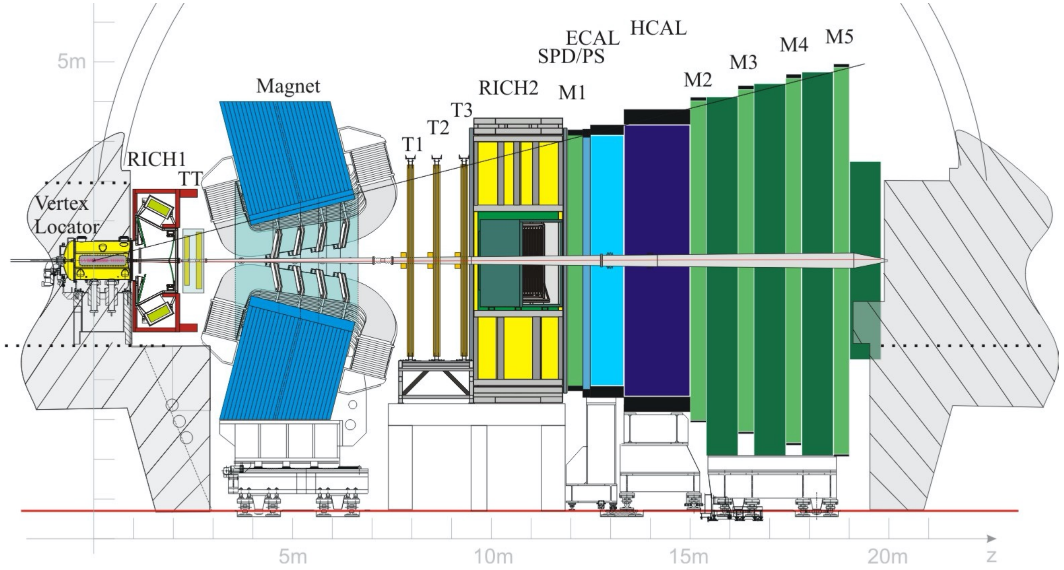
Heavy flavour production in pp collisions at LHCb

Li XU, Tsinghua University
on behalf of the LHCb collaboration

July 5, 2021

Selected topics

- Recent heavy flavour production measurements in pp collisions
  - J/ψ production cross-sections at 5.02 TeV *New*
  - Precise measurement of f_s/f_d [arXiv:2103.06810]
  - Λ_b^0 production asymmetry at 7 and 8 TeV *New*

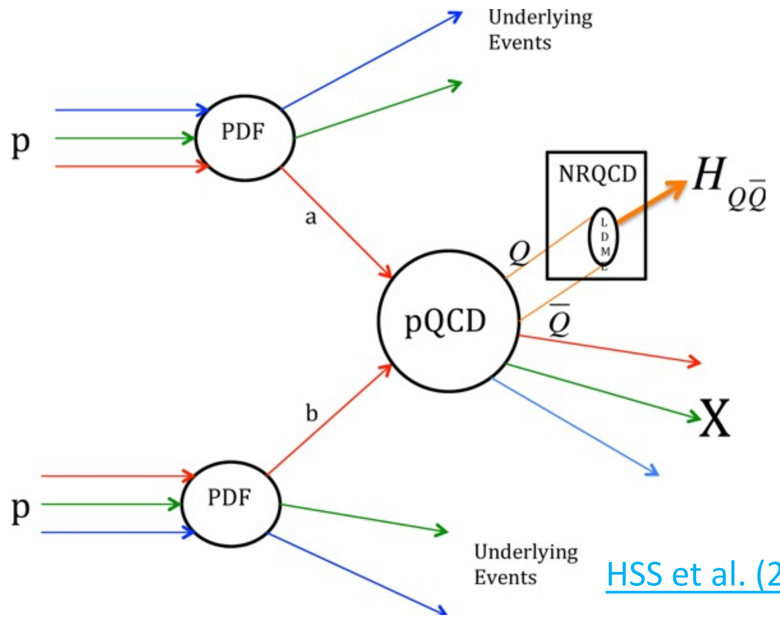


J/ψ production cross-sections at 5.02 TeV

LHCb-PAPER-2021-020, in preparation

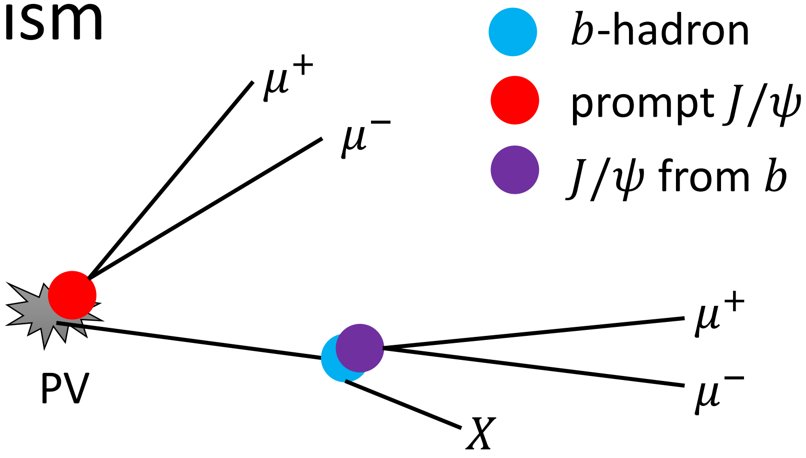
Motivation: probe QCD

- Prompt J/ψ: probe J/ψ production mechanism
  - The process involves:
    - $c\bar{c}$ pair production: perturbative QCD
    - Hadronisation: non-perturbative QCD
  - Theory model: Non-Relativistic QCD (NRQCD)



HSS et al. (2015)

- J/ψ from b: probe b-hadron production mechanism
  - Theory model: Fixed Order plus Next-to-Leading Logarithms (FONLL)
- Reference for cold/hot nuclear matter effect research in proton-lead and lead-lead collisions

