ALICE

The University of Texas at Austin

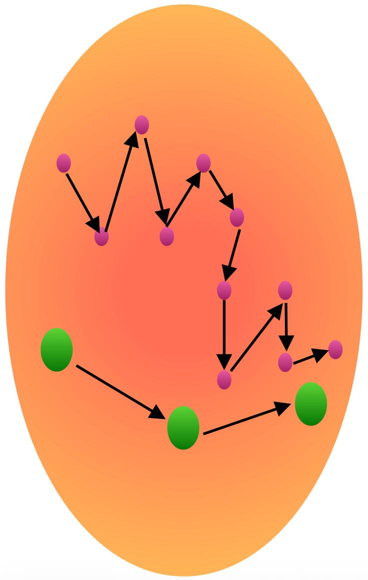
Beauty Production with ALICE at the LHC

Deepa Thomas
for the ALICE Collaboration

Quark Matter 2019
Wuhan, China 4-9 November

Motivation

- **Beauty quarks** produced in hard scattering processes in the initial stages of the collisions, before the formation of QGP.
  - $\tau_b \sim 0.02 < \tau_c \sim 0.07 < \tau_{QGP} \sim 0.1\text{-}1$ fm/c
  - Production well controlled and calculable with pQCD —> **Calibrated probe.**
- Undergoes elastic (collisional) and inelastic (radiational) collisions —> **sensitive to transport properties of QGP.**
- **Lose less energy in QGP compared to light and charm quarks.**
  - Color charge effects: $\Delta E_{gluons} > \Delta E_{quarks}$ due to stronger coupling.
  - Mass effects: $M_{gluons} < M_{u,d,s} < M_c < M_b$ <—> $\Delta E_{gluons} > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- Collectivity in QGP.
- Not created or destroyed in the medium —> **identity is preserved** in the medium, thus tagged up to hadronization.
- **pp collisions:** test pQCD calculations at LHC energies.
- **p-Pb collisions:** isolate initial state and cold nuclear matter effects.



charm ~ 1 GeV/c^2
beauty ~ 4 GeV/c^2

Beauty measurements with ALICE

Central barrel coverage: $|\eta| < 0.9$
Muon spectrometer coverage: $-4 < \eta < -2.5$

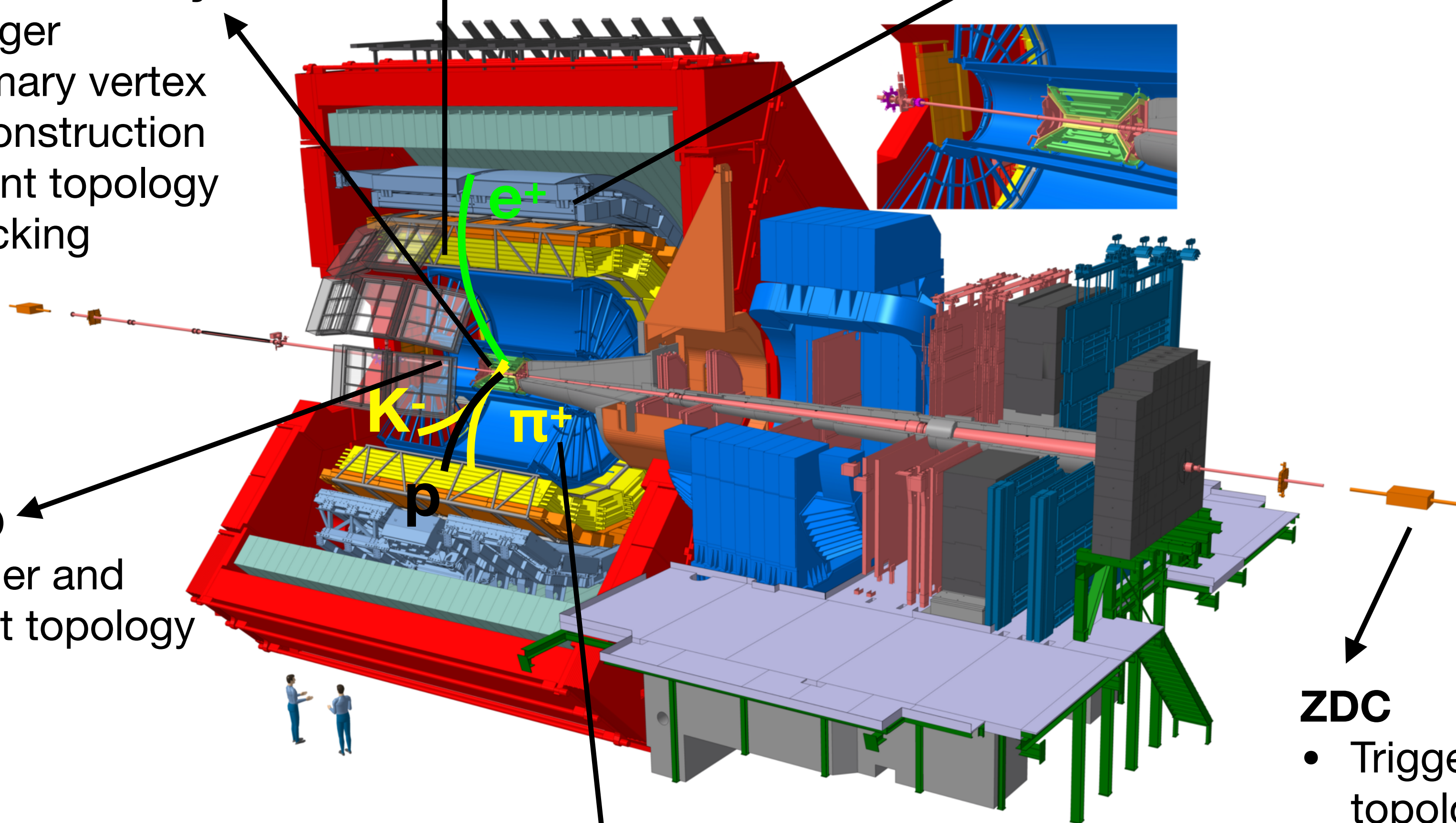
Beauty measurements:

- **Beauty-decay electrons (b->e)**
- **Beauty-decay D^0 (b->D^0 (->$K^-\pi^+$)) {non-prompt D^0}**
- **Beauty-decay J/Ψ (b->J/Ψ (->e^+e^-)) {non-prompt J/Ψ}**
- **b-tagged jets**

Time of Flight
- PID

Electromagnetic Calorimeter
- Trigger and PID

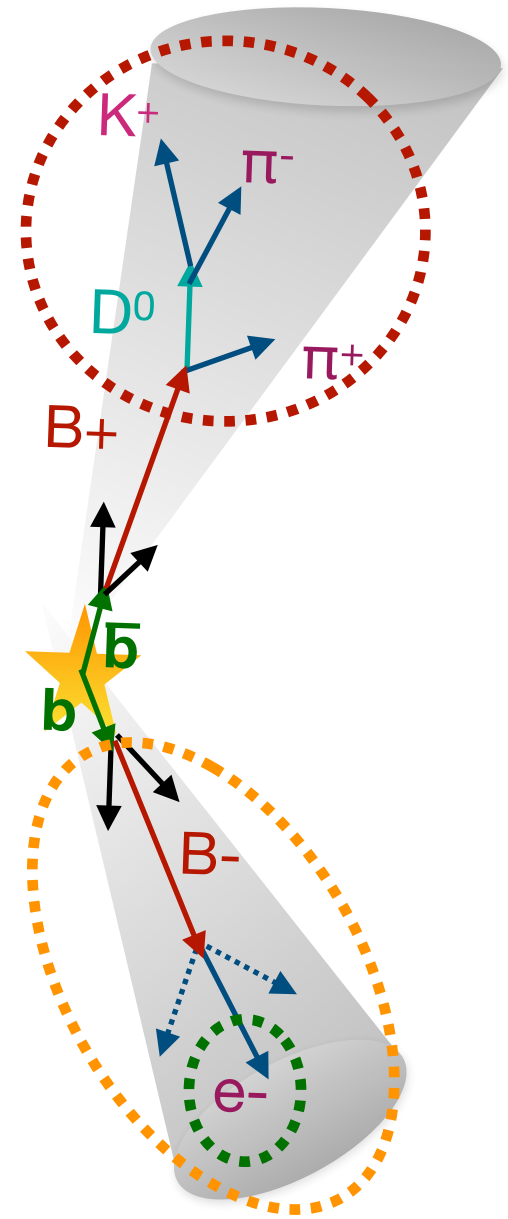
Inner Tracker System
- Trigger
- Primary vertex reconstruction
- Event topology
- Tracking
- PID



VZERO
- Trigger and event topology

ZDC
- Trigger and event topology

Time Projection Chamber
- Tracking and PID

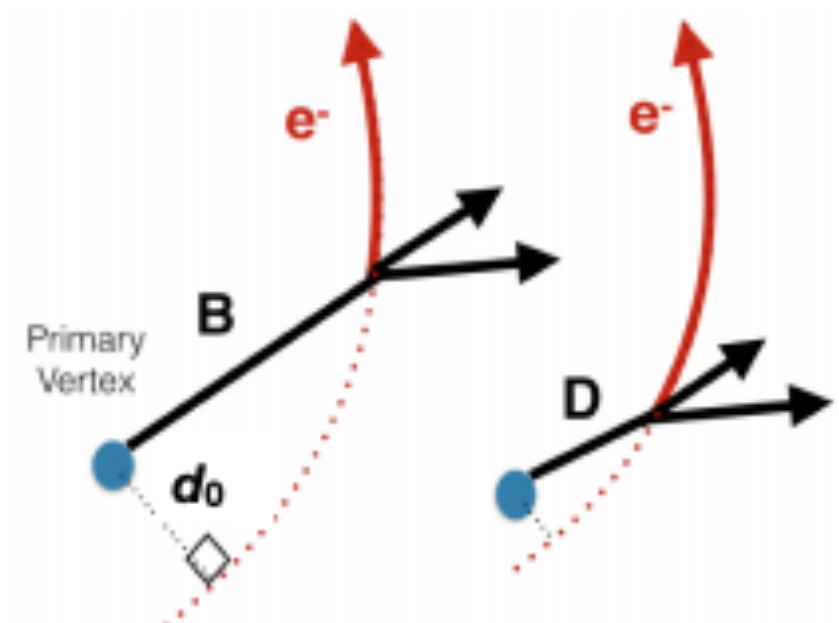


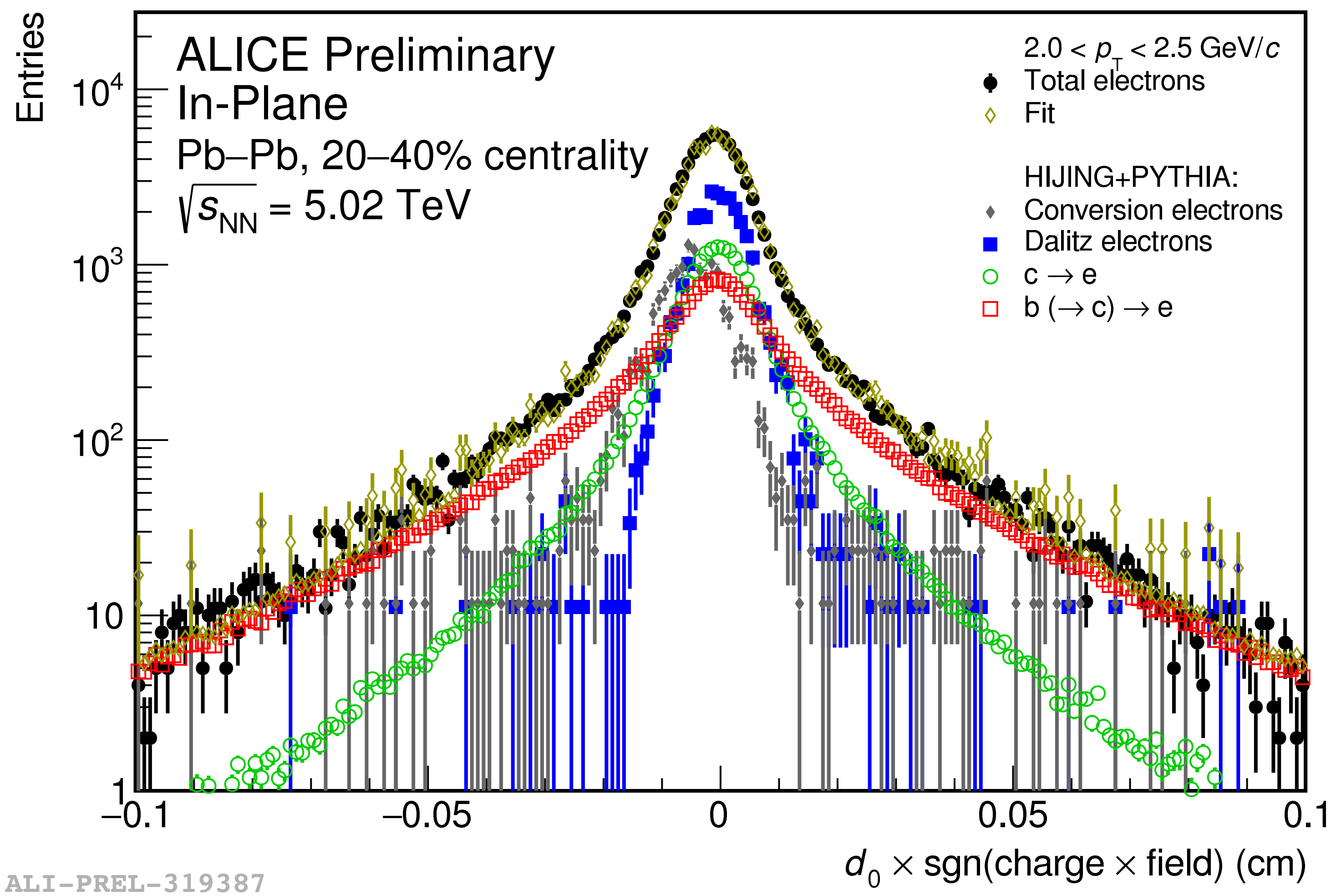
Analysis Procedure

Beauty-decay electrons (b —> e)

beauty hadrons τ ~ 500 μm/*c*
charm hadrons τ < 300 μm/*c*

- Beauty hadrons have longer lifetime than charm and other electron sources.
  —> Larger distance of closest approach (d_0) w.r.t primary vertex



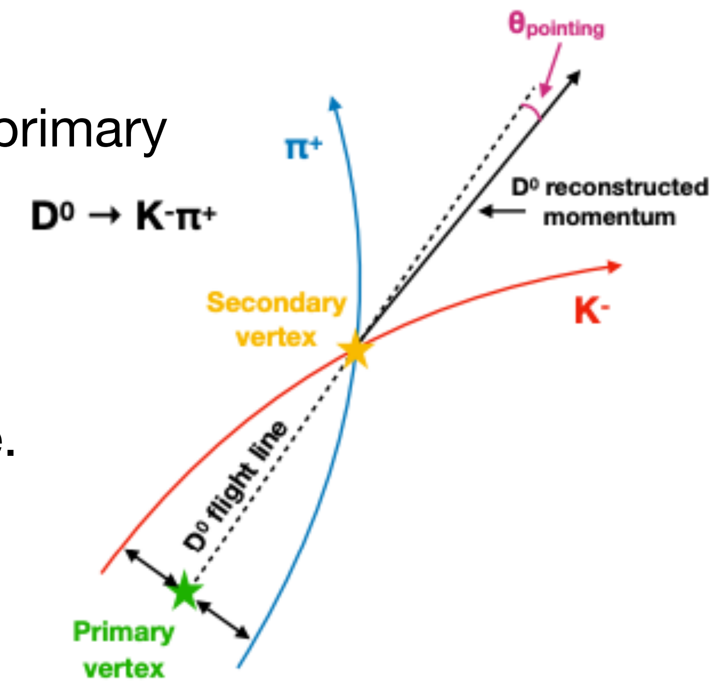


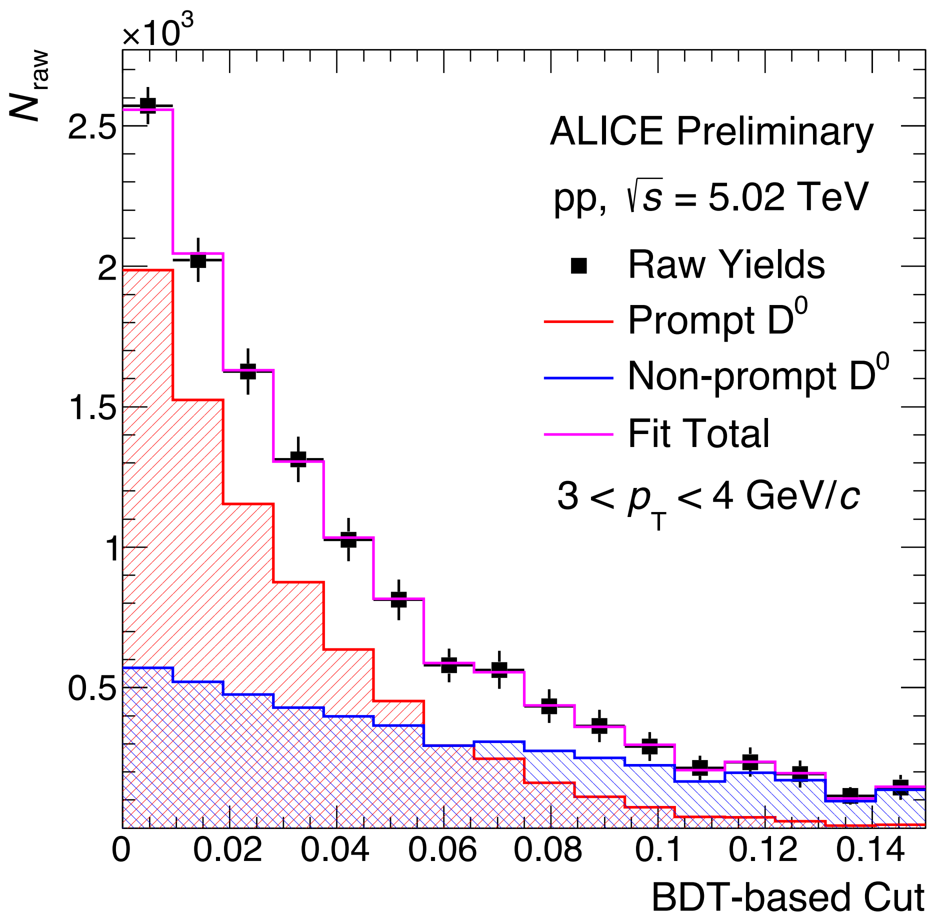
Monte-Carlo templates of b->e, c->e and other sources
-> Fitted to data to separate different sources.

