Measurements of Non-photonic Electrons Production and Azimuthal Anistropy in STAR at RHIC

Results:

- NPE spectra measurements:
  - New Au + Au at $\sqrt{s_{NN}}$ = 200 GeV.
  - Nuclear Modification Factor at $\sqrt{s_{NN}}$ = 200 GeV.
  - Au + Au at $\sqrt{s_{NN}}$ = 62.4 GeV.

- NPE Azimuthal Anisotropy measurements:
  - $\mathbf{v_2}$ Au + Au at $\sqrt{s_{NN}}$ = 200 GeV.
  - $\mathbf{v_2\{2\}}$ Au + Au at $\sqrt{s_{NN}}$ =39 GeV and 62.4GeV.

Mustafa Mustafa

for the STAR Collaboration

Purdue University

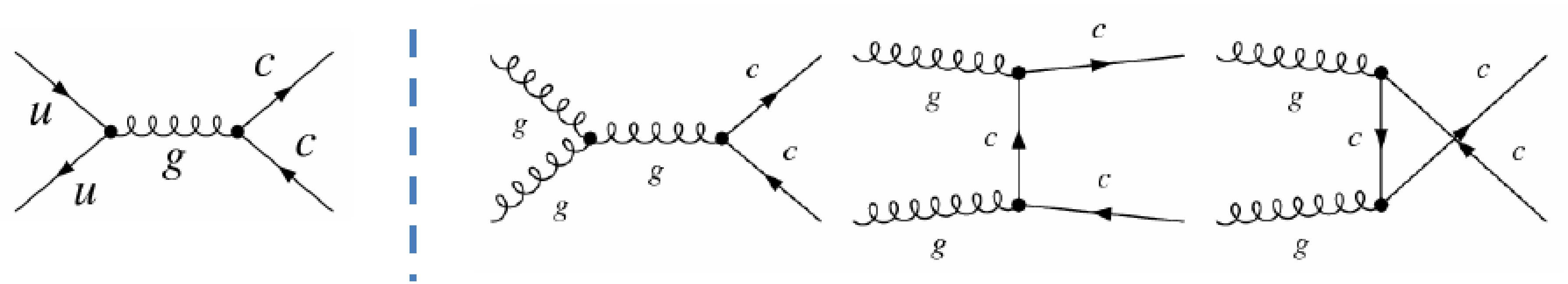
STAR

5th International workshop on heavy quark production in heavy-ion collisions, Utrecht

PURDUE UNIVERSITY

Why Heavy Flavor?

- Due to their large masses, heavy quarks are created at the early stage of HIC through initial hard scattering



Leading order diagrams of charm (HQ) production.

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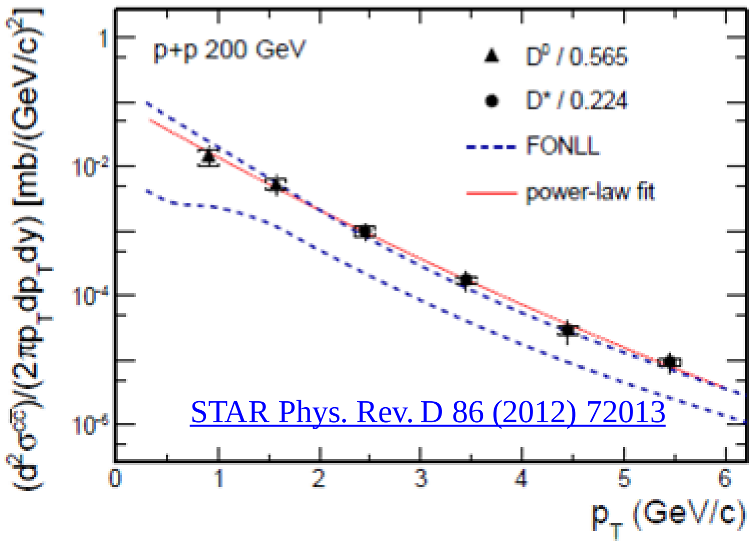

Example: Charm production compared to FONLL calculation.

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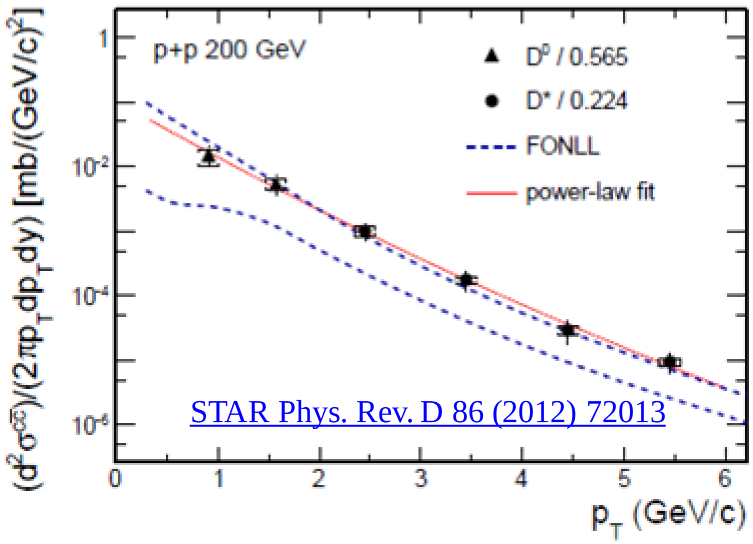

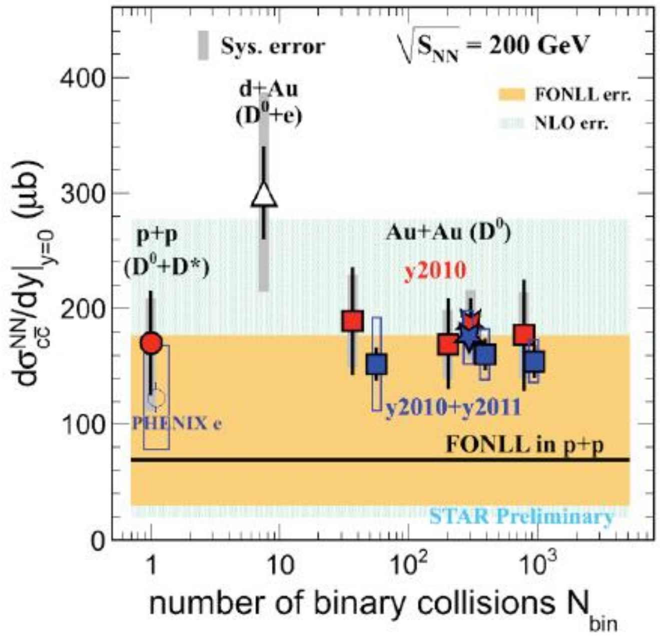

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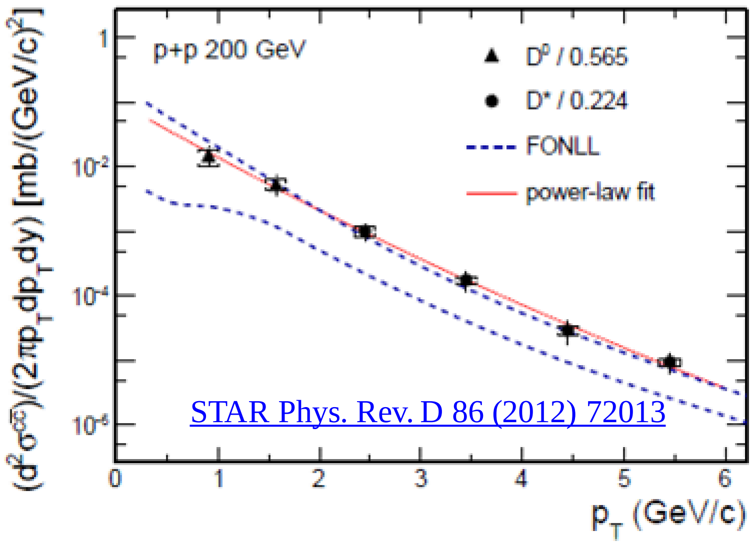
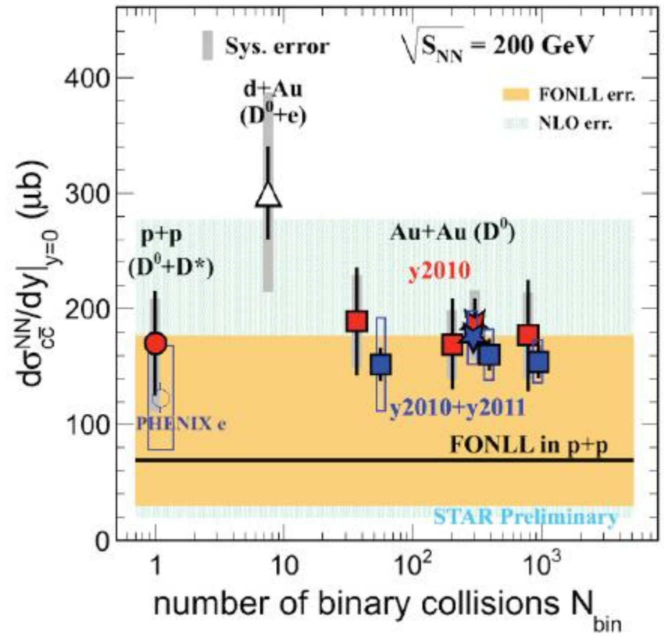
  - experience all stages of medium evolution.





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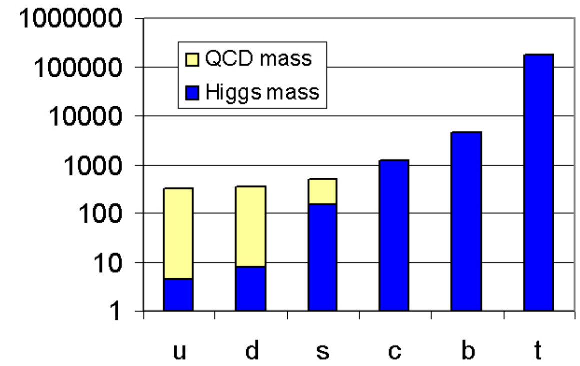
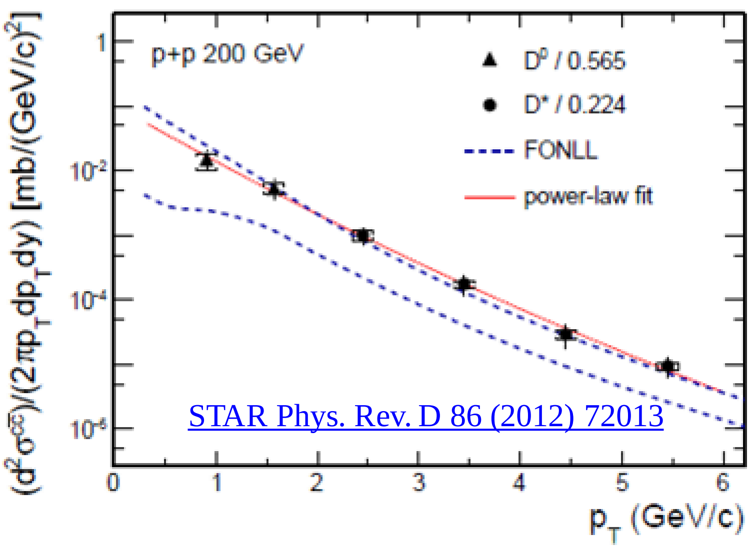
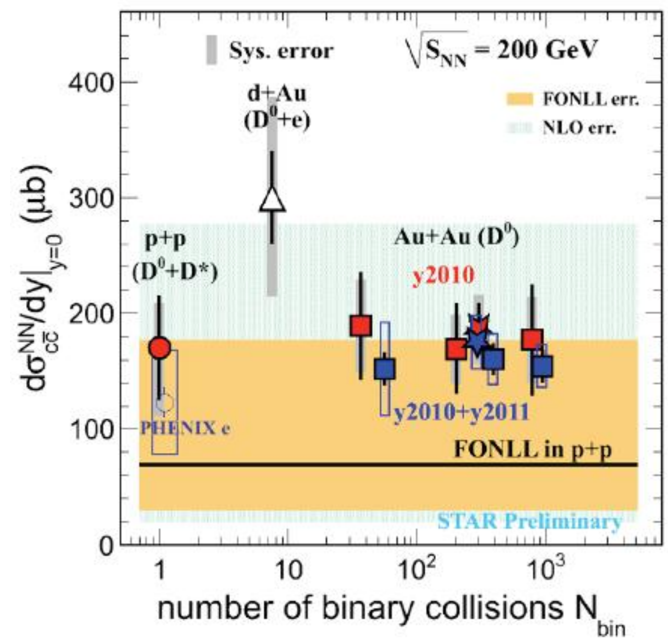


B. Müller, Nucl. Phys. A, 750(2005), p. 84–97





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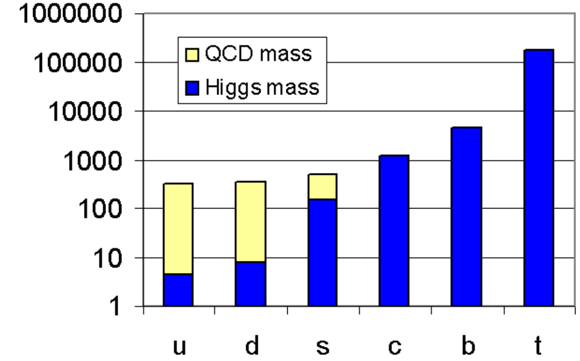

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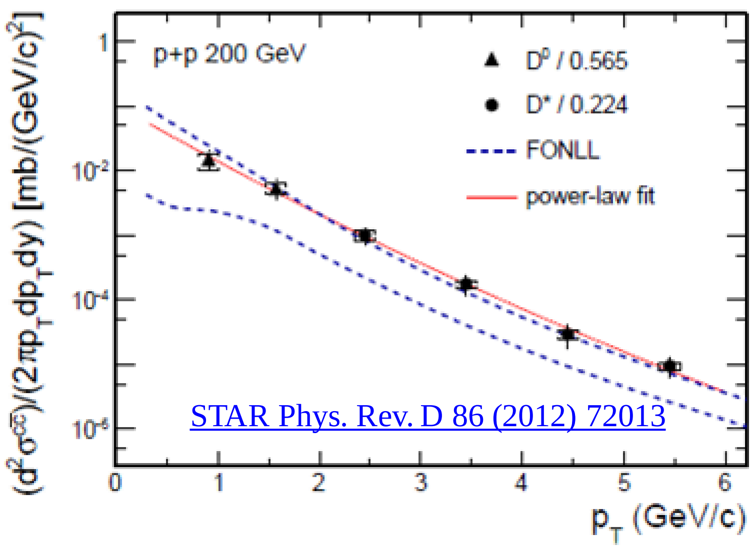

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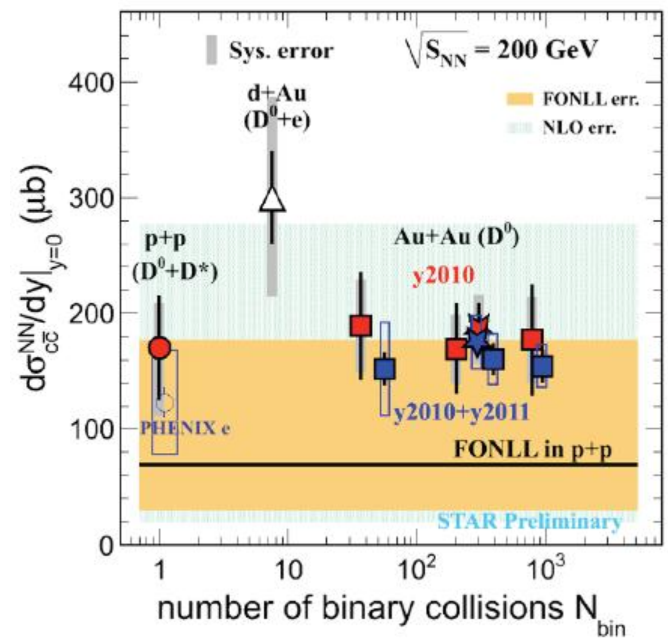

Heavy Quarks are clean probes
("almost" external to the "thermal" bulk matter)
to study the bulk matter created in heavy-ion collisions.

