Jet Quenching at RHIC
vs LHC in Light of Recent dAu vs pPb Controls

RIKEN BNL Research Center Workshop
April 15-17, 2013 at Brookhaven National Laboratory

Experimental status of flavour tomography

Andrea Dainese
(INFN Padova, Italy)

Outline of the Talk

- Introduction: HF probes of the medium (→ see A.Buzzatti)
- Calibrating HF probes: pp results
- HF production in nucleus-nucleus:
  - Semi-leptonic decays
  - D mesons
  - B and b-jets

RHIC	PHENIX, STAR STAR
LHC	ALICE, ATLAS ALICE CMS

- Proton-nucleus control data
- HF azimuthal anisotropy
- Outlook: detector upgrades at RHIC and LHC

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Heavy flavour production in pp

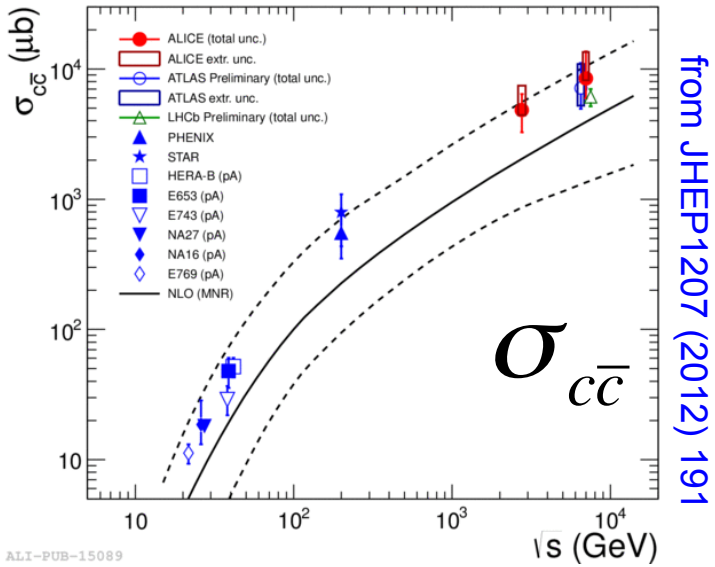
- State-of-the-art pQCD calculation: Fixed Order Next-to-Leading Log

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

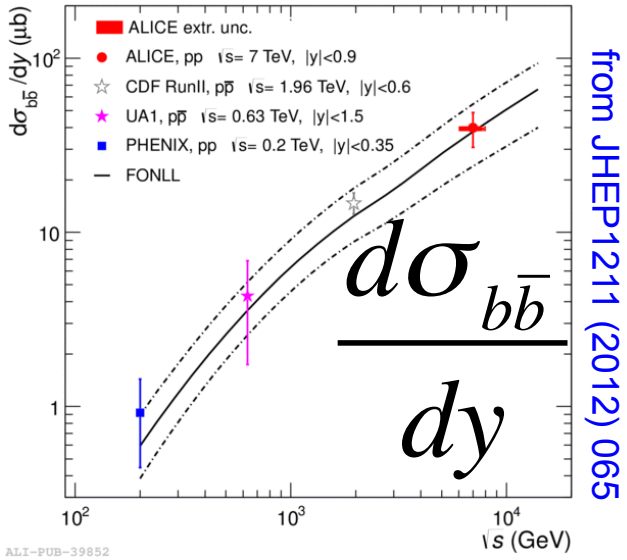
$\mu \approx p_T$

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 JHEP1207 (2012) 191

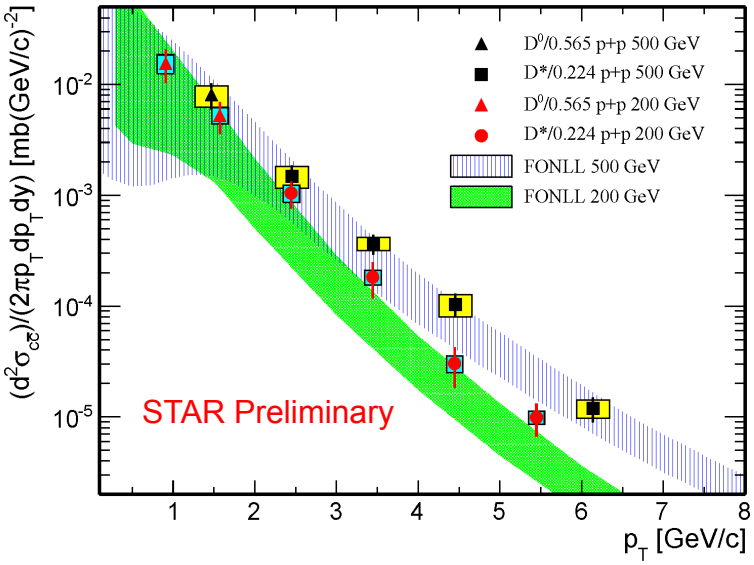


from JHEP1211 (2012) 065

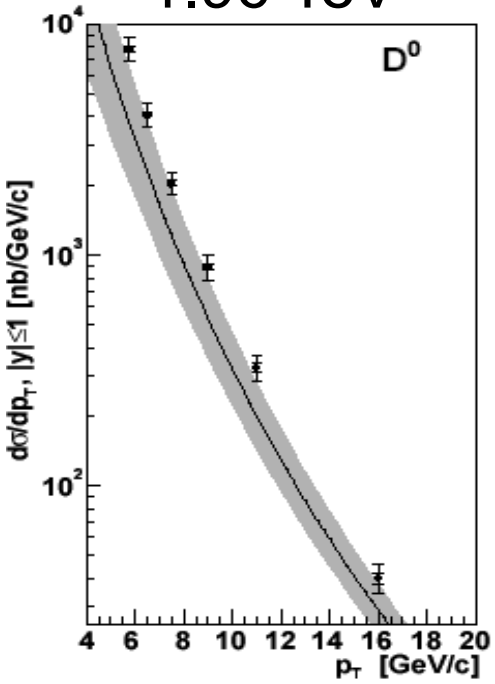
- Describes consistently energy dependence of total cross sections
- Charm (beauty) x10 (100) from 0.2 to 2.76 TeV

pp: pQCD calculations vs data
Charm p_T-differential cross section

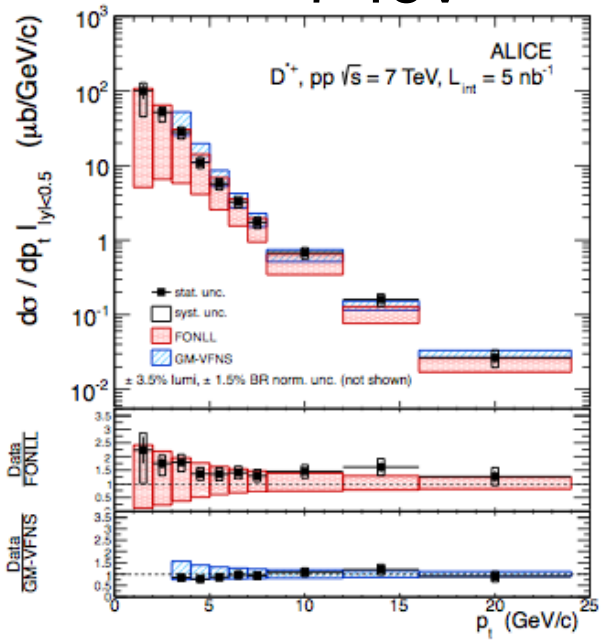
200, 500 GeV



1.96 TeV



7 TeV



STAR, PRD 86 (2012) 72013 (200 GeV)
J. Bielcik (Moriond2013)

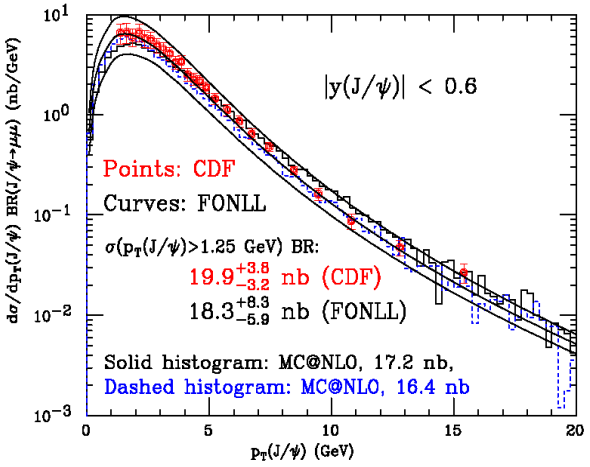
CDF, PRL91 (2003) 241804

ALICE, JHEP01 (2012) 128

- Charm production described within uncertainties
- Consistently at upper limit of theoretical band from 0.2 to 7 TeV

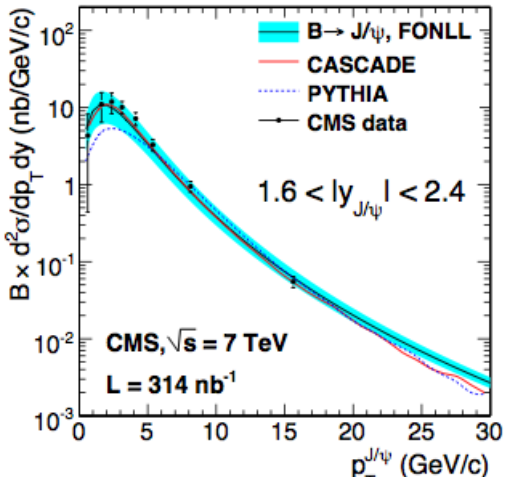
pp: pQCD calculations vs data
Beauty p_T-differential cross section

1.96 TeV

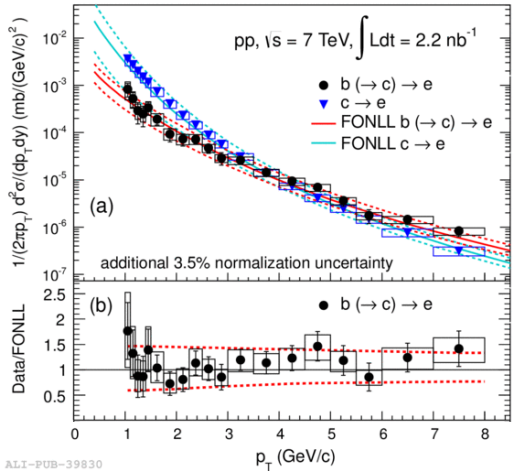


CDF, PRD71 (2005) 032001

7 TeV



CMS, EPJC71 (2011) 1575

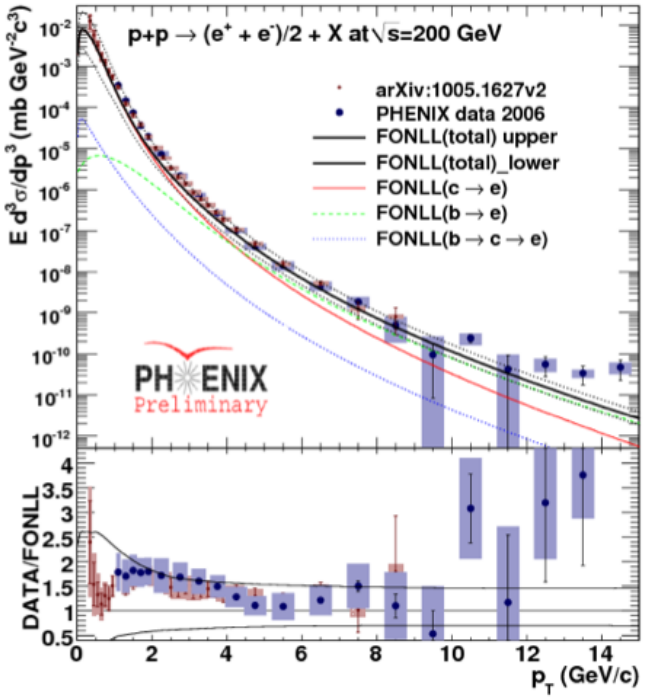


ALICE, PLB721 (2013) 13

- Beauty production described very well by central value of calculation

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

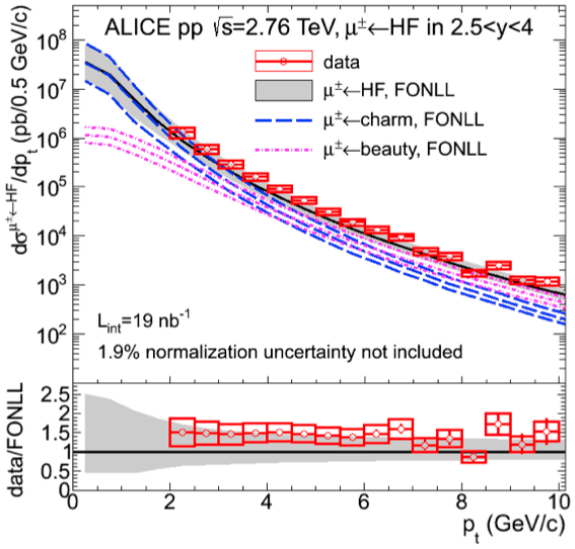
200 GeV



PHENIX, PRC84 (2011) 044905

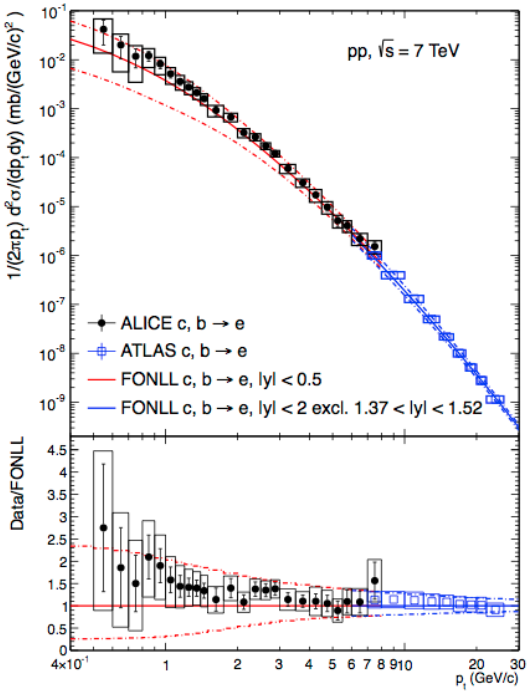
N.Apadula (WWND2013)

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)

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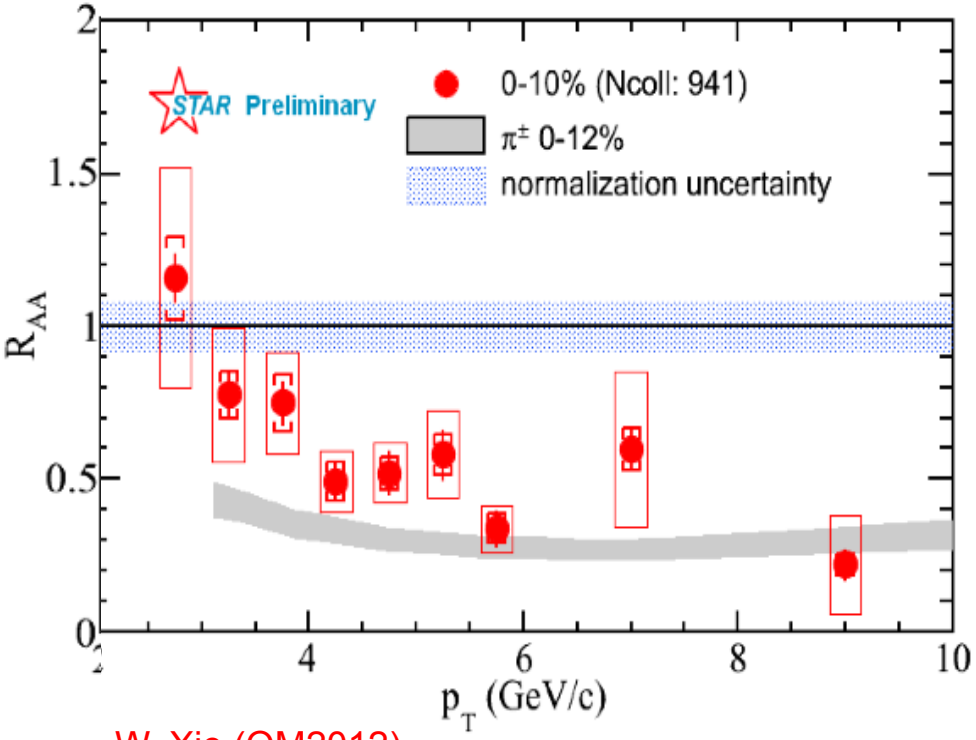
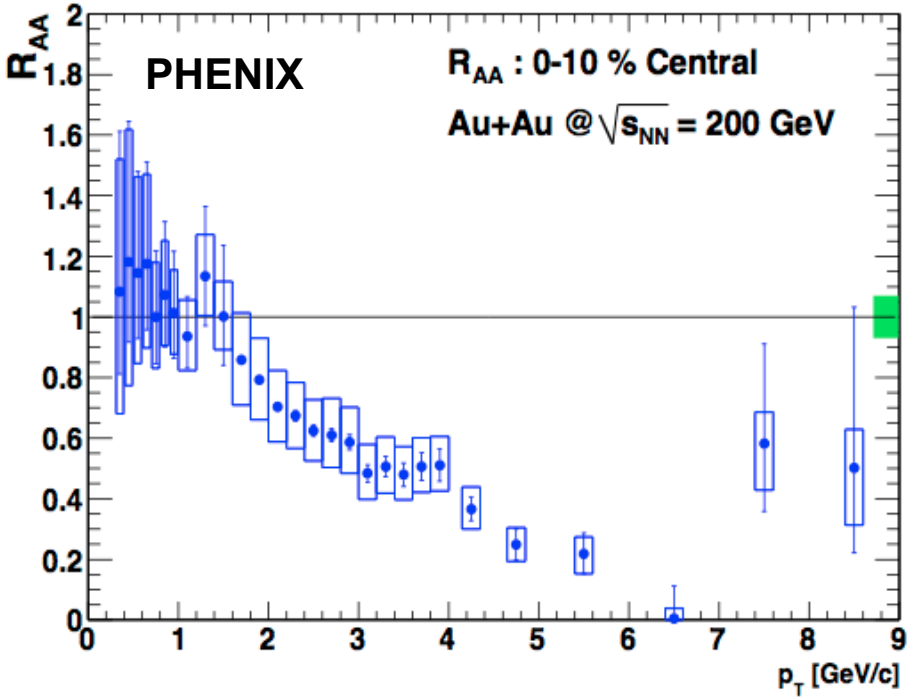
RHIC: PHENIX, STAR; STAR

LHC: ALICE, ATLAS; ALICE; CMS

HF-decay electrons at RHIC (Au-Au)

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



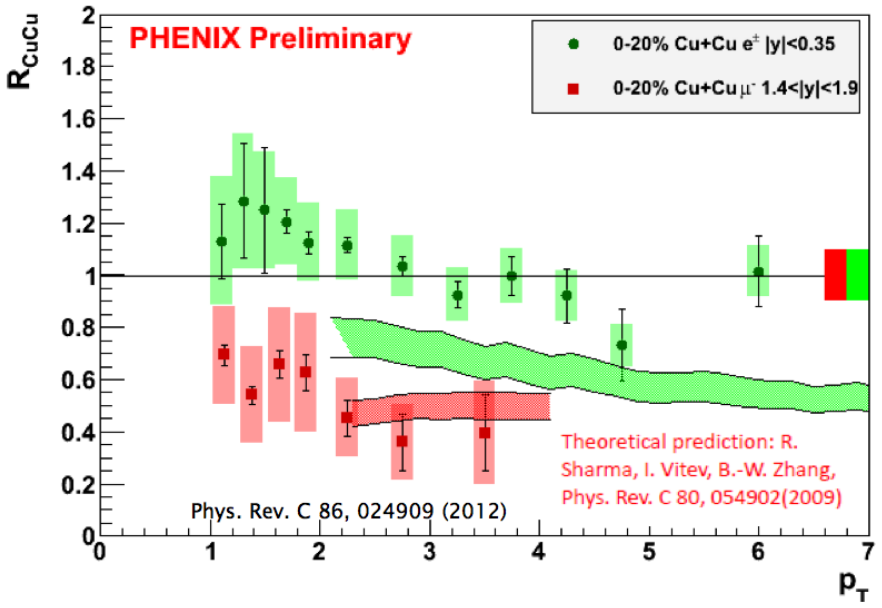


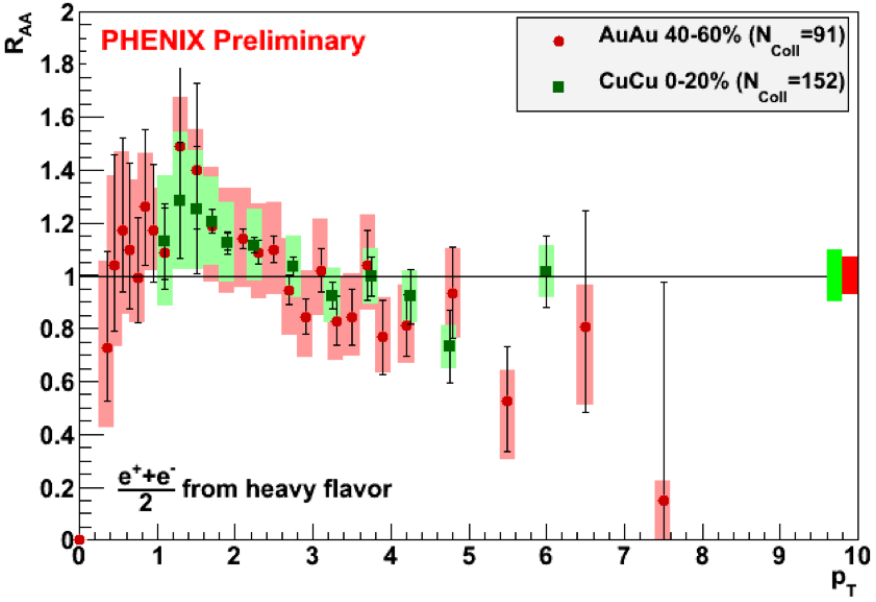
W. Xie (QM2012)
see also Phys. Rev. Lett. 98, 192301 (2007)

Phys. Rev. C 84, 044905 (2011)

- Same suppression as for light-flavour hadrons above 5 GeV/*c*
  - Mass already irrelevant?
- Smaller suppression at 2-3 GeV/c: is this the dead cone??

