Open heavy flavor production at STAR

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INNOVATIVE ECONOMY
NATIONAL COHESION STRATEGY

FNP
Foundation for Polish Science

EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND

Top RHIC energy: QGP properties

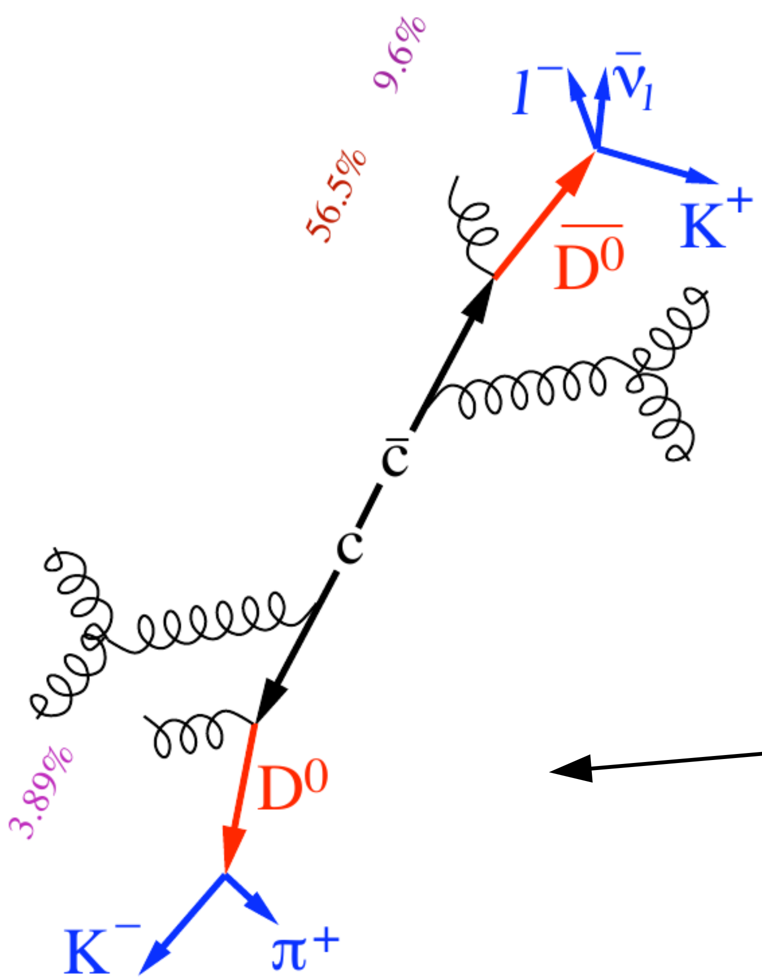
→ Energy loss, degree of thermalization (charm flow)

Heavy flavor production vs energy

→ Study of QCD phase diagram

→ Is nuclear medium similar/different at 200 GeV and 62 and 39 GeV?

Open heavy flavor at STAR



Courtesy of David Tlusty

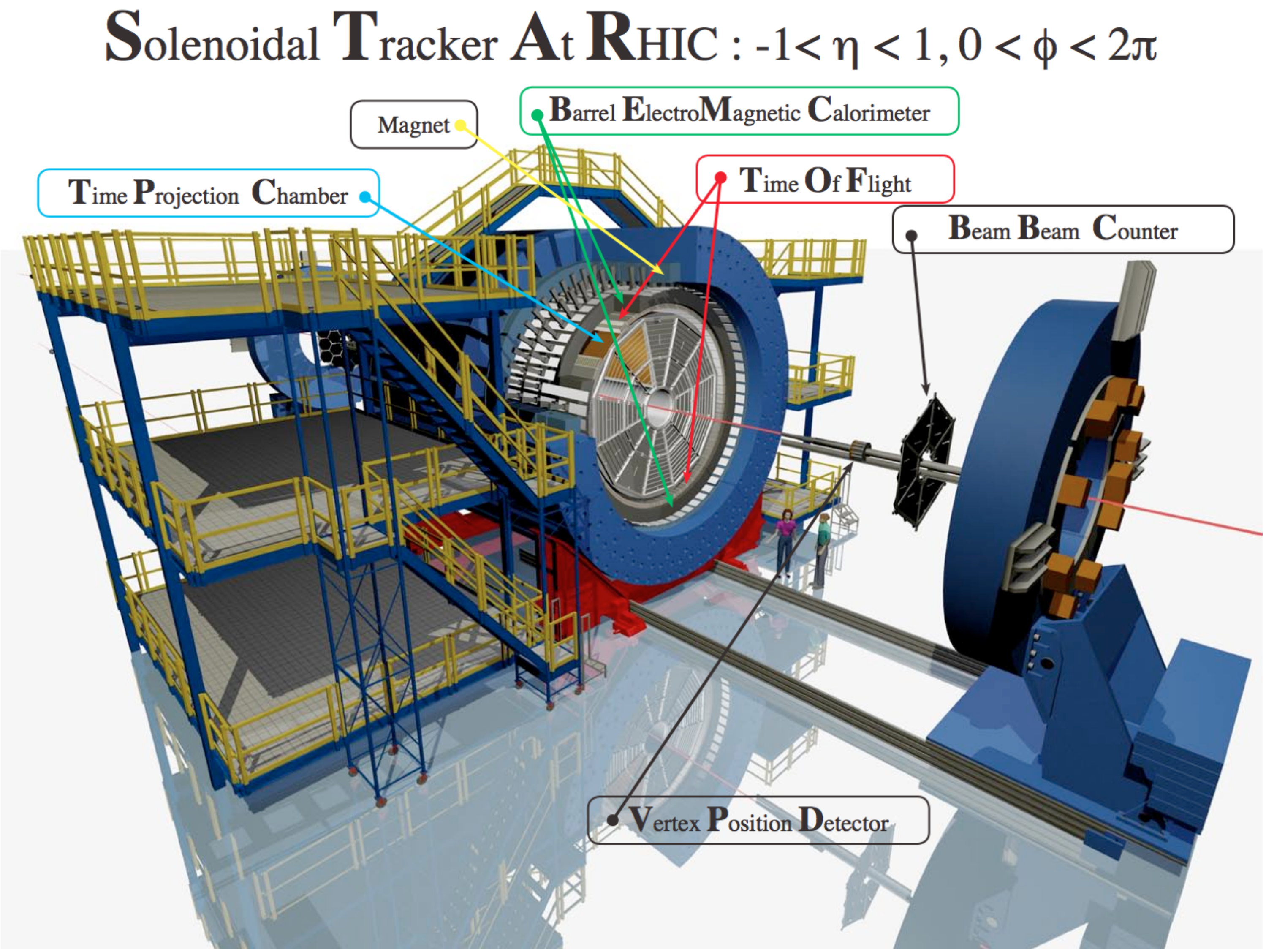
Electrons from semi-leptonic heavy flavor hadron decays (Non-photonic electrons)

- high p_T reach
- indirect access to the parent hadron kinematics

<u>Direct open charm reconstruction</u>

- direct access to the heavy meson kinematics
- large background without vertex detector
- difficult to trigger

The STAR detector



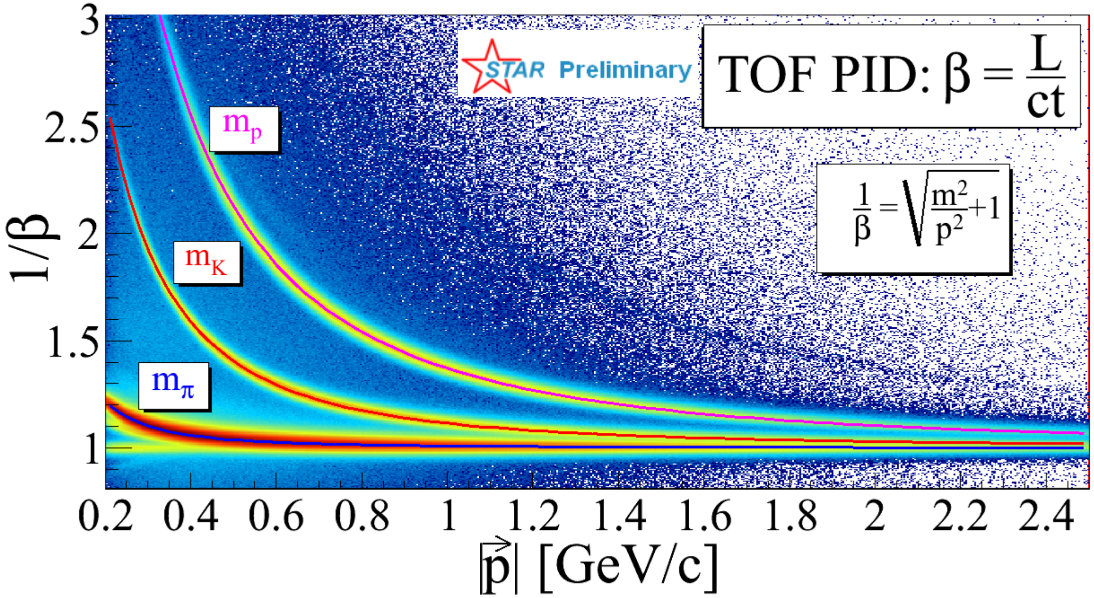
VPD: minimum bias trigger.

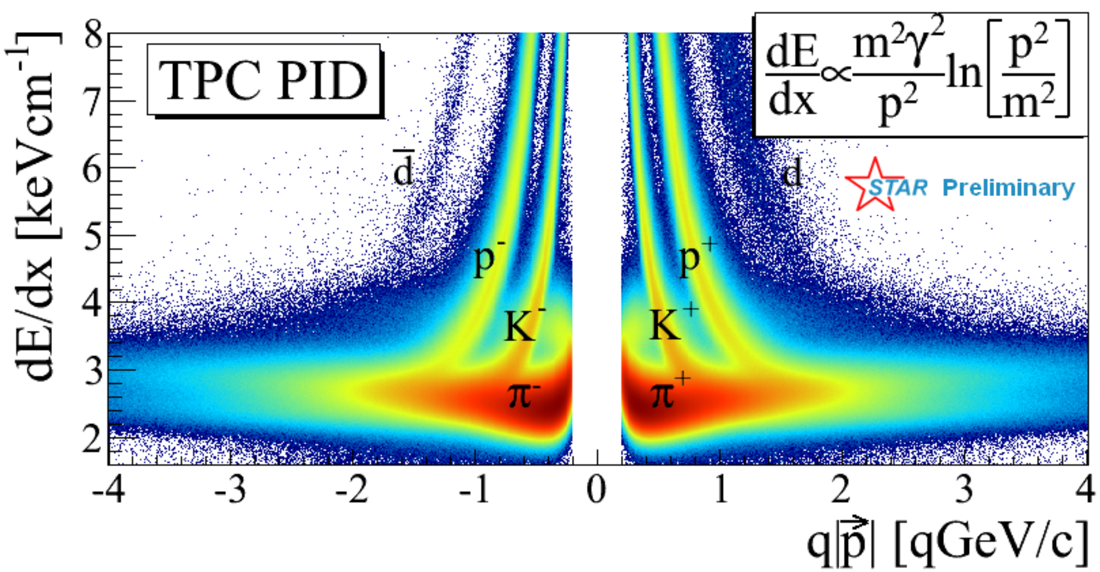
TPC: PID via dE/dx, tracking

TOF: PID.

