Charm production at hadron colliders

Alessandro Grelli

Universiteit Utrecht

NWO
Netherlands Organisation for Scientific Research

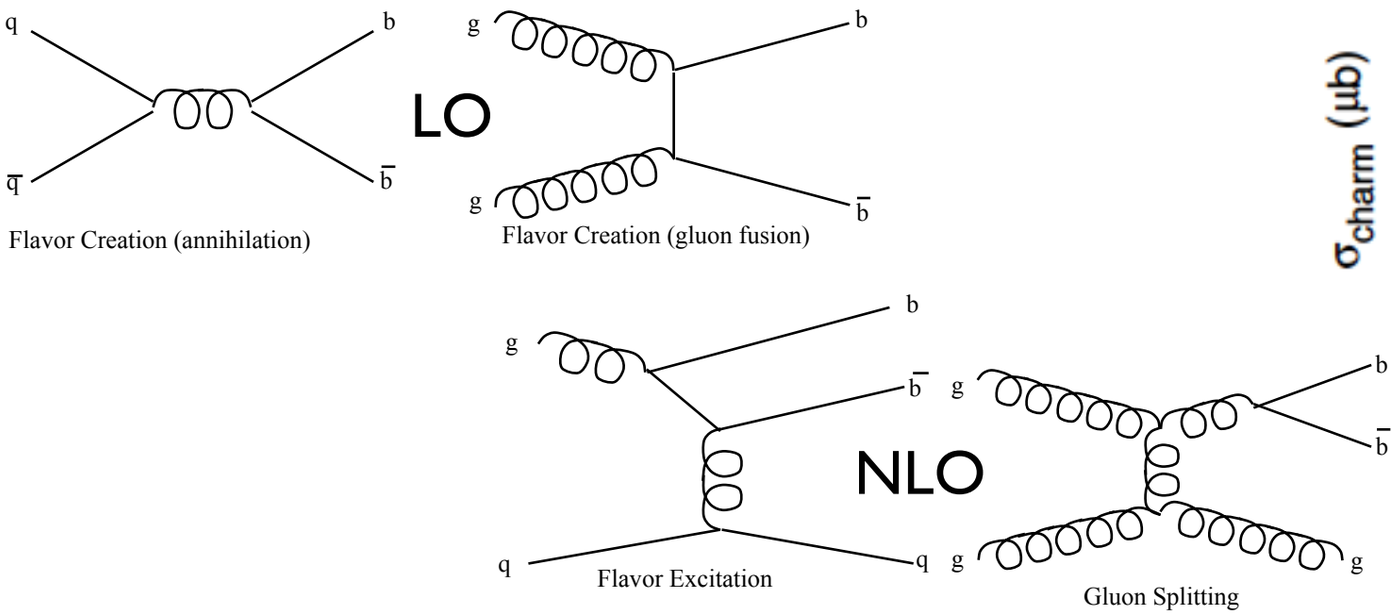
Outline

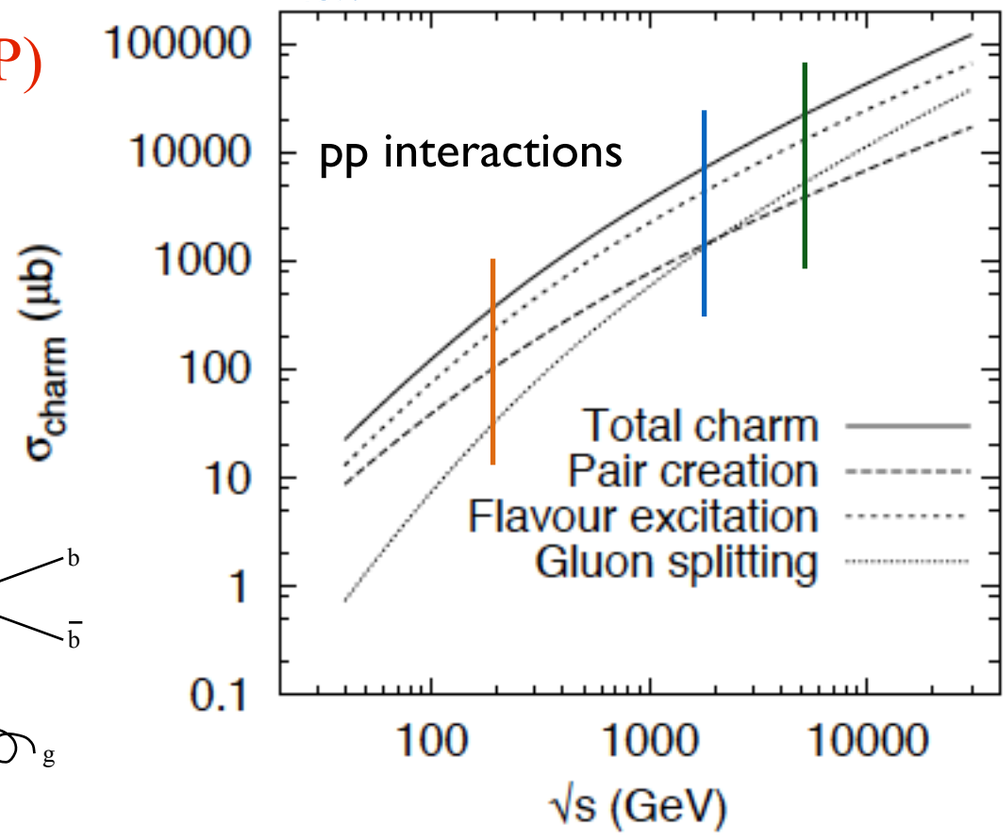
- Why heavy-flavours?
- Charm production in pp collisions
  - Rewiew of open charm results
  - Intrinsic charm at forward rapidities?
  - Possible intrinsic charm signatures at LHC energies
- Charm production in p-Nucleus
- Charm production in Nucleus-Nucleus
- Conclusions

Outline

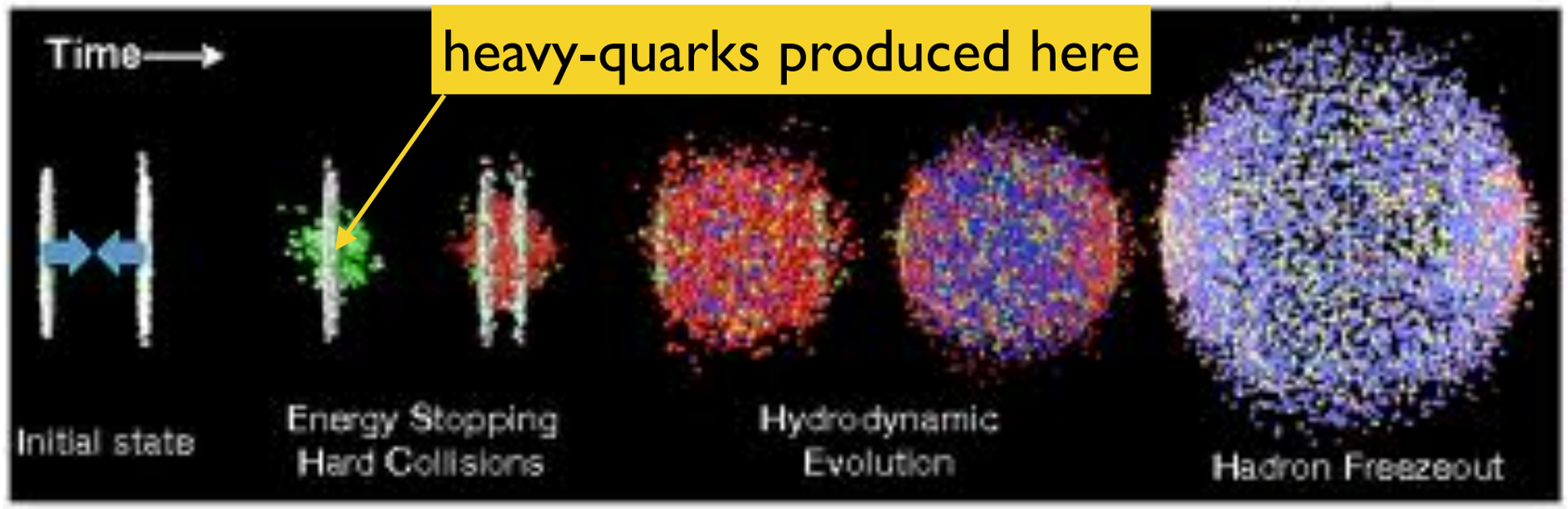
- Focus on Tevatron, Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC).
- Heavy-flavour production provides an excellent QCD test tool.
  - **pp** : test perturbative QCD predictions, (pp baseline for p-A and A-A collisions)
  - **p-A** : assess cold nuclear matter effects
  - **A-A** : probe the high density medium (QGP)

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





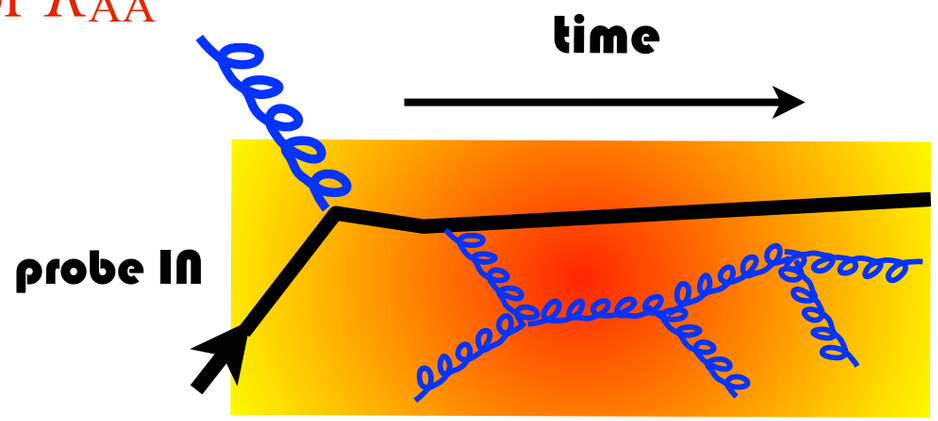
A probe for the QCD medium in A-A collisions



☑ Heavy quarks are expected to lose less energy than light quarks and gluons due to color-charge and dead cone effect (radiative energy loss) → higher penetrating power into QCD medium.
Observable: Nuclear modification factor R_{AA}

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

$\Delta E(g) \gtrsim \Delta E(\pi) > \Delta E(D) > \Delta E(B)$



Few caveats going from the hierarchy in E_{loss} to the one in R_{AA} (i.e: Steepness of the parton spectra, fragmentation functions, soft particles production at low p_T)

N. Armesto, C. A. Salgado and U. A. Wiedemann. PRD 69 (2004) 114003

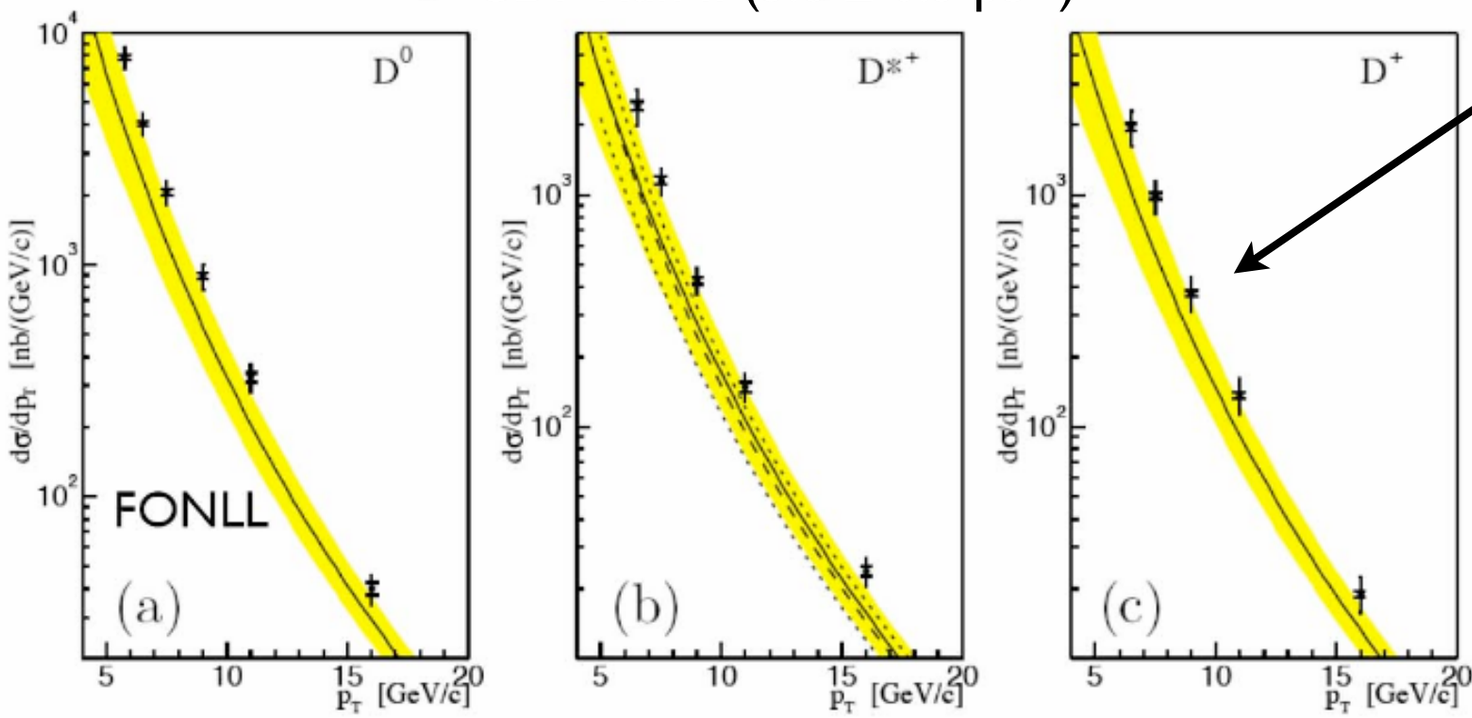
M. Djordjevic, M. Gyulassy, Nucl. Phys. A733 (2004) 265.

Charm production in proton-proton collisions

- [x] D meson in hadronic decay channels
- [ ] Heavy flavour decay electrons
- [ ] Single muons from heavy flavour decays
- [ ] Intrinsic charm?

Charm at Tevatron in $p\bar{p}$ at $\sqrt{s}$ = 1.96 TeV - D mesons

CDF Run II (5.8 ± 0.3 pb^{-1})



Measurements are at the edge of theoretical uncertainties.

