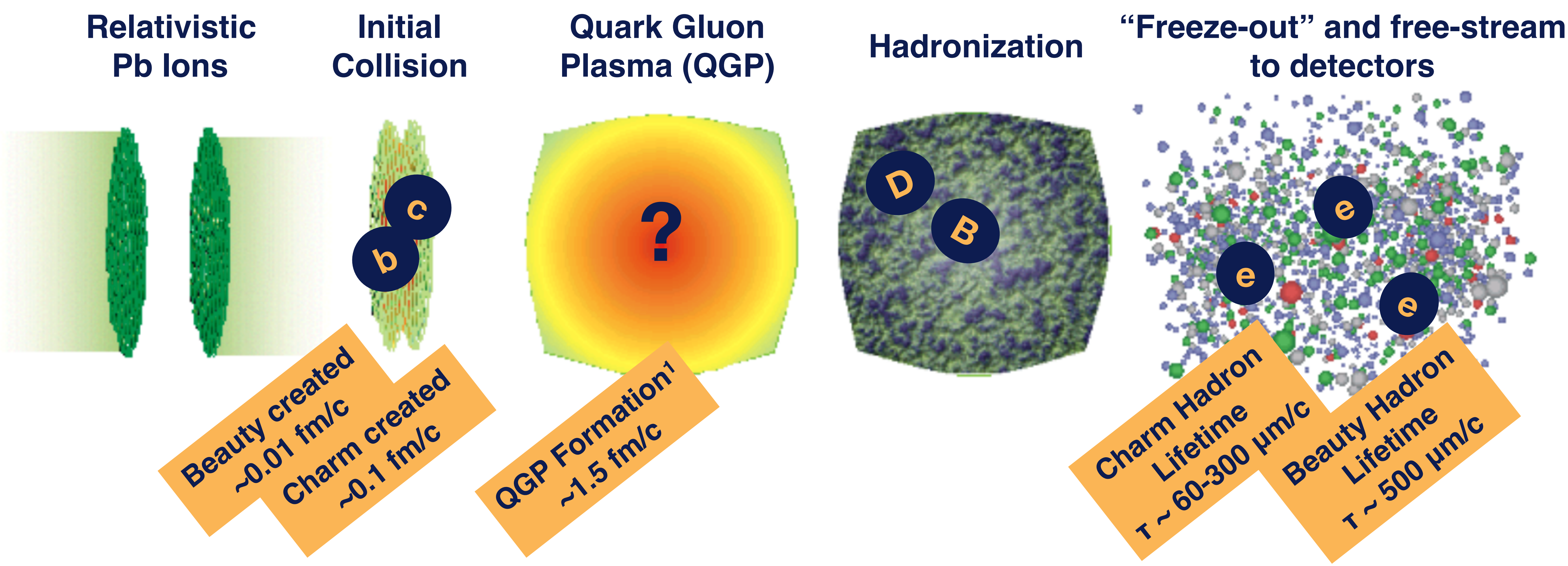
Beauty production with ALICE at the LHC

Erin Gauger* for the ALICE Collaboration
*University of Texas at Austin

Strangeness in Quark Matter
June 11, 2019

Physics Motivation: Heavy-flavor quarks

- Heavy mass → charm and beauty (“heavy-flavor quarks”) produced early in collisions via hard parton-parton scattering
- Experience full evolution of Pb-Pb collisions, including…
  - **The QGP - Quark-Gluon Plasma**, state of matter in which partons are deconfined
    - Interact with QGP constituents and loses energy



[1]Liu and Liu, (2014) arXiv: 1212.6587 [nucl-th]

Collision systems

pp collisions

- Provide baseline for p-Pb and Pb-Pb collisions
- Test perturbative QCD calculations

p-Pb collisions

- Isolate initial state, cold nuclear matter effects
- Investigate the origin of observed collective effects in high-multiplicity events

Pb-Pb collisions

- Energy loss in the medium
  - Path-length dependence
  - Color charge effects: $\Delta E_{\mathrm{gluons}} > \Delta E_{\mathrm{quarks}}$ due to stronger coupling
  - Mass effects: collisional and radiative (dead cone effect) scattering has less effect on more massive objects

    $M_{\mathrm{gluons}} < M_{\mathrm{u,d,s}} < M_{\mathrm{c}} < M_{\mathrm{b}}$

    $\Delta E_{\mathrm{gluons}} > \Delta E_{\mathrm{u,d,s}} > \Delta E_{\mathrm{c}} > \Delta E_{\mathrm{b}}$
- Collectivity of particles in medium

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    $\Delta E_{gluons} > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- Collectivity of particles in medium

Compare beauty with charm to understand the mass dependence of energy loss and collective behavior!

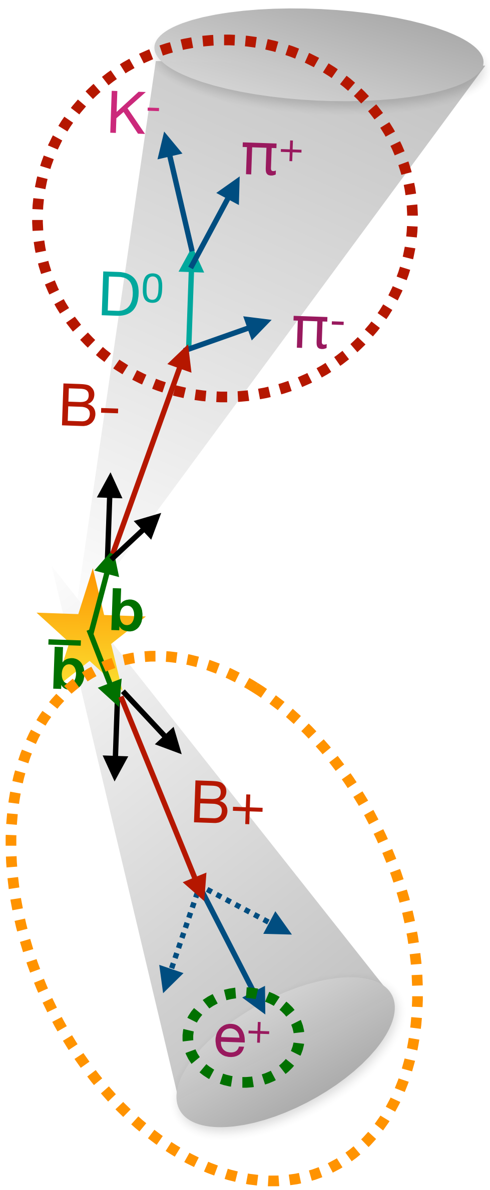
Recent beauty measurements in ALICE

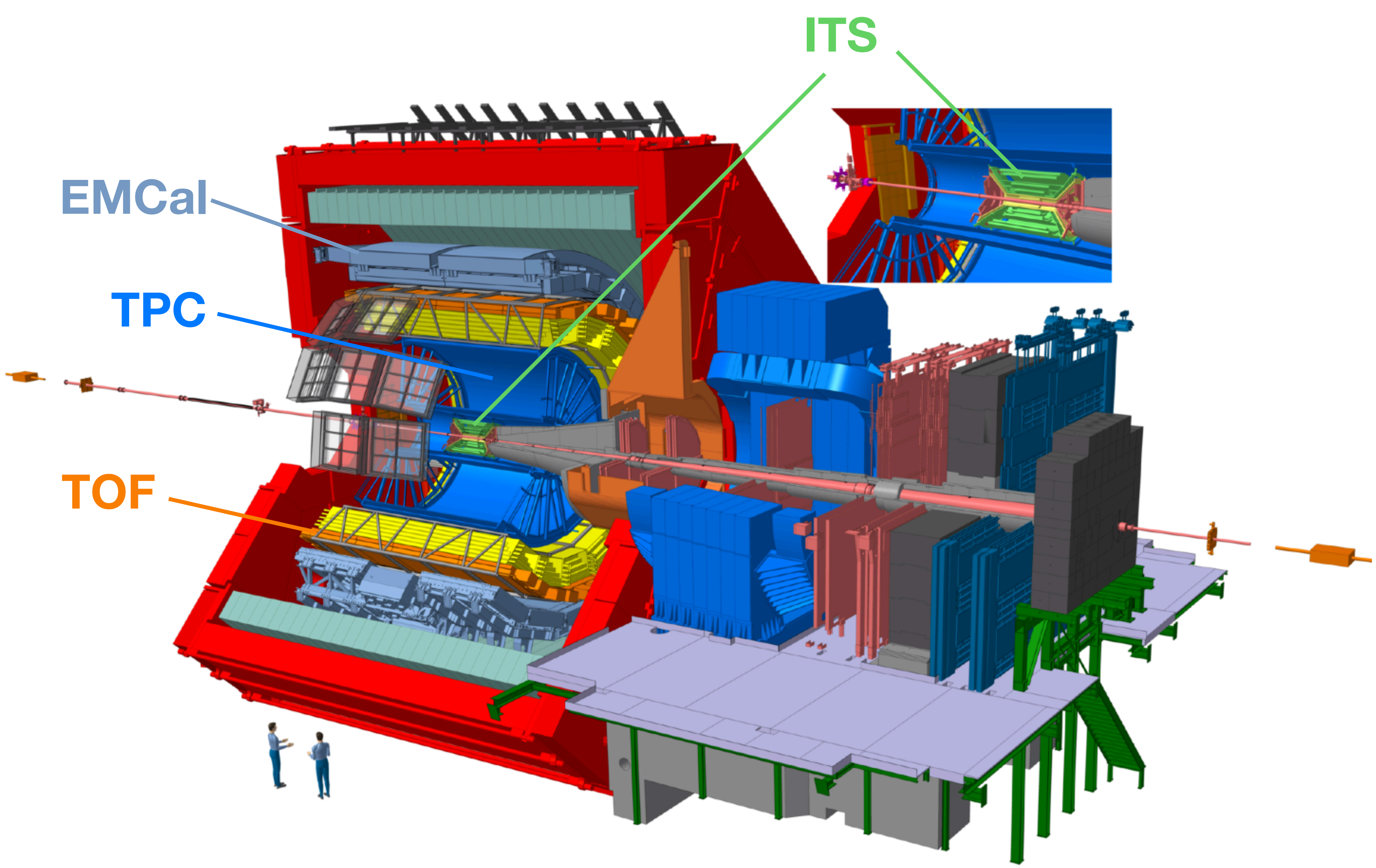
In ALICE, beauty measured with the following:

- **Beauty-decay electrons**
- **Non-prompt D^0**
- **b-tagged jets**

→ Possible with excellent PID, vertex reconstruction, and impact parameter resolution of the ALICE detector

ITS (Inner tracking system): tracking & vertexing
TPC (time projection chamber): tracking & PID
EMCal (electromagnetic calorimeter) + TOF (time-of-flight): PID



