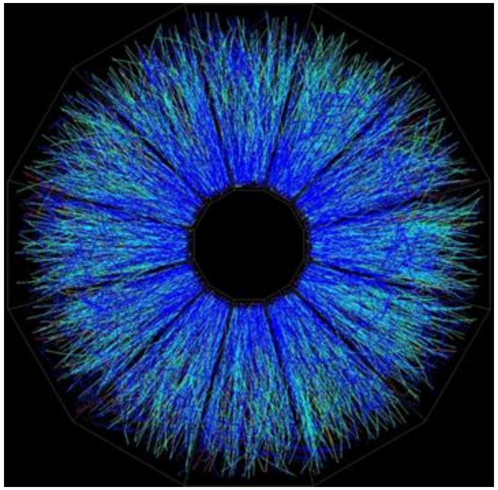
Open heavy flavor at RHIC

Jaroslav Bielčík

Czech Technical University
in Prague



4th International Conference on New Frontiers in Physics
23 - 30 August 2015, Crete, Greece

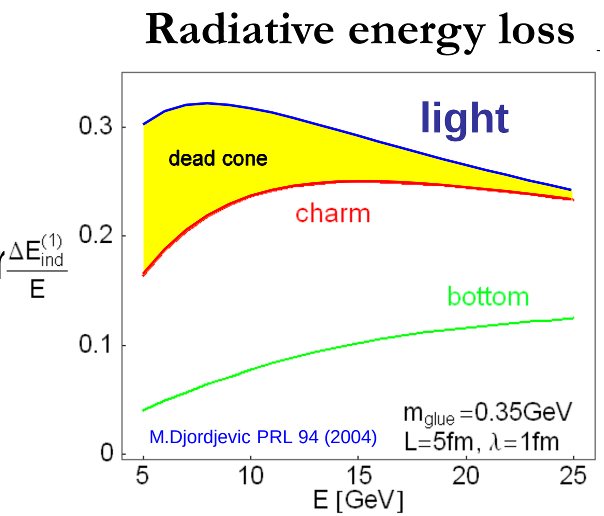
jaroslav.bielcik@fjfi.cvut.cz

Heavy quarks as a probe of QGP

- p+p data:

→ baseline of heavy ion measurements.
→ test of pQCD calculations.

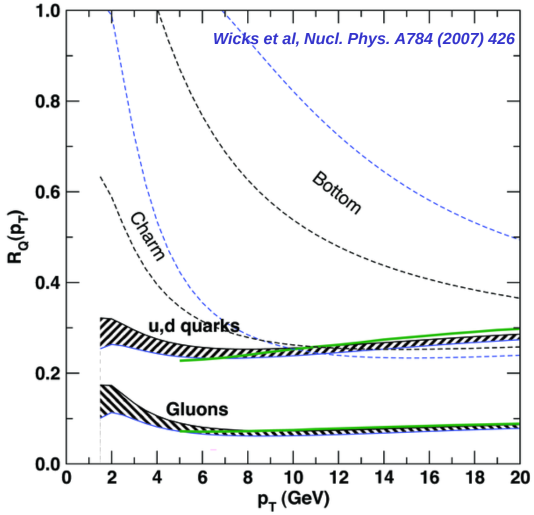
- Due to their large mass heavy quarks are primarily produced by gluon fusion in early stage of collision.
  → production rates calculable by pQCD
  M. Gyulassy and Z. Lin, PRC 51, 2177 (1995)



- heavy ion data:

- Studying energy loss of heavy quarks.
→ independent way to extract properties of the medium.

- Azimuthal Anisotropy.
  → testing the thermalization of the bulk matter,
  → path length dependence of energy loss.



jaroslav.bielcik@fjfi.cvut.cz

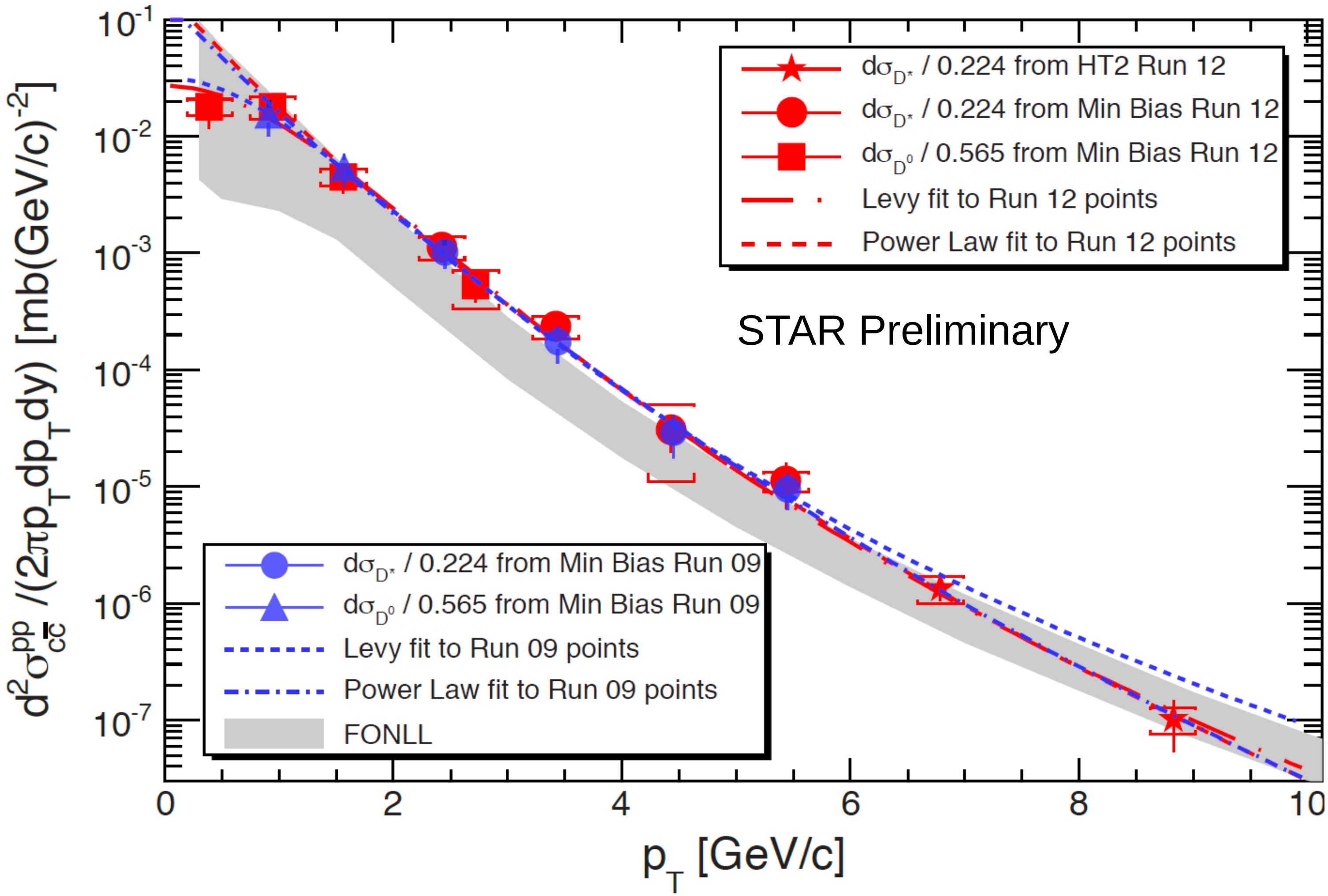
Heavy quarks – open questions

- **Colour charge** and quark mass **dependence of energy loss**
  - Expectation $\mathbf{E_c < E_{u,d,s} < E_g}$ vs. observation $\mathbf{R_{AA}(D) \approx R_{AA}(\pi)}$
  - Low p_T (<10 GeV/c): mass effect on energy loss + radial flow?
  - At which p_T does R_{AA}(b) become compatible with R_{AA}(light)?
- **Energy loss** mechanism: **collisional** vs. **radiative**
  - Path length dependence of energy loss (via v_2 at high p_T)
  - Correlation measurements
- **Cold nuclear matter effects** in the initial and final state
  - d+Au, system and energy scan
- **Collectivity and thermalization**
  - charm v_2 and R_{AA} measurements at low p_T
- **Hadronization mechanism: coalescence vs. fragmentation**
  - D_s, Λ_s measurements; v_2 and R_{AA} measurements at low pT

SaporeGravis network review arXiv:1506.03981

jaroslav.bielcik@fjfi.cvut.cz

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

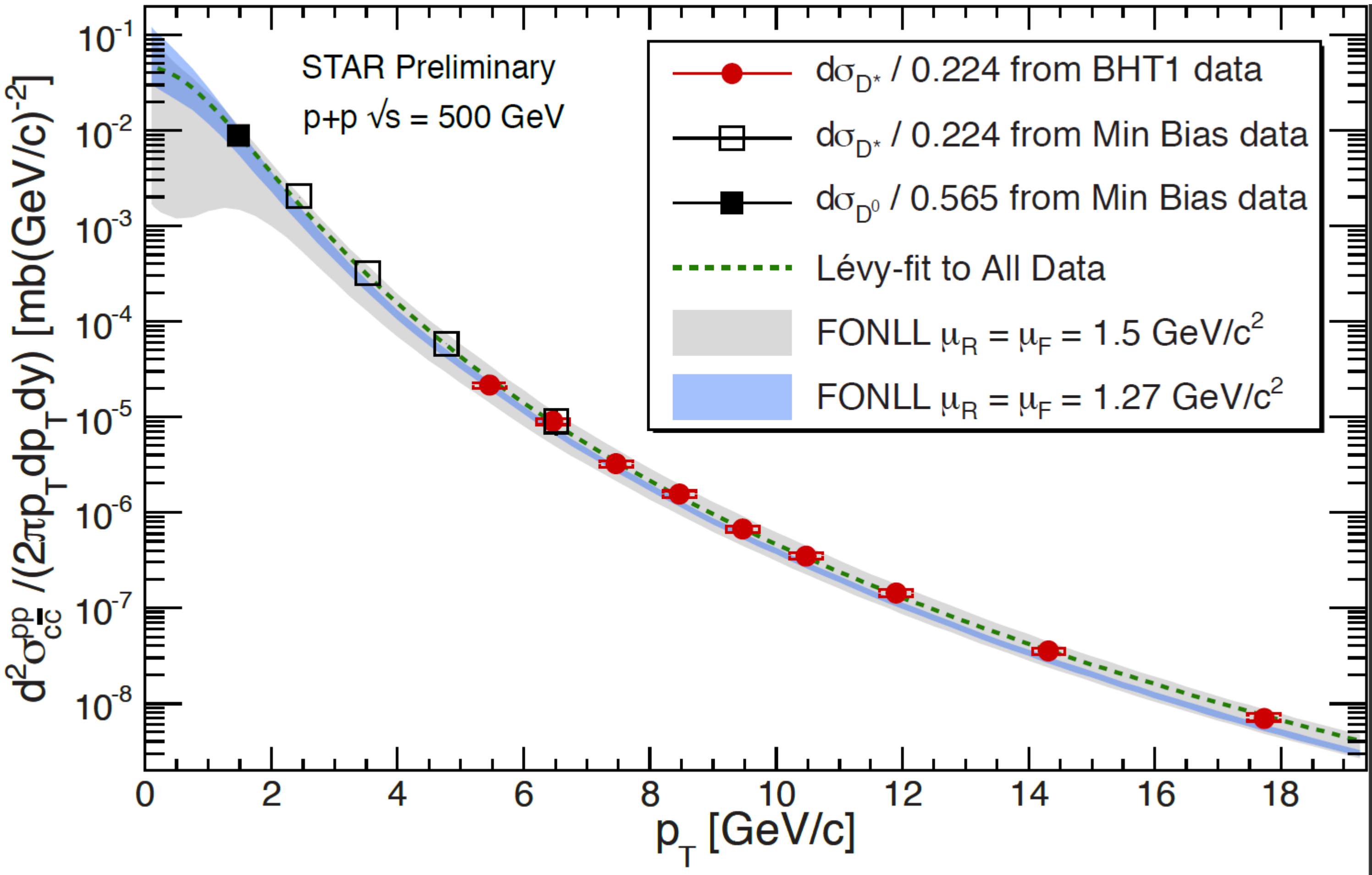


- New measurement from Run 12 extents the range towards low-$p_{T.}$
- FONLL upper band is consistent with charm spectra.

FONLL: 200 GeV M. Cacciari, PRL 95 (2005) 122001
Run 09: Phys. Rev. D 86 (2012) 72013

jaroslav.bielcik@fjfi.cvut.cz

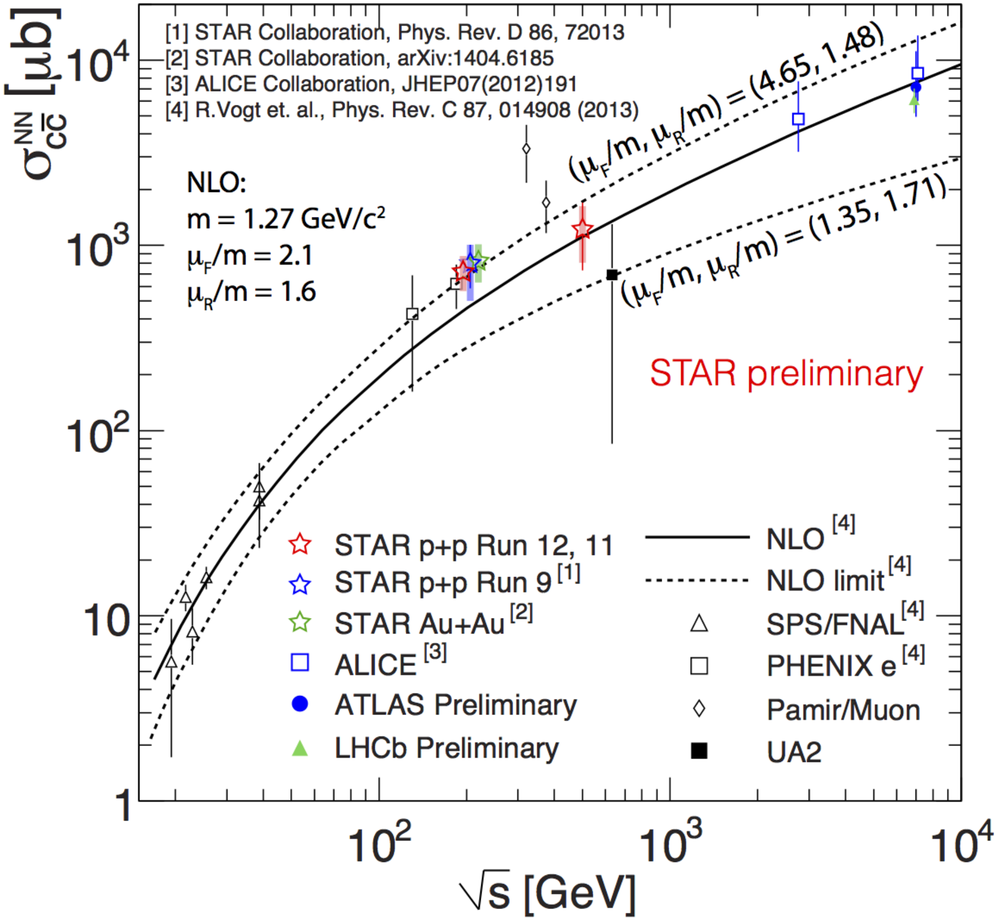
D^0 and D* p_T spectra in p+p 500 GeV collisions



- D* measurement in p+p 500 GeV up to p_T ~ 18 GeV/c.
- FONLL is consistent with data.

FONLL: 500 GeV R.Vogt priv. comm., |y| < 1
.

