Open heavy flavour in heavy-ion collisions at the CERN-LHC

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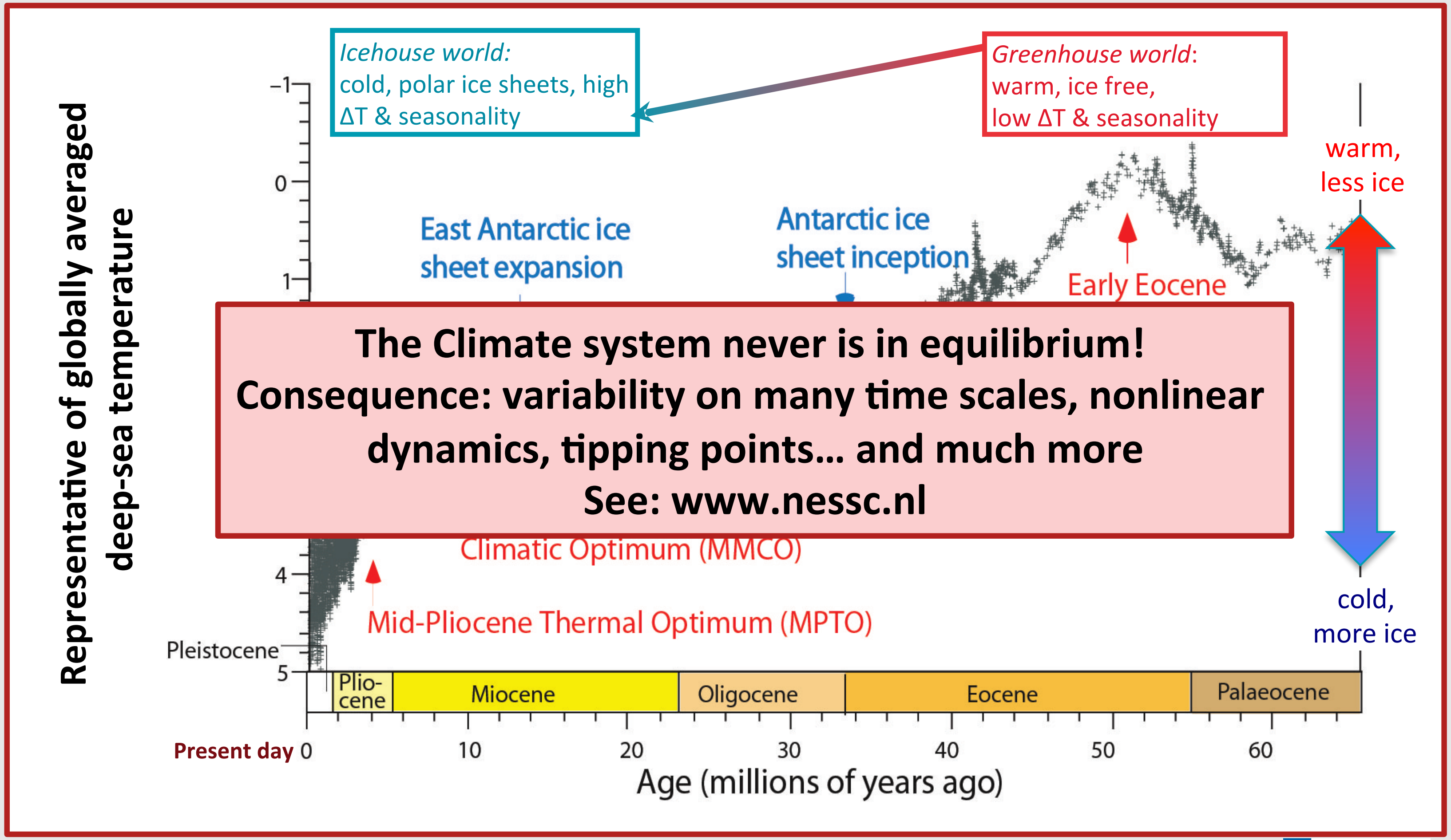
Dr. Anna von der Heydt:
Past climate variability = non-equilibrium (thermo-) dynamics



The Climate system never is in equilibrium!
Consequence: variability on many time scales, nonlinear dynamics, tipping points… and much more
See: www.nessc.nl

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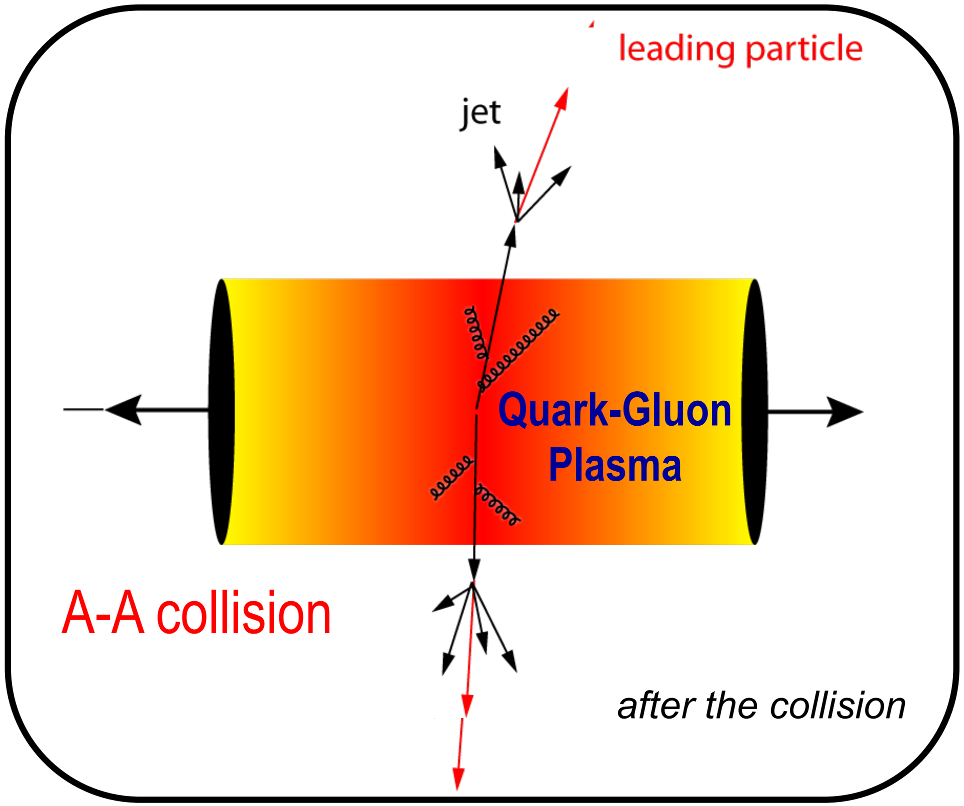
Physics and Astronomy]

Outline

- Open heavy flavour (charm and beauty) allows study of the dynamical properties of hot QCD matter and degree of thermalisation
- **Probes**
  - D and B (new!) mesons and heavy-flavour decay leptons (e and μ)
- **Collision systems (at LHC facility)**
  - pp: test QCD and important baseline for heavy-ion measurements
  - A-A: study hot QCD matter (final state); determine medium properties
  - p-A: study cold nuclear matter effects (initial state)
- **Observables**
  - R_{AA} and v_2 (versus p_T and centrality)
  - Multiplicity dependence of the yield
  - Angular azimuthal correlations and jets
- **Summary and outlook**

Probing hot and dense QCD matter



- "Simplest way" to establish the properties of a system
  - calibrated probe
  - calibrated interaction
  - suppression pattern tells about density profile
- Heavy-ion collision

  formation time $\tau \sim 1/2m_Q$

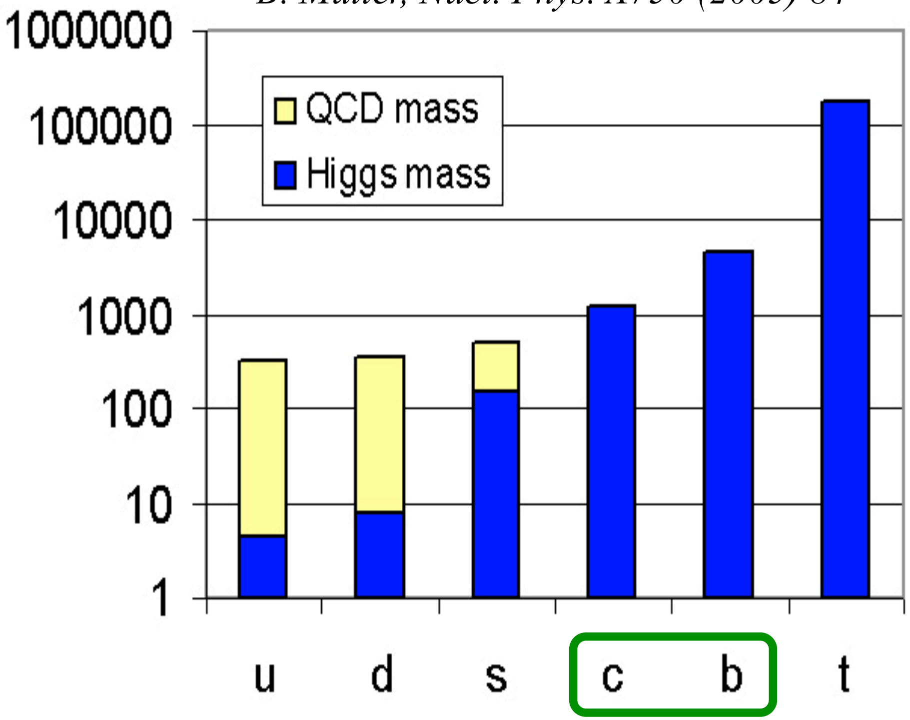
  - hard processes serve as calibrated probe (pQCD)
  - partons traverse through the medium and interact strongly
  - suppression pattern provides density measurement

General picture

- parton energy loss through medium-induced gluon radiation
- collisions with medium constituents

Heavy quarks are ideal probes

B. Müller, Nucl. Phys. A750 (2005) 84



- Symmetry breaking
  - Higgs mass: electro-weak symmetry breaking → current quark mass
  - QCD mass: chiral symmetry breaking → constituent quark mass

- Charm and beauty quark masses are not affected by QCD vacuum → ideal probes to study QGP

- Test QCD at transition from perturbative to non-perturbative regime: Charm and beauty quarks provide hard scale for QCD calculations

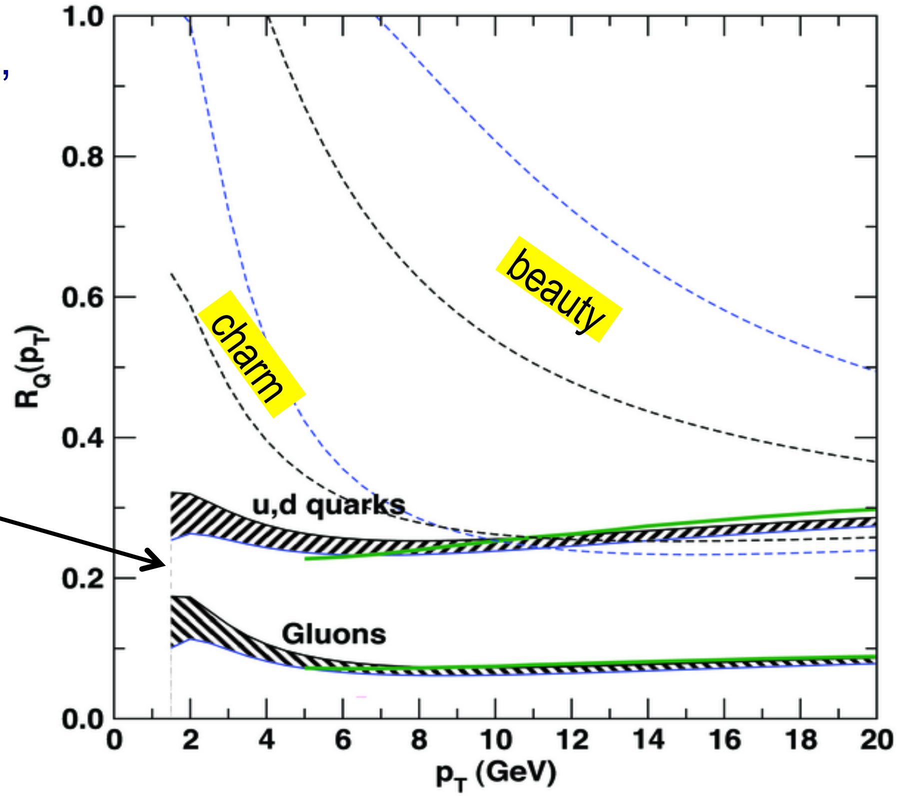
Radiative parton energy loss

- …depends on
  - medium properties (e.g. density, temperature, mean free path)
    → transport coefficients ($\hat{q}$)
  - path length in the medium (L)
  - parton properties (colour charge and mass); traversing the medium → Casimir coupling factor (C_R):
    C_R = 4/3 for quarks and 3 for gluons

    R. Baier et al., Nucl. Phys. B483 (1997) 291 (BDMPS)

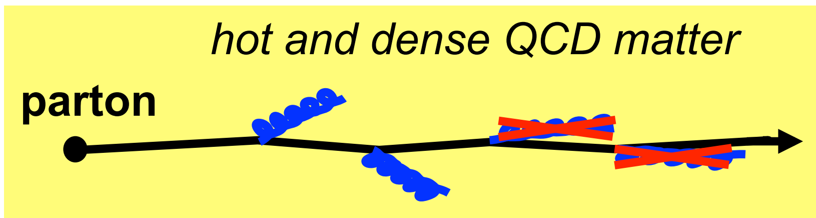
$$\langle \Delta E_{medium} \rangle \propto \alpha_S C_R \hat{q} L^2$$

S. Wicks et al., Nucl. Phys. A 784 (2007) 426



- Dead-cone effect: gluon radiation suppressed at small angles ($\theta < m_Q/E_Q$)