HF-decay e at RHIC (Cu-Cu vs. Au-Au)



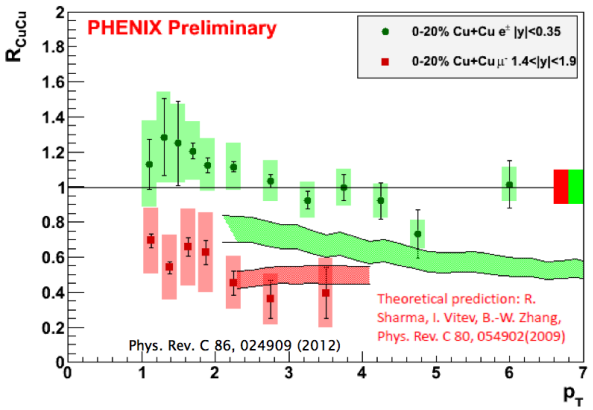


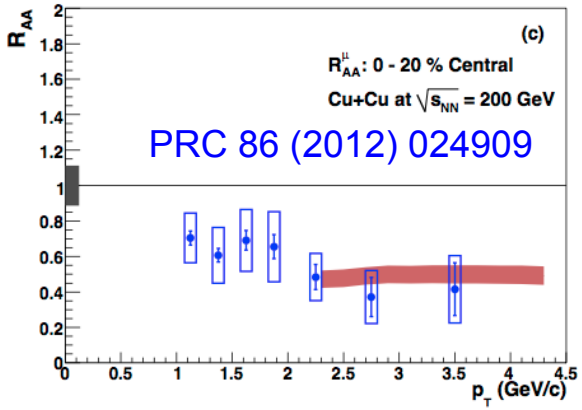
- Cu-Cu:
  - low p_T enhancement in central collisions?
  - no suppression even at 6 GeV/c: not expected in models!?
- Similar R_{AA} as in Au-Au for similar N_{coll} values

N.Apadula (WWND2013)

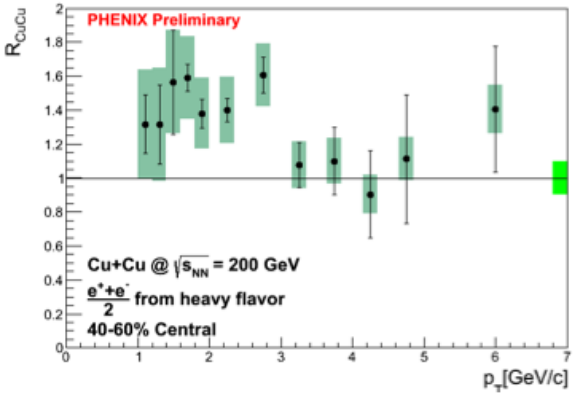
HF-decay e and μ at RHIC (Cu-Cu)

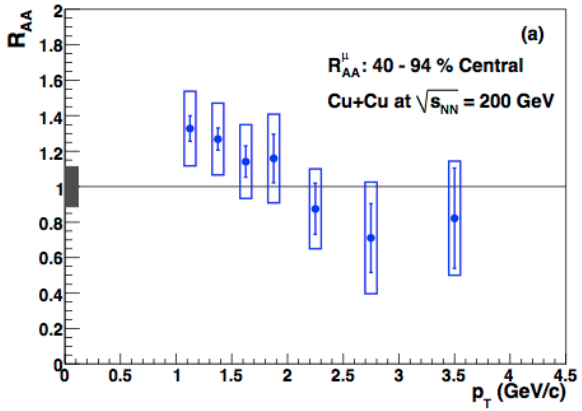
- Mid-rapidity (e): R_{AA}~1 → enhancement (from centr. to periph.)
- Forward rapidity (μ): suppression → R_{AA}~1





Theoretical prediction: R. Sharma, I. Vitev, B.-W. Zhang, Phys. Rev. C 80, 054902(2009)

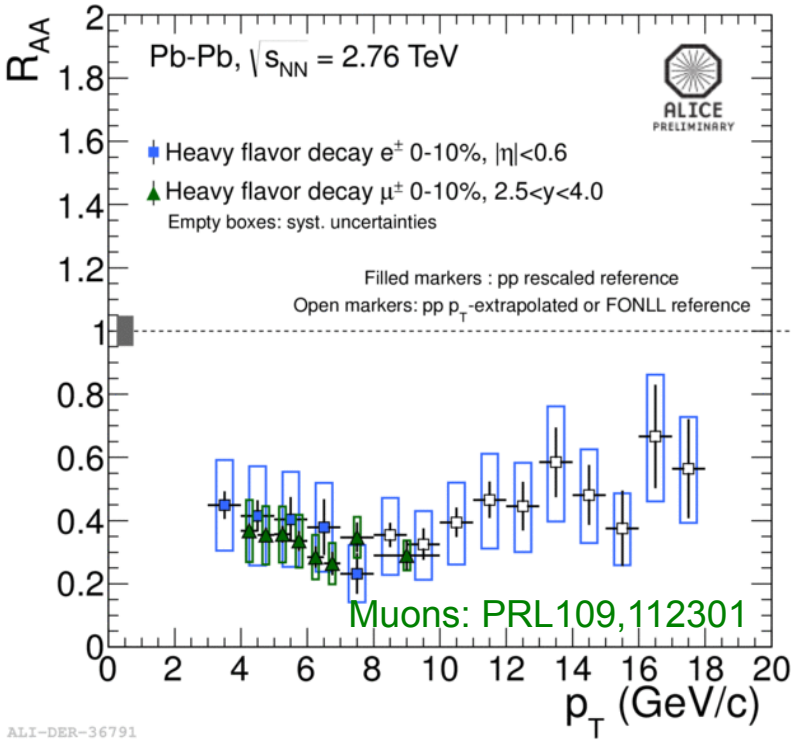




N.Apadula (WWND2013)

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

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

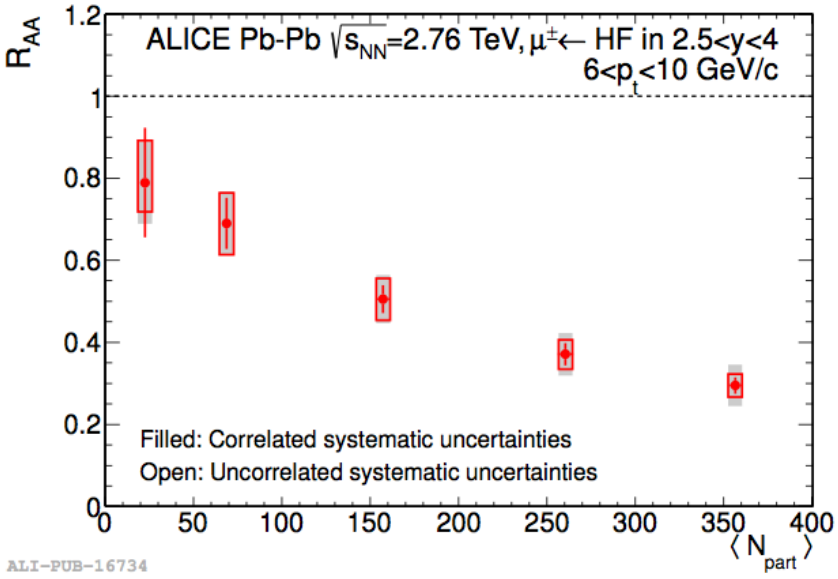


- Comparable suppression at central (|y|<0.6) and forward (2.5<y<4) rapidity

- Suppression by a factor about 2 up to 18 GeV/c
  - Dominated by beauty at such high p_T

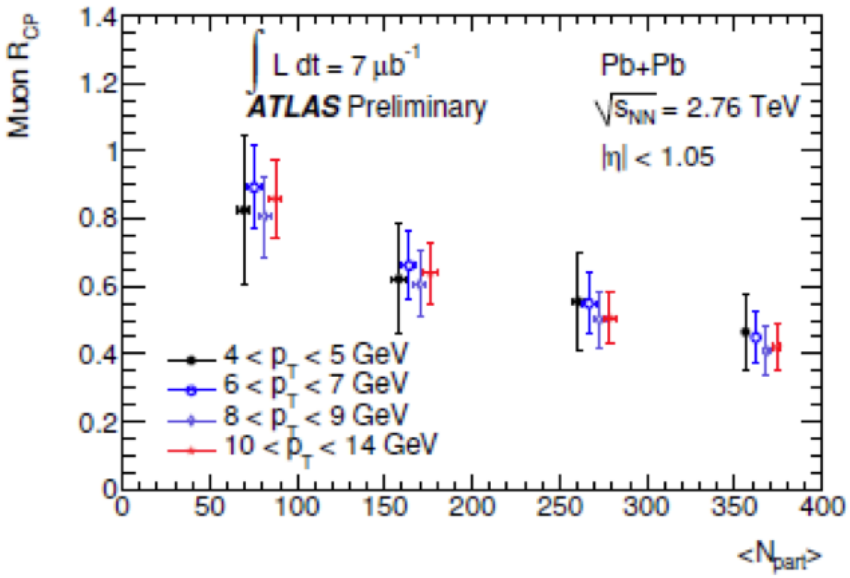
Z.Conesa (QM2012)

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

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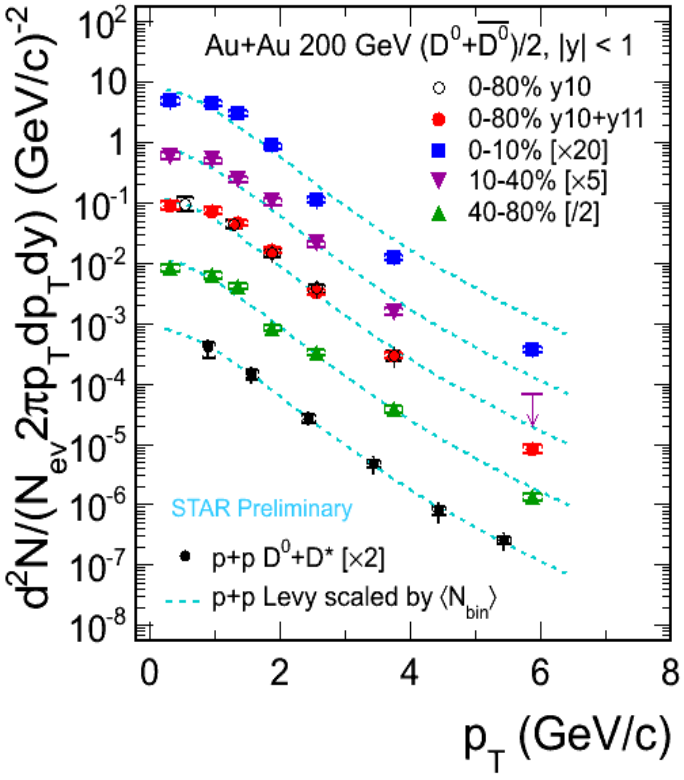
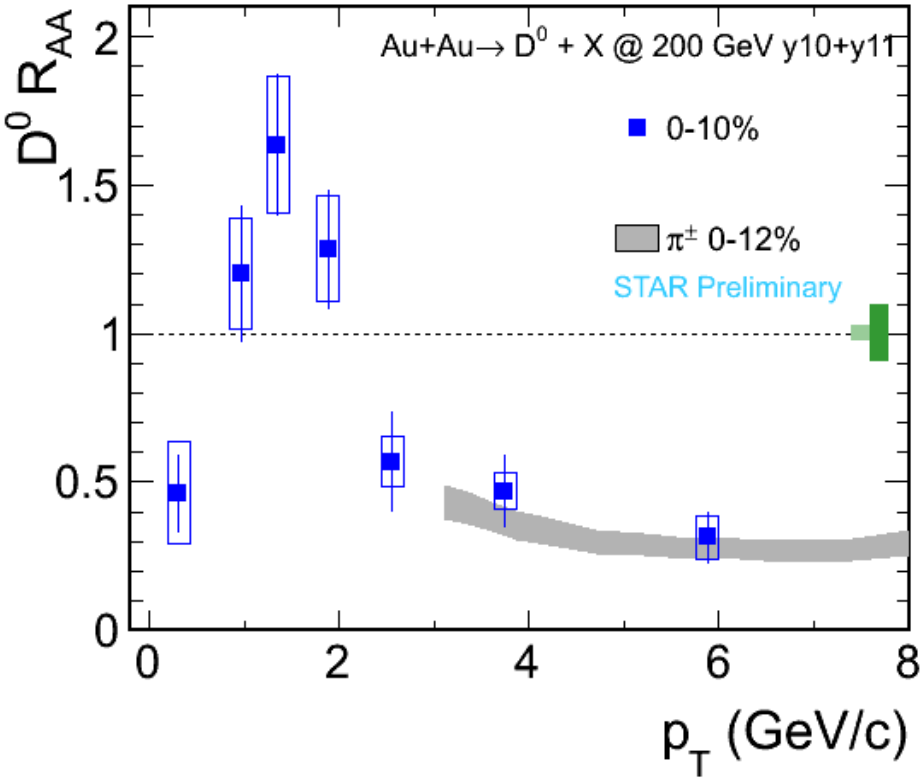
Charm: D mesons at RHIC

- STAR: first D R_{AA} in central Au-Au at RHIC

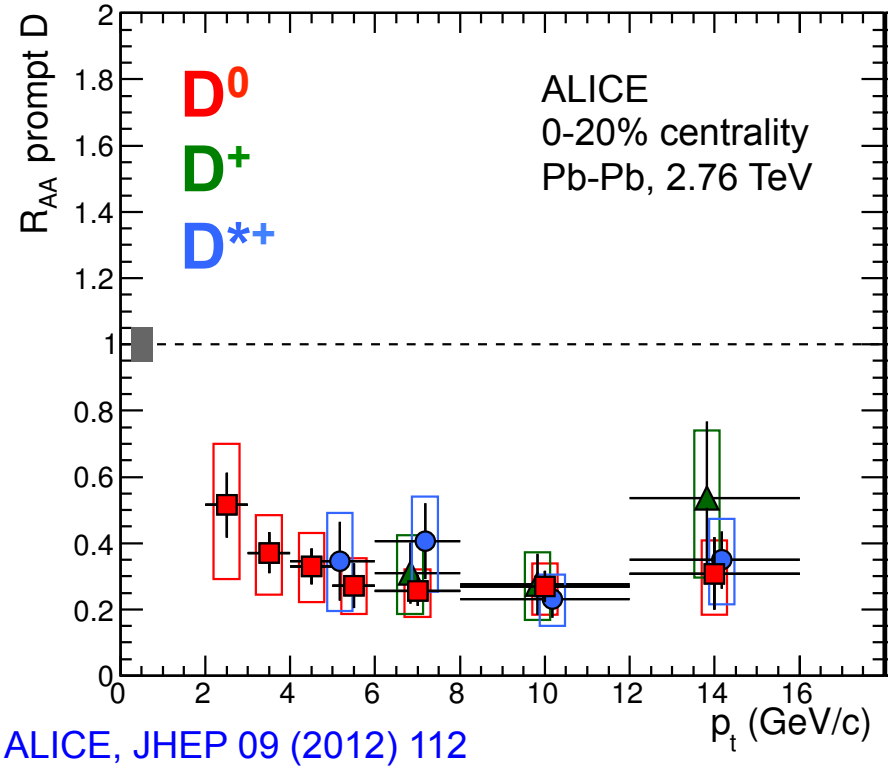




- Suppressed as much as pions at high p_T: no mass effect?
- Large enhancement at 1.5 GeV/c: radial flow + coalescence?

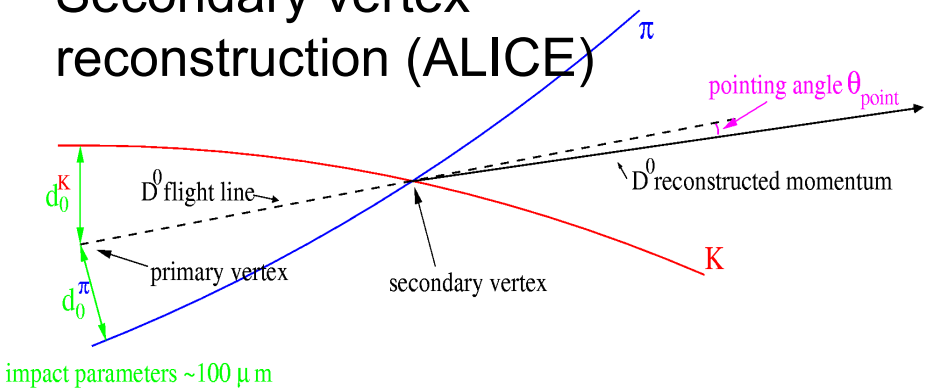
W.Xie (QM2012)