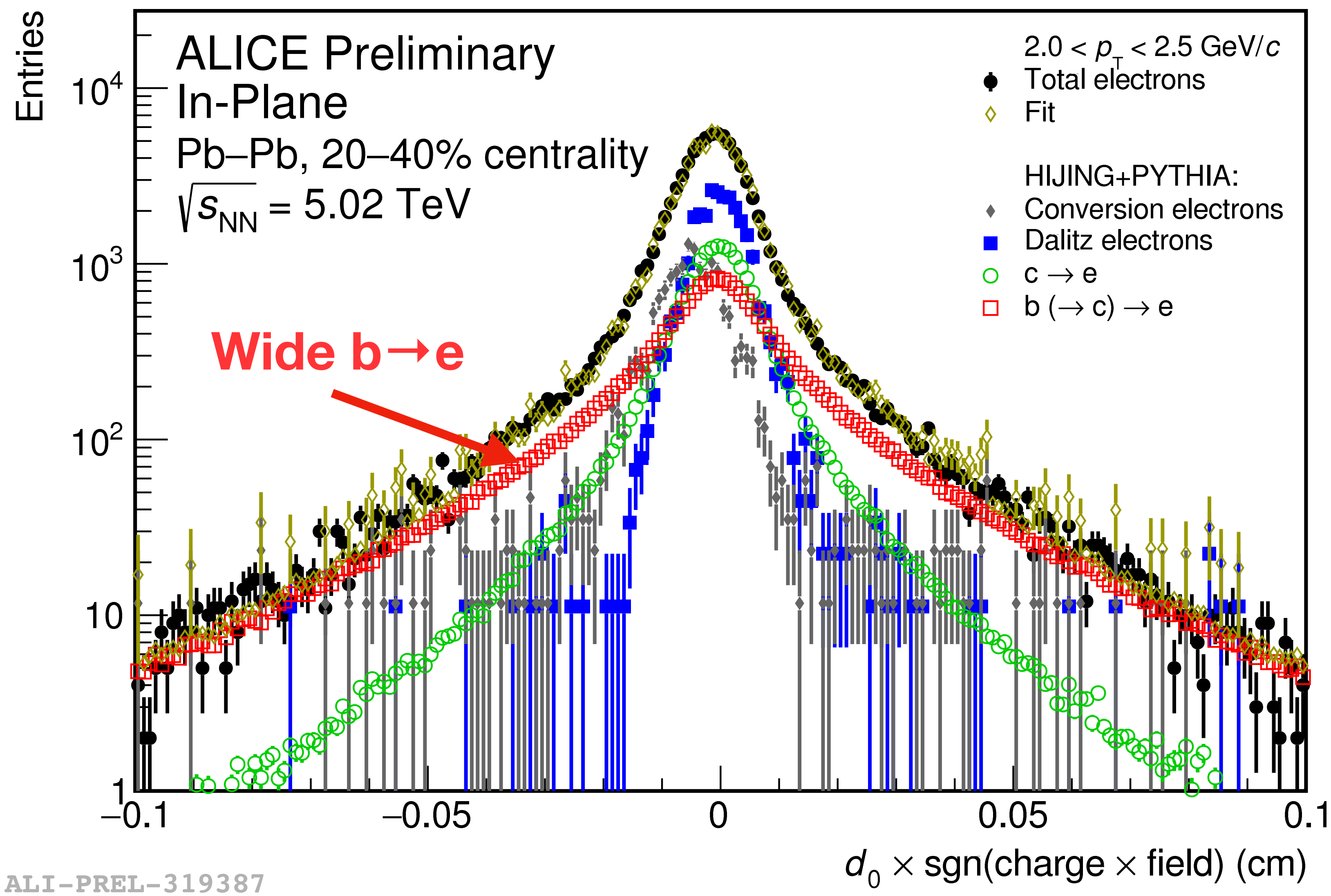


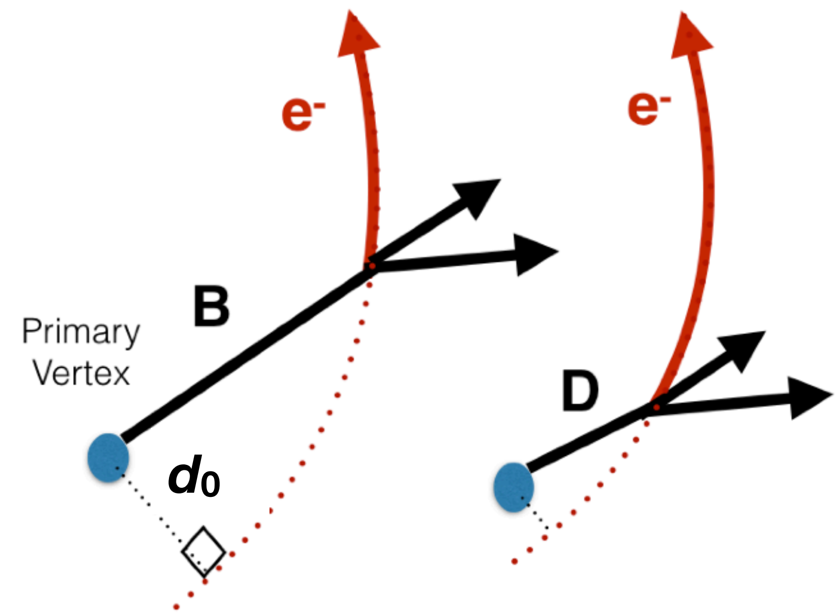
- Methods -

Measuring beauty-decay electrons

- Large branching ratios:
  - b → e + X (~10%), b (→ c) → e + X (~10%)
- Beauty hadrons have a longer lifetime than other electron sources
  → Larger distance of closest approach (d_0) to the primary vertex

beauty hadrons τ ~ 500 μm/c
charm hadrons τ ~ 60-300 μm/c

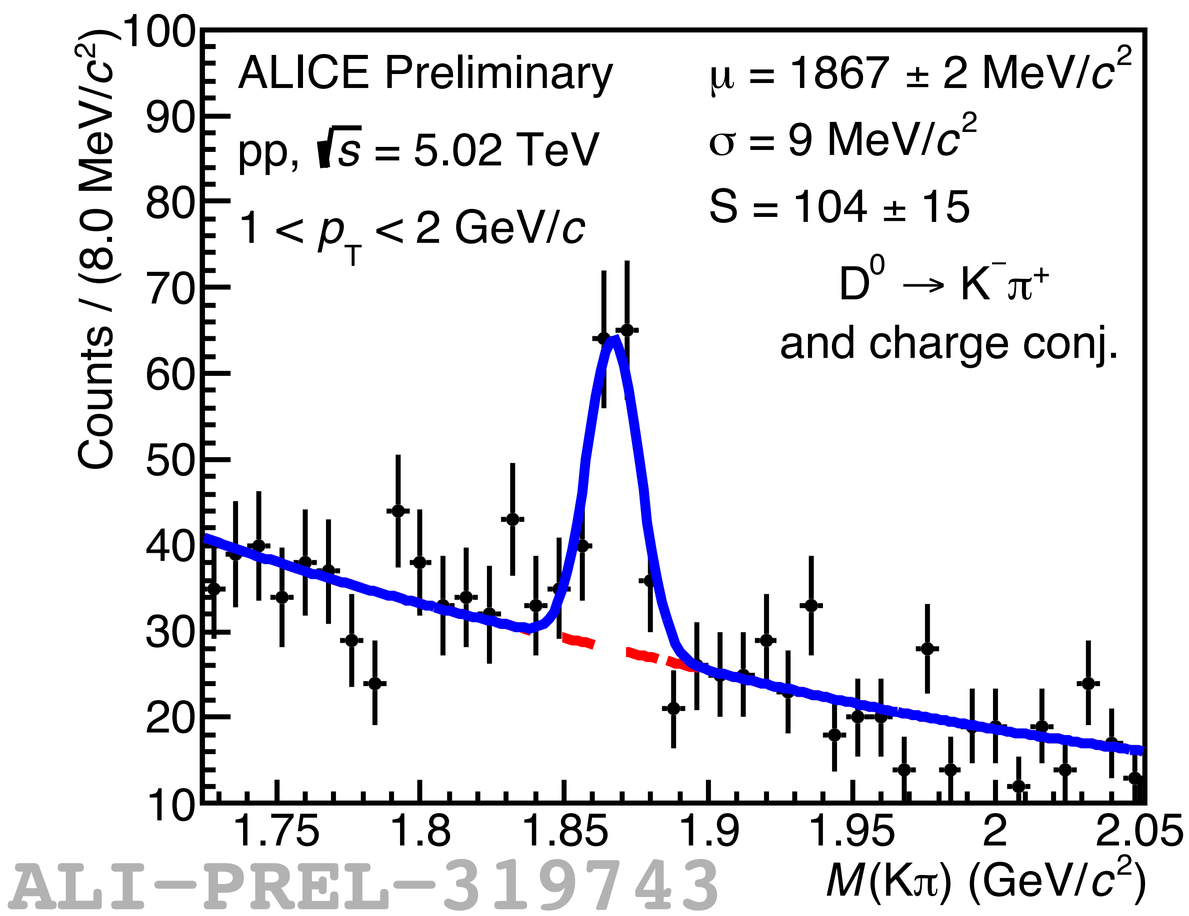




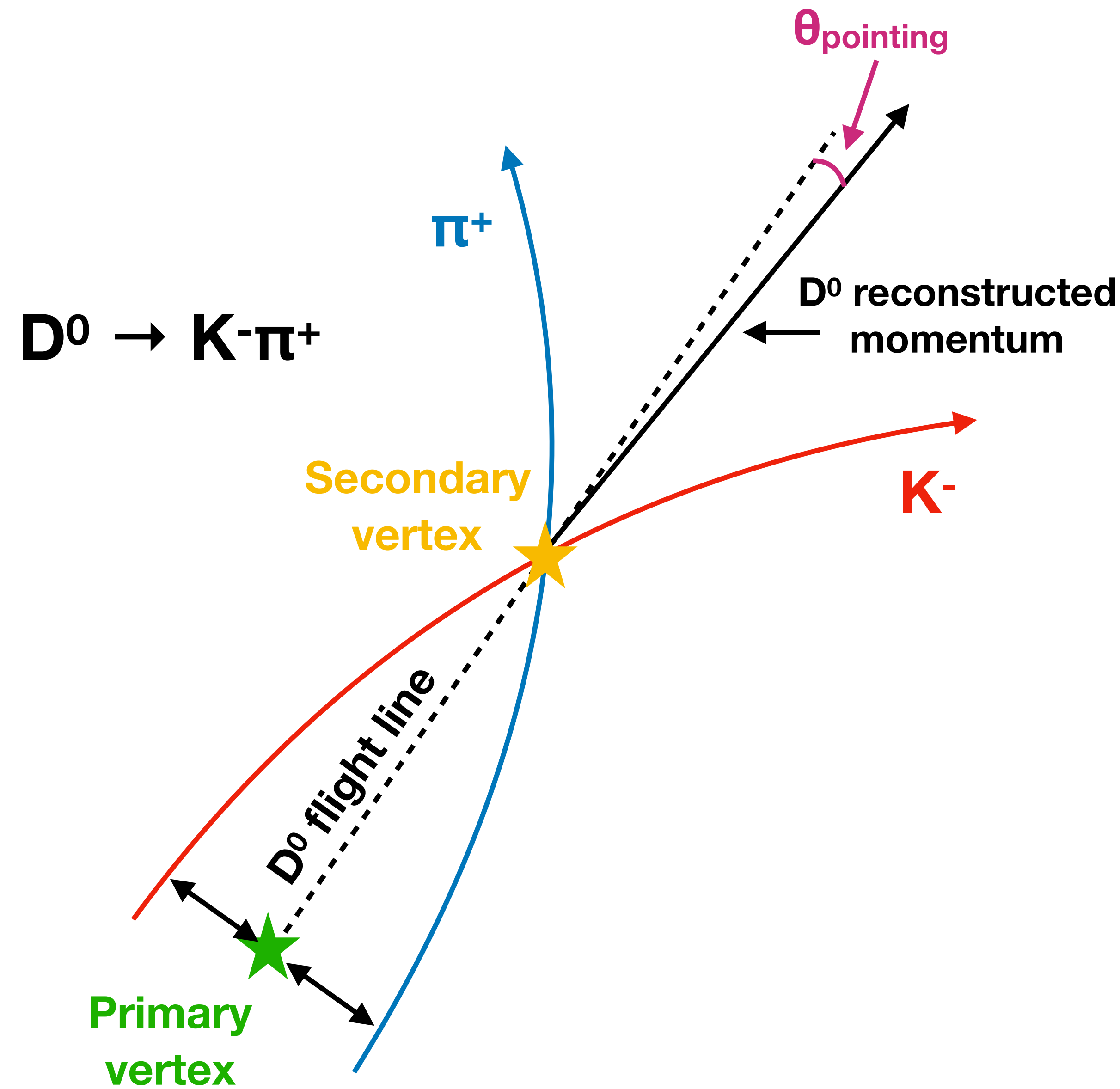
- d_0 templates made with Monte Carlo simulations and fitted to d_0 in data to separate different sources of electrons

