Understanding the Quark-Gluon Plasma

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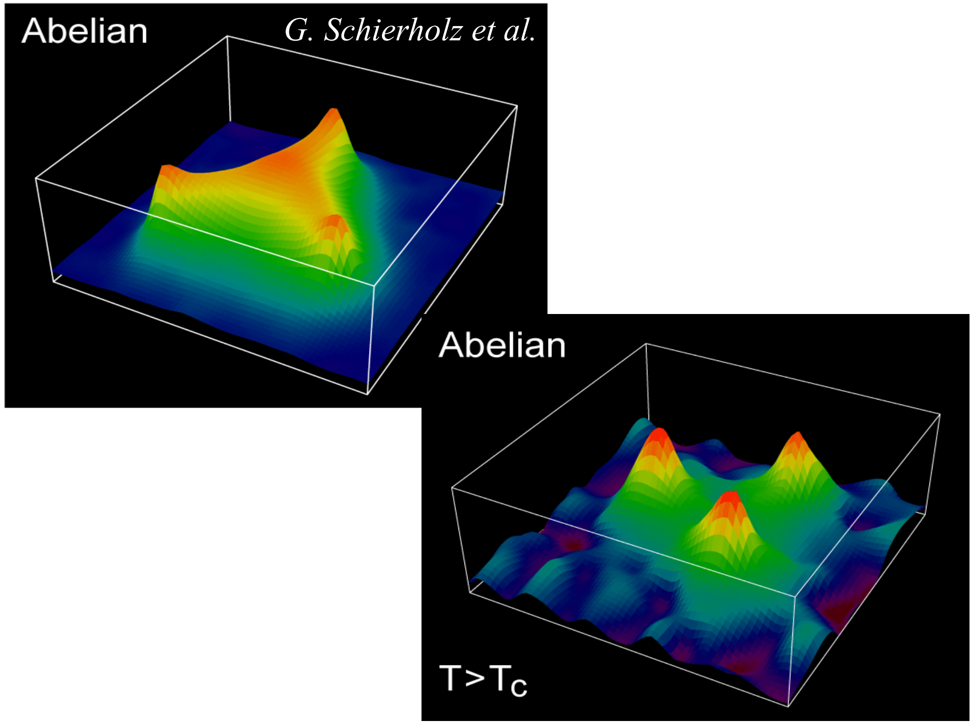
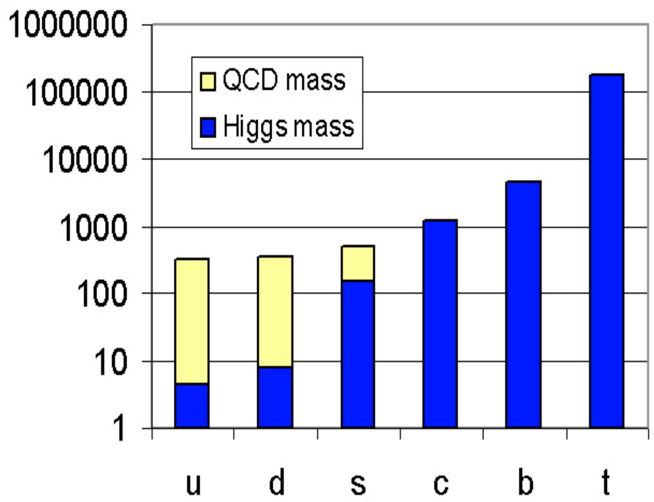
Outline

- Introduction
- Probes: focus on fully reconstructed D and B mesons
  - pp: test QCD and important baseline for heavy-ion measurements
  - A-A: study hot QCD matter (final state); determine medium properties
    - Open heavy flavour (charm and beauty) allows study of the dynamical properties of QCD matter (drag and diffusion coefficient) and degree of thermalisation
  - p-A: study cold nuclear matter effects (initial state)
- Summary and outlook

Quark-Gluon Plasma phase

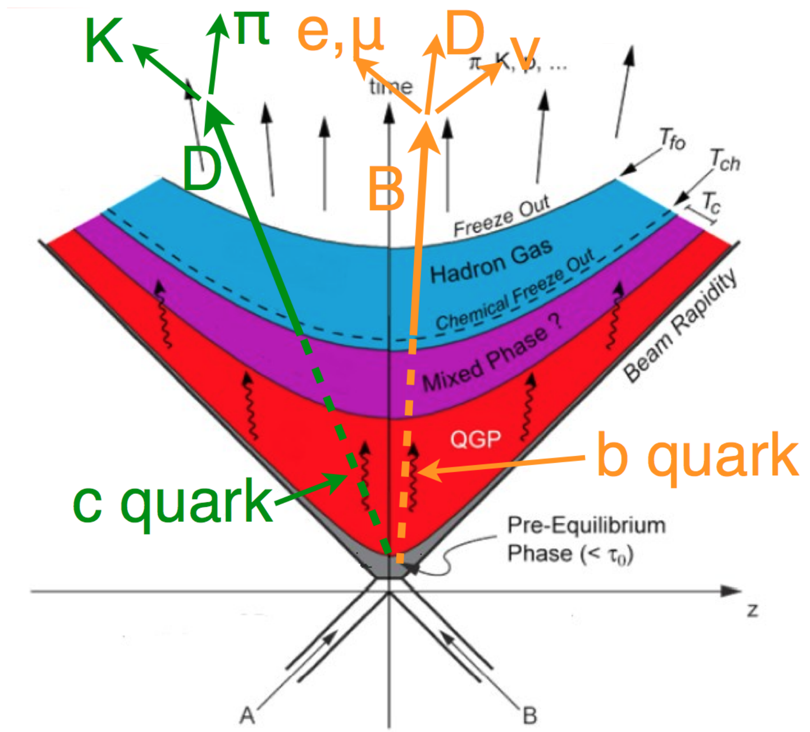
- Deconfined strongly interacting matter with color degrees of freedom
- QGP properties are in principle calculable from the QCD Lagrangian using lattice QCD
- Restoration of chiral symmetry breaking: Hadrons are much heavier than their constituents

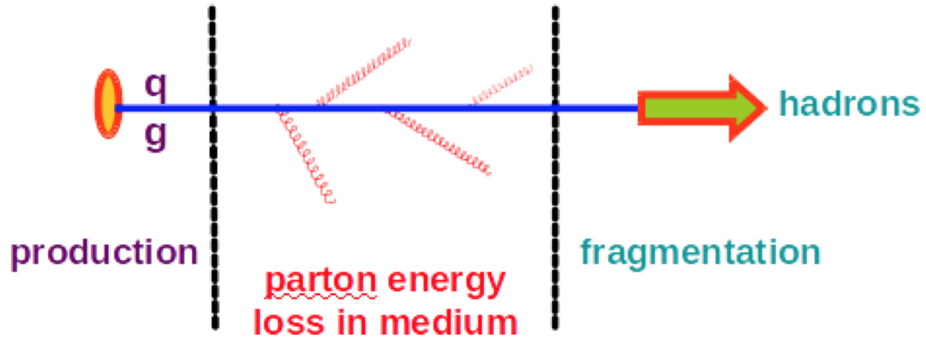




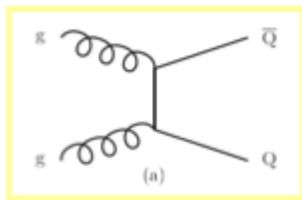
B. Müller, Nucl. Phys. A750 (2005) 84

Heavy quarks as probes



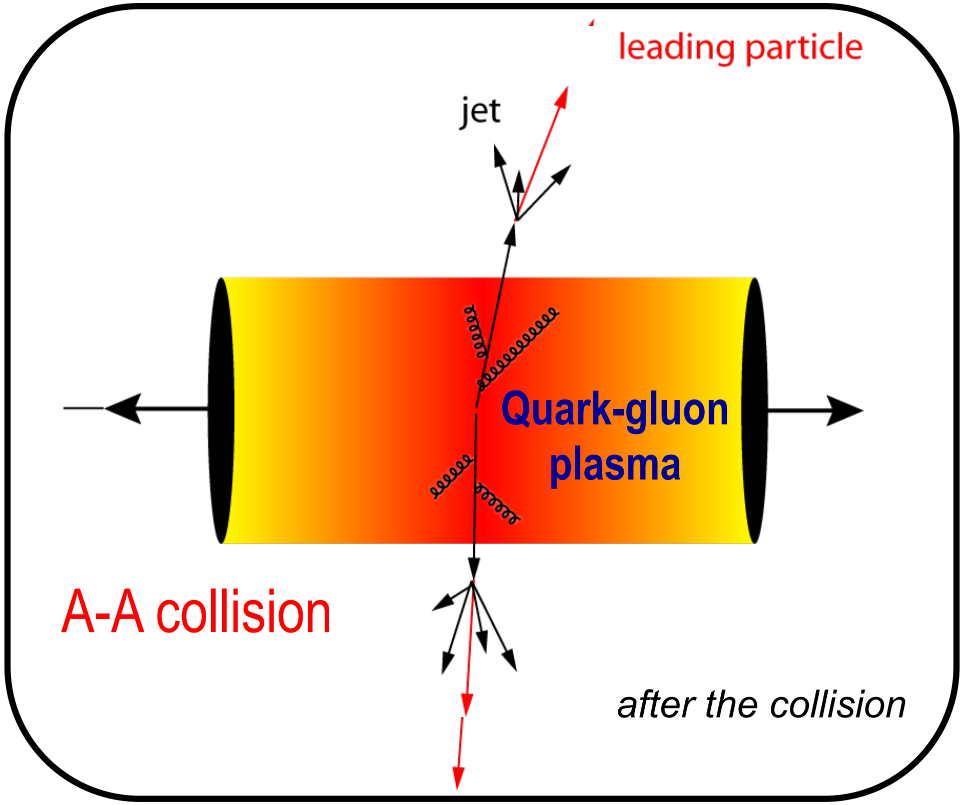


Important to understand interplay between production, interaction with medium, and fragmentation



- Heavy quarks produced in initial hard scattering processes
- Time scale: charm and beauty are produced before thermalised plasma phase
- Heavy flavors experience the full evolution of the medium → medium transport coefficients

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 $\tau \sim 1/2m_Q$

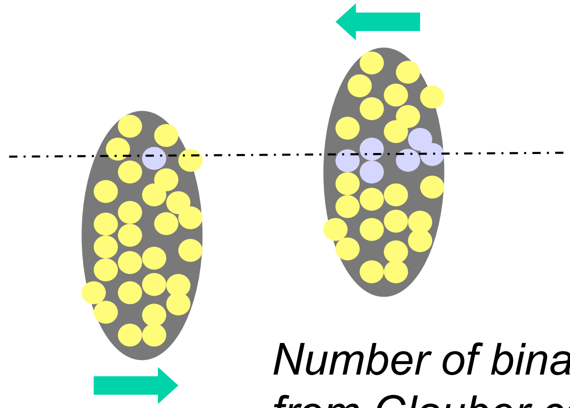
  - hard processes serve as calibrated probe (pQCD)
  - partons traverse through the medium and interact strongly
  - suppression pattern provides density measurement

General picture:

- Parton energy loss through medium-induced gluon radiation
- Collisions with medium constituents

Quantification of medium effects

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

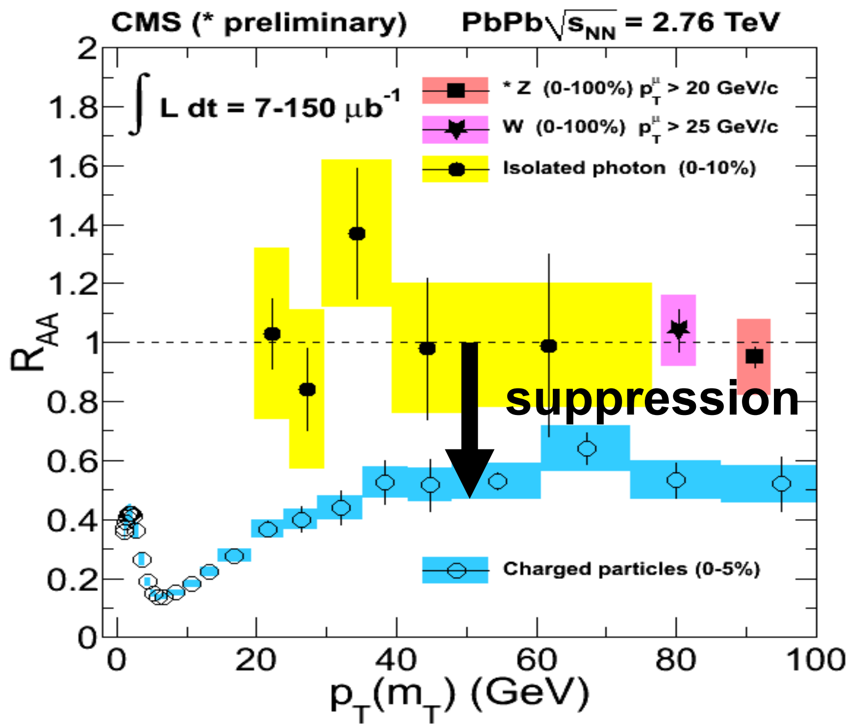


Number of binary collisions from Glauber calculations

Nuclear modification factor:

Deviations from binary scaling of hard collisions

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

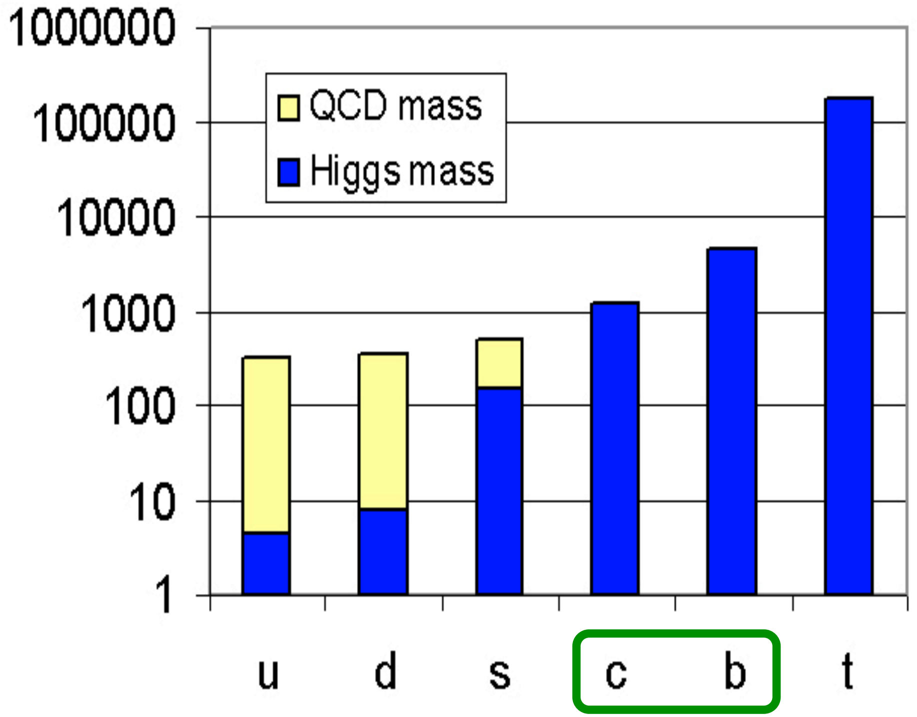


Expectation:

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

Heavy quark mass

B. Müller, Nucl. Phys. A750 (2005) 84



Formation time:

$\tau \sim 1/2m_Q \sim 0.1\text{fm} << \tau_{QGP} \sim 5\text{-}10\text{ fm}$

- 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

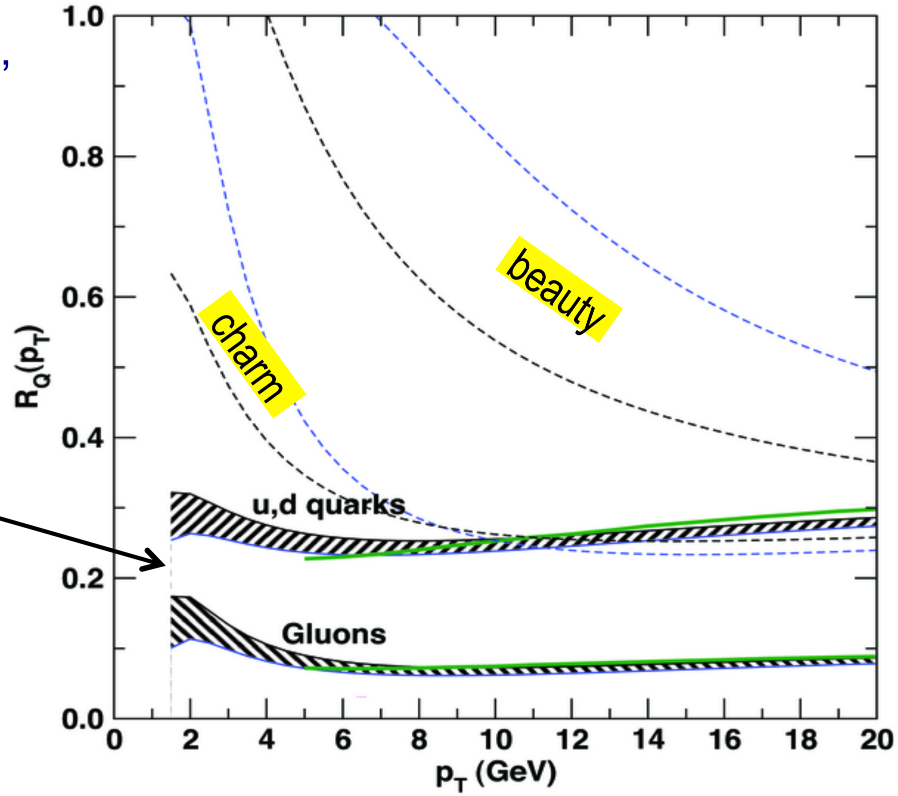
Radiative parton energy loss

- …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)

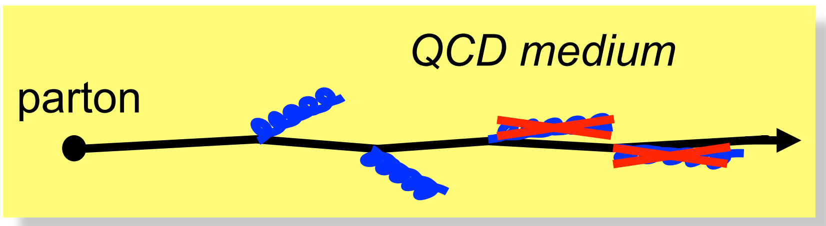
$$\langle \Delta E_{medium} \rangle \propto \alpha_S C_R \hat{q} L^2$$

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

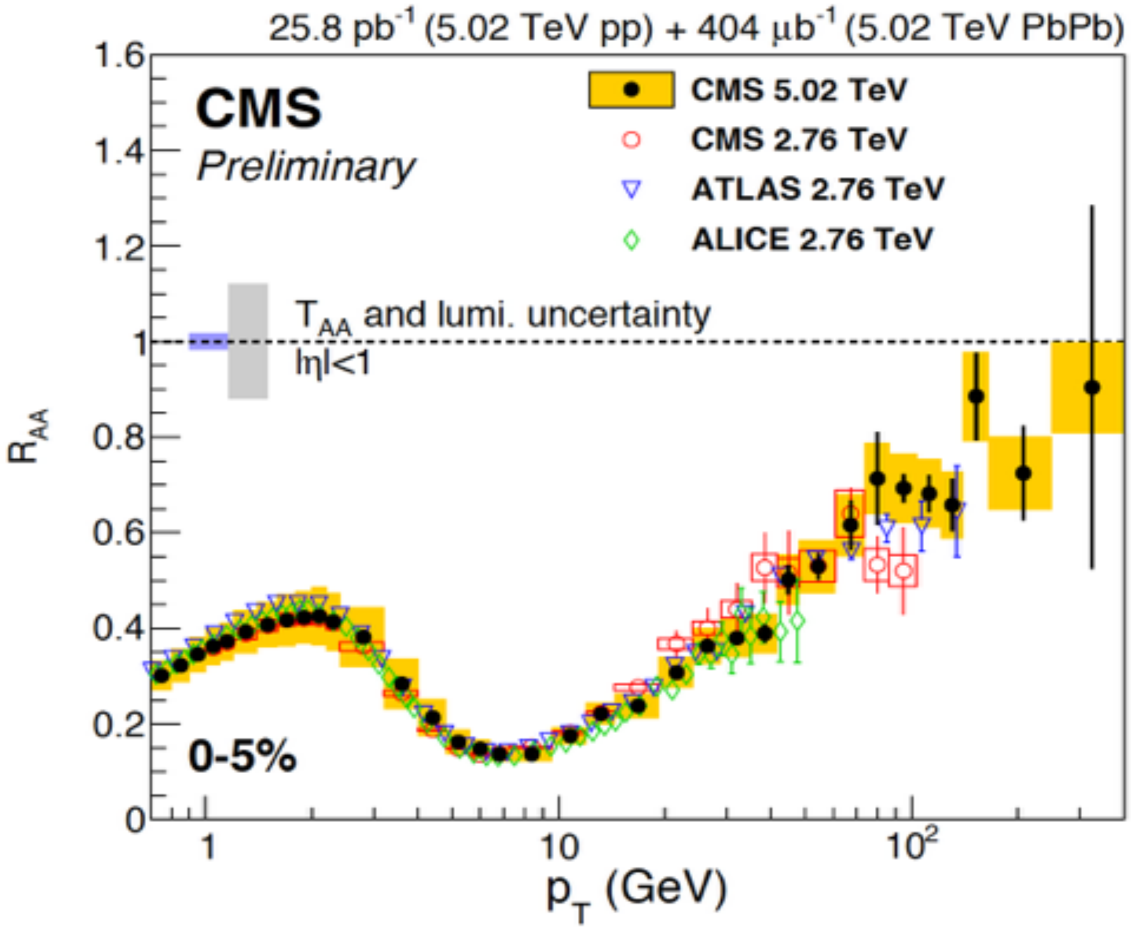


- Expectation: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

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

R_{AA} for inclusive charged hadrons

ATLAS, JHEP 09 (2015) 050 and CMS-PAS-HIN-15-015



- Measurement in a broad momentum range: $0.5 < p_T < 150$ GeV/c
- Strong suppression in most central Pb-Pb collisions
- Very good agreement between experiments
- Plateau at high p_T (?)