  Y. Dokshitzer, D. Kharzeev, PLB 519 (2001) 199, hep-ph/0106202

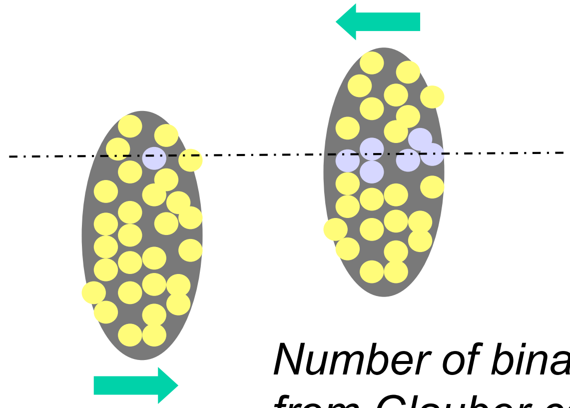


- Expectation: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

  Mass dependence

Quantification of medium effects

Comparison of the production yield in heavy-ion collisions with the one in proton-proton

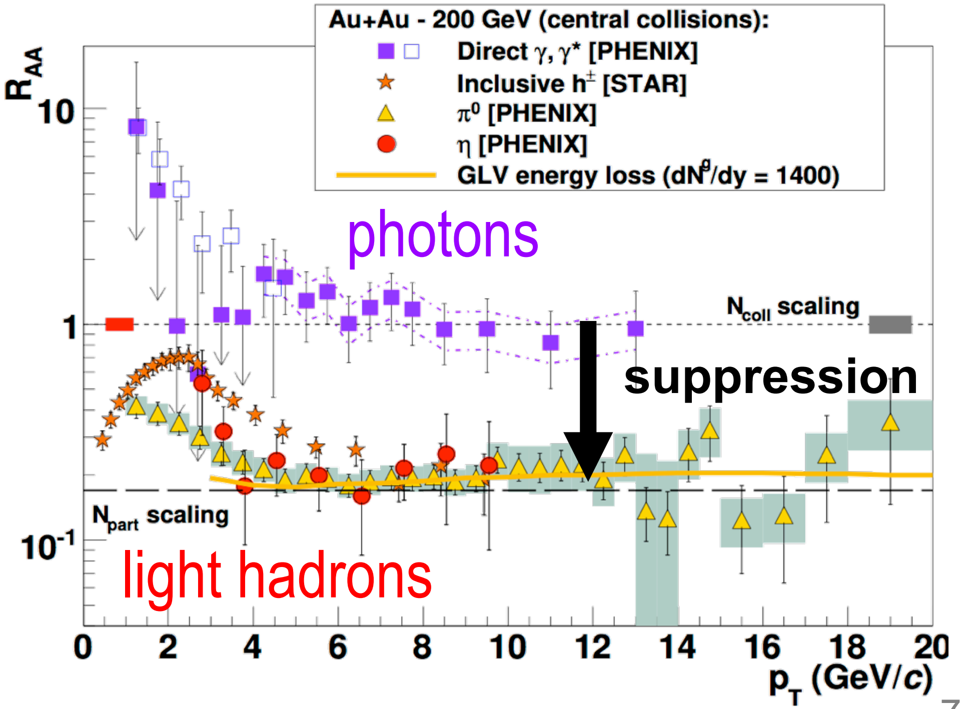


Number of binary collisions from Glauber calculations

Nuclear modification factor

$$R_{\mathrm{AA}}(p_T) = \frac{\mathrm{Yield}_{\mathrm{AA}}(p_T)}{\langle N_{bin} \rangle_{\mathrm{AA}} \, \mathrm{Yield}_{\mathrm{pp}}(p_T)}$$

D'Enterria, Nucl. Phys. A 827 (2009) 356c



Expectation:

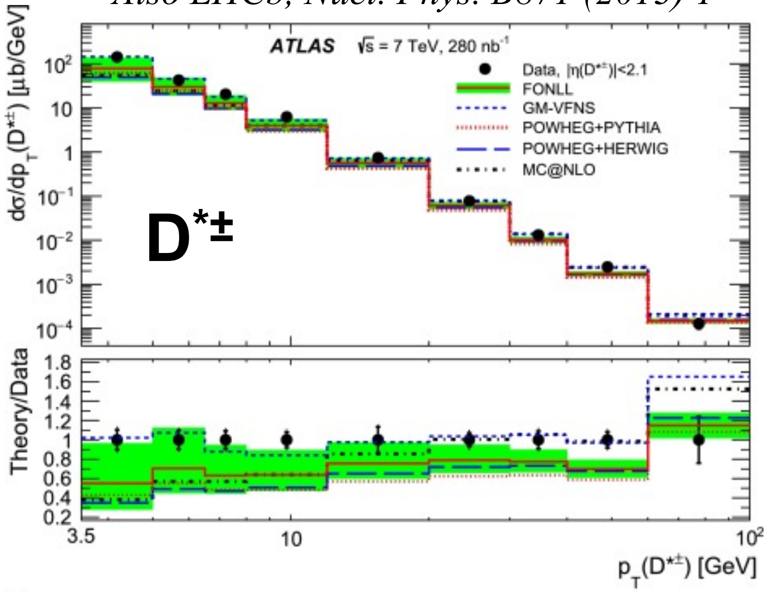
- R_{AA} = 1 for photons
- R_{AA} < 1 for hadrons

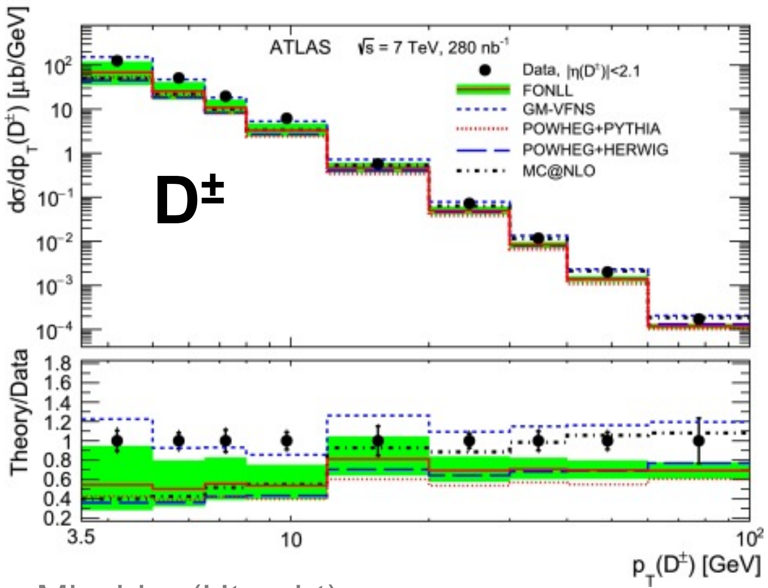
$$\boldsymbol{R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)}$$

pp system: QCD vacuum

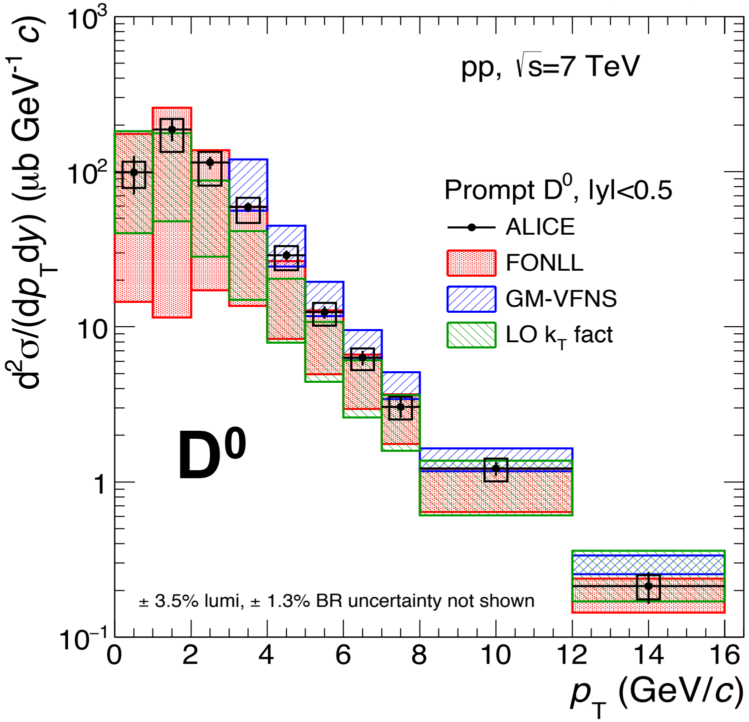
D-meson production x-section in 7 TeV pp

ATLAS, Nucl. Phys. B 907 (2016) 717
Also LHCb, Nucl. Phys. B871 (2013) 1





ALICE, 1605.07569 and JHEP 1201 (2012) 128

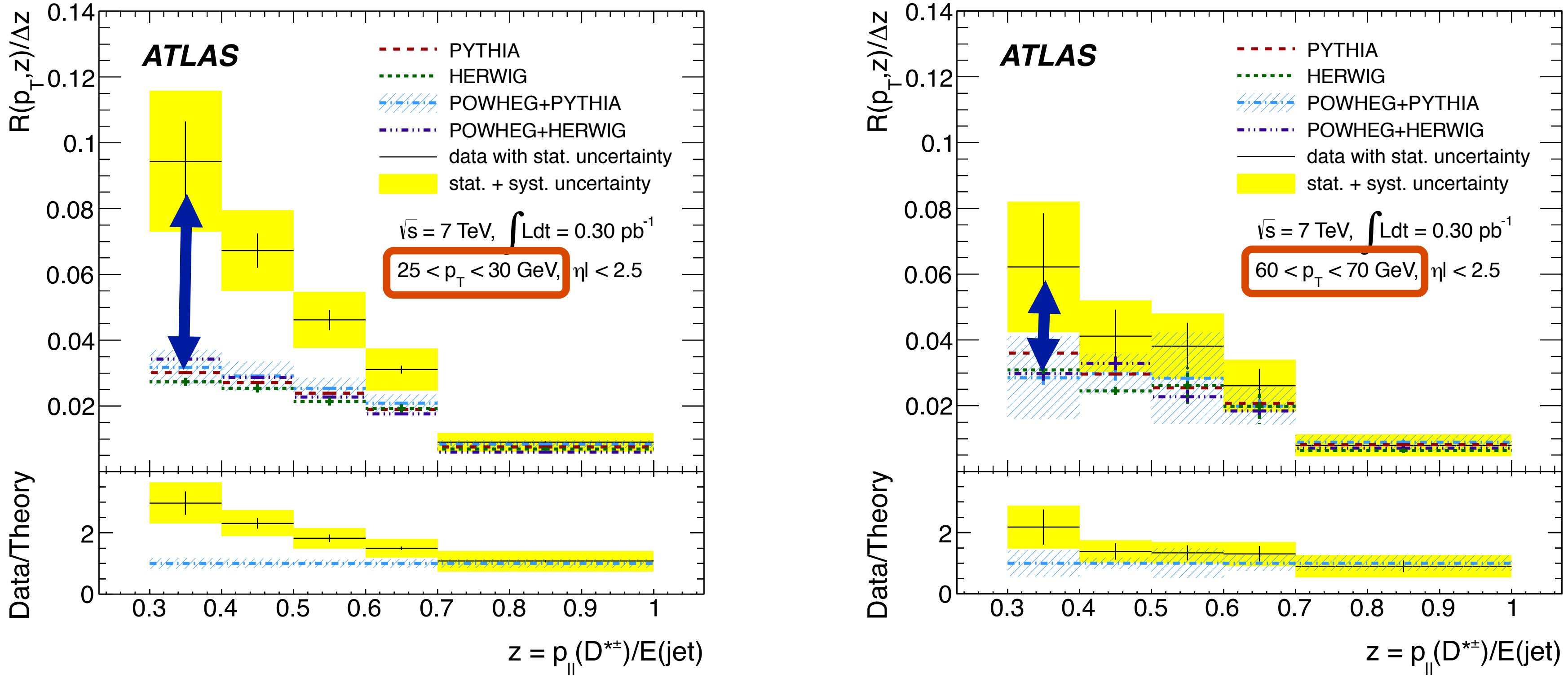


Multiplicity dependence also studied

- Down to zero p_T for ALICE!
- Data well described by NLO pQCD within the large theoretical uncertainties although at the upper bound