Heavy Quarks as probes of sQGP

Heavy Quarks experience all the stages of medium evolution

→ their kinematics carry information about their interaction with the medium.

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- Azimuthal Anistropy
  - Low $\mathbf{p_T}$ v_2
    - degree of thermalization of the bulk matter.
    - NCQ-scaling? ⟶ Hadronization mechanisms.
    - Important to understand Quarkonia production mechanisms in HIC.

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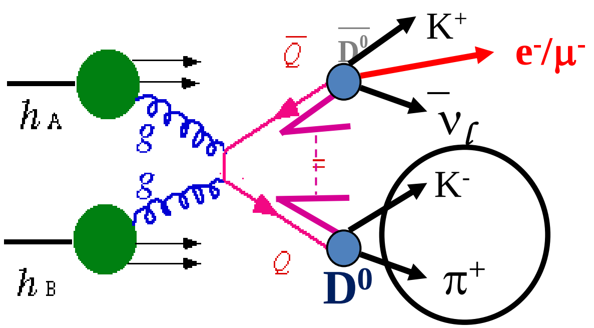
    - Important to understand Quarkonia production mechanisms in HIC.
  - High $\mathbf{p_T}$ v_2
    - path length dependence of energy loss (an important differential measurement to test parton energy loss models).

Reconstructing Open Heavy Flavour

- Direct reconstruction through hadronic decay channels
  - ✓ Allows direct access to the heavy quark kinematics.
  - Hard to trigger.
    - Limit the p_T reach .
  - Small(er) Branching Ratio:
    - $B^+ \to K^+ + J/\psi \to ee$: BR: $\sim 6 \times 10^{-5}$
    - $B^0 \to K\pi$: BR: $\sim 5 \times 10^{-6}$
    - $D^0 \to K\pi$: BR: $\sim 4\%$
    - $D^+ \to K\pi\pi$: BR: $\sim 9.4\%$ (lower acceptance)



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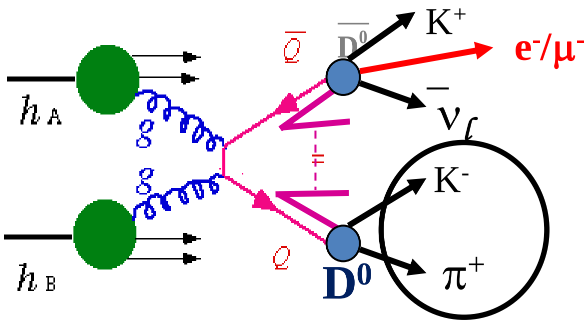
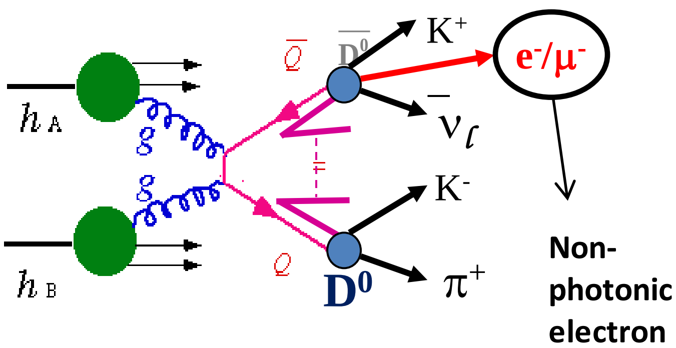
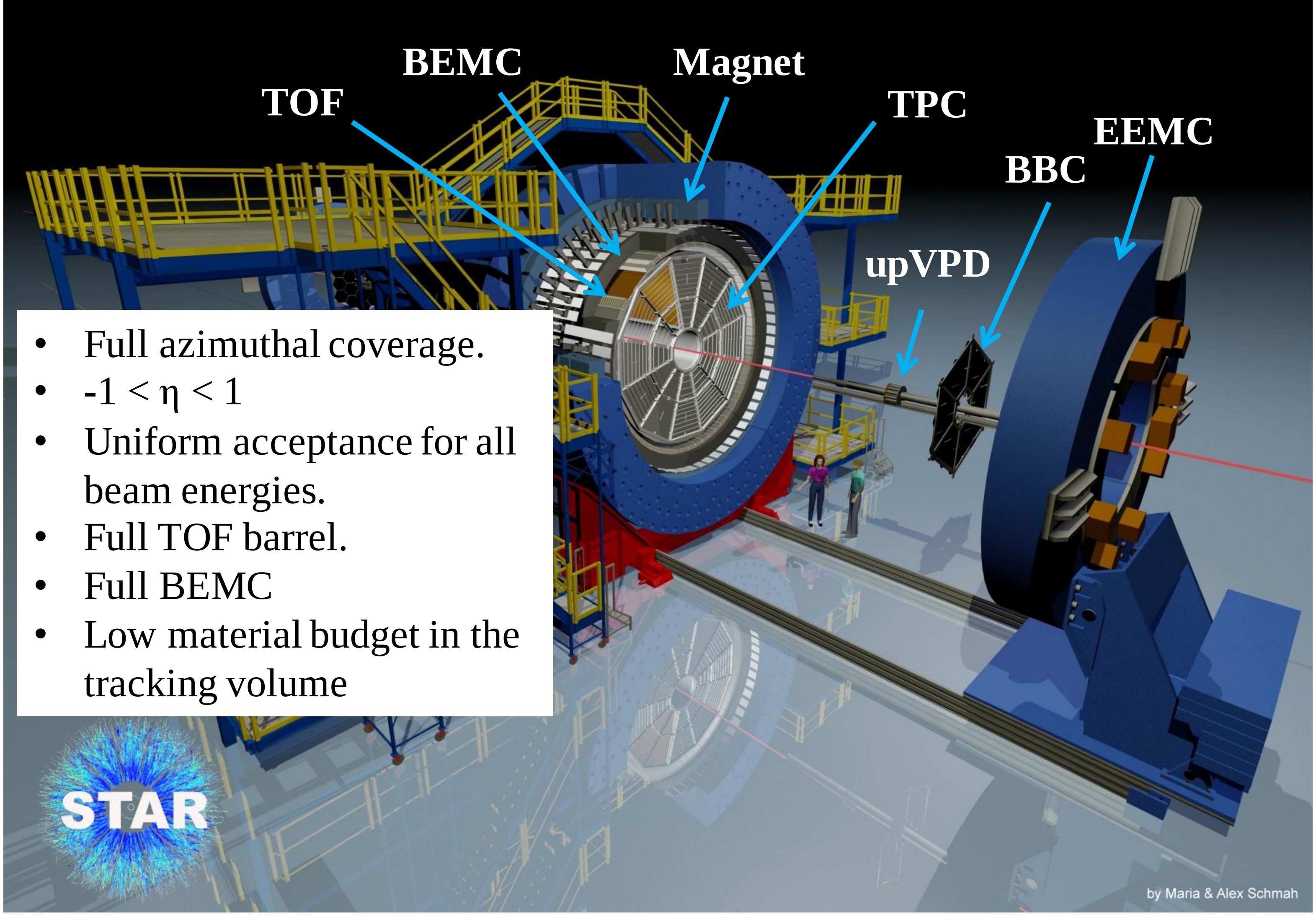


- Indirect measurement through semi-leptonic decay channels
  - Indirect access to the heavy quark kinematics
  - ✓ Can be triggered easily.
    - Ideal for high p_T measurements
  - ✓ High(er) branching ratio
    - $B \to e^+ + X$: BR: $\sim 10\%$
    - $D^0 \to e^+ + X$: BR: $\sim 6.5\%$
    - $D^+ \to e^+ + X$: BR: $\sim 16\%$
    - $\Lambda_c \to e^+ + X$: BR: $\sim 4.5\%$ (Lightest charmed baryon)



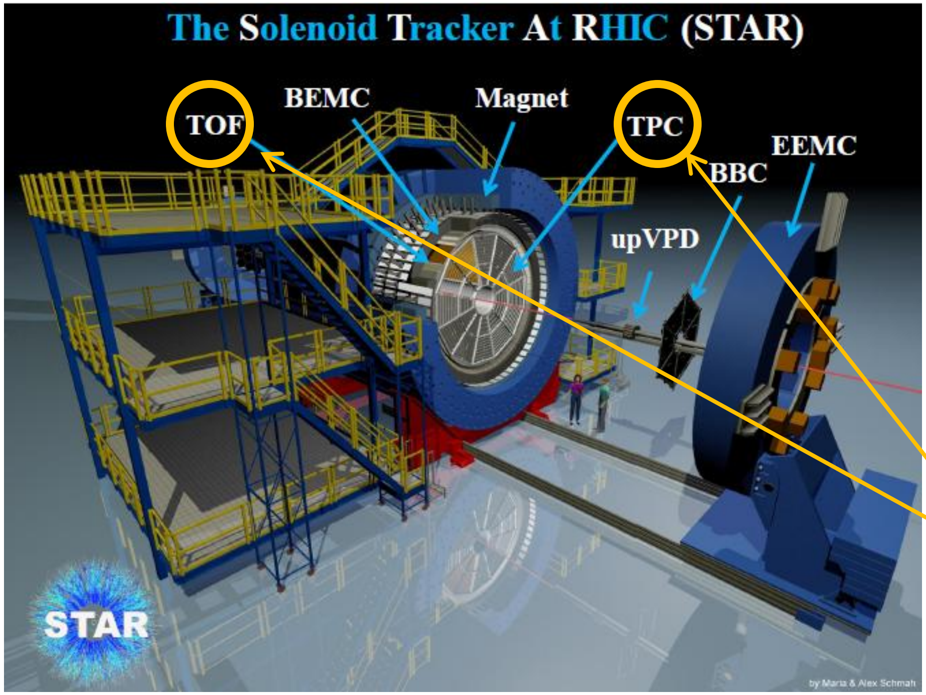
Experimental Setup

The Solenoid Tracker At RHIC (STAR)



- Full azimuthal coverage.
- $-1 < \eta < 1$
- Uniform acceptance for all beam energies.
- Full TOF barrel.
- Full BEMC
- Low material budget in the tracking volume

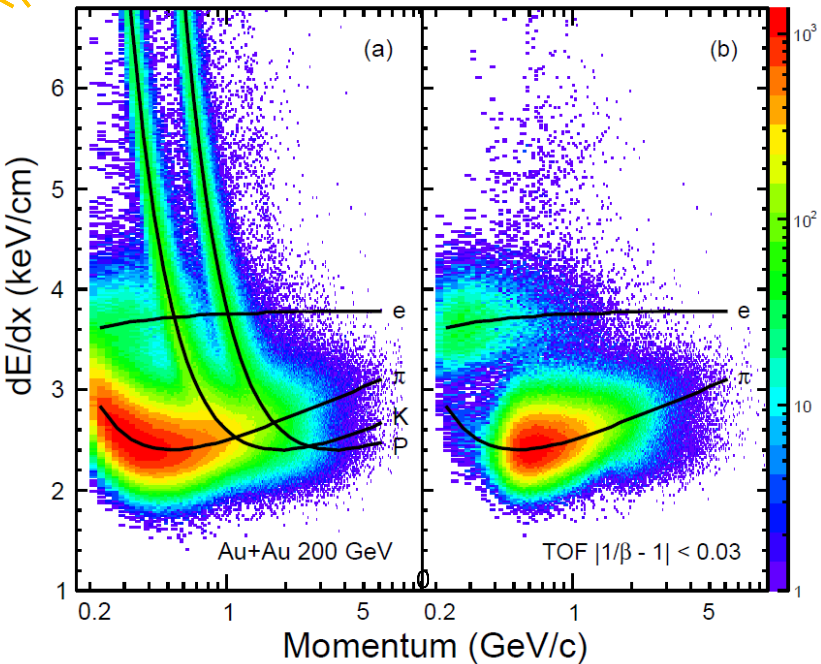
Electrons Identification



TPC dEdx +
Time Of Flight (TOF):

Low $\mathbf{p_T}$ (0.2-2.0 GeV/c)

The combination of TPC dEdx and β from TOF provides +95% purity down to the lowest reachable $\mathbf{p_T}$ at STAR (0.2GeV/c) .



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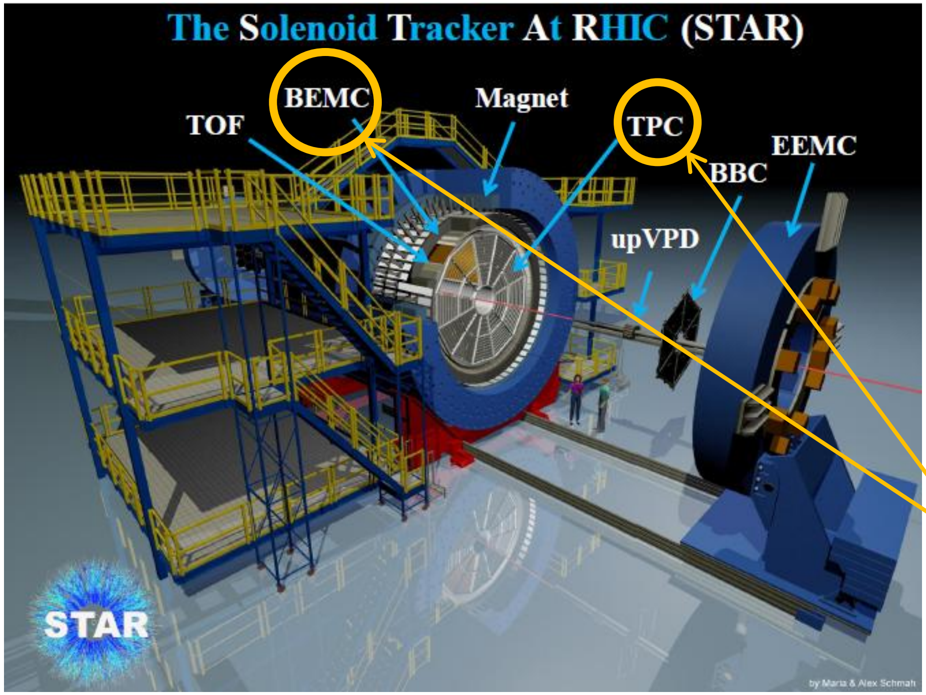
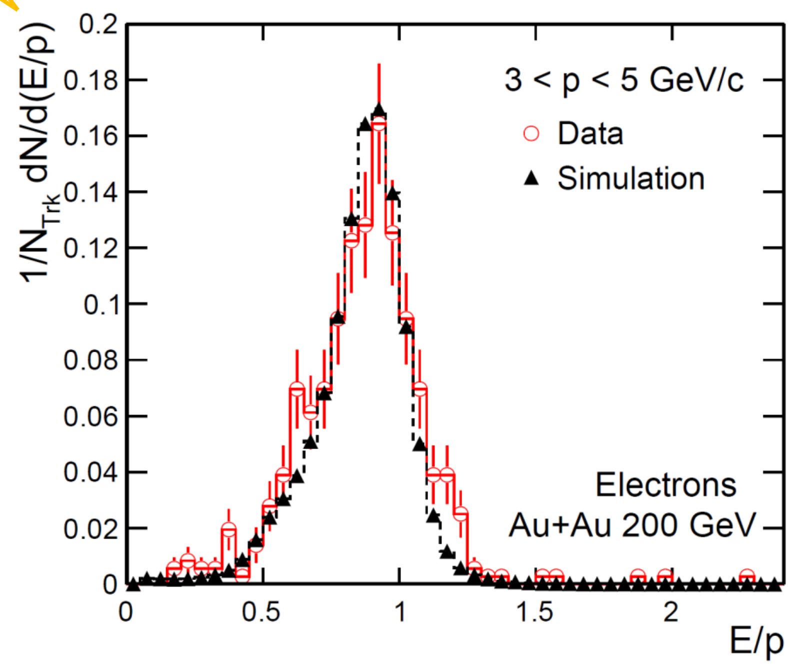


TPC dEdx +
Barrel ElectorMagnetic Calorimeter (BEMC):
High $\mathbf{p_T}$ (> 1 GeV/c)

1- Associating TPC tracks with BTOW and BSMD clusters.