D^0 (cu)→$K^+\pi^-$ (BR ~3.89%),

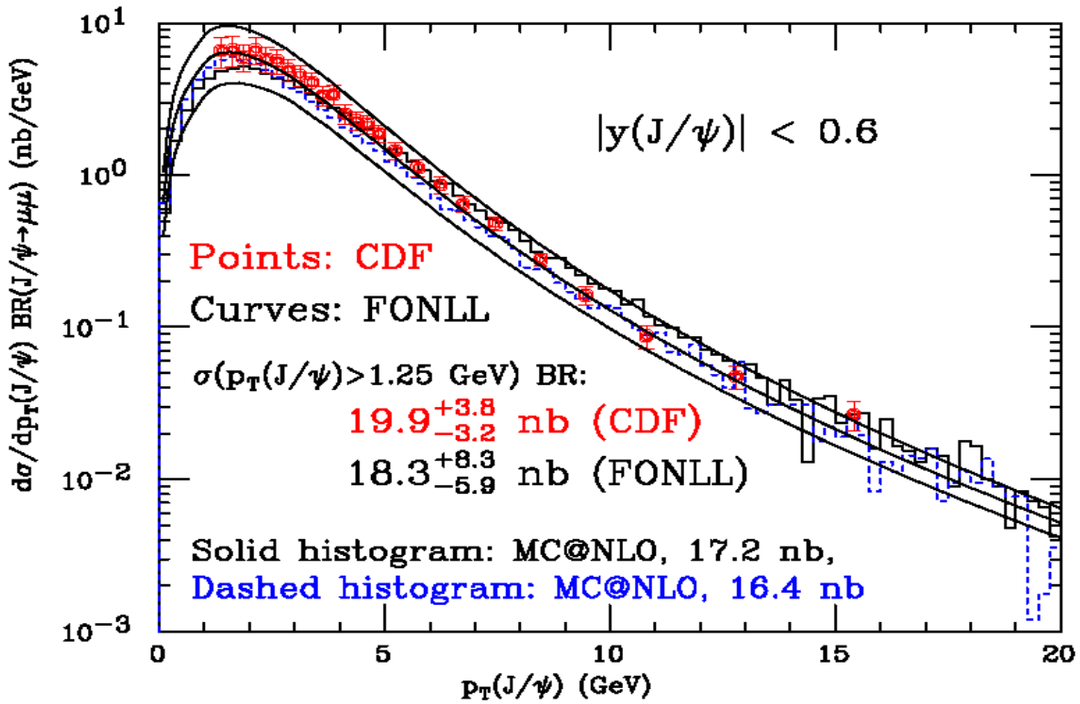
D^+ (cu)→$K^-\pi^+\pi^+$ (BR ~9.13%),

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

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

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

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



Charm at RHIC - D mesons in STAR

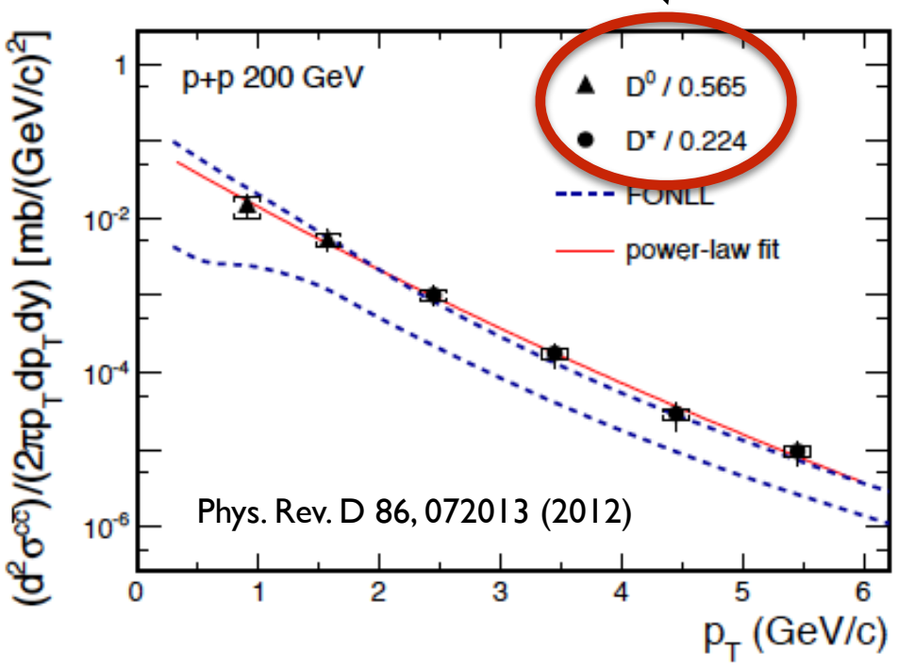
☑ Charmed hadron (D^{*+} and D^0) production cross section measured at mid-rapidity at $\sqrt{s}$ = 200 GeV. 105M min-bias events analized from 2009 data taking

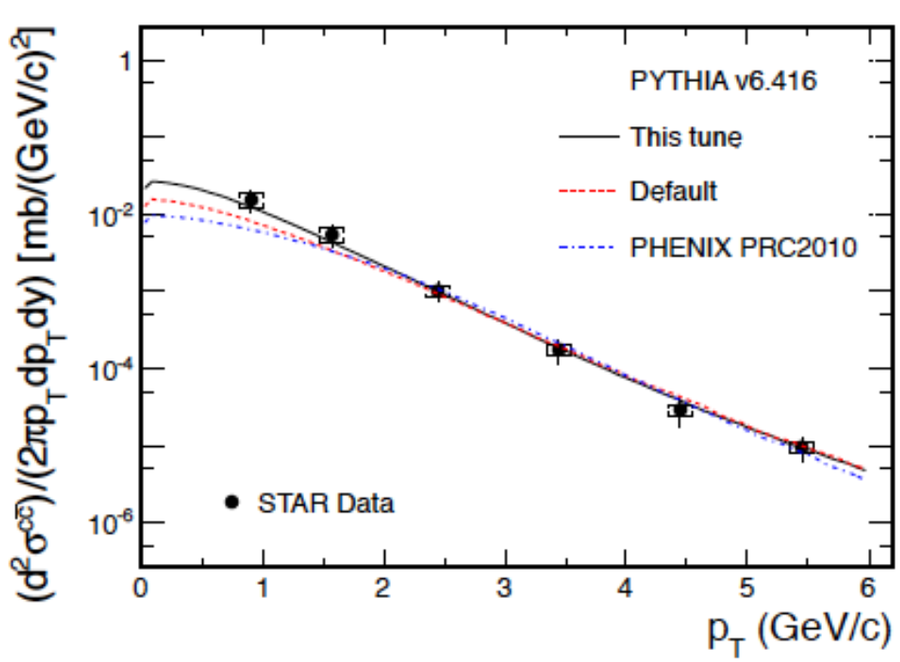
$D^0\,(c\bar{u}) \rightarrow K^+\pi^-\,(BR \sim 3.89\%)$, p_T range [0.6,2] GeV/c.

$D^{*+}(c\bar{d}) \rightarrow D^0(K^+\pi^-)\pi^+(BR \sim 2.63\%)$, p_T range [2,6] GeV/c.

☑ Total $c\bar{c}$ cross section in pp collisions at $\sqrt{s}$ = 200 GeV evaluated.

Data points divided by the charm quark fragmentation ratios to convert the measured cross section in $c\bar{c}$ production cross-section



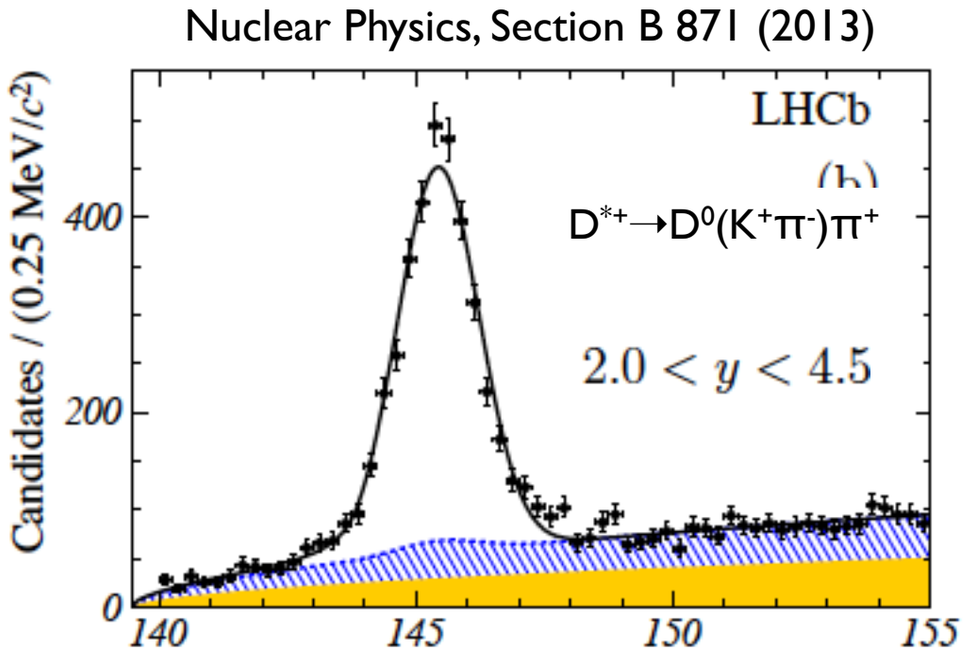


FONLL: M. Cacciari, P. Nason and R. Vogt, Phys. Rev. Lett. 95, 122001 (2005)

Charm via D mesons hadronic decays at LHC

☑ Fairly similar reconstruction strategy between the different experiments at LHC:

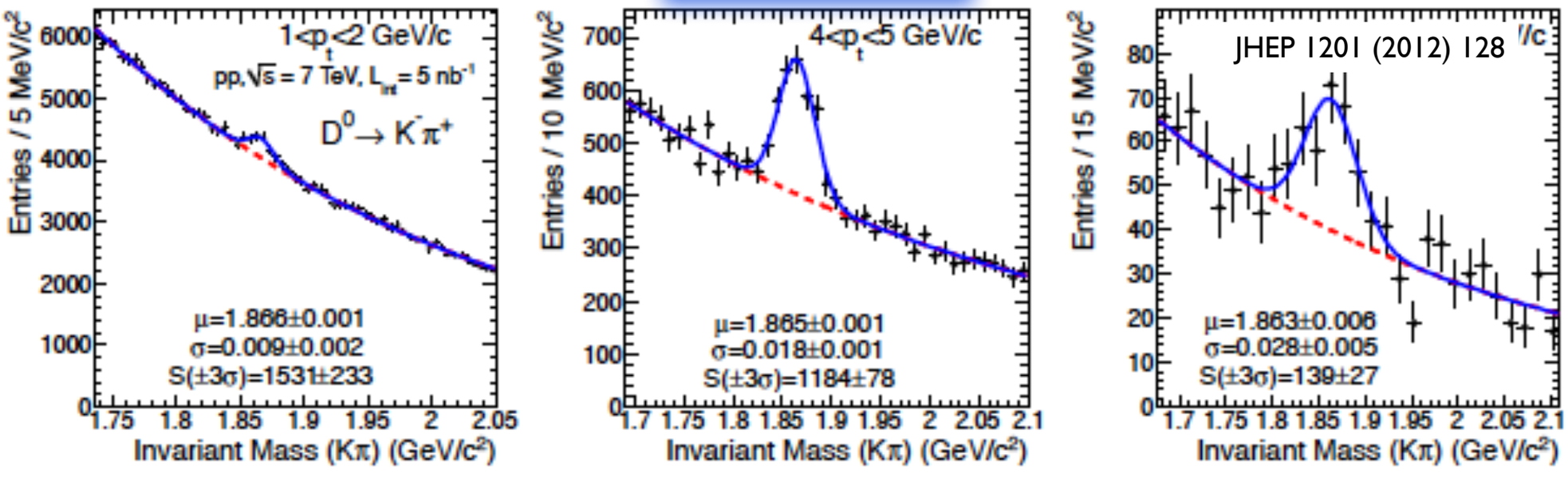
It consists in the resolution of the secondary (decay) vertex. Once the topology is reconstructed topological selections are applied in order to reduce the combinatorial background. D mesons cτ~ 123-312 μm



☑ Selection cuts complemented by the Particle Identification (PID) in ALICE.

☑ Wide range of rapidity covered: |y|<0.5 (ALICE) (|y|<2) and 2.0<y<4.5 (LHCb)

