Beauty Production with ALICE at the LHC

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For the ALICE Collaboration

Hard Probes 2020

Online, 1-5 June 2020

MOTIVATION

- **Heavy flavours (charm and beauty)** are produced in hard scattering processes in the initial stages of the collision because of their large masses
  - $\tau_b \sim 0.02 < \tau_c \sim 0.07 \quad < \tau_{QGP} \sim 0.1 - 1$ fm/c
  - Production calculation is possible via pQCD

- Neither created nor destroyed in the medium → **identity is preserved** thus tagged up to hadronization

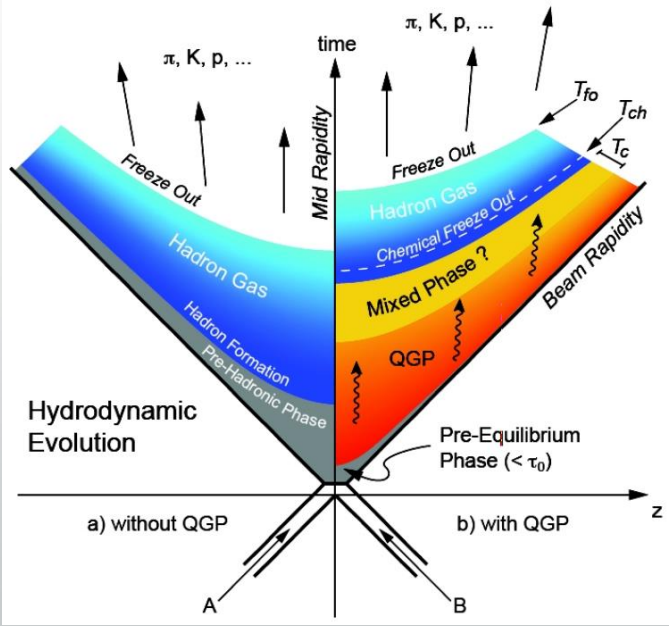
- Undergo elastic (collisional) and inelastic (radiational) collisions → **transport properties of QGP**

- Beauty quarks **lose less energy in QGP** than light quarks and charm quarks
  - Color charge effect: $\Delta E_{gluons} > \Delta E_{quarks}$ due to stronger coupling
  - Mass dependency: $\Delta E_{gluons} > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

- **Collectivity in QGP** → azimuthal anisotropy via flow measurements

- **pp collisions** : test pQCD calculation at LHC energies

- **p-Pb collisions** : constrain initial state and cold nuclear matter effects



BEAUTY MEASUREMENTS WITH ALICE

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

Inner Tracking System
- Primary vertex reconstruction
- Tracking
- PID

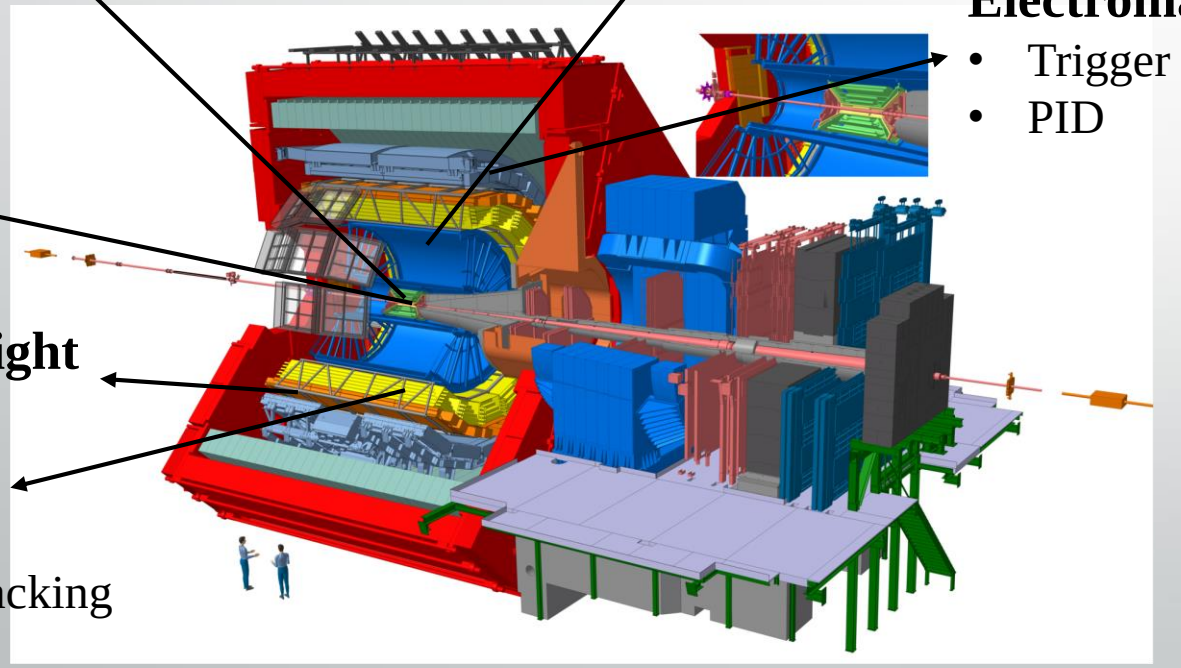
Time Projection Chamber
- Tracking
- PID

Electromagnetic Calorimeter
- Trigger
- PID

V0
- Trigger

Time-of-Flight
- PID

TRD
- Tracking

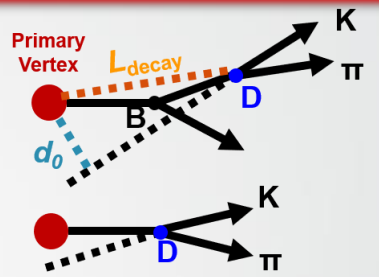


Beauty measurements *in this talk*
- **Non-prompt D (hadronic channel)**
- **Non-prompt J/ψ → $e^+ e^-$**
- **B-decay electrons (b → e)**
- **b-tagged jets**

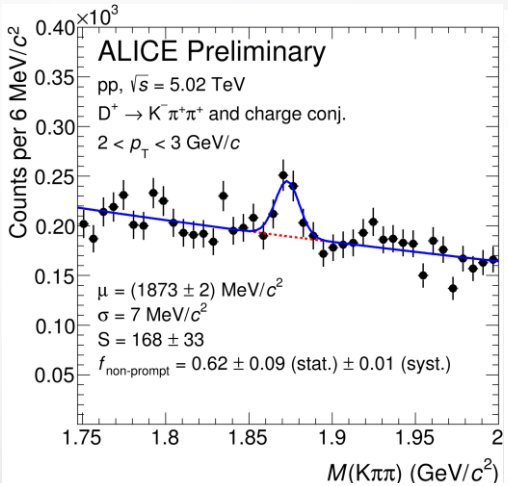
2015 Pb-Pb 5.02 TeV
$\mathscr{L}_{int} \sim 13\ \mu b^{-1}$
2018 Pb-Pb 5.02 TeV
$\mathscr{L}_{int}$ (0-10%) $\sim 130\ \mu b^{-1}$
$\mathscr{L}_{int}$ (30-50%) $\sim 56\ \mu b^{-1}$
pp 13 TeV $\mathscr{L}_{int} \sim 30\ pb^{-1}$
pp 5.02 TeV $\mathscr{L}_{int} \sim 2\ pb^{-1}$
p-Pb 5.02 TeV $\mathscr{L}_{int} \sim 3\ nb^{-1}$

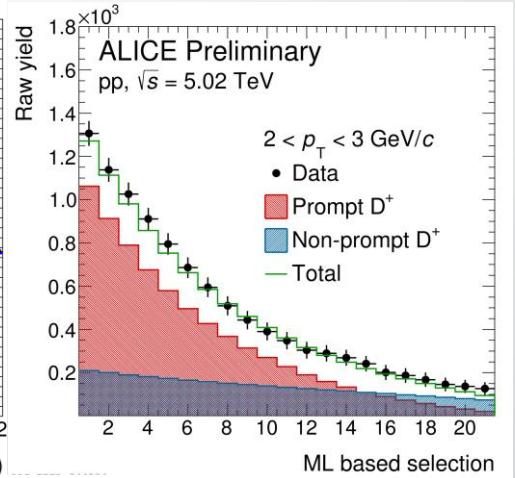
ANALYSIS PROCEDURE

Non-prompt D mesons ($b \rightarrow D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$ **)**



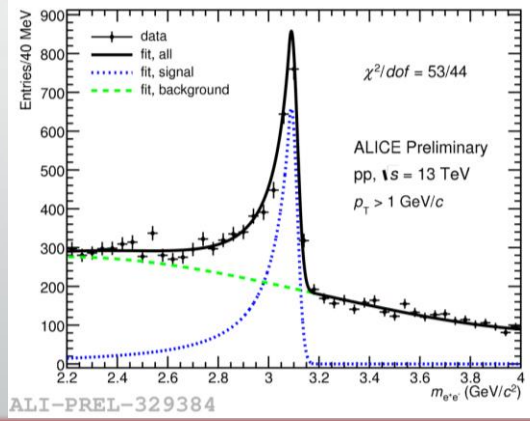
- Reconstruction of D mesons using invariant mass spectrum of tracks displaced from primary vertex
- Use **Machine Learning** method that utilizing topological parameters and PID to
  - Enhance b→D fraction and reduce combinatorial background
- b → D fraction is obtained by min-χ^2 approach on different responses of ML model to **prompt** or **non-prompt**

