Netherlands Organisation for Scientific Research

Charm physics at hadron colliders and beyond

Alessandro Grelli

Universiteit Utrecht

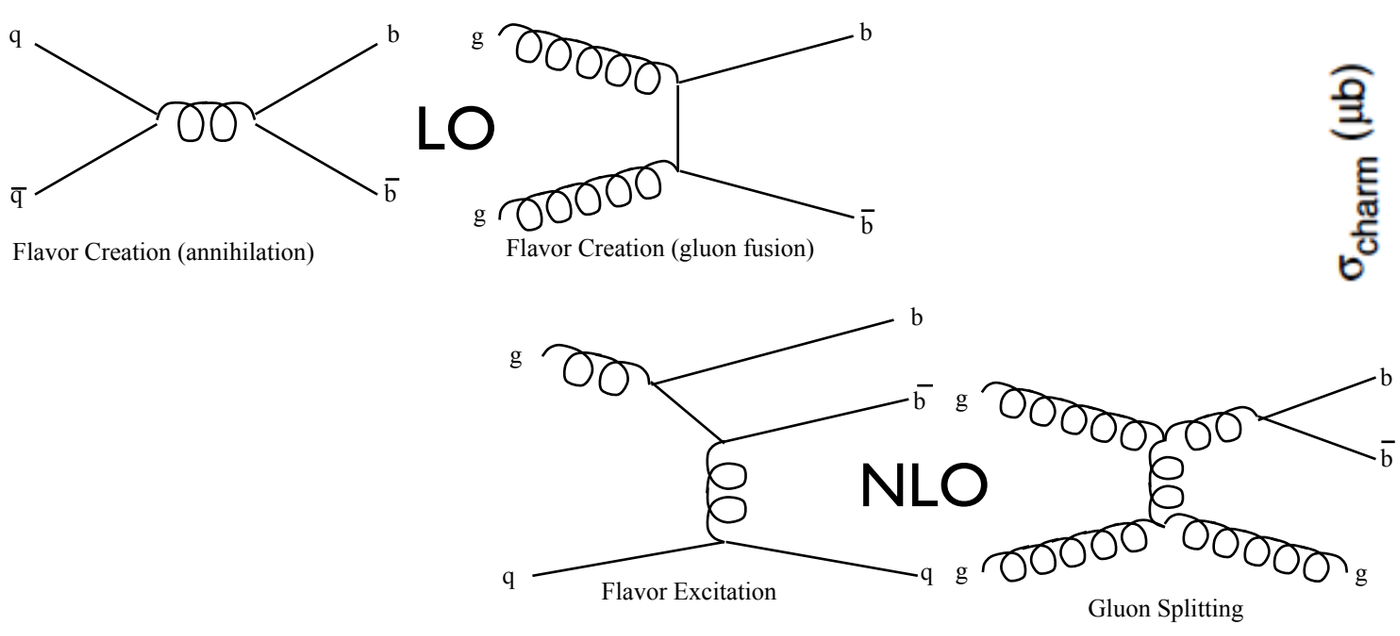
53rd International Winter Meeting on Nuclear Physics
Bormio

Outline

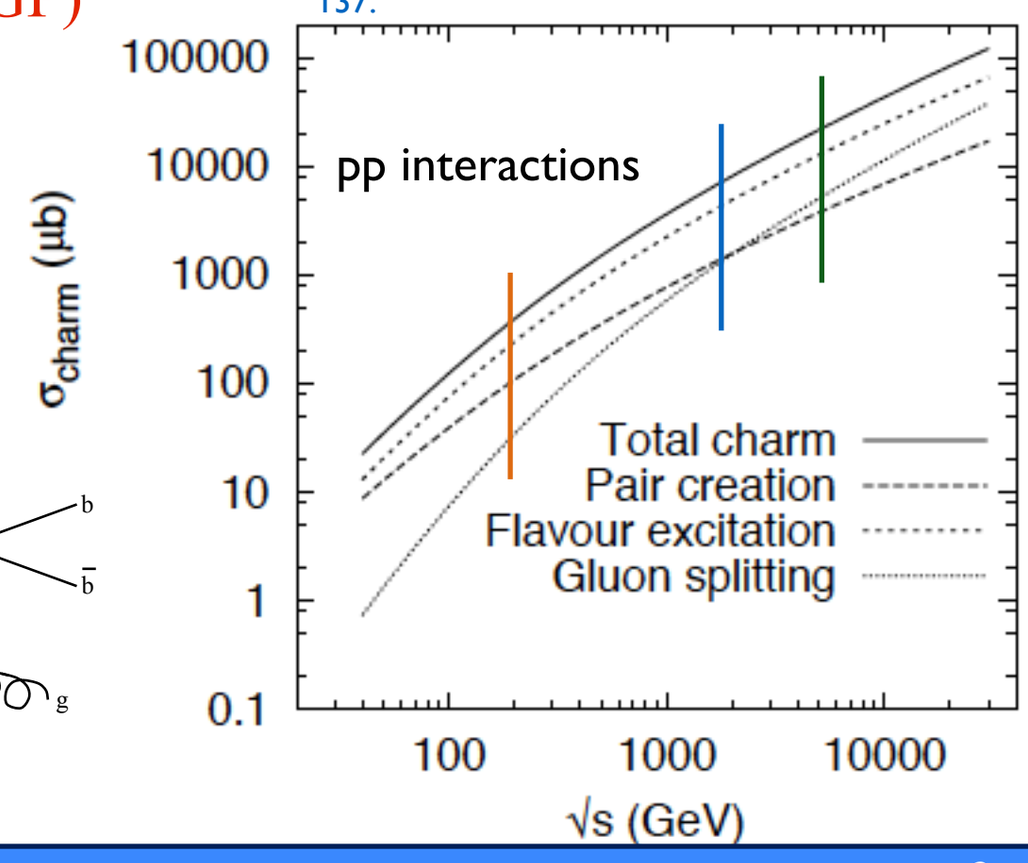
- **Why heavy quarks**
- **Charm production**
  - pp collisions
  - p-A collisions
  - A-A collisions
- **Intrinsic charm?**
- **Conclusions**

Why heavy flavour production?

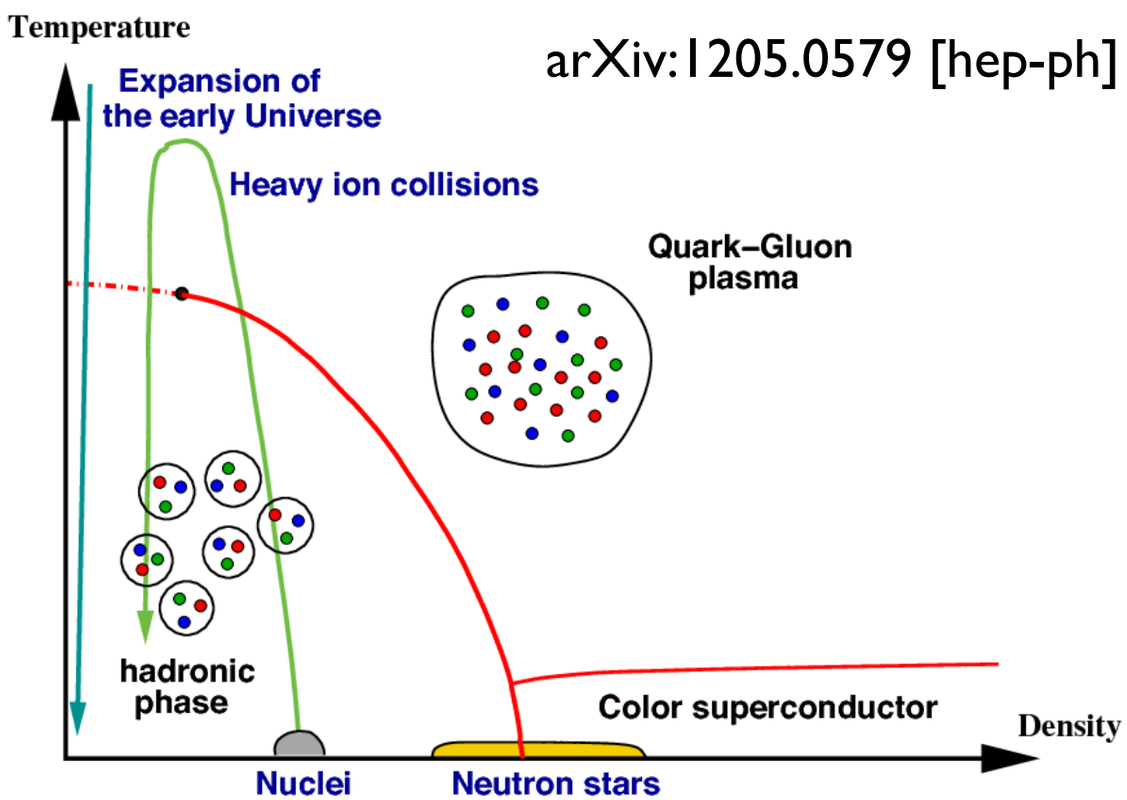
- Focus on open charm production; charmonium discussed
- Heavy-flavour production provides an excellent QCD test tool.
  - **pp** : test perturbative QCD predictions, baseline for p-A and A-A collisions
  - **p-A** : assess cold nuclear matter effects (shadowing, multiple scattering, etc) - baseline for A-A
  - **A-A** : probe the high density medium (QGP)



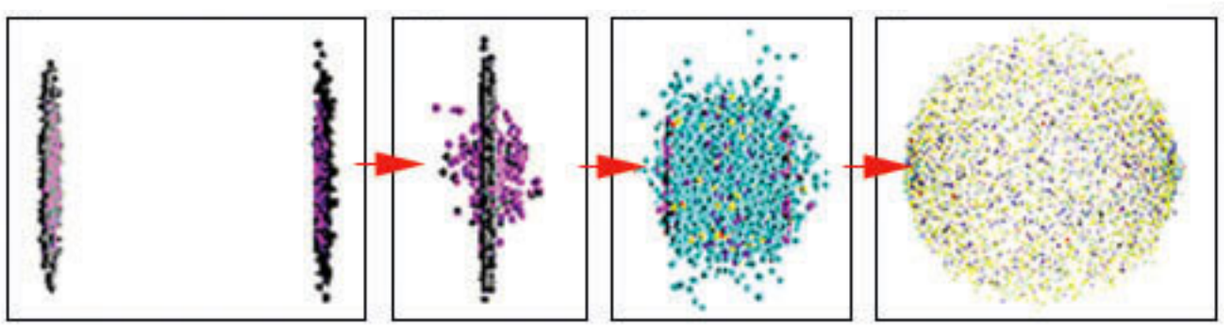
Norrbin and Sjostrand, Eur. J. Phys. C17 (2000) 137.



A probe for QCD medium in A-A collisions



arXiv:1205.0579 [hep-ph]



☑ Goal: Study the properties of the nuclear matter at extreme conditions of temperature and density

➡ transition to Quark Gluon Plasma, QGP (a state where quark and gluons are deconfined)

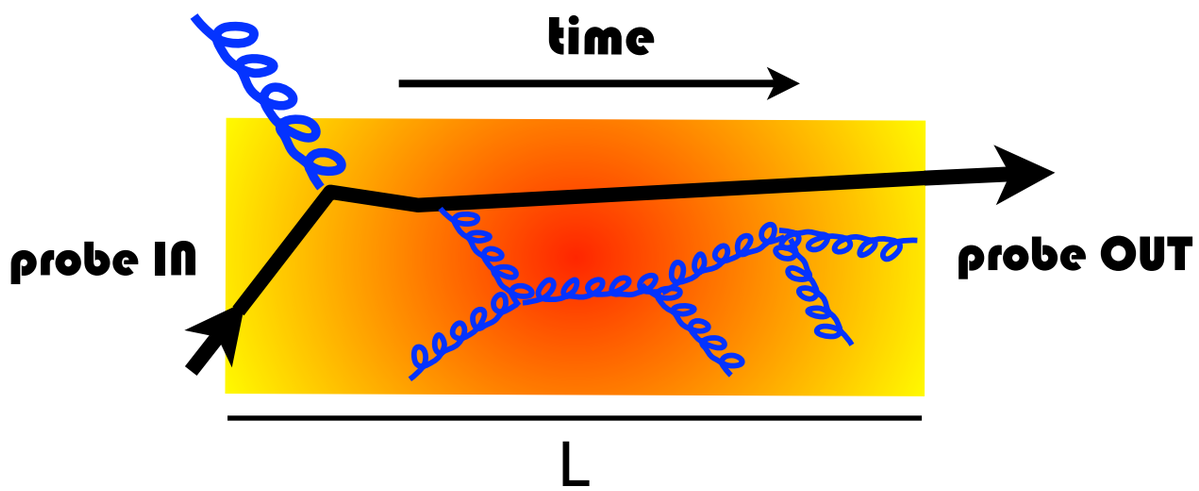
☑ Hard probes:

- 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 (i.e beauty)
- 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

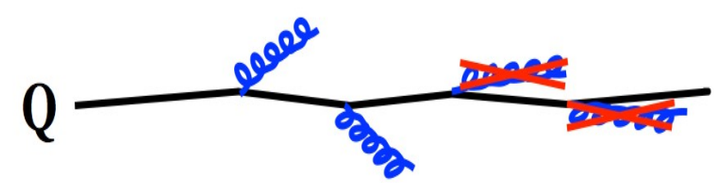
Heavy quarks as probes for QGP - Energy Loss

☑ Loss of energy while travelling through the medium depends on:

- Properties of the medium: *density, temperature, mean free path*
- Path length in the medium (L)
- Properties of the parton (Casimir coupling factor, mass of the quark (Dead Cone Effect))



Gluon radiation supressed:



Gluonsstrahlung probability

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

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

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

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

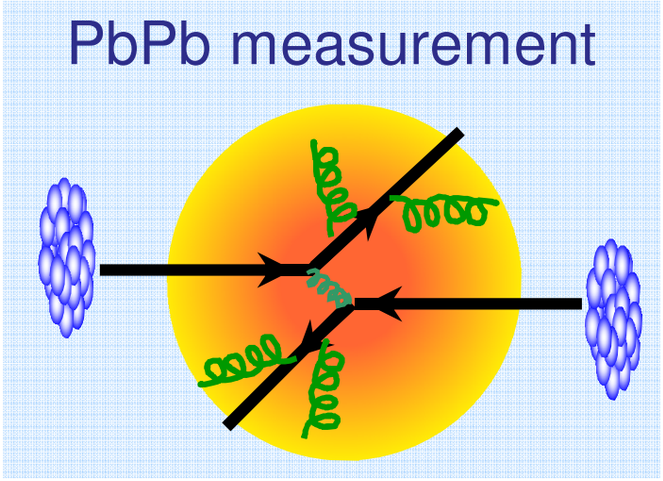
M. Djordjevic, M. Gyulassy, Nucl. Phys. A733 (2004) 265.

