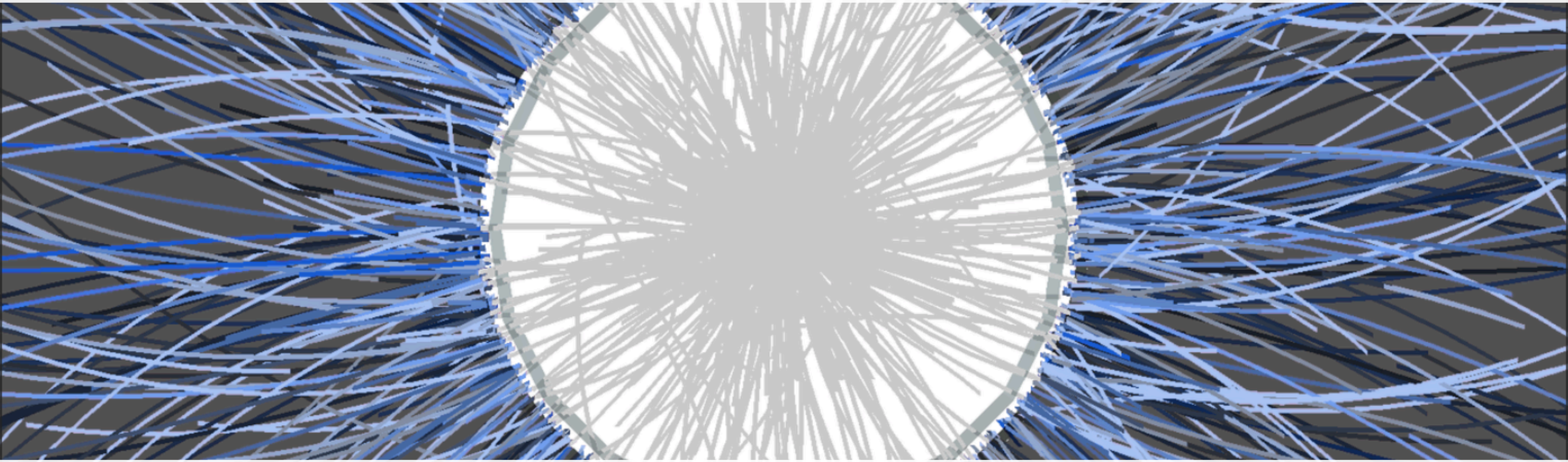
Measurements of beauty-hadron production in pp and Pb–Pb collisions with ALICE



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CERN

XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects
Virtual Event @ Stony Brook University | 12-16 April 2021

Introduction: beauty-hadron production in proton–proton collisions

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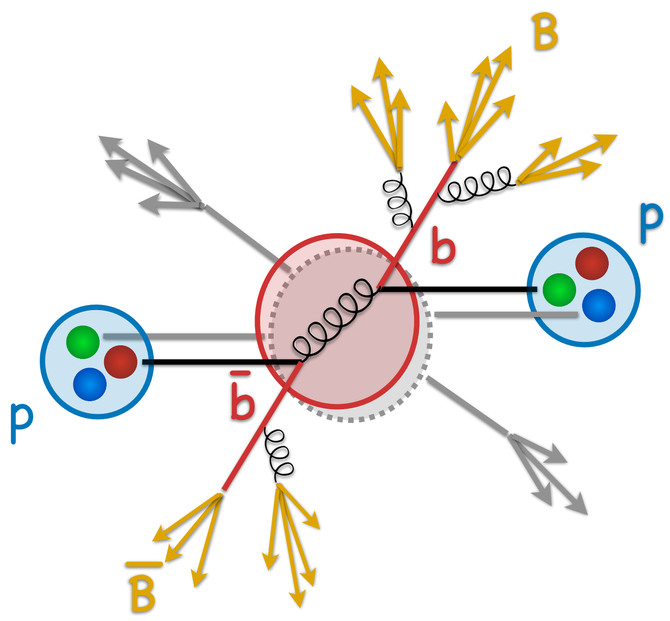
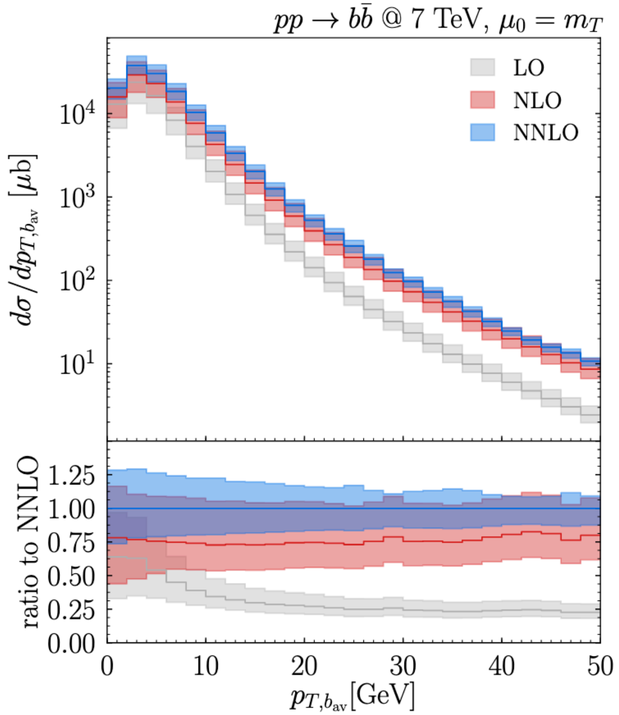


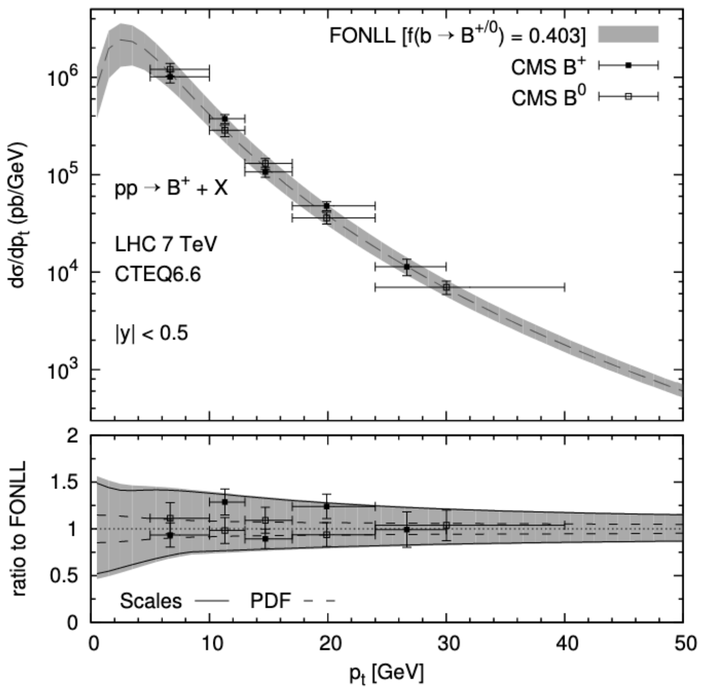
- Beauty quarks are produced in hard-scattering processes
- Described with perturbative QCD calculations (pQCD) based on the factorisation theorem

$$\sigma_{\mathrm{hh}\to\mathrm{Hh}} = \mathrm{PDF}(x_{\mathrm{a}}, Q^2)\ \mathrm{PDF}(x_{\mathrm{b}}, Q^2) \otimes \sigma_{\mathrm{ab}\to\mathrm{q}\bar{\mathrm{q}}} \otimes D_{\mathrm{q}\to\mathrm{h}}(z_q, Q^2)$$

- Parton distribution functions (non perturbative)
- Partonic cross section (perturbative)
  - ➡ Calculations available at different perturbative orders
- Fragmentation functions (non perturbative):
  - ➡ Typically parametrised from e^+e^- measurements



NNLO Catani et al, JHEP 03 (2021) 029



FONLL Cacciari et al, JHEP 1210 (2012) 137

Beauty-hadron production in heavy–ion collisions

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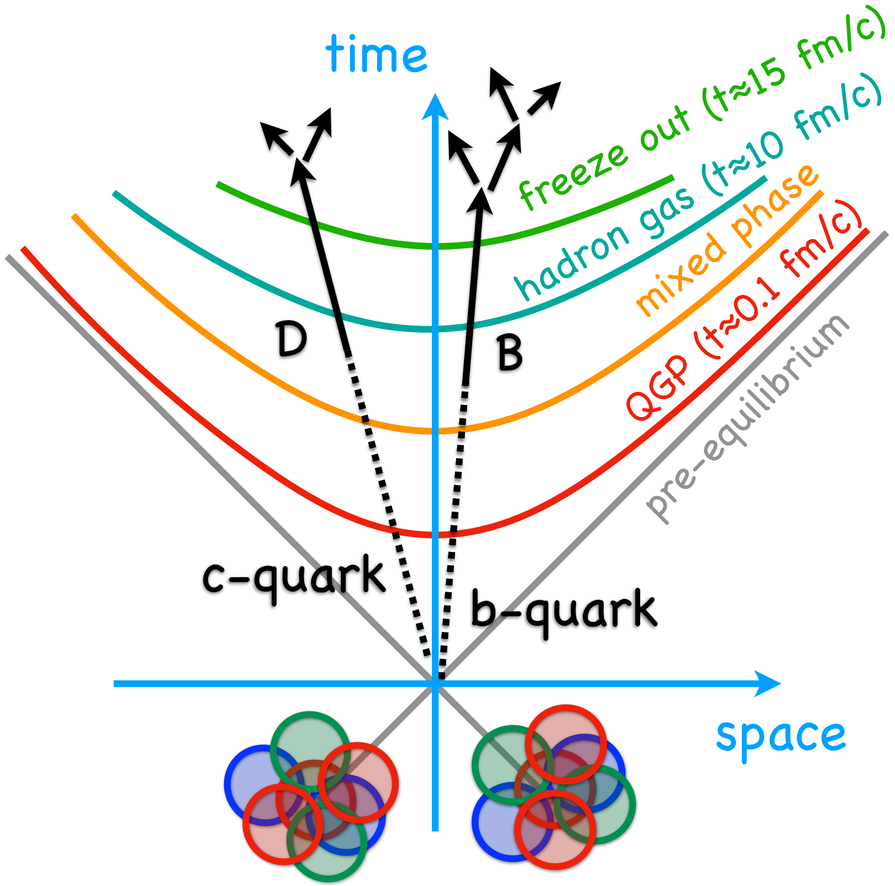

- QCD calculations on lattice predict a phase transition from the ordinary nuclear matter to a colour-deconfined medium, called *quark–gluon plasma* (QGP)
  - ➡ created in ultra-relativistic heavy-ion collisions
  - ➡ after a pre-equilibrium phase expands hydrodynamically

- Heavy flavours: produced in shorter time scales than QGP formation time
  - ➡ HF experience the full system evolution
  - ➡ Lose energy interacting with medium constituents via elastic collisions and radiative processes
  - ➡ Beauty and charm hadrons: study properties of in-medium energy loss
    - ‣ quark-mass and colour-charge dependencies

A Large Ion Collider Experiment

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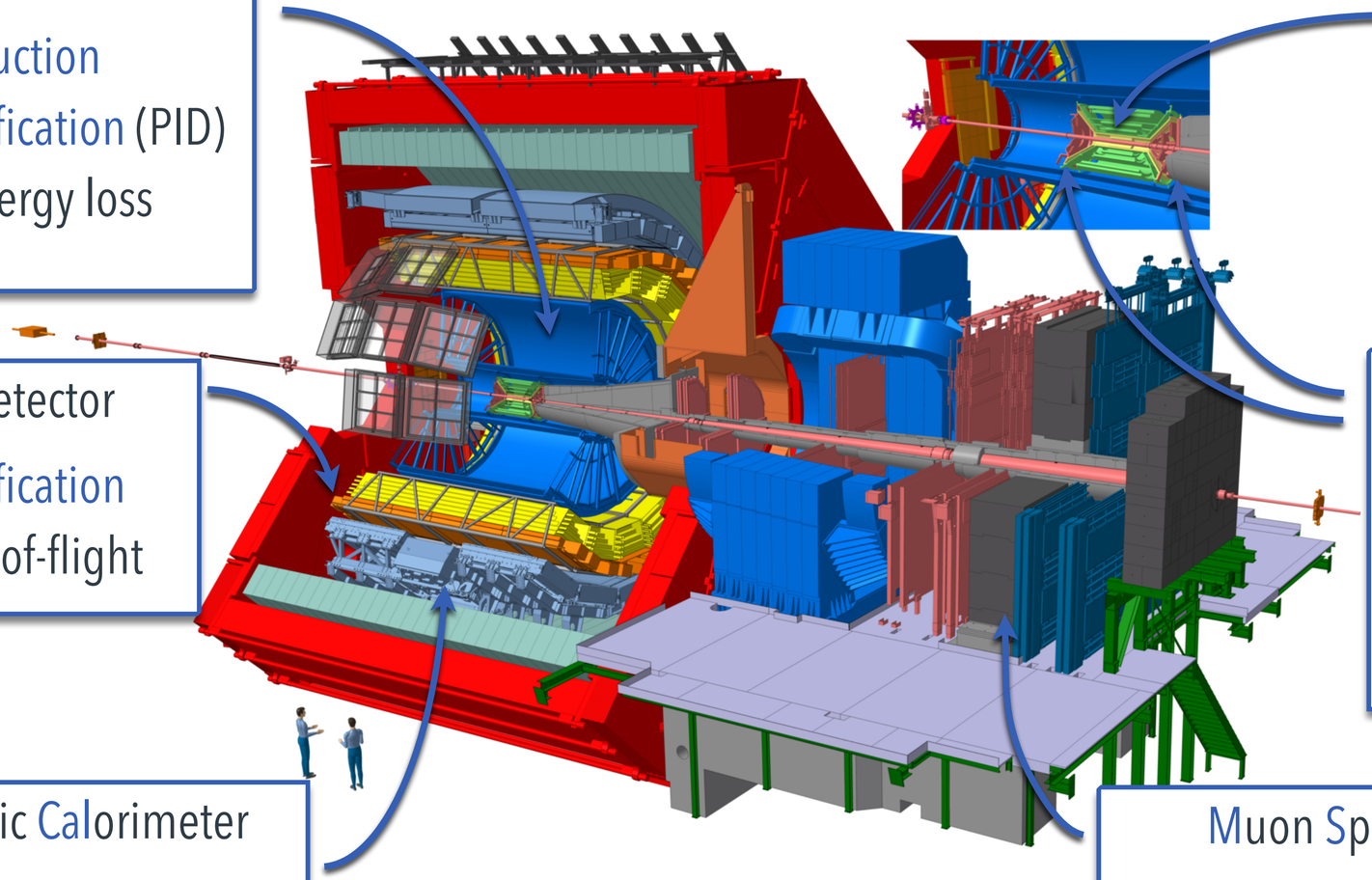
Time Projection Chamber

- ➡ Track reconstruction
- ➡ Particle identification (PID) via specific energy loss

Inner Tracking System

- ➡ Track reconstruction
- ➡ Primary and decay vertices reconstruction



Time-of-Flight detector

- ➡ Particle identification (PID) via time-of-flight

V0 detectors

- ➡ Trigger
- ➡ Centrality determination
- ➡ Event-plane estimation

Electromagnetic Calorimeter

- ➡ Particle identification (PID) via energy deposited
- ➡ Trigger

Muon Spectrometer

- ➡ Muon identification and trigger
- ➡ Track reconstruction

Measurements of beauty-hadrons with ALICE: dielectrons

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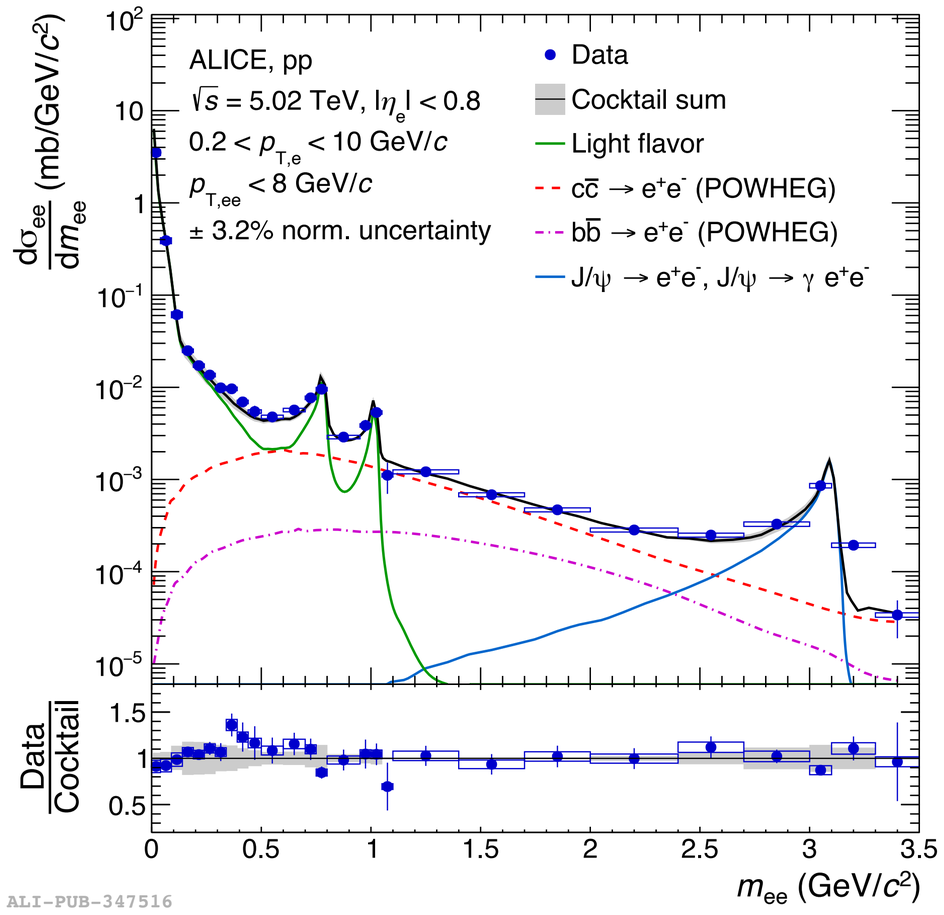
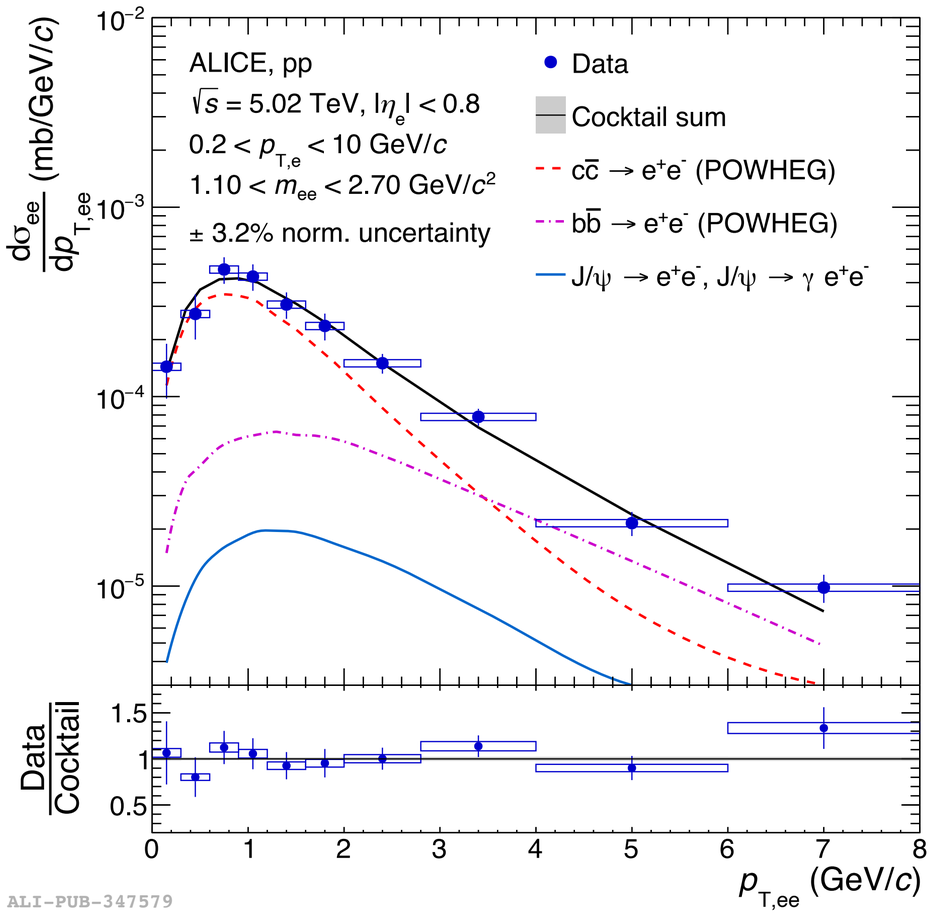
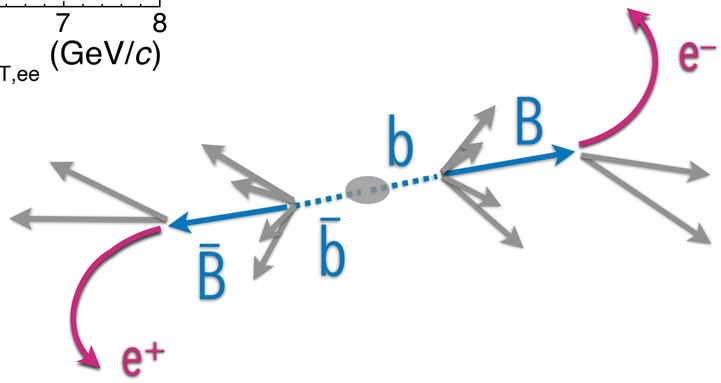




