INT Program INT-14-3

Heavy Flavor and Electromagnetic Probes in Heavy Ion Collisions

September 15 - October 10, 2014

Open heavy flavour probes at RHIC and LHC

Andrea Dainese

(INFN Padova, Italy)

Outline of the Talk

- Introduction: HF probes of the medium
- Calibrating HF probes: pp results (see back-up)
- HF production in nucleus-nucleus (and proton-nucleus)
  - Semi-leptonic decays
  - D mesons
  - B and b-jets
- HF azimuthal anisotropy
- Outlook: detector upgrades at RHIC and LHC

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What's special about heavy quarks: probes through the full system history

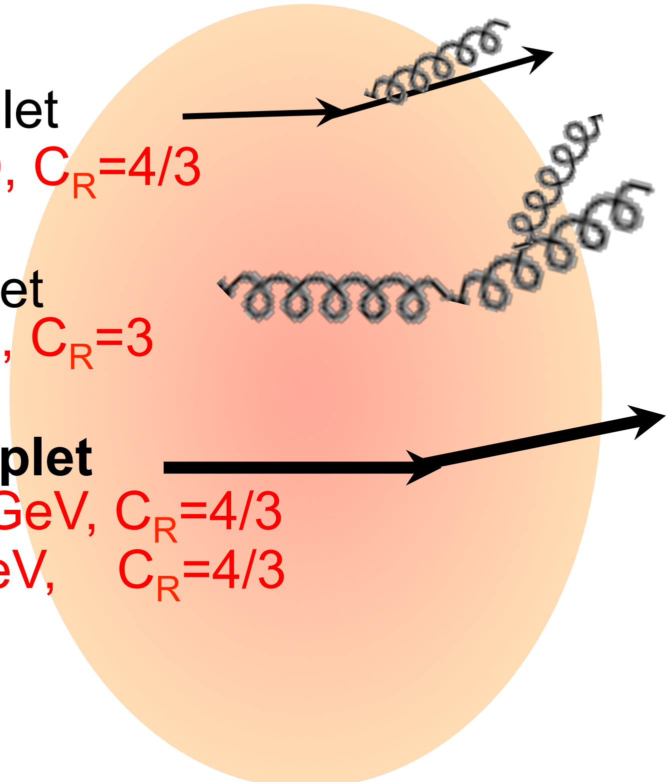
- Large mass (m_c~1.5 GeV, m_b~5 GeV) → produced in large virtuality Q^2 processes at the initial stage of the collision with short formation time $\Delta t < 1/2m \sim 0.1$ fm $<< \tau_{QGP} \sim 5\text{-}10$ fm
- Characteristic flavour, conserved in strong interactions
  - Production in the QGP is subdominant
  - Interactions with QGP don't change flavour identity
- Uniqueness of heavy quarks: cannot be "destroyed/created" in the medium → transported through the full system evolution
- **Effective probes of:**
  - **The mechanisms of quark-medium interaction: energy loss (and gain)**
  - **The strength of the collective expansion of the system**

The parton palette and the properties of QCD energy loss

q: colour triplet
u,d,s: m~0, C_R=4/3

g: colour octet
g: m=0, C_R=3

Q: colour triplet
c: m~1.5 GeV, C_R=4/3
b: m~5 GeV, C_R=4/3



'QCD medium'

Parton Energy Loss by
- medium-induced gluon radiation
- collisions with medium gluons

$$\Delta E(\varepsilon_{medium}; C_R, m, L)$$

C_R: colour charge dep.
m: mass dependence

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

See e.g.:
Dokshitzer and Kharzeev, PLB 519 (2001) 199. Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003.
Djordjevic, Gyulassy, Horowitz, Wicks, NPA 783 (2007) 493.

From energy loss to R_{AA}

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

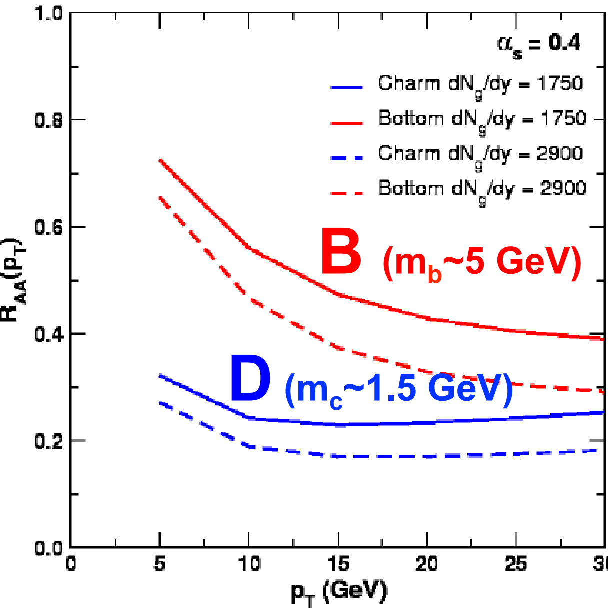
$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

- What is the expected R_{AA} pattern?
  - No trivial relation between ΔE and R_{AA}
  - Need to account for different steepness of partonic p_T spectrum and different fragmentation functions

From energy loss to R_{AA}

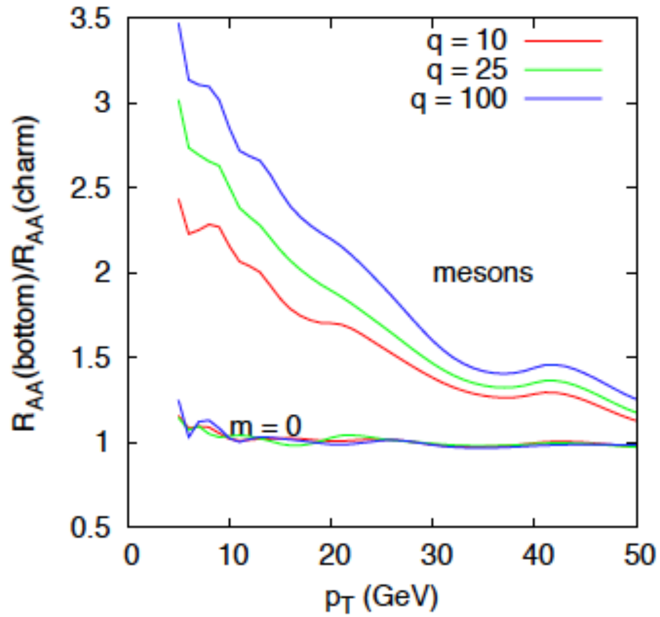
1. Comparing D and B: $R_{AA}^{D} < R_{AA}^{B}$ (below 30 GeV/c)
   - For essentially *all* mechanisms / models
   - Small effect from partonic p_T steepness and fragmentation (at LHC)

Radiative E loss



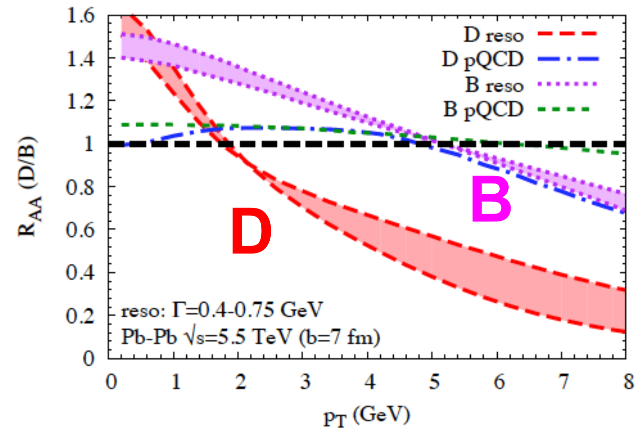
Wicks, Gyulassy, "Last Call for LHC Predictions" workshop, 2007

Radiative E loss



Cacciari et al., "Last Call for LHC Predictions" workshop, 2007

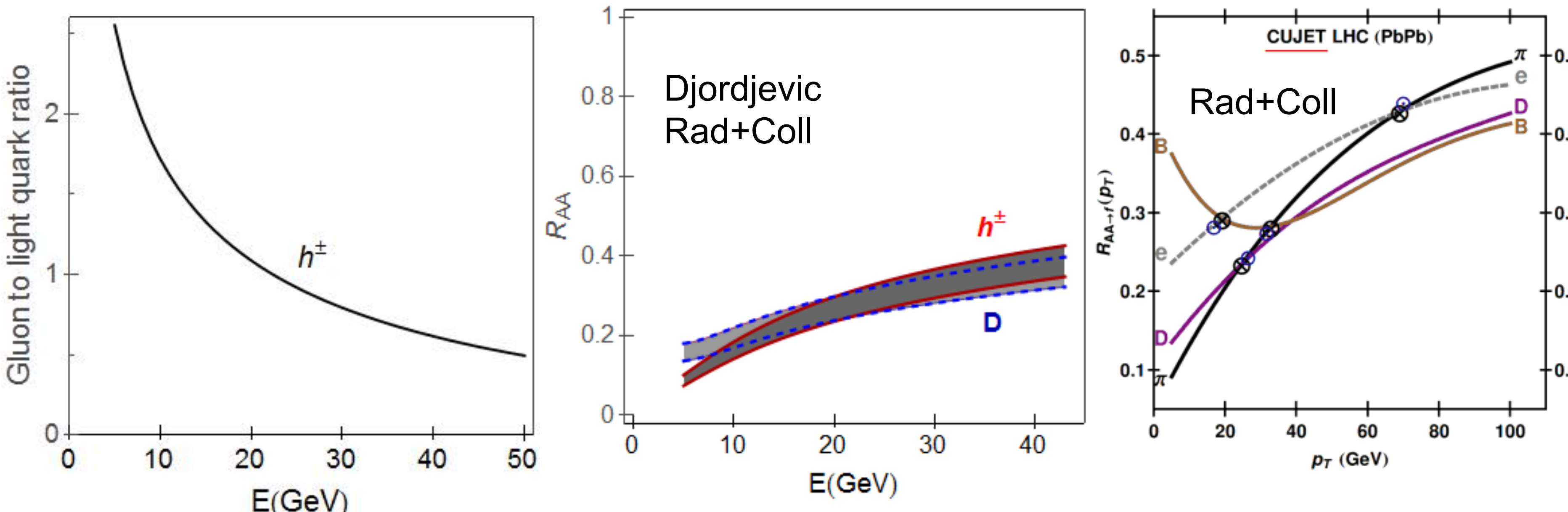
Collisional E loss



Greco et al., "Last Call for LHC Predictions" workshop, 2007

From energy loss to R_{AA}

1. Comparing D and B: $R^D_{AA} < R^B_{AA}$ (below 30 GeV/c)
2. Comparing π and D: $R^\pi_{AA} \leq R^D_{AA}$ (below 30 GeV/c)
   - Pions at LHC originate predominantly from gluons, below 10-15 GeV/c
   - Since R_{AA} rises with p_T, the softer p_T spectrum and fragmentation of gluons tend to reduce the impact on R_{AA} of their larger energy loss (colour charge)
   - Predictions range from a moderate difference to almost no difference



M. Djordjevic and M. Djordjevic, PRL112 (2014) 042302

A.Buzzatti et al., NPA904-905 (2013) 779c

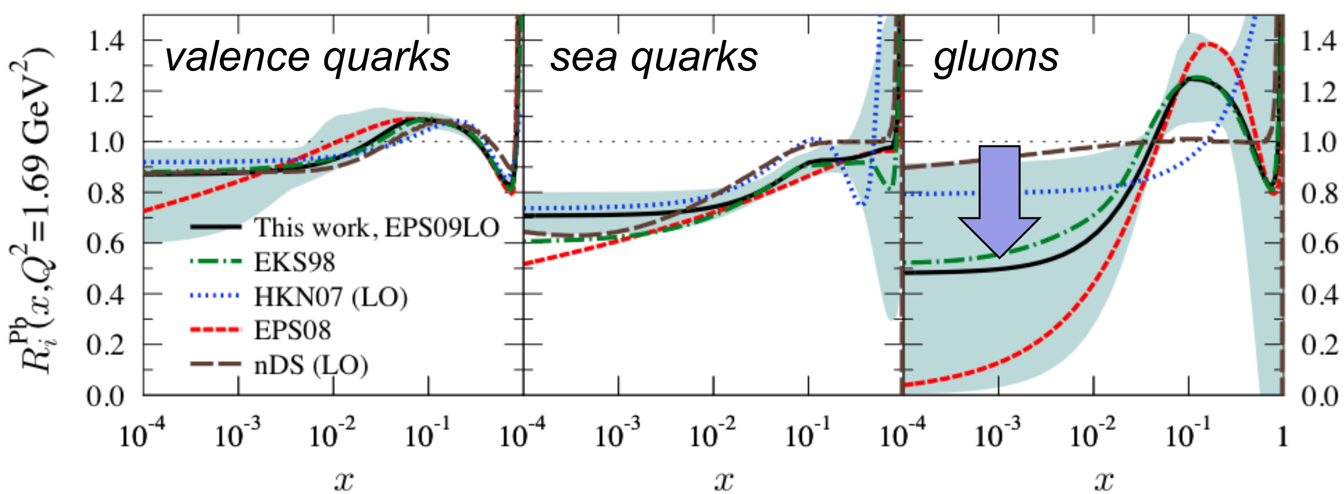
Initial-state effects ?

- The observed nuclear modification can have a contribution from initial-state effects, not related to the hot QCD medium
- High parton density in high-energy nuclei leads to reduction/saturation/shadowing of the $PDFs$ at small x (and small Q^2)

$$\frac{dN^D_{PbPb}}{dp_T} = PDF(x_1)PDF(x_2) \otimes \frac{d\hat{\sigma}^c}{dp_T} \otimes P(\Delta E) \otimes D_{c\to D}(z)$$

Nuclear modification of PDFs

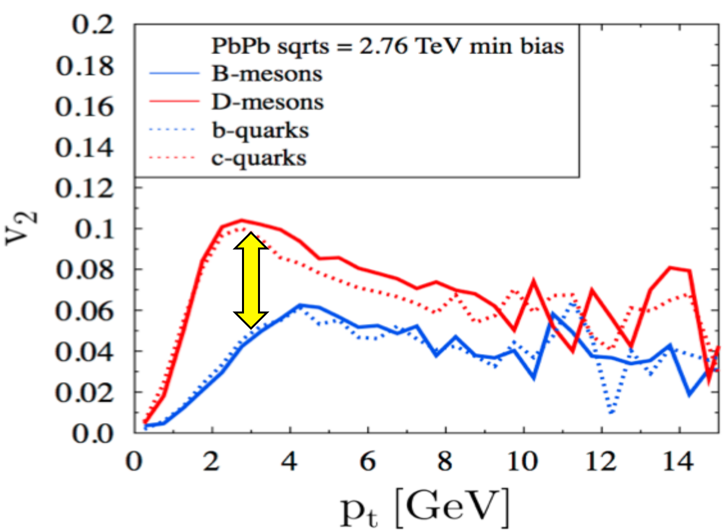
see e.g. Eskola et al. JHEP0904(2009)065



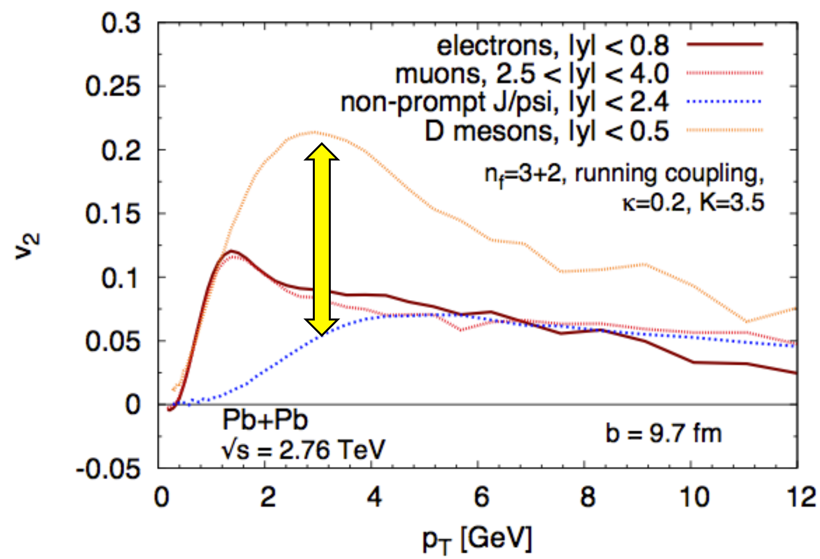
pA data crucial to measure initial-state effects

Heavy flavour v_2: a two-fold observable

- Low p_T: do heavy quarks take part in the "collectivity"?
  - Due to their large mass, c and b quarks should "feel" less the collective expansion
    - → need frequent interactions with large coupling to build v_2
    - → $v_2^b < v_2^c$
- High p_T: probe path length dependence of HQ energy loss



J. Aichelin et al. in arXiv:1201.4192



J. Uphoff et al. in arXiv:1205.4945

Summary of available measurements: AA

	PHENIX	STAR	ALICE	ATLAS	CMS
HF electrons	✔	✔	✔		
HF muons	✔		✔	✔	
D^0, D^+, D^{*+}		✔	✔		
D_s^+			✔		
$B \rightarrow J/\psi$					✔
B jets					✔
B electrons			✔		

Originally compiled by Z. Conesa dV

Summary of available measurements: p(d)A

	PHENIX	STAR	ALICE	ATLAS	CMS	LHCb
HF electrons	✔		✔			
HF muons	✔		✔			
D^0, D^+, D^{*+}		✔	✔			
D_s^+			✔			
$B \to J/\psi$						✔
B jets					✔	
B electrons			✔			
B					✔	

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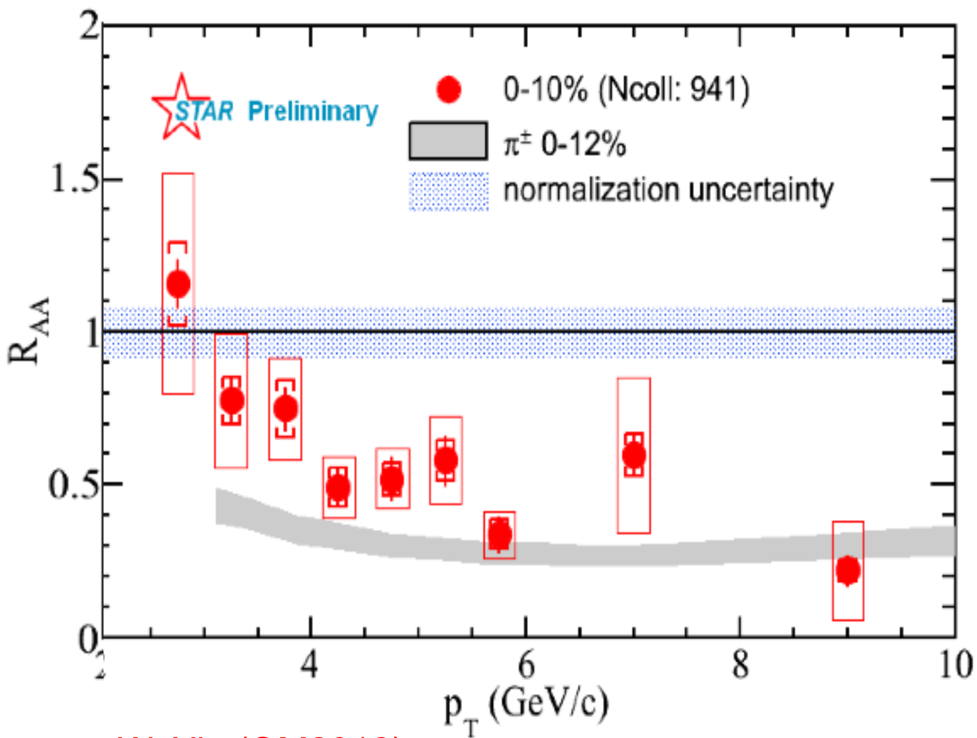
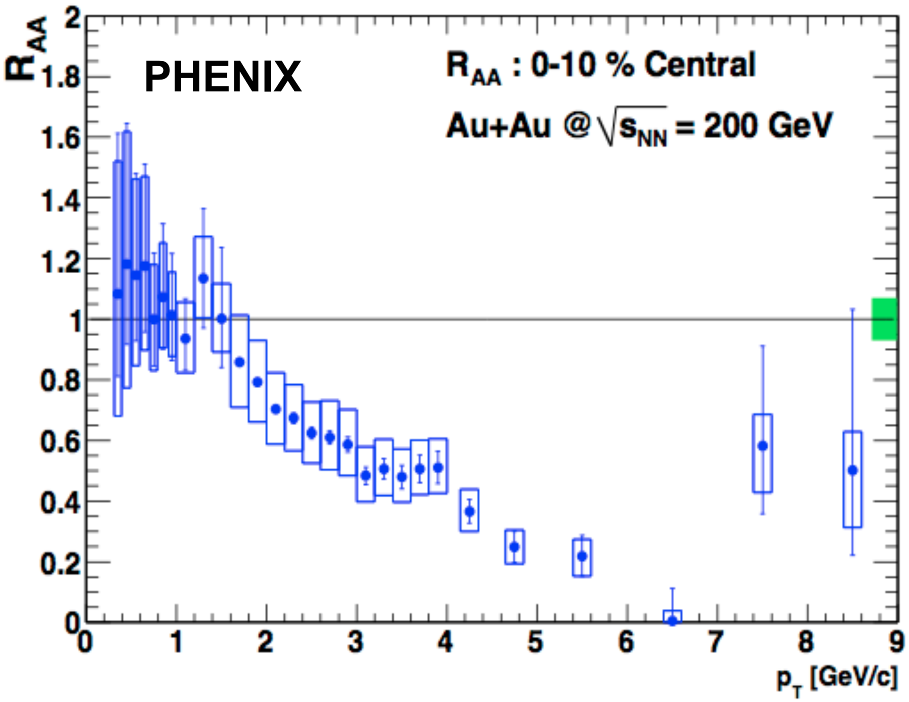
HF-decay electrons at RHIC (200 GeV)

- Inclusive measurement (c+b) using non-photonic electrons



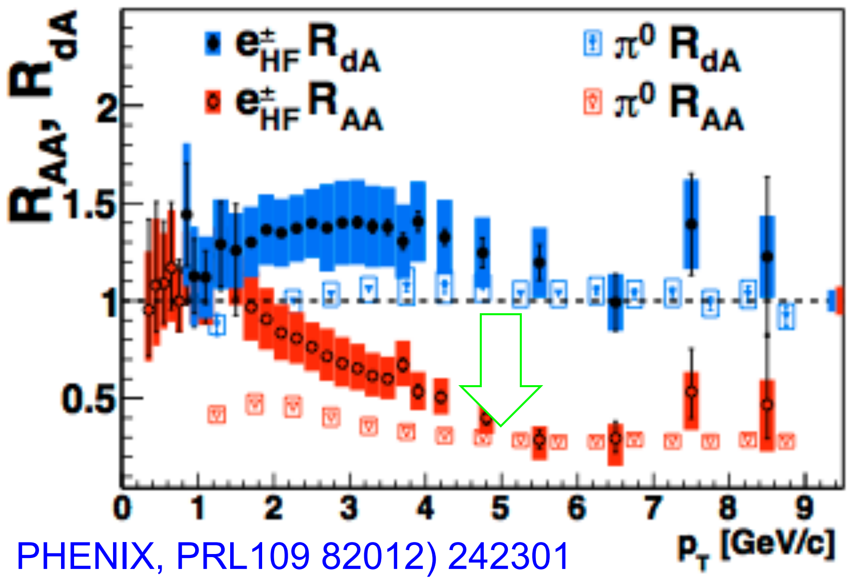


W. Xie (QM2012)
see also Phys. Rev. Lett. 98, 192301 (2007)

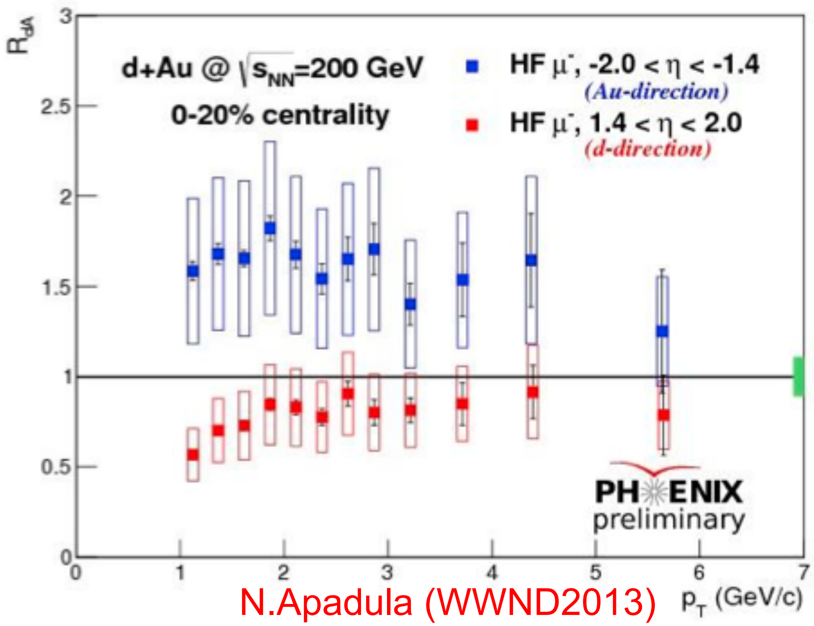
Phys. Rev. C 84, 044905 (2011)