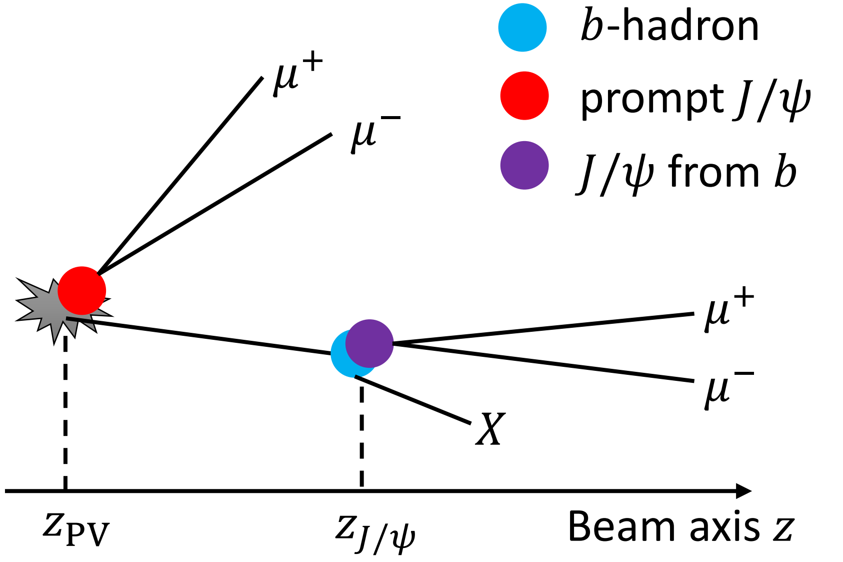


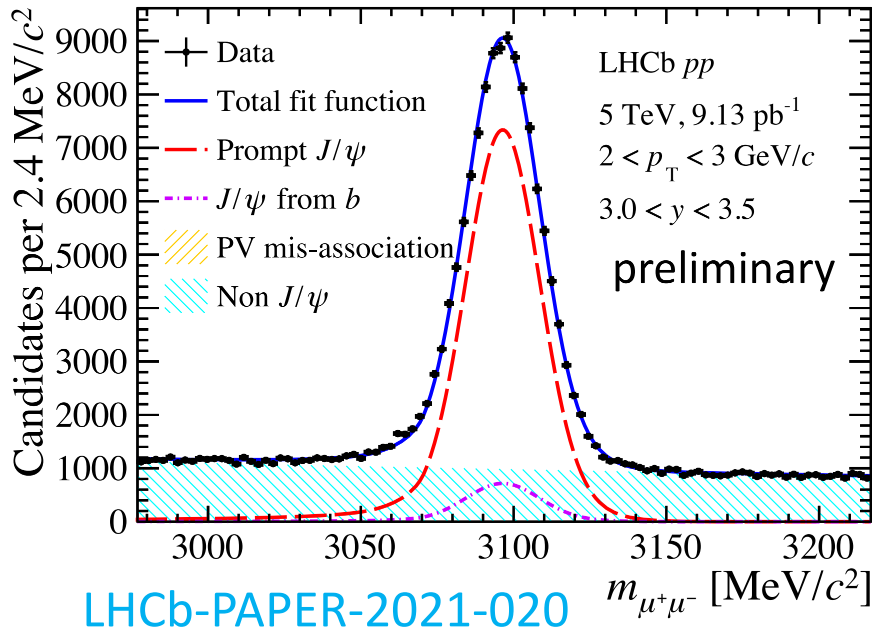
Analysis strategy

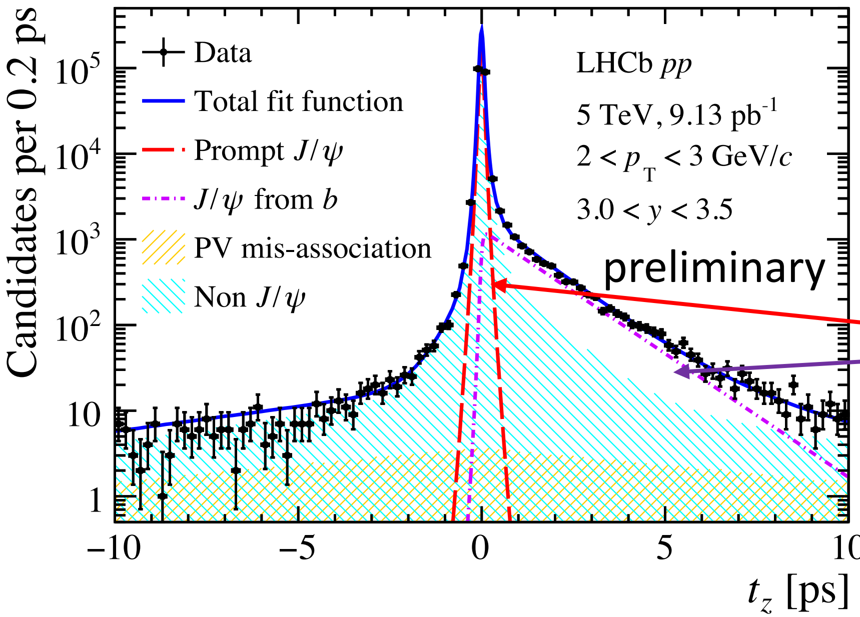
- Differential cross-section:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}y\mathrm{d}p_\mathrm{T}} = \frac{N(J/\psi \to \mu^+\mu^-)}{\mathcal{L}\times\varepsilon_\mathrm{tot}\times\mathcal{B}(J/\psi \to \mu^+\mu^-)\times\Delta y\times\Delta p_\mathrm{T}}$$

- Kinematic range: $p_\mathrm{T} < 20\ \mathrm{GeV}/c,\ 2.0 < y < 4.5$
- Two-dimentional fit to **mass** and **pseudo decay time t_z**







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$$t_z = \frac{z_{J/\psi} - z_\mathrm{PV}}{p_z/m_{J/\psi}}$$

- Use t_z to separate prompt J/ψ and J/ψ from b
- Yields N are corrected by efficiency ε_tot in each (p_T, y) bin

Cross-sections at 5.02 TeV

- Integrated cross-sections ($p_{\mathrm{T}} < 20\ \mathrm{GeV}/c,\ 2.0 < y < 4.5$) assuming zero polarisation
  - $\sigma_{\mathrm{prompt}} = 8.154 \pm 0.010\ (\mathrm{stat.}) \pm 0.283\ (\mathrm{syst.})\ \mu\mathrm{b}$
  - $\sigma_{\mathrm{from-}b} = 0.820 \pm 0.002\ (\mathrm{stat.}) \pm 0.034\ (\mathrm{syst.})\ \mu\mathrm{b}$

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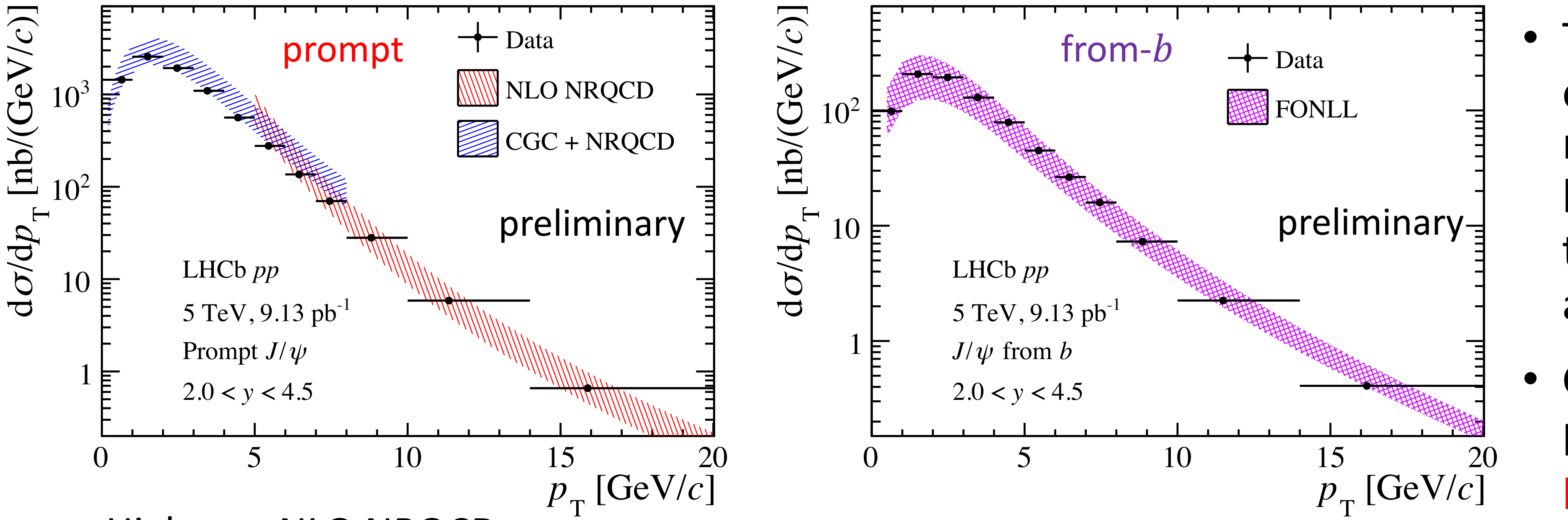

- The inclusion of CGC effects achieves a reasonable agreement between data and theory for prompt J/ψ at low p_{T}
- Good agreement with predictions both for prompt J/ψ and J/ψ from b

- High p_T : NLO NRQCD Phys. Rev. Lett. 106, 042002
- Low p_T : combine NRQCD with color glass condensate (CGC) effective theory Phys. Rev. Lett. 113, 192301
- FONLL JHEP 10 (2012) 137 Eur. Phys. J. C75 (2015) 610