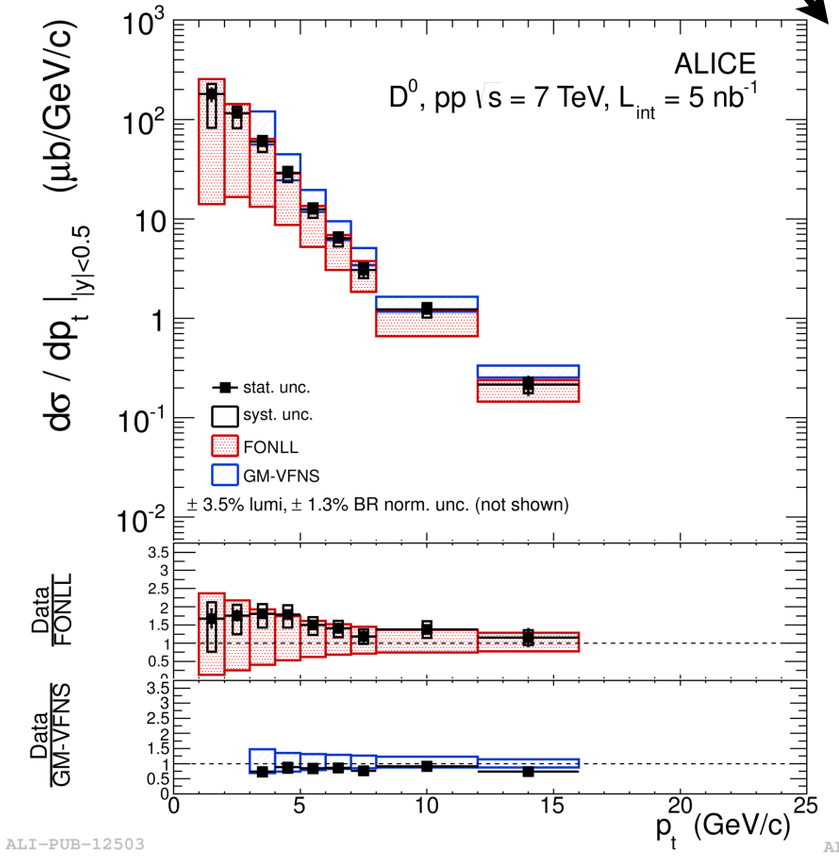
ALICE: $D^0\to K^+\pi^-$

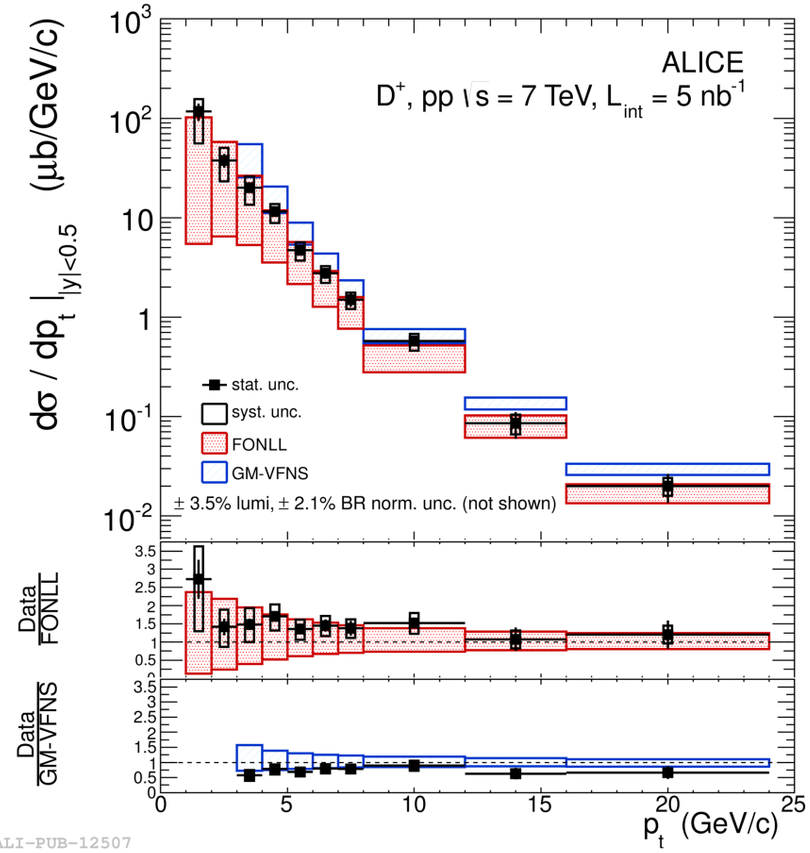


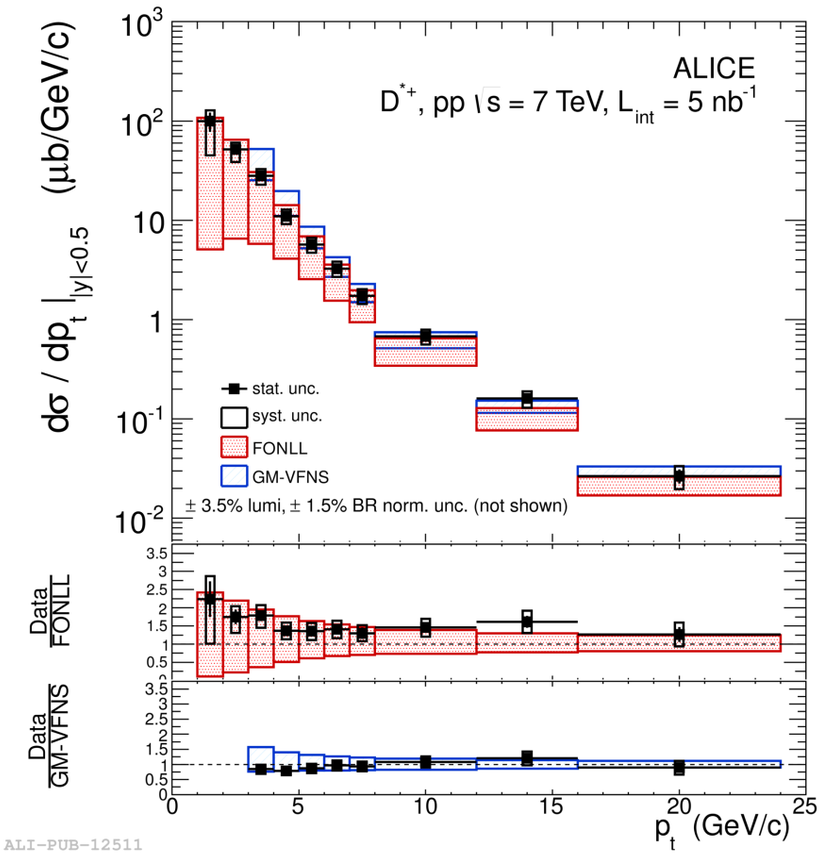
Prompt D meson cross-section at mid-rapidity

D^0, D^+ and D^{*+} cross section at $\sqrt{s} = 7$ TeV, $|y|<0.5$

ALICE







JHEP 1201 (2012) 128

☑ Large p_T coverage [1,24] GeV/c and well described by pQCD predictions.

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

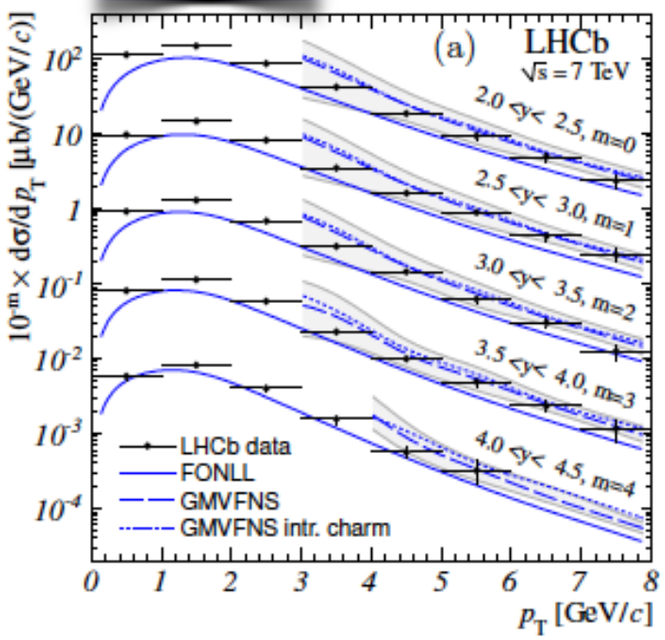
Prompt D meson cross-section at forward rapidity

- ☑ LHCb analyzed D^0, D^+, D^{*+} and D^+_s hadronic decays in a data sample of **$15nb^{-1}$**
- ☑ Differential cross-section $d\sigma/dp_T$ analyzed in bins of pt and rapidity in the rapidity range **2.0<y<4.5**
- ☑ Charm cross-section evaluated in **2.0<y<4.5** and extrapolated to the full phase-space

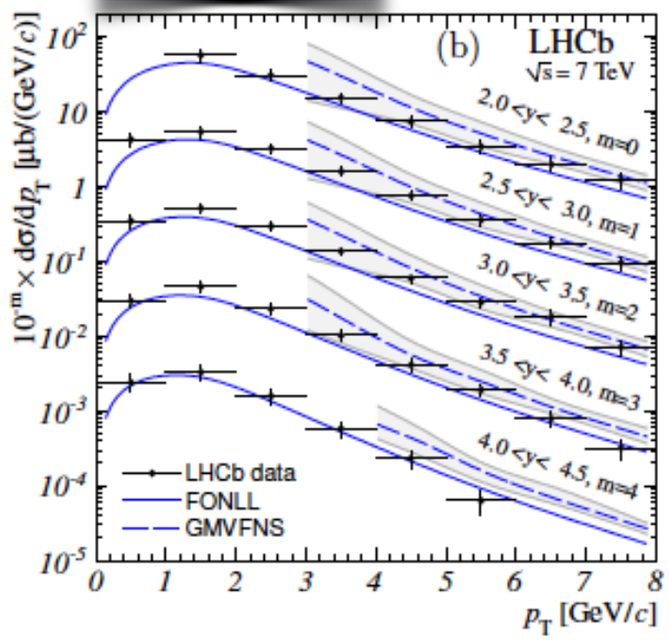
Nuclear Physics, Section B 871 (2013)

LHCb

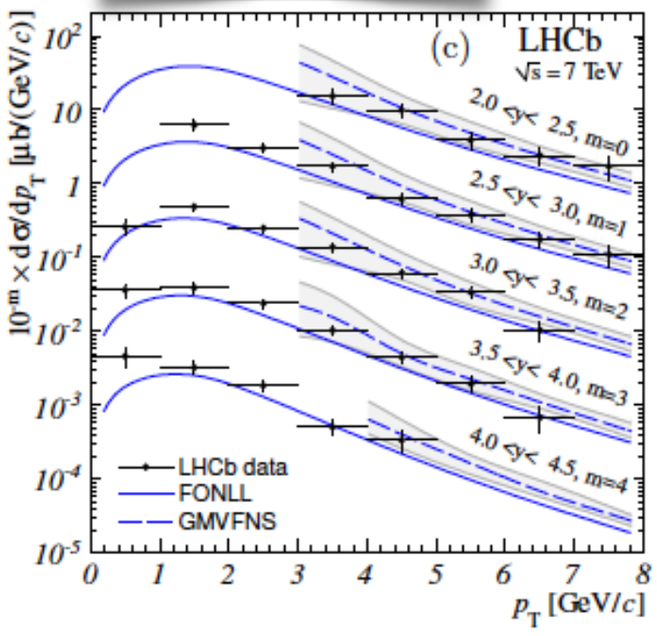
$D^0 \to K^+\pi^-$



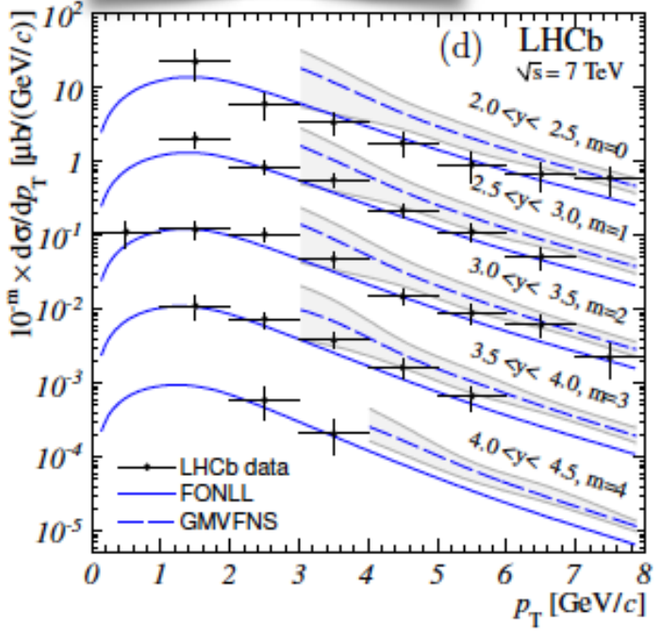
$D^+ \to K^-\pi^+\pi^+$



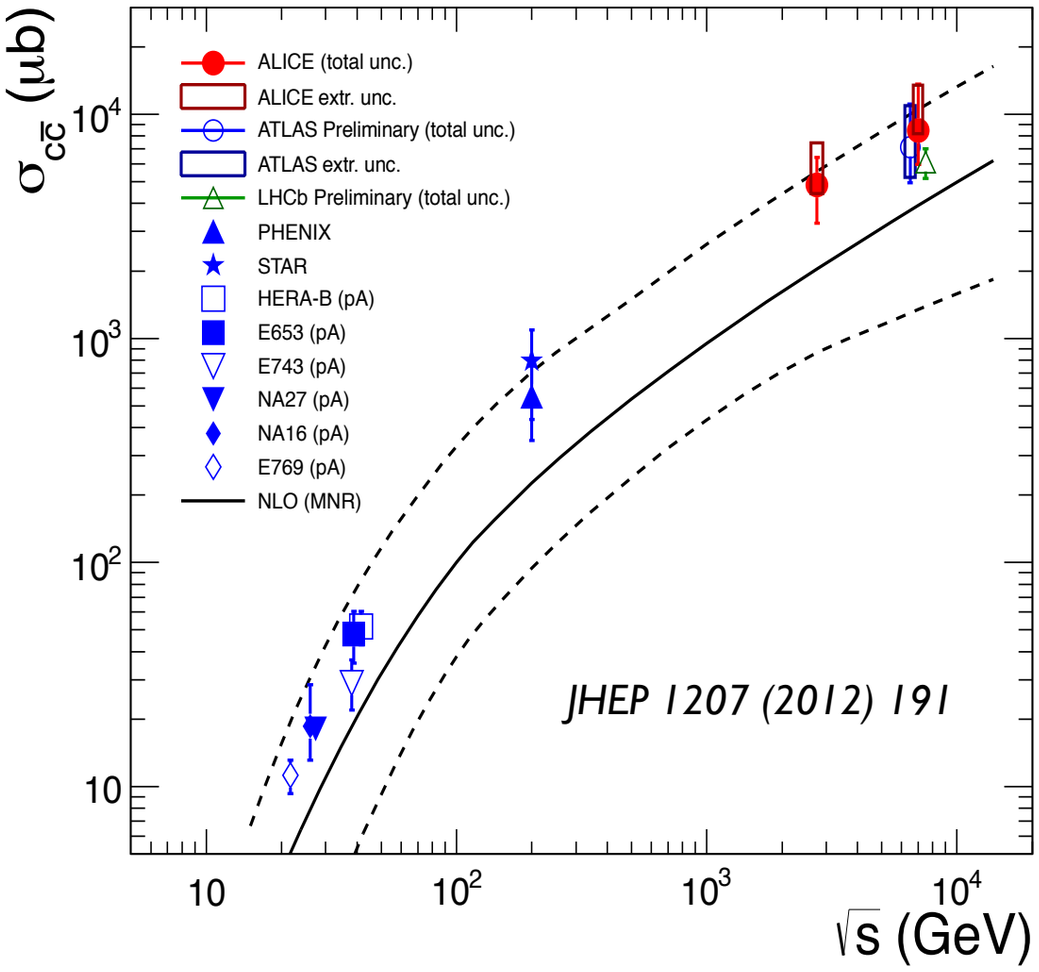
$D^{*+} \to D^0(K^+\pi^-)\pi^+$



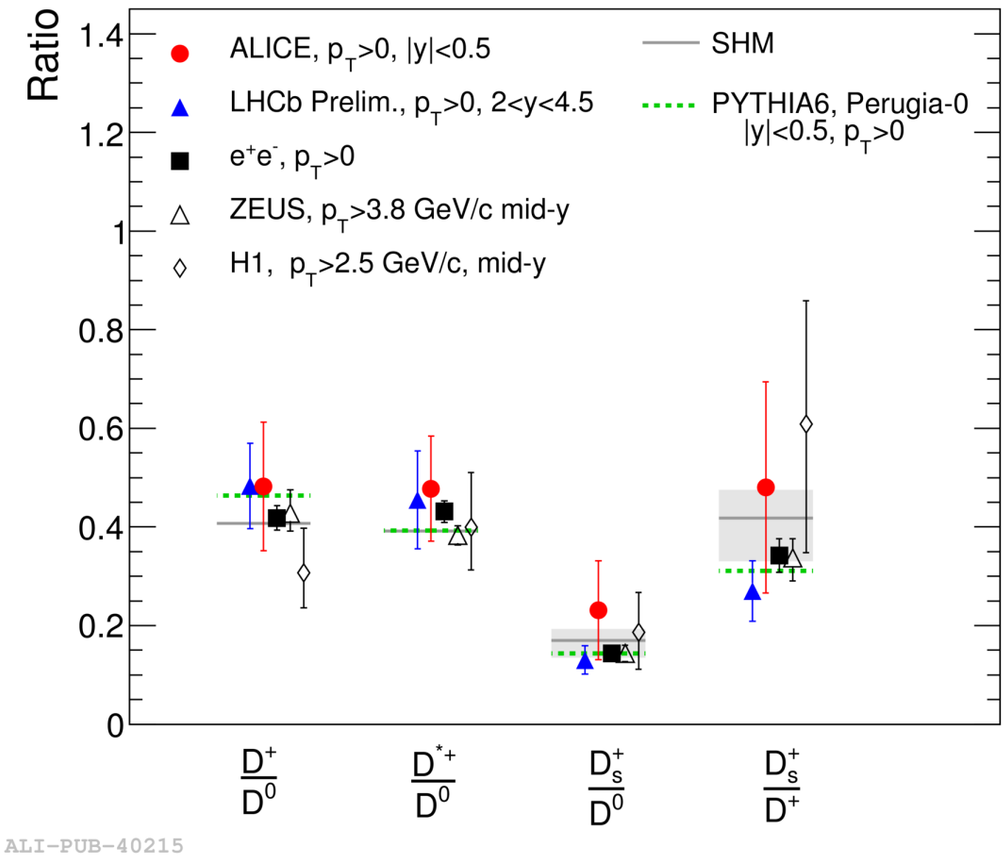
$D^+_s \to \Phi(K^-K^+)\pi^+$



Total charm cross section and D meson ratios



- ☑ Energy dependence of the nucleon-nucleon charm production cross section. In case of proton-nucleus collisions the measured cross-section is scaled down by the number of binary collisions.
- ☑ Comparison with models shows similar trend. In agreement within errors.