Charm: D mesons at LHC



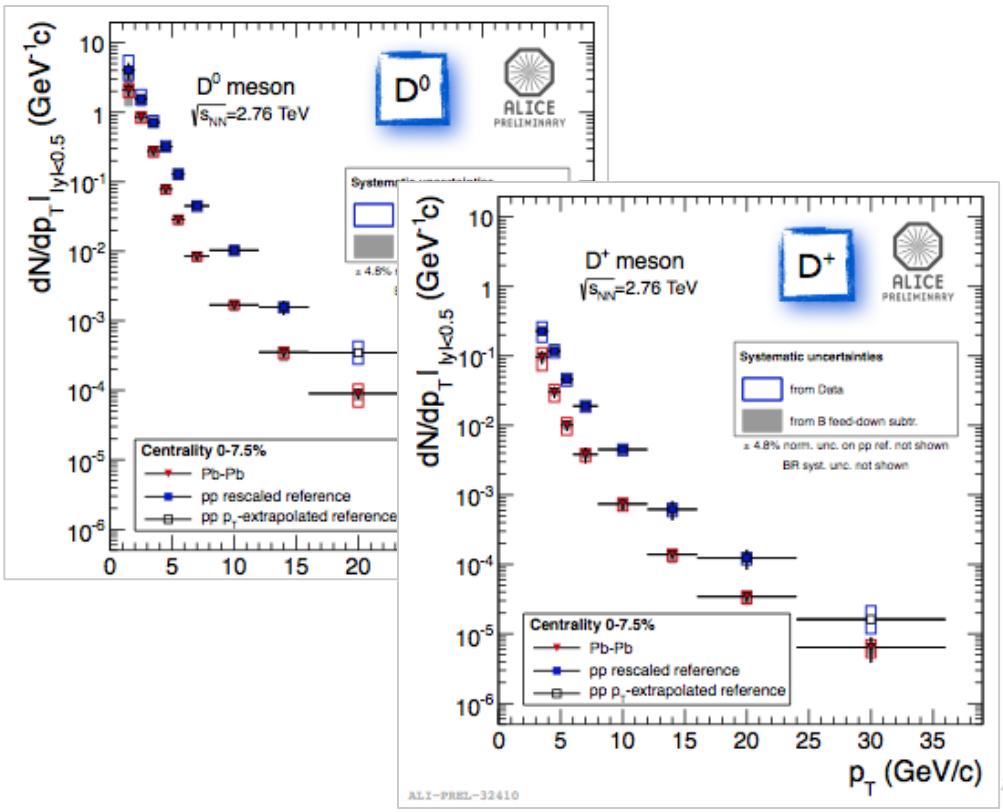
ALICE, JHEP 09 (2012) 112

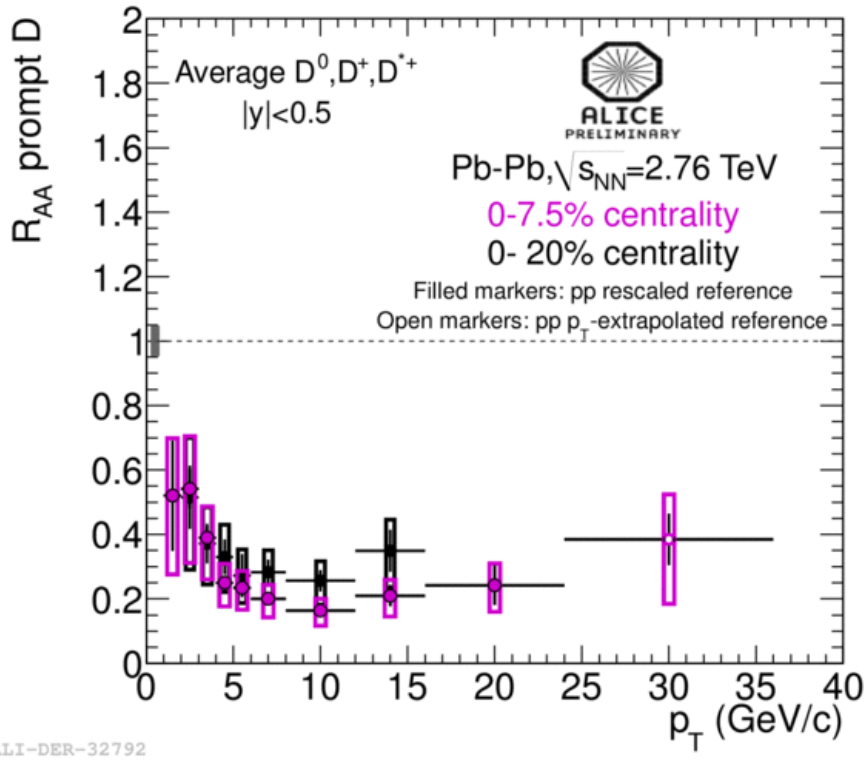
Secondary vertex reconstruction (ALICE)



- First D R_{AA} measurement in heavy-ion collisions, presented by ALICE at QM2011 (LHC run 2010)
  - Strong suppression observed

Charm: D mesons at LHC

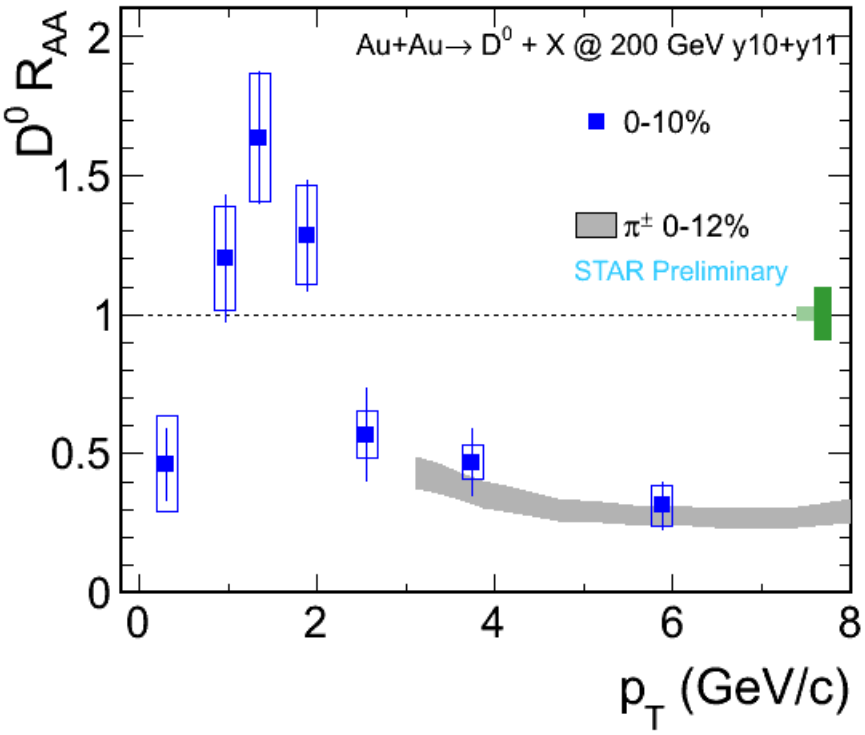


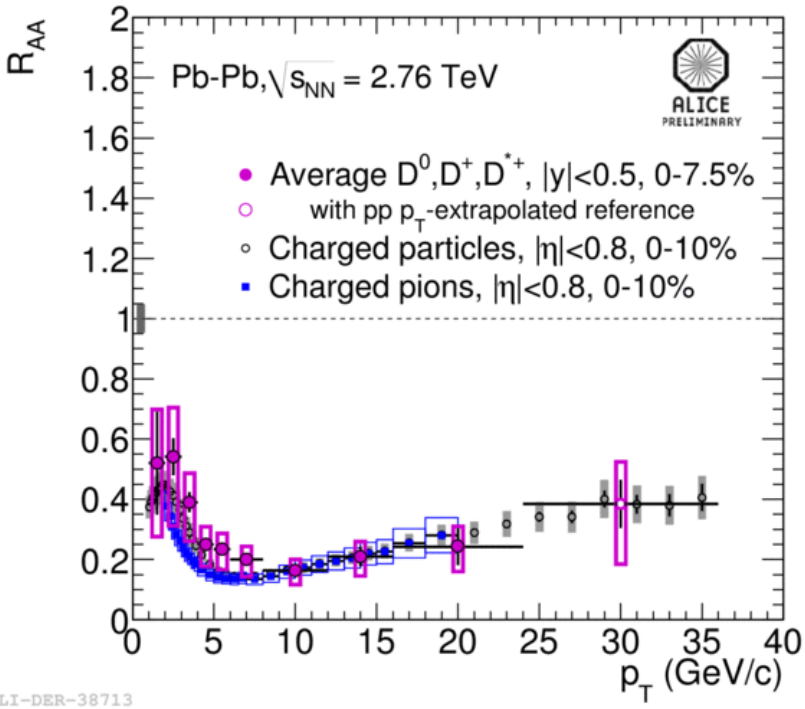


- First D R_{AA} measurement in heavy-ion collisions, presented by ALICE at QM2011 (LHC run 2010)
  - Strong suppression observed
- Measurement extended with LHC run 2011, from 1 to 30 GeV/c

Z.Conesa (QM2012)

Charm: D mesons vs. pions at RHIC and LHC

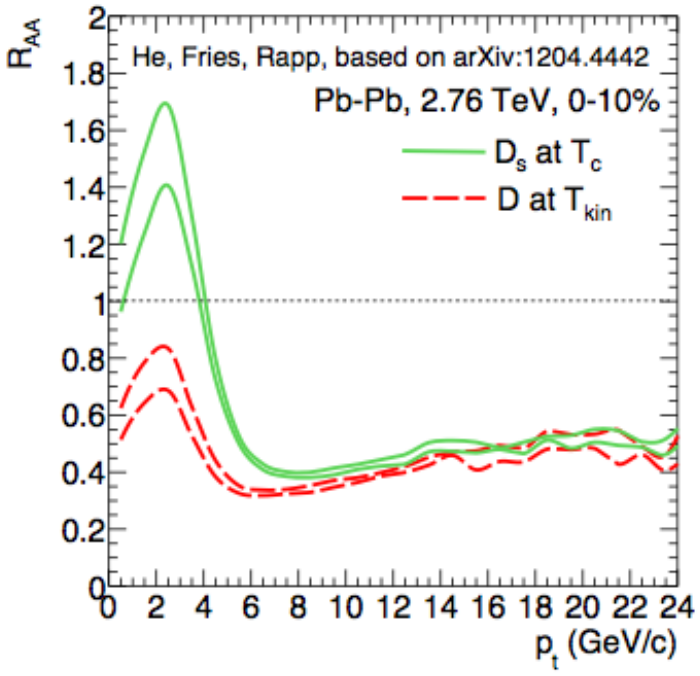


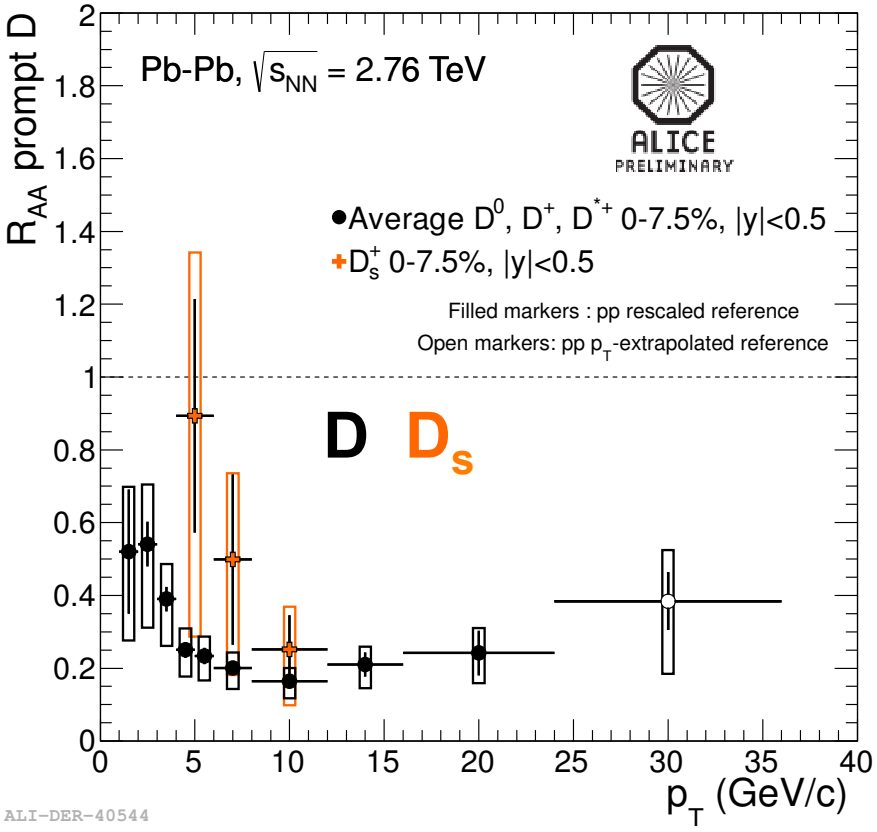


- D consistent with pions at both energies
  - Hint for D > π in 3-6 GeV/c at LHC?
- D meson R_{AA} similar at RHIC and LHC at 6 GeV/c
- Strikingly different at 1-2 GeV/c: stronger effect from coalescence at RHIC due to steeper spectra?

D_s meson R_{AA} at LHC

- First measurement of D_s in heavy ions
  - Large D_s enhancement expected, if *c* quarks recombine in the QGP





  - Data very intriguing, but not conclusive (→next LHC run, upgrades)

Z.Conesa (QM2012)

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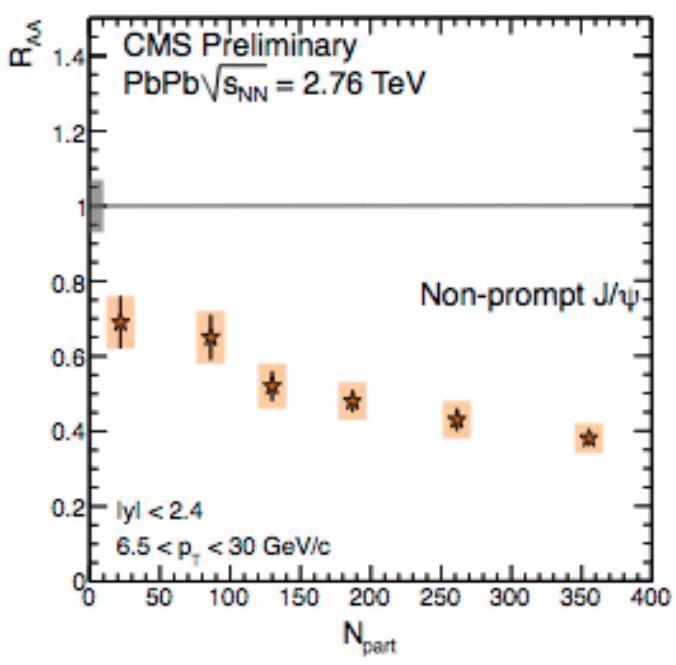
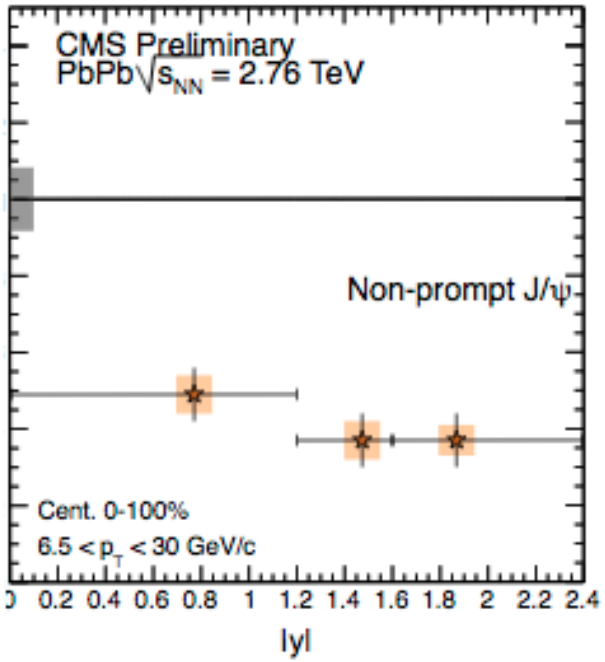
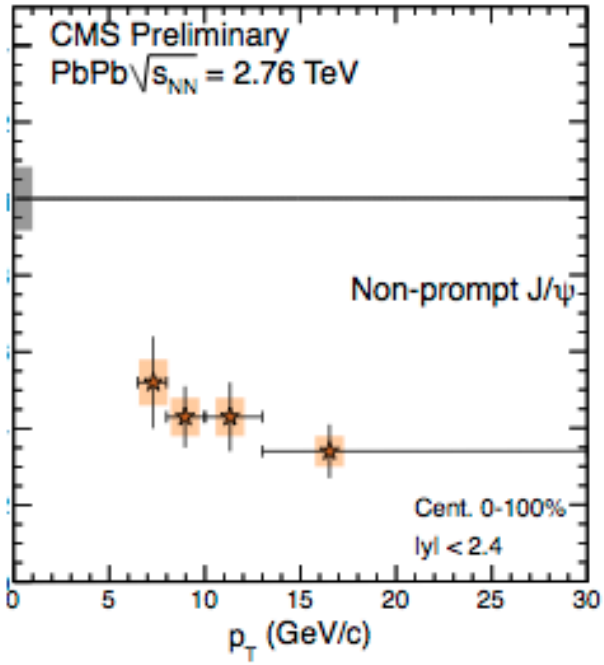
LHC: ALICE, ATLAS; ALICE; CMS

Beauty suppression at LHC

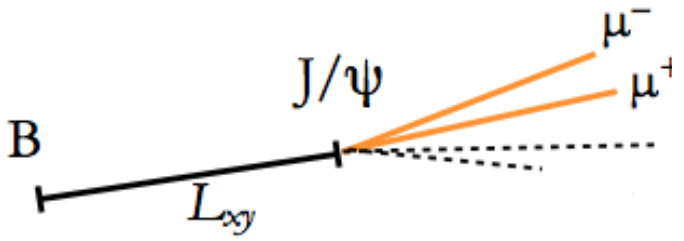
- First measurement of beauty R_{AA} by CMS (CMS-PAS-HIN-12-014)





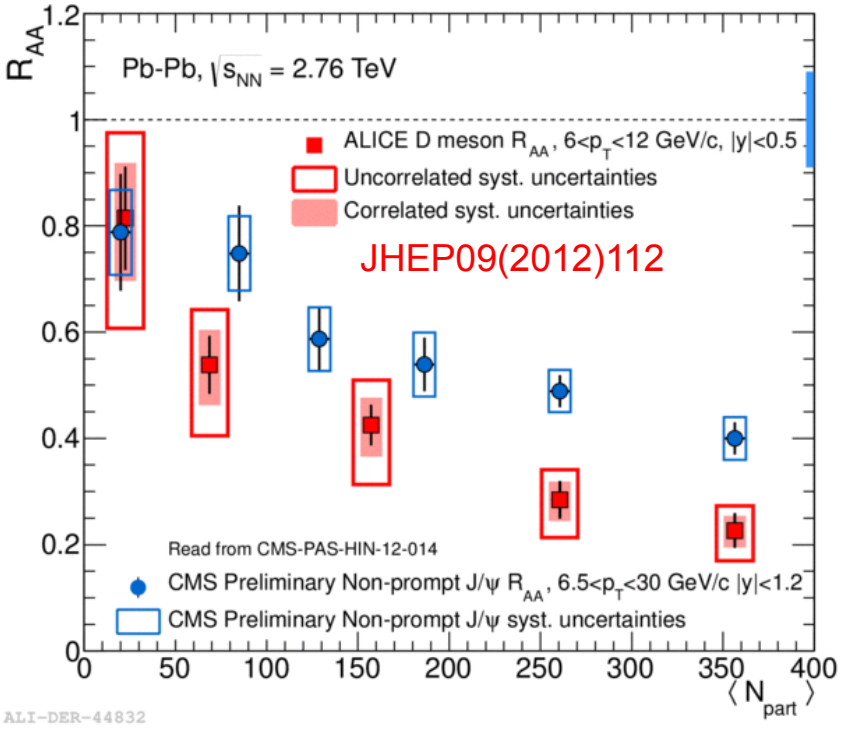


- Centrality dependence of B→J/ψ R_{AA}
  - 50-100%: factor ~1.4 → 0-5%: factor ~2.5
- Hint of less suppression at mid-rapidity
- Hint of larger suppression at higher p_T



Is this the dead cone?