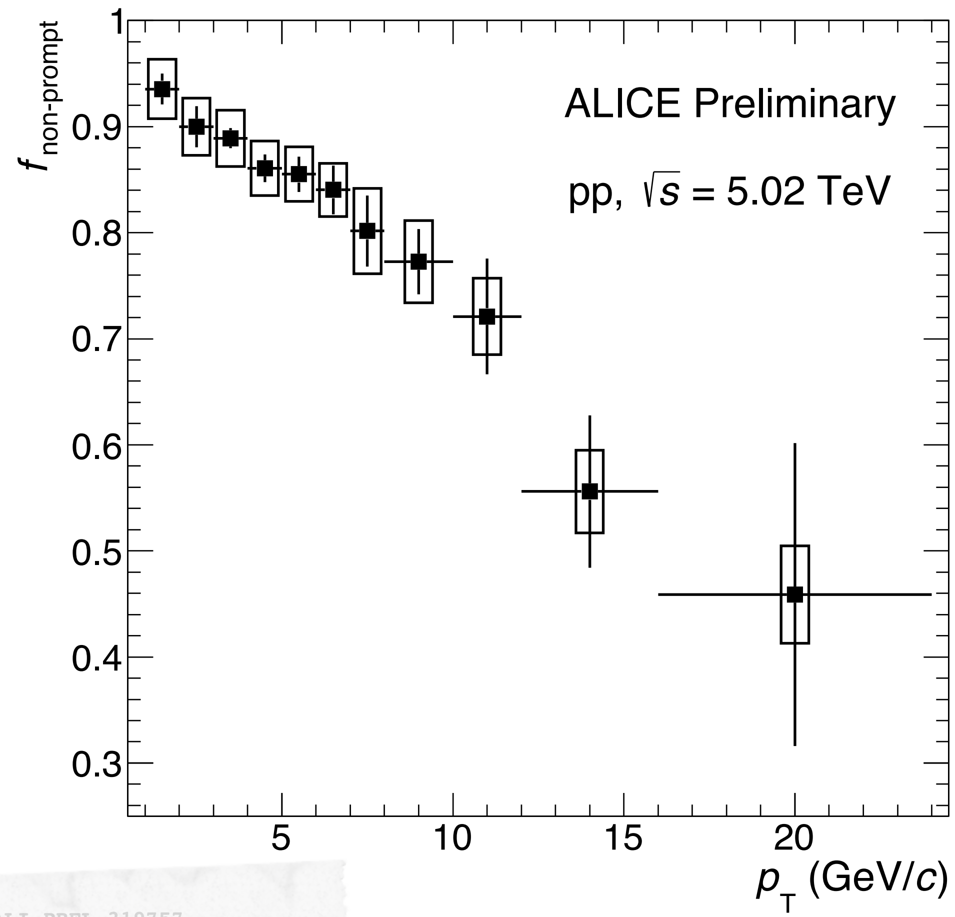
Analysis Procedure

Beauty-decay D⁰ (b—>D⁰ (—> K⁻π⁺))

- Reconstruct b->D⁰ using invariant mass of secondary vertices displaced from primary vertex (due to longer lifetime of B decays).
- Use boosted decision trees (BDT) to optimize topological cuts
  - Enhance b->D⁰ fraction and reduce combinatorial background.
- Beauty fraction of the raw yield is obtained by template fit of the BDT cut value.







$$f_{b->D^0} = \frac{N_b \epsilon_b}{N_c \epsilon_c + N_b \epsilon_b}$$

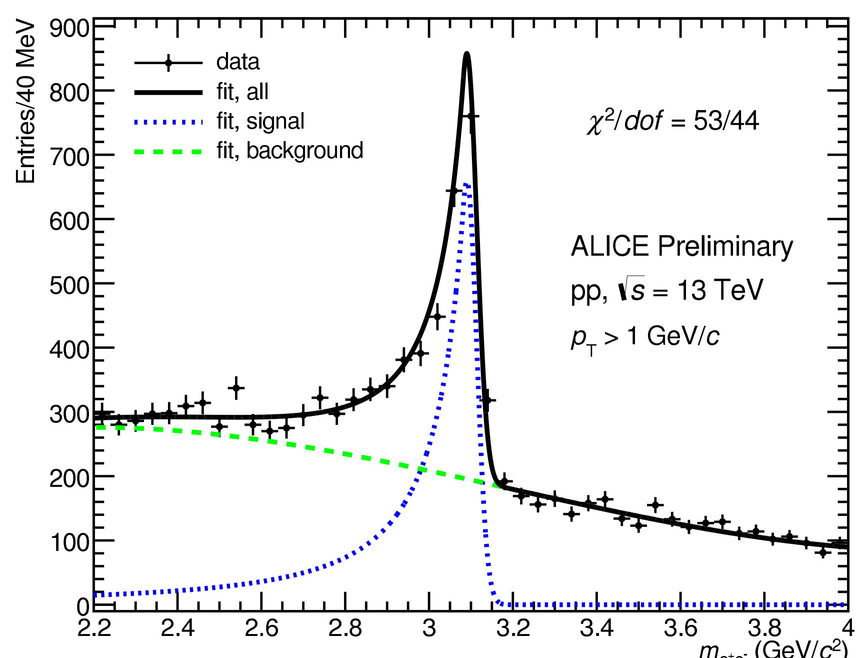
$$\frac{d^2\sigma_{b->D^0}}{dp_T d\eta} = \frac{f_{b->D^0} \times N_{raw}}{\Delta p_T \Delta y BR^{D^0->K\pi} (Acc \times \epsilon)_{b->D^0}}$$

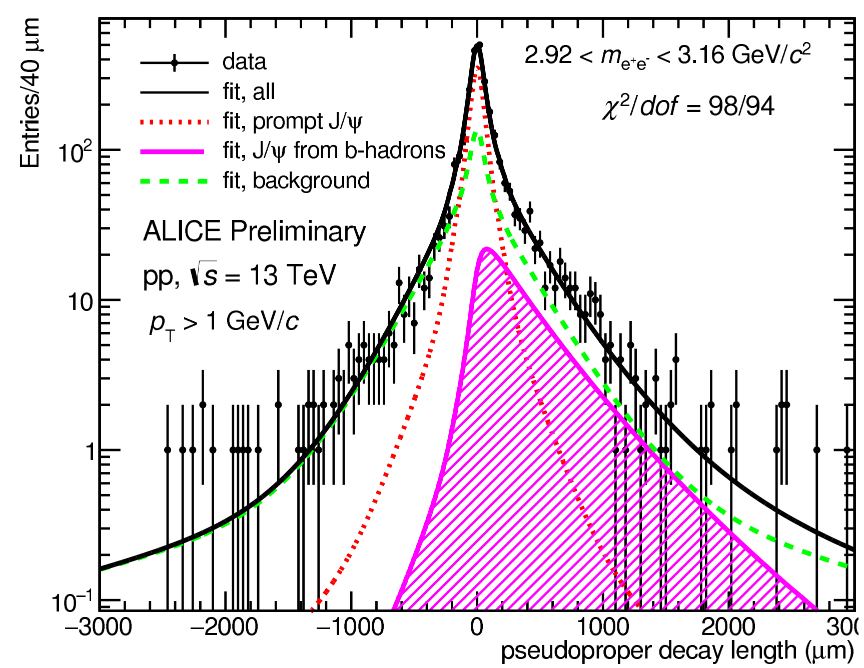
Analysis Procedure

Beauty-decay J/Ψ (b—> J/Ψ(—> e+e-))

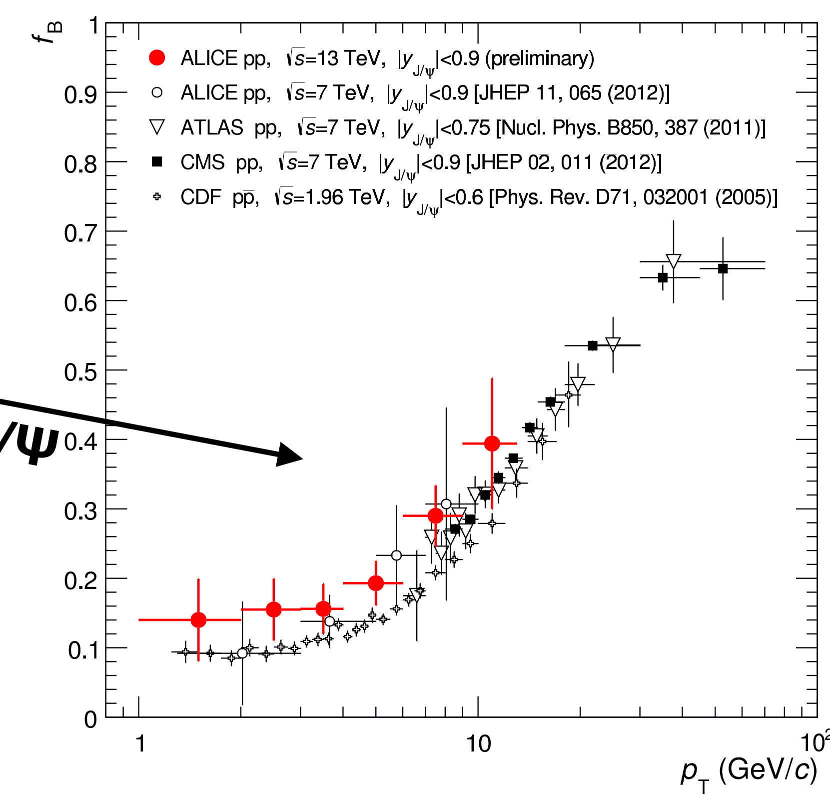
$$x = \frac{\vec{L} \cdot \vec{p_T}}{p_T} \cdot \frac{c \cdot m_{J/\Psi}}{p_T}$$

- Reconstruct J/Ψ through their decay channel J/Ψ->e^+e^-.
- Fraction of non-prompt J/Ψ (b—> J/Ψ) relies on **pseudo-proper decay length (*x*)** from the primary vertex.
- Perform un-binned likelihood fit of 2D distributions of **invariant mass m_{e+e-} and *x*** on both signal and background.





Fraction of b-> J/Ψ

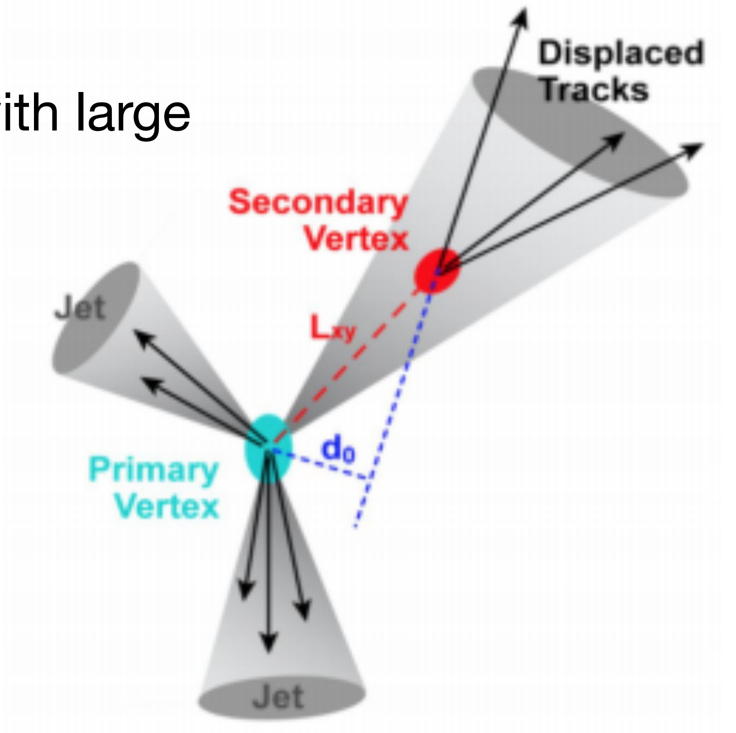


$$f_B = \frac{N_{h_B \to J/\Psi}}{N_{h_B \to J/\Psi} + N_{prompt\ J/\Psi}}$$

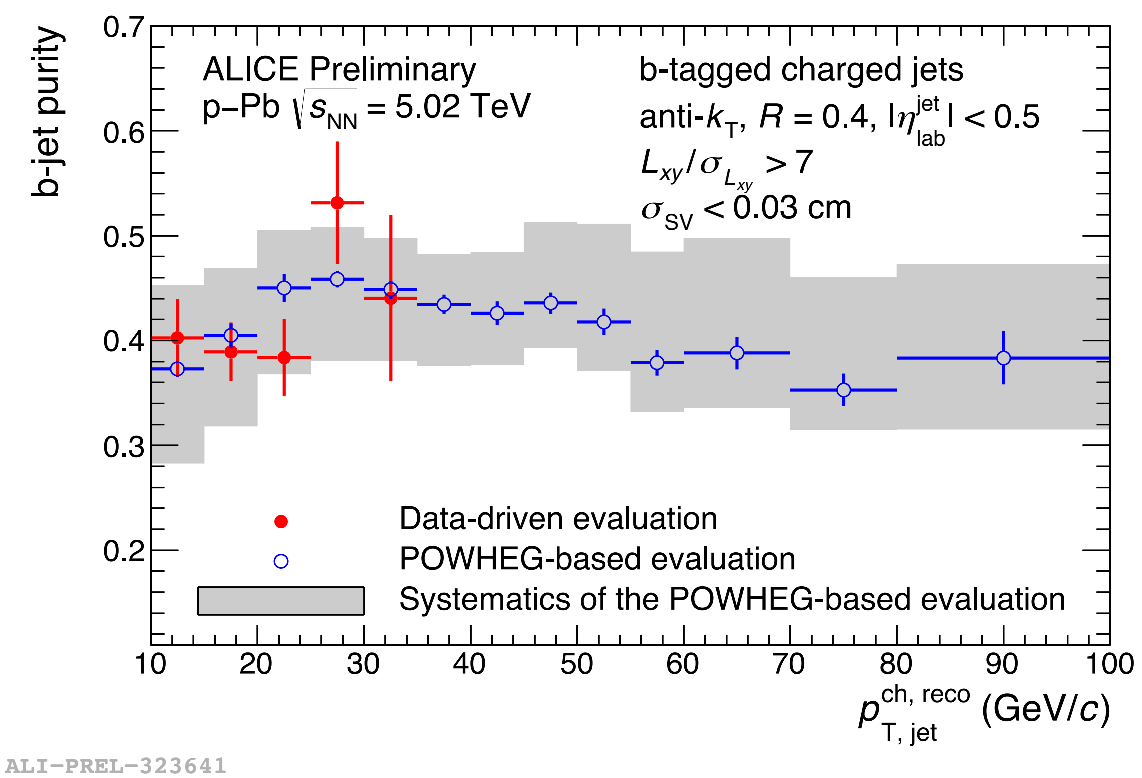
Analysis Procedure

b-Tagged Jets

- Select jets containing displaced secondary vertex (SV) or minimum N tracks with large impact parameter.
- Jets reconstructed with Anti-k_T algorithm, R = 0.4
- Apply topological cuts to increase b-jet fraction
  - Method 1: Significance of the SV displacement - $SL_{xy} = L_{xy}/\sigma_{L_{xy}} > \alpha$
  - Method 2: Minimum no. of tracks in a jet with $d_{xy} > d_{xy}^{threshold}$
- Fraction of b-jets (Purity) obtained using Monte-Carlo templates fit to data.



