Beauty production and energy loss in the QGP at LHC energies using the ALICE detector

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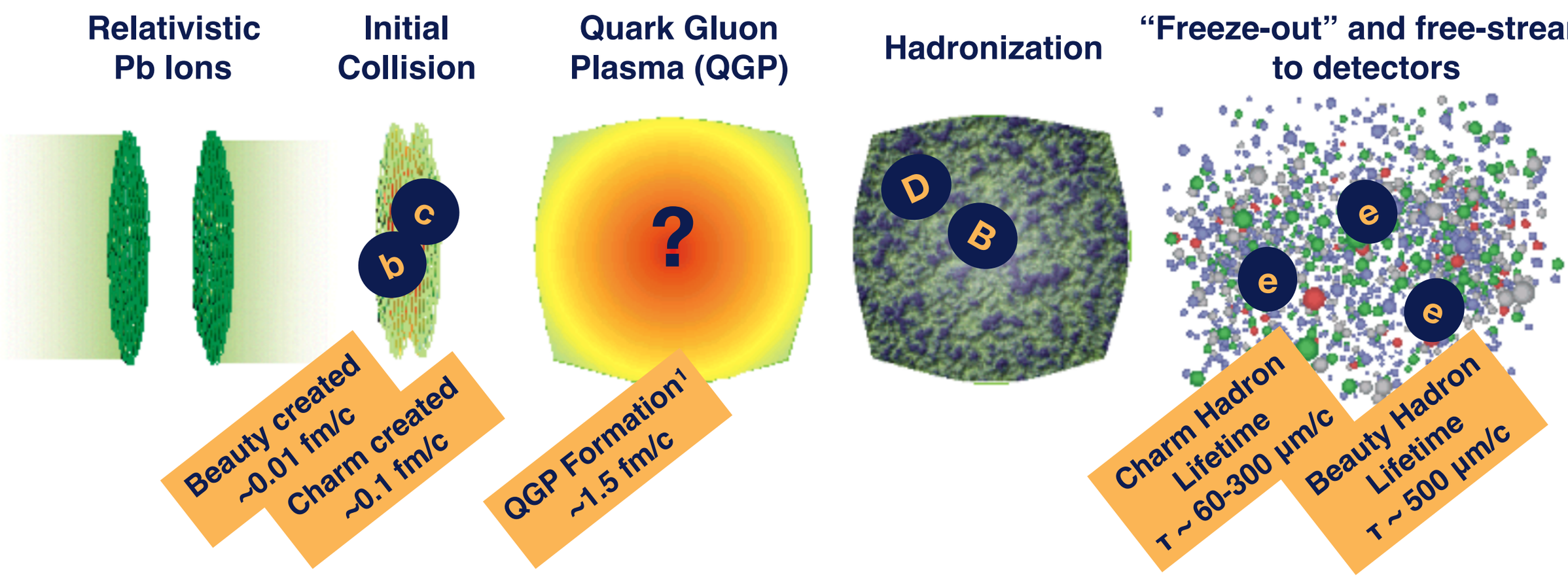
TEXAS

ALICE

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]

Motivation: Collision Systems

Pb-Pb collisions, $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV

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

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

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

pp collisions, $\sqrt{s}$ = 2.76 and 7 TeV

- provides baseline for Pb-Pb collisions
- test perturbative QCD calculations

p-Pb collisions, $\sqrt{s_{NN}}$ = 5.02 TeV

- isolate initial state, cold nuclear matter effects
  - parton distribution function (PDF) modification within Pb ions
  - k_{T} broadening due to intra-nucleus parton interactions
  - energy loss in cold nuclear matter
- investigate the origin of observed collective effects in high-multiplicity events

Motivation: Collision Systems

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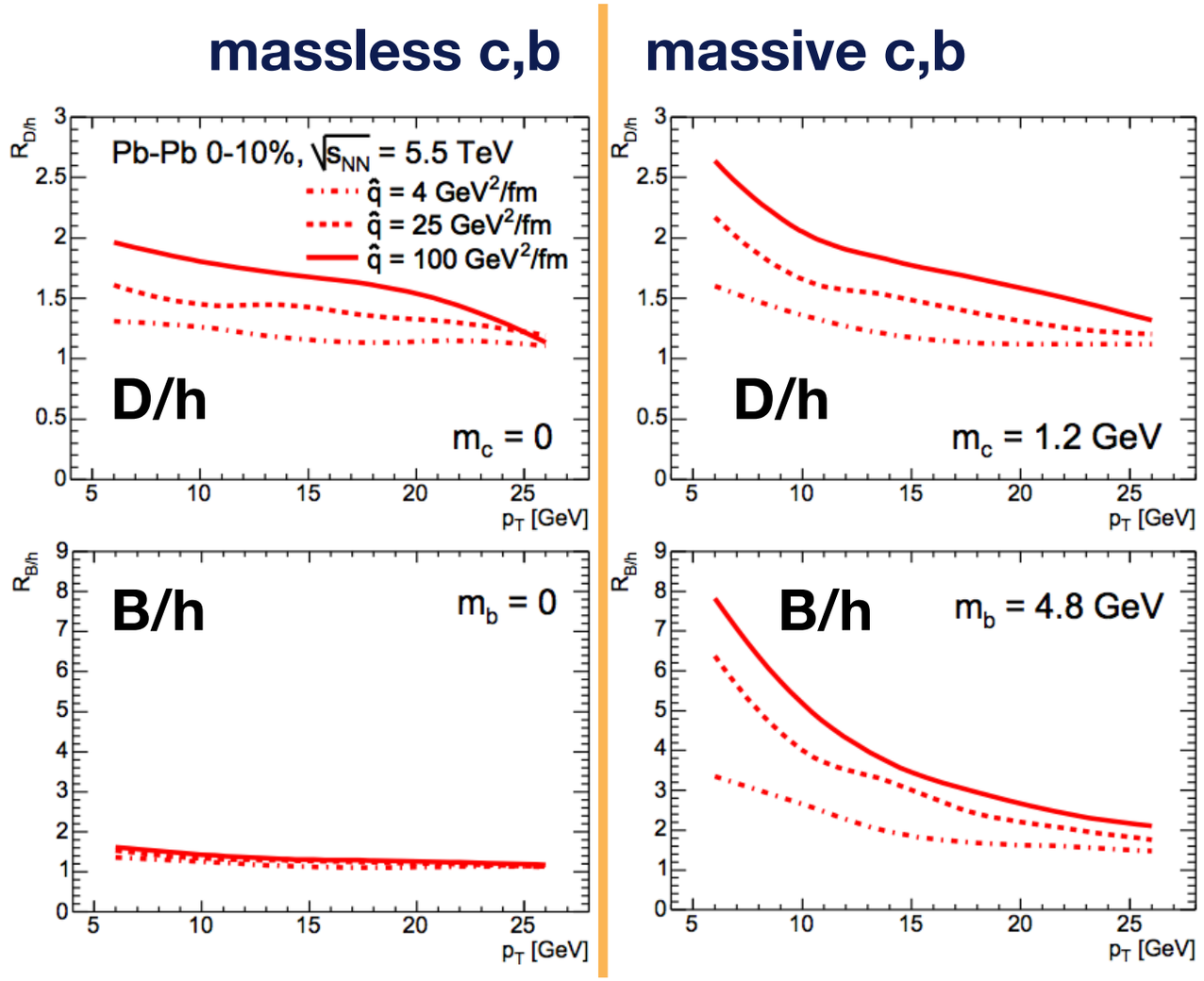
    $M_{gluons} < M_{u,d,s} < M_c < M_b$

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

Where beauty fits in:

- **comparison with charm to test mass dependence of energy loss**
- **mass effects for beauty visible at higher p_T than charm**
  - $m_{charm}/p_T \rightarrow 0$ at high p_T, mass dependence of charm energy loss expected to become negligible



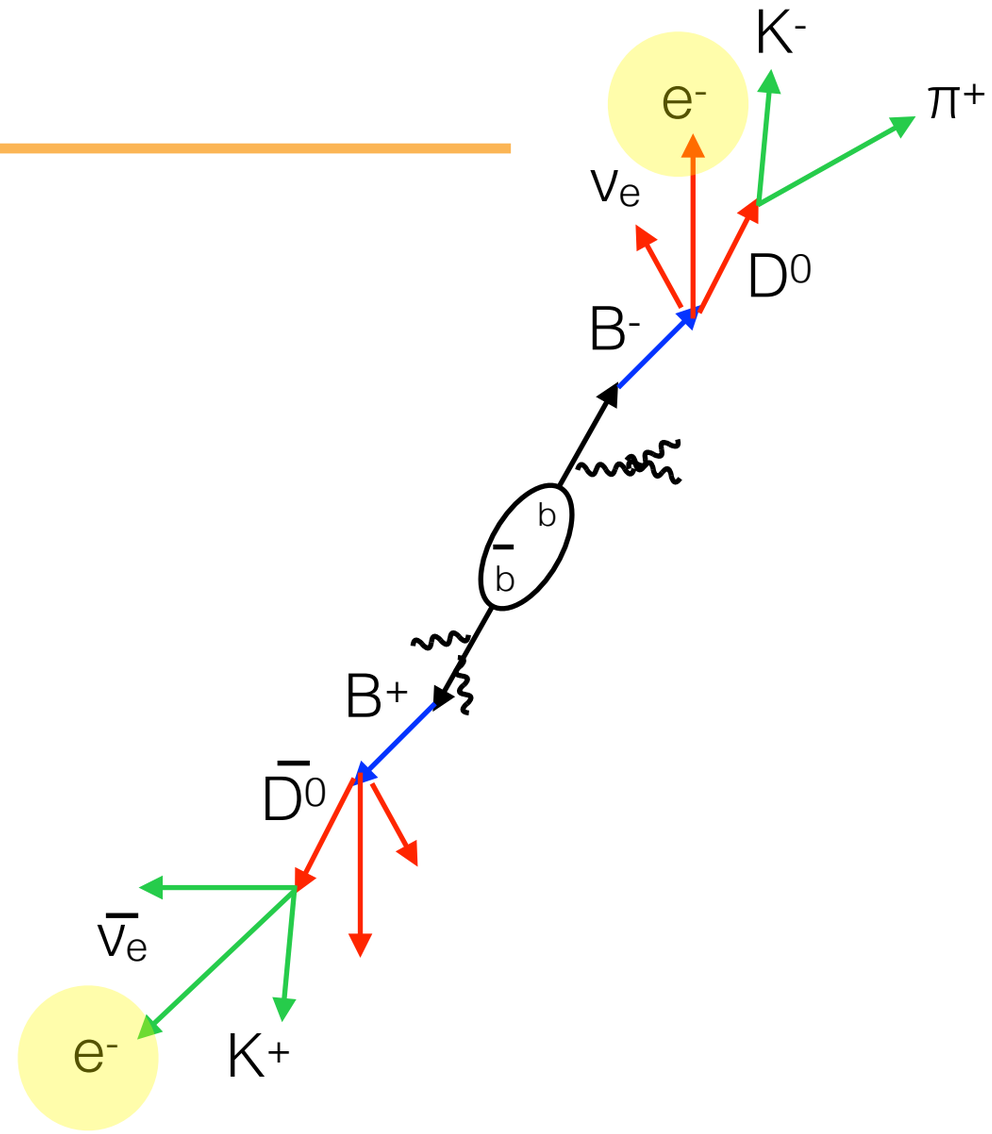
Armesto et al., Phys.Rev.D71:054027 (2005) arXiv:hep-ph/0501225

Beauty in ALICE

In ALICE, beauty measured with the following:

- heavy-flavor (charm + beauty) decay leptons
  - electrons at mid-rapidity
  - muons at forward rapidity*
- beauty-decay electrons (separate charm and beauty via DCA analysis)
- Non-prompt J/ψ*

**not discussed in this talk*



Today, focus on **beauty-decay electron measurements**.

