Heavy Flavor Production in pp and Heavy Ion Collisions at LHCb

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on behalf of the LHCb collaboration

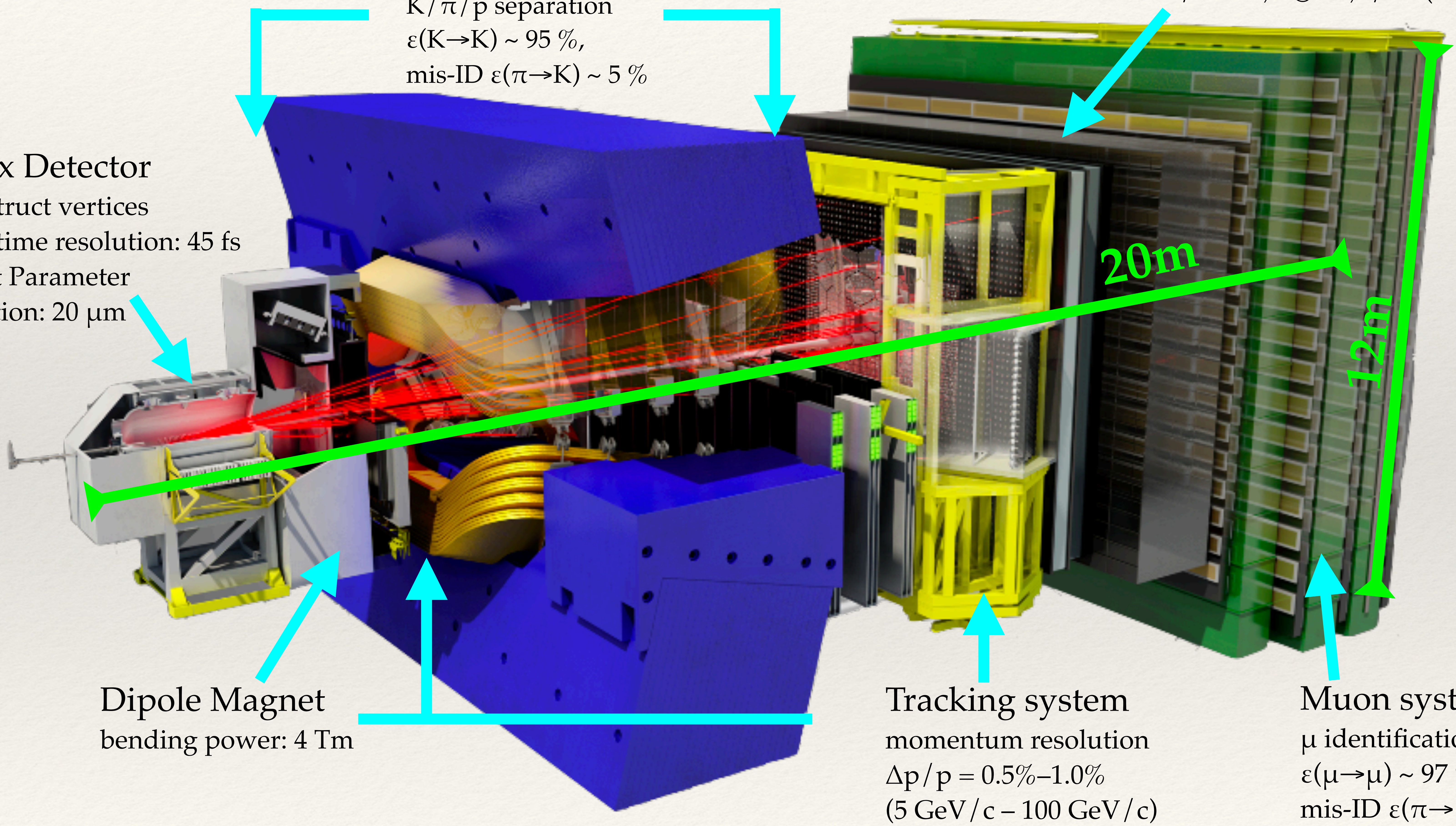
The LHCb detector is special

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

- LHCb is the only detector fully instrumented in forward region
- Unique kinematic coverage

  $2 < \text{Eta} < 5$

- A high precision device, down to very low-p_T, excellent particle ID, precision vertex reconstruction and tracking.



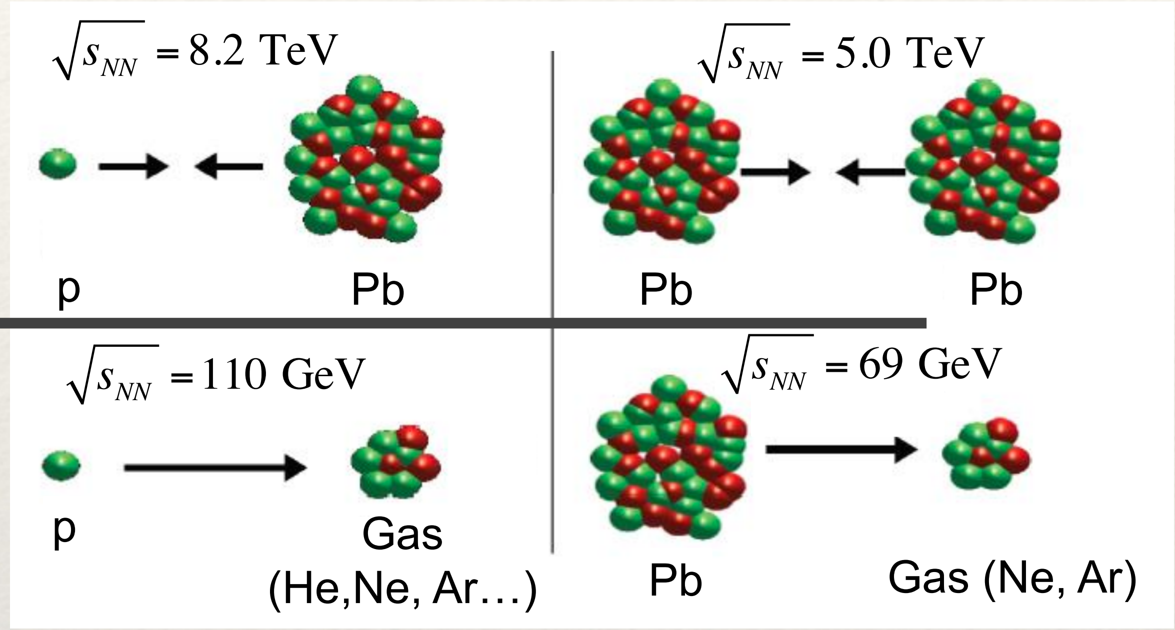
LHCb running modes and kinematic coverage

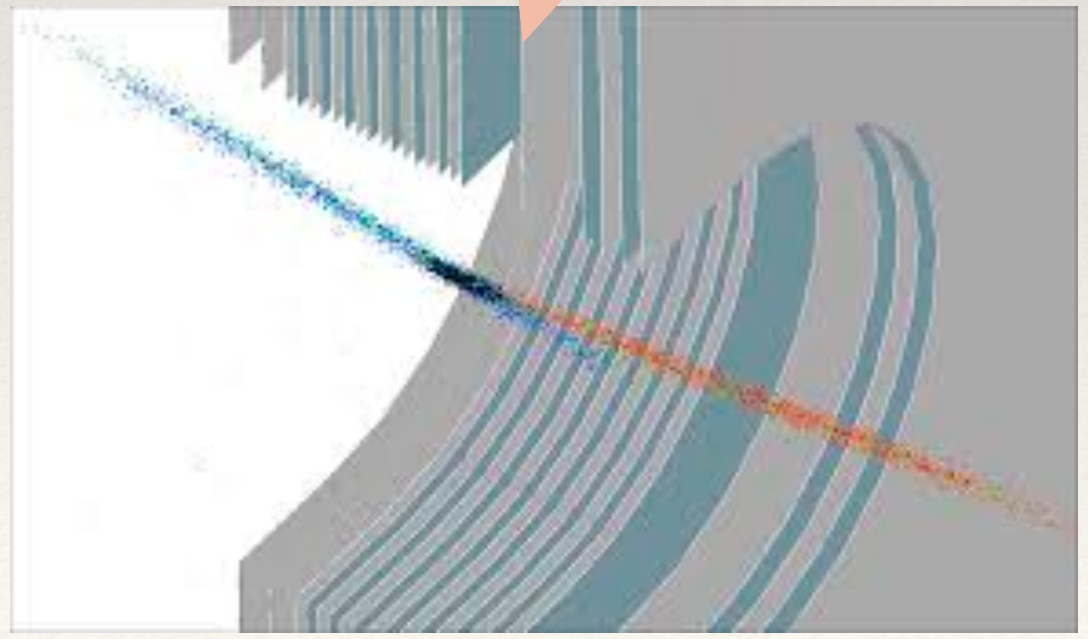
Both the collider mode and fixed target mode running at the same time:

$\sqrt{s} = 7, 8, 13$ TeV

Collider Mode

Fixed-target Mode (SMOG)





Collider mode:

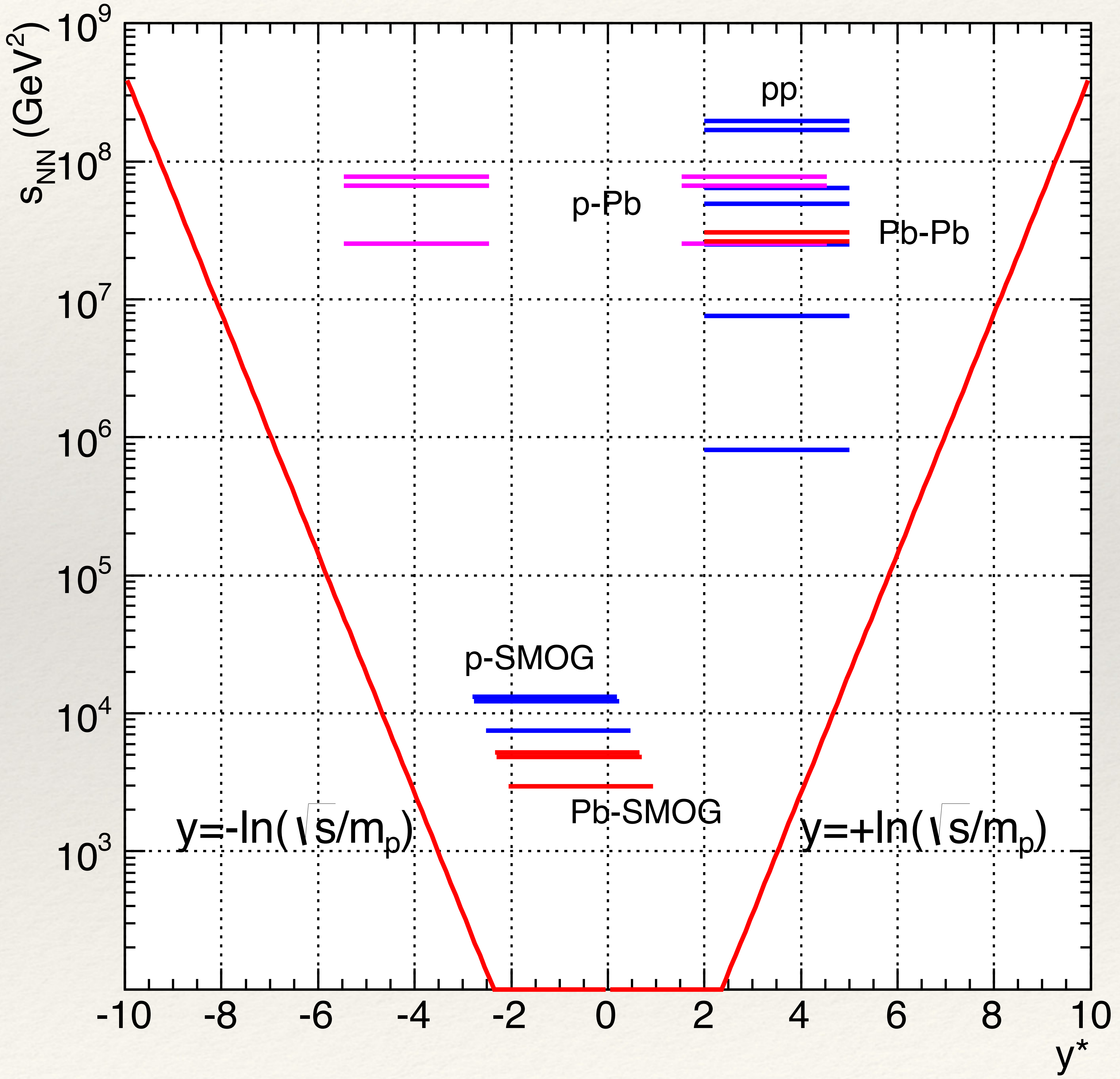
Forward and backward coverage

Fixed target mode:

Central and backward coverage

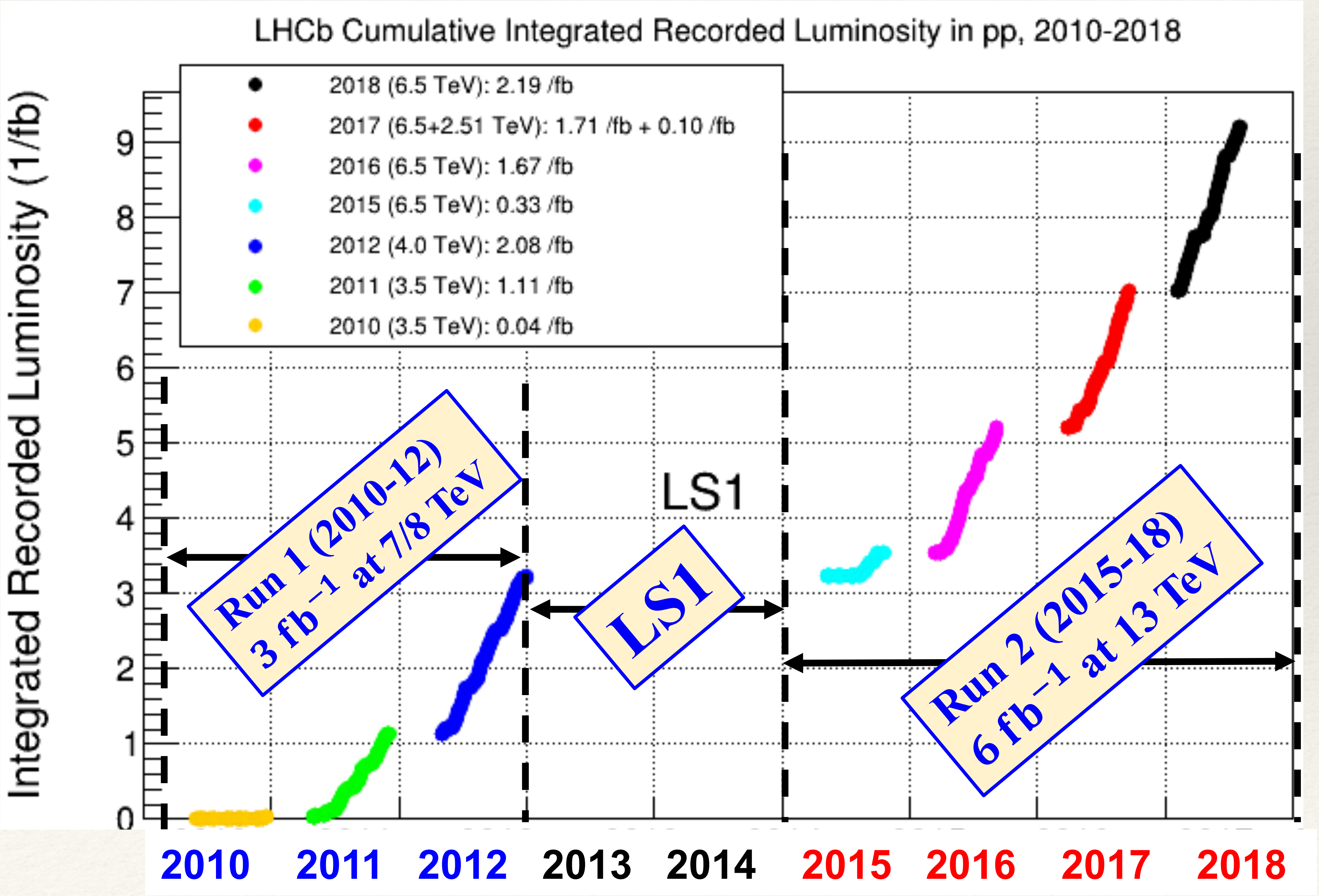
$\sqrt{s_{NN}}$: 69 - 110 GeV, fills the gap between SPS (20 GeV) and RHIC (200 GeV) energy scales

Kinematic Acceptance



Data samples

- Colliding beam mode (pp):
  - More than 9 fb^{-1} accumulated in Run1+Run2
  - A huge amount of $b\bar{b}$ and $c\bar{c}$ have been produced
    - ~10^{12} $b\bar{b}$ and ~10^{13} $c\bar{c}$

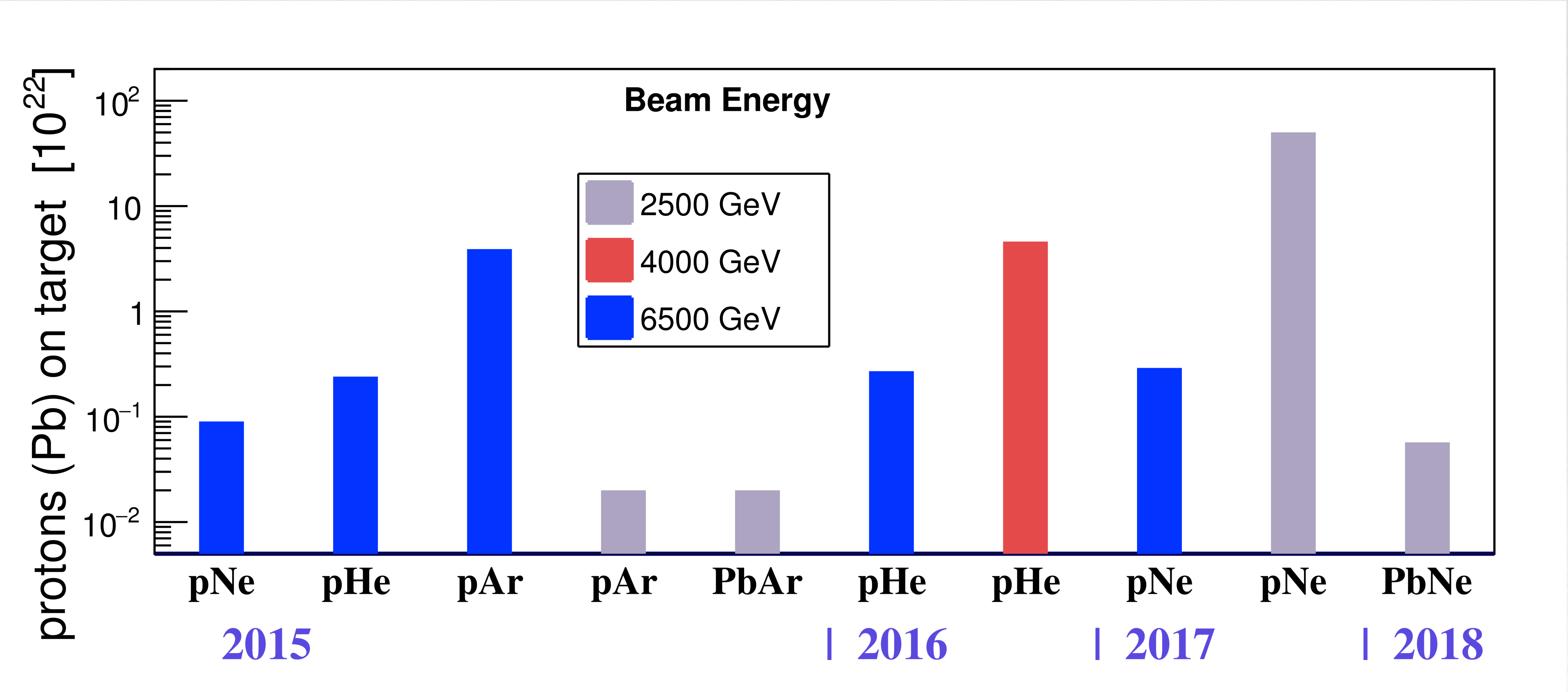


- Colliding beam mode (pPb and PbPb):

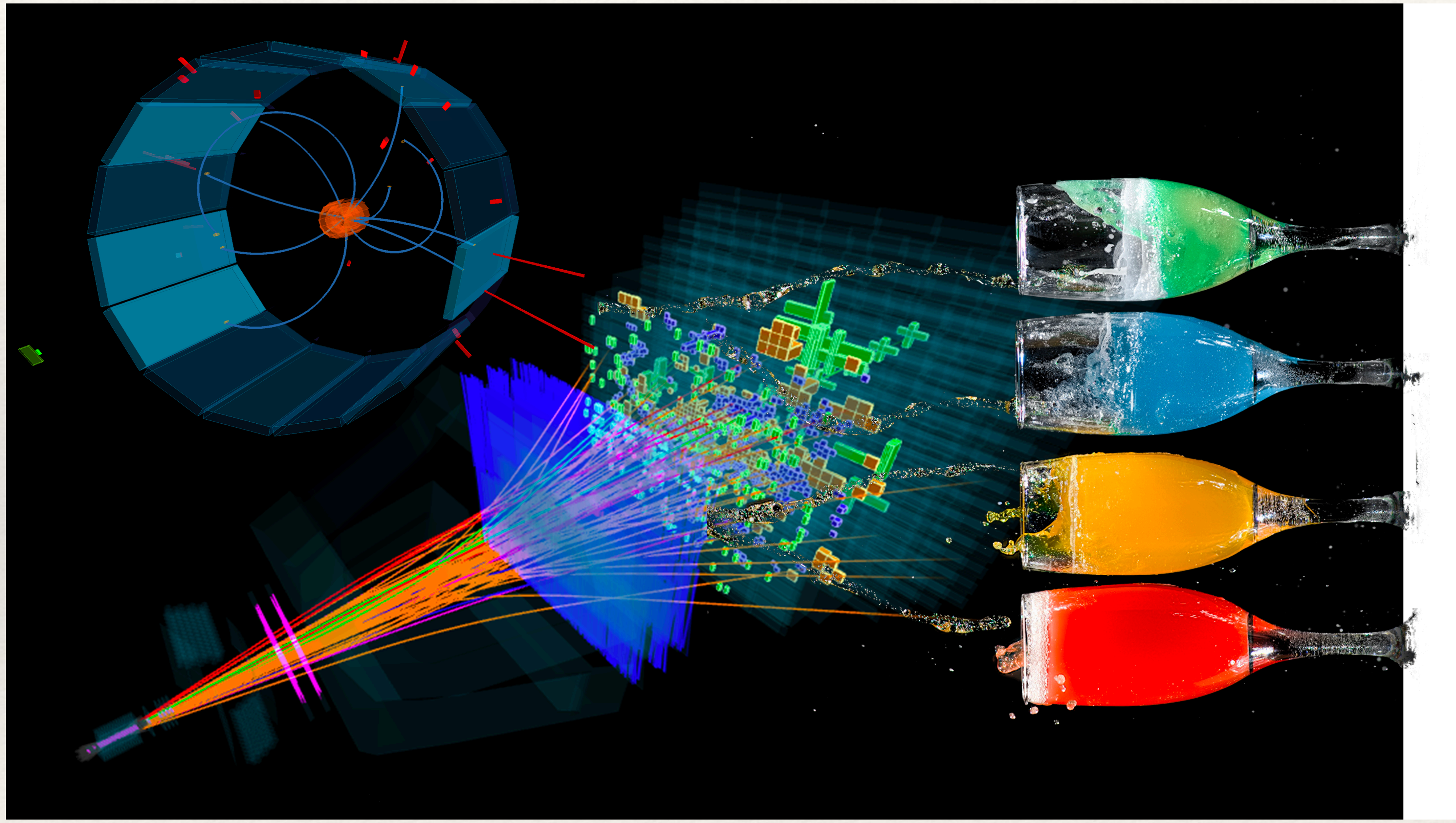
$\sqrt{s_{NN}}$	2013 5.02 TeV		2016 8.16 TeV		2015 5.02 TeV	2017 5.02 TeV	2018 5.02 TeV
$\mathcal{L}$	pPb 1.1 nb^{-1}	Pbp 0.5 nb^{-1}	pPb 13.6 nb^{-1}	Pbp 20.8 nb^{-1}	PbPb 10 μb^{-1}	XeXe 0.4 μb^{-1}	PbPb ~ 210 μb^{-1}

- Fixed Target mode (SMOG):
  - $\sqrt{s_{NN}}$: 69-110GeV

$$\int \mathcal{L}dt \sim 5\text{nb}^{-1} \times \frac{(protons\ on\ target)}{10^{22}} \times \frac{p_{gas}}{2 \times 10^{-7}\text{mbar}} \times \text{Exp\_efficiency}$$



Heavy flavor physics at LHCb



Heavy Flavor Production

- Production cross-section measurements
  - Provide powerful QCD test needed for tuning of event generators
  - Crucial ingredients for searches and measurements of rare or new processes
  - Crucial for precise measurements of b-hadron decay properties
- Studies of heavy hadron properties at production:
  - Measurement of CP violation observables ==>particle-antiparticle asymmetry
  - Amplitude analysis of heavy hadron decays ==> hadron polarization
  - Branching fractions and ratio measurements ==> b-hadron fragmentation functions

Recent LHCb Heavy Flavor Results

- **Heavy Quarkonium in pp**
  - Production of $\psi(2S)$ at 7 and 13 TeV
  - Production of $\eta_c(1S)$
- **Open charm and beauty in pp**
  - Λ_b and B_s production fractions at 13 TeV
  - B_c production fraction at 7 and 13 TeV
  - Ξ_b production fraction and asymmetry at 7, 8 and 13 TeV
  - Ξ_{cc} production rate at 13 TeV ==> Submitted to Chin. Phys. C
- **Pentaquark progresses ==> Zoom into the peak!**

