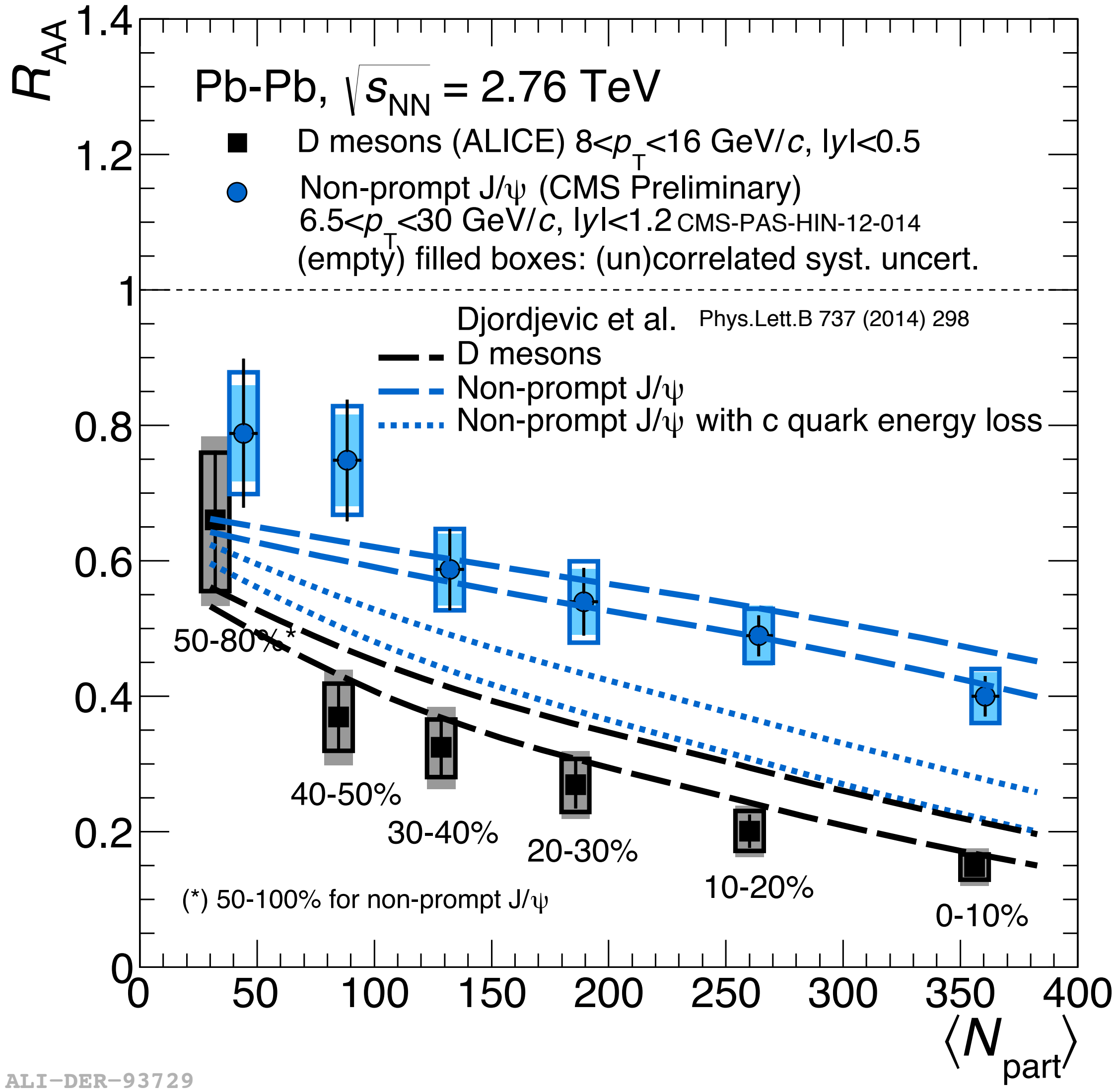
Charm results review with ALICE Run 1 data.

A biased review of heavy-flavour production results in heavy-ions collisions.

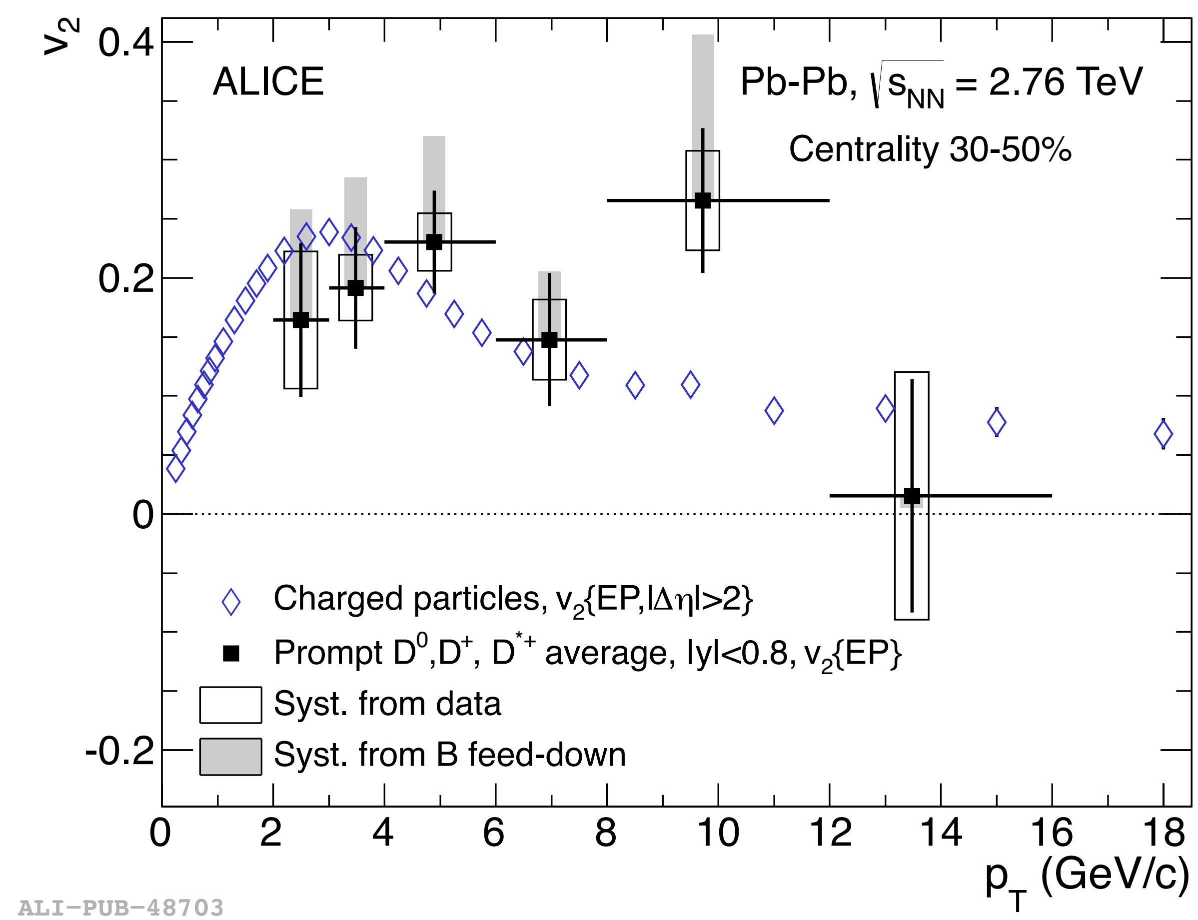
Davide Caffarri (CERN)

A very quick review

JHEP11(2015)205

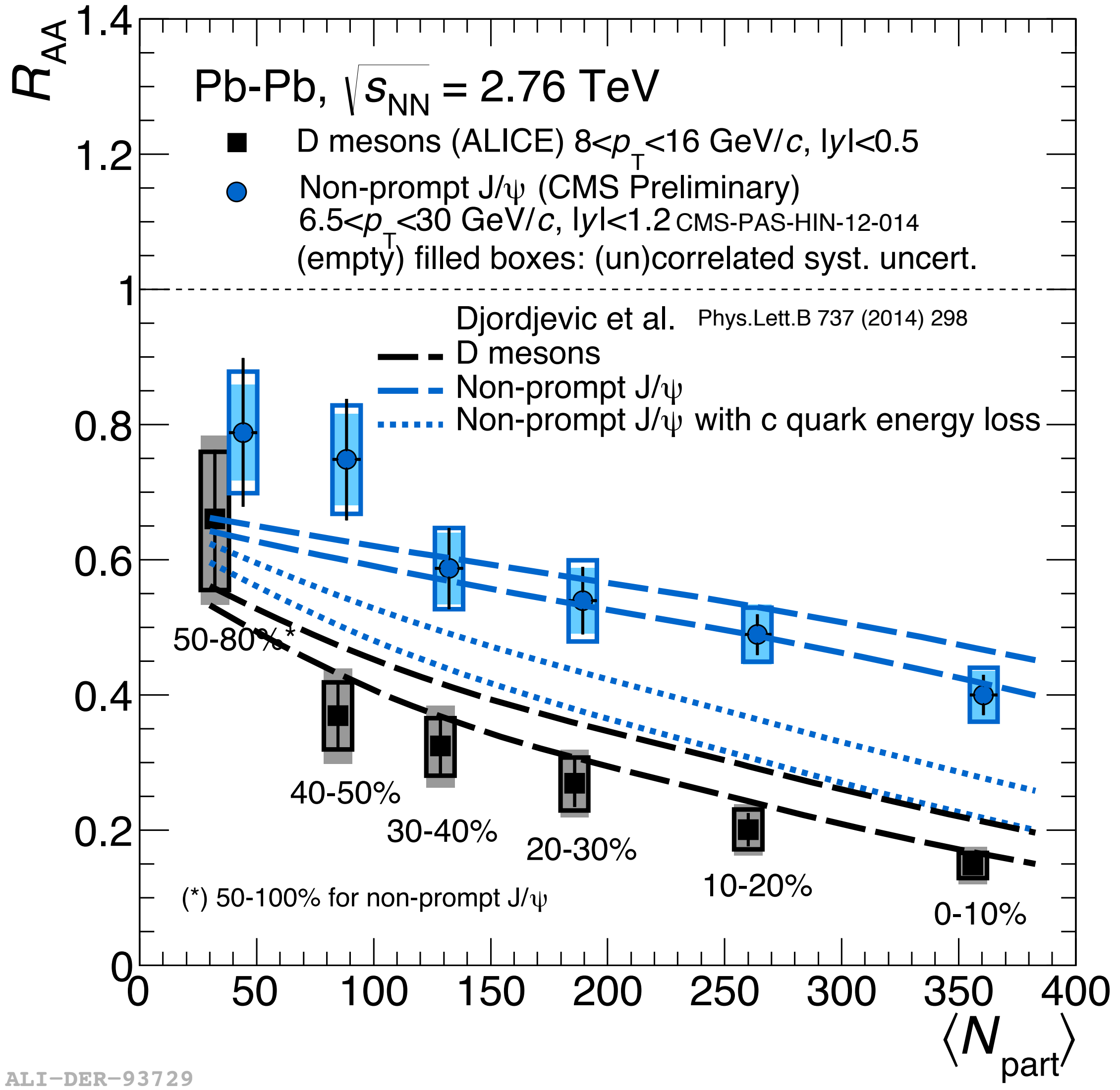


Phys. Rev. Lett. 111, 102301 (2013)



A very quick review

JHEP11(2015)205



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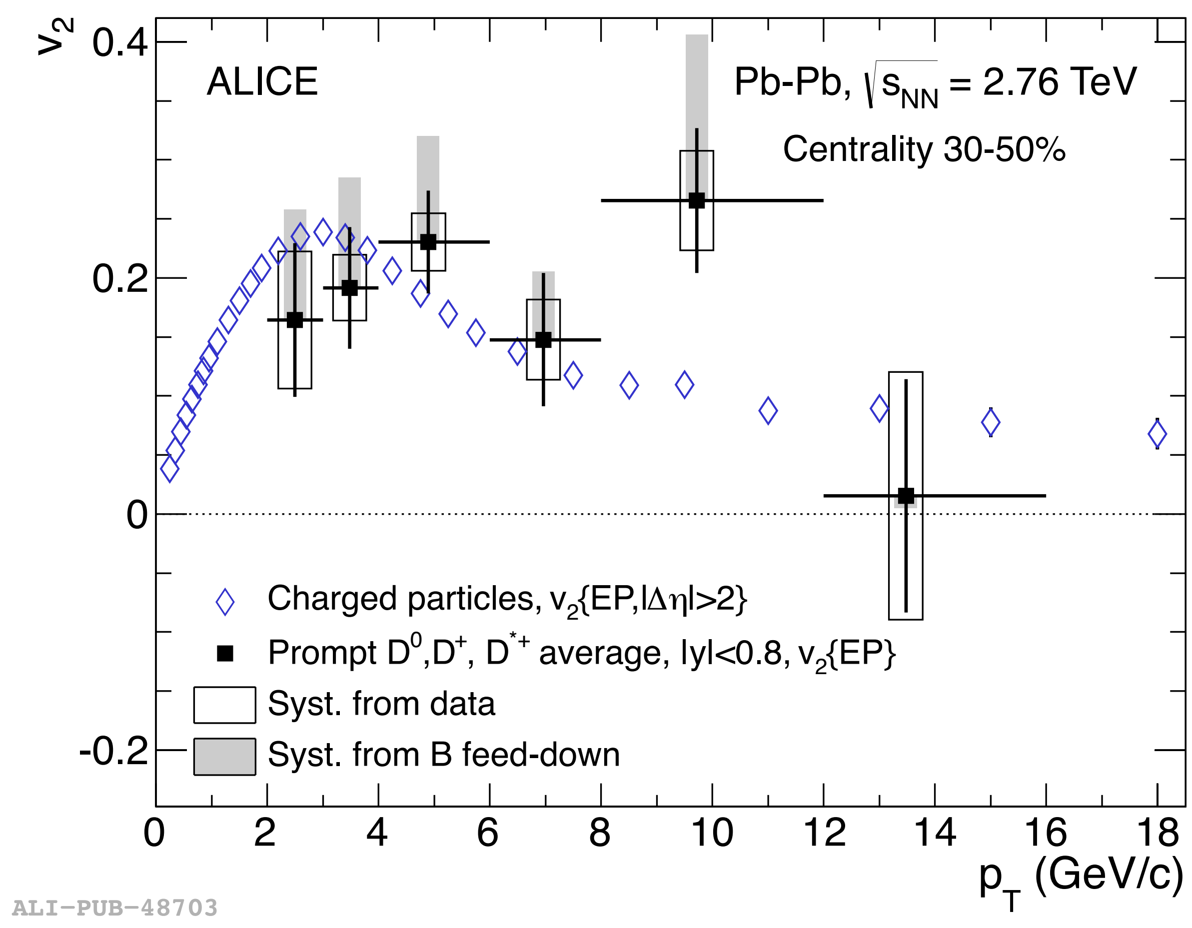
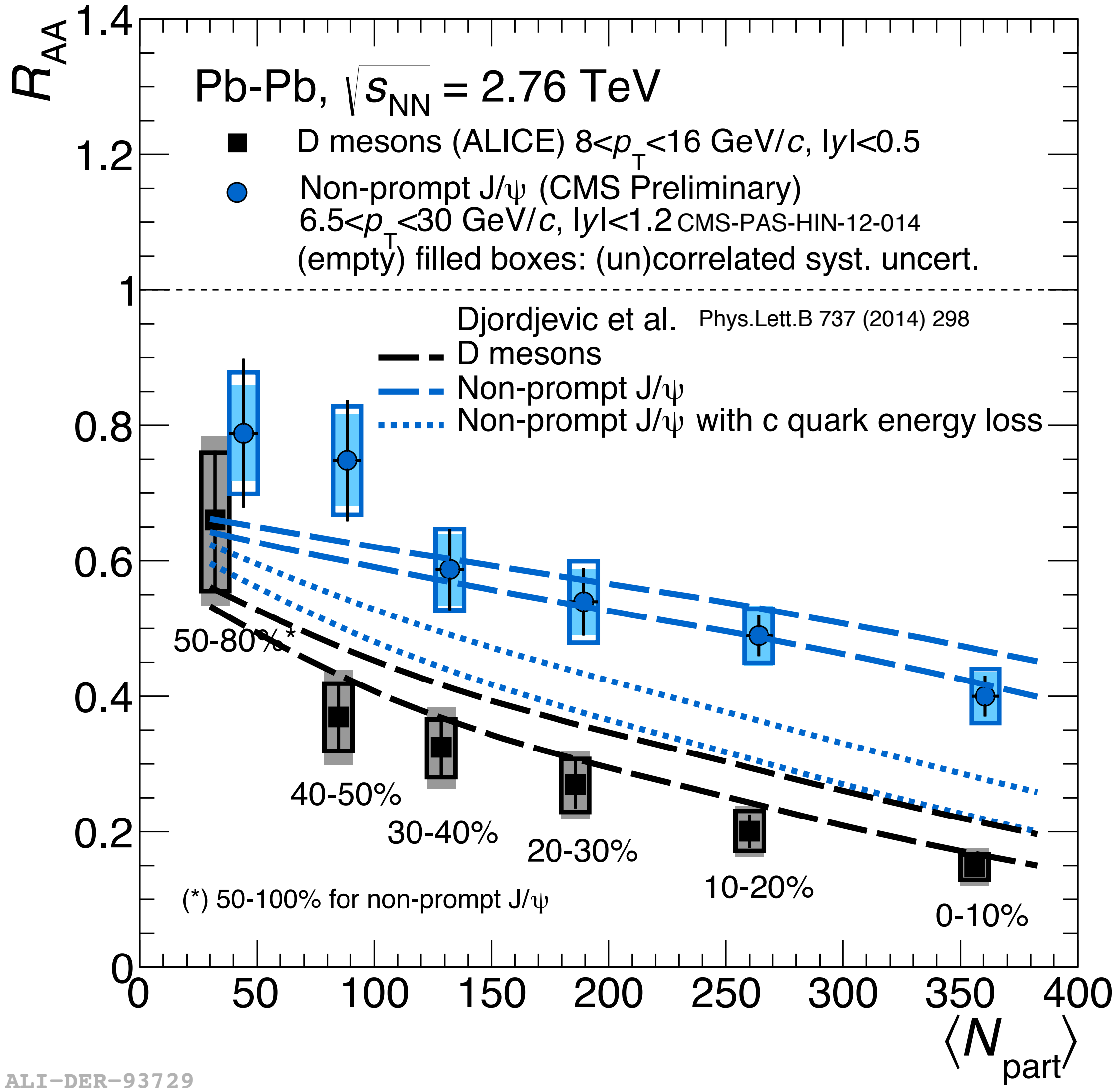


- In central heavy-ion collisions **D mesons** are more suppressed than **Non-prompt J/ψ**.
- Models that include a different energy loss in the QGP for **charm** and **beauty** quarks describe the data.
- The medium transfer information of its collective expansion to the **charm** quarks.

A very quick review / outline

JHEP11(2015)205



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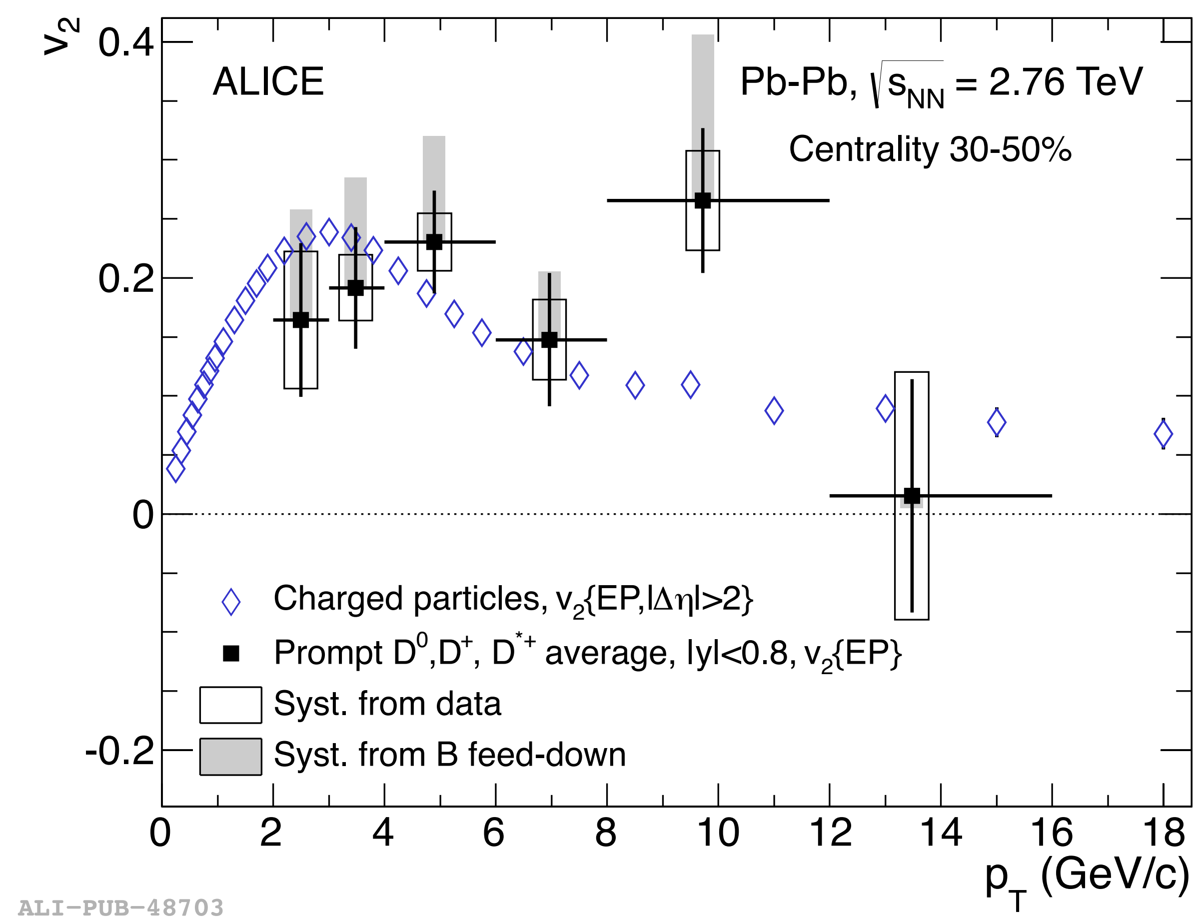

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- Models that include a **different energy loss in the QGP** for charm and beauty quarks describe the data.
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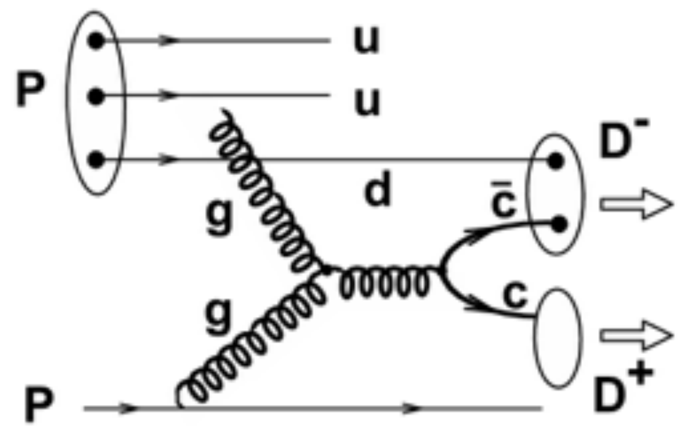
Heavy-flavour production in pp collisions

Heavy-flavour production in pp collisions

@ LO:

$g + g \rightarrow Q + \overline{Q}$

$q + \overline{q} \rightarrow Q + \overline{Q}$



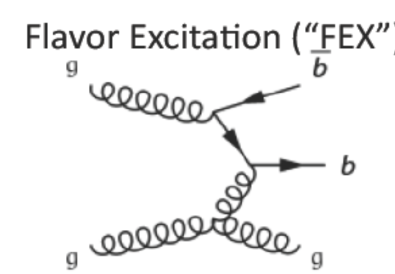
Gluon fusion mechanism is the dominant at LHC energies

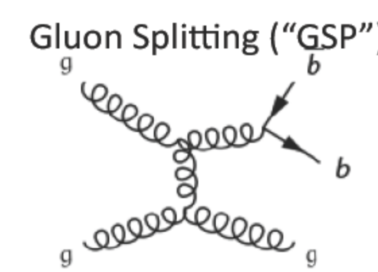
@ NLO:

$g \rightarrow Q + \overline{Q}$ gluon splitting

$Q^* \rightarrow Q + \overline{Q}$ flavour excitation

This processes require a detailed study to better understand which is their contribution at different p_T.





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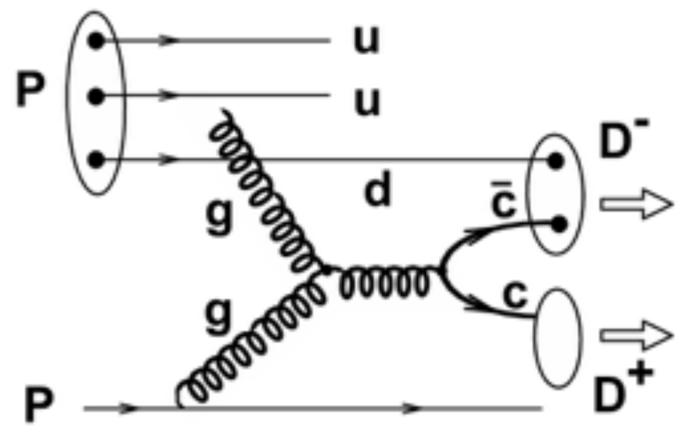

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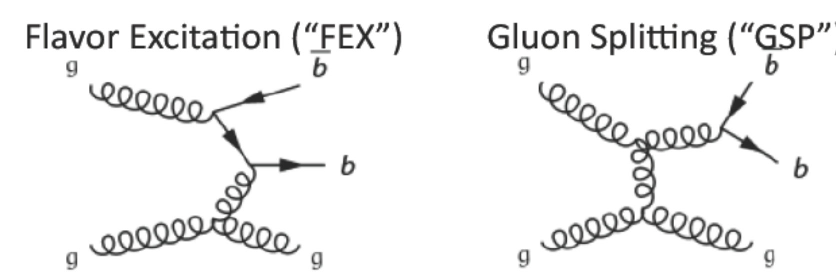


Since $\mu \approx m_Q \Rightarrow \alpha_s(\mu) << 1 \Rightarrow$ pQCD calculations.

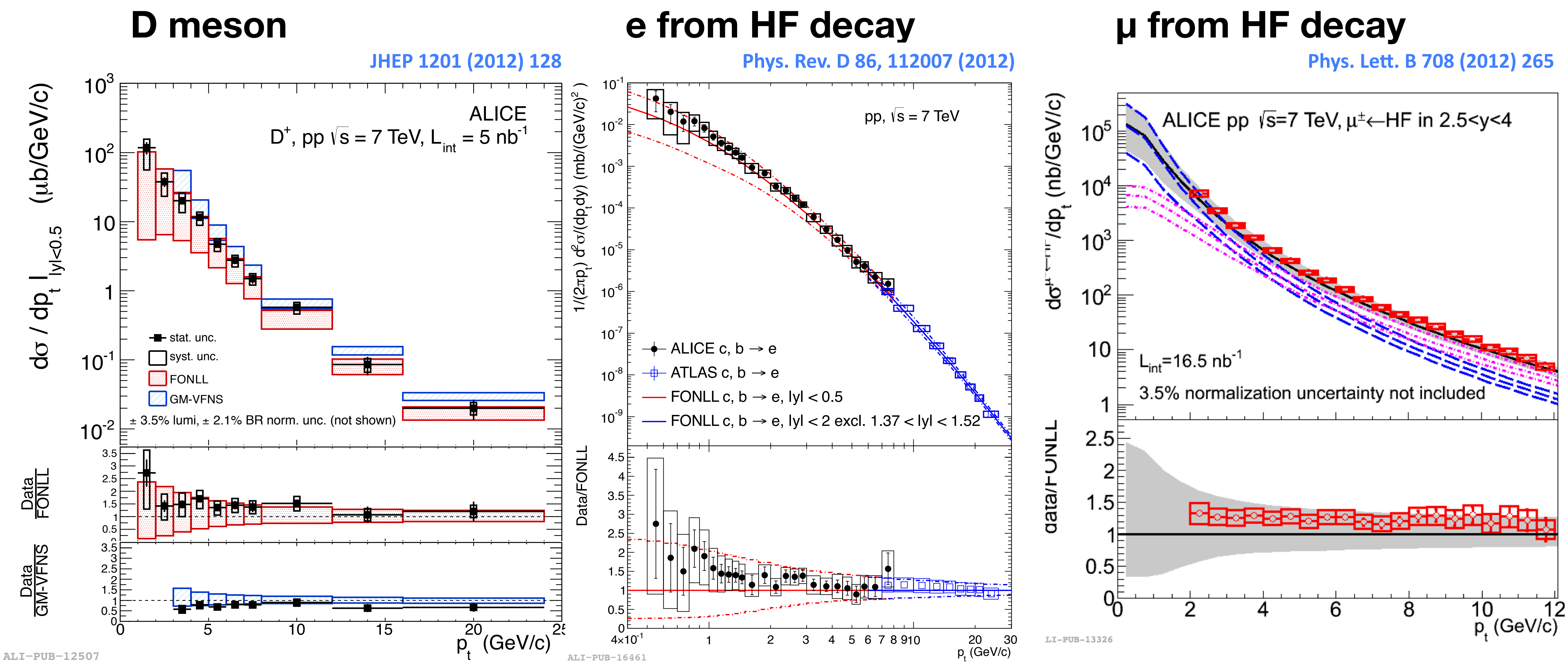
- **Fixed-Order-Next-to-Leading-Log (FONLL):**
  - large log beyond NLO are taken into account in the NLO resummation (at high p_T).
  - Fit of the moments of the fragmentation distributions

JHEP 0407, 033 (2004)

- **General Mass Variable Flavour Number Scheme (GM-VFNS):**
  - large log beyond NLO are absorbed in the c-quarks PDF and the fragmentation function of c → hadron

PRL 96 (2006) 012001

Charm production in pp collisions @ $\sqrt{s}$ = 7 TeV



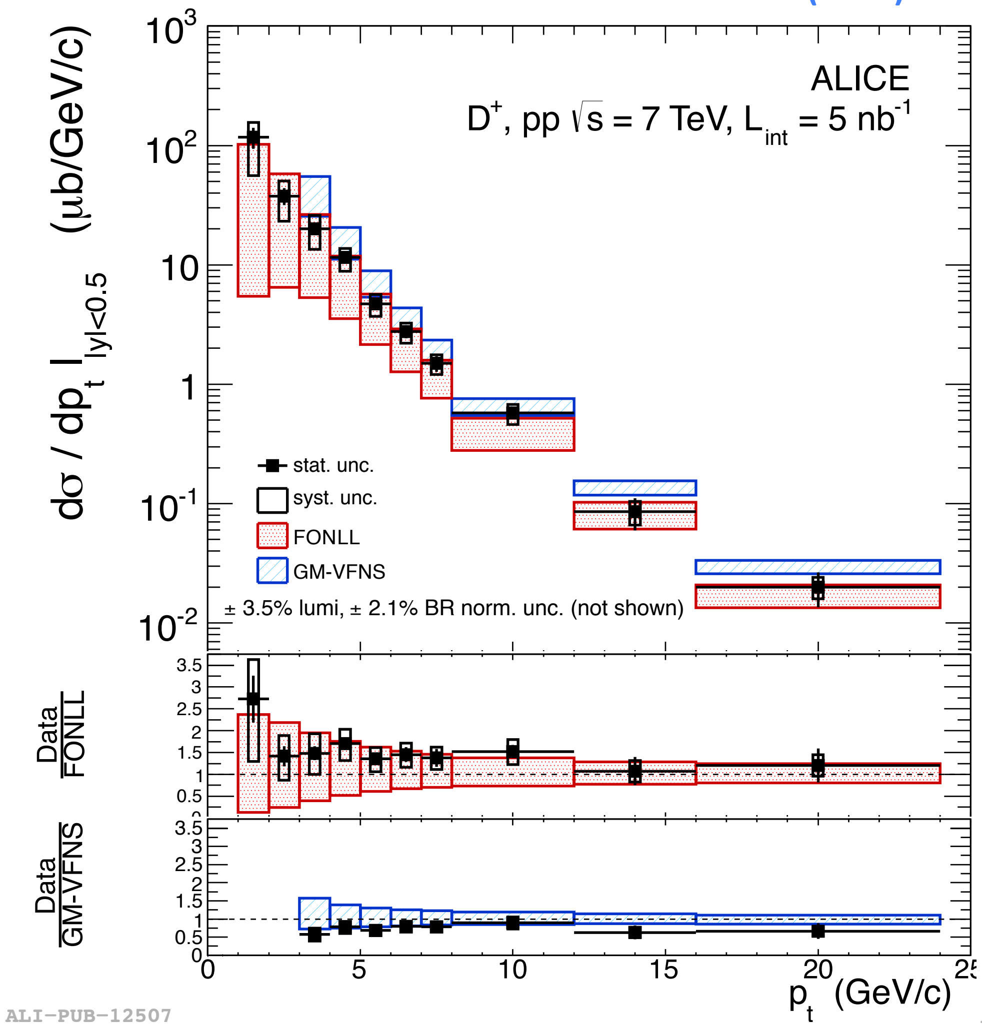
- pQCD based calculations (FONLL, k_T-factorization, GM-VFNS) are compatible with data.

FONLL: JHEP 1210 (2012) 137, GM-VFNS: Eur. Phys. J. C 72 (2012) 2082, k_T factorisation: arXiv:1301.3033

Charm production in pp collisions @ $\sqrt{s}$ = 7 TeV

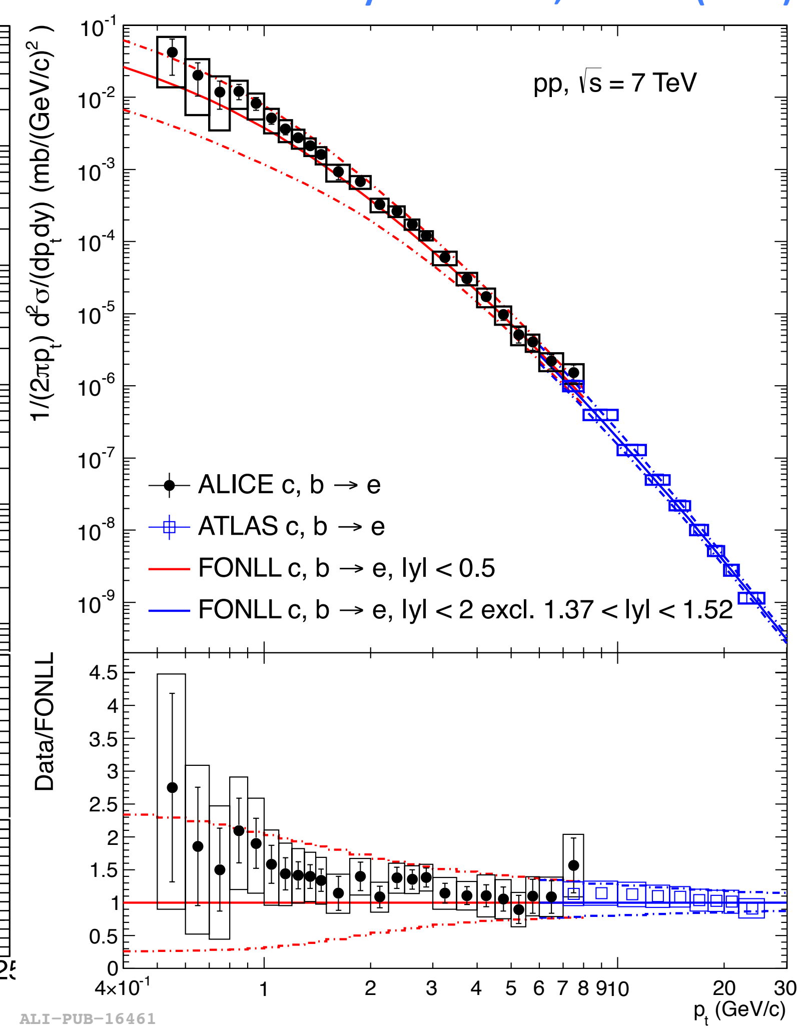
D meson

JHEP 1201 (2012) 128



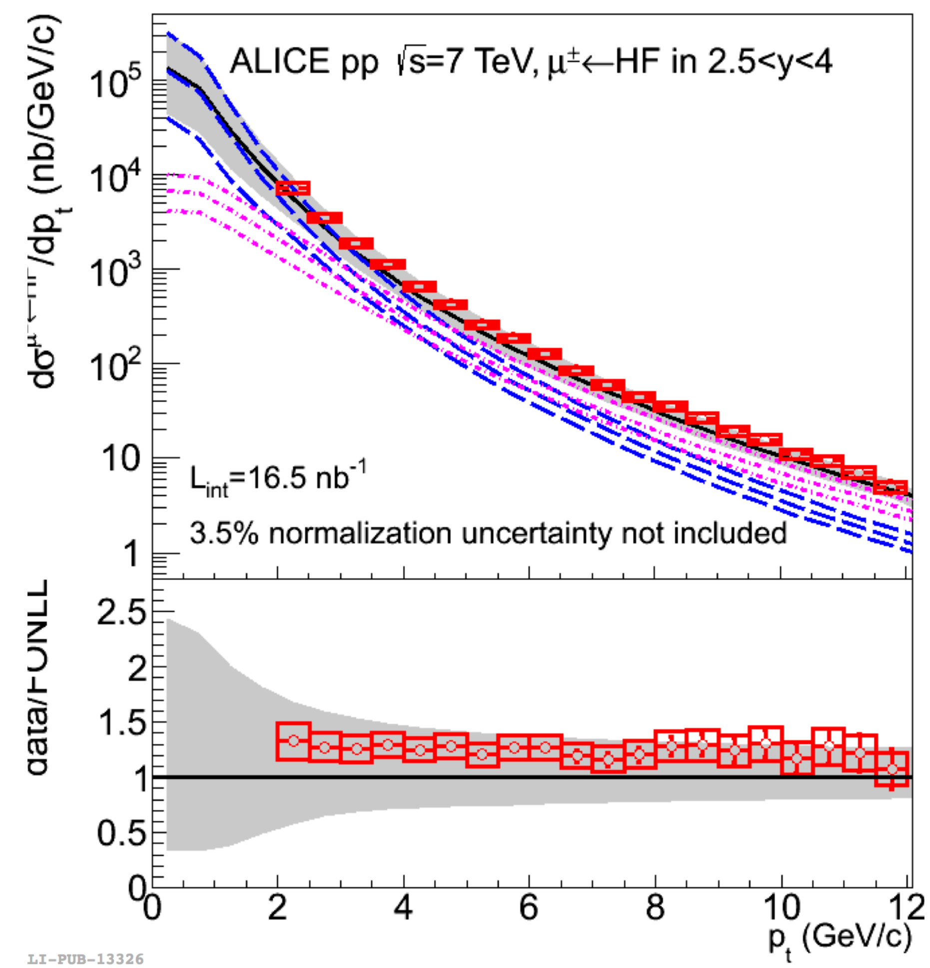
e from HF decay

Phys. Rev. D 86, 112007 (2012)



μ from HF decay

Phys. Lett. B 708 (2012) 265



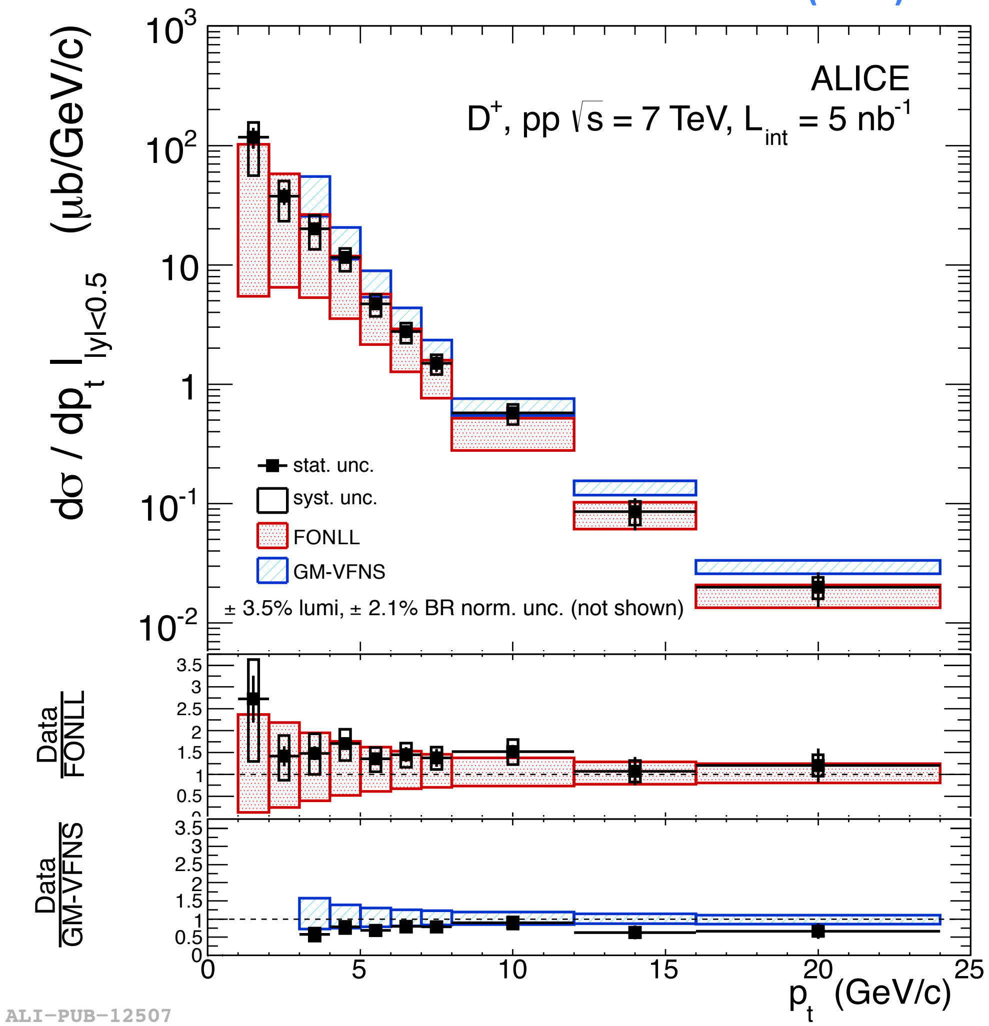
- pQCD based calculations (FONLL, k_T-factorization, GM-VFNS) are compatible with data.
- Even if slightly closer to the higher/lower band of the theoretical calculations.

FONLL: JHEP 1210 (2012) 137, GM-VFNS: Eur. Phys. J. C 72 (2012) 2082, k_T factorisation: arXiv:1301.3033

HF production in pp collisions @ $\sqrt{s}$ = 7 TeV

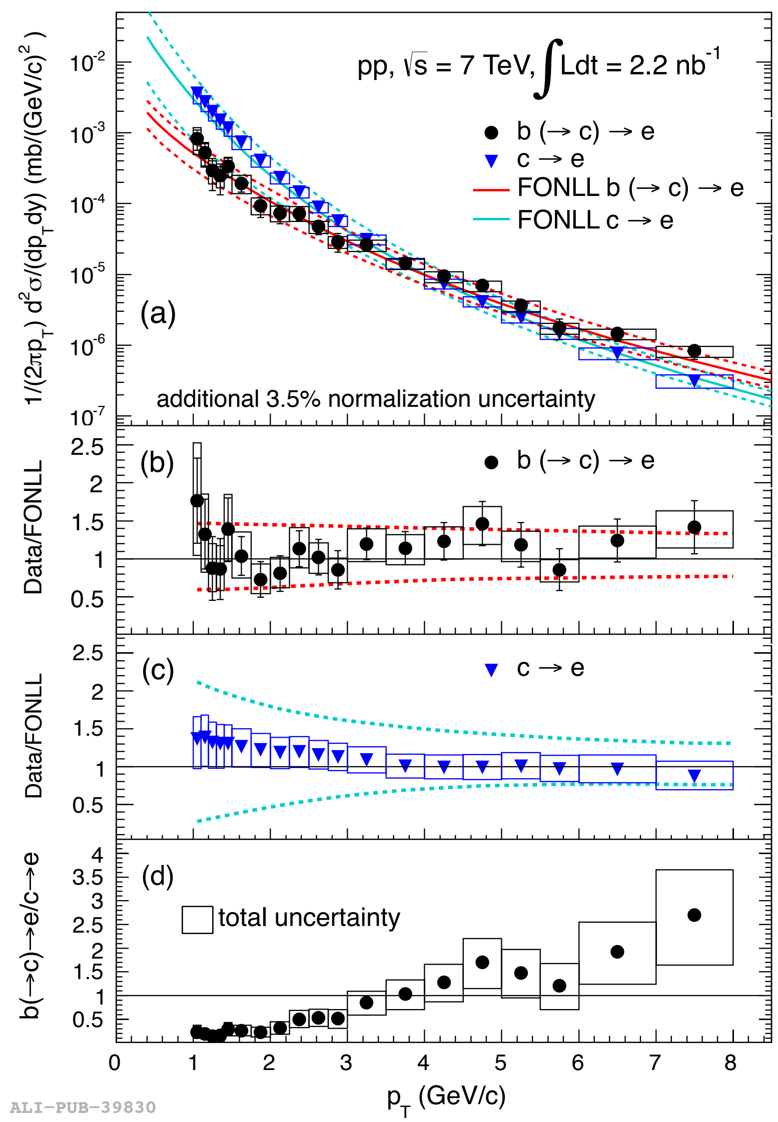
D meson

JHEP 1201 (2012) 128



e from B hadrons decay

PLB 721 (2013) 13–23



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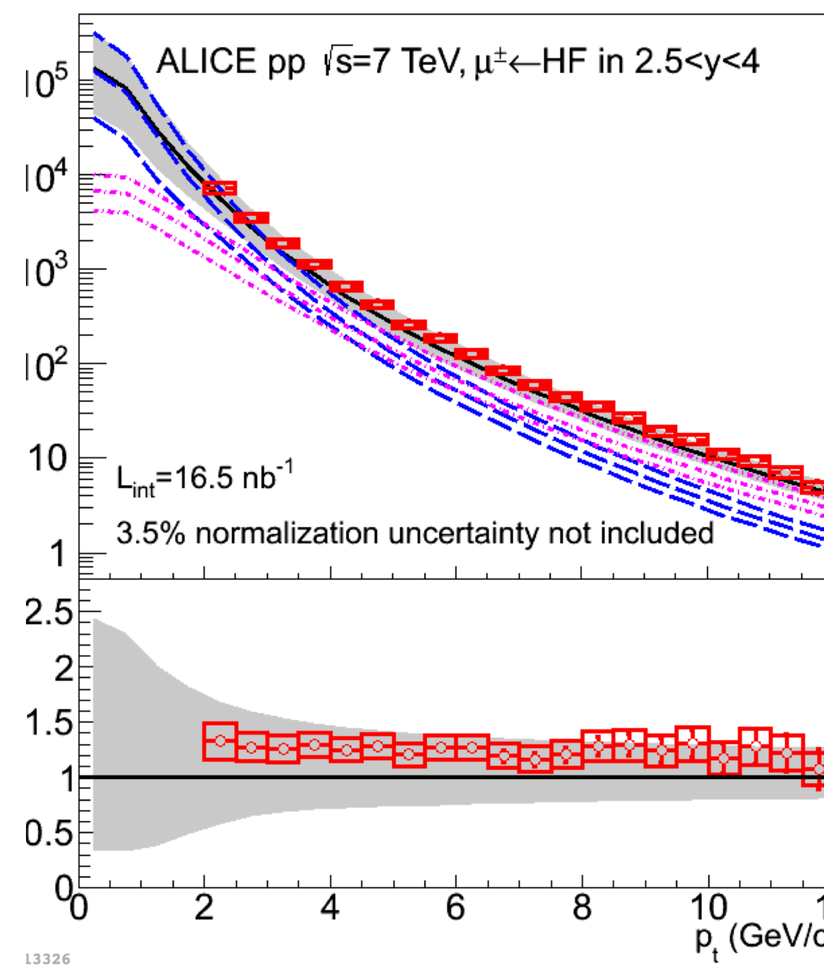
Phys. Lett. B 708 (2012) 265

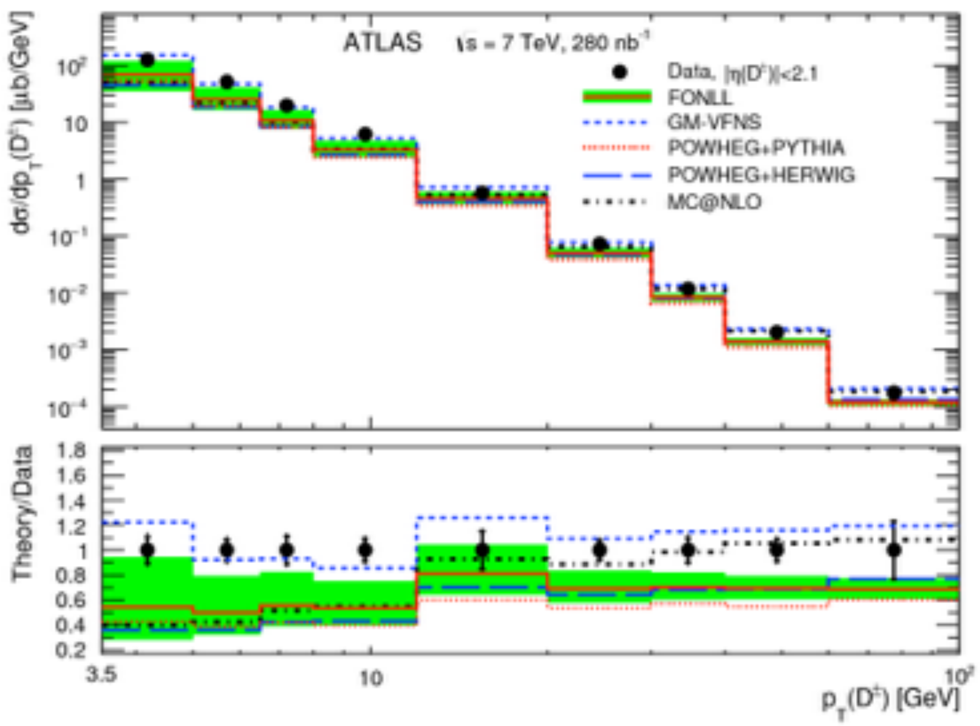


- pQCD based calculations (FONLL, k_T-factorization, GM-VFNS) are compatible with data.
- Beauty production described well by the central value theoretical calculations

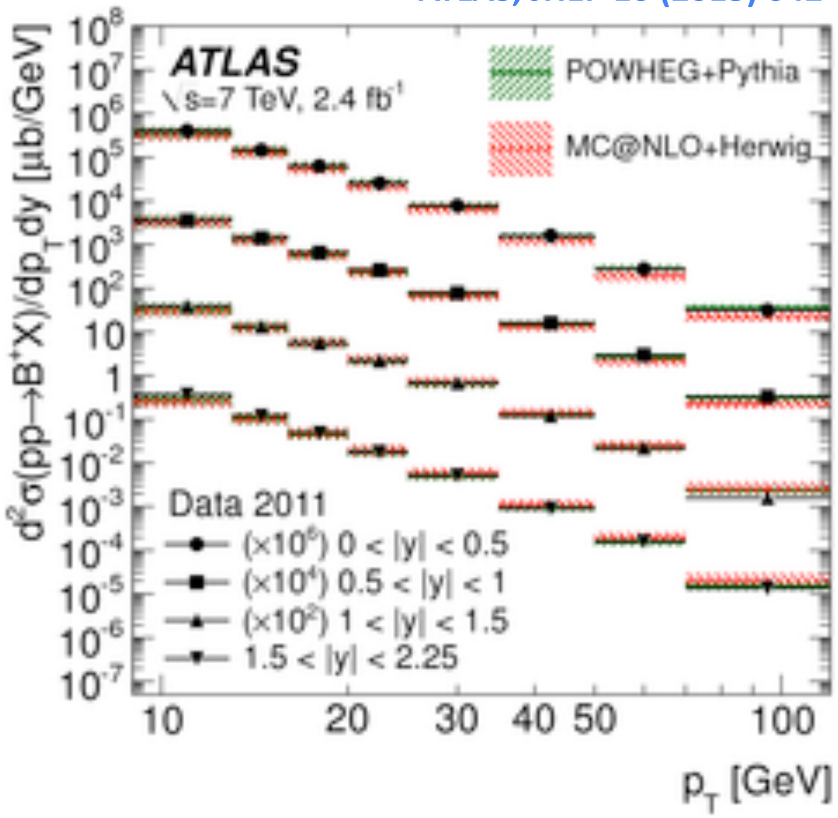
FONLL: JHEP 1210 (2012) 137, GM-VFNS: Eur. Phys. J. C 72 (2012) 2082, k_T factorisation: arXiv:1301.3033

Charm and Beauty production in pp collisions @ $\sqrt{s}$ = 7 TeV

ATLAS, arxiv:1512.02913



ATLAS, JHEP 10 (2013) 042

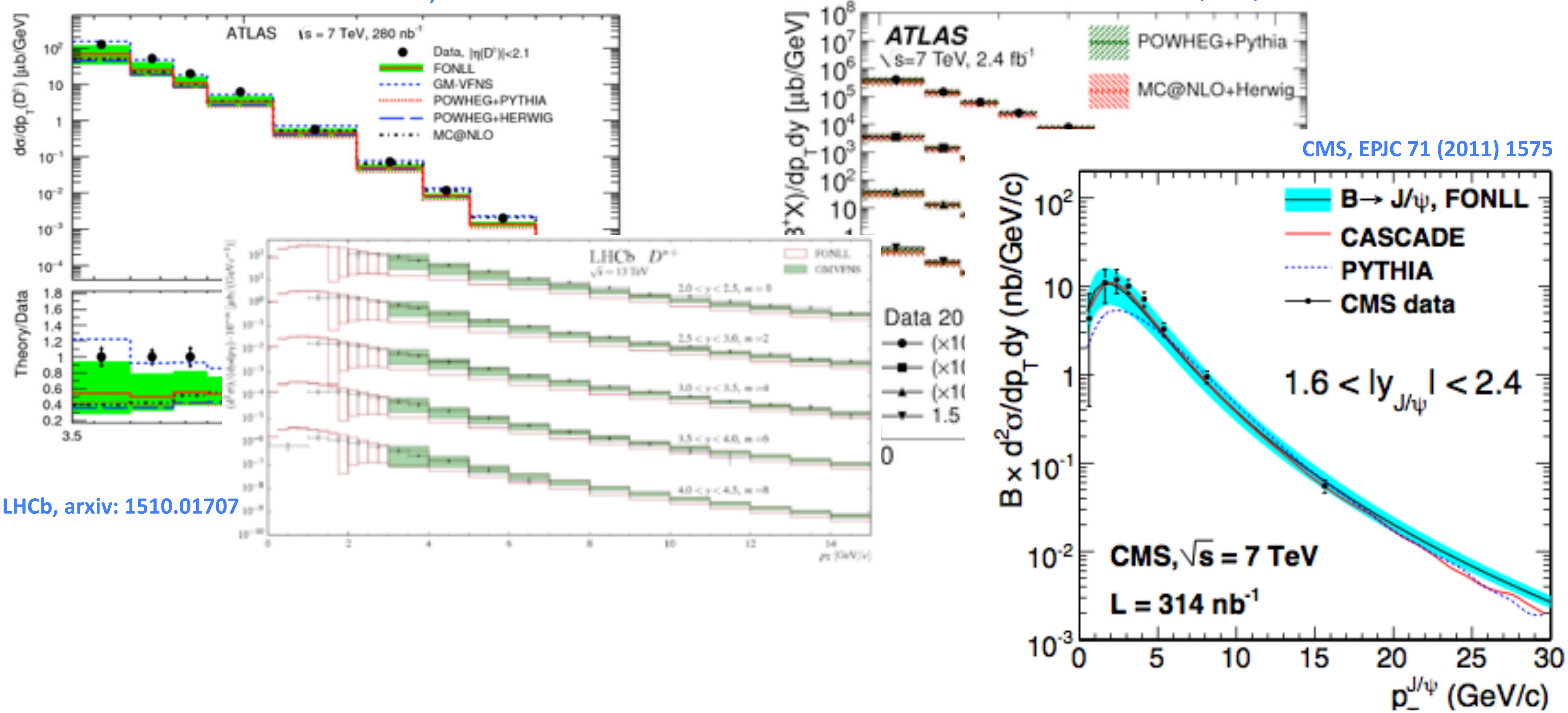


Charm and Beauty production in pp collisions @ $\sqrt{s}$ = 7 TeV

ATLAS, arxiv:1512.02913

ATLAS, JHEP 10 (2013) 042

CMS, EPJC 71 (2011) 1575

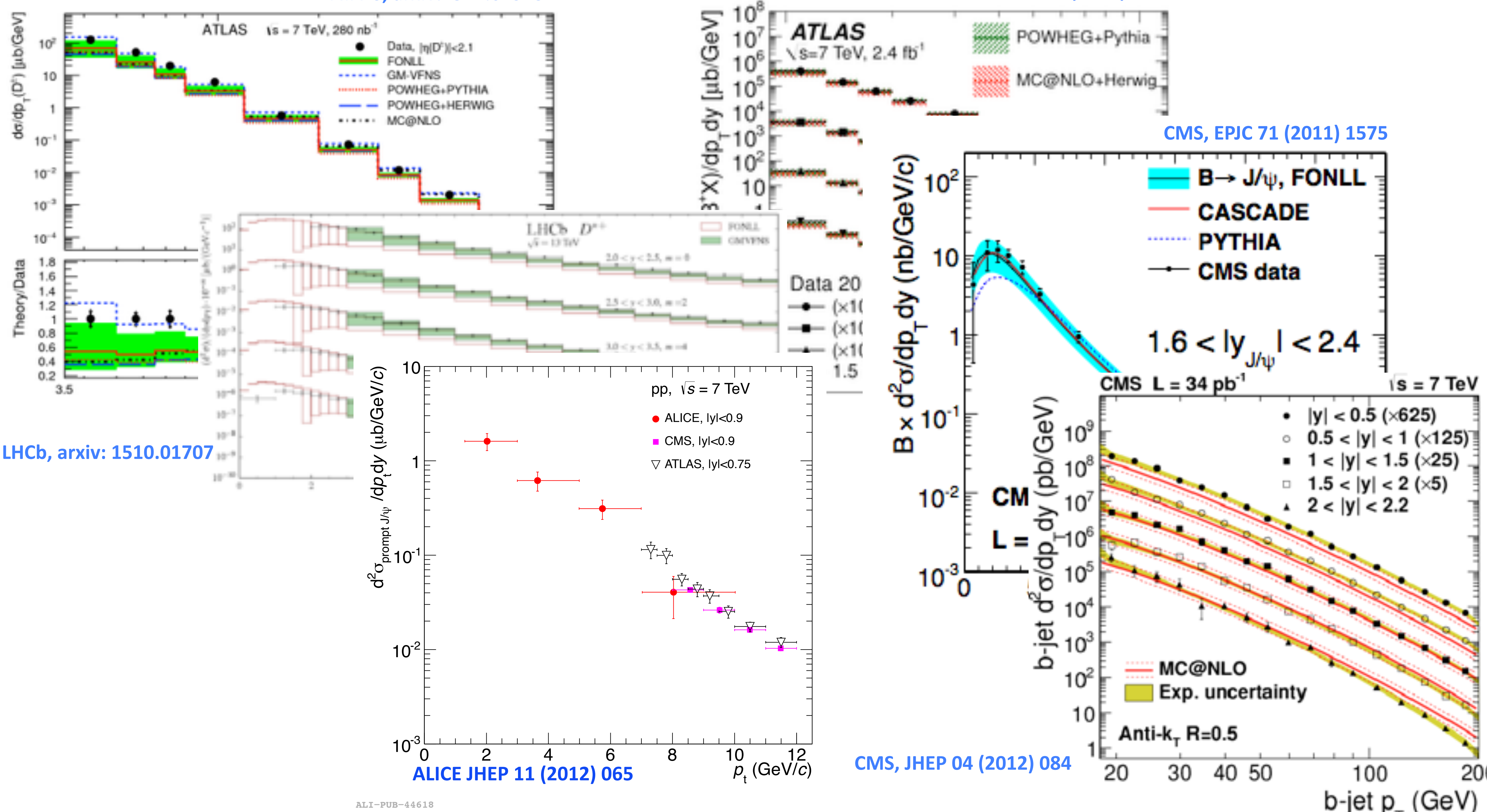


LHCb, arxiv: 1510.01707

Charm and Beauty production in pp collisions @ √s = 7 TeV

ATALS, arxiv:1512.02913

ATLAS, JHEP 10 (2013) 042



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LHCb, arxiv: 1510.01707

ALICE JHEP 11 (2012) 065

CMS, JHEP 04 (2012) 084

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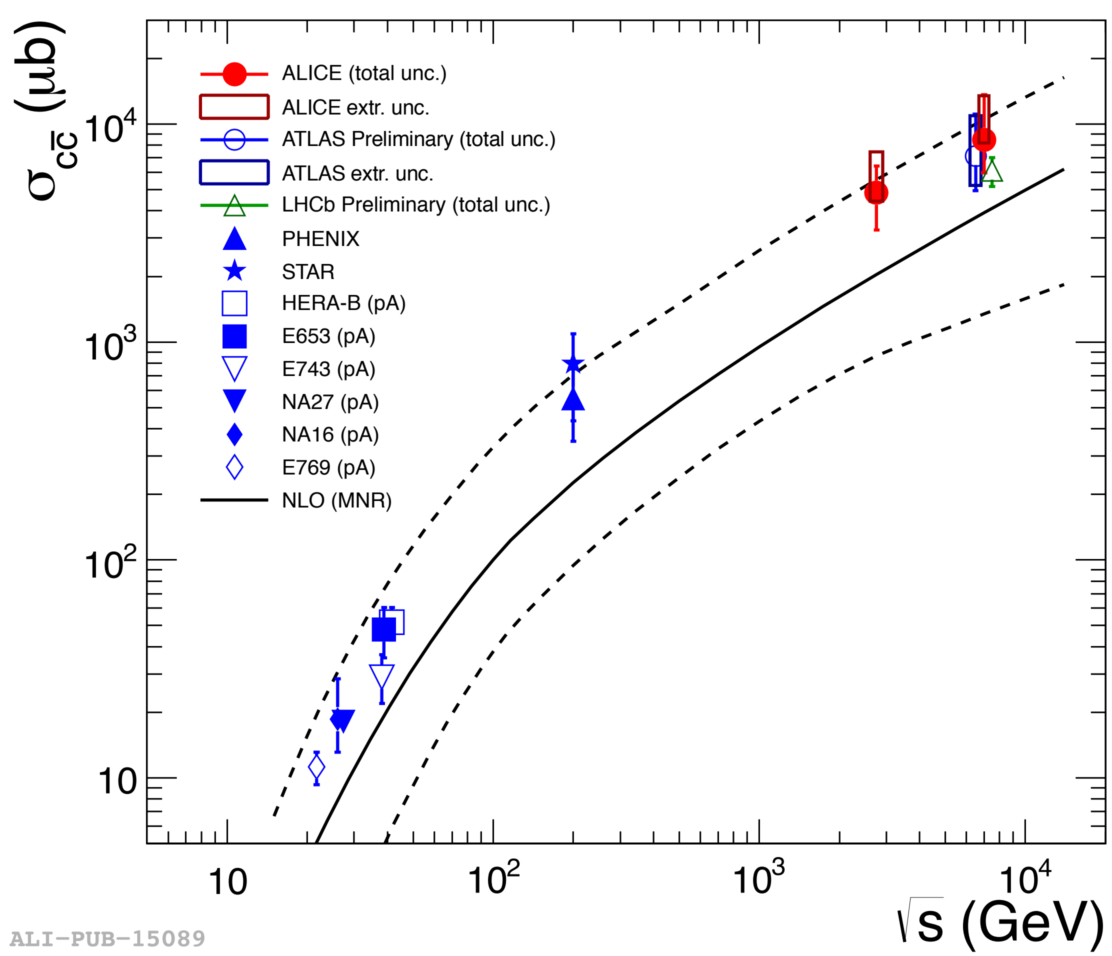
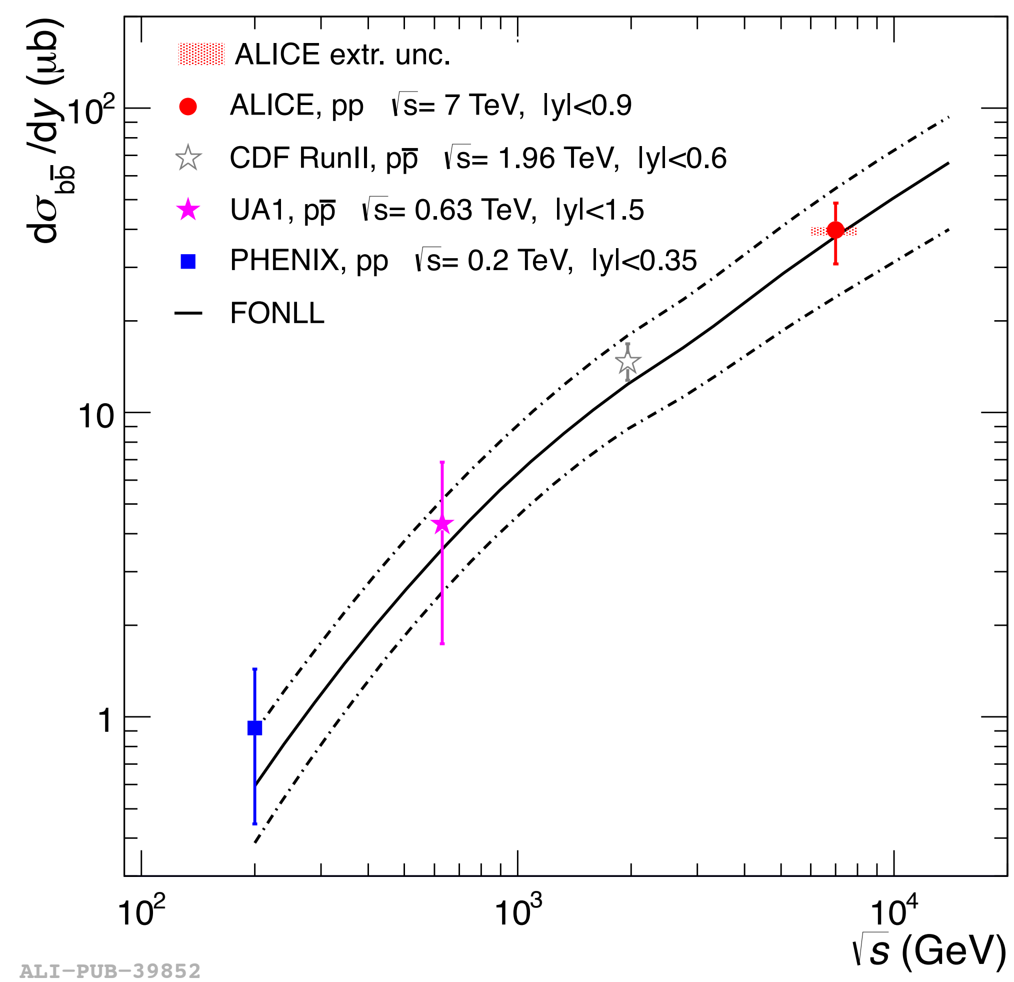




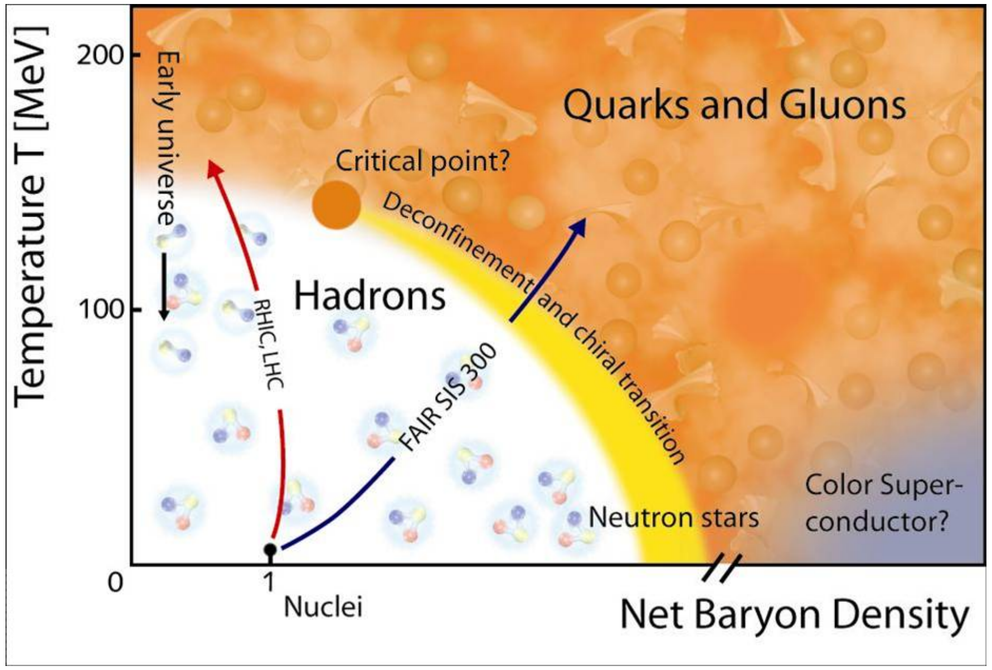
- Total charm and beauty cross sections production have been evaluated
- In both cases the cross section evolution is well reproduced by pQCD-based calculations.
- ~x10 cc pairs and ~x2 bb pairs produced at LHC Run1 energy with respect to RHIC.

Why heavy flavour in Pb-Pb collisions?

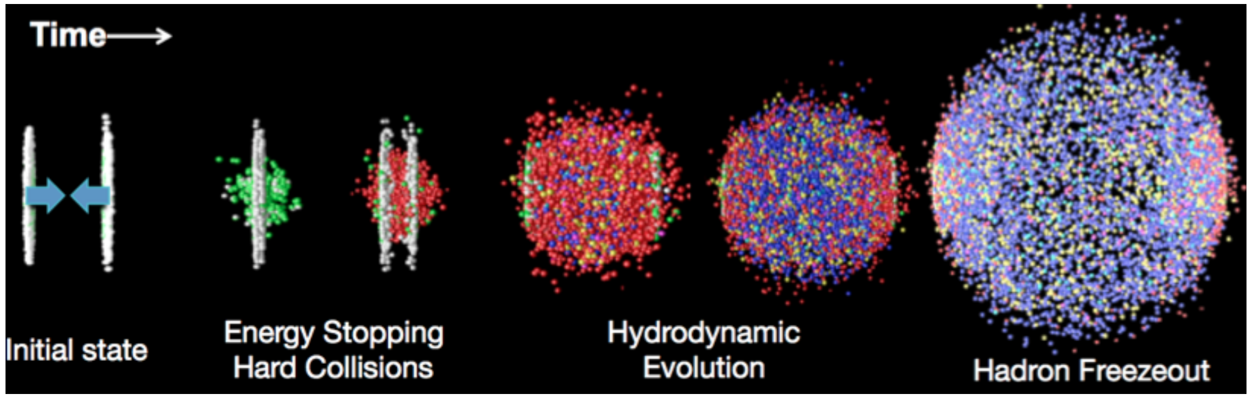
Why Pb-Pb collisions?

High-density and high-temperature QCD

- Ultra-relativistic heavy ions allow to study the phase diagram of the nuclear matter.



- They are “good tools” to compress and heat nuclear matter in order to recreate
  - a very high energy density
  - strongly interacting
  - deconfined medium.

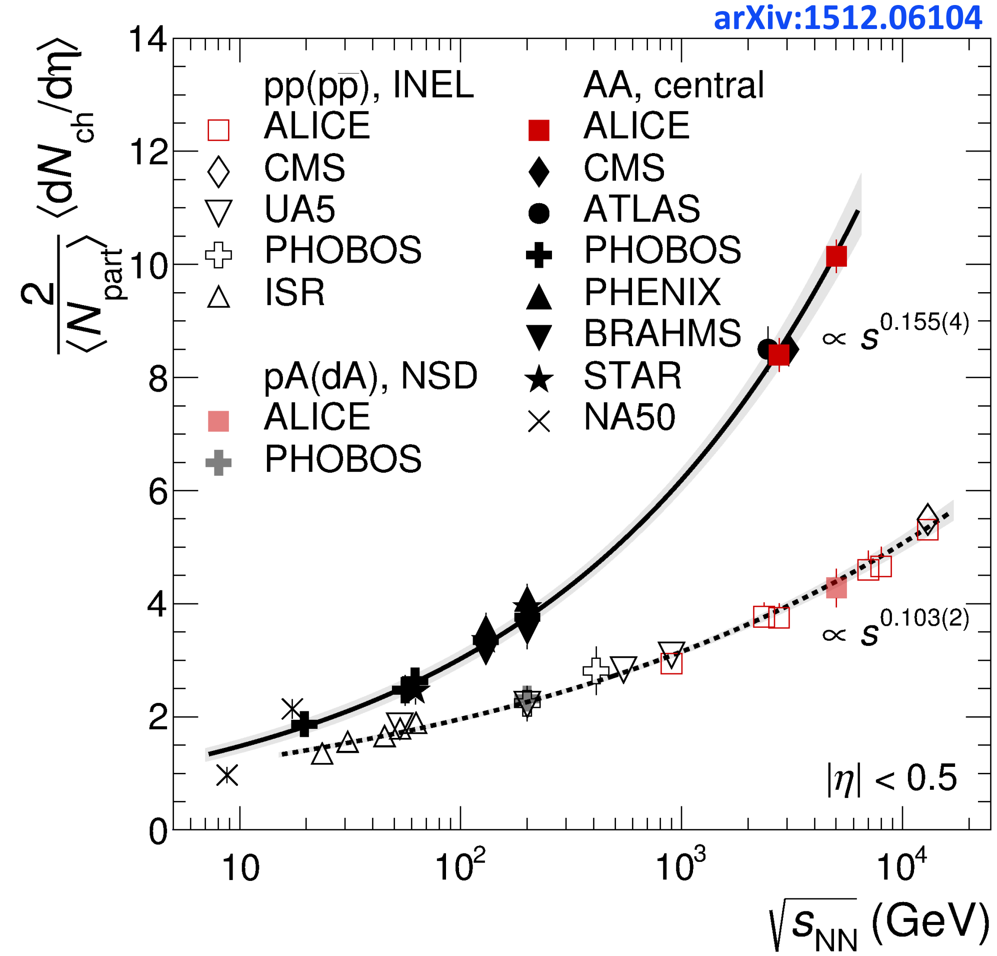


- Characterization of the state of the nuclear matter with hydrodynamics quantities, given its complexity and its extension.