- Comparison of charmed mesons (ALICE) with J/ψ from beauty decays (CMS)

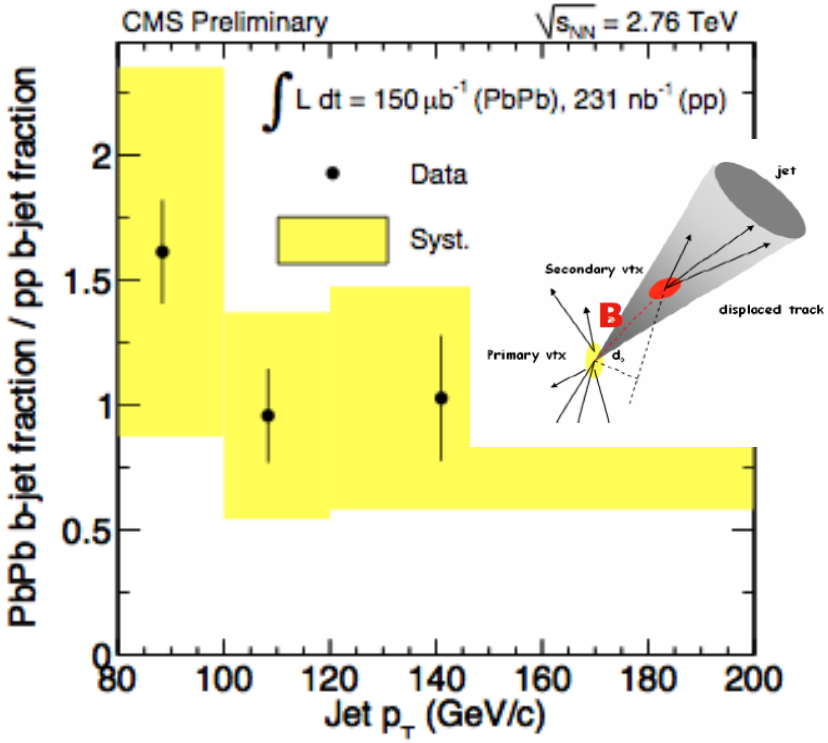


- First indication of a dependence on heavy quark mass:

$$R_{AA}^{B} > R_{AA}^{D}$$

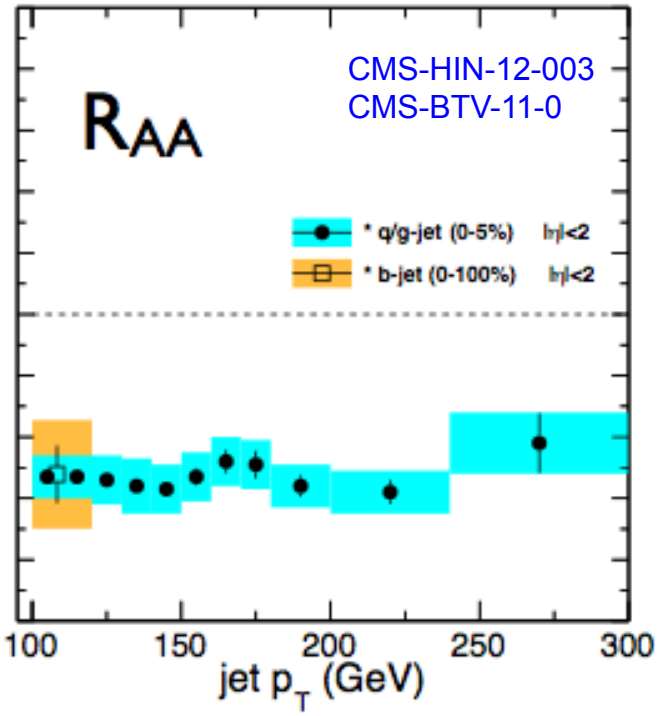
  - However, kinematical ranges are not exactly the same

Large b-jet suppression at LHC



b-jet double_ratio =

b-fraction in PbPb / b-fraction in pp



b-jet R_{AA} =

inclusive-jet R_{AA} * b-jet double_ratio

- CMS finds the same R_{AA} for b-jets as for q/g-jets, as expected at this p_T

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Initial state effects on heavy quarks

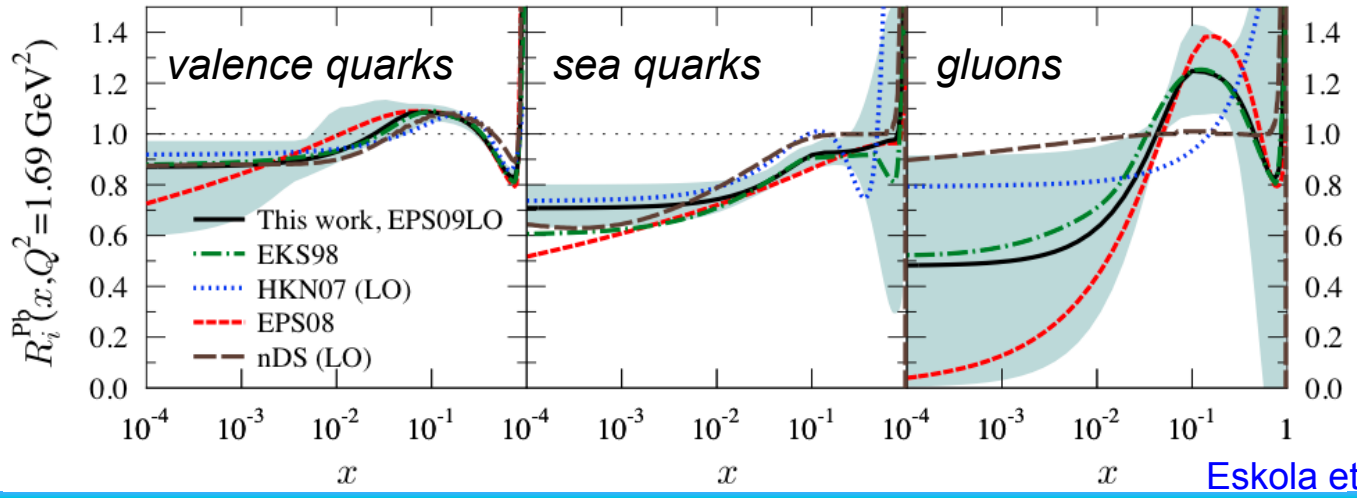
- Charm production at low p_T: **Q^2 ($4m_c^2 \sim$ 5-10 GeV^2)**

Machine	SPS	RHIC	LHC	LHC
System	Pb–Pb	Au–Au	Pb–Pb	pp
$\sqrt{s_{NN}}$	17 GeV	200 GeV	5.5 TeV	14 TeV
$c\bar{c}$	$x \simeq 10^{-1}$	$x \simeq 10^{-2}$	$x \simeq 4 \times 10^{-4}$	$x \simeq 2 \times 10^{-4}$
$b\bar{b}$	–	–	$x \simeq 2 \times 10^{-3}$	$x \simeq 6 \times 10^{-4}$

→ interpretation of HF (charm) measurements in AA requires pA reference

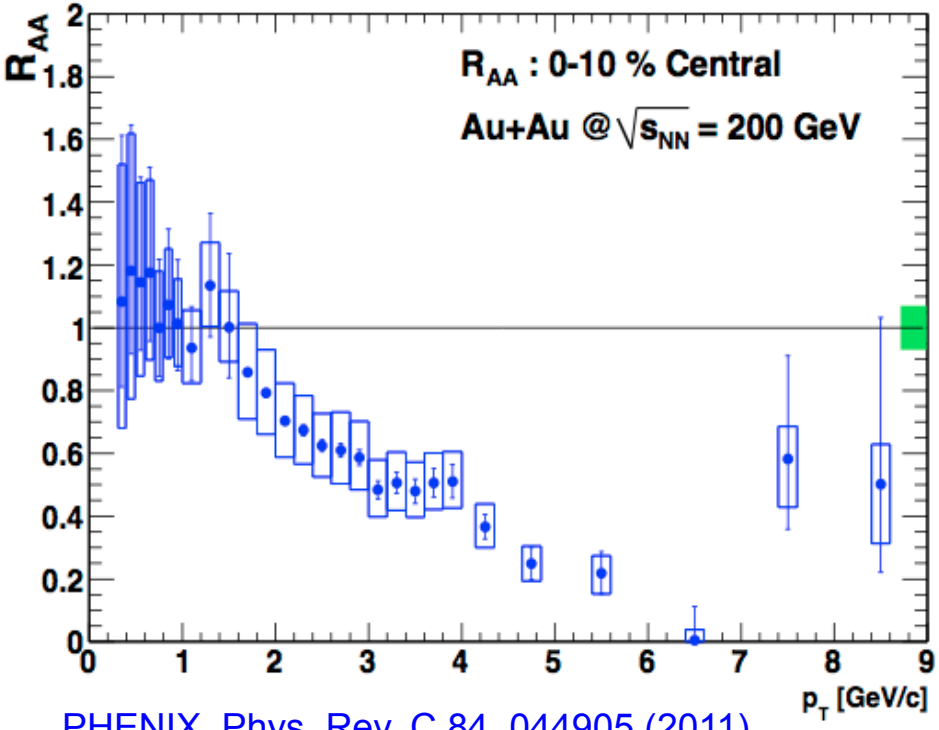
→ charm in pA: access to small-x gluons with perturbative probes

Nuclear modification of PDFs

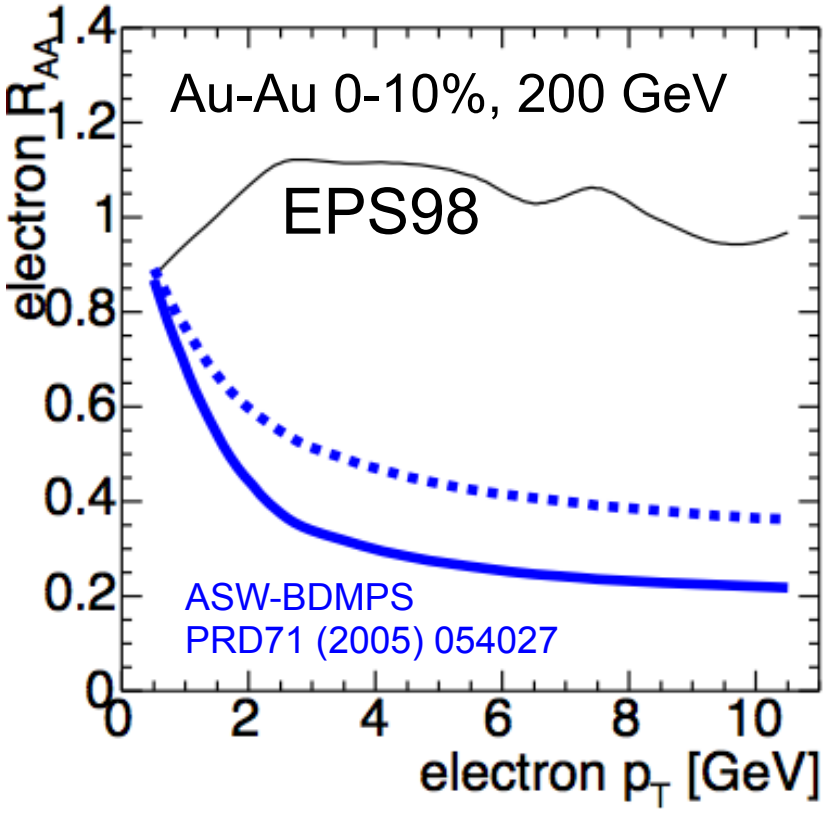


Eskola et al. JHEP0904(2009)065

Only a QCD medium effect? RHIC

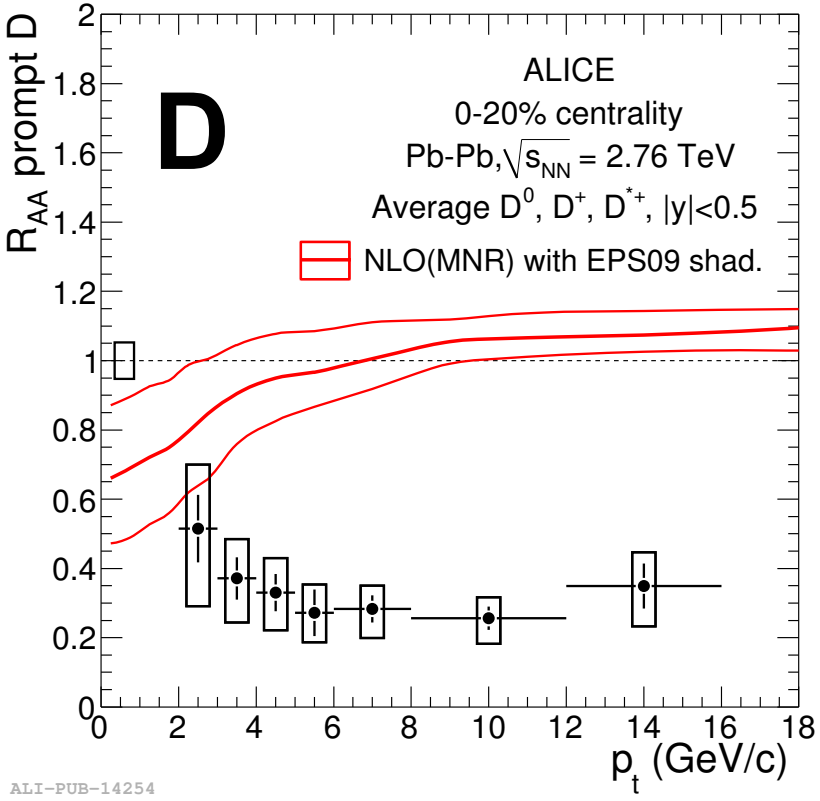


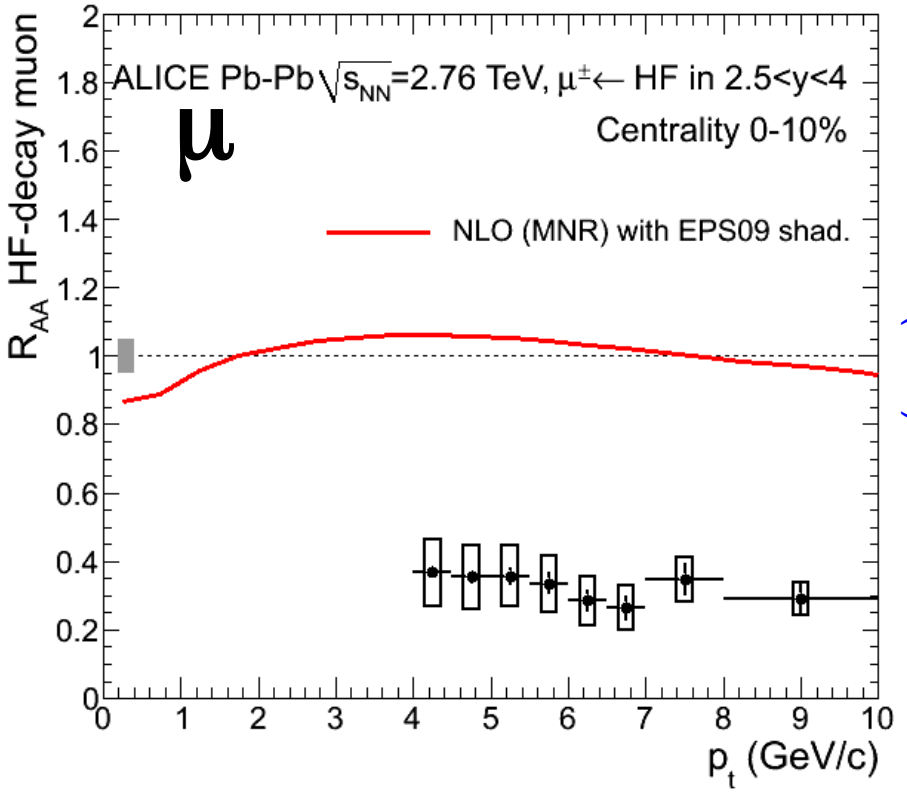
PHENIX, Phys. Rev. C 84, 044905 (2011)



- Small effect expected from PDFs shadowing (<10%)
- Mostly a hot medium effect?
- p/d-A control crucial to quantify initial-state effects

Only a QCD medium effect? LHC





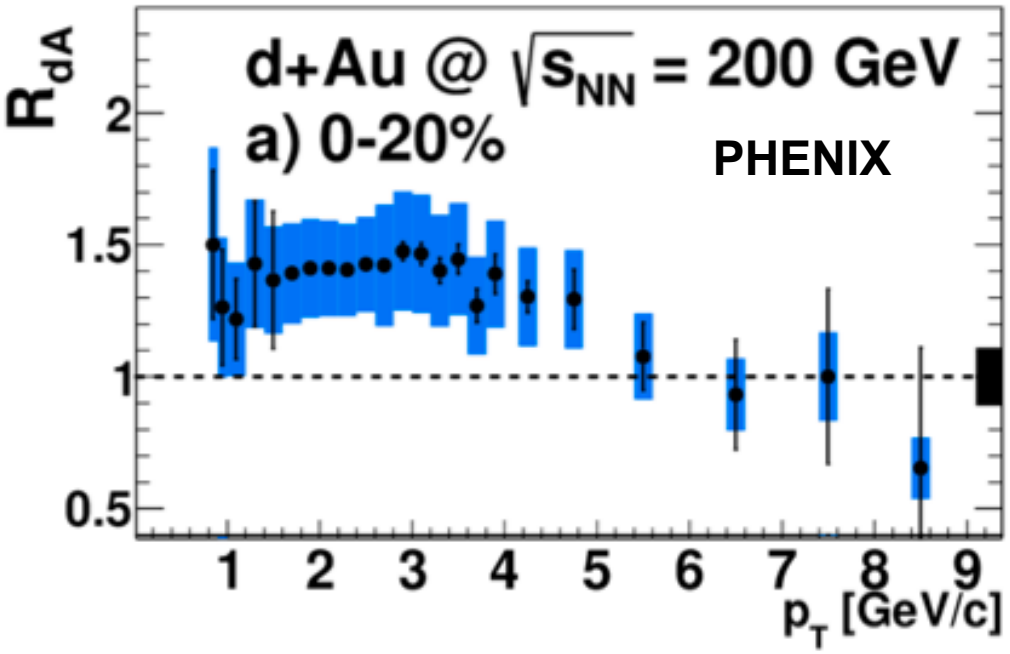
JHEP 09 (2012) 112
PRL 109 (2012) 112301

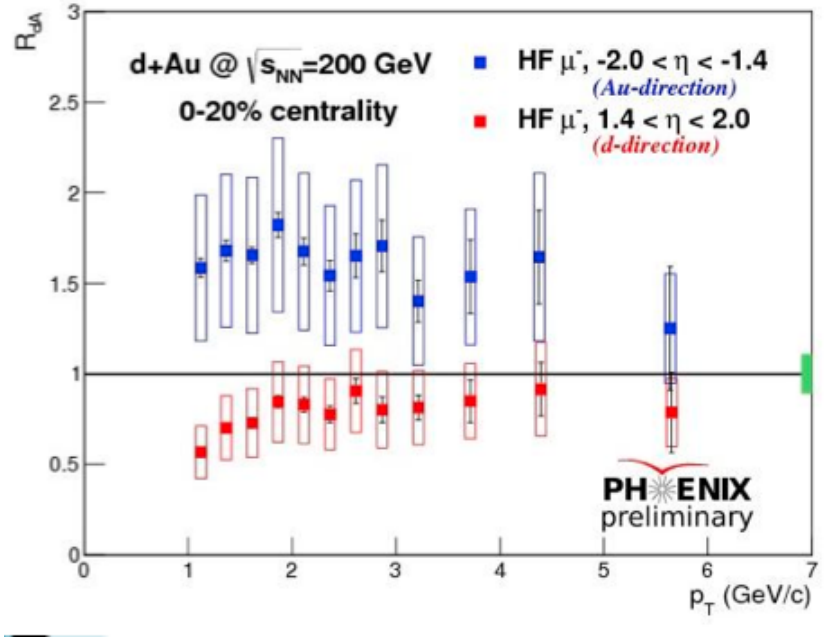
- Small effect expected from PDFs shadowing above 5 GeV/c
- Mostly a hot medium effect above 5 GeV/c?
- p/d-A control crucial to quantify initial-state effects

EPS09: Eskola et al. JHEP0904(2009)065

HF e in d-Au: RHIC results

Phys. Rev. Lett. 109, 242301 (2012)

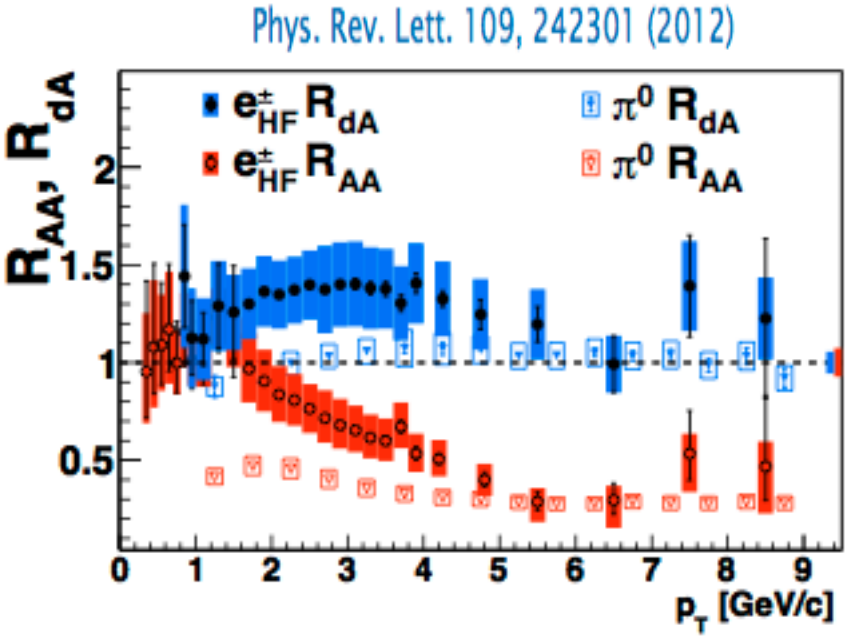


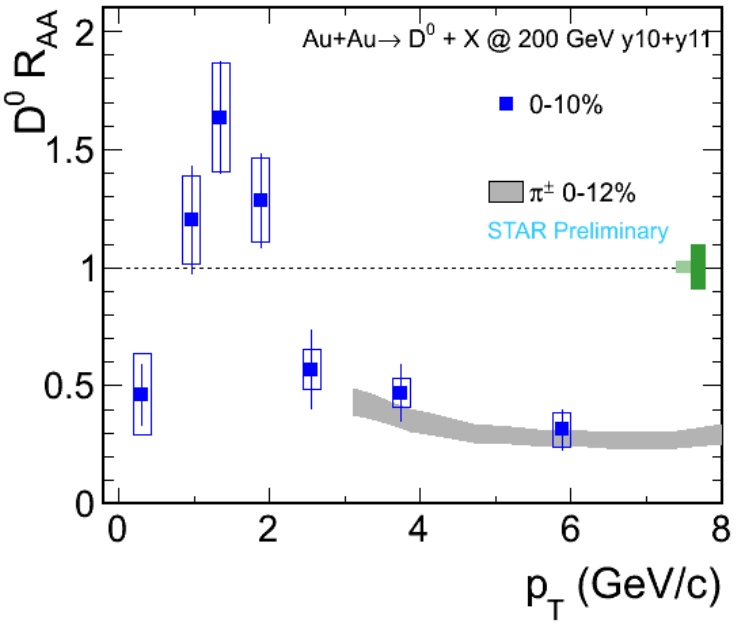


- Low-p_T electrons (mid-y) and muons (forward y) largely enhanced
- More than expected from anti-shadowing?