Displaced SV method



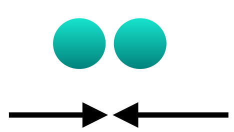
$$dN_{b-jet}(p_{T,jet}^{ch,reco}) = dN^{raw}(p_{T,jet}^{ch,reco}) \times \frac{P_b}{\epsilon_b}$$

$$P_b = \frac{N_b\epsilon_b}{N_b\epsilon_b + N_c\epsilon_c + N_{LF}\epsilon_{LF}}$$

$\epsilon_{c,b,LF}$ = Efficiency from MC

Results

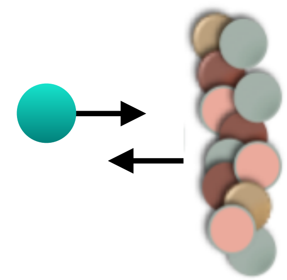
pp collisions



$\sqrt{s} = 5.02,\ 13$ TeV

- **b->e cross-section**
- b->D^0 (non-prompt D^0) cross-section
- **b->J/Ψ cross-section**
- **b-tagged jet cross-section**

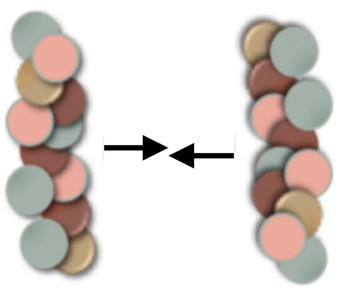
p-Pb collisions



$\sqrt{s_{NN}} = 5.02$ TeV

- **b->J/Ψ cross-section**
- b-tagged jet cross-section
- **R_{pPb} of b-tagged jets**

Pb-Pb collisions



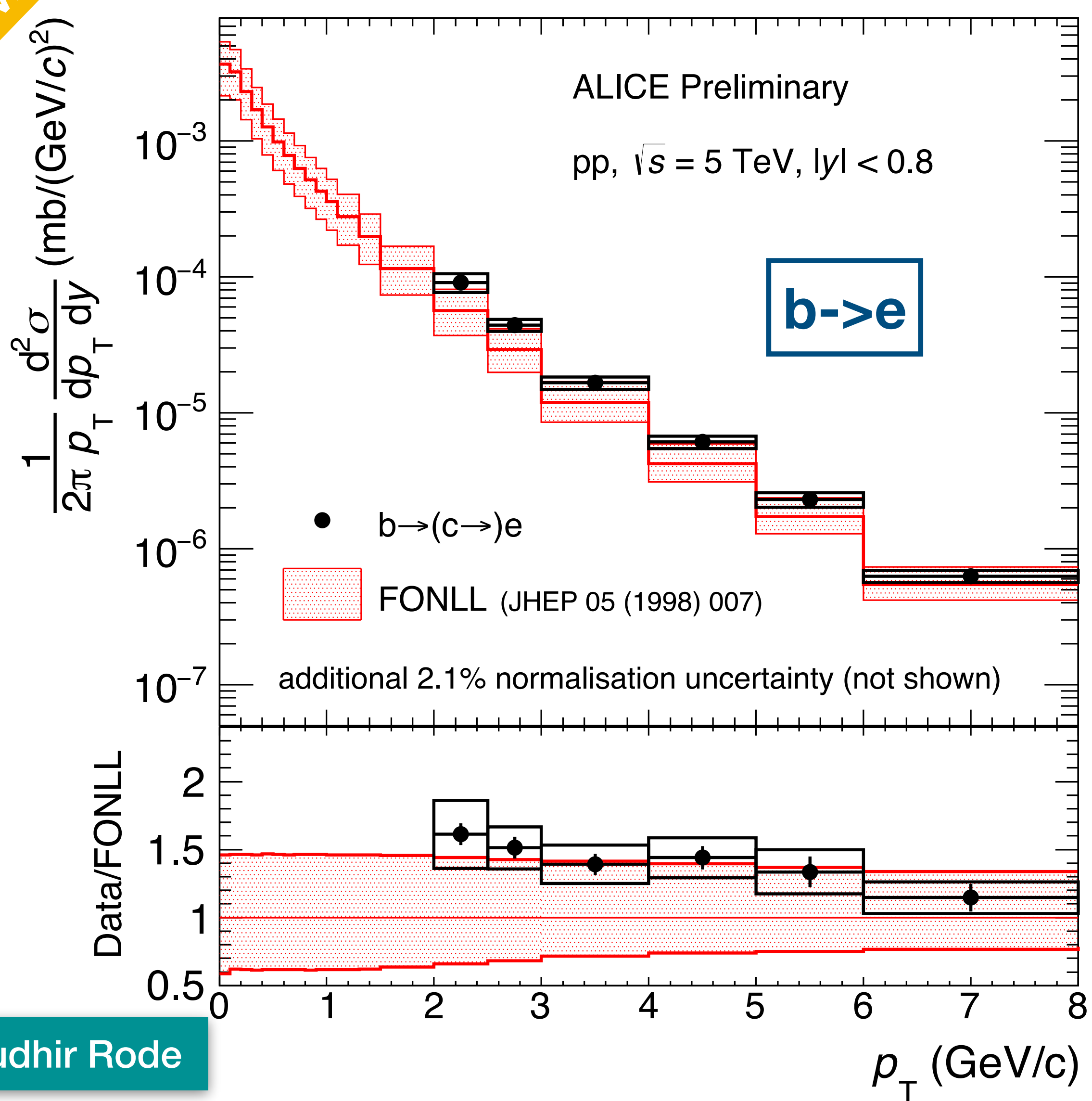
$\sqrt{s_{NN}} = 5.02$ TeV

- **R_{AA} of b->e (2015 data), b->D^0 (2018 data)**
- v_2 of b->e

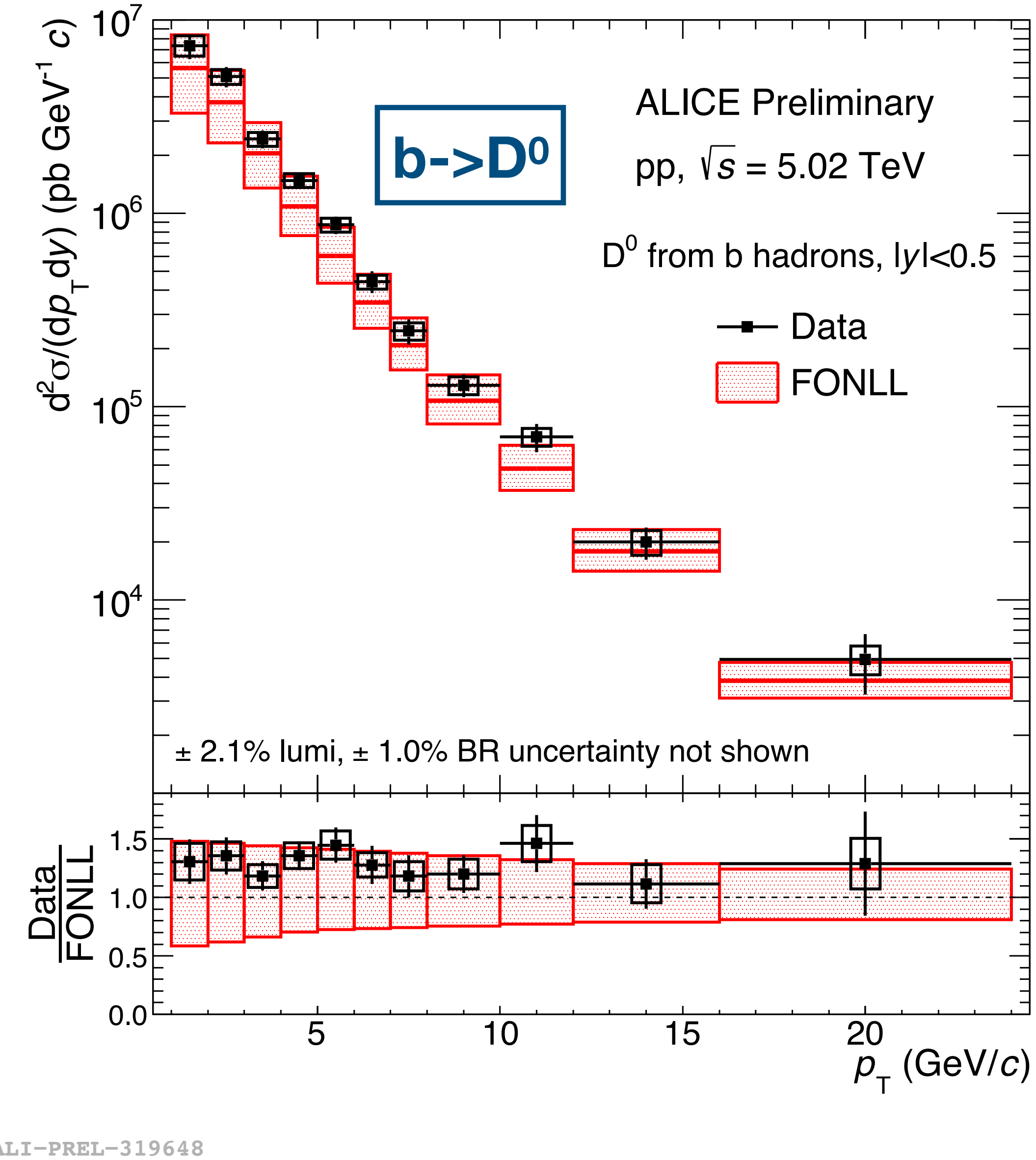
***new for QM**

b->e & b->D⁰ cross-section

New for QM



Poster by Sudhir Rode

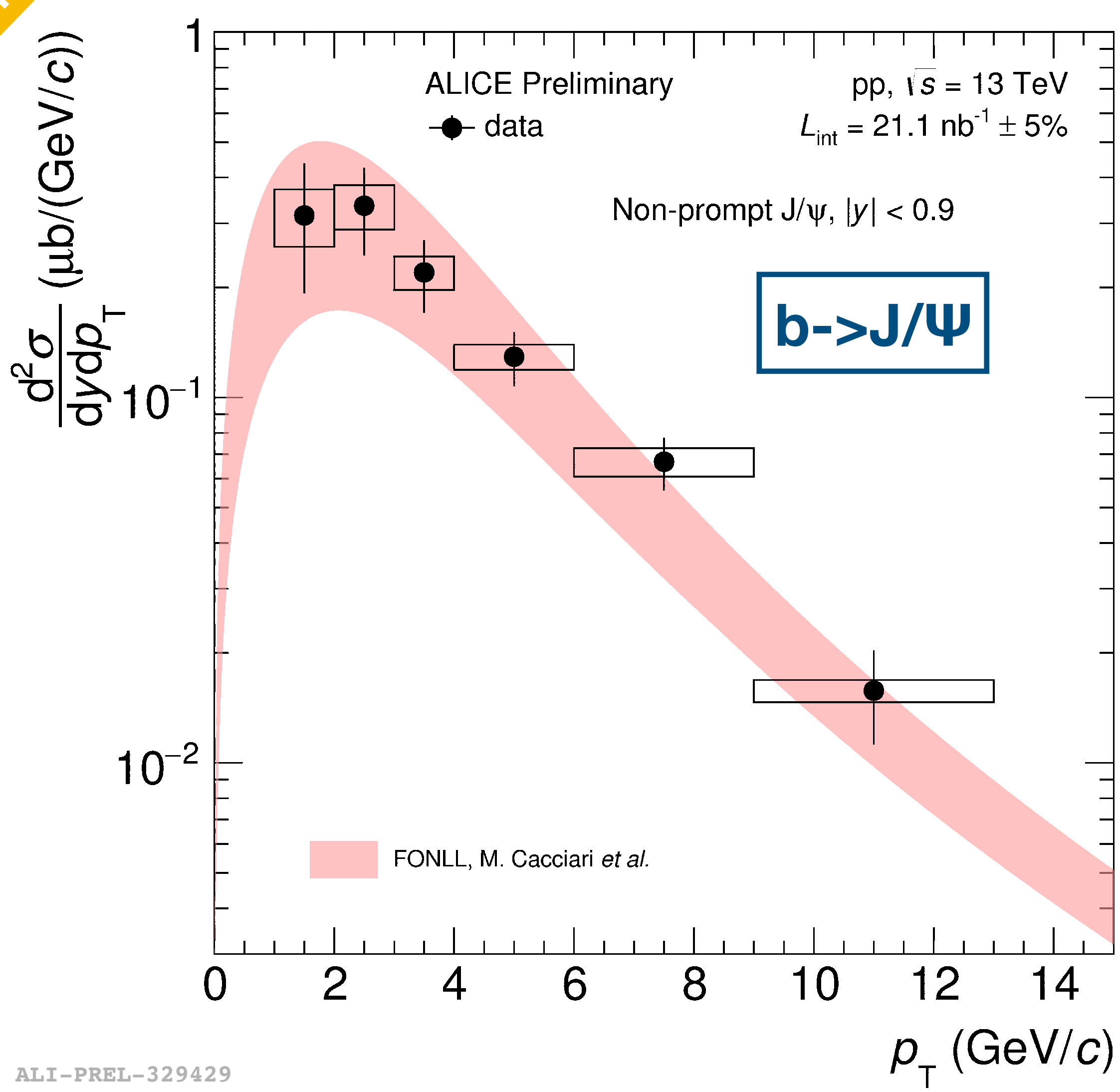


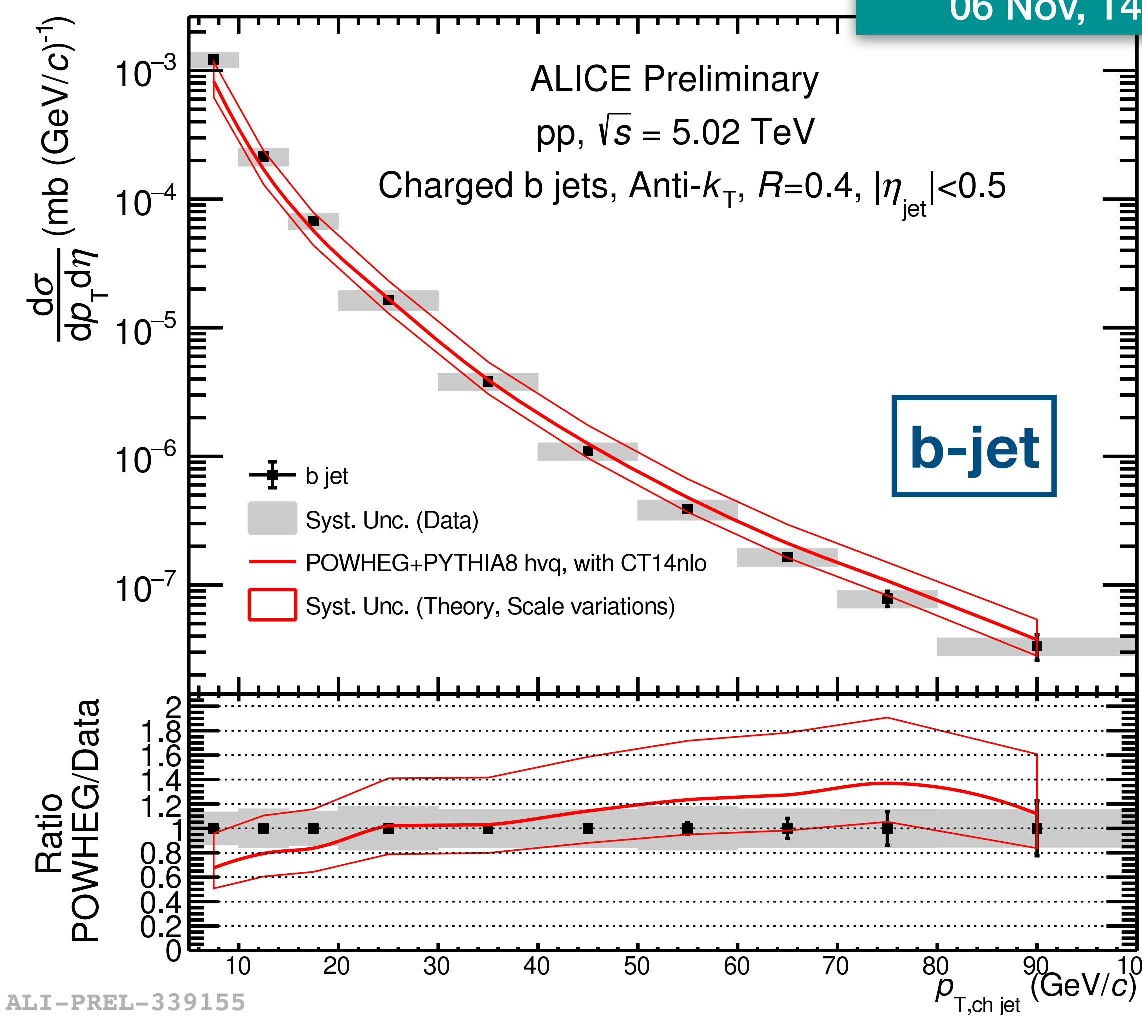
- **b->e and b->D⁰ cross-section measured in pp** at $\sqrt{s} = 5.02$ TeV
  - b->e: $2 < p_T < 8$ GeV/c
  - b->D⁰: $1 < p_T < 24$ GeV/c
- **Measurement described by FONLL calculations within uncertainties —> lie on the upper edge of FONLL.**

