Measurements of heavy flavours

Alessandro Grelli

Physics Utrecht
ΕΜΜΕΦ

Outline

- **Heavy-flavours**
  - Indroduction
  - Heavy quark energy loss
  - Observables
- **Charm-Beauty production**
  - pp collisions
  - A-A collisions
- **Conclusions**

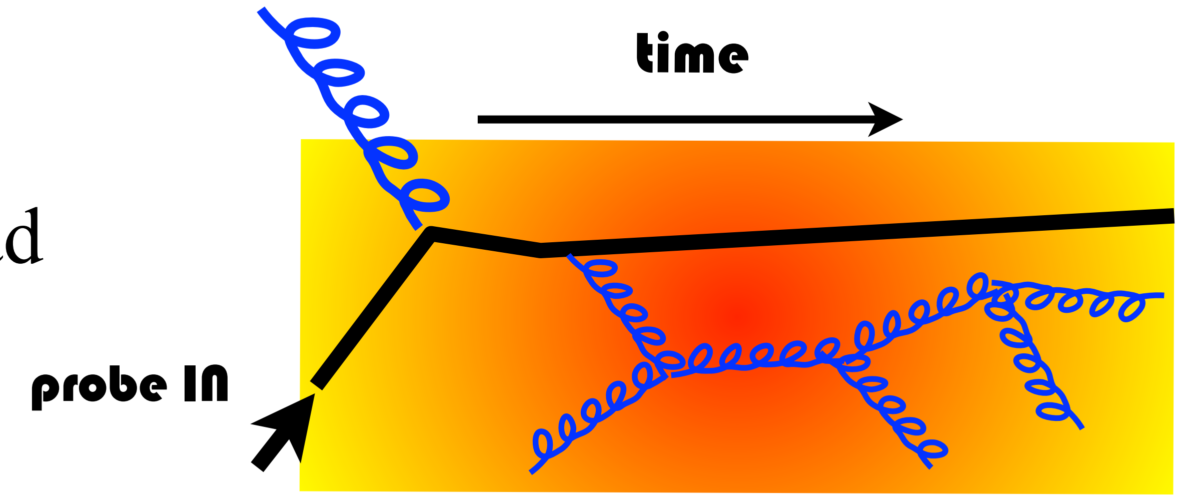
Heavy quark: *General Picture*

Hard probe (charm and beauty quarks):

- Produced at the early stage of the collision (*large mass requires high* Q^2, $\Delta t \sim 0.1\ fm$)
- pQCD can be used to calculate initial cross sections
- Charm is abundant with respect heavier quarks
- Traverse the hot and dense medium:
  - ✓ Thermal production in the medium from QGP expected to do not play a major role (depend from initial temperature) ***Phys. Rev. C56, 2707 (1997)***
  - ✓ Thermal production from hadronic matter (i.e $\pi N \rightarrow \Lambda_c D$) expected to play a minor effect
- Can be accessed by studying heavy-mesons production (i.e D and B meson production)

Heavy quark: *General Picture*

- ☑ Heavy quarks are expected to lose less energy than light quarks and gluons due to color-charge and dead cone effect → higher penetrating power into QCD medium.



Yu. Dokshitzer and D.E. Kharzeev, Phys.Lett. B 519 199-206 (2001).
Armesto, Carlos A. Salgado and Urs A. Wiedemann. PRD 69 (2004) 114003

M. Djordjevic, M. Gyulassy, Nucl. Phys. A733 (2004) 265.

$E_{loss}(light) > E_{loss}(c) > E_{loss}(b)$

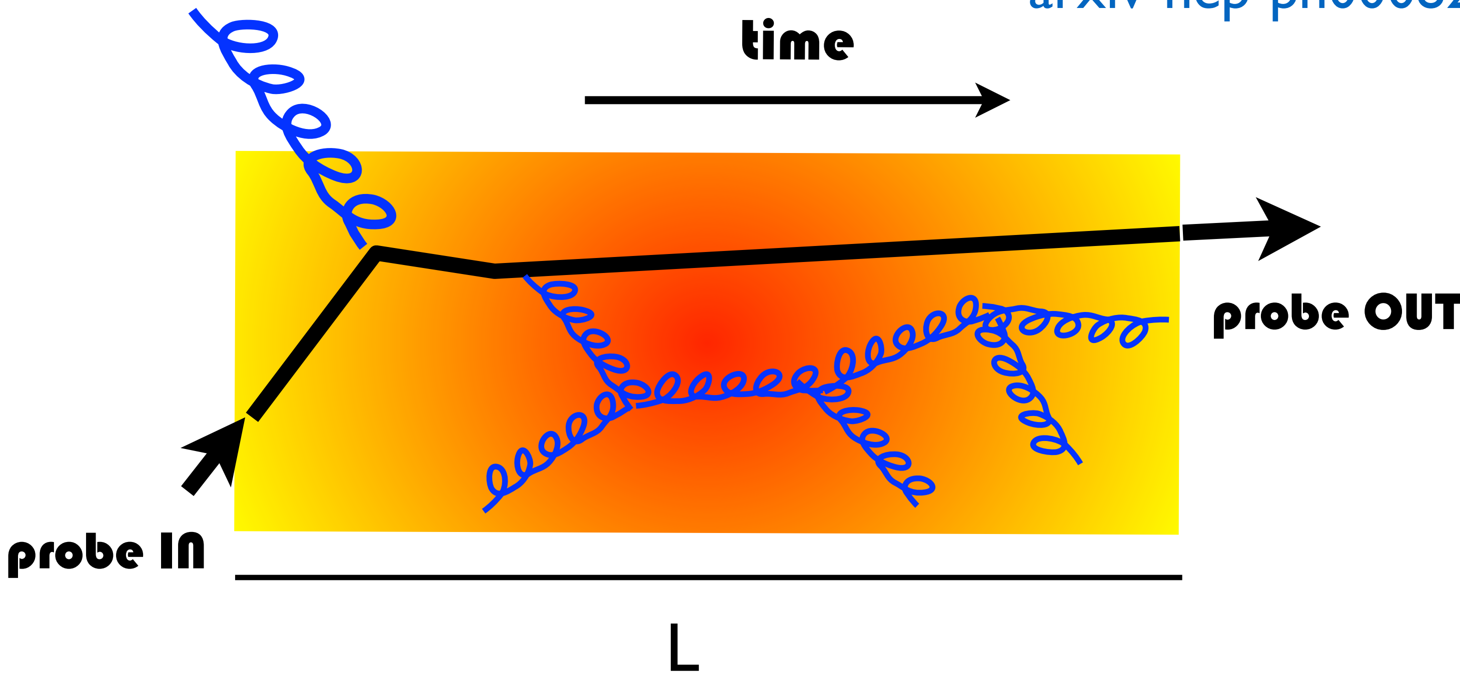
➔ *Let's see it a bit more in detail*

Radiative Energy Loss: *Color charge dependence*

- Example BDMPS-Z formalism:

Phys.Rev.D71:054027, 2005

arxiv-hep-ph0008241



Radiated gluon energy:

$$\hat{q} = \frac{\langle k_T^2 \rangle}{\lambda}$$

transport coeff.

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R \sqrt{\frac{\hat{q} L^2}{\omega}}$$

Casimir coupling factor: 4/3 for quarks and 3 for gluons

⇨ Color charge dependence of radiative Eloss

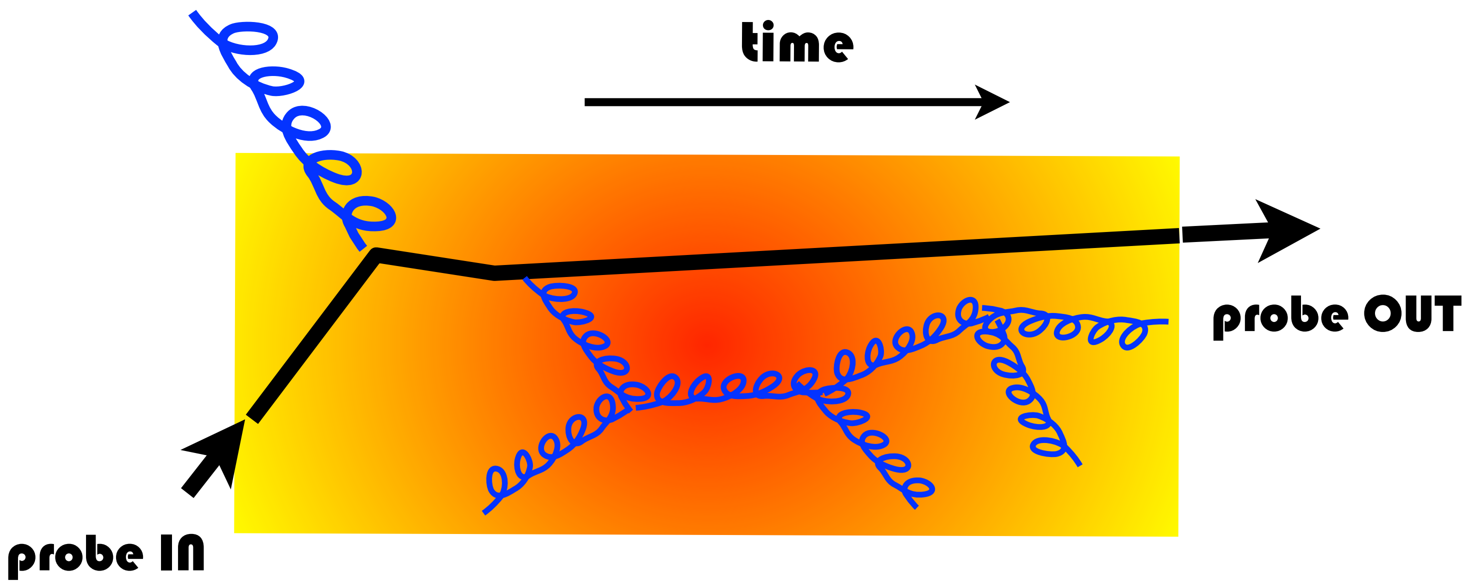
$$\Delta E_g > \Delta E_{c \approx q}$$

M. Djordjevic, M. Gyulassy, Nucl. Phys. A733 (2004) 265.

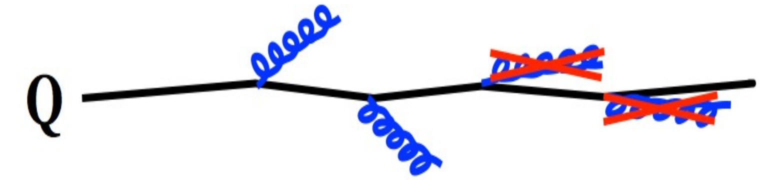
Yu. Dokshitzer and D.E. Kharzeev, Phys.Lett. B 519 199–206 (2001). N. Armesto, C. A. Salgado and U. A. Wiedemann. PRD 69 (2004) 114003

Radiative Energy Loss: *Mass dependence*

- In vacuum gluon radiation suppressed for $\theta < m_Q/E_Q$ (dead cone effect)



Gluon radiation supressed:



Gluonsstrahlung probability

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

- With dead cone → lower energy loss due to “angle-dependent” factor

Yu. Dokshitzer and D.E. Kharzeev, Phys.Lett. B 519 199–206 (2001).

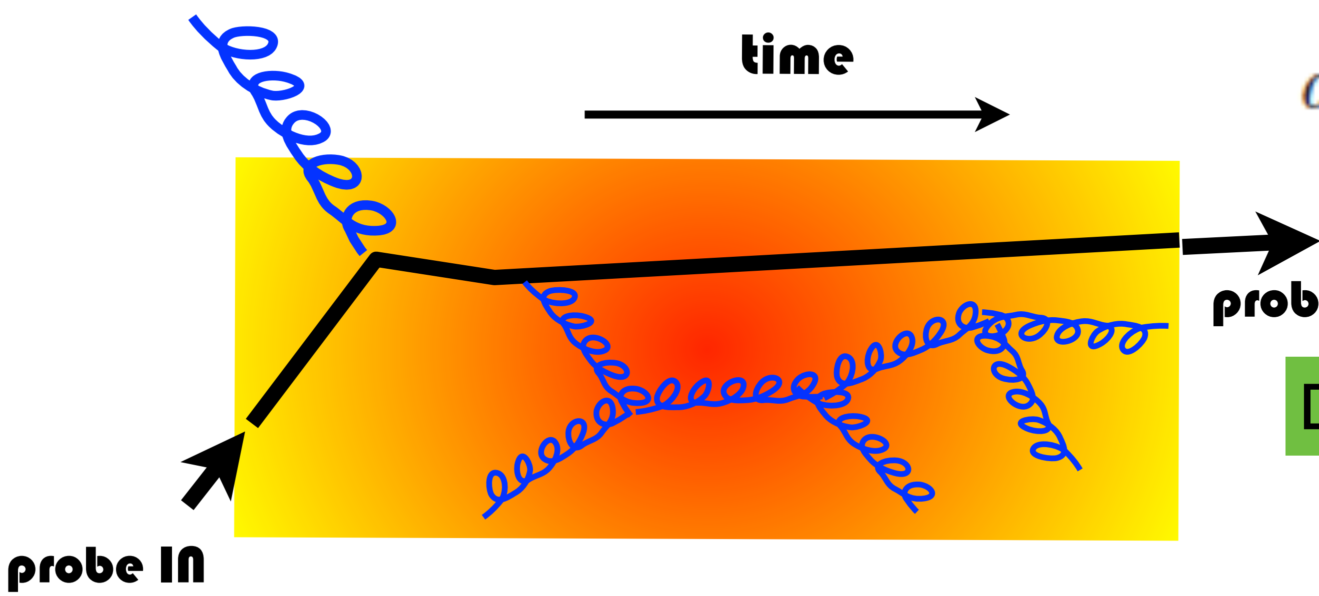
$$\omega \frac{dI}{d\omega}\bigg|_{HEAVY} = \omega \frac{dI}{d\omega}\bigg|_{LIGHT} \times \left(1 + \left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^{-2}$$