- Same suppression as for light-flavour hadrons above 5 GeV/*c*
- Smaller suppression at 2-3 GeV/c, but cannot conclude on mass effects

HF-decay e and μ in d-Au at RHIC



PHENIX, PRL109 82012) 242301

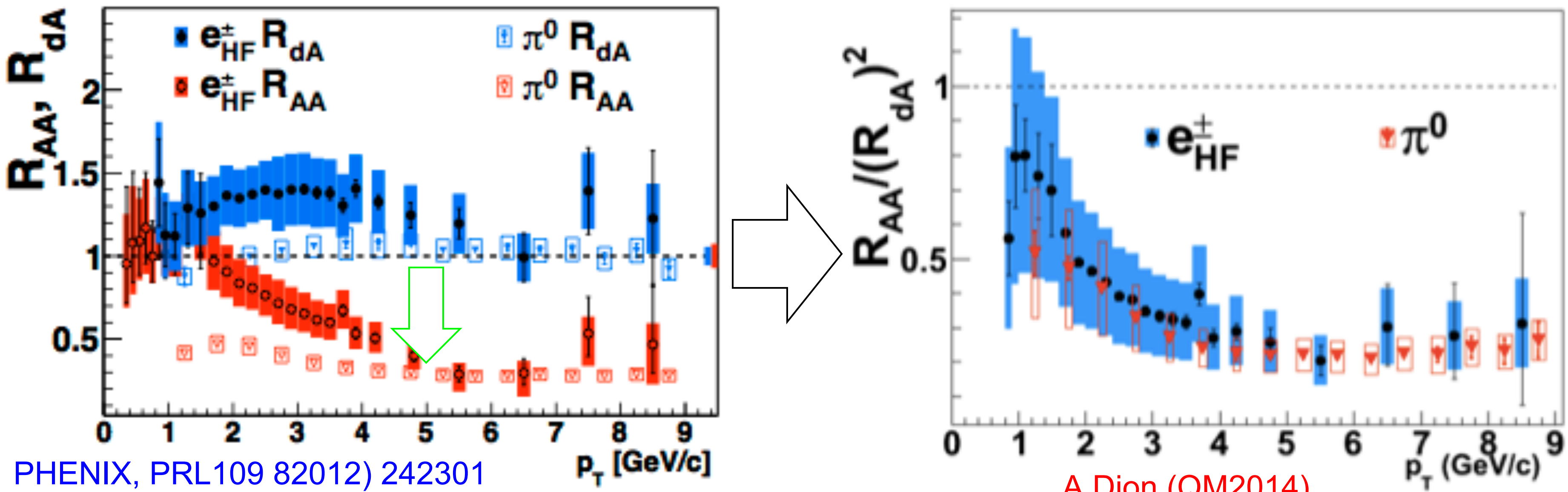


N.Apadula (WWND2013)

- Low-p_T electrons (mid-y) and muons (backward y) largely enhanced
  - More than expected from anti-shadowing?
  - Significant role of (mass-dependent?) k_T broadening?

→ Au-Au high-p_T suppression is a final state effect

HF-decay e and μ in d-Au at RHIC



PHENIX, PRL109 82012) 242301

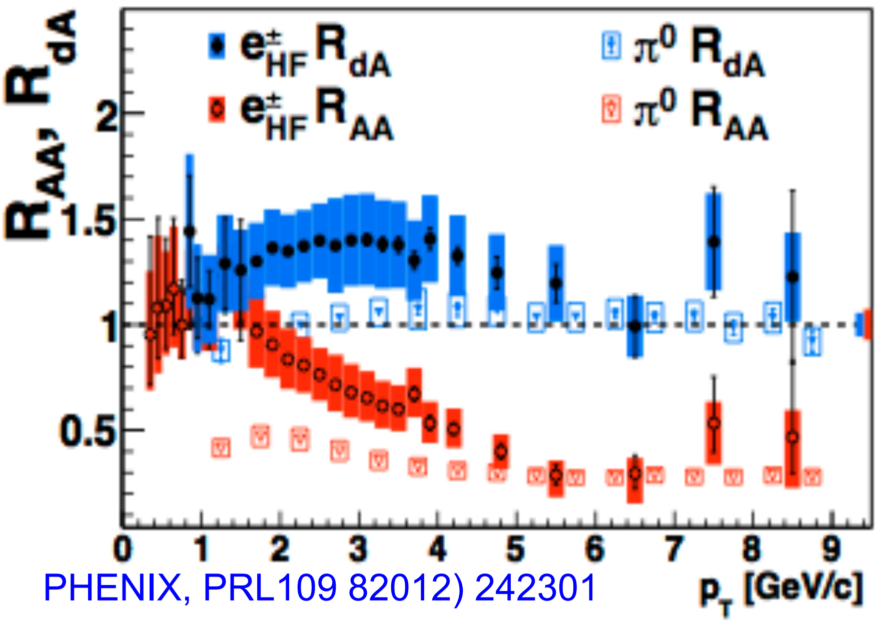
A.Dion (QM2014)

- Low-p_T electrons (mid-y) and muons (backward y) largely enhanced
  - More than expected from anti-shadowing?
  - Significant role of (mass-dependent?) k_T broadening?

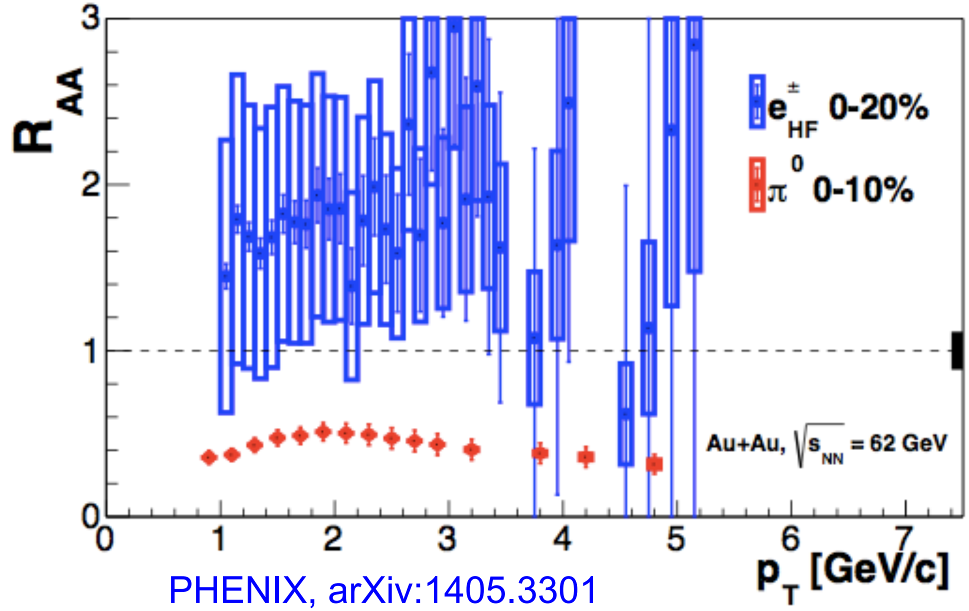
→ Au-Au high-p_T suppression is a final state effect

→ Simple(istic?) "propagation" of initial state effects (with R_{dA}^2) gives consistent "final-state-only R_{AA}" for π and e also at low p_T

HF-decay electrons at RHIC (62 GeV)



PHENIX, PRL109 82012) 242301

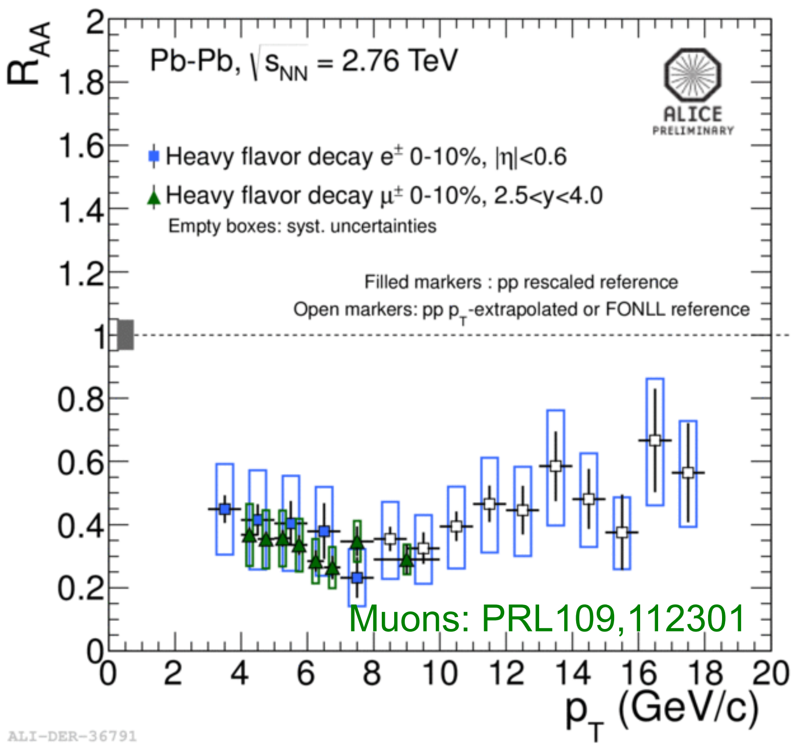


PHENIX, arXiv:1405.3301

- Lower energy RHIC runs give the unique opportunity to study the onset of the suppression
- R_{AA} at 62 GeV obtained with reference data from ISR
- Large uncertainties show the need for a high-stat RHIC pp run at 62 GeV

HF-decay e and μ at LHC: R_{AA} vs p_T

- Electrons and muons from D+B → e,μ decays

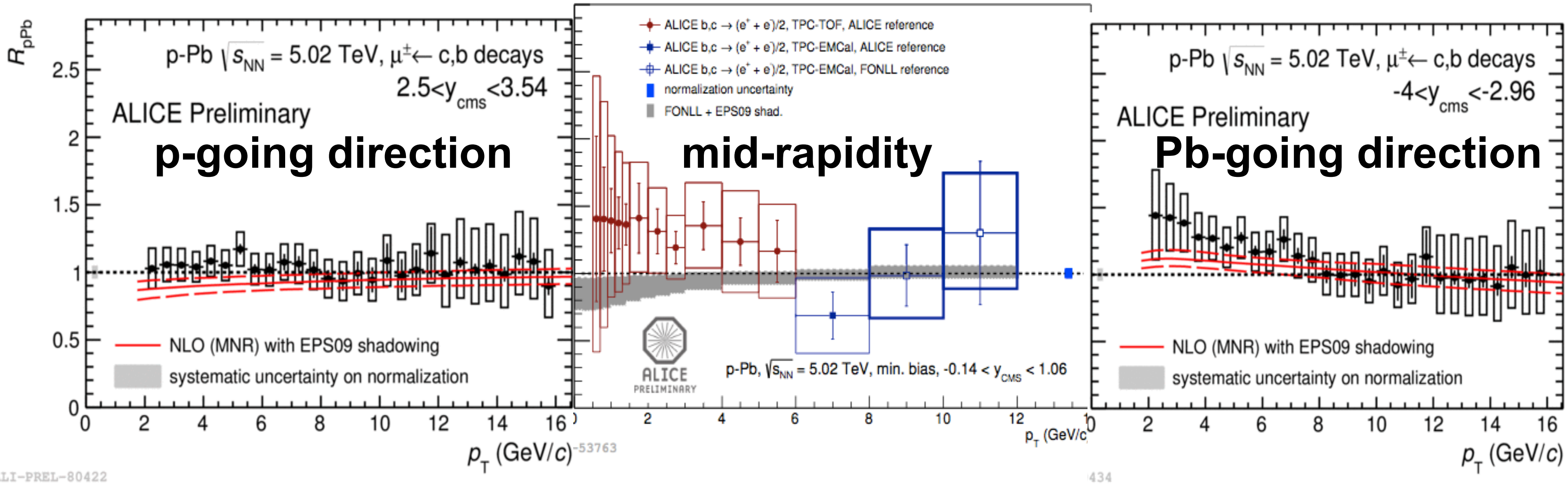


- Comparable suppression at central (|y|<0.6) and forward (2.5<y<4) rapidity

- Suppression by a factor about 2 up to 18 GeV/c
  - Dominated by beauty at such high p_T
  - Note: $p_T^{hadron} \sim 2\ p_T^{lepton}$

A.Festanti (QM2014)

HF-decay e and μ in p-Pb at LHC



- HF-decay muon R_{pA} (p_T>2 GeV/c):
  - Consistent with unity in p-going direction (small x in the Pb)
  - Somewhat enhanced in Pb-going direction (large x in the Pb)
- HF-decay electron R_{pA} consistent with unity
- pQCD+Shadowing (EPS09) can describe the data

→ Pb-Pb high-p_T suppression is a final state effect

R.Russo, S.Li (QM2014), Eskola et al., JHEP 0904 (2009) 065

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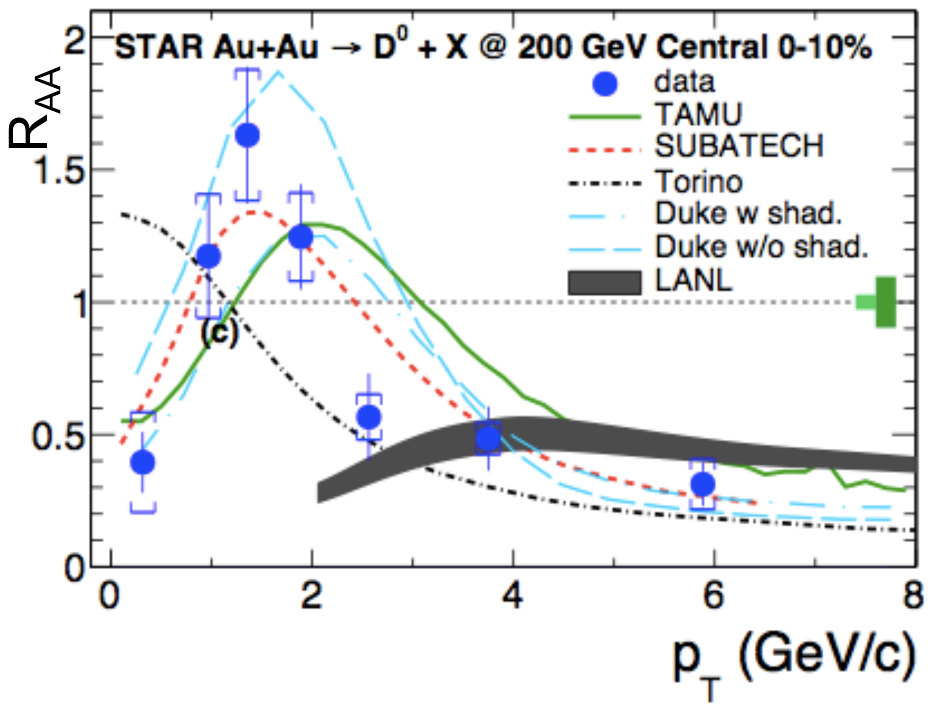
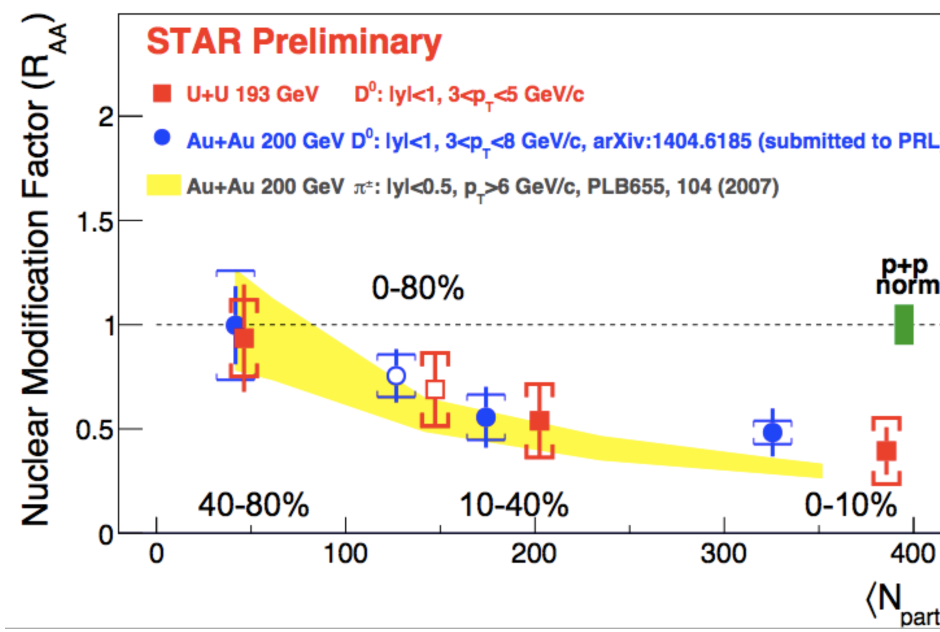
Charm: D mesons at RHIC

- STAR: D^0 R_{AA} in Au-Au and U-U at RHIC
  - Without secondary vertex reco (~800M Au-Au events)

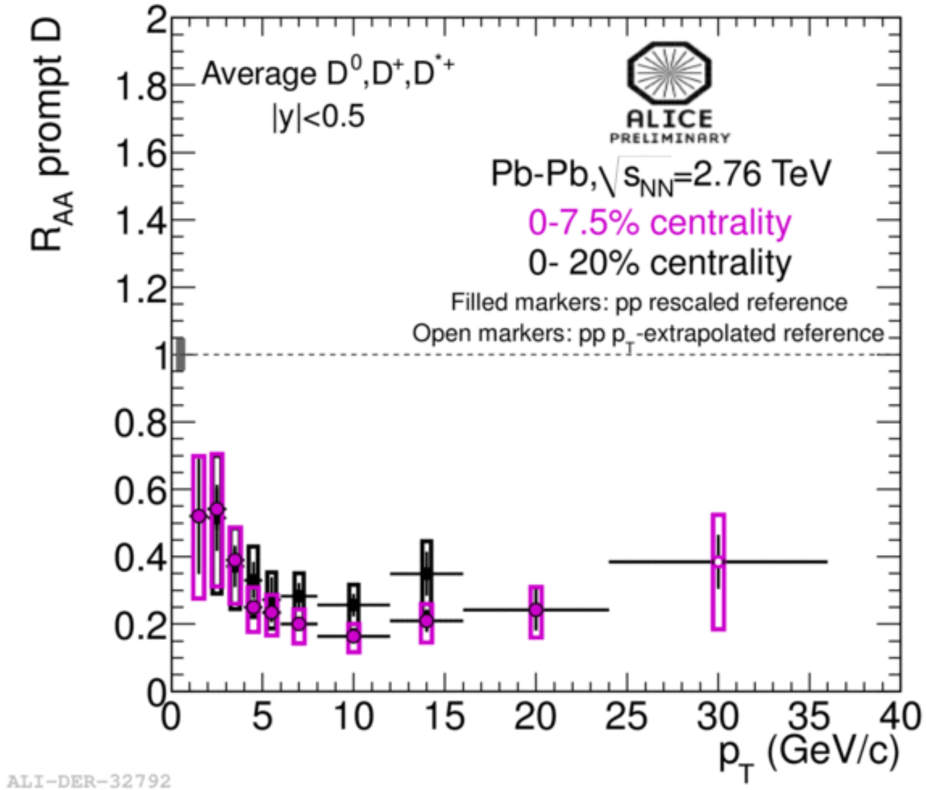




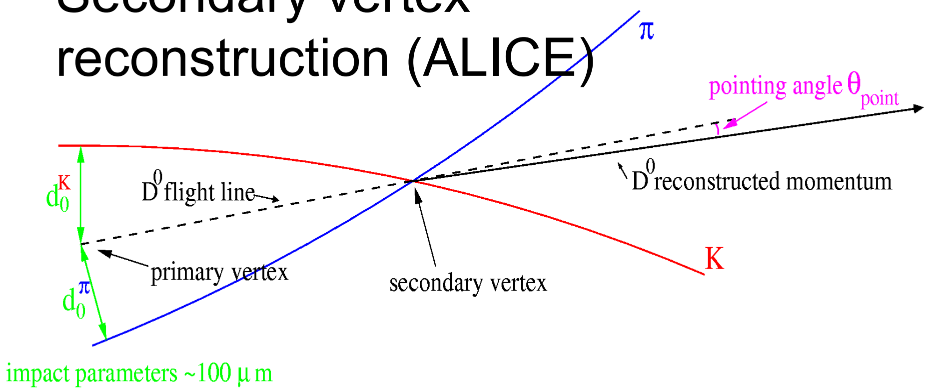
- Suppressed by a factor ~3 at high p_T in central Au-Au
- Large enhancement at 1.5 GeV/c: radial flow + coalescence?

STAR, arXiv:1404.6185, Z. Ye (QM2014)

Charm: D mesons at LHC



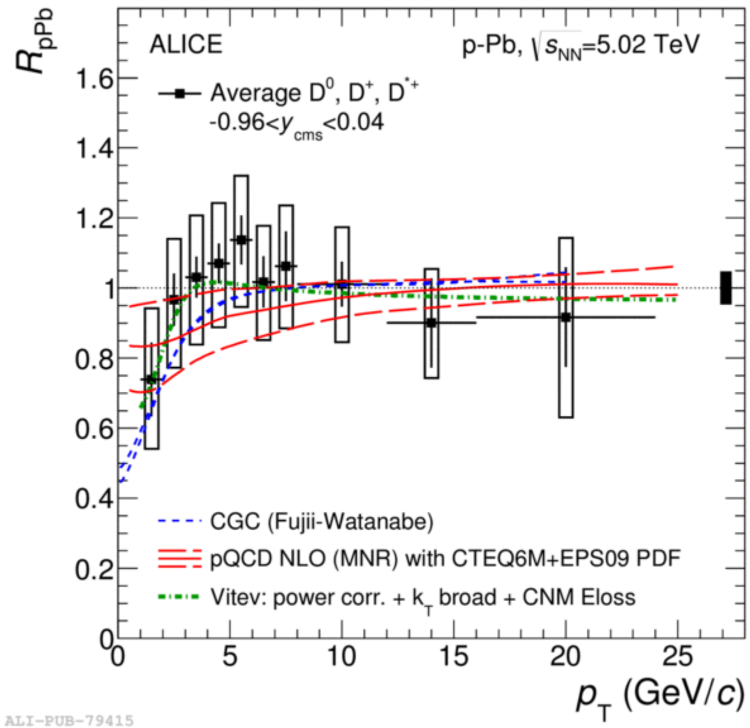
Secondary vertex reconstruction (ALICE)

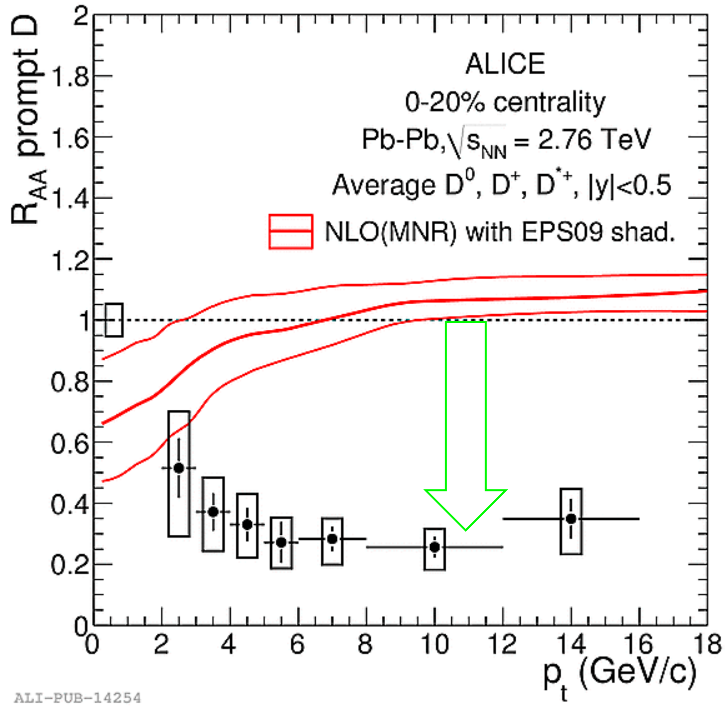


- First D R_{AA} measurement in heavy-ion collisions with data from LHC 2010 run (0-20% centr.) ALICE, JHEP 09 (2012) 112
- Extended with LHC 2011 run, from 1 to 30 GeV/c
- Factor ~5 suppression at ~10 GeV/c in 0-7.5% centr.