2- E/P cuts. (Due to their negligible mass, electrons have E/P ~ 1).



Analysis Technique – Background Sources

The trick is to find all electrons and then subtract all the uninteresting ones.

Most of the "uninteresting" electrons are coming from photonic sources (Photonic Electrons).

$\pi^0 \rightarrow \gamma + e^+ + e^-$ BR: 1.2%.

$\eta \rightarrow \gamma + e^+ + e^-$ BR: 0.7%.

⇒ Same for all experiments

$\gamma \rightarrow e^+ + e^-$

•Mostly from $\pi^0(\eta) \rightarrow \gamma + \gamma$

⇒ Depends on material budget

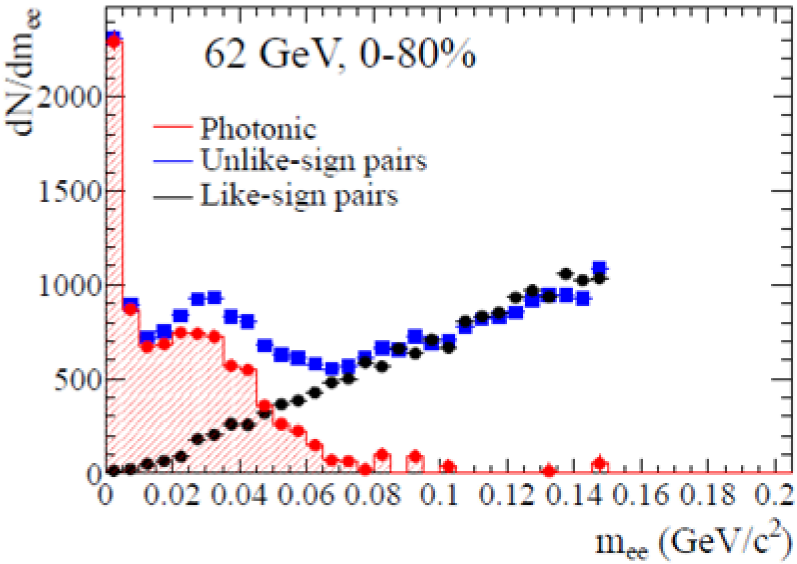
Other sources of background include:

- Drell-Yan and heavy quarkonia contributions (J/psi).
- Vector mesons di-electron decays (ρ,ω,Φ,…) .
- Single electron background sources, Ke3 ($K^+ \rightarrow \pi^0 e^+ \nu_e$).

Analysis Technique – Background Subtraction

At STAR, we use the "Reconstruction Method" to estimate the contribution of Photonic electrons.

- Photonic e^+e^- pairs invariant mass peaks at 0.
- Almost all reconstructable pairs have invariant mass < 0.24 GeV/c^2 .



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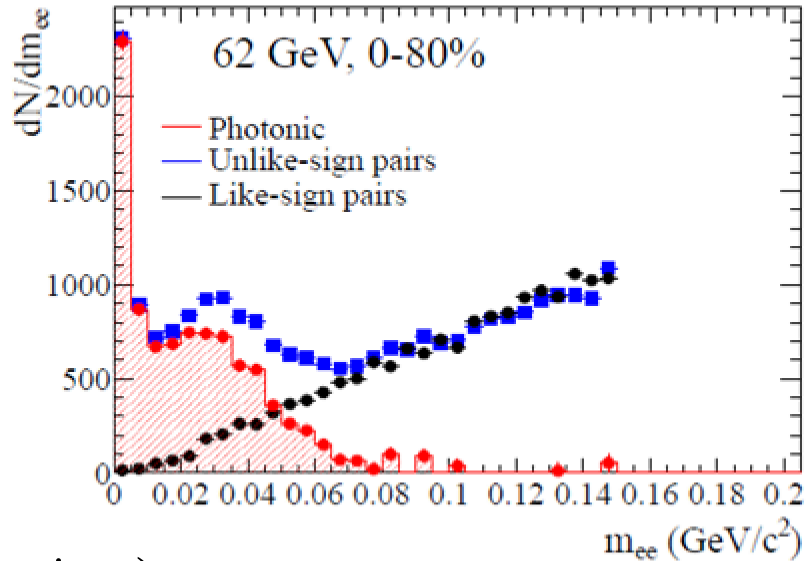
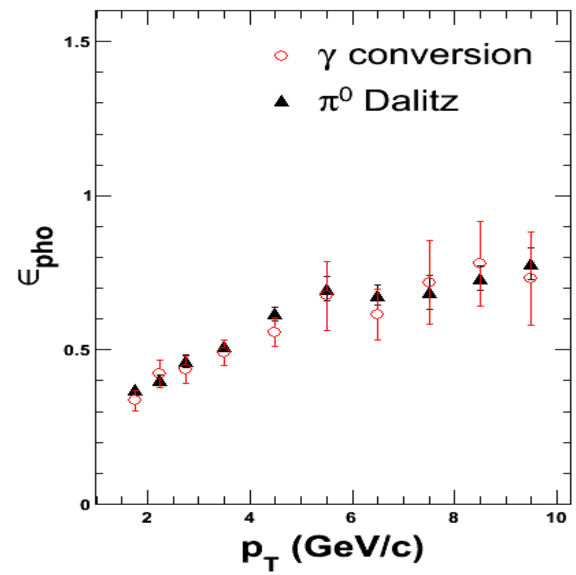


$$N(npe) = \varepsilon_{purity} * N(inclusive) - \frac{N(photonic)}{\varepsilon_{reco}}$$

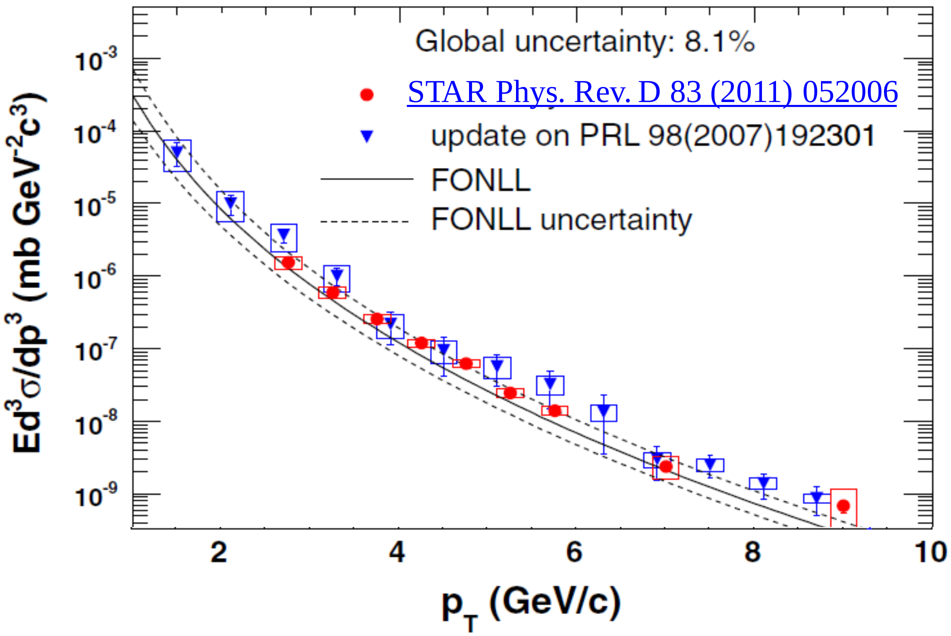
ε_{purity} : purity of inclusive electrons sample. Calculated from data.

ε_{reco} : photonic electrons reconstruction efficiency. Calculated from embedding.



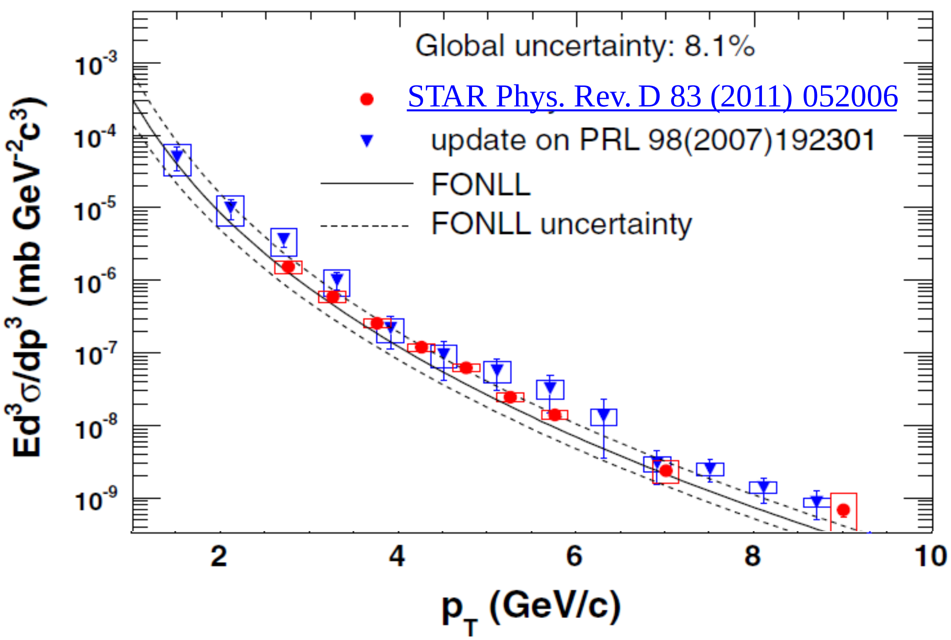
Measurements in p + p at $\sqrt{s_{NN}}$ = 200 GeV

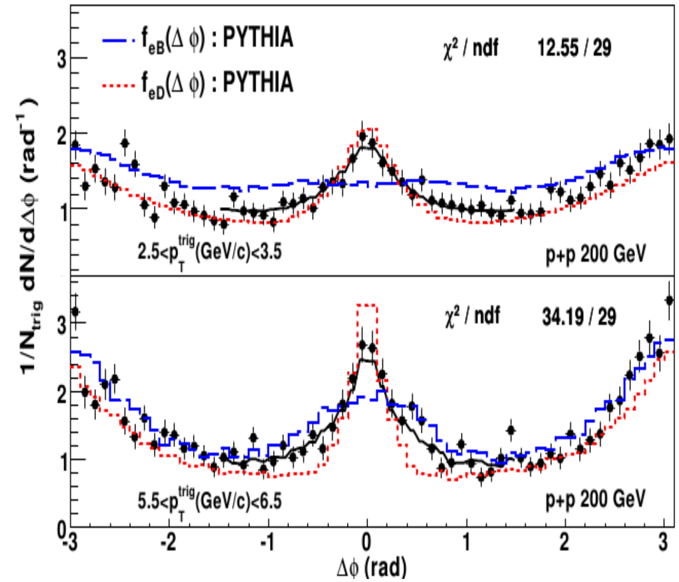
- p + p baseline.



Measurements in p + p at $\sqrt{s_{NN}}$ = 200 GeV

- p + p baseline.
- NPE-hadron correlation.
  used to disentangle charm and bottom contribution to NPE spectra.





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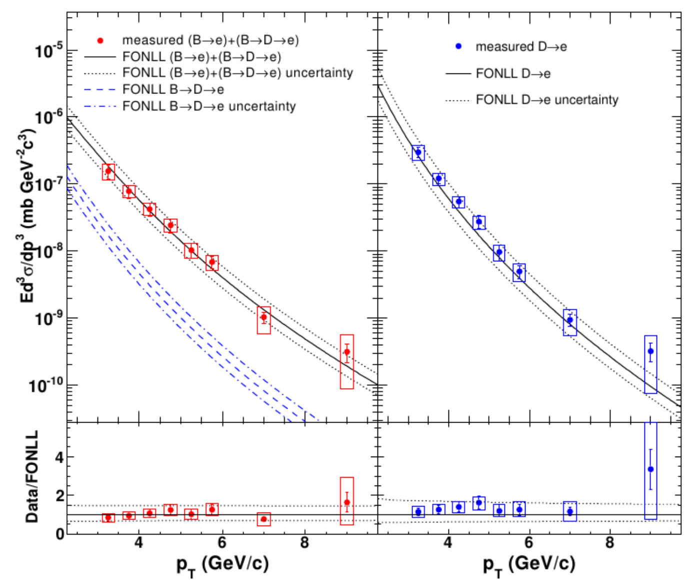
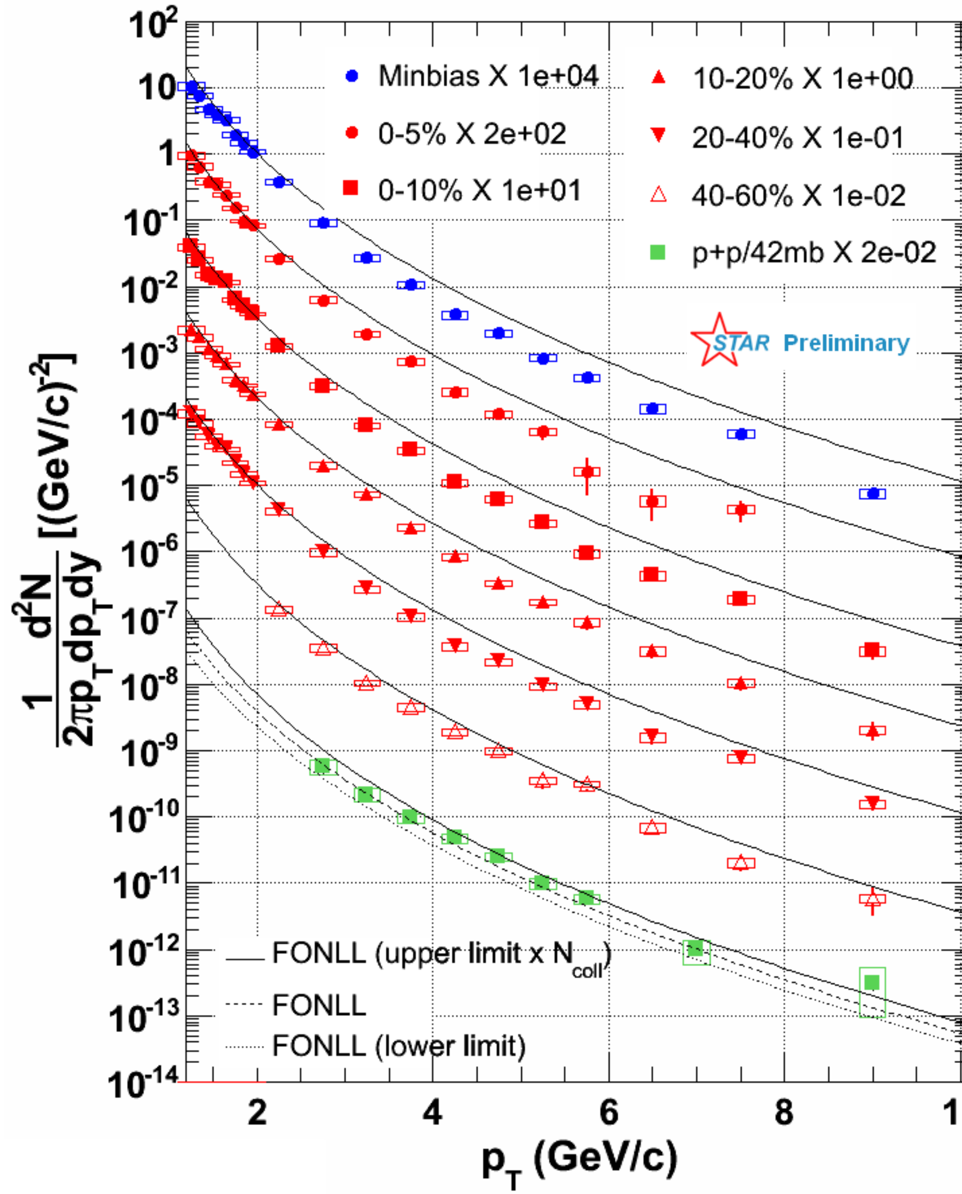