Hot nuclear matter

- Ultra-relativistic heavy ions as “tools” to compress and heat nuclear matter in order to recreate
  - a very high density
  - strongly interacting
  - deconfined medium.

arXiv:1512.06104



- Multiplicity of particle produced directly proportional to the energy density of the system. **ε ~ 12 GeV/fm³** a LHC

$$\varepsilon = \frac{E}{V} = \frac{1}{Sc\tau_0} \frac{dE_T}{dy}\bigg|_{y=0}$$

S = transverse dimension of nucleus

τ_0 = "formation time" ~ 1 fm/c

Hot nuclear matter

- Ultra-relativistic heavy ions as “tools” to compress and heat nuclear matter in order to recreate
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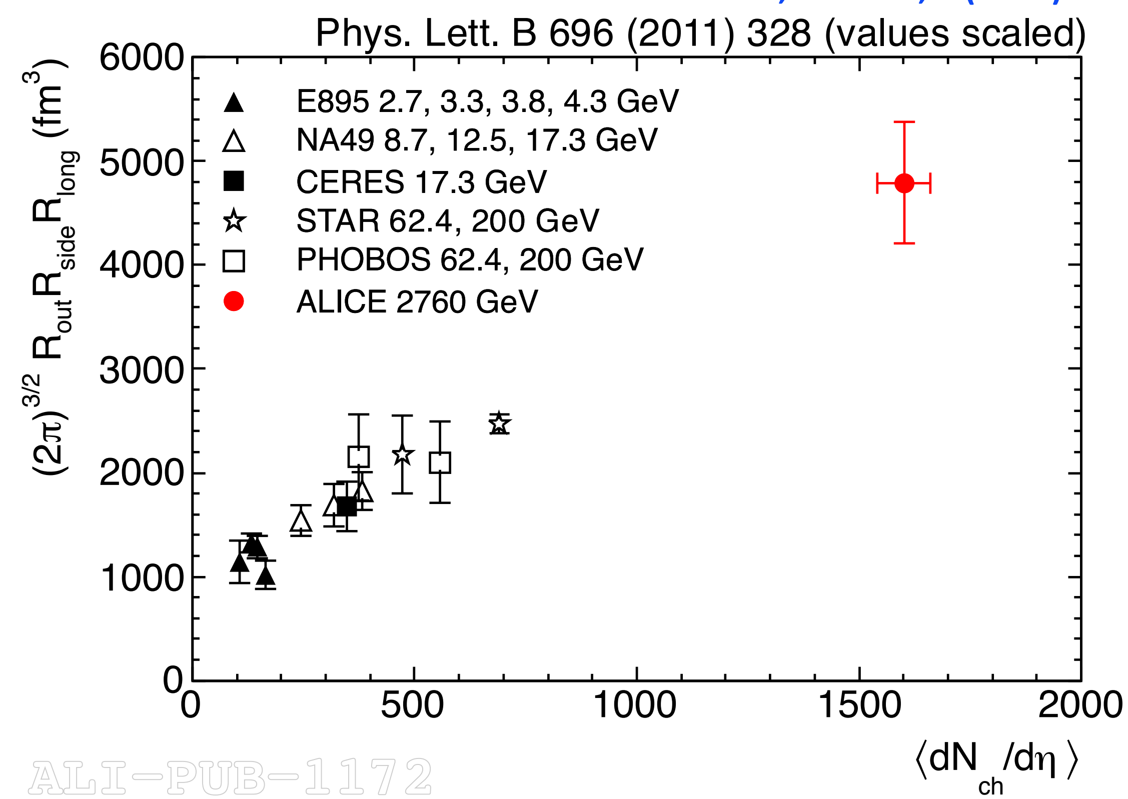
- Multiplicity of particle produced directly proportional to the energy density of the system. **$\varepsilon \sim$ 12 GeV/fm^3** a LHC

- Bose Einstein correlation between identical bosons allow to study the extension of the system. **“homogeneity” $V \sim$ 5000 fm^3**

ALICE, PLB 696, 4 (2011)



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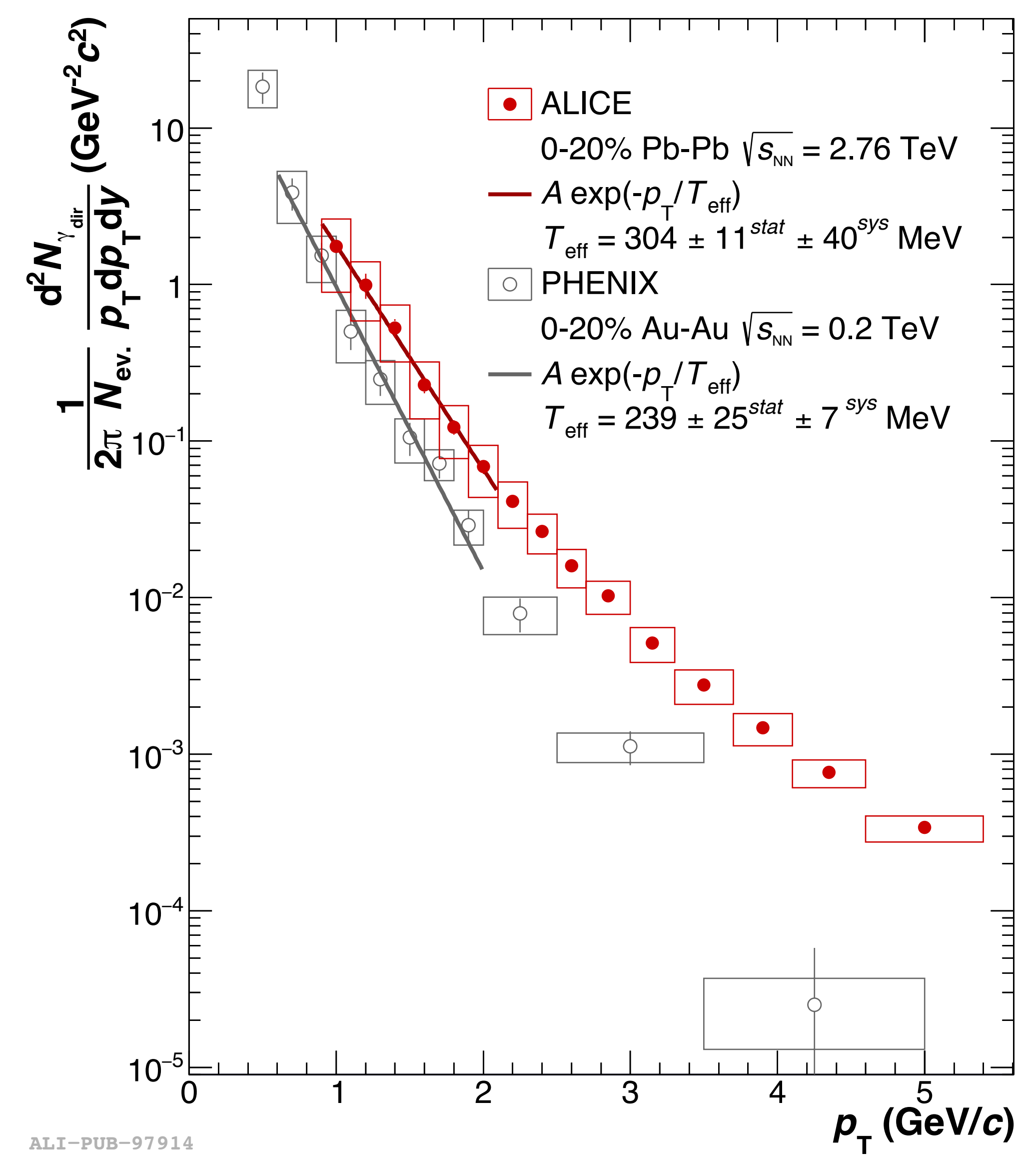
PLB 754, 235-248 (2016)



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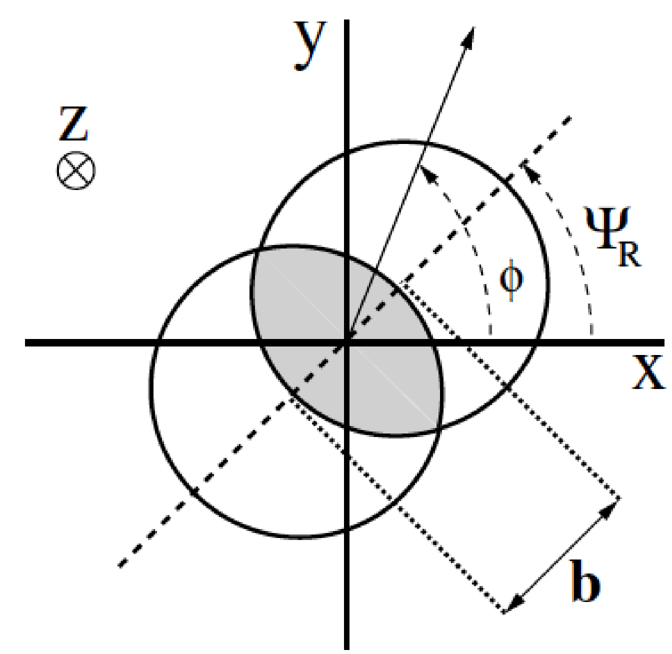
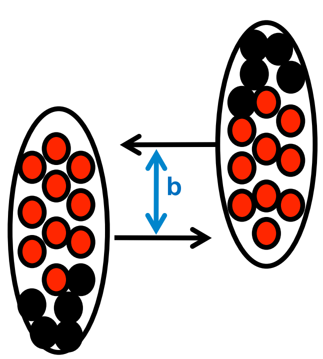
- Bose Einstein correlation between identical bosons allow to study the extension of the system. **“homogeneity” *V* ~ 5000 fm^3**

- Direct photon emitted by the hot system (as black body radiation) ***T* ~ 304 ± 11 ± 40 MeV**

Centrality and reaction plane

- **Centrality**:
  - Quantity to determine the overlap region of the two nuclei during the collisions.
  - Geometrical model allow to determine the **number of participant to the collision**.
  - Events are classify in “centrality classes” in terms of the percentiles of the total AA cross section.





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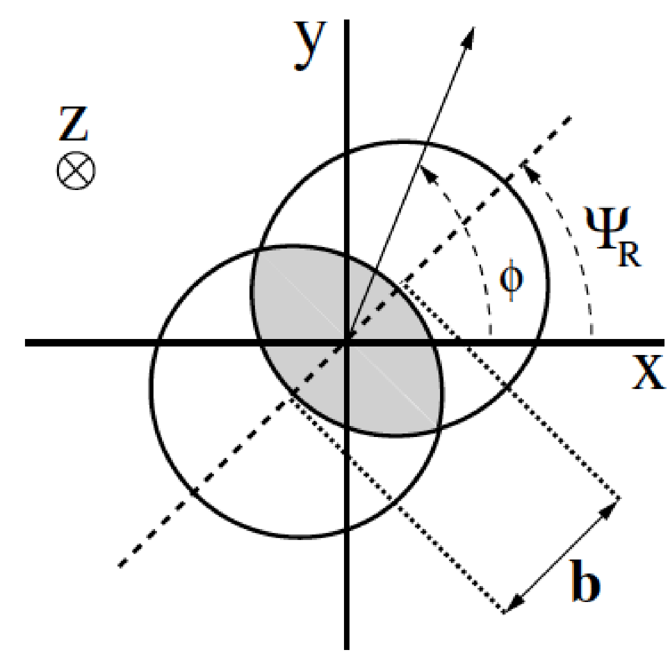
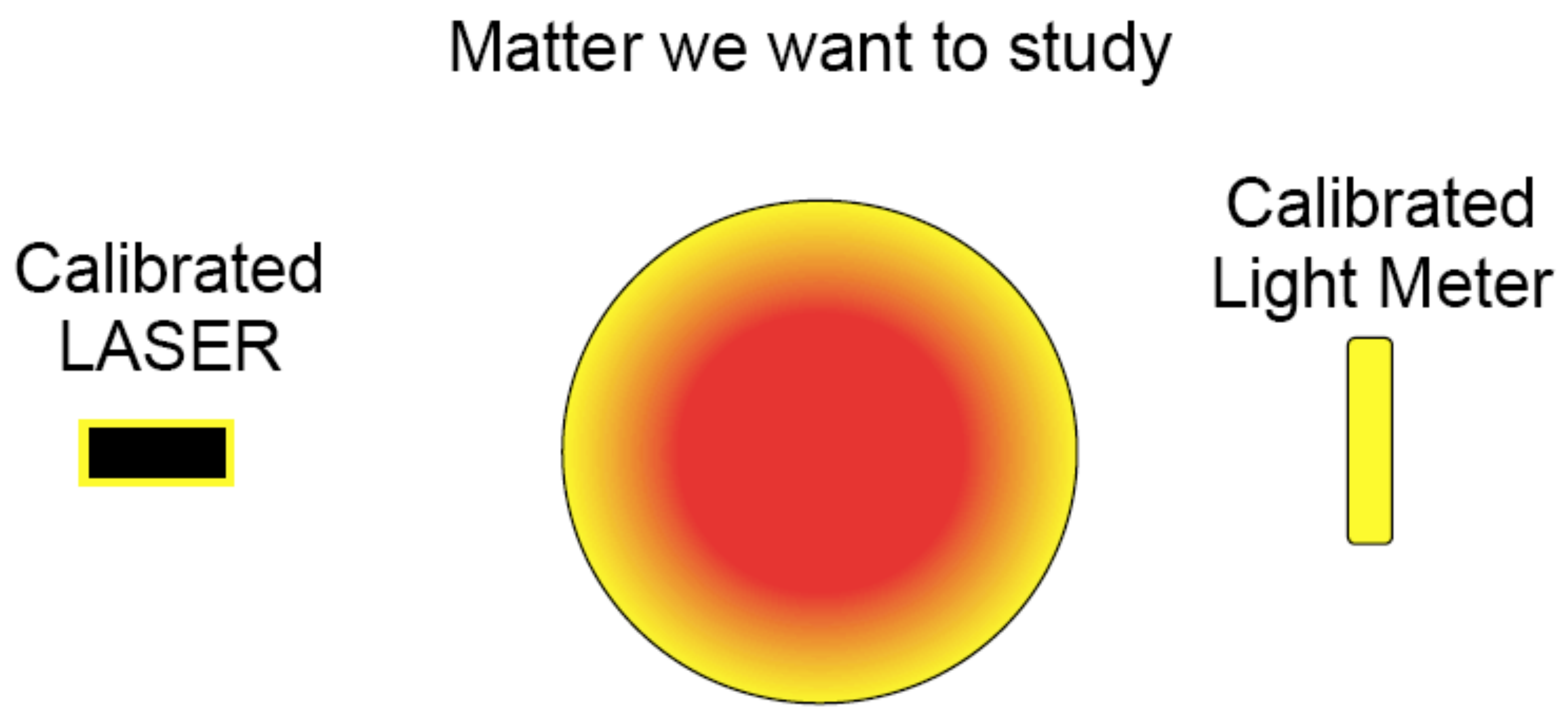


- **Reaction Plane**:
  - Quantity to determine the "orientation" of the two nuclei during the collisions.
  - The angle Ψ_R **between the x axis and the impact parameter (b) direction** identifies the reaction plane.
  - The event plane can be measured using the azimuthal distribution of measured particles.

How to investigate nuclear matter?



courtesy T.Ullrich

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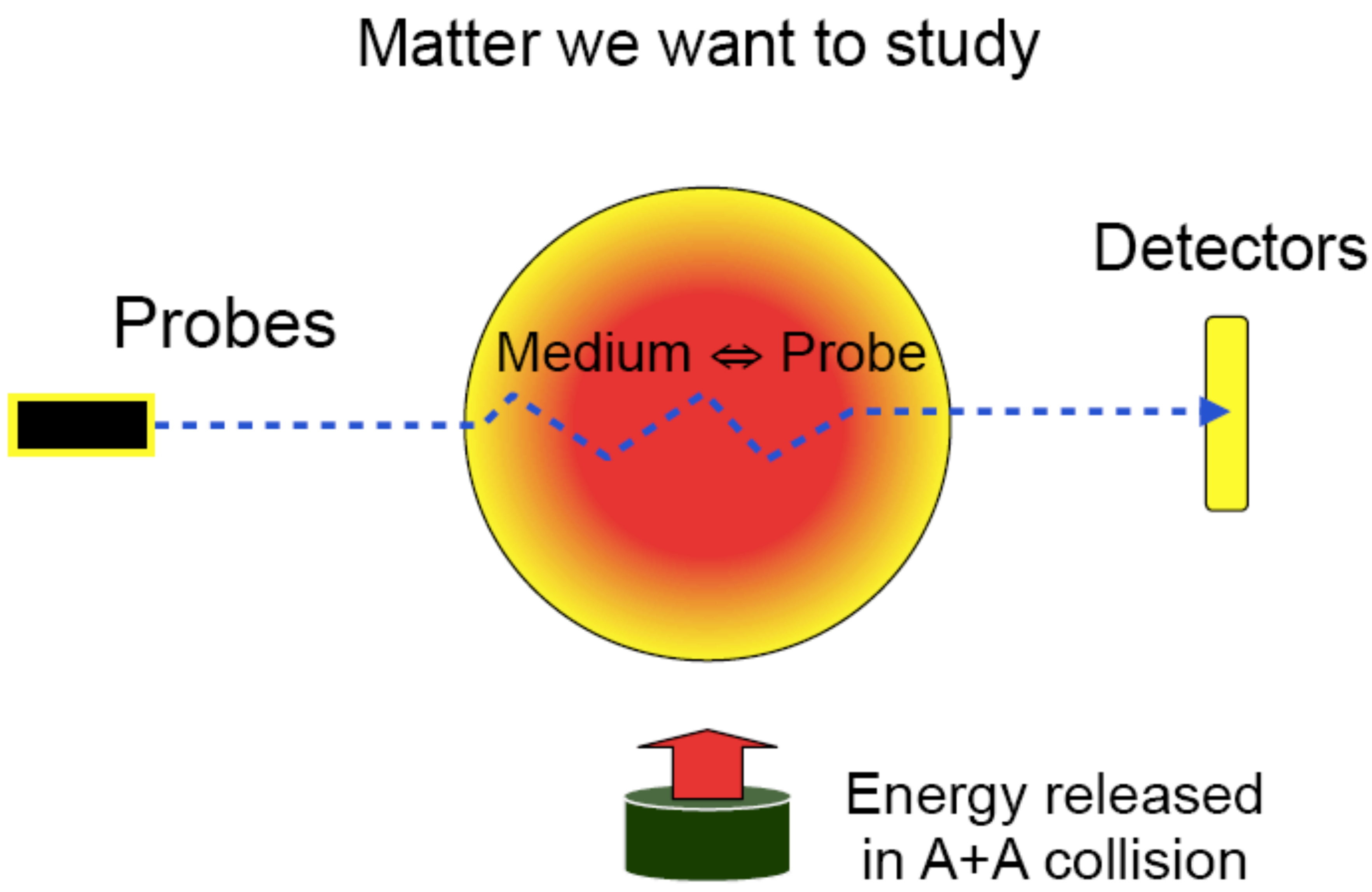
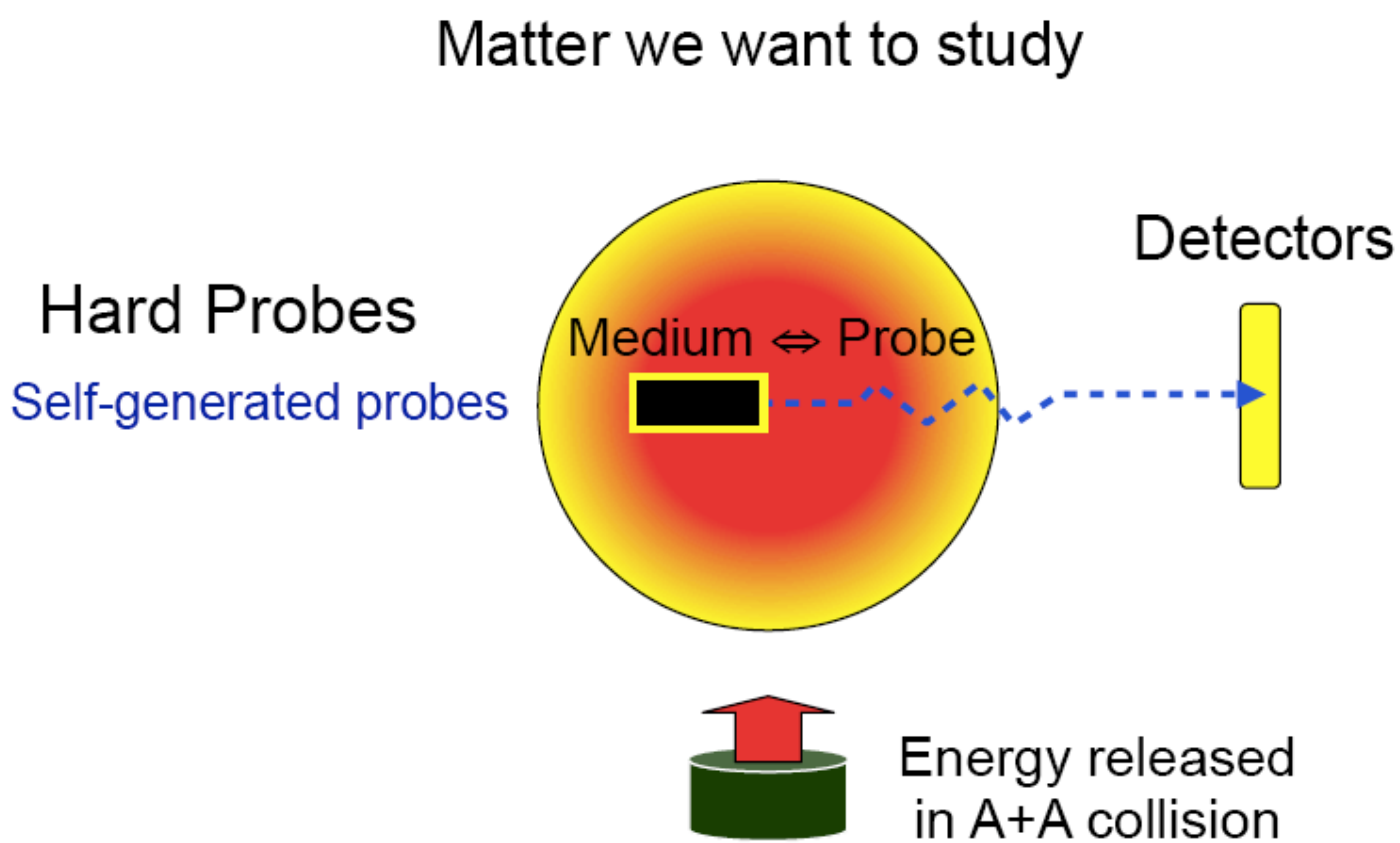


courtesy T.Ullrich

Hard and self-generated probes



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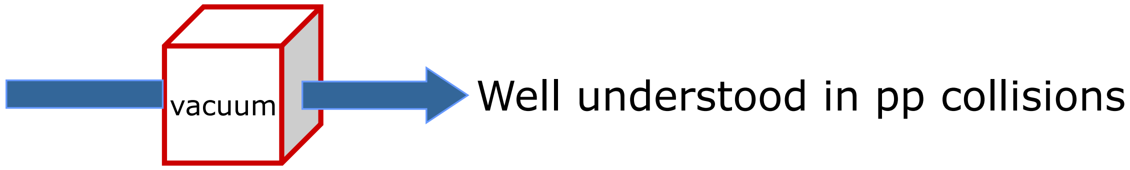
Hard, self-generated and calibrated probes

- The behaviour of the probes should be well understood in **"standard matter"** (pp collisions).



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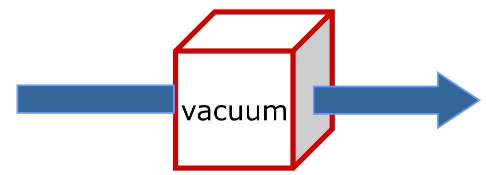
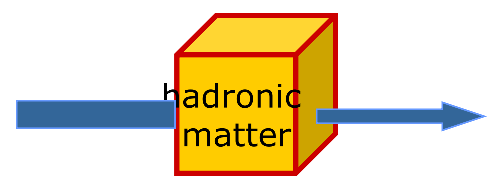


Well understood in pp collisions

- p-A collisions allows to investigate the **Cold Nuclear Matter** effects. Those effects are related to the difference for a parton of being wounded in a nucleons or in a nucleus.



Slightly affected by the hadronic matter and in a well understood way

Hard, self-generated and calibrated probes

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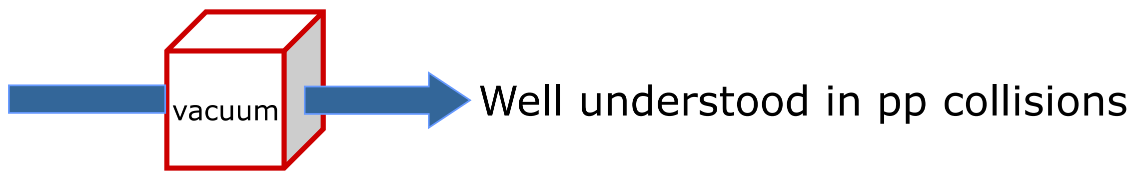

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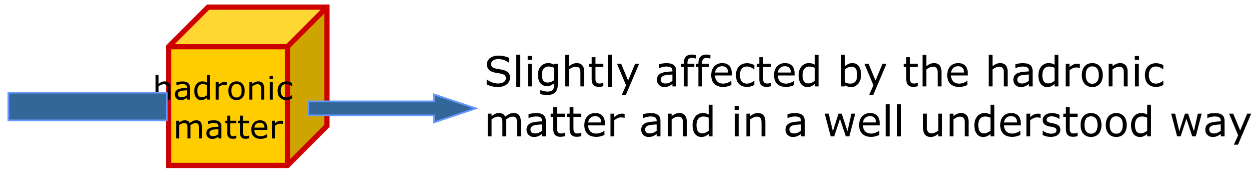
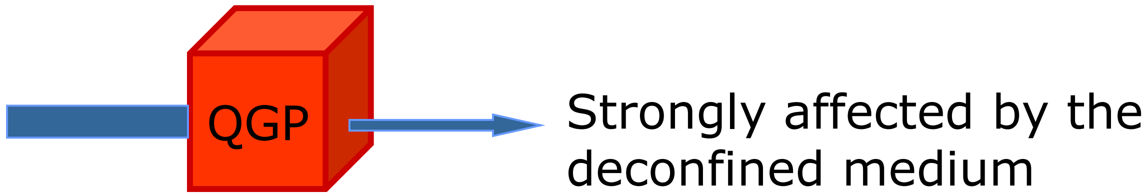


- A-A collisions allows to investigate **Hot Nuclear Matter** effects
  Interaction of the probes with the hot, dense and deconfined nuclear matter



So why heavy flavour in Pb-Pb collisions?

- Since they originate from **hard processes**, where large momentum transfer μ is involved, their production can be **computed using pQCD**.
  - **And we already discussed that these calculations are in good agreement with data.**

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- Hard probes are usually produced in hard parton-parton scatterings in the **early stage of the collisions.**
  - $\Delta t < 1/m_Q \Rightarrow$ ~0.1 fm/c for charm and ~0.01 fm/c for beauty quarks
  - τ_{QGP} ~ 0.3 - 1 fm/c

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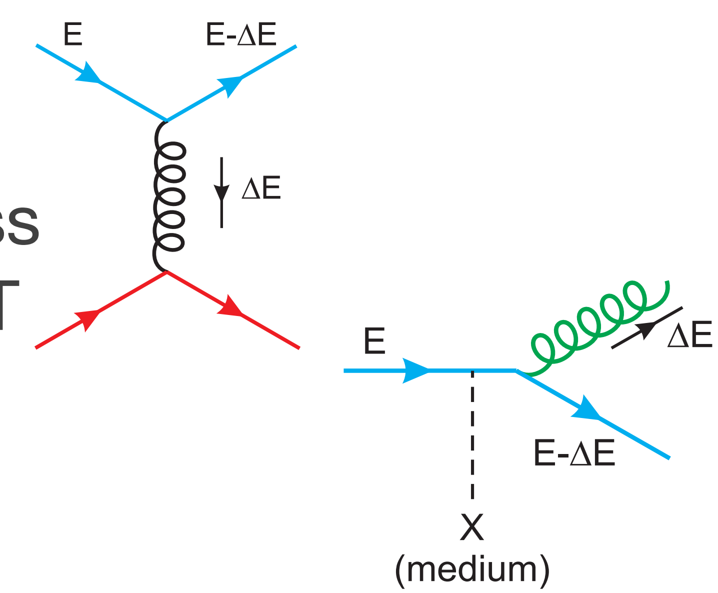
  - $\tau_{QGP} \sim 0.3 - 1$ fm/c

- They can “observe” the full evolution of the hot nuclear matter and interact with it if they are color charged.

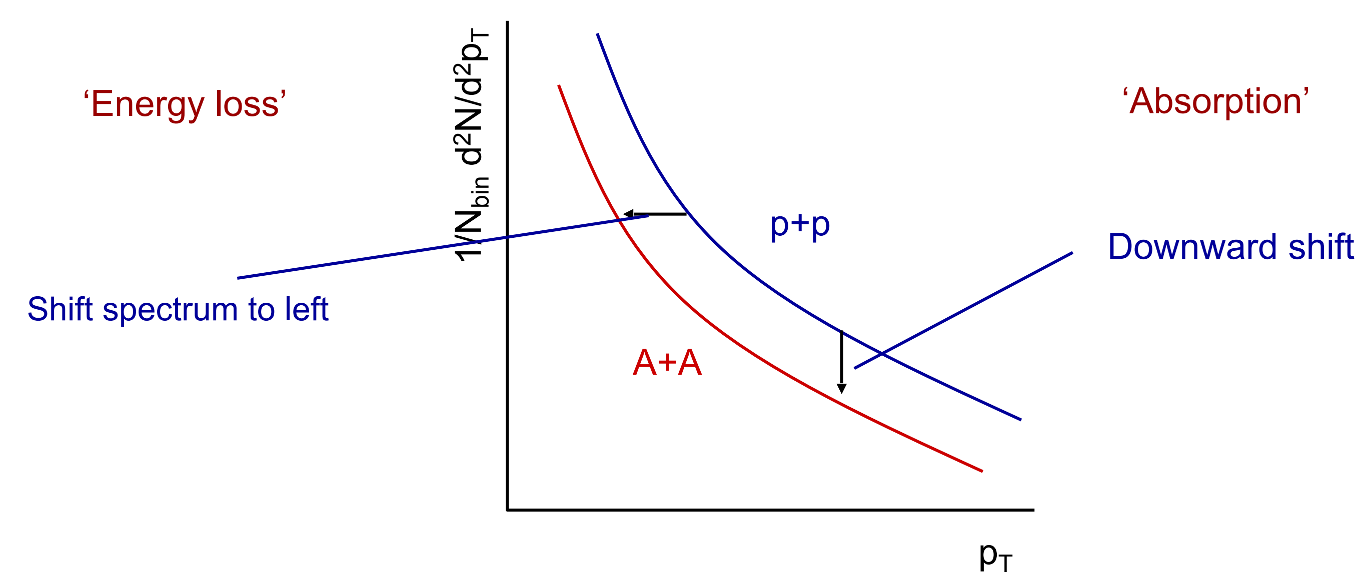
Heavy quarks interactions with the medium: Energy Loss

- Partons travel ~4 fm in the high colour-density medium.

- In their path they can loose energy for two mechanisms:
  Scatterings with other partons ➜ collisional energy loss
  ➜ dominates at low-pT
  Gluon radiation ➜ radiative energy loss
  ➜ dominates at high energy



- The reduction of the parton energy translates to a reduction in the average momentum of the produced hadron.

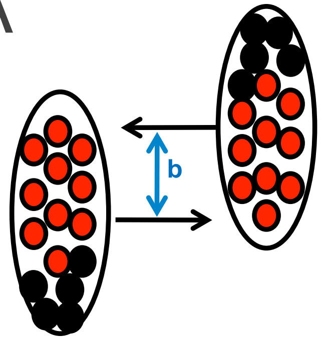


Observables:

- **Nuclear modification factor (R_{AA}):**
  - Comparison of the spectra in pp and AA collisions.
  - If AA collisions would be a "simple" superposition of many pp collisions $R_{AA} = 1$

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{1}{< N_{coll} >} \times \frac{d^2N_{AA}/dp_T d\eta}{d^2N_{pp}/dp_T d\eta}$$

  - Similar ratio can be build comparing central and peripheral AA collisions (R_{CP})



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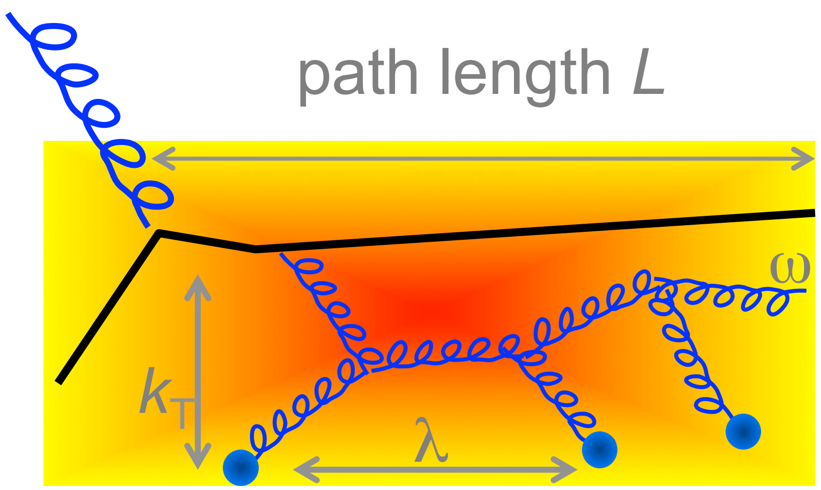
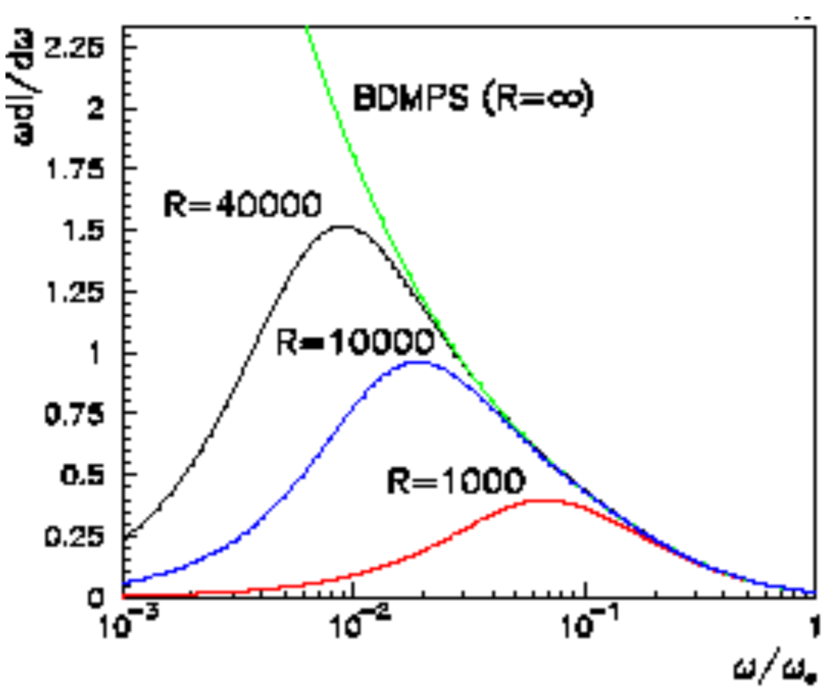
Energy Loss

Baier, Dokshitzer, Mueller, Peigne', Schiff, NPB 483 (1997) 291.
Zakharov, JTEPL 63 (1996) 952.
Salgado, Wiedemann, PRD 68(2003) 014008.

- Medium modeled with static scattering centers
- Coherent gluon wave function accumulate k_T due to multiple scatterings ➜ the gluon decoheres and it is radiated.





Radiated gluon energy distrib:

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \propto \alpha_s C_R \begin{cases} \sqrt{\omega_c/\omega} & \text{for } \omega < \omega_c \\ (\omega_c/\omega)^2 & \text{for } \omega \geq \omega_c \end{cases}$$

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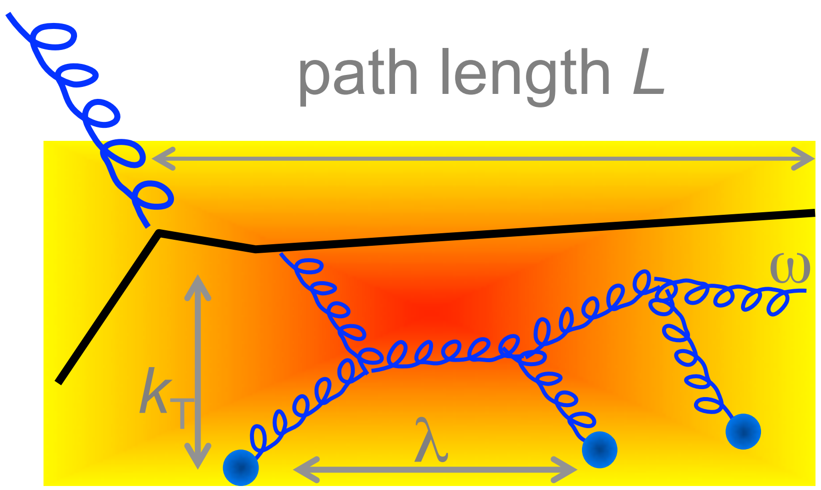
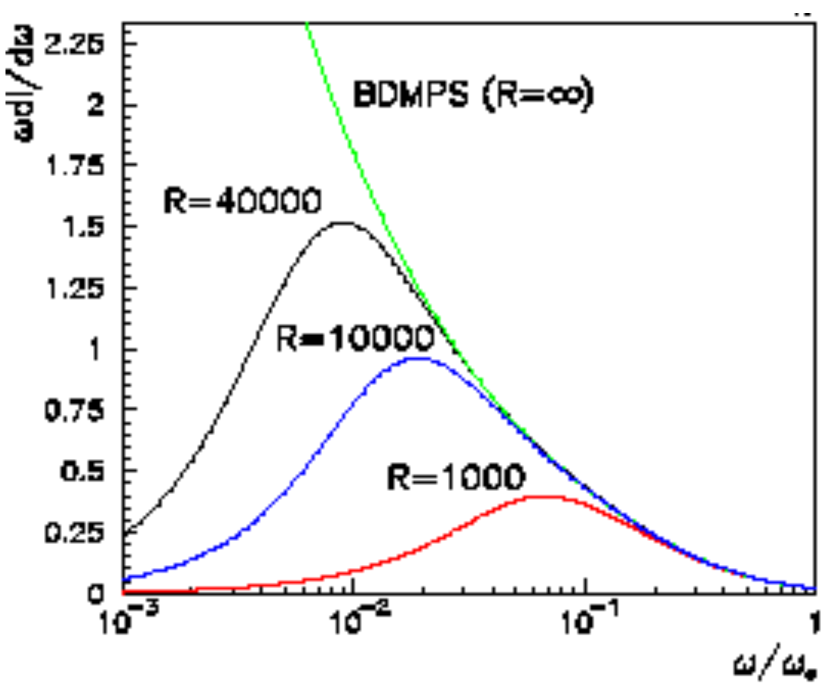
- Coherent gluon wave function accumulate k_T due to multiple scatterings ➜ the gluon decoheres and it is radiated.



Radiated gluon energy distrib:

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R \begin{cases} \sqrt{\omega_c / \omega} & \text{for } \omega < \omega_c \\ (\omega_c / \omega)^2 & \text{for } \omega \geq \omega_c \end{cases}$$



C_R Casimir Factor: 4/3 for q, 3 for g

$\omega_c = \hat{q} L^2 / 2$ Scale of the radiated energy

$R = \omega_c L$ Constraint: $k_T < \omega$

$$\hat{q} = \frac{< k_T^2 >}{\lambda}$$

Transport coefficient related to the **medium characteristics** and to the **gluon density**

Heavy quarks interactions with the medium:
Energy Loss

Baier, Dokshitzer, Mueller, Peigne', Schiff, NPB 483 (1997) 291.
Zakharov, JTEPL 63 (1996) 952.
Salgado, Wiedemann, PRD 68(2003) 014008.

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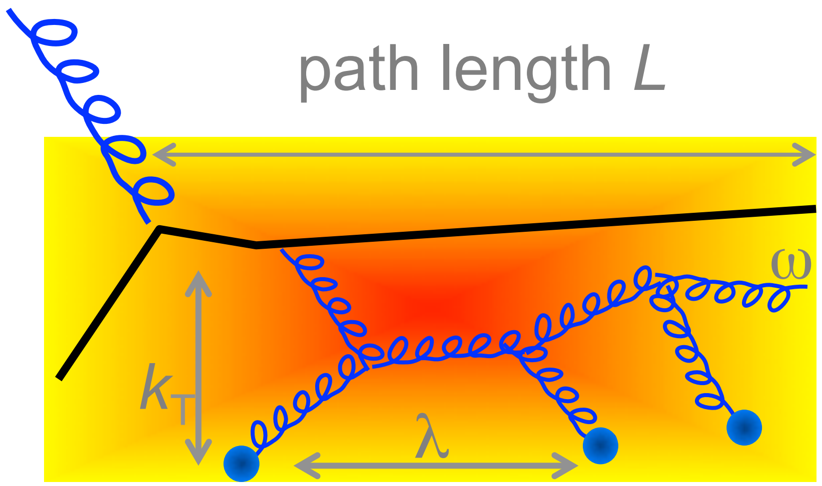

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Color charge dependence of radiative energy loss

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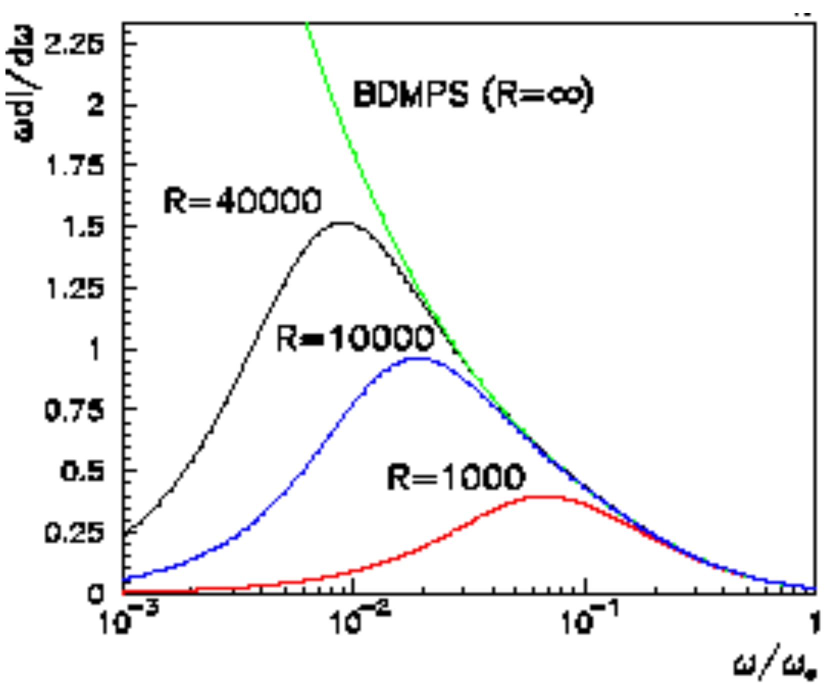

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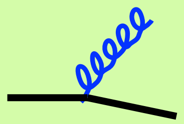
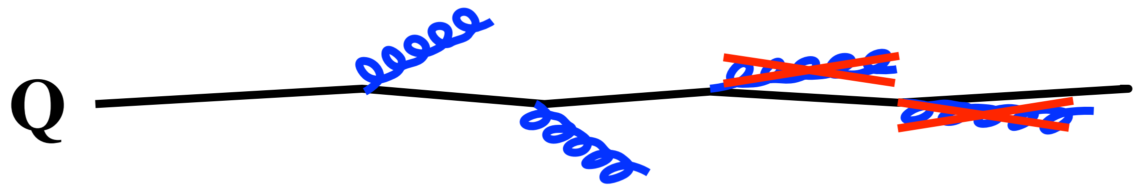
Heavy quarks interactions with the medium:
Mass dependence of the Energy Loss

- Gluon radiation of heavy quarks is suppressed due to the introduction of a mass term in the propagator:
  - **Dead cone effect**

Gluonsstrahlung probability



$$\propto \frac{1}{[\theta^2 + (m_Q / E_Q)^2]^2}$$



Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602.
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

$$\omega \frac{dI}{d\omega}\bigg|_{HEAVY} = \omega \frac{dI}{d\omega}\bigg|_{LIGHT} \times \left(1 + \left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^{-2}$$

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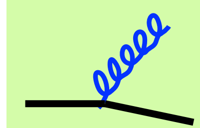

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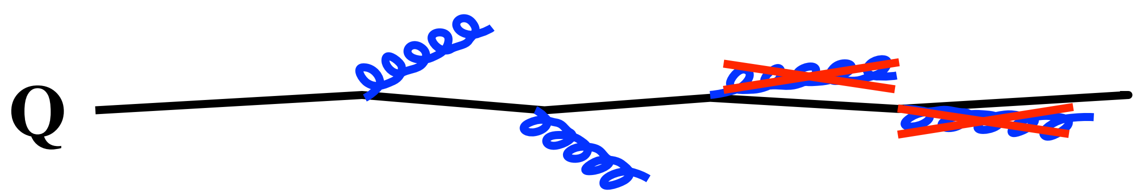

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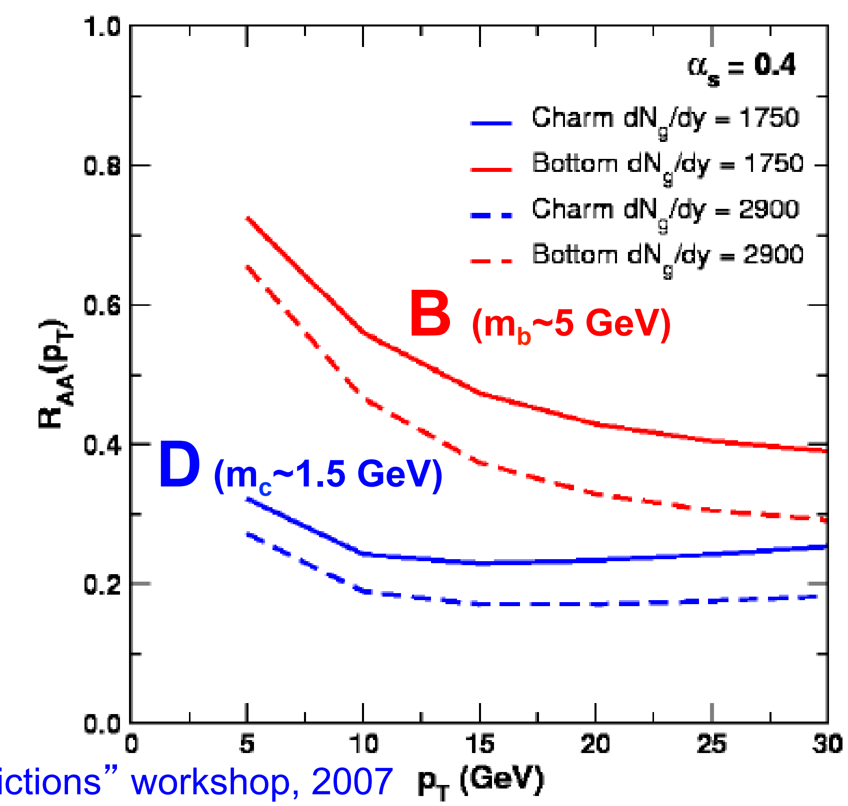
- Energy distribution of radiated gluons is suppressed by an angle-dependent factor: **heavy quarks might lose less energy in the medium ?**



Wicks, Gyulassy, "Last Call for LHC Predictions" workshop, 2007

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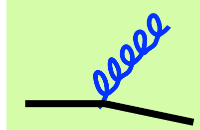

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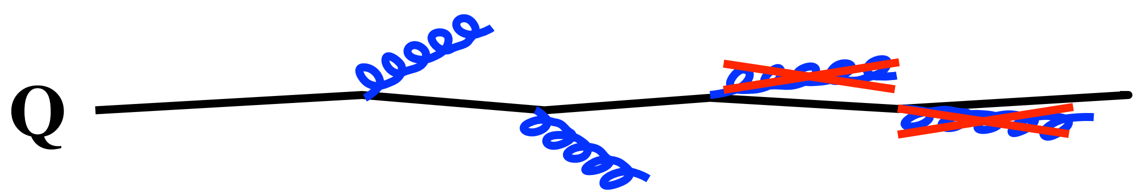

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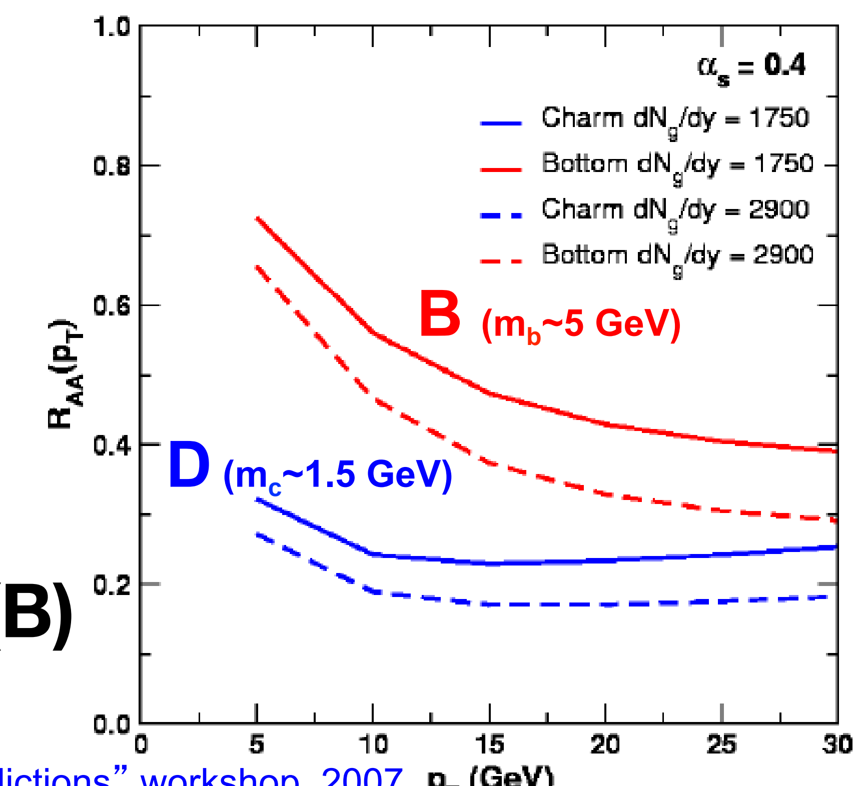
?

ΔE(light) >ΔE(c) > ΔE(b) ➜ $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

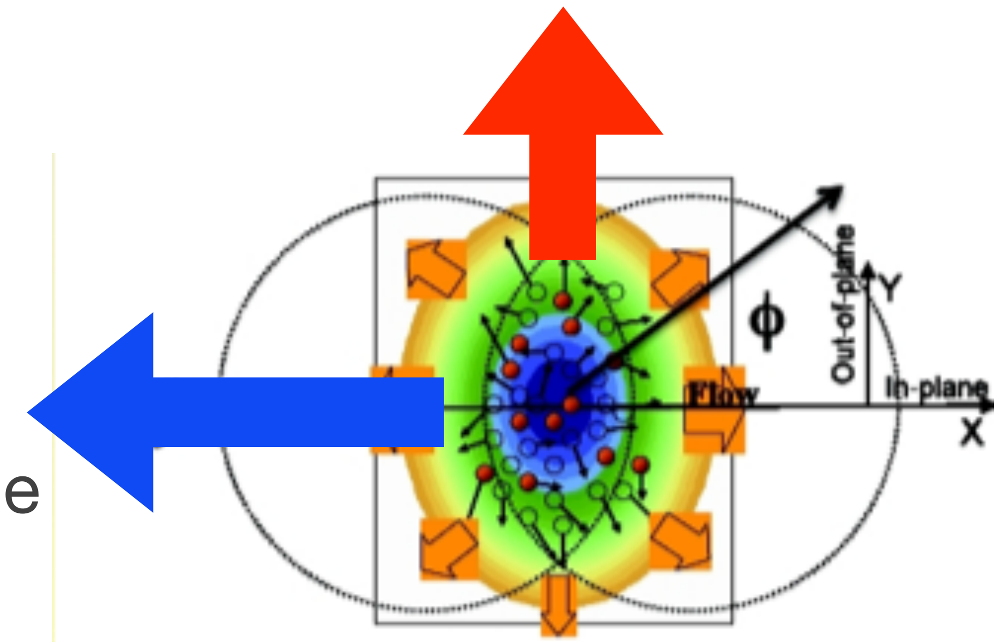


Wicks, Gyulassy, "Last Call for LHC Predictions" workshop, 2007

Heavy quarks interactions with the medium: Take part in the collective expansion

- Due to the extended size of the nuclei overlap regions of the collisions, produced particles undergo collective effects.

- Different pressure gradients, due to the different geometry of the collisions might modify the particle distribution:
  - All particles in the same region might be push apart all together (collectively)
  - Particle that have to traverse longer path might loose more energy in the medium.



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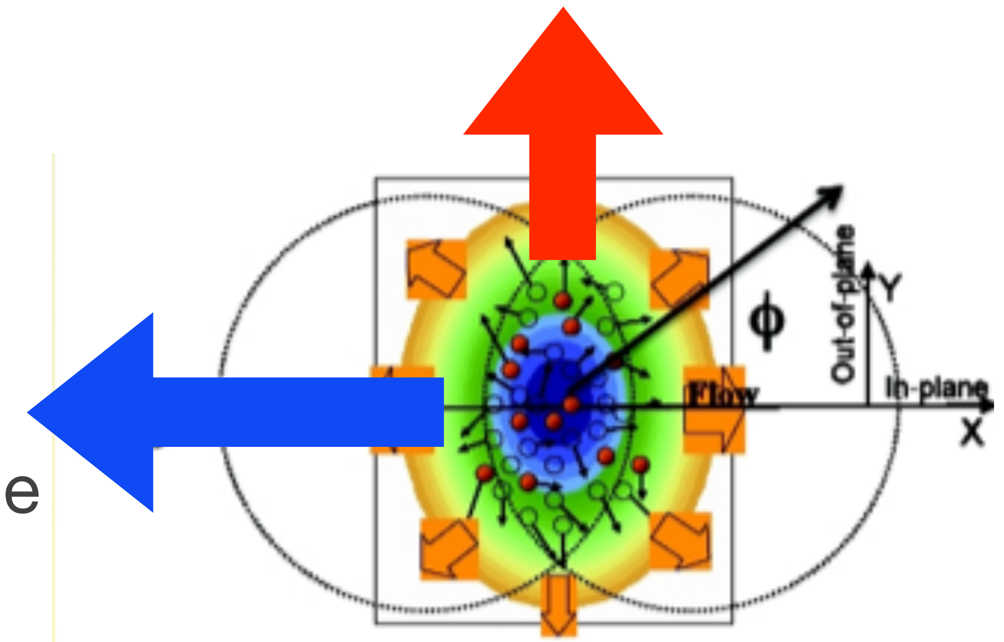


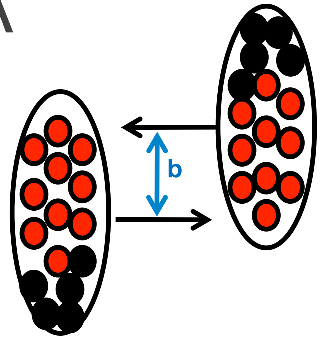
- **Soft particle**, whose quarks come mainly from the medium, feel these common behavior.
- What about **charm** (and beauty) that are produced at a **previous and independent stage**? And that they are way heavier?

Observables:

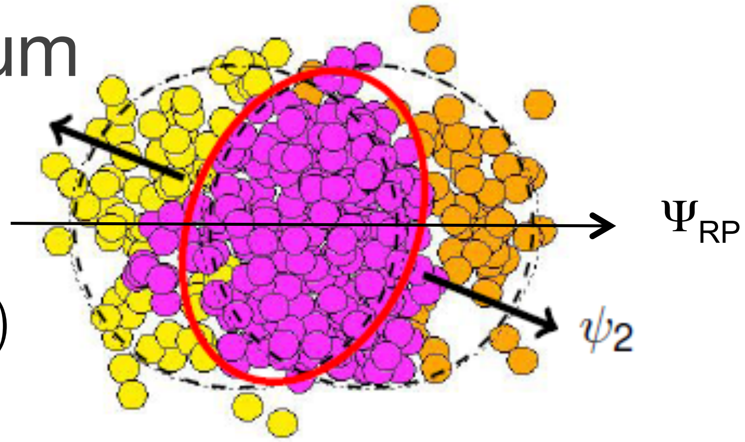
- **Nuclear modification factor (R_{AA}):**
  - Comparison of the spectra in pp and AA collisions.
  - If AA collisions would be a “simple” superposition of many pp collisions $R_{AA} = 1$

$$R_{\rm AA}(p_{\rm T}) = \frac{1}{< N_{coll} >} \times \frac{d^2 N_{AA}/dp_T d\eta}{d^2 N_{pp}/dp_T d\eta}$$

  - Similar ratio can be build comparing central and peripheral AA collisions (R_{CP})



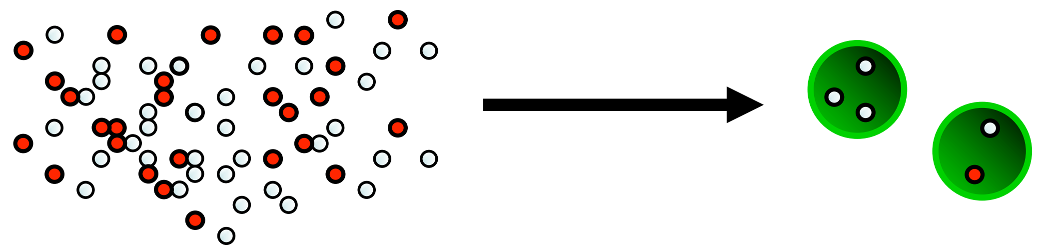
- **Azimuthal anisotropy (v_2) :**
  - Initial spatial anisotropy transferred to the momentum anisotropy of particles.

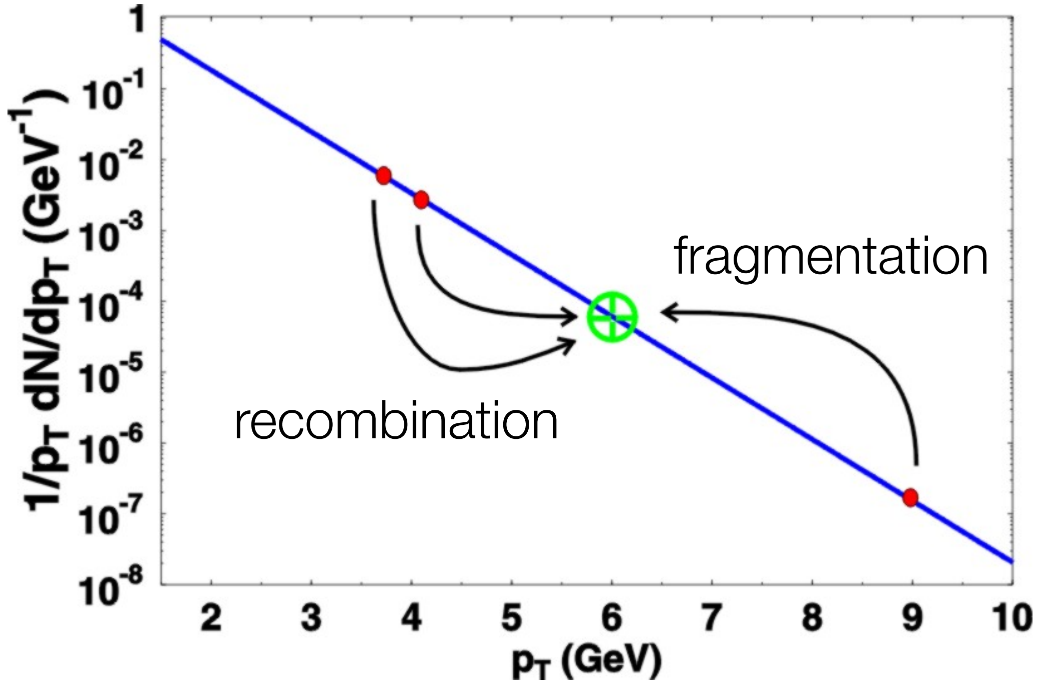


$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2(p_T)\cos[2(\varphi - \Psi_2)] + \ldots)$$

Heavy quarks interactions with the medium: Recombination

- Due to the high density of the medium, low pT partons combine to form higher pT hadrons, instead of higher pT partons fragmenting into lower pT hadrons





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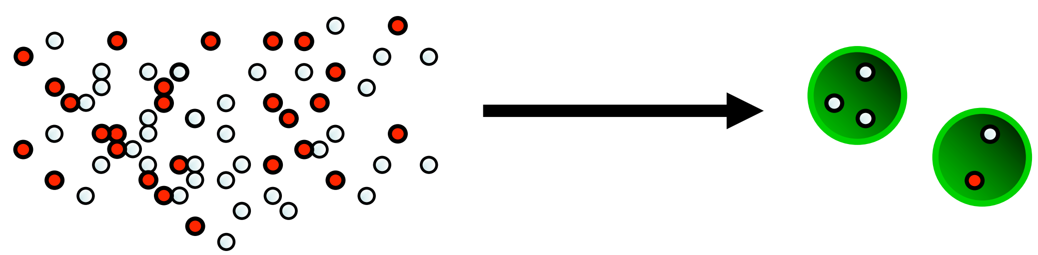
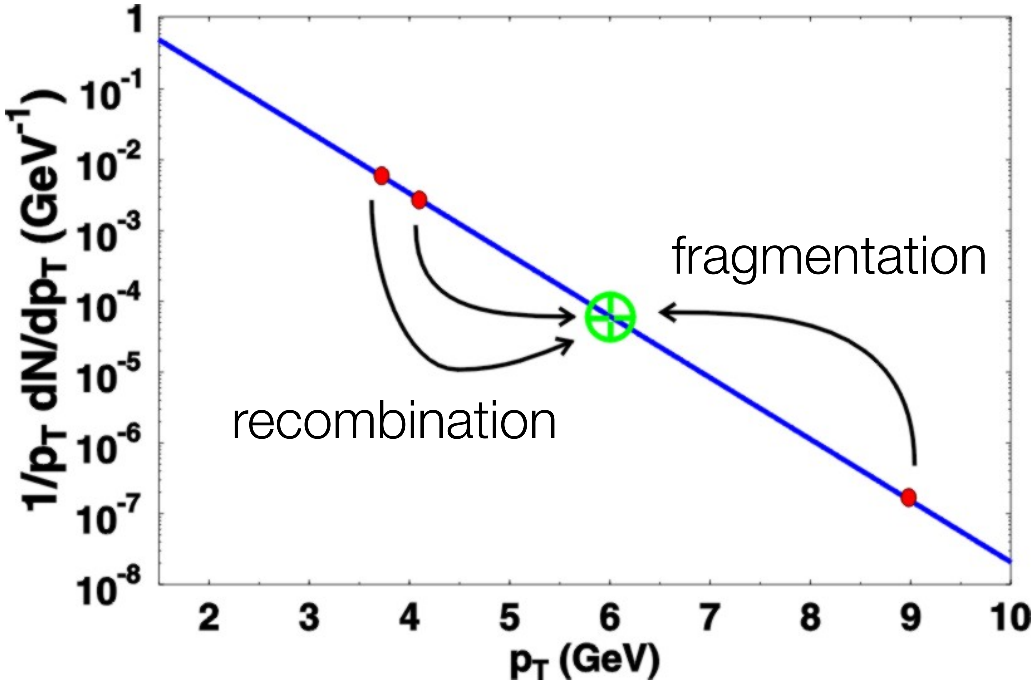


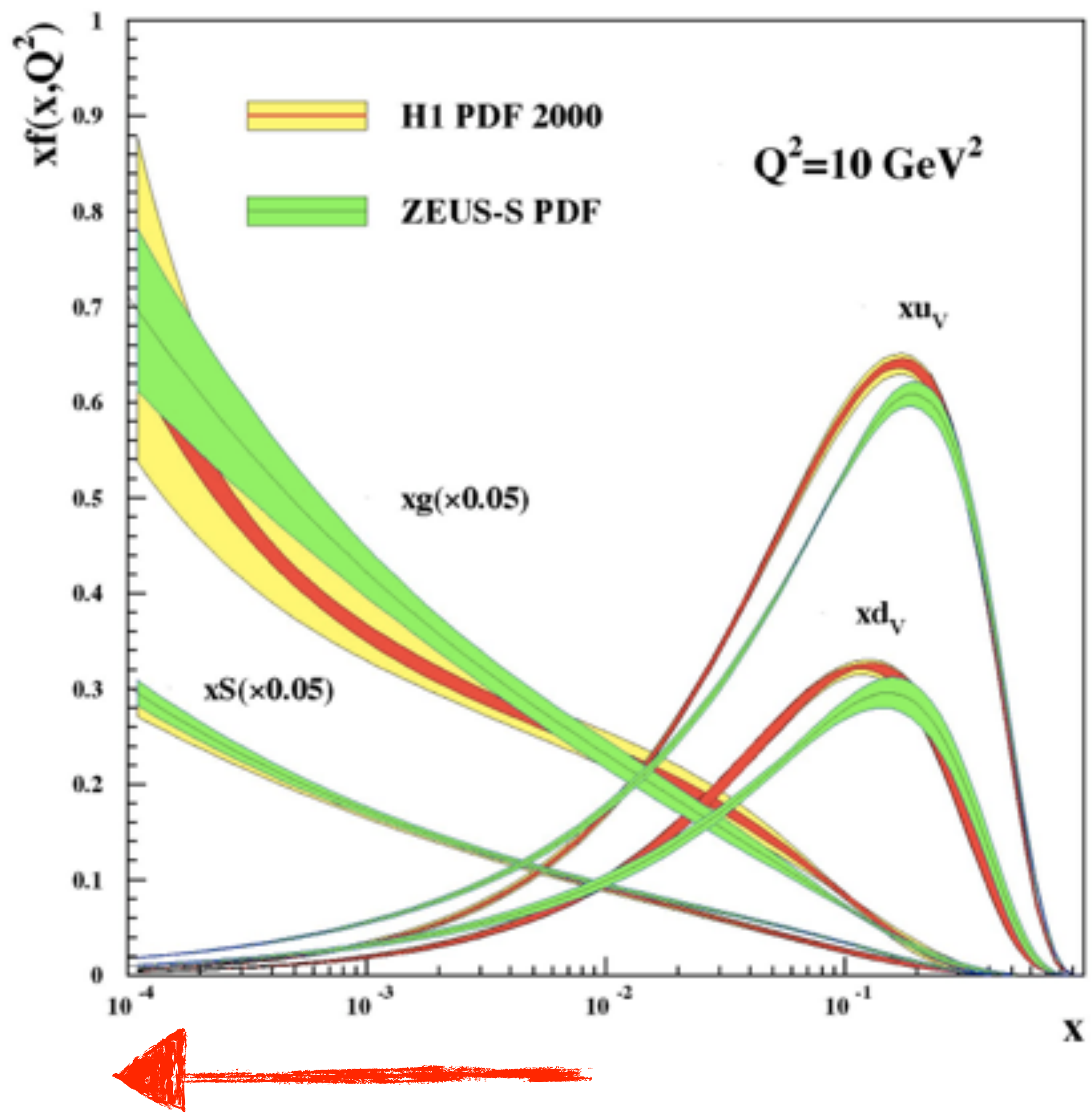


- Recombination and radial flow can push even further hadrons formed by partons "taken from the medium".

- **Is charm (and beauty) so "part of the medium" (i.e. thermalized) that follow this mechanism to create hadrons, getting together with light partons of the medium?**

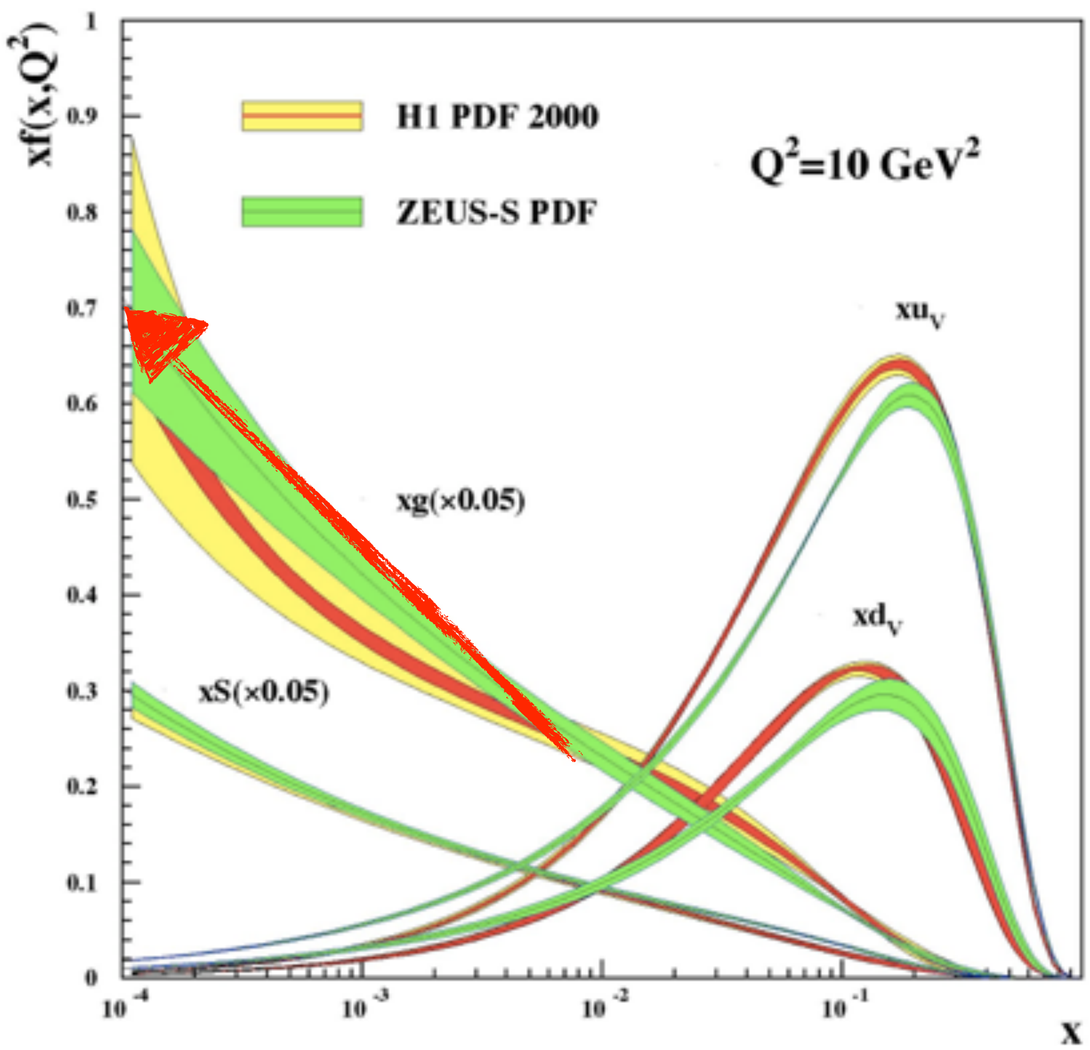
Cold nuclear matter effects: **Saturation**

- Bjorken x probed with HF production at the LHC < 10^{-2} (usually called small-x)



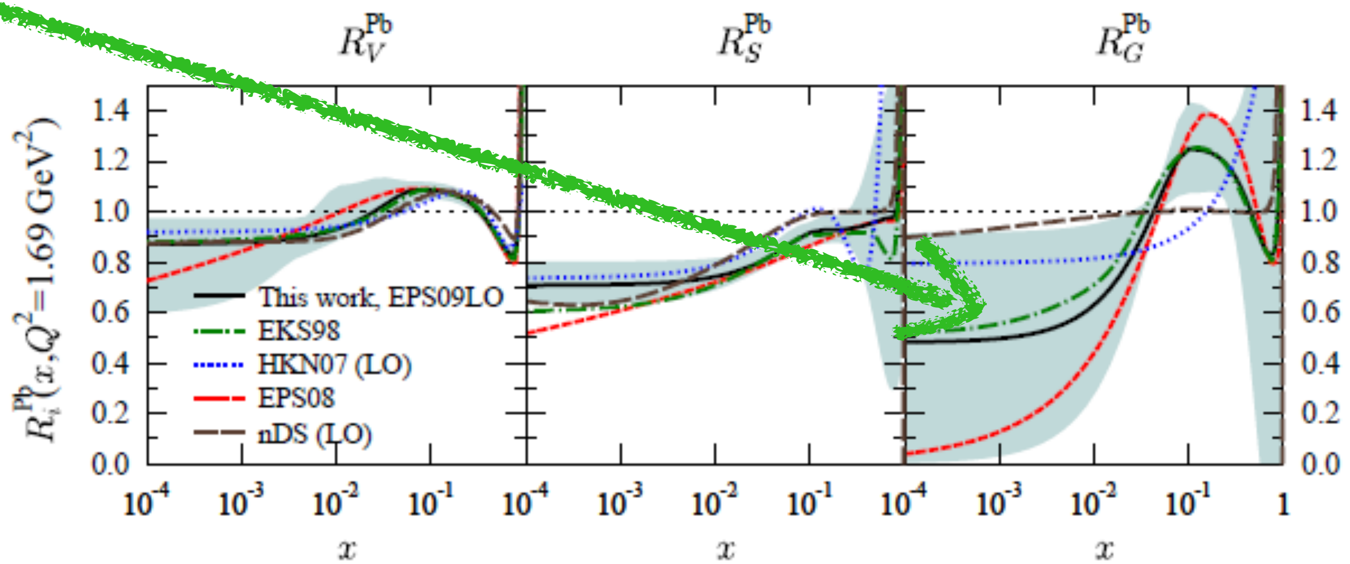
Cold nuclear matter effects: Saturation

- Bjorken x probed with HF production at the LHC < 10^{-2} (usually called small-x)
- Strong rise of the gluons density in the nucleus for this regime (factor $A^{1/3} \sim 6$).
- New QCD regime where gluons are dense and "extended" (low-μ) they can overlap → **Saturation**



Cold nuclear matter effects: **Shadowing**

- Due to the high density of gluons present in the nucleons (saturation regime), possible modification of the PDF could be considered.
- **Shadowing**: parton densities in nuclei are depleted with respect to free patrons ("low-x gluon fusion").
  $xG_A(x, Q^2) = A\ xg(x, Q^2)\ R_G^A(x, Q^2)$



see e.g. Eskola et al. JHEP0904(2009)065

- Most of the low-x data are in non-perturbative range
- Difficult to constraint the pQCD calculations
- Large uncertainties on $R_G^A(x, Q^2)$

Other cold nuclear matter effects

- **Colour Glass Condensate:**
  - Effective theory used to approximate the saturation regime.
  - Based on the hight density of gluons that don't change their position rapidly.

McLerran,Venugopalan PRD49 (1994) 2233, Fujii-Watanabe, arXiv:1308.1258

- **kT broadening:**
  - partons can reduce their transverse momentum due to multiple soft collisions before the hard scattering occurs.

