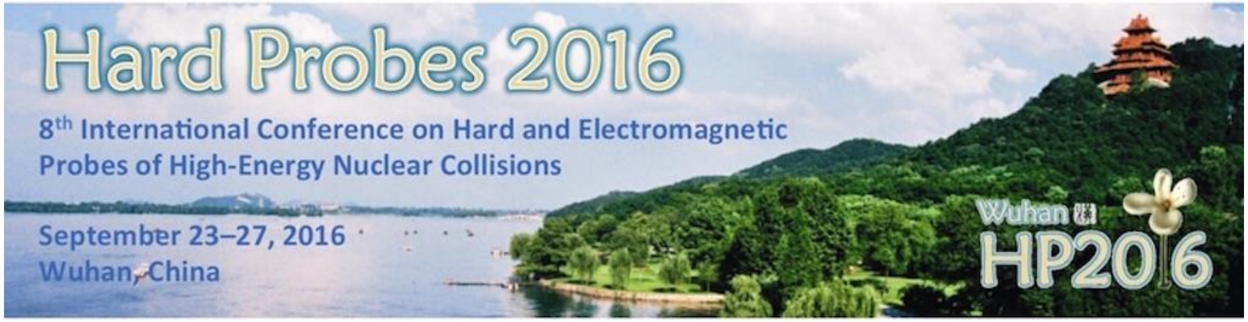
Heavy Flavor Physics: Experimental Results at RHIC

Wei Xie

(Purdue University, West Lafayette)

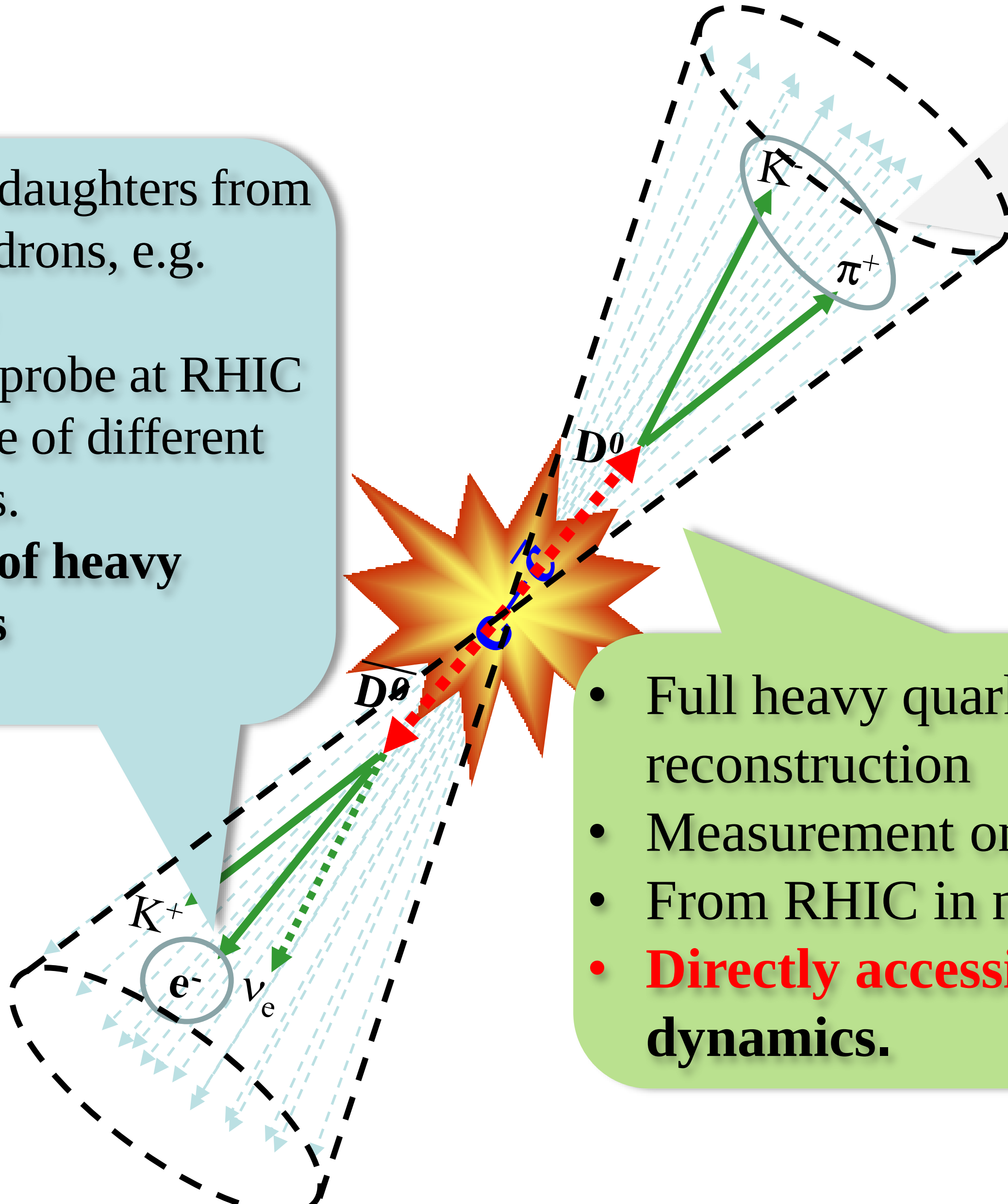


Motivations

- One of the most important probes for sQGP
  - Heavy quark involve more abundant E-loss mechanisms.
    - *gluon radiation, collisional energy loss, collisional disassociation, etc*
  - Allow further understanding of the medium properties.
  - Cold Nuclear effects
    - *Gluon shadowing , Color glass condensate, etc*
  - Sensitive to the gluon nPDF distribution.
    - *produced mostly from gluon fusion*
- A good reference to quarkonia production
  - Similar initial state effect.
    - *CGC, Shadowing, initial state energy loss, etc.*
  - Large cross section (compared to J/ψ).
    - *Accurate reference measurements.*
- A "**Gold Mine**" being fully explored.

How to study Heavy Quarks

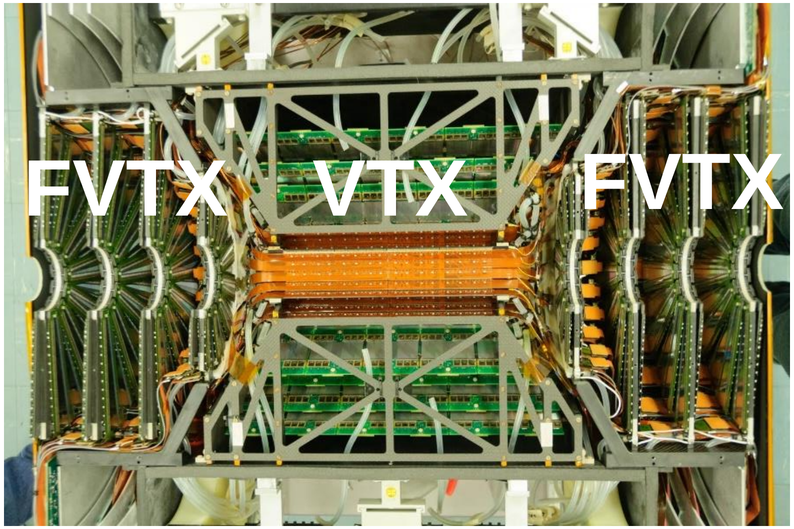
- Decay daughters from HF Hadrons, e.g. HF→e
- A Key probe at RHIC
- Mixture of different sources.
- **Proxy of heavy quarks**

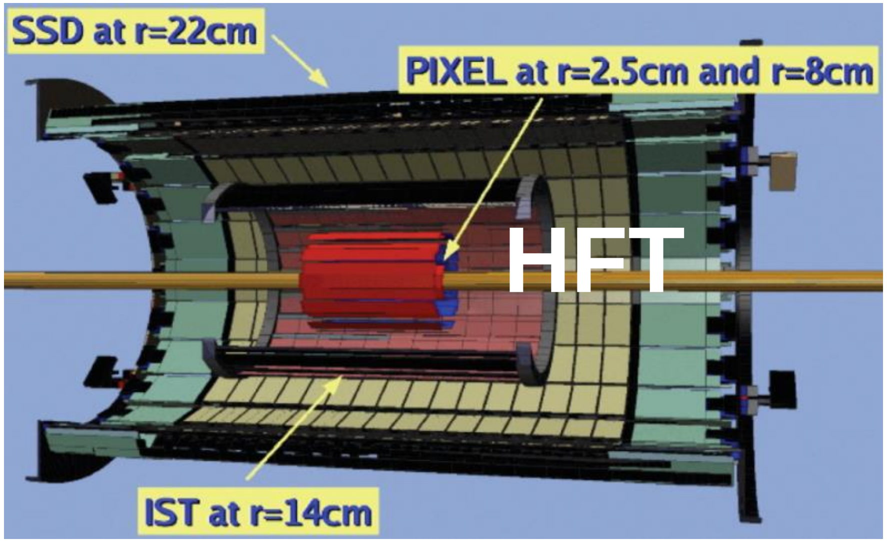


- Direct reco. of HF hadrons
- One of the Key probes at LHC and at RHIC after svtx upgrade
- **Better Proxy of heavy quarks**

- Full heavy quark jet reconstruction
- Measurement only from LHC
- From RHIC in near future
- **Directly accessing heavy quark dynamics.**

How are Heavy Quarks Studied at RHIC

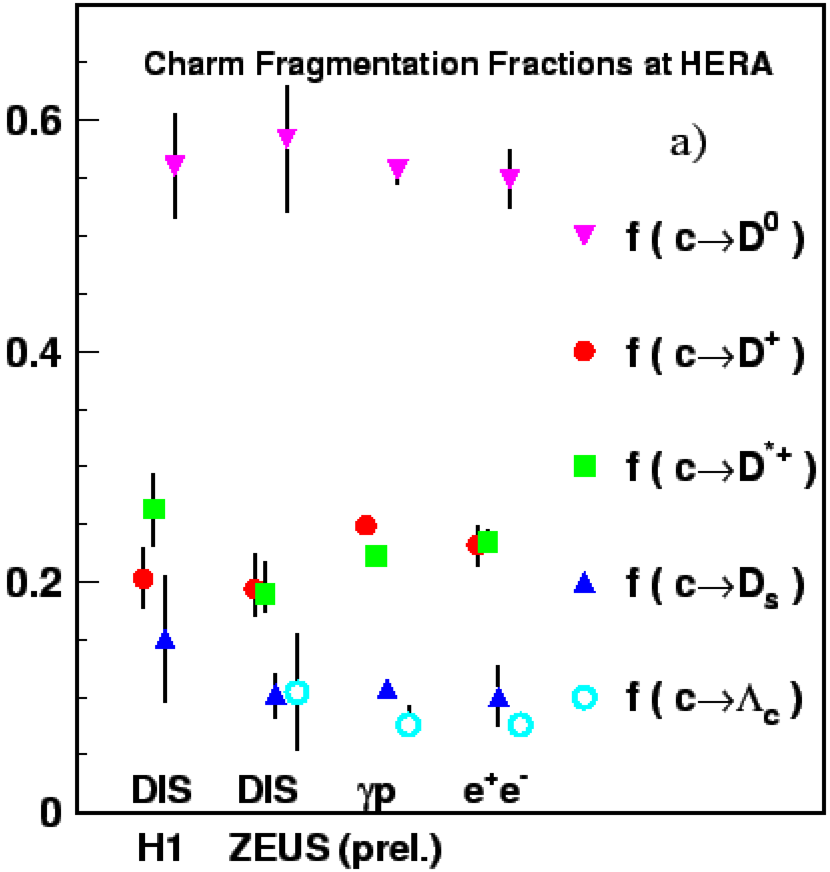


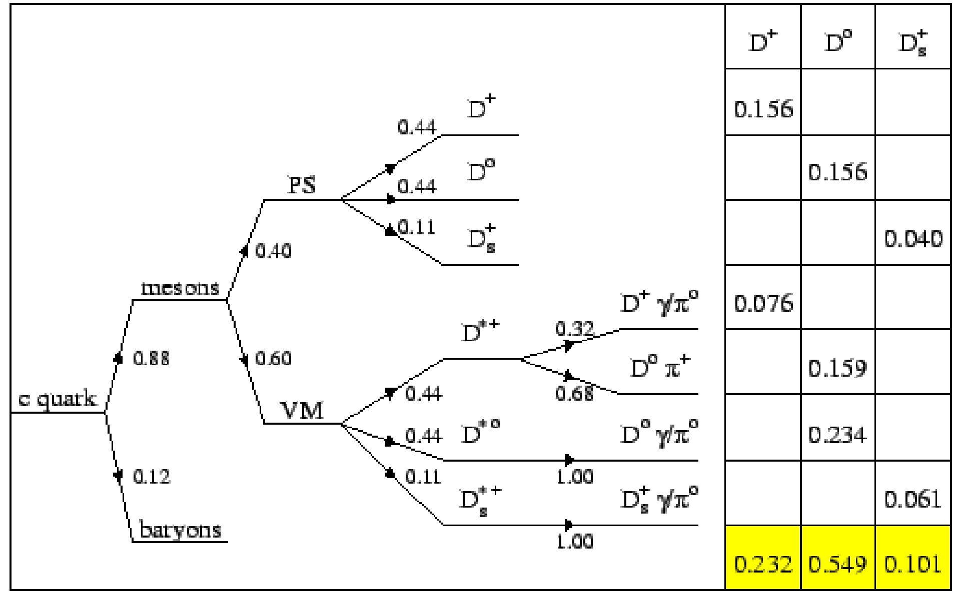


- **Full reconstruction of HF hadrons**
  - More direct access to the heavy quark kinematics,
  - hard to trigger.
    - *Limit the p_T reach of the measurements*
  - small(er) Branching Ratio:
    - $D^0 \to K^-\pi^+$: BR: ~4.0%
    - $D_s^+ \to K^+K^-\pi^+$: BR: ~2.3%
    - $B^+ \to K^+ + J/\psi$: BR: ~6×10^{-5}