⇨ $E_{loss}(c) > E_{loss}(b)$

M. Djordjevic, M. Gyulassy, Nucl. Phys. A733 (2004) 265. A. Salgado and U. A. Wiedemann. PRD 69 (2004) 114003

Mass dependence in collisional energy loss

- If use **Langevin formalism:**



$$dx = \frac{p}{E}dt,$$
$$dp = -\Gamma(p)\,p\,dt + \sqrt{2D(p+dp)\,dt}\,\rho$$

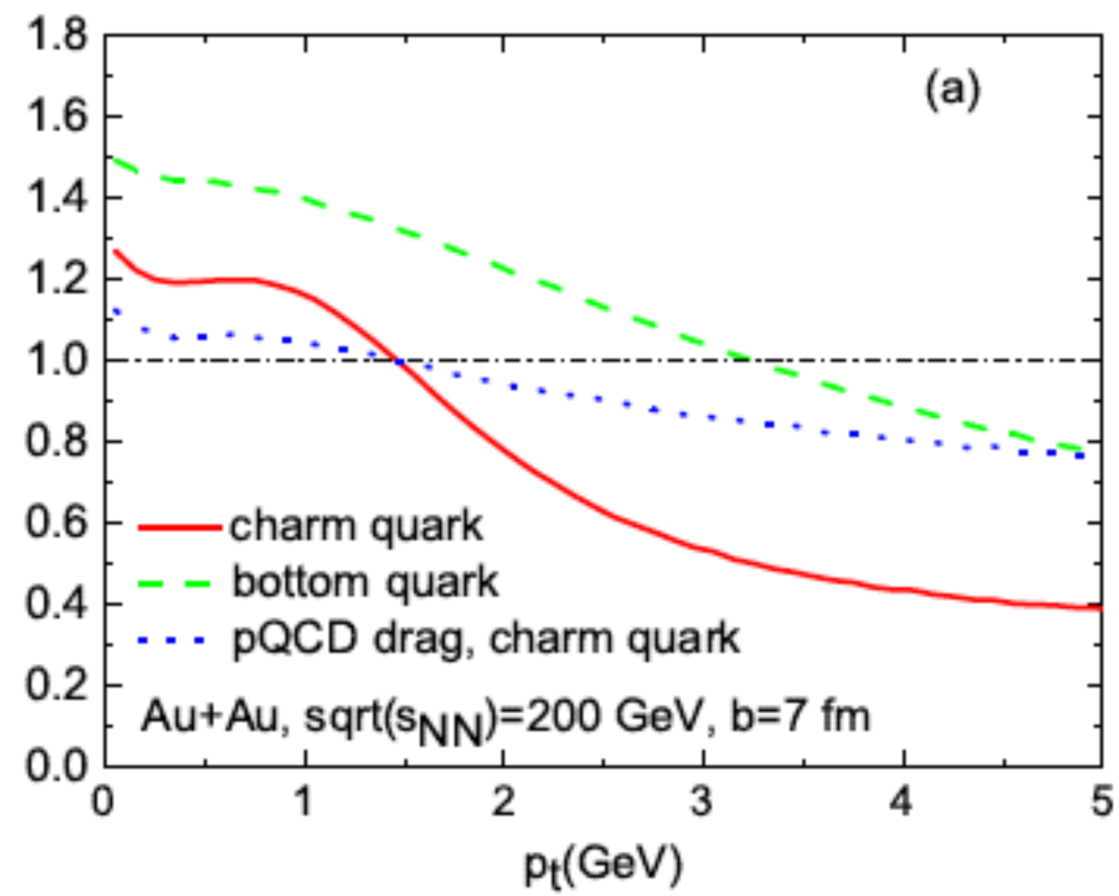
Drag coefficient: E_{loss} term

Diffusion term

- Both the terms: $\Gamma(p)$ e D are proportional to $1/m_Q$

- Lower E_{loss} for *b* quark

He, Rapp, Fries, PRC86 (2012) 014903



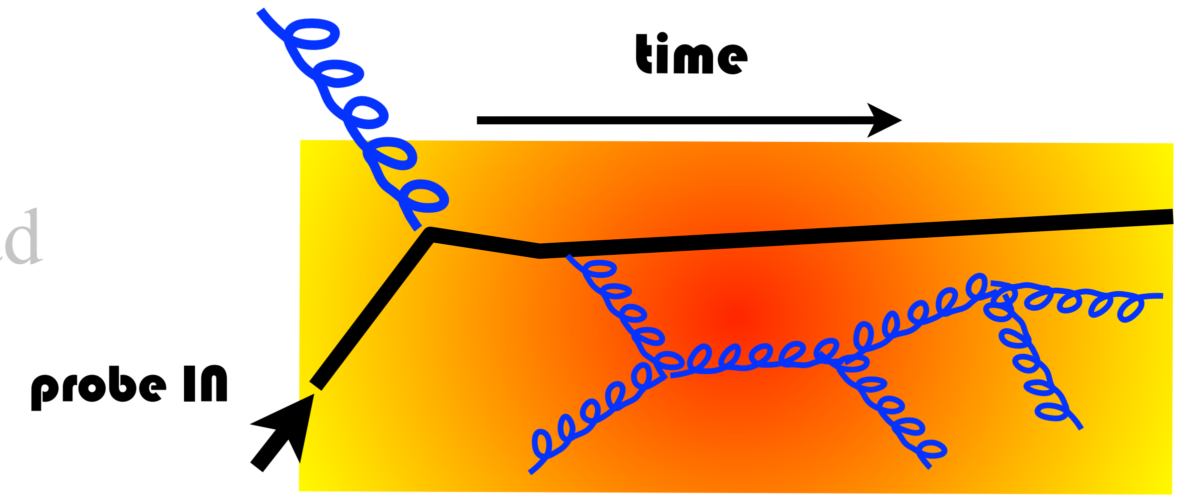
Heavy quark: *General Picture*

- Heavy quarks are expected to lose less energy than light quarks and gluons due to color-charge and dead cone effect → higher penetrating po

Therefore ....

Yu. Dokshitzer and D.E. Kharzeev, Phys.Lett. B 519 199-206 (2001).
Armesto, Carlos A. Salgado and Urs A. Wiedemann. PRD 69 (2004) 114003

M. Djordjevic, M. Gyulassy, Nucl. Phys. A733 (2004) 26



- What about charm strange hadrons (D dominant mechanism of charm hadron fo ion at low p charm hadrons largely enhanced.

I. Kuznetsova and J. Rafelski, Eur.Phys.J. C51 (2007) 113-133.

M. He, R. J. Fries and R. Rapp, arXiv:1204.4442 [nucl-th].

E_{loss}(light) > E_{loss}(c) > E_{loss}(b)

Nuclear Modification Factor

- Production of hard probes in AA expected to scale with the number of nucleon-nucleon collisions N_{coll} (binary scaling)

Nuclear Modification Factor

- Production of hard probes in AA expected to scale with the number of nucleon-nucleon collisions N_{coll} (binary scaling)
- Osservabile: Nuclear Modification Factor

$$R_{AA}^{D}(p_T) = \frac{dN_{AA}^{D}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}^{D}/dp_T}$$

particle production in A-A

Nuclear Modification Factor

- Production of hard probes in AA expected to scale with the number of nucleon-nucleon collisions N_{coll} (binary scaling)
- Osservabile: Nuclear Modification Factor

$$R_{AA}^{D}(p_T) = \frac{dN_{AA}^{D}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}^{D}/dp_T}$$

Production cross-section in pp

Nuclear Modification Factor

- Production of hard probes in AA expected to scale with the number of nucleon-nucleon collisions N_{coll} (binary scaling)
- Osservabile: Nuclear Modification Factor

$$R_{AA}^{D}(p_T) = \frac{dN_{AA}^{D}/dp_T}{\langle T_{AA} \rangle \times d\sigma_{pp}^{D}/dp_T}$$

Nuclear overlap function

Nuclear Modification Factor

- Production of hard probes in AA expected to scale with the number of nucleon-nucleon collisions N_{coll} (binary scaling)
- Osservabile: Nuclear Modification Factor

$$R^D_{AA}(p_T) = \frac{dN^D_{AA}/dp_T}{\langle T_{AA}\rangle \times d\sigma^D_{pp}/dp_T}$$

Nuclear overlap function

Convolution of the thinkness function of A and B(A), $T_{A(B)} = \int \rho_{A,B}(\vec{b},z)dz$

$$T_{AB}(\vec{b}) = \int d\vec{s}\, T_A(\vec{s})T_B(\vec{s}-\vec{b}),$$

$$\langle T_{AB}\rangle \equiv \frac{\int T_{AB}(\vec{b})(1-e^{-\sigma^{inel}_{nn}T_{AB}(\vec{b})})\,d\vec{b}}{\int(1-e^{-\sigma^{inel}_{nn}T_{AB}(\vec{b})})\,d\vec{b}} = \langle N_{coll}\rangle/\sigma^{inel}_{nn}$$

$\langle N_{coll}\rangle$ from Glauber model calculation

arXiv:0907.4175v2 [nucl-th] 3 Aug 2009

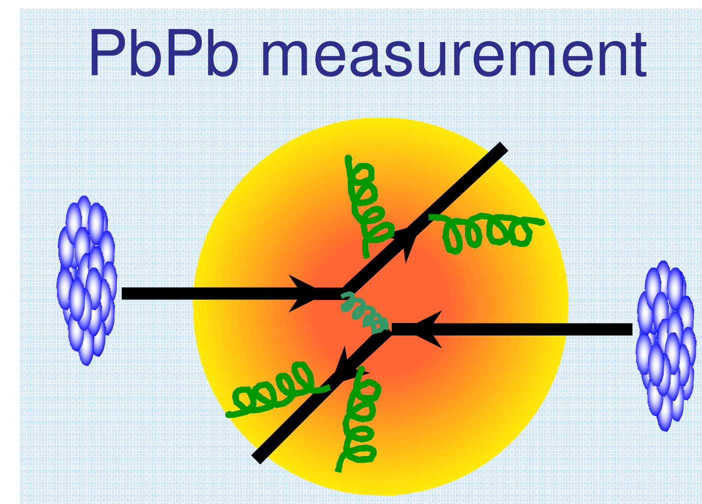
arXiv:nucl-ex/0302016v3 4 Dec 2004

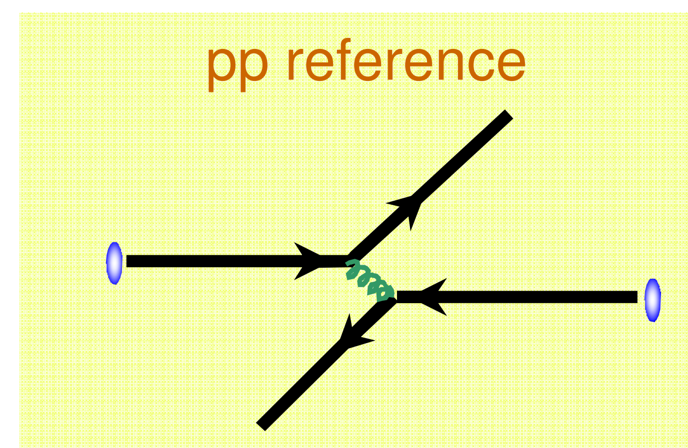
Nuclear Modification Factor

- Production of hard probes in AA expected to scale with the number of nucleon-nucleon collisions N_{coll} (binary scaling)

- Osservabile: Nuclear Modification Factor

$$R_{AA}^{D}(p_T) = \frac{dN_{AA}^{D}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}^{D}/dp_T} = \frac{QCD\ Medium}{QCD\ vacuum}$$



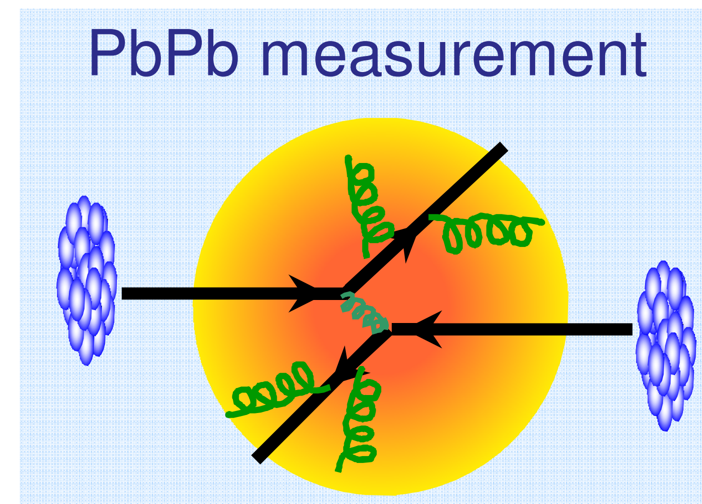


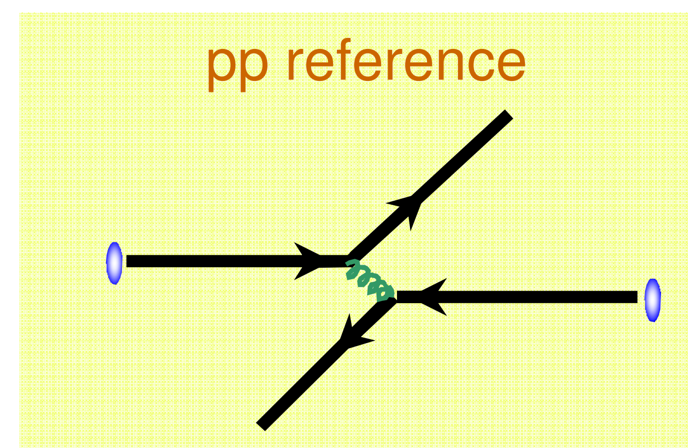
Nuclear Modification Factor

- Production of hard probes in AA expected to scale with the number of nucleon-nucleon collisions N_{coll} (binary scaling)

- Osservabile: Nuclear Modification Factor

$$R^D_{AA}(p_T) = \frac{dN^D_{AA}/dp_T}{\langle T_{AA}\rangle \times d\sigma^D_{pp}/dp_T} = \frac{\text{QCD Medium}}{\text{QCD vacuum}}$$





- What are the possibilities?
  - If no nuclear effects present: $R_{AA} = 1$
  - Effects of the hot and dense medium produced in the collision breakup binary scaling: $R_{AA} \neq 1$

$R_{AA}(\text{light}) < R_{AA}(D) < R_{AA}(B)$

- But also cold nuclear matter effects may lead to $R_{AA} \neq 1$ (needs solid pA reference)

Therefore?

$E_{loss}(light) > E_{loss}(c) > E_{loss}(b)$

$R_{AA}(light) < R_{AA}(D) < R_{AA}(B)$

- However, not so fast and easy: the relation between the E_{loss} hyeararchy to R_{AA} hyerarchy requires to account for:
  - Steepness of the parton spectra
  - Fragmentation functions
  - Soft particle production at low p_T

HF production in pp

Probe calibration: *Heavy flavour production in pp*

- Several methods to study heavy-flavour production (i.e HF-decay electrons, single muons, D and B mesons ….)

- Focus on fully reconstructed D mesons in hadronic decay channels.