N.Apadula (WWND2013)

HF e in d-Au: RHIC results

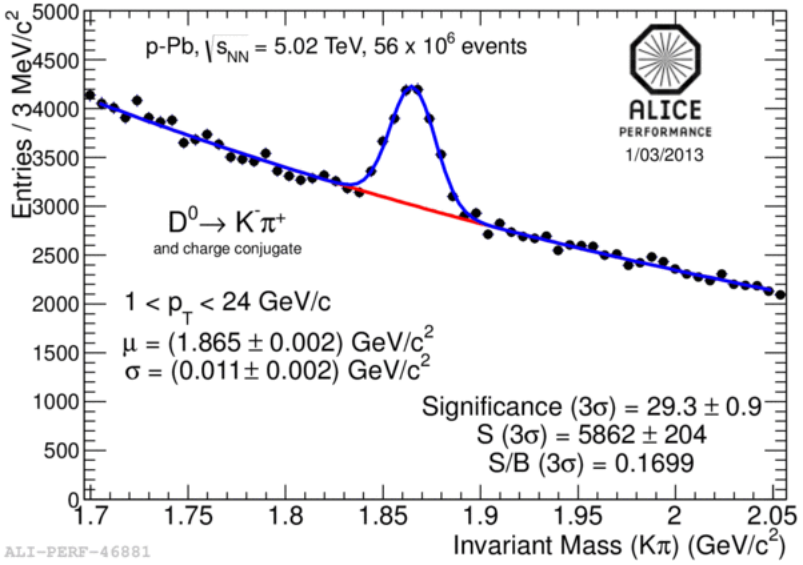


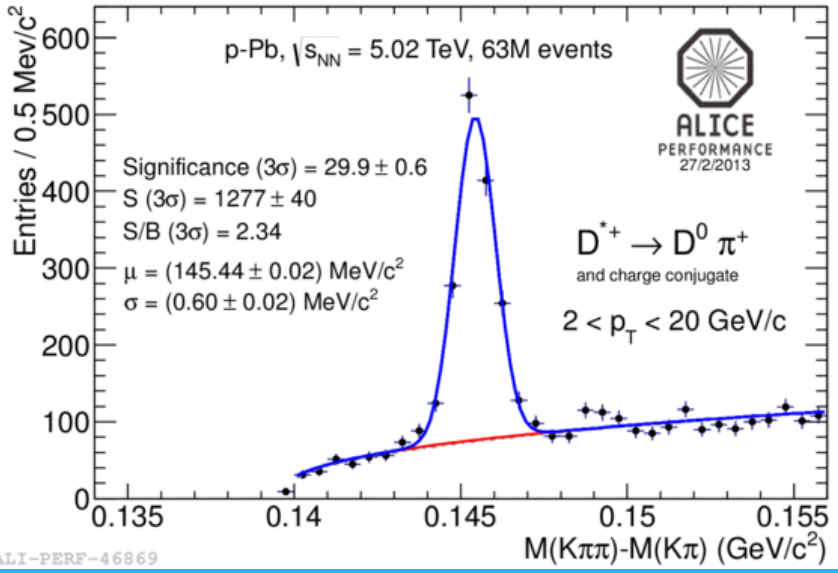


- Low-p_T electrons (mid-y) and muons (forward y) largely enhanced
- More than expected from anti-shadowing?
- Significant role of (mass-dependent?) k_T broadening / initial-state partonic scattering?
- Or is there some final-state "activity"? → need D mesons!!!

HF in p-Pb at LHC: analyses ongoing …

- Large integrated lumi of the p-Pb run (~30/nb) will allow the experiments (including LHCb!) to measure, with precision ~PbPb2011:
  - HF-decay electrons and muons
  - D mesons, including D_s
  - B→J/ψ, b-jets
- Example: D meson signals in ALICE





Outline of the Talk

- Introduction: HF probes of the medium
- Calibrating HF probes: pp results
- HF production in nucleus-nucleus:
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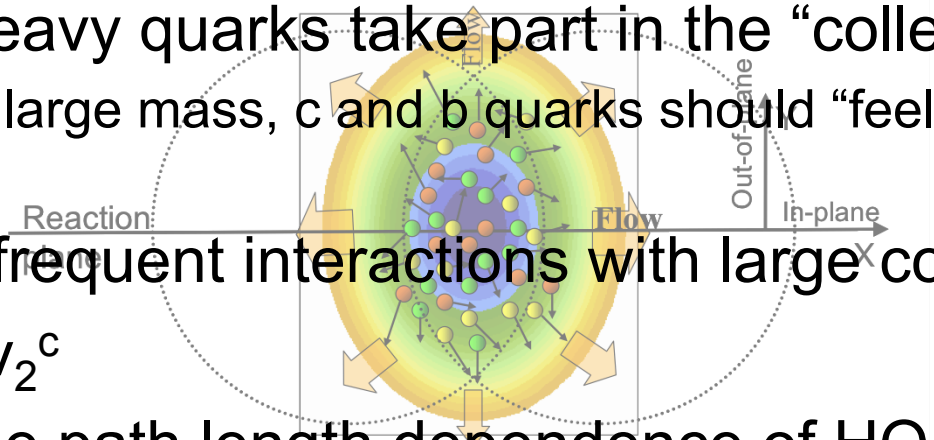
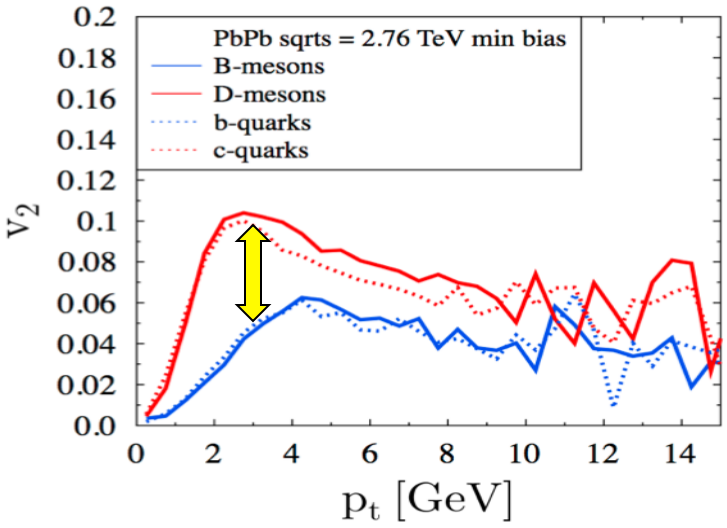
  - D mesons
  - B and b-jets
- Proton-nucleus control data
- HF azimuthal anisotropy
- Outlook: detector upgrades at RHIC and LHC

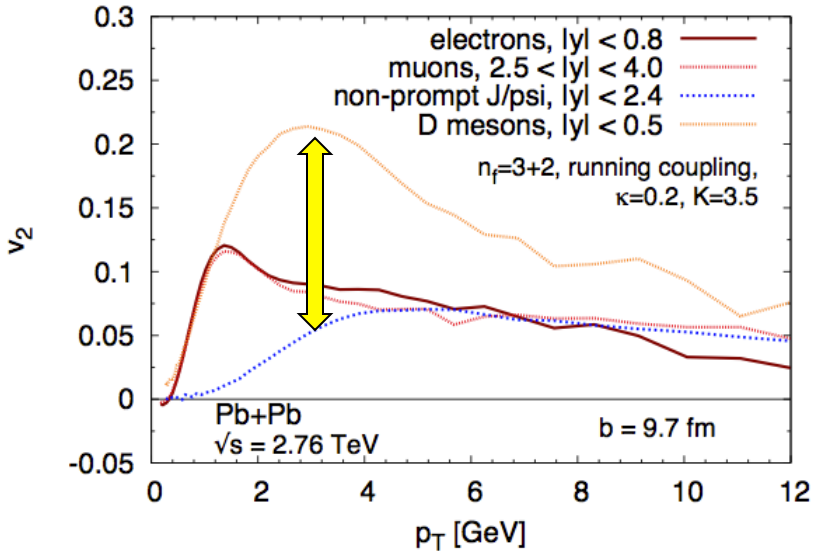
Heavy flavour v_2: a two-fold observable

- 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





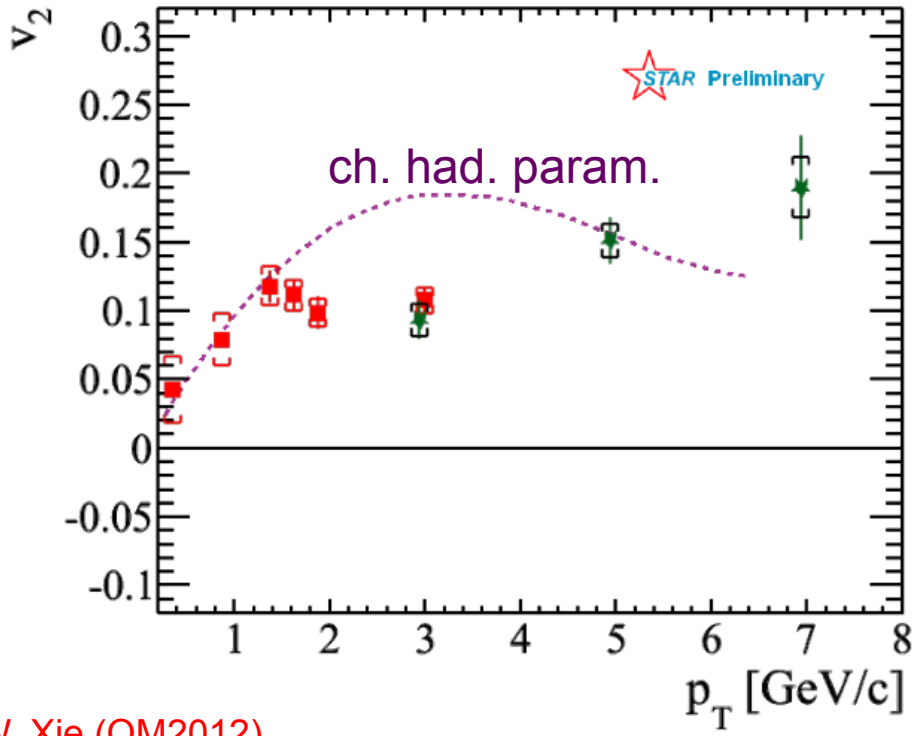
J. Aichelin et al. in arXiv:1201.4192



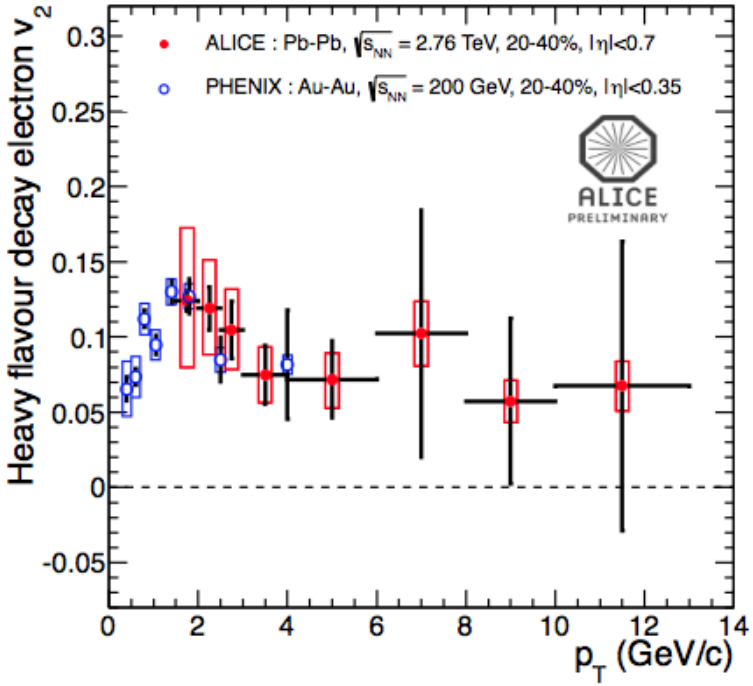
J. Uphoff et al. in arXiv:1205.4945

Heavy-flavour azimuthal anisotropy, from RHIC to LHC

- Electrons from HF show a v_2 of up to 0.15 at RHIC (PHENIX, STAR)
  - Charm does flow!
  - v_2 significantly smaller than for pions above 2 GeV/c (might be decay kinematics, rather than a difference heavy vs. light)
- First measurements at the LHC (ALICE): electron v_2 comparable to RHIC



W. Xie (QM2012)

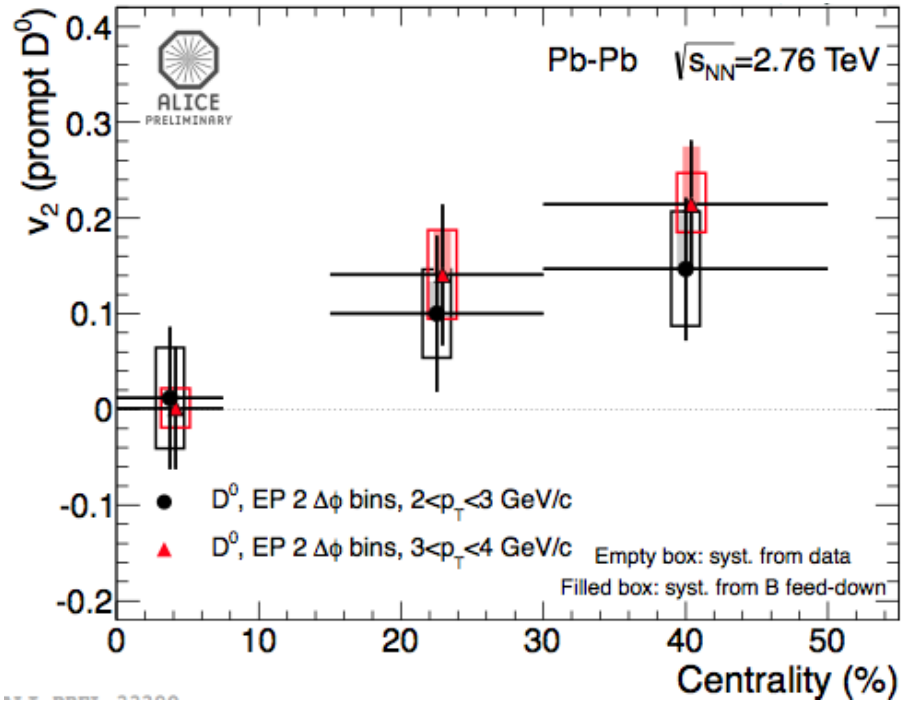


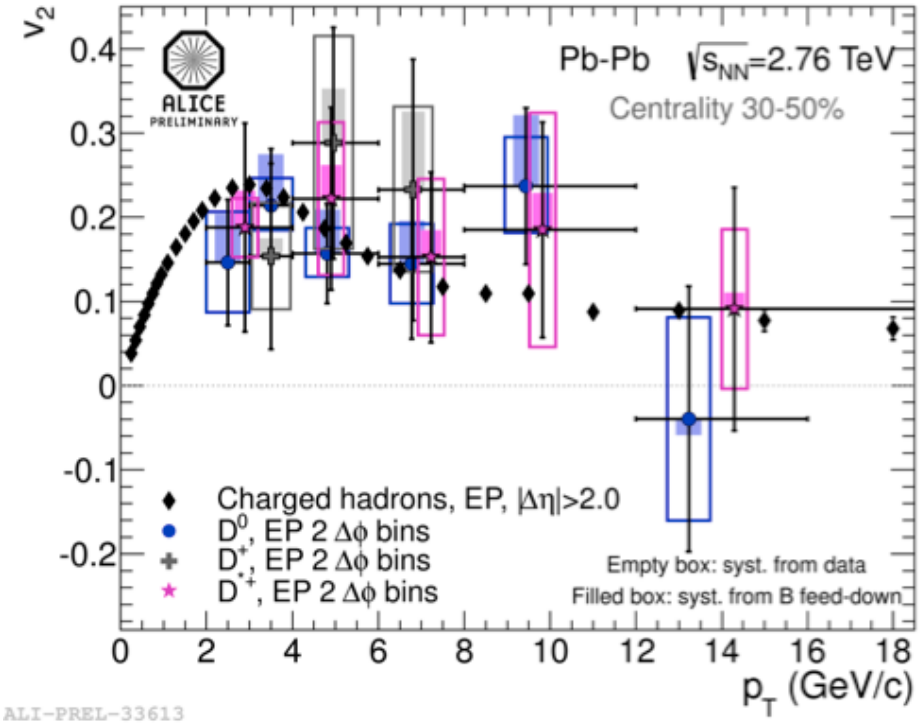
PHENIX, PRC84 (2011) 044905

Z. Conesa (QM2012)

Heavy-flavour azimuthal anisotropy, from RHIC to LHC

- First D measurements at the LHC (ALICE): D meson v_2>0 in 30-50% class
  - D meson v_2>0 in 30-50% class & Comparable to v_2 of charged hadrons
  - Suggests flow at low p_T and path-length dependent suppression at high p_T
- First D v_2 measurement at RHIC presented at QM by STAR (not shown)



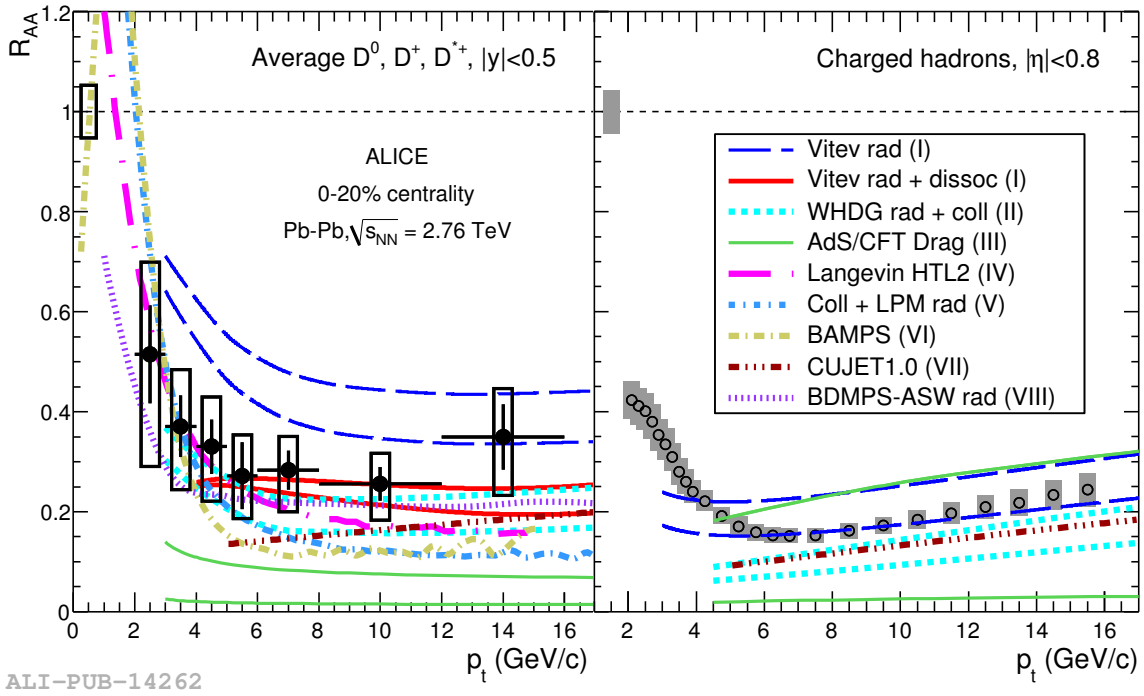


Z. Conesa (QM2012)

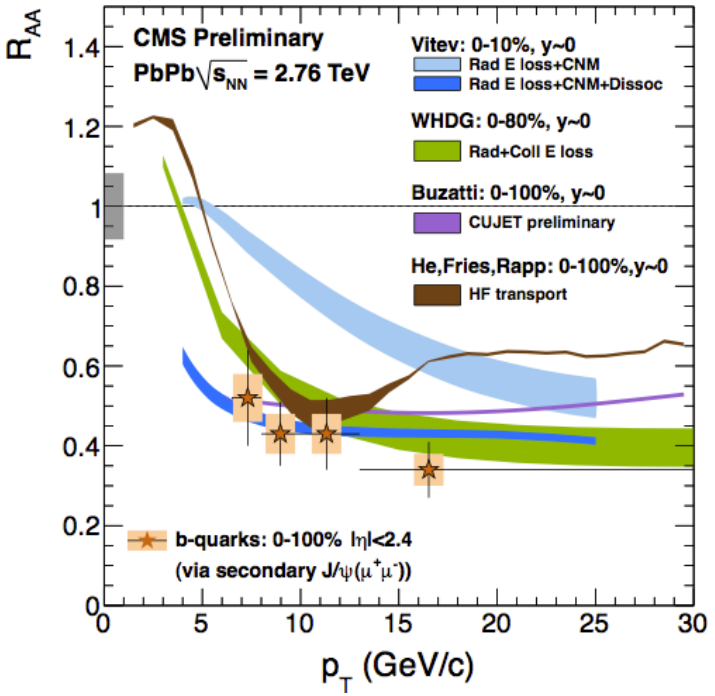
LHC: comparison with models (R_{AA})