b->J/Ψ & b-jet cross-section

New for QM

Talk by Jakub Kvapil, Jet Modification IV 06 Nov, 14:00





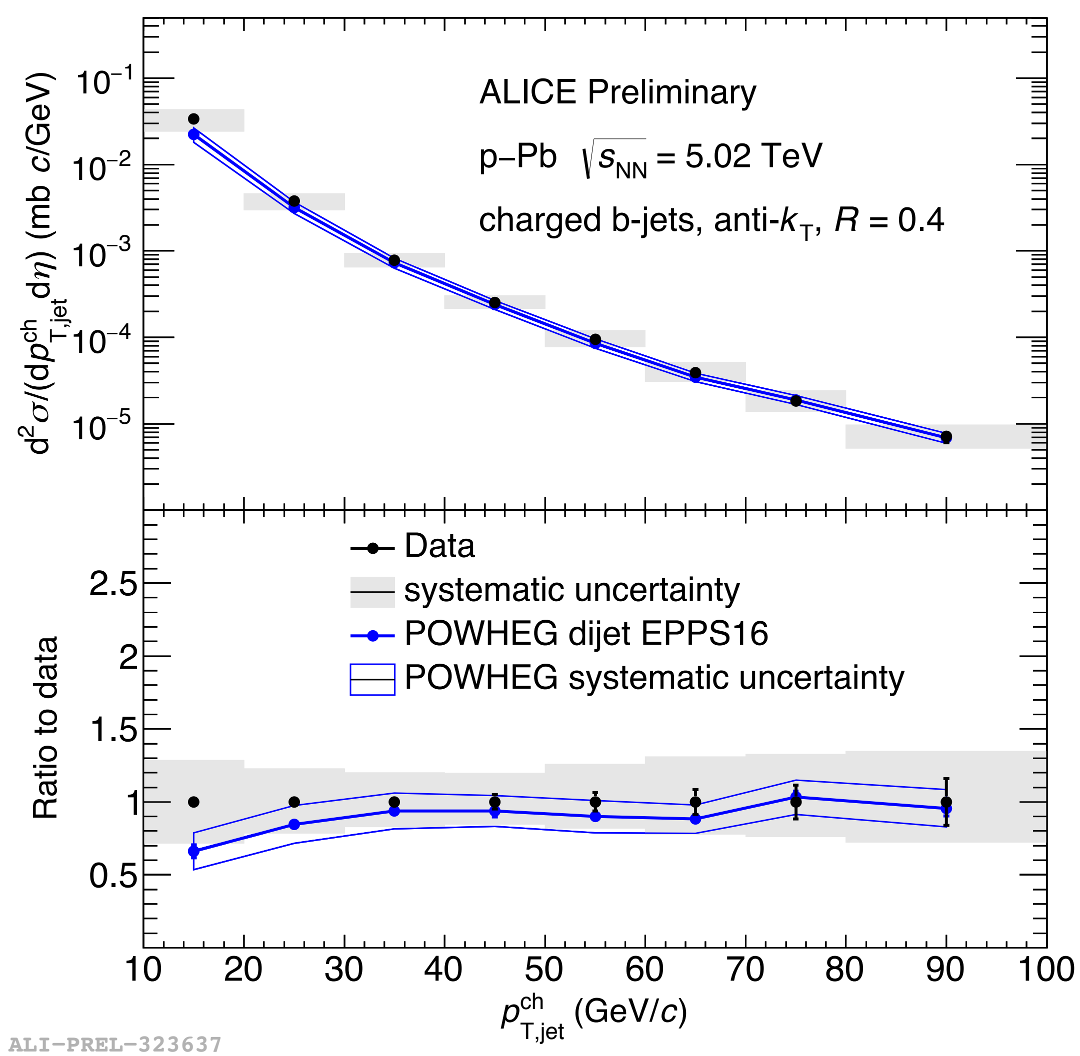
- **b->J/Ψ cross-section measured in pp** at $\sqrt{s} = 13$ TeV for 1 < p_T < 13 GeV/c —> **described by FONLL.**
- **First ALICE measurement of b-tagged jet cross-section measured in pp** at $\sqrt{s} = 5.02$ TeV for 5 < p_T < 100 GeV/c.
- **Data well described by different POWHEG +PYTHIA8 simulations within uncertainties** (HVQ and Dijet).

Beauty-tagged jet cross-section

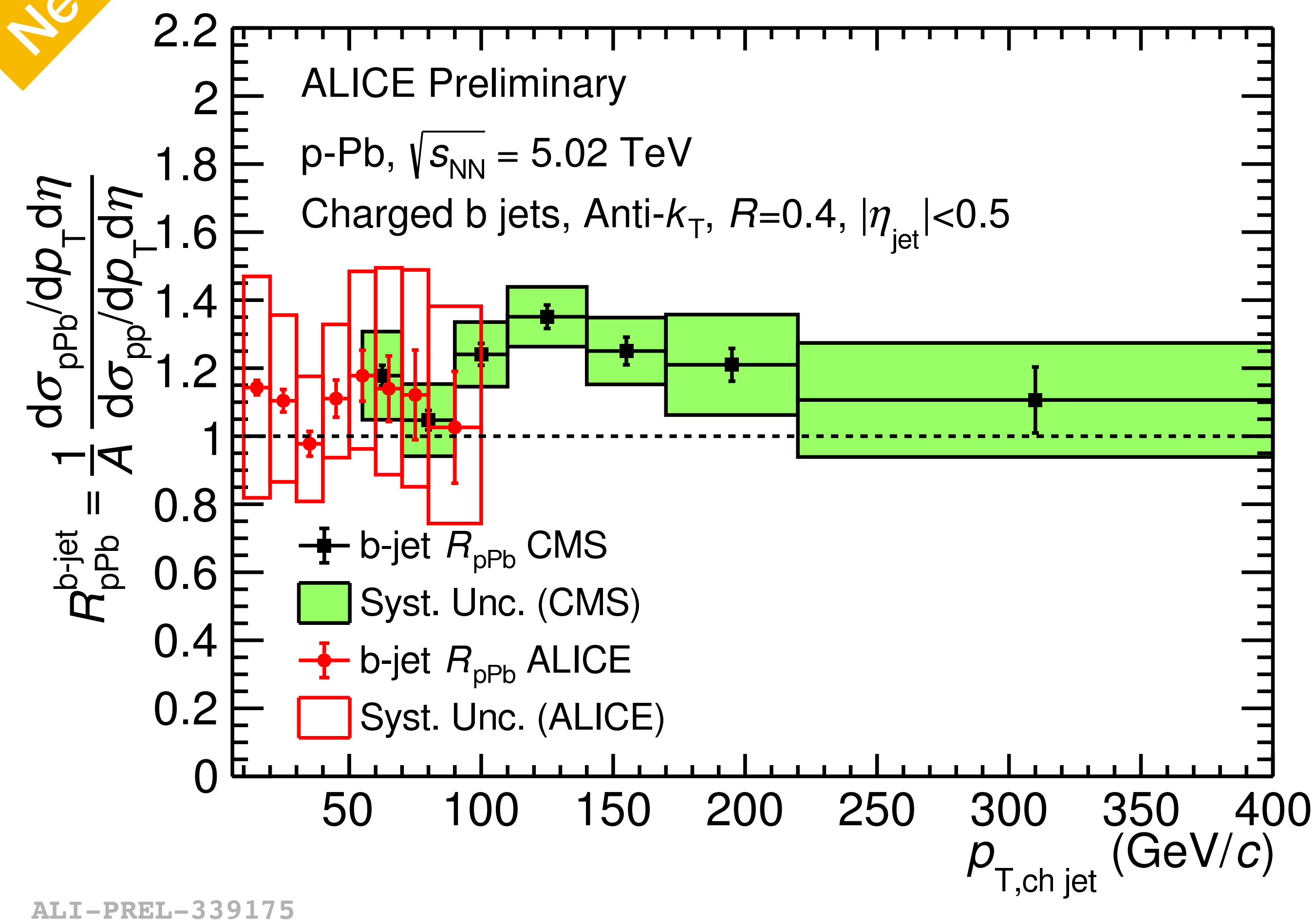
Talk by Jakub Kvapil, Jet Modification IV 06 Nov, 14:00

New for QM

b-jet cross-section



b-jet R_{pPb}

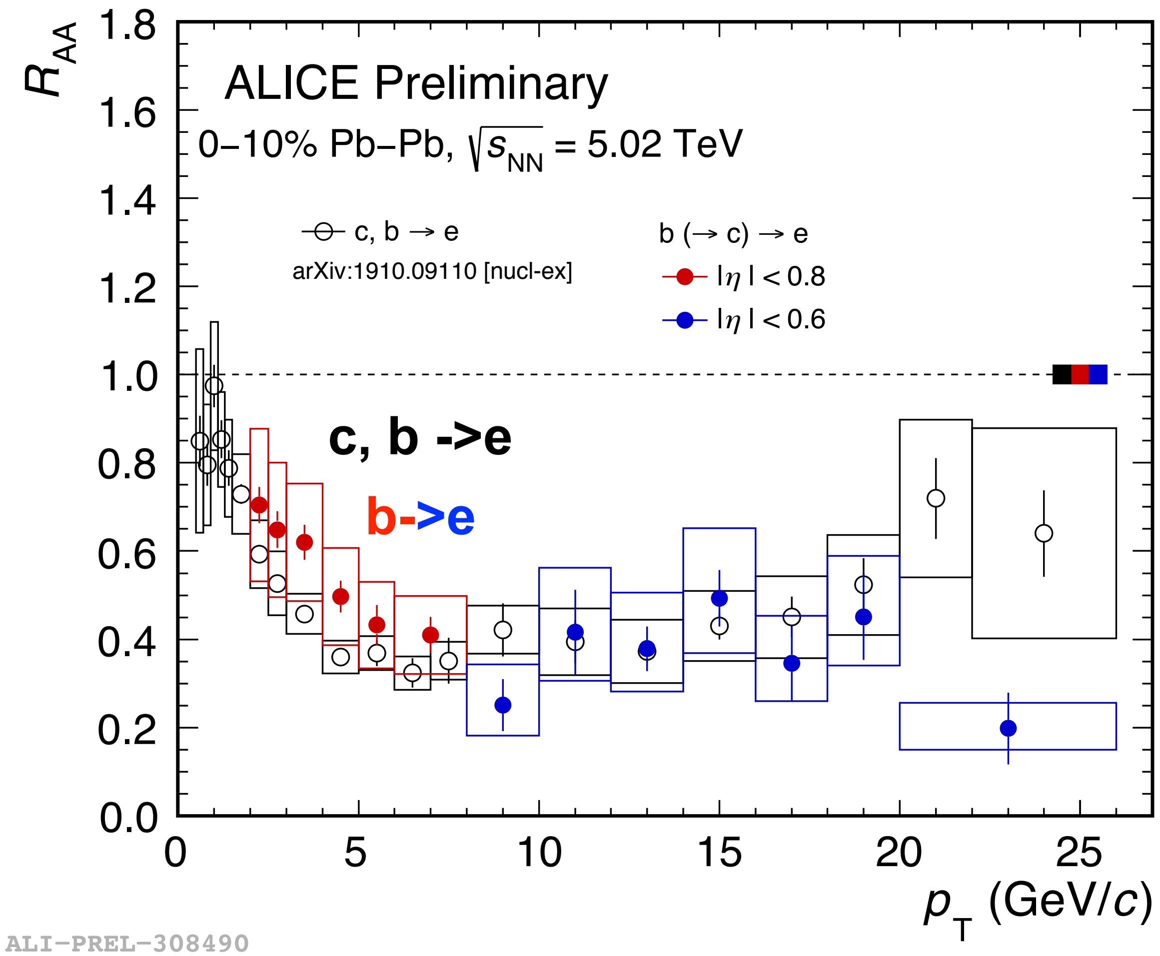


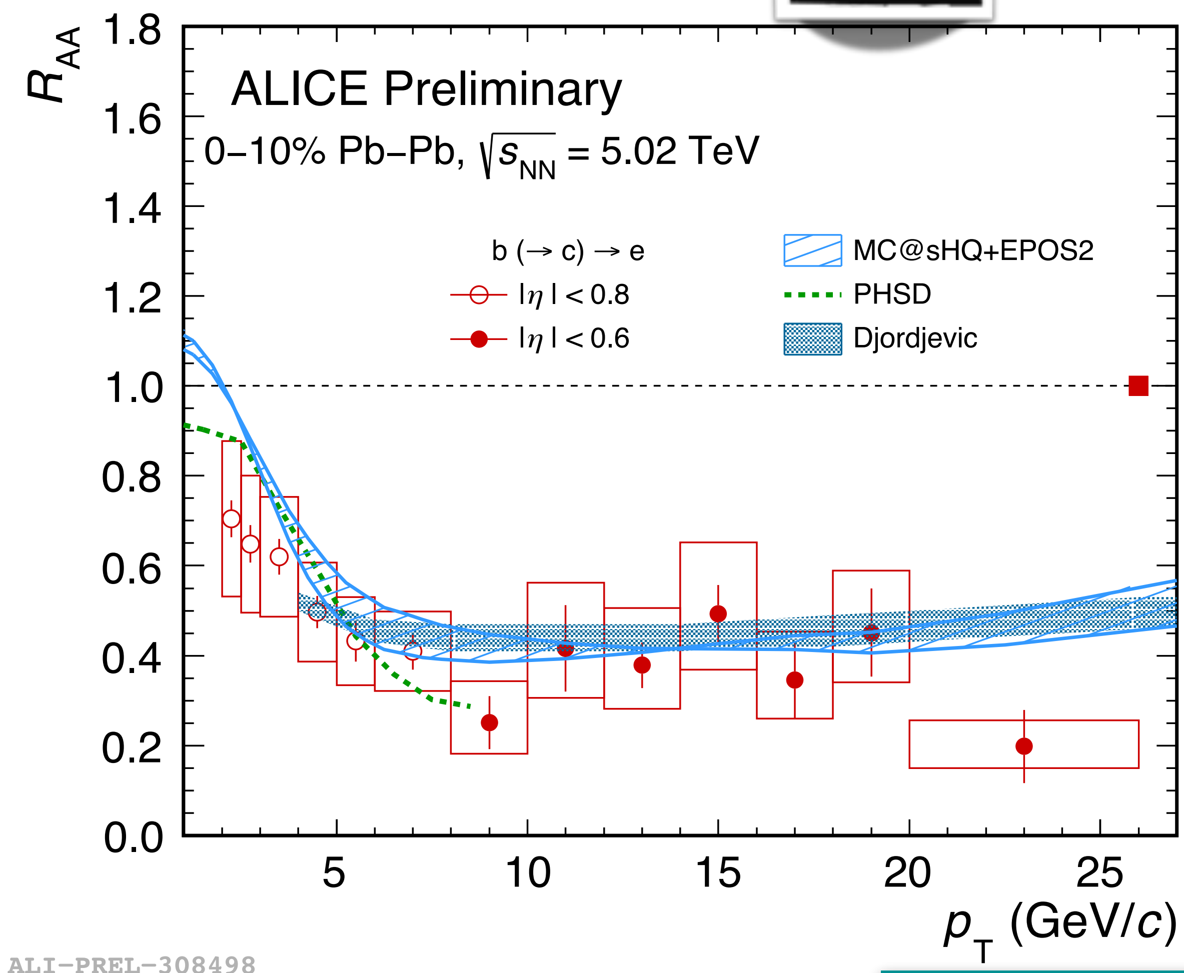
- **b-tagged jet cross-section and R_{pPb} measured in p-Pb collisions** at $\sqrt{s_{NN}} = 5.02$ TeV for $15 < p_T < 90$ GeV/c.
- **Data well described by different POWHEG simulations within uncertainties** (HVQ and Dijet)
- ***R_{pPb}* consistent with unity within uncertainties in the measured *p_T* range.**
  - ALICE measurement consistent with CMS in the overlapping p_T range of $50 < p_T < 100$ GeV/c.