Z.Conesa (QM2012)

D mesons in p-Pb at LHC





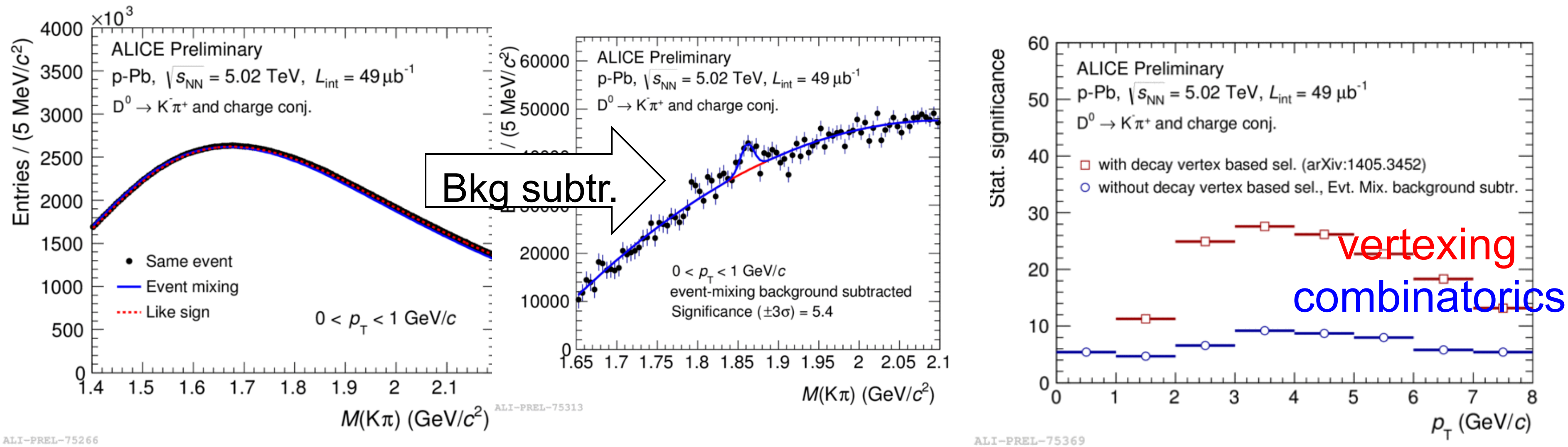
- D meson R_{pA} consistent with unity (and with 0.5 at 1 GeV/c…)
  - pQCD+Shadowing (EPS09) or k_T broadening and CNM E loss, and Colour Glass Condensate can describe the data

→ Pb-Pb high-p_T suppression is a final state effect

ALICE, arXiv:1405.3452

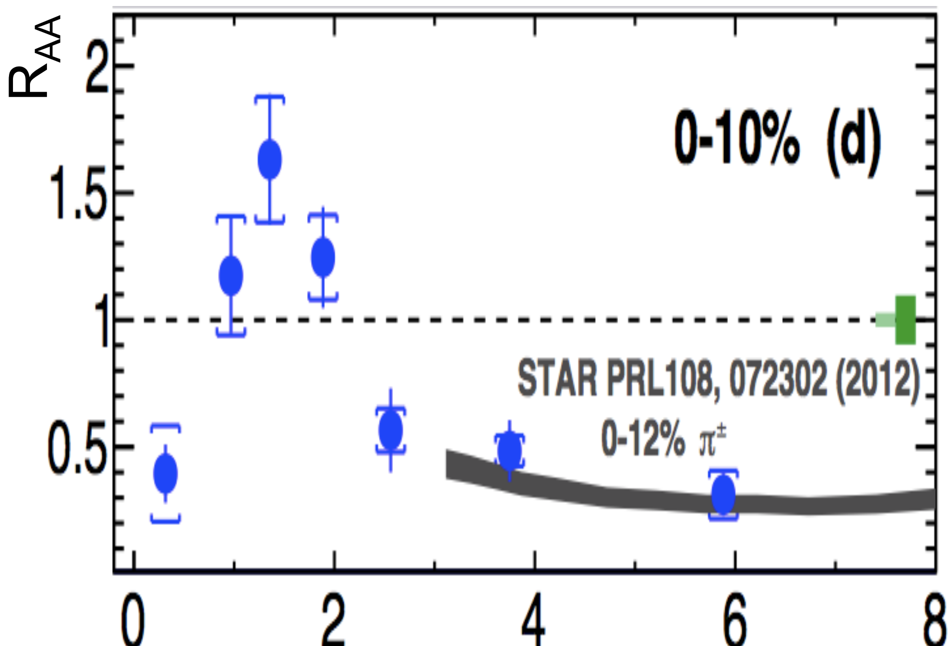
Total charm cross section at LHC ?

- PHENIX and STAR have measured the total charm cross section (using electrons and D mesons down to p_T=0)
- Example: D mesons at low p_T
  - Below 1 GeV/c the vertexing method becomes inefficient, the brute-force combinatorics becomes better *if very large stat is available*

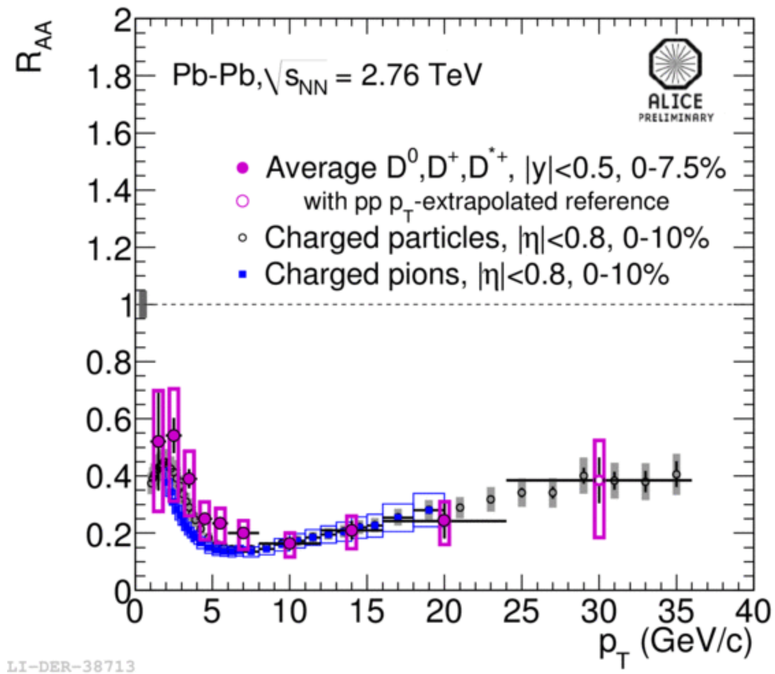


- A matter of statistics:
  - STAR used a sample of 800M Au-Au collisions
  - ALICE Run-1 sample is of about 50M Pb-Pb collisions
  - Run-2 might allow a first measurement; precision with Runs-3 and 4

Looking for colour charge dependence: D mesons vs. pions at RHIC and LHC

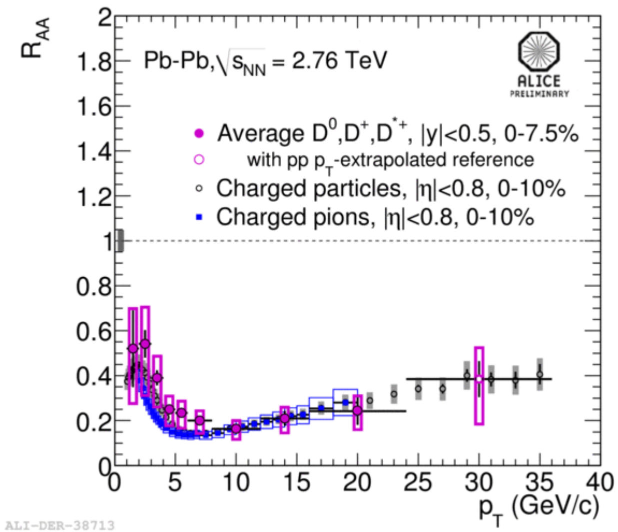


STAR, arXiv:1404.6185

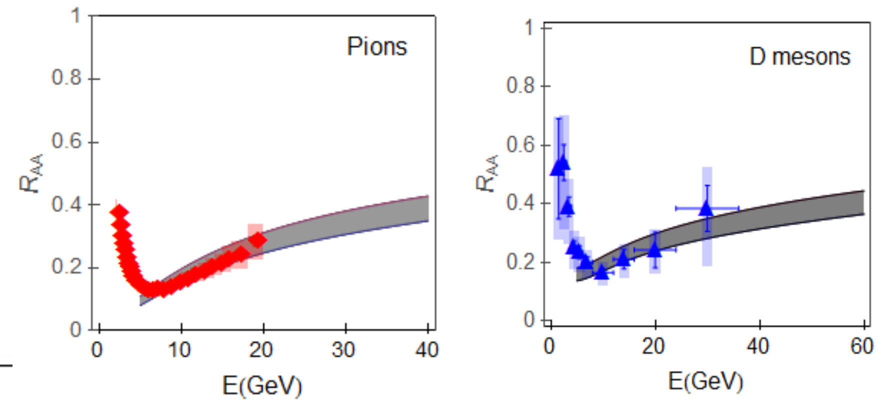


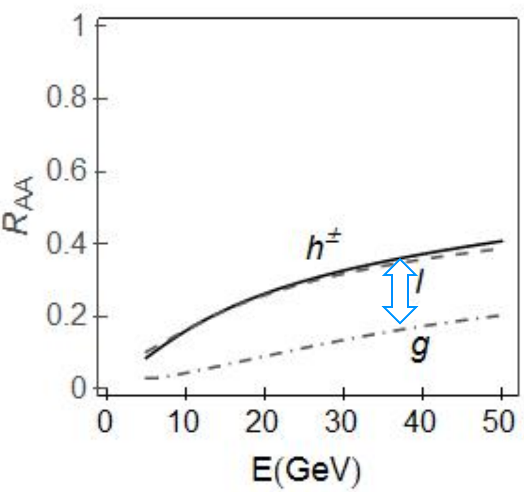
- R_{AA} of D and pions consistent within current uncertainties
- Hint for D > π in 2-5 GeV/c?
  - Below 2 GeV/c: no direct comparison, π not expected to scale with N_{coll}
- Is it consistent with the colour charge dependence?

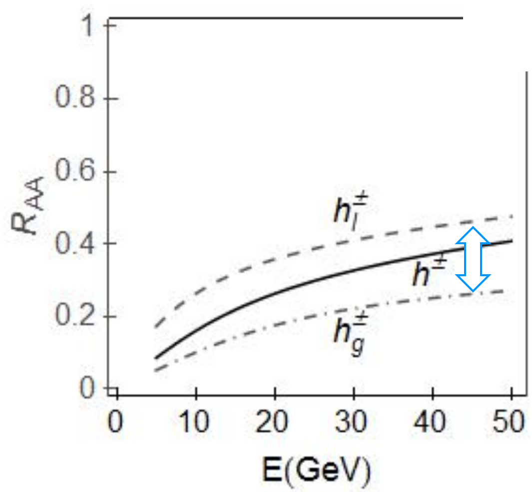
D mesons vs. pions at LHC



- Calculation by M. Djordjevic (rad+coll energy loss) can describe both R_{AA}
- Shows strong colour charge effect in partonic R_{AA} (g vs. light and c)







Suggests that colour charge effect helps to describe the observed $R_{AA}^D \sim R_{AA}^\pi$

M. Djordjevic and M. Djordjevic, PRL112 (2014) 042302

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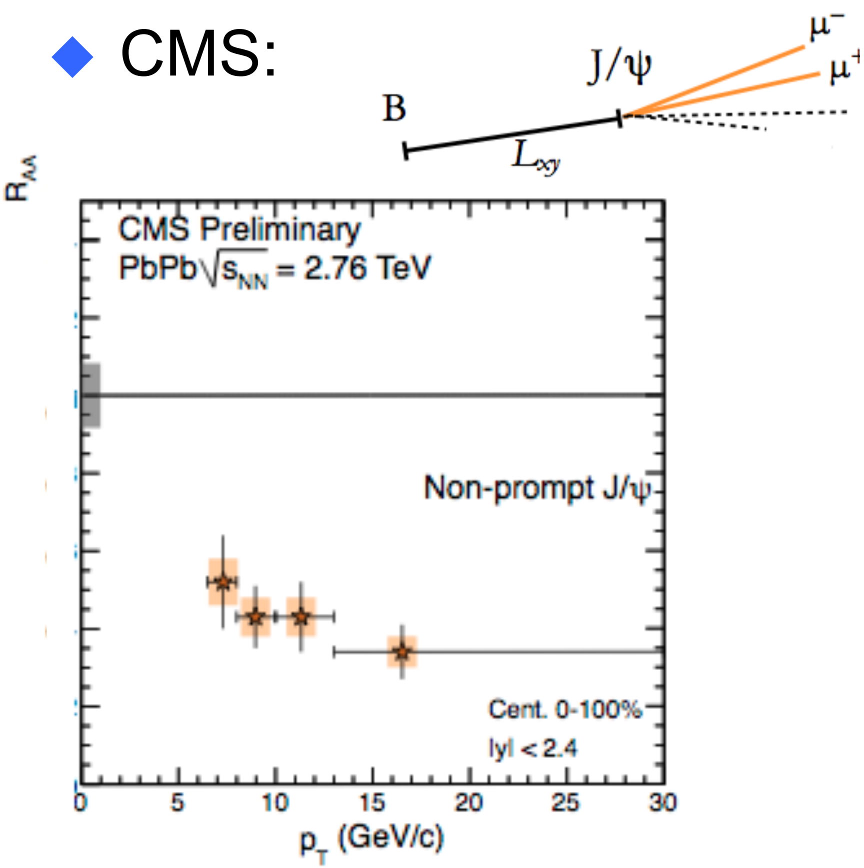
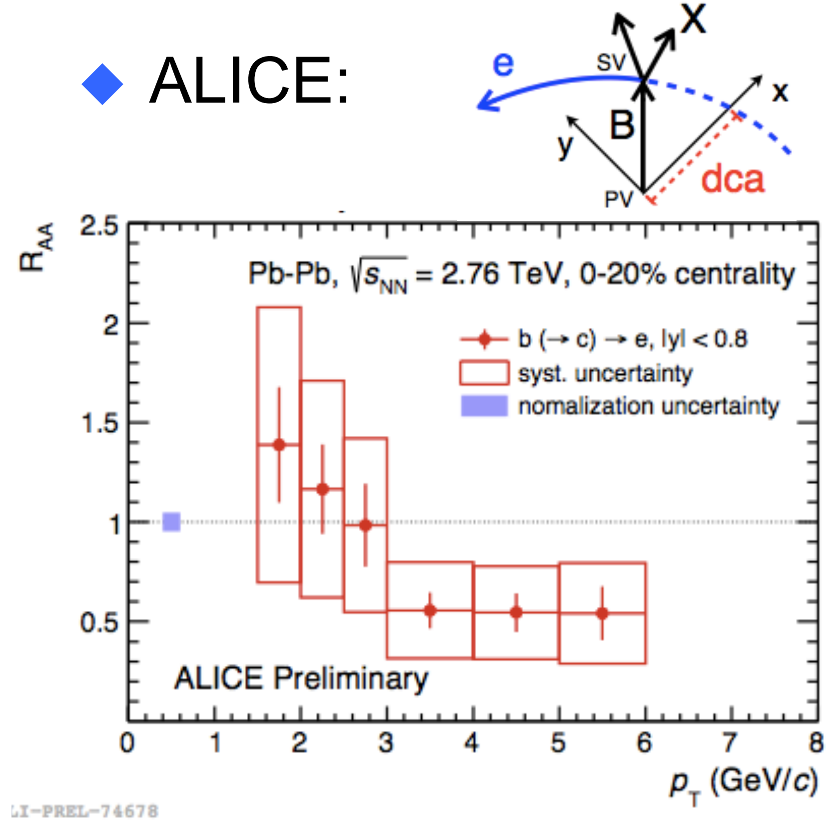
Beauty R_{AA} at LHC

- CMS:



- ALICE:



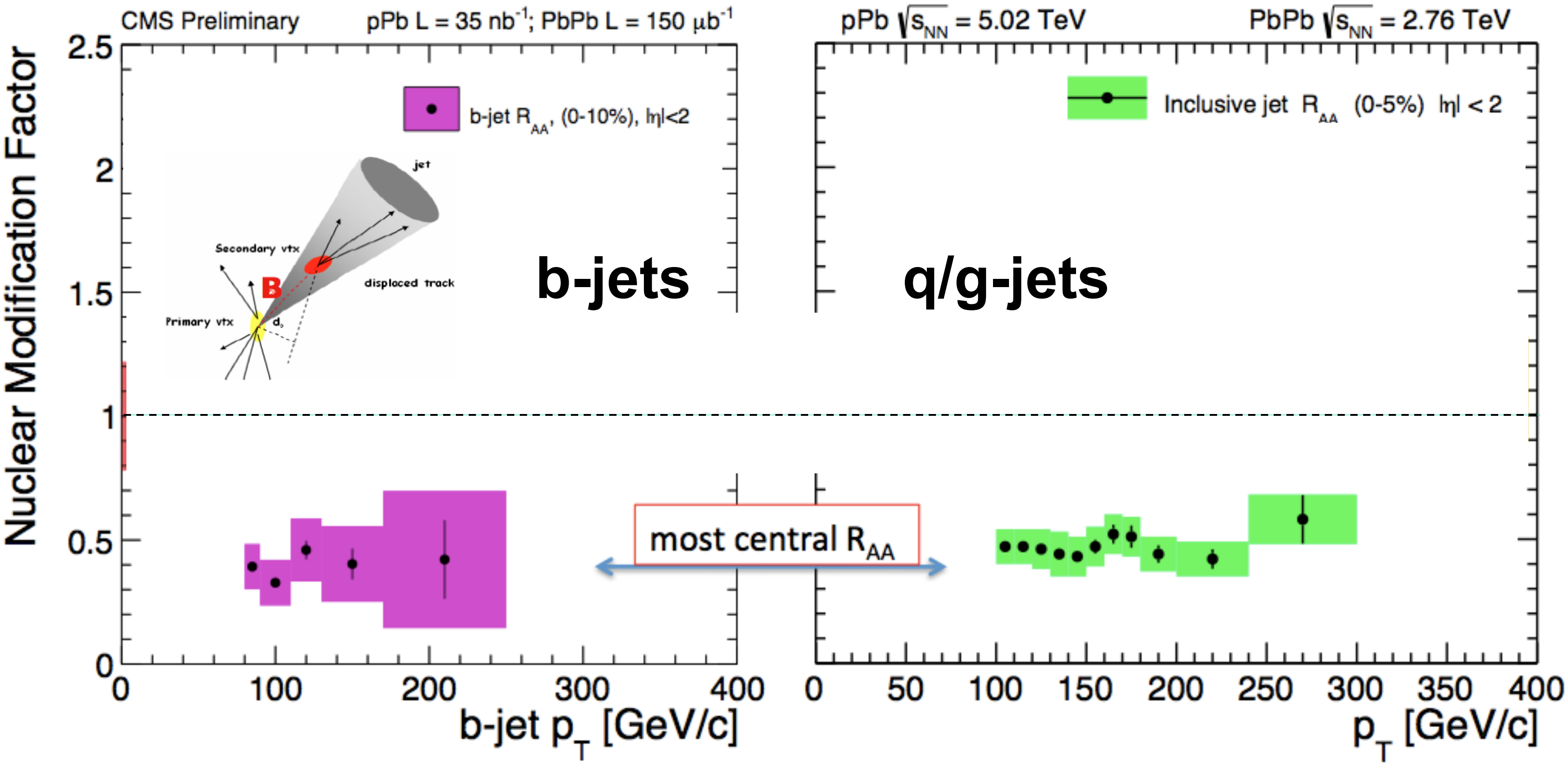
- Larger suppression at higher p_T in min. bias
- Centrality dep. in next slide

- Indication of R_{AA}<1 for electron p_T>3 GeV/c

CMS-PAS-HIN-12-014

A. Festanti (QM2014)

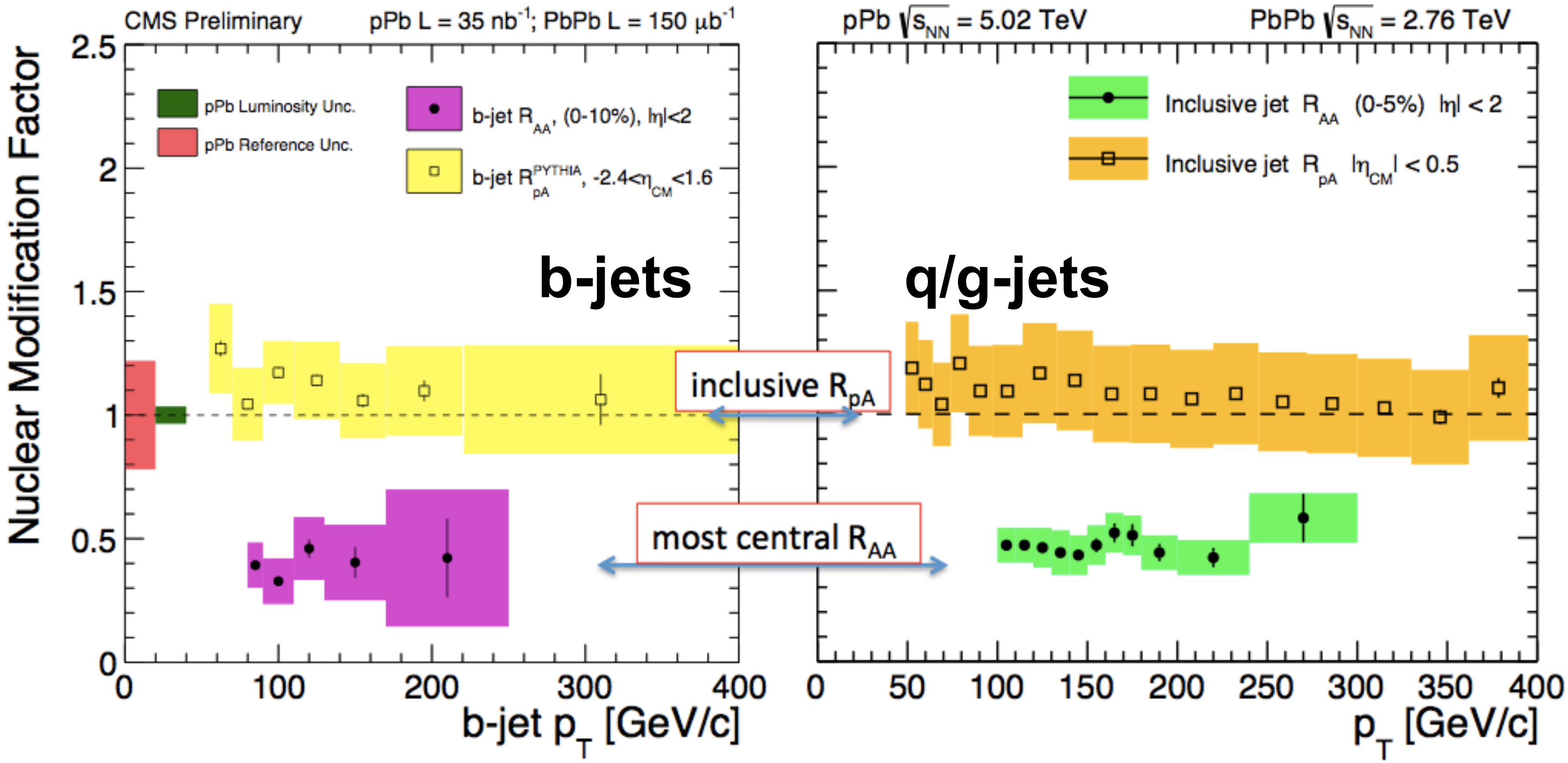
b-jet R_{AA} at LHC



- CMS measured b-jets with p_T>80 GeV/c in Pb-Pb and p-Pb
- Same R_{AA} for b-jets as for q/g-jets, as expected at this p_T

