\psi\pi$, define

$$\mathcal{R} = \frac{\sigma(B_c^+)\times\mathcal{B}(B_c^+\to J/\psi\,\pi^+)}{\sigma(B^+)\times\mathcal{B}(B^+\to J/\psi\,K^+)}$$



- Distributions well described by complete α_s^4 calculations





[C.-H. Chang *et al.*, Comput. Phys. Commun. 174 (2006) 241]

Open heavy flavor production

- In heavy flavor production, quark mass acts as long-distance cut-off allowing calculation of cross-sections in perturbative QCD down to low p_T

$$
\begin{aligned}
&\mathrm{d}\sigma^{Q+X}[s, p_{\mathrm{T}}, y, m_Q] \\
&\quad \simeq \sum_{i,j} \int_0^1 \mathrm{d}x_i \int_0^1 dx_j \, f_i^A(x_i, \mu_F) f_j^B(x_j, \mu_F) \\
&\quad \times \mathrm{d}\tilde{\sigma}_{ij \to Q+X}[x_i, x_j, s, p_{\mathrm{T}}, y, m_Q, \mu_F, \mu_R],
\end{aligned}
$$

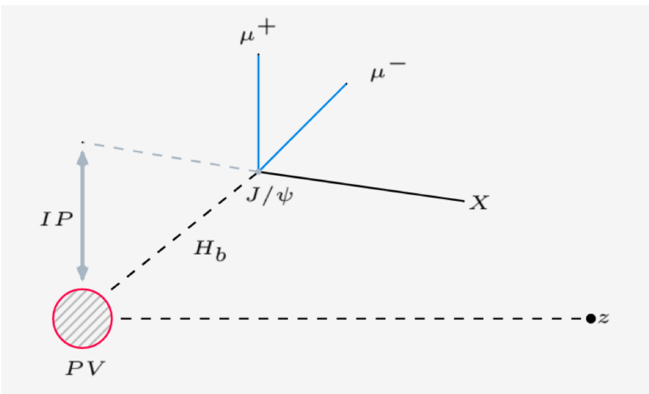
- Cross-section measurements provide test of pQCD - FONLL calculations

- Cross-sections are sensitive to PDFs

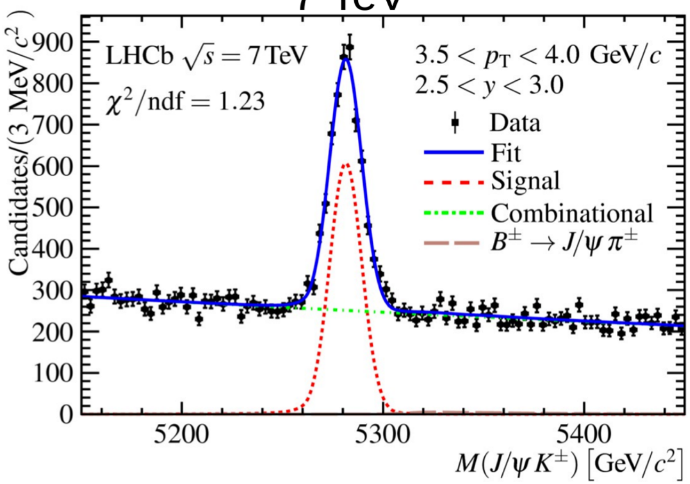
$B^{\pm}$ production at 7/13 TeV

LHCb, JHEP 12 (2017) 026

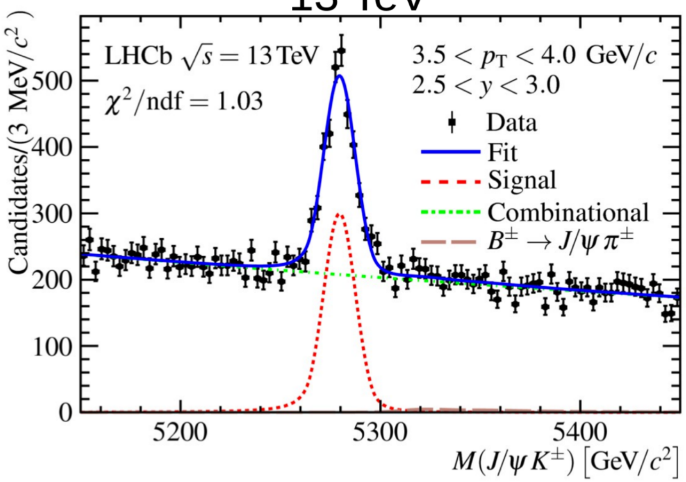
- Use $B^{\pm} \to J/\psi K^{\pm}$ decays



7 TeV



13 TeV

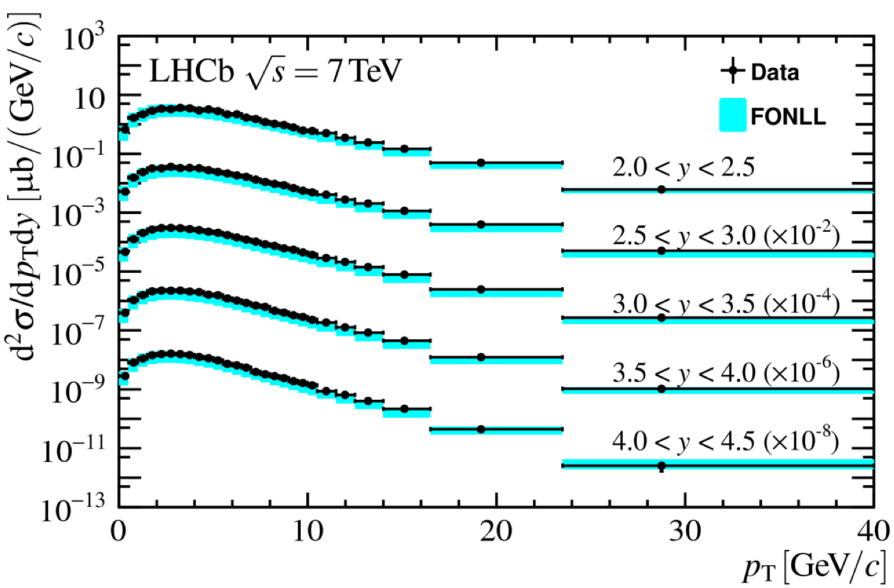


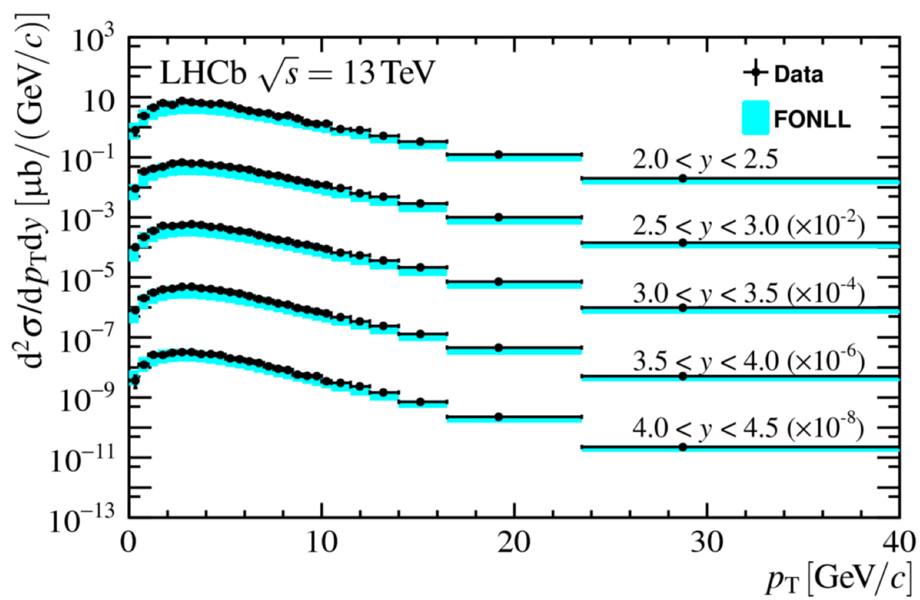
$B^{\pm}$ production at 7/13 TeV

LHCb, JHEP 12 (2017) 026

- Results in agreement with FONLL calculations

Compare results to FONLL calculations $m_b = 4.75\text{GeV}$, $\mu_R = \mu_F = \mu_0 = \sqrt{m_Q^2 + p_T^2}$ using CTEQ6.6 PDFs. Eur. Phys. J. C 75 (2015) 610

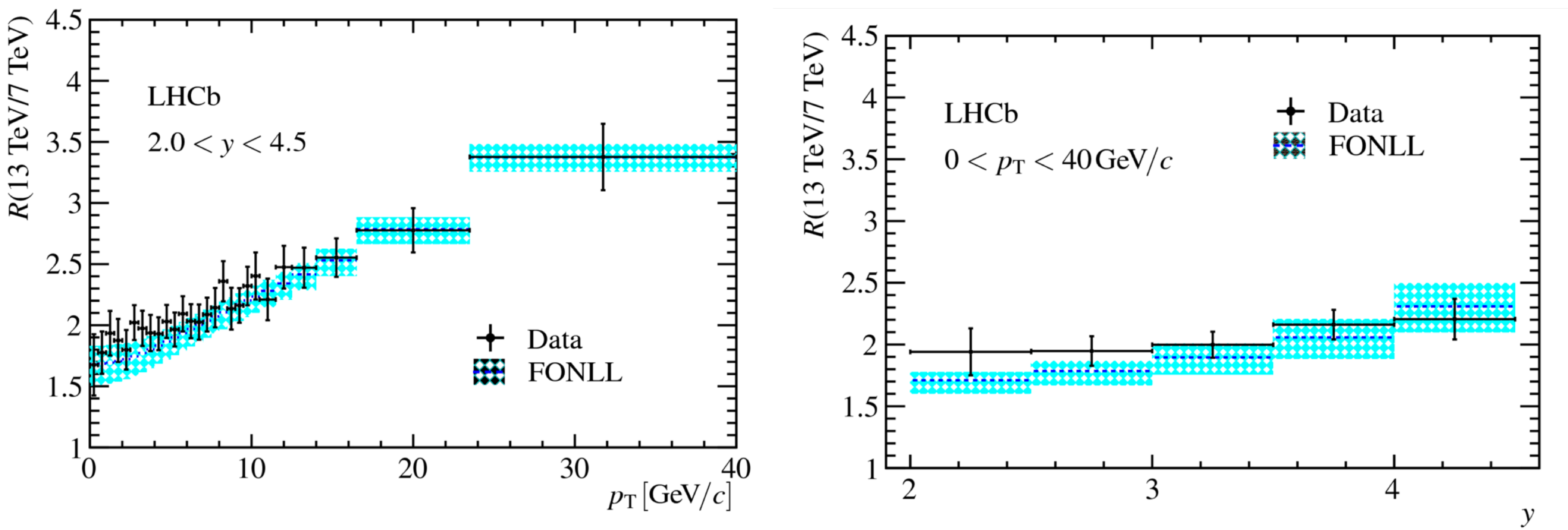




$B^{\pm}$ production at 7/13 TeV

LHCb, JHEP 12 (2017) 026

- In ratio of 13 TeV / 7 TeV, FONLL uncertainties largely cancel

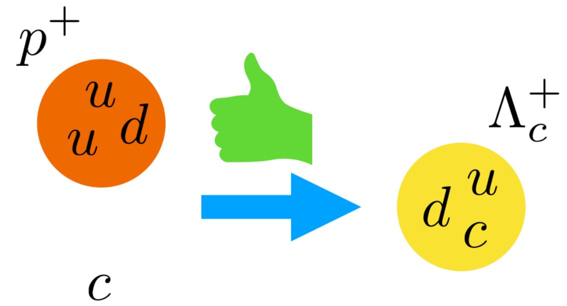


$D_s^{\pm}$ production asymmetry at 7/13 TeV

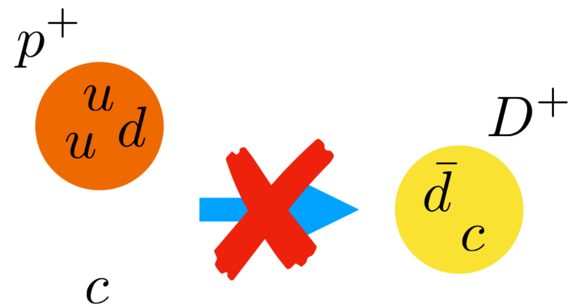
LHCb, JHEP 08 (2018) 008

- Assumed for most charm production asymmetries

Arise from ability of charm quarks to form charm baryons with proton valence quarks