M. Lev and B. Petersson, Z. Phys. C 21 (1983) 155. , X. N. Wang, Phys. Rev. C 61 (2000) 064910.

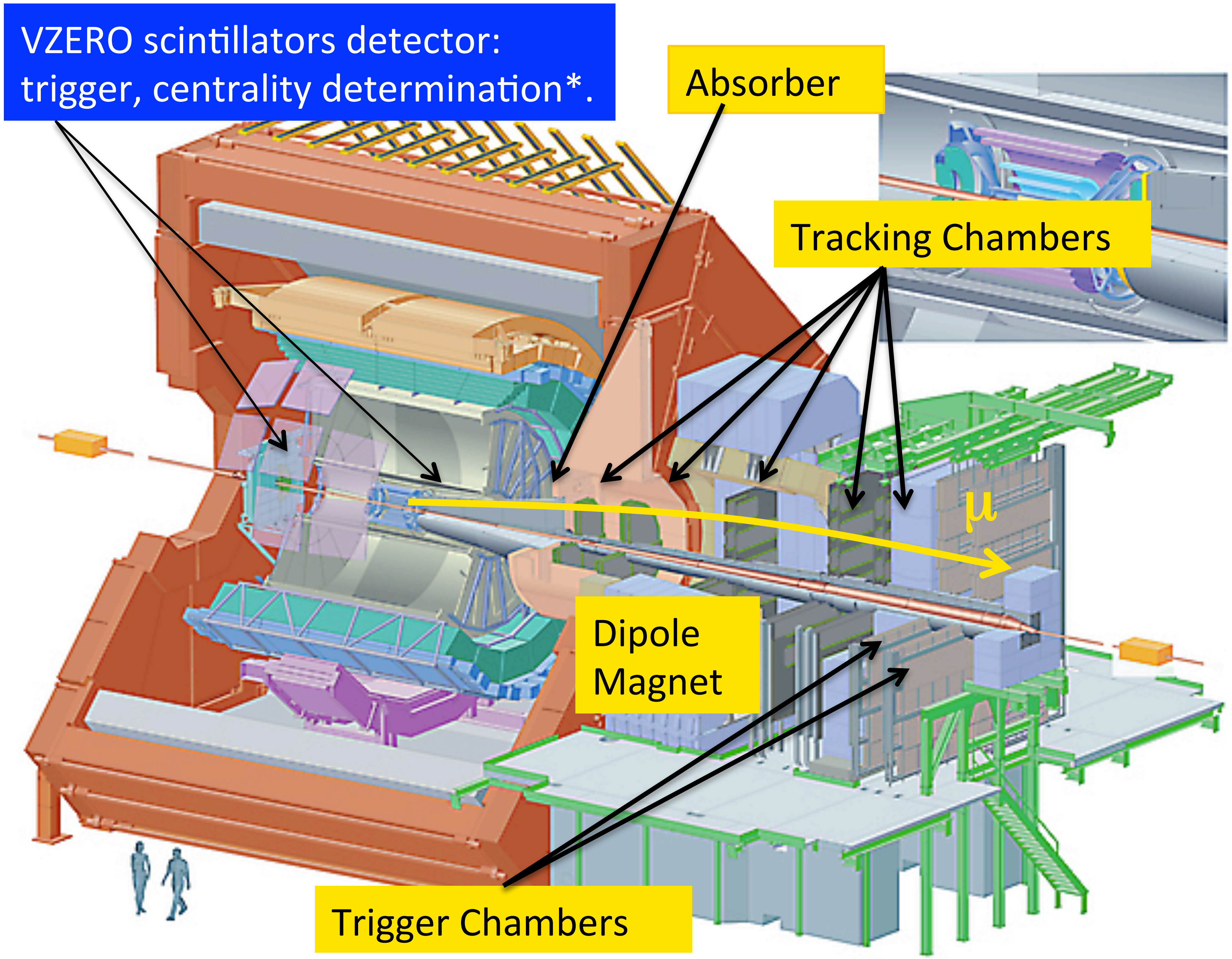
- **Parton energy loss**:
  - recent calculations based on the possibility that cc pair are also affected by energy loss in pPb due to the high energy density reached at LHC energies.

F. Arleo, S. Peigne, T. Sami, Phys. Rev. D 83 (2011) 114036.

How do we measure HF in Pb-Pb collisions ?

How do we measure HF in Pb-Pb collisions with ALICE?

HF decay muons reconstruction in ALICE

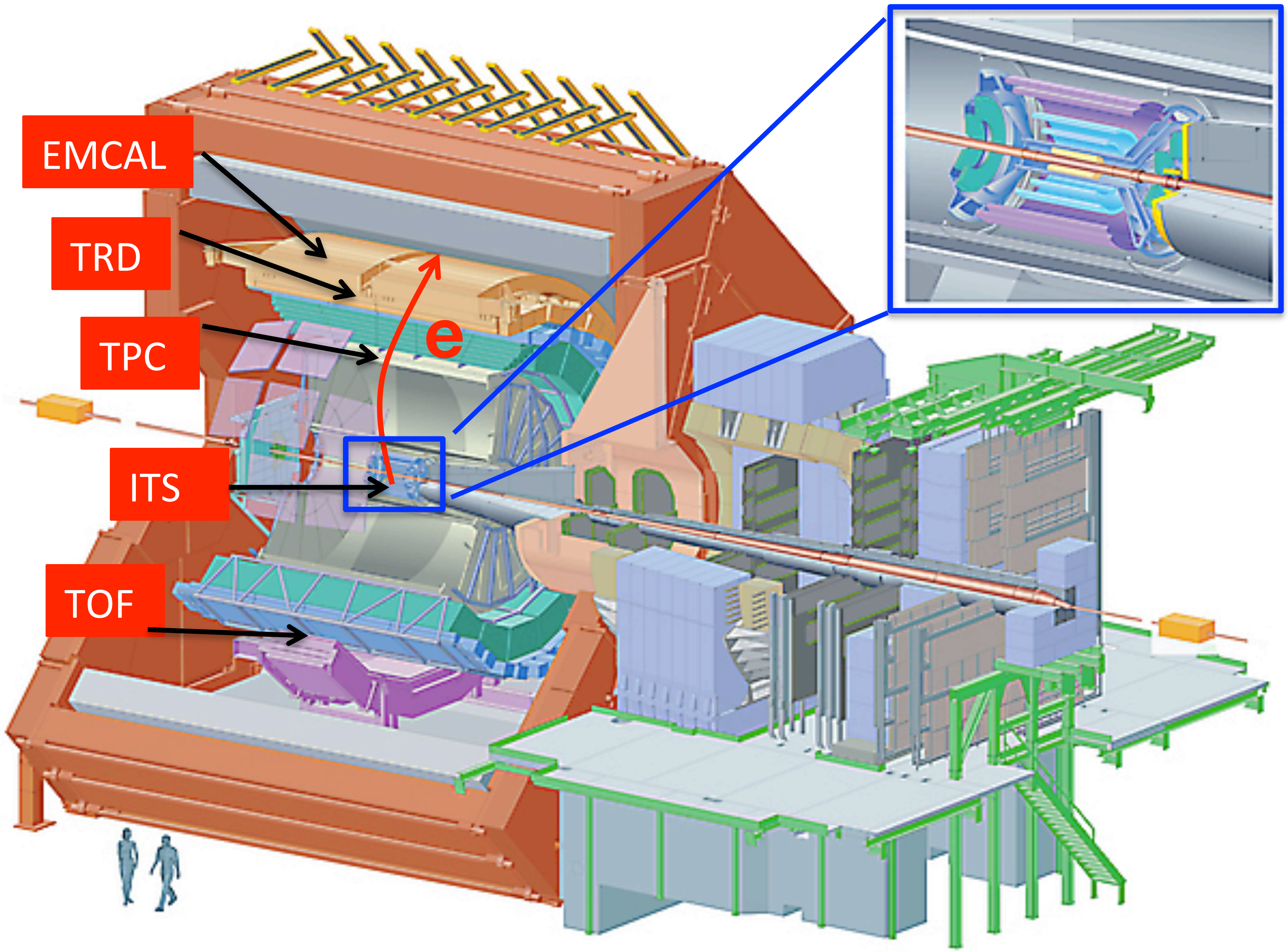


✔ D,B, Λ_c,… → μ+X

- Muon spectrometer: μ-ID via tracks matched with and trigger system $-4 < \eta < -2.5$

- Background coming from K and π decays removed with Pythia MC simulations.

HF decay electrons reconstruction in ALICE

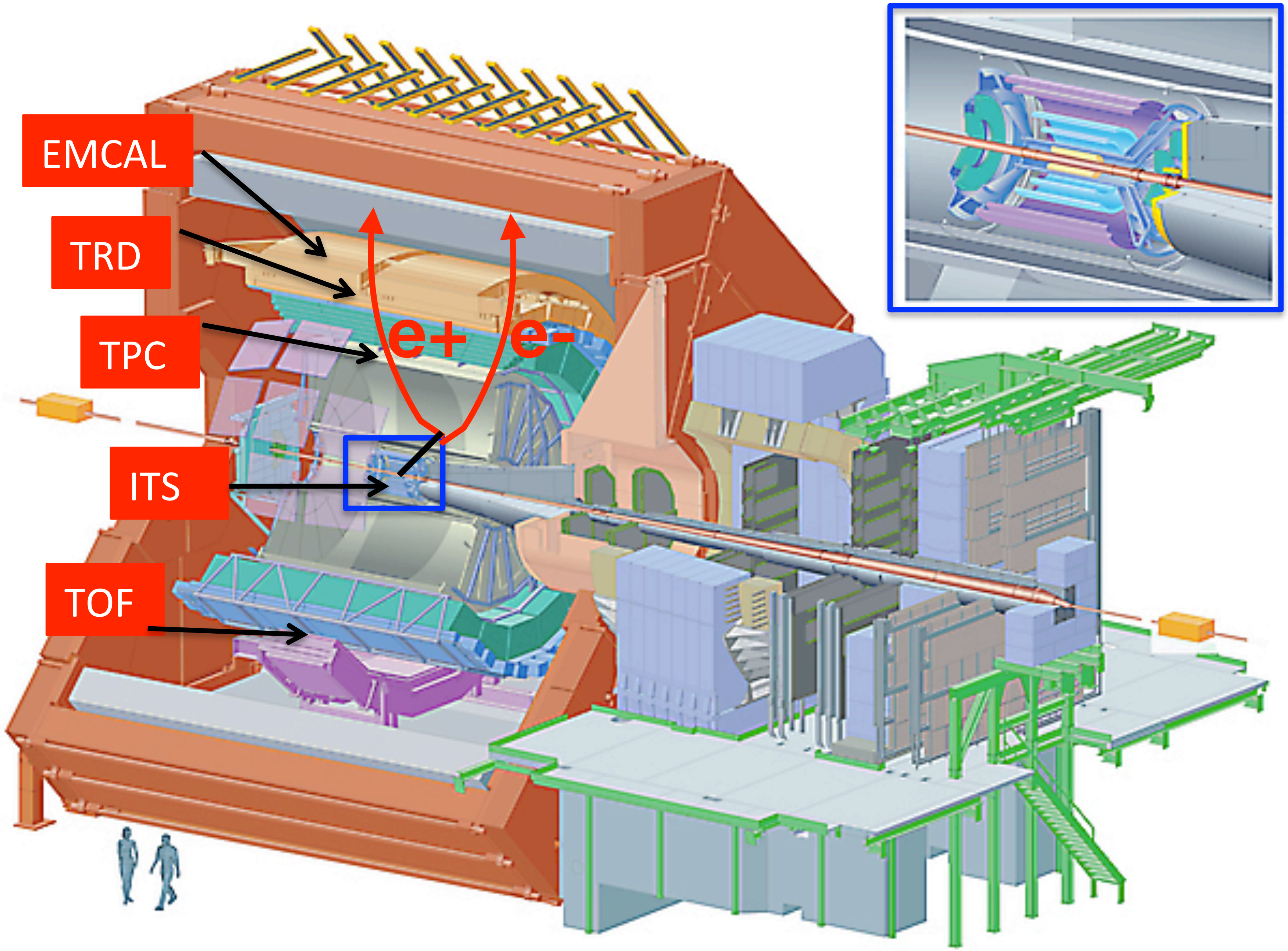


✔ D,B, Λ_c,… → e+X

|η| < 0.9
ITS: tracking, vertexing
TPC: tracking, PID
TOF, EMCAL, TRD: e-ID

- Background subtraction based on cocktail method and removal of Dalitz decay and photon conversion

Non prompt J/ψ reconstruction in ALICE

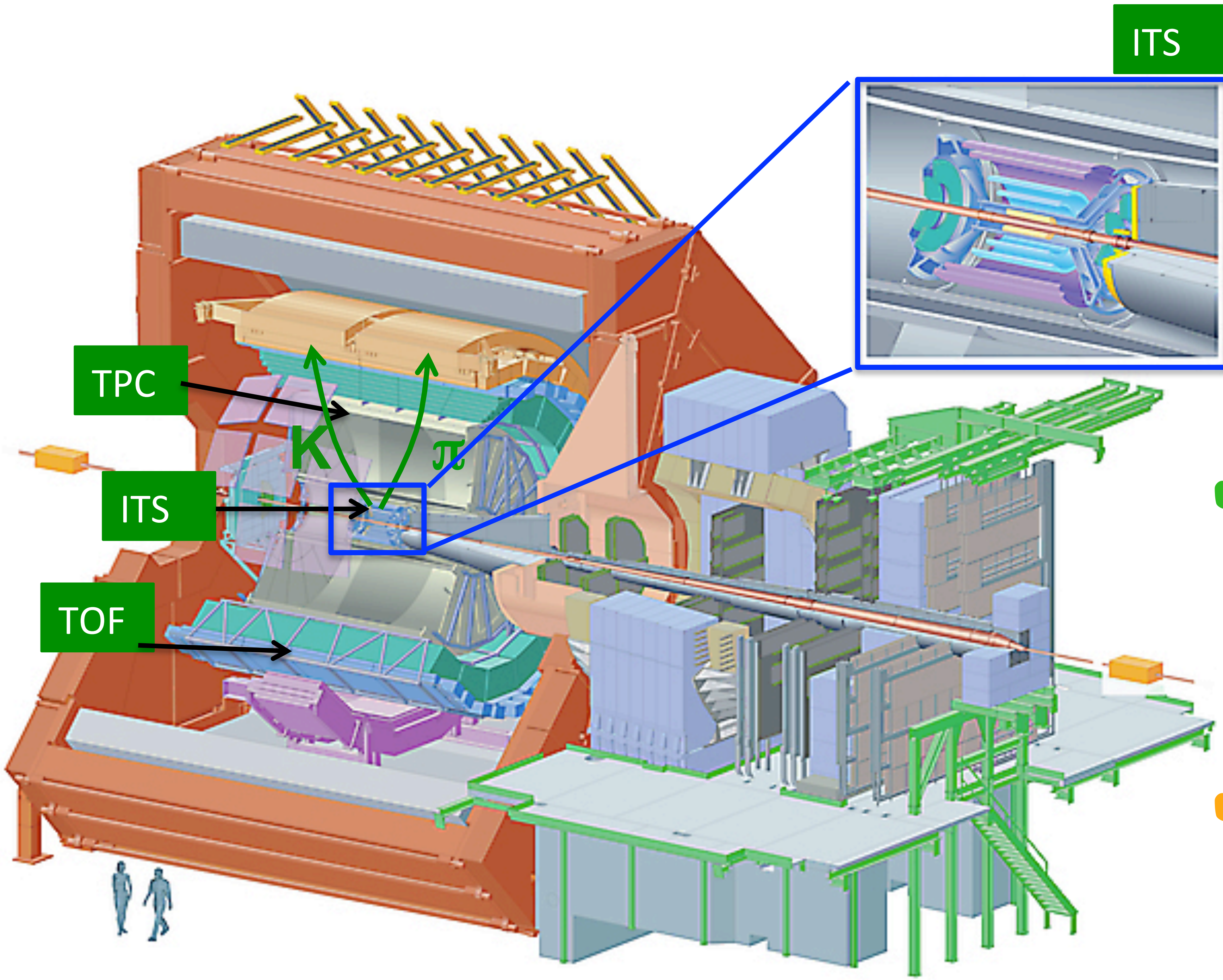


✔ $B \rightarrow J/\psi + X$

$|\eta| < 0.9$
ITS: tracking, vertexing
TPC: tracking, PID
TOF, TRD: e-ID

- Exploit the displacement of J/ψ of ~hundreds μm in the transverse plane.
- Simultaneous fit of pseudo-proper decay length (L_{xy}) and invariant mass.

D meson reconstruction in ALICE



$|\eta| < 0.9$
ITS: tracking, vertexing
TPC: tracking, PID
TOF: K-ID

$D^0 \rightarrow K^- \pi^+$
$D^+ \rightarrow K^- \pi^+ \pi^+$
✔ $D^{*+} \rightarrow D^0 \pi^+$
$D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$

$D^+ \rightarrow K^0_s \pi^+$
✔ $D_s^+ \rightarrow K^0_s K^+$
$\Lambda_c^+ \rightarrow pK\pi$
$\Lambda_c^+ \rightarrow K^0_s p$

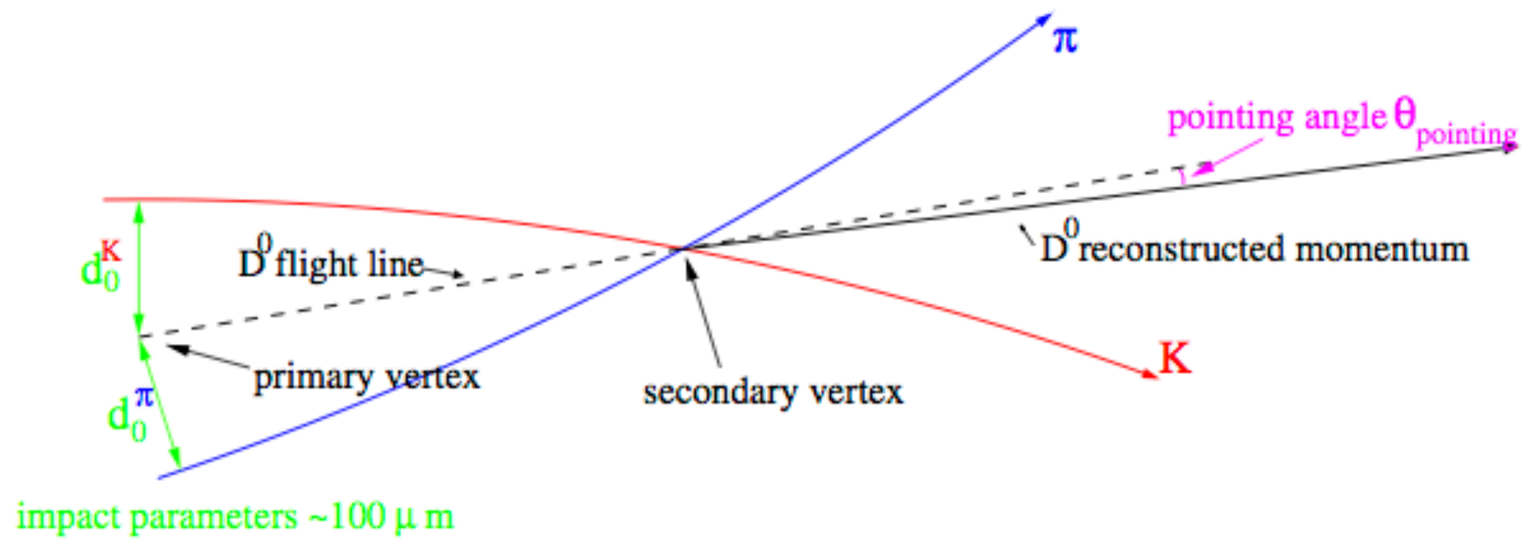
D meson reconstruction in ALICE

D mesons full hadronic recons

$D^0 \rightarrow K^-\pi^+$
Mass = 1864.80 ± 0.14 MeV
$c\tau$ = 123 μm

$D^+ \rightarrow K^+\pi^-\pi^+$
Mass = 1869.60 ± 0.16 MeV
$c\tau$ = 311.8 μm

$D^{*+} \rightarrow D^0\,\pi^+$
Mass = 2010.25± 0.14 MeV



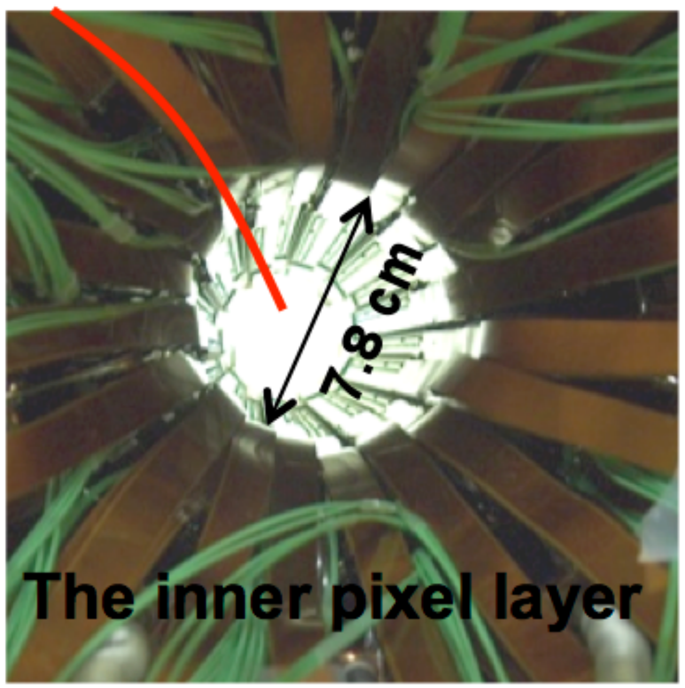
Invariant mass analysis mainly based on:

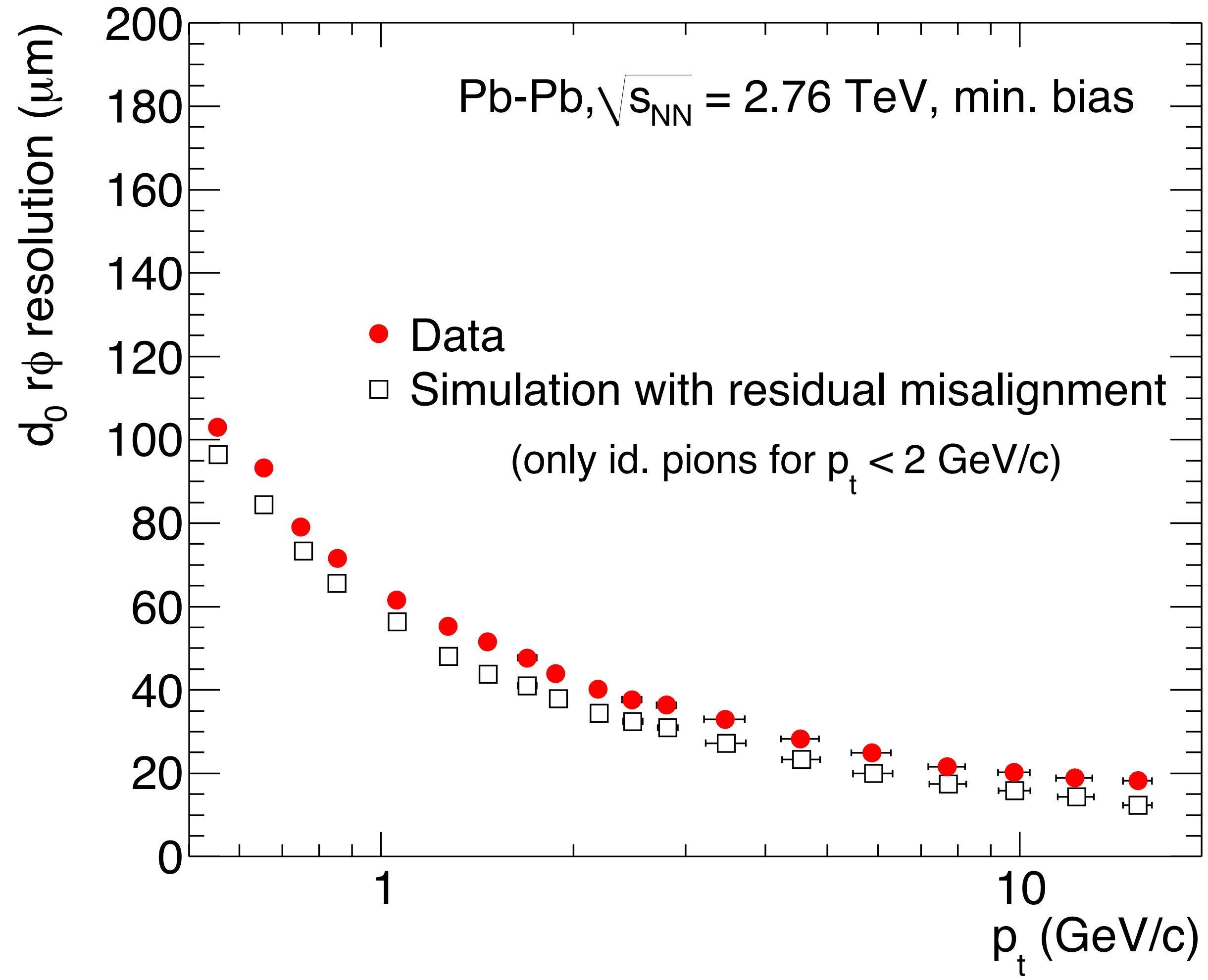
- secondary vertex reconstruction
- kaon identification

D meson reconstruction in ALICE

- Displaced vertex topology:
  - tracking and vertexing precision crucial for heavy flavour analysis
  - Inner Tracking System with 6 Si layers:
    two pixel layers at 3.9 cm and 7 cm

JHEP 09 (2012) 112

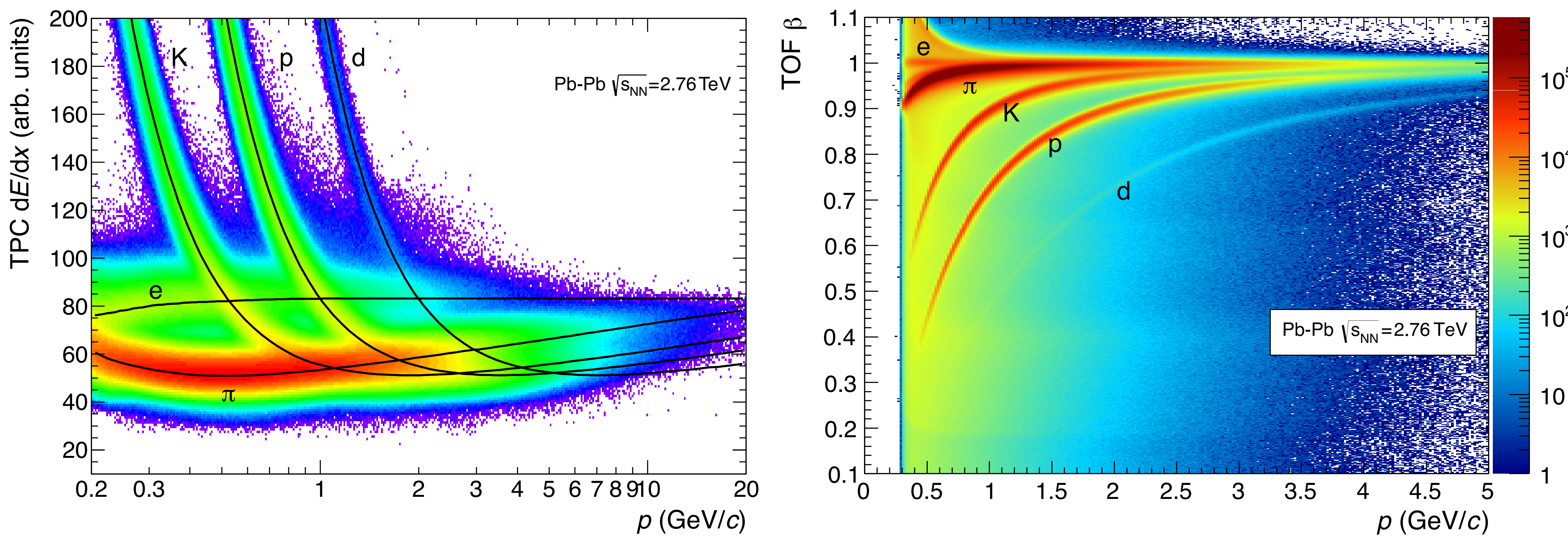




- Impact parameter resolution ~ 60μm for p_T = 1 GeV/c

D meson reconstruction in ALICE

- Conservative PID strategy used to identify the kaon candidates.
- Kaons are identified via:
  - the energy loss deposit in the TPC (0.6 < p < 0.8 GeV/c 2σ cut)
  - the velocity measurement in the TOF (p < 2 GeV/c 3σ cut)



Int. J. Mod. Phys. A 29 (2014) 1430044

- Keep the signal loss as small as possible
- Background reduction by a factor 3 for central Pb-Pb collisions

Results:

- pp collisions @ $\sqrt{s}$ = 2.76, 7 TeV
- p-Pb collisions @ $\sqrt{s_{NN}}$ = 5.02 TeV
- Pb-Pb collisions @ $\sqrt{s_{NN}}$ = 2.76 TeV

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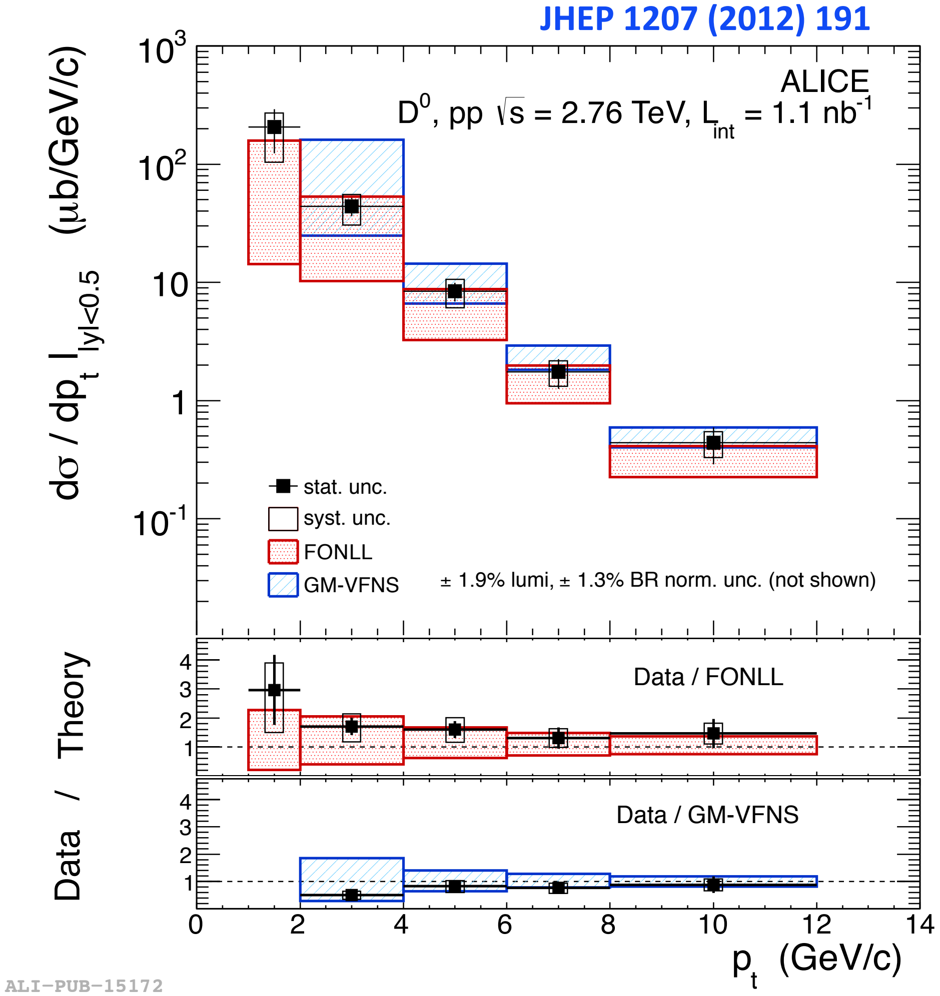
- p-Pb collisions @ $\sqrt{s_{NN}}$ = 5.02 TeV
- Pb-Pb collisions @ $\sqrt{s_{NN}}$ = 2.76 TeV

Charm production in pp collisions @ √s = 2.76 TeV

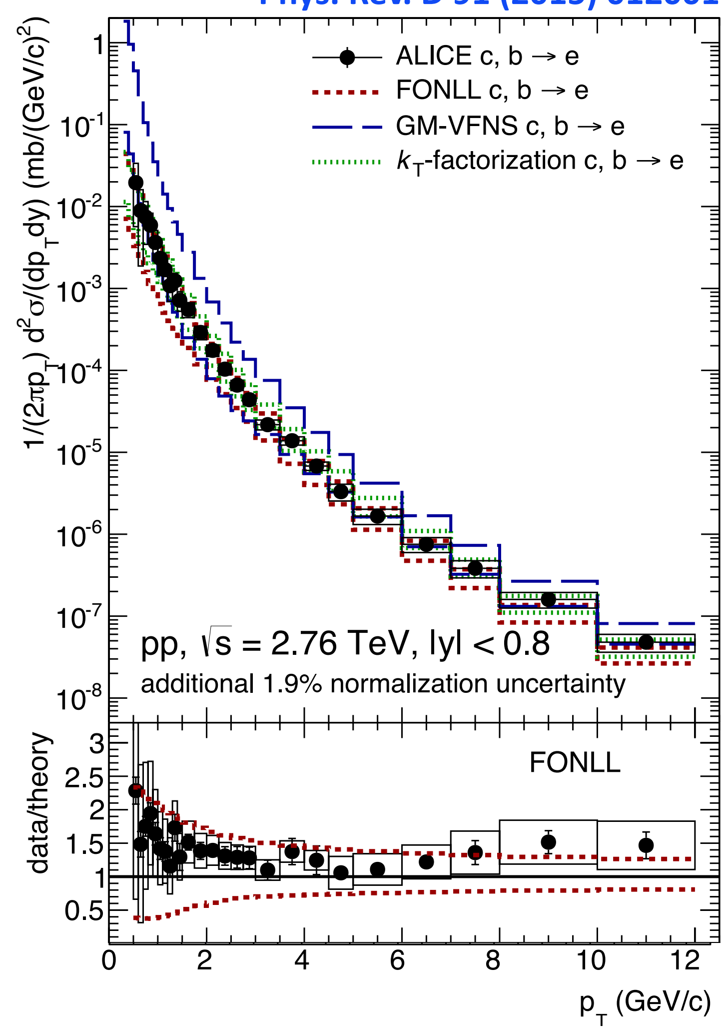
D meson

JHEP 1207 (2012) 191



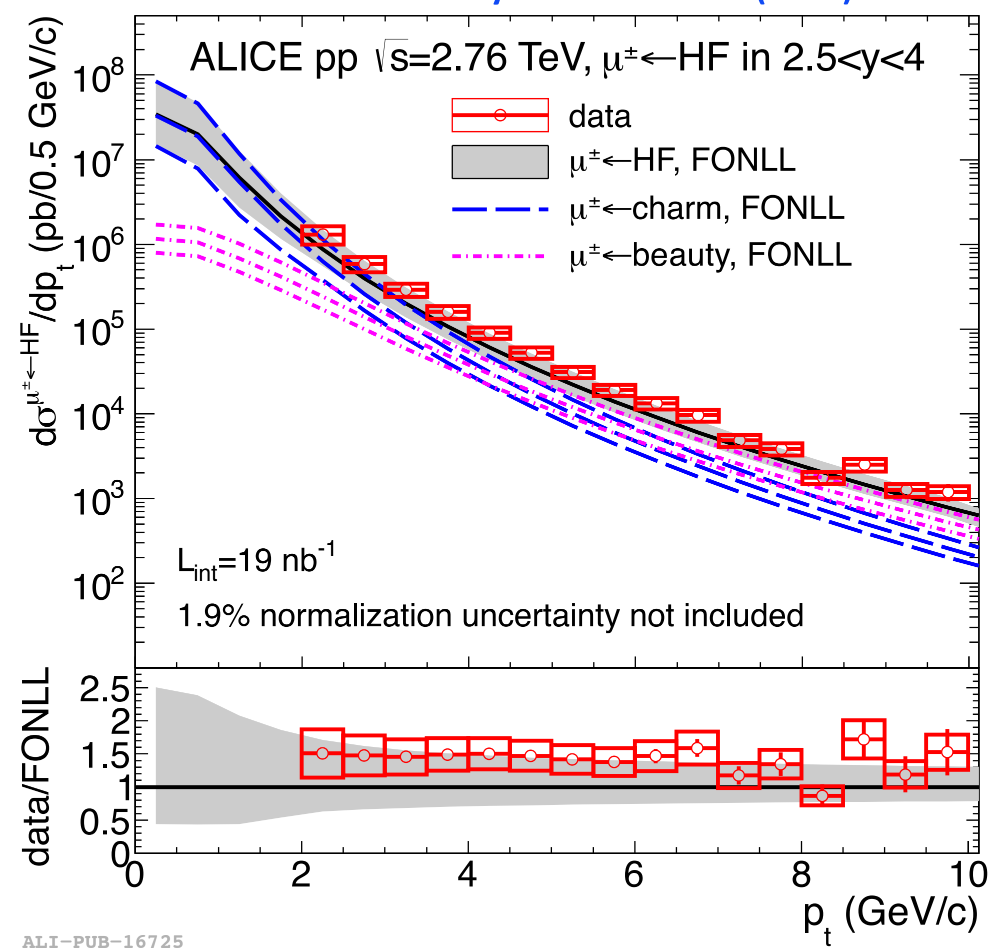
e from HF decay

Phys. Rev. D 91 (2015) 012001



μ from HF decay

Phys. Rev. Lett. 109 (2012) 112301



- pQCD-based calculations (FONLL, GM-VFNS, k_T factorization) compatible with data
- HF muon data used as **reference for Pb-Pb** at the same energy.
- For other channels a √s extrapolation based on pQCD calculations is used.

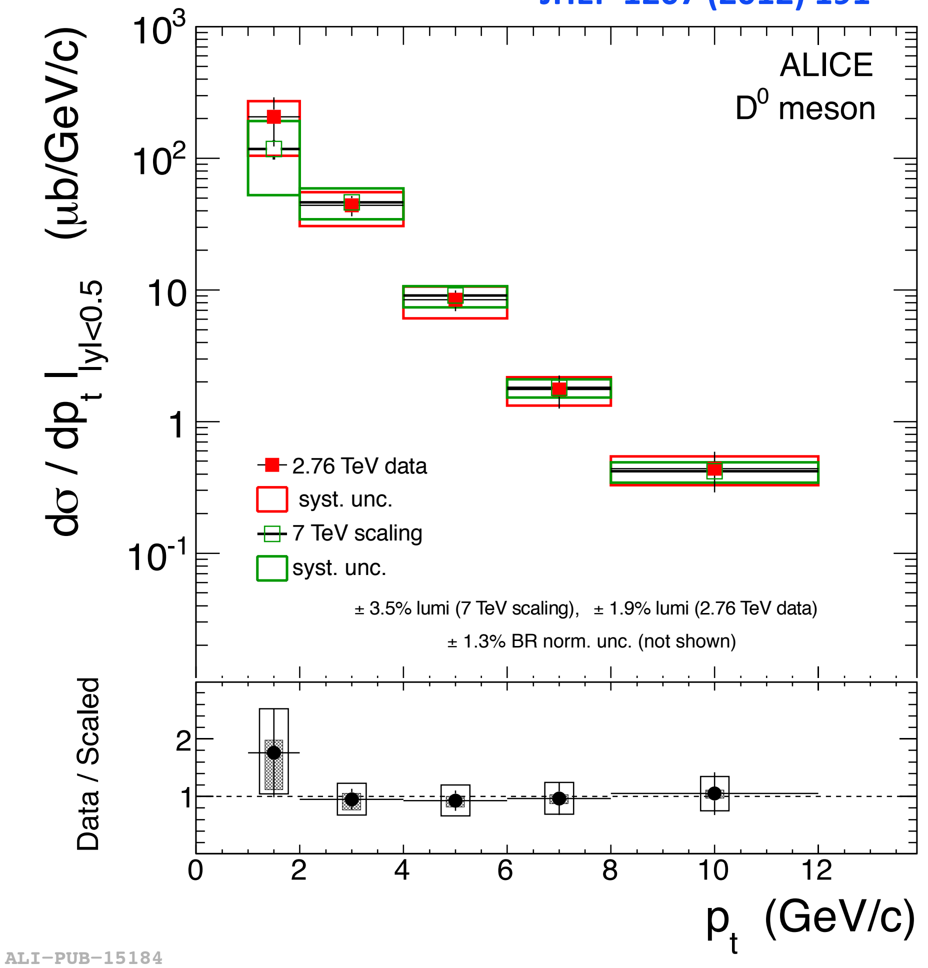
R.Averbeck et al., arXiv:1107.3243

FONLL: JHEP 1210 (2012) 137, GM-VFNS: Eur. Phys. J. C 72 (2012) 2082, k_T factorisation: arXiv:1301.3033

Charm production in pp collisions @ $\sqrt{s}$ = 2.76 TeV

D meson

JHEP 1207 (2012) 191



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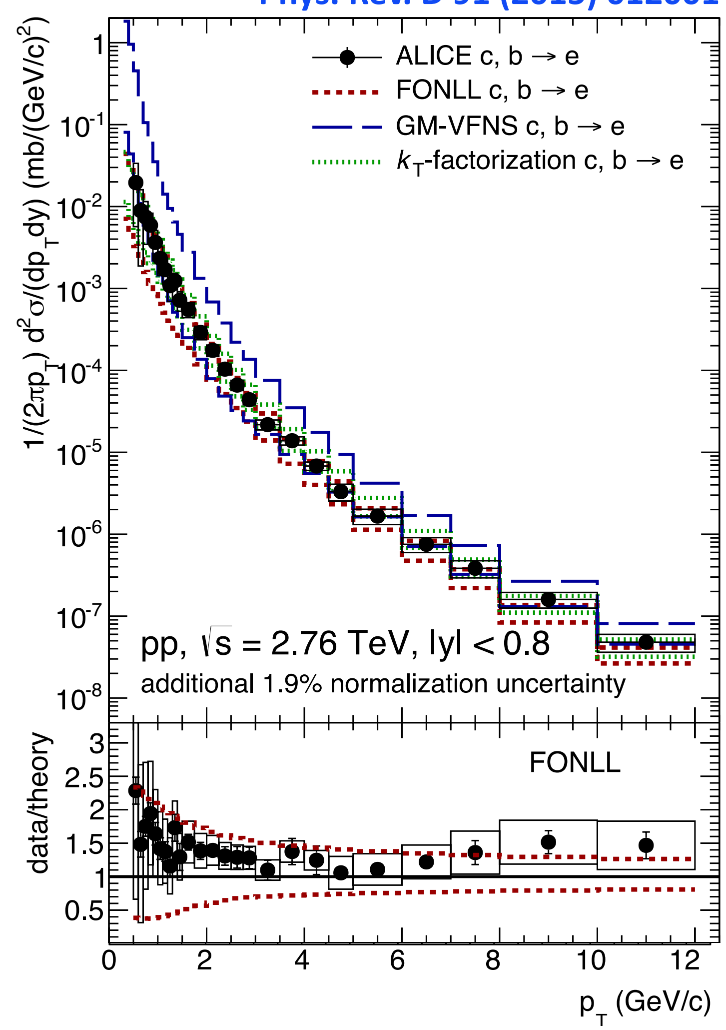
Phys. Rev. D 91 (2015) 012001



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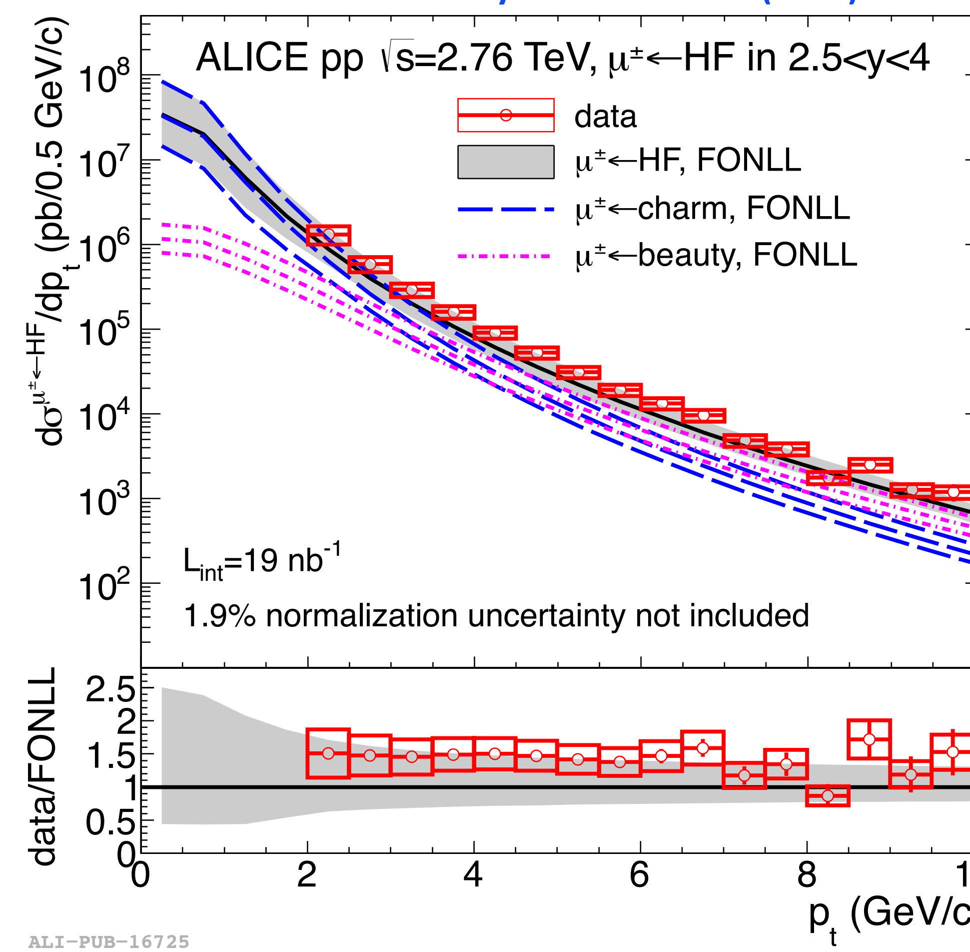
Phys. Rev. Lett. 109 (2012) 112301



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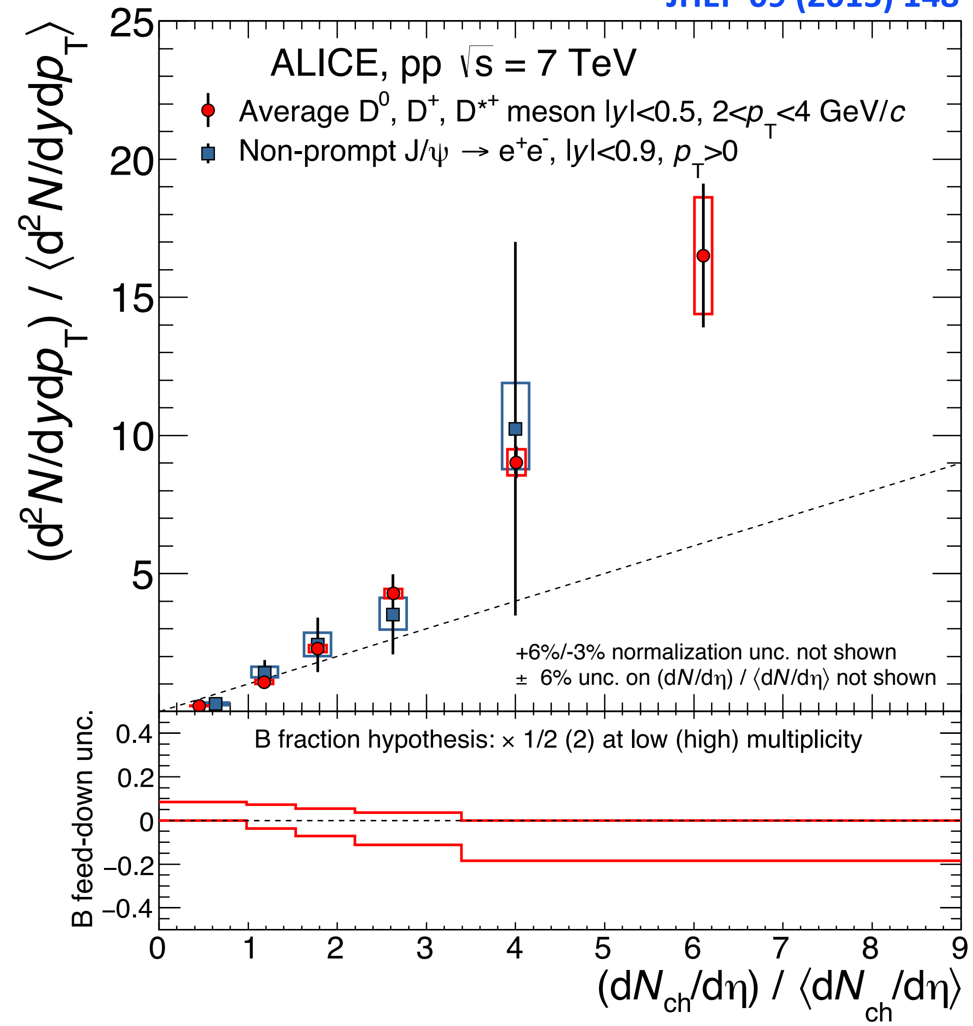
Heavy flavor production vs multiplicity

* Studied observable: self-normalized yields in multiplicity intervals relative to the multiplicity integrated ones

$$\frac{d^2N^D/dydp_T}{< d^2N^D/dydp_T >} = \frac{(d^2N^D/dydp_T)^{mult}/(\epsilon^{mult} \times N^{mult}_{event})}{(d^2N^D/dydp_T)^{tot}/(\epsilon^{tot} \times N^{tot}_{event})}$$

JHEP 09 (2015) 148

* Results for both D meson and non-prompt J/ψ show an **increase of the yield with charged-particle production.**



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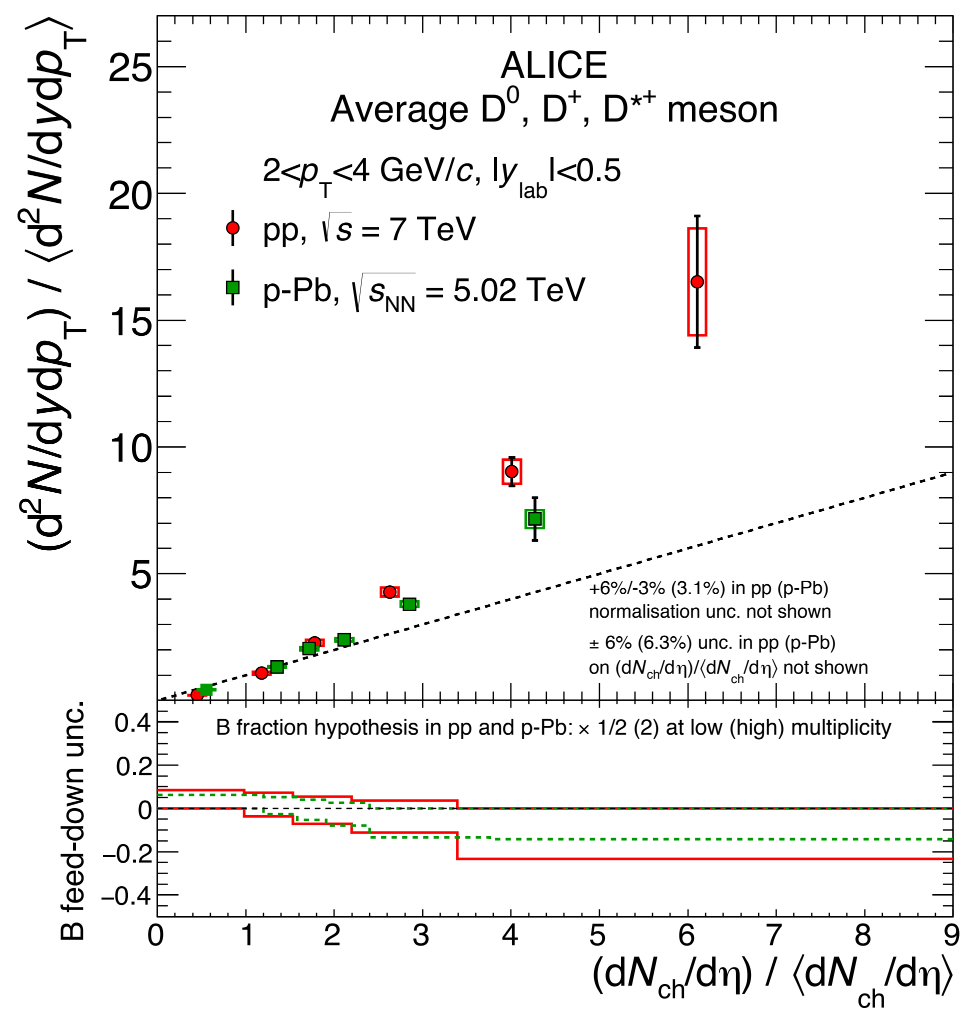
arXiv:1602.07240

* Results for both D meson and non-prompt J/ψ show an **increase of the yield with charged-particle production.**

  * in pp collisions, high multiplicity events come mainly from MPIs,

  * in p-Pb collisions, high multiplicity events are also originated from collisions with $N_{coll} > 1$



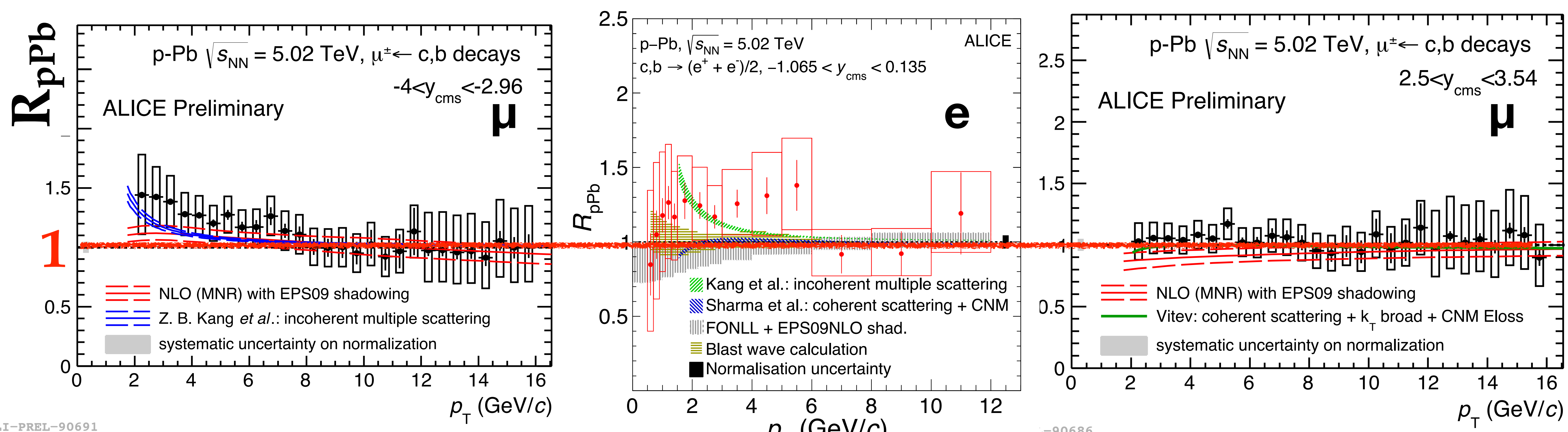
Results:

* pp collisions @ $\sqrt{s}$ = 2.76, 7 TeV
* p-Pb collisions @ $\sqrt{s_{NN}}$ = 5.02 TeV
* Pb-Pb collisions @ $\sqrt{s_{NN}}$ = 2.76 TeV

HF decay leptons in p-Pb collisions

- R_{pPb} measurement is compatible with unity within uncertainties for **backward**, **central** and **forward** rapidity.
  - Slightly enhanced at backward rapidity (large-x in the Pb).

- Results are described by models that include Cold nuclear matter effects



Z. B. Kang, et al., Phys. Lett.B740(2015) 23–29

R. Sharma et al., Phys. Rev.C80(2009) 054902
M. Sickles, "Phys.Lett.B731 (2014) 51–56

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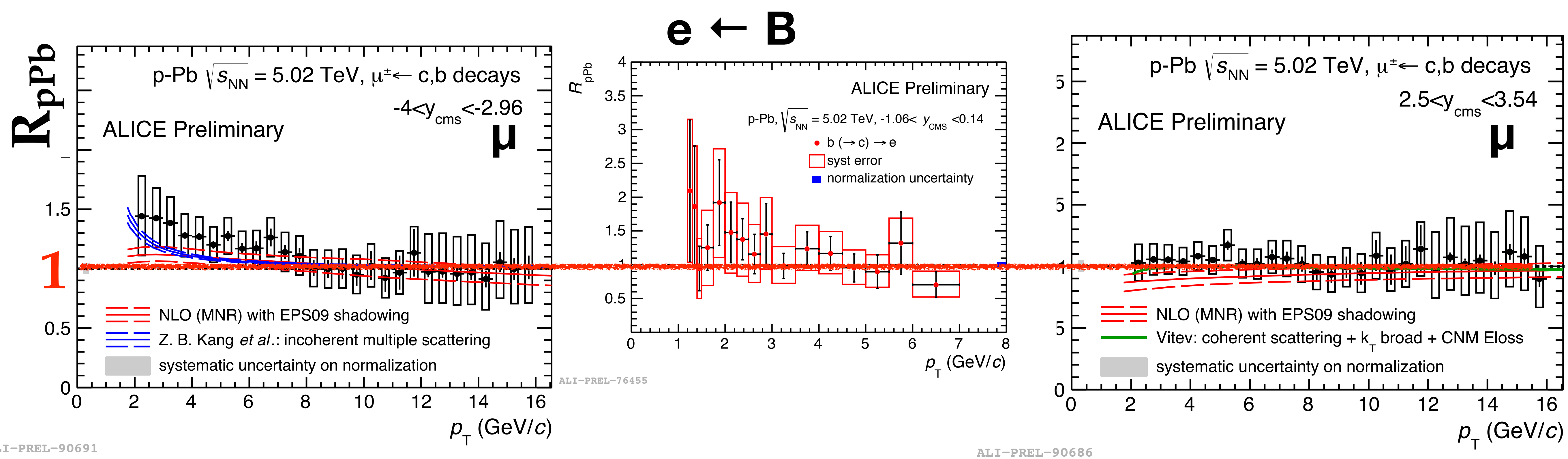

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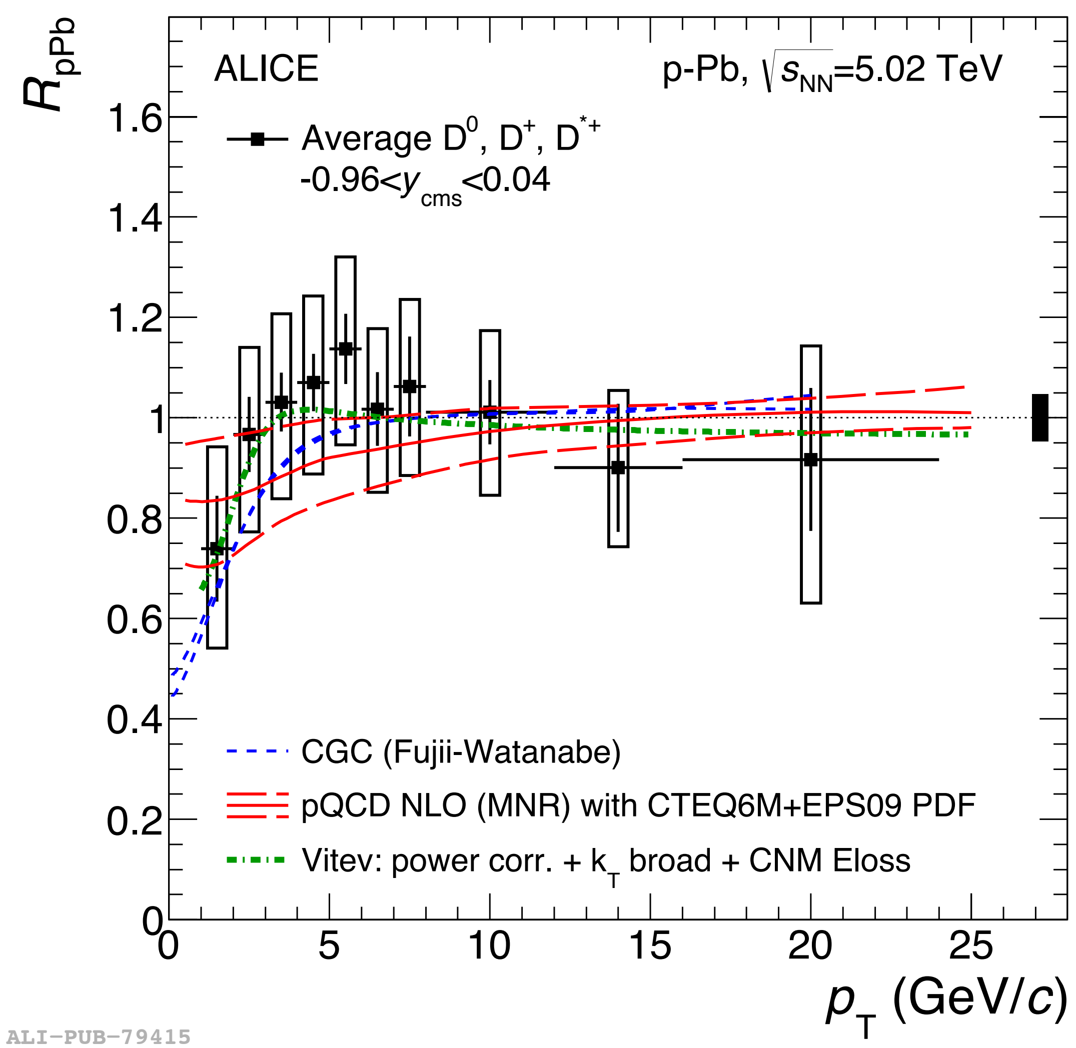
D meson in p-Pb collisions

- **D meson R_{pPb} compatible with unity within uncertainties.**
- Models that include Cold Nuclear Matter effects describe the data:
  - MNR calculation for heavy-flavour production with EPS09 parametrizations of nuclear PDF Mangano et al., Nucl. Phys. B 373 (1992) 295. Eskola et al., JHEP 0904 (2009) 065
  - CGC predictions
    Fujii-Watanabe, arXiv:1308.1258
  - Vitev: k_T broadening+CNM energy loss
    R. Sharma et al., PRC 80 (2009) 054902.

PRL 113 232301 (2014)



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- **D meson dσ/dy measurements do not show rapidity dependence in the range $-1.265 < y_{cms} < 0.35$**
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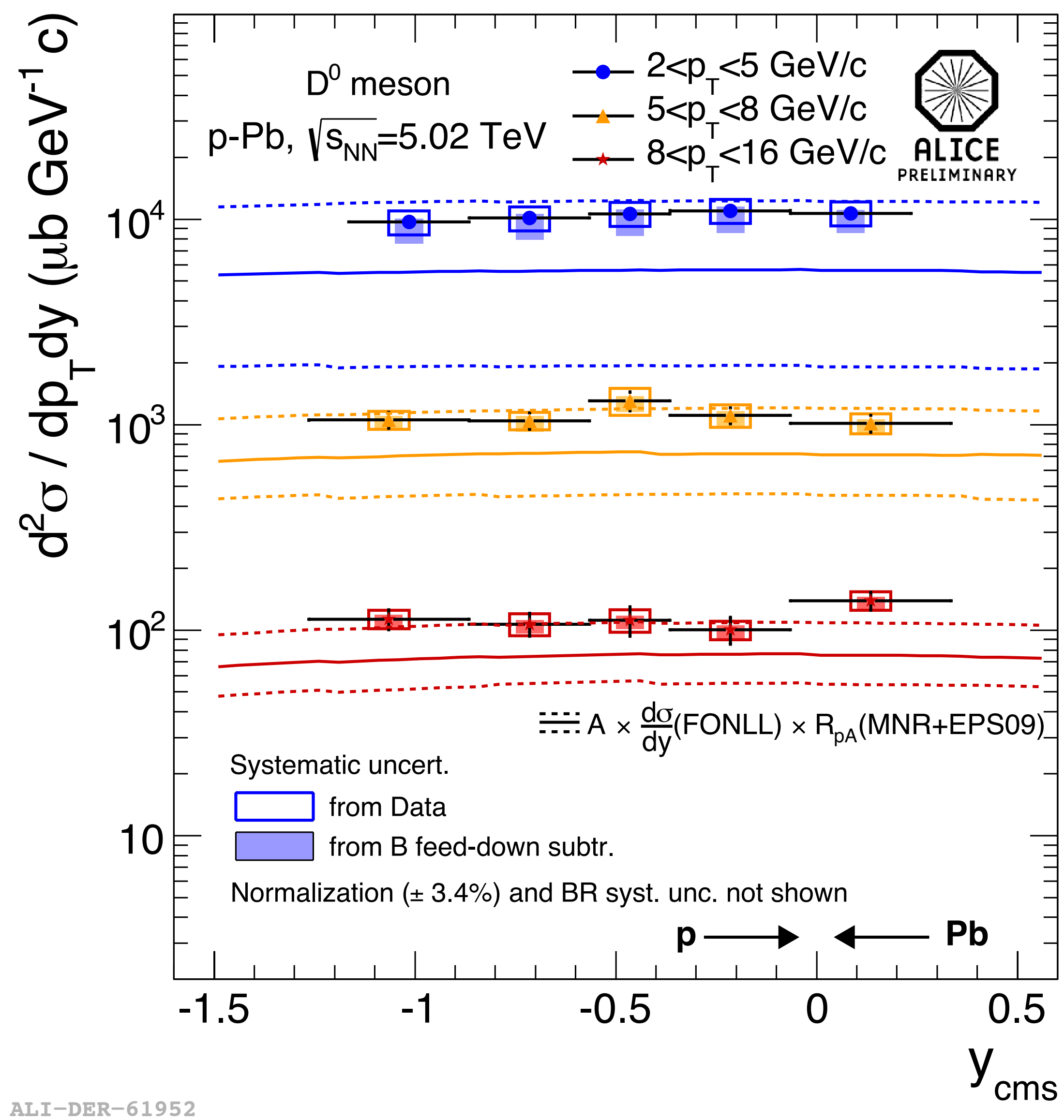

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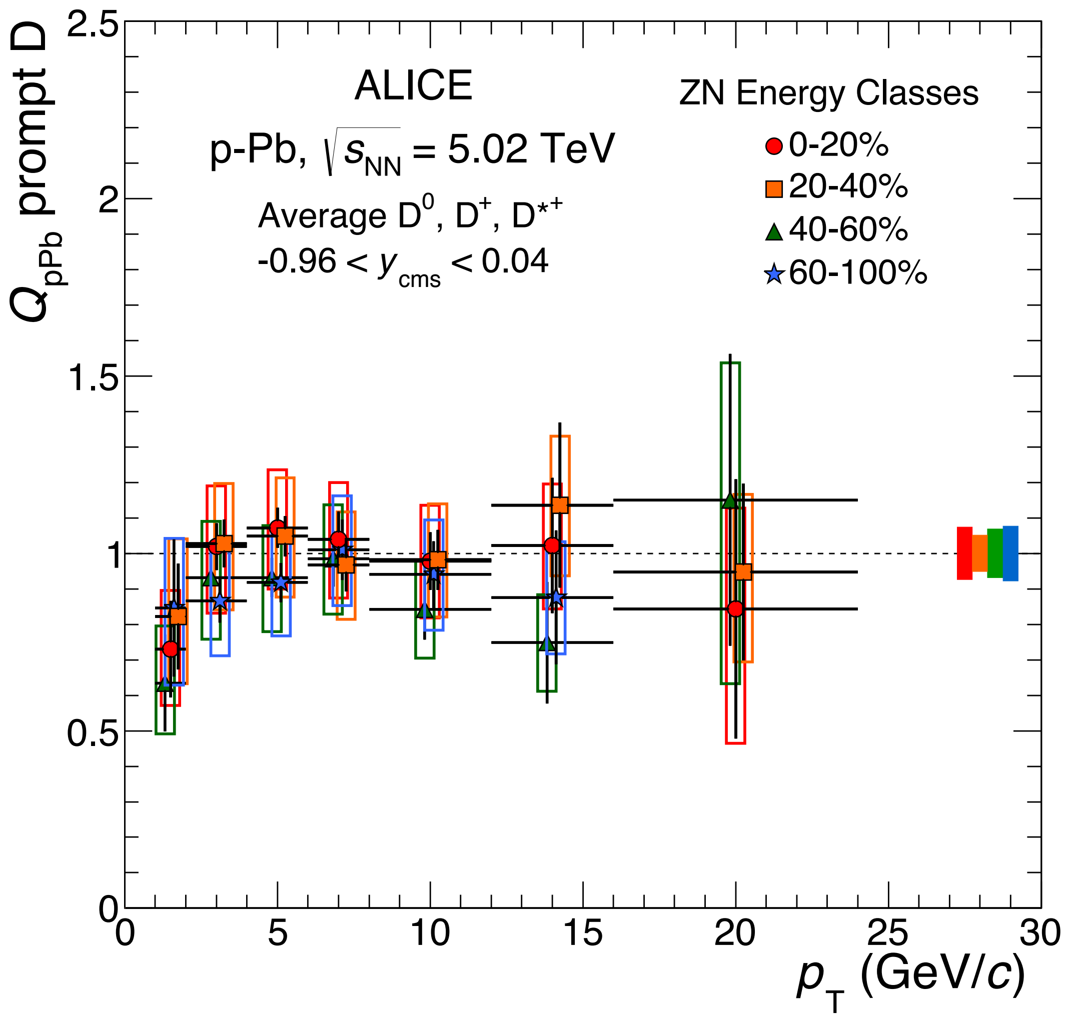
arXiv:1602.07240

* **R_{pPb} also consistent with unity for central and peripheral events within uncertainties**



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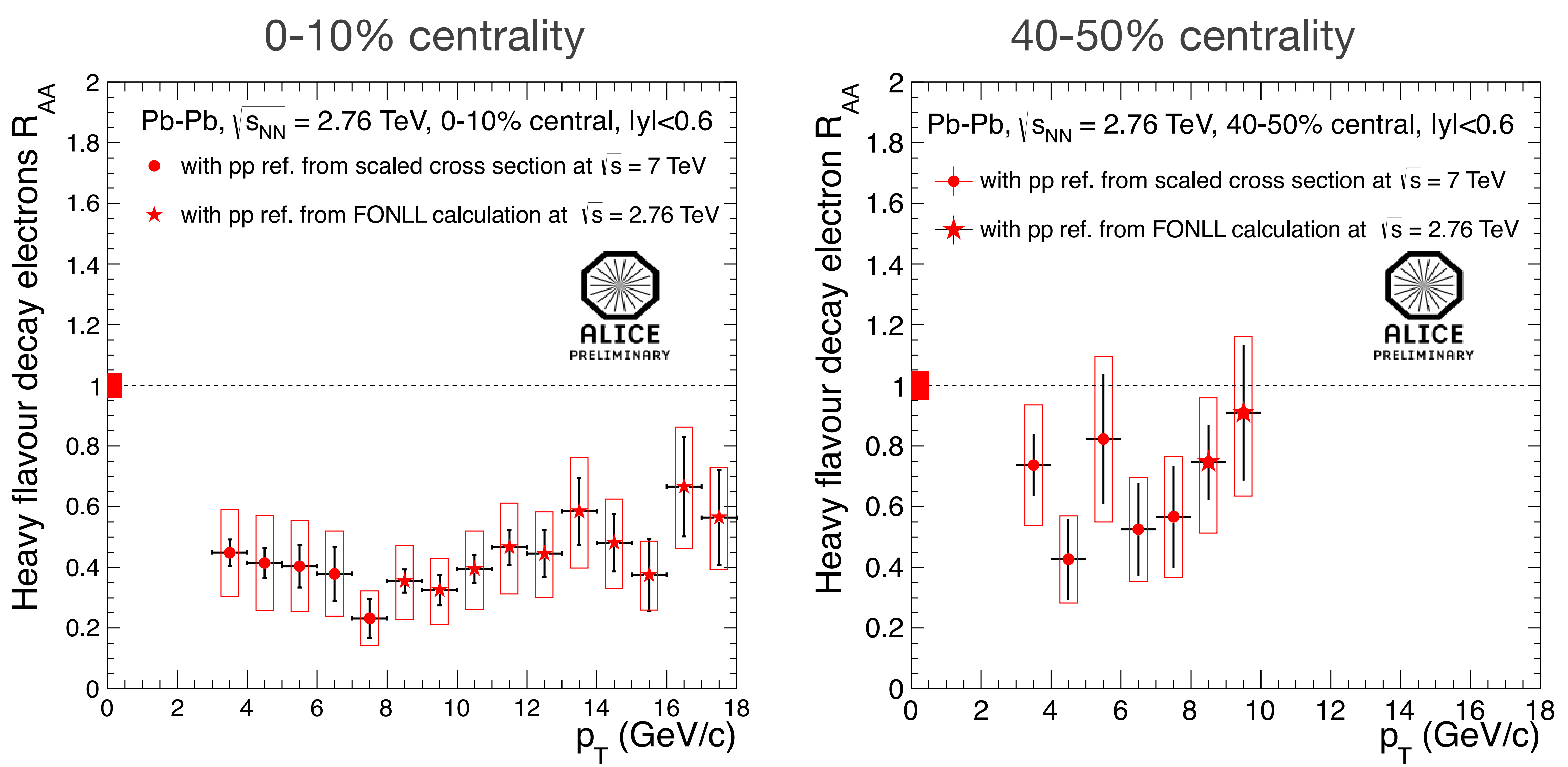
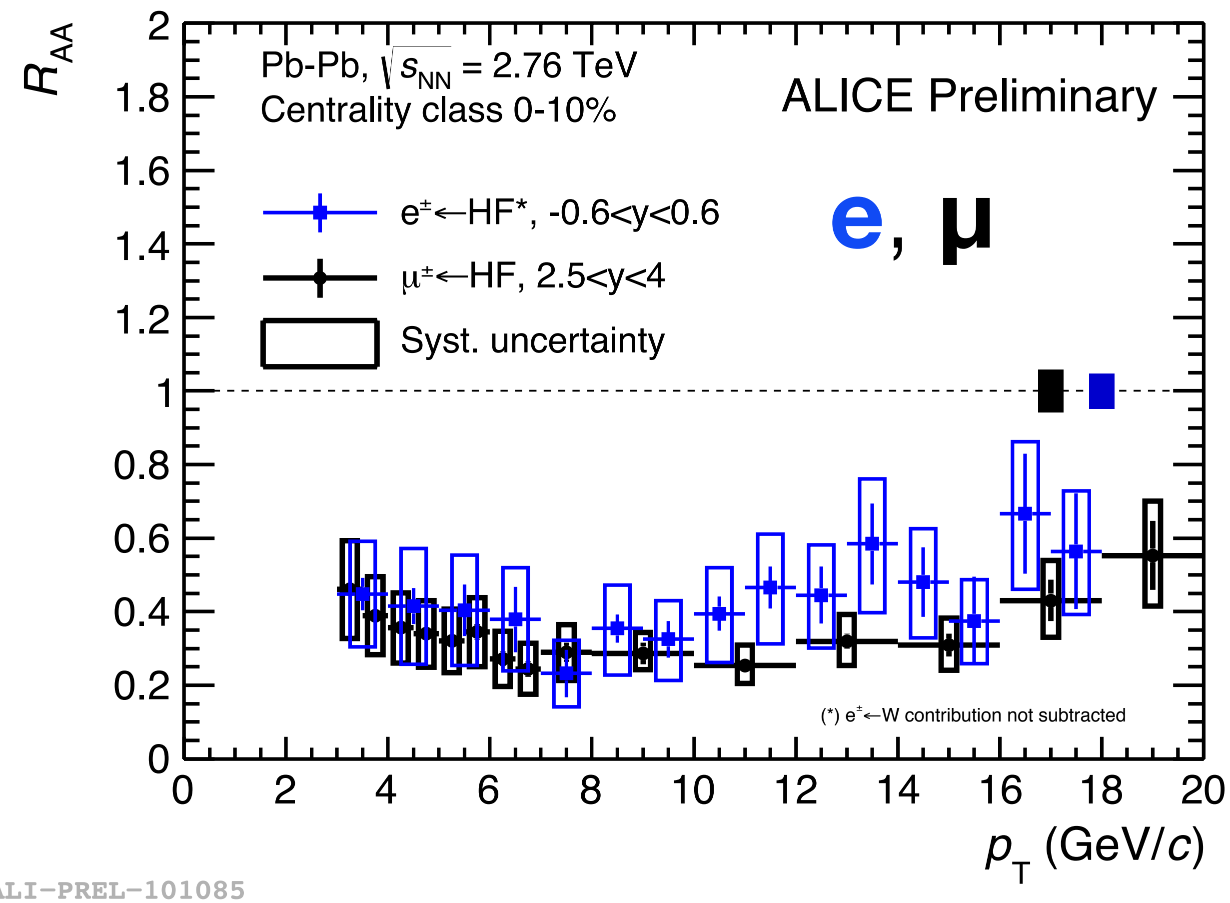