Detection of open heavy-flavour particles

1. Full reconstruction of open charm mesons

e.g.: $D^0 \rightarrow K^- + \pi^+$ BR = 3.93%, $c\tau$ = 123 μm

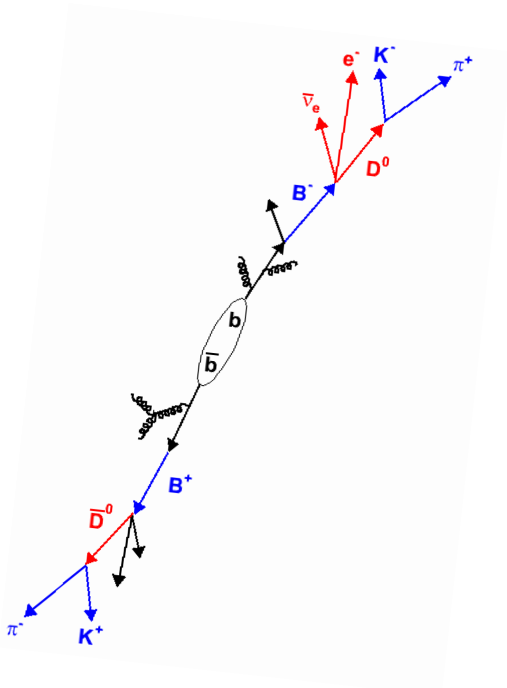
- direct clean probe: signal in invariant mass distribution
- difficulty: large combinatorial background especially in a high multiplicity environment
- mixed-event subtraction and/or vertex tracker needed

$f(c \rightarrow D^0) = 0.565 \pm 0.032$

$f(c \rightarrow D^+) = 0.246 \pm 0.020$

$f(c \rightarrow D^{*+}) = 0.224 \pm 0.028$

$f(c \rightarrow D_s^+) = 0.080 \pm 0.017$



2. Semi-leptonic decay of D and B mesons

$c \rightarrow$ lepton + X	BR = 9.6%
$D^0 \rightarrow e^+ + X$	BR = 6.87%
$D^0 \rightarrow \mu^+ + X$	BR = 6.5%
$b \rightarrow$ lepton + X	BR = 10.9%

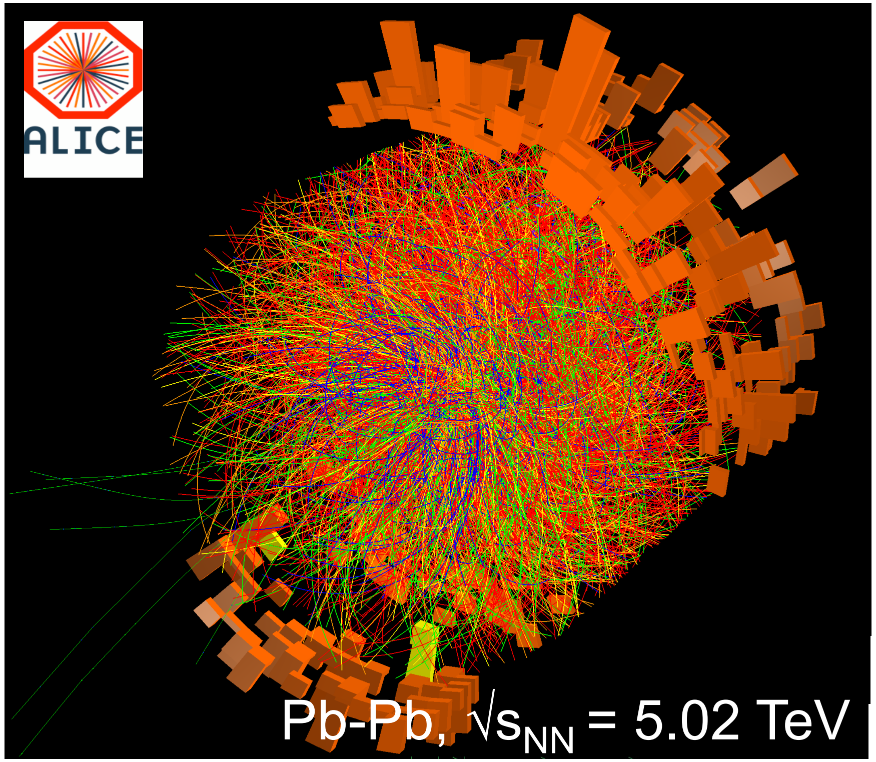
- robust electron trigger
- needs handle on photonic electron background

3. Beauty via non-prompt J/ψ and hadronic decays

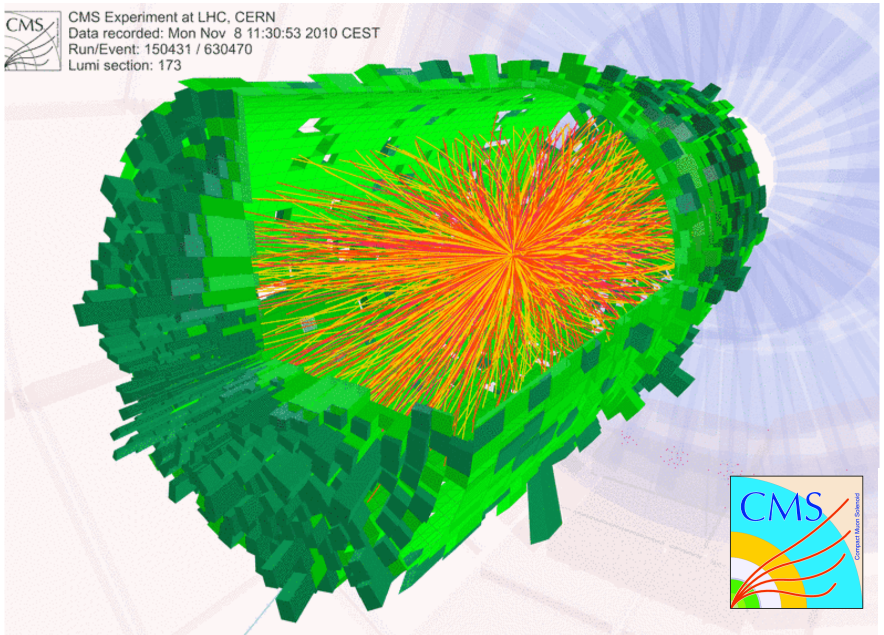
Impact parameter resolution

- STAR: 30μm @ p = 1 GeV/c
- ALICE: 65μm @ p_T = 1 GeV/c
- ATLAS/CMS: 100μm @ p_T = 1 GeV/c

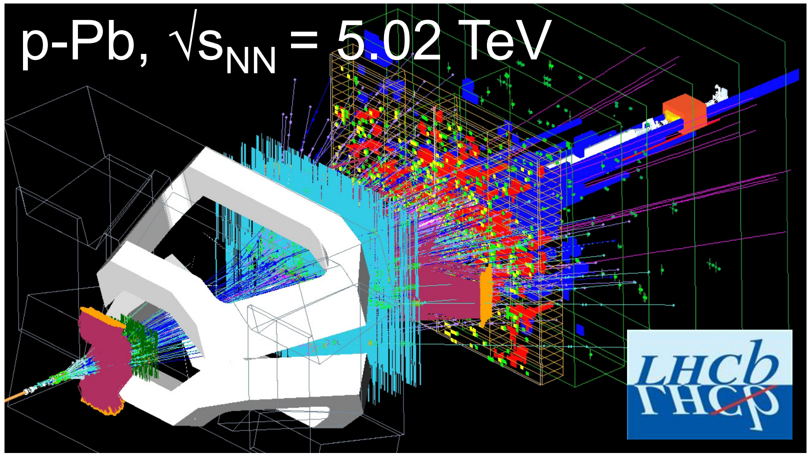
Typical event displays: LHC experiments



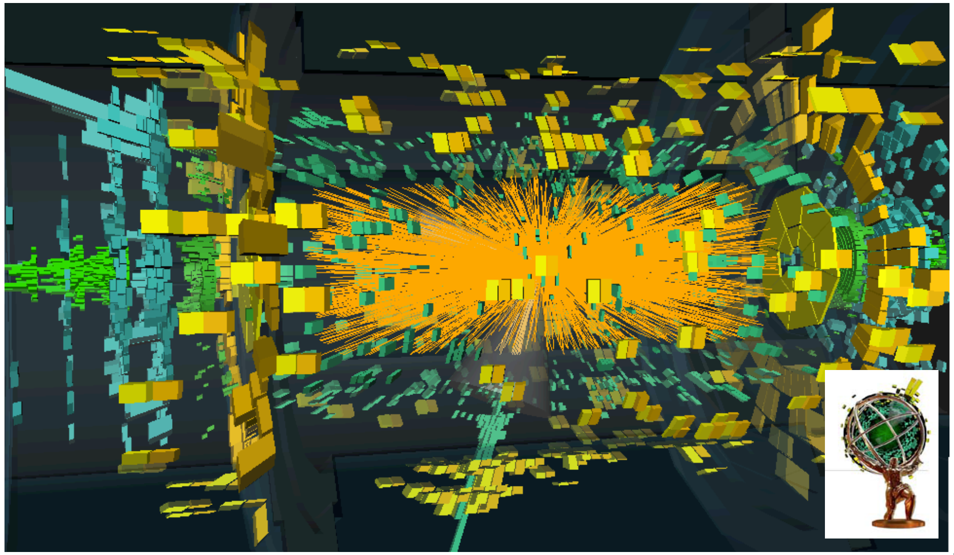
Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV



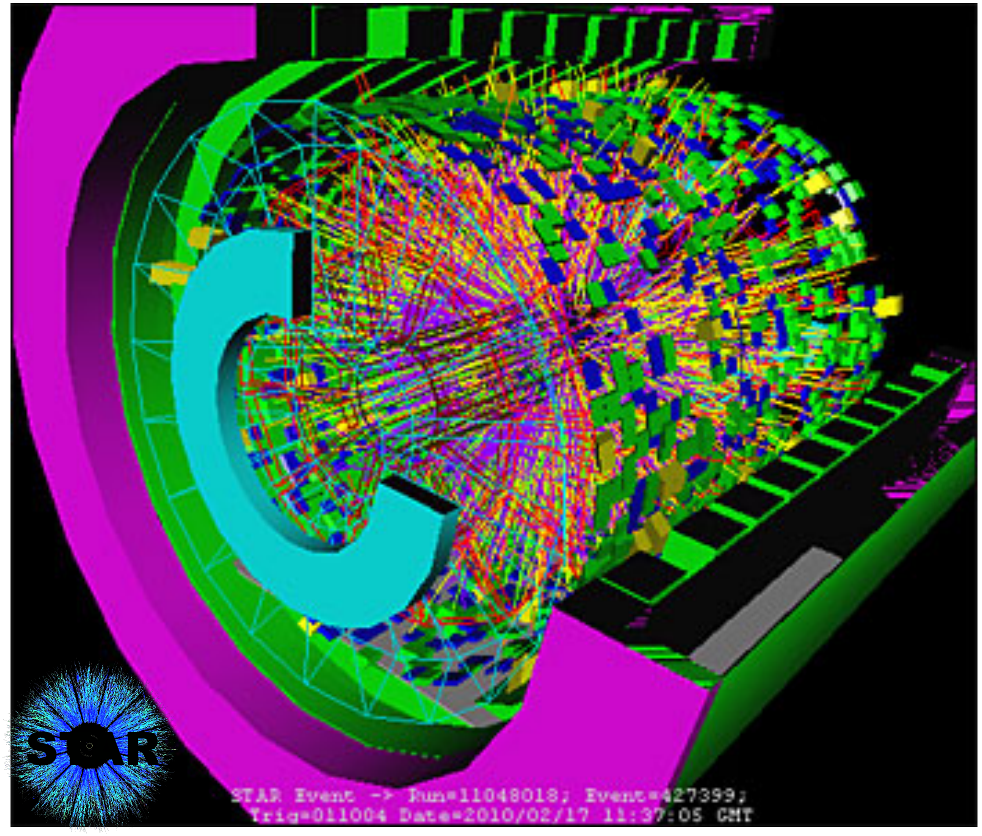
Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV

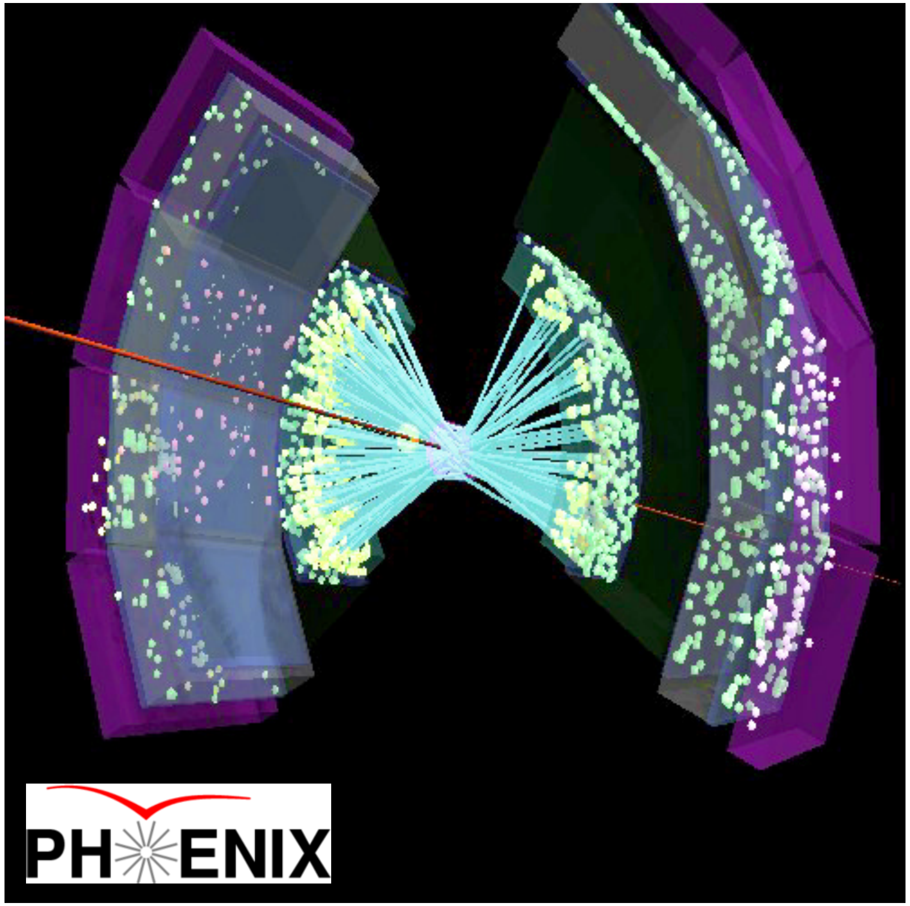


p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV



Typical event displays: RHIC experiments

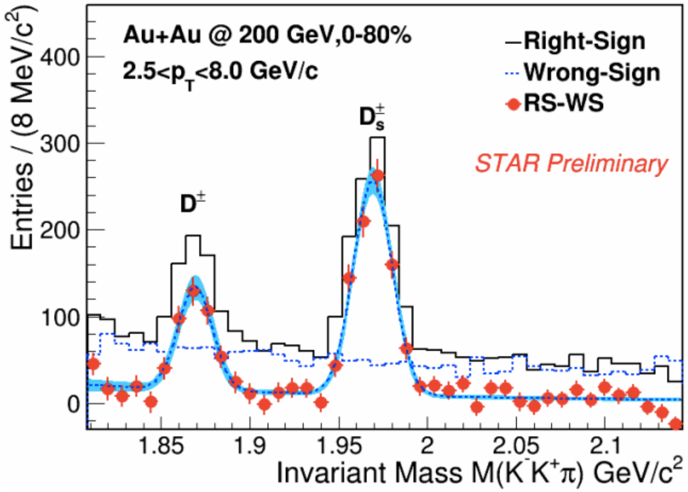




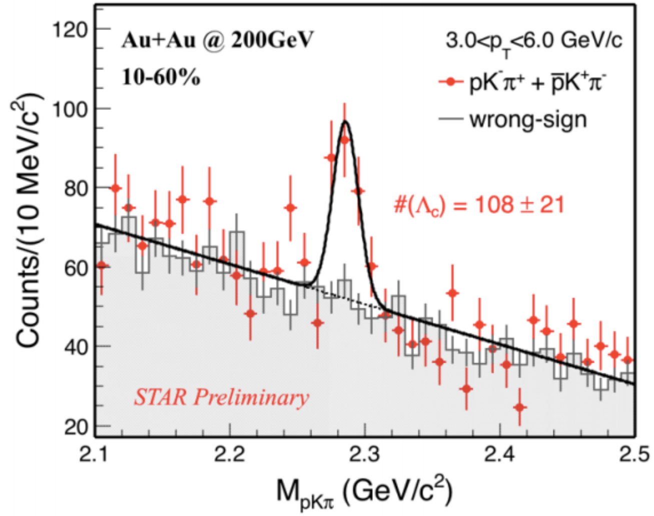
Au-Au, $\sqrt{s_{NN}}$ = 0.2 TeV

Exclusive reconstruction of heavy-flavour hadrons

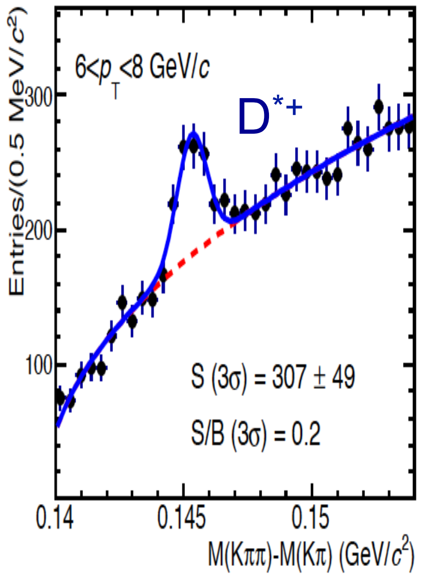
$D_s^+ \rightarrow K^+K^-\pi^+$ (BR = 5.5%)