$D^{*\pm}$ production in jets in 7 TeV pp

ATLAS, Phys. Rev. D 85 (2012) 052005

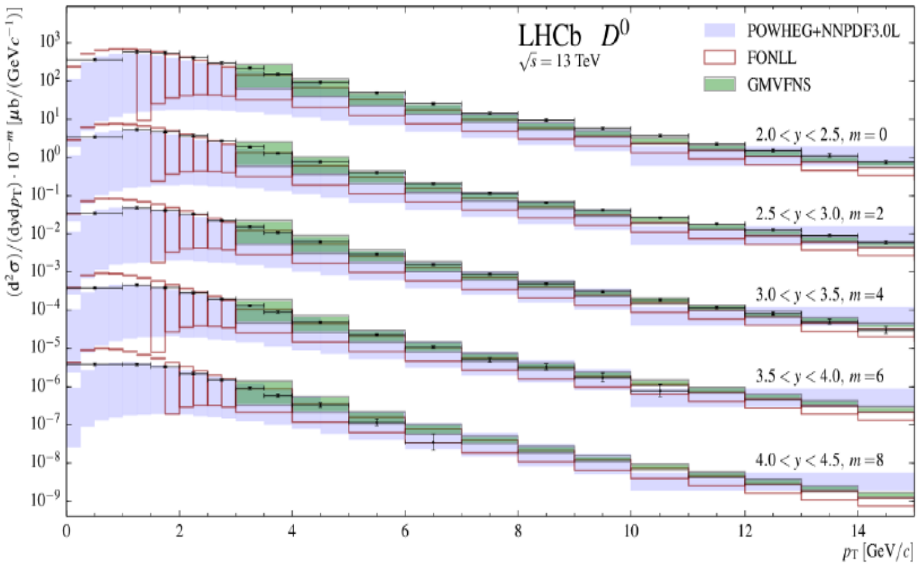


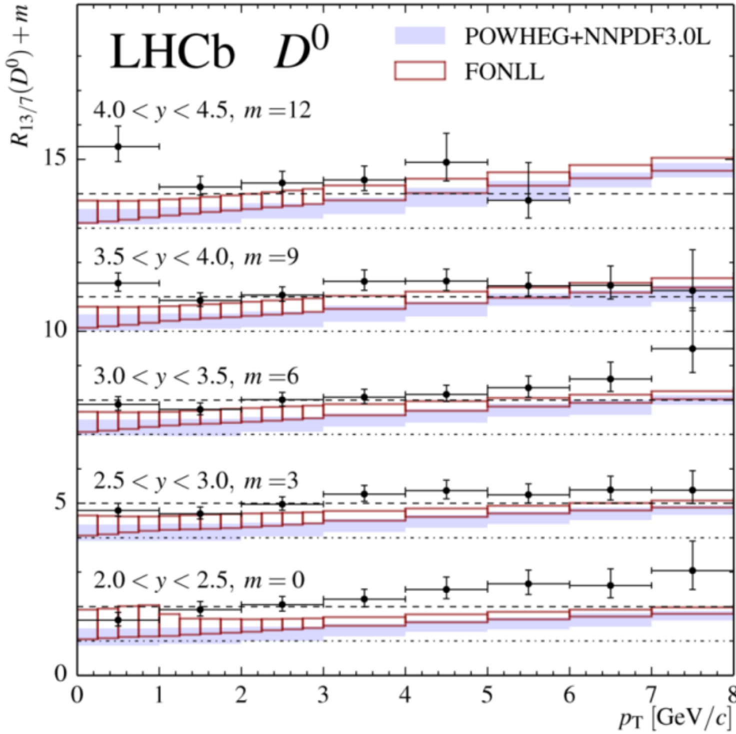
- MC calculations fail to describe data at small z; strongest at low jet transverse momentum
- Indication that jet fragmentation into $D^{*\pm}$ mesons not well modeled in current MC generators

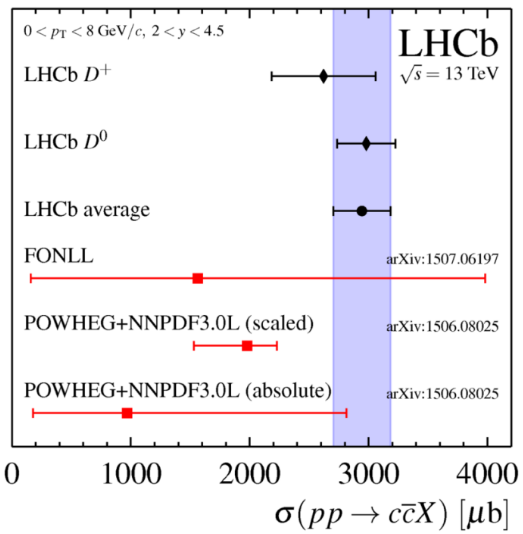
Open charm production x-section in 13 TeV pp

- double-differential D^0 cross-section
- forward rapidities

JHEP 03 (2016) 159 (Errat.: JHEP 09 (2016) 013)

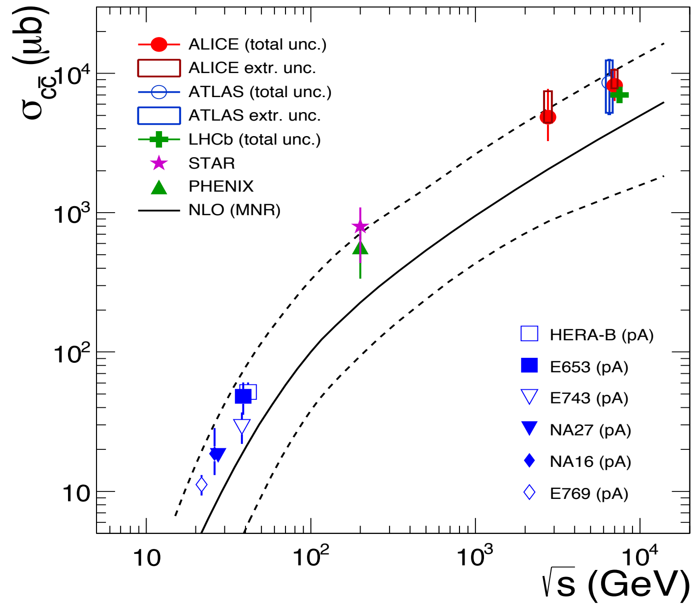


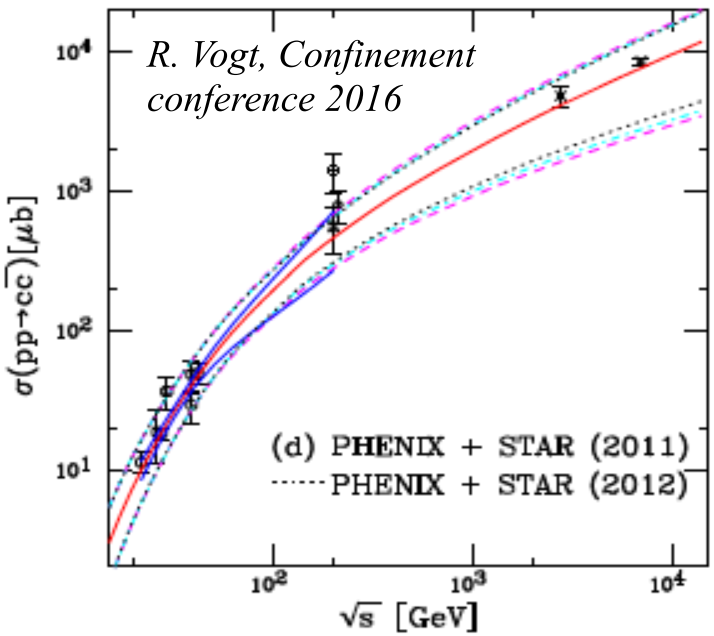




NLO pQCD calculations underpredict cross section ratios $R_{13TeV/7TeV}$ and $R_{13TeV/8TeV}$ (not shown)

Total charm production cross section in pp



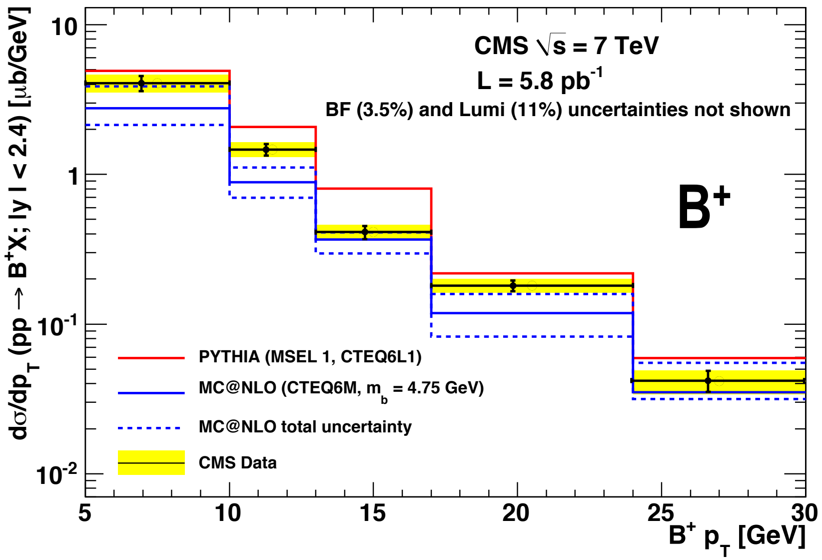


ALICE, JHEP in press (1605.07569)
NLO, M.L. Mangano et al., NPB 373 (1992) 295

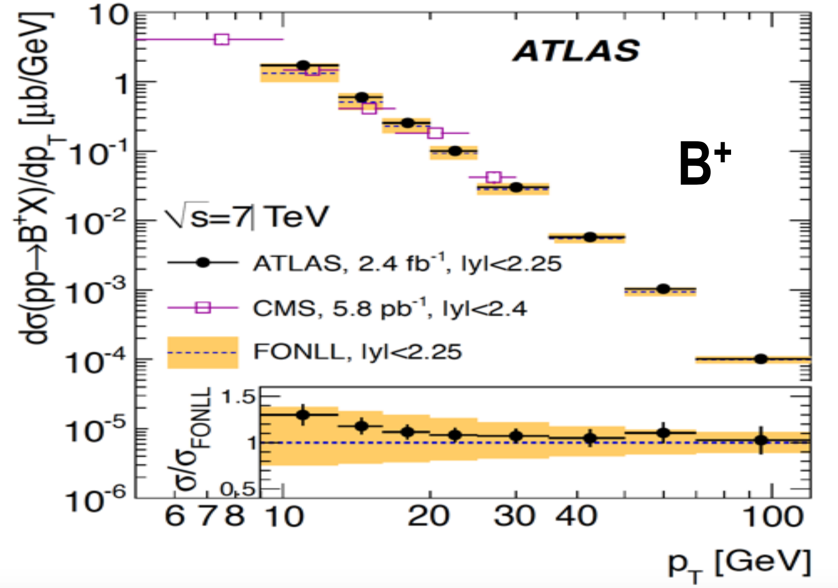
- Very good agreement between LHC experiments
- Consistency with NLO pQCD calculations within uncertainties, although systematically at the upper limit
- 8 and 13 TeV data will provide further constraints
- Note: Parton spectra from pQCD input for energy loss models; baseline for measurements in Pb-Pb

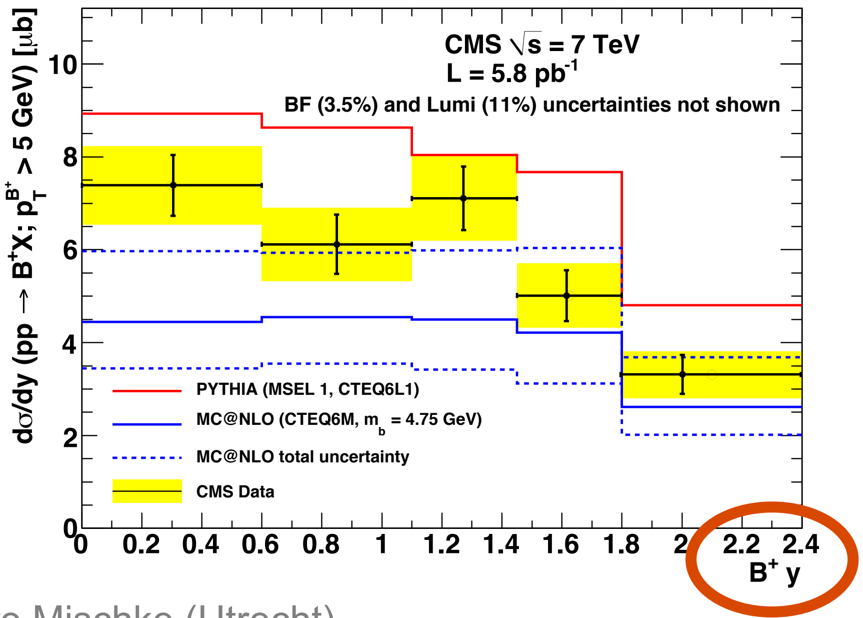
Differential B production cross section in 7 TeV pp

Phys. Rev. Lett. 106 (2011) 112001

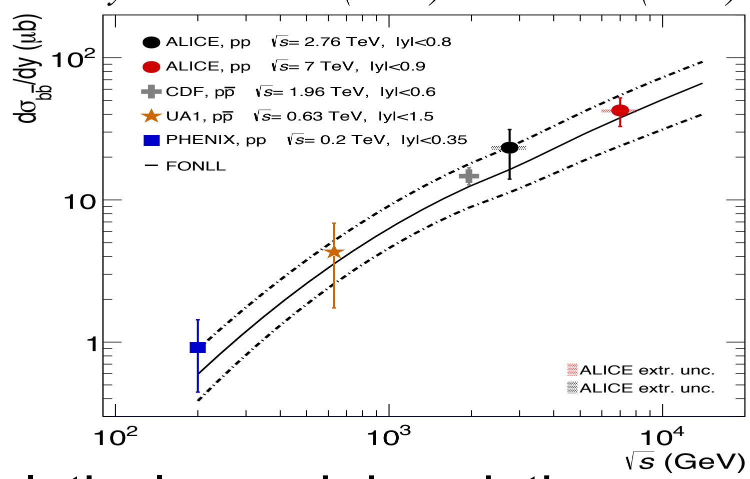


JHEP 10 (2013) 042





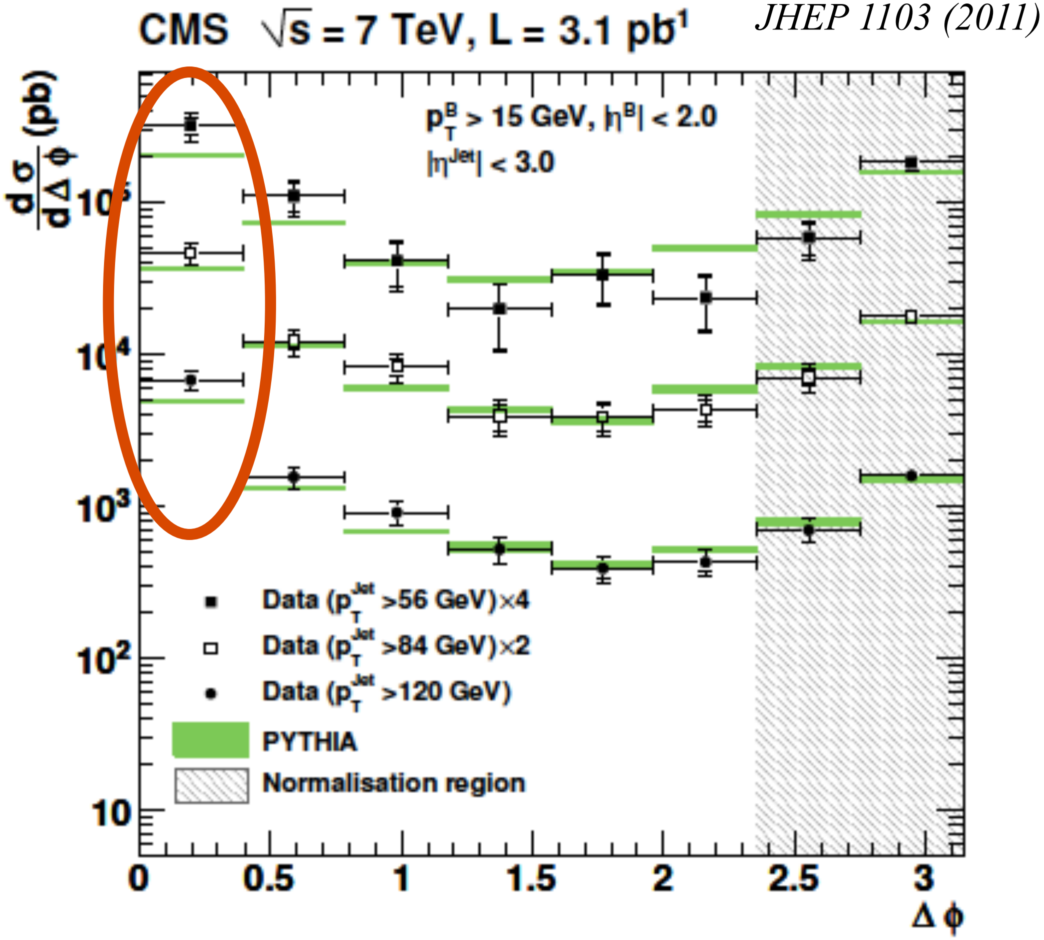
Phys. Lett. B 721 (2013) 13 and 738 (2014) 97