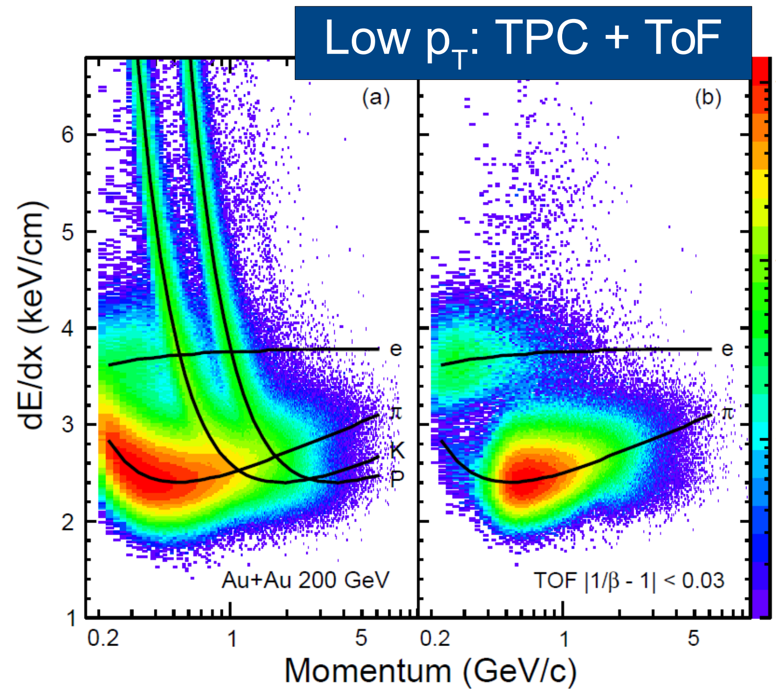
BEMC: PID via E/p, fast online trigger

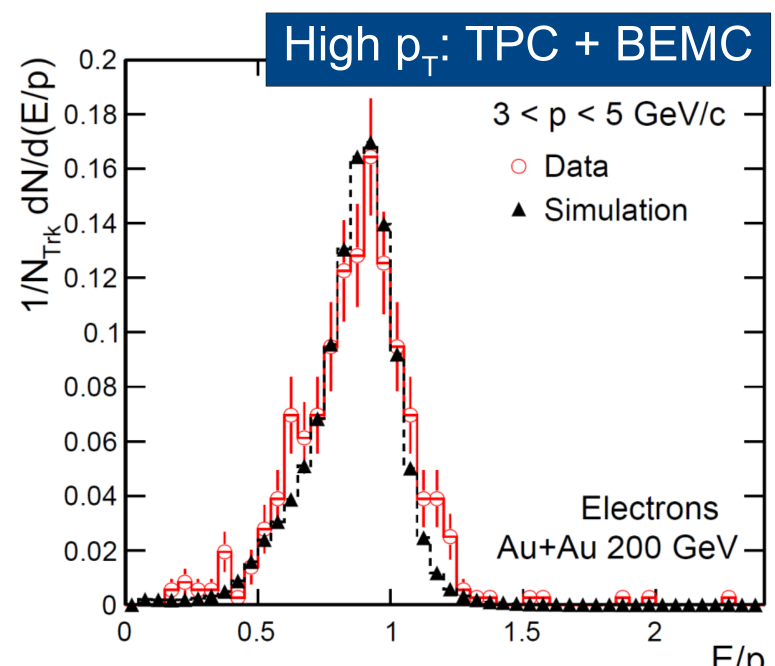
Particle Identification at STAR





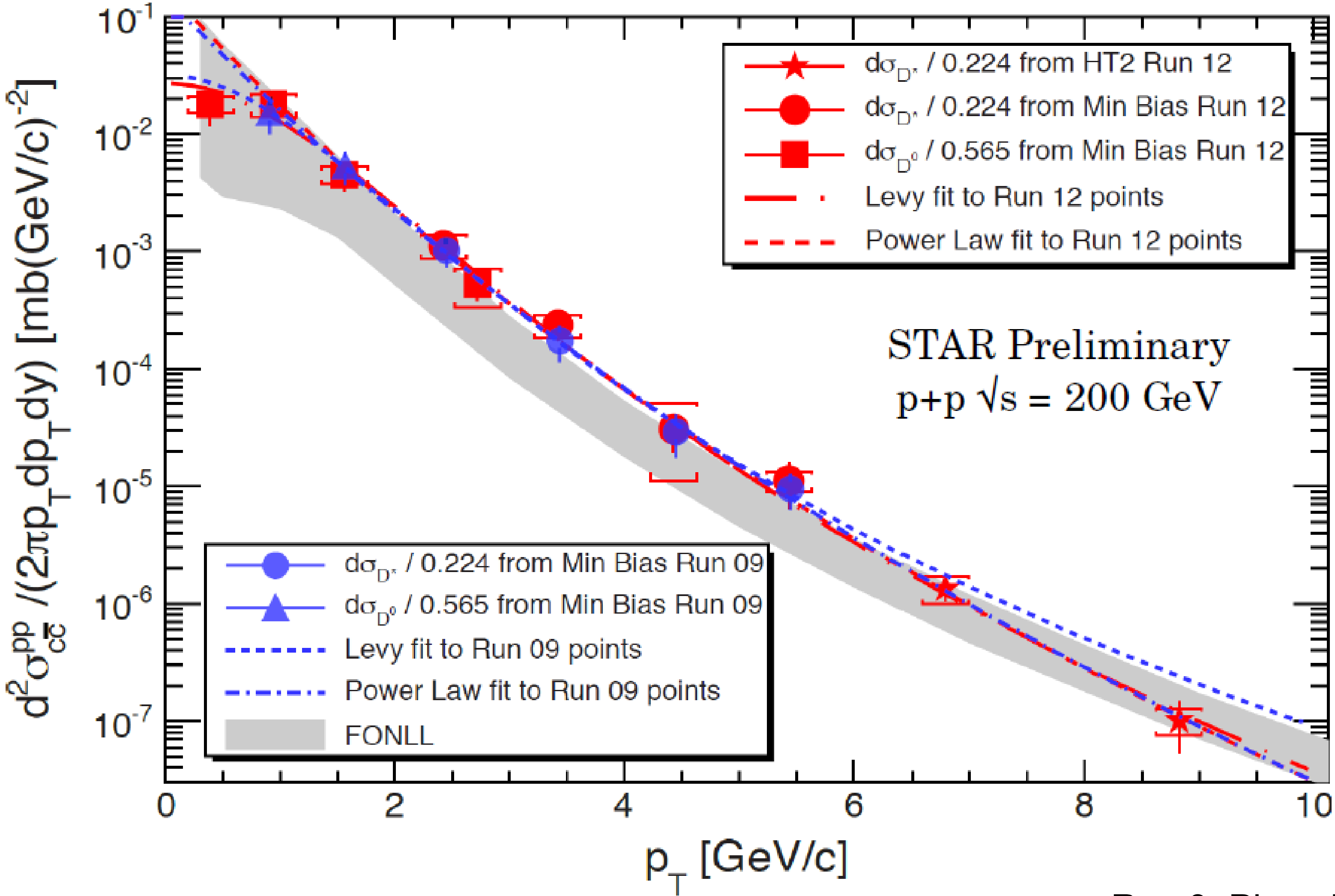
Electron Identification





Heavy flavor in p+p and A+A 200 GeV

D^0, D* p_T spectra in p+p 200 GeV



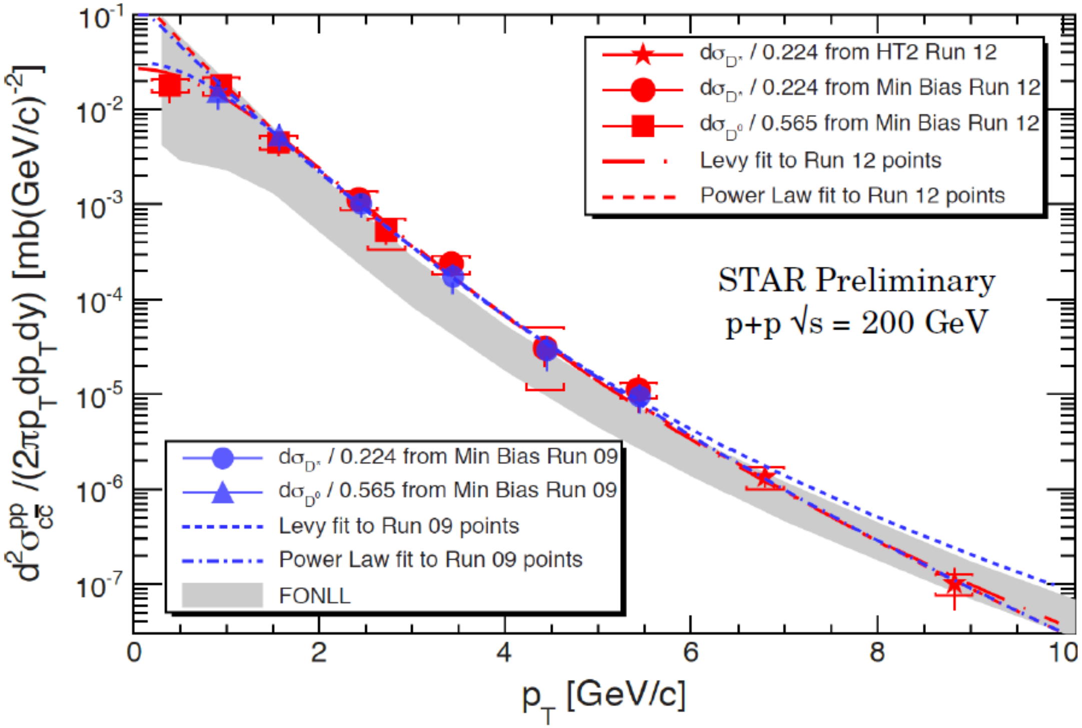
Run 9: Phys. Rev. D 86 (2012) 72013

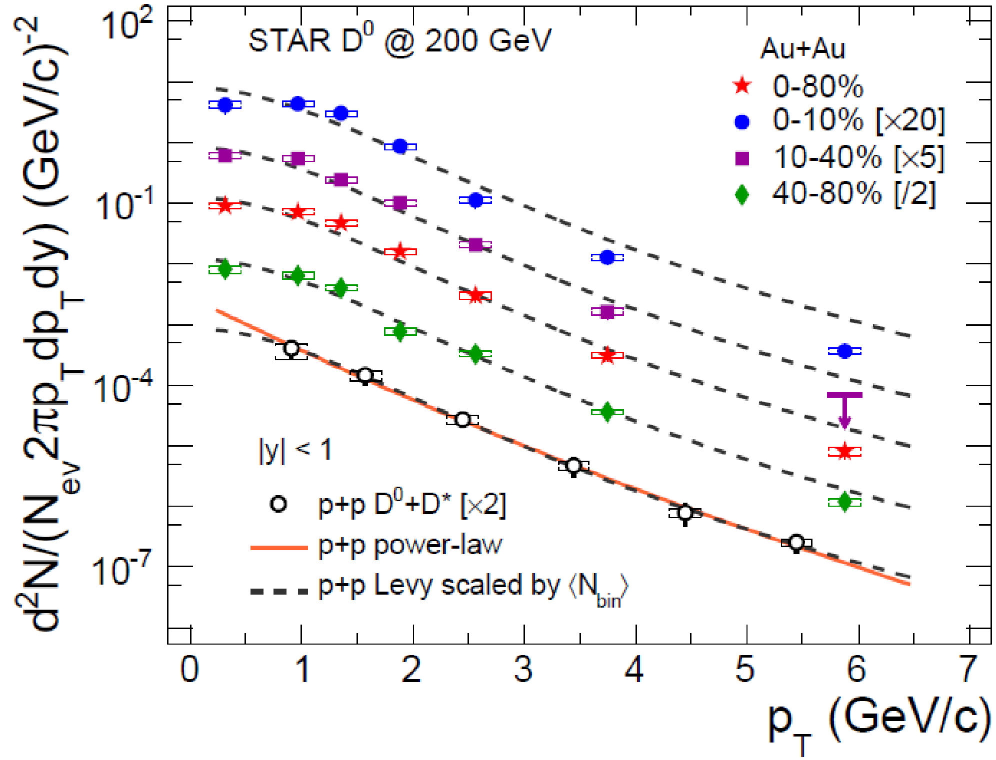
Run 12: STAR Preliminary

(FONLL: Fixed Order plus Next-to-Leading Logarithms calculation, μ_F = μ_R = m_c, $|y| < 1$, *R. Nelson, R. Vogt, A. D. Frawley, arXiv: 1210.4610*)

New low p_T (0-0.7 GeV/c) measurement constrains the total charm cross-section. Results consistent with FONLL upper limit.

D^0, D^* p_T spectra in p+p and Au+Au 200 GeV



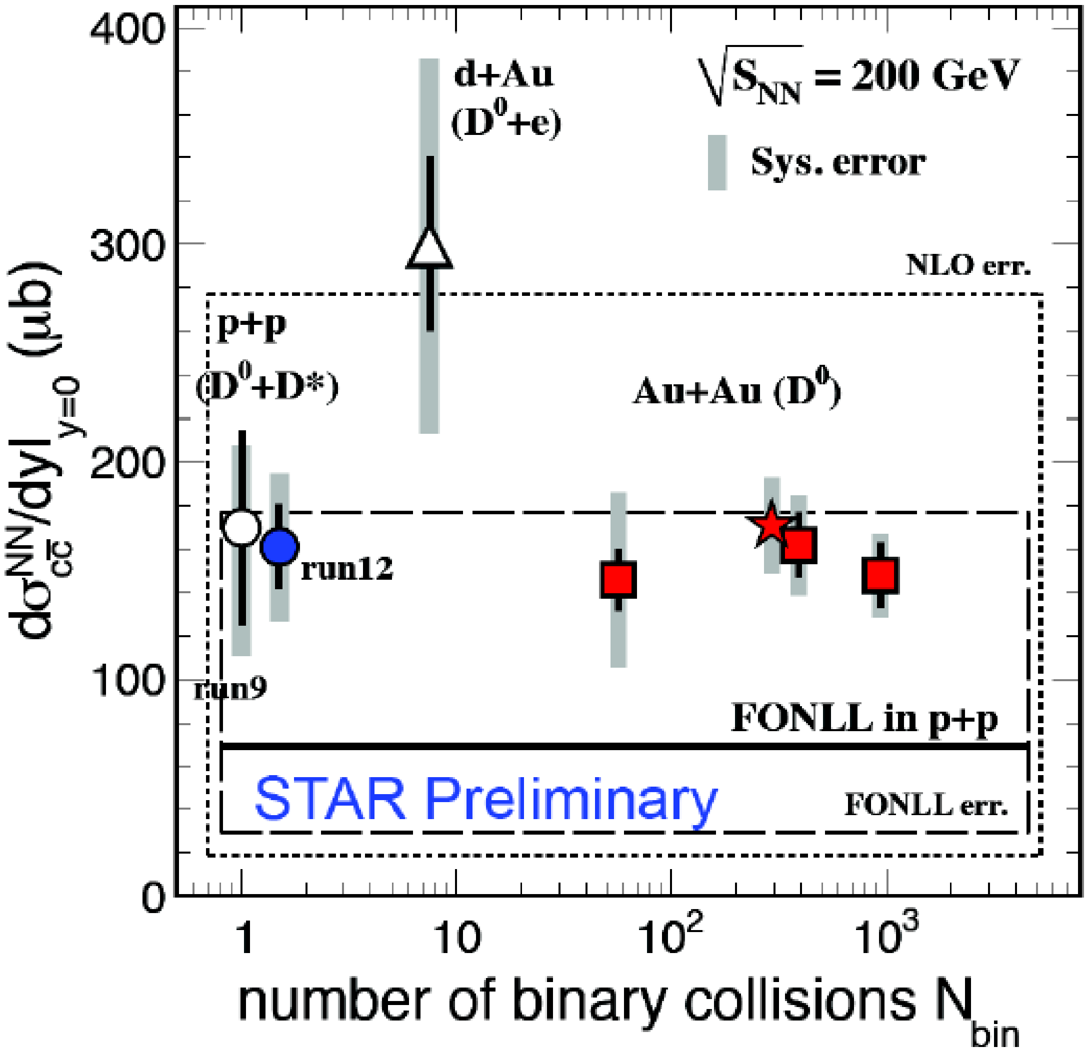


Run 9: Phys. Rev. D 86 (2012) 72013

Run 12: STAR Preliminary

arXiv:1404.6185, submitted to PRL

Charm cross section at 200 GeV



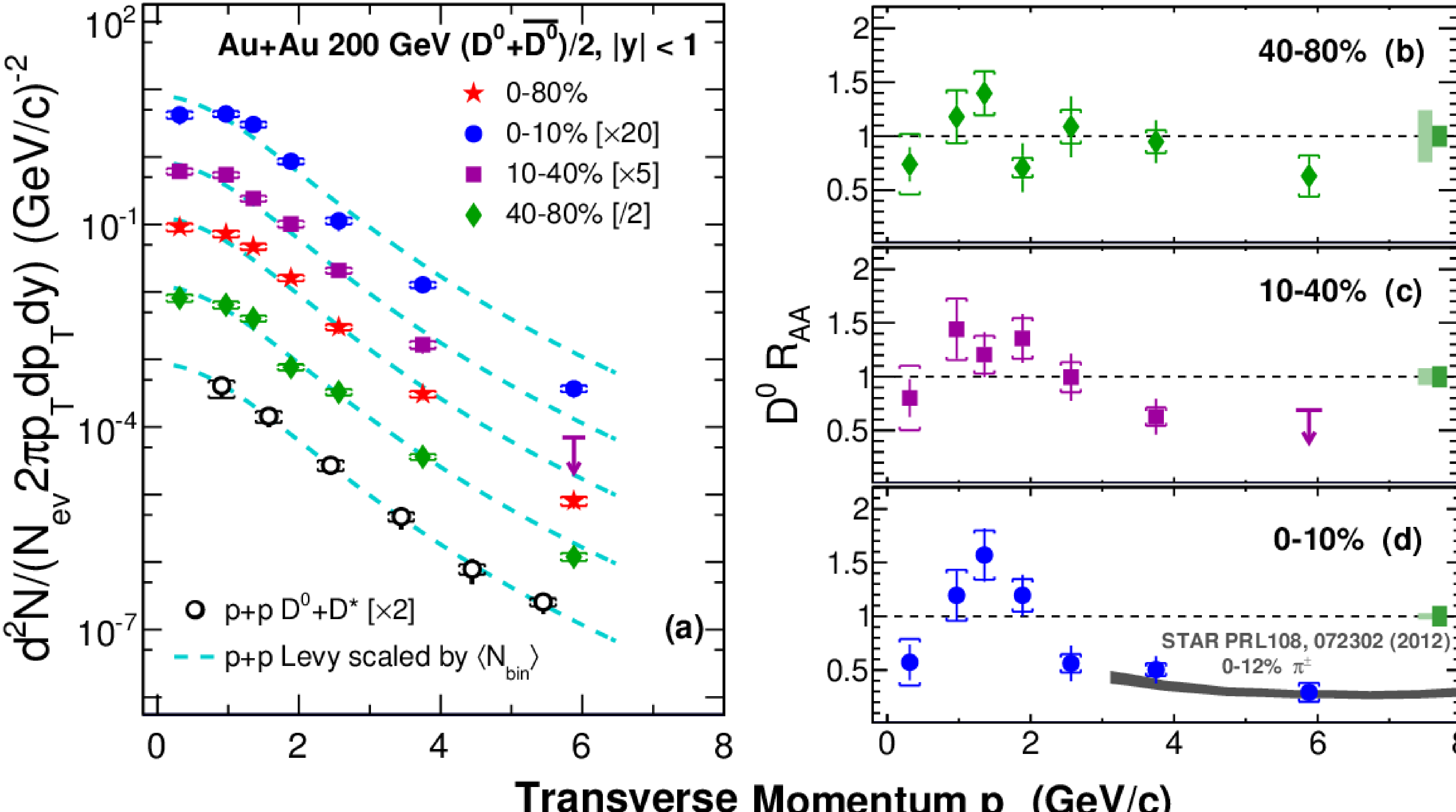
Charm cross section follows N_{bin} scaling

→ 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

D^0 in Au+Au at 200 GeV

arXiv:1404.6185, submitted to PRL

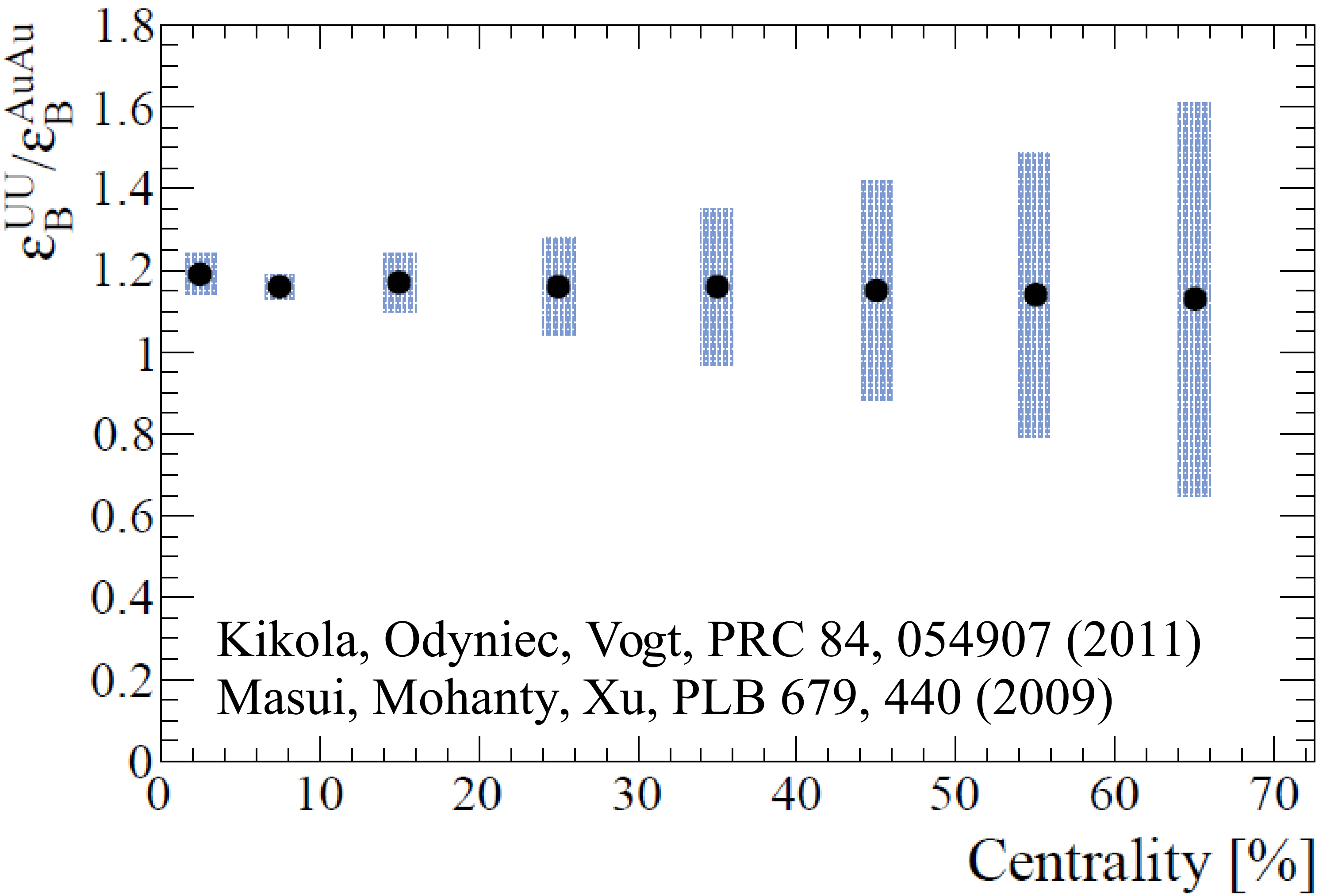


Suppression at high p_T in central and mid-central collisions.