- **Decay daughters from HF hadrons**
  - Indirect access to the heavy quark kinematics
  - can be triggered easily.
    - *Ideal for higher p_T measurements*
  - High(er) branching ratio
    - $B^0/B^+ \to e^+ + X$: BR: ~10%
    - $B \to J/\psi + X$: BR: ~1%
    - $D^0 \to e^+ + X$: BR: ~7%
    - $D^+ \to e^+ + X$: BR: ~17%

Charm Fragmentation Fraction

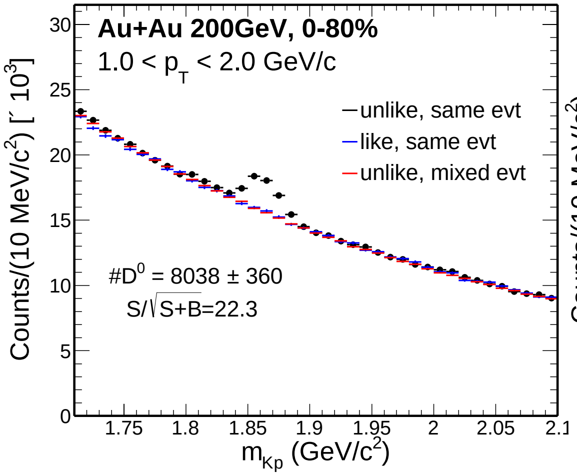


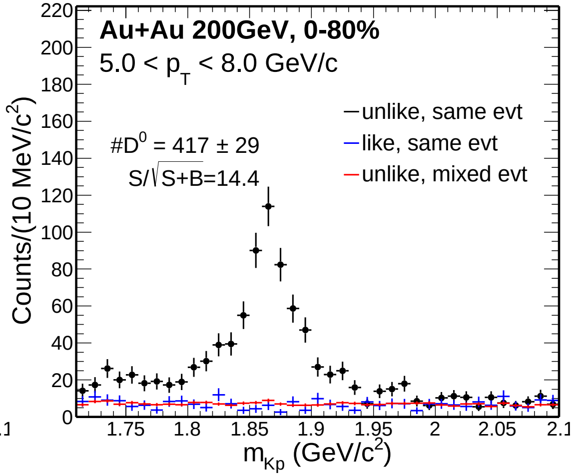


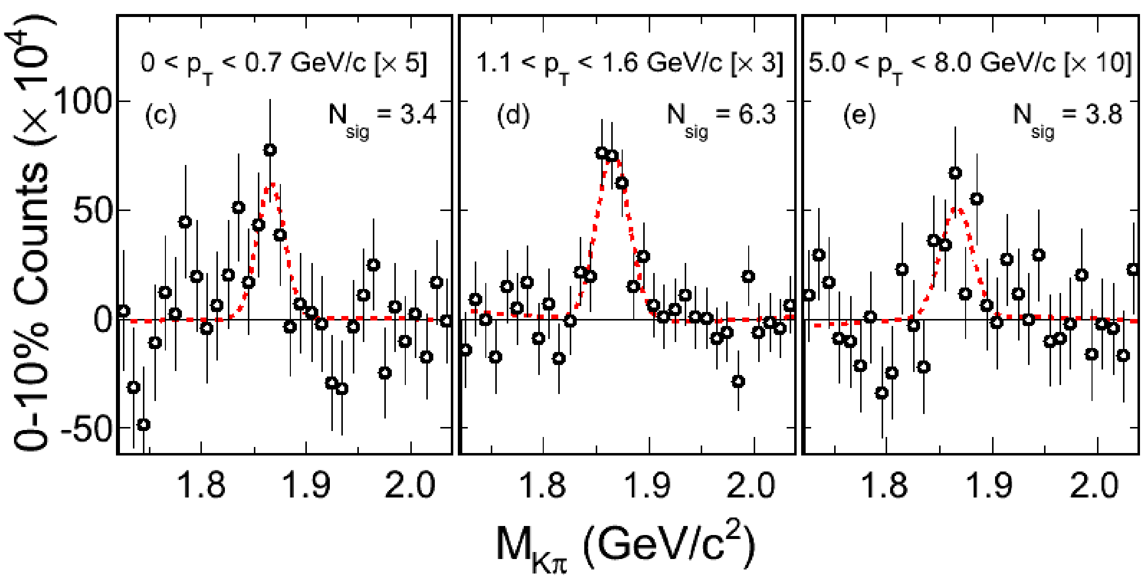
- E. Groom *et al.* [Particle Data Group Collaboration], Eur. Phys. J. C **15** (2000) 1.
- http://www.desy.de/~ameyer/hq/node38.html

- ❑ ~55% ➔ D^0 (cτ = 122.9 μm): $D^0 \to K^-\pi^+$ *BR: 4.0%*
- ❑ ~10% ➔ D_s^+ (cτ = 149.9 μm): $D_s^+ \to \pi^+ + (\phi \to) K^+K^-$ *BR: 2.3%*
- ❑ ~23% ➔ D^+ (cτ = 311.8 μm): $D^+ \to K^-\pi^+\pi^-$ *BR: 9.4%*
- ❑ ~10% ➔ Λ_c^+ (cτ = 59.9 μm): $\Lambda_c^+ \to p^+K^-\pi^+$ *BR: 5.0%*

D^0 Signal in Au+Au at 200 GeV

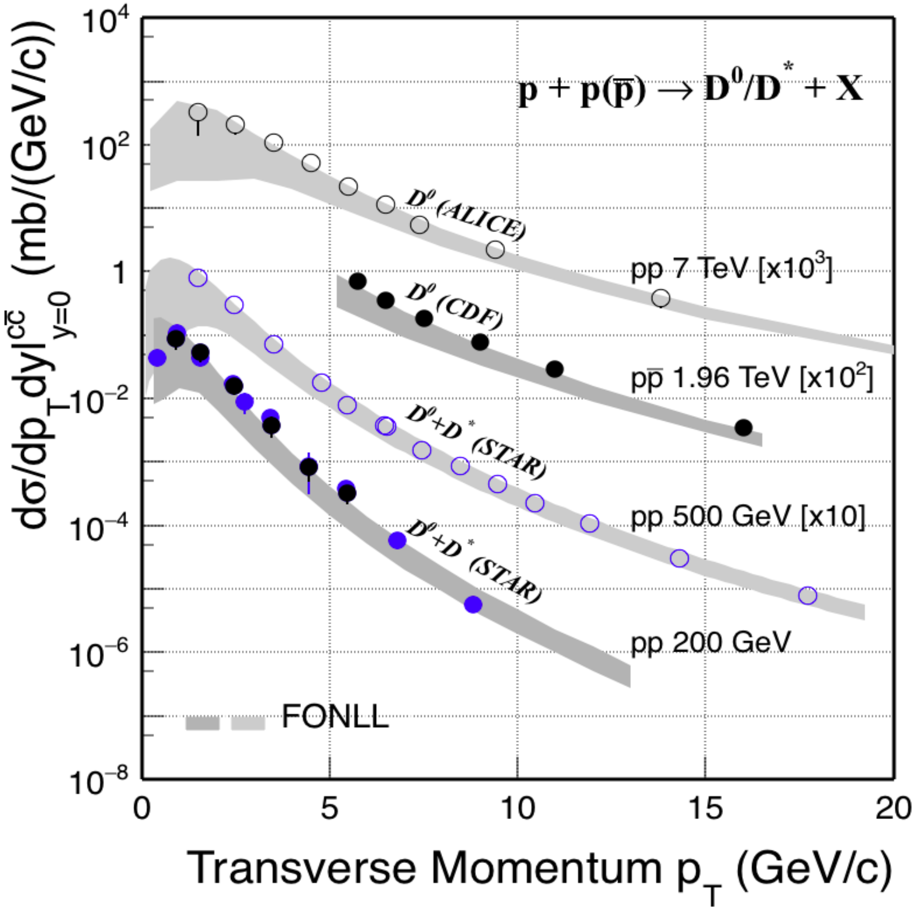


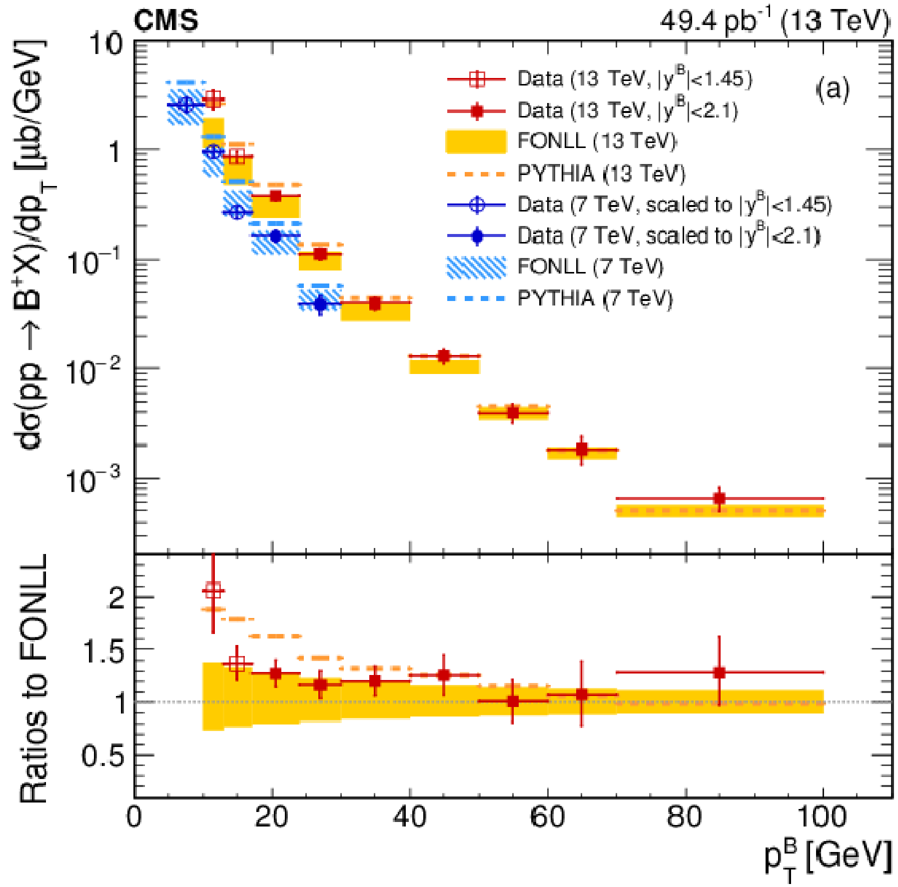




- **Run2010 & 2011 w/o HFT.**
  - Total: ~800 M Min.Bias events
  - $S/\sqrt{S+B}$ (p_T~1-2 GeV/c): **~6.0**
  - $S/\sqrt{S+B}$ (p_T~5-8 GeV/c): **3.8**
- **Run2014 w/ HFT.**
  - Total: ~1 B Min.Bias events
  - $S/\sqrt{S+B}$ (p_T~1-2 GeV/c): **~22.3**
  - $S/\sqrt{S+B}$ (p_T~5-8 GeV/c): **14.4**