...but not charm mesons



- Results in a different kinematic distribution between D_s^+ & D_s^-

$D_s^{\pm}$ production asymmetry at 7/13 TeV

LHCb, JHEP 08 (2018) 008

Production asymmetry: $A_{\rm P}(D_s^+) = \dfrac{\sigma(D_s^+) - \sigma(D_s^-)}{\sigma(D_s^+) + \sigma(D_s^-)}$

$D_s^+ \to \phi(K^+K^-)\pi^+$, and $A_{\rm raw} = \dfrac{N(D_s^+) - N(D_s^-)}{N(D_s^+) + N(D_s^-)}$

$$A_{\rm P}(D_s^+) = \frac{1}{1 - f_{\rm bkg}}(A_{\rm raw} - A_{\rm D} - f_{\rm bkg} A_{\rm P}(B))$$

Fraction of non-prompt D_s^+ decays (from b-hadrons) → $f_{\rm bkg}$

Detection asymmetries → $A_{\rm D}$

Production asymmetry of b-hadrons → $A_{\rm P}(B)$

$f_{\rm bkg} = (4.12 \pm 1.23)\%$ → Determined from simulation, known cross sections and branching fractions

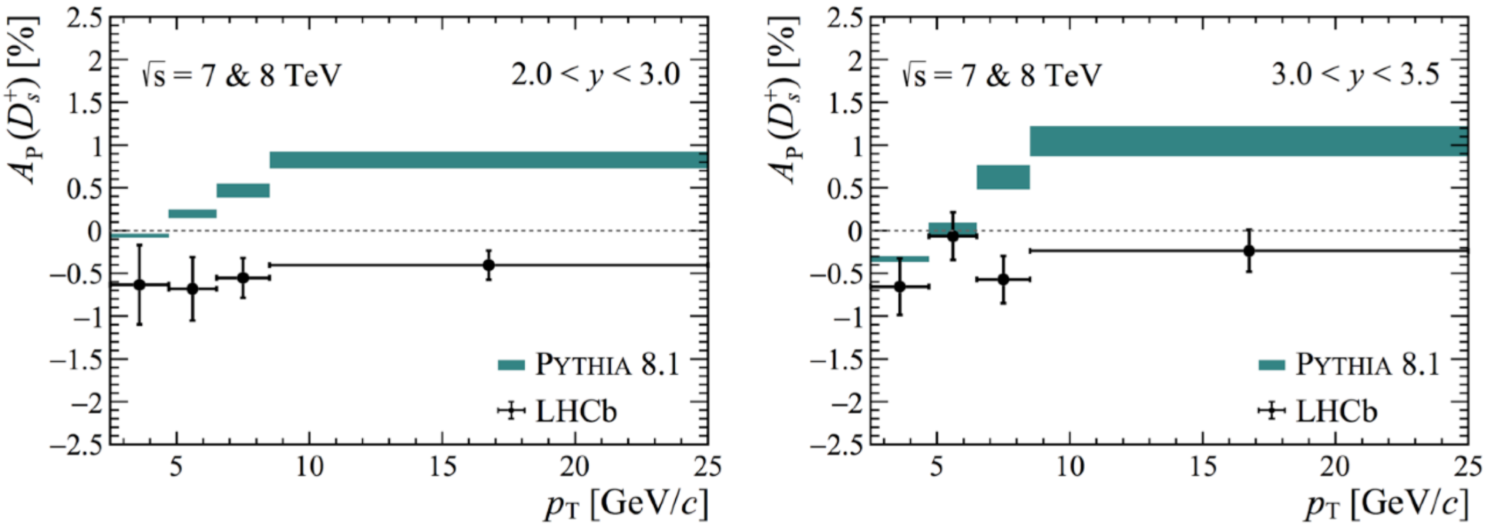
$A_{\rm D} = A^{\pi}_{\rm track} + A^{KK}_{\rm track} + A_{\rm PID} + A^{\rm software}_{\rm trigger} + A^{\rm hardware}_{\rm trigger}$ → Data driven corrections

$f_{\rm bkg} A_{\rm P} = (0.3 \pm 1.0) \times 10^{-4}$ (7 TeV)
$f_{\rm bkg} A_{\rm P} = (1.7 \pm 0.8) \times 10^{-4}$ (8TeV)
→ From published LHCb production asymmetries

$D_s^{\pm}$ production asymmetry at 7/13 TeV

LHCb, JHEP 08 (2018) 008

- A essential input to LHCb CP violation measurements



$$A_P(D_s^+) = (-0.52 \pm 0.13\ (\text{stat.}) \pm 0.10\ (\text{syst.}))\%$$

(Averaged over 7 and 8 TeV)

b hadron production asymmetry at 7/8 TeV

$$
\begin{aligned}
A_{\mathrm{P}}(B^{+})_{\sqrt{s}=7\,\mathrm{TeV}} &= -0.0023 \pm 0.0024\ (\mathrm{stat}) \pm 0.0037\ (\mathrm{syst}),\\
A_{\mathrm{P}}(B^{+})_{\sqrt{s}=8\,\mathrm{TeV}} &= -0.0074 \pm 0.0015\ (\mathrm{stat}) \pm 0.0032\ (\mathrm{syst}),\\
A_{\mathrm{P}}(B^{0})_{\sqrt{s}=7\,\mathrm{TeV}} &= 0.0044 \pm 0.0088\ (\mathrm{stat}) \pm 0.0011\ (\mathrm{syst}),\\
A_{\mathrm{P}}(B^{0})_{\sqrt{s}=8\,\mathrm{TeV}} &= -0.0140 \pm 0.0055\ (\mathrm{stat}) \pm 0.0010\ (\mathrm{syst}),\\
A_{\mathrm{P}}(B^{0}_{s})_{\sqrt{s}=7\,\mathrm{TeV}} &= -0.0065 \pm 0.0288\ (\mathrm{stat}) \pm 0.0059\ (\mathrm{syst}),\\
A_{\mathrm{P}}(B^{0}_{s})_{\sqrt{s}=8\,\mathrm{TeV}} &= 0.0198 \pm 0.0190\ (\mathrm{stat}) \pm 0.0059\ (\mathrm{syst}),\\
A_{\mathrm{P}}(\Lambda^{0}_{b})_{\sqrt{s}=7\,\mathrm{TeV}} &= -0.0011 \pm 0.0253\ (\mathrm{stat}) \pm 0.0108\ (\mathrm{syst}),\\
A_{\mathrm{P}}(\Lambda^{0}_{b})_{\sqrt{s}=8\,\mathrm{TeV}} &= 0.0344 \pm 0.0161\ (\mathrm{stat}) \pm 0.0076\ (\mathrm{syst}).
\end{aligned}
$$

- All consistent with zero with 2.5 sigma

H-F productions in pPb collisions

p-Pb

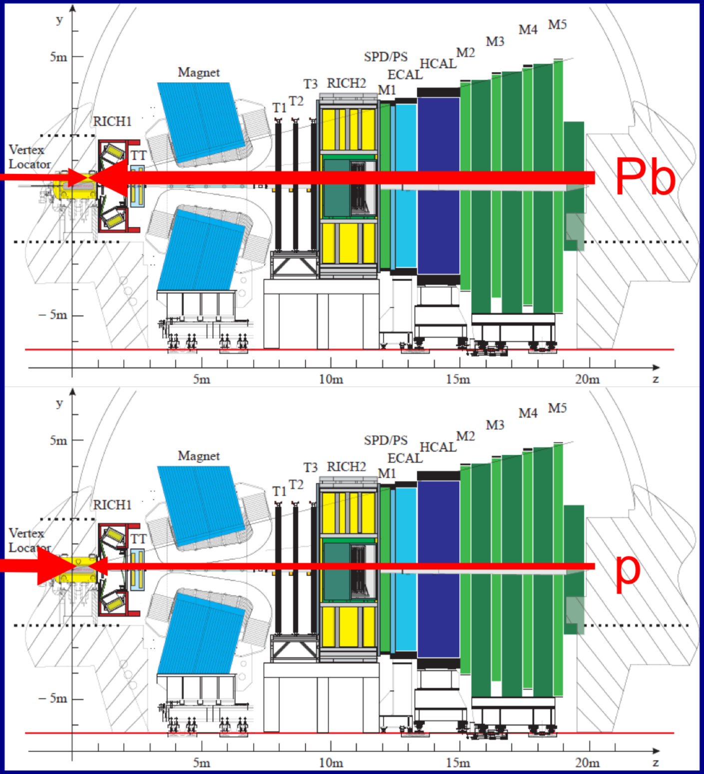
p

E_p=6.5 TeV

Pb-p

Pb

E_N= 2.56 TeV



Rapidity coverage

pp: 2 < y < 5

Forward production

y = 0.47 in lab

p-Pb: 1.5 < y* < 4.5

Data taken in 2016: ~13.6/nb

Backward production

y = -0.47 in lab

Pb-p: -5.5 < y* < -2.5

Data taken in 2016: ~20.8/nb

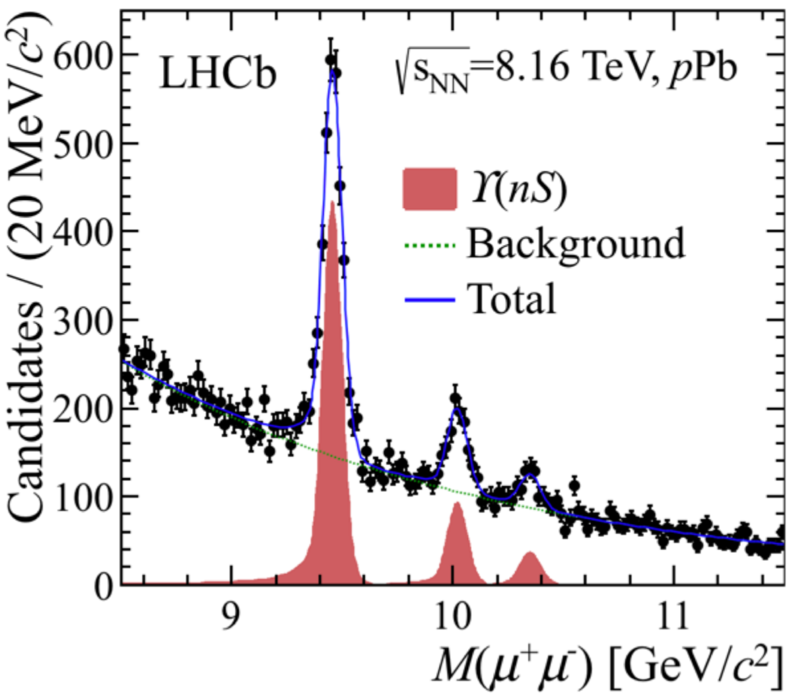
- Common range for measurements: 2.5 < |y*| < 4.5
- Centre of mass energy in 2016 : 8.16 TeV, L=34 pb^{-1}, about 20x 2013 !

