beauty production in pp and Pb–Pb collisions with ALICE

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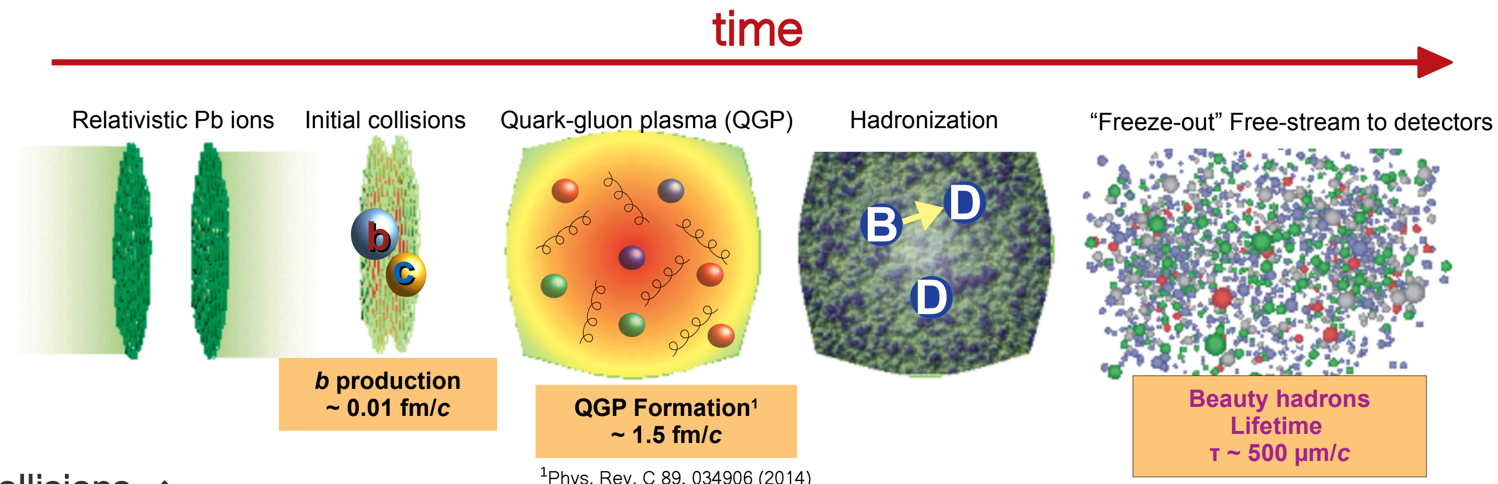
Outline

- Motivation
- Experimental Analysis
- Results
- Summary and Outlook

Motivation

- Heavy flavor quarks (**beauty** & charm) are produced at the early stages of collisions via hard parton-parton scatterings.
- Experience full evolution of heavy ion collisions.



[1]Phys. Rev. C 89, 034906 (2014)

Pb-Pb collisions ➞

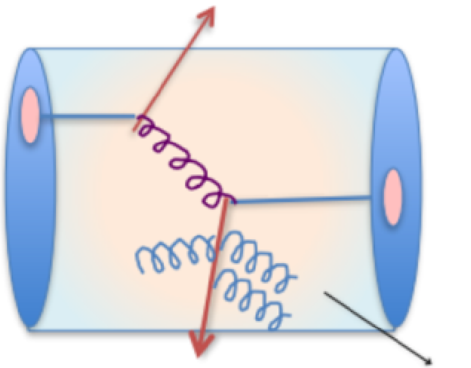
- The QGP - quark-gluon plasma, state of matter in which partons are deconfined
- Interaction of ***b*** and ***c*** quarks in the QGP and their energy loss (depends on quark mass)

***pp* collisions ➞**

- Test of perturbative quantum chromodynamics (pQCD)
- Provides a reference to study the larger collision systems (p-Pb, Pb—Pb)

Experimental Observables

- Nuclear Modification factor (***R*****AA**)
  - Efffects of energy loss can be studied using R_{AA}



Inealstic nucleon-nucleon cross section

transverse-momentum differential production yields in nucleus-nucleus collisions

$$R_{\mathrm{AA}} = \frac{\sigma_{\mathrm{inel}}^{\mathrm{pp}}}{\langle N_{\mathrm{coll}} \rangle} \cdot \frac{dN_{\mathrm{AA}}/dp_{\mathrm{T}}}{d\sigma_{\mathrm{pp}}/dp_{\mathrm{T}}}$$

Average number of binary nucleon-nucleon collisions

Differential production cross section of particles in pp collisions

$R_{\mathrm{AA}} = 1$: Pb–Pb behaves as scaled pp collisions
$R_{\mathrm{AA}} < 1$: Suppression observed by the medium (QGP)

Energy loss in QGP:

→ Heavier quarks loss less energy in the medium:

- $m_{u,d,s} < m_c < m_b$
- $\Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

Experimental Observables

- **Collective flow**
  - In the non-central collisions, overlap region is asymetric
    - → **Collective motion is azimuthally dependent**
  - Azimuthal dependence of particle production can be characterized by Fourier expansion:

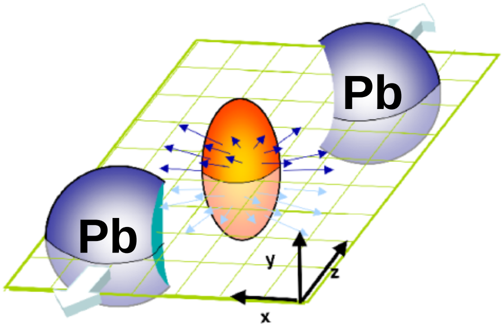
Reaction -plane angle

$$E\frac{d^3N}{d^3\mathbf{p}} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_{RP})]\right)$$

Flow-coefficients

  - Elliptic flow (ν_2) → Most dominant in contribution in azimuthal dependence

$$v_2 = \langle\cos[2(\phi - \Psi_{RP})]\rangle$$



- ν_2 of beauty-hadrons (or their decay products) is important to study the interaction of *b*-quark with the QGP

The ALICE experiment

- **Central-barrel coverage: | η | < 0.9**
- **Muon spectrometer coverage: - 4 < η < -2.5**

Integrated Luminosity for √s = 5.02 TeV

- pp collisions $\mathcal{L}_{int} \sim 19.3\ nb^{-1}$
- Pb–Pb collisions
  - 2015: $\mathcal{L}_{int} \sim 13\ \mu b^{-1}$
  - 2018: (0 -10%) $\mathcal{L}_{int} \sim 130\ \mu b^{-1}$
  - 2018: (30-50%) $\mathcal{L}_{int} \sim 56\ \mu b^{-1}$

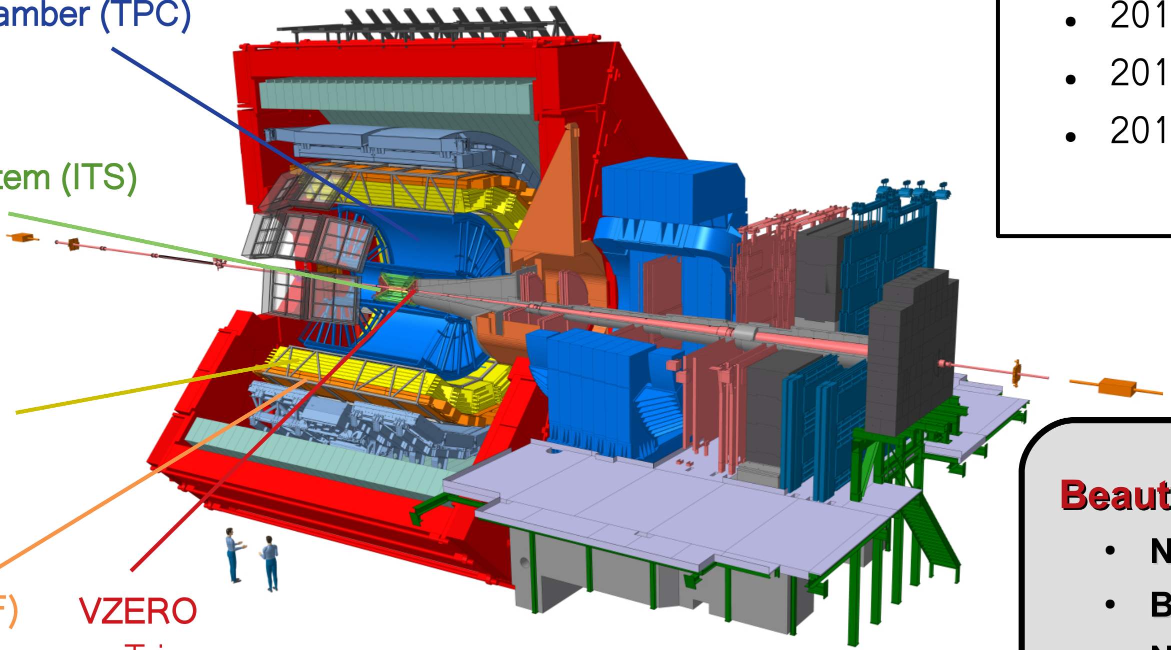
Time projection Chamber (TPC)
- Tracking
- PID