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

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

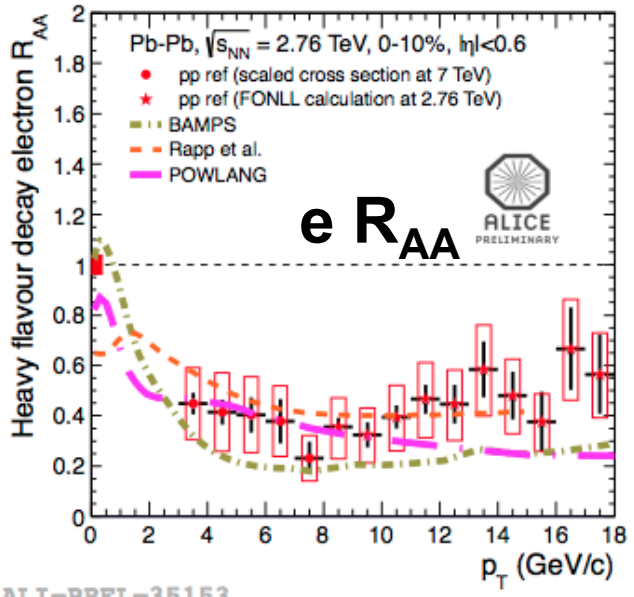


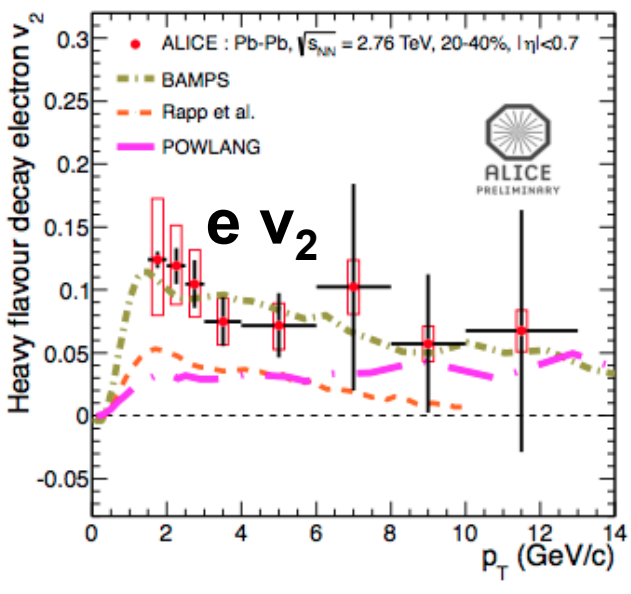
ALICE, JHEP 09 (2012) 112

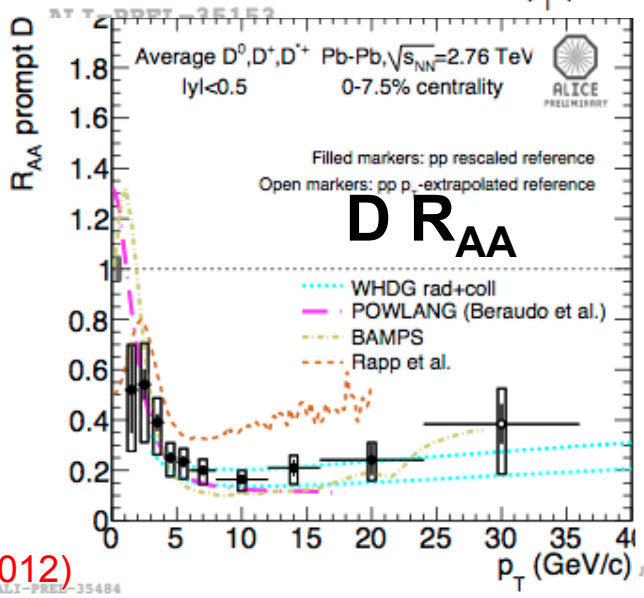


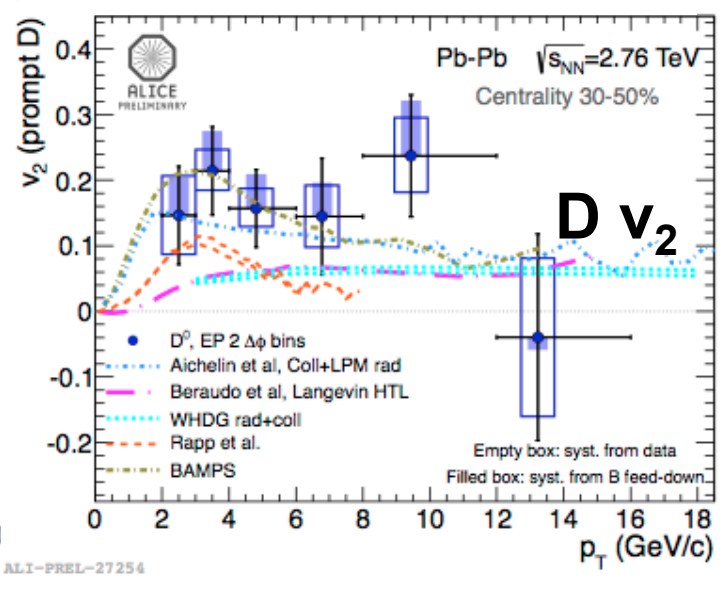
CMS-PAS-HIN-12-014

LHC: comparison with models (R_{AA} and v_2)



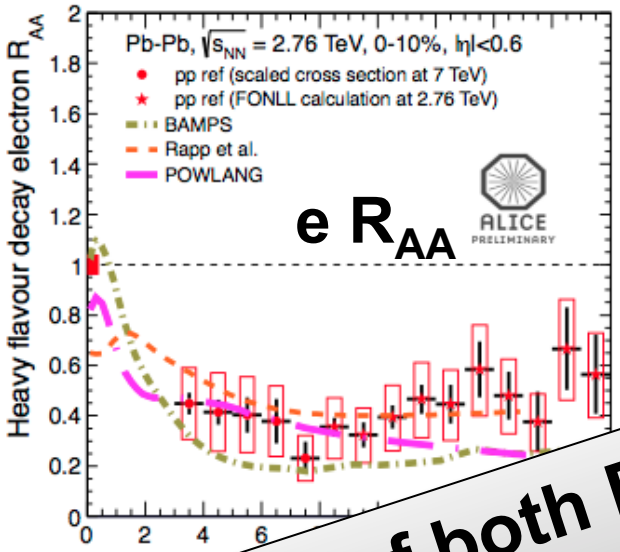


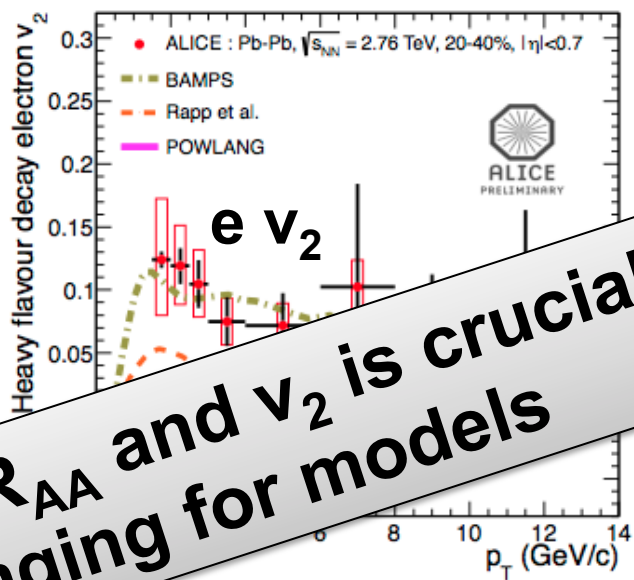




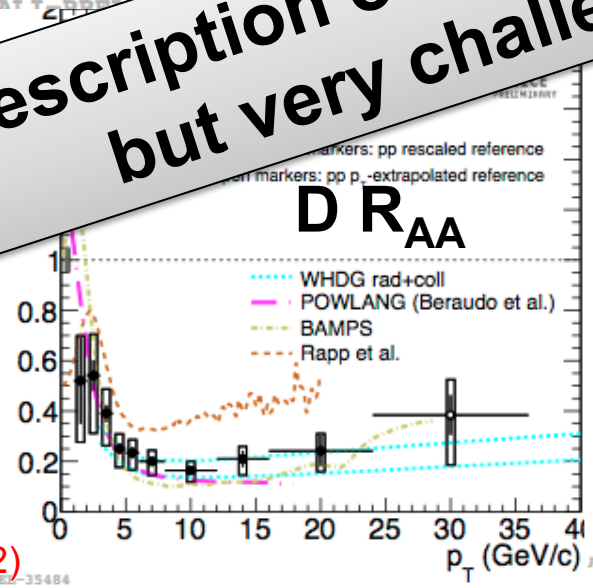
Z. Conesa (QM2012)

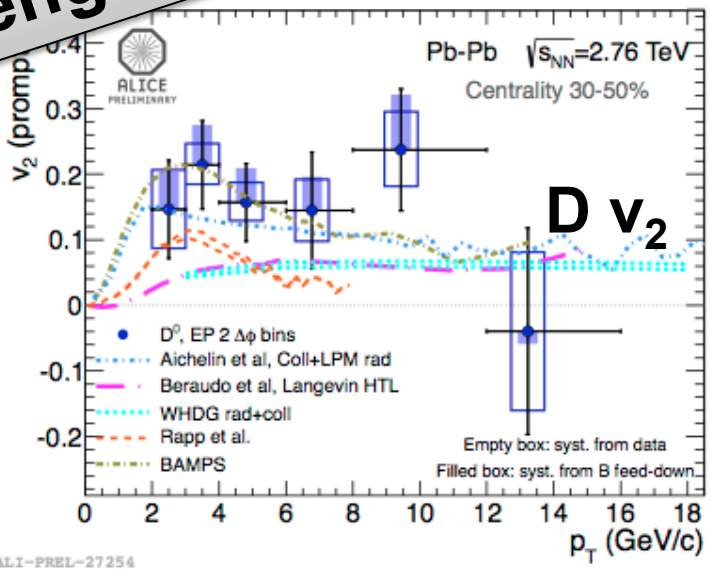
LHC: comparison with models (R_{AA} and v_2)





Description of both R_{AA} and v_2 is crucial, but very challenging for models

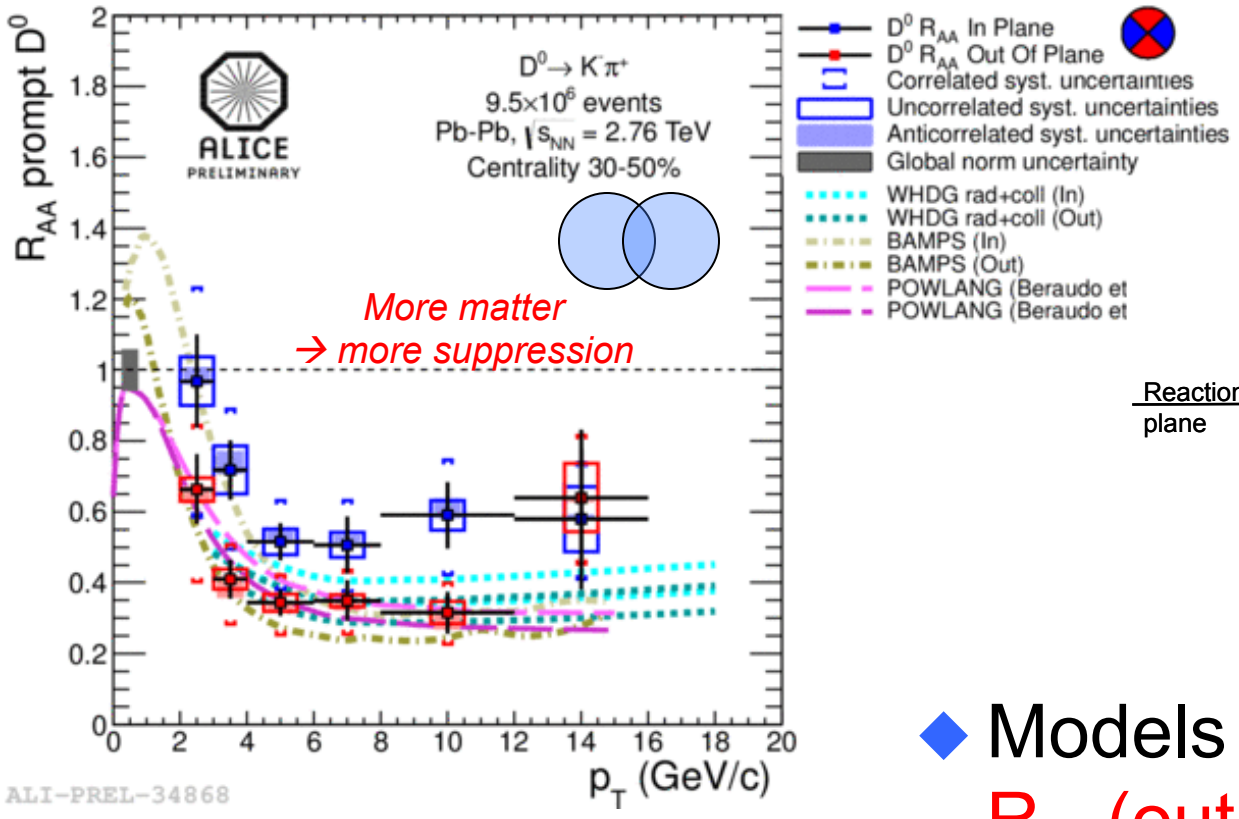


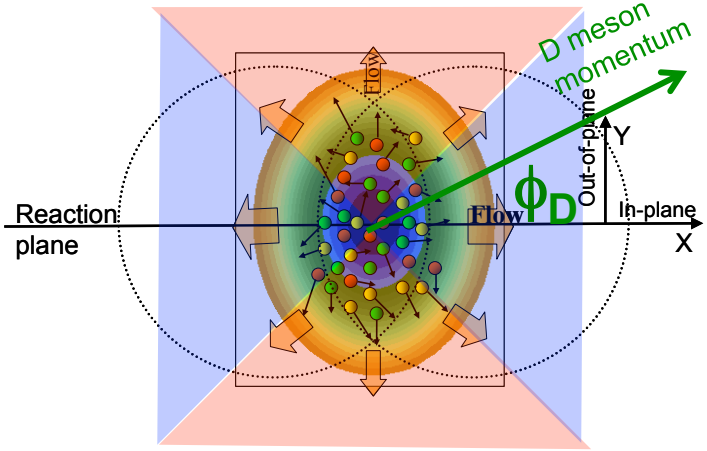


Z. Conesa (QM2012)

Towards HF tomography

- D suppression in different azimuthal directions





much more of this with next LHC run, then upgrades

- Models tend to describe R_{AA}(out-of-plane) better than R_{AA}(in-plane)

Z.Conesa (QM2012)

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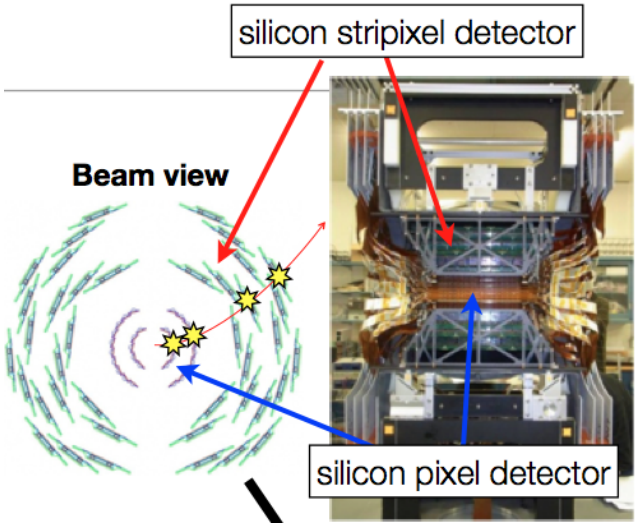
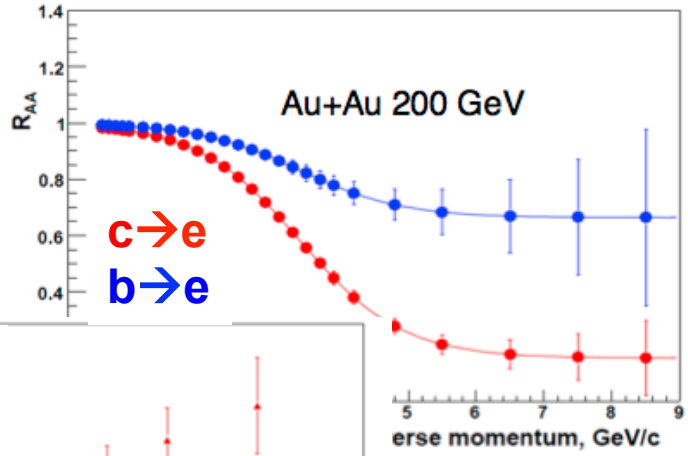
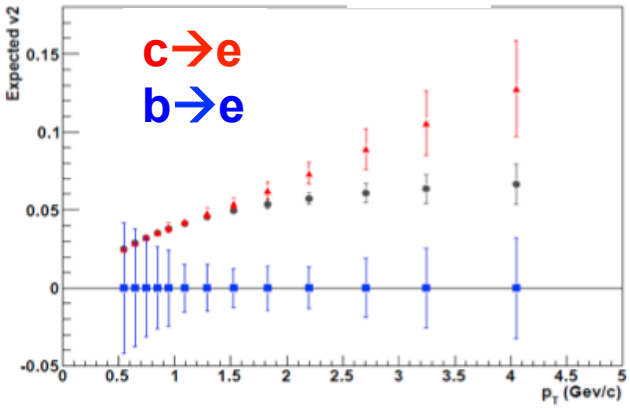
- Calibrating HF probes: pp results
- HF production in nucleus-nucleus:
  - Semi-leptonic decays
  - D mesons
  - B and b-jets
- Proton-nucleus control data
- HF azimuthal anisotropy
- Outlook: detector upgrades at RHIC and LHC
  - Heavy flavour: a central topic for upgrades of all the HI experiments!