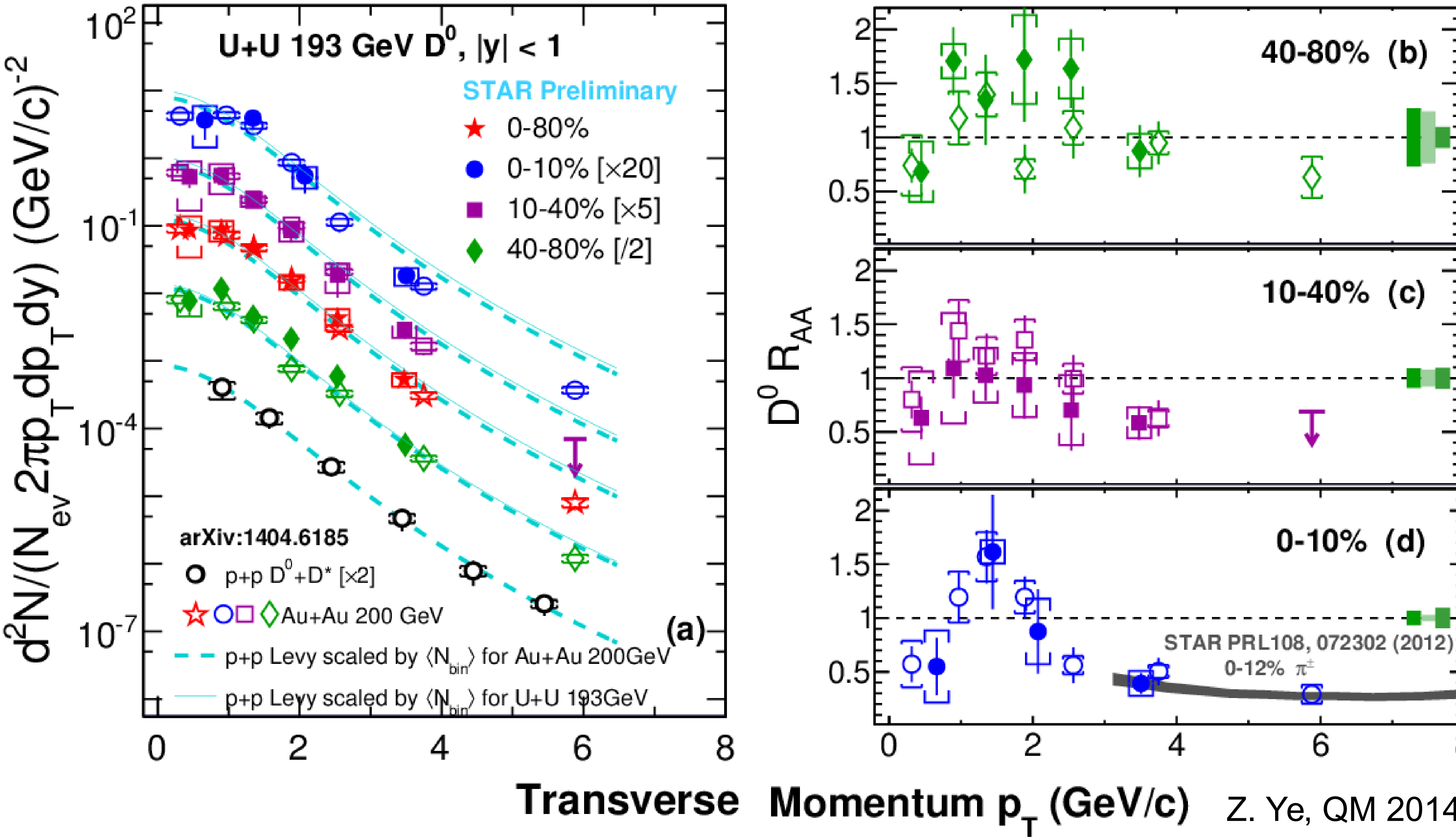
Enhancement at intermediate p_T

Au+Au vs U+U collisions

U+U: 20% increase of energy density



D^0 in Au+Au and U+U at 200 GeV

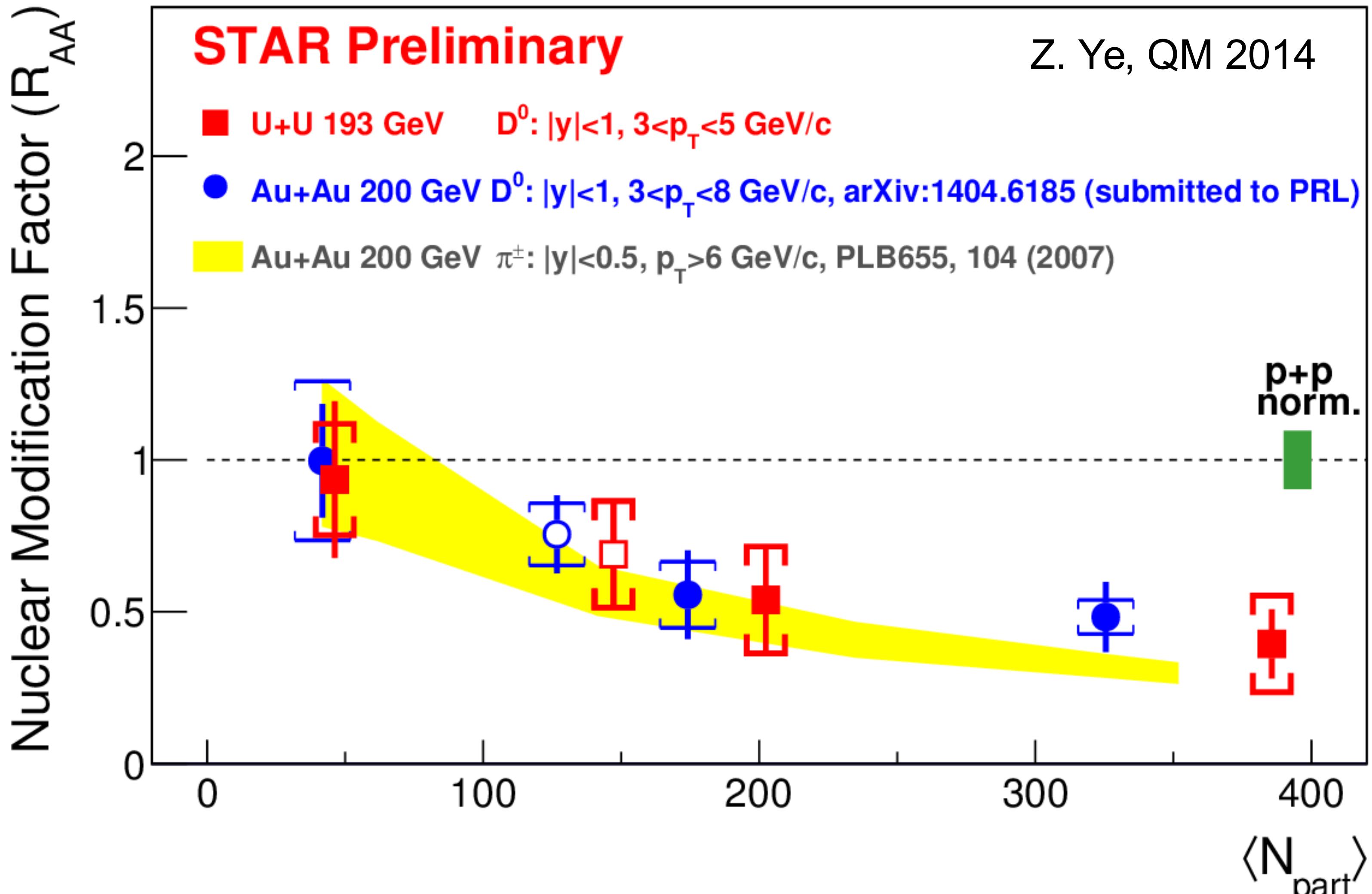


Z. Ye, QM 2014

Suppression at high p_T in central and mid-central collisions.

Enhancement at intermediate p_T

High p_T suppression at RHIC

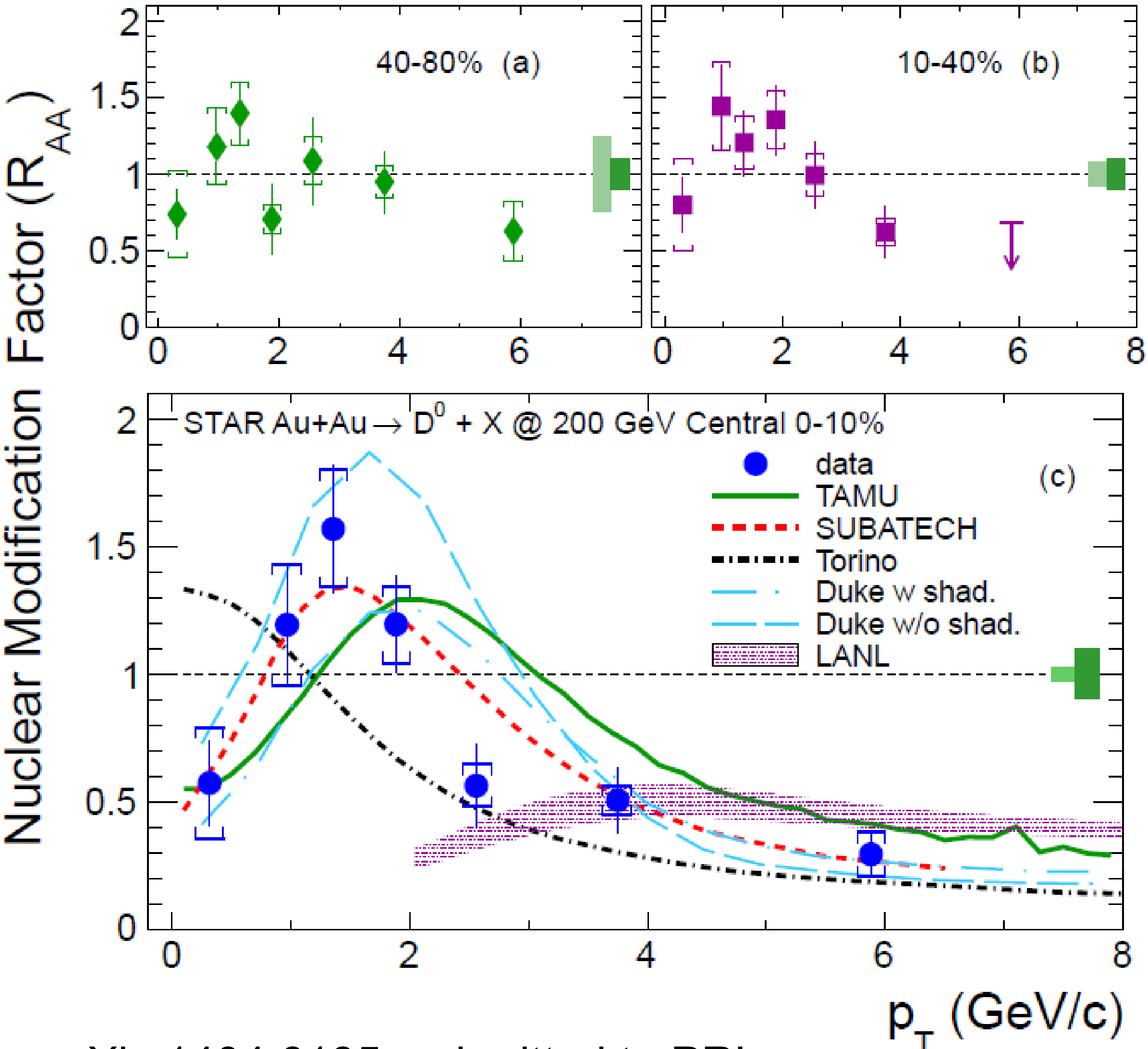


D^0: Similar suppression in U+U and Au+Au collisions

Similar trend vs system size as for pions

D^0 suppression suggests strong charm-medium interaction

D^0 R_{AA} in Au+Au 200 GeV vs models



arXiv:1404.6185, submitted to PRL

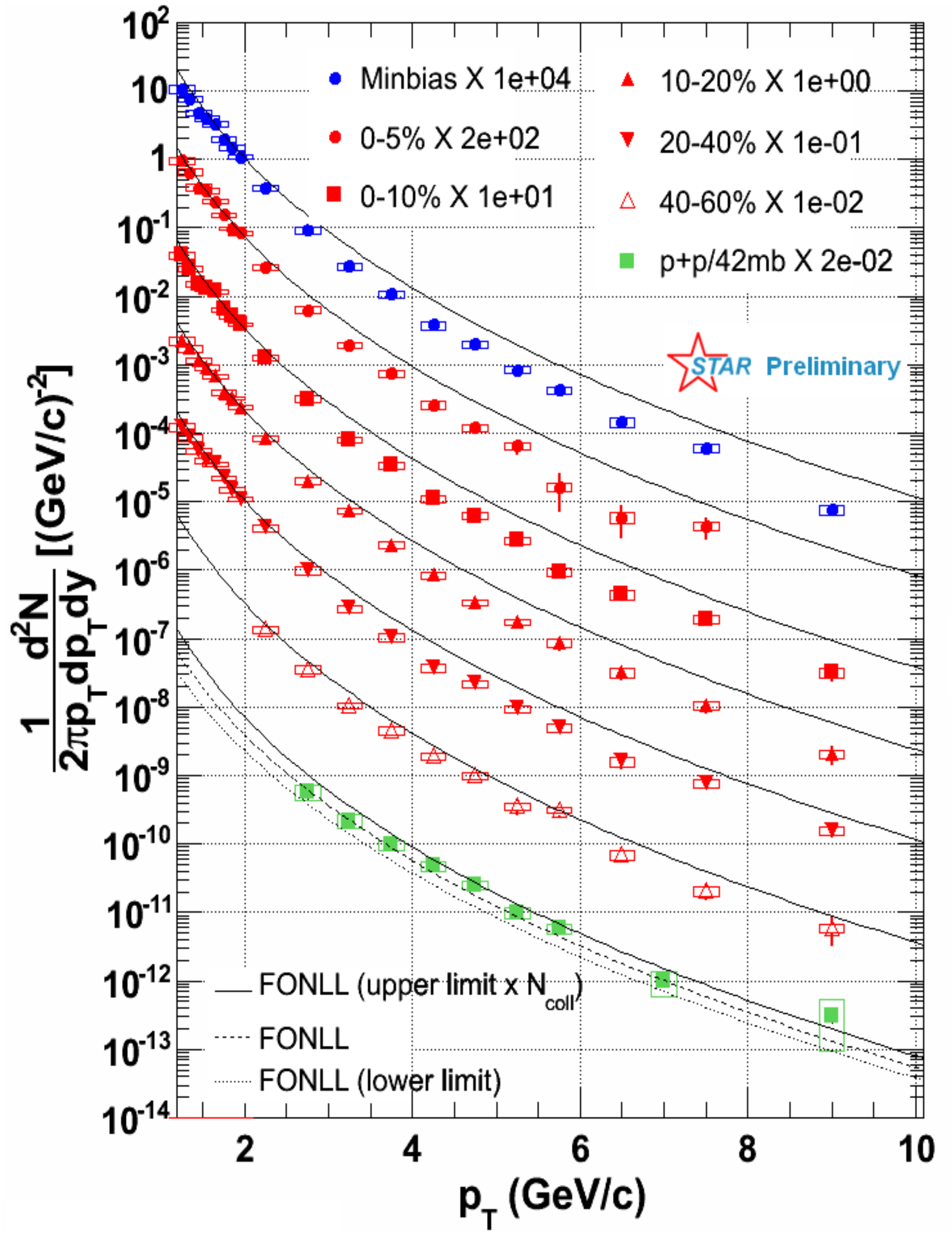
Models with strong charm-medium interaction and fragmentation+coalescence hadronization reproduce suppression at high p_T and enhancement at intermediate p_T.

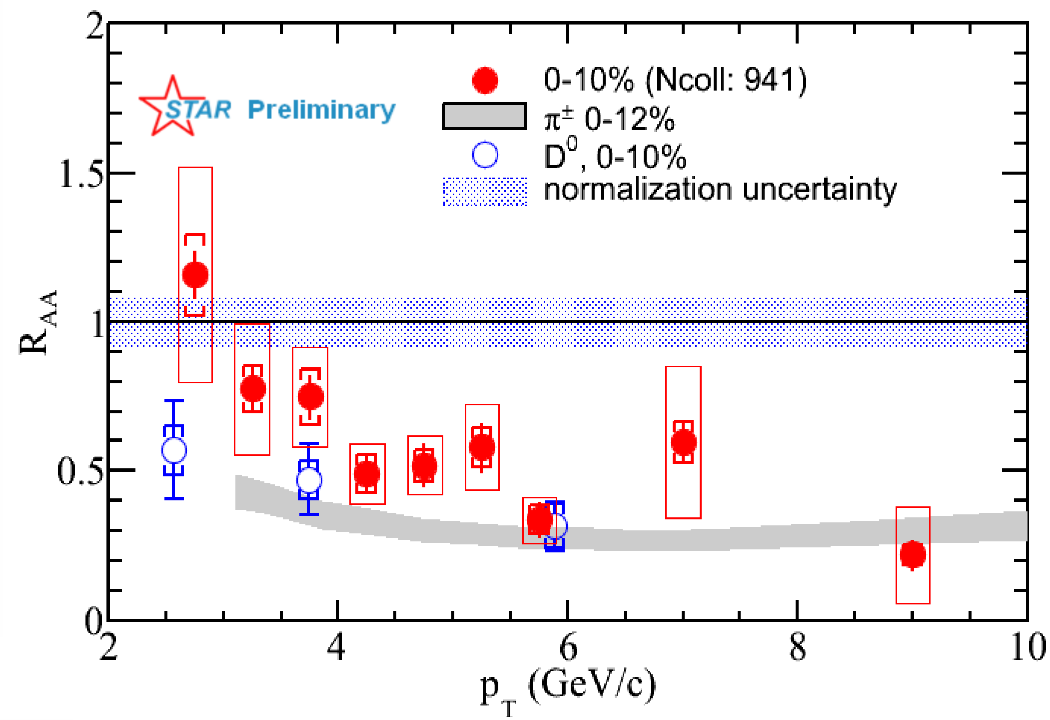
Torino model with hadronization through fragmentation only doesn't reproduce the “bump”.

LANL energy loss model with mesons dissociation also reproduce the observed suppression.

Do CNM effects contribute to observed enhancement ?