Cross-section ratio

- Ratio between 13 TeV and 5.02 TeV measurements

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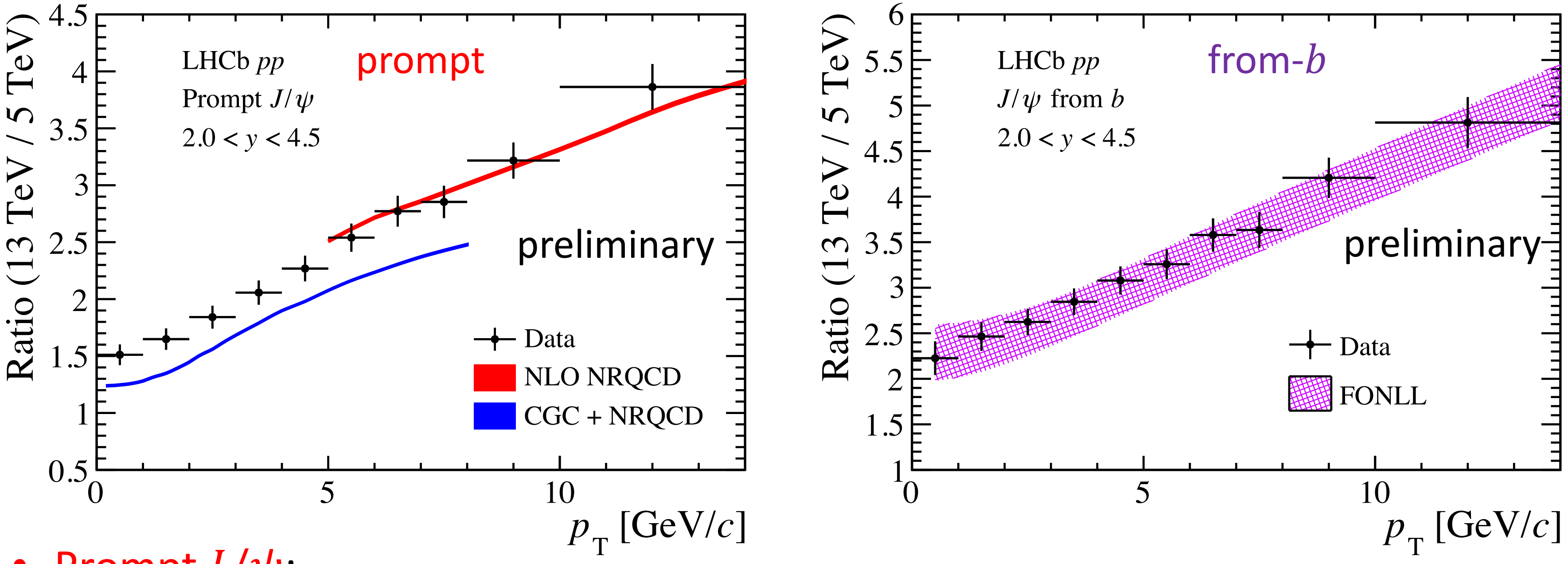

- Prompt J/ψ:
  - High p_{T}: good agreement between data and NLO NRQCD
  - Low p_{T}: a small tension between data and CGC + NRQCD
    - Need for further corrections in the theory model?
- J/ψ from b: good agreement between data and FONLL
- Same conclusion for the ratio between 8 TeV and 5.02 TeV measurements

Nuclear modification factor $R_{p\mathrm{Pb}}$

- $R_{p\mathrm{Pb}}$ at 5.02 TeV was calculated using interpolated pp collision cross-sections JHEP 02 (2014) 072
- $R_{p\mathrm{Pb}}$ is updated using direct measured pp collision cross-sections
  - consistent with previous result

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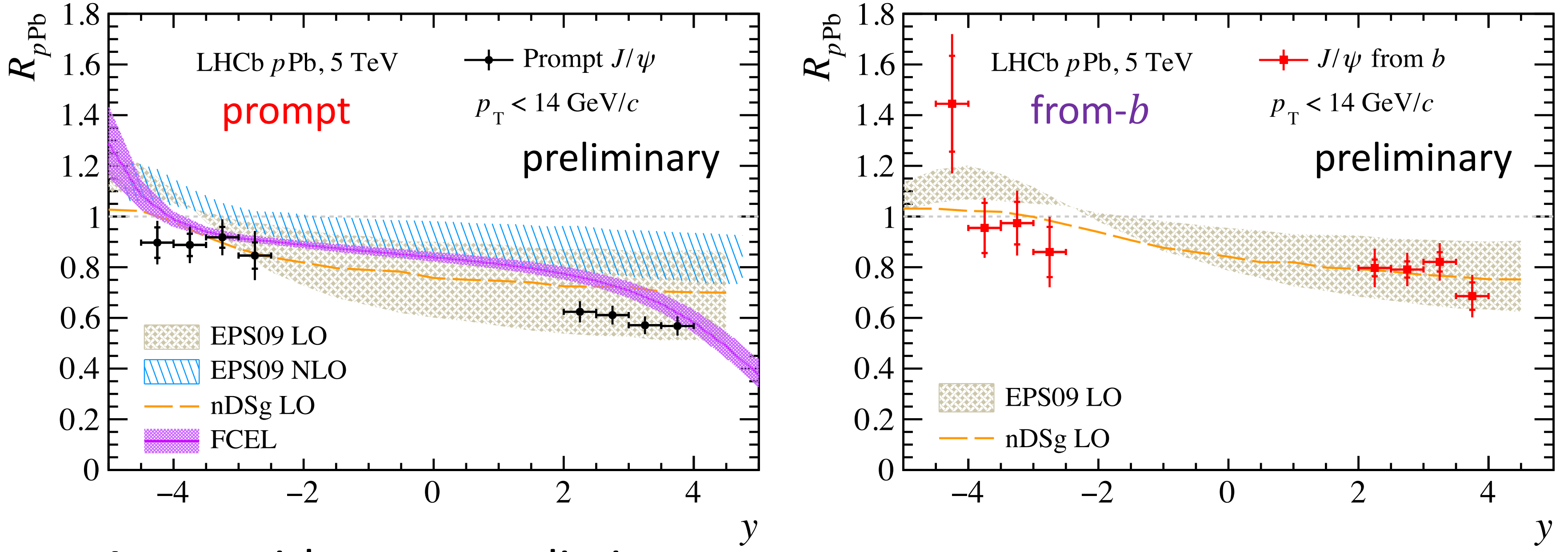


EPS09 LO

Phys. Rev. C88, 047901

EPS09 NLO

Int. J. Mod. Phys. E22, 1330007

nDSg LO

Phys. Rev. C88, 047901

FCEL

Phys. Rev. Lett. 109, 122301

- Agree with most predictions
- EPS09 NLO provides a poorer description in the forward region for prompt J/ψ

Precise measurement of f_s/f_d

arXiv:2103.06810

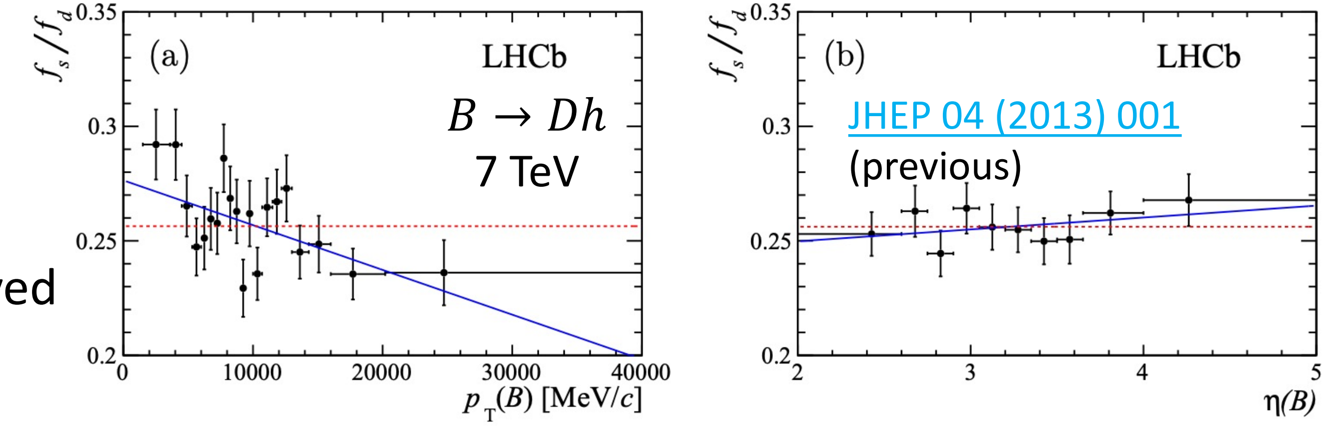
Introduction

- The ratio of b-hadron fragmentation fractions f_s/f_d

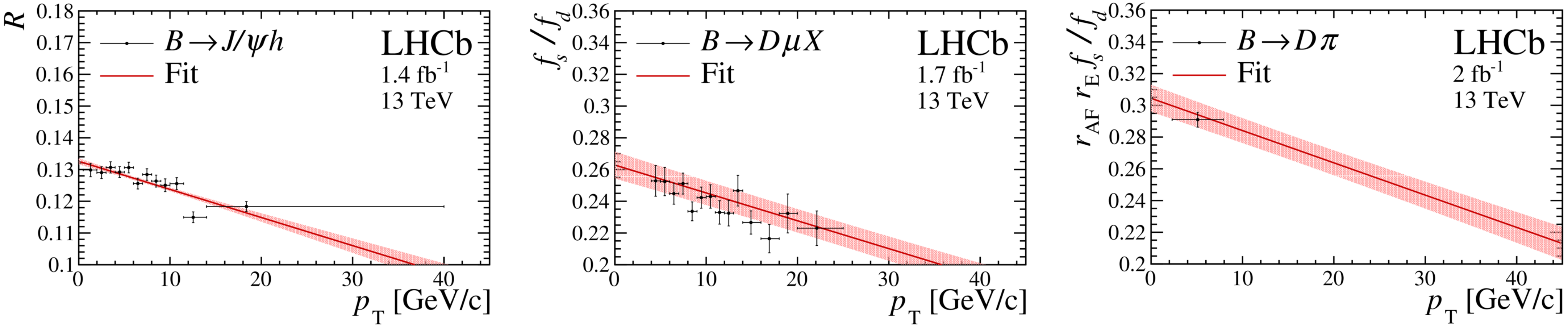
$$\frac{n_{\text{corr}}(B_s^0 \to X)}{n_{\text{corr}}(B^{0(+)} \to Y)} = \frac{\mathcal{B}(B_s^0 \to X)}{\mathcal{B}(B^{0(+)} \to Y)} \frac{f_s}{f_{d(u)}}$$

