Heavy flavour overview

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ΕΜΜΕΦ

Outline

- **Heavy Quarks**
  - Introduction
  - Energy loss
  - Quarkonium: Color screening and regeneration
- **Charm and beauty production**
  - pp collisions
  - A-A collisions
- **What about pA collisions?**
- **Conclusions**

Outline

- **Heavy Quarks**
  - Introduction
  - Energy loss
  - Quarkonium: Color screening and regeneration

two pillars of heavy quark physics

- **Charm and beauty production**
  - pp collisions
  - A-A collisions
- **What about pA collisions?**
- **Conclusions**

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  - Energy loss
  - Quarkonium: Color screening and regeneration
- **Charm and beauty production**
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- **What about pA collisions?**
- **Conclusions**

Selection of results from RHIC and LHC

Heavy quark: *General Picture*

Hard probes (charm and beauty quarks):

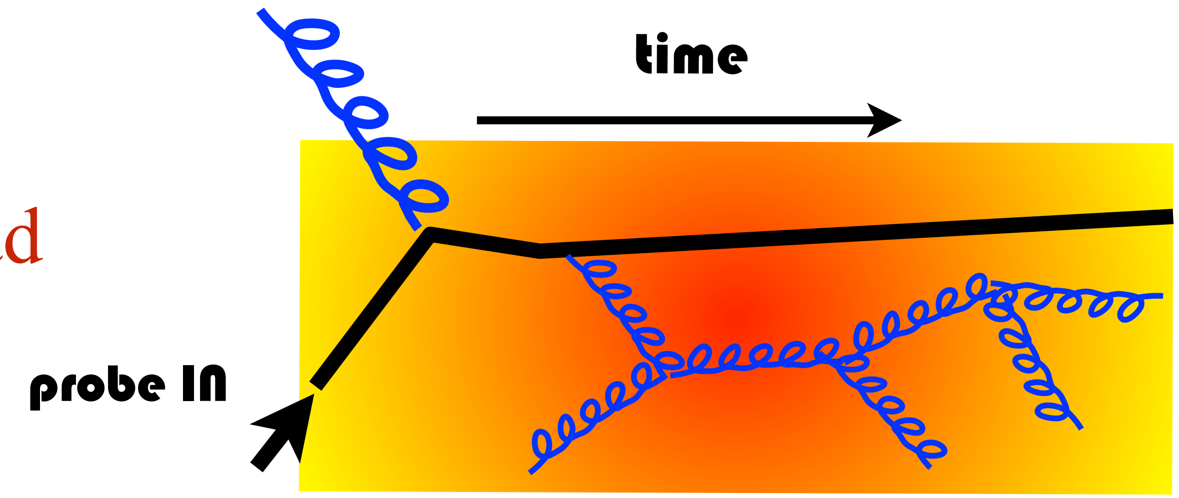
$m_c \sim 1.3$ GeV/c^2,
$m_b \sim 4.5$ GeV/c^2

- Produced at the early stage of the collision (*large mass requires high Q^2, $\Delta t \sim 0.01$-0.13 fm*) $\tau_{charm} \sim 1/2m_c \sim 0.1$ fm/c
- pQCD can be used to calculate initial cross sections
- 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)
  - Thermal production from hadronic matter (i.e $\pi N \rightarrow \Lambda_c D$) expected to play a minor effect

Phys. Rev. C56, 2707 (1997)

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.

- What about charm strange hadrons (D_s)? If in-medium hadronization dominant mechanism of charm hadron formation at low p_T → strange charm hadrons largely enhanced.

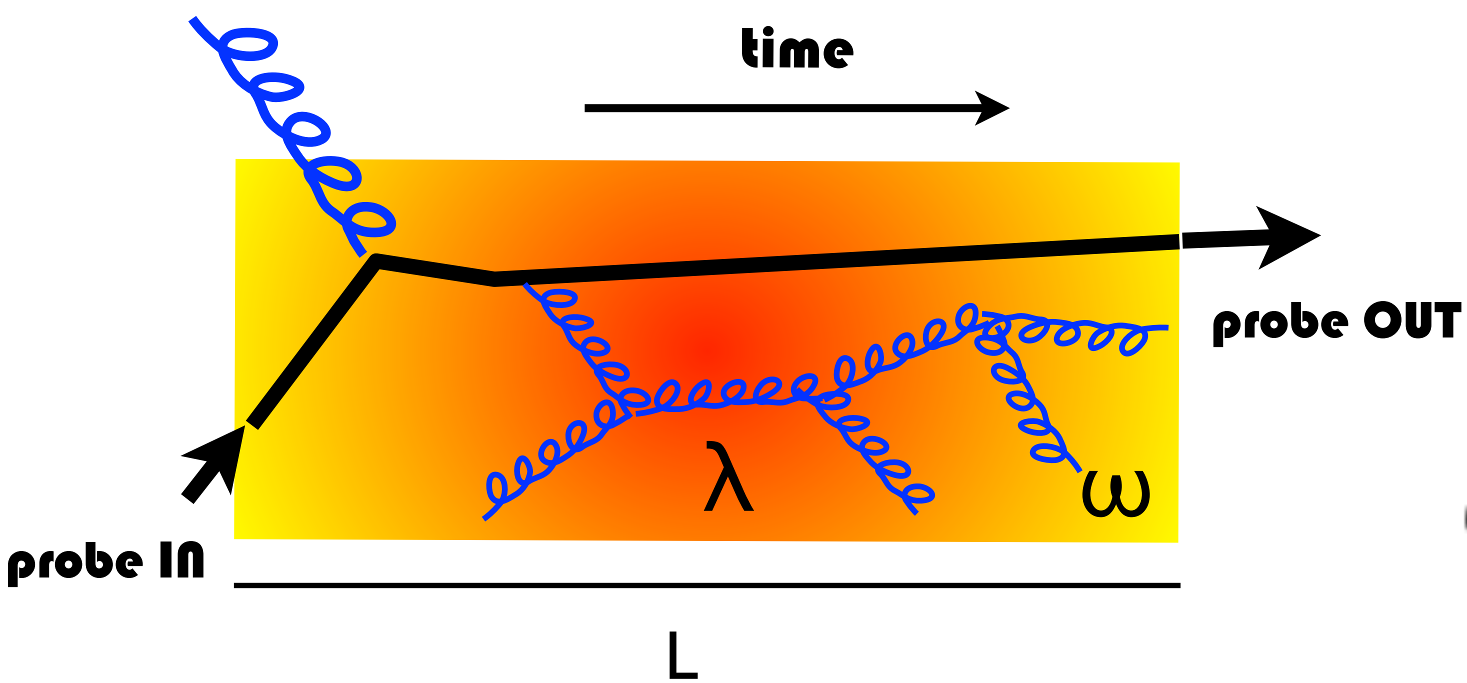
I. Kuznetsova and J. Rafelski, Eur.Phys.J. C51 (2007) 113-133.

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

E_{loss}(light) > E_{loss}(charm) > E_{loss}(beauty)

➔ *Let's see it a bit more in detail*

Radiative Energy Loss: *Color charge dependence*



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

arxiv-hep-ph0008241
Phys.Rev.D71:054027, 2005

⇨ Color charge dependence of radiative E_{loss}

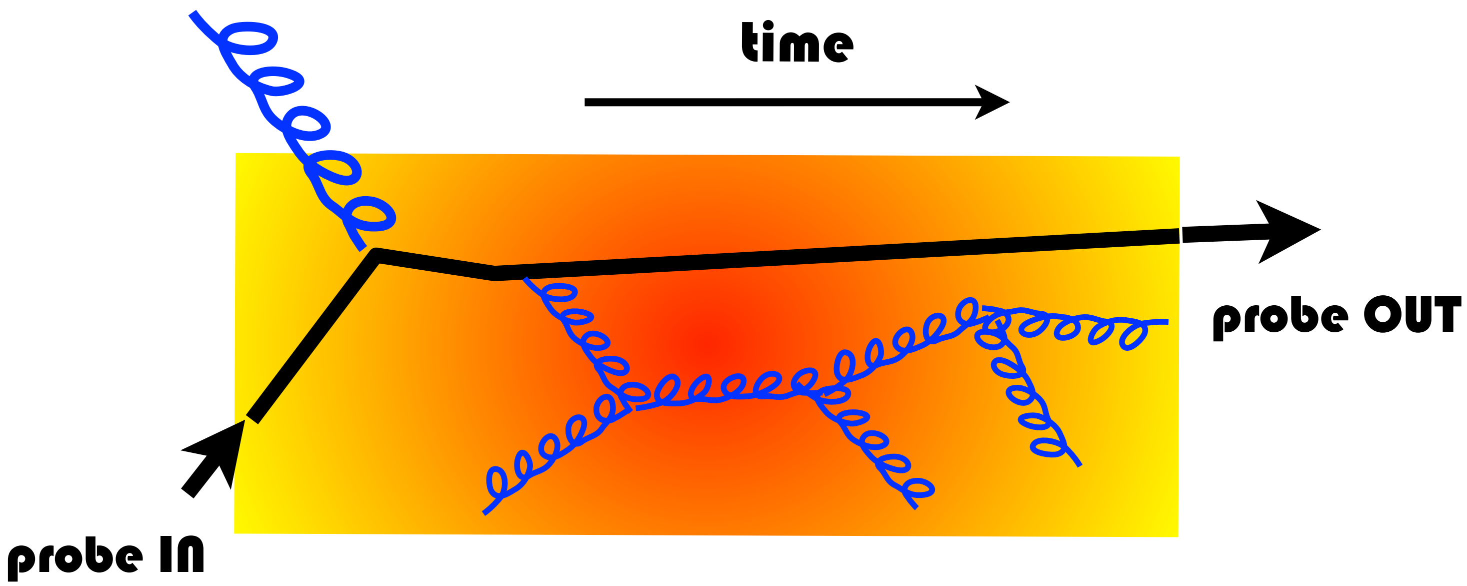
$$\Delta E_g > \Delta E_{c \approx q}$$

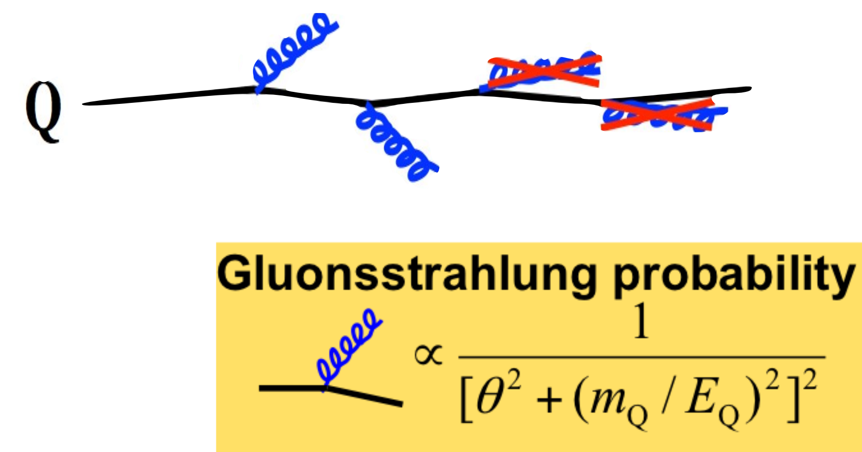
M. Djordjevic, M. Gyulassy, Nucl. Phys. A733 (2004) 265.

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)





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

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

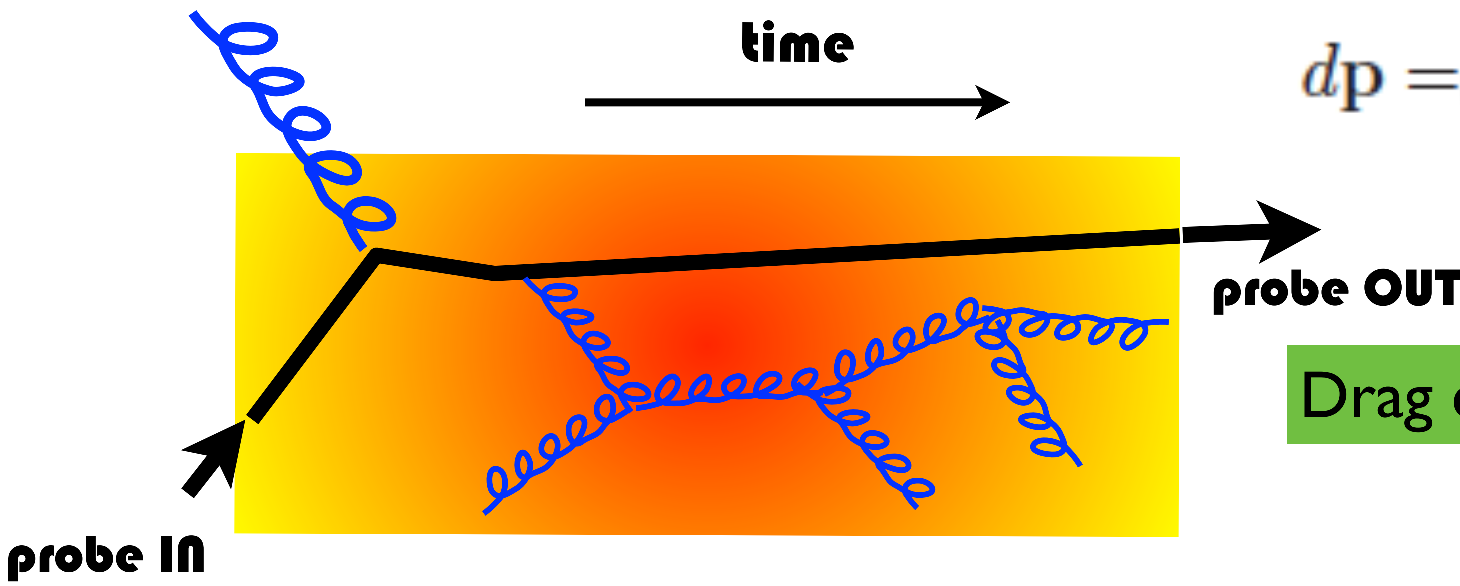
$$\omega \frac{dI}{d\omega}\Big|_{Heavy} = \omega \frac{dI}{d\omega}\Big|_{Light} \times \left(1 + \left(\frac{m_Q}{E_Q}\right)^2\right)\frac{1}{\theta^2}\Big)^{-2}$$

⇨ $E_{loss}(c) > E_{loss}(b)$

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:**



$$dx = \frac{p}{E} dt,$$

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

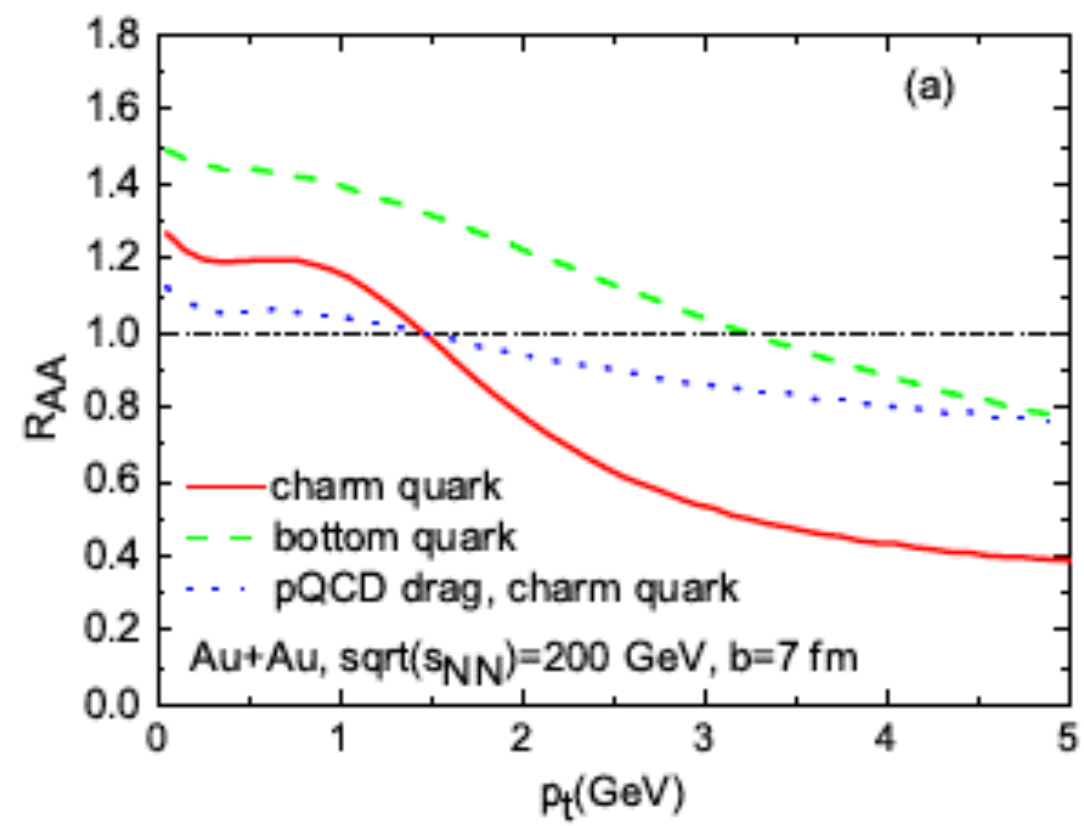
Drag coefficient: E_{loss} term

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

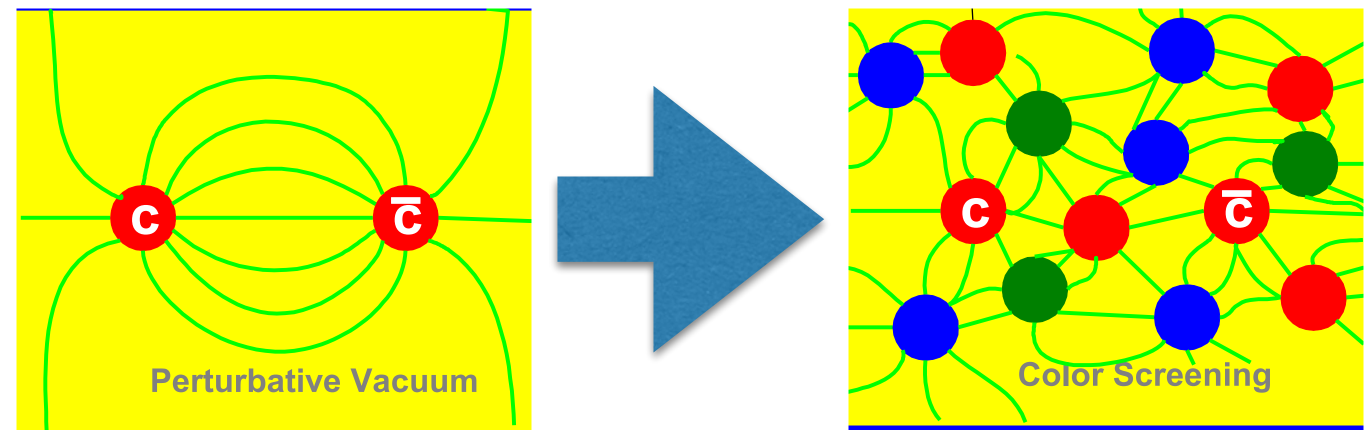


What about quarkonium?

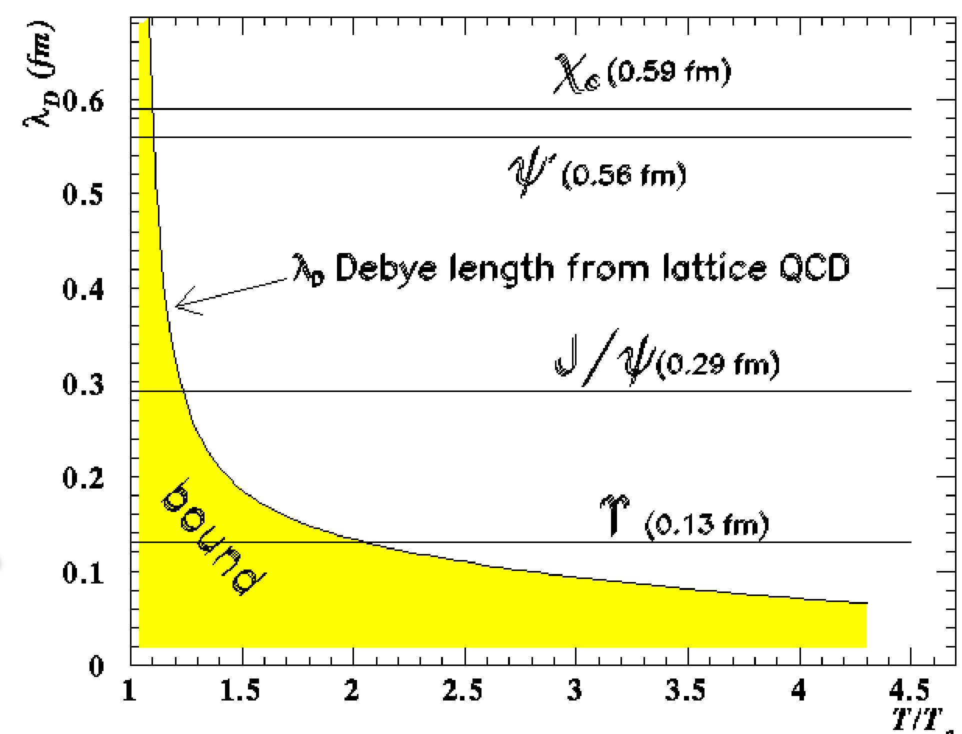
☑ Dissociation of $Q\overline{Q}$ via color-screening:

Screening of strong interactions in QGP

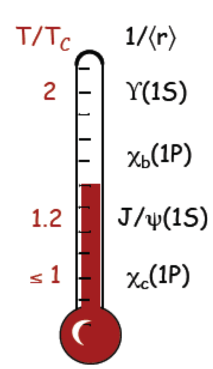
PLB178 (1986) 416



- Screening stronger at high-p_T
- Maximum size of a bound state decrease with T increasing
- Different states → Different sizes



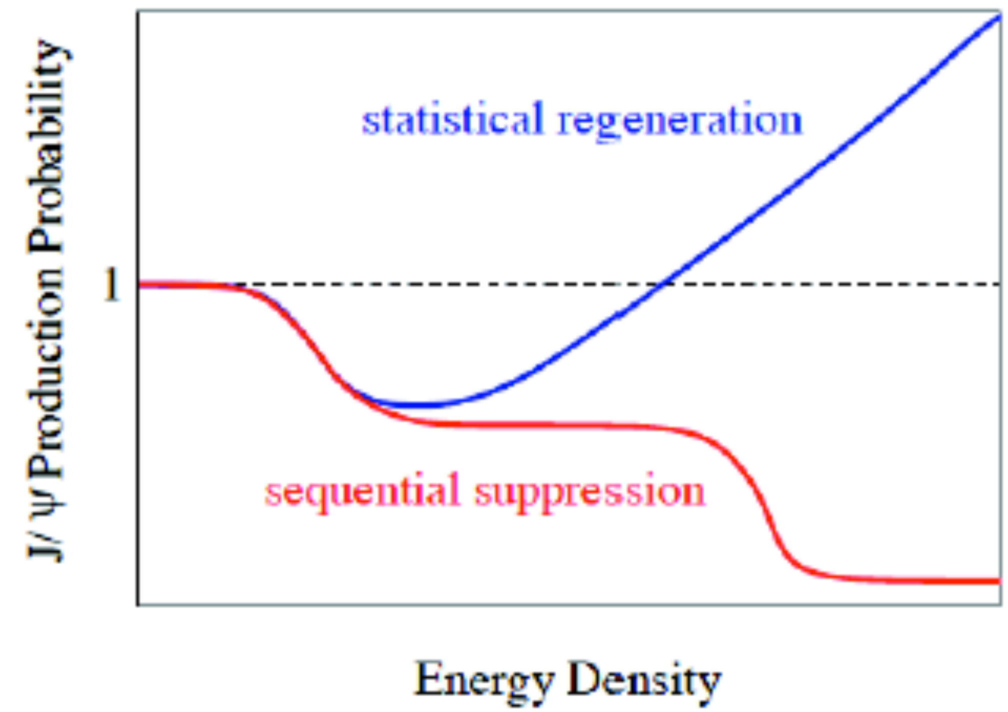
QGP Thermometer!