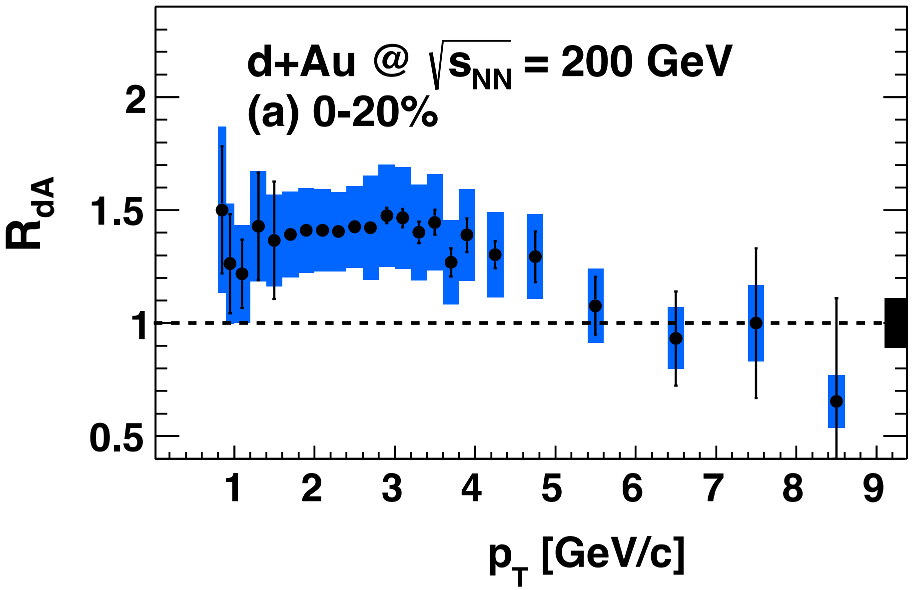
Total inclusive charm cross-section

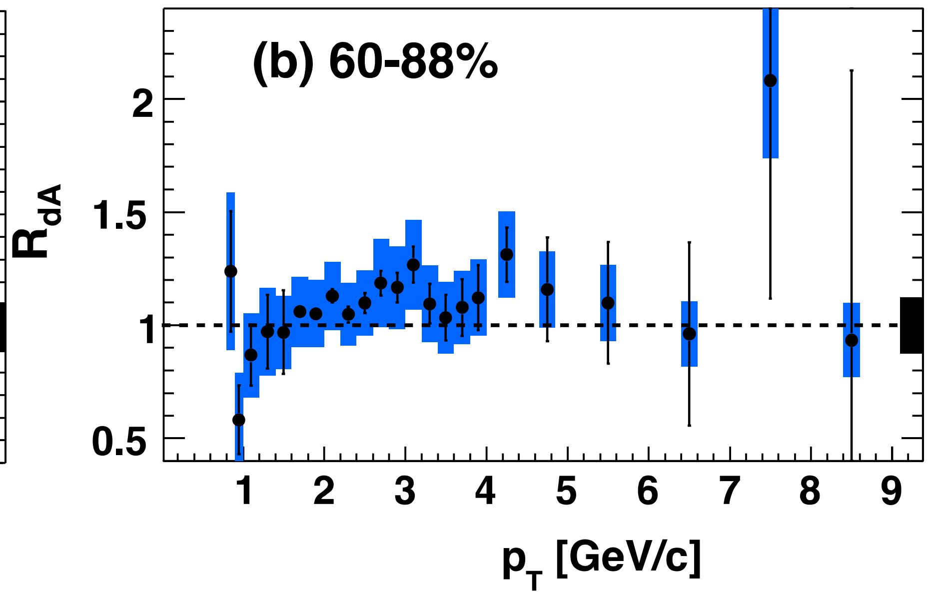


- STAR 200GeV and 500 GeV data points are in world data trend.
- NLO pQCD calculations reproduce the data well.

Cold nuclear matter@dAu 200GeV

- Non-photonic electrons at midrapidity (PHENIX)

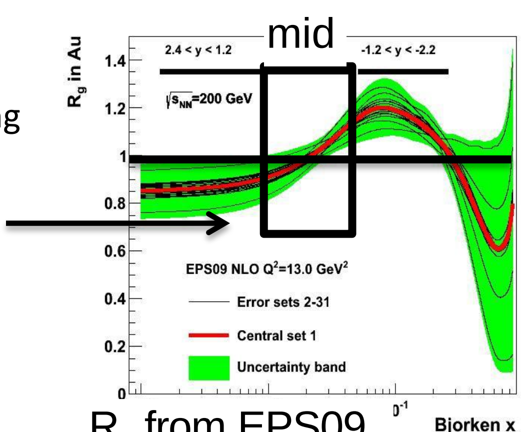




Central - Enhancement at intermediate p_T

Peripheral - Consistent with scaled p+p results

Shadowing/Anti-Shadowing Transition

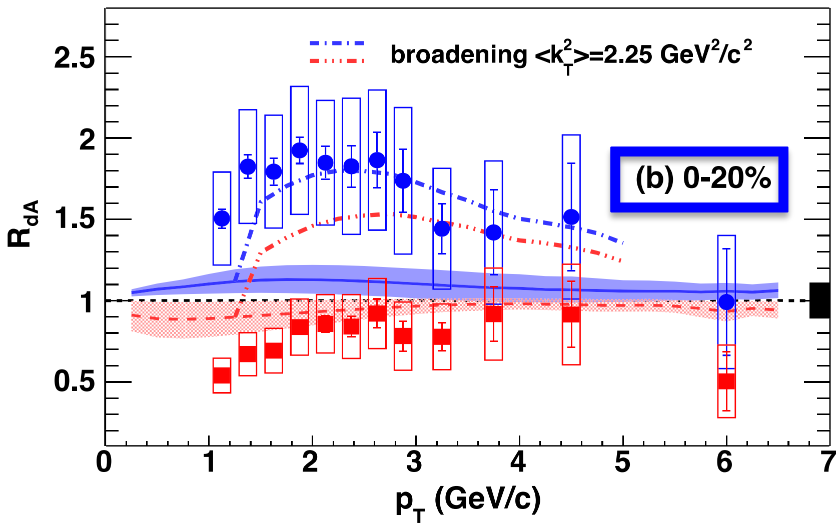


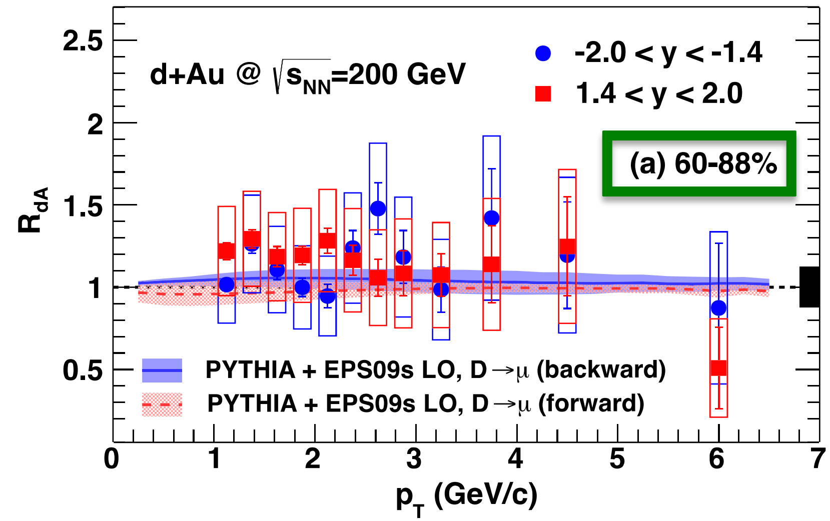
R_g from EPS09

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

Muons at Forward/Backward Rapidity@PHENIX

PHENIX Phys. Rev. Lett. 112, 252301 (2014)





Central:

Suppression at forward rapidity

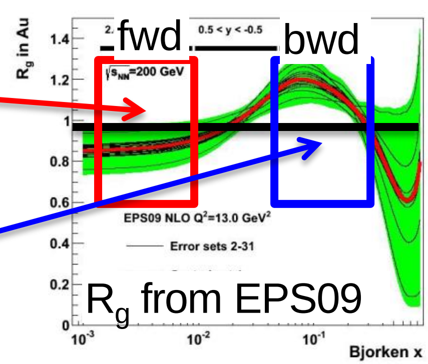
Enhancement at backward rapidity

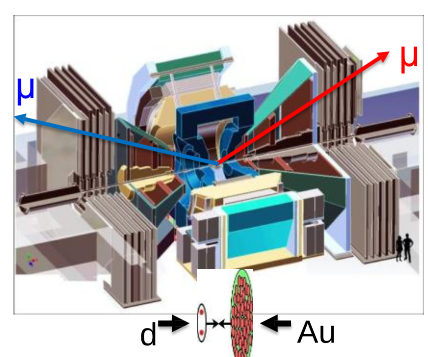
Peripheral:

Consistent with scaled p+p results

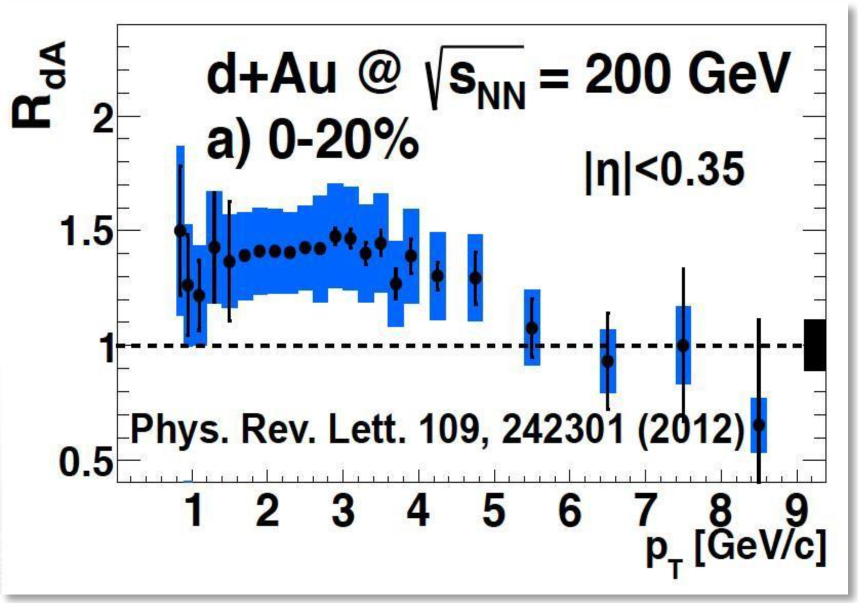
Shadowing Region

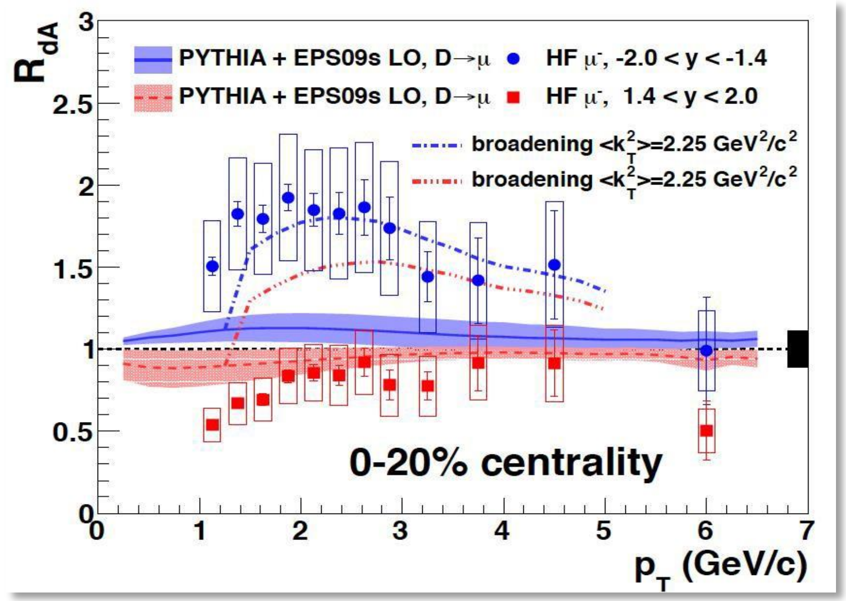
Anti-Shadowing Region





R_{dAu}@PHENIX

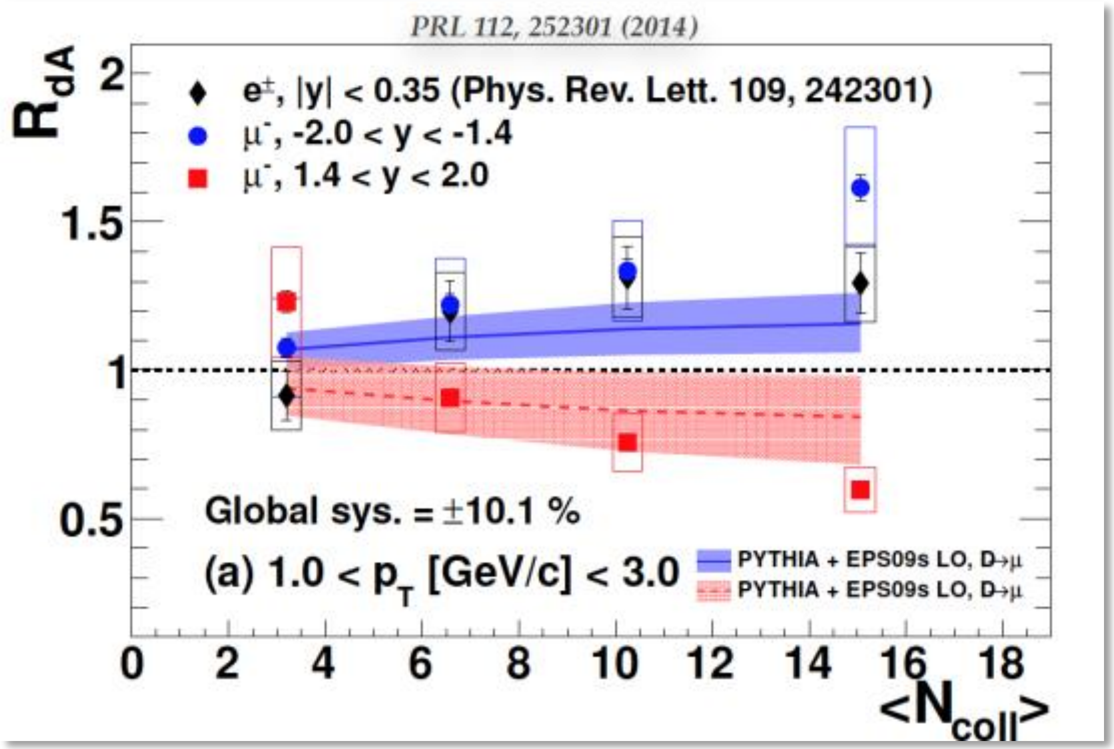




- Initial-state effects fail to reproduce the data at both rapidity simultaneously
  - Modification of nPDF
  - Initial k_T broadening
- Cronin enhancement?
  - Initial k_T component due to multiple scattering of incoming partons

Phys. Rev. C. 88, 024906 (2013)