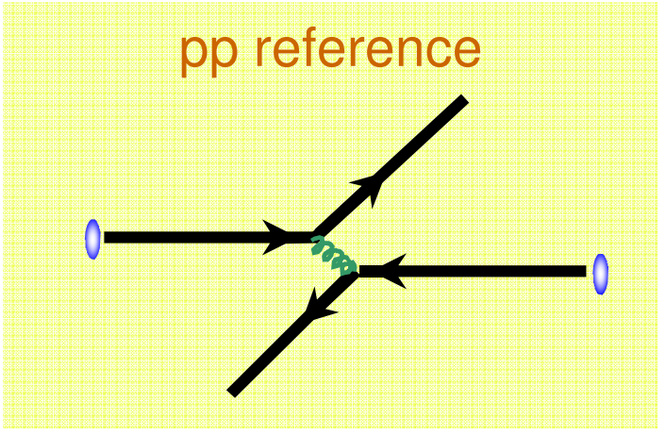
Nuclear Modification Factor

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

- Osservabile: Nuclear Modification Factor

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



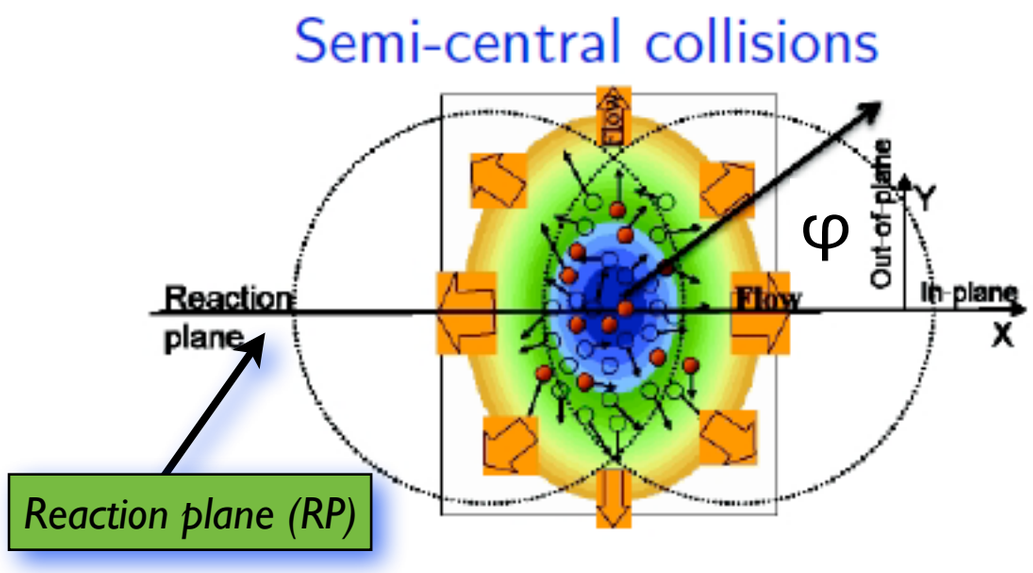


- What are the possibilities?
  - If no nuclear effects present: $R_{AA} = 1$
  - Effects of the hot and dense medium produced in the collision breakup binary scaling: $R_{AA} \neq 1$

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

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

Thermalization and path-length dependence



- Interaction among medium constituents convert the initial geometrical anisotropy into momentum anisotropy of final-state particles

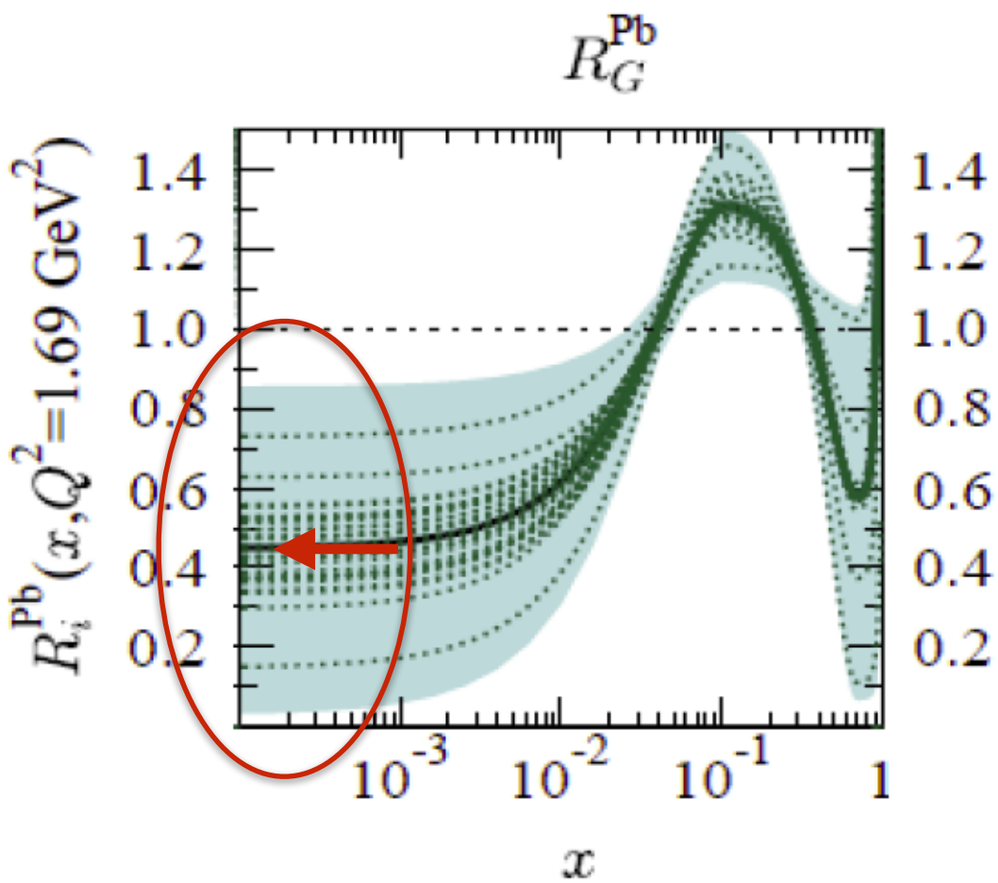
- Quantified via the 2nd order Fourier coefficient **v_2 (Elliptic flow)**

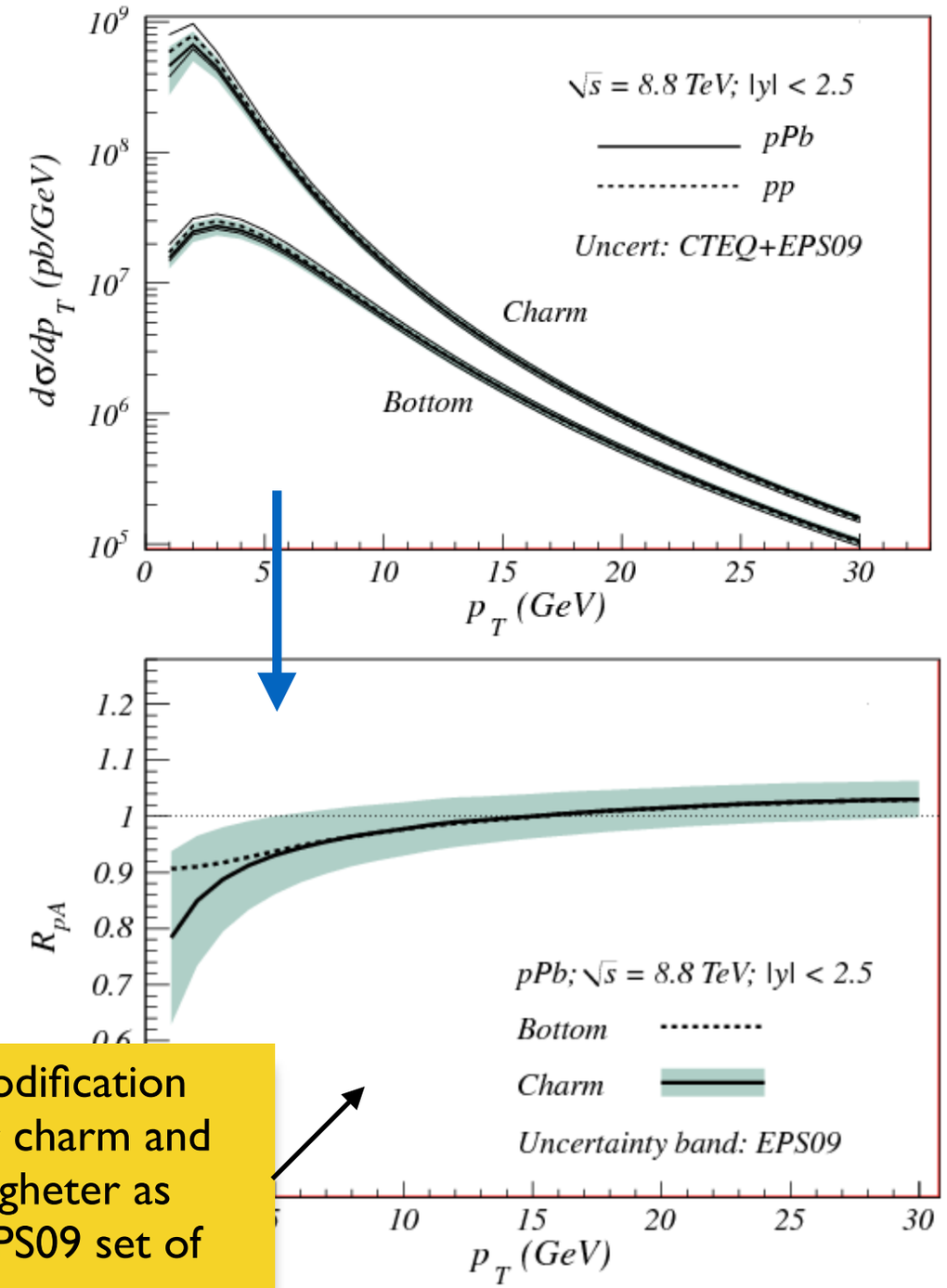
$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}(1+2v_1\cos(\varphi-\Psi_{RP})+2v_2\cos 2(\varphi-\Psi_{RP})+.....)$$

- Carries information on medium transport properties:
  - **Degree of thermalization of charm quark in QGP (low p_T)**
  - **Path-length dependence of parton energy loss (high p_T)**

p-A collisions

- ☑ Study cold-nuclear matter effects, reference for Pb-Pb
- ☑ Low-x region accessed at the LHC
- ☑ Shadowing/saturation at low-x (Color Glass Condensate, CGC?)





nuclear modification factors for charm and bottom togheter as given by EPS09 set of nPDFs