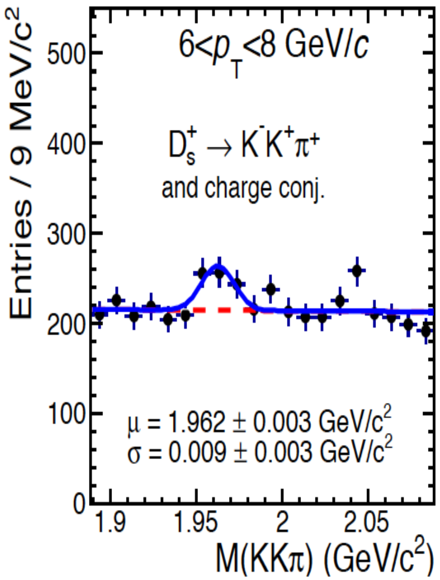


$\Lambda_c^+ \rightarrow pK^-\pi^+$ (BR = 6.35%)

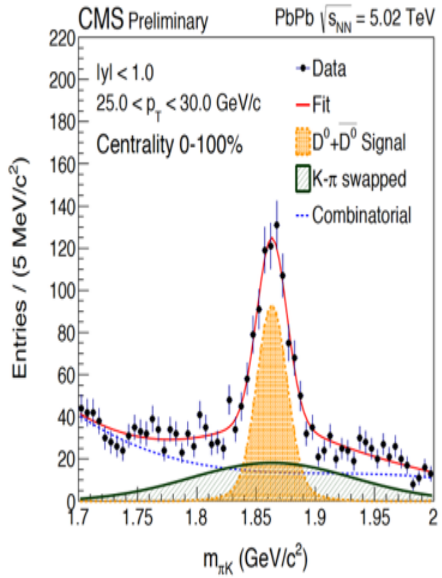


$D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+_s$ (BR = 67.7%x3.93%)

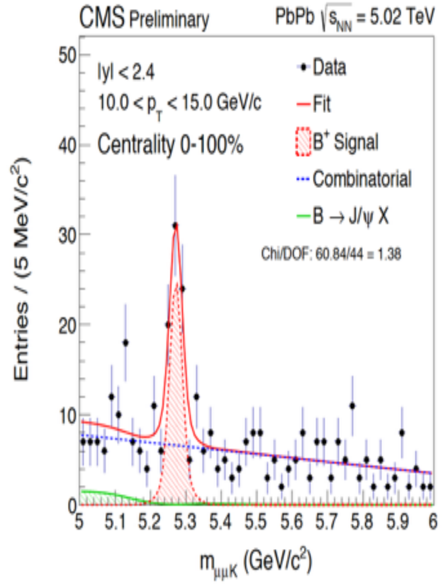




$D^0 \rightarrow K^-\pi^+$ (BR = 3.93%)



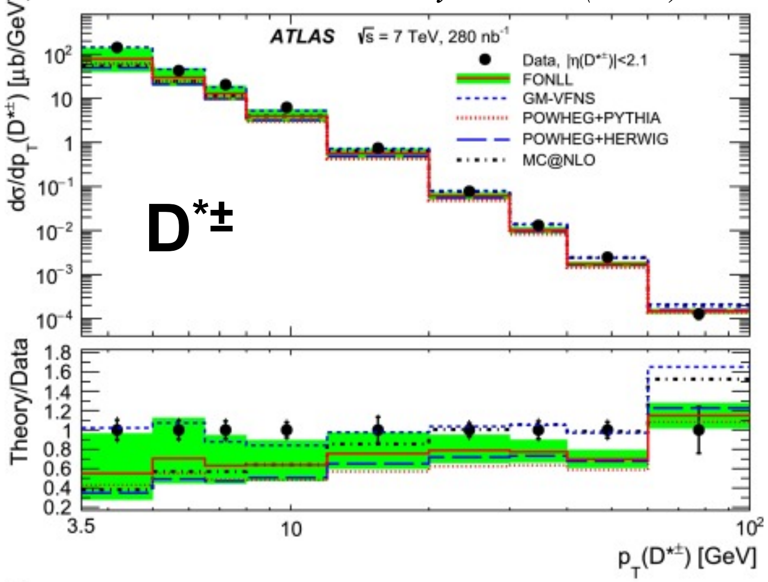
$B^+ \rightarrow J/\Psi(\rightarrow \mu^+\mu^-)K^+$ (BR = 10^{-3})

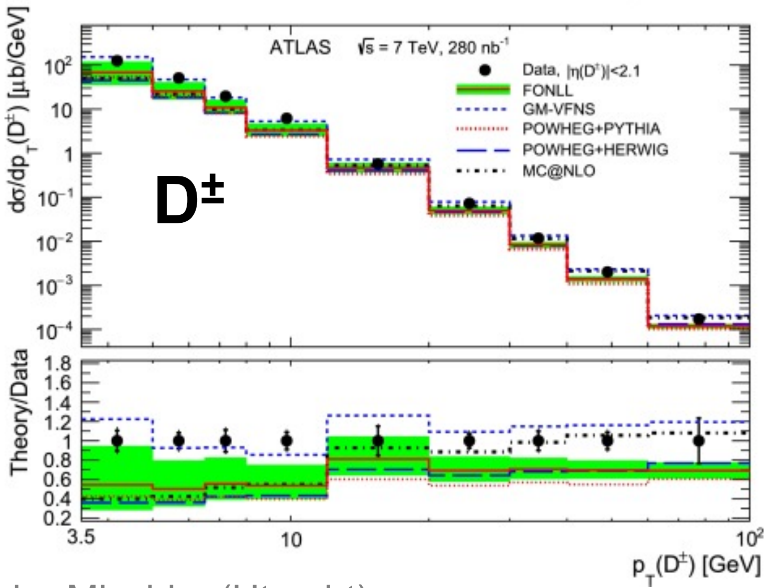


pp system: “QCD vacuum”

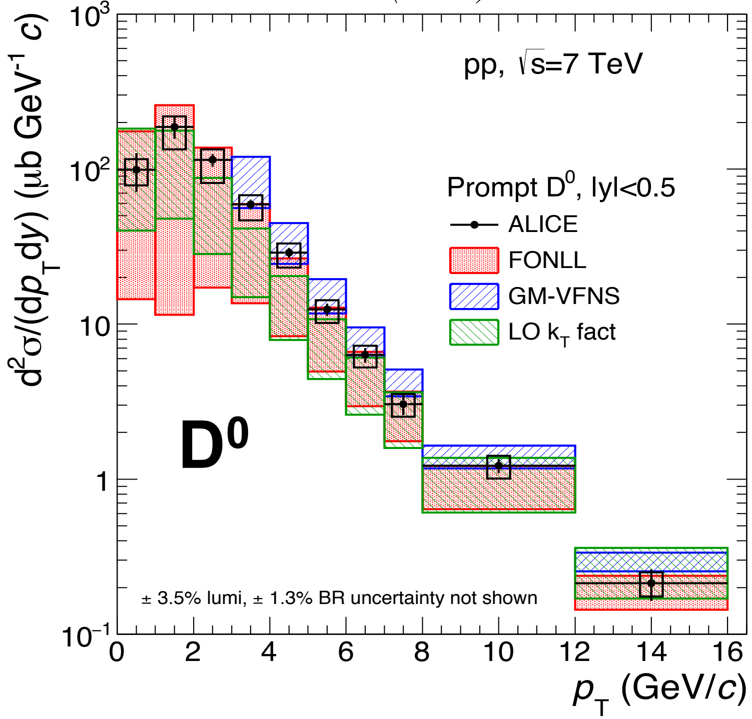
D-meson production x-section in pp at LHC

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





ALICE, Phys. Rev. C 94 (2016) 054908
and JHEP 1201 (2012) 128

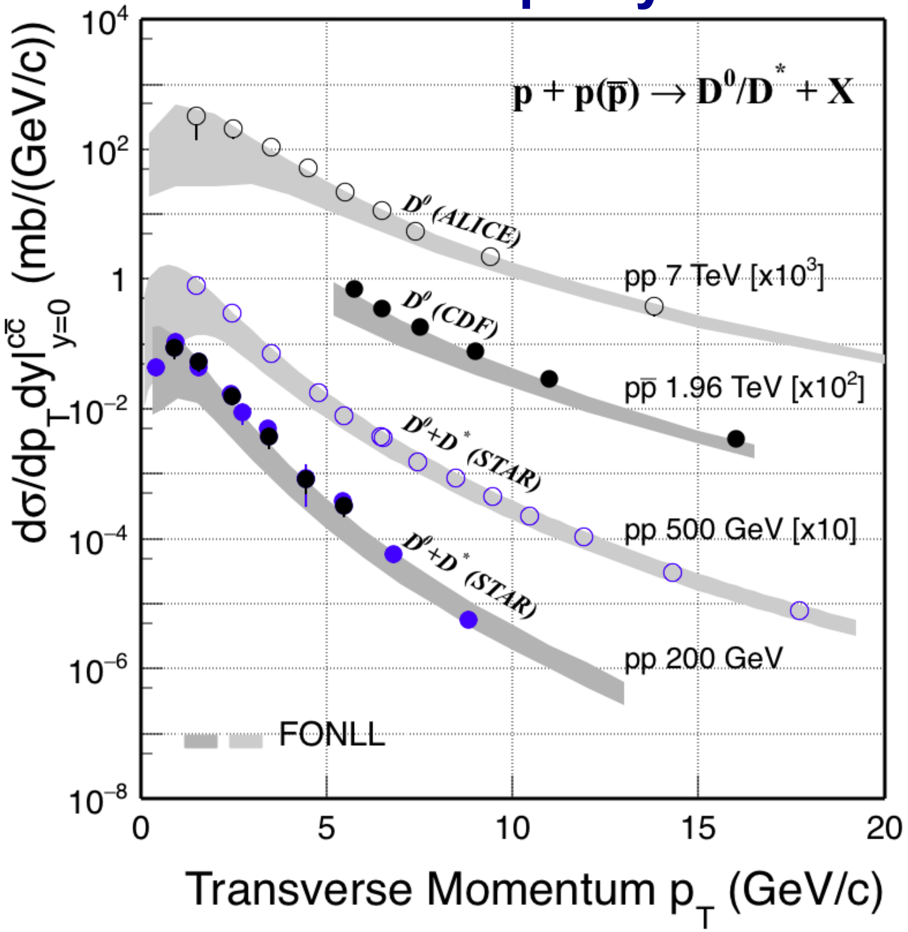


Multiplicity dependence also studied

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

Open charm production x-section in pp (cont'd)

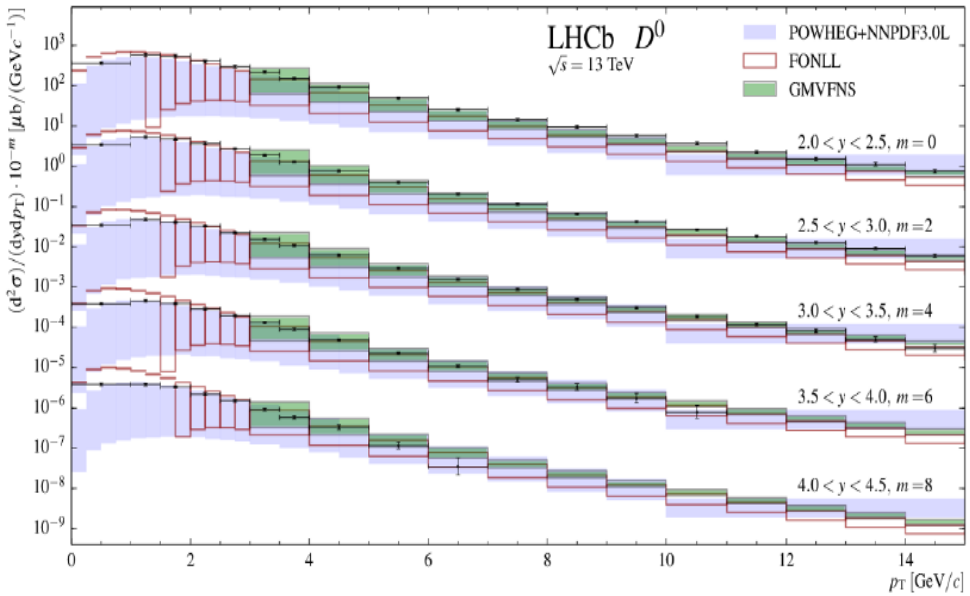
Mid-rapidity



Forward rapidities

double-differential D^0 cross-section in 13 TeV pp

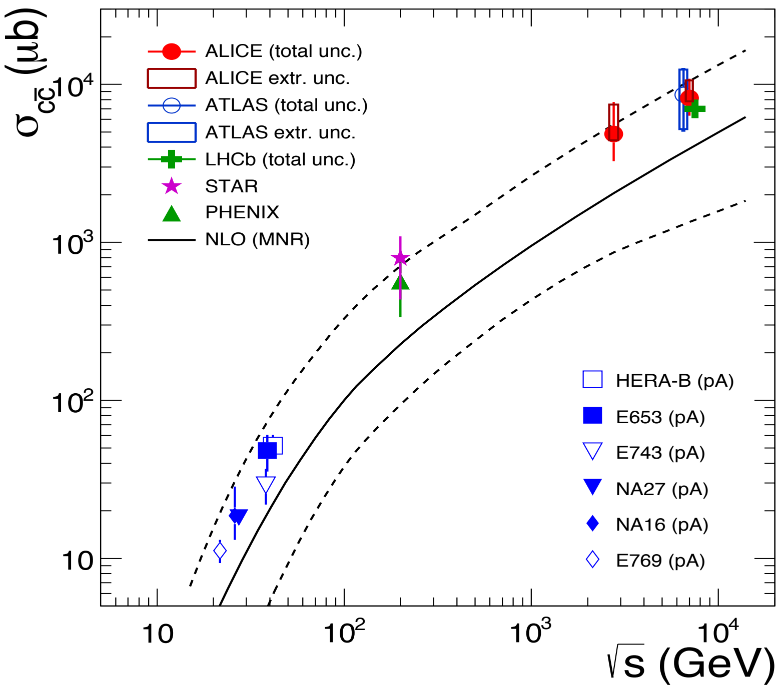
LHCb, JHEP 03 (2016) 159 (Errat.: JHEP 09 (2016) 013)



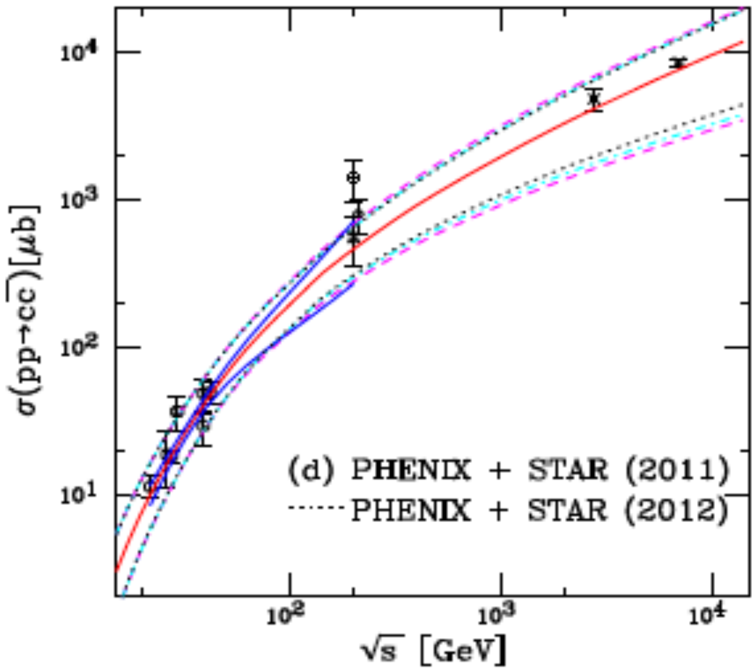
Consistency with NLO pQCD calculations within uncertainties, although systematically at the upper limit

Total charm production cross section in pp

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



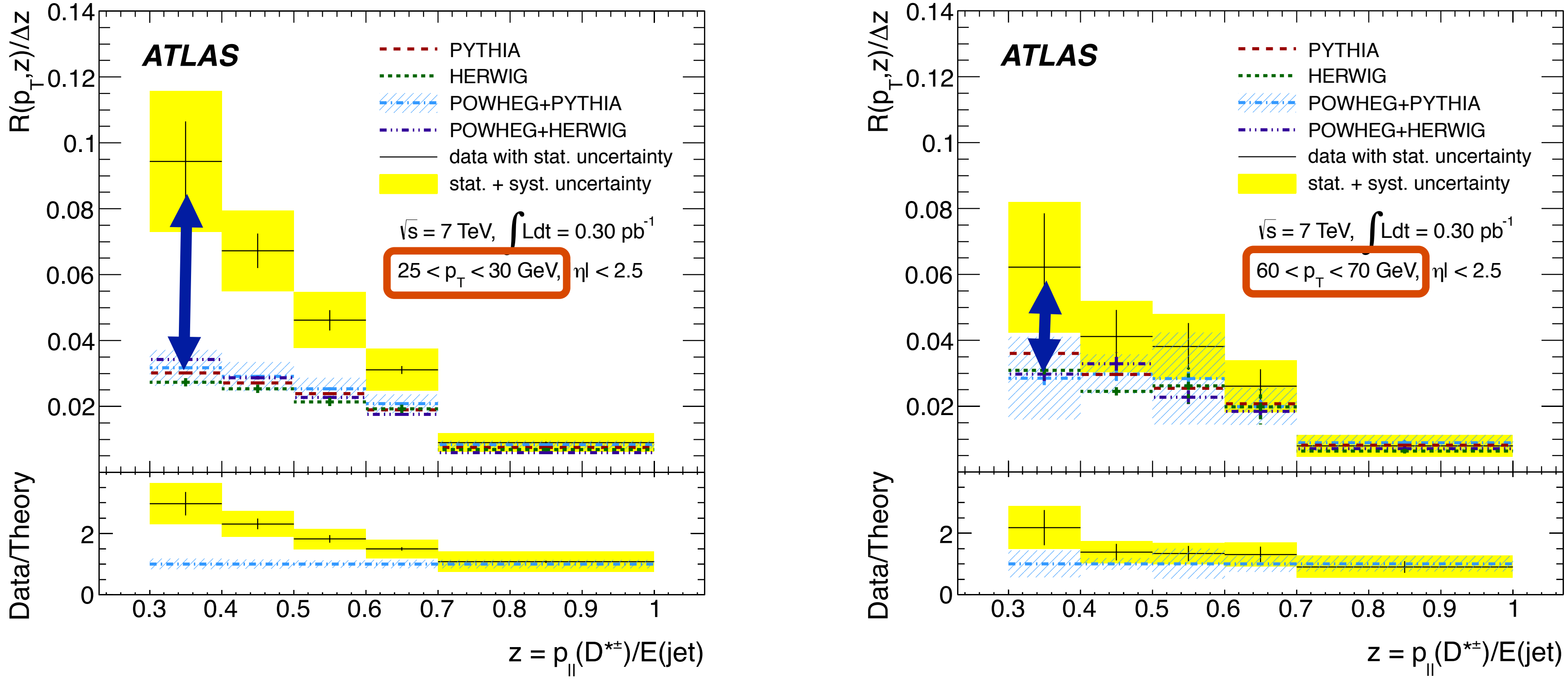
R.E. Nelson, R. Vogt and A.D. Frawley, Phys. Rev. C 87 (2013) 014908