Measuring non-prompt D^0

- Reconstruct $b \rightarrow D^0(\rightarrow K^-\pi^+)$ using invariant mass of **secondary vertices (SV)** displaced from primary vertex
- Use boosted decision trees (BDT) to combine and optimize topological cuts on SV to enhance non-prompt D^0 vs. prompt and reduce combinatorial background
  - Decay length is one of the cuts, again exploiting long B meson lifetime



Fit = gaussian (signal) + exponential (combinatorial background)

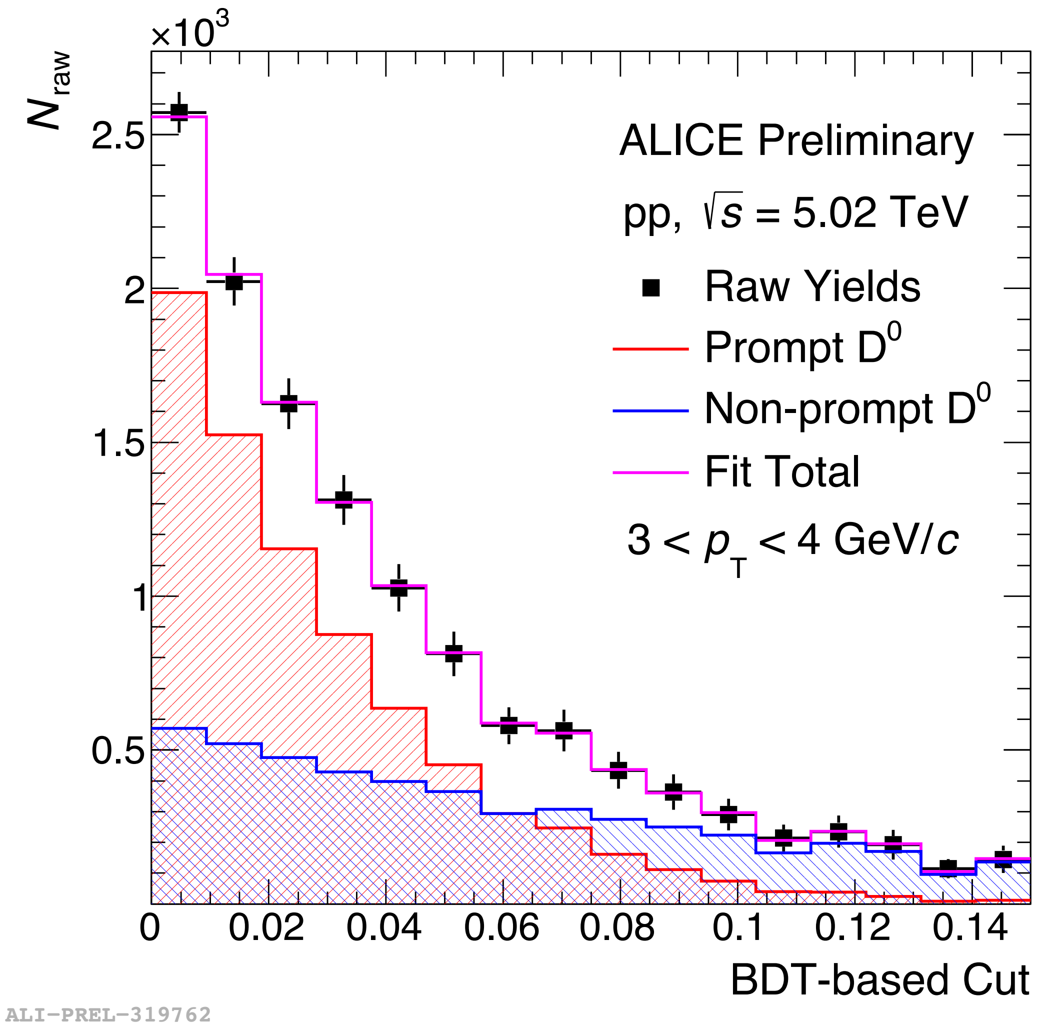


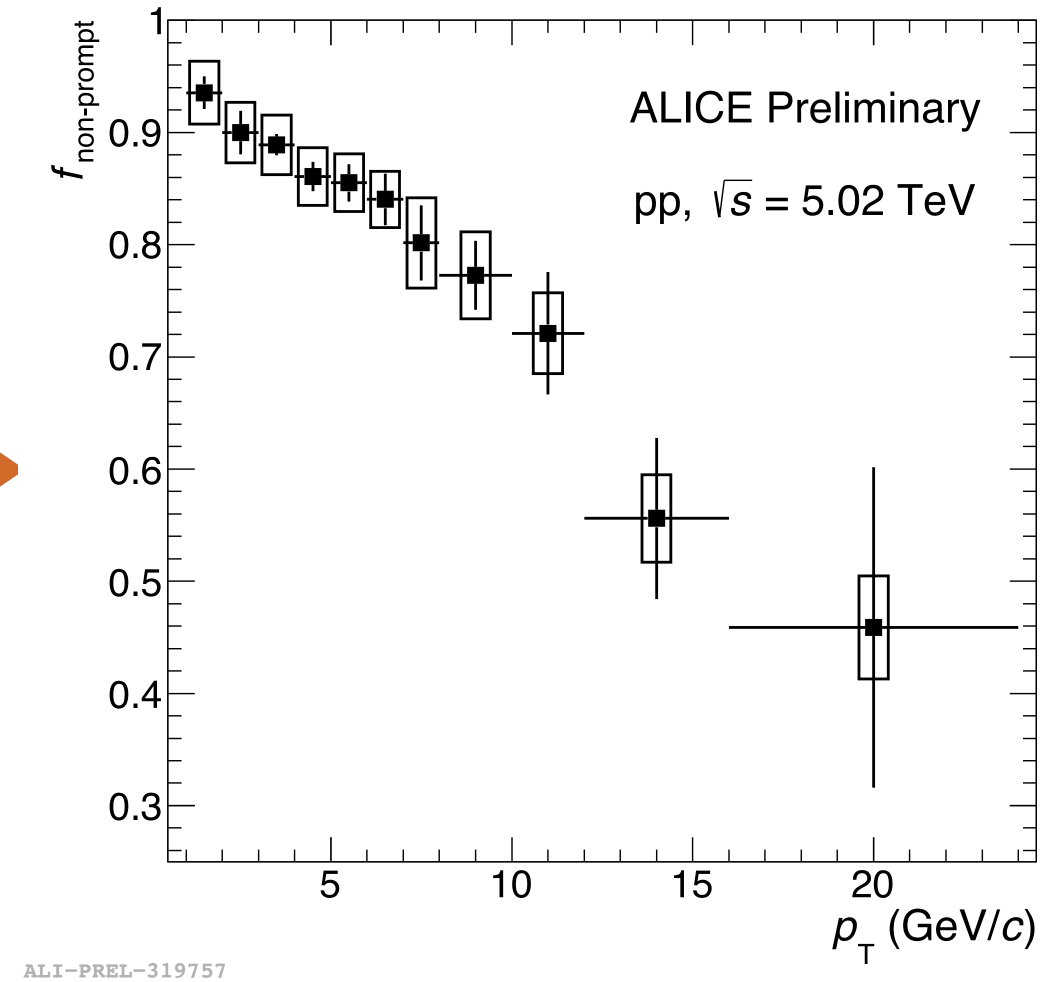
Measuring non-prompt D^0

- Correct the raw yield with the fraction of non-prompt/prompt D^0 (f_{np})
- Calculate using a template fit of the raw yield vs. BDT cut value

fraction of non-prompt in raw sample

$$\left(\frac{d^2\sigma}{dp_T dy}\right)_{np} = \frac{f_{np} N_{raw}/2}{\Delta p_T \Delta y BR^{D^0 \to K\pi} L (Acc \times \varepsilon)_{np}}$$





$$N_{raw}(x) \approx N_c \cdot \varepsilon_c(x) + N_b \cdot \varepsilon_b(x)$$

$\varepsilon_{c,b}$ = efficiency for c,b→D^0

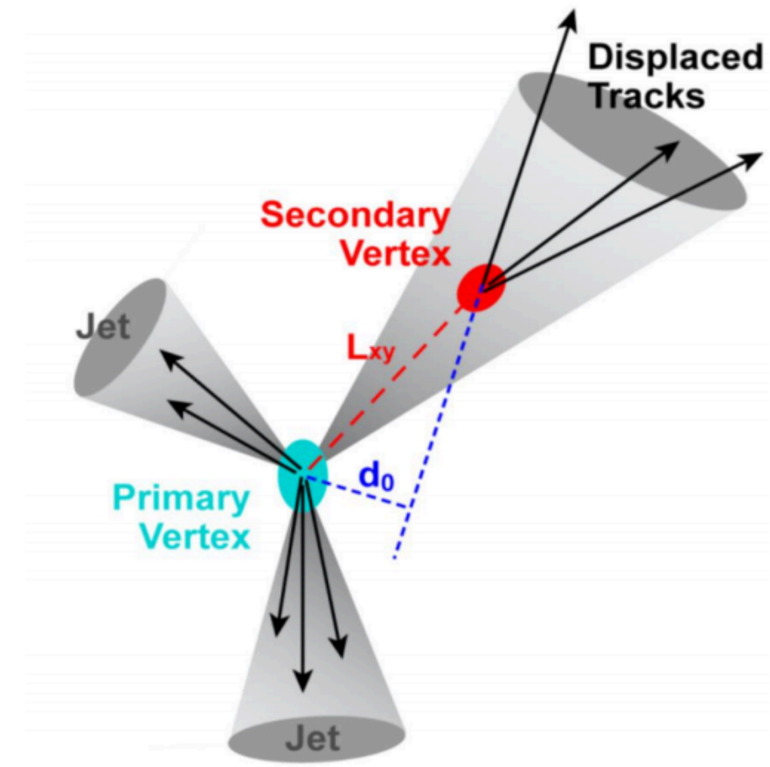
$$f_{np}(x) = \frac{N_b \varepsilon_b(x)}{N_c \varepsilon_c(x) + N_b \varepsilon_b(x)}$$