- Dielectrons: arXiv:2005.11995
- PYTHIA6: JHEP 05 (2006) 026
- POWHEG: JHEP 11 (2007) 070

- Open charm and beauty contribution obtained from simultaneous fit of e^+e^- invariant-mass and transverse momentum differential cross section with POWHEG or PYTHIA templates



Measurements of b hadrons in ALICE: non-prompt J/ψ and electrons

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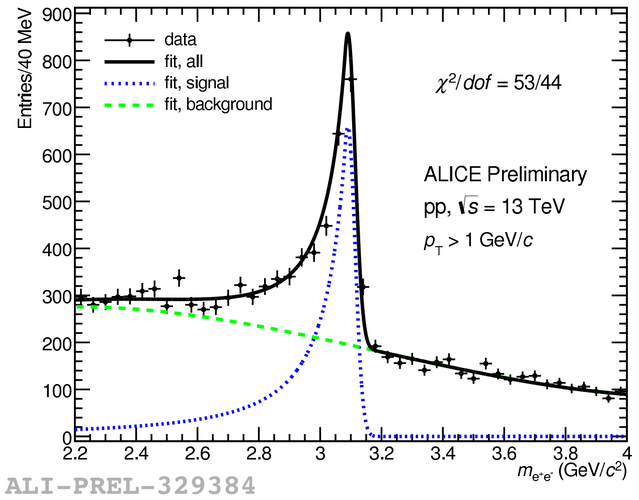
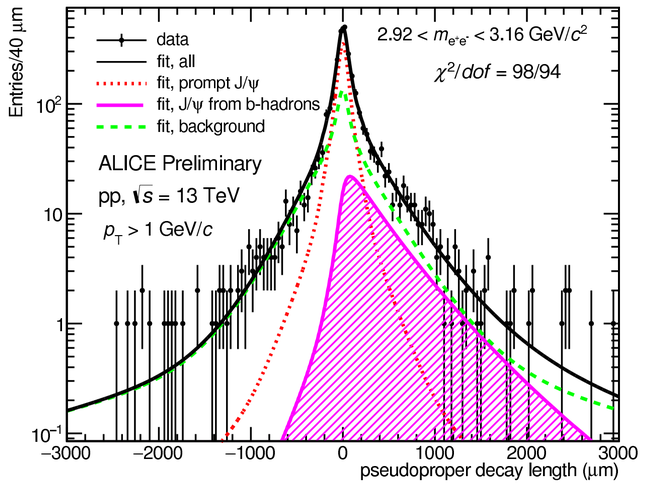
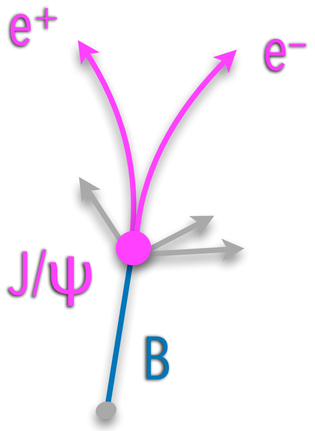
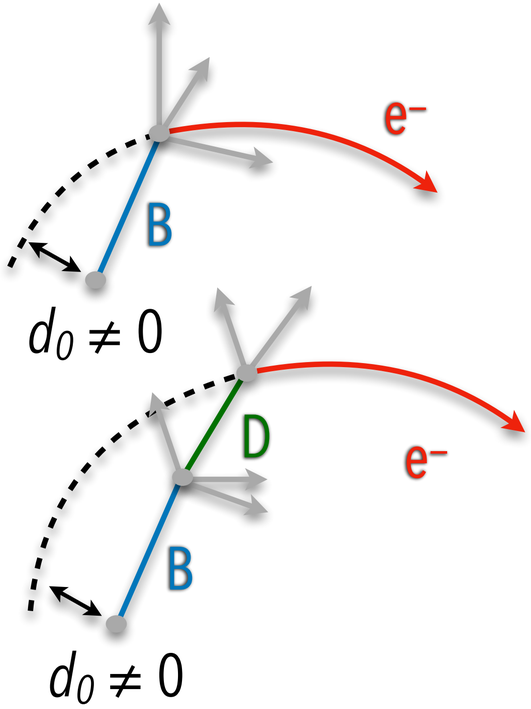
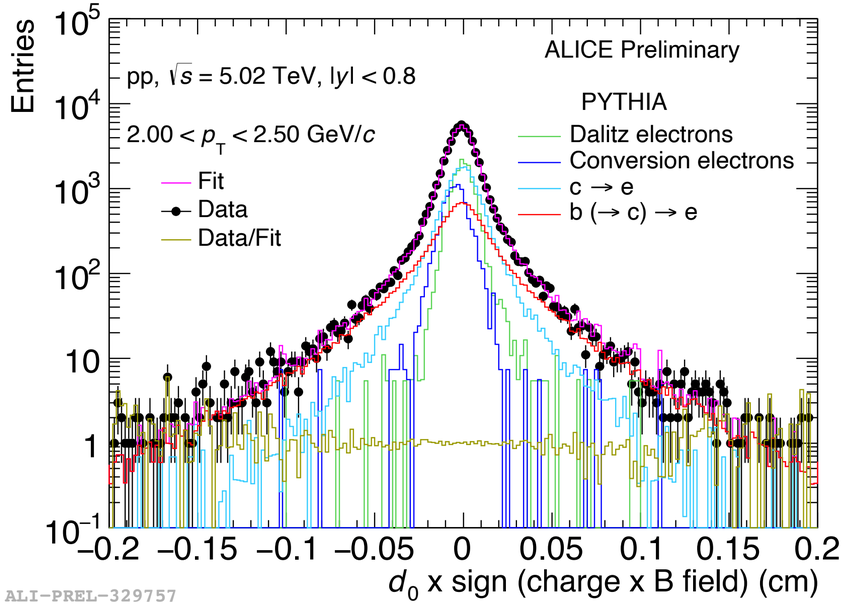
- J/ψ candidates built from e^+e^- pairs
  - ➡ BR(J/ψ → e^+e^-) = 5.971 ± 0.032 %
    - PDG, Prog. Theor. Exp. Phys. 2020 083C01
  - ➡ Simultaneous unbinned fit of invariant-mass and pseudoproper decay length distributions











pseudoproper decay length

$$x = \frac{c(\vec{L} \cdot \vec{p}_T / p_T) m_{J/\psi}}{p_T}$$

- Multi-component template fit to the impact parameter distribution of electrons:
  - ➡ wider distribution for electrons from b due to b-hadron proper decay length (~ 500 mum)

Measurements of b hadrons in ALICE: non-prompt D mesons

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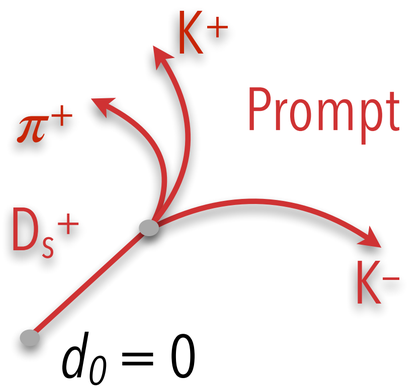
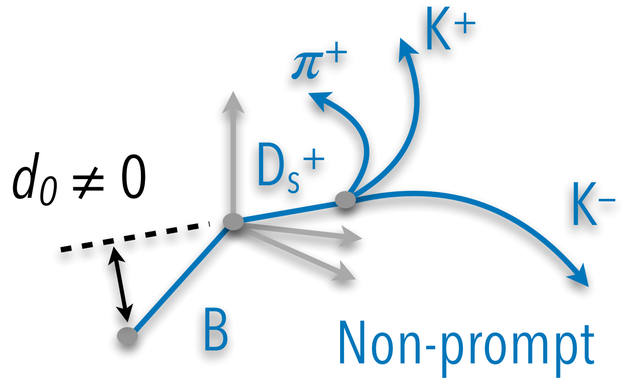
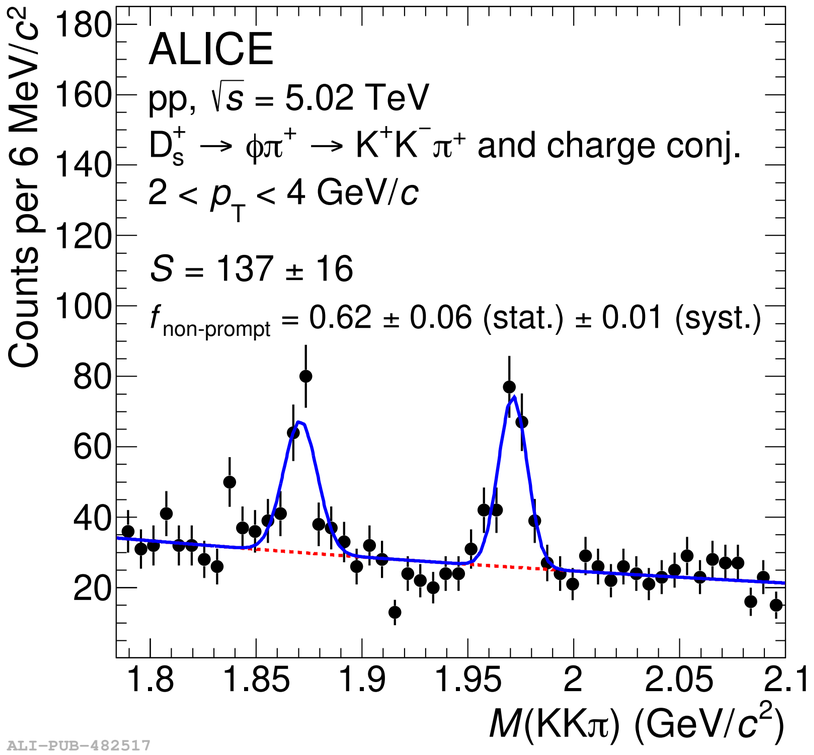
Meson	$c\tau$ (μm)	decay	BR (%)
D^0	123	$K^-\pi^+$	3.95
D^+	312	$K^-\pi^+\pi^+$	9.38
D_s^+	151	$\phi(\rightarrow K^-K^+)\,\pi^+$	2.24

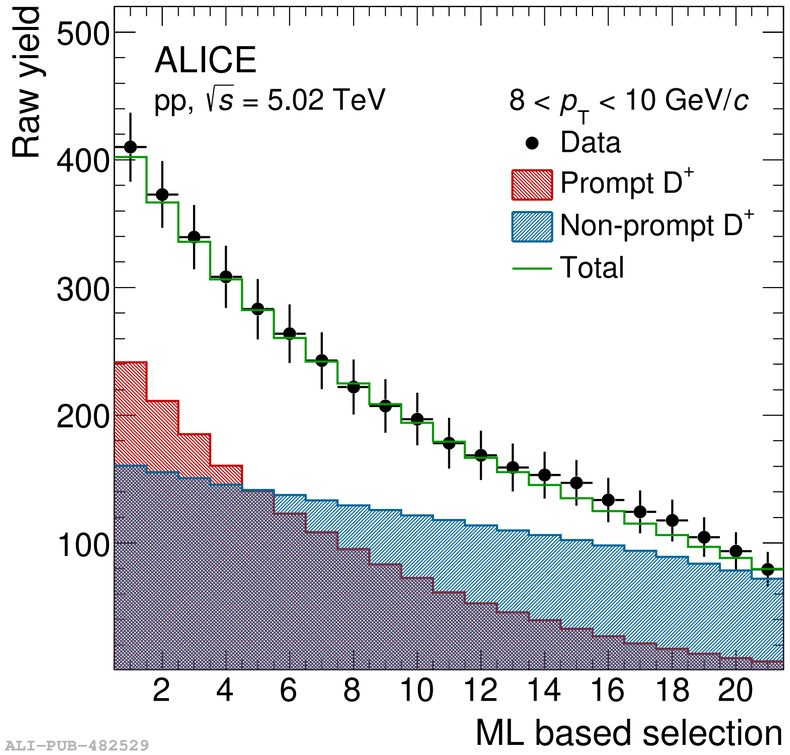
PDG, Prog. Theor. Exp. Phys. 2020 083C01





- D candidates built as pairs/triplets of tracks with proper charge sign
- Candidates classified as prompt D, non-prompt D, or background using Boosted Decision Trees (BDT)
  - ➡ BDT trained exploiting:
    - decay-vertex topology (b-hadron $c\tau$ ~ 500 μm)
    - PID of decay tracks





Non-prompt D: arXiv:2102.13601

Non-prompt J/ψ and e ← b vs. pQCD calculations

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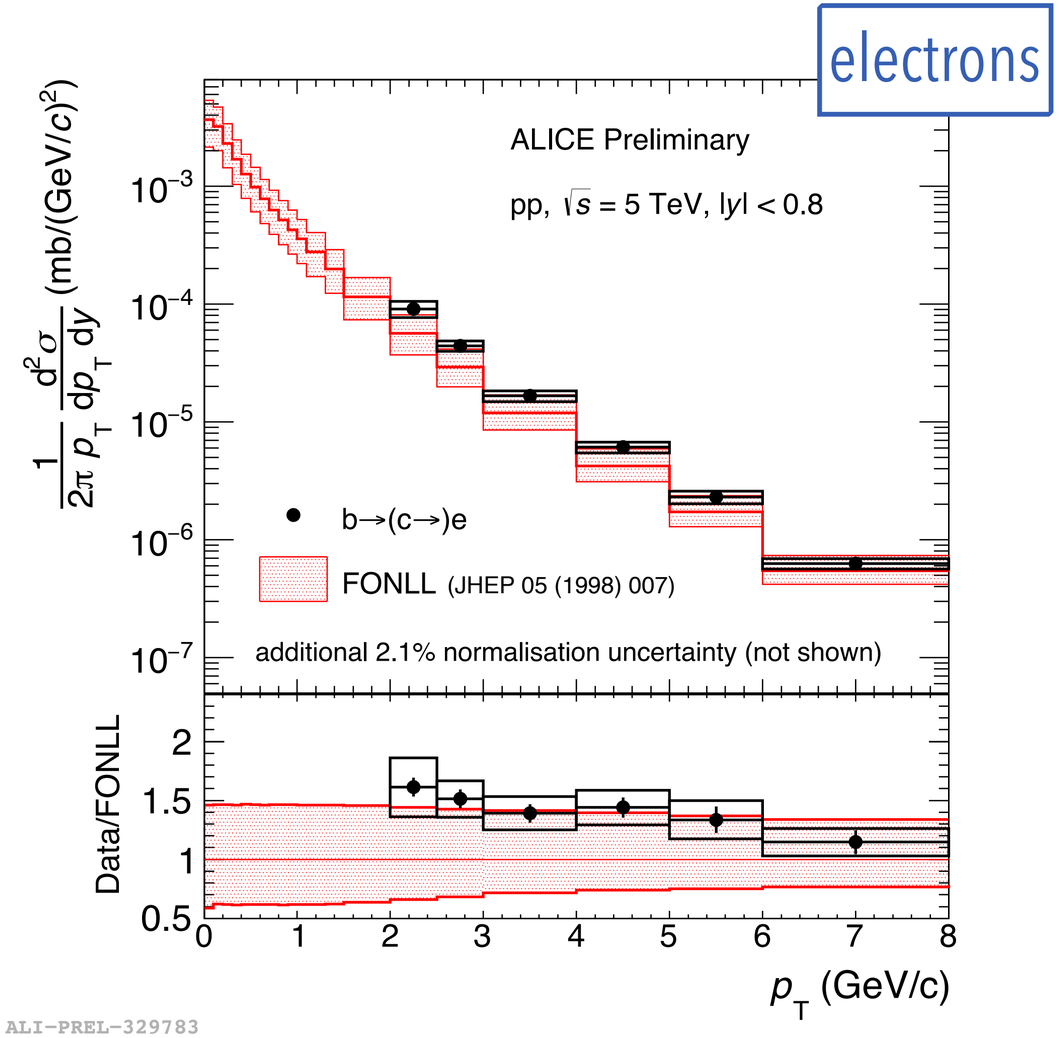