  - Isospin symmetry is assumed: $f_u = f_d$
- Motivation:
  - Test desciptions of heavy flavour hadronisation
  - Crucial input for B_s^0 decay branching fraction measurements at LHCb
    - Dominant systematic uncertainty for some channels
- Combine previous f_s/f_d measurements at LHCb
  - Semileptonic modes: $B \to D\mu X$ — Phys. Rev. D85, 032008 Phys. Rev. D100, 031102
  - Hadronic modes: $B \to Dh$ — JHEP 04 (2013) 001 Eur. Phys. J. C81 (2021) 314
  - Charmonium modes: $B_s^0 \to J/\psi\phi$ and $B^+ \to J/\psi K^+$ — Phys. Rev. Lett. 214, 122002

Analysis strategy



- From previous results
  - Significant dependence on p_{T} observed
  - No dependence on η
- Combine previous measurements with external inputs updated
- Simultaneous fit to f_s/f_d-sensitive observables versus p_{T} for 7, 8 and 13 TeV



- Nominal: linear function

arXiv:2103.06810

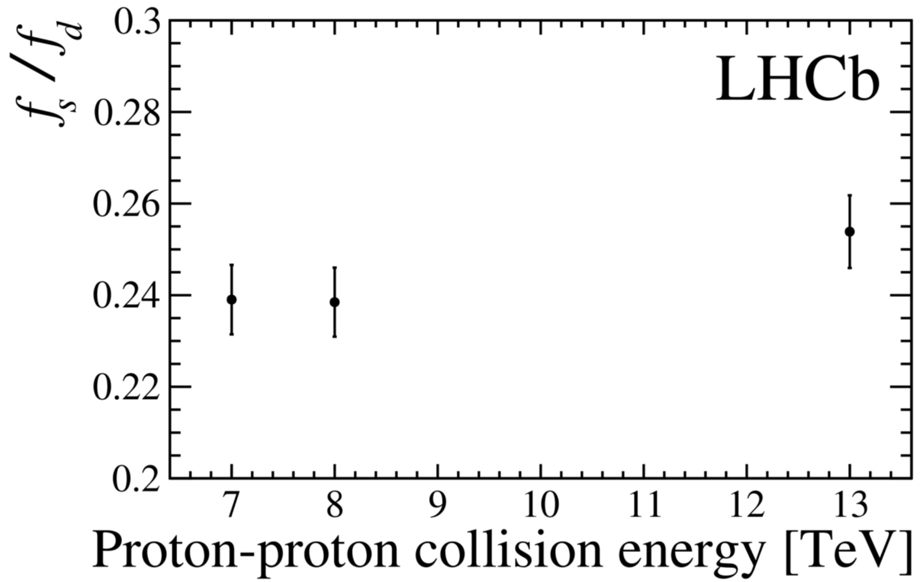
f_s/f_d result

- $f_s/f_d\ (p_\mathrm{T}, 7\ \mathrm{TeV}) = (0.244 \pm 0.008) + \left((-10.3 \pm 2.7)\times10^{-4}\right) \cdot p_\mathrm{T}$
- $f_s/f_d\ (p_\mathrm{T}, 8\ \mathrm{TeV}) = (0.240 \pm 0.008) + \left((-\ \ 3.4 \pm 2.3)\times10^{-4}\right) \cdot p_\mathrm{T}$
- $f_s/f_d\ (p_\mathrm{T}, 13\ \mathrm{TeV}) = (0.263 \pm 0.008) + \left((-17.6 \pm 2.1)\times10^{-4}\right) \cdot p_\mathrm{T}$

p_T in unit of GeV/c

arXiv:2103.06810

- Branching fractions of B_s^0 decays remeasured
  - $\mathcal{B}(B_s^0 \to J/\psi\phi) = (1.018 \pm 0.032 \pm 0.037)\times10^{-3}$
  - $\mathcal{B}(B_s^0 \to D_s^-\pi^+) = (3.20 \pm 0.10 \pm 0.16)\times10^{-3}$
  - Halving uncertainties with respect to previous world average (PDG 2020)

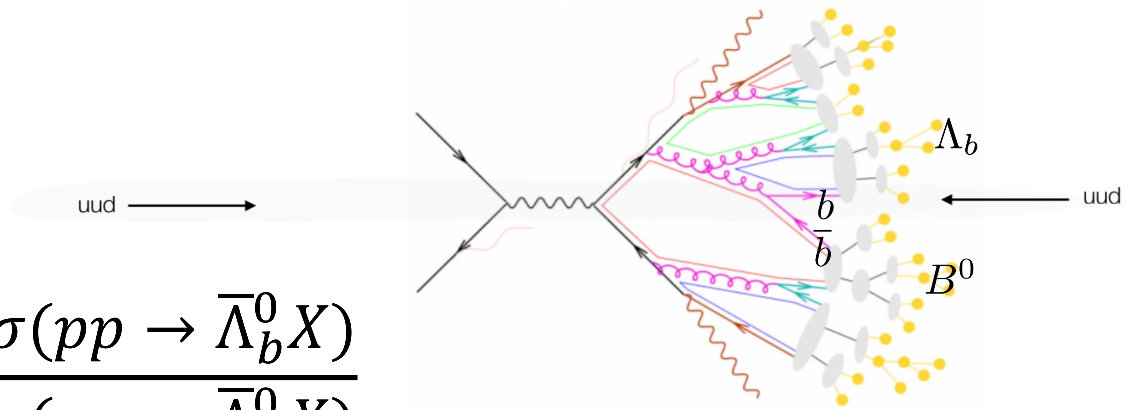


Integrated f_s/f_d versus $\sqrt{s}$

Λ_b^0 production asymmetry at 7 and 8 TeV

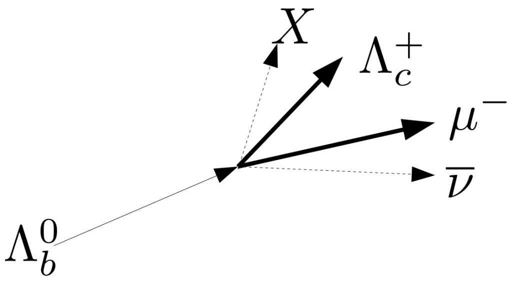
LHCb-PAPER-2021-016, in preparation

Introduction



$$A_P(\Lambda_b^0) = \frac{\sigma(pp \to \Lambda_b^0 X) - \sigma(pp \to \overline{\Lambda}_b^0 X)}{\sigma(pp \to \Lambda_b^0 X) + \sigma(pp \to \overline{\Lambda}_b^0 X)}$$