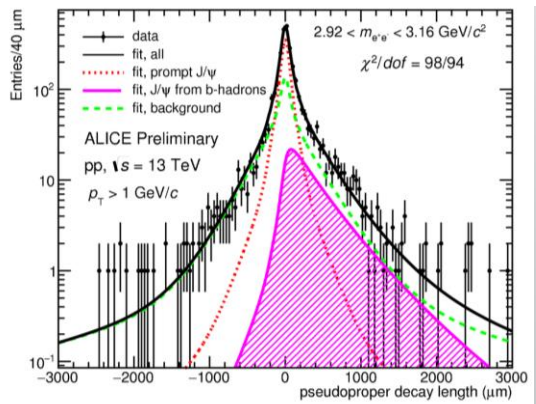




Non-prompt J/ψ ($b \rightarrow J/\psi \rightarrow e^- e^+$ **)**

- Reconstructed J/ψ with di-electrons
- **Non-prompt J/ψ fraction** estimated with 2D-unbinned likelihood method on **invariant mass** and **pseudo proper decay length**

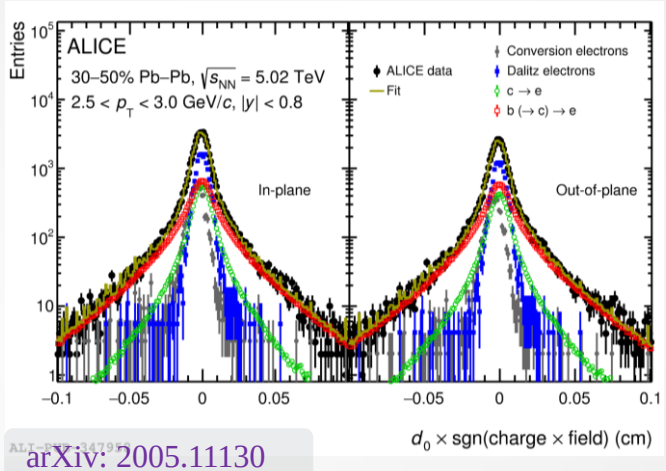




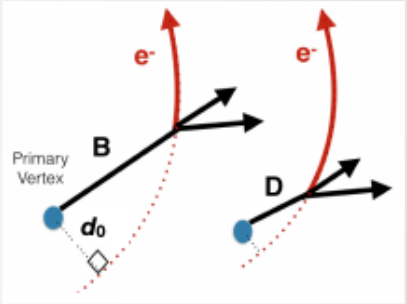
ANALYSIS PROCEDURE

Beauty-decay electrons

- b-hadrons have longer life-time than charm and other electron sources → **Larger impact parameter (d_0)**
- b → D fraction is obtained with template fit on impact parameter distribution



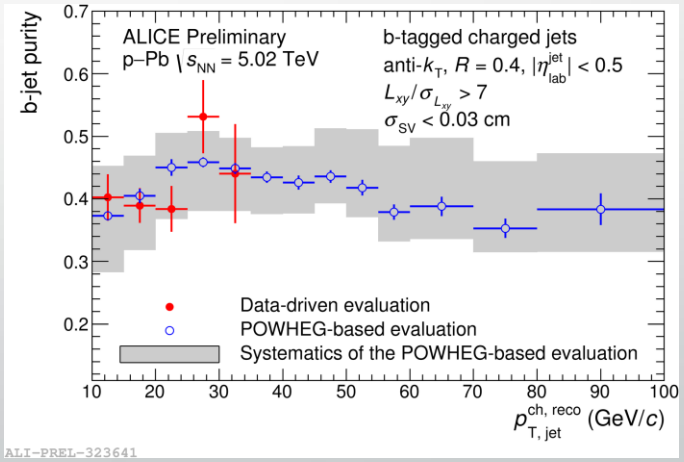
arXiv: 2005.11130

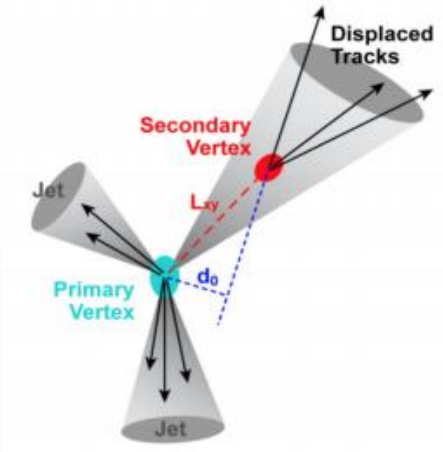


b hadrons τ ~ 500 μm/c
c hadrons τ < 300 μm/c

b-tagged Jet

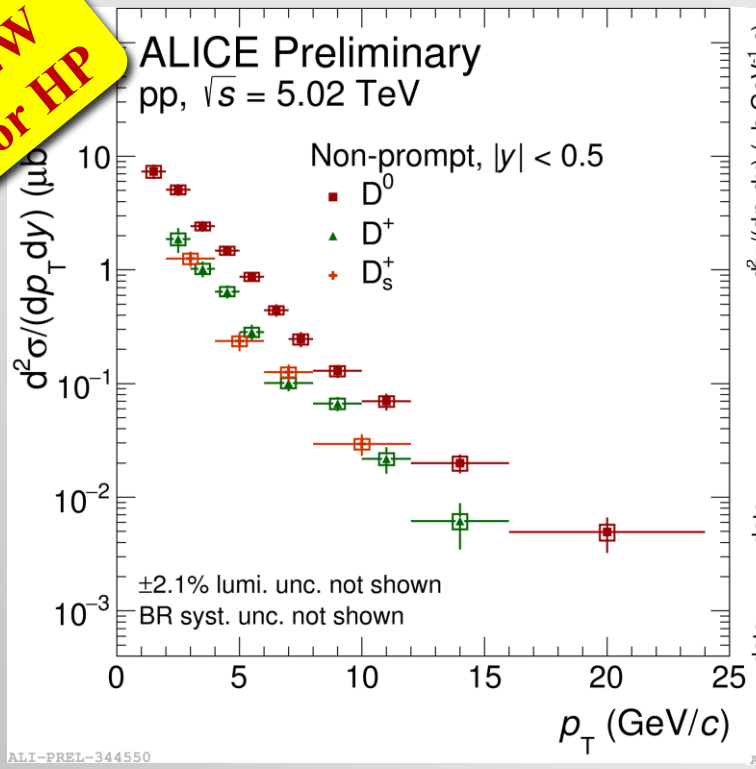
- Jet reconstructed with anti-k_T algorithm (R = 0.4)
- Apply **topological cuts** to increase the b-jet purity
- b-jet purity is obtained with template fit with MC jet probability templates to the data