Relatively good description with NLO pQCD calculations

B-Bbar Δφ correlations in 7 TeV pp

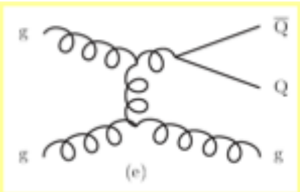
JHEP 1103 (2011) 136



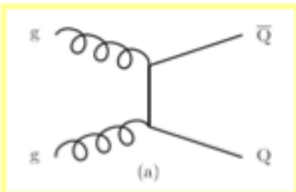
- Gluon splitting (GS) contribution not well modeled by most of the calculations

→ GS contribution underestimated by PYTHIA (shown here)

Gluon splitting

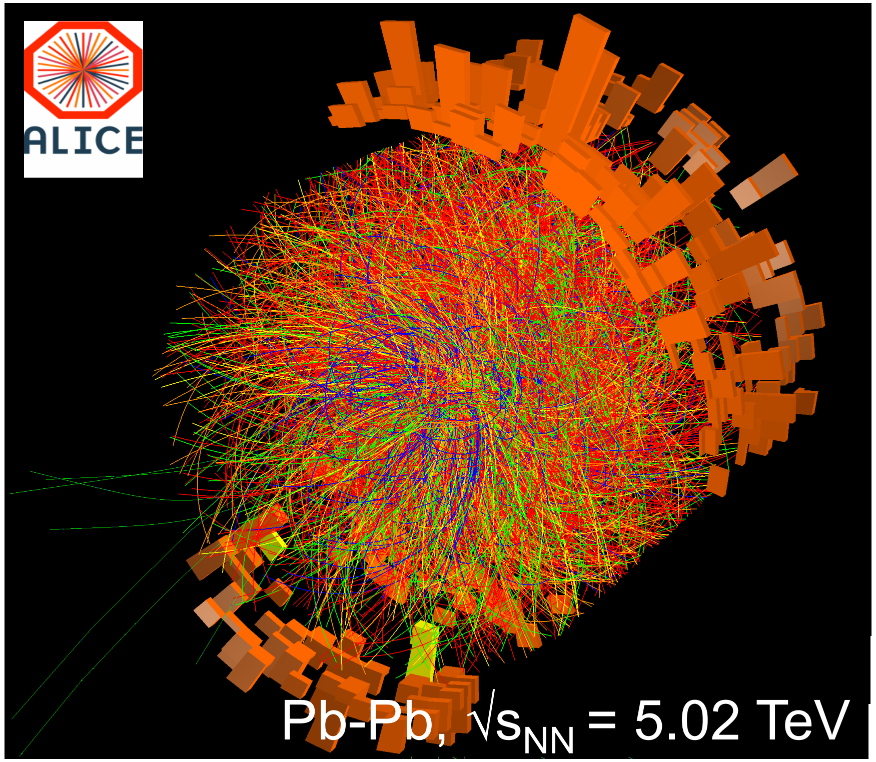


Flavour creation

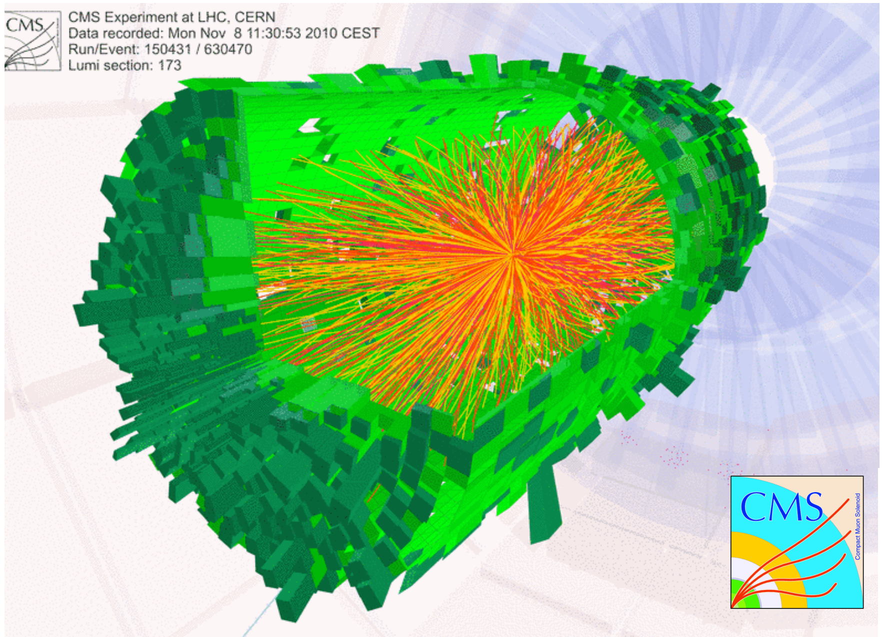


A-A system: QGP formation
(hot and dense QCD medium)

Typical event displays

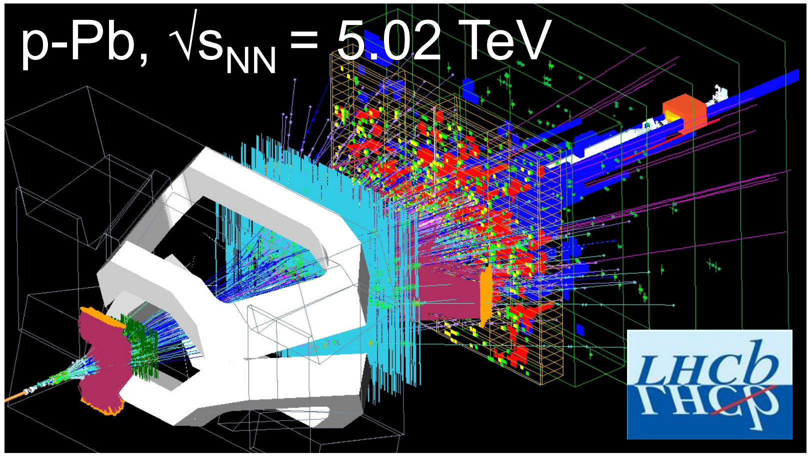


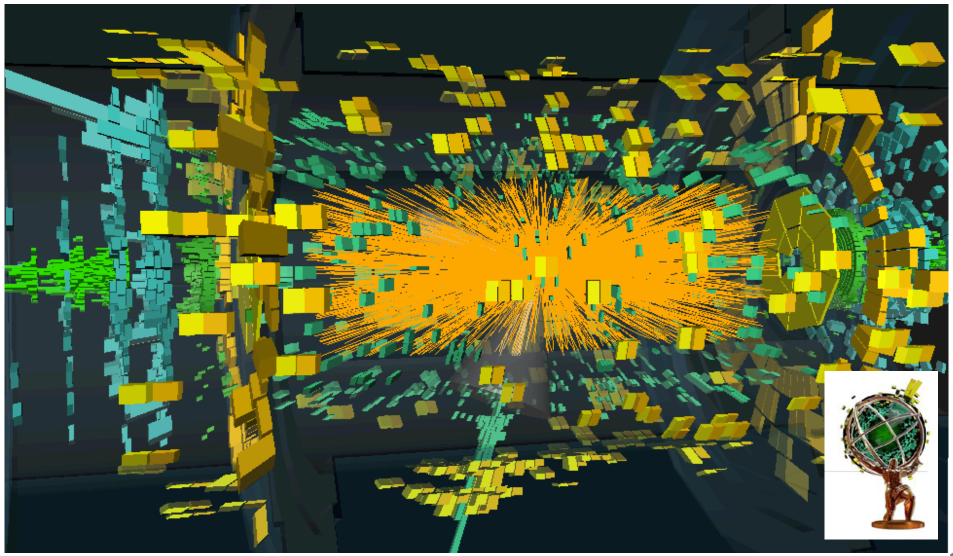
Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV



Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV

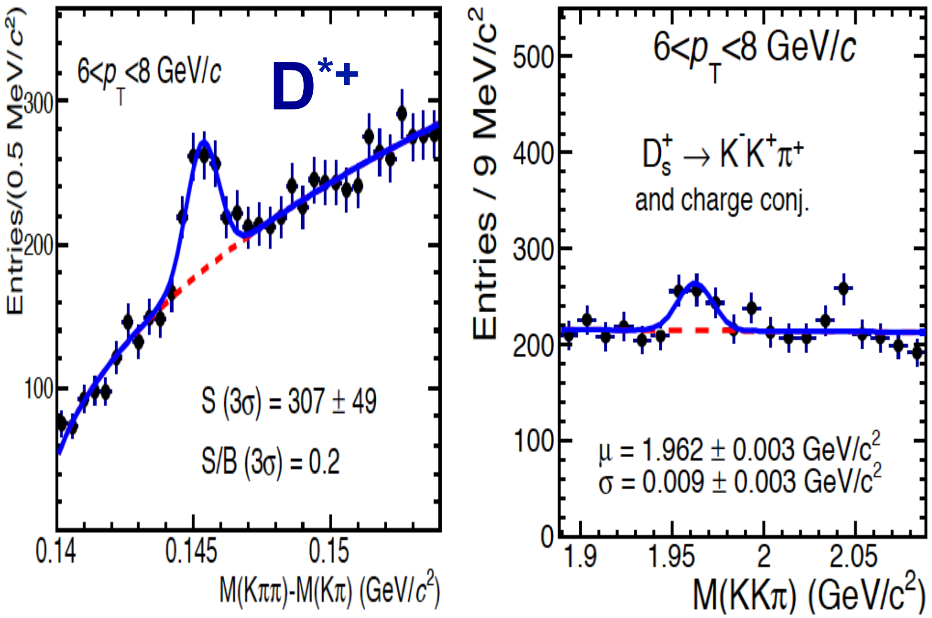
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

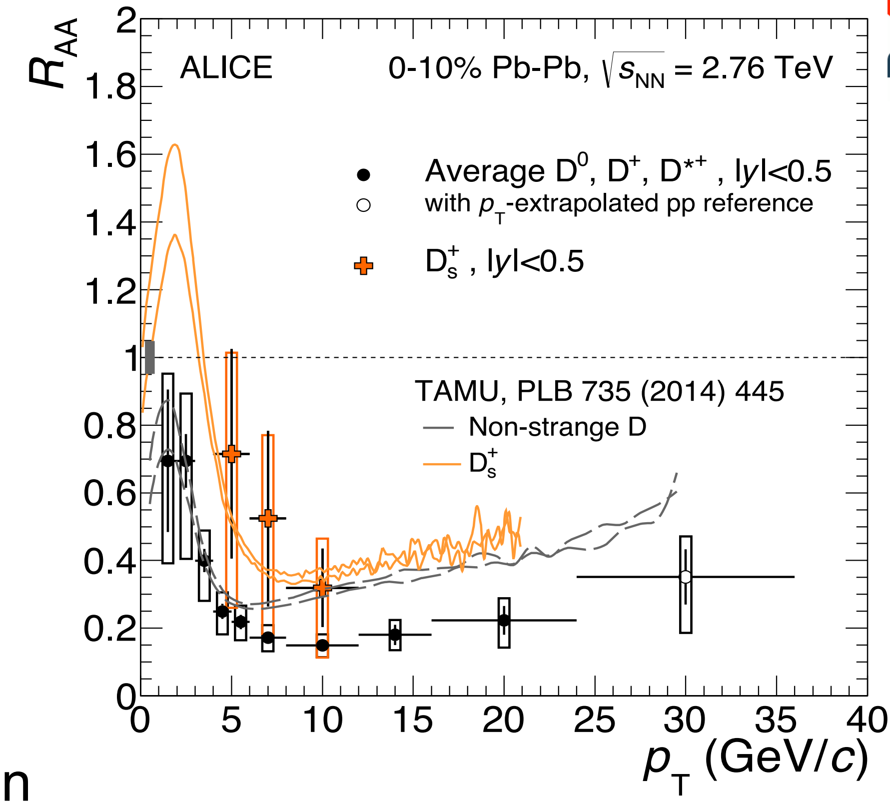




Prompt D-meson R_{AA} in 2.76 TeV Pb-Pb

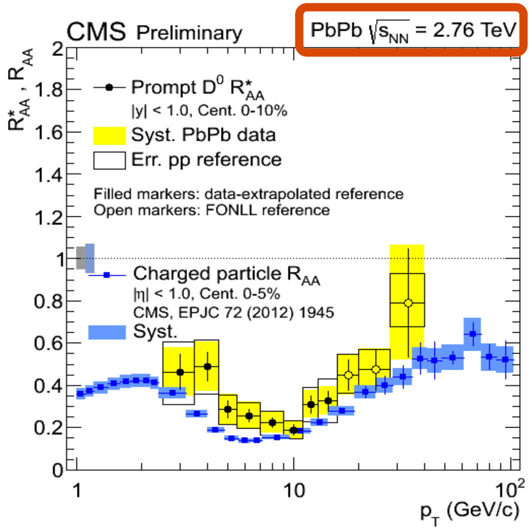
ALICE, JHEP 03 (2016) 081 and JHEP 03 (2016) 082