Advantages:

- beauty hadrons have large branching ratios to electronic final states
  - b → e + X (~10%), b (→ c) → e + X (~10%)
  - can trigger on electrons with EMCal to extend our p_T reach

→ large, clean electron signal for differential measurement in p_T (and centrality)

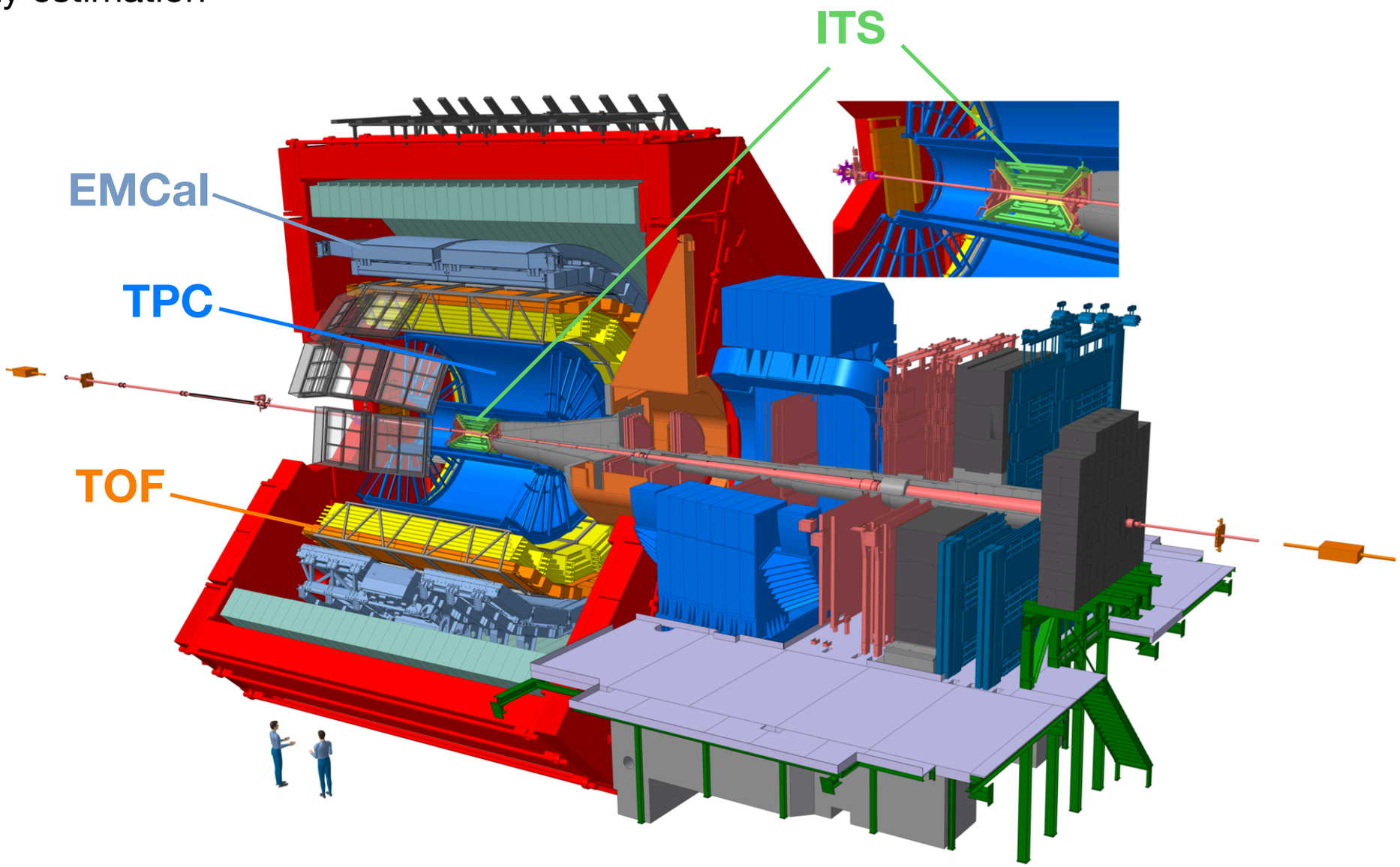
- can compare with measurements of heavy-flavor (charm + beauty) decay electrons

Disadvantages:

- not a direct measurement → does not have full info about the beauty quark
- affected by decay kinematics

Beauty in ALICE

Sub-detectors used in beauty-electron analysis:
Inner Tracking System (ITS) - Tracking + primary vertex reconstruction
Time Projection Chamber (TPC)- Tracking + particle identification
Time-of-flight detector (TOF) - Particle identification
Electromagnetic calorimeter (EMCal) - Particle identification + trigger for high-p_T analysis
V0 - centrality estimation



- Methods -

- Electron identification with TPC, TOF and EMCal
- Subtract background sources of electrons

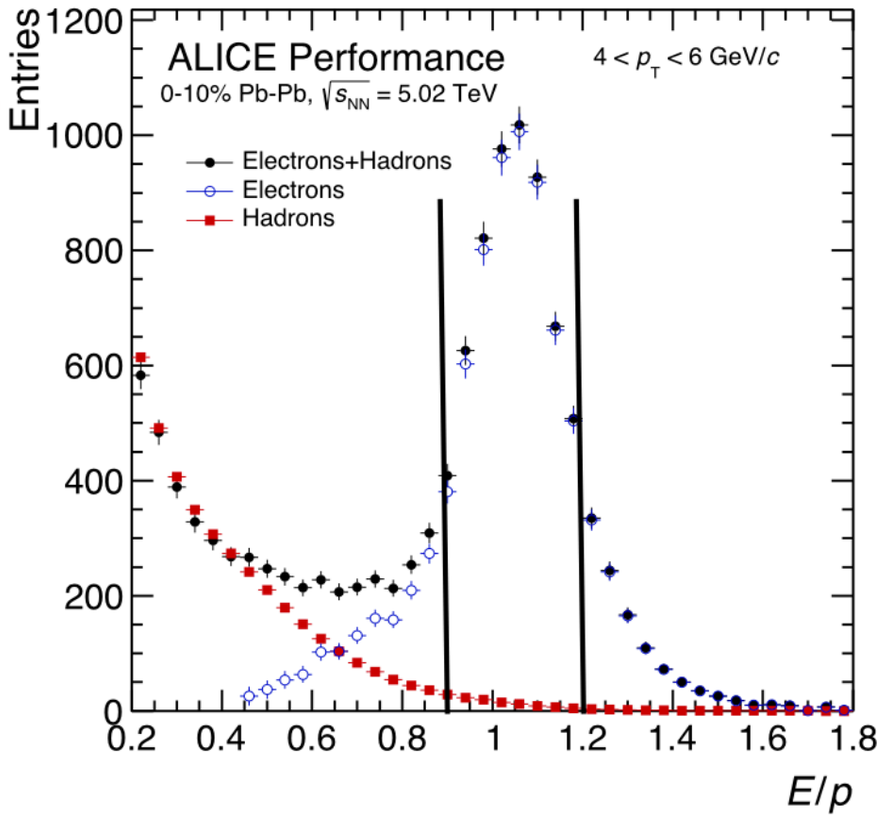
Electron Identification

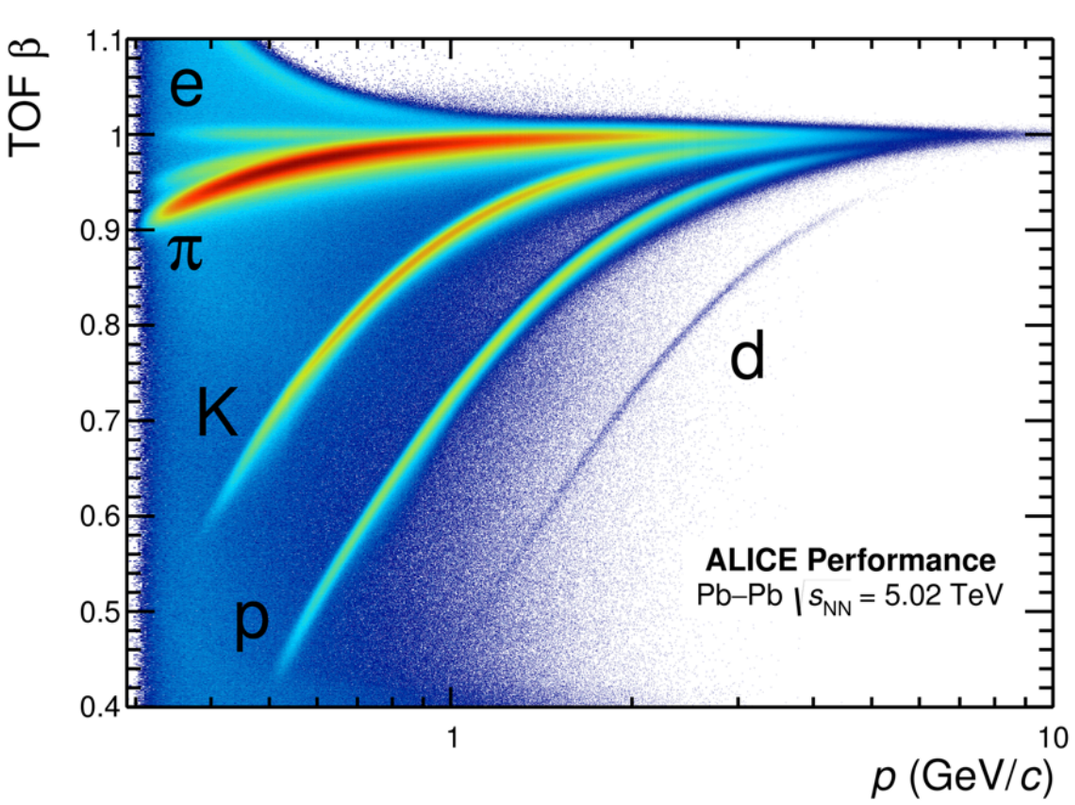
Use the following to identify electrons:

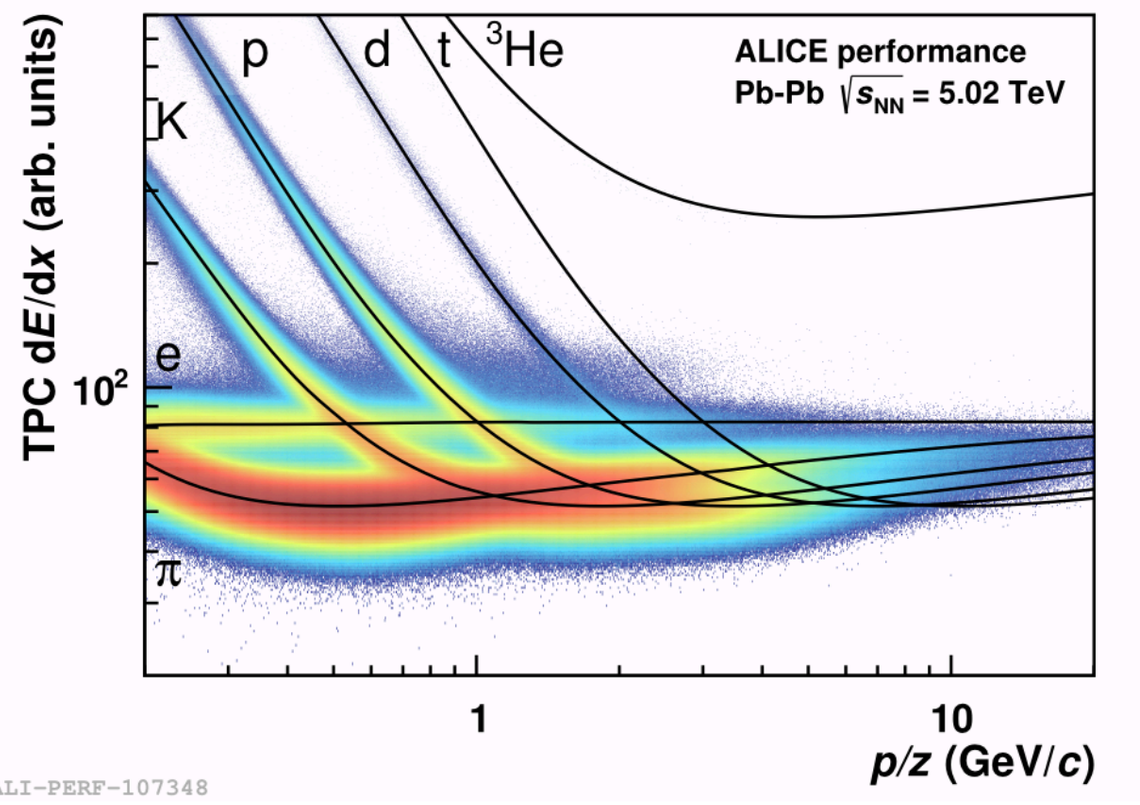
- d*E*/d*x* in the TPC
  - cut on the nσ from the expected electron d*E*/d*x*
- velocity β with the TOF
  - $|n\sigma_{TOF}| < 3$
- energy deposited in the EMCal / track momentum:

$$E/p = \left(\sqrt{m^2 + p^2}\right)/p \approx 1$$

- cuts vary depending on p_T range







- Methods -

- Electron identification with TPC, TOF and EMCal
- Subtract background sources of electrons