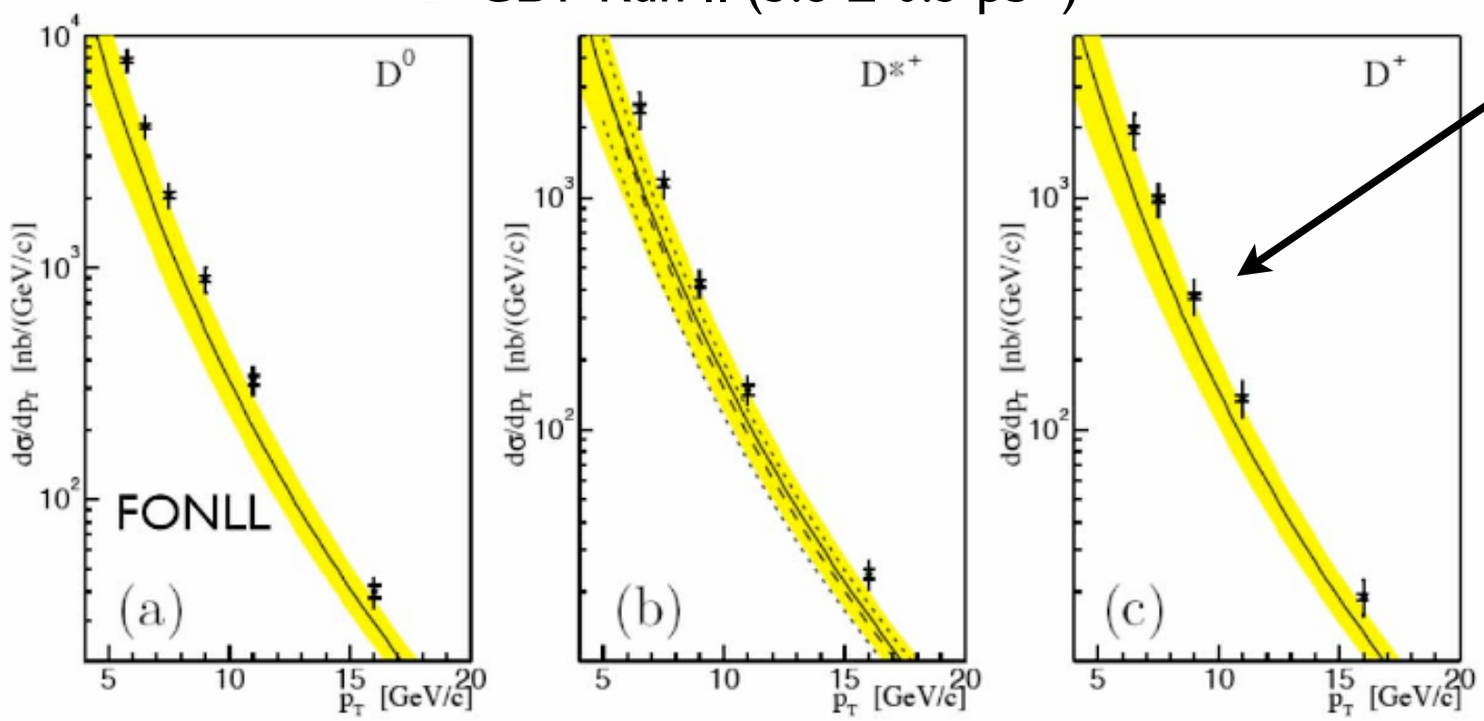
J.Phys. G39 (2012) 015010

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

pp colllisions

D meson production cross sections in pp at √s = 1.96 TeV

CDF Run II (5.8 ± 0.3 pb^{-1})



Measurements are at the edge of theoretical uncertainties.

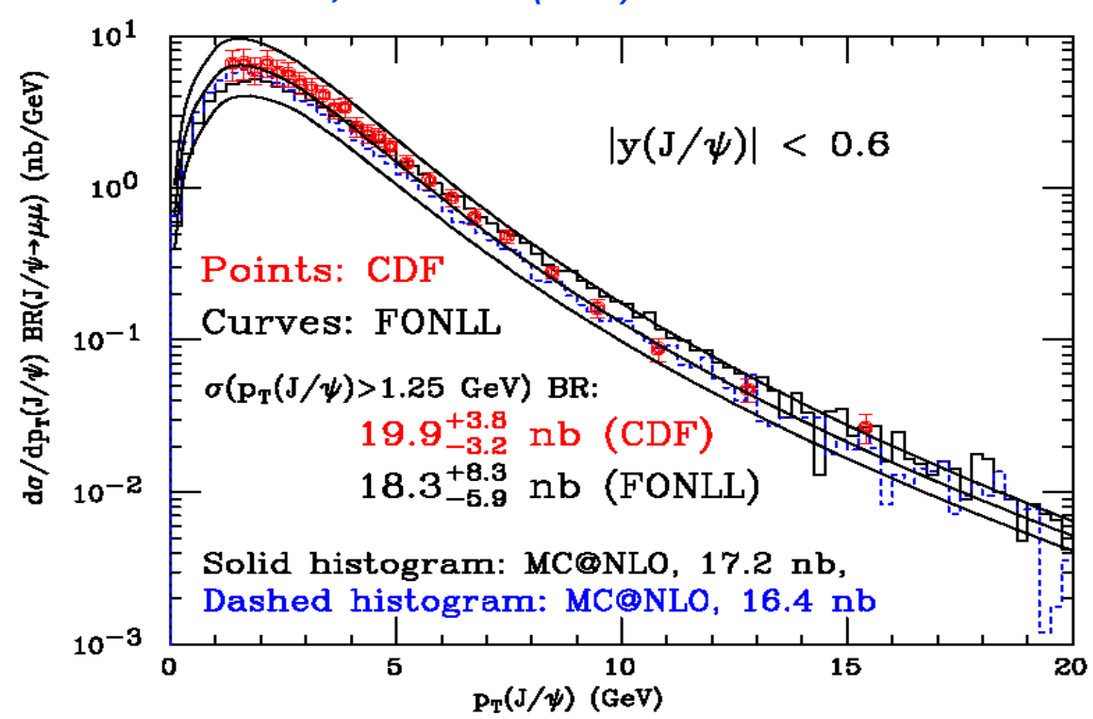
$D^0\,(cu) \rightarrow K^+\pi^-$ (*BR ~3.89%*),

$D^+\,(cu) \rightarrow K^-\pi^+\pi^+$ (*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

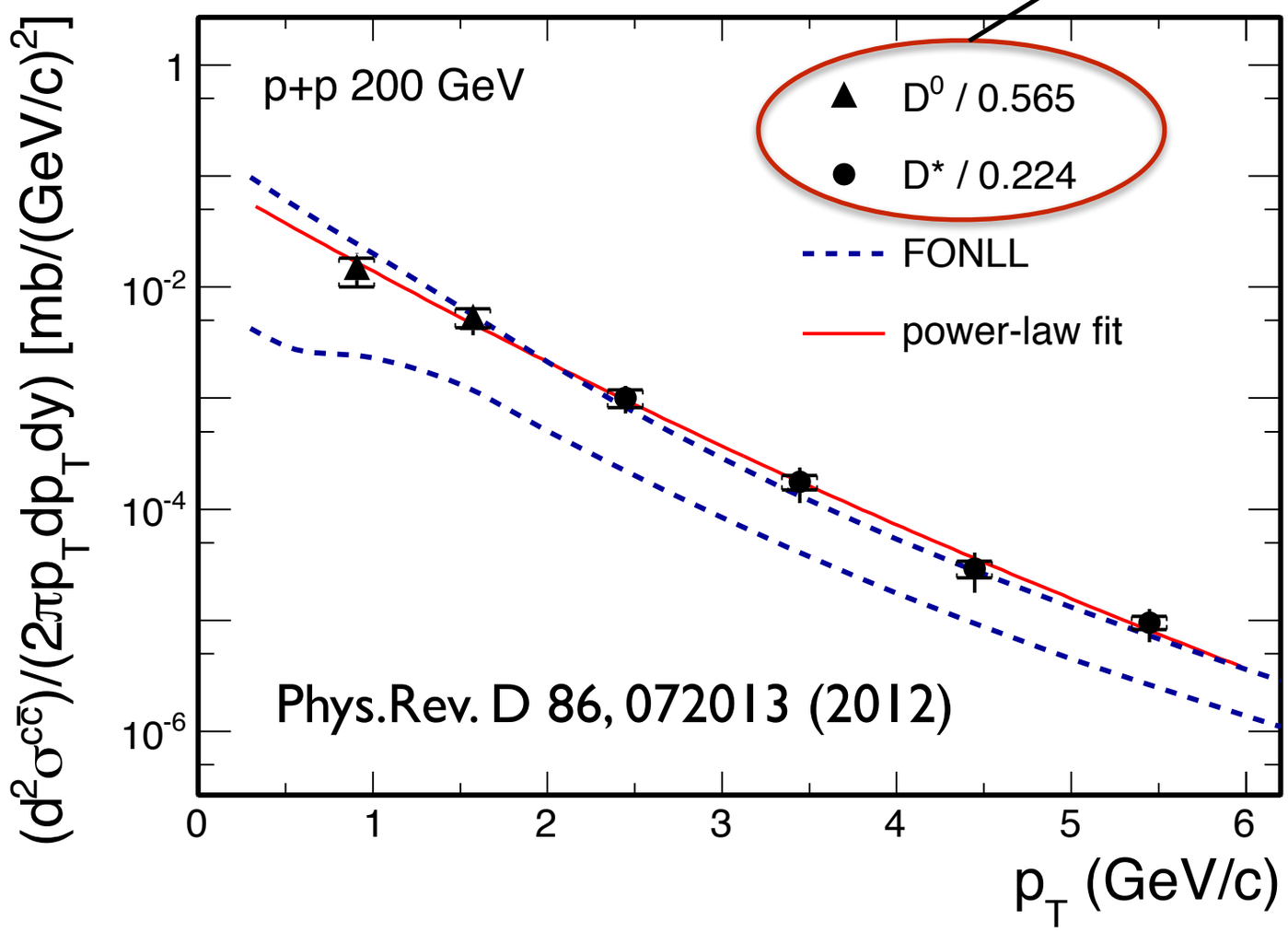


- ☑ Good understanding, within the errors, of b production at Tevatron (and LHC energies).
- ☑ Charm cross section studies, more complex, available since Tevatron Run II.

D meson production cross sections in pp at √s = 200 GeV

STAR

Data points divided by the charm quark fragmentation ratios so that D^{*+} and D^0 overlap in the plot



☑ D^0 points in [0.6,2] GeV/c, D^{*+} points in [2,6] GeV/c

Charm via D mesons hadronic decays at LHC

- Wide rapidity range: |y|<0.5 (ALICE), |y|<2 (ATLAS) and 2.0<y<4.5 (LHCb)

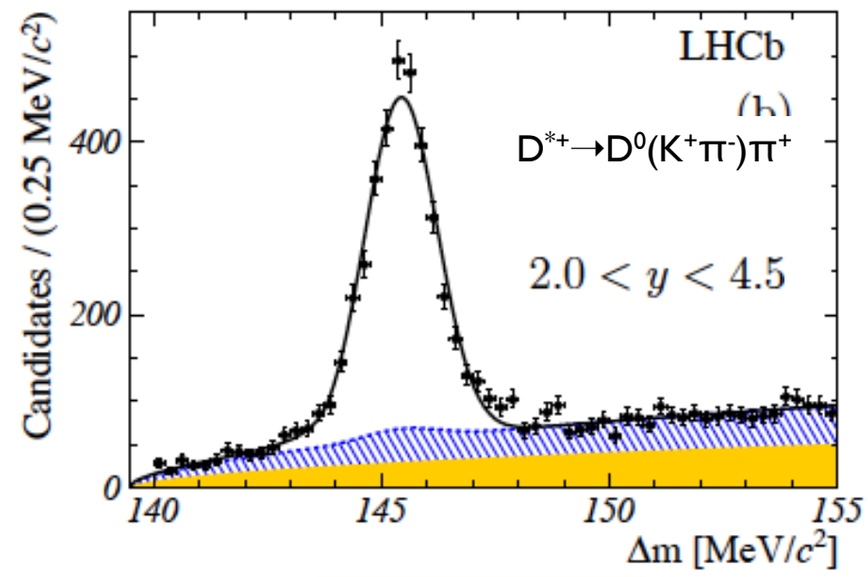
- Fairly similar reconstruction strategy between the different experiments

  Reconstruction of the secondary decay vertex. Once the topology of the decay is reconstructed topological selection can be applied to reduce combinatorial