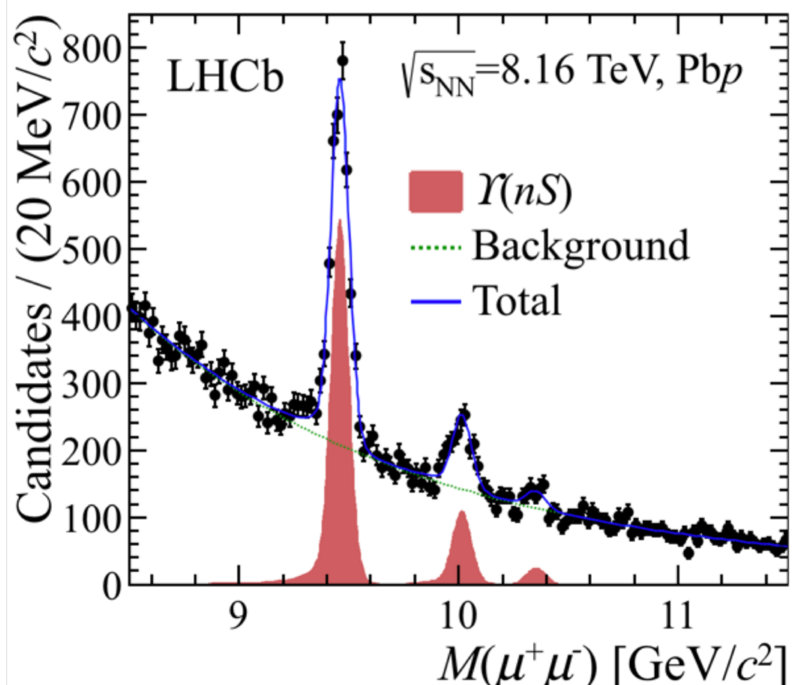
$\Upsilon(nS)$ production in pPb

LHCb-PAPER-2018-035

- Higher statistics at RUNII

Yields	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\mathcal{L}$
pPb	2705 ± 87	584 ± 49	262 ± 44	12.5 nb^{-1}
Pbp	3072 ± 82	679 ± 54	159 ± 39	19.3 nb^{-1}



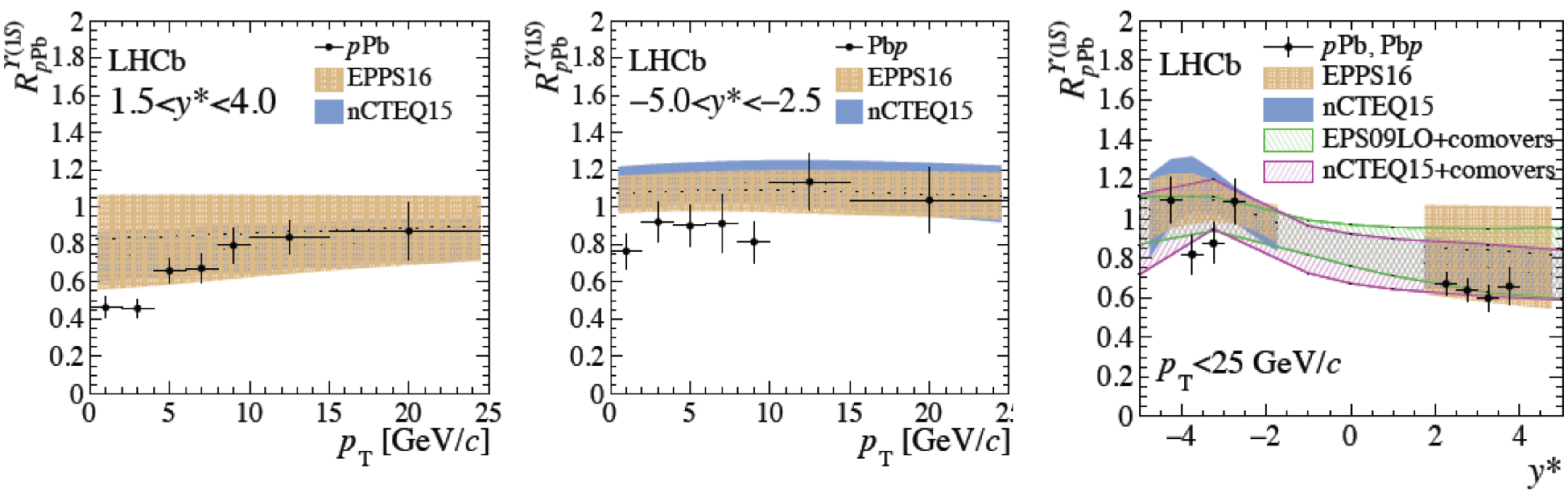


$\Upsilon(\mathrm{nS})$ production in pPb

LHCb-PAPER-2018-035

- $\boldsymbol{\Upsilon(1S)}$ Nuclear modification factor

$$R_{p\mathrm{Pb}}(p_{\mathrm{T}}, y^*) = \frac{1}{208}\frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_{\mathrm{T}}, y^*)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_{\mathrm{T}}, y^*)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*},$$

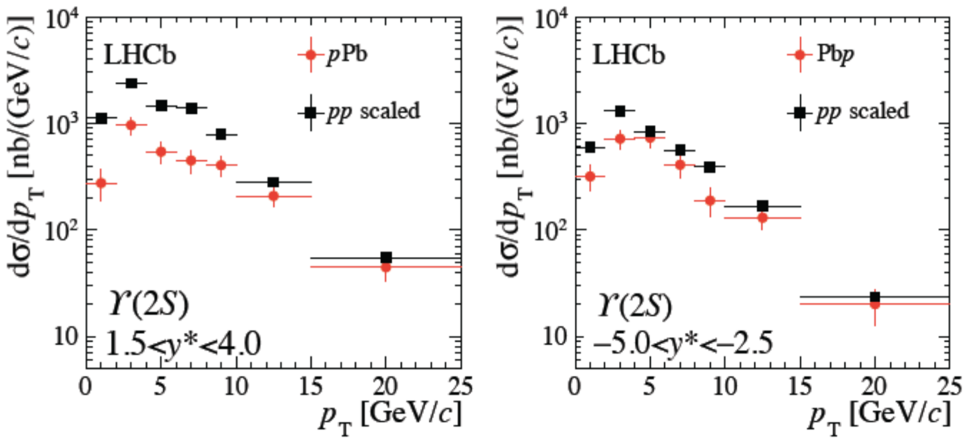


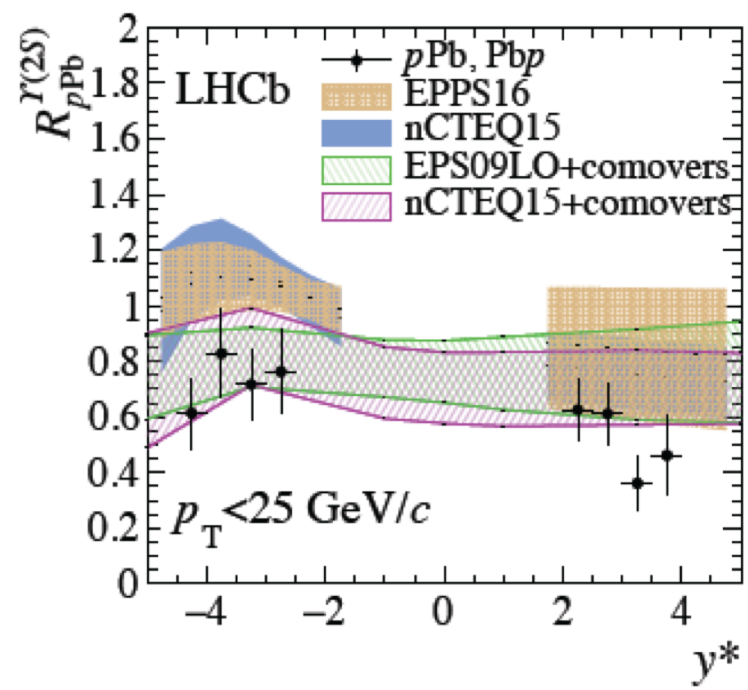
$\Upsilon(nS)$ production in pPb

LHCb-PAPER-2018-035

- $\boldsymbol{\Upsilon(2S)}$ Nuclear modification factor

$$R_{p\text{Pb}}(p_{\text{T}}, y^*) = \frac{1}{208}\frac{\mathrm{d}^2\sigma_{p\text{Pb}}(p_{\text{T}}, y^*)/\mathrm{d}p_{\text{T}}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_{\text{T}}, y^*)/\mathrm{d}p_{\text{T}}\mathrm{d}y^*},$$

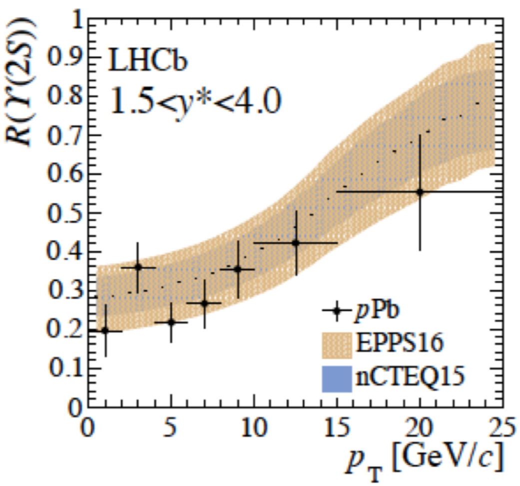


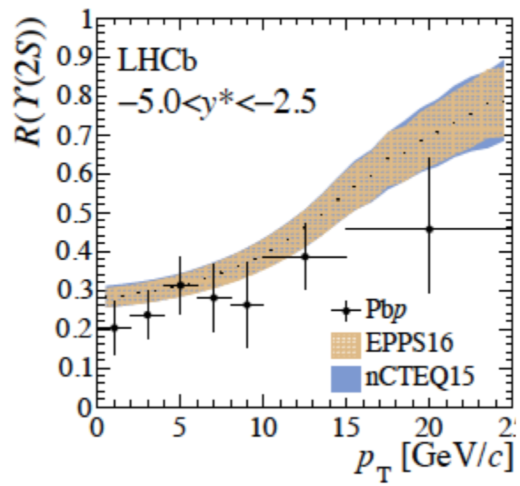


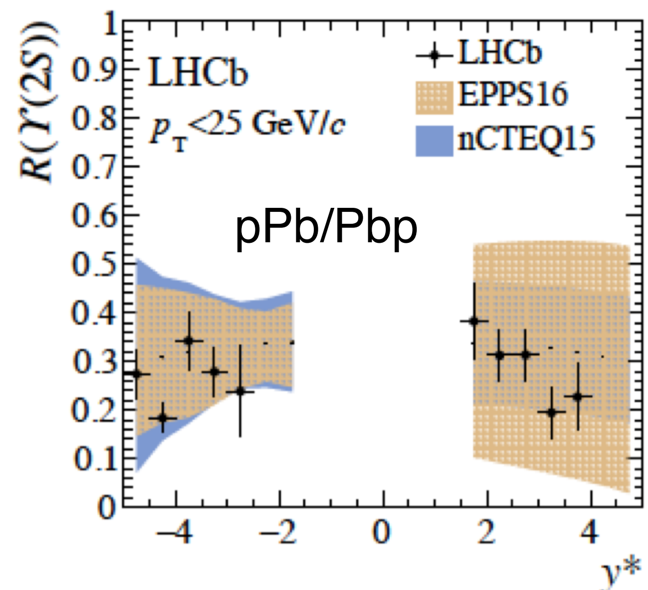
$\Upsilon(\mathrm{nS})$production in pPb

