5 Things You Should Know About Heavy Flavor Measurements

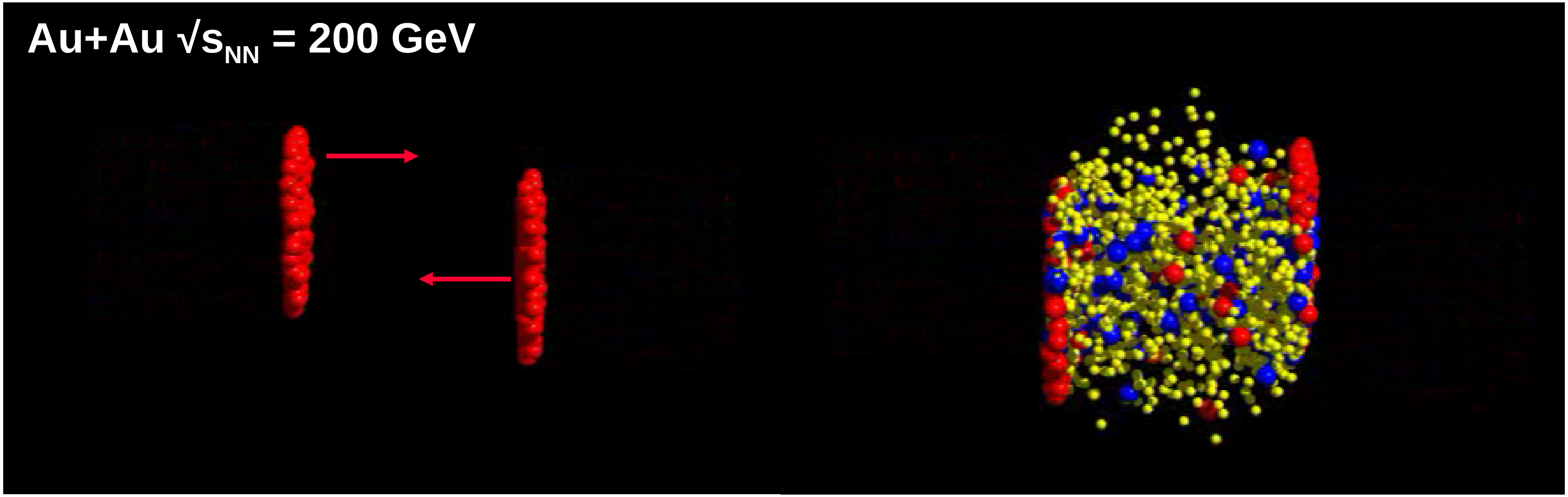
Daniel Kikoła

INNOVATIVE ECONOMY
NATIONAL COHESION STRATEGY

FNP
Foundation for Polish Science

EUROPEAN UNION
EUROPEAN REGIONAL
DEVELOPMENT FUND

Relativistic Heavy Ion Collisions



UrQMD Frankfurt

- **c, b → produced early**

$M(c\bar{c}) \sim 3$ GeV

$M(b\bar{b}) \sim 9$ GeV

1. Open heavy flavor vs quarkonia

→ different tools

Quarkonia

→ color-neutral object in the Quark-Gluon Plasma

(complication: produced via intermediate color-octet state?)

Open heavy flavor

→ heavy quark in QGP → color charge

Matsui & Satz (1986):

Quark-Gluon Plasma

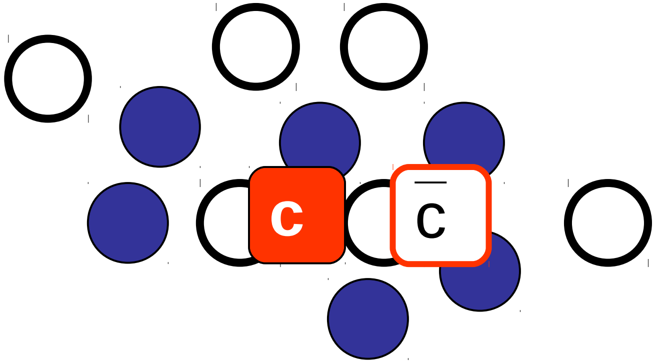
= J/ψ production suppression

c $\bar{c}$

Matsui & Satz (1986):

Quark-Gluon Plasma

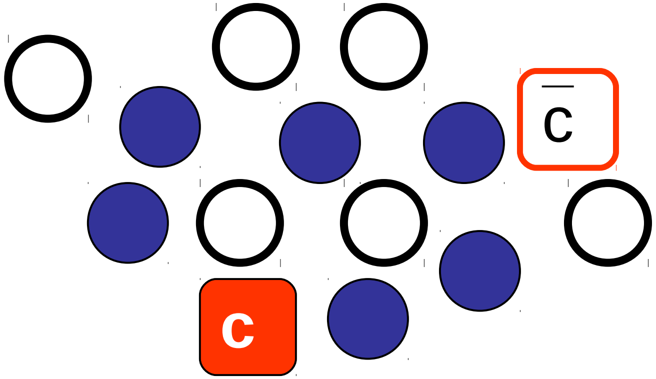
= J/ψ production suppression



Matsui & Satz (1986):

Quark-Gluon Plasma

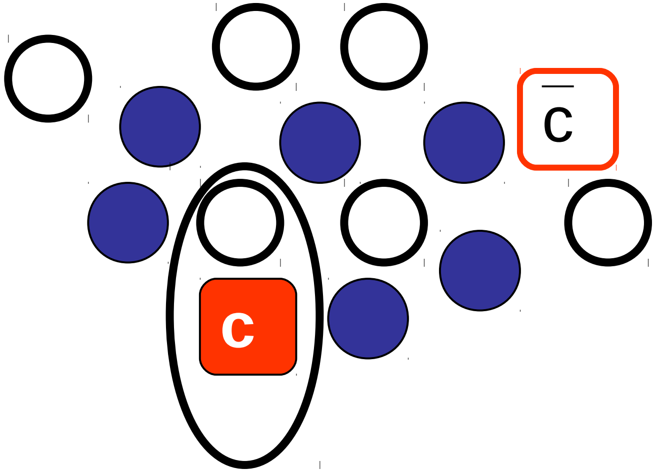
= J/ψ production suppression



Matsui & Satz (1986):

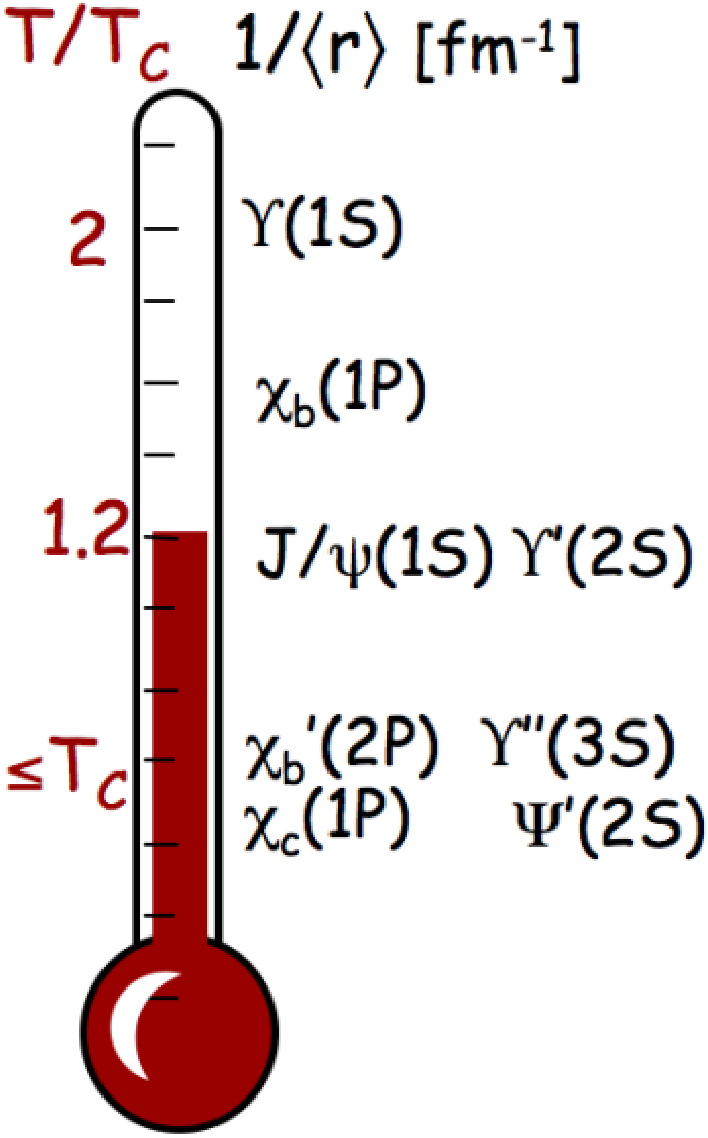
Quark-Gluon Plasma

= J/ψ production suppression



Sequential melting

→ Temperature of QGP



EPJC 61; 705-710, 209

Open heavy flavor

energy loss → transport properties

$$\frac{-dE}{dx} \simeq \alpha_s \left\langle q^2(L) \right\rangle = \alpha_s \, \hat{q} \, L$$

Ann.Rev.Nucl.Part.Sci.
50 (2000) 37-69

q-hat → mean momentum transfer^2 per collision

Open heavy flavor

energy loss → transport properties

elliptic flow → medium thermalization

Quarkonia

→ color-neutral object in the Quark-Gluon Plasma

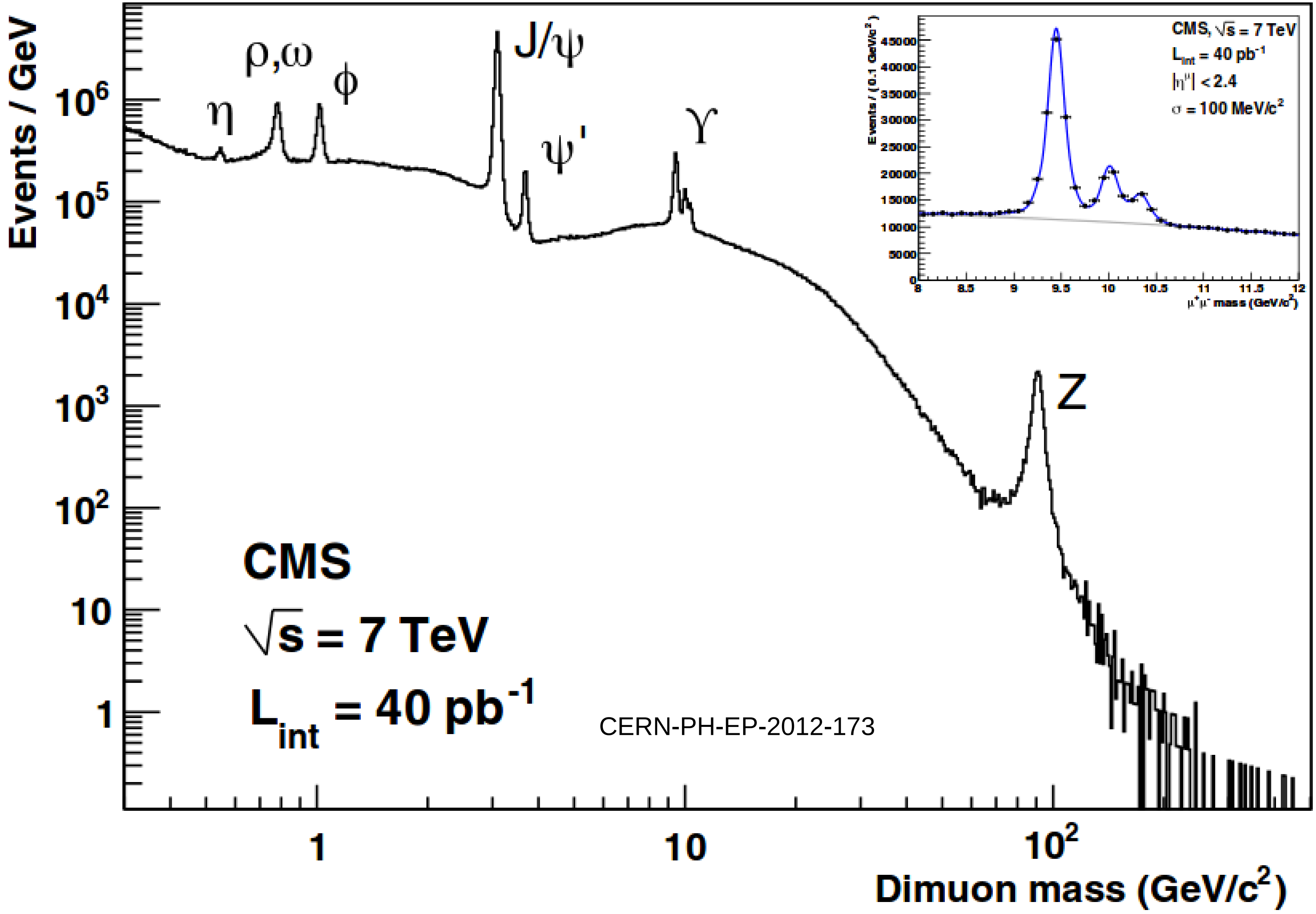
→ thermodynamics properties
(in color screening scenario)

Open heavy flavor

→ heavy quark in QGP → color charge
→ transport properties, thermalization

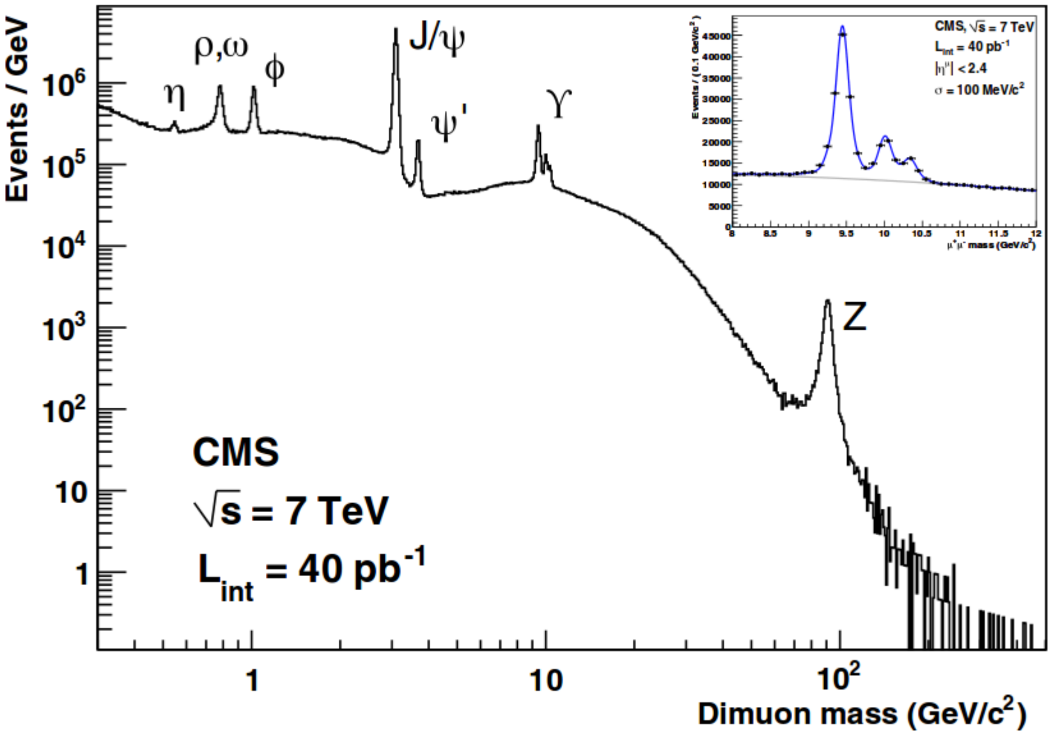
2. We cannot measure heavy quark production

Quarkonium



CERN-PH-EP-2012-173

Quarkonium



Issues:

- rates
- feed-down:

$\chi_{b1} \rightarrow \Upsilon(1S) + \gamma$ (25%) , $\chi_{b2} \rightarrow \Upsilon(1S) + \gamma$ (10%)

$\Upsilon(2s) \rightarrow \Upsilon(1s) + \pi\pi$ (10%)

$\chi_c \longrightarrow J/\psi + \gamma$ (~10%)

Issues:

→ ~0.5 GeV γ reconstruction

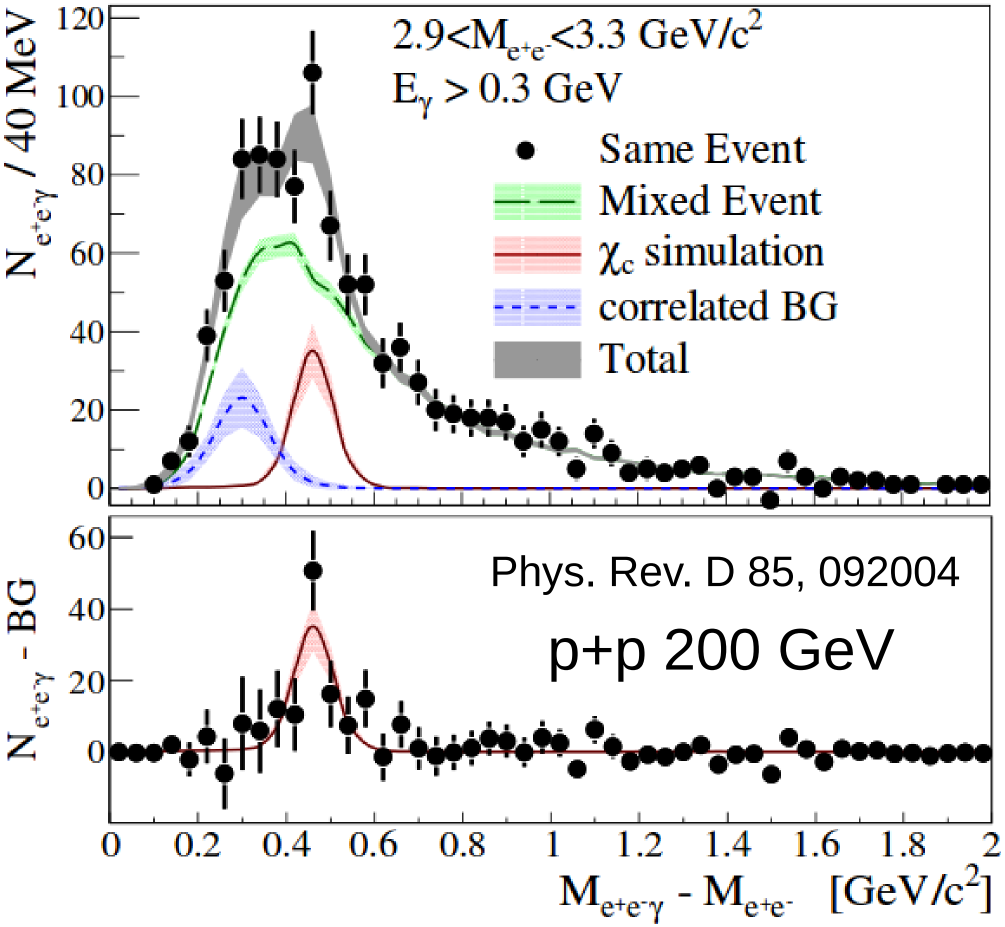
$M(\chi_{b1,2}) = 9.9$ GeV/c^2,

$M(\Upsilon(1S)) = 9.5$ GeV/c^2

$M(\chi_c) = 3.6$ GeV/c^2,

$m(J/\psi) = 3.1$ GeV/c^2

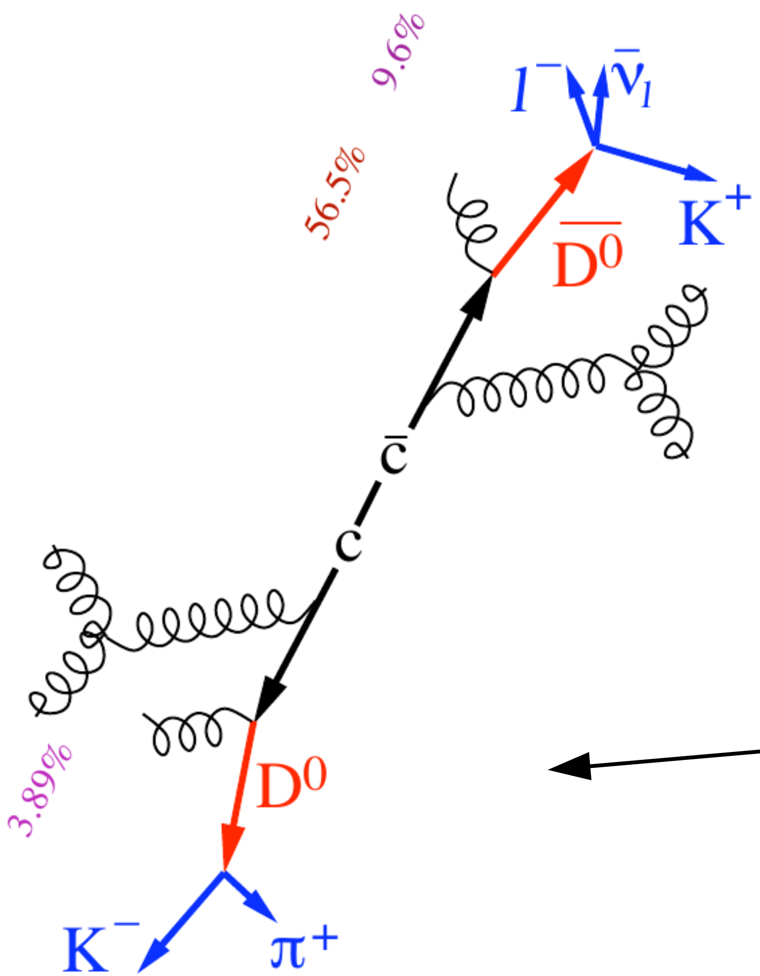
→ background in $\Upsilon(2s) \rightarrow \Upsilon(1s) + \pi\pi$



Phys. Rev. D 85, 092004

p+p 200 GeV

Open heavy flavor

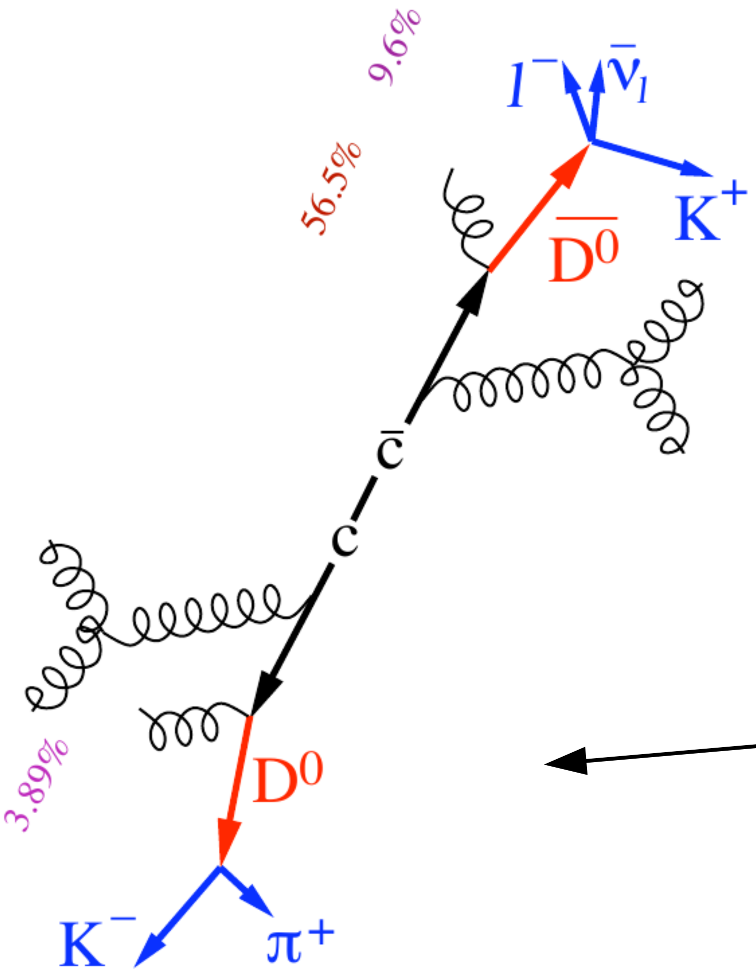


leptons from semi-leptonic heavy flavor hadron decays

Direct open charm or bottom reconstruction

Courtesy of David Tlusty

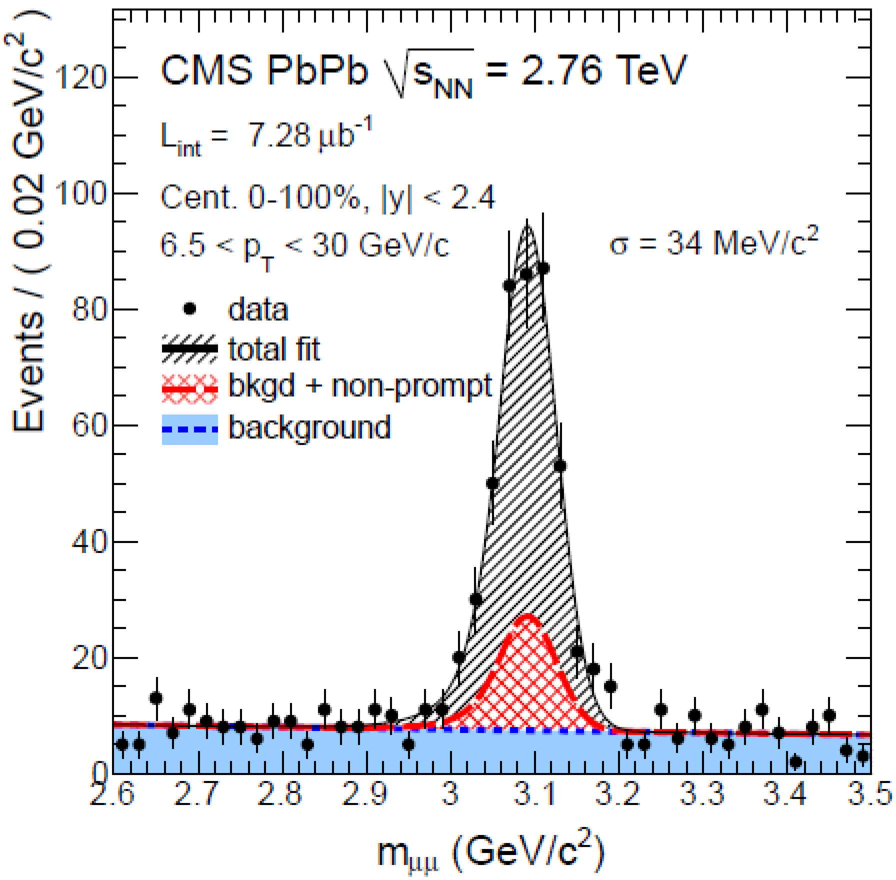
Open heavy flavor

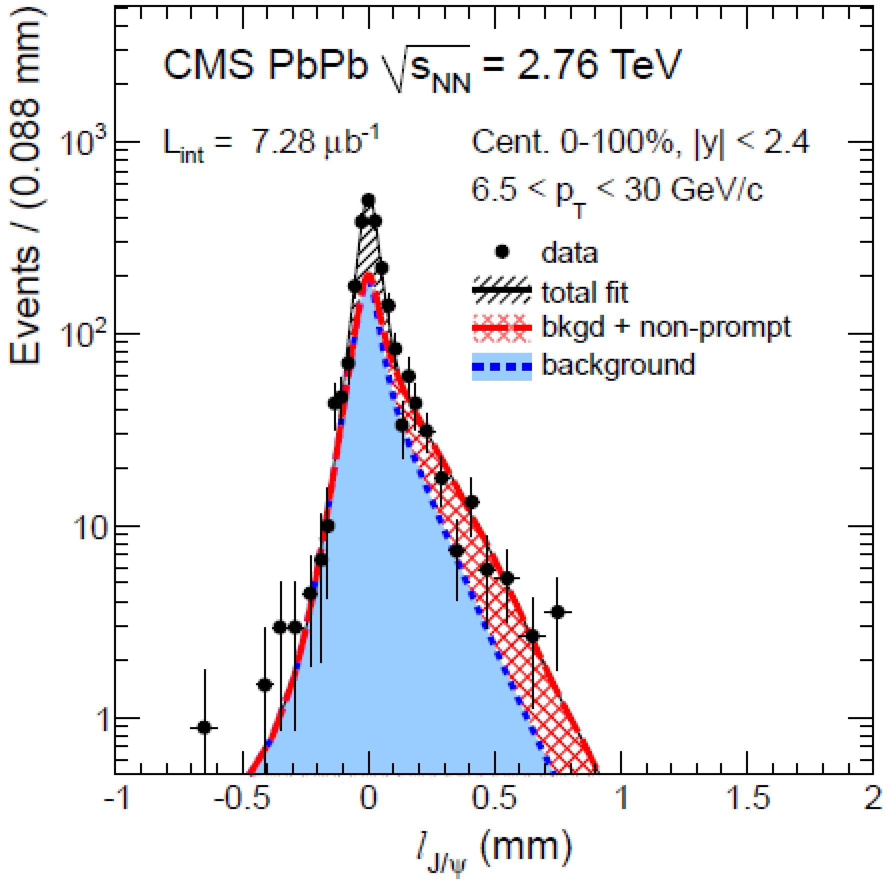


- indirect access to parent kinematics
- c/b mixture (difficult to separate)