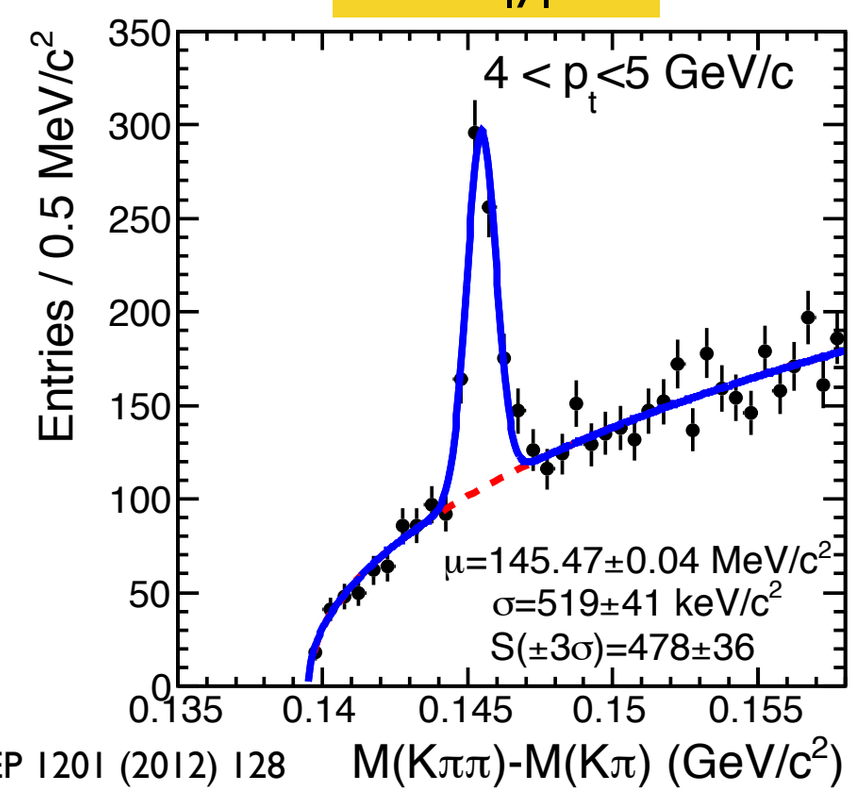
- In addition ALICE complements selection cuts with particle identification (PID)

LHCb: 2.0<y<4.5

Nuclear Physics, Section B 871 (2013)



ALICE: |y|<0.5

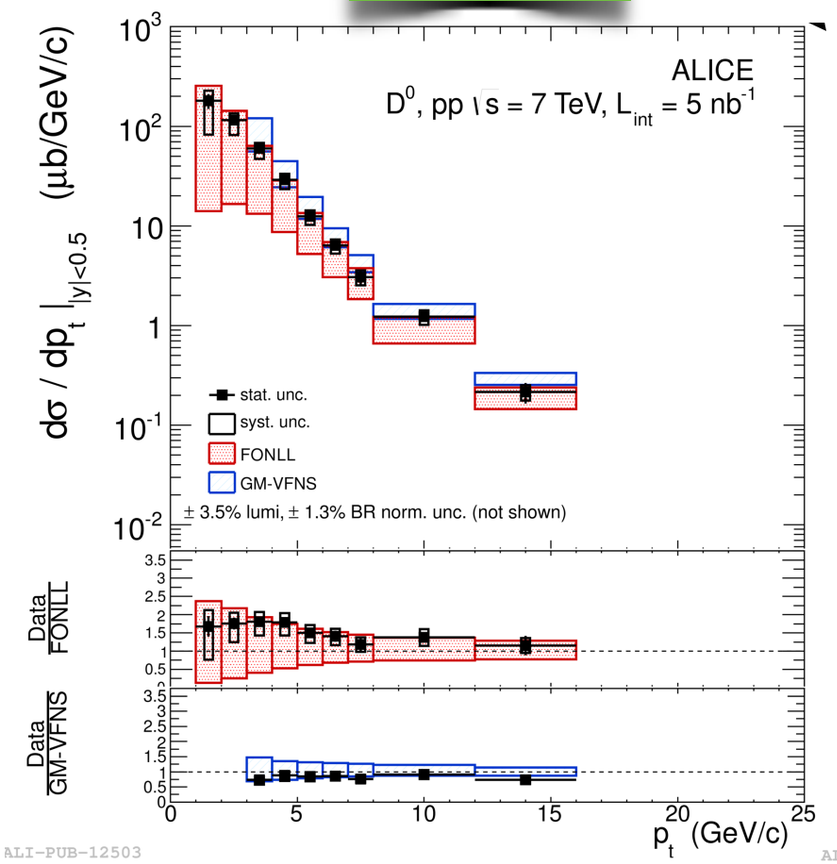


JHEP 1201 (2012) 128

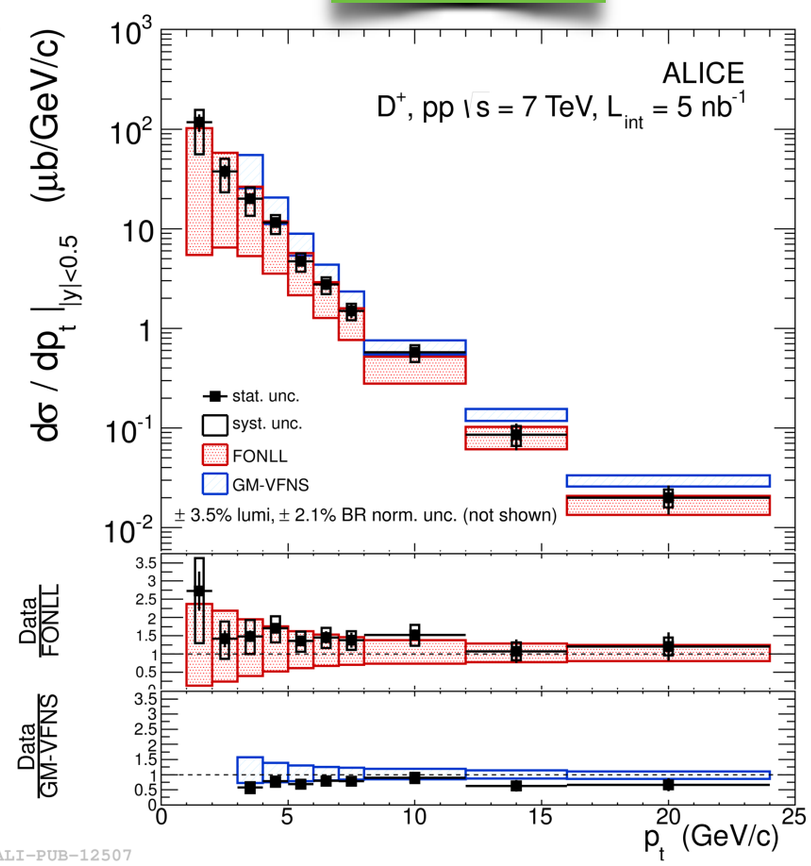
Charm via D mesons hadronic decays at LHC

ALICE

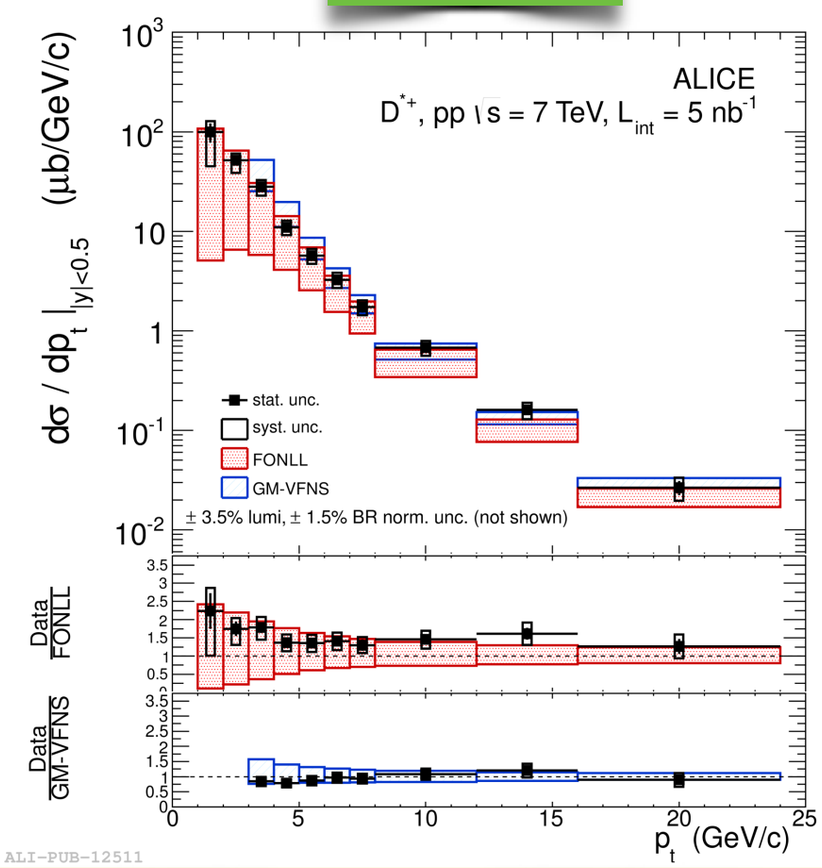
$D^0 \rightarrow K^-\pi^+$



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



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



ALICE Coll., JHEP 1201 (2012) 128

☑ Results are in agreement with pQCD 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

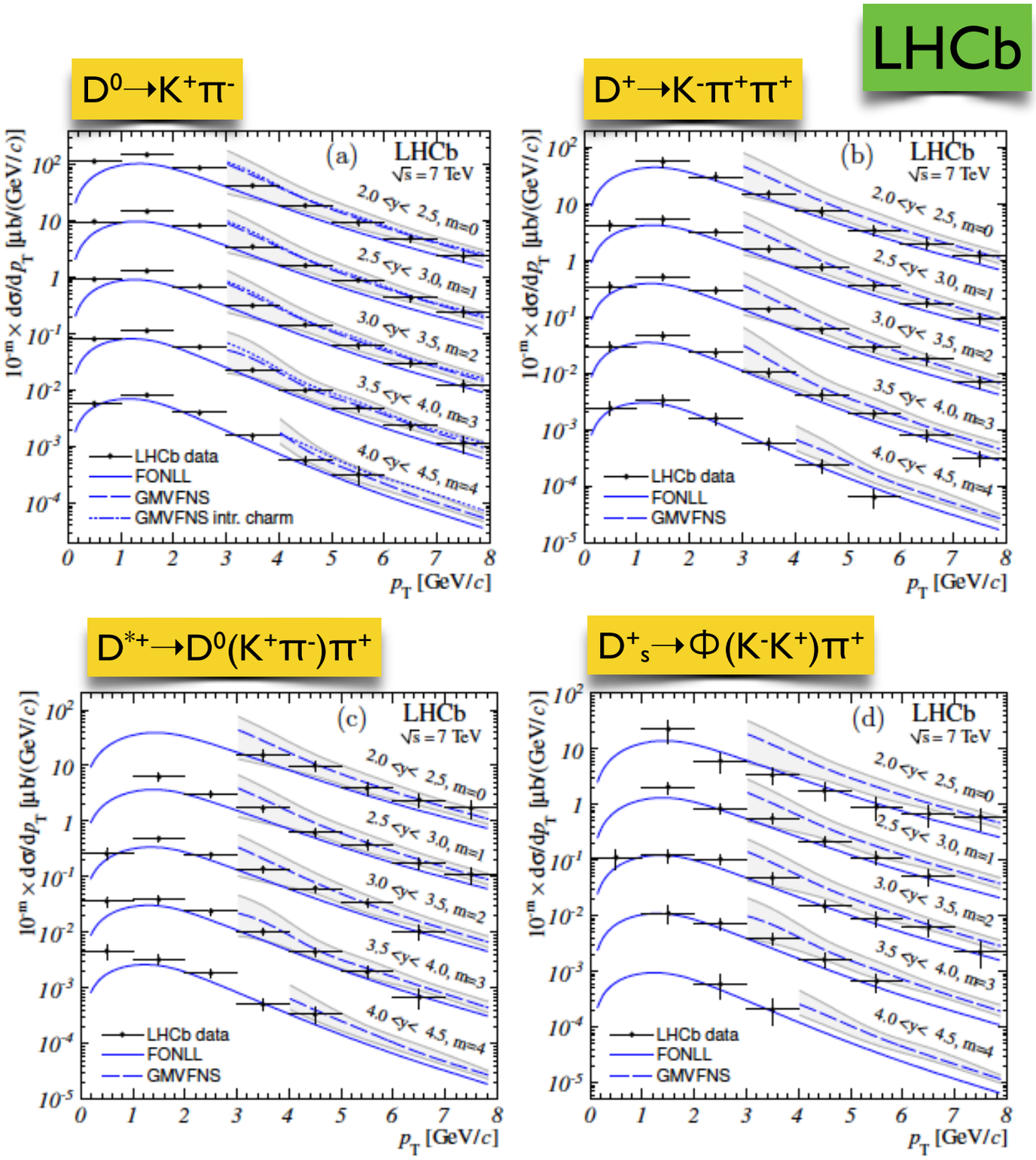
Charm via D mesons hadronic decays at LHC