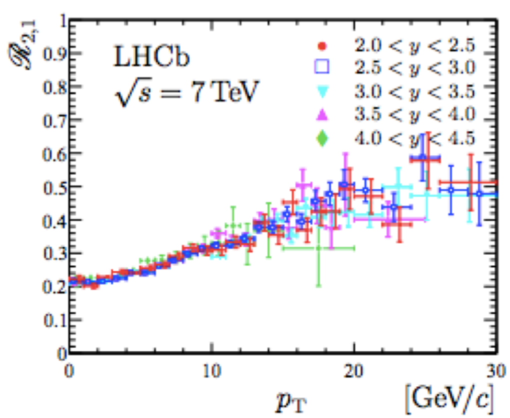
LHCb-PAPER-2018-035

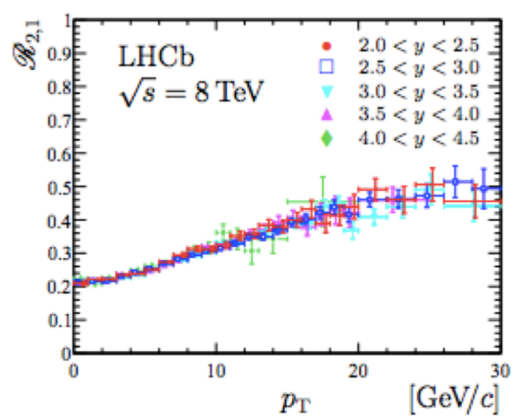
- Ratios $$R(\Upsilon(nS)) = \frac{[\mathrm{d}^2\sigma/\mathrm{d}p_\mathrm{T}dy^*]\,(\Upsilon(nS))}{[\mathrm{d}^2\sigma/\mathrm{d}p_\mathrm{T}dy^*]\,(\Upsilon(1S))}.$$





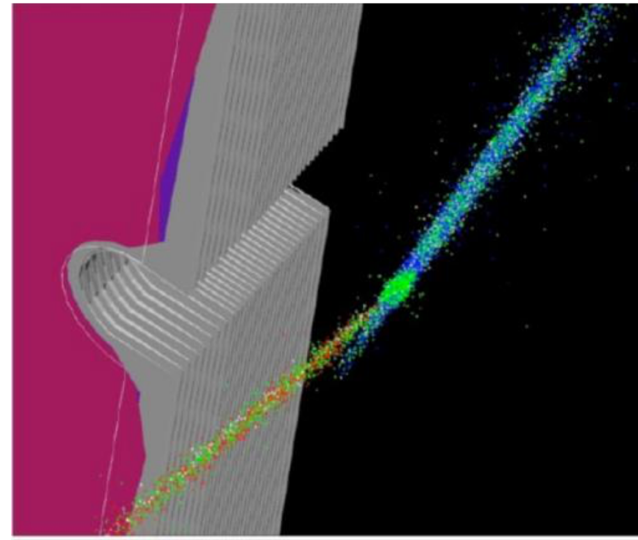






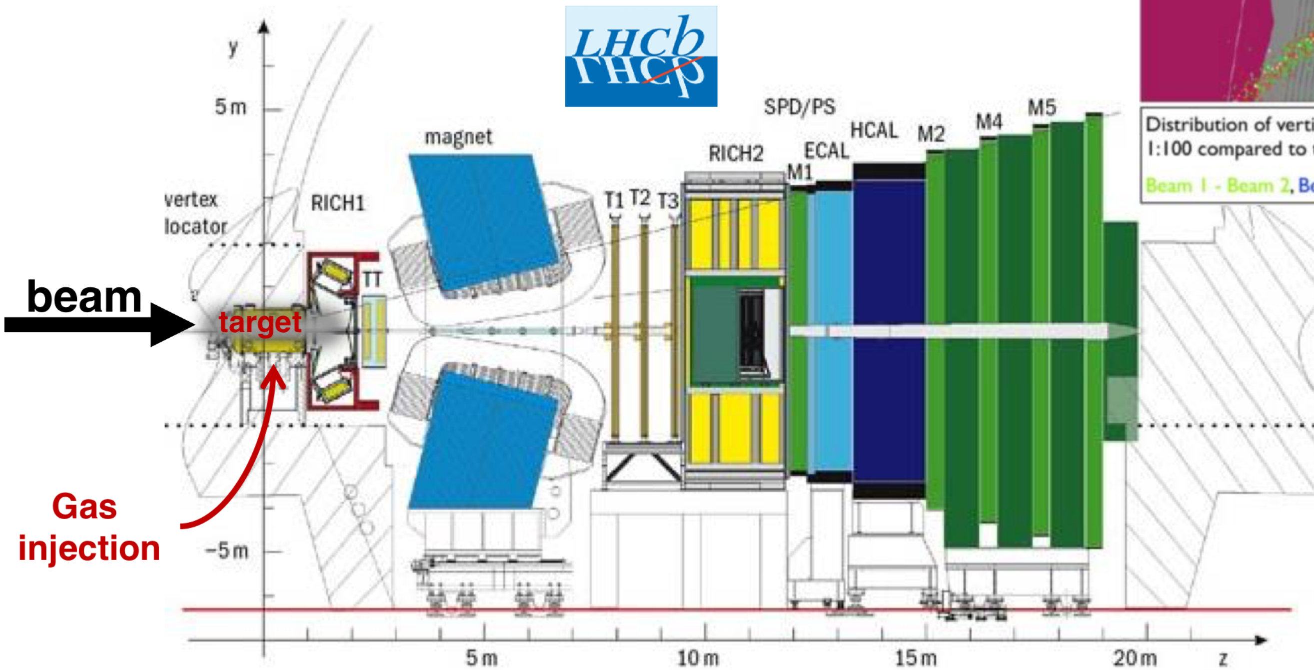
LHCb in fixed target mode

- **Can also operate in fixed-target mode: unique at LHC**
  - Injecting gas in the LHCb VErtex LOcator (VELO) tank, originally done to perform luminosity measurement.
  - Can be used as an **internal gas target**
  - Allows measurement of *p*-gas and ion-gas interactions



Distribution of vertices overlaid on detector display. z-axis is scaled by 1:100 compared to transverse dimensions to see the beam angle.

Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.



Noble gas only :
(very low chemical reactivity)

He, Ne, Ar, …
A = 4, 20, 40

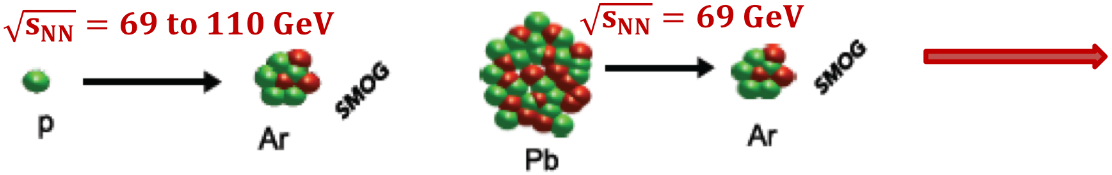
Gas pressure:
10^{-7} to 10^{-6} mbar

LHCb in fixed target mode

- **The LHCb fixed-target program fills the gap between SPS and RHIC energies**

$\sqrt{s_{NN}} = 69 \text{ to } 110 \text{ GeV}$

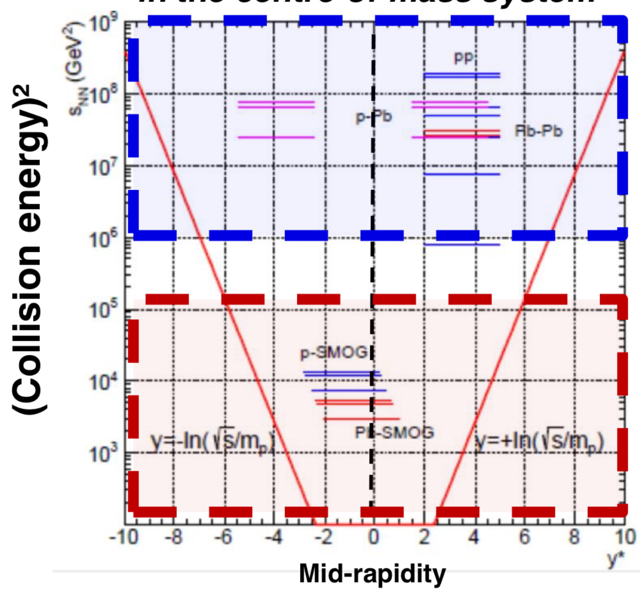
$\sqrt{s_{NN}} = 69 \text{ GeV}$



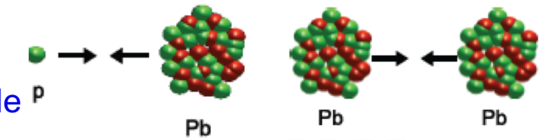
$\sqrt{s_{NN}^{SPS}} \sim 20$ GeV
$\sqrt{s_{NN}^{LHCb-FT}} \sim 70$ **GeV**
$\sqrt{s_{NN}^{RHIC}} = 200$ GeV
$\sqrt{s_{NN}^{LHC}} = 5$ TeV

- **Gives access to the large Bjorken-x region in the target**

LHCb rapidity coverage in the centre-of-mass system

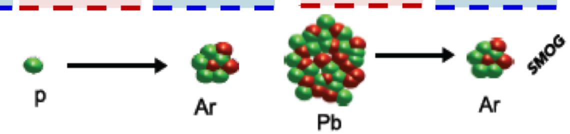


Colliding beam mode



E_{beam}(p)	pp	p-SMOG	p-Pb/Pb-p	Pb-SMOG	Pb-Pb
450 GeV	0.90 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	5.02 TeV
7.0 TeV	14 TeV	115 GeV	8.8 TeV	72 GeV	5.5 TeV