Non-photonic electrons in Au+Au 200 GeV

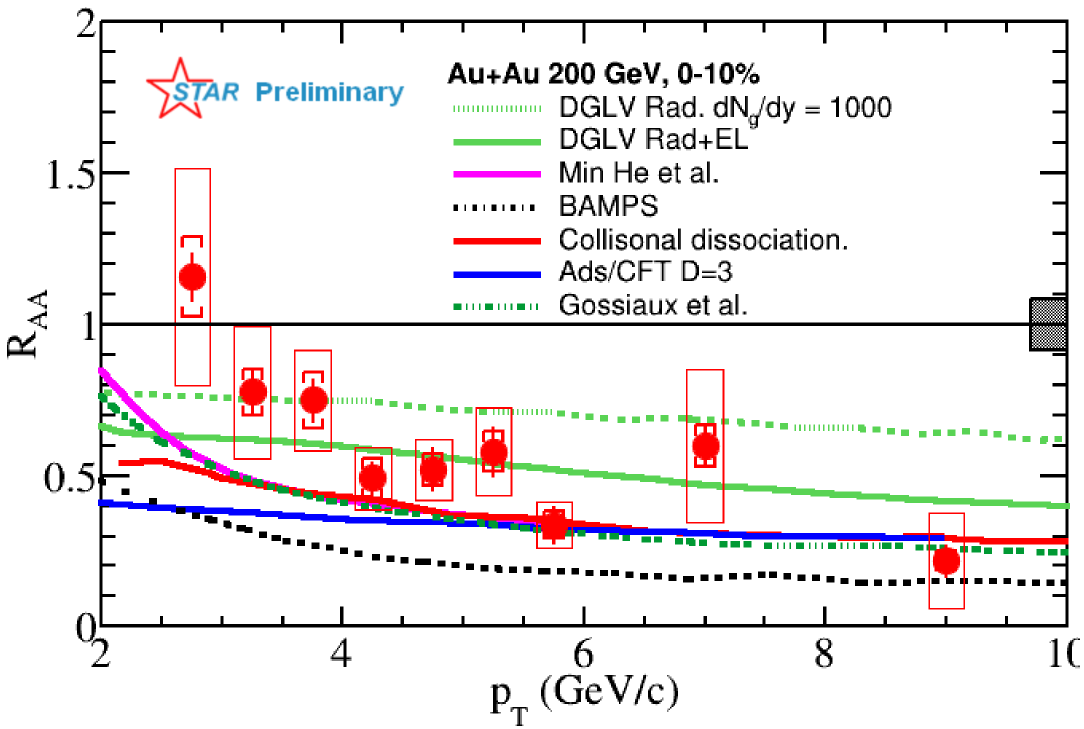


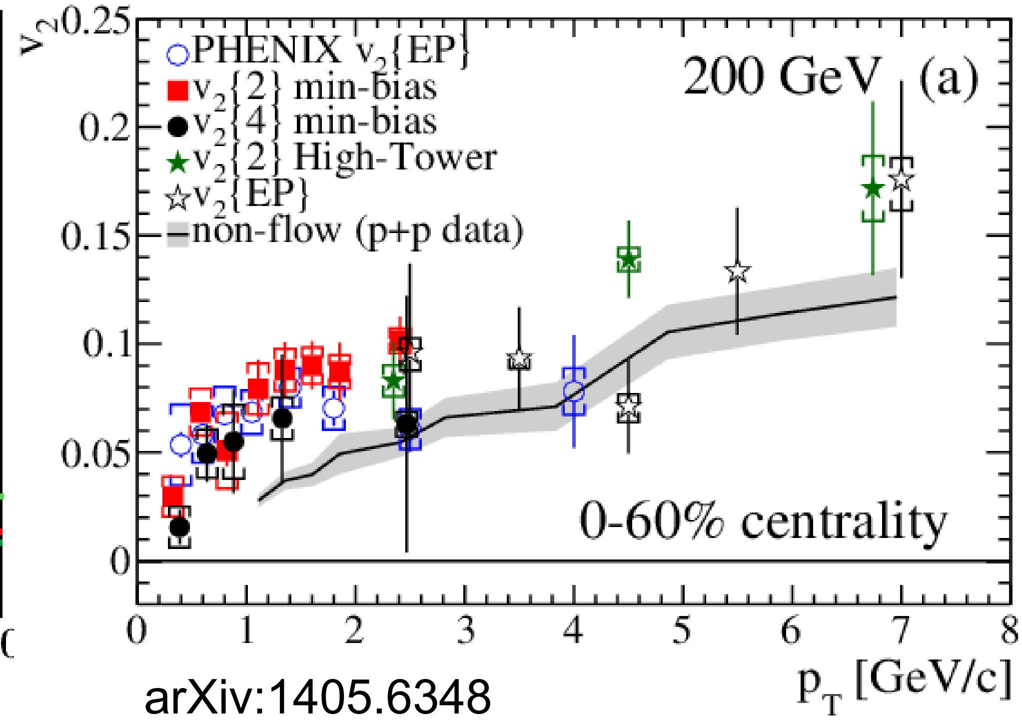


Strong suppression at high p_T in central collisions

D^0 and NPE suppression are similar

NPE v_2 and R_{AA} in Au+Au 200 GeV

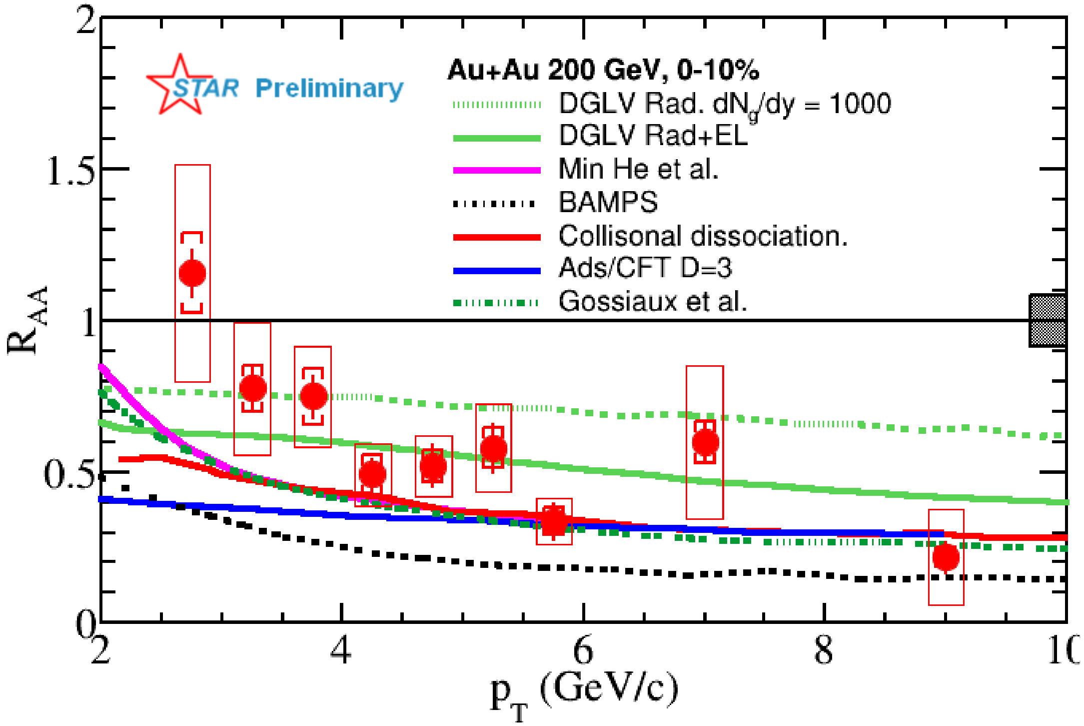


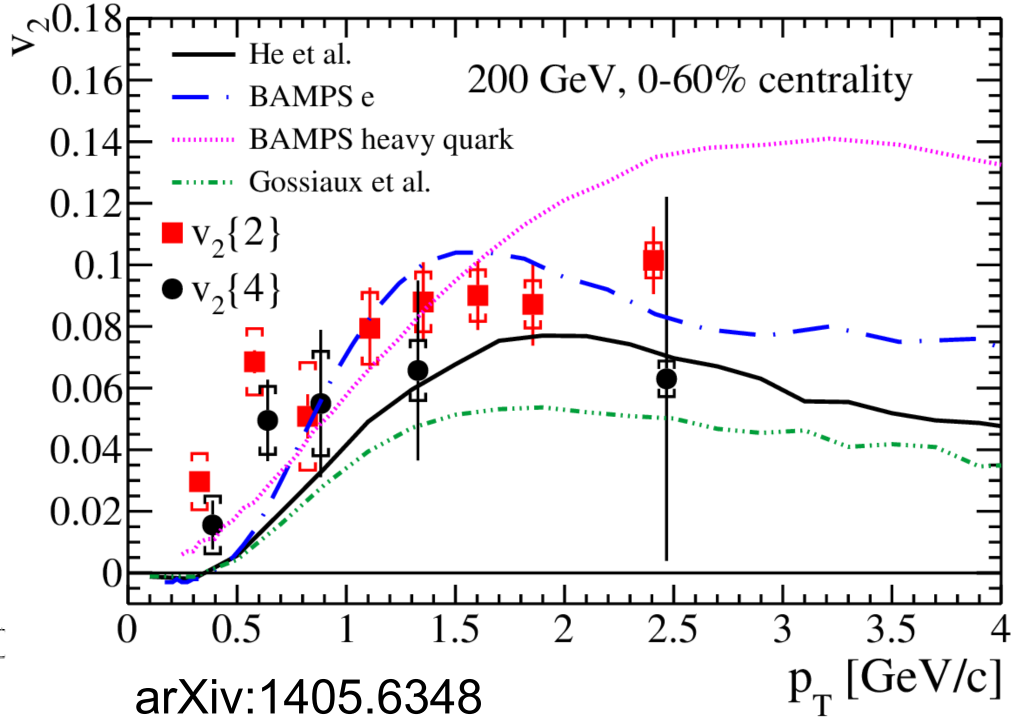


- Data disfavor radiative energy loss as the only energy loss mechanism
- Finite v_2 at low and intermediate p_T
- Increase of v_2 at high p_T likely due to jet-like correlation

DGLV: Djordjevic, PLB632, 81 (2006), **BAMPS**: arXiv:1205.4945.
He et al.: PRC 86, 014903 (2012), **Coll. Dissoc.** R. Sharma et al., PRC 80, 054902(2009).
Ads/CFT: W. Horowitz Ph.D thesis, **Gossiaux et al.** : PRC 78, 014904 (2008)

NPE v_2 and R_{AA} in Au+Au 200 GeV





arXiv:1405.6348

- Data disfavor radiative energy loss as the only energy loss mechanism
- Finite v_2 at low and intermediate p_T
- Increase of v_2 at high p_T likely due to jet-like correlation
- Difficult to describe suppression and v_2 simultaneously

DGLV: Djordjevic, PLB632, 81 (2006), **BAMPS**: arXiv:1205.4945.
He et al.: PRC 86, 014903 (2012), **Coll. Dissoc.** R. Sharma et al., PRC 80, 054902(2009).
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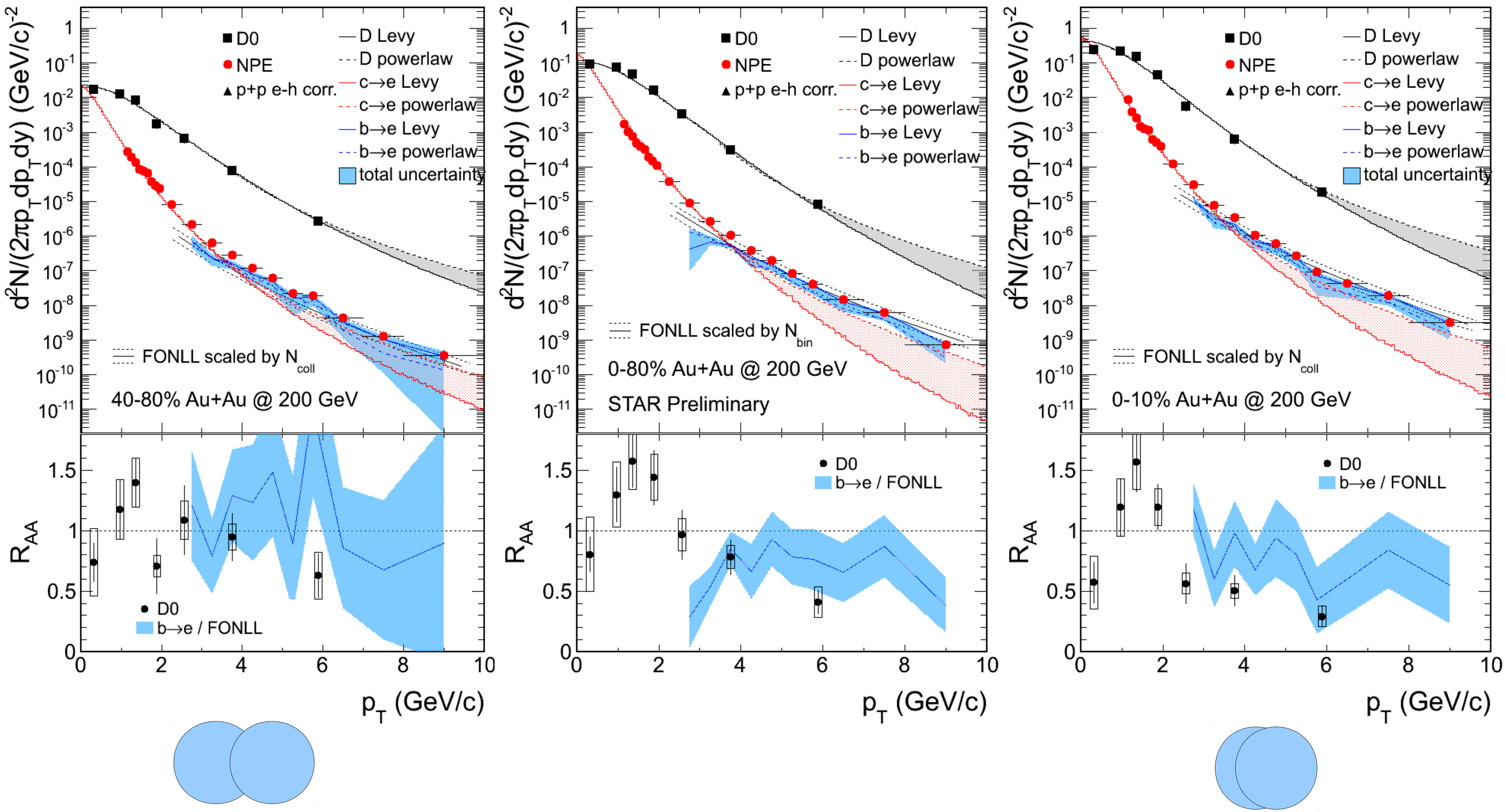
Bottom suppression

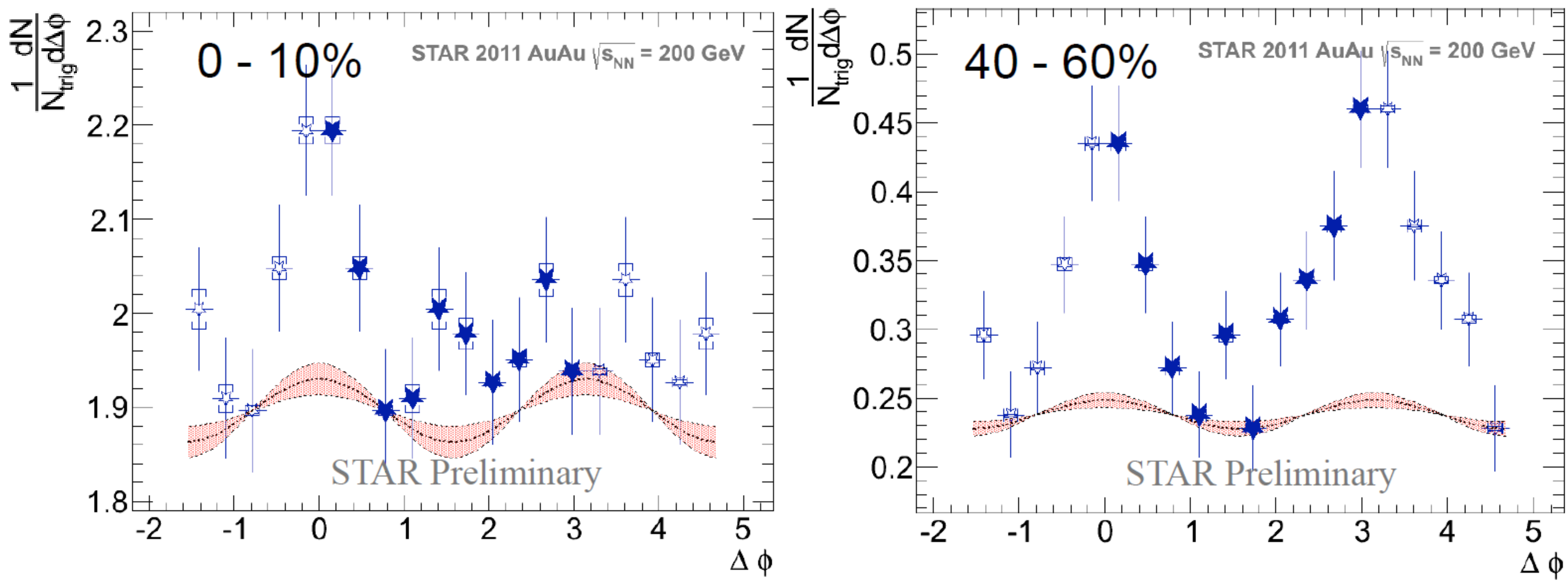


Data still limited in precision to draw solid conclusion

NPE – hadron correlations in Au+Au 200 GeV

Proxy for heavy flavor jets azimuthal correlations

Additional means to constrain models

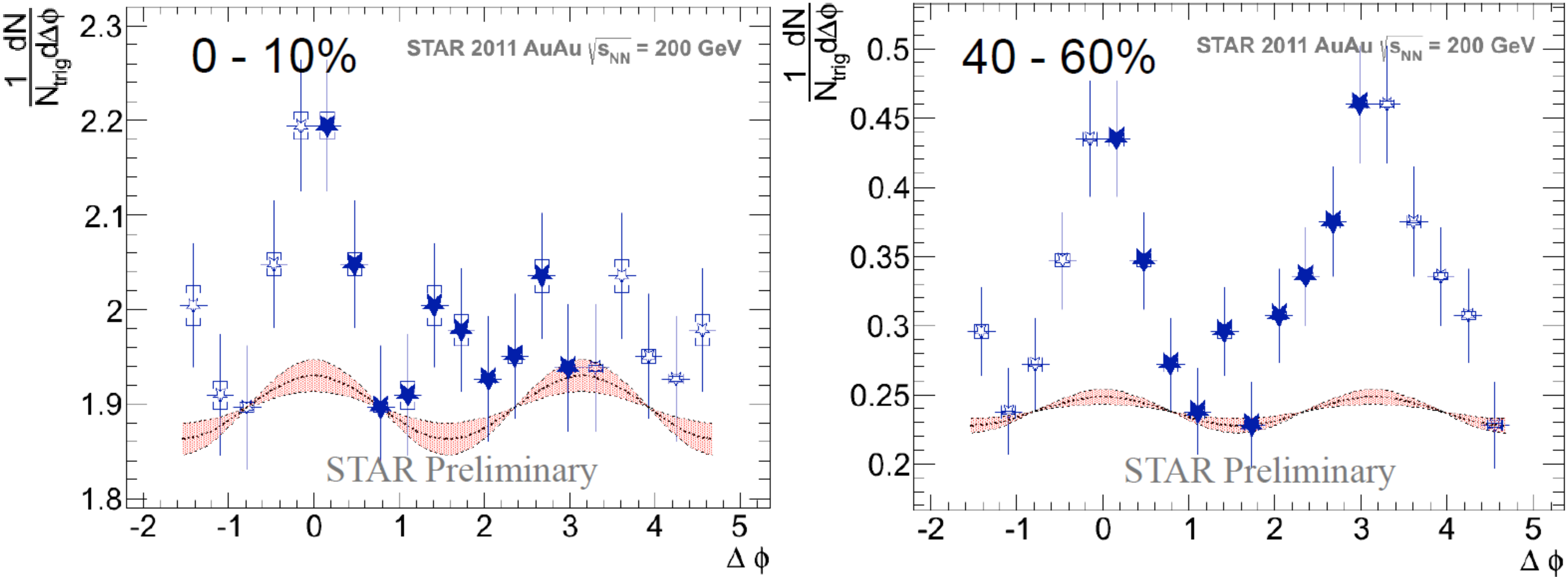


3 GeV/c < $p_{T,e}$ < 6 GeV/c 2 GeV/c < $p_{T,h}$

J. Dunkelberger, QM 2014

flow background: $1 + 2v_2^h v_2^e \cos(2\Delta\phi)$

NPE – hadron correlations in Au+Au 200 GeV



3 GeV/c < $p_{T,e}$ < 6 GeV/c   2 GeV/c < $p_{T,h}$

J. Dunkelberger,
QM 2014

flow background: $1 + 2v_2^h v_2^e \cos(2\Delta\phi)$

Similar trend to di-hadron correlations:
→ larger away side broadening and suppression in central events

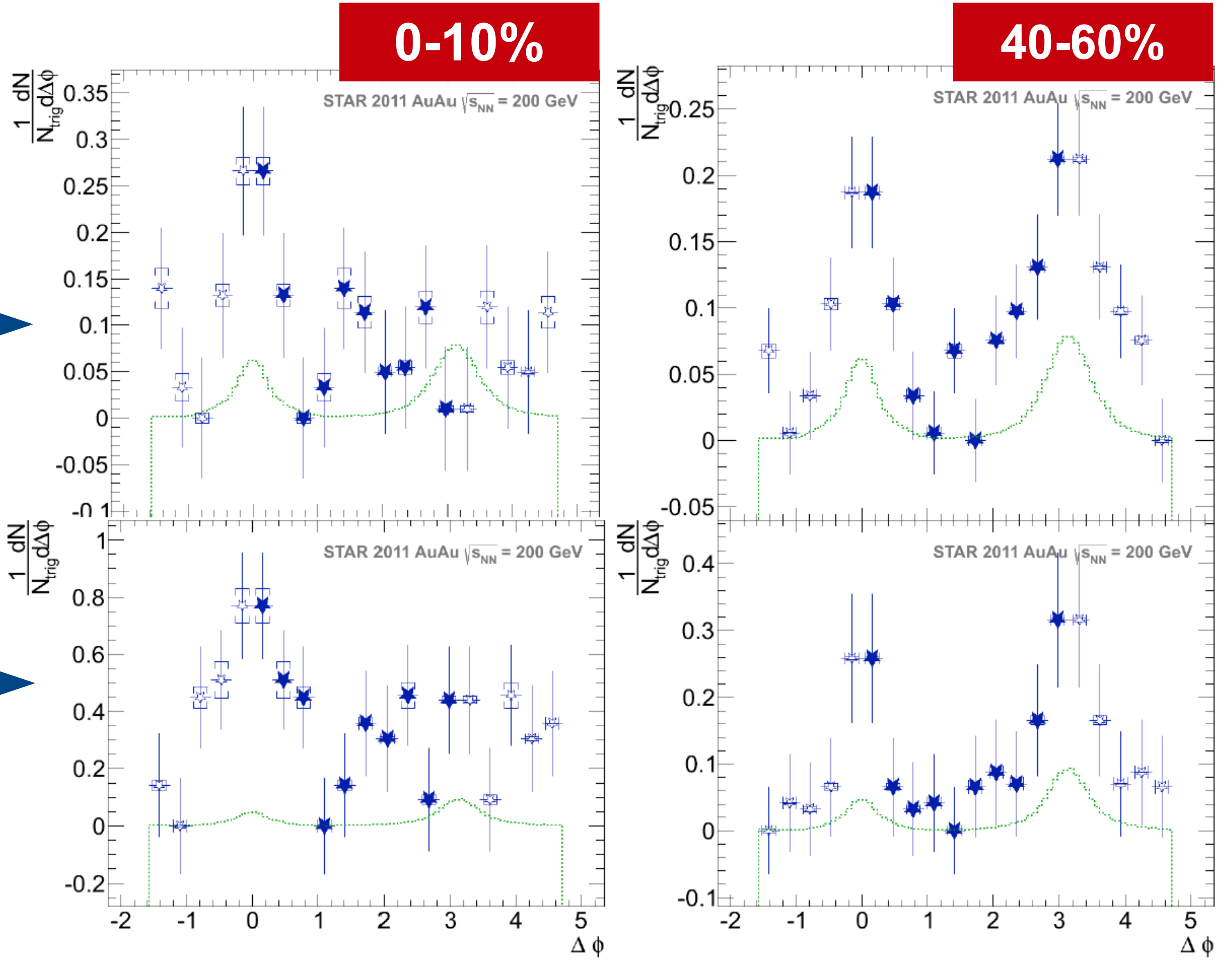
NPE – hadron correlations in Au+Au 200 GeV