Inner Tracking System (ITS)
- Primary vertex reconstruction
- Tracking
- PID

Tracking Radiation Detector (TRD)
- Tracking

Time-of-flight (TOF)
- PID

VZERO
- Trigger
- Centrality determination

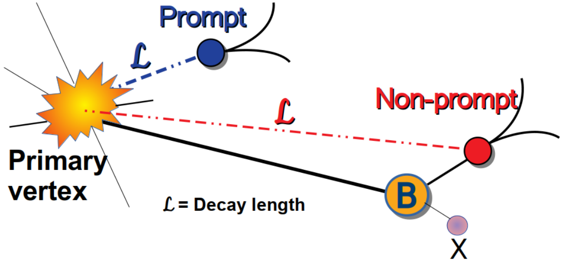


Beauty measurements in this talk:
- **Non-prompt D meson (b→D)**
- **B-decay electrons (b→e)**
- **Non-prompt J/Ψ (b→J/Ψ)**

Analysis Procedure

b→D & b→J/Ψ

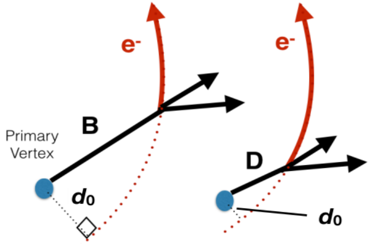
- Signal extraction through invariant mass analysis
- ML techniques used to separate prompt D mesons, non-prompt D mesons and combinatorial background
- b→J/Ψ fraction is measured by unbinned likelihood fits on invariant mass and pseudoproper decay length

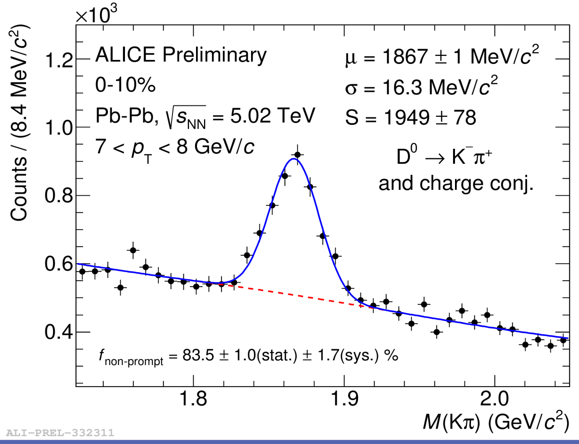


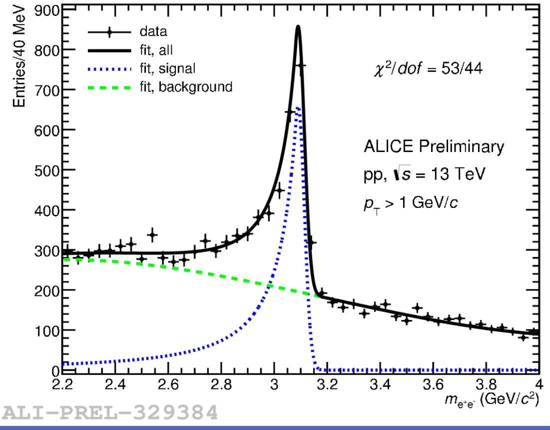
b hadrons cτ ~ 500 μm
c hadrons cτ < 300 μm

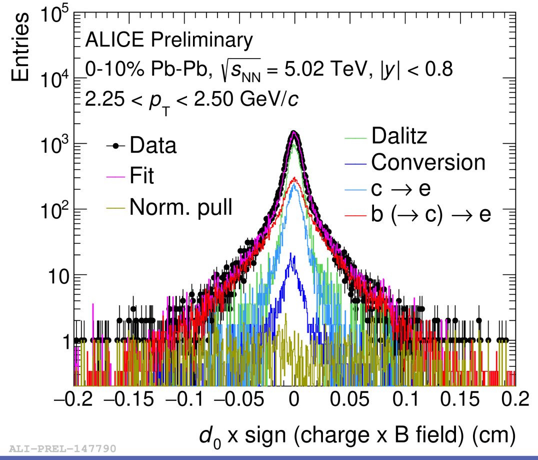
b→e

- Separated using distance to closest approach (d_0)
- Longer lifetime → larger d_0
- Template fit on impact parameter distribution

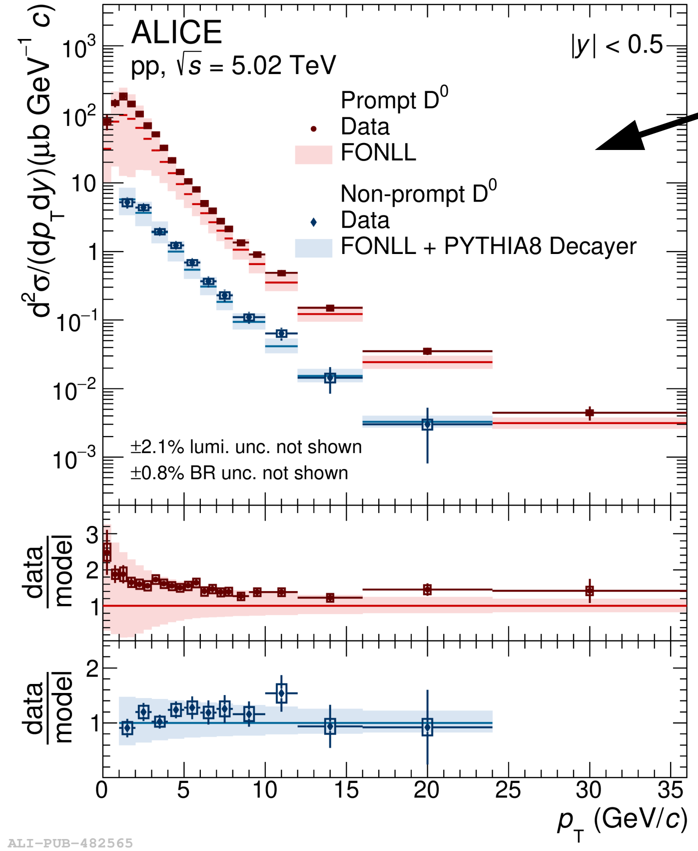








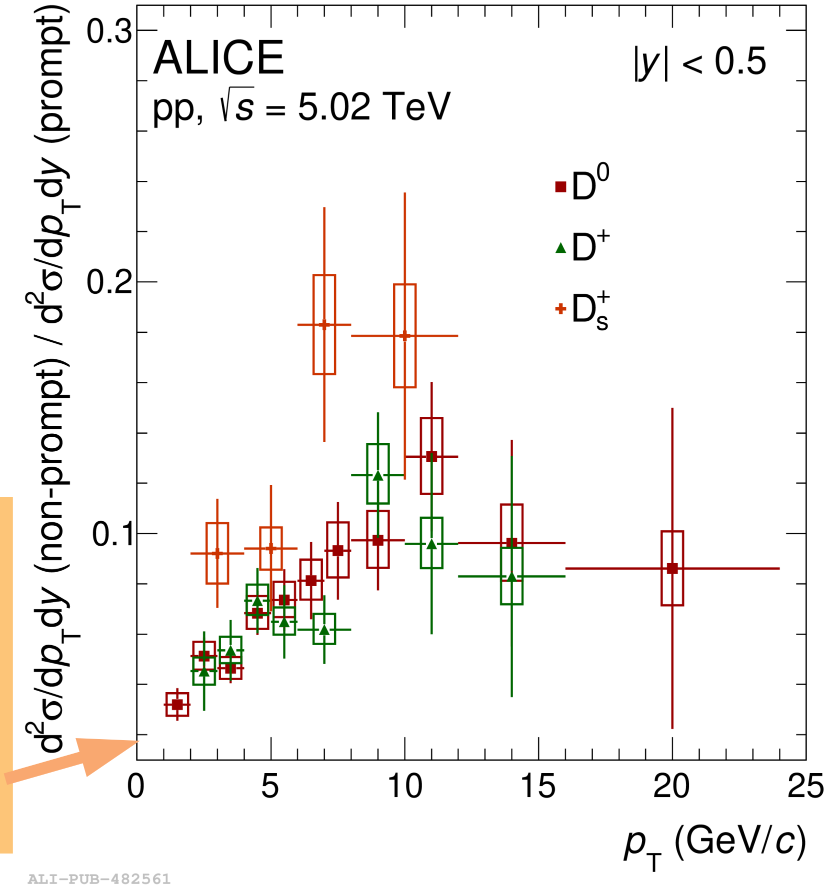
Results: b→D meson production cross-section



Measured p_T-differential cross sections are described by FONLL calculations within uncertainty:

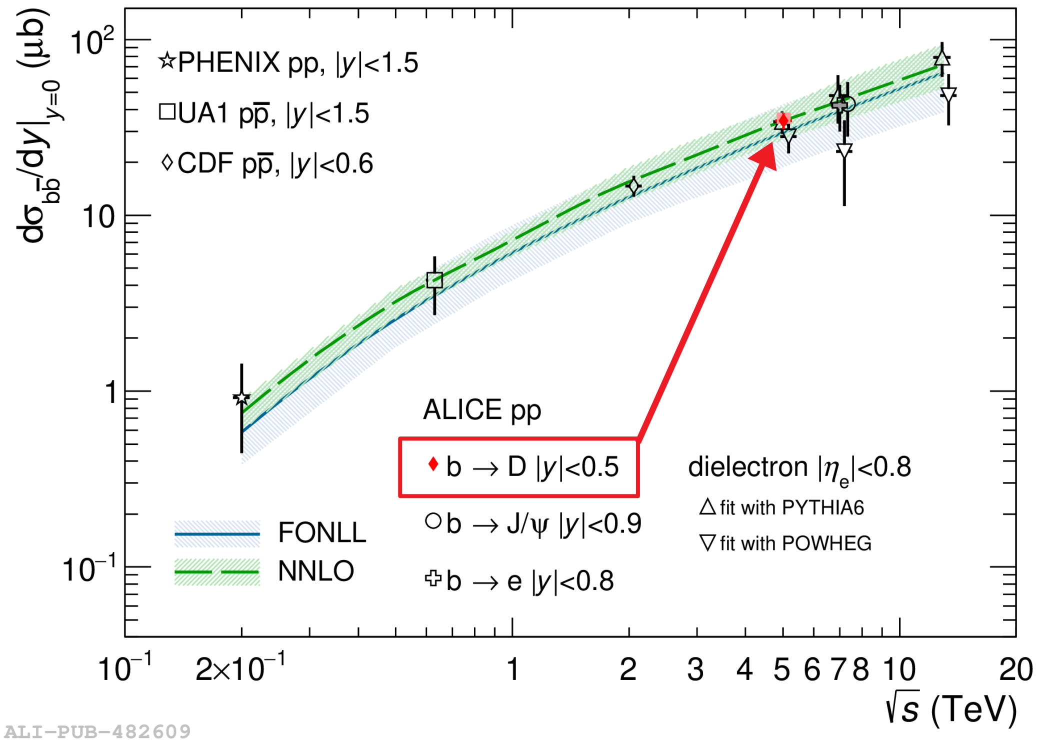
- Prompt D^0 meson compatible with upper edge
- Non-prompt D^0 meson compatible with the central values

- Ratio increases for all the D meson species upto p_T ~12 GeV/*c*
- Hint of a larger contribution of $H_b \rightarrow D_s^+$ than to $H_b \rightarrow$ non-strange D-meson



Prompt D0 : EPJC 79 388 (2019) PYTHIA8: T. Sjöstrand et al. JHEP 05 026 (2006) FONLL: M. Cacciari et al. JHEP 1210 137 (2012)

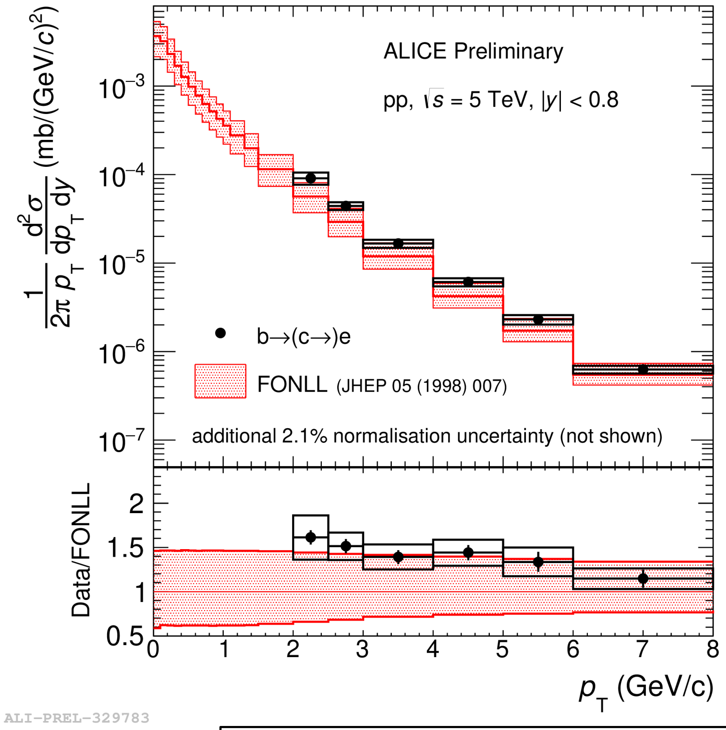
Results: $b\bar{b}$ production cross-section

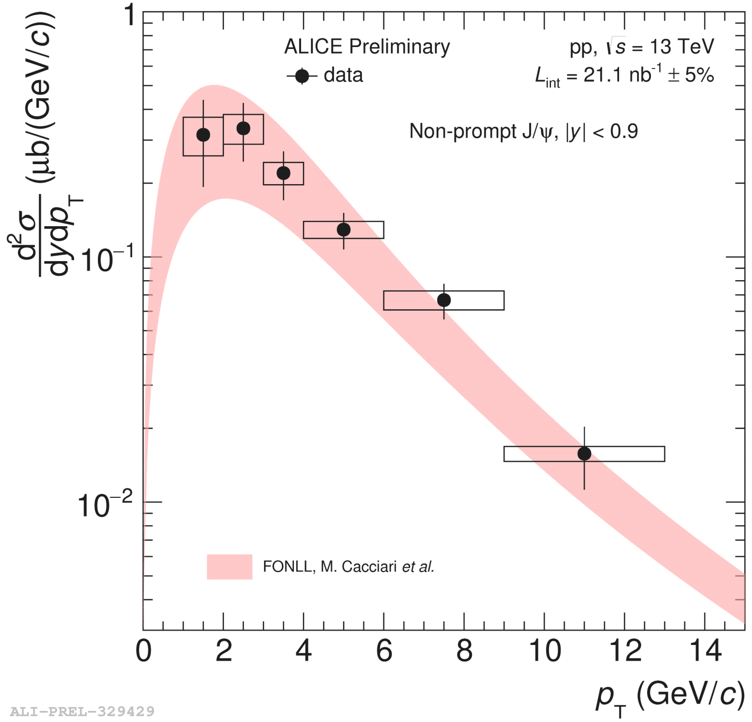


- Beauty-quark production is described by FONLL and NNLO calculations over wide range of center-of-mass energies
- Estimated from measured production cross-sections of non-prompt D^0, D^+ and D_s^+
  - In agreement with FONLL & NNLO calculations
  - Centered with respect to more precise NNLO calculation
  - Measured value is compatible with the previous ALICE measurements

PHENIX: PRL 103 082002 (2009)
UA1: PLB 256 121–128 (1991)
CDF: Phys. Rev. D 75 012010 (2007)
b → J/Ψ: JHEP 11 065 (2012)
b → e: PLB 721 13-23 (2013)
Dielectron, 5 TeV: PRC 102 055204 (2020)
Dielectron, 7 TeV: JHEP 09 064 (2018)
Dielectron, 13 TeV: PLB 788 505-518 (2019)
NNLO: S. Catani et al. JHEP 03 029 (2021)
FONLL: M. Cacciari et al. JHEP 1210 137 (2012)

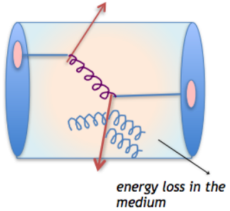
Results: b→e & b→J/Ψ production cross-section

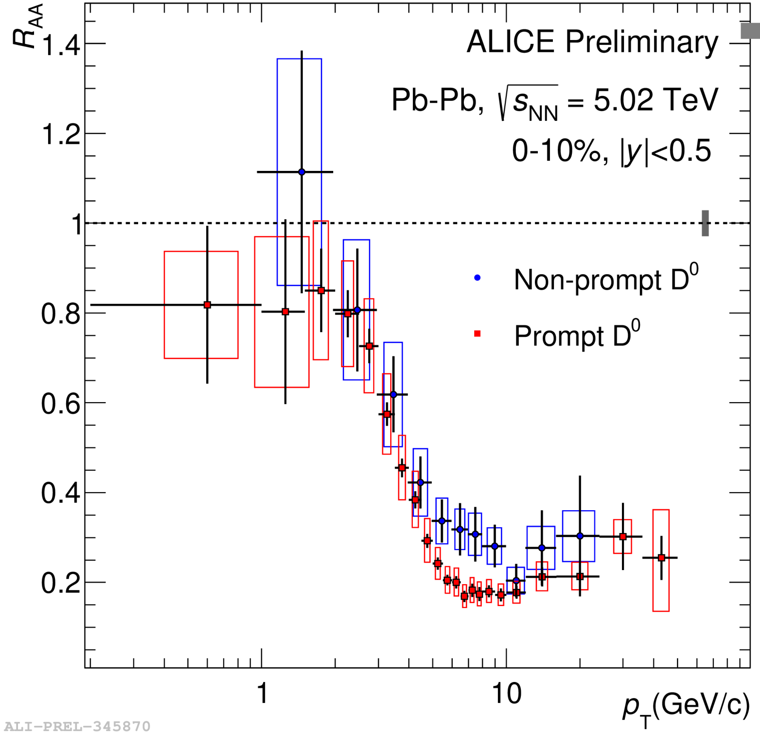




- Beauty-decay electron cross section measured at √s = 5.02 TeV
- Non-prompt J/Ψ cross section for 1 < p_T < 13 GeV/c at √s =13 TeV
  - Described by FONLL within uncertainties
  - Will be finalized soon for √s = 5.02 TeV & 13 TeV