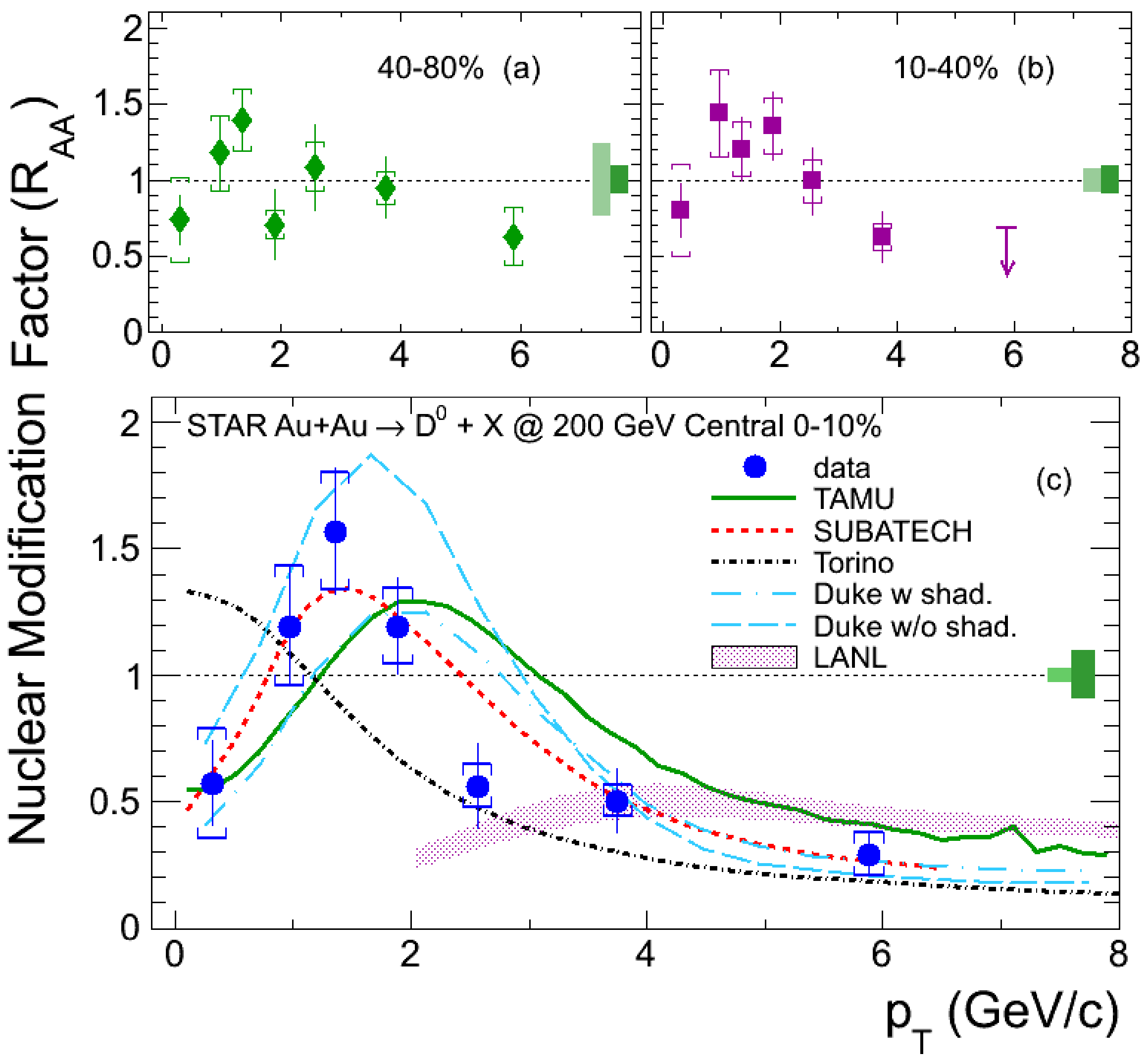
D^0 Signal in p+p Collisions





- ❑ FONLL provide a good description on HF production in pp collisions
  - *From 200 GeV – 13 TeV*

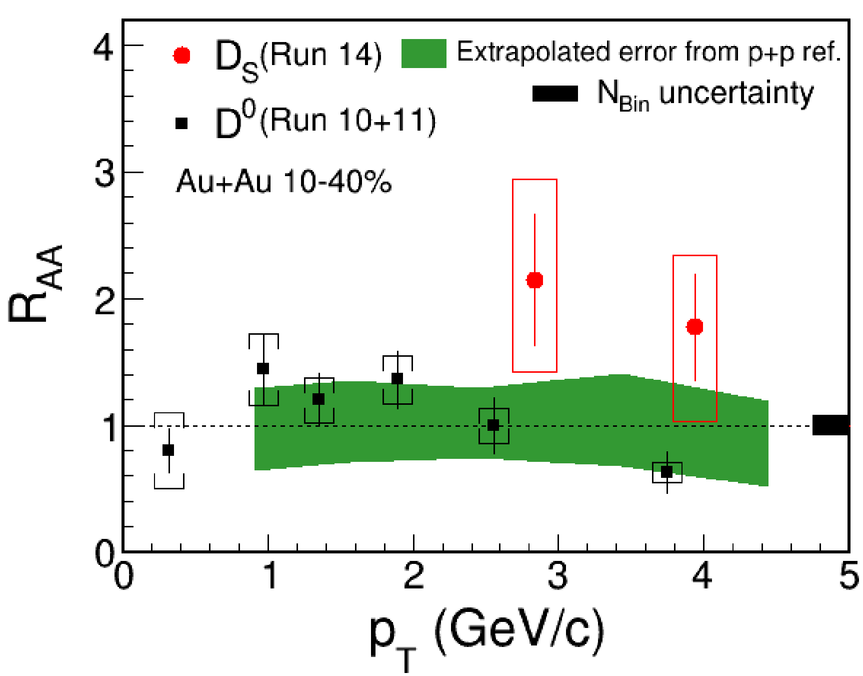
Enhancement of D^0 production at Intermediate p_T in Au+Au at 200 GeV

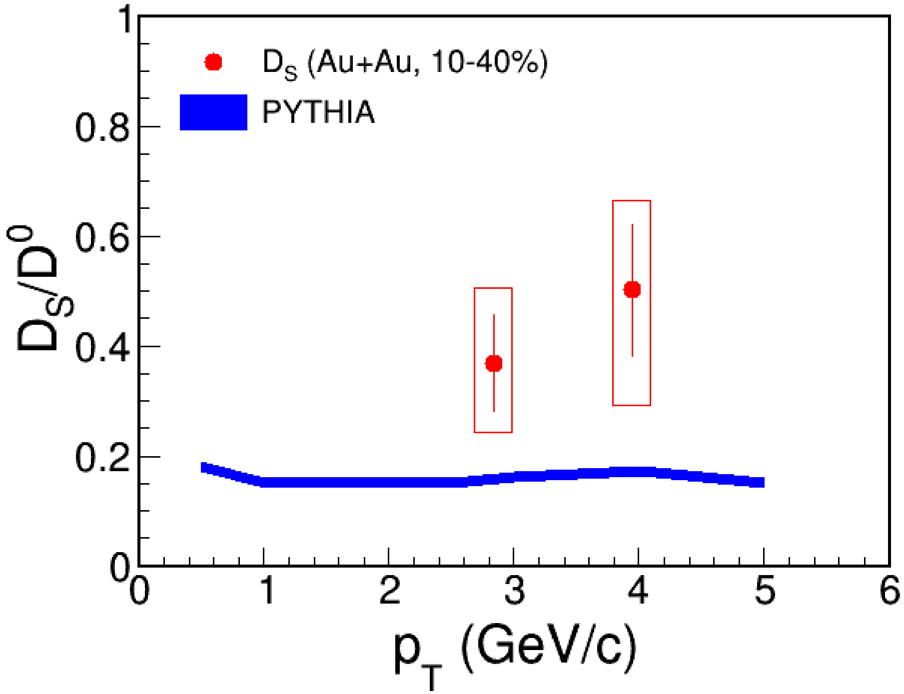


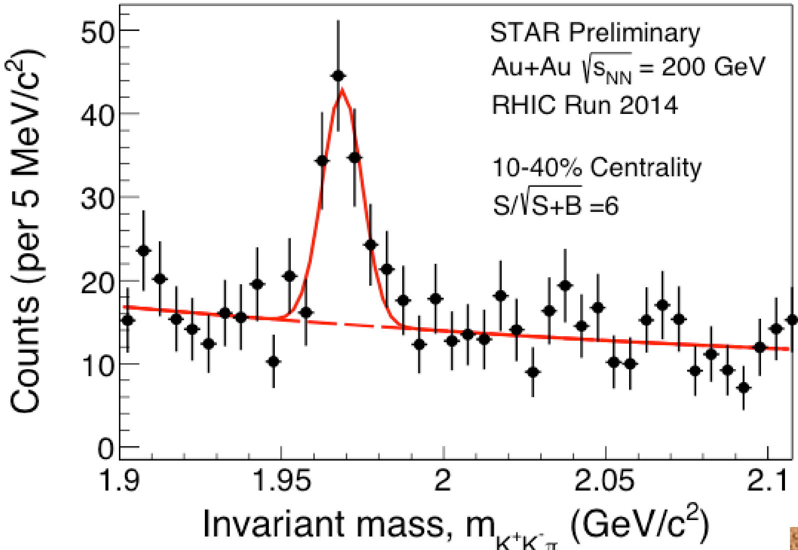
- Enhancement at intermediate p_T
  - Can be described by models including coalescence between charm quark and light quark
  - Cold nuclear matter effects may also contribute

STAR: PRL113, 142301 (2014)

First Ds R_{AA} Measurement in Au+Au at 200 GeV

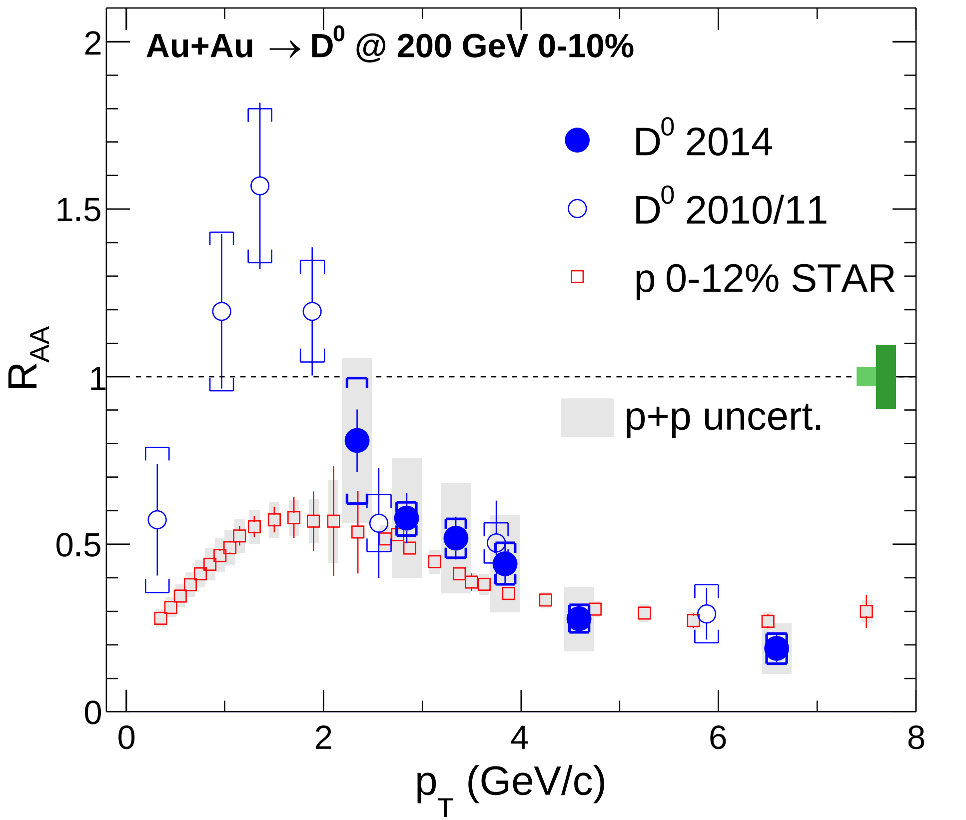


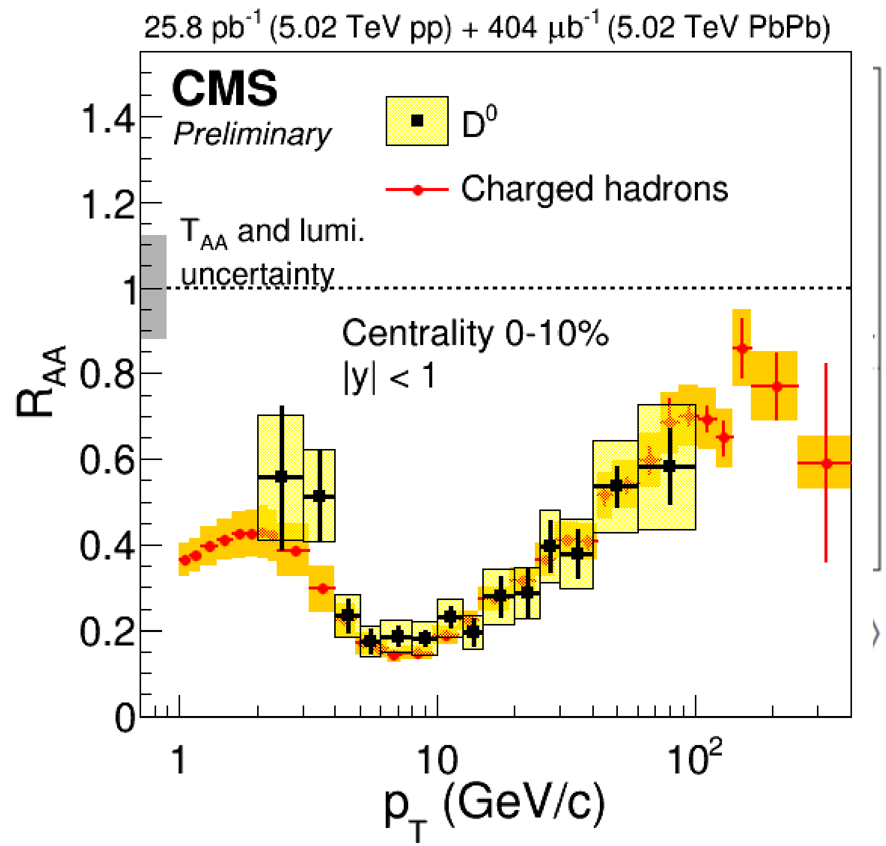




- Coalescence + Strangeness enhancement
  ➔R_{AA} (Ds) > R_{AA} (D^0)
- First Ds meson reconstruction at RHIC
- pp reference calculated from measured charm cross section [Phys. Rev. D86, 72013 (2012)].
- indication of R_{AA} (Ds) > R_{AA} (D^0)
  - *More statistics is needed for conclusion*