– Pythia simulations

$3 < p_{T,e} < 6$ GeV/c

$6 < p_{T,e} < 9$ GeV/c

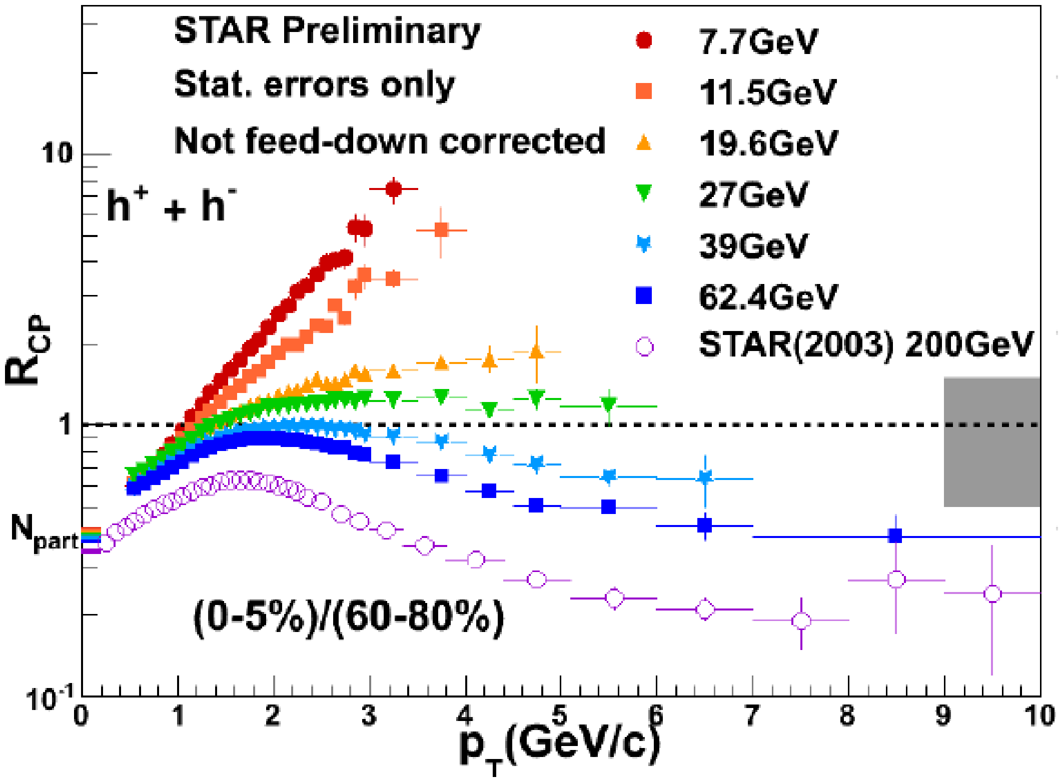
$p_{T,h} > 2$ GeV/c



Similar trend to di-hadron correlations:
→ larger away side broadening and suppression in central events and at lower trigger p_T

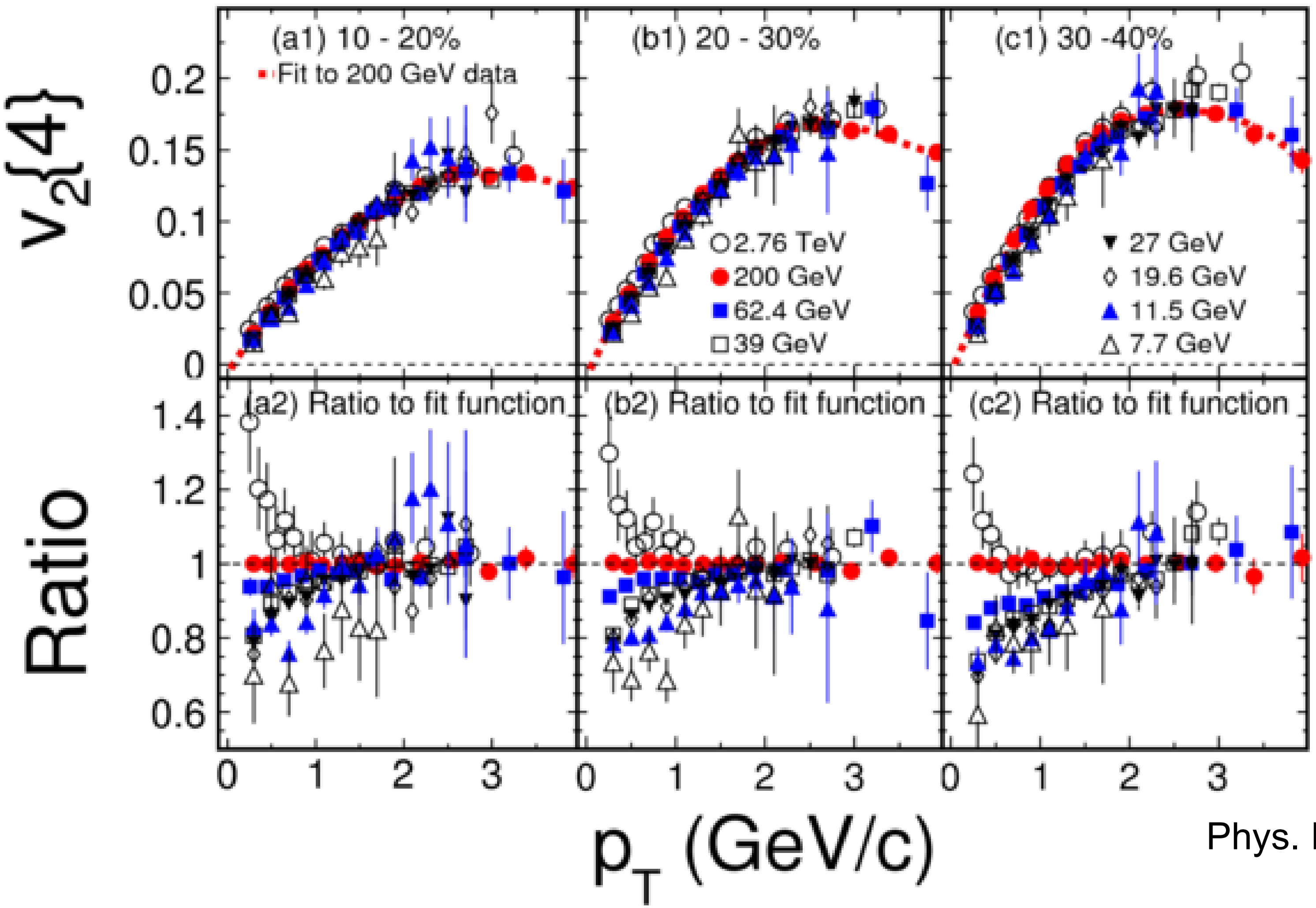
Heavy flavor production vs energy

Jet quenching at RHIC



Light hadrons suppressed at high p_T at 39 - 200 GeV

Elliptic flow at RHIC



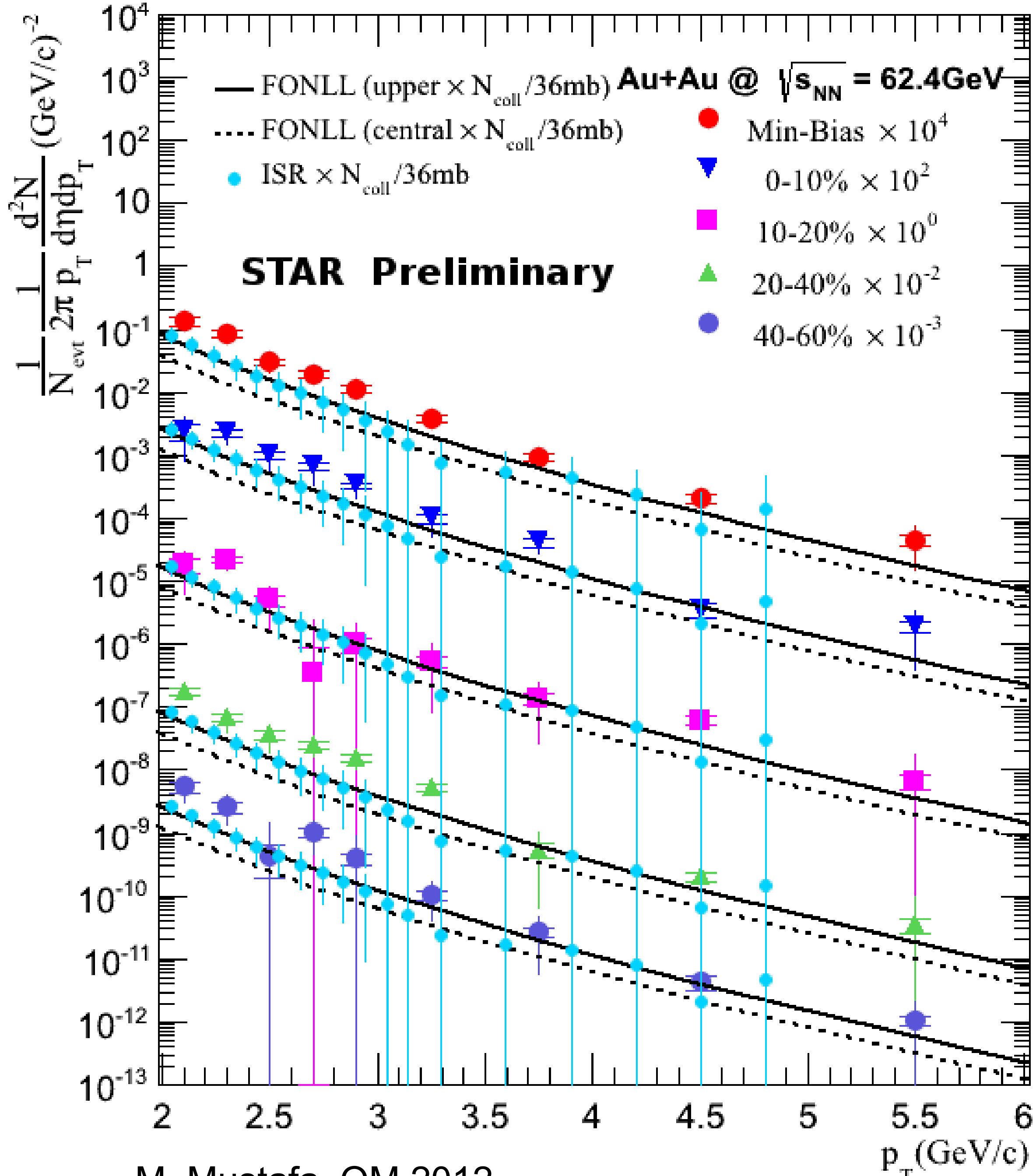
Phys. Rev. C 86 (2012) 54908

Light hadrons suppressed at high p_T at 39 - 200 GeV

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

NPE spectra in Au+Au at $\sqrt{s_{NN}}$ = 62 GeV

No NPE suppression compared to pQCD calculations for $p_T < 5.5$ GeV

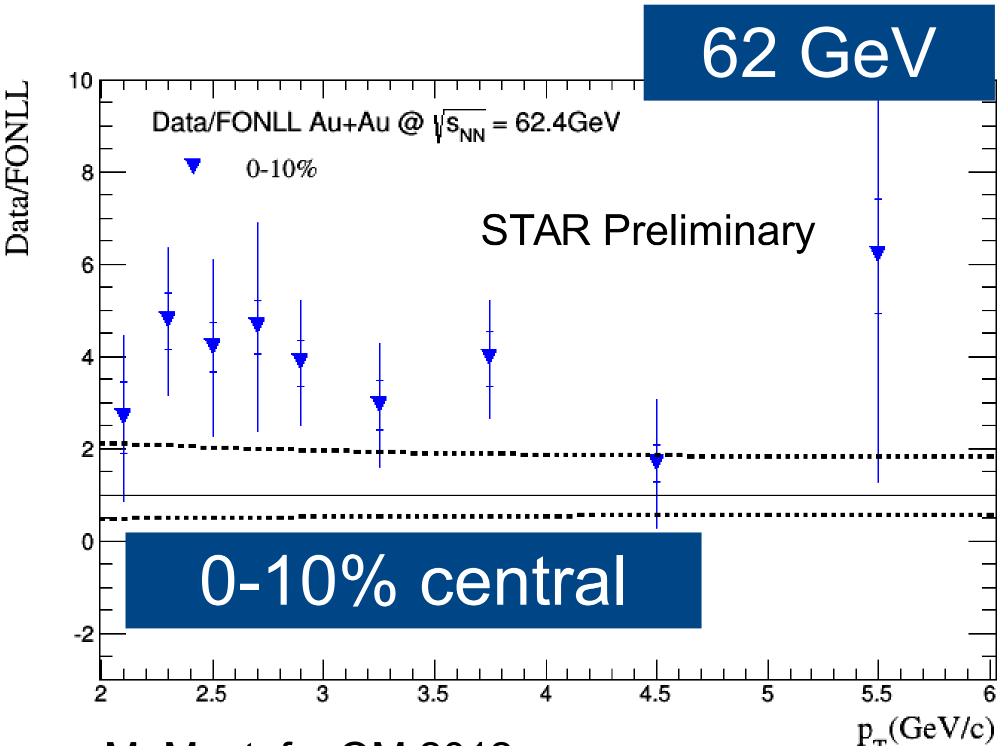


M. Mustafa, QM 2012

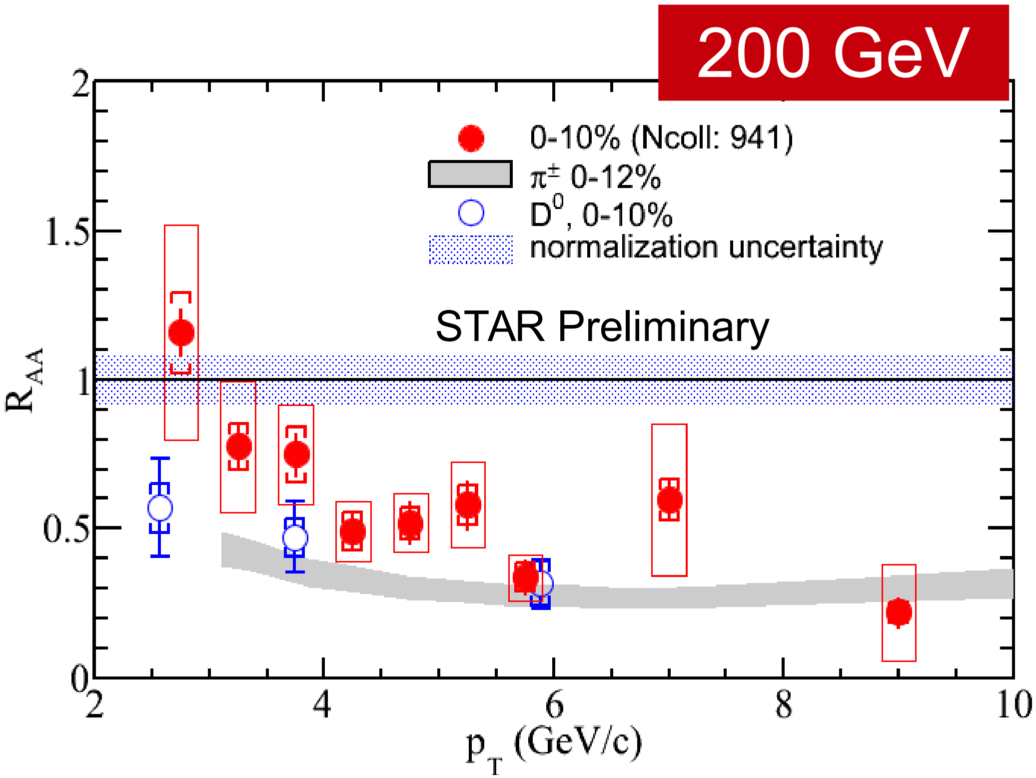
J/ψ contribution not subtracted

ISR: Il Nuovo Cimento (1981), 65A, N
421-456
FONLL: R. Vogt, private communicati

NPE R_{AA}: 62 GeV vs 200 GeV



M. Mustafa, QM 2012

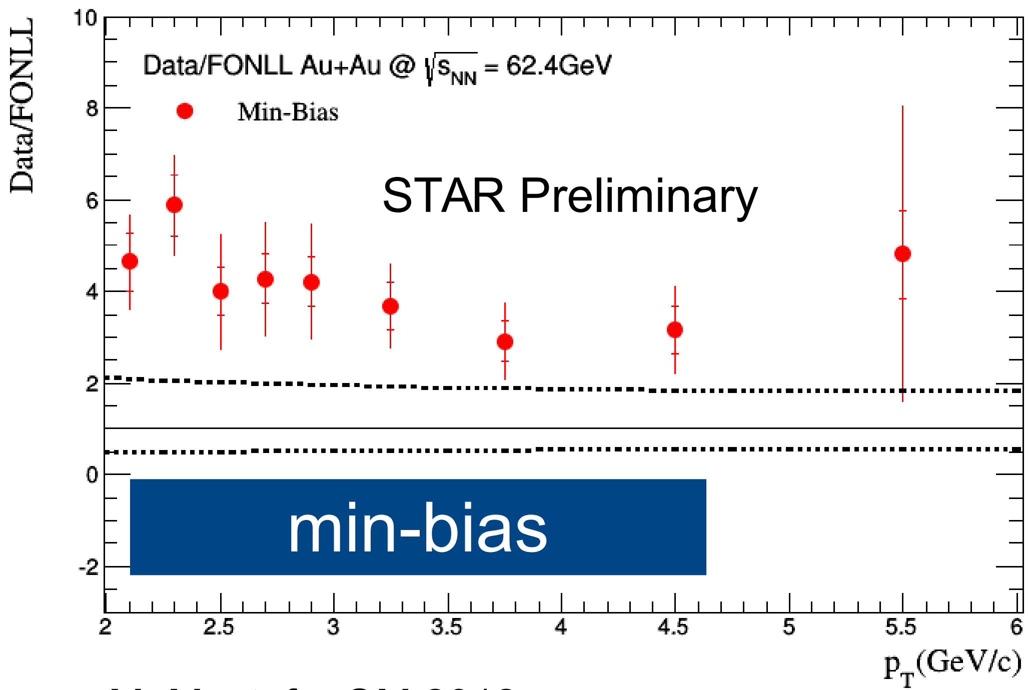


62 GeV: No suppression compared to pQCD calculations for p_T < 5.5 GeV

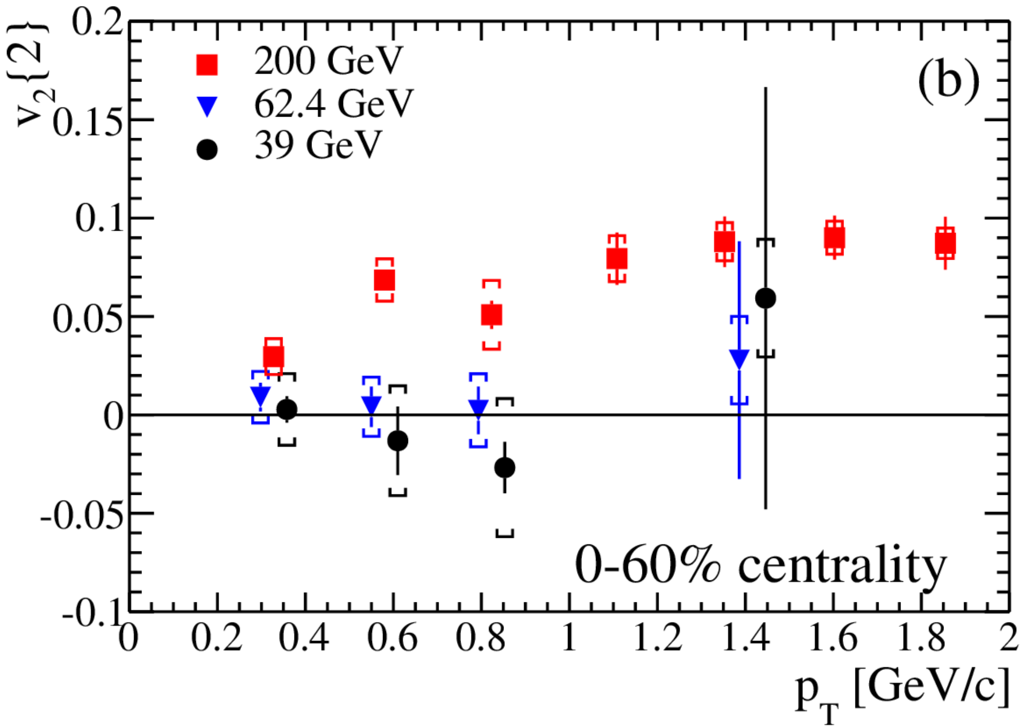
200 GeV: strong suppression for p_T > 4 GeV/c