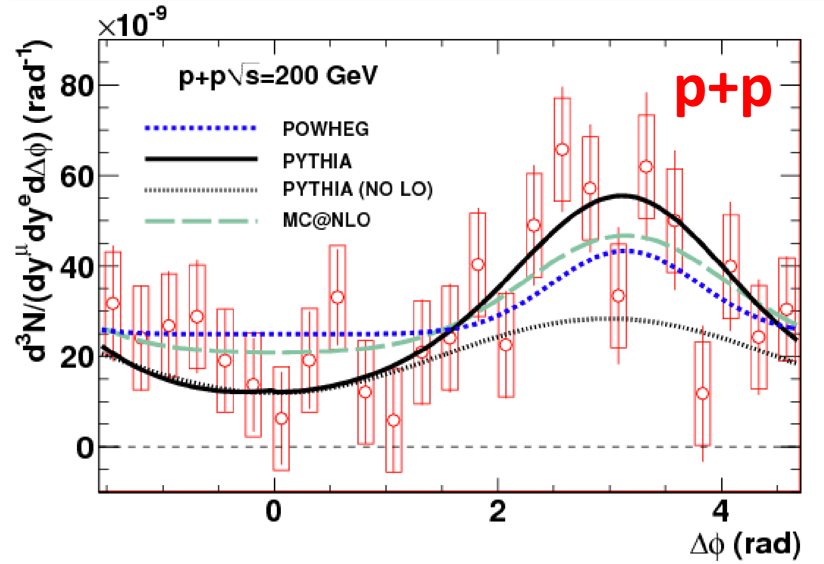
R_{dAu} v.s. N_{coll}

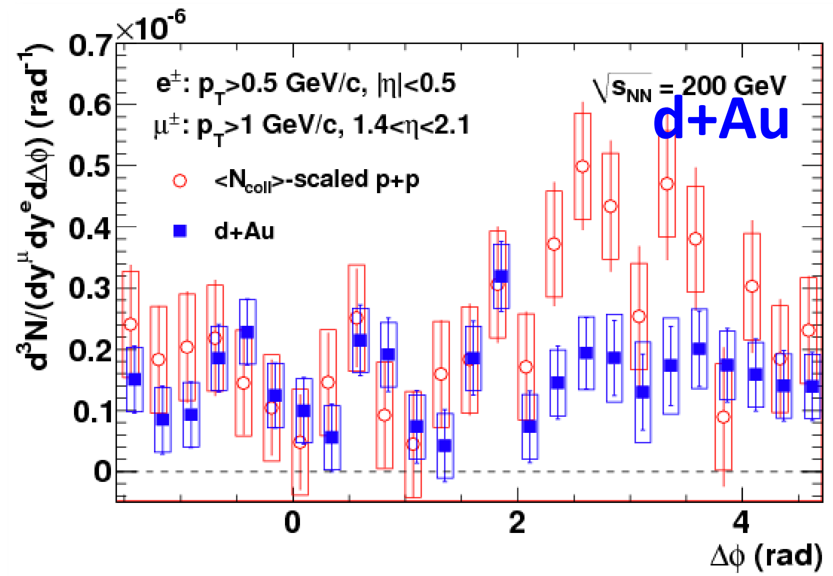


- **Peripheral** $R_{dA} \approx 1$
- **Central** Mid/Backward- $R_{dA} > 1$

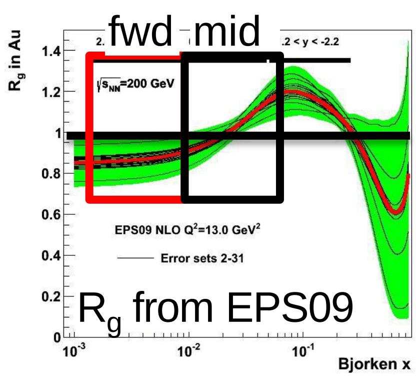
  Forward-y $R_{dA} < 1$
- Difference Back/Forward beyond EPS09s nPDF

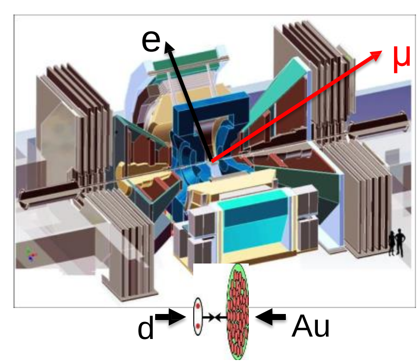
Electron-Muon Correlation@dAu200GeV





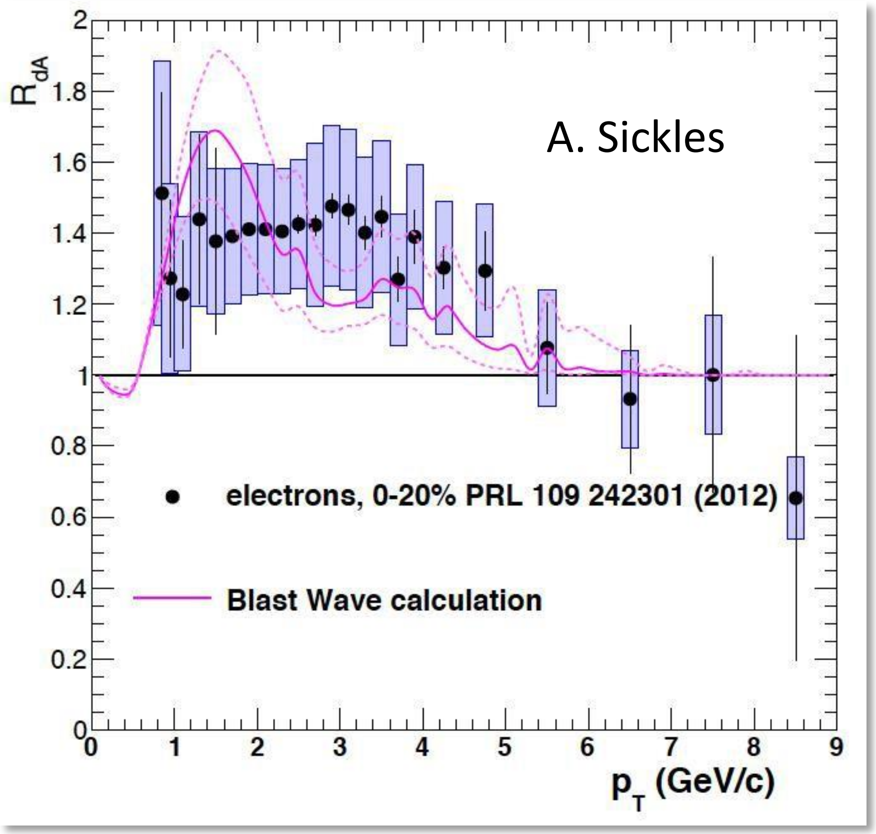
- pQCD-based models agree with the data in p+p collisions
- ***Clear suppression*** of e-mu correlation in d+Au collisions
  - CNM effects from heavy nuclei





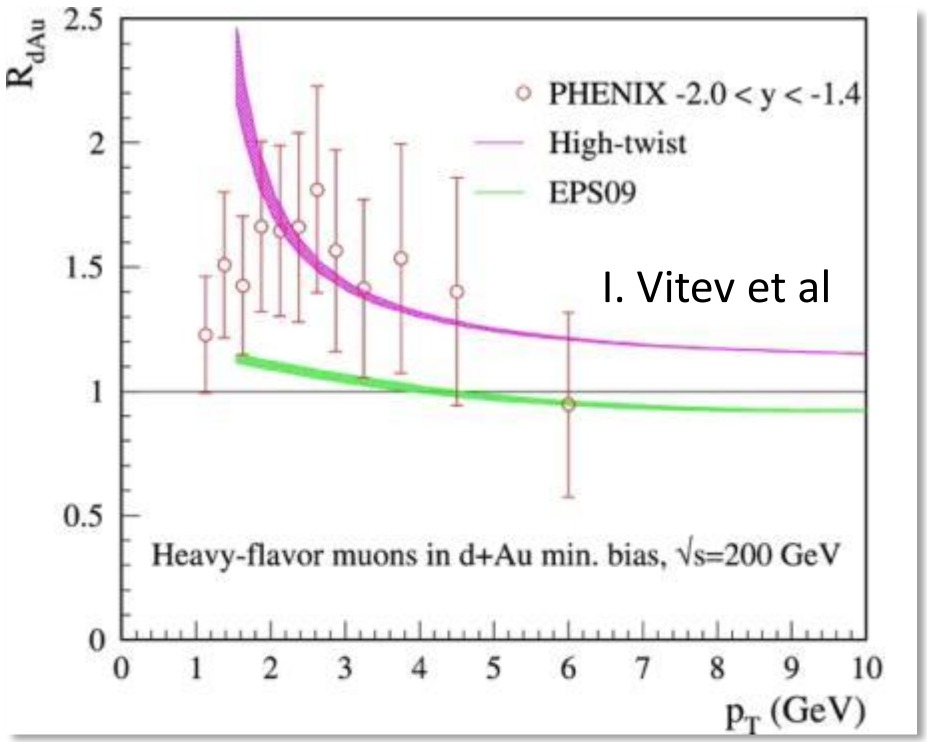
Phys. Rev. C. 89, 034915 (2014)

Models backward@dAu



Phys. Lett. B731 (2014) 51

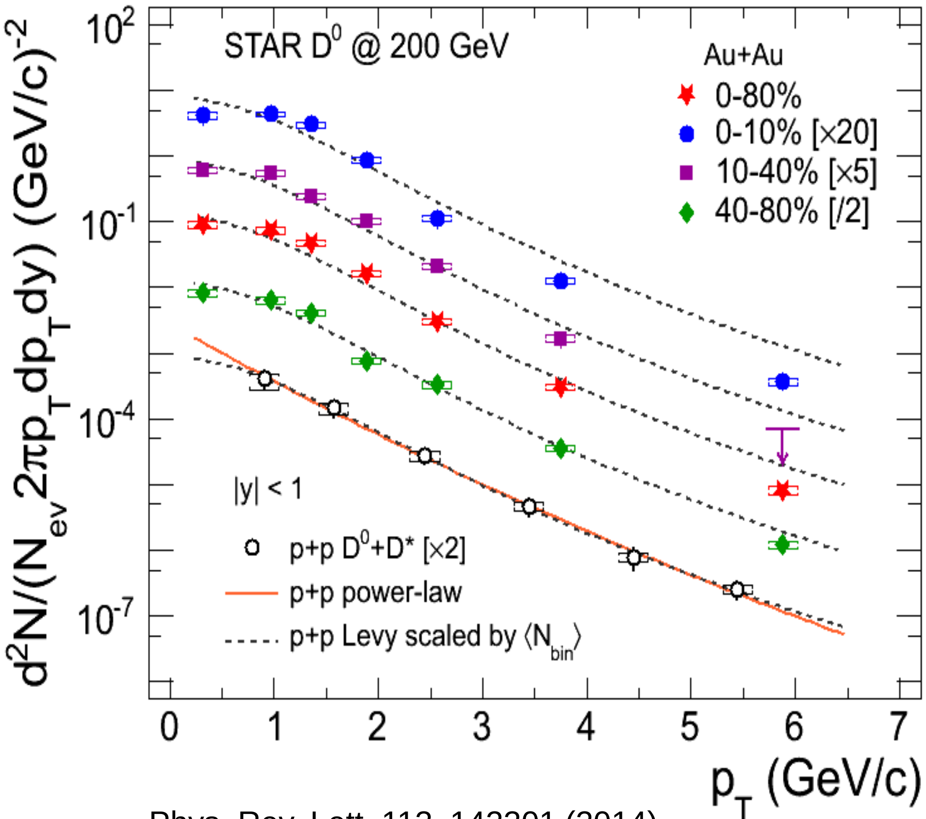
- Radial flow also qualitatively reproduce the enhancement



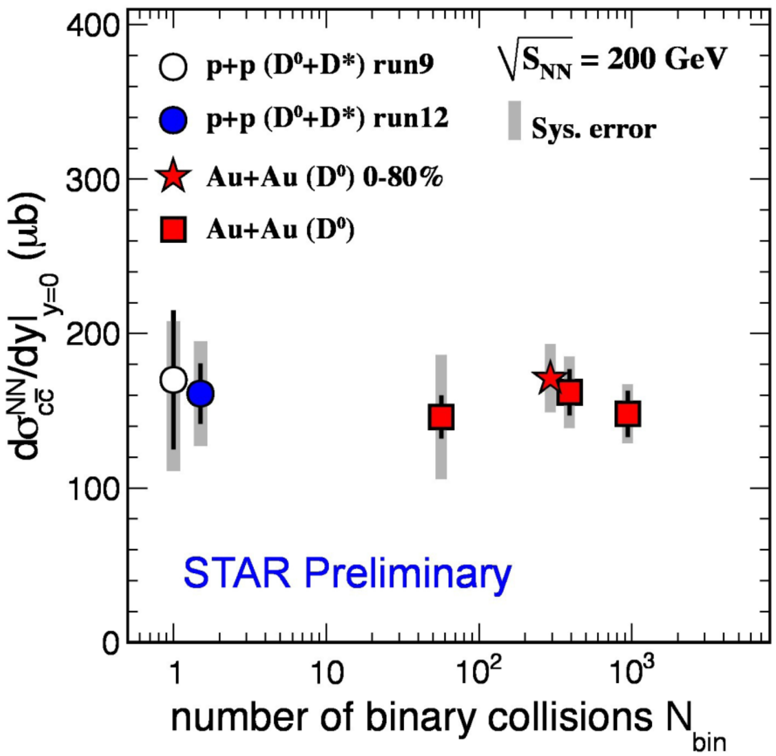
Phys. Lett. B740 (2015) 25

- pQCD calculation considering incoherent multiple scattering reproduce the enhancement at backward rapidity

D^0 spectra in Au+Au 200 GeV



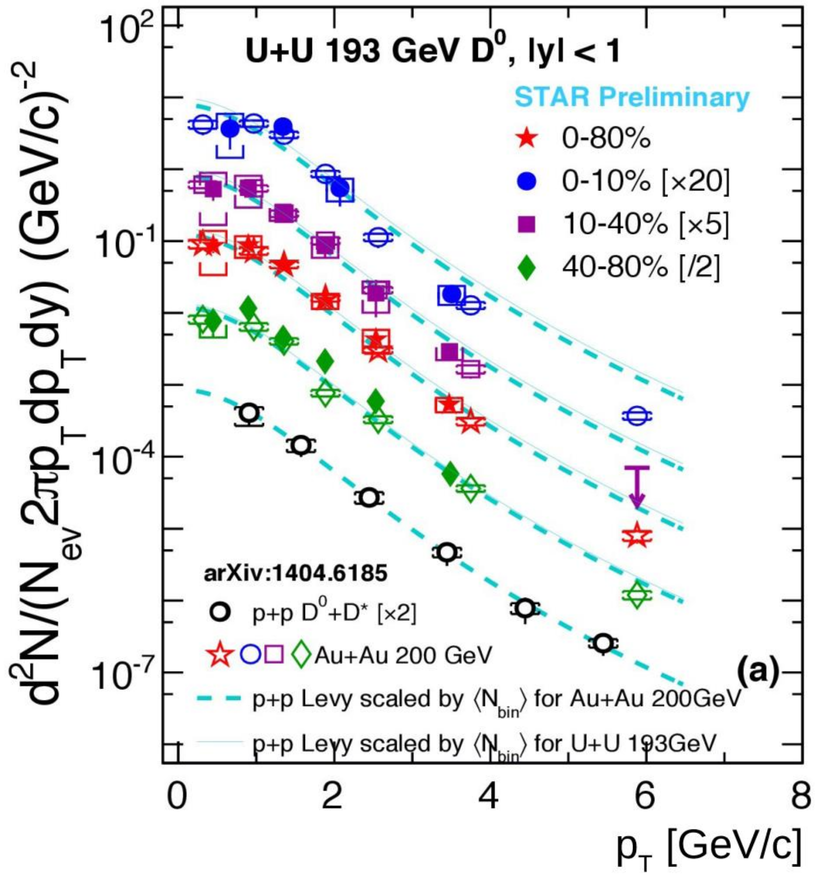
Phys. Rev. Lett. 113, 142301 (2014)

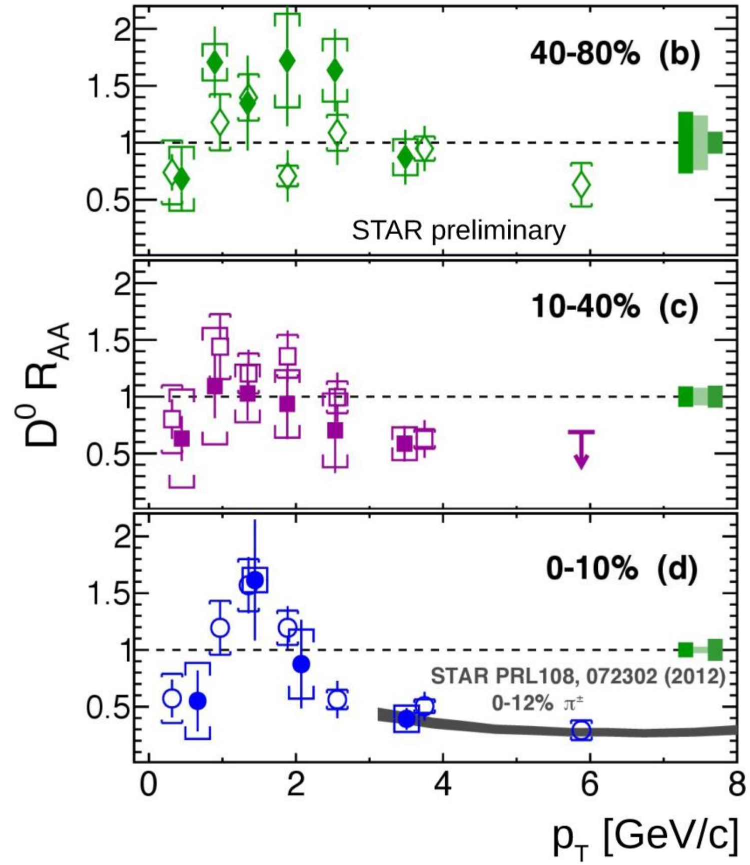


- Total charm cross section scales with the number of binary collisions as expected for hard production