Heavy Quarkonium production

- Two scales of production
  - Hard process for $Q\bar{Q}$ formation
  - Hadronisation of $Q\bar{Q}$ at softer scale
- Several models proposed to describe the underlying dynamics
  - Color-Singlet Model (CS)
  - Non-relativistic QCD (NRQCD)

$$d\sigma(pp \to H + X) = \sum_n d\sigma(pp \to Q\overline{Q}_n + X) \times \langle \mathcal{O}_n^H \rangle$$

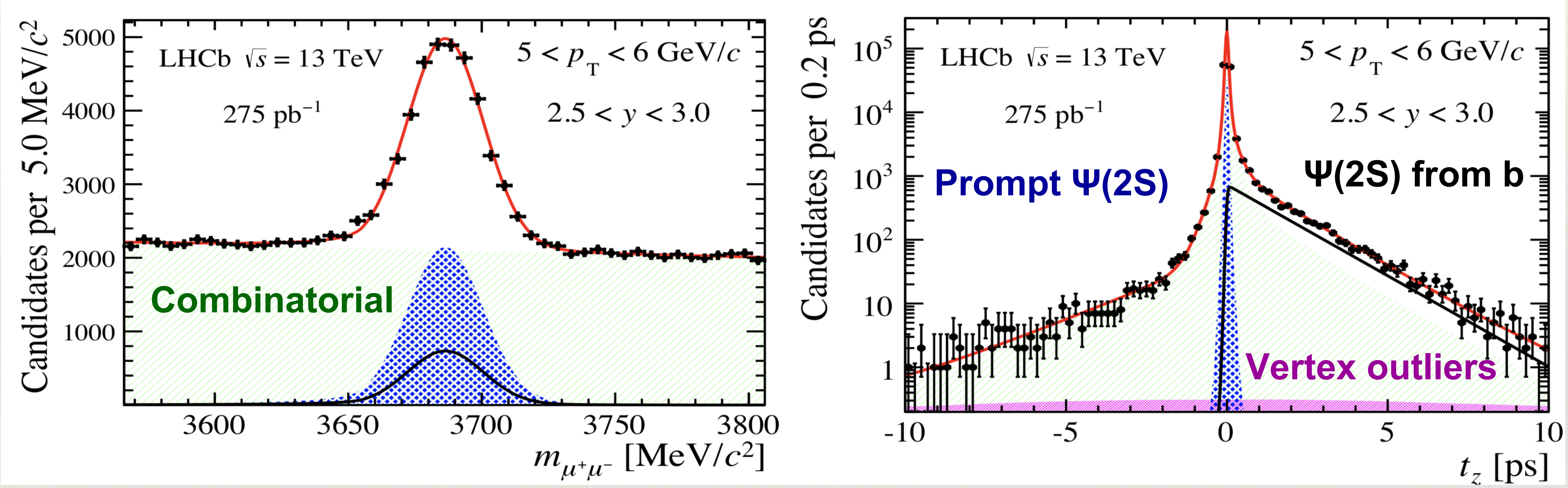
$Q\bar{Q}$ production:
short distance, perturbative cross sections and PDFs
Hadron production:
long distance matrix elements, non-perturbative part

Production of ψ(2S) at 7 and 13 TeV

arXiv:1908.03099

- Study separately prompt production (pp collision vertex) and production in b-decays
- From simultaneous fit to m(μ+μ-) and pseudo-lifetime distribution

L= 614 pb^{-1} at 7 TeV
L = 275 pb^{-1} at 13 TeV



$$t_z = \frac{(z_{\psi(2S)} - z_{\rm PV}) \times M_{\psi(2S)}}{p_z}$$

Integrated cross sections

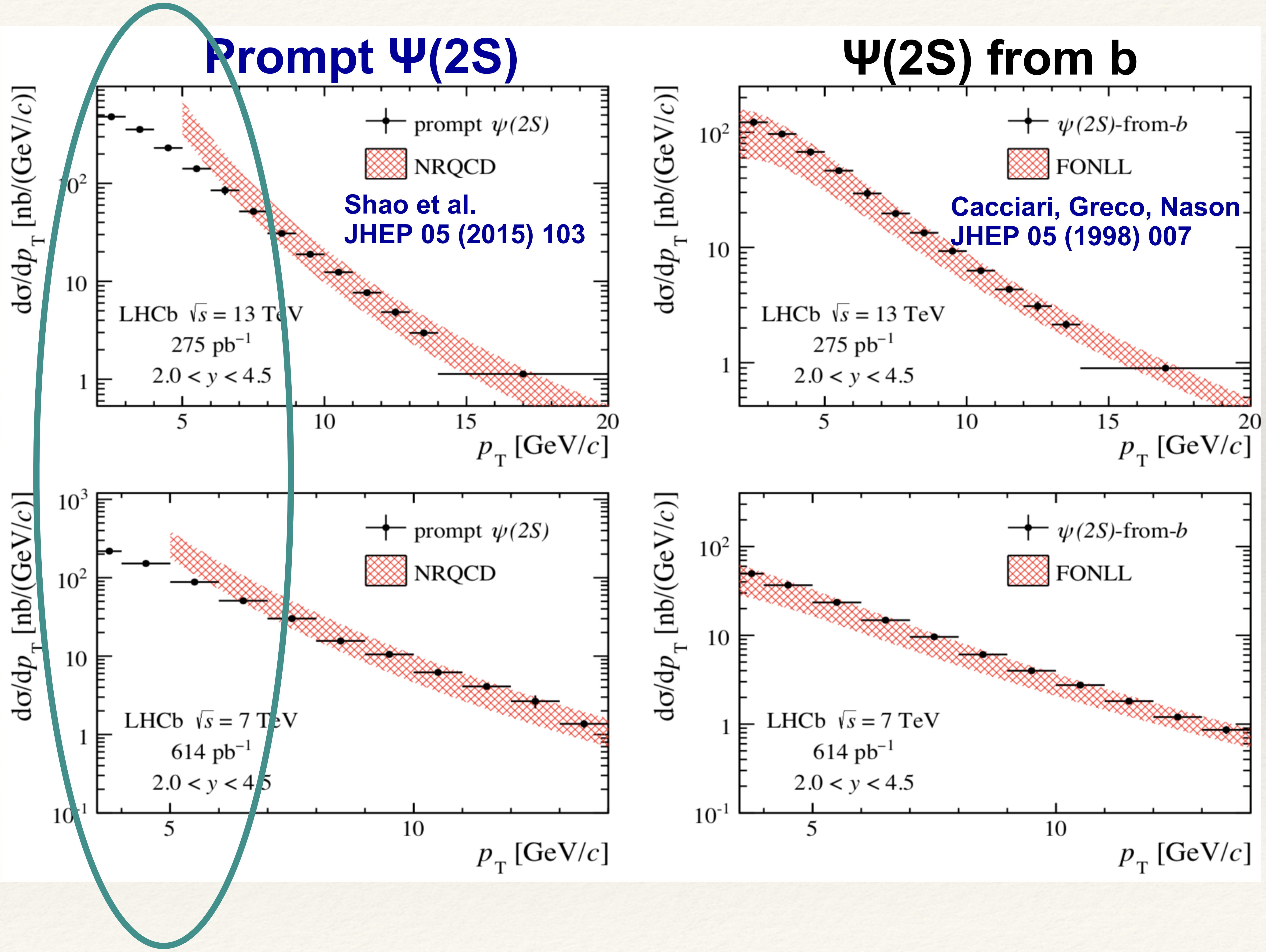
$$\sigma(\text{prompt } \psi(2S), 7\,\text{TeV}) = 0.471 \pm 0.001\,(\text{stat}) \pm 0.025\,(\text{syst})\,\mu\text{b}$$
$$\sigma(\psi(2S)\text{-from-}b, 7\,\text{TeV}) = 0.126 \pm 0.001\,(\text{stat}) \pm 0.008\,(\text{syst})\,\mu\text{b}$$

$$\sigma(\text{prompt } \psi(2S), 13\,\text{TeV}) = 1.430 \pm 0.005\,(\text{stat}) \pm 0.099\,(\text{syst})\,\mu\text{b}$$
$$\sigma(\psi(2S)\text{-from-}b, 13\,\text{TeV}) = 0.426 \pm 0.002\,(\text{stat}) \pm 0.030\,(\text{syst})\,\mu\text{b}$$

Assuming zero polarization
No large polarization observed at
7 TeV LHCb EPJC74(2014) 2872

Production of ψ(2S) at 7 and 13 TeV

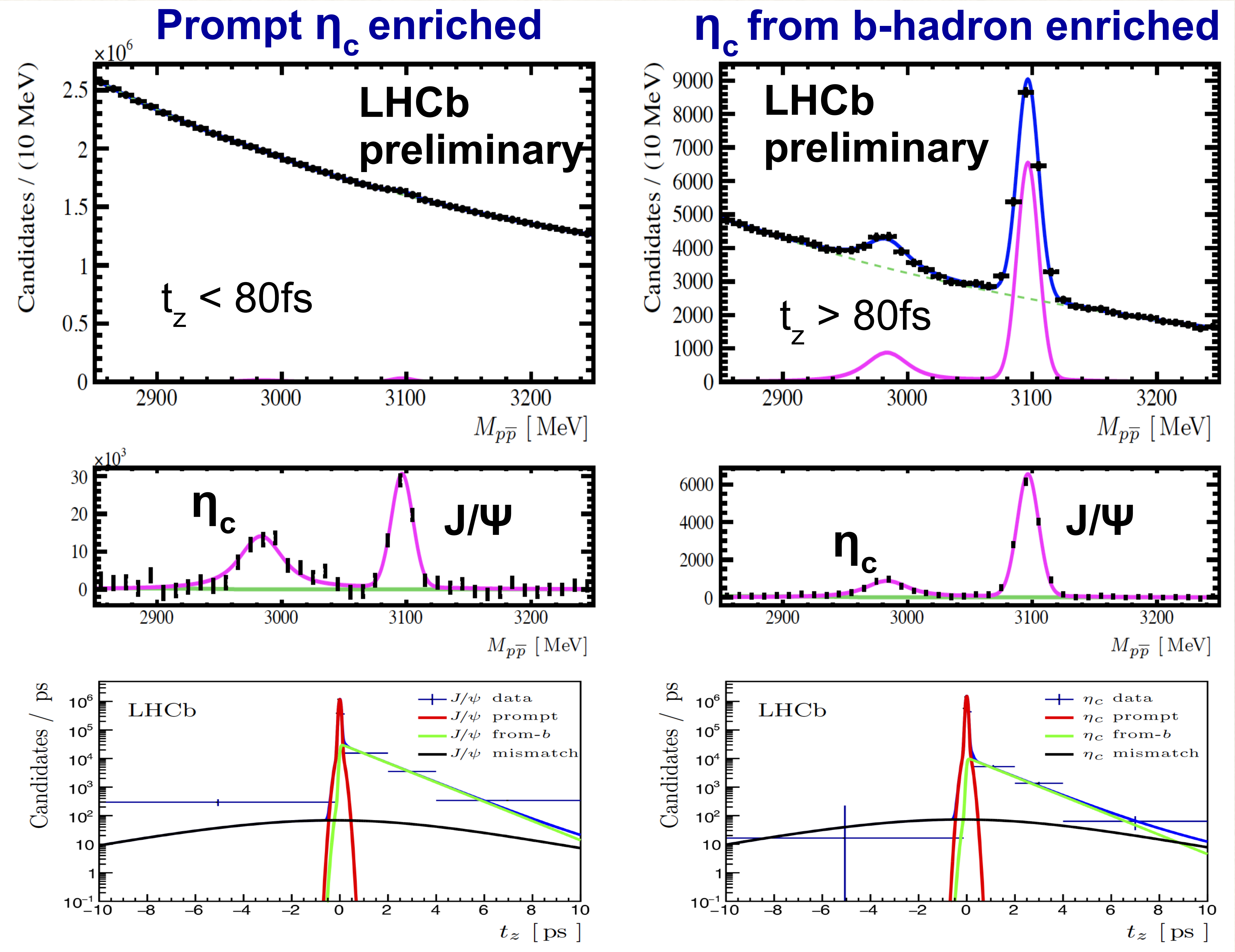
- Differential cross section
  - New measurement at 7 TeV supersedes earlier result based on smaller event sample
- Overall good agreement with predictions
- Deviation at low pT for prompt ψ(2S): important to extend theory predictions to low pT



Production of $\eta_c(1S)$

PAPER-2019-024

- Update of the analysis of the first prompt $\eta_c(1S) \to p\bar{p}$ production measurement at 7 and 8 TeV: LHCb EPJC75(2015) 311
- Measurement relative to $J/\psi \to p\bar{p}$ to cancel uncertainties
- Method1:
  Prompt and from b-hadron decays are separated cutting on t_z (Strategy used also at 7 and 8 TeV), then do mass fit.
- Method2:
  Yields extracted directly from a fit to t_z
- Both techniques yield consistent results

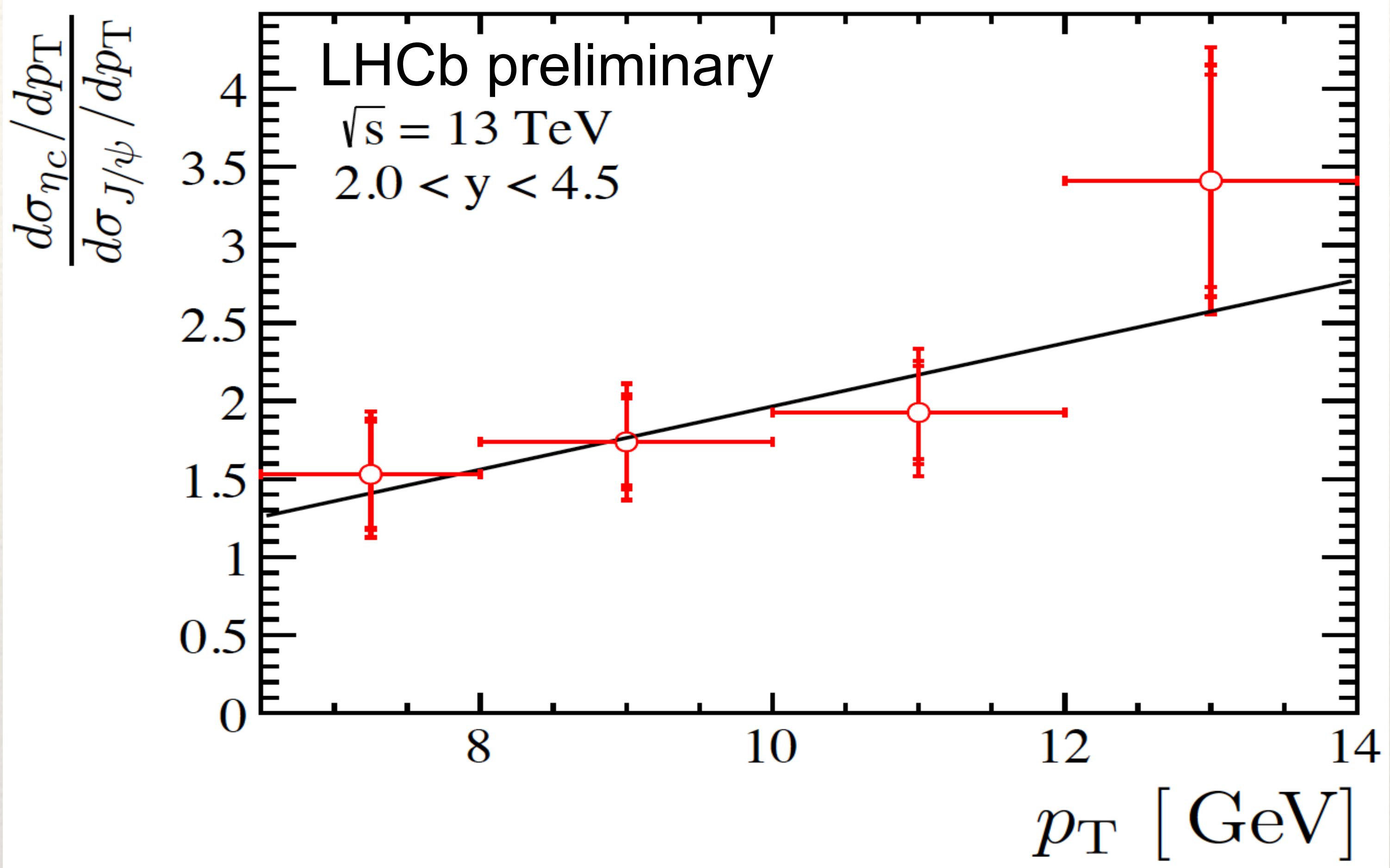


Production of $\eta_c(1S)$

PAPER-2019-024

- First measurement of $\eta_c(1S)$ production measurement at 13 TeV

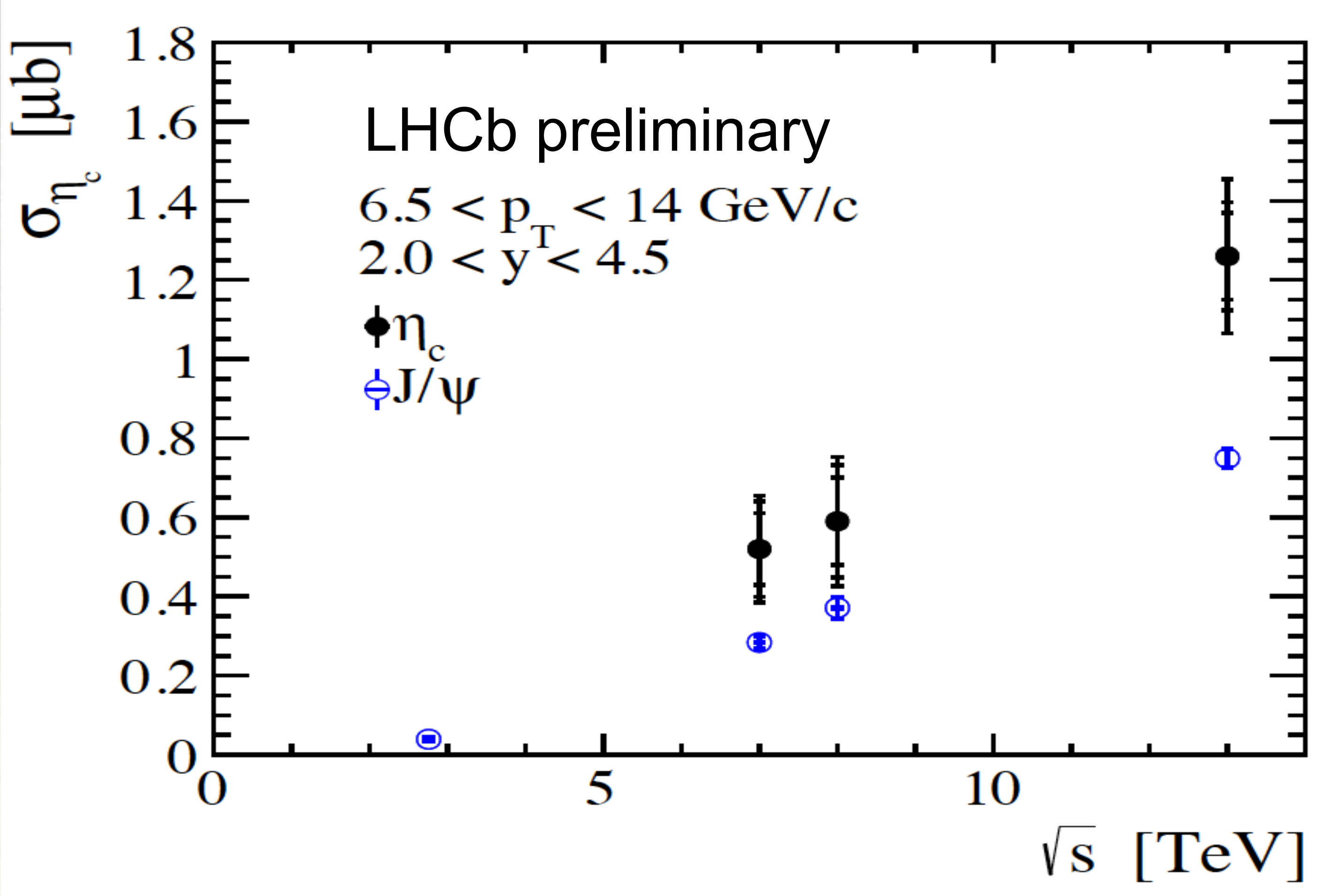
$$(\sigma_{\eta_c})^{6.5\,\mathrm{GeV}<p_T<14.0\,\mathrm{GeV},\,2.0<y<4.5}_{13\,\mathrm{TeV}} = 1.26 \pm 0.11 \pm 0.08 \pm 0.14\,\mu\mathrm{b}$$



- Result consistent with CS model prediction (Feng et al. NPB 945 (2019) 114662):

$$\sigma_{\eta_c} = 1.56^{+0.83+0.38}_{-0.49-0.17}$$

- With present statistics no energy dependence on $\sigma(\eta_c)/\sigma(J/\psi)$ has been observed



- Inclusive production in b-decays consistent with previous results

$$\mathcal{B}_{b\to\eta_c X} = (5.51 \pm 0.32 \pm 0.29 \pm 0.77) \times 10^{-3}$$

Measurements of *b*-hadron fragmentation fractions

- **The b-hadron production cross section can be expressed as a convolution of dσ(pp→b$\bar{b}$) and the b hadron fragmentation function $D_{b\to B}(x)$**

$$\frac{d\sigma^B}{dp_T^B} = \int dp_T^b dx \frac{d\sigma^{pp\to b\bar{b}}}{dp_T^b} \mathscr{D}_{b\to B}(x) \delta\left(p_T - x p_T^b\right)$$

Perturbative:
can be computed

Non-perturbative:
not known from first principles

- **The relative b-hadron production in bins of B meson kinematics allows us to experimentally probe the shape of the b quark fragmentation functions**
- **The probabilities for a b quark to hadronize in a specific hadron H_b (fragmentation fractions) are essential to determine absolute branching fractions of H_b**

$$f_{H_b} = \text{Prob}\left(b \to H_b\right)$$

Relative Λ_b and B_s production at 13 TeV

PRD 100 (2019) 031102

- Measure $f_s/(f_u + f_d)$ and $f_{\Lambda b}/(f_u + f_d)$ with inclusive semileptonic decays

$$\frac{N^{\rm obs}_{\rm SL}\left(\bar{B}^0_s\right)}{N^{\rm obs}_{\rm SL}(B^- + B^0)} = \frac{\sigma_{b\bar{b}} f_s}{\sigma_{b\bar{b}}\left(f_u + f_d\right)} \frac{\mathscr{B}_{\rm SL}\left(\bar{\boldsymbol{B}}^0_s\right)}{\mathscr{B}_{\rm SL}(\boldsymbol{B})} \frac{\varepsilon\left(\bar{B}^0_s\right)}{\varepsilon(B)}$$

$$= \frac{f_s}{f_u + f_d} \frac{\Gamma_{\rm SL}\left(\bar{\boldsymbol{B}}^0_s\right)\tau_{\bar{B}^0_s}}{\Gamma_{\rm SL}(\boldsymbol{B})\left(\tau_{B^-} + \tau_{\bar{B}^0}\right)/2} \frac{\varepsilon\left(\bar{B}^0_s\right)}{\varepsilon(B)}$$

Theoretical basis: Semileptonic widths for all b-hadrons are almost equal ($\Gamma_{SL}(H_b)=\Gamma_{SL}$) [I. Bigi et al, JHEP 09 (2011) 012]

Differences predicted to be around *1%* (heavy quark expansion)

Particle	τ (ps) measured	$\mathcal{B}_{\rm SL}$ (%) measured	Correction (%) [5]	$\mathcal{B}_{\rm SL}$ (%) used
$\bar{B}^0$	1.520 ± 0.004	10.30 ± 0.19		10.30 ± 0.19
B^-	1.638 ± 0.004	11.08 ± 0.20		11.08 ± 0.20
$\langle \bar{B}^0 + B^- \rangle$		10.70 ± 0.19		10.70 ± 0.19
$\bar{B}^0_s$	1.526 ± 0.015		-1.0 ± 0.5	10.24 ± 0.21
Λ^0_b	1.470 ± 0.010		3.0 ± 1.5	10.24 ± 0.25

Known

Translation for people who don't familiar with B physics:

$B^0_s/\bar{B}^0_s = (s\bar{b})/(\bar{s}b)$
$B^0/\bar{B}^0 = (d\bar{b})/(\bar{d}b)$
$B^+/B^- = (u\bar{b})/(\bar{u}b)$
$\Lambda^0_b = (udb)$

Measurable

$$\frac{f_s}{f_u + f_d} = \frac{n_{\rm corr}(\bar{B}^0_s \to D_s\mu)}{n_{\rm corr}(B \to D^0\mu) + n_{\rm corr}(B \to D^+\mu)} \frac{\tau_{B^-} + \tau_{\bar{B}^0}}{2\tau_{\bar{B}^0_s}} (1 - \xi_s) - \frac{\mathcal{B}(B \to D_s K\mu)}{\langle \mathcal{B}_{SL} \rangle} \frac{\epsilon(\bar{B} \to D^+_s)}{\epsilon(\bar{B}^0_s \to D^+_s)}$$

SU(3) breaking correction $\xi_s = (-1 \pm 0.5)\%$

Corrected yields of $\bar{B}^0_s$, $\bar{B}^0$, B^-

Subtraction of $\bar{B}^0(B^-) \to D^+_s K\mu^-\bar{\nu}_\mu X$ contributions in $\bar{B}^0_s$ signals