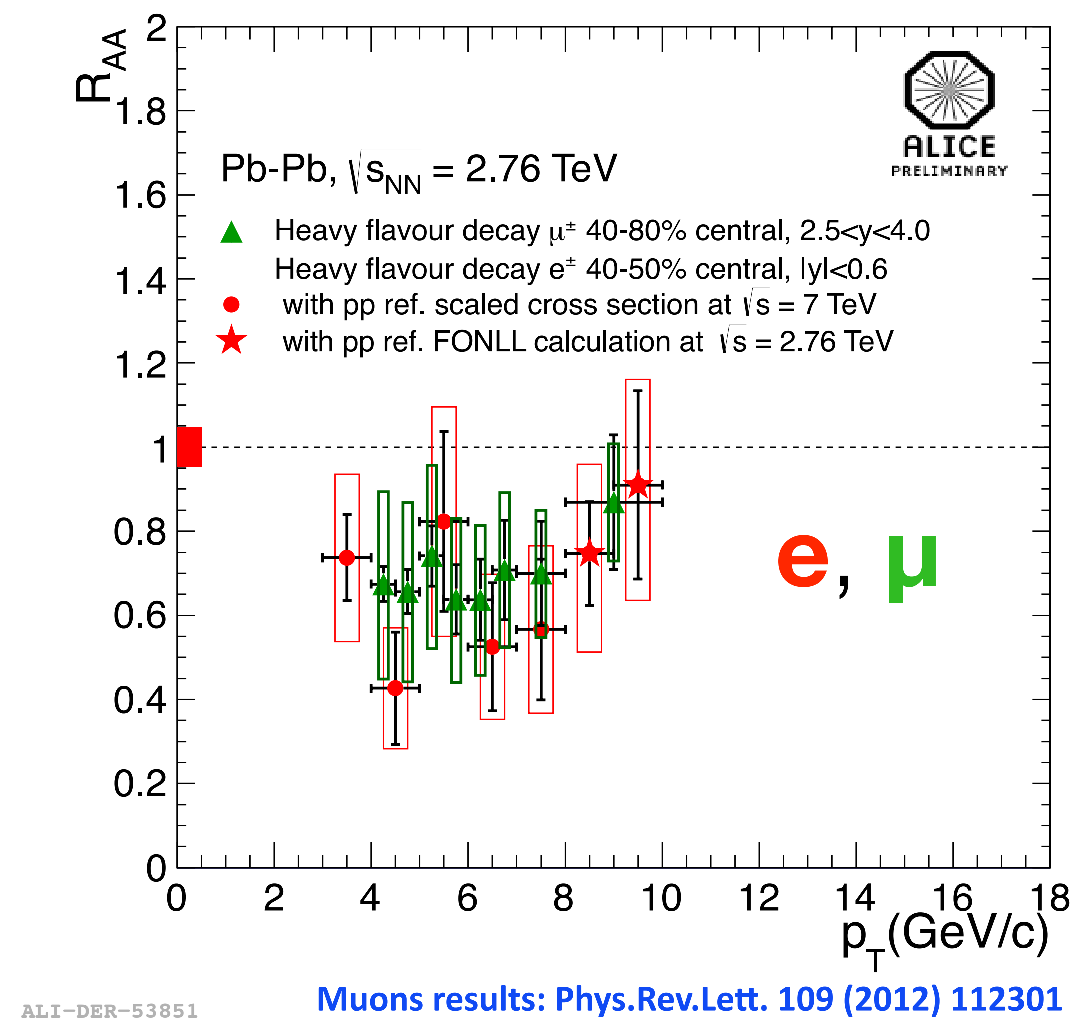
- **Clear suppression observed for 3 < p_T < 18 GeV/c for central collisions**
- Hint for difference of the HF decay electron R_{AA} measured in central (0-10%) and semiperipheral collisions (40-50%)

HF decay electrons and muons in Pb-Pb collisions

0-10% centrality



40-50% centrality

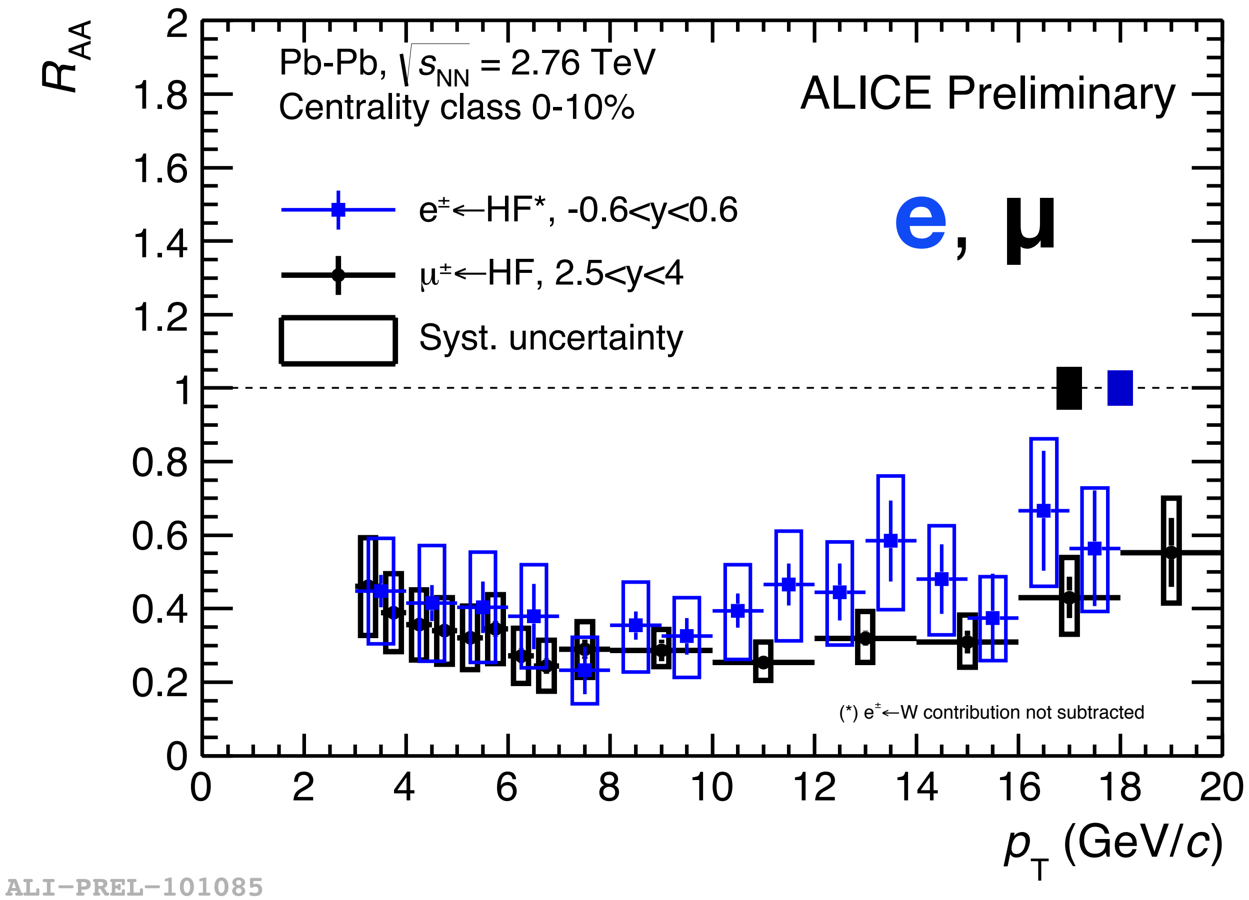


Muons results: Phys.Rev.Lett. 109 (2012) 112301

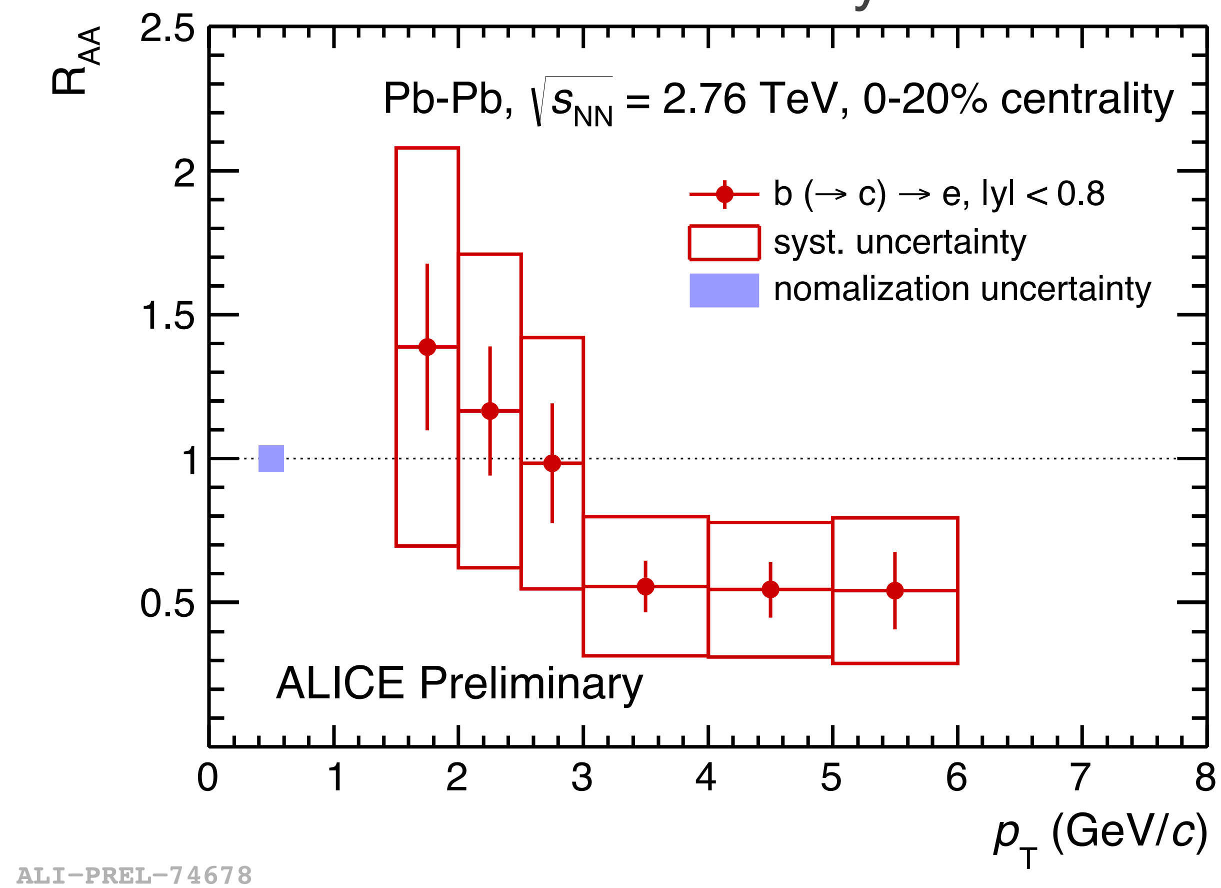
- **Clear suppression observed for 3 <p_T< 20 GeV/c for central collisions**
- Hint for difference of the HF decay electron R_{AA} measured in central (0-10%) and semiperipheral collisions (40-50%)
- Similar suppression in central (electrons) and forward (muons) rapidity

HF decay electrons from B decay in Pb-Pb collisions

HF decay e,μ (from c and b)
0-10% centrality



HF decay e (from b)
0-20% centrality

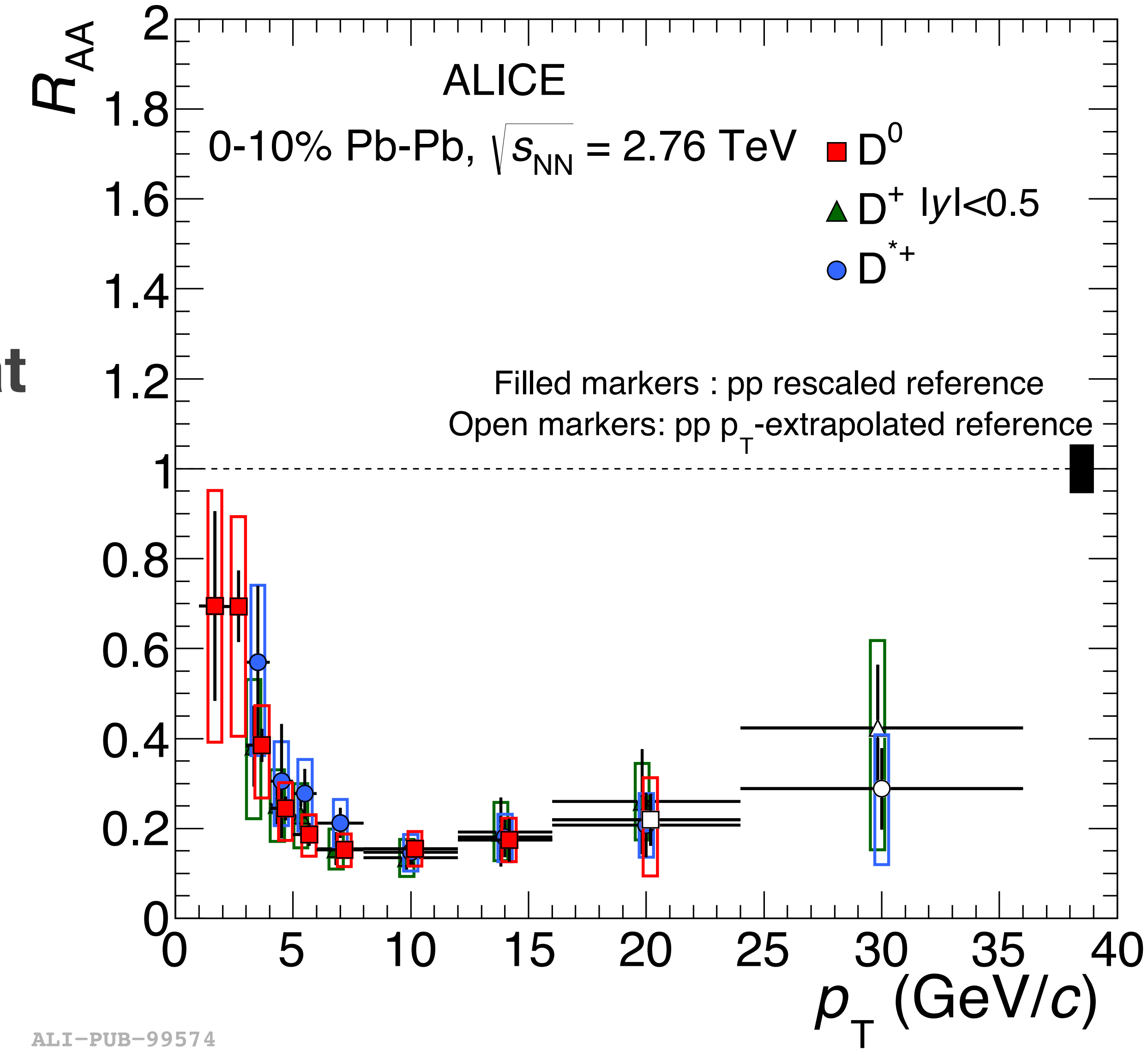


- **Clear suppression observed for 3 < p_T < 20 GeV/c for central collisions**
- Suppression also for HFe from B decays but systematics still large to conclude

D-meson R_{AA} vs p_T

- D meson R_{AA} measured from 2010 data. JHEP 09 (2012) 112
- p_T reach extended and uncertainties reduced with data from 2011.
- **Suppression up to a factor of 5-6 at p_T ~10 GeV/c for 0-10% central collisions.**

arXiv:1509.06888



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JHEP 09 (2012) 112

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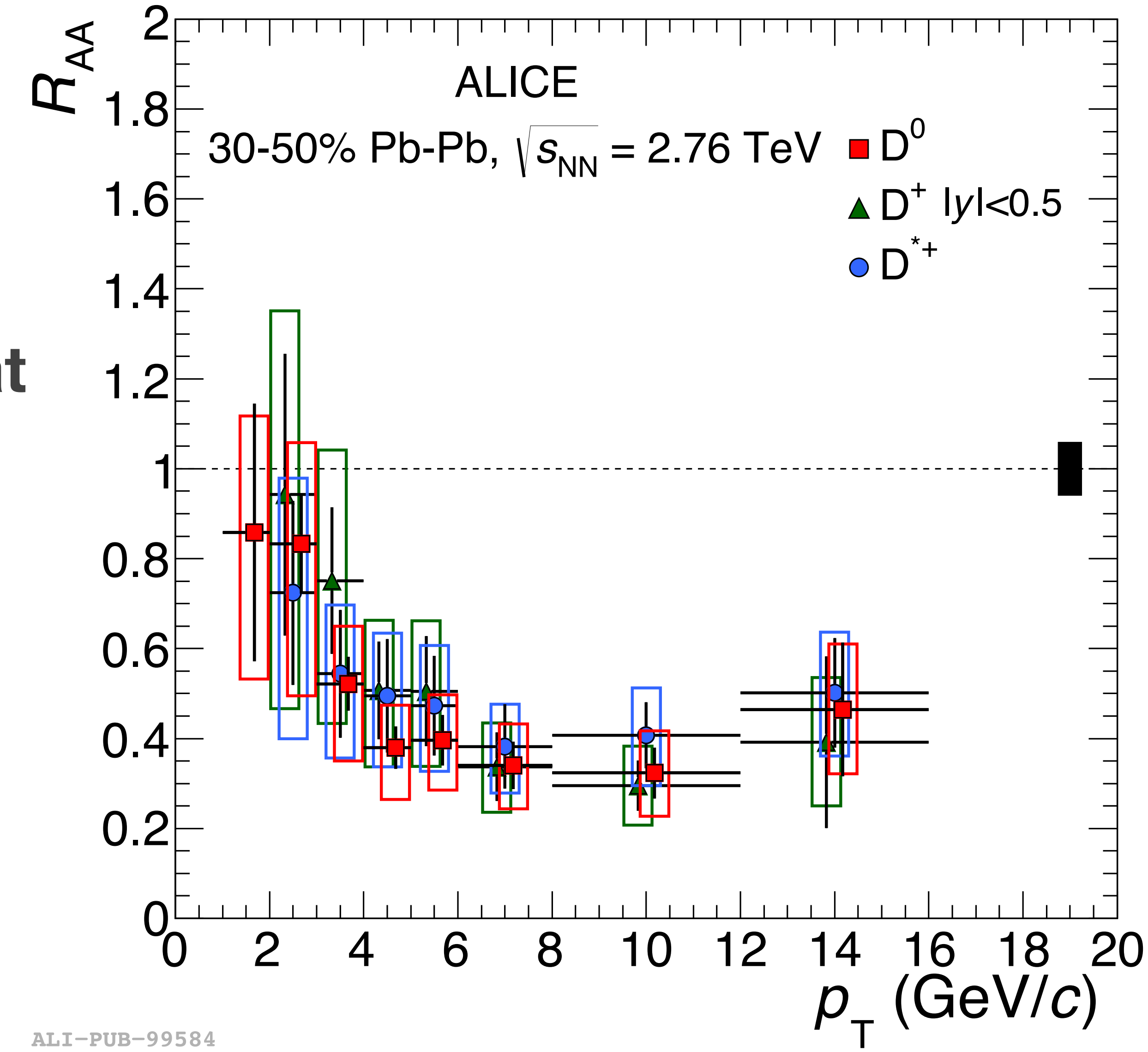

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JHEP 09 (2012) 112

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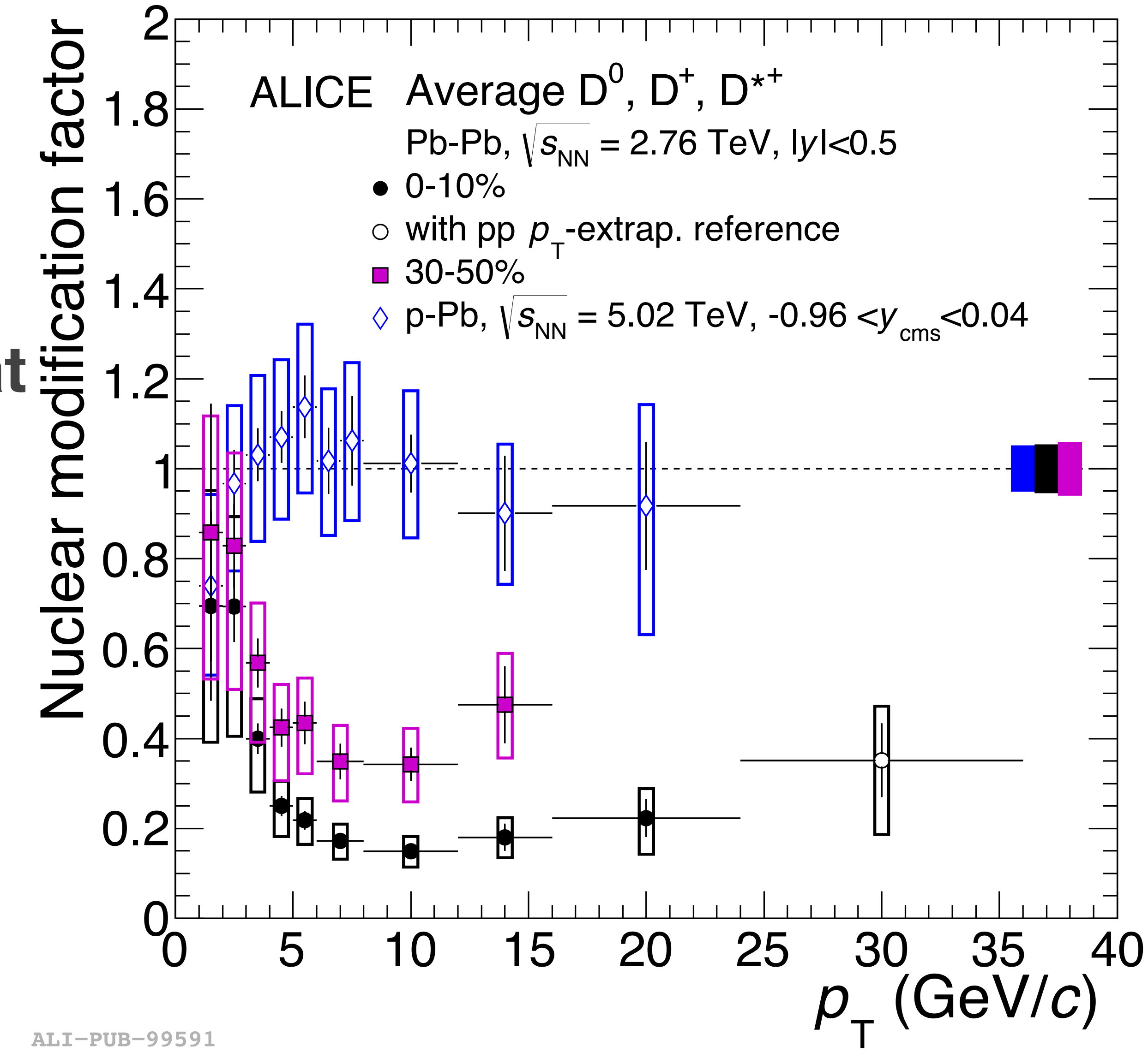
- **The p-Pb results indicate that the suppression comes from a final state effect.**

arXiv:1509.06888



D-meson R_{AA} vs p_T

- D-meson R_{AA} measured also by STAR at RHIC for $\sqrt{s_{NN}}$ = 0.2 TeV.

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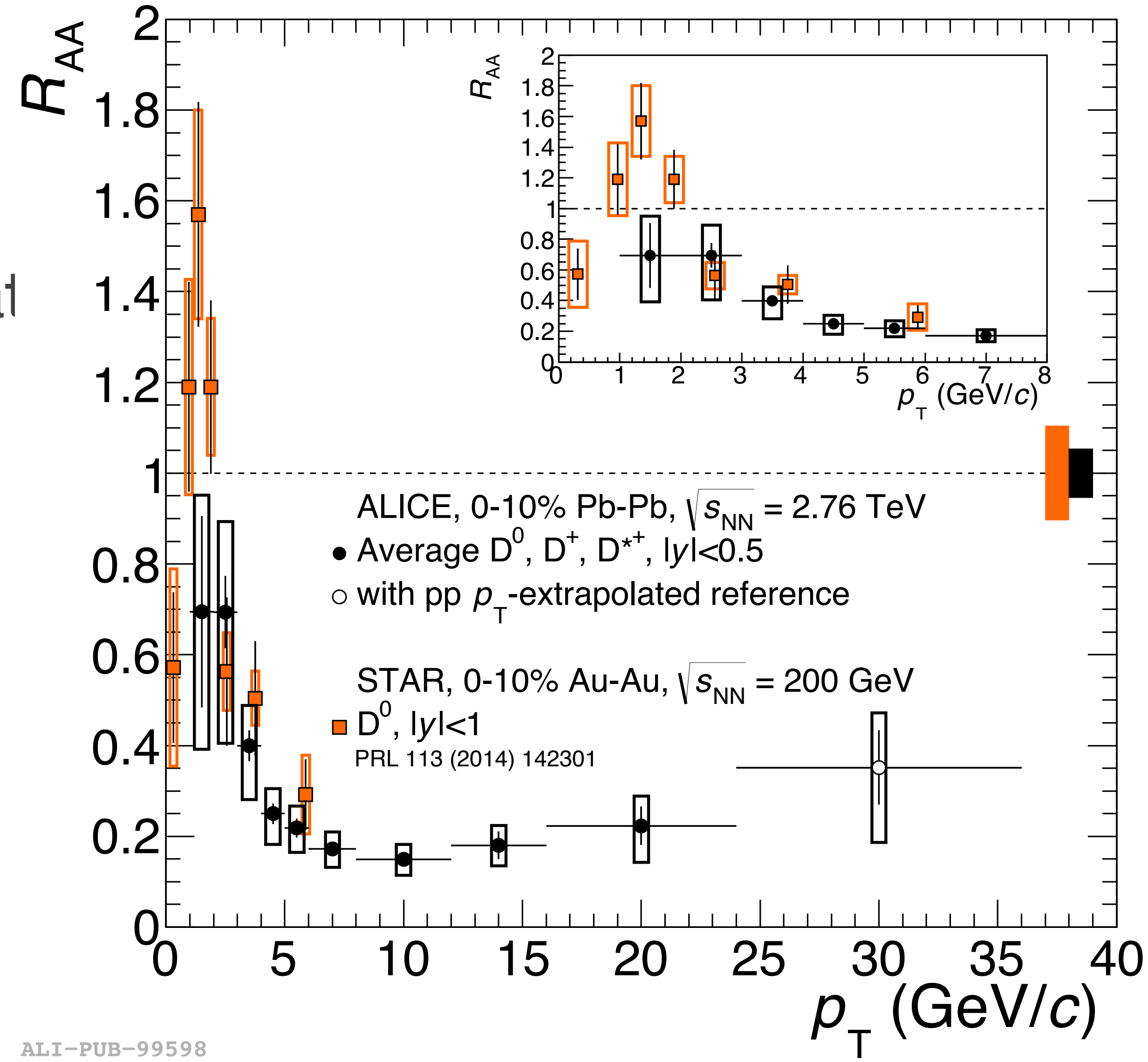

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  - different pT shapes
  - different initial state effects (CNM)
  - different collective radial flow
  - larger hadronisation via recombination?

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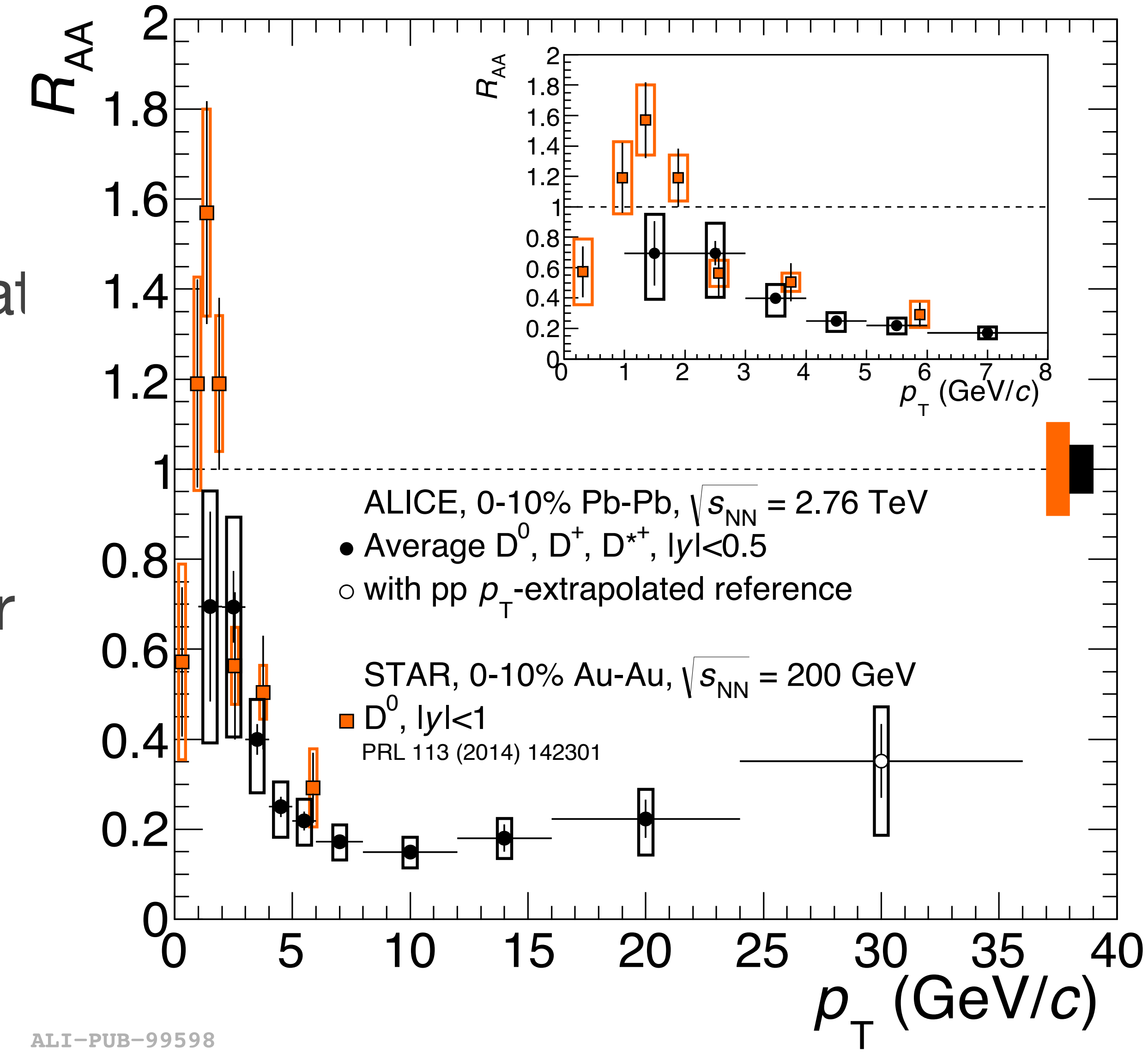

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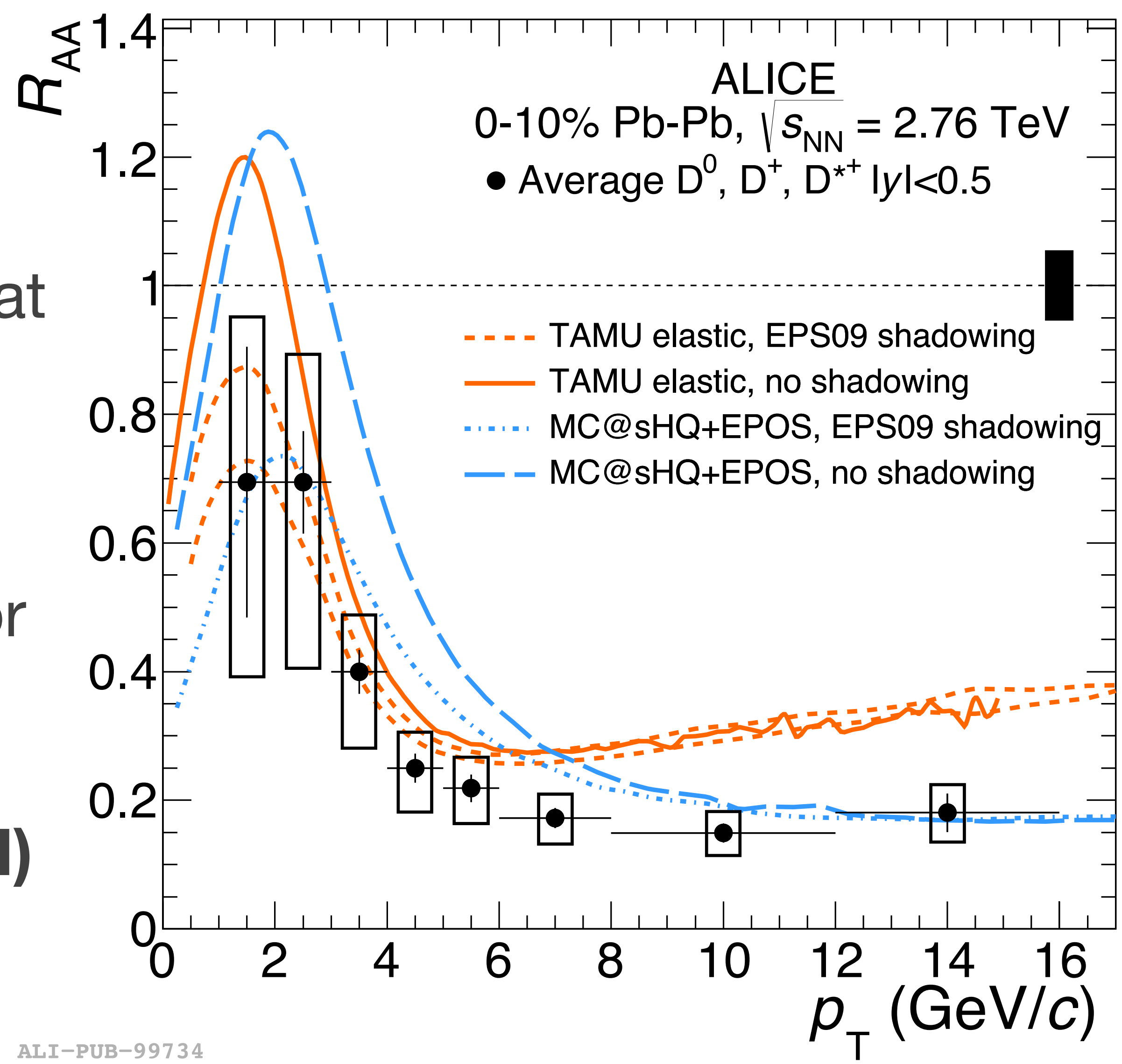
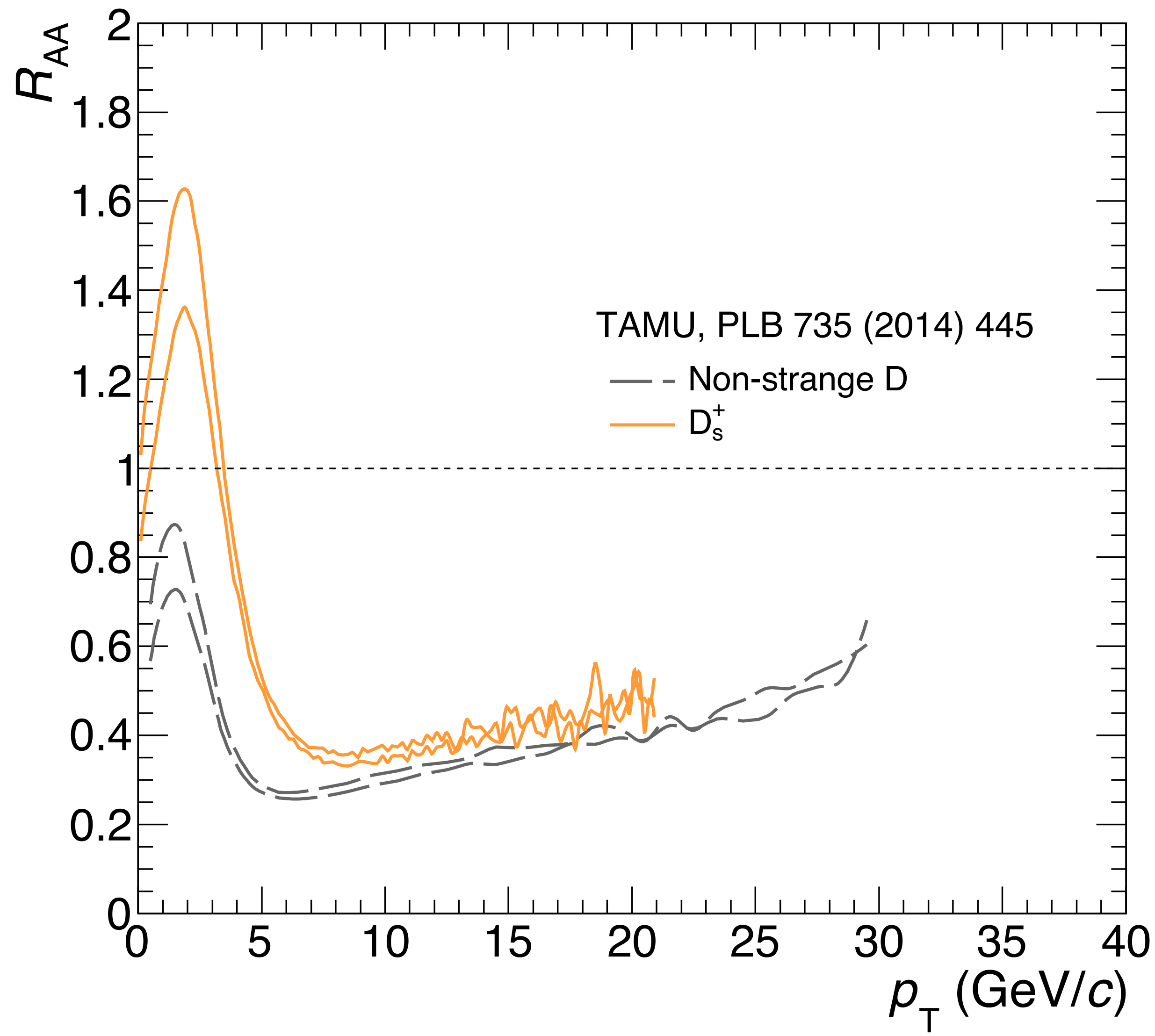


ALI-PUB-99734

D_s-meson R_{AA} vs p_T

- **D_s-meson** yields could be sensitive to strangeness enhancement observed in heavy-ion collisions
- charm - strangeness recombination effects?



D_s-meson R_{AA} vs p_T

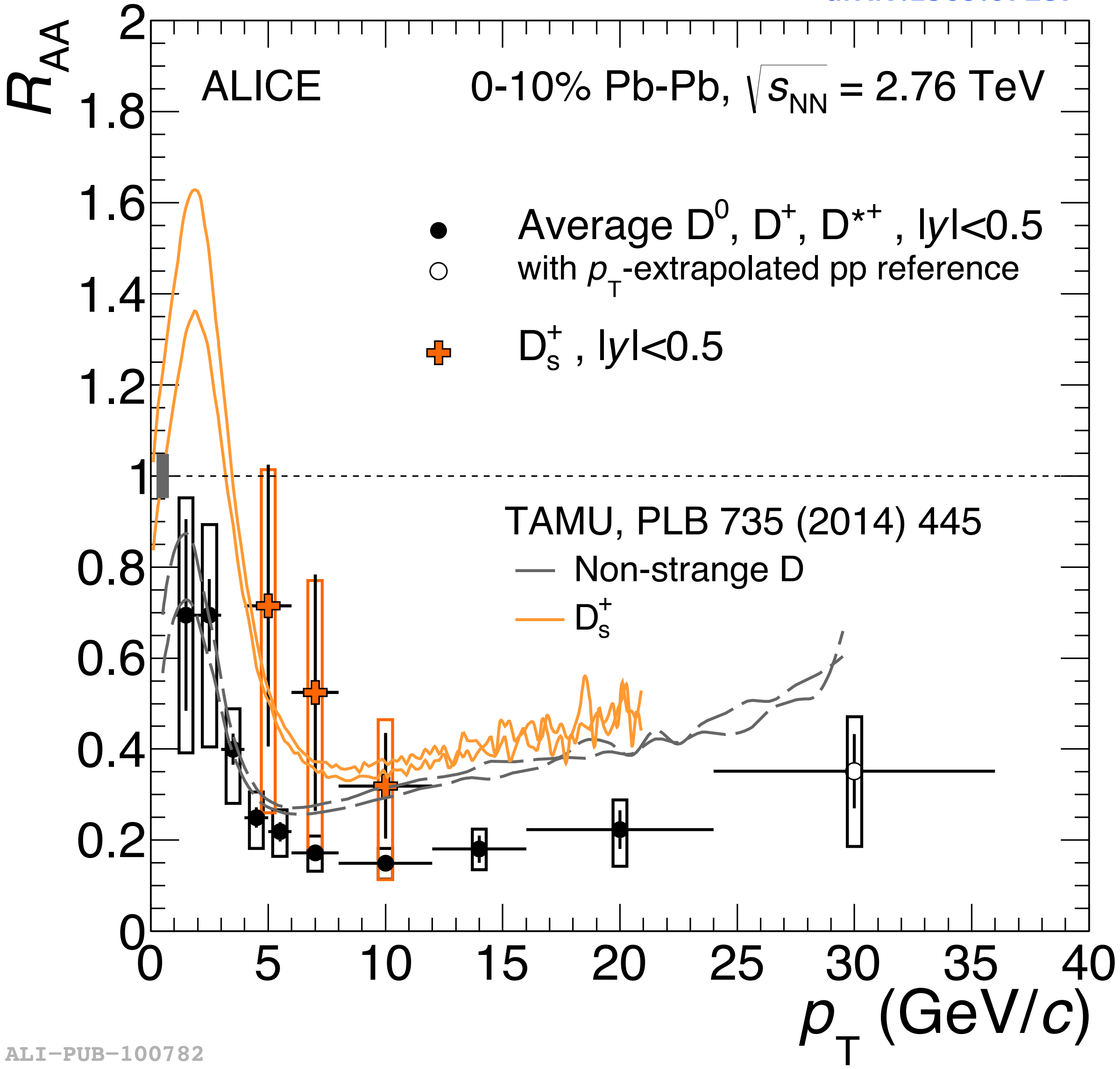
- **D_s-meson** yields could be sensitive to strangeness enhancement observed in heavy-ion collisions
- charm - strangeness recombination effects?

- **D_s-meson R_{AA}** measured for the first time in heavy-ion collisions

- **Although compatible within uncertainties all three D_s point are above the non-strange D meson R_{AA}.**

- Run2 data needed to improve the R_{AA} measurement and performe the v_2 one.

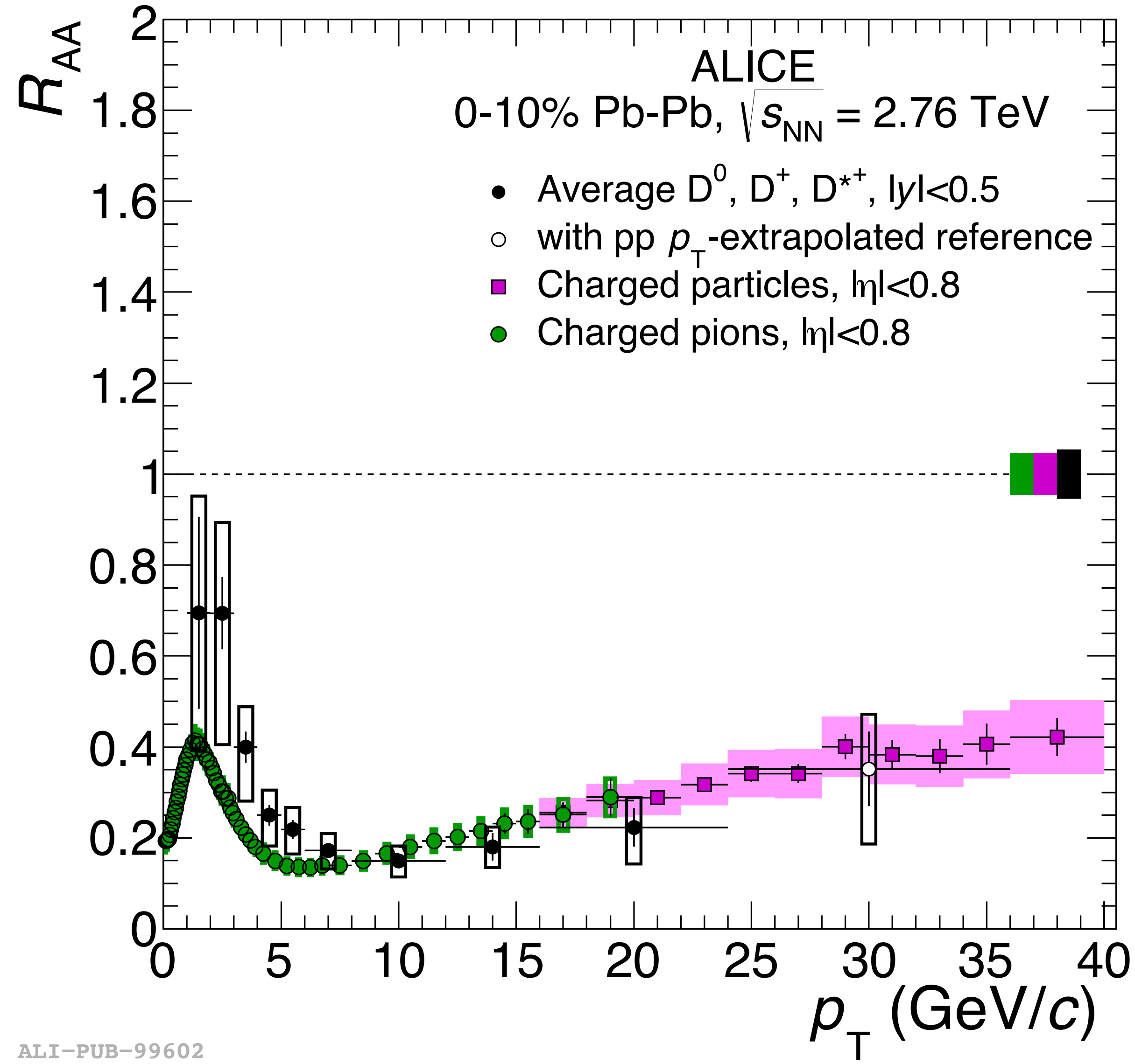
arXiv:1509.07287



? $\Delta E(\text{light}) > \Delta E(c) > \Delta E(b) \rightarrow R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

- D-meson R_{AA} is compared with charged pions and charged hadrons R_{AA} for 0-10% central collisions
- R_{AA} results are consistent for $p_T > 6$ GeV/c.
- For $p_T < 6$ GeV/c, D-meson R_{AA} is slightly larger than R_{AA} of π.
  - 1σ effect in 4 p_T bins

arXiv:1509.06888



ALI-PUB-99602

?
ΔE(light) >ΔE(c) > ΔE(b) ➜ $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

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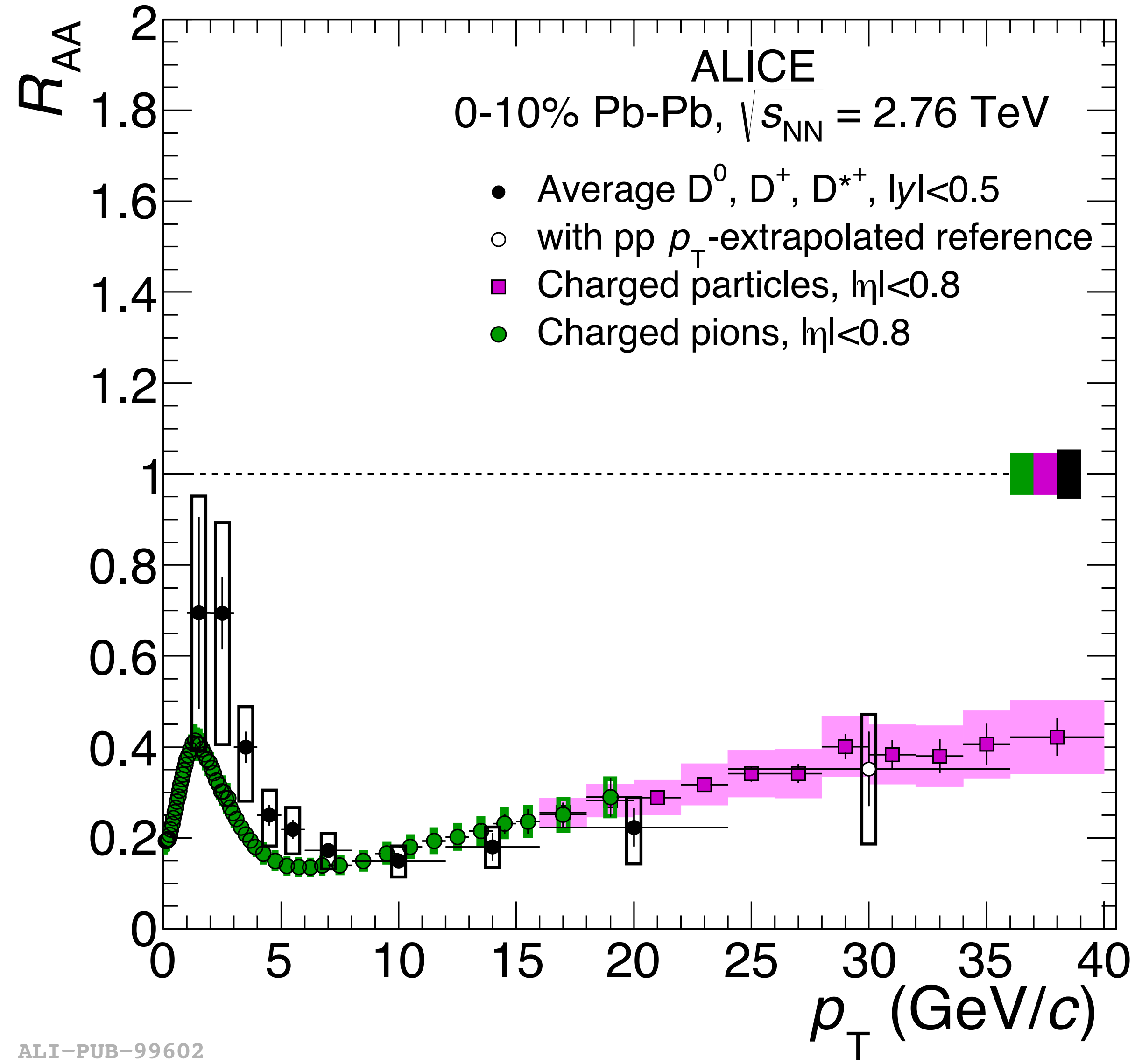
- For $p_T < 6$ GeV/c, D-meson R_{AA} is slightly larger than R_{AA} of π.
  - 1σ effect in 4 p_T bins

- Direct interpretation of results complicated by:
  - harder p_T distribution and fragmentation of charm quarks
  - pions can have a large contribution from radial flow
  - different CNM effects for π and D

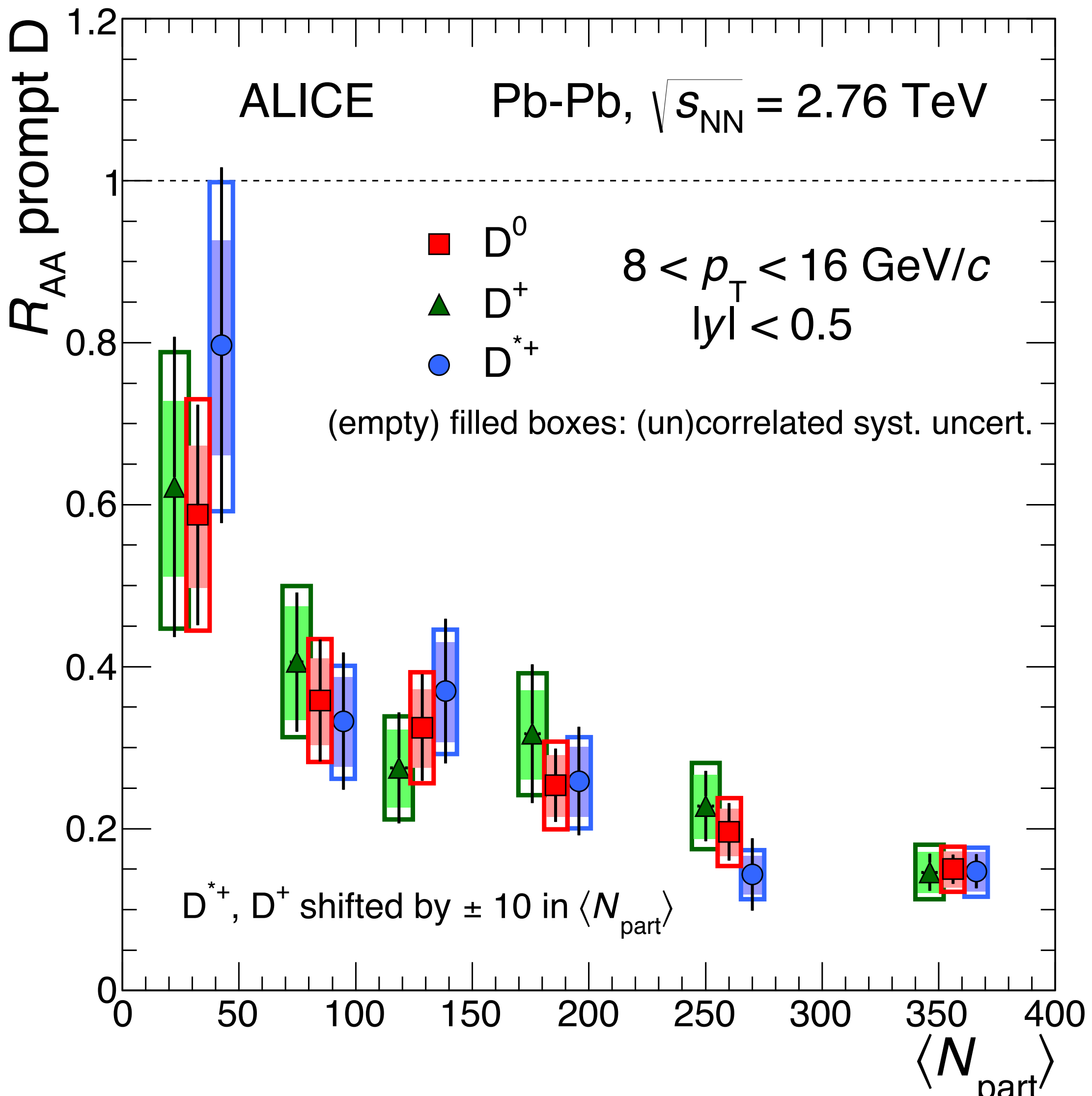
arXiv:1509.06888



D-meson R_{AA} vs N_{part}

- D-meson R_{AA} measured as a function of the centrality of the collisions
- Stronger suppression observed at intermediate and high-p_T going from peripheral to central events.
- Compatible results for **D^0**, **D^+**, **D^{*+}** measurements

JHEP11(2015)205



ALI-PUB-93554

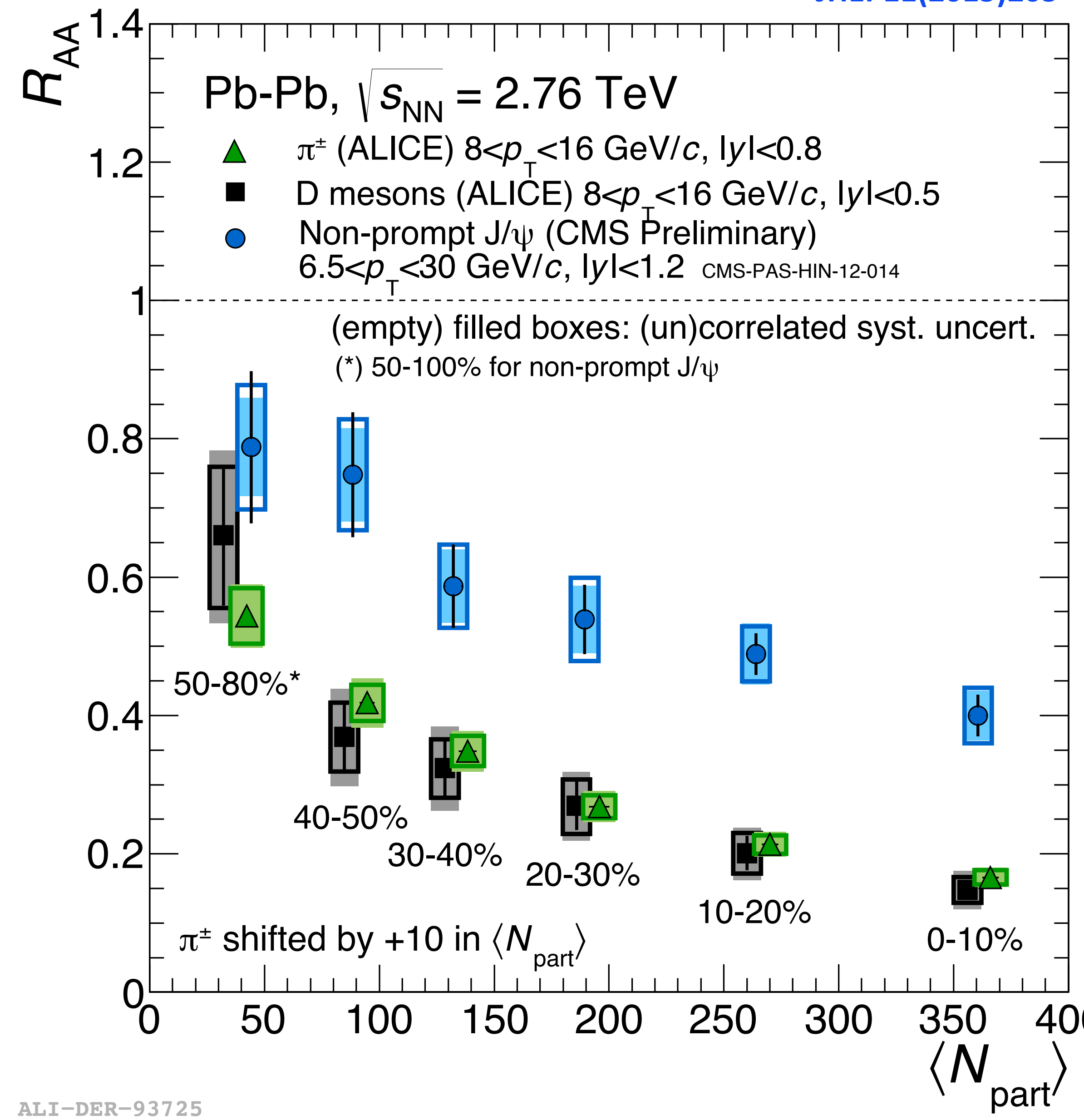
?

ΔE(light) >ΔE(c) > ΔE(b) ➜ R_{AA} (π) < R_{AA} (D) < R_{AA} (B)

- **D-meson R_{AA}** vs N_{part} is compared with **non-prompt J/ψ** from CMS and **π** from ALICE in a similar kinematic range:
  - central rapidity region
  - $<p_T>$ ~10 GeV/c

- **Larger suppression observed for D mesons than B mesons:**
  - R_{AA} **(B) >** R_{AA} **(D)**
- **Similar suppression observed for D mesons and π:**
  - R_{AA} **(π) ≈** R_{AA} **(D)**

JHEP11(2015)205



ALI-DER-93725

?
ΔE(light) >ΔE(c) > ΔE(b) → R_{AA} (π) < R_{AA} (D) < R_{AA} (B)

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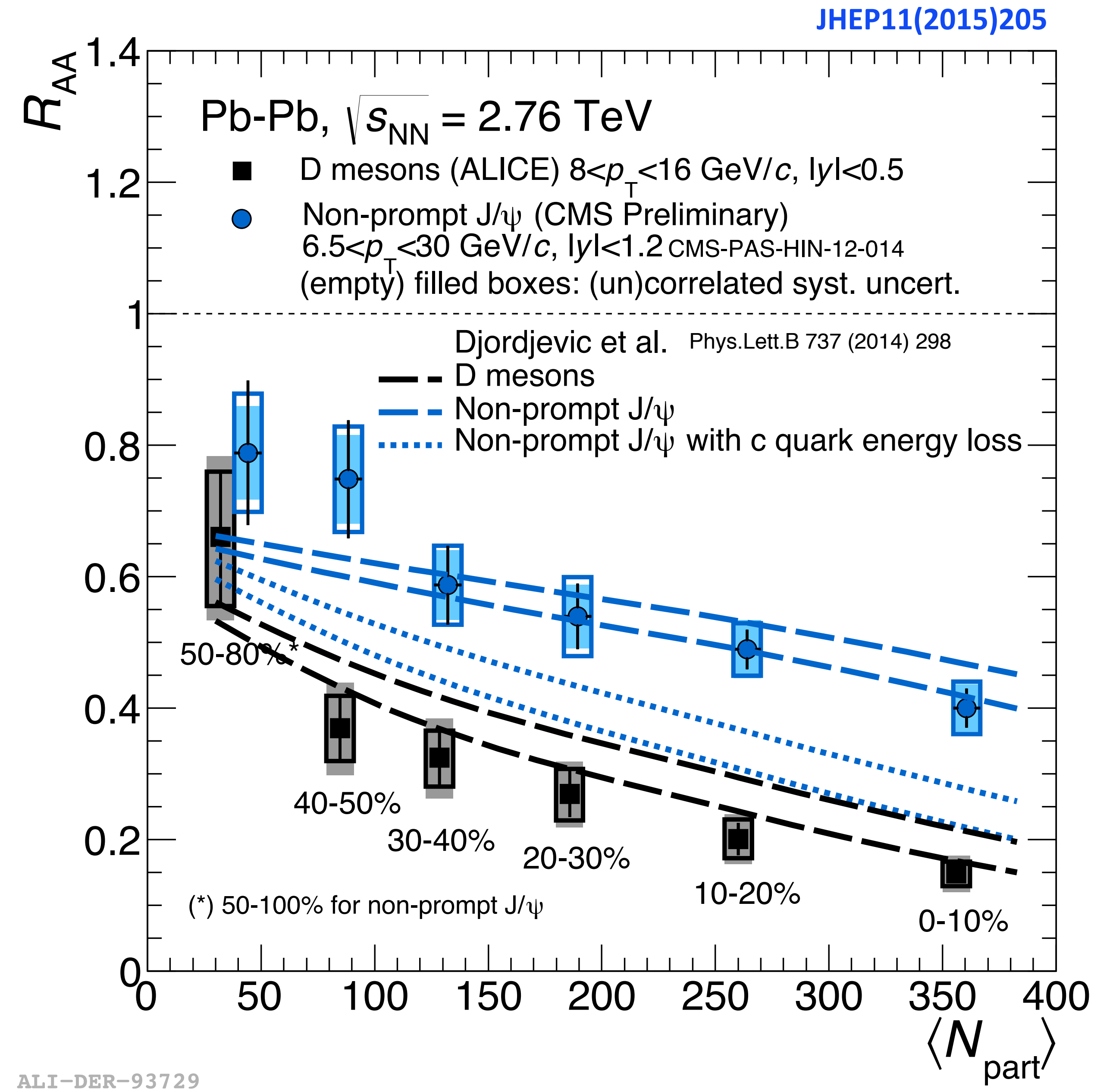
  - $\langle p_T \rangle$ ~10 GeV/c

- **Larger suppression observed for D mesons than B mesons:**
  - ***R*$_{AA}$ (B) > *R*$_{AA}$ (D)**

- **Models that include mass dependence of the energy loss predict a difference in the *R*$_{AA}$ of D and B mesons**

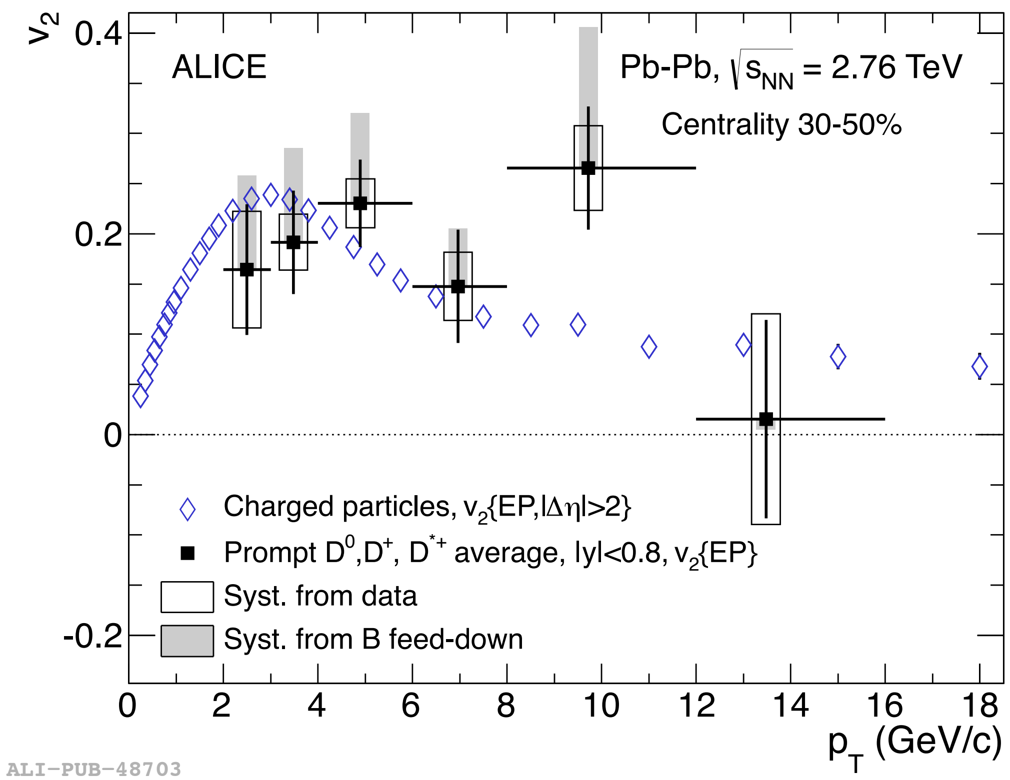


Azimuthal anisotropy v_2

D meson

Phys. Rev. Lett. 111, 102301 (2013)

- Smilar amount of v_2 for D mesons and π.

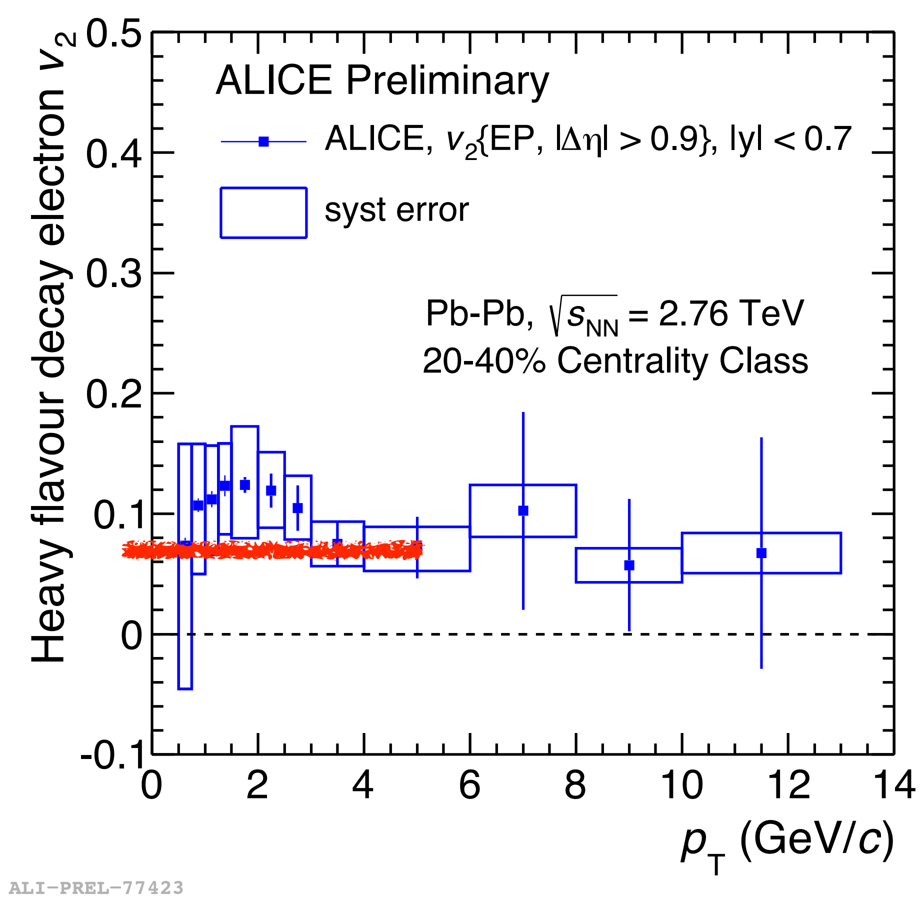


Azimuthal anisotropy v_2

- Similar amount of v_2 for D mesons and π.