R_{AA} of b->e

$$R_{AA} = \frac{dN_{AA}/dp_T}{< T_{AA} > d\sigma_{pp}/dp_T}$$

Pb-Pb 0-10%





Poster by Jonghan Park

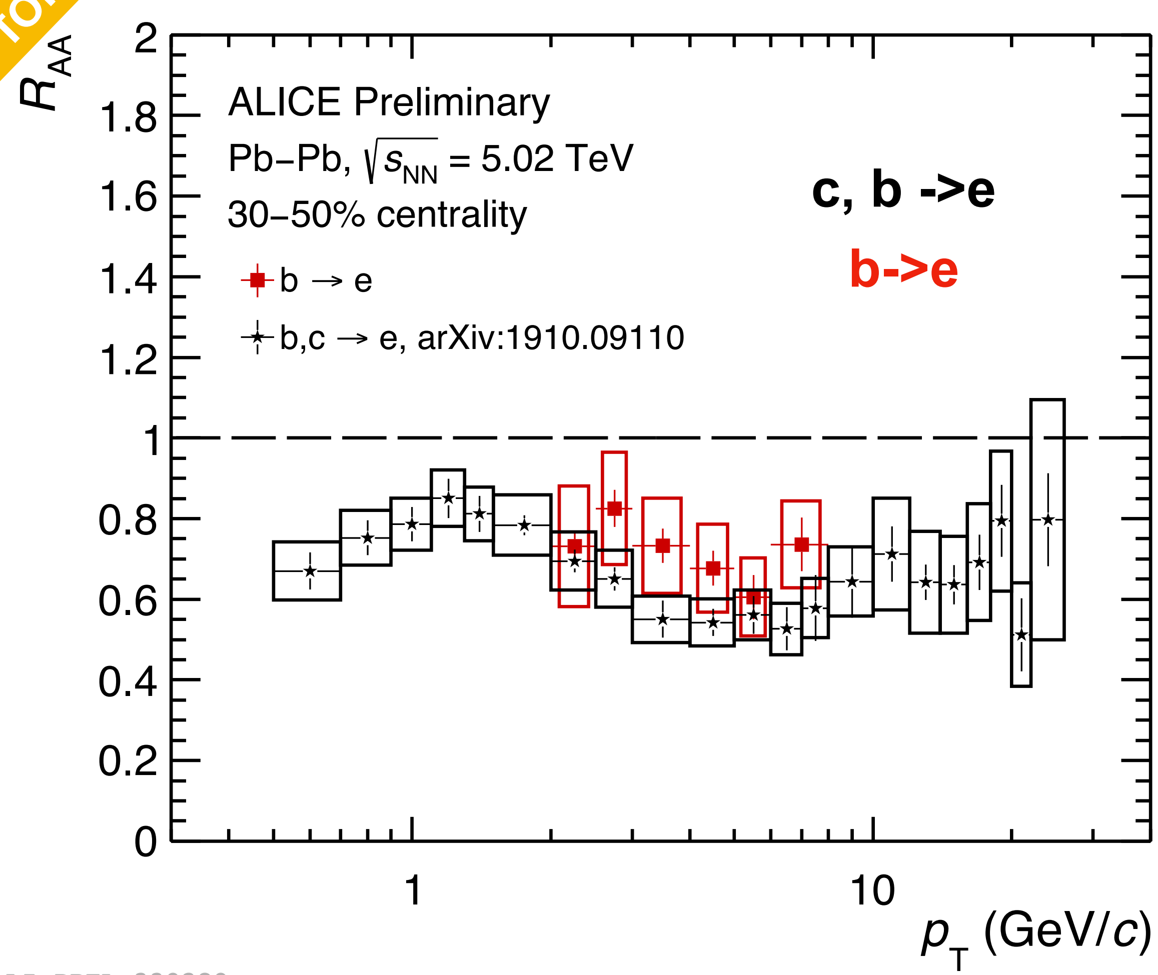
- **Nuclear modification factor measured for b->e in 0-10% and 30-50% Pb-Pb collisions** at $\sqrt{s_{NN}} = 5.02$ TeV —> Suppression of beauty-decay electrons observed.
- Comparison of b->e with c,b->e
  - Hint of beauty quarks undergoing less energy loss than charm quarks at low p_T.
  - At high p_T: b->e and b,c->e overlap as beauty decays dominate at high p_T.
- **Measurement well described by models that include both collisional and radiative energy loss.**

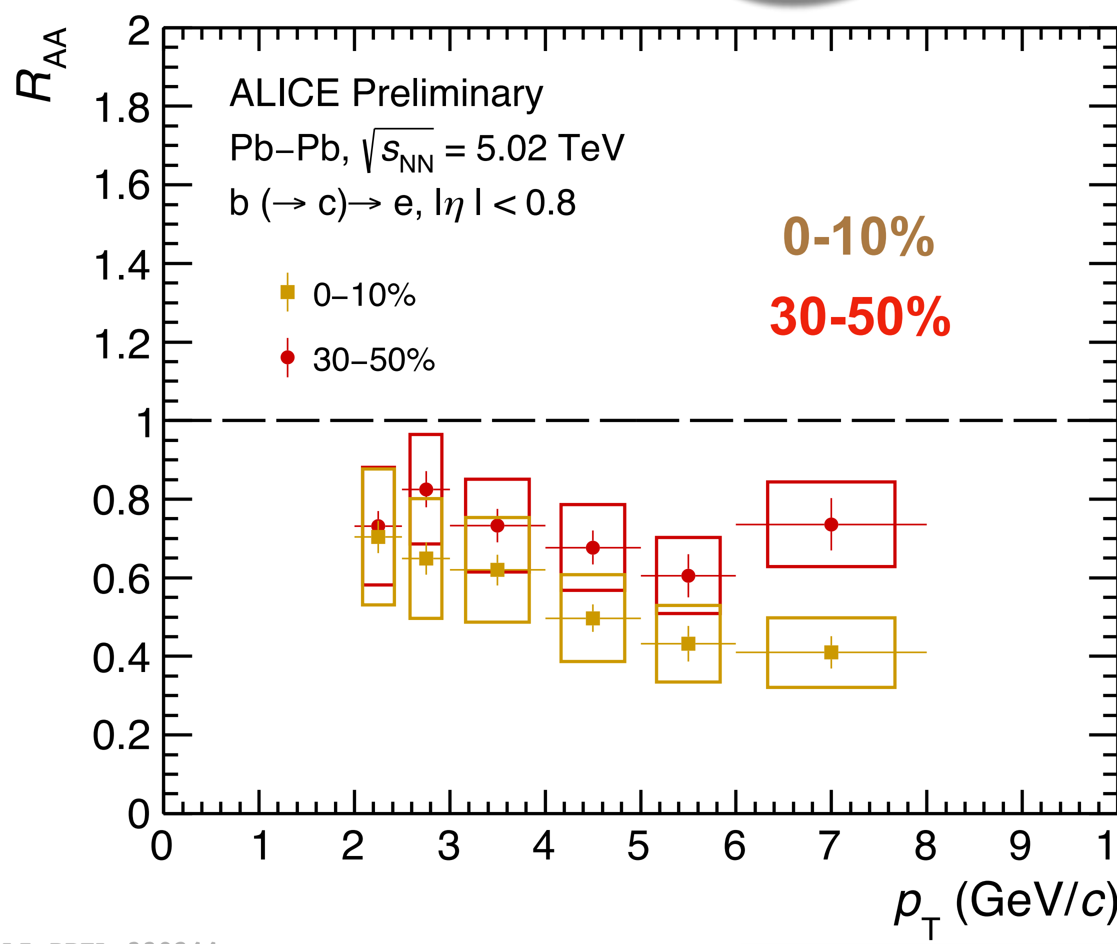
R_{AA} of b->e

New for QM

$$R_{AA} = \frac{dN_{AA}/dp_T}{< T_{AA} > d\sigma_{pp}/dp_T}$$

Pb-Pb 30-50%





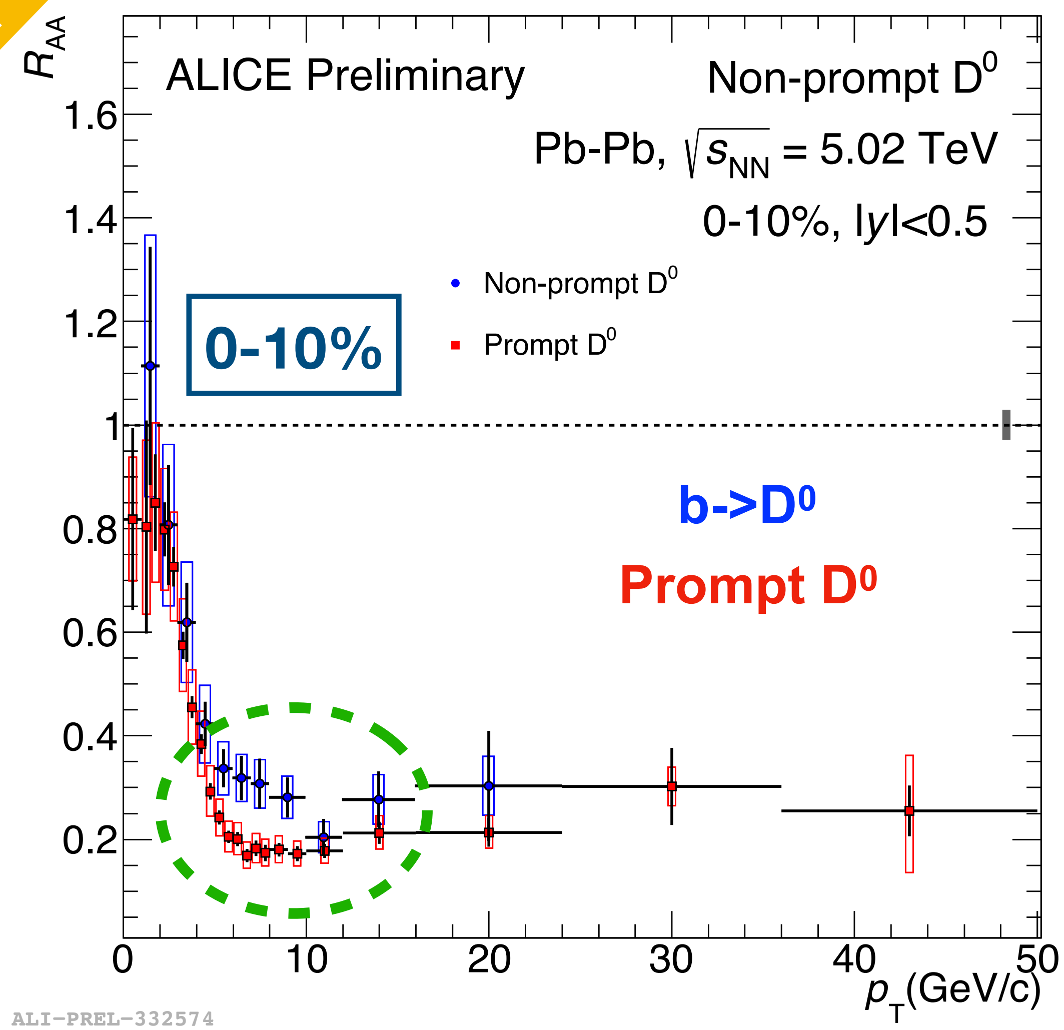
Poster by Jonghan Park

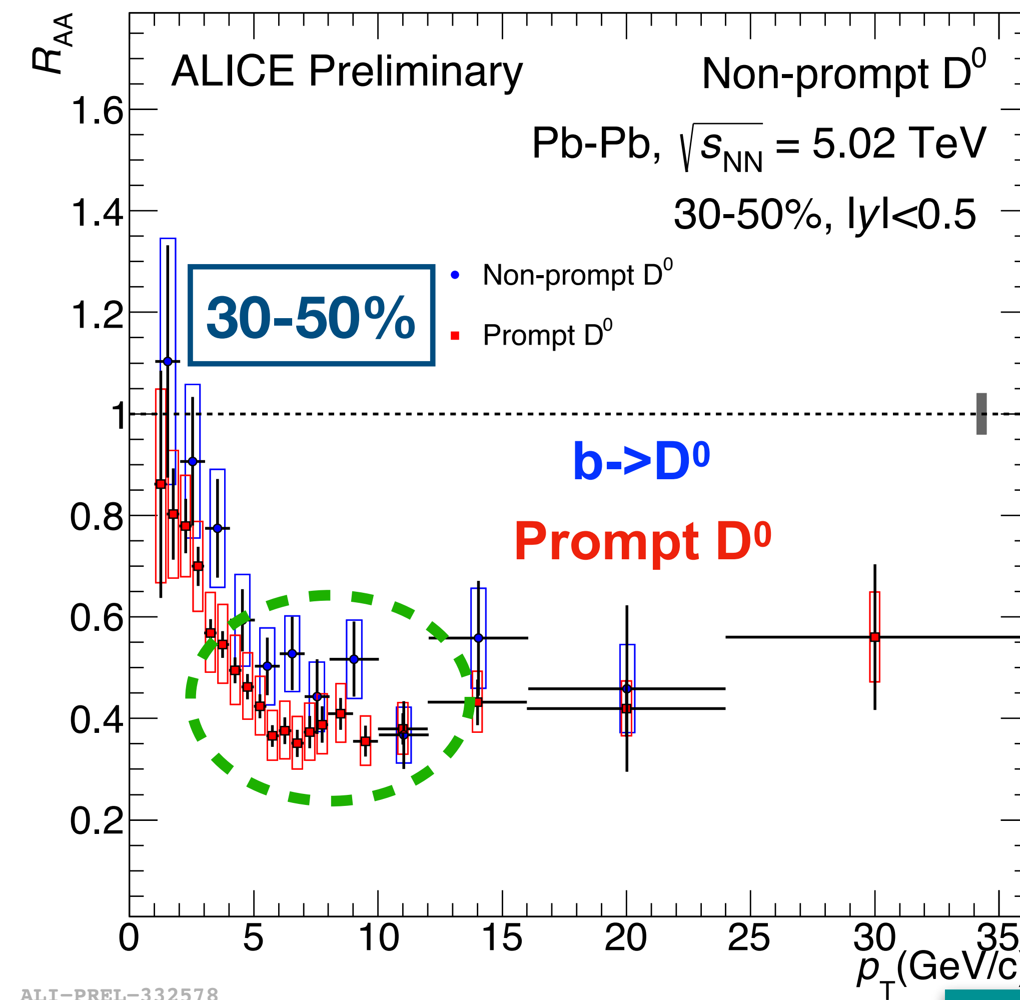
- R_{AA} of b->e in 30-50% Pb-Pb collisions.
- Comparison of b->e with c,b->e
  - **Hint of beauty quarks undergoing less energy loss than charm quarks at low p_T.**
- **R_{AA} (0-10%)** < **R_{AA} (30-50%)** for 4 < p_T < 8 GeV/c.