Large Suppression of D^0 production at High p_T in Au+Au at 200 GeV

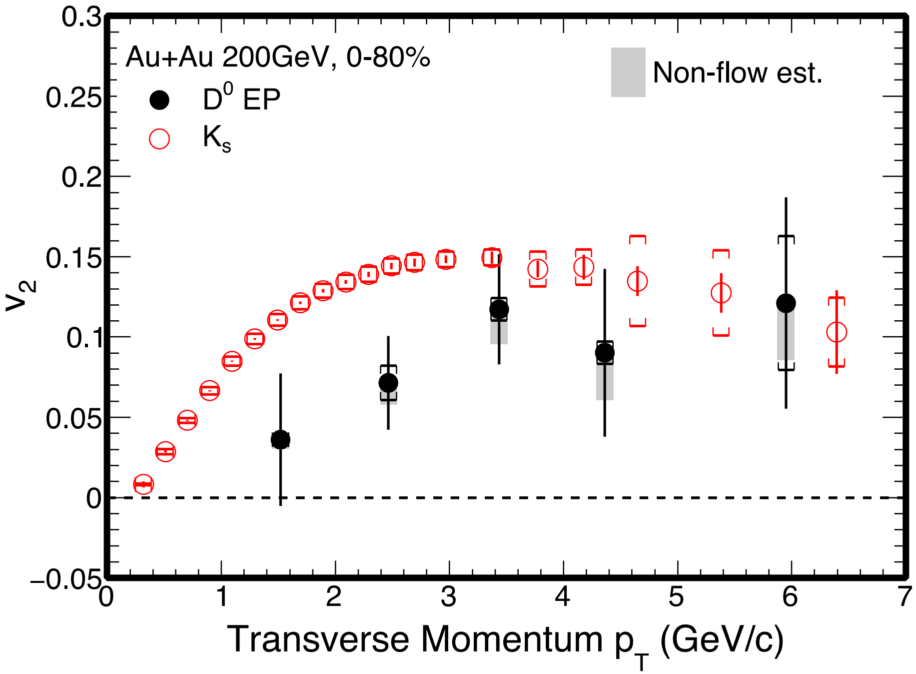


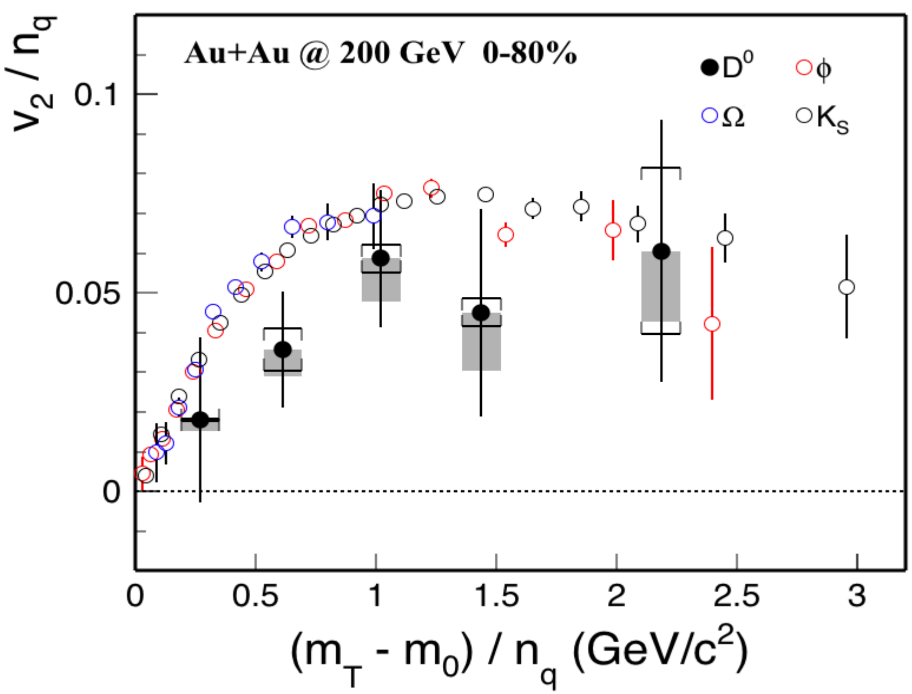


- ❑ New result with HFT has improved precision.
- ❑ Large suppression (5x) of D^0 production at high p_T
- ❑ R_{AA} (D0) ≈ R_{AA}(charged) for p_T > 2 GeV/c within uncertainties
  - *at both **RHIC** and the **LHC***

Guannan Xie @HF(I)

Significant D^0 v_2 Observed





- ❑ v_2 (D^0) is measured using EP and Correlation method.
- ❑ v_2 (D^0) < v_2 (hardon) for specific p_T bins.

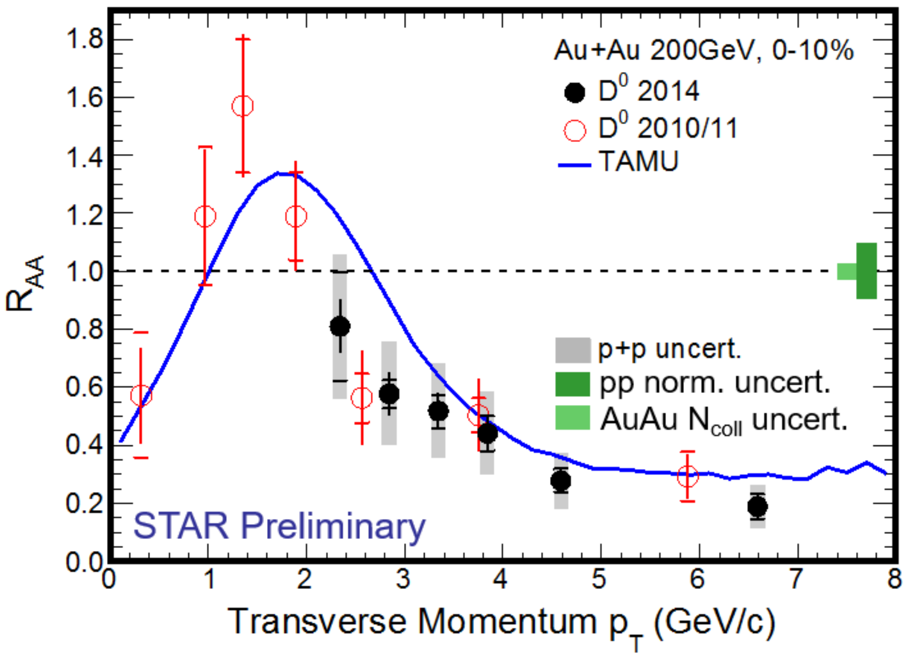
Centrality differential results are needed for a better comparison

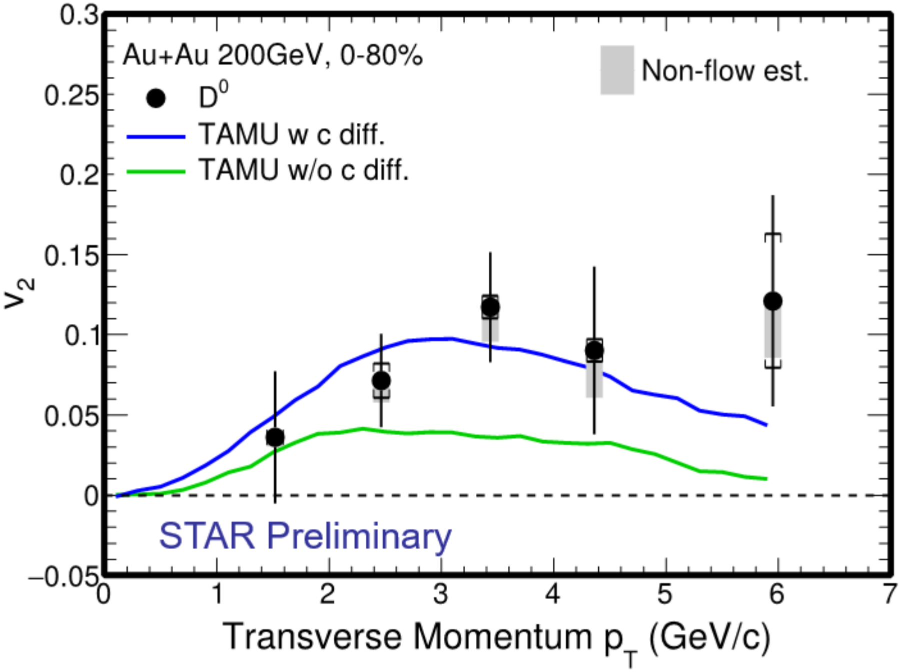
- ❑ NCQ scaling for light hadrons at RHIC
  - *Hint of v_2/n_q (D^0) < v_2/n_q(hadrons)*
- ❑ **Not a fair comparison**
  - $N(D^0) \propto N_{coll} \times R_{AA}(D^0)$
  - $N(hadron) \propto (N_{part})^{\alpha} \times R_{AA}(hadron)$

PRC 77 (2008) 54901

PRL 116 (2016) 62301

Data/MC Comparison of D^0 Measurments

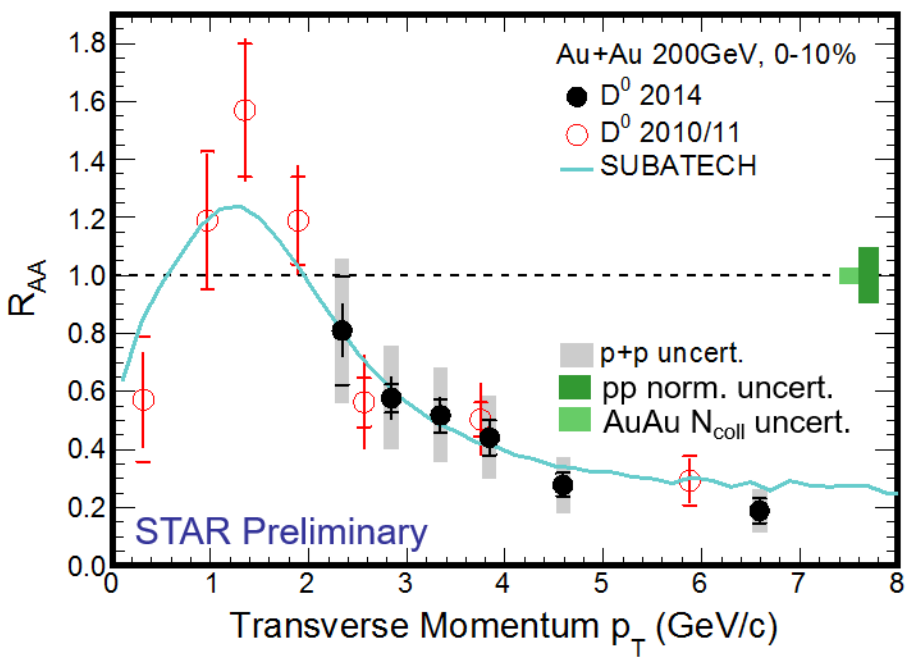


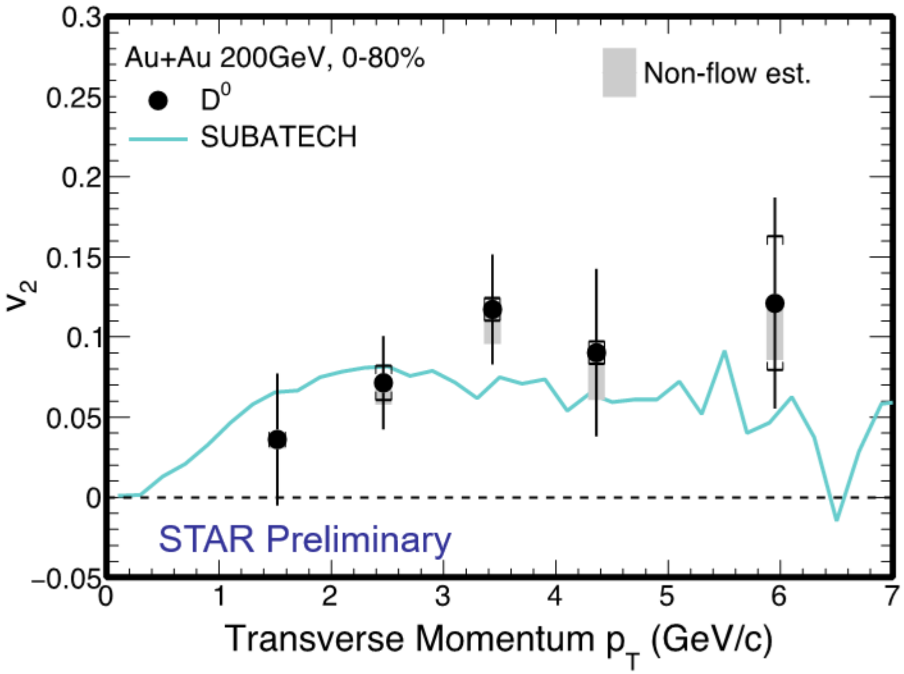


❑ T-Matrix:

- Full T-matrix treatment, non-perturbative model with internal energy as heavy quark potential
- Spatial diffusion coefficient: $2\pi T \times D = 3\text{-}11$
- Data favor charm quark diffusion inside the medium.