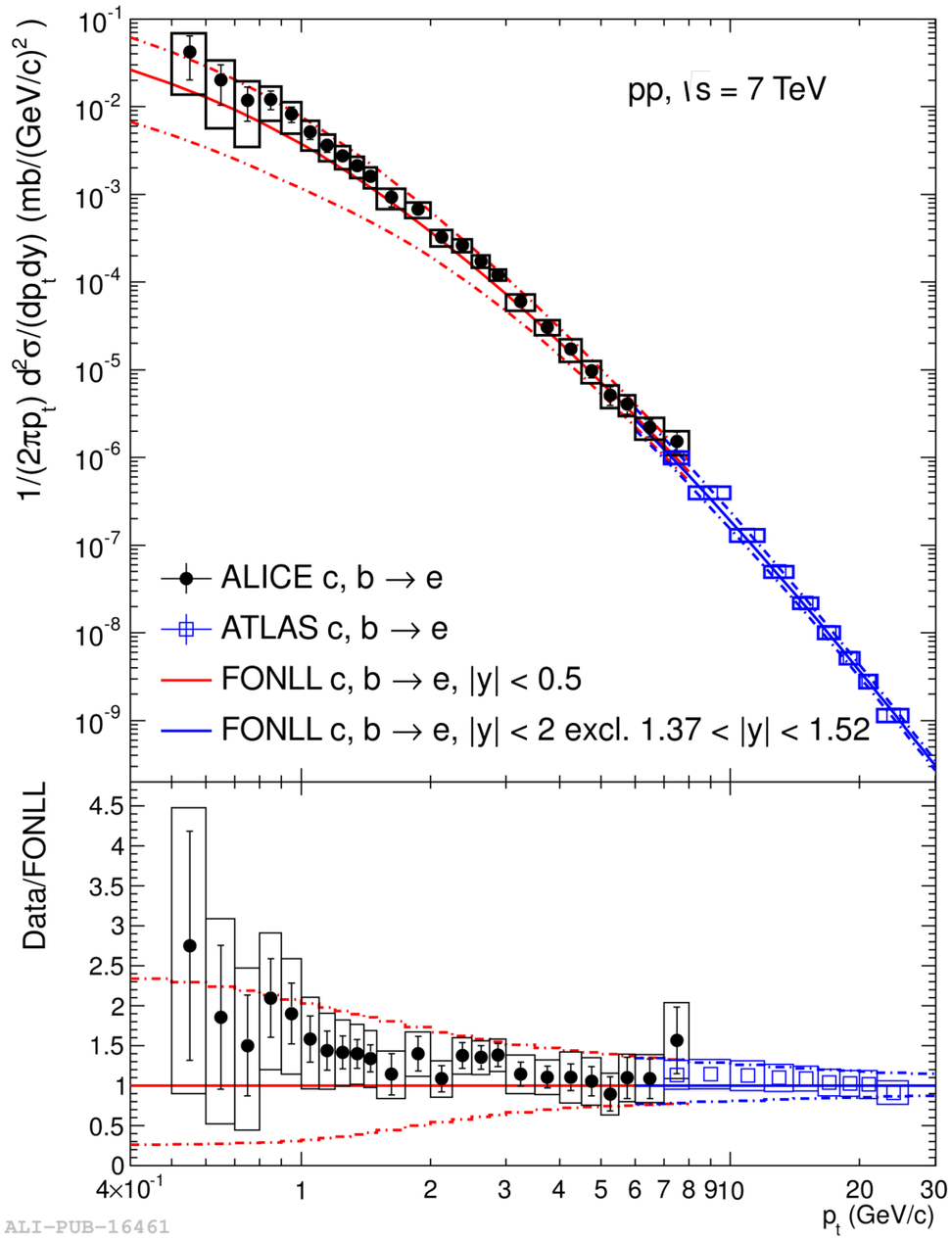


- ☑ D meson ratios in agreement with models

Charm production in proton-proton collisions

- [ ] D meson in hadronic decay channels
- [x] Heavy flavour decay electrons
- [x] Single muons from heavy flavour decays
- [ ] Intrinsic charm?

Heavy-flavour decay electrons in pp at $\sqrt{s}$ = 7 TeV



ATLAS and ALICE

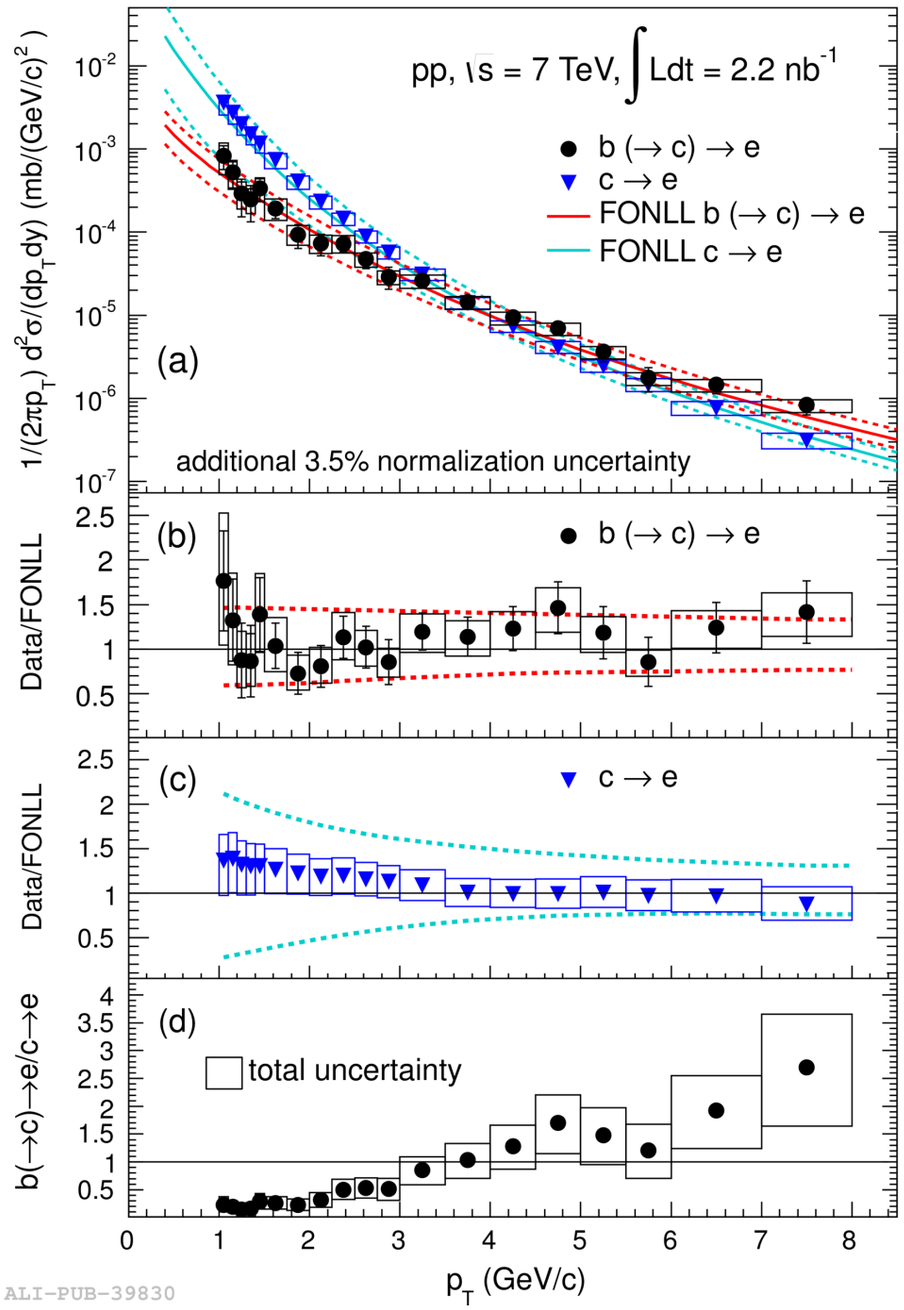
- ALICE (black) and ATLAS (blue) measurements performed in different rapidity regions.
- Excellent electron identification required.
- Electron background from non semileptonic heavy-flavour hadron decays evaluated and subtracted from the inclusive spectra.
- Good agreement between the different measurements.

ALICE: Phys.Rev. D86 (2012) 112007

ATLAS: Phys. Lett., B707:438–458, 2012

Heavy-flavour decay electrons: charm and beauty

ALICE



Phys.Lett. B721 (2013) 13-23

- ALICE data recorded during the 2010 pp run. Beauty and Charm contributions separated in range $1<p_T<8$ GeV/*c* at mid-rapidity $|y|<0.8$

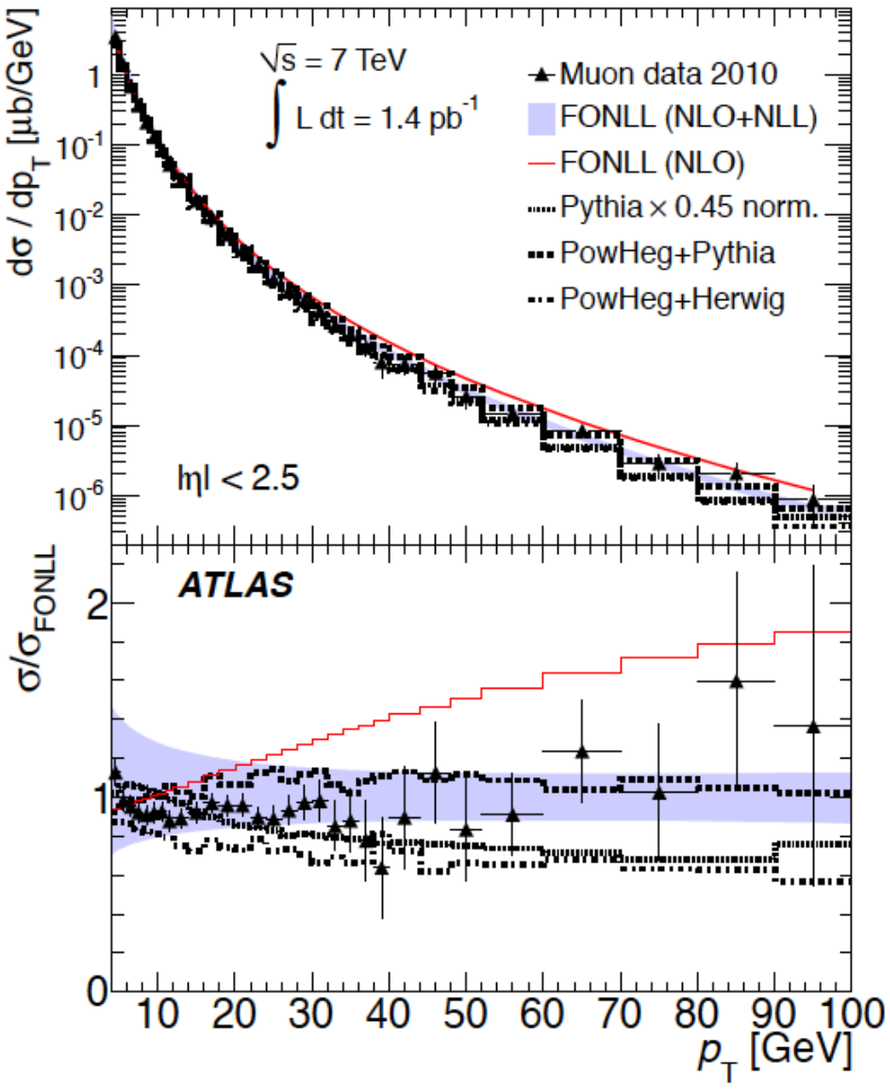
- Exploit the large displacement of B-decay electrons. Cut on impact parameter and or secondary vertex reconstruction.

  B mesons cτ~ 500 μm

- Total charm cross section in pp at $\sqrt{s} = 7$ TeV calculated. Good agreement with the D meson result.

Muon from heavy flavour production |η|<2.5

ATLAS



ATLAS: Phys. Lett., B707:438–458, 2012

- ATLAS published muon results in the transverse momentum range $4<p_T<100$ GeV/c at $|\eta|<2.5$
- In order to obtain the heavy-flavour muon cross section, background from W/Z/γ* as well as muons from π and K decay in flight are subtracted .
- above 25 GeV/c deviation from NLO central prediction → sensitivity to NLL hith-p_T resummation terms

Charm production in proton-proton collisions

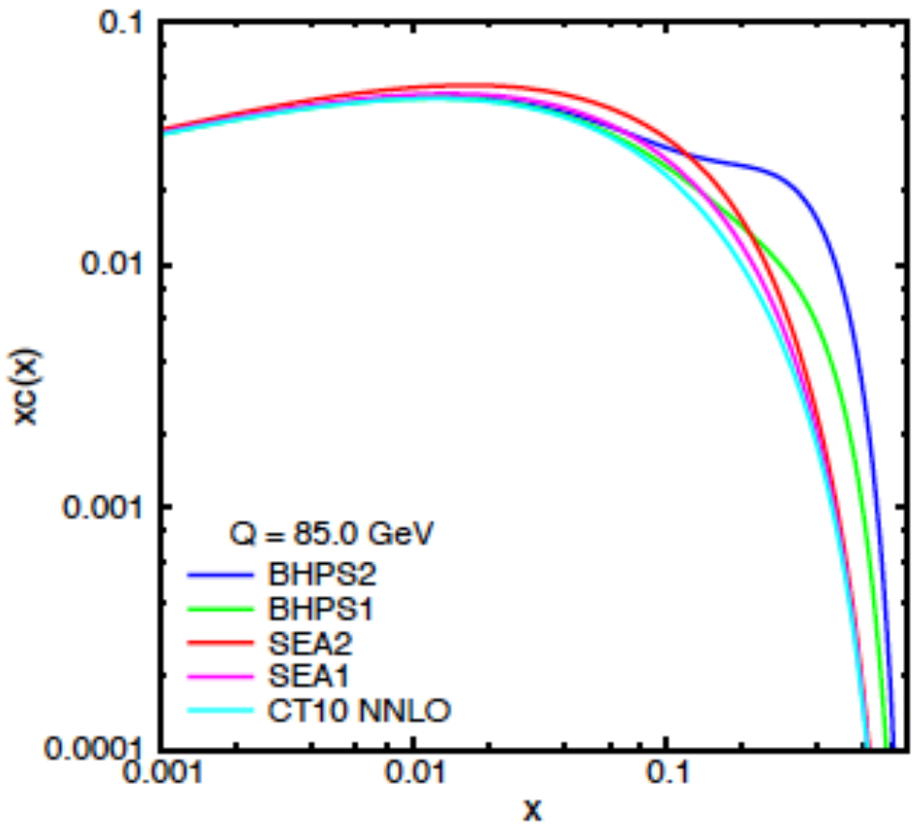
- [ ] D meson in hadronic decay channels
- [ ] Heavy flavour decay electrons
- [ ] Single muons from heavy flavour decays
- [x] Intrinsic charm?