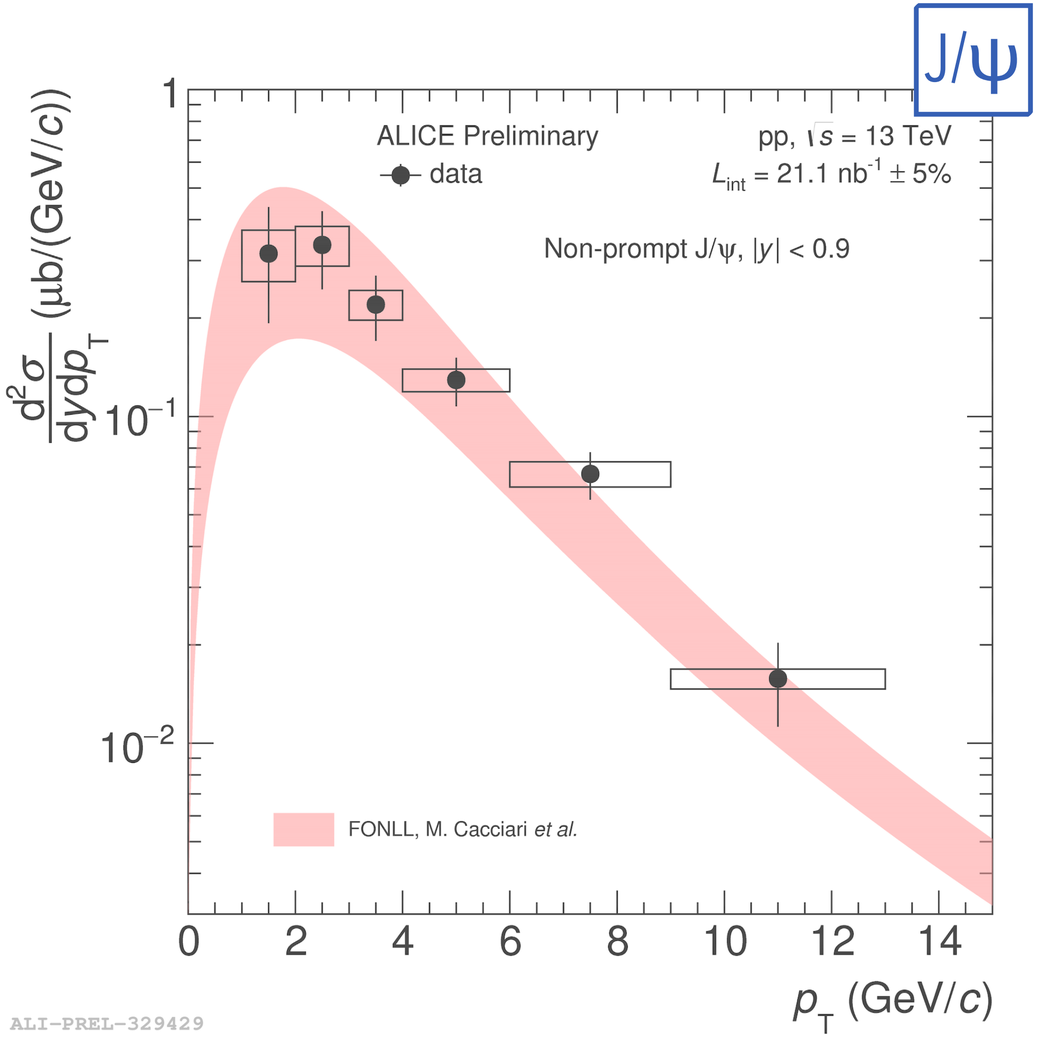

- Non-prompt J/ψ and e ← b cross sections described by FONLL calculations
  - ➡ description of beauty-hadron decays also relevant

📚 FONLL: JHEP 1210 (2012) 137

D mesons vs. pQCD calculations

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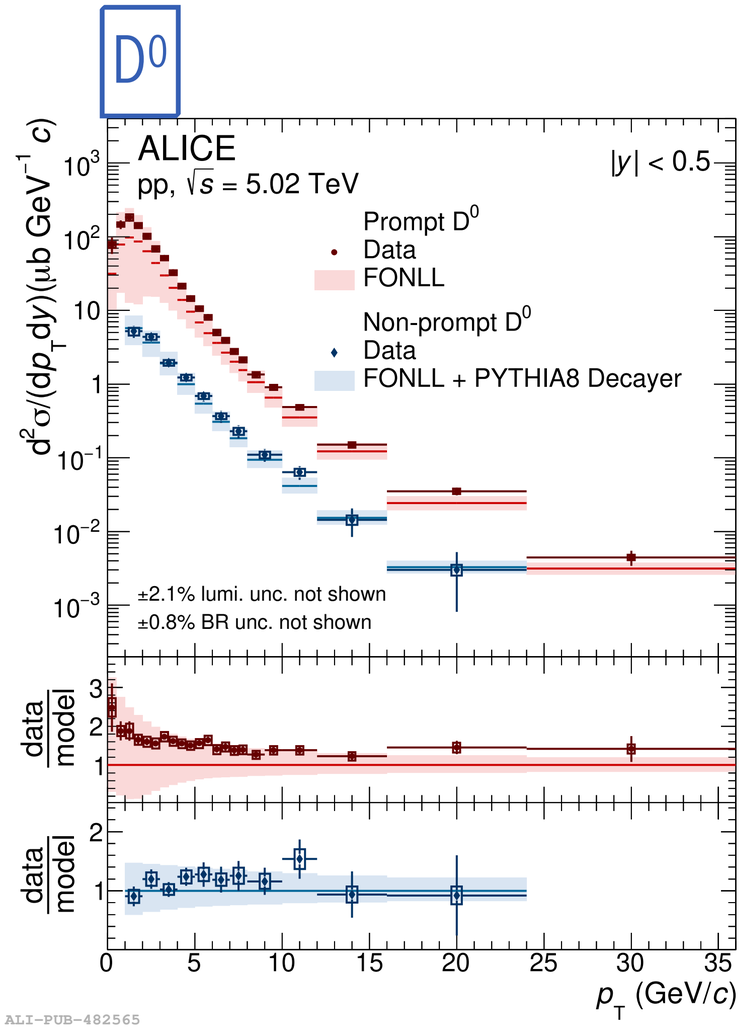

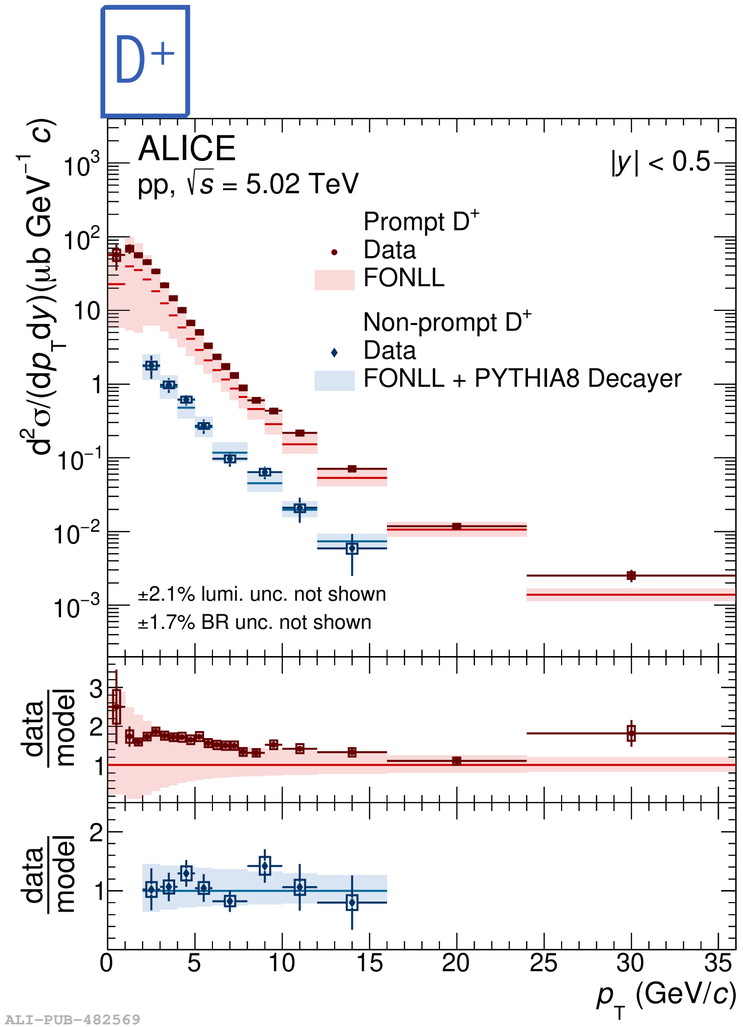

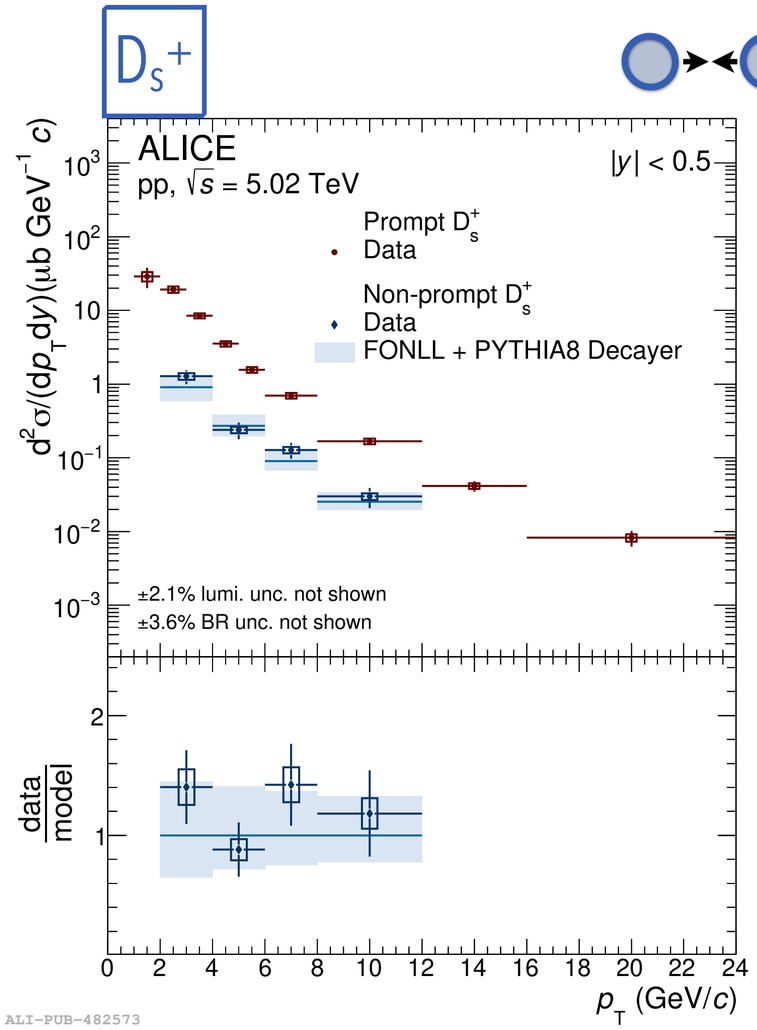

- p_T-differential cross section described by pQCD (FONLL) calculations down to low p_T
  - ➡ For non-prompt D mesons $H_b \rightarrow D + X$ decay kinematics from PYTHIA8 decayer and $f(b \rightarrow H_b)$ from e+e− measurements

Non-prompt D: arXiv:2102.13601
Prompt D: EPJC (2019) 79:388
FONLL: JHEP 1210 (2012) 137
PYTHIA8: CPC 191 (2015) 159-177

Fraction of J/ψ from b-hadron decays

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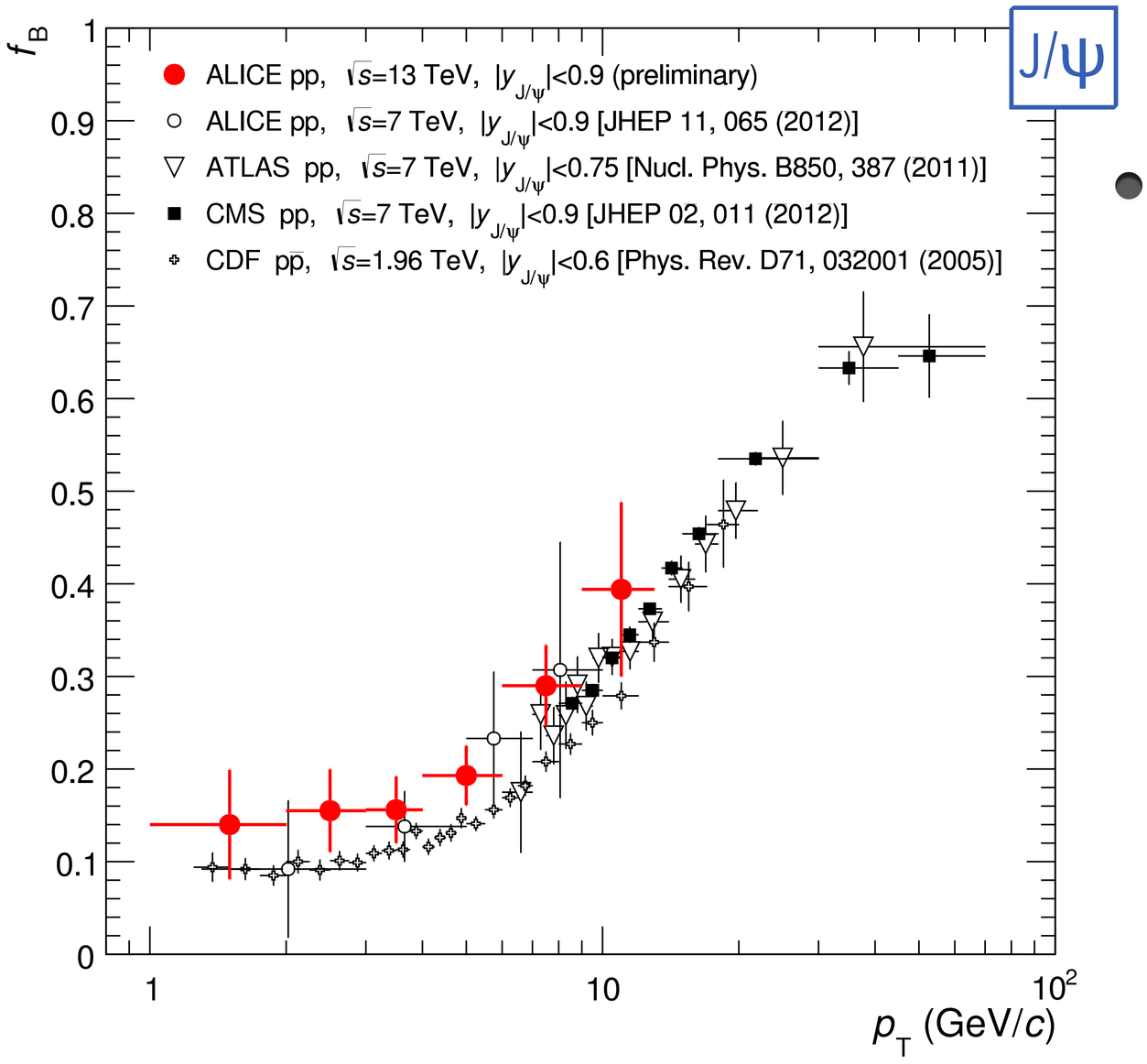

- Measurement down to very low p_T by ALICE complementary to high-p_T measurements by CMS and ATLAS
  - ➡ Fraction varies from about 10-20% for $p_T < 5$ GeV/c to 70% for $p_T > 30$ GeV/c
  - ➡ Low-p_T measurement important for the determination of p_T-integrated cross sections
    - Extrapolation to p_T=0 computed exploiting pQCD calculations

ALICE: JHEP 11 (2015) 065
ATLAS: NPB 850 (2011) 387
CMS: JHEP 02 (2012) 011
CDF: PRD 71 (2005) 032001

Beauty-quark fragmentation fraction to beauty-strange mesons

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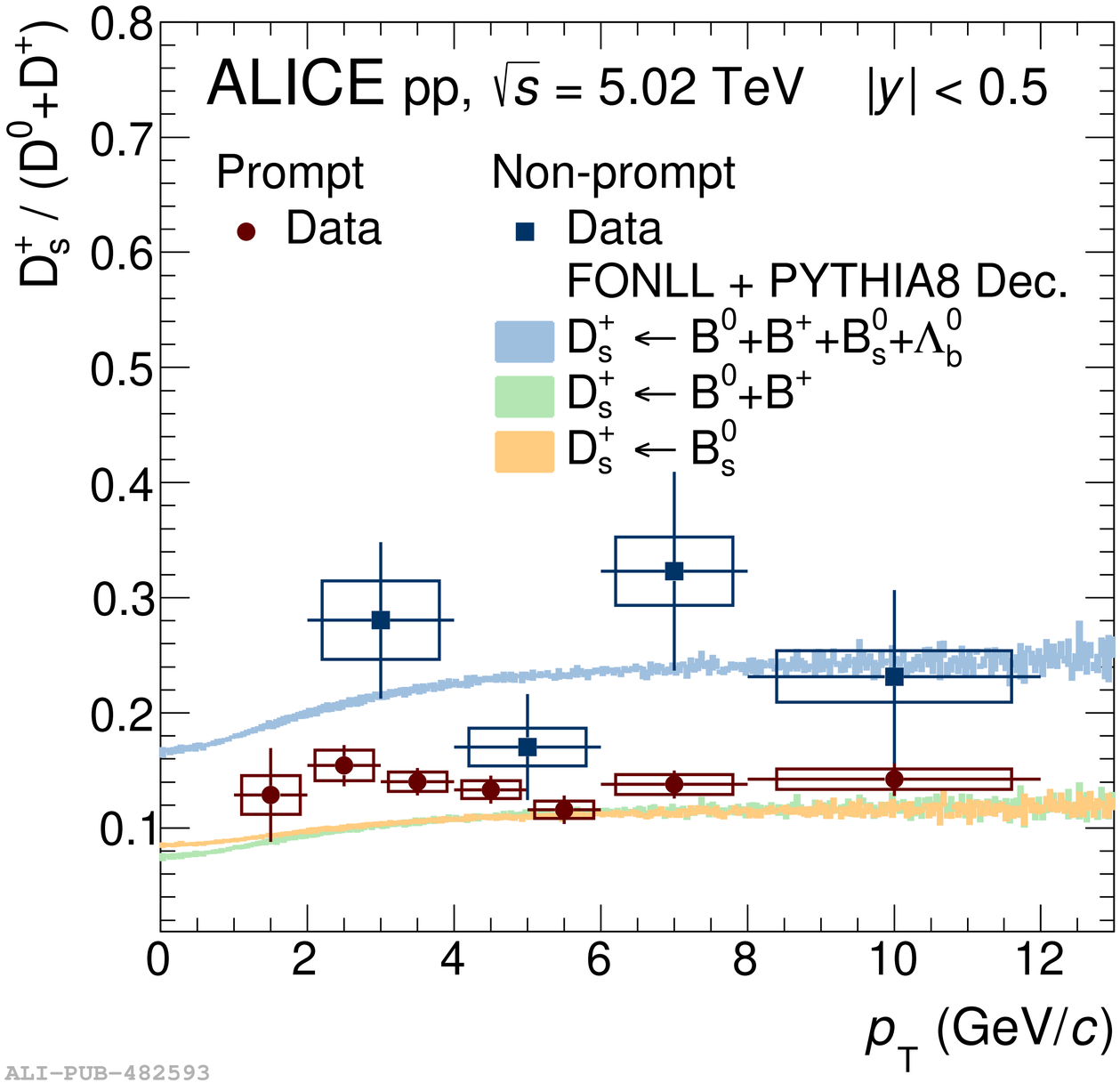
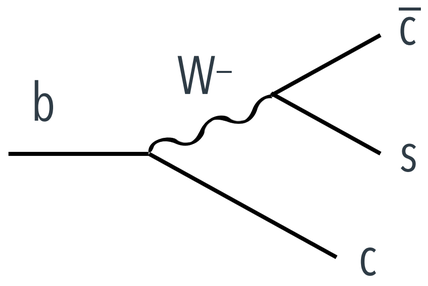


- $D_s^+/(D^0+D^+)$ larger for non-prompt than prompt D
  - ➡ Expected from beauty-quark decays via W bosons



- Significant contribution of D_s^+ from B_s^0 decays
  - ➡ Sensitivity to b-quark fragmentation fraction to beauty mesons with and without strange-quark content

Non-prompt D: arXiv:2102.13601
FONLL: JHEP 1210 (2012) 137
PYTHIA8: CPC 191 (2015) 159-177