Measurable

Relative Λ_b and B_s production at 13 TeV

- **Measure $f_s/(f_u + f_d)$ and $f_{\Lambda b}/(f_u + f_d)$ with inclusive semileptonic decays**

PRD 100 (2019) 031102

$$\frac{f_s}{f_u+f_d} = \frac{n_{\rm corr}(\bar{B}^0_s \to D_s\mu)}{n_{\rm corr}(B\to D^0\mu)+n_{\rm corr}(B\to D^+\mu)}\frac{\tau_{B^-}+\tau_{\bar{B}^0}}{2\tau_{\bar{B}^0_s}}(1-\xi_s)$$

$$-\frac{\mathcal{B}(B\to D_s K\mu)}{\langle\mathcal{B}_{SL}\rangle}\frac{\epsilon(\bar{B}\to D_s^+)}{\epsilon(\bar{B}^0_s\to D_s^+)}$$

Corrected yields of $\bar{B}^0_s$, $\bar{B}^0$, B^-

SU(3) breaking correction $\xi_s = (-1 \pm 0.5)\%$

Subtraction of $\bar{B}^0(B^-) \to D_s^+ K\mu^-\bar{\nu}_\mu X$ contributions in $\bar{B}^0_s$ signals

$$\frac{f_{\Lambda^0_b}}{f_u+f_d} = \frac{n_{\rm corr}(\Lambda^0_b \to H_c\mu^-)}{n_{\rm corr}(B\to D^0\mu^-)+n_{\rm corr}(B\to D^+\mu^-)}\frac{\tau_{B^-}+\tau_{\bar{B}^0}}{2\tau_{\Lambda^0_b}}(1-\xi_{\Lambda^0_b})$$

Corrected yields of Λ^0_b, $\bar{B}^0$, B^-

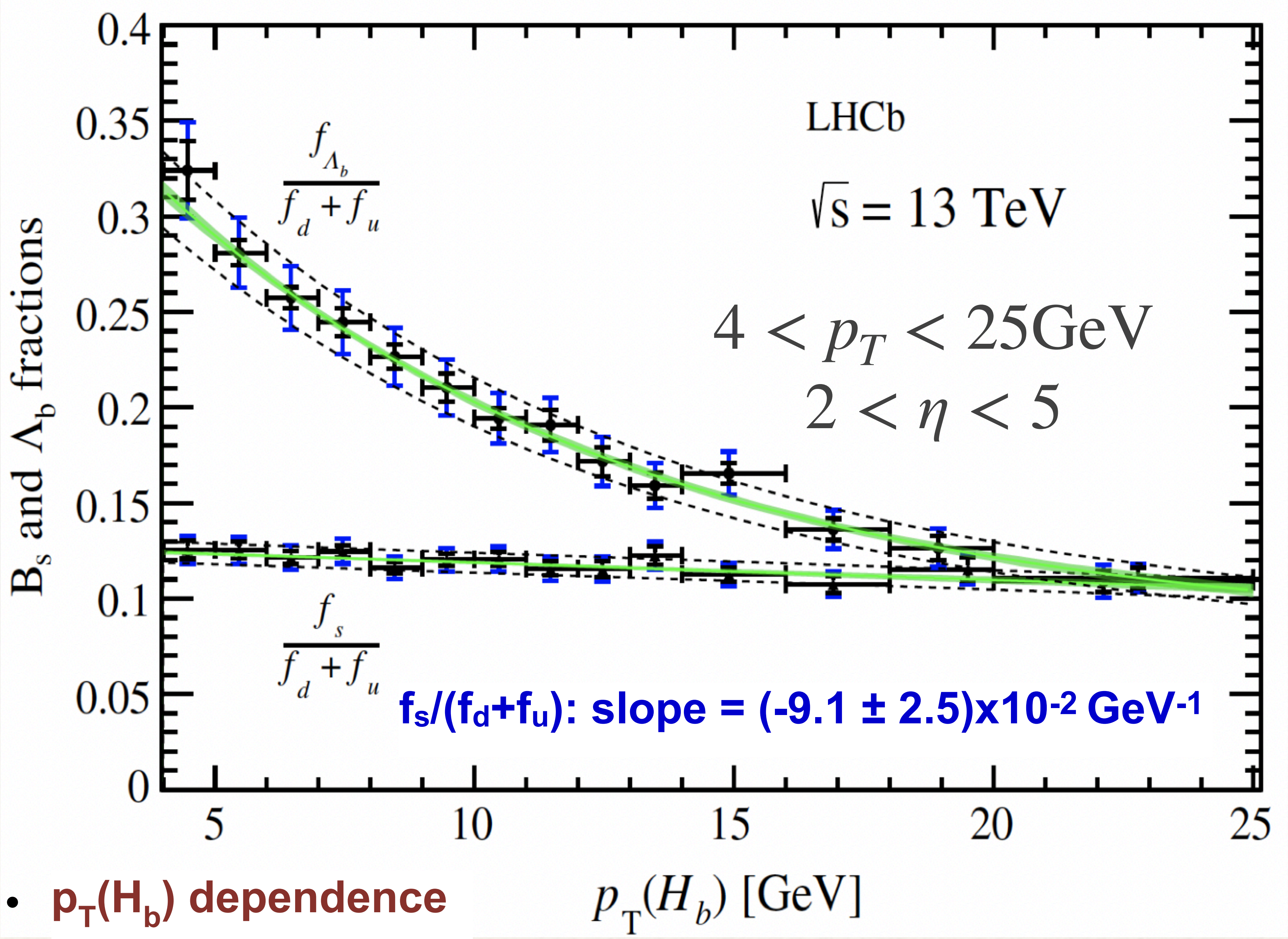
Chromomagnetic correction $\xi_{\Lambda^0_b} = (3 \pm 1.5)\%$

Relative Λ_b and B_s production at 13 TeV

PRD 100 (2019) 031102

- The measurements at 13 TeV, L=1.67 fb^{-1} give:

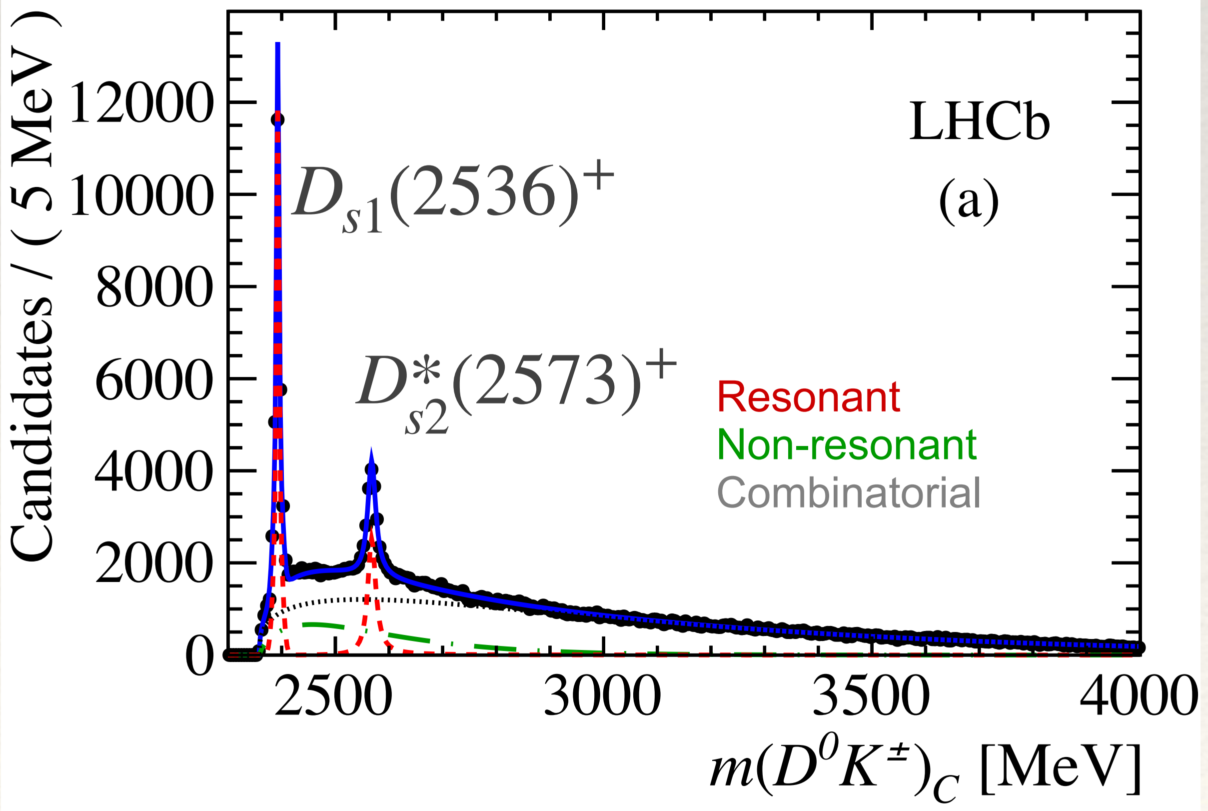
$$\frac{f_s}{f_u + f_d} = 0.122 \pm 0.006, \quad \frac{f_{\Lambda_b^0}}{f_u + f_d} = 0.259 \pm 0.018,$$

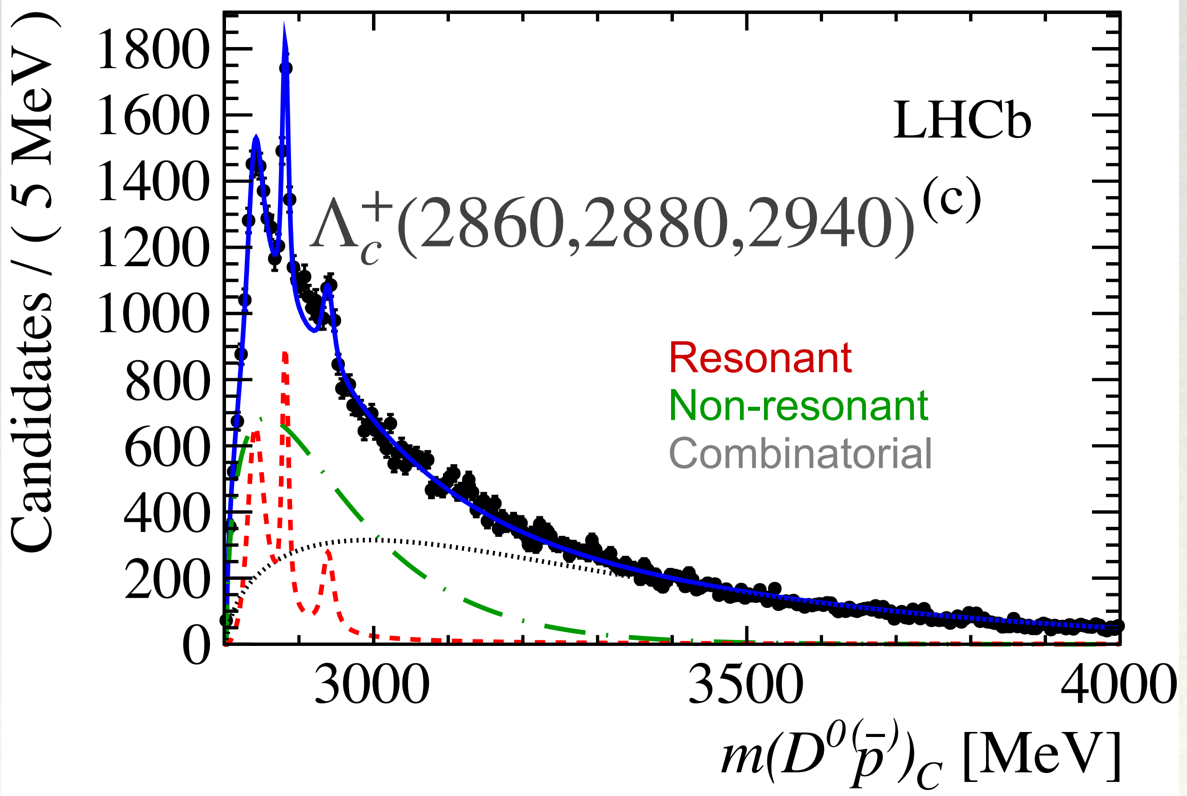


- $p_T(H_b)$ dependence
- No η dependence

Update of the previous measurement at 7TeV
LHCb PRD 85(2012)032008
(different $0 < p_T < 25$ GeV)

- The yields n_{corr} are corrected for efficiency and branching ratios, and also have additional contributions added, with background subtracted.
  - e.g, $n_{corr}(\bar{B}_s^0 \to D_s^+ \mu^-)$ has contributions from $D^0 K^+ \mu^-$ yields added (both exciting states D_{s1}^+ and D_{s2}^{*+}, and non-resonance), and has small components of $B \to D_s^+ \bar{K}^0$ subtracted.
  - Similar treatment for $n_{corr}(B \to D^0 \mu^-)$, $n_{corr}(B \to D^+ \mu^-)$, and $n_{corr}(\Lambda_b^0 \to H_c \mu^-)$
  - where the $D^0 K^+ \mu^-$ and $D^0 p \mu^-$ yields are extracted from a simultaneous fit to the $m(D^0 K^\pm)$ or $m(D^0 p)$ and vertex likelihood difference $\log(\Delta\chi_V^2)$





B_c production fraction

PAPER-2019-033

7, 13 TeV, L=1, 1.6 fb^{-1}
$4.5 < p_T < 25\text{GeV},\ 2.5 < \eta < 4.5$

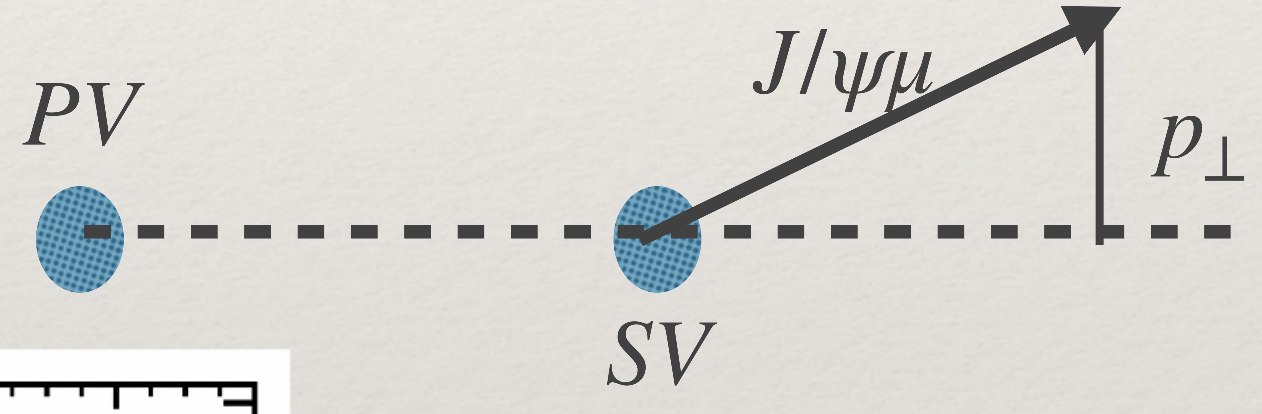
- **With a similar approach used to extract $f_{s,\Lambda b}$ /(f_d+ f_u)**
- **Using semileptonic $B_c \to J/\psi\mu\nu$ decays**

$$\frac{f_c}{f_u+f_d} \equiv \frac{n_{\rm cor}(B_c^- \to J/\psi\,\mu^-\overline{\nu})}{n_{\rm cor}(B \to D^0 X \mu^-\overline{\nu}) + n_{\rm cor}(B \to D^+ X \mu^-\overline{\nu})} \cdot \frac{\langle \mathcal{B}_{\rm sl}\rangle}{\mathcal{B}(B_c^- \to J/\psi\,\mu^-\overline{\nu})}$$

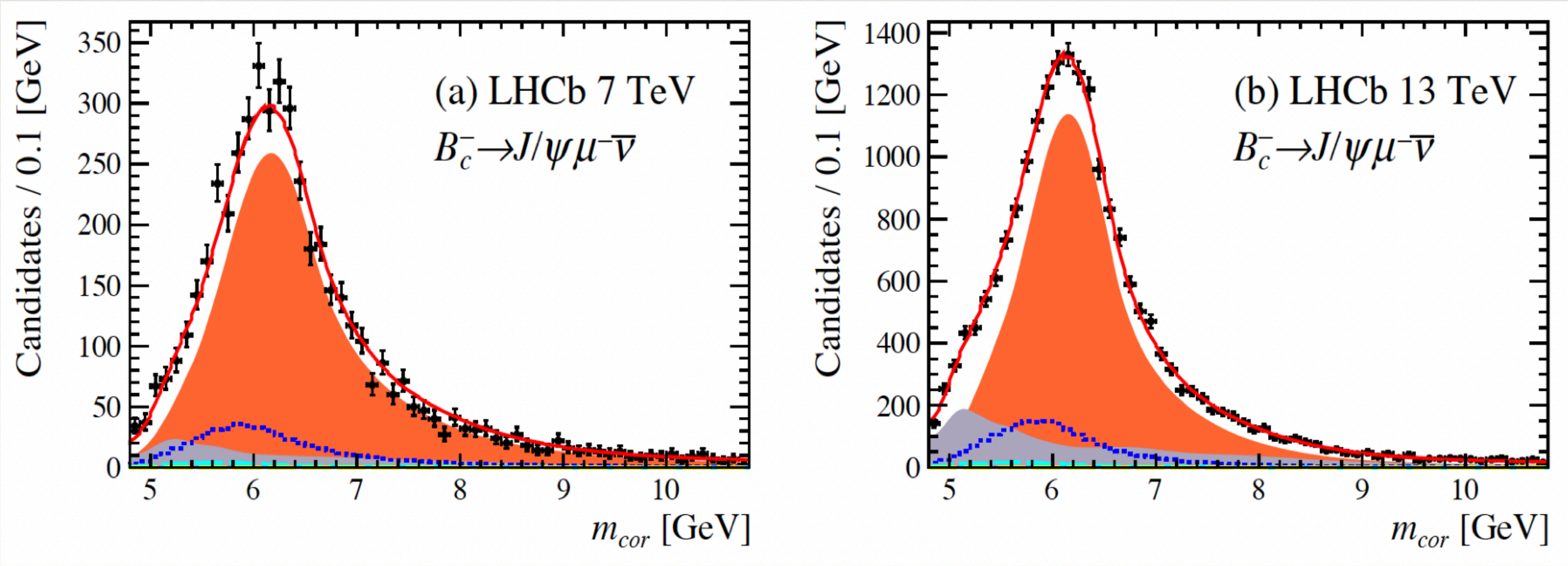
$\Gamma_{SL}(B_c) \neq \Gamma_{SL}(B)$

Need inputs from theory: large discrepancies between models

- **Signal yields extracted by fitting** $m_{\rm cor} \equiv \sqrt{m^2_{H_c\mu} + p_\perp^2} + p_\perp$



Potential background from
$B_c \to \psi(2S)\,\mu\,\nu$
found to be negligible



$B_c \to J/\psi\ \mu\ \nu$
$B_c \to J/\psi\ \tau\ \nu$
$B_c \to \chi_{c0,1,2}\ \mu\ \nu$
Combinatorial

B_c production fraction

PAPER-2019-033

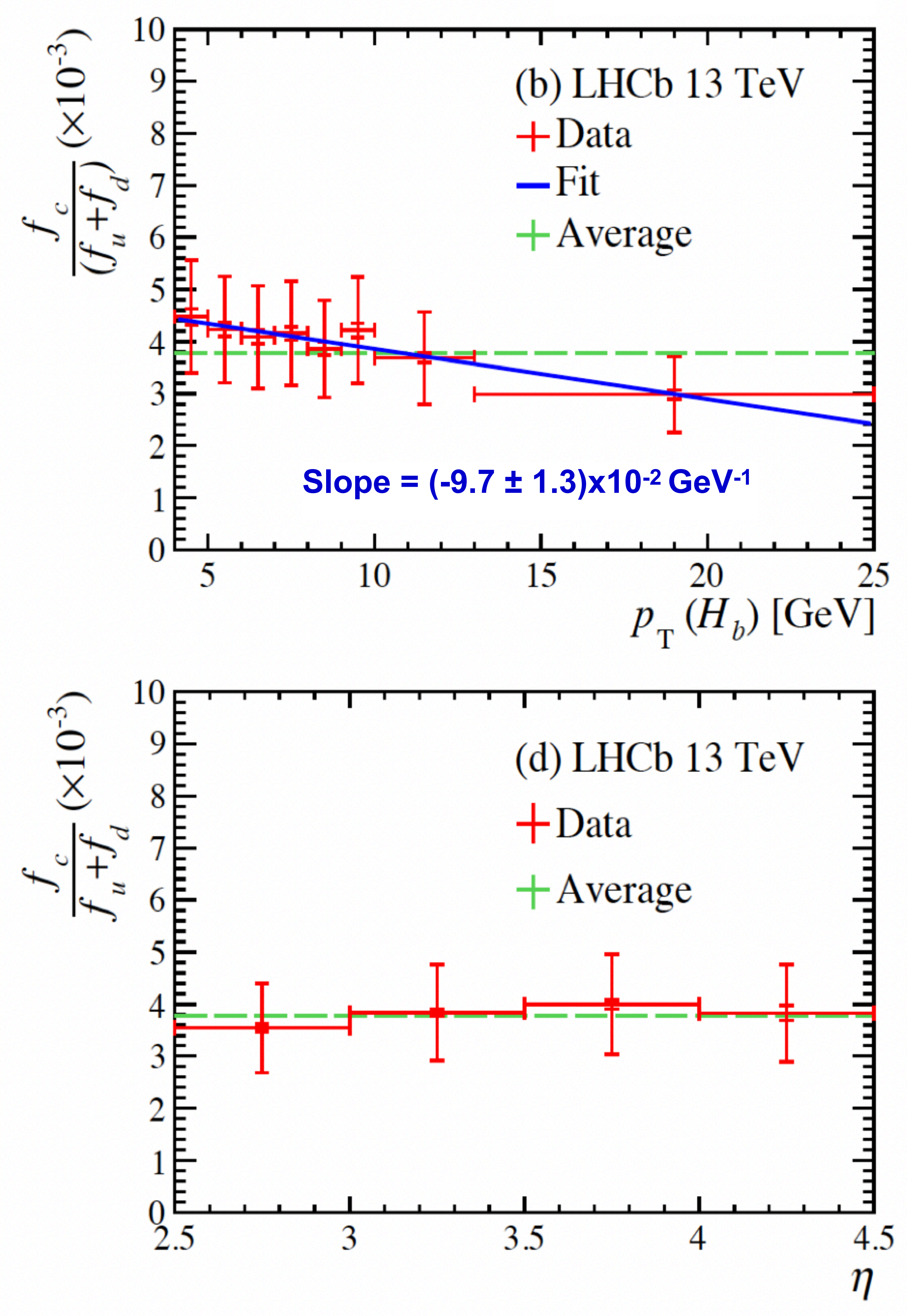
- **Measured:**

$$\frac{f_c}{f_u+f_d}\cdot\mathcal{B}(B_c^-\to J/\psi\mu^-\overline{\nu}) = (7.07\pm0.15\pm0.24)\cdot10^{-5} \text{ for 7 TeV},$$
$$\frac{f_c}{f_u+f_d}\cdot\mathcal{B}(B_c^-\to J/\psi\mu^-\overline{\nu}) = (7.36\pm0.08\pm0.30)\cdot10^{-5} \text{ for 13 TeV}.$$

- **Assume BF(Bc→J/ψμν)=(1.95 ± 0.46)%, where the uncertainty reflects the spread in the calculations**

$$\frac{f_c}{f_u+f_d} = (3.63\pm0.08\pm0.12\pm0.86)\cdot10^{-3} \text{ for 7 TeV},$$
$$\frac{f_c}{f_u+f_d} = (3.78\pm0.04\pm0.15\pm0.89)\cdot10^{-3} \text{ for 13 TeV},$$

- **Measurement of the form factors and precise lattice calculations would pin down the error on f_c /(f_d+ f_u)**
- **The slope of the p_T dependence is similar to the one measured for the B_s**
- **Ratio(13 TeV/7 TeV)=1.02 ± 0.02 ± 0.04: no increase of B_c fraction with √s**



Ξ_b production fraction

PRD 99, (2019) 052006

- **Decay chain: $\Xi_b^- \to J/\psi\Xi^-$, $\Xi^- \to \Lambda\pi^-$**
- **Production rate measured as ratio to kinematically similar decay $\Lambda_b \to J/\psi\Lambda$**

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = \frac{n_{\text{corr}}\left(\Xi_b^- \to J/\psi\Xi^-\right)}{n_{\text{corr}}\left(\Lambda_b^0 \to J/\psi\Lambda\right)} \frac{\Gamma\left(\Lambda_b^0 \to J/\psi\Lambda\right)}{\Gamma\left(\Xi_b^- \to J/\psi\Xi^-\right)} \frac{\tau_{\Lambda_b^0}}{\tau_{\Xi_b^-}}$$