Regeneration

- High-energy → large number of ccbar pairs
  ~80 pairs in central Pb-Pb collisions at √sNN = 5 TeV

- Statistical approach:
  - charmonium fully melted in QGP
  - charmonium produced at chemical feeeze-out
- Kinematic recombination:
  - Continous dissociation/regeneration over QGP lifetime



Robert L. Thews, Martin Schroedter, and Johann Rafelski, Phys. Rev. C 63, 054905

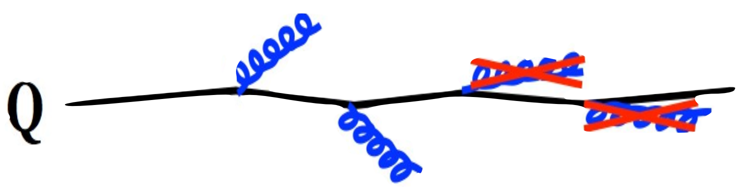
P. Braun-Munzinger and J. Stachel, Phys.Lett. B490 (2000) 196-202

Regeneration → charmonium enhanced contrary to color screening

Heavy quark: *simplifying a bit …*

Pillar one:

Mass dependent energy loss (dead cone effect)



Gluonsstrahlung probability

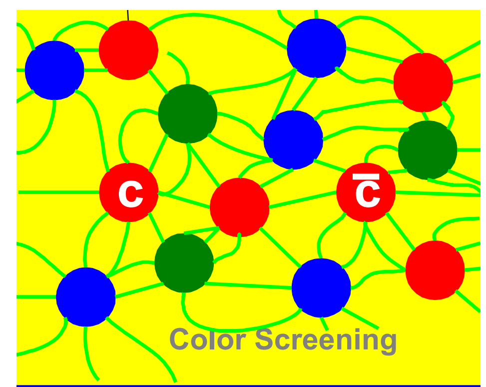
$$\propto \frac{1}{[\theta^2 + (m_Q / E_Q)^2]^2}$$

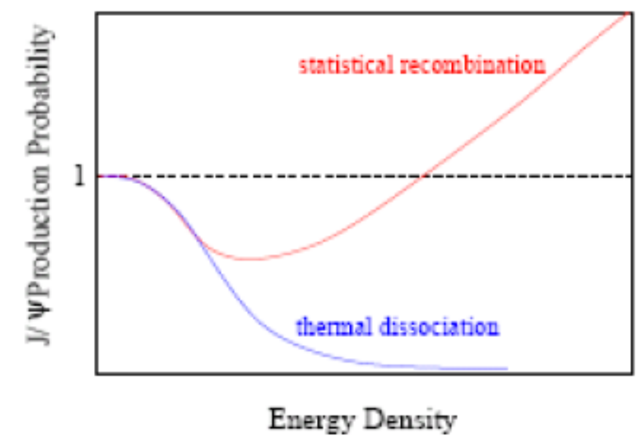
E_{loss}(light) > E_{loss}(charm) > E_{loss}(beauty)

Probe the QCD interaction dynamics over an extended medium

Pillar two:

Color Screening of $Q\bar{Q}$ pair in QGP - recombination



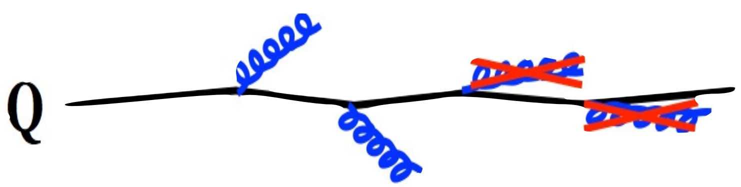


Probe medium deconfinement and temperature

Heavy quark: *simplifying a bit …*

Pillar one:

Mass dependent energy loss (dead cone effect)



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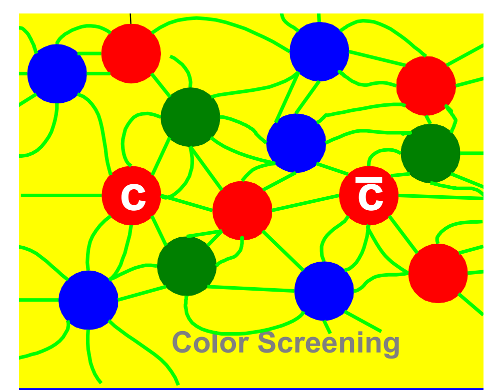
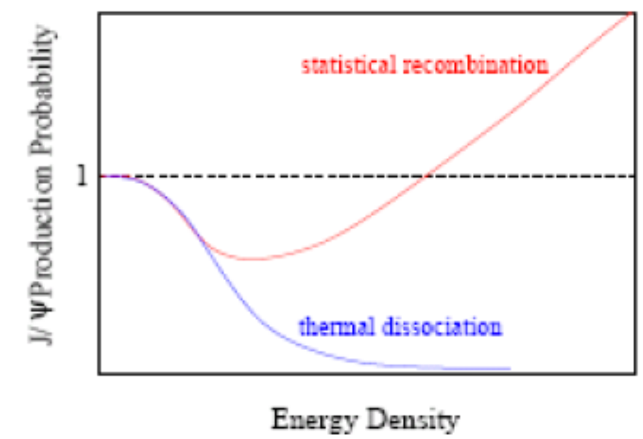
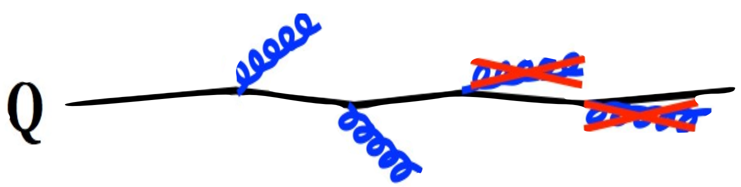




Probe medium deconfinement and temperature

Heavy quark: *simplifying a bit …*

Pillar one:
Mass dependent energy loss (dead cone effect)



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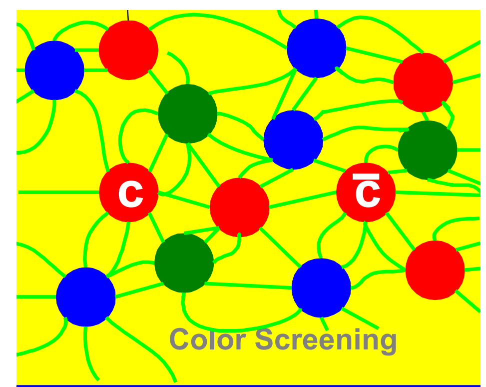
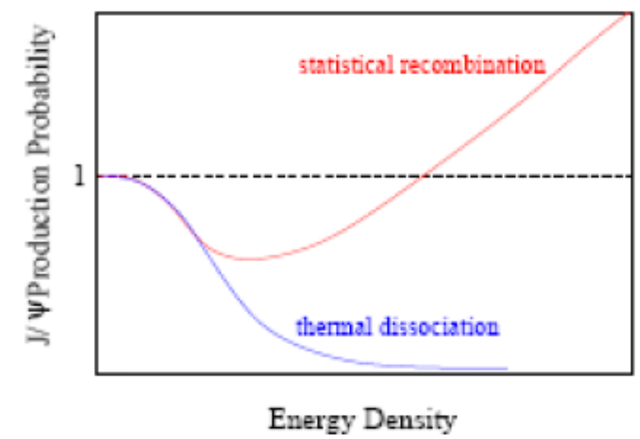




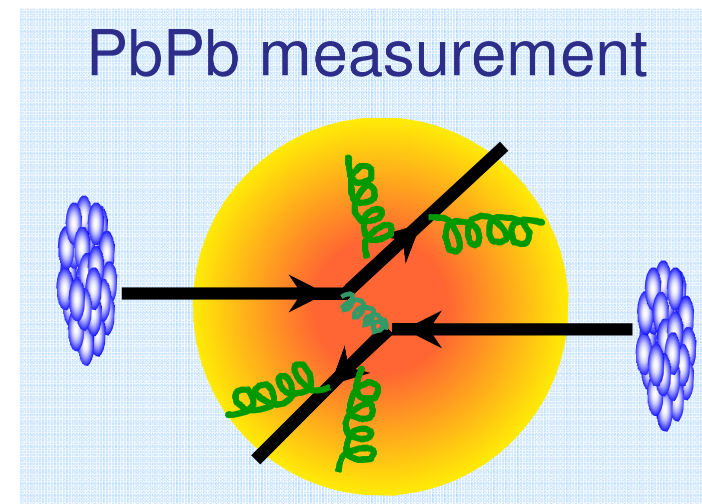
Probe medium deconfinement and temperature

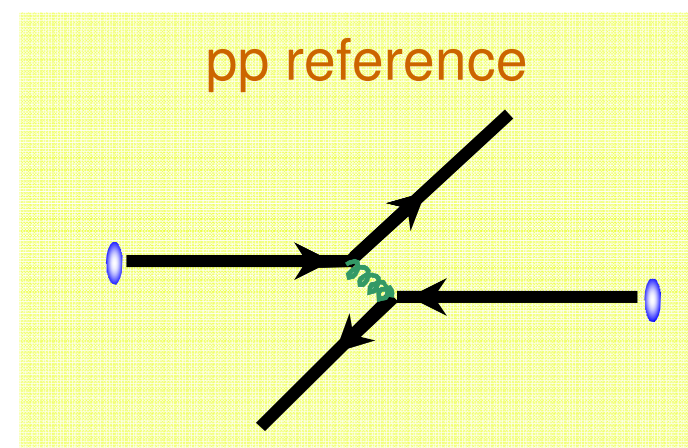
- Heavy Quarks
  - Indroduction
  - Energy loss
  - Observables
- Charm-Beauty production
  - pp collisions
  - A-A collisions
- What about pA collisions?
- What next?
- Conclusions

Nuclear Modification Factor

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

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





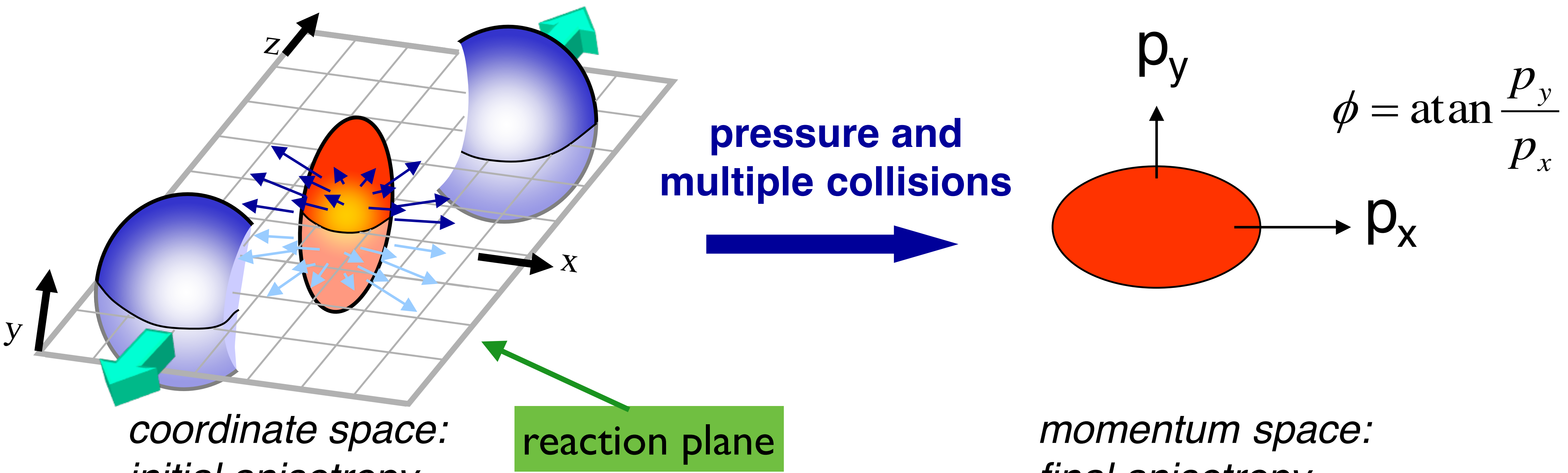
- What are the possibilities?
  - If no nuclear effects present: $R_{AA} = 1$
  - Effects of the hot and dense medium produced in the collision breakup binary scaling: $R_{AA} \neq 1$

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

several caveat to take into account!!

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

… a more differential study: Elliptic flow



coordinate space: initial anisotropy

momentum space: final anisotropy

- Quantified via the 2nd order Fourier coefficient **v_2 (Elliptic flow)**

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1+2v_1\cos(\varphi-\Psi_{RP}) + 2v_2\cos 2(\varphi-\Psi_{RP}) + ...\right)$$

- Carries information on medium transport properties:
  - **Low p_T: Do *b* and *c* take part to the collective motion?**
- High p_T: Path-length dependence of parton energy loss

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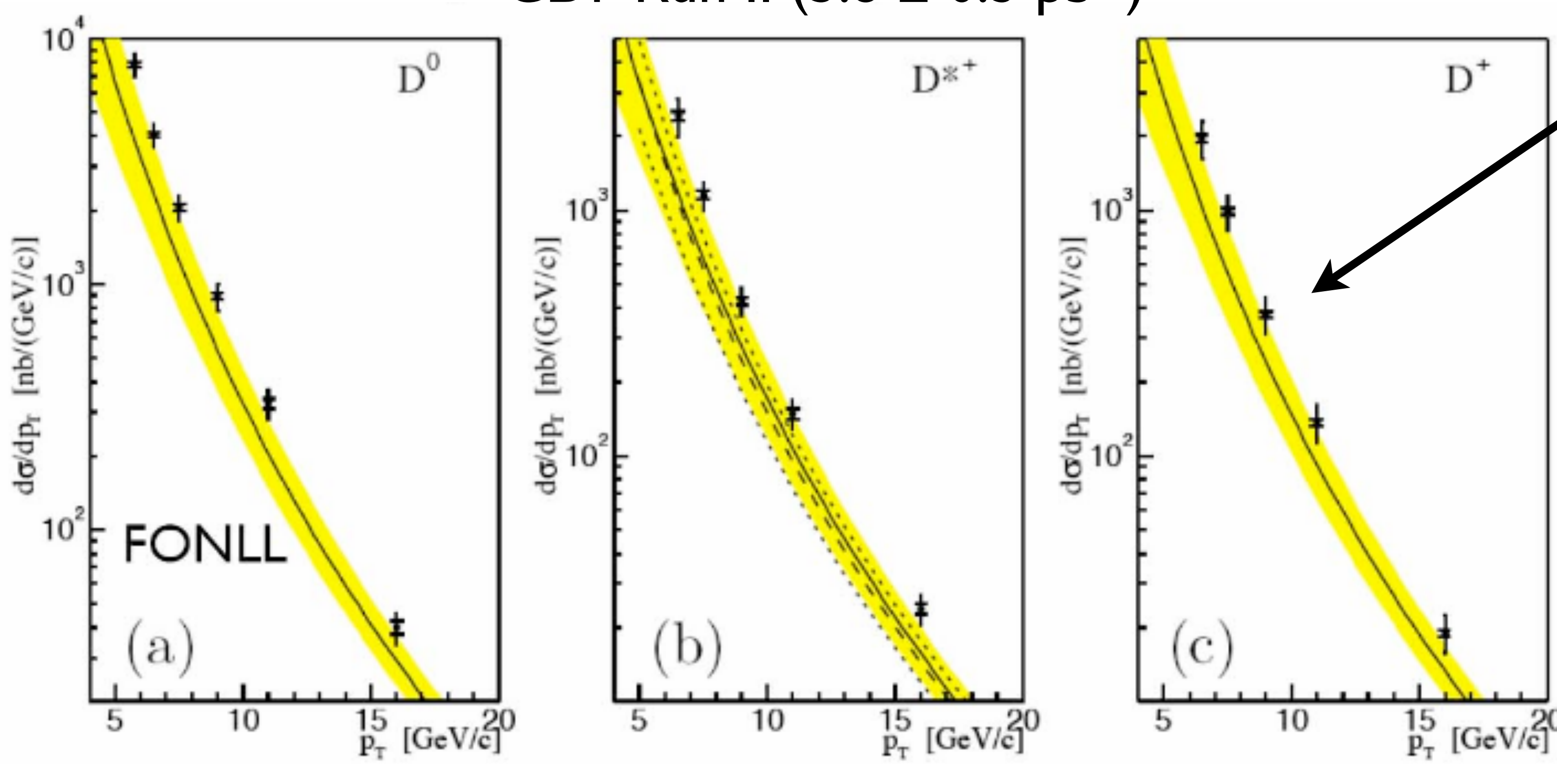
Back to 2003 - Tevatron results @ 1.96 TeV

CDF Run II (5.8 ± 0.3 pb^{-1})



Measurements are at the edge of theoretical uncertainties.

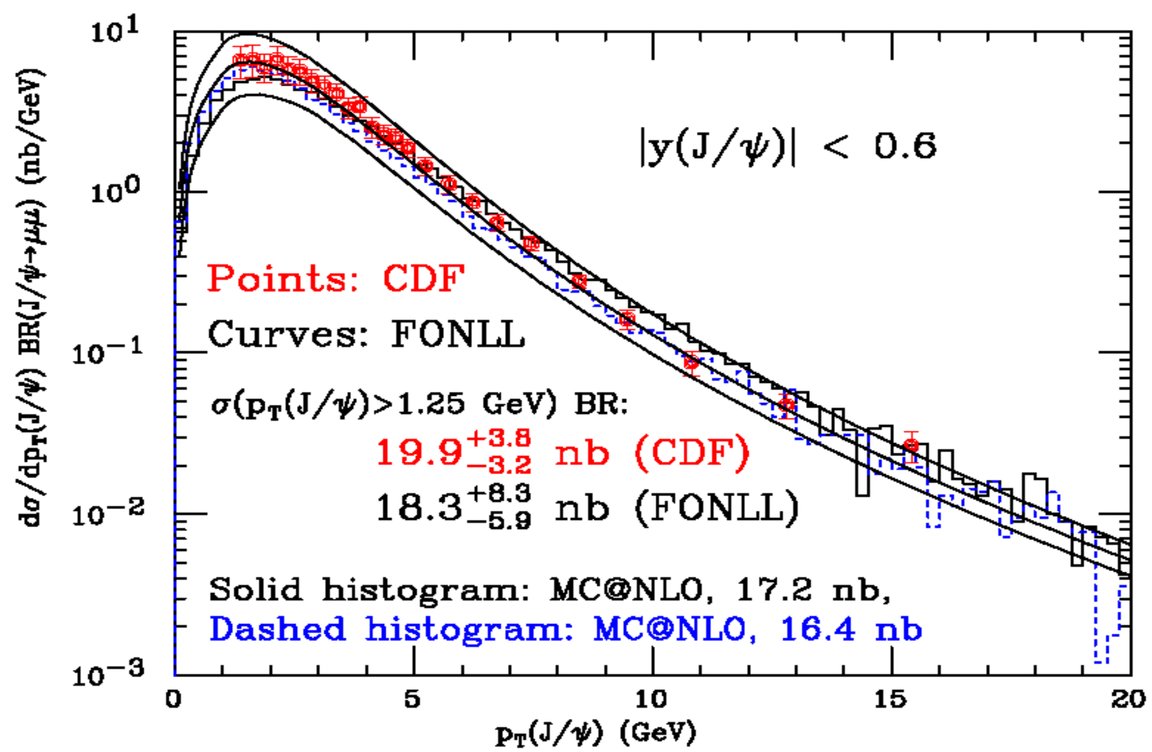
D^0 $(cu)\rightarrow K^+\pi^-$ (*BR ~3.89%*),

D$^+$ $(cu)\rightarrow K^-\pi^+\pi^+$ (*BR ~9.13%*),

D^{*+}$(cd)\rightarrow D^0(K^+\pi^-)\pi^+$(*BR~2.63%*),

CDF, PRL91 (2003) 241804,
FONLL: M. Cacciari and P. Nason, JHEP 0309, 006 (2003)

FONLL, MC@NLO: Cacciari, Frixione, Mangano, Nason and Ridolfi, JHEP0407 (2004) 033



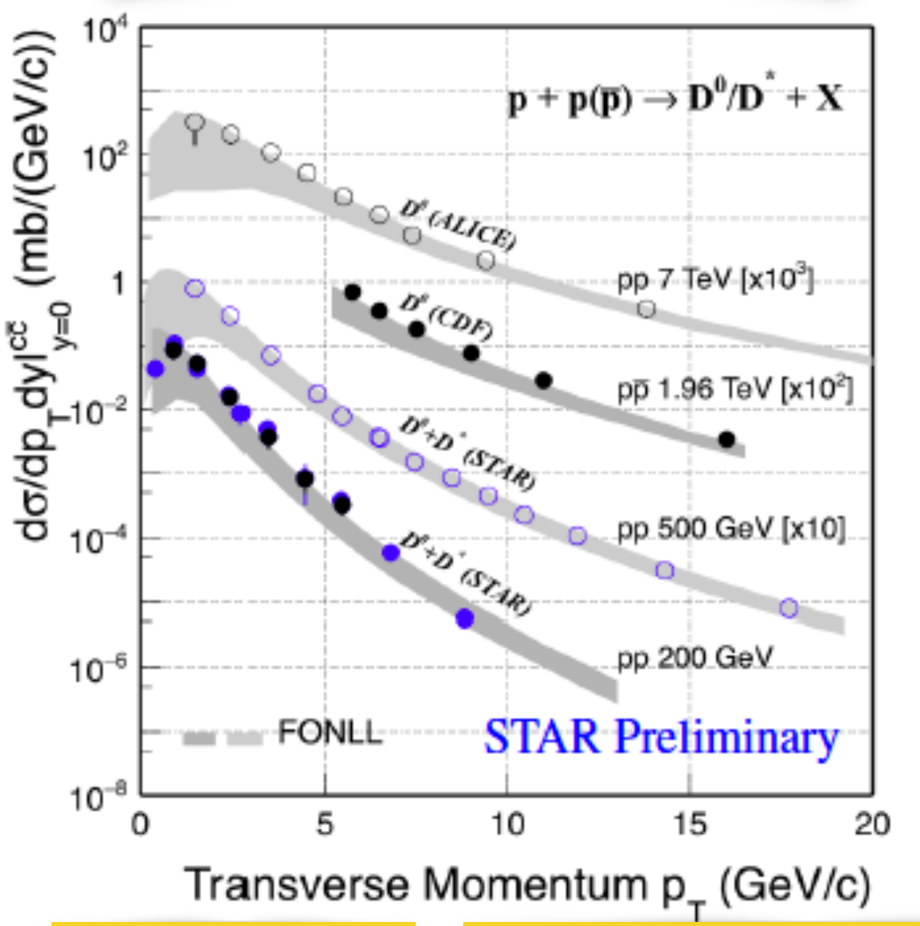
- ☑ Good understanding, within the errors, of b production at Tevatron (and LHC energies).
- ☑ Charm cross section studies, more complex, available since Tevatron Run II.