Beauty-quark fragmentation fraction to beauty-strange mesons

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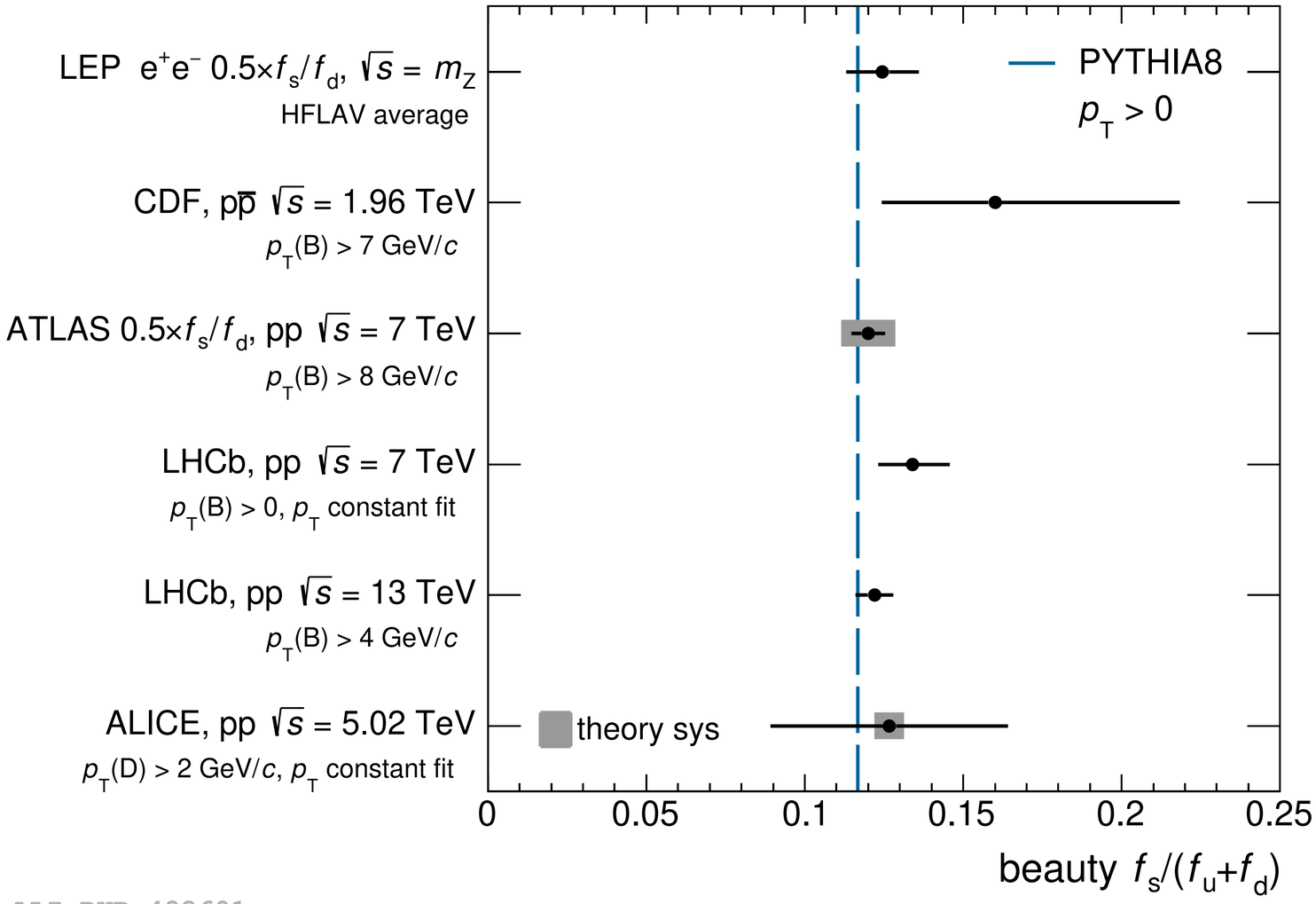

ALI-PUB-482601

- Ratio of b-quark fragmentation fraction to b-mesons with and without strangeness $f_s/(f_u+f_d)$ obtained from non-prompt $D_s^+/(D^0+D^+)$
  - ➡ correction to account for fraction of D_s^+ from B^+ and B^0 decays from FONLL + PYTHIA8
- In agreement with previous measurements at LEP, CDF, and LHC and with PYTHIA8

ALICE: arXiv:2102.13601
ATLAS: PRL 115 (2015) 262001
LHCb 7 TeV: PRD 85 (2012) 032008
LHCb 13 TeV: PRD 100 (2019) no.3, 031102
LEP: arXiv:1909.12524
CDF: PRD 77 (2008) 072003
PYTHIA8: CPC 191 (2015) 159-177

Beauty production cross section

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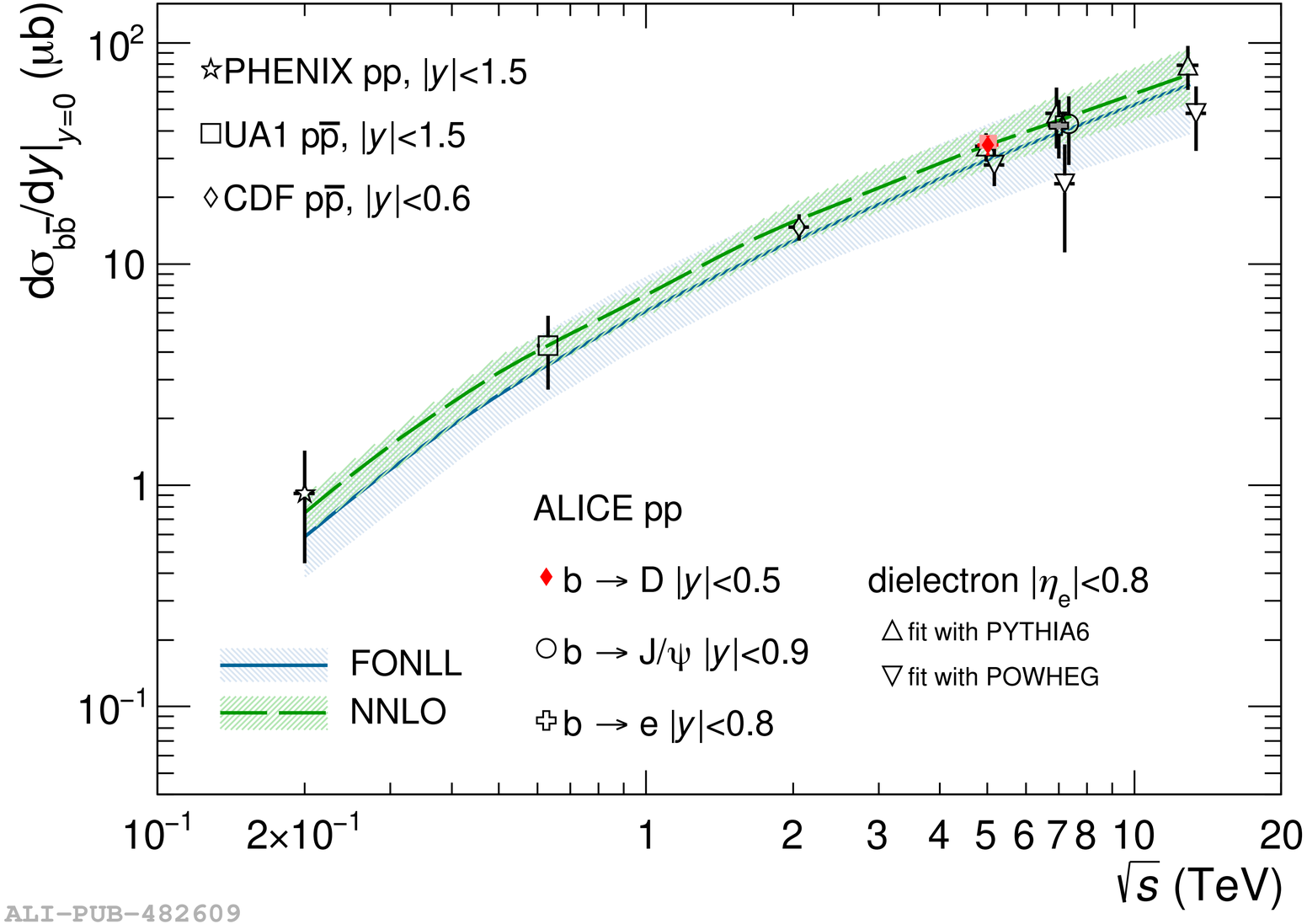

- Beauty production cross section at midrapidity obtained via FONLL extrapolations
  - ➡ Measurements described over a wide range of energy by FONLL and the more precise NNLO calculations

ALICE Non-prompt D: arXiv:2102.13601
ALICE Non-prompt J/ψ: JHEP 11 (2015) 065
ALICE b→e: PLB 721 (2013) 13-23
ALICE Dielectrons: arXiv:2005.11995
PHENIX: PRL (2009) 103, 082002
UA1: PLB 256 (1991) 121–128
CDF: PRL 91 (2003) 241804
FONLL: JHEP 1210 (2012) 137
NNLO: JHEP 03 (2021) 029

In-medium energy loss: charm vs. beauty

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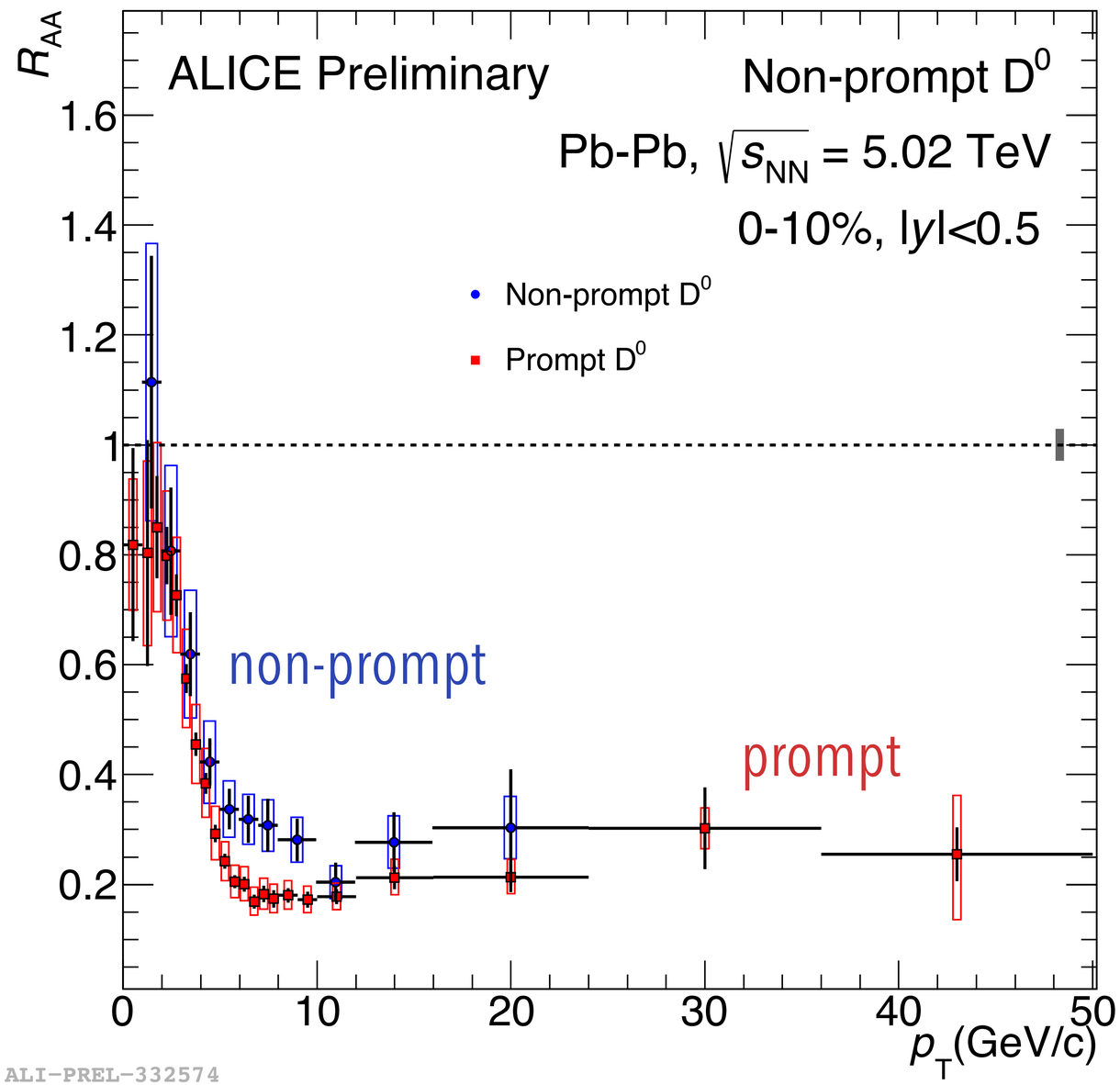


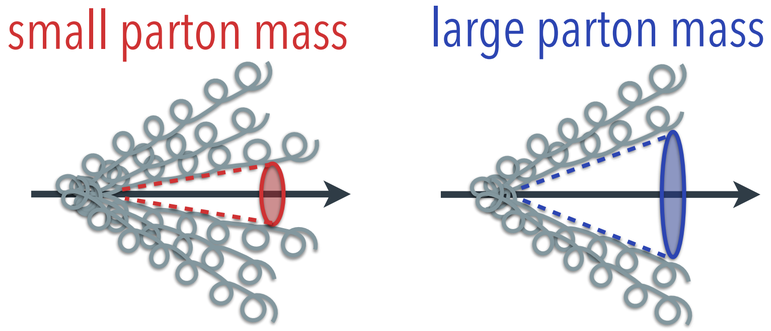
$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

production yield in AA collisions

binary nucleon-nucleon collisions

production yield in pp collisions

- R_{AA} (prompt D) < R_{AA} (non-prompt D)
  - ➡ parton-mass dependence of energy loss
    - dead cone effect: gluon radiation suppressed for small angles (ϑ < m/E)



In-medium energy loss: charm vs. beauty

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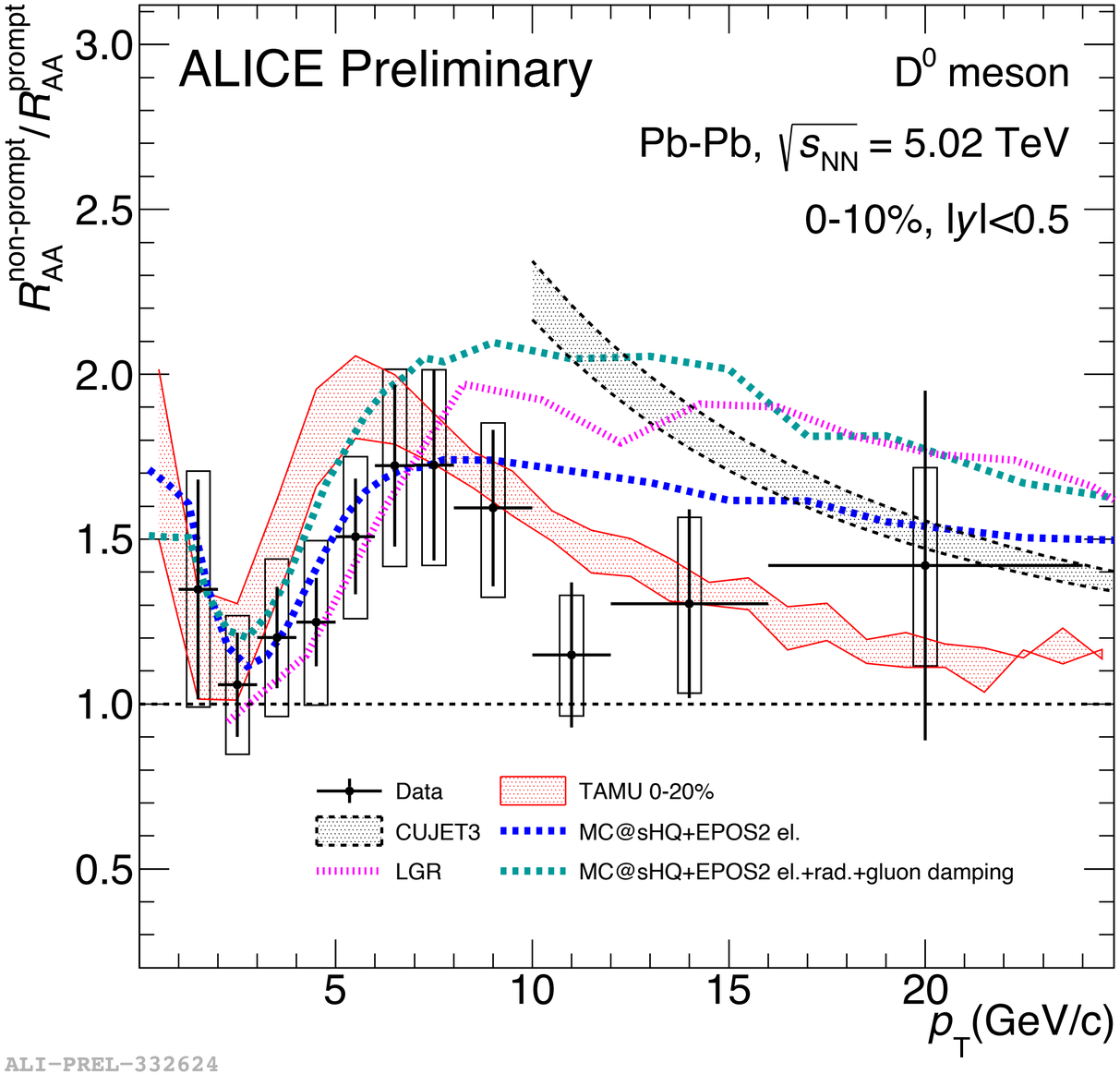
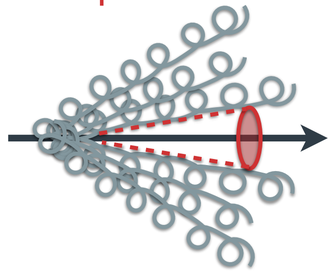


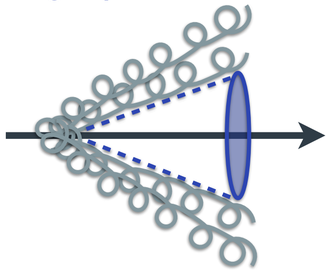
- CUJET3.0: JHEP02(2016)169
- LGR: arXiv:1912.08965
- TAMU: PLB 735 (2014) 445-450
- MC@sHQ+EPOS2: PRC 89 (2014) 014905