Background Subtraction Method 1

- **Subtract non-heavy flavor** background using a data-driven method
- Fit **two** DCA templates to separate charm and beauty electrons

Background Subtraction Method 2

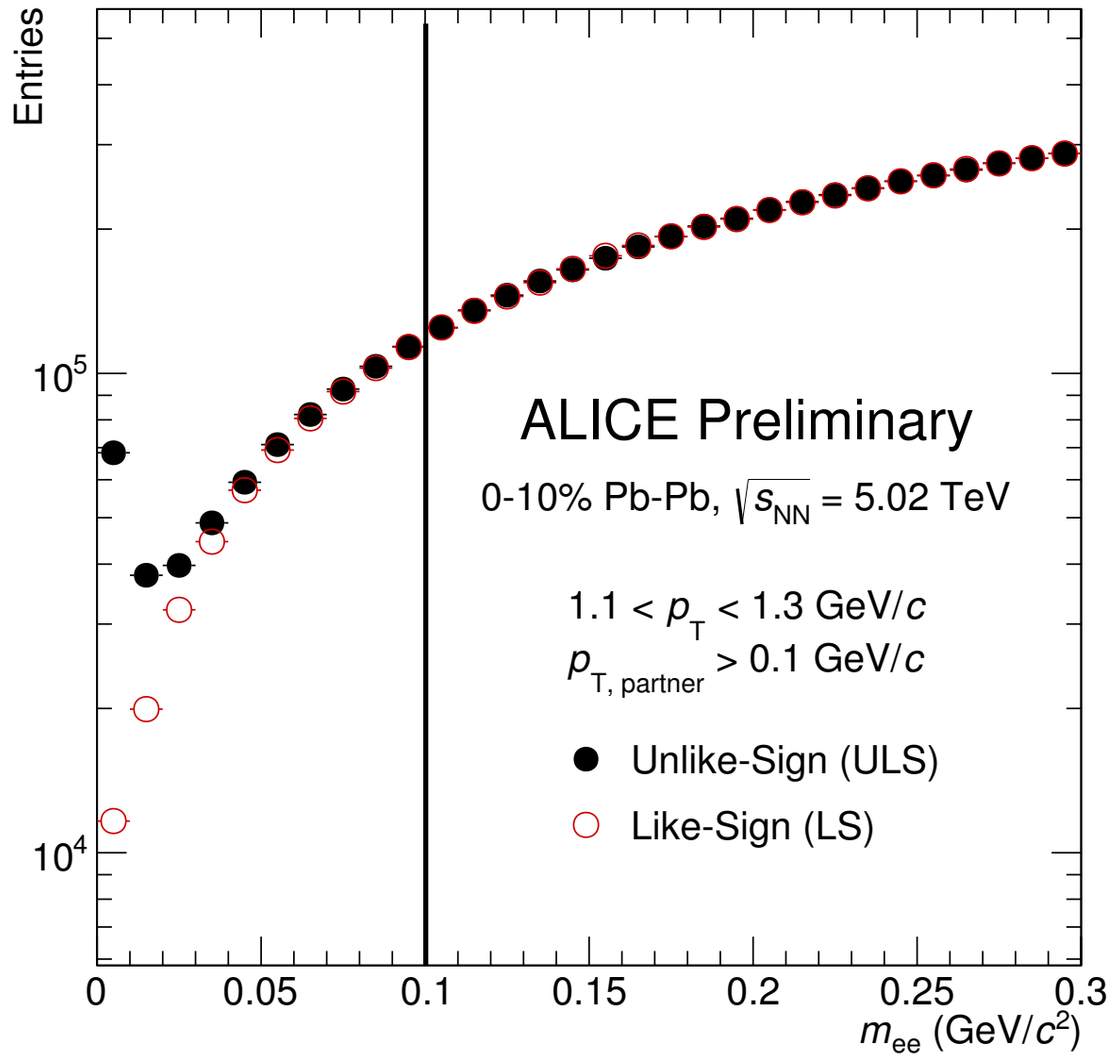
- Fit **four** DCA templates to separate charm, beauty, Dalitz, and photonic conversion electrons

Background Subtraction: Non-Heavy Flavor

- Non-heavy flavor sources (~80% at 1 GeV/*c*, then drops)
  - Dalitz decay from π⁰, η: $\pi^0 \to e^+e^-\gamma$ $M_{\pi^0} \approx 0.135\mathrm{GeV/c^2}$ $M_\eta \approx 548\mathrm{GeV/c^2}$
  - Photonic conversion: $\gamma \to e^+e^-$ $M_\gamma = 0$
- Dominant source of background at low p_T

- Decay mothers have low mass
- Flag electrons that form an invariant mass pair of e^+e^- with $M_{inv} < 0.1$ GeV/c^2
- Remove combinatorial background with like-sign pairs

$$M_{inv} = \sqrt{(E_1 + E_2)^2 - (\boldsymbol{p}_1 + \boldsymbol{p}_2)^2}$$



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- Methods -

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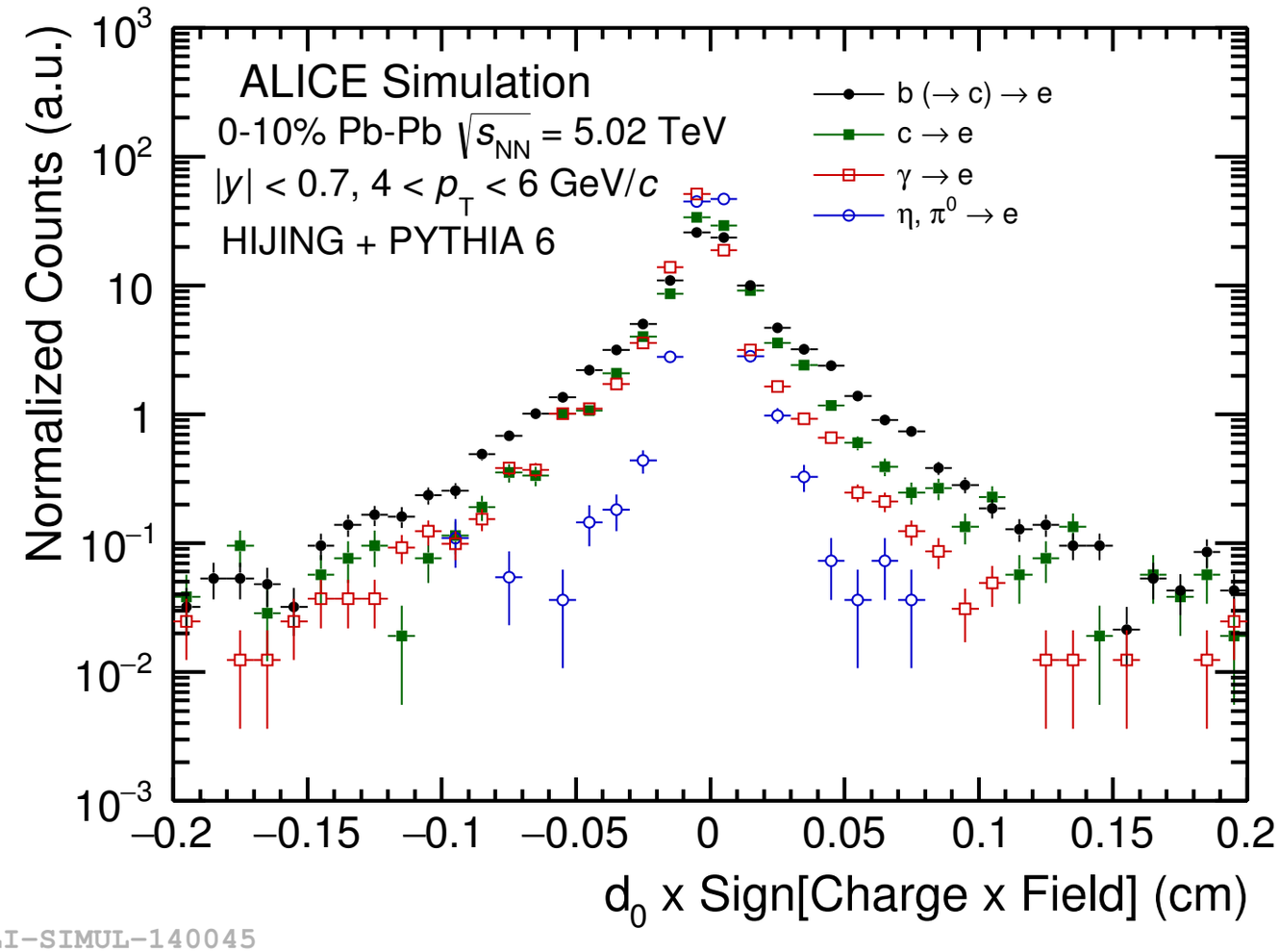
Background Subtraction: Charm-decay

- Charm- and beauty-decay electrons separated using Distance of Closest Approach (DCA or d_0)
- Create DCA templates for c→e and b→e in MC and fit to data
  - Method 2: templates also used to separate Dalitz and conversion electrons

- longer lifetime → larger DCA → wider "template" from MC



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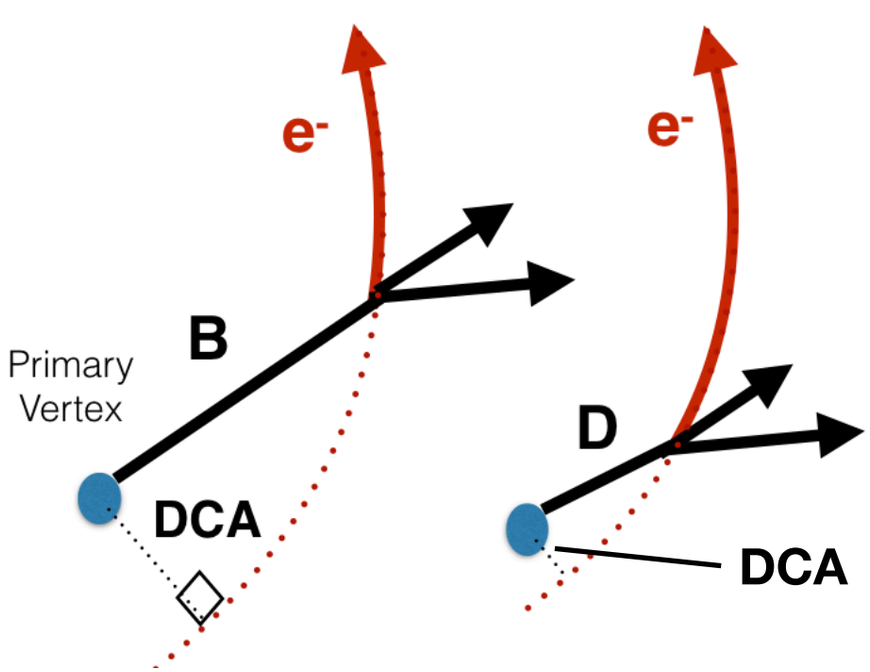
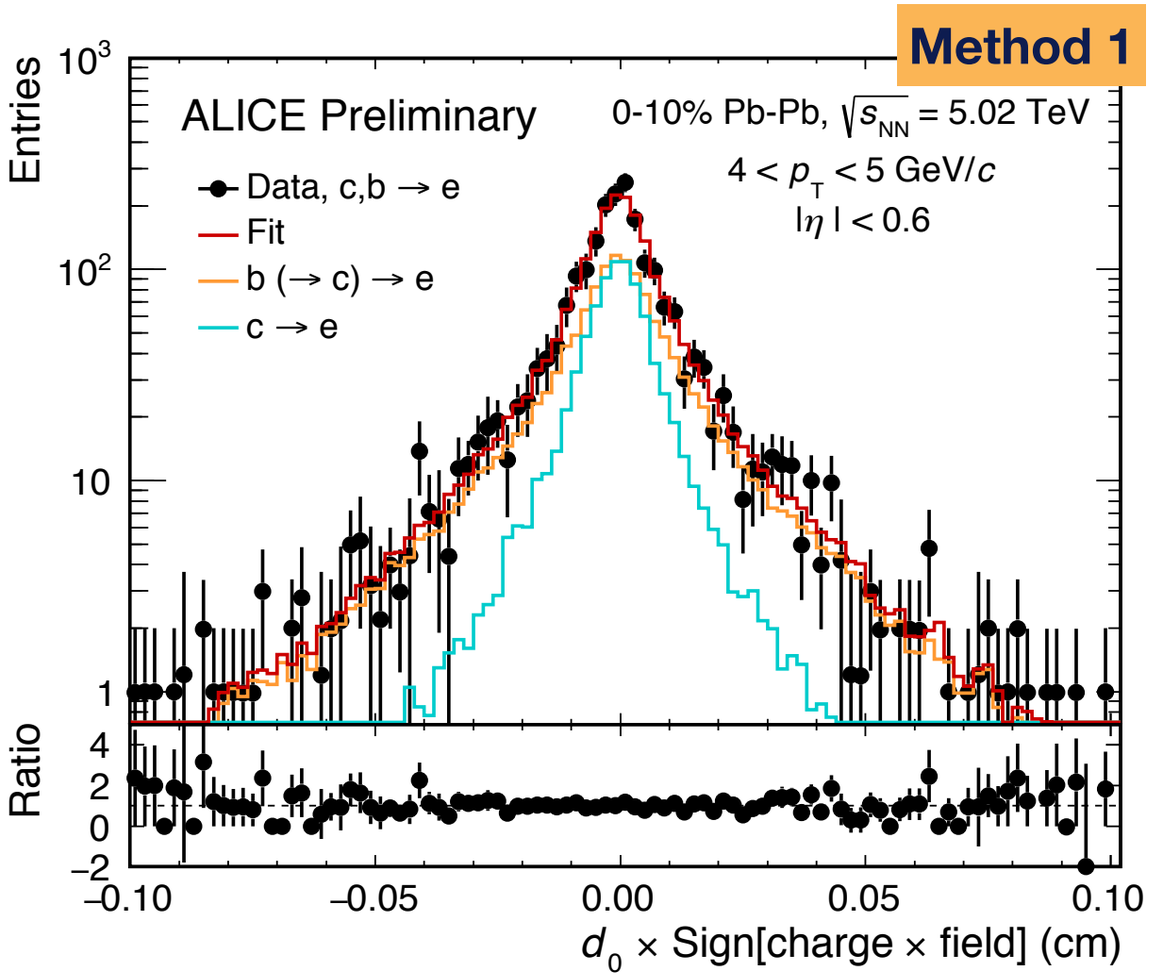
beauty hadrons τ ~ 500 μm/c
charm hadrons τ ~ 60-300 μm/c