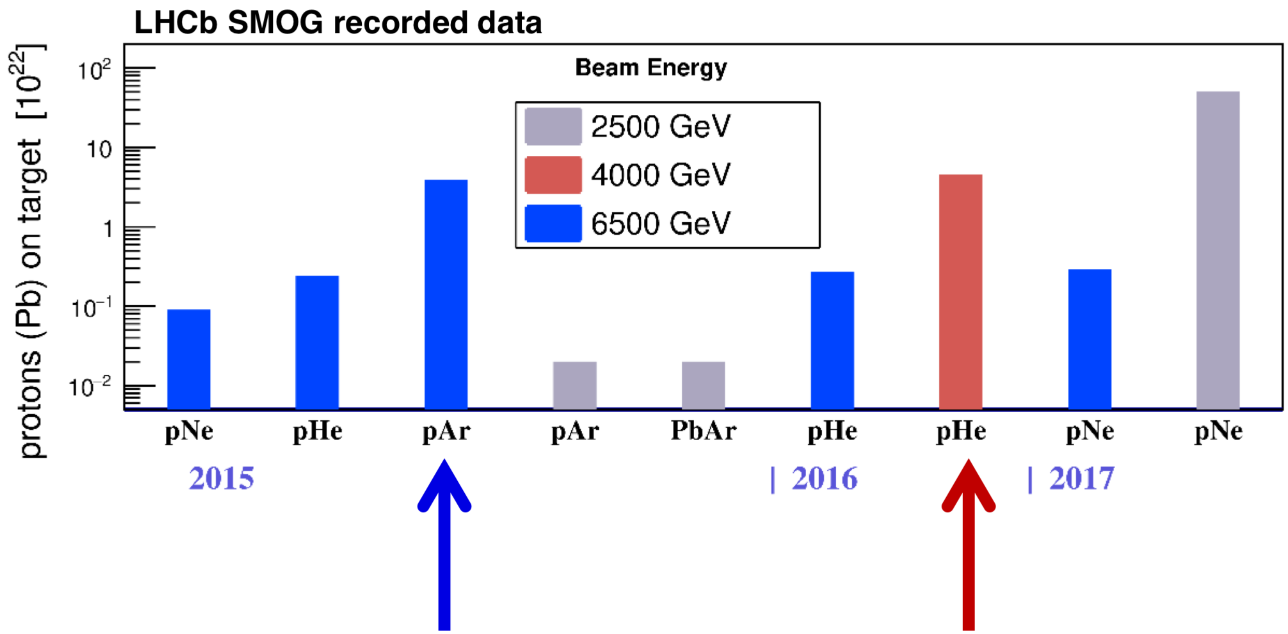
Fixed-target mode



At $\sqrt{s_{NN}} = 110$ GeV $y^* = y_{lab} - 4.77$

LHCb in fixed target mode

- Data sample



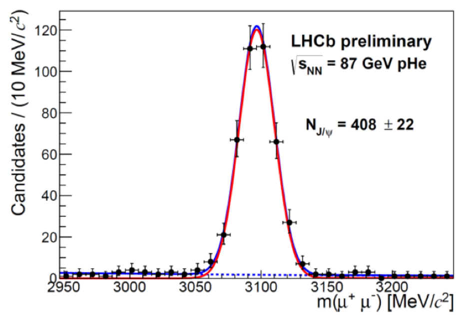
$\sqrt{s_{NN}}$ = 110 GeV proton-Ar interactions 2015
~ 4×10^{22} Protons On Target (17h)

$\sqrt{s_{NN}}$ = 86.6 GeV proton-He interactions 2016
~ 4×10^{22} POTs (87h)
$\mathcal{L}_{pHe} = 7.6 \pm 0.5\ \mathrm{nb}^{-1}$

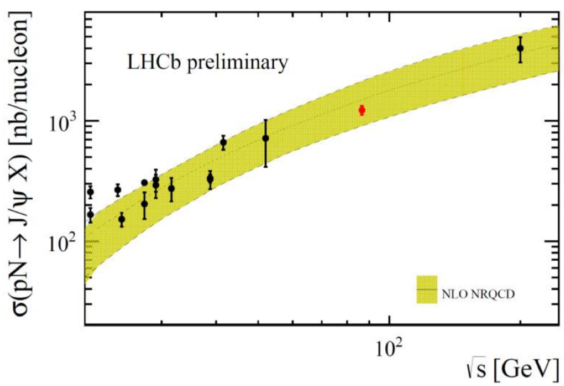
LHCb in fixed target mode

LHCb-PAPER-2018-023

- $J/\psi \to \mu\mu, D^0 \to K\pi$ in *p*He at 86.6 GeV



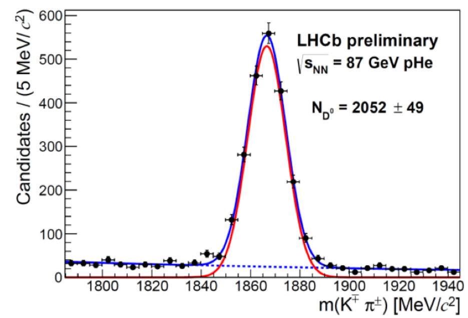
$\sigma_{J/\psi} = 1225.6 \pm 62.0$ (stat) ± 81.6 (syst) nb/nucleon



LHCb result in good agreement with NRQCD fit and other measurements

J/ψ

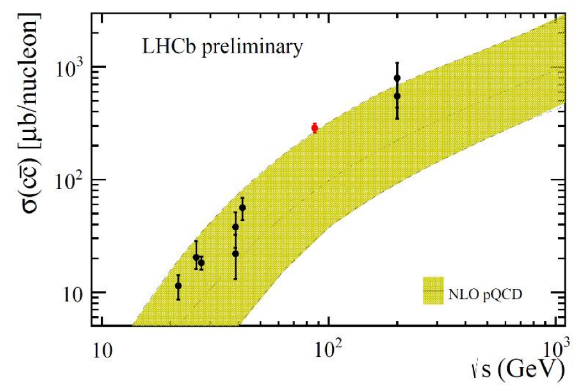
D^0



$\sigma_{D^0} = 156.0 \pm 4.6\ (stat) \pm 12.3\ (syst)$ μb/nucleon

with fraction (c→D^0) = 0.542±0.024

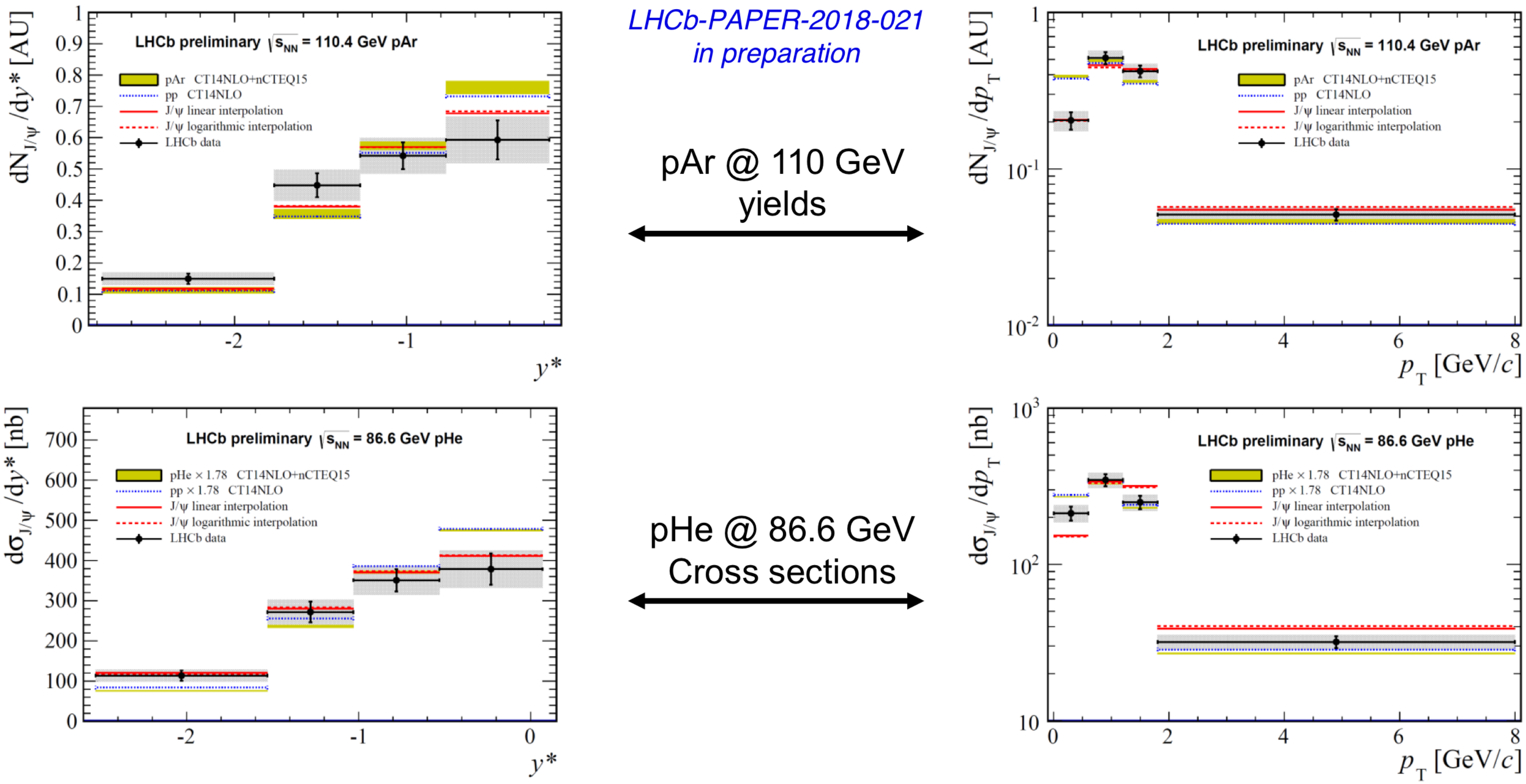
$\sigma_{c\bar{c}} = 287.8 \pm 8.5\ (stat) \pm 25.7\ (syst)$ μb/nucleon



LHCb result in reasonable agreement with NLO pQCD (MNR) predictions and other measurements

LHCb in fixed target mode

- **J/ψ differential yields (pAr@110 GeV) and cross sections (pHe@86.6 GeV)**
  - Plain and dashed **red lines**, **phenomenological parametrization**: JHEP 05 (2013) 155
  - **HELAC-ONIA** predictions for pp (blue lines) and pA (yellow boxes): EPJC(2017) 77:1



  - **HELAC-ONIA underestimate the J/ψ cross section (pHe) by a factor 1.78**
  - **Good shape agreement with phenomenological predictions**

Summary

- HF productions have been studied at LHCb
  - in pp, pA/Ap, AA collisions
  - with unique forward phase space

- With RUNII and the upgraded detector, more to come
  - excited hadrons
  - doubly charmed baryons
  - X Y Z and pentaquarks
  - ....

Stay tuned !

Backup slides

Charmonia from $B^+ \to p\bar{p}K^+$

- Exclusive reconstruction: clean sample, better control of background and resolution effects