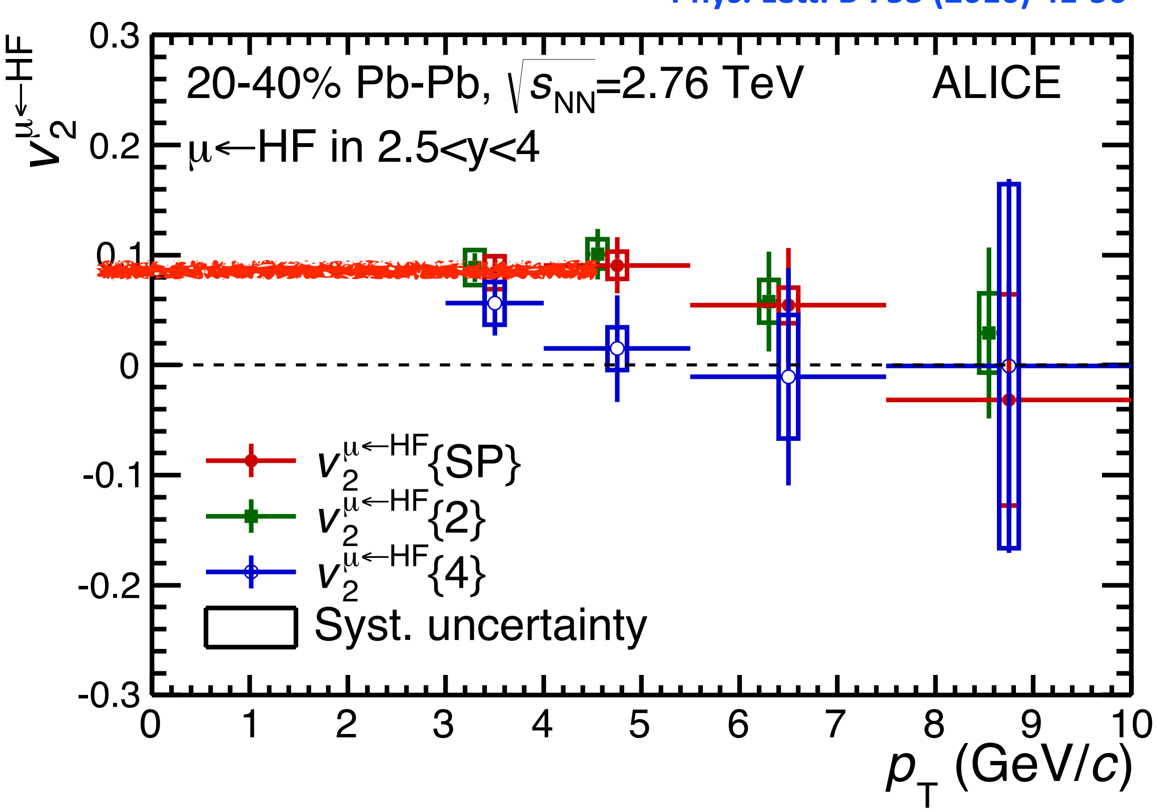
- Similar amount for HF decay muons and electrons in different rapidity regions ($v_2 \sim 0.08$ for $p_T \sim 5$ GeV/c)

e from HF decay



μ from HF decay

Phys. Lett. B 753 (2016) 41-56



Azimuthal anisotropy v_2

- All channels show positive v_2 for semi-peripheral classes (30-50% or 20-40%).
  - $> 3\sigma$ effect

- Indication that v_2 for charm particles increases from central to peripheral collisions, as expected by the collisions geometry

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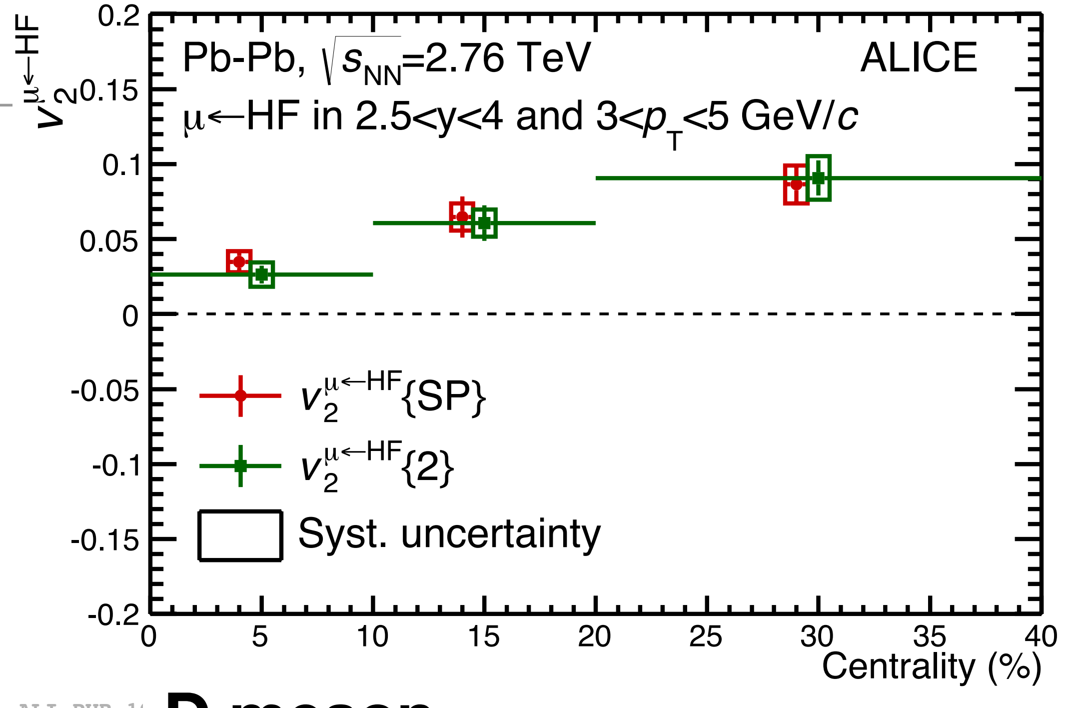
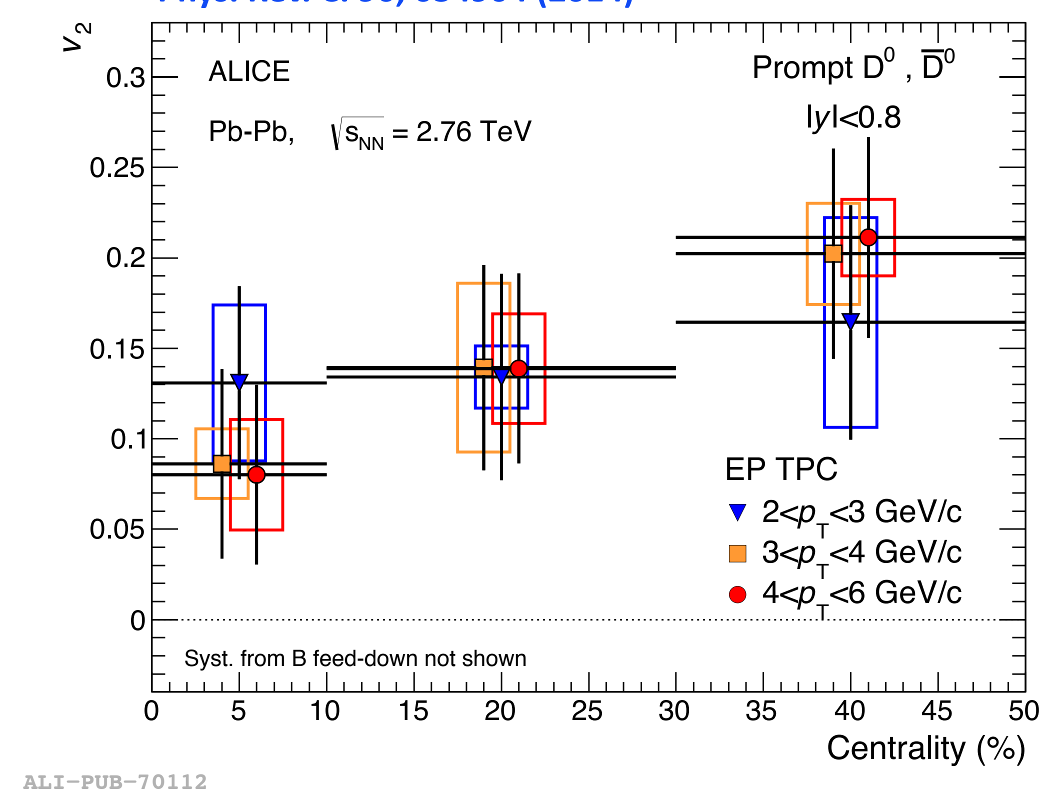


D meson

Phys. Rev. C. 90, 034904 (2014)



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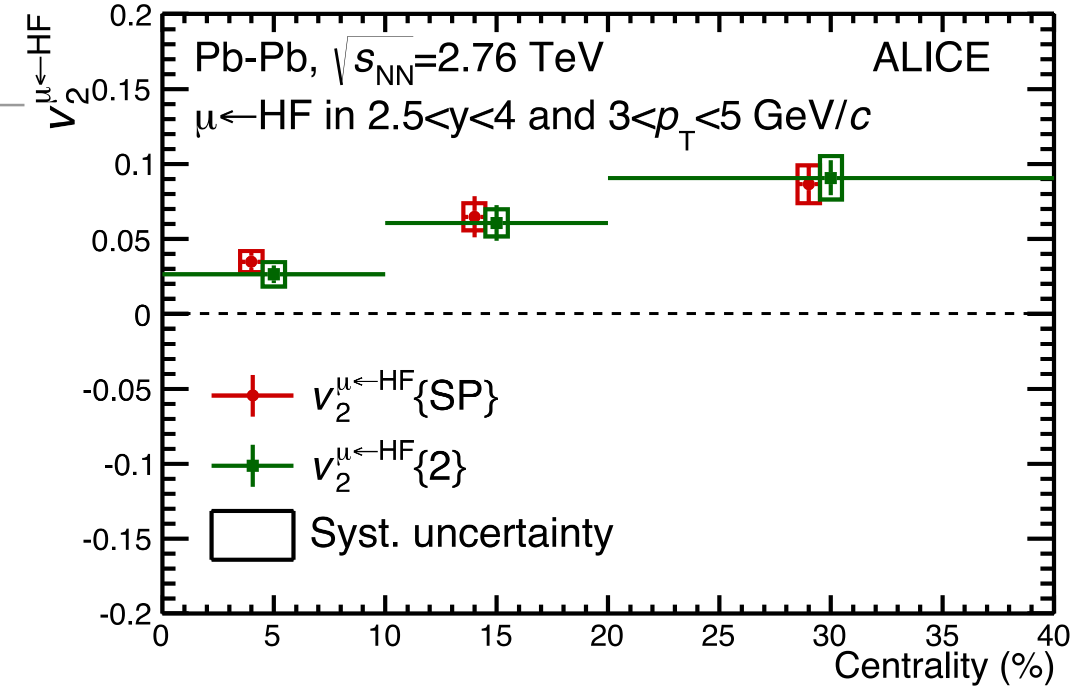
- All channels show positive v_2 for semi-peripheral classes (30-50% or 20-40%).
  - > 3σ effect

- Indication that v_2 for charm particles increases from central to peripheral collisions, as expected by the collisions geometry

- **Information on the initial azimuthal anisotropy transferred to charm quarks**

μ from HF decay

Phys. Lett. B 753 (2016) 41-56



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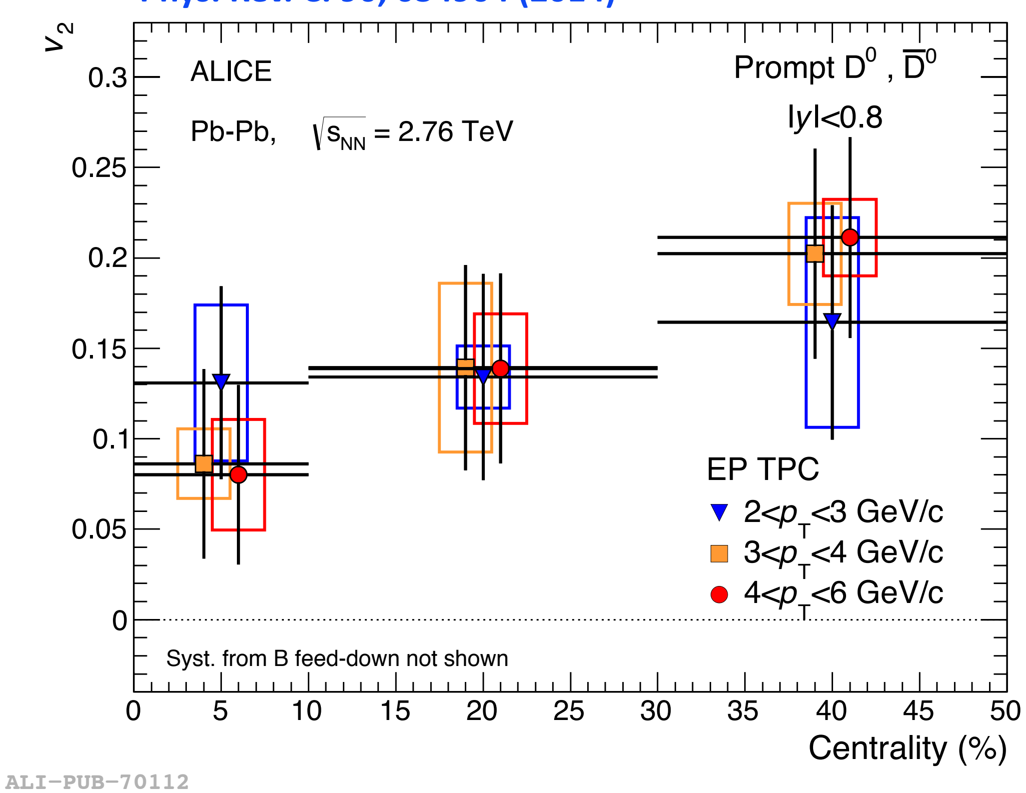
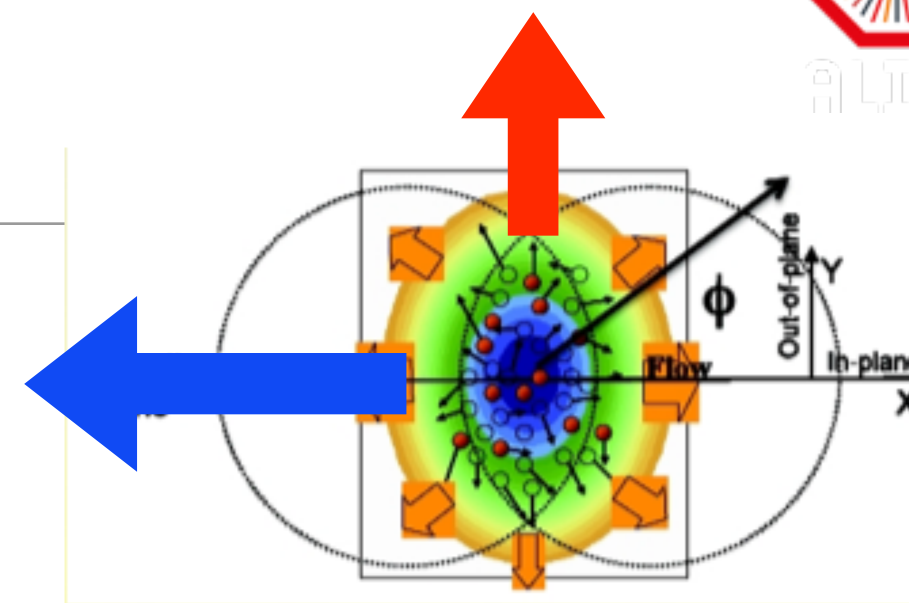


Azimuthal anisotropy v_2 and R_{AA}



- Azimuthal anisotropy can be related with:
  - **Low p_T v_2** → pressure gradients in medium expansion → measure of strength of collectivity (mean free path of outgoing partons)

  - **High p_T v_2** → path-length dependent energy loss in an almond-shaped medium → asymmetry in momentum space

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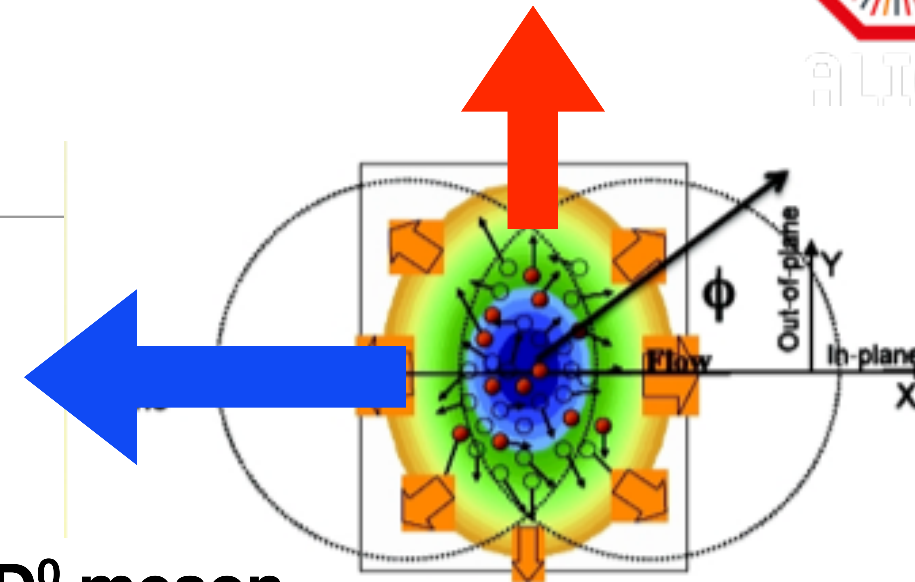
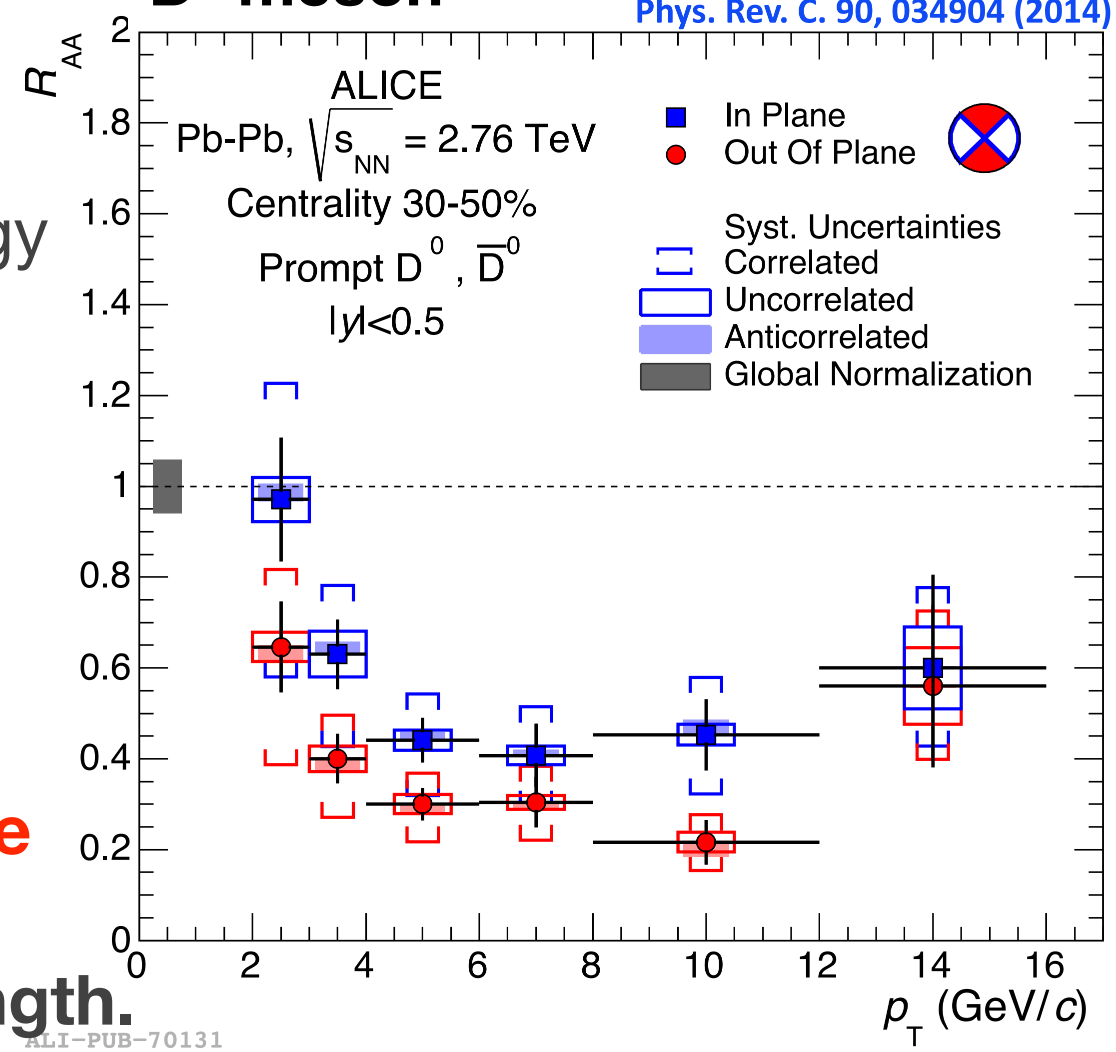
  - **High p_T v_2** → path-length dependent energy loss in an almond-shaped medium → asymmetry in momentum space
- R_{AA} measured in the two azimuthal regions: in-plane and out-of-plane.
- **More suppression is observed out-of-plane with respect to in-plane region.**
  - **as expected due to the different path length.**



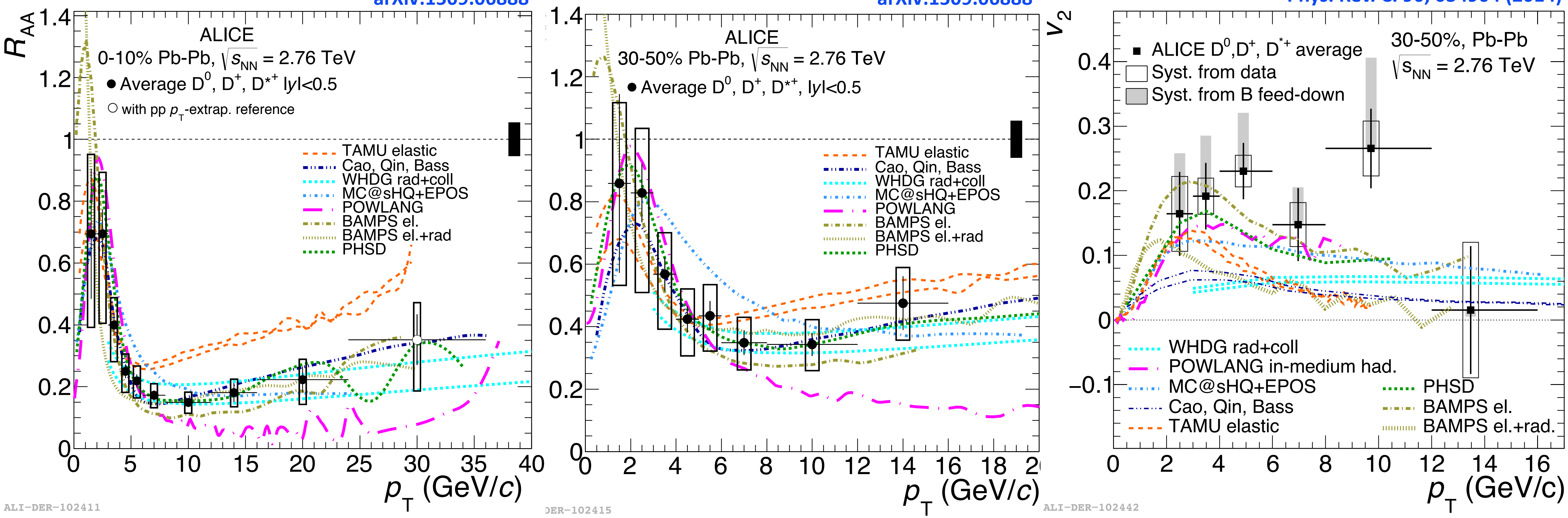
D⁰ meson



R_{AA} and v_2: comparison with models

- ✳ Simultaneous measurement/description of v_2 and R_{AA}
  → understanding of heavy quark transport coefficients of the medium

arXiv:1509.06888 arXiv:1509.06888 Phys. Rev. C. 90, 034904 (2014)



- ✳ **TAMU model does not include radiative energy loss and overestimate the R_{AA}.**
  → **Radiative energy loss needed to describe the R_{AA} in central collisions**

M. He et al, PLB 735 (2014) 445-450

R_{AA} and v_2: comparison with models

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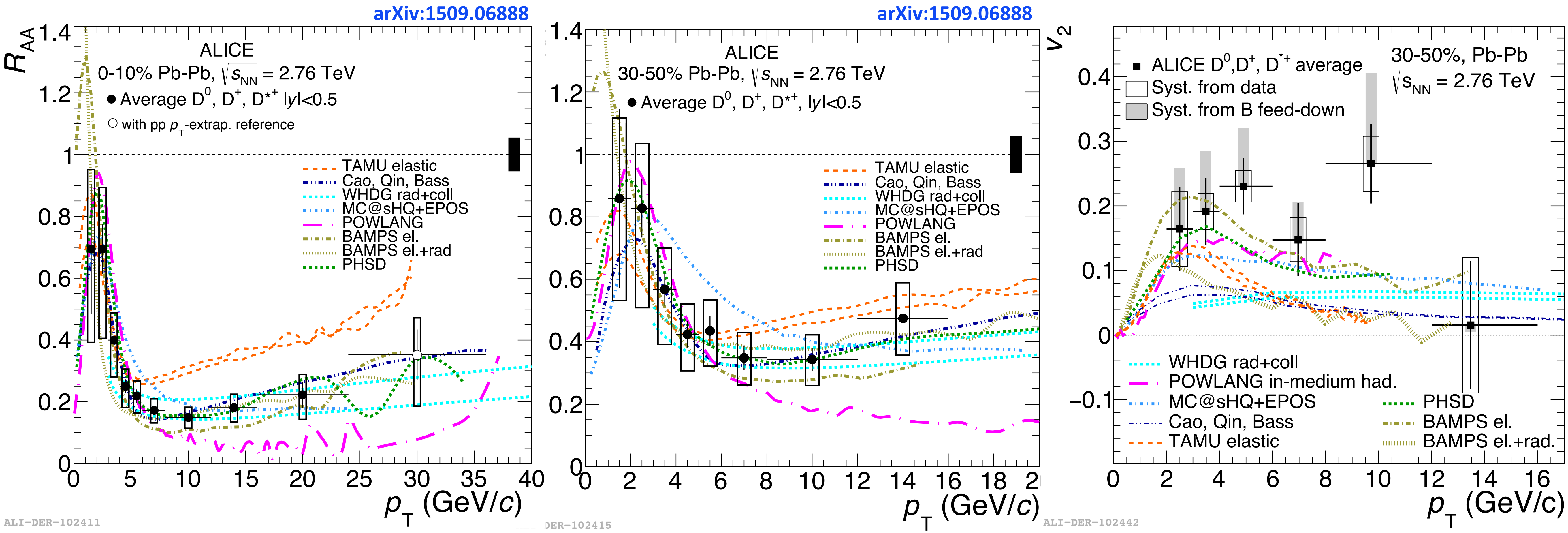

- **WHDG does not include an expanding medium and underestimate v_2.**
- **BAMPS, TAMU, MC@sHQ include both collisional energy loss in an expanding medium and recombination → better agreement with v_2 data**

M. He et al, PLB 735 (2014), S.Wicks et al, Nucl. Pyhs. A784 (2007), J.Uphoff et al, PLB 717 (2010), M.Nahrgang et al., PRC 89 (2014)

D-meson and π R_{AA}: comparison with models

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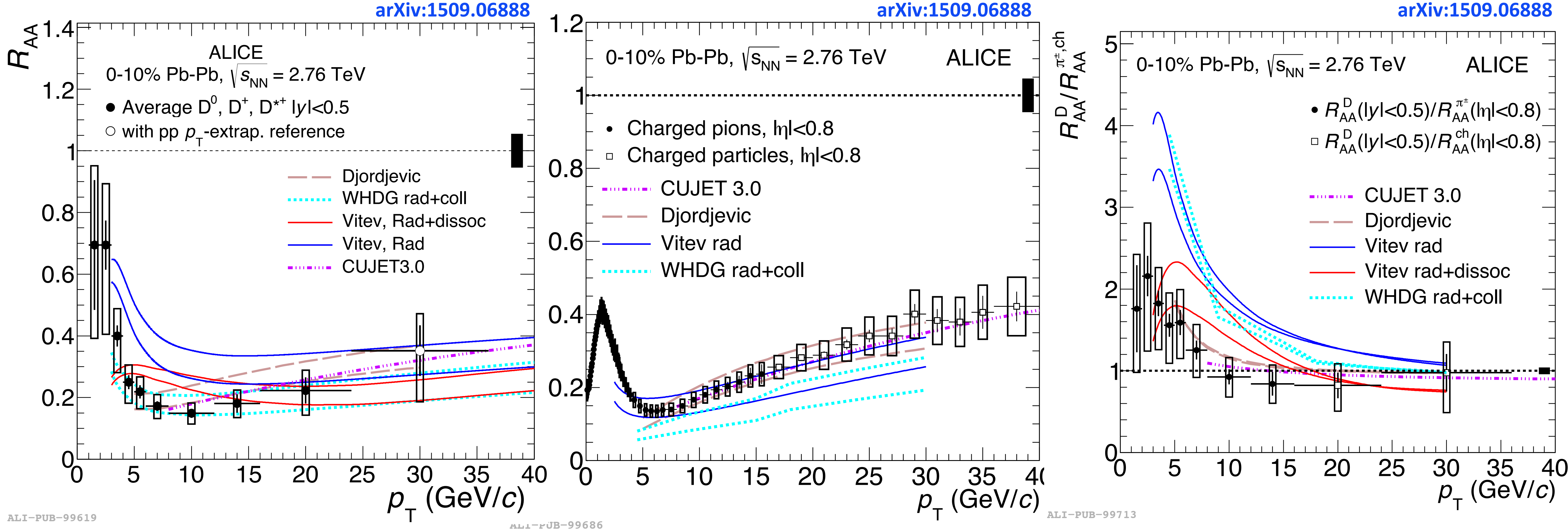

- **Only Djordjevic and CUJET 3.0 models can describe the two R_{AA} (p_T>5 GeV/c).**
  →they both include radiative and collisional energy loss.

Djordjevic et al., PLB 737 (2014), J. Xu et al.,arXiv:1508.00552

Conclusions and outlook

- **Many different measurements of heavy flavour productions in pp collisions at LHC shows good agreement with pQCD calculations.**
  - More differential measurement (D-h, yields vs multiplicity, …) can be a good tool to investigate further this sector.

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- **In p-Pb collisions, no clear evidence of effects due to cold nuclear matter or collectivity have been measured in the heavy flavour sector with Run1 data.**
  - Something could be there (also looking at model predictions) at very low-p_T. Further investigation (and data) needed!

- **In Pb-Pb collisions, heavy flavour particles are suppressed with respect to pp collisions. An interaction with the medium is clearly observed for those particles.**
  - The mechanisms that might play a role in this interactions are still not clearly accessed. More precise data and more “sophisticated” model comparison are needed to better understand them.

HF with the ALICE upgrade

- Characterise mechanisms of quark-medium interaction:
  - Heavy Flavour dynamics and hadronsation at low p_{T}.

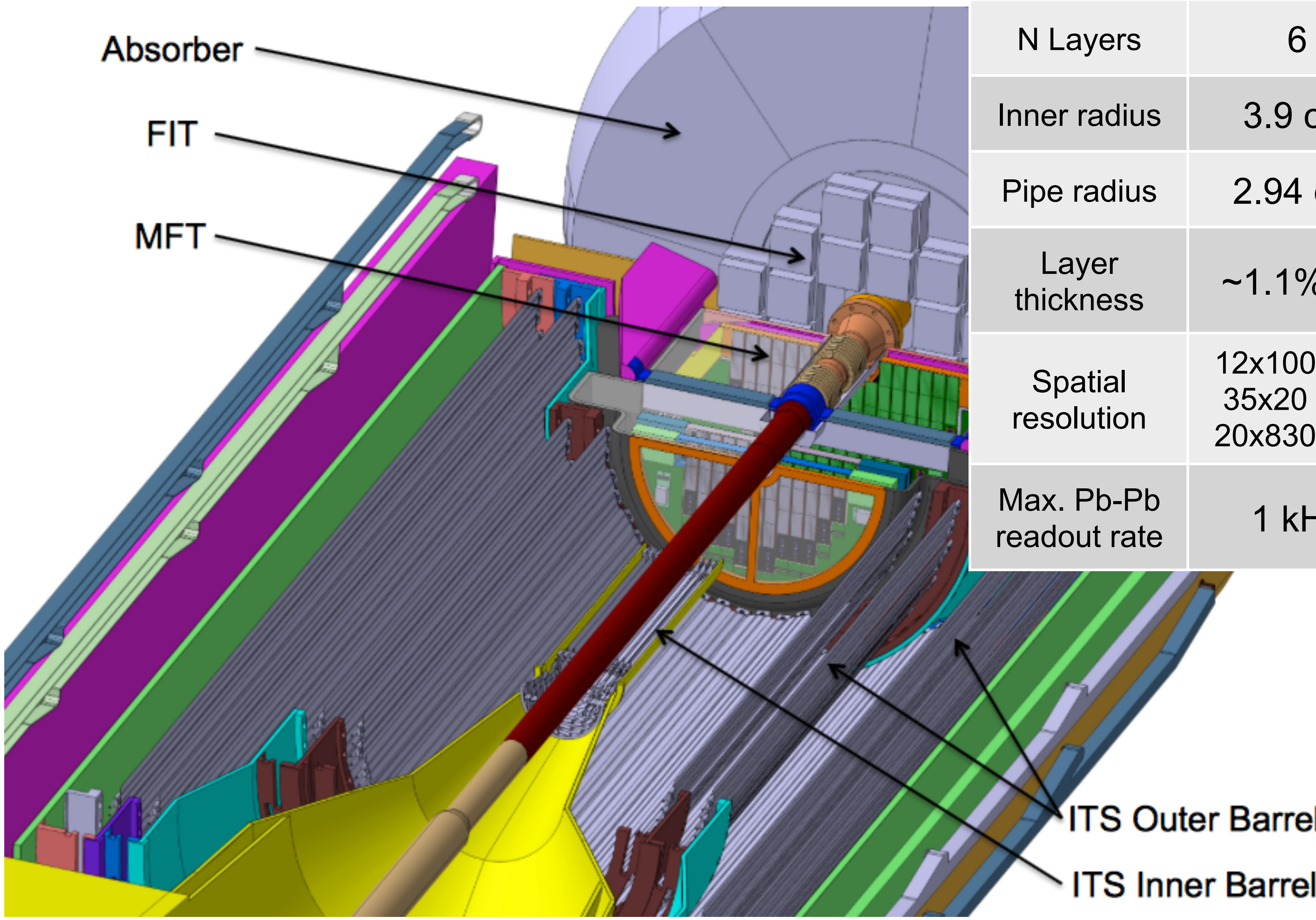
  - What is needed?
    - Precision measurements also down to $p_{T} = 0$.

  - How this can reach?
    - Improve vertexing resolution
    - Preserve particle identification (to reject the background)
    - Large statistics (no dedicated trigger)

New pixel system: ITS and MFT

- Both trackers fully based on Monolithic Active Pixel Sensor (MAPS)

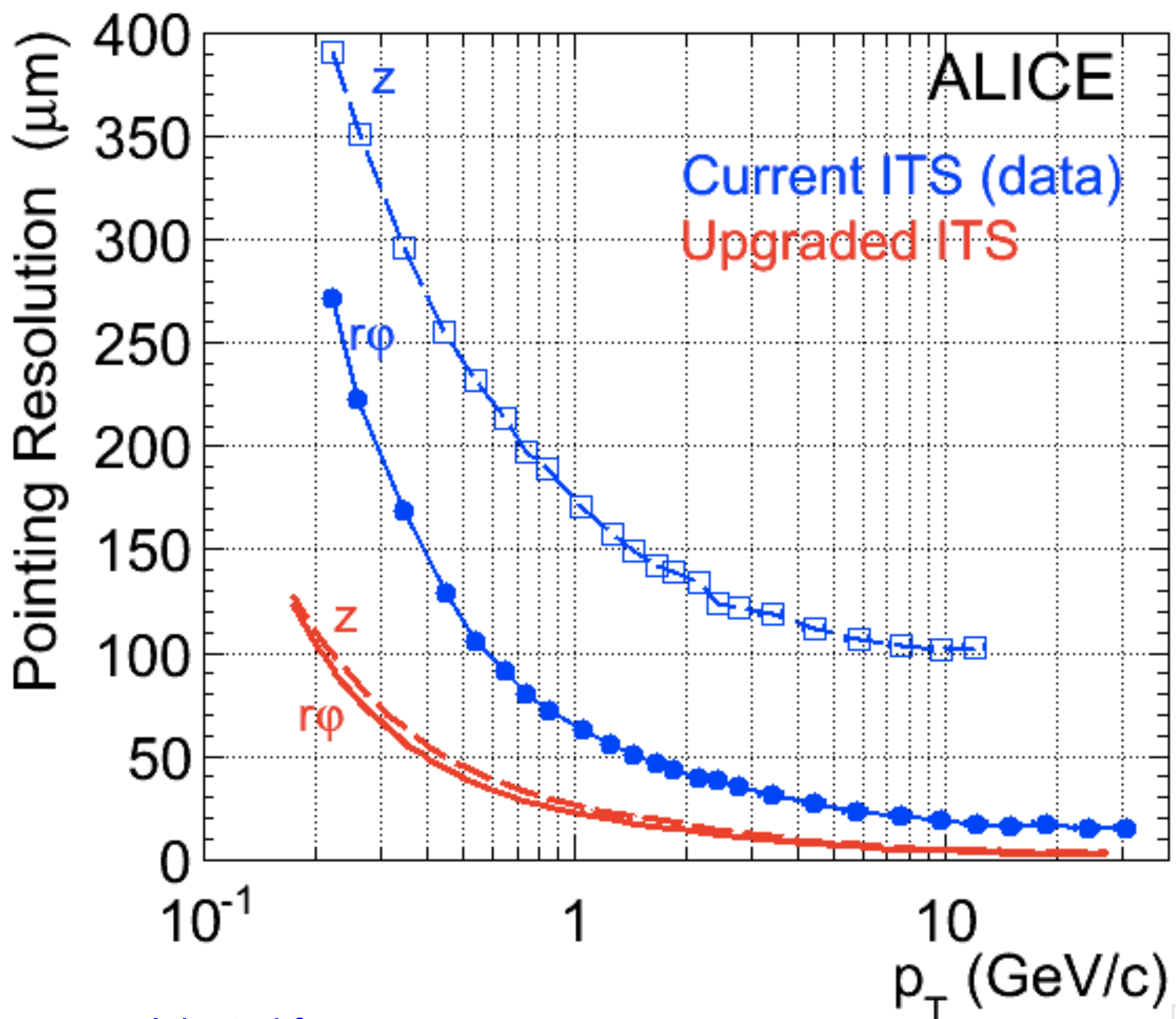
	Pres. ITS	New ITS	MFT
Acceptance	$\|\eta\|<0.9$	$\|\eta\|<1.5$	$-3.6<\eta<-2.3$
N Layers	6	7	5
Inner radius	3.9 cm	2.3 cm	/
Pipe radius	2.94 cm	1.86 cm	/
Layer thickness	~1.1% X_0	0.3-0.8% X_0	0.6% X_0
Spatial resolution	12x100 μm^2 35x20 μm^2 20x830 μm^2	~5x5 μm^2	~5x5 μm^2
Max. Pb-Pb readout rate	1 kHz	100 kHz	100 kHz



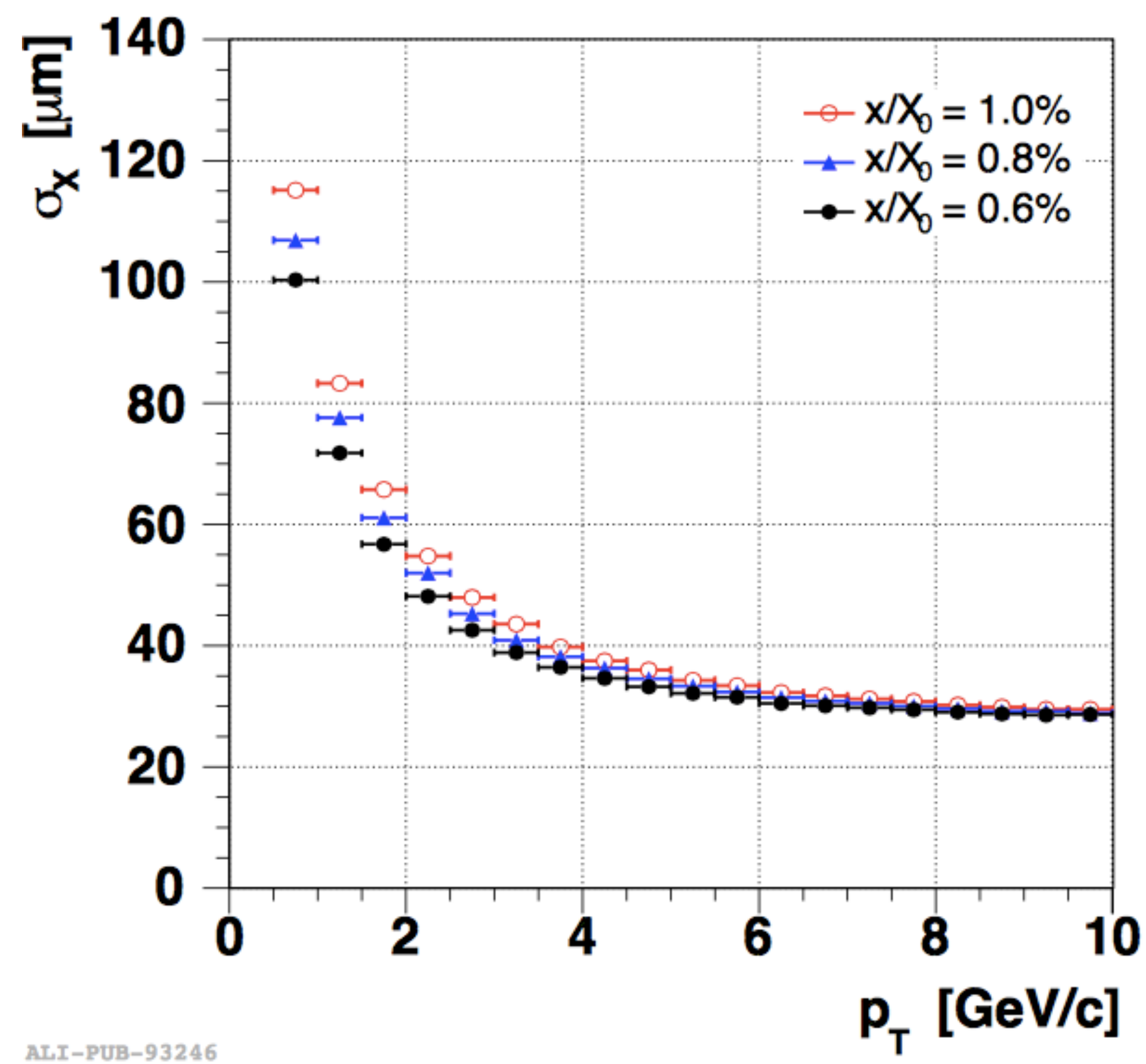
ITS: CERN-LHCC-2013-024
MFT: CERN-LHCC-2015-001

Tracking precision

- ITS pointing resolution
  - x3 better in transverse plane
  - x6 better along the beam
- MFT pointing resolution better than 100μm for $p_T > 1$ GeV/c



Adapted from CERN-LHCC-2013-024

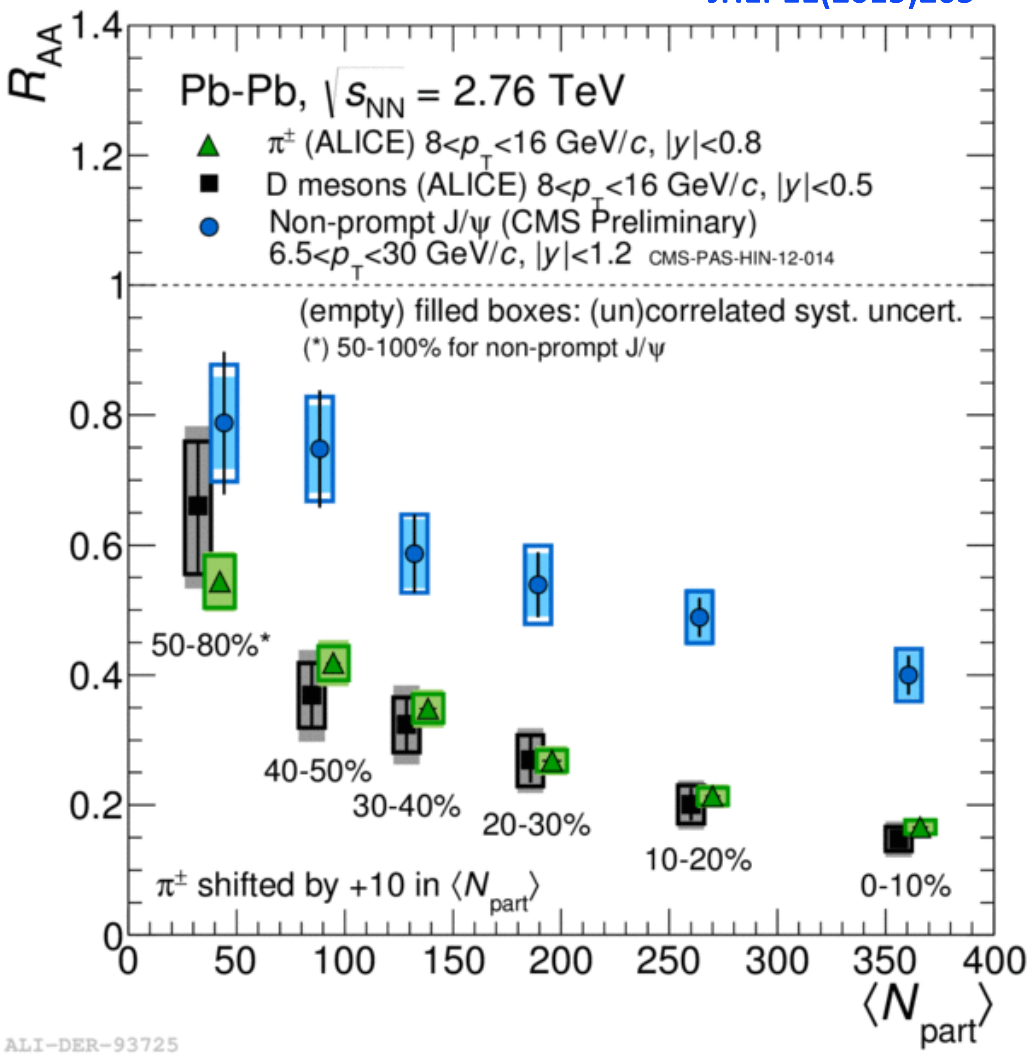


CERN-LHCC-2015-001

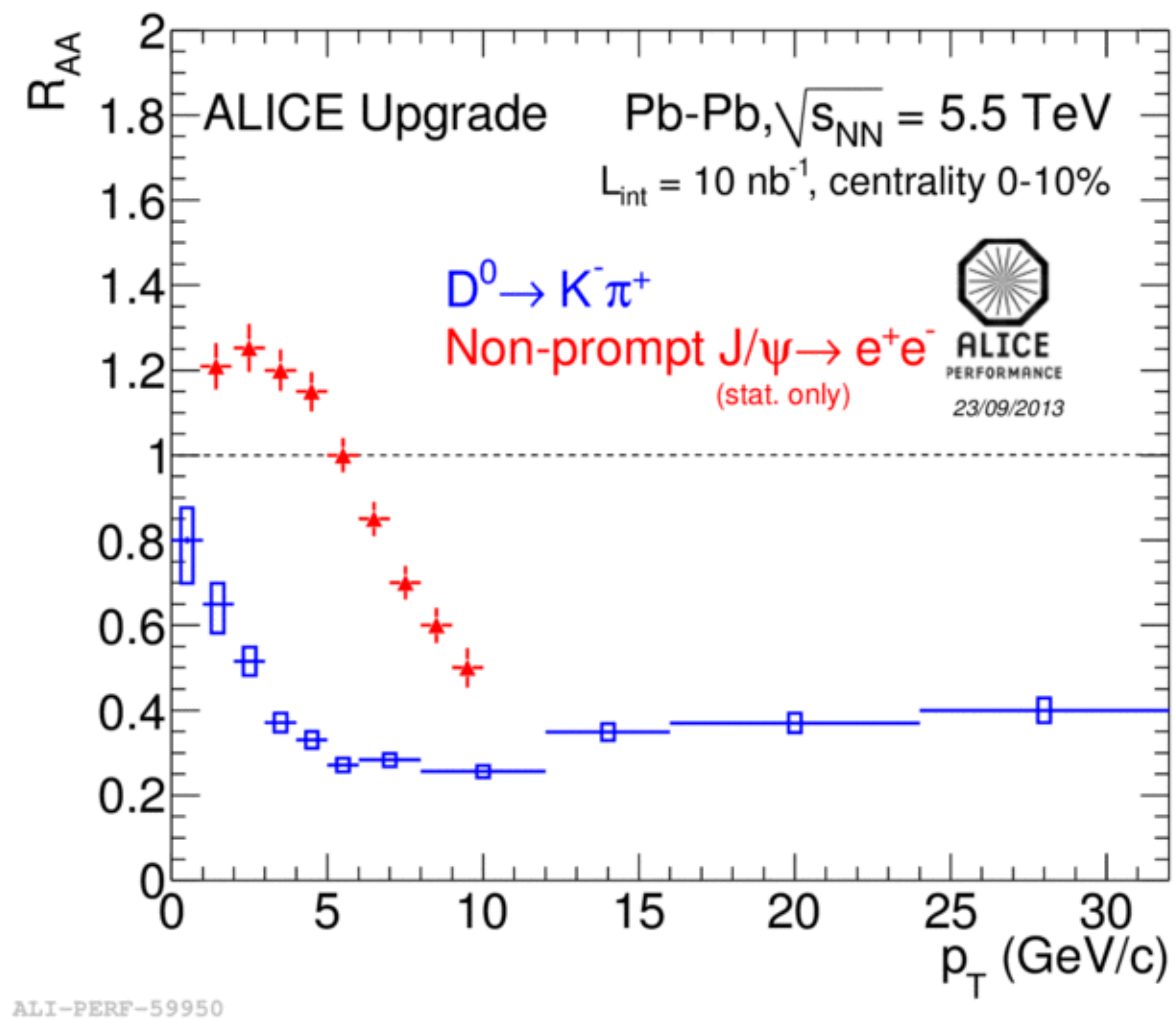
Tracking precision

What we have now at p_T~ 10 GeV/c

JHEP11(2015)205

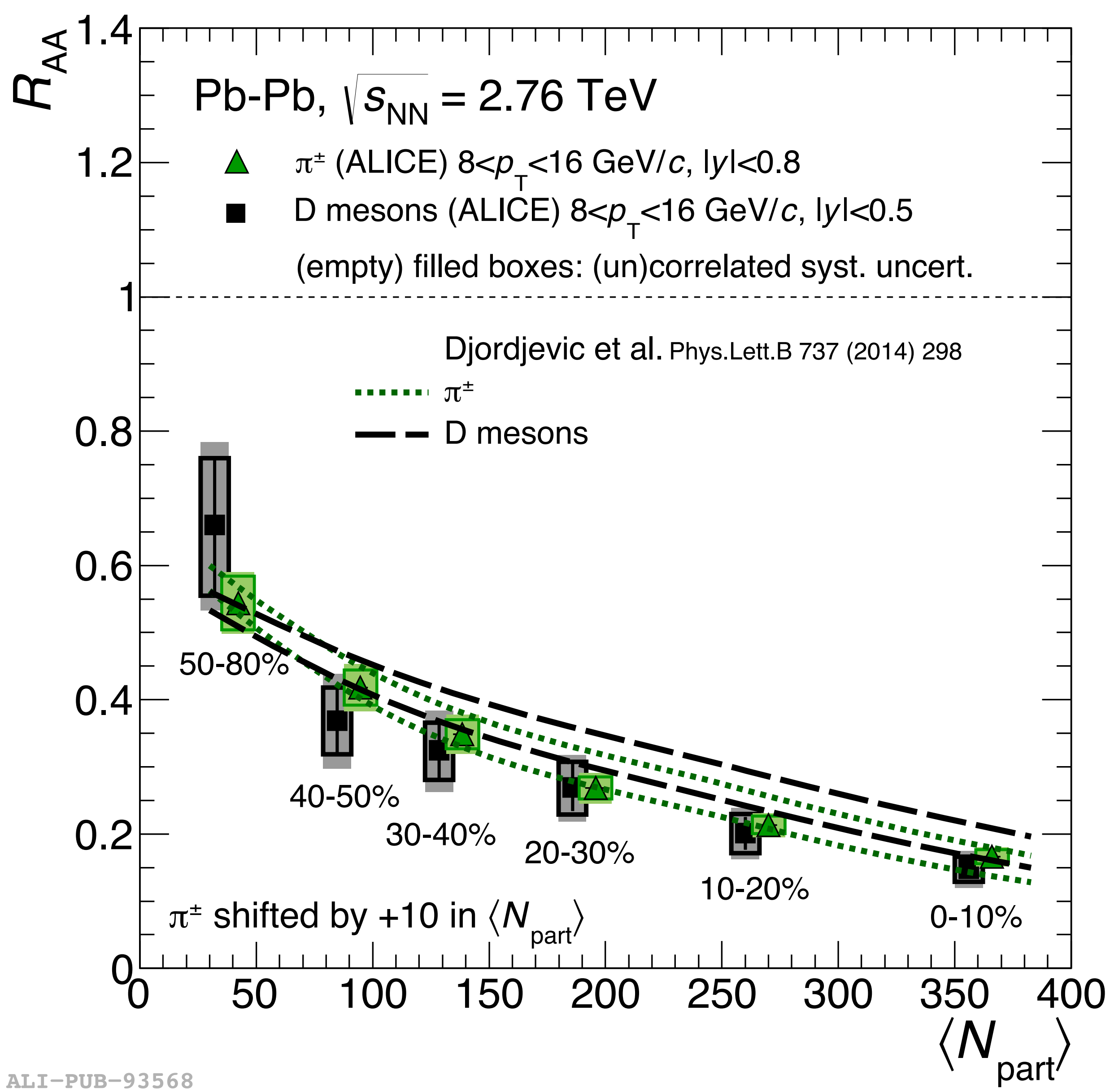


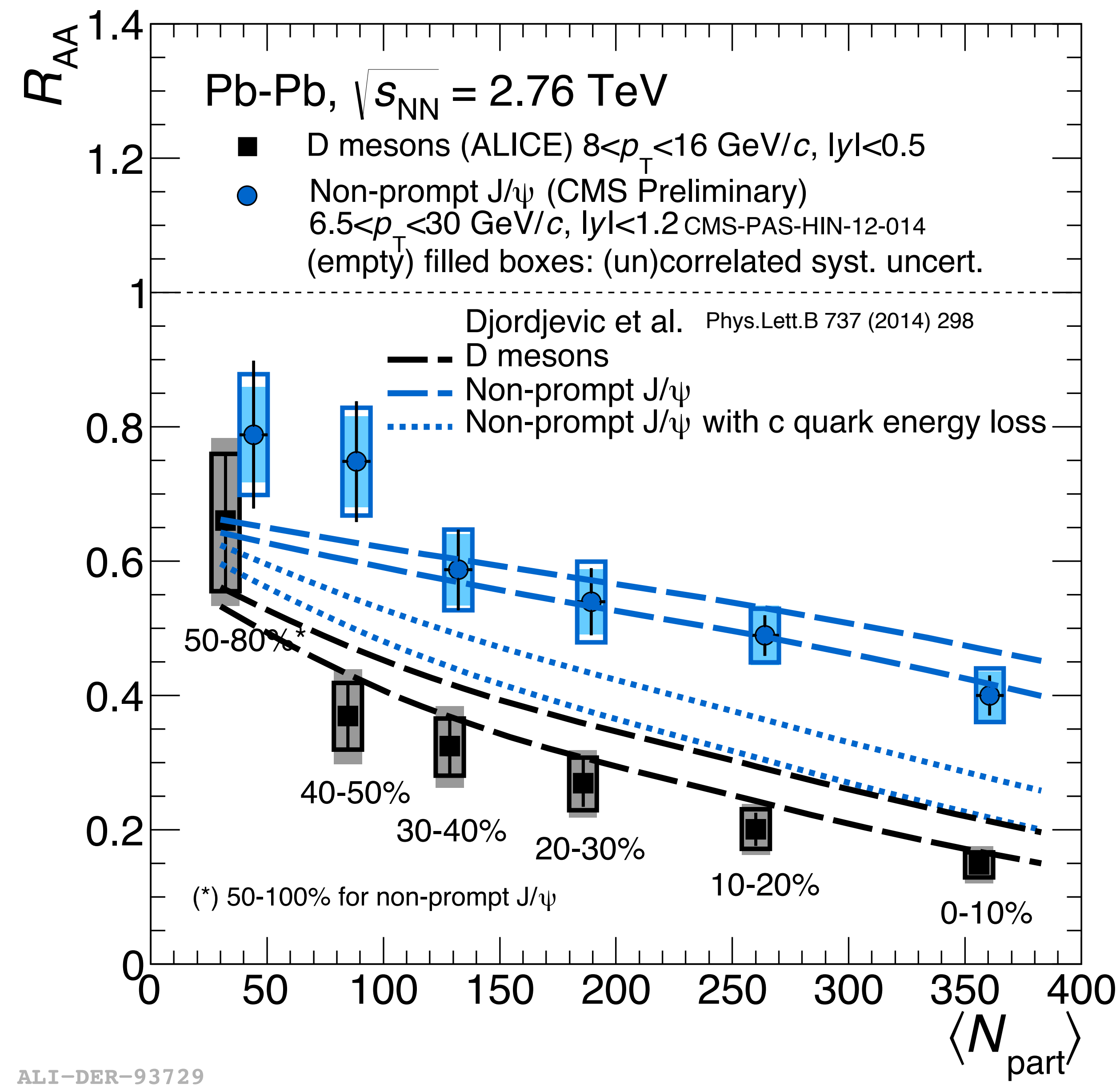
Upgraded detector performance: D and non-prompt J/ψ R_{AA} vs p_T down to **p_T=0**



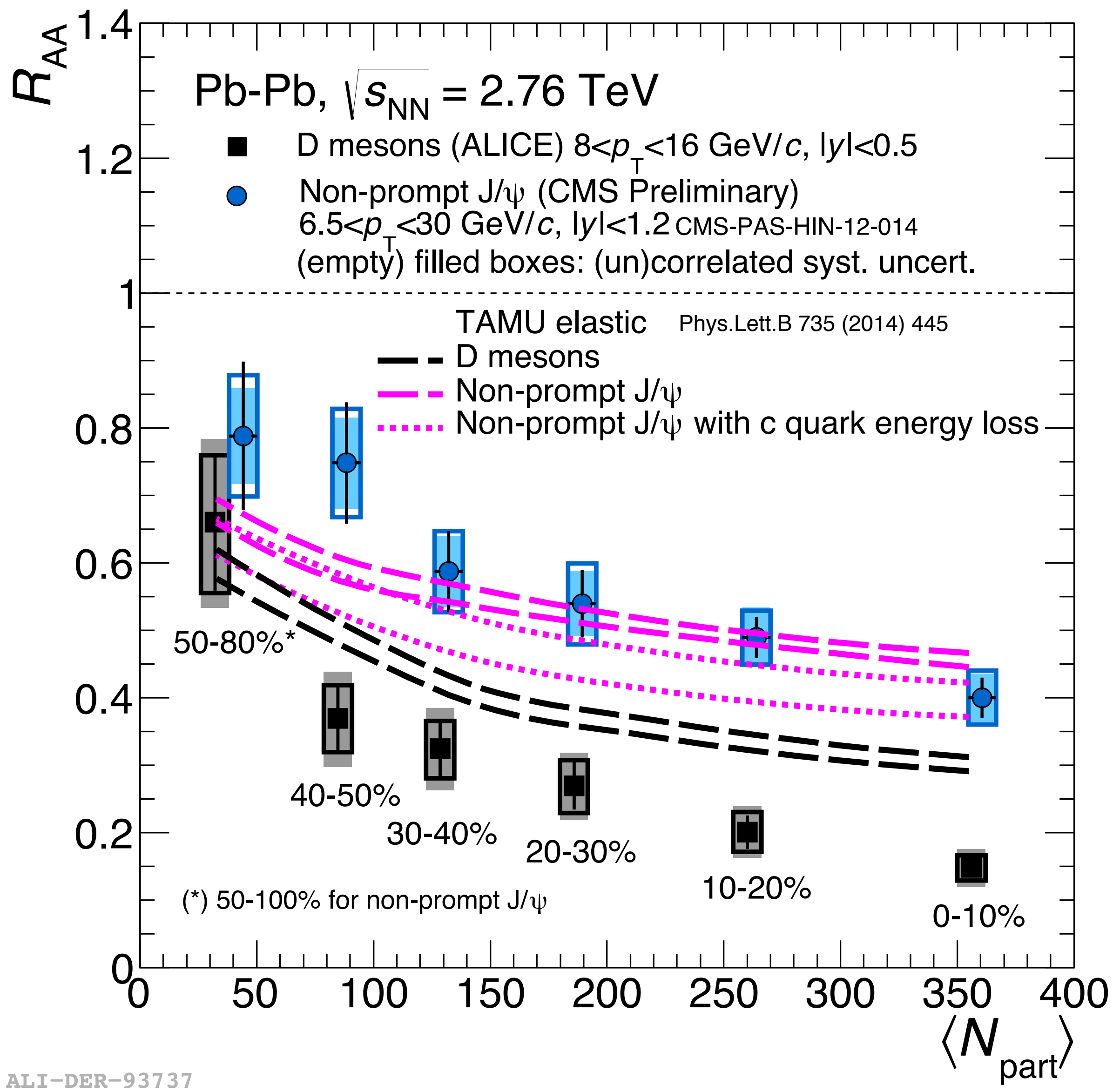
Back up

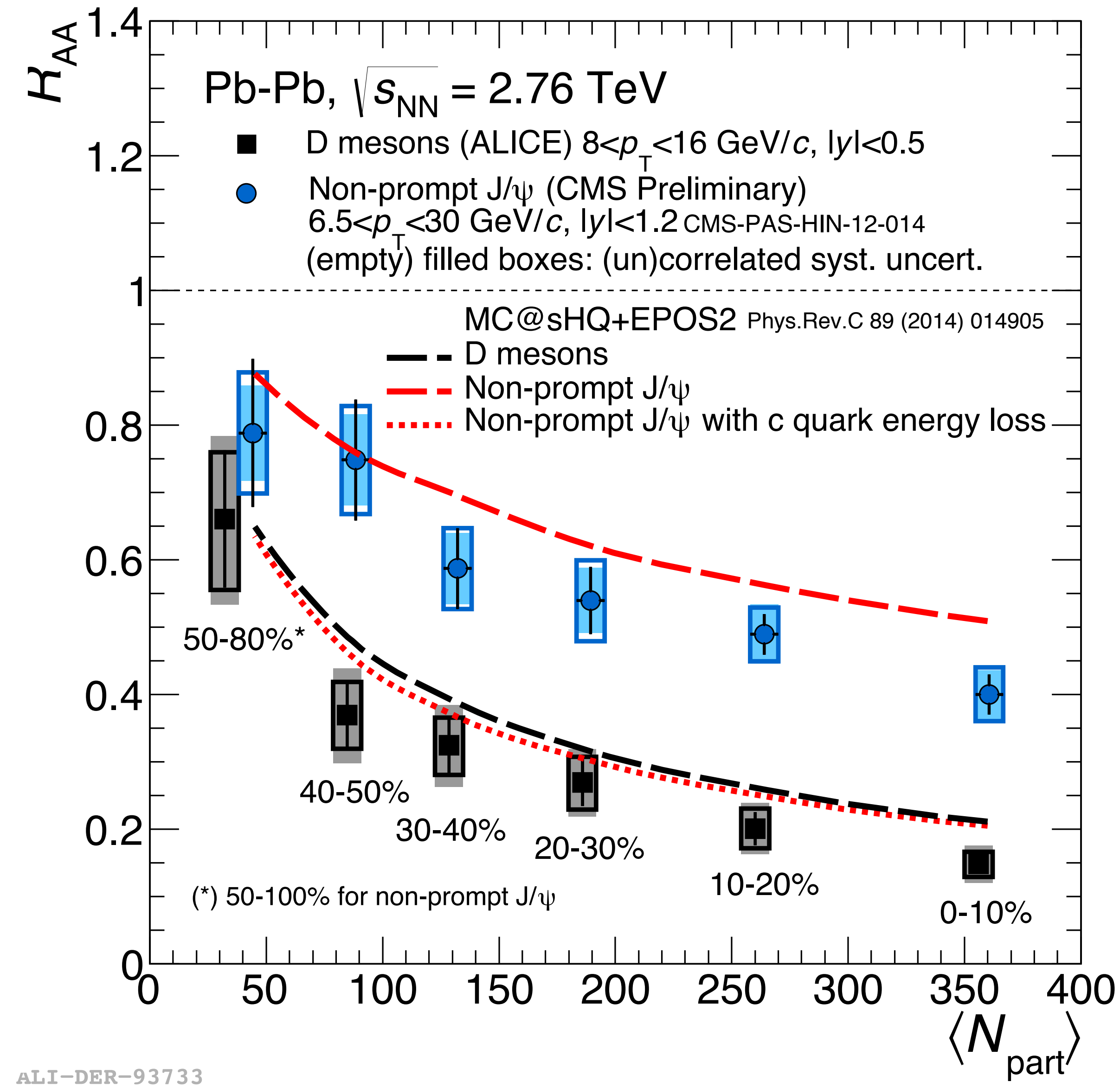
R_{AA} vs N_{part} (other models)





R_{AA} vs N_{part} (other models)



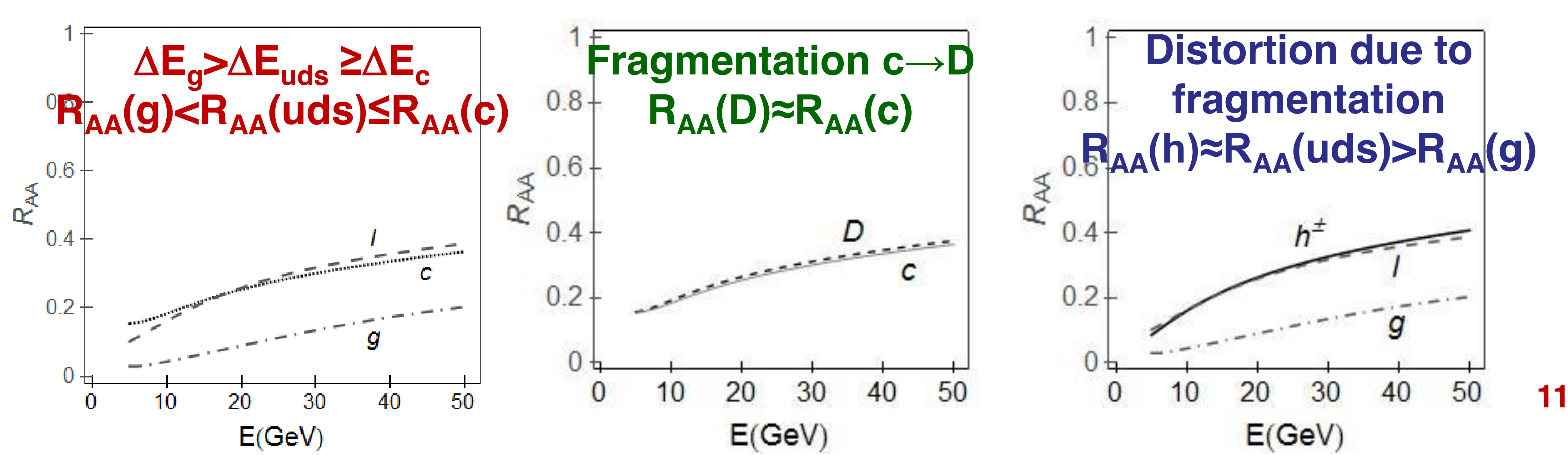


Summary of the models

	HQ production	Medium Modeling	Heavy quarks interactions	Hadronization
WHDG (AIP Conf Proc. 1441 (2012) 889	FONLL, no shadowing	Glauber model collision geometry, no hydro evolution	radiative + collisional energy loss	fragmentation
POWLANG (J. Phys. G 38 (2011) 124144)	POWEG (NLO) + EPS09 shadowing	2+1d expanding medium with viscos hydro evolution	HQ transport (Langevin) + collisional energy loss	fragmentation
Cao, Quin, Bass (Phys Rev C 88 (2013) 044907)	LO pQCD + EPS09 shadowing	2+1d expanding medium with viscous hydro evolution	HQ transport (Langevin) + quasi elastic scattering + radiative energy loss	recombination + fragmentation
MC@sHQ+EPOS2 (Phys Rev C 89 (2014) 014905)	FONLL, no shadowing	3+1d fluid dynamical expansion (EPOS)	HQ transport (Boltzmann) + radiative + collisional energy loss.	recombination + fragmentation
BAMPS (Phys Lett B 717 (2012) 430)	MC@NLO, no shadowing	3+1d fully dynamic parton transport model	HQ transport (Boltzmann) + collisional energy loss	fragmentation
TAMU elastic (arXiv:1401.3817)	FONLL + EPS09 shadowing	transport + 3+1d ideal hydro evolution	HQ transport (Langevin) + collisional energy loss + diffusion in hadronic phase	recombination + fragmentation
UrQMD (arXiv:1211.6912)	PYTHIA, no shadowing	3+1d ideal hydro evolution	HQ transport (Langevin) + collisional energy loss	recombination + fragmentation

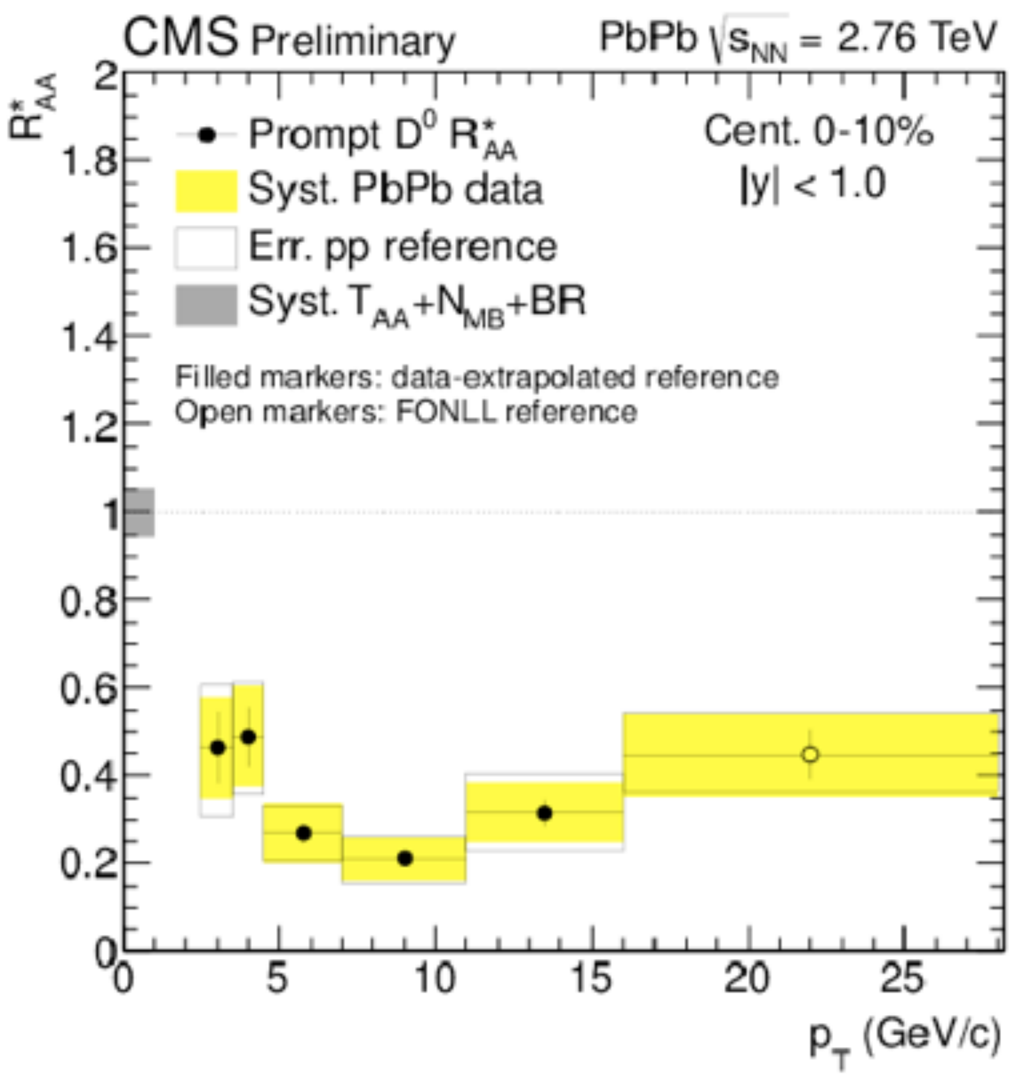
Djordjevic calcluations

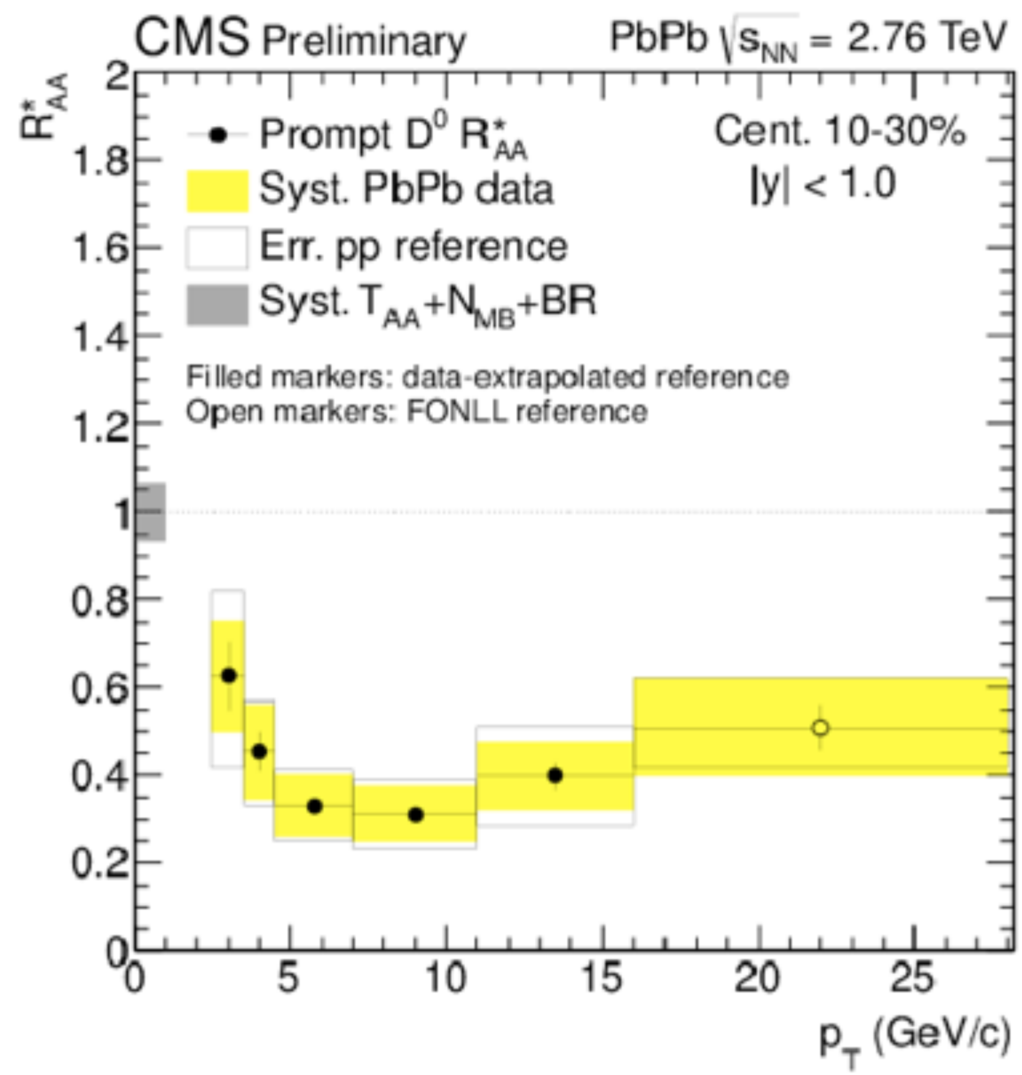
Djordjevic, Djordjevic, PRL 112 (2014) 042302



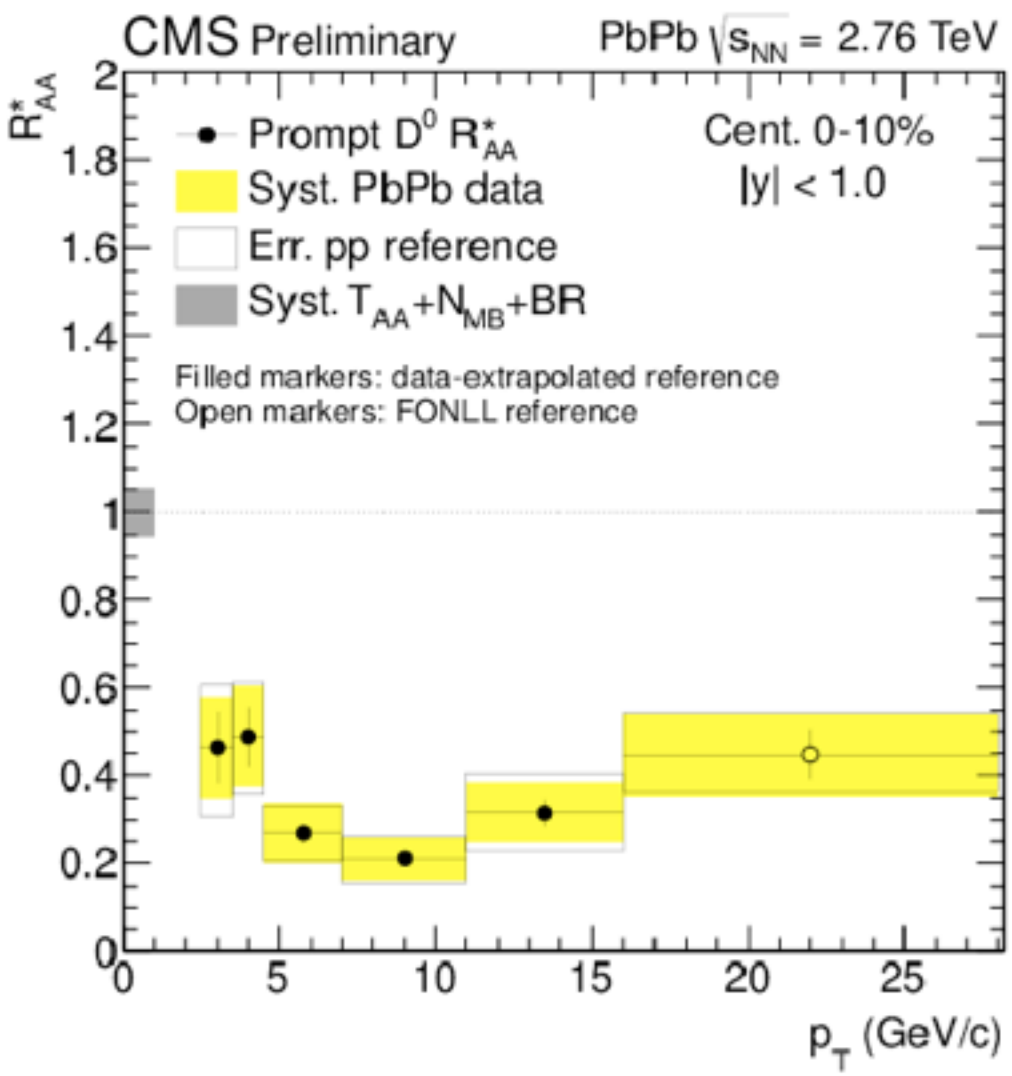
- ✳ Gluons loose more energy due to a larger Casimir factor
- ✳ Energy loss is not sensitive to charm fragmentation into hadrons
- ✳ Softer fragmentation of gluons than light quark and their larger energy loss makes their contribution to the Raa “less strong” than the one of light quarks