STAR Phys. Rev. D 83 (2011) 052006

Spectra in Au + Au at $\sqrt{s_{NN}}$ = 200 GeV

- With ~1 nb^{-1} sampled luminosity in Run2010 Au+Au collisions, STAR provides a new measurement of NPE with a highly improved result at high $\mathbf{p_T}$.
- < (5-10)% statistical errors in all 4 centralities.
- An independent central trigger provides 0-5% centrality.



p+p NPE STAR Phys. Rev. D 83 (2011) 052006

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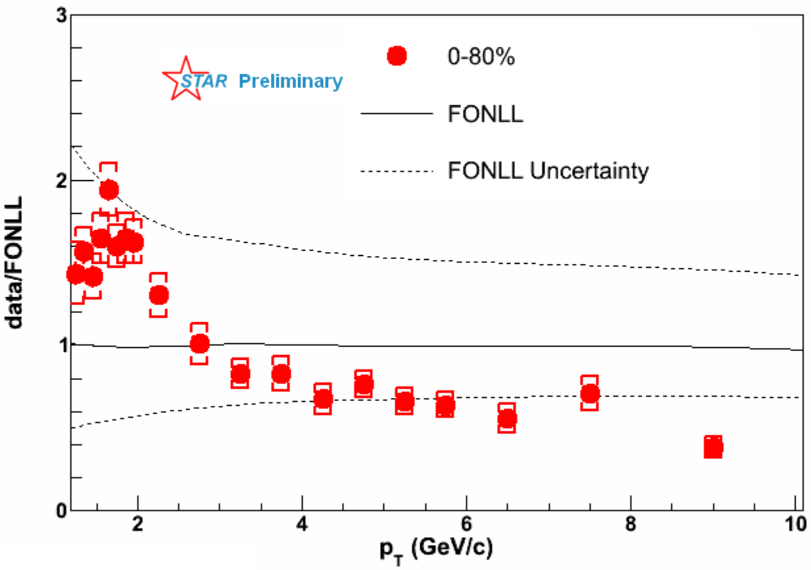
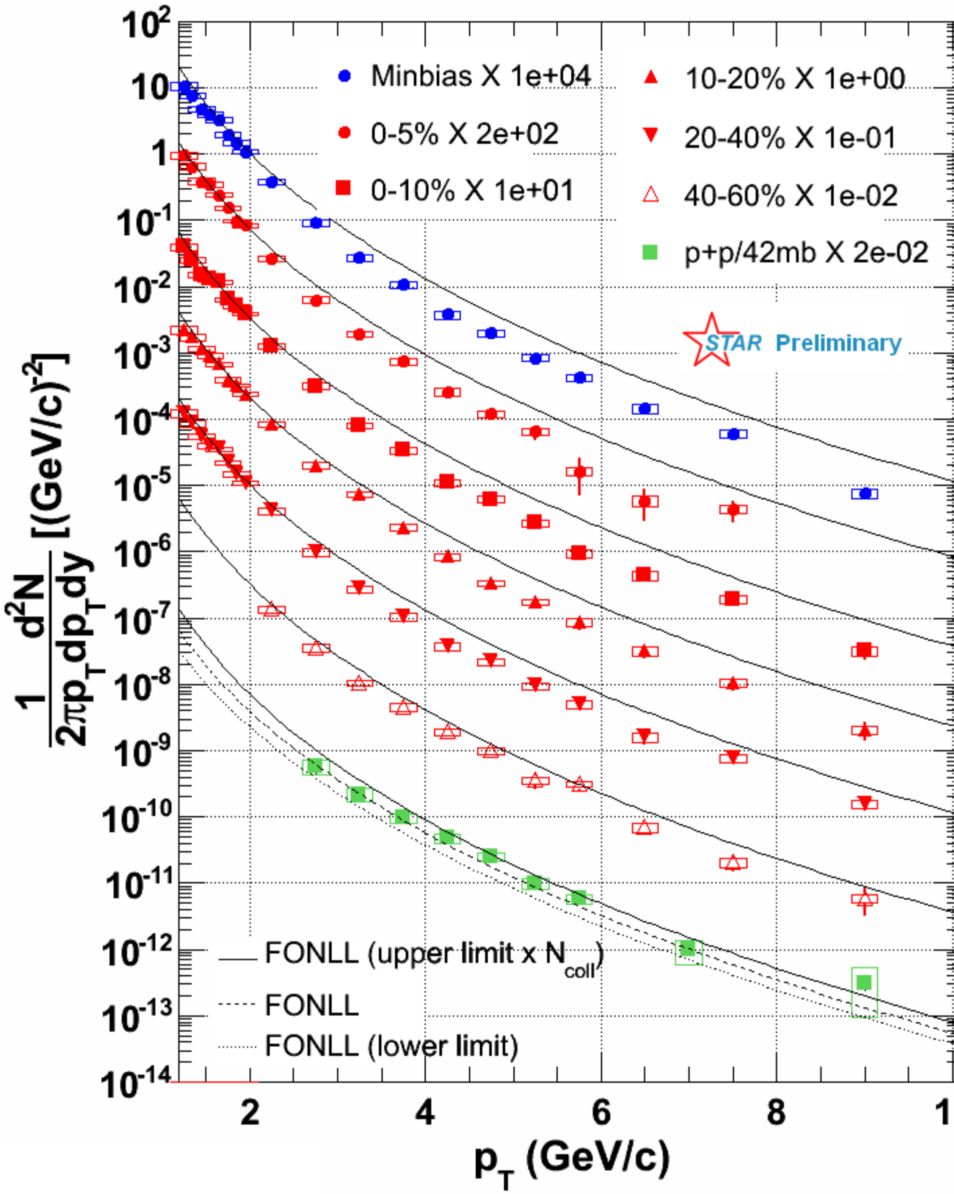
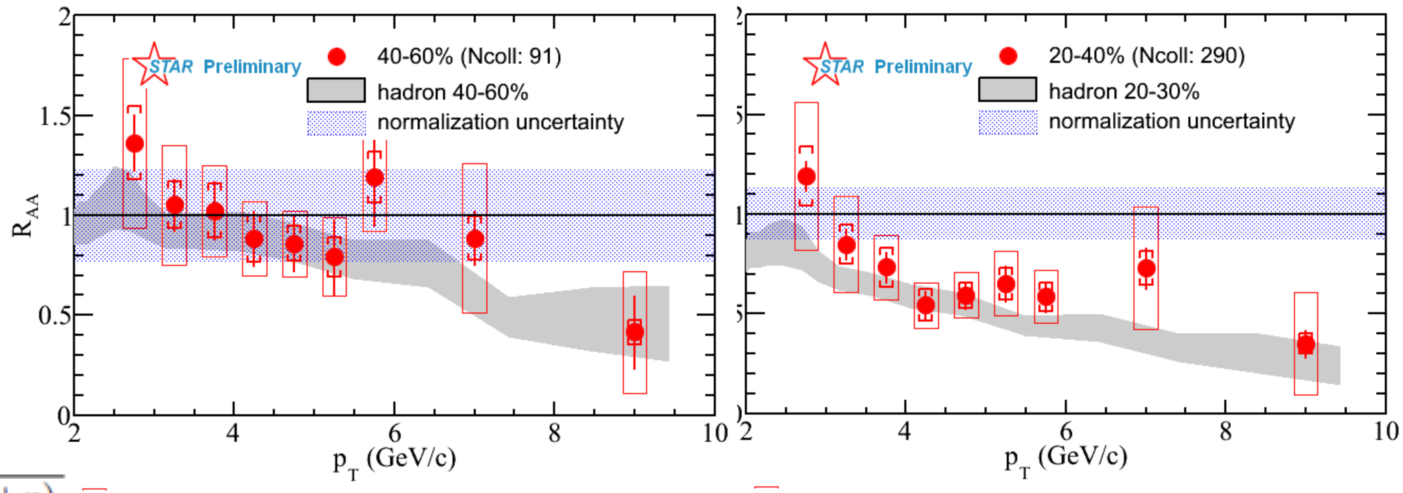




p+p NPE STAR Phys. Rev. D 83 (2011) 052006

Nuclear Modification Factor (R_{AA}) in Au + Au at $\sqrt{s_{NN}}$ = 200 GeV

$$R_{AA} \equiv \frac{\frac{d^2N(A+A)}{dp_T dy}}{\langle N_{binary}\rangle \frac{d^2N(p+p)}{dp_T dy}}$$



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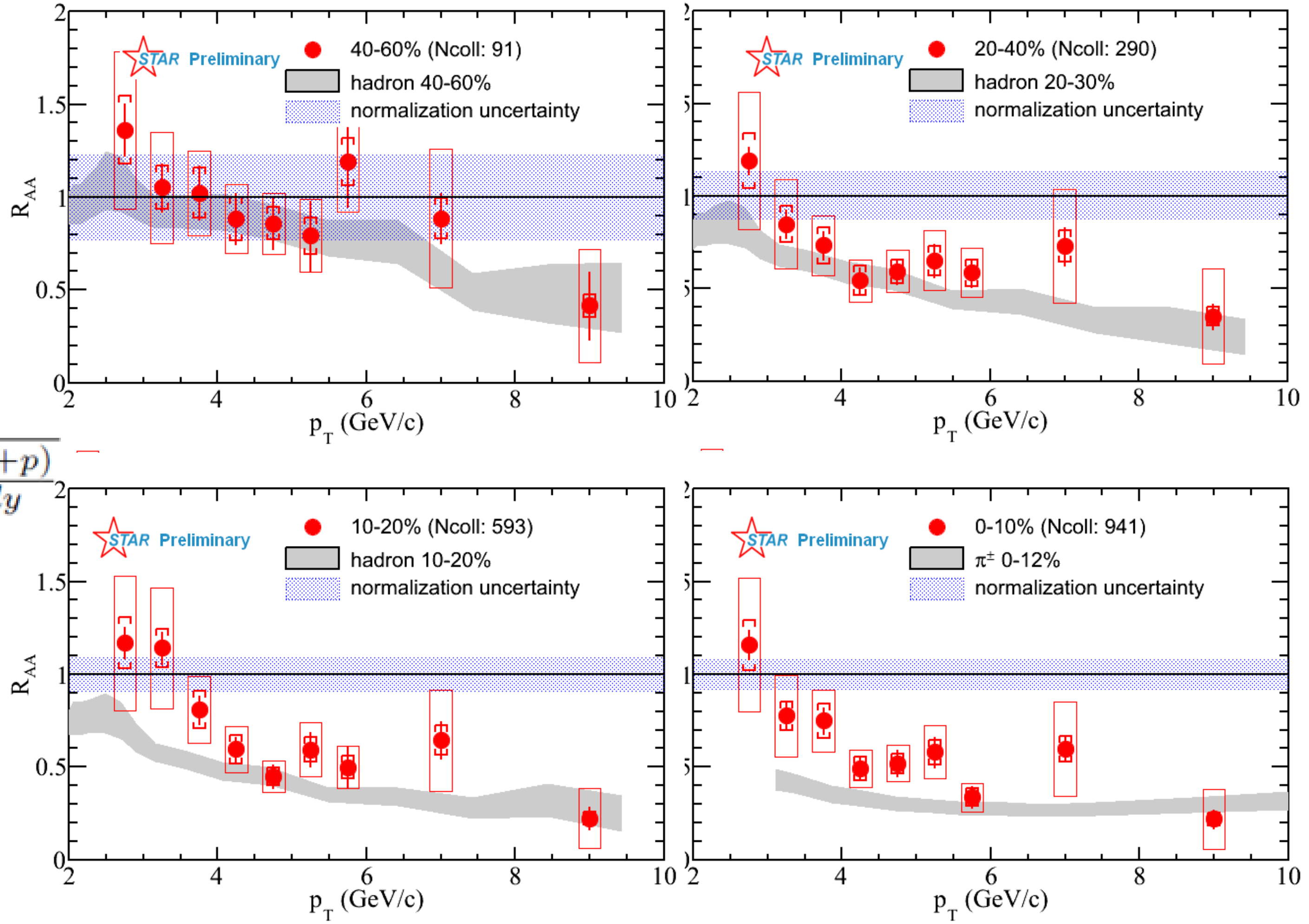