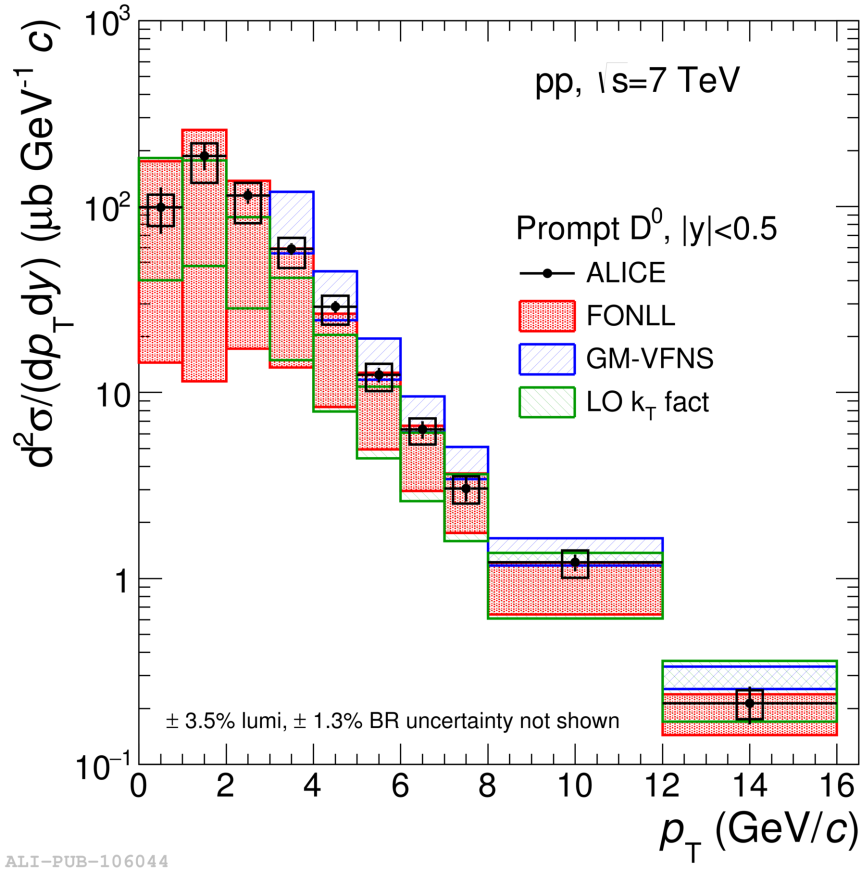
D meson - production cross-section: 0.2-7 TeV

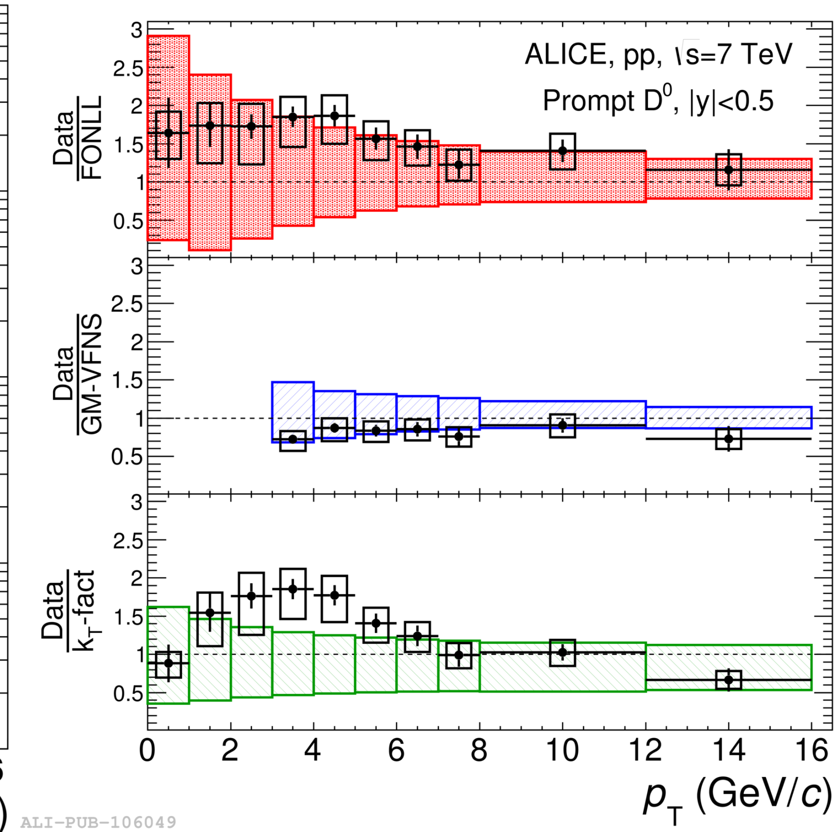
$D^0 \rightarrow K^- \pi^+$

STAR@ 0.2 and 0.5 TeV

ALICE@ 7 TeV







ArXiv: 1601.00695

2015 J. Phys.: Conf. Ser. 589 012002

arXiv:1605.07569

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

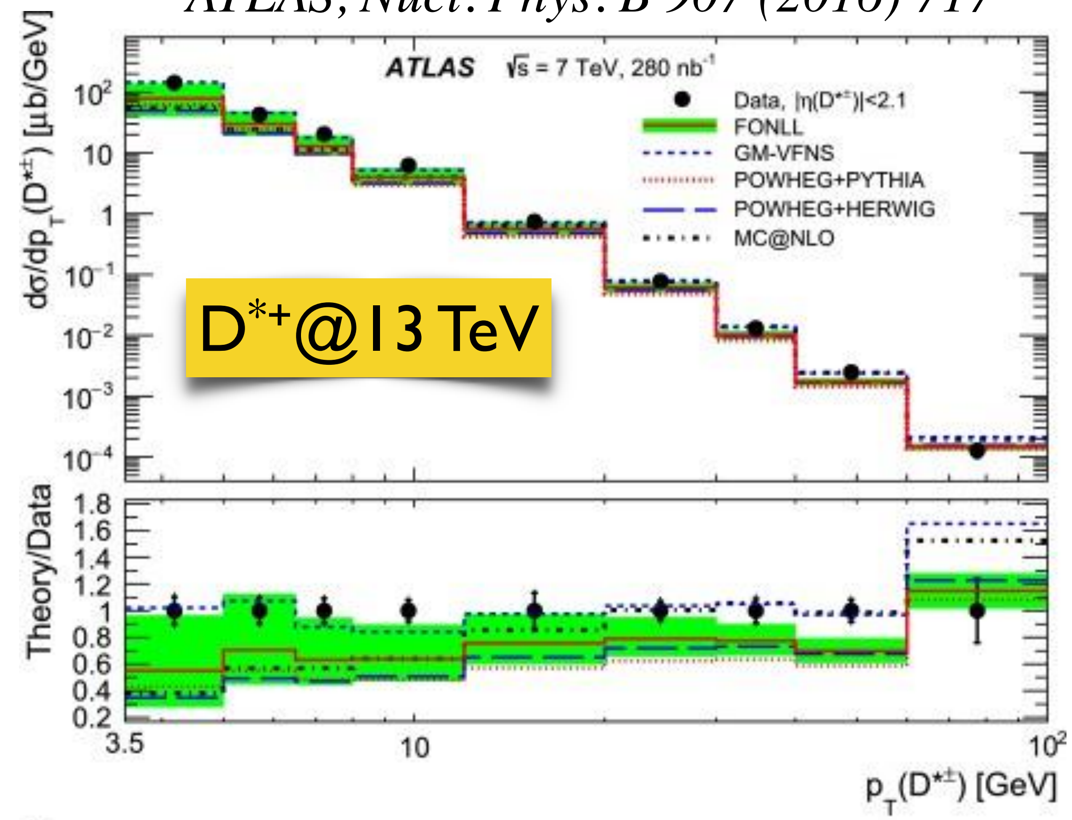
B.A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger, arXiv:1202.0439, DESY-12-013, MZ-TH-12-07, LPSC-12019

D meson - production cross-section: 13 TeV

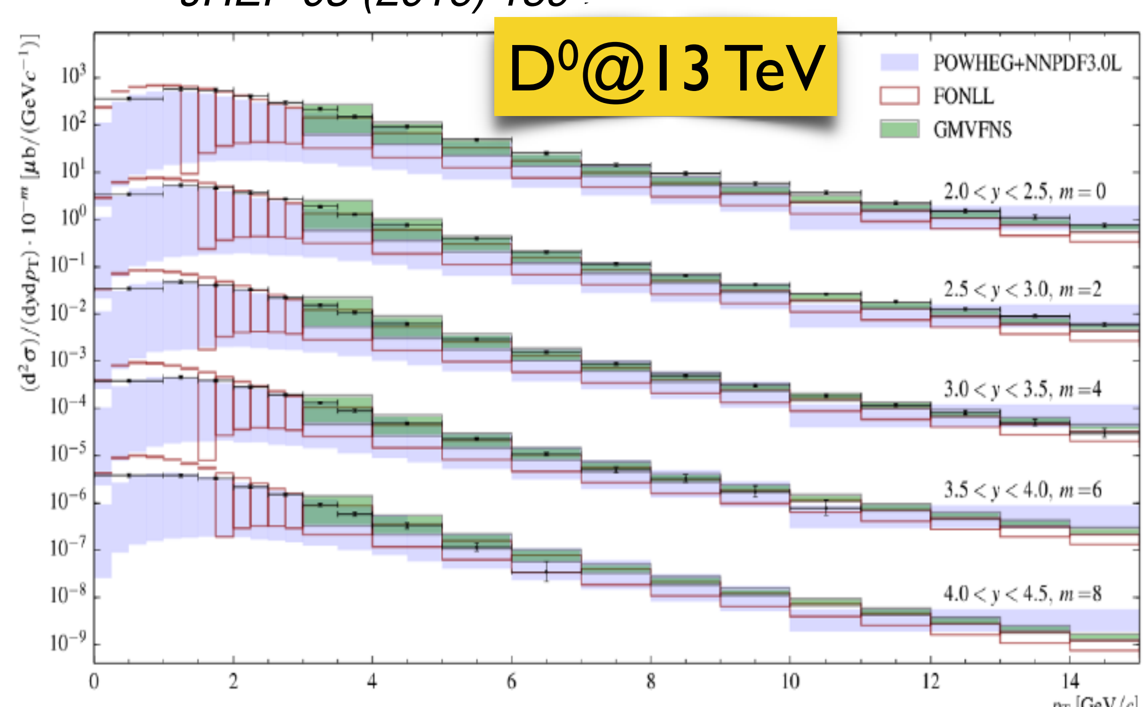
- D mesons measured by ATLAS down to $p_T = 3.5$ GeV/c. Results on the upper side of the FONLL error band.

- LHCb measured D mesons (including D_s) down to 0 p_T at forward rapidity 2<y<4.5 both at 7 and 13 TeV. Agreement with FONLL similar as the one found by ALICE and ATLAS at central rapidity.

ATLAS, Nucl. Phys. B 907 (2016) 717



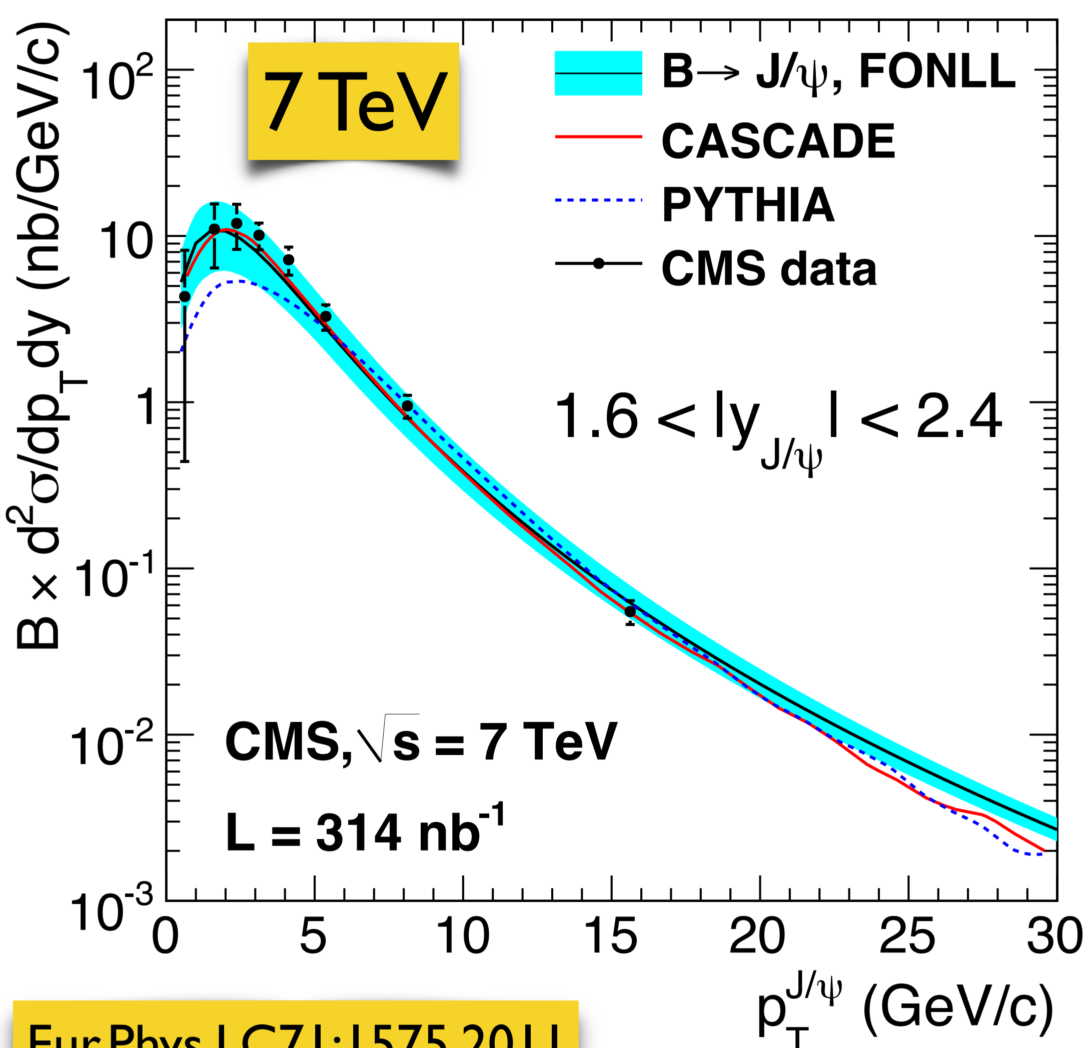
JHEP 03 (2016) 159



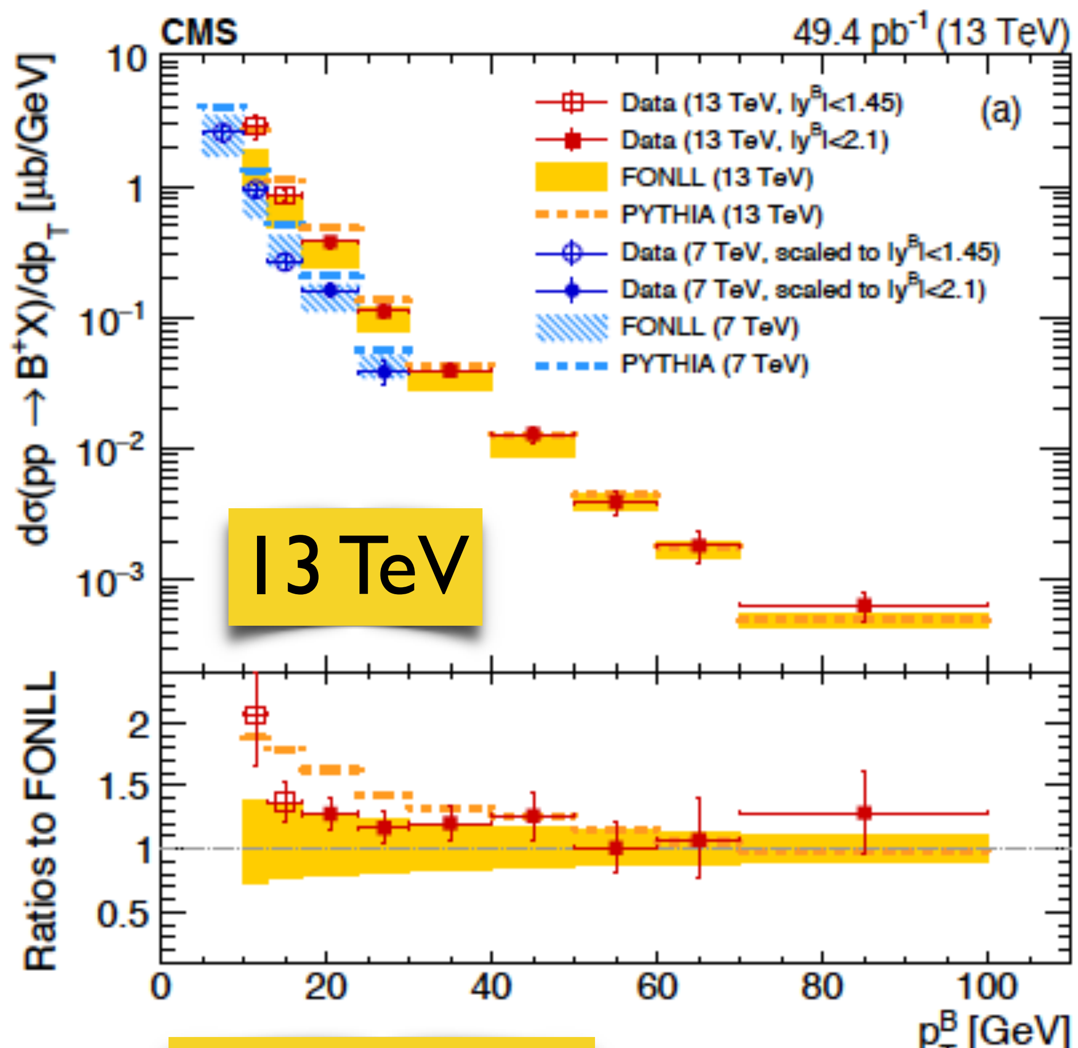
Nuclear Physics, Section B 871 (2013)

Beauty hadron: production cross-section

- CMS measured the non-prompt J/Ψ production in different rapidity intervals from -2.4<y<2.4 at 7 TeV and, recently, the fully reconstructed $B^+ \rightarrow J/\Psi K$ at 13 TeV.
- Good understanding, within uncertanties, of *b* production at 7 TeV. Some tension build-up at 13 TeV.