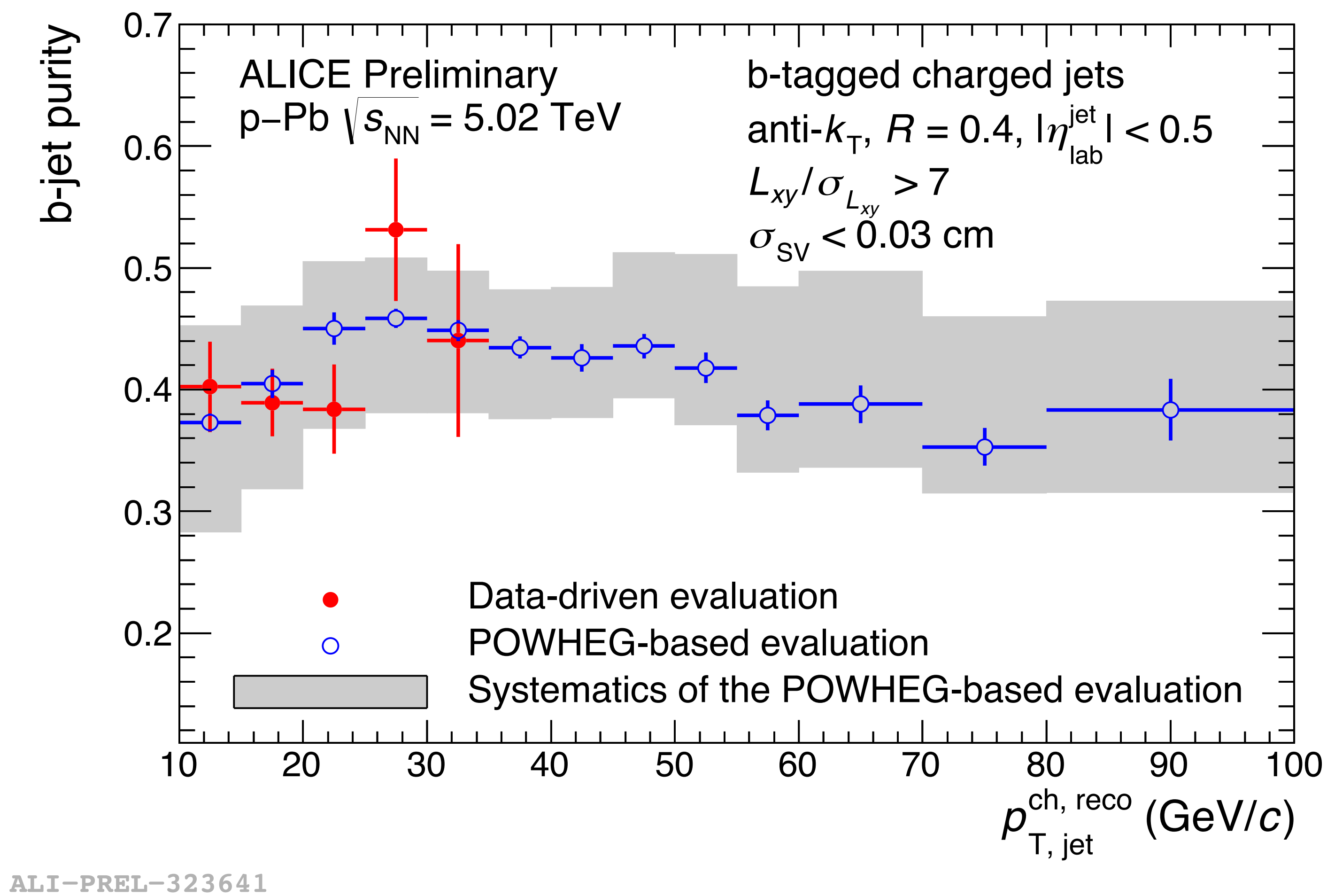
b-Tagged Jets

- Select jets with a 3-pronged secondary vertex
- Apply topological cuts on secondary vertex (SV) to increase b-jets in raw yield:

$$SL_{\mathrm{xy}} = L_{\mathrm{xy}}/\sigma_{\mathrm{Lxy}}$$

Displacement significance
= distance between primary and SV in xy-plane / resolution
→ b-jets tend to have longer L_{xy} due to long B meson lifetime





Correct raw yield with efficiency & purity of b-jets in sample:

$$N^{\mathrm{corr}}_{\mathrm{b\ jet}}\left(p^{\mathrm{ch,reco}}_{\mathrm{T,jet}}\right) = N^{\mathrm{raw}}_{\mathrm{b\ jet}}\left(p^{\mathrm{ch,reco}}_{\mathrm{T,jet}}\right) \times \frac{P_{\mathrm{b}}}{\varepsilon_{\mathrm{b}}}$$

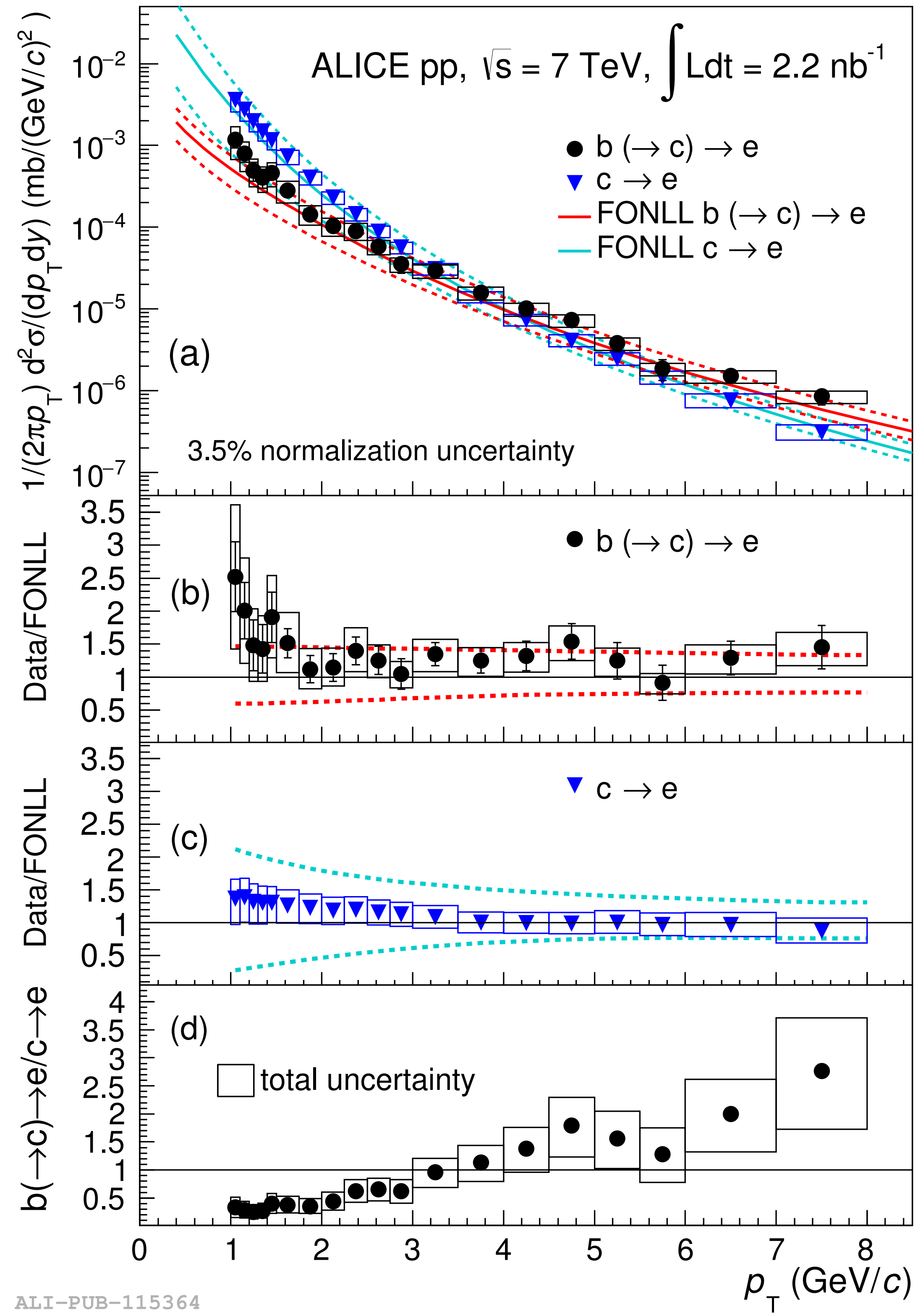
$$P_{\mathrm{b}} = \frac{N_{\mathrm{b}}\varepsilon_{\mathrm{b}}}{N_{\mathrm{b}}\varepsilon_{\mathrm{b}} + N_{\mathrm{c}}\varepsilon_{\mathrm{c}} + N_{\mathrm{LF}}\varepsilon_{\mathrm{LF}}}$$

- N_c, N_b from POWHEG, multiplied by response matrix
- N_{LF} = raw inclusive from data minus N_c and N_b
- $\varepsilon_{c,b,LF}$ = tagging efficiency from MC

- Results in pp Collisions -

Results in pp collisions: Beauty-decay electrons

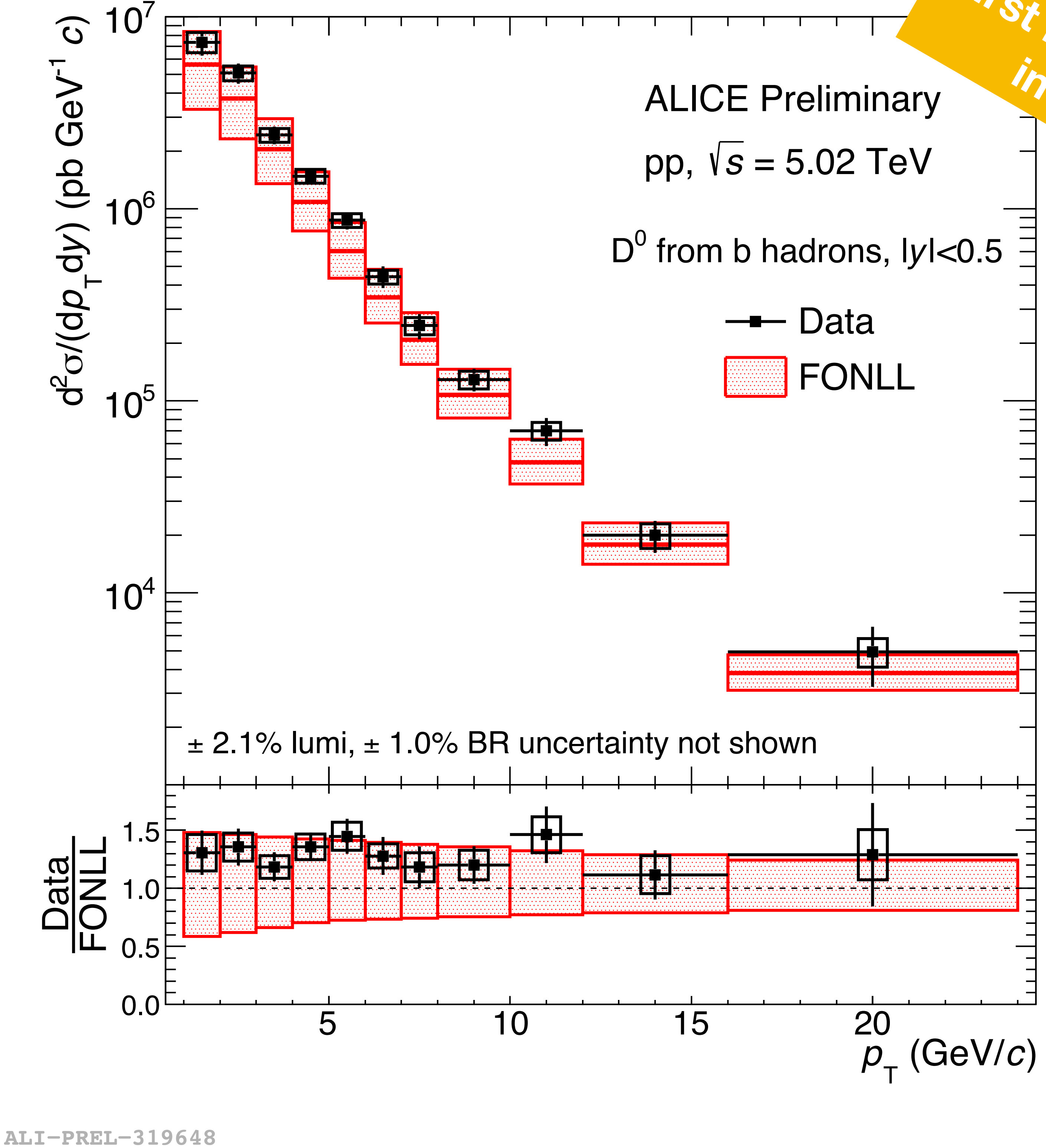
- b→e and c→e yields in 7 TeV pp collisions
- Both are in agreement with pQCD theory (FONLL*), though on the upper edge of the systematic error
- Bottom window: b→e/c→e increases with p_T, the b→e contribution surpassing c→e for $p_T > 4$ GeV/c
- Good baseline to compare with p-Pb and Pb-Pb results