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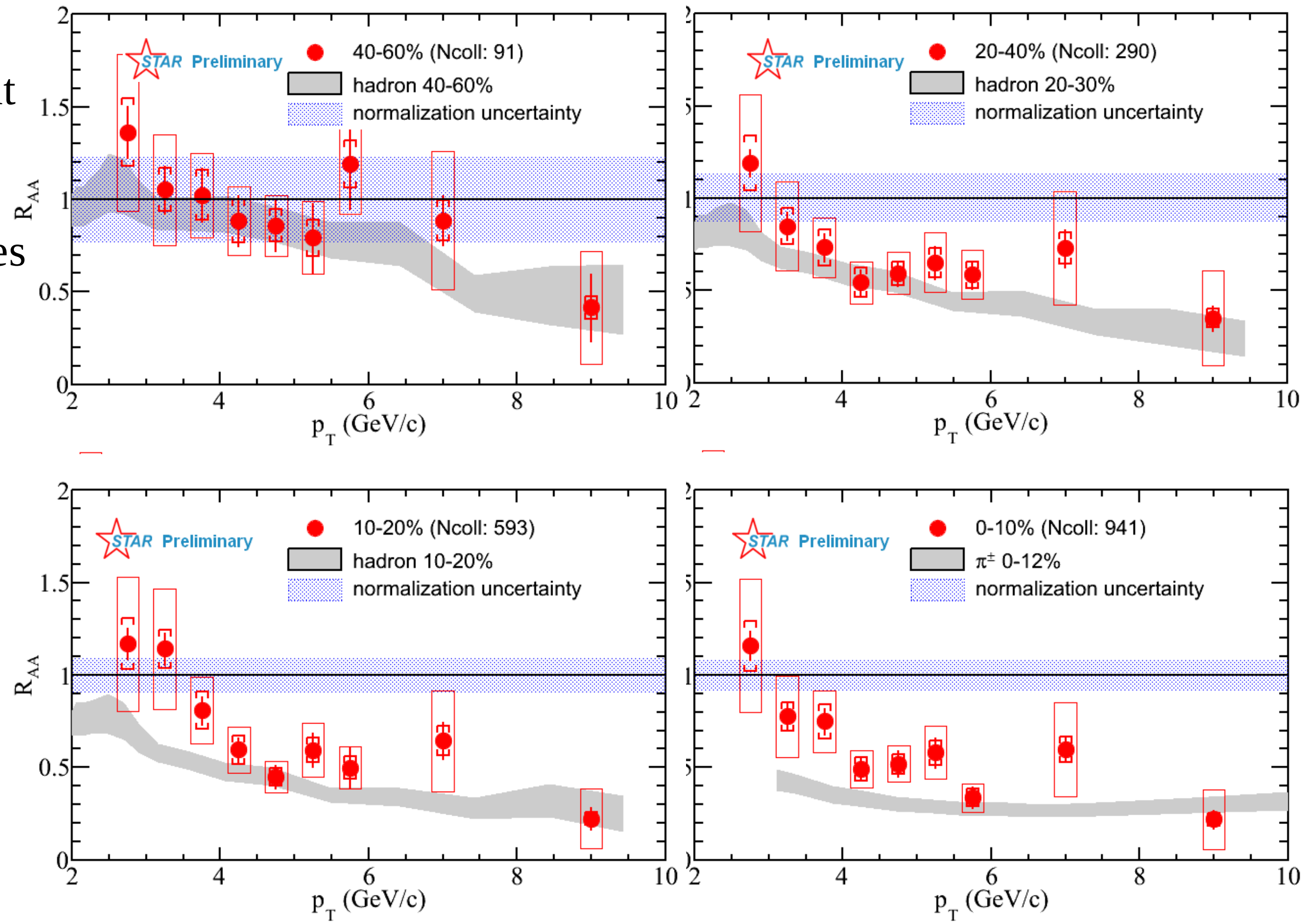
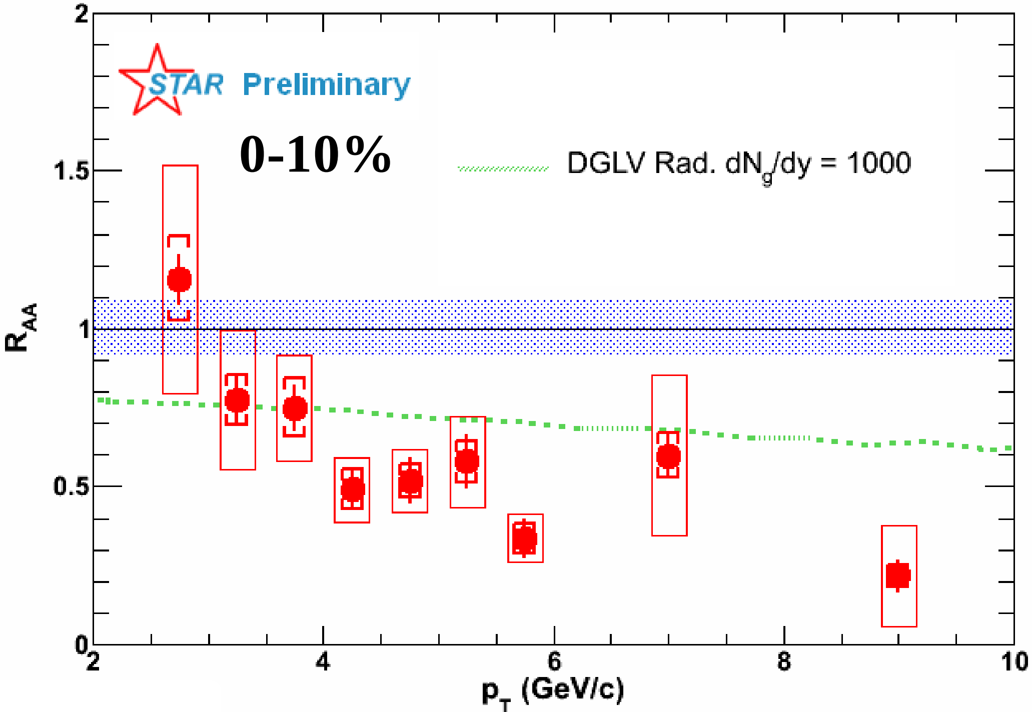
- Strong suppression at high $\mathbf{p_T}$.
- Suppression increases as a function of $\mathbf{p_T}$.
- $\mathbf{R_{AA}}$ uncertainty is dominated by Run2005+Run2008 p+p uncertainty.
- Should be improved with Run2009+2012 large statistics high quality p+p data.



Nuclear Modification Factor (R_{AA}) in Au + Au at $\sqrt{s_{NN}}$ = 200 GeV

- Measurement at high $\mathbf{p_T}$ clearly disfavors radiative energy loss as the only mechanism.



DGLV:
Djordjevic, PLB632, 81 (2006) and references within.

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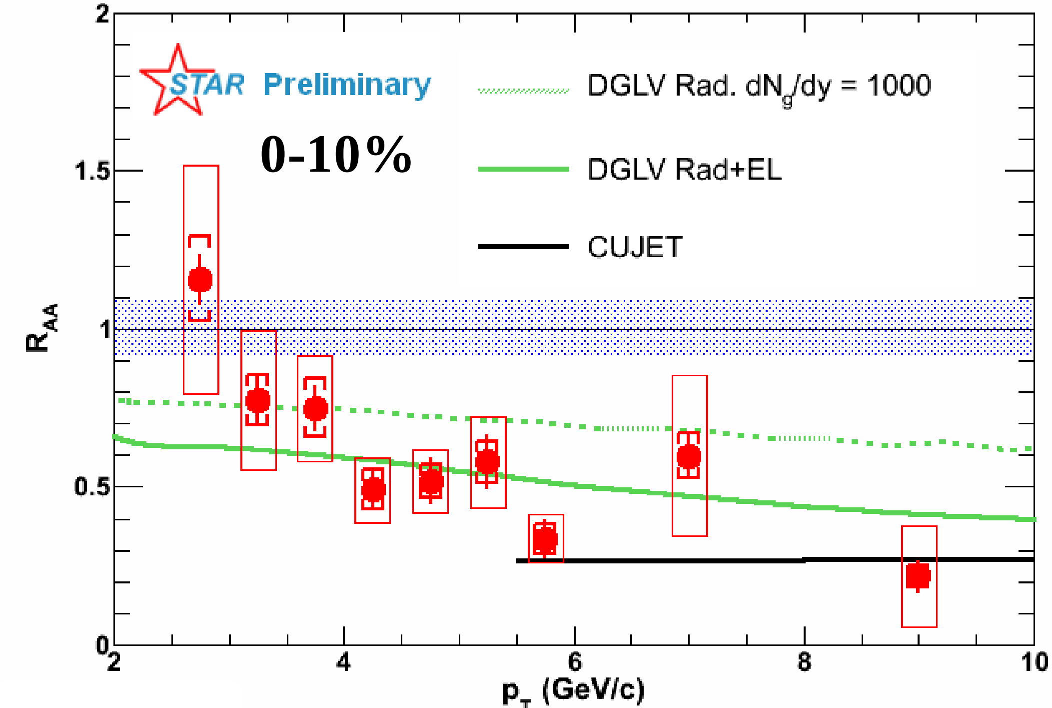

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CUJET:
Buzzatti, arXiv:1207.6020

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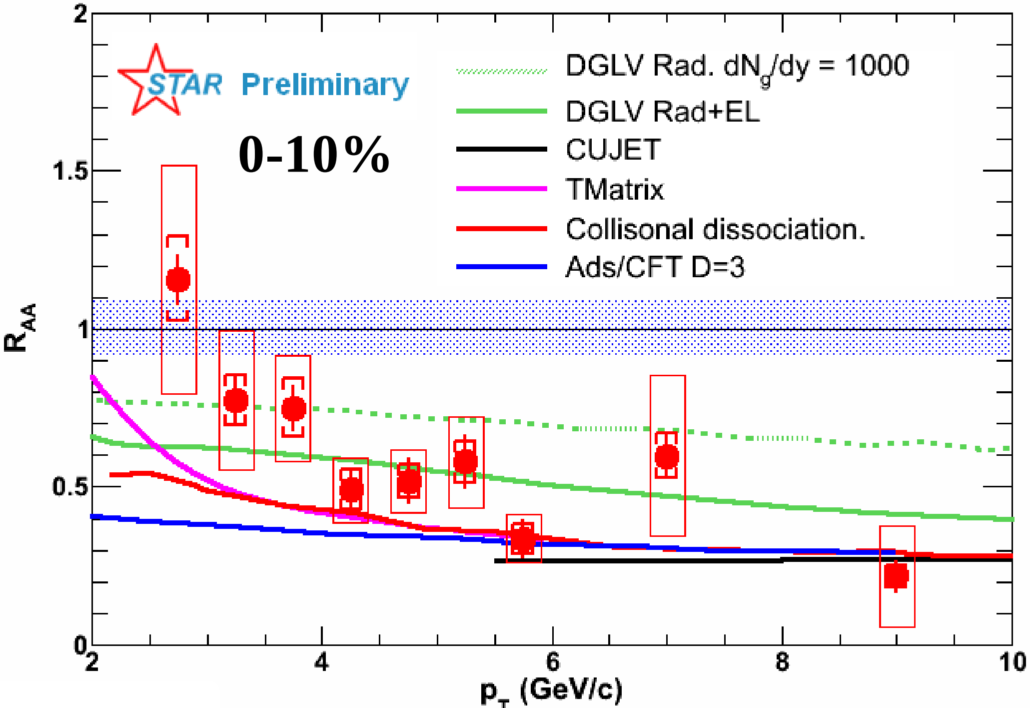
- CUJET is the new improvement over the DGLV/DGLV+EL efforts. It is consistent with our measurement.
- All plotted energy loss mechanisms agree with our measurement:
  - T-Matrix.
  - Collisional Dissociation.
  - Ads/CFT.



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Buzzatti, arXiv:1207.6020

T-Matrix:
Van Hees et al., PRL100,192301(2008).

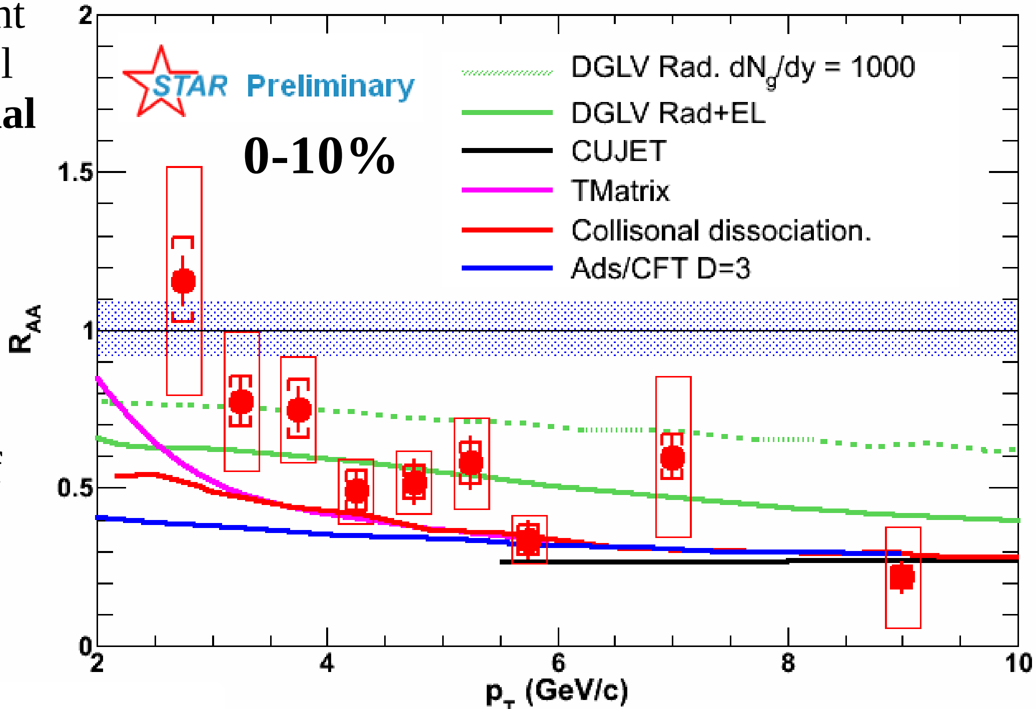
Coll. Dissoc.
R. Sharma et al., PRC 80, 054902(2009).

Ads/CFT:
W. Horowitz Ph.D thesis.

Nuclear Modification Factor (R_{AA}) in Au + Au at $\sqrt{s_{NN}}$ = 200 GeV

Looking at the current status of the different experimental measurements and theoretical predictions, it is clear that **more differential measurements are needed** to distinguish the different proposed mechanisms:

- Bottom/charm measurement separation.
- Simultaneous prediction of R_{AA} and v_2.
- Measurements and predictions of centrality and p_T dependence.
- Collision energy dependence.