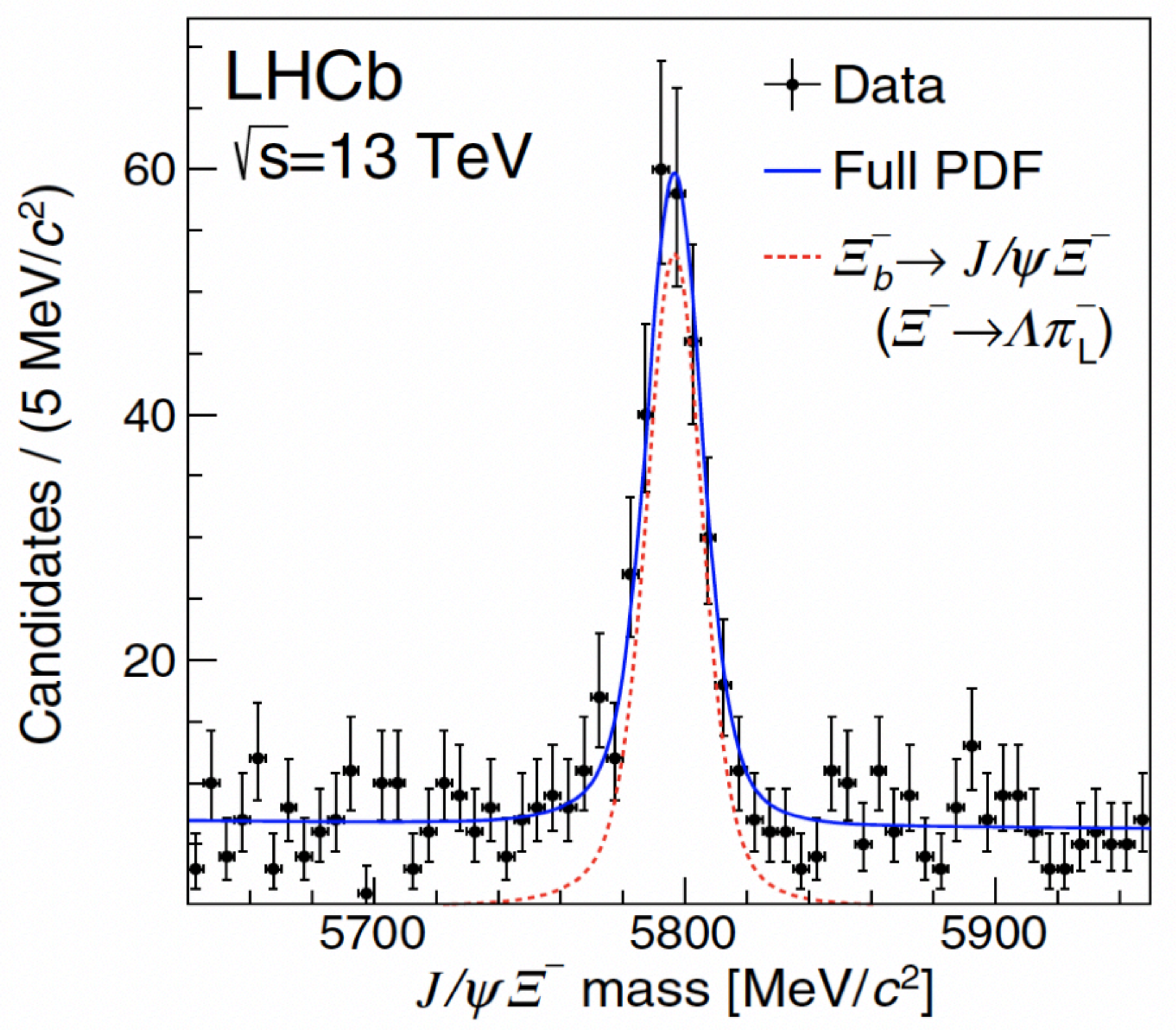
Measured yields corrected for efficiencies — 3/2 in SU(3) flavor symmetry — PDG values

7, 8,13 TeV,
L=1, 2, 1.6 fb-1
$4.5 < p_T < 25\text{GeV}$
$2.5 < \eta < 4.5$

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (6.7 \pm 0.5 \pm 0.5 \pm 2.0) \times 10^{-2} \quad [\sqrt{s} = 7, 8 \text{ TeV}]$$

SU(3) flavor symmetry (30%)

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (8.2 \pm 0.7 \pm 0.6 \pm 2.5) \times 10^{-2} \quad [\sqrt{s} = 13 \text{ TeV}].$$



- **Predictions:**

$f_{\Xi_b^0}/f_{\Lambda_b^0} = 0.065 \pm 0.020$ Wang, EPJC 79 5 (2019) 429

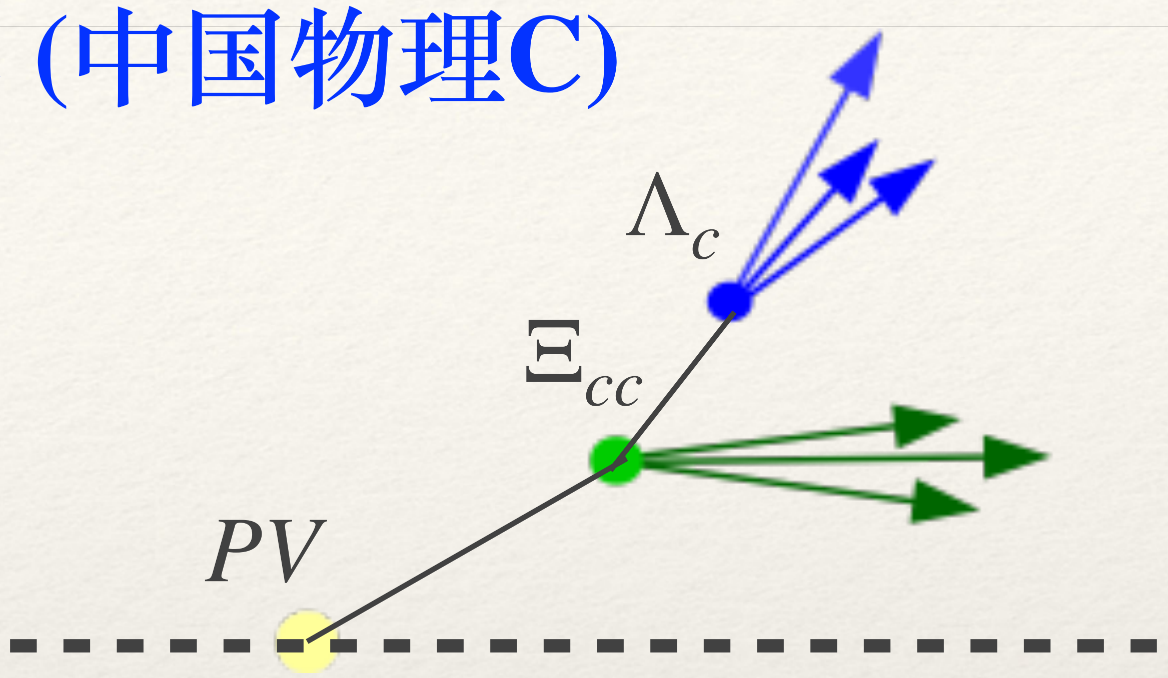
$f_{\Xi_b^0}/f_{\Lambda_b^0} = 0.050 \pm 0.020$ Jiang, Yu EPJC 78, (2018) 224

- First measurement of Ξ_b production
- Also first measured of the Ξ_b production asymmetry
- Precise determination of the Ξ_b mass

Ξ_{cc}^{++} production at 13 TeV

PAPER-2019-035

Submitted to Chin. Phys. C (中国物理C)



13 TeV
L=1.65 fb^{-1}
$4 < p_T < 15$GeV
$2.0 < \eta < 4.5$

- **Ξ_{cc}^{++} observed by LHCb: $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$**

  M(Ξ_{cc}^{++}) = 3621.40 ± 0.78 MeV [LHCb PRL119(2017)112001]
  Lifetime: τ = 0.256 ± 0.028 ps [LHCb PRL121(2018)052002]
  Observation of $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ [LHCb PRL121(2018)162002]
  Non-observation of $\Xi_{cc}^{++} \to DpK\pi$ [LHCb arXiv:1905.02421 (JHEP)]

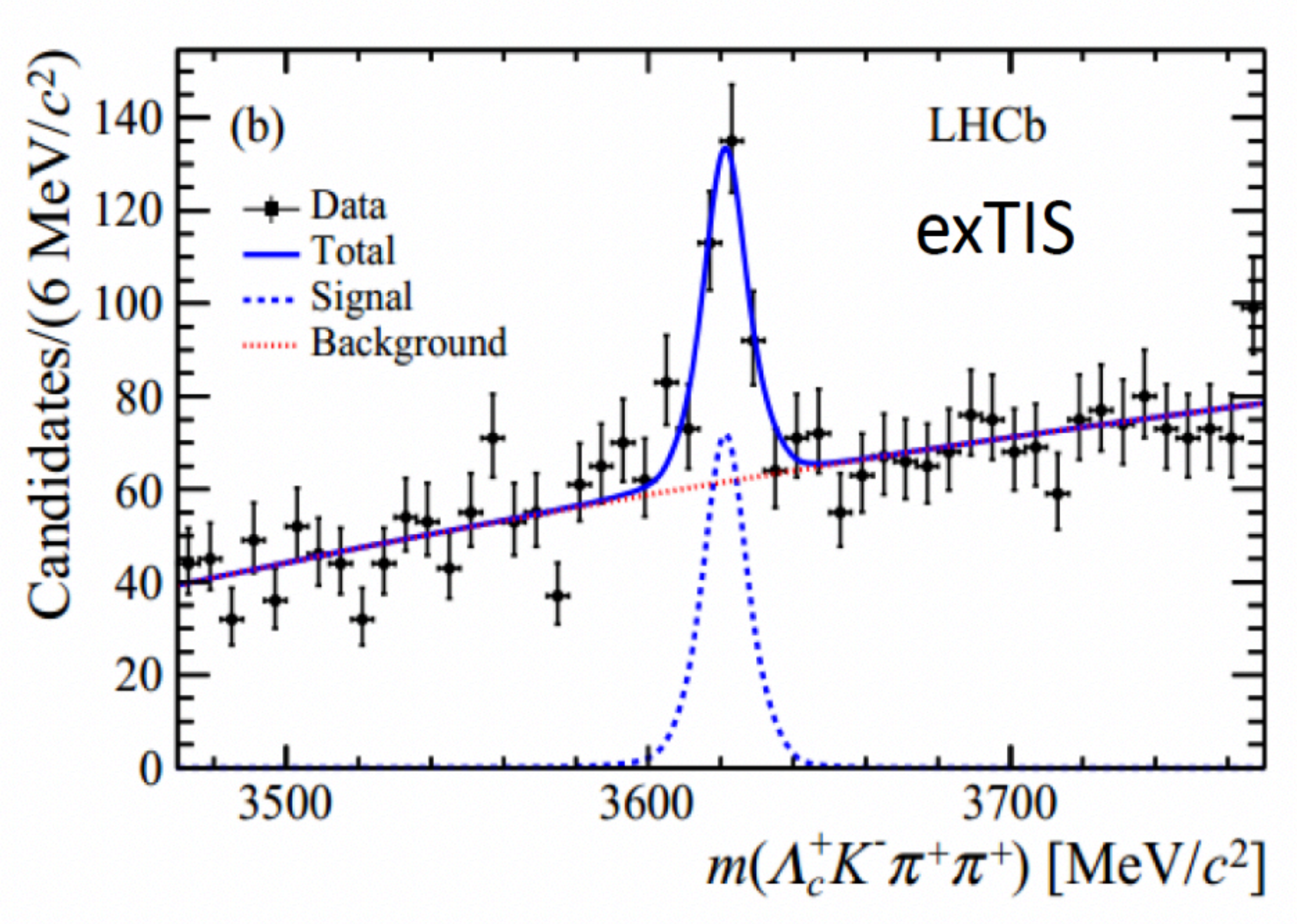
- **Ξ_{cc}^{++} production ratio with respect to prompt Λ_c**

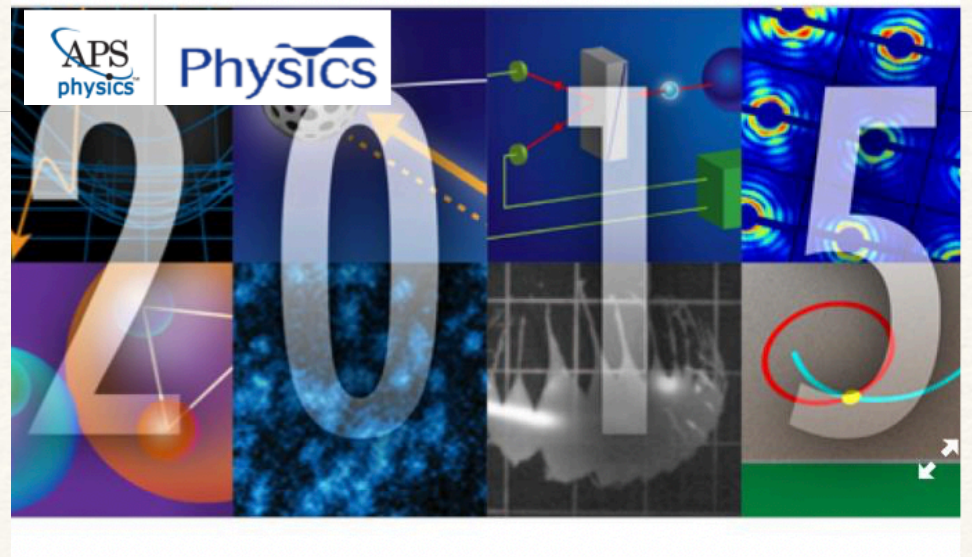
$$R \equiv \frac{\sigma(\Xi_{cc}^{++})\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}{\sigma(\Lambda_c^+)} = \frac{N_{\rm sig}}{N_{\rm con}} \frac{\varepsilon_{\rm con}}{\varepsilon_{\rm sig}}$$

- **Trigger acceptance (and systematics) depends on the assumed Ξ_{cc}^{++} lifetime**

- **First measurement of Ξ_{cc}^{++} production rate**

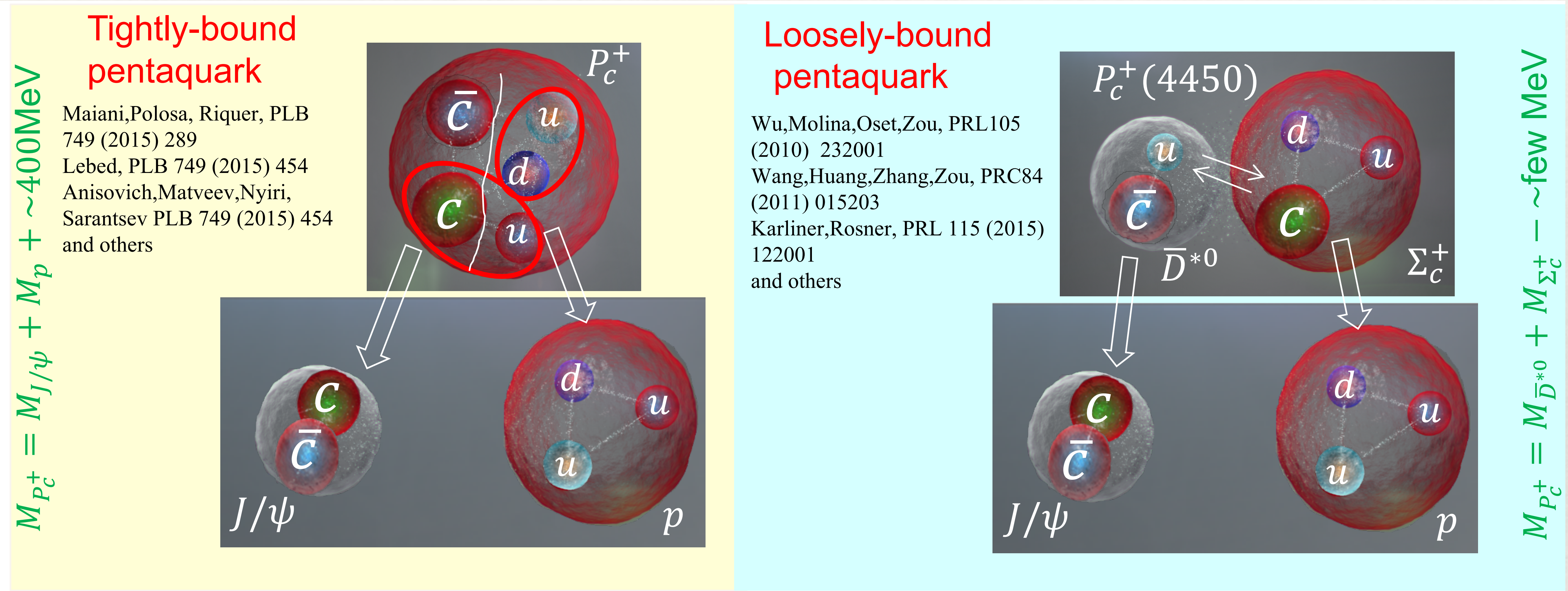
$$\frac{\sigma(\Xi_{cc}^{++})}{\sigma(\Lambda_c^+)} \cdot \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) = (2.22 \pm 0.27 \pm 0.29) \times 10^{-4}$$

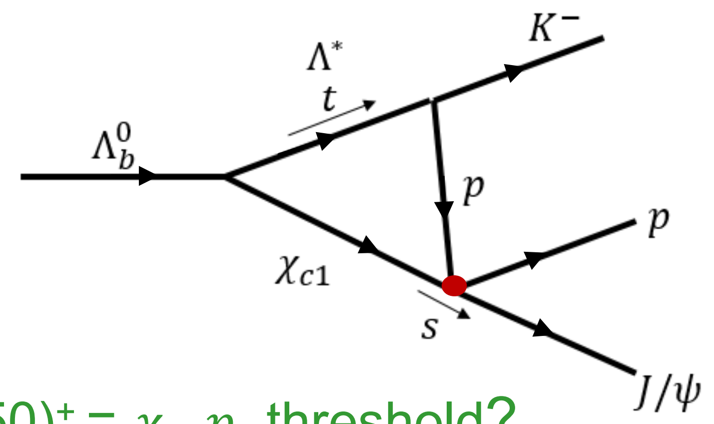




Pentaquark

- Interest in pentaquarks arises from the fact that they would be new type of particles beyond the the simplest quark combination:



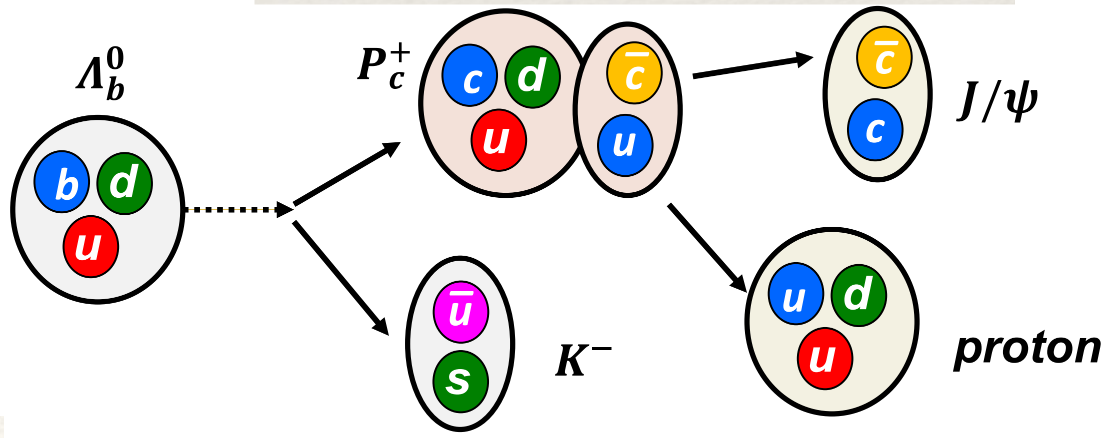


$P_c(4450)^+ = \chi_{c1}p$ threshold?

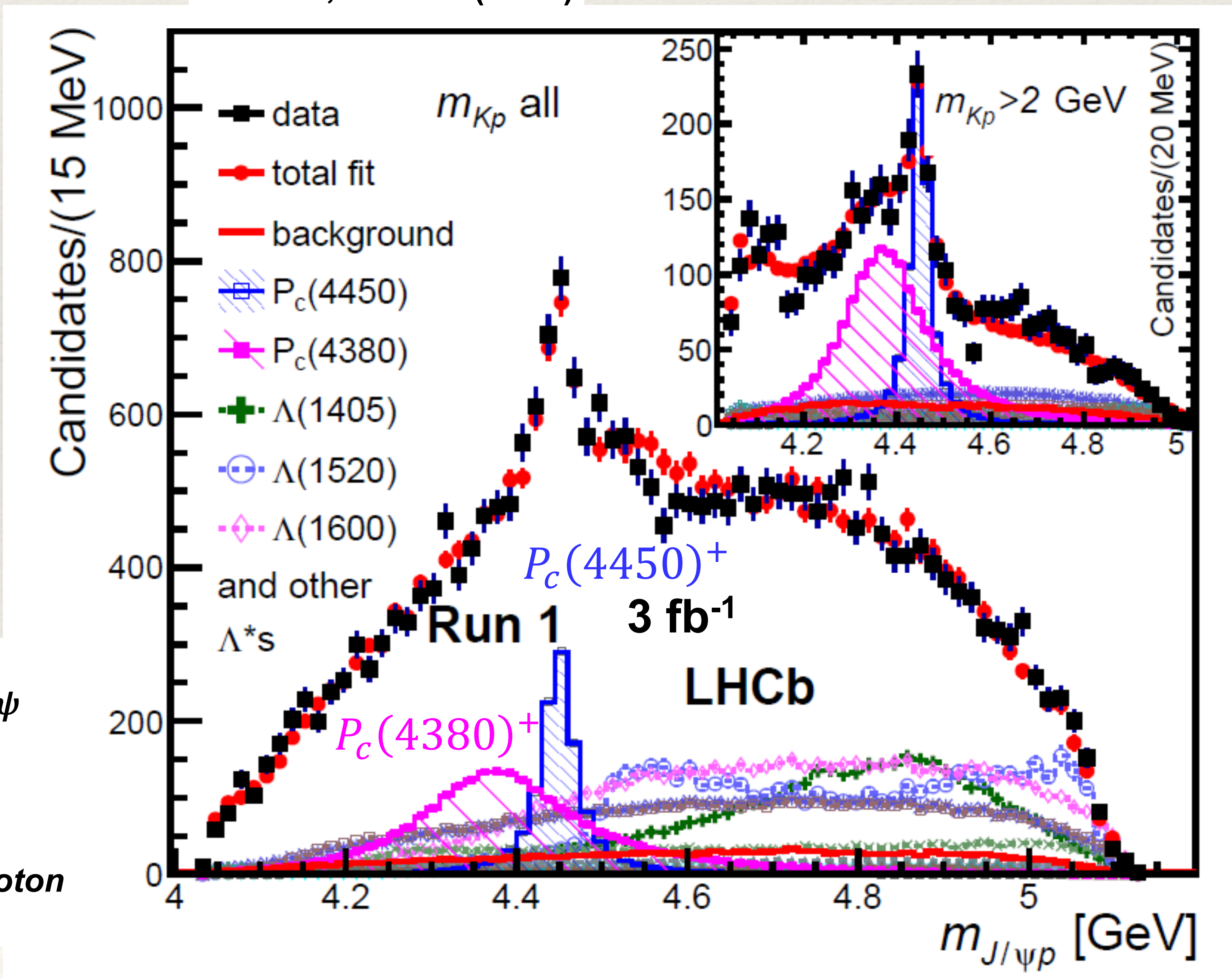
Triangle diagram

Guo,Meissner,Wang,Yang, PRD 92 (2015) 071502
Liu, Wang, Zhao, PLB 757 (2016) 231
Mikhasenko, arXiv:1507.06552
Szczepaniak, PLB 757 (2016) 61
and others

- After 50 years of experimental searches, only LHCb has given a convincing results in 2015
  - Two $J/\psi p$ resonances, consistent with pentaquarks, are found in $\Lambda^0_b \to J/\psi p K^-$ decays : $P_c(4450)^+$ and $P_c(4380)^+$



PRL 115, 072001 (2015)