R_{AA} of b->D^0

New for QM

$$R_{AA} = \frac{dN_{AA}/dp_T}{< T_{AA} > d\sigma_{pp}/dp_T}$$





Poster by Mengke Cai

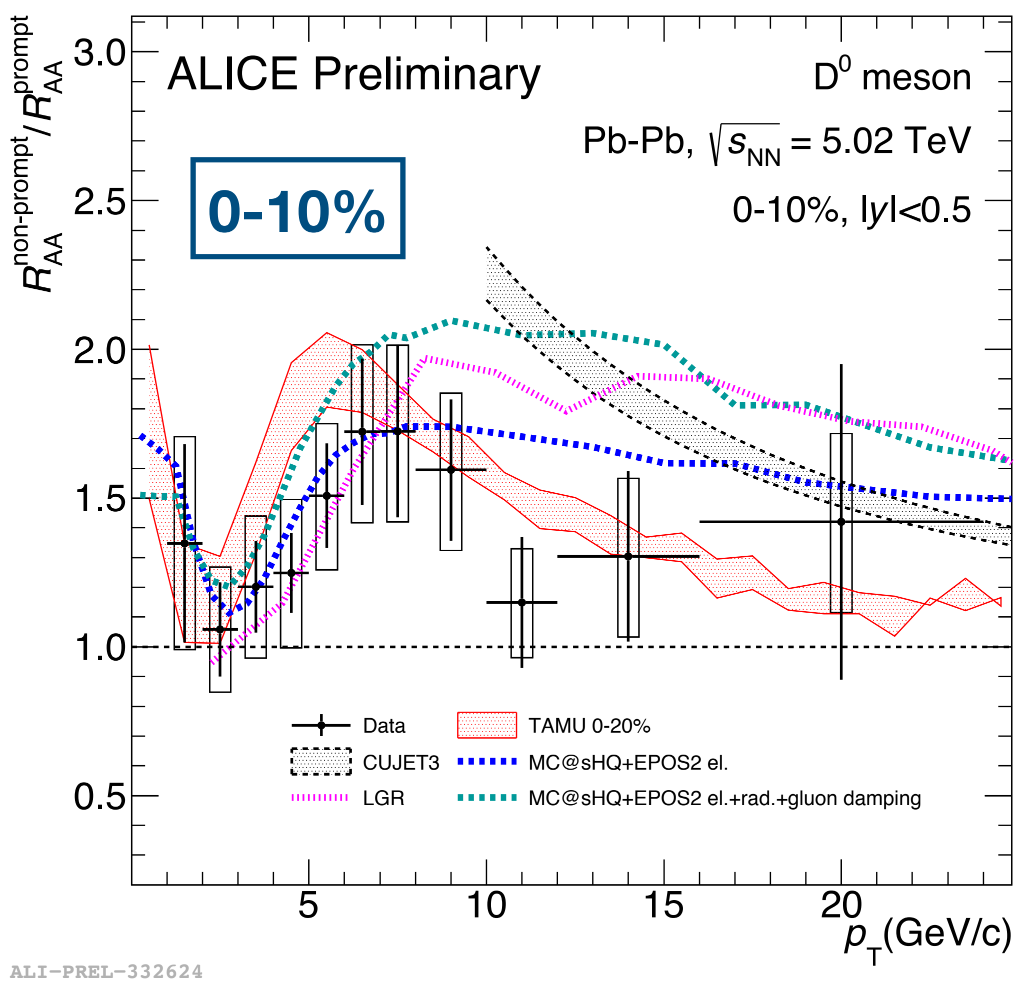
- **Nuclear modification factor measured for b->D^0 in 0-10% and 30-50% Pb-Pb collisions** at $\sqrt{s_{NN}} = 5.02$ TeV —> Suppression of b->D^0 observed.
- Comparison of b->D^0 with prompt D^0
  - **Beauty quarks undergoes less energy loss than charm quarks at intermediate p_T.**
- **R_{AA} (0-10%) < R_{AA} (30-50%) at intermediate p_T.**

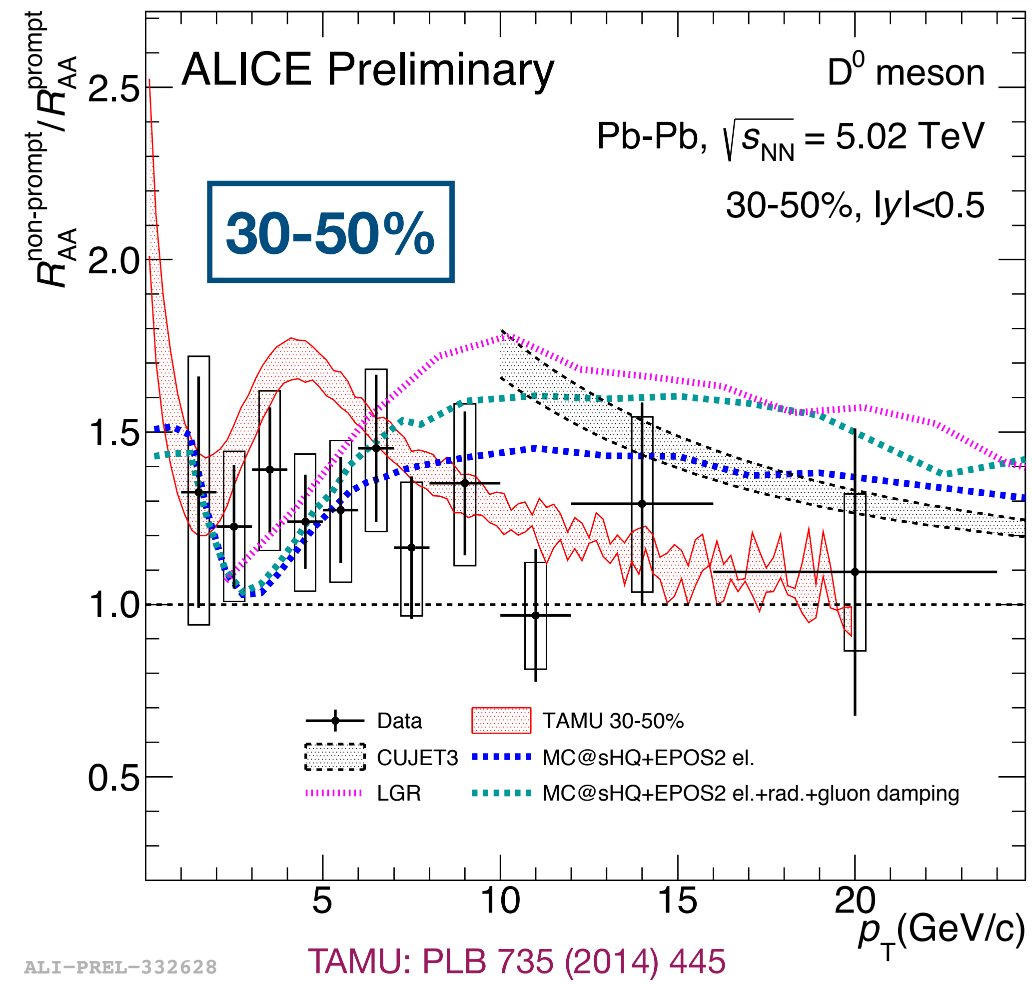
R_{AA} of b->D^0

New for QM

$$\frac{R_{AA}^{b->D^0}}{R_{AA}^{prompt\ D^0}}$$

Poster by Mengke Cai





TAMU: PLB 735 (2014) 445
MC@sHQ+EPOS2: PRC 89 (2014) 014905
LGR: arXiv:1901.04600; 1805.05807
CUJET3: arXiv:1411.3673; 1508.00552; 1804.01915; 1808.05461

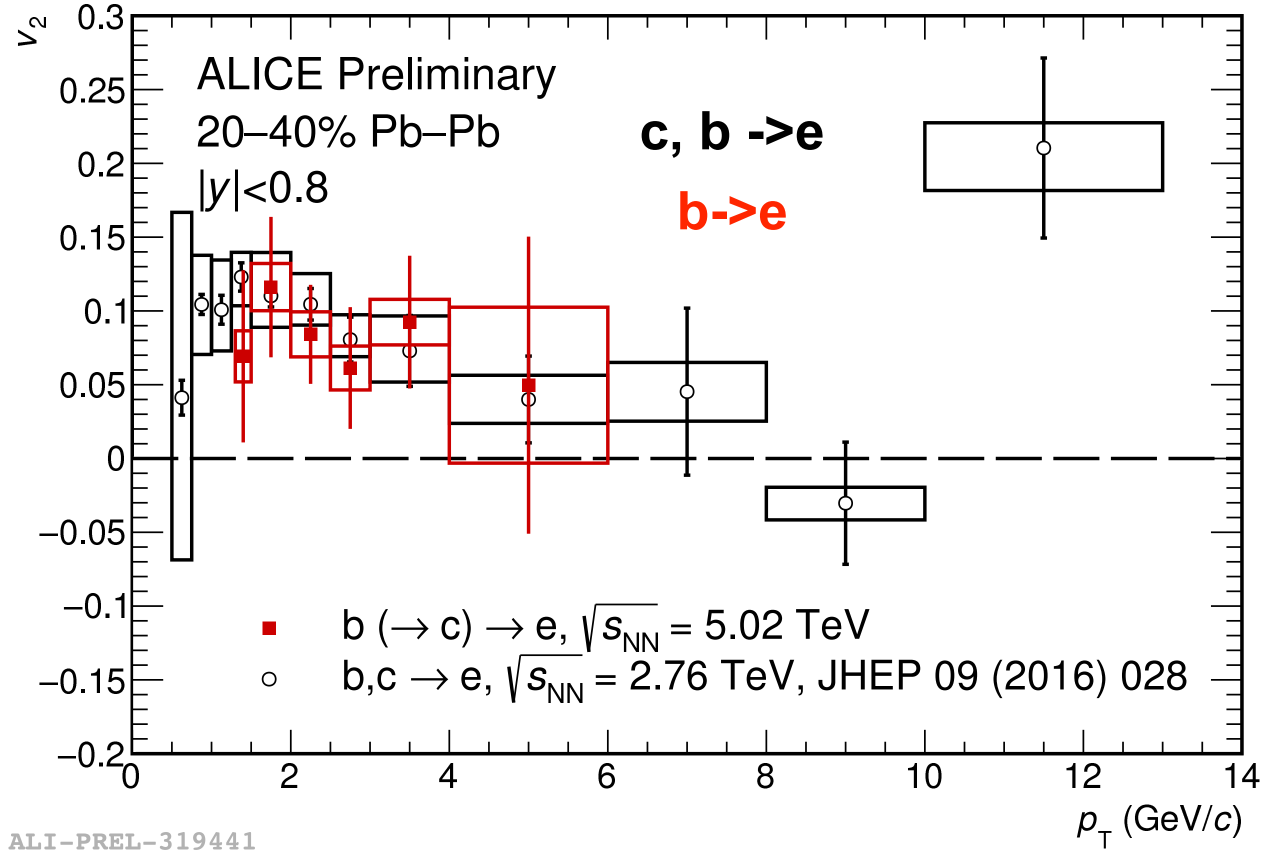
- **Ratio of the R_{AA} of non-prompt to prompt D^0**
  - $p_T < 5$ GeV/c : bumpy structure —> different effects of flow and shadowing on c and b quarks affecting the kinematics?
  - $p_T > 5$ GeV/c : beauty quarks undergo less suppression than charm quarks.

- **Theoretical models that include collisional and radiative energy loss describe the data well within uncertainties.**

Collective flow

$v_2 = < \cos[2(\phi - \Psi_2)] >$

v_2 vs p_T, 20-40% Pb-Pb

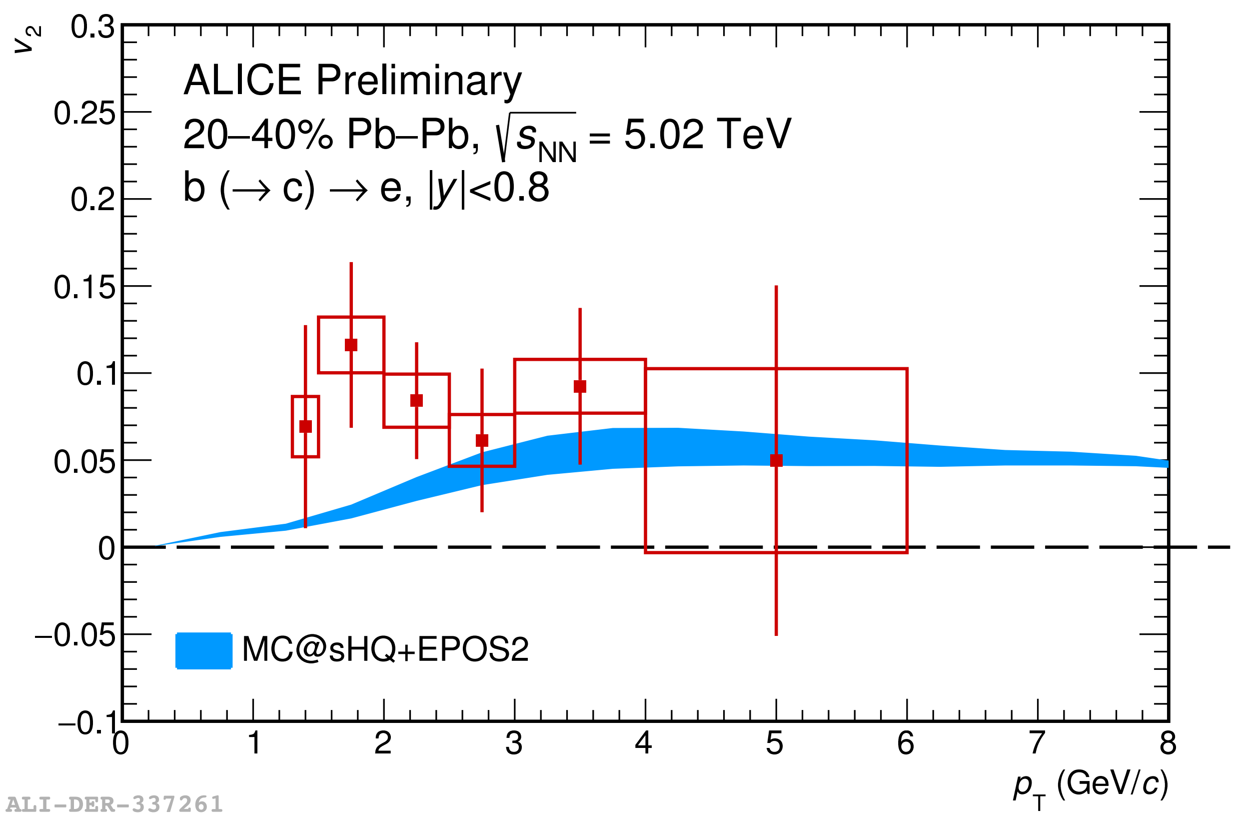


- **Non-zero v_2 for b->e**
  - Significance of 3.49 σ for $1.3 < p_T < 4$ GeV/c.

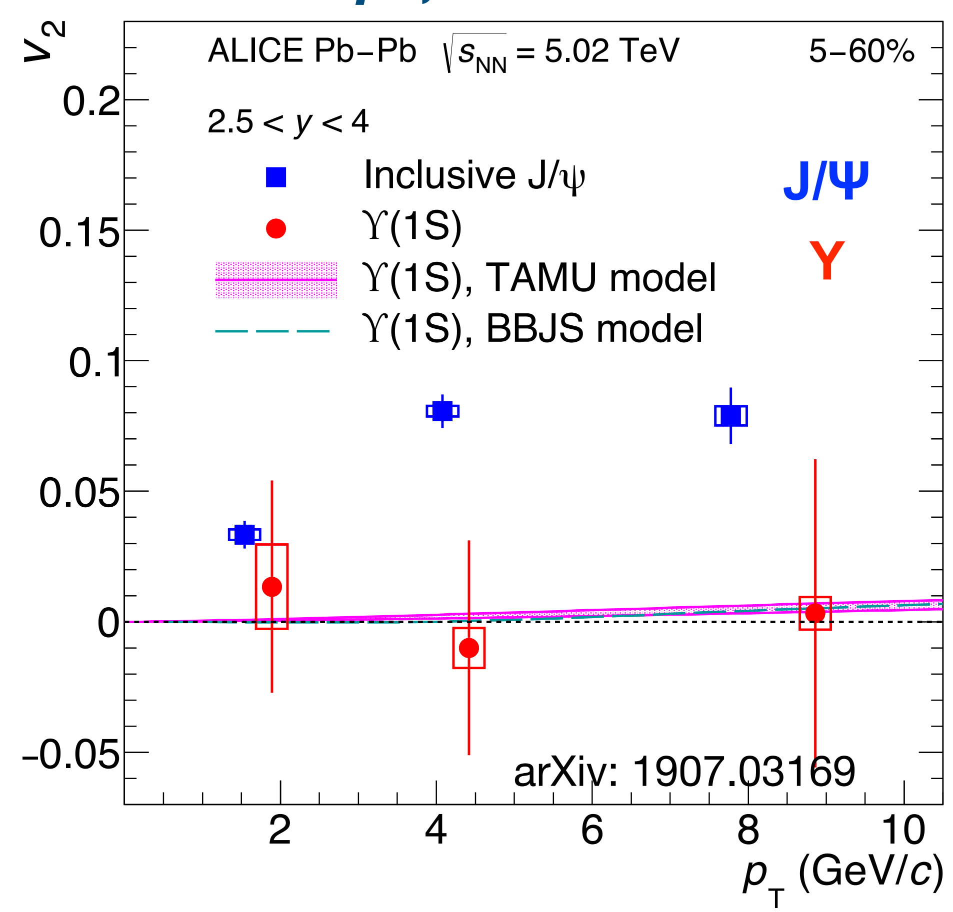
Collective flow

$$v_2 = < \cos[2(\phi - \Psi_2)] >$$

v_2 vs p_T, 20-40% Pb-Pb



v_2 vs p_T, 5-60% Pb-Pb



- **Non-zero v_2 for b->e**
  - Significance of 3.49 σ for 1.3 < p_T < 4 GeV/c.
  - **Model describes the data well at high p_T.**
- **Open-beauty v_2 > 0, while bottomonia v_2 ~ 0**
  - ϒ v_2 ~ 0 vs. p_T and collisional centralities.
  - Impact of path-length dependent energy loss and coalescence on b->e?