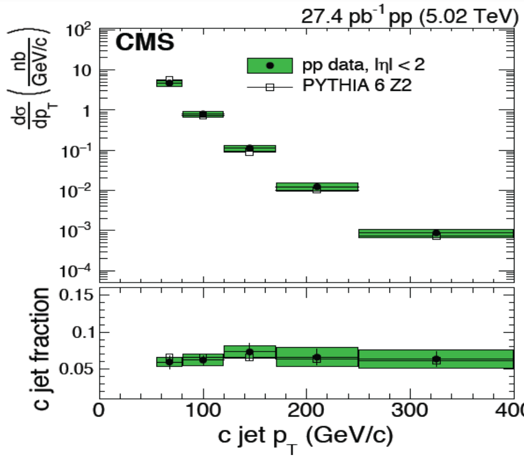
- Consistency with NLO pQCD calculations within uncertainties, although systematically at the upper limit
- 8 and 13 TeV data will provide further constraints
- Parton spectra from pQCD input for energy-loss models

‘D*± 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-p_T
- Indication that jet fragmentation into D*± mesons not well modeled in current MC generators

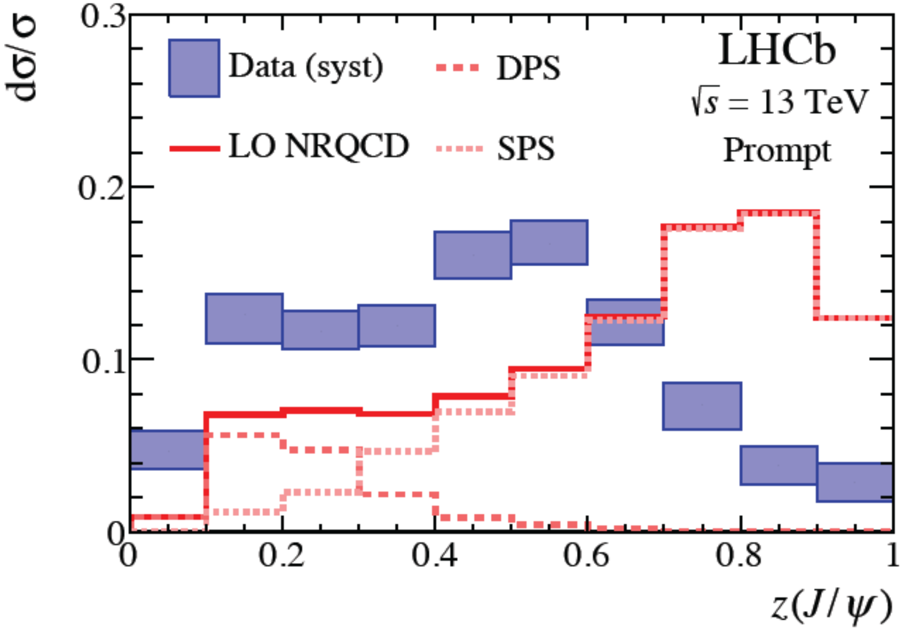


CMS, arXiv:1612.08972

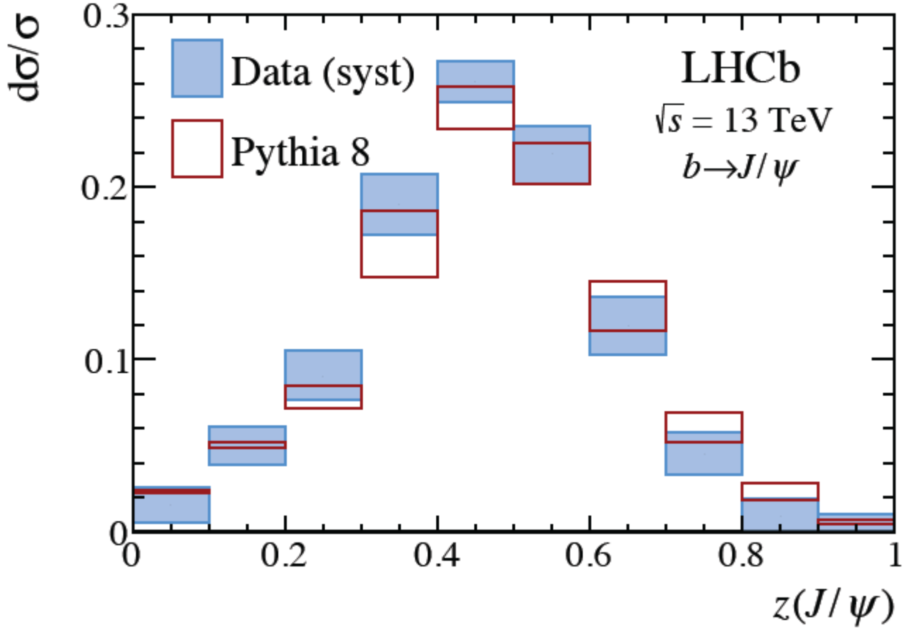
'J/ψ production in jets' in 13 TeV pp

LHCb, Phys. Rev. Lett. 118 (2017) 192001

Prompt J/ψ



B→J/ψ



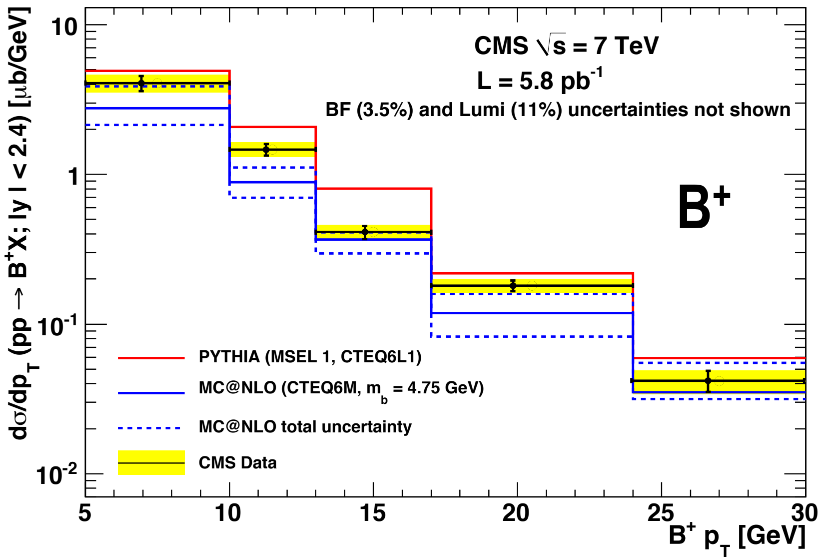
- J/ψ from beauty-hadron decays are consistent with expectations
- Prompt J/ψ production do *not* agree with predictions based on fixed-order QCD

$$z(J/\psi) = p_T(J/\psi)/p_T(\text{jet})$$

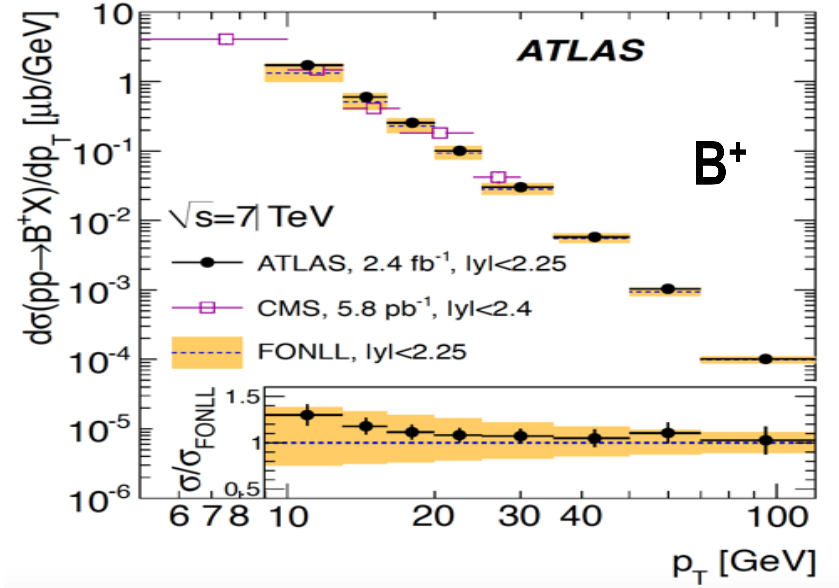
$p_T(\text{jet}) > 20$ GeV/c
$2.5 < \eta(\text{jet}) < 4.0$
$2.0 < \eta\,(J/\psi) < 4.5$

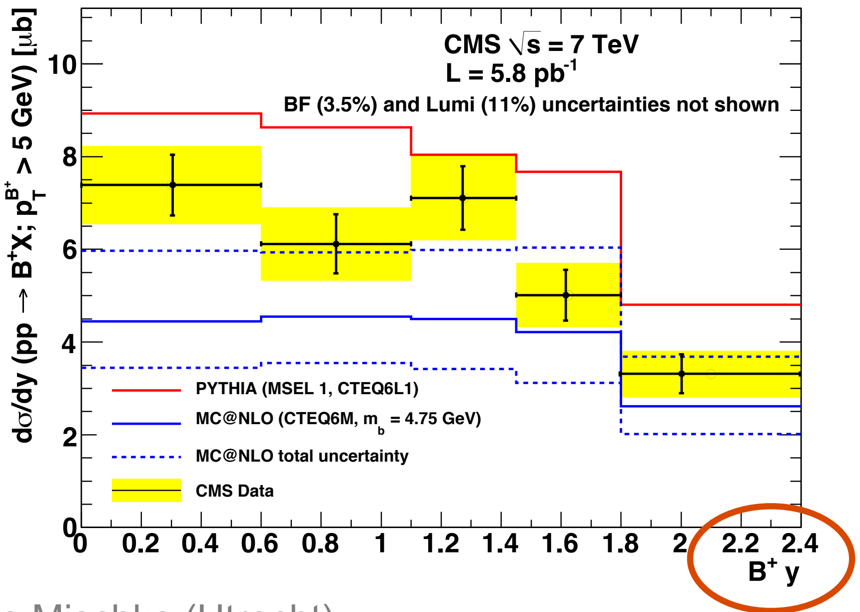
B production cross section in 7 TeV pp

Phys. Rev. Lett. 106 (2011) 112001

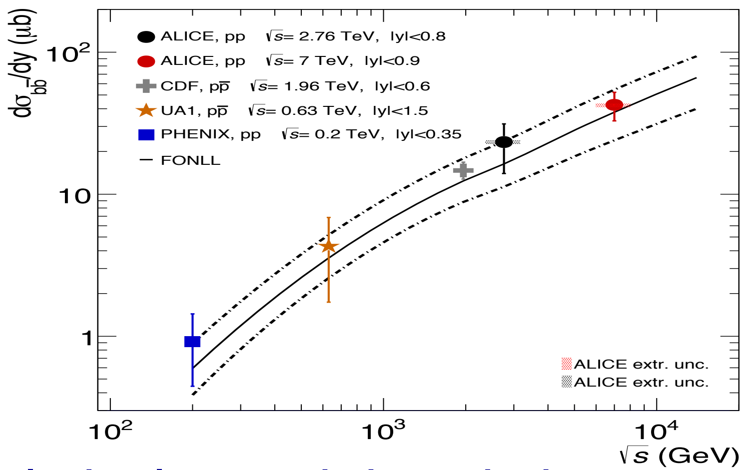


JHEP 10 (2013) 042



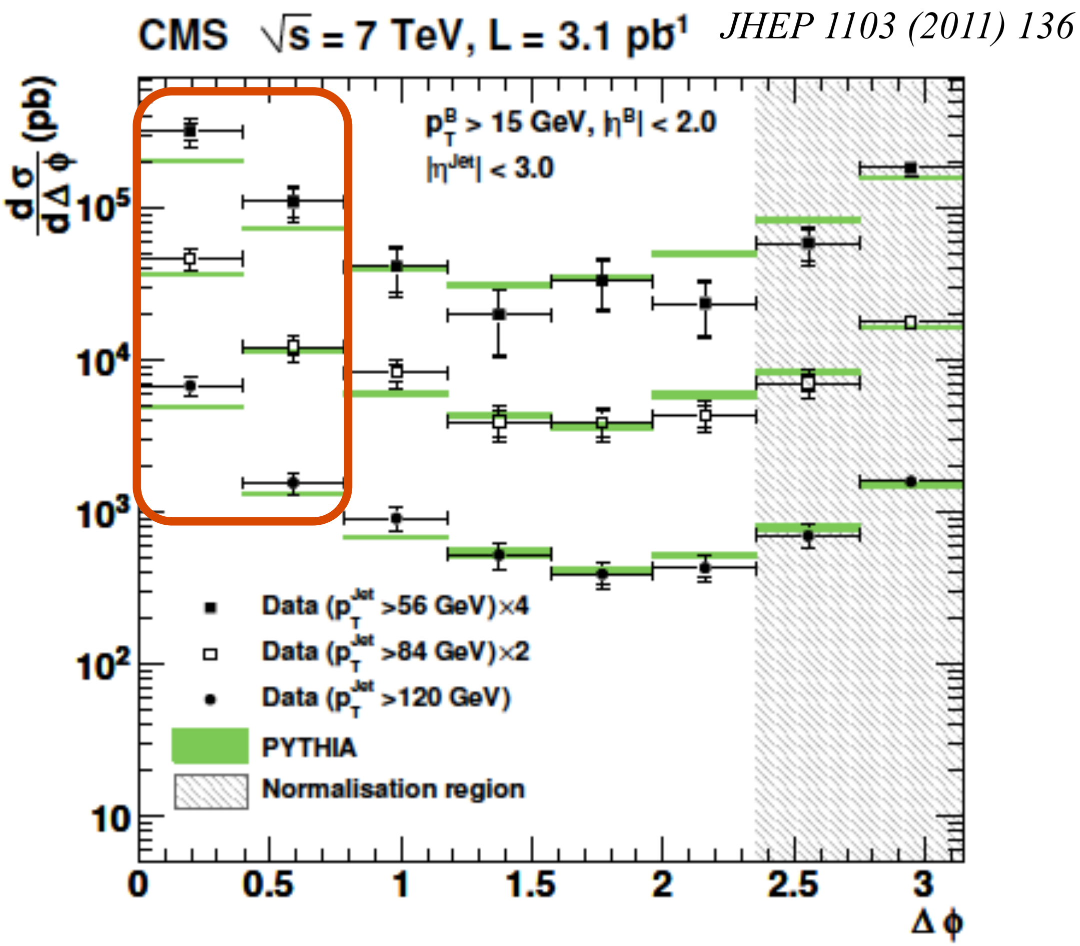


Phys. Lett. B 721 (2013) 13 and 738 (2014) 97



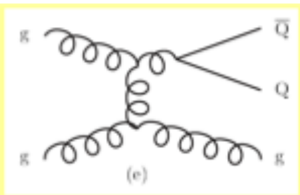
Relatively good description with NLO pQCD calculations