- R_{AA} (prompt D) < R_{AA} (non-prompt D)
  - ➡ p_T < 5 GeV/c: different decay kinematics / radial flow
  - ➡ p_T > 5 GeV/c: smaller energy loss for beauty than charm
  - ➡ described by models including collisional and radiative energy loss

small parton mass



large parton mass



Prospects for LHC Run 3

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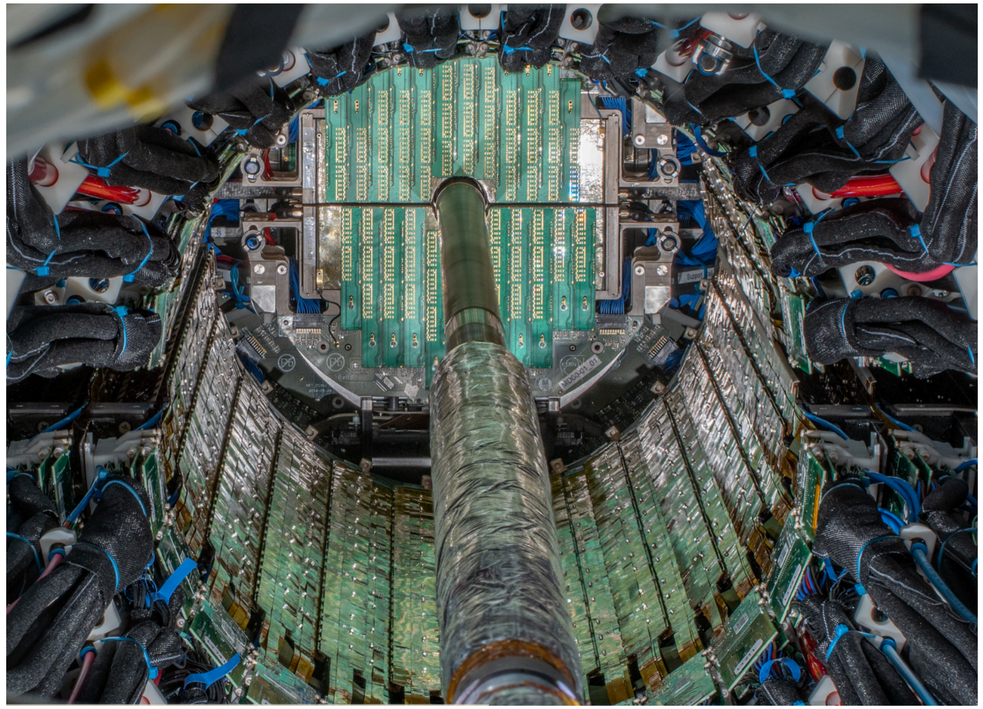
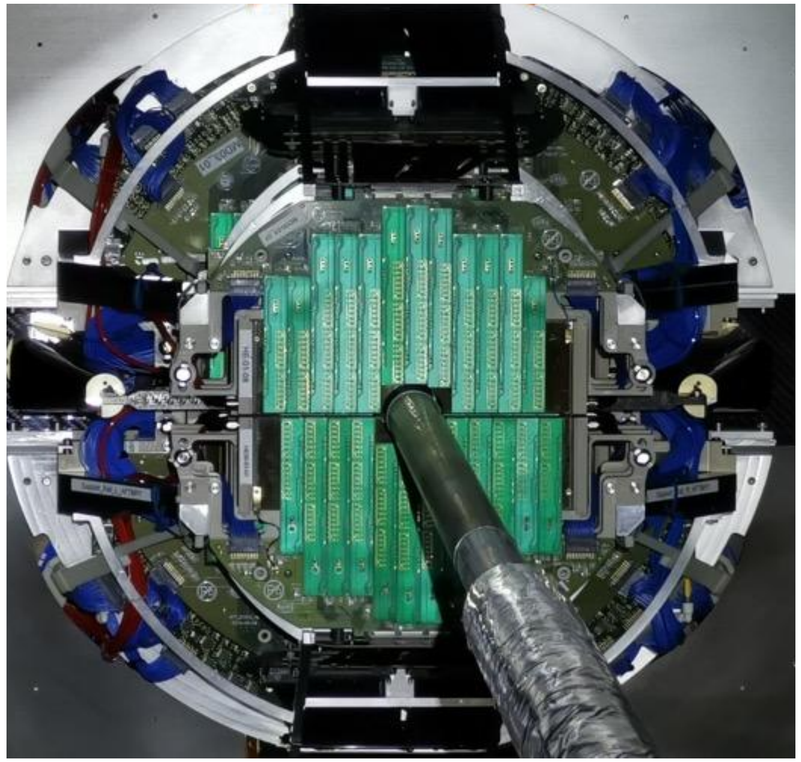


CERN-LHCC-2013-024

- New ALICE inner tracking system (ITS)
  - ➡ improved impact-parameter resolution by a factor 3 (5) in the transverse (longitudinal) direction
  - ➡ crucial for HF measurements

CERN-LHCC-2015-001



- New ALICE muon forward tracker (MFT)
  - ➡ match muon tracks reconstructed in the forward muon spectrometer to the primary vertex
  - ➡ allow measurement of J/ψ mesons from beauty-hadron decays at forward rapidity

Prospects for LHC Run 3

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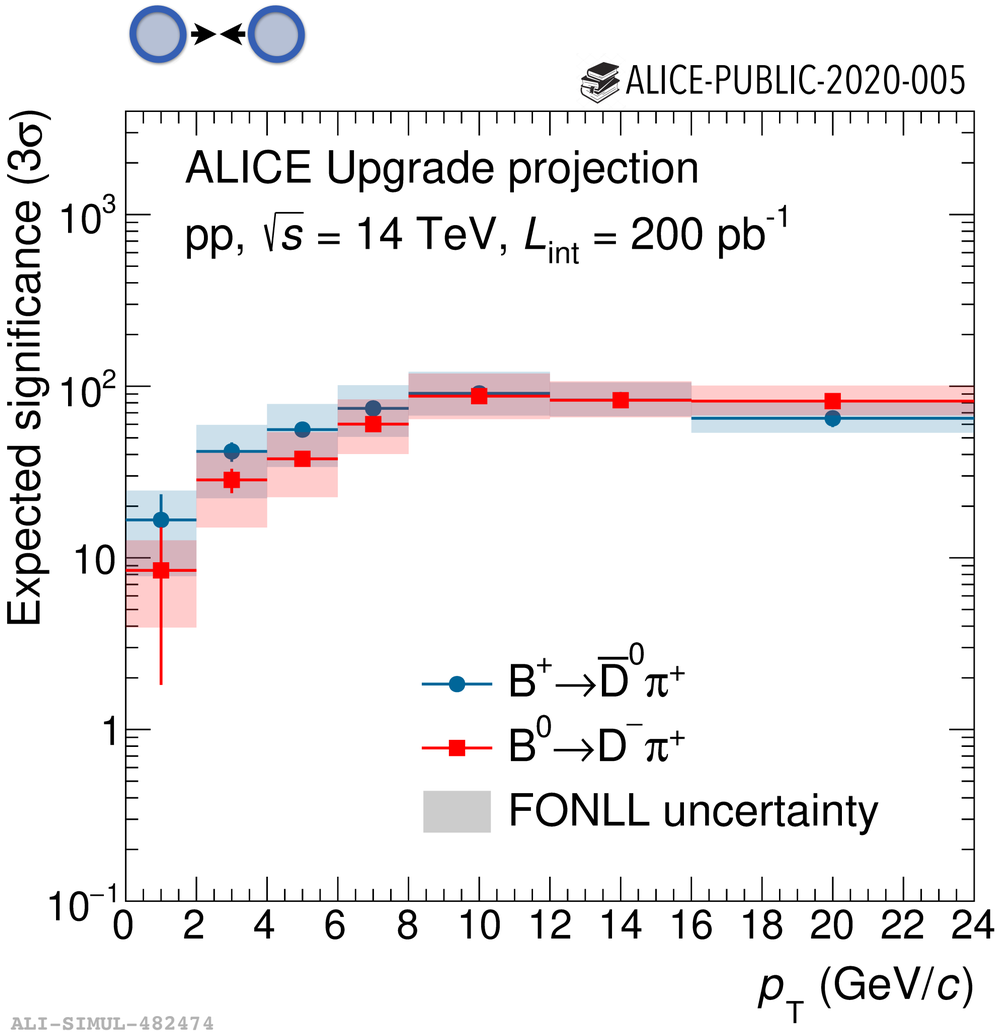

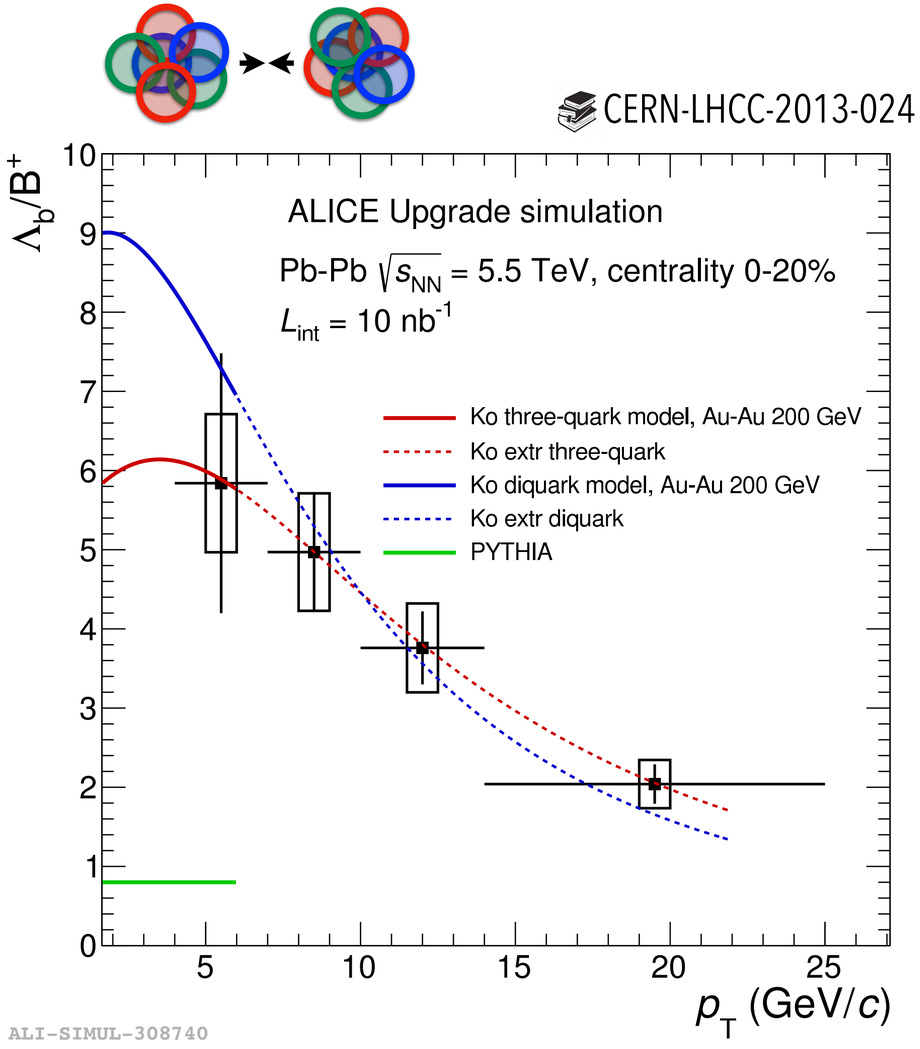

- Expected increased integrated luminosity by more than a factor 10^3 in pp collisions and Pb–Pb collisions
- Possibility to measure beauty mesons and baryons via their reconstruction in exclusive decays down to very low p_T

Summary

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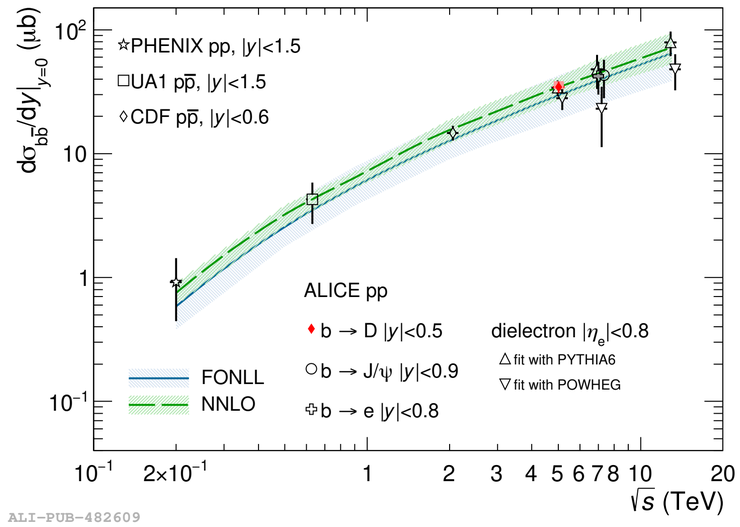
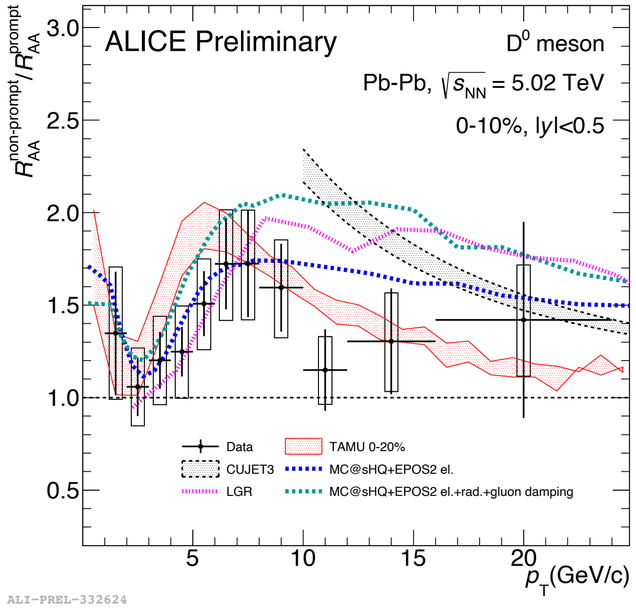
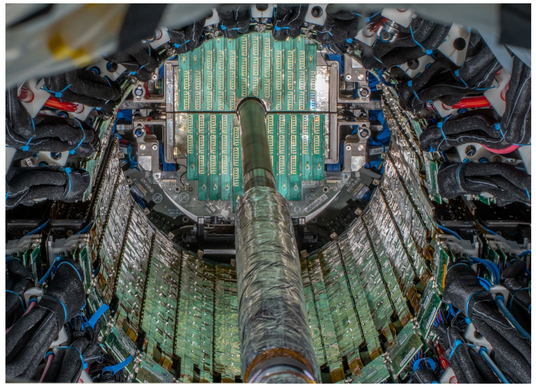
- Beauty production measured in pp collisions exploiting several channels
  - ➡ Beauty production cross sections described by pQCD calculations
  - ➡ Ratio of beauty-quark fragmentation to beauty-mesons with and without strange-quark content compatible in different colliding systems

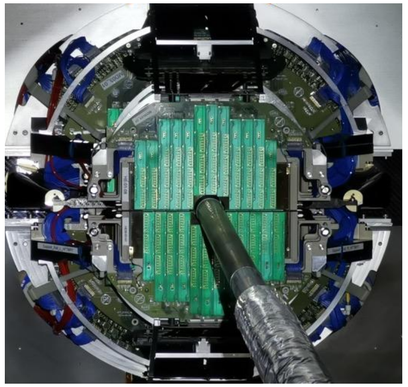




- Beauty production measured in Pb–Pb collisions via non-prompt D mesons
  - ➡ Important insights in quark-mass dependence and in-medium energy loss (dead cone effect)

- New ITS and MFT detectors and increased integrated luminosity for LHC Run 3:
  - ➡ Precise measurements of beauty hadrons at mid and forward rapidities





ADDITIONAL SLIDES

Multi-class Boosted Decision Trees

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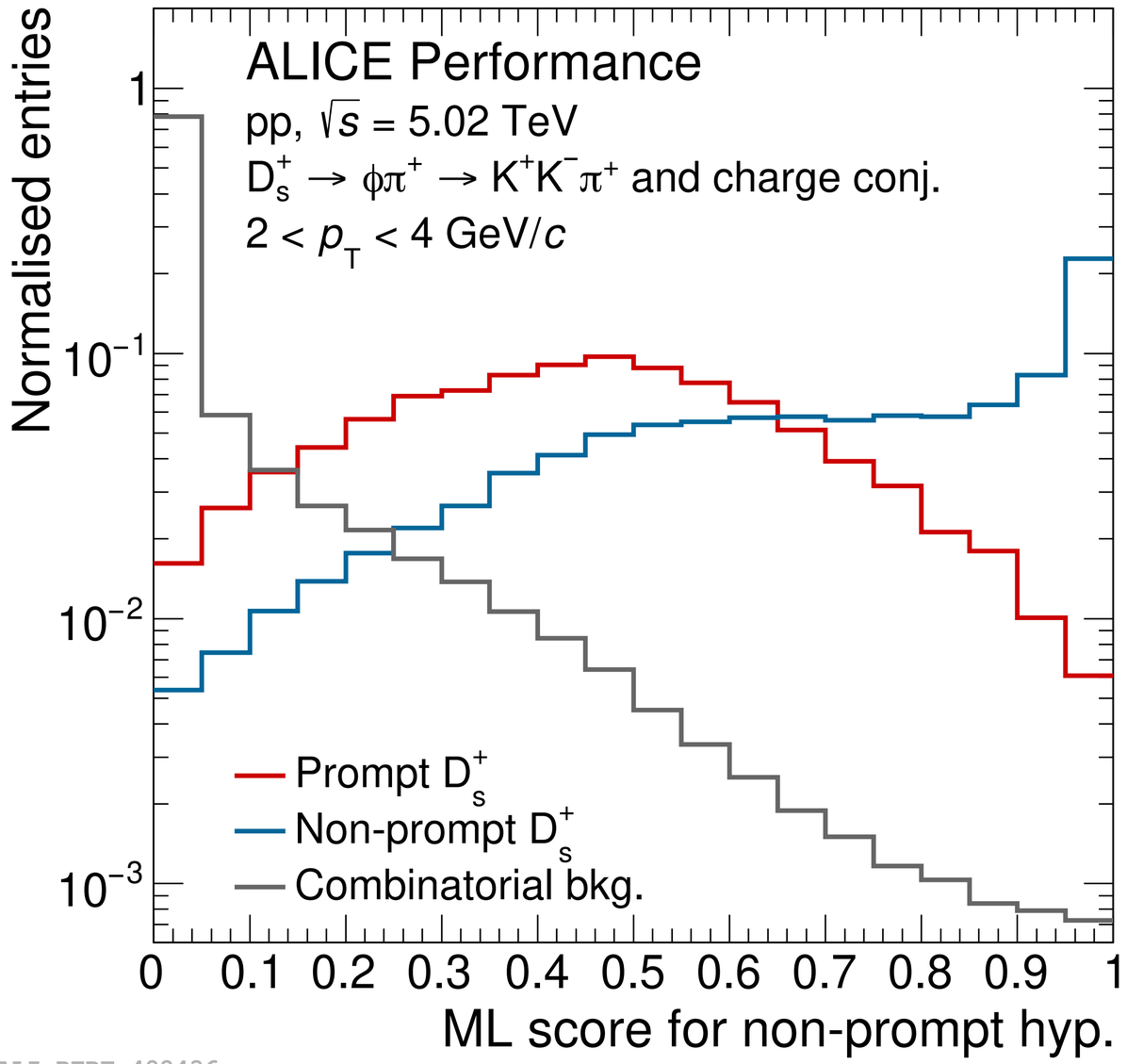

- Multi-class Boosted Decision Tree:
  - ➡ 3 classes of candidates:
    - prompt D, non-prompt D, combinatorial background
- Training:
  - ➡ input variables related to decay-vertex topology (e.g. decay length) and particle identification of decay tracks
- Output:
  - ➡ 3 BDT scores related to the probability of belonging to each class

Measurement of D-meson non-prompt fraction

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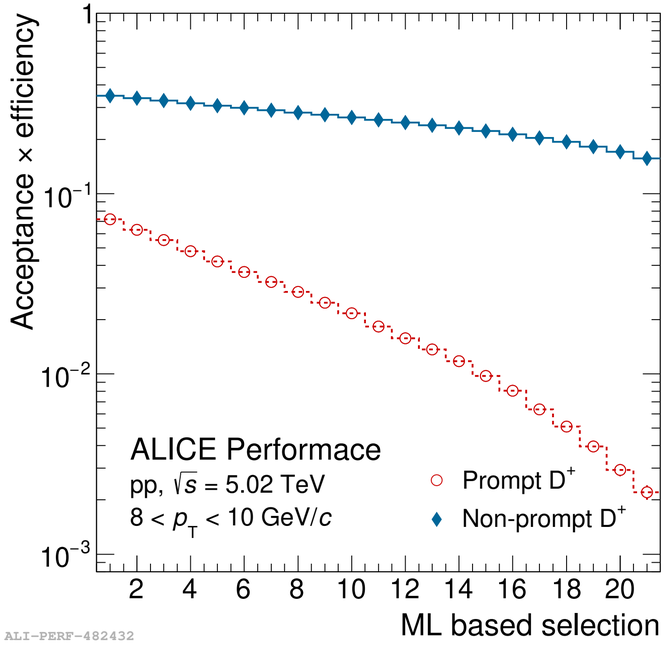