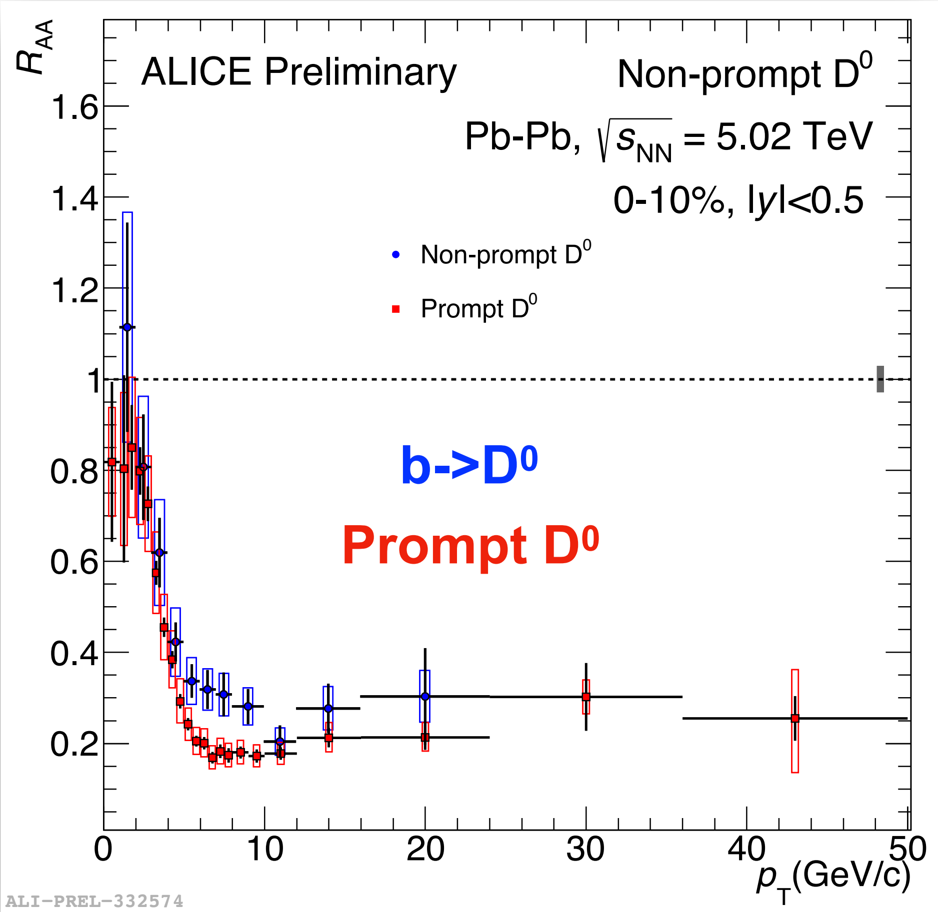
Summary & Conclusions

- **Beauty production studied in pp, p-Pb and Pb-Pb collisions with the ALICE detector.**

- **pp collisions:**
  - Production cross-section of b->e, b->D^0 and b-tagged jets well described by pQCD calculations (FONLL, POWHEG).

- **p-Pb collisions:**
  - Production cross-section of b-tagged jets well by POWHEG simulations.
  - R_{pPb} of b-tagged jets consistent with unity.

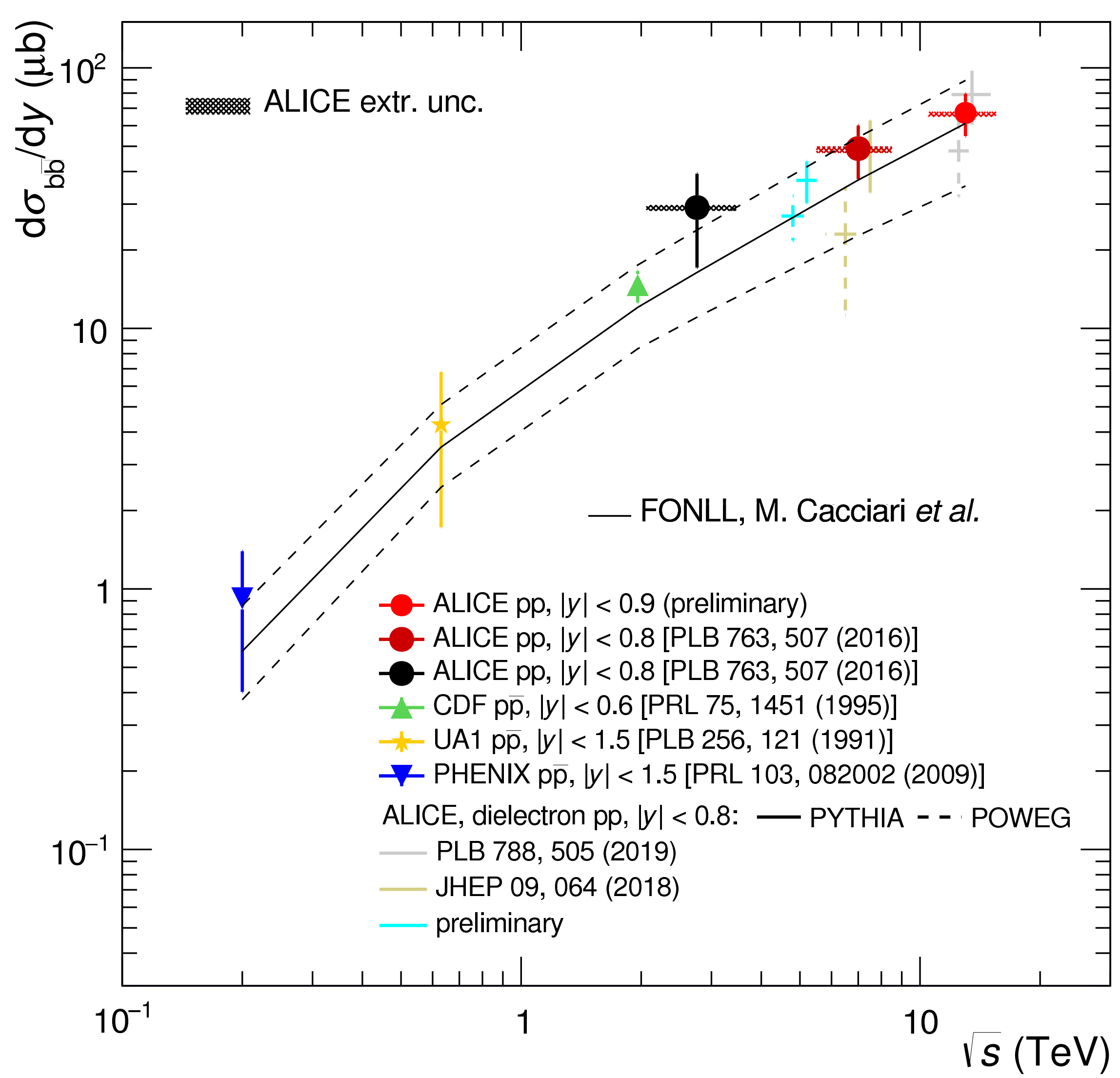
- **Pb-Pb collisions:**
  - Beauty quarks undergoes energy loss —> less suppression than charm quarks at intermediate p_T.
  - Measurements described by models that include collisional and radiative energy loss.
  - Non-zero v_2 of beauty-decay electrons —> beauty $v_2 > 0$?