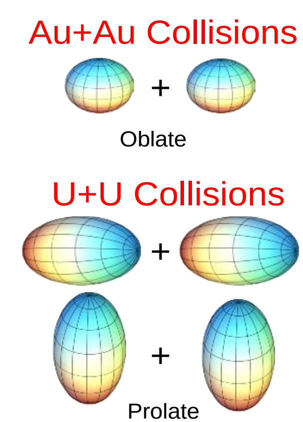
jaroslav.bielcik@fjfi.cvut.cz

D^0 spectra in U+U 193 GeV





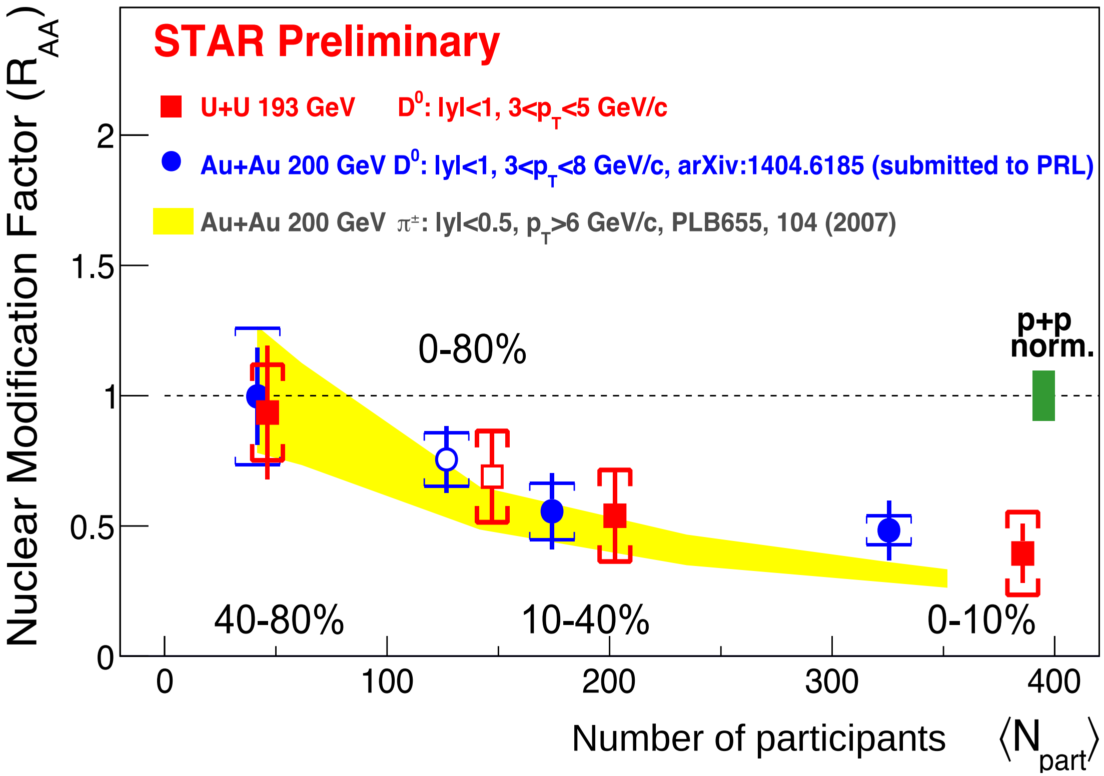
Phys. Rev. Lett. 113, 142301 (2014))



- U+U collisions can reach 20% more energy density.
- Similar suppression pattern in U+U collisions.

jaroslav.bielcik@fjfi.cvut.cz

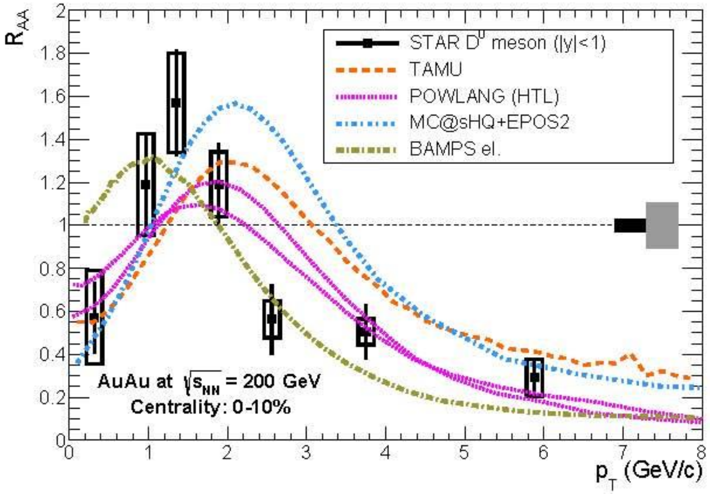
D^0 spectra in Au+Au vs. U+U collisions



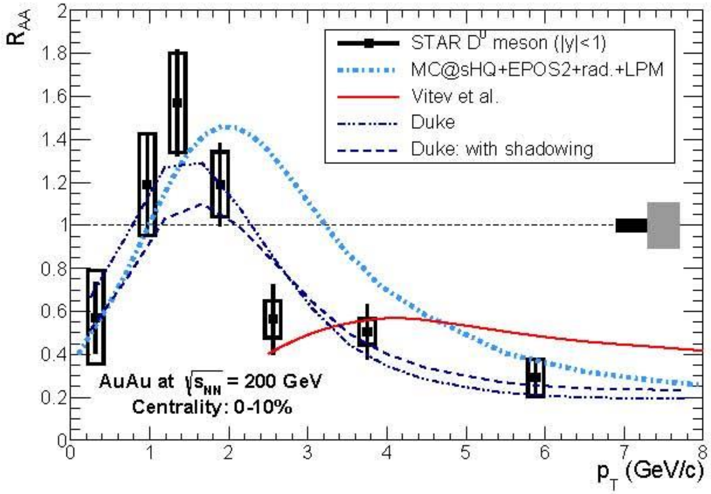
- Similar suppression of charm mesons and pions.
- Increasing suppression with $N_{part.}$

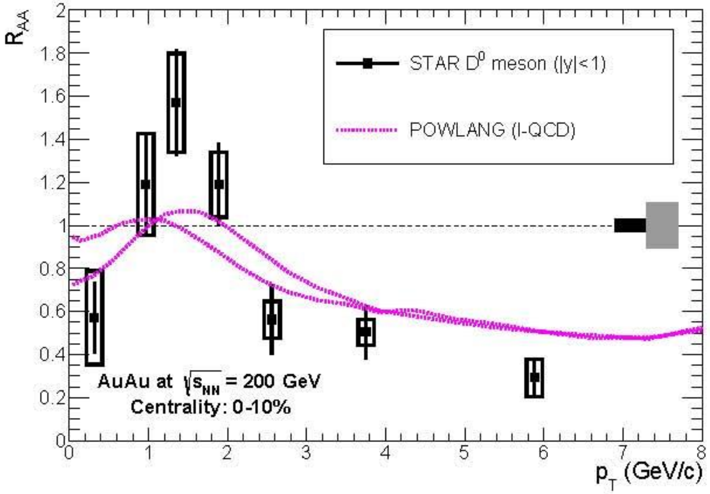
Charm mesons vs models

Collisional



Collisional + radiative





- Bump due to effect of radial flow

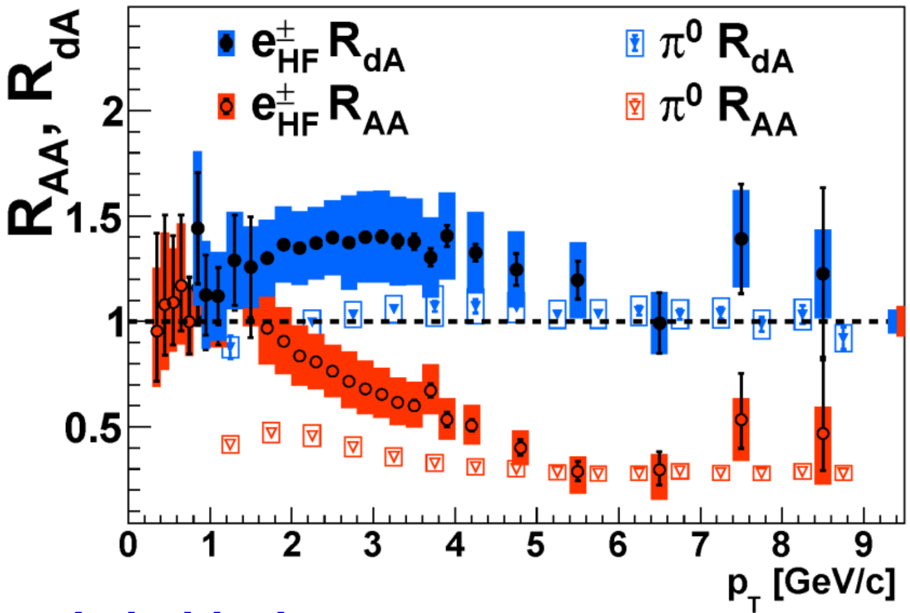
arXiv:1506.03981

Phys. Rev. Lett. 113, 142301 (2014)

jaroslav.bielcik@fjfi.cvut.cz

Non-photonic electrons in 200 GeV Au+Au

PHENIX: PRL 109 242301



Au+Au 200 GeV (min.bias)

1.0 < p_T < 5 GeV/c : $R_{AA}(e_{HF}) > R_{AA}(\pi^0)$

p_T > 5 GeV/c : $R_{AA}(e_{HF}) \sim R_{AA}(\pi^0)$

At high-p_T:suppression similar to pions

d+Au 200 GeV

1.0 < p_T < 5 GeV/c : $R_{AA}(e_{HF}) > R_{AA}(\pi^0)$

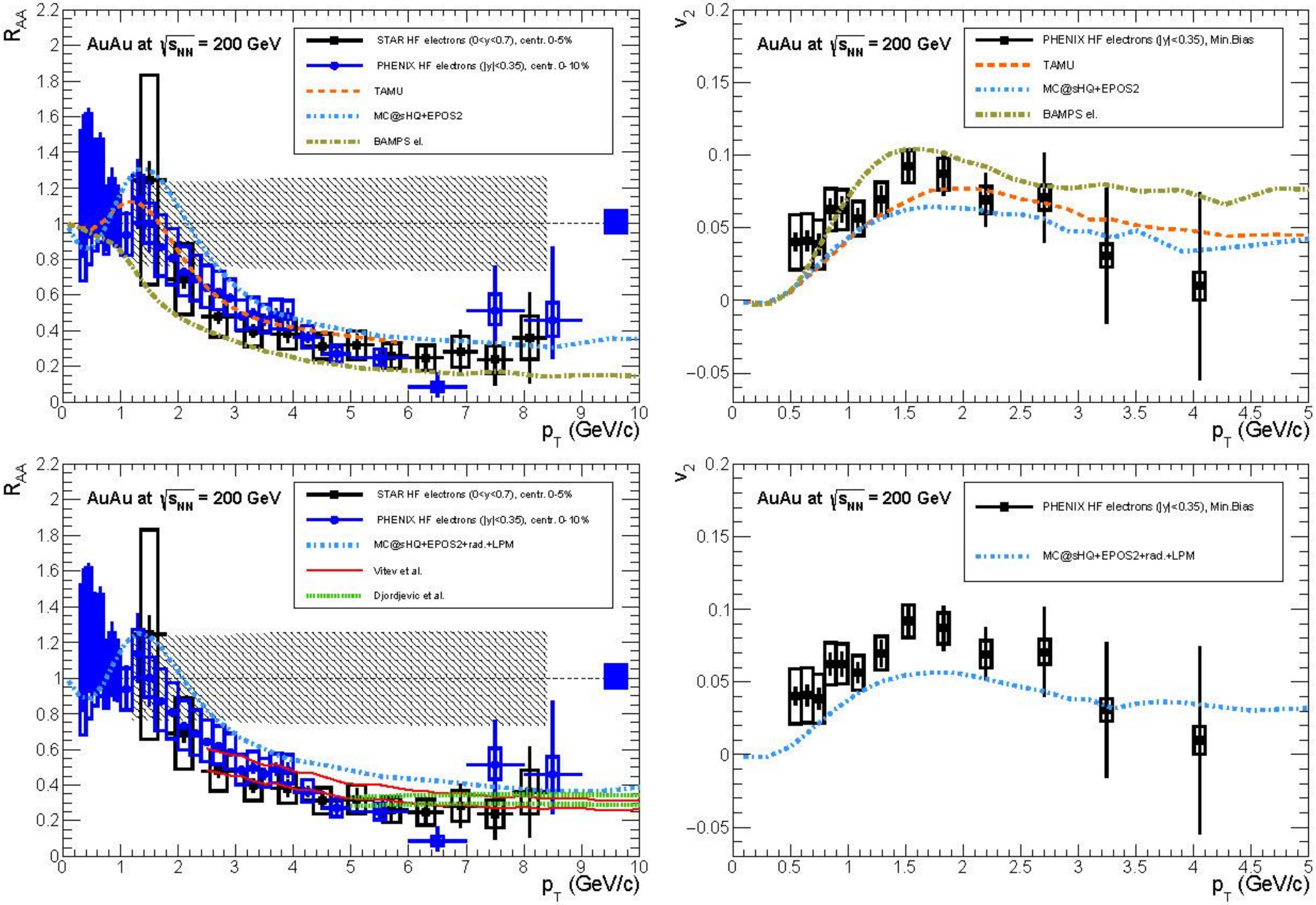
p_T > 5 GeV/c : $R_{AA}(e_{HF}) \sim R_{AA}(\pi^0)$

At high-p_T: suppression similar to pions

Heavy flavor are suppressed due to final state effects in hot and dense nuclear medium in Au+Au 200 GeV.
No difference vs, pions observed.