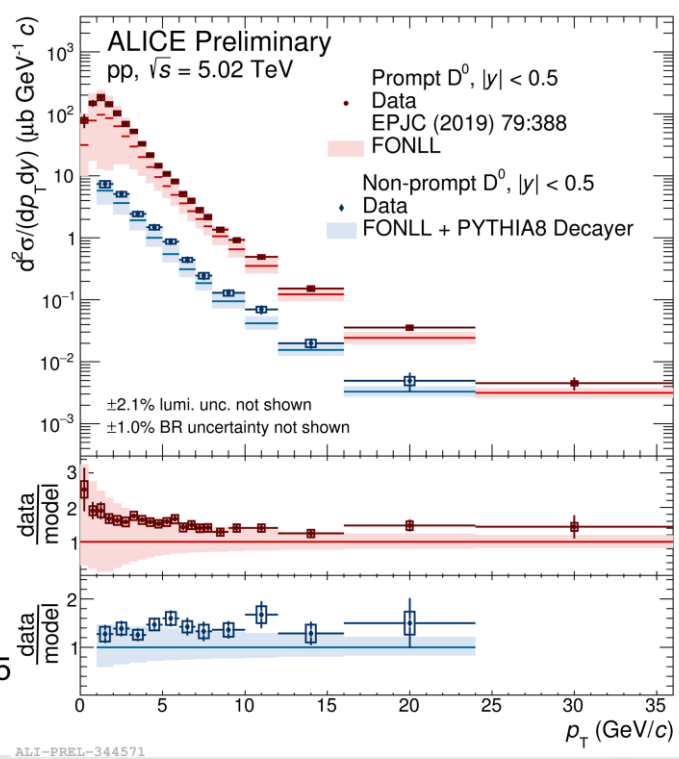


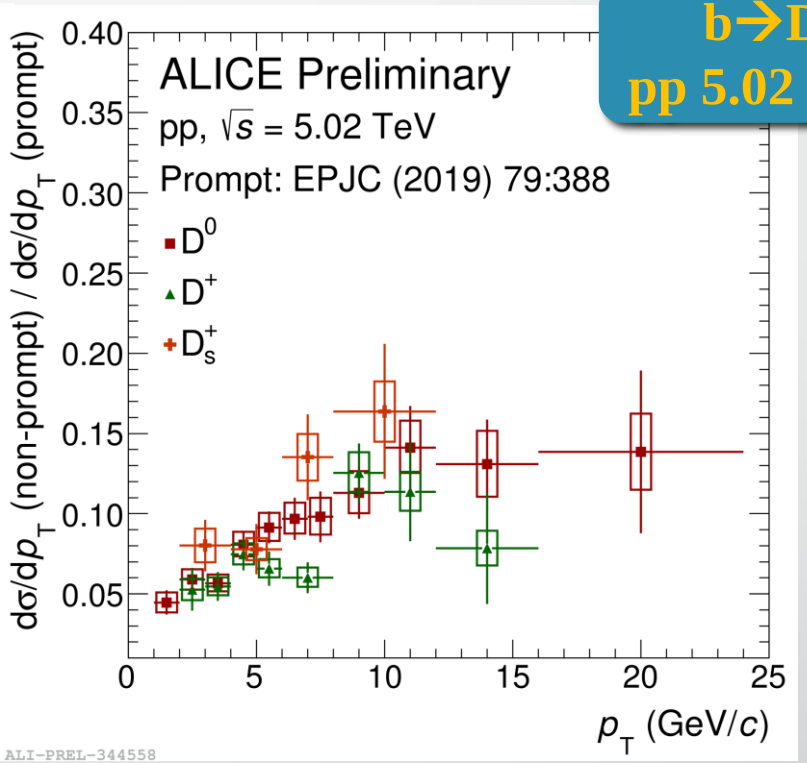


b→D MESONS CROSS SECTION

NEW For HP





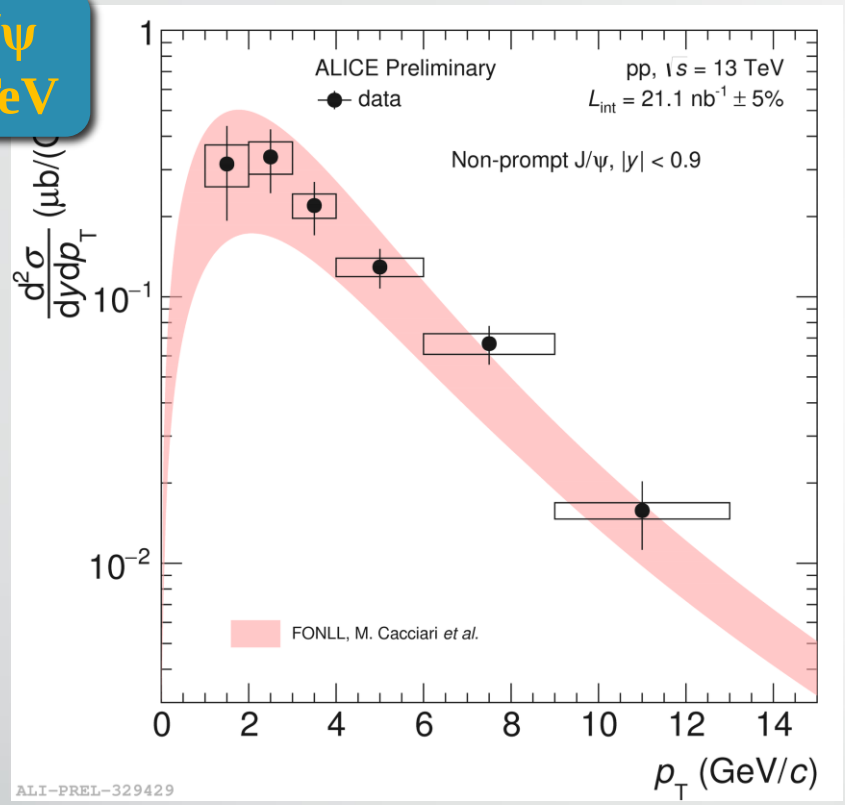


b→D pp 5.02 TeV

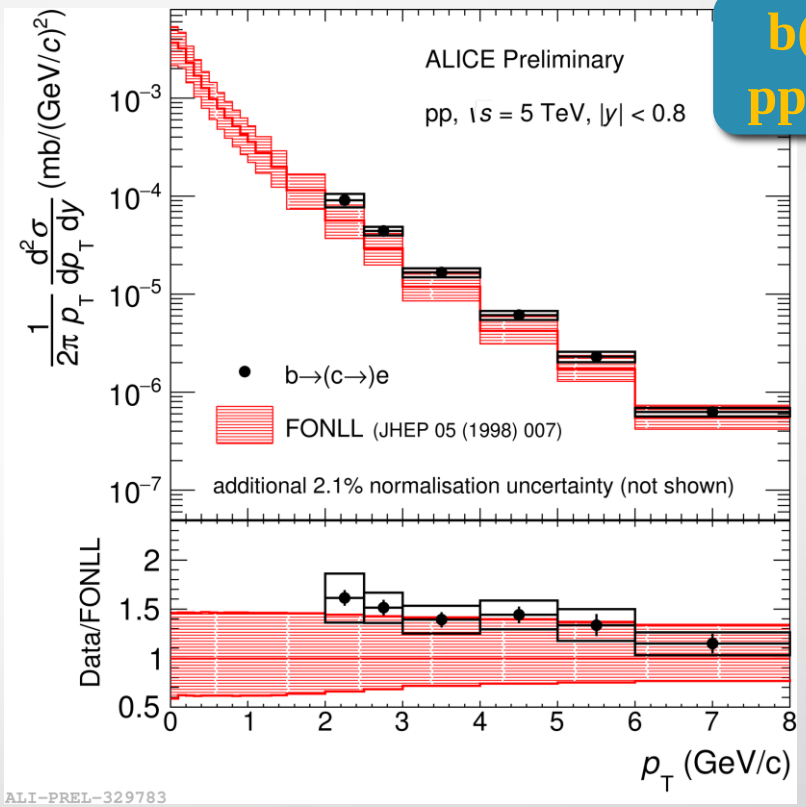
- Non-prompt D mesons cross section in pp at 5.02 TeV
  - $f_{nprompt}$ ~ 80% for D^0, ~ 60% for D^+, ~ 50% for D_s^+
- Measurement **described by FONLL calculations within uncertainties** → better constrain on than FONLL at low p_T
- Non-prompt to prompt ratio → Different p_T shapes / constraint on B→D decay branching ratios