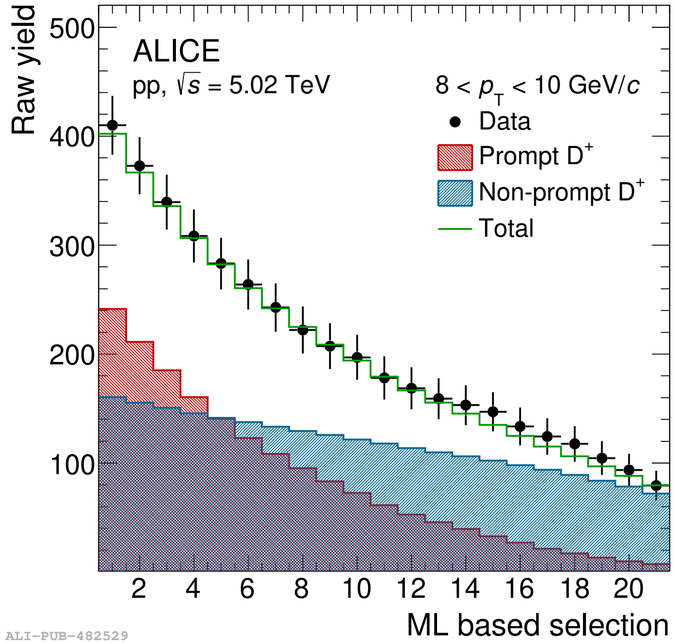

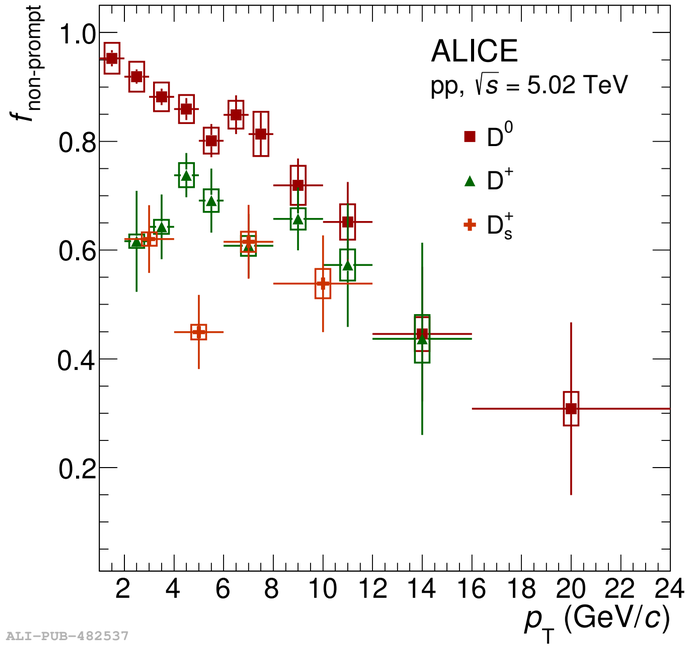

- Non-prompt fraction determined by defining different set of selections that enhance prompt or non-prompt contribution
  - ➡ each selection corresponds to an equation:

$$\begin{cases} \epsilon^1_{\text{prompt}} \cdot N_{\text{prompt}} + \epsilon^1_{\text{non-prompt}} \cdot N_{\text{non-prompt}} = Y^1 \\ \cdots \\ \cdots \\ \epsilon^n_{\text{prompt}} \cdot N_{\text{prompt}} + \epsilon^n_{\text{non-prompt}} \cdot N_{\text{non-prompt}} = Y^n \end{cases}$$

acceptance times efficiency

raw yield

- System of equation solved by minimising a χ^2
- Fraction of non-prompt D for a given selection:

$$f^j_{\text{non-prompt}} = \frac{\epsilon^j_{\text{non-prompt}} \cdot N_{\text{non-prompt}}}{\epsilon^j_{\text{non-prompt}} \cdot N_{\text{non-prompt}} + \epsilon^j_{\text{prompt}} \cdot N_{\text{prompt}}}$$

Charm and beauty cross sections from dielectron measurements

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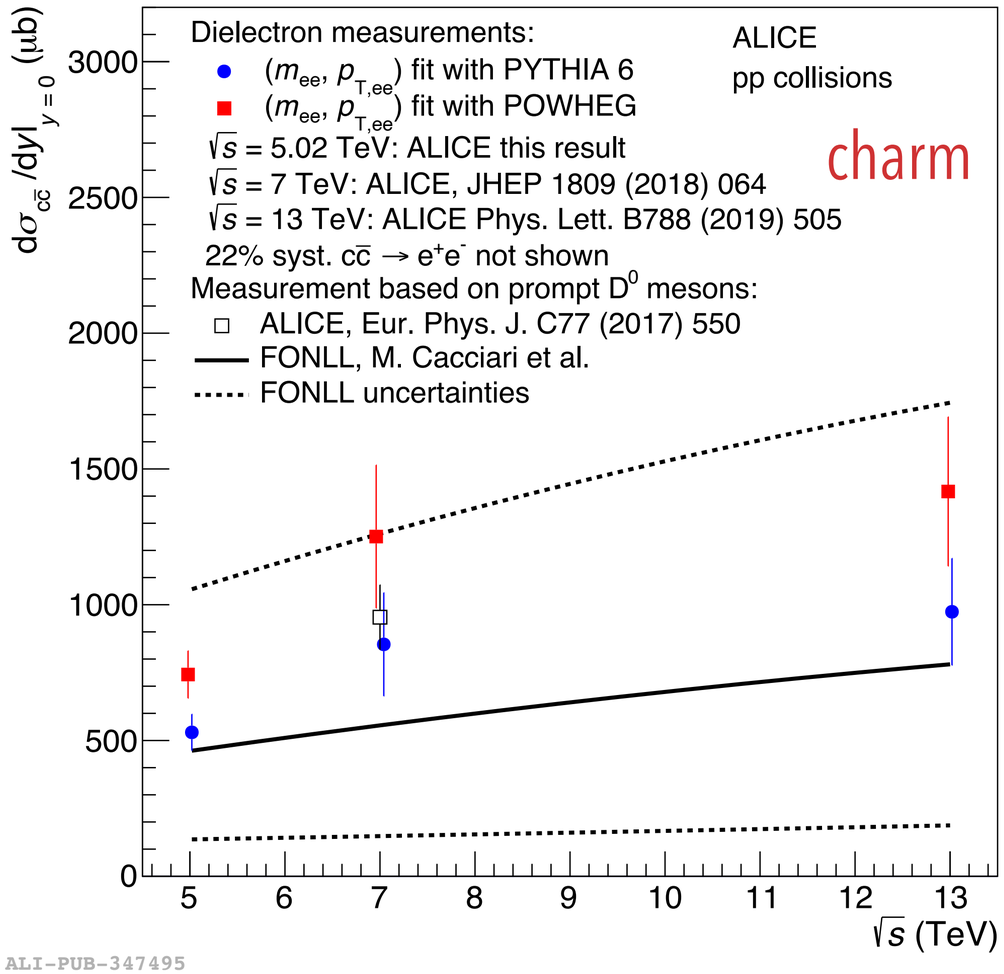

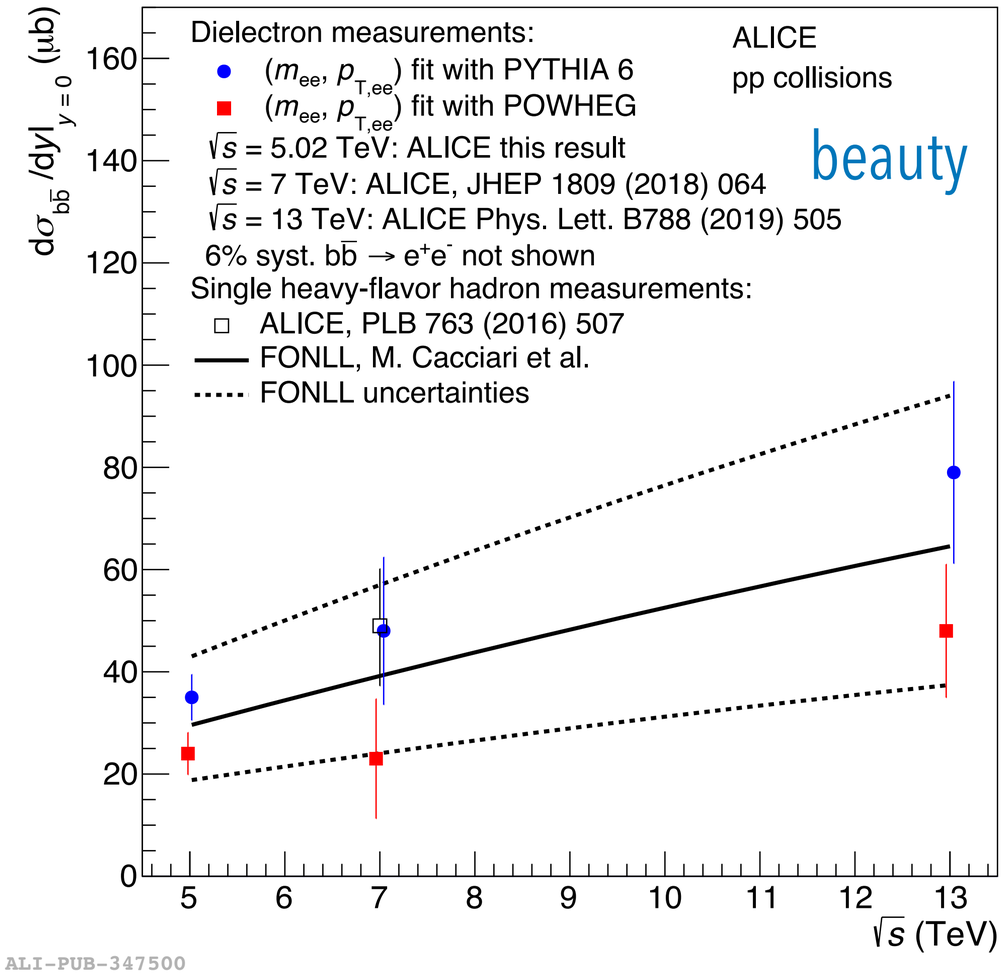

- Measurements of $c\bar{c}$ and $b\bar{b}$ production cross sections at mid rapidity obtained with POWHEG and PYTHIA fits compatible with pQCD (FONLL) predictions
- Compatible with extrapolations from full reconstructed decays for charm and displaced $e^{\pm}$ for beauty

Dielectrons: arXiv:2005.11995
PYTHIA6: JHEP 05 (2006) 026
POWHEG: JHEP 11 (2007) 070
FONLL: JHEP 1210 (2012) 137

Electrons from charm and beauty decays

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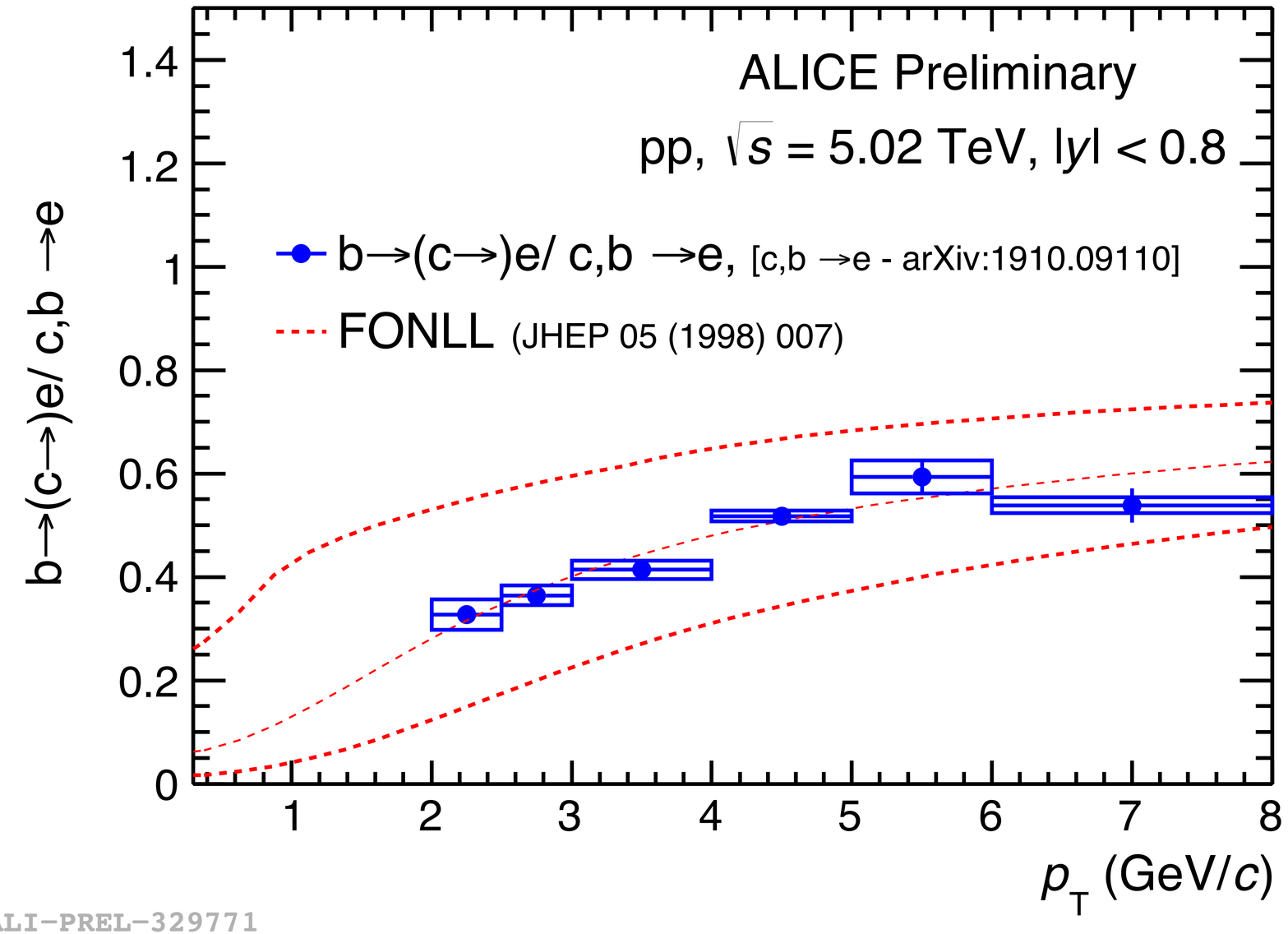

- Fraction of electrons from beauty decays described by FONLL within uncertainties

FONLL: JHEP 1210 (2012) 137

D-meson ratios

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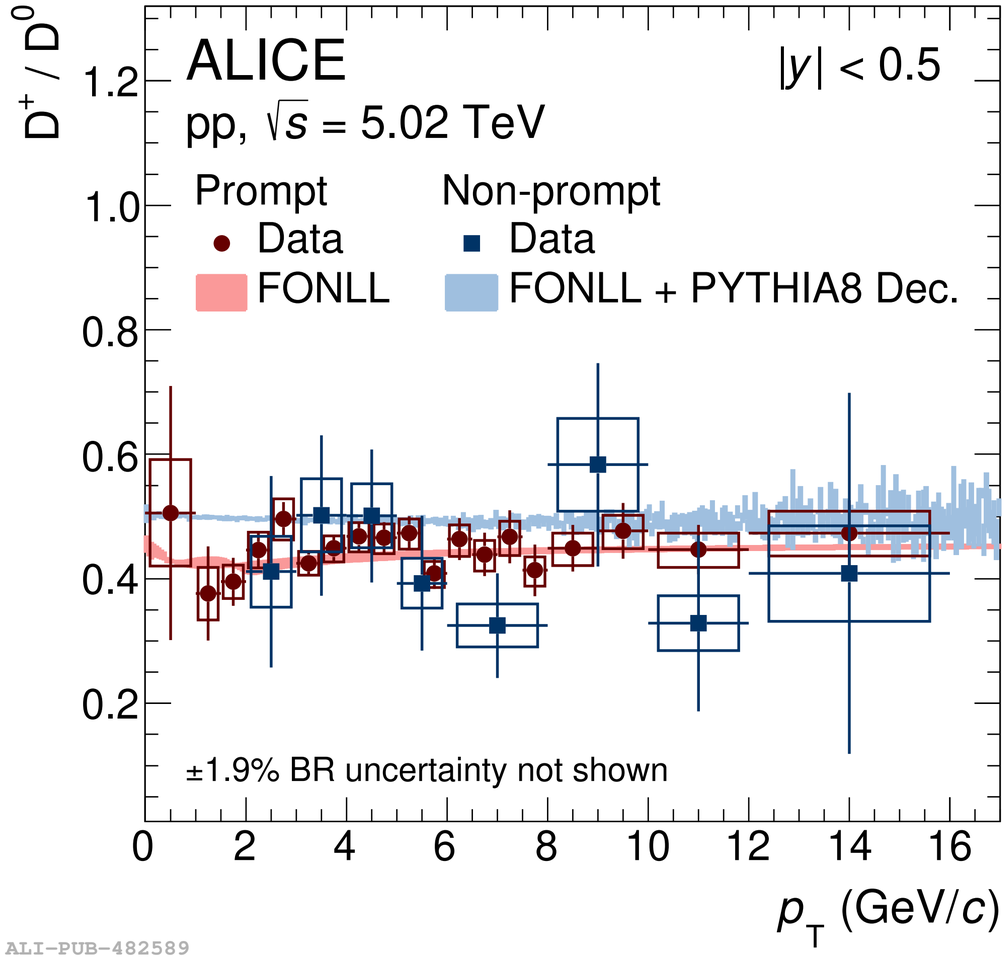

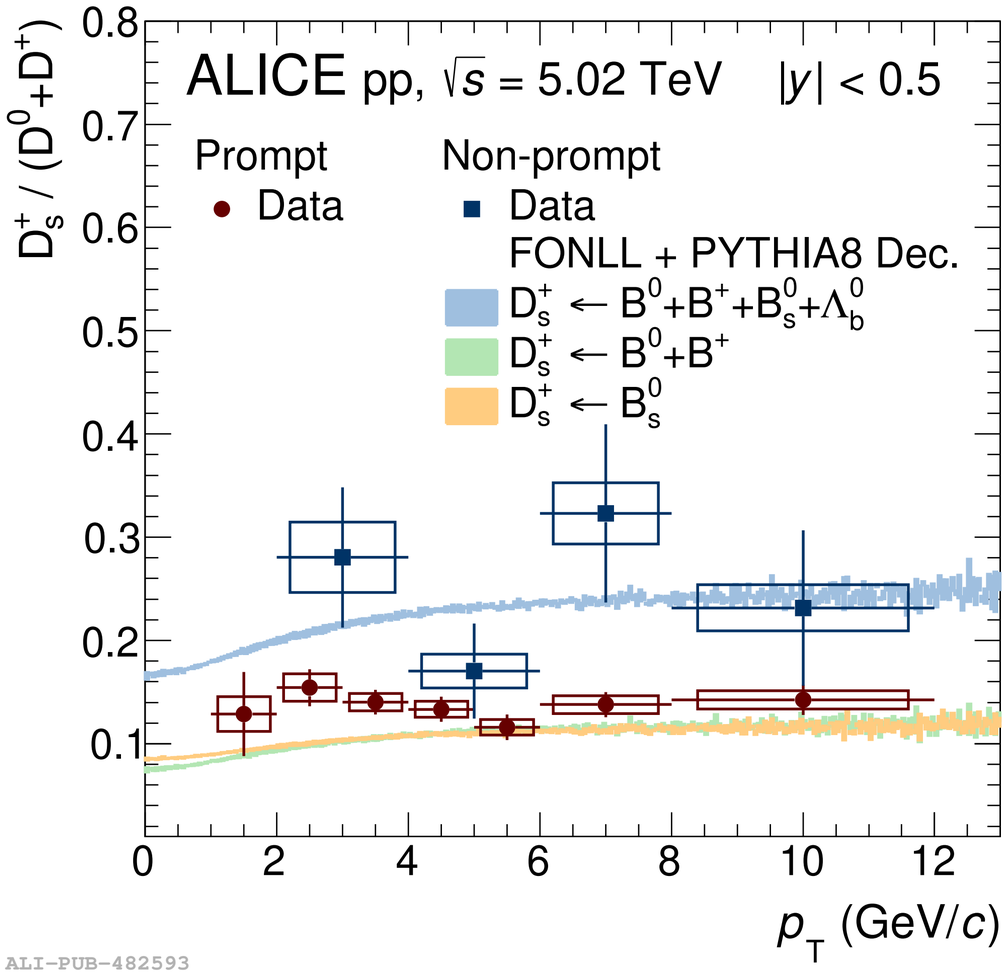

Non-prompt D: arXiv:2102.13601
FONLL: JHEP 1210 (2012) 137
PYTHIA8: CPC 191 (2015) 159-177