Eur.Phys.J.C71:1575,2011

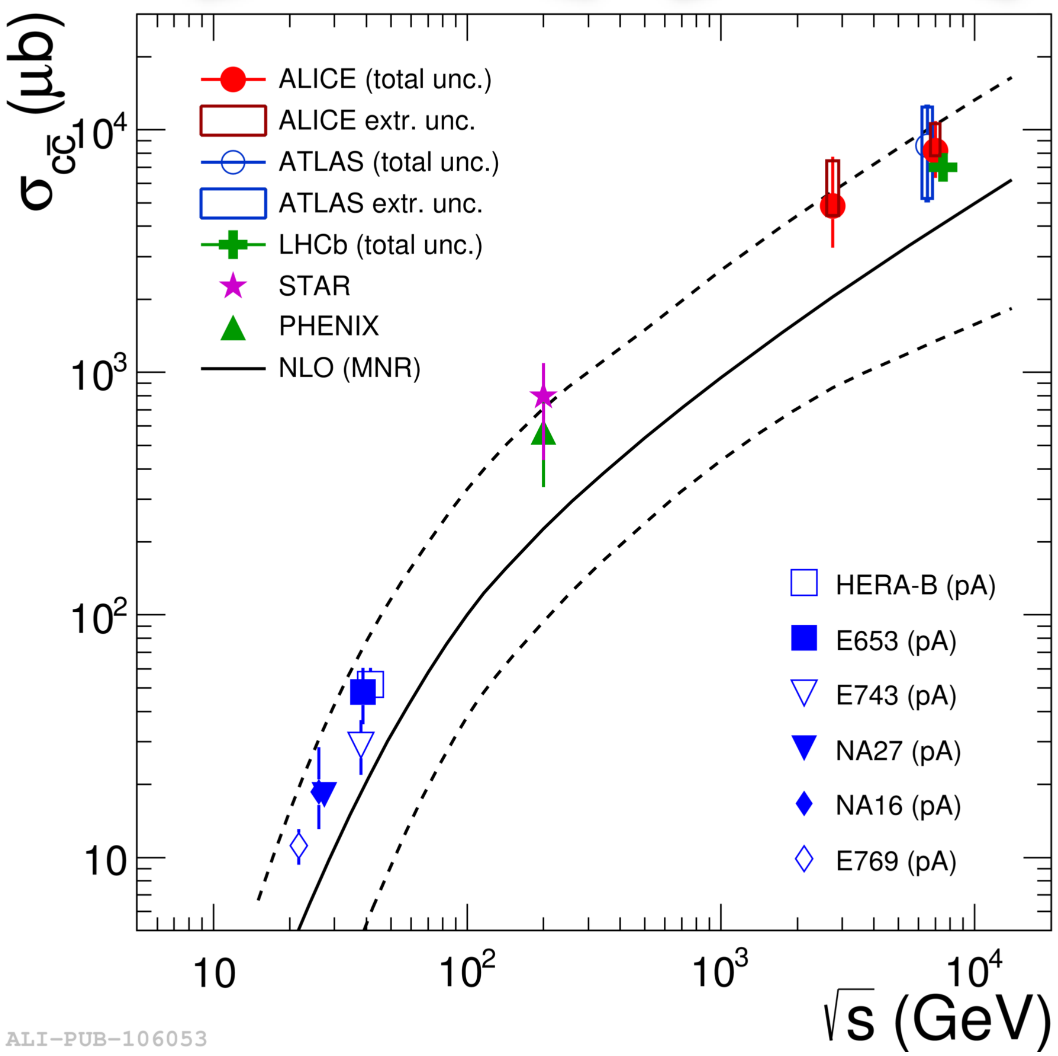


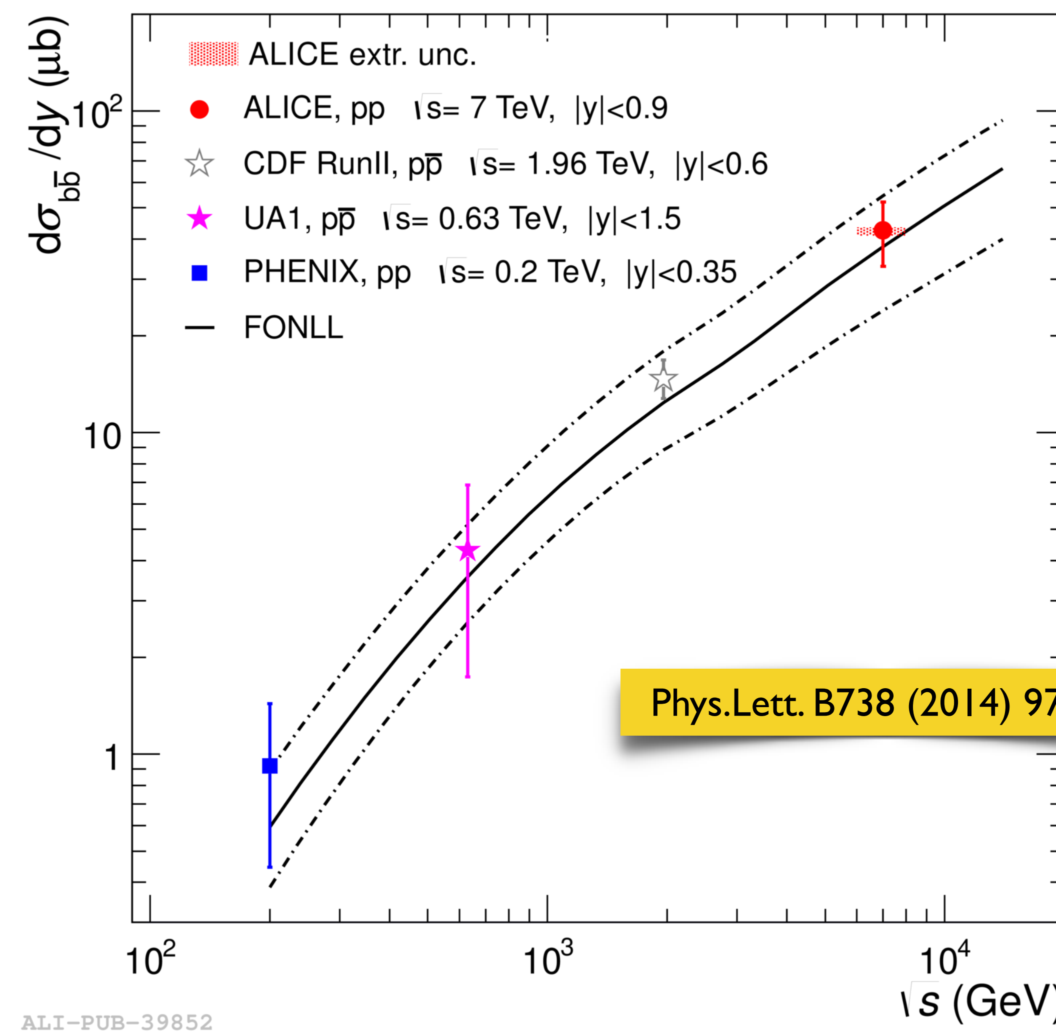
ArXiv: 1609.00873

Total cross section

JHEP 1207 (2012) 191

arXiv:1605.07569



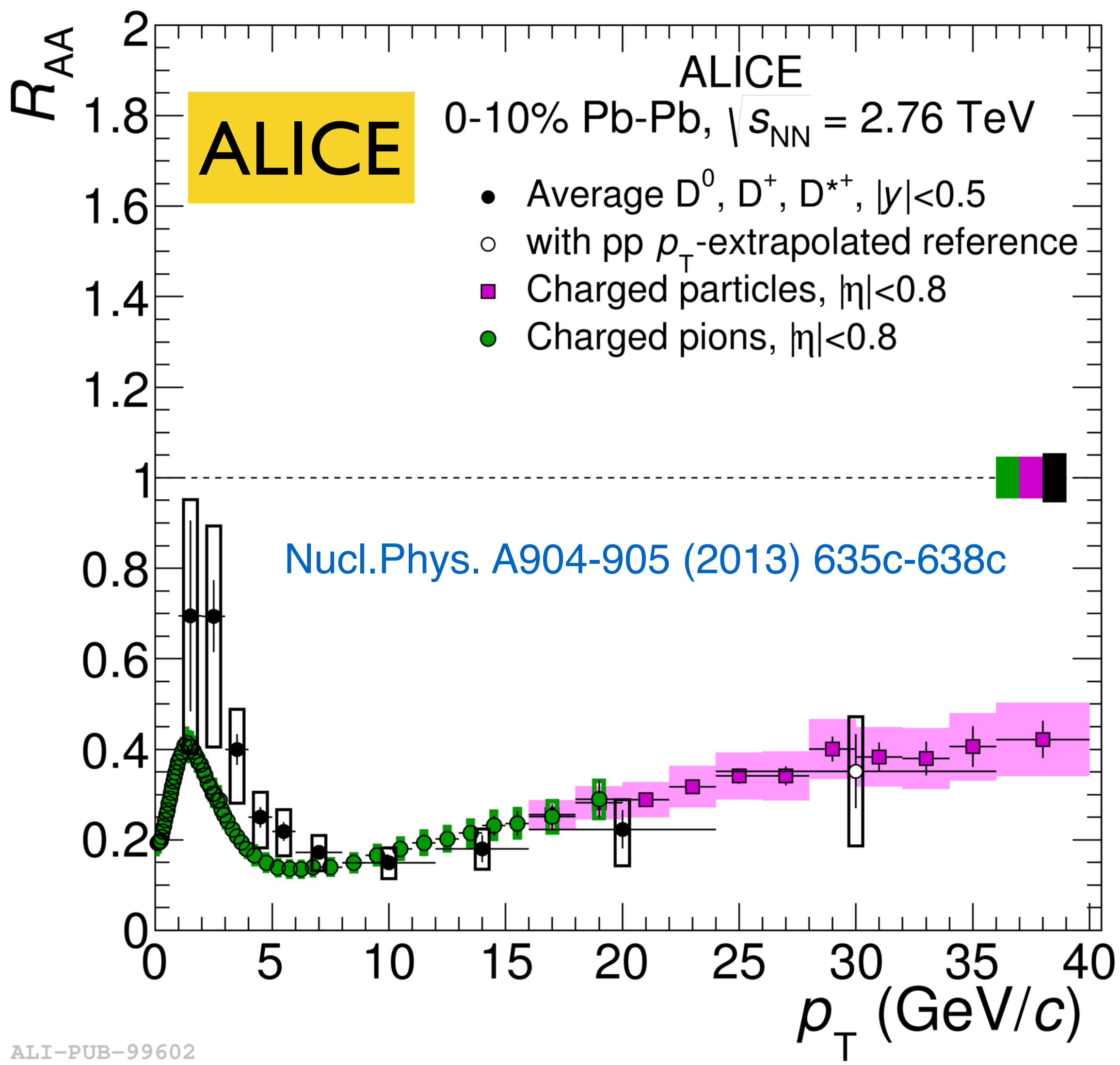


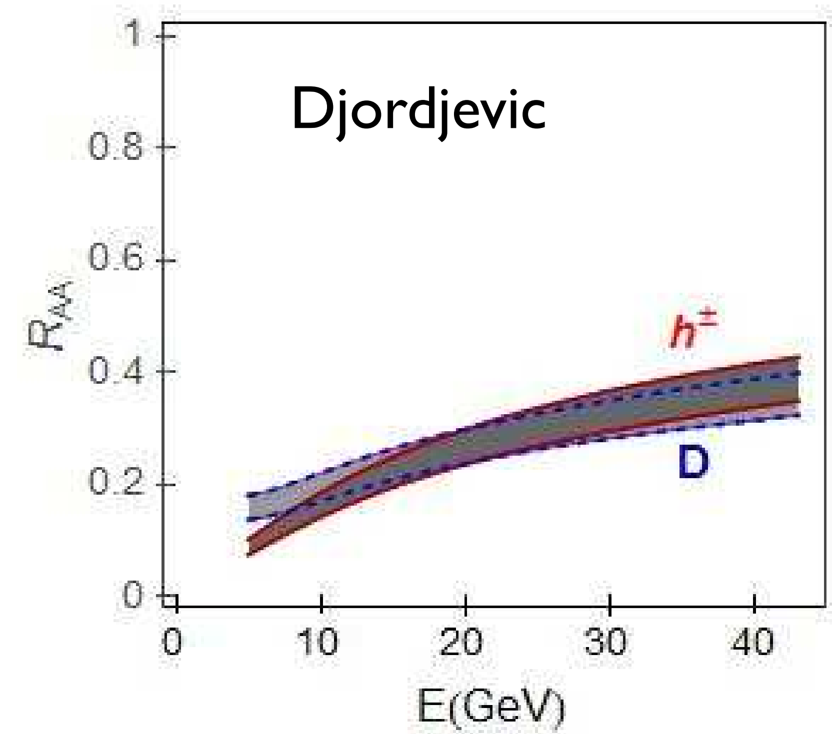
- Production well described vs $\sqrt{s}$ however, systematically in the higher side (expecially for charm)

- pp@ $\sqrt{s}$ = 8 and 13 TeV data will set additional constraints.

HF production in nucleus-nucleus

R_{AA} : D mesons vs charged particles





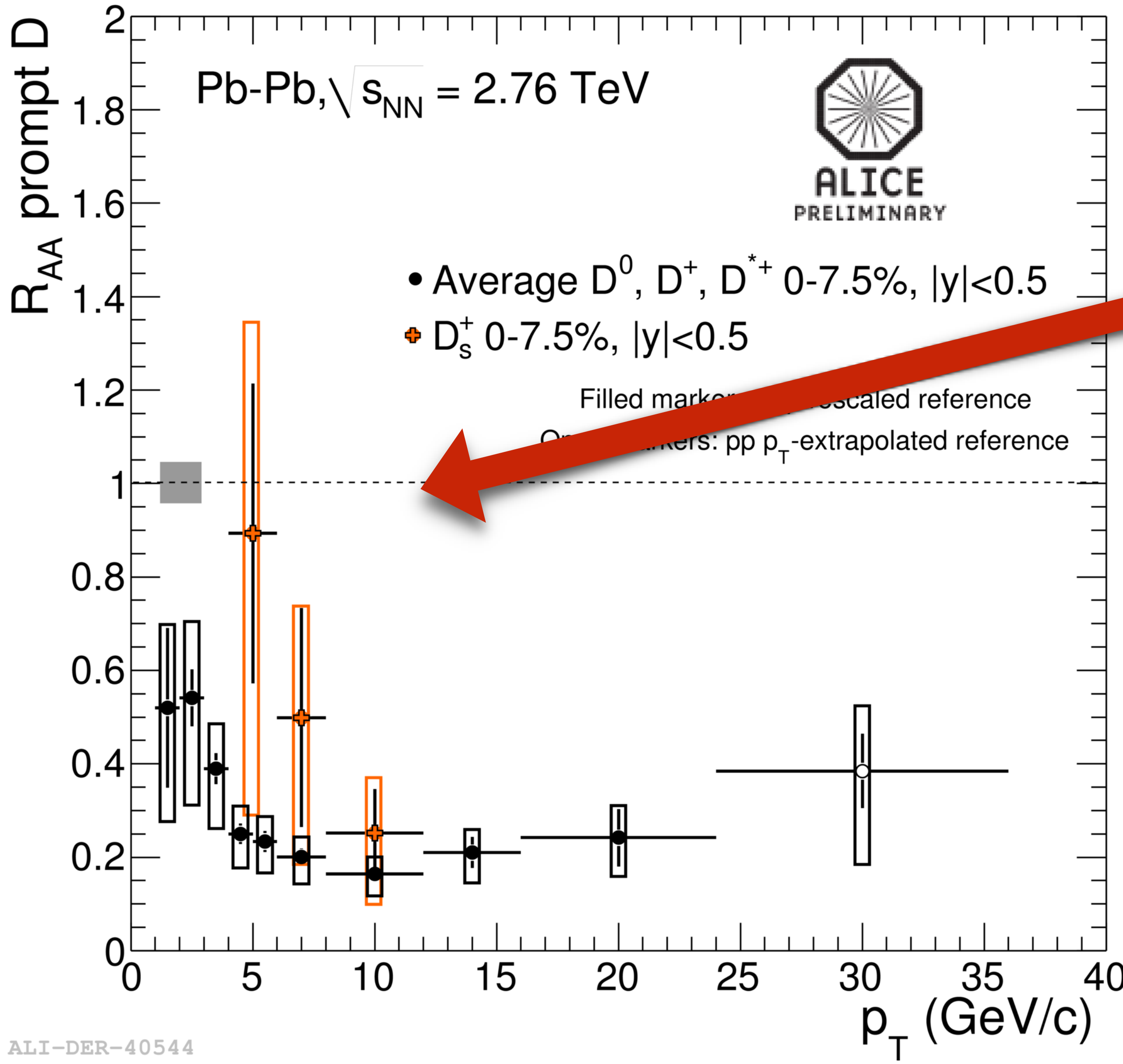
Phys. Rev. Lett. 112, 042302 (2014)

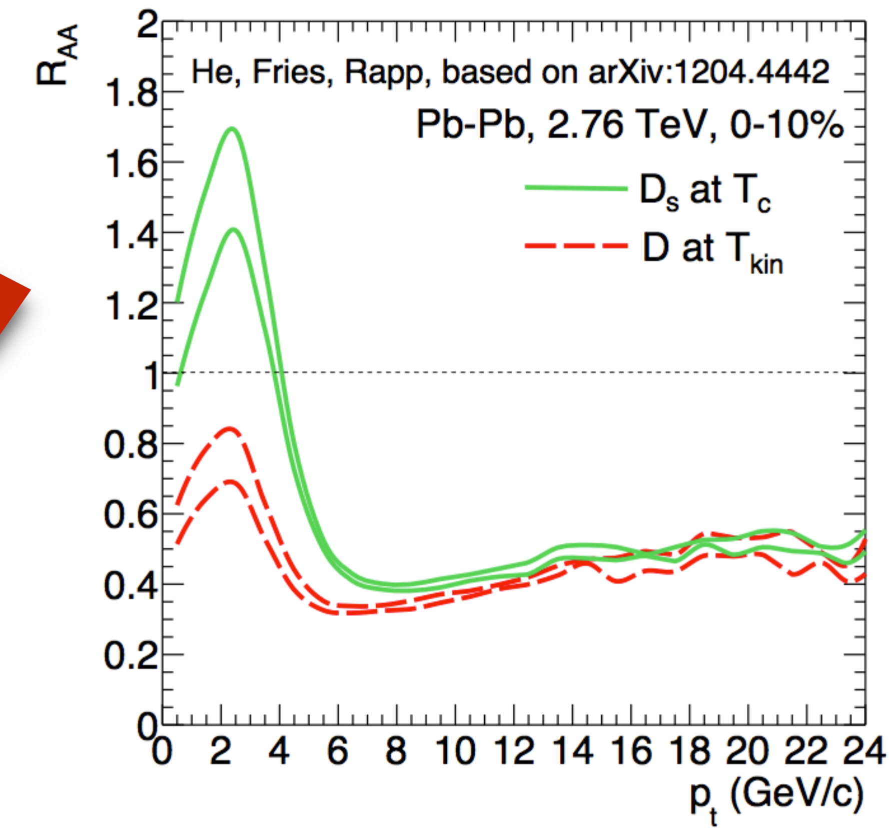
- D mesons and pions consistent for $p_T \geq 5$ GeV/c. Strong suppression, factor 5 at $p_T = 10$ GeV/c
- For $p_T \leq 5$ GeV/c we have and hint of lower suppression for pions. Need more statistic!
- Is it consistent with the picture of dead cone effect?

D_s meson in QGP, a probe for coalescence?

ALICE

- If coalescence processes play a major role in charm hadronization, the R_{AA} of D_s is expected to be largely enhanced with respect the other D R_{AA}



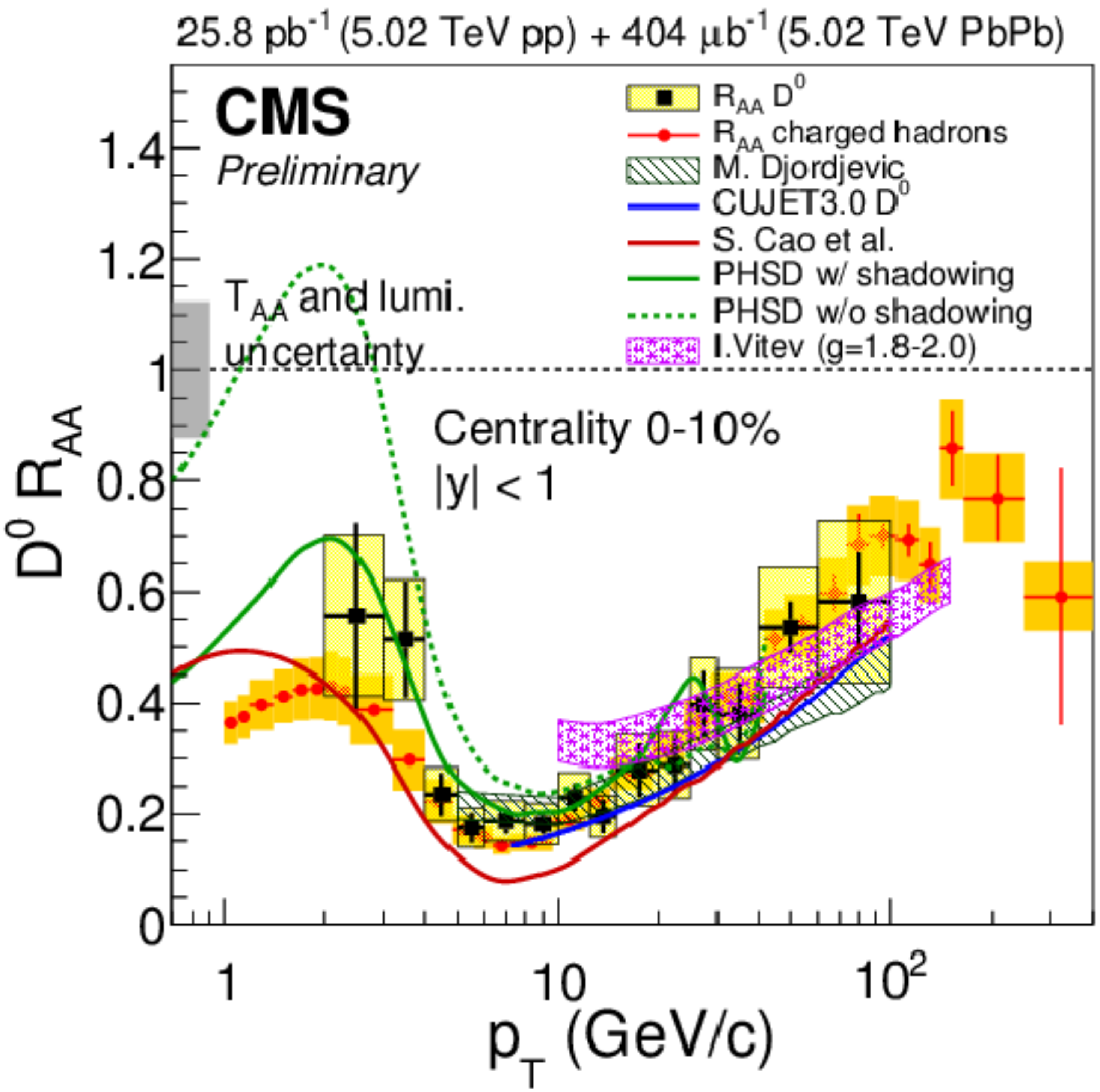


JHEP 1511 (2015) 205

JHEP 1603 (2016) 082

- TAMU: HF transport code based on Langevin equation: collisional energy loss + hydrodynamical evolution

D mesons R_{AA}: CMS results at 5.02 TeV



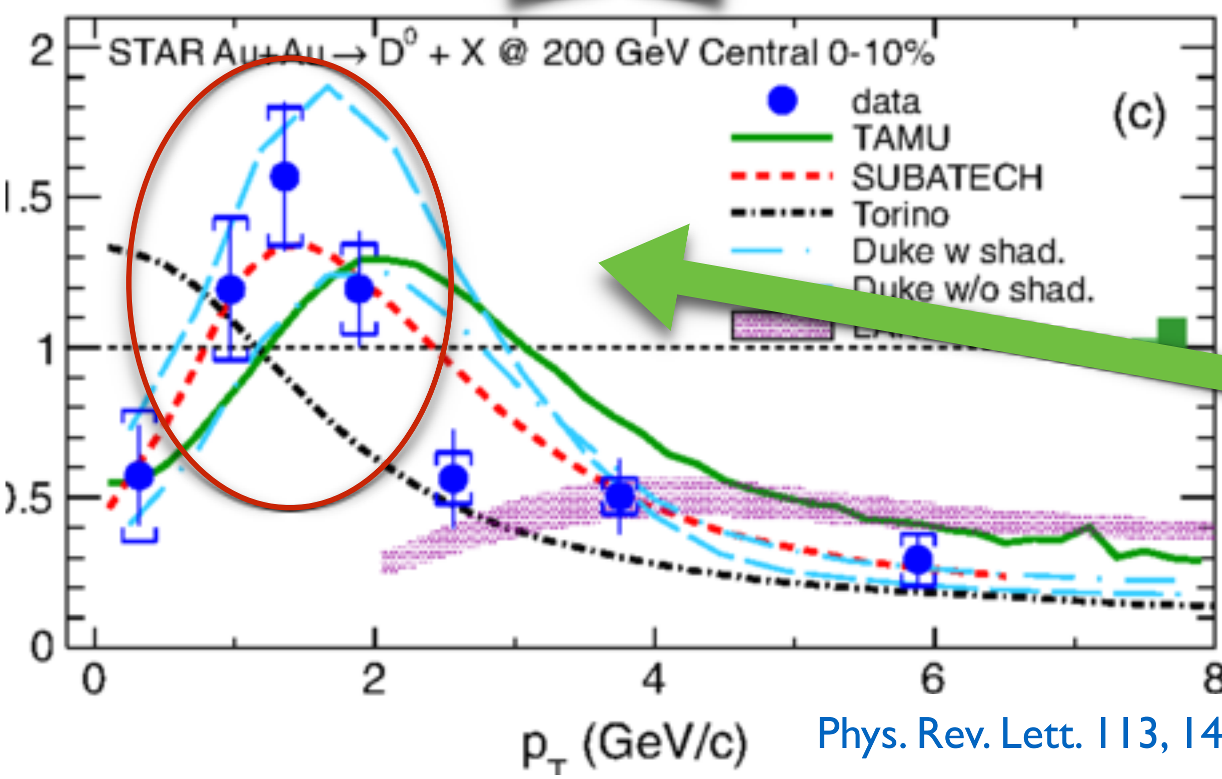
CMS PAS HIN-15-015

CMS PAS HIN-16-001

- Very large p_T coverage (up to 100 GeV/c!). Consistent with ALICE results.