Data/MC Comparison of D^0 Measurments



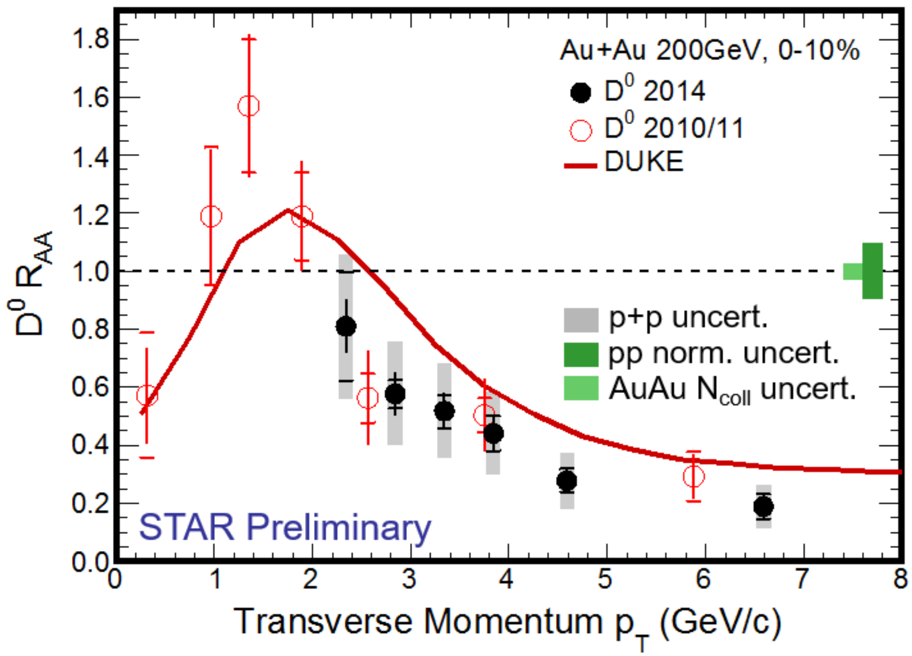


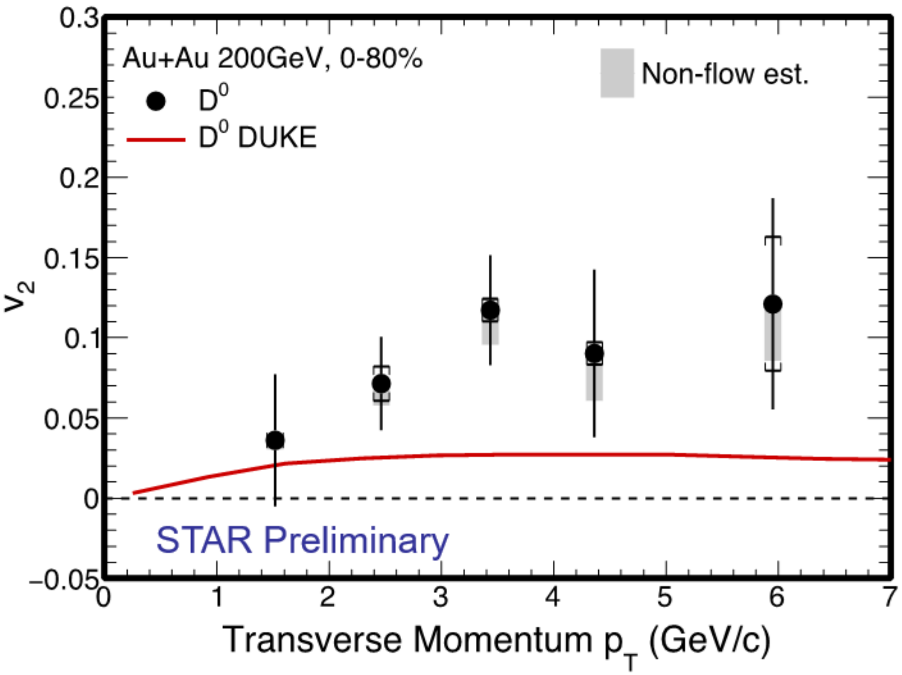
❑ SUBATECH:

- MC@sHQ calculation with latest EPOS3 initial conditions
- Spatial diffusion coefficient: $2\pi T \times D = 2\text{-}4$
- Describe the both v_2 and R_{AA} data well.

Guannan Xie @HF(I)

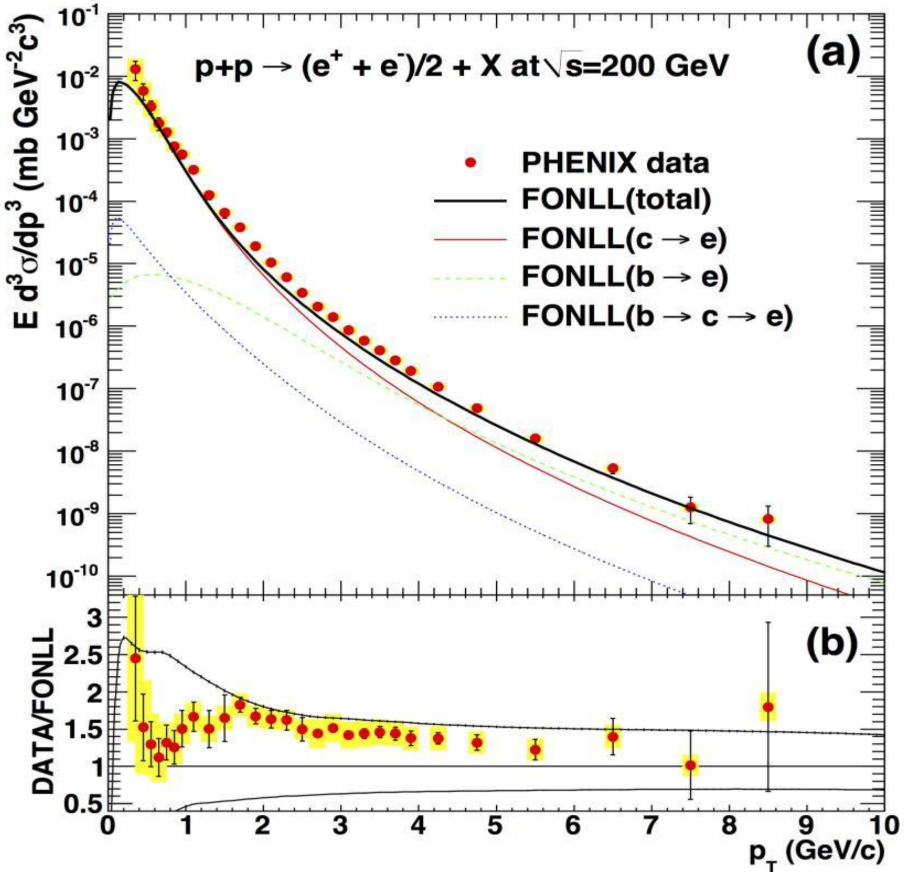
Data/MC Comparison of D^0 Measurments

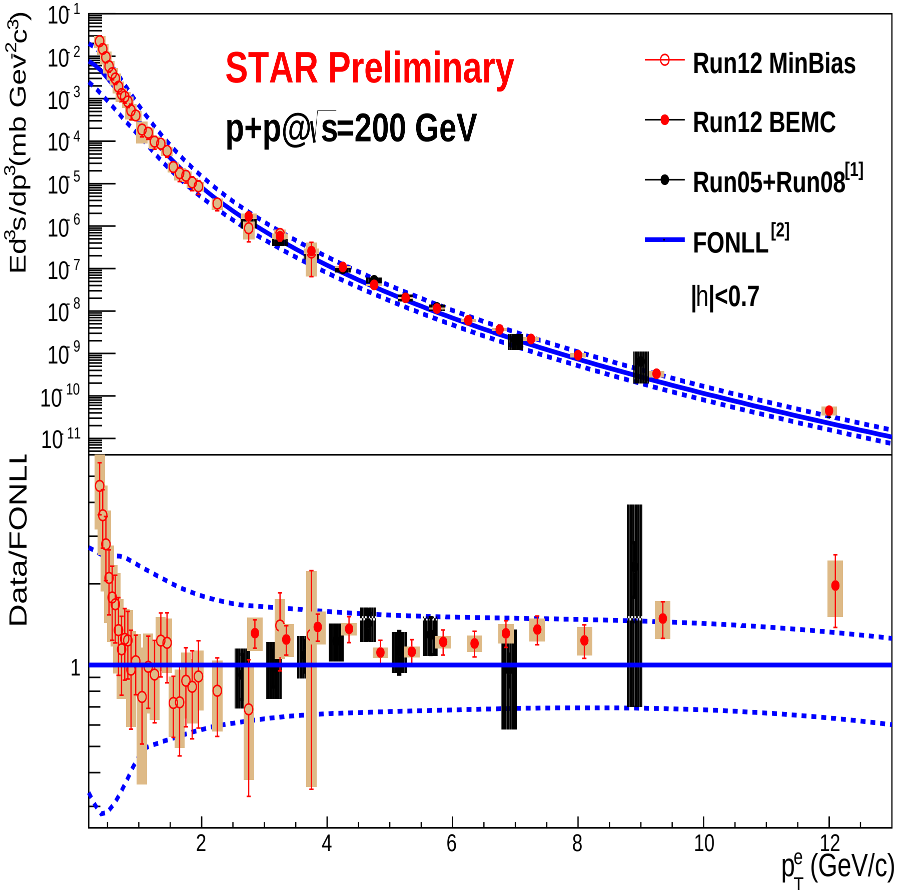




- DUKE
  - A Linearized Boltzmann Transport Model
  - Spatial diffusion coefficient: $2\pi T \times D = 7$ from fitting to LHC results
  - Describe v_2 well, underestimate v_2.