*JHEP 9805 (1998) 007
JHEP 0103 (2001) 006

Phys. Lett. B 721 (2013) 13-23

Results in pp collisions: Non-prompt D^0



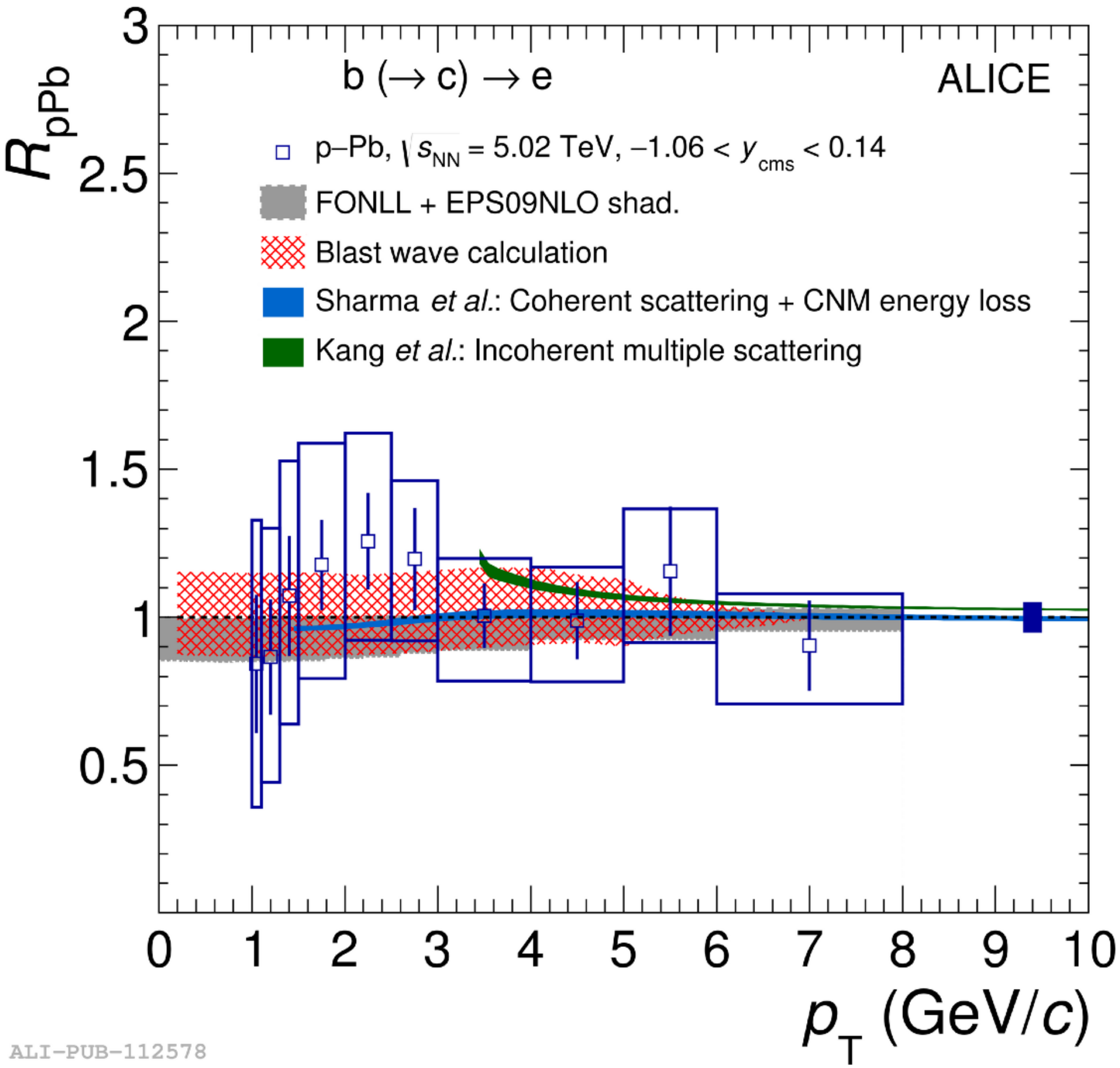
First measurement in ALICE!

- Fully-corrected cross section down to p_T = 1 GeV/c
- Results agree with FONLL, but lie on the upper edge of the FONLL uncertainty across all p_T
- Good precision, especially at low p_T

Poster by Mengke Cai
"Non-prompt D^0-meson production in pp collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ALICE"

- Results in p-Pb Collisions -

Results in p-Pb: b→e R_{pPb}



JHEP 07 (2017) 052

cross section in p-Pb

$$R_{\mathrm{pPb}} = \frac{\mathrm{d}\sigma_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}}{A_{\mathrm{Pb}} \cdot \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

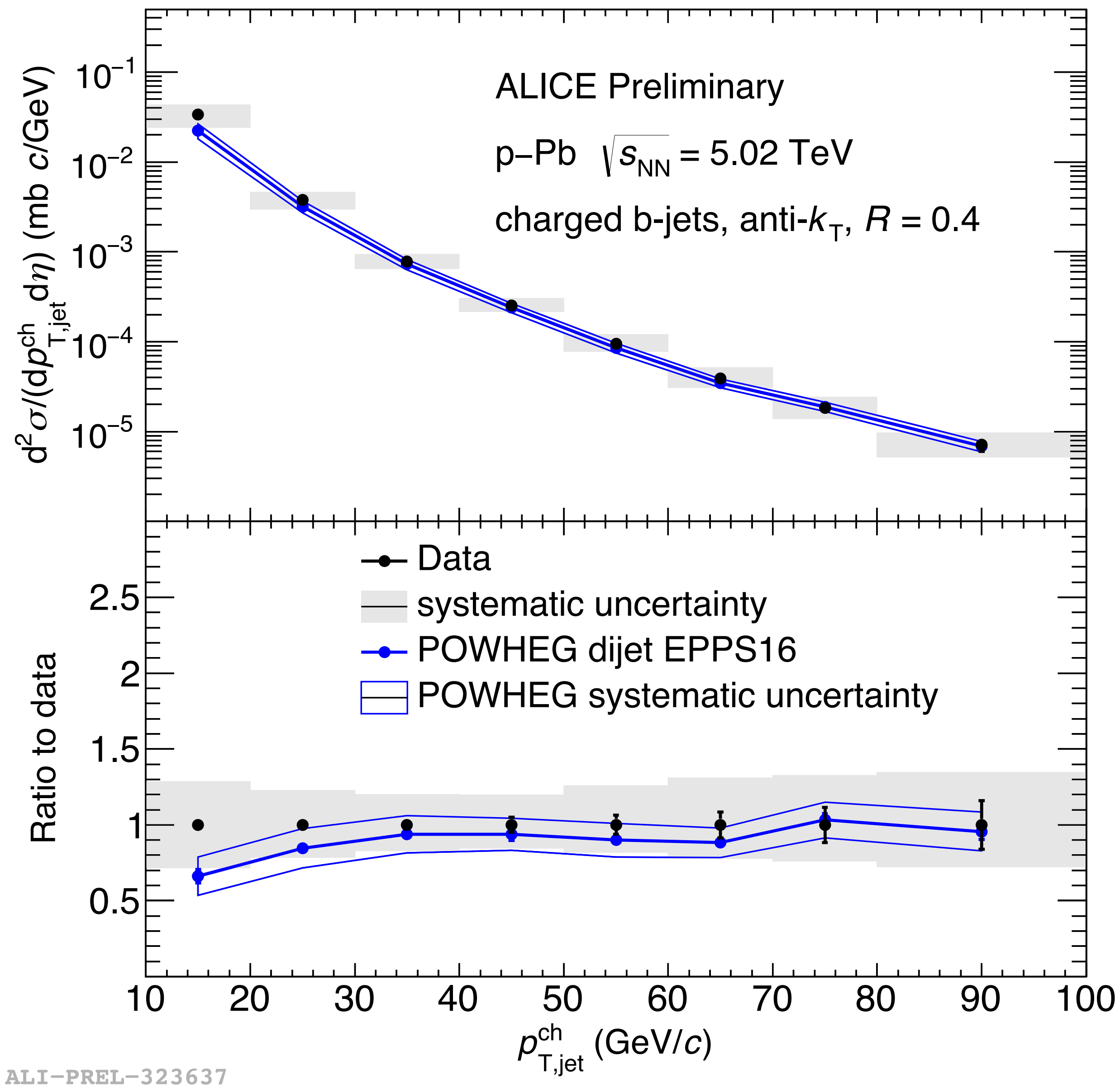
nucleons in Pb nucleus (208)