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.

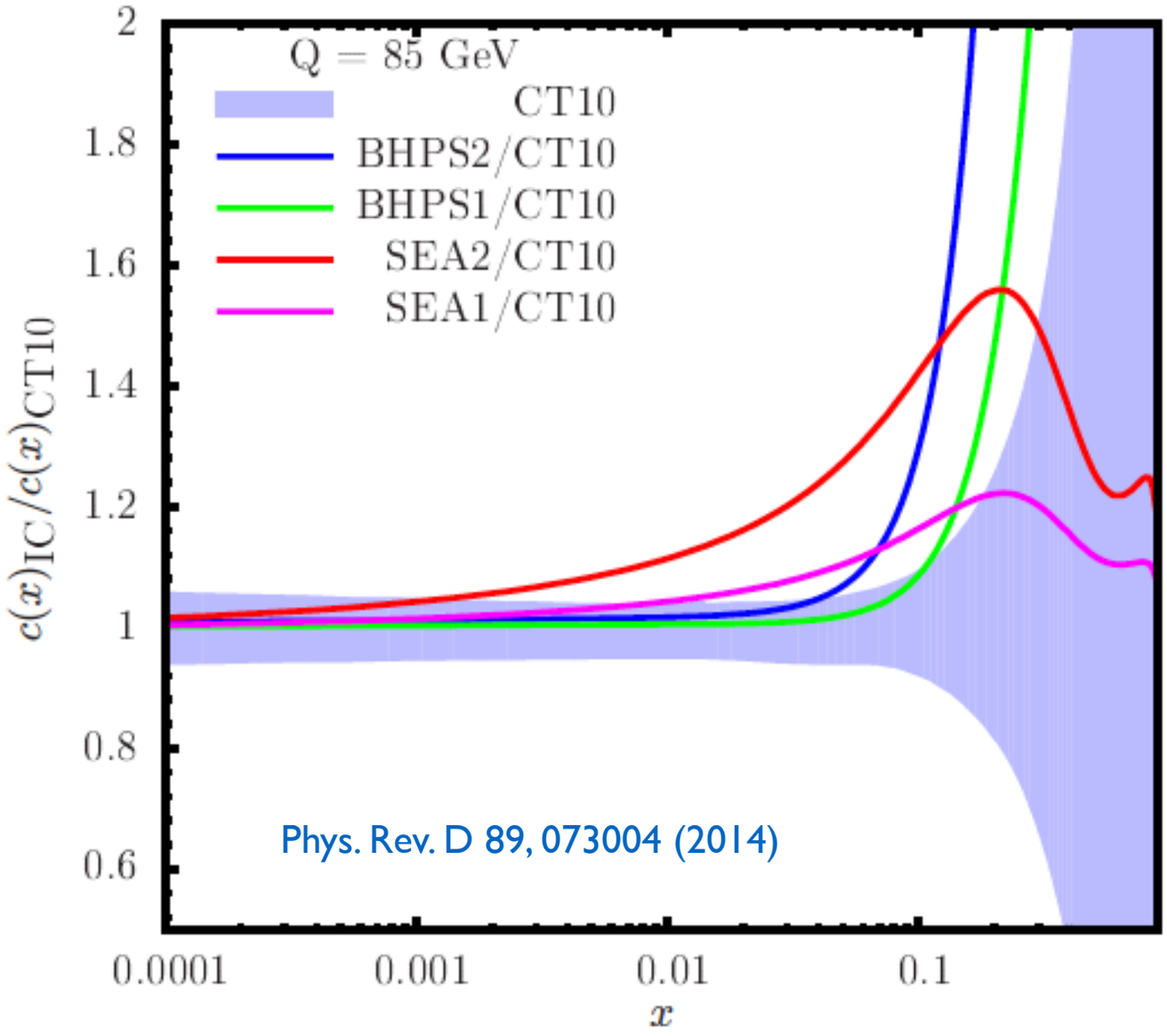
Phys. C 20, 71 (1983)
Nucl. Phys. B461,181 (1996)
arXiv:1305.3548
Phys. Rev. D 73, 114015 (2006)



Phys. Rev. D 89, 073004 (2014)

☑ 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.

Modification of the charm distribution

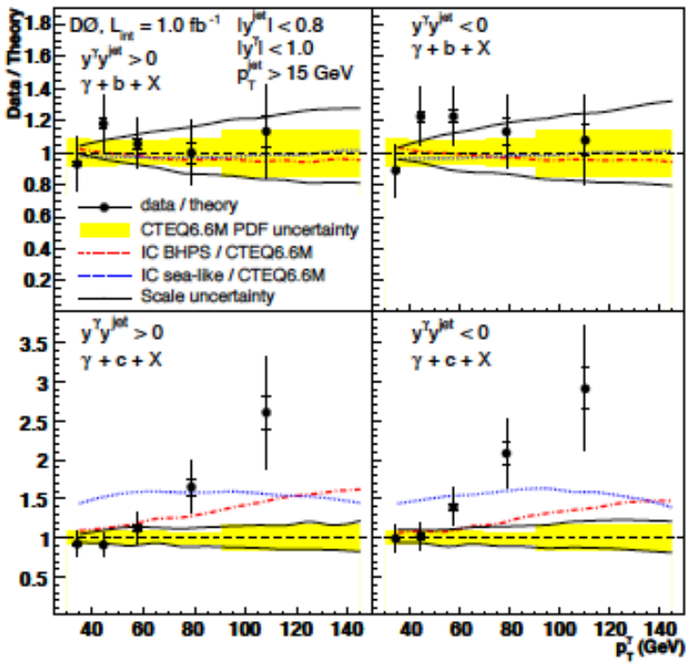


☑ Recent studies, based on the most up-to-date informations on PDFs and on the HERA (Zeus + H1 data) results point to and intrinsic charm contribution small if any (<2% for BHPS model)

Available experimental data at TeV energies

D0 coll. @ TEVATRON

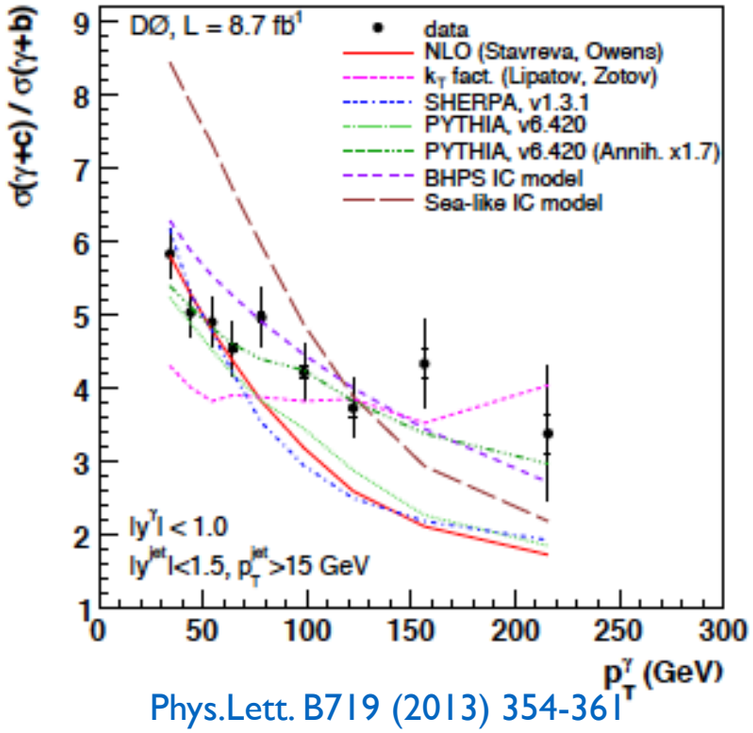
☑ At TeV energy scale the D0 collaboration measured the differential cross section of γ+c(b) jets and their ratio (g,c and b PDF for 0.01<x<0.3).



Phys.Lett. B714 (2012) 32-39

☑ Data point were compared with NLO calculations and models based on IC calculations.

☑ Results, for p_T> 80 GeV/c, point toward the possibility of an underestimated g→cc component (gluon splitting) or to an intrinsic charm contribution.



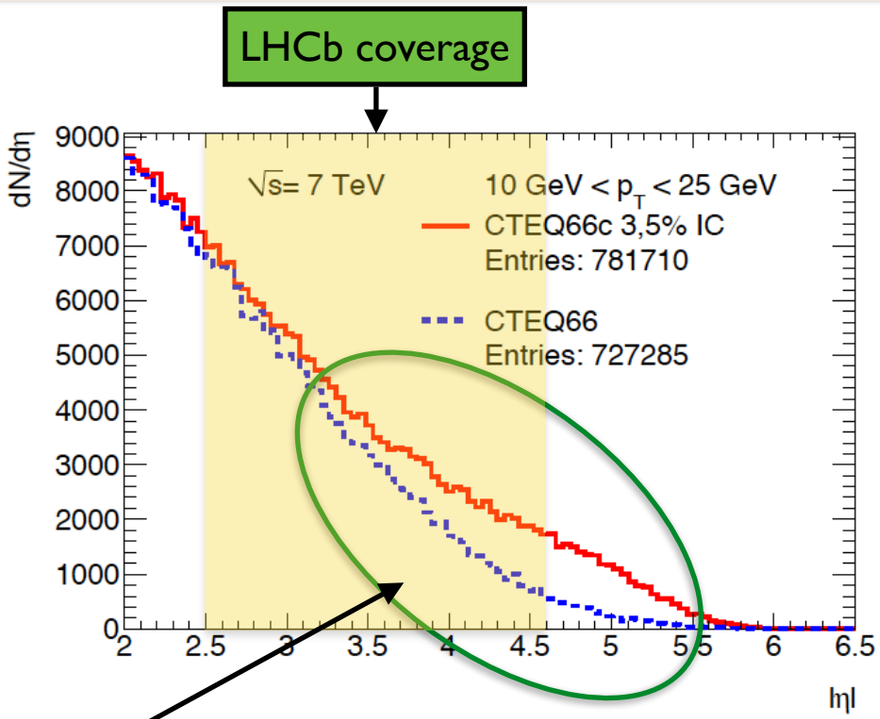
Phys.Lett. B719 (2013) 354-361

☑ No clear evidence of intrinsic charm in data.

Intrinsic charm at LHC energies

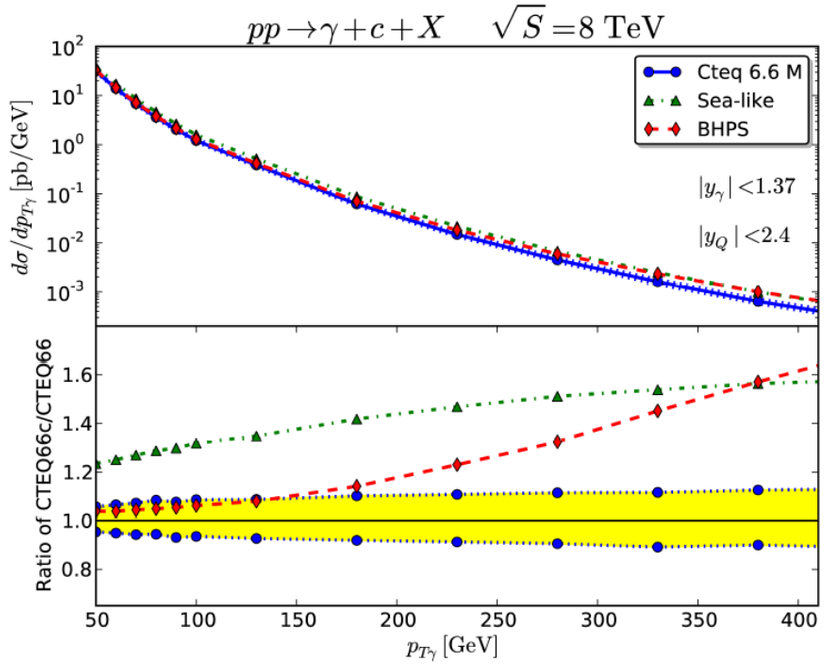
- ☑ Studies, based on Pythia8, show that if an intrinsic charm exists we can see it as a large signature in the D mesons production at forward rapidities (LHCb range)

- ☑ 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



Eur.Phys.Lett. 99 (2012) 21002

- ☑ 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.



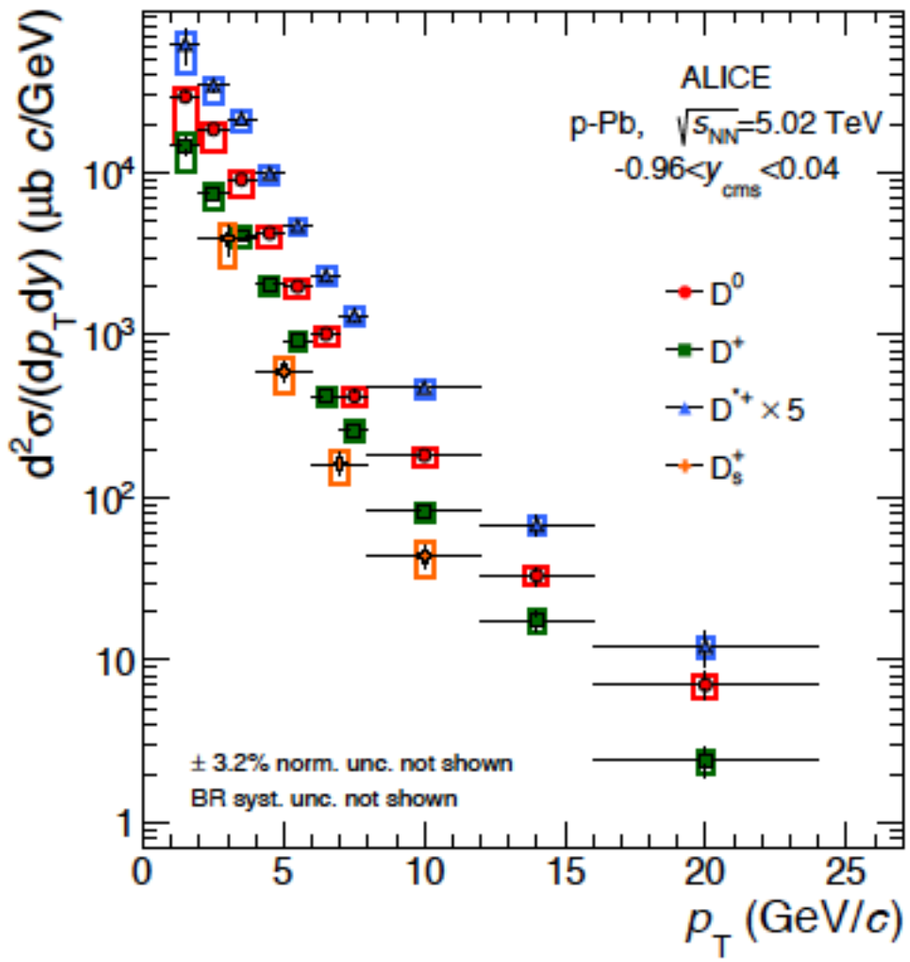
Phys. Rev. D 89, 073004 (2014)