Cold nuclear matter effects unknown, could be different at 62 and 200 GeV

NPE R_{AA} and v_2 at $\sqrt{s_{NN}}$ = 62 GeV



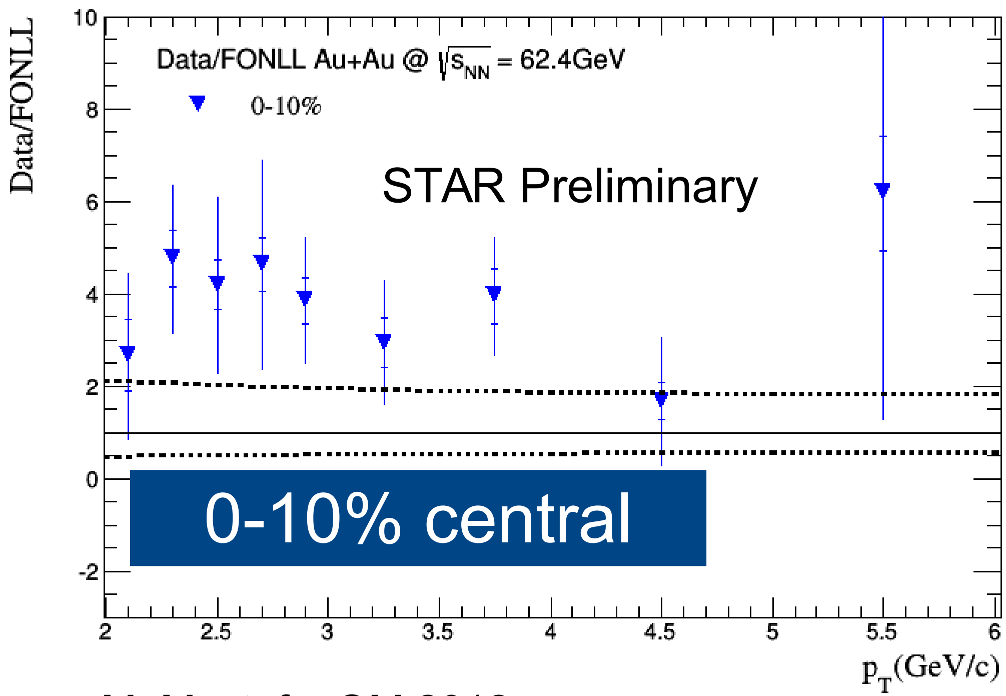
M. Mustafa, QM 2012



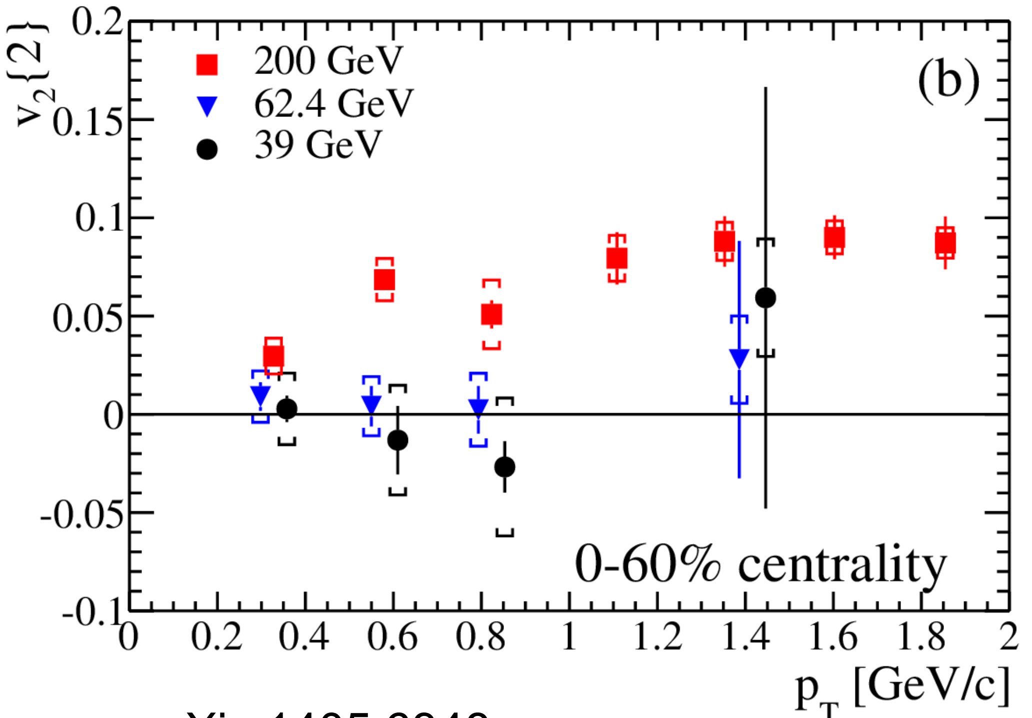
No NPE suppression compared to pQCD calculations for p_T < 5.5 GeV

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

NPE R_{AA} and v_2 at $\sqrt{s_{NN}}$ = 62 GeV



M. Mustafa, QM 2012

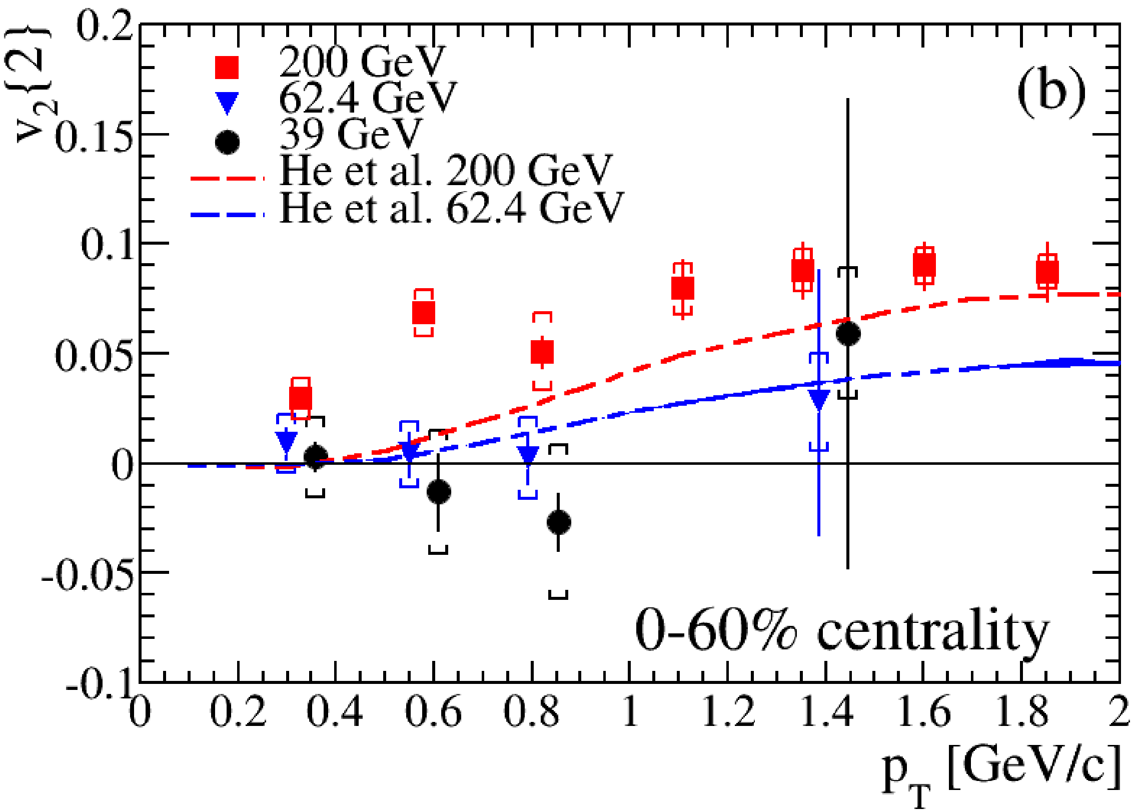


arXiv:1405.6348

No NPE suppression compared to pQCD calculations for p_T < 5.5 GeV

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

NPE v_2 at $\sqrt{s_{NN}}$ = 62 and 200 GeV

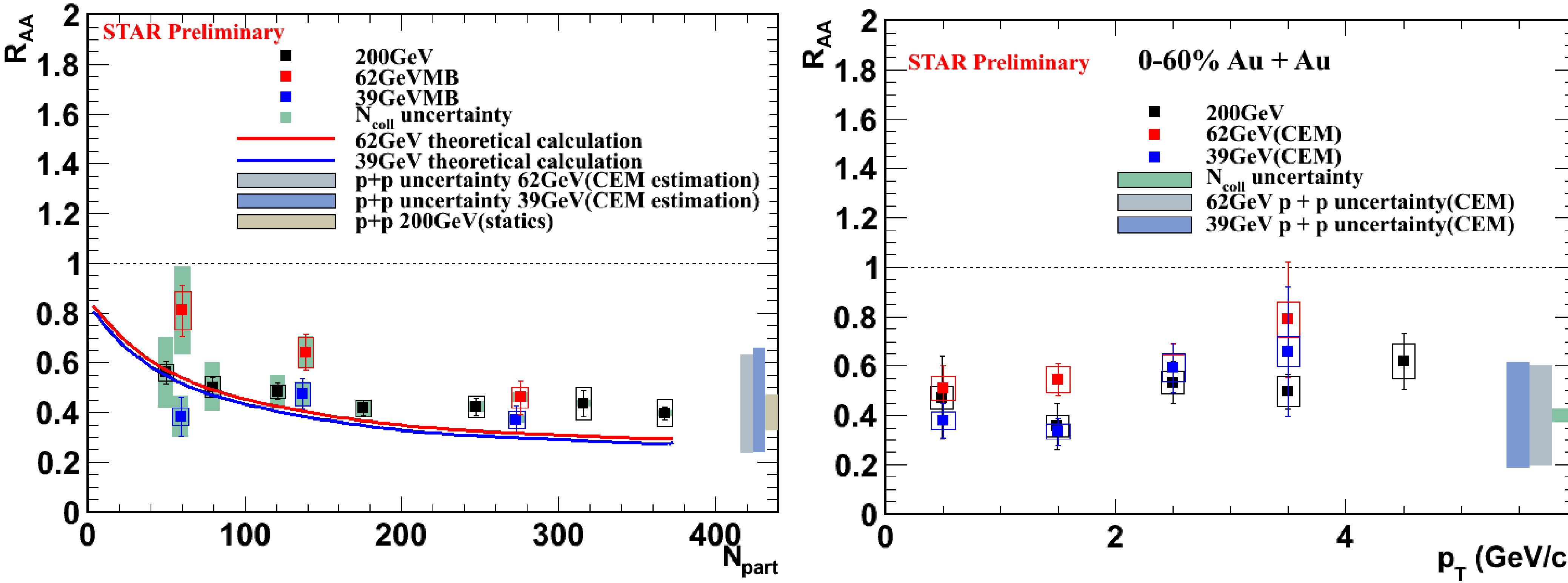


Model: PRC 82 (2010) 035201,
PRL 110 (2013), 112301

He et al: difference between 200 and 62.4 GeV from modification of input heavy flavor spectrum and different v_2 of light quarks

J/ψ suppression at 39 and 62.4 GeV

Model: Zhao, Rapp Phys Rev C.82.064905



Significant suppression at 39 and 62 GeV, similar as at 200 GeV

39 and 62 GeV p+p reference: Color Evaporation Model (CEM)

QCD medium at RHIC:

Au+Au 200 GeV

- Hot (J/ψ, Upsilon suppressed)
- Dense (D^0, NPE quenching)

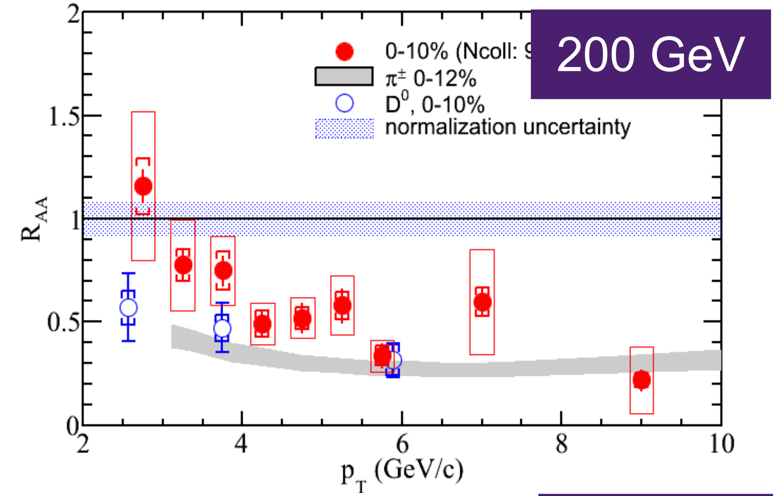
Au+Au 62.4 GeV

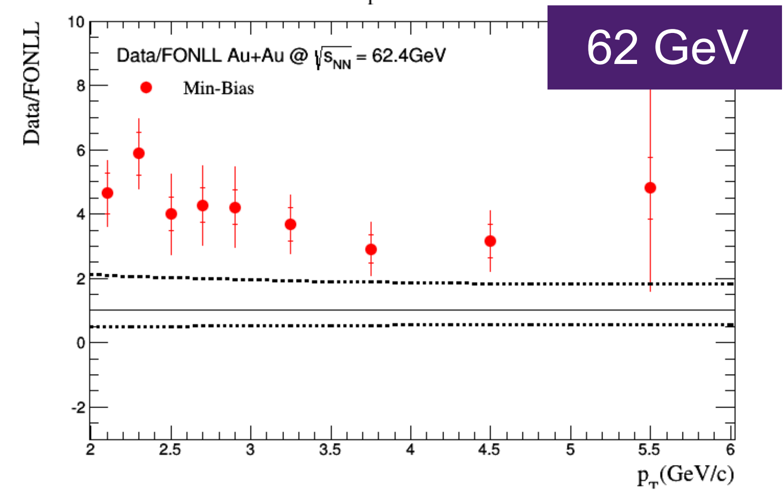
- Hot (J/ψ suppressed)
- Not so dense (?)