B-Bbar Δφ correlations in 7 TeV pp

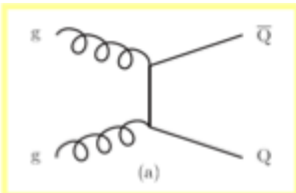


Gluon splitting contribution underestimated in PYTHIA

Gluon splitting



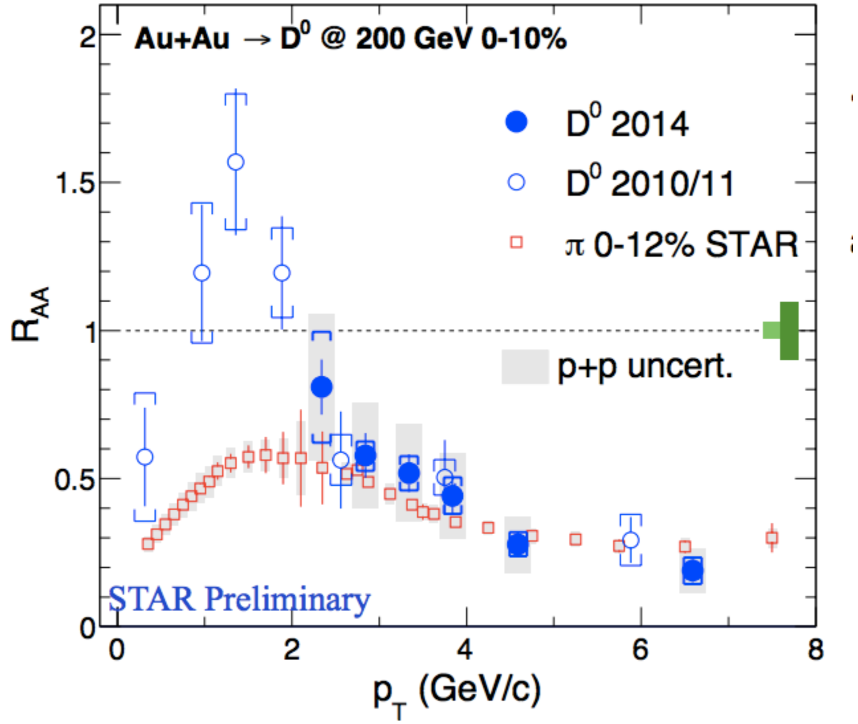
Flavour creation

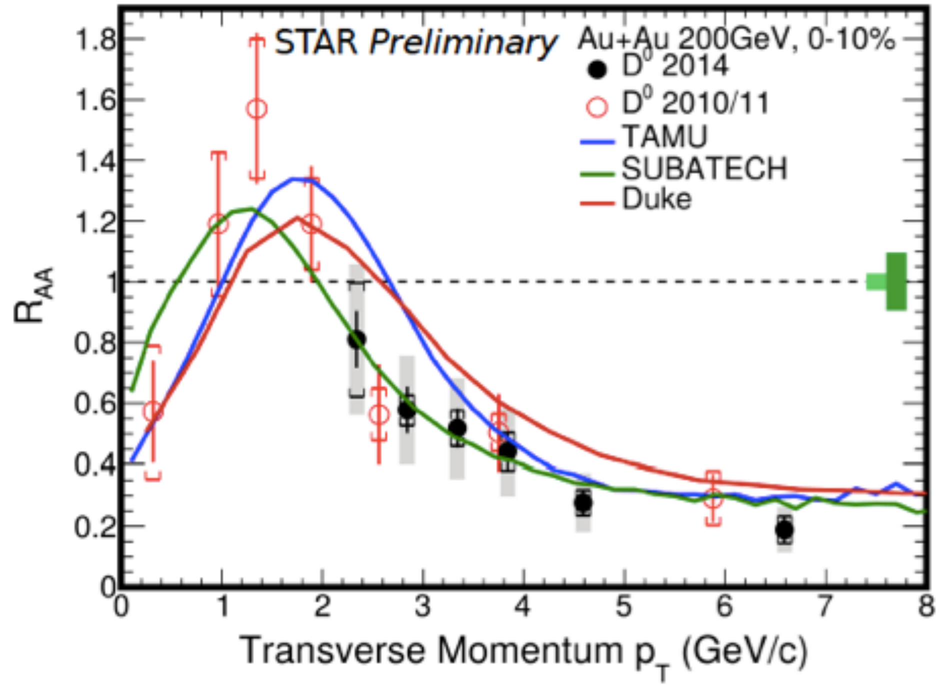


A-A system:
hot and dense QCD medium

Prompt D-meson R_{AA} at RHIC

STAR, 2010/11 data: Phys. Rev. Lett. 113 (2014) 142301
2014 data, QM 2015

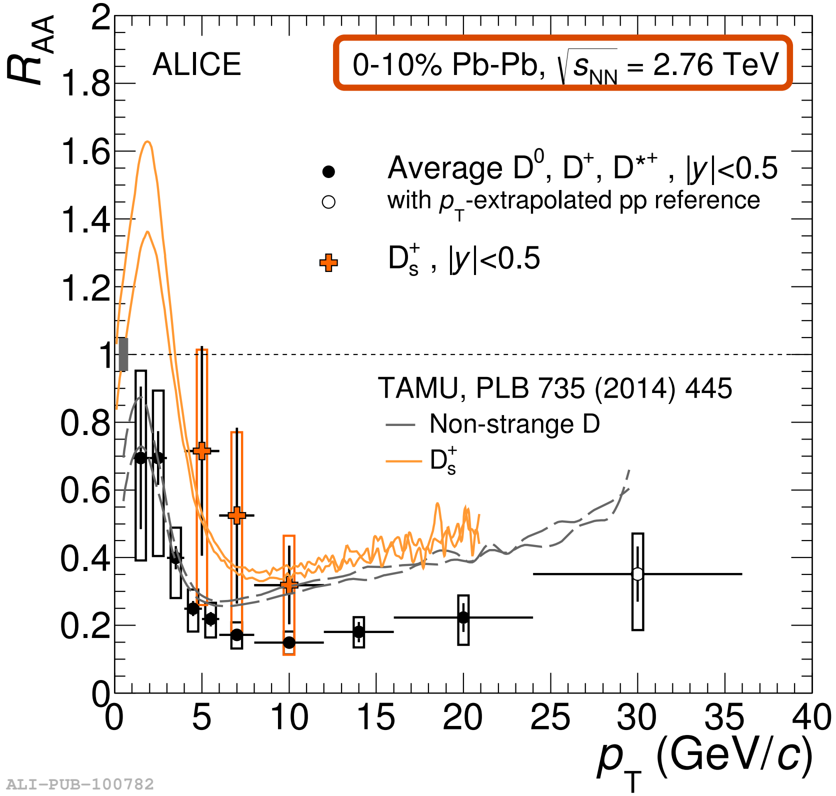




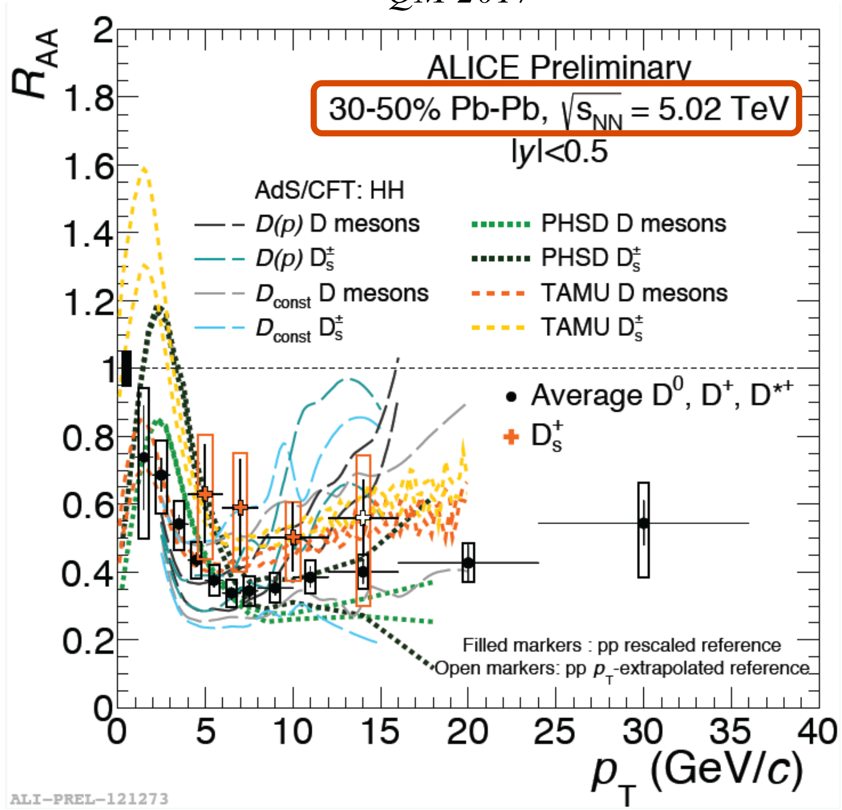
- Suppression of D-meson yield by a factor ~5 at high p_T in most central Au-Au (same trend in 193 GeV U+U)
- Enhancement at around 1.5 GeV/c: radial flow (and coalescence?)

Prompt D-meson R_{AA} at LHC

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



QM 2017



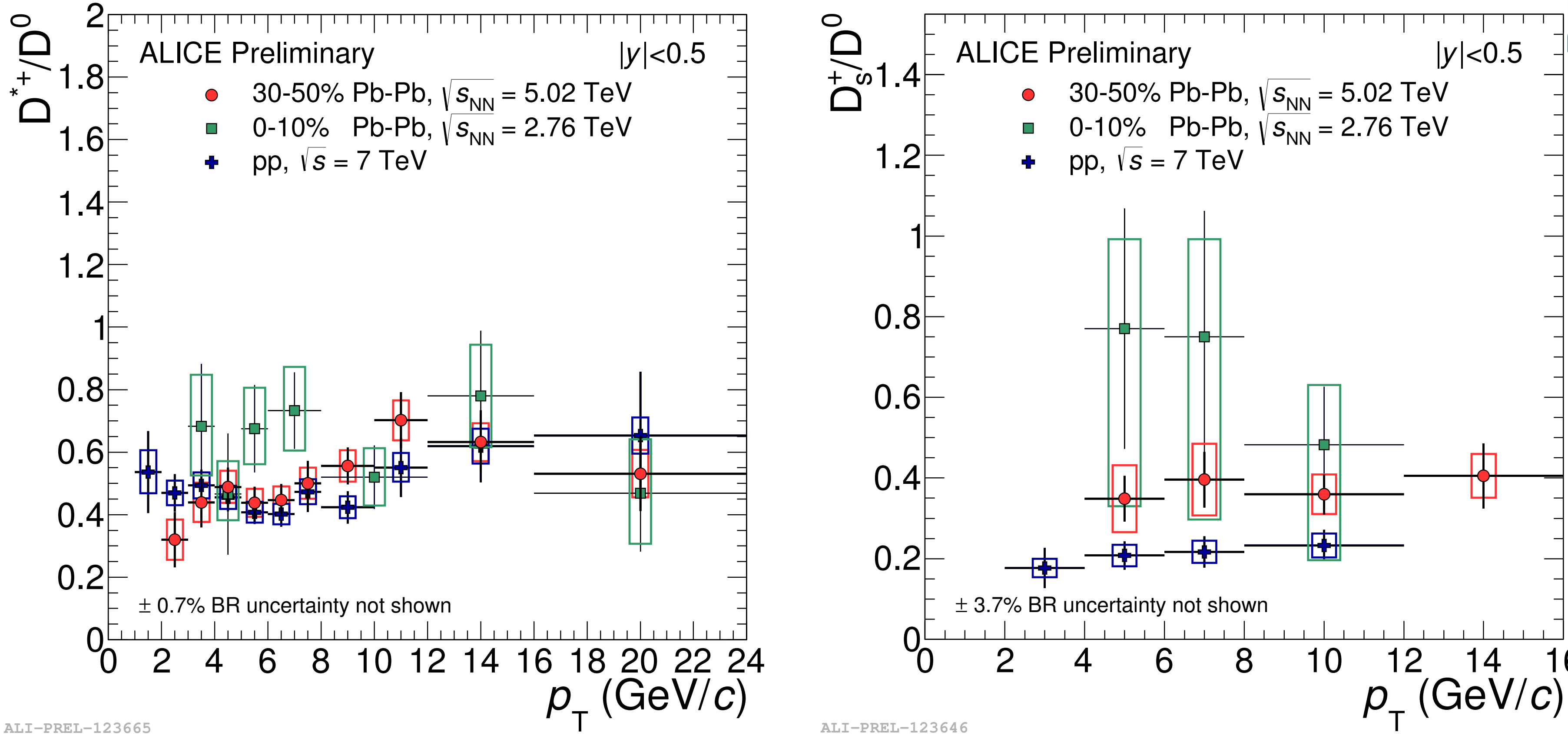
ALICE

0-10% 5.02 TeV for EPS-HEP/SQM

- First D_s measurement in HIC
- Above 5 GeV/c suppression (factor ~5) in central Pb-Pb
- Expectation: enhancement of strange D-meson yield at intermediate p_T if charm hadronises via recombination

D-meson ratios at LHC

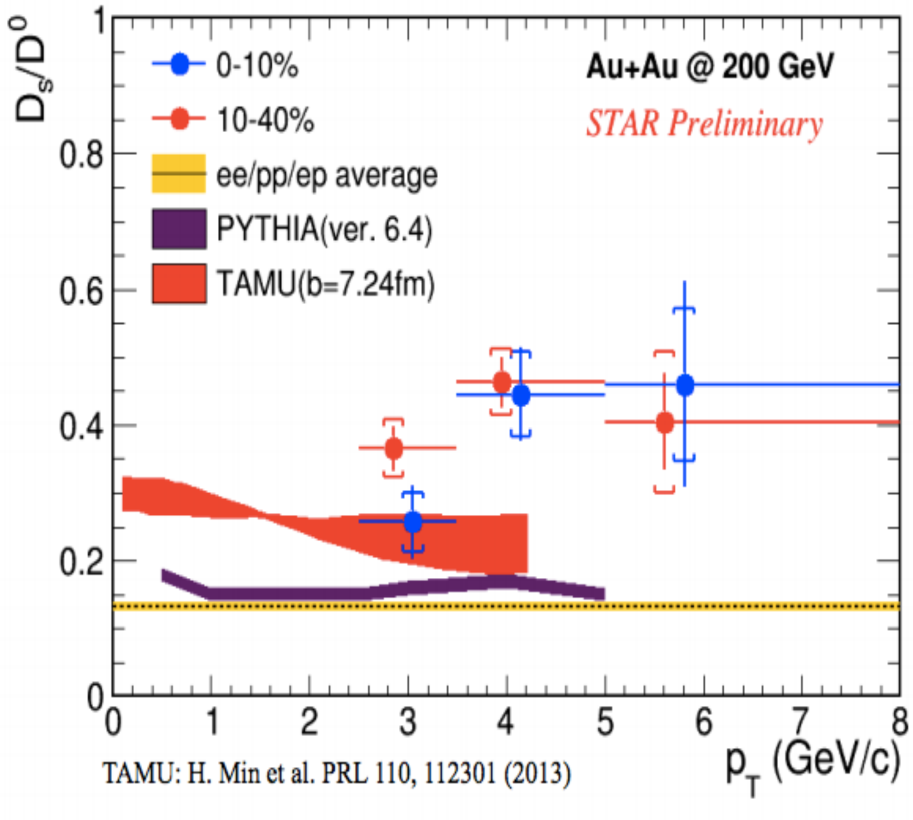
ALICE, QM 2017

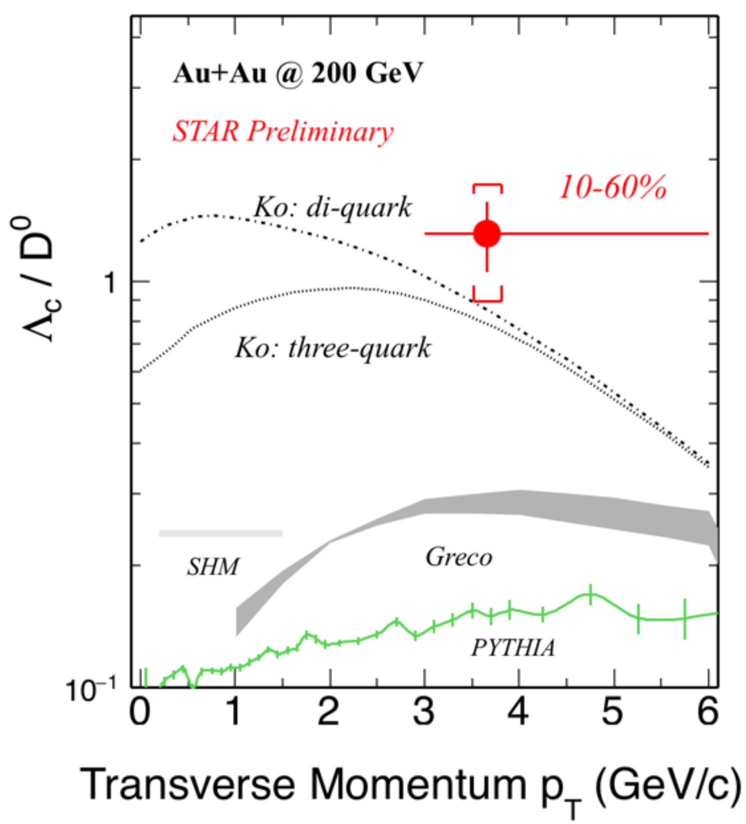


- Similar D^{*+}/D^0 and D^+/D^0 ratio (not shown) for pp and Pb-Pb
- Enhancement for D^+_s/D^0 and D^+_s/D^+ (not shown)?
- Theoretical model calculations needed

Charm-hadron ratios at RHIC

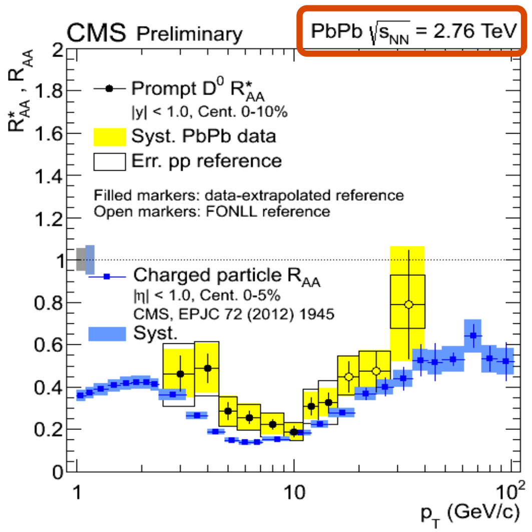
STAR, QM 2017 (arXiv:1704.04364)



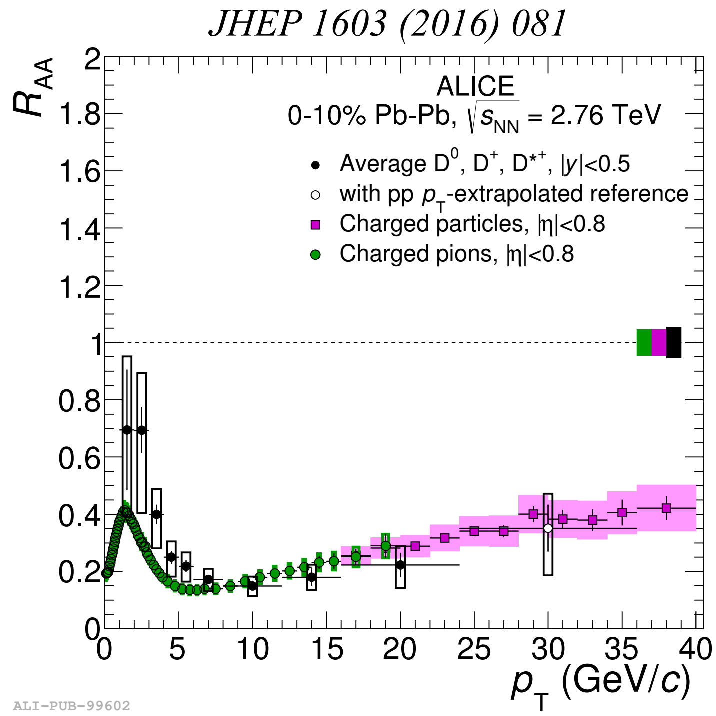


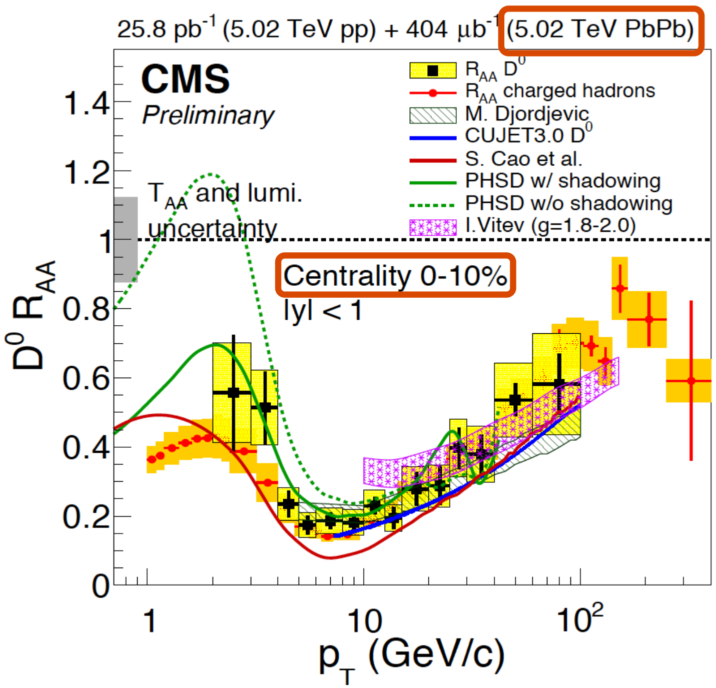
- First Λ_c measurement in HIC
- Strong enhancement observed, compared to PYTHIA
- Coalescence processes seems important during hadronisation

R_{AA}: light versus heavy-quark hadrons



CMS-HIN-16-001



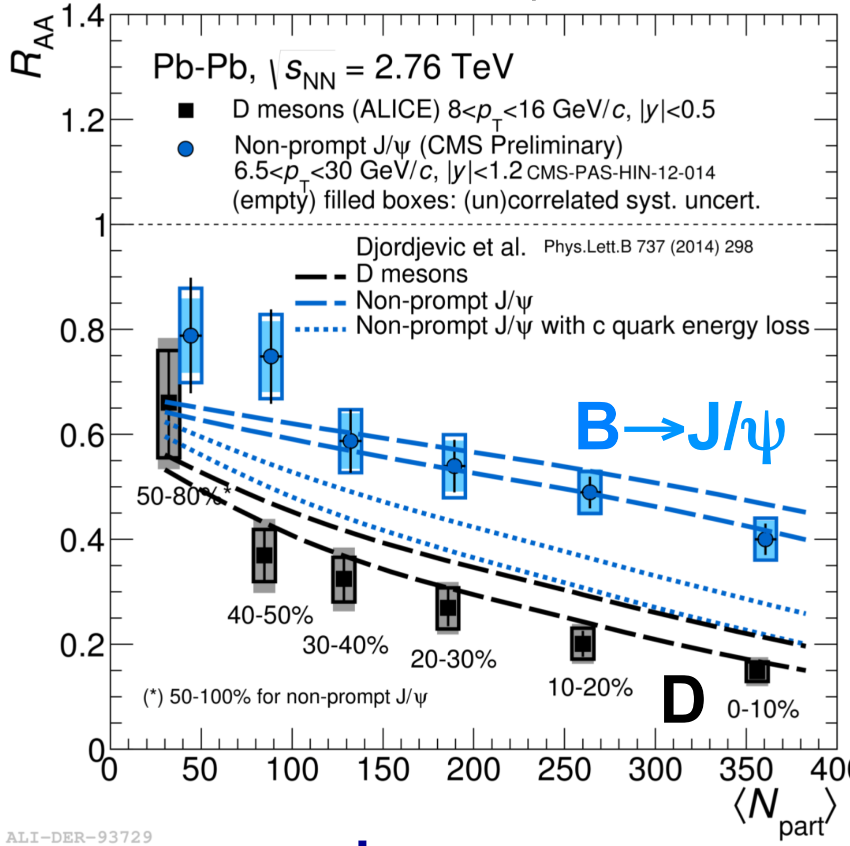


- D^0 suppression measured up to 100 GeV/c (CMS)
- Indication for R_{AA}(D) > R_{AA}(pions) at low p_T for 10% most central collisions?
- Well described by theo. model calculations that include both collisional and radiative energy loss (and shadowing)