CMS-HIN-12-003, CMS-HIN-14-007

b-jet R_{AA} at LHC

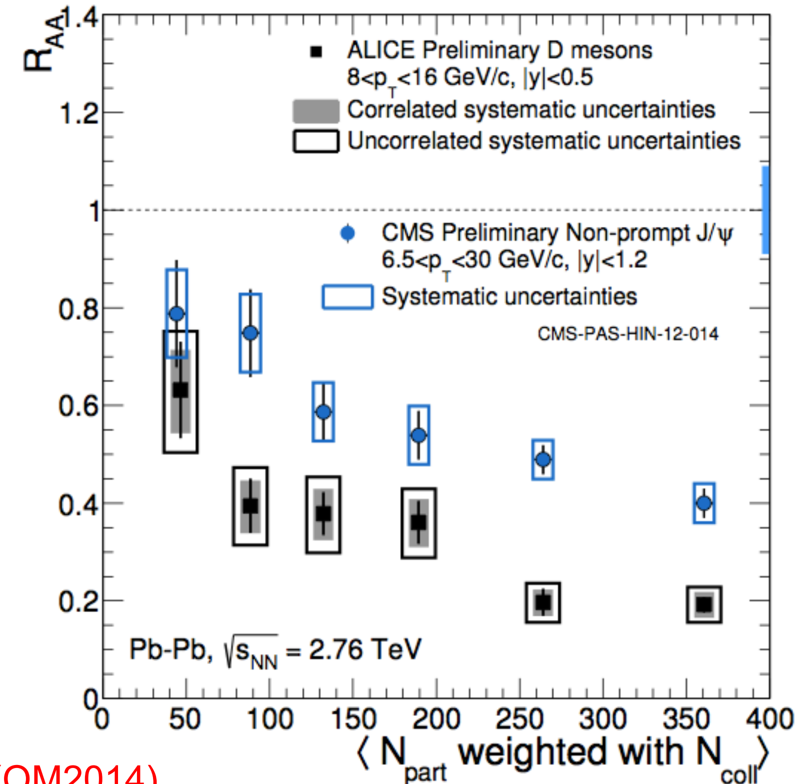


- CMS measured b-jets with p_T>80 GeV/c in Pb-Pb and p-Pb
- Same R_{AA} for b-jets as for q/g-jets, as expected at this p_T
- R_{pA} consistent with unity: no strong initial-state effects

CMS-HIN-12-003, CMS-HIN-14-007

Looking for mass dependence: R_{AA} of D and B at the LHC

- **D mesons (ALICE)** and **J/ψ from B decays (CMS)**



A. Festanti (QM2014)

Similar $\langle p_T \rangle$ for B and D:

- **B $\langle p_T \rangle$ ~ 11 GeV (FONLL +EvGen)**
- **D $\langle p_T \rangle$ ~ 10 GeV**

- First clear indication of: $R_{AA}^{B} > R_{AA}^{D}$

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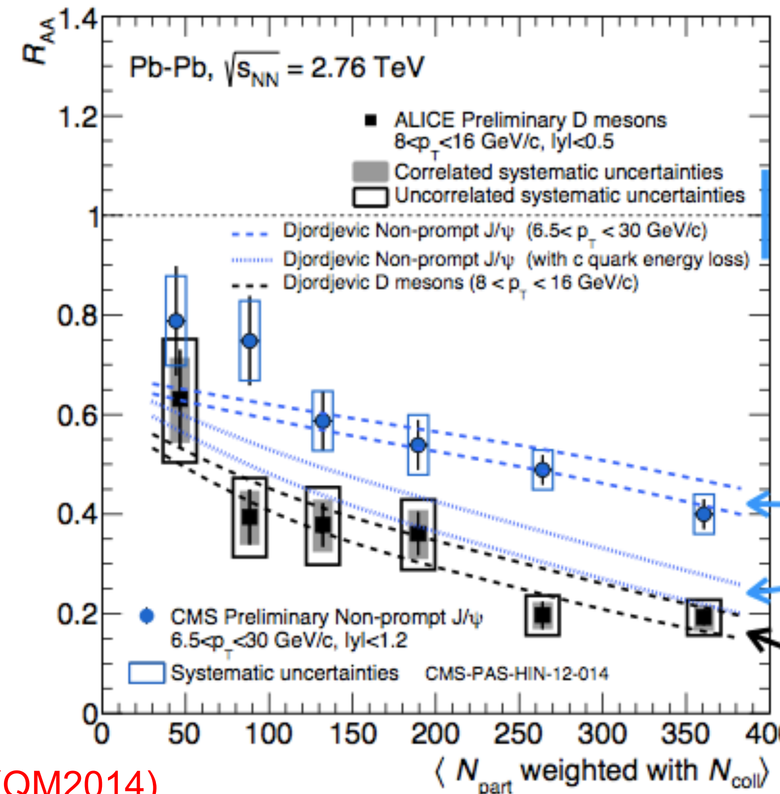

A. Festanti (QM2014)

Similar <p_T> for B and D:

- **B <p_T> ~ 11 GeV (FONLL +EvGen)**
- **D <p_T> ~ 10 GeV**

✓ Djordjevic: non-prompt J/ψ R_{AA} considering for energy loss
- b quark mass
- c quark mass

} to test the mass dependence

✓ Djordjevic: D meson R_{AA}

M. Djordjevic et al., PRL112 (2014) 042302

- Described by model calculations with $\Delta E_c > \Delta E_b$
  - Also WHDG, Aichelin et al, Vitev, TAMU

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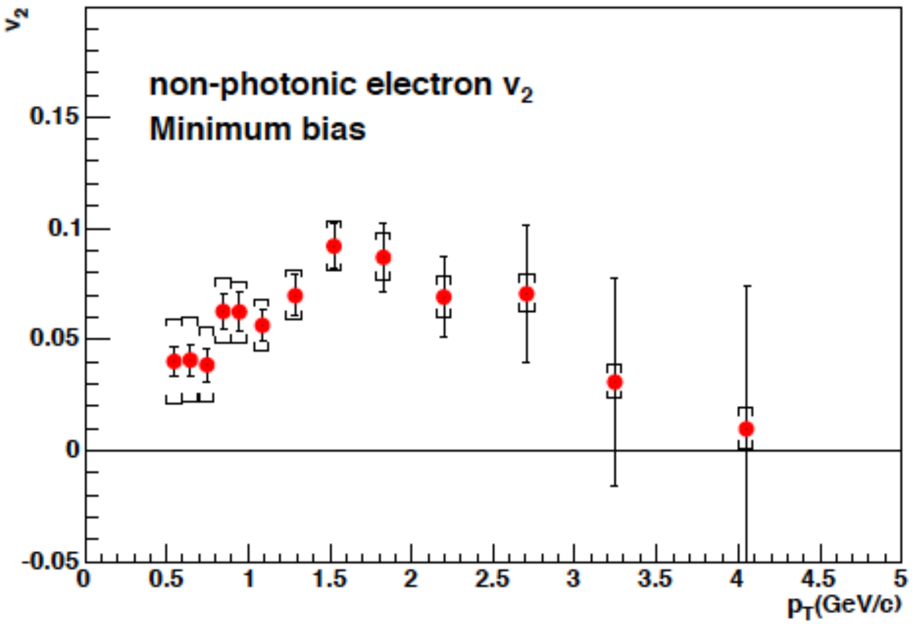
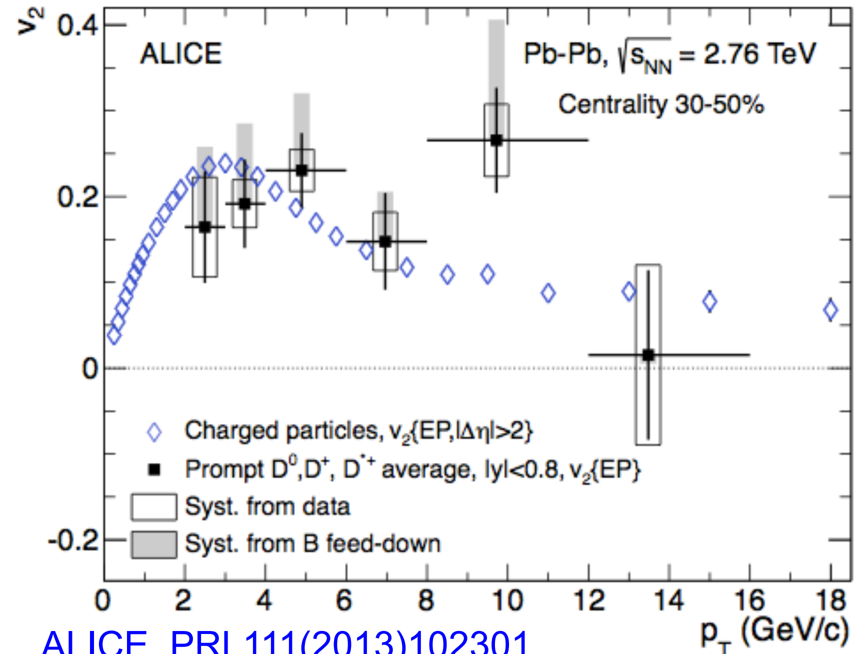
Heavy Flavour v_2 at RHIC and LHC



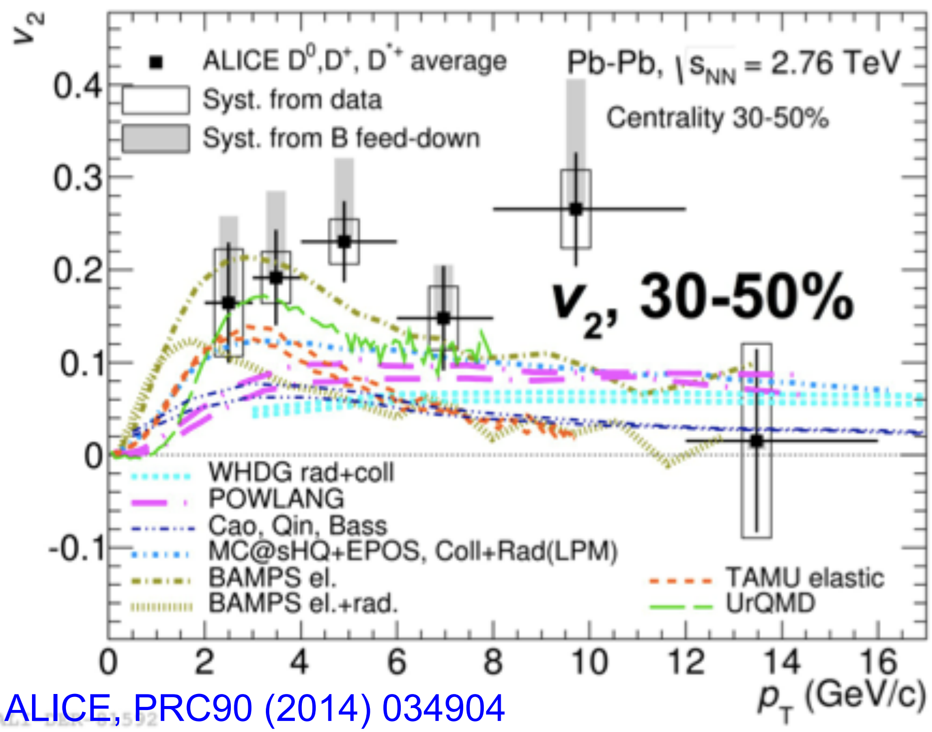
PHENIX, PRC84 (2011) 044905

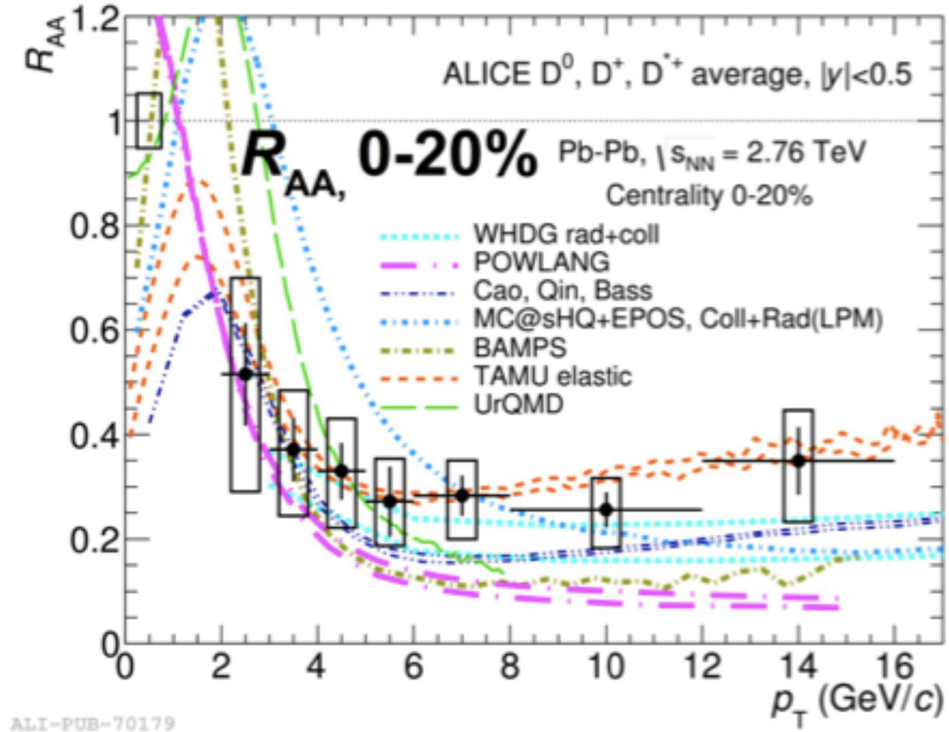


ALICE, PRL111(2013)102301

- Electrons from HF show a v_2 of up to 0.15 at RHIC (PHENIX, STAR)
- D meson v_2 in 30-50%: ~0.2 in 2-6 GeV/c
  - Comparable with charged particle v_2
- What is the origin of this v_2? c quark flow? coalescence?
- Much more to learn with future data

Comparison with models at LHC



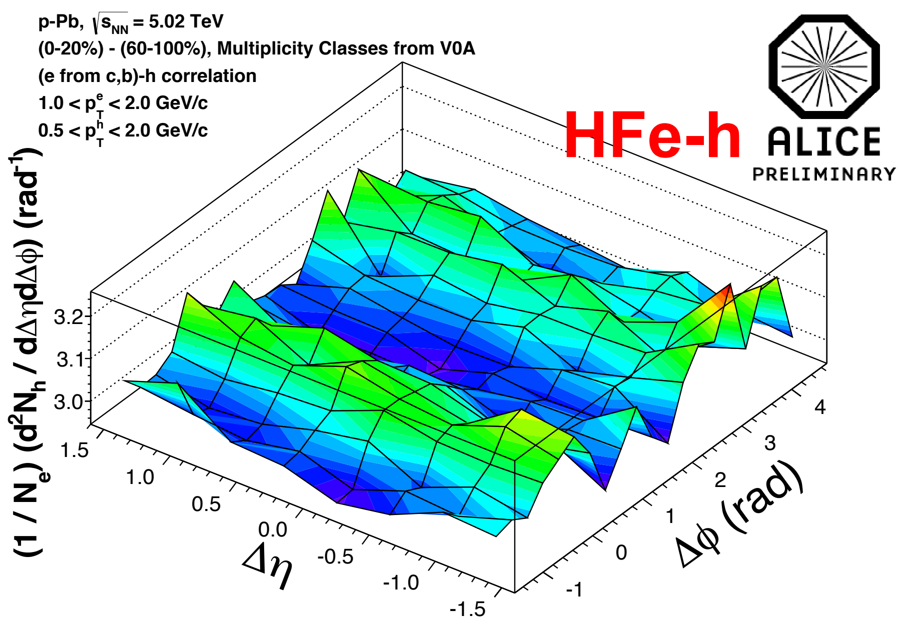


ALICE, PRC90 (2014) 034904

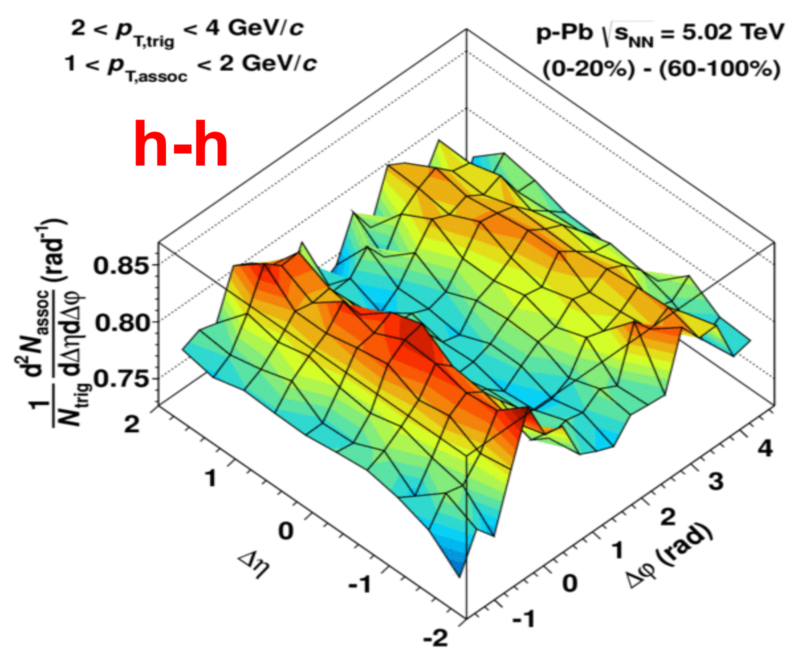
- Models without HQ interactions with expanding medium underestimate v_2 (WHDG, POWLANG), but are among the best for R_{AA}
- Max v_2~0.15-0.20 is best described by models that include **collisional energy loss** of heavy quarks in expanding medium (BAMPS, UrQMD, TAMU, MC@sHQ); they also include a component of **recombination**
- Suggests that these mechanisms play a role in HQ-medium interactions

e-h correlations in high-mult collisions

- Correlation between HF-decay electrons and hadrons in (high-mult) – (low-mult) p-Pb collisions: a "double ridge" similar to what observed for hadron-hadron



D.Caffarri, HP2013

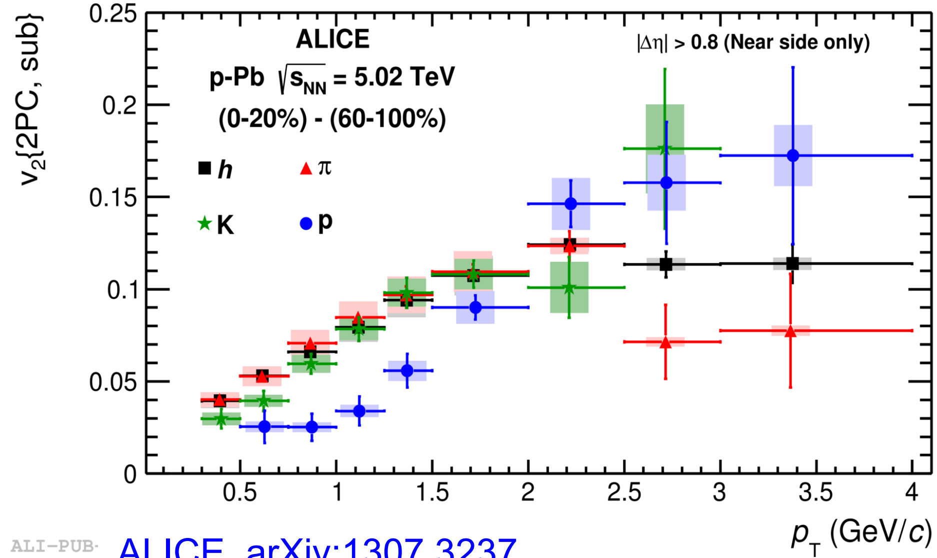


ALICE, PLB719 (2013) 29

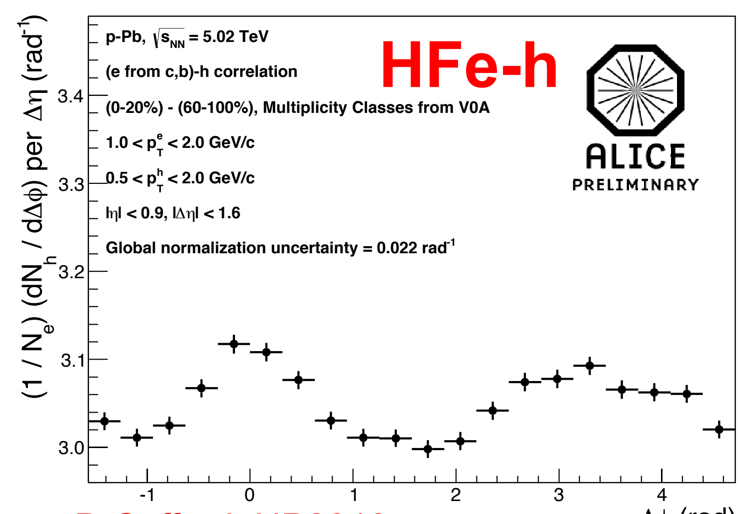
- Resembles the structure that in AA is interpreted in terms of collective flow

p-Pb at LHC: more than a control experiment?
e-h correlations in high-mult collisions

- For hadrons, a flow-like mass ordering is observed
- Alternative interpretations include initial-state effects (Color Glass Condensate) and “vacuum QCD” effects (color reconnection of strings)
- Heavy flavour can provide important additional information



ALICE, arXiv:1307.3237



D.Caffarri, HP2013

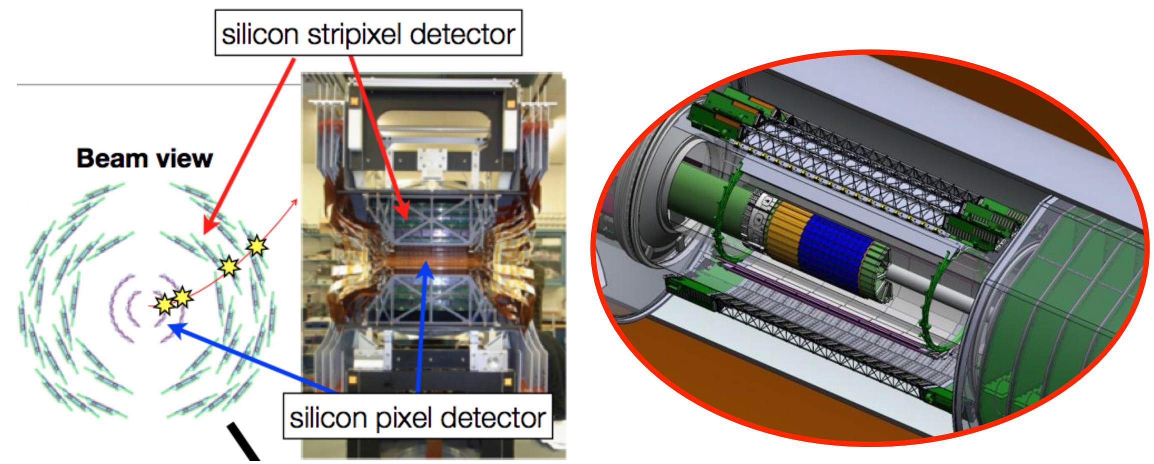
Outline of the Talk

- Introduction: HF probes of the medium
- Calibrating HF probes: pp results (see back-up)
- HF production in nucleus-nucleus (and proton-nucleus)
  - Semi-leptonic decays
  - D mesons
  - B and b-jets
- HF azimuthal anisotropy
- Outlook: detector upgrades at RHIC and LHC

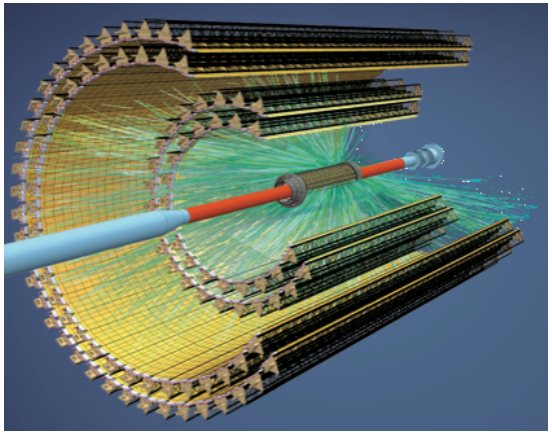
Detector upgrades at RHIC and LHC

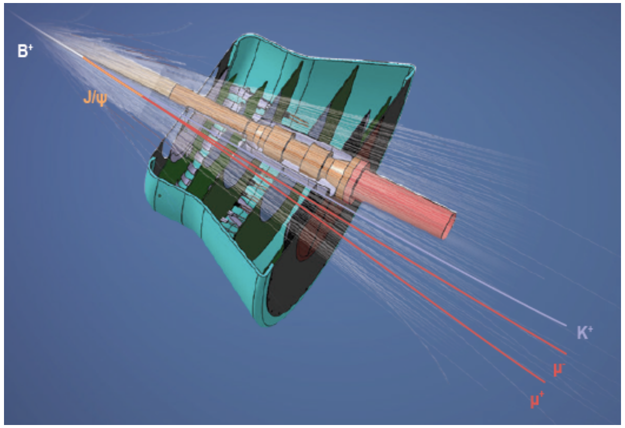
- **Heavy flavour: a central topic for upgrades of all HI experiments!**
  - **c/b decay leptons**
  - **Low-p_T D, D_s, B**
  - **HF baryons**
  - **…**