b→J/ψ & b→e CROSS SECTION

b → J/ψ
pp 13 TeV



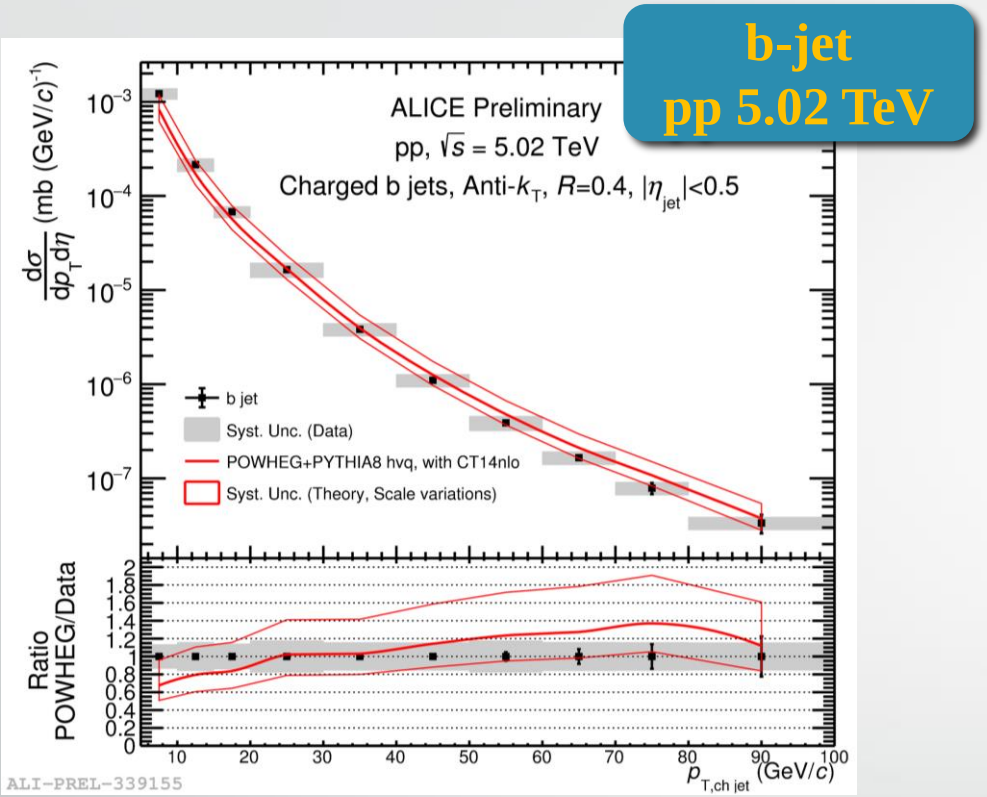
b(→c)→ e
pp 5.02 TeV

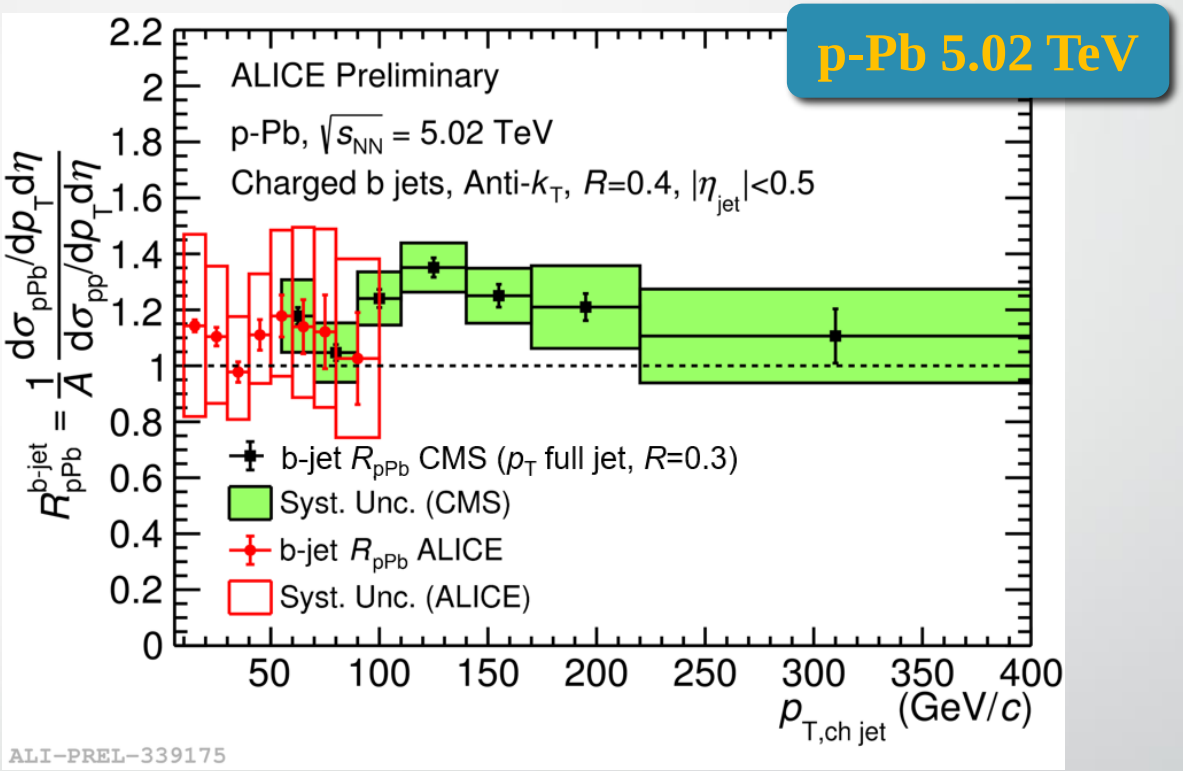


Poster by J. Park

- Non-prompt J/ψ cross section in pp at 13 TeV for $1 < p_T < 13$ GeV/c
- Beauty-decay electron cross section measured in pp at 5.02 TeV
  - Measurement **described by FONLL within uncertainties**

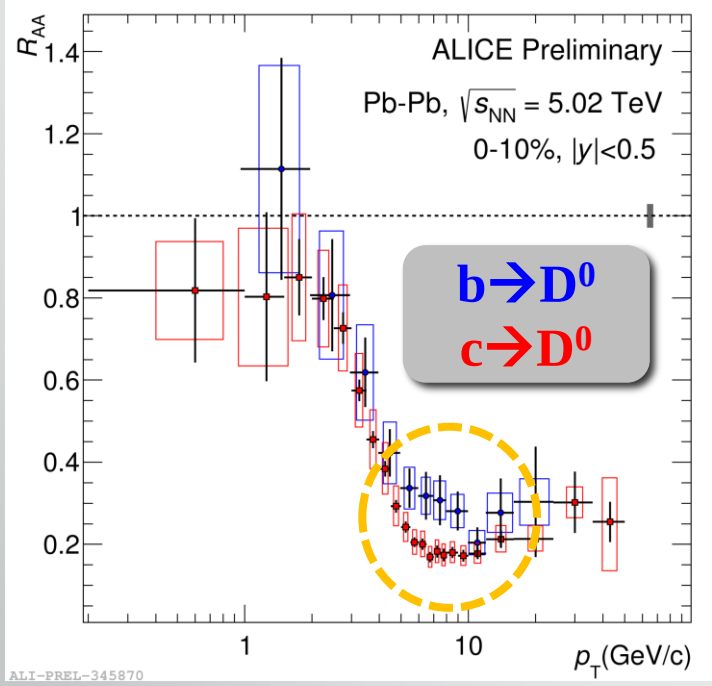
b-TAGGED JET

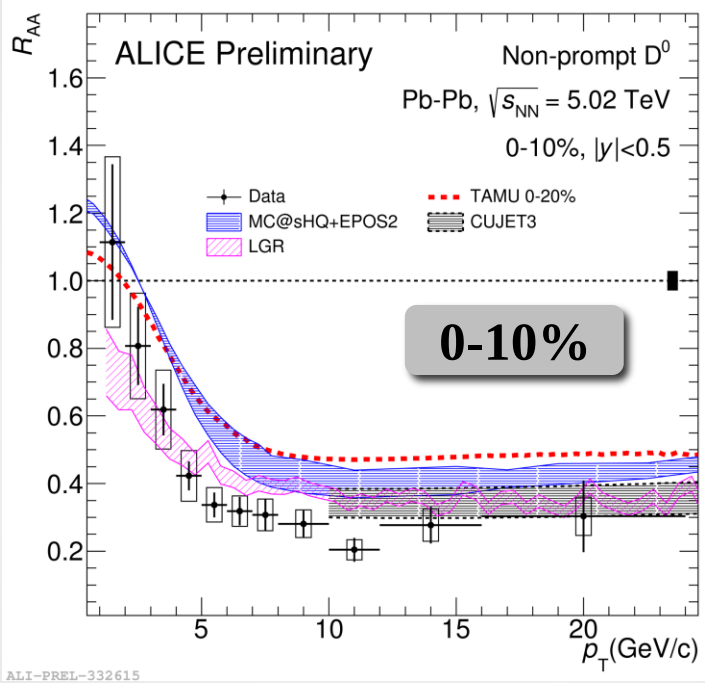


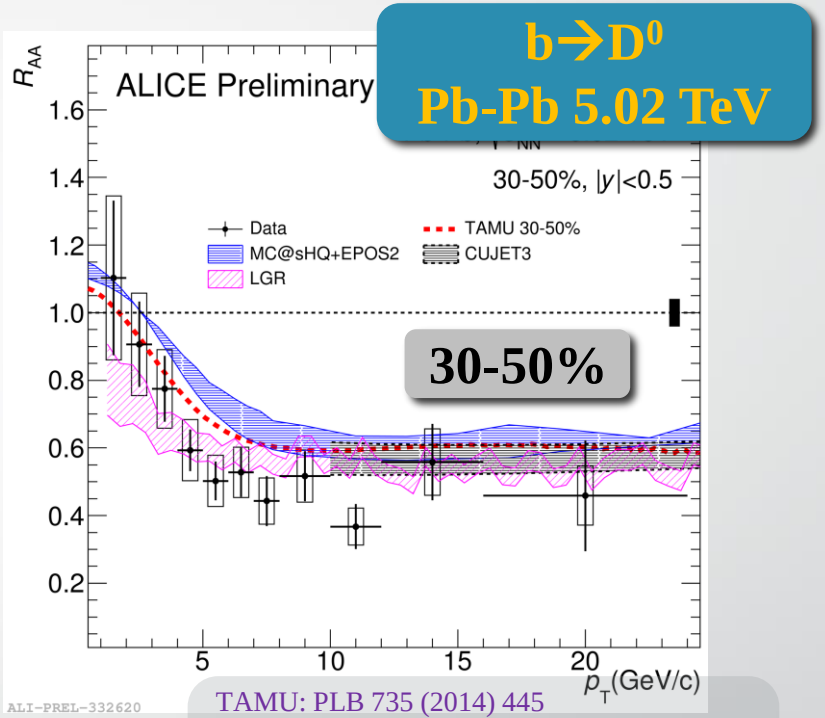


- First ALICE measurement of b-tagged jet cross section in pp at 5.02 TeV to low p_T
  - Described by POWHEG + PYTHIA8 within uncertainties
- Measured b-tagged jet cross section and R_{pPb} in p-Pb at 5.02 TeV for $10 < p_{T,\,ch\,jet} < 100$ GeV/c
  - **The measurement is consistent with unity**