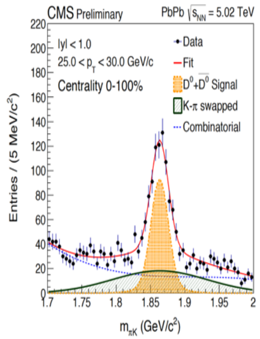




- Above 5 GeV/c strong suppression (factor 4-5) of D-meson yield in central Pb-Pb, compared to binary scaling from pp
- First $D_s^+(c\bar{s})$ measurement in heavy-ion collisions
- Expectation: enhancement of strange D-meson yield at intermediate p_T if charm hadronises via recombination in the medium

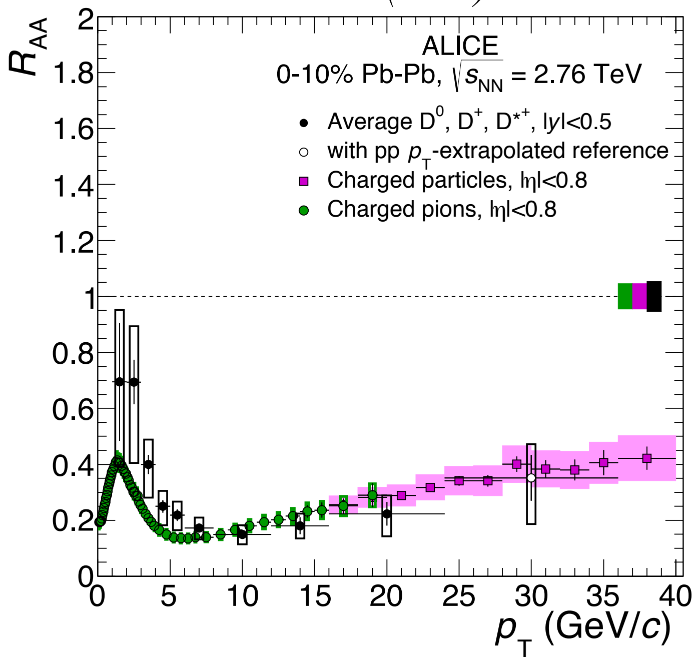
R_{AA}: light versus heavy-quark hadrons

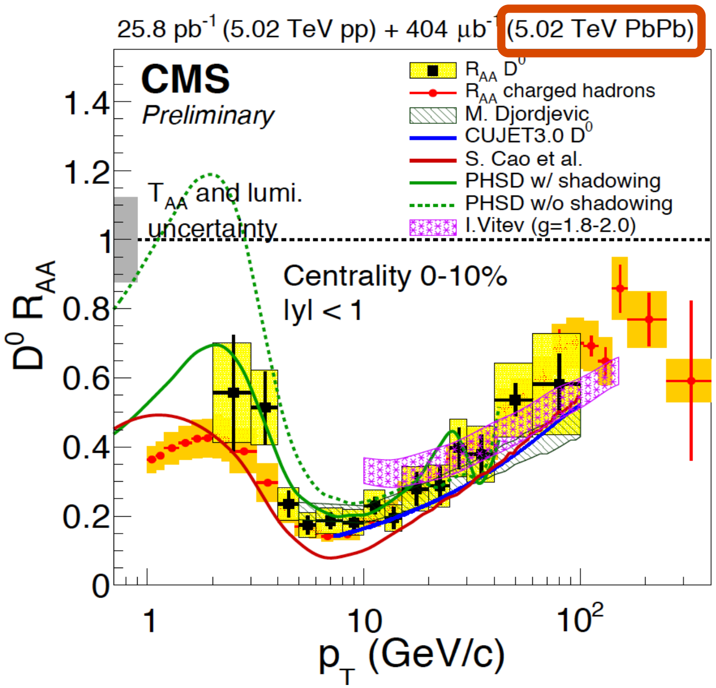




CMS-HIN-16-001

JHEP 1603 (2016) 081

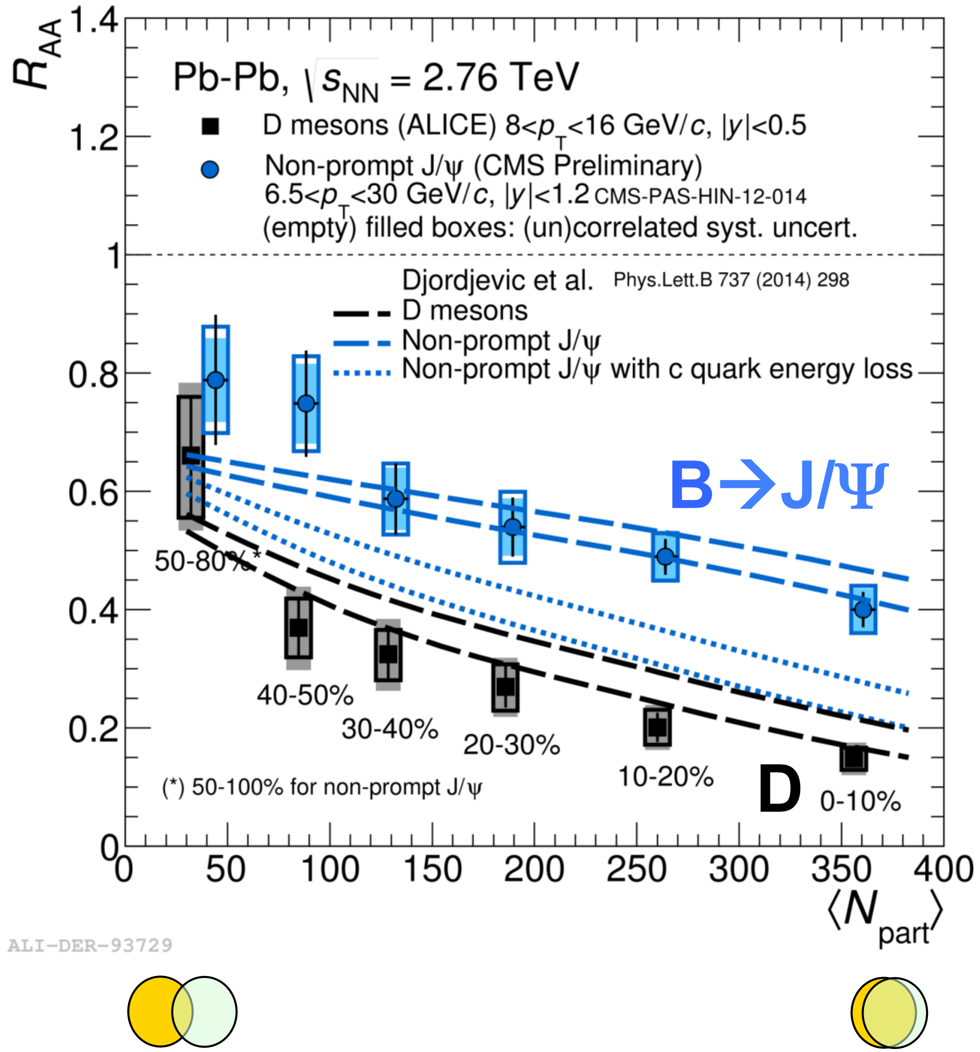




- D^0 suppression is measured up to 100 GeV/c (CMS)
- Indication for $R_{AA}^{D} > R_{AA}^{pions}$ at low p_T for 10% most central collisions
- Well described by theo. calculations that include both collisional and radiative energy loss (& shadowing)

Prompt D and B-meson R_{AA} in 2.76 TeV Pb-Pb

ALICE, JHEP 11 (2015) 205
CMS-PAS-HIN-12-014, CMS-PAS-HIN-15-005

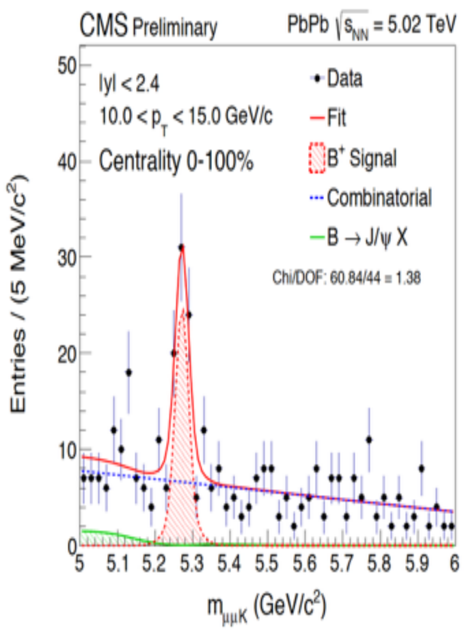


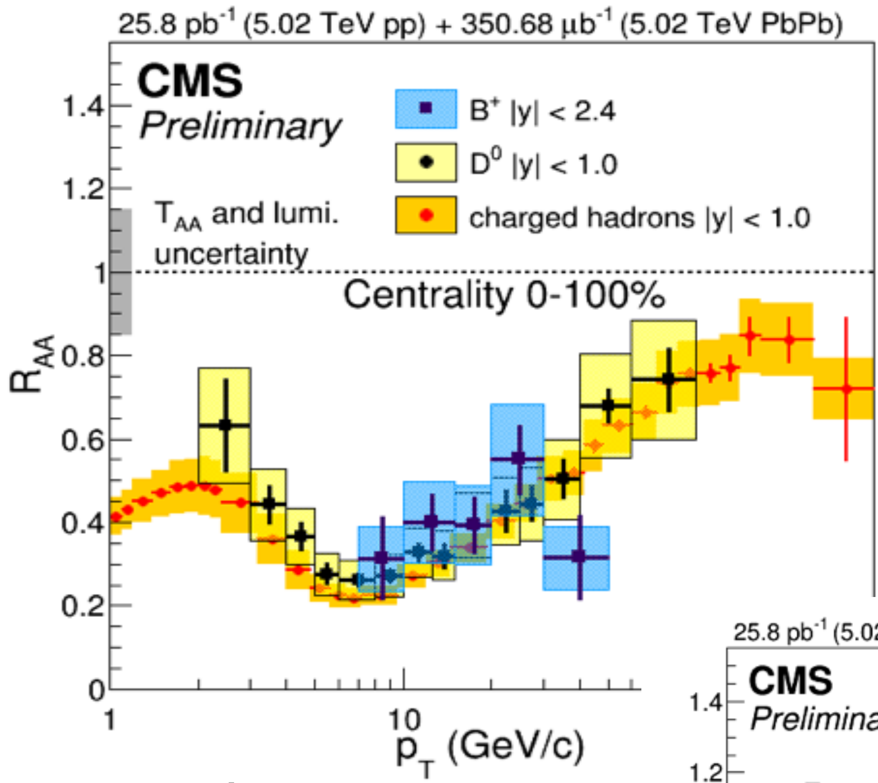
- Comparison of prompt D mesons (ALICE) with J/ψ from beauty decays (CMS)
- D and B meson <p_T> ~10 GeV/c
- Described by theoretical model calculations including quark-mass dependent energy loss ($R_{AA}^D < R_{AA}^B$) in the studied p_T range