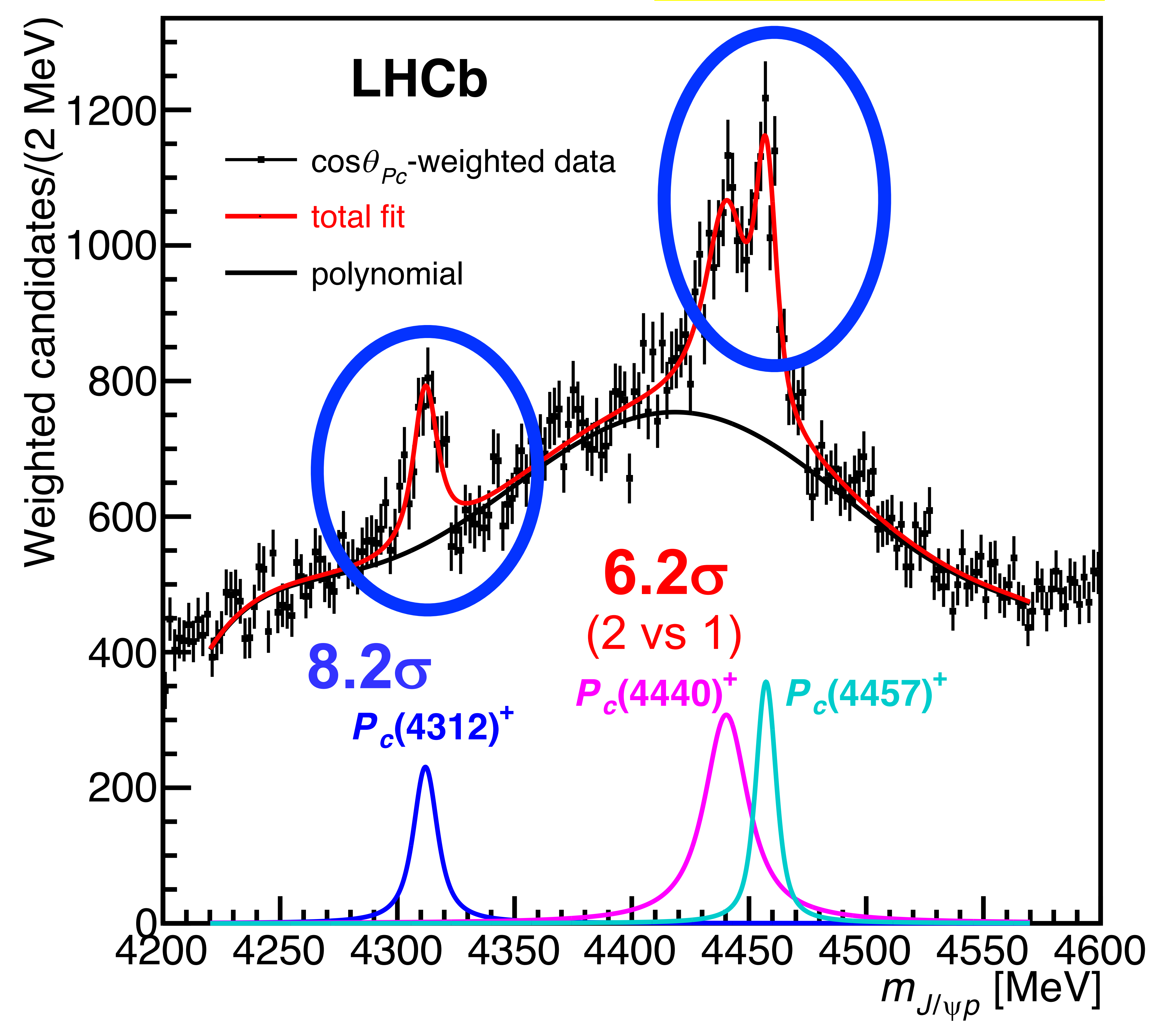


Pentaquark: New double peaks

PRL122 (2019) 222001

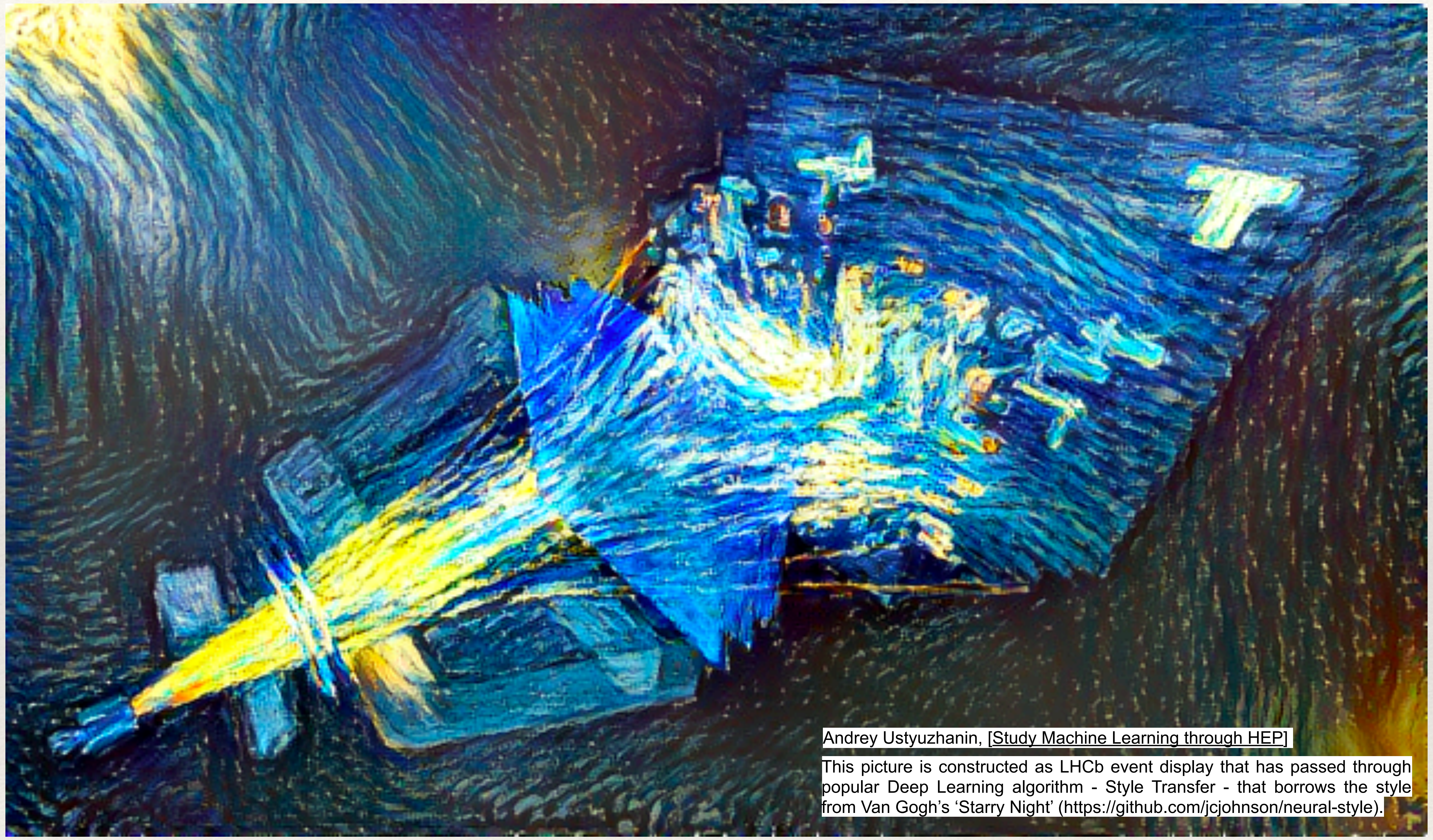
- With Run1+Run2 about 9 fb^{-1} , 10 times more statistics:
  - Two narrower pentaquark states are observed at previous 4450 MeV:
    $Pc(4440)^+$ and $Pc(4457)^+$
  - A new narrow peak at lower mass is also uncovered:
    $Pc(4312)^+$
- Masses and widths are determined by 1D mass fits

State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$



- 6D amplitude analysis are on going for spin and parity

Heavy Ion Collisions at LHCb

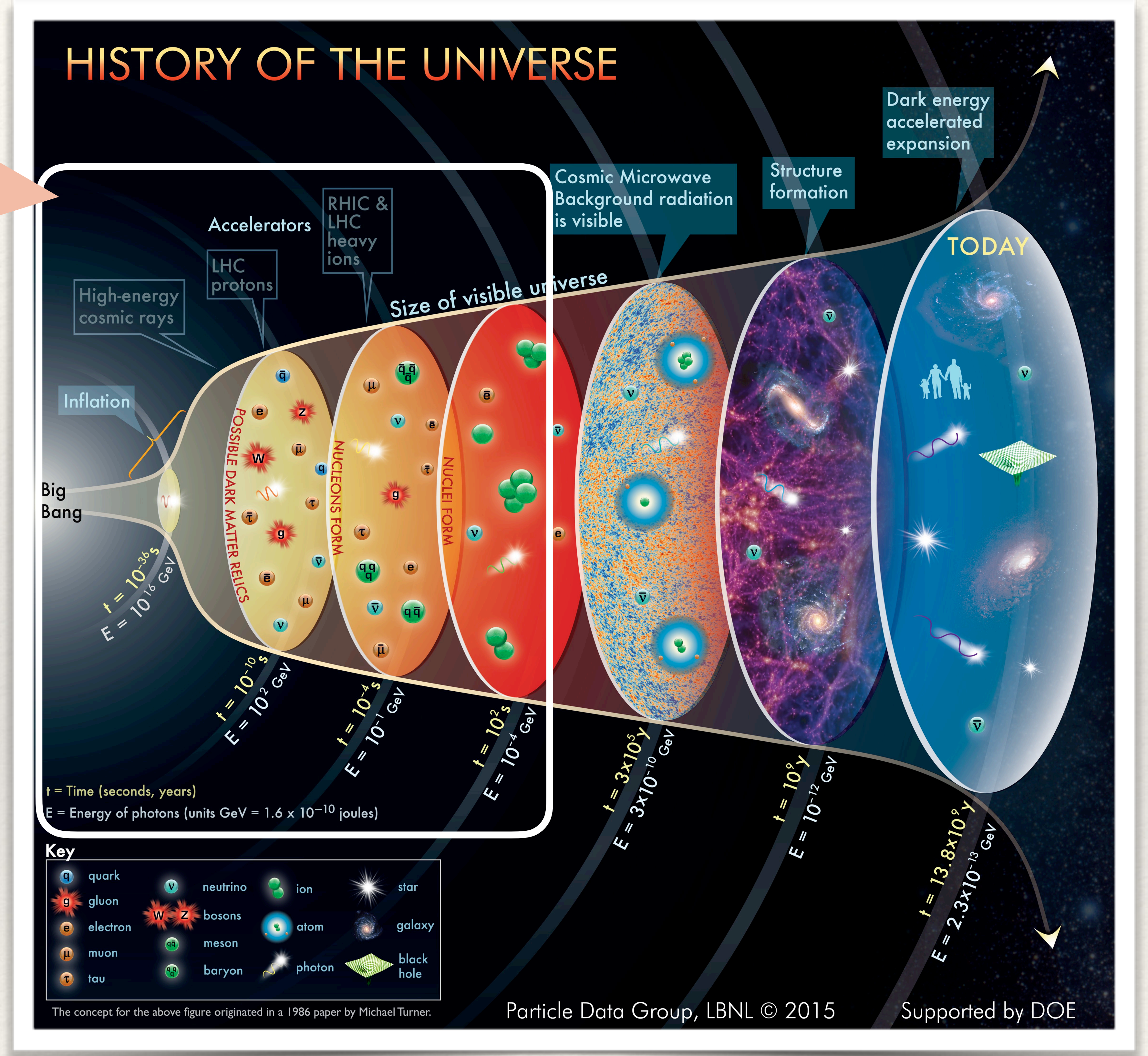


Andrey Ustyuzhanin, [Study Machine Learning through HEP]

This picture is constructed as LHCb event display that has passed through popular Deep Learning algorithm - Style Transfer - that borrows the style from Van Gogh's 'Starry Night' (https://github.com/jcjohnson/neural-style).

Heavy ion studies

- Ultra-relativistic heavy ion collisions can help us to understand what happened in the very beginning after the Big Bang.
  - Explore phase diagram of nuclear matter
  - Study QCD matter under extreme conditions
    - Formation of Quark Gluon Plasma at high T and/or energy density.
  - Many other things to explore in pA/AA: nucleon structure, intrinsic charm, QED at extreme field strengths, diffractive processes...

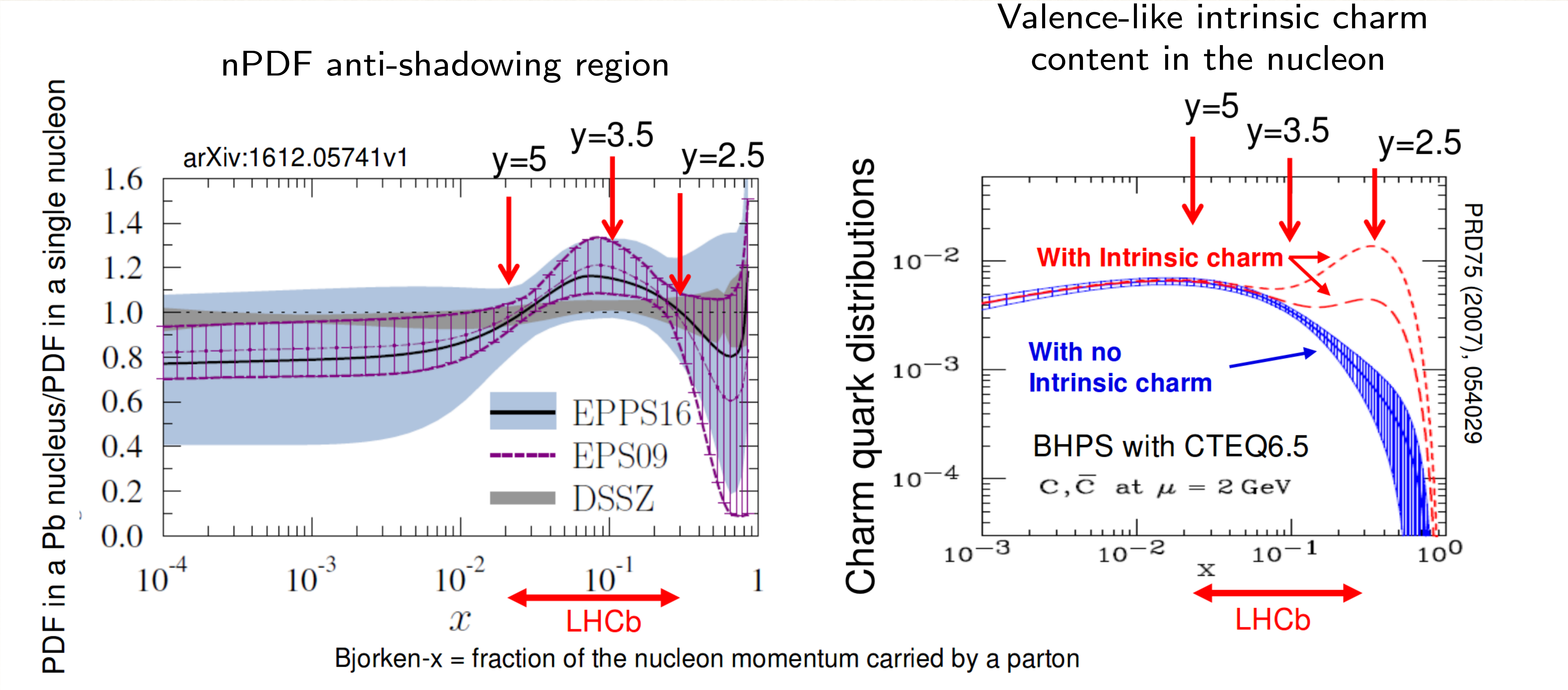


Recent LHCb Heavy Ion Results

- **Charm production in fixed-target collisions:**
  - LHCb-PAPER-2018-023, arXiv:1810.07907
- **Anti-proton production in fixed-target collisions:**
  - PRL. 121, 222001 (2018)
- **Heavy flavor production in pPb collisions:**
  - D^0 at 5.02TeV: LHCb-PAPER-2017-015, JHEP (2017) 090 [backup slides]
  - Λ_c^+ at 5.02TeV: LHCb-PAPER-2018-021, arXiv:1809.01404
  - J/ψ at 8.16TeV: LHCb-PAPER-2017-014, PLB774 (2017) 159 [backup slides]
  - B^+, B^0, Λ_b^0 at 8.16TeV: LHCb-CONF-2018-004
  - $\Upsilon(nS)$ at 8.16TeV: JHEP 11 (2018) 194
- **Exclusive photonuclear J/Psi production in ultra-peripheral PbPb collisions:**
  - LHCb-CONF-2018-003

Charm production in fixed-target

- Access to the anti-shadowing region of nPDF and probe the intrinsic charm content in the nucleons.



Charm production in fixed-target collisions

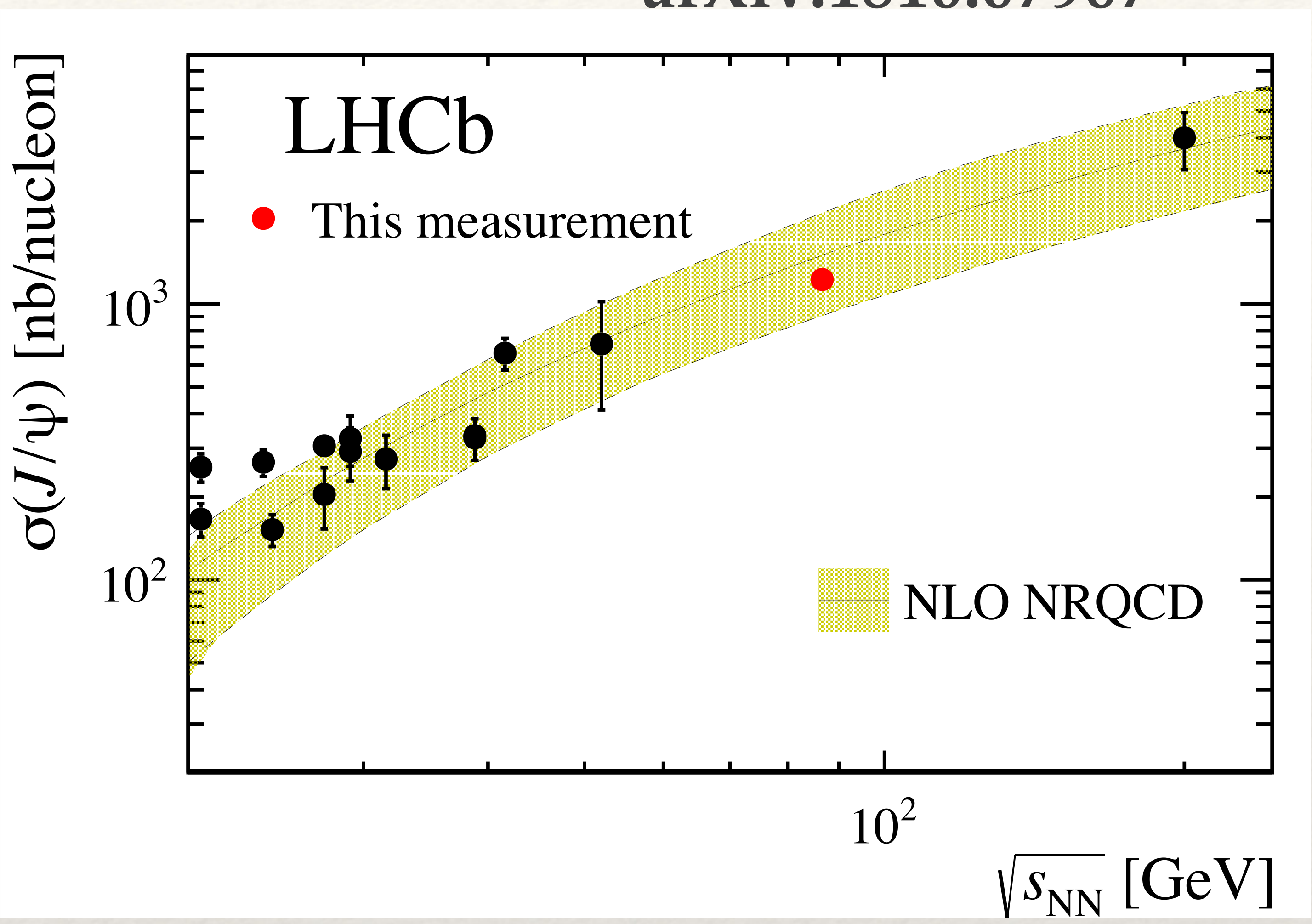
LHCb-PAPER-2018-023
arXiv:1810.07907

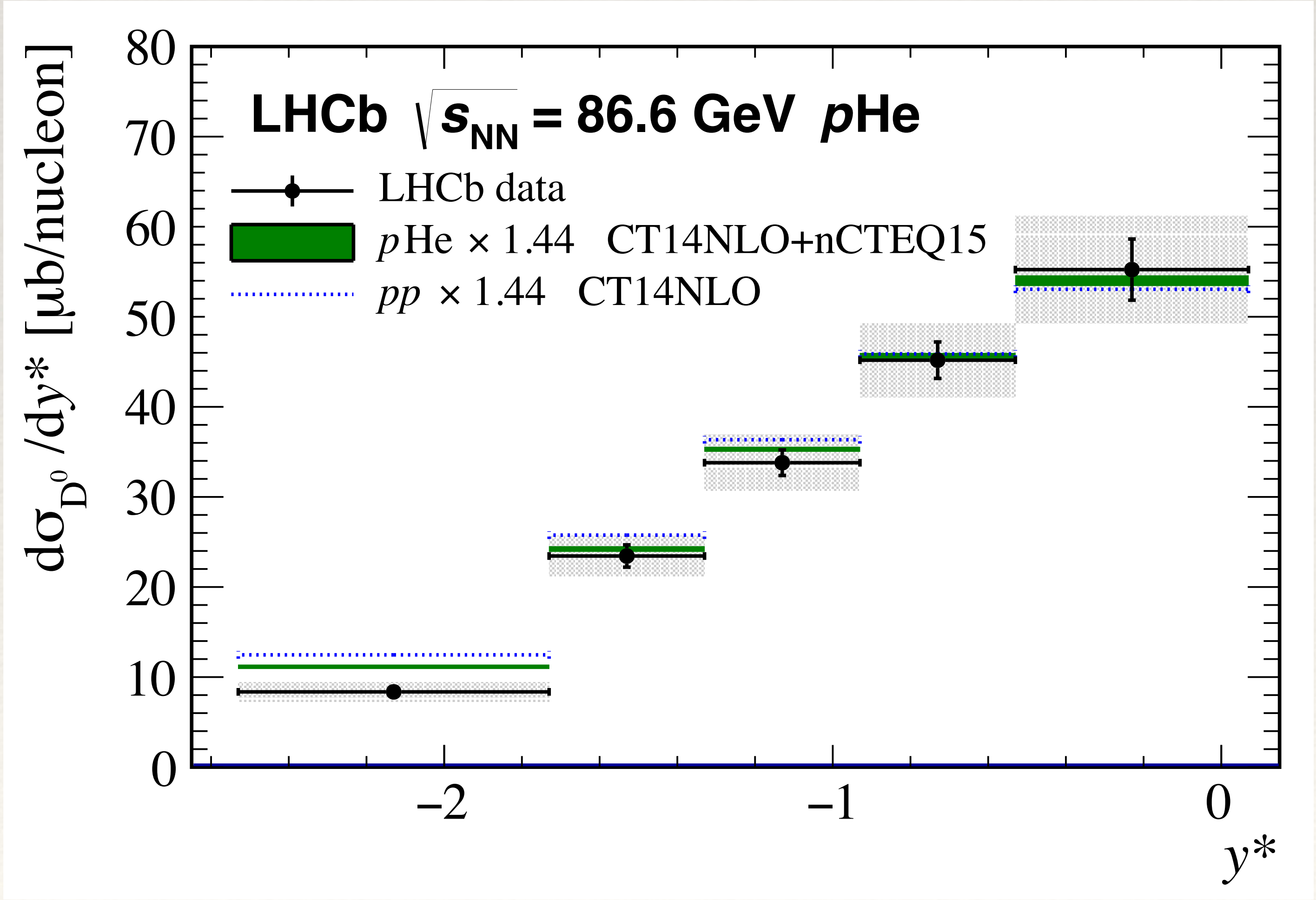
- J/ψ and D^0 inclusive cross section in pHe collisions $\sqrt{s_{NN}}$ = 86.6 GeV:
  - Cross section measured in $J/\psi \to \mu^+\mu^-$ and $D^0 \to K^- \pi^+$ decays

$$\sigma_{J/\psi} = 1225.6 \pm 100.7\,\text{nb/nucleon},$$
$$\sigma_{D^0} = 156.0 \pm 13.1\,\mu\text{b/nucleon},$$

- Scaling the D^0 cross-section with the global fragmentation ratio f(c→D^0) = 0.542±0.024 , the $c\bar{c}$ production cross section can be obtained: $\sigma_{c\bar{c}} = 288 \pm 24.2 \pm 6.9\,\mu\text{b/nucleon}$

- LHCb results in good agreement with NLO NRQCD fit (J/ψ) and NLO pQCD predictions ($c\bar{c}$) and other measurements
- No strong intrinsic charm content is observed.