R_{AA} OF b→D^0



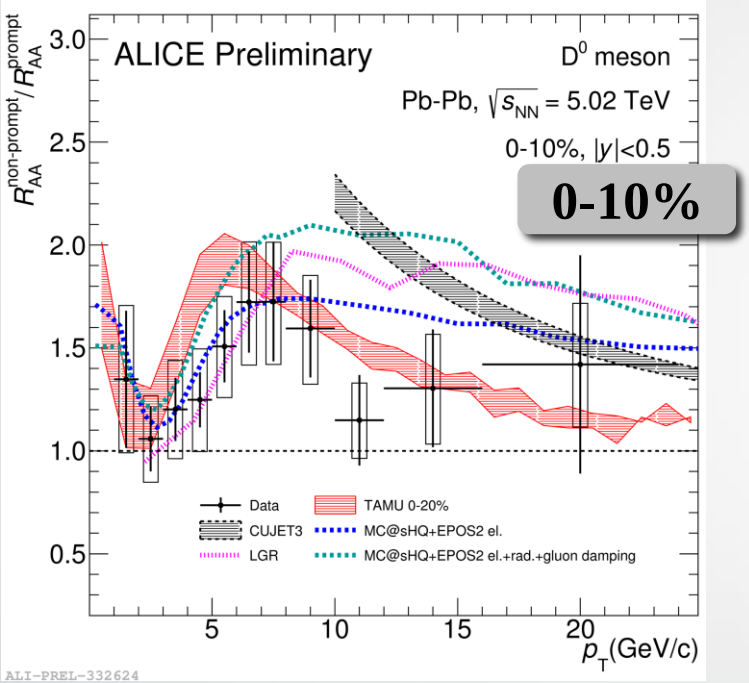


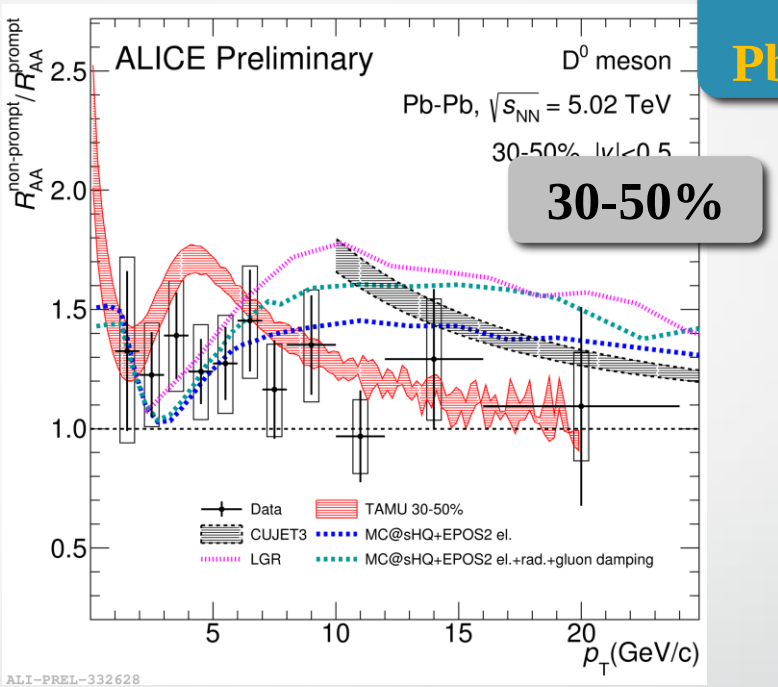


TAMU: PLB 735 (2014) 445
MC@sHQ+EPOS2: PRC 89 (2014) 014905
LGR arXiv:1901.04600; 1805.05807
CUJET3: arXiv:1411.3673; 1508.00552; 1804.01915; 1808.05461

- R_{AA} measured for non-prompt D^0 in 0-10% and 30-50% Pb-Pb collisions at 5.02 TeV
  - ➢ Suppression of beauty production is observed
- Hint of **ordering $R_{AA,c\to D} < R_{AA,b\to D}$ at intermediate p_T**
- **R_{AA} (0-10%) < R_{AA} (30-50%)**
- **Theoretical models that include collisional and radiative energy loss describe the data within uncertainties**

R_{AA} OF b→D^0

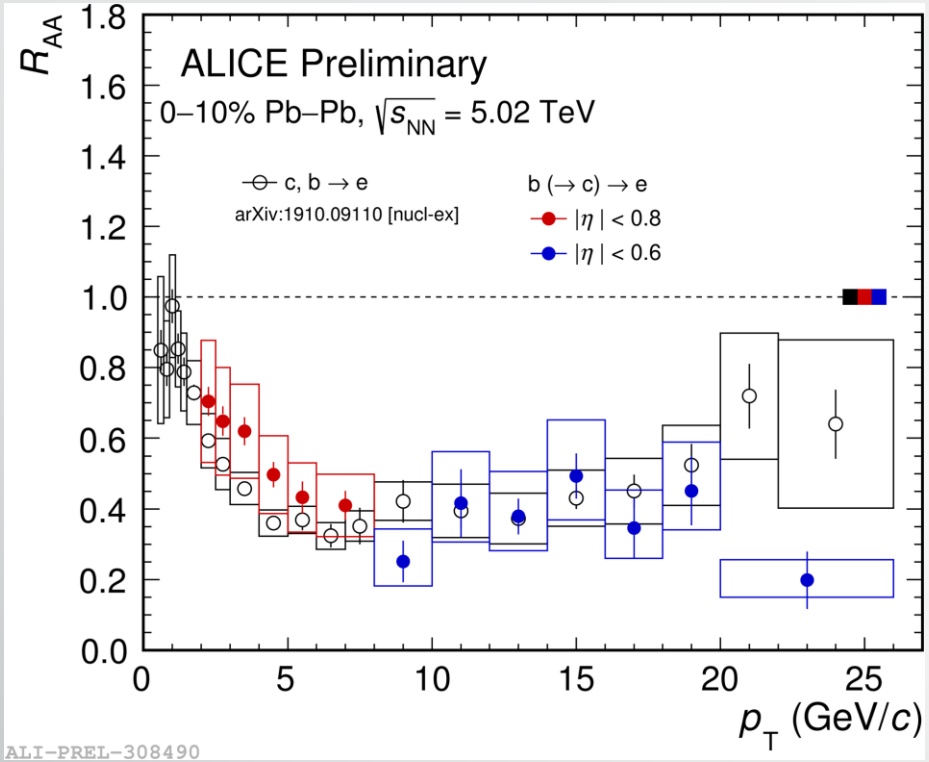


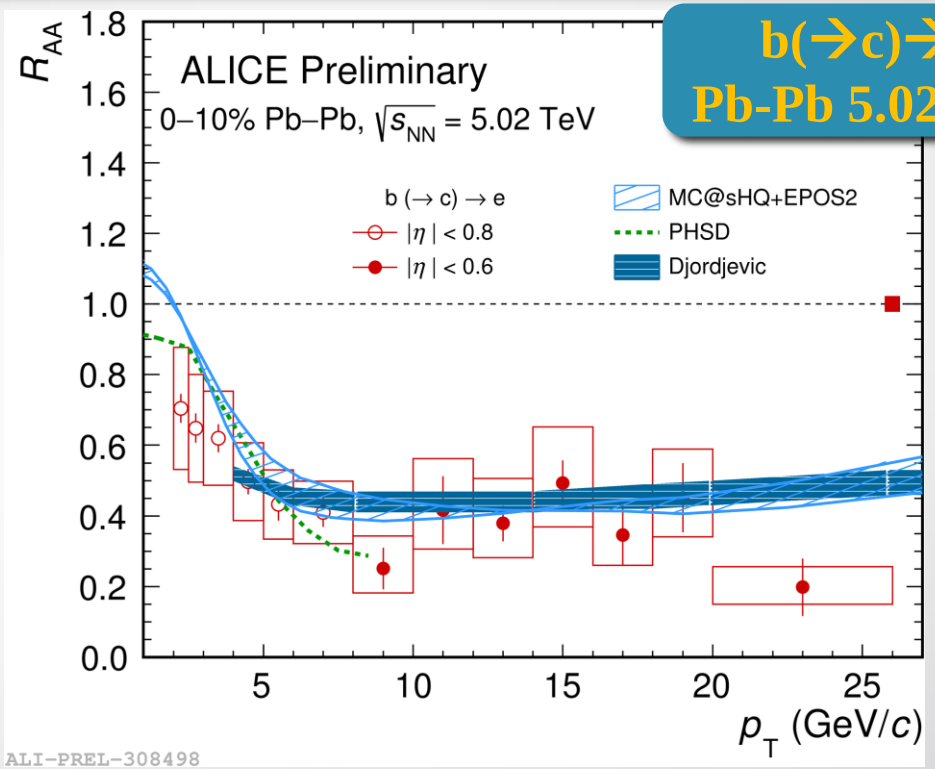


b→D^0
Pb-Pb 5.02 TeV

- **Ratio of the R_{AA} of non-prompt to prompt D^0 (beauty/charm)**
  - p_T < 5 GeV/c : bumpy structure hint difference in **shadowing / flow / decay kinematics** for charm and beauty
  - p_T > 5 GeV/c : beauty quarks undergo less suppression than charm quarks → **mass dependence of energy loss**