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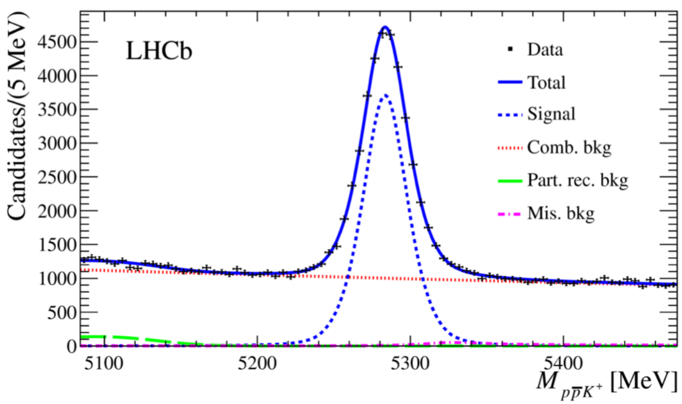


$$m_{J/\psi} - m_{\eta_c(1S)} = 110.2 \pm 0.5 \pm 0.9 \text{ MeV}$$

$$m_{\psi(2S)} - m_{\eta_c(2S)} = 52.2 \pm 1.7 \pm 0.6 \text{ MeV}$$

$$\Gamma_{\eta_c(1S)} = 34.0 \pm 1.9 \pm 1.3 \text{ MeV}$$

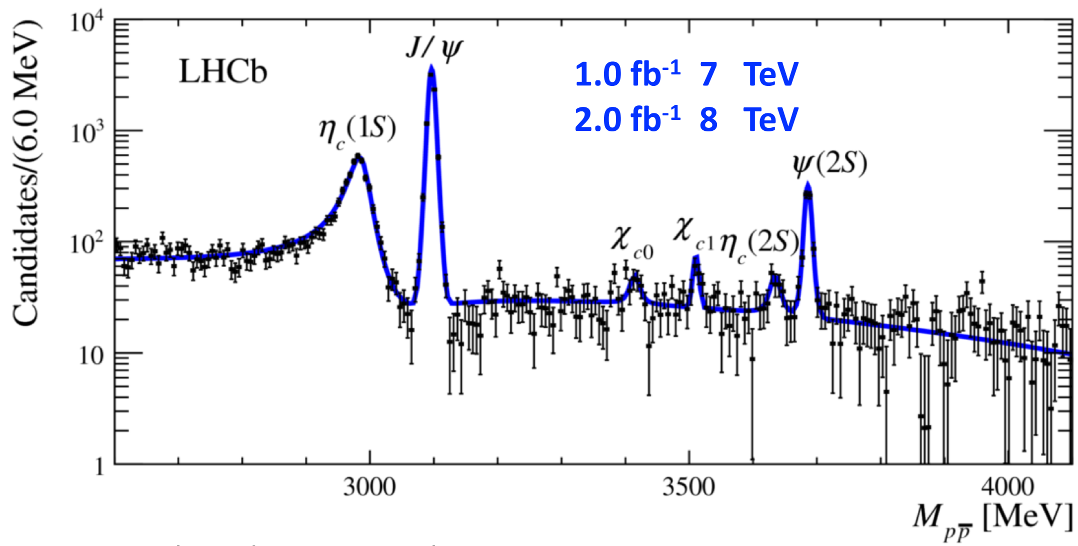
$$\mathcal{R}_{[c\bar{c}]} = \frac{\mathcal{B}(B^+ \to [c\bar{c}]K^+)\times\mathcal{B}([c\bar{c}] \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+)\times\mathcal{B}(J/\psi \to p\bar{p})}$$

$$\mathcal{R}_{\eta_c(2S)} = (1.58 \pm 0.33 \pm 0.09)\times 10^{-2}$$

1 st Observation

$$\mathcal{R}_{\psi(3770)} < 10\times 10^{-2}$$

$$\mathcal{R}_{X(3872)} < 0.25 \times 10^{-2}$$



Charmonia from $b \to \phi\phi + X$

- Allow to measure production ratios

LHCb-PAPER-2017-007
EPJC 77 (2017) 609

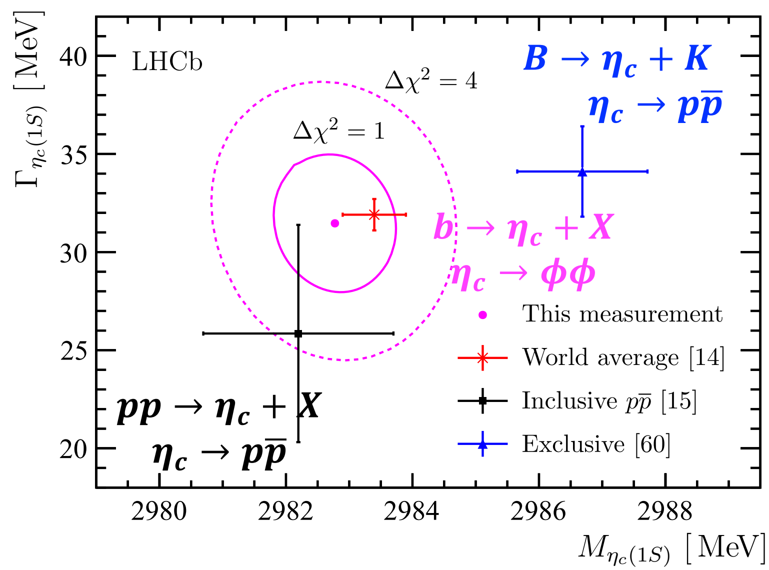
$$R^{C_1}_{C_2} \equiv \frac{\mathcal{B}(b \to C_1\, X) \times \mathcal{B}(C_1 \to \phi\,\phi)}{\mathcal{B}(b \to C_2\, X) \times \mathcal{B}(C_2 \to \phi\,\phi)}$$

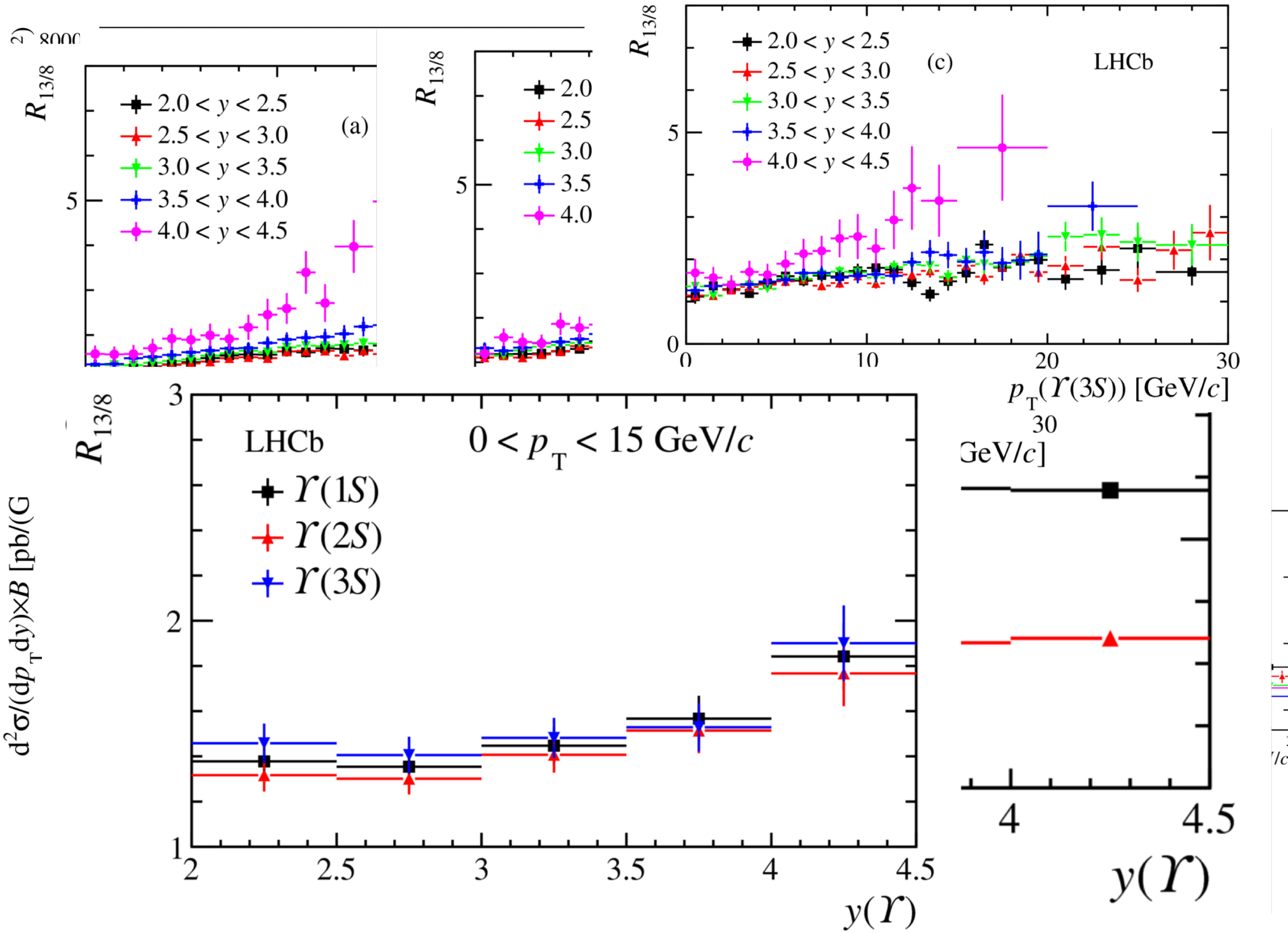
$$R^{\chi_{c0}}_{\eta_c(1S)} = 0.147 \pm 0.023 \pm 0.011,$$
$$R^{\chi_{c1}}_{\eta_c(1S)} = 0.073 \pm 0.016 \pm 0.006,$$
$$R^{\chi_{c2}}_{\eta_c(1S)} = 0.081 \pm 0.013 \pm 0.005,$$
$$R^{\chi_{c1}}_{\chi_{c0}} = 0.50 \pm 0.11 \pm 0.01,$$
$$R^{\chi_{c2}}_{\chi_{c0}} = 0.56 \pm 0.10 \pm 0.01,$$
$$R^{\eta_c(2S)}_{\eta_c(1S)} = 0.040 \pm 0.011 \pm 0.004,$$

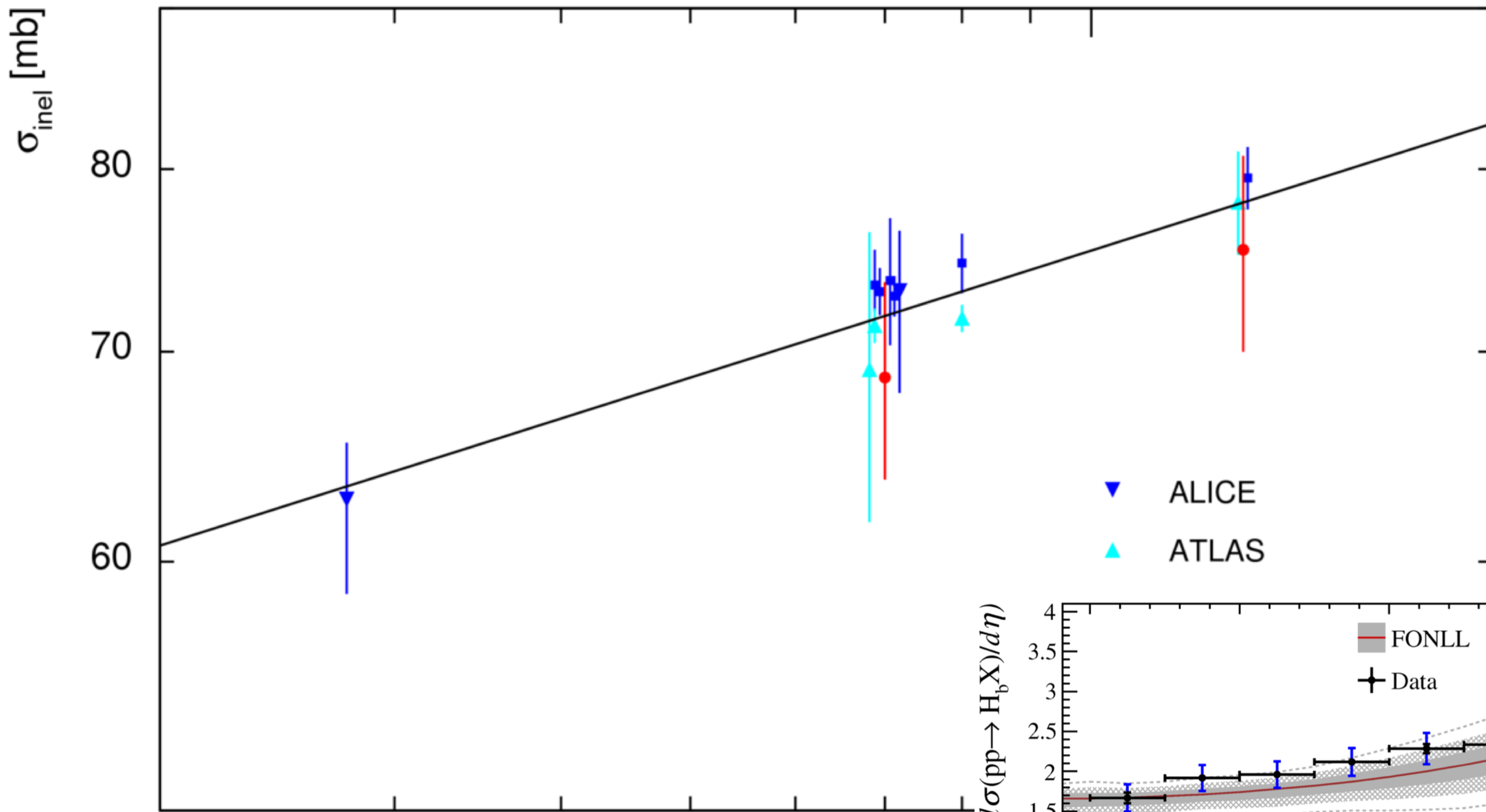
1[st] Observation of $\eta_c(2S) \to \phi\phi$