Already online: PHENIX VTX, STAR HFT

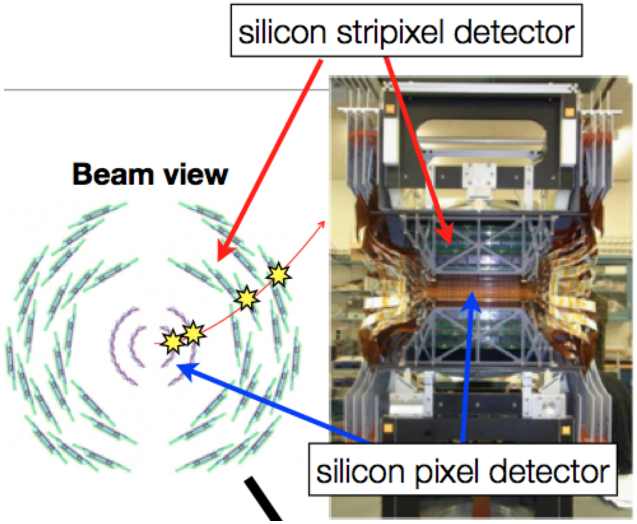


Planned for 2018-19: ALICE new ITS and MFT

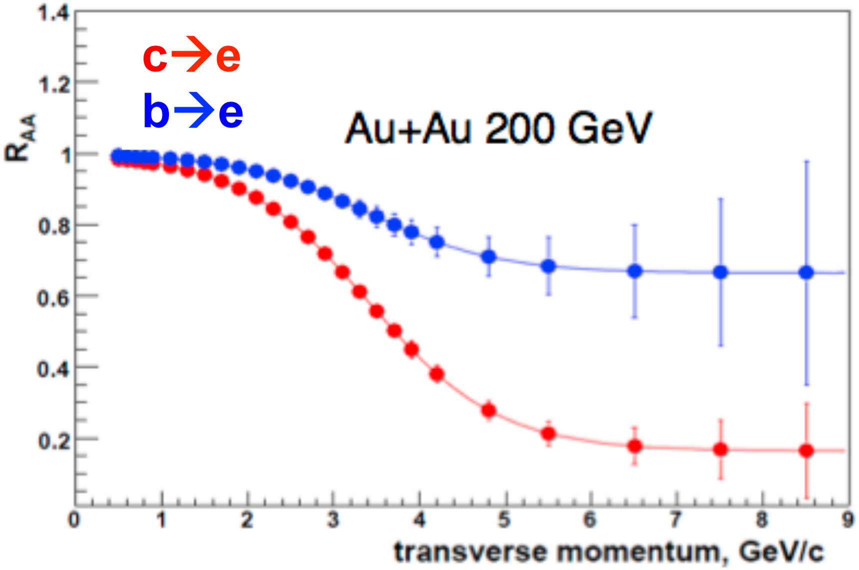




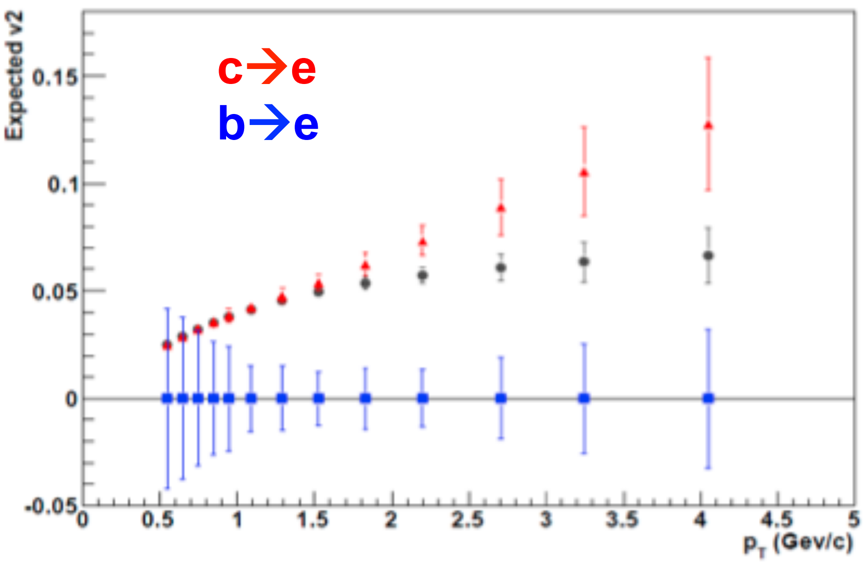
PHENIX: Vertex Tracker (VTX)



Electron R_{AA}

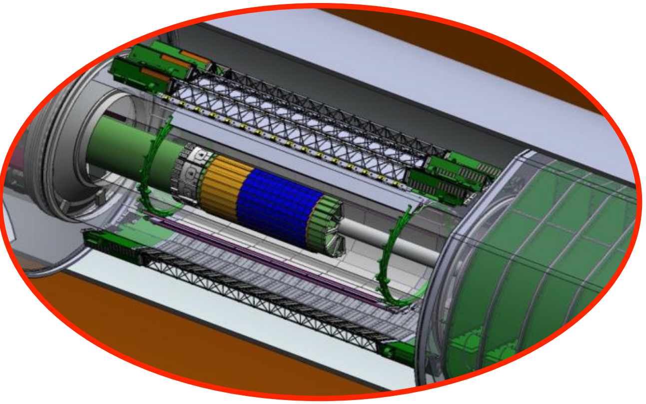


Electron v_2



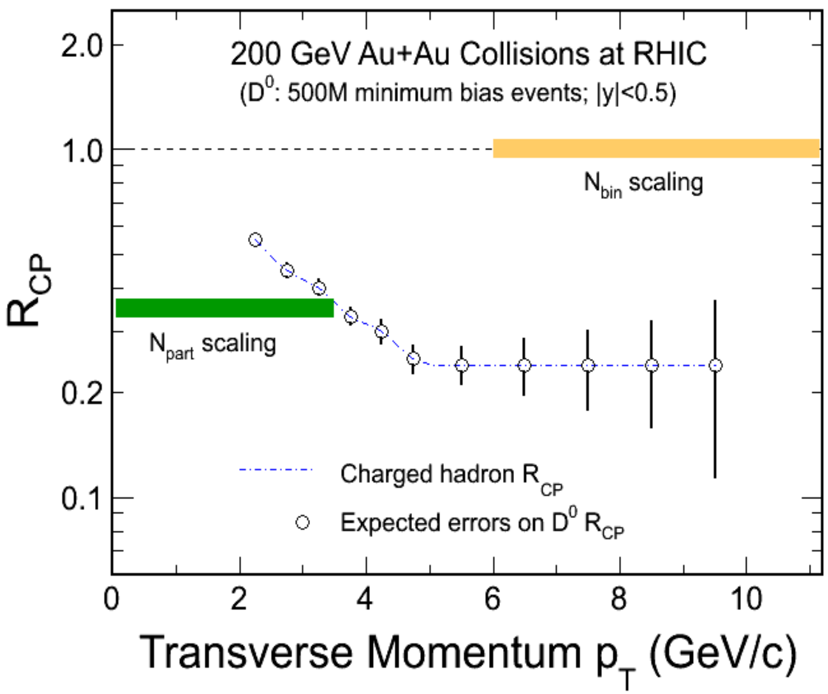
Projections $5x10^9$ evts

M. Rosati, QM2012

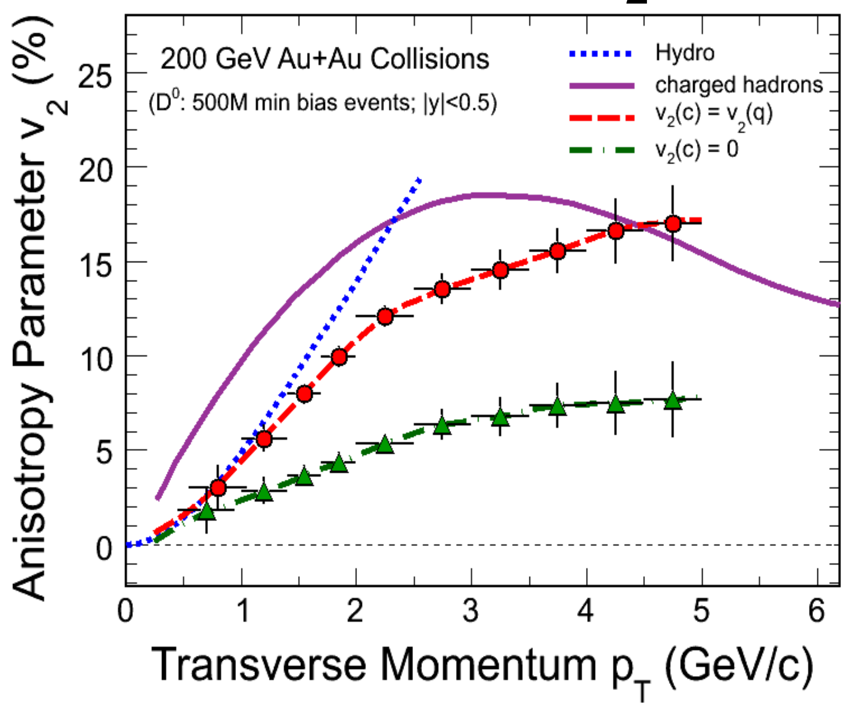


STAR: Heavy Flavour Tracker

D meson R_{CP}



D meson v_2

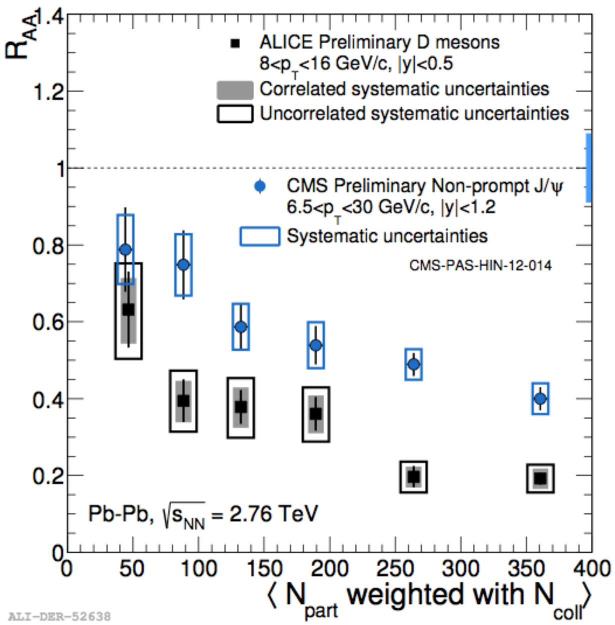


Projections 0.5×10^9 evts

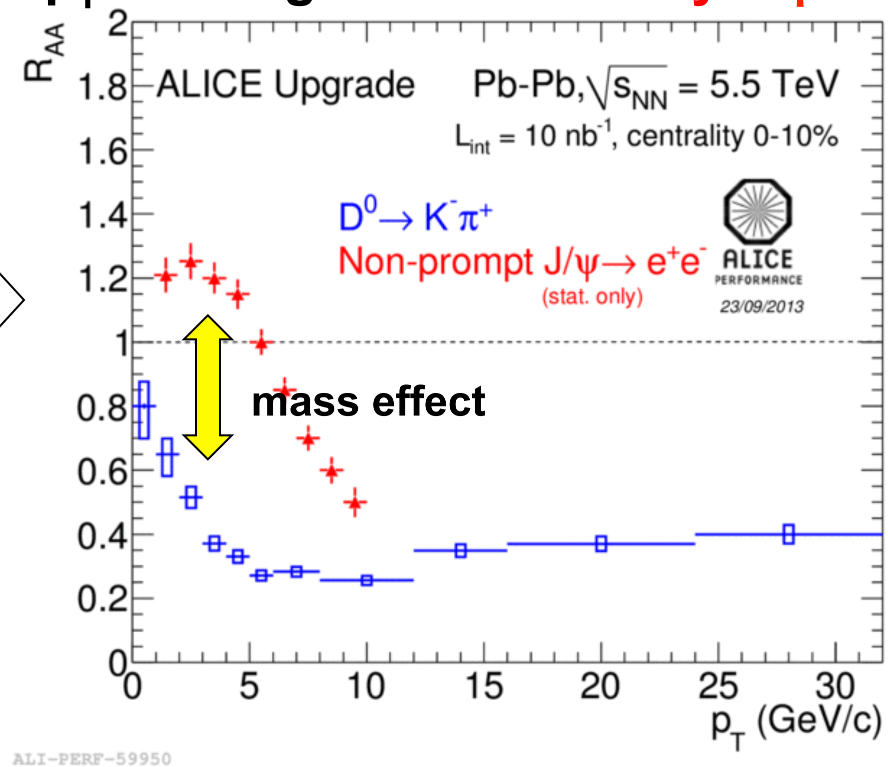
J. Bielcik, Moriond2013

ALICE Upgrade: Heavy flavour R_{AA}

Present data at p_T~10 GeV



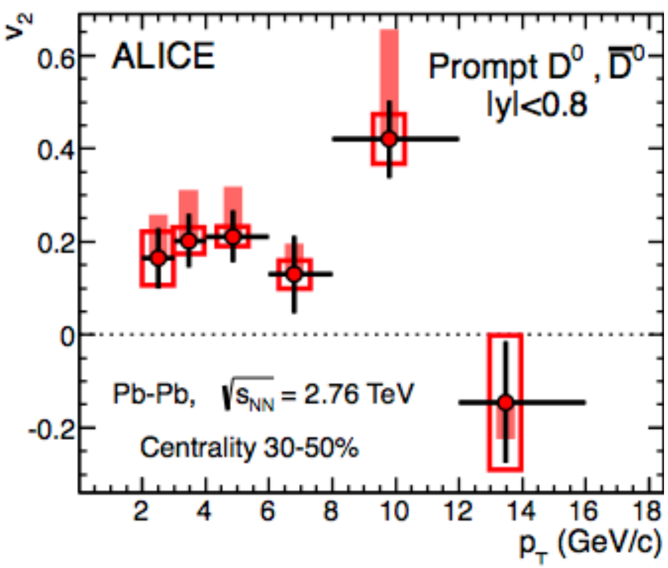
Upgrade: Charm and beauty R_{AA} down to p_T~0 using D^0 and B-decay J/ψ



ALICE, CERN-LHCC-2013-024

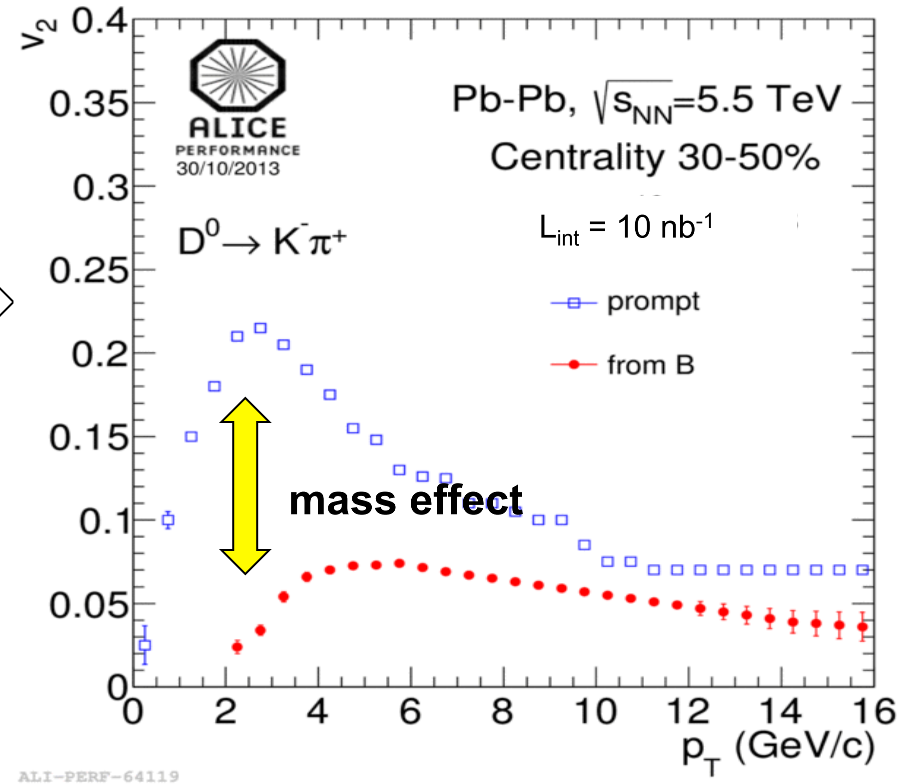
ALICE Upgrade: Heavy flavour flow

Present data on charm v_2



ALICE, PRL 111 (2013) 102301

Upgrade: Charm and beauty v_2 down to p_T~0 using prompt and B-decay D^0



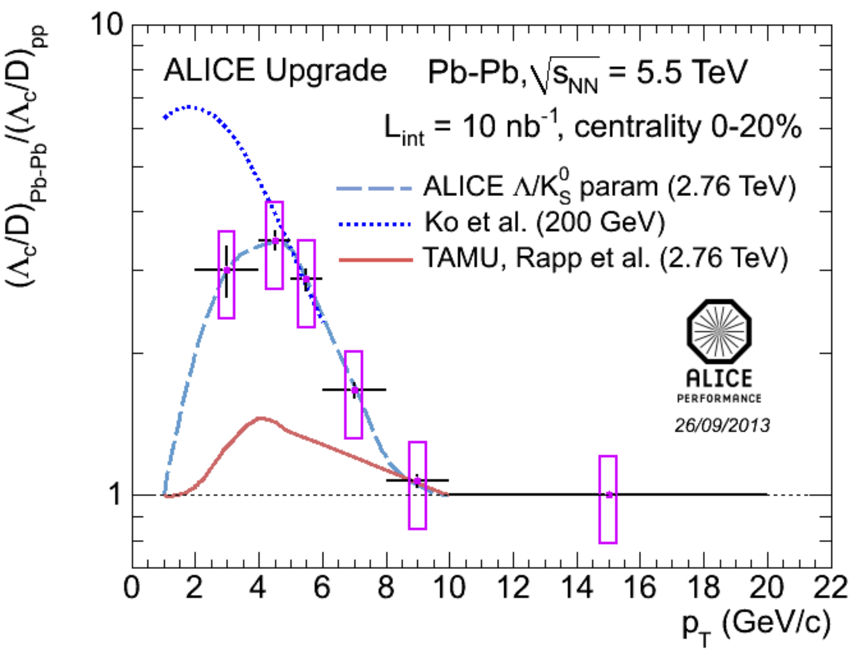
ALICE, CERN-LHCC-2013-024

Input values from BAMPS model:
C. Greiner et al. arXiv:1205.4945

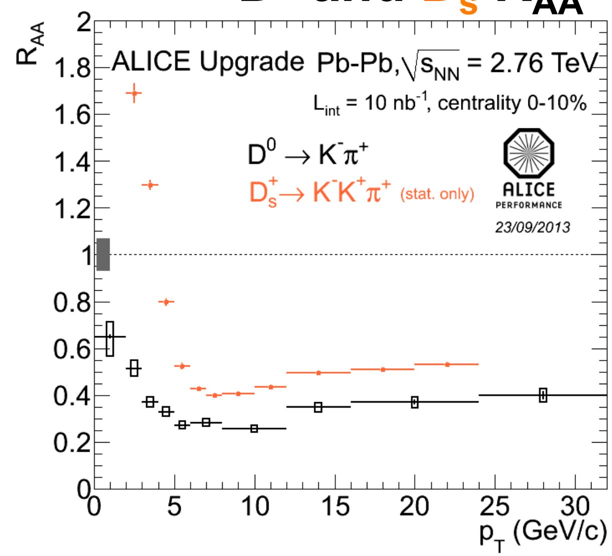
ALICE Upgrade: HF "hadrochemistry"

- $\Lambda_c \rightarrow pK\pi$ and $D_s \rightarrow KK\pi$ ($c\tau$=60 and 150 μm) measured with good precision in ALICE with upgrades and 10/nb

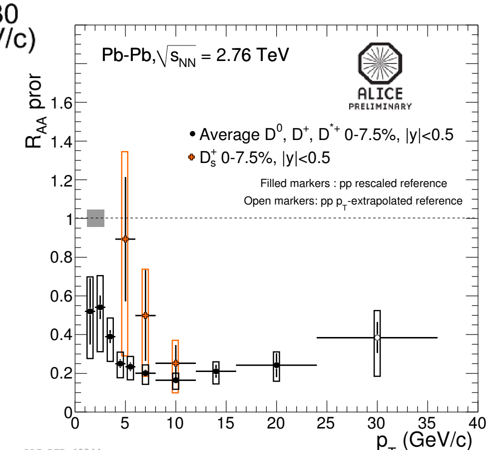
Λ_c/D enhancement
(full detector sim.)



D^0 and D_s R_{AA}



2011 data



ALICE, CERN-LHCC-2013-024

Instead of a summary …
… questions for discussion

Properties of energy loss

- Colour charge dependence of radiative E loss: how to observe to determine it in a model-independent way?
- First hint of mass dependence of energy loss? Can precise measurements given information on the radiated gluon properties (angular distribution, formation time…)?
- How to Relative weight of radiative and collisional energy loss?

Collectivity and hadronization

- Are HQs flowing (radial, elliptic)? If, yes, what do we learn?
- What are the signals of HQ coalescence? Which measurements to make a final statement?

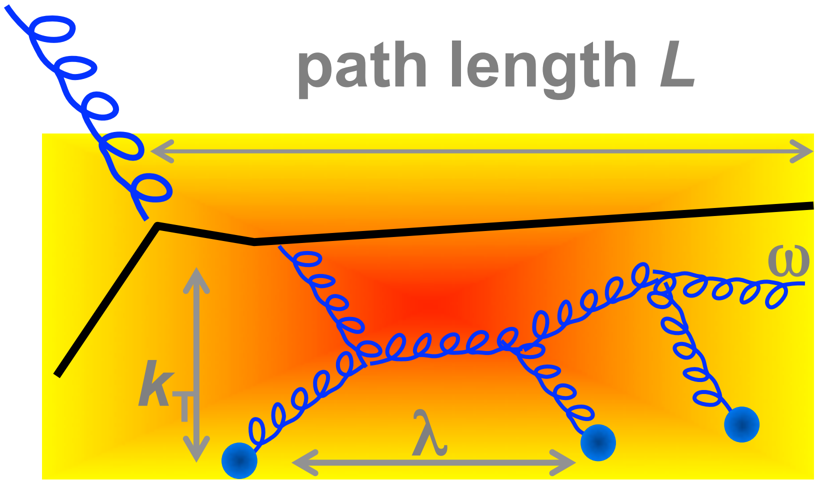
Medium properties

- Which properties can be accessed (uniquely) with HQs?
- Which theoretical approaches are most sensitive? Is theory ready?

Thank You !

EXTRA SLIDES

Radiative energy loss: colour charge dependence …



Example: BDMPS-Z formalism

$$\hat{q} = \frac{\langle k_T^2 \rangle}{\lambda}$$ transport coefficient

Radiated-gluon energy distrib.:

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \propto \alpha_s C_R \sqrt{\frac{\hat{q} L^2}{\omega}}$$

C_R = Casimir coupling factor: 4/3 for q, 3 for g

→ Colour charge dependence of radiative energy loss

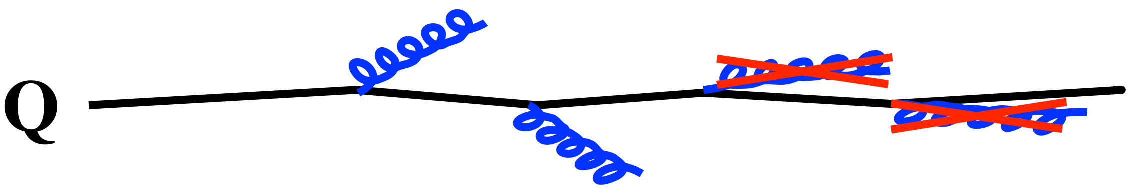
$$\Delta E_g > \Delta E_{c \approx q}$$

Baier, Dokshitzer, Mueller, Peigné, Schiff, NPB 483 (1997) 291.
Zakharov, JTEPL 63 (1996) 952.
Salgado, Wiedemann, PRD 68(2003) 014008.