- Motivation:
  - Test effective descriptions of the strong interaction
  - Improve understanding of collision dynamics
    - Input to generator tuning
  - Provide precise knowledge for b-baryon CP measurements
- Decay mode: $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\mu^-\bar{\nu}X$
  - High branching fraction
  - Partially reconstructed
  - Assume no CP violation in Λ_b^0 and Λ_c^+ decays



$$p(\Lambda_b^0) \approx p(\Lambda_c^+) + p(\mu^-)$$

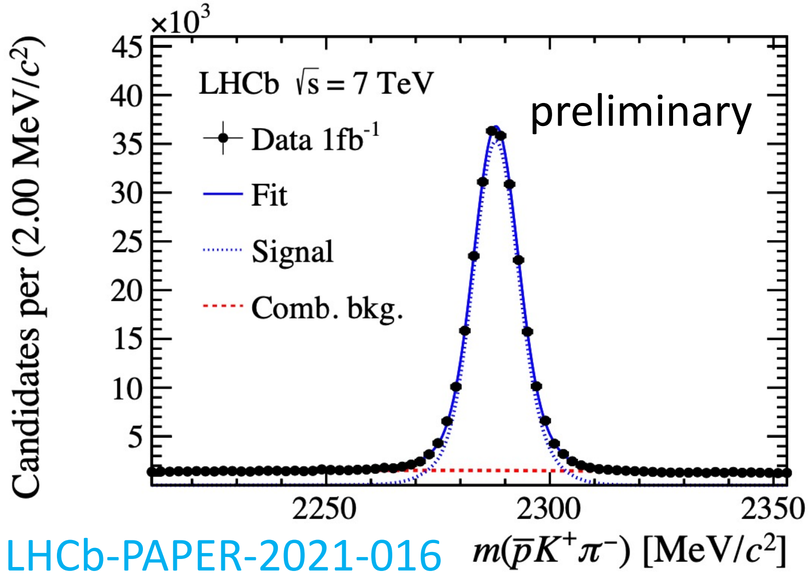
Analysis strategy

$$A_P(\Lambda_b^0) = \frac{\sigma(pp\to\Lambda_b^0 X) - \sigma(pp\to\overline{\Lambda}_b^0 X)}{\sigma(pp\to\Lambda_b^0 X) + \sigma(pp\to\overline{\Lambda}_b^0 X)} \qquad A_{\text{raw}}(\Lambda_b^0) = \frac{N(\Lambda_b^0\to\Lambda_c^+\mu^- X) - N(\overline{\Lambda}_b^0\to\Lambda_c^-\mu^+ X)}{N(\Lambda_b^0\to\Lambda_c^+\mu^- X) + N(\overline{\Lambda}_b^0\to\Lambda_c^-\mu^+ X)}$$

$$A_P(\Lambda_b^0) = A_{\text{raw}}(\Lambda_b^0) - A_D(pK^-\pi^+\mu^-)$$

- Measure production asymmetry as a function of y and p_{T}
  - $y \approx y(\Lambda_c^+\mu^-)$, checked with simulation, $2.15 < y < 4.10$
  - $p_{\text{T}} = p_{\text{T}}(\Lambda_c^+\mu^-)/k(m(\Lambda_c^+\mu^-))$, k correction factor is obtained from simulation, $2 < p_T < 27\ \text{GeV}/c$
- Raw asymmetry A_{raw}
  - Fit to Λ_c^+ invariant mass (Λ_b^0 candidates selected)
- Detection asymmetry A_D
  - Measured for each particle

$$A_D(h^\pm) = \frac{\varepsilon(h^\pm) - \varepsilon(h^\mp)}{\varepsilon(h^\pm) + \varepsilon(h^\mp)}$$



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Production asymmetry

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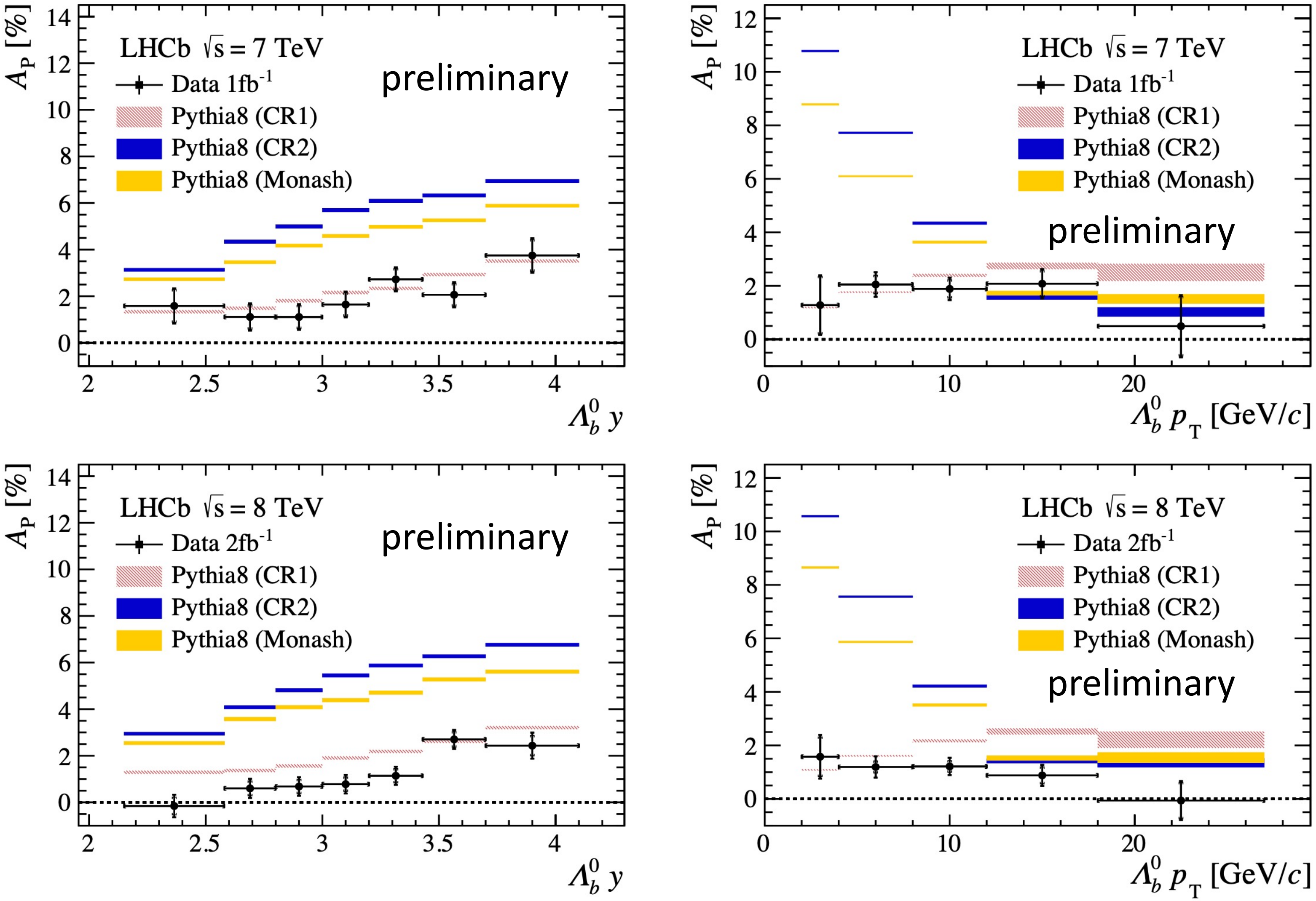

- A production asymmetry is observed (few percent level)
  - Evidence for a dependence on y
- Pythia8 model
  - standard Monash setting
    Eur. Phys. J. C74 (2014) 3024
  - with colour-reconnection (CR) models implemented
    - CR1: QCD-inspired model
      JHEP 11 (2014) 043 JHEP 08 (2015) 003
    - CR2: gluon-move model
      JHEP 11 (2014) 043 Eur. Phys. J. C75 (2015) 441
- Disfavour the Pythia8 Monash and CR2 tunes