Non-photonic electrons vs models

Collisional



Collisional + radiative

arXiv:1506.03981

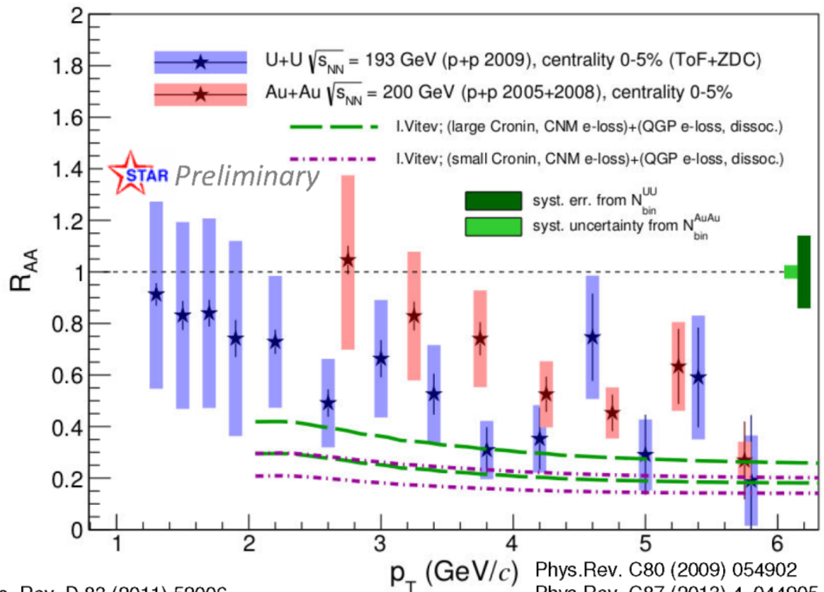
NPE UU193GeV

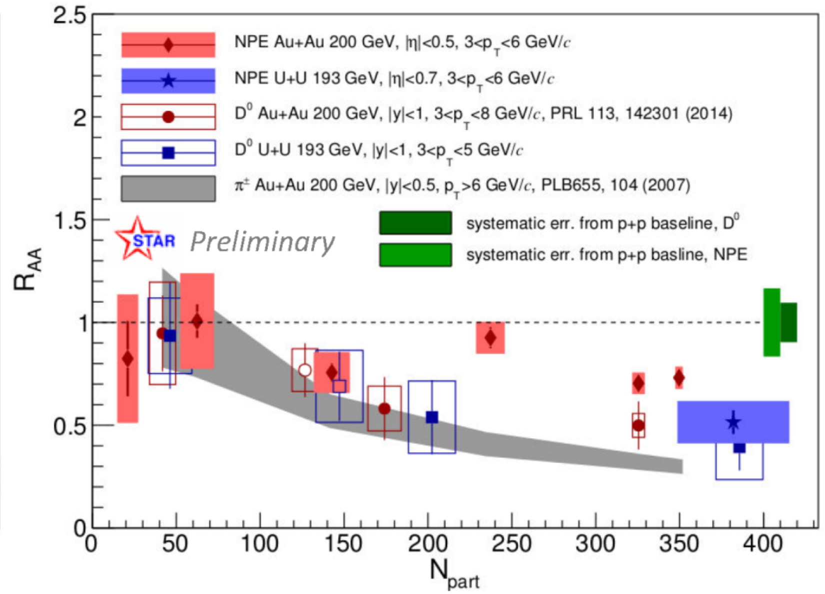
Nuclear modification factor

CZECH TECHNICAL UNIVERSITY IN PRAGUE

- Nuclear modification factor of NPE in U+U collisions is consistent within errors, but systematically lower than Au+Au collisions

$$R_{AA} = \frac{1}{\langle N_{bin} \rangle} \frac{d^2 N_{AA}/dp_T dy}{d^2 N_{pp}/dp_T dy}$$



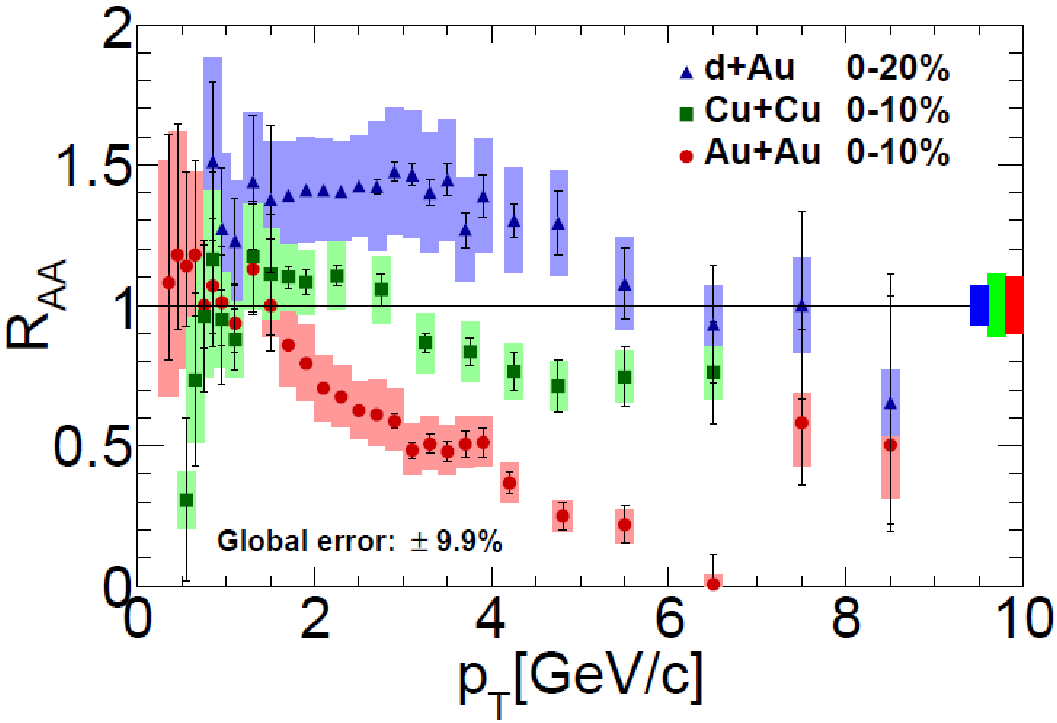


Phys. Rev. D 83 (2011) 52006
Phys.Rev.Lett.98:192301,2007; Erratum-ibid.106:159902,2011
Phys.Rev. C80 (2009) 054902
Phys.Rev. C87 (2013) 4, 044905
Phys.Rev.Lett. 114 (2015) 9, 092002

K. Gajdosova ICNFP 2015 - new

Non-photonic electrons in Cu+Cu 200GeV

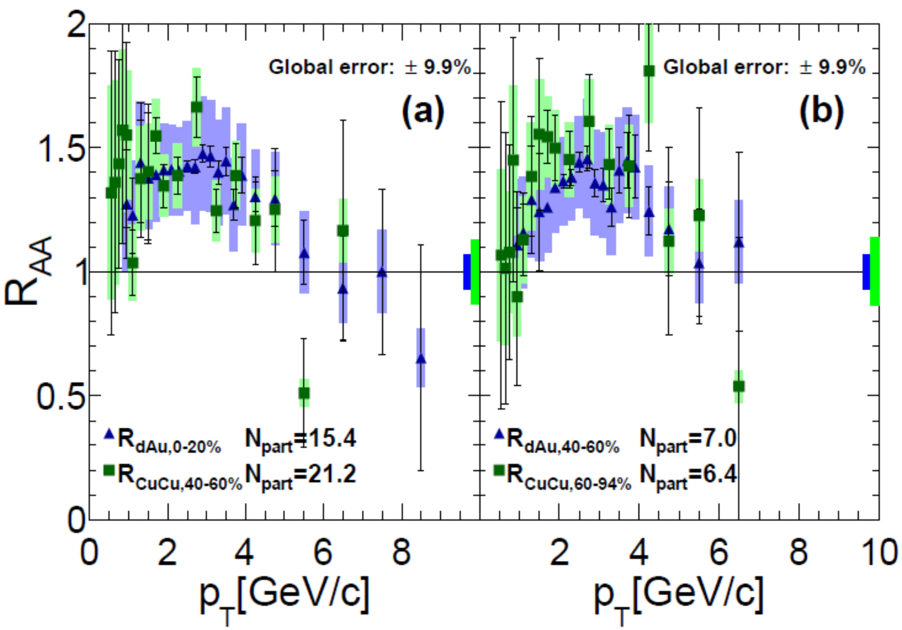
PHENIX: Phys.Rev. C90 (2014) 034903

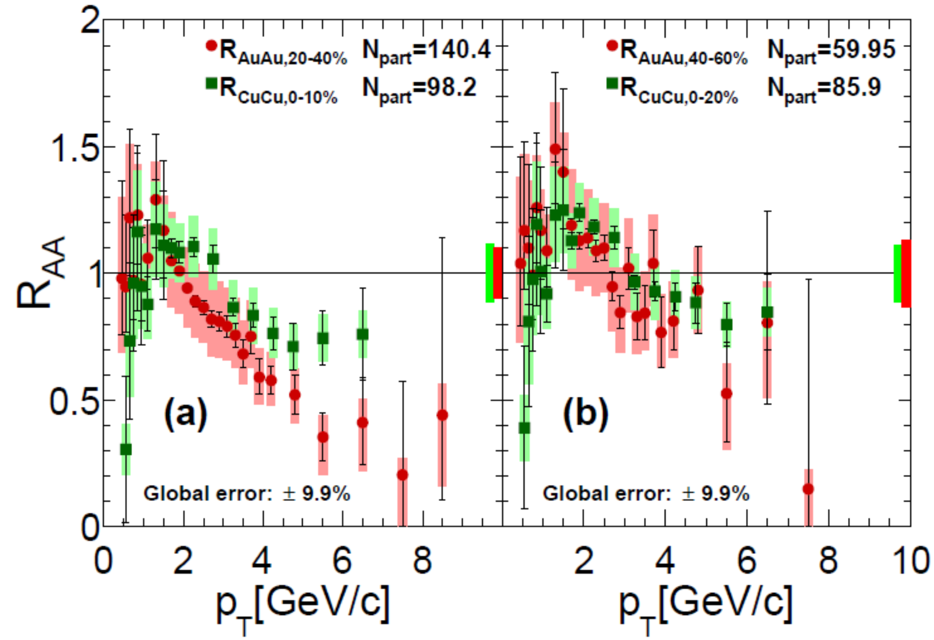


- Clear enhancement in d + Au
  Cold nuclear matter effects
- Large suppression in Au + Au
  Hot Medium effects
- Cu + Cu system intermediate
  R_{AA} between that in d + Au and Au + Au
  Interplay between CNM and Hot Medium effects.

Nuclear modification for similar $\langle N_{part} \rangle$

PHENIX: Phys.Rev. C90 (2014) 034903





$\langle N_{part} \rangle$ = 15 in d+Au
$\langle N_{part} \rangle$ = 20 in Cu+Cu

$\langle N_{part} \rangle$ = 7 in d+Au
$\langle N_{part} \rangle$ = 6 in Cu+Cu

$\langle N_{part} \rangle$ = 100 in Cu+Cu
$\langle N_{part} \rangle$ = 140 in Au+Au

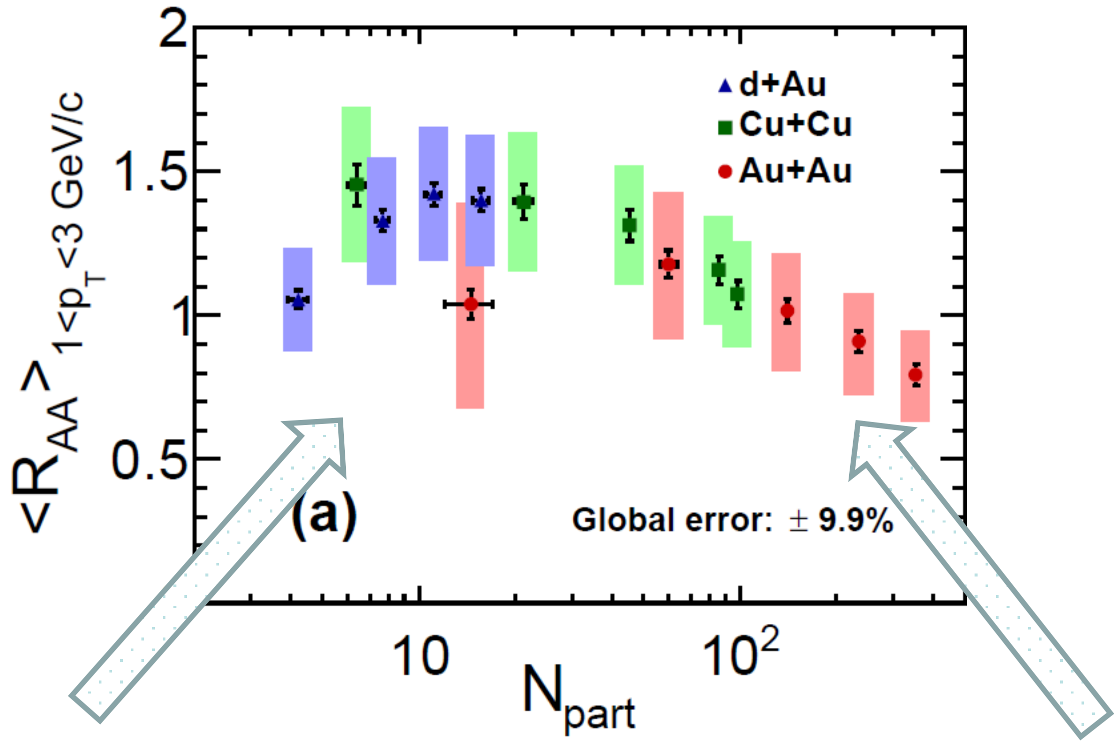
$\langle N_{part} \rangle$ = 86 in Cu+Cu
$\langle N_{part} \rangle$ = 60 in Au+AU

Similar enhancement and suppression are seen for the different system at similar $\langle N_{part} \rangle$

jaroslav.bielcik@fjfi.cvut.cz

N_{part} dependence of R_{AA}

PHENIX: Phys.Rev. C90 (2014) 034903



Increase of enhancement
CNM effects

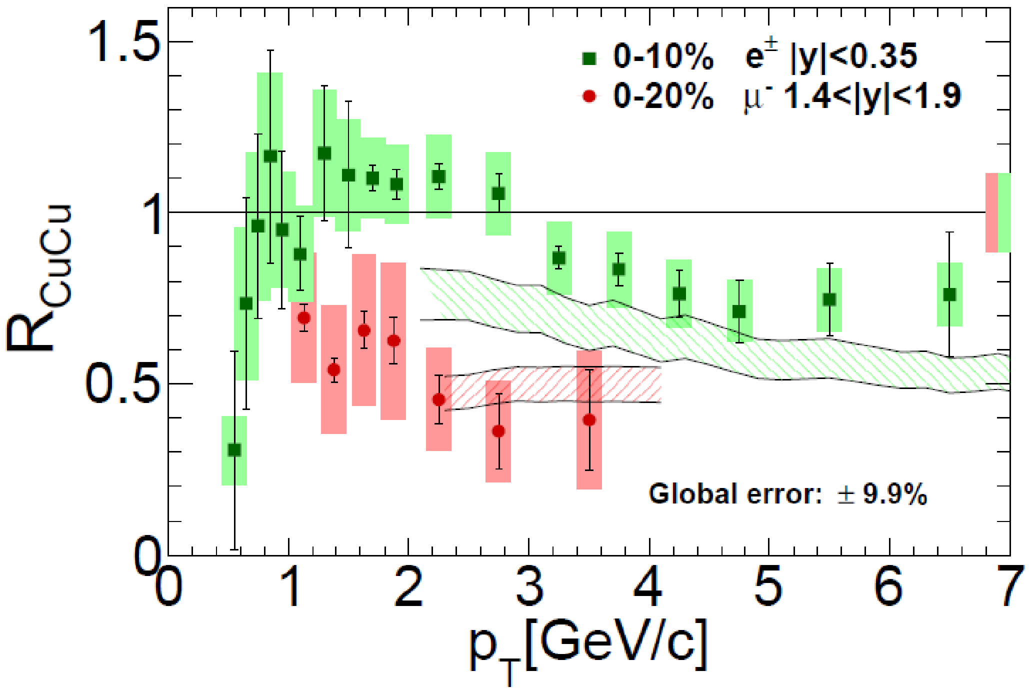
Onset of suppression
Hot matter effects take over

Enhancement and suppression effects depend on system size

jaroslav.bielcik@fjfi.cvut.cz

Cu+Cu 200 GeV
$e^{+/-}$ midrapidity vs. μ^- for forward rapidity

PHENIX: Phys.Rev. C90 (2014) 034903



More suppression in μ^- yield

- Additional CNM effects like shadowing and initial state energy loss

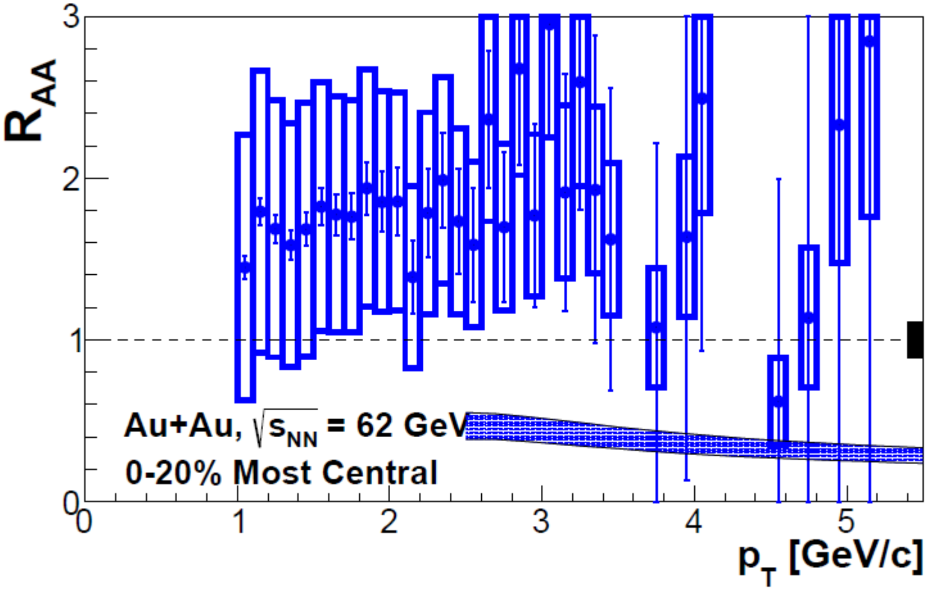
Theoretical calculation
R.Sharma et al. Phys.Rev. C 80 (2009) 054902