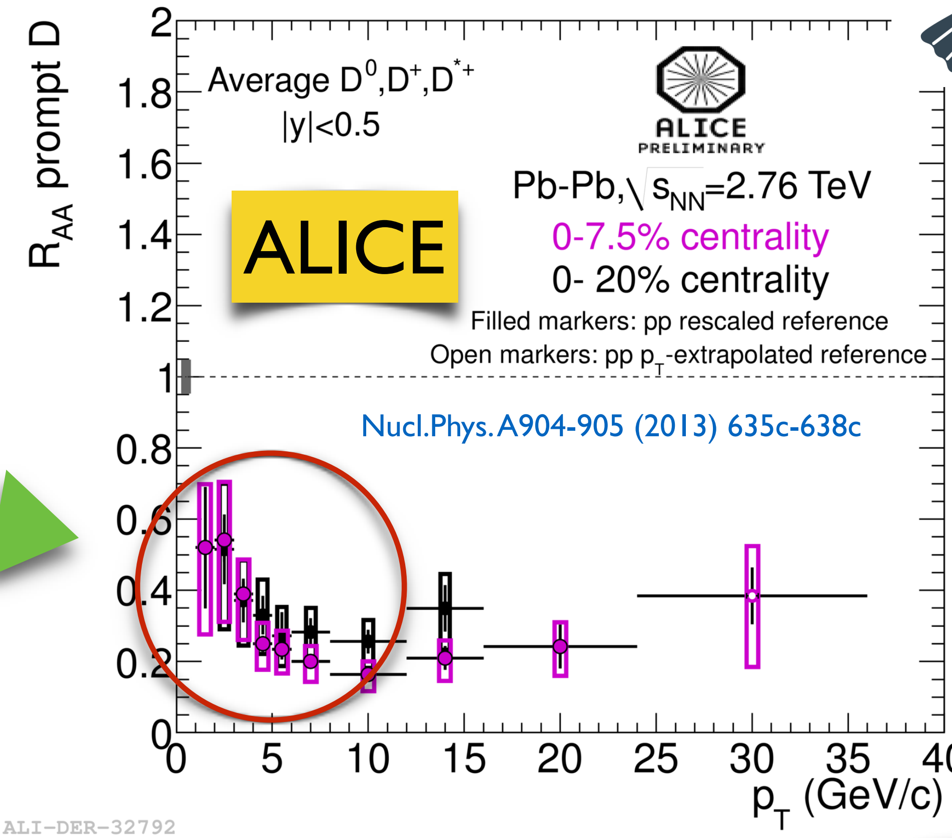
D mesons R_{AA}: from RHIC to LHC

STAR



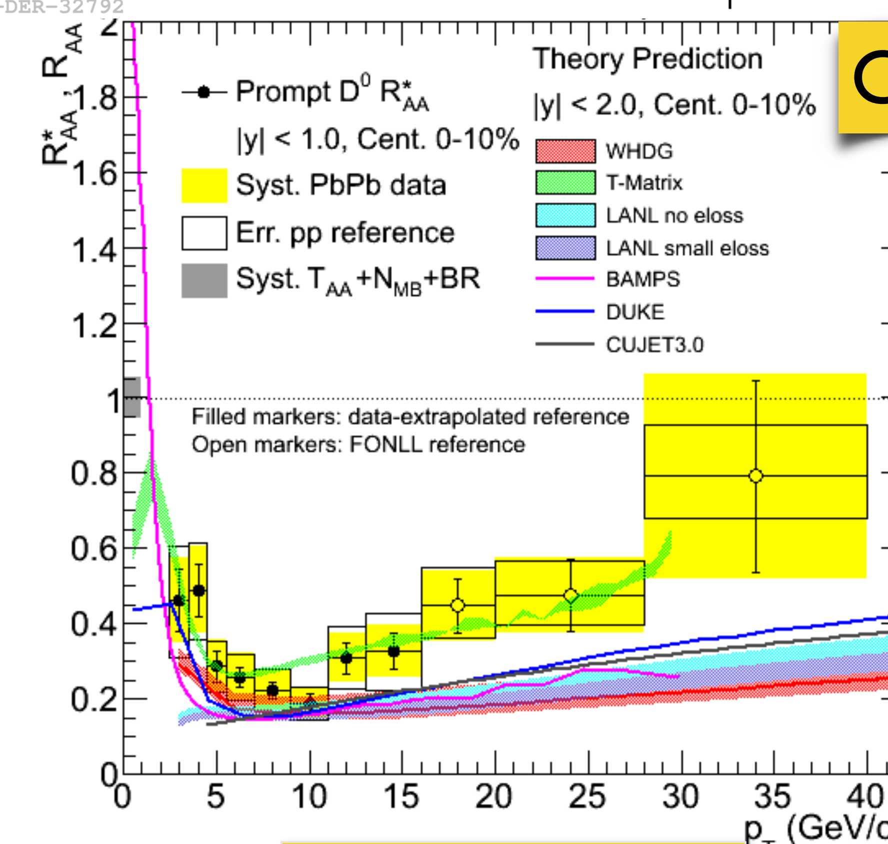
Phys. Rev. Lett. 113, 142301 (2014)

ALICE



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

CMS

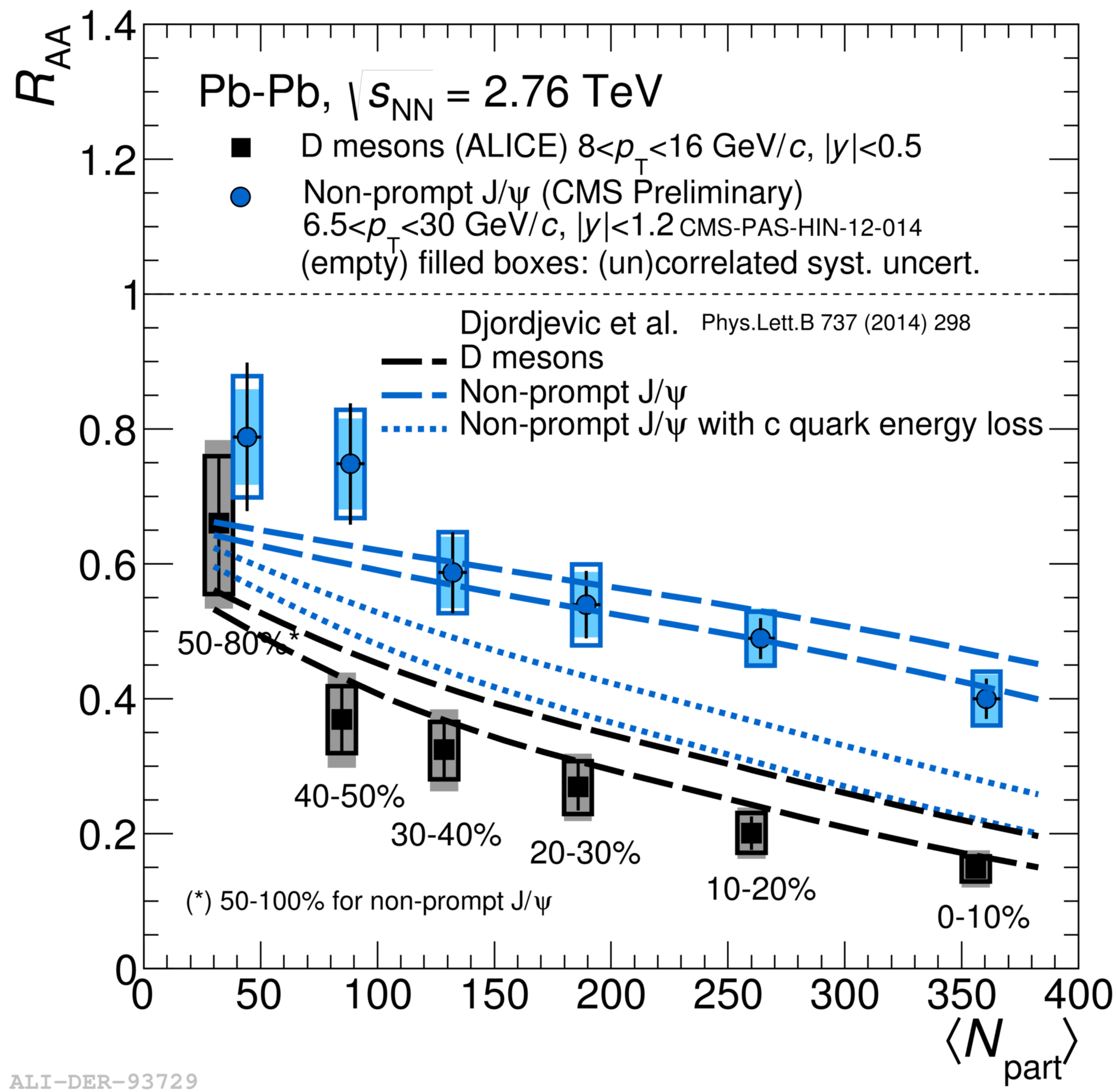


CMS PAS HIN-15-005

- Different behavior in the p_T region [1,2] GeV/c
  - Could it be a combined effect of shadowing, recombination and radial flow? TAMU model would predict an R_{AA} of 1.3 (at 2 GeV/c) at RHIC and ~0.8 at LHC.

Mass dependence: D vs B

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



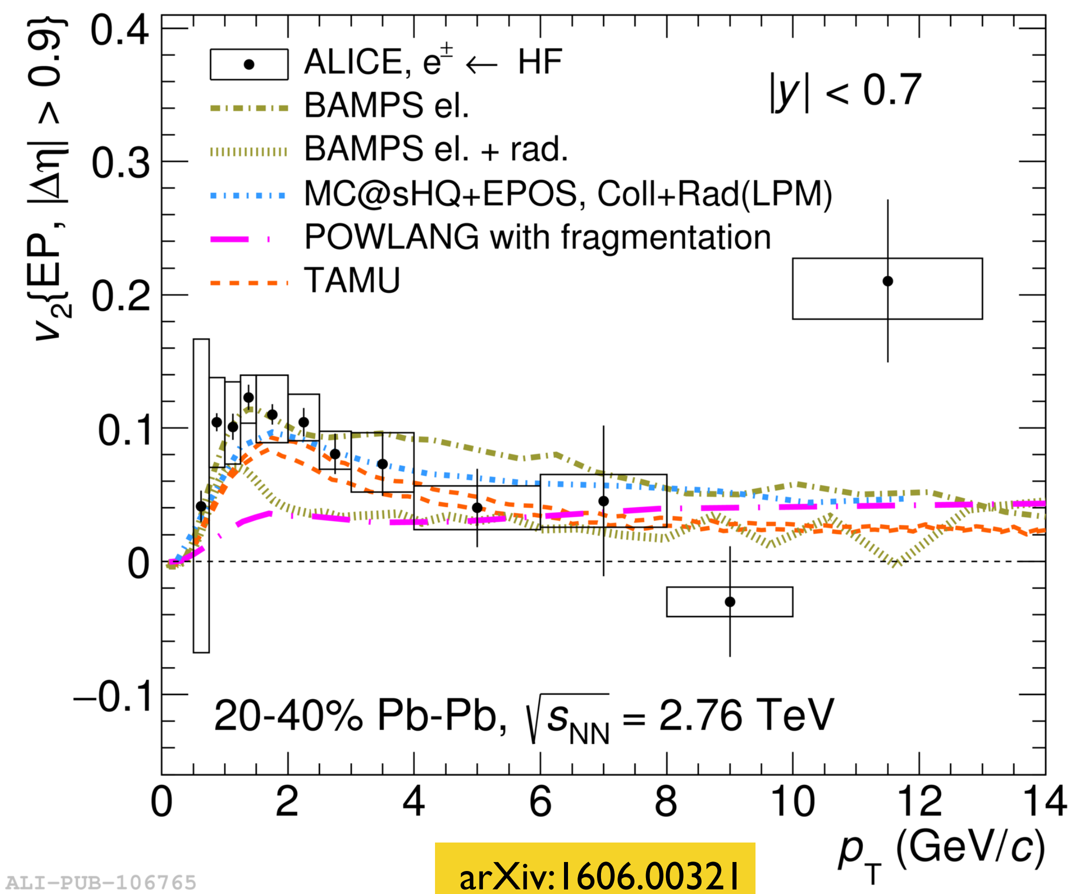
consequence of mass difference in pQCD based model calculation

CMS-PAS-HIN-12_14
arXiv:1411.2442
J.Phys.Conf.Ser. 509 (2014) 012080
Djordjevic: Phys.Lett. B734 (2014)

Elliptic flow (v_2)

ALICE

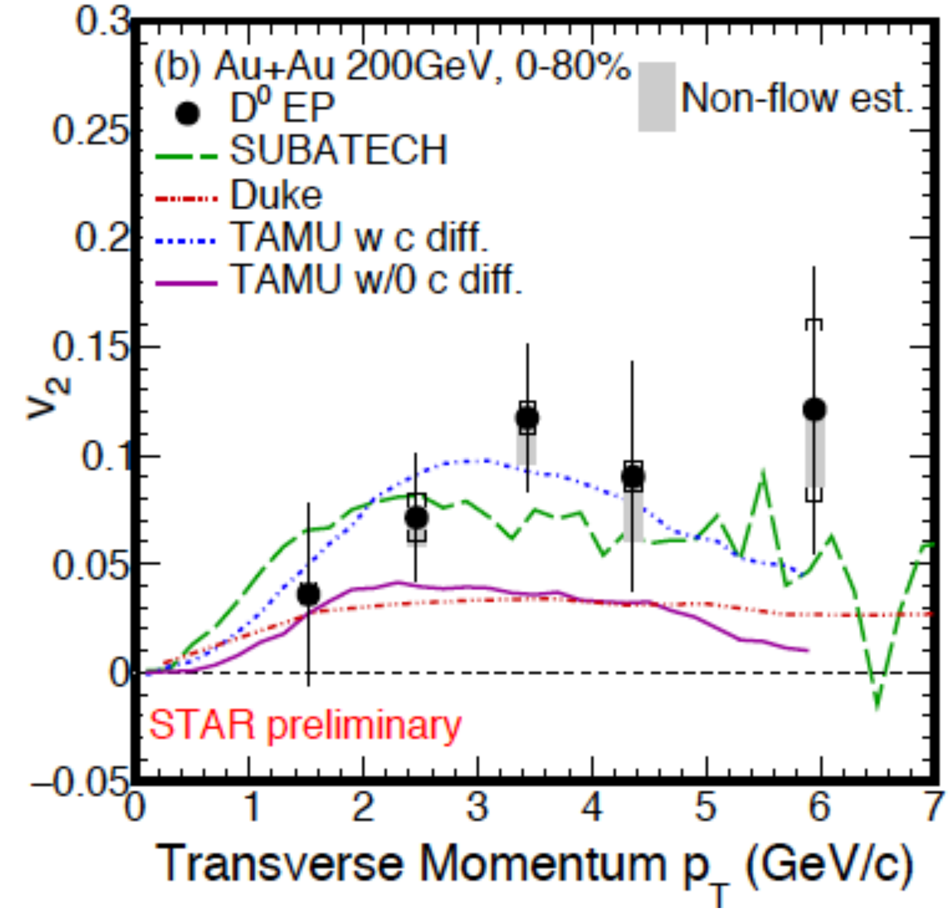
HF-decay electrons



arXiv:1606.00321

STAR

D mesons

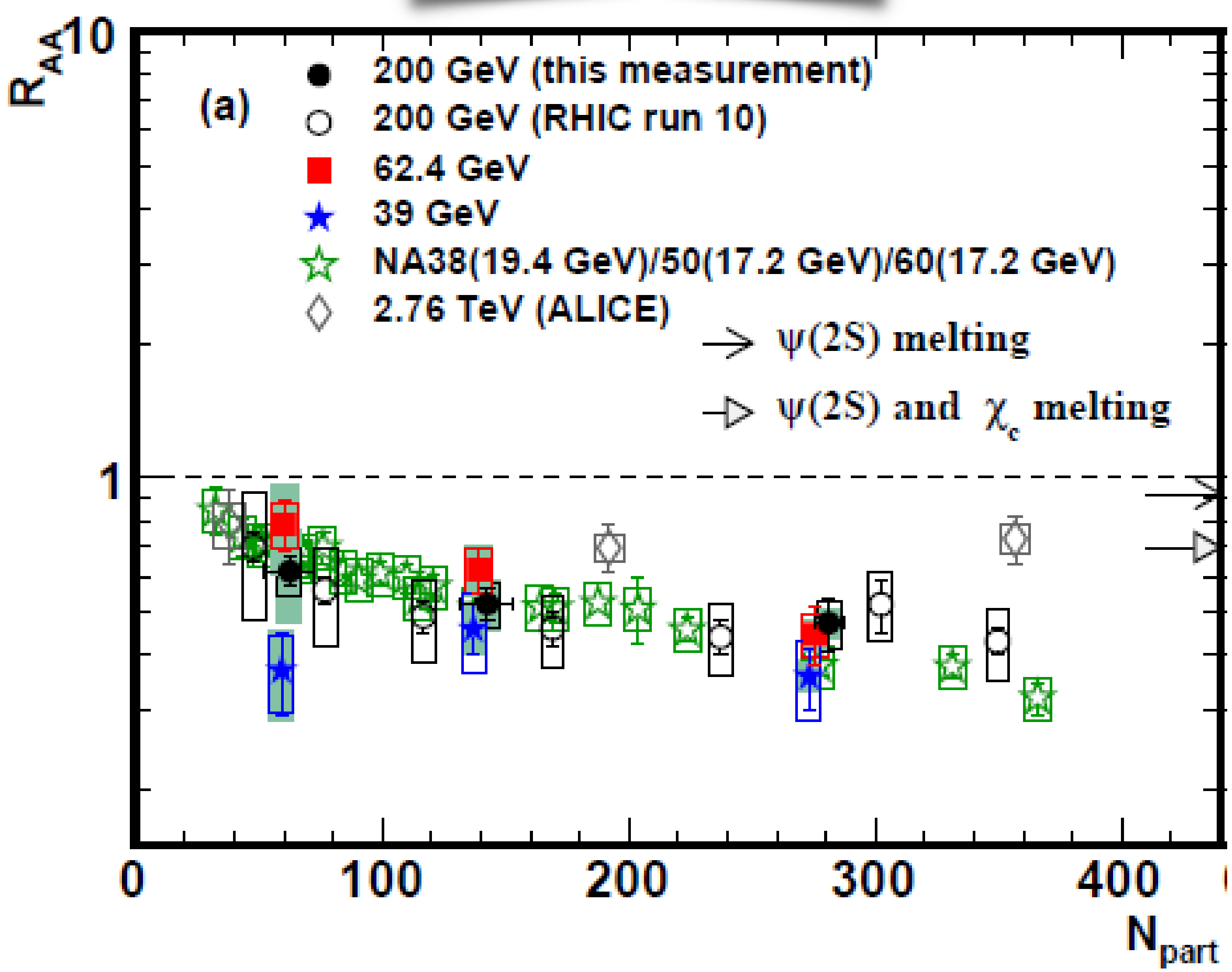


arXiv:1601.00743

- Elliptic flow measured with D mesons, HF-decay electrons and HF decay muons. Evidence that charm takes part to the collective motion at > **5σ** level (in the region 2-6 GeV/*c*).
- Still measurement uncertanties too large to confirm/exclude models. Need more data (run II and III of LHC and new runs at RHIC)

What about J/Ψ?

STAR, arXiv:1607.07517



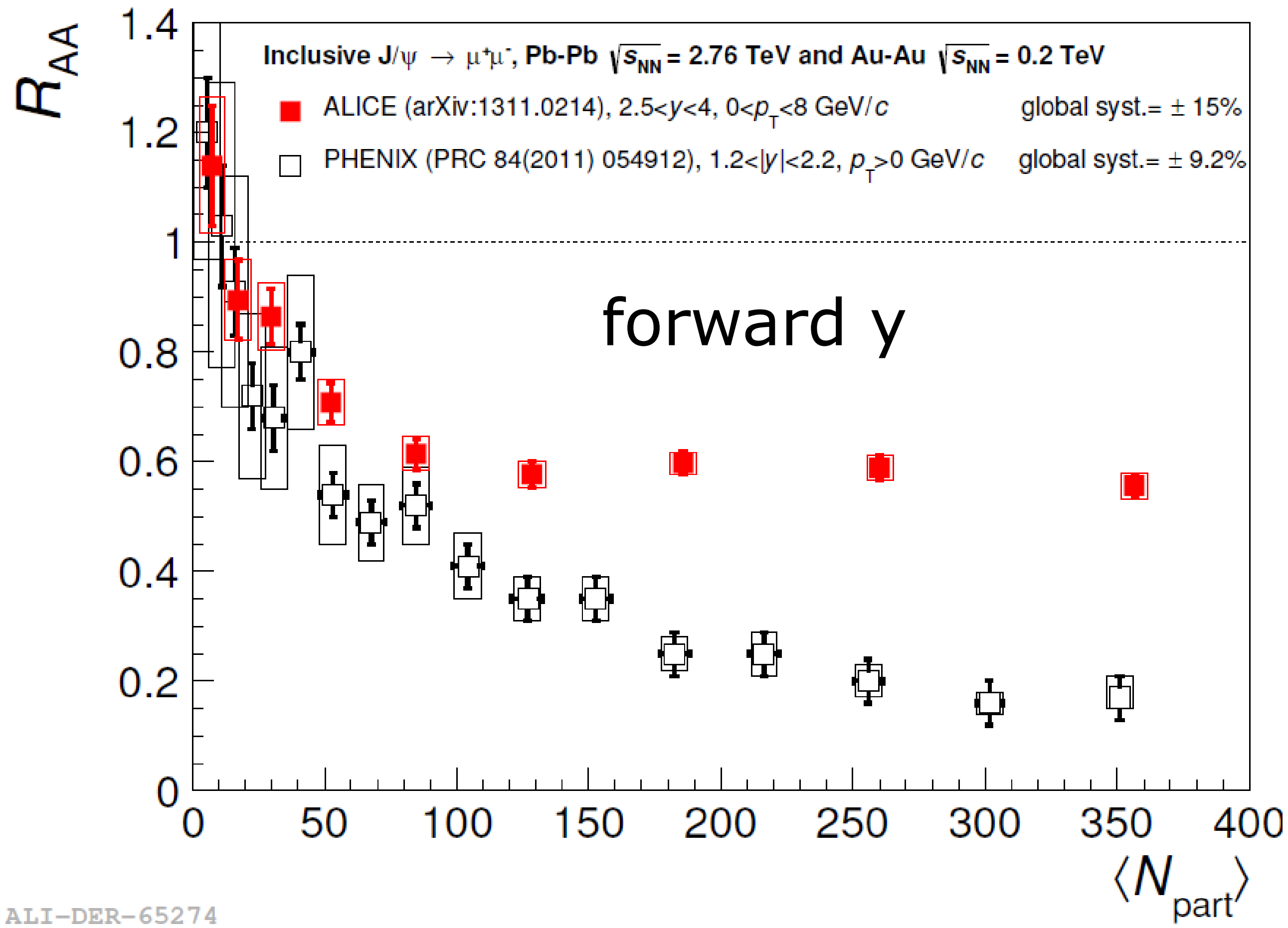
- No significant $\sqrt{s_{NN}}$ dependence up to 200 GeV