arXiv:1305.3548

Charm production in proton-nucleus collisions

D mesons in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE

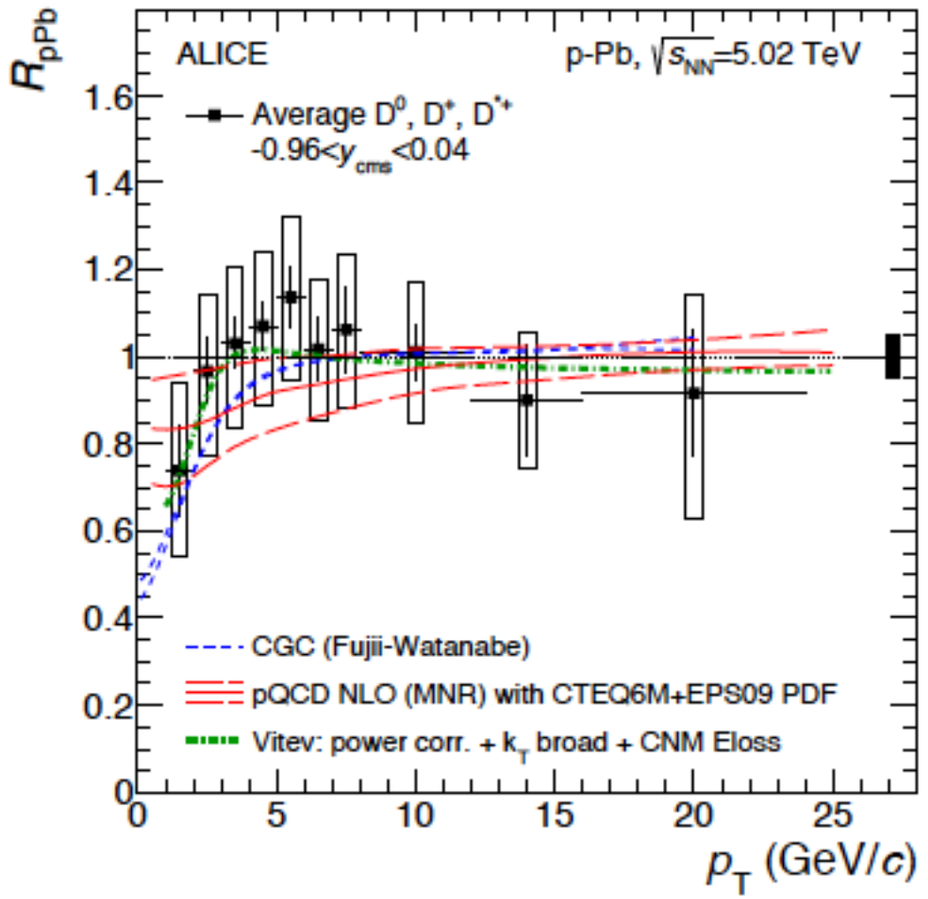


- Production cross-sections of prompt D^0, D^{*+}, D^+ and D^+_s measured in the rapidity intervall $-0.96<y_{cms}<0.04$

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

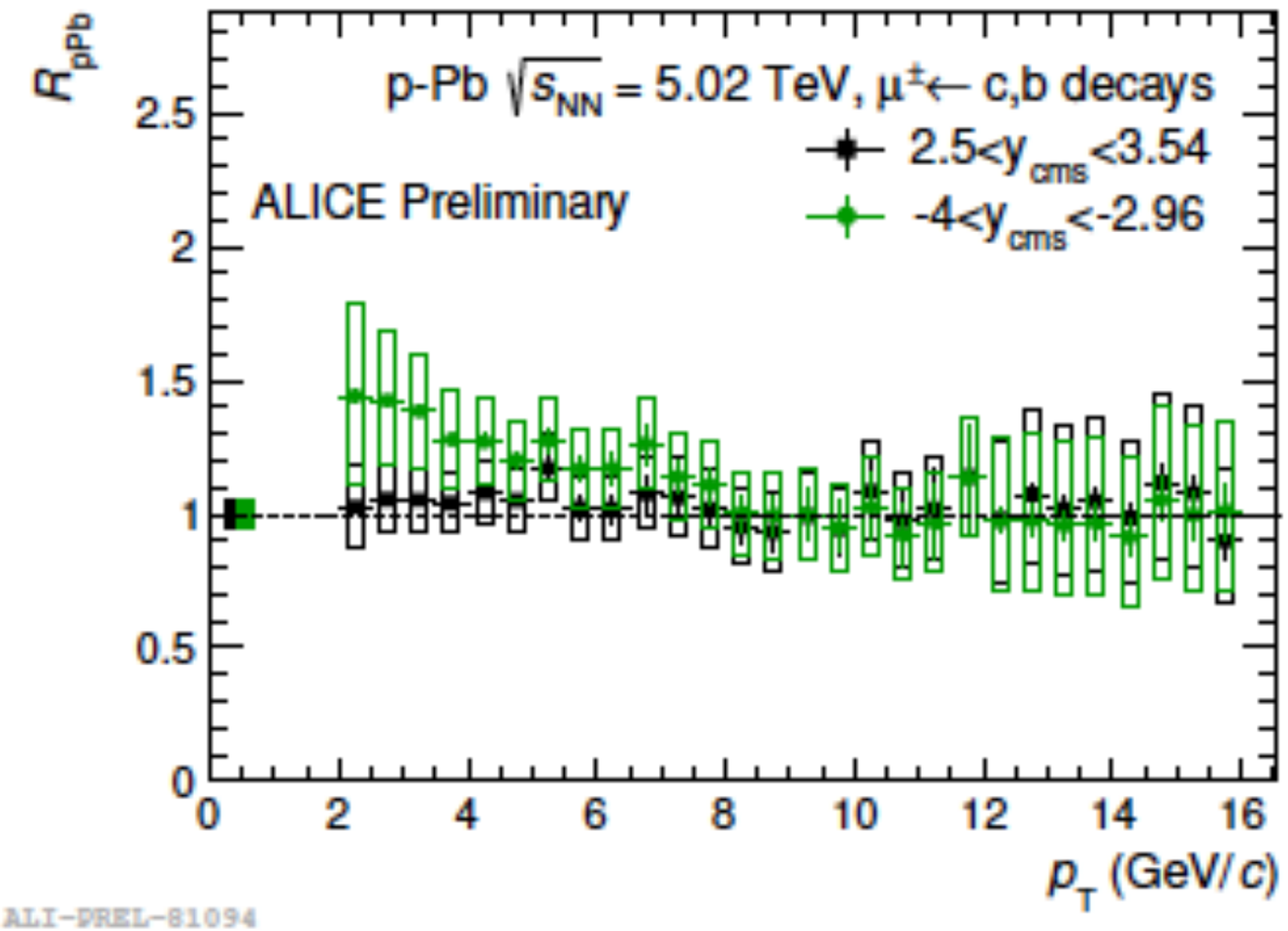
- Initial state effects play a small role for $p_T > 2$ GeV/c

arXiv:1405.3452



Muons from HF decays in p-Pb collisions

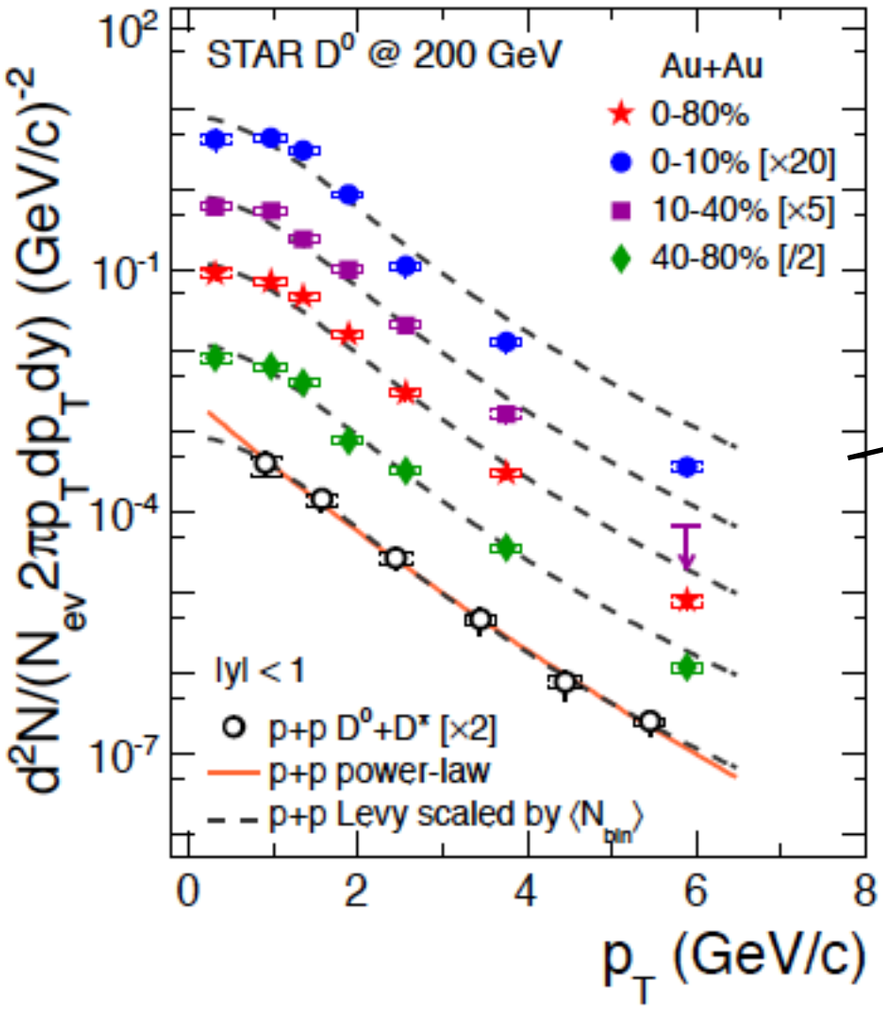
ALICE

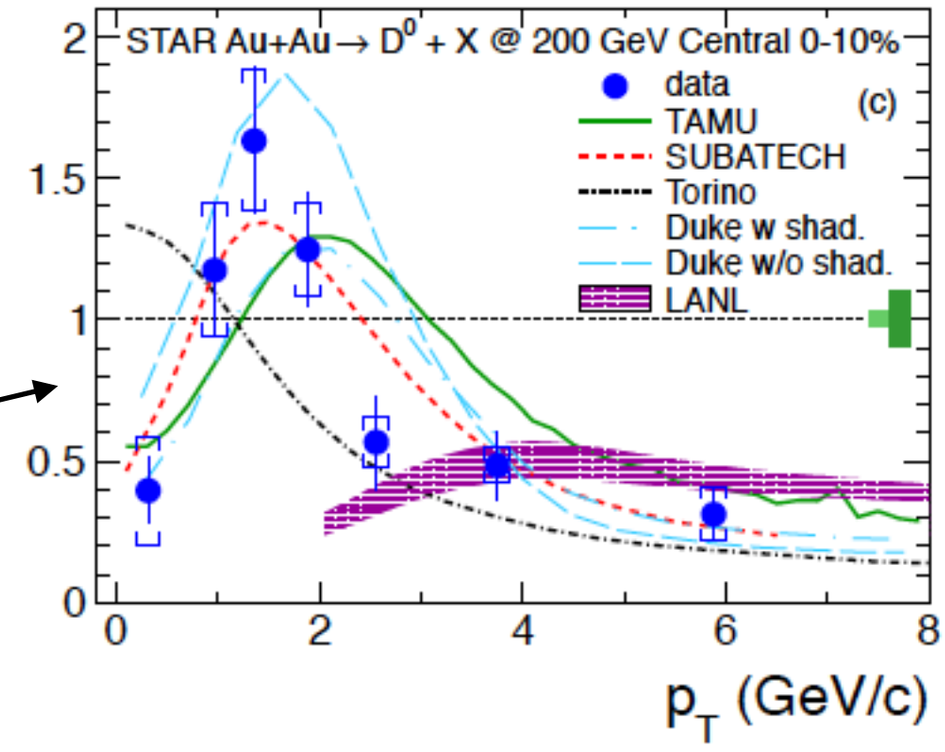


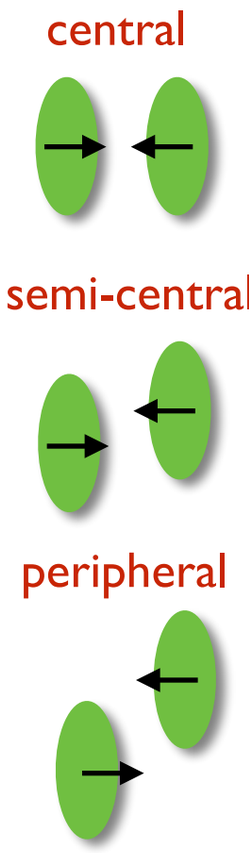
Charm production in nucleus-nucleus collisions

D mesons production in Au-Au @ RHIC with STAR

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







☑ Total charm production cross section at mid-rapidity per nucleon nucleon collisions from pp to Au-Au show a binary collision scaling.

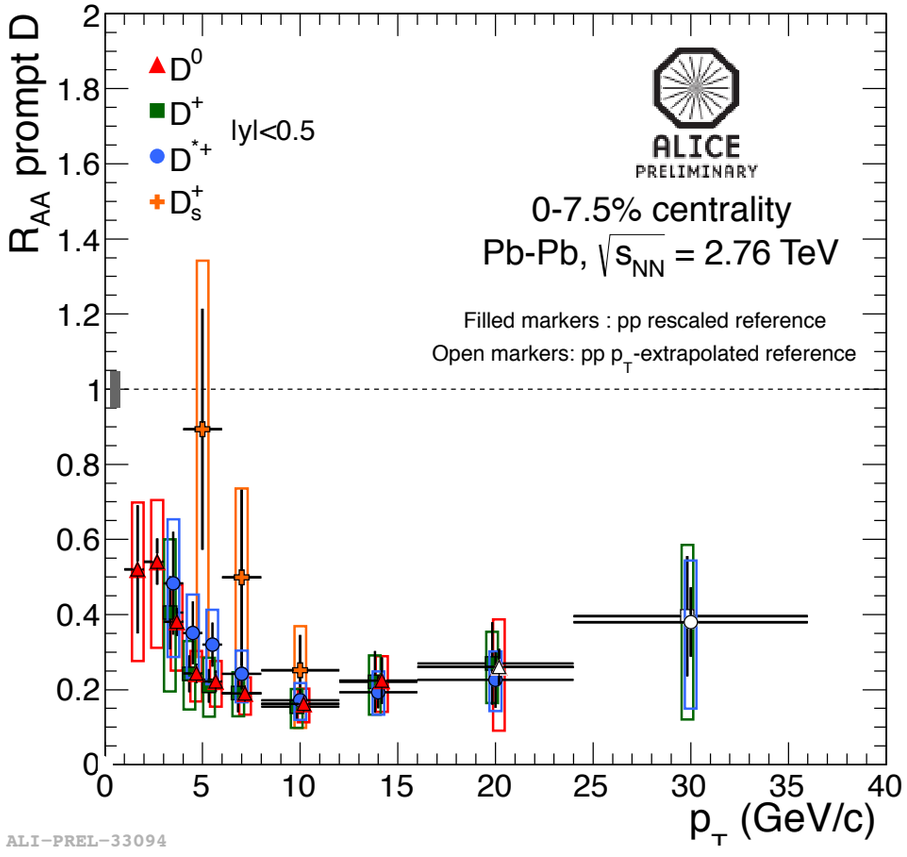
☑ Total charm production cross section at mid-rapidity per nucleon nucleon collisions from pp to Au-Au show a binary collision scaling.