Low p_T

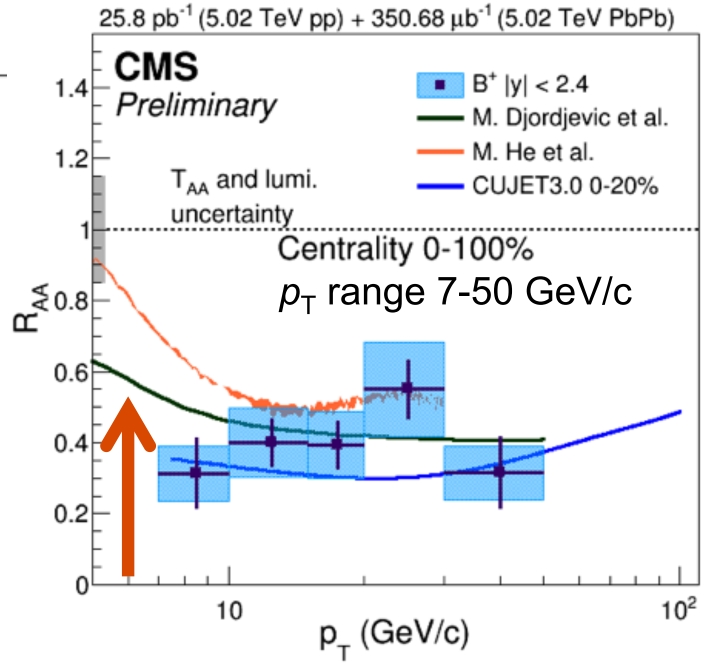
B-meson R_{AA} in 5.02 TeV Pb-Pb

CMS-PAS-HIN-16-011





High p_T

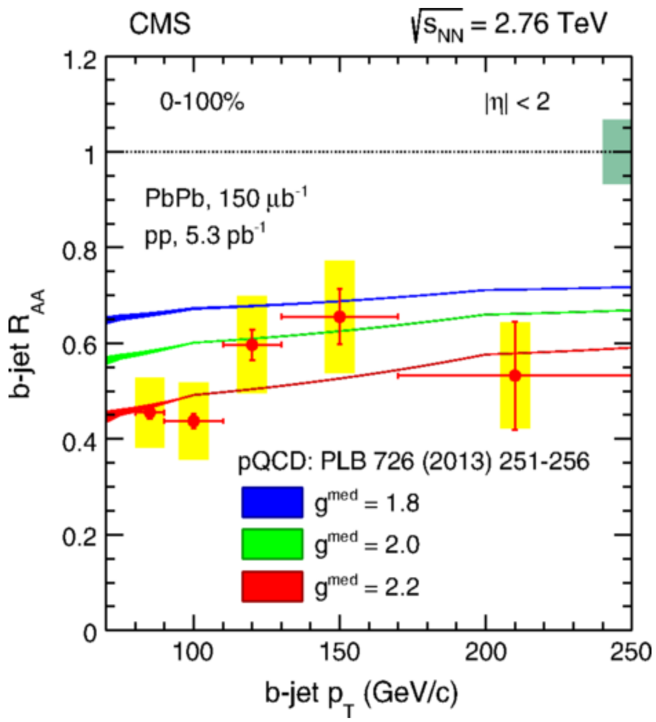


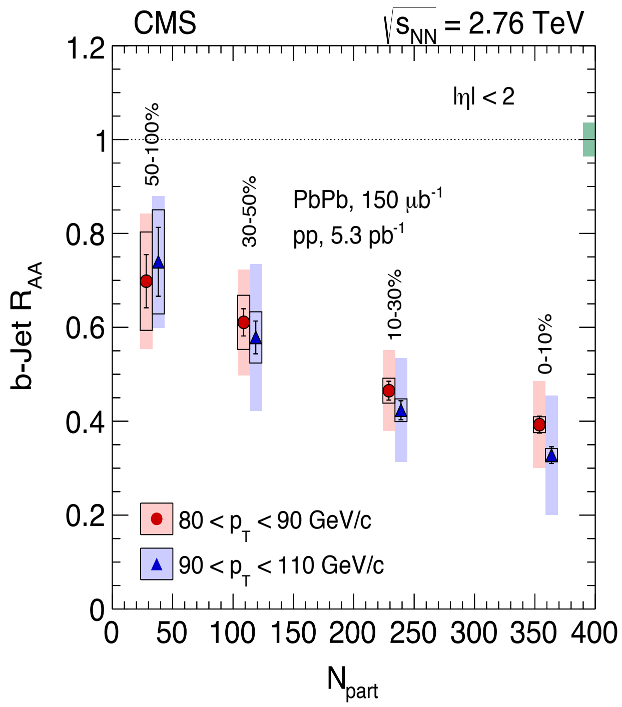
- R_{AA} of fully reconstructed B mesons (for the first time in HIC!)
- Sizeable suppression of the yield for charm and beauty
- Difficult to make conclusive statement at the moment

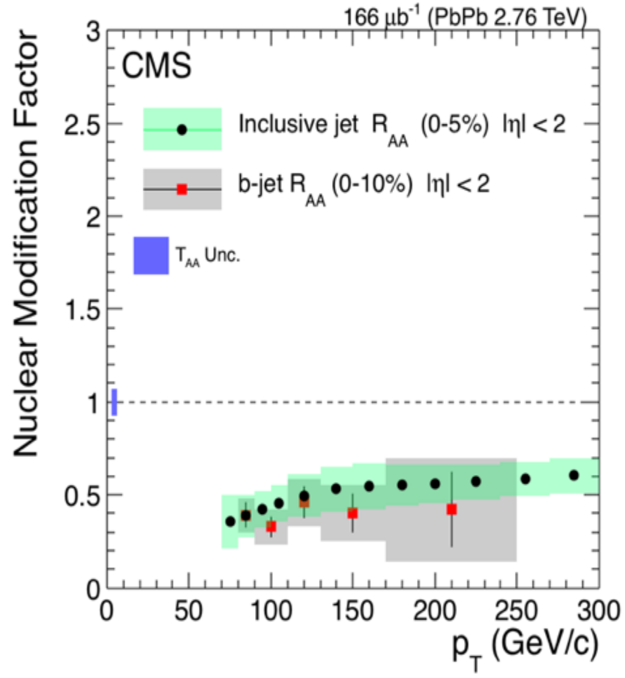
R_{AA} of b-tagged jets in 2.76 TeV Pb-Pb

Phys. Rev. Lett. 113 (2014) 132301

High p_T





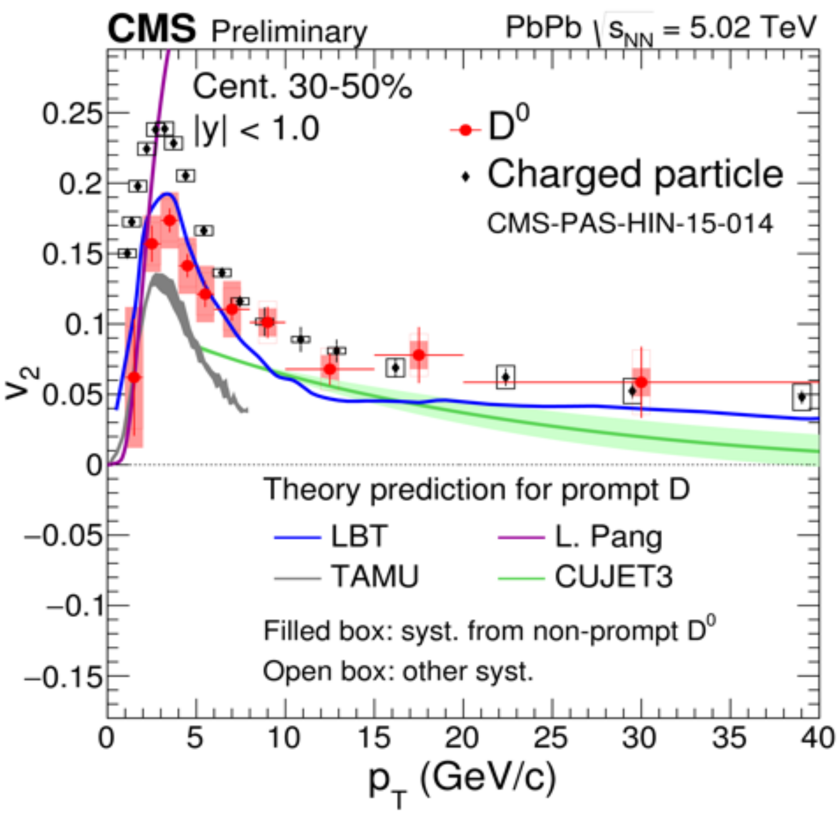


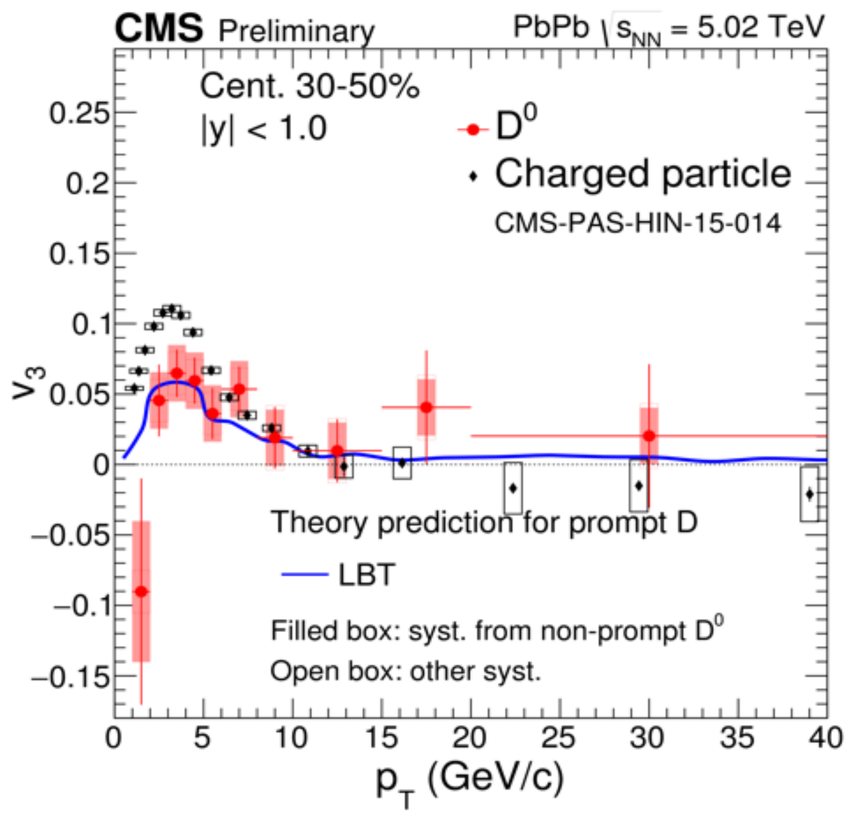
- Towards constrain of quark-medium coupling parameter g^{med}
- Same suppression for b-tagged jets and inclusive jets at high p_T
  → mass difference negligible
  → B mesons are sensitive to lower p_T b-quarks than b-jets

Note: sizable fraction of b-tagged jets arise from gluon splitting

D-meson v_n in 5.02 TeV Pb-Pb

Key question: Does charm flow / thermalise in the medium?



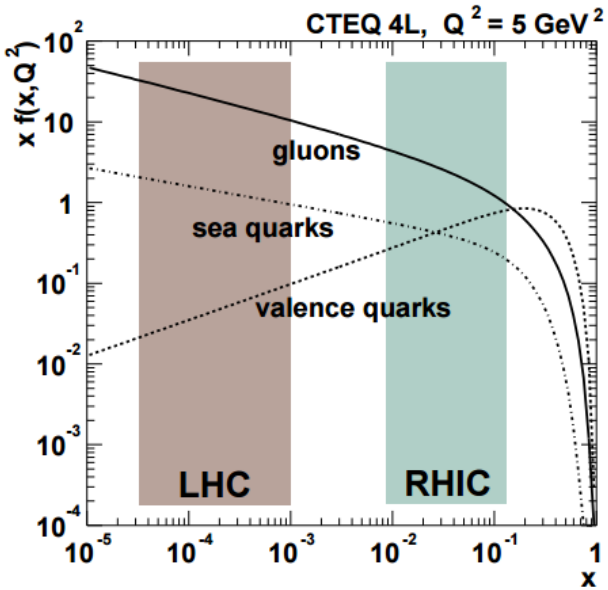


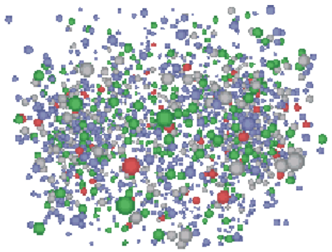
- $v_2(D^0) < v_2(h^{\pm})$ at low p_T (< 5 GeV/c)
- v_2 and v_3 are well described by models that include both charm diffusion and charm recombination in the medium → means charm participates in the collective motion of the system

p-A system: Cold nuclear matter effects

Cold nuclear matter (CNM) effects

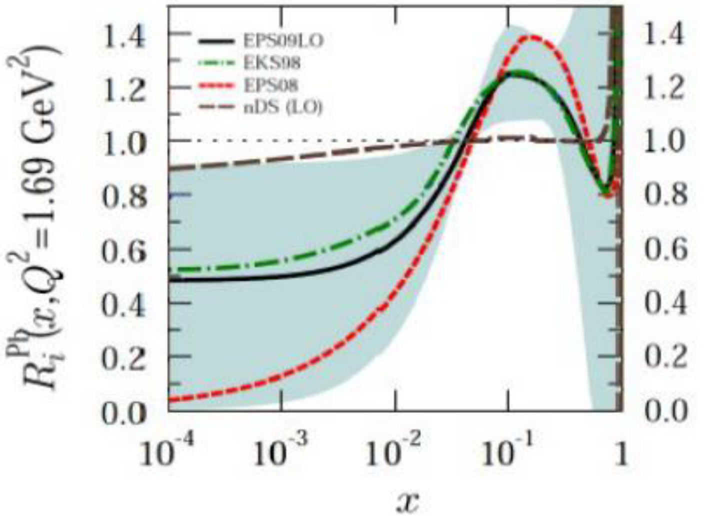
- CNM effects (**from initial state**) such as
  - Nuclear modification of PDFs → **shadowing** at low Bjørken-x (dominant at LHC)
  - Gluon **saturation** from evolution equations (DGLAP and BFKL)
  - k_T broadening and Cronin enhancement from multiple parton scatterings
  - Initial-state energy loss





- Final-state effects
  - Energy loss?
  - Interactions between final-state particles (collective expansion?)