R_{AA} OF b→e





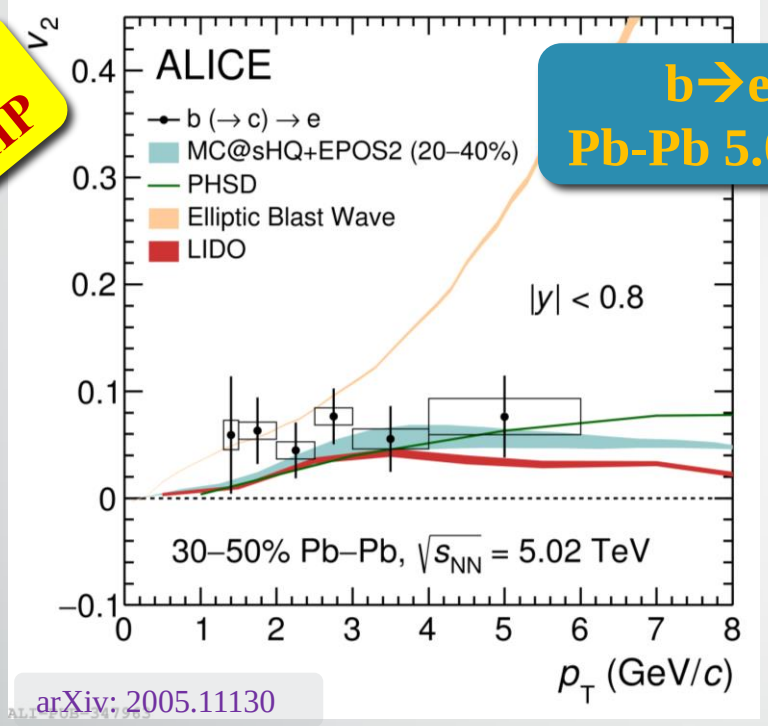
b(→c)→e
Pb-Pb 5.02 TeV

- Nuclear modification factor measured for b→e in 0-10% and 30-50% Pb-Pb collisions at 5.02 TeV
  - Suppression of beauty-decay electrons observed
- Comparison of **b→e** and b, c→e: consistent with mass dependence of ΔE
  - Hint of higher $R_{AA,\, b\to e}$ than $R_{AA,\, c,b\to e}$ at low p_T, while overlapping at high p_T (beauty decays dominate)
- **Measurement described by models which include both collisional and radiative energy loss**

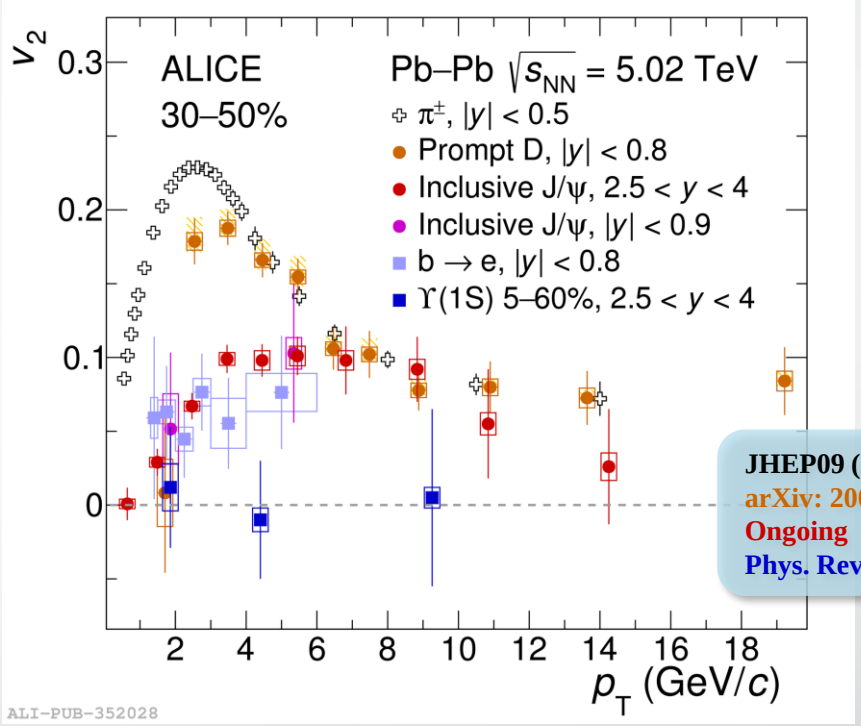
Poster by J. Park

COLLECTIVE FLOW

NEW For HP



b→e v_2
Pb-Pb 5.02 TeV



JHEP09 (2018) 006
arXiv: 2005.11130
Ongoing
Phys. Rev. Lett. 123, 192301

- **Non-zero elliptic flow** for **beauty-decay electrons**
  - High significance (3.75σ) for $1.3 < p_T < 6$ GeV/c
  - Model prediction describes data within uncertainty
- **Bottomonium $v_2 \sim 0$, while open-beauty $v_2 > 0$**

SUMMARY

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

- **pp collisions:**
  - Production cross section of b→D mesons, b→e and b-tagged jets described by pQCD calculations (FONLL, POWHEG)

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

- **Pb-Pb collisions:**
  - **Beauty quarks undergo energy loss from the medium --- important constraint of mass dependence of ΔE**
  - Measurement described by models that include collisional and radiative energy loss
  - **Non-zero (3.75σ) v_2 of beauty-decay electrons**

THANK YOU

BACK-UP

pp collisions

- Non-prompt D mesons cross-section at 5 TeV
- Non-prompt J/psi cross-section at 13 TeV
- Beauty-decay electron cross-section at 5 TeV
- b-tagged jet cross-section at 5 TeV

p-Pb collisions

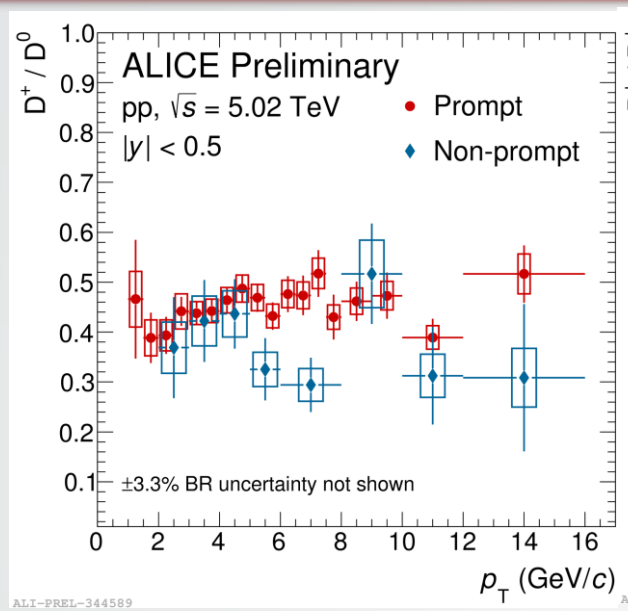
- b-tagged jet cross-section and RpPb at 5 TeV

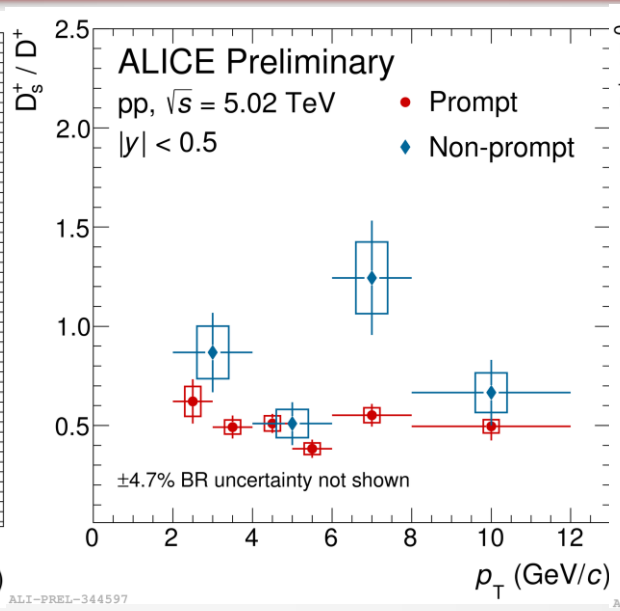
Pb-Pb collisions

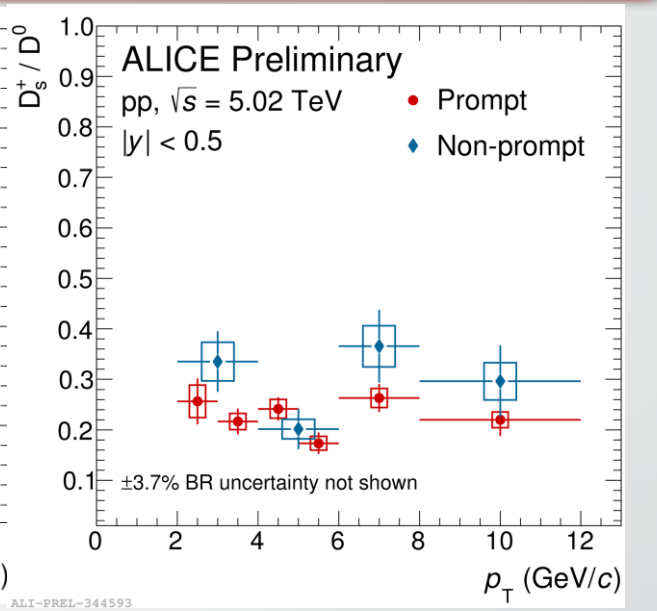
- RAA of non-prompt D0 at 5 TeV (2018 data)
- RAA of beauty-decay electron at 5 TeV (2015 data)
- v2 of beauty-decay electron at 5 TeV