STAR *arXiv:1404.6185*

D meson R_{AA} @ LHC with ALICE

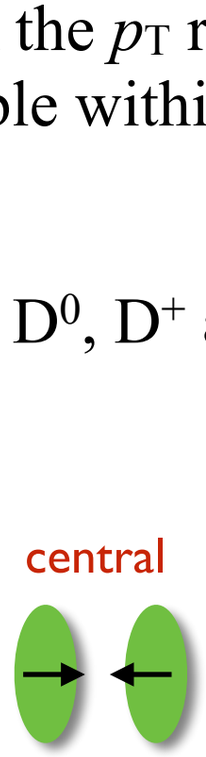
- D^0, D^+ and D^{*+} R_{AA} measured in the p_T range [1,36] GeV/c with 2011 data. Compatible within uncertainties.

- Suppression up to a factor 5 for D^0, D^+ and D^{*+} at p_T~10 GeV/c.

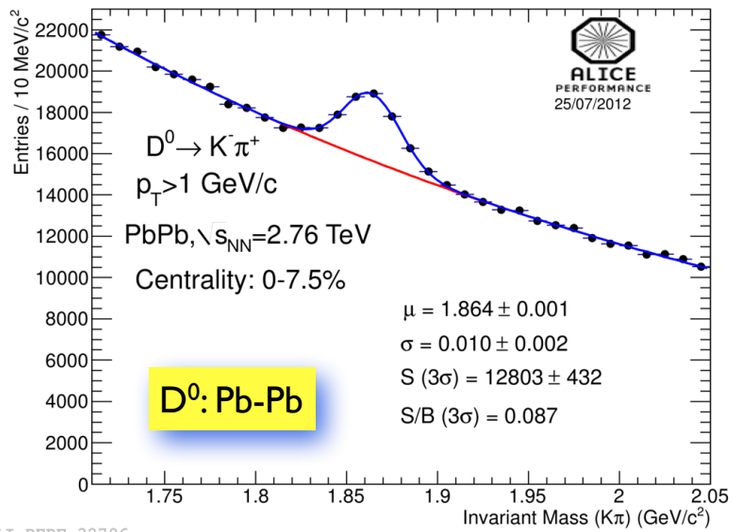


Nucl. Phys. A904-905 (2013)

central



Nucl.Phys. A904-905 (2013)



- First measurement of D^+_s R_{AA}, data not conclusive on comparison with other mesons.

- The large suppression in Pb-Pb, together with the small suppression in p-Pb suggest that the attenuation we see in the R_{AA} is a final state effect.

Conclusions

- ☑ Charm production has been intensively studied at hadron colliders in pp, p-A and A-A collison systems.

- ☑ The comparison with models, like FONLL, show a good agreement within the uncertanties. Slitely in the higher side of the error band. Pythia event generator, properly tuned gives reasonable results

- ☑ The results obtained by different experiments and, within the same experiment with different methods, are consistent.

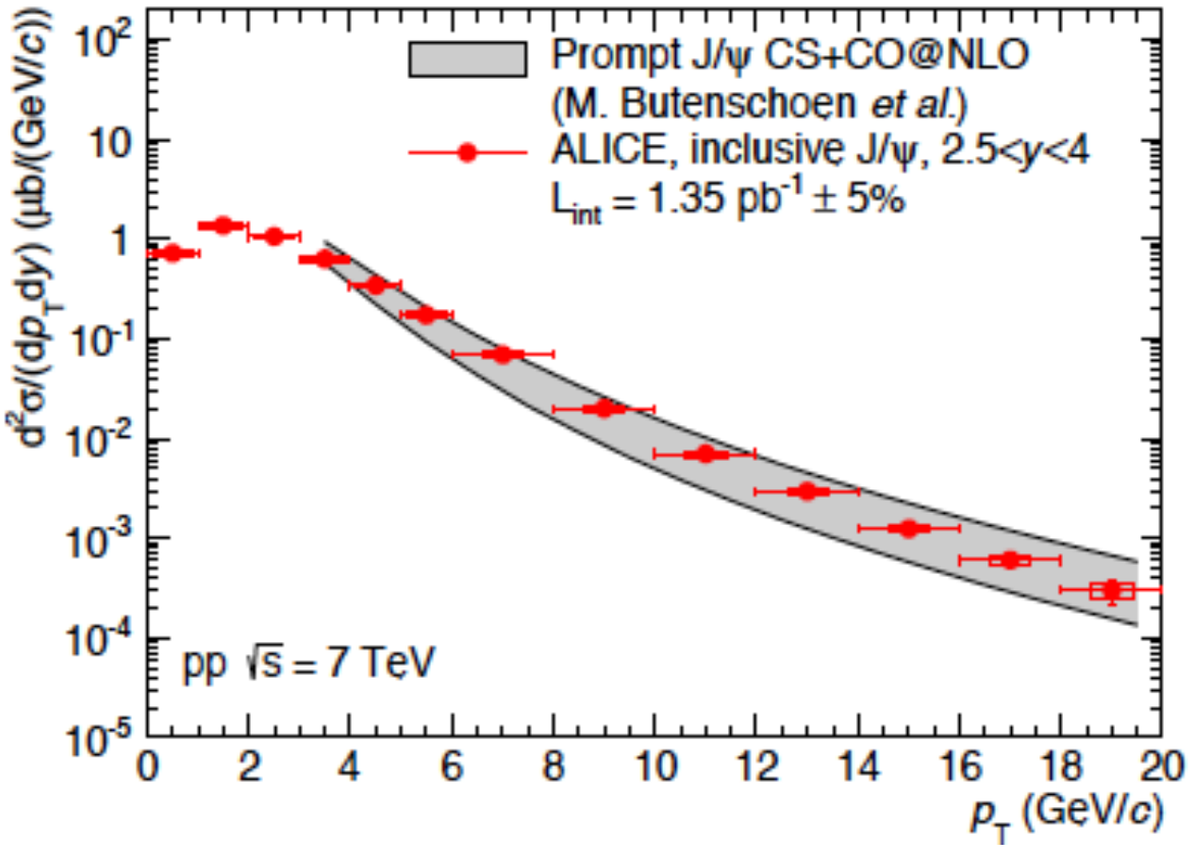
- ☑ Models based on intrinsic charm propose the possibility of a non-perturnative approach to charm production at large x_f with a probability of 2-3% . It would have a large effect at high pt and large x. Experimental results do not esclude such component but no final statement can be made at the moment. LHC run 2 will pose strich constraints on such hypothesis.

Backup

a.grelli@uu.nl

Inclusive J/ψ production: $J/\psi \rightarrow \mu^+\mu^-$

CERN-PH-EP-2014-042, arXiv:1403.3648



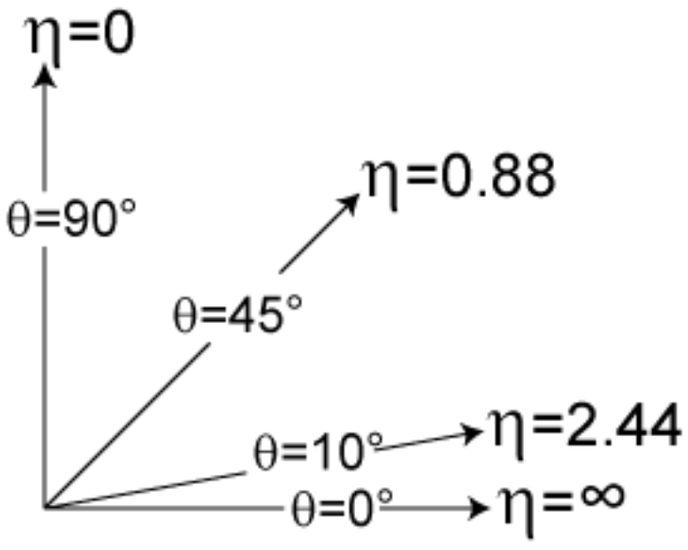
- ☑ The J/ψ p_T differential cross-section is compared with a NRQCD calculation at NLO
- ☑ The model calculation is in reasonable agreement with data in the pt region [4,20] GeV/c

Definitions

$$y = \frac{1}{2} \ln \frac{E + p_z c}{E - p_z c}$$

This is the rapidity of the boost along the beam axis which takes an observer from the lab frame to a frame in which the particle moves only perpendicular to the beam. Related to this is the concept of pseudorapidity

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right], \qquad \eta = \frac{1}{2}\ln\left(\frac{|\mathbf{p}| + p_{\mathrm{L}}}{|\mathbf{p}| - p_{\mathrm{L}}}\right),$$



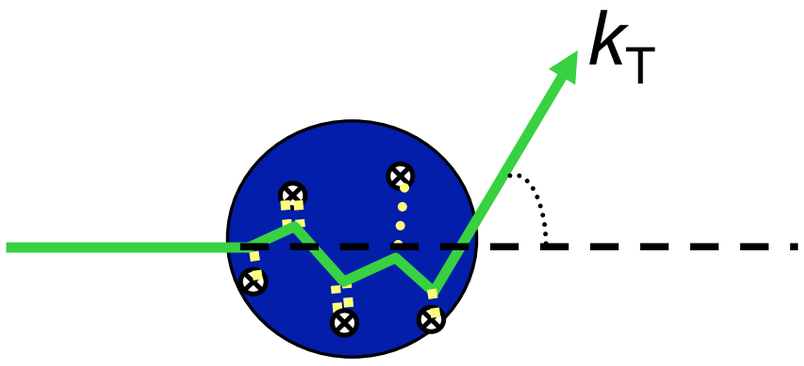
travelling close to the speed of light or for 0 mass approximation rapidity and pseudorapidity are close

Initial state effects - Cronin

- In pA collisions, in the p_T region 2-4 GeV/c the R_{pA} has values > 1.

- It derives from the fact that the pA collsions the dN/dp_T is moved to higher pt values. It derives from the fact that partons in the projectile undergo elastic collisions with the nuclens of the targhet before the hard scattering.

- In this way the parton of the proiettile acquire e transverse momentum k_T that is proportional to the square root of the number of elastici collisions.



Prompt D meson cross-section - ALICE

$$\left.\frac{\mathrm{d}\sigma^{\mathrm{D}^+}}{\mathrm{d}p_{\mathrm{t}}}\right|_{|y|<0.5} = \frac{1}{2}\frac{1}{\Delta y \Delta p_{\mathrm{t}}}\frac{\left. f_{\mathrm{prompt}}(p_{\mathrm{t}}) \cdot N^{\mathrm{D}^\pm\ \mathrm{raw}}(p_{\mathrm{t}})\right|_{|y|<y_{\mathrm{fid}}}}{(\mathrm{Acc}\times\varepsilon)_{\mathrm{prompt}}(p_{\mathrm{t}}) \cdot \mathrm{BR} \cdot L_{\mathrm{int}}}.$$

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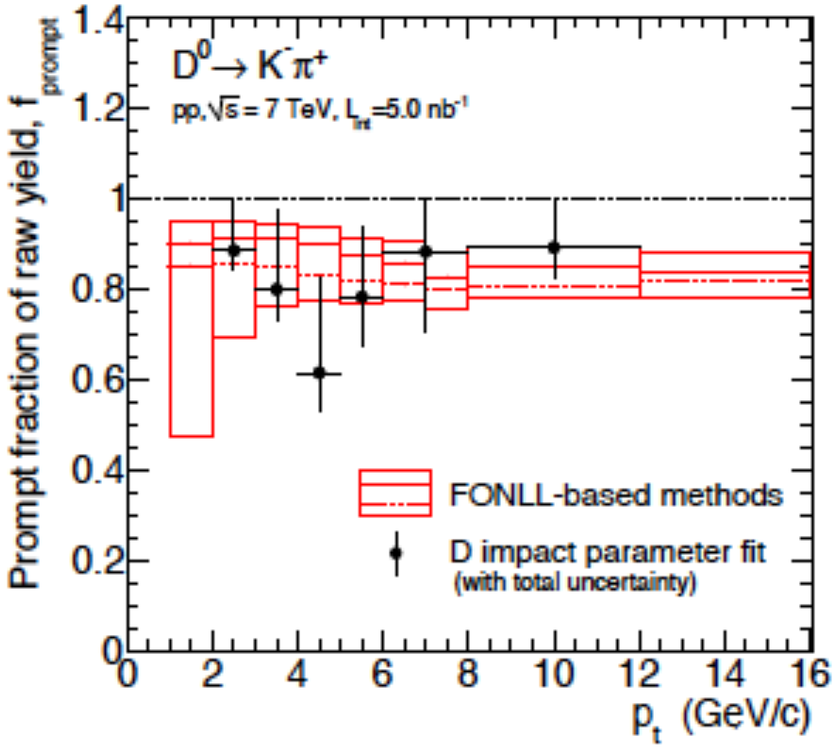
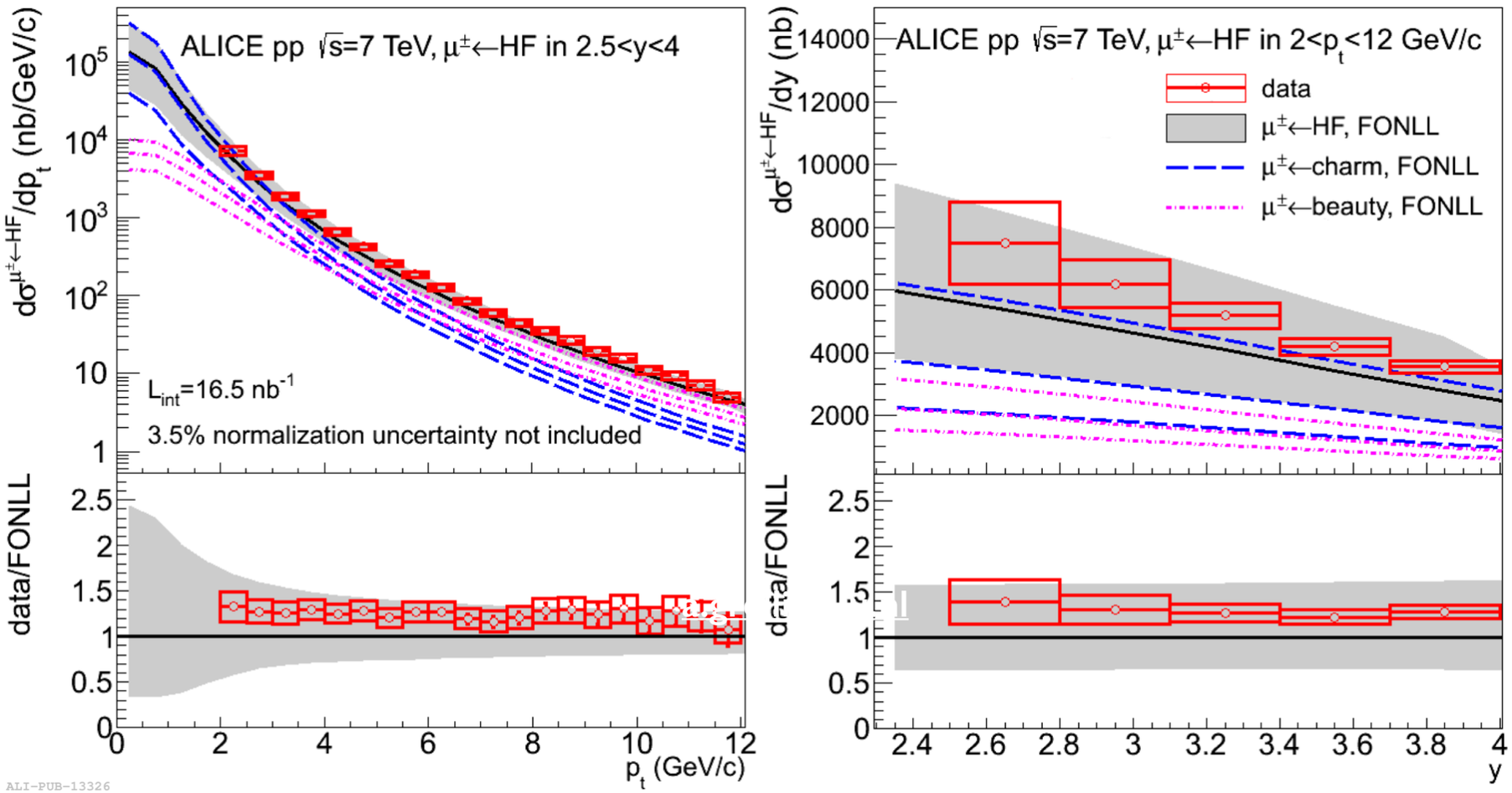