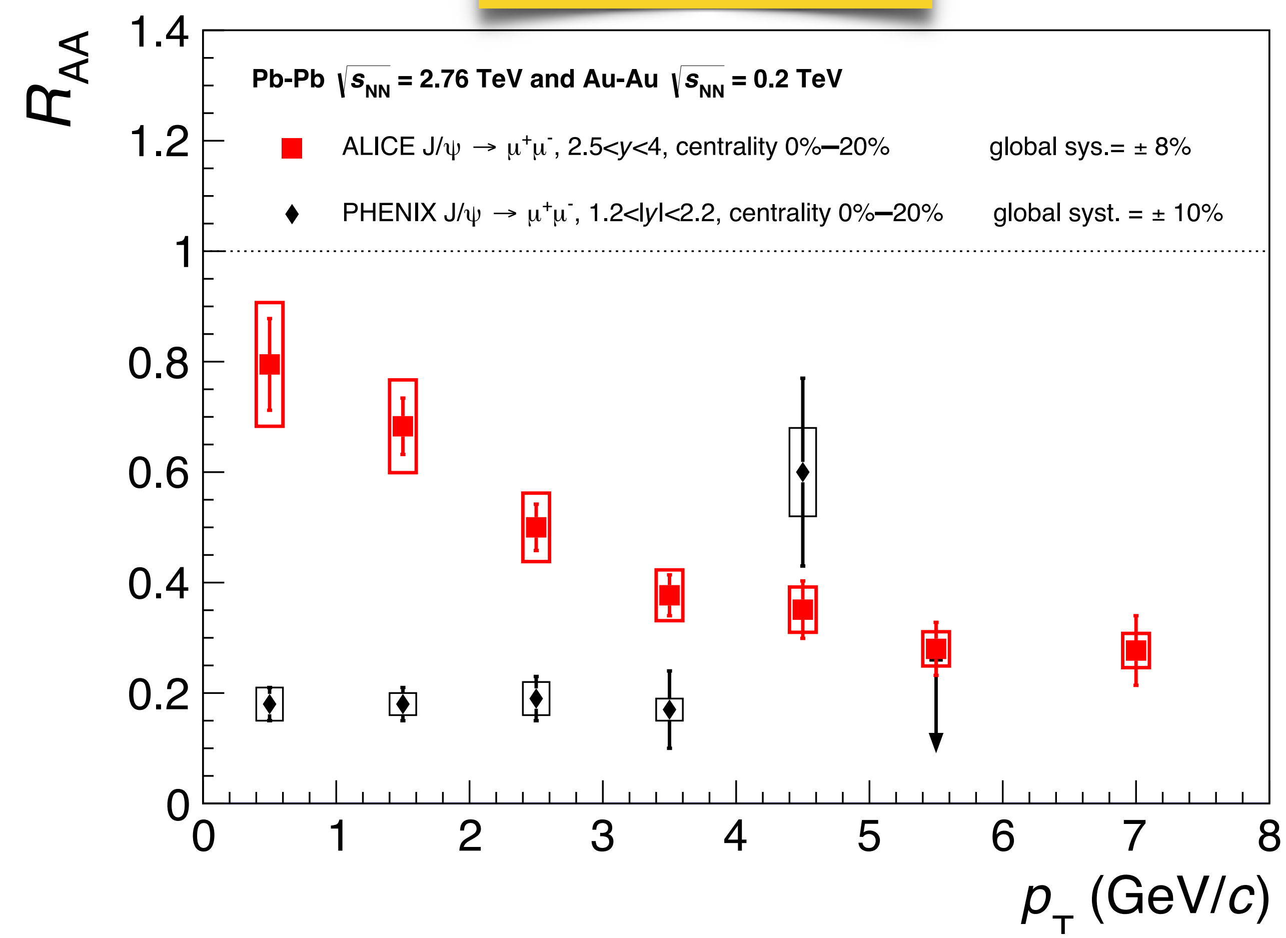
ALICE results differs!
see next slides

- Similar results from PHENIX at forward rapidity

ALICE vs PHENIX: from $\sqrt{s_{NN}}$ = 0.2 to 2.76 TeV

PLB 734 (2014) 314



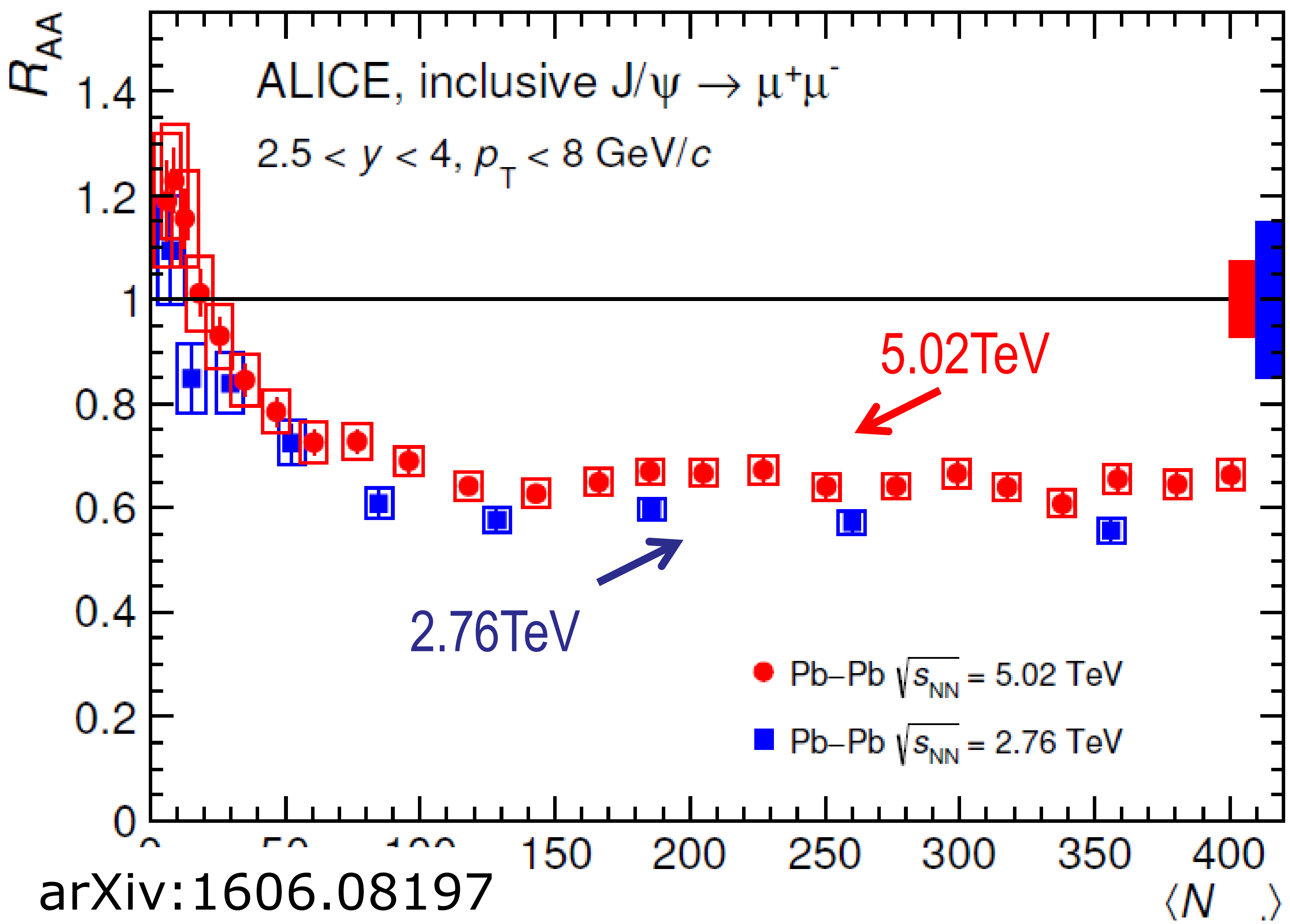


- ☑ Sistematically larger R_{AA} in central events at LHC.
- ☑ At LHC R_{AA} increases at low-p_T.

RHIC → Suppression effects dominate
LHC → Suppression + regeneration

Results at $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE



arXiv:1606.08197

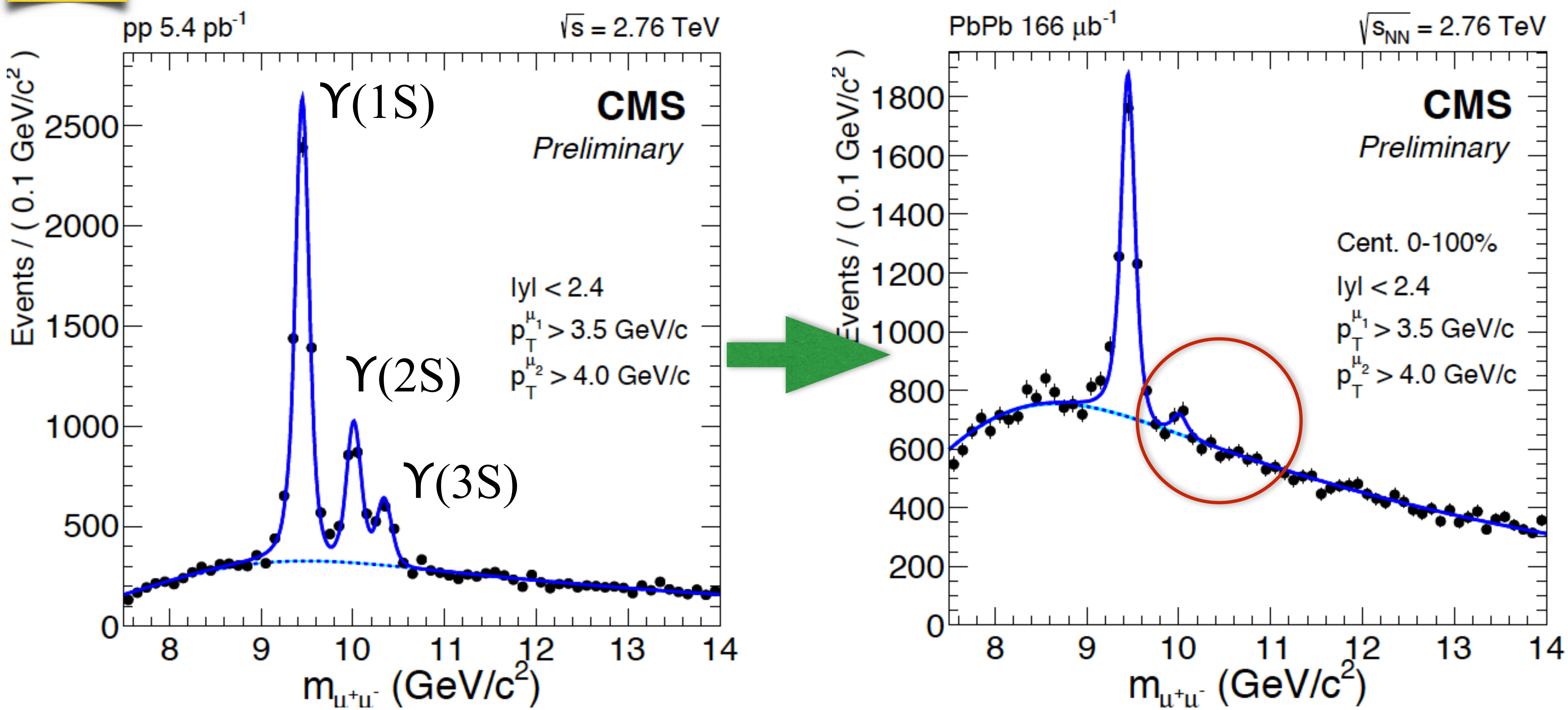
- Run II statistic much larger -> reduced statistical error and finer p_T binning
- Similar centrality dependence with plateau in the suppression for N_{part} > 100
- R_{AA} at 5.02 TeV looks about 15% higher than at 2.76 TeV (even if within the large uncertanties)

and bottomiun: Υ

CMS

pp collisions

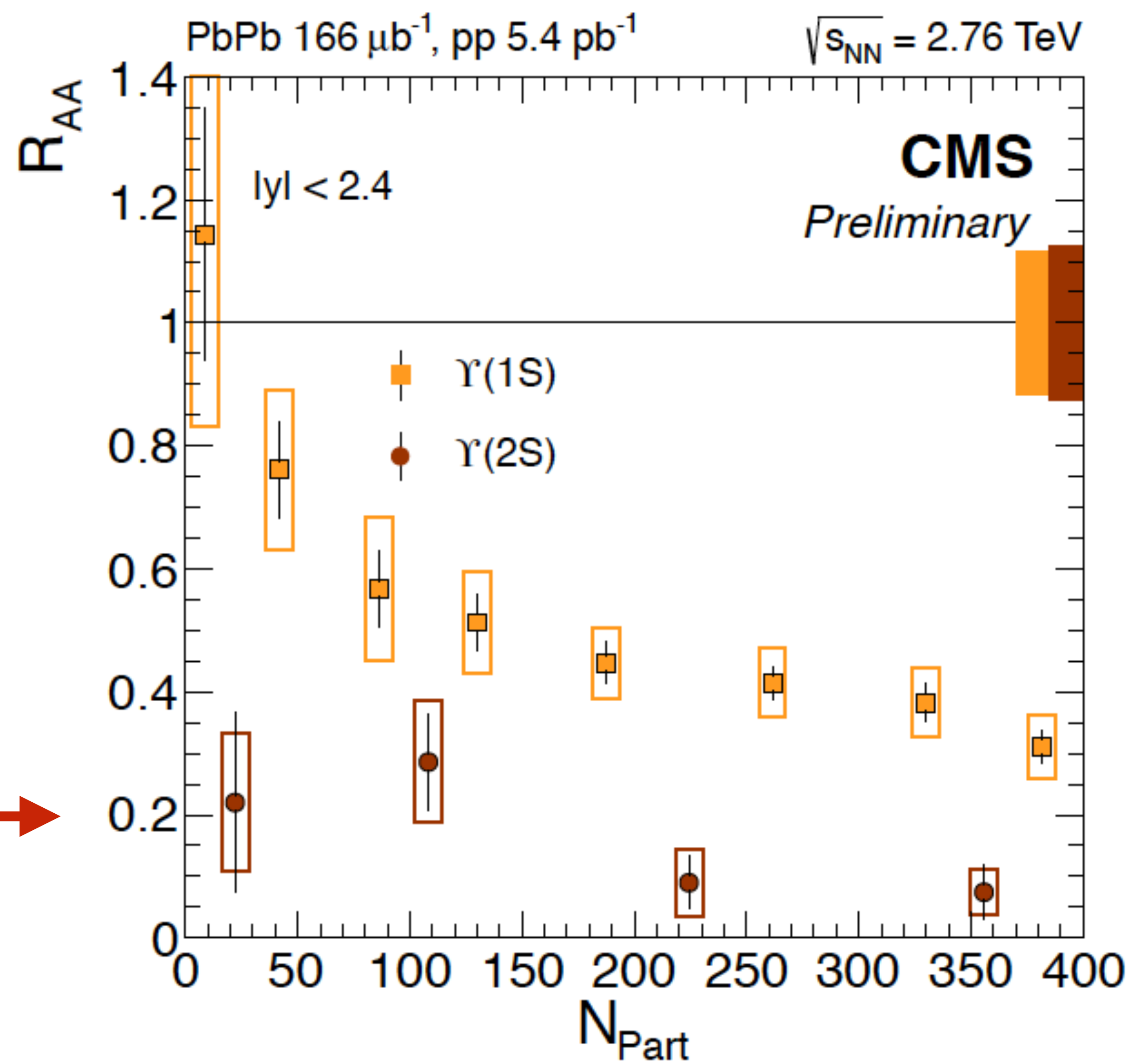
Pb-Pb collisions



- ☑ Low beauty cross-section → weak regeneration effects
- ☑ Strong relative suppression of more loosely bound states (Υ(3S) not visible at all in Pb-Pb)

and bottomiun: Υ

CMS



PRL109 (2012) 222301

PAS-HIN-15-001

- Strong Υ(1S) suppression. Similar at RHIC and LHC

STAR, PLB735 (2014) 127

- Binding energy of Υ(2S) similar as the one of J/Ψ but R_{AA} much lower (much more suppressed) → Regeneration negligible?

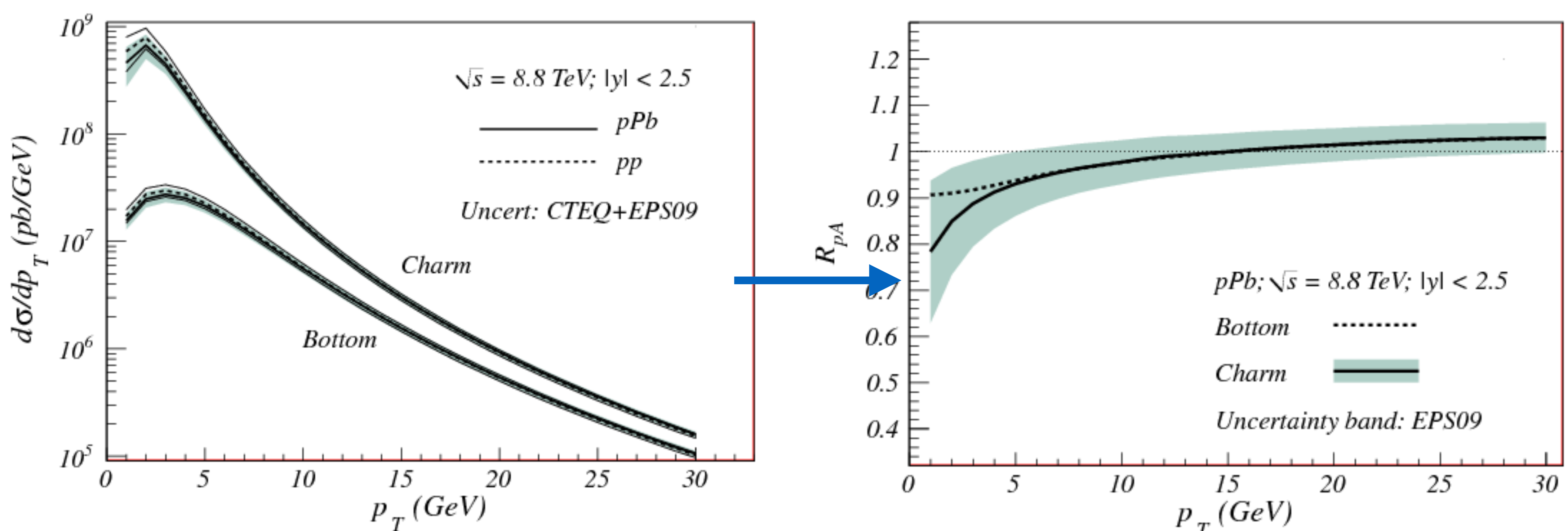
- **Heavy Quarks**
  - Indroduction
  - Energy loss
  - Observables
- **Charm-Beauty production**
  - pp collisions
  - A-A collisions
- **What about pA collisions?**
- **What next?**
- **Conclusions**

p-A collisions

- Study cold-nuclear matter effects, reference.
  - Initial state effects can mimic final state effects (K_T broadening) X.N.Wang ,PRC 61(2000)064910
  - Energy loss in cold nuclear matter. I.Vitev at al., PRC 75(2007)064906
  - Modification of the PDF in the nucleus: nuclear shadowning

K.J.Eskola et al., JHEP 0904(2009)65;

- Nuclear PDF (nPDF) poorly known at LHC kinematic region

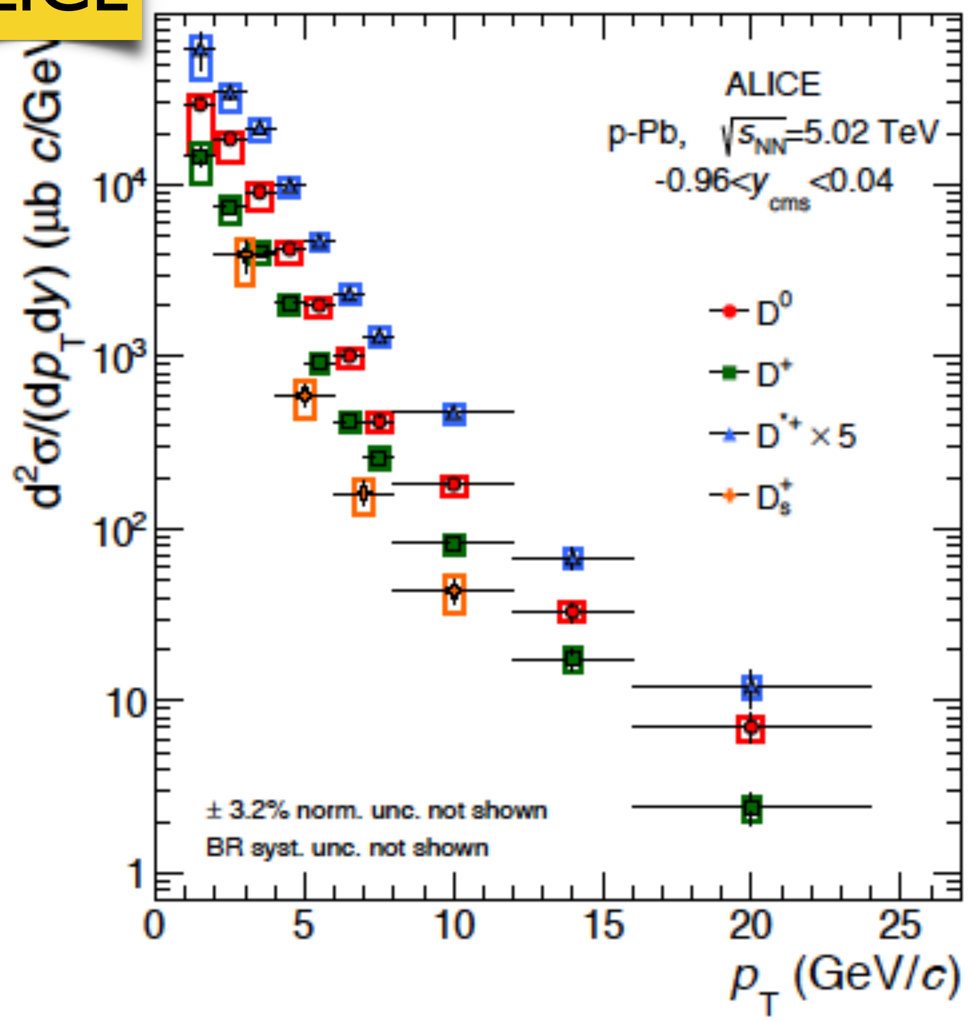


J.Phys. G39 (2012) 015010

Prog.Part.Nucl.Phys. 76 (2014)

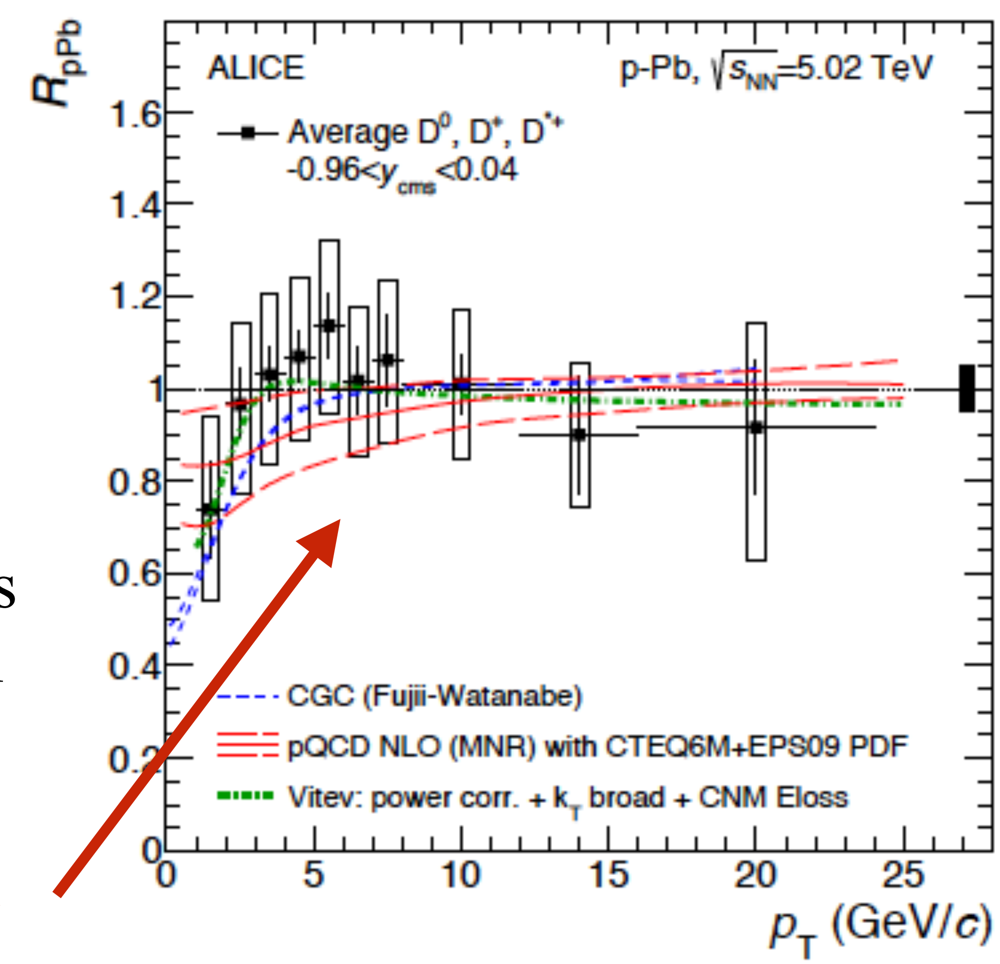
Production of D mesons in p-Pb collisions