HF→e Production in p+p Collisions



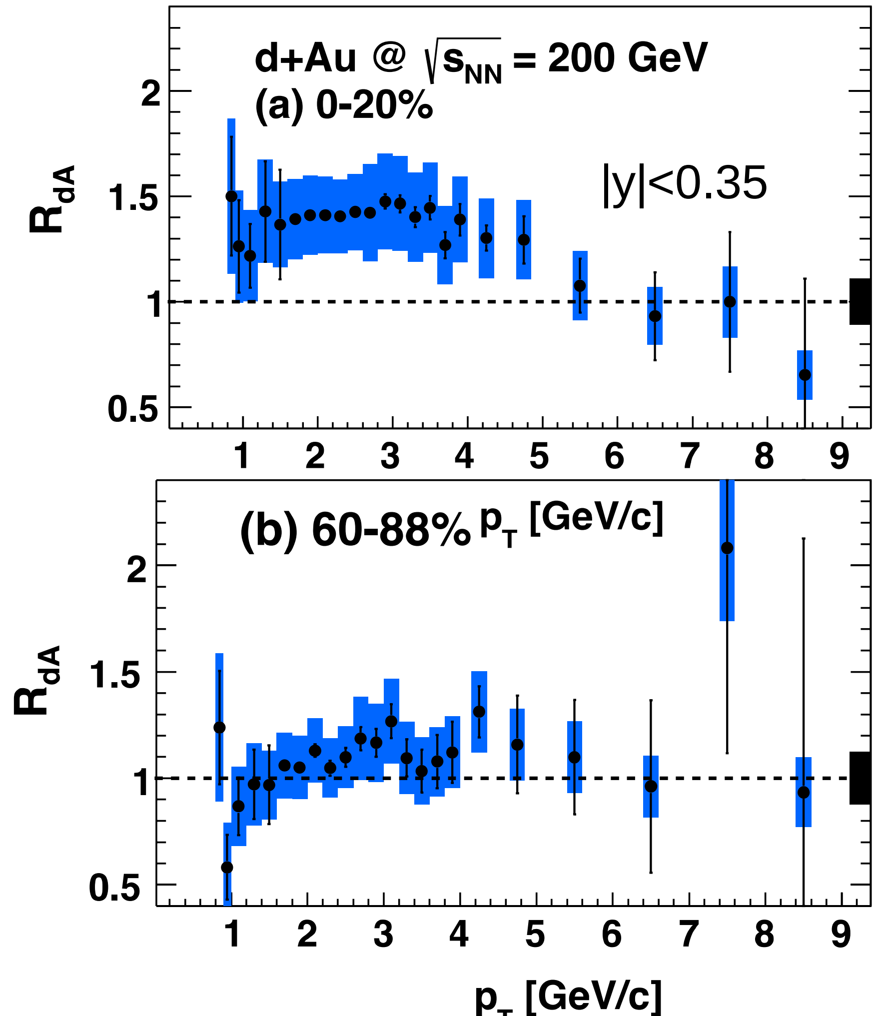


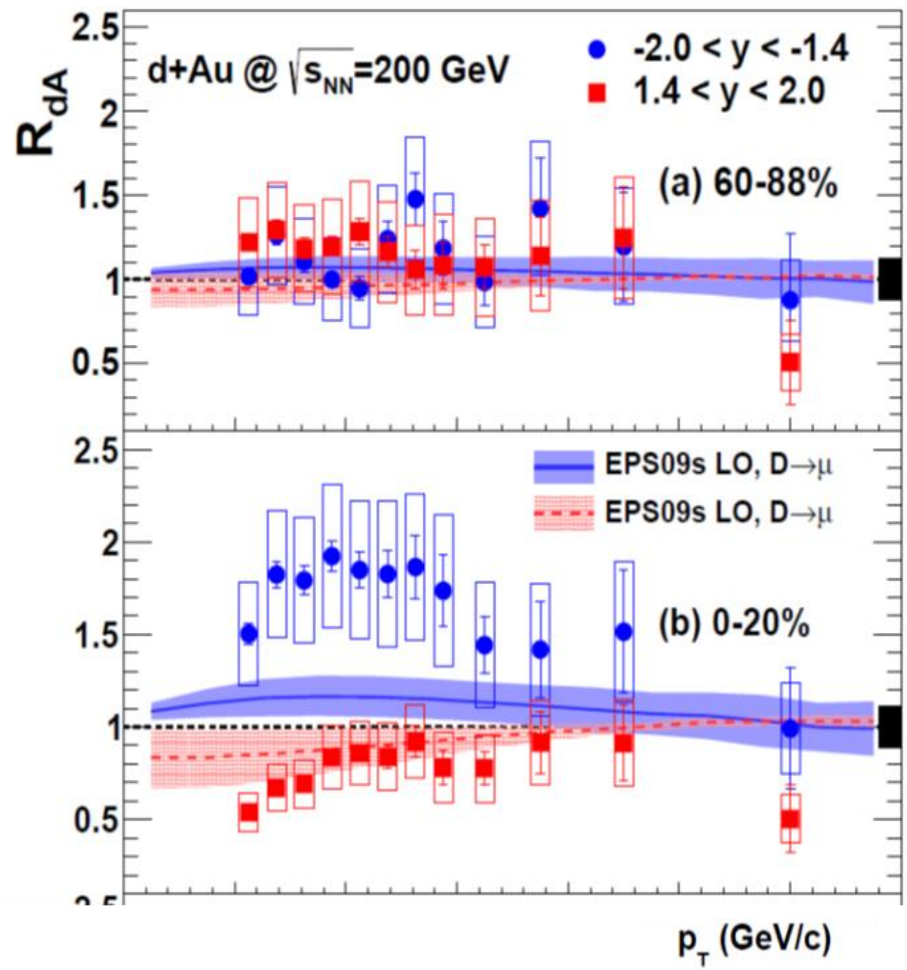
- FONLL can describe well the HF→e production in p+p collisions
  - As for the directly reconstructed D and B meson.

PHENIX: PRC 84, 044905 (2011)

Yaping Wang@HF(IV)

HF→e Production in d+Au Collisions





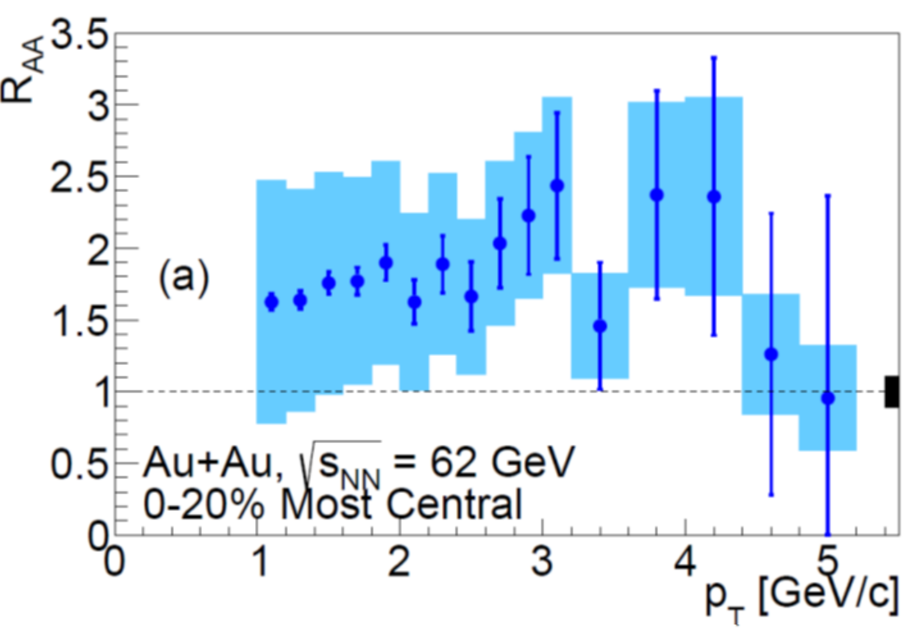
- ❑ Significant enhancement in 0-20%
  - |y|<0.35
  - -2.0<y<-1.4 (Au-going)

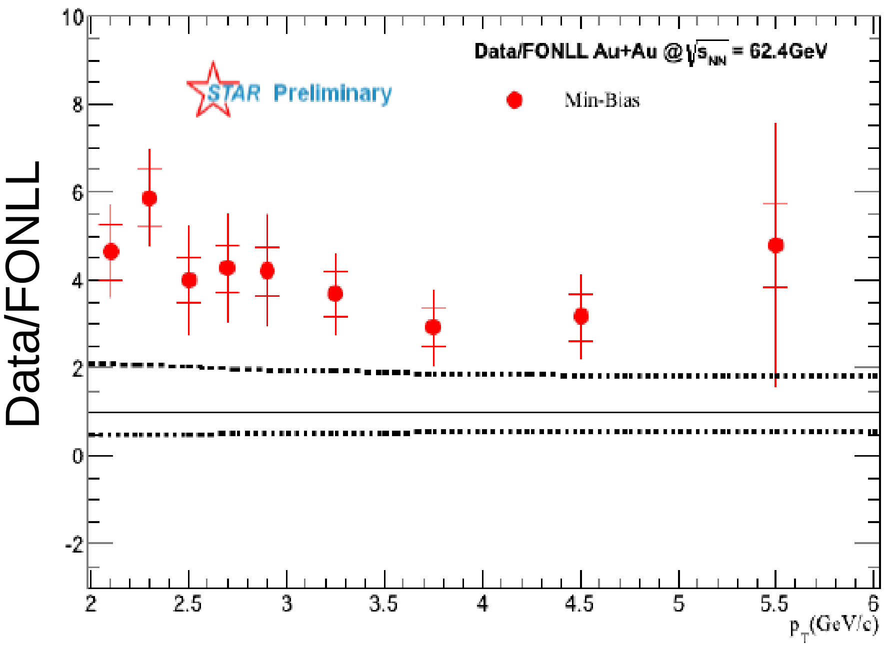
- ❑ $R_{AA} \approx 1.0$ in 60-88% for |y|<0.35
- ❑ Significant suppression in 0-20%
  - 1.4 < y< 2.0 (d-going)

PHENIX: PRL109, 242301 (2012)

PHENIX: PRL 112, 252301(2014)

HF→e Enhancement at 62.4 GeV





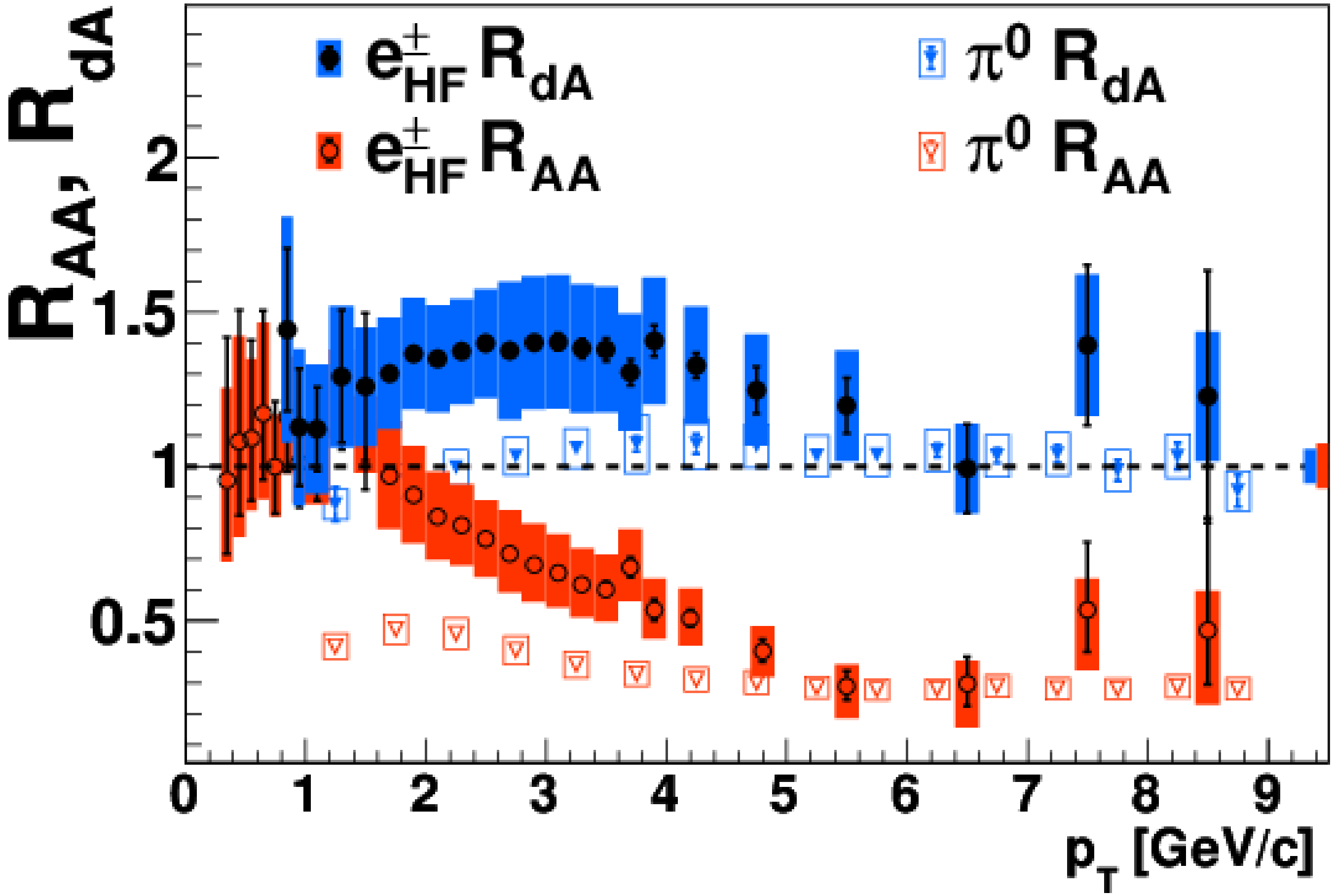
- ❑ Reference from ISR HF→e
  - well described by FONLL.
- ❑ Indication of "enhancement"

- ❑ 62.4 GeV pp well described by FONLL. NC A 65, 421 (1981).
- ❑ Indication of "enhancement"

Radial flow and/or CNM enhancement compensate suppression at lower energy?