- In this talk:

Except for D^{*+}, the $c\tau$ of the other D mesons ranges from ~123 to 312 μm

→Decay vertices displaced by few hundreds of μm from the primary vertex.

$$D^0 \rightarrow K^- \pi^+$$

$$D^+ \rightarrow K^- \pi^+ \pi^+$$

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

$$D^+_s \rightarrow \phi \pi^+ \rightarrow K^+ K^- \pi^+$$

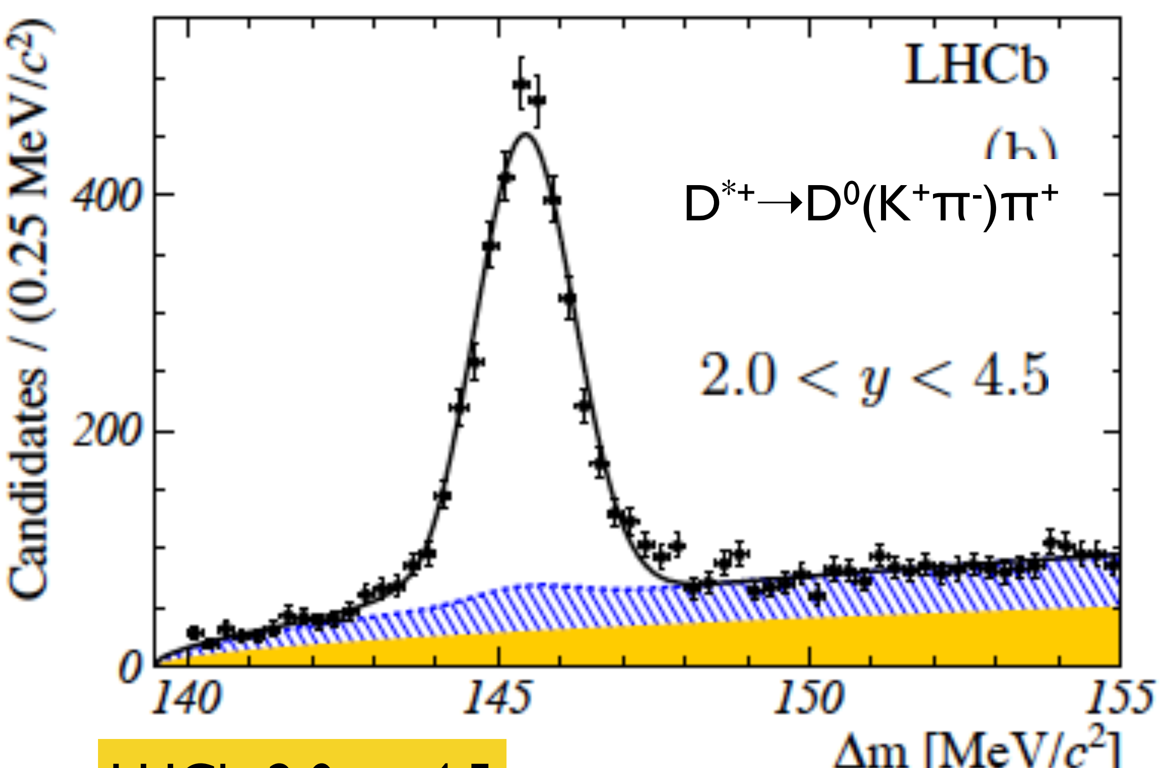
- and B meson (via non-prompt J/ψ):

D meson reconstruction (LHC example)

- Wide rapidity range: $|y|<0.5$ (ALICE), $|y|<2$ (ATLAS) and $2.0<y<4.5$ (LHCb)
- Fairly similar reconstruction strategy between the different experiments

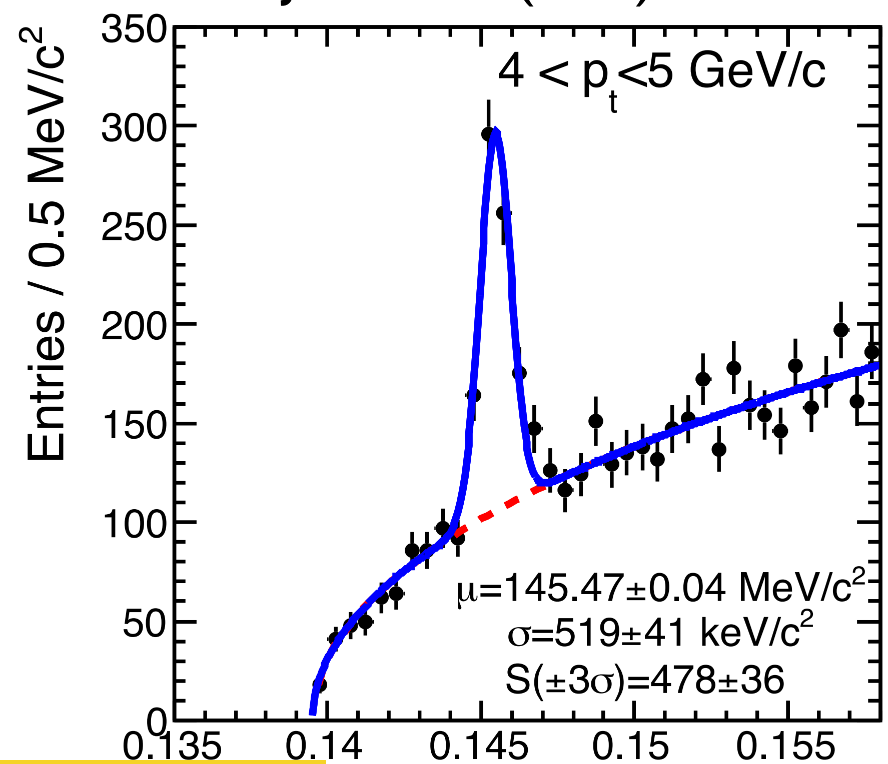
  Take advantage of the displacement of the daughters tracks

Nuclear Physics, Section B 871 (2013)



LHCb: 2.0<y<4.5

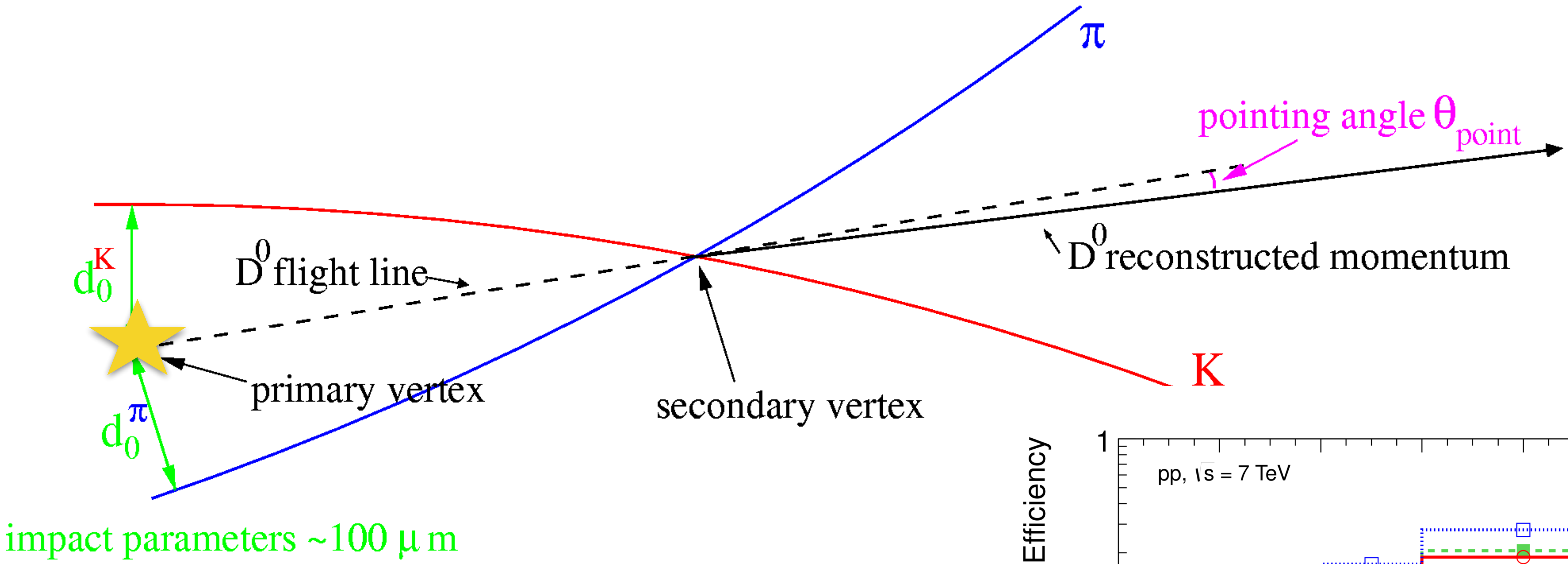
JHEP 1201 (2012) 128



ALICE: |y|<0.5

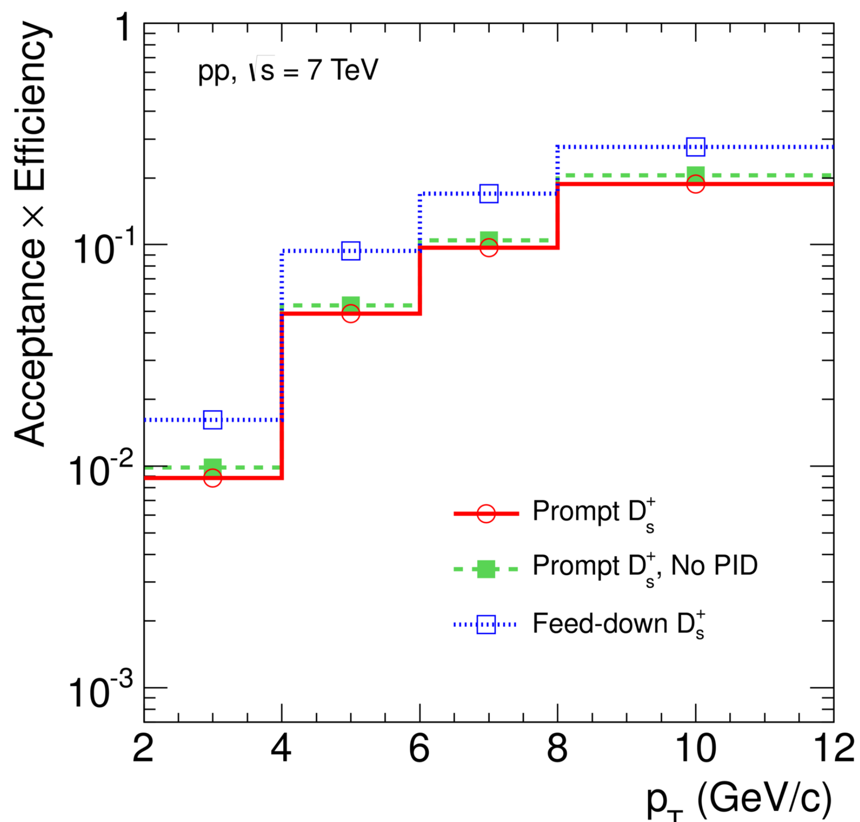
Just an example: $D^0 \rightarrow K^-\pi^+$ in ALICE

- First step toward D^0 reconstruction is to resolve the topology of the decay. It allows to apply topological selections:



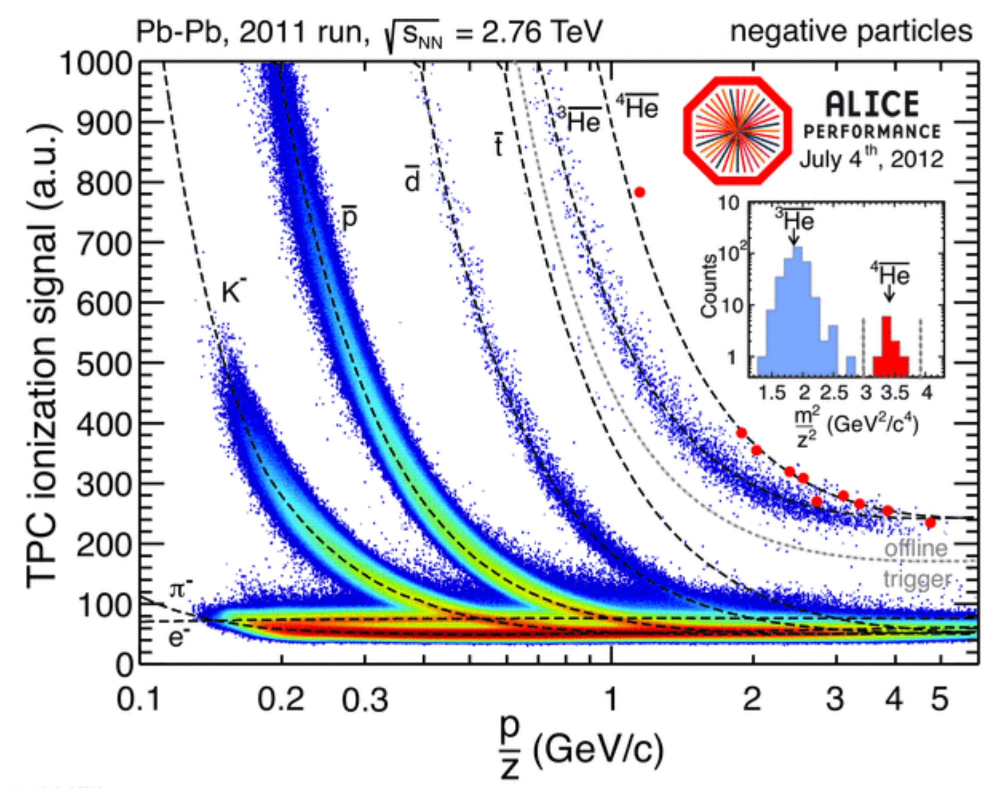
- Topological selections implies efficiencies of the order of 1-20% depending on p_T

JHEP 121 (2012) 128

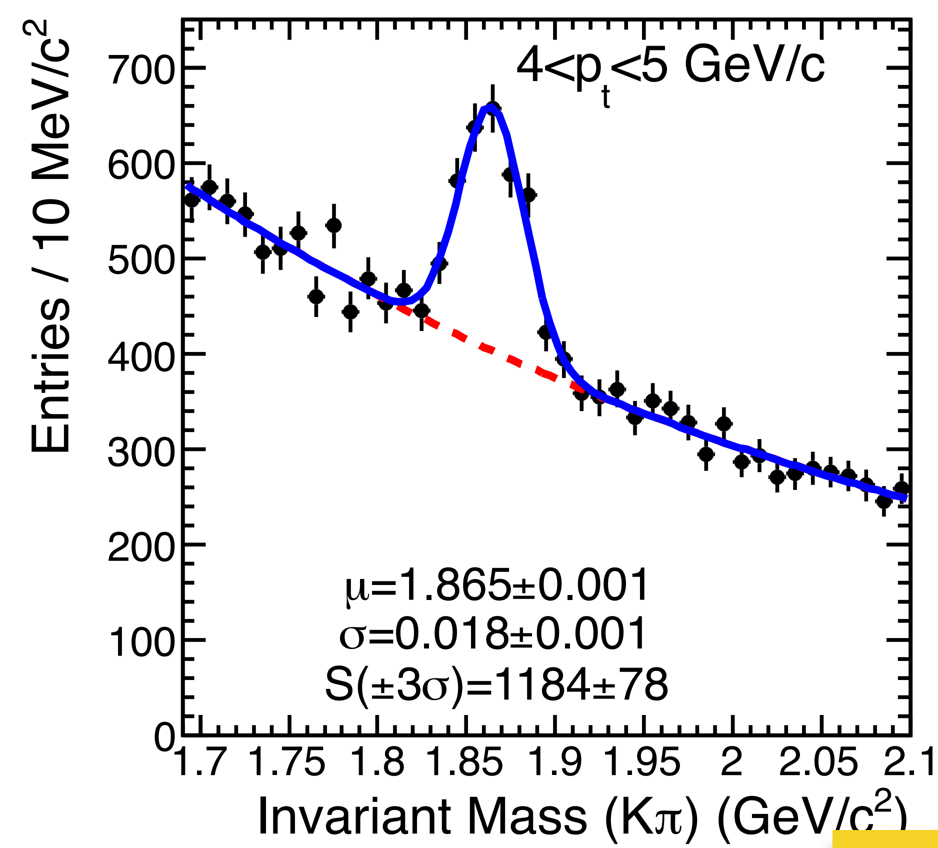


Just an example: $D^0 \rightarrow K^- \pi^+$ in ALICE

- Then use particle identification: Specific energy loss in the TPC and time-of-flight using TOF.