- hard to trigger

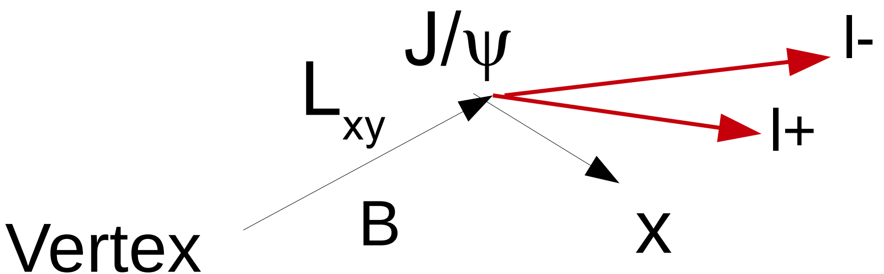
Courtesy of David Tlusty





$$l_{J/\psi} = L_{xy}\, m_{J/\psi}/p_T$$

B → J/ψ = non-prompt J/ψ



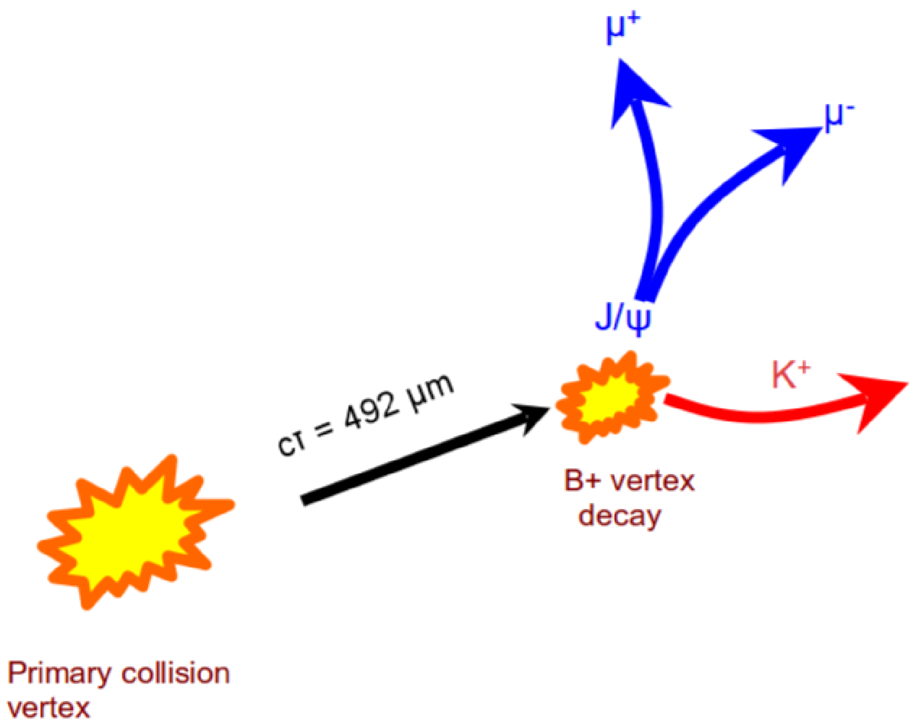
pseudo-proper decay length

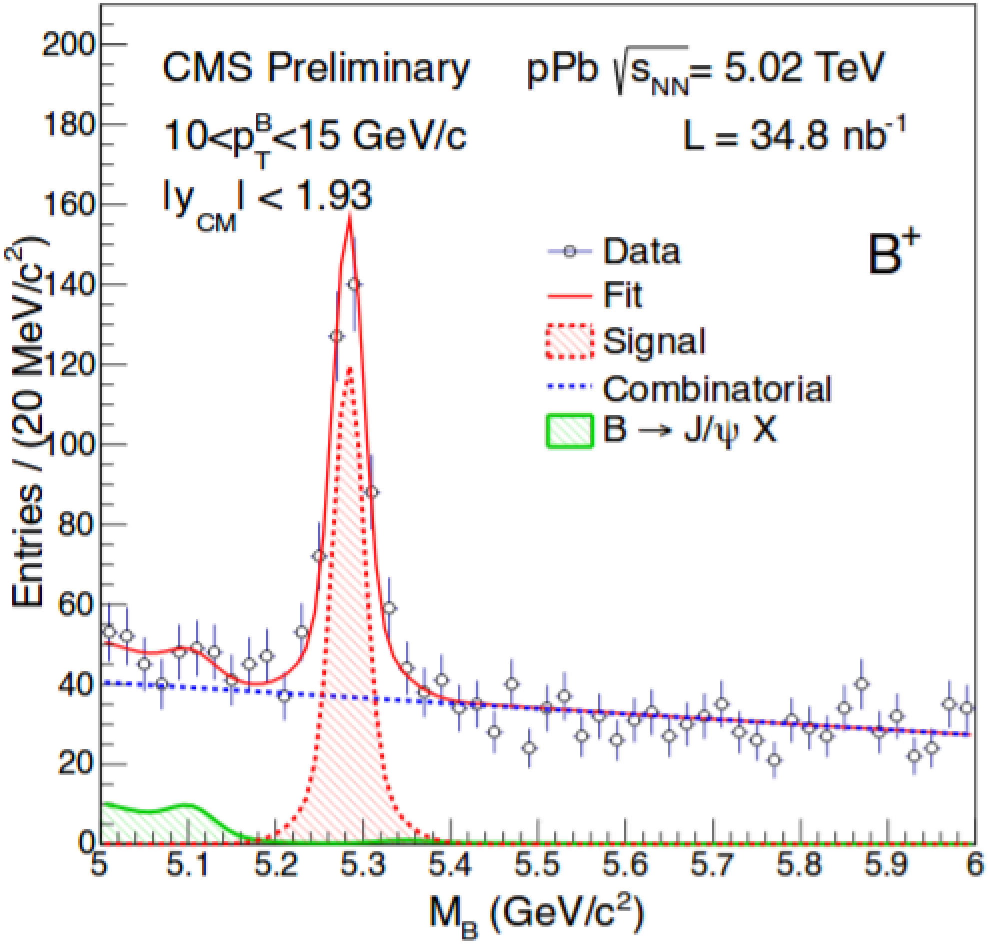
Incomplete kinematics information

$B^+ \rightarrow J/\psi\, K^+ \rightarrow \mu^+\mu^-\, K^+$,

$B^0 \rightarrow J/\psi\, K^{0*} \rightarrow \mu^+\mu^-\, K^+\pi^-$

$B_s \rightarrow J/\psi\, \phi \rightarrow \mu^+\mu^-\, K^+K^-$

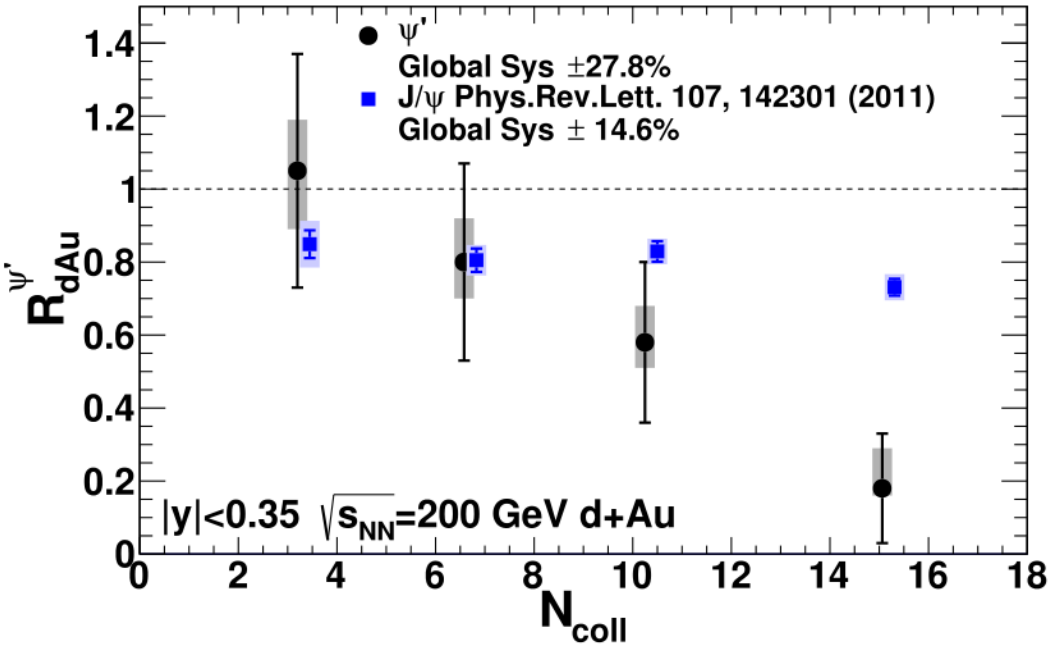




G. Michele, QM 2014

3. Understanding of reference (p+A) is crucial

Phys. Rev. Lett. 111, 202301 (2013)



Cold nuclear matter effects

nuclear PDF ≠ free proton PDF

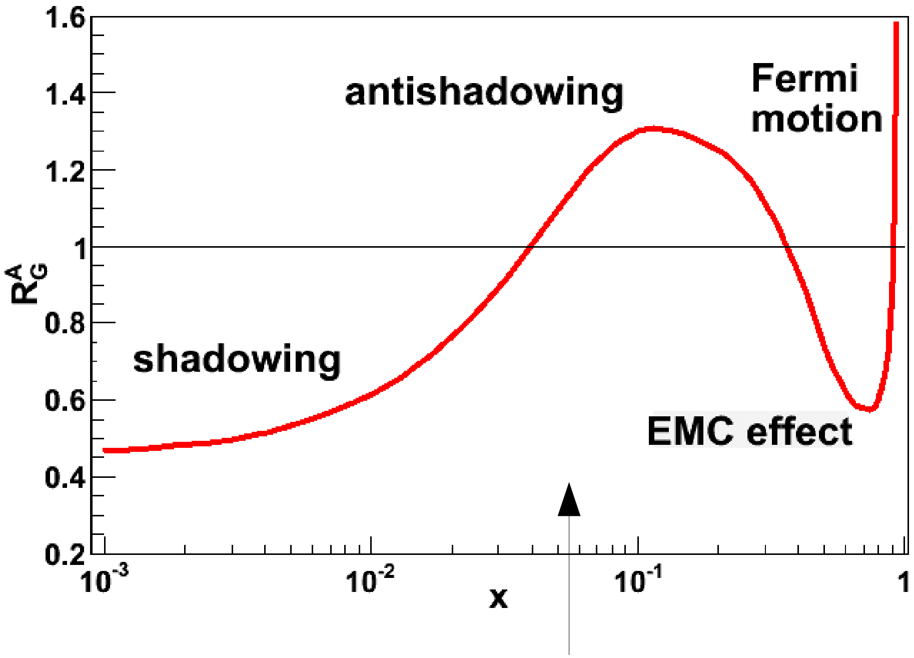
2 → 2 process (gg → $Q\bar{Q}$):

$$x_{1,2} = \frac{\sqrt{M^2 + p_T^2}}{\sqrt{s_{NN}}} e^{\pm y}$$

↓

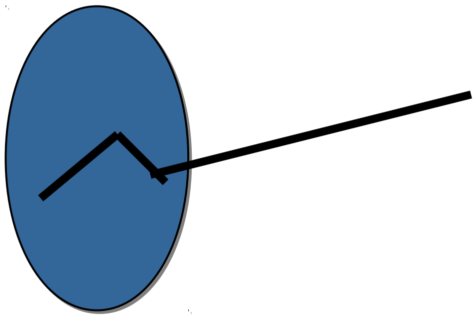
$x_{1,2}$ depend on:

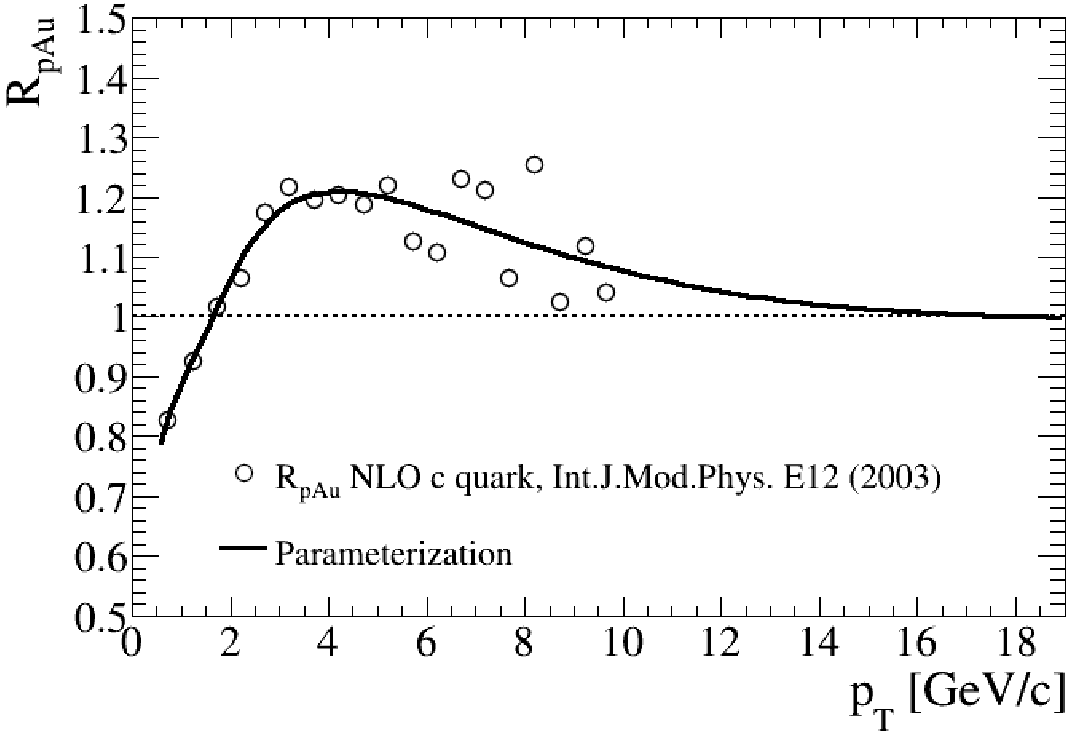
- mass and p_T
- rapidity
- beam energy
- production process



Depends on Q^2

“Cronin effect”

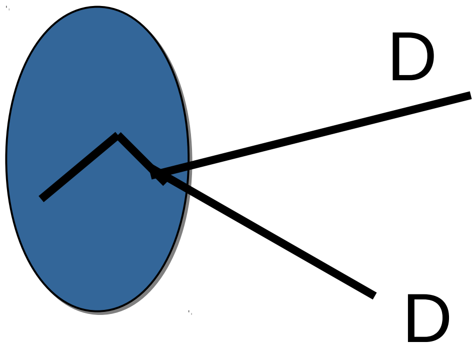




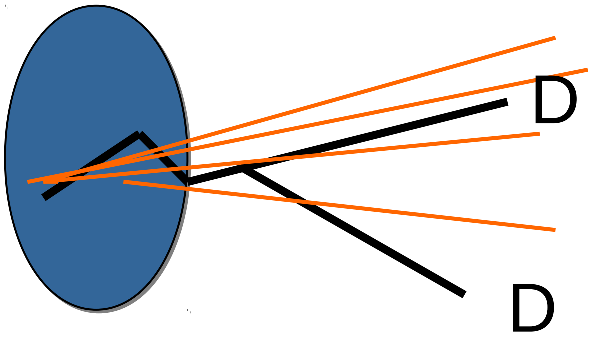
Multiple collisions with partons/nucleons

→ random kicks → larger $\langle k_T \rangle$ than in p+p

Quarkonia: final state “absorption”



nuclear absorption

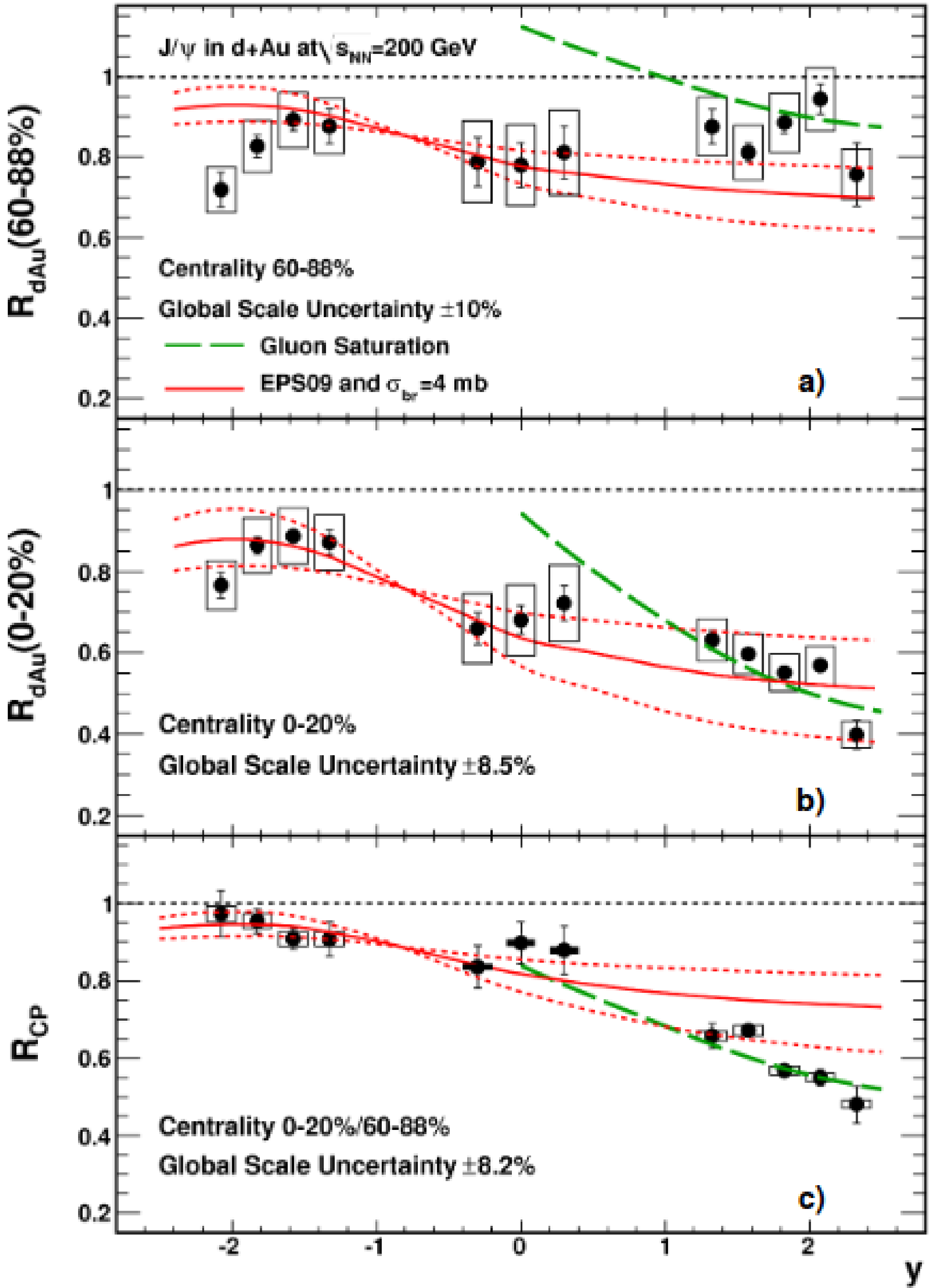


“co-mover” absorption

Typical approach: nuclear PDF + effective absorption σ_{abs}

Quarkonia: CNM effects

nuclear PDF + effective absorption σ_{abs} →

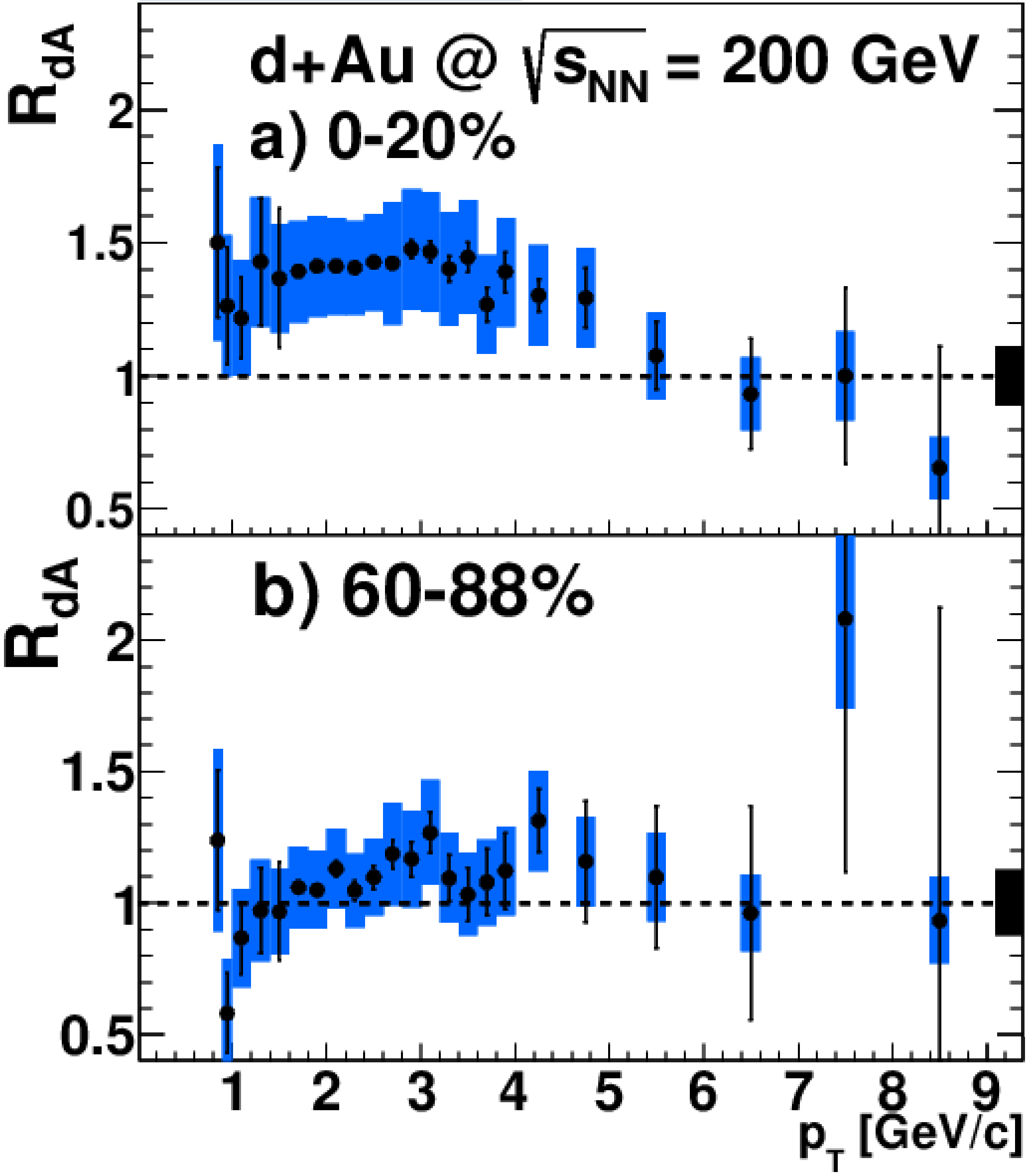


Issue:

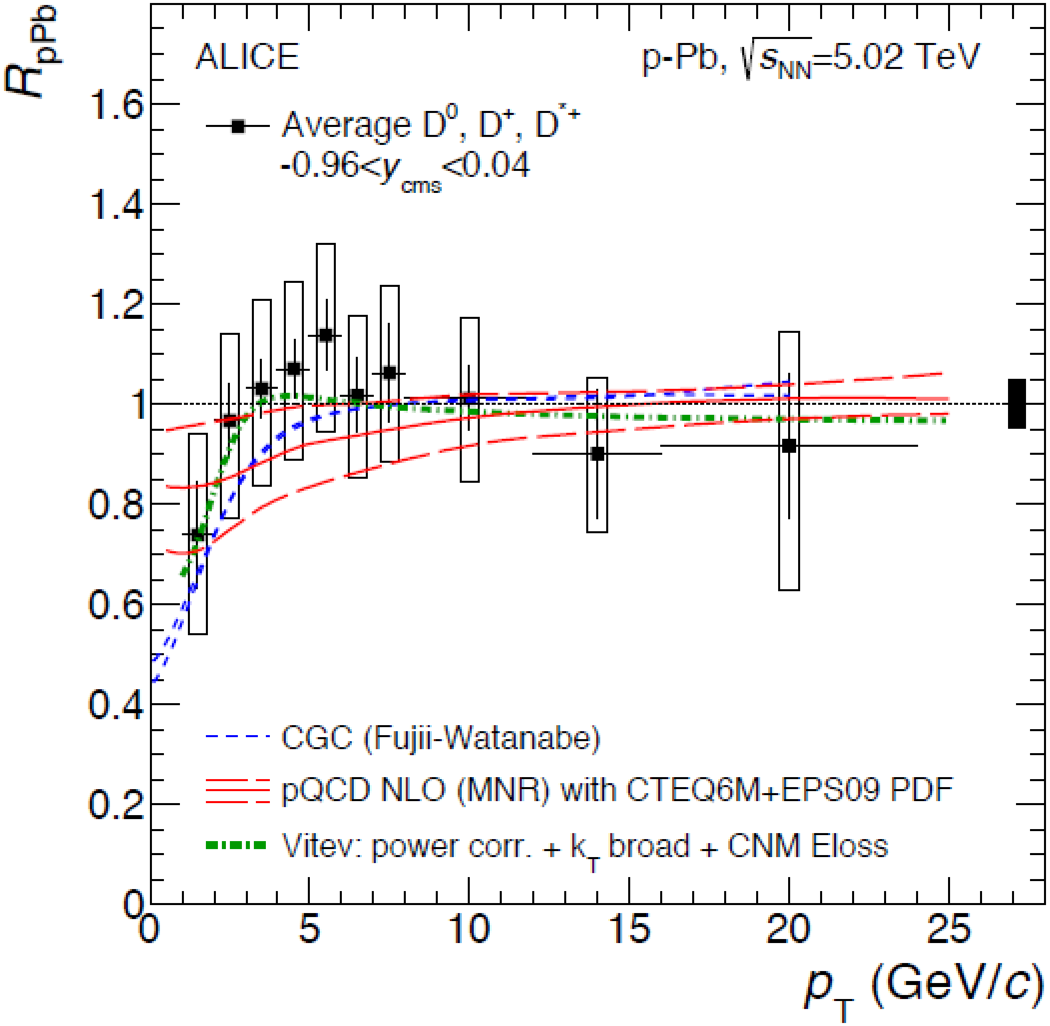
pA → AA not straightforward

Open HF - CNM effects

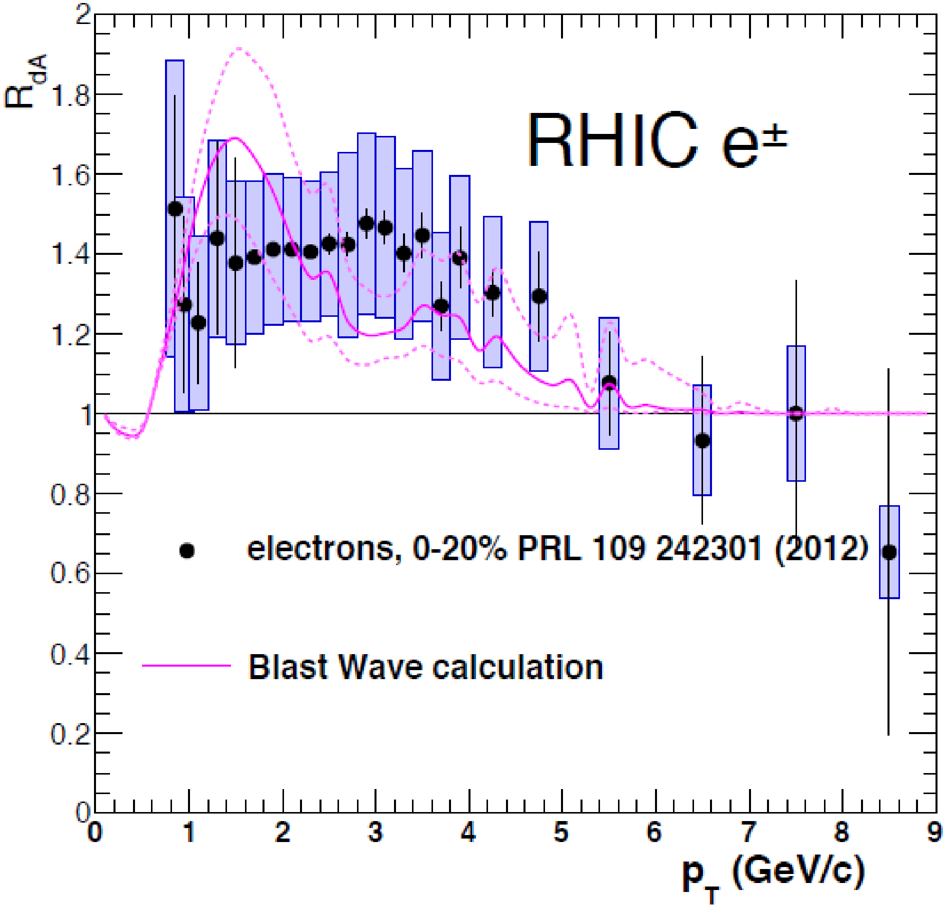
RHIC, e^{HF}

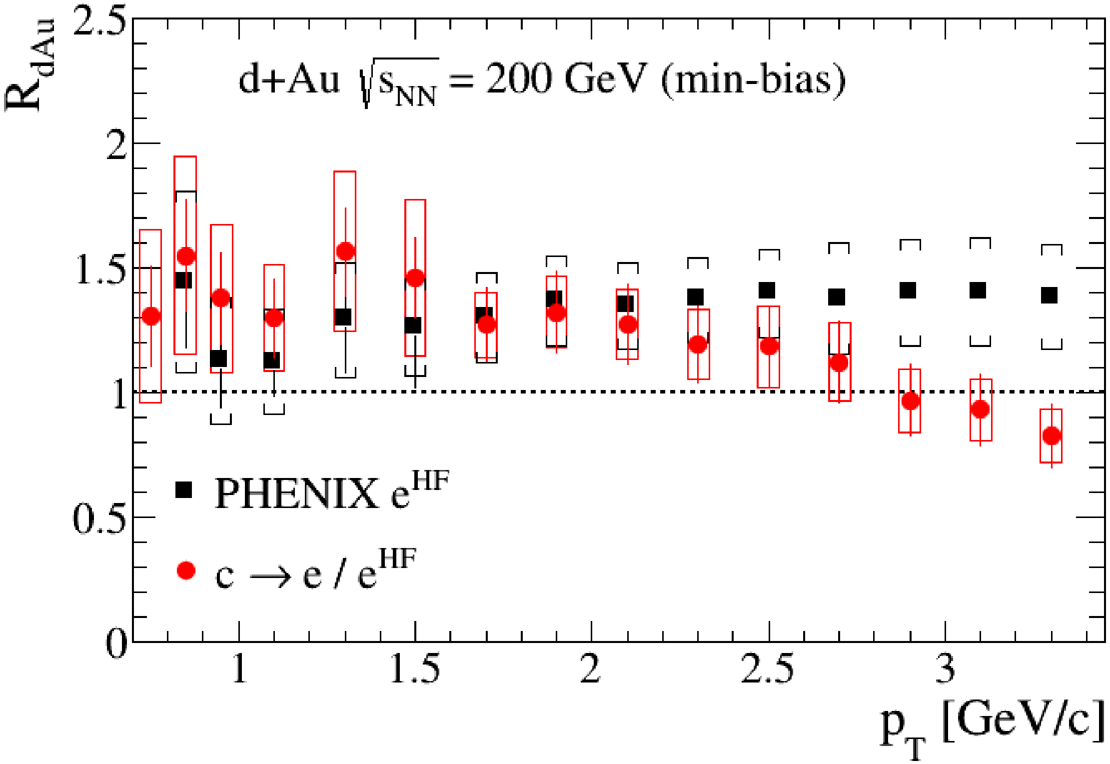


LHC, D



d+Au → reference or “mini QGP” ?



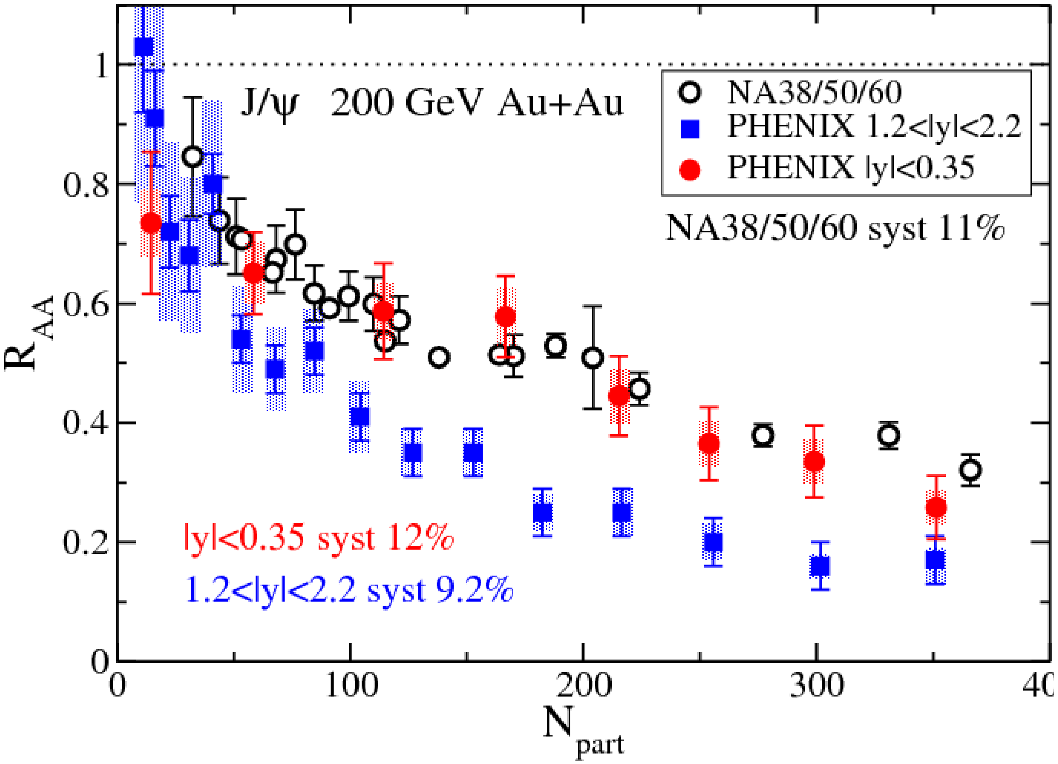


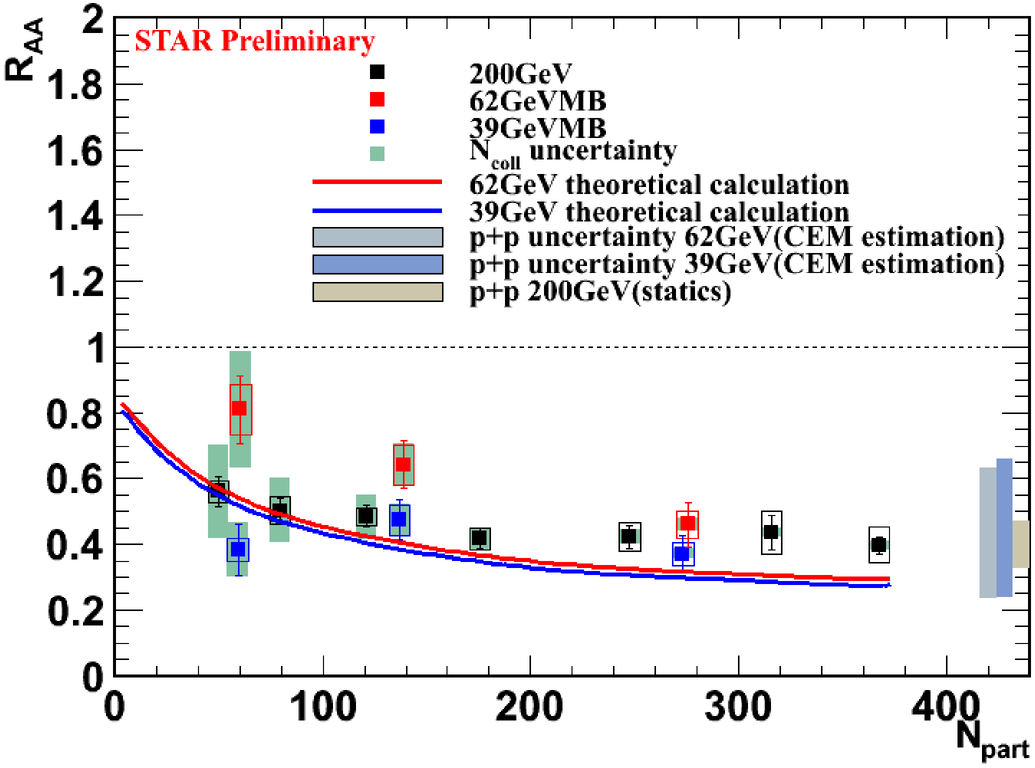
„Possible evidence for radial flow of heavy mesons in d+Au collisions”
Phys. Lett. B731 51-56 (2014)

nPDF + initial k_T breadboarding for charm quarks due to multiple scattering of incoming partons.
D.K. GDRE workshop, Nantes 2014

4. Color screening is a hypothesis (one of many)

J/ψ suppression at SPS and RHIC



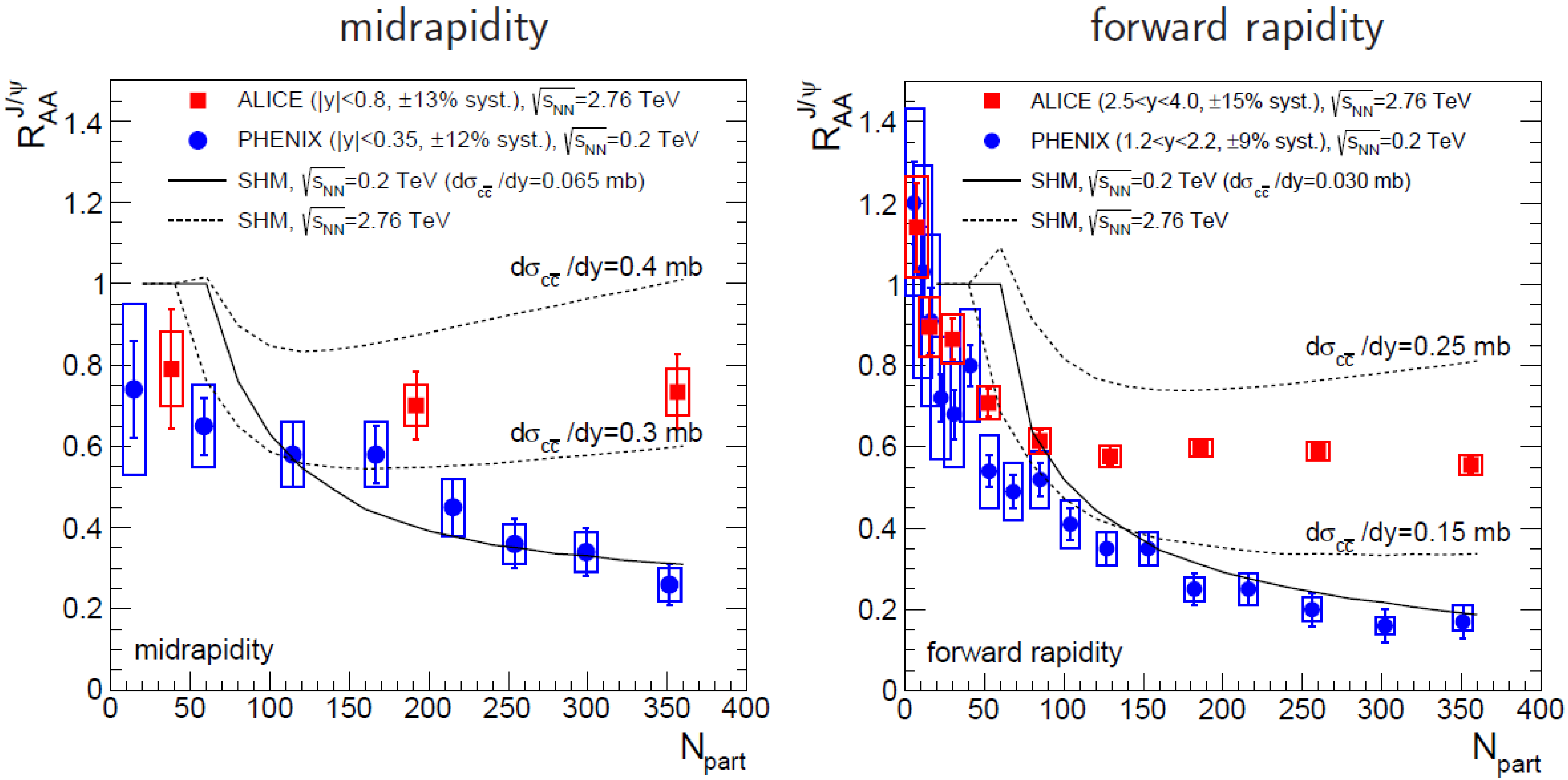


Significant suppression, similar at 39 – 200 GeV

→ Idea: color screening + secondary production in QGP

Model: Zhao, Rapp Phys Rev C.82.064905

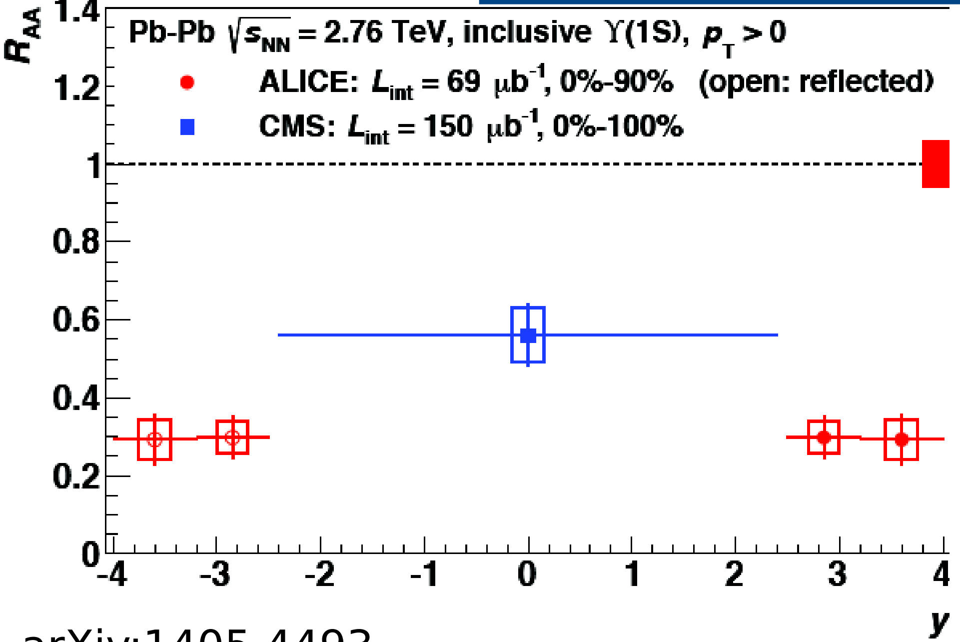
J/ψ suppression at SPS and LHC



SHM – statistical hadronization model

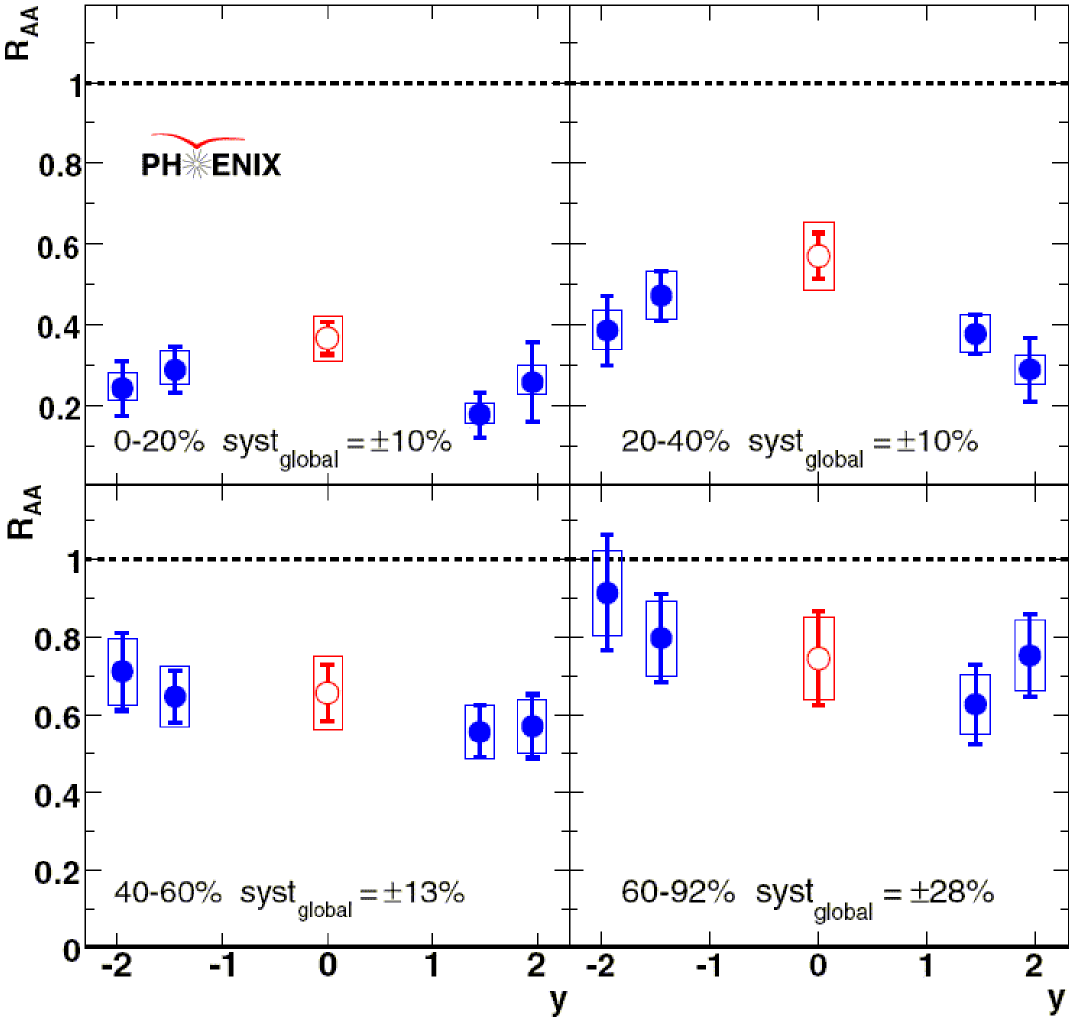
ϒ at LHC ≈ J/ψ at RHIC

ϒ(1s) at LHC



arXiv:1405.4493

J/ψ at RHIC



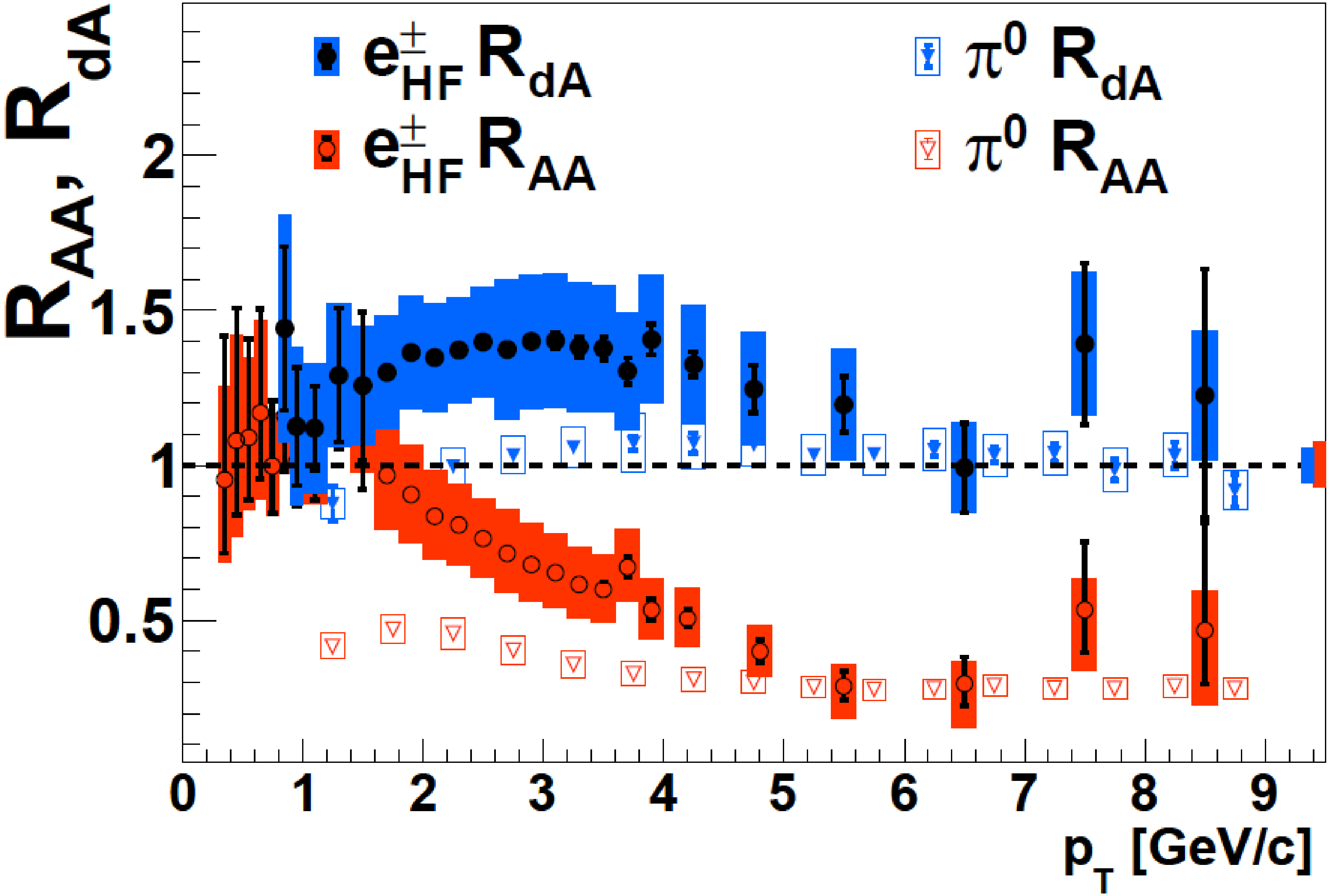
Phys.Rev.Lett.98:232301,2007

Statistical production ?
$b\bar{b}$ regeneration ?