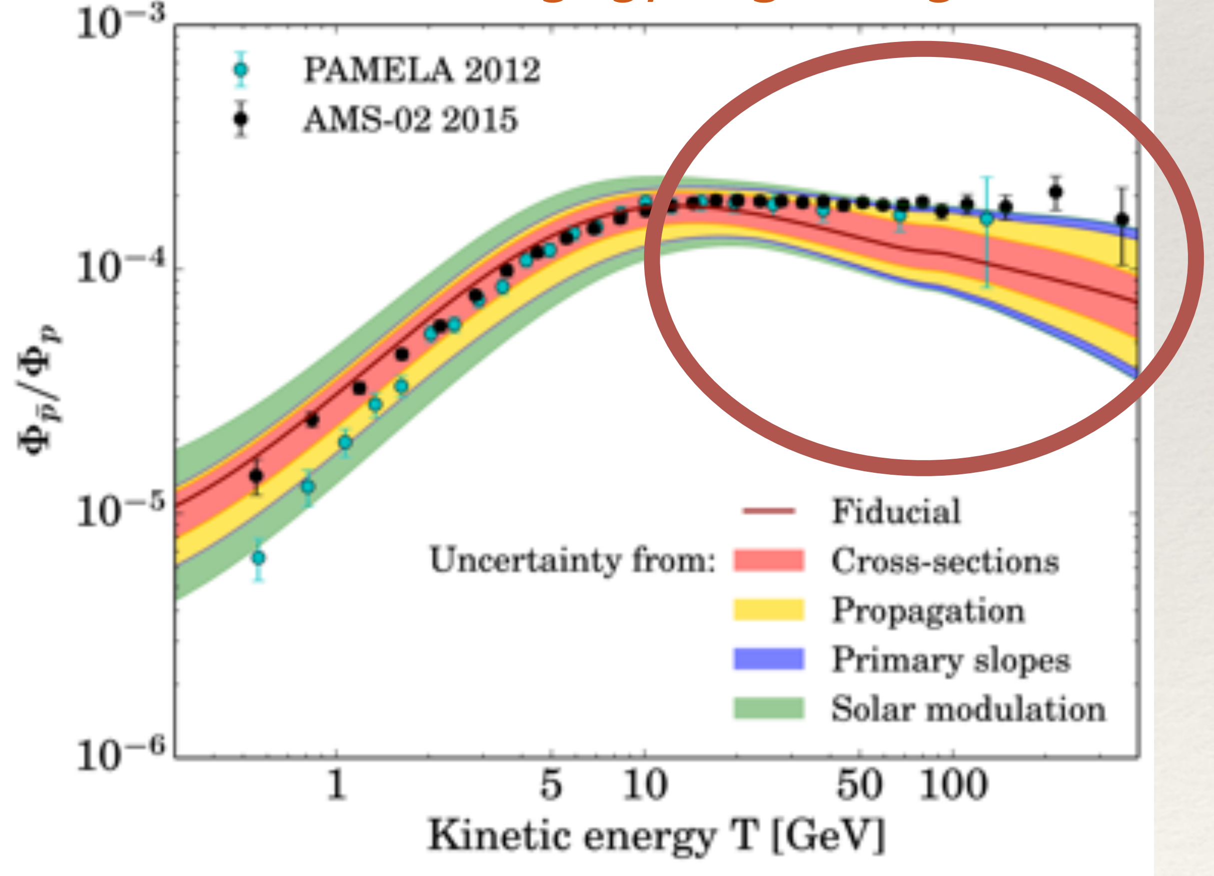




Anti-proton production in fixed-target

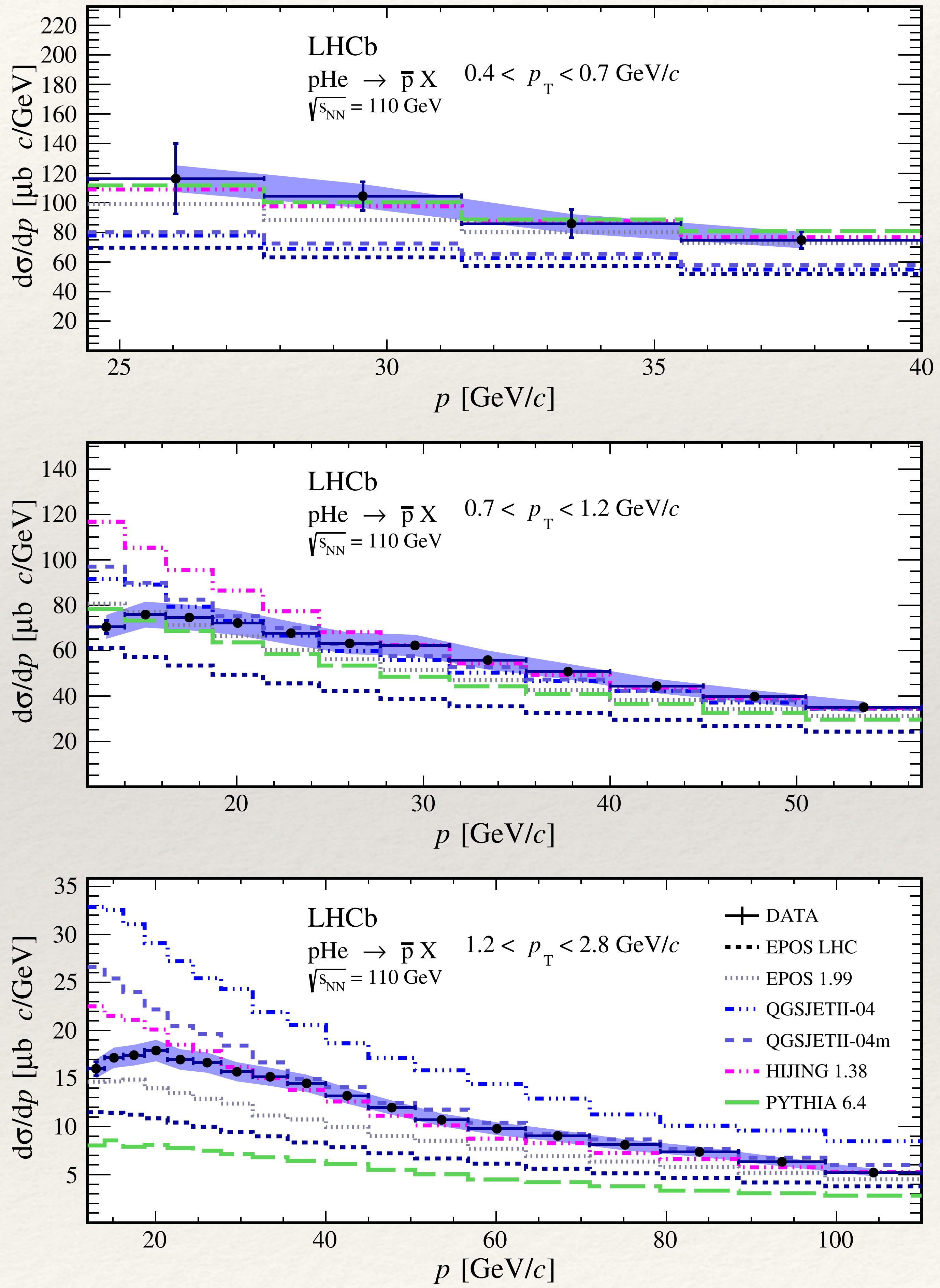
- $\bar{p}$-production measurement in fixed-target p-He collisions (2016, $\sqrt{s_{NN}}$ = 110 GeV) at LHCb can help to constrain the theoretical uncertainties for Dark Matter searches.
  - AMS2 and PAMELA give precise measurement of anti-proton/proton ratio results.
  - But hard to draw a conclusion because imperfect knowledge of the $\bar{p}$-production cross-sections when comparing with theoretical predictions

[JCAP 1509, 023 (2015)]



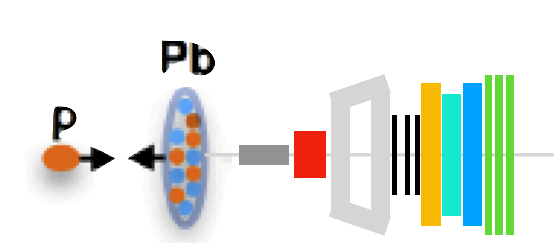
- The unique and precise LHCb $\bar{p}$-production results give a strong constraint to theoretical prediction.
- Gives a decisive contribution to shrink background uncertainties in dark matter searches in space

PRL. 121, 222001 (2018)

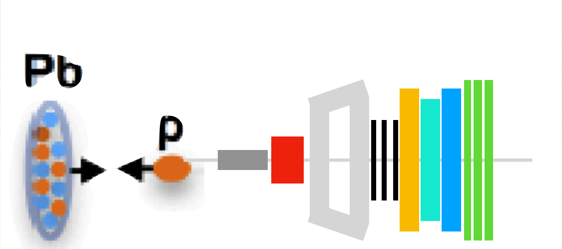


Prompt Λ^+_c production

- Baryon-to-meson cross-section ratio Λ^+_c/D^0 is sensitive to charm hadronisation mechanism
  - Forward rapidity: discrepancies at high-p_T between data and models tuned to pp
  - Backward rapidity: good agreement between data and model predictions
- Compared with nPDFs:
  EPS09LO: [Comput. Phys. Commun. 184 (2013) 2562]
  EPS09NLO: [Comput. Phys. Commun. 198 (2016) 238]
  nCTEQ15: [EPJC 77 (2017) 1]

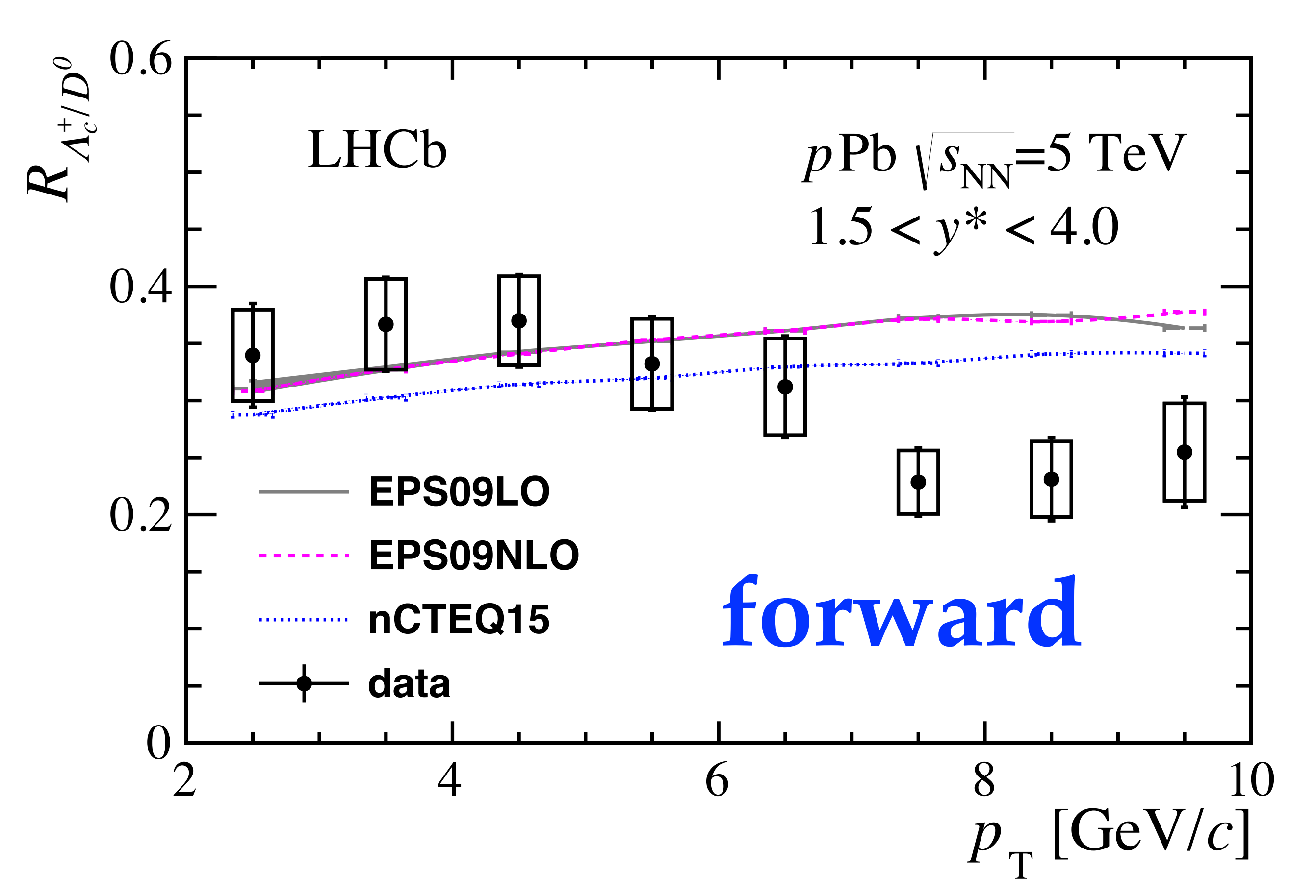


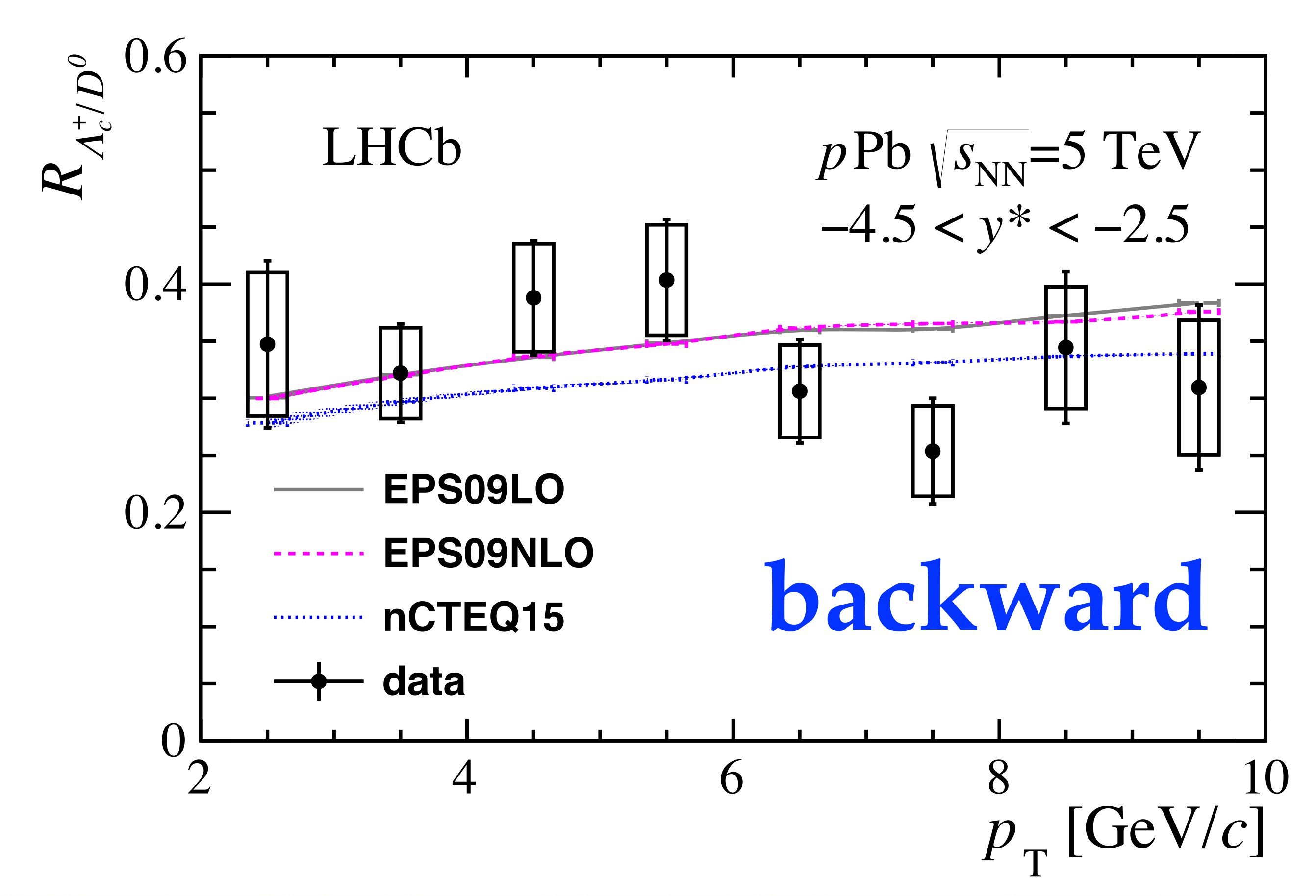
forward



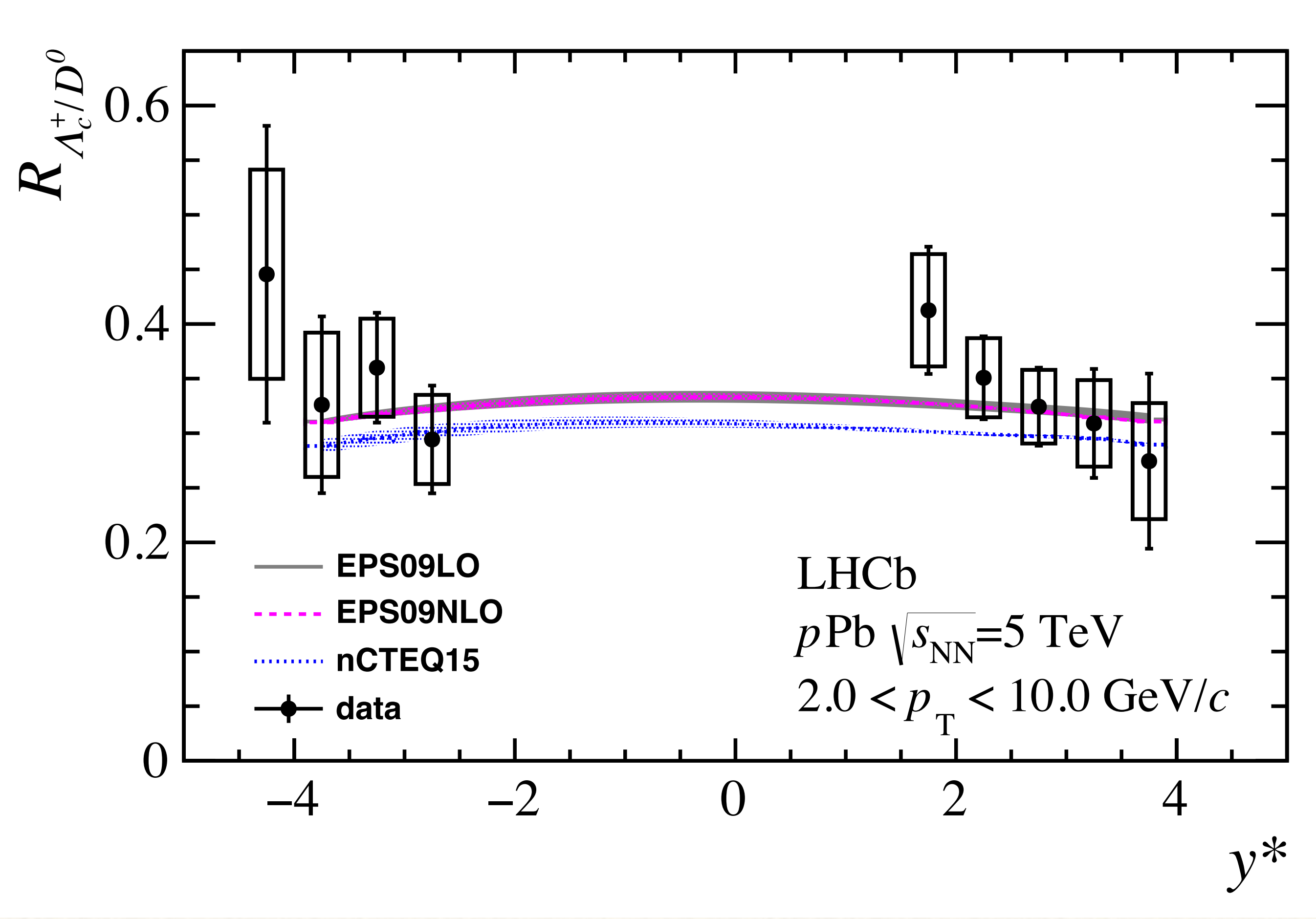
backward

Λ^+_c/D^0 Ratio vs. pT





Λ^+_c/D^0 Ratio vs. Rapidity

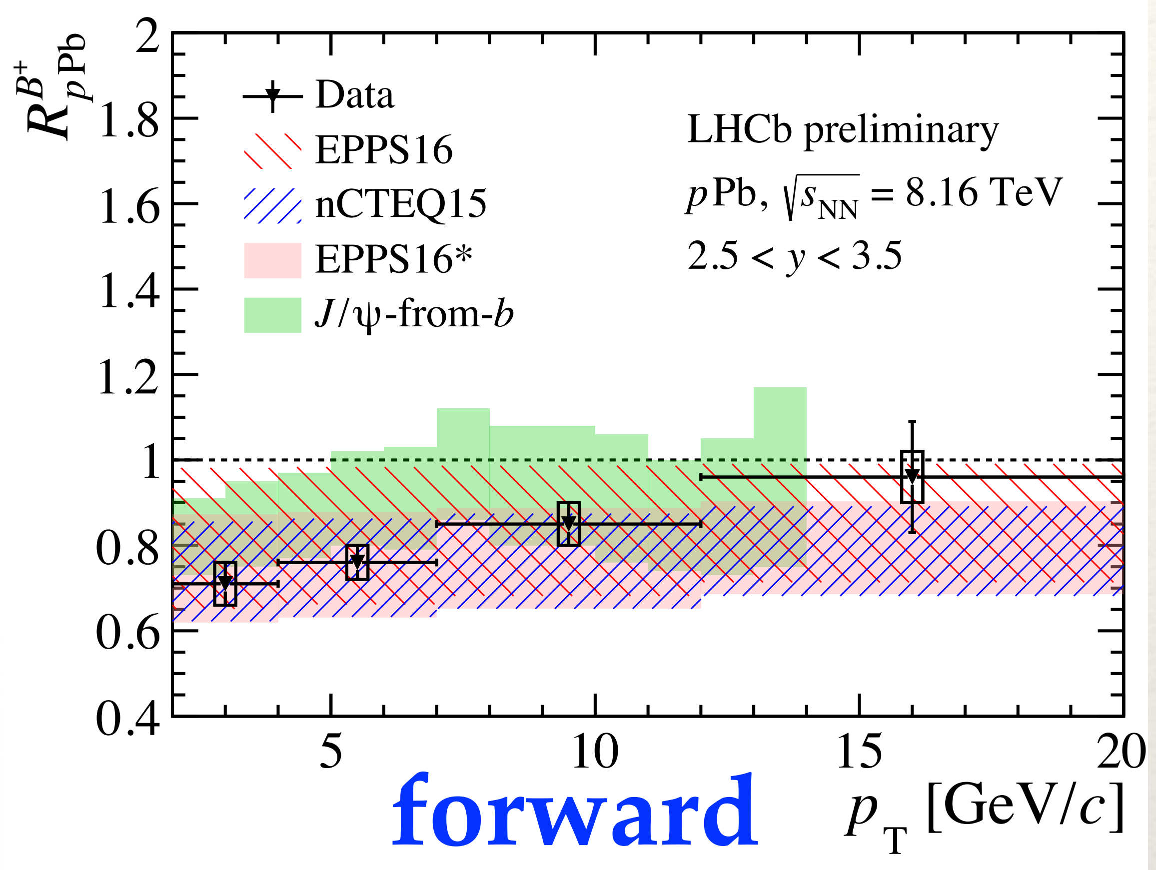


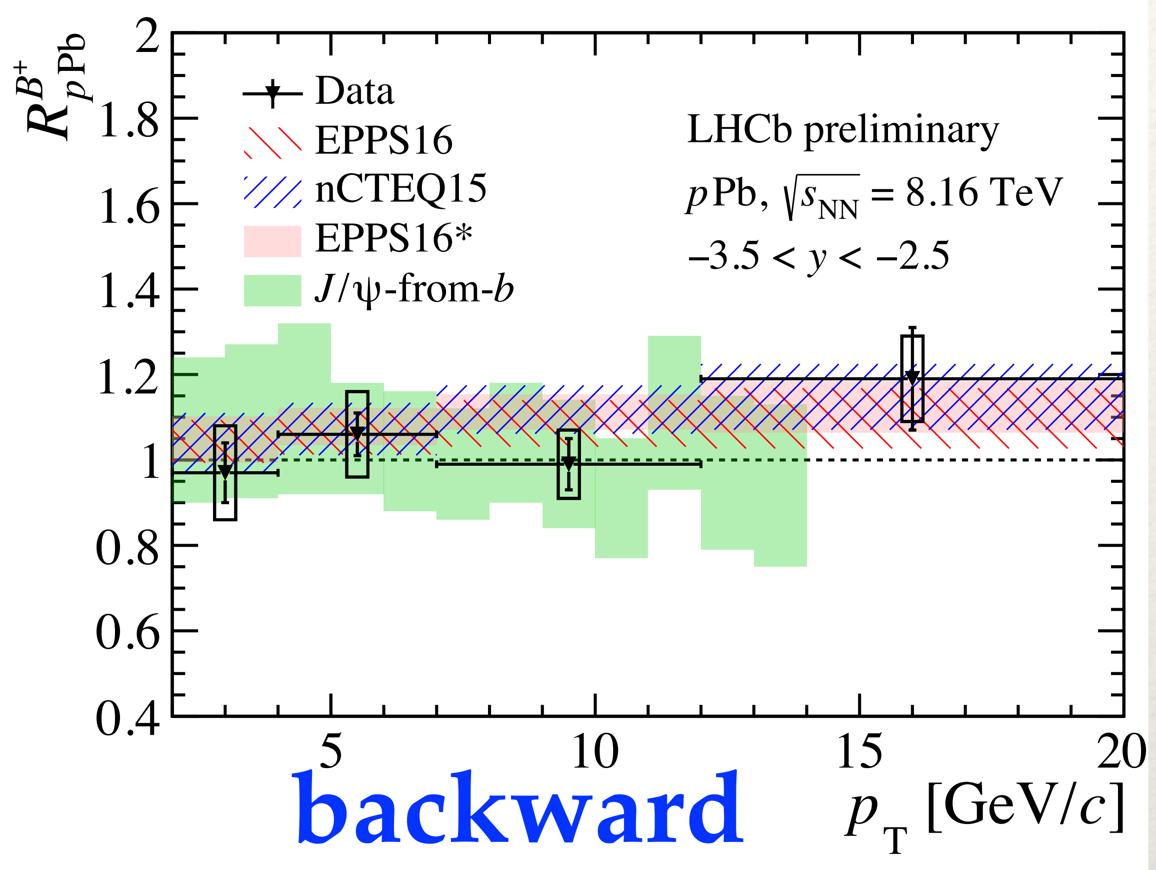
LHCb-PAPER-2018-021
arXiv:1809.01404

b - hadron production in pPb

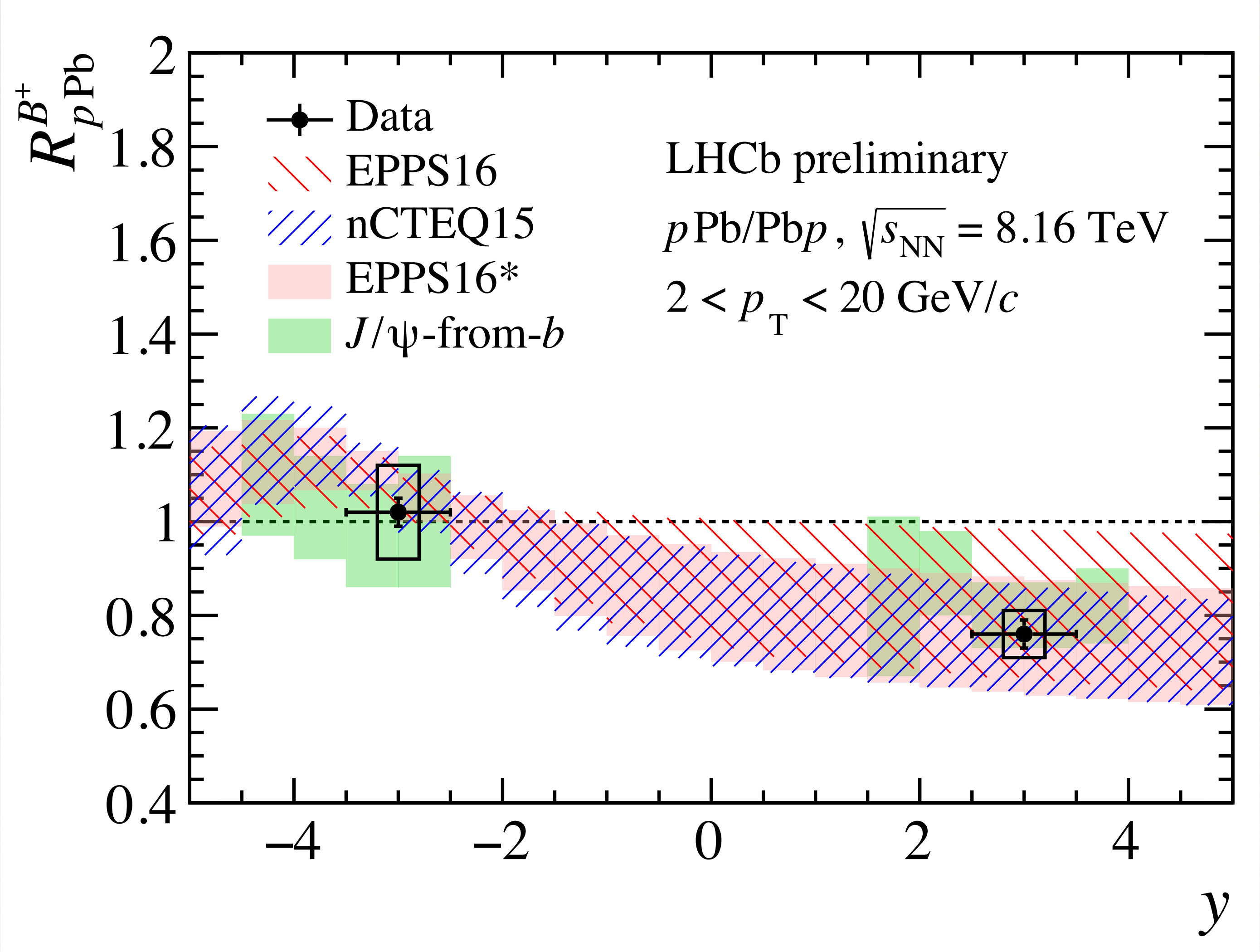
- **Exclusive decay modes:**
  $B^+ \to J/\psi K^+$, $B^+ \to D^0 \pi^+$, $B^0 \to D^- \pi^+$, $\Lambda_b^0 \to \Lambda_c^+ \pi^-$
- Pattern consistent with R_{pA} of D^0 mesons
- Significant suppression (≈ 25%) in fwd rapidity, suppression decreases at large p_T
- Consistent with unity at backward rapidity
- Measurements in good agreement with J/ψ-from-b decay data and calculations using nPDF sets [JHEP 04 (2009) 065, EPJ C77 (2017) 1, CPC. 198 (2016) 238]