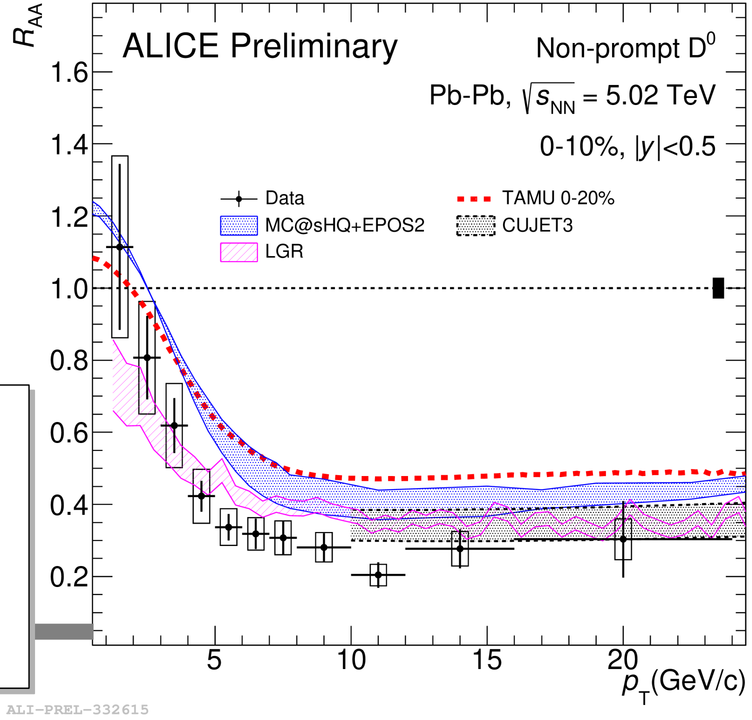
Results: R_{AA} of b→D^0 meson





- Suppression of beauty production is observed
- Hint of ordering at intermediate p_T
  - R_{AA} (c→D) < R_{AA} (b→D)

- Results are described by theoretical models within uncertainties
  - Including radiative and collisional energy loss



TAMU: PLB 735 (2014) 445

MC@sHQ+EPOS2: PRC 89 (2014) 014905

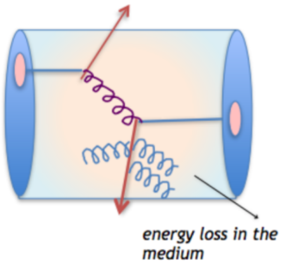
LGR: Phys. Rev. C 99, 054909 (2019) ; Phys. Rev. C 98, 034914 (2018)

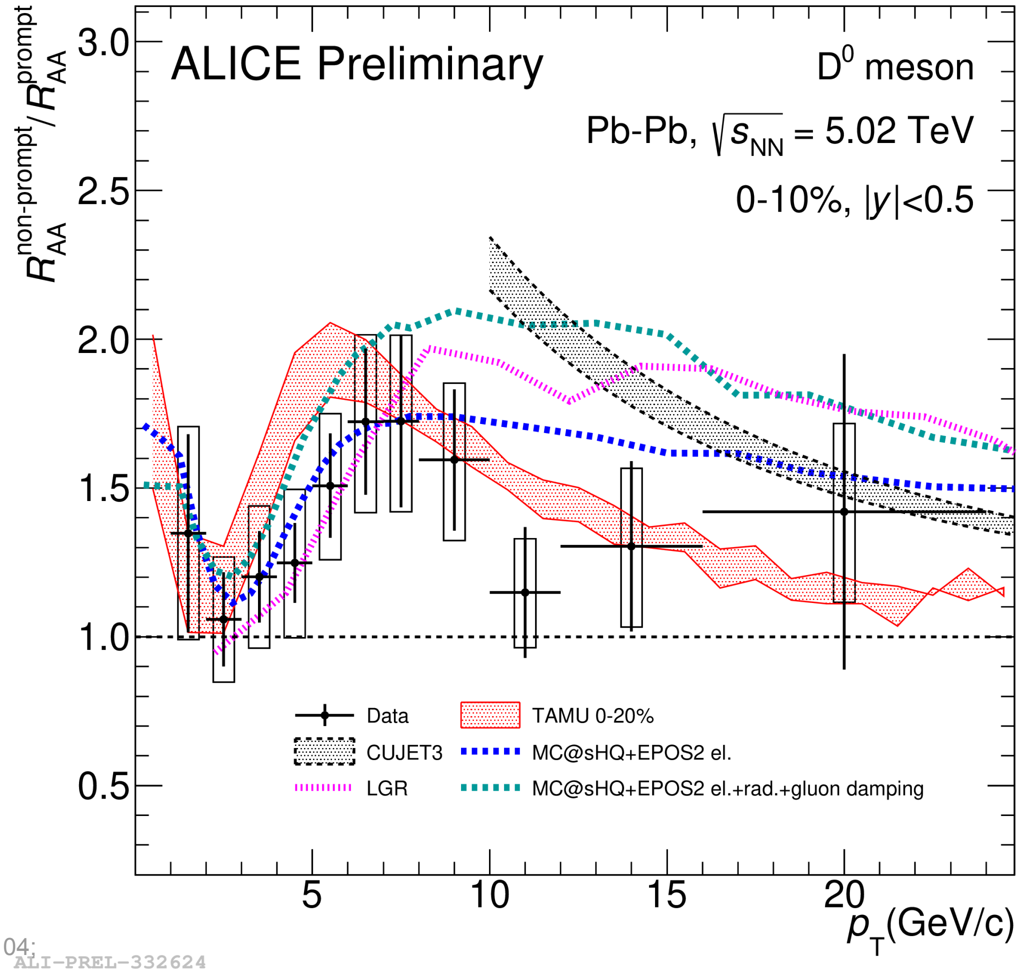
CUJET3: Chin. Phys. Lett. 32, 092501 (2015); JHEP 1602 (2016) 169; Chinese Phys. C 42 104104;

Results: R_{AA} of b→D^0 meson

Ratio of R_{AA} measured for non-prompt to prompt D^0

- $p_T < 5$ GeV/c → **hint** of difference in shadowing / flow / decay kinematics for charm and beauty quarks
- $p_T > 5$ GeV/c → hint of lower suppression of b-quarks than c-quarks → mass dependence of energy loss





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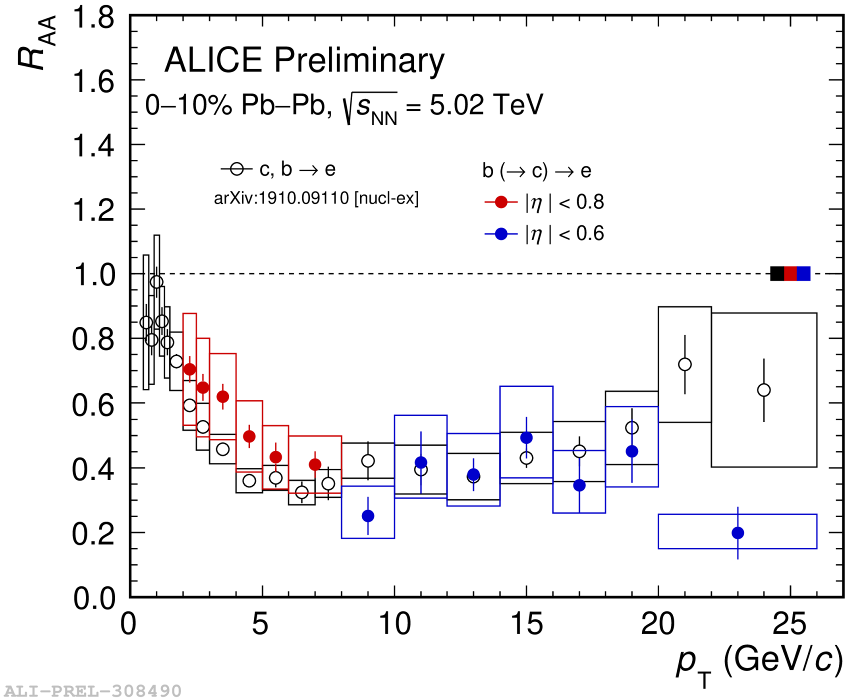
Results: R_{AA} of b→e

Djordjevic: Phys. Rev. C 92, 024918 (2015)
MC@sHQ+EPOS2: Phys. Rev. C 89, 014905 (2014)
PHSD: Phys. Rev. C 93, 034906 (2016)