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Ads/CFT:
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Finally, one also needs to study:

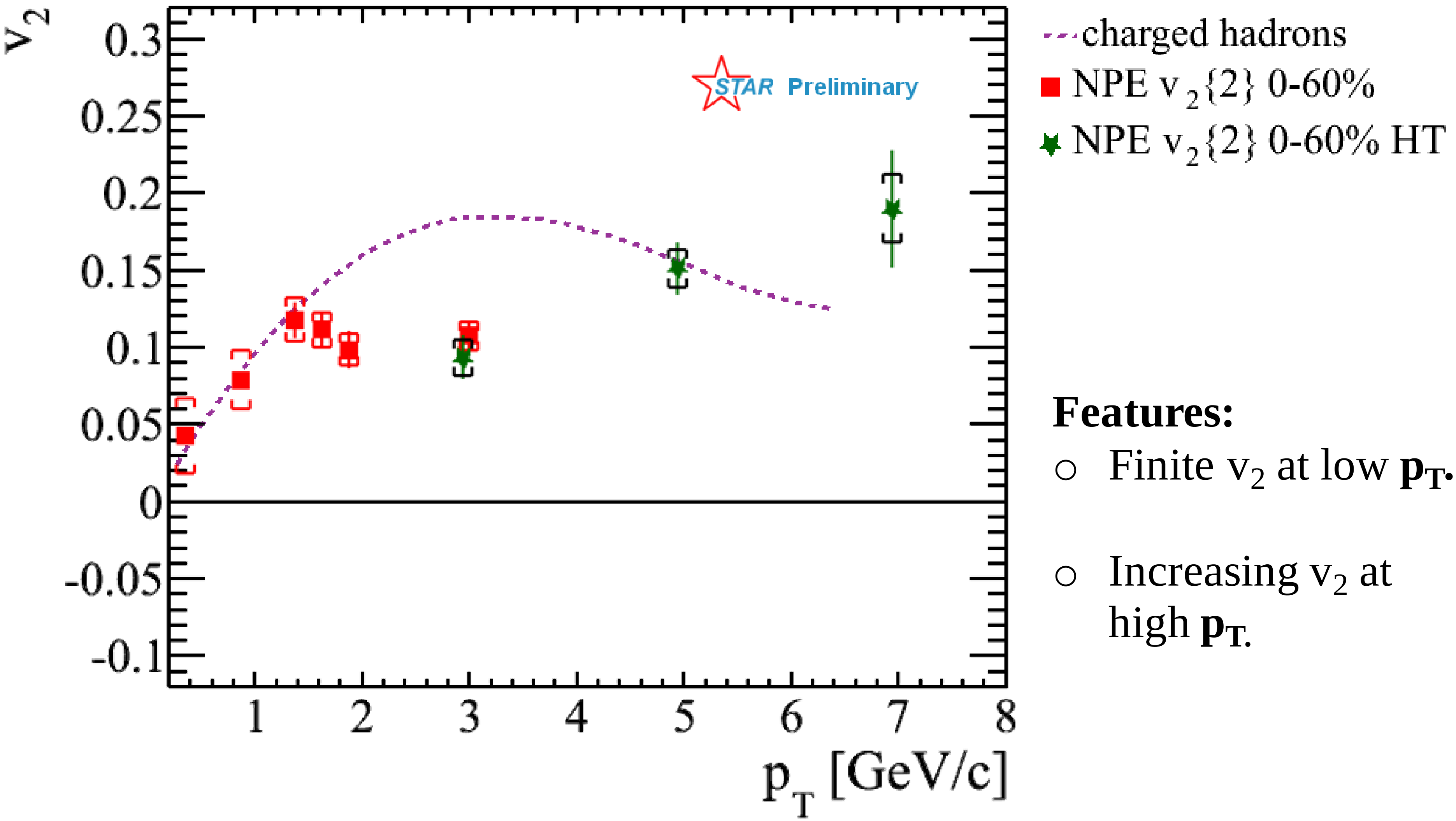
- CNM. PHENIX, arXiv:1208.1293

- Charmed baryon enhancement.

P.Sorenson, et al. PRC74, (2006) 024902
Martínez-García, et al. J.Phys.G 35 (2008) 044023

- Charmed mesons ratios D^0/D, D^{+-}/D, D_s/D compared to production in vacuum.

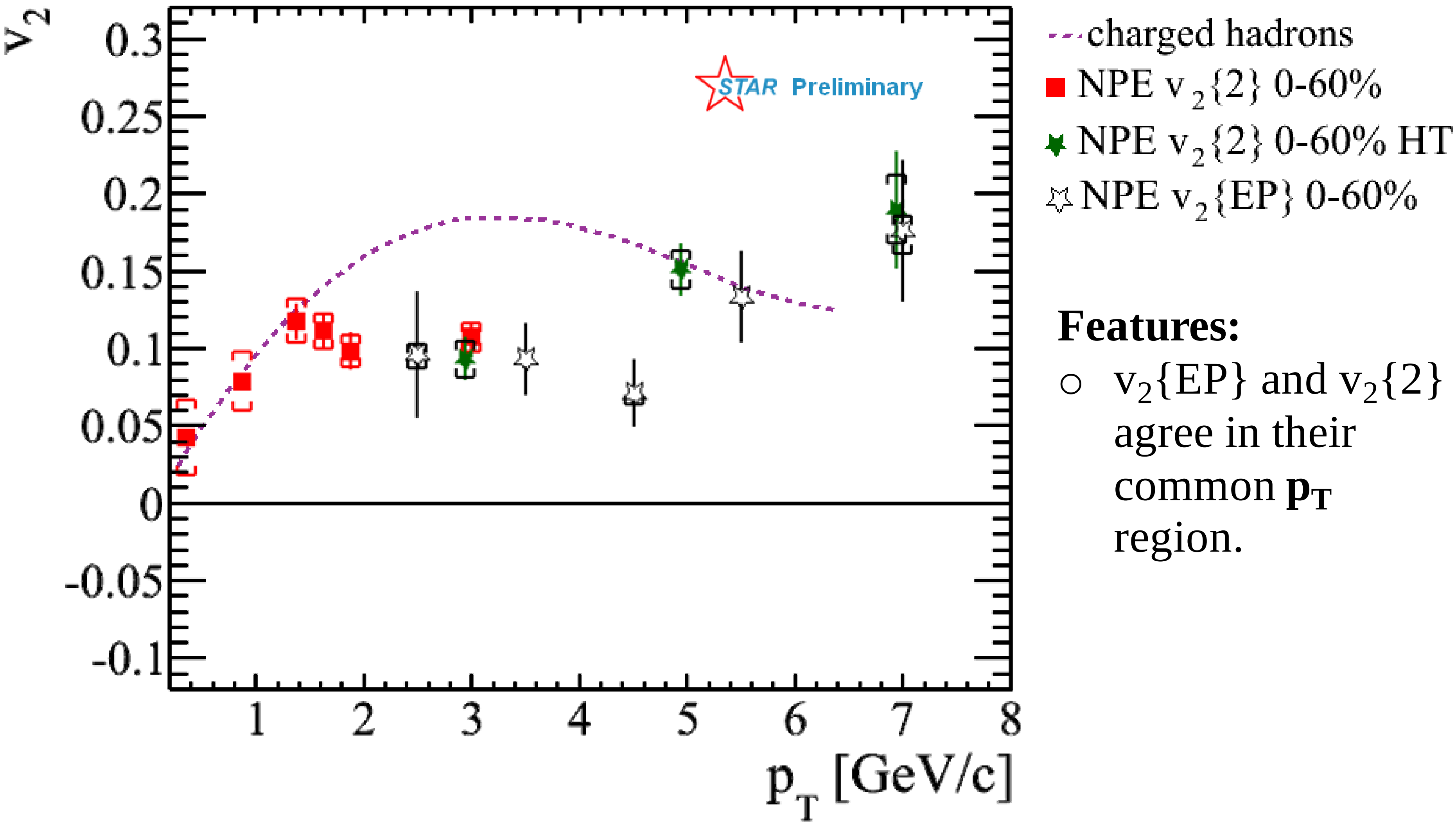
NPE v_2 in Au + Au at $\sqrt{s_{NN}}$ = 200 GeV



Features:

- Finite v_2 at low $\mathbf{p_T}$.
- Increasing v_2 at high $\mathbf{p_T}$.

NPE v_2 in Au + Au at $\sqrt{s_{NN}}$ = 200 GeV



Features:

- $v_2\{EP\}$ and $v_2\{2\}$ agree in their common $\mathbf{p_T}$ region.

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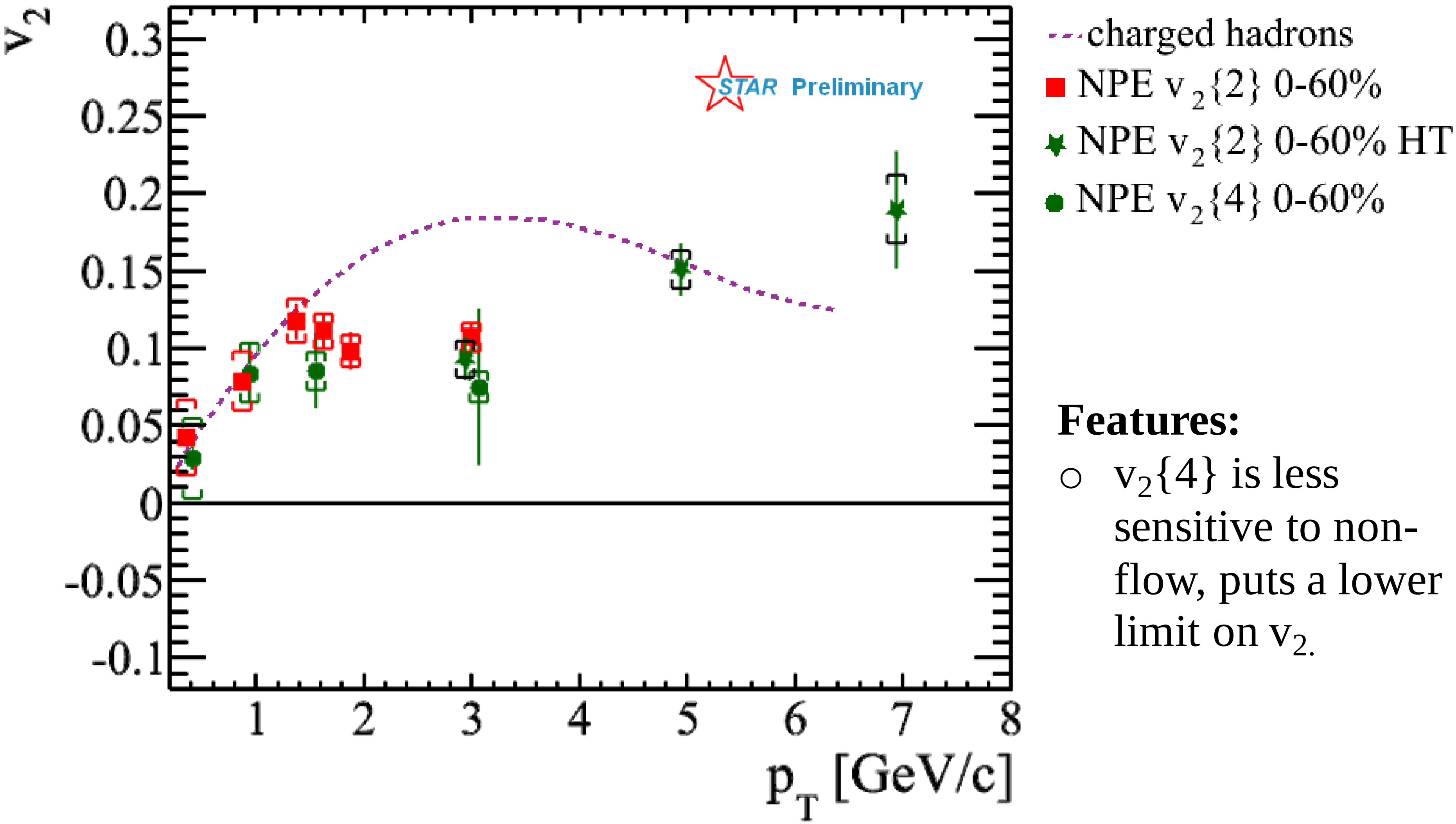
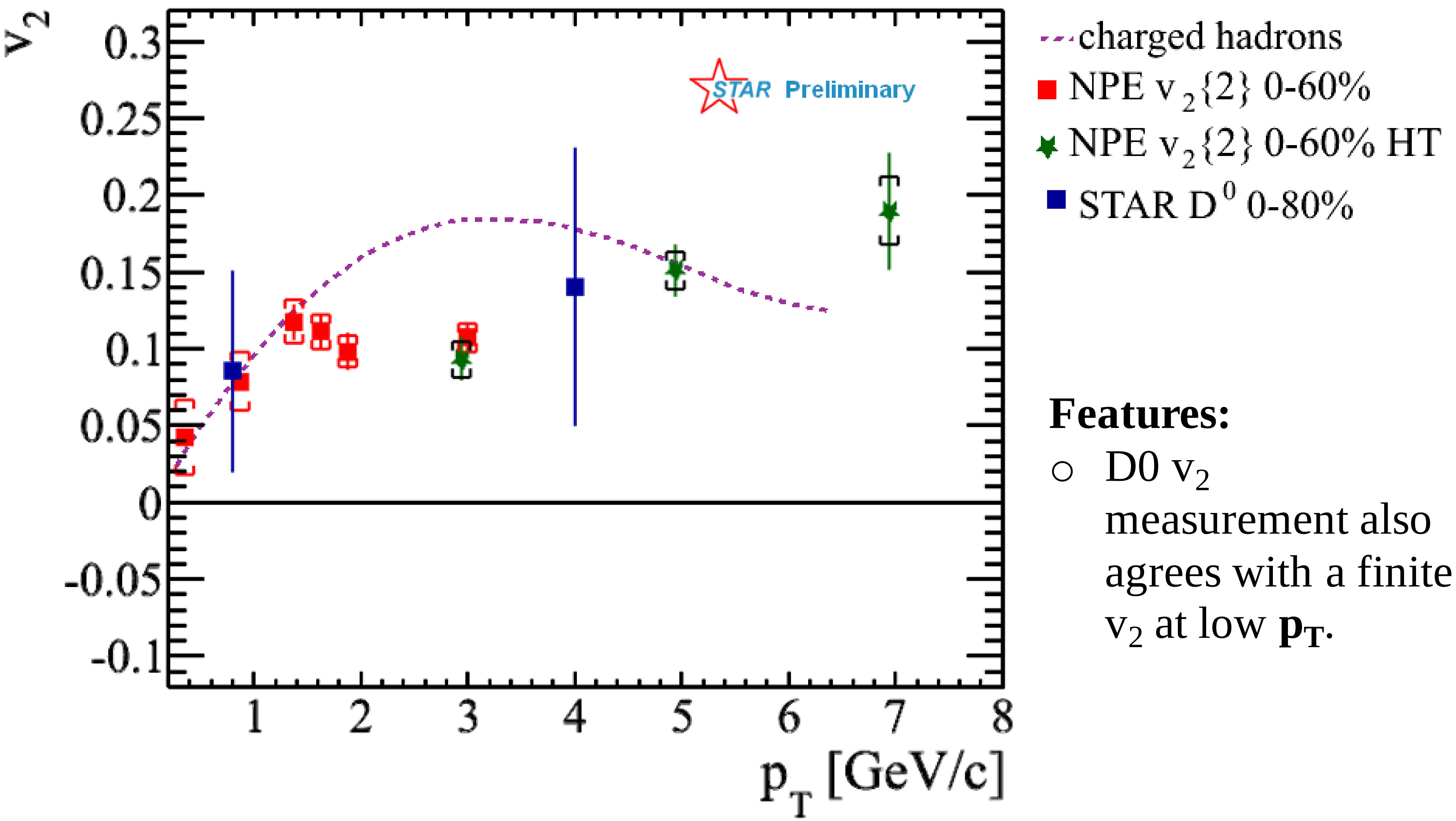


Features:

- $v_2\{4\}$ is less sensitive to non-flow, puts a lower limit on v_2.