5. Heavy Flavor production suppressed at LHC and top RHIC energy

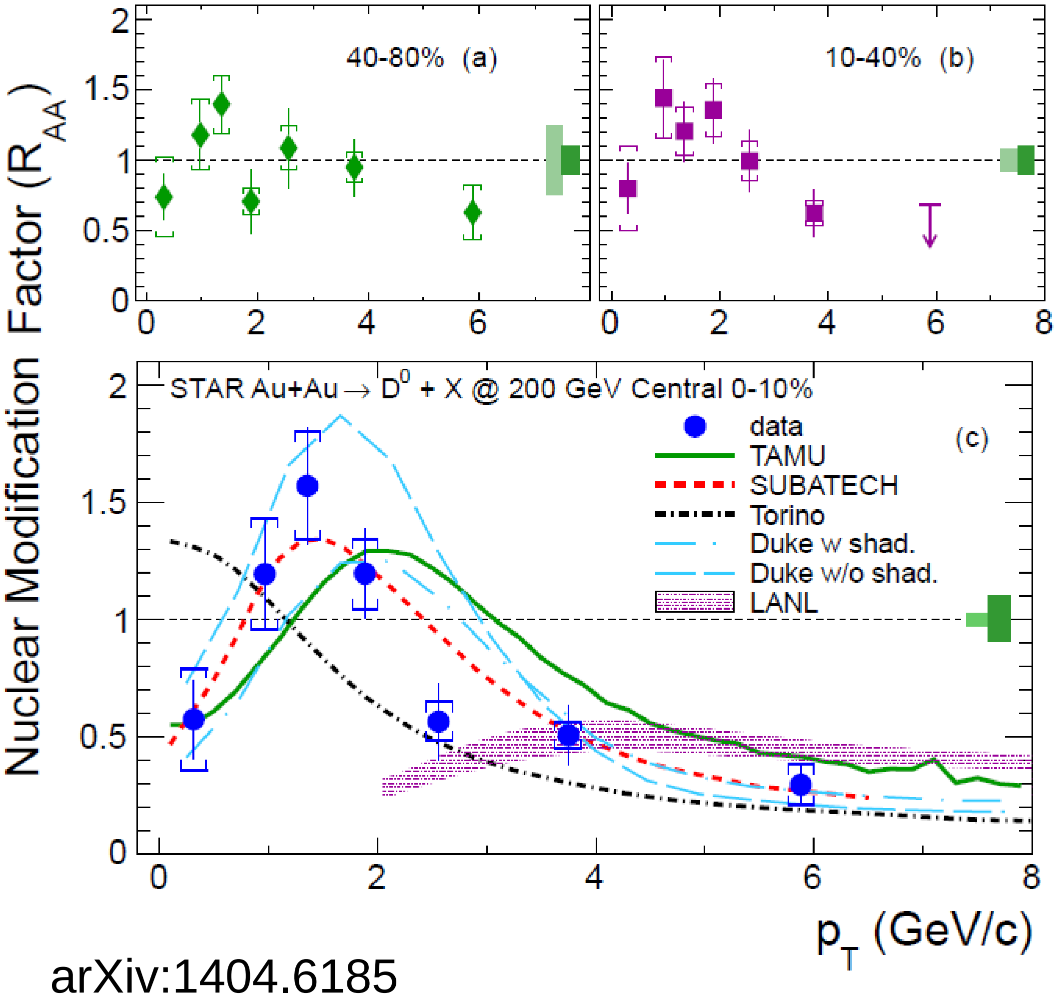
… but not at lower energies

e^{HF}: Cold vs Hot Nuclear matter at RHIC

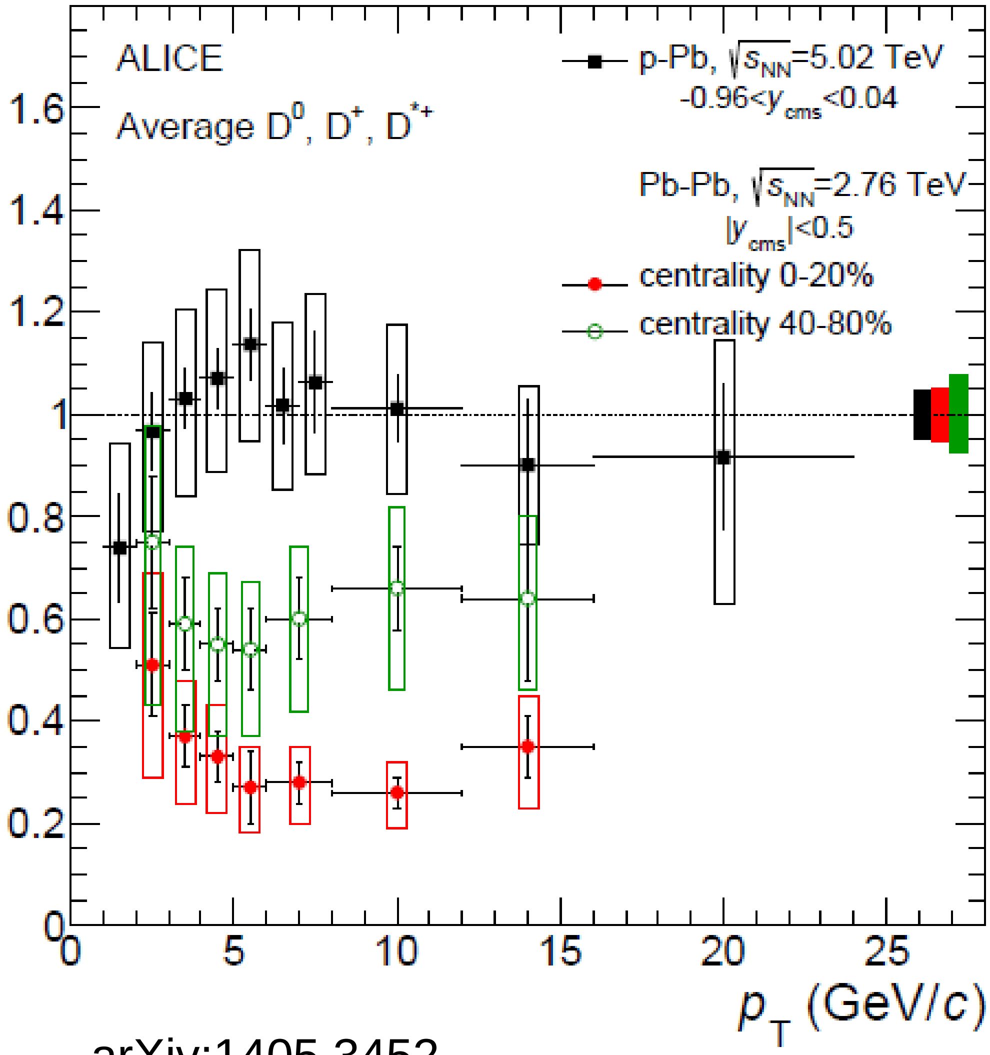


e^{HF} (b → e, c → e) suppressed at high p_T in Au+Au 200 GeV

charm suppression at RHIC and LHC



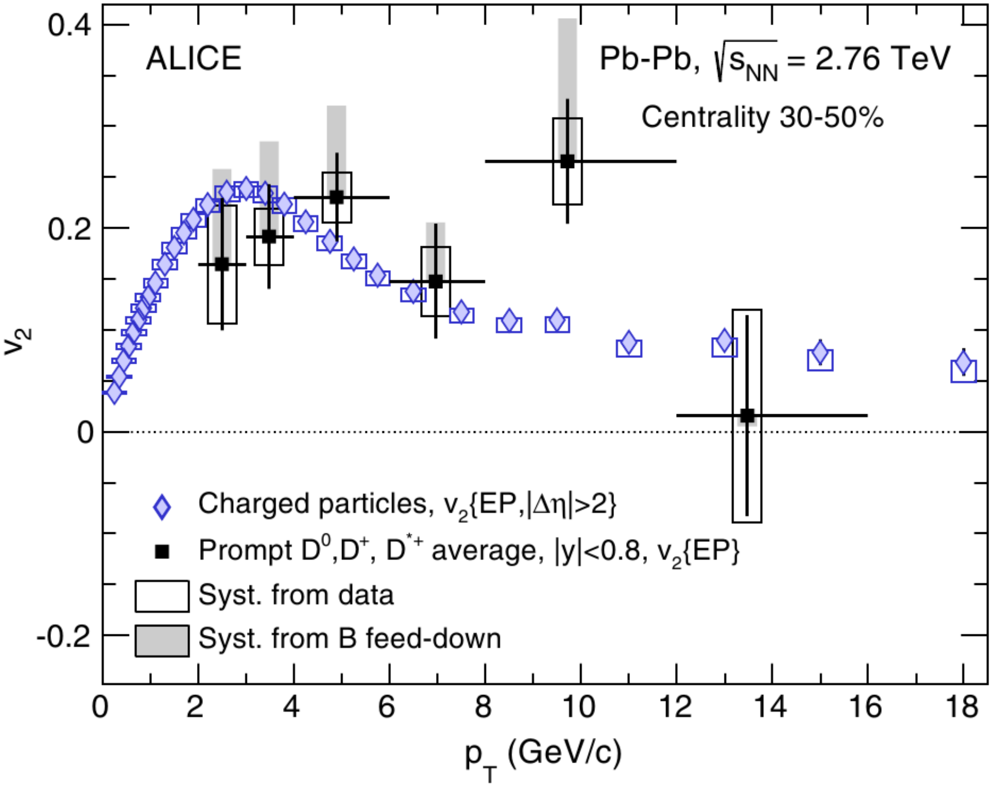
arXiv:1404.6185



arXiv:1405.3452

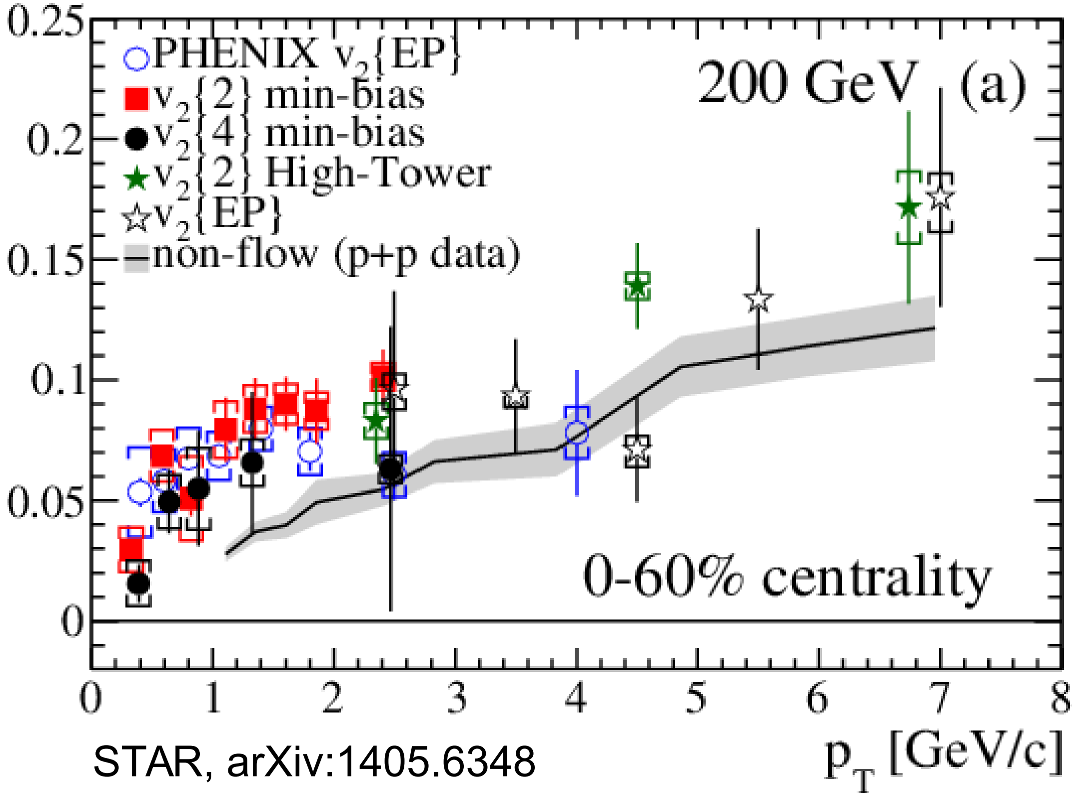
Heavy flavor v_2 in at RHIC and LHC

LHC, 2.76 TeV



PRL 111, 102301 (2013)

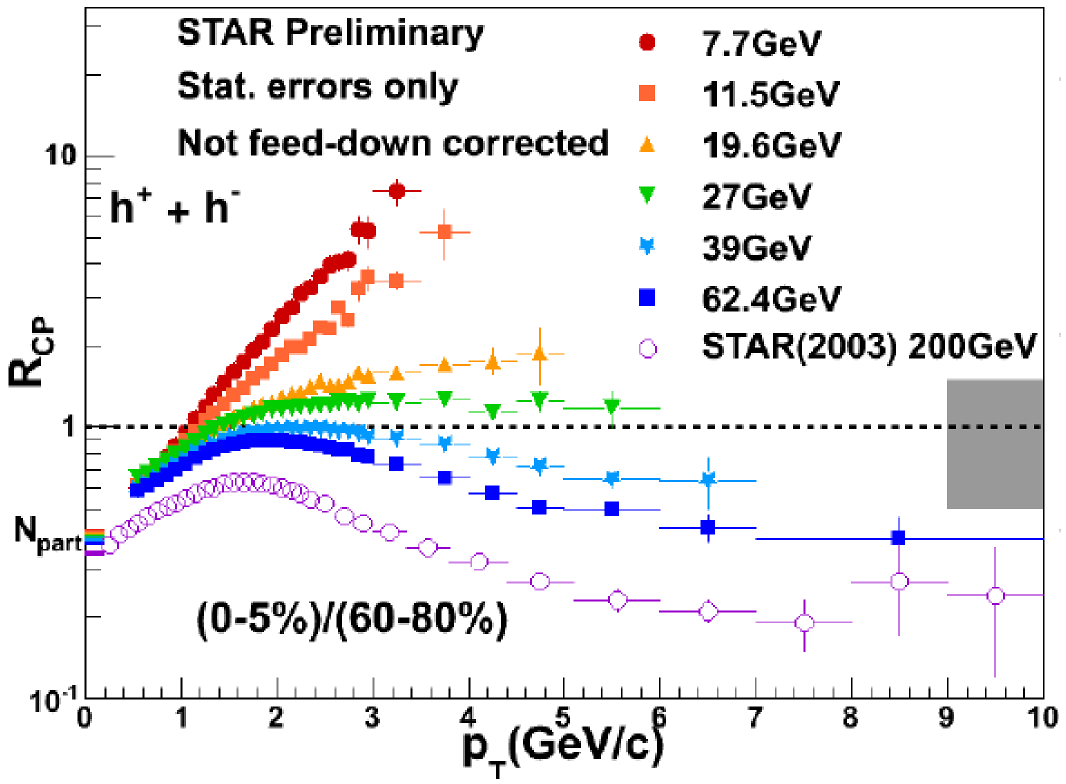
RHIC, 200 GeV



STAR, arXiv:1405.6348

How much charm v_2 in D-meson v_2?

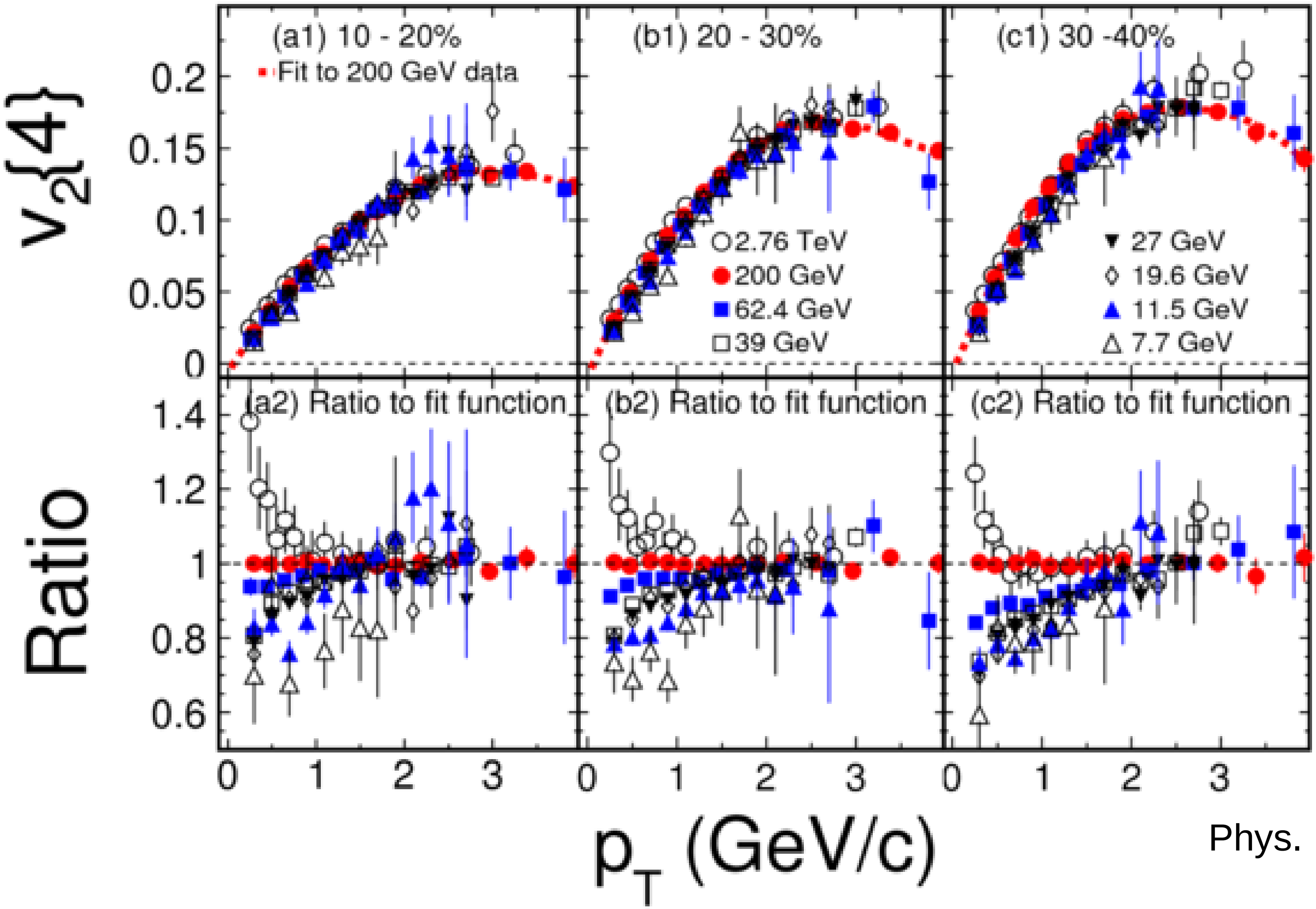
Jet quenching at RHIC



Light hadrons suppressed at high p_T at 39 - 200 GeV

eHF – no suppression at 62 GeV

Elliptic flow at RHIC

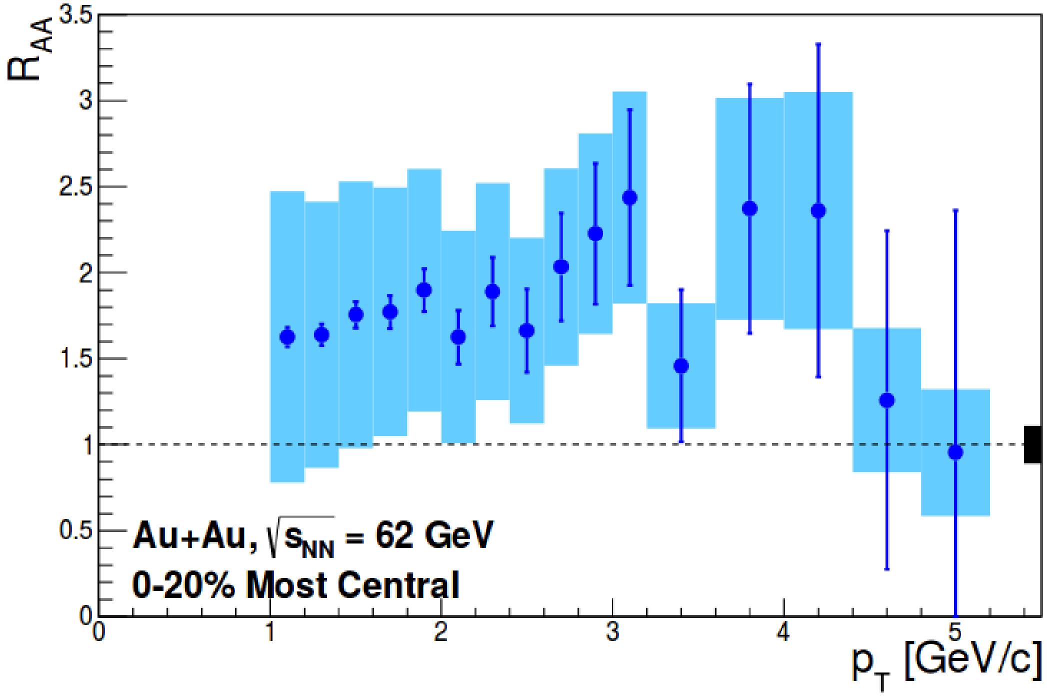


Phys. Rev. C 86 (2012) 54908

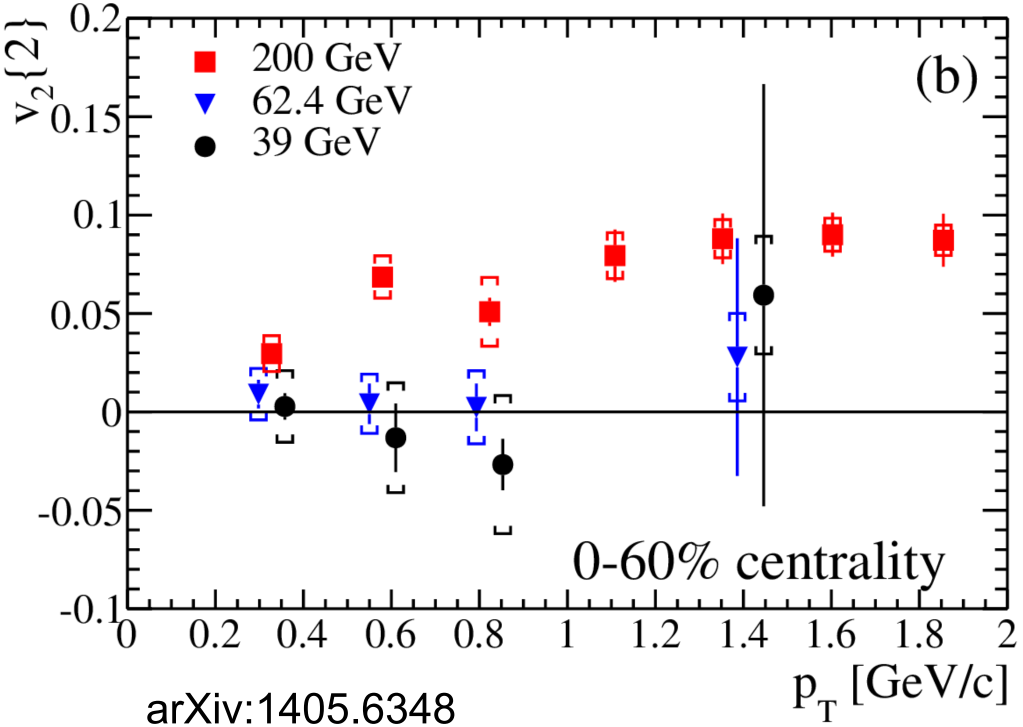
Light hadrons suppressed at high p_T at 39 - 200 GeV

Positive v_2 of charged hadrons, small difference for 39 – 200 GeV

e^{HF} R_{AA} and v_2 at $\sqrt{s_{NN}}$ = 62 GeV



arXiv:1405.3301



arXiv:1405.6348

No eHF suppression for $p_T < 5$ GeV

v_2 lower at 39 and 62 GeV than at 200 GeV for **$p_T < 1$ GeV/c**

1. Open heavy flavor vs quarkonia
→ different tools

2. We cannot measure heavy quark production
→ model-dependent interpretation

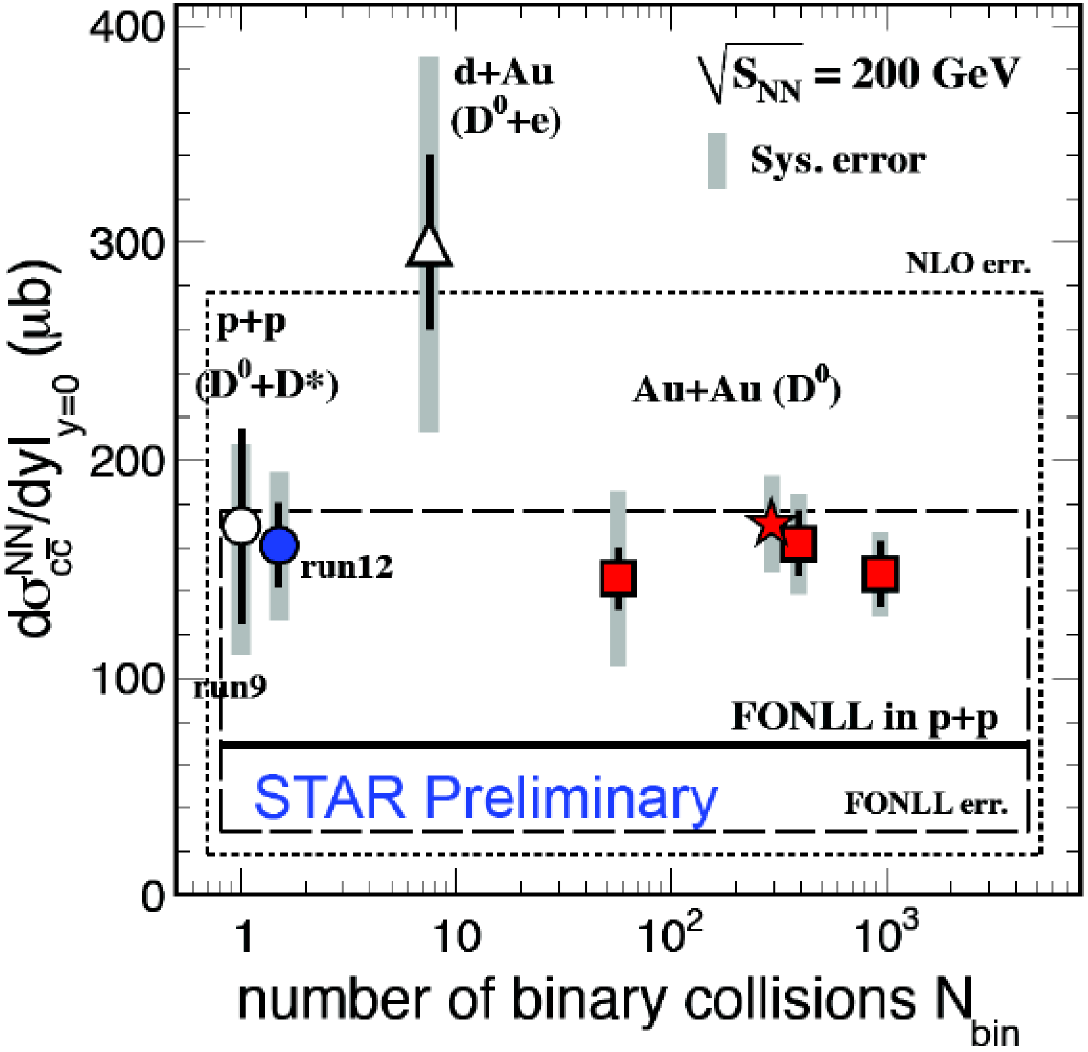
3. Understanding of p+A reference is crucial
→ so far no evidence for “mini-QGP” from HF perspective
→ pA → AA not straightforward