Production asymmetry

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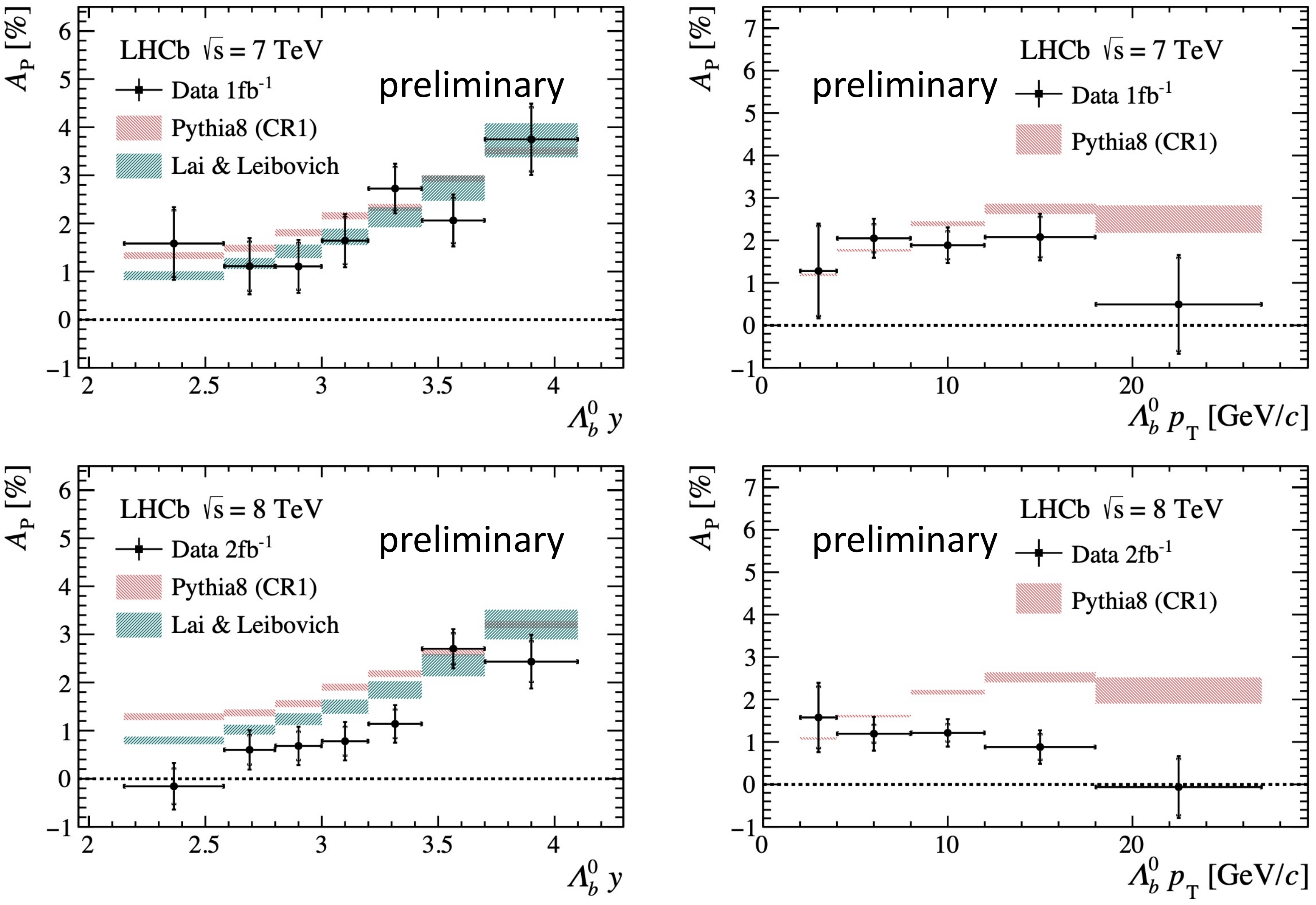


- Compatible with these two theory models
  - Lai & Leibovich:

    heavy-quark recombination predictions

    Phys. Rev. D91, 054022
  - Pythia8 CR1:

    QCD-inspired model

    JHEP 11 (2014) 043 JHEP 08 (2015) 003

Summary

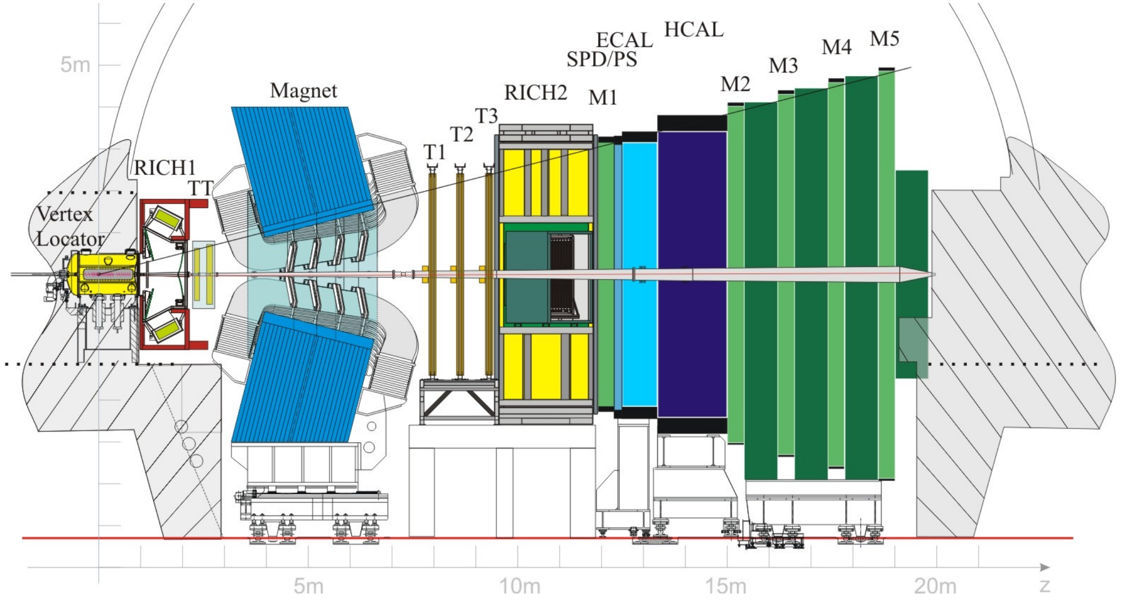
- Many results in heavy flavour production in pp collisions at LHCb
- Recent ones are reported here
  - J/ψ production cross-sections at 5.02 TeV
  - Precise measurement of f_s/f_d
  - Λ_b^0 production asymmetry at 7 and 8 TeV
- These measurements provide important information to improve QCD predictions and crucial inputs for MC tuning
- New results from LHCb are on the way
  - $\chi_{c1}(3872)$ production at 8 and 13 TeV

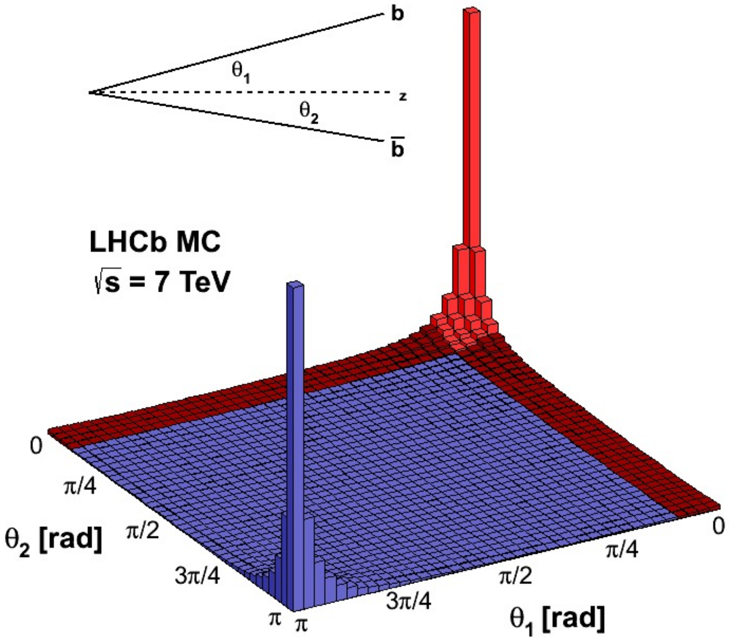
Thank you!

Backup Slides

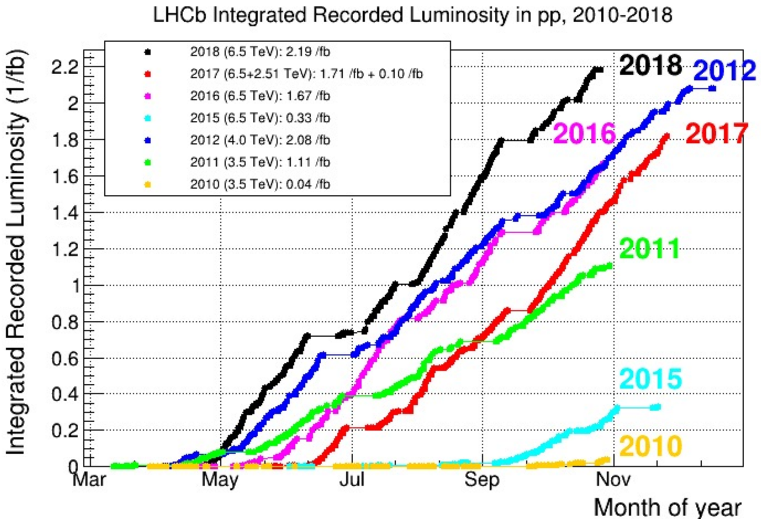
LHCb experiment

- Single-arm forward spectrometer
- Designed for the study of b and c physics
- Forward region $2 < \eta < 5$
  - $\sim$4% of solid angle, but $\sim$25% of $b\bar{b}$ quark pairs accepted