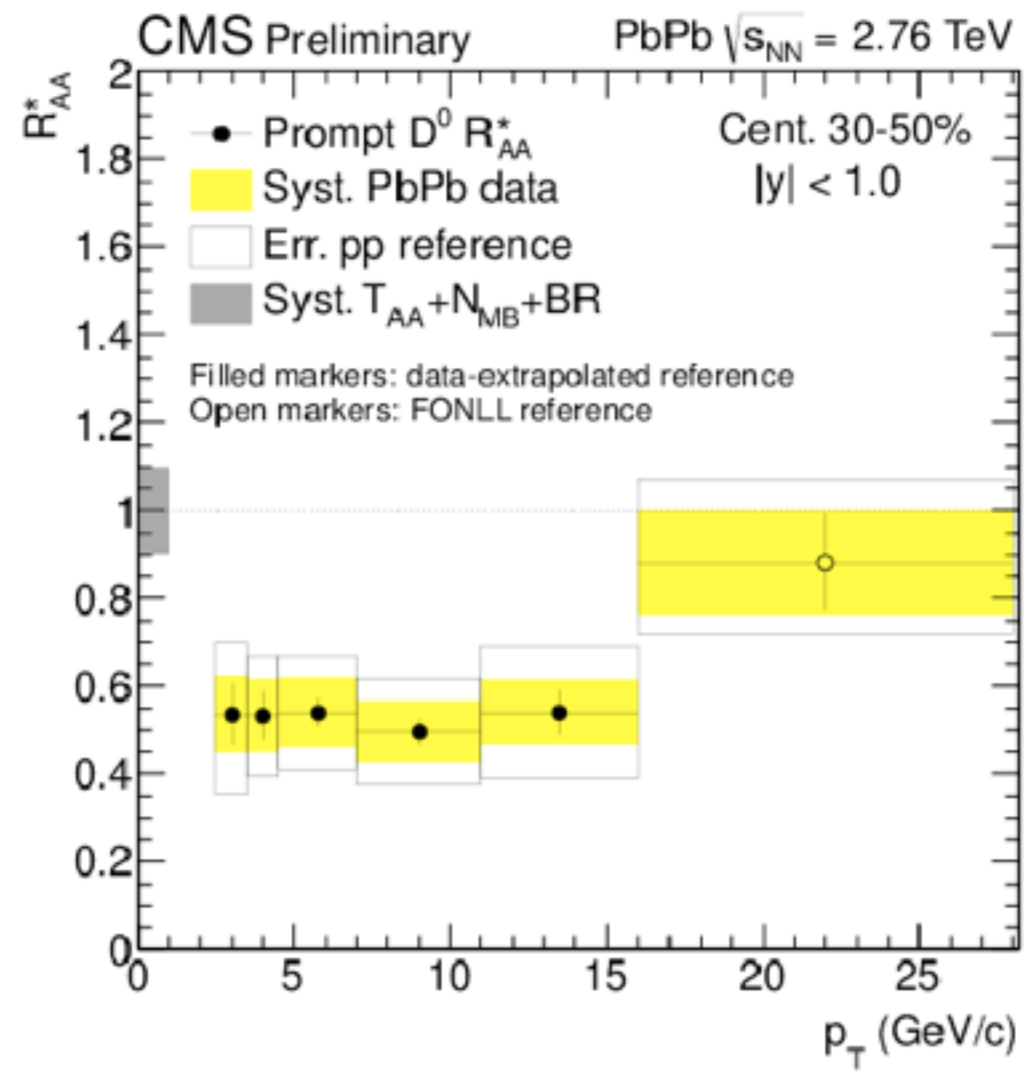
CMS D^0 results



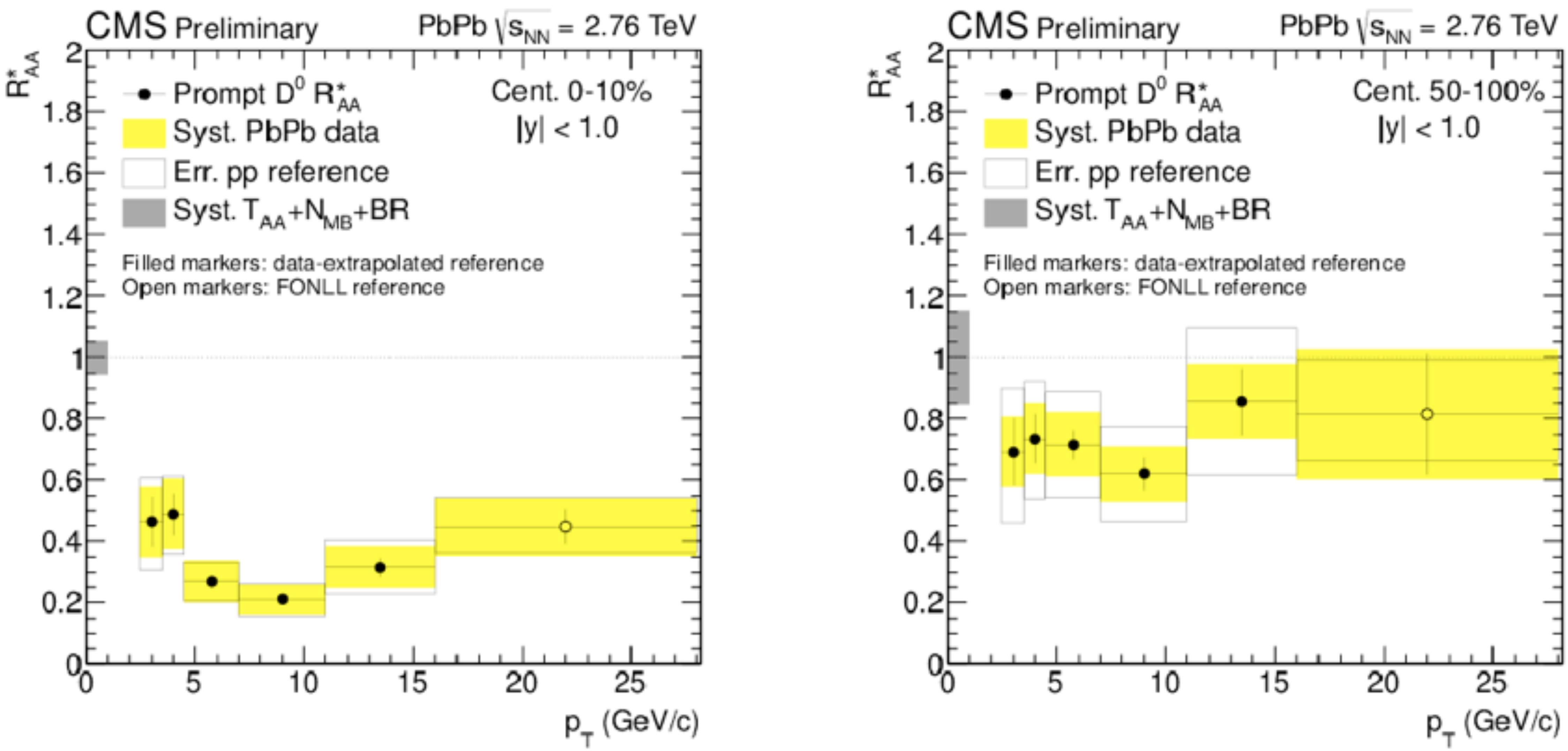


CMS D^0 results

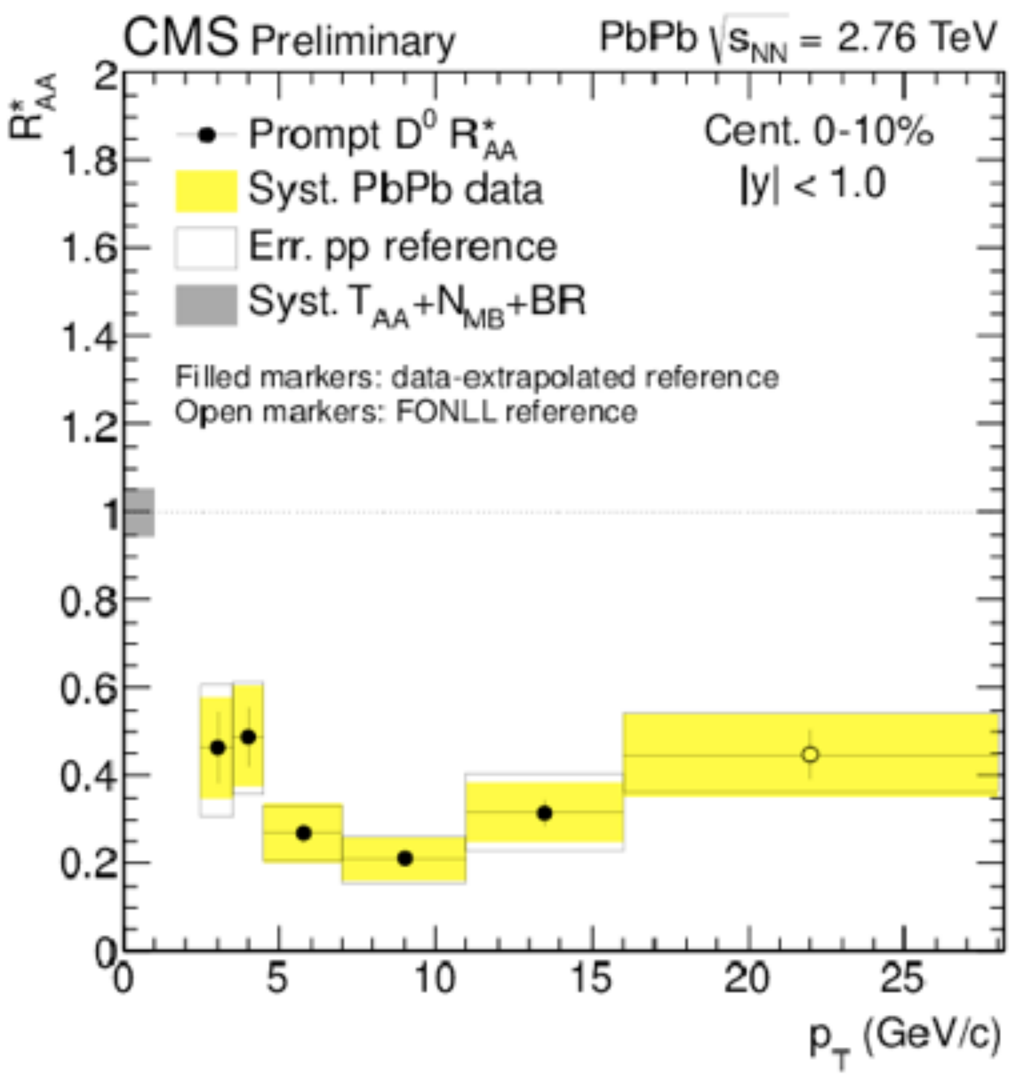


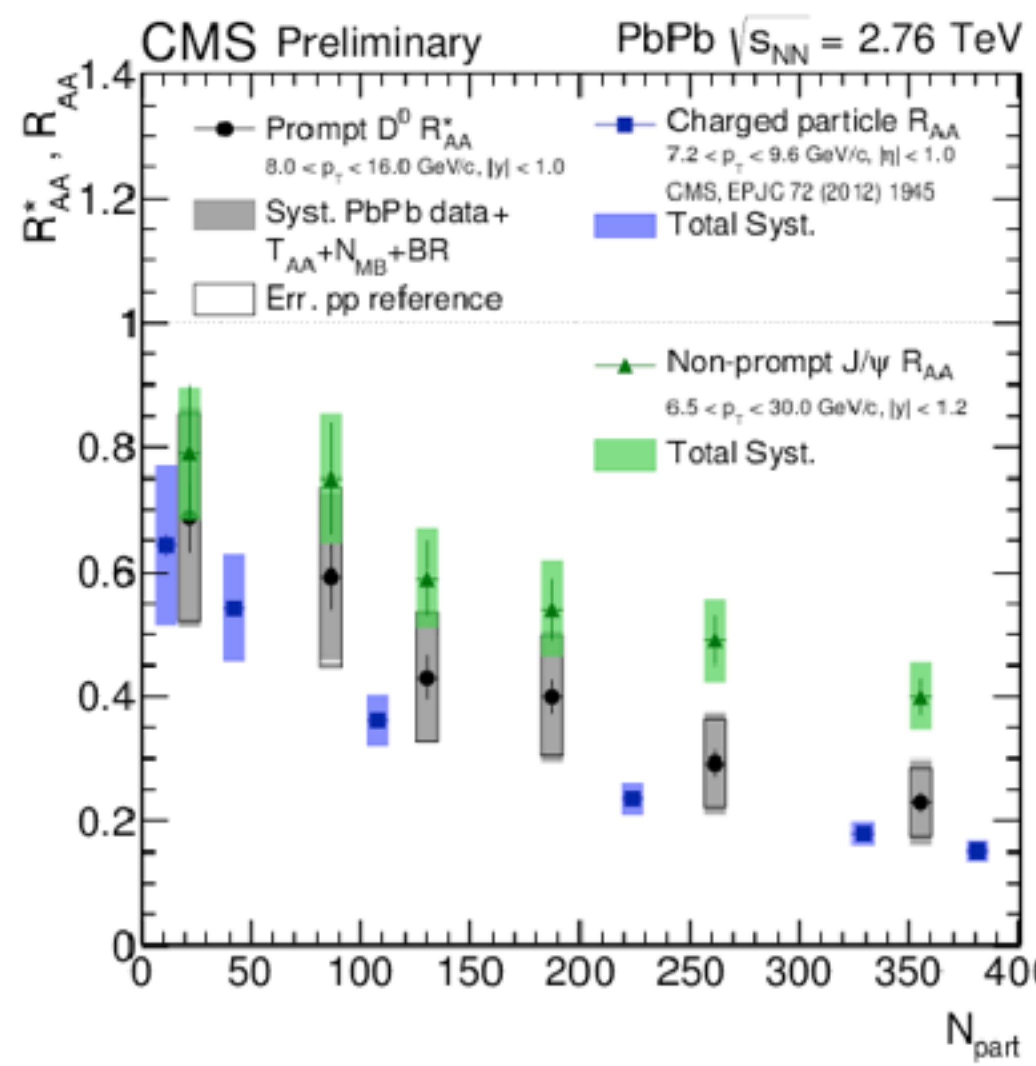


CMS D^0 results



CMS D^0 results

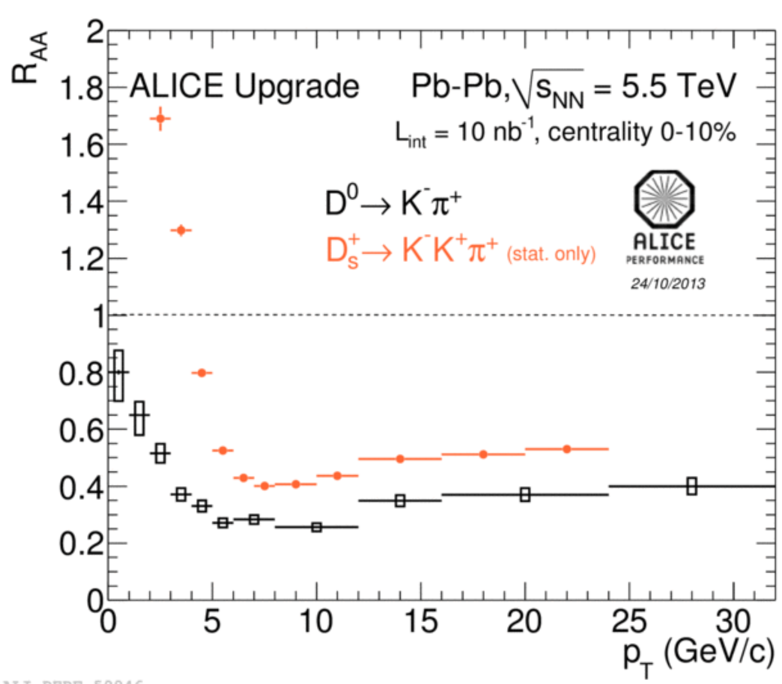




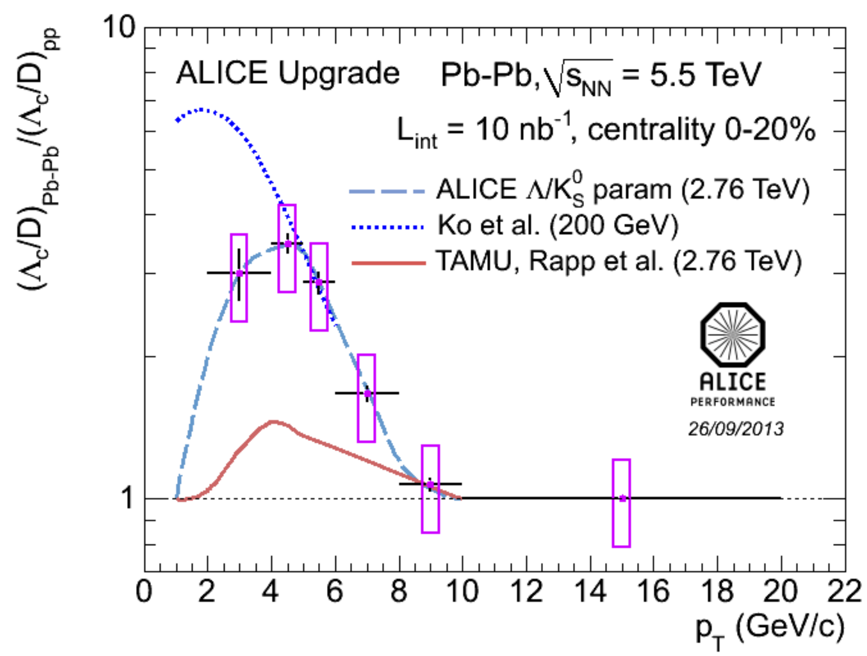
ITS upgrade: Charm “hadrochemistry”

- $\Lambda c \rightarrow pK\pi$ and Ds $\rightarrow K K\pi$ ($c\tau$=60 and 150 μm) will be measured with good precision for pT>2 GeV/c.
- $\Lambda b \rightarrow \Lambda c\pi$ ($c\tau$=450 μm) accessible for pT>7 GeV/c.

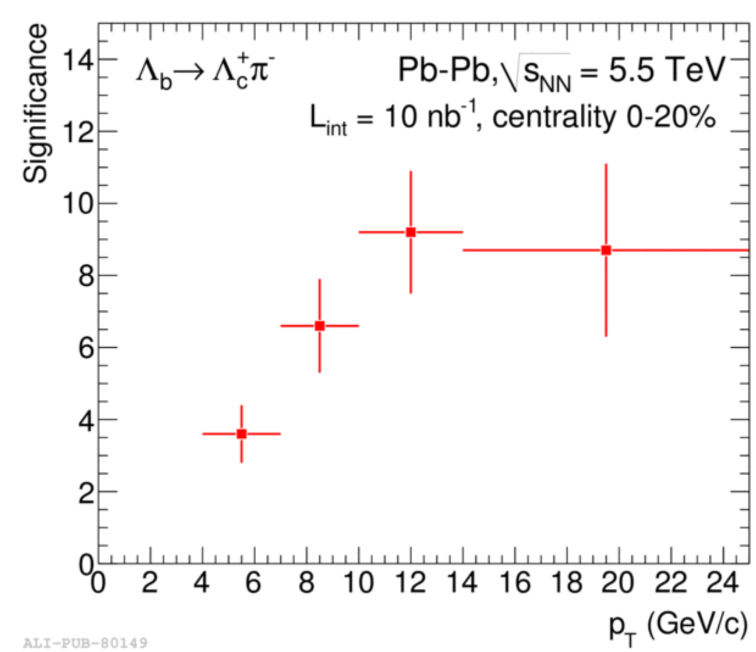
D^0 and D_s R_{AA}



Λ_c/D “enhancement”

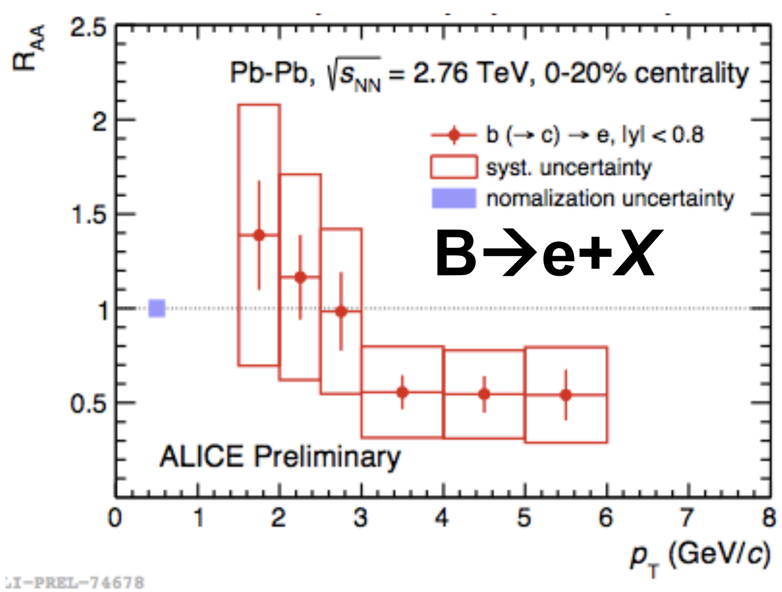


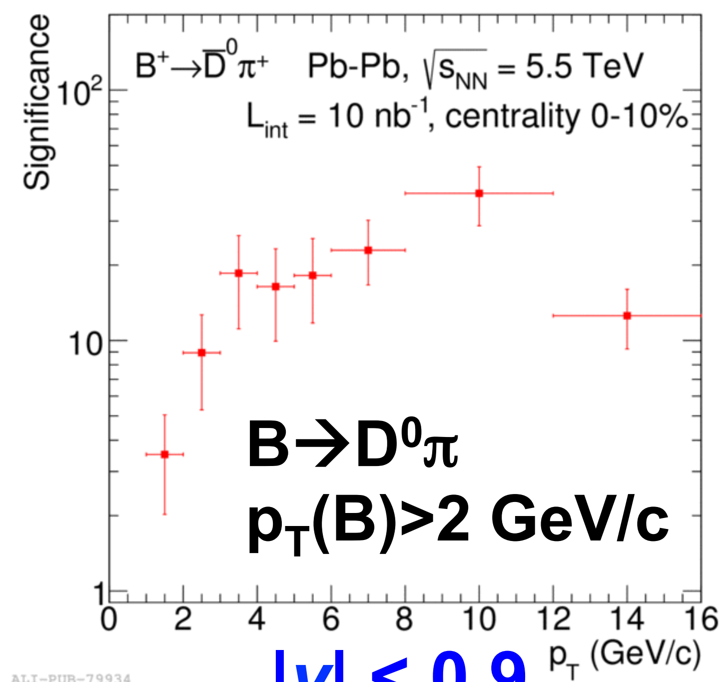
Λ_b significance

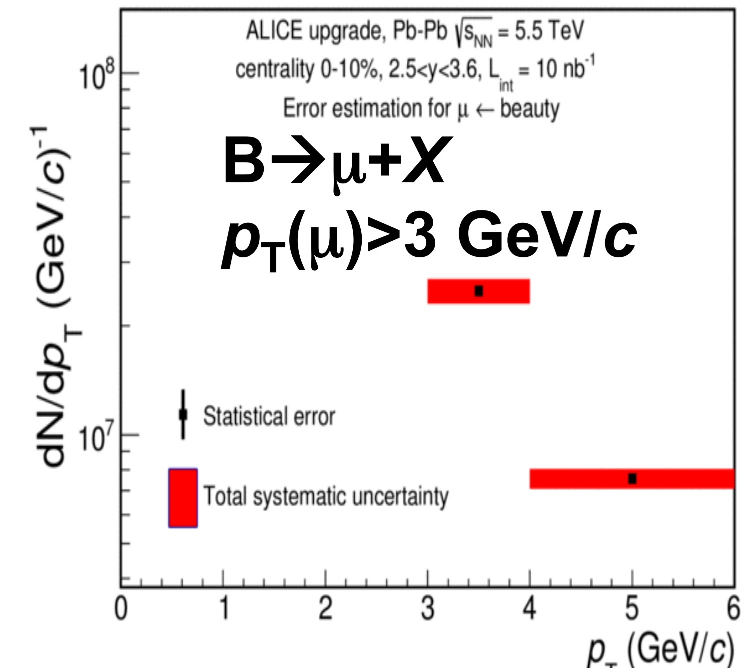


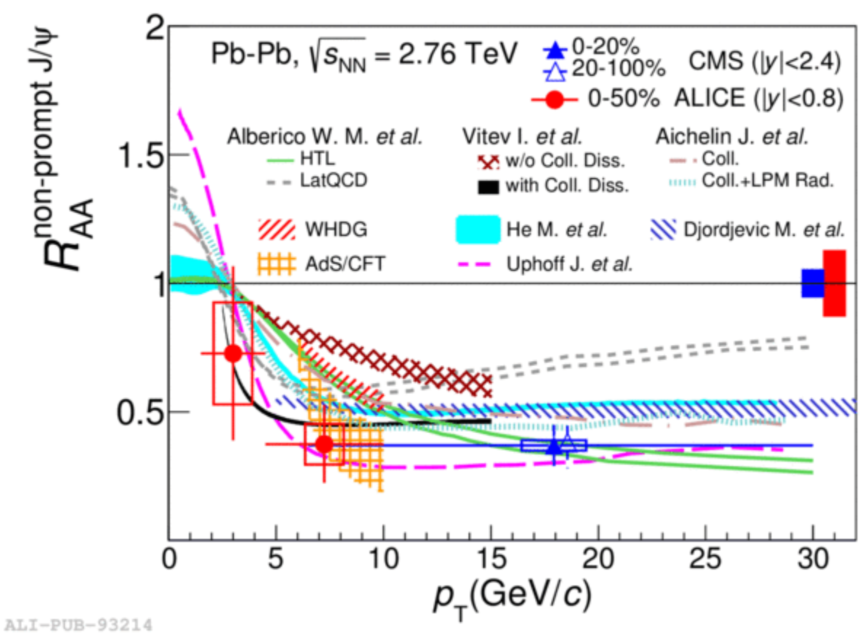
ALICE, CERN-LHCC-2013-024

ITS upgrade: Beauty

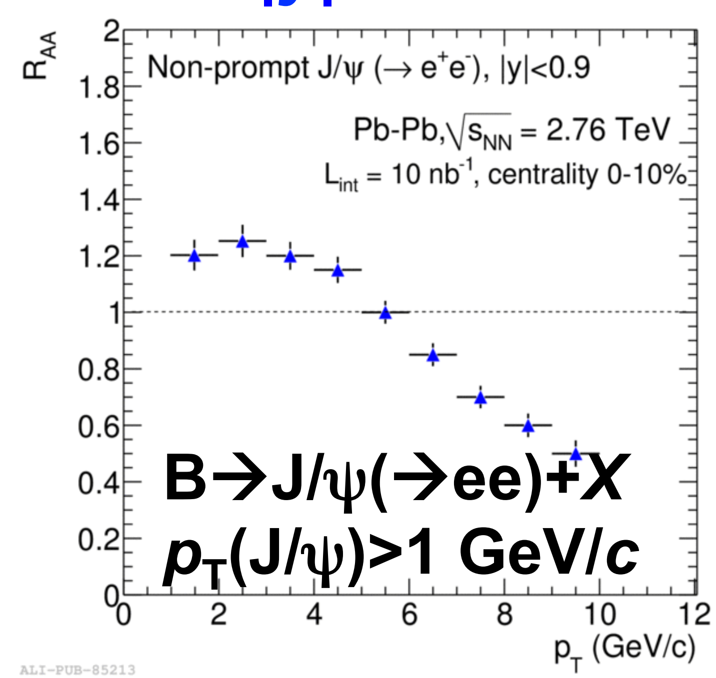


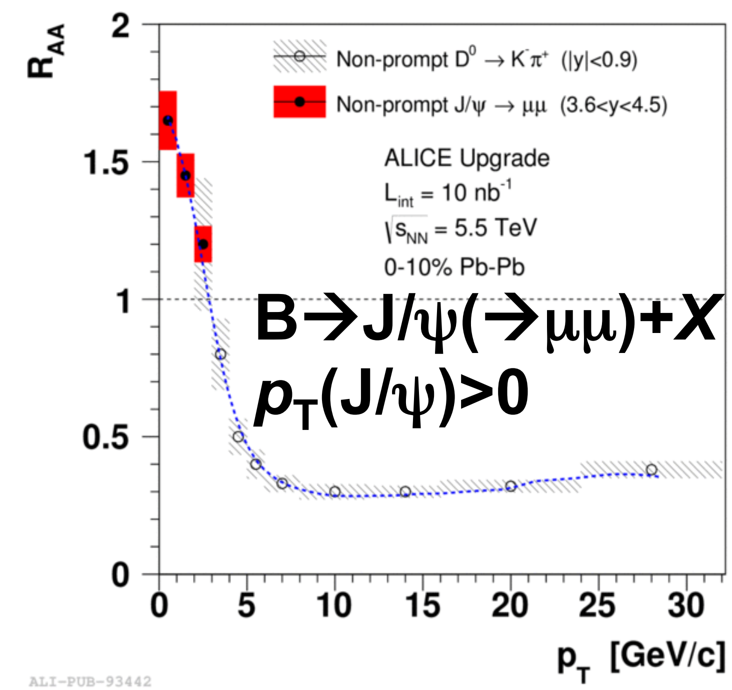






ALICE, arXiv:1504.07151



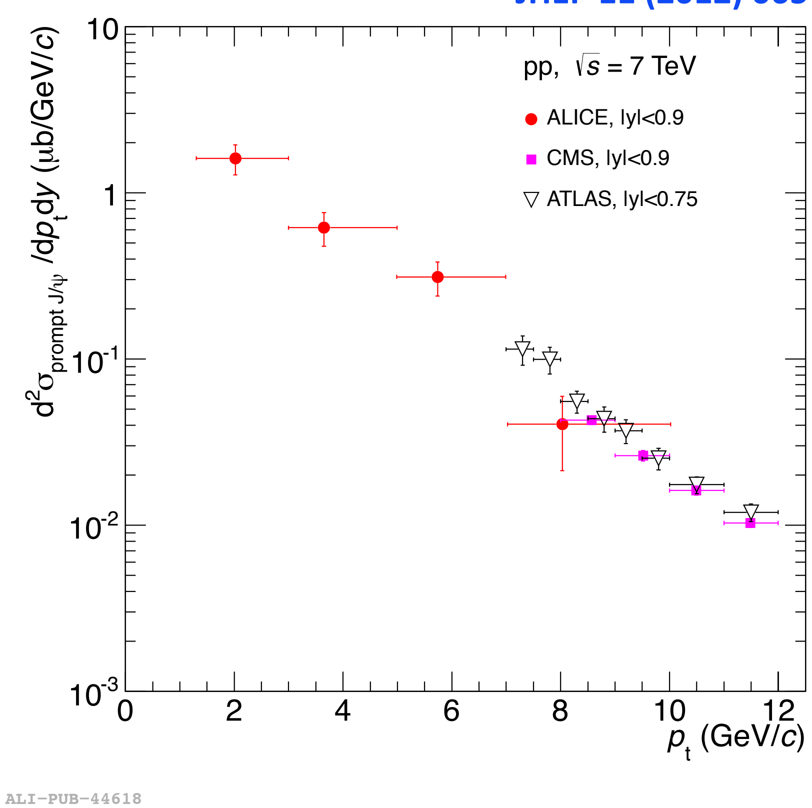


ALICE, CERN-LHCC-2013-024, CERN-LHCC-2015-001

Beauty production in pp collisions @ √s = 7 TeV

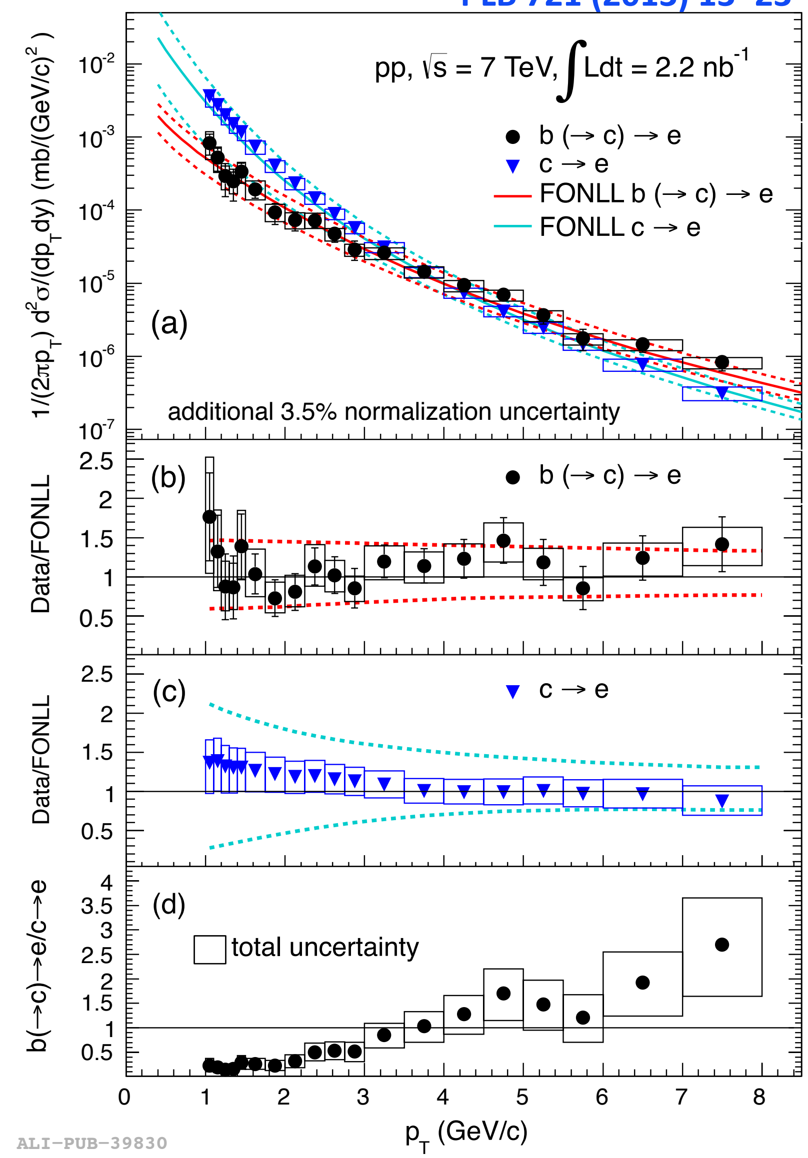
non-prompt J/ψ

JHEP 11 (2012) 065



e from B hadrons decay

PLB 721 (2013) 13–23

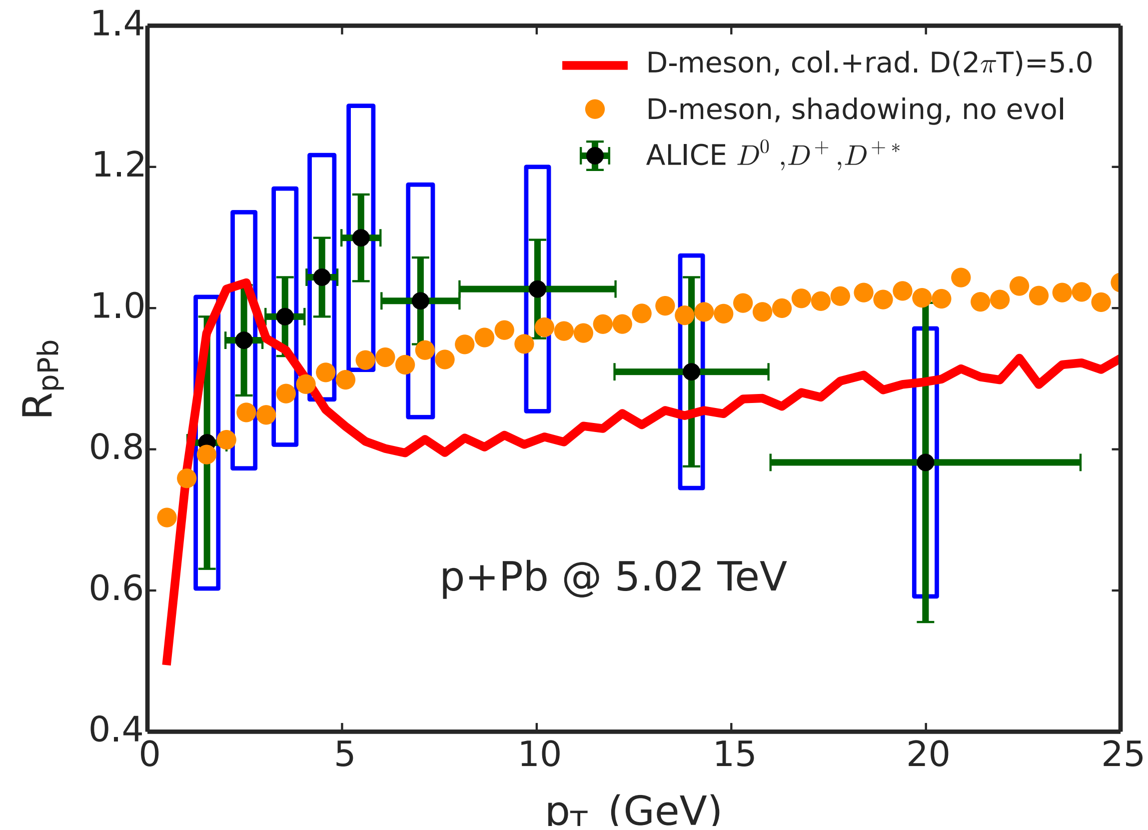


- pQCD based calculations (FONLL) are compatible with data.
- Beauty production described well by the central value theoretical calculations

D meson in p-Pb collisions

- **D meson R_{pPb} compatible with unity within uncertainties.**
- Models that include Cold Nuclear Matter effects describe the data:
  - MNR calculation for heavy-flavour production with EPS09 parametrizations of nuclear PDF **Mangano et al., Nucl. Phys. B 373 (1992) 295. Eskola et al., JHEP 0904 (2009) 065**
  - CGC predictions **Fujii-Watanabe, arXiv:1308.1258**
  - Vitev: k_T broadening+CNM energy loss **R. Sharma et al., PRC 80 (2009) 054902.**
  - Y. Xu et al. (arXiv:1510.07520
    - **Shadowing only**
    - **Shadowing + Energy loss**

Y. Xu, arXiv:1510.07520



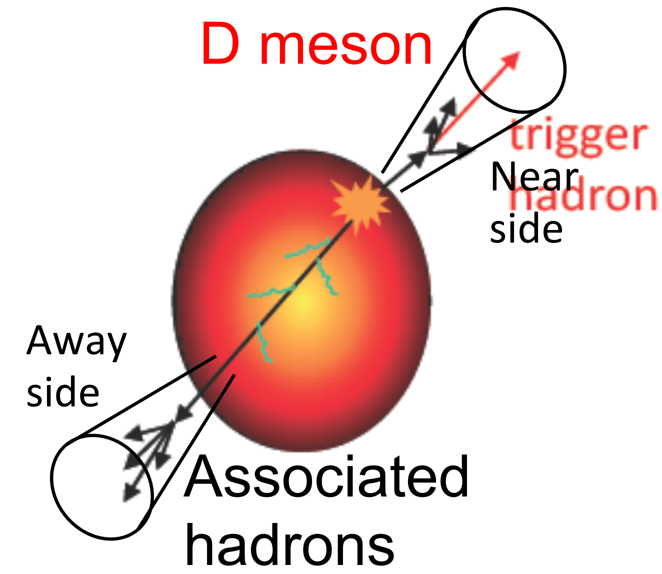
D-hadron correlation in pp @ collisions at √s = 7 TeV

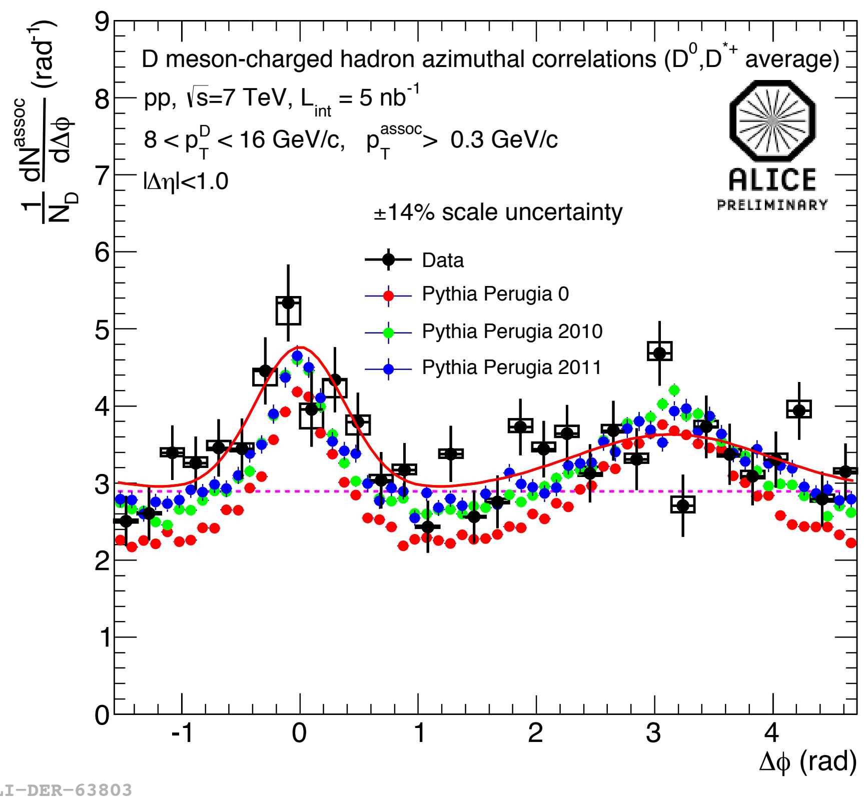
Goals:

- ✳ Study charm production mechanism (pp, p-Pb)
- ✳ Address possible modification to charm fragmentation properties and path-length dependence of energy loss (Pb-Pb)

Method:

- ✳ Measure the associated hadron yields in the near and away side regions





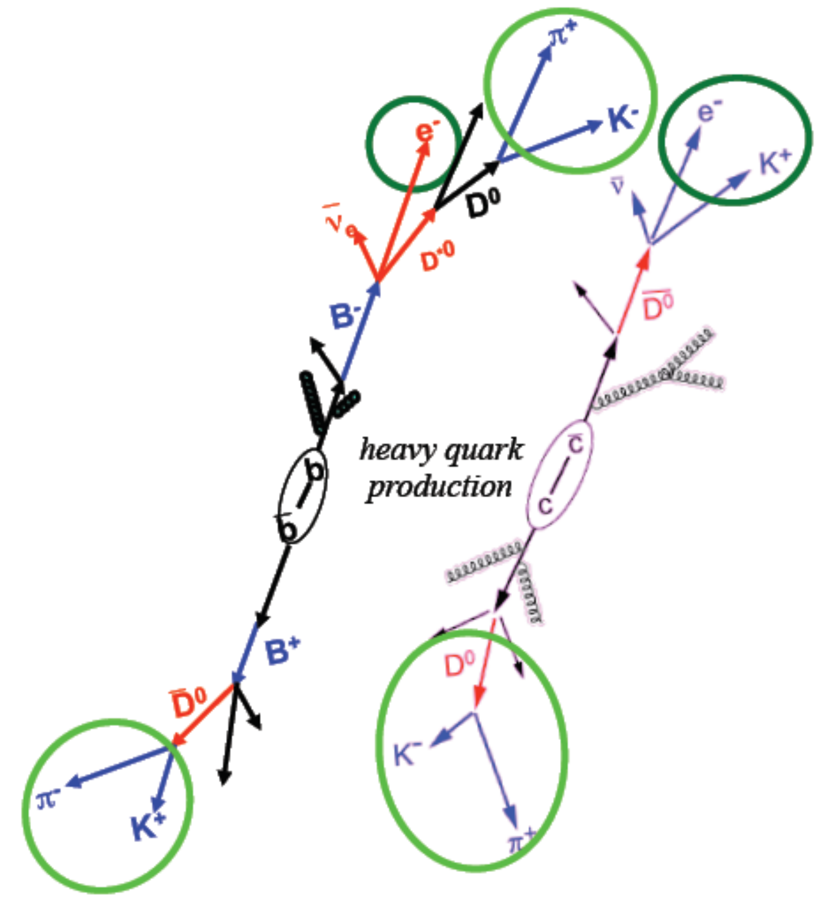
$$\frac{1}{N_{trig}}\frac{d^2N_{assoc}}{d\Delta\varphi\Delta\eta} = \frac{S(\Delta\varphi,\Delta\eta)}{B(\Delta\varphi,\Delta\eta)}$$

- ✳ Correlation measurements are in agreement with Pythia within large statistical and systematic uncertainties.

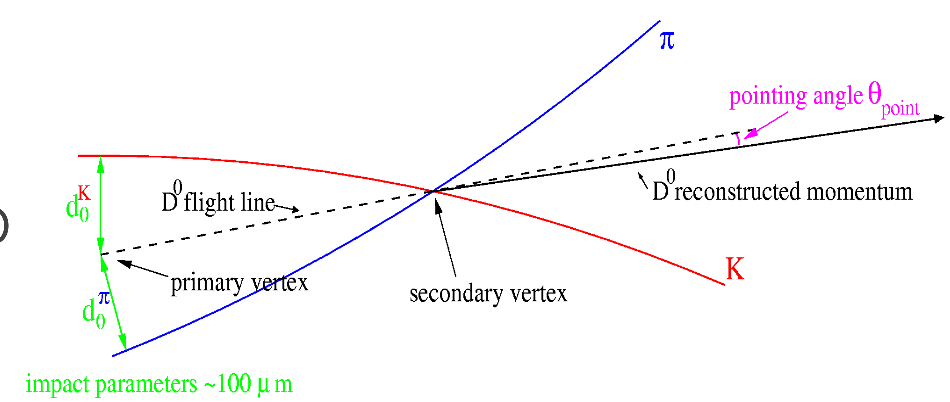
- ✳ Precise measurement expected from LHC Run2

How to measure heavy quarks?

* Leptons (e, μ) from semileptonic decays of hadrons containing heavy quarks.
    * Inclusive measurement (i.e. cannot distinguish between charm and beauty decay)
    * Larger BR for those channels than exclusive reconstruction.
    * Broad correlation between leptons and hadron.

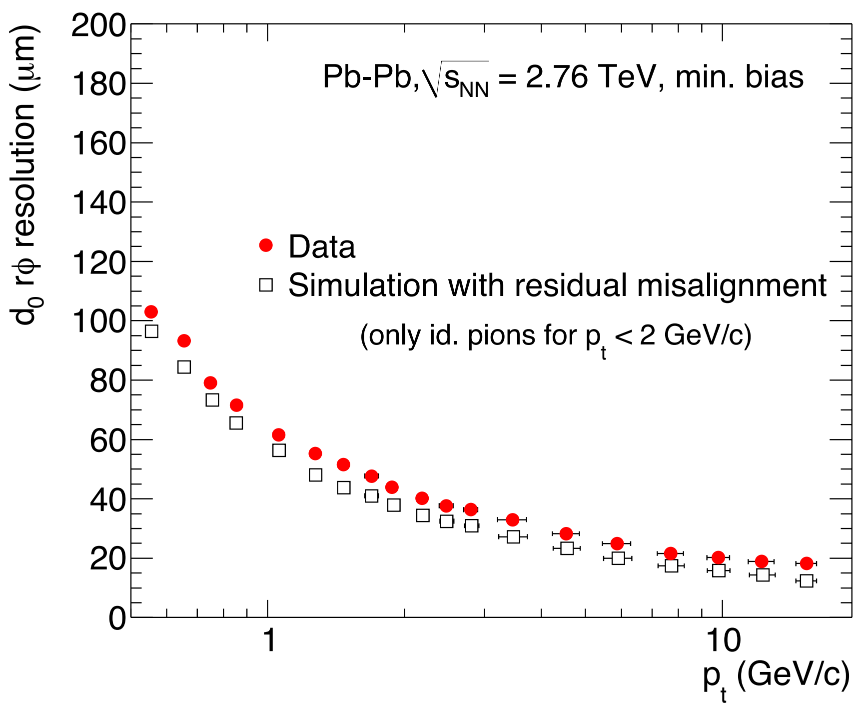


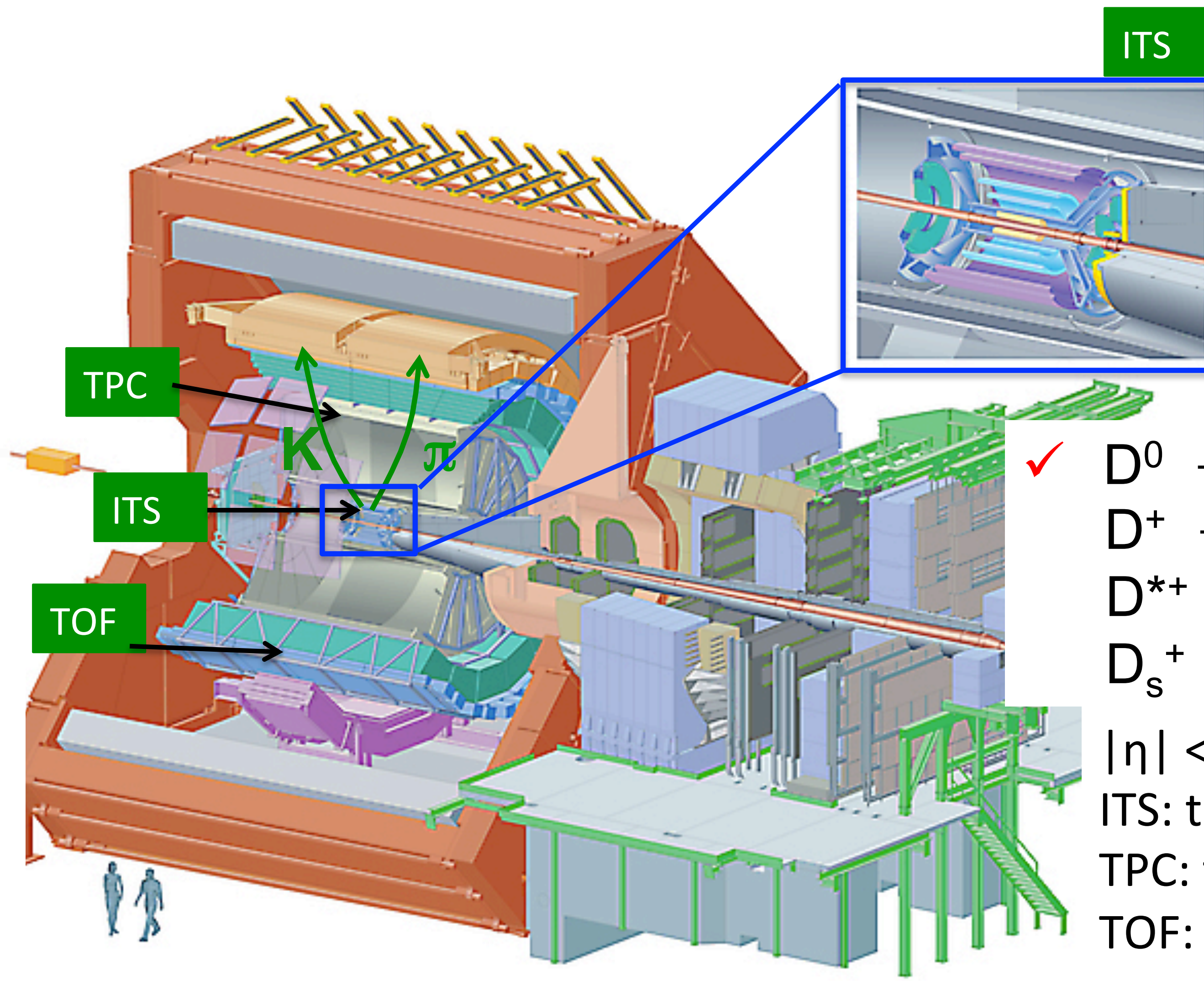
* Fully reconstructed D mesons:
  Exclusive measurement (charm only !)
  Secondary vertex reconstruction important to reduce the background!
    Vertex detector !!



D mesons in ALICE

- Displaced vertex topology used in the reconstruction.
- Inner Tracking System with 6 Si layers: two pixels layers at 3.9 and 7 cm





- $D^0 \rightarrow K^- \pi^+$
- $D^+ \rightarrow K^-\pi^+\pi^+$
- $D^{*+} \rightarrow D^0\pi^+$
- $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$

$|\eta| < 0.9$

ITS: tracking, vertexing

TPC: tracking, PID

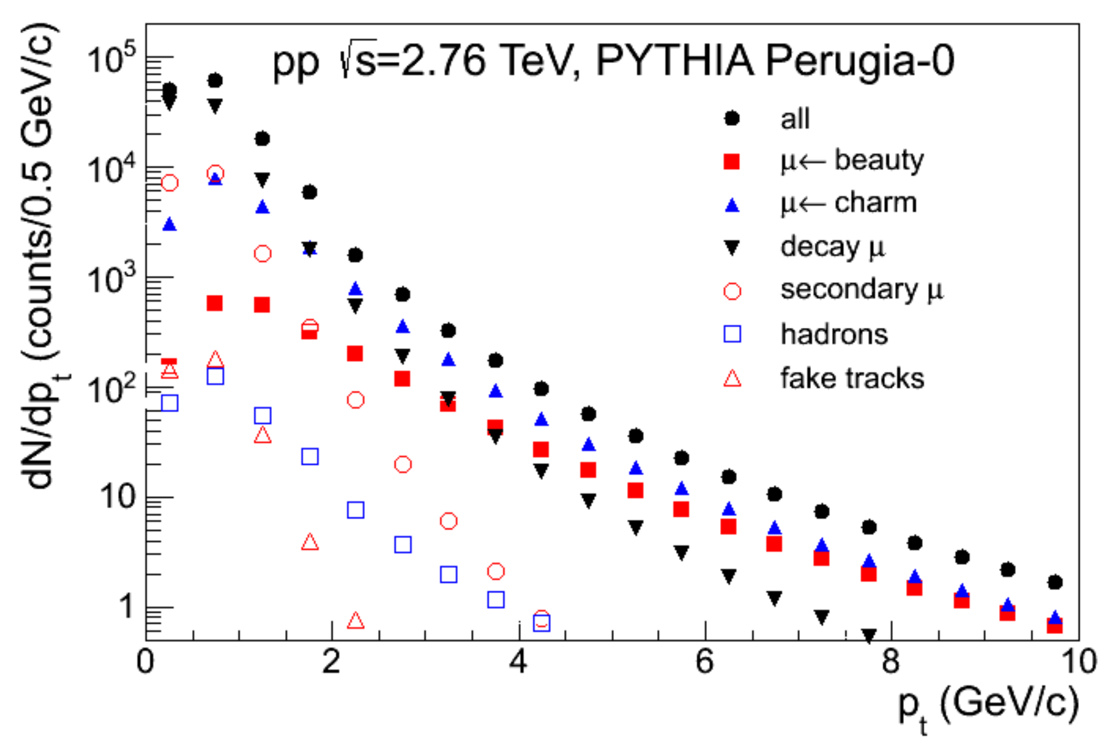
TOF: K-ID

- Impact parameter resolution ~60μm for pT = 1 GeV/c

μ reconstruction in ALICE

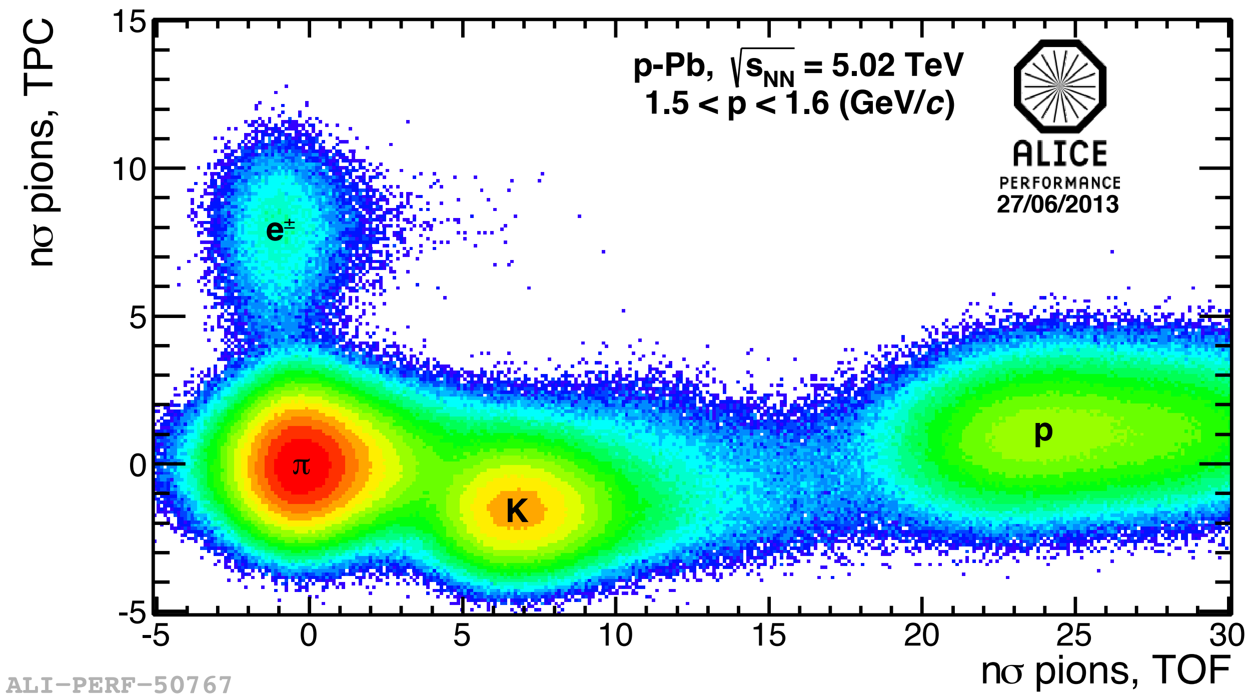
- μ-defined as matched tracks with tracklet in the trigger chambers
  remove punch-through hadrons
- Cut on the p x DCA   reject tracks from beam-gas interaction

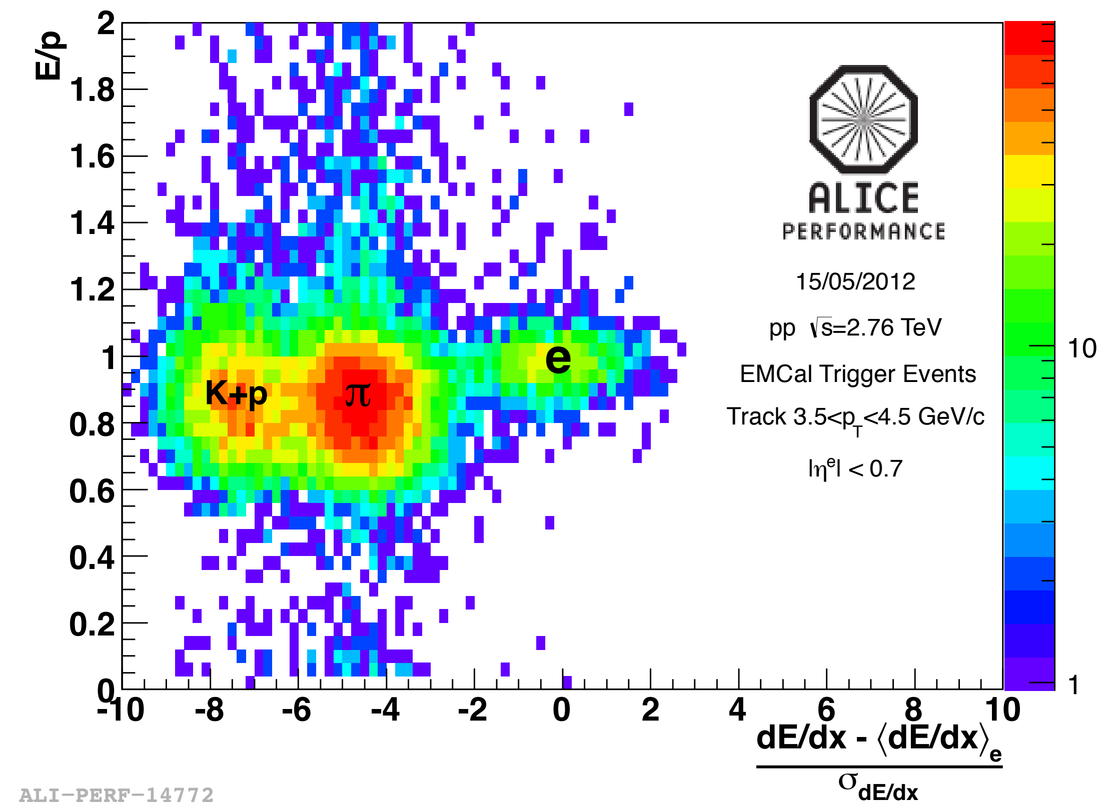
- Background subtraction:
- background contribution decreases with p_T → measurement for $p_T > 2$ GeV/c
  - Main source: muon from pions and kaons decays
  - Subtracting using MC simulation as input (Pythia, Phojet)



e-ID in ALICE

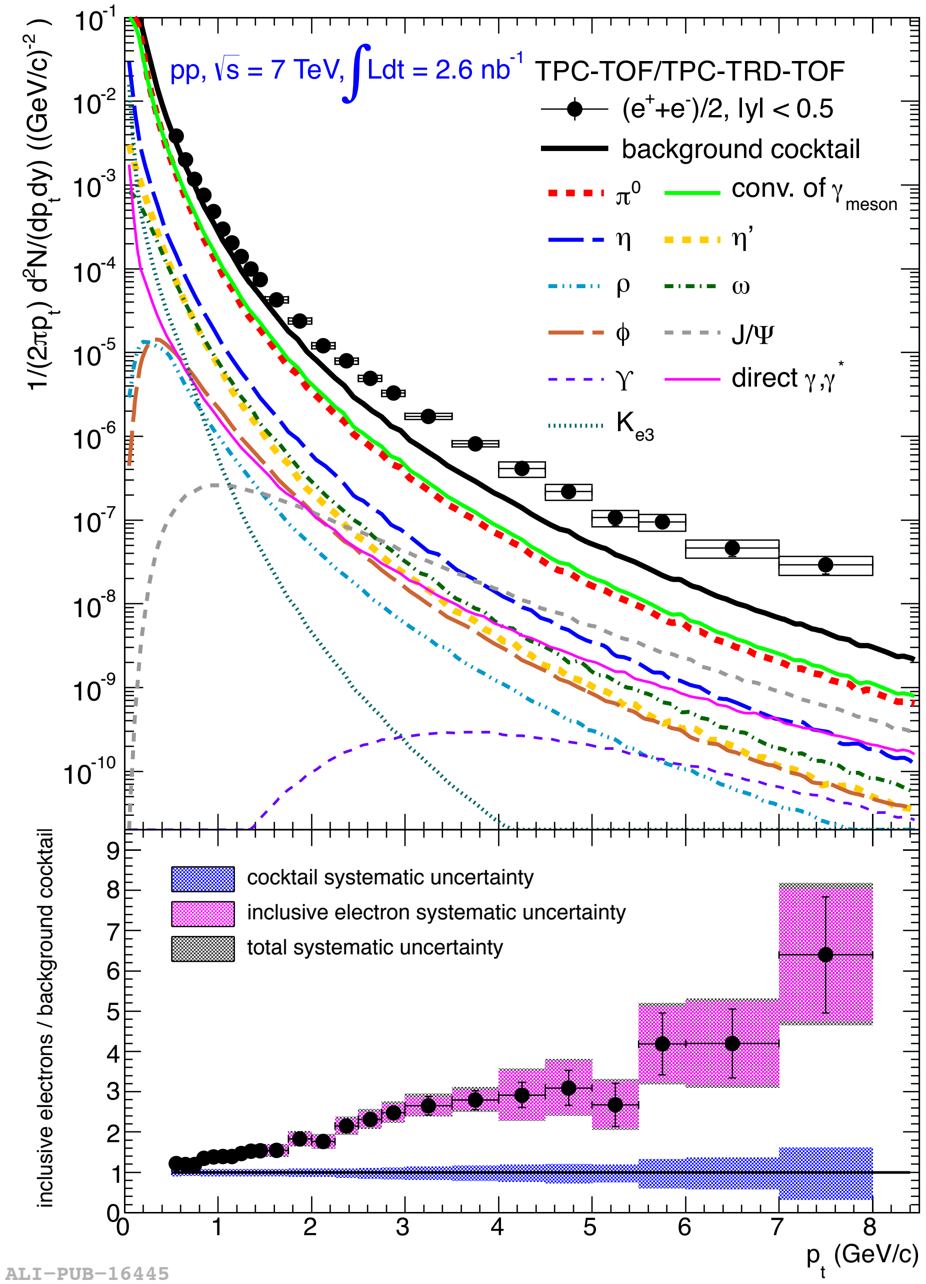
- ✧ TPC (dE/dx) + TOF + TRD
- ✧ TPC (dE/dx) + EMCAL

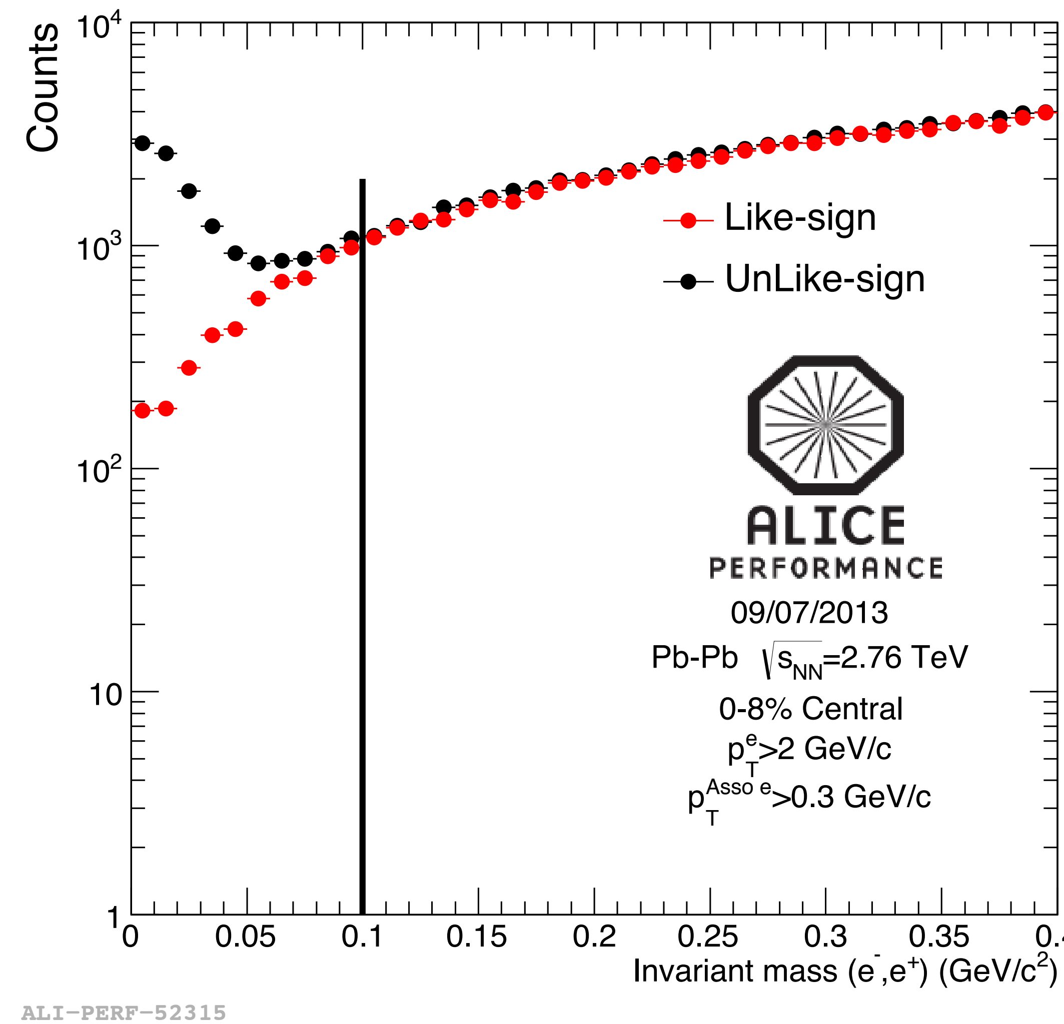




e reconstruction in ALICE

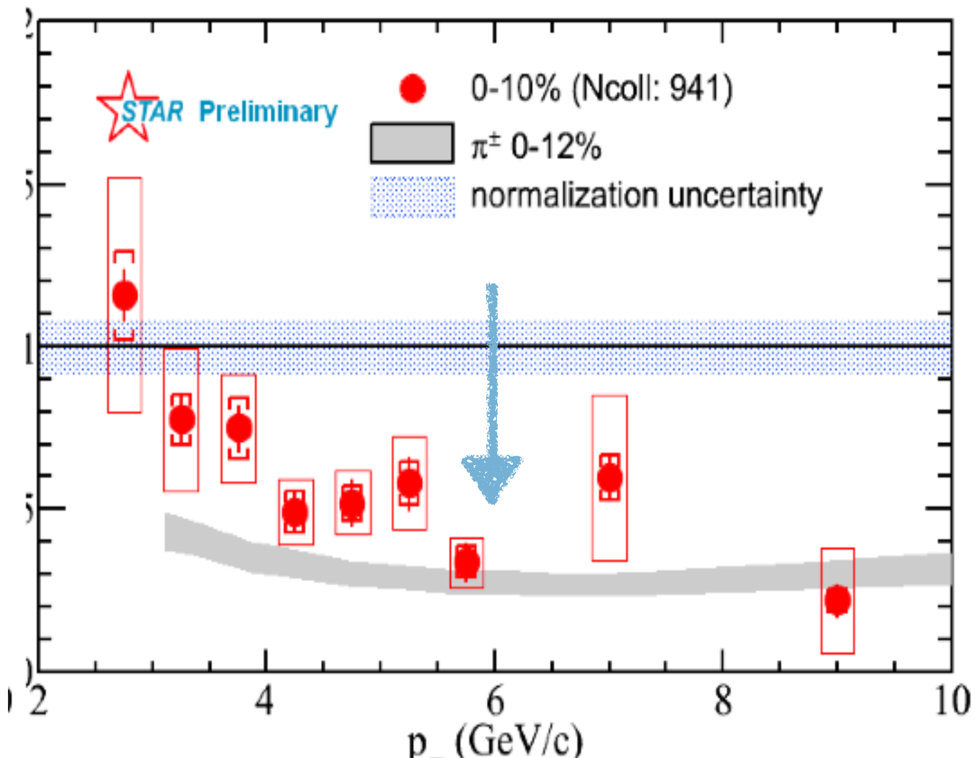
- Background subtraction:
  - cocktail method : MC hadron generator for different background sources
  - e^+e^- invariant mass method to remove Dalitz decay and photon conversion



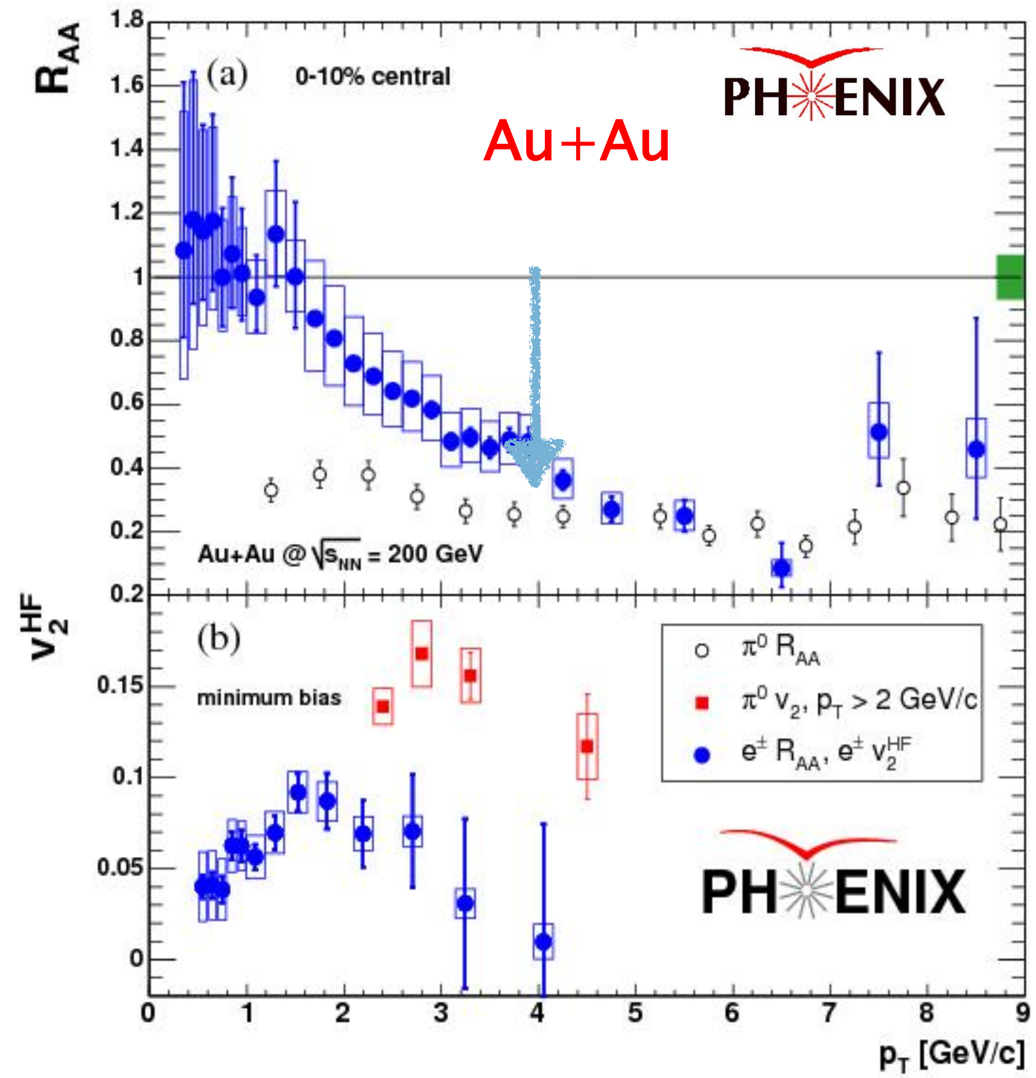


HF electrons @ RHIC

- Inclusive measurement (c+b) using electrons



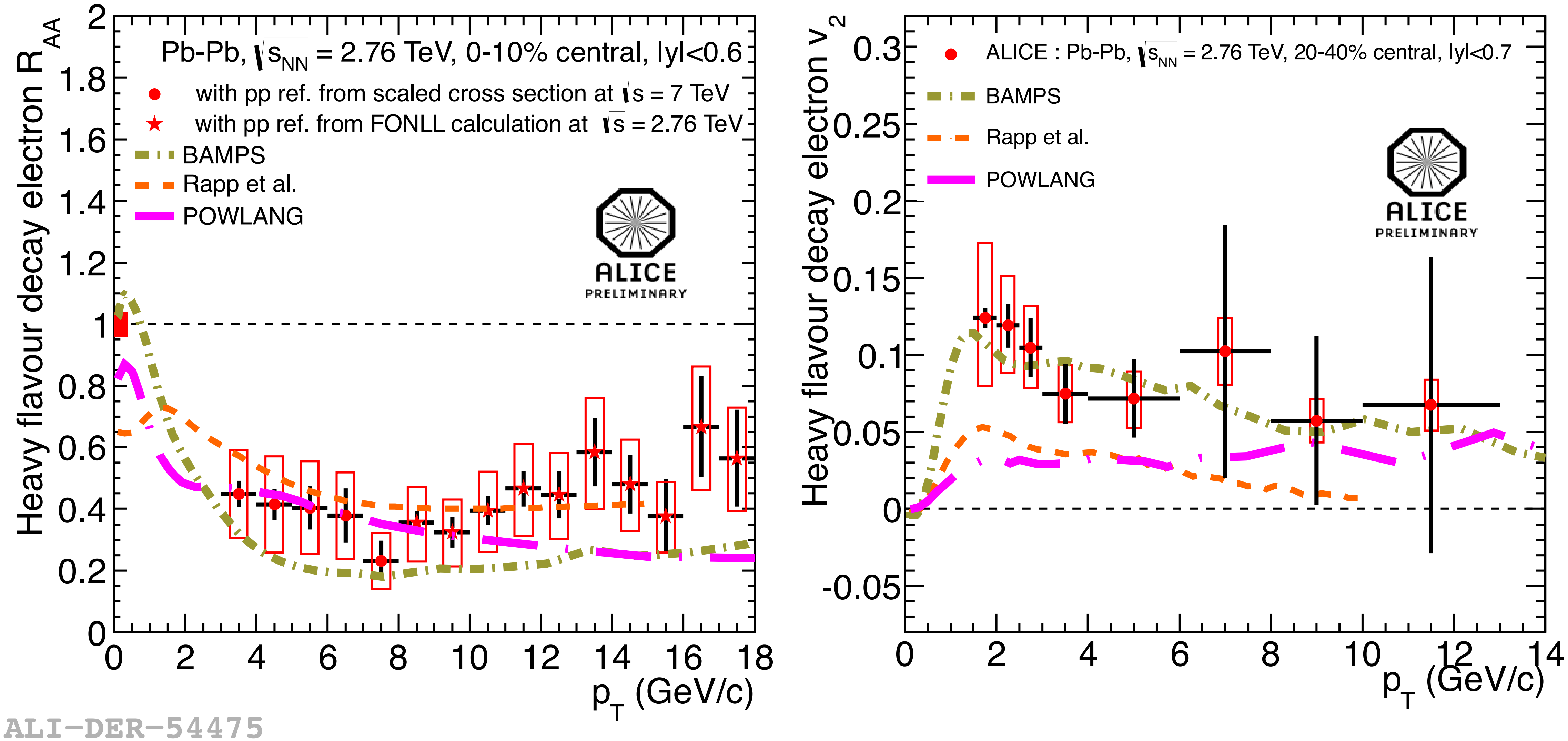
PRL 98, 192301 (2007)



PHENIX, PRC 84, 044905 (2011)

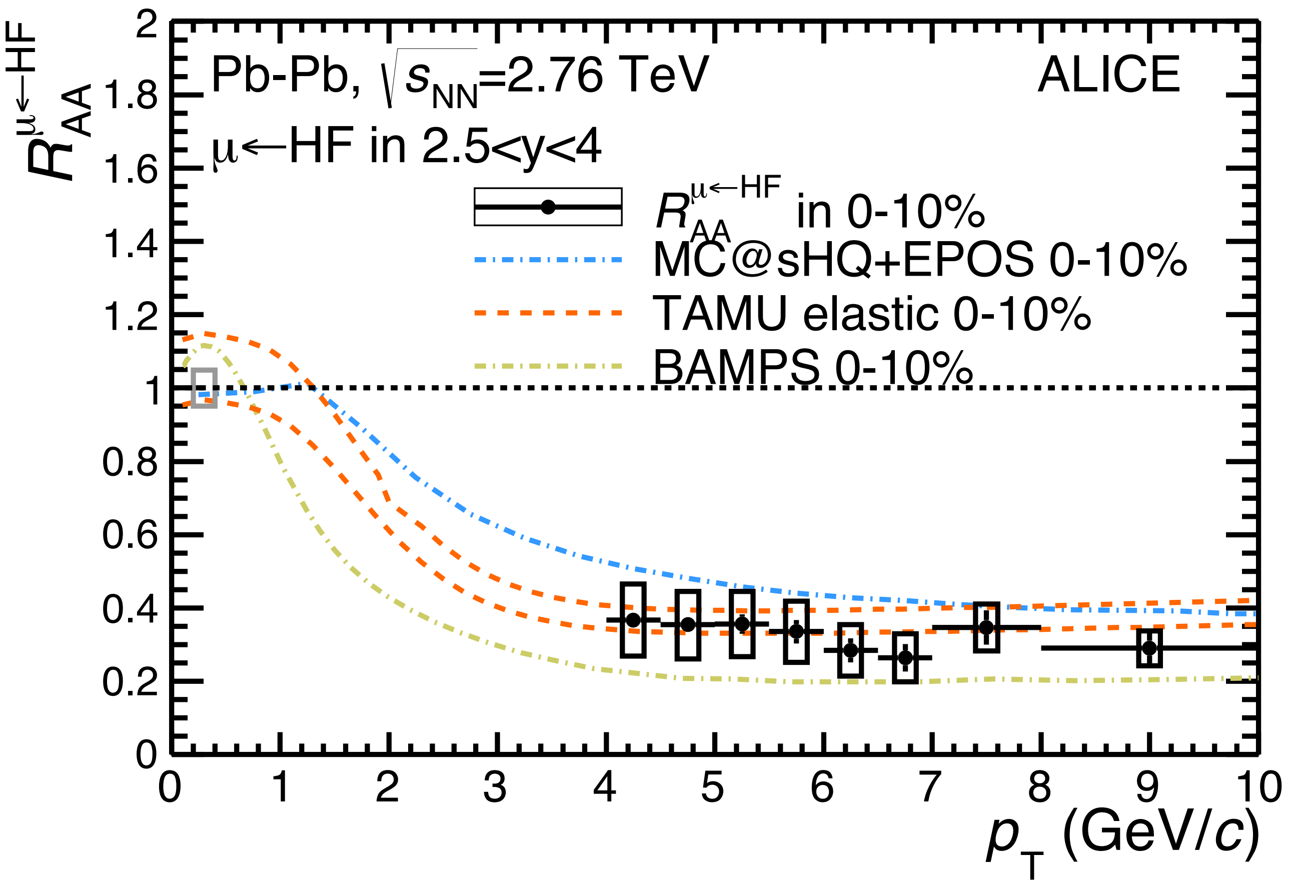
- Same suppression as for light-flavour hadrons above 5 GeV/c
- Smaller suppression at 2-3 GeV/c but cannot conclude on mass effects.