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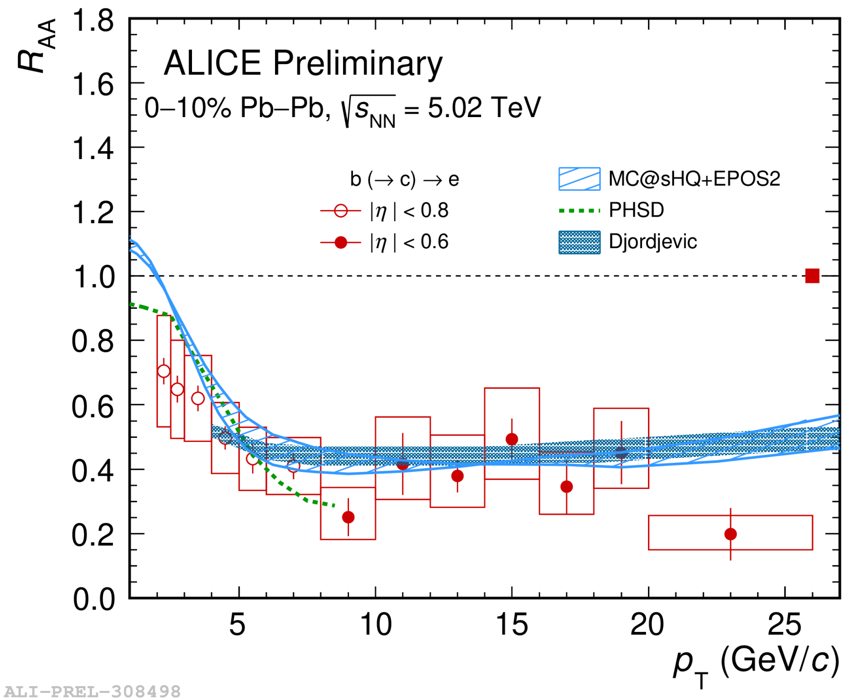
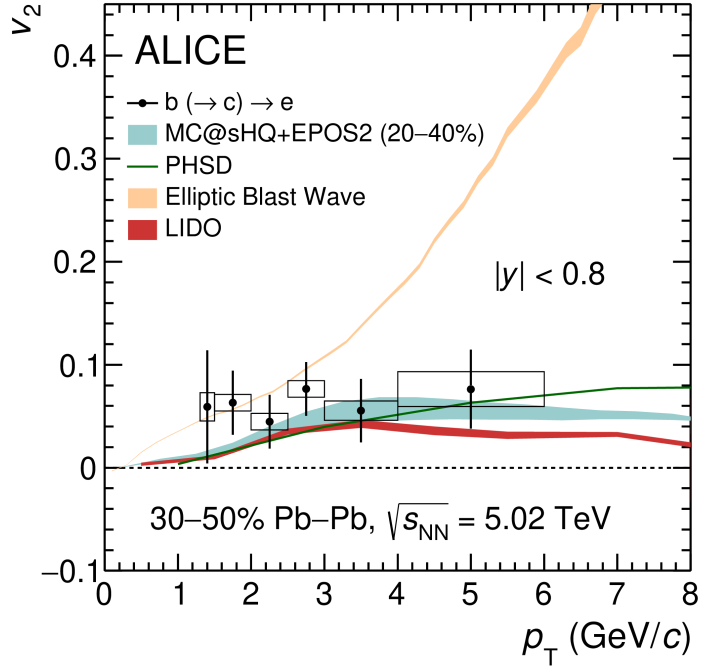


ALI-PREL-308498

- Suppression of beauty-decay electrons is observed
- Hint of ordering at low p_T
  - R_{AA} (b,c→e) < R_{AA} (b→e)

- Comparison of b→e and b,c→e : compatible with mass dependence of ΔE
- Results are described by theoretical model within uncertainties
  - Including radiative and collisional energy loss

Results: Elliptic flow (ν_2) of beauty-electrons



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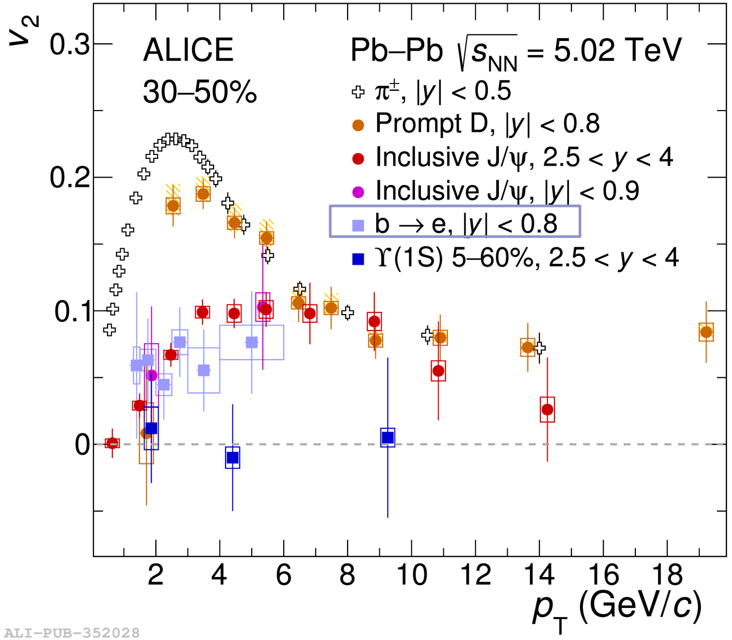


ALI-PUB-352028

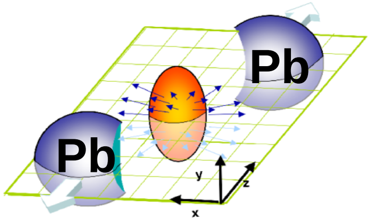
MC@sHQ+EPOS2:
Phys. Rev. C 89, 014905 (2014)

PHSD:
Phys. Rev. C 93, 034906 (2016)

LIDO:
Phys. Rev. C 100, 064911 (2019)

Blast-wave model (extension):
Phys. Rev. C 101, 064905 (2020)

ALICE Publication:
Phys. Rev. Lett. 126, 162001 (2021)



- **Non-zero elliptic flow** for beauty-decay electrons (significance 3.75σ) in the low p_T range 1.3-6 GeV/c measured for the first time
- Measurements are fairly described by various transport models within uncertainty
- Comparison suggests that ***b*-quark may not fully thermalize with QGP**

> - Mass ordering in p_T < 4 GeV/c → Hydrodynamic behaviour
> - Bottomonium flow $\nu_2 \sim 0$, open-beauty $\nu_2 > 0$

Summary

- Beauty production is studied in pp, Pb—Pb collisions with ALICE.
- pp collisions:
  - Production cross section of b→D, b→e and b→J/Ψ described by pQCD calculations (FONLL).
- Pb—Pb collisions:
  - ***b***-quarks undergo energy loss from the medium
  - Measurements are described by theoretical models including collisional & radiative energy loss
  - Non-zero ν_2 of beauty-decay electrons

Outlook

- Measurements of b→J/Ψ for Pb—Pb collisions for $\sqrt{s_{NN}}$ = 5.02 TeV
- Prospects for LHC Run 3
  - Corresponds to **100 x** more statistics
  - Improved Track and vertex resolution → More precise heavy-flavour measurements in both central and forward rapidity region

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Backup

$b\bar{b}$ production cross-section

Multiplying extrapolation factor ($\alpha^{b\bar{b}}_{extr}$) by p_T-integrated cross section of D-meson

$$\alpha_{\mathrm{extr}}^{\mathrm{b\bar{b}}} = \frac{\mathrm{d}\sigma_{\mathrm{b\bar{b}}}/\mathrm{d}y|_{|y|<0.5}^{\mathrm{FONLL}}}{\sigma_{\mathrm{b\to D}}^{\mathrm{FONLL+PYTHIA\ 8}}(p_{\mathrm{T}}^{\mathrm{min}} < p_{\mathrm{T}} < p_{\mathrm{T}}^{\mathrm{max}}, |y| < 0.5)}$$

- Predictions from FONLL: for *b*-hadrons cross sections
- PYTHIA8: for $H_B \rightarrow D + X$ decay kinematics