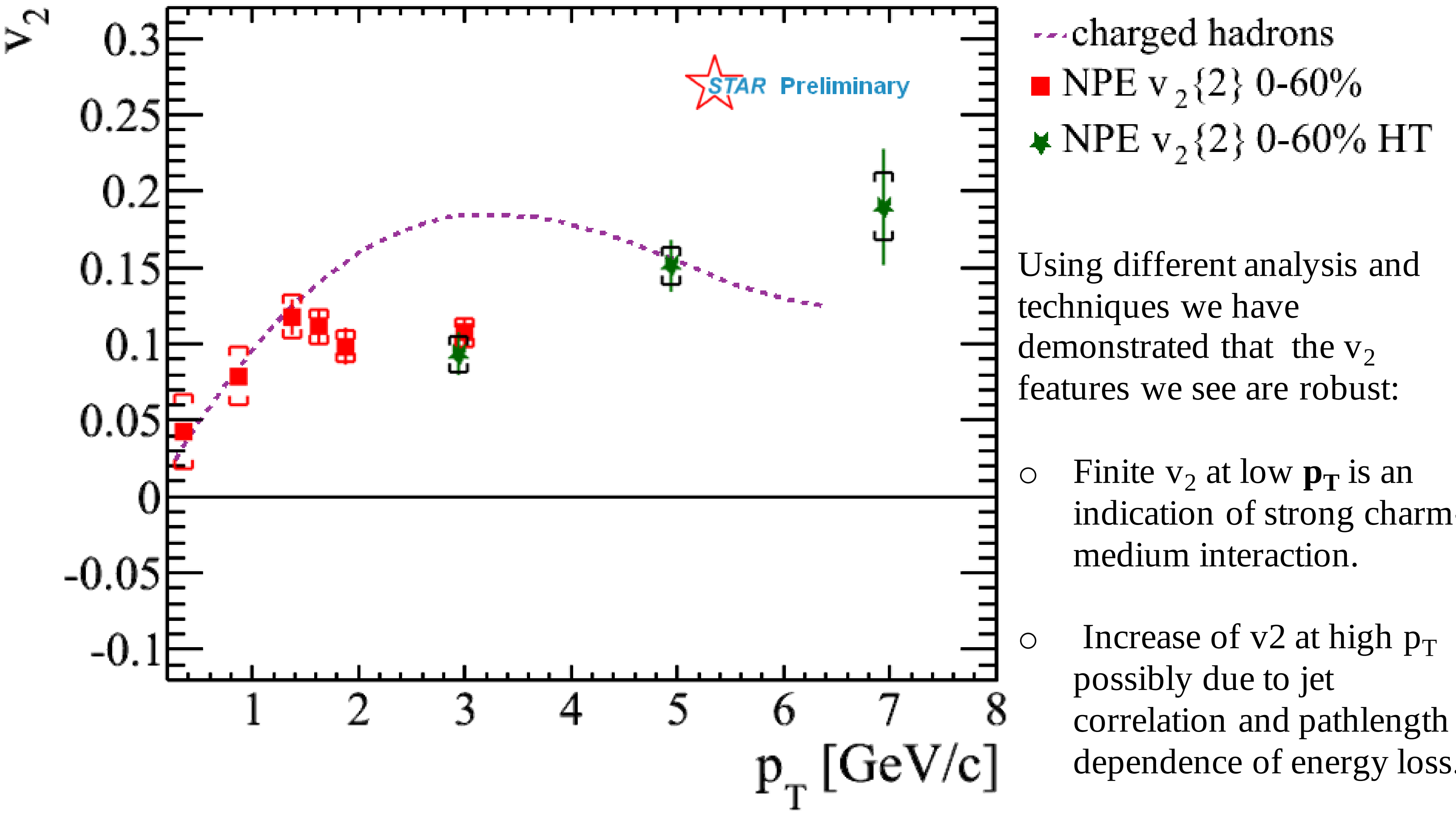
NPE v_2 in Au + Au at $\sqrt{s_{NN}}$ = 200 GeV



Features:

- D0 v_2 measurement also agrees with a finite v_2 at low $\mathbf{p_T}$.

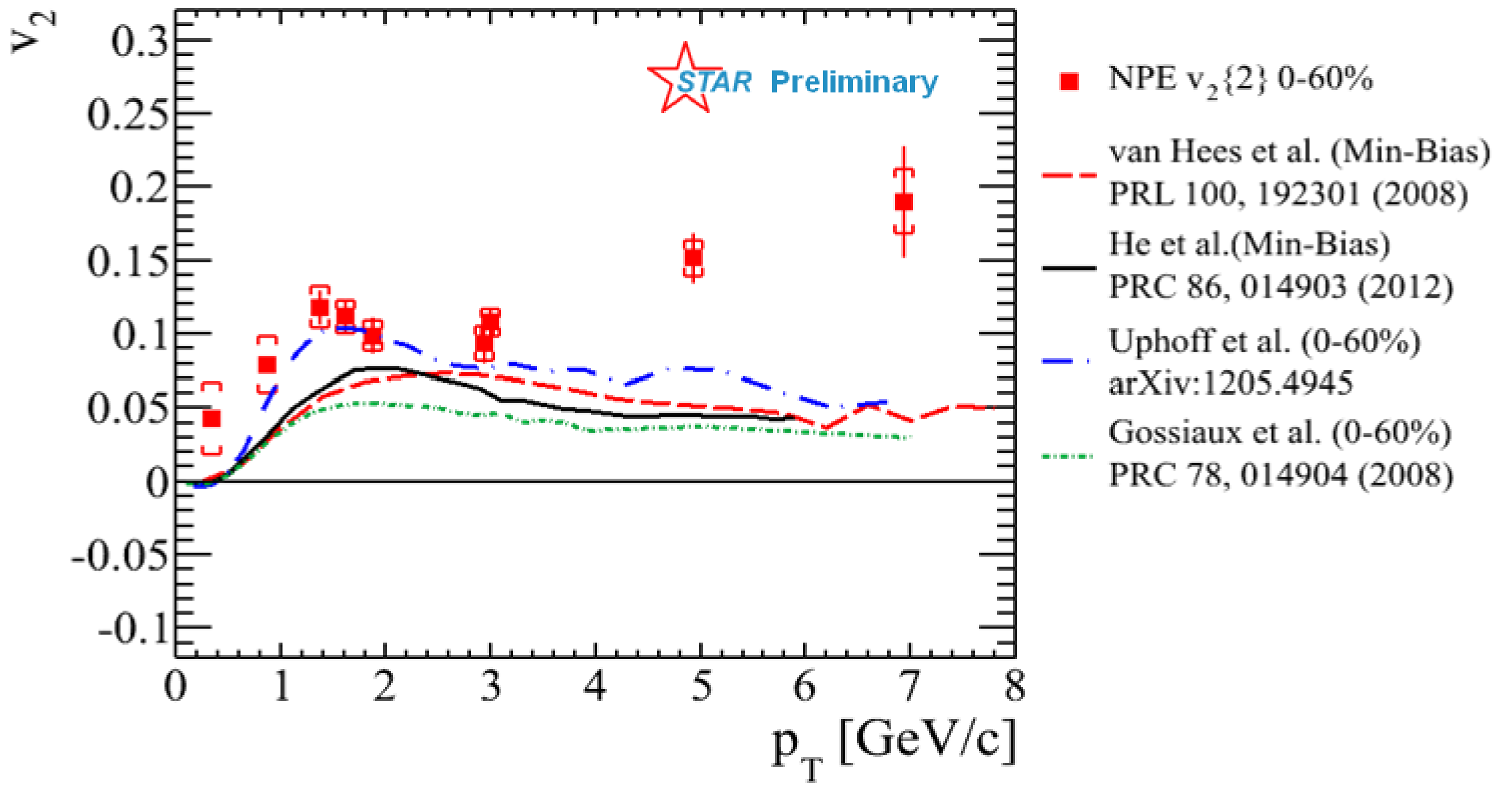
NPE v_2 in Au + Au at $\sqrt{s_{NN}}$ = 200 GeV



Using different analysis and techniques we have demonstrated that the v_2 features we see are robust:

- Finite v_2 at low $\mathbf{p_T}$ is an indication of strong charm-medium interaction.
- Increase of v2 at high p_T possibly due to jet correlation and pathlength dependence of energy loss.

NPE v_2 in Au + Au at $\sqrt{s_{NN}}$ = 200 GeV



- With the contribution of non-flow (jet correlations) at high $\mathbf{p_T}$ it is difficult to directly compare to models.

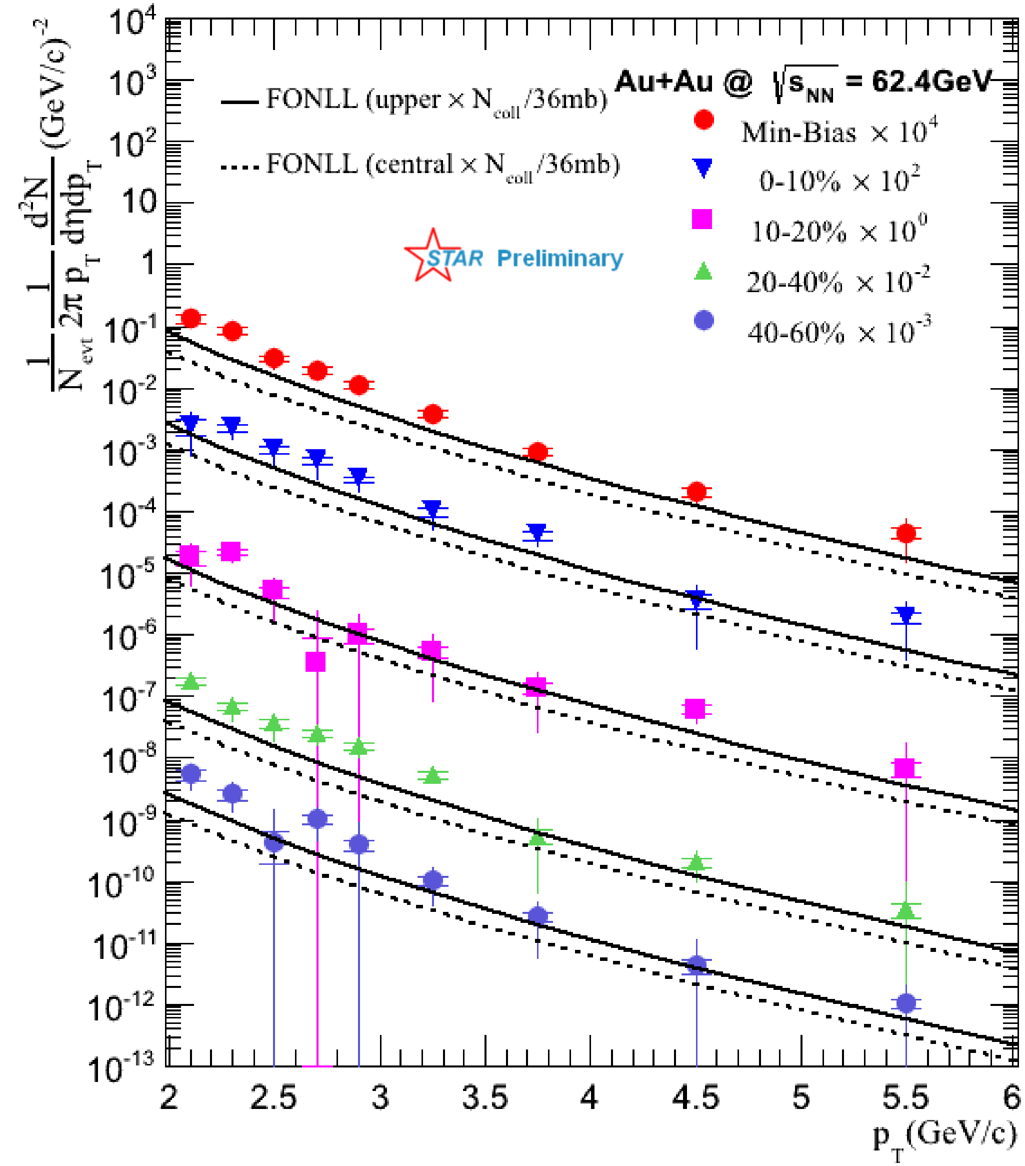
- It is interesting that the BAMPS model can reproduce the bump-feature we see at $\mathbf{p_T}$ 1-2 GeV/c. Nevertheless, more precision is needed for decisive comparison to models.

Spectra in Au + Au at $\sqrt{s_{NN}}$ = 62.4 GeV

To provide more experimental discrimination power for theoretical models STAR is extending its NPE program to lower energies.

The quest is to see if the energy loss of heavy quarks
is lessened or turned o
at lower energies.

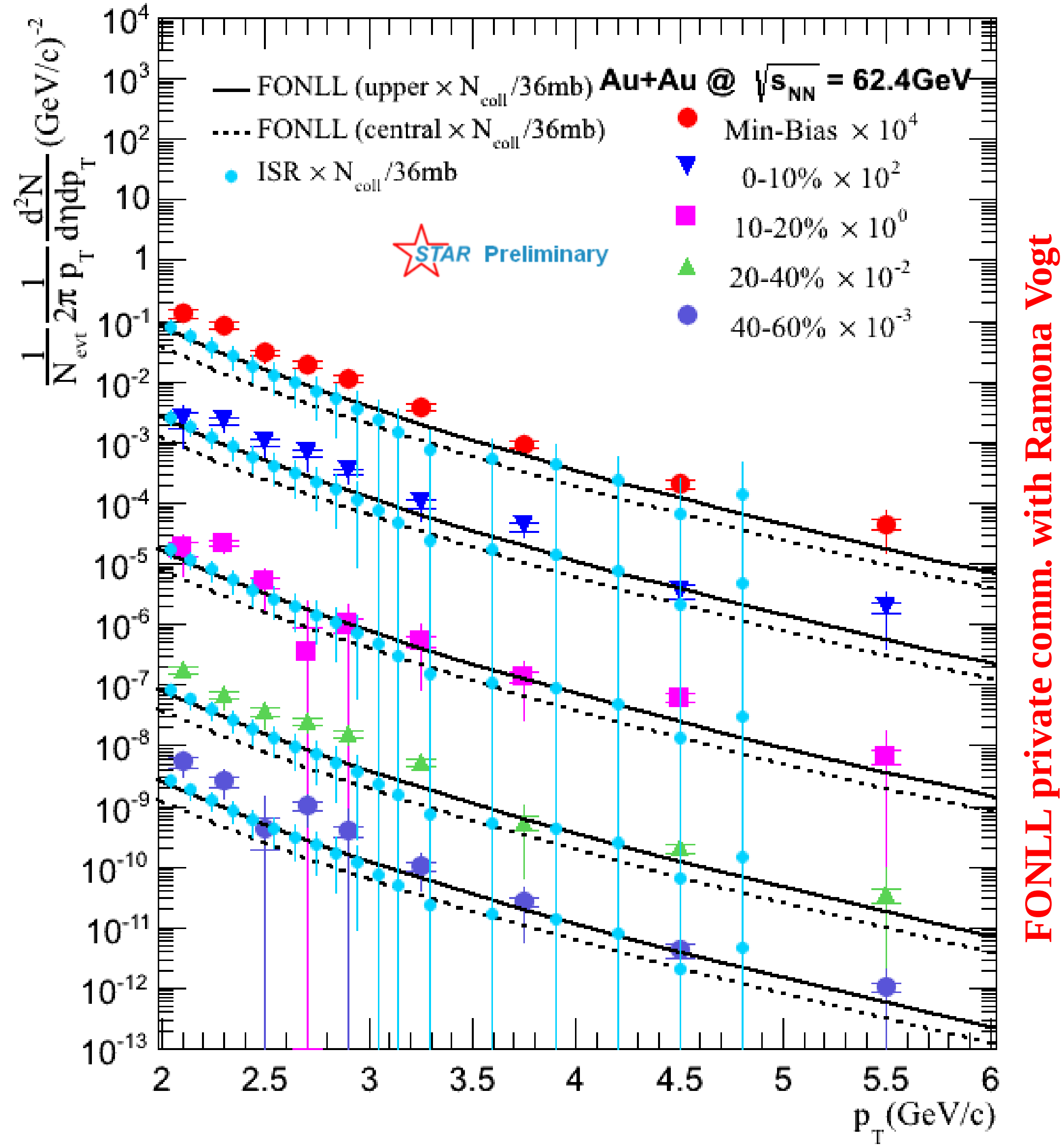
- J/ψ not subtracted.