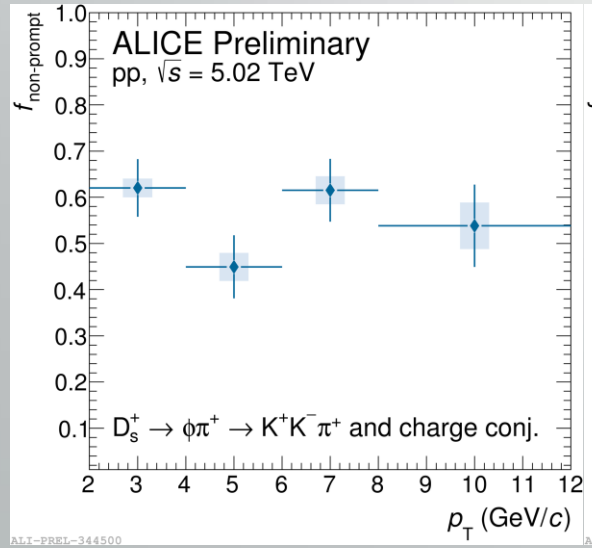
BACK-UP

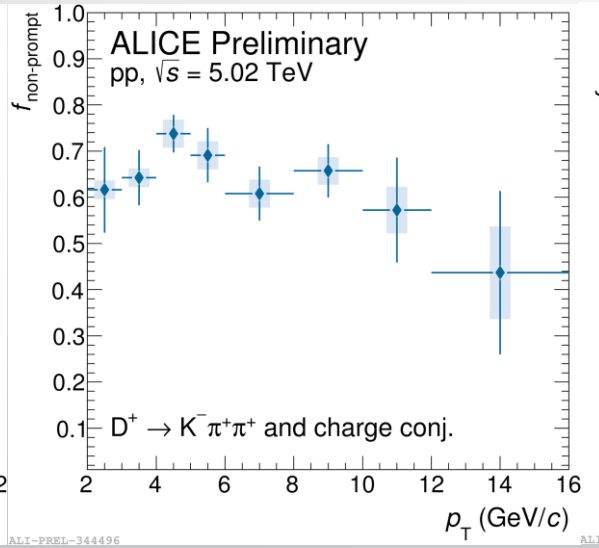
Non-prompt D mesons

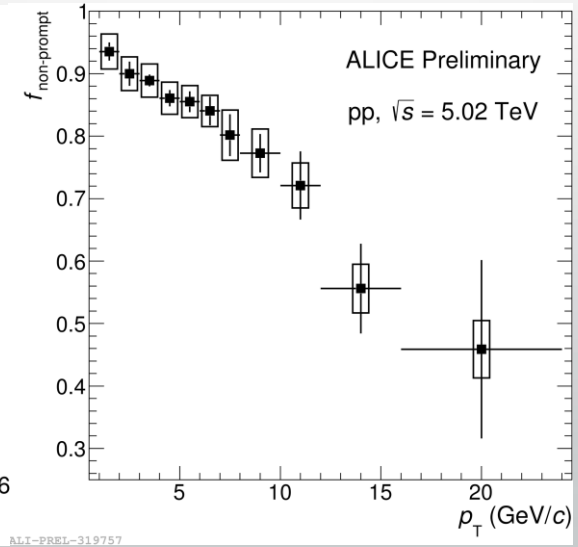






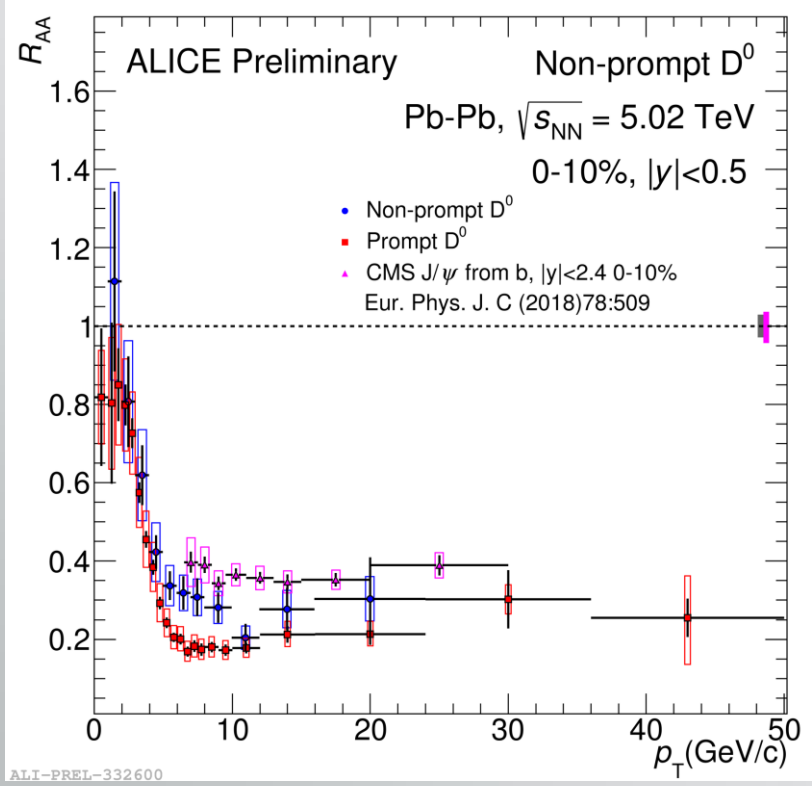


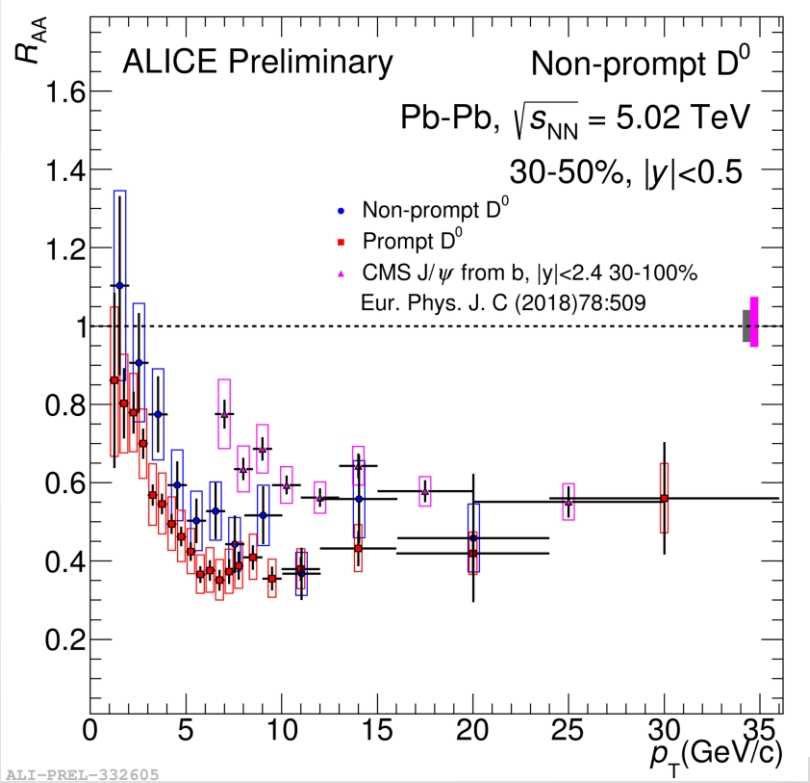


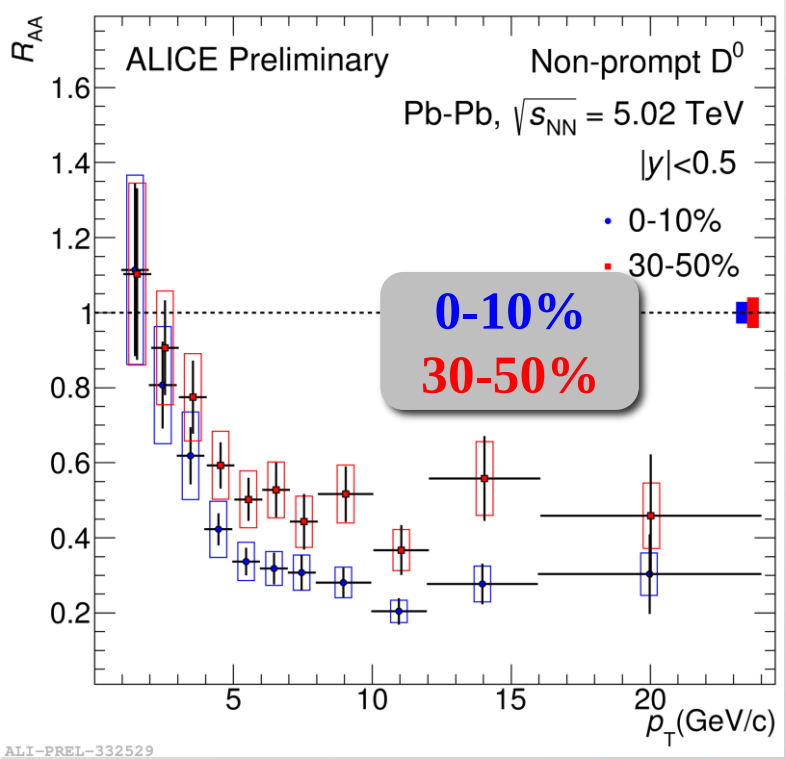


BACK-UP

Non-prompt D mesons

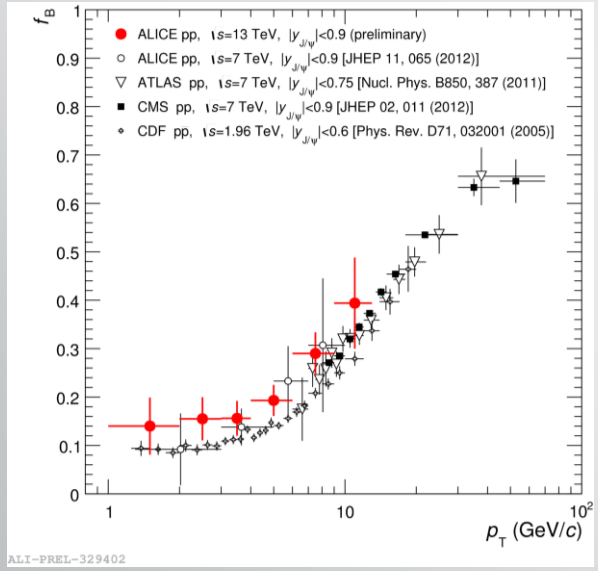


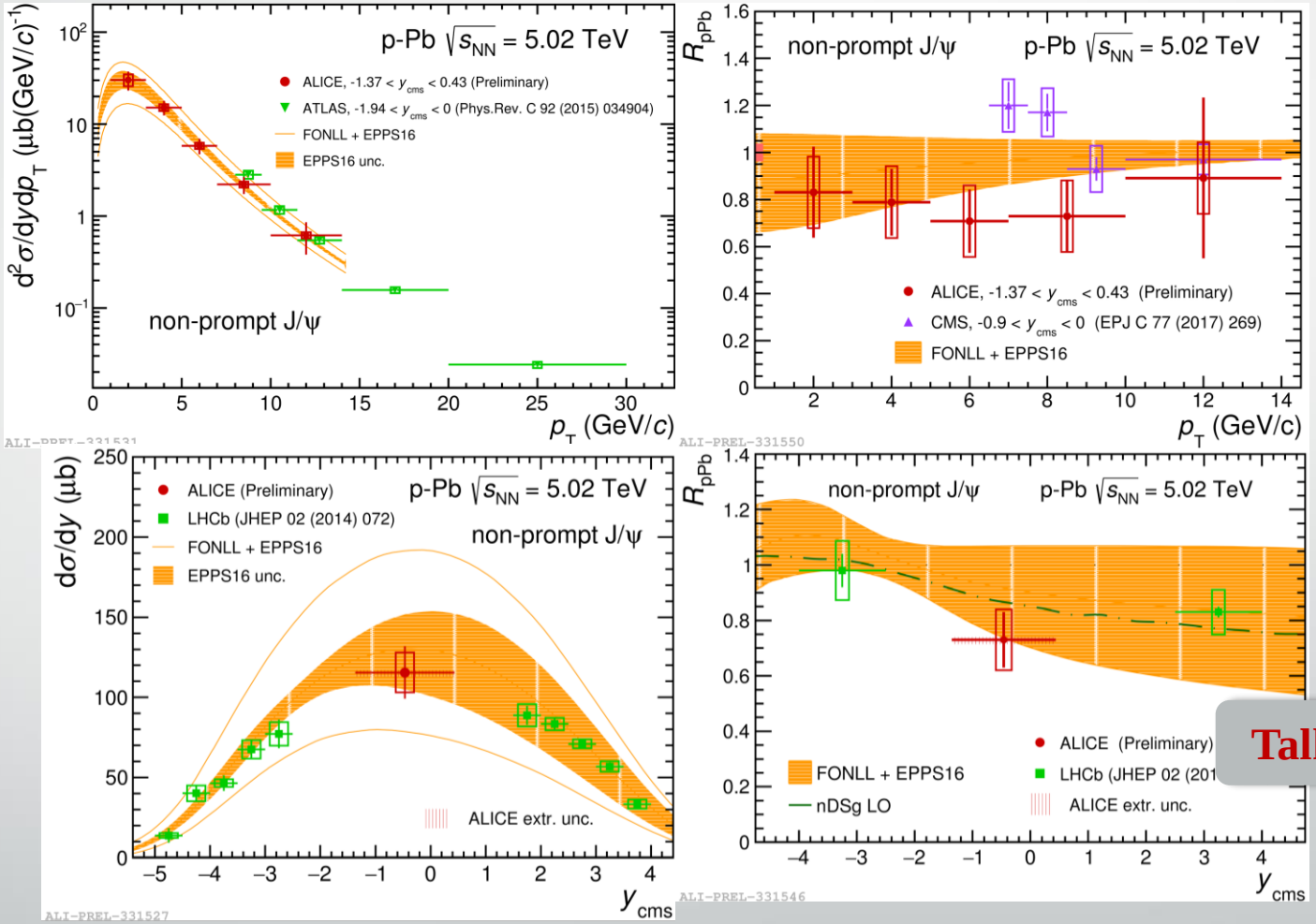