PHENIX: PRC 91, 044907 (2015) *STAR:* NPA904,905, 665c(2013)

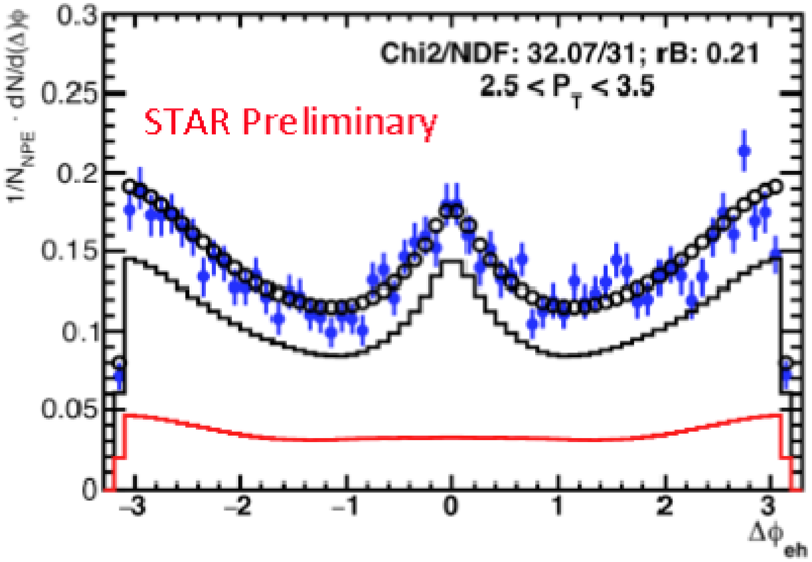
Production of HF→e in Au+Au Collisions

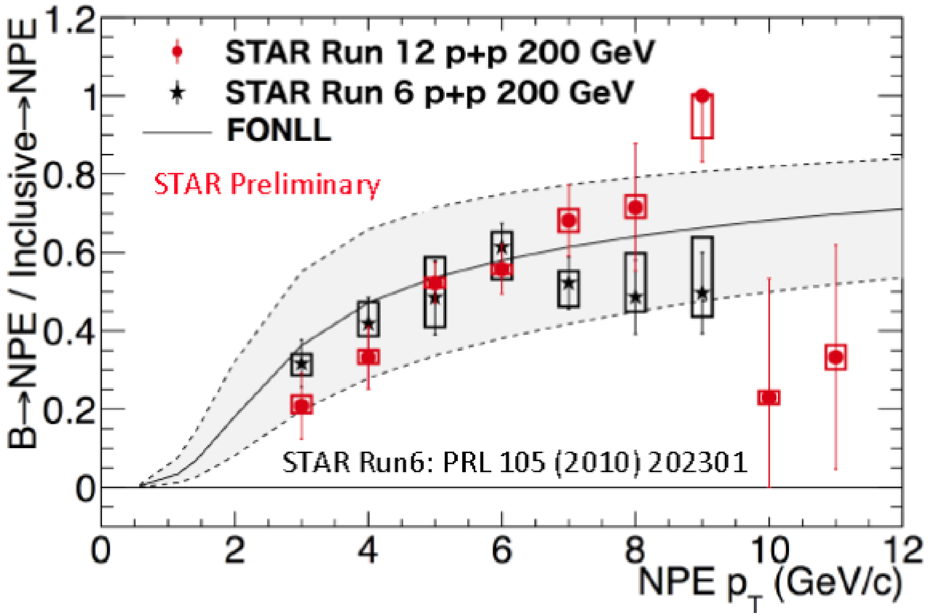


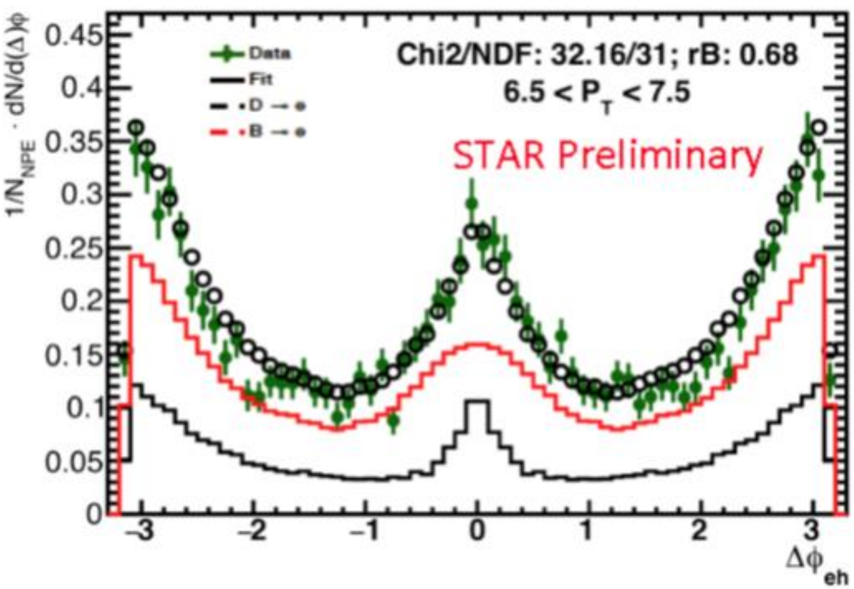
- Large Suppression of HF→e production at high p_T
- R_{AA} (HF→e) ≈ $R_{AA}(\pi^0)$ for p_T > ~5 GeV/c
  - *similar in the case of D^0 production*
- R_{AA} (HF→e) > $R_{AA}(\pi^0)$ for p_T =1- 5 GeV/c
- Large CNM effect observed
  - *(at least) partially responsible for the difference.*
- HF→e = D→e + B→e
  - **What about the mass-dependent R_{AA}?**

PHENIX: PRC 84, 044905 (2011)

B→e is significant in HF→e

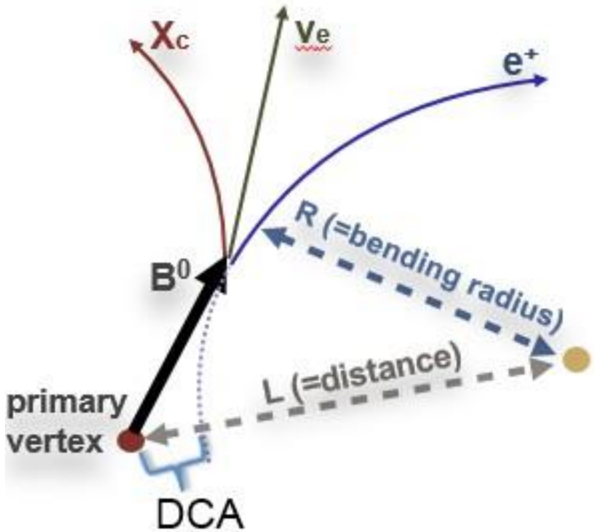


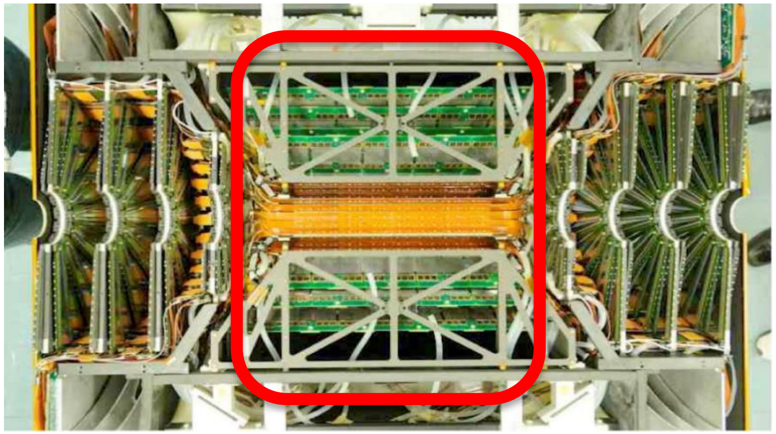


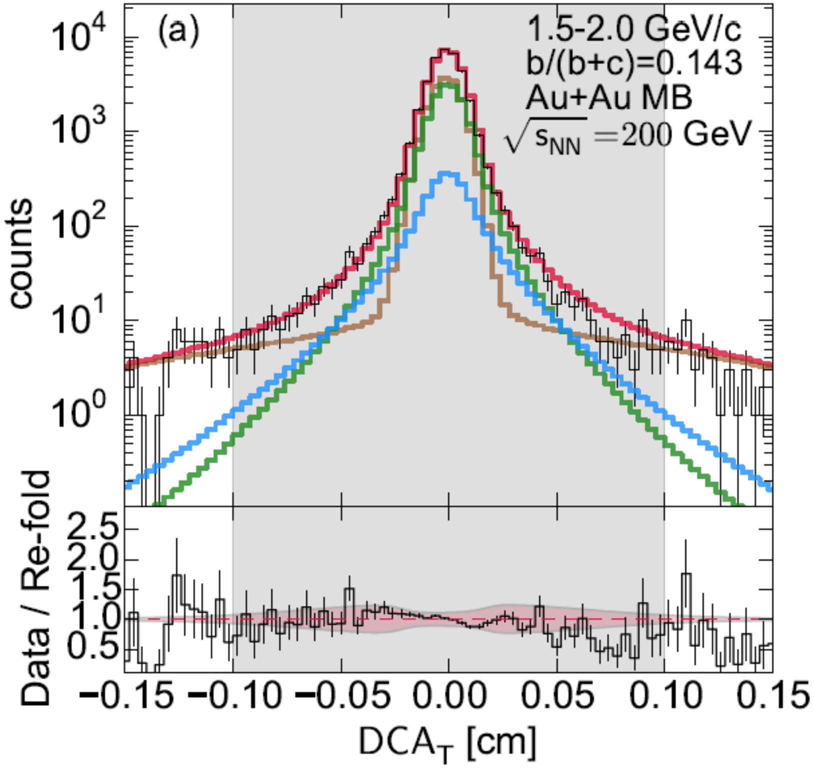


- $\Delta\phi_{e-h} = r_B \Delta\phi_{e-h}^{B} + (1 - r_B)\, \Delta\phi_{e-h}^{D}$, $r_B = (B \rightarrow e)/(D \rightarrow e + B \rightarrow e)$
- Wider $\Delta\phi$ distribution for B→e because of the larger mass.
- Combined fit on data to obtain the B→e contribution to HF→e.
- **r_B > 20% for p_T(e) > 2 GeV/c**

Disentangle B→e from D→e in Au+Au





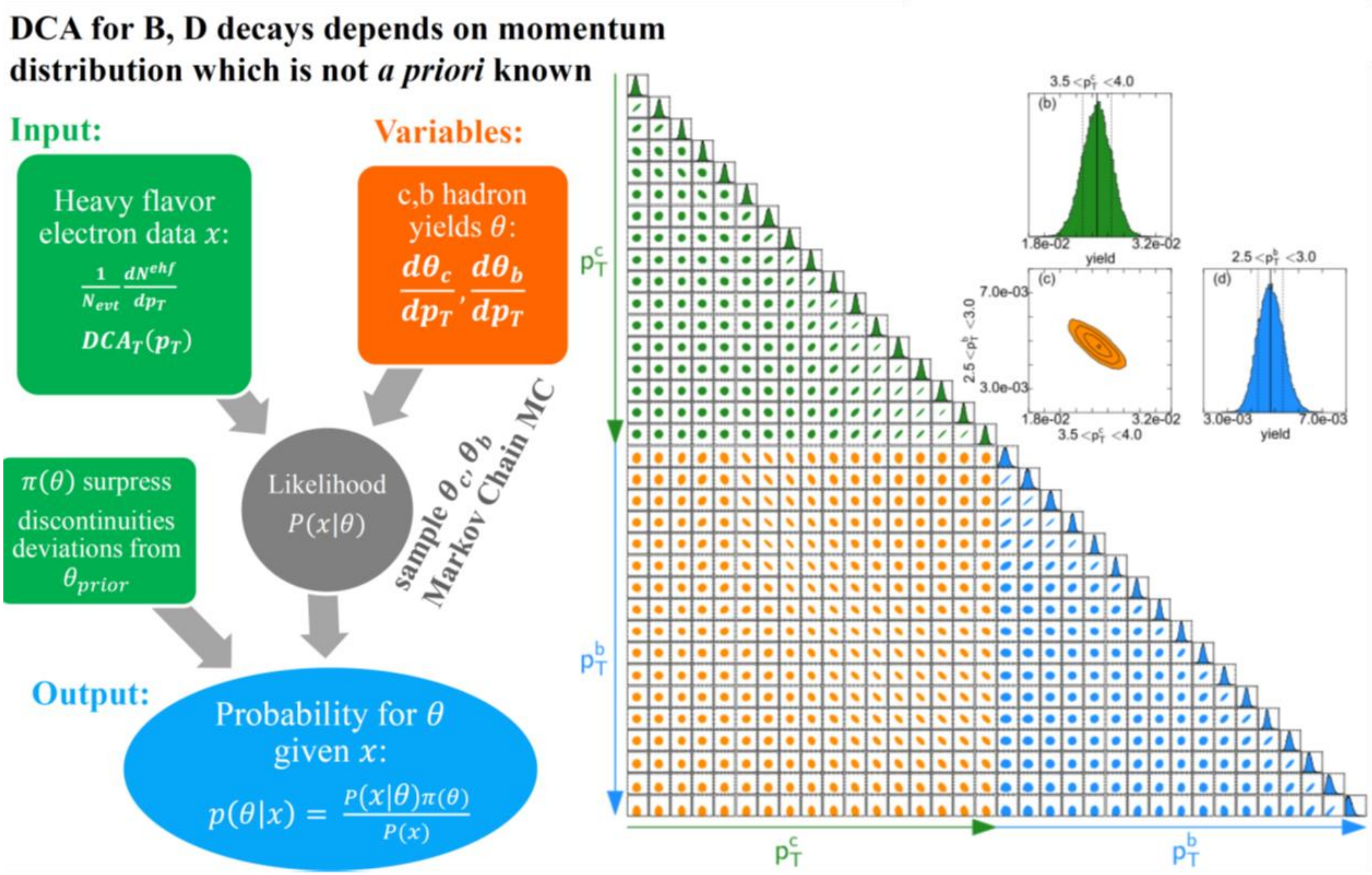


- **Electrons from background**
  - Dalitz+convernsion+J/ψ→e + Ke3 +hadron misPID + VTX hits misAssocition.
- **D→e and B→e from D, B spectra through an unfolding procedure.**

PHENIX: PRC 93, 034904 (2016)