ALICE



Phys. Rev. Lett. 113, 232301 (2014)

- Production cross-sections of prompt D^0, D^{*+}, D^+ and D^+_s measured in the rapidity intervall $-0.96<y_{cms}<0.04$



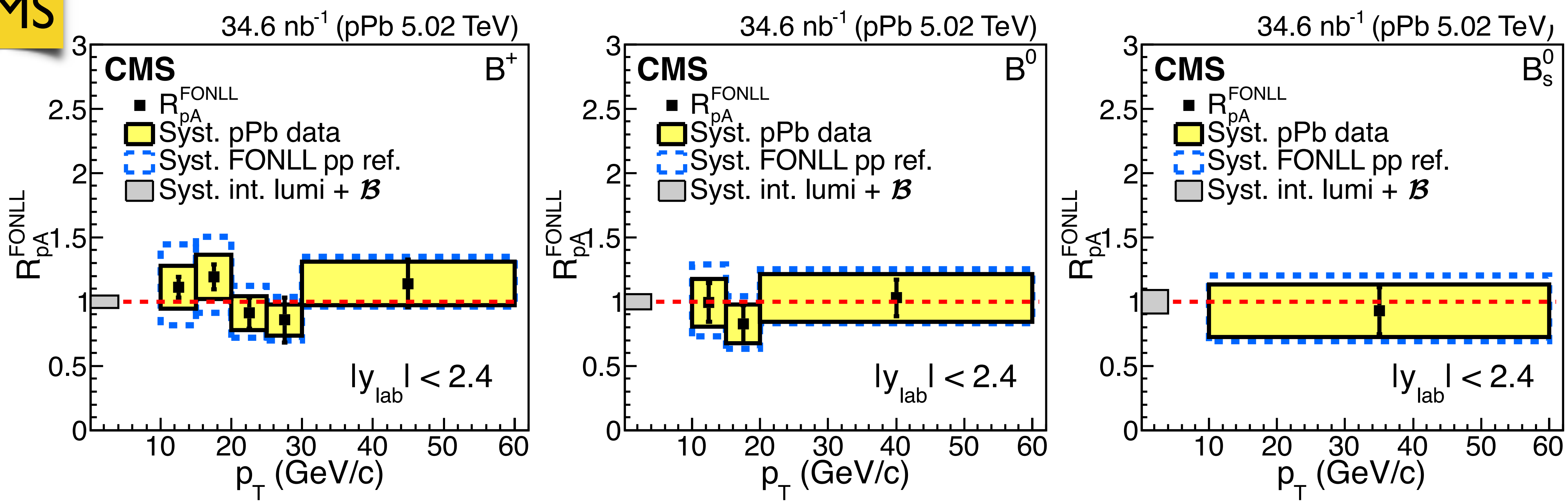
- Nuclear modification factor in p-Pb collisions is compatibile with unity and with theoretical calculations including gluon saturation

- Initial state effects play a small role for p_T> 2 GeV/c

(H.Fujii,K.Watanabe arXiv: 1308.1258
M.Mangano et al., Nucl.Phys.B 373(1992)295; K.Eskola et al., JHEP 04467(2009)065

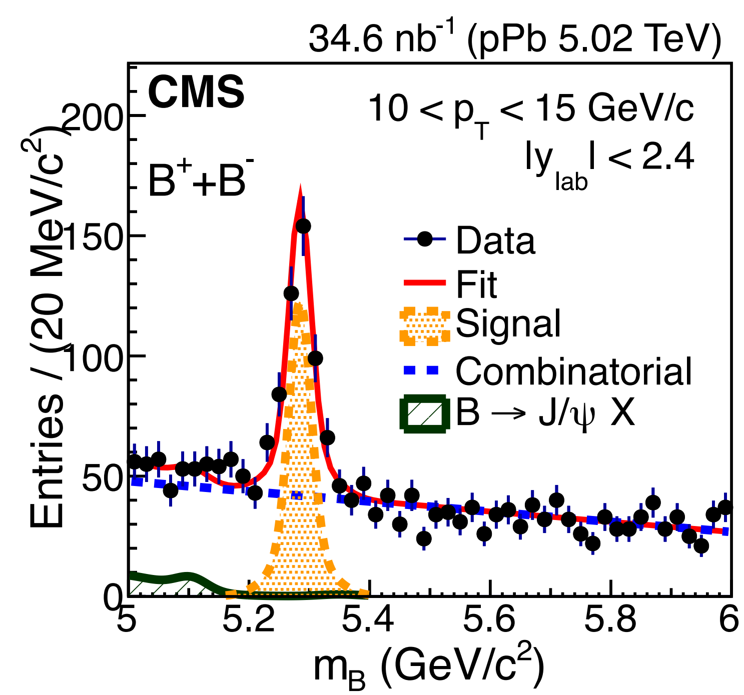
B meson R_{pPb}

CMS



Phys. Rev. Lett. 116, 032301

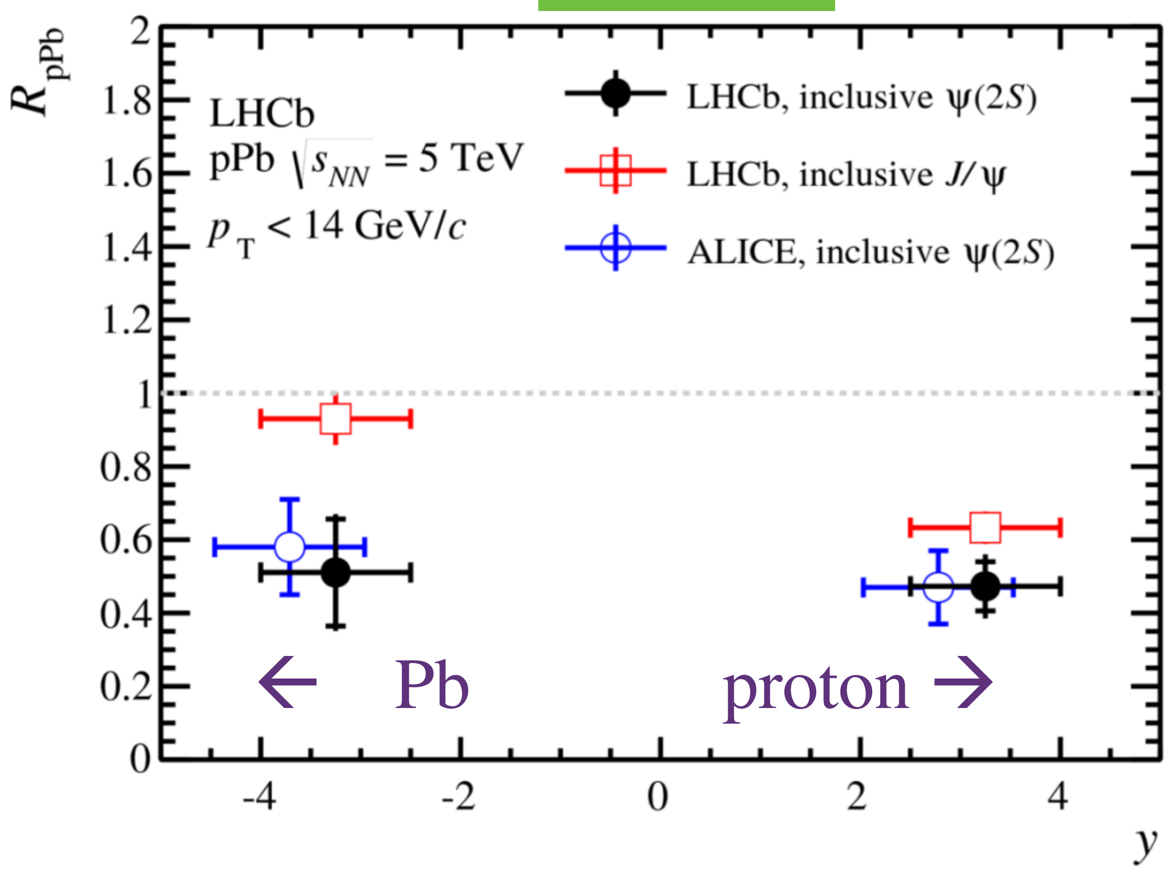
- ☑ CMS performed the first measurement of the fully reconstructed B mesons (B^+, B^0 and B_s) in p-Pb
- ☑ R_{pPb} consistent with 1, no evident initial state effects



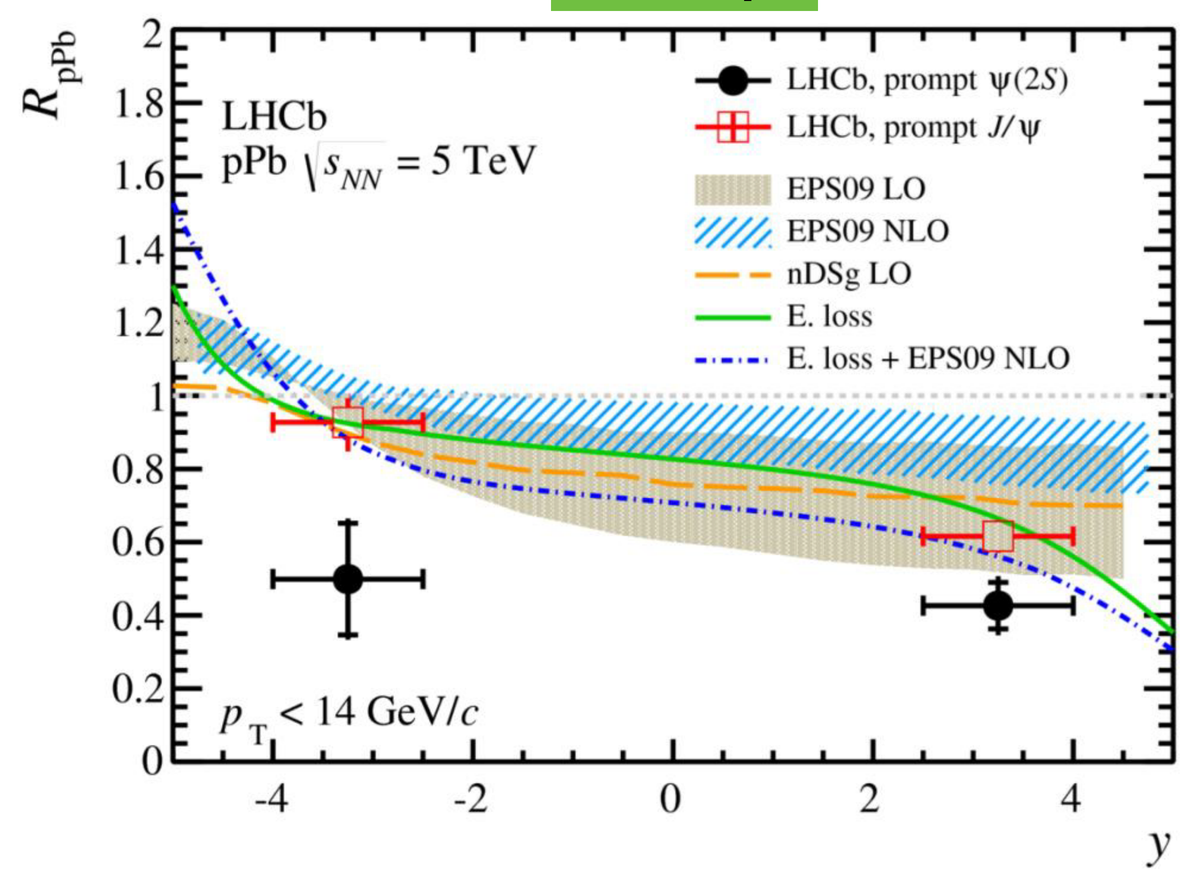
NOTE: p_T > 10 GeV/c!

J/Ψ and Υ(2S)

Inclusive



Prompt



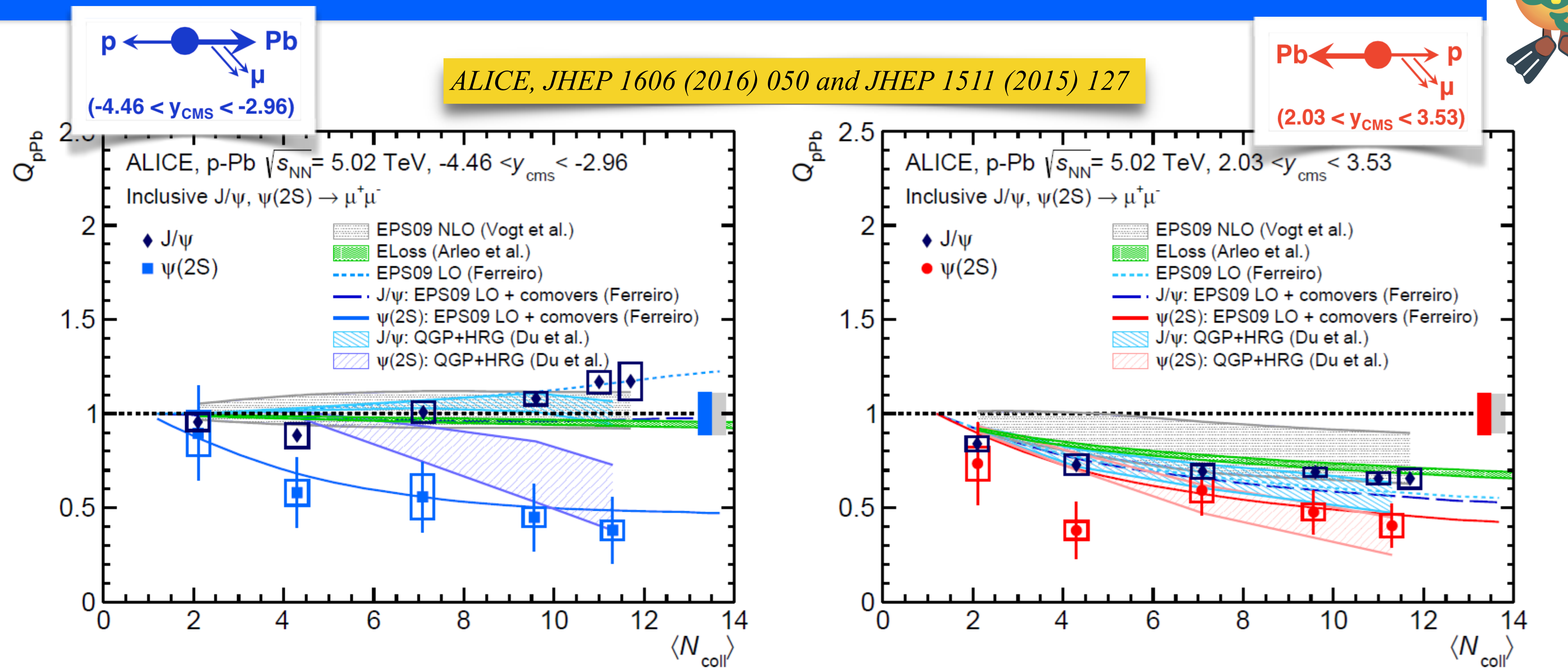
- **J/Ψ** *R*pPb described reasonably well by CNM effects
- **Υ(2S)** production suppressed relative to J/y at both backward and forward rapidity
  - ☑ Shadowing & energy loss expected to be the same for J/y and Y(2S). Threfore, these mechanisms cannot describe the result.

ALICE, JHEP 1402 (2014) 073 and JHEP 1412 (2014) 073

LHCb, JHEP 1402 (2014) 072 and JHEP 1603 (2016) 133

J/Ψ and Υ(2S): multiplicity dependence

ALICE, JHEP 1606 (2016) 050 and JHEP 1511 (2015) 127



Backward rapidity (Pb-going side) Forward rapidity (p-going side)

- **J/Ψ**: Mult. dependent suppression in p-going direction, no suppression in Pb-going direction → indication of shadowing (?)
- **Υ(2S)**: Multiplicity dependent suppression in both directions
  - ☑ Not described by (anti)shadowing and energy loss only
  - ☑ Needs additional effect (final state?)

- Heavy Quarks
  - Indroduction
  - Energy loss
  - Observables
- Charm-Beauty production
  - pp collisions
  - A-A collisions
- What about pA collisions?
- What next?
- **Conclusions**

Conclusions

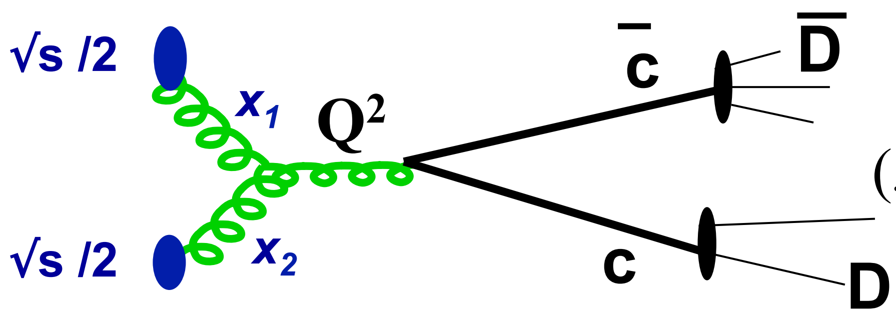
- Heavy Flavours are qualitatively and quantitatively excellent probes for the hot and dense medium produced in A-A collisions
- Heavy Flavour saga in relativistic heavy ion collisions started (more than) 10 years ago with the first measurements.
- In pp collision system: several measurements available (i.e D and B mesons, HF-decay electrons and HF-decay muons). Results tend to confirm pQCD calculations. However, charm measurements sit on the upper side of the theory error band.
- In A-A collision system: Results tend to confirm charm loose energy in the hot and dense medium (remember p-Pb!). Is dead code effect as we expected? Evidence that charm takes part to the collective motion. Quarkonium results from LHC hints a consistent regeneration while it looks not being the case of RHIC

Thanks
for your attention

Backup

HQ
2016
HOT QUARKS
SEPTEMBER 12-17 SOUTH PADRE ISLAND TX, USA
A WORKSHOP FOR YOUNG SCIENTISTS ON THE PHYSICS OF ULTRARELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS
QCD at high temperature/density and lattice QCD
Initial state effects and Color Glass Condensate
Relativistic hydrodynamic and collective phenomena
Correlations and fluctuations
Jets in the vacuum and in the medium
Baryons and strangeness
Heavy flavor, dileptons and photons
Applications of String Theory and AdS/CFT
Experimental techniques and future programs
Javier Albacete (Universidad de Granada, Spain)
Jana Bielcikova (NPI of the CAS, Czech Republic)
Rainer Fries (Texas A&M University, USA)
Jiangyong Jia (Stony Brook University & BNL, USA)
Andre Mischke (Utrecht University and Nikhef Amsterdam)
Lijuan Ruan (BNL, USA)
Sevil Salur (Rutgers University, USA)
CYCLOTRON INSTITUTE
HELMHOLTZ ASSOCIATION
Netherlands Organisation for Scientific Research
HQ2016.BNL.GOV

Open HF production in pp



$$(x_1 x_2 s \sim Q^2 \sim M^2_{c\bar{c}})$$

$$\mu^2_{F,R} \sim Q^2$$

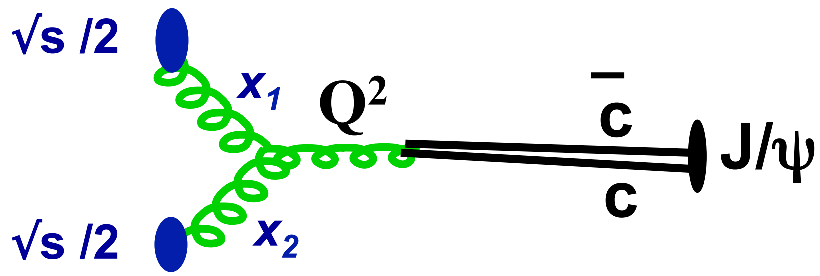
Q2 evolution from pQCD, initial cond. from HERA

non-perturbative phenomenology. e+e- data from HERA

$$\frac{d\sigma^D}{dp_T^D}(\mu_F, \mu_R) = PDFs(x_1, x_2, \mu_F^2) \otimes \frac{d\hat{\sigma}^c}{dp_T^c}(\alpha_S(\mu_R^2)) \otimes D_{c\rightarrow D}(\mu_F^2, \frac{p_D}{p_c})$$

perturbative series of strong coupling α_s

Quarkonia production in pp



$(x_1 x_2 s \sim Q^2 \sim M^2_{c\bar{c}})$

$$\frac{d\sigma^{\psi}}{dp_T^{\psi}}(\mu_F,\mu_R) = PDF(x_1)PDF(x_2) \otimes \frac{d\hat{\sigma}^{c\bar{c}}}{dp_T^{c\bar{c}}} \otimes P(c\bar{c} \rightarrow \psi)$$

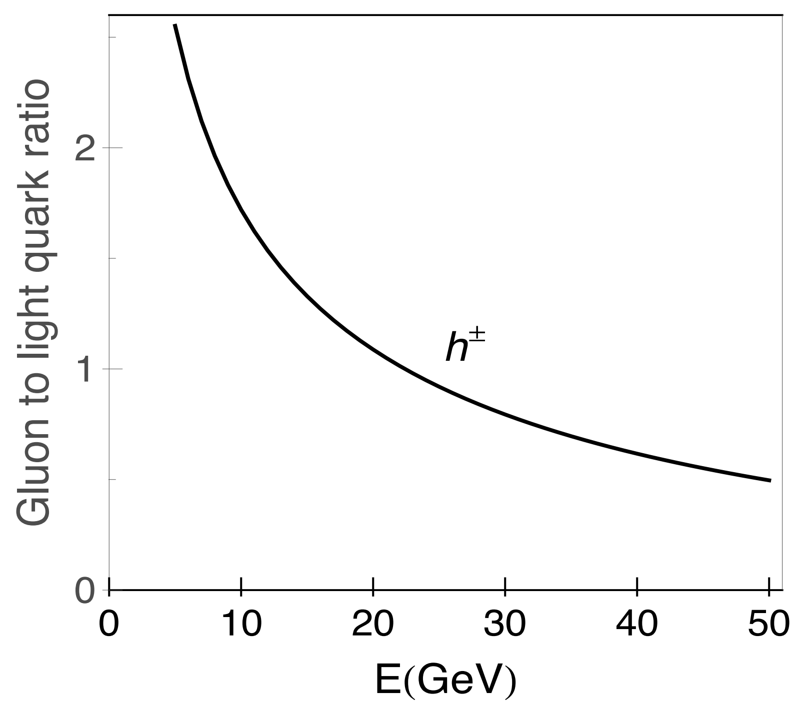
Long distance non perturbative term. Cannot be take from e^+e^- data