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

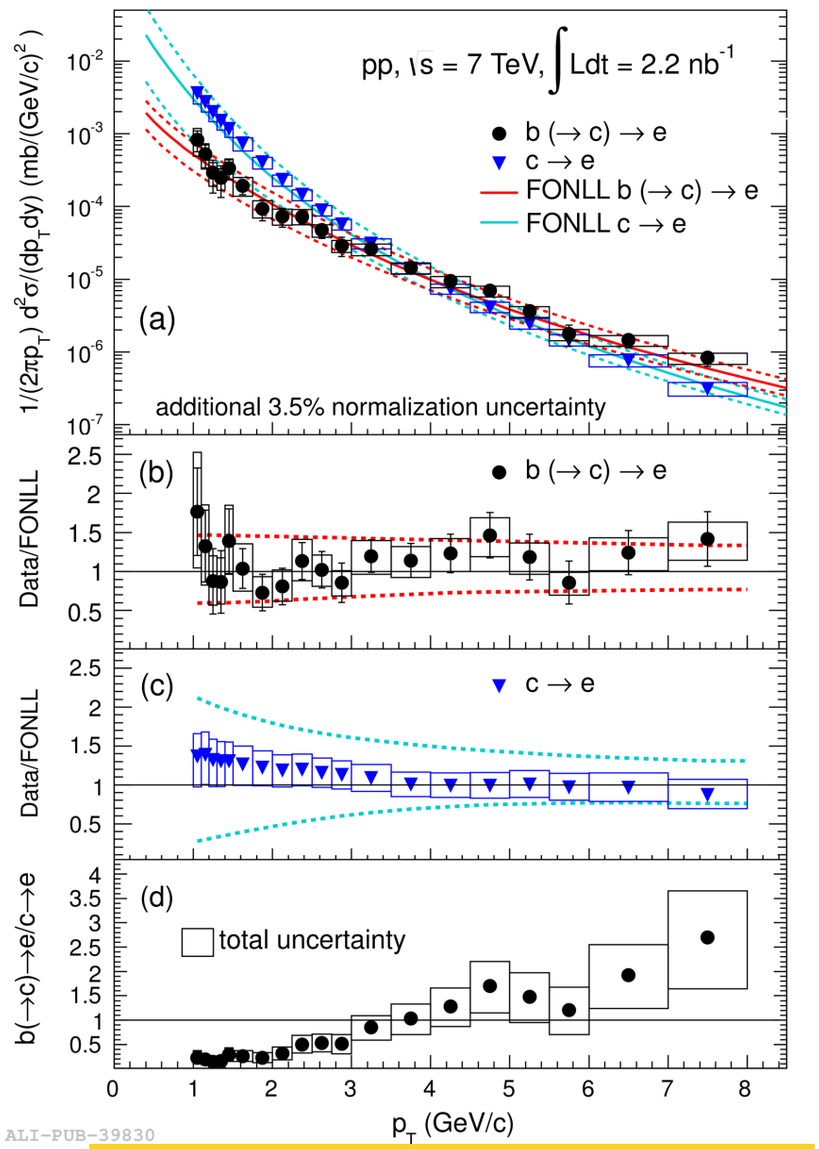
- Results are in agreement with pQCD within errors. Note: same models as ALICE used for the comparison

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

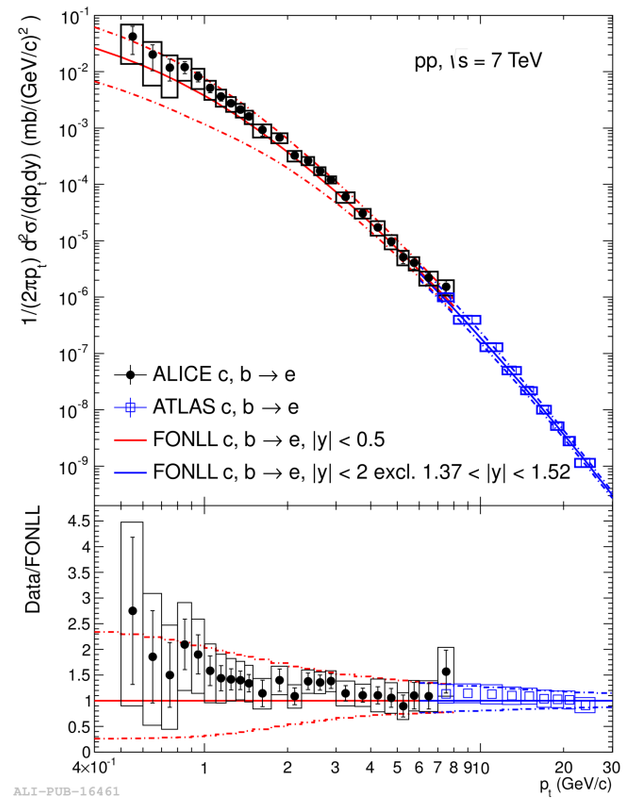
Nuclear Physics, Section B 871 (2013)



Heavy-flavour decay electron: charm and beauty



Phys.Lett. B721 (2013) 13-23



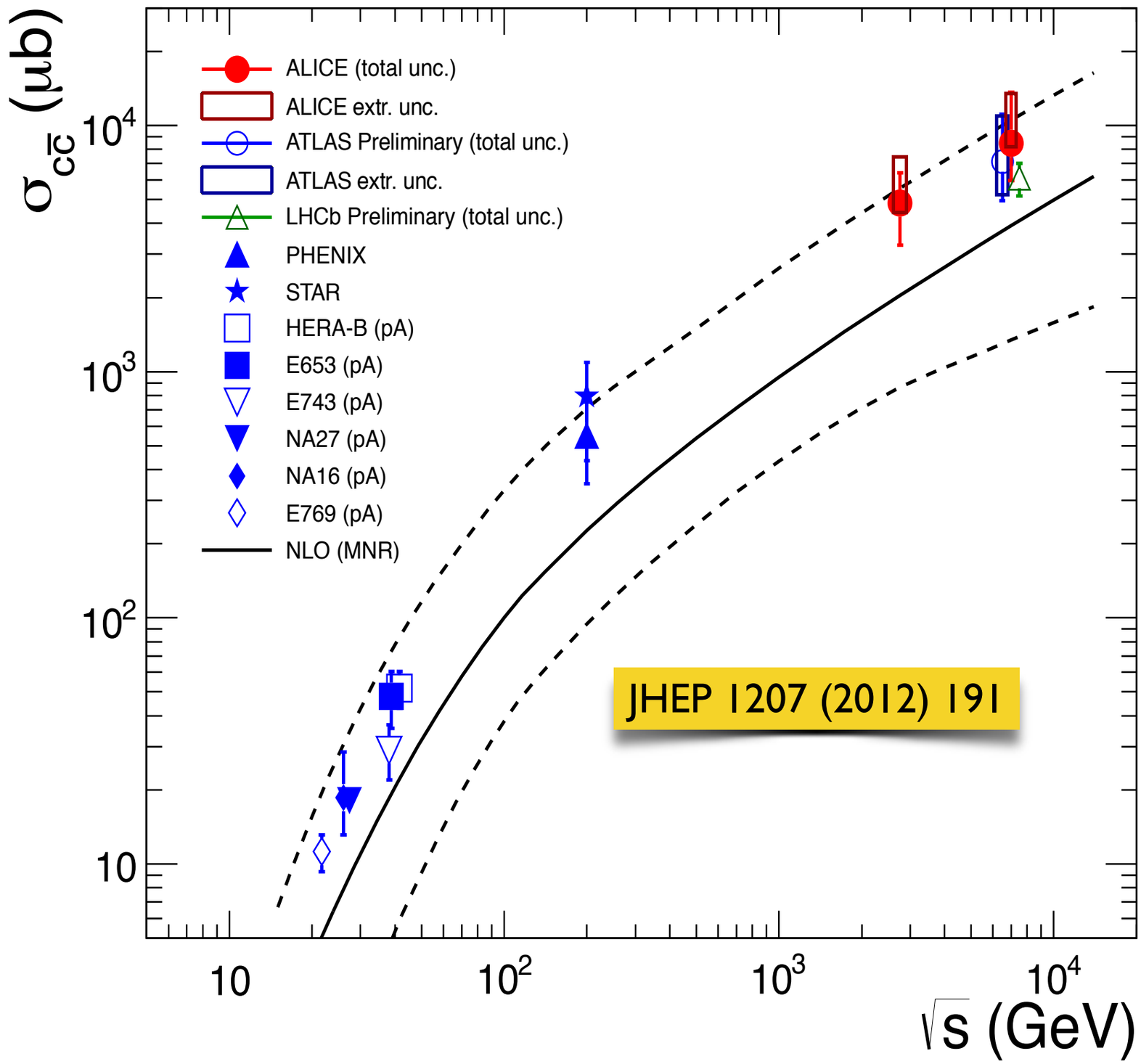
ALICE: Rhys.Rev.D86 (2012) 112007

ATLAS: Rhys.Lett. B707:483-458,2012

- Beauty fraction from two independent methods:
  - Different azimuthal correlation shape of charm and beauty electrons.
  - Impact parameter method

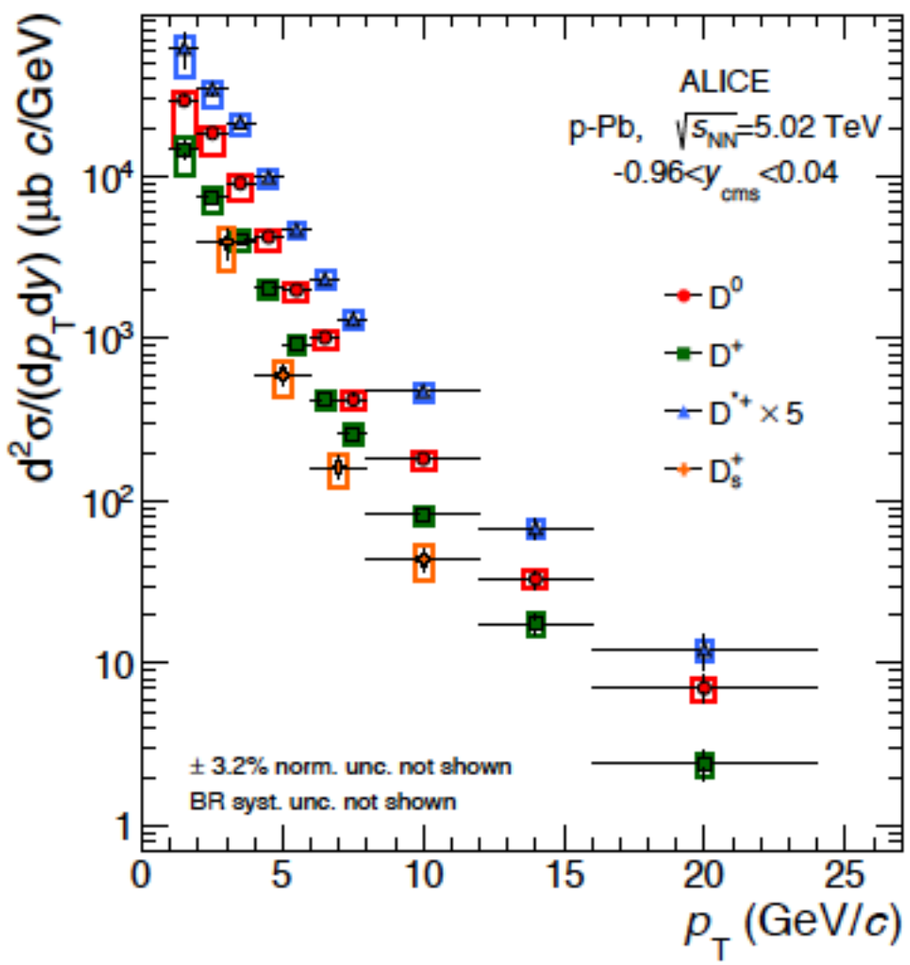
- Total heavy flavour electron yield scaled by the beauty fraction to have the beauty cross-section

Total charm cross-section



Charm p-A @ 5.02 TeV

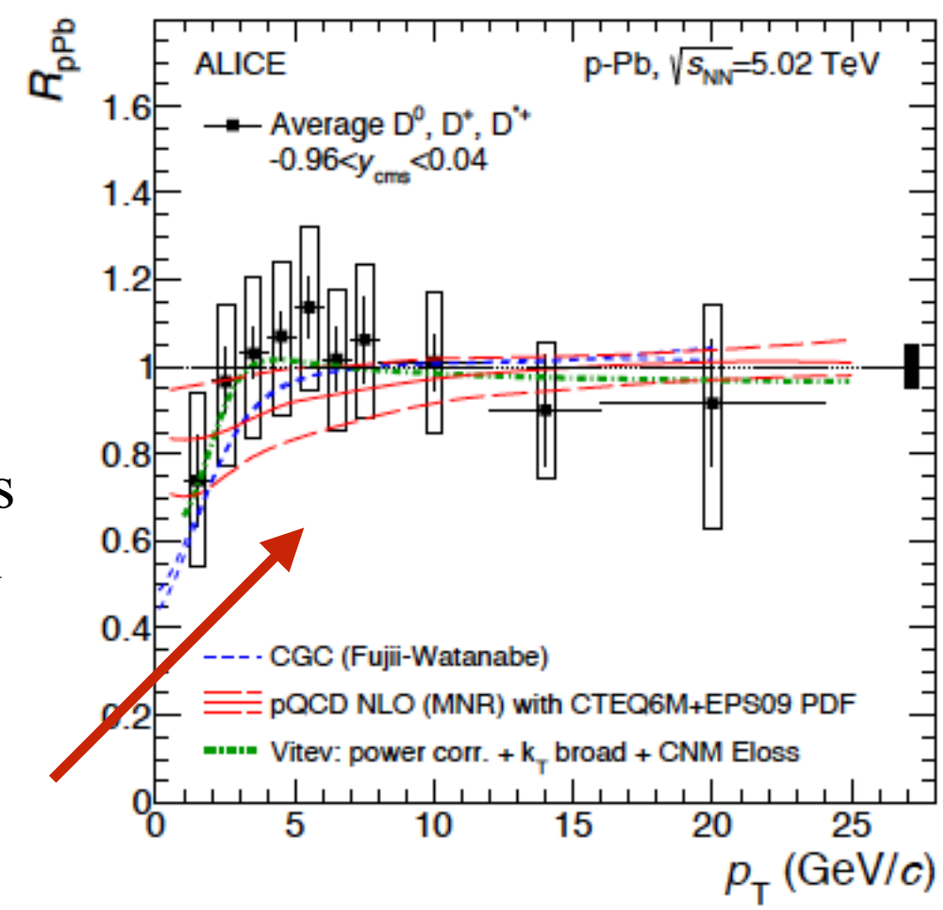
Production of D mesons in p-Pb collisions