Background Subtraction: DCA Template Fitting

- DCA templates made with Monte Carlo simulations
  - corrections made to better match data (e.g. correct resolution to match data)
- Log-likelihood fit method was used
  - Method 1, fit heavy-flavor electron DCA with two templates
  - Method 2, fit electron DCA with four templates



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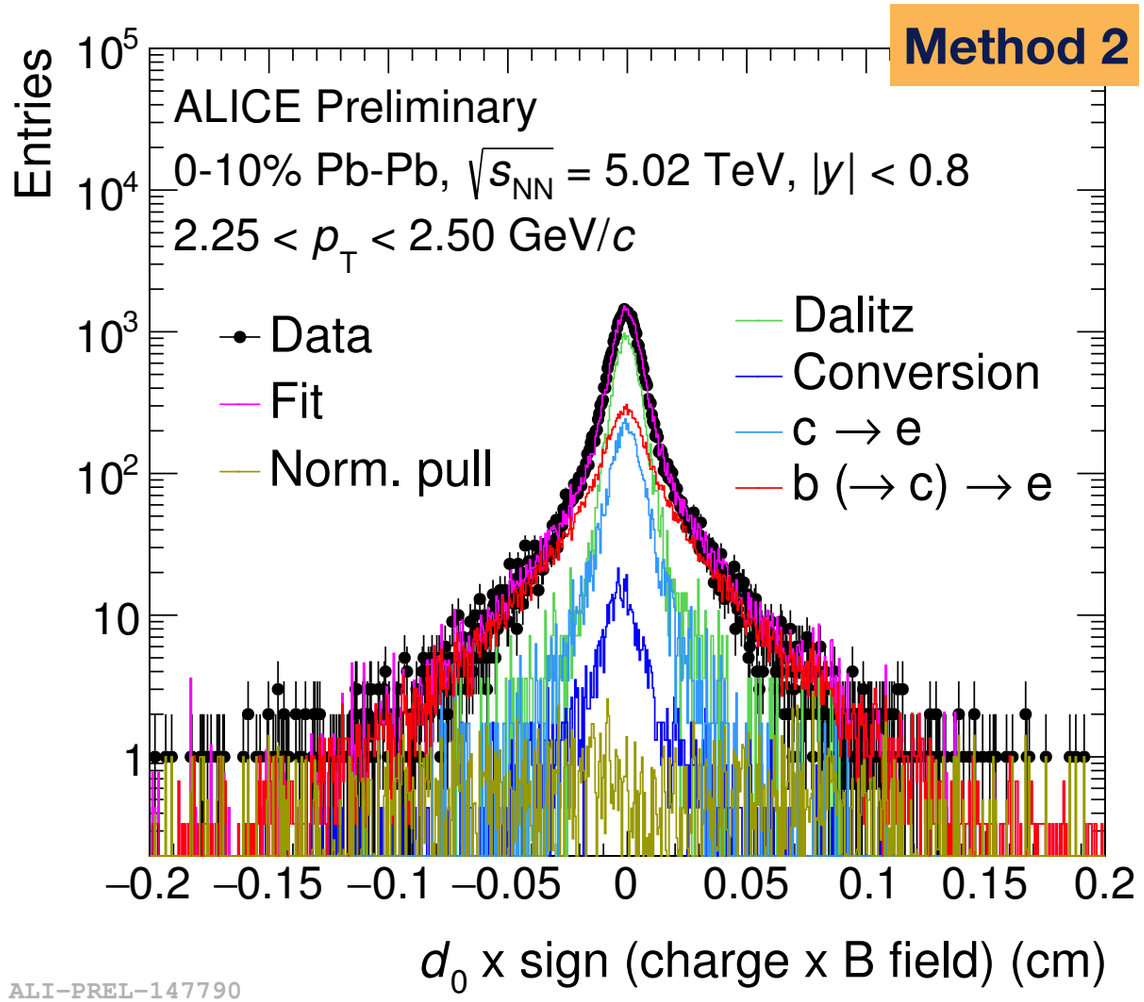

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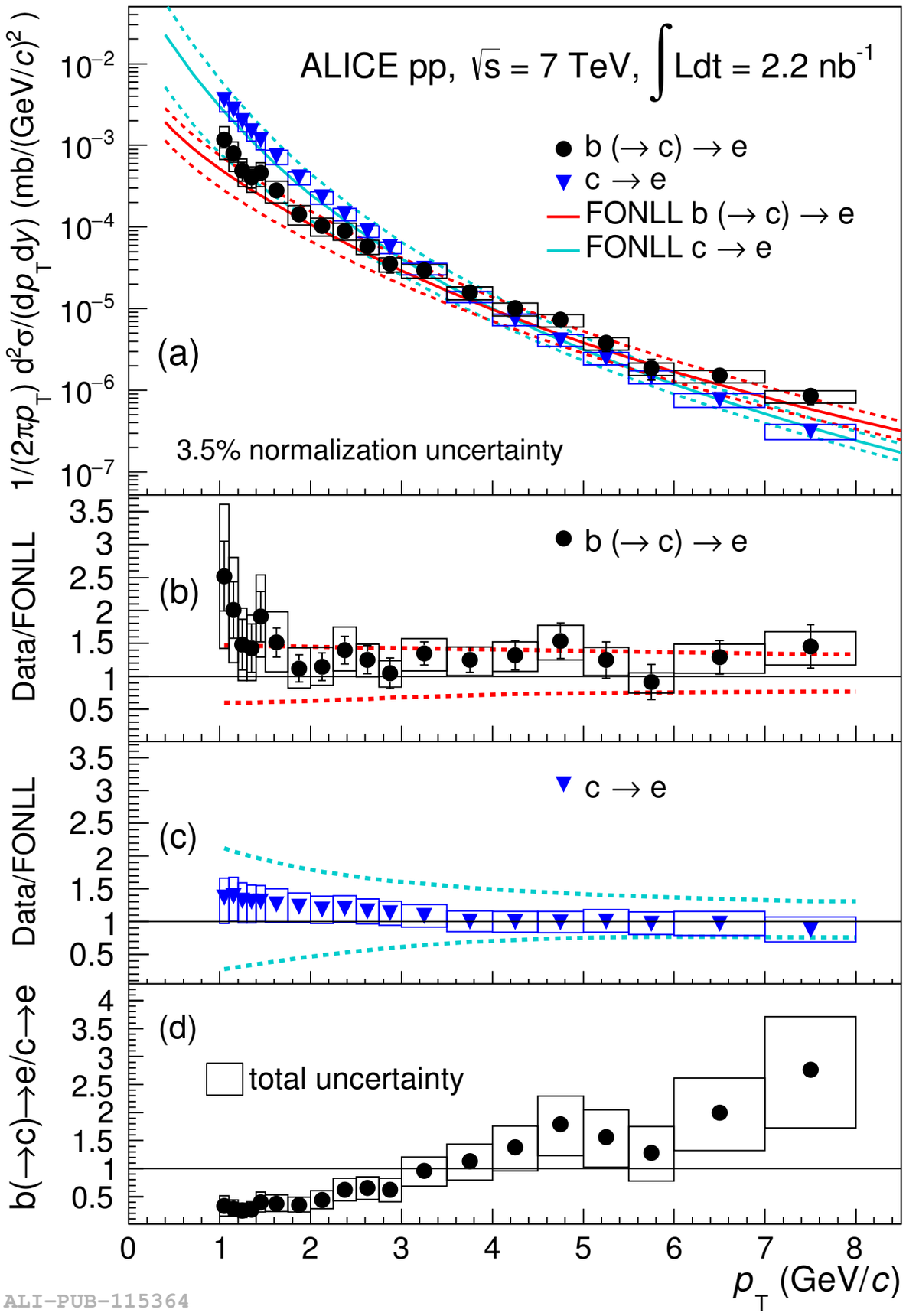
- Results -

pp Results

- b→e and c→e yield in 7 TeV pp collisions
- Both are in agreement with pQCD theory (FONLL)
- Bottom window: b→e/c→e increases with p_T, reaching ~2.75 at 7-8 GeV/c
  - keep in mind for later
- Measurement used a baseline to compare with p-Pb and Pb-Pb results



Phys. Lett. B 721 (2013) 13-23, arXiv:1208.1902

p-Pb Results

- Compare with the yield in pp collisions using the nuclear modification factor (R_{pPb})