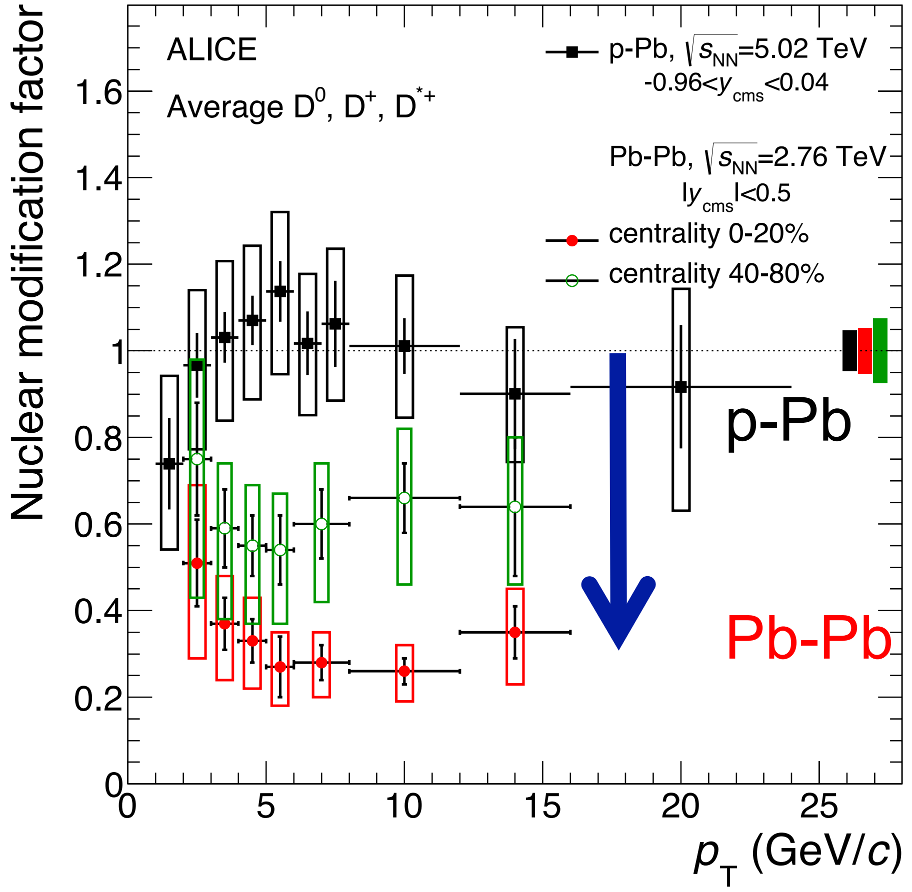
K.J. Eskola, H. Paukkunen, C.A. Salgado, JHEP 04, 65 (2009)



- Crucial for test of pQCD calculations and interpretation of heavy-ion results

Prompt D-meson R_{pPb} at 5.02 TeV

Phys. Rev. Lett. 113 (2014) 232301

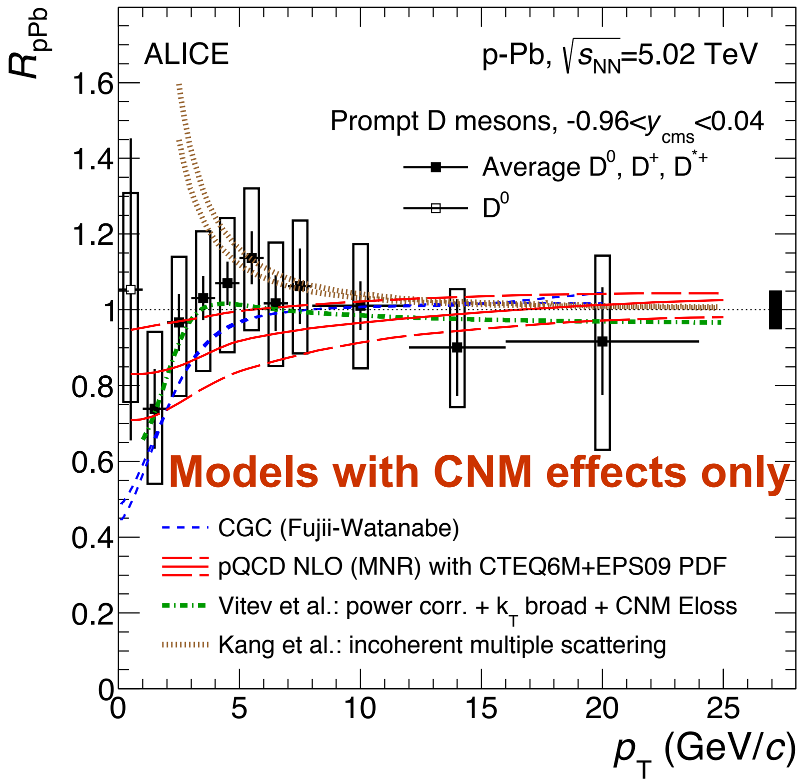


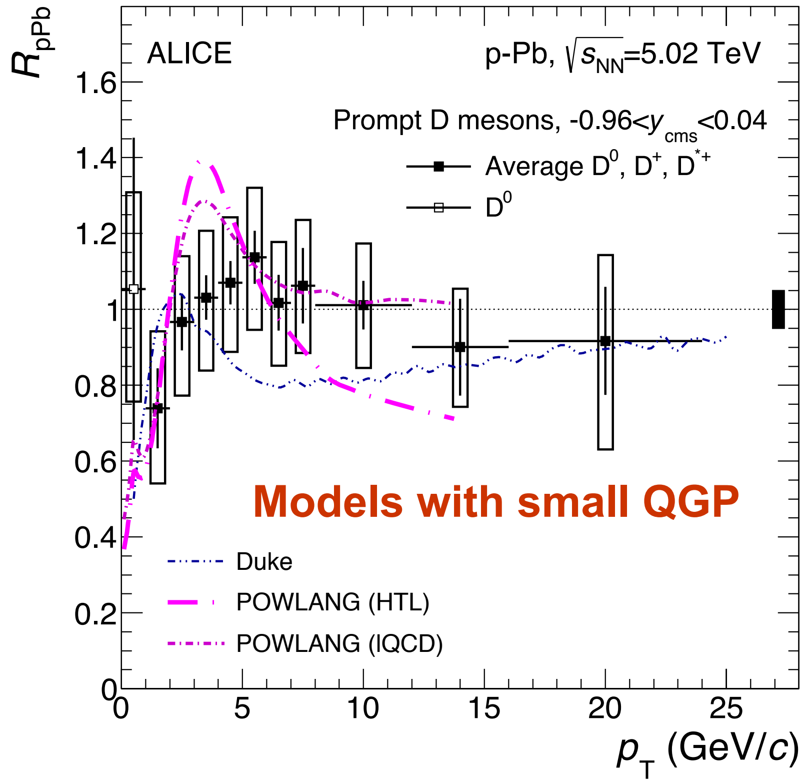
- D-meson R_{pA} shows consistency with unity
- High-p_T suppression of production yield in Pb-Pb is a **final state effect**

→ Due to interactions of charm quarks with the QCD medium

Open charm R_{pPb} vs. models

ALICE, JHEP in press (arXiv:1605.07569), Phys. Rev. Lett. 113 (2014) 232301

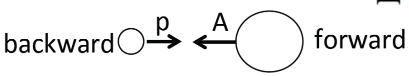




- R_{pA} (measured down to $p_T = 0$) compatible with unity; no centrality dependence (not shown)
  - Consistent with predictions from shadowing and CGC model
- Data disfavour suppression larger than 15% at high p_T

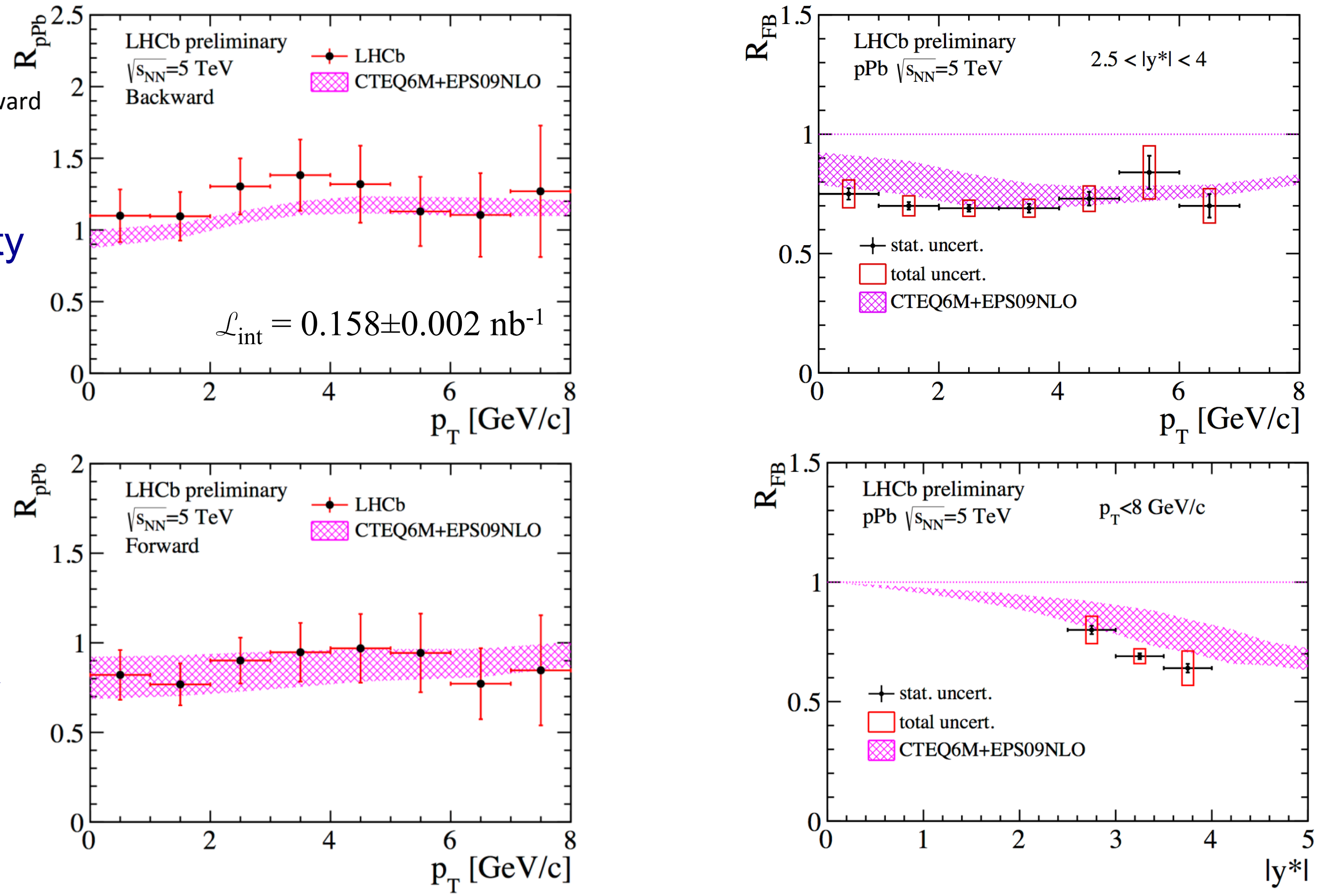
Prompt D^0 mesons at for/backward rapidity

LHCb-CONF-2016-003



Backward rapidity
-2.5 > y > -4.0
(Pb-going side)

Forward rapidity
2.5 < y < 4.0
(p-going side)



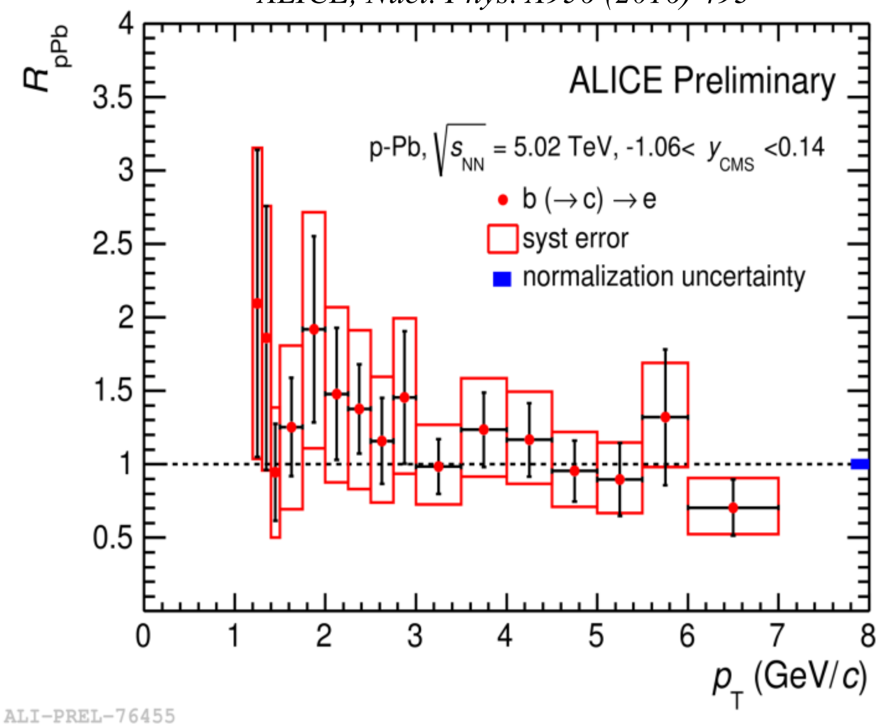
- Charm production described by pQCD calculations including nPDF
- Large asymmetry in forward-backward production is observed, suggesting non negligible CNM effect
- Indication that data is slightly more suppressed at high-y*