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

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

arXiv:1405.3452

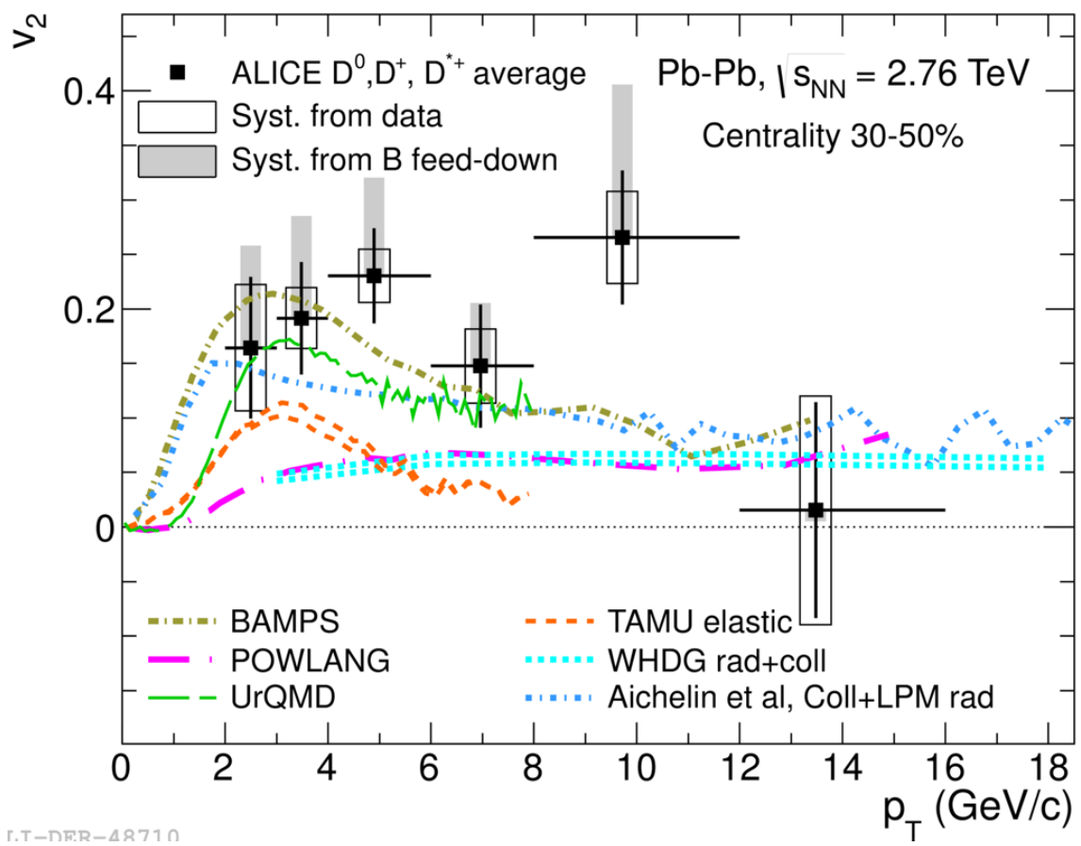


- Nuclear modification factor in p-Pb collisions is compatibile with unity and with theoretical calculations including gluon saturation

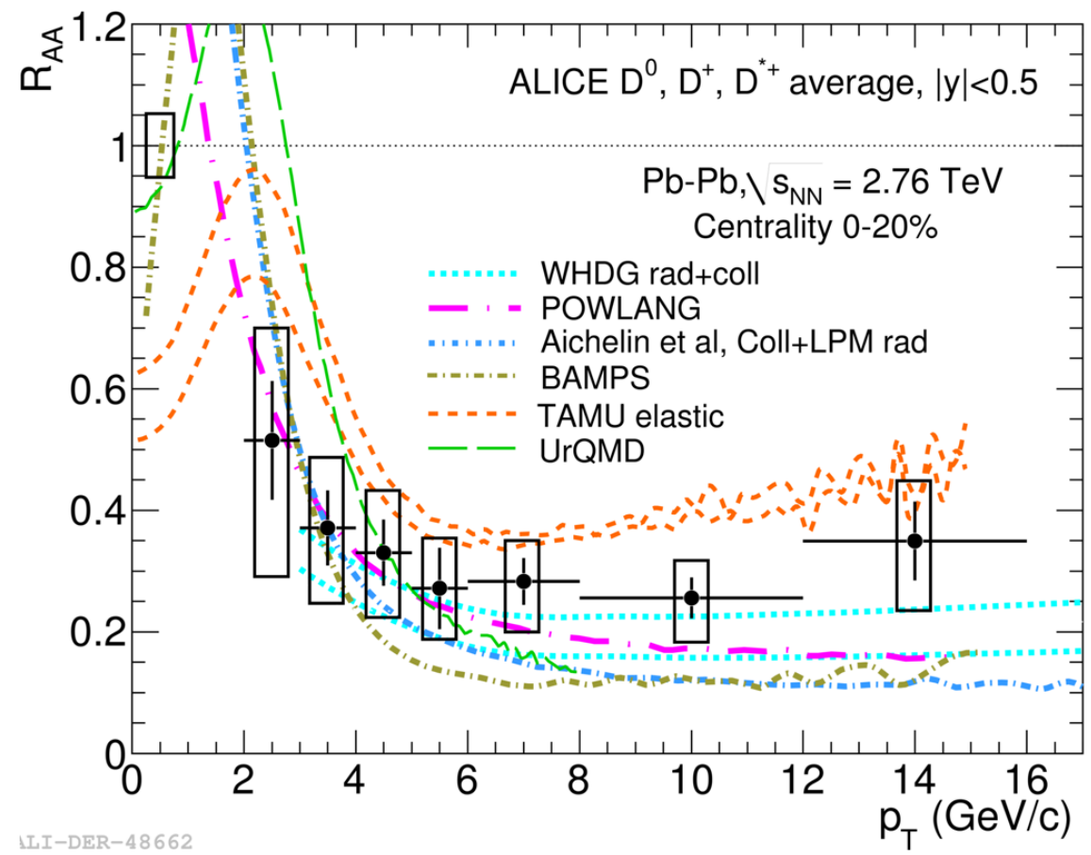
- Initial state effects play a small role for p_T> 2 GeV/c

Charm in A-A

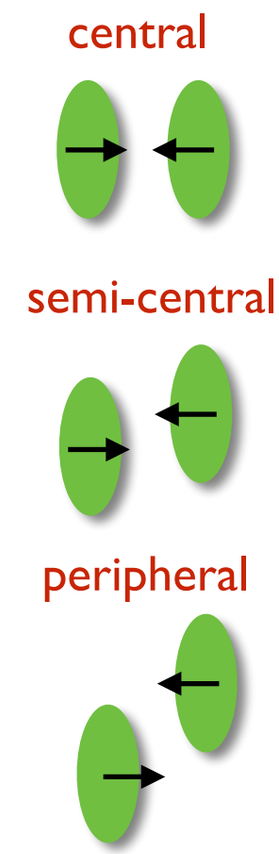
D meson flow vs D meson R_{AA} at LHC



Phys.Rev. C90 (2014) 034904



Phys.Rev.Lett. 111 (2013) 102301

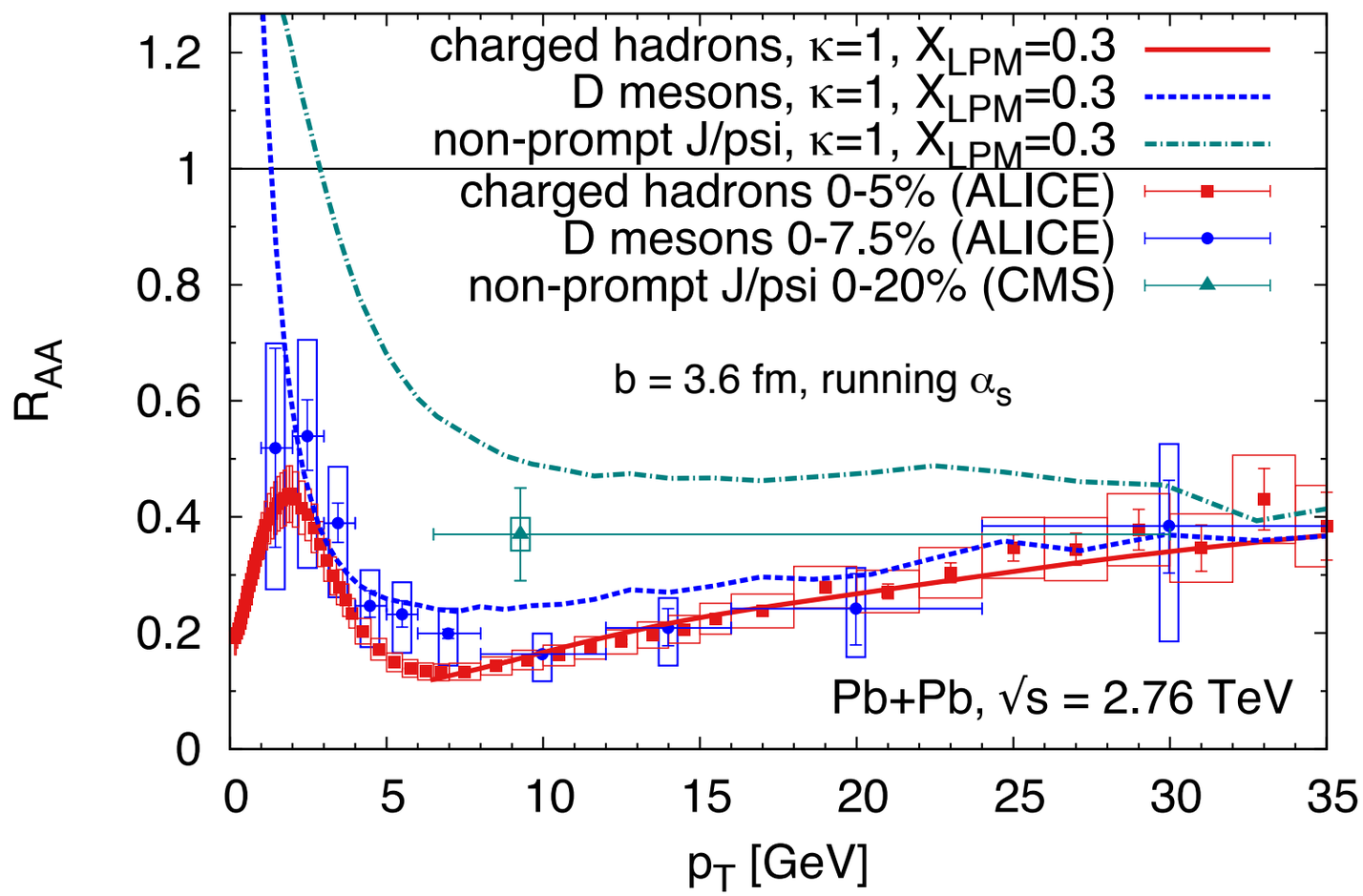


☑ Simultaneous description of D-meson R_{AA} and v_2 → understanding of heavy-quark transport coefficients of the medium (challenging for models)

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

Comparison with charged hadrons and non-prompt J/Psi



J. Uphoff et al, arXiv:1408.2964

- Average D^0, D^+ and D^{*+} R_{AA} measured in the p_T range [1,36] GeV/c with ALICE.
  Non-prompt J/ψ released by CMS collaboration.

- The suppression of D mesons reach factor 5-6 at 10 GeV/c. Non-prompt J/Psi suppressed by factor 2.5 for p_T>6 GeV/c

- Work is ongoing. The comparison of D mesons and non-prompt J/Psi is being refined. Although not conclusive we start to have an hint of a different behaviur of charmed and beauty mesons

Intrinsic charm

Why to go back(or forward) with intrinsic charm

- In the last few years most of the neutrino collaborations (i.e IceCube) started to have a good statistic to study high energy extra galactical neutrinos

- One of the main sources of background is due to atmospheric neutrinos originated from charm decays:
  - It cames from high energy (TeV scale) p-A collisions. Mostly are p-O collisions
  - Charm is produced at forward rapidity. Typically much forward than what we can reach at LHC, however there is a partial overlap in rapidity ($\sim 3<y<4.5$)
  - The general idea is to profit from collider and fixed target esperiments to extrapolate the results and estimate the contamination

- If the charm production is well described by pQCD then the background can be estimated with some confidence. But what about the non-perturbative part?