Nuclear modification factor vs. B^+ p_T





Nuclear modification factor vs. B^+ rapidity



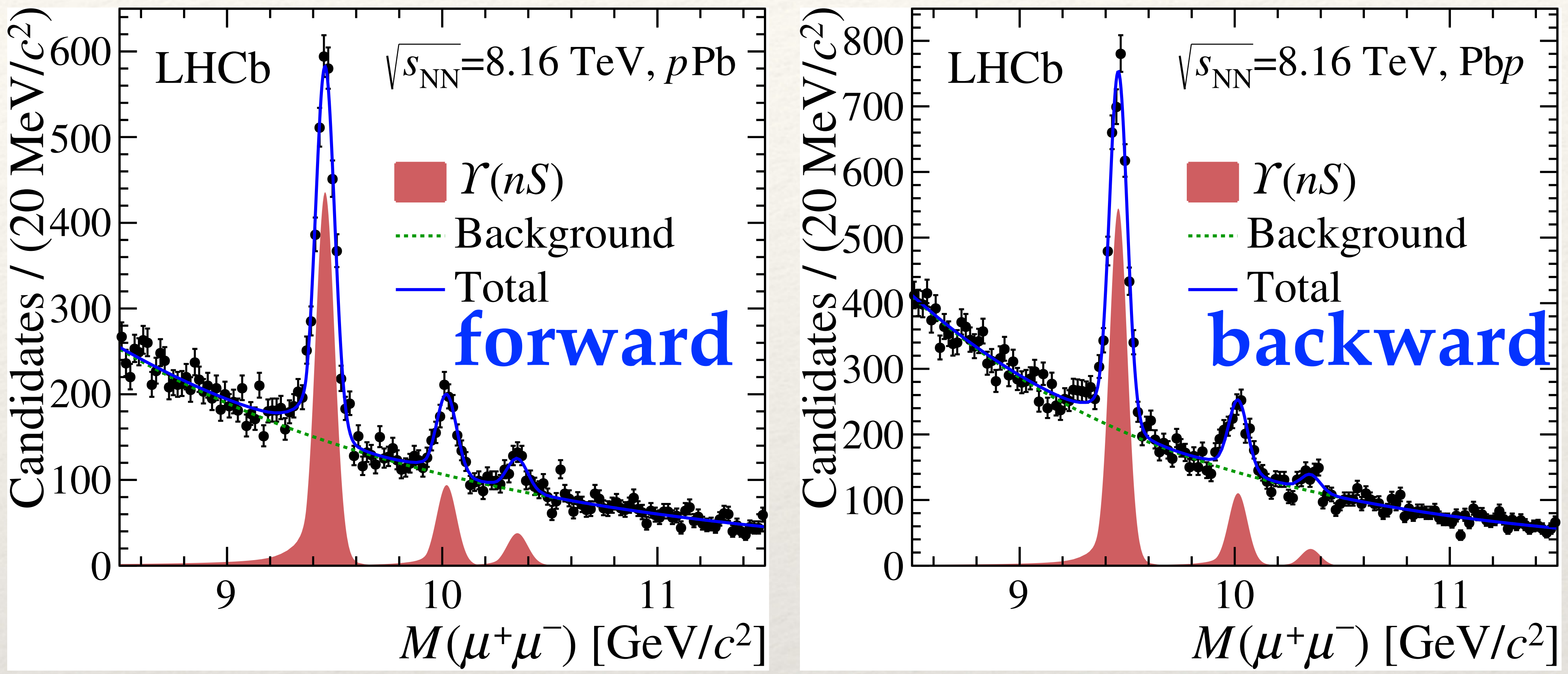
LHCb-CONF-2018-004

Υ(nS) production in pPb

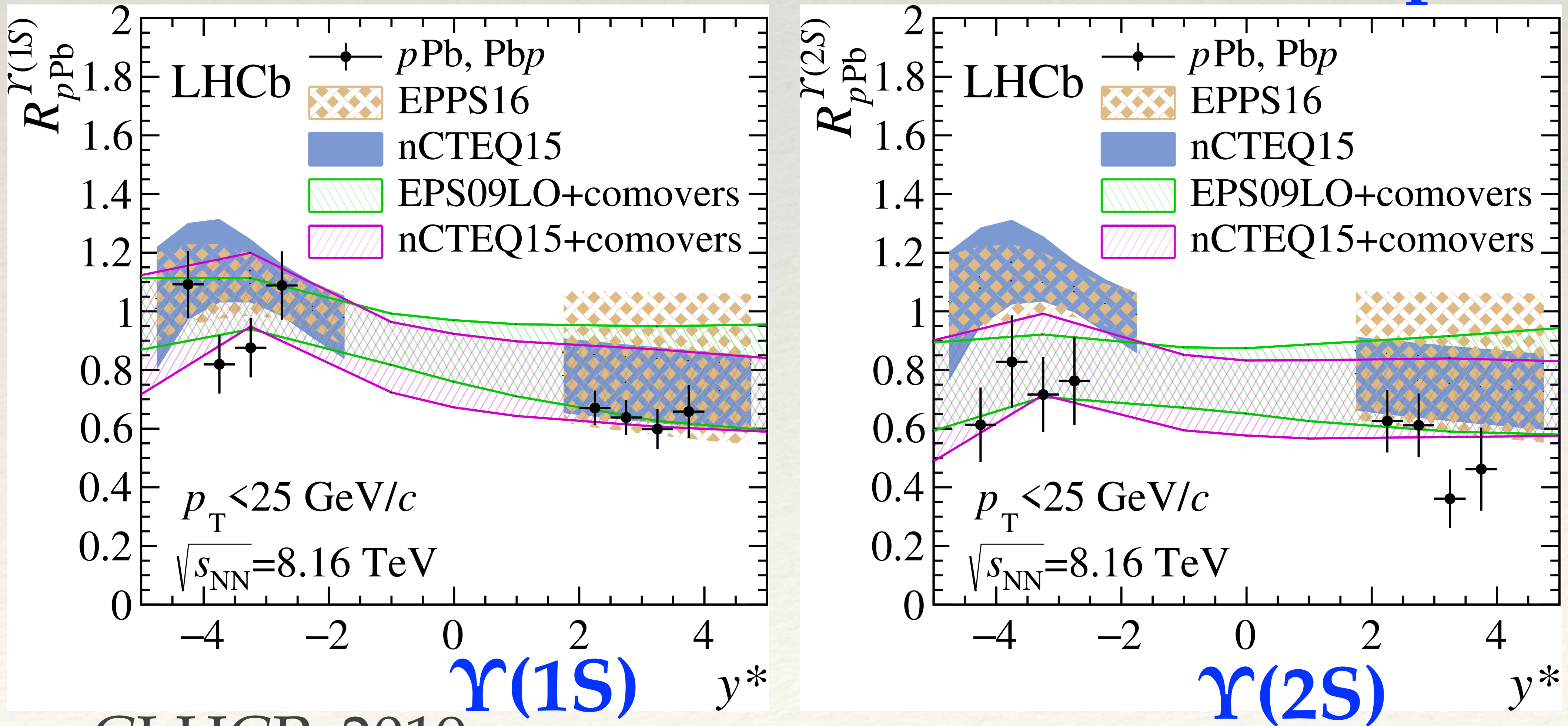
JHEP 11 (2018) 194

- Υ(nS) suppression observed in PbPb and pPb/Pbp by CMS and ALICE at low-pT
- LHCb results at 8.16 TeV:
  - Clear Υ(3S) signal in both forward and backward rapidity
  - Υ(1S) forward suppressed by ~30%
  - Υ(1S) backward compatible with 1 within nPDF uncertainties
  - Υ(2S) additional suppression confirmed
- Comparing with models:
  - EPPS16: Eur. Phys. J. C (2017) 77 163
  - EPS09: JHEP 04 (2009) 065
  - nCTEQ15: Phys.Rev.D93 (2016) 085037
  - Comovers: Phys. Lett. B749 (2015) 98

Di-muon invariant mass



Nuclear modification factor vs. Υ(nS) rapidity



J/ψ production in ultra-peripheral PbPb collisions

❖ Ultra-peripheral collisions: Two nuclei bypass each other with an impact parameter larger than the sum of their radii.

❖ Photon-induced J/ψ production cross-section is enhanced by the strong electromagnetic field of the nucleus

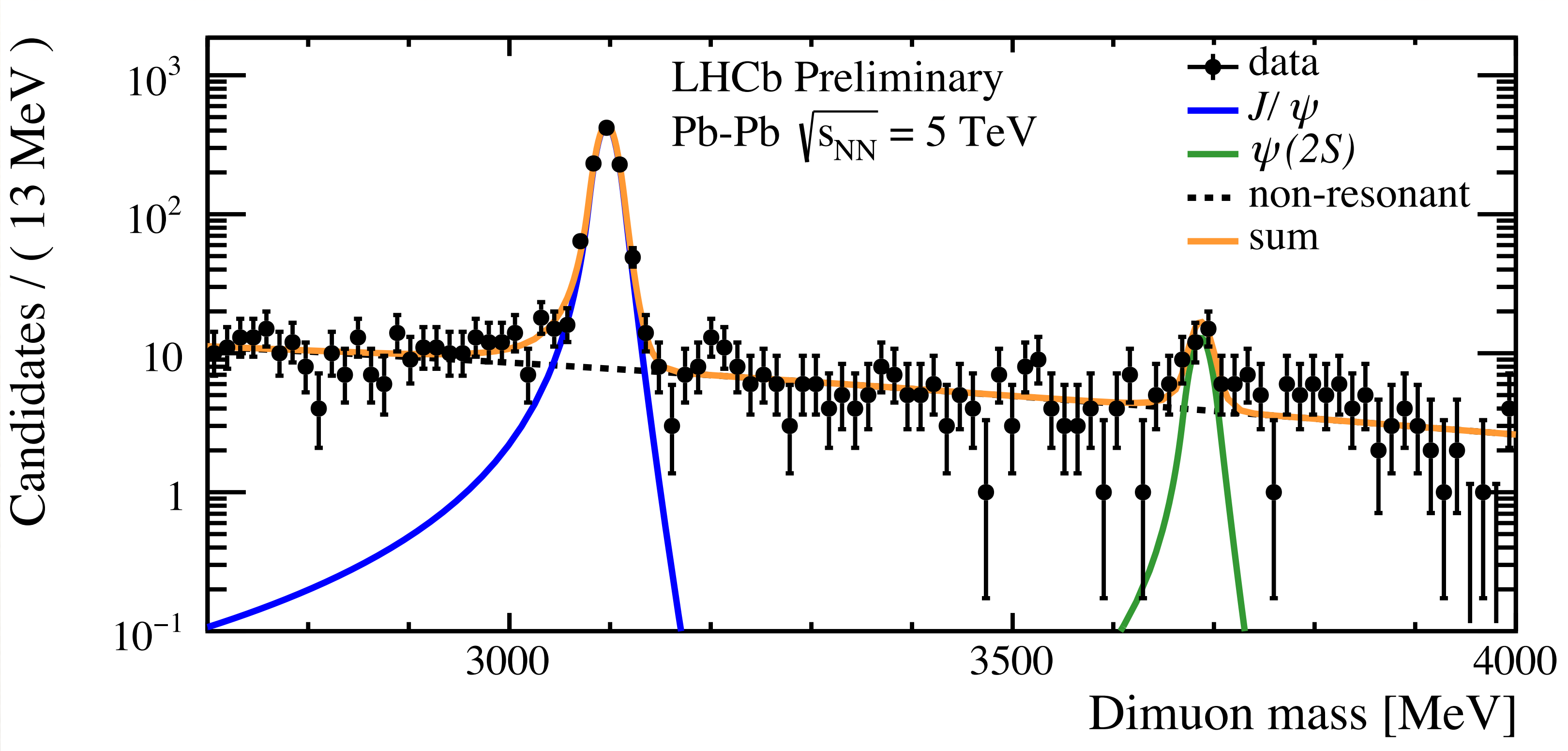
❖ Coherent (photon couples to all nucleons) J/ψ production gives constraints to nPDF

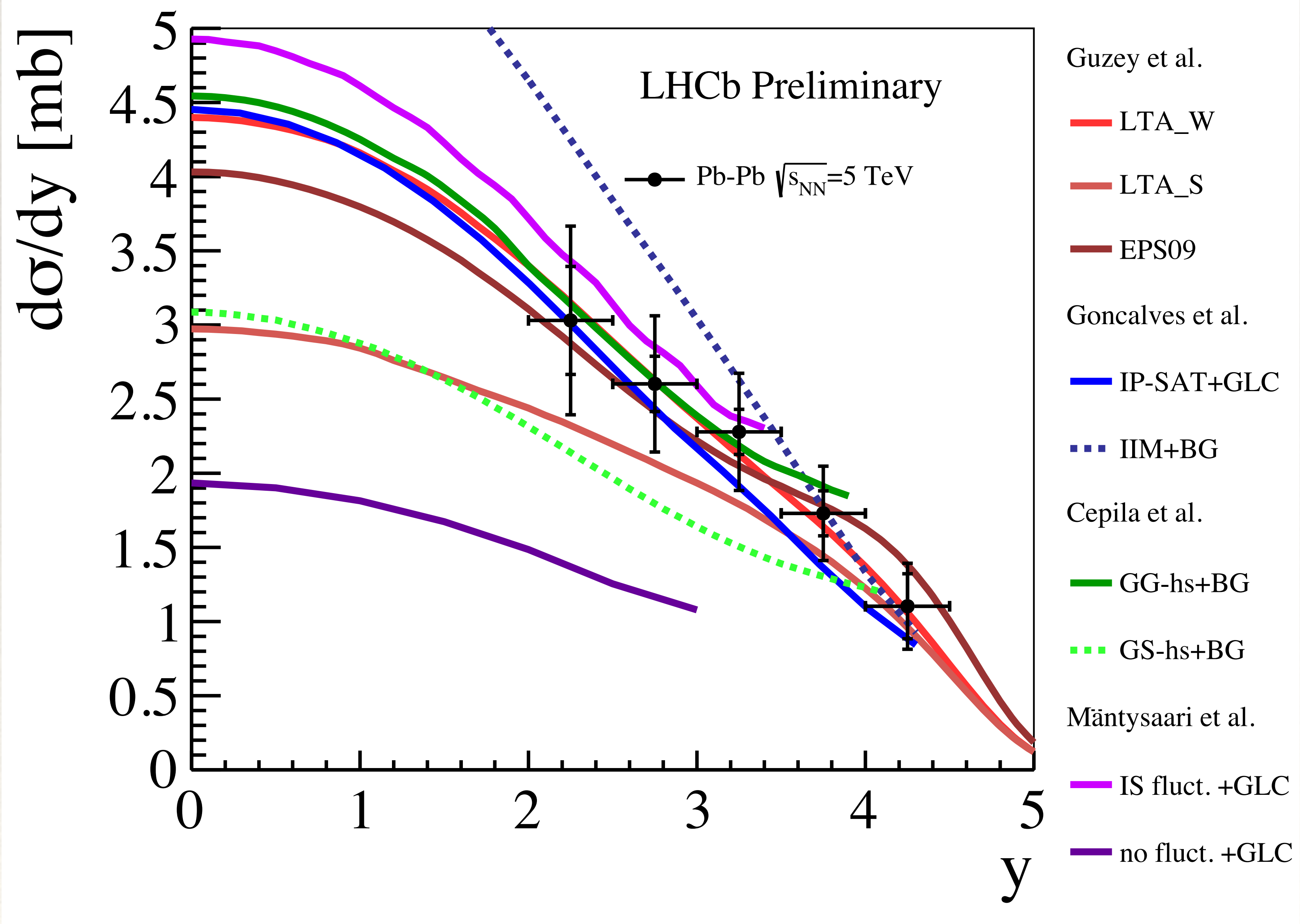
❖ Cross section for coherent J/ψ production at 5 TeV:

$$\sigma = 5.3 \pm 0.2\ (\text{stat}) \pm 0.5\ (\text{syst}) \pm 0.7\ (\text{lumi})\,\text{mb}$$

❖ Phenomenological models:
PRC 97 024901 (2018), PRD 96 094027 (2017), PRC 93 055206 (2016), PLB 772 (2017) 832

LHCb-CONF-2018-003





Conclusions

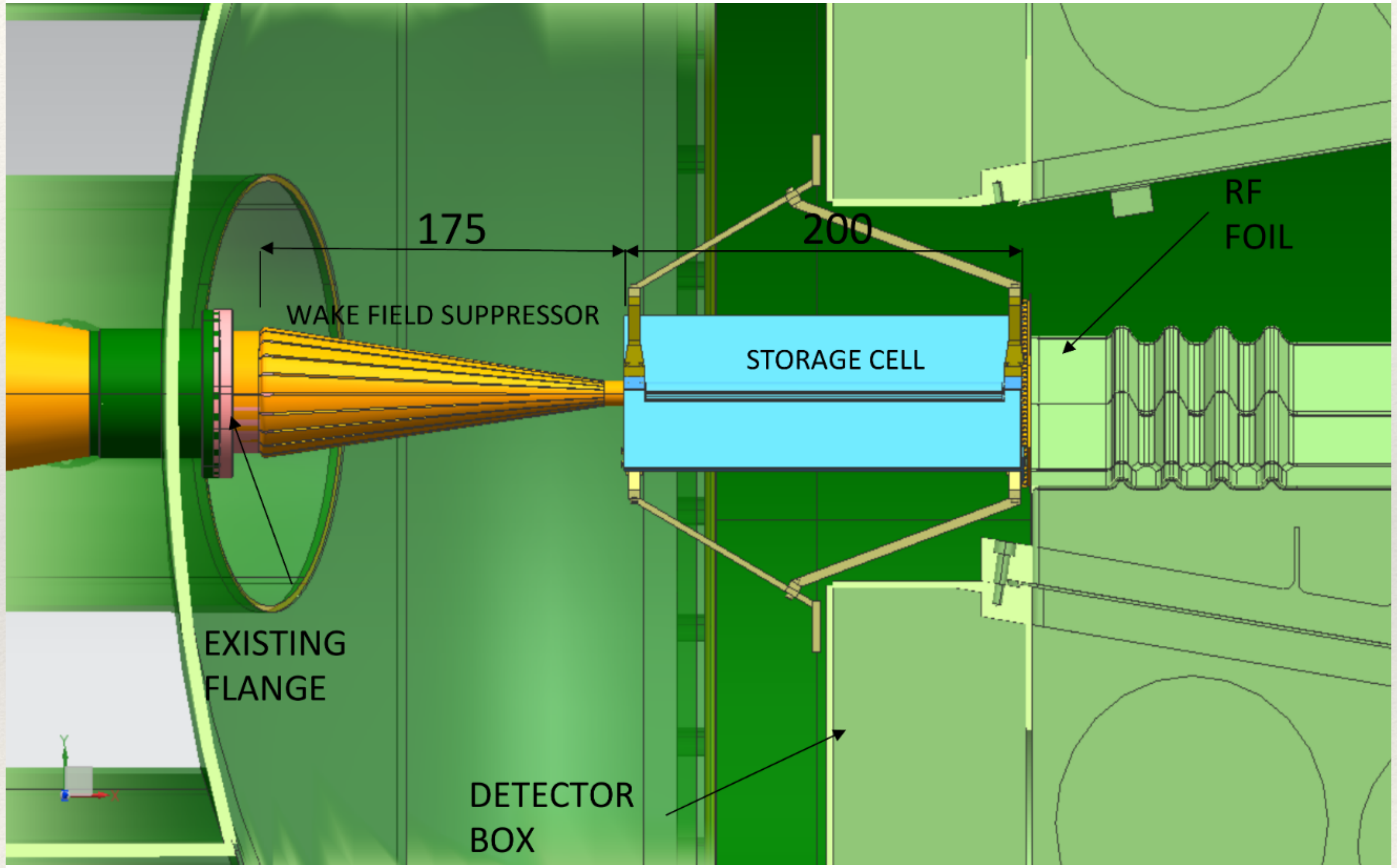
- Many results in Heavy Flavour production from LHCb
  - Great progress in the theory/experiment agreements, but still many inconsistencies remain
    - Efforts needed in both theory and experiment to establish a consistent model for Heavy Flavour production
  - These measurements provide crucial inputs for tuning of MC needed for precise measurements in LHC
- LHCb provides unique datasets for Heavy Ion physics studies.
  - The collider mode gives unique constraints on nuclear modifications in proton-nucleus collisions at low-x and high-x
  - The fixed-target mode covers the center-of-mass energy gap between SPS and RHIC, sensitive to nuclear modification of PDFs & intrinsic charm contents
  - Rich heavy ion program with LHCb upgrade and the fixed-target upgrade

Backup slides

Fixed-target system (SMOG) upgrade!

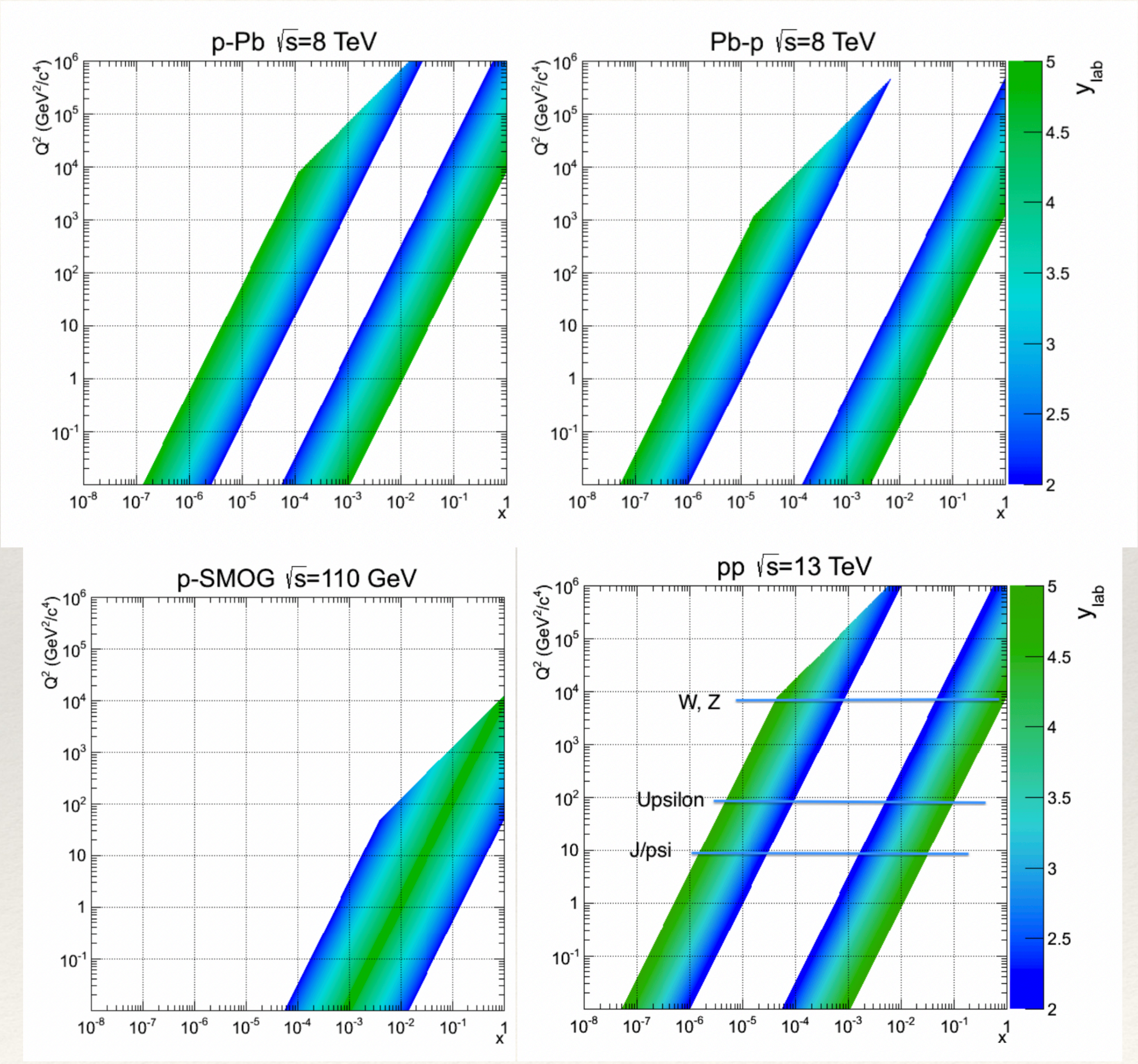
- Current LHCb fixed-target setup will be upgraded for Run 3
- Plan for a storage cell, placed upstream
  - Injection of noble gases but also H_2 and D_2 gas as references
  - 10–100 times larger instantaneous luminosity per unit length
- Other upgrades (crystal target, polarised target, wire target) under discussion

Stay tuned!