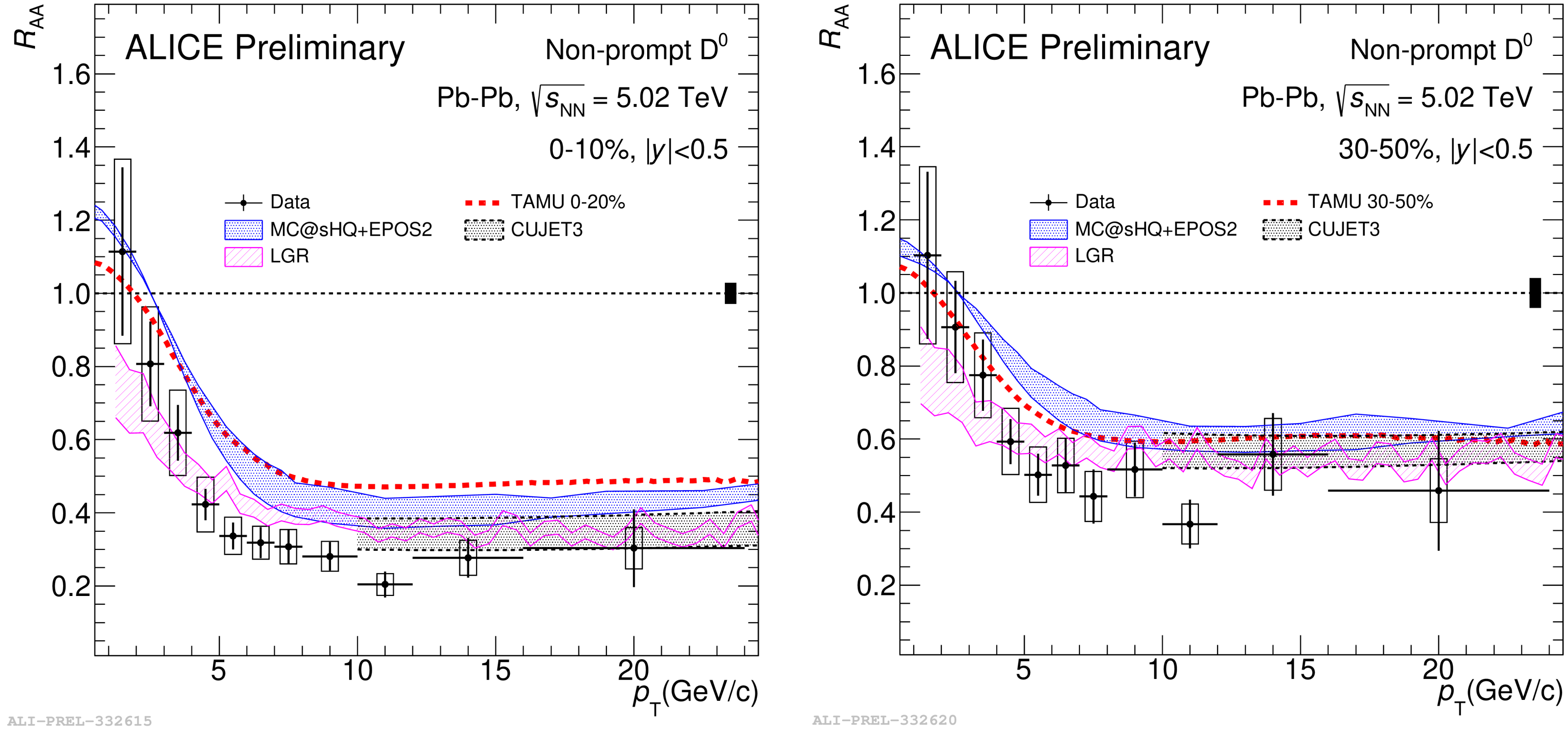
Non-prompt D meson

- Reconstruction of displaced D-meson decay vertices at mid rapidity

- Signal extraction through invariant mass analysis;

- ML tecniqhes to separate prompt D mesons, non-prompt D mesons and combinatorial background;

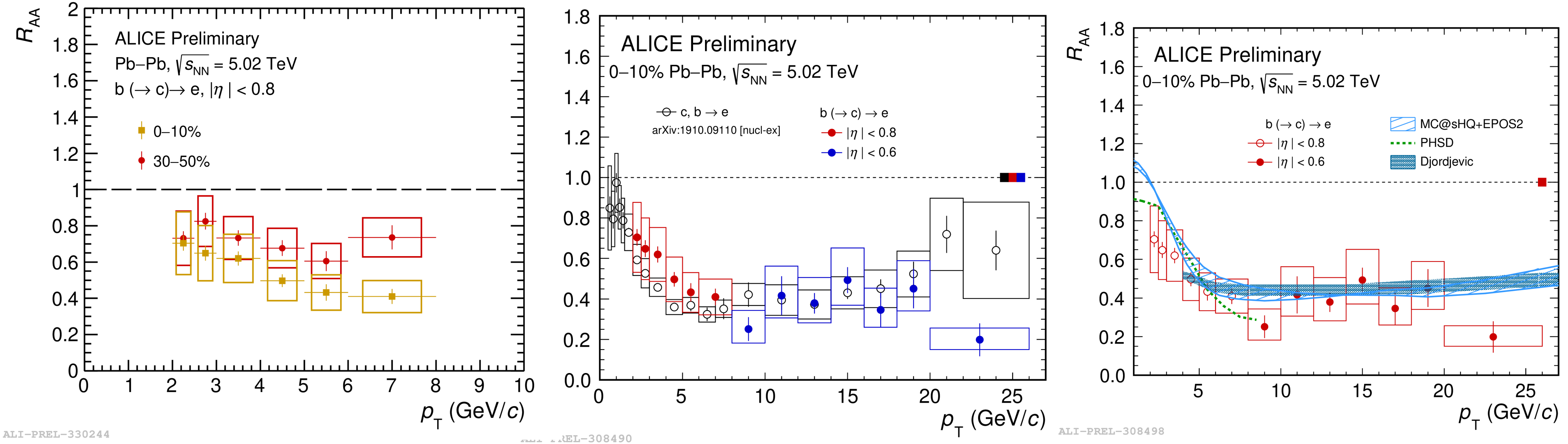
- b→ D fraction obtained by $\chi 2$ minimization of the system of n sets of selections with different prompt and non-prompt D-meson contributions.



R_{AA} measured for non-prompt D^0 in 0-10% and 10-30% Pb-Pb collisions

R_{AA}(0-10%) < R_{AA} (30-50%)

Results: R_{AA} of b→e



- R_{AA} measured for b→e in 0-10% and 10-30% Pb-Pb collisions
  - Hint of less energy loss in 30-50% → QGP system size smaller for 30-50% collisions than central
- Comparison of b→e and b,c→e : compatible with mass dependence of ΔE
- Results are described by theoretical model within uncertainties
  - Including radiative and collisional energy loss

- Suppression of beauty-decay electrons is observed
- Hint of ordering at low p_T
  - R_{AA}(b,c→e) < R_{AA} (b→e)

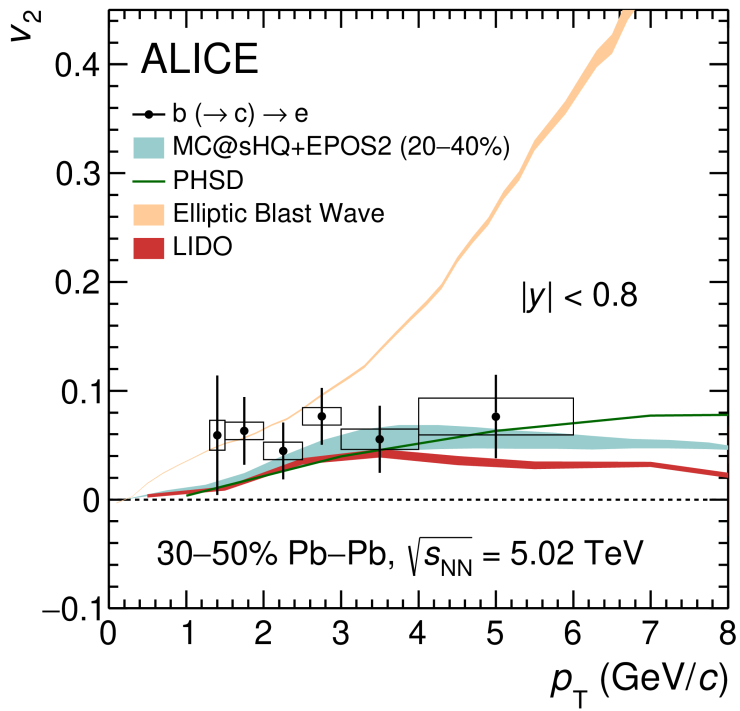
Models for b→e v_2

- The measurement is crucial for the understanding of the degree of thermalization of beauty quarks in the QGP.
- Compared with the predictions from several transport models, which include significant interaction of beauty quarks with a hydrodynamically-expanding QGP
  - MC@sHQ+EPOS [Phys. Rev. C 89, 014905 (2014)] ,
  - PHSD [Phys. Rev. C 93, 034906 (2016)],
  - LIDO [Phys. Rev. C 100, 064911 (2019)] [Phys. Rev. C 98, 064901]

- MC@sHQ+EPOS is a perturbative QCD model, which includes radiative and collisional energy loss. Modification of nuclear parton distribution functions, like shadowing, is not considered for b quarks.
- The PHSD model is a microscopic off-shell transport model based on a Boltzmann approach which **includes only collisional energy loss.**
- Models differ in several aspects related to the interactions both in the QGP and in the hadronic phase as well as to the medium expansion
- Elliptic blast wave: This model assumes full thermalization → at higher pT (> 5GeV/c) it diverges does not explain the data, suggests b-quarks may not fully thermalize in this pT interval.

Elliptic blast-wave Model:

- Assuming full thermalization, this model predicts a v_2 of ϒ(1S) close to zero in the range measured by ALICE, which is consistent with the measurement.
- The results for beauty hadron decay electrons give a much larger v_2 due to mass ordering effect
- qualitatively in agreement with the measurement within the uncertainties for p_T < 3 GeV/c, while it significantly diverges from the data at higher p_T
- Within this model, the v_2 in the measured p_T range mainly comes from beauty hadrons below p_T = 10 GeV/c, suggesting that beauty quarks may not fully thermalize in this p_T interval.