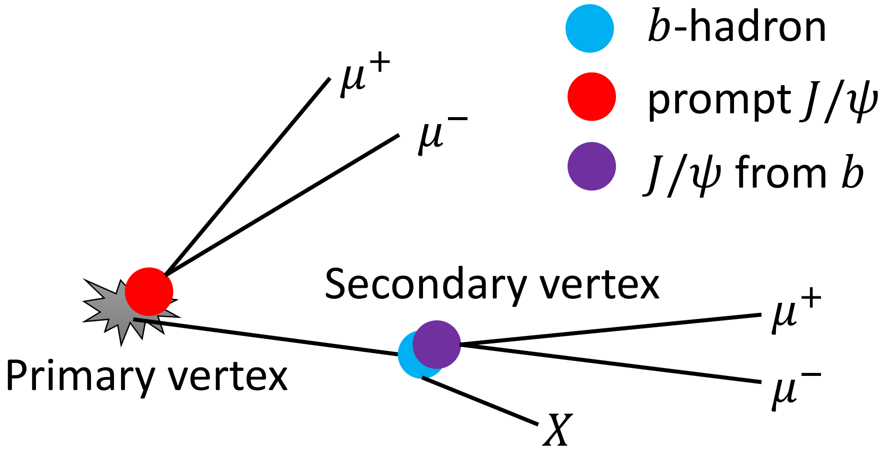
- Data collection
  - Totally $\sim$9 fb^{-1} pp collision data at 5/7/8/13 TeV



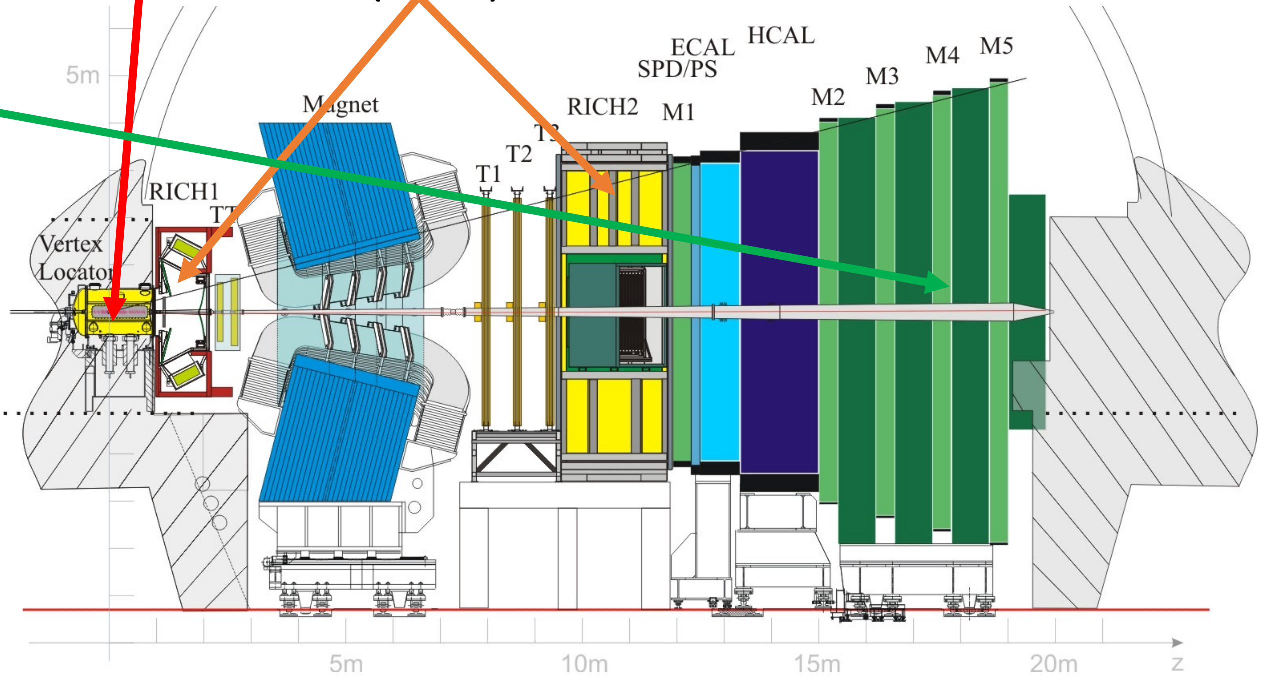
LHCb experiment

- Key detector systems for heavy flavour production
  - Vertex reconstruction with Vertex Locator (Velo)
    - Separate primary and secondary vertices
  - Particle identification
    - Charged hadron: ring-imaging Cherenkov detector (RICH)
    - μ: muon detector

- An ideal laboratory for heavy flaour production studies



Example: J/ψ production



[Int. J. Mod. Phys. A 30, 1530022 (2015)](#)

J/ψ cross-sections at 5.02 TeV

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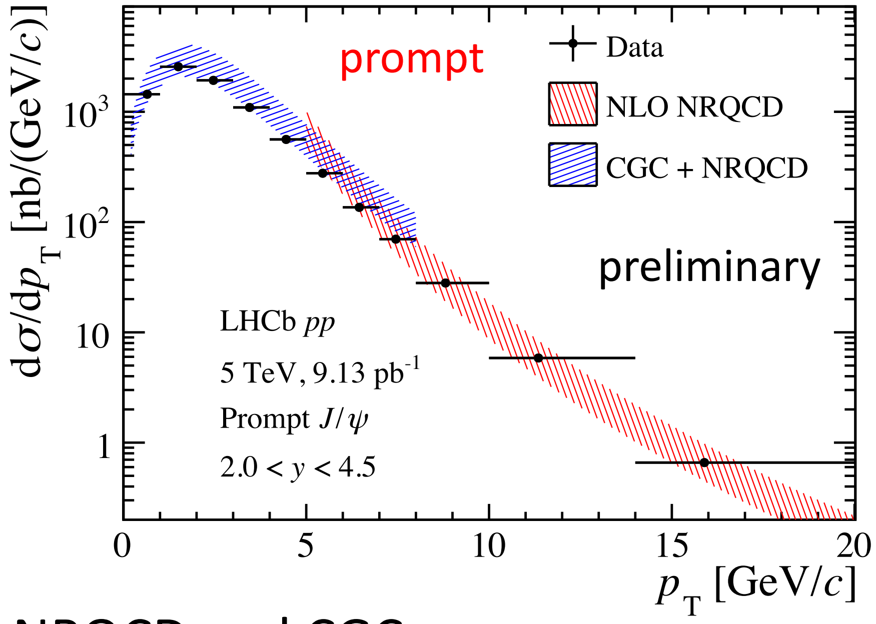

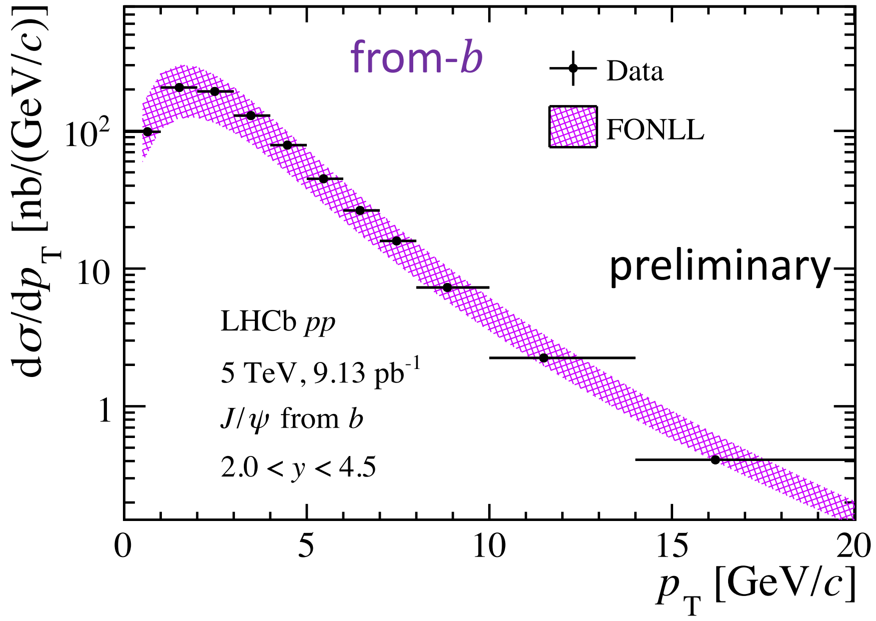

- NRQCD and CGC
  - Uncertainties due to LDMEs determination, renormalisation scales, and factorisation scales
  - Cancel most in ratios
- FONLL
  - PDFs uncertainties, the uncertainty due to the b-quark mass, and that due to the scales of renormalisation and factorisation