BACK-UP

Non-prompt Jpsi

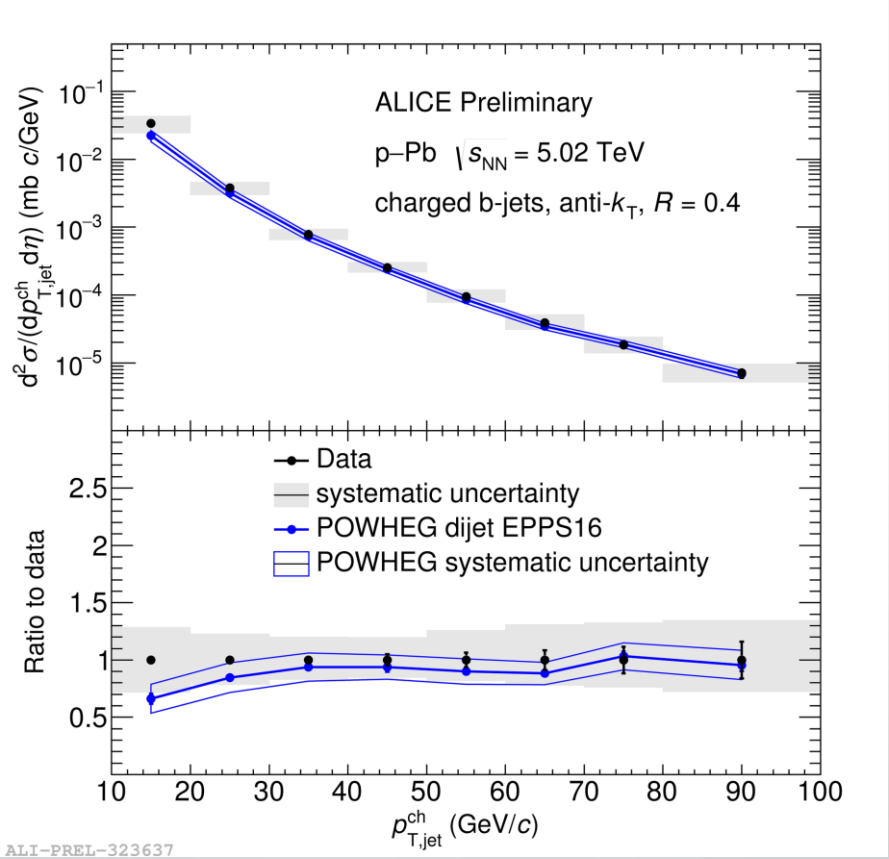




Talk by F. Damas

BACK-UP

b-jet


ALICE Preliminary
p–Pb $\sqrt{s_{NN}}$ = 5.02 TeV
charged b-jets, anti-k_T, R = 0.4
$d^2\sigma/(dp^{ch}_{T,jet}\, d\eta)$ (mb c/GeV)
Data
systematic uncertainty
POWHEG dijet EPPS16
POWHEG systematic uncertainty
Ratio to data
$p^{ch}_{T,jet}$ (GeV/c)
ALI-PREL-323637

BACK-UP

Beauty-decay electron