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Models

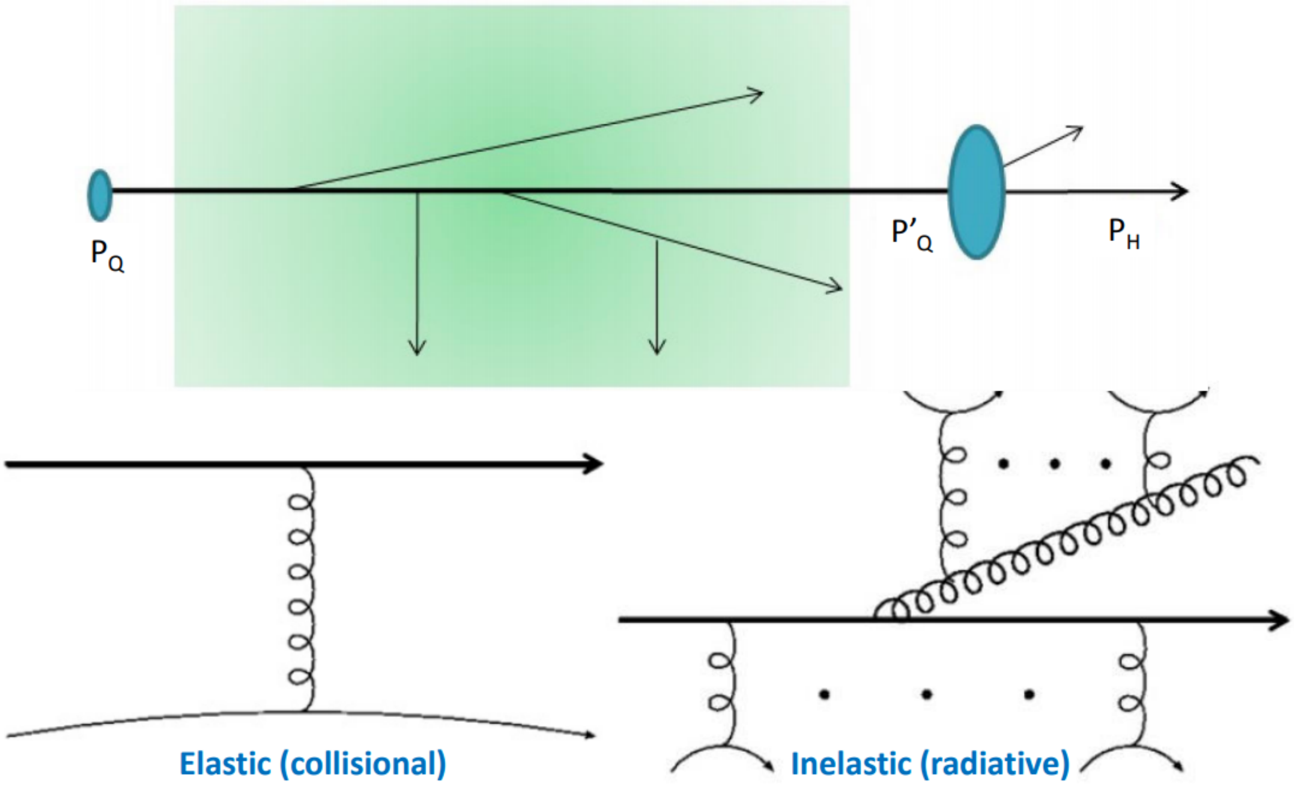
- MC@sHQ+EPOS2 and PHSD (Parton-Hadron-String Dynamics): **M**onte **C**arlo with running αS for **H**eavy **Q**uarks
  - includes nuclear-modified PDFs (EPS09), PDF shadowing, medium expansion, fragmentation and coalescence 1908.00451 [nucl-th]
  - Shadowing affects HQ-production at low pT.
  - Shadowing has impact on final R_{AA}
  - Collisional energy loss dominates at low energy, while radiative energy loss dominates at high energy
  - PHSD only includes collisional energy loss
- MC@sHQ+EPOS2 and Djordjevic:
  - include both collisional and radiative energy loss;
- Djordjevic:
  - dynamic partons in finite-size medium; no PDF shadowing, medium evolution/fluid dynamic expansion, or coalescence [Phys.Rev.C 92 (2015) 2, 024918]
- Langevin-transport with Gluon Radiation, LGR: Eur. Phys. J. C 80, 671 (2020)

- FONLL → Fixed Order + Next-to-Leading Logrithms
- NNLO → Next-to-next-to Leading order

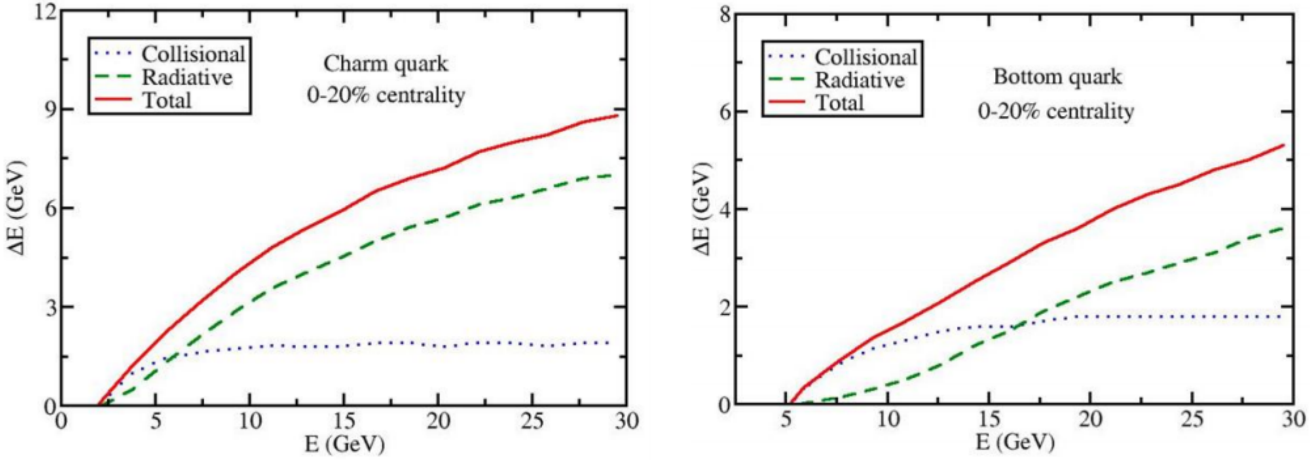
Heavy quark hadronization

- Most high momentum heavy quarks fragment into heavy mesons
  - Use PYTHIA 6.4 “independent fragmentation model”
- Most low momentum heavy quarks hadronize to heavy mesons via recombination (coalescence) mechanism

Heavy quark energy loss in QGP



Heavy quark energy loss in QGP (LHC)

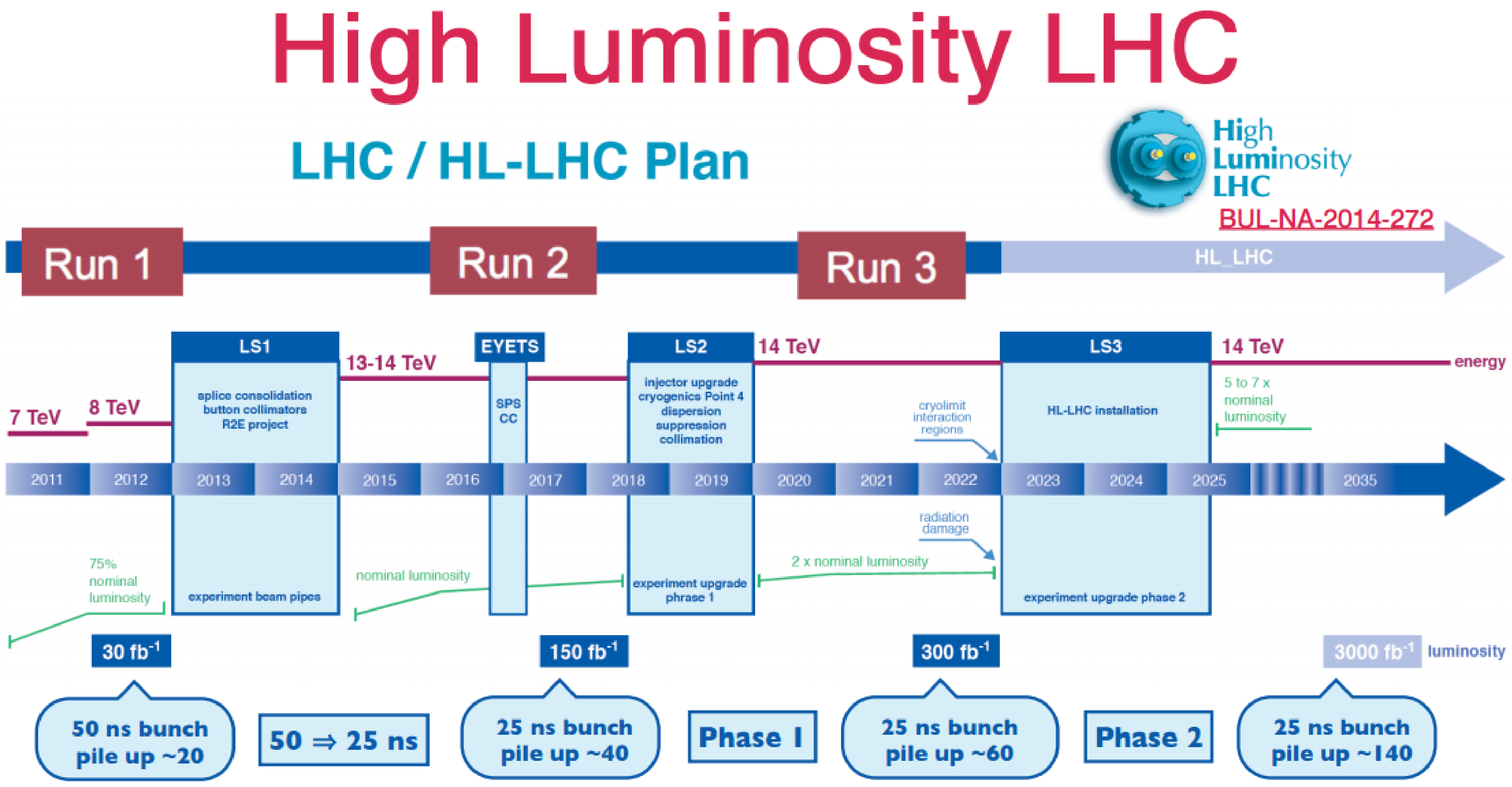


- **QGP medium: (2+1)-D viscous hydrodynamics (OSU)**
- **D=6/(2πT), i.e., q^{hat} ~ 2 GeV²/fm at a temperature around 350 MeV**
- **Collisional energy loss dominates at low energy, while radiative energy loss dominates at high energy**
- **The crossing point is larger for bottom than charm quarks due to the mass effect**