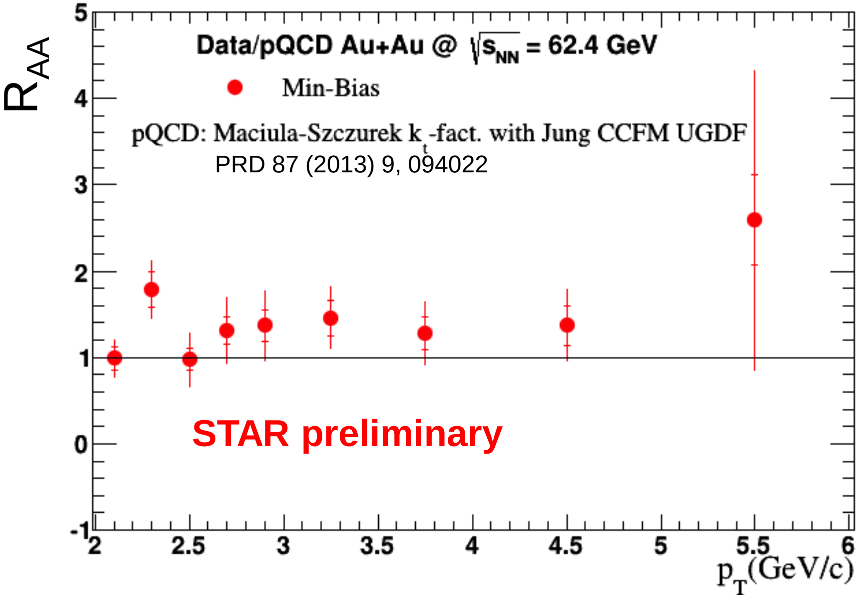
- partonic energy loss
- suppression due to fragmentation and dissociation of heavy-flavor hadrons
- shadowing effect
- Cronin effect

No theoretical calculation to explain both data

jaroslav.bielcik@fjfi.cvut.cz

Non-photonic electrons Au+Au 62.4 GeV





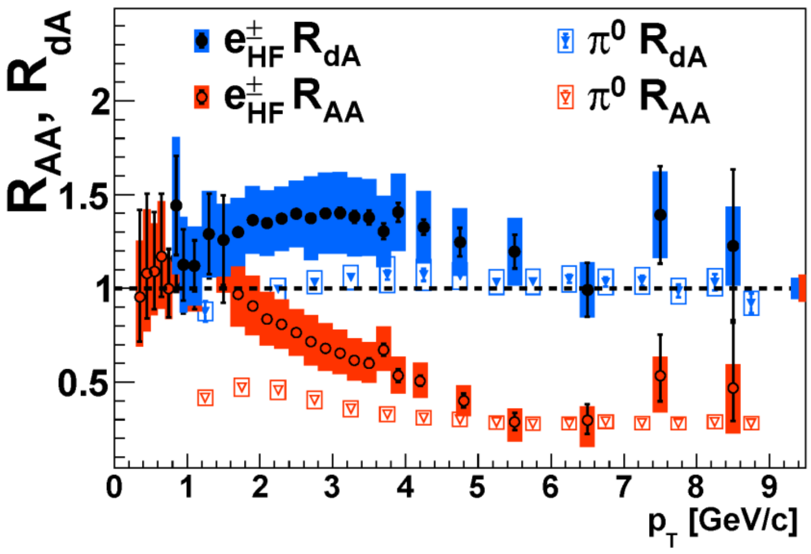
Vitev model can describes 200 GeV suppression but it underpredicts 62.4 GeV data.

No suppression of NPE observed in 62.4 GeV Au+Au collisions.
Cold nuclear matter effects are not known.
Note: pQCD-scaled p+p reference

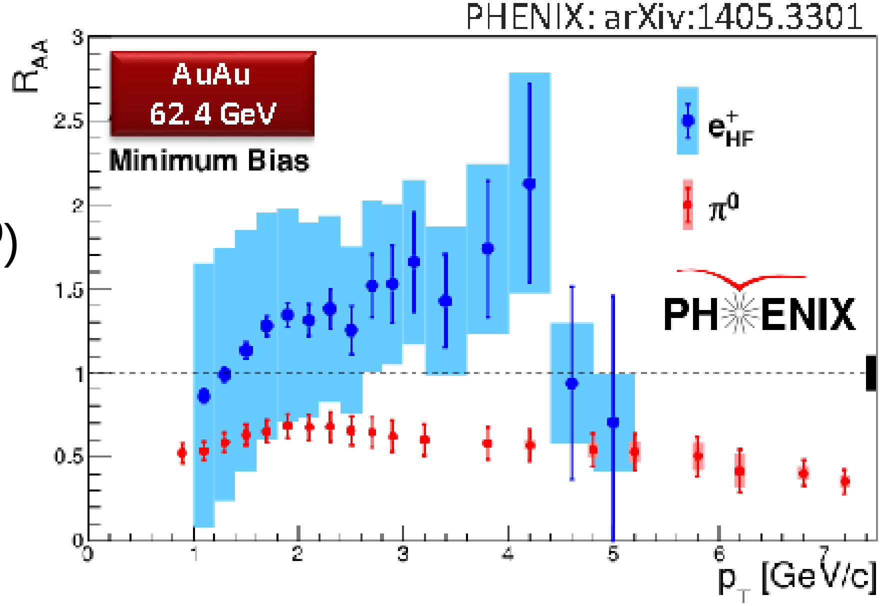
jaroslav.bielcik@fjfi.cvut.cz

R_{AA} heavy flavor vs. pions

PHENIX: PRL 109 242301



PHENIX: arXiv:1405.3301

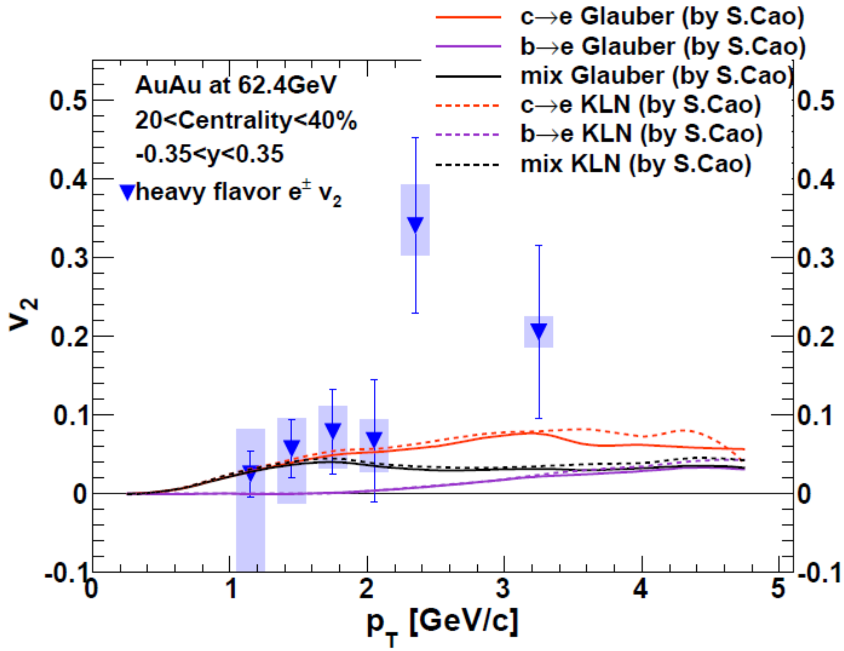


Au+Au 62 GeV

1.0 < p_T < 4-5 GeV/c : $R_{AA}(e_{HF}) > R_{AA}(\pi^0)$
There is enhancement at Au+Au 62 GeV

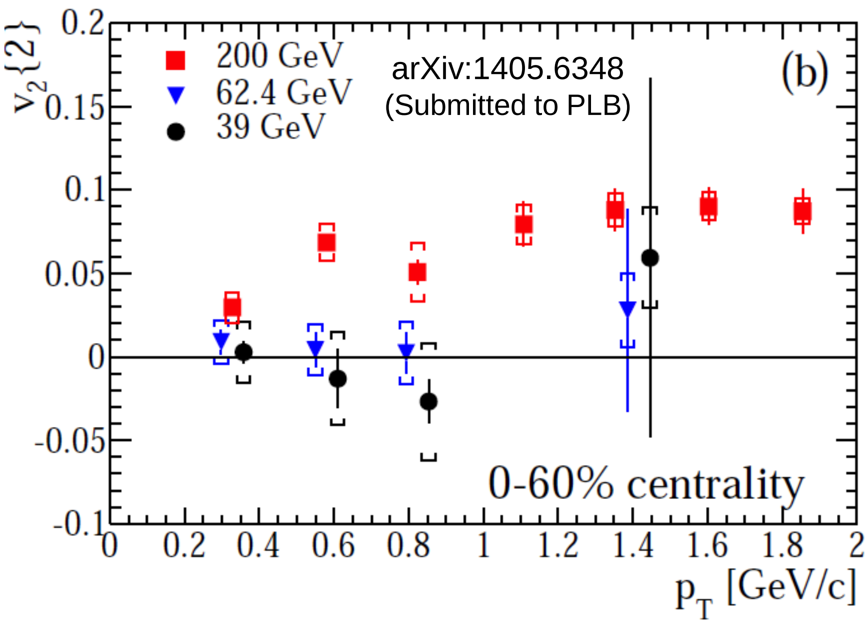
What is the source of this difference?
Initial state effects might be different.

Non-photonic electrons Au+Au 39, 62.4 GeV



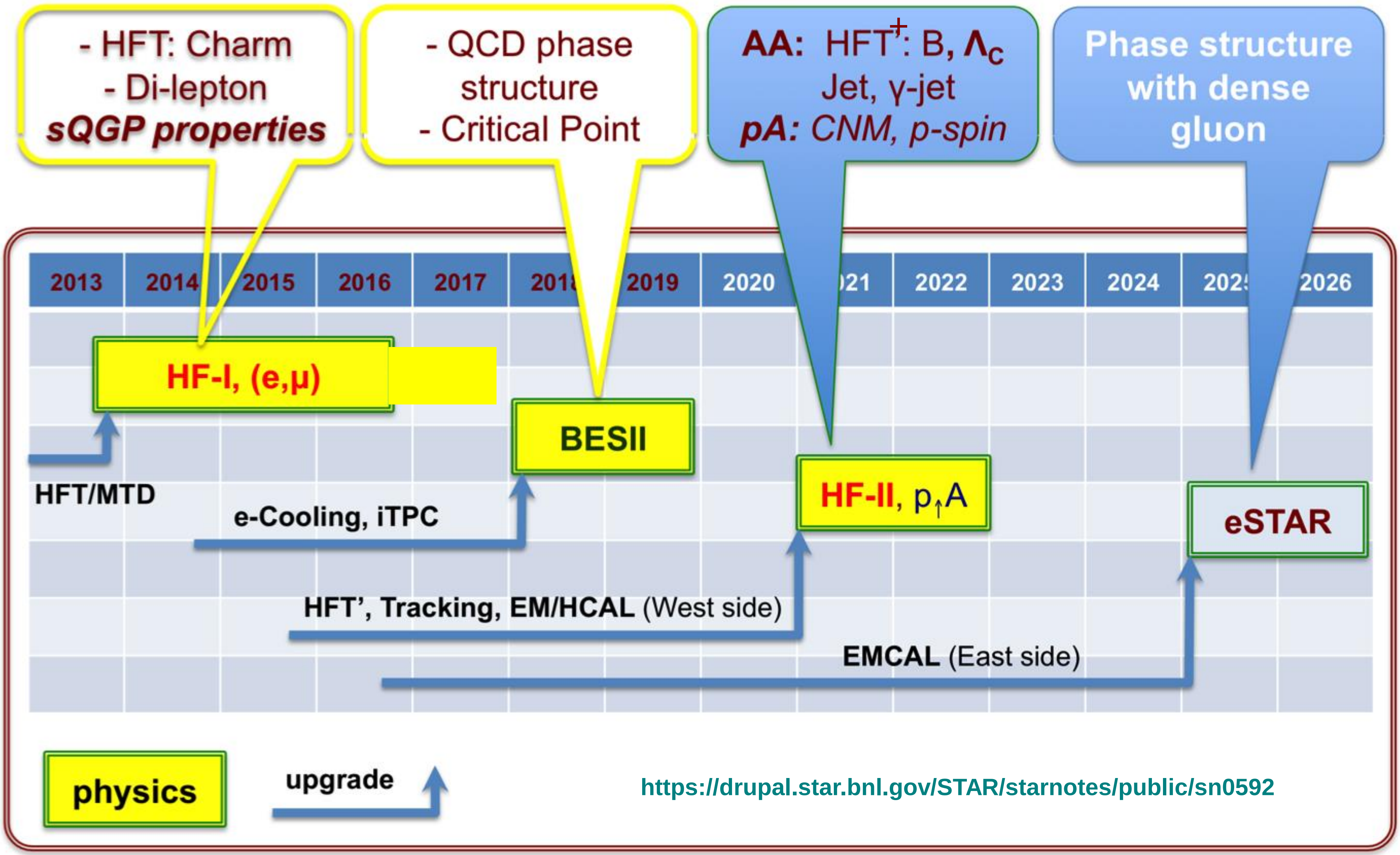
Anisotropy (v_2)

- Charm has a positive v_2 in 62 GeV Au + Au p_T> 1GeV.
- Collective motion of charm itself?
- Collective motion of charmed hadrons through recombination with flowing light partons?

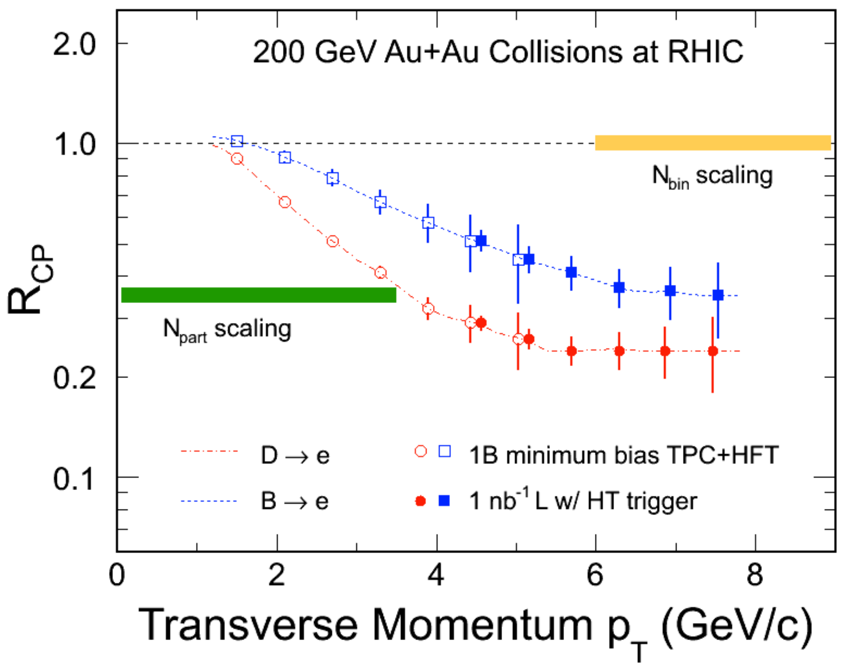


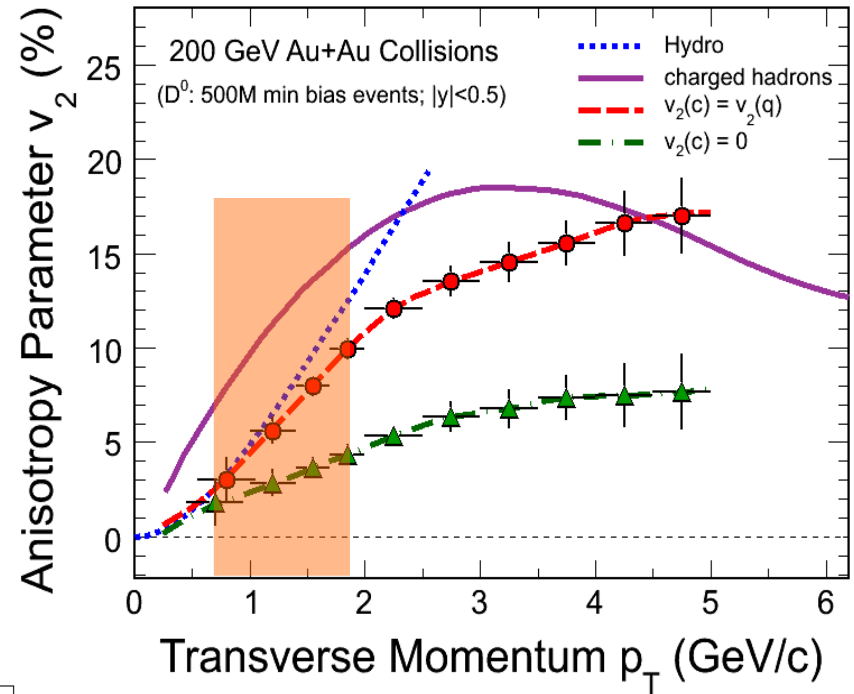
- NPE in 39 and 62.4 GeV Au+Au collisions **consistent with no flow.**
- Statistically different from 200 GeV for p_T < 1 GeV/c.