Heavy-quark fragmentation fraction to beauty-strange mesons

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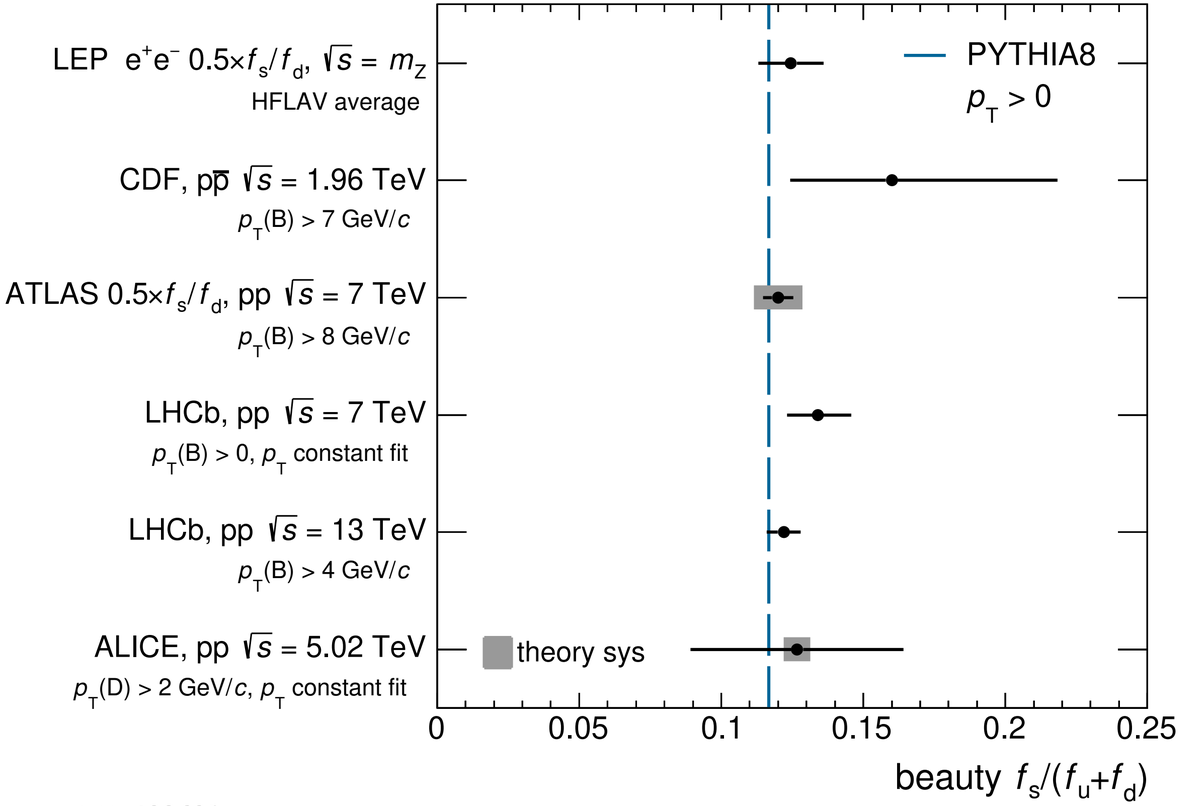

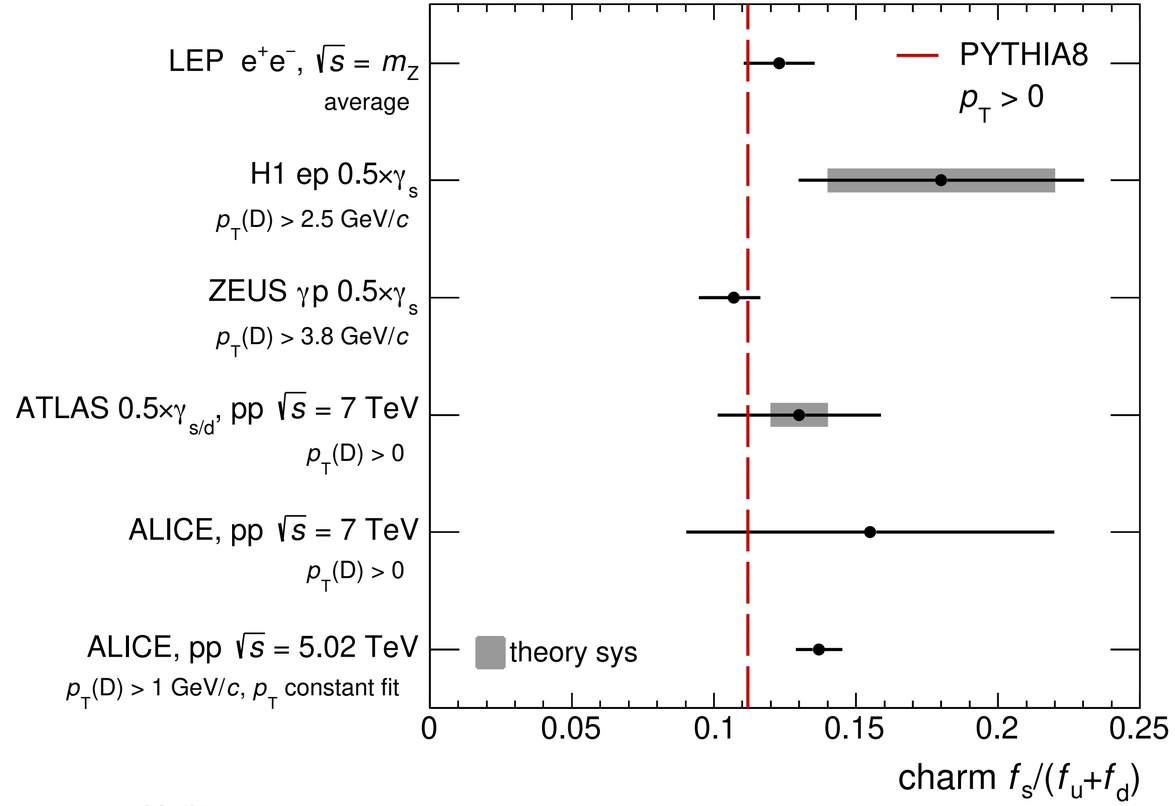

- Ratio of fragmentation fraction to mesons with and without strange quark-content similar for charm and beauty
- No significant dependence on energy and collision system

Total beauty cross section vs. rapidity

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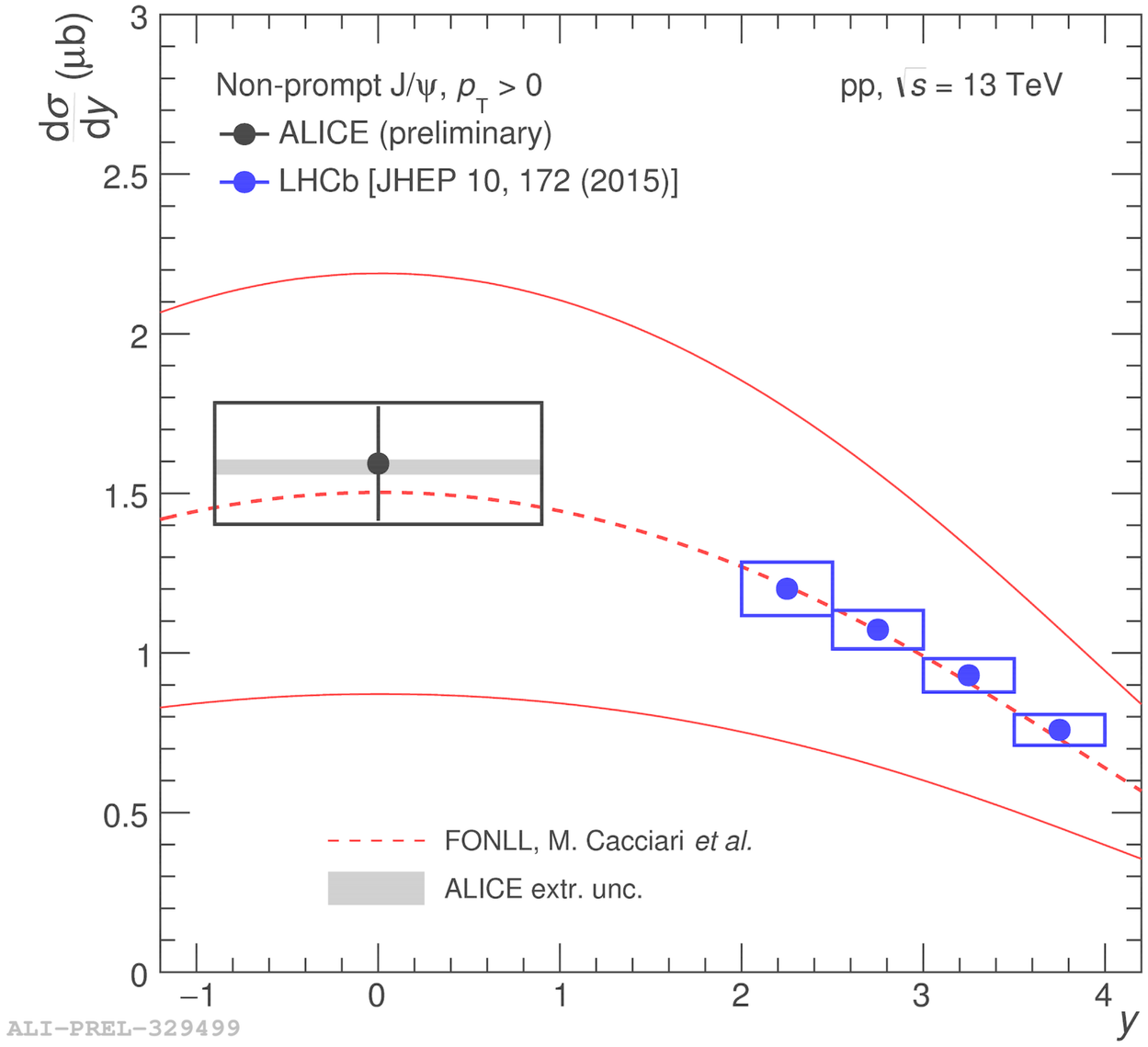

- Measurements at mid-rapidity by ALICE and forward rapidity by LHCb described by FONLL calculations
- Can be used for the determination of the total beauty production cross section

Beauty production cross section

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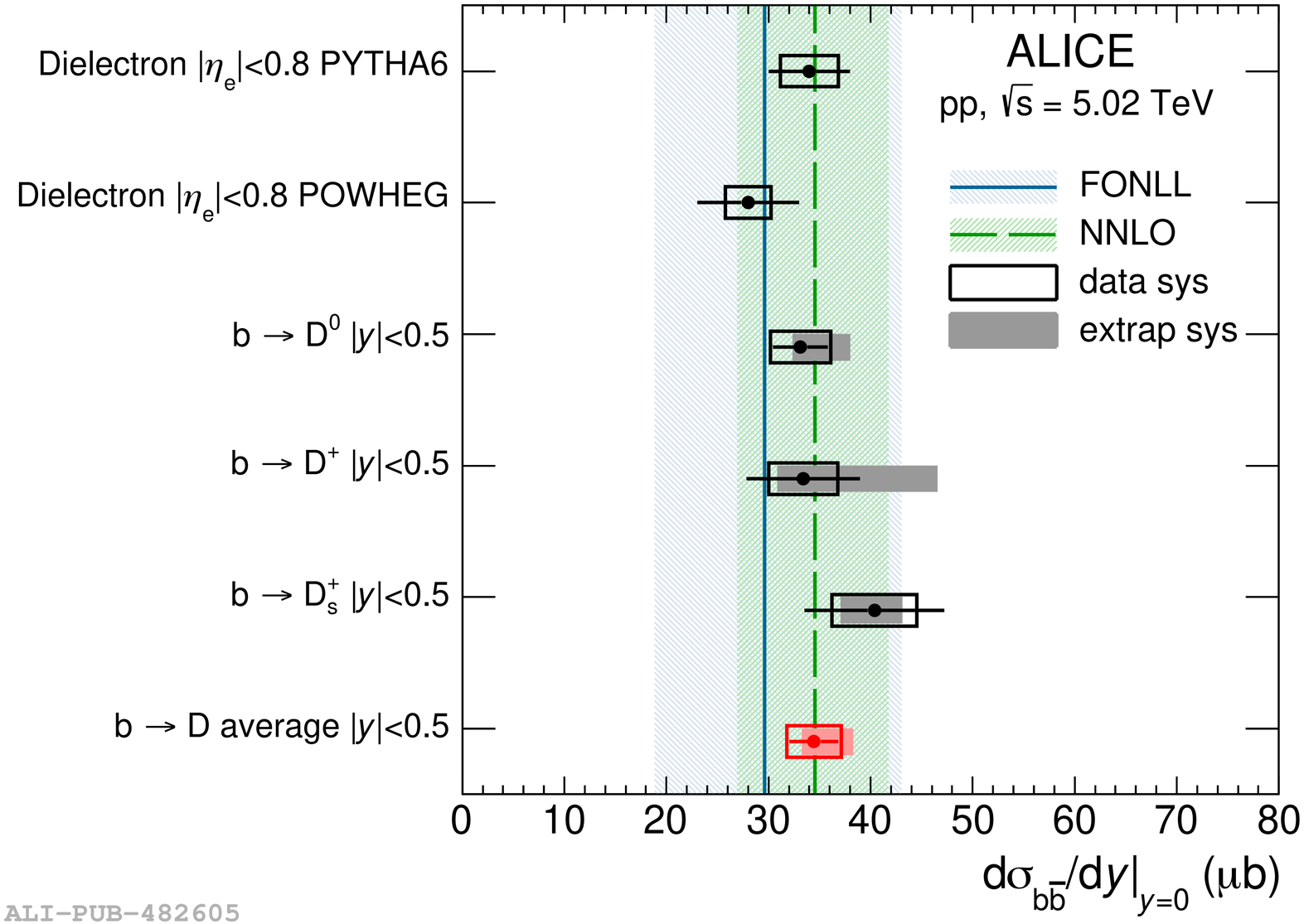

- Beauty production cross section at midrapidity obtained via FONLL extrapolations
  - ➡ Measurements described over a wide range of energy by FONLL and the more precise NNLO calculations

ALICE Non-prompt D: arXiv:2102.13601
ALICE Dielectrons: arXiv:2005.11995
FONLL: JHEP 1210 (2012) 137
NNLO: JHEP 03 (2021) 029

Azimuthal anisotropy of electrons from b-hadron decays

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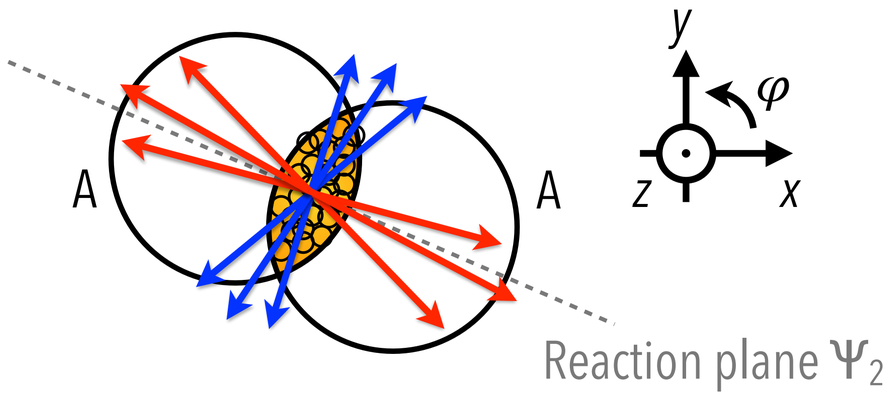
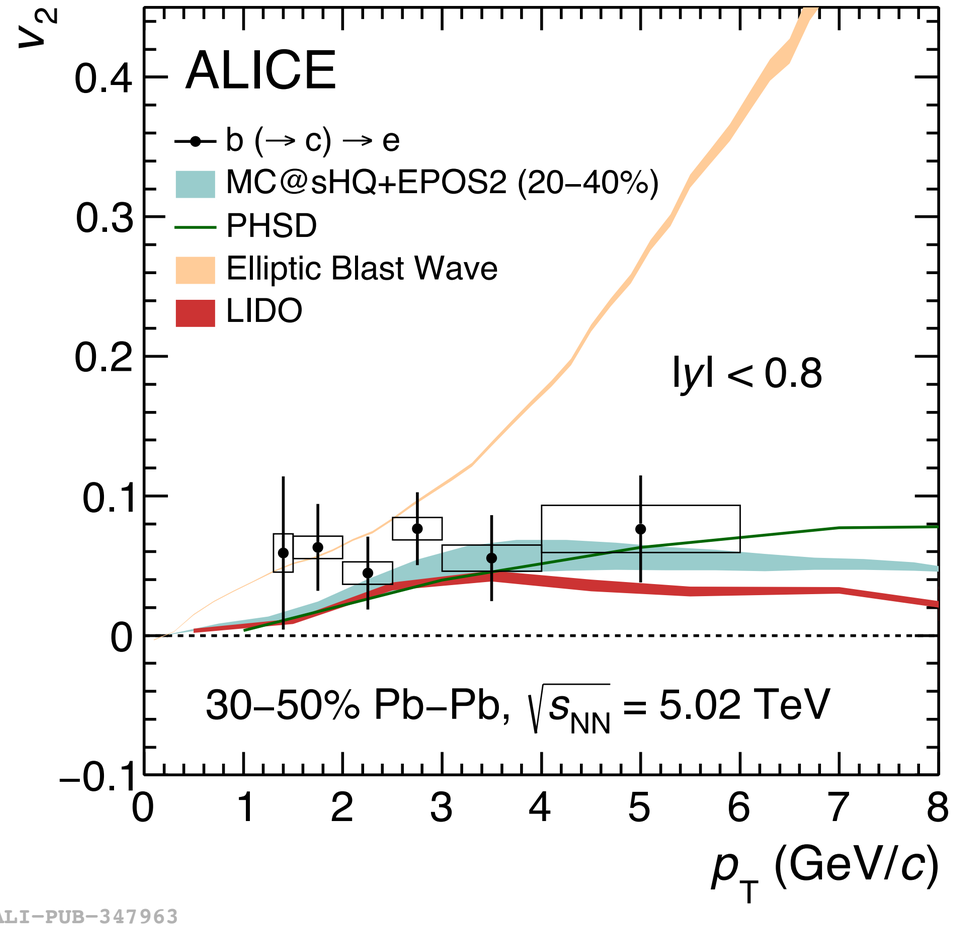
- The interaction region of a heavy-ion collision exhibits a geometrical anisotropy
- The initial geometrical anisotropy is transferred to a momentum anisotropy by the pressure gradients



arXiv2005.11130



ALI-PUB-347963

$$E\frac{d^3N}{dp_T} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left\{1 + \sum_{i=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right\}$$

$$v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$$

- Second harmonic coefficient, elliptic flow: asymmetry of particle production between in-plane and out-of-plane directions
  - ➡ participation of beauty quarks to the collective motion of the system and their possible thermalisation