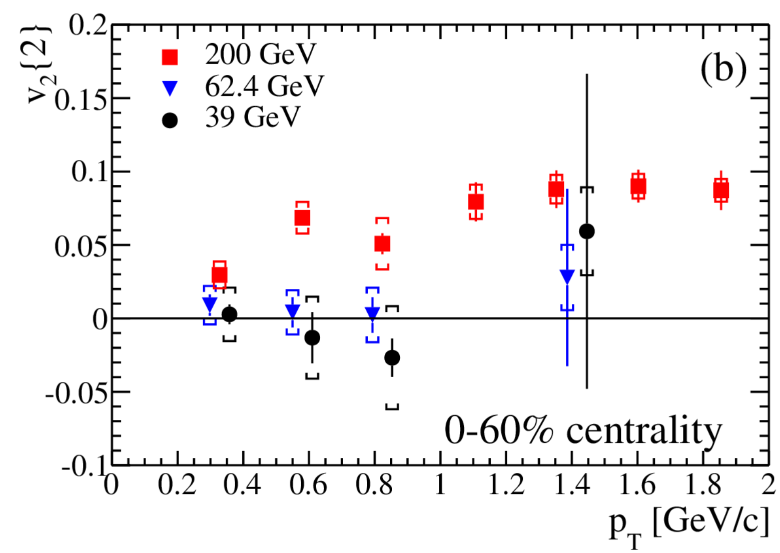
→ light hadrons: **jet quenching, v_2 > 0**

→ **NPE v_2** consistent with **0**

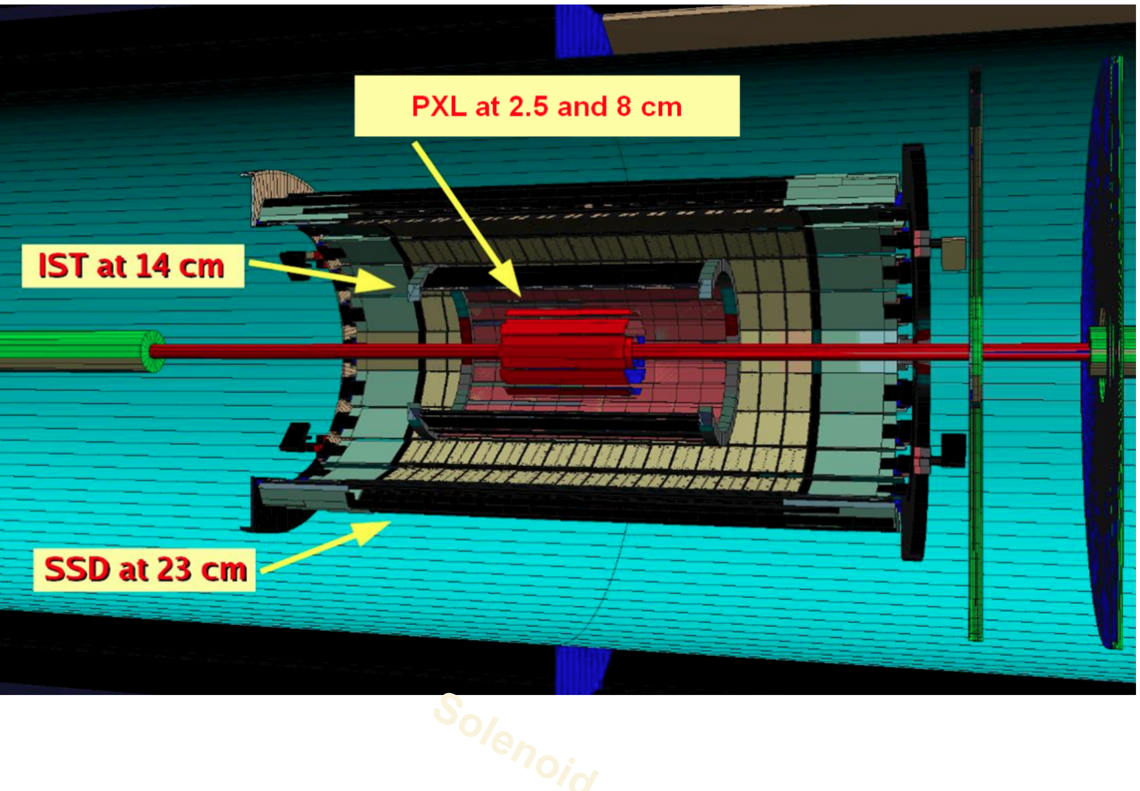
→ **no NPE suppression** at p_T < 5.5 GeV



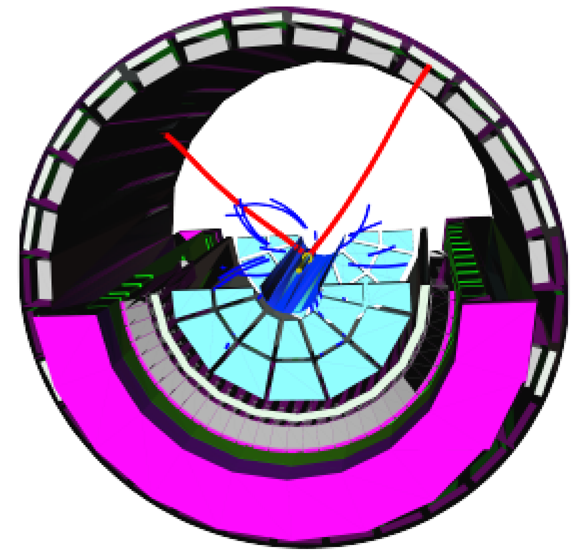




Heavy Flavor Tracker



Muon Telescope Detector



J/ψ event in p+p 500 GeV

Full HFT assembly (PIXEL, IST and SSD) and MTD available in 2014 RHIC run (a long Au-Au 200 GeV run)

Summary

- Strong **heavy flavor (D^0, NPE) suppression** at **200 GeV**
- **D^0 production enhanced** at intermediate p_T
- **NPE not suppressed** compared to pQCD calculations for p_T < 5.5 GeV at **62 GeV**
- **NPE v_2 consistent with zero** in Au+Au 39 and 62.4 GeV
- **NPE v_2** at lower energies **significantly lower than at 200 GeV** for **p_T < 1 GeV/c**

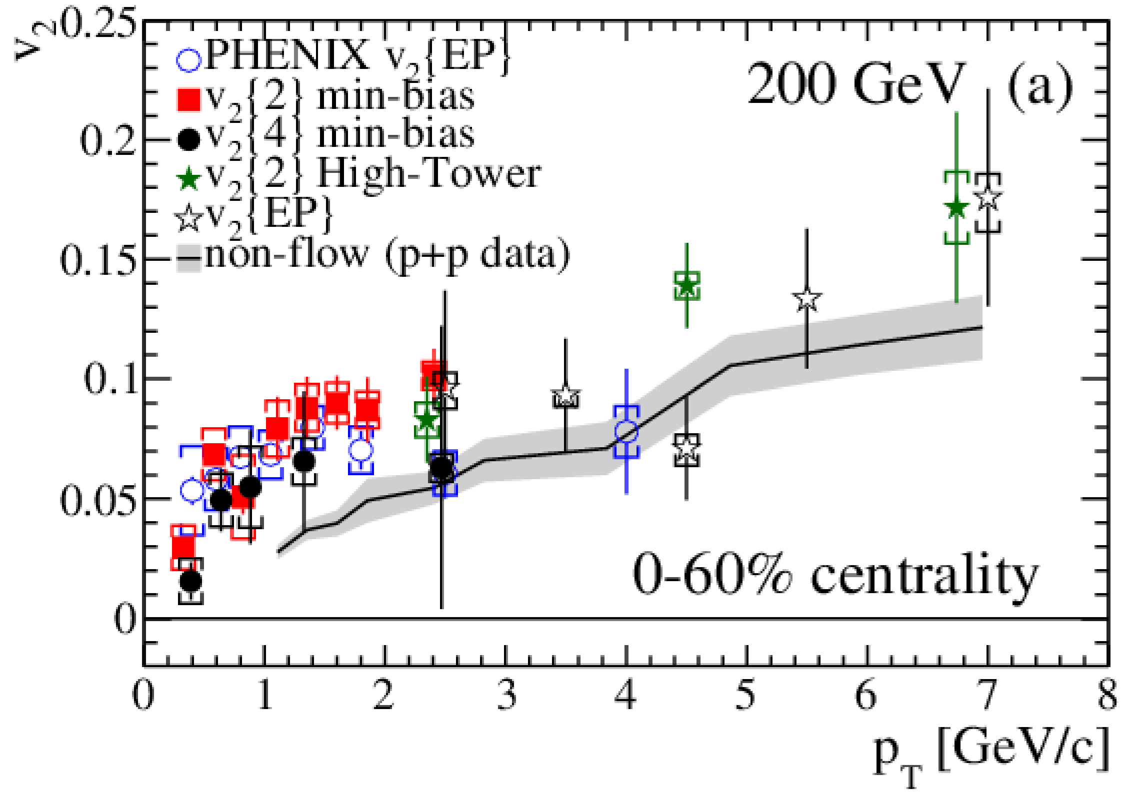
Backup

NPE elliptic flow

- $v_2\{2\}$ and $v_2\{4\}$ – upper and lower limit on elliptic flow:

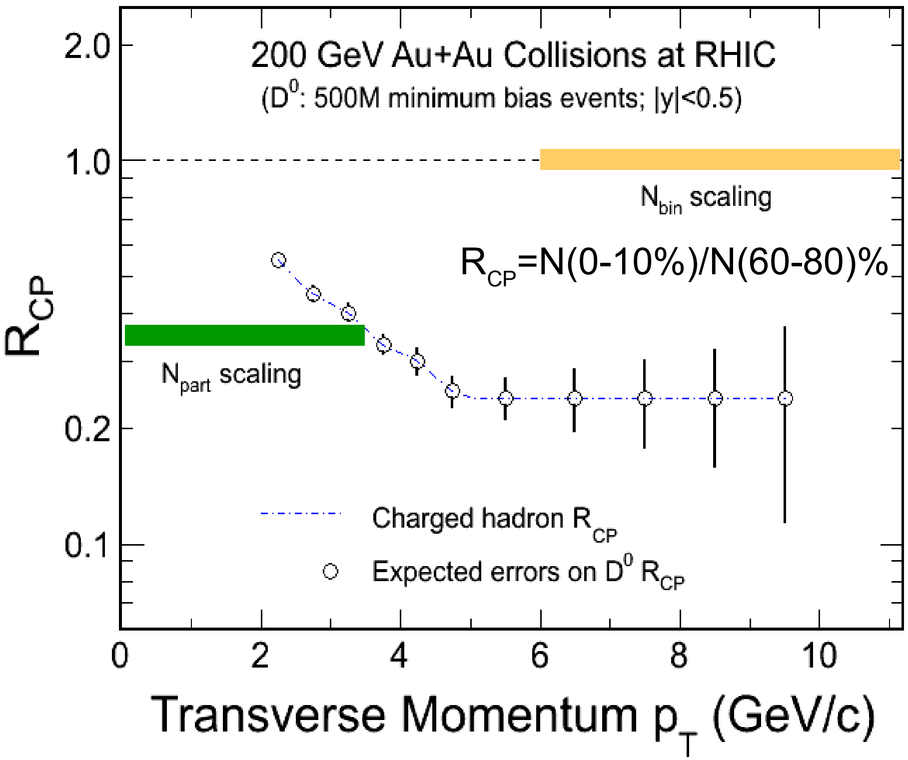
$$v_2\{2\}^2 = \langle v \rangle^2 + \sigma^2 + \delta$$
$$v_2\{4\}^2 \approx \langle v \rangle^2 - \sigma^2$$

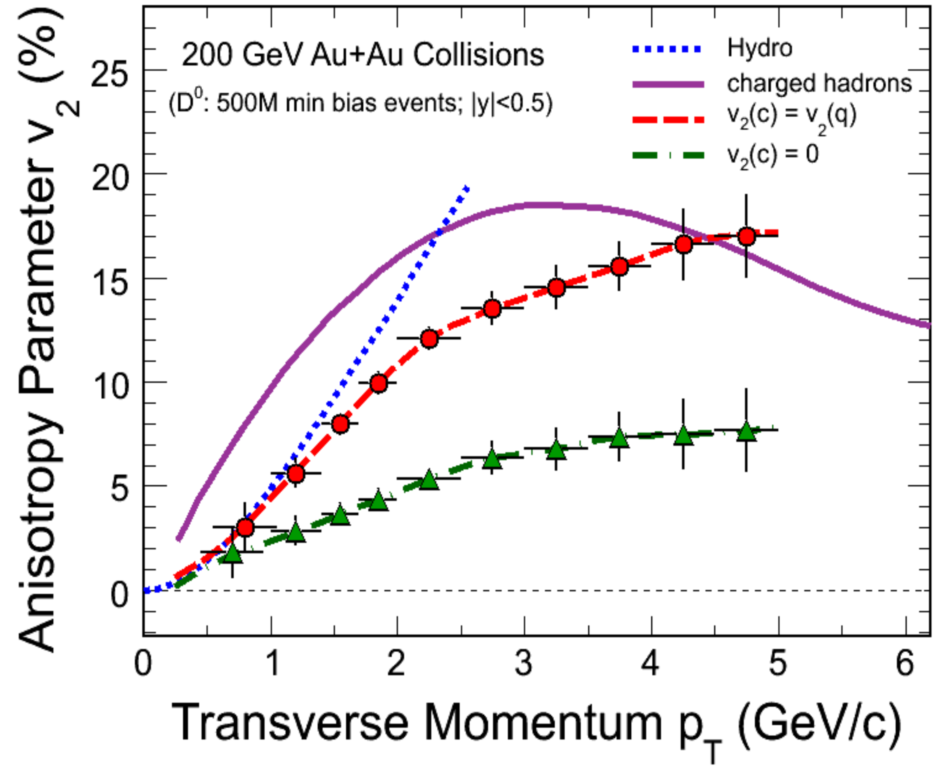
Phys.Lett. B659, 537 (2008)



- Positive v_2 at low and intermediate p_T
- Increase of v_2 at high p_T likely due to jet-like correlation and/or path length dependence

Charm v_2 and R_{AA} – projections for 2014



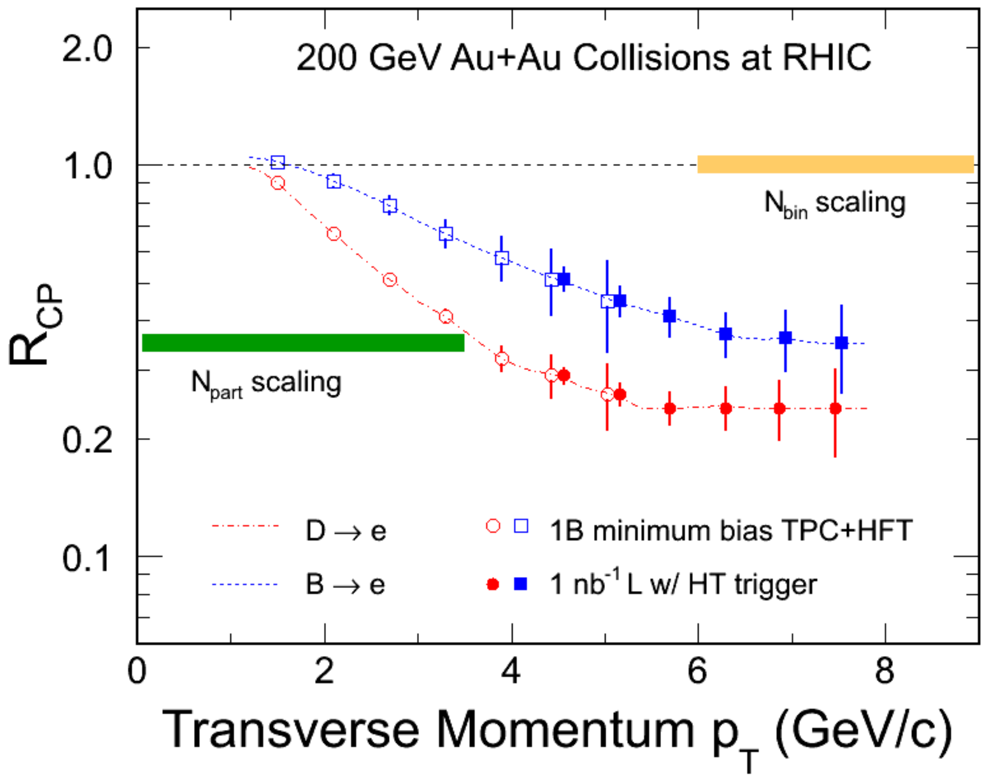


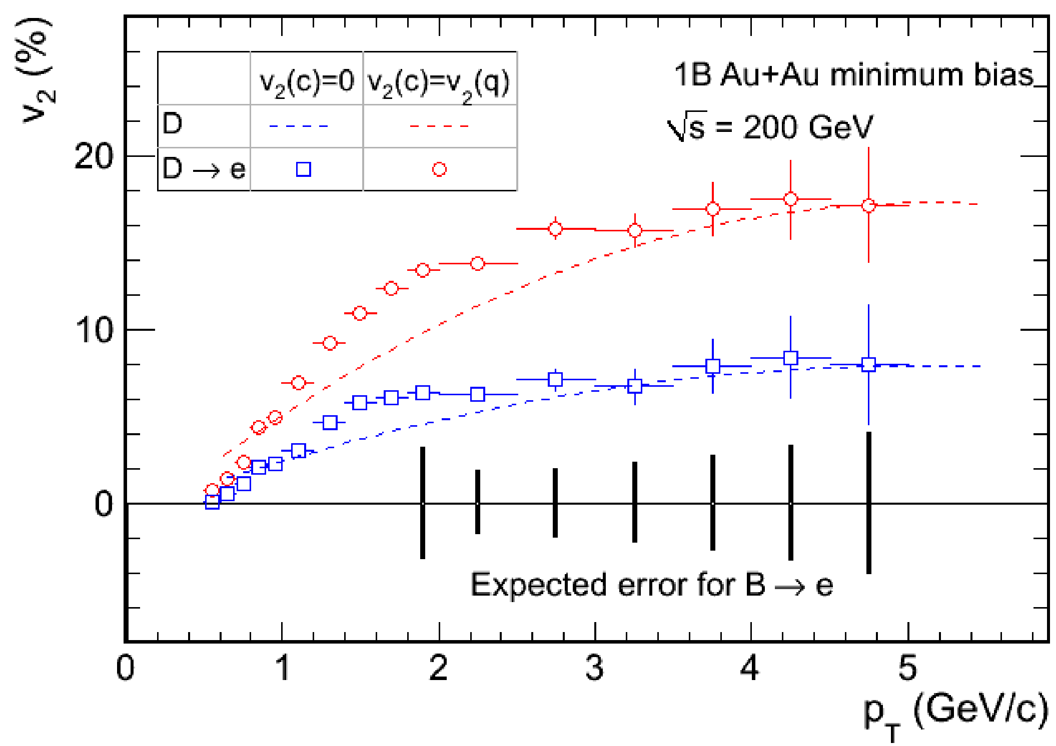
Assuming D^0 v_2 distribution from quark coalescence.

Precision charm v_2 and R_{AA} measurements:

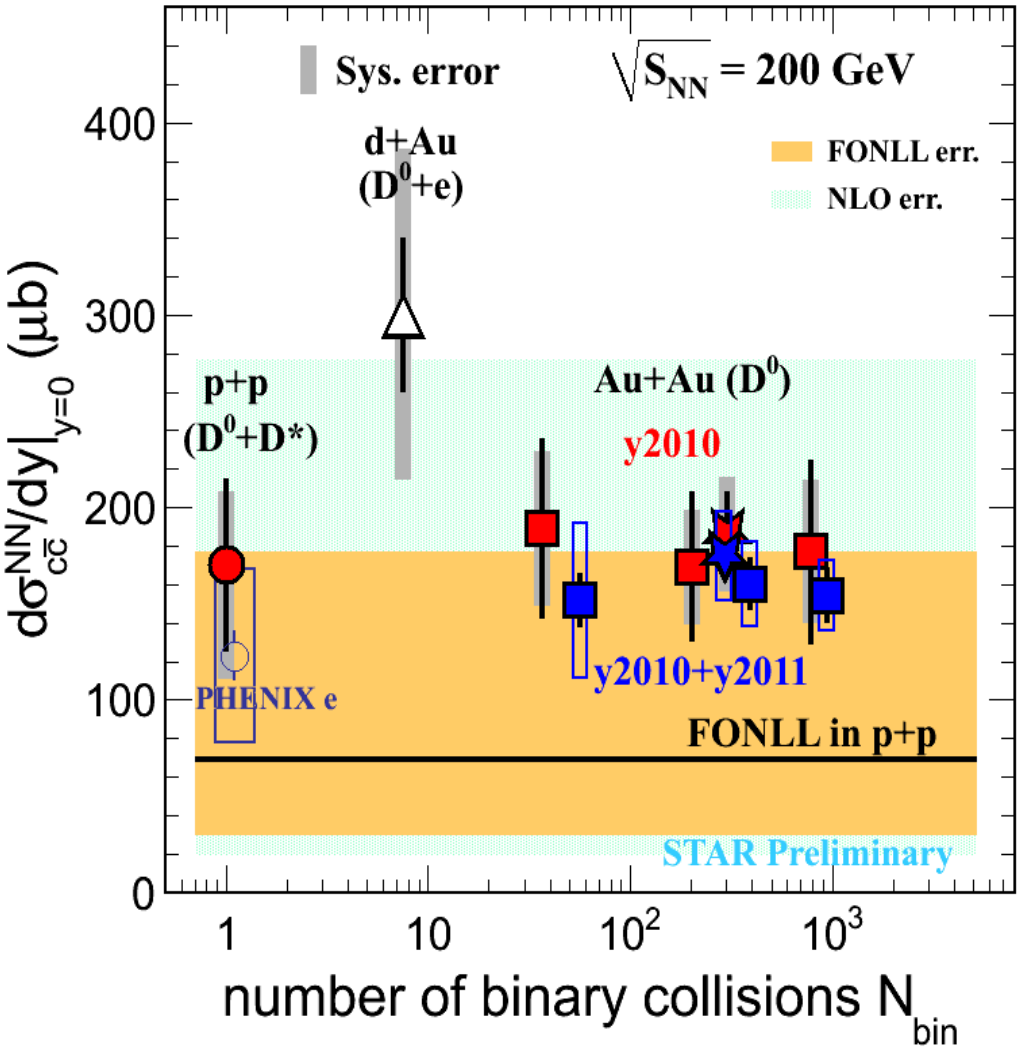
→ energy loss mechanism
→ charm interaction with the QCD matter
→ medium thermalization degree
→ transport coefficients