Prompt D and B-meson R_{AA} at LHC

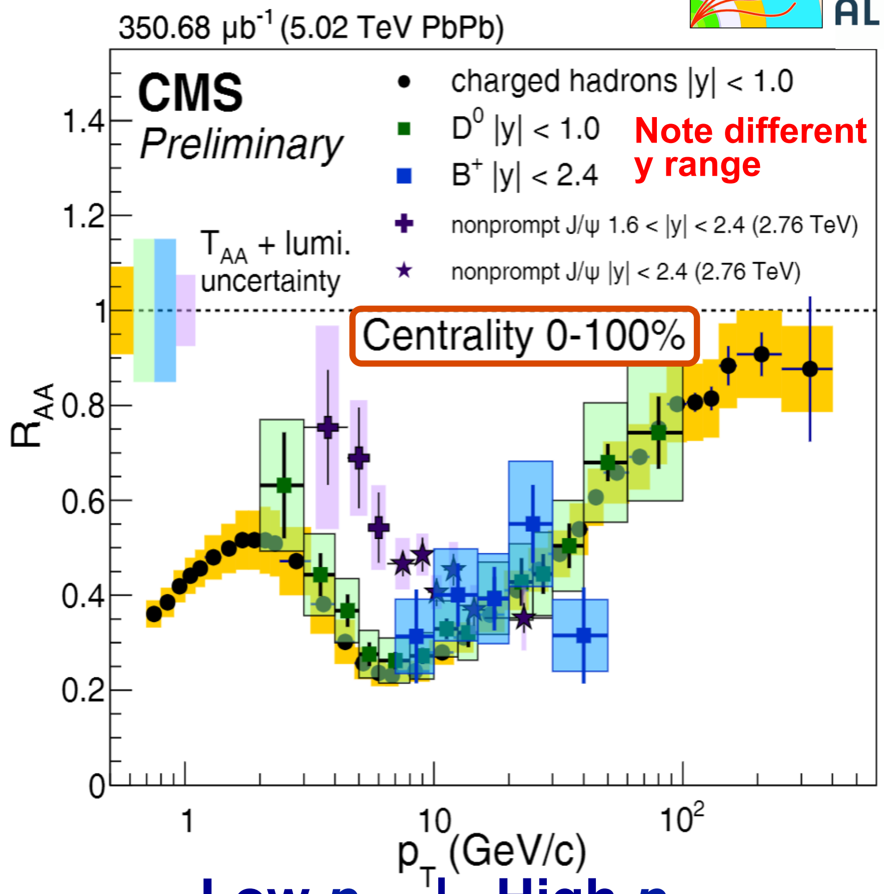
ALICE, JHEP 11 (2015) 205
CMS-PAS-HIN-12-014, CMS-PAS-HIN-15-005

D and B meson <p_T> ~10 GeV/c



Low p_T

CMS-PAS-HIN-16-011
J/ψ: Eur. Phys. J. C 77 (2017) 252

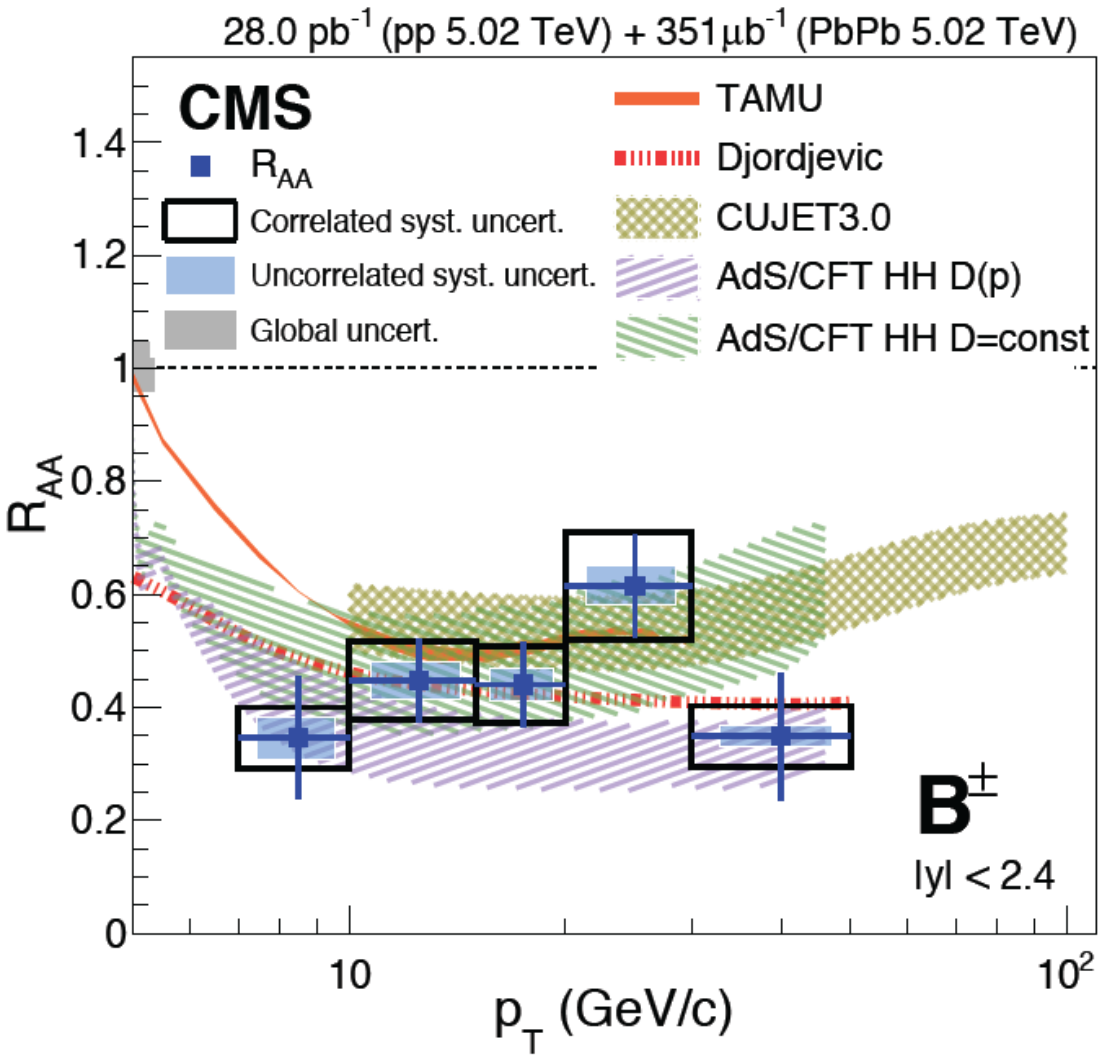


Low p_T | High p_T

- Sizeable suppression of the yield for charm and beauty
- Data well described by theo. model calculations including flavour-dependent energy loss ($R_{AA}^D < R_{AA}^B$)

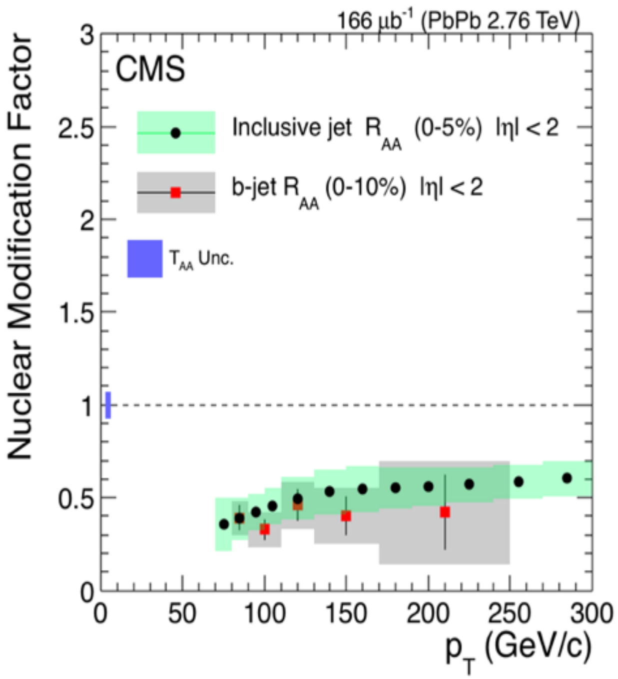
$B^{\pm}$-meson R_{AA}: model comparison

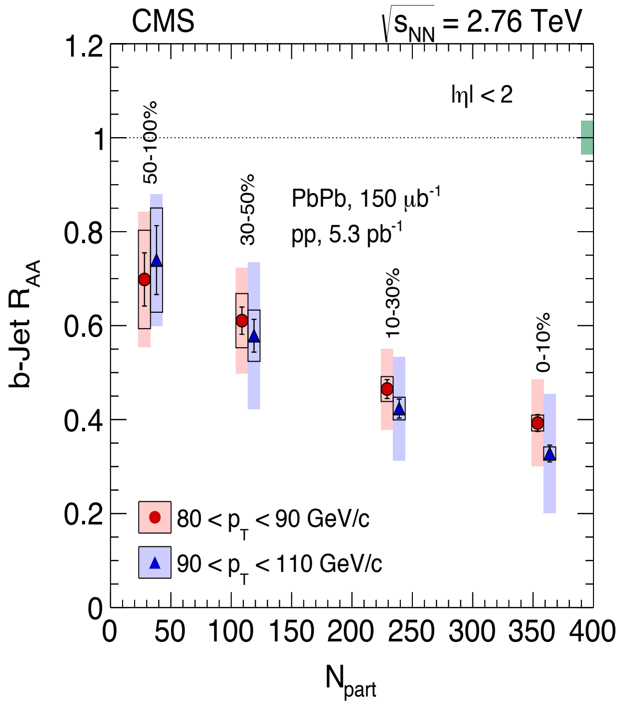
Submitted to PRL (arXiv:1705.04727)



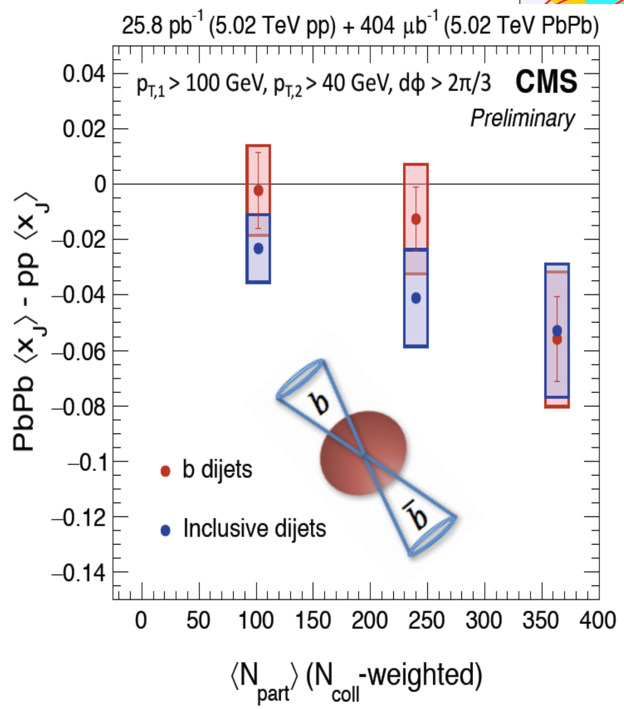
R_{AA} of b-tagged jets in 2.76 TeV Pb-Pb

CMS, Phys. Rev. Lett. 113 (2014) 132301

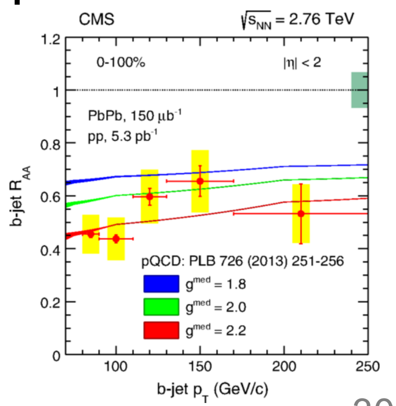




QM 2017



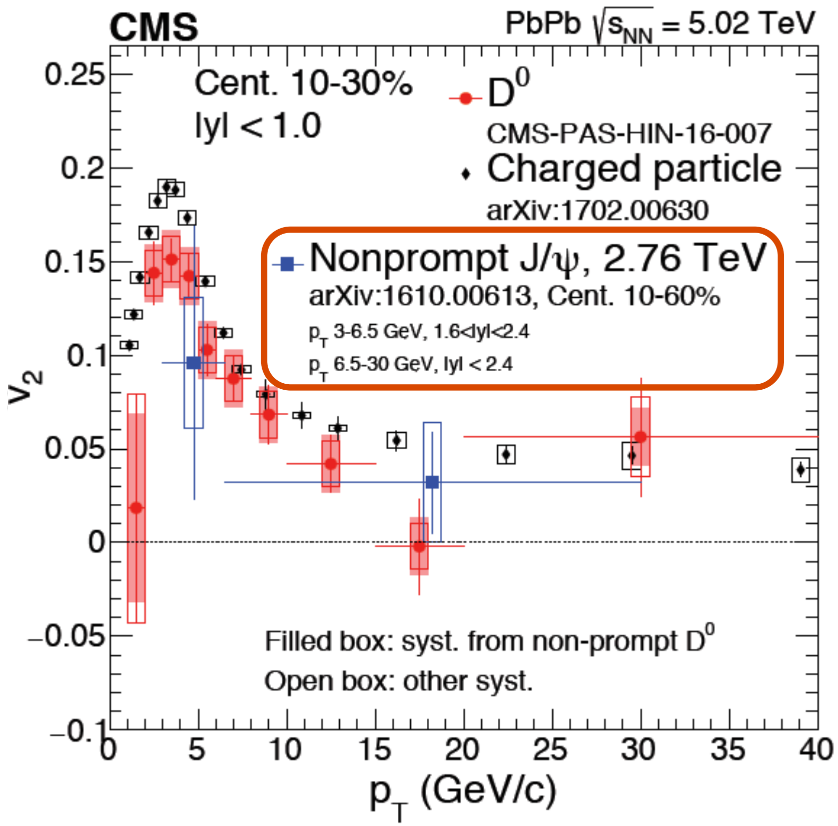
- Same level of suppression for b-tagged and incl. jets at **high p_T**
  → mass difference negligible
  → B mesons are sensitive to lower p_T b-quarks than b-jets
- ***Dijet asymmetry*** *similar for beauty and incl. jets*
- Towards constrain of quark-medium coupling parameter g^{med}

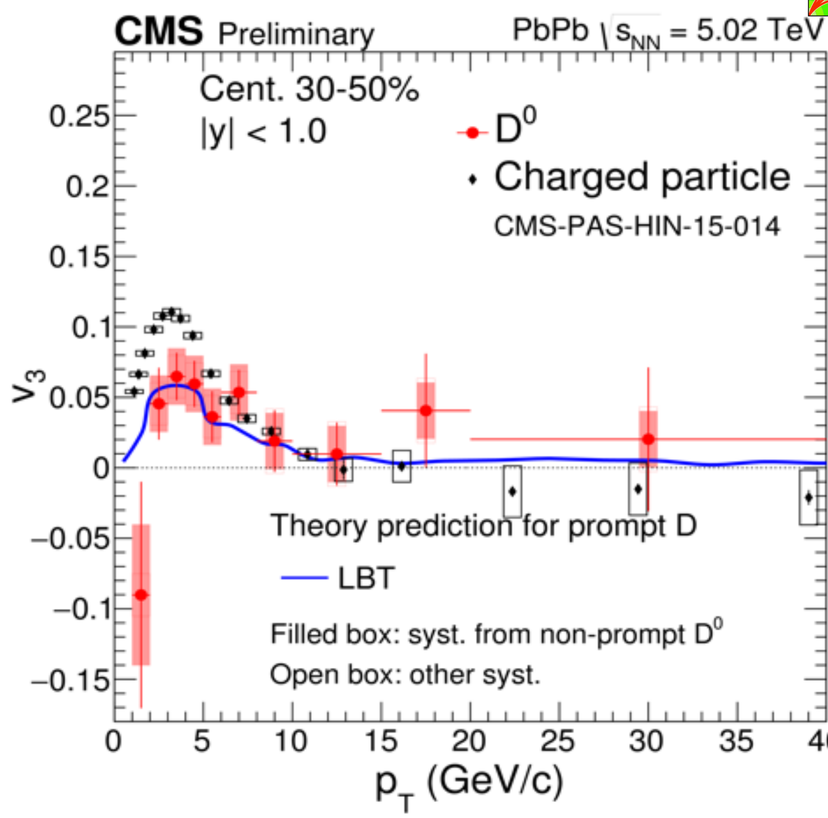


Note: sizable fraction of b-tagged jets arise from gluon splitting

D-meson v_n at LHC

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





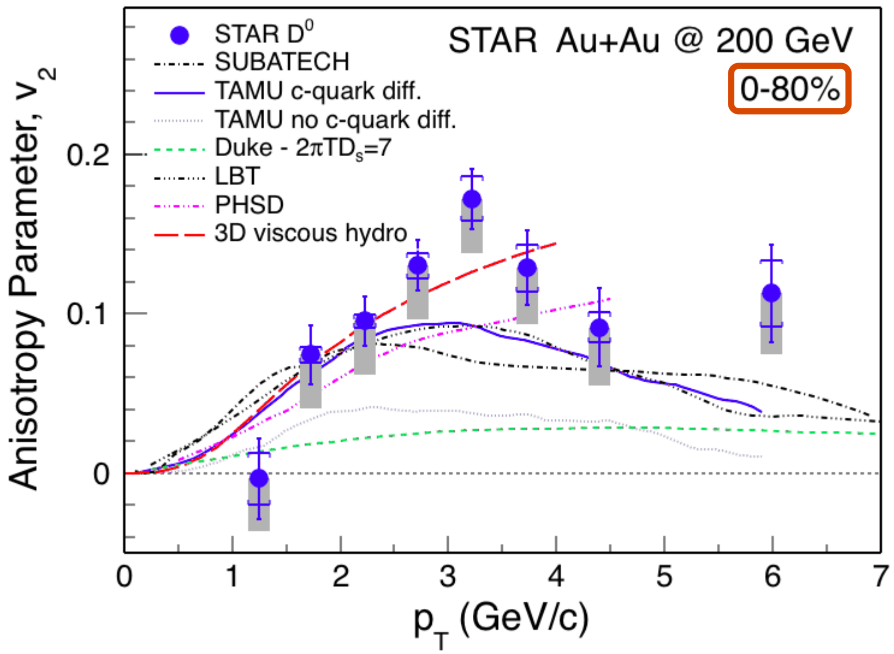
- $v_2(D^0) < v_2(h^{\pm})$ at low p_T (< 5 GeV/c)

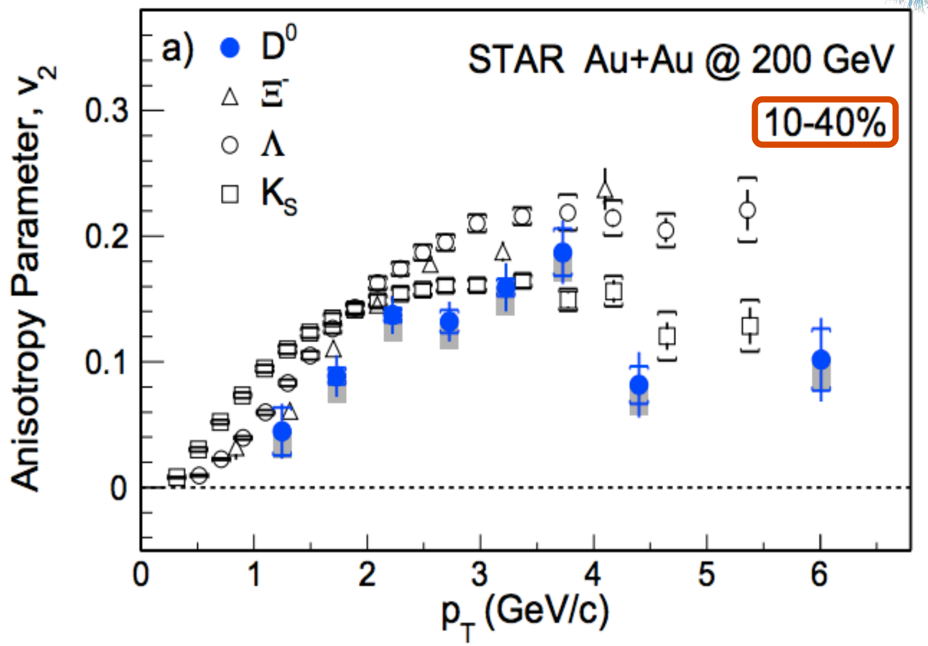
Also ALICE data (incl. D^+_s)
QM 2017

- v_2 and v_3 are well described by models that include both charm diffusion and charm recombination in the medium