Direct observation of dead cone effect

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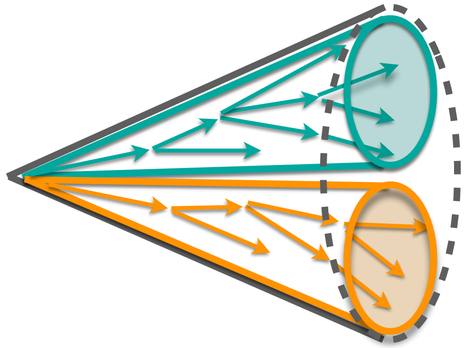
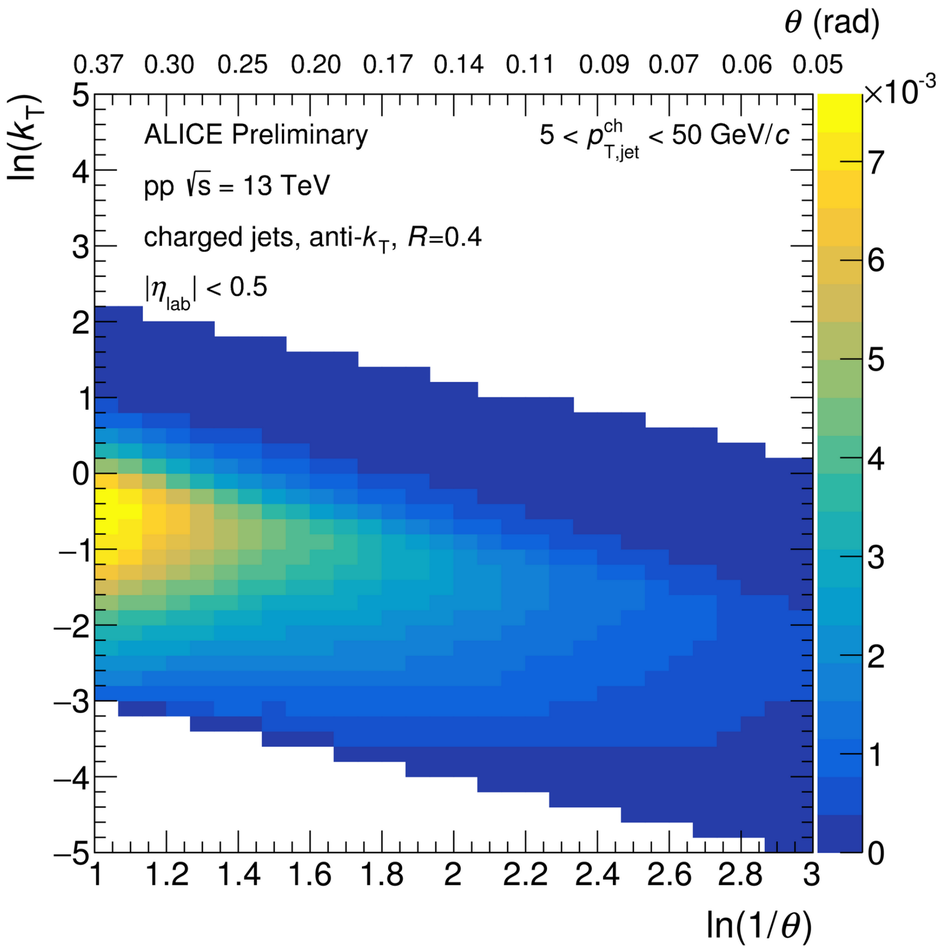


$\theta = \Delta R$

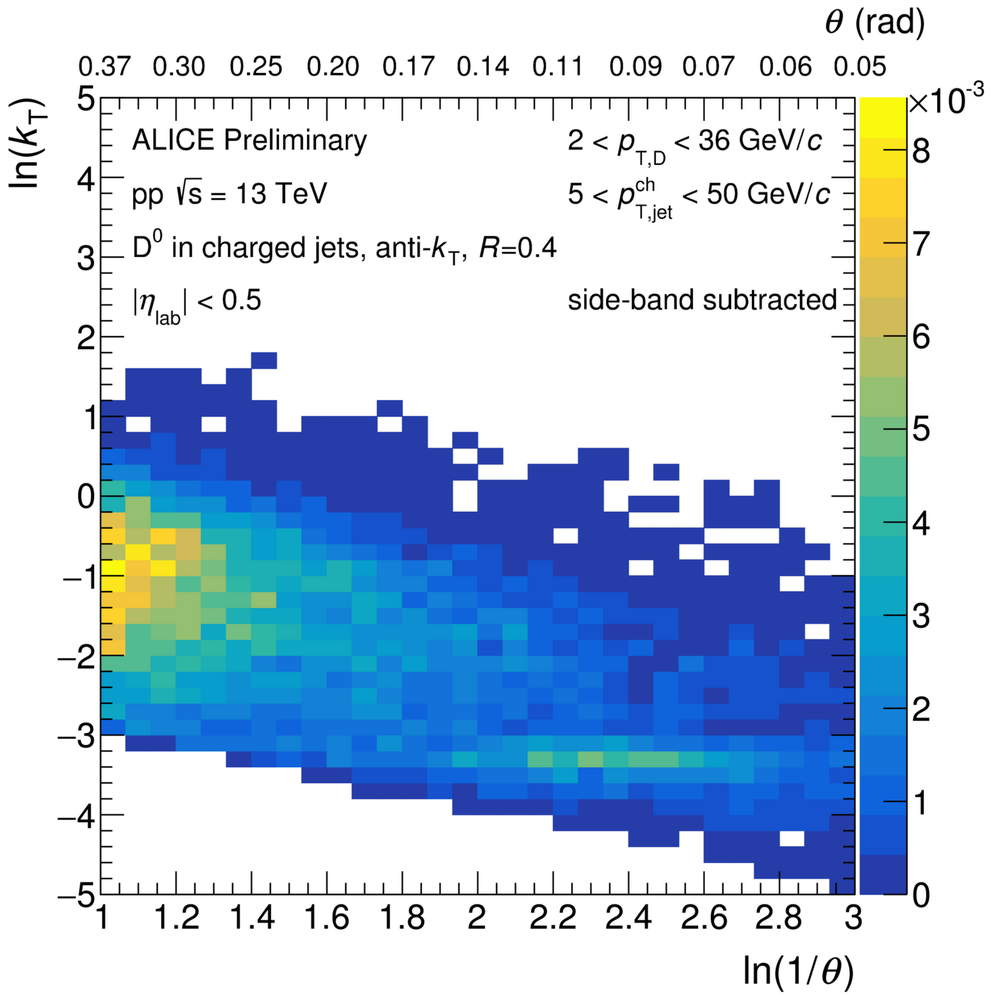
opening angle between subjets

$k_T = z p_T \sin(\Delta R)$

relative transverse momentum of subjets



ALI-PREL-339786



ALI-PREL-339746

Direct observation of dead cone effect

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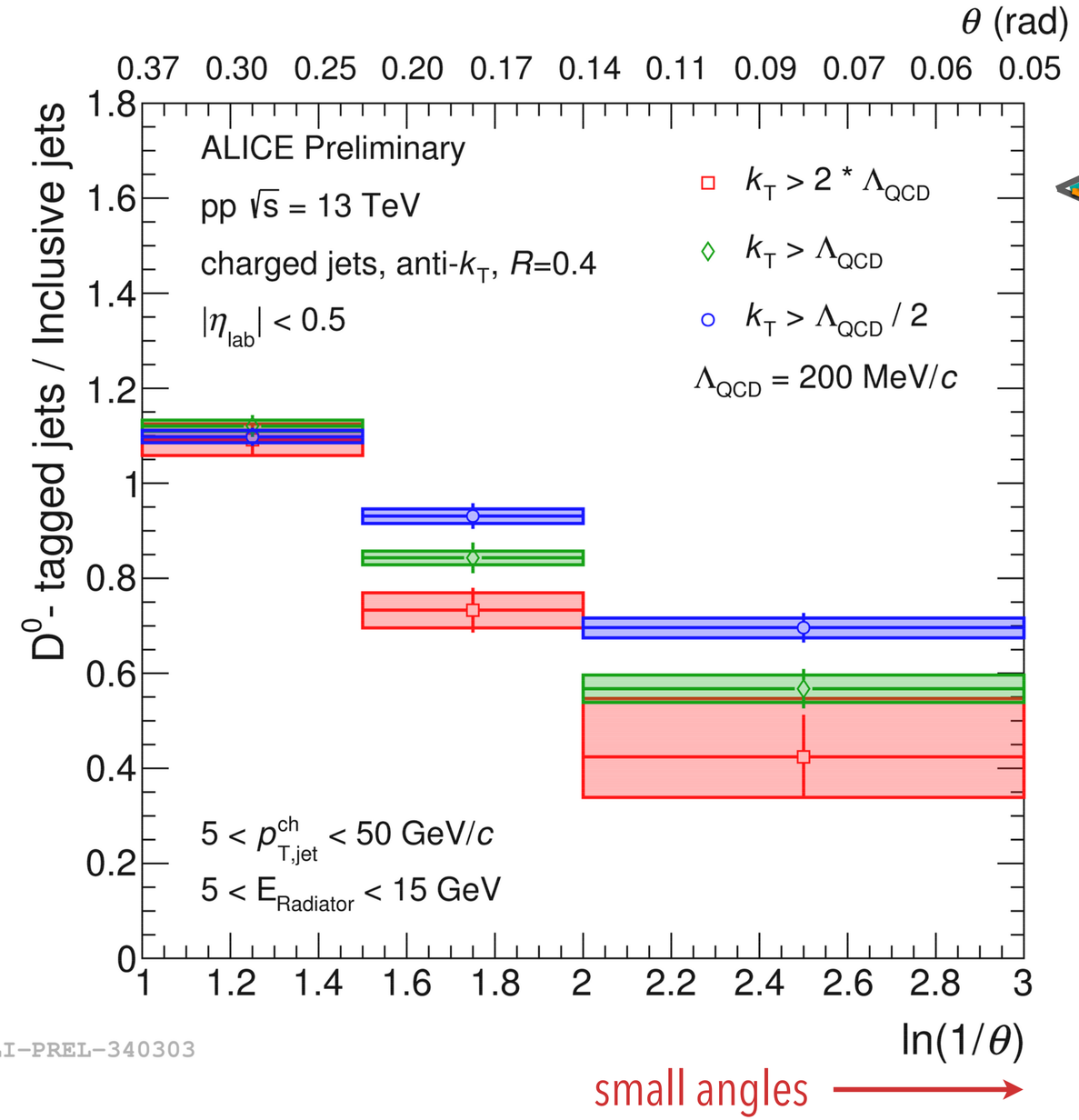
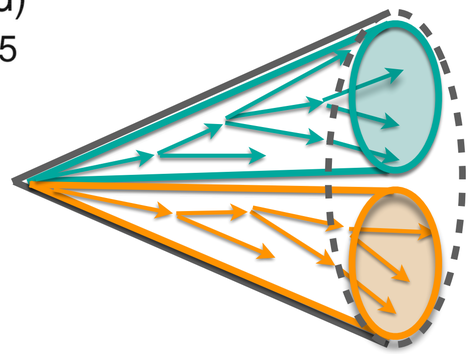
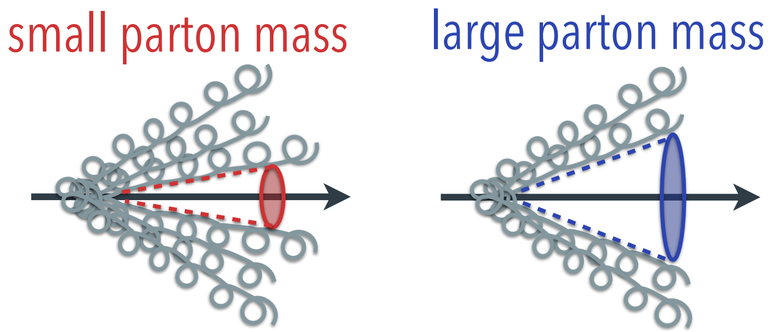


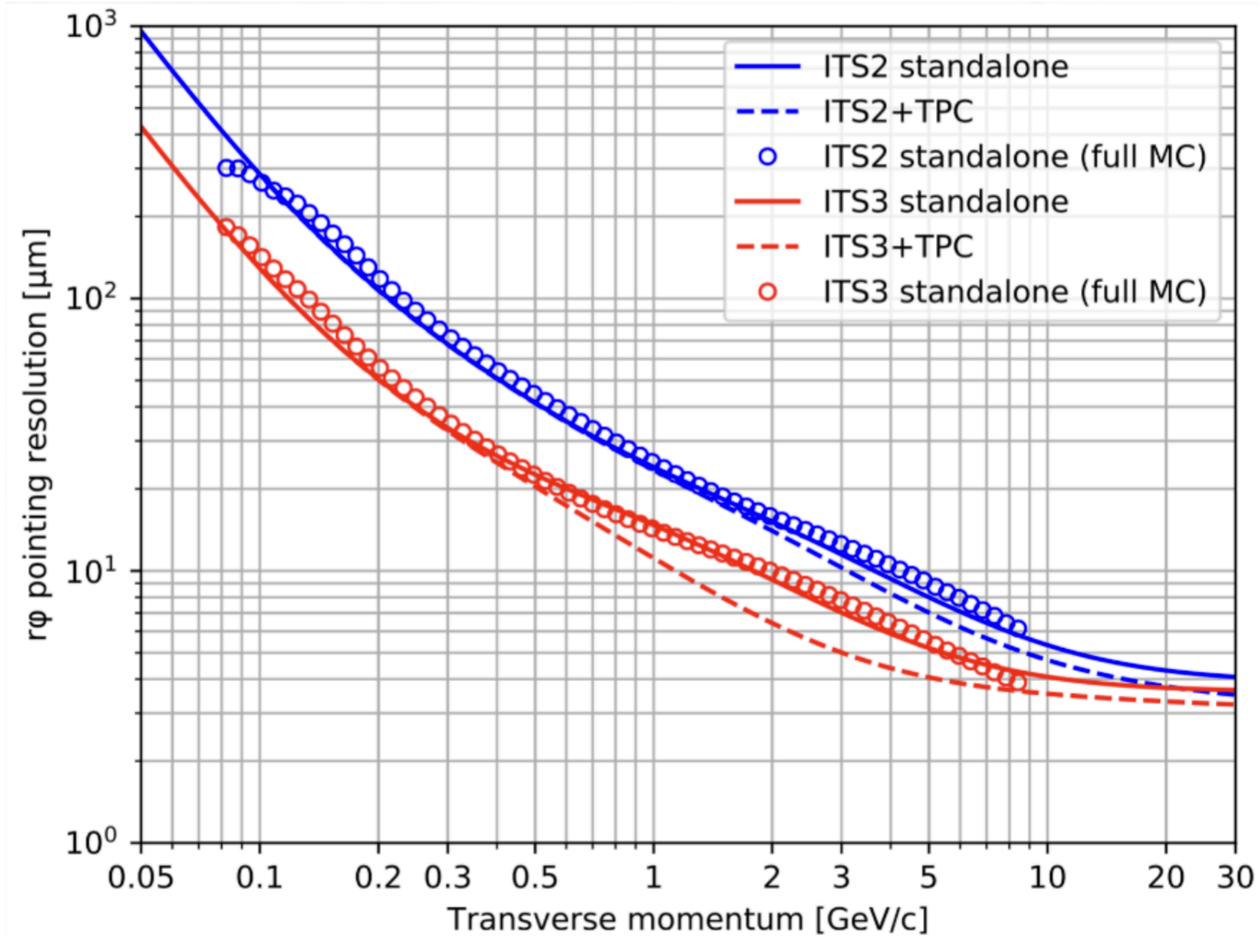
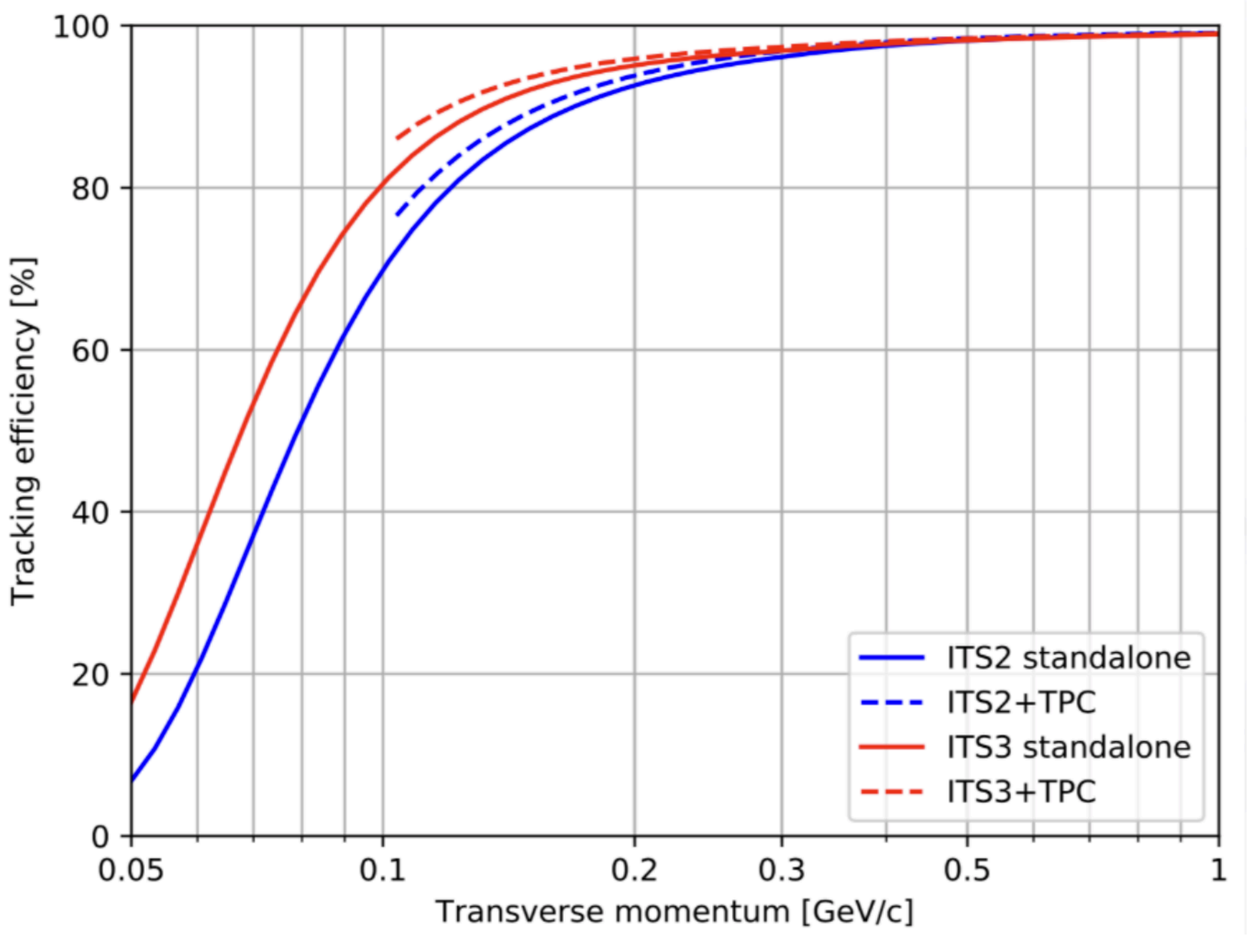


$\theta = \Delta R$ opening angle between subjets

$k_T = z p_T \sin(\Delta R)$ relative transverse momentum of subjets

- Suppression of splittings at small angles in D^0-tagged jets compared to inclusive jets
  - ➡ dead cone effect
- More results on jets in Laura Havener CERN-EP seminar



ITS2 performance

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