- Finally perform an invariant mass analysis

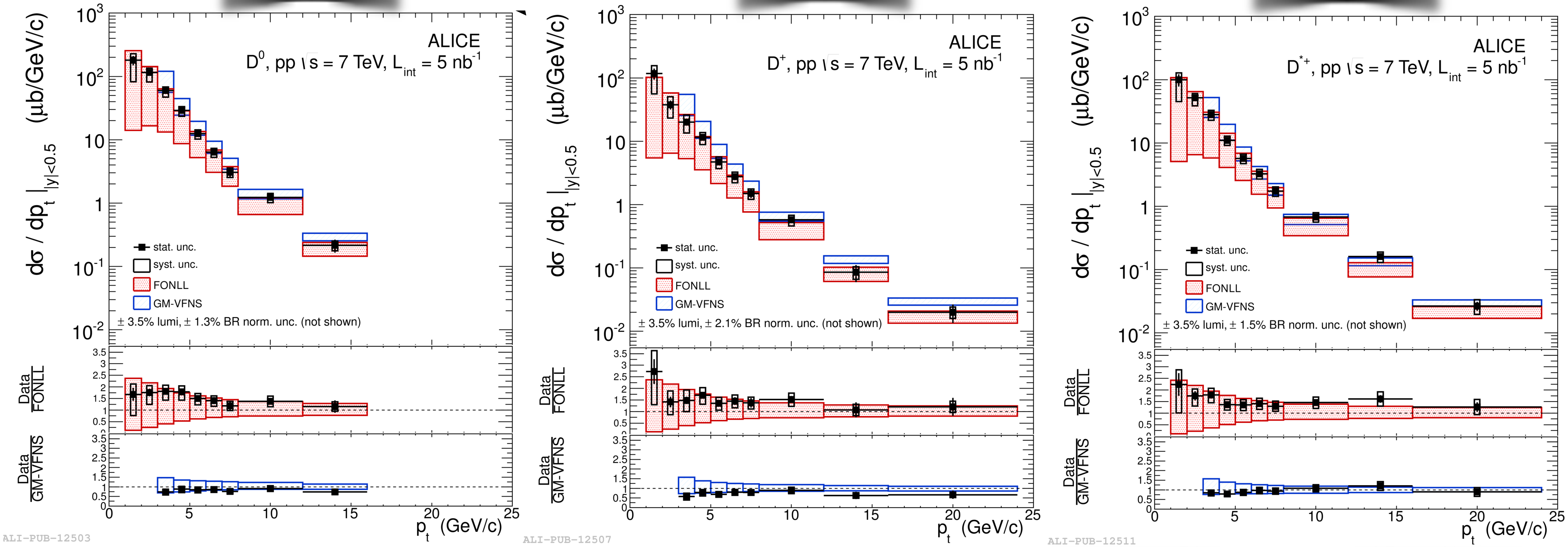


JHEP 1201 (2012) 128

D meson - p_T differential production cross-section

ALICE

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



ALICE Coll., JHEP 1201 (2012) 128

☑ Results are in agreement with *p*QCD within errors

M. Cacciari, M. Greco and P. Nason, JHEP 9805 (1998) 007;
M. Cacciari, S. Frixione, N. Houdeau, M. L. Mangano, P. Nason, G. Ridolfi, arXiv:1205.6344

B.A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger, arXiv:1202.0439, DESY-12-013, MZ-TH-12-07, LPSC-12019

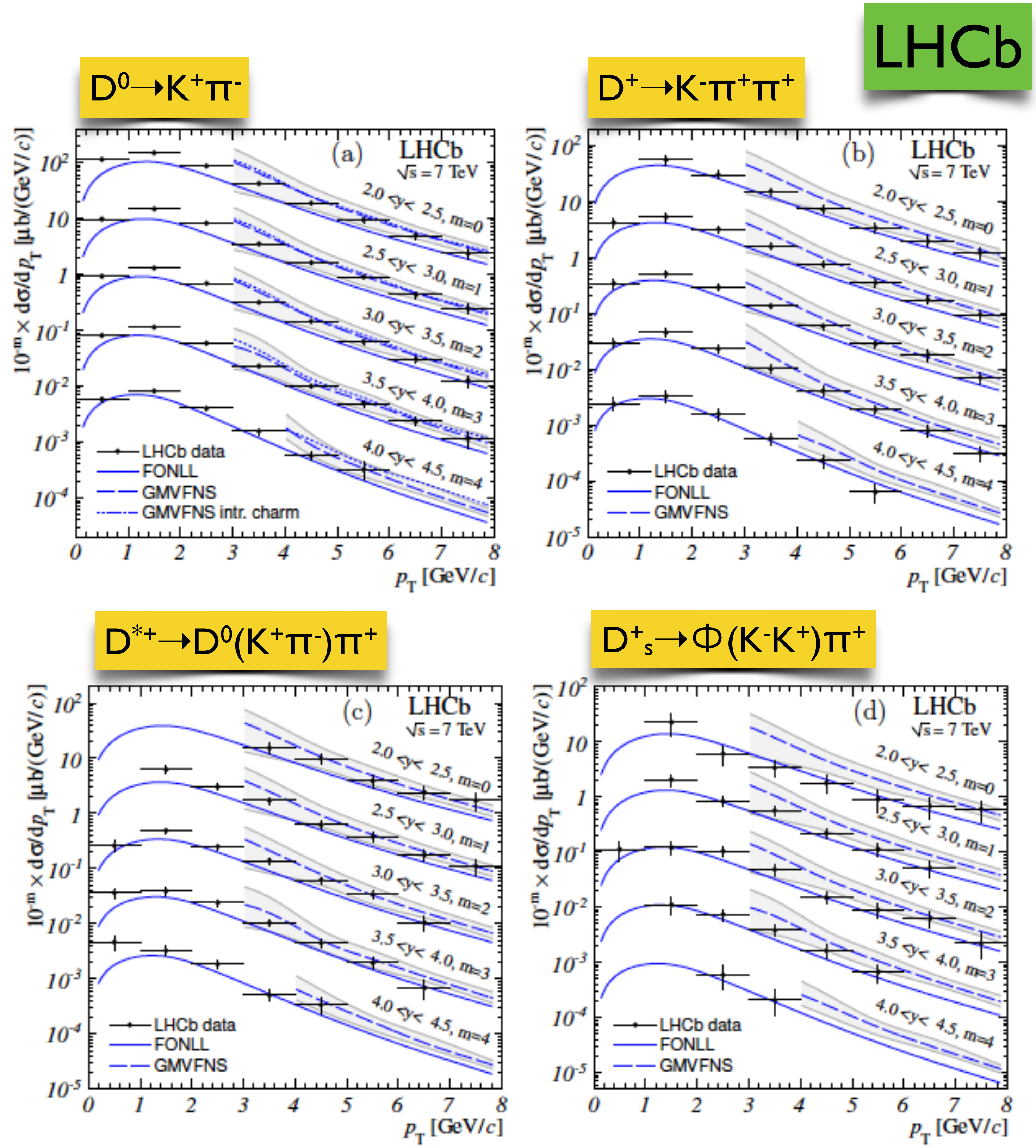
D meson - p_T differential production cross-section

- ☑ D^{*+}, D^0, D^+ and D_s production cross section were measured at LHC in a wide rapidity and p_T range.

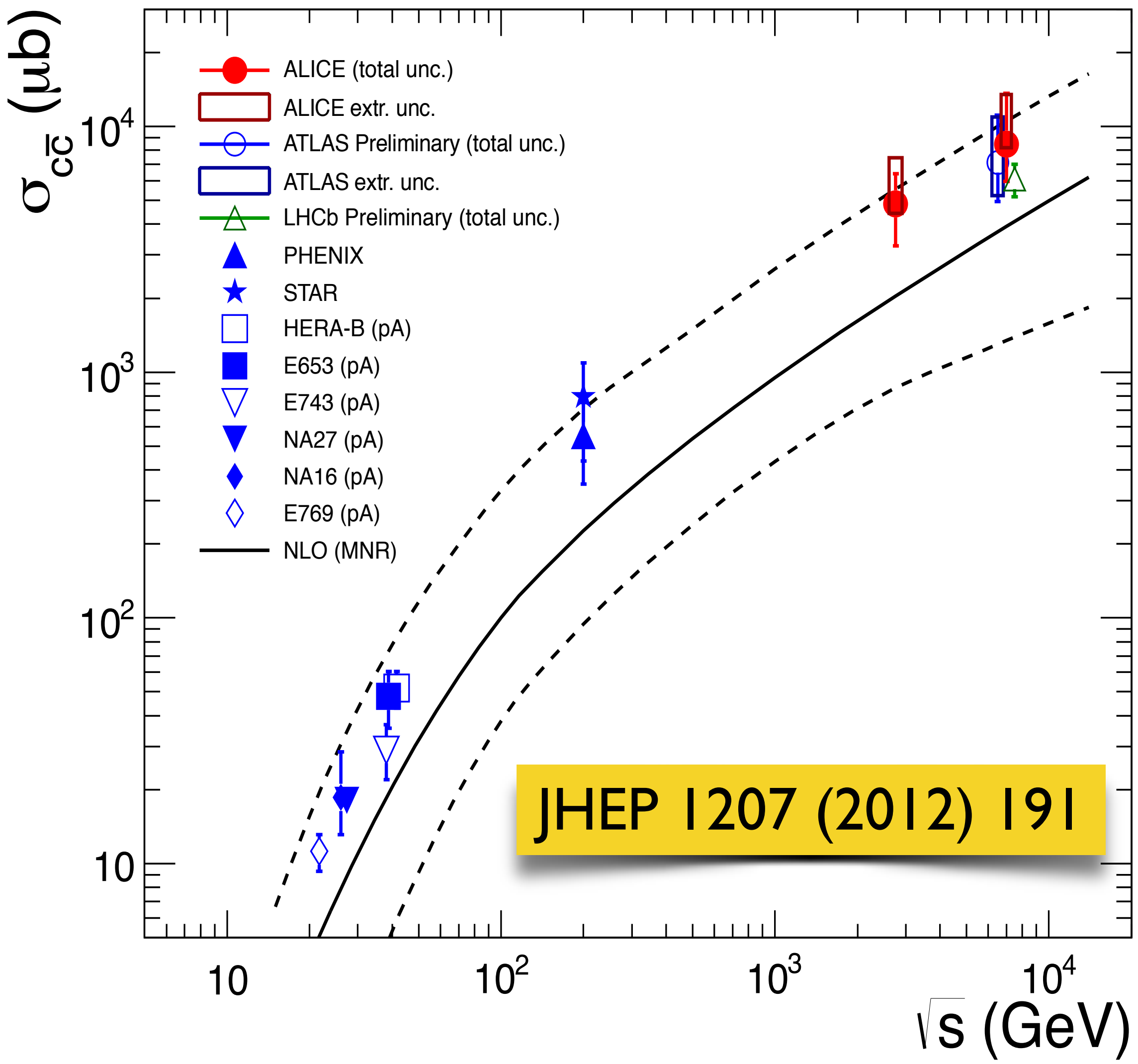
- ☑ Results are in agreement with pQCD within errors. Note: same models as ALICE used for the comparison

- ☑ Charm cross-section evaluated in a wide rapidity range 2.0<y<4.5

Nuclear Physics, Section B 871 (2013)



Total cross section (only topological)



- Production well described vs √s
- Important (!) … since at LHC energy scaling is needed for the calculation of the R_{AA}. the pp@7 TeV needs to be scaled down to 2.76 TeV

Energy scaling (*ALICE example*)

$$R_{AA}^{D}(p_T) = \frac{dN_{AA}^{D}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}^{D}/dp_T}$$

- The R_{AA} calculation requires the pp and Pb-Pb producion to be studied at the same √s energy

Energy scaling (*ALICE example*)

$$R_{AA}^{D}(p_T) = \frac{dN_{AA}^{D}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}^{D}/dp_T}$$

- The R_{AA} calculation requires the pp and Pb-Pb producion to be studied at the same √s energy

- At LHC run I the proton-proton collisions were at √s = 7 TeV while the Pb-Pb collisions were at $\sqrt{s_{NN}}$ = 2.76 TeV ⟹ Need to scale down the pp result

Energy scaling (*ALICE example*)

$$R_{AA}^{D}(p_T) = \frac{dN_{AA}^{D}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}^{D}/dp_T}$$

- The R_{AA} calculation requires the pp and Pb-Pb producion to be studied at the same $\sqrt{s}$ energy

- At LHC run I the proton-proton collisions were at $\sqrt{s} = 7$ TeV while the Pb-Pb collisions were at $\sqrt{s_{NN}} = 2.76$ TeV $\Longrightarrow$ Need to scale down the pp result