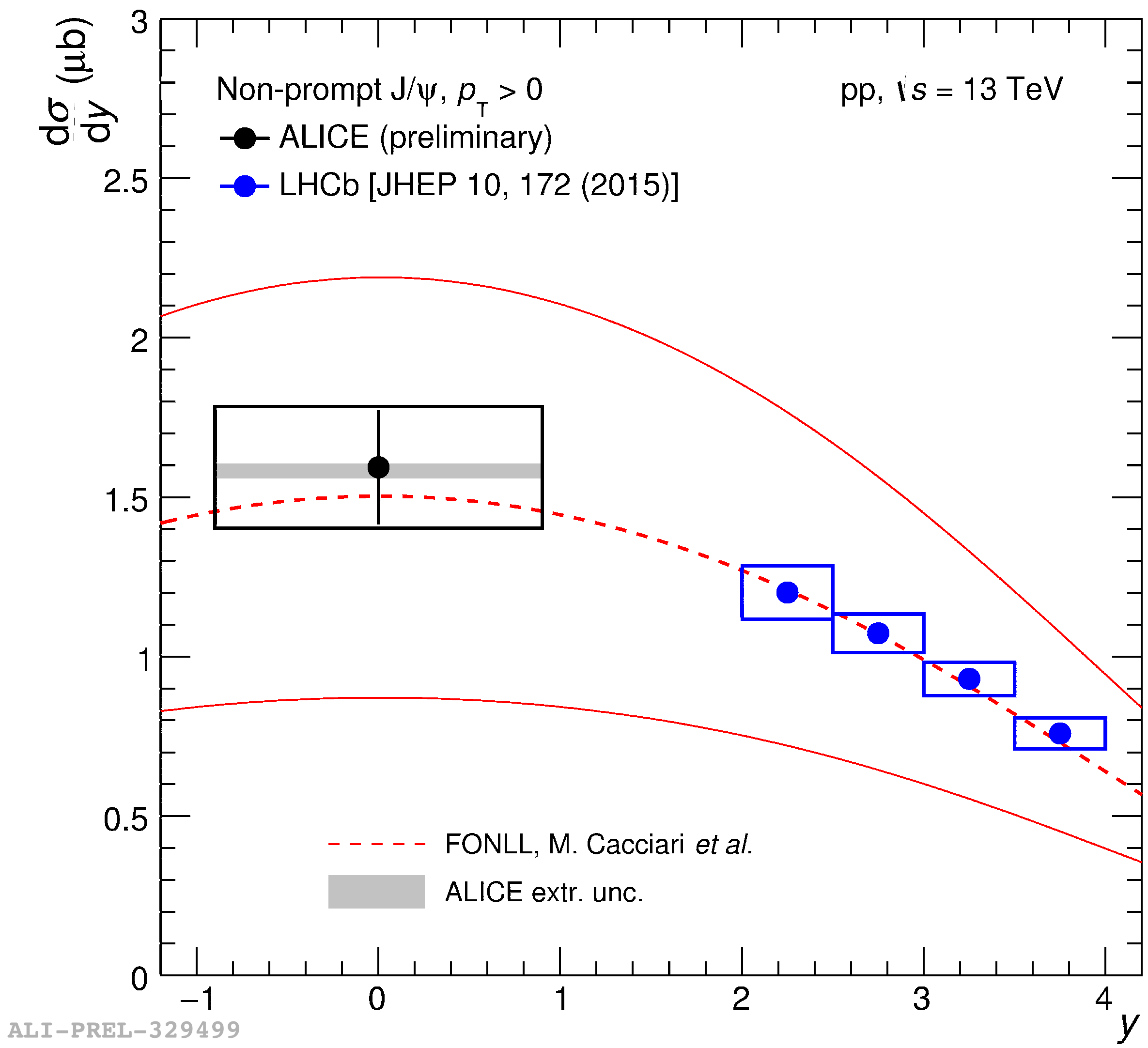
Back-up

b->J/Ψ in pp

Total cross-section of b->J/Ψ

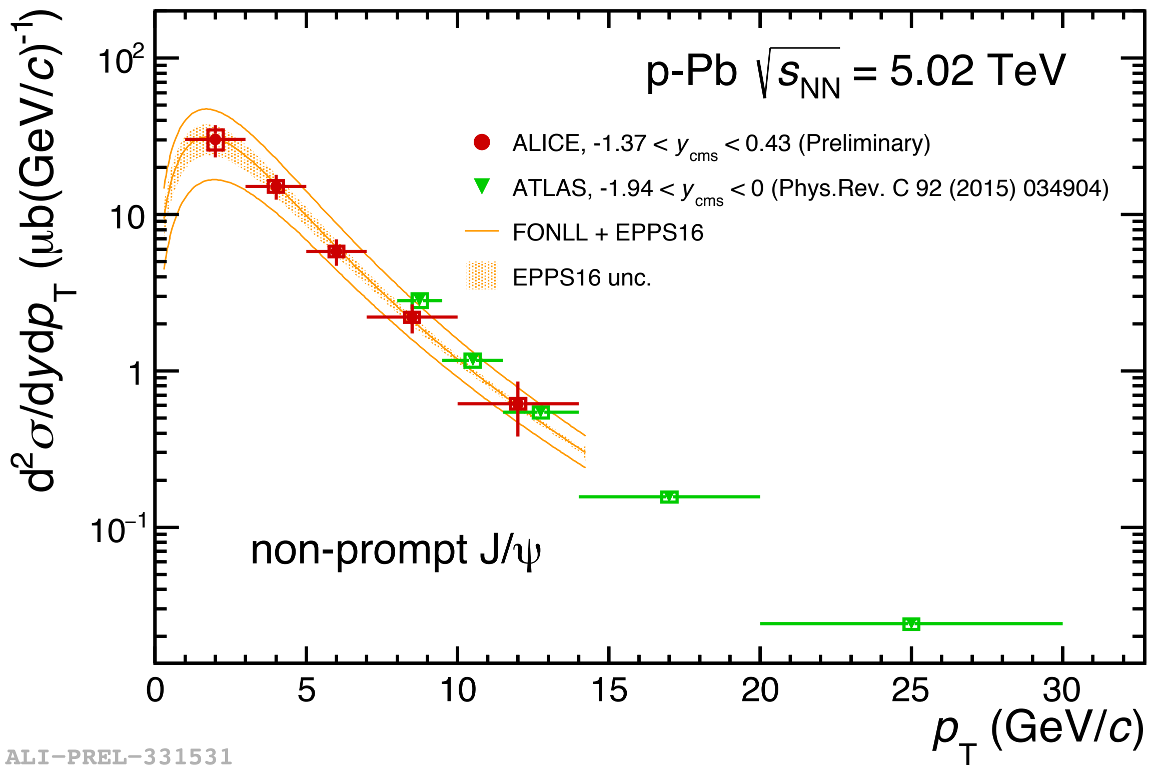


b->J/Ψ vs *y*

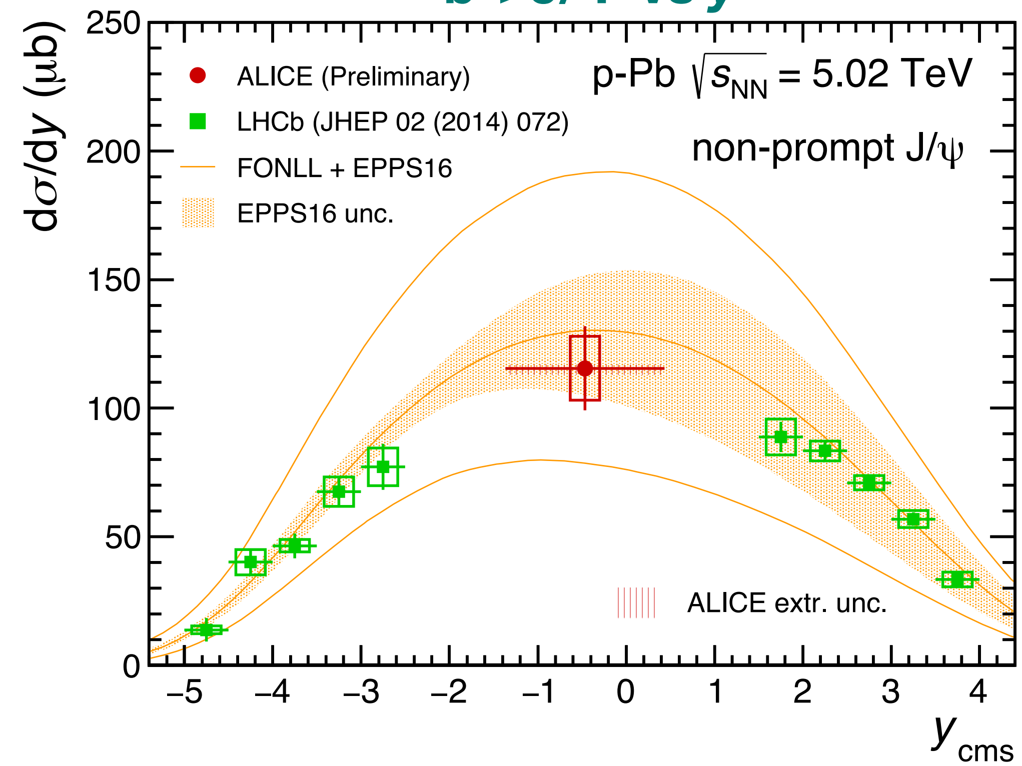


b->J/Ψ in p-Pb

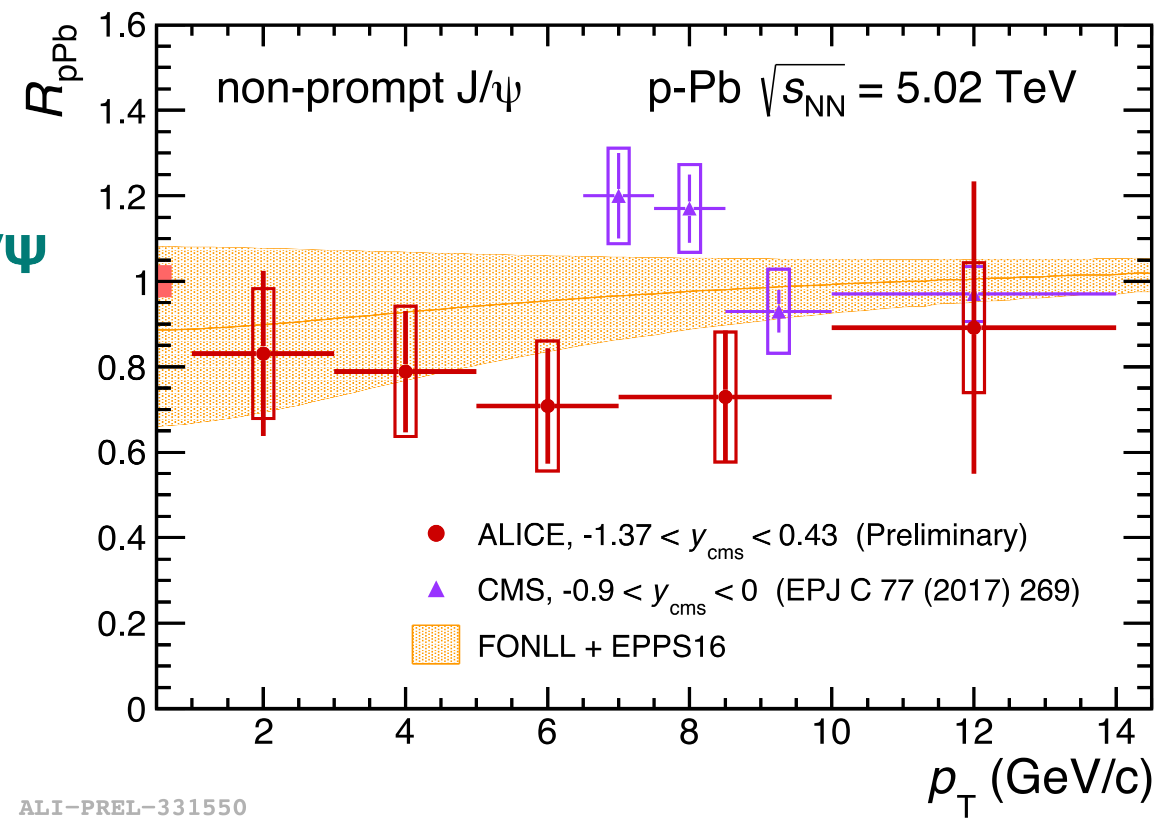
b->J/Ψ vs p_T



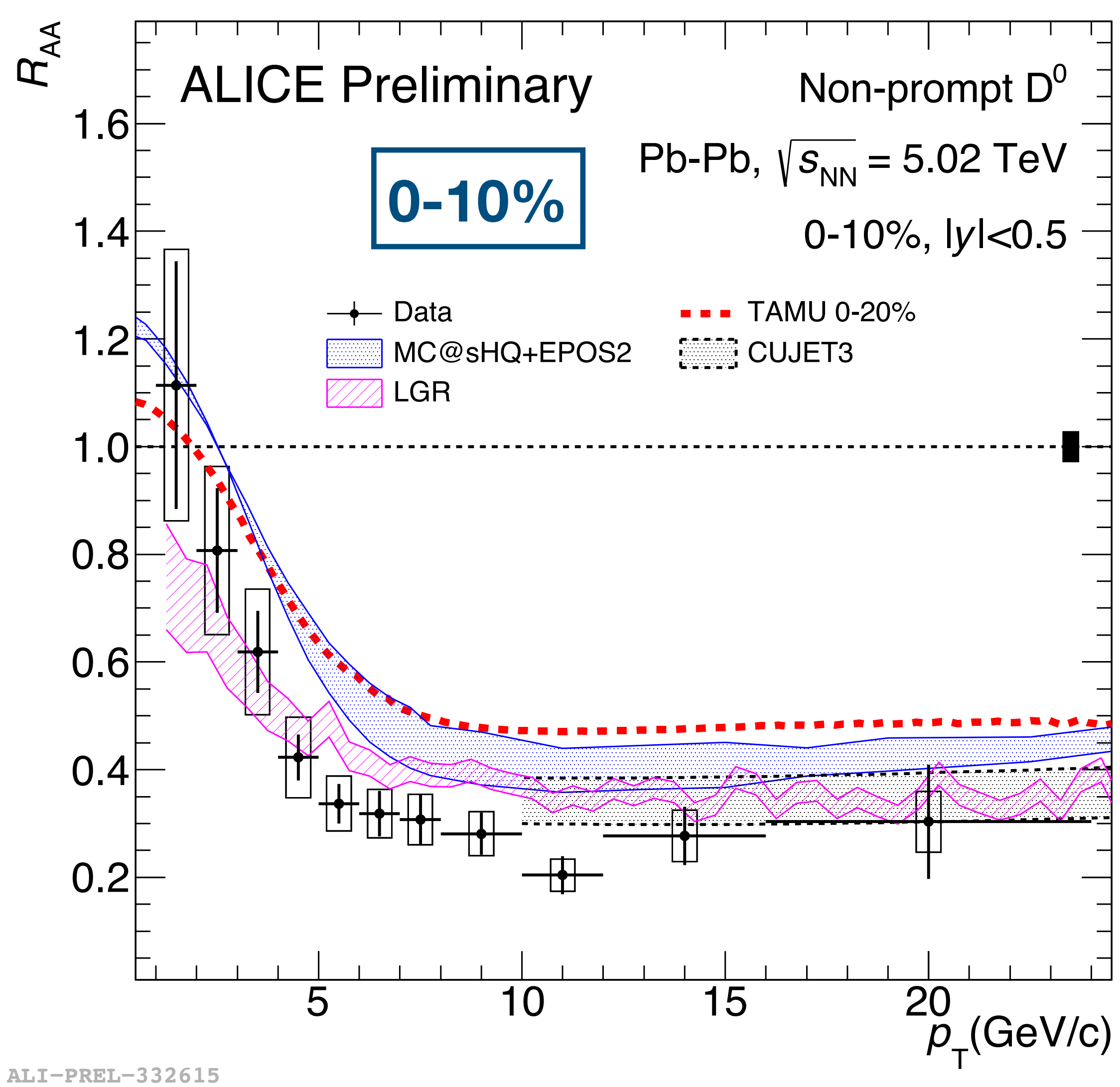
b->J/Ψ vs y

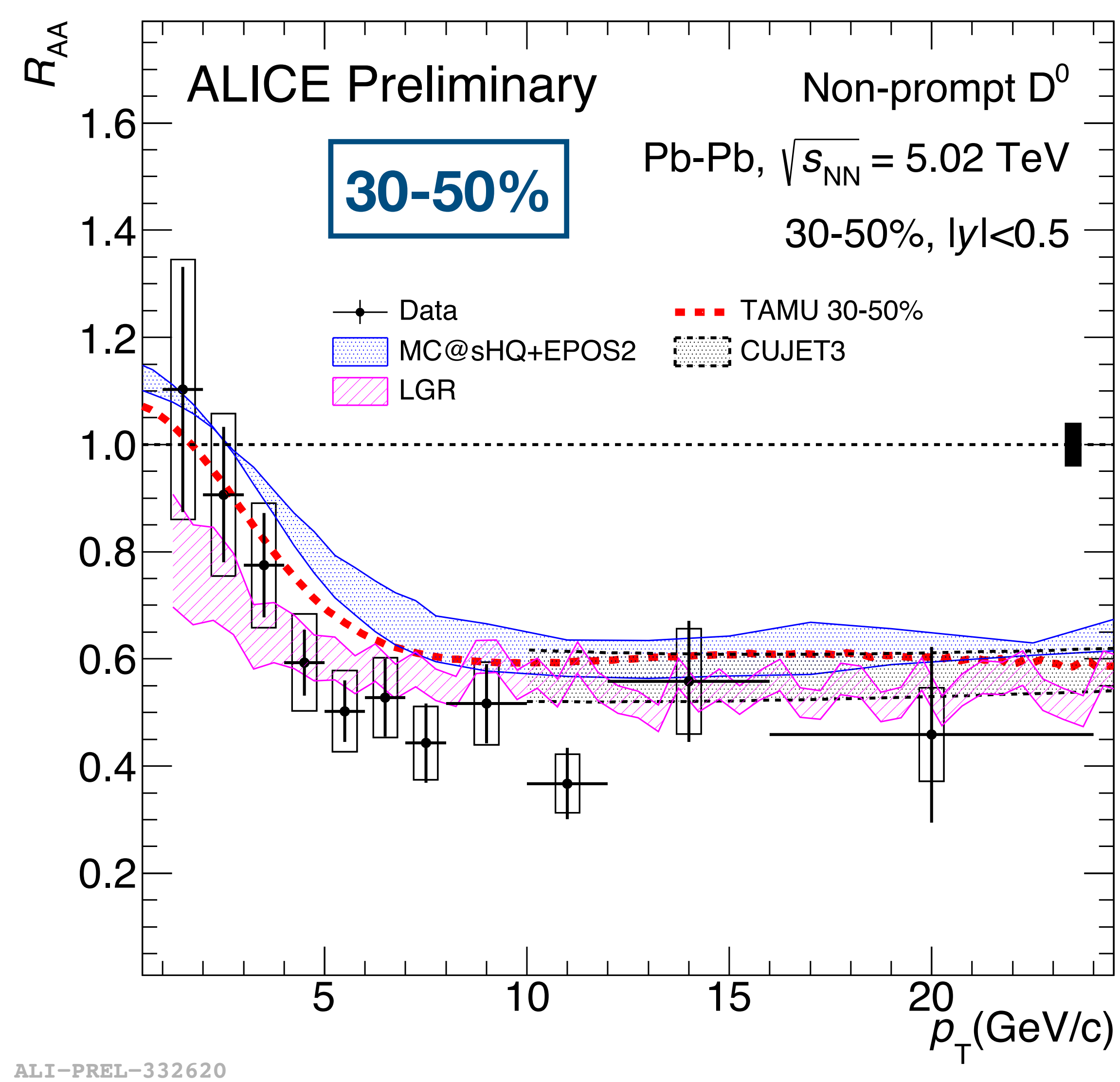


R_{pPb} of b->J/Ψ



R_{AA} of b->D^0

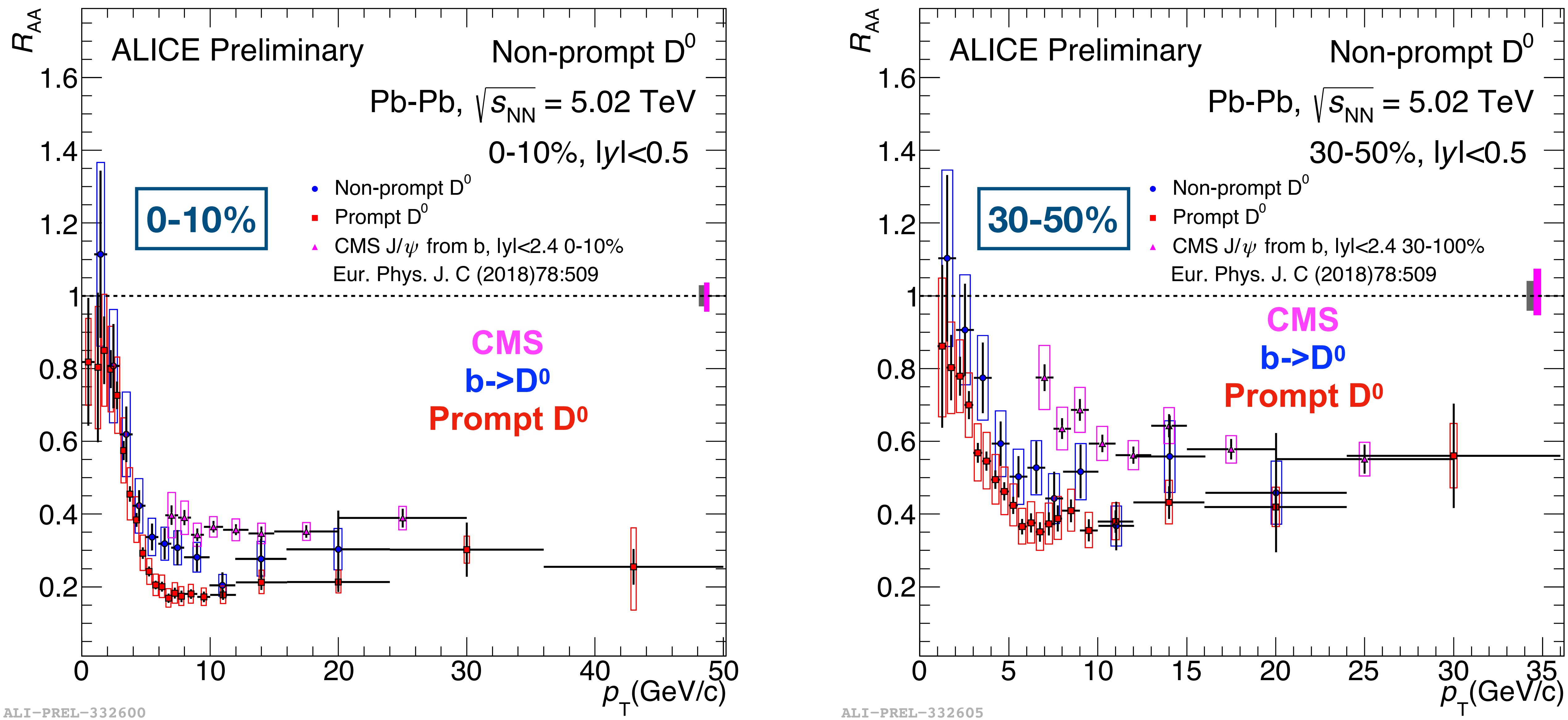




TAMU: PLB 735 (2014) 445
MC@sHQ+EPOS2: PRC 89 (2014) 014905
LGR: arXiv:1901.04600; 1805.05807
CUJET3: arXiv:1411.3673; 1508.00552; 1804.01915; 1808.05461

Models describe the data within their uncertainties.

R_{AA} of b->D^0



R_{AA}
ALICE Preliminary
Non-prompt D^0
Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
0-10%, |y|<0.5
0-10%
Non-prompt D^0
Prompt D^0
CMS J/ψ from b, |y|<2.4 0-10%
Eur. Phys. J. C (2018)78:509
CMS
b->D^0
Prompt D^0
p_T(GeV/c)
ALI-PREL-332600
R_{AA}
ALICE Preliminary
Non-prompt D^0
Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
30-50%, |y|<0.5
30-50%
Non-prompt D^0
Prompt D^0
CMS J/ψ from b, |y|<2.4 30-100%
Eur. Phys. J. C (2018)78:509
CMS
b->D^0
Prompt D^0
p_T(GeV/c)
ALI-PREL-332605