D-meson v_2 at RHIC

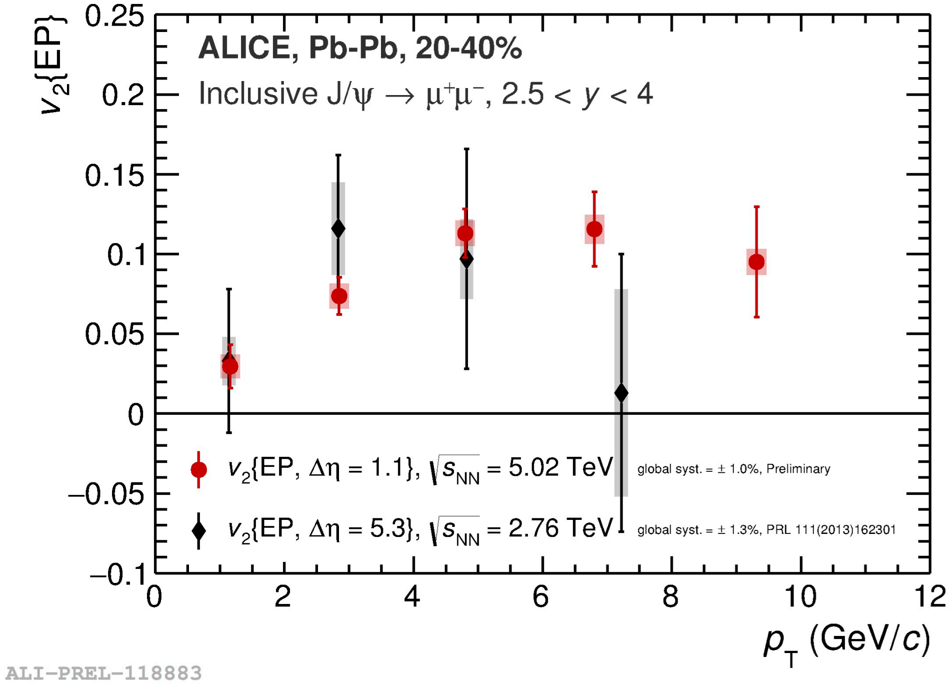
STAR, Phys. Rev. Lett. 118 (2017) 212301 (arXiv:1701.06060)

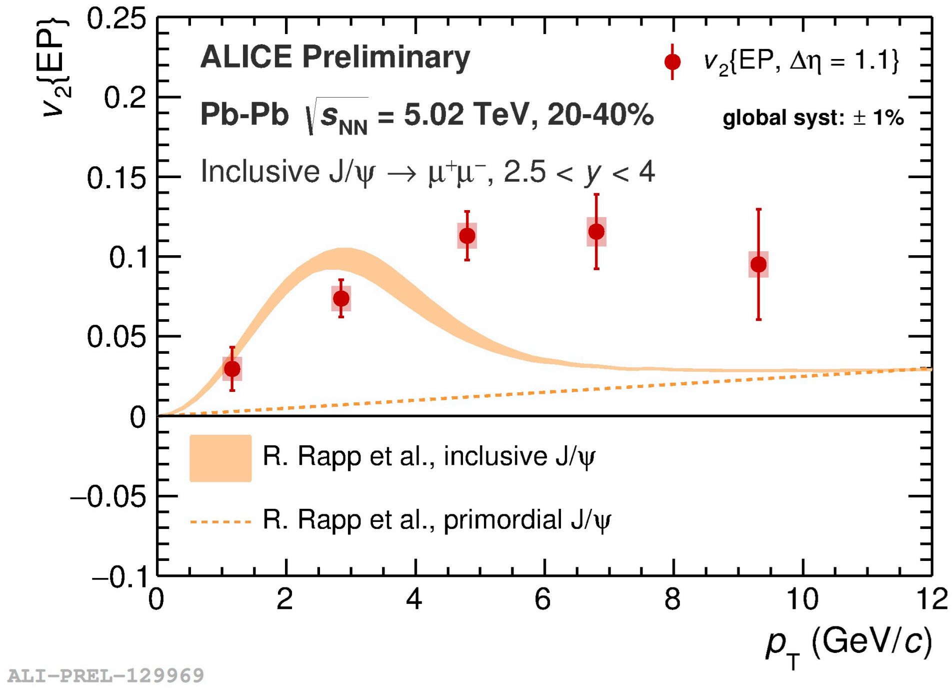




- Charm participates in collective motion of the system
- Also v_3 measurement available

J/ψ elliptic flow parameter at LHC



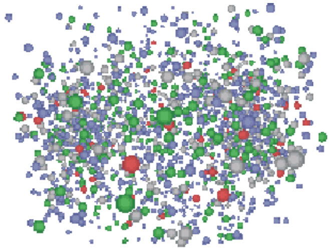


- The observed v_2 suggests that J/ψ are formed by "flowing" charm quarks
- The transport model calculations do not data at high-p_T

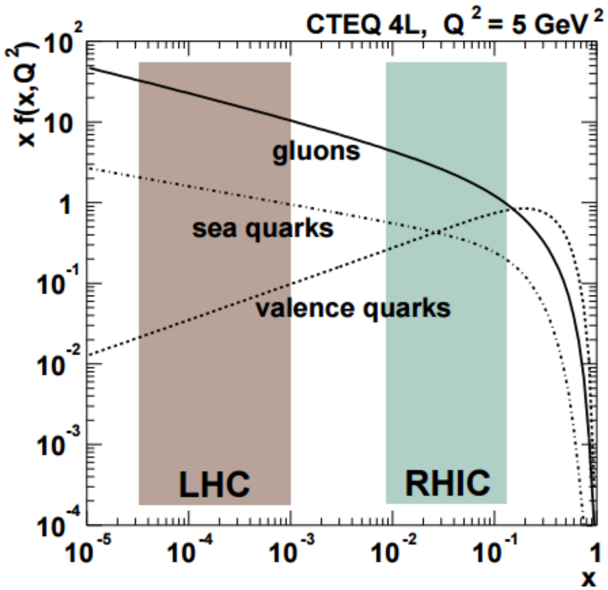
p-A system: Cold nuclear matter effects

Cold nuclear matter (CNM) effects

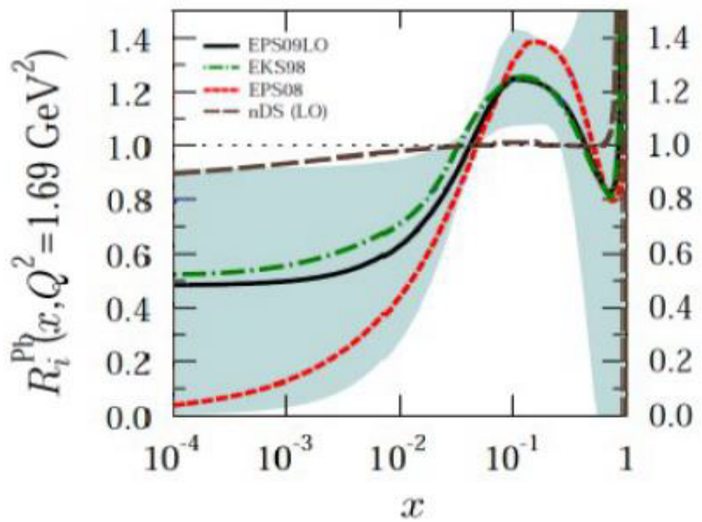
- CNM effects (**from initial state**) such as
  - Nuclear modification of PDFs → **shadowing** at low Bjørken-x (dominant at LHC)
  - Gluon **saturation** from evolution equations (DGLAP and BFKL)
  - k_T broadening and Cronin enhancement from multiple parton scatterings
  - Initial-state energy loss



- Final-state effects
  - Energy loss?
  - Interactions between final-state particles (collective expansion?)
- Crucial for test of pQCD calculations and interpretation of heavy-ion results

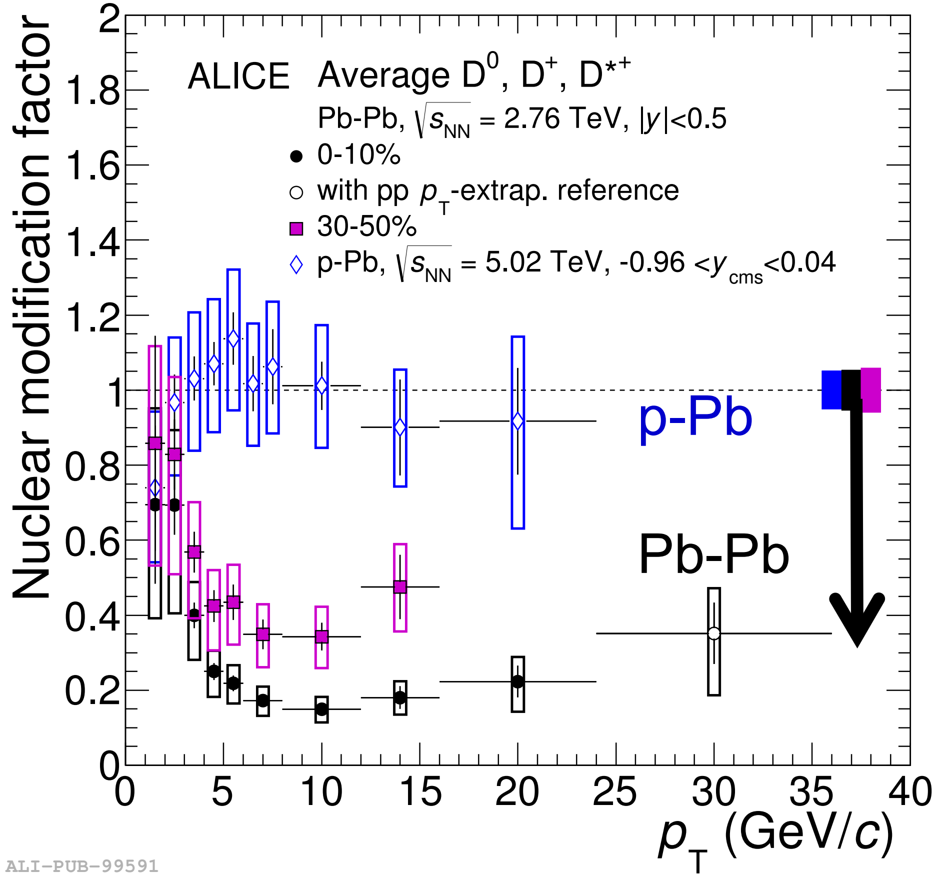


K.J. Eskola, H. Paukkunen, C.A. Salgado, JHEP 04, 65 (2009)



Prompt D-meson R_{pPb} at 5.02 TeV

ALICE, Phys. Rev. C 94, 054908 (2016)
and Phys. Rev. Lett. 113 (2014) 232301



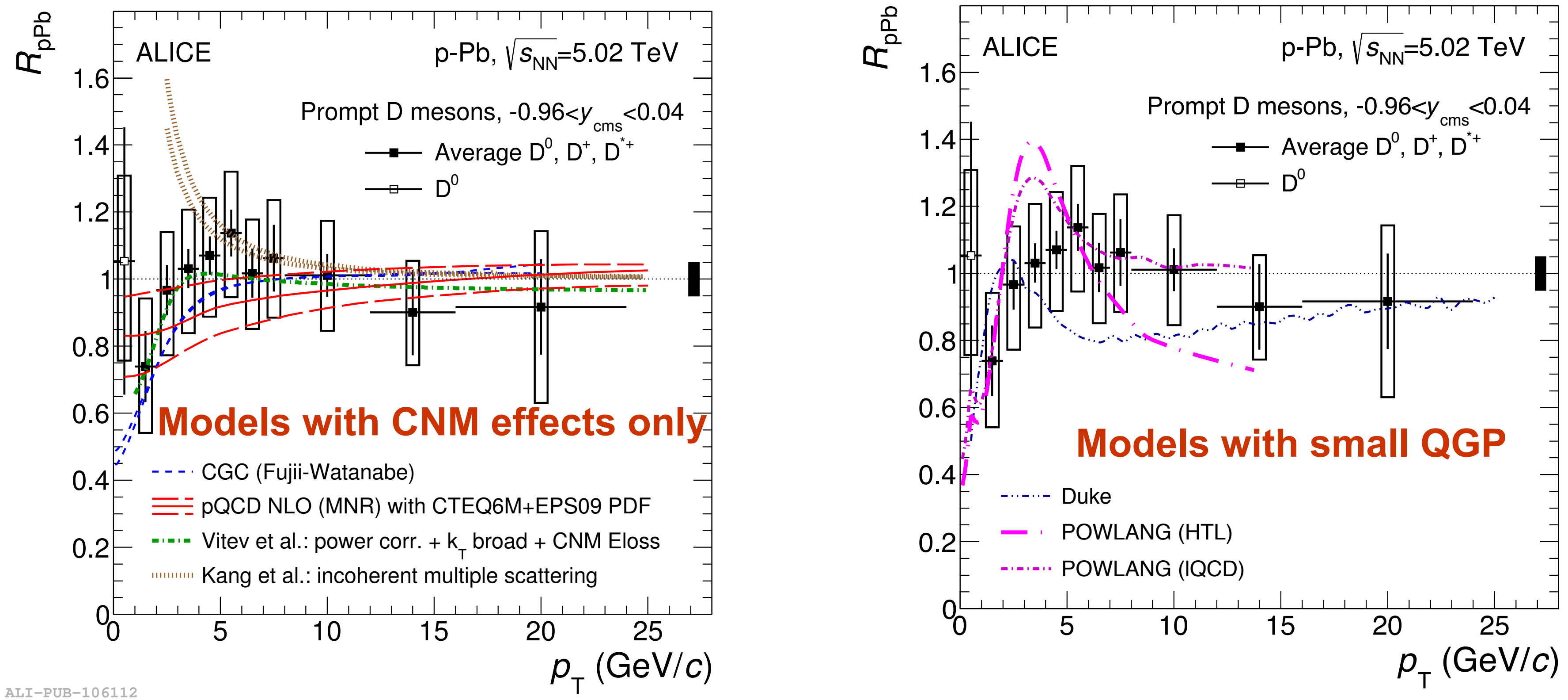
- D-meson R_{pA} shows consistency with unity
- High-p_T suppression of production yield in Pb-Pb is a **final-state effect**

→ Due to interactions of charm quarks with the medium

Run-2 5.02 TeV D and Λ_c for EPS-HEP/SQM

Open charm R_{pPb} vs. models

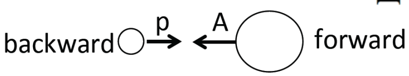
ALICE, Phys. Rev. C 94 (2016) 054908 and Phys. Rev. Lett. 113 (2014) 232301

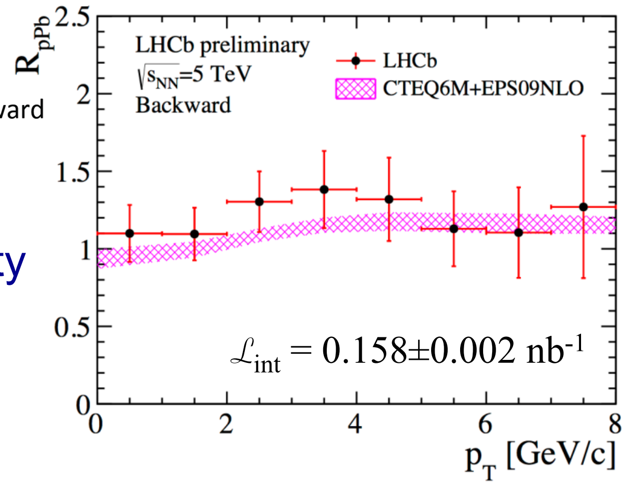


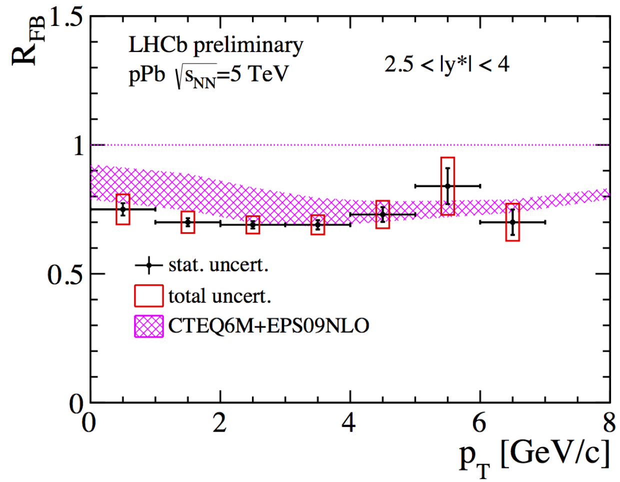
- R_{pA} (measured down to $p_T = 0$) compatible with unity; no centrality dependence (not shown)
  - Consistent with predictions from shadowing and CGC model
- Data disfavour suppression larger than 15% at high p_T

Prompt D^0 mesons at for/backward rapidity

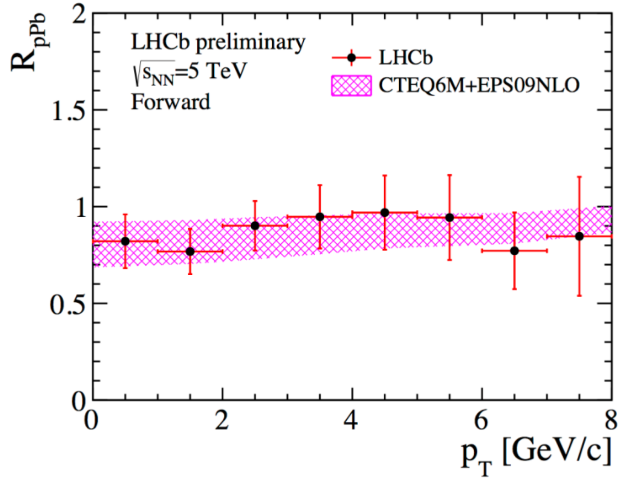
LHCb-CONF-2016-003

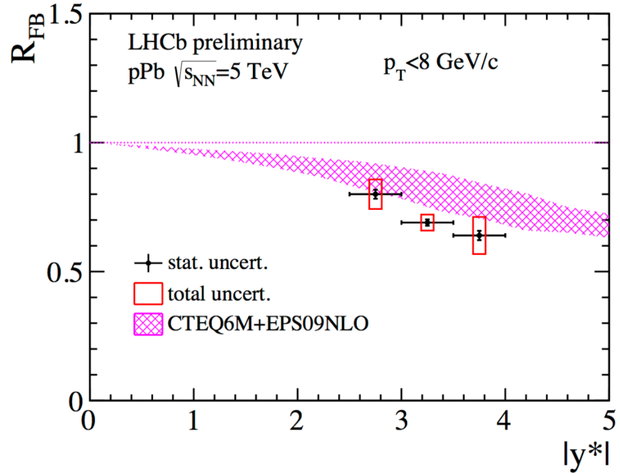






Backward rapidity
-2.5 > y > -4.0
(Pb-going side)