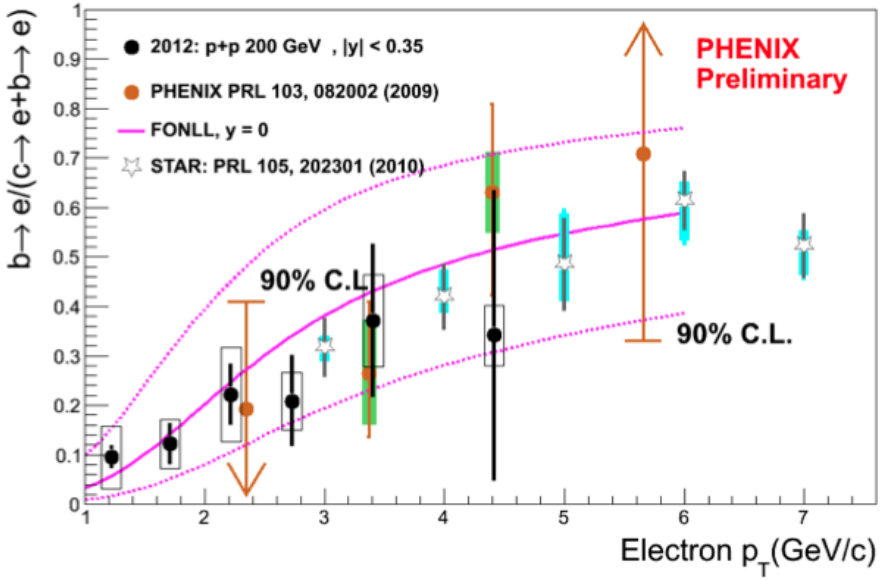
PHENIX: Vertex Tracker (VTX)



Projections 5B evts



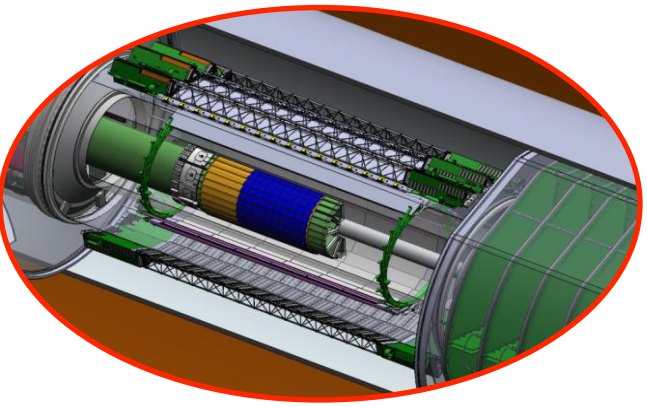




Electron b-fraction in pp

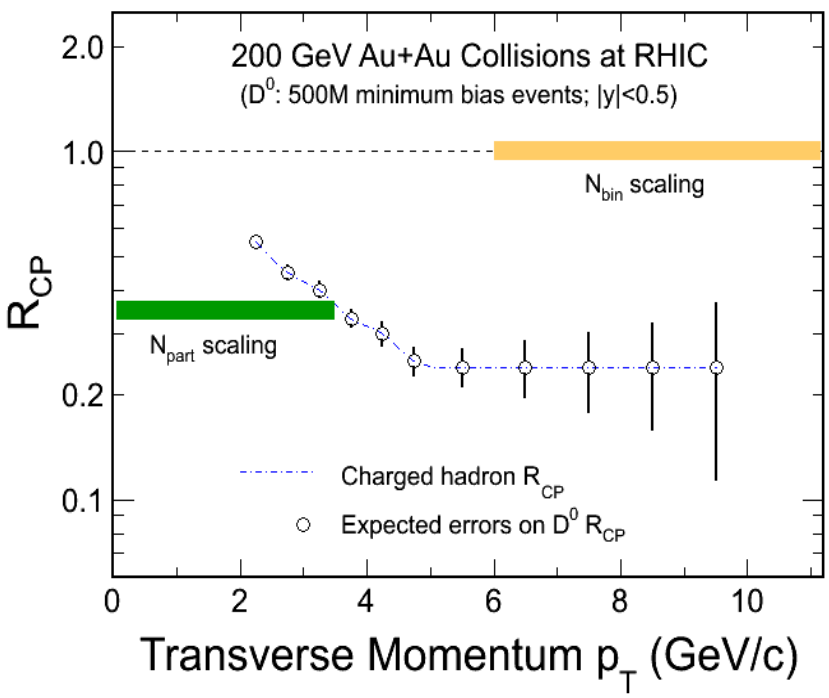
- Ongoing in Au-Au

M. Rosati, QM2012

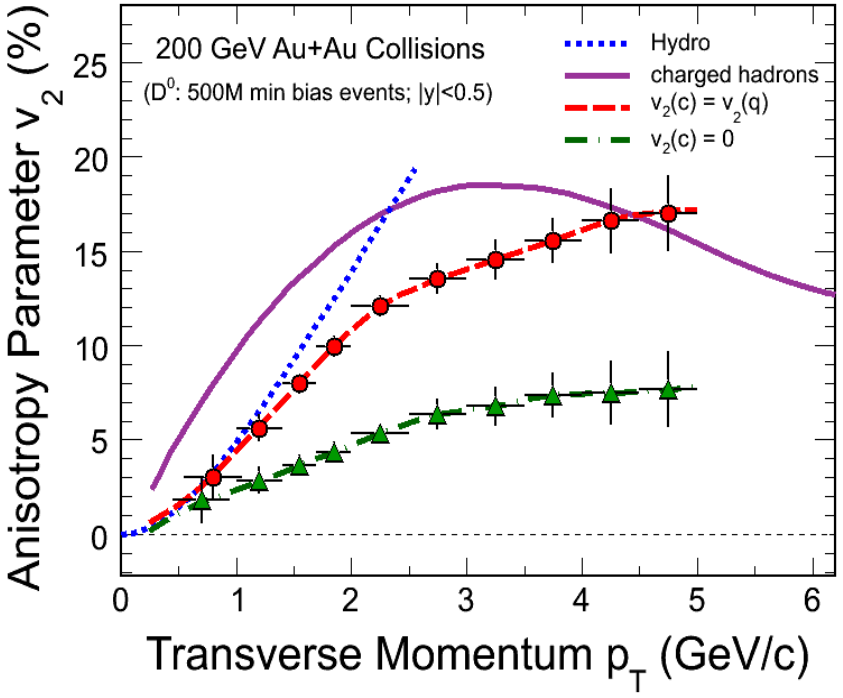


STAR: Heavy Flavour Tracker

Projections 500M evts

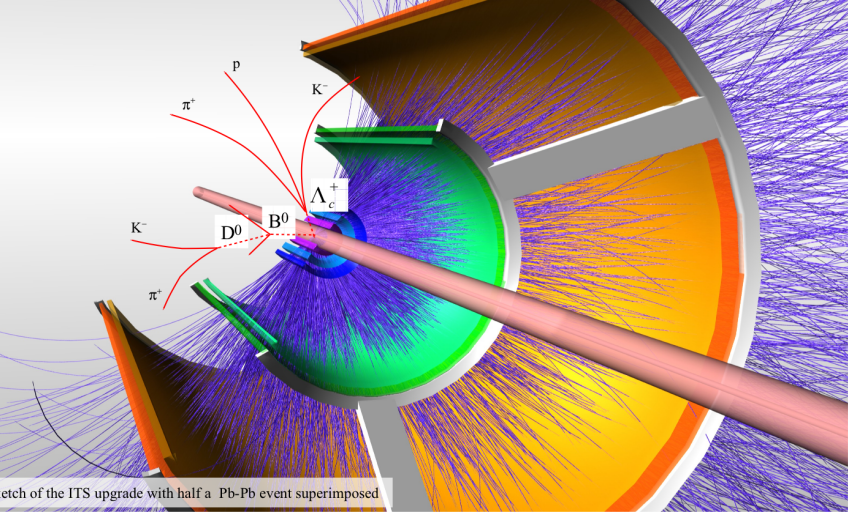


D meson R_{CP}



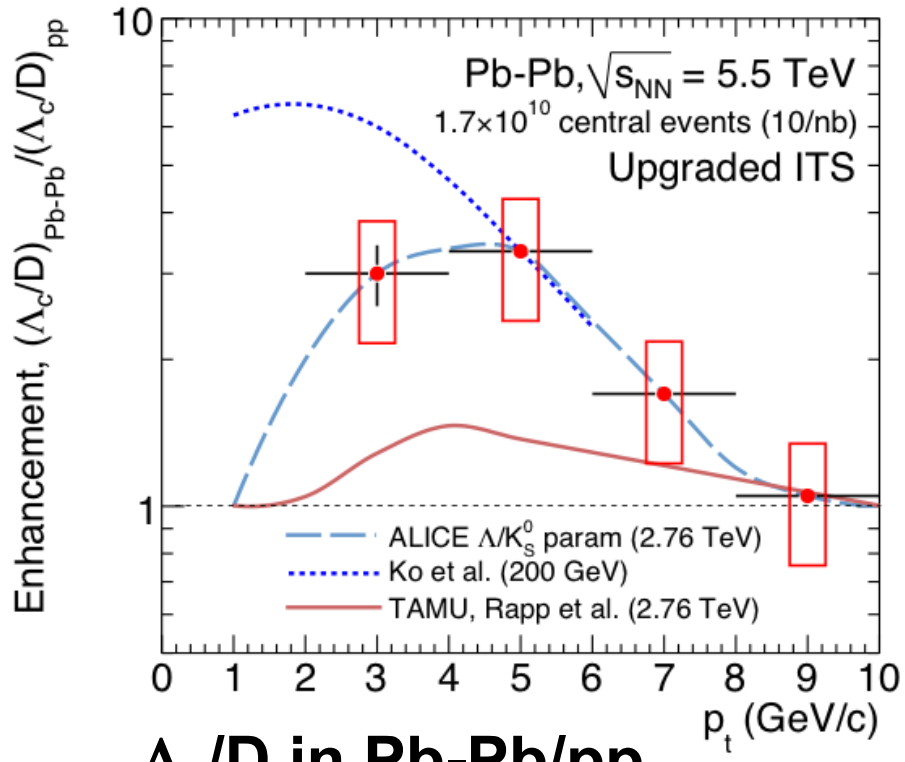
D meson v_2

J. Bielcik, Moriond2013

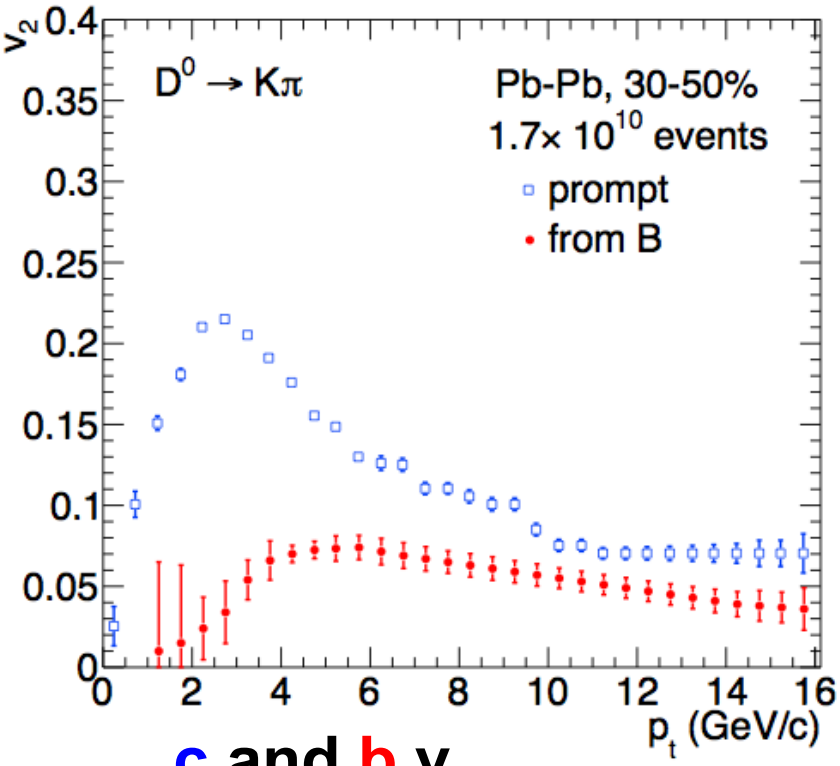


ALICE: new Inner Tracking System

Projections LHC Run3 (10/nb)



Λ_c/D in Pb-Pb/pp



c and b v_2

CERN-LHCC-2012-013

Conclusions

- From the experimental point of view, we have just entered the “golden age” for heavy-flavour observables in HI collisions
  - Thanks to the LHC detectors and RHIC upgrades

Whom and What (in AA, as of today)

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

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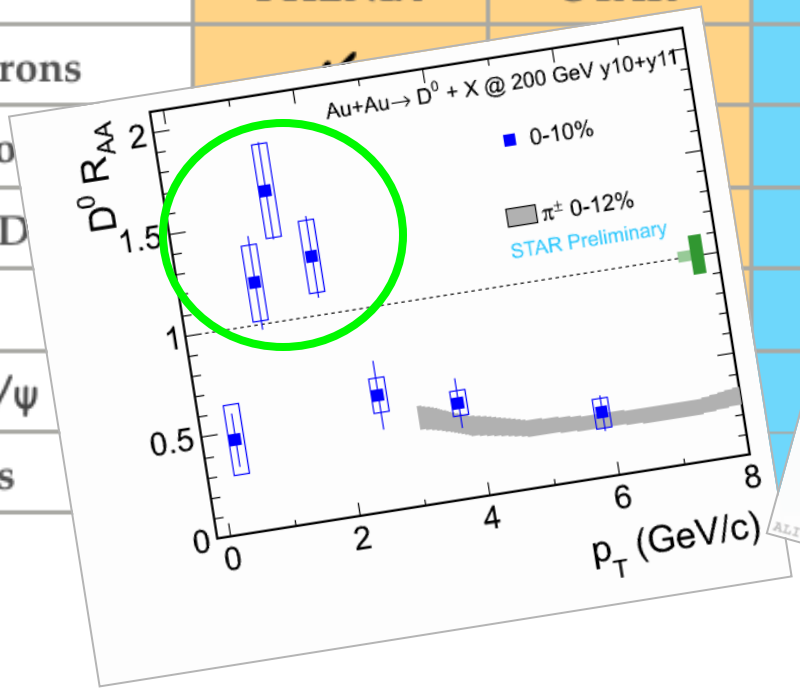
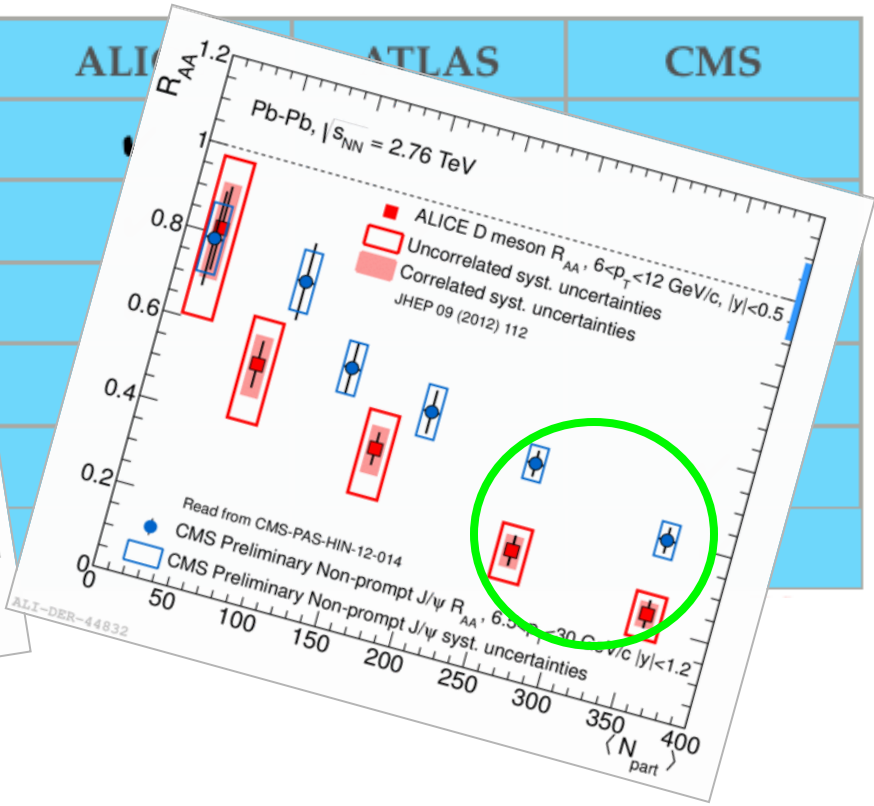
Whom and What (in AA, as of today)

	PHENIX	STAR	ALI	ATLAS	CMS
HF electrons	✓		●		
HF muo					
D^0, D^+, D					
D_s^+					
$B \rightarrow J/\psi$					
B jets					





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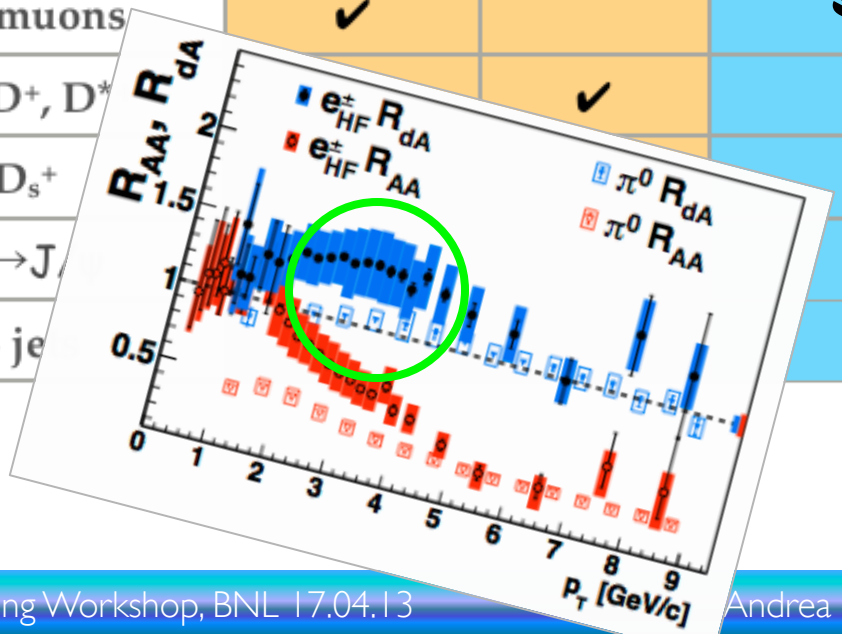
  - Thanks to the LHC detectors and RHIC upgrades

Whom and What (in dA, as of today)

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



Eagerly waiting for LHC results!