Beauty v_2 and R_{AA} – projections for 2014





Charm cross section at 200 GeV



Charm cross section at mid-rapidity:

$$\left.\frac{d\sigma}{dy}\right|_{y=0}^{pp} = 170 \pm 45^{+38}_{-59}\,\mu b \qquad \left.\frac{d\sigma}{dy}\right|_{y=0}^{AuAu} = 175 \pm 13 \pm 23\,\mu b$$

Total charm cross section:

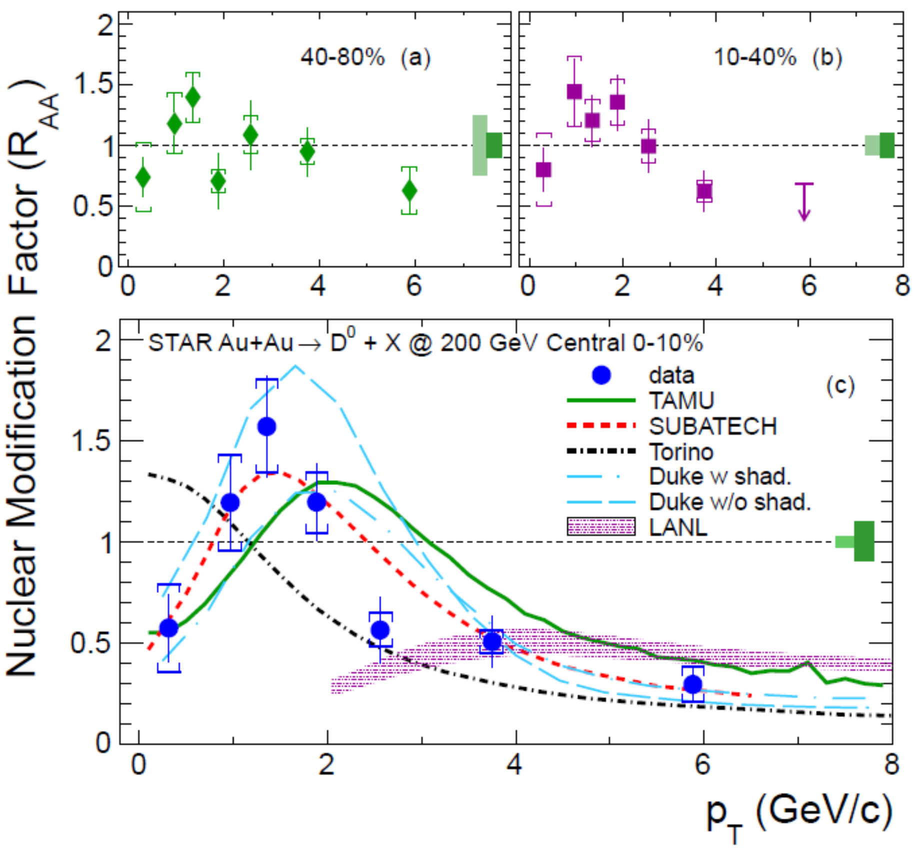
$$\sigma_{c\bar{c}}^{pp} = 797 \pm 210^{+208}_{-295}\,\mu b \qquad \sigma_{c\bar{c}}^{AuAu} = 822 \pm 62 \pm 192\,\mu b$$

Charm cross section follows number of binary collisions scaling

→ Charm quarks produced mostly via initial hard scatterings

[1] STAR d+Au: J. Adams, et al., PRL 94 (2005) 62301
[2] FONLL: M. Cacciari, PRL 95 (2005) 122001.
[3] NLO: R. Vogt, Eur.Phys.J.ST 155 (2008) 213
[4] PHENIX e: A. Adare, et al., PRL 97 (2006) 252002.

Charm R_{AA} in Au+Au 200 GeV

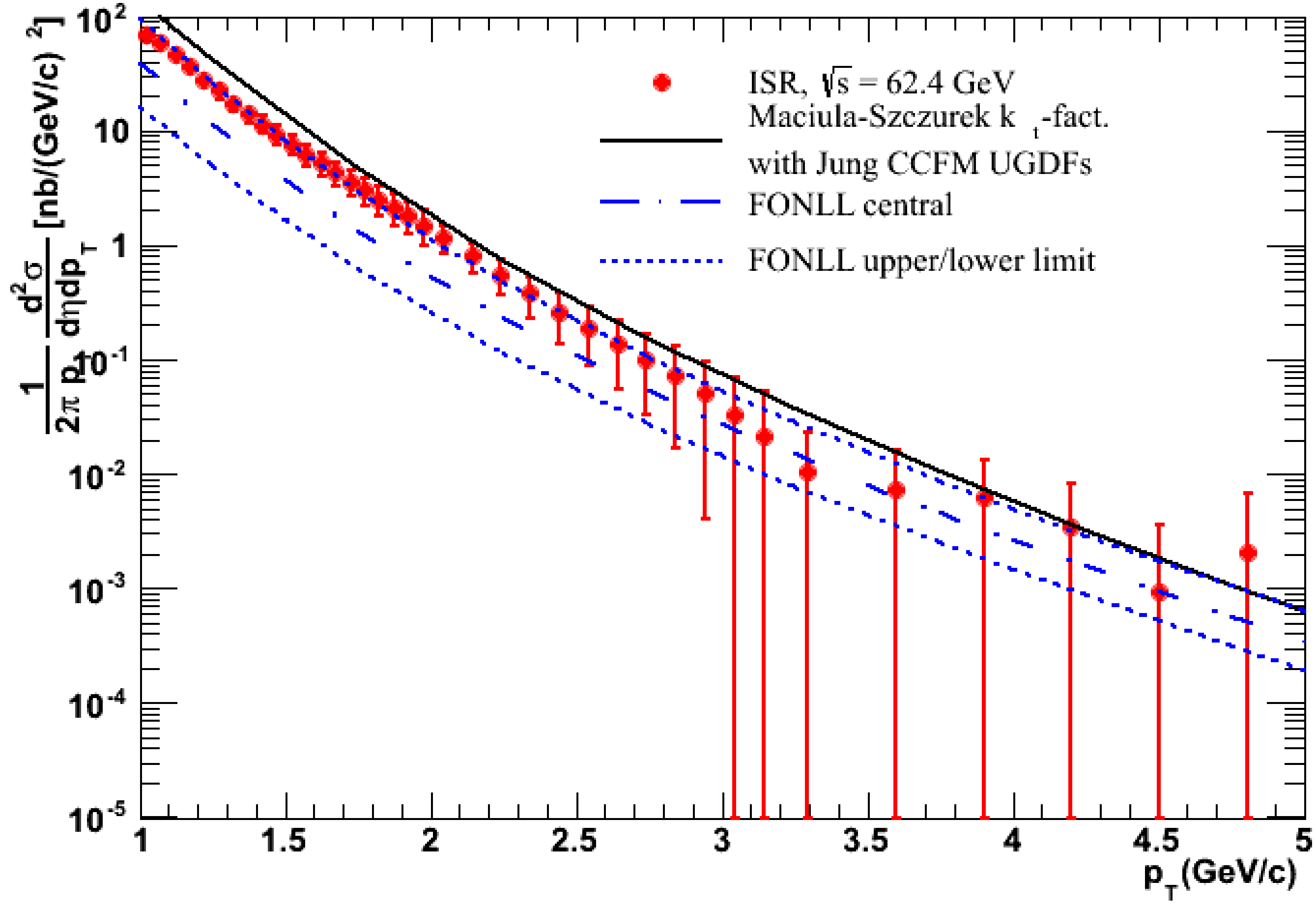


arXiv:1404.6185, submitted to PRL

	TAMU	SUBATECH	Torino	Duke	LANL
HQ prod.	LO	FNOLL	NLO	LO	LO
QGP-Hydro	ideal	ideal	viscous	viscous	ideal
HQ eLoss	coll.	coll. +rad.	coll. +rad.	coll. +rad.	diss. +rad.
Coalescence	Yes	Yes	No	Yes	No
Cronin effect	Yes	Yes	No	No	Yes
Shadowing	No	No	Yes	Yes/No	Yes

- Large suppression at high p_T points to strong charm-medium interaction;
- Indication of enhancement p_T~0.7-2GeV/c, described by models with charm quarks coalescence with light quarks;
- CNM effects could be important

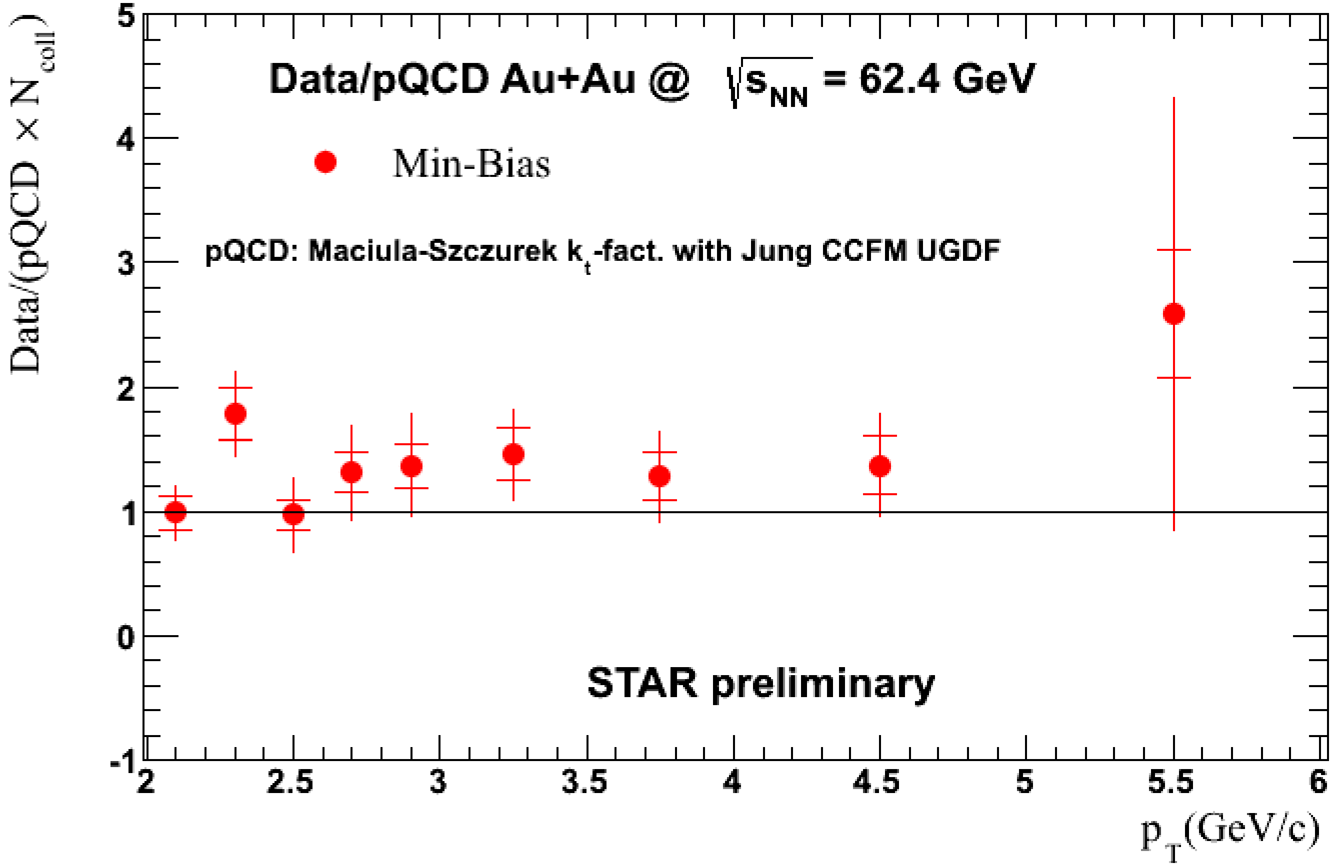
NPE in p+p 62.4 GeV



ISR: IL NUOVO CIMENTO (1981), 65A, N4, 421-456
FONLL: R. Vogt, private communication
k_T-factorization: Phys. Rev. D 79, 034009 (2009) and private communication with R. Maciula

NPE R_{AA} at $\sqrt{s_{NN}}$ = 62 GeV

Min-Bias

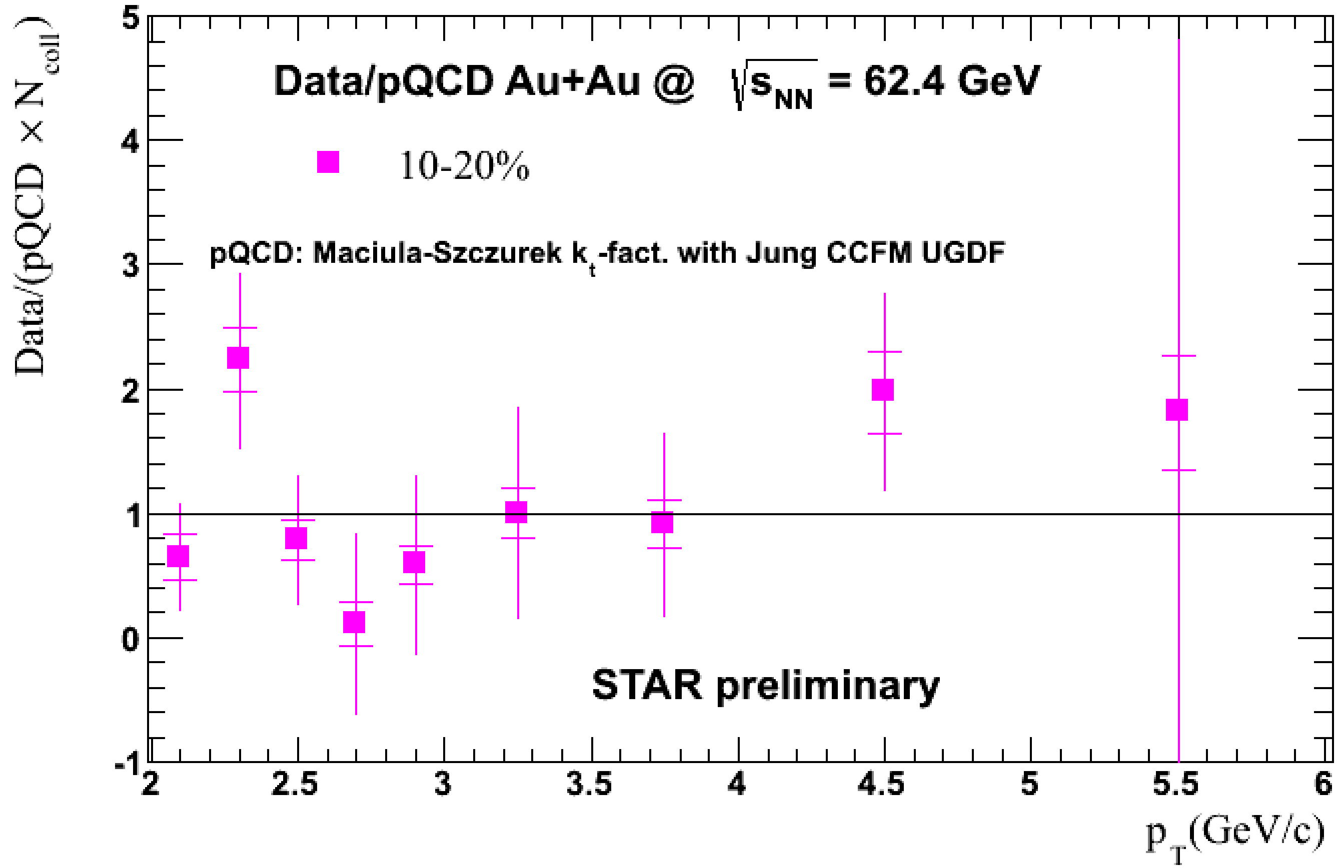


k_T-factorization: Phys. Rev. D 79, 034009 (2009)
and private communication with R. Maciula

No NPE suppression compared to ISR p+p data and pQCD calculations

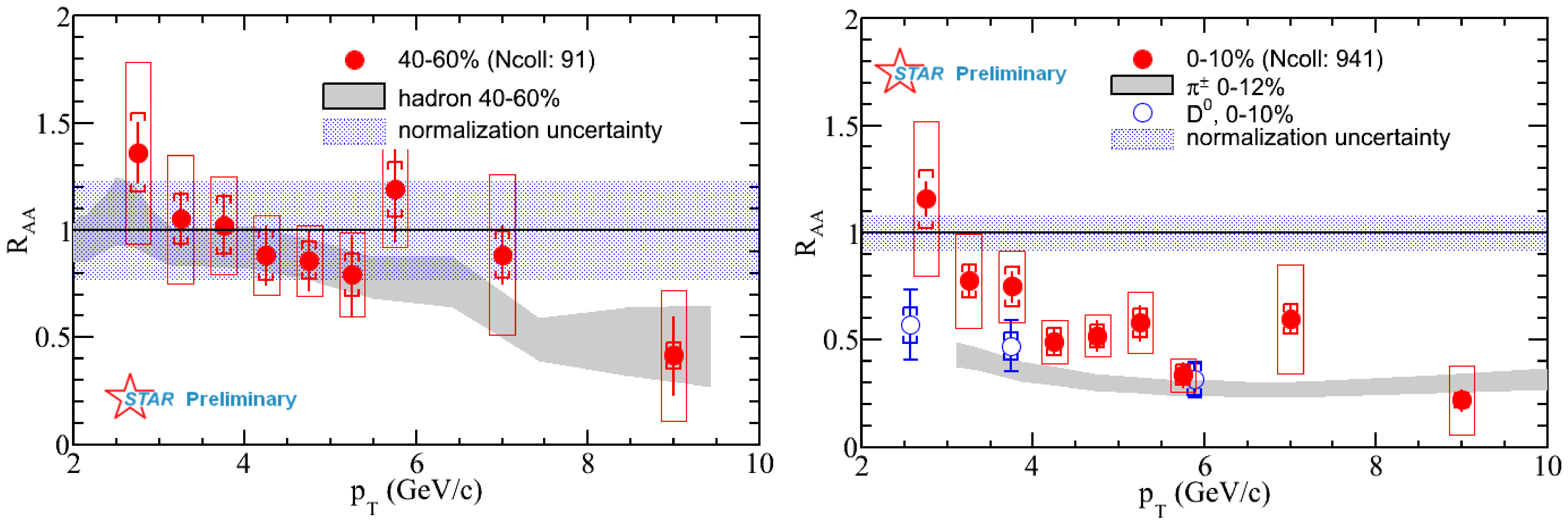
NPE R_{AA} at $\sqrt{s_{NN}}$ = 62 GeV

Central: 10-20%



No NPE suppression compared to ISR p+p data and pQCD calculations

Non-photonic electron R_{AA} in Au+Au 200 GeV



- Strong suppression at high p_T in central collisions
- D^0 and NPE suppression are similar
- Uncertainty dominated by p+p baseline

D^0 elliptic flow