- SOLUTION: pQCD-based (FONLL) energy scaling of the 7 TeV production cross-section down to 2.76 TeV
  - Scaling factor as the ratio of the theoretical cross sections at those energies
  - Uncertanties from vaiation of the (FONLL) calculation parameters

Energy scaling (*ALICE example*)

$$R_{AA}^{D}(p_T) = \frac{dN_{AA}^{D}/dp_T}{\langle T_{AA} \rangle \times d\sigma_{pp}^{D}/dp_T}$$

- The R_{AA} calculation requires the pp and Pb-Pb producion to be studied at the same $\sqrt{s}$ energy

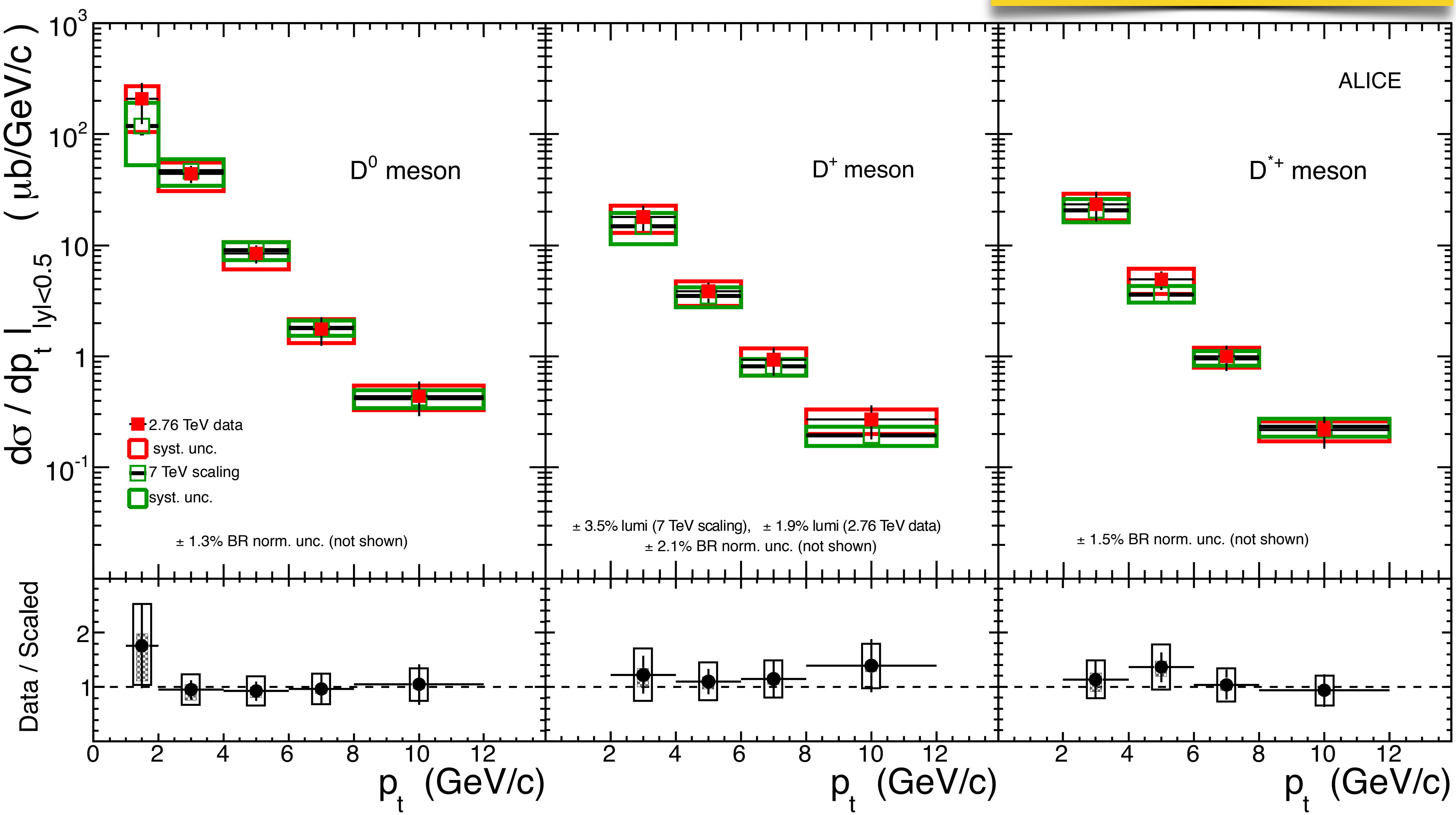
- At LHC run I the proton-proton collisions were at $\sqrt{s} = 7$ TeV while the Pb-Pb collisions were at $\sqrt{s_{NN}} = 2.76$ TeV $\Longrightarrow$ Need to scale down the pp result

- SOLUTION: pQCD-based (FONLL) energy scaling of the 7 TeV production cross-section down to 2.76 TeV
  - Scaling factor as the ratio of the theoretical cross sections at those energies
  - Uncertanties from vaiation of the (FONLL) calculation parameters

- Small pp run at 2.76 TeV performed in order to compare the scaled result with a measure one (with relatively large statistical uncertanties)

Energy scaling (*ALICE example*)

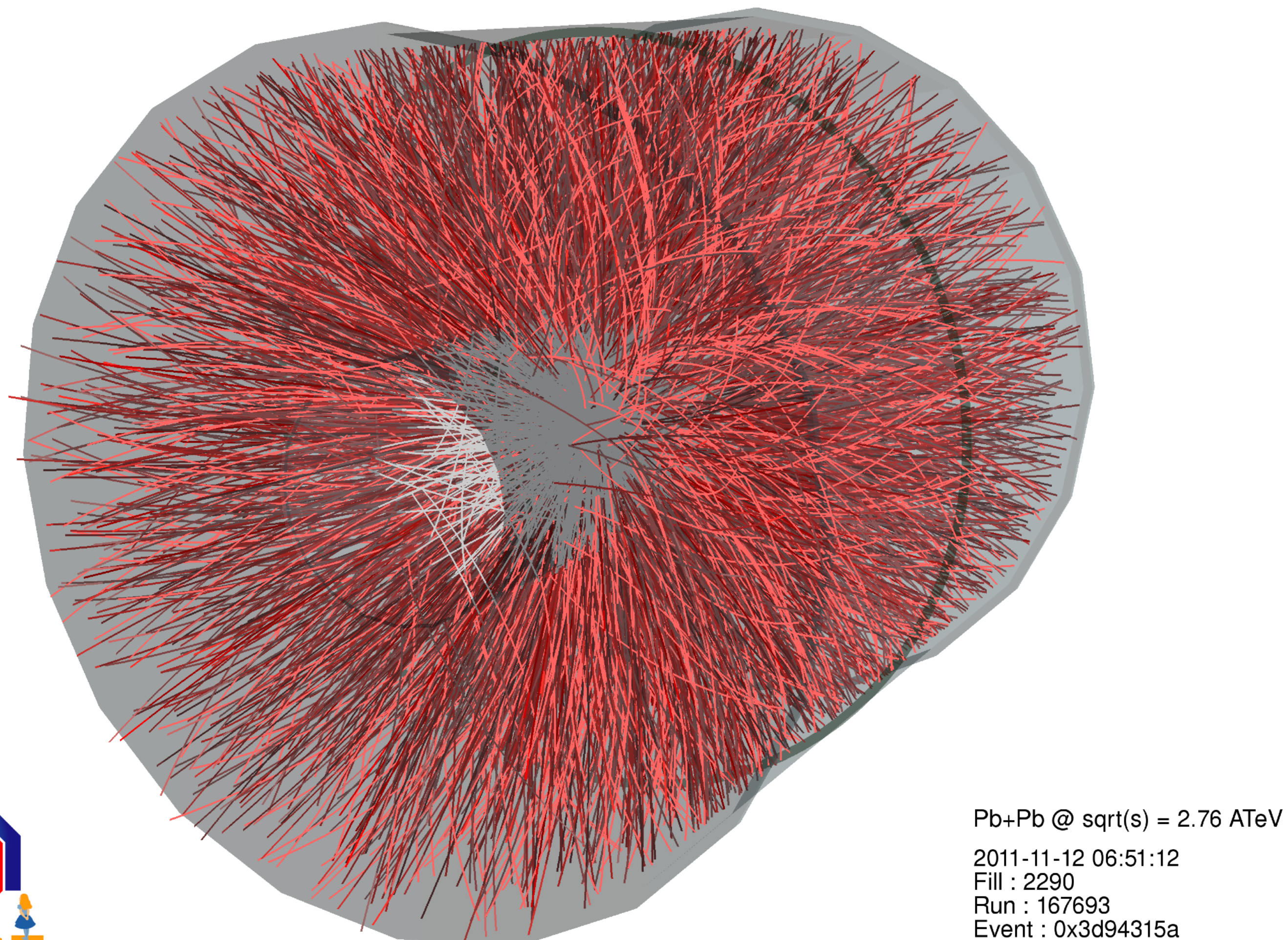
JHEP 1207 (2012) 191

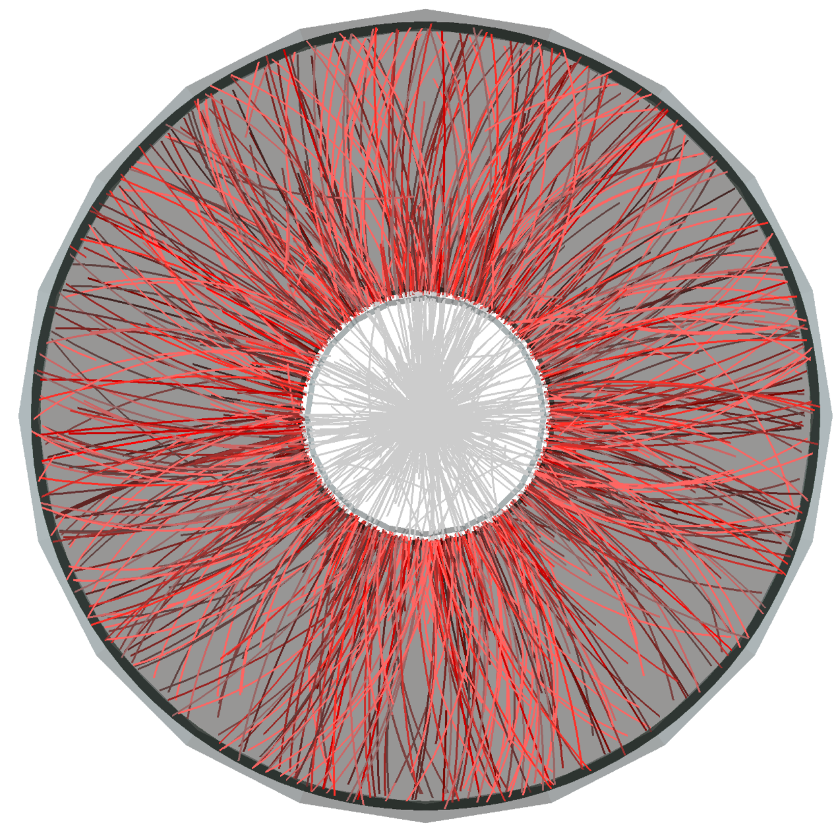


☑ Scaling procedure validated with experimental data! ⇒ Solid understnading of the pp reference …. we can proceed with R_{AA} calculation

HF production in nucleus-nucleus

Tipical Pb-Pb collision

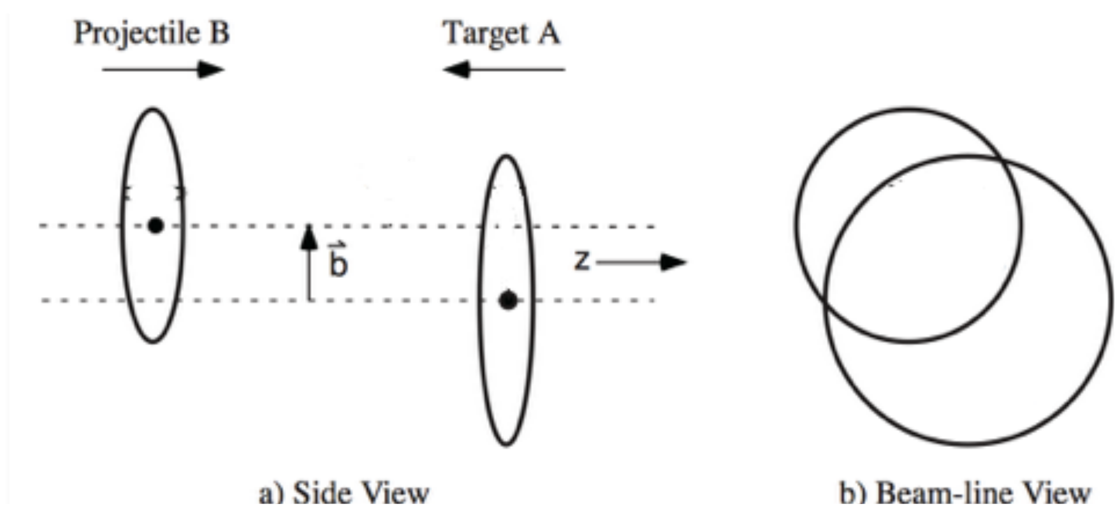




ALICE

http://aliceinfo.cern.ch/Public

Event characterization: centrality

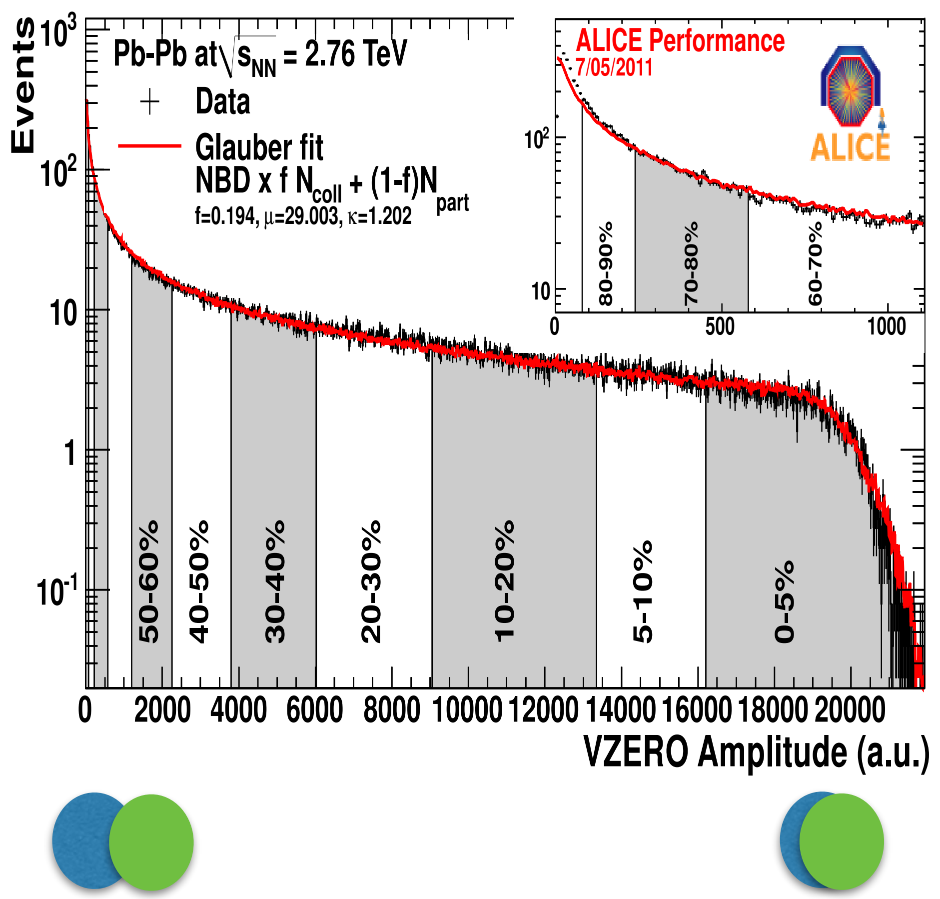


- Collisions are classified based on the amount of overlapping surface between the 2 lead ions defined by the impact parameter b. We define such classification centrality of the collision