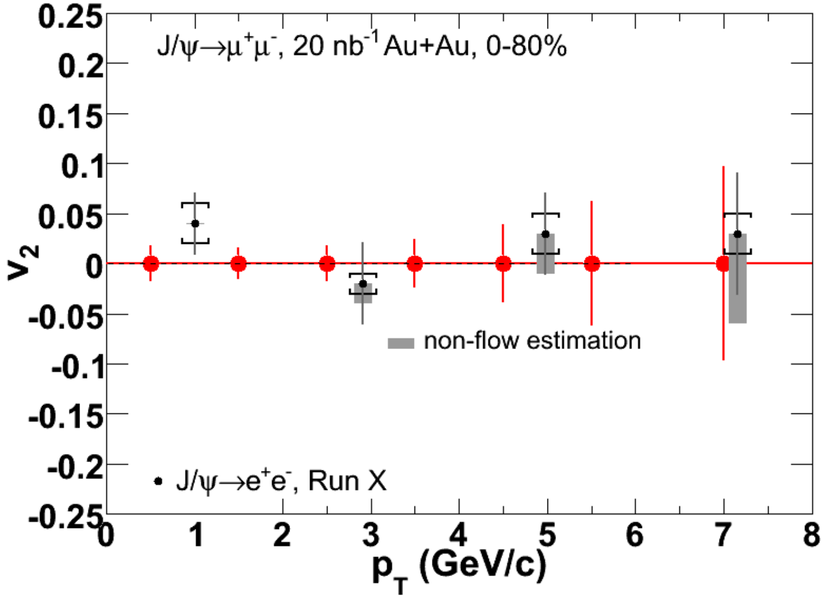
STAR focus in next decade

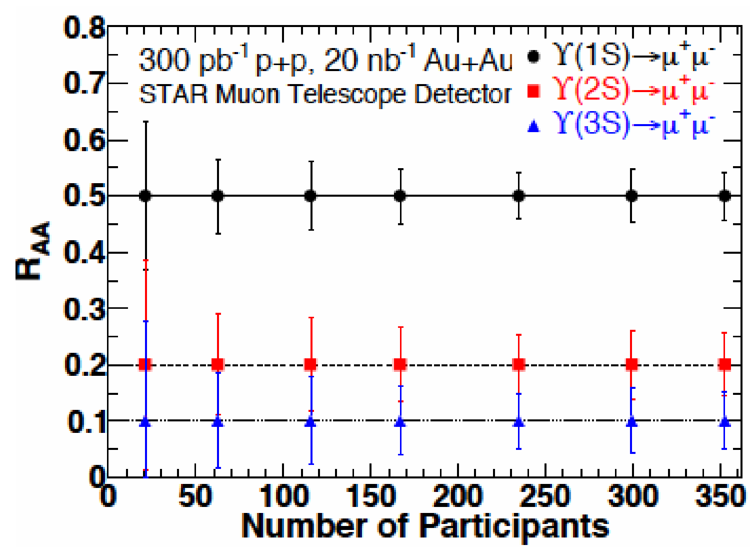


Heavy flavor with HFT 2014-2016



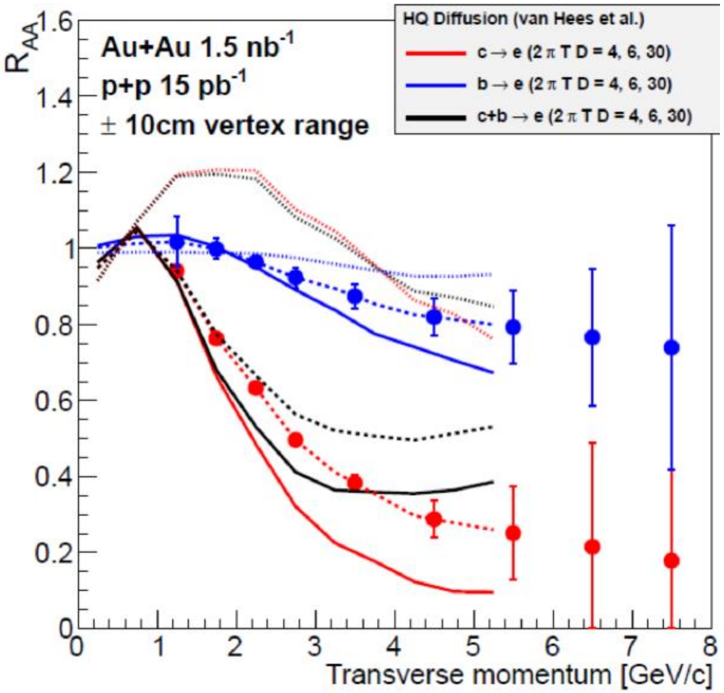


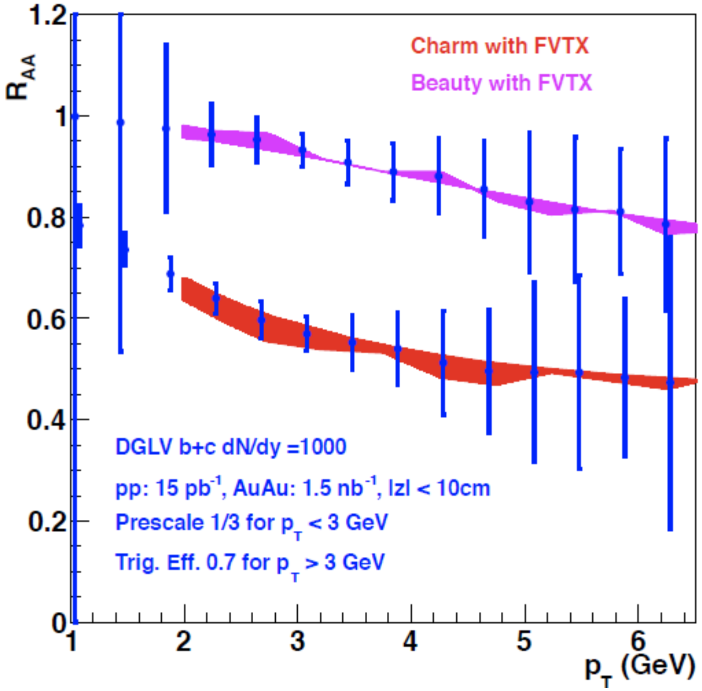




Simulated Performance in Run-14 200GeV Au + Au PHENIX

Simulated performance of nuclear modification for VTX and FVTX





New results with VTX/FVTX will come soon

jaroslav.bielcik@fjfi.cvut.cz

Summary

- Recent charm production measurement in p+p at 200 and 500 GeV in extented p_T range. The pQCD calculations are consistent with data.

- Large suppression of heavy quark production at high-p_T in D^0 and non-photonic electrons measurements in 200 GeV central Au+Au and U+U collisions. Similar to light quarks. Dead cone effect?

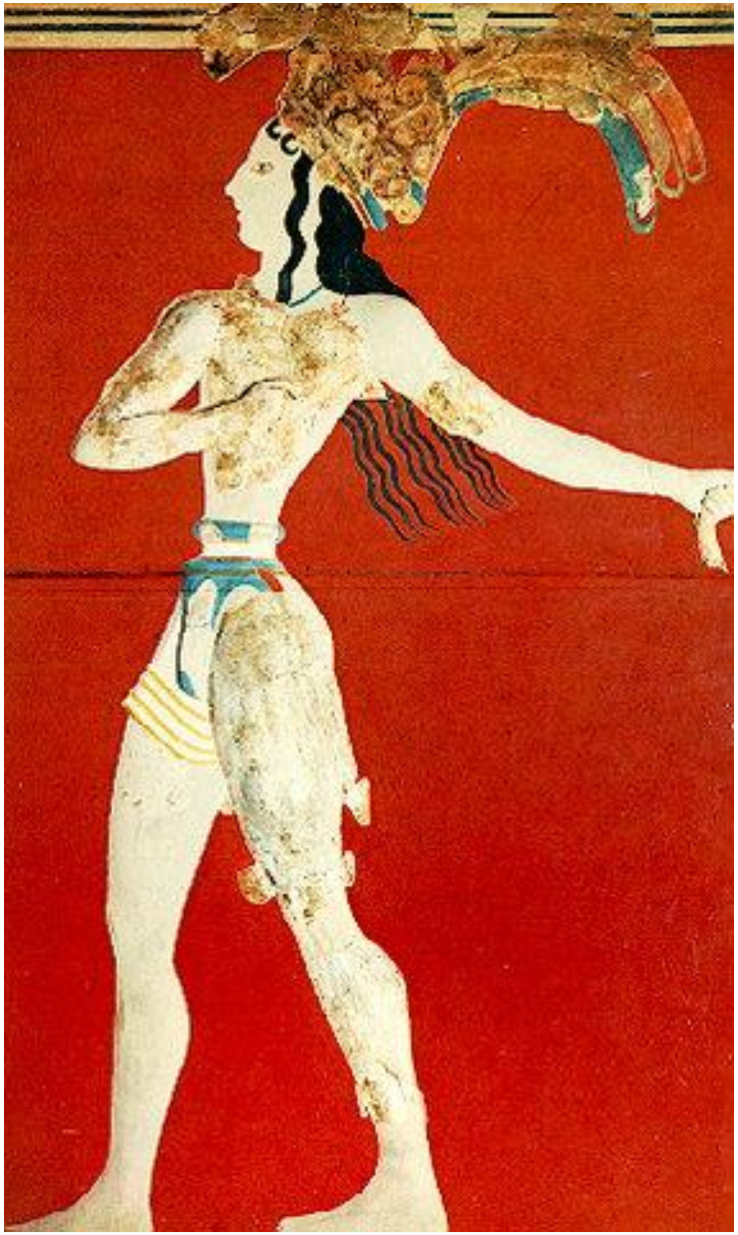
- d+Au, Cu+Cu, Au+Au 200 GeV
  Similar enhancement and suppression for the different system at similar <Npart>

- Au+Au 62 GeV , need for better reference
  Importance of CNM effects at low energies.

- Finite v_2 of non-photonic electrons at 200 GeV
  Consistent with zero at lower energies p_T<1GeV/c, nonzero for p_T>1GeV/c.
  Charm flow?

- STAR & PHENIX in Run 2014 entered Heavy flavor precision era
  Significant improvement of heavy flavor, quarkonium and dilepton measurements.

jaroslav.bielcik@fjfi.cvut.cz



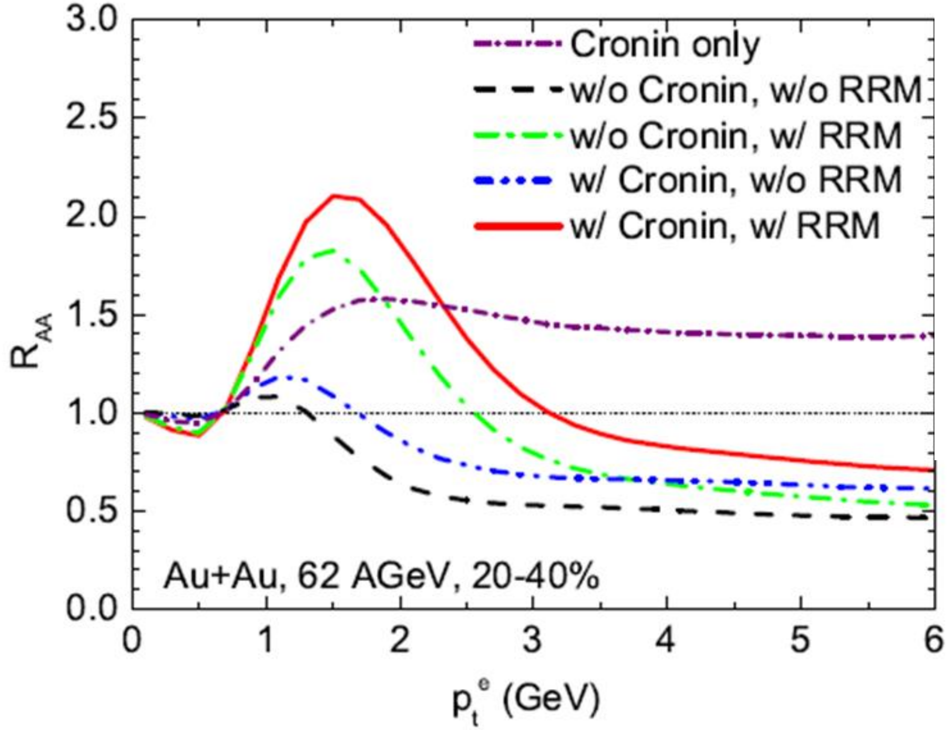
We should be more happy that archeologists