4. Color screening is just a hypothesis
→ stay open-minded

5. Heavy Flavor production suppressed at LHC and top RHIC energy but not at lower energies
→ interesting physics below LHC regime

Backup

Charm cross section at 200 GeV



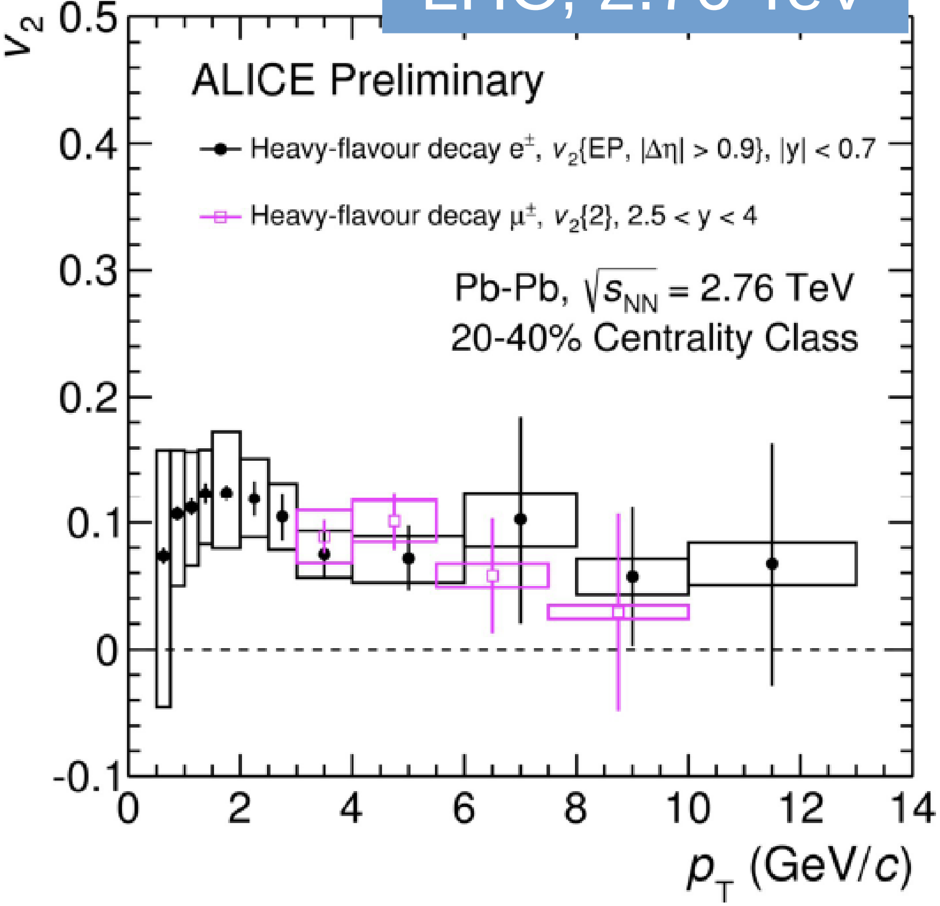
Charm cross section follows N_{bin} scaling

→ Charm quarks produced mostly in initial hard scatterings

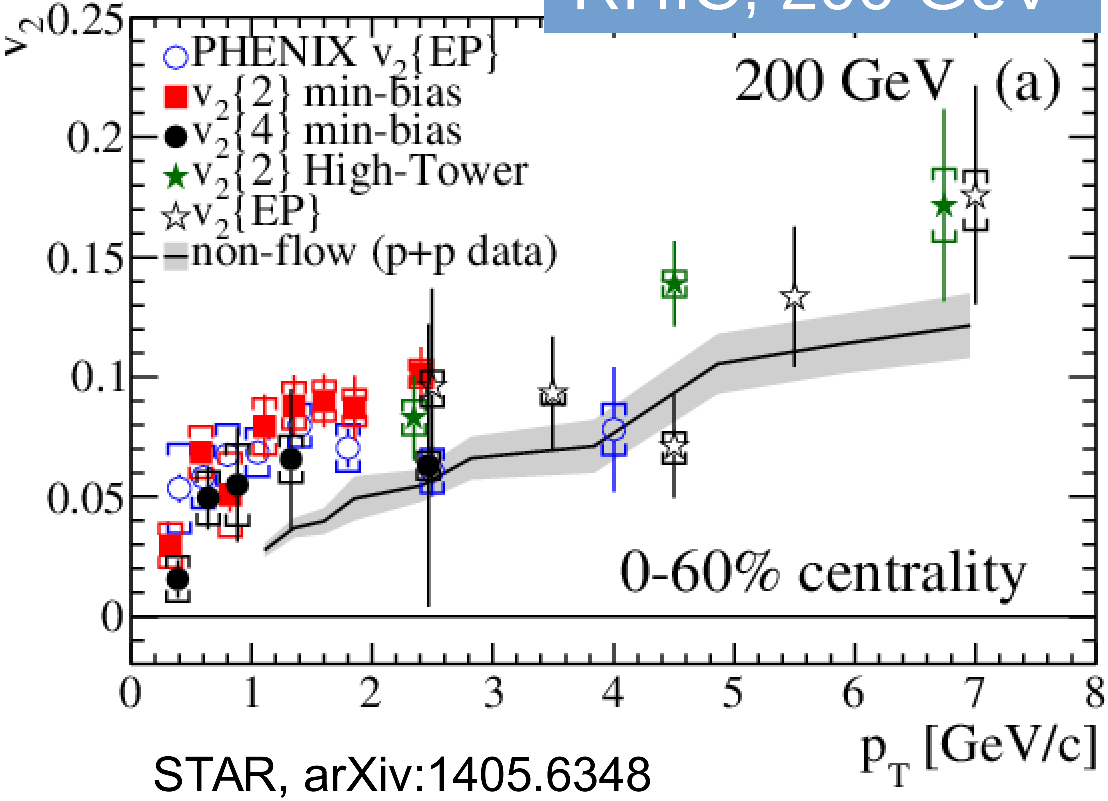
[1] STAR d+Au: J. Adams, et al., PRL 94 (2005) 62301
[2] STAR p+p Run 9: Phys. Rev. D 86 (2012) 72013
[3] FONLL: M. Cacciari, PRL 95 (2005) 122001.
[4] NLO: R. Vogt, Eur.Phys.J.ST 155 (2008) 213

e^{HF} v_2 in at RHIC and LHC

LHC, 2.76 TeV

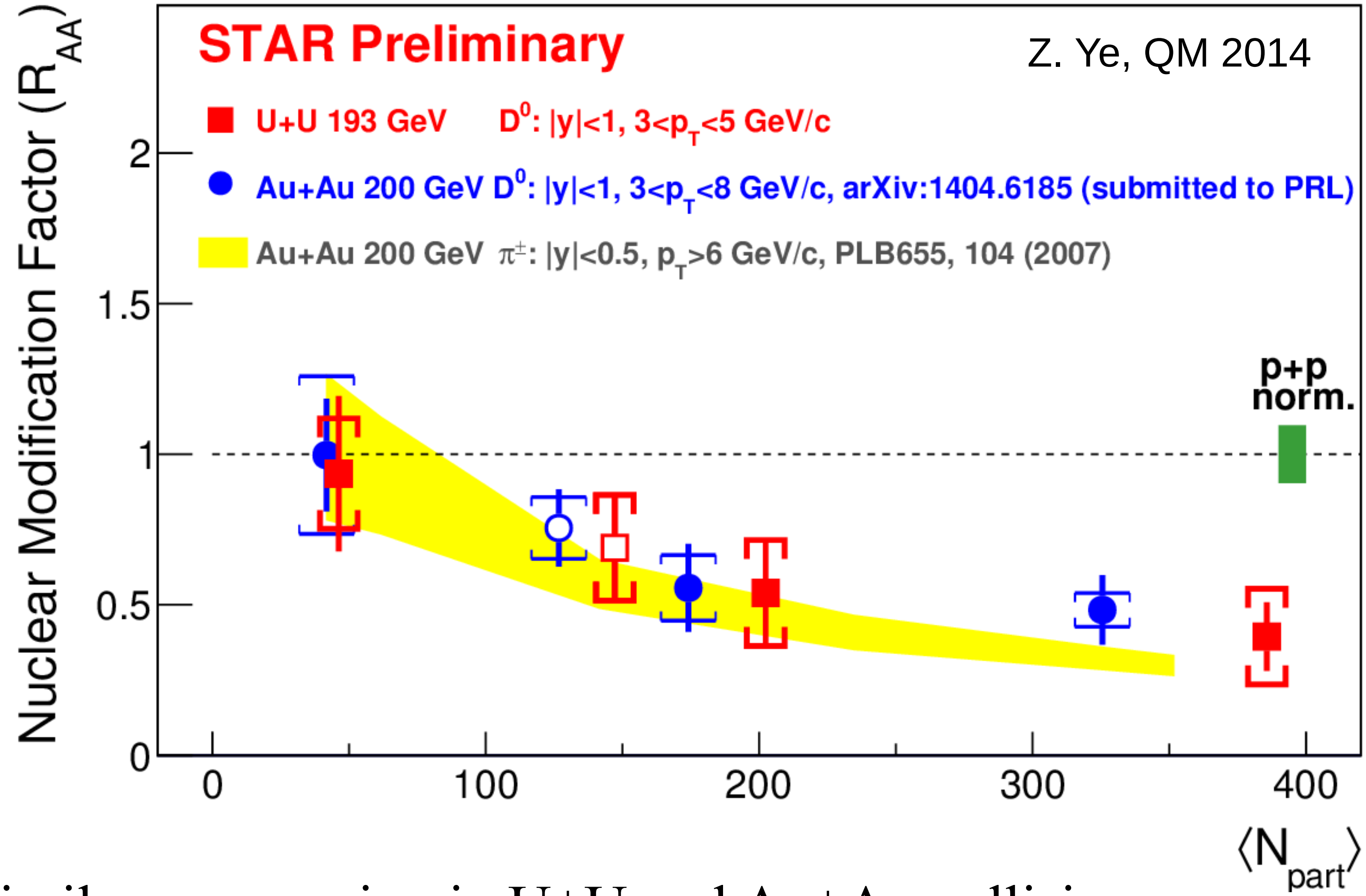


RHIC, 200 GeV



STAR, arXiv:1405.6348

High p_T suppression at RHIC



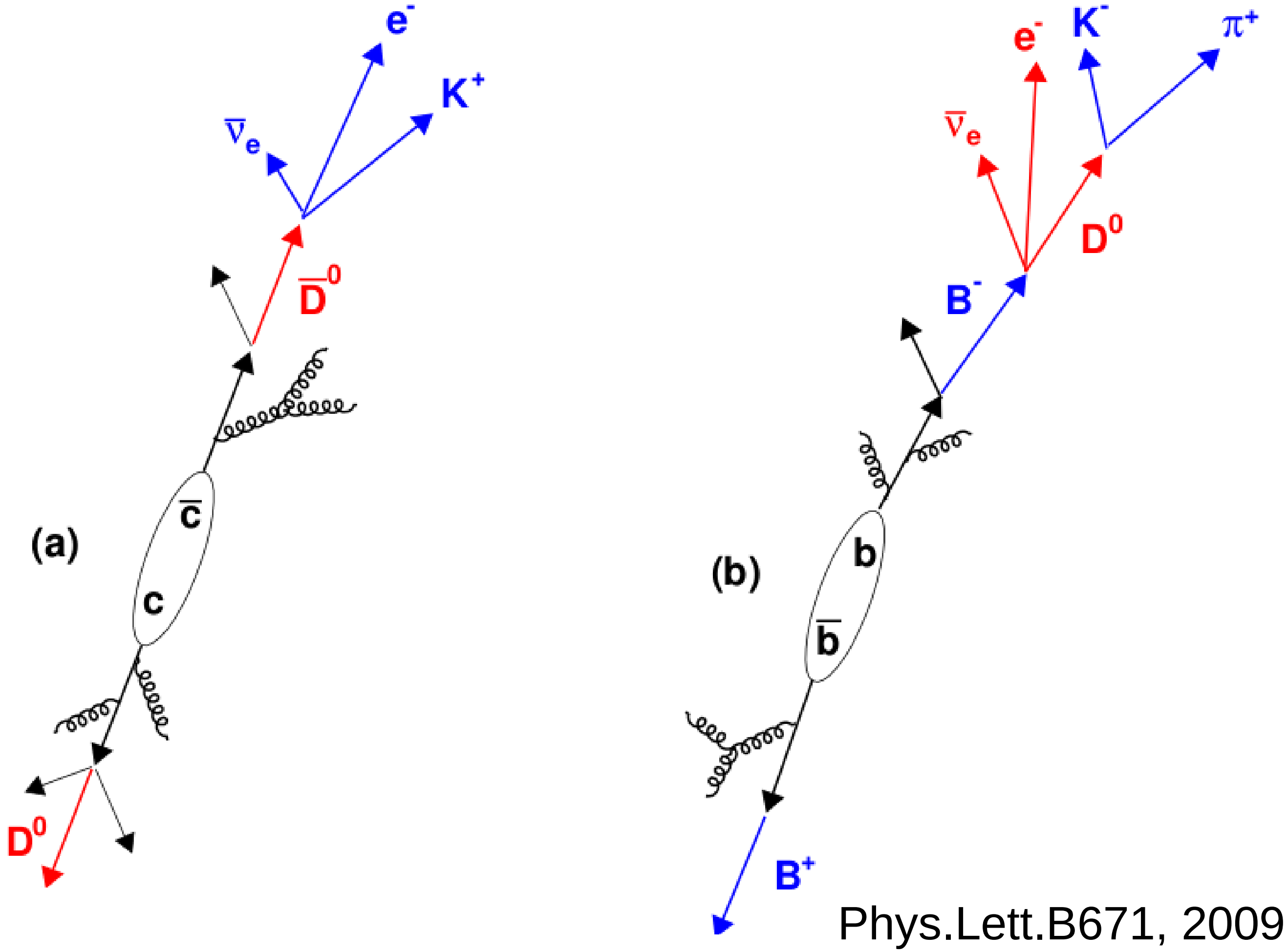
D^0: Similar suppression in U+U and Au+Au collisions

Similar trend vs system size as for pions

D^0 suppression suggests strong charm-medium interaction

Non-photonic electrons

Proxies for heavy flavor quarks

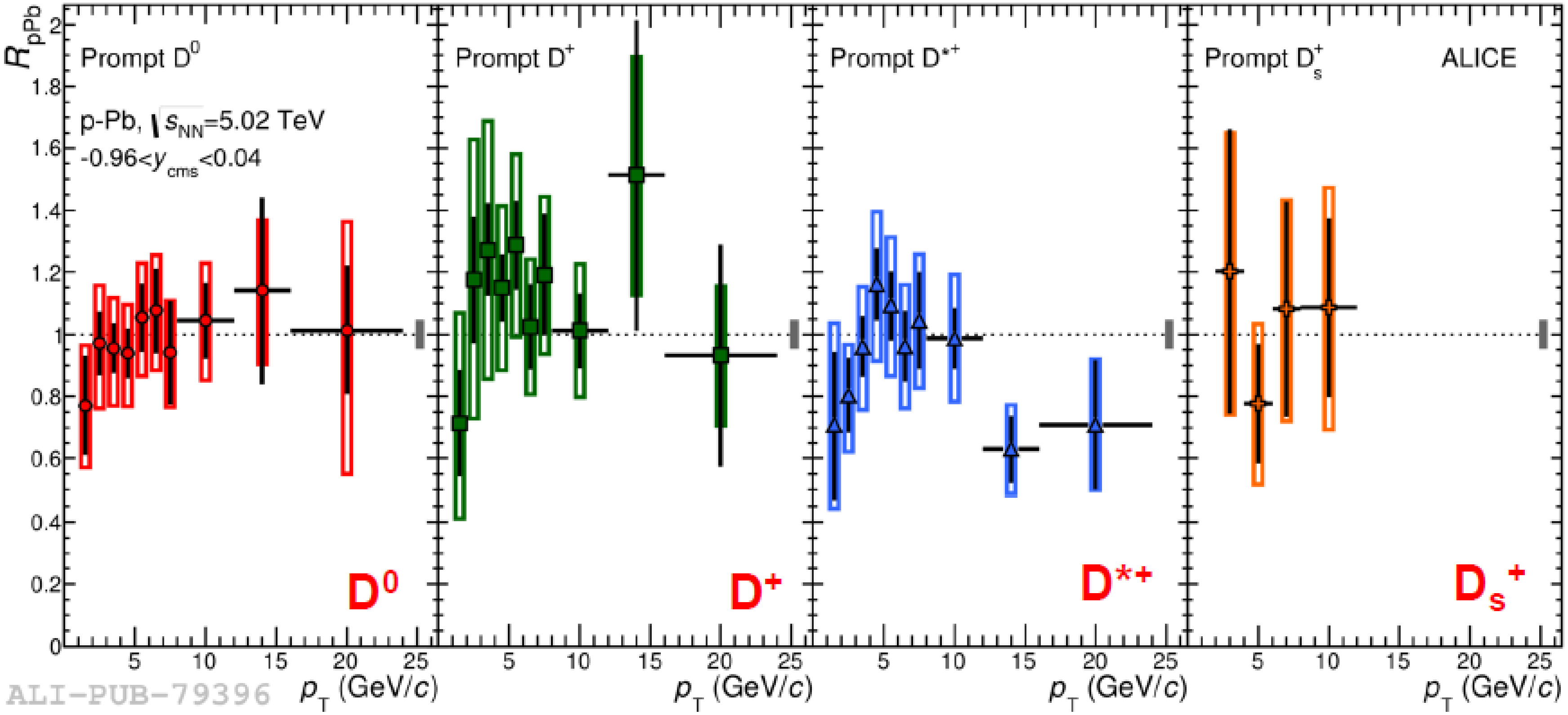


Phys.Lett.B671, 2009

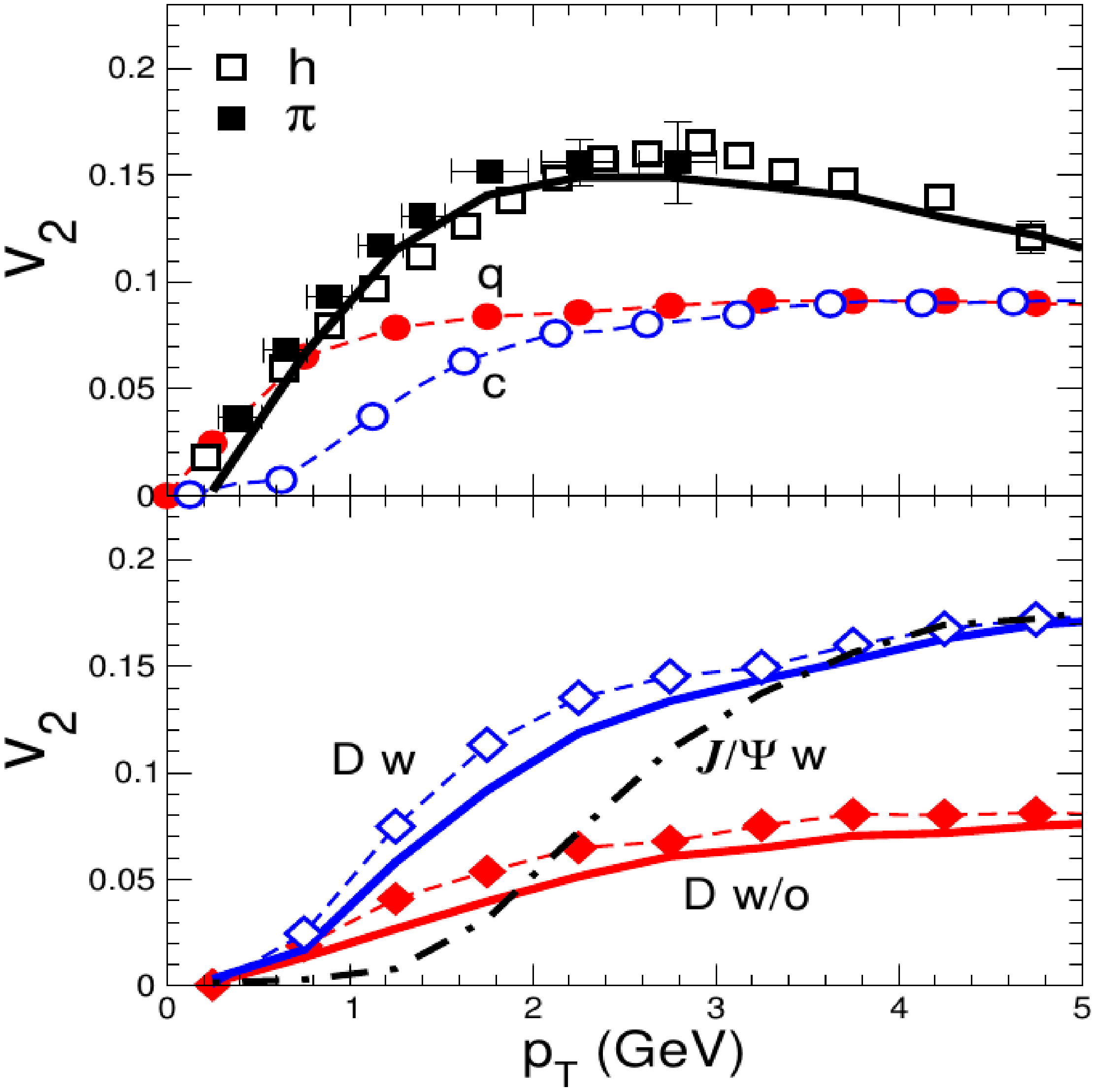
Background:

- photonic electrons: $\gamma \rightarrow ee$, $\pi^0 \rightarrow ee\gamma$, $\eta \rightarrow ee\gamma$
- K_{e3} ($K \rightarrow \pi\nu e$)

ALICE Collaboration, arXiv:1405.3452 [nucl-ex]



HF production via coalescence

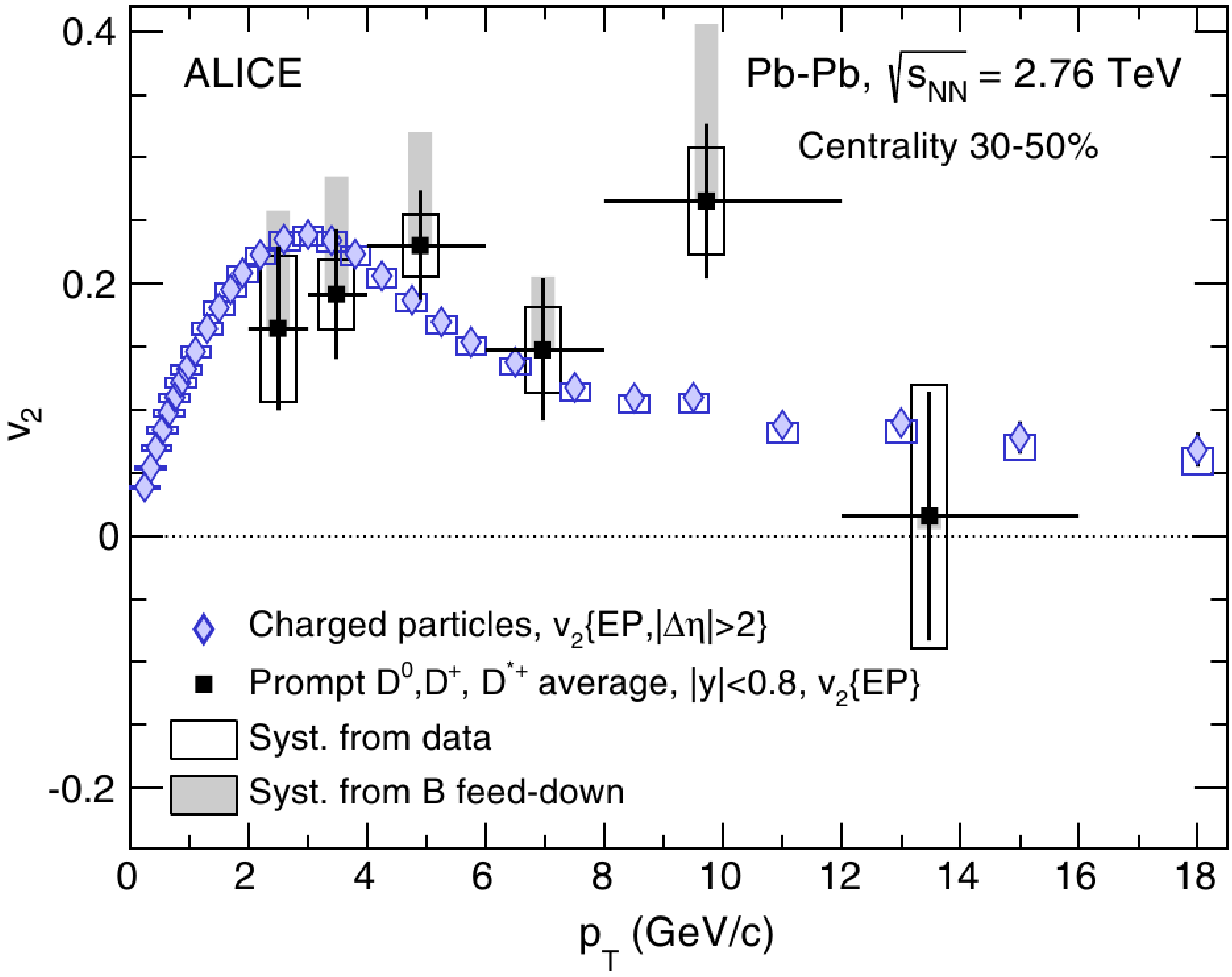


minimum bias Au+Au
200 GeV

50% of D v_2 could be from light quark

Phys.Lett. B595 (2004)

How much charm v_2 in D-meson v_2?