Motivation for Heavy Ion Studies at LHCb

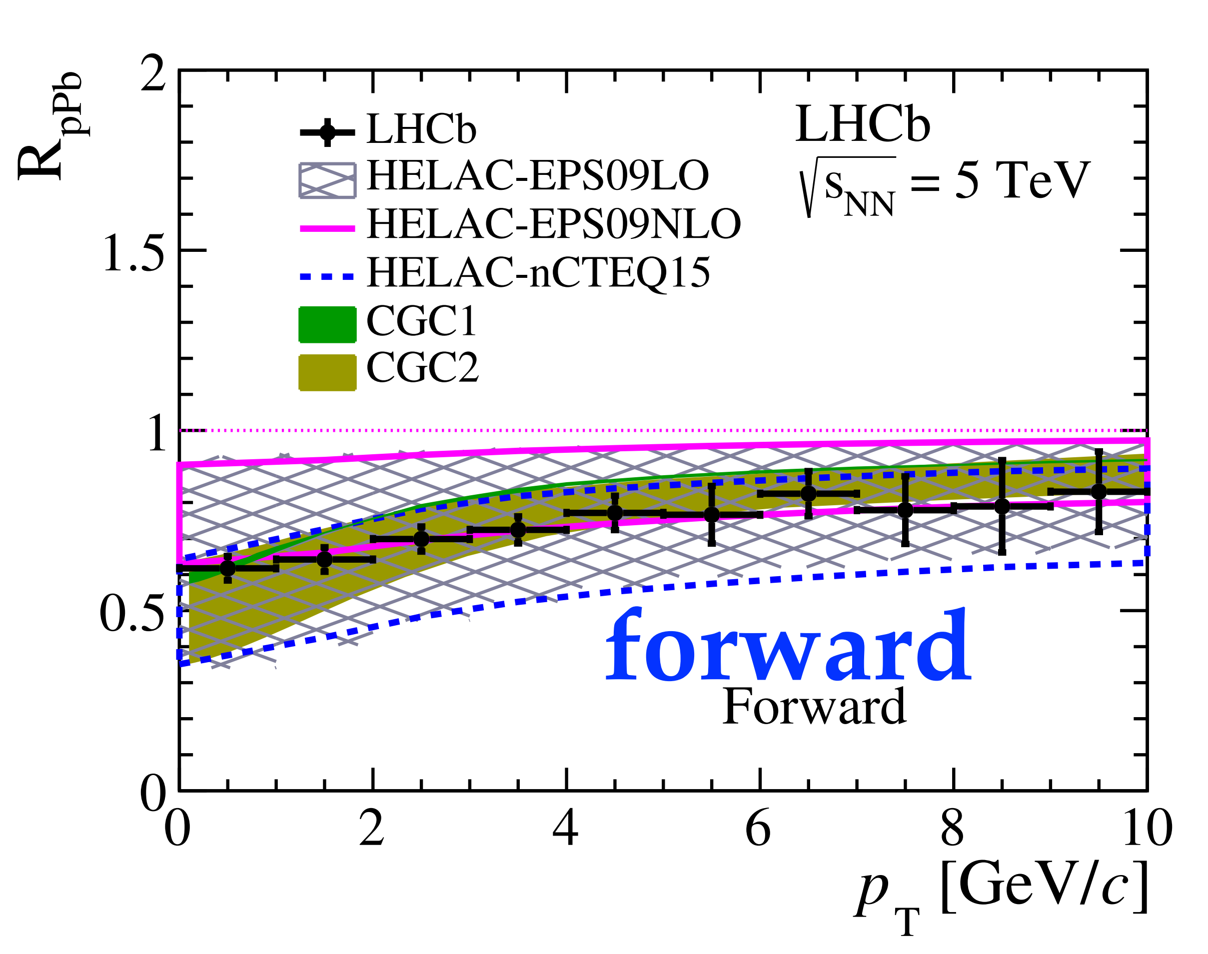
- Investigate the nucleon structure by comparing free p-p interactions versus bound nucleons (pA) inside the nucleus
  - nPDFs can be probed via quarkonia, electroweak bosons, Drell-Yan measurements, etc..
  - Access to very small x (colliding beam mode) and large x (fixed target mode)
- Dynamics of hadronization process [nuclear matter effects]
  - Measurement of total cross sections, energy flow, particle multiplicities, etc…
- Complementary probes of QCD
  - Ultra-peripheral collisions: exclusive ρ^0 production, exclusive photo-production of J/ψ...

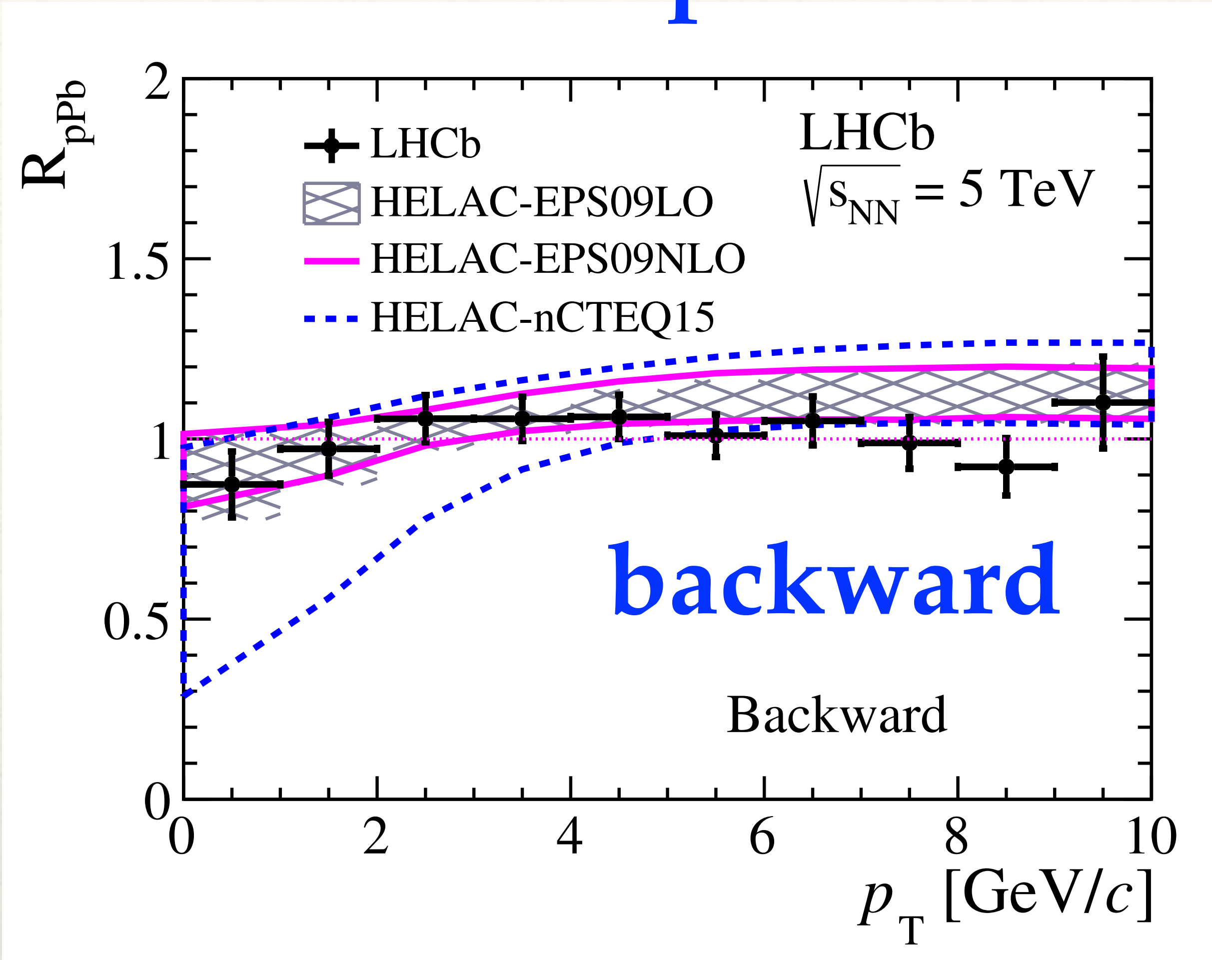


Prompt D^0 modification factor

- D^0 cross-section and modification factor in pPb at $\sqrt{s}$ = 5.02 TeV
- D^0 fully reconstructed through $D^0 \to K^- \pi^+$ decays
- R_{pPb} suppressed in forward region (~30%), no suppression in backward region, hint of small excess at large backward rapidity (y*<-4)
- Measurements consistent with predictions using nPDFs or CGC framework: [EPJC 77 (2017) 1, Comp. Phys. Com. 198 (2016) 238, Comp. Phys. Com. 184 (2013) 2562]
- At forward rapidity measurement also consistent with CGC models: [Phys. Rev. D91 (2015) 114005, arXiv:1706.06728]

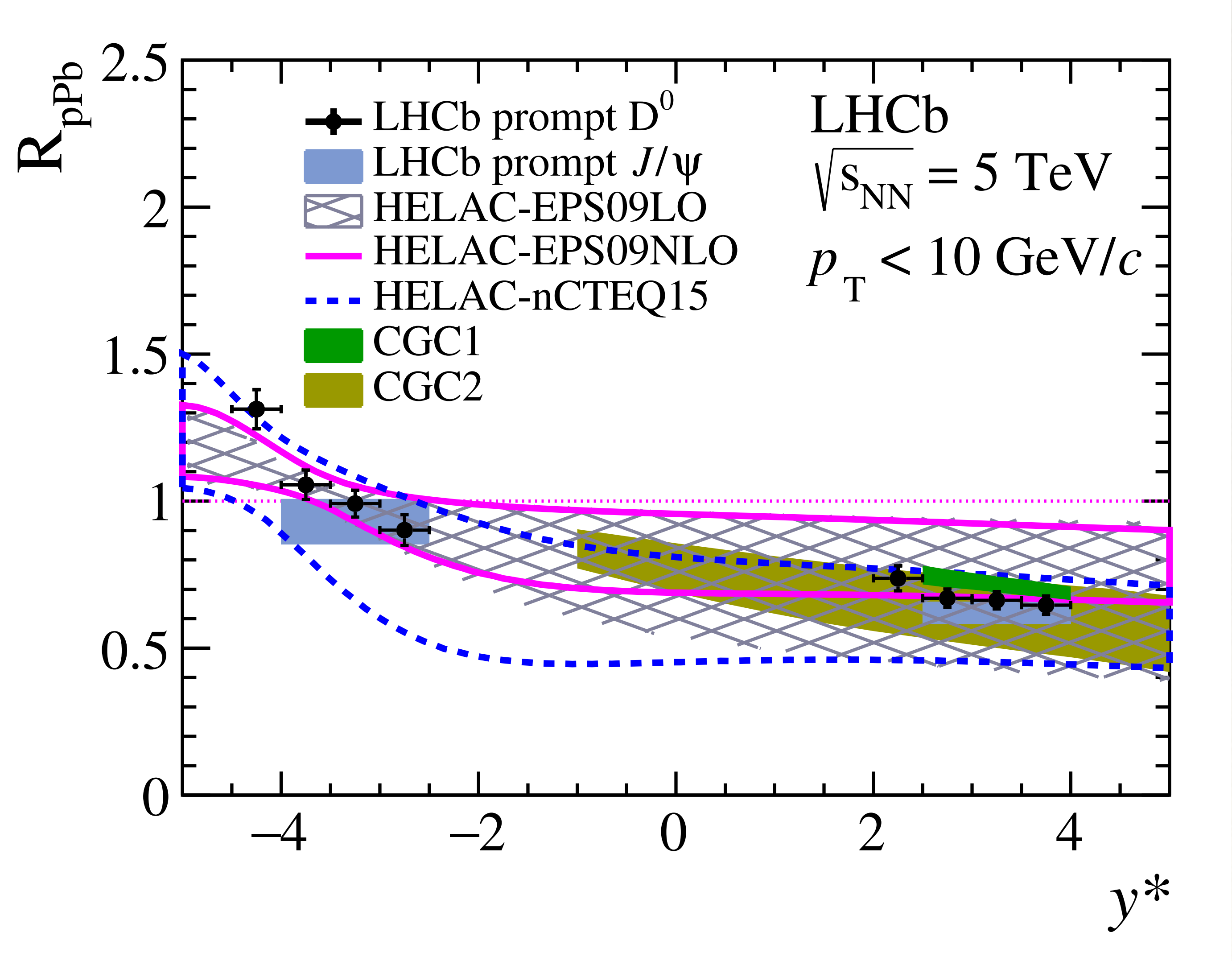
Nuclear modification factor vs. D^0 pT





JHEP 2017 090

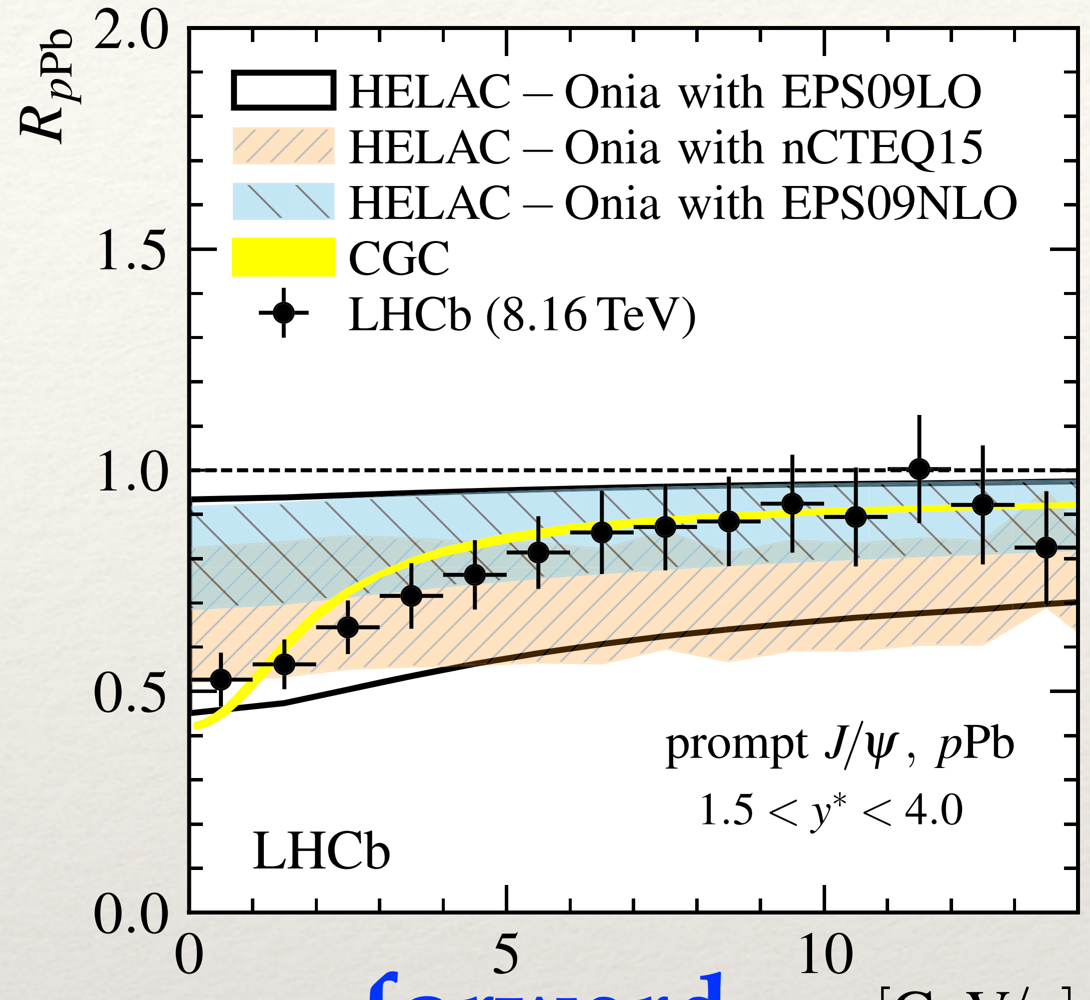
Nuclear modification factor vs. D^0 rapidity



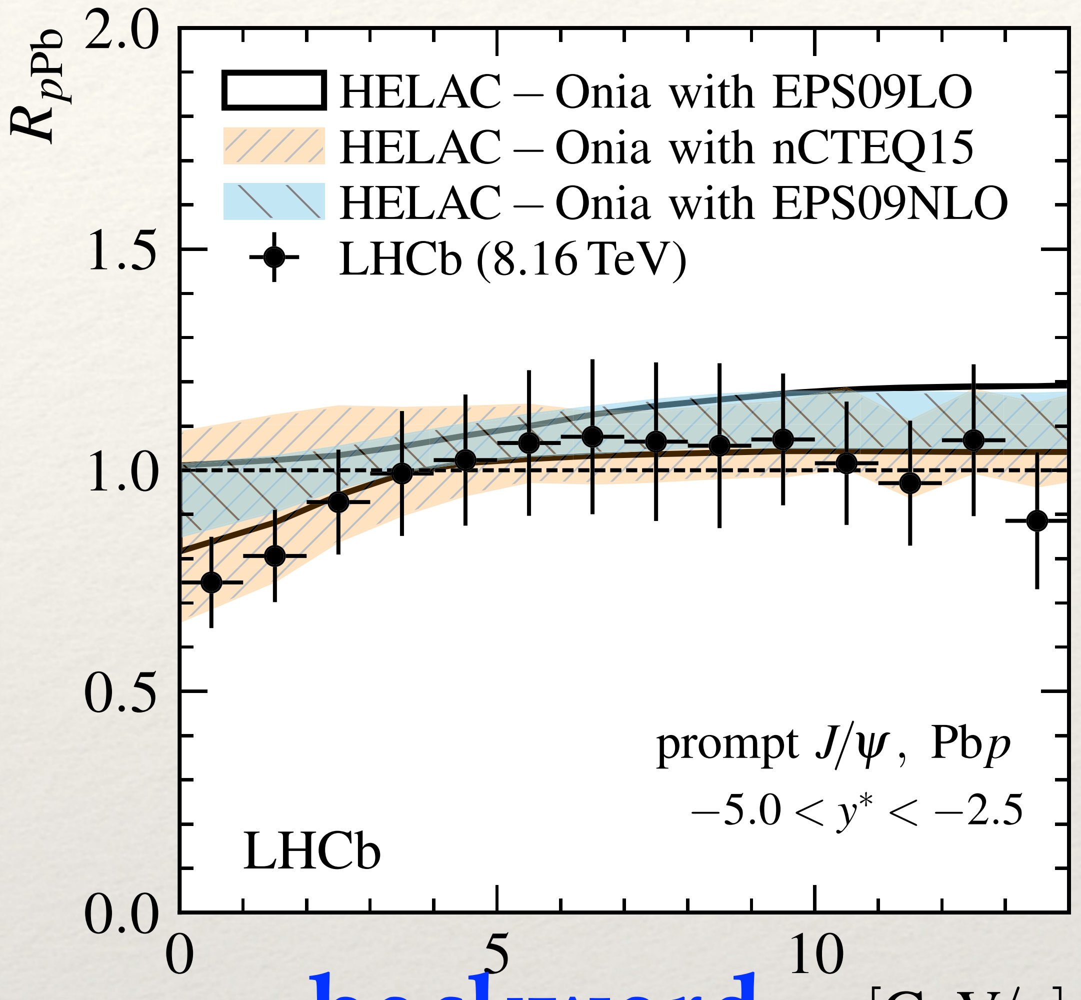
Prompt J/ψ modification factor

- In forward region: up to 50% suppression at low p_T , converging to unity at high p_T
- In backward region: R_{pPb} closer to unity, intriguing low values at low p_T
- Overall good agreement with models, but some have large uncertainties
- Results are compatible with LHCb results at 5 TeV [JHEP 02 (2014) 072]
- Result on Ψ(2S) modification factor is coming soon

Nuclear modification factor vs. J/ψ pT



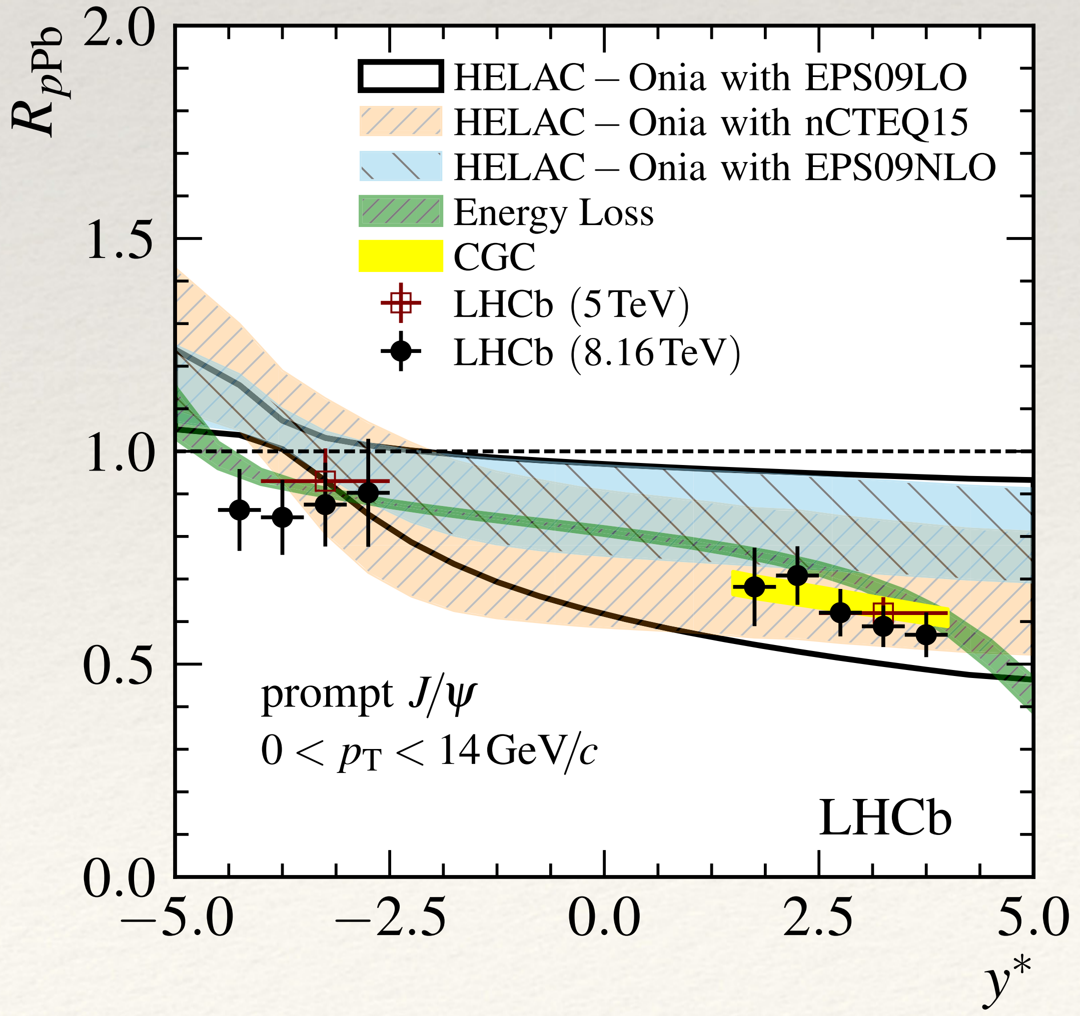
forward



backward

PLB774 (2017) 159

Nuclear modification factor vs. J/ψ rapidity



Centrality of the PbPb collisions

- **Detector limitation: Saturation in the Vertex Locator and the Tracking System for the most central PbPb collisions**
  - **Current LHCb tracking algorithm, efficient for centrality above 50%**
- **Centrality measured using the total energy deposited in the calorimeters:**
  - **A good centrality estimator.**
  - **No saturation of calorimeter signals even for most central collisions**