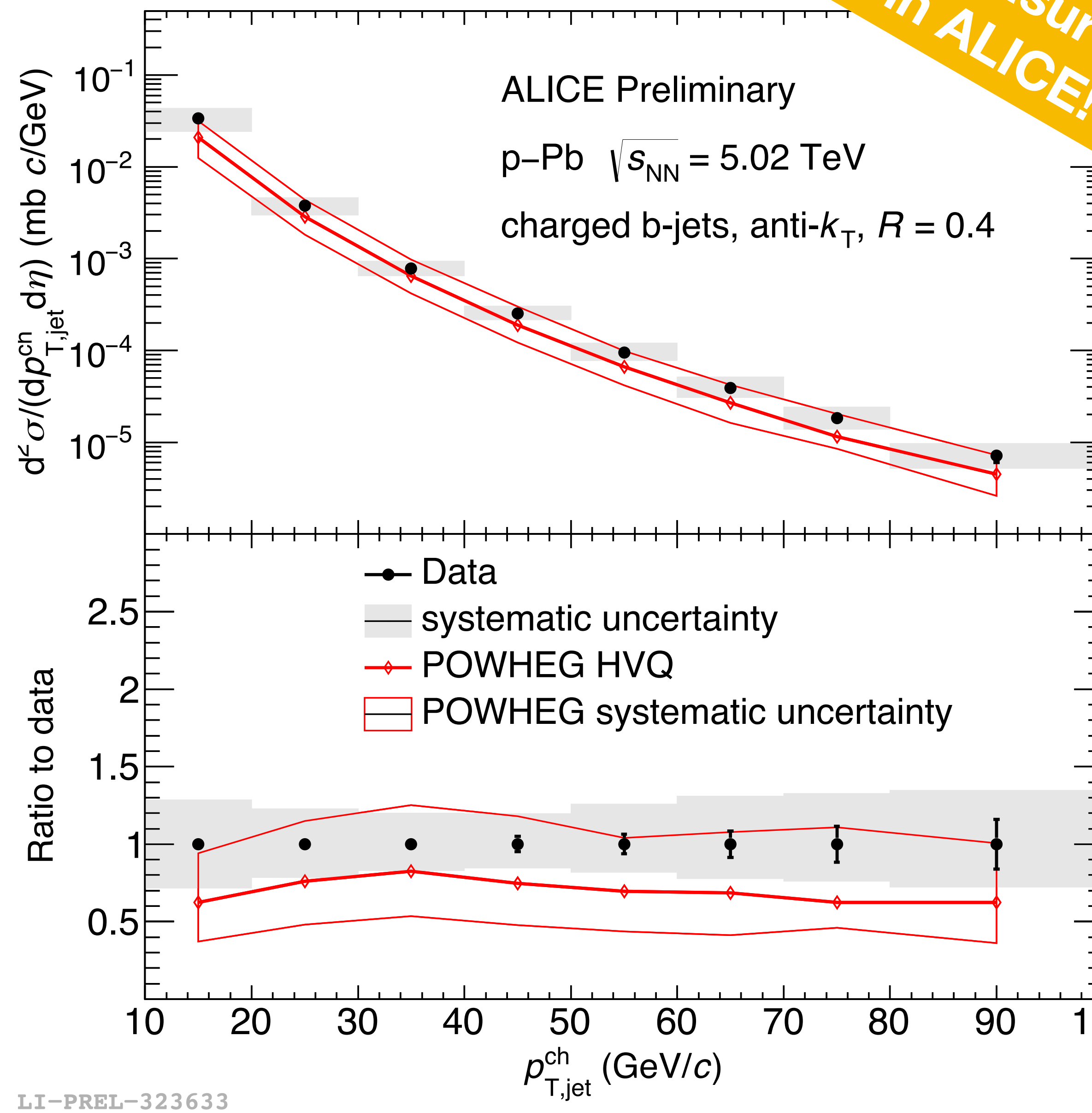
cross section in pp

- Compare with the yield in pp collisions using the nuclear modification factor (R_{pPb})
- Within error bars, R_{pPb} is consistent with unity → suggests cold nuclear matter effects are small
- Consistent with models that include cold nuclear matter effects

Results in p-Pb: b-Tagged Jets

First measurement in ALICE!



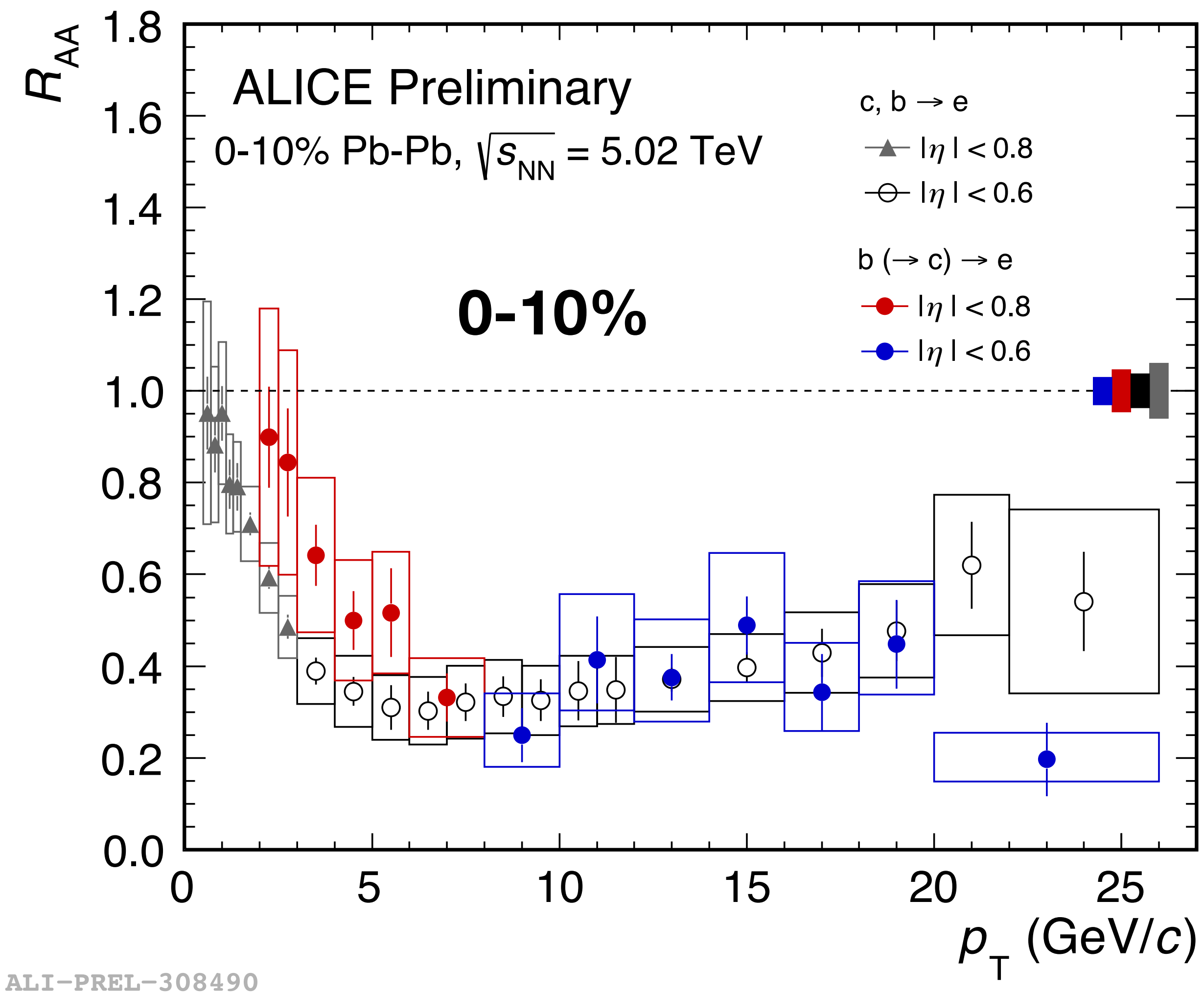


- Fully-corrected cross section
- Results agree with different POWHEG simulations within uncertainties (**POWHEG Dijet EPPS16** and **POWHEG HVQ EPS09NLO**)
- First measurement of b-tagged jets in ALICE!

Talk by Auro Mohanty
13 June, 16:50
“Heavy-flavor jet production and charm fragmentation with ALICE at LHC”

- Results in Pb-Pb Collisions -

Results in Pb-Pb: b→e R_{AA}

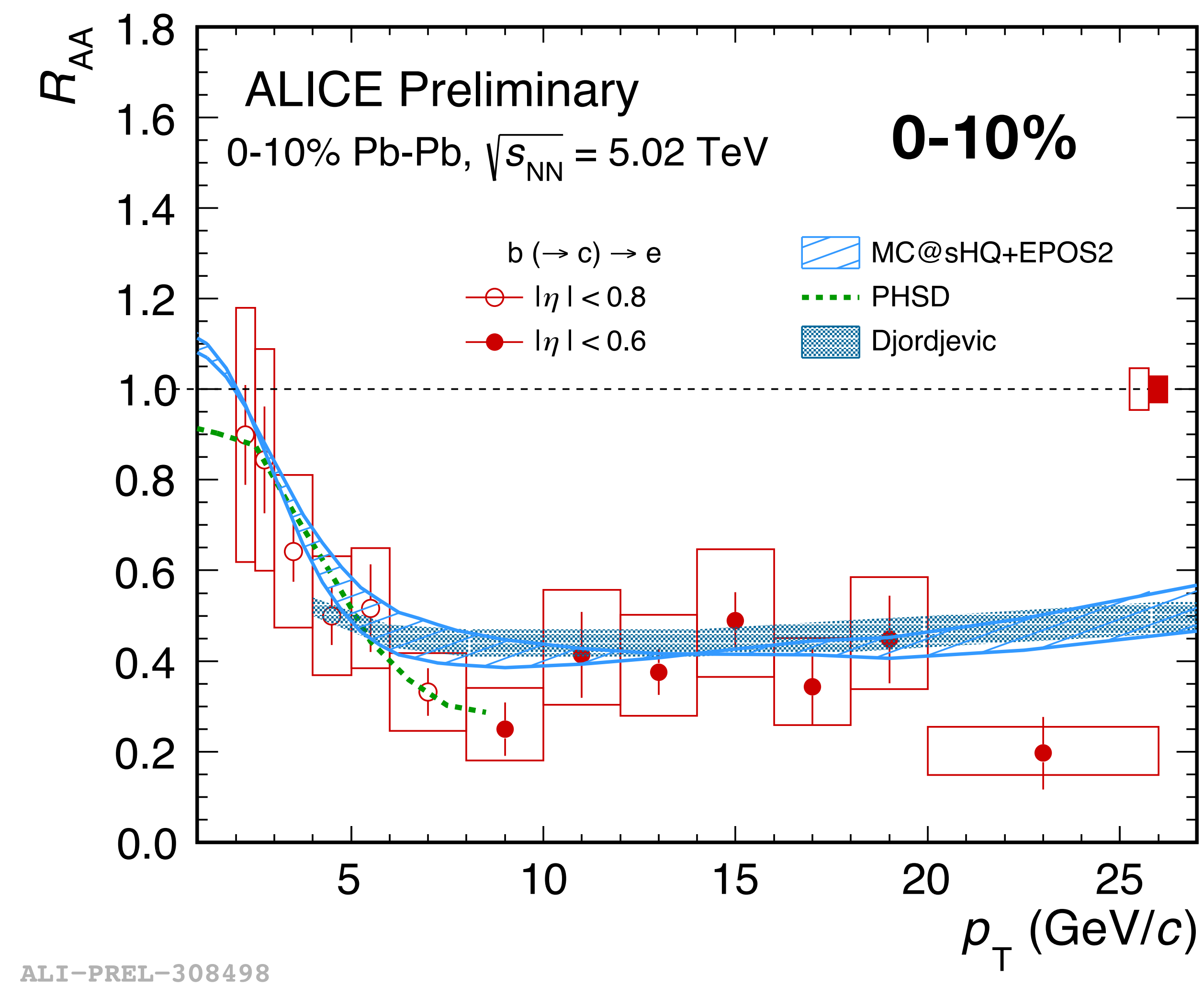


$$R_{\mathrm{PbPb}} = \frac{\mathrm{d}N_{\mathrm{PbPb}}/\mathrm{d}p_{\mathrm{T}}}{\langle T_{\mathrm{PbPb}} \rangle \cdot \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

yield in p-Pb

avg. nuclear overlap function

cross-section in pp

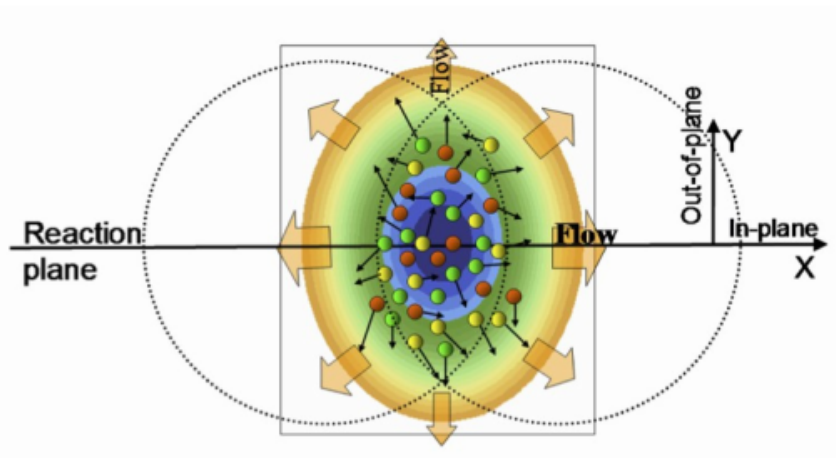


- Compare Pb-Pb to pp production with R_{AA}
  → Reduced particle yield in Pb-Pb vs. pp, due to energy loss in the QGP
- Compare b→e with combined c,b→e
  → Hint that R_{AA}(b→e) > R_{AA}(c,b→e) at low p_T
- High p_T, results fully overlap, recall that b→e/c→e increases with p_T from the pp results