a.grelli@uu.nl

Muons from heavy-flavour decays at forward rapidity

ALICE



Phys.Lett. B708 (2012) 265-275

- ☑ ALICE measured the cross section of single muons from heavy-flavour decays at forward rapidities.
- ☑ Good agreement with FONLL in the whole transverse momentum and rapidity range

a.grelli@uu.nl

Measurement of D meson production in jets

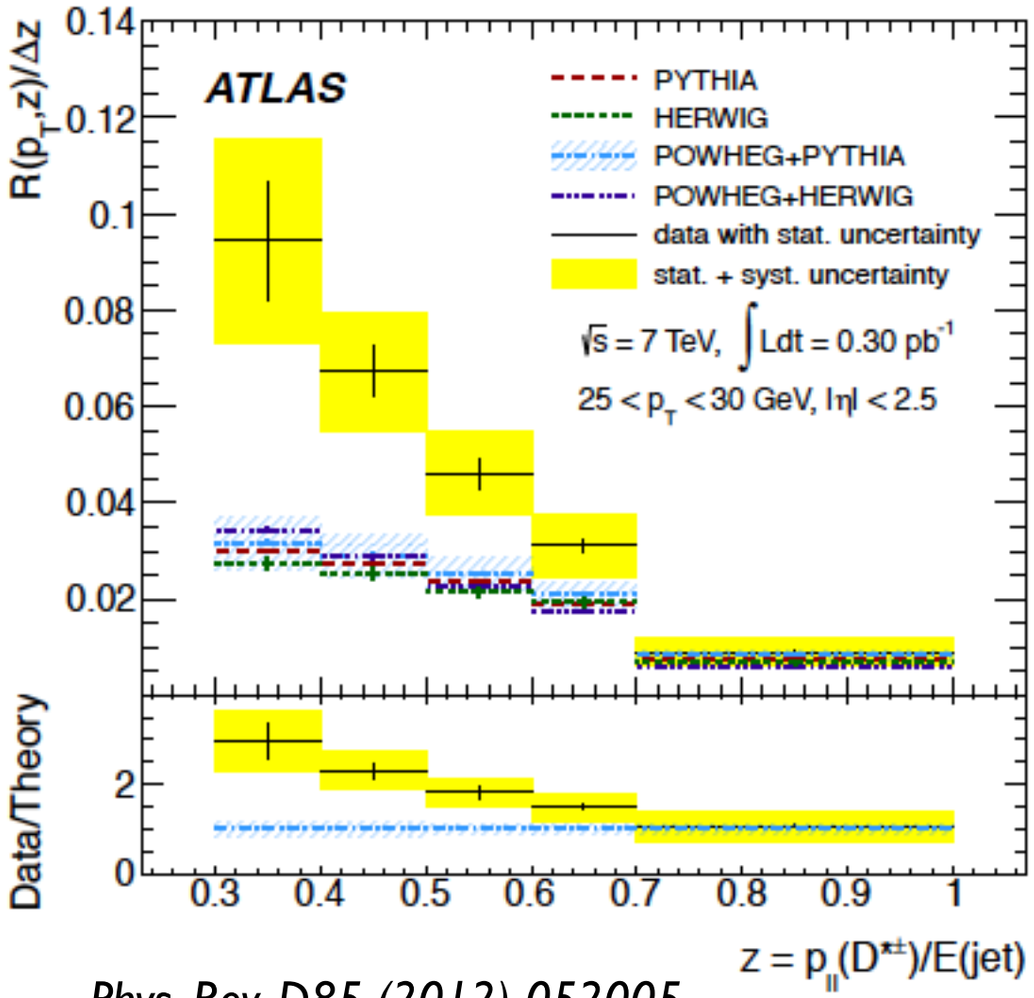
ATLAS

- ☑ Analysis performed at $\sqrt{s}$ = 7 TeV with an integrated lumosity of 0.30 pb^{-1}
- ☑ Jets transverse momentum [25,70] GeV/c and $|\eta|<2.5$.
- ☑ D^{*+} fully reconstructed in the channel $D^{*+}\rightarrow D^0(K^+\pi^-)\pi^+$

$$\mathcal{R}(p_{\mathrm{T}}, z) = \frac{N_{D^{*\pm}}(p_{\mathrm{T}}, z)}{\mathcal{B}(D^{*\pm} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}) N_{\mathrm{jet}}(p_{\mathrm{T}})},$$

- ☑ Production rate:

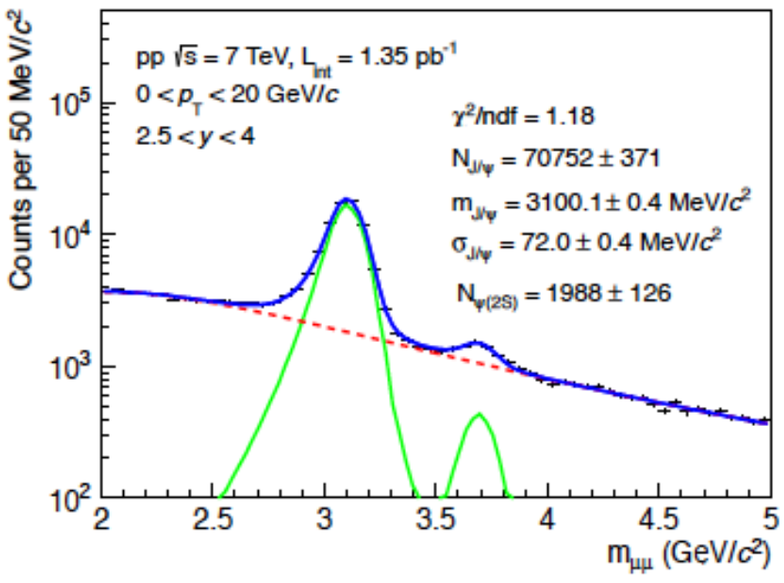
  $N(D^{*+})/N(jet) = 0.025\pm0.001(stat.)$ $\pm0.004(syst)$ for D^{*+} that carry a fraction z of the jet momentum in the range $0.3 < z < 1$



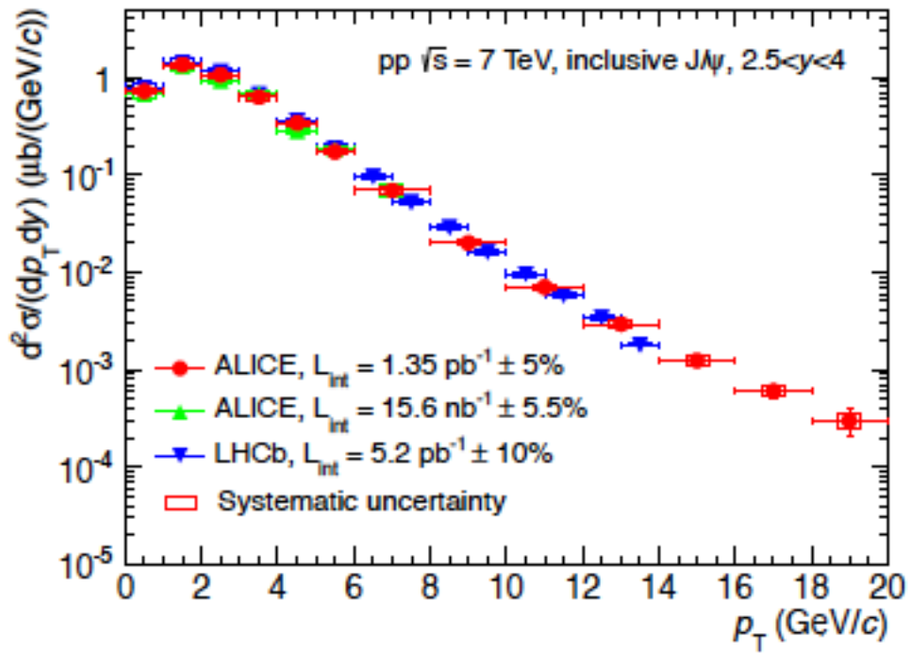
Phys. Rev. D85 (2012) 052005

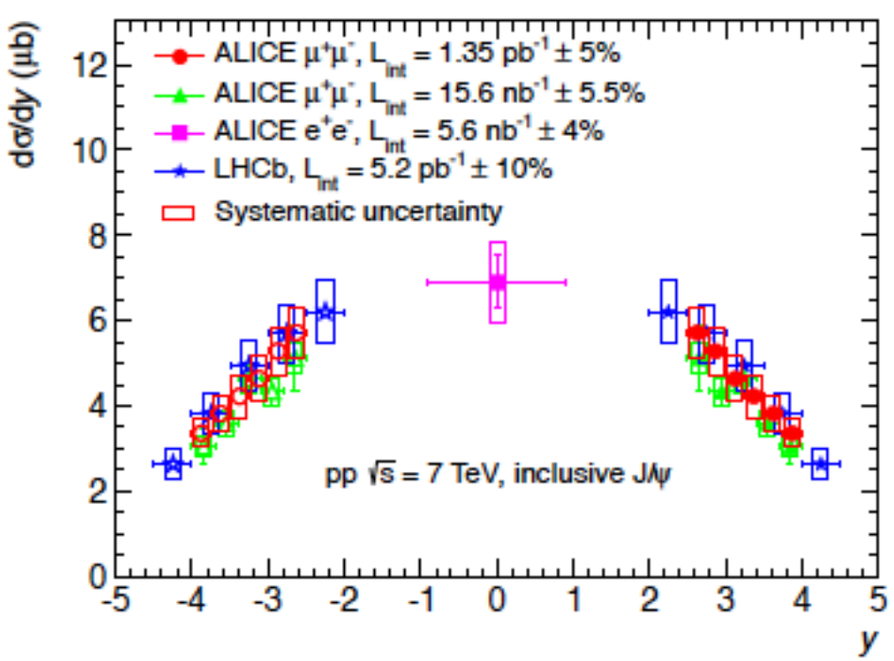
- ☑ Monte carlo fails to describe the data at small z. Indication that the production of c-jets or the fagmentation in D^{*+} is not well modelled in current MC generators.

Quarkonium at forward rapidity: J/ψ→μ⁺μ⁻



- ☑ All the major experiments at LHC (as well as in the other hadron colliders) studied the J/ψ production.
- ☑ Production mechamism described by models based on QCD. In general seen as a two step process:
  - Creation of a $c\bar{c}$ pair in hard scattering (pQCD).
  - Evolution of the pair toward a bound state (non-perturbative).





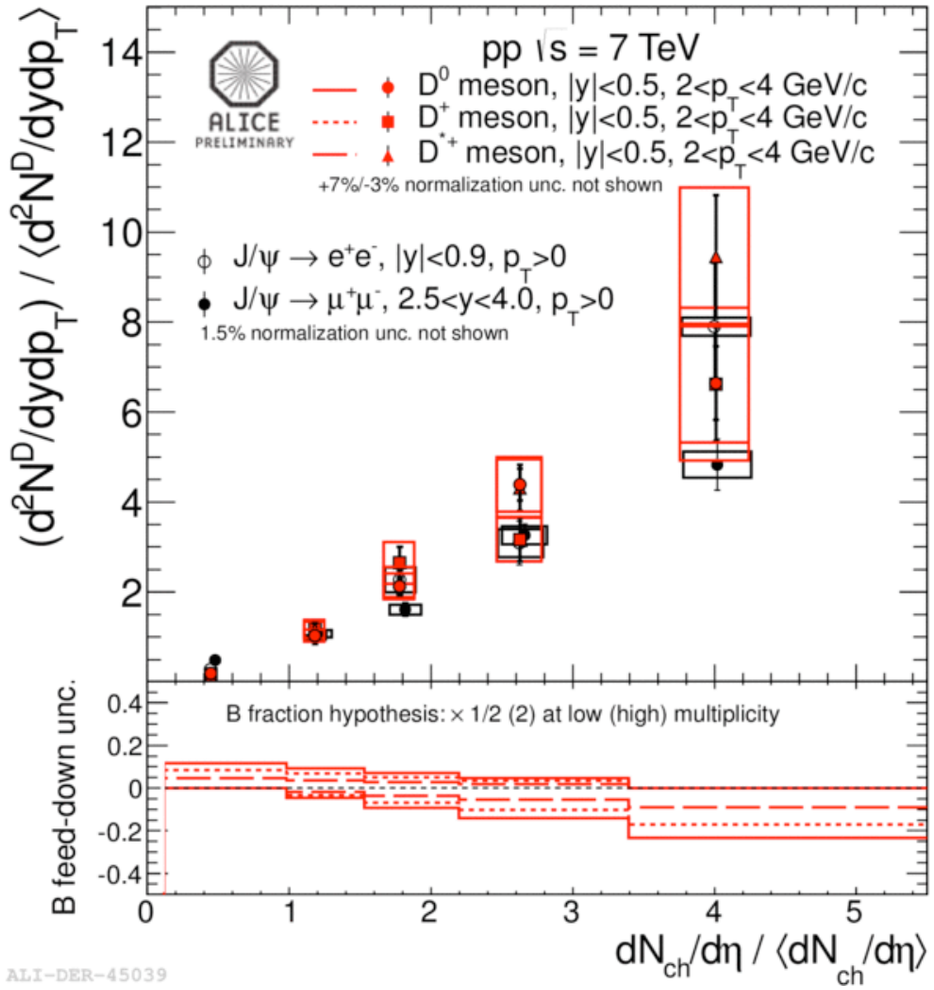
CERN-PH-EP-2014-042, arXiv:1403.3648

ALICE (2.5<y<4) and LHCb (2<y<4.5)

a.grelli@uu.nl

Production vs charged particle multiplicity

☑ Deeper insight on charm production in pp collisions - multi-parton scattering?



☑ D^0, D^+ and D^{*+} meson, $|y|<0.5$, $2<p_T<4$ GeV/c

☑ $J/\psi \rightarrow e^+e^-$, $|y|<0.9$, $p_T>0$ GeV/c

☑ $J/\psi \rightarrow \mu^+\mu^-$, $2.5<y<4$, $p_T>0$ GeV/c

☑ Approximately linear increase of the yield with charged-particle density. Consistency of the D^0, D^{*+} and D^+ mesons.

☑ D mesons and J/ψ consistent within uncertanties

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PLB, 712-3 (2012), arXiv:1202.2816

a.grelli@uu.nl