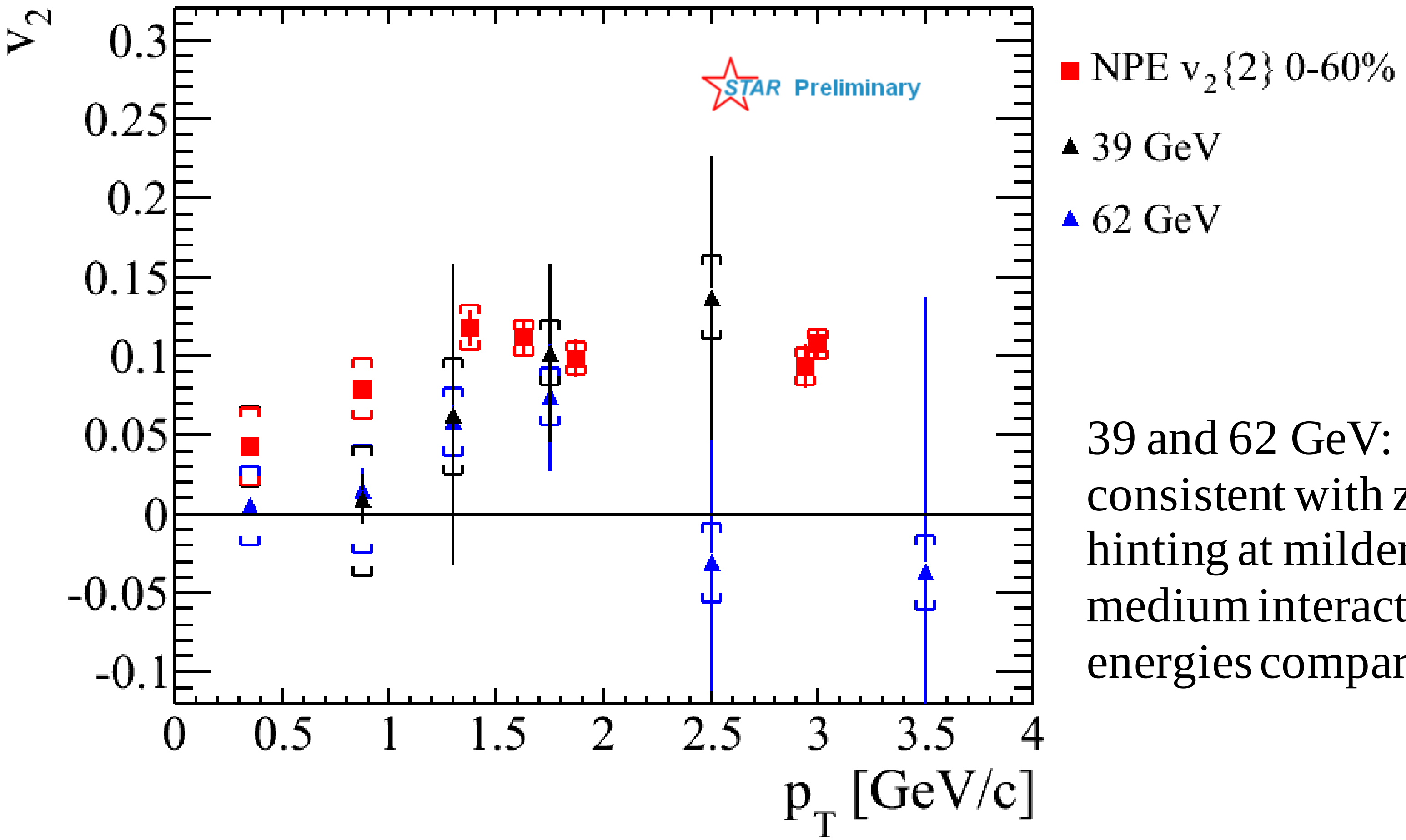
FONLL private comm. with Ramona Vogt

Spectra in Au + Au at $\sqrt{s_{NN}}$ = 62.4 GeV

- Measurement is systematically higher than FONLL upper limit.
- ISR measurement is consistent with FONLL upper limit.
  IL NUOVO CIMENTO (1981), 65A, N4, 421-456



NPE $v_2\{2\}$ in Au + Au at $\sqrt{s_{NN}}$ = 62.4 and 39 GeV



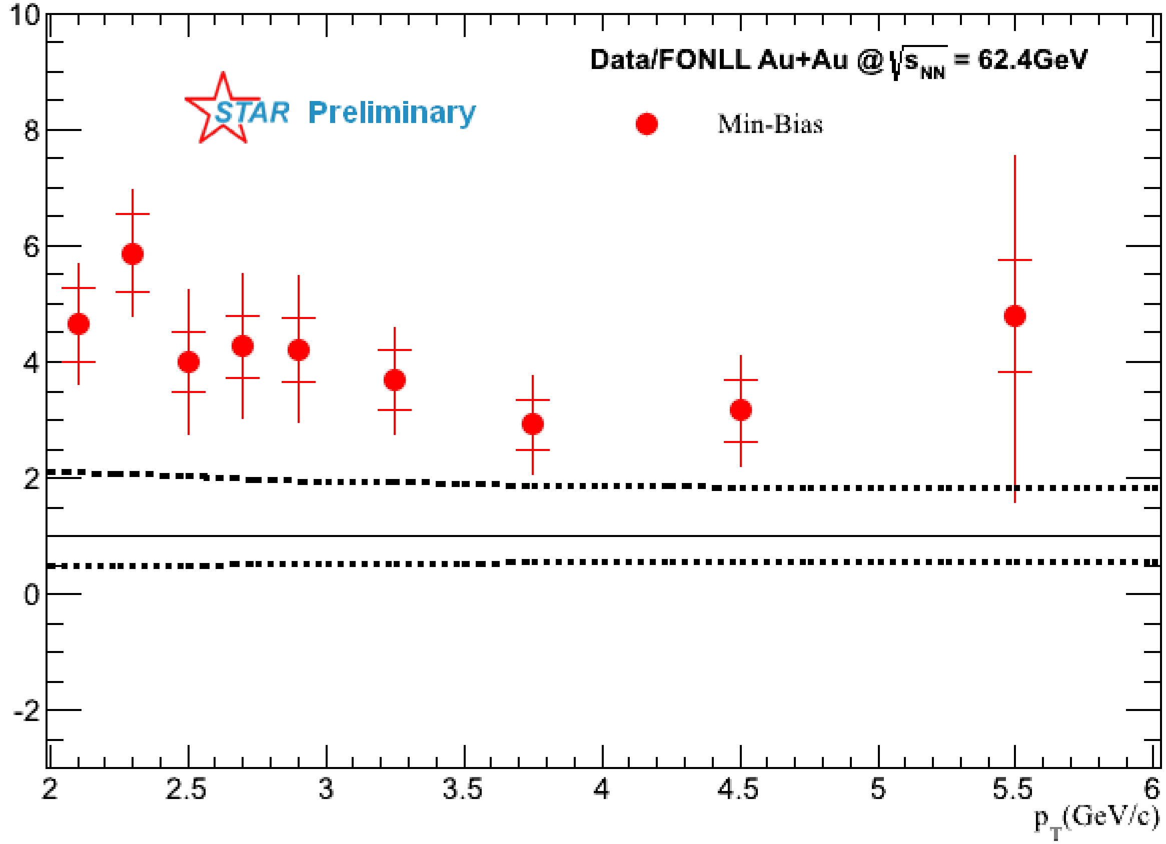
39 and 62 GeV: $v_2\{2\}$ consistent with zero at low-$\mathbf{p_T}$ hinting at milder charm-medium interaction at lower energies compared to 200GeV.

Summary of New Results

- **New measurement of NPE in Au+Au at $\sqrt{s_{NN}}$ = 200GeV:**
  - High precision at high $\mathbf{p_T}$.
  - R_{AA} indicates strong suppression of heavy quarks, and disfavors radiative energy loss as the only energy loss mechanism for heavy quarks.
  - NPE Azimuthal Anisotropy shows a finite v_2 at low $\mathbf{p_T}$ this is an important indication of strong charm-medium interaction.
  - Possibly due to jet correlations and likely path-length dependence of energy loss, we see an increasing in $\mathbf{v_2}$ towards high $\mathbf{p_T}$.
- **NPE at lower energies:**
  - NPE spectra in Au+Au $\sqrt{s_{NN}}$ = 62.4 GeV is systematically higher than FONLL.
  - Measurement of NPE V2{2} at √sNN = 62.4 and 39GeV is consistent with zero at low pT which might indicate a difference in the degree of charmed-medium interaction compared to 200GeV.

Backup Slides

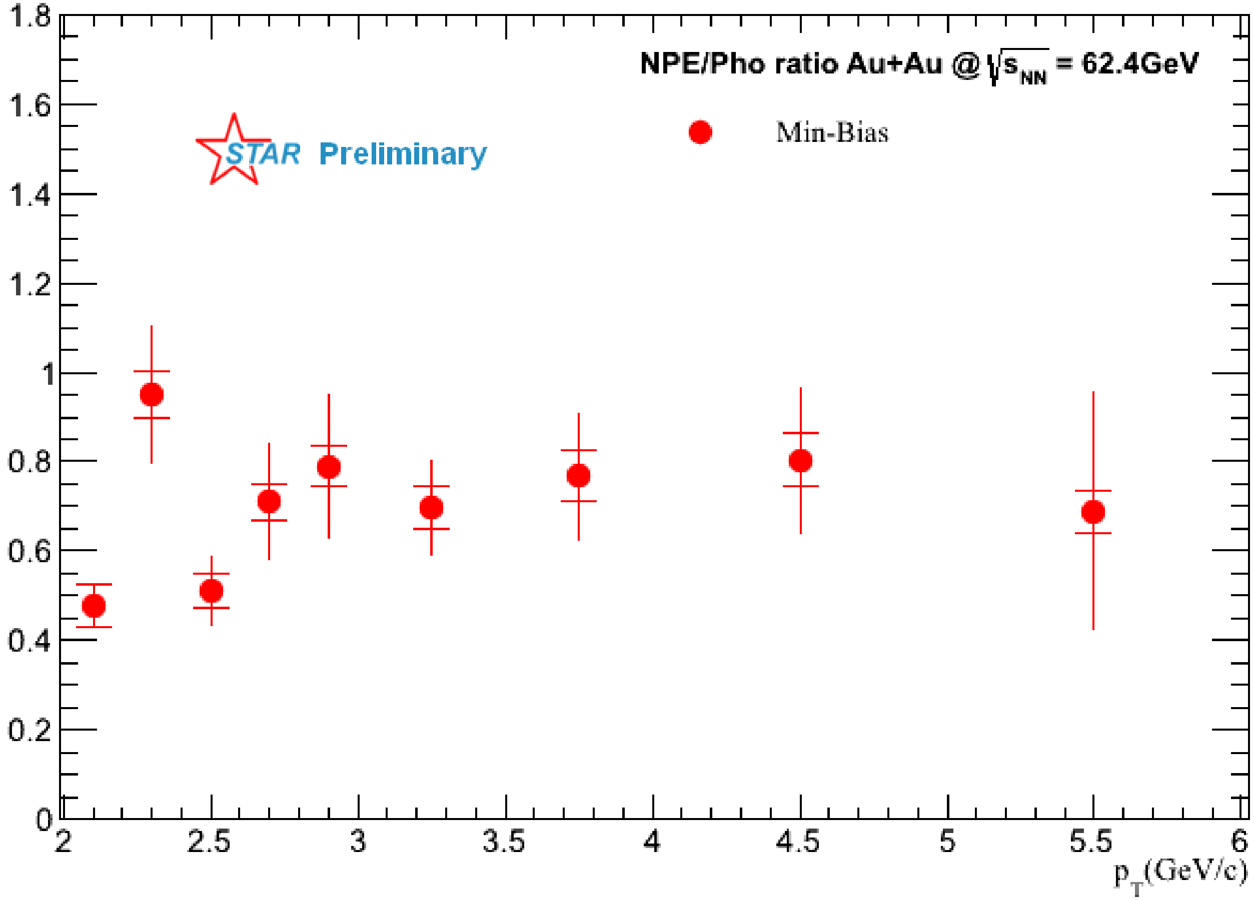
Spectra in Au + Au at $\sqrt{s_{NN}}$ = 62.4 GeV



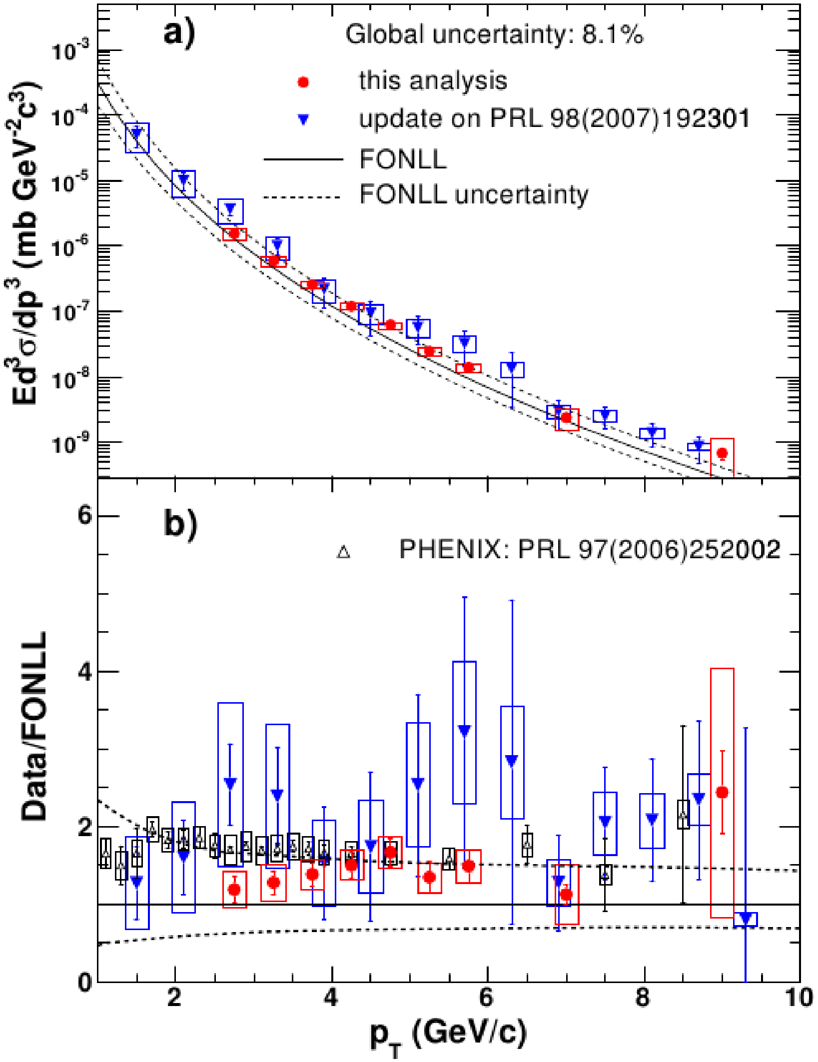
FONLL private comm. with Ramona Vogt

- Measurement is systematically higher than FONLL upper limit.

Spectra in Au + Au at $\sqrt{s_{NN}}$ = 62.4 GeV – NPE/Photonic Ratio



NPE p + p at $\sqrt{s}$ = 200 GeV



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