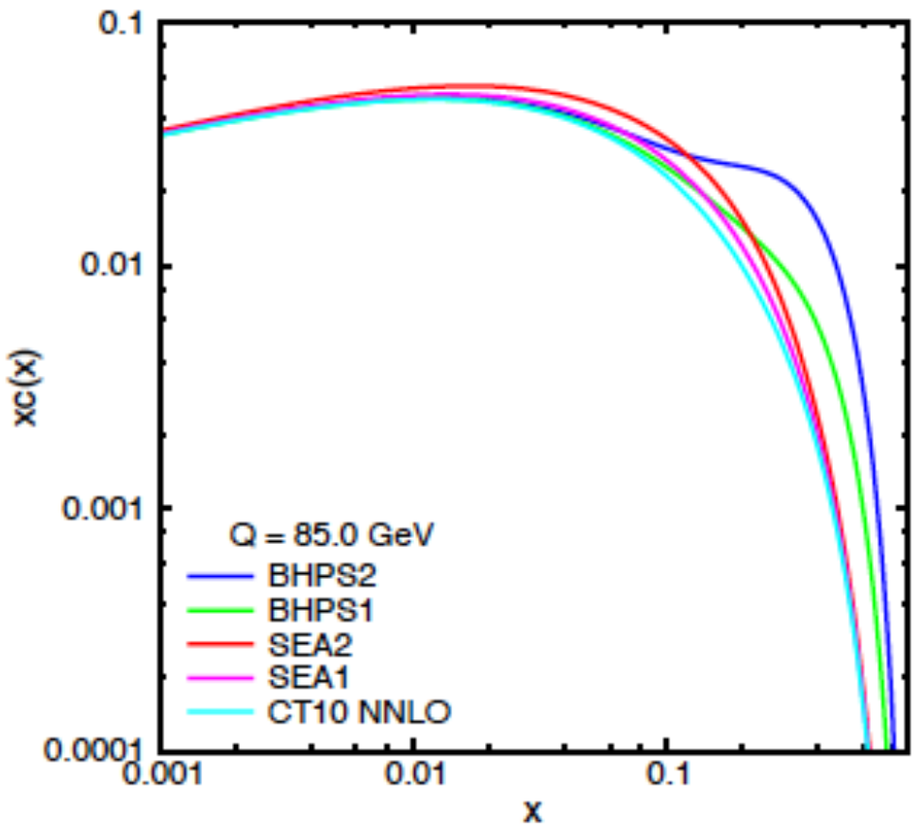
Intrinsic charm (IC)

- In 1980 in order to explain the experimental data on charm production it was proposed, in addition to the usual perturbative component an additional "intrinsic" (long time scale) charm component in the proton.

- Several works proposed the probability to find this "uudc$\bar{c}$" component in the proton to be rather small ranging from 0.5 to 3%.
  In general the problem has to be threated as non perturbative so the probabilities are based on many non-trivial approximations.

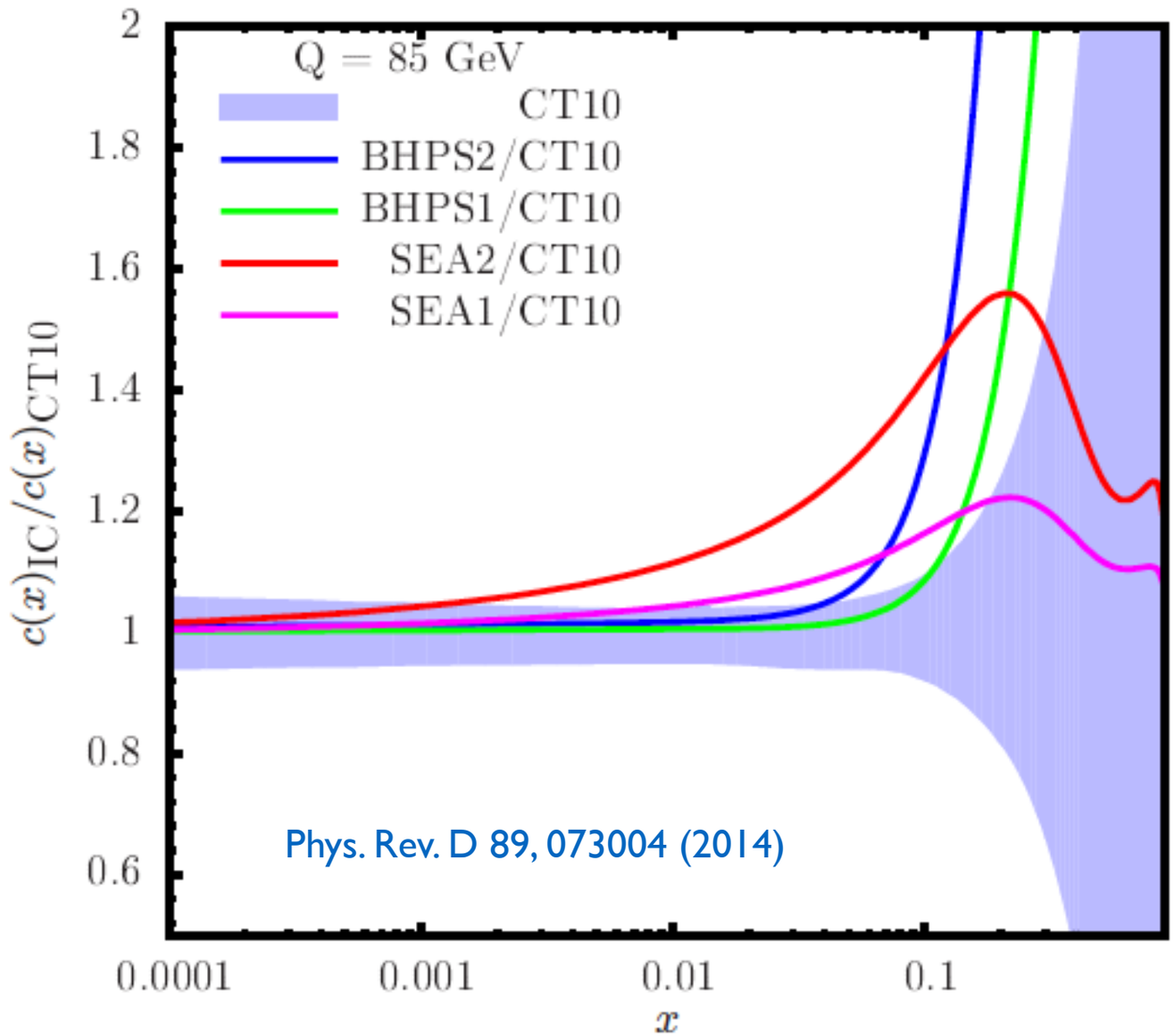
- Several experiments (i.e. European Muon Collaboration (CERN), SELEX and D0 (TEVATRON) ad at HERA) investigated charm production and proposed, in same cases, the possibility of the effect of the IC as one of the explanations of the results. Nowever, no clear conclusion was ever made.

Phys. C 20, 71 (1983)
Nucl. Phys. B461,181 (1996)
arXiv:1305.3548
Phys. Rev. D 73, 114015 (2006)



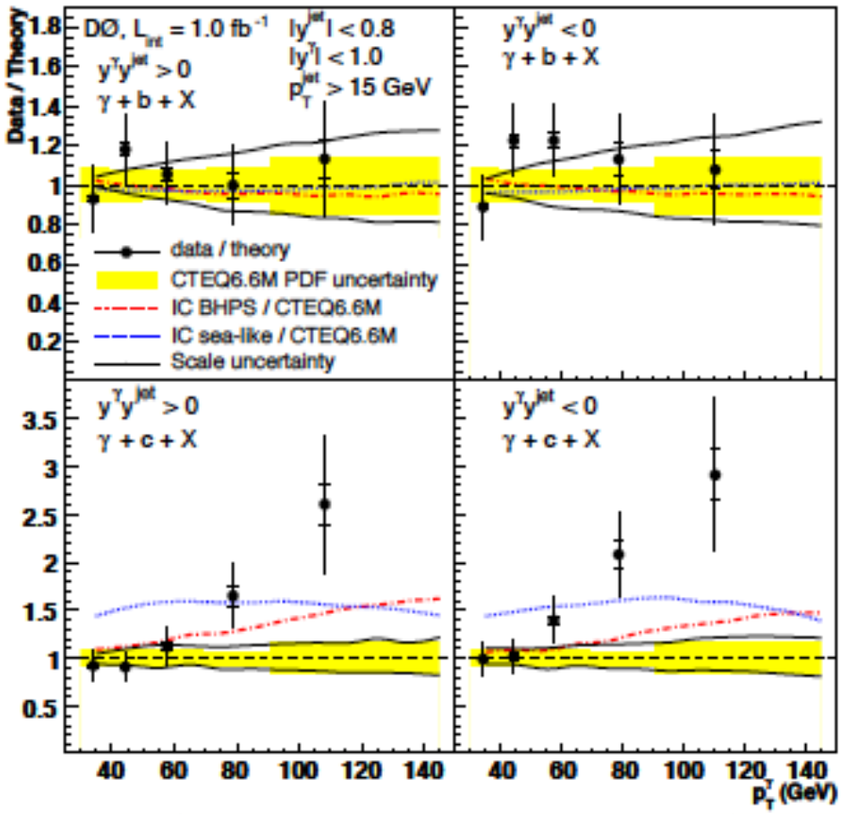
Phys. Rev. D 89, 073004 (2014)

Modification of the charm distribution

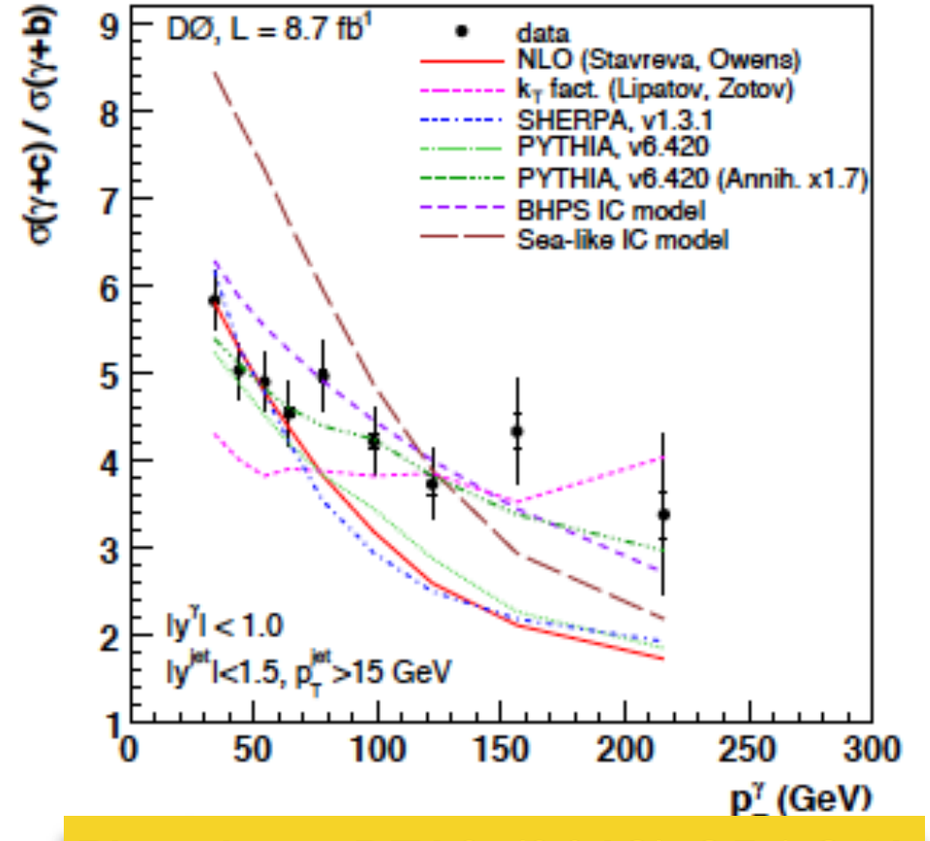


- ☑ Recent studies, based on the most up-to-date informations on PDFs and on the HERA (Zeus + H1 data) results point to and intrinsic charm contribution small if any (<2% for BHPS model)

Experimental data at TeV energies



Phys. Lett. B714 (2012) 32-39

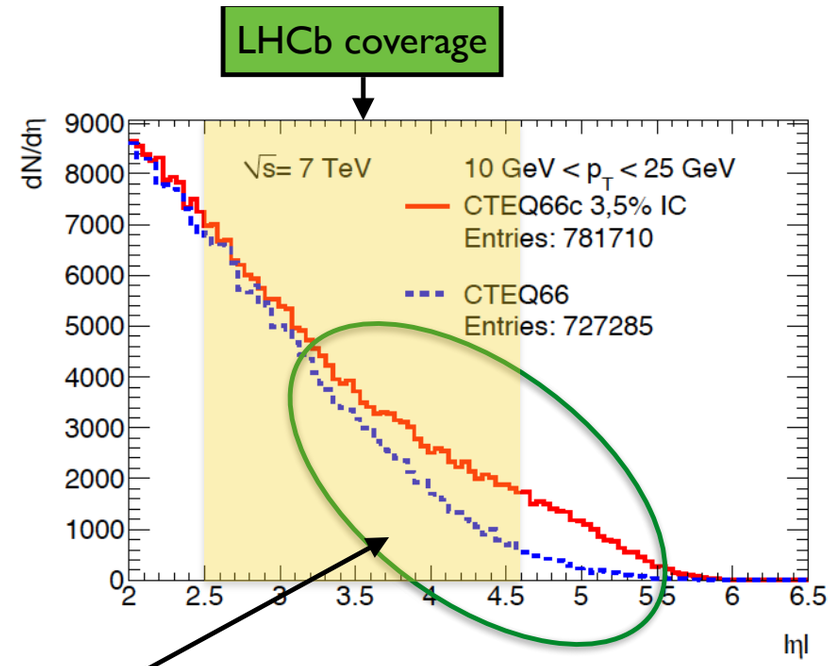


Phys. Lett. B719 (2013) 354-361

- At TeV energy scale the D^0 collaboration measured the differential cross section of γ+c(b) jets and their measurement. ratio (g,c and b PDF for $0.01<x<0.3$).
- Results, for $p > 80$ GeV/c, point toward the possibility of an underestimated g→cc component or to an intrinsic charm contribution.