- **PROBLEM:** we cannot directly measure b

- **SOLUTION**: We model the expected number of produced particles for each possible b and then we compare with the one measured from data so that we can assign a centrality to each collision

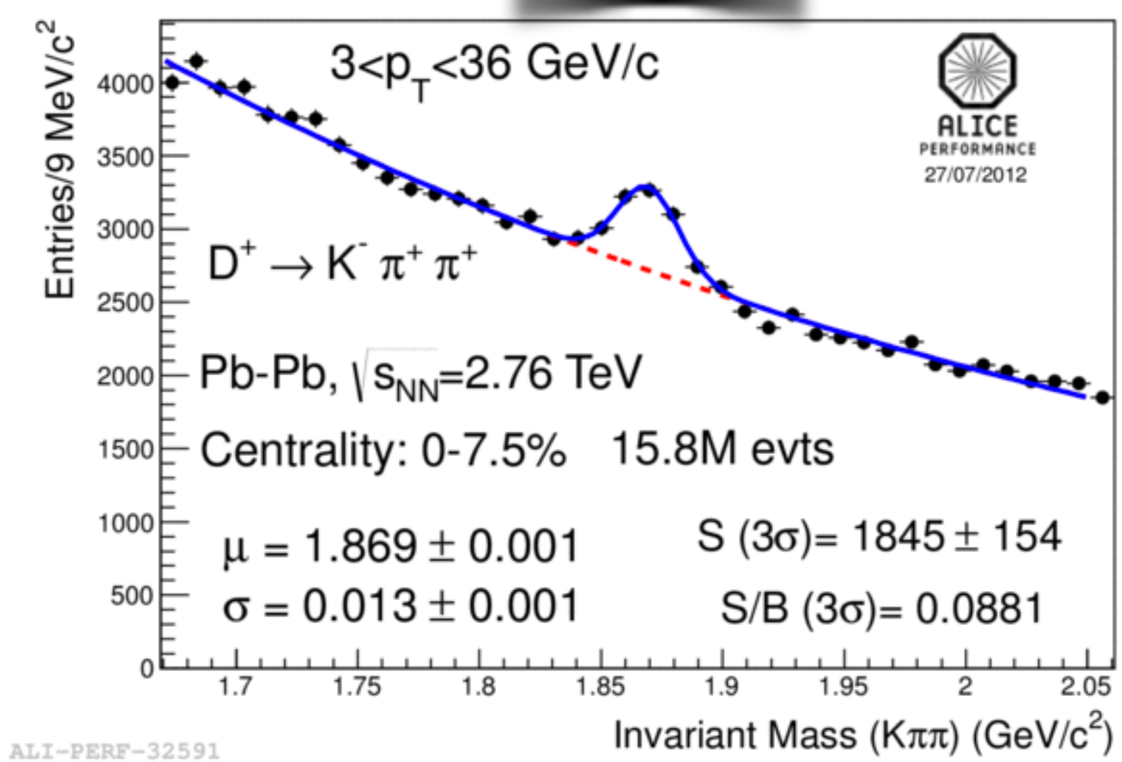
- It allows to control the collision geometry!



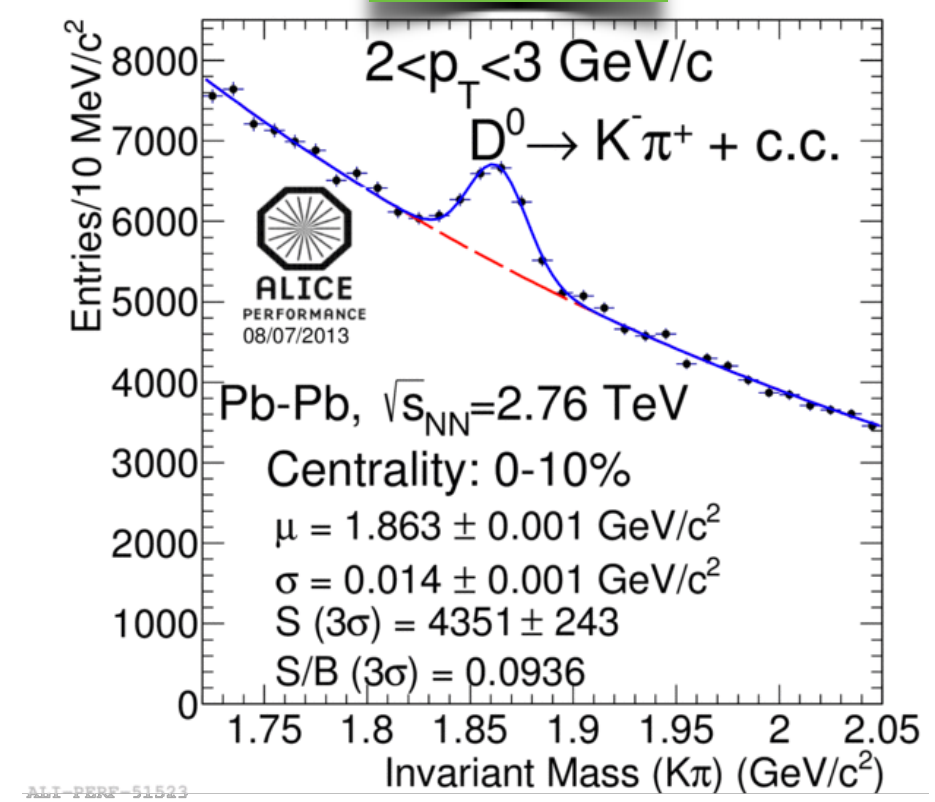
Phys.Rev.Lett.105:252302,2010

D mesons in Pb-Pb

$D^+ \rightarrow K\pi\pi$



$D^0 \rightarrow K^- \pi^+$

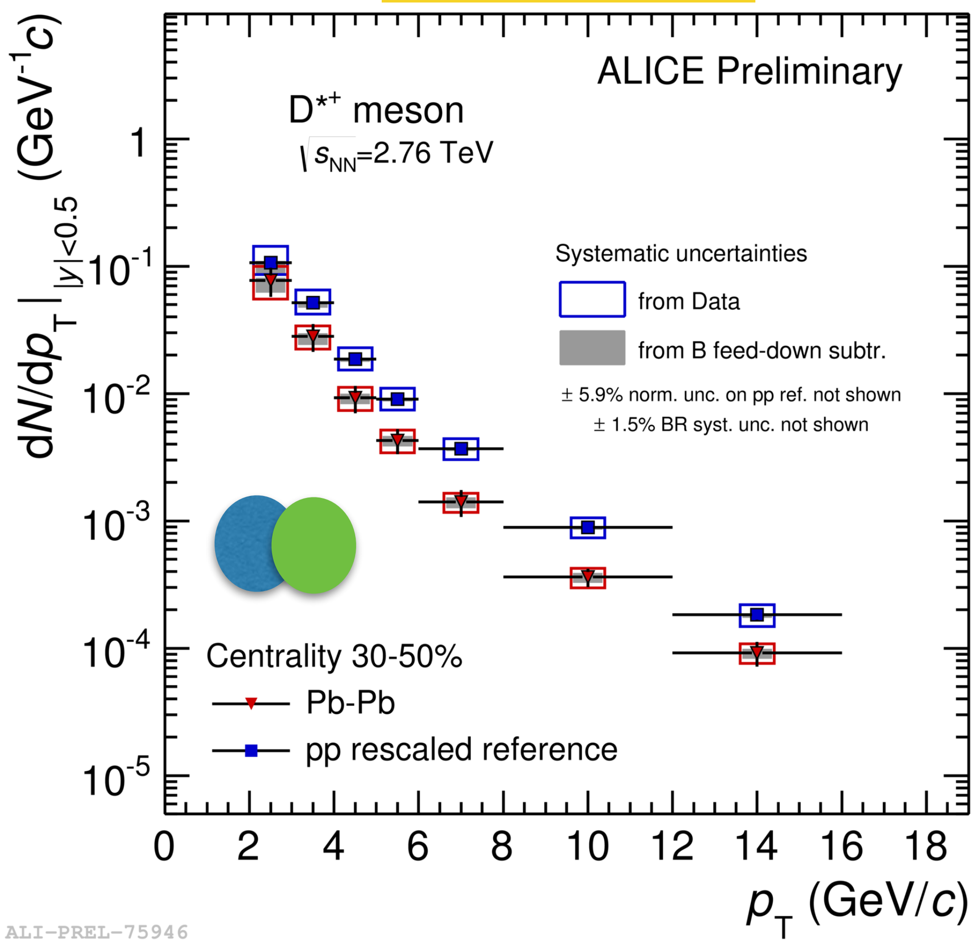


- ☑ Similar reconstruction strategy as in pp collisions
- ☑ Possible recostruction with background simulation methods under investigation

D mesons dN/dp_T and R_{AA}

D^{*+} 30-50%

ALICE



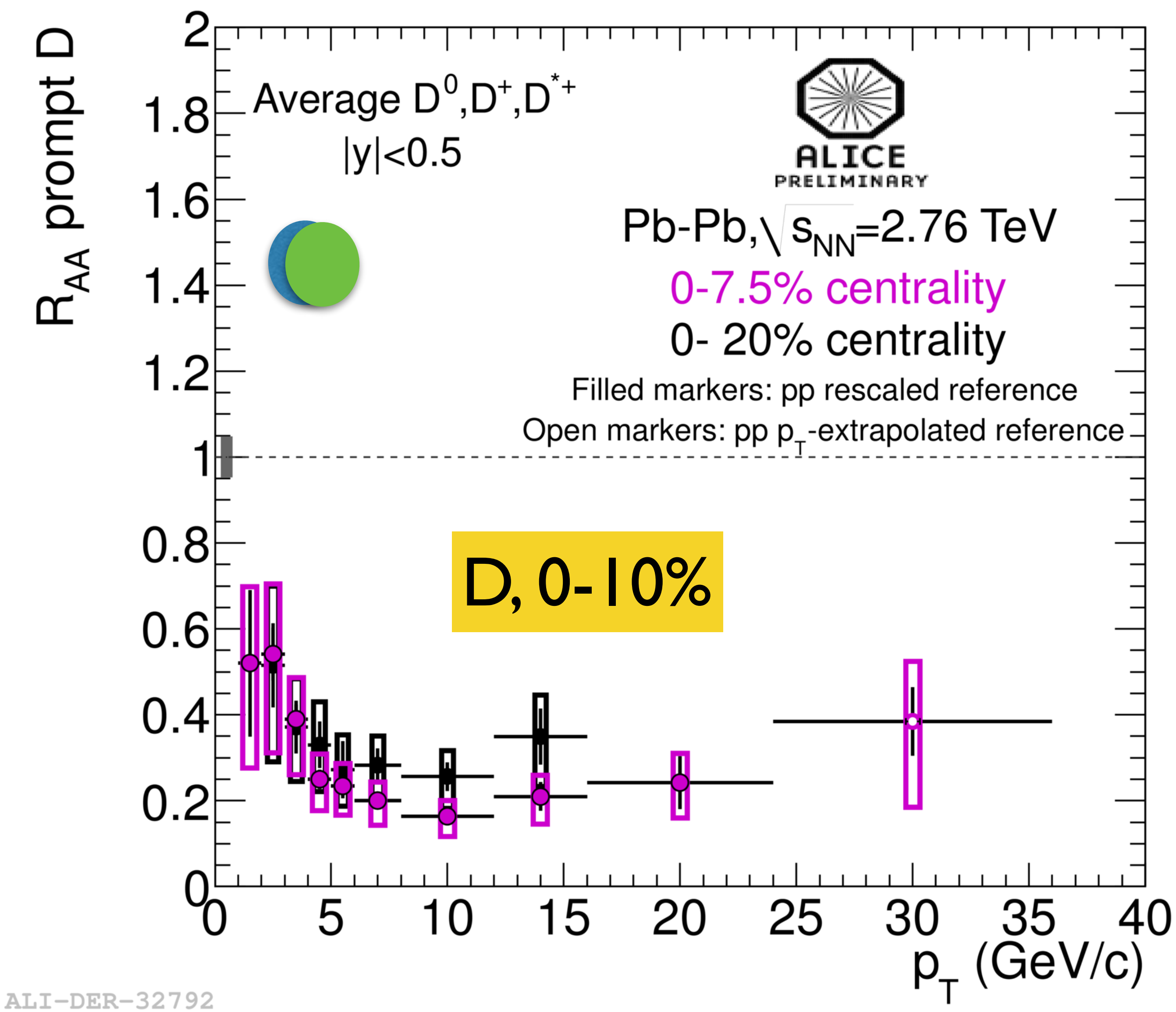
- ☑ D^{*+}, D^0 and D^+ average R_{AA} shows a suppression of about factor 5 at 10 GeV/*c*.