Nuclear modification factor $R_{p\mathrm{Pb}}$

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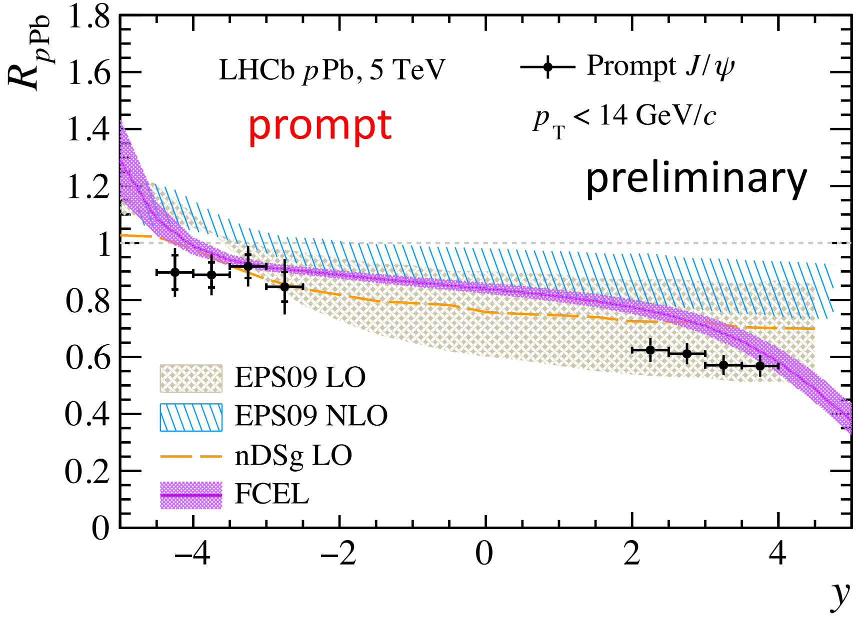
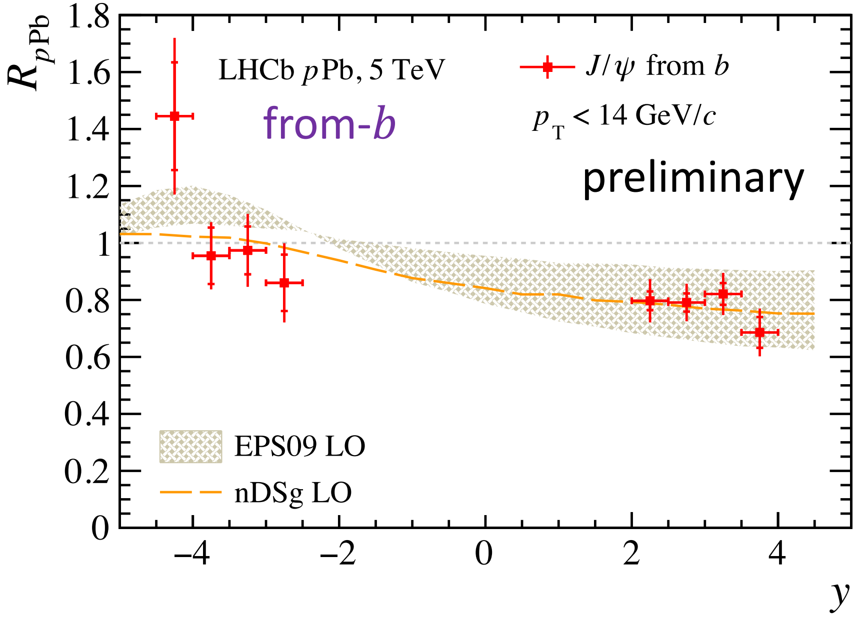
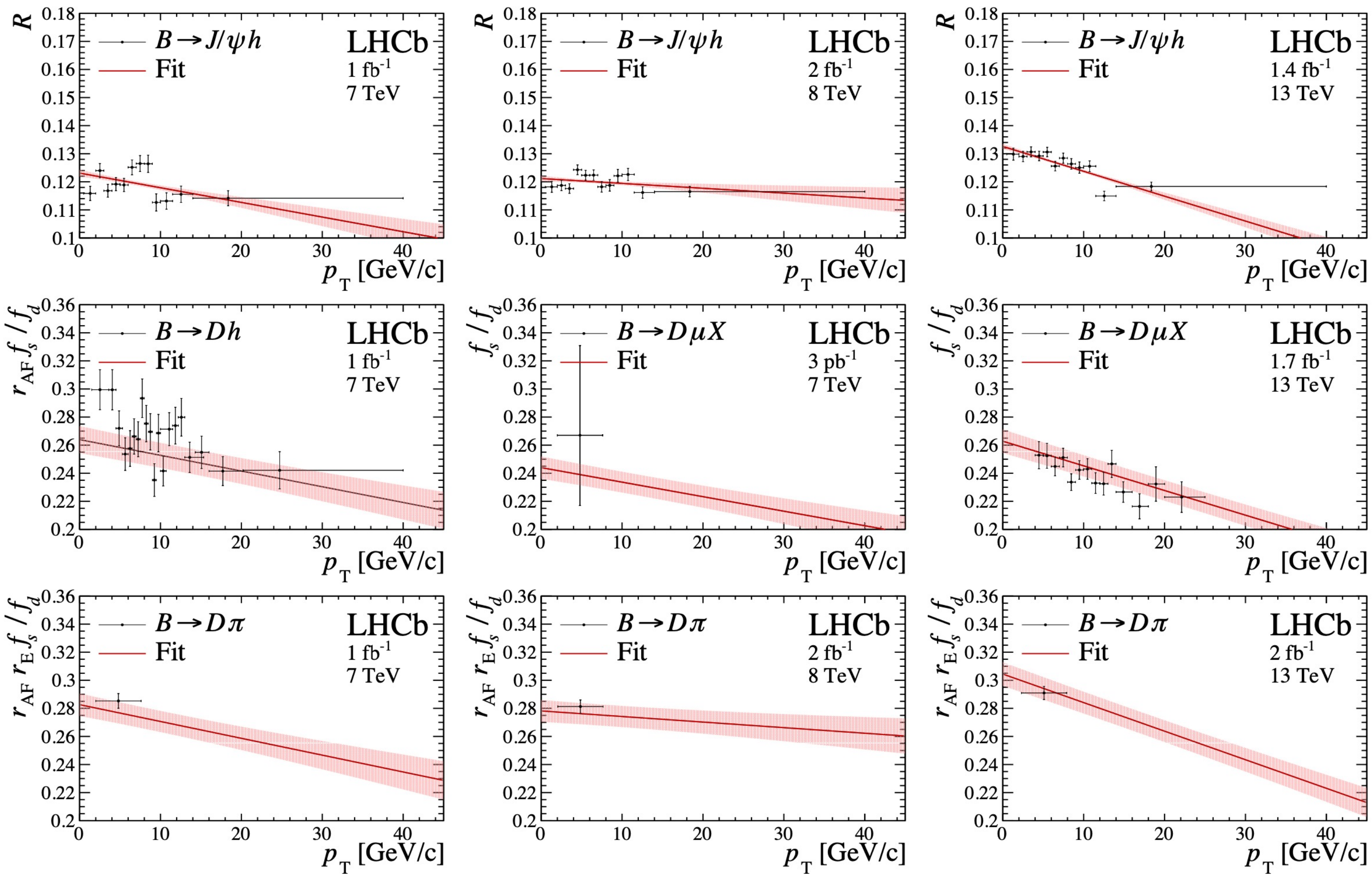




- EPS09 LO: the calculation with EPS LO parameterisation [arXiv:1305.4569]
- EPS09 NLO: the calculation with EPS NLO parameterisation [arXiv:1301.3395]
- nDSg LO: the calculation with nDSg LO parameterisation [arXiv:1305.4569]
- FCEL: fully coherent energy loss model [arXiv:1212.0434]

f_s/f_d

arXiv:2103.06810



f_s/f_d

arXiv:2103.06810

$$\frac{dN}{dp_{\mathrm{T}}} = C\frac{(n-1)(n-2)}{nT(nT+Mc^2(n-2))}p_{\mathrm{T}}\left[1+\frac{\sqrt{M^2c^4+p_T^2c^2}-Mc^2}{nT}\right]^{-n}$$

Tsallis-statistics inspired function

J. Statist. Phys. 52 (1988) 479

Braz. J. Phys. 29 (1999) 1