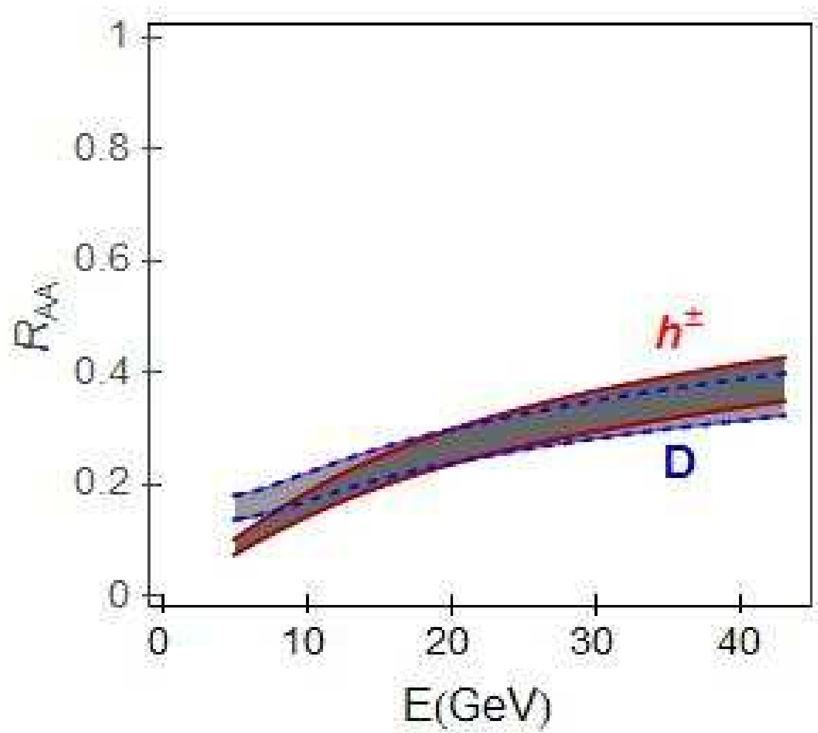
Colour Singlet Model (CSM): the color of the QQ neutralizes in the hard process

Non-relativistic QCD (NRQCD): the color can neutralize also in the long distance part. Hard scattering -> singlet and octet

Connecting E_{loss} and R_{AA}: Color charge

- Comparing pions and D mesons R_{AA}:
  - **At LHC hadrons below ~15 GeV/c originate predominantly from gluons**
    - The softer fragmentation of gluons tends to counterbalance the larger E_{loss}
  - **Predictions on the R_{AA} results in very small difference if any.**

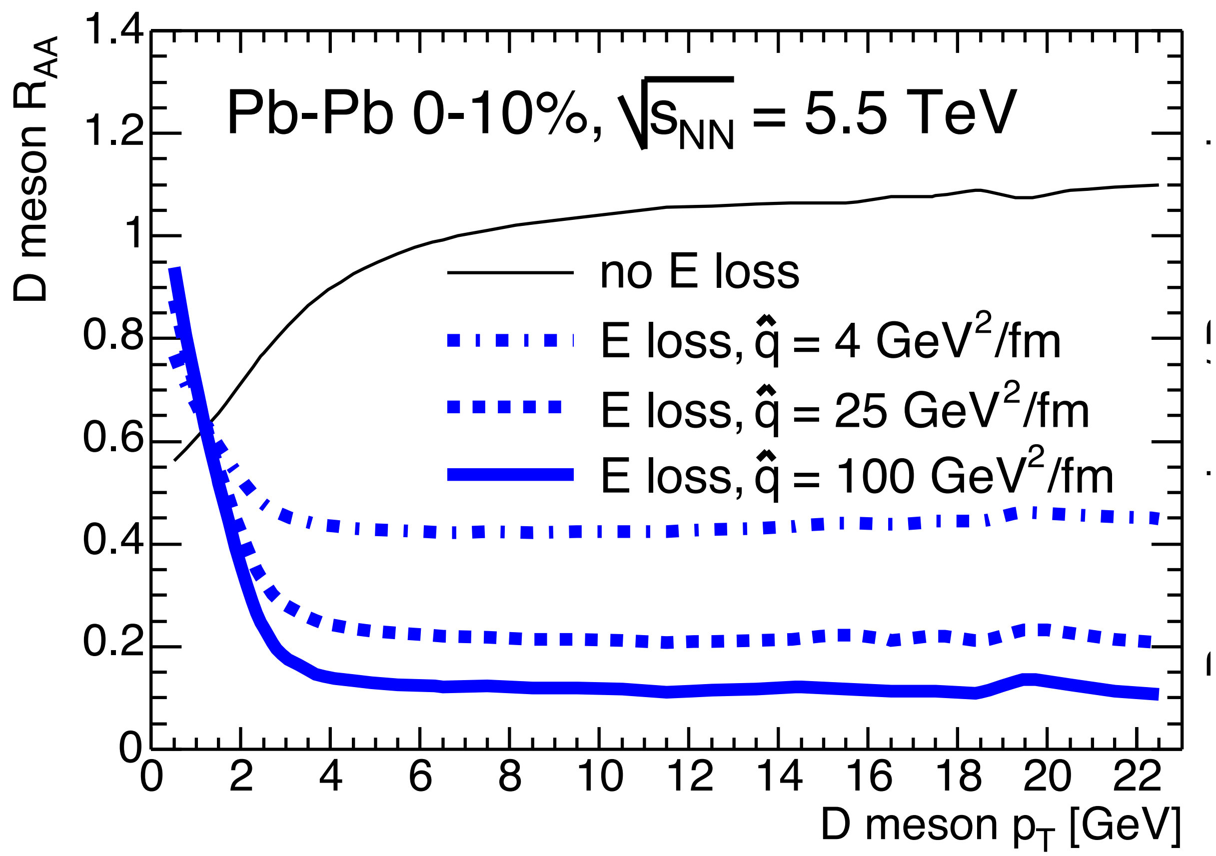


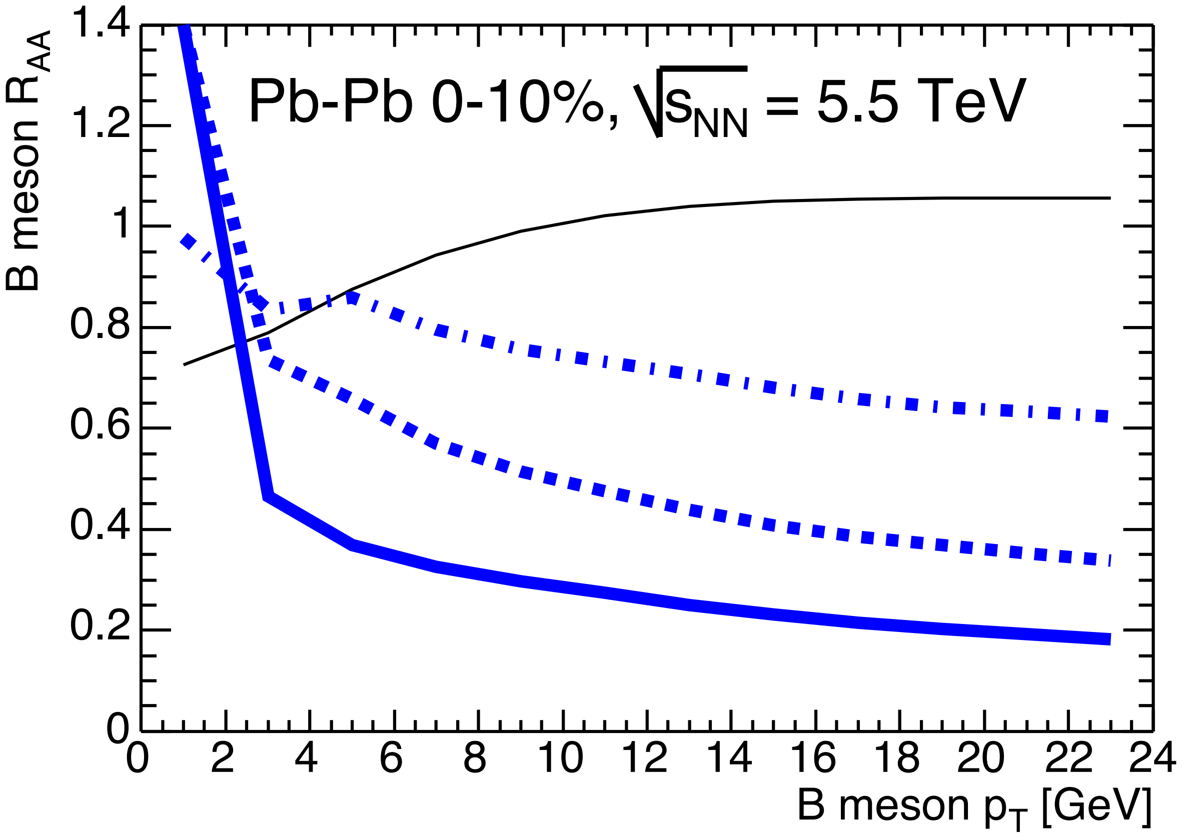


Phys. Rev. Lett. 112, 042302 (2014)

Connecting E_{loss} and R_{AA}: Mass effect

- Comparing D and B mesons R_{AA}:
  - **Essentially all models predict a difference in the suppession**
  - **Small effects from patronic p_T shape and fragmentation**

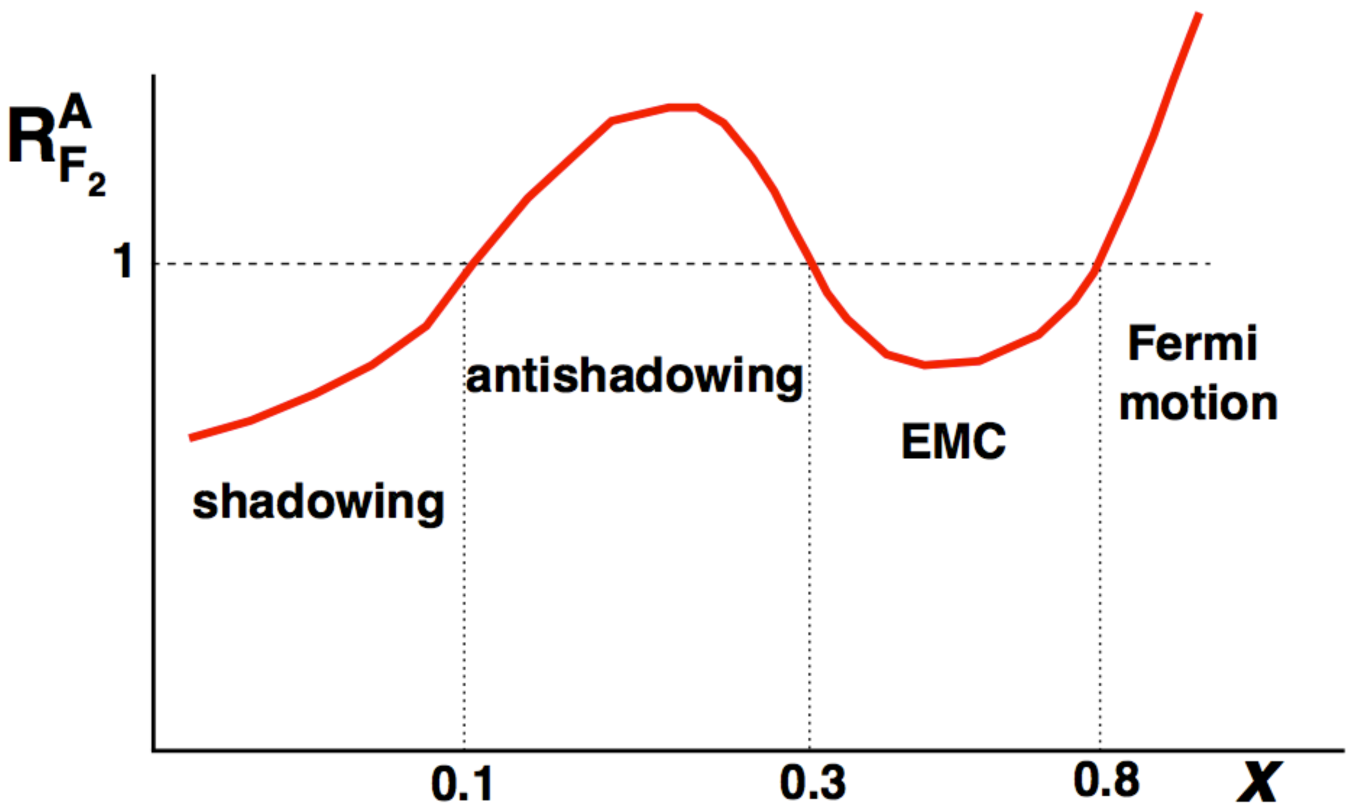




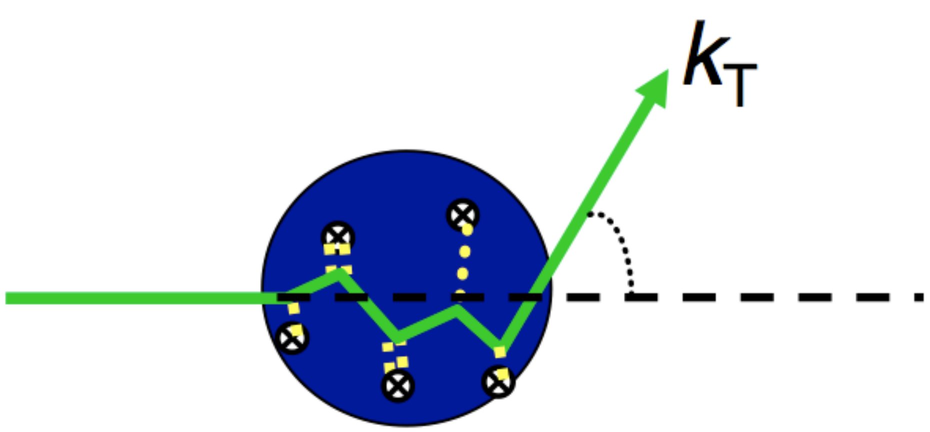
Phys. Rev. D 71:054027, 2005

Initial state effect

nPDF modification



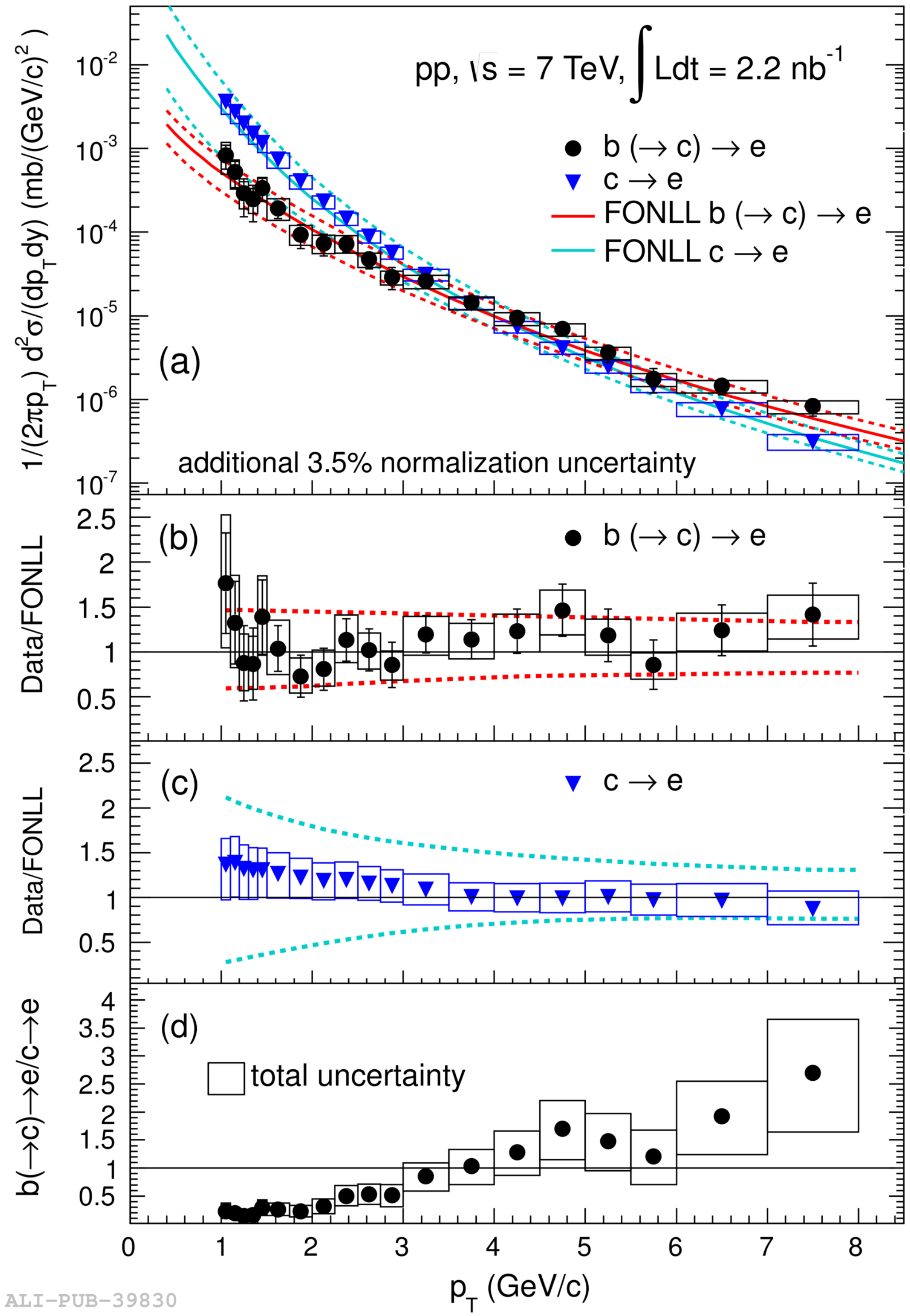
KT broadening



HF-decay electrons in pp collisions

ALICE

pp @ 7 TeV

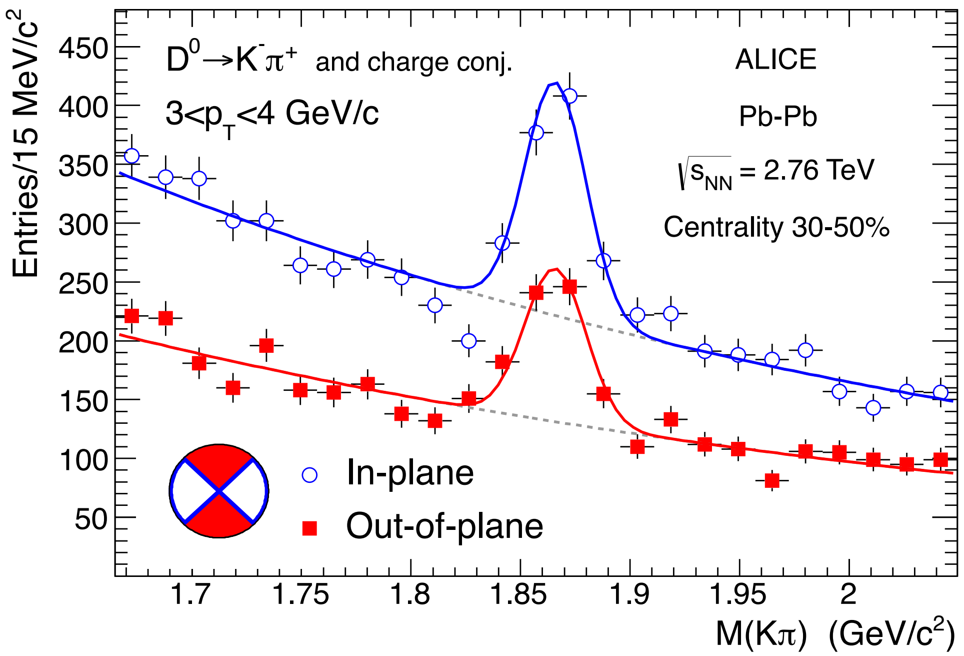


- Exploit the large displacement of B-decay electrons. Cut on impact parameter and or secondary vertex reconstruction.
- Good agremeent with FONLL.
- At LHC beauty starts to dominate above $p_T = 5$ GeV/c
- Similar measurements at RHIC (STAR and PHENIX)

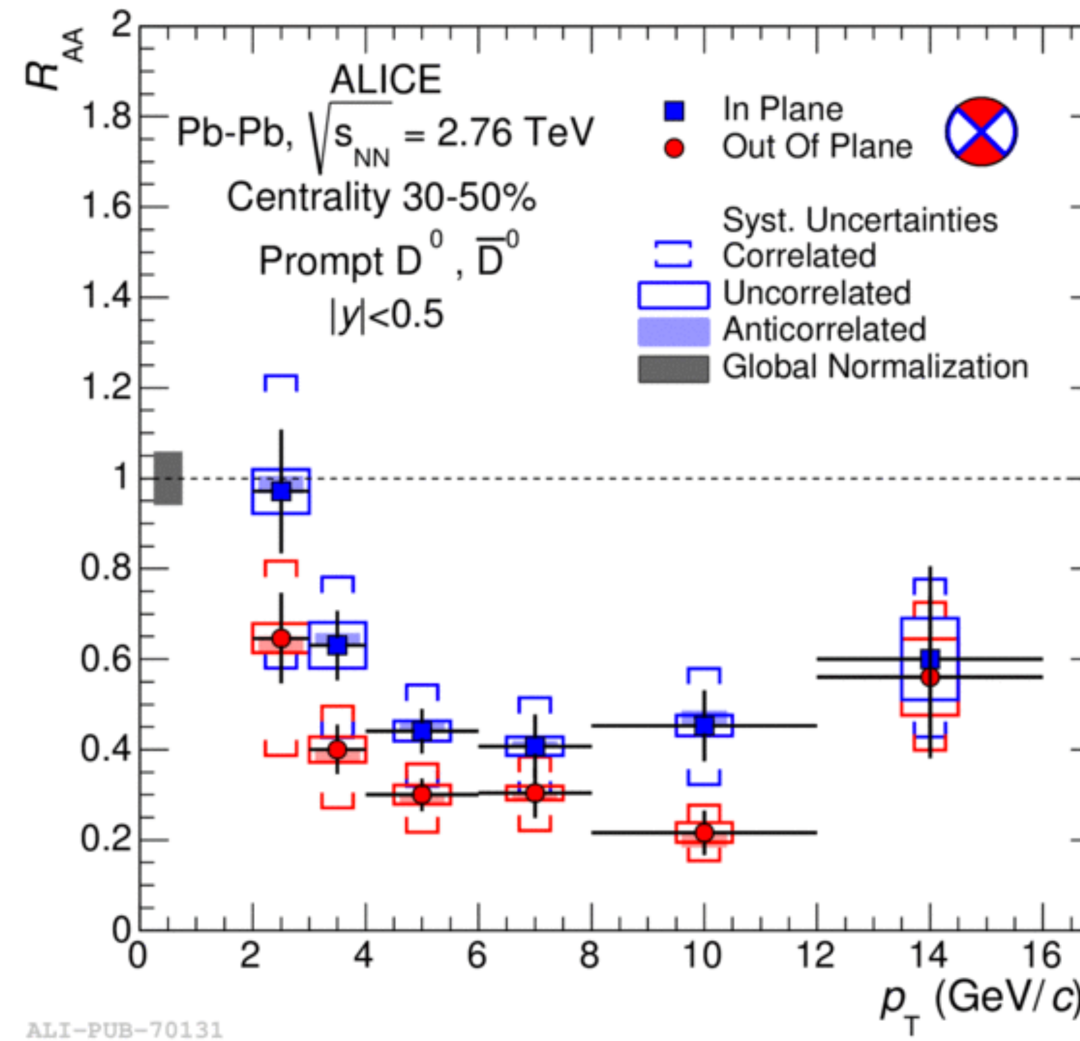
Phys.Lett. B721 (2013) 13-23

D mesons Elliptic flow: R_{AA} vs event plane

ALICE



- D mesons candidates are put in two classes based on their relative azimuthal coord. with respect the event plane (in plane, out of plane)



- A stronger suppression relative to proton–proton collisions is observed in the out-of-plane direction, where the average path length of heavy quarks through the medium is larger.

Phys.Rev. C90 (2014) 3, 034904