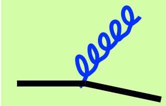
… and mass dependence

- In vacuum, gluon radiation suppressed at $\theta < m_Q/E_Q$

  → "dead cone" effect



Gluonsstrahlung probability

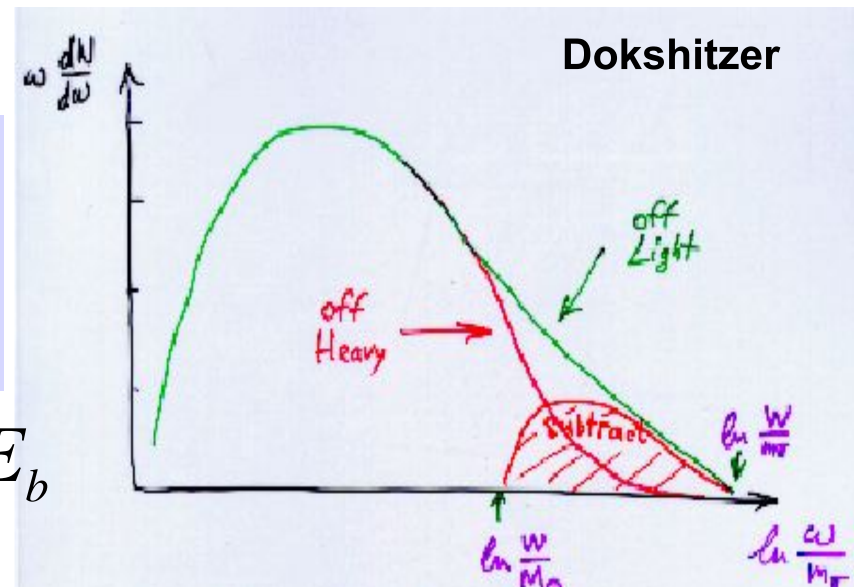


$$\propto \frac{1}{[\theta^2 + (m_Q/E_Q)^2]^2}$$

- *Dead cone implies lower energy loss* (Dokshitzer-Kharzeev, 2001):
  - energy distribution $\omega dI/d\omega$ of radiated gluons suppressed by angle-dependent factor
  - suppresses high-ω tail

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

$$\Delta E_c > \Delta E_b$$



Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602.
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

Mass dependence in collisional energy loss

Example: Langevin formalism

- Langevin equation gives momentum (**p**) evolution vs. time (*t*):

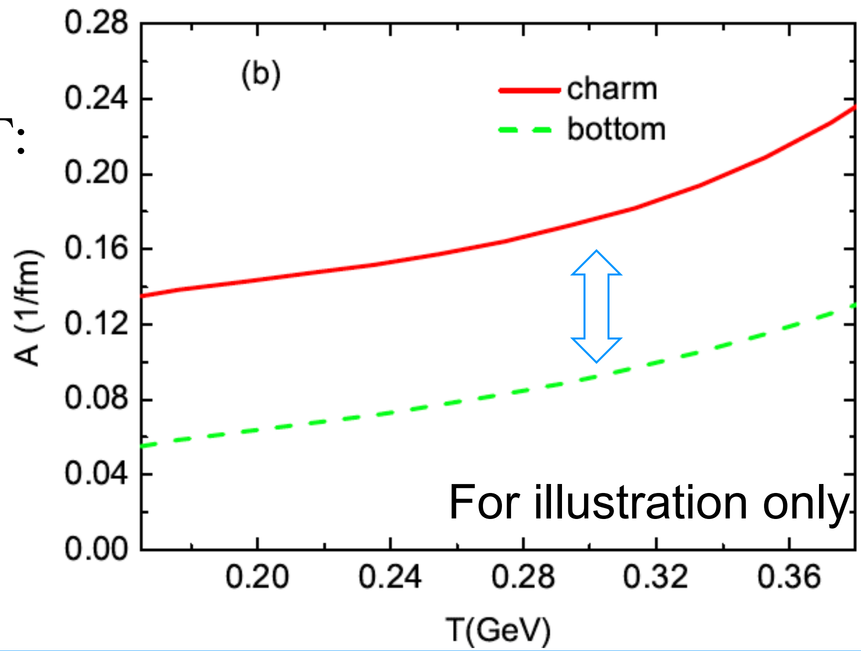
$$d\mathbf{p} = -\Gamma(p)\ \mathbf{p}\ dt + \sqrt{2D(\mathbf{p} + d\mathbf{p})\, dt}\ \rho$$

Loss term → energy loss

Gain term → flow (radial, elliptic)

- Both Γ (drag) and D (diffusion) ~ $1/m_Q$

Thermal relaxation rate A ~ Γ:



$$\Delta E_c > \Delta E_b$$

He, Rapp, Fries, PRC86 (2012) 014903

Heavy flavour production in pp

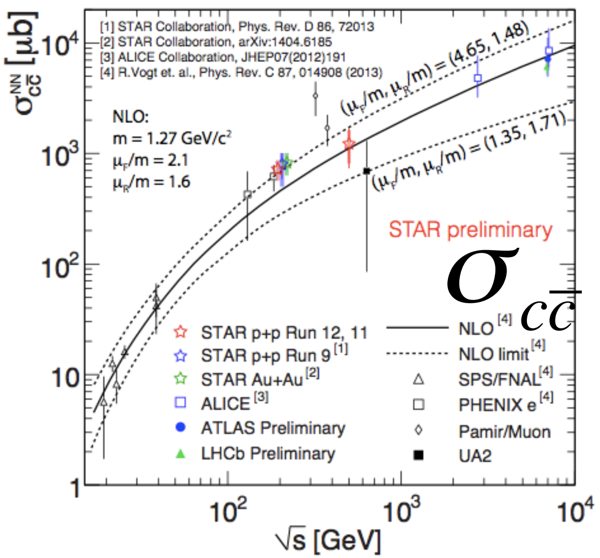
- Example pQCD calculation: Fixed Order Next-to-Leading Log

$$\frac{d\sigma}{dp_T} = A(m)\,\alpha_s^2 + B(m)\,\alpha_s^3 + G(m,p_T)\left[\alpha_s^2 \sum_{i=2}^{\infty} a_i\,[\alpha_s \log(\mu/m)]^i + \alpha_s^3 \sum_{i=1}^{\infty} b_i\,[\alpha_s \log(\mu/m)]^i\right]$$

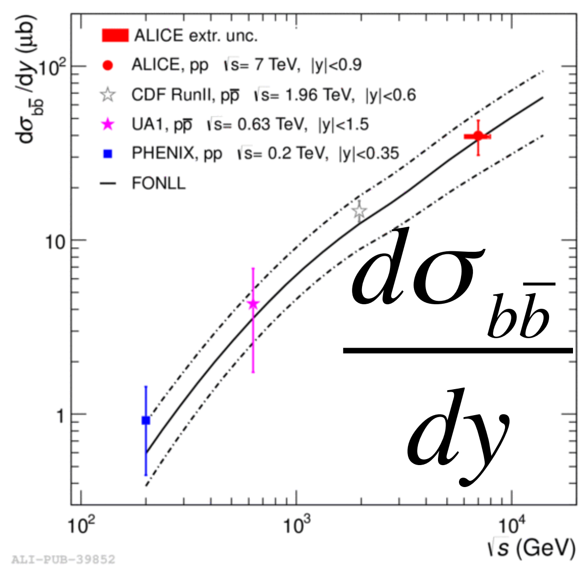
$\mu \approx p_T$

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

[coincides with NLO for low p_T (total cross section); more accurate at high p_T]



from Z. Ye (QM2014)



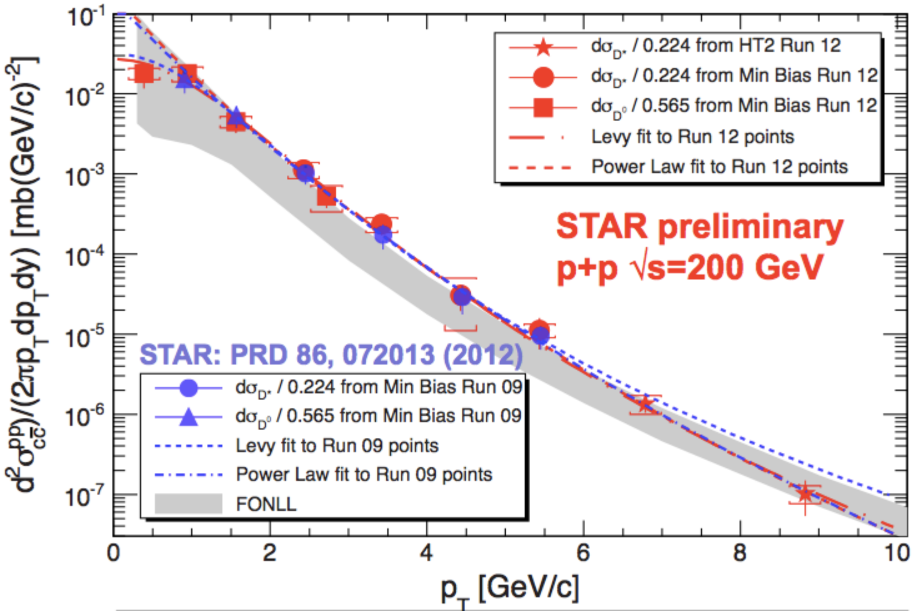
from JHEP1211 (2012) 065

- Describes consistently energy dependence of total cross sections
- Charm (beauty) x10 (100) from 0.2 to 2.76 TeV

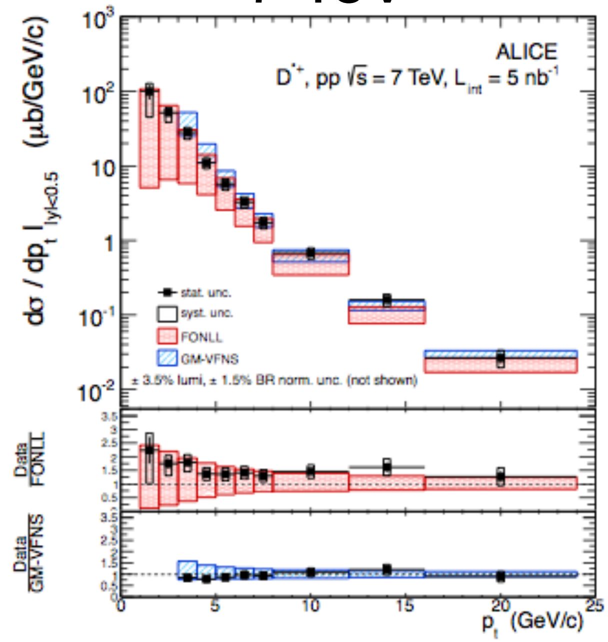
pp: pQCD calculations vs data

Charm p_T-differential cross section

200 GeV



7 TeV



STAR, PRD 86 (2012) 72013 (200 GeV)
Z. Ye (QM2013)

ALICE, JHEP01 (2012) 128

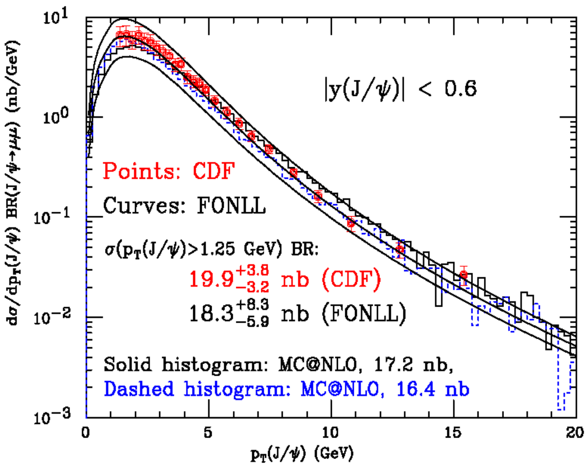
- Charm production described within uncertainties
- Consistently at upper limit of theoretical band from 0.2 to 7 TeV
  - also at 0.5, 1.96 and 2.76 TeV (not shown)
  - deviation below 1 GeV?

pp: pQCD calculations vs data

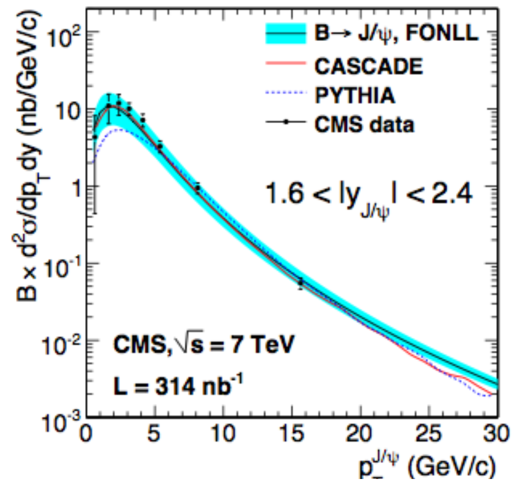
Beauty p_T-differential cross section

1.96 TeV

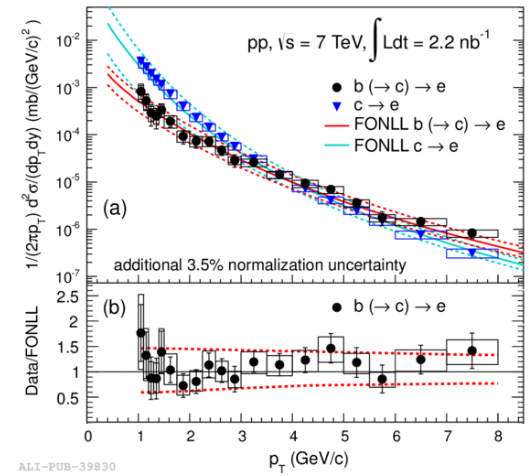
7 TeV



CDF, PRD71 (2005) 032001



CMS, EPJC71 (2011) 1575

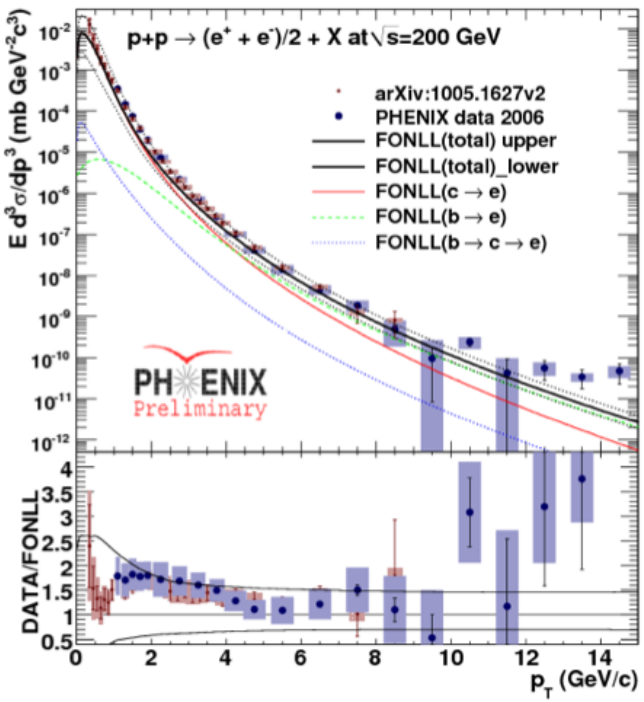


ALICE, PLB721 (2013) 13

- Beauty production described very well by central value of calculation

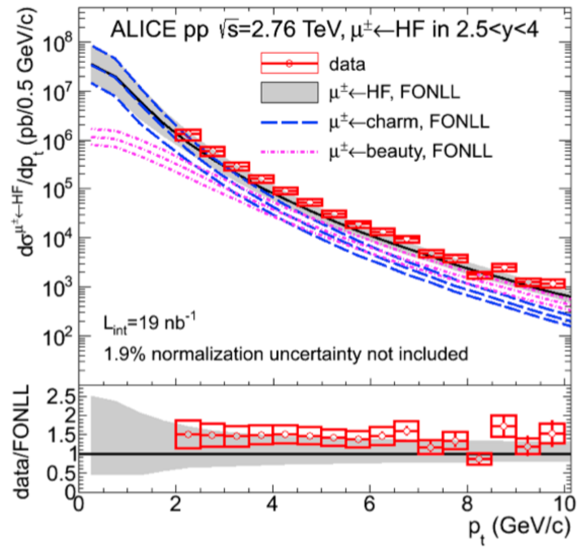
pp: pQCD calculations vs data
HF-decay lepton p_T-differential cross section

200 GeV



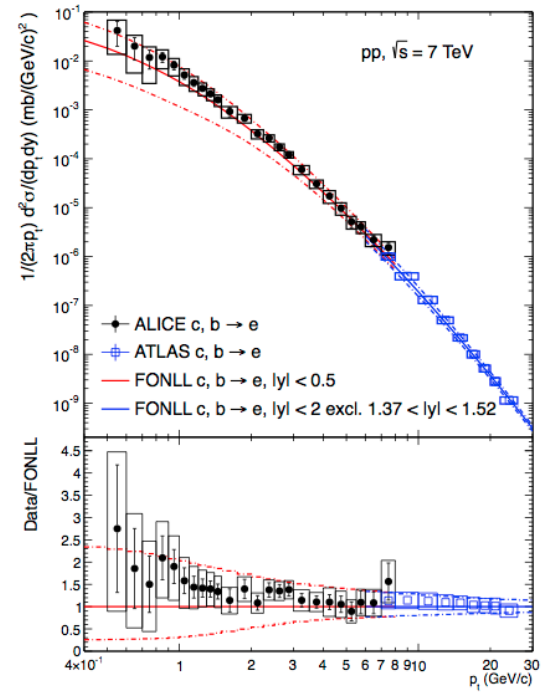
PHENIX, PRC84 (2011) 044905
S. Lim (QM2014)

2.76 TeV



ALICE, PRL 109 (2012) 112301

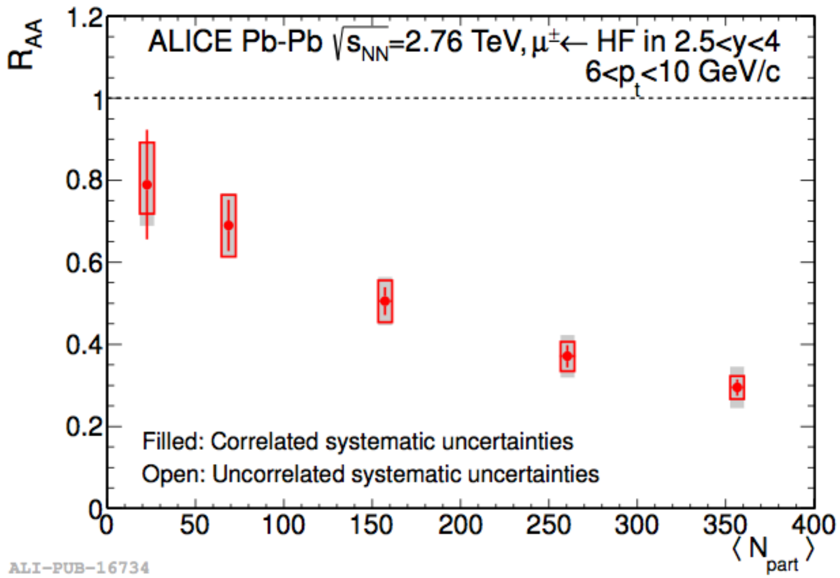
7 TeV



ALICE, PRD86 (2012) 112007
ATLAS, PLB707 (2012) 438

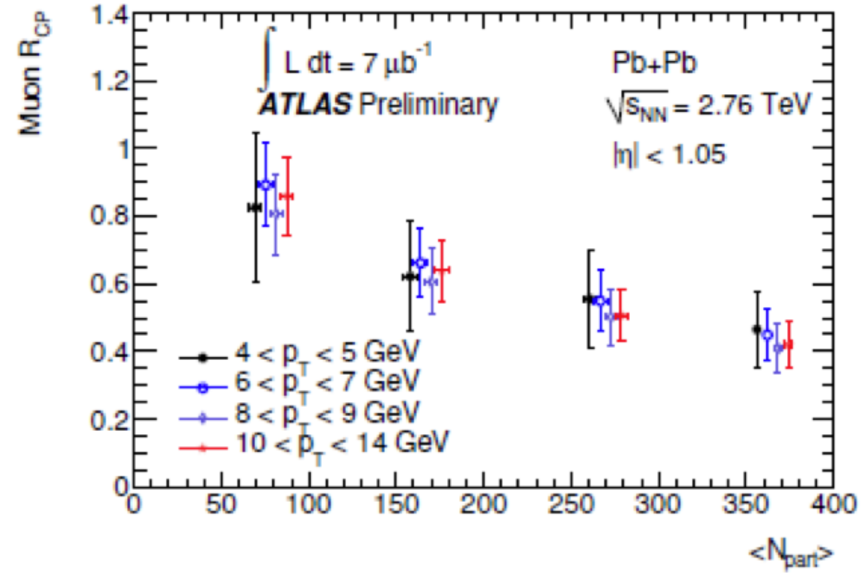
- HF-decay electrons and muons at central and forward y
- FONLL: "b > c" for p_T > 4 (5) GeV/c at RHIC (LHC)

HF-decay μ at LHC vs. centrality



PRL 109 (2012) 112301

ATLAS-CONF-2012-081



- Clear and consistent centrality dependence for
  - R_{AA} of muons at forward rapidity (ALICE)
  - R_{CP} of muons at central rapidity (ATLAS)
- No sign of p_T dependence from 4 to 12 GeV/c

ALICE Upgrade Physics Motivation

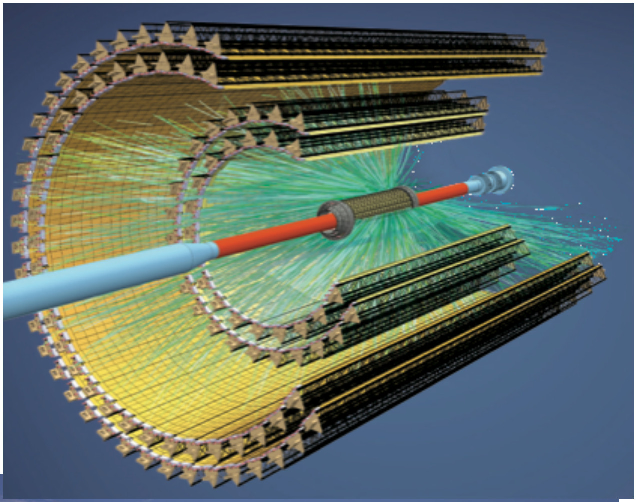
Three main physics topics that are unique of the upgraded ALICE detector:

1. **Heavy-flavour transport parameters in the QGP**
   - Heavy-quark diffusion coefficient (→ QGP equation of state, viscosity of the QGP fluid), via precise HQ v_2
   - Heavy-quark thermalization and hadronization in the QGP, via v_2 and baryons
   - Mass dependence of parton energy loss in QGP medium
2. **Low-mass dielectrons: thermal photons and vector mesons from the QGP**
   - Photons from the QGP ($\gamma \rightarrow e^+e^-$) → map temperature during system evolution
   - Modification of ρ spectral function ($\rho \rightarrow e^+e^-$) → chiral symmetry restoration
3. **Charmonia (J/ψ and ψ') down to zero p_T**
   - Only the comparison of the two states can shed light on the suppression/regeneration mechanism
   - Study QGP-density dependence with measurements at central and forward rapidity

ALICE Upgrade LOI, CERN-LHCC-2012-012

ALICE Upgrade strategy (2018)

- ***Requirements:***
  1. High tracking precision at low p_T
  2. High-rate capability to exploit envisaged Pb luminosity increase of LHC



New Inner Tracking System

- Improve precision x3 (rϕ), x6 (z)