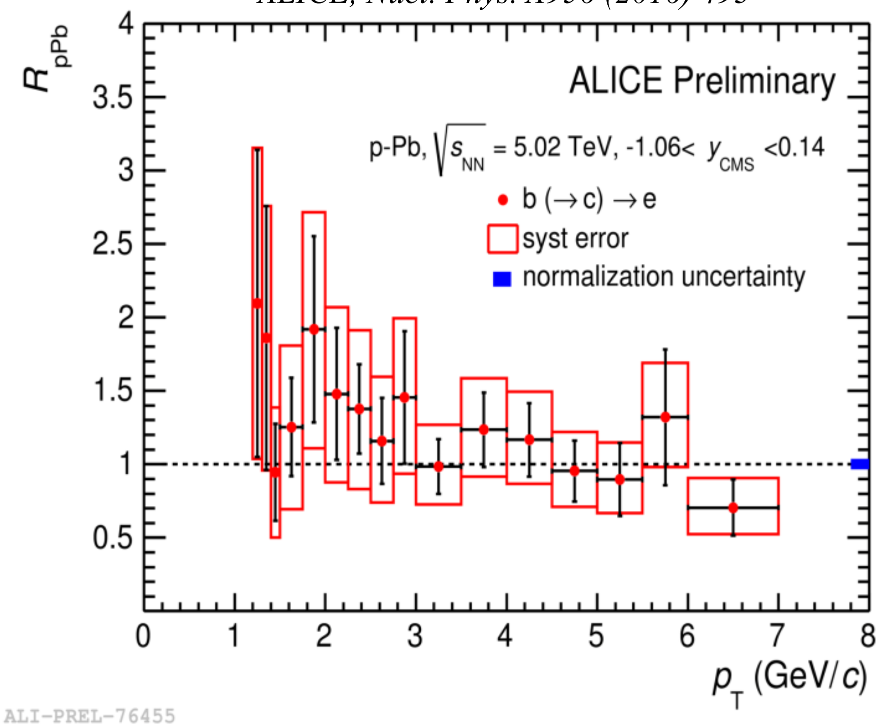
Forward rapidity
2.5 < y < 4.0
(p-going side)

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

Open beauty R_{pPb}

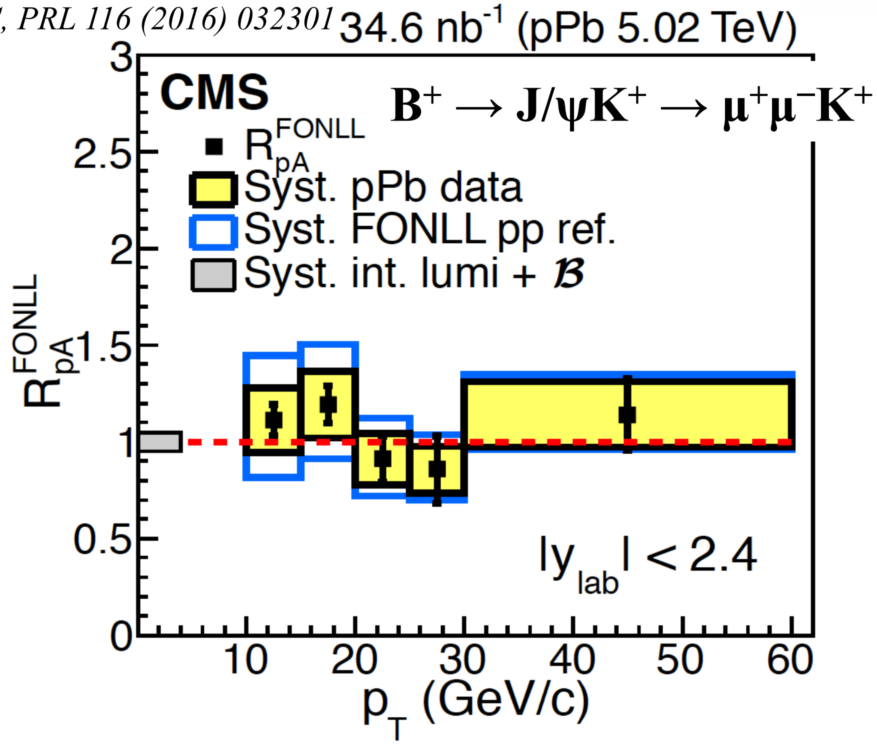
Beauty-decay electrons

ALICE, Nucl. Phys. A956 (2016) 493



B mesons

CMS, PRL 116 (2016) 032301

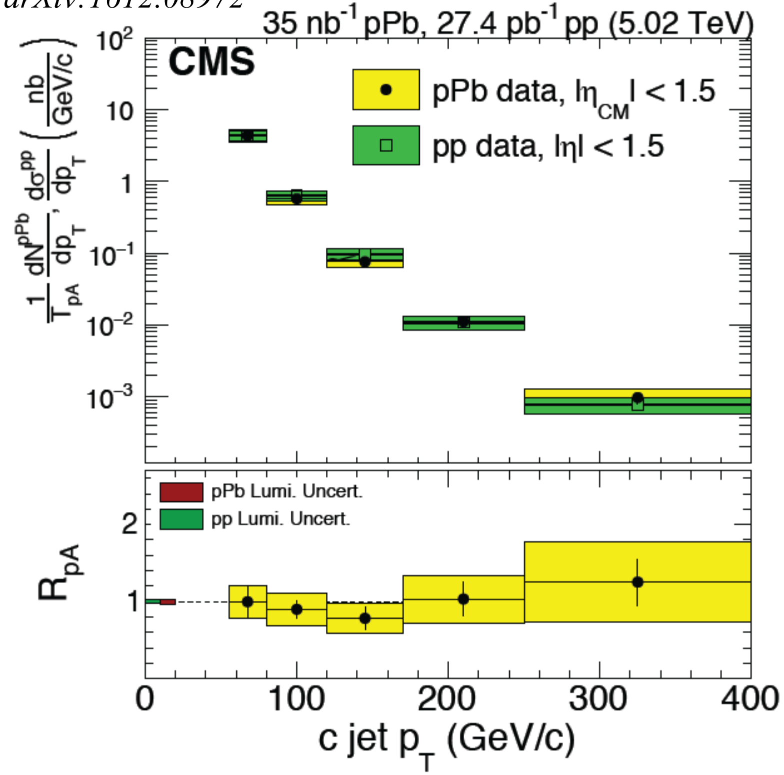


- R_{pPb} of beauty-decay electrons at low p_T and B mesons in $10 < p_T < 60$ GeV/c consistent with unity; same for B^0 and B_s^0 $R_{p\text{-}Pb}$ (not shown)
- No indication of significant cold nuclear matter effects on beauty production

Heavy-flavour jets

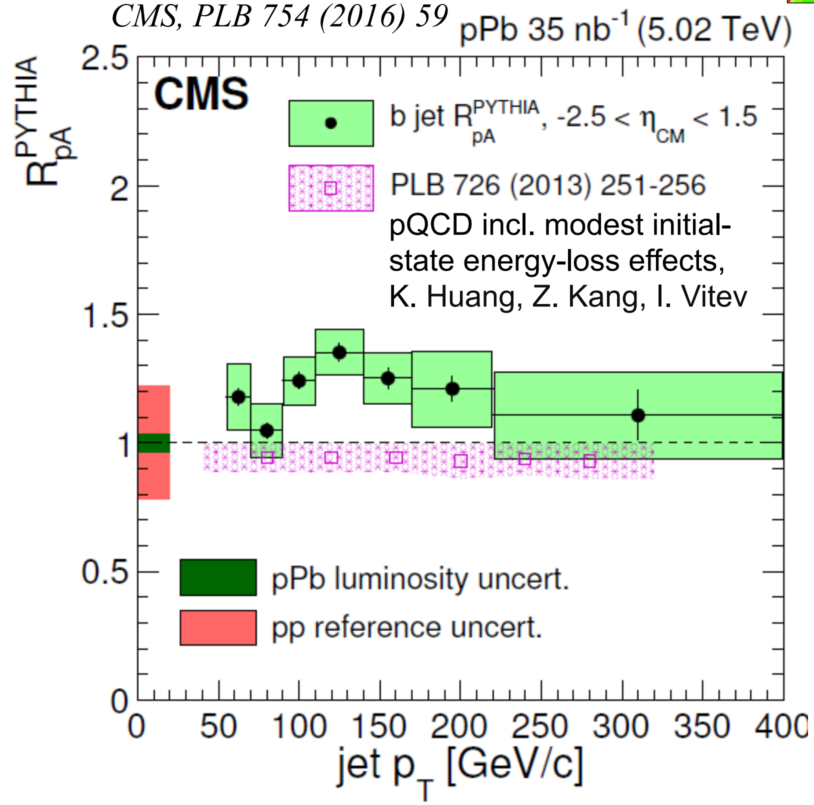
Charm jets

CMS, arXiv:1612.08972



Beauty jets

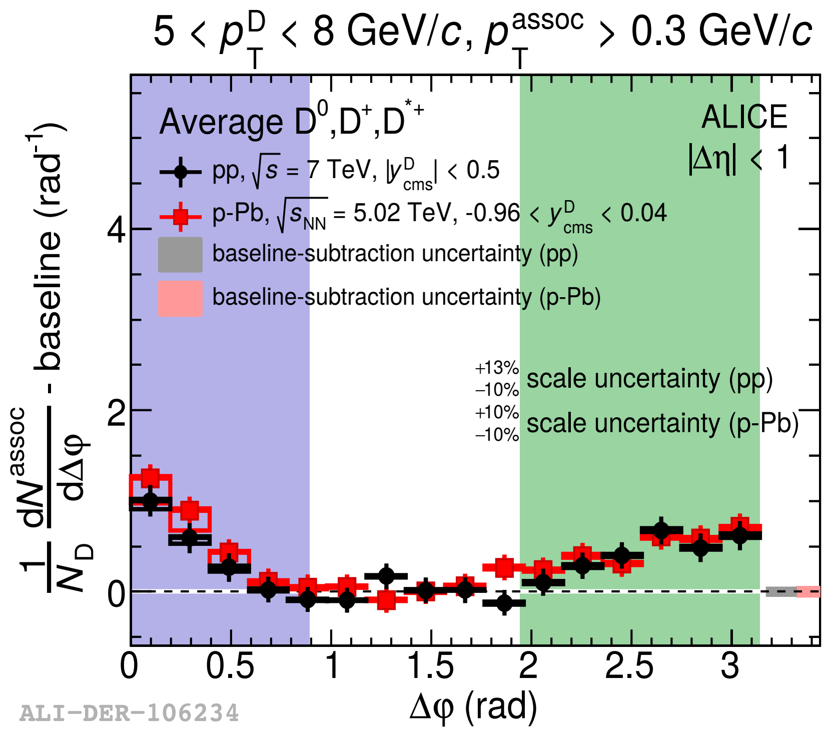
CMS, PLB 754 (2016) 59



- 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

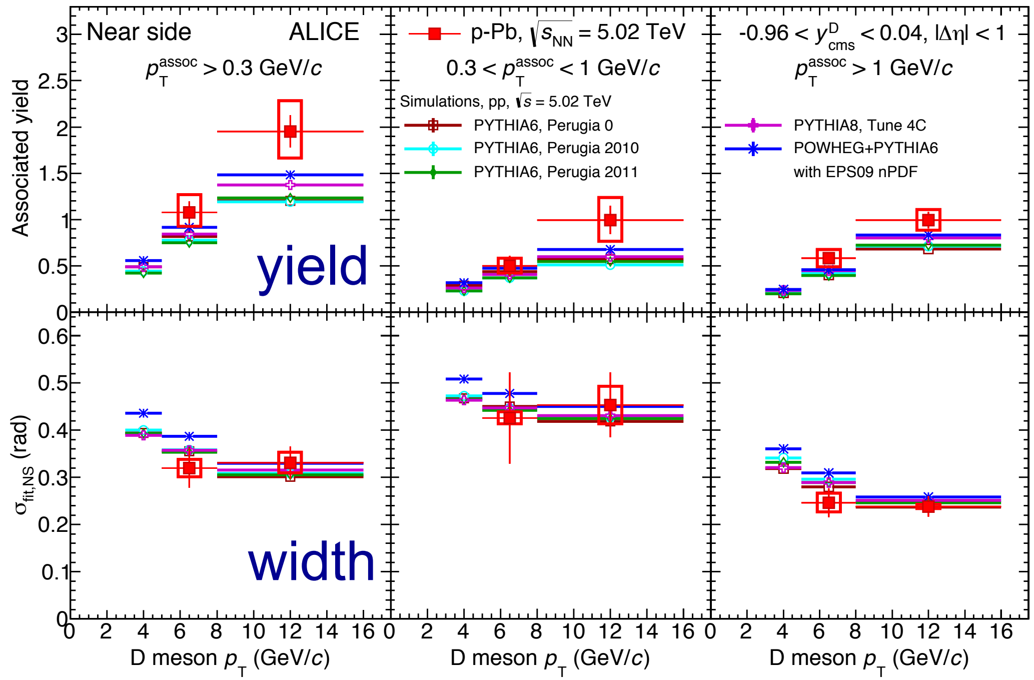
D-tagged charged particle azimuthal correlations

Δφ distribution



Near-side correlation yield/width

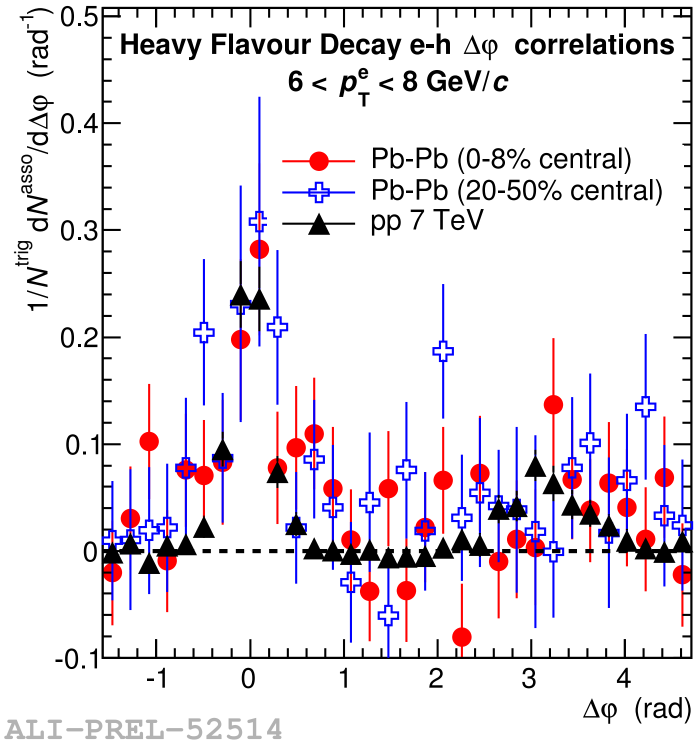
ALICE, Eur. Phys. J. C77 (2017) 245

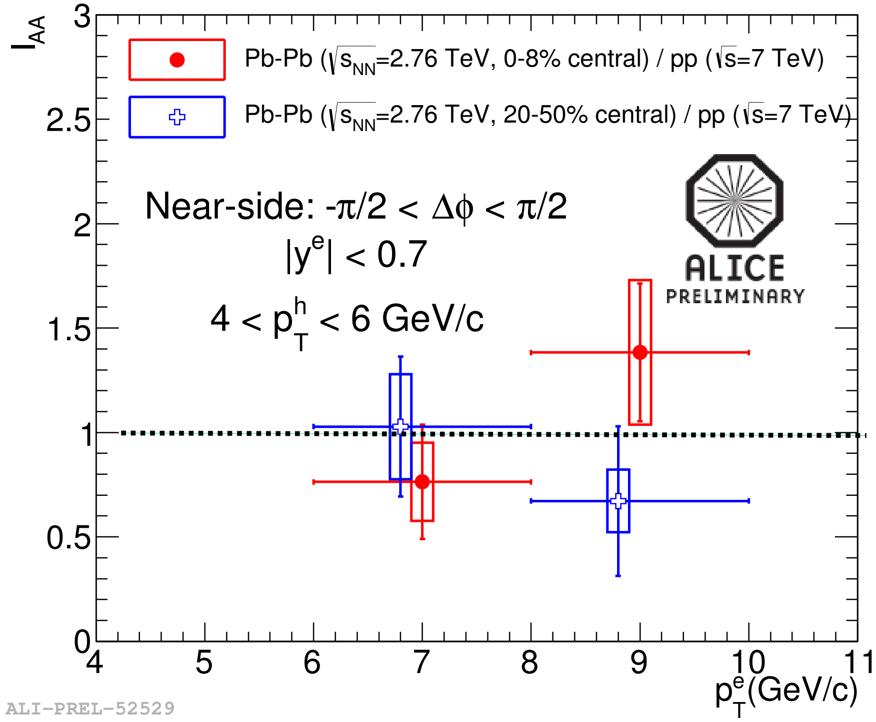


- Near-side correlation peak is sensitive to characteristics of jet containing D meson
- Similar correlation yields for p-Pb and pp (not shown)
- Data well reproduced by PYTHIA (in all kinematic ranges)

HF decay electron-hadron Δφ correlations in Pb-Pb

ALICE, SQM 2013, J. Phys. Conf. Ser. 509 (2014) 012079





$$I_{AA} = \frac{dN^{Asso}_{Pb-Pb}/dN^{Trig}}{dN^{Asso}_{p-p}/dN^{Trig}}$$

Needs more statistics

Summary

- LHC (and RHIC) ideal for the study of the properties of hot and dense QCD matter
  - energy density $\varepsilon_{initial} \gg \varepsilon_{critical}$
  - large volume
  - long lifetime
  - high production rates for rare probes (jets and heavy flavour)
- …
- …

Summary and conclusions

- Yield measurement: prove **flavour/mass dependence of parton E_{loss}**
  - At low p_T (<10 GeV/c): $R_{AA}(\pi)$ ~? R_{AA}(D) <? $R_{AA}(B \rightarrow J/\psi)$
  - At high p_T (>10 GeV/c): $R_{AA}(\pi)$ ~ R_{AA}(D) ~ R_{AA}(B, min.bias) !
    - Also proved with tagged jets and di-jet asymmetry

→ Urgent need for measurement of fully reconstructed B mesons at low p_T (<10 GeV/c) in most central collisions; fully explore beauty probe

→ Precision determination of heavy-quark diffusion coefficient; also input from Lattice

- Charm hadron ratios: prove **hadron chemistry**
  - Enhancement of D^+_s/D^0 and Λ_c/D^0 ratio: hadronisation via coalescence

→ Theoretical model calculations needed

- Elliptic flow measurement: prove **thermalisation of charm quarks**
  - Evidence for sizable v_2 at RHIC and LHC; suggests strong re-interactions of charm quarks within the medium and thermalisation

→ Does beauty flow?

Summary and conclusions (cont'd)

- Reference measurements:
  - "Vacuum" (pp)
    - Is pp baseline of fully under theoretical control?
    - What are the uncertainties in E_{loss} predictions due to the theoretical uncertainties from pp baseline?

→ Uncertainties in the pp baseline should be propagated through E_{loss} models to A-A predictions

  - Cold nuclear matter effects (p-A): No indication for substantial modification

→ Long-range correlation in η also present for heavy flavour?

Color Glass Condensate in initial state: Dusling, Venugopalan, PRD 87 (2013) 094034
Hydrodynamics in final state: Bozek, Broniowski, PLB 718 (2013) 1557

- Next to come
  - HF tagged jets and correlations in A-A:
    also way to separate radiative and collisional E_{loss} (?)
    - Azimuthal angular and momentum correlations
    - Difficulty: NLO processes (gluon splitting and flavour excitation)
  - Possible other sensitive observables [discussed at e.g. Lorentz workshop]

Dedicated workshops


Heavy-flavour and quarkonium production in the LHC era:
from proton-proton to heavy-ion collisions

arXiv:1506.03981v1 [nucl-ex] 12 Jun 2015

Sapore Gravis European network

Heavy-flavor production and medium properties in high-energy nuclear collisions – What next?

EPJ A53 (2017) 93 (arXiv:1612.08032)

Heavy-flavour and quarkonium production in the LHC era: from proton-proton to heavy-ion collisions

EPJ C76 (2016) 107 (arXiv:1506.03981)