Nucl.Phys. A931 (2014) 514-519

Nucl.Phys. A904-905 (2013) 635c-638c

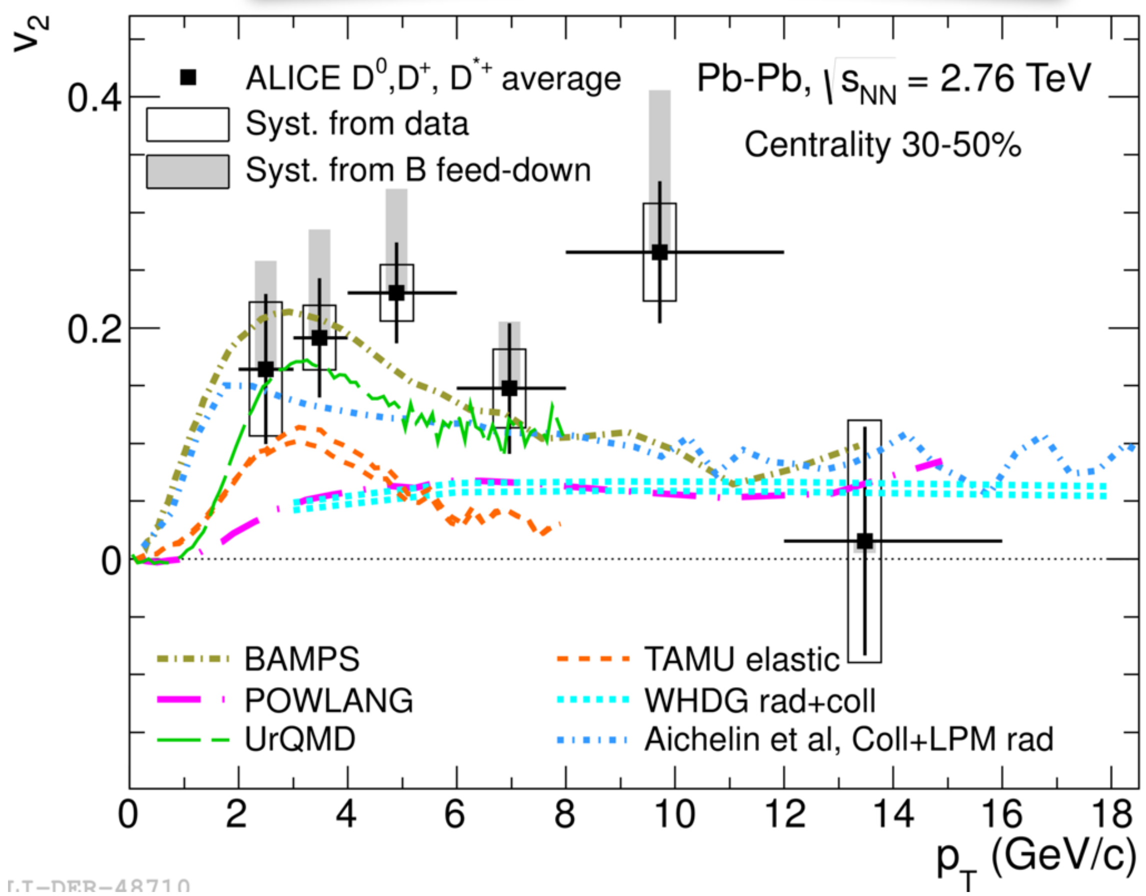
J.Phys.Conf.Ser. 509 (2014) 012080

- ☑ D^{*+}, D^0 and D^+ average R_{AA} shows a suppression of about factor 5 at 10 GeV/*c*.

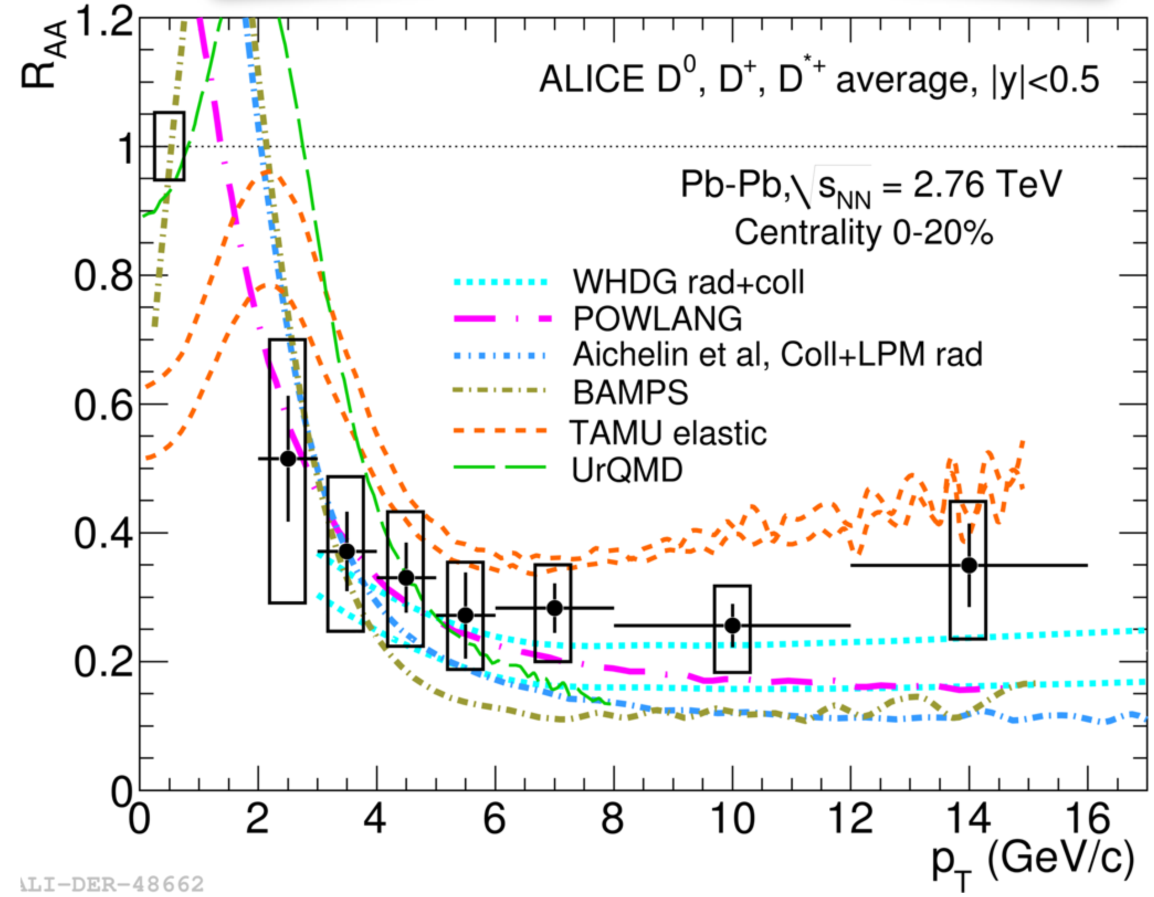


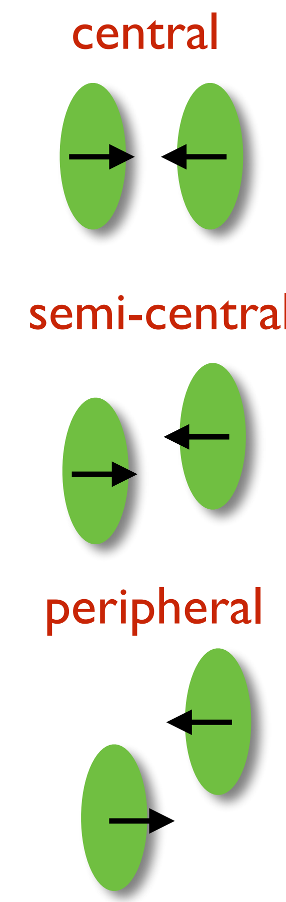
D mesons R_{AA} and flow: comparison with models

Phys.Rev. C90 (2014) 034904



Phys.Rev.Lett. 111 (2013) 102301





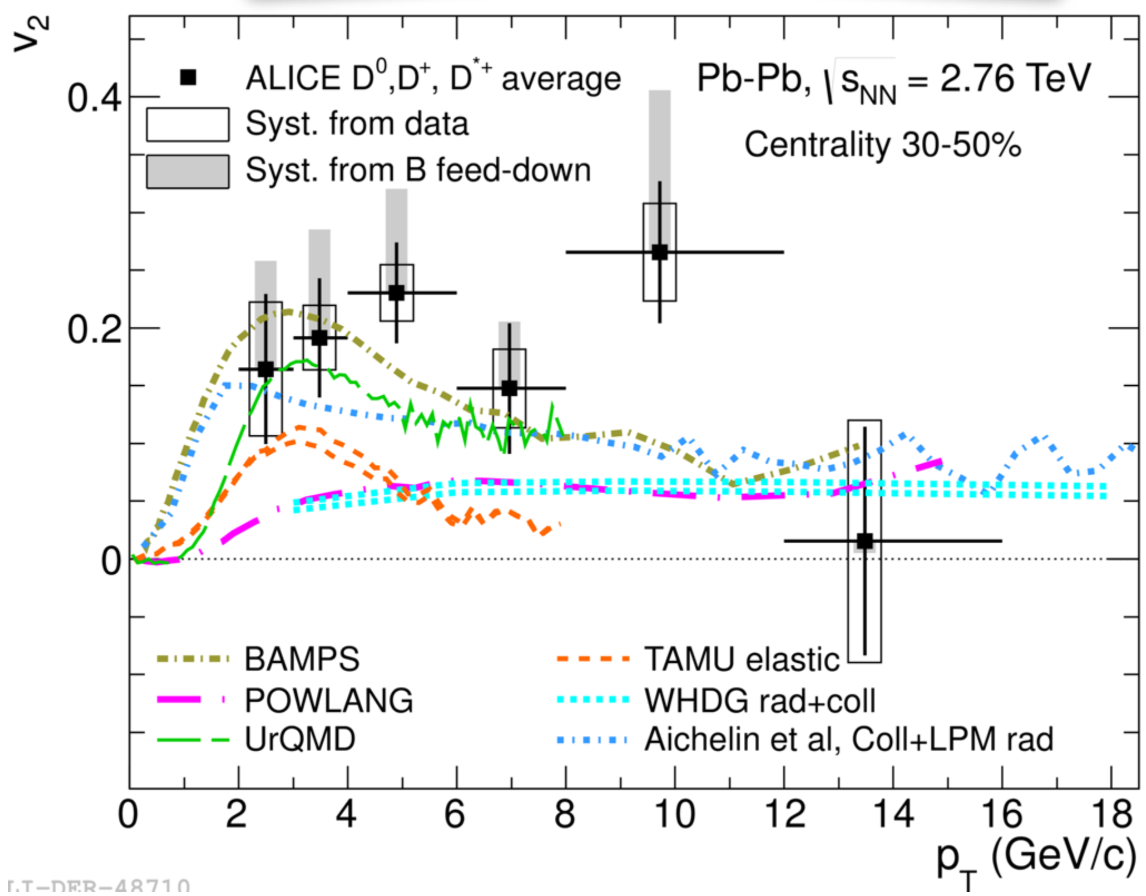
☑ Simultaneous description of D-meson R_{AA} and v_2 → understanding of heavy-quark transport coefficients of the medium (challenging for models)

BAMPS: Uphoff et al. arXiv:1112.1559., O. Fochler, J. Uphoff, Z. Xu and C. Greiner, J. Phys. G38 (2011) 124152.
Aichelin et al. Phys. rev. C 79 (2009) 044906,
W.A. Horowitz et al. J. Phys. G38, 124064 (2011).,W. A. Horowitz and M. Gyulassy, J. Phys. G38 (2011) 124114.
W. M. Alberico et al. Eur. Phys. J. C 71, 1666 (2011). M. He, R.J Fries and R. Rapp, arXiv:1204.4442 [nucl-th]

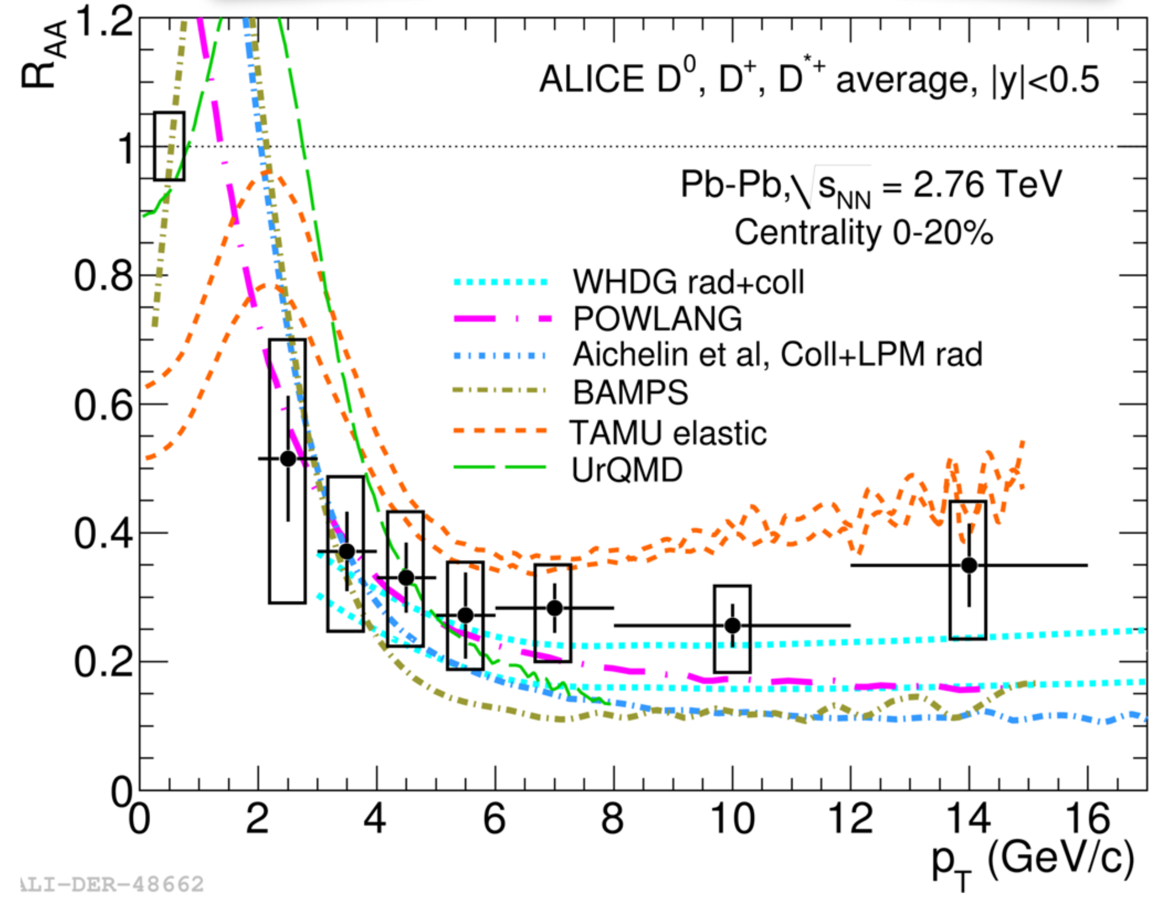
JHEP 09 (2012) 112

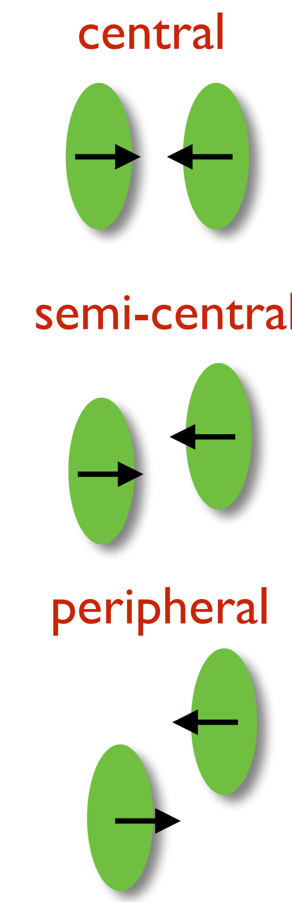
D mesons R_{AA} and flow: comparison with models