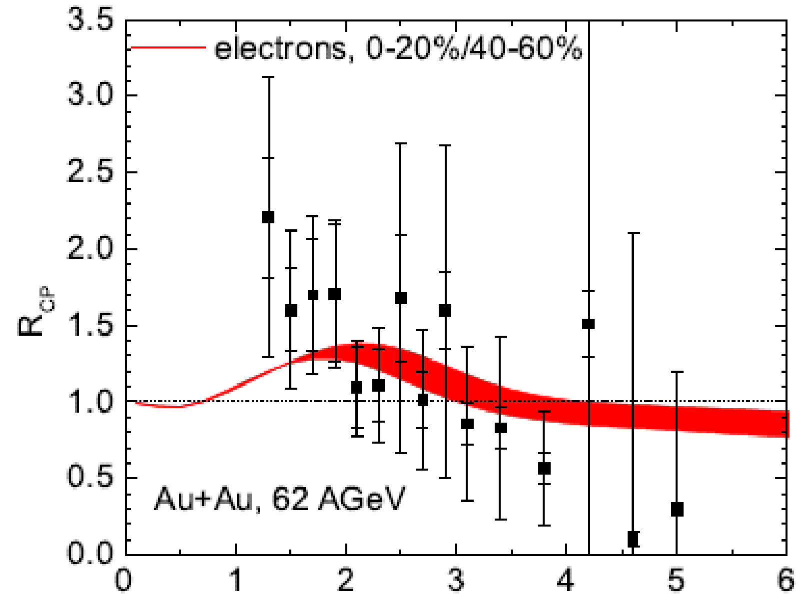
With one piece – hard to guess

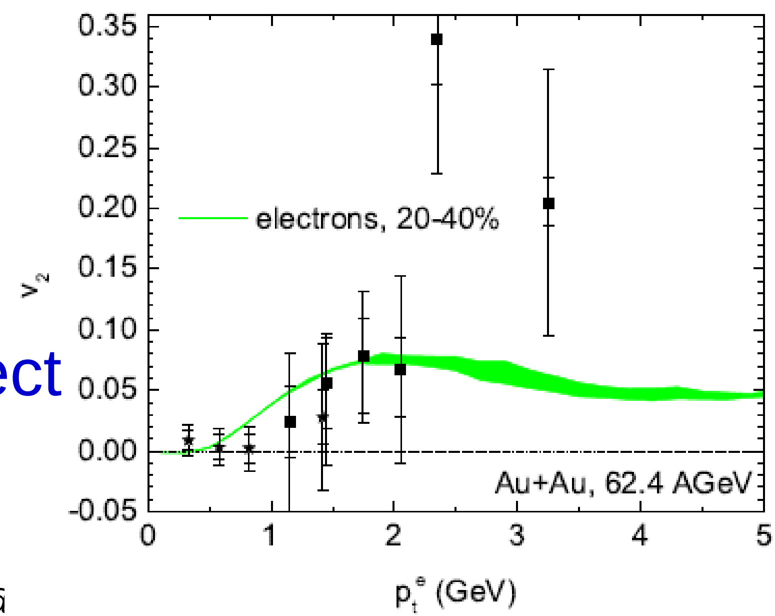
With more pieces and hard work
– more clear picture will emerge

jaroslav.bielcik@fjfi.cvut.cz

Ralf Rapp @ SaporeGravis workshop 2014



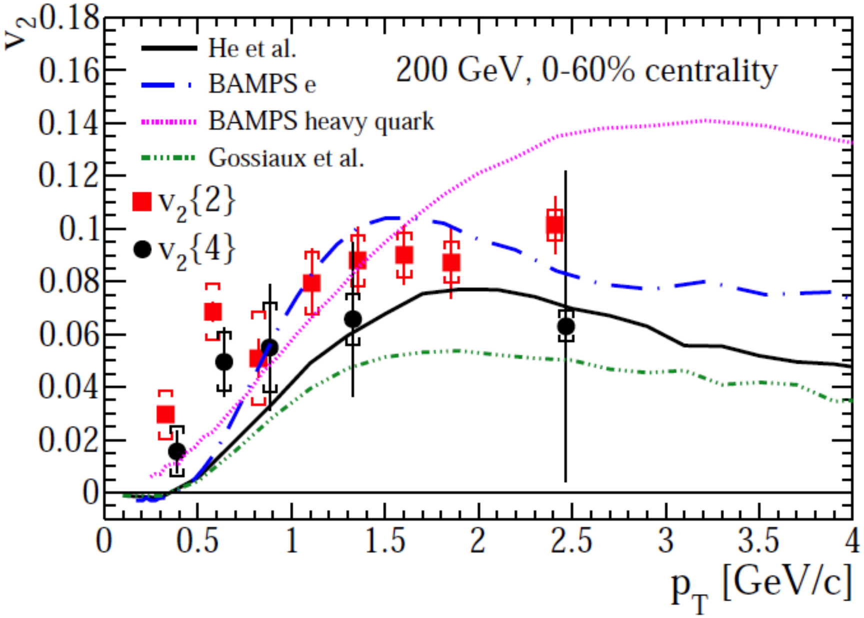


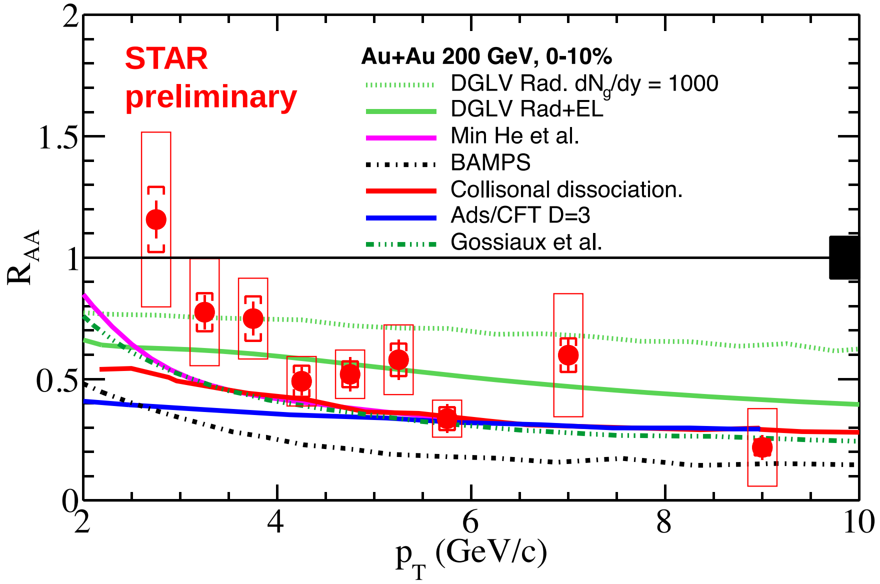


- importance of flow + Cronin effect at lower energies

Non-photonic electrons azimuthal anisotropy

STAR arXiv:1405.6348

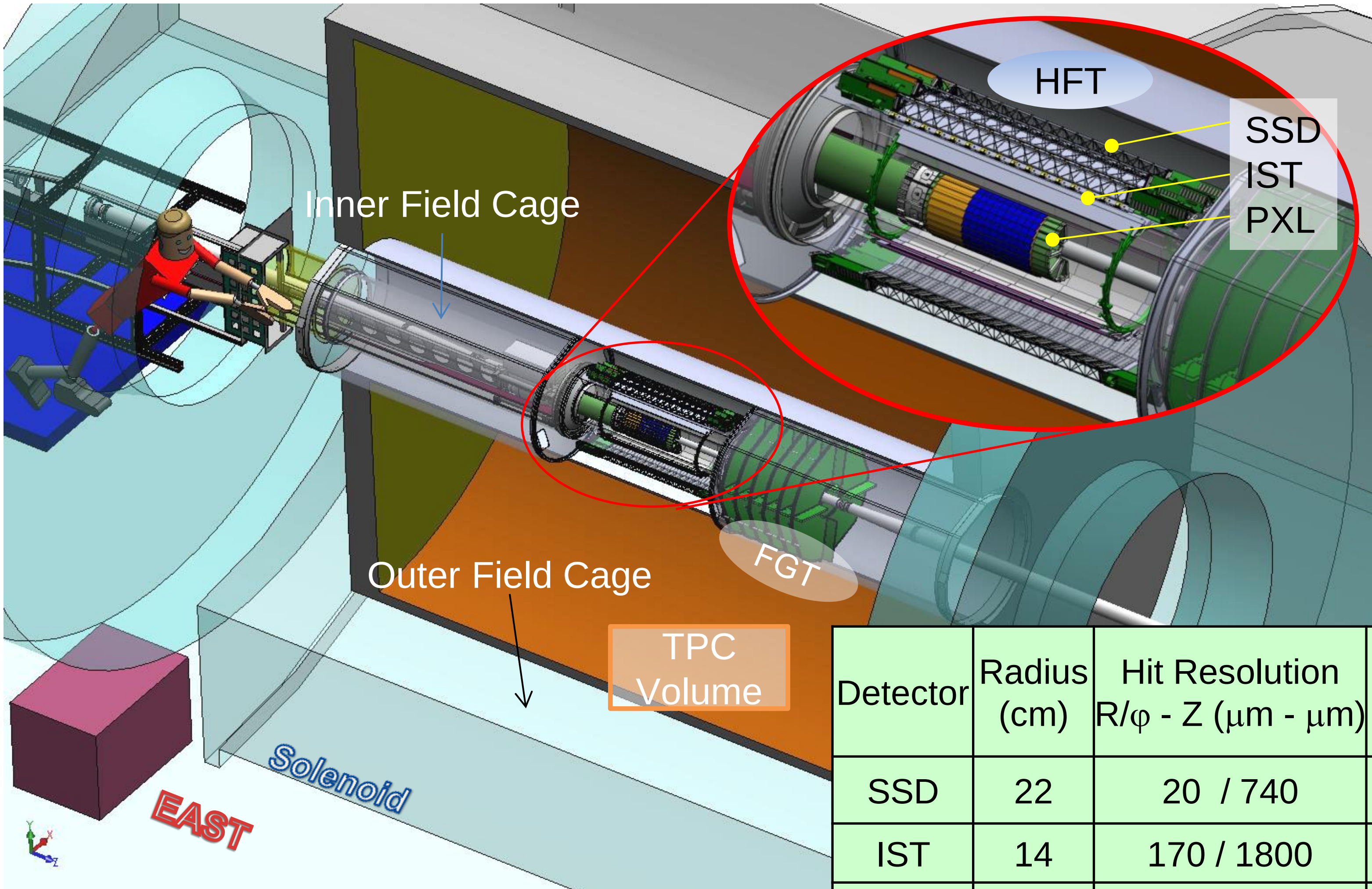




Anisotropy (v_2)

- Substantial elliptic flow of NPE is seen in 200 GeV Au+Au collisions.
- Models with strong charm medium coupling are consistent with the data within the current uncertainties.
- it's challenging for models to describe suppression and flow at the same time.

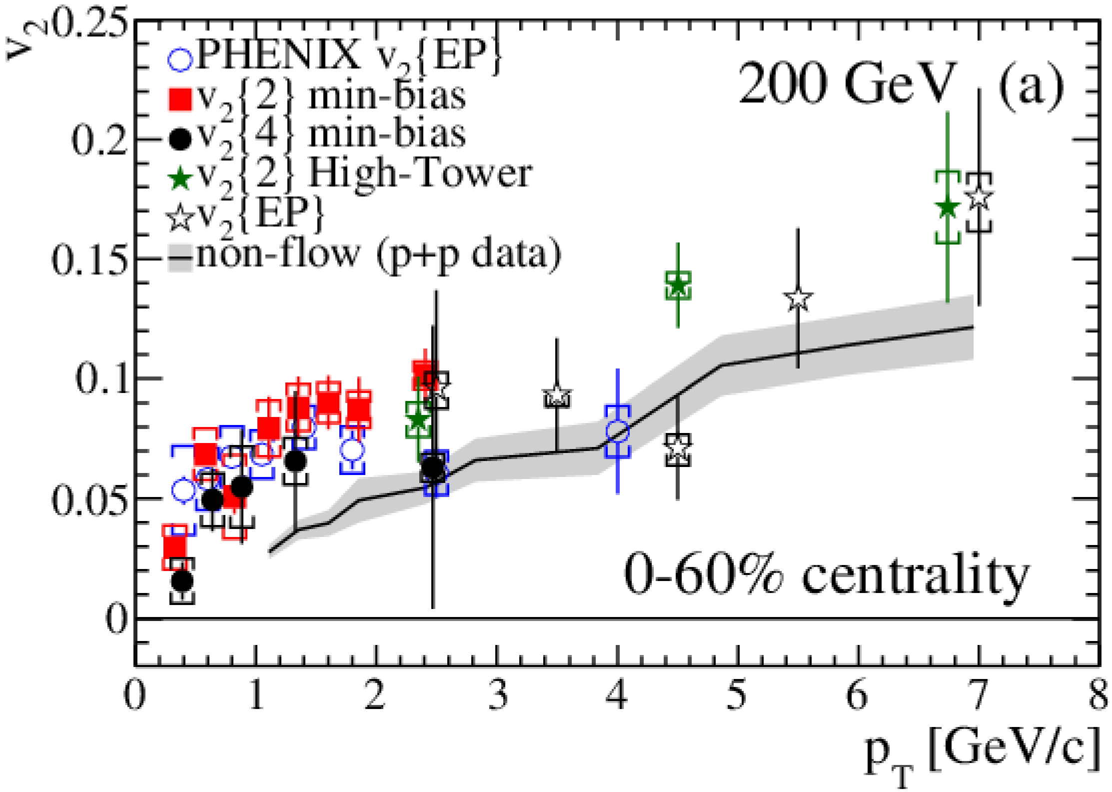
Heavy Flavor Tracker



Detector	Radius (cm)	Hit Resolution R/φ - Z (μm - μm)	Radiation length
SSD	22	20 / 740	1% X_0
IST	14	170 / 1800	<1.5% X_0
PIXEL	8	12 / 12	~0.4% X_0
	2.5	12 / 12	~0.4% X_0

jaroslav.bielcik@fjfi.cvut.cz

NPE flow in Au+Au 200 GeV



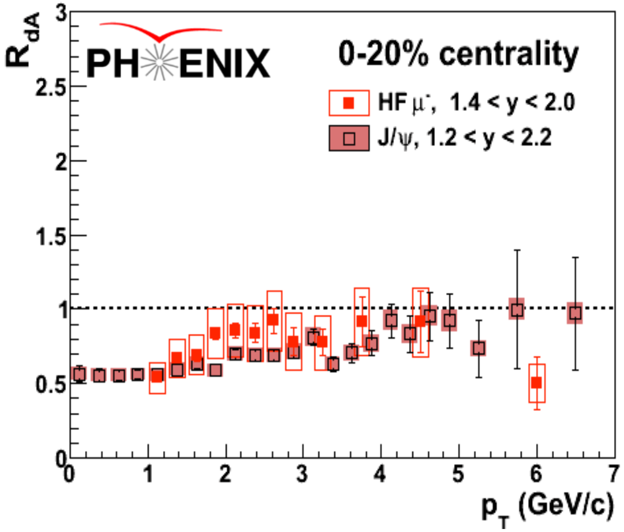
arXiv:1405.6348

- Finite v2 at low and intermediate pT
- Increase of v2 at high pT likely due to jet-like correlation

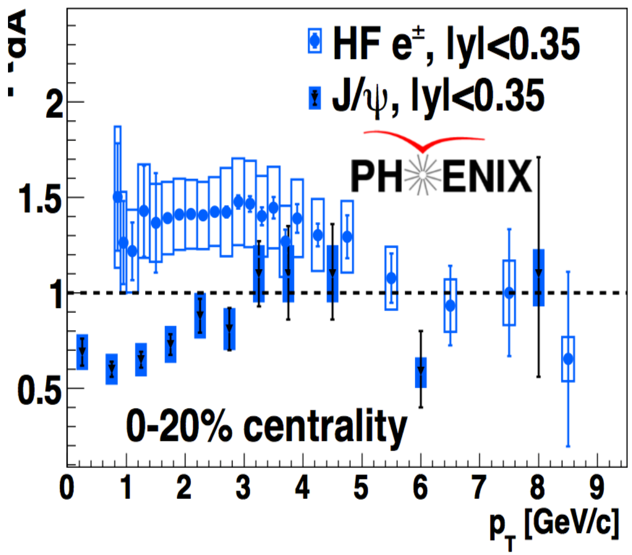
jaroslav.bielcik@fjfi.cvut.cz

Heavy Flavor Comparison with *J/ψ*

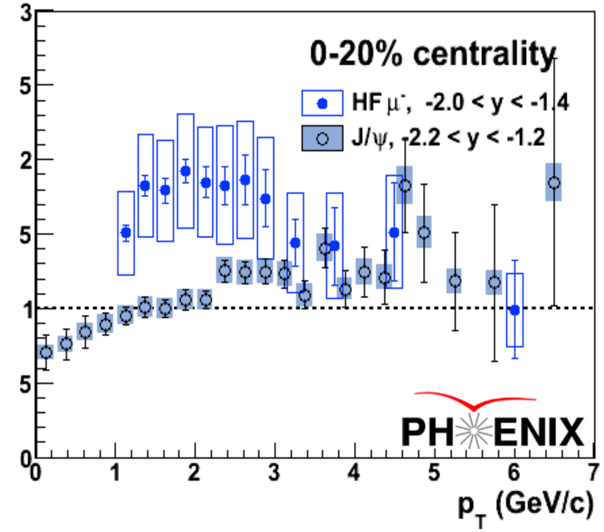
d-Going



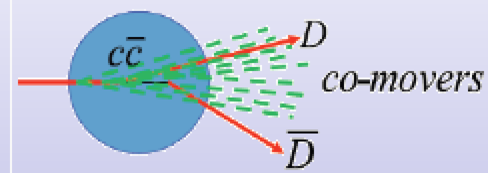
Mid-Rapidity



Au-Going



- Similar suppression at forward rapidity
  - Low co-mover density
  - Same suppression mechanism
- Different behavior at mid and backward rapidity
  - Different suppression mechanism
- Larger nuclear break-up effects at higher-density region



J/ψ: Phys. Rev. C. 87, 034904 (2013)