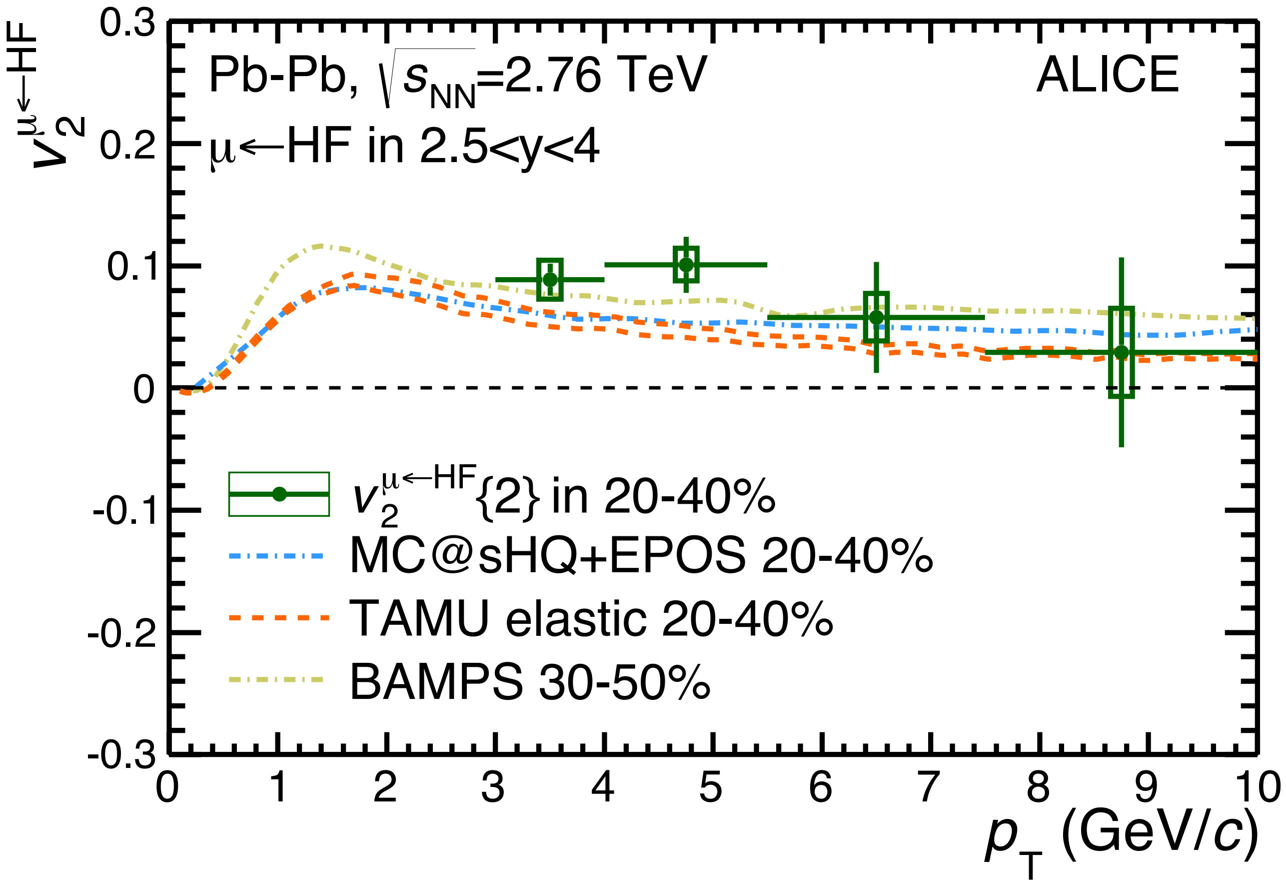
HF e comparison with models



BAMPS Uphoff et al. arXiv: 1112.1559, TAMU M. He, R. J. Fries and R. Rapp, arXiv:1204.4442[nucl-th]
POWLANG W. M. Alberico et al. Eur. Phyis J. C 71

HF μ comparison with models





BAMPS Uphoff et al. arXiv: 1112.1559, TAMU M. He, R. J. Fries and R. Rapp, arXiv:1204.4442[nucl-th], MC@sHQ+EPOS

D mesons: systematic uncertainties

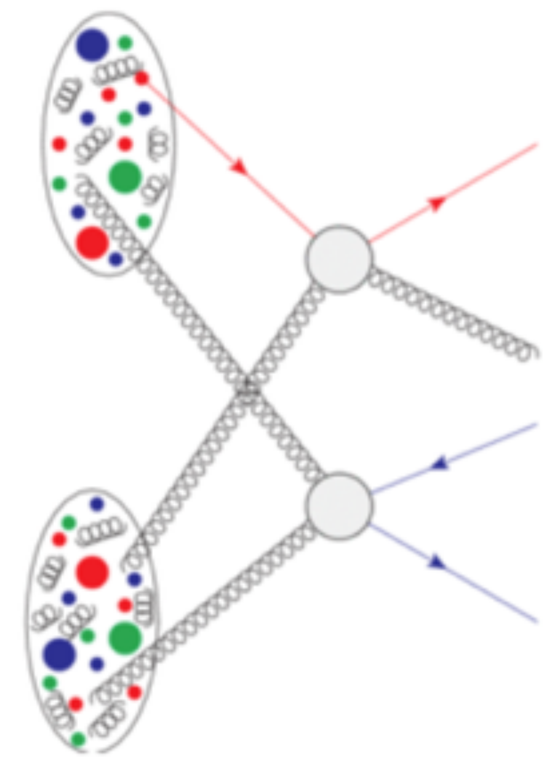
Cross section systematic uncertainties

p_T interval (GeV/c)	1–2	16–24
Data systematics		
Yield extraction	8%	11%
Correction for reflections	3%	4%
Tracking efficiency	6%	6%
Cut efficiency	8%	5%
PID efficiency	0	0
D^0 p_T distribution in MC	2%	0
B feed-down yield	$^{+5}_{-47}$%	$^{+4}_{-9}$%
Total	$^{+14}_{-49}$%	$^{+15}_{-17}$%

R_{pPb} systematic uncertainties

p_T interval (GeV/c)	1–2	16–24
B feed-down yield	$^{+1.3}_{-7.4}$%	$^{+4.3}_{-10.8}$%
pp reference	21%	$^{+31}_{-42}$%
Total	$^{+25}_{-26}$%	$^{+34}_{-45.6}$%

D mesons vs multiplicity



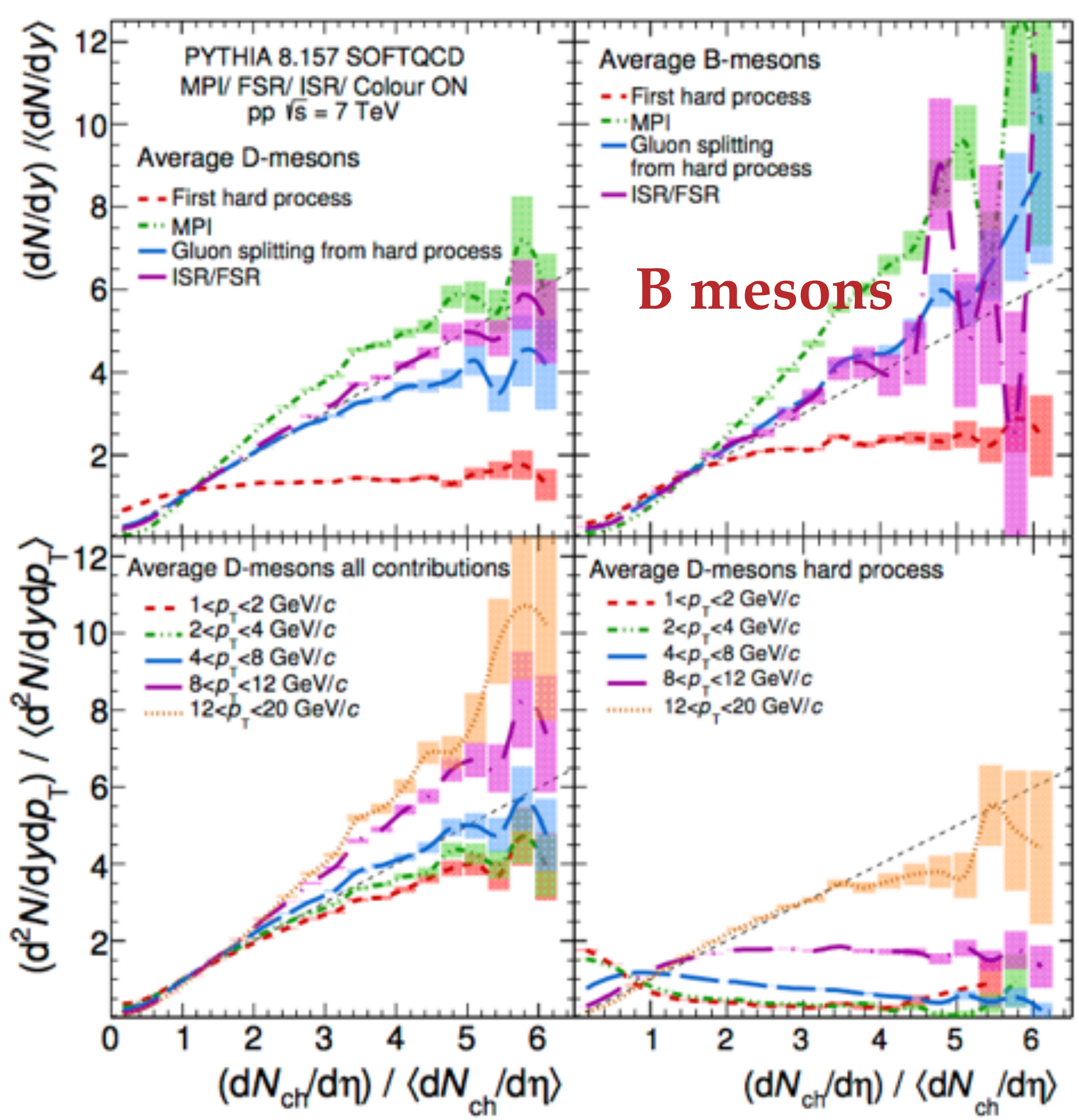
- **Multi-Parton Interactions at the LHC ?**
  - MPIs are expected to play an important role at LHC energies:
    - CMS measurement of jets and underlying events show a better agreement with models including MPIs
      Eur. Phys. J C73 (2013) 2674
    - ALICE measurement of mini-jets shows an increase of MPI contribution with increasing charged particle multiplicity
      JHEP 09 (2013) 049
- **MPIs and heavy-flavour ?**
  - NA27 measured that events with charm production have larger charged particle multiplicity (pp collisions, $\sqrt{s}$ = 28 GeV) Z. Phys C41:!91
  - LHCb measured double charm production that shows a better agreement with models including double parton scattering J. High Energy Phys., 06 (2012) 141
  - ALICE measured an increase of J/ψ yield vs multiplicity Phys.Lett. B712 (2012) 165-175

HF vs mult in pp

PYTHIA mechanisms of HF production:

1. **First hard process** (gg ➜ $c\bar{c}$, c+u ➜ c+u)
2. **Hard MPI process**
3. **Gluon splitting from hard process** (g ➜ $b\bar{b}$)
4. **Gluon splitting with the gluon coming from ISR/FSR**

D mesons



HF vs mult in pp

D mesons

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3. **Gluon splitting from hard process** (g ➜ $b\bar{b}$)
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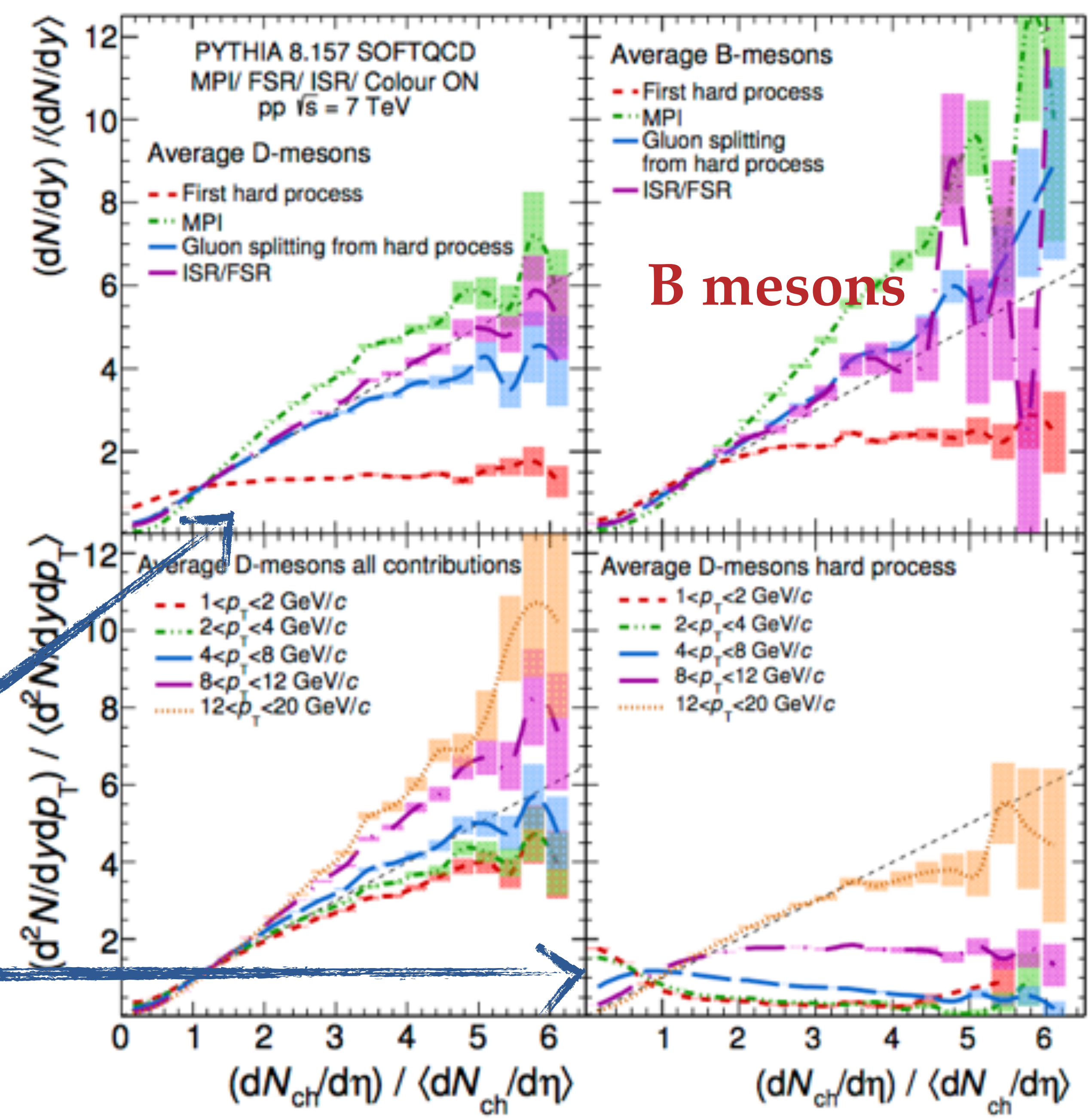


In Pythia 8 first hard process independent of multiplicity but dependent on the p_T

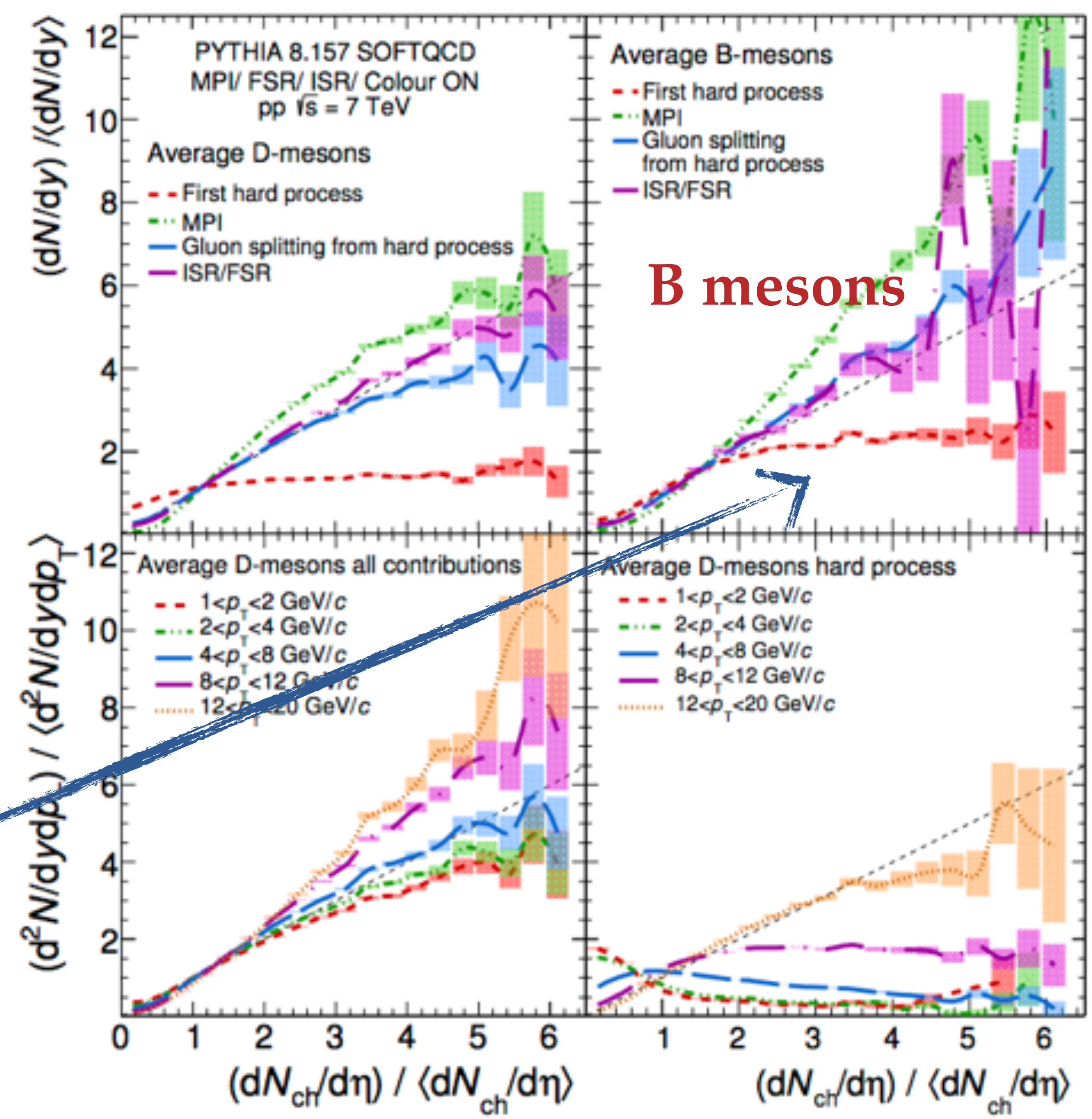
HF vs mult in pp

PYTHIA mechanisms of HF production:

1. **First hard process** (gg ➜ $c\bar{c}$, c+u ➜ c+u)
2. **Hard MPI process**
3. **Gluon splitting from hard process** (g ➜ $b\bar{b}$)
4. **Gluon splitting with the gluon coming from ISR/FSR**

Similar trend for D and B mesons but different "saturation" threshold

D mesons



HF vs mult in pp

PYTHIA mechanisms of HF production:

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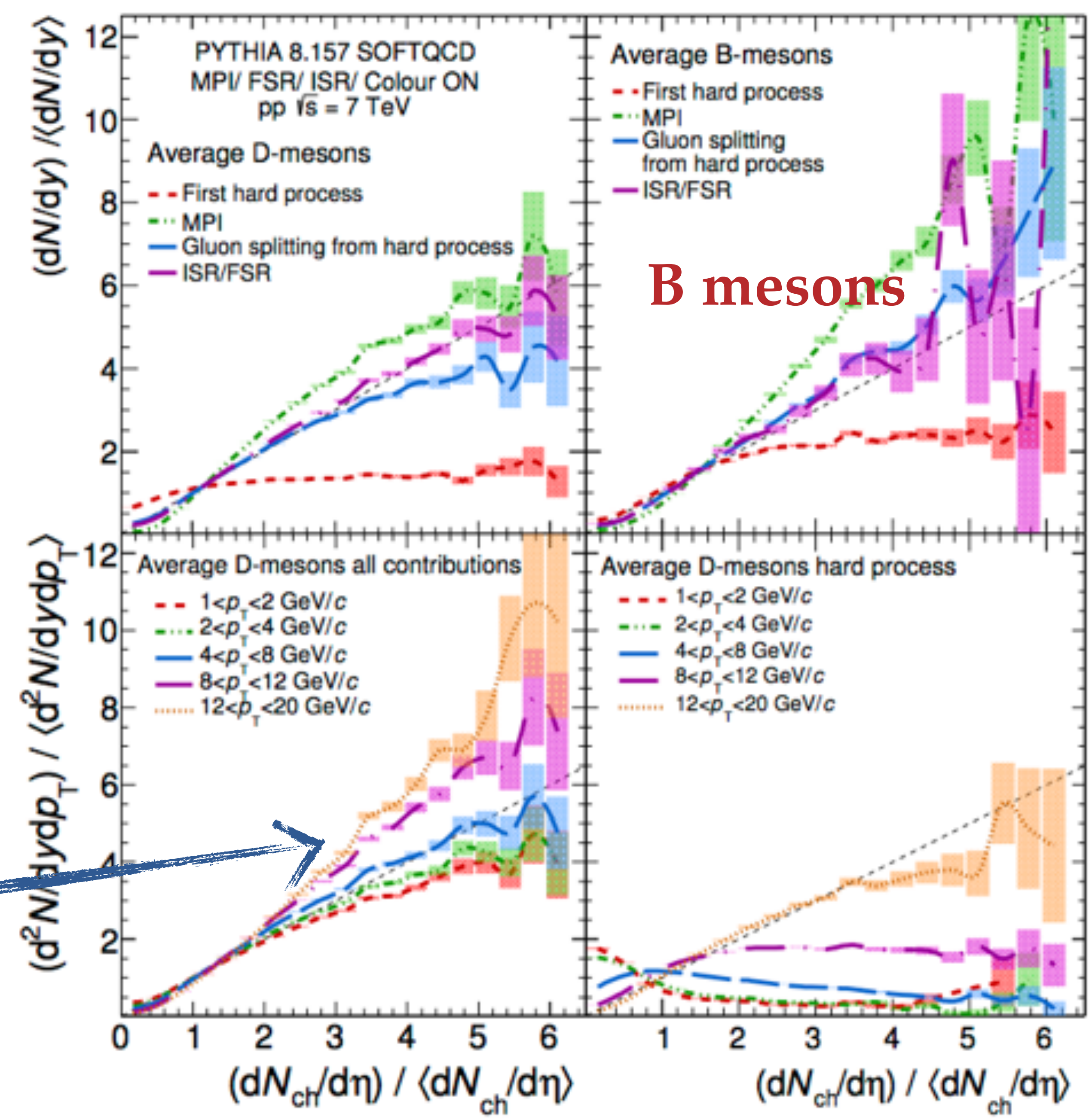
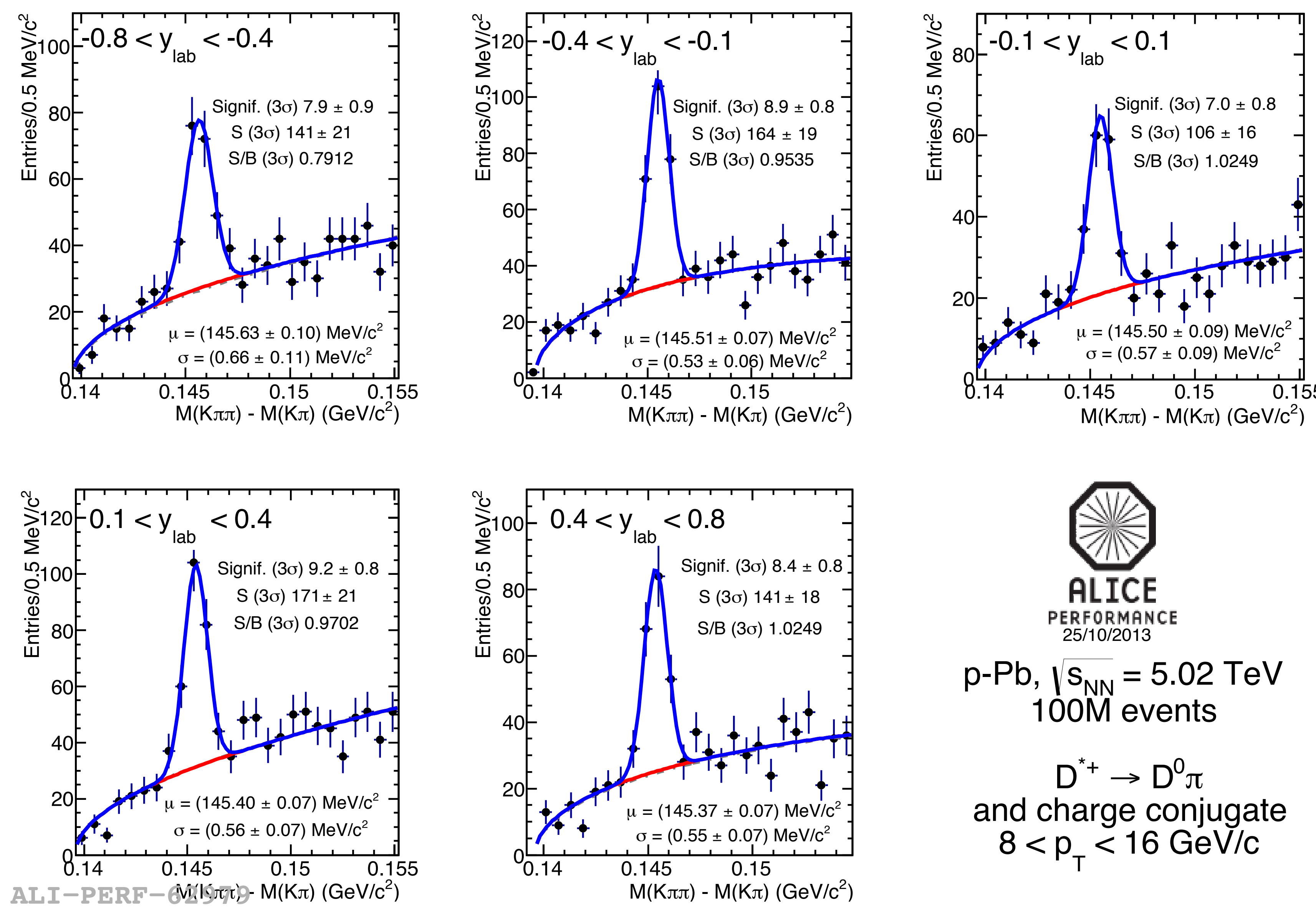
D mesons



At high multiplicity at p_T ordering is expected for all processes.
For first hard process also at low-multiplicity

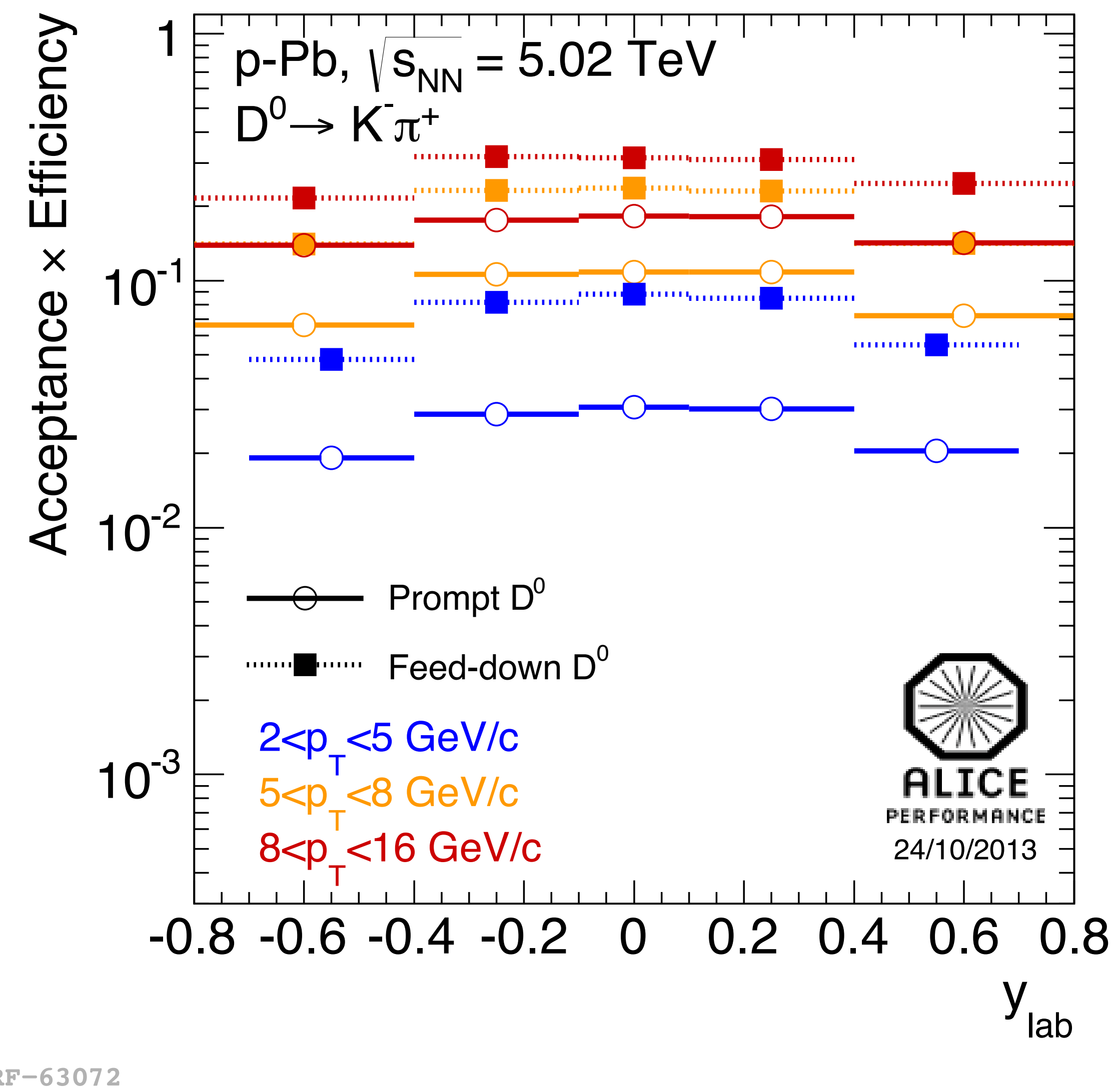
D mesons: Cross section vs *y*

Invariant mass analysis in different *y* bins



D mesons: Cross section vs *y*

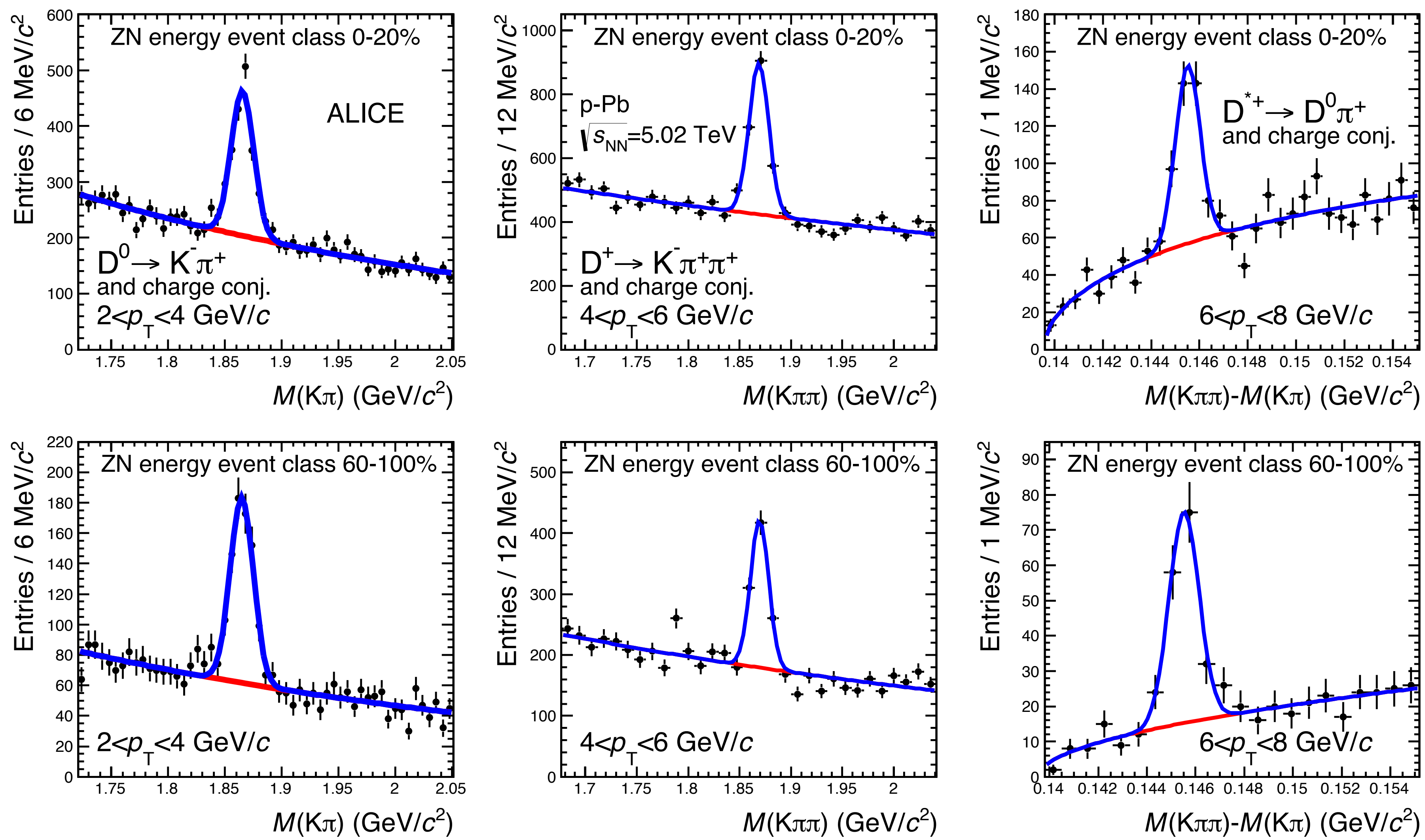
Acceptance x efficiencies vs *y* for three p_T intervals



D vs multiplicity: multiplicity differential raw yields

$$\frac{d^2N^D/dydp_T}{< d^2N^D/dydp_T >} = \frac{(d^2N^D/dydp_T)^{mult}/(\epsilon^{mult} \times N^{mult}_{event})}{(d^2N^D/dydp_T)^{tot}/(\epsilon^{tot} \times N^{tot}_{event})}$$

Multiplicity differential yields in p_T intervals



D vs multiplicity: Feed down subtraction

Assumption: the fraction of prompt D mesons f_{prompt} does not depend on multiplicity

$$\frac{d^2N^D/dydp_T}{< d^2N^D/dydp_T >} = \frac{(d^2N^D/dydp_T)^{mult}/(\epsilon^{mult} \times N^{mult}_{event})\ * f_{\mathrm{prompt}}}{(d^2N^D/dydp_T)^{tot}/(\epsilon^{tot} \times N^{tot}_{event})\ * f_{\mathrm{prompt}}}$$

D vs multiplicity: Feed down subtraction

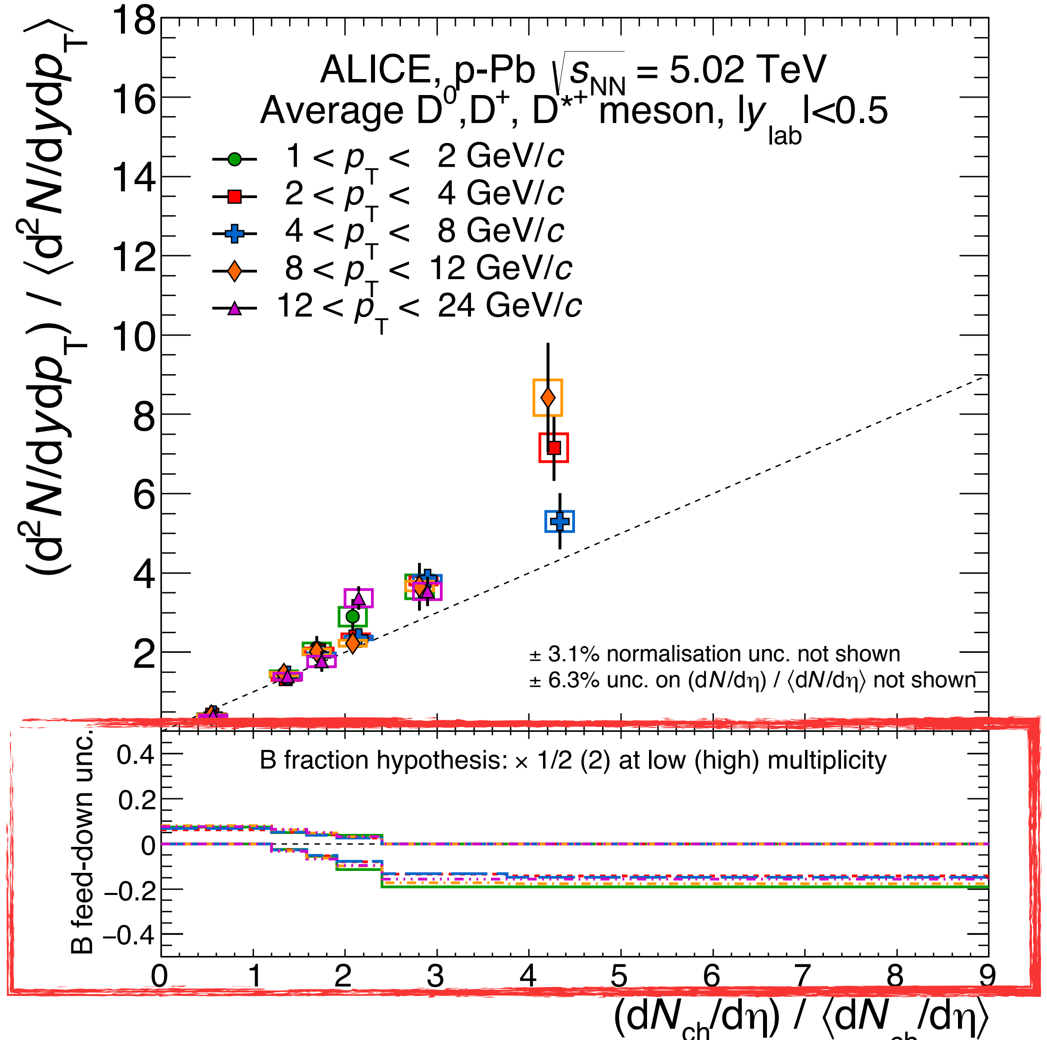
Assumption: the fraction of prompt D mesons f_{prompt} does not depend on multiplicity

$$\frac{d^2N^D/dydp_T}{< d^2N^D/dydp_T >} = \frac{(d^2N^D/dydp_T)^{mult}/(\epsilon^{mult} \times N^{mult}_{event})}{(d^2N^D/dydp_T)^{tot}/(\epsilon^{tot} \times N^{tot}_{event})} \frac{* \cancel{f_{\text{prompt}}}}{* \cancel{f_{\text{prompt}}}}$$

Systematic uncertainties assigned due to beauty feed down fraction:

variation of beauty contribution vs multiplicity up to a factor of 2

maxium 20% at high p_T



D vs multiplicity: systematic uncertainties

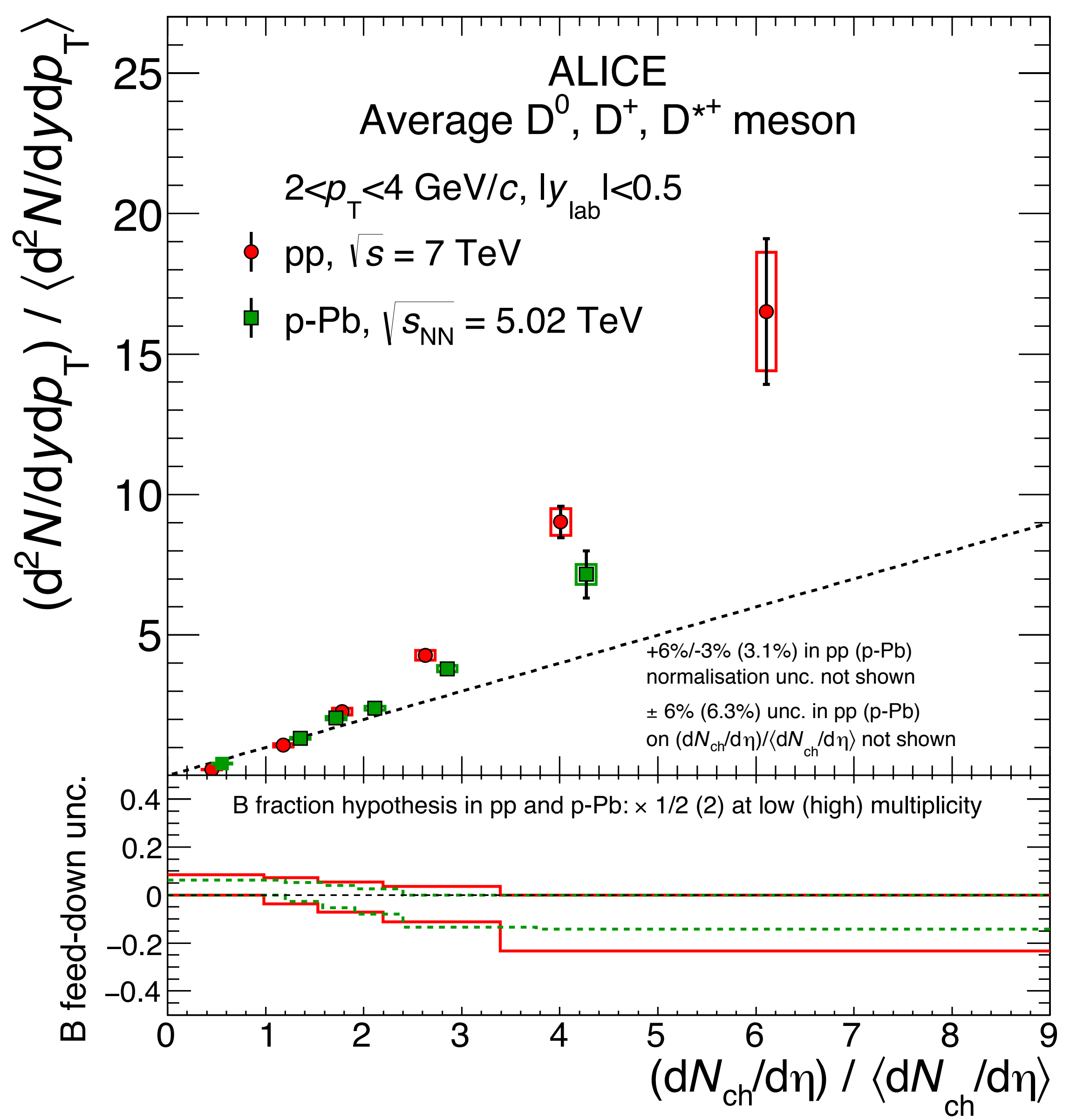
Yield extraction systematic uncertainties

p_T (GeV/c)	Multiplicity bin					
	1-24	25-44	45-59	60-74	75-99	100-199
1-2	4%	3%	3%	5%	6%	-
2-4	3%	3%	3%	3%	3%	5%
4-8	3%	3%	3%	3%	3%	5%
8-12	4%	3%	3%	3%	4%	5%
12-24	6%	3%	3%	5%	5%	-

Comparison of pp and p-Pb collisions

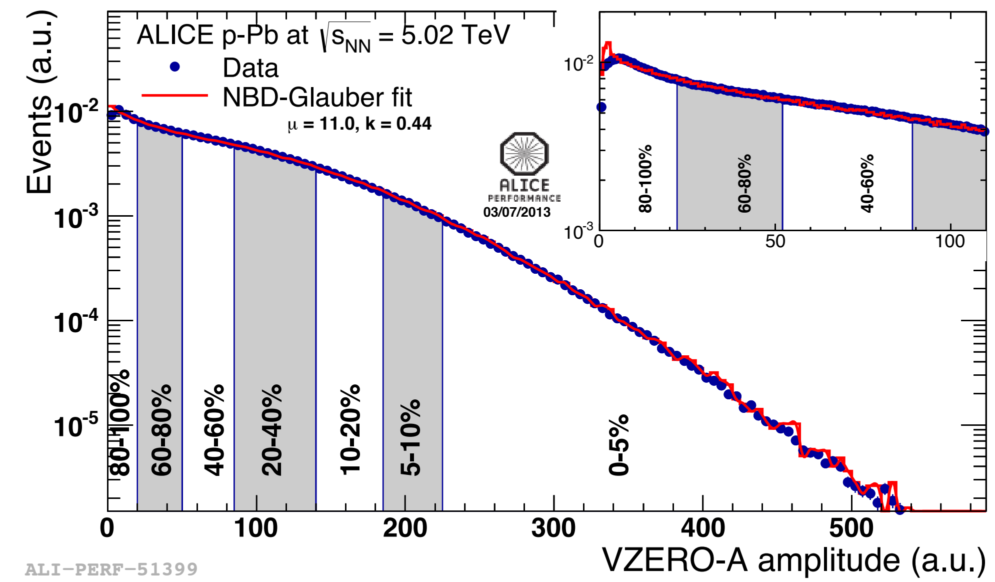
- ☑ The trend seems to be similar also when we compare Pb-Pb results, but…

  - ☑ highest multiplicity bin in Pb-Pb collisions corresponds to 10% of the total cross section, for pp to only 1%.

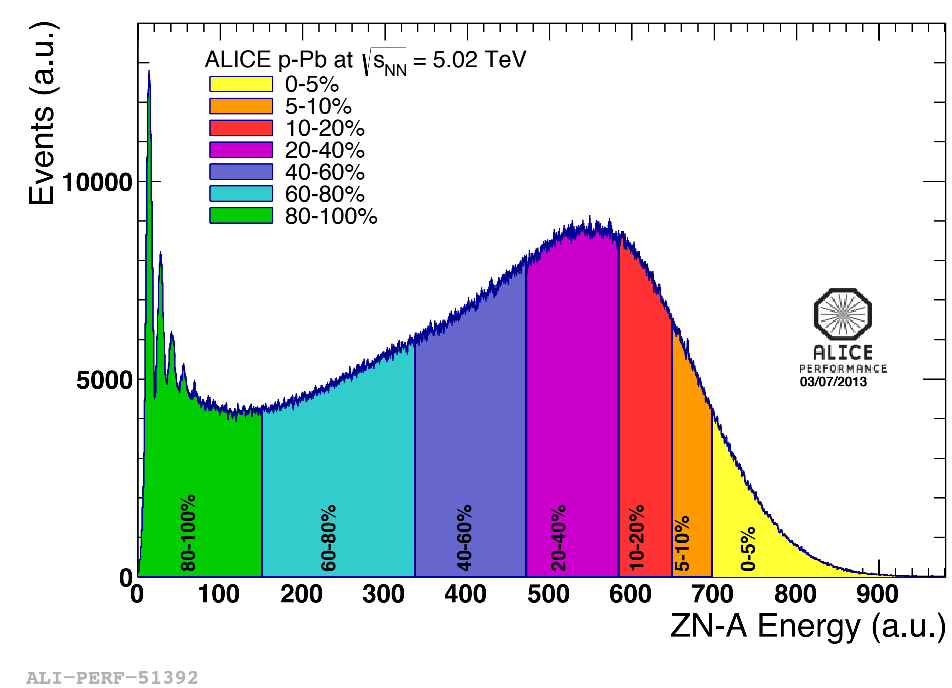


Q_{pPb}: multiplicity estimator definitions

- **V0A:**
  - $< N_{coll}^{Glaub} >$ from Glauber fit to V0A amplitude
  - multiplicity from Negative Binomial Distribution (NBD)



- **ZNA:** $< N_{coll}^{mult} >$ obtained with an Hybrid method
  - Slice events in ZN energy (Pb going side)
  - $< N_{part} >$ in ZN energy class obtained by scaling it to the minimum bias multiplicity at mid-rapidity.



QpPb: Hybrid method some details

Assumption 1 : ZN insensitive to dynamical biases ➜ slice events in ZN

Assumption 2:

a. mid-rapidity dN/dη scales with N_{part}

b. Pb-side dN/dη scales with N_{part} (= N_{coll} for p-Pb collisions)

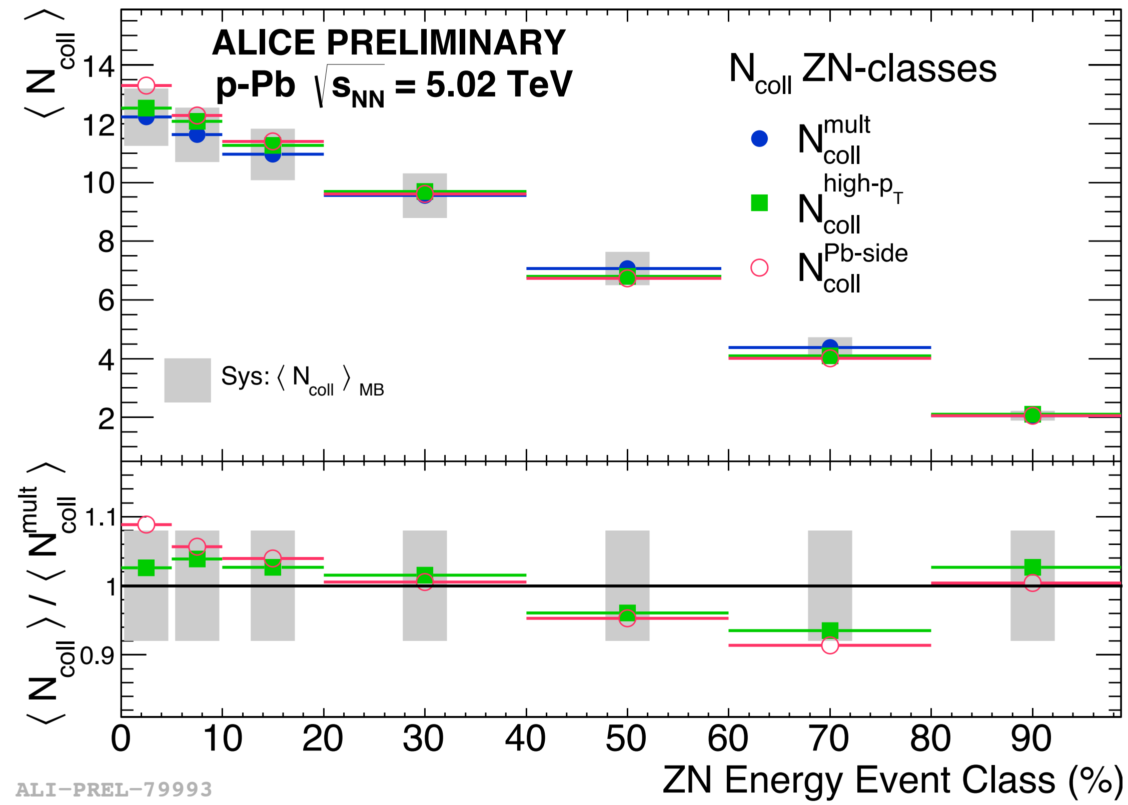
c. Yields at high-pT scales with N_{coll}

$$\langle N_{part}\rangle_i^{mult} = \langle N_{part}\rangle_{MB} \cdot \frac{\langle S\rangle_i}{\langle S\rangle_{MB}}$$

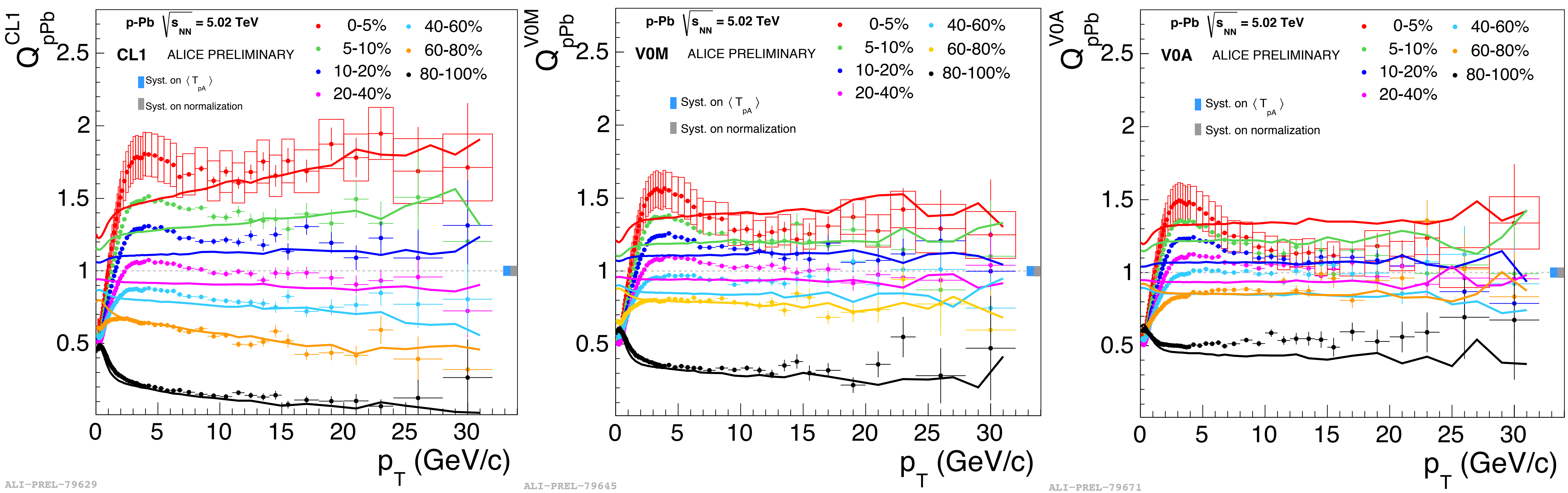
$$\langle N_{coll}\rangle_i^{mult} = \langle N_{part}\rangle_i^{mult} - 1$$

$$\langle N_{coll}\rangle_i^{Pb-side} = \langle N_{coll}\rangle_{MB} \cdot \frac{\langle S\rangle_i}{\langle S\rangle_{MB}}$$

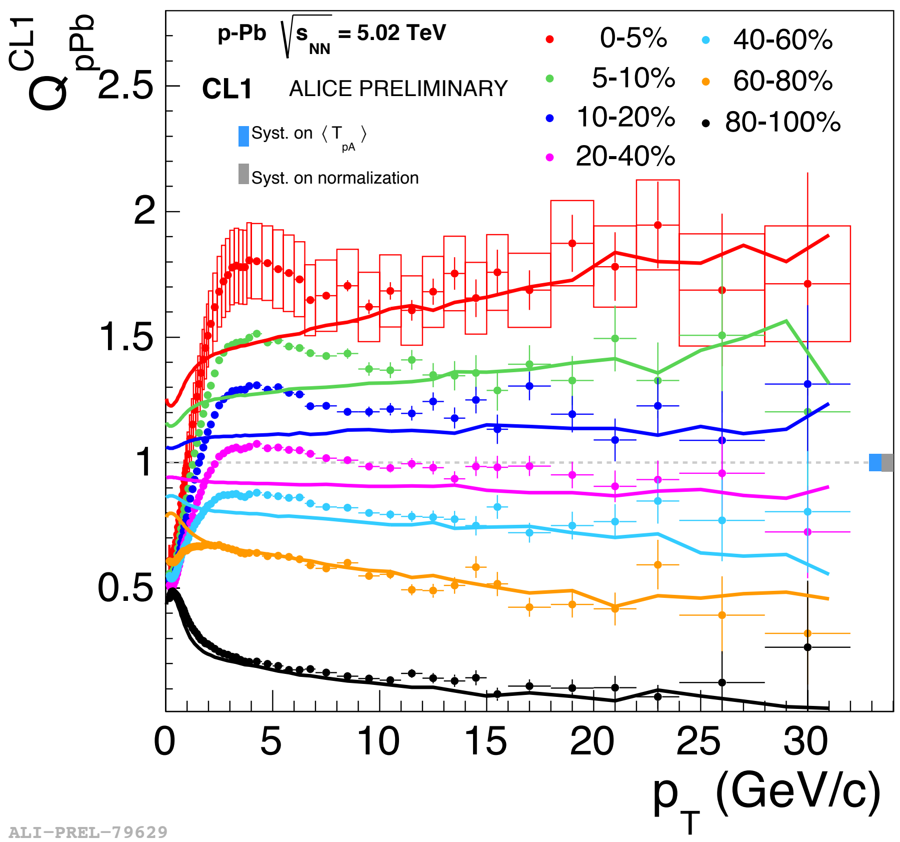
$$\langle N_{coll}\rangle_i^{high-p_T} = \langle N_{coll}\rangle_{MB} \cdot \frac{\langle S\rangle_i}{\langle S\rangle_{MB}}$$

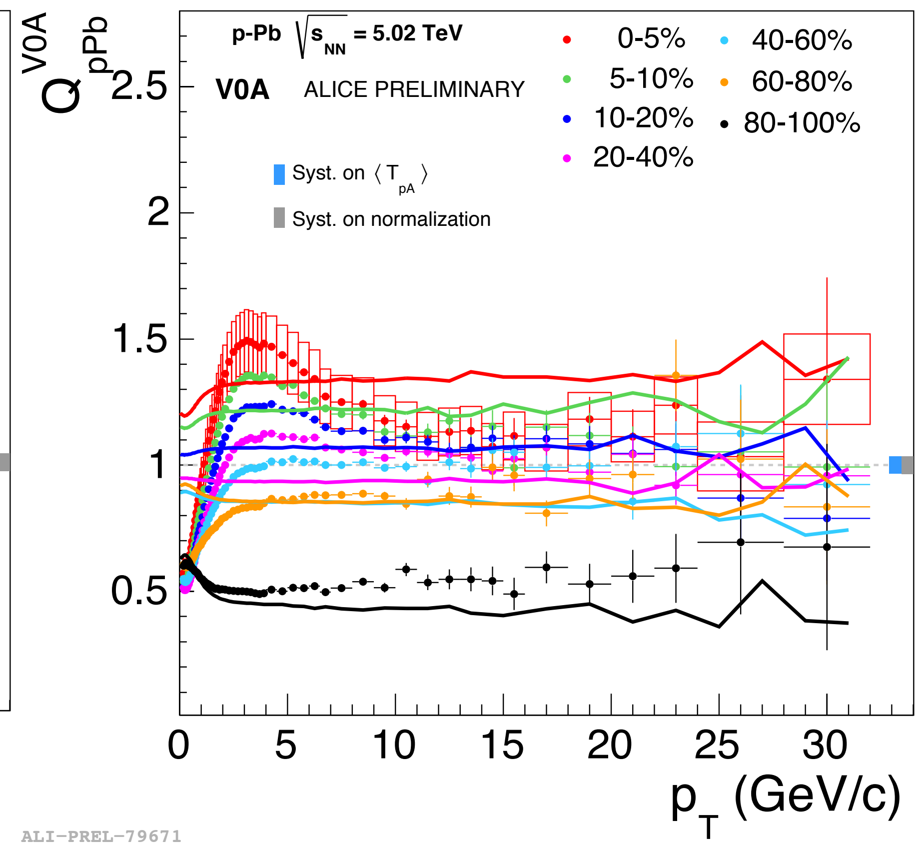


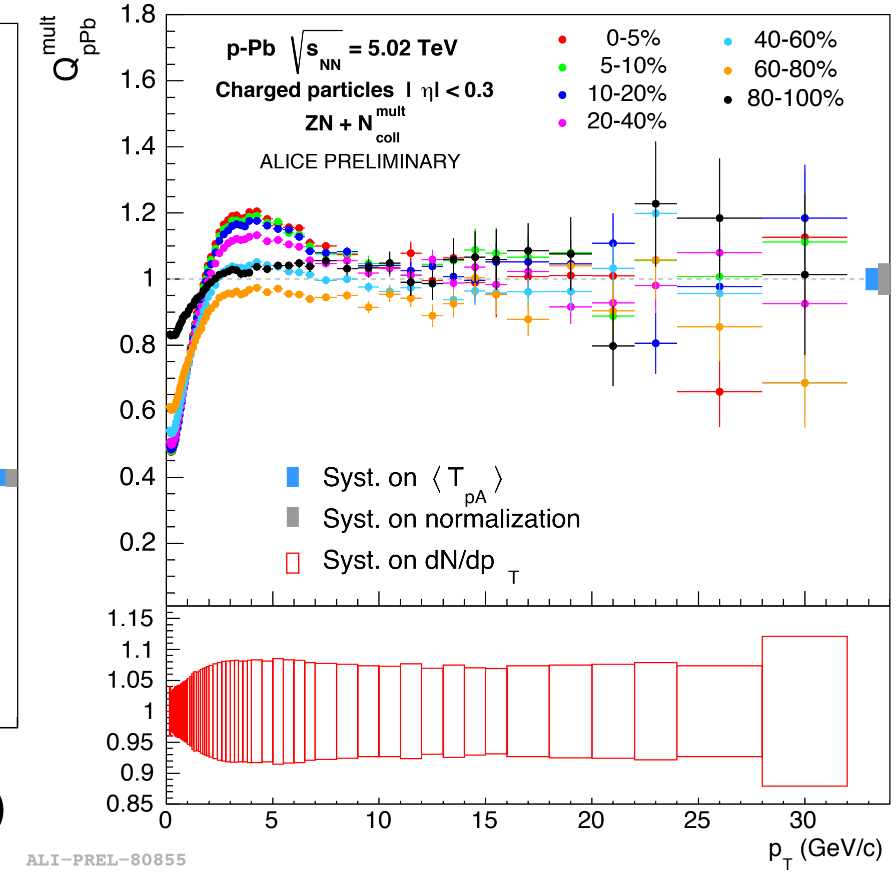
QpPb: other estimators



QpPb: other estimators

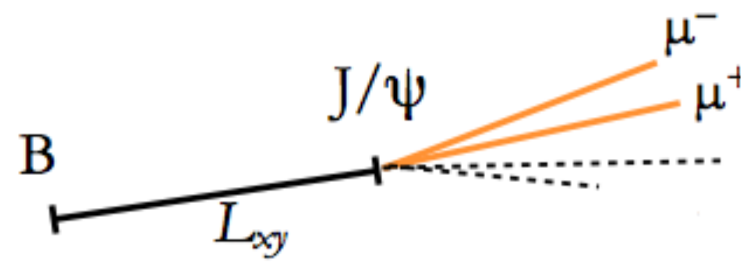




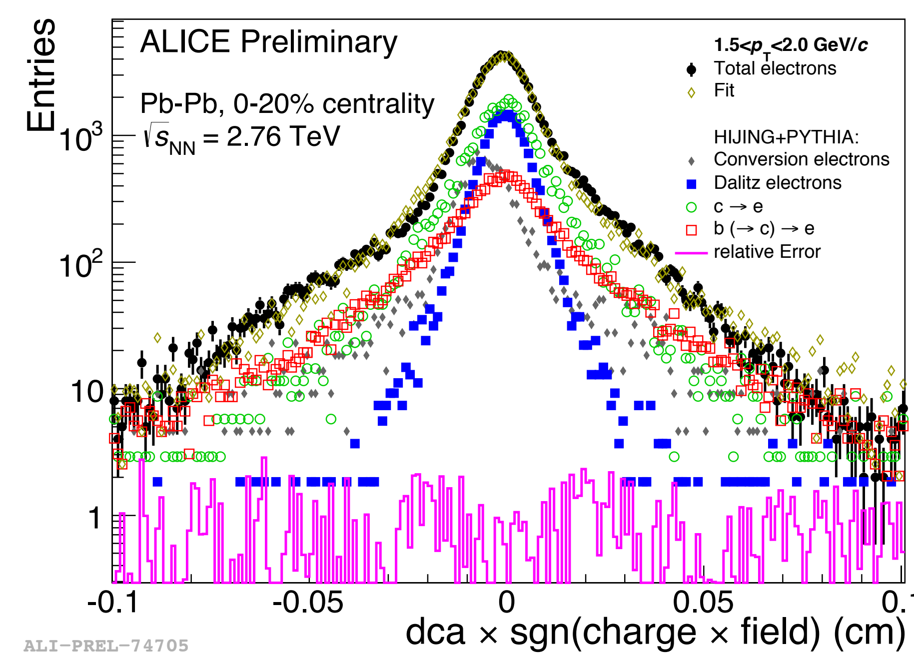


How to measure heavy quarks?

* Non-prompt J/ψ from B hadron decays.
  * First "direct" beauty measurement
  * Exploit the displacement of J/ψ of ~hundreds μm in the transverse plane.
  * Simultaneous fit of pseudo-proper decay length (L_{xy}) and invariant mass.

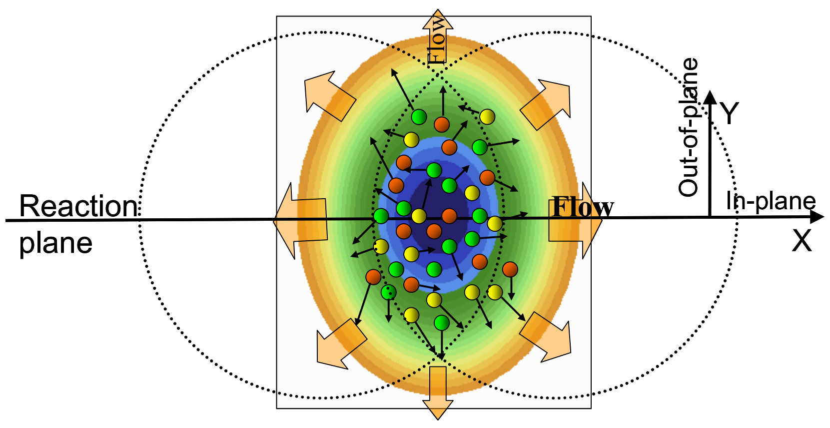


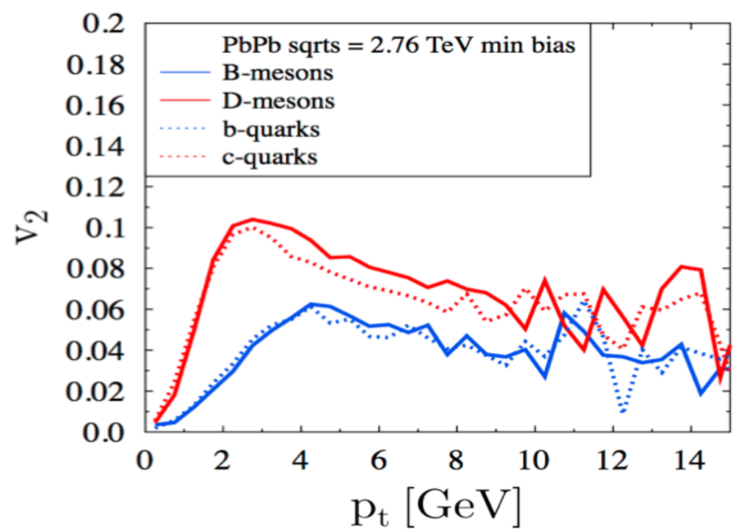
* Displaced electrons coming from B hadron decays.
  * Isolate the contribution of electrons coming for B hadrons using the larger impact parameter.
  * Fit of the different component in the impact parameter distributions.