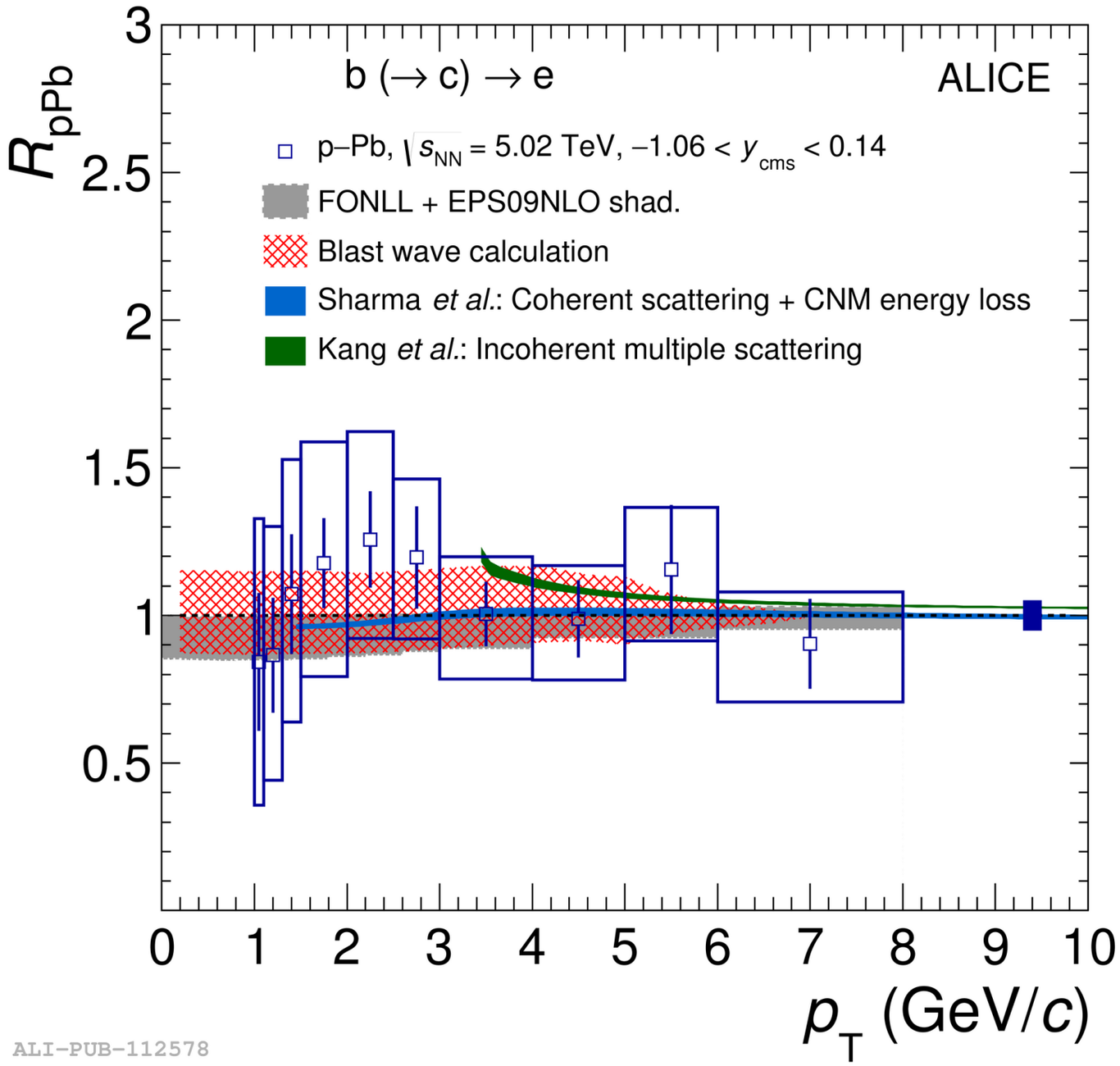
$$R_{pPb} = \frac{dN_{pPb}/dp_T}{\langle T_{pPb} \rangle \cdot d\sigma_{pp}/dp_T}$$

yield in p-Pb

avg. nuclear overlap function

cross-section in pp

JHEP 07 (2017) 052, arXiv: 1609.03898

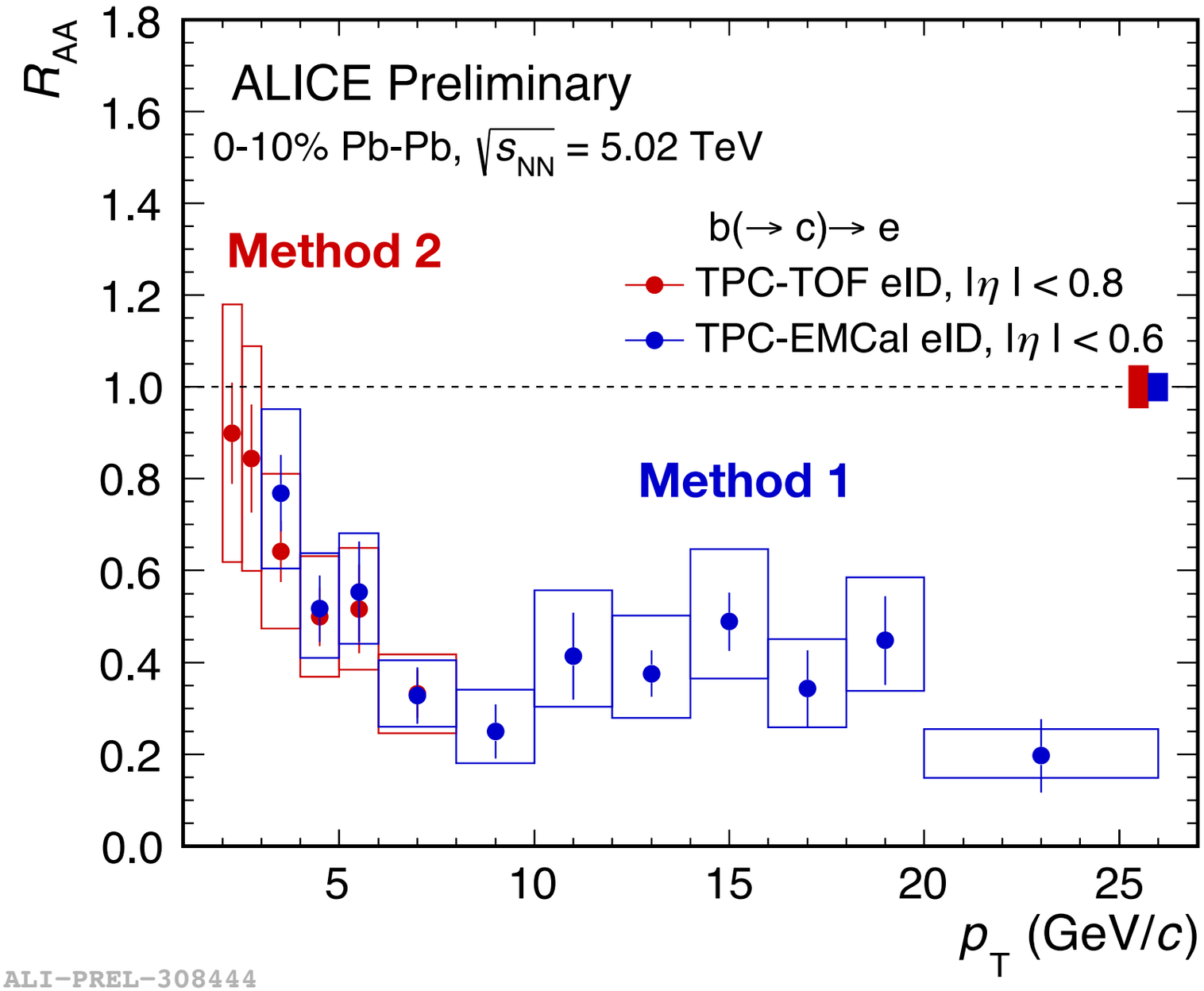


- Within error bars, R_{pPb} is consistent with unity → suggests cold nuclear matter effects are small

- Consistent with models that include cold nuclear matter effects
- **FONLL + EPS09NLO shad.**: pQCD predictions with nuclear modification of the PDFs and shadowing
- **Blast wave**: assumes full thermalization, uses light-flavor hadron spectra to extract parameters
- **Sharma et al.**: CNM energy loss, nuclear shadowing, and coherent multiple scattering of partons
- **Kang et al.**: shows rise at mid-p_{T} may be caused by incoherent multiple scattering

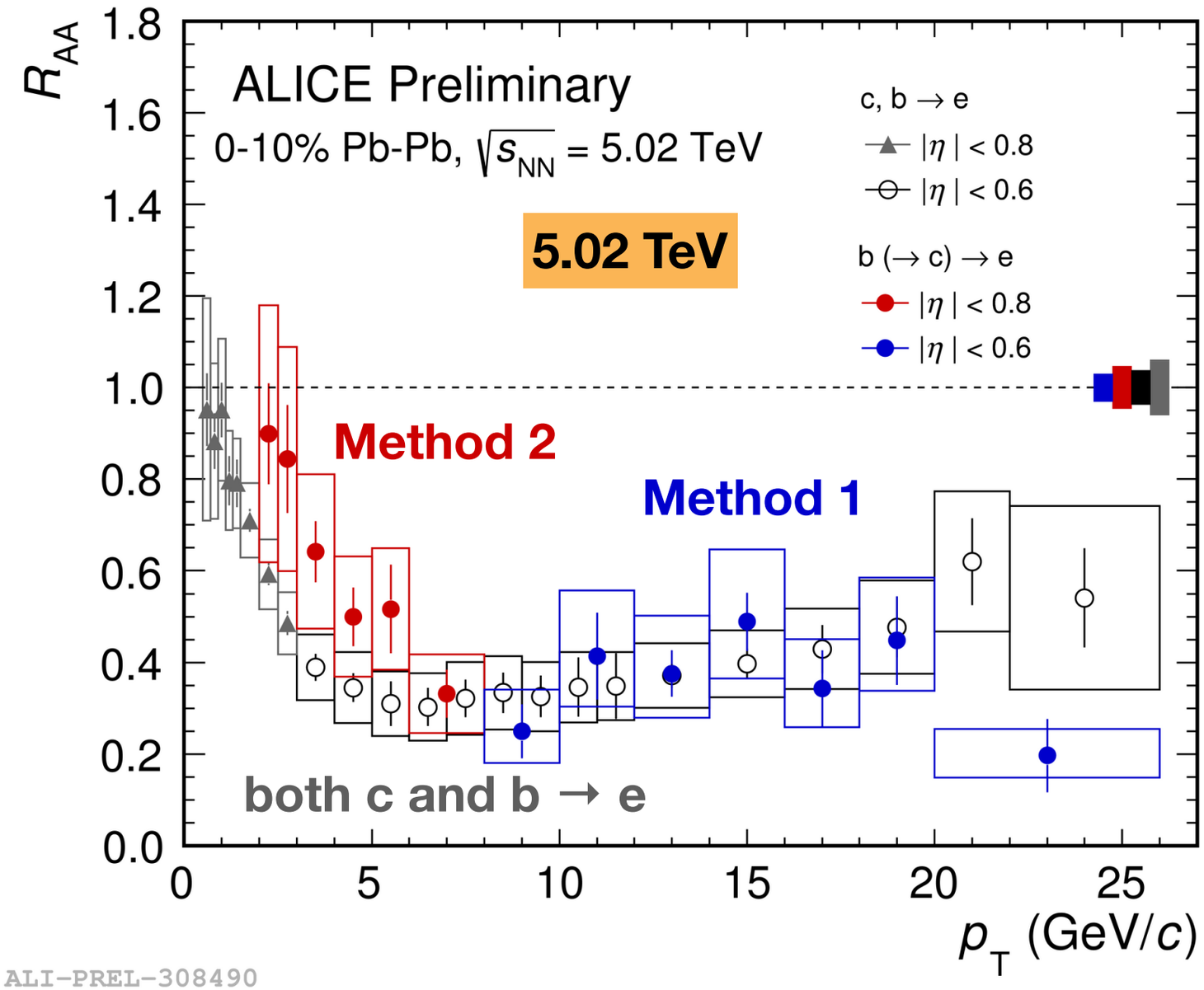
Pb-Pb Results

$$R_{PbPb} = \frac{dN_{PbPb}/dp_T}{\langle T_{PbPb} \rangle \cdot d\sigma_{pp}/dp_T}$$



- $R_{AA} < 1$ → reduced particle yield in Pb-Pb vs. pp, due to energy loss in QGP
  - cannot be explained by CNM effects measured with p-Pb collisions
- Method 1 and 2 agree where they overlap → robust method

Pb-Pb Results: Mass effects?