- Measurement is consistent with models that include both collisional and radiative energy loss

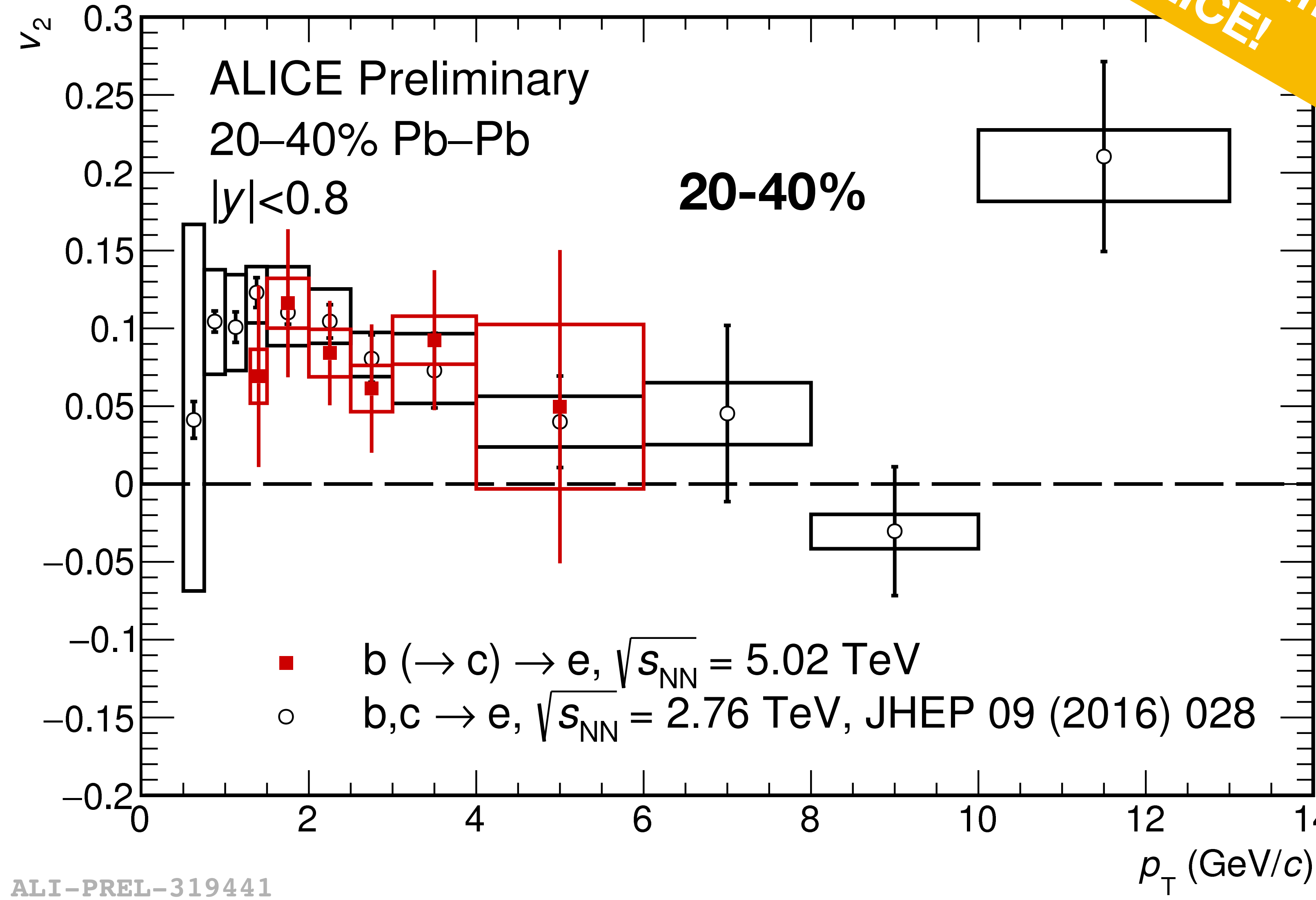
Results in Pb-Pb: b→e v_2

First measurement in ALICE!



$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{in-plane} - N_{out-of-plane}}{N_{in-plane} + N_{out-of-plane}}$$

Poster by Martin Völkl
"Azimuthal anisotropy studies of beauty-decay electrons in Pb-Pb collisions with ALICE"



- Non-zero v_2 measured for **b→e**
  - In $1.3 < p_T < 4$ GeV/c, v_2 significance above 0 is 3.49σ
- Hint that b quarks participate in collective behavior of the medium
- Compatible with **b,c→e**

Summary

pp Collisions

- Non-prompt D^0 and b→e
  - Provides baseline for comparison with Pb-Pb
  - On upper edge of uncertainty of FONLL
  - Non-prompt D^0 measured for the first time in ALICE

p-Pb Collisions

- b→e R_{pPb}
  - Suggests cold nuclear matter effects are small
- b-jets
  - First measurement in ALICE
  - Agrees with POWHEG simulations

Pb-Pb Collisions

- b→e R_{AA}
  - Hint of less suppression at low p_{T} of b→e vs. c,b→e
  - Agreement with models that include collisional and radiative energy loss
- b→e v_2
  - First measurement in ALICE
  - Hint that b quark participates in collective behavior of the system
  - Consistent with b,c→e v_2

Related talks & posters

For heavy flavor in small systems with ALICE:

TODAY, Collectivity in Small Systems session

Talk by Preeti Dhankher
TODAY, 17:30
"Study of open heavy-flavor hadron production in pp and p-Pb collisions with ALICE"

For non-prompt J/ψ measurements in ALICE:

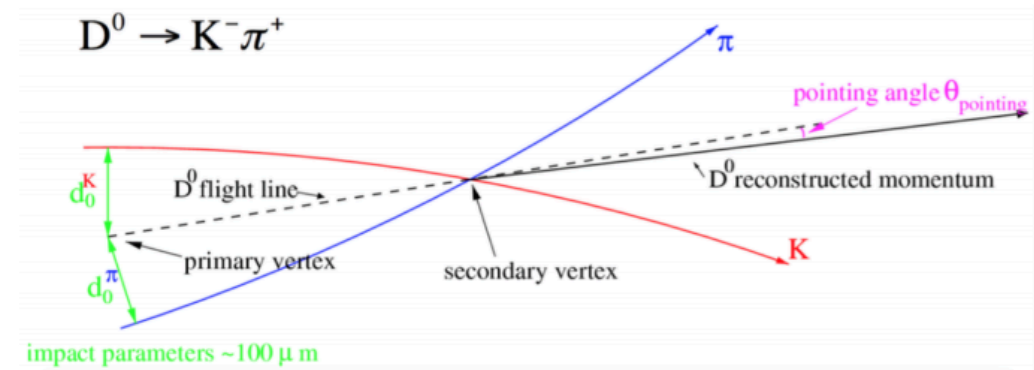
Talk by Minjung Kim
13 June, 14:40
"J/ψ production measurements in pp, p-Pb and Pb-Pb collisions at mid-rapidity using the ALICE detector at LHC"

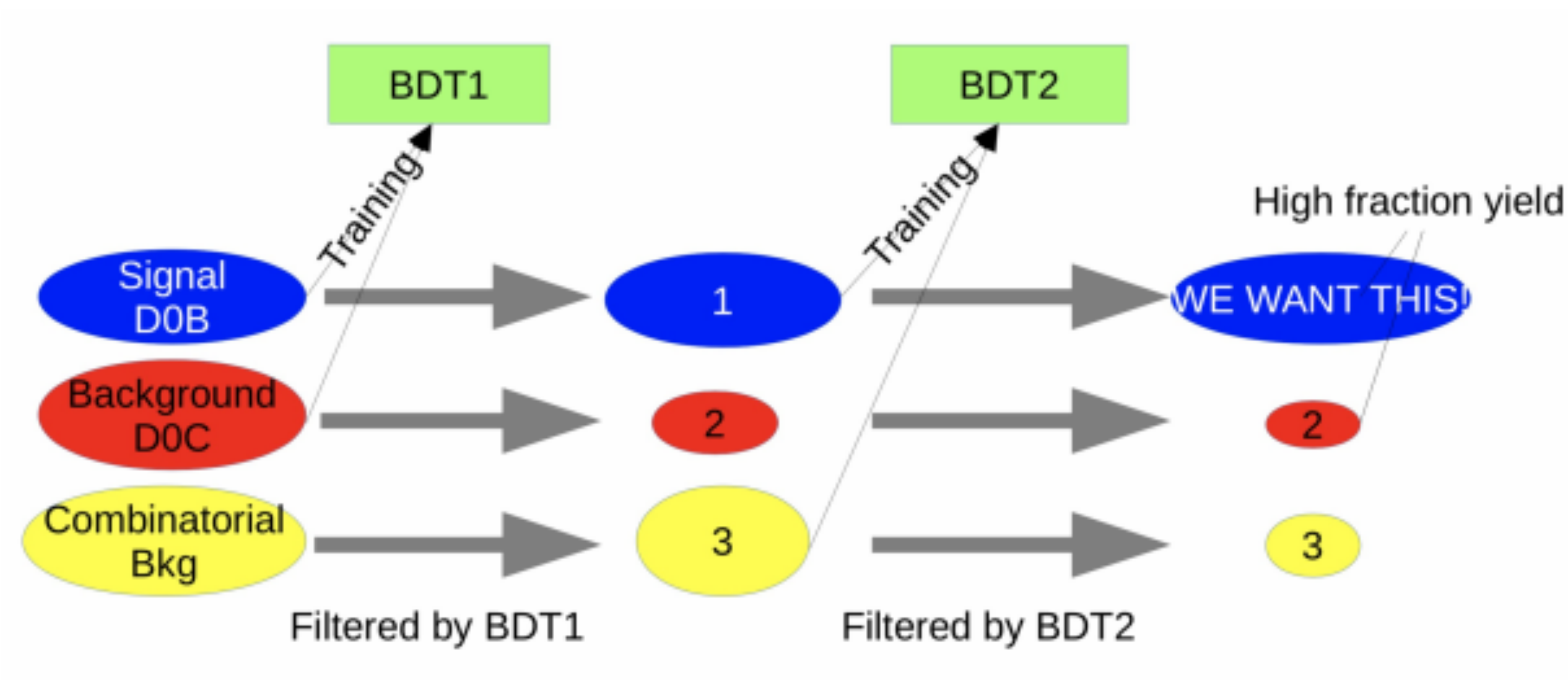
Poster by Giuseppe Trombetta
"Measurement of prompt and non-prompt J/ψ production at mid-rapidity in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE"