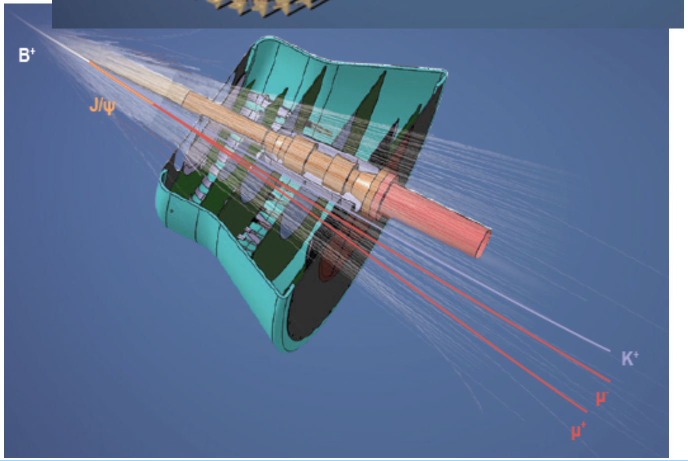
New Muon Forward Tracker

- Separation of displaced (di)muons from B

New read-out for TPC (MWPC→GEM), …

Upgraded DAQ/HLT/Offline

- Record Pb data at 50 kHz (currently <0.5 kHz)
- Integrate L_{int}=10 nb^{-1} after LS2 (~10^{11} minimum-bias Pb-Pb events)



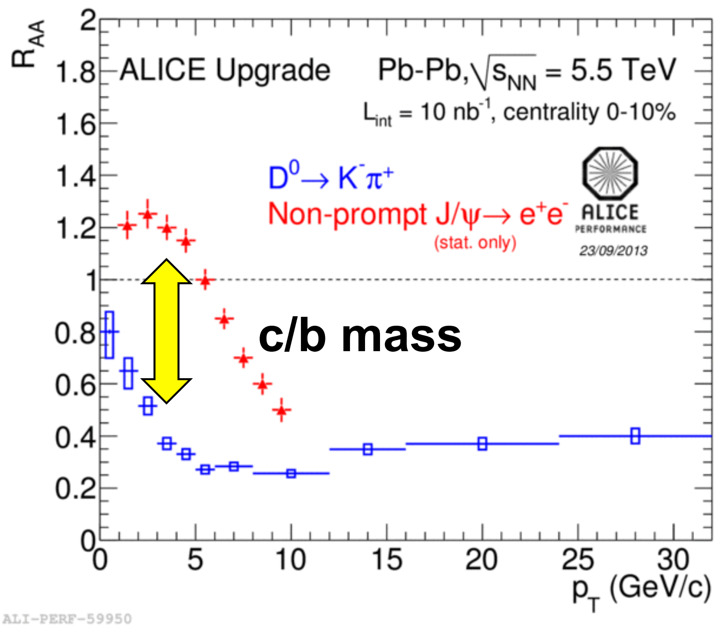
CERN-LHCC-2012-012, CERN-LHCC-2012-013, CERN-LHCC-2013-014, CERN-LHCC-2013-024

ALICE Upgrade: HF suppression and flow

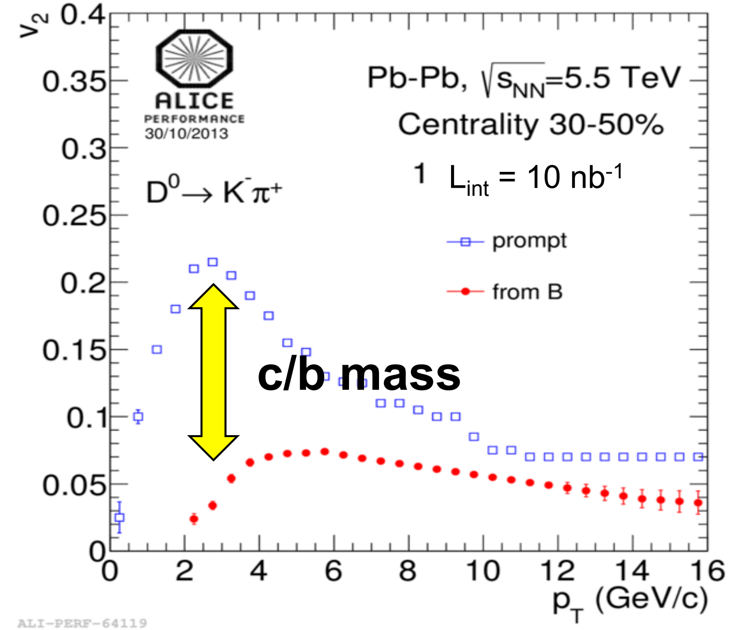
- Pin down mass dependence of energy loss
- Investigate transport of heavy quarks in the QGP
  - Sensitive to medium viscosity and equation of state

R_{AA} and v_2 of D and B in a wide p_T range

Prompt D^0 and Non-prompt J/ψ R_{AA}



Prompt and non-prompt D^0 v_2



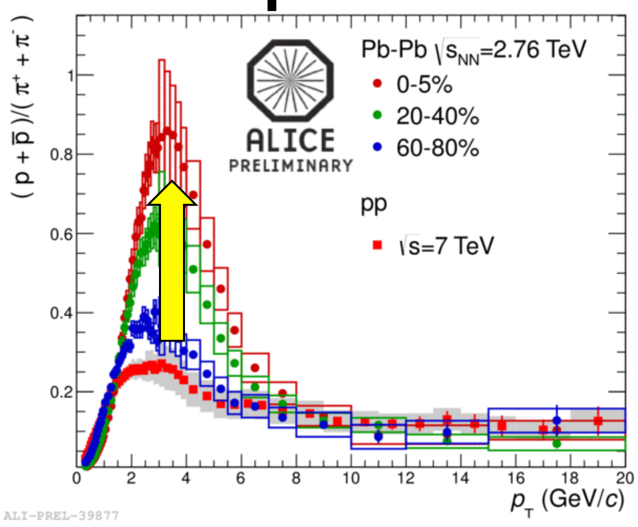
Input values from BAMPS model:
C. Greiner et al. arXiv:1205.4945

ALICE, CERN-LHCC-2013-024

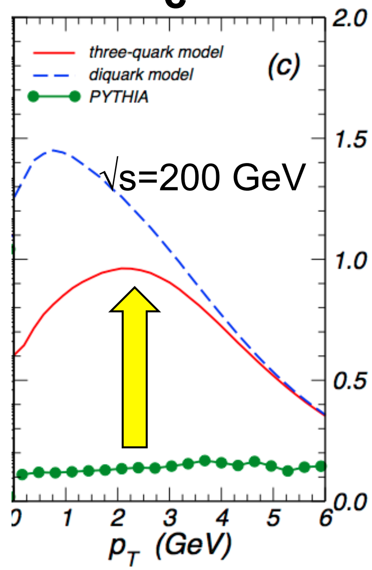
Heavy flavour in-medium hadronization?

- Baryon/meson enhancement and strange-enh. → most direct indication of light-quark hadronization in a partonic system
  - ➡ Measure this in the HF sector! Does it hold for charm?
  - ➡ Charm baryons (Λ_c) and charm-strange mesons (D_s)

p/π

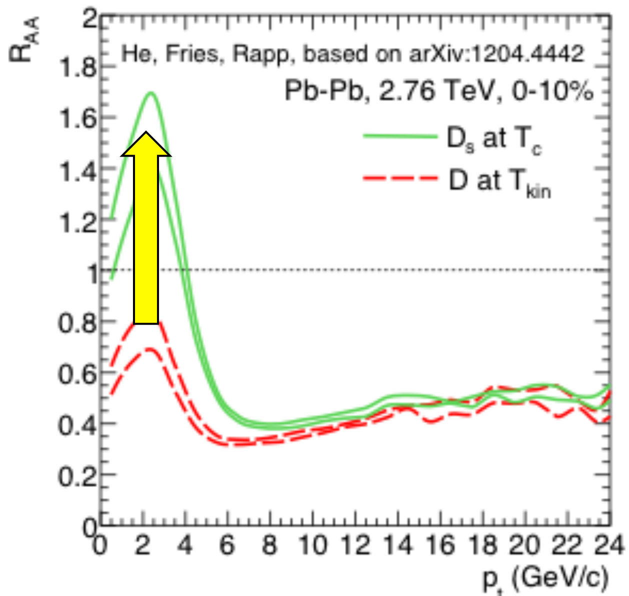


Λ_c/D



Ko et al. PRC79

D_s vs D



Rapp et al. arXiv:1204.4442

ALICE Upgrade: HF physics reach

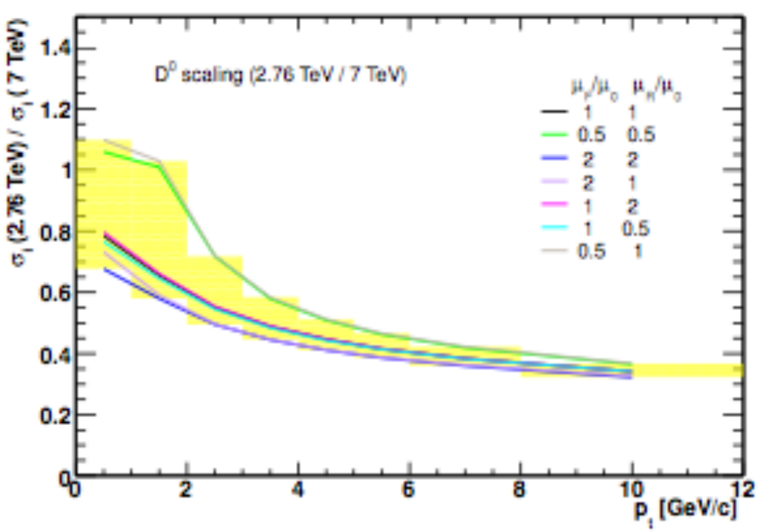
Observable	$p_{\mathrm{T}}^{\min}$ (GeV/c)	statistical uncertainty
	Heavy Flavour	(at 2 GeV/c)
D meson R_{AA}	0	0.3 %
$\mathrm{D_s}$ meson R_{AA}	< 2	3 %
D meson from B decays R_{AA}	2	2 %
J/ψ from B R_{AA}	1	5 %
B^{+} yield	3	10 % (> 3 GeV/c)
Λ_{c} R_{AA}	2	15 %
Charm baryon-to-meson ratio	2	15 %
Λ_{b} yield	7	20 % (7–10 GeV/c)
D meson elliptic flow ($v_2 = 0.2$)	0	3 %
$\mathrm{D_s}$ meson elliptic flow ($v_2 = 0.2$)	< 2	8 %
D from B elliptic flow ($v_2 = 0.1$)	2	20 %
J/ψ from B elliptic flow ($v_2 = 0.1$)	1	30 %
Λ_{c} elliptic flow ($v_2 = 0.15$)	3	20 % (3–6 GeV/c)

ALICE, CERN-LHCC-2013-024

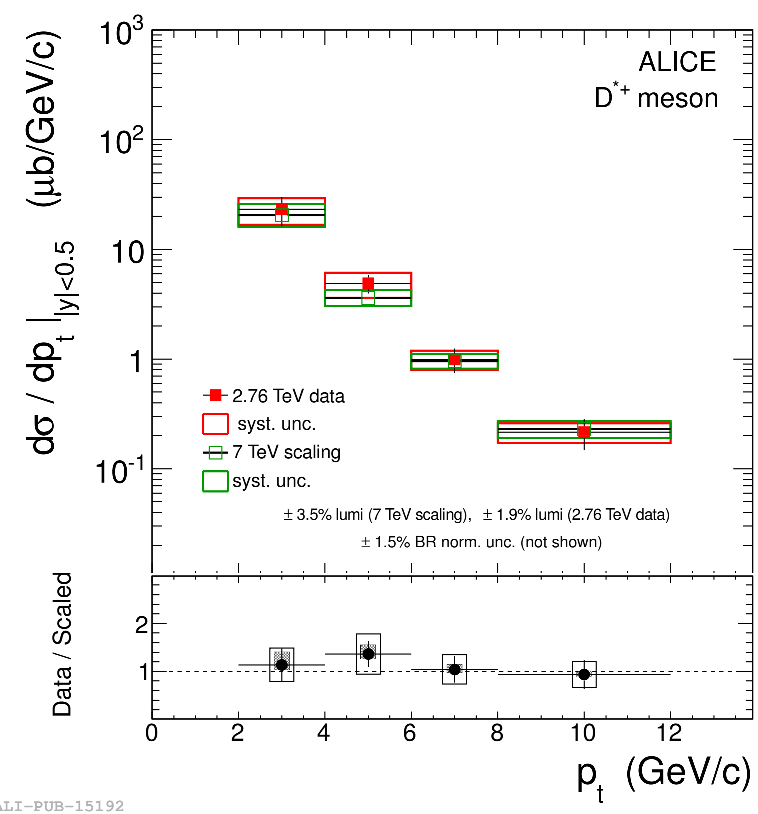
pp reference at 2.76 TeV via $\sqrt{s}$-scaling (ALICE D mesons and electrons)

- Scale the 7 TeV cross sections by the 2.76/7 factor from FONLL, with full theoretical uncertainty
  - relative scaling uncertainty: 30% → 5% in the p_t range 2 → 16 GeV/c
- Validated by comparing to measured cross section at 2.76 TeV (fewer p_t bins)

$$R_{AA}(p_t) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_t}{d\sigma_{pp}/dp_t}$$



Averbeck et al., arXiv:1107.3243

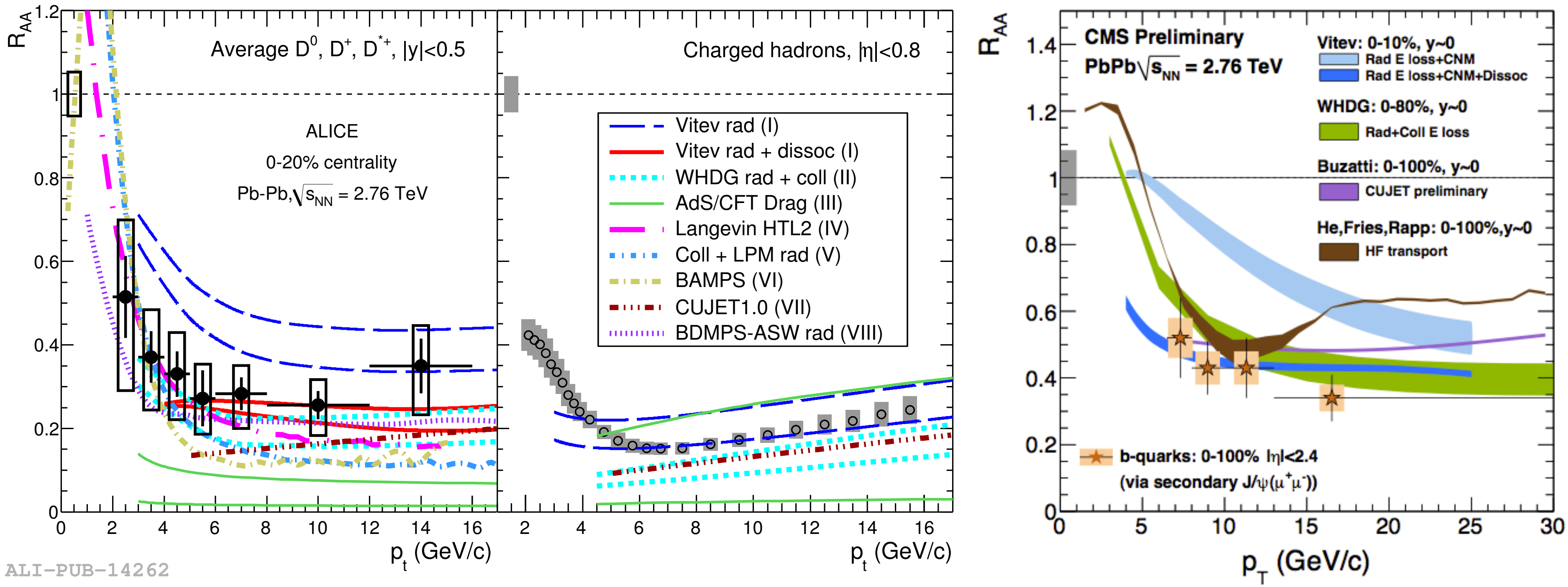


JHEP1207 (2012) 191

LHC: comparison with models (R_{AA})

- Several models based on E-loss and heavy-quark transport describe qualitatively the measured light, charm, and beauty R_{AA}

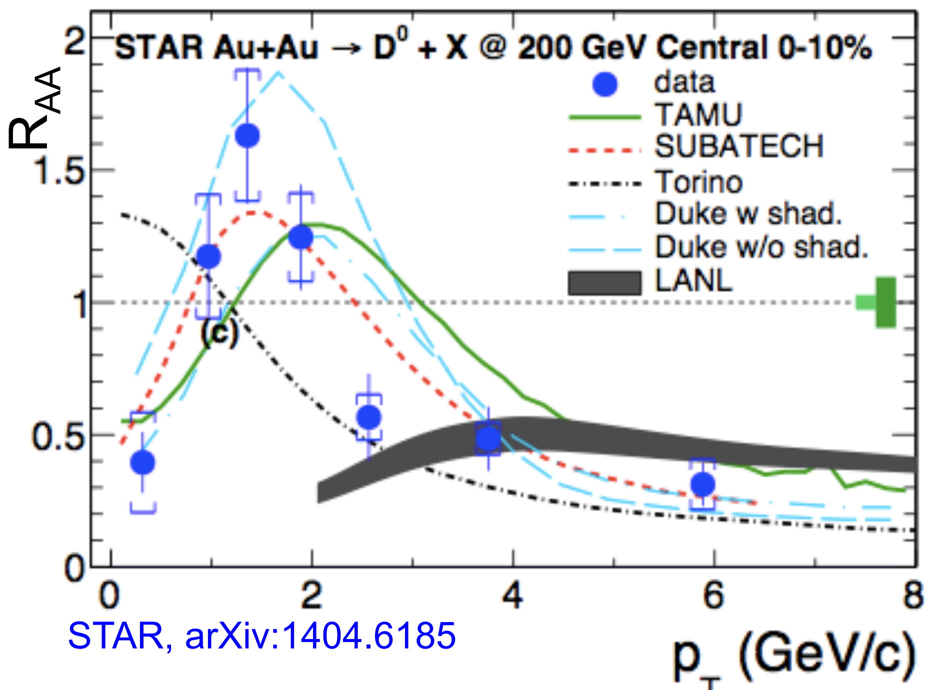
charm **"light"** **beauty**



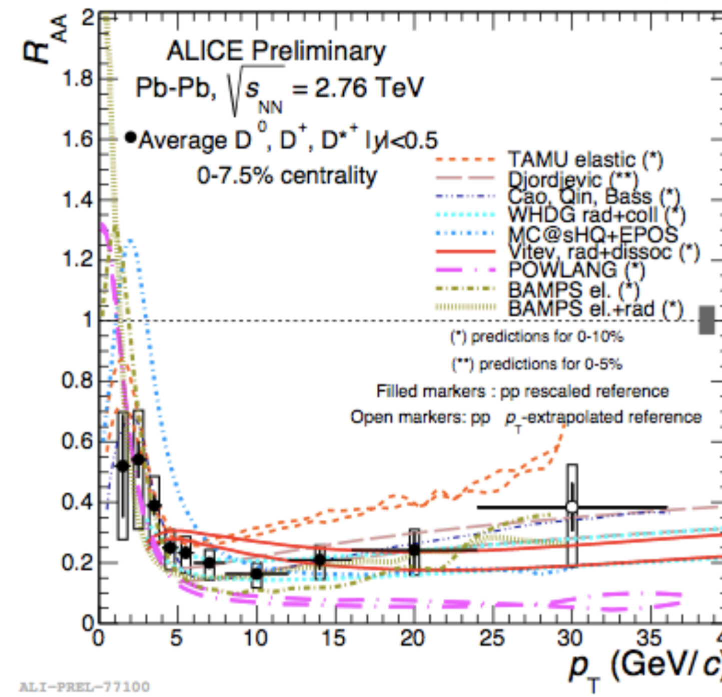
ALICE, JHEP 09 (2012) 112

CMS-PAS-HIN-12-014

D R_{AA} at RHIC and LHC



STAR, arXiv:1404.6185

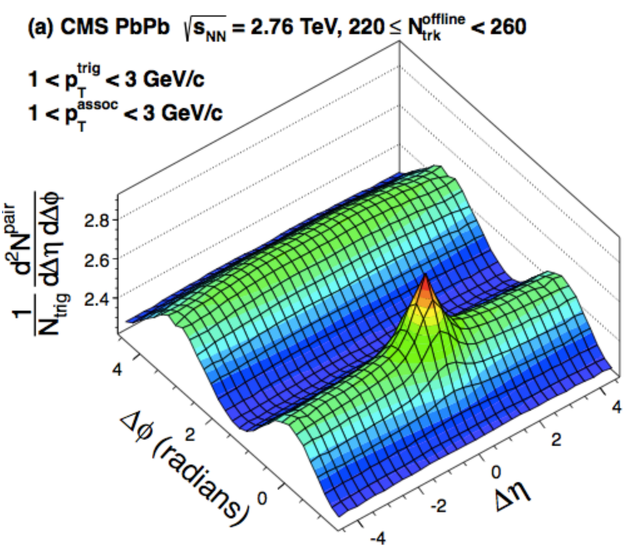


- D R_{AA} similar at RHIC and LHC at 5-6 GeV/c
- Looks quite different at 1-2 GeV/c:
  - Could it be shadowing + recombination + radial flow? (stronger effect at RHIC because of steeper dN/dp_T)
  - Two transport models (TAMU and Duke) with these ingredients predict maximum R_{AA} ~1.3-1.5 at RHIC and ~0.7-0.8 at LHC

High-multiplicity pp and p-Pb collisions

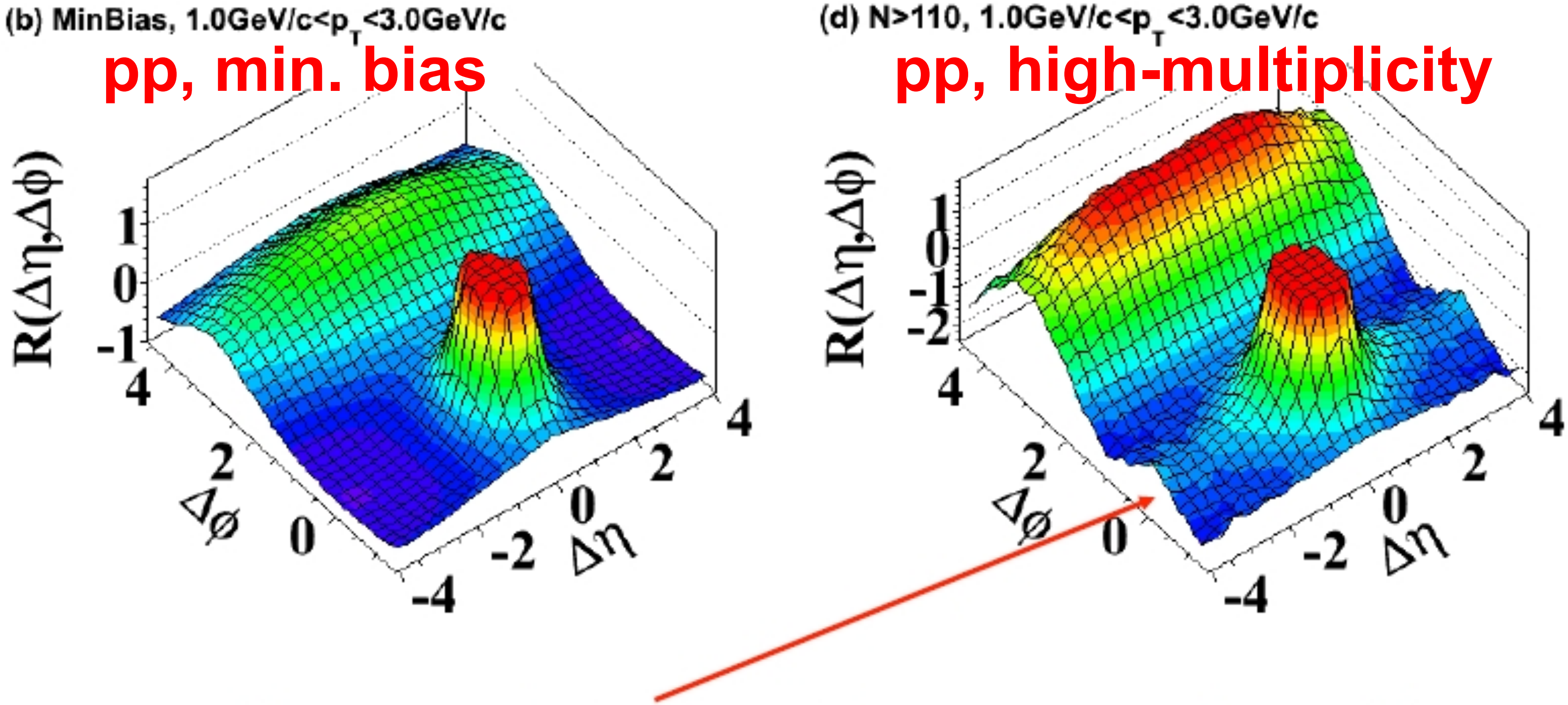
- LHC energy and luminosity allow for study of pp and p-Pb collisions with very high particle multiplicity
  - e.g. pp or p-Pb events with same multiplicity as non-central nucleus-nucleus at RHIC energy
- Look for similar effects as seen in nucleus-nucleus!
- E.g. characteristic patterns in two-particle correlations

PbPb



Two-particle correlations: near-side ridge

- Near-side ridge (long-range correlation in η at $\Delta\phi$=0) observed in high-multiplicity pp and p-Pb (CMS)



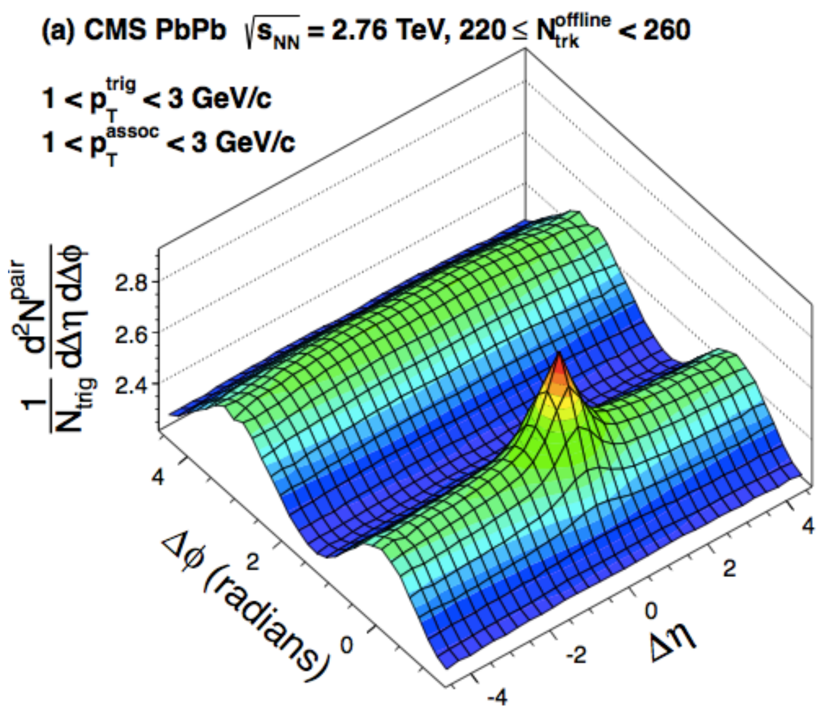
Pronounced structure at large $\Delta\eta$ around $\Delta\phi \sim 0$!