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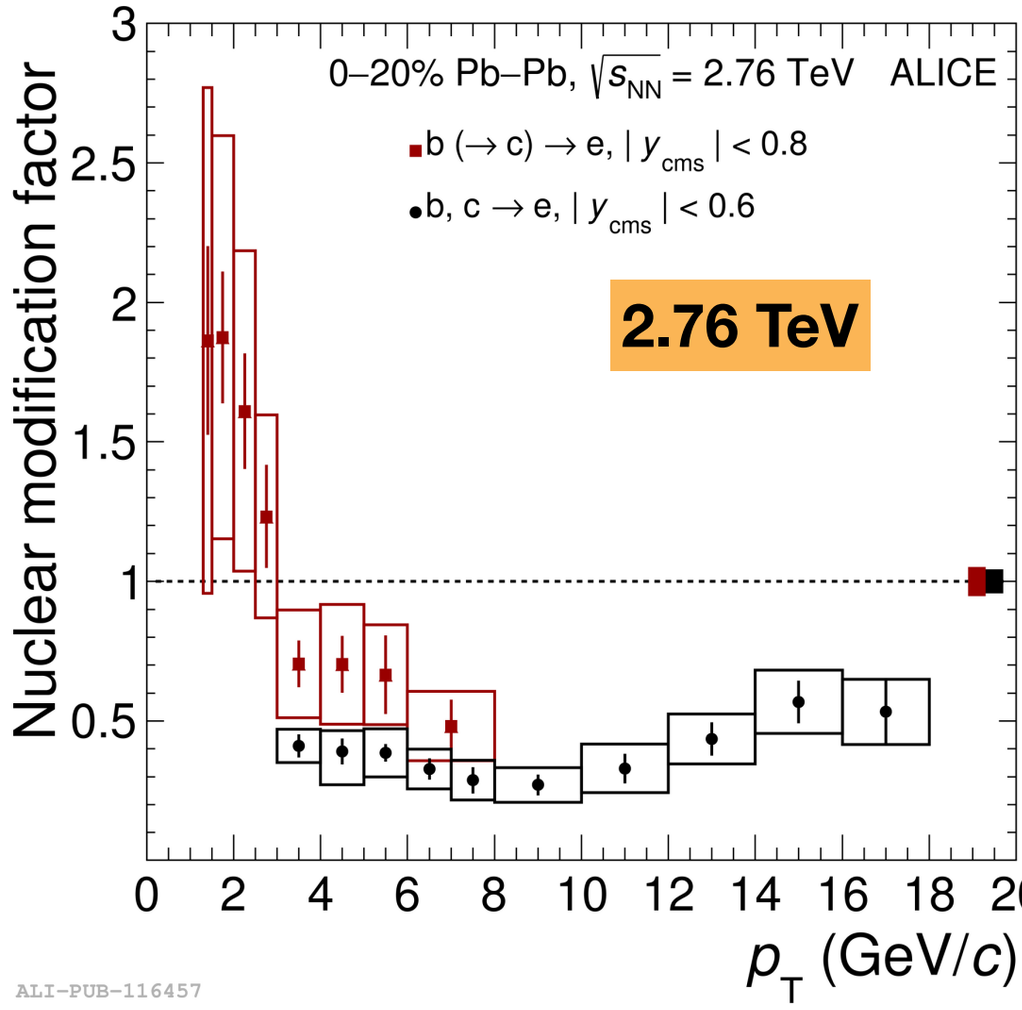
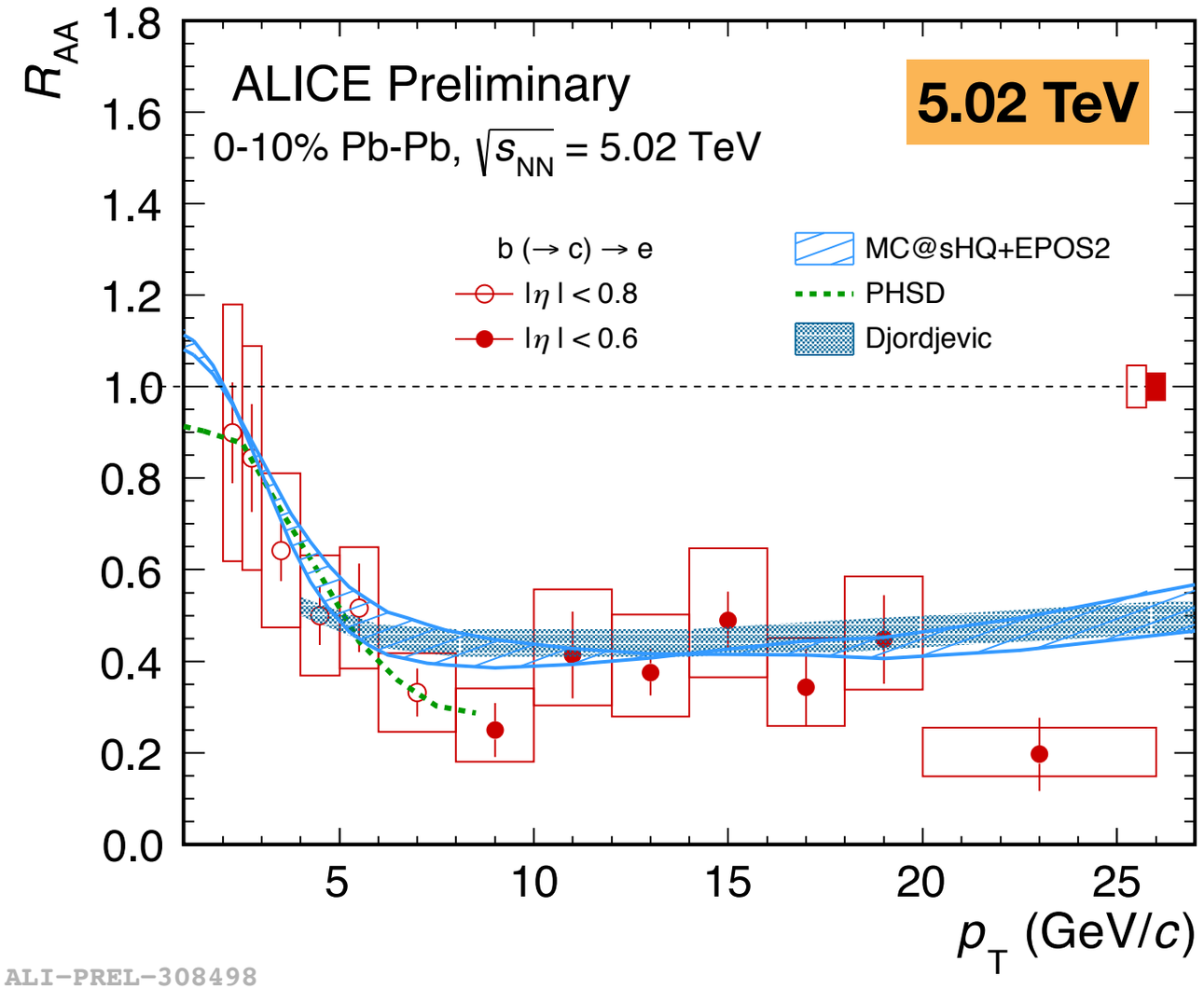


ALI-PUB-116457

JHEP 07 (2017) 052, arXiv: 1609.03898

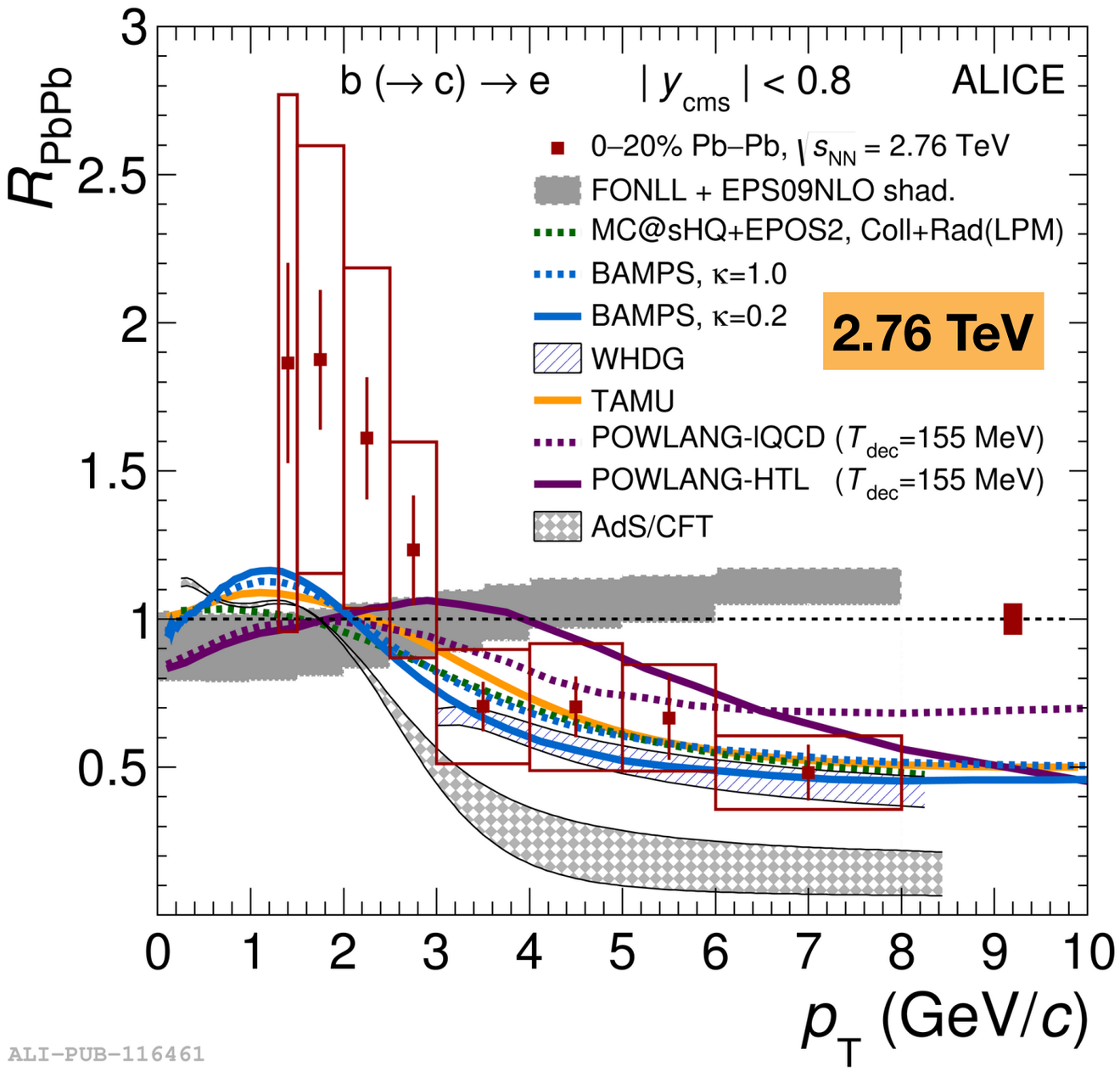
- Compare b→e with combined c,b→e
- See hint that R_{AA}(b→e) > R_{AA}(c,b→e) at low p_T
- High p_T, results fully overlap, recall that b→e/c→e increases with p_T from the pp results

Pb-Pb Results: Model Comparisons



- 5.02 TeV measurement is consistent with models that include both collisional and radiative energy loss
  - MC@sHQ+EPOS2 and PHSD: includes nuclear-modified PDFs (EPS09), PDF shadowing, medium expansion, fragmentation and coalescence
  - Djordjevic: dynamic partons in finite-size medium; no PDF shadowing, medium evolution/ fluid dynamic expansion, or coalescence

Pb-Pb Results: Model Comparisons



JHEP 07 (2017) 052, arXiv: 1609.03898

- Previously published 2.76 TeV results are fairly reproduced by the models shown here
  - AdS/CFT predicts more suppression at high p_T
  - CNM effects (shown with FONLL + EPOS09NLO shad.) does not predict Pb-Pb results
    → extra suppression from hot and dense medium

Conclusion

- **pp results**
  - consistent with pQCD predictions

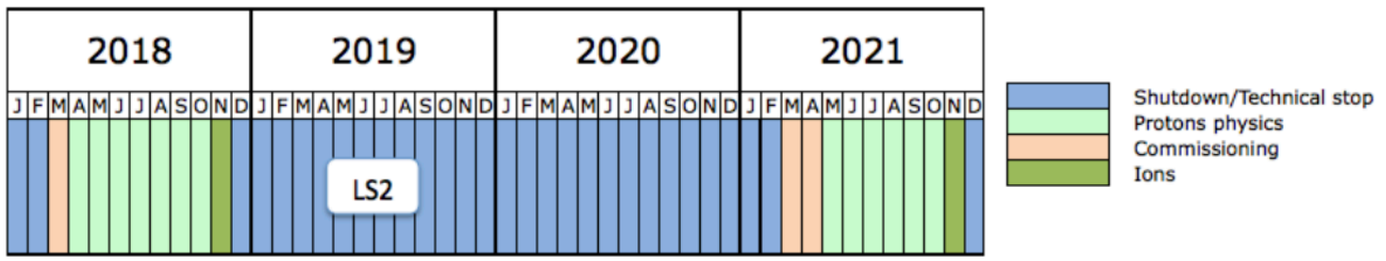
- **p-Pb results**
  - consistent with unity
  - consistent with models that include CNM

→ CNM effects are small

- **Pb-Pb results**
  - agreement using two independent DCA template methods
  - hint of $\Delta E_b < \Delta E_c$, particularly at low p_T
  - agreement with available models