Phys.Rev. C90 (2014) 034904



Phys.Rev.Lett. 111 (2013) 102301

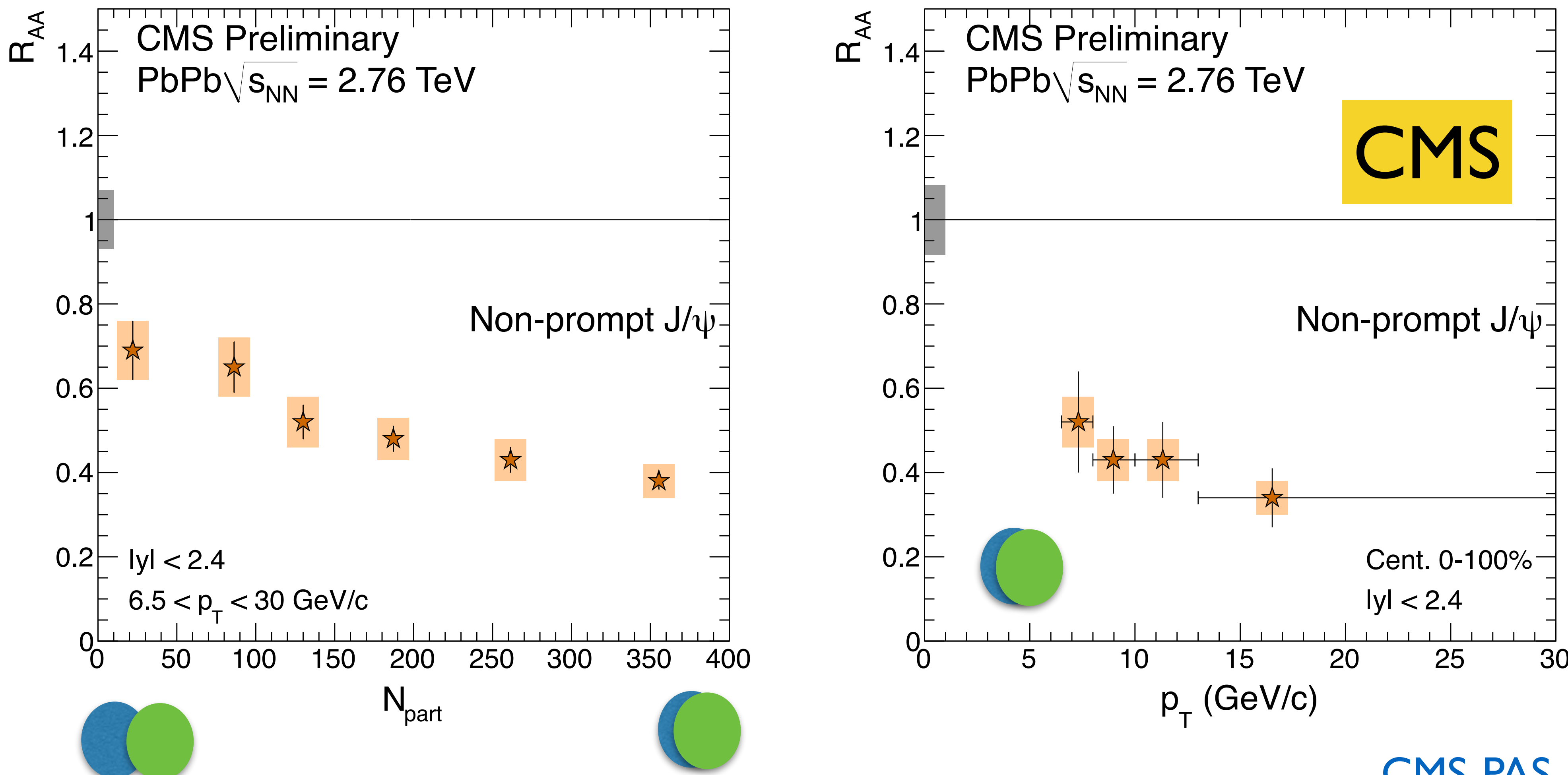




- Models without HQ interactions with expanding medium underestimate v2 (WHDG, POWLANG), but are among the best for R_{AA}
- Max v_2~0.15-0.20 is better described by models that include collisional energy loss of heavy quarks in expanding medium (BAMPS, UrQMD, Aichelin et al). Some include coalescence (UrQMD, Aichelin et al)
- Models that describe flow resonably well tends to do not describe R_{AA}

B mesons R_{AA}

- First measurement of B mesons R_{AA} performed by CMS using non-prompt J/Ψ

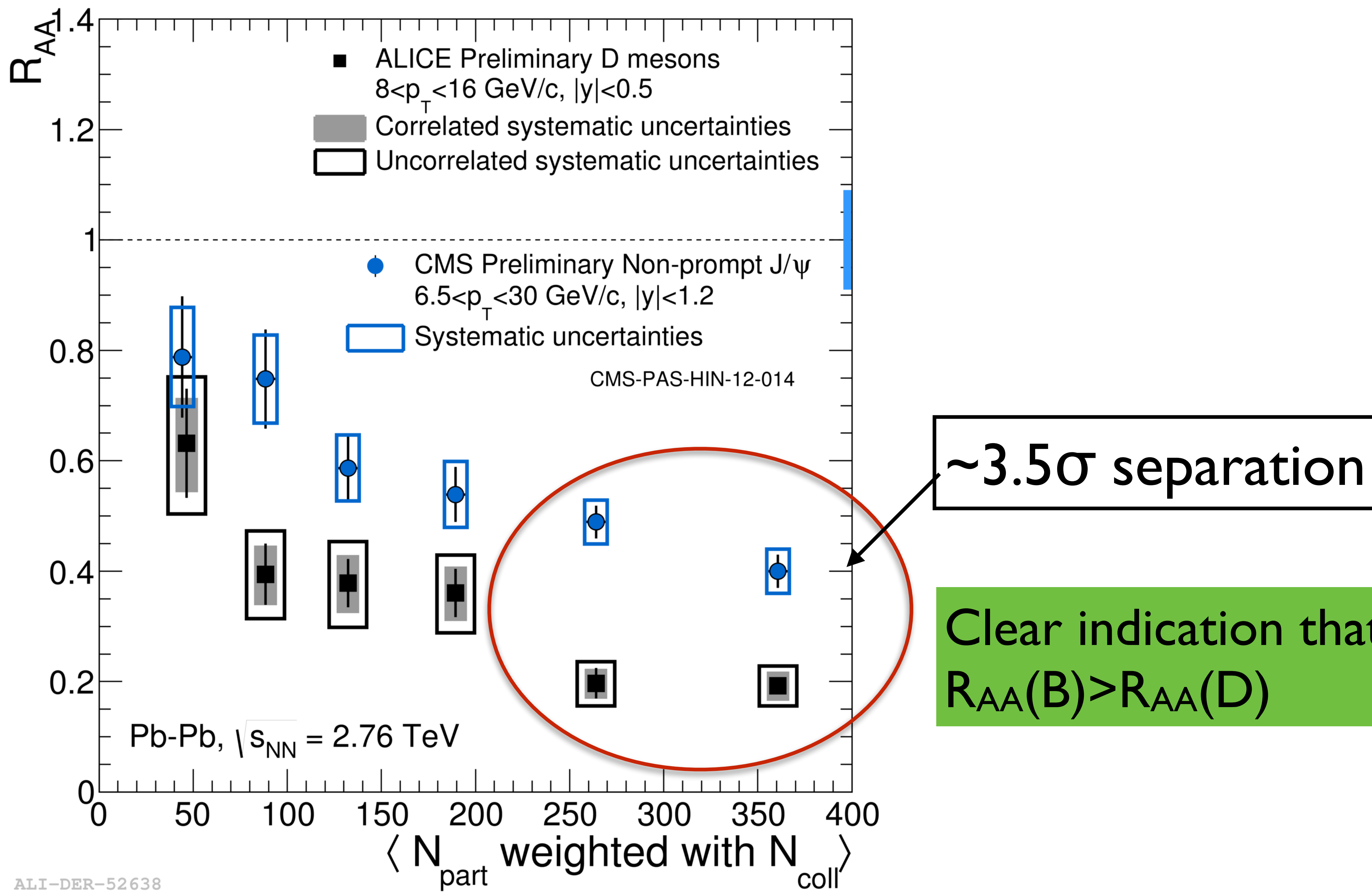


CMS-PAS-HIN-12-014

- Clear dependence of the suppression from the collision centrality and the p_T of the non-prompt J/Ψ

Mass dependence: D vs B

- D meson from ALICE and non-prompt J/ψ from CMS

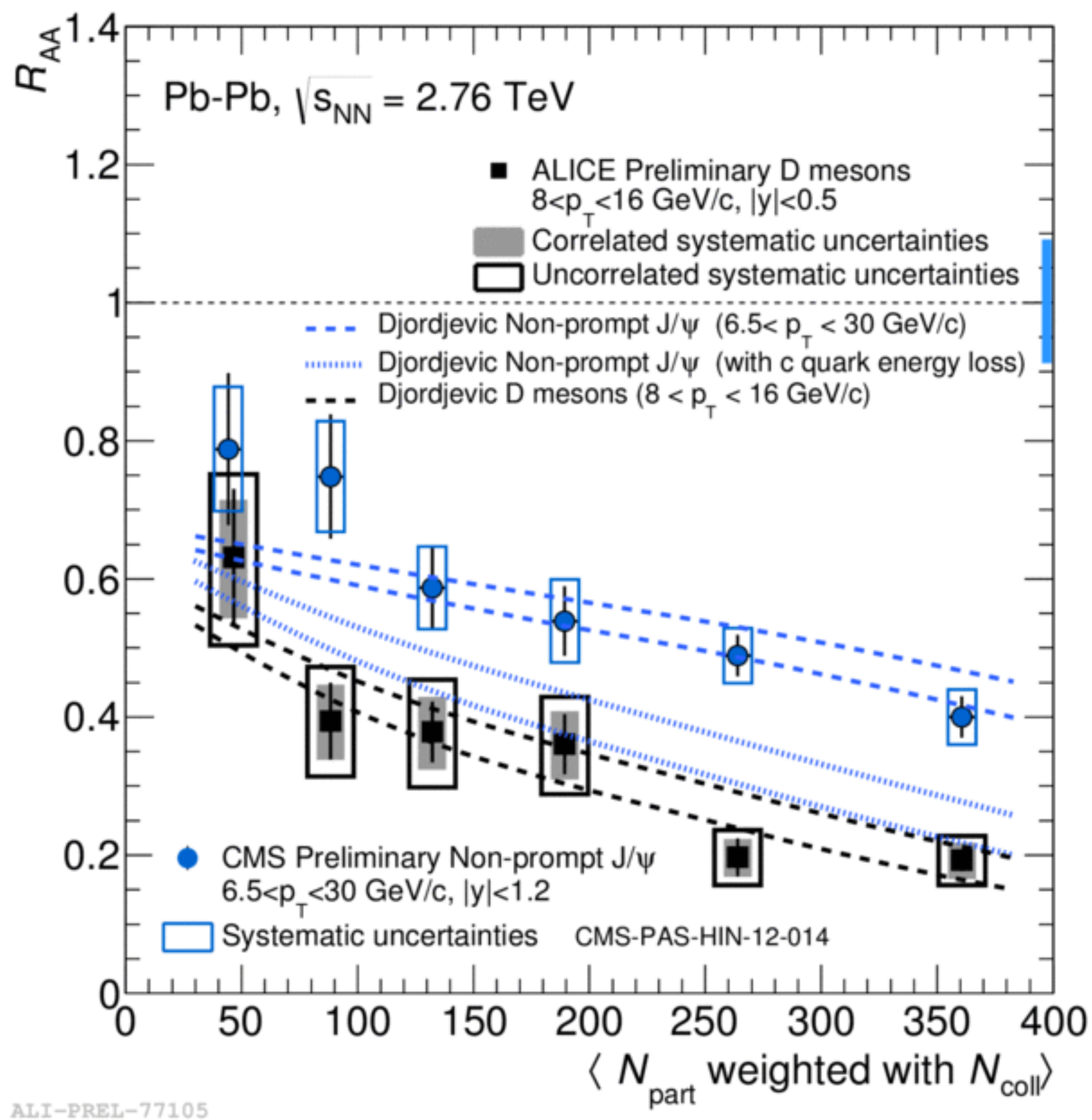


Clear indication that $R_{AA}(B)>R_{AA}(D)$

PoS EPS-HEP2013 (2013) 175

Mass dependence: D vs B

- D meson from ALICE and non-prompt J/ψ from CMS



Clear indication that $R_{AA}(B)>R_{AA}(D)$

PoS EPS-HEP2013 (2013) 175

Conclusions

- Charm and Beauty quark can be used as a probe for the hot and dense QCD matter produced during ultra-relativistic heavy-bon collisions
- One of the possible observables is the nuclear modification factor (R_{AA})
- The R_{AA} is defined as the ratio of the production in A-A and in pp collisions scaled by the number of binary collisions.
- At LHC we find an R_{AA} of D mesons suppressed up to a factor 5-6 at p_T = 10 GeV/c compatibile with the production of a hot and dense medium.
- Comparison of D mesons R_{AA} and non-prompt J/Ψ R_{AA} show a larger suppression of D mesons R_{AA} in qualitative agreement with the mass scaling hypothesis.