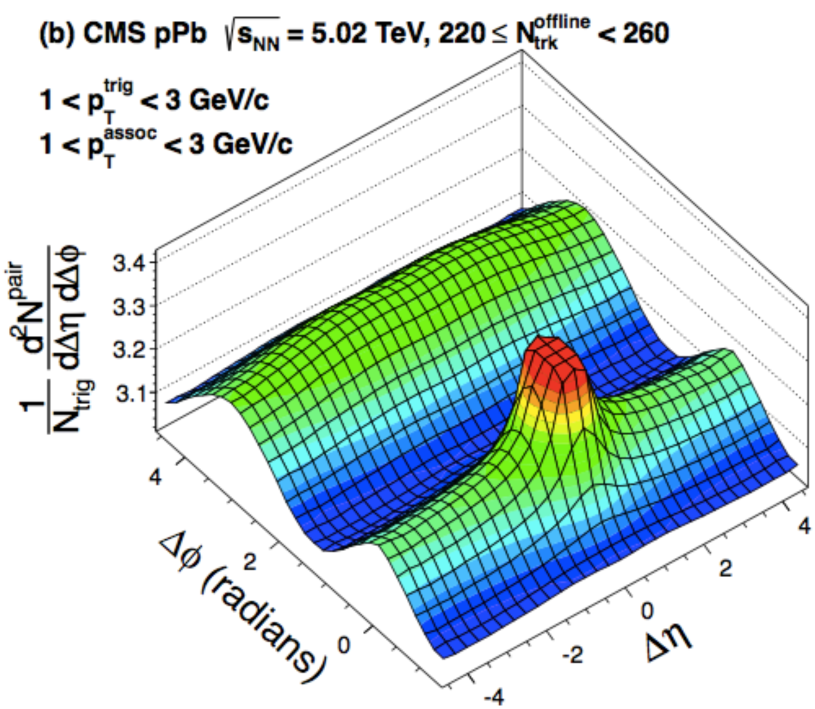
CMS, JHEP 1009 (2010) 091

Two-particle correlations: near-side ridge

- Near-side ridge (long-range correlation in η at $\Delta\phi=0$) observed in high-multiplicity pp and p-Pb (CMS)

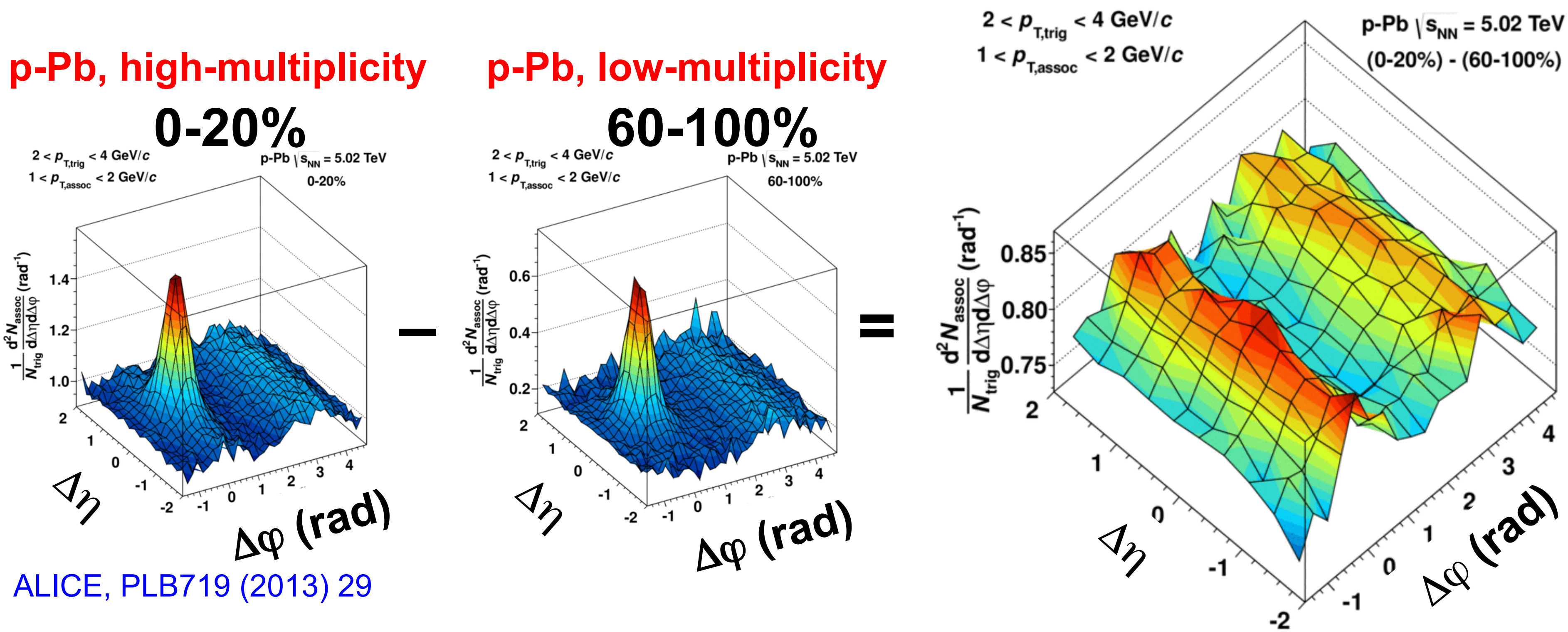
Pb-Pb **p-Pb, high-multiplicity**





CMS, PLB 724 (2013) 213

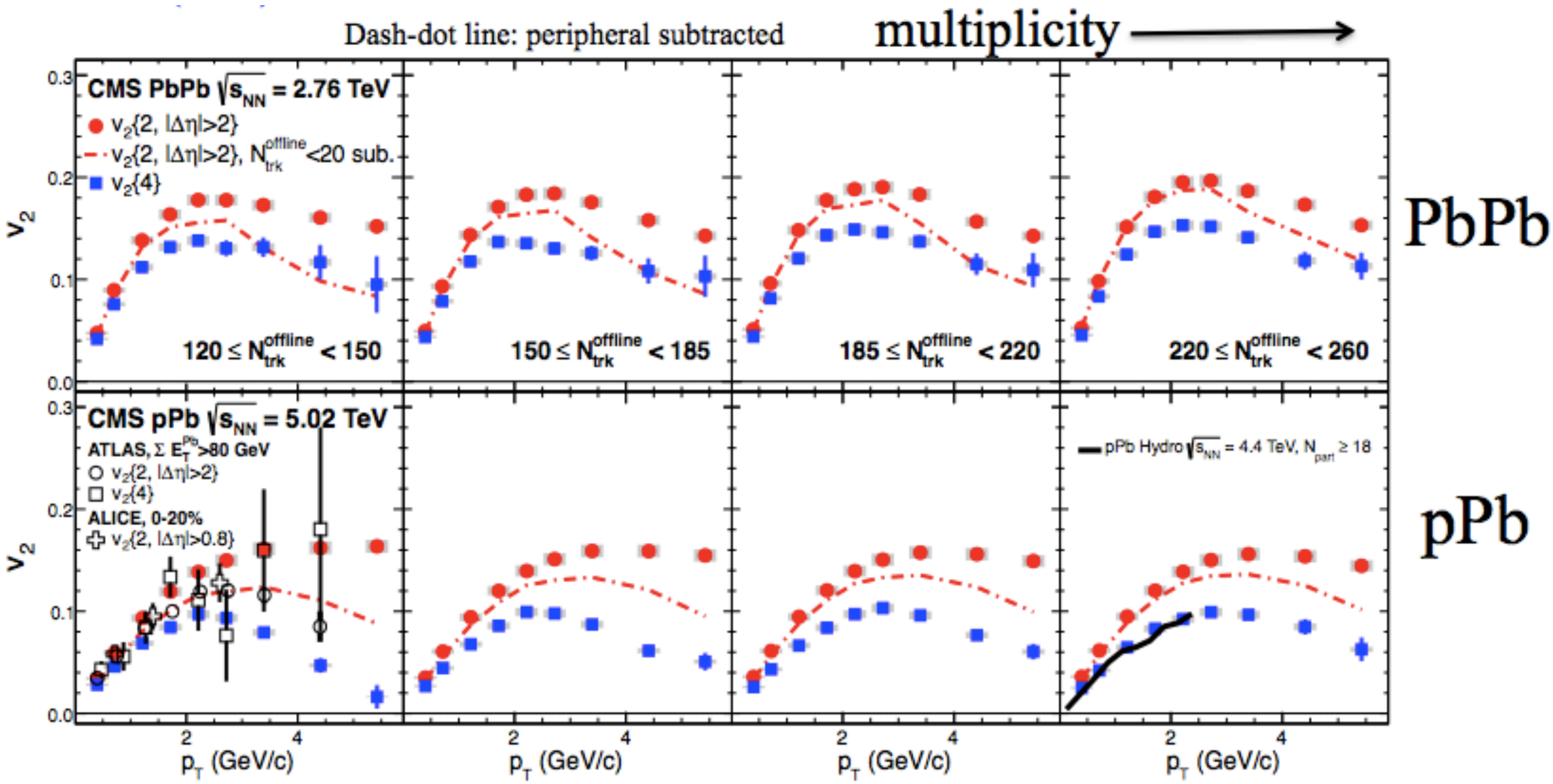
Two-particle correlations: double-ridge!



ALICE, PLB719 (2013) 29

- Idea: subtract the “pp-like” structure of low-multiplicity p-Pb from the structure of high-multiplicity p-Pb
- Double ridge discovered by ALICE, followed by ATLAS
- Resembles the structure that in Pb-Pb is attributed to collective flow

Quantifying the modulation: v_2

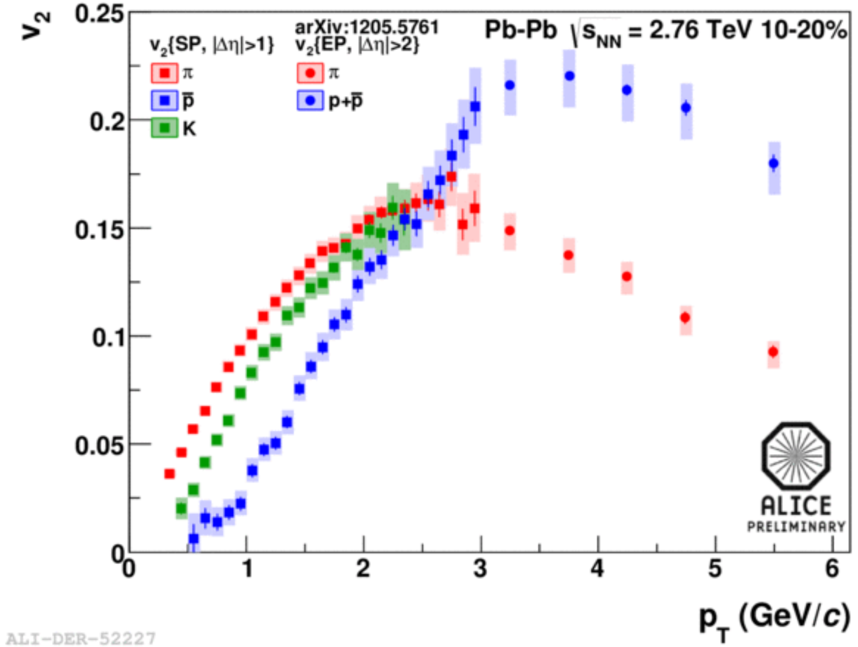


- v_2 vs. p_T and multiplicity with various methods
- Similar pattern in p-Pb and Pb-Pb
- v_2 rises to 2 GeV, then ~flattens out to 5

CMS, PLB 724 (2013) 213

Is it *flow* in p-Pb?
Look at identified particles

Pb-Pb



- Mass ordering, interpreted in terms of collective radial and elliptic flow

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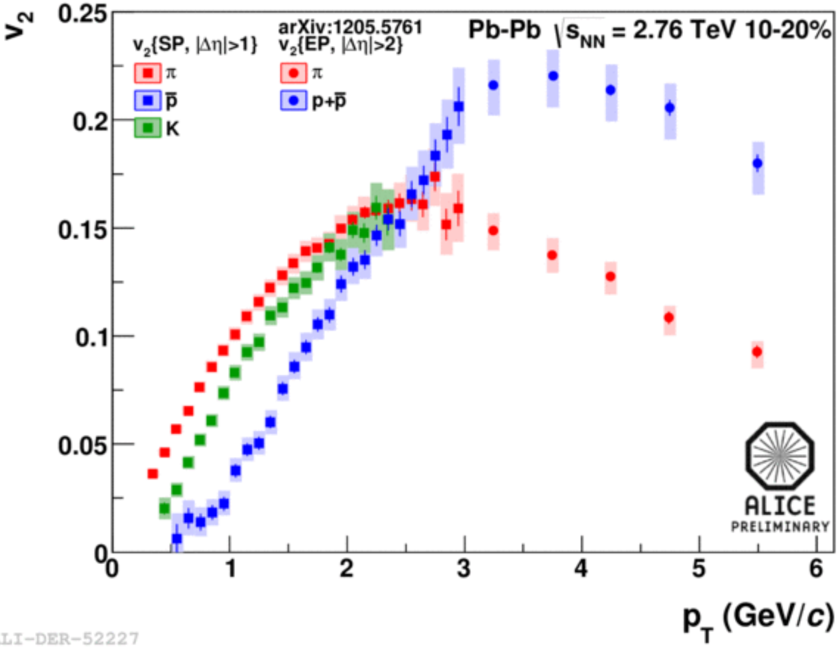
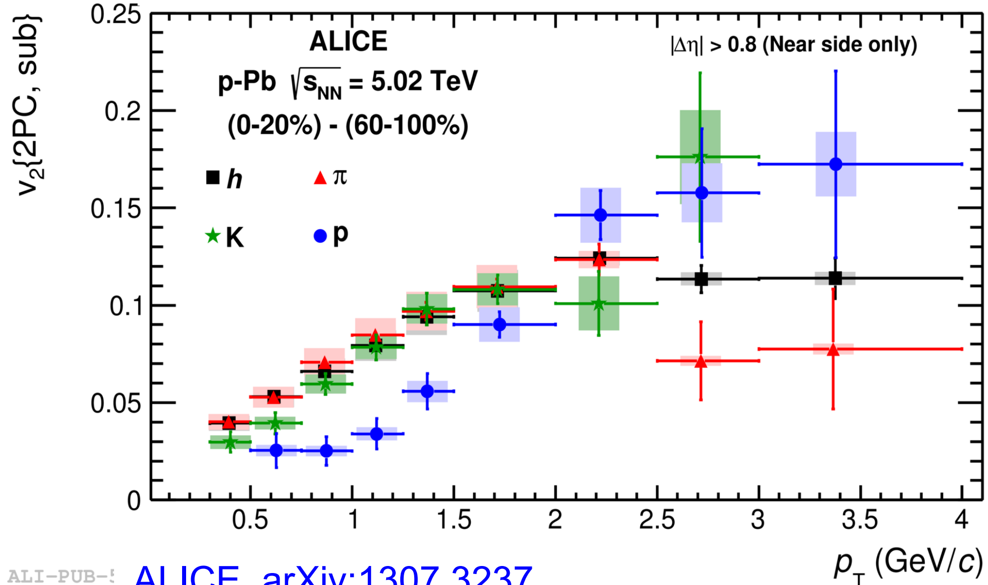


p-Pb, high-multiplicity



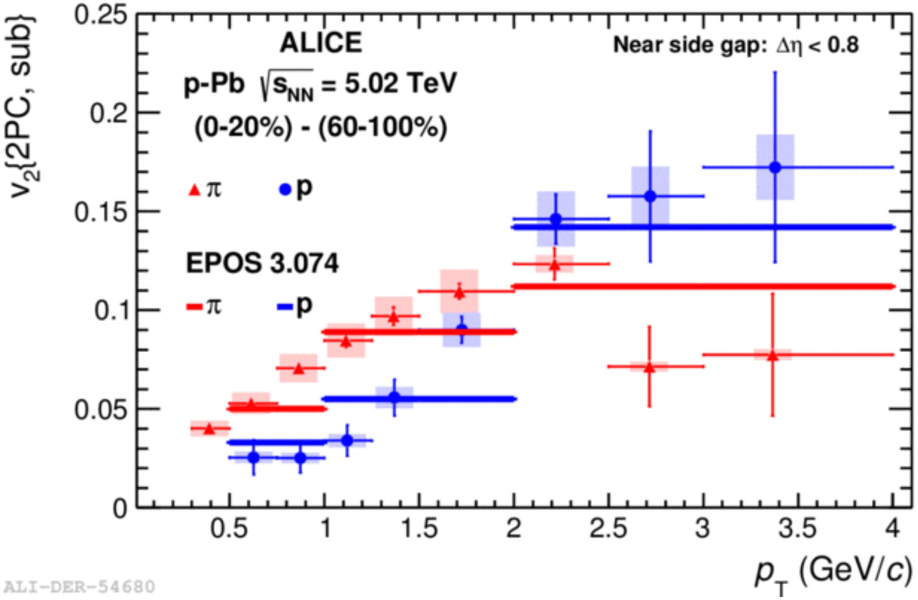
ALICE, arXiv:1307.3237

- Mass ordering, interpreted in terms of collective radial and elliptic flow

- Clear indication for mass ordering in p-Pb
- Resembles Pb-Pb and supports “flow” picture

Possible interpretations

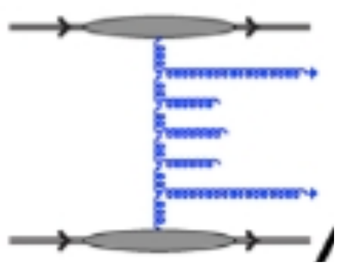
- High-multiplicity p-Pb presents several aspects that in Pb-Pb are explained by collective flow of an expanding medium
- Models including hydrodynamical expansion can describe the observations (e.g. EPOS)

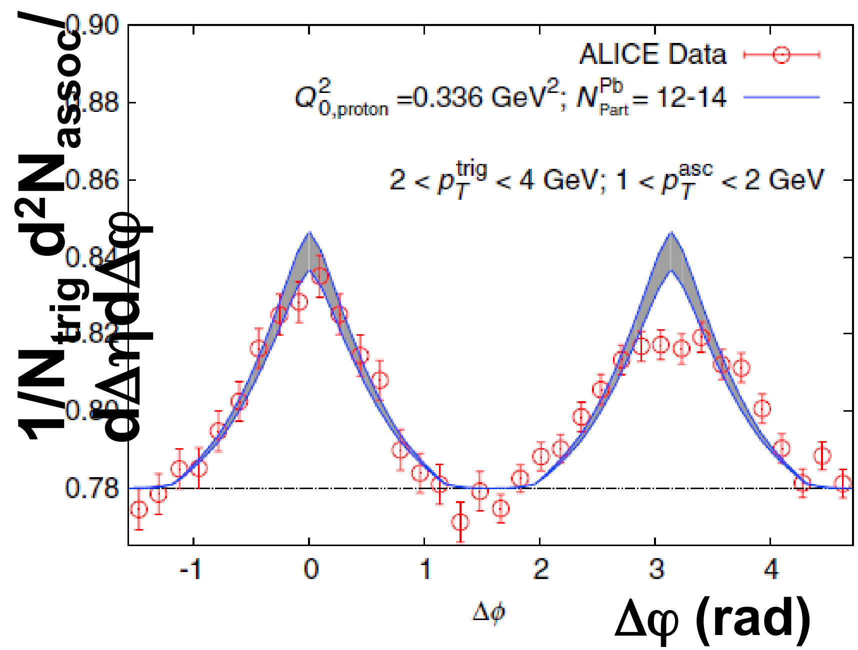


EPOS: Klaus Werner, arXiv:1307.4379

Possible interpretations

- High-multiplicity p-Pb presents several aspects that in Pb-Pb are explained by collective flow of an expanding medium
- Hydrodynamical expansion
- Alternative explanation (1): Initial-state effect, CGC (Colour Glass Condensate) many-gluon processes can yield correlations

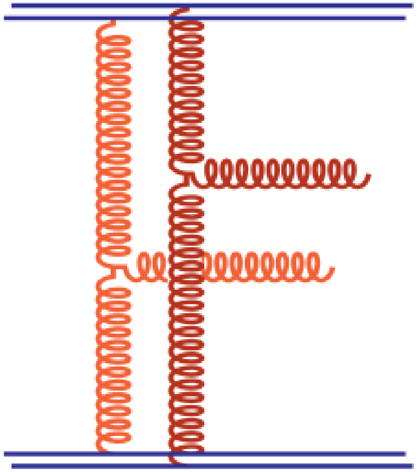


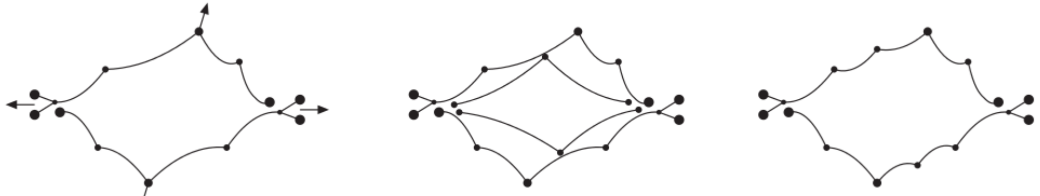


Dusling, Venugopalan, PRD 87, 094034 (2013)

Possible interpretations

- High-multiplicity p-Pb presents several aspects that in Pb-Pb are explained by collective flow of an expanding medium
- Hydrodynamical expansion
- Alternative explanation (1): Initial-state effect
- Alternative explanation (2): MPI (multi-parton interactions) and "colour reconnection" (as implemented in PYTHIA8) can induce flow-like effects





see e.g. Ortiz et al, PRL111, 042001 (2013)

Possible interpretations

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- Hydrodynamical expansion
- Alternative explanation (1): Initial-state effect
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These results are clearly intriguing, several interpretations are being put forward, and new measurements from the experiments will provide stringent tests for theory