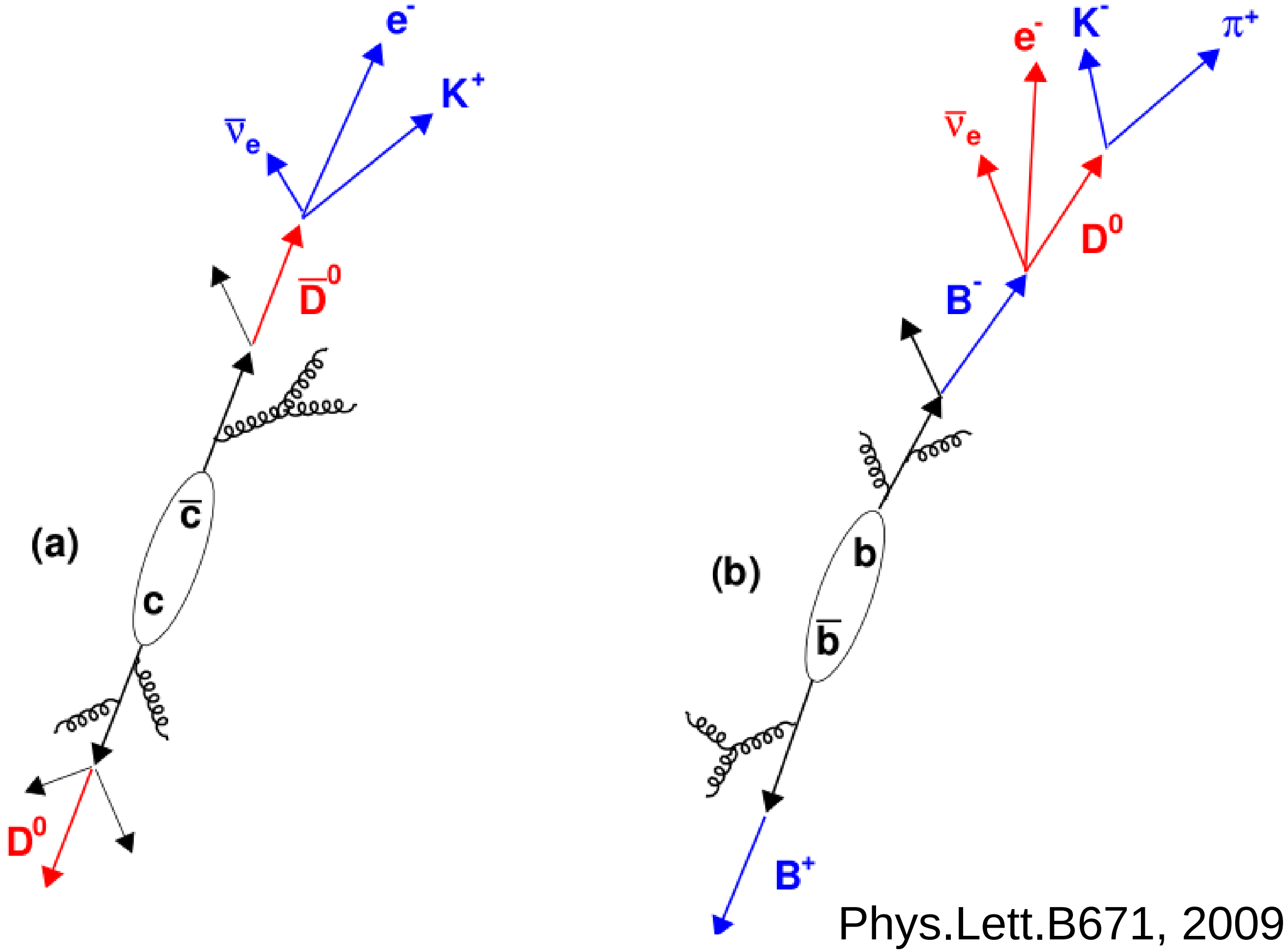
PRL 111, 102301 (2013)

Non-photonic electrons

Proxies for heavy flavor quarks

p_T shift compared to parent quark

ϕ angle smeared

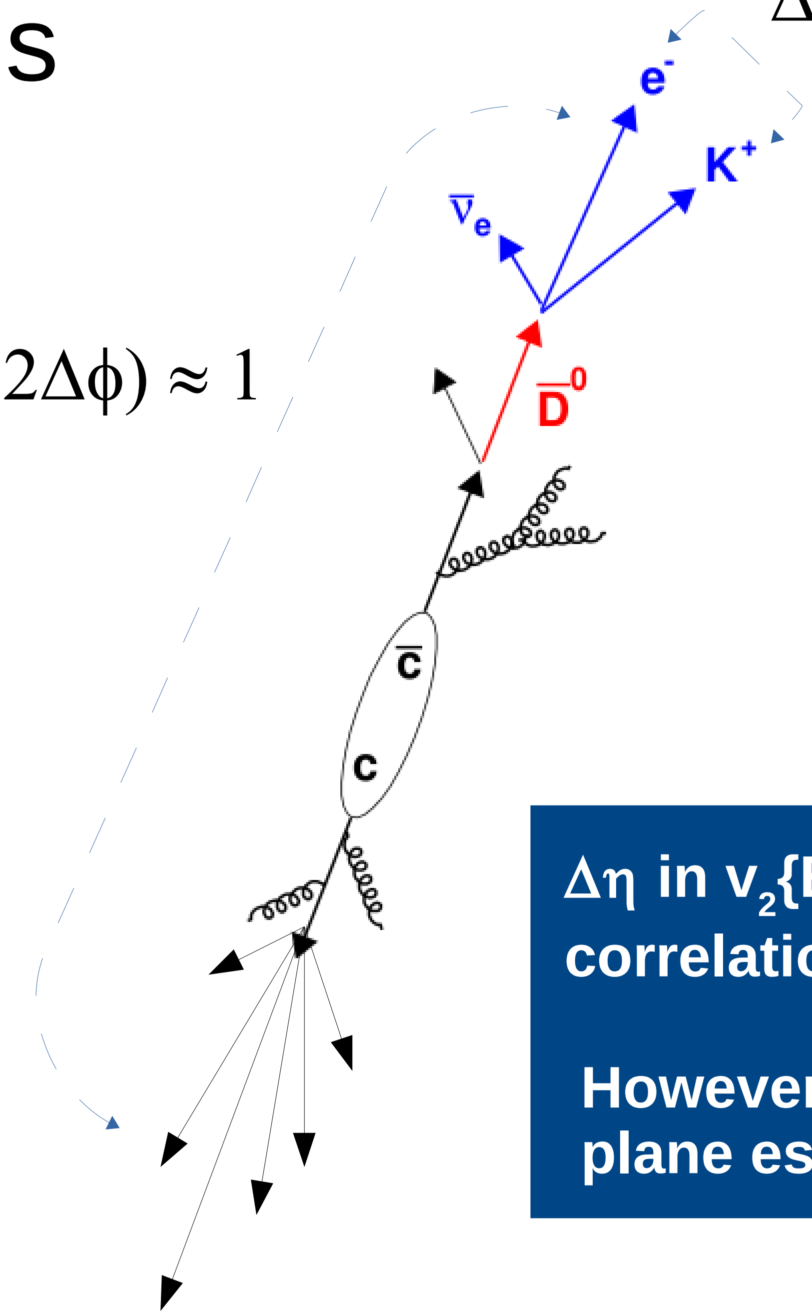


Phys.Lett.B671, 2009

Jet-like correlations

$\Delta\phi \approx 0 \rightarrow \cos(2\Delta\phi) \approx 1$

$\Delta\phi \approx \pi \rightarrow \cos(2\Delta\phi) \approx 1$



$\Delta\eta$ in $v_2\{EP\}$ reduces jet-like correlations

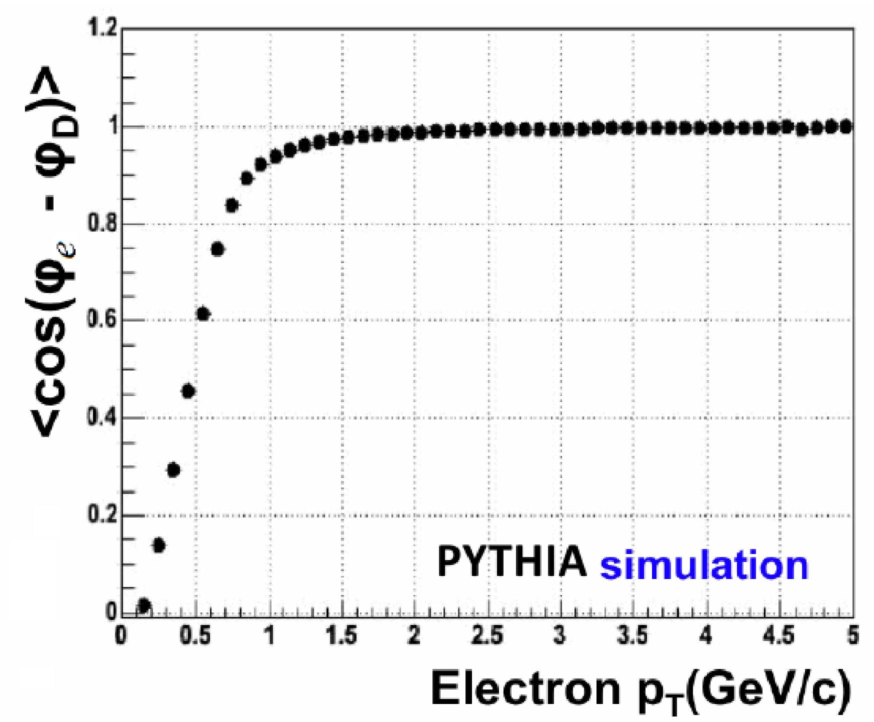
However, effect of jets on event plane estimation not really known

e_{HF} represents parent momentum direction well when:

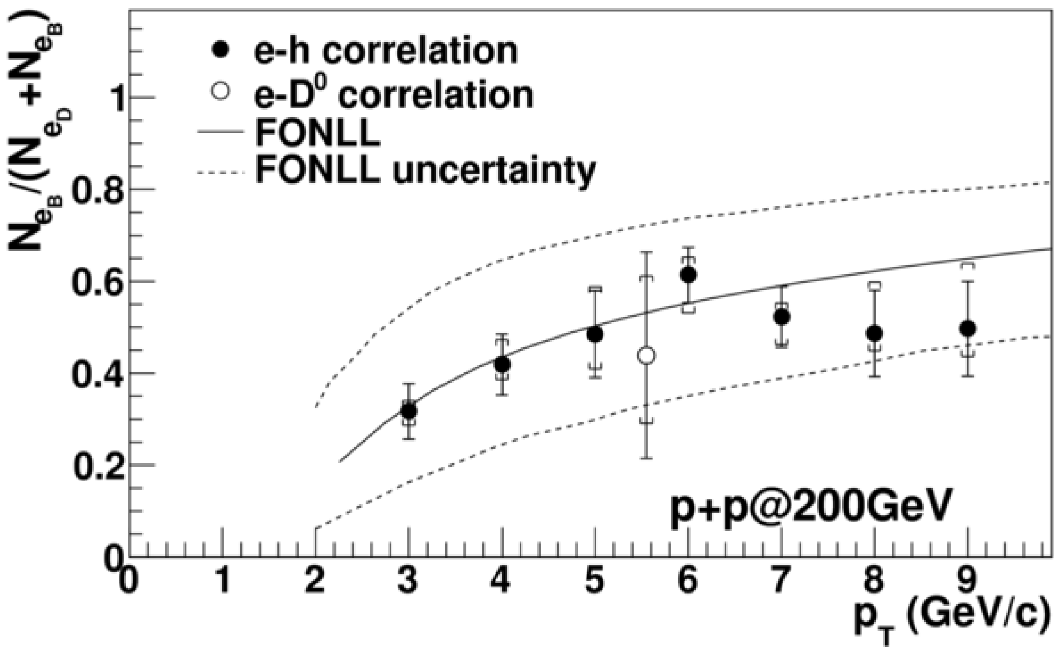
p^e_T >1.5 GeV/c for D

p^e_T > 3 GeV/c for B

p^e_T ~1.5 – 2 GeV/c for charm v_2 study

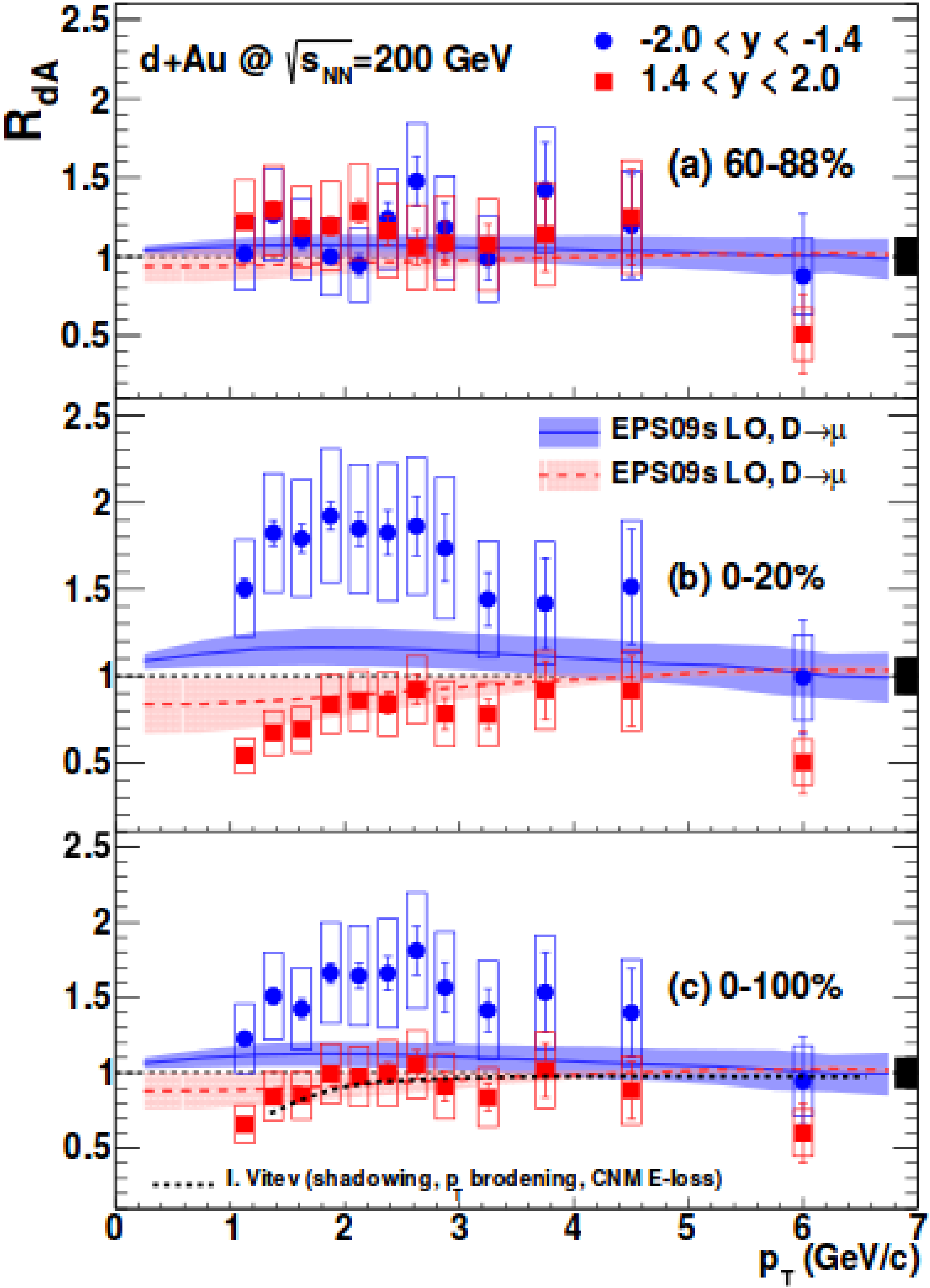


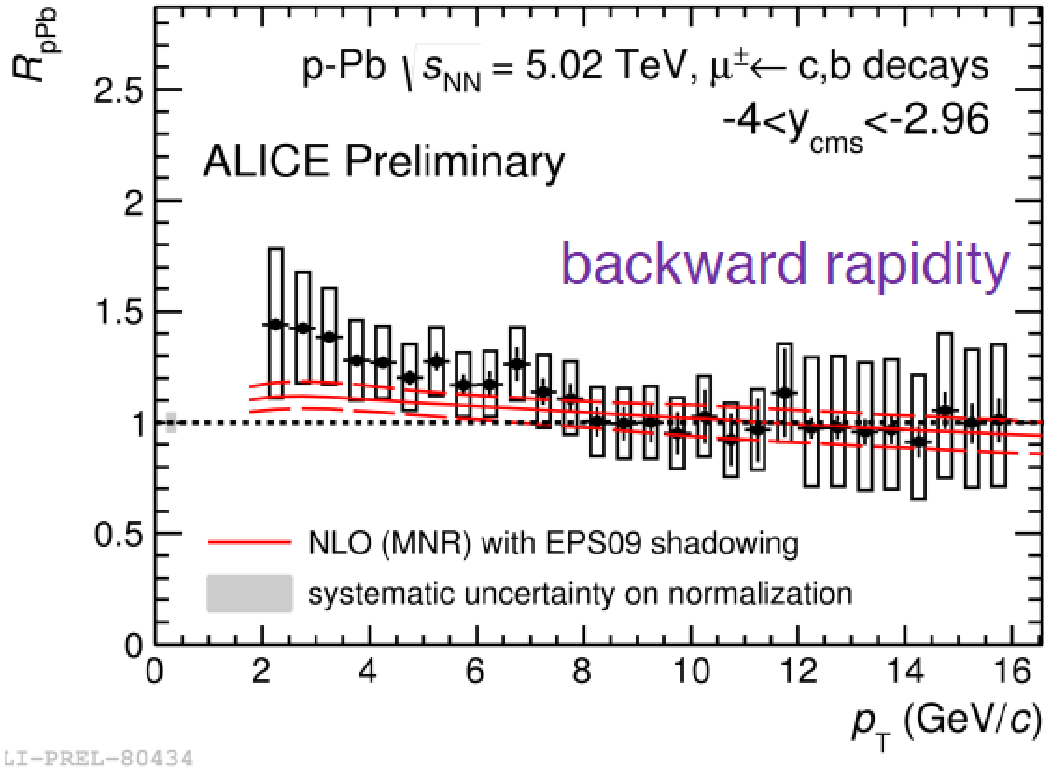
W. Xu, QM 2011

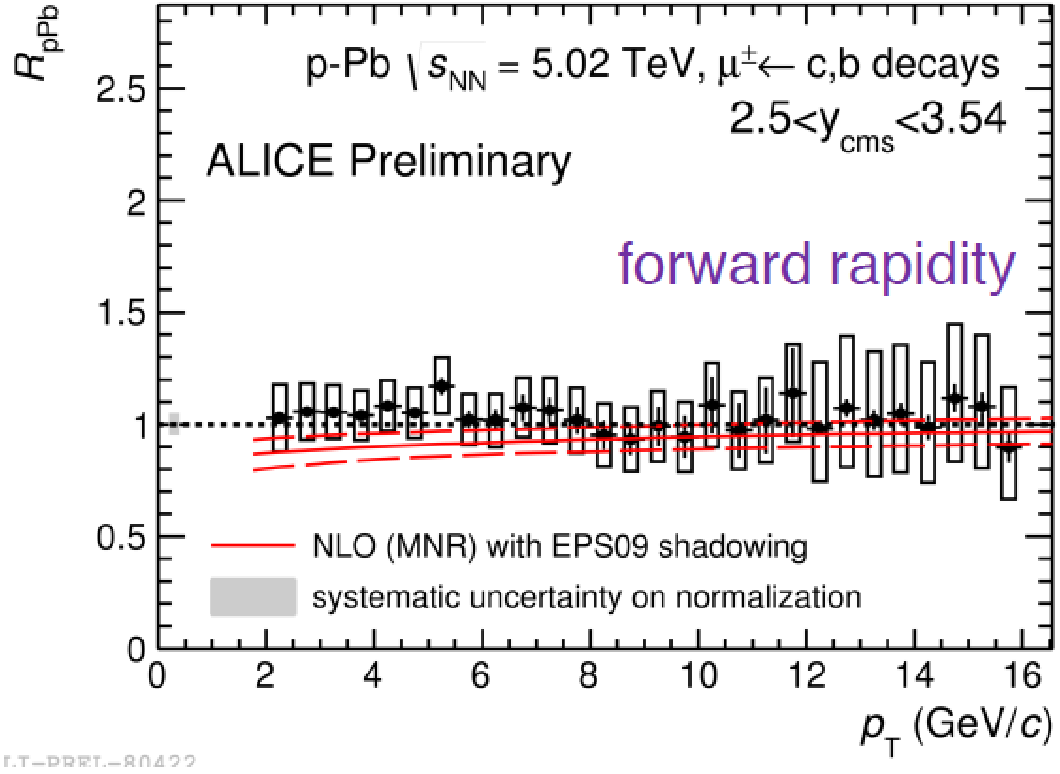


At ~2 GeV, up to 40% from B → p_T shift and v_2 smearing

What effect of D/B suppression?

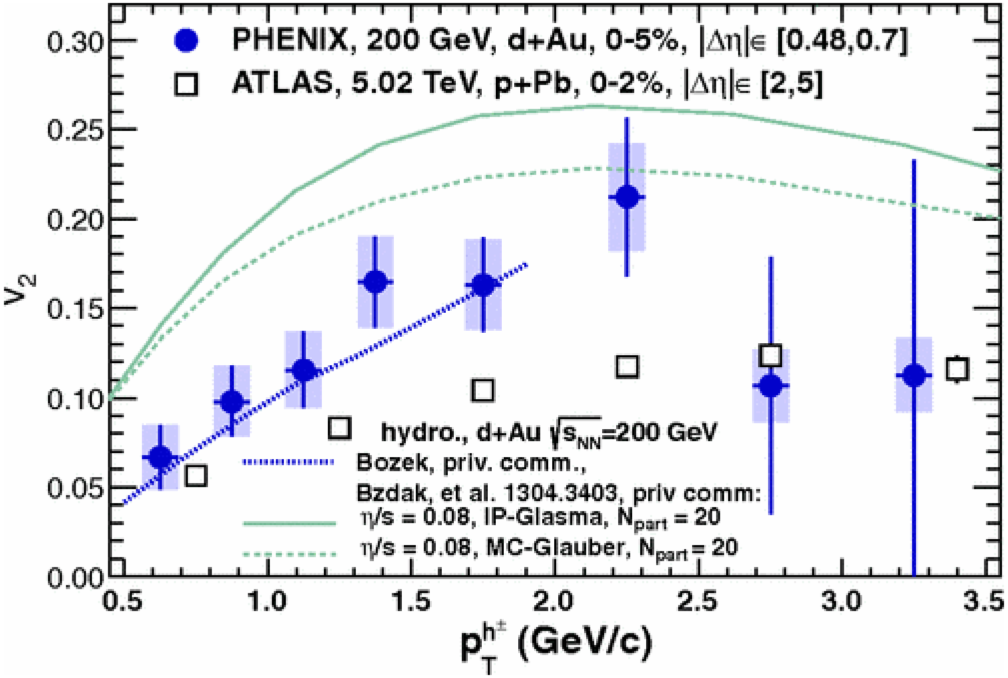

d+Au @ $\sqrt{s_{NN}}$=200 GeV
● -2.0 < y < -1.4
■ 1.4 < y < 2.0
(a) 60-88%
EPS09s LO, D→μ
EPS09s LO, D→μ
(b) 0-20%
(c) 0-100%
I. Vitev (shadowing, p_T brodening, CNM E-loss)
R_{dA}
p_T (GeV/c)
0
0.5
1
1.5
2
2.5
1
2
3
4
5
6
7


R_{pPb}
p-Pb $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV, $\mu^{\pm} \leftarrow$ c,b decays
$-4<y_{\mathrm{cms}}<-2.96$
ALICE Preliminary
backward rapidity
NLO (MNR) with EPS09 shadowing
systematic uncertainty on normalization
0
0.5
1
1.5
2
2.5
0
2
4
6
8
10
12
14
16
p_{T} (GeV/c)
LI-PREL-80434


R_{pPb}
p-Pb $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV, $\mu^{\pm} \leftarrow$ c,b decays
$2.5<y_{\mathrm{cms}}<3.54$
ALICE Preliminary
forward rapidity
NLO (MNR) with EPS09 shadowing
systematic uncertainty on normalization
0
0.5
1
1.5
2
2.5
0
2
4
6
8
10
12
14
16
p_{T} (GeV/c)
LI-PREL-80422

d+Au: reference or “mini-QGP” ?

Charged hadrons

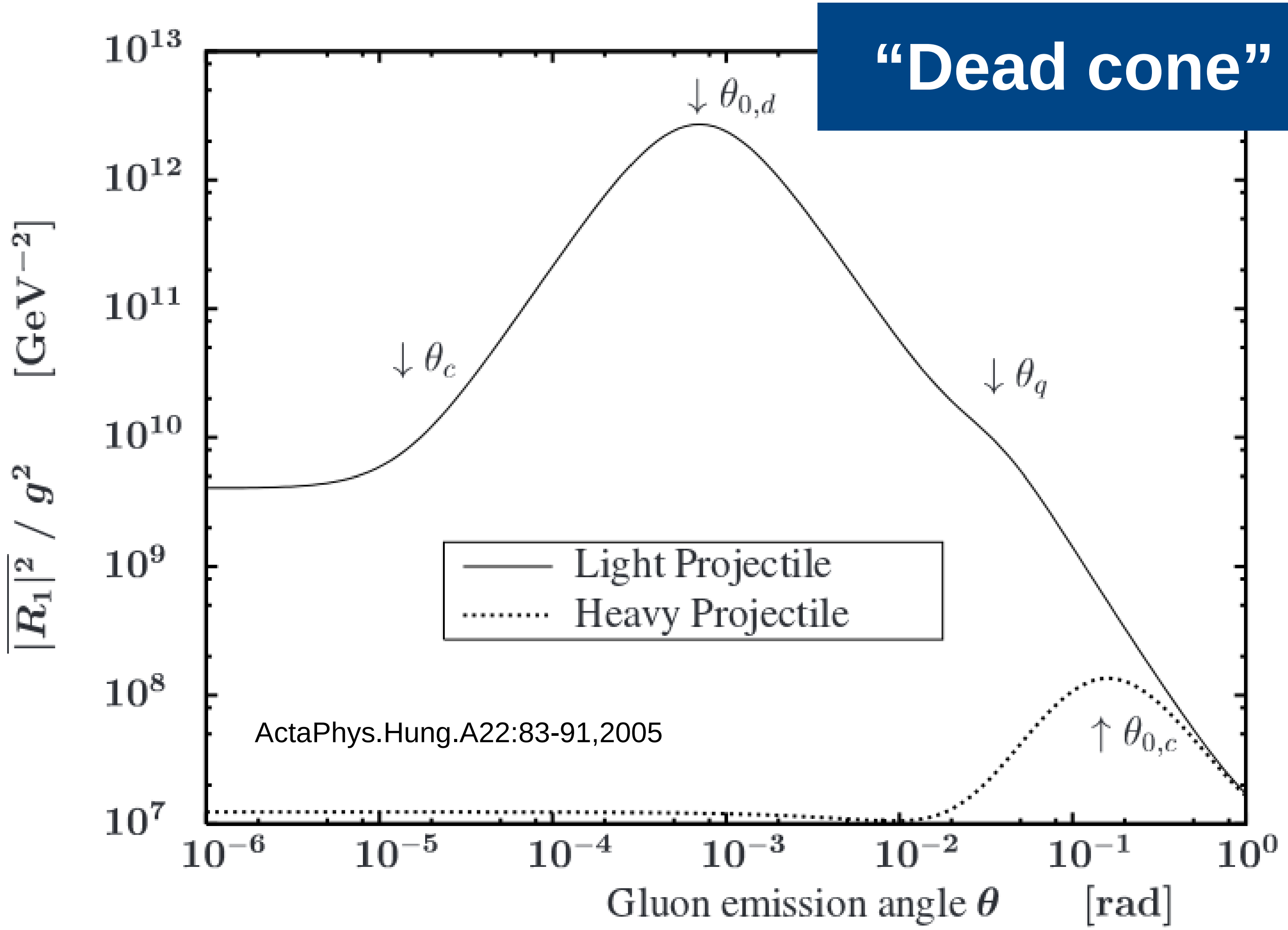


Phys. Rev. Lett. 111, 212301 (2013)