EXTRA SLIDES

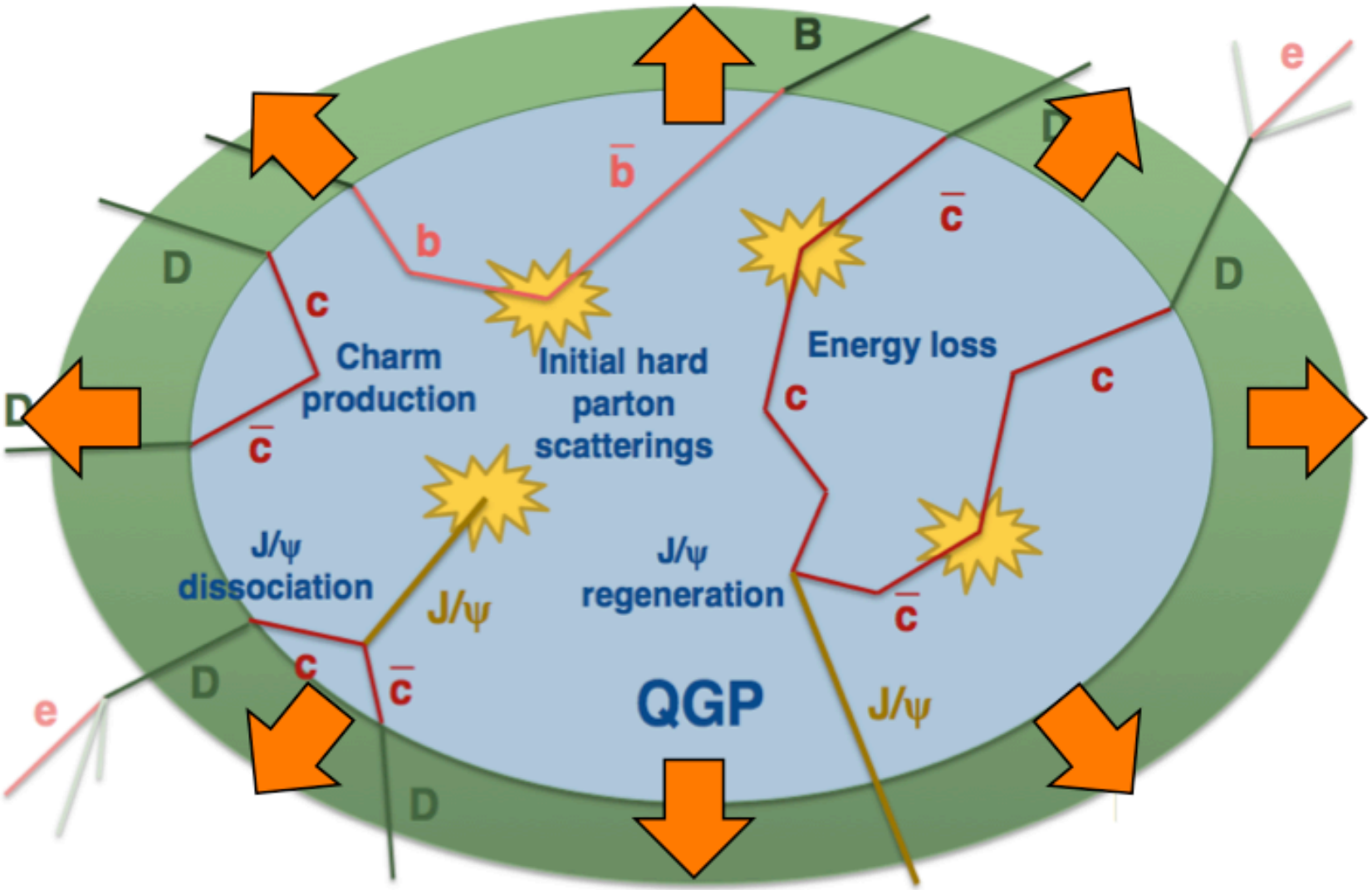
What's special about heavy quarks: probes through the full system history

- 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 << $\tau_{QGP} \sim 5$-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

  → "Brownian motion markers of the medium" (*)

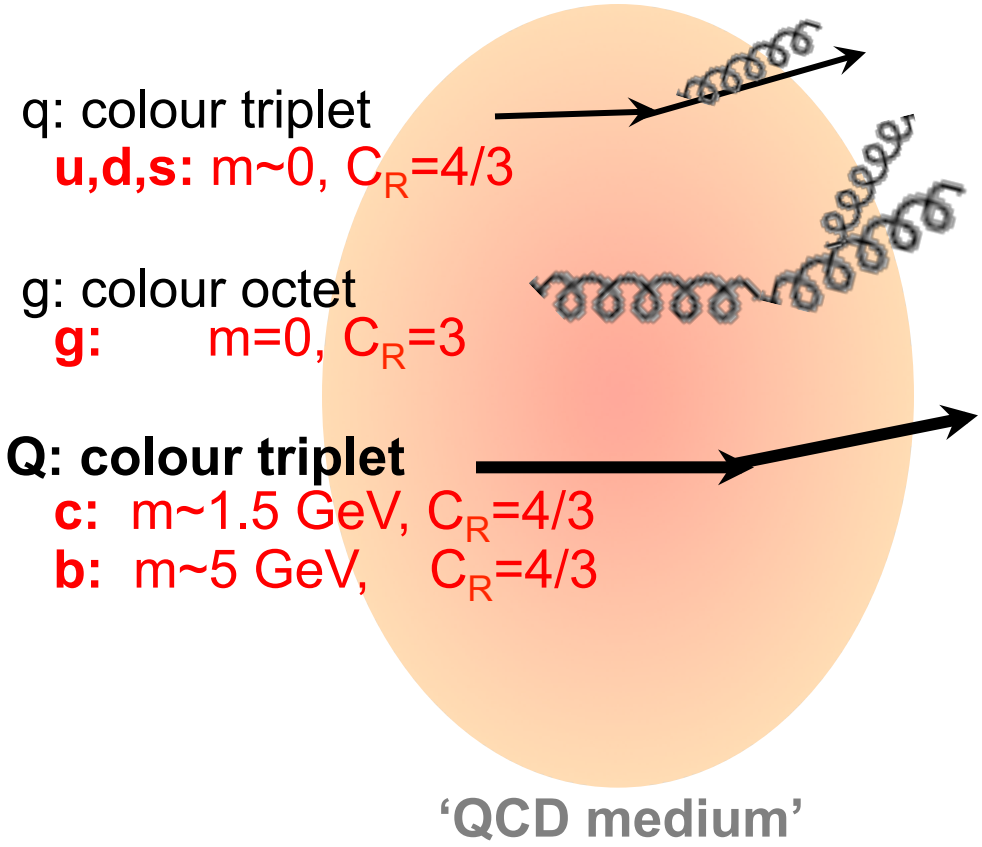
(*) Ralf Rapp

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



graphics courtesy J. Uphoff

What's special about heavy quarks: probing the properties of QCD E-loss



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 dep. (dead cone, …)

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

pred: $$R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}$$

Much more on this in the talk of A. Buzzatti

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.

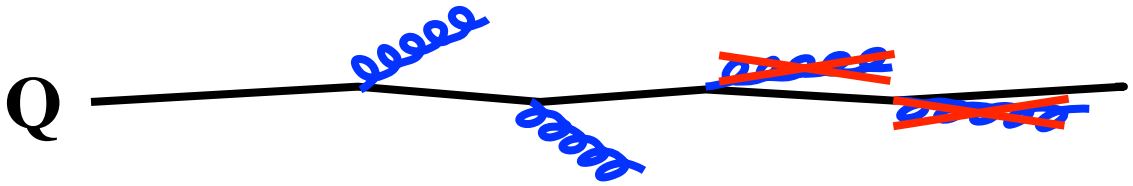
HF in heavy ion collisions: Who and What

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

Less gluon radiation for heavy quarks ?

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

  → "dead cone" effect

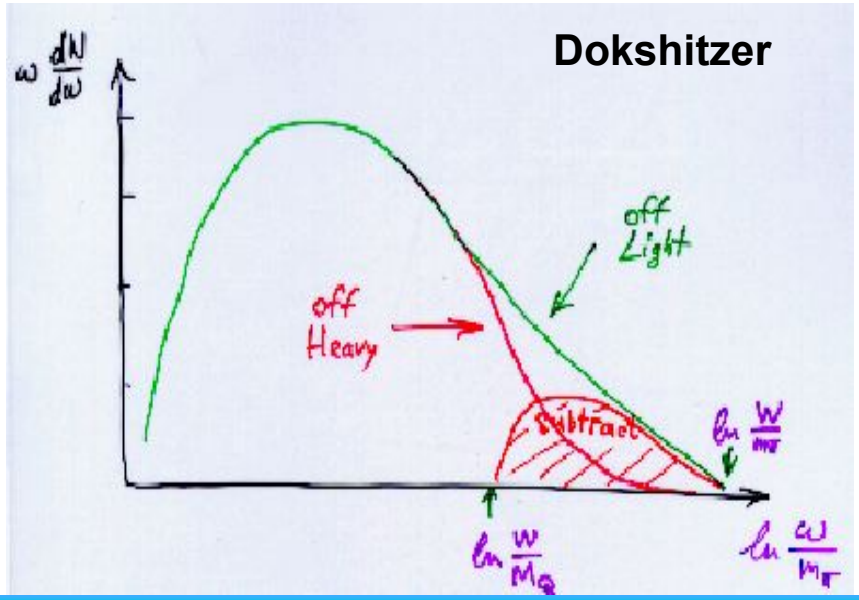


Gluonsstrahlung probability

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

- *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

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



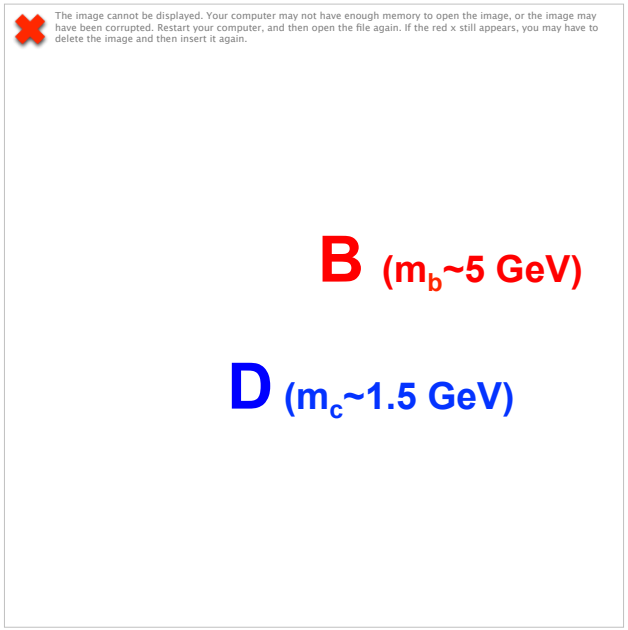
Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602.
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

HQs E loss: some expectations …

- Energy loss based predictions: factor 3-5 suppression for D mesons
- Significantly smaller suppression for B

$$R_{AA}^{D}(p_T) \text{ and } R_{AA}^{B}(p_T)$$

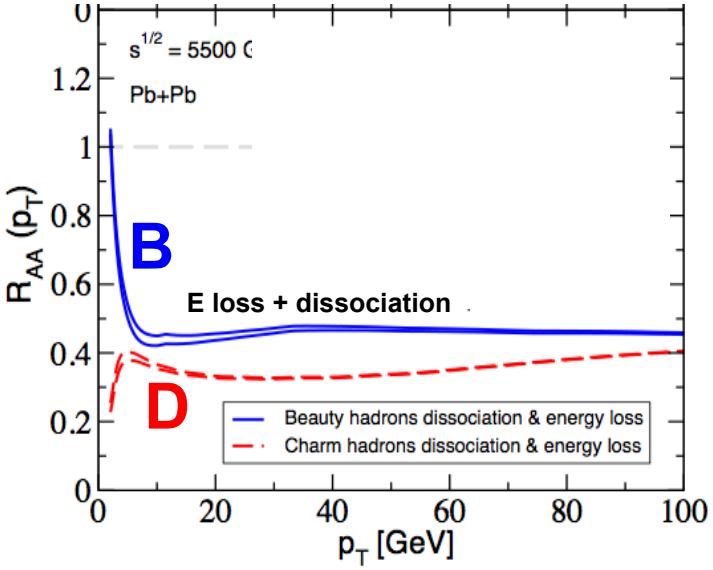
Radiative E loss



B (m_b~5 GeV)

D (m_c~1.5 GeV)

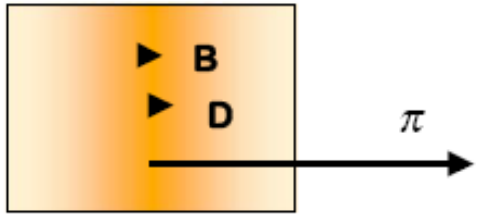
Radiative E loss + dissociation



- Shorter formation time of heavy hadrons → additional R_{AA} suppression due to in-medium dissociation?

$$\tau_{form}(p_T = 10\ GeV)$$

π	D	B
25 fm	1.6 fm	0.4 fm

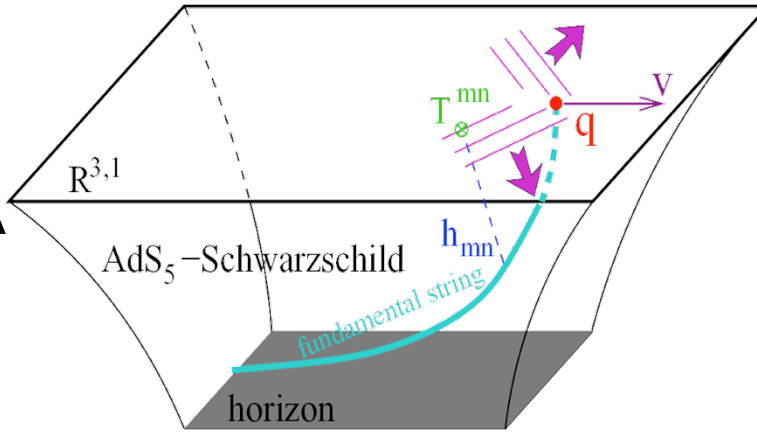


Wicks, Gyulassy, "Last Call for LHC Predictions" workshop, 2007

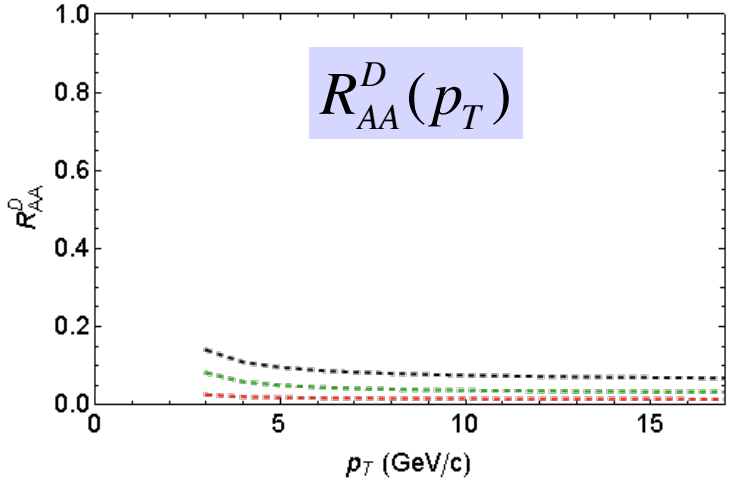
Vitev, et al, PRC80 (2009)

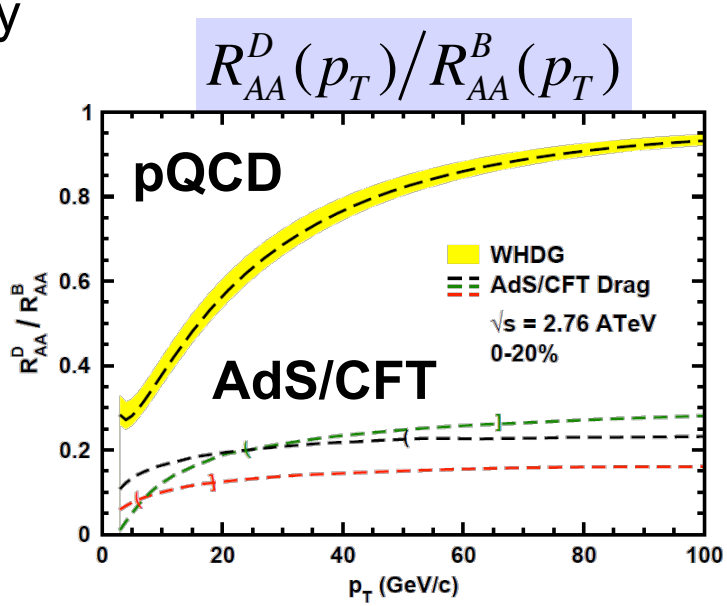
HQs E loss: the AdS/CFT way…?

- Maldacena conjecture: correspondence between super-gravity (Super Yang Mills) and QCD
- → calculate strongly-coupled QCD in SUGRA
- Model energy loss by embedding a string in AdS space
- One distinctive prediction:
  - Very strong suppression for charm
  - Small suppression for beauty up to very large p_T



Friess, Phys Rev D75 (2007)



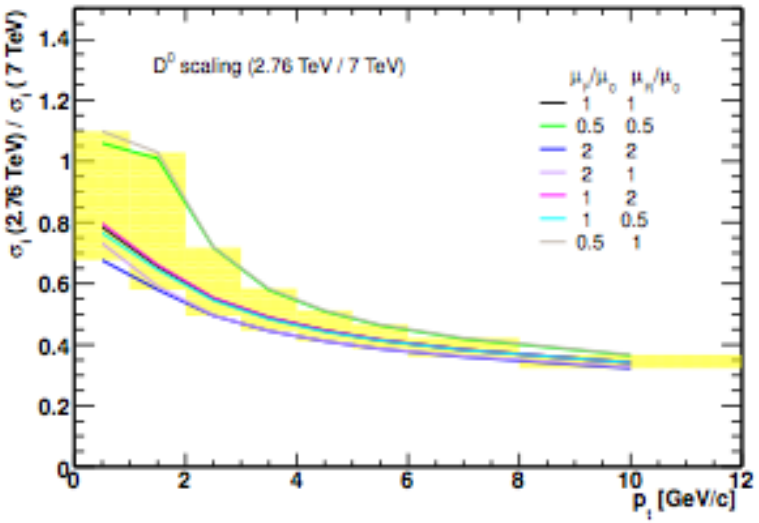


Horowitz, Gyulassy, PLB666 (2008), Horowitz, arXiv:1108.5876

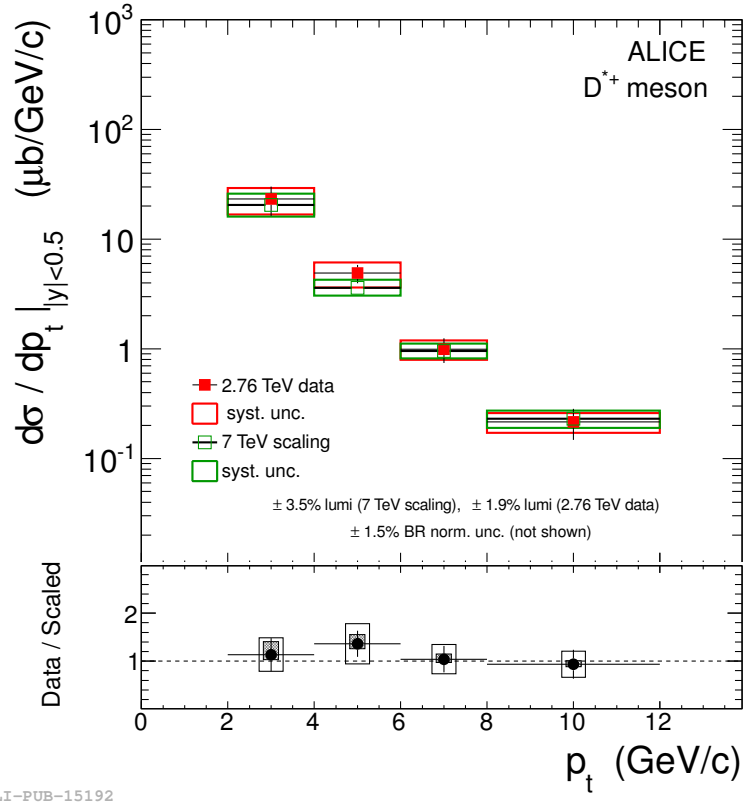
pp reference at 2.76 TeV via $\sqrt{s}$-scaling (ALICE D mesons and electrons)

- 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



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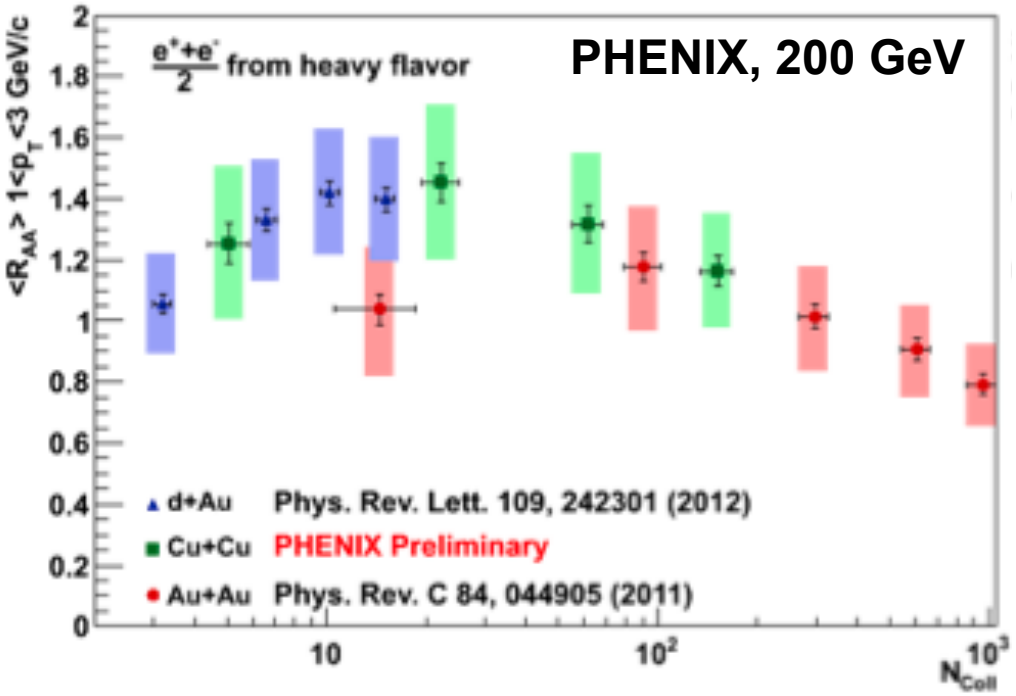
HF e in d-Au: RHIC results



- Consistent N_{coll}-dependence in d-Au, Cu-Cu, Au-Au
- Move from initial-state effects in d-Au/peripheral Cu-Cu to where the hot medium takes over as system size increases in Cu-Cu and Au-Au

N.Apadula (WWND2013)