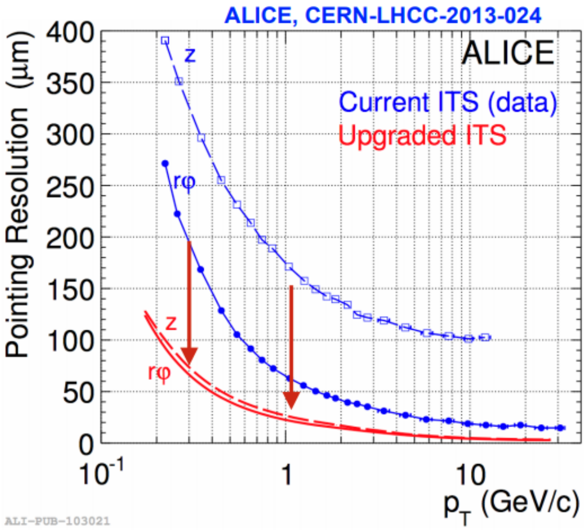
Cao, GYQ, Bass, PRC 2013; JPG 2013

Link to presentation

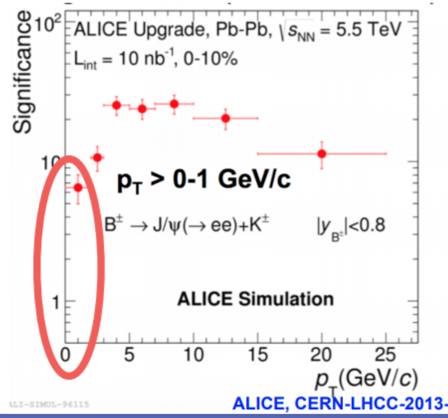
High Luminosity LHC

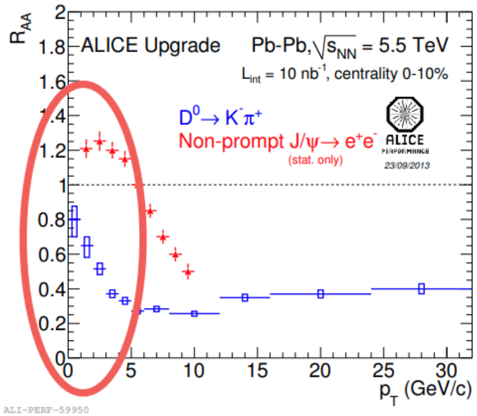


After ALICE Upgrade: Run 3 > 2021



Uniqueness: Excellent tracking **down to 0 p_T** and **PID capability** for hadron identification, in a broad momentum range: 0.1-3GeV/*c*

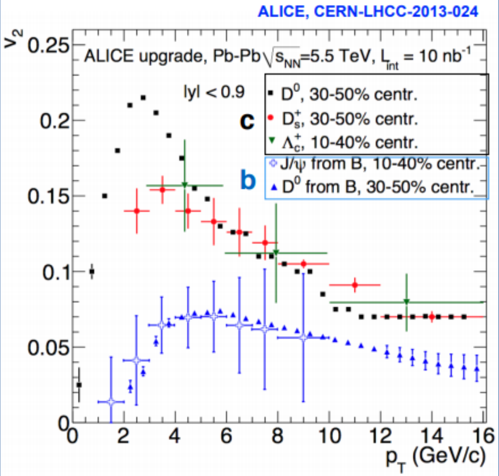




Upgrade

D-meson reconstruction with the upgraded ALICE detector:

- **D^0 R_{AA} down to p_T=0 and higher precision**
- **D^0 from B meson: B-meson measurement via displaced D^0 and J/ψ**



Upgrade (ALICE studies)

- Precise v_2 measurement of prompt D,D_s
- D from B and Λ_c v_2 accessible

Follow the presentation for more details by: C.Terrevoli

TAMU Phys. Lett. B735:445 (2014)

- The transport coefficients are implemented via Fokker-Planck Langevin dynamics within hydrodynamic simulations of the bulk medium in nuclear collisions.
- The hydro expansion is quantitatively constrained by transverse-momentum spectra and elliptic flow of light hadrons.
- Model incorporates the paradigm of a strongly coupled medium in both bulk and HF dynamics throughout the thermal evolution of the system.
- At low and intermediate , HF observables at LHC are reasonably well accounted for, while discrepancies at high are indicative for radiative mechanisms not included in this model.

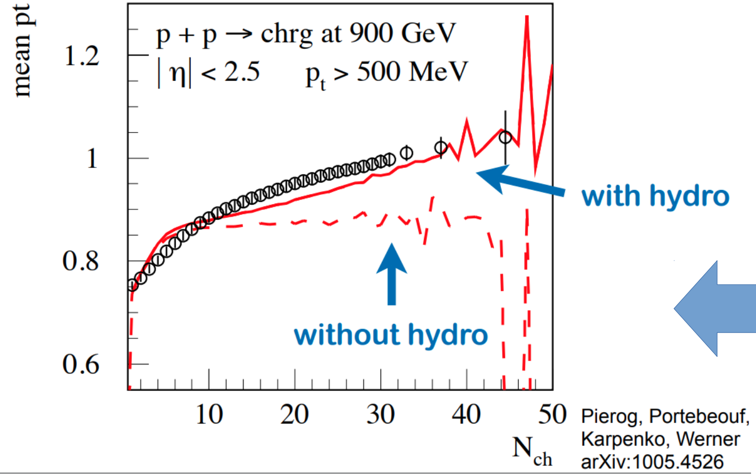
MC@sHQ+EPOS2 PRC 89 (2014) 014905

- Heavy quark evolution according to Boltzmann equation
- Medium description by EPOS+Hydro

EPOS

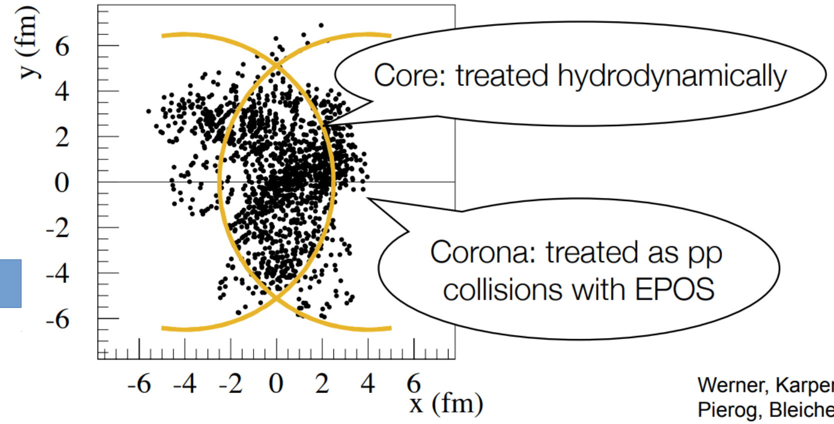
- Energy conserving quantum mechanical multiple scattering approach,based on
- Partons (parton ladders)
- Off-shell remnants, and
- Splitting of parton ladders

EPOS



arXiv:1005.4526

Core / Corona



Werner, Karpenko, Pierog, Bleicher, Mikhailov arXiv:1004.0805

Phys. Rev. C 82, 044904

LGR

Phys. Rev. C 99, 054909 (2019) ; Phys. Rev. C 98, 034914 (2018)

- The heavy quark propagation behavior inside the QGP, is usually described in terms of the Boltzmann dynamics, which can be reduced to the Langevin approach by assuming a small momentum transfer for the scattering processes between heavy quarks and the QGP constituents.
- Only ellastic scatterings are considered for better agreement between both approaches
- The missing inelastic contributions allow reducing the discrepancy with data

PHSD (parton-hadron-string-dynamics) transport model Phys. Rev. C 93, 034906 (2016)

- c-quarks are produced by Event generator PYTHIA
- (anti)-Shadowing incorporated
- Hadronization into D-meson through coalescence or fragmentation
- In final stages, interact with hadrons according to cross section by effective lagrangian theory