Conclusion and Outlook

- On-going analysis in 5.02 TeV
  - b (→ c) → e R_{AA} at 30-50% in Pb-Pb
  - b (→ c) → e production cross sections in pp



- LHC just started the 2nd long shutdown (LS2) → Run-3 (2021-2023)
  - improved tracking and primary vertex resolution with new ITS
  - Muon-Forward Tracker for charm/beauty muon and J/ψ at forward rapidity
  - ~10x more statistics with higher luminosity and read-out capabilities

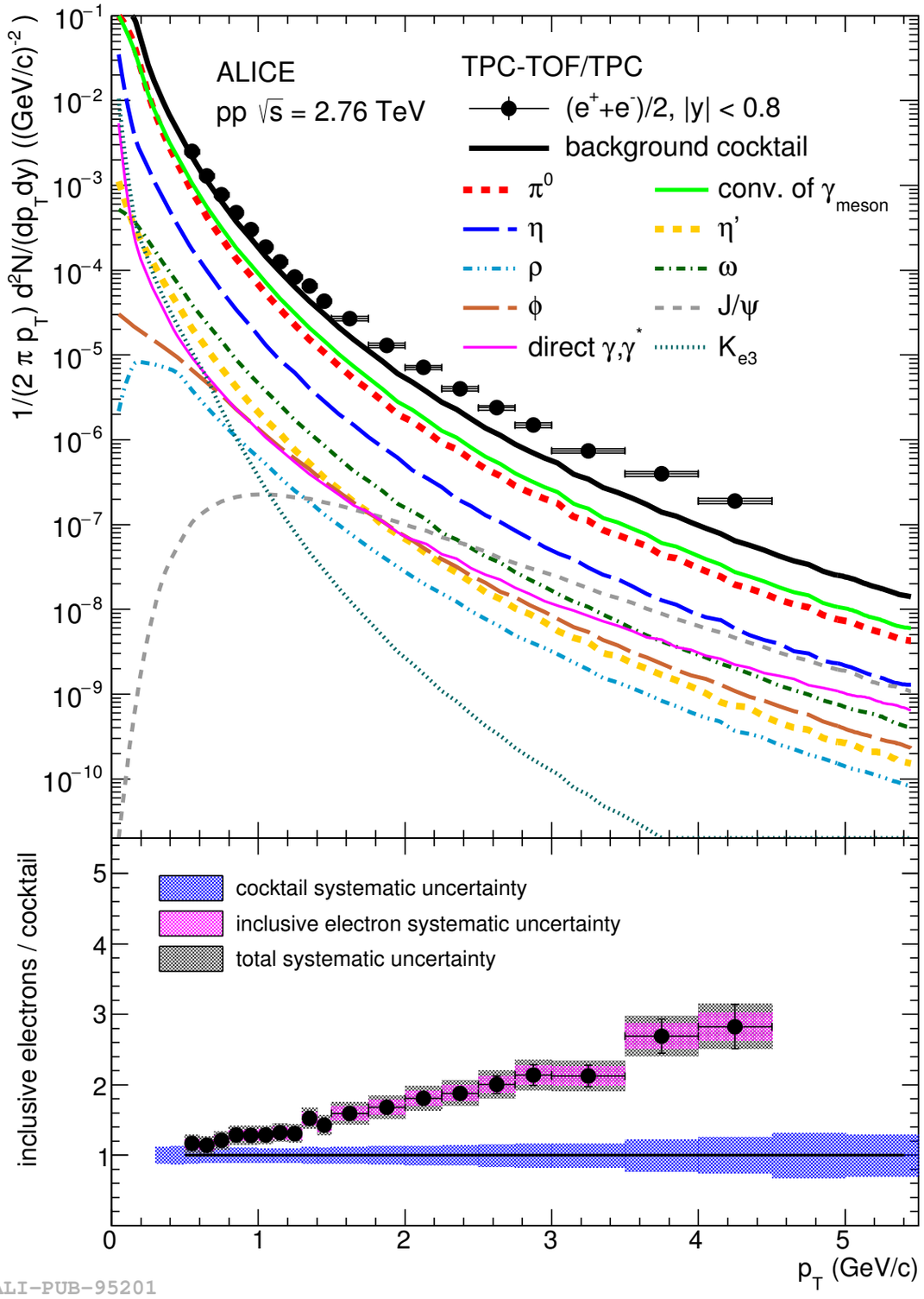
→ New and improved beauty measurements!

- Extend non-prompt J/ψ to low p_T (1 GeV/c)
- Fully-reconstructed B-meson decays (e.g. $B^+ \rightarrow \bar{D}^0\pi^+$) down to 2 GeV/$c$
- Λ_b reconstruction for $p_T > 7$ GeV/c

Technical Design Report for the Upgrade of the ALICE Inner Tracking System J.Phys. G41 (2014) 087002

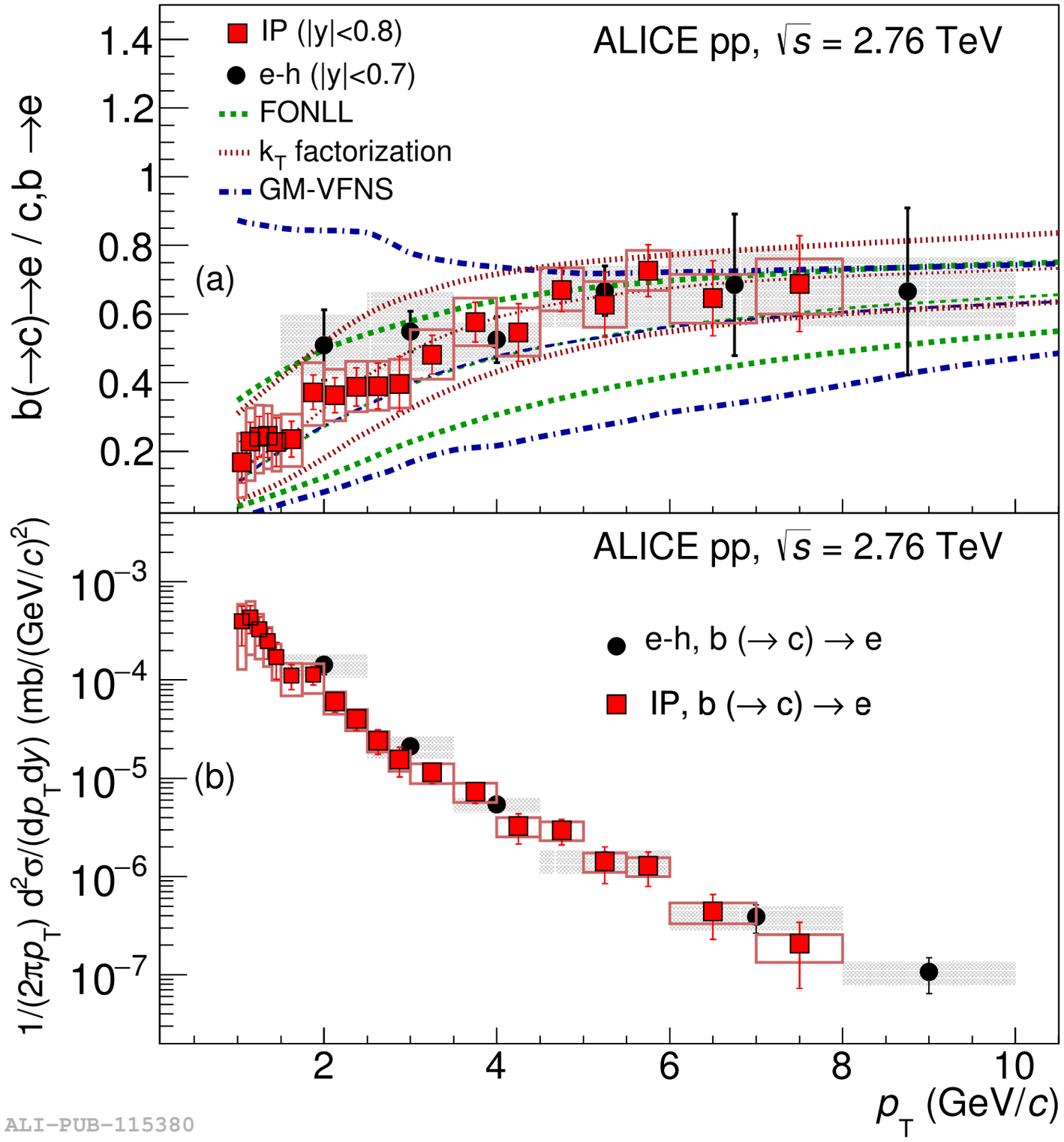
- Back-up -

Background Sources of Electrons



Phys. Rev. D 91 (2015) 012001
arXiv:1405.4117

Fraction b→e in HFe



Phys. Lett. B 738 (2014) 97,
arXiv:1405.4144

Pb-Pb Results

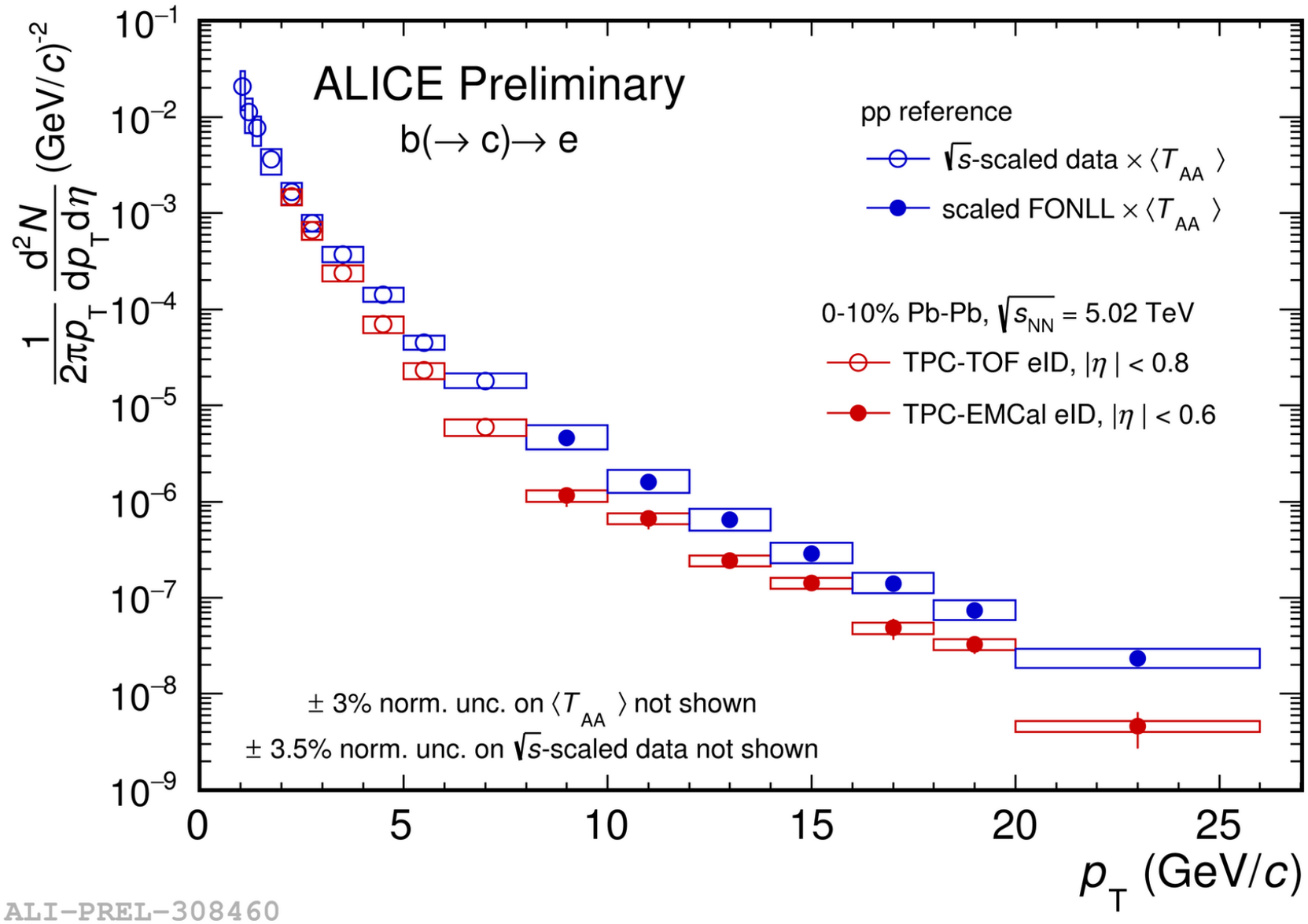
- All this gives the b→e yield in Pb-Pb collisions
- To learn more, we can compare this with the yield in pp collisions using the nuclear modification factor (R_{AA})