- Competitive measurements of masses of widths

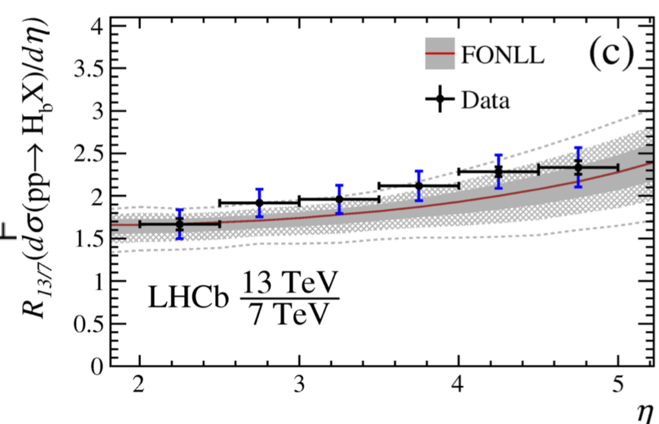
	Measured value	World average [14]
$M_{\eta_c(1S)}$	$2982.8 \pm 1.0 \pm 0.5$	2983.4 ± 0.5
$M_{\chi_{c0}}$	$3413.0 \pm 1.9 \pm 0.6$	3414.75 ± 0.31
$M_{\chi_{c1}}$	$3508.4 \pm 1.9 \pm 0.7$	3510.66 ± 0.07
$M_{\chi_{c2}}$	$3557.3 \pm 1.7 \pm 0.7$	3556.20 ± 0.09
$M_{\eta_c(2S)}$	$3636.4 \pm 4.1 \pm 0.7$	3639.2 ± 1.2
$\Gamma_{\eta_c(1S)}$	$31.4 \pm 3.5 \pm 2.0$	31.8 ± 0.8
$\Gamma_{\eta_c(2S)}$	–	$11.3\,^{+\,3.2}_{-\,2.9}$



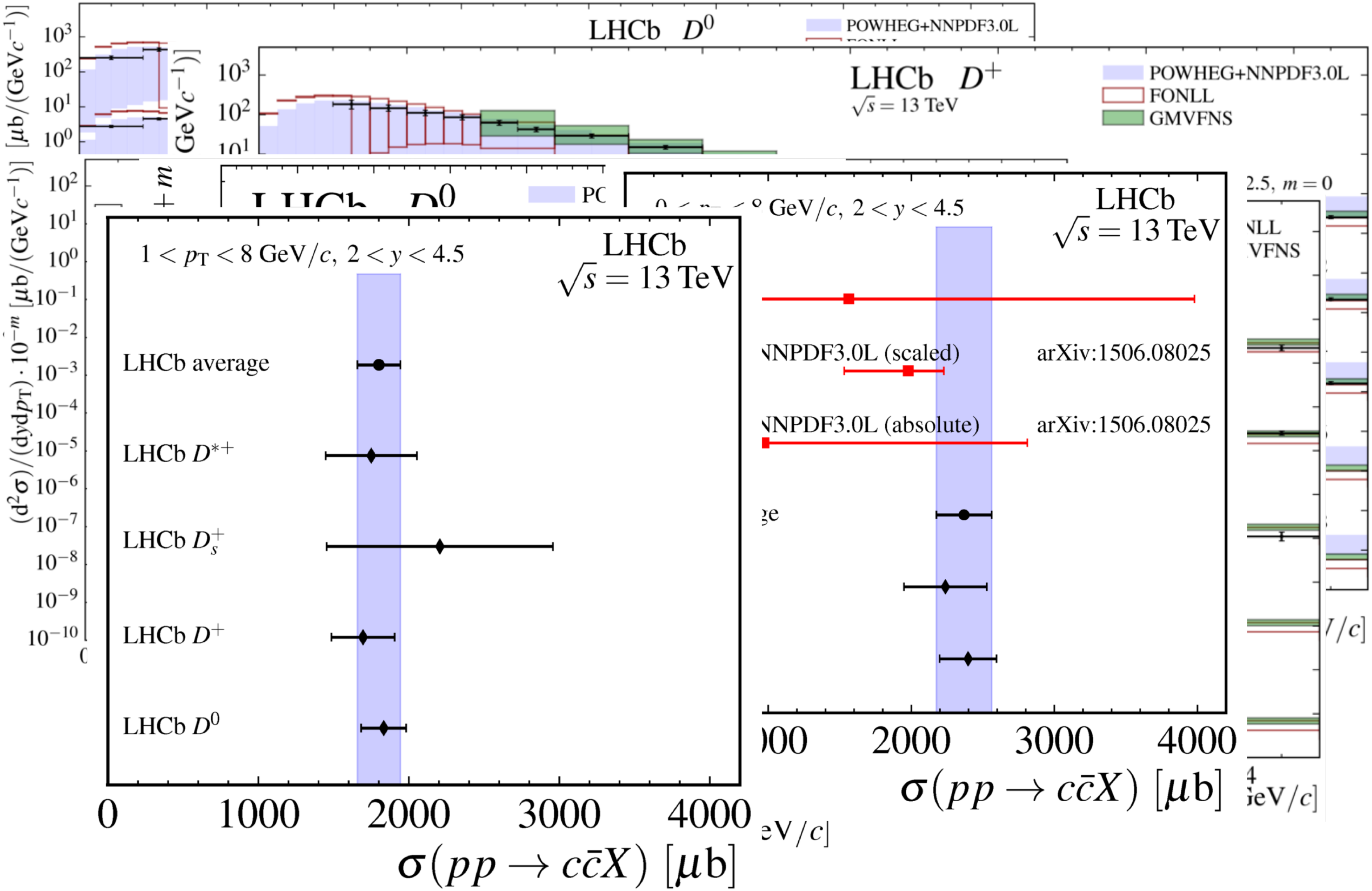

$R_{13/8}$
2.0 < y < 2.5
2.5 < y < 3.0
3.0 < y < 3.5
3.5 < y < 4.0
4.0 < y < 4.5
(a)
(c)
LHCb
$p_T(\Upsilon(3S))$ [GeV/c]
0 < p_T < 15 GeV/c
$\Upsilon(1S)$
$\Upsilon(2S)$
$\Upsilon(3S)$
$y(\Upsilon)$
$d^2\sigma/(dp_T dy)\times B$ [pb/(G

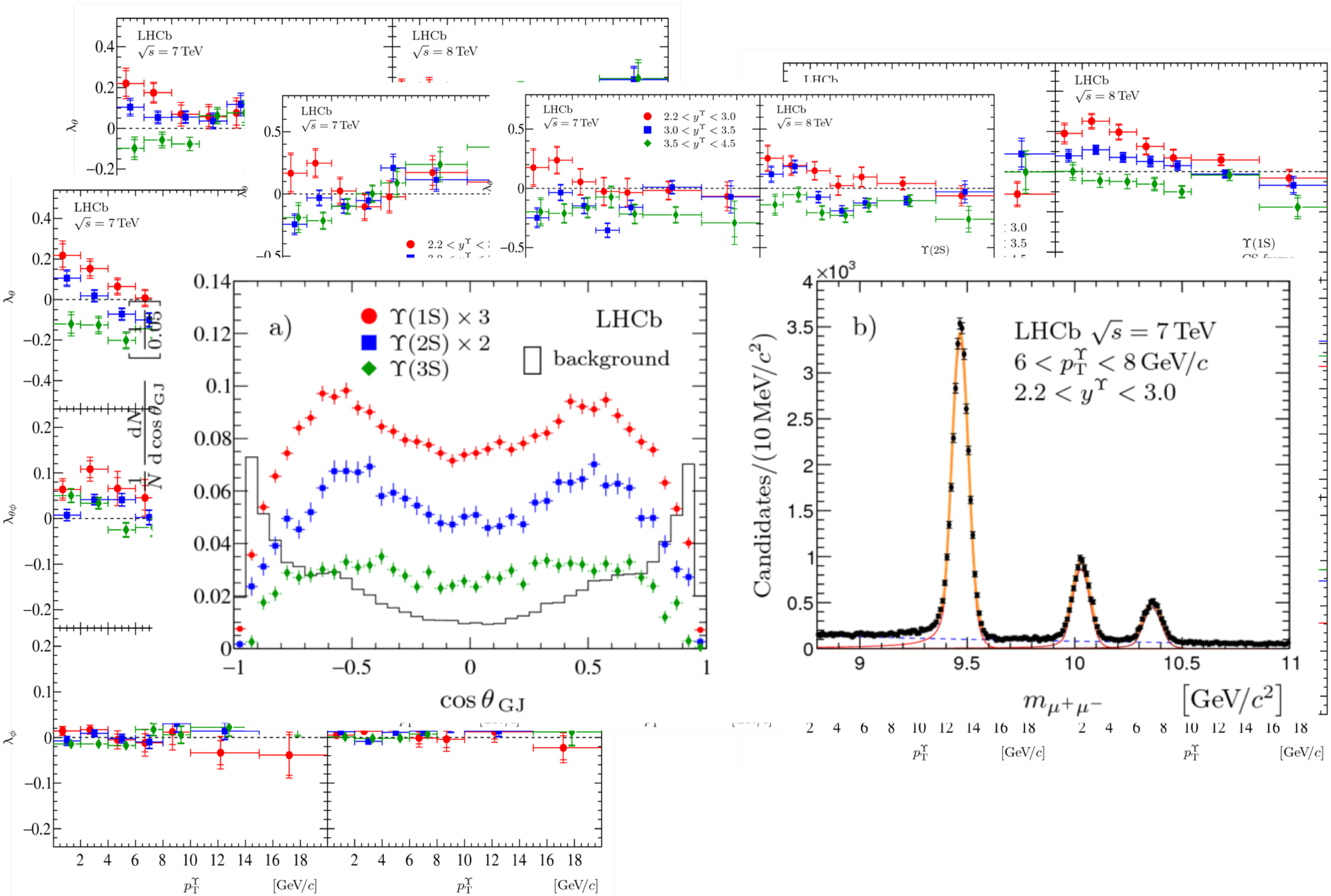


σinel [mb]
80
70
60
ALICE
ATLAS

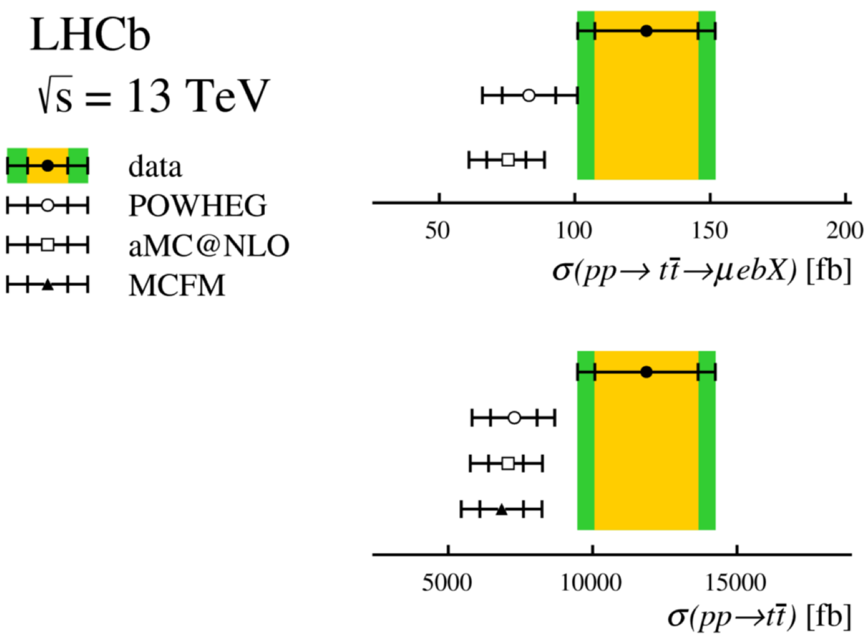


$R_{13/7}(d\sigma(pp \to H_b X)/d\eta)$
4
3.5
3
2.5
2
1.5
1
0.5
0
FONLL
(c)
Data
LHCb $\frac{13\ \text{TeV}}{7\ \text{TeV}}$
2
3
4
5
η