- Back-up -

Non-prompt D^0 in pp @ 5.02 TeV

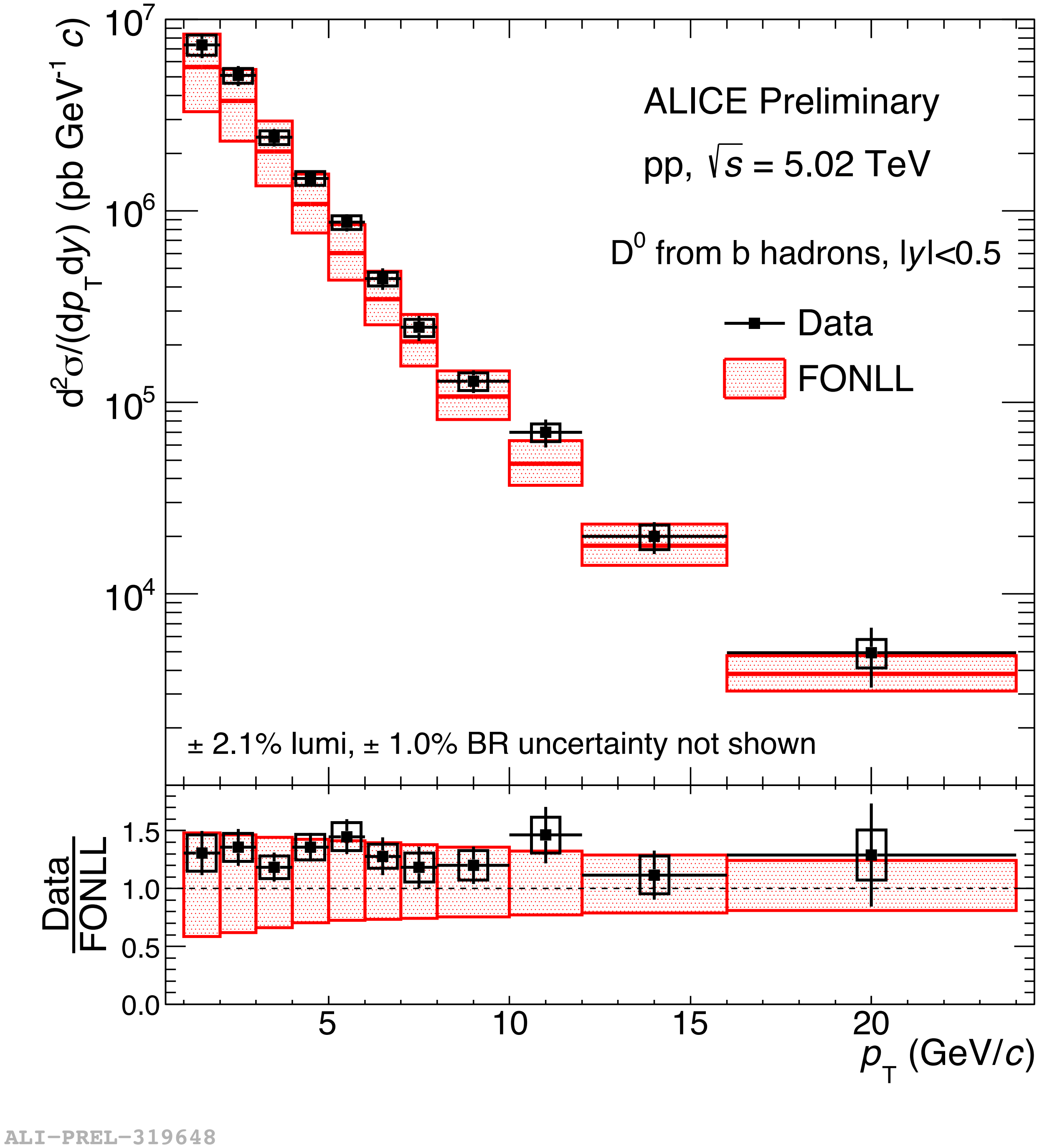
- Two BDT used:
    1. Separate prompt and non-prompt (BDT1)
    2. Separate non-prompt and combinatorial background (BDT2)
- Trained using MC simulation for prompt and non-prompt D^0, data D^0 invariant mass side band for combinatorial background

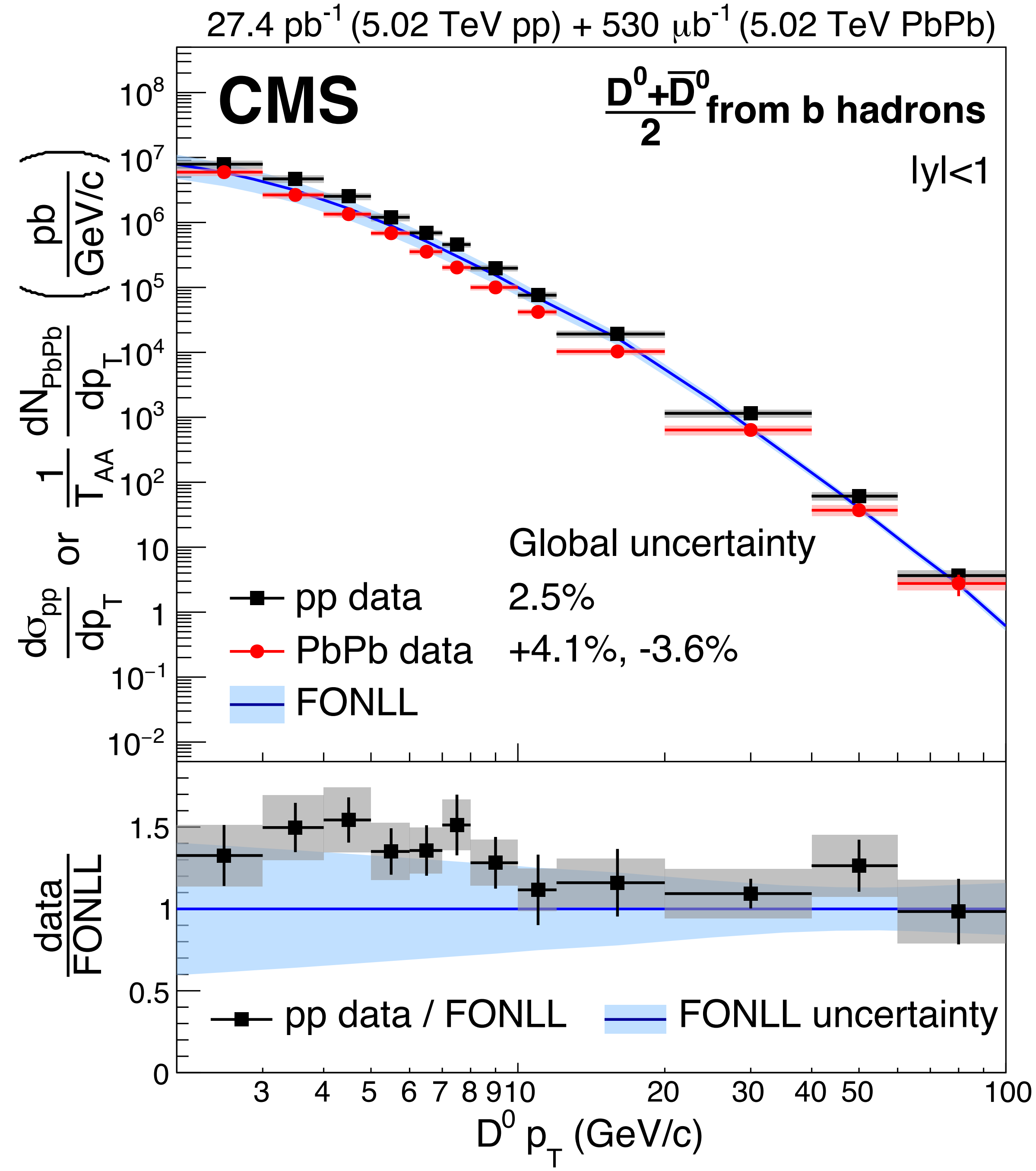




variables
$\lvert d_0 - d_0^{exp} \rvert^{prong} (n\sigma)$
Dec.Length XY
Norm L_{XY}
$d_0 * d_0$
DCA
$\mathrm{Cos}(\theta_{point})$
$\mathrm{Cos}(\theta_{point})$XY
$d_{0,k}$
$d_{0,\pi}$
$\mathrm{Cos}(\theta^*)$

Results in pp collisions: Non-prompt D^0



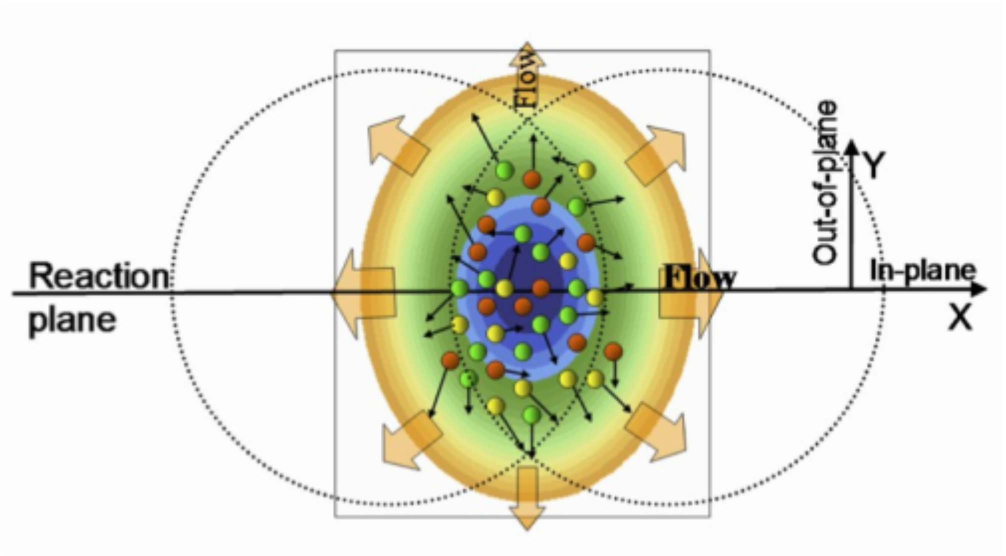


arXiv:1810.11102 [hep-ex]

- Comparison with CMS measurement

b→e R_{AA} and v_2 in Pb-Pb @ 5.02 TeV: Analysis Methods

- Log-likelihood fit method was used
  - Four templates: c→e, b→e, Dalitz-decay, and conversion electrons
- For v_2, repeat process for in- and out-of-plane



$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{in-plane} - N_{out-of-plane}}{N_{in-plane} + N_{out-of-plane}}$$