No. of binary nucleon-nucleon collisions

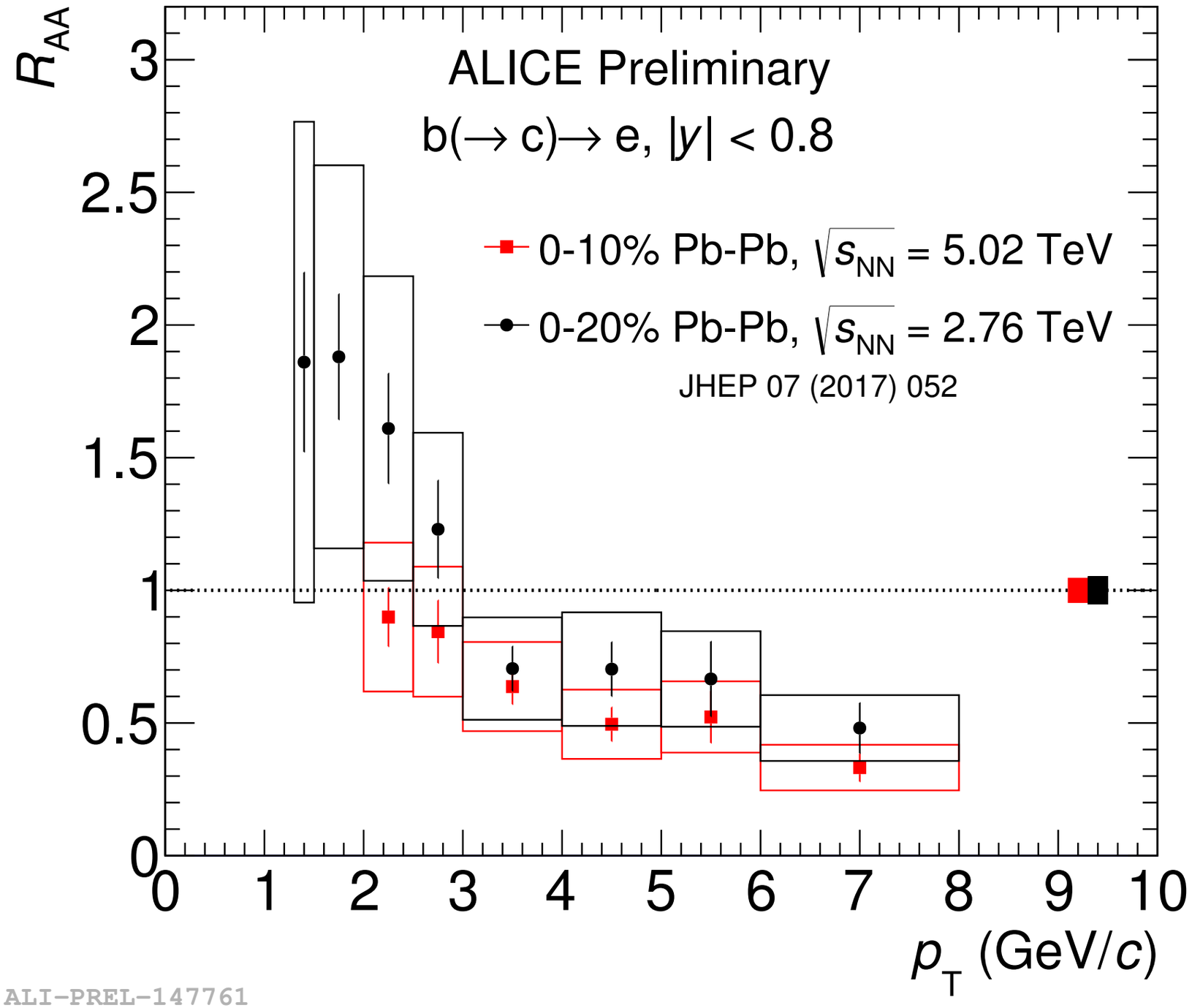
yield in Pb-Pb

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

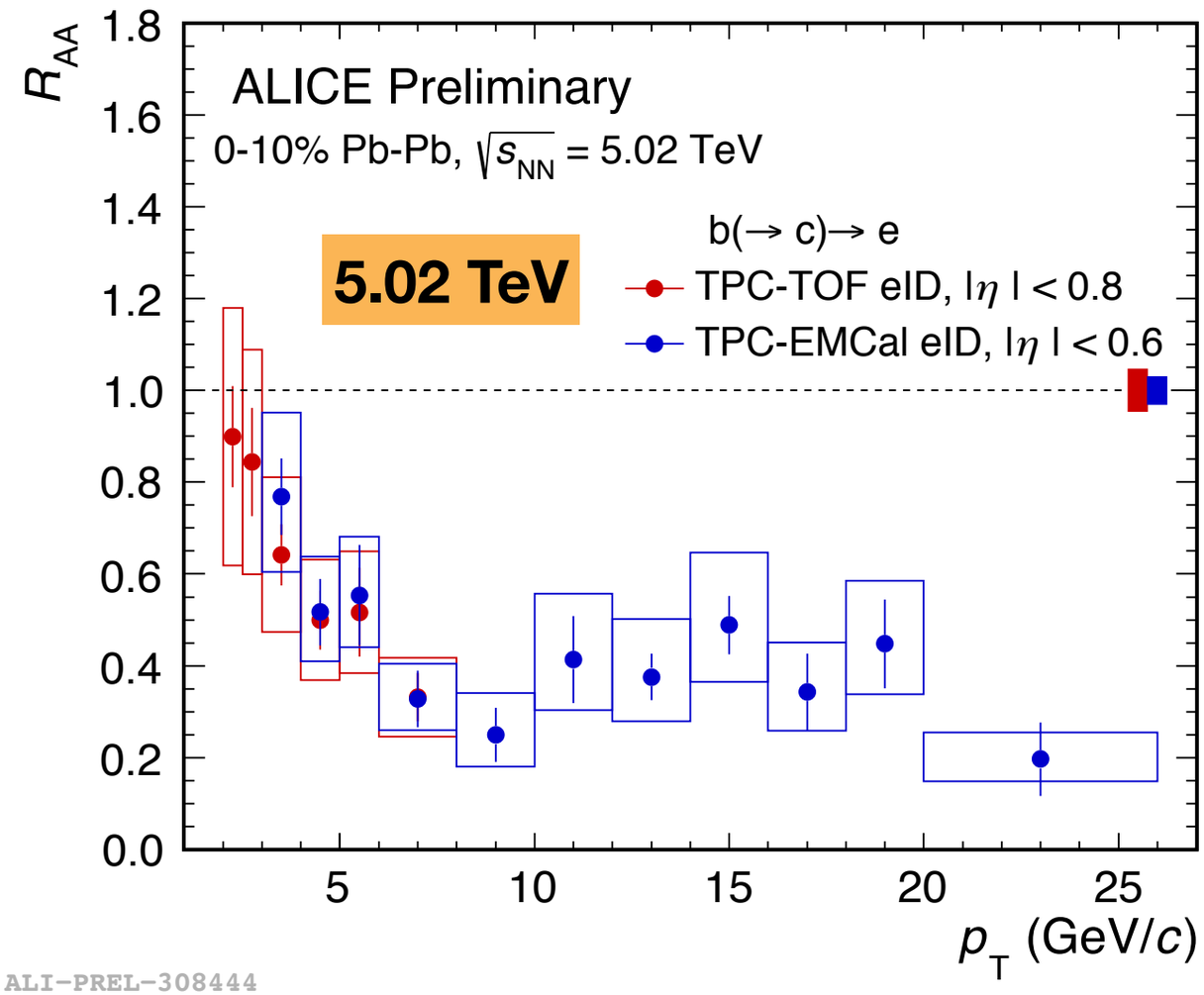
yield in pp



Comparison 2.76 TeV and 5.02 TeV



Pb-Pb + p-Pb Results



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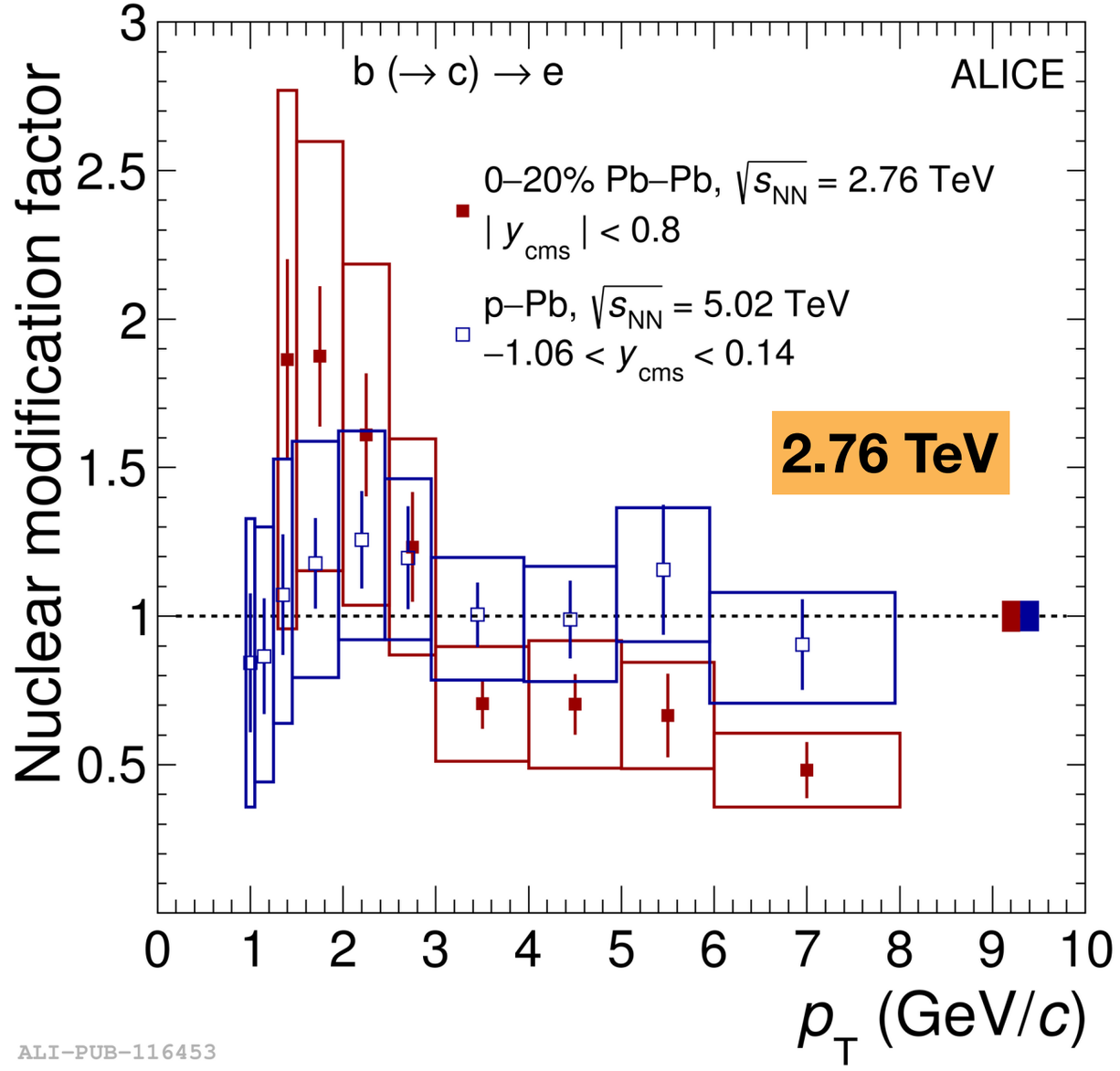

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- $R_{AA} < 1$ → reduced particle yield in Pb-Pb vs. pp, perhaps due to energy loss in QGP
  - **Right plot: R_{pPb} and R_{PbPb} at 2.76 TeV → see suppression in Pb-Pb cannot be explained by cold nuclear matter effects; R_{pPb} consistent with unity**

- The two analyses at low-p_T and higher p_T agree where they overlap → robust method