Intrinsic charm at LHC energies

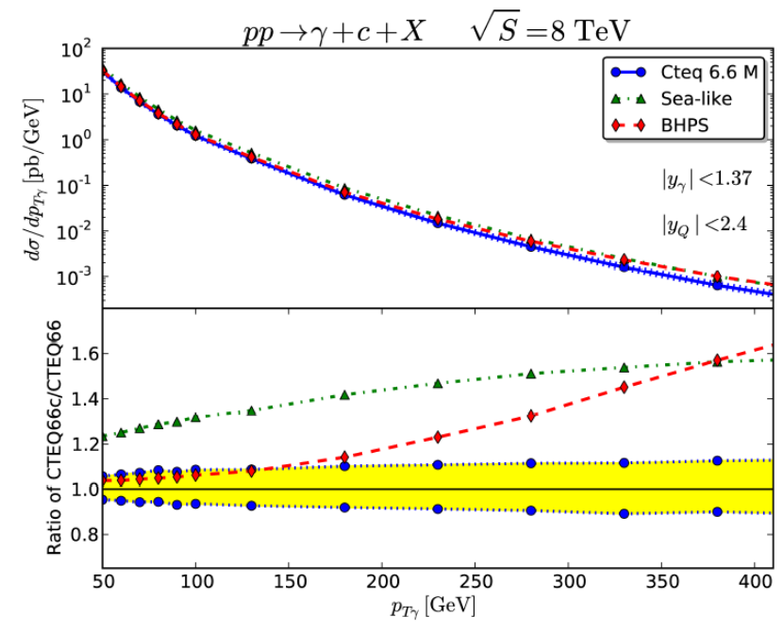
- Studies, based on Pythia8, show that if an intrinsic charm exists we can see it as a large signature in the D mesons production at forward rapidities (LHCb range)



Eur.Phys.Lett. 99 (2012) 21002

- LHCb published D mesons up to a p_T of 8 GeV/c. The IC effect is expected to be strong (factor 2 to 3) in the region $10<p_T<25$ GeV/c. Next data taking and the comparison with ALICE central rapidity results will pose strong constaints on the hypothesis of IC

- A strong effect of about factor 2 at p_T of 400 GeV/c is expected to be seen in the cross section of γ produced in association with charm jets. CMS and ATLAS may be able to verify it.



Phys. Rev. D 89, 073004 (2014)

arXiv:1305.3548

Conclusions

- ☑ Charm production has been measured by several experiments in pp at different center of mass energies. Results agree with perturbative QCD calculations within uncertanties.

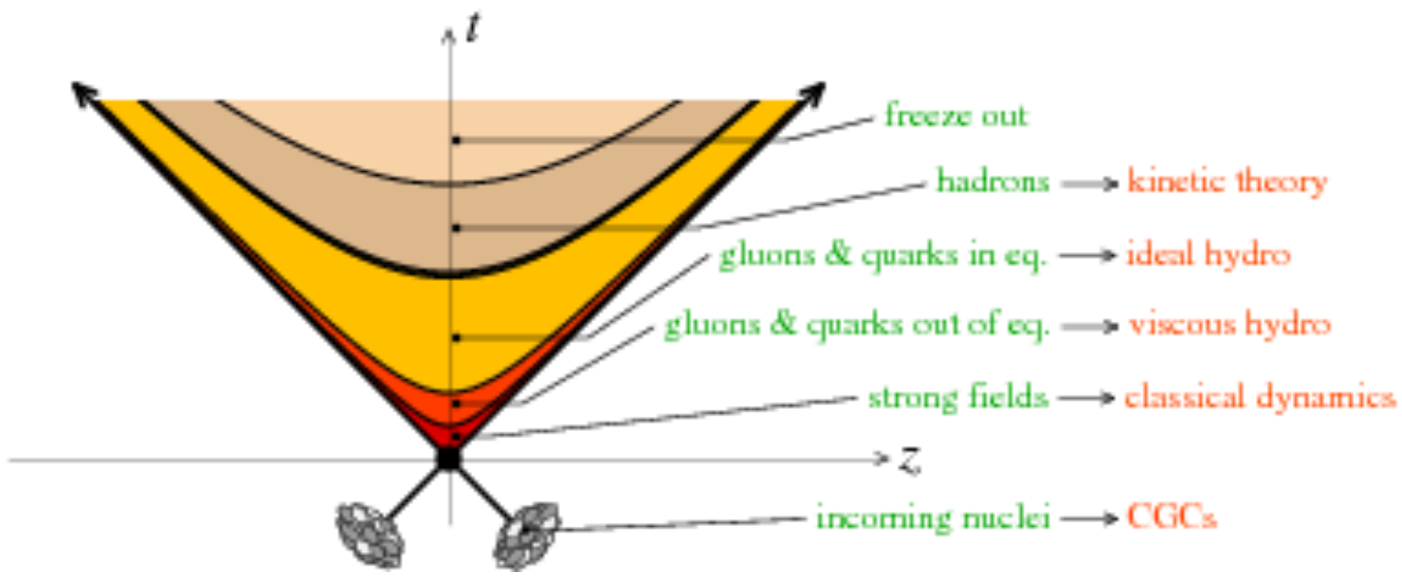
- ☑ At LHC the measurement of charmed D mesons in p-Pb collisions shows that the cold nuclear matter effects play a marginal role in the charm production

- ☑ In A-A collisions charm is qualitatively and quantitatively a good probe for the QGP. The nuclear modification factor and elliptic flow were measured. LHC data, once compared with p-A results, shows an R_{AA} compatible with final state effects. Movere, charm has a non zero-positive elliptic flow.

- ☑ The possibility of an intrinsic component of charm in the proton is a long standing issue. If such component exists it may represents a major source of background for neutrino experiments. At LHC we have the chance to put strict constraints on it.

Backup

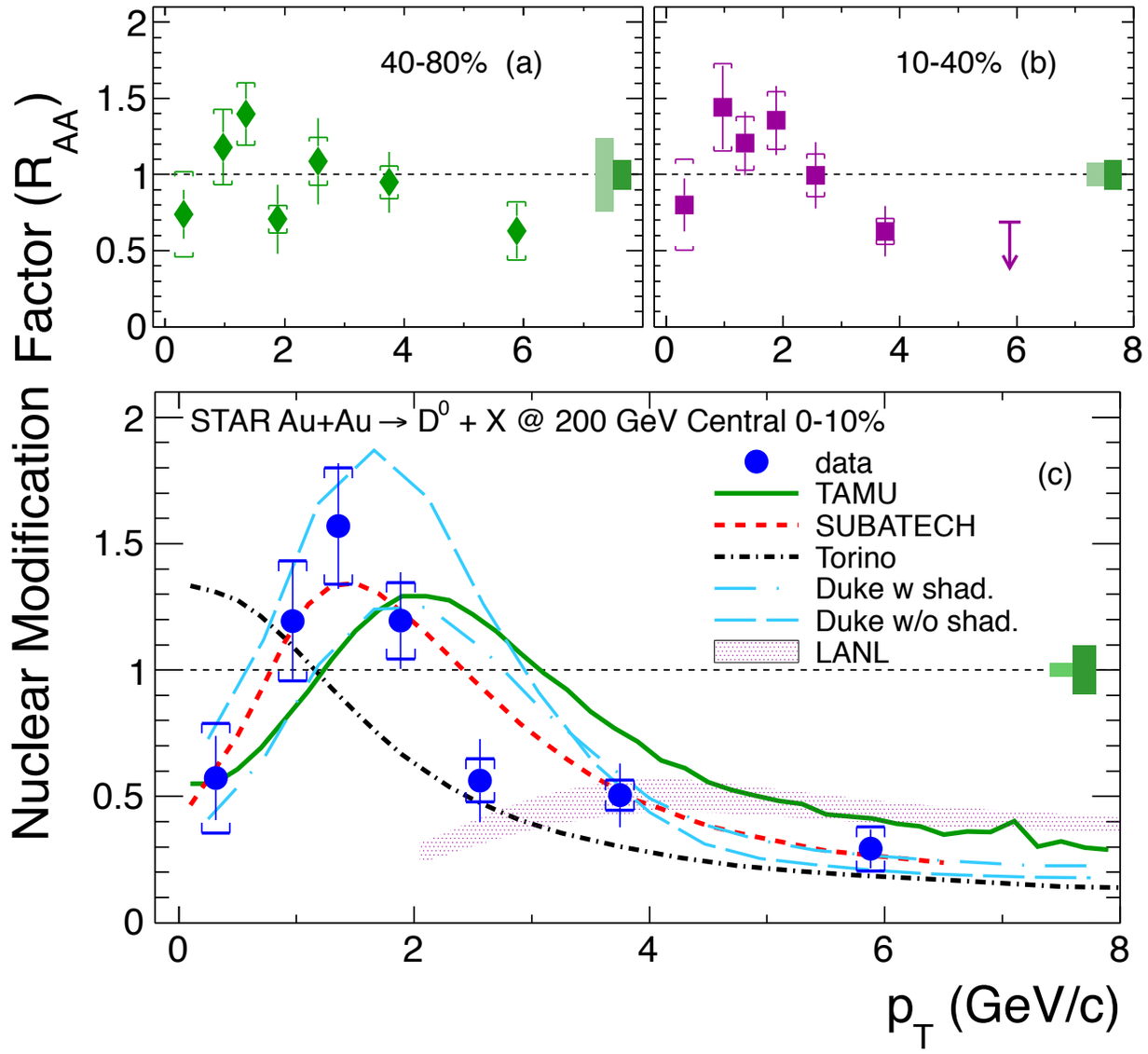
Stages of a HIC

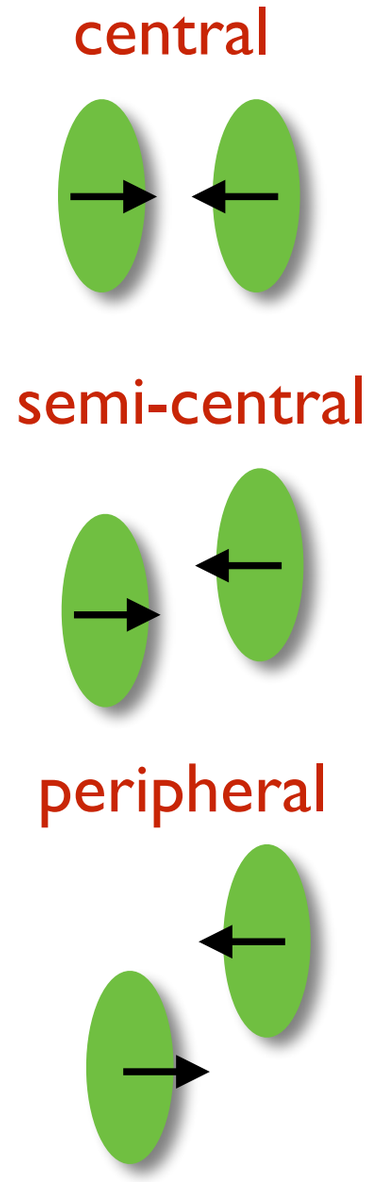


- Schematic representation of the several stages of a HIC as a function of time and trasversal coordinate z

D meson nuclear modification factor at RHIC

- D^0 production measured by STAR Collaboration in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV





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