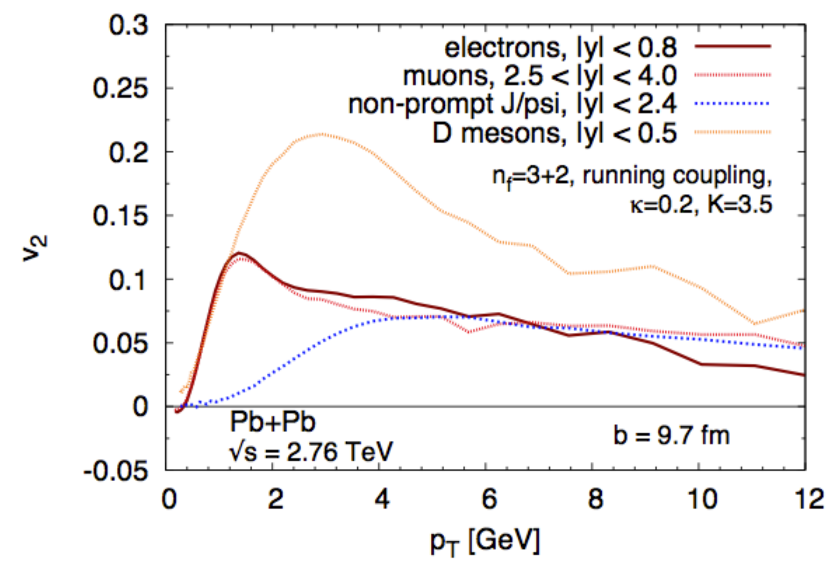
Heavy flavour v_2

* Low-pT: do heavy quarks take part in the collectivity?
  * Due to their large mass they should "feel" less the collective expansion
* High-pT" probe the path length dependence of the heavy quarks energy loss

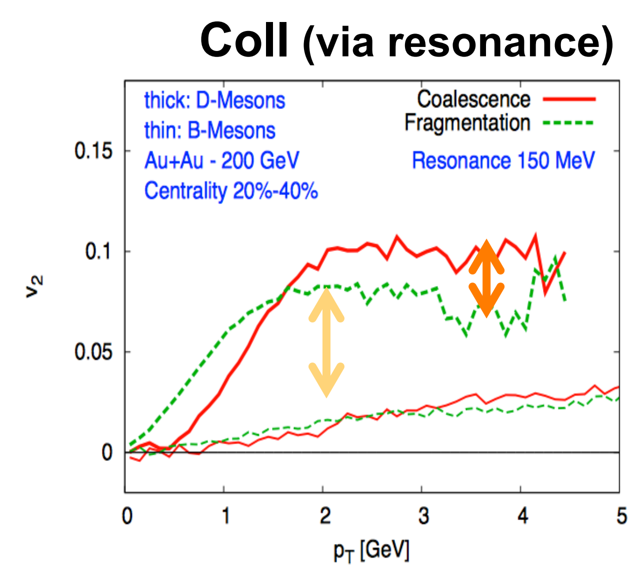




J. Aichelin et al. in arXiv:1201.4192



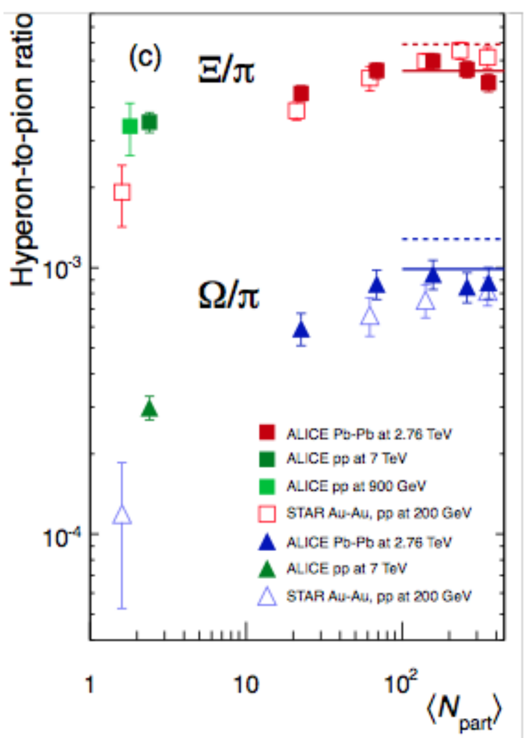
J. Uphoff et al. in arXiv:1205.4945

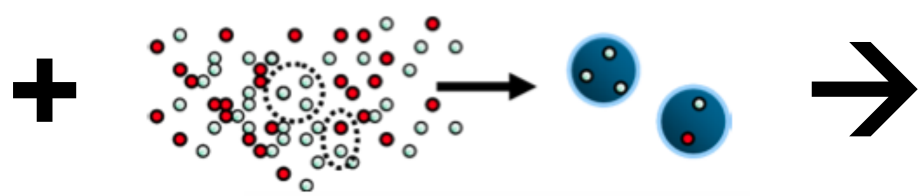


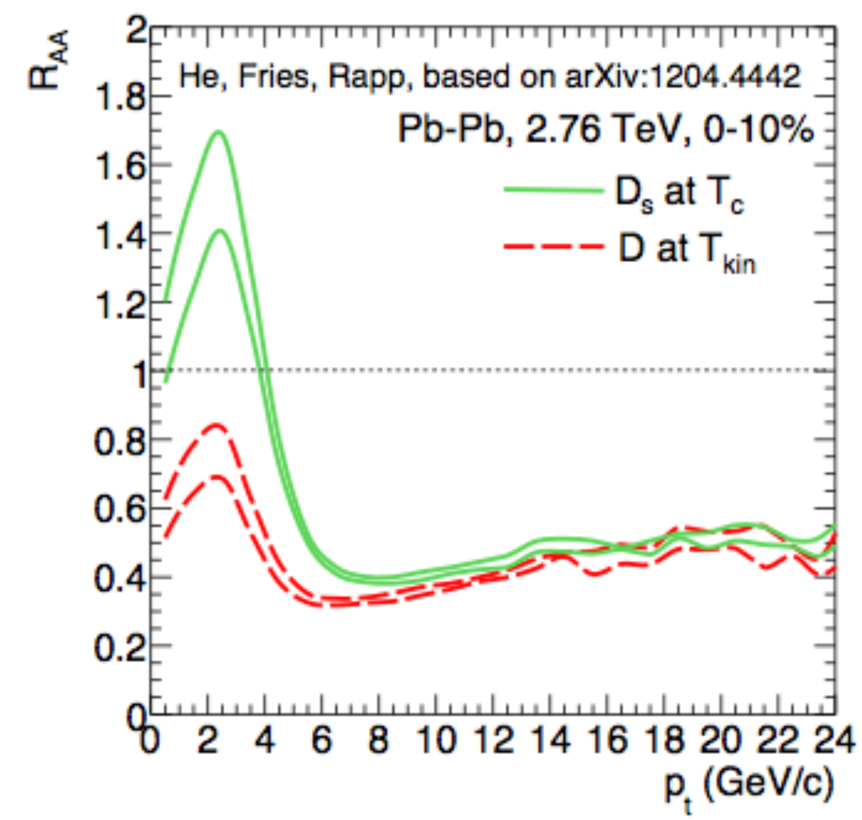
T. Lang et al., arXiv:1211.6912

Ds in PbPb collisions

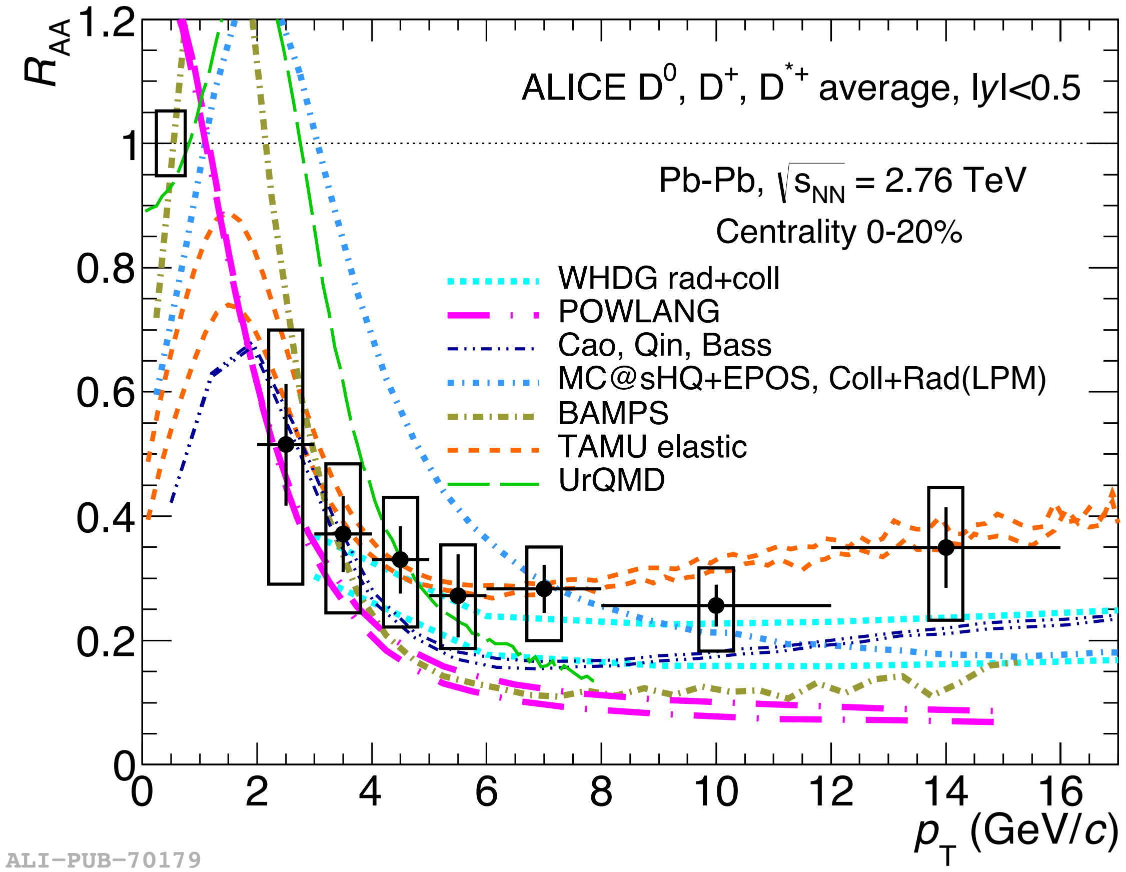
- Abundance of strange quarks in the QGP (strangeness enhancement)
- Large D_s enhancement expected if c quarks recombine in the QGP (recombination/coalesence models)

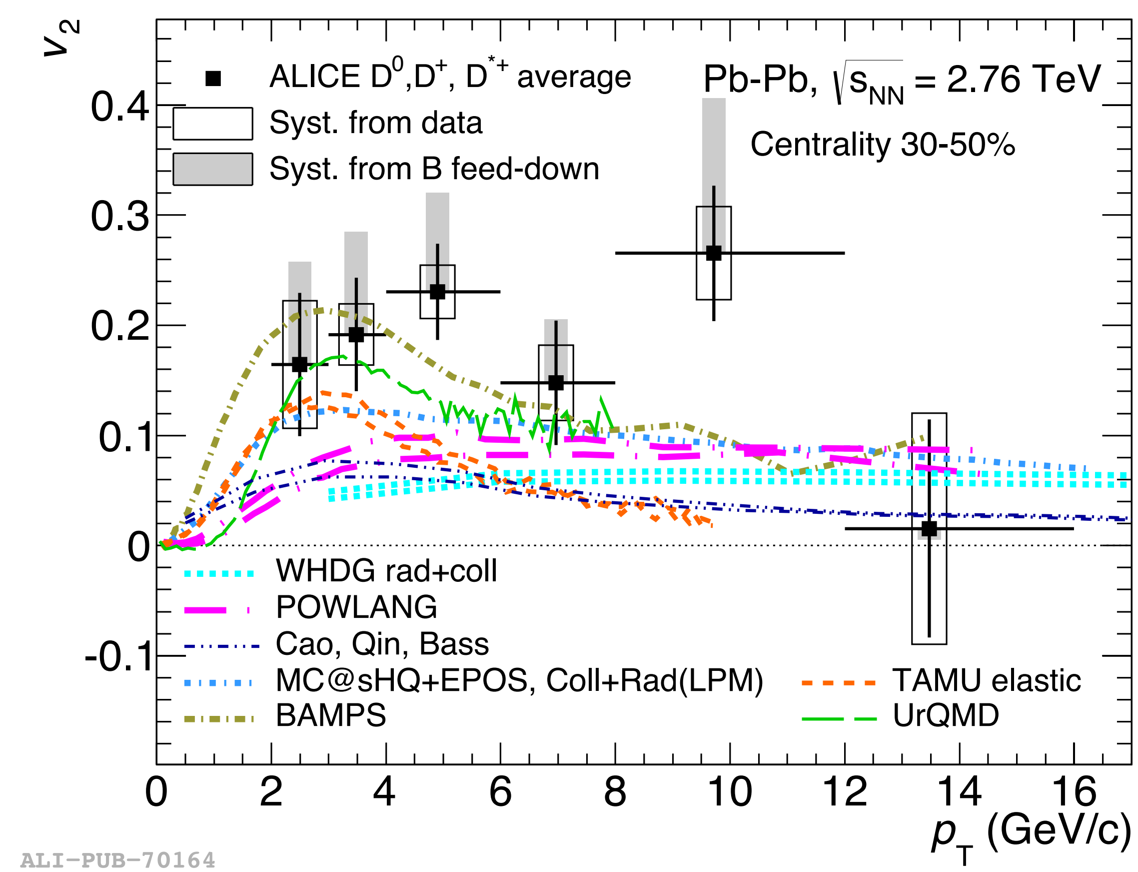






I. Kuznetsova and J. Rafelski, EPJC51, 113 (2007)
M. He et al. arXiv:1204.4442

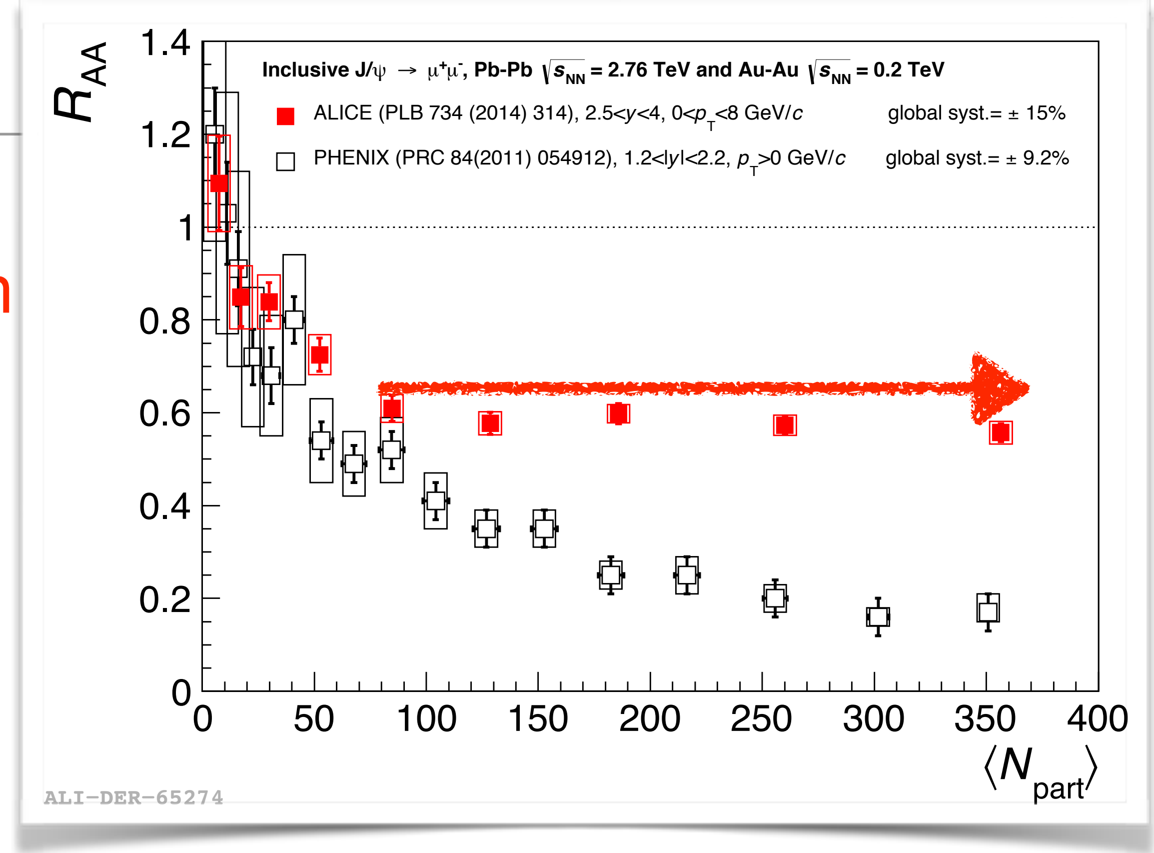




	HQ production	Medium Modeling	Heavy quarks interactions	Hadronization
WHDG (AIP Conf Proc. 1441 (2012) 889	FONLL, no shadowing	Glauber model collision geometry, no hydro evolution	radiative + collisional energy loss	fragmentation
POWLANG (J. Phys. G 38 (2011) 124144)	POWEG (NLO) + EPS09 shadowing	2+1d expanding medium with viscos hydro evolution	HQ transport (Langevin) + collisional energy loss	fragmentation
Cao, Quin, Bass (Phys Rev C 88 (2013) 044907)	LO pQCD + EPS09 shadowing	2+1d expanding medium with viscous hydro evolution	HQ transport (Langevin) + quasi elastic scattering + radiative energy loss	recombination + fragmentation
MC@sHQ+EPOS2 (Phys Rev C 89 (2014) 014905)	FONLL, no shadowing	3+1d fluid dynamical expansion (EPOS)	HQ transport (Boltzmann) + radiative + collisional energy loss.	recombination + fragmentation
BAMPS (Phys Lett B 717 (2012) 430)	MC@NLO, no shadowing	3+1d fully dynamic parton transport model	HQ transport (Boltzmann) + collisional energy loss	fragmentation
TAMU elastic (arXiv:1401.3817)	FONLL + EPS09 shadowing	transport + 3+1d ideal hydro evolution	HQ transport (Langevin) + collisional energy loss + diffusion in hadronic phase	recombination + fragmentation
UrQMD (arXiv:1211.6912)	PYTHIA, no shadowing	3+1d ideal hydro evolution	HQ transport (Langevin) + collisional energy loss	recombination + fragmentation

Quarkonia

- **At the low-p_T (p_T > 0) :**
  - ALICE observes a constant suppression vs centrality.
  - The suppression is smaller than what was observed at RHIC:
    - predicted signature for regeneration



Quarkonia

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  - ✳ ALICE observes a constant suppression vs centrality.
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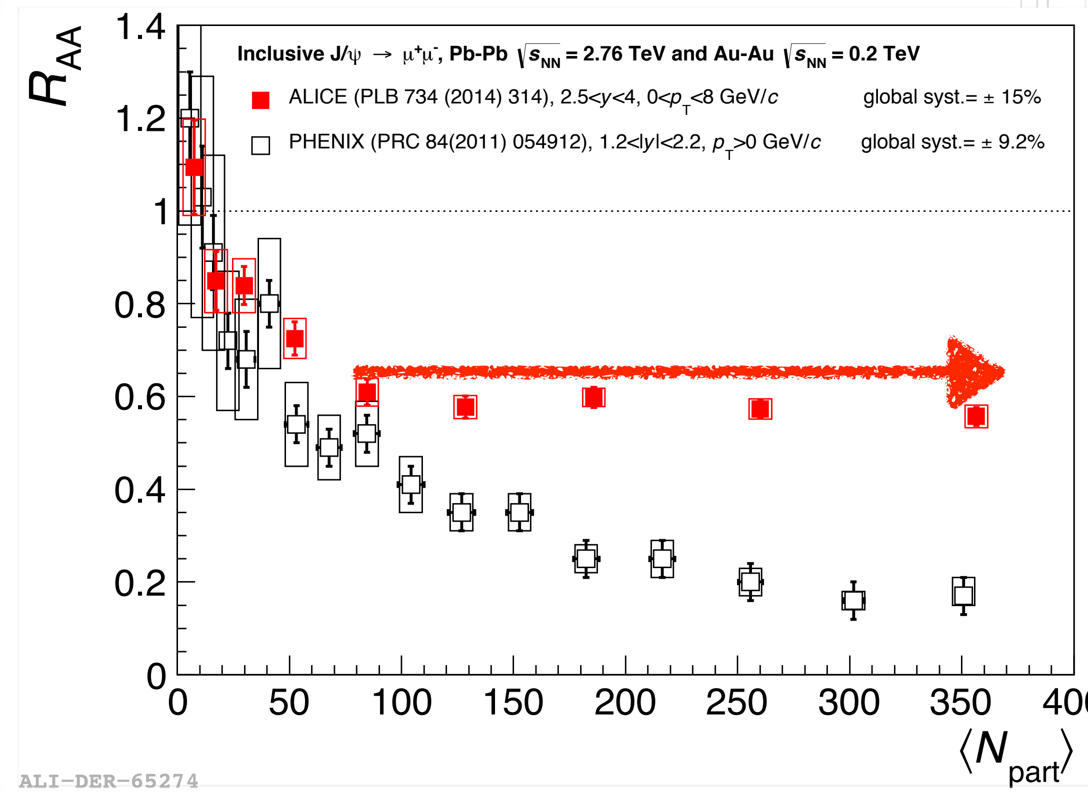
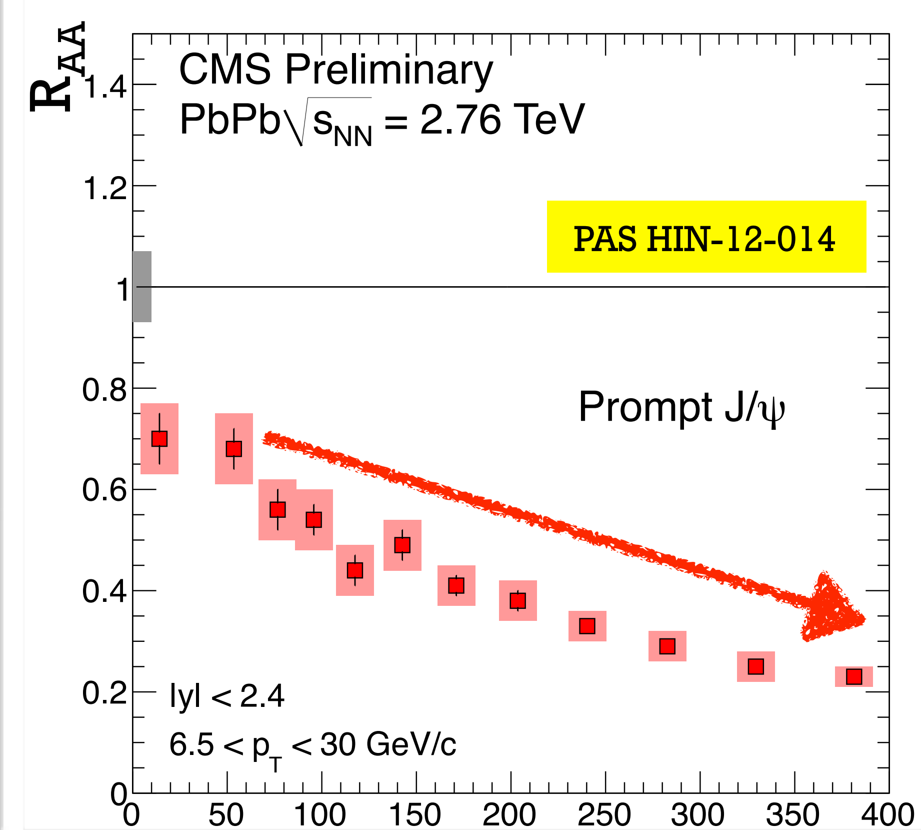


- ✳ **At high-p_T (p_T > 6.5 GeV/c)** :
  - ✳ CMS observed a suppression for J/ψ with $p_T > 6.5$ GeV/c.
  - ✳ Similar (but slightly smaller) suppression than at RHIC.

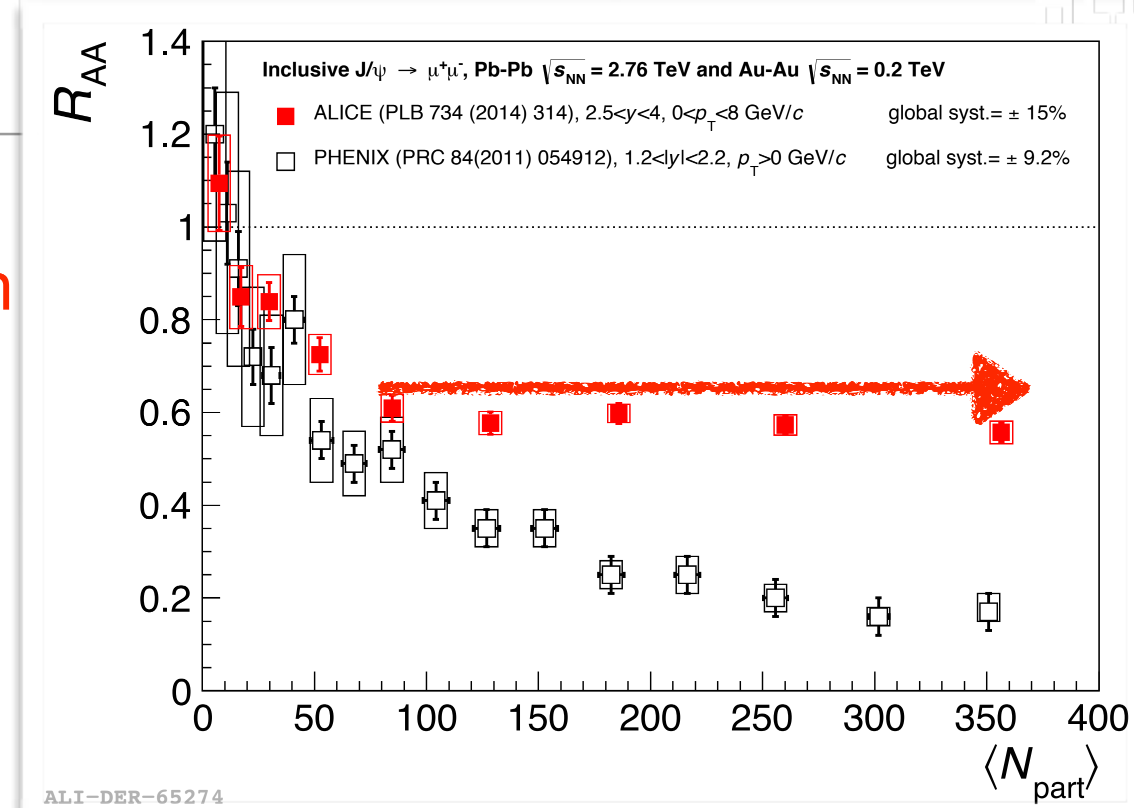


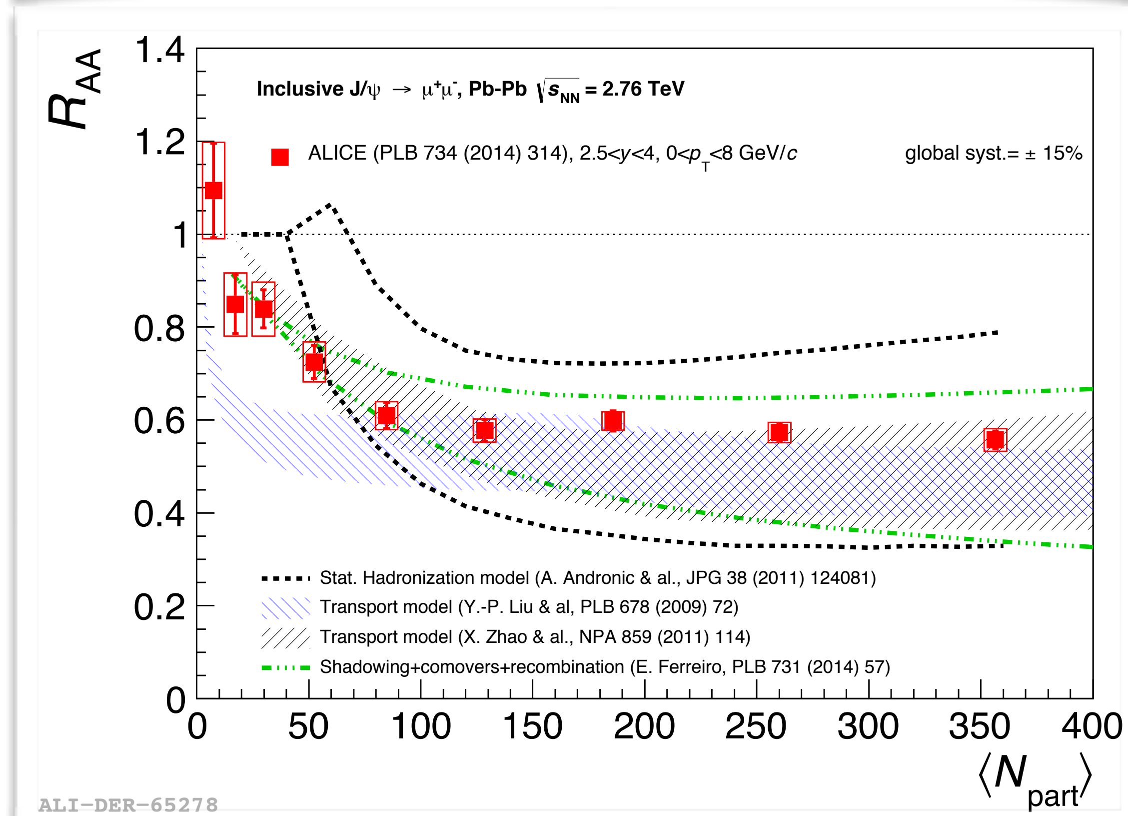
Quarkonia

- **At the low-p_T (p_T > 0) :**
  - ALICE observes a constant suppression vs centrality.
  - The suppression is smaller than what was observed at RHIC:
    - predicted signature for regeneration

Regeneration involves mainly low-p_T charm quarks?
Charm quarks take part in the evolution of the system?

- Models that include recombination of charm quark in a deconfined system can describe J/ψ suppression.

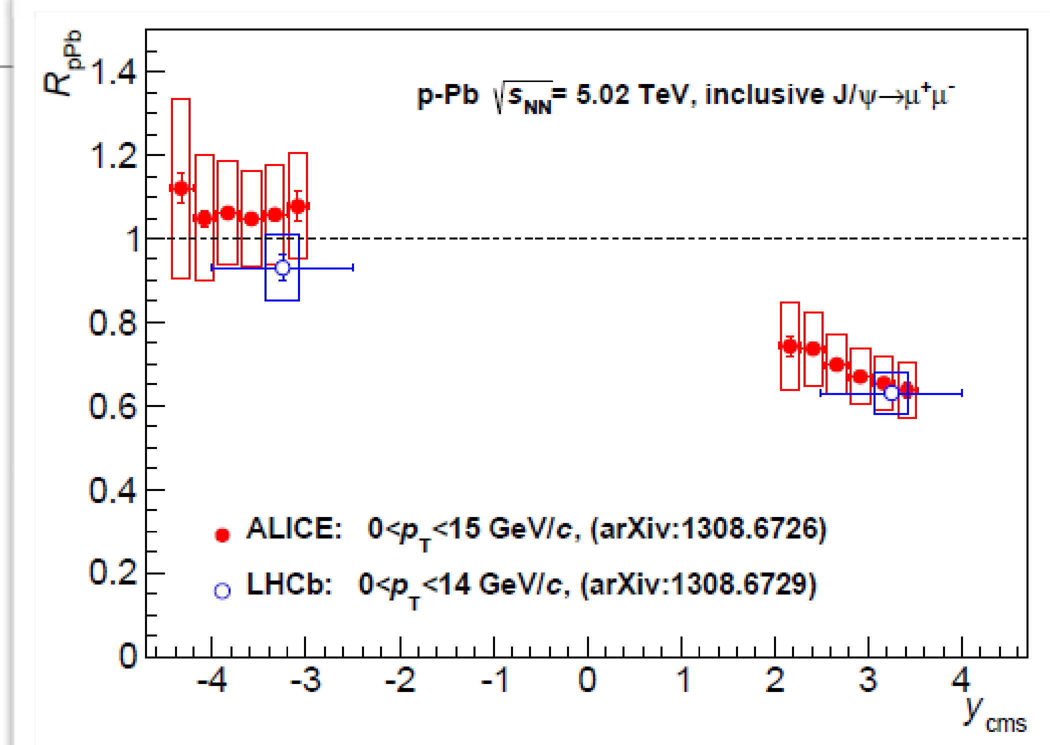


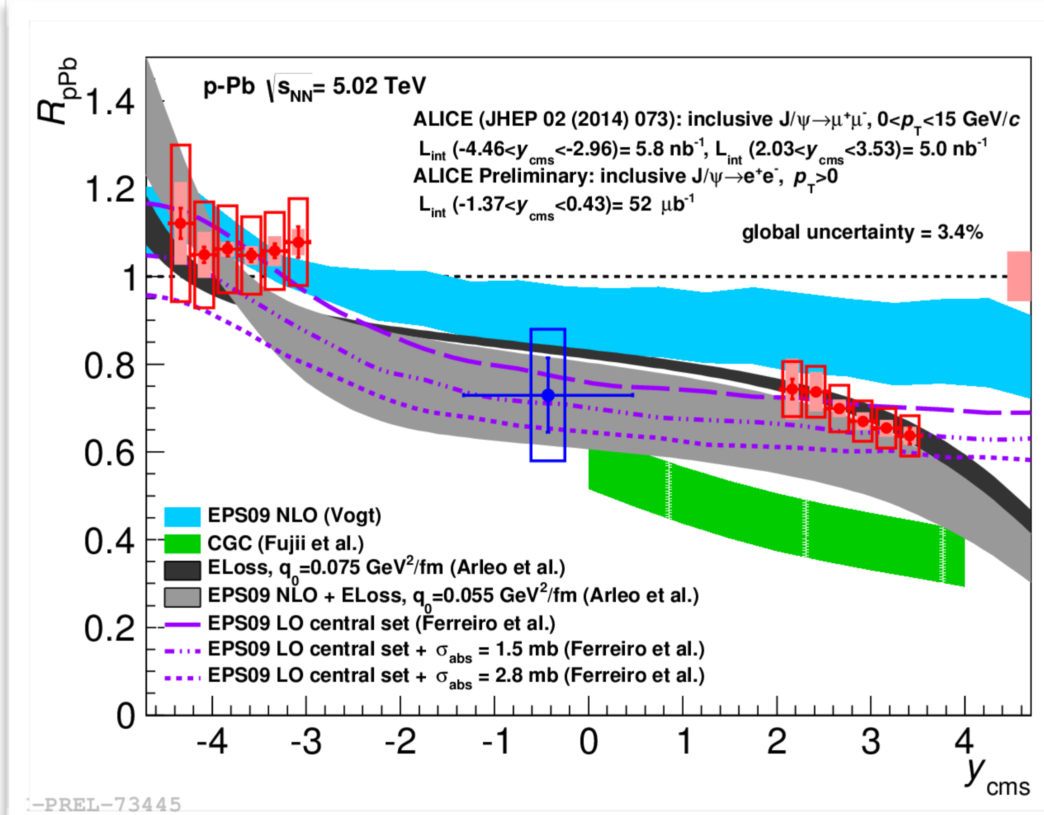


Quarkonia in pPb

arXiv:1308.6726

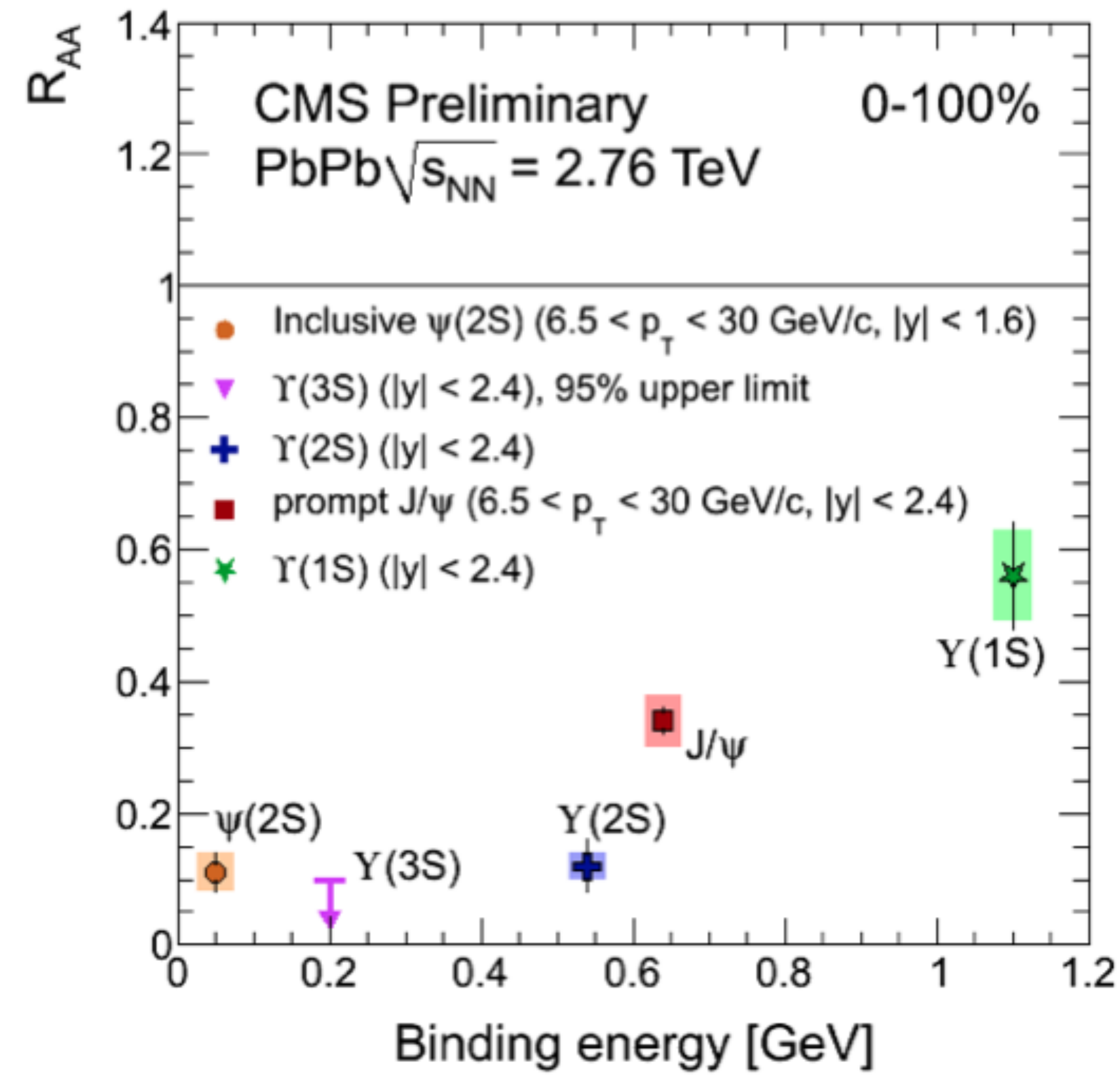
- Differently from open HF, J/ψ production is sensitive to cold nuclear matter effects:
- at forward rapidity the J/ψ production is suppressed by about 20%
- models including shadowing and coherent energy loss





-onia suppression at LHC

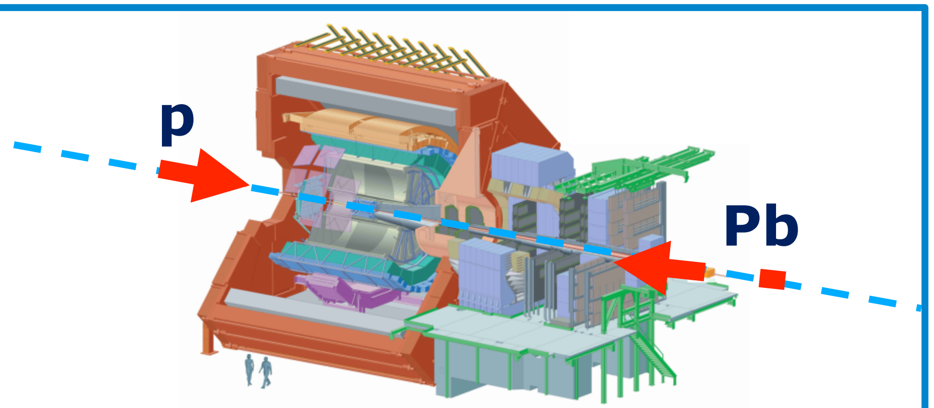
- Putting all quarkonia results together from the CMS experiment:
  - Excited states are always more suppressed than the ground state.
  - Is really binding energy driving the quarkonia suppression?
  - Important caveats:
    - centrality and pT ranges
    - regenerations
    - initial state effects (pA!!)



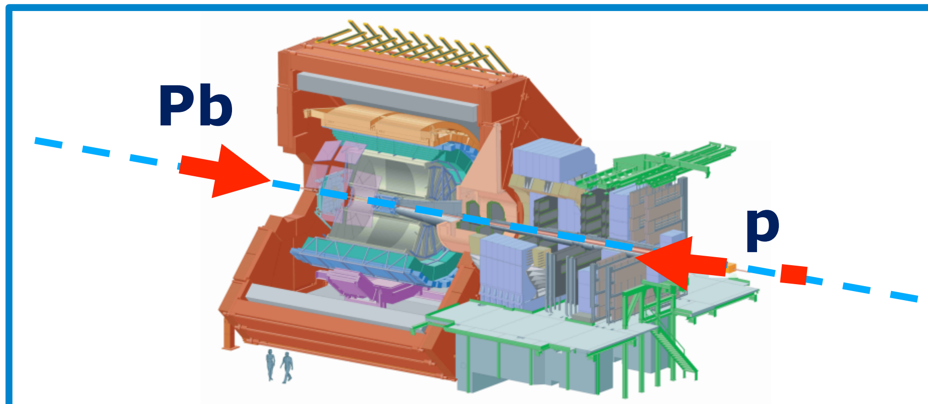
J/ψ in pA collisions

- J/ψ production in pA collisions measured by the ALICE and LHCb detectors.
  - Both of them are “asymmetric” detector for what concerns J/ψ reconstruction.

- Data collected in two configurations:
  - p-Pb:
    - p going through the muon arm (forward direction)
    - x investigated:
  - Pb-p:
    - Pb going though the muon arm (backward direction)
    - x investigated:



$2.03 < y_{CMS} < 3.53$



$-4.46 < y_{CMS} < -2.96$

J/ψ in pA collisions

arXiv:1308.6726

* Differently from open HF, J/ψ production is sensitive to cold nuclear matter effects:
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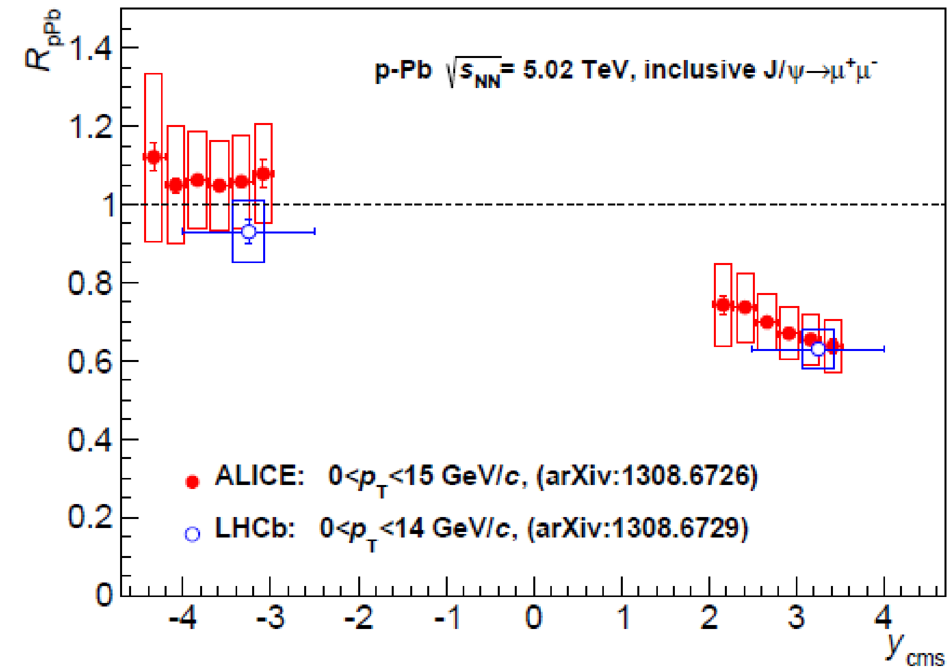
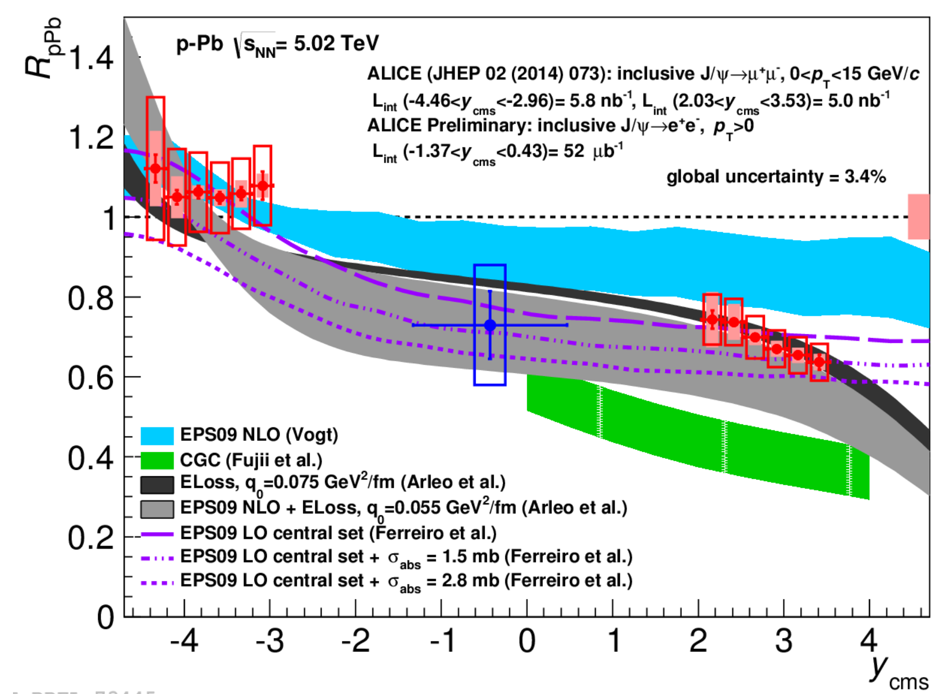
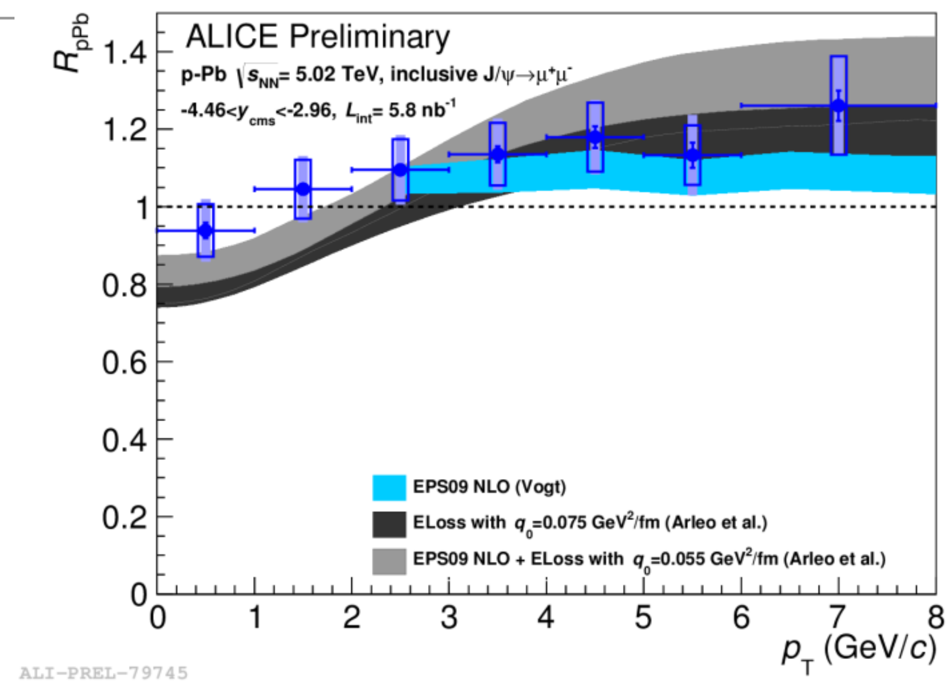


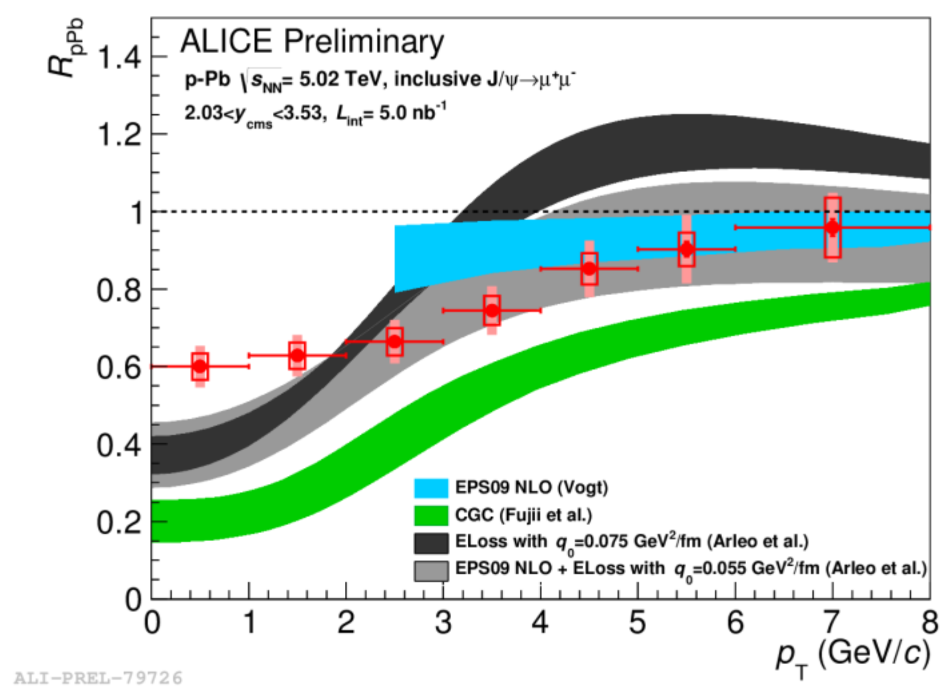


I-PREL-73445

J/ψ in pA collisions

- Differently from open HF, J/ψ production is sensitive to cold nuclear matter effects:
  - at forward rapidity the J/ψ production is suppressed by about 20%
  - models including shadowing and coherent energy loss
  - at forward rapidity the suppression seems to be driven by low-pT J/ψ
  - at backward rapidity the slight enhancement seems to be driven by high-pT J/ψ



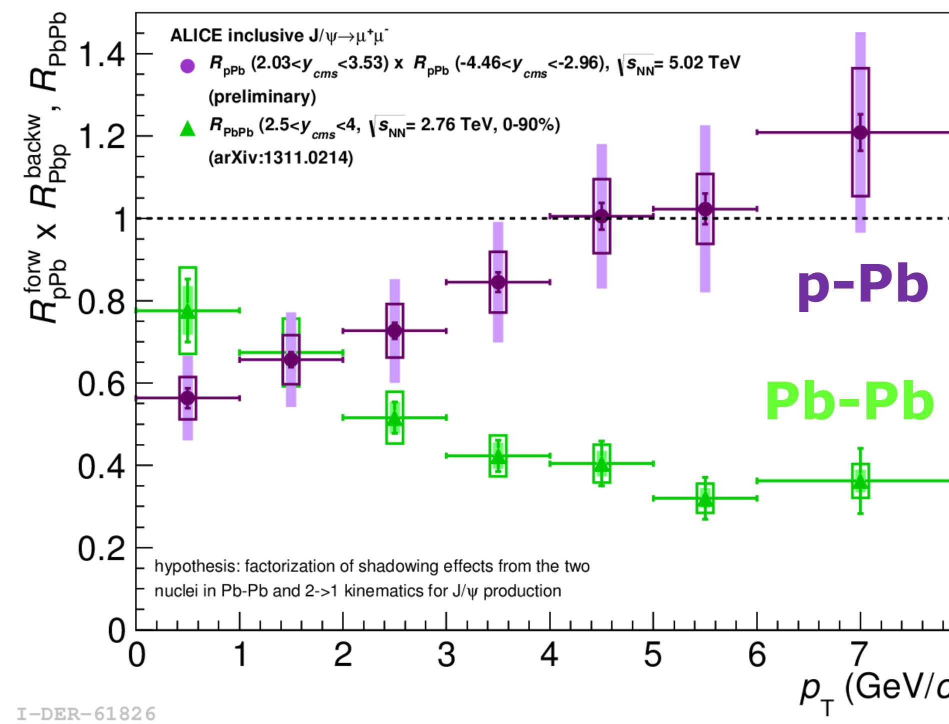


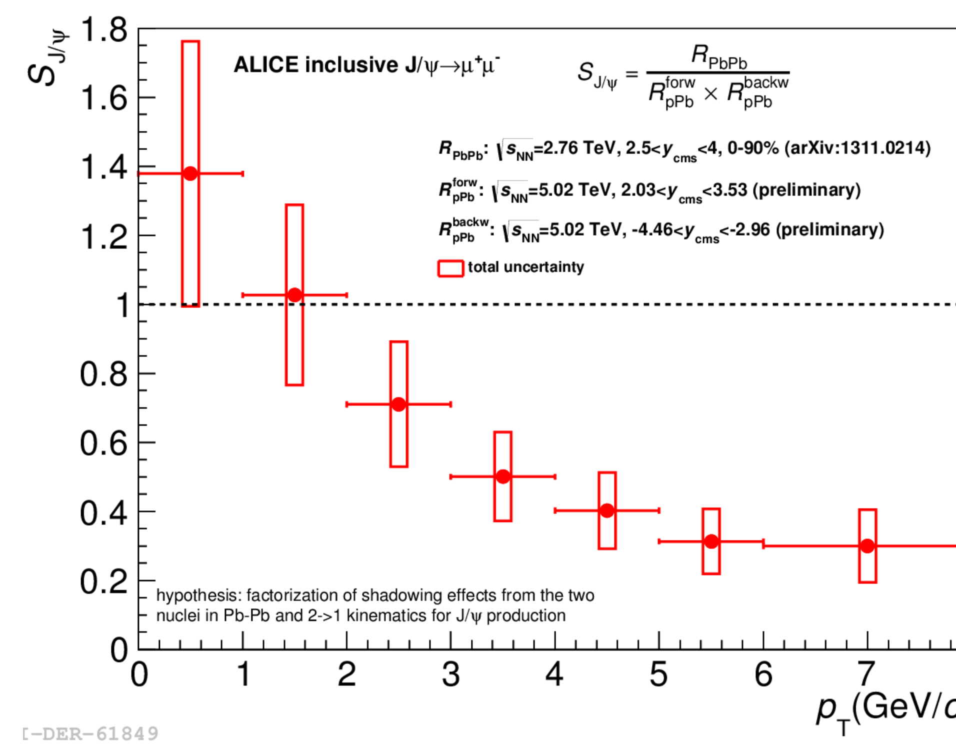
When we consider all data together…

- Evaluate CNM effects with pA data:
  - 2 ➜ 1 kinematics for J/ψ production
  - CNM effects factorize in pA
  - CNM evaluated as R_{pA} x R_{Ap} since the x coverage is similar as PbPb

- CNM effects don't explain the suppression observed at high-pT, that it is then coming from hot medium effects.

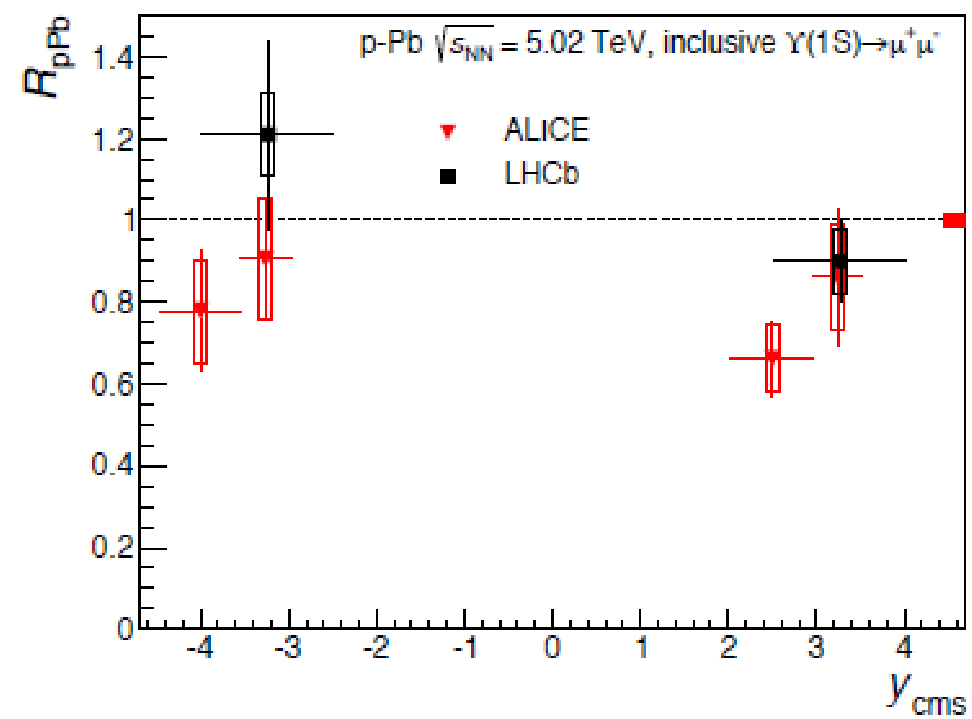
- Clear pT trend observed when considering the ratio of the R_{AA} in the two collisions system:
  - suppression at high-pT
  - enhancement at low-pT

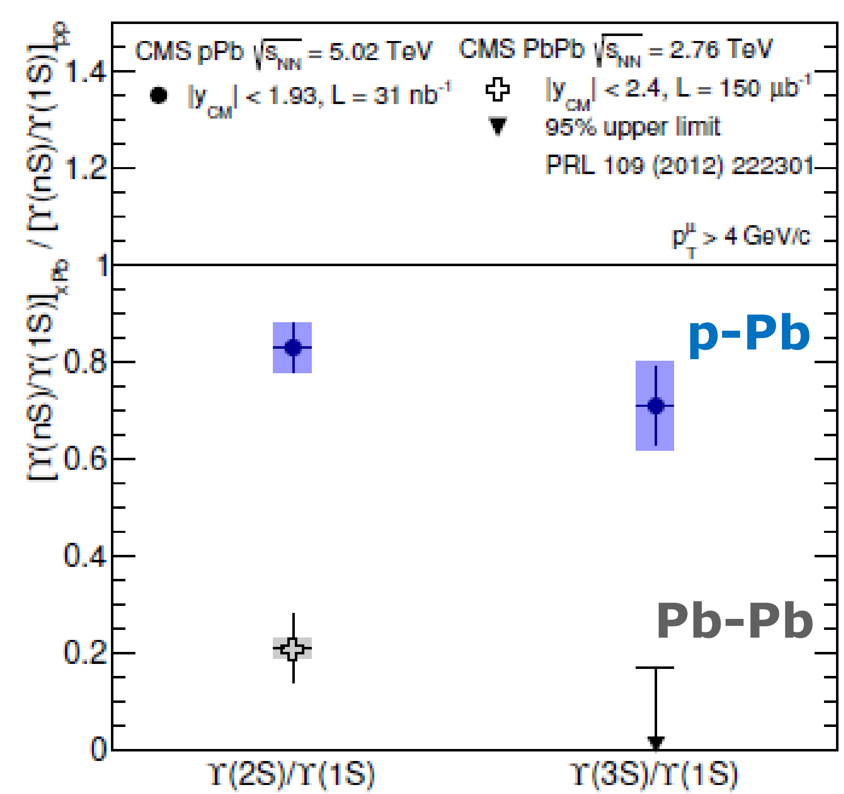




ϒ production in p-Pb

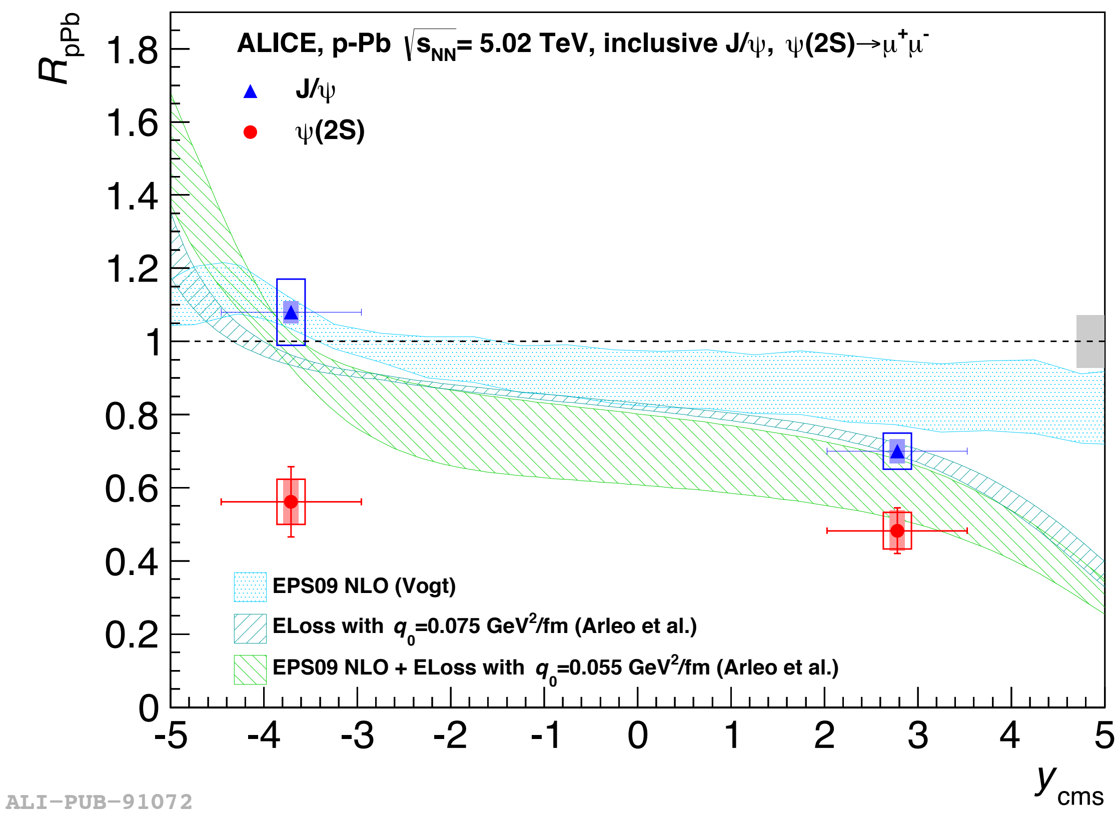
* ϒ production in p-Pb collisions measured by ALICE and LHCb at forward rapidity, by CMS at mid-rapidity.
    * Similar suppression for ϒ(1S) at forward and backward rapidity, even if LHCb data systematically higher than ALICE ones
    * In p-Pb collisions excited ϒ states suppressed with respect to pp collisions.
    * Similar effects for the ϒ(2S) and ϒ(3S) with respect to the ground state.





ψ(2S) in pPb

- R_{pPb} multiplicity and momentum integrated:
  - Both backward and forward rapidity clear suppression observed. Final state effect?



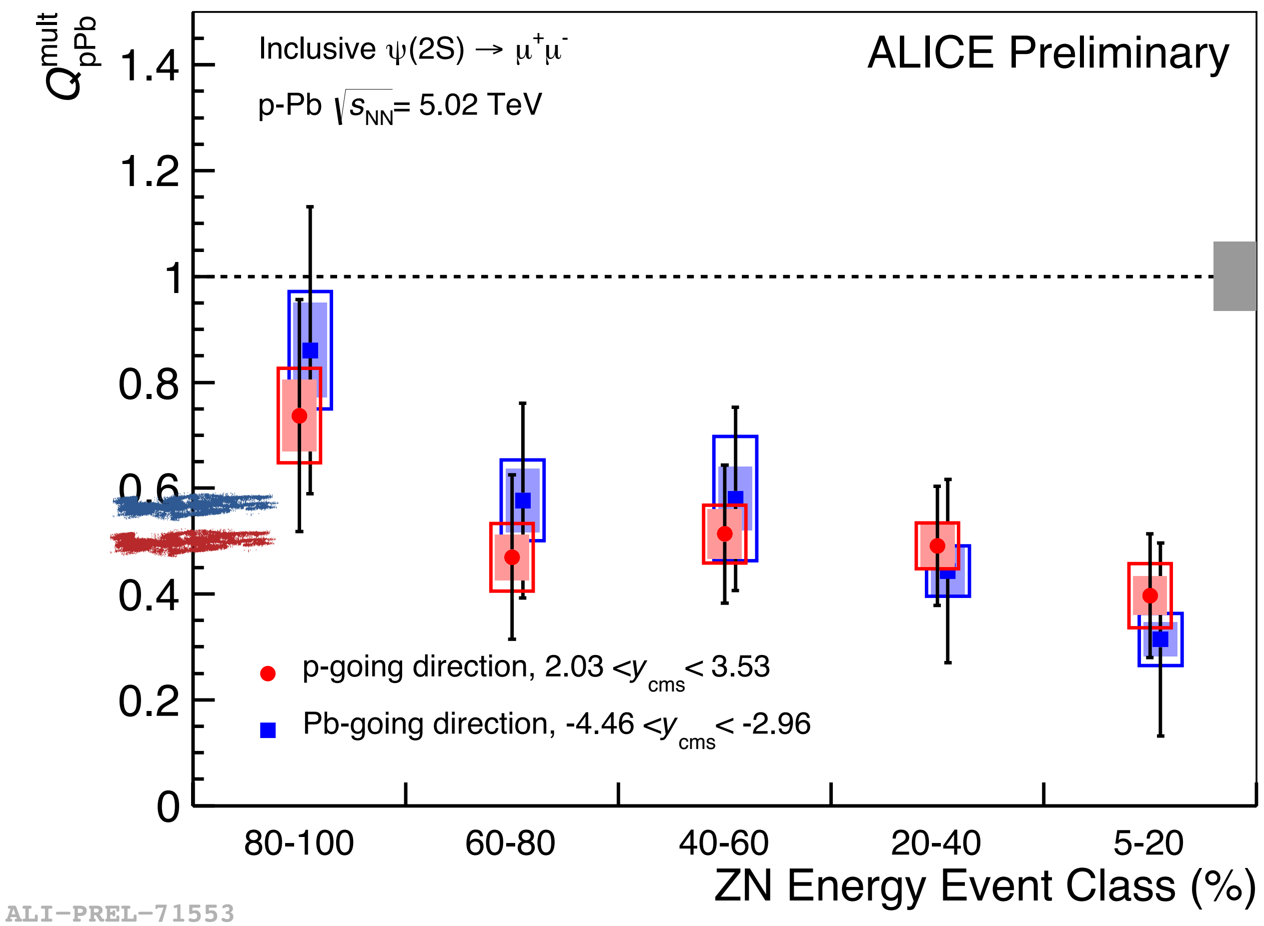
ψ(2S) measured in

- **forward rapidity region**
  - **$2.03 < y_{CMS} < 3.53$ (forward)**
  - **$-4.46 < y_{CMS} < -2.96$ (backward)**
  - **$p_T > 0$**

ψ(2S) Q_{pPb}

ψ(2S) ➜ μ+μ- measured in

- forward rapidity region
  - **2.03 < y_{CMS} < 3.53 (forward)**
  - **-4.46 < y_{CMS} < -2.96 (backward**



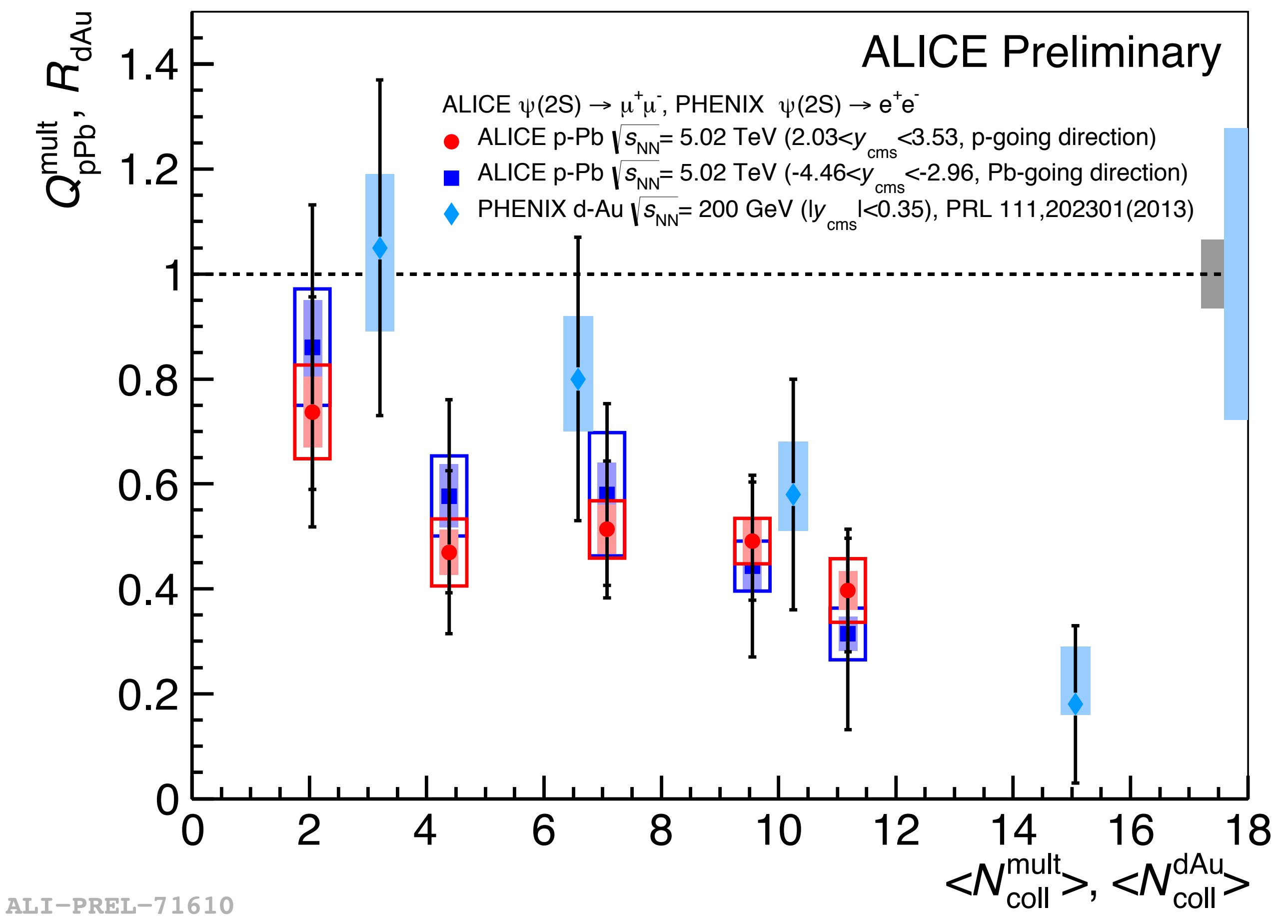
- Focus on the ZN estimator that it is considered to be the less biased.
- Multiplicity integrated values for **backward** and **forward** rapidity

Clear suppression of ψ(2S)
Increasing suppression from low to high multiplicity events
Similar suppression at both backward and forward rapidity

ψ(2S) Q_{pPb}

ψ(2S) ➜ μ+μ- measured in

- forward rapidity region
  - **2.03 < y_{CMS} < 3.53 (forward)**
  - **-4.46 < y_{CMS} < -2.96 (backward**

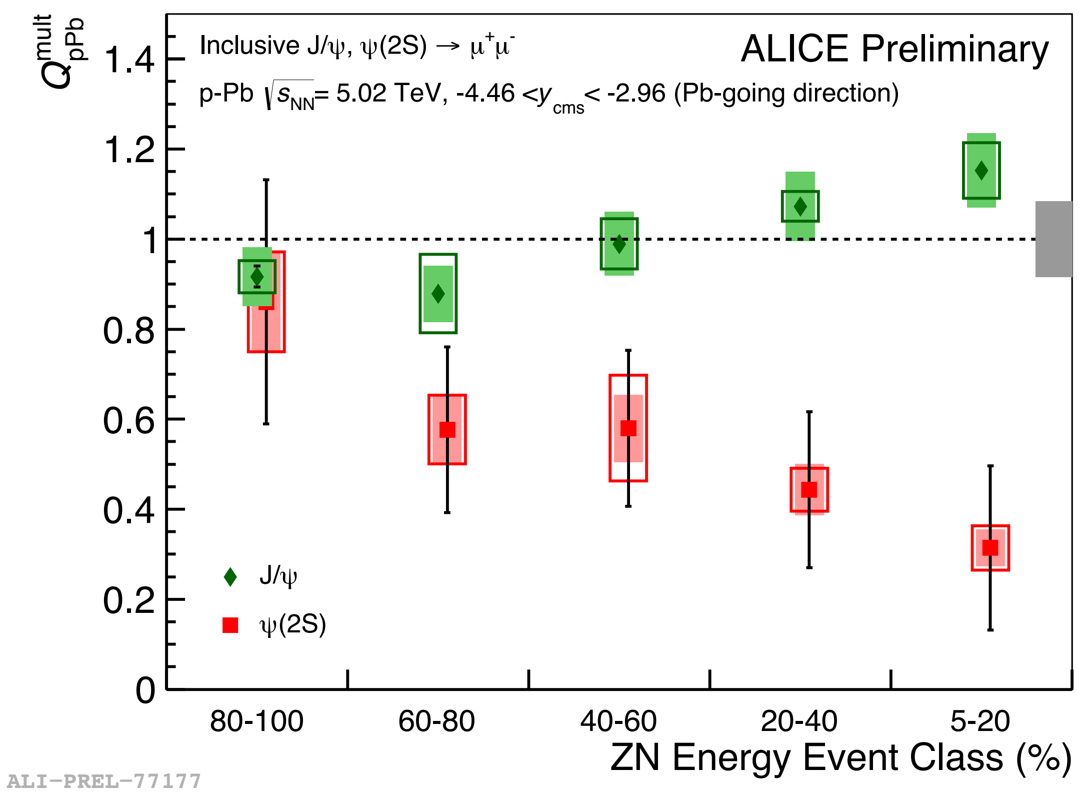


- Focus on the ZN estimator that it is considered to be the less biased.
- Multiplicity integrated values for **backward** and **forward** rapidity

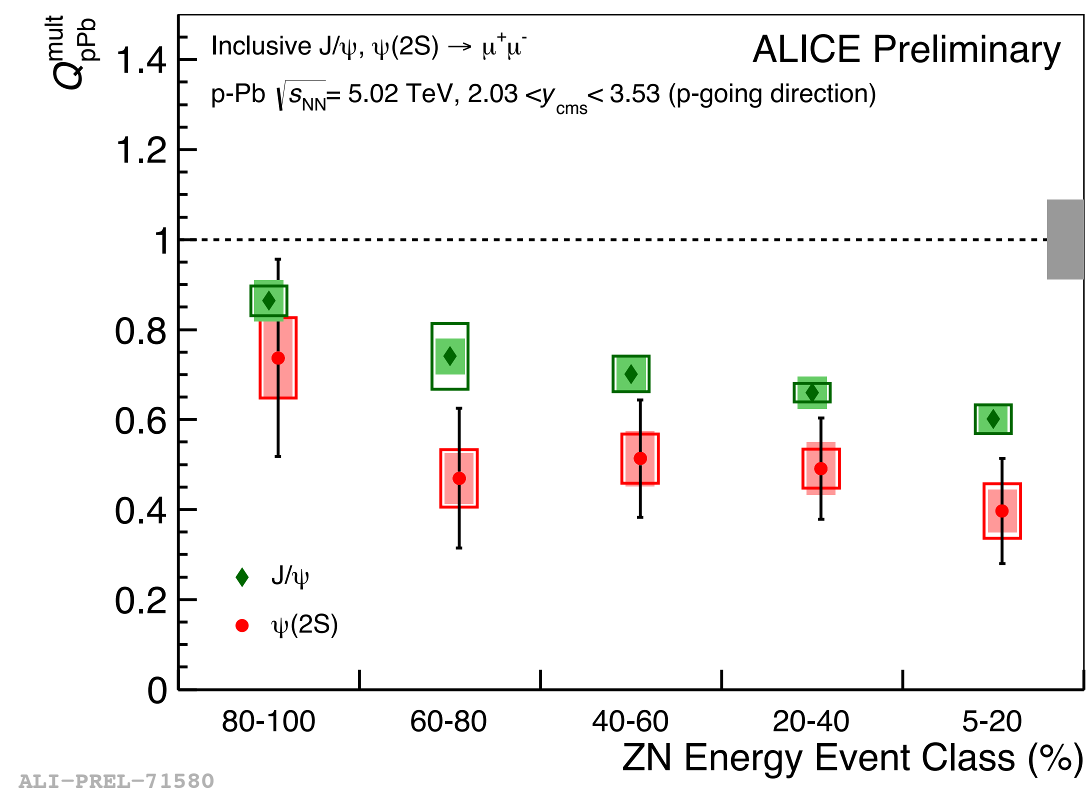
Clear suppression of ψ(2S)
Increasing suppression from low to high multiplicity events
Similar suppression at both backward and forward rapidity
Similar trend observed at RHIC!

ψ(2S) Q_{pPb}

Backward rapidity



Forward rapidity



Forward rapidity: J/ψ and ψ(2S) show a similar decreasing trend vs event activity
Backward rapidity: J/ψ and ψ(2S) clear different behavior, ψ(2S) is more suppressed in high multiplicity events.

Wrap up (IV): Q_{pPb}

- D mesons: no multiplicity dependent modification of the spectra is observed within uncertainties.

- J/ψ Q_{pPb}:
  - **Backward rapidity**: Increase of Q_{pPb} for increased event activity; stronger enhancement at high-p_T
  - **Forward rapidity**: Decrease of Q_{pPb} for increased event activity; stronger suppression at low-pT

- ψ(2S) Q_{pPb}:
  Increasing suppression from low to high multiplicity events
  Similar suppression at both rapidities