Open beauty R_{pPb}

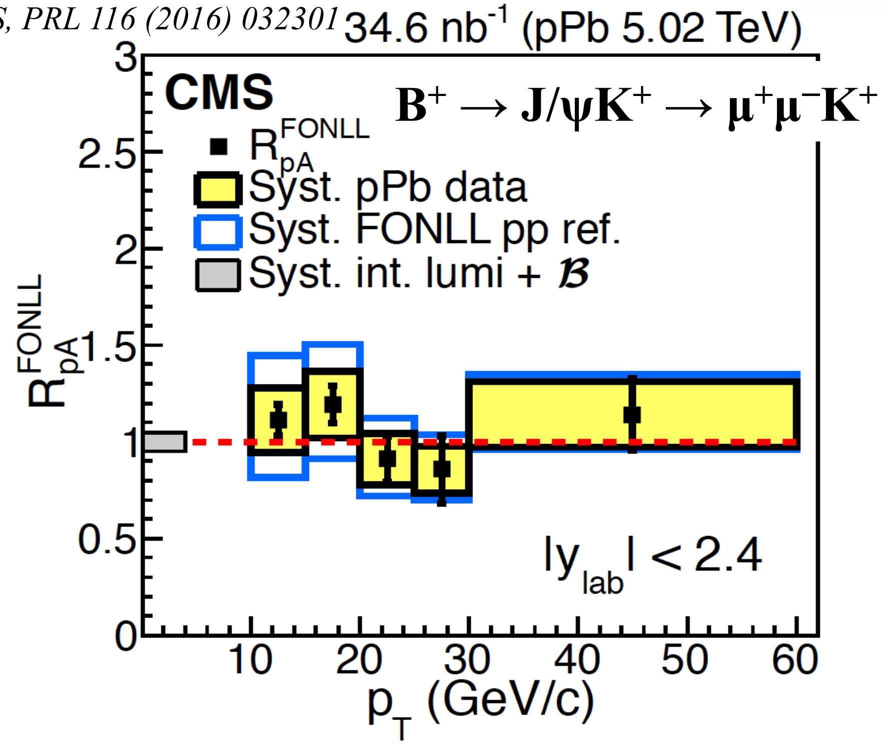
b-decay electrons

B mesons

ALICE, Nucl. Phys. A956 (2016) 493



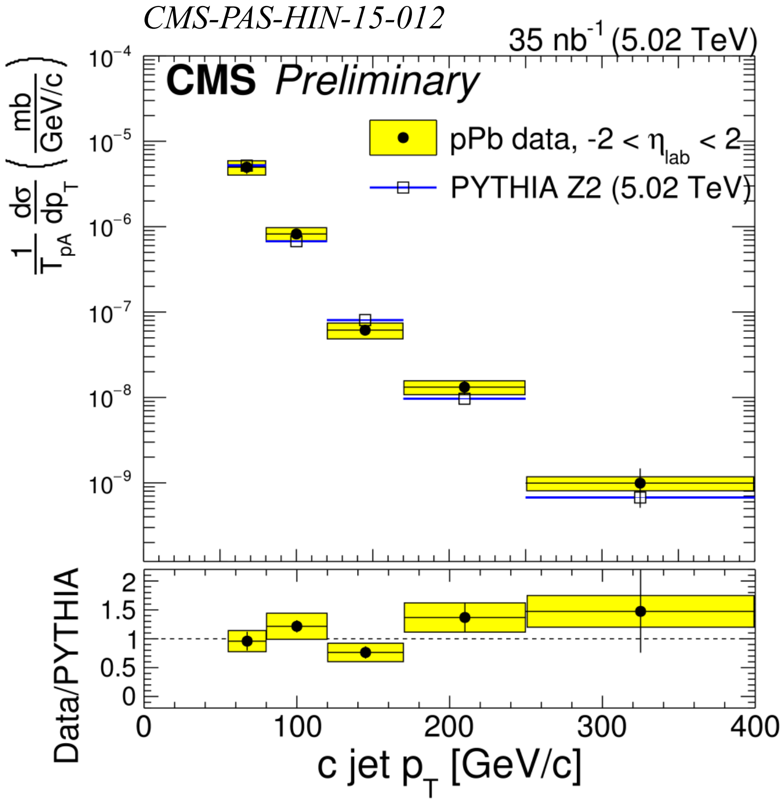
CMS, PRL 116 (2016) 032301



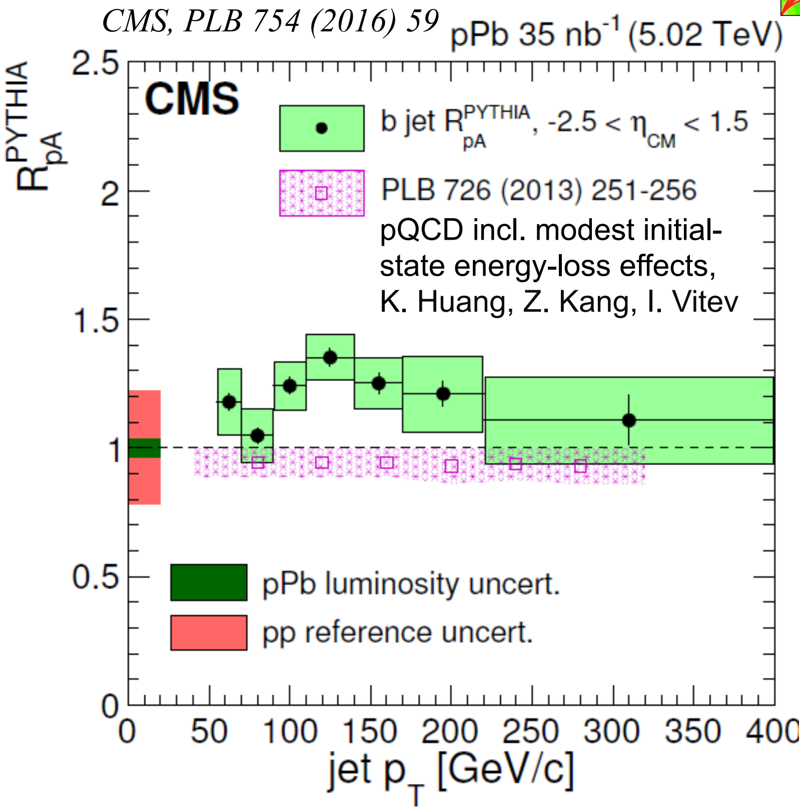
- R_{pPb} of beauty-decay electrons at low p_T and B mesons in $10 < p_T < 60$ GeV/c consistent with unity; same for B^0 and B_s^0 $R_{p\text{-}Pb}$ (not shown)
- No indication of significant cold nuclear matter effects on beauty production

Heavy-flavour jets

Charm jets



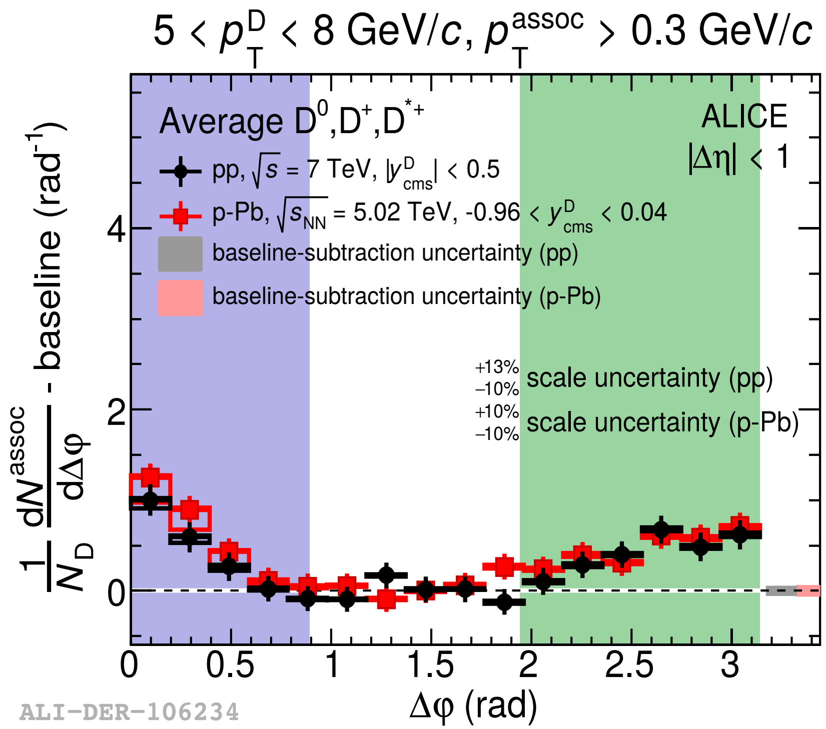
Beauty jets



- Charm-jet p_T differential cross section consistent with PYTHIA
- Inclusive beauty jet $R_{p\text{-}Pb}$ in agreement with pp reference
- No significant CNM effects on heavy-flavour production at high p_T

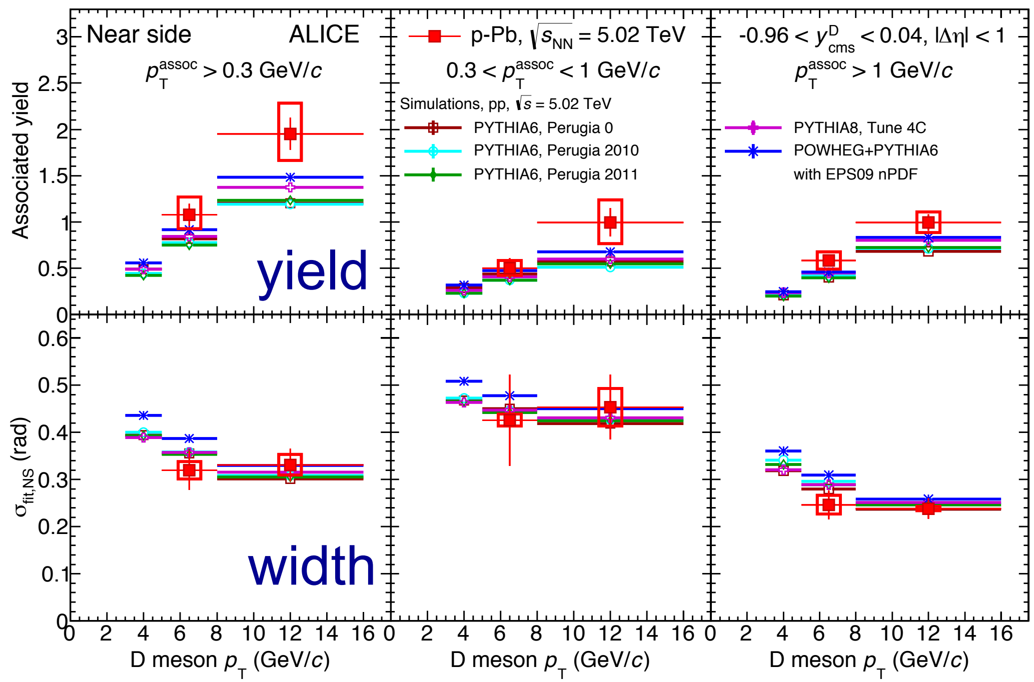
D-tagged charged particle azimuthal correlations

Δφ distribution



Near-side correlation yield/width

ALICE, subm. to EPJC (arXiv:1605.06963)



- First D-meson - charged hadron correlation measurement at the LHC
- Near-side correlation peak is sensitive to characteristics of jet containing D meson
- Similar yields for p-Pb and pp (not shown)
- Data well reproduced by PYTHIA (in all kinematic ranges)

Summary

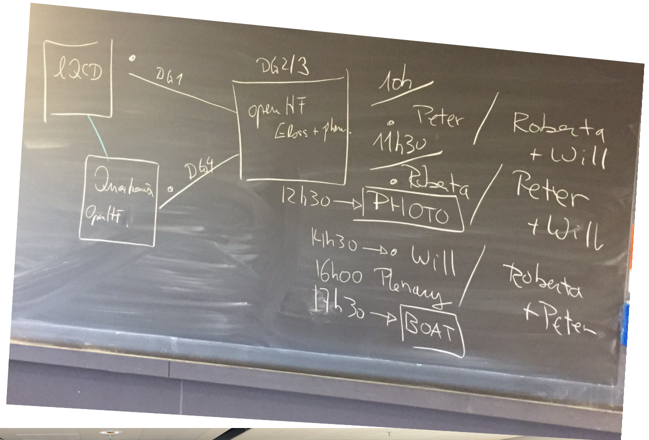
- Lots of pp data on heavy-flavour hadron production to test QCD and address open questions (e.g. double parton scattering)
- Heavy quarks are particularly good probes to study transport properties (e.g. drag and diffusion coefficient) in Pb-Pb
  - R_{AA} and v_2 of prompt D mesons and single leptons
    - strong suppression of the yield at high p_T (6-10 GeV/c) observed in central collisions → more insight on energy loss mechanisms
    - non-zero elliptic flow → suggest strong re-interactions within the medium
  - Quark-mass dependence: **$R_{AA}(\pi) \sim R_{AA}$(D, single leptons) < R_{AA}(B, B→J/ψ)**
  - Precision measurements in extended p_T ranges needed to further constraint theoretical model calculations (**note limitations!**)
- Open heavy-flavour results from p-Pb
  - No indication for substantial modification due to cold nuclear matter effects (except for quarkonia, not discussed)
- Many more exciting results ahead of us
  - Pb-Pb data from Run-2 at $\sqrt{s_{NN}}$ = 5.02 TeV and after upgrades in 2019/20
  - p-Pb data taking at $\sqrt{s_{NN}}$ = 5.02 and 8 TeV in 2016

Lorentz workshop: future directions of the field

Goals

- Develop common understanding of implications and identify open questions left by experiment and theory
- Develop strategies (for the upcoming ~5 years)

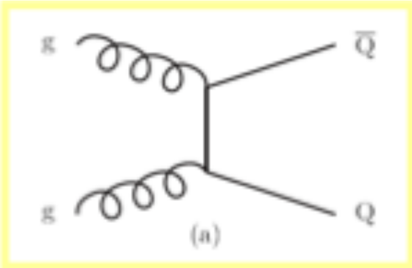
Dedicated discussion groups



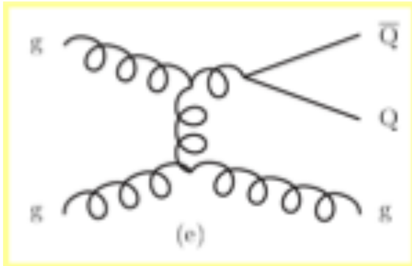
Future directions

- Further development of the understanding of pp reference
    - Disentangle contribution from different production mechanisms (higher order processes)

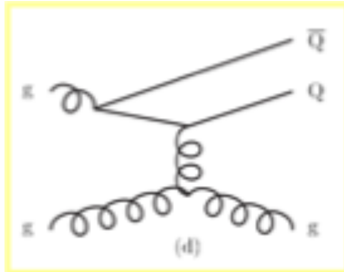
E. Norrbin and T. Sjostrand, Eur. Phys. J. C17, 137 (2000)



Pair production (LO)



Gluon splitting (NLO)



Flavour excitation (NLO)

- Experimental separation of radiative E_{loss} and collisional E_{loss} (using e.g. two heavy-flavour particle correlations and di-jets)
- Fully explore beauty probe: differential R_{AA}, v_2 and b-tagged correlations and jets
- Study heavy-flavour baryons (e,g. Λ_c^+ and Λ_b^0) to address hadronisation mechanisms