LHCb D^0
POWHEG+NNPDF3.0L
LHCb D^+
$\sqrt{s} = 13$ TeV
POWHEG+NNPDF3.0L
FONLL
GMVFNS
$1 < p_T < 8$ GeV/c, $2 < y < 4.5$
LHCb
$\sqrt{s} = 13$ TeV
LHCb average
LHCb D^{*+}
LHCb D_s^+
LHCb D^+
LHCb D^0
0
1000
2000
3000
4000
$\sigma(pp \to c\bar{c}X)$ [μb]
arXiv:1506.08025
arXiv:1506.08025
2000
3000
4000
$\sigma(pp \to c\bar{c}X)$ [μb]


LHCb
$\sqrt{s} = 7$ TeV
$\sqrt{s} = 8$ TeV
λ_θ
$\lambda_{\theta\phi}$
λ_ϕ
$2.2 < y^\Upsilon < 3.0$
$3.0 < y^\Upsilon < 3.5$
$3.5 < y^\Upsilon < 4.5$
Υ(1S)
Υ(2S)
p_T^Υ [GeV/c]
a)
Υ(1S) × 3
Υ(2S) × 2
Υ(3S)
LHCb
background
$\frac{1}{N}\frac{dN}{d\cos\theta_{GJ}}\left[\frac{1}{0.05}\right]$
$\cos\theta_{GJ}$
b)
LHCb $\sqrt{s} = 7$ TeV
$6 < p_T^\Upsilon < 8$ GeV/c
$2.2 < y^\Upsilon < 3.0$
Candidates/(10 MeV/c^2)
×10³
$m_{\mu^+\mu^-}$ [GeV/c^2]

1.93 fb^{-1}



LHCb
√s = 13 TeV
data
POWHEG
aMC@NLO
MCFM
50
100
150
200
σ(pp→ tt̄→μebX) [fb]
5000
10000
15000
σ(pp→tt̄) [fb]

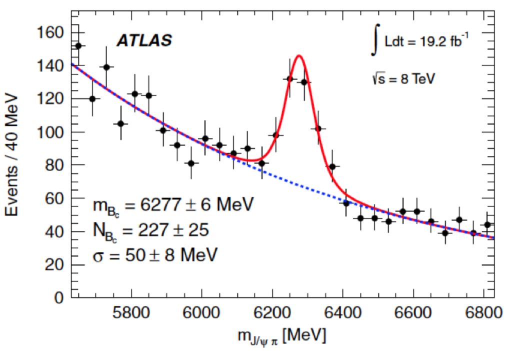
$B_c^{(*)}(2S) \to B_c^{(*)}\pi^+\pi^-$

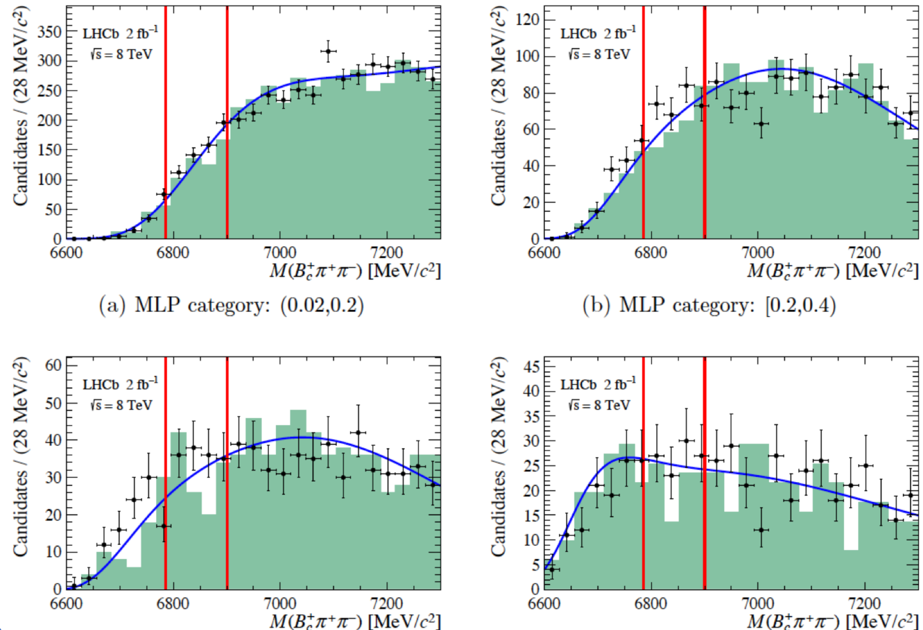
LHCb-PAPER-2017-042
arXiv:1712.04094

ATLAS, PRL 113 (2014) 212004

Data	Signal events
7 TeV	100 ± 23
8 TeV	227 ± 25

$N_{B_c}^{\text{ATLAS}}$





(a) MLP category: (0.02,0.2)

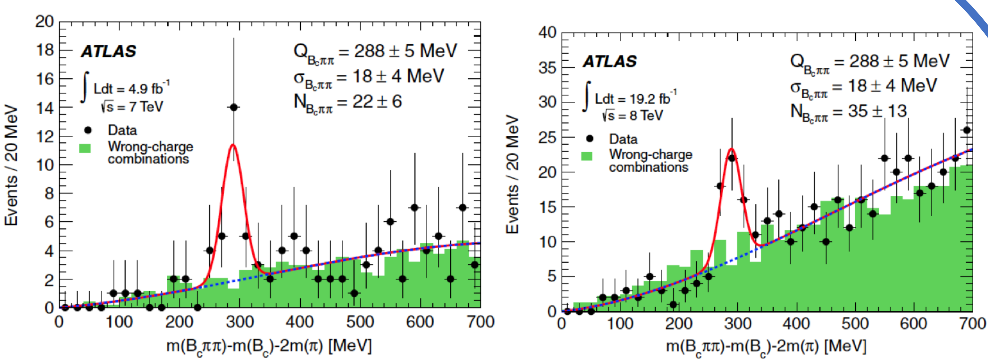
(b) MLP category: [0.2,0.4)

(c) MLP category: [0.4,0.6)

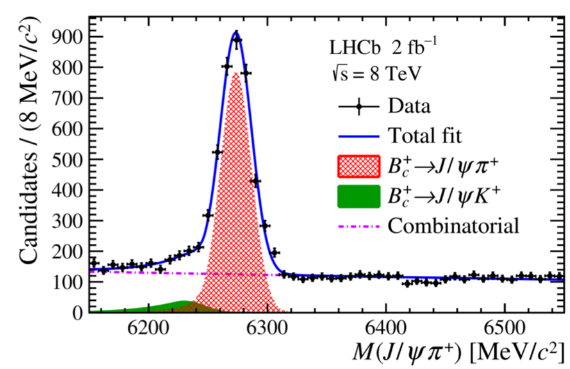
(d) MLP category: [0.6,1.0]

$$m_{B_c(2S)} = 6842 \pm 4 \pm 5 \text{ MeV}$$

5.2σ



$$N_{B_c}^{\text{LHCb 8TeV}} = 3325 \pm 73$$



$$\mathcal{R} = \frac{\sigma_{B_c^{(*)}(2S)^+}}{\sigma_{B_c^+}} \cdot \mathcal{B}(B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-)$$
$$= \frac{N_{B_c^{(*)}(2S)^+}}{N_{B_c^+}} \cdot \frac{\varepsilon_{B_c^+}}{\varepsilon_{B_c^{(*)}(2S)^+}},$$

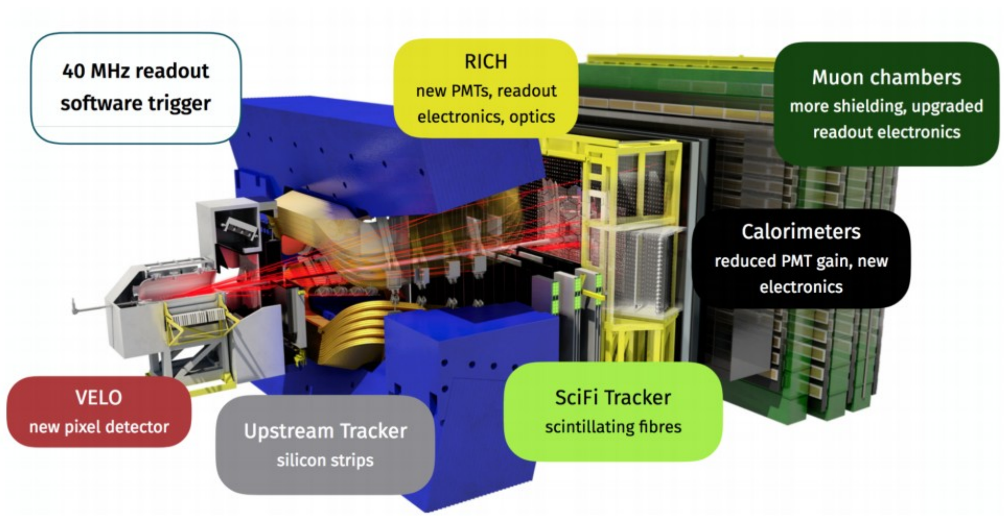
	$\sqrt{s} = 7\,\text{TeV}$	$\sqrt{s} = 8\,\text{TeV}$
ATLAS	$(0.22 \pm 0.08\,(\text{stat}))/\varepsilon_7$	$(0.15 \pm 0.06\,(\text{stat}))/\varepsilon_8$
LHCb	–	$< [0.04, 0.09]$

$\varepsilon_7, \varepsilon_8$: **relative efficiencies of reconstructing $B_c^{(*)}(2S)^+$ wrt B_c^+**

- **ATLAS did not publish $\varepsilon_7, \varepsilon_8$**
- **More studies needed to resolve the large tension between ATLAS and LHCb.**

Spectroscopy with the upgraded LHCb

- LHCb will be upgraded in 2019, software trigger with 40MHz



- Allow PID at the trigger level – great increase (~2x) of trigger efficiency on full hadronic final states

- A new computing approach to data-analysis is needed