Open heavy flavor

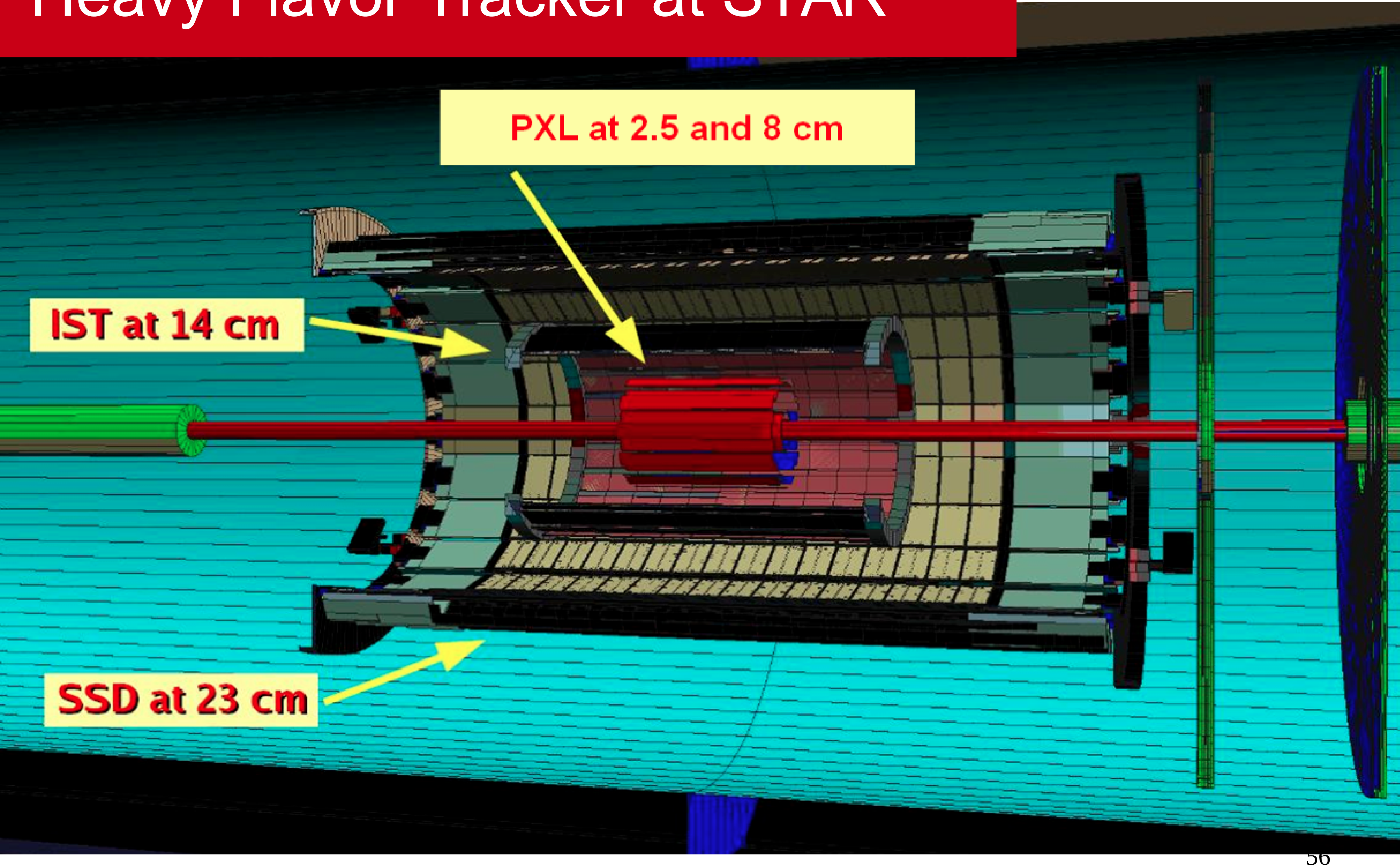
$\rightarrow \Delta E(g) > \Delta E(q) > \Delta E(c) > \Delta E(g)$

“Dead cone”



ActaPhys.Hung.A22:83-91,2005

Heavy Flavor Tracker at STAR

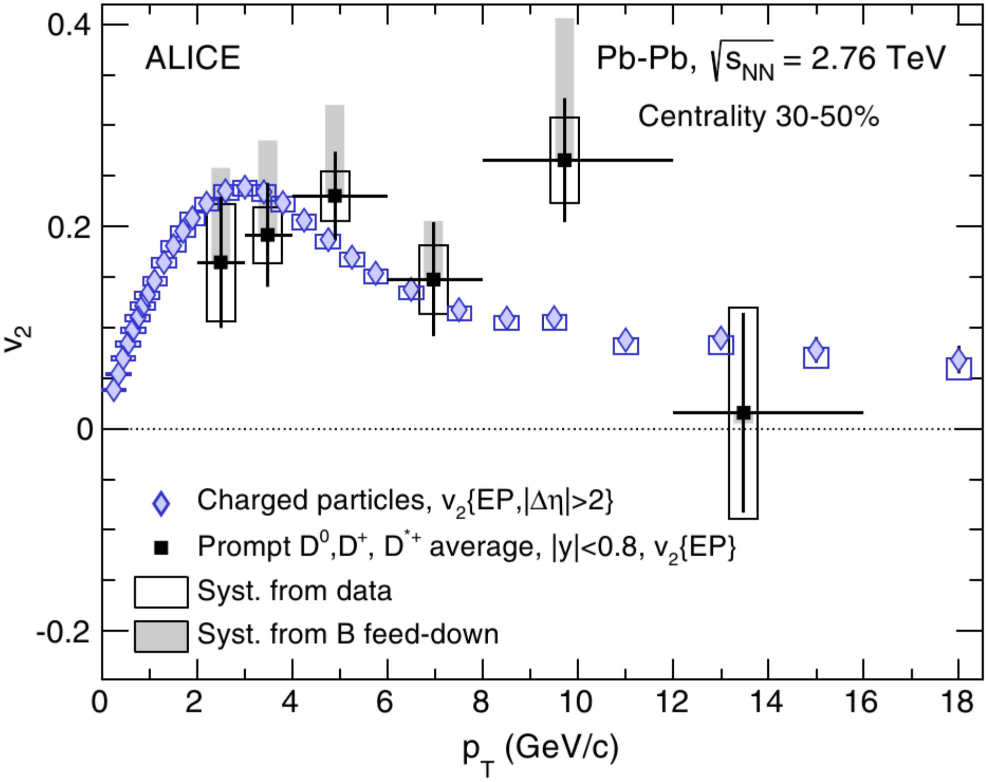


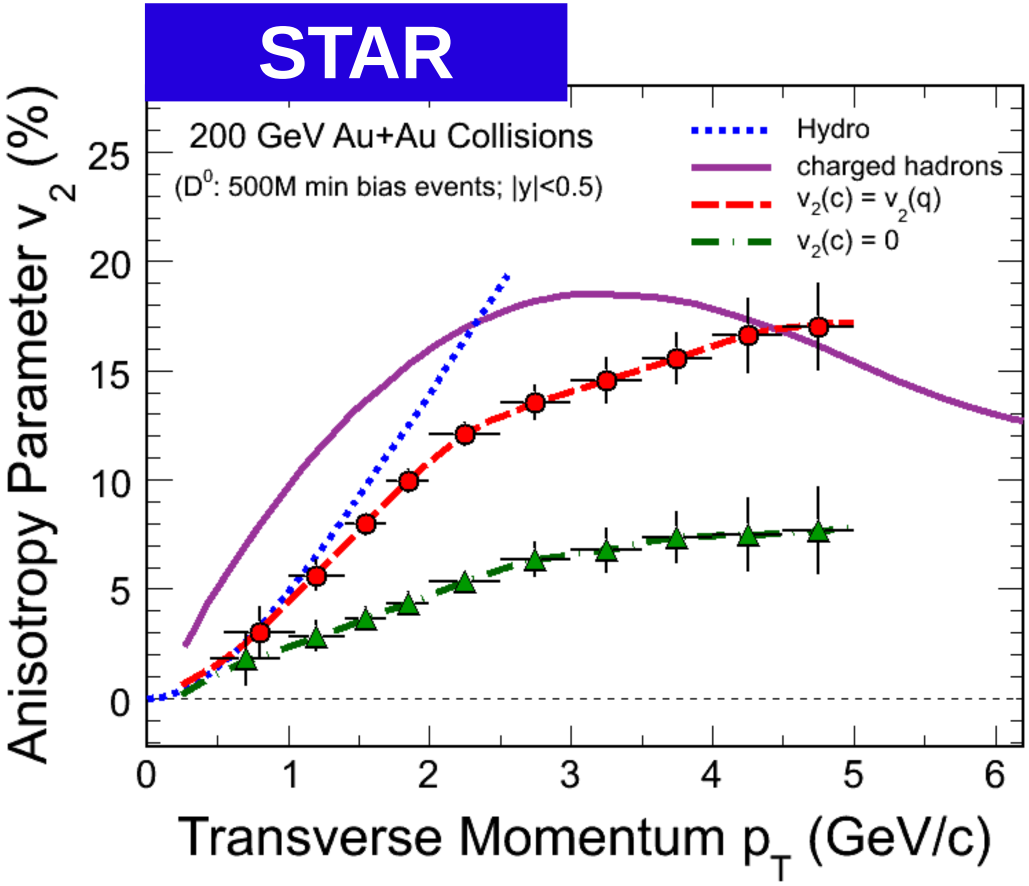
PXL at 2.5 and 8 cm

IST at 14 cm

SSD at 23 cm

STAR data with Heavy Flavor Tracker

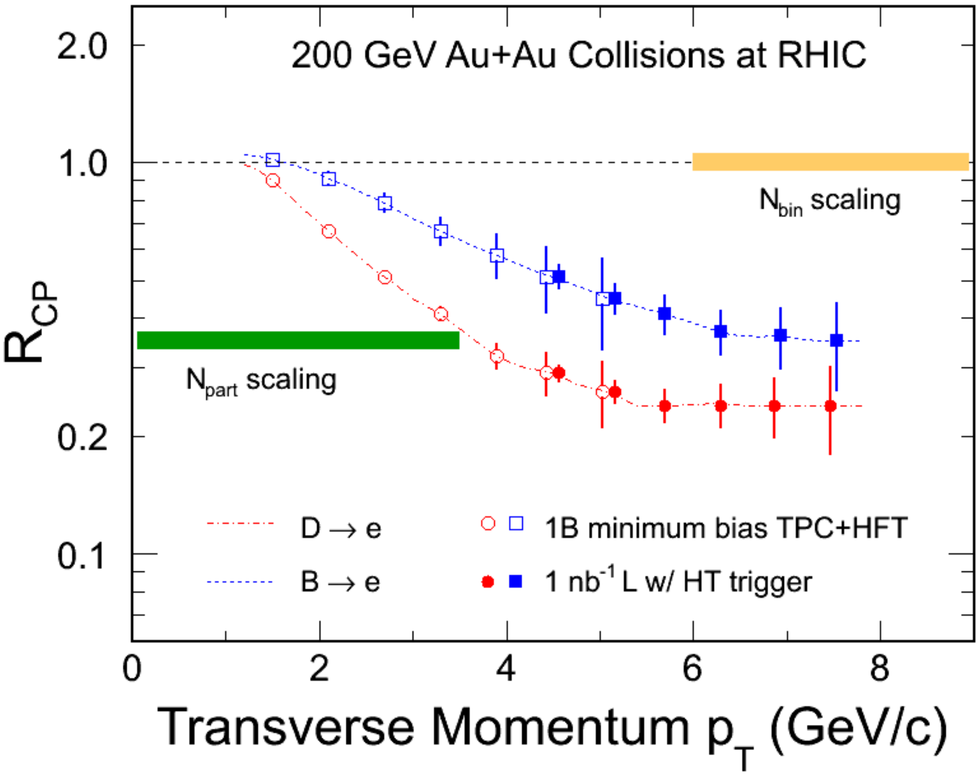


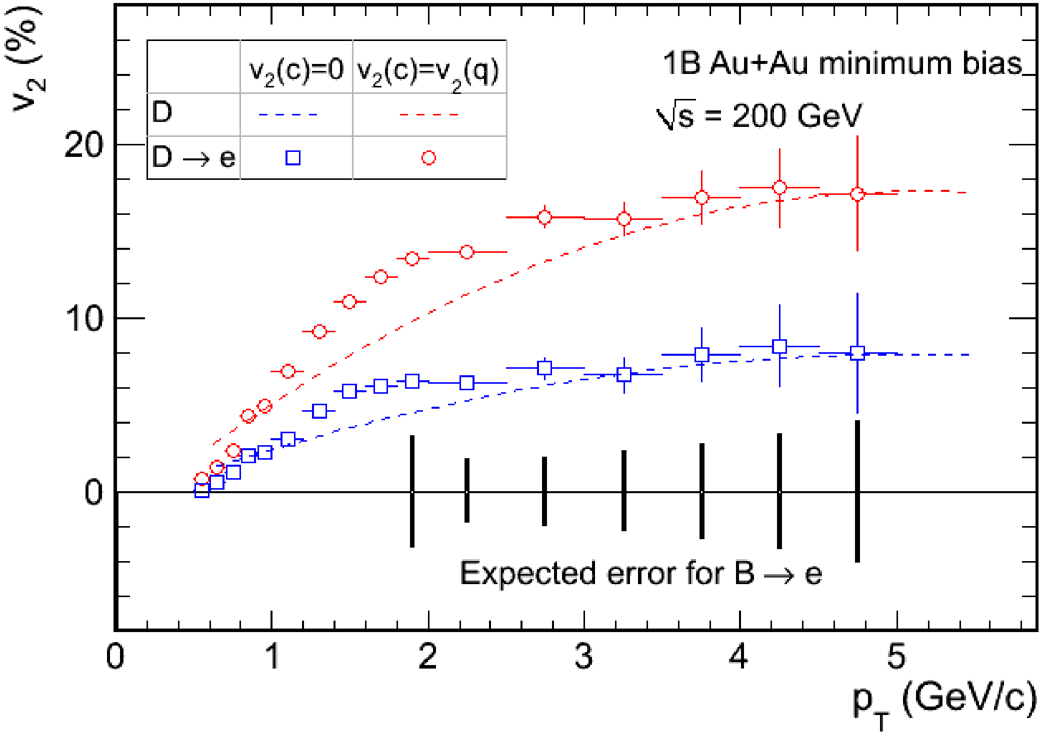


PRL 111, 102301 (2013)

HFT Conceptual Design Report

STAR data with Heavy Flavor Tracker

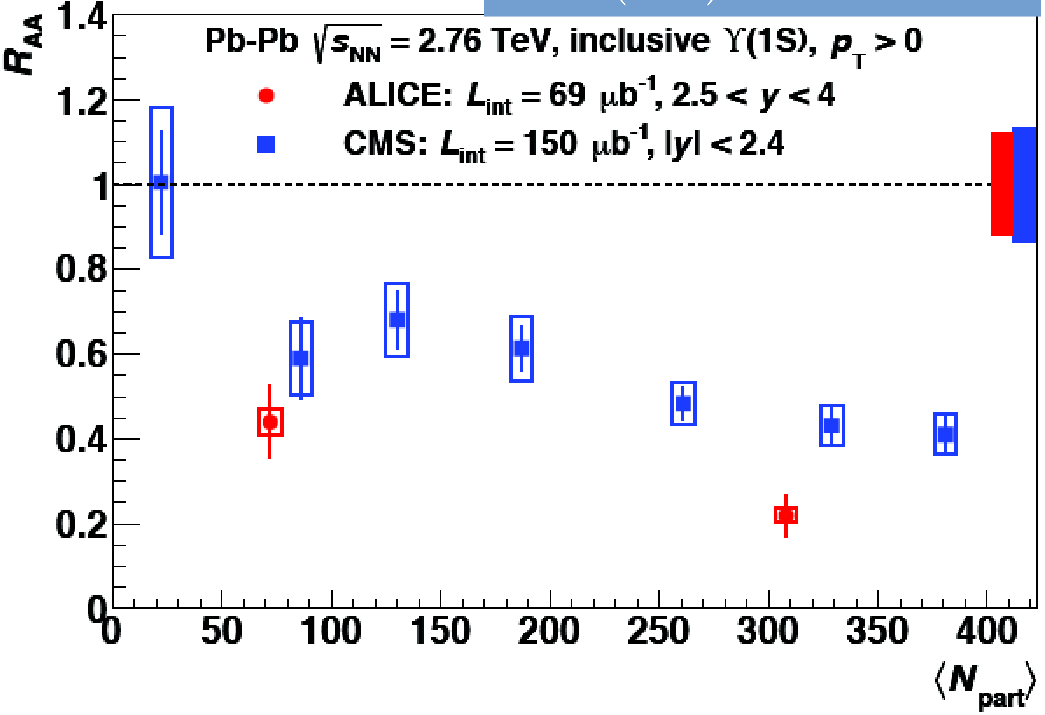




HFT Conceptual Design Report

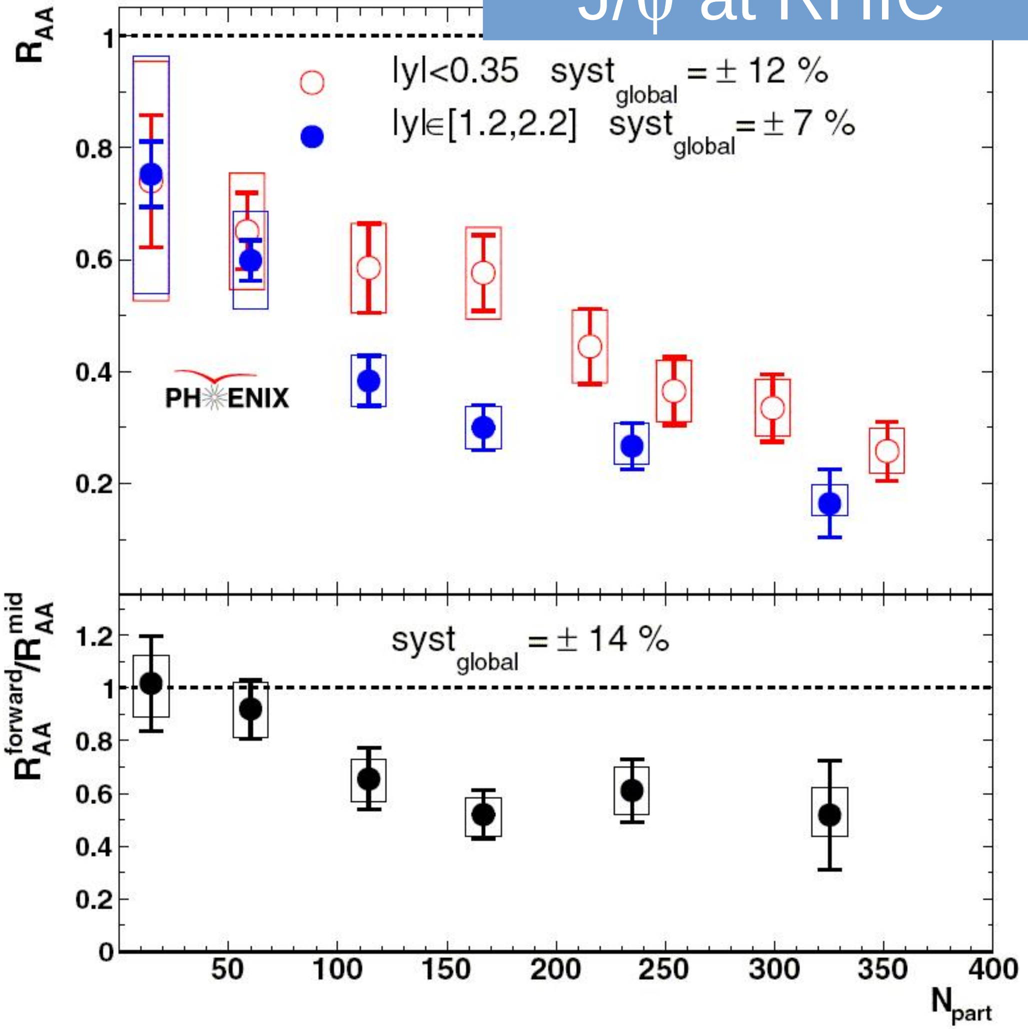
ϒ at LHC ≈ J/ψ at RHIC

ϒ(1s) at LHC



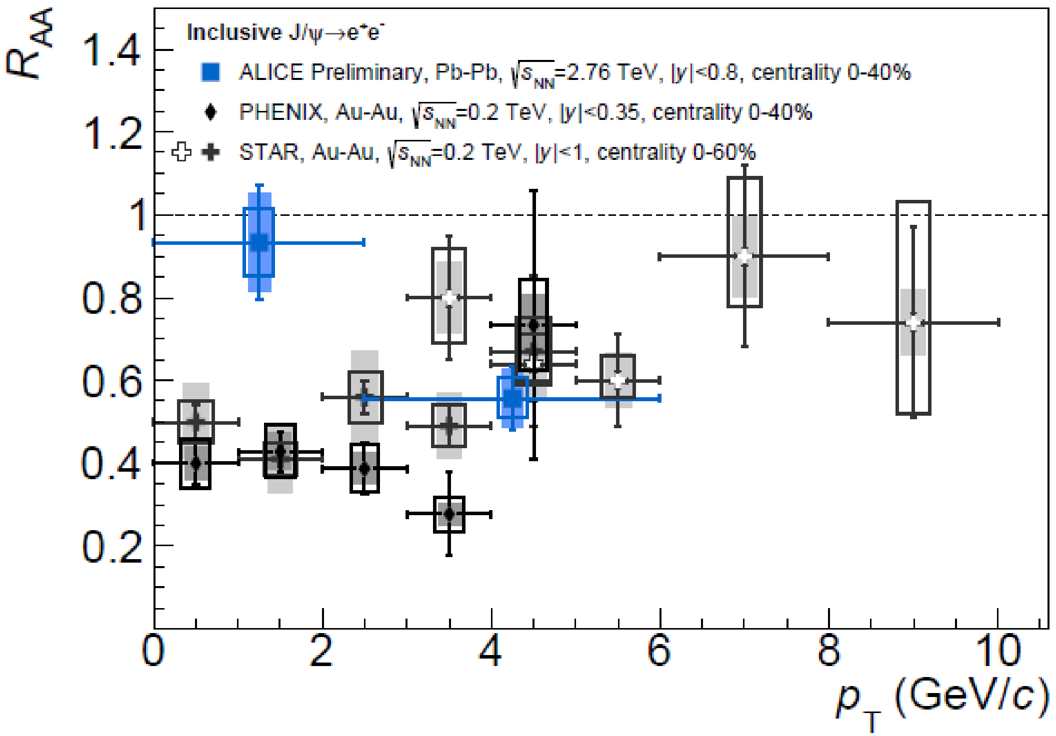
arXiv:1405.4493

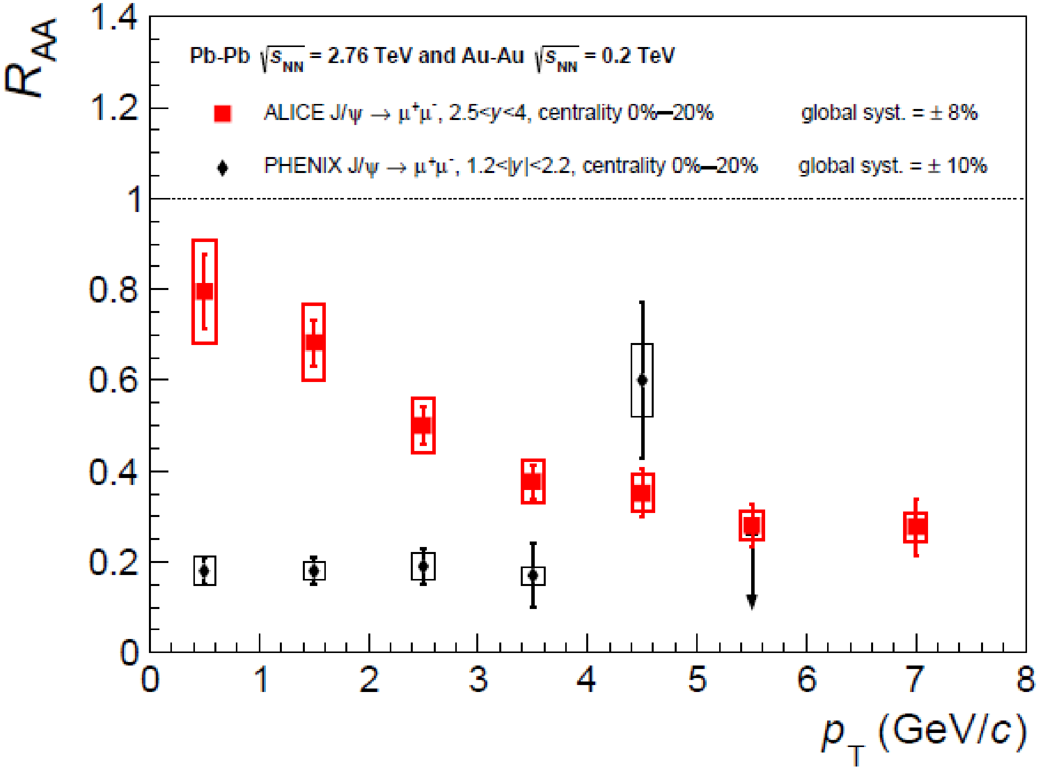
J/ψ at RHIC



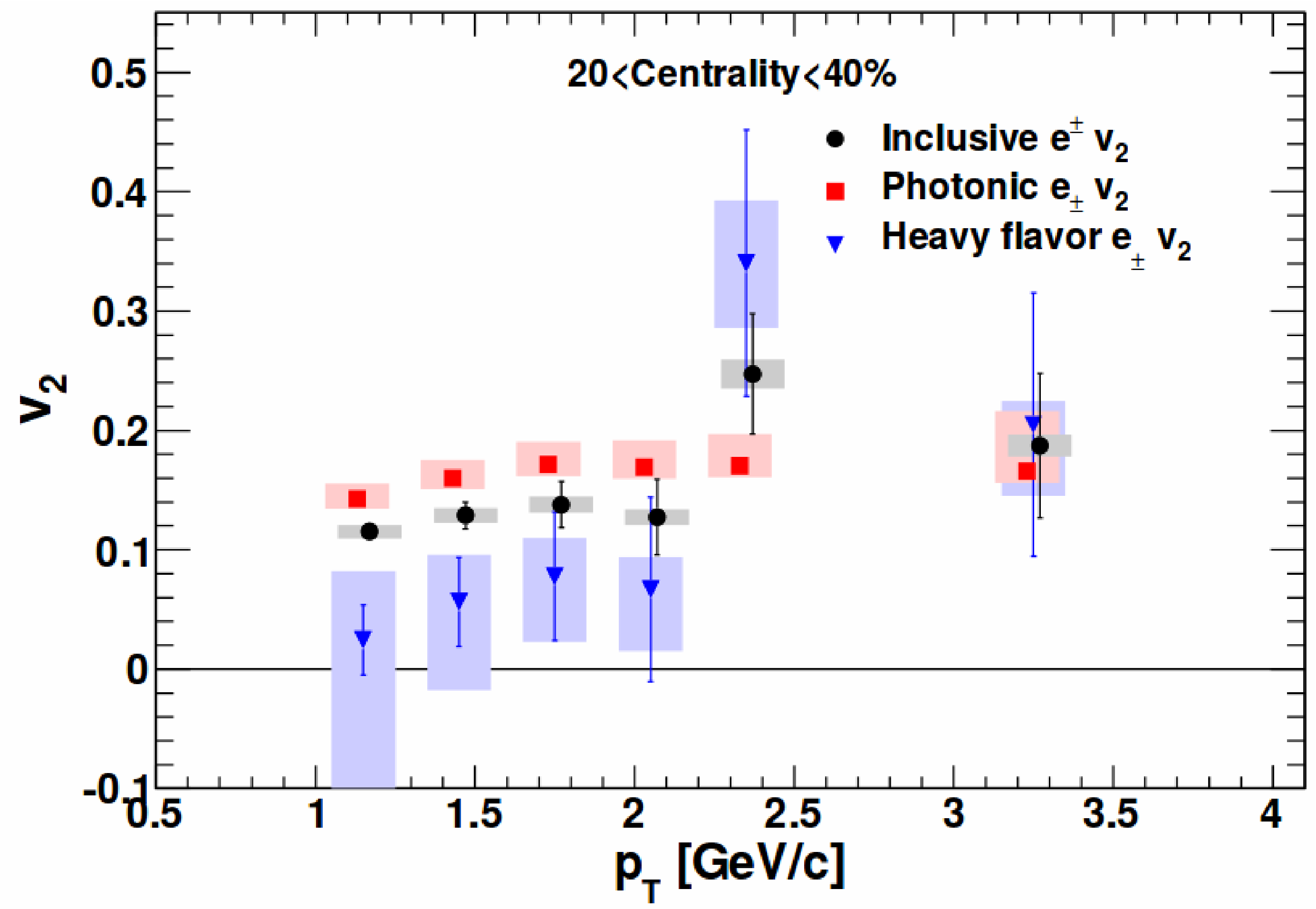
Phys.Rev.Lett.98:232301,2007

J/ψ

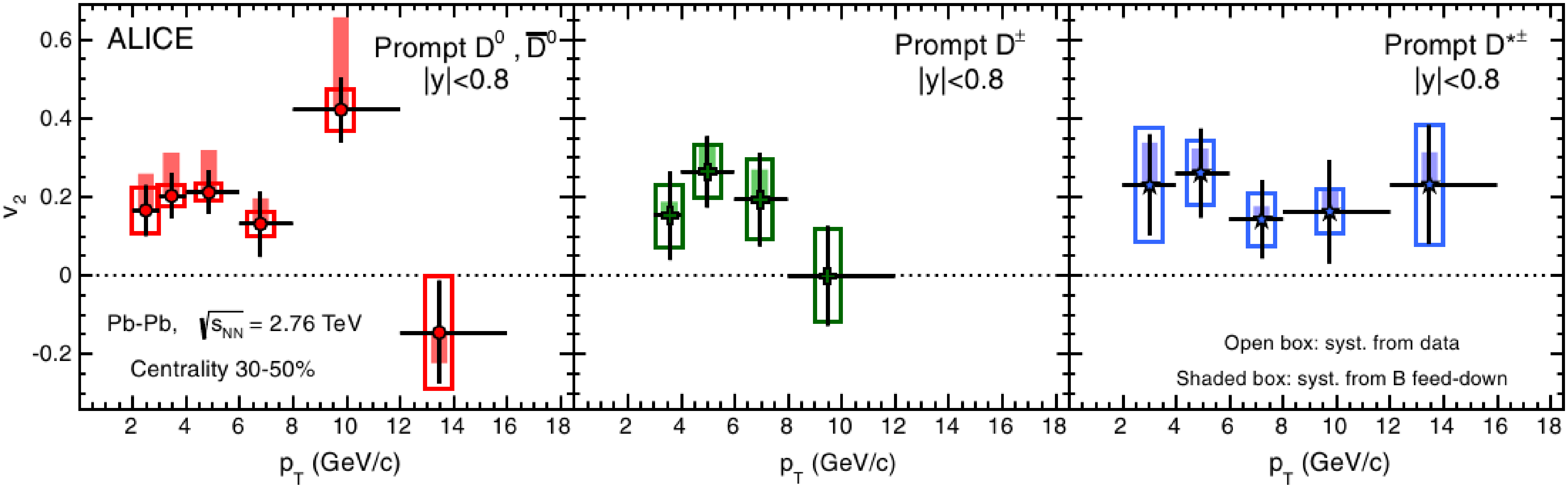

Inclusive J/ψ→e+e-
ALICE Preliminary, Pb-Pb, √sNN=2.76 TeV, |y|<0.8, centrality 0-40%
PHENIX, Au-Au, √sNN=0.2 TeV, |y|<0.35, centrality 0-40%
STAR, Au-Au, √sNN=0.2 TeV, |y|<1, centrality 0-60%
RAA
1.4
1.2
1
0.8
0.6
0.4
0.2
0
2
4
6
8
10
pT (GeV/c)


Pb-Pb √sNN = 2.76 TeV and Au-Au √sNN = 0.2 TeV
ALICE J/ψ → μ+μ-, 2.5<y<4, centrality 0%—20%
global syst. = ± 8%
PHENIX J/ψ → μ+μ-, 1.2<|y|<2.2, centrality 0%—20%
global syst. = ± 10%
RAA
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
2
3
4
5
6
7
8
pT (GeV/c)

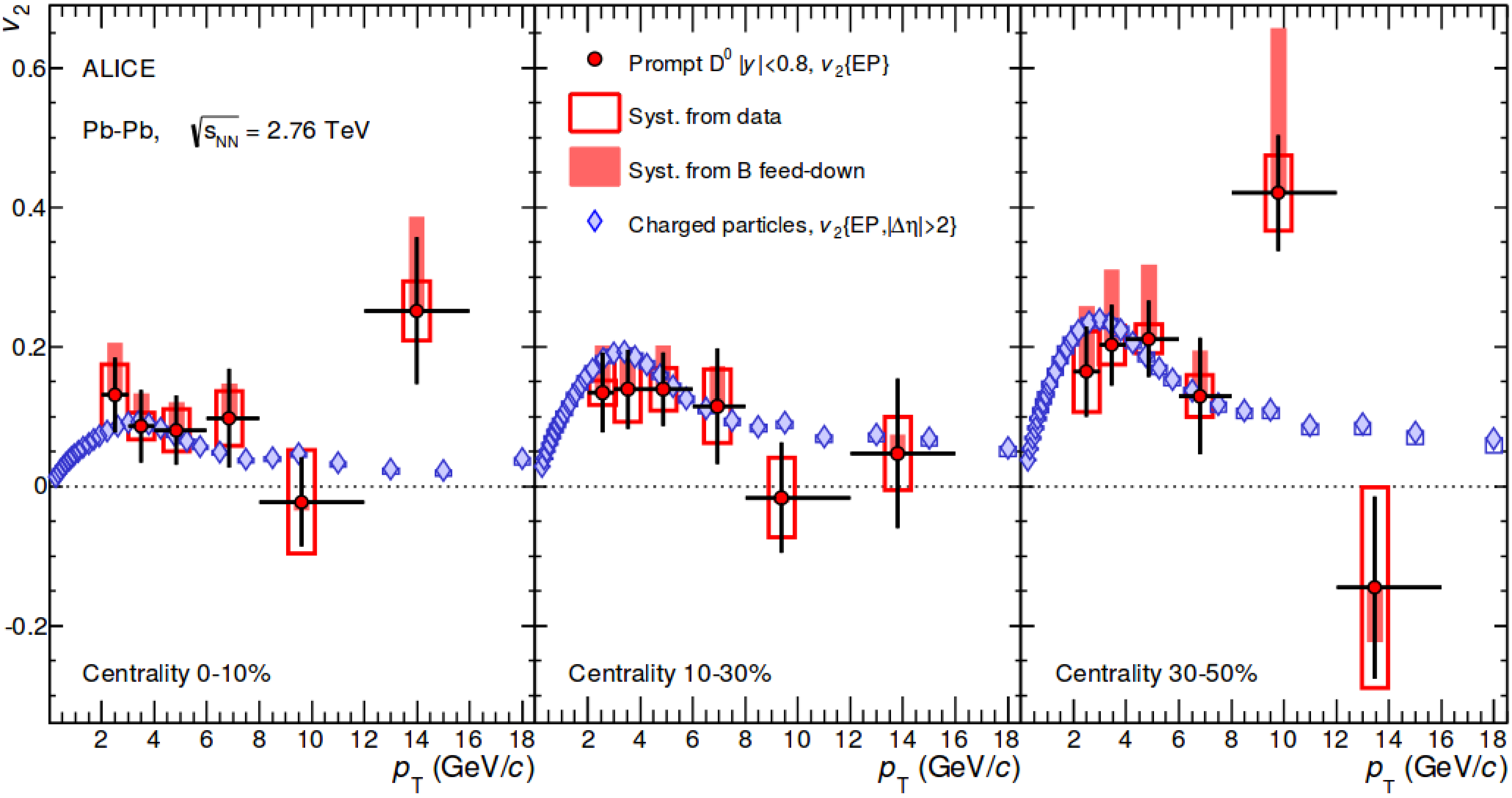
Au+AU 62.4 GeV



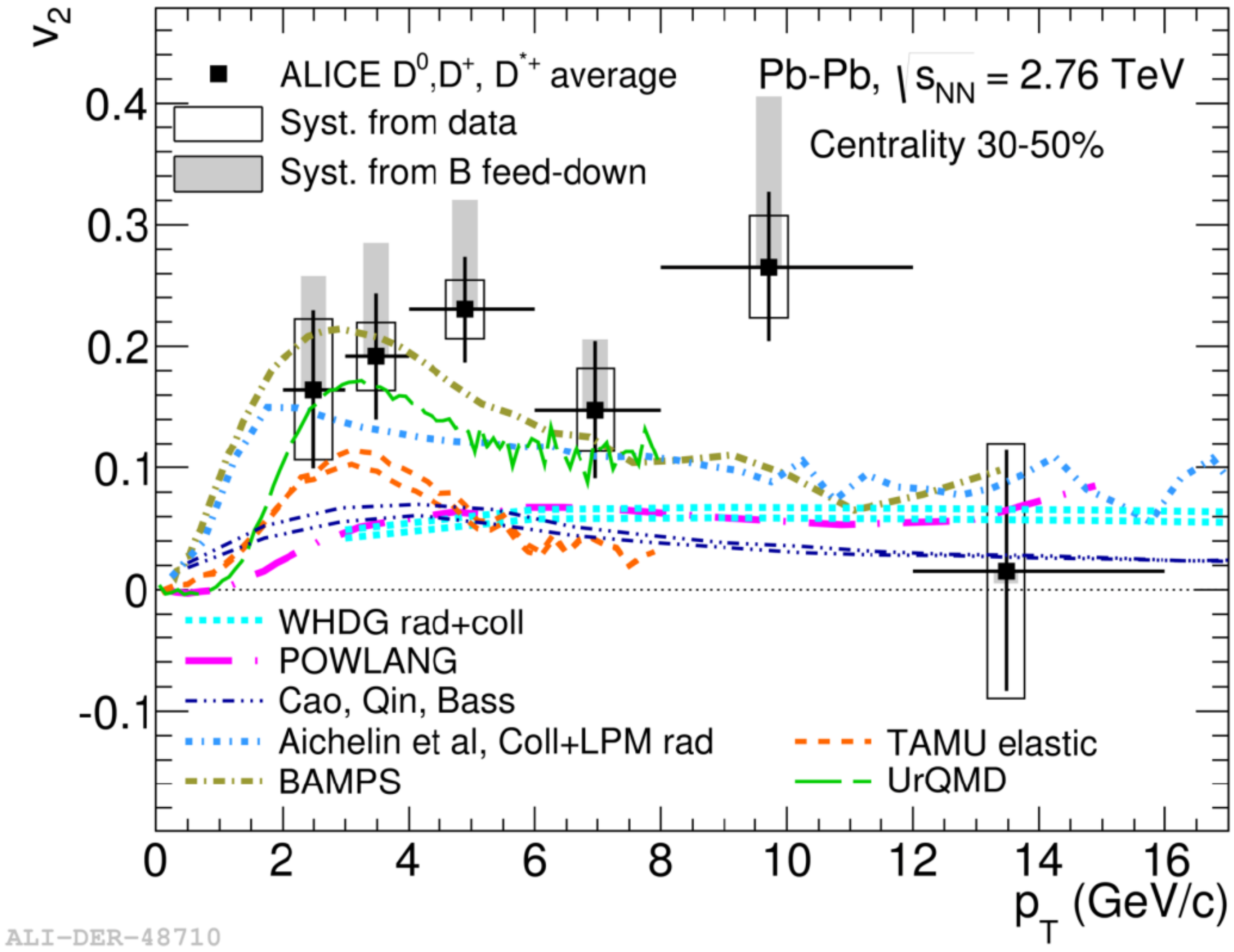
arxiv:1405.3301



PRL 111, 102301 (2013)



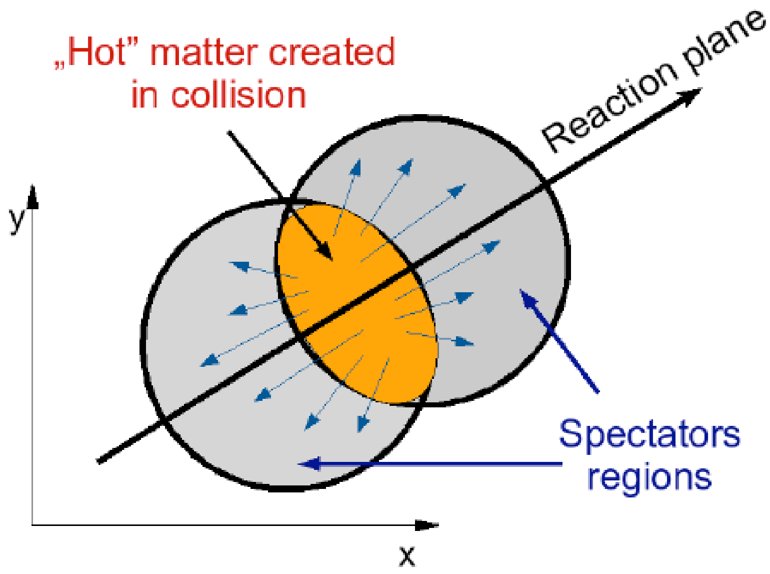
Phys. Rev. C 90 (2014) 034904



BAMPS – fragmentation – large v_2

TAMU – coalescence (at low p_T) → smaller v_2

→ results depend on mechanism employed



$$v_n \equiv \langle \cos n\phi \rangle = \frac{\int_0^{2\pi} \cos n\phi \frac{dN_j}{d^3\mathbf{p}} d\phi}{\int_0^{2\pi} \frac{dN_j}{d^3\mathbf{p}} d\phi}$$

Two-particle distribution = sum of an uncorrelated distribution and two-particle (direct) correlations

$$\frac{dN_{jk}}{d^3\mathbf{p_1} d^3\mathbf{p_2}} = \frac{dN_j}{d^3\mathbf{p_1}} \frac{dN_k}{d^3\mathbf{p_2}} \left(1 + C_{jk}(\mathbf{p}_1, \mathbf{p}_2)\right)$$

$$\langle \cos n(\phi_1 - \phi_2) \rangle = \upsilon_n^2 + nonflow$$

nonflow: jets, resonance decays, HBT ..

If nonflow $\delta \approx 0$ and negligible fluctuations ($\sigma \approx 0$):

Using 2-particle correlations: $\upsilon_n\{2\}^2 = \langle \cos n(\phi_1 - \phi_2) \rangle = \langle \upsilon_n \rangle^2$

Using 4-particle correlations:

$$\upsilon_n\{4\}^4 = 2\langle \cos n(\phi_1 - \phi_2) \rangle - \langle \cos n(\phi_1 + \phi_2 - \phi_3 - \phi_4) \rangle$$
$$= 2\langle \upsilon_n^2 \rangle^2 - \langle \upsilon_n \rangle^4 = \langle \upsilon_n \rangle^4$$

If nonflow $\delta \neq 0$ and non-negligible fluctuations ($\sigma \neq 0$):

$$\upsilon_n\{2\}^2 = \langle \upsilon_n^2 \rangle + \sigma^2 + \delta$$
$$\upsilon_n\{4\}^4 = (\langle \upsilon_n \rangle^2 + \sigma^2)^2 - 2\sigma^4$$

L. Yi, et al. arxiv: 1101.4646
(assuming Gaussian fluctuations)

→ upper and lower limit on elliptic flow

Initial k_T broadening

Arises from multiple scattering of the projectile partons in the target:

$$\langle k_T^2 \rangle_A = \langle k_T^2 \rangle_p + (\langle \nu \rangle - 1)\Delta^2(\mu)$$

$$\langle k_T^2 \rangle_p = 1 \text{ GeV}^2$$

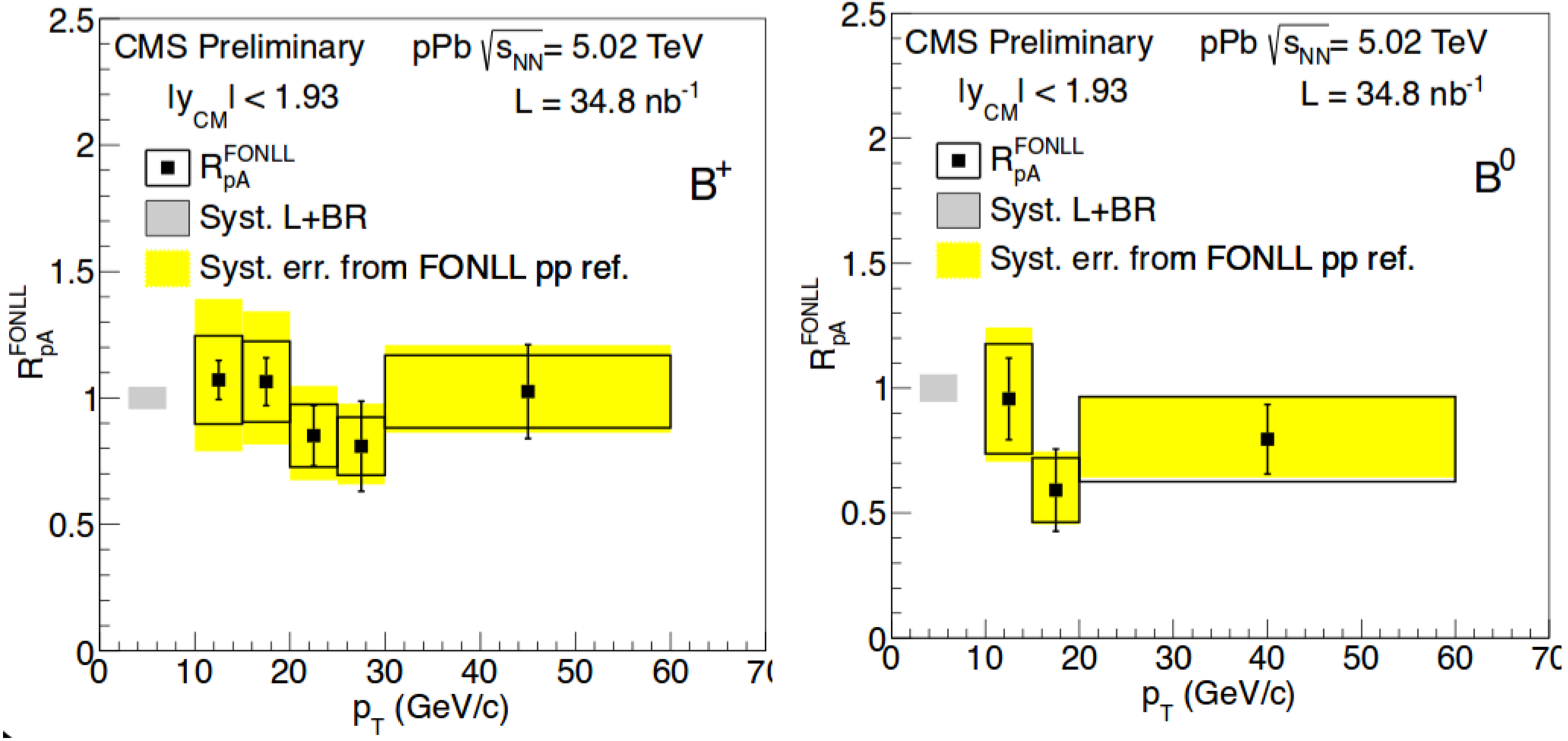
$$\langle \nu \rangle = \sigma_{NN} \frac{\int d^2b \, T_A^2(b)}{\int d^2b \, T_A(b)} = \frac{3}{2}\sigma_{NN}\rho_0 R_A$$

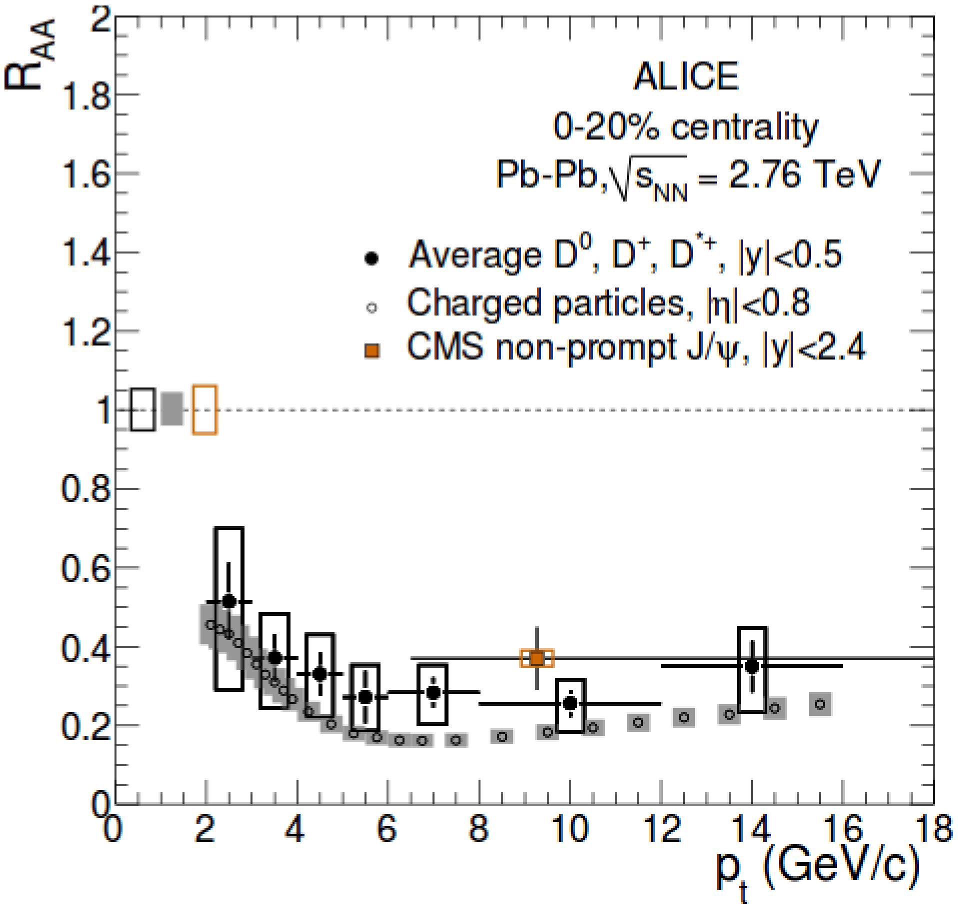
number of collisions
in a p-A interaction

$$\Delta^2(\mu) = 0.225 \frac{\ln^2(\mu/\text{GeV})}{1 + \ln(\mu/\text{GeV})} \text{GeV}^2$$

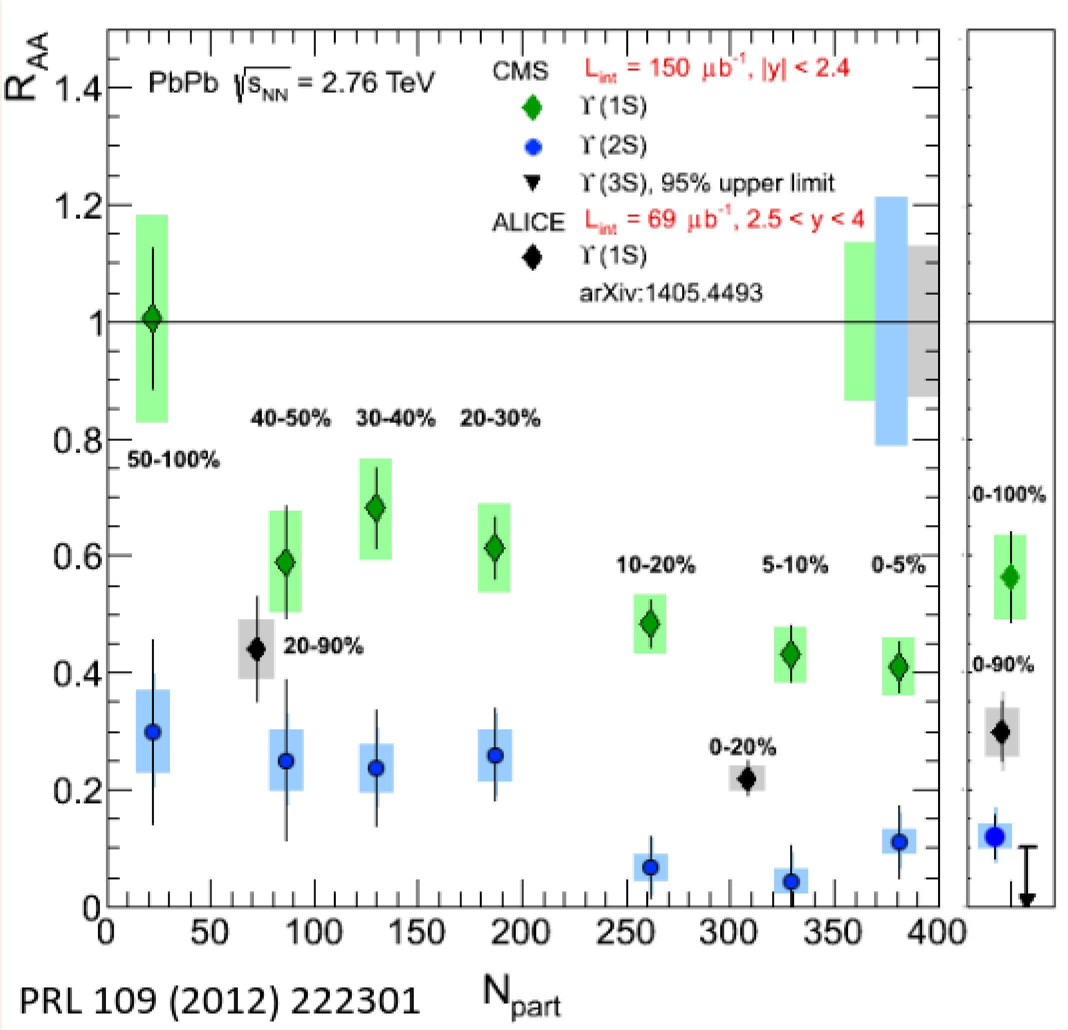
$\mu = 2m_Q$ - scale, m_c = 1.2 GeV

Bottom R_{pA} at LHC





JHEP 09 (2012) 112



PRL 109 (2012) 222301