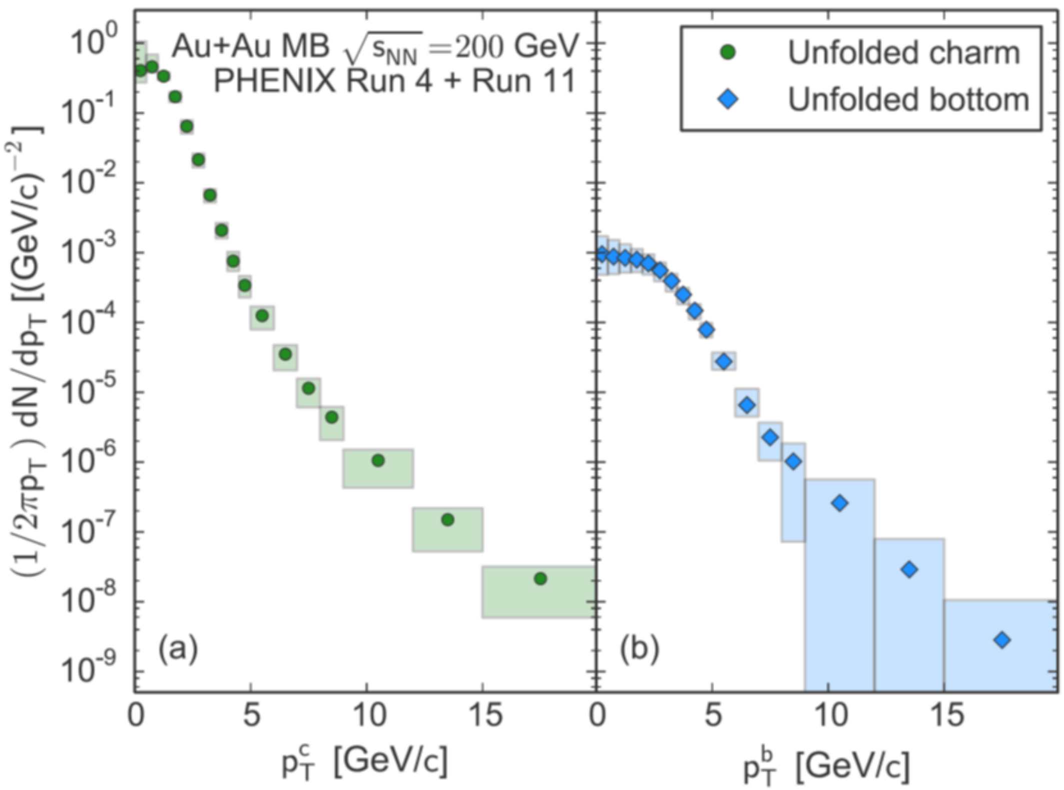
Unfolding D and B hadron Spectra

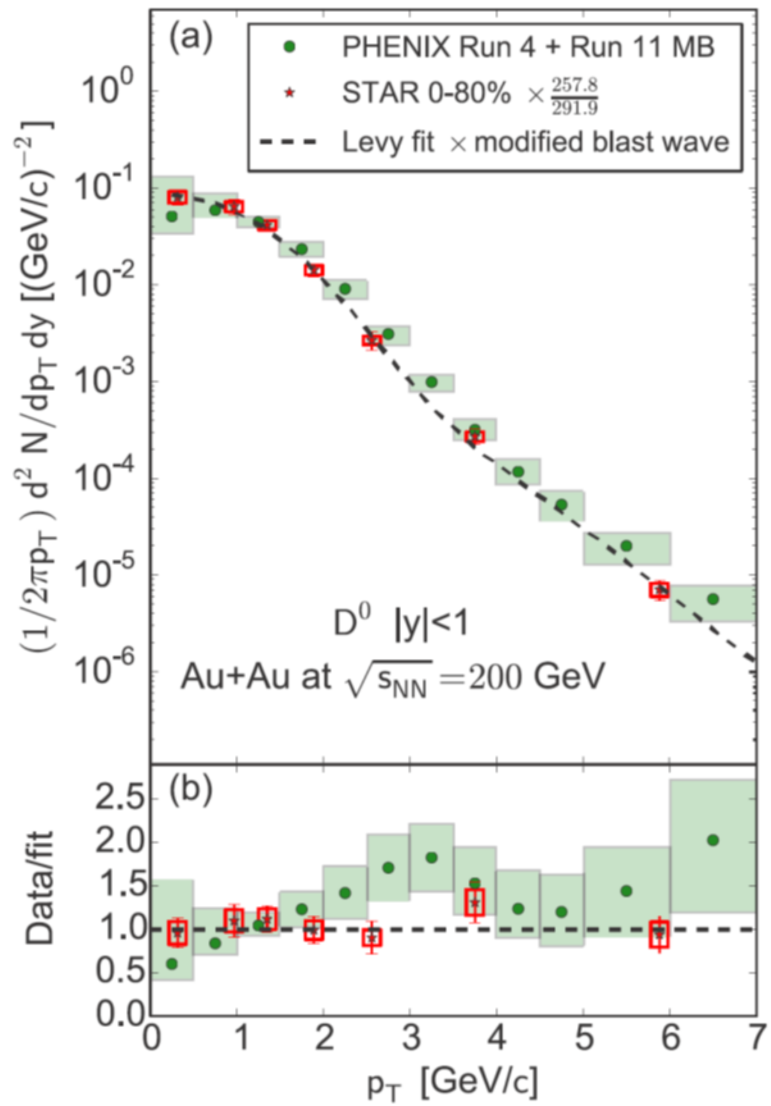
From A. Dree: QM2015 PHENIX highlight



PHENIX: PRC 93, 034904 (2016)

Unfolding D and B hadron Spectra

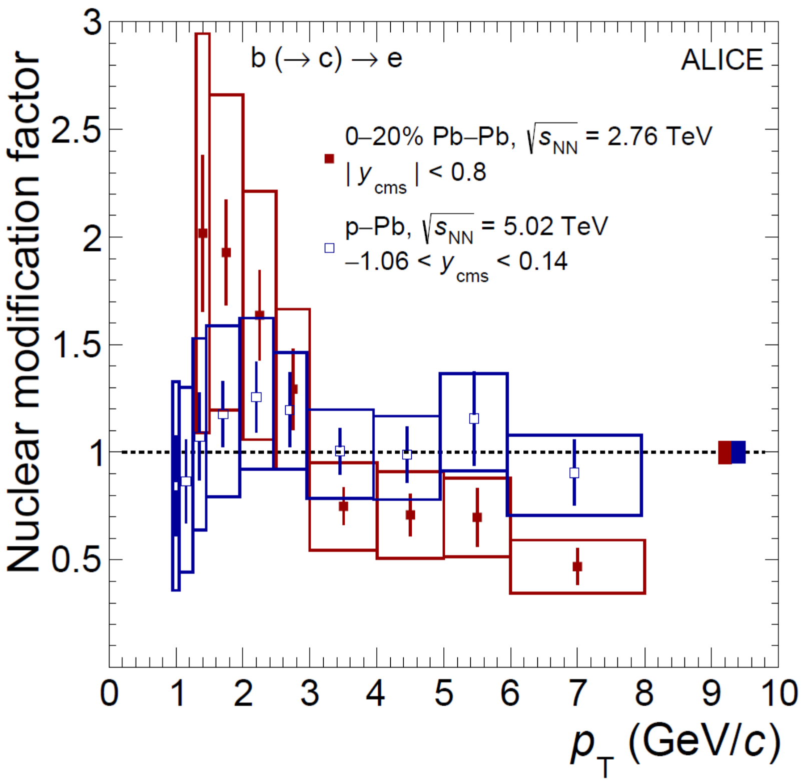


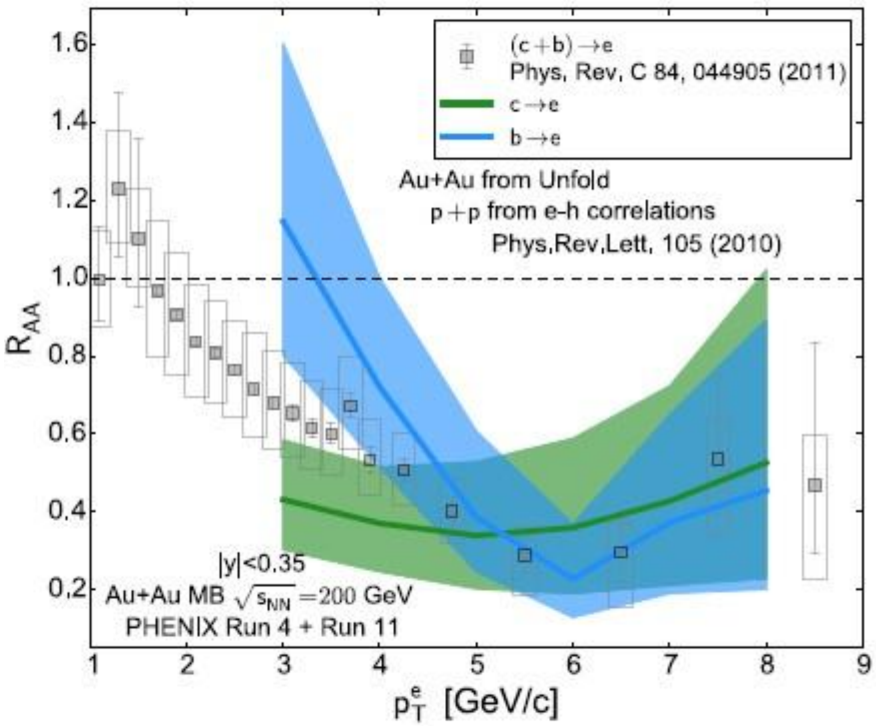


- ❑ D^0 p_T spectra is obtained from PYTHIA prediction on D^0 fraction.
- ❑ Unfolded D^0 spectra consistent with the STAR measurements.

PHENIX: PRC 93, 034904 (2016)

Separate D→e and B→e R_{AA}





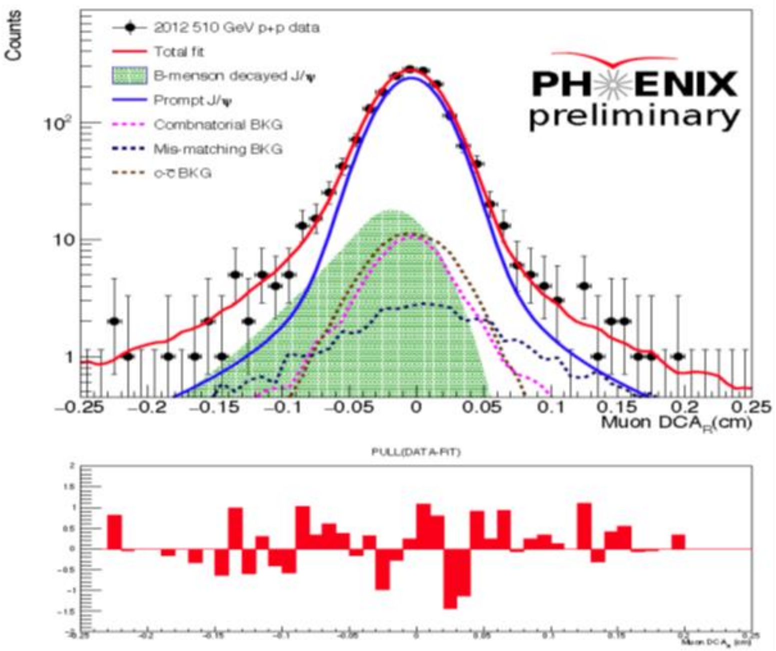
$$R_{AA}^{c\to e} = \frac{(1-F_{AuAu})}{(1-F_{pp})} R_{AA}^{HF}$$

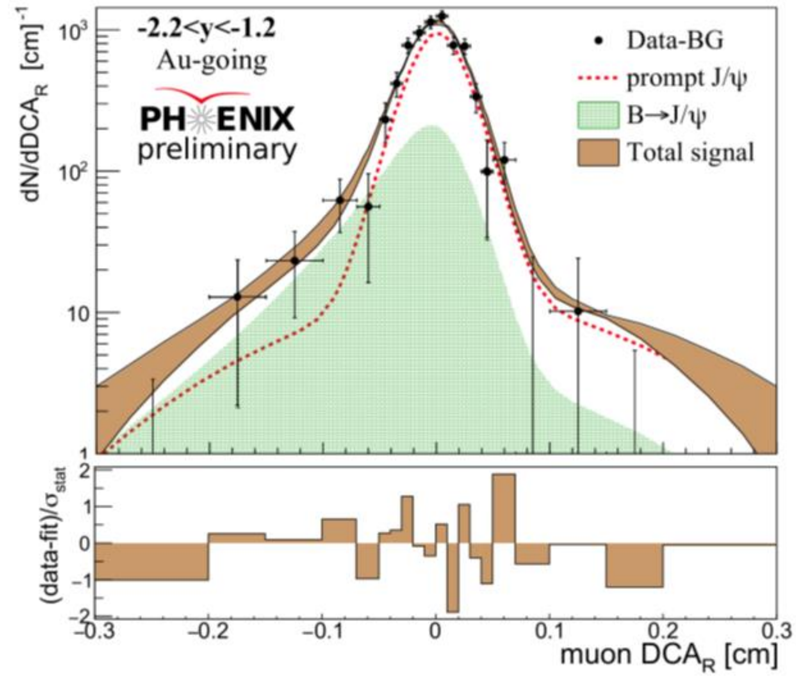
$$R_{AA}^{b\to e} = \frac{F_{AuAu}}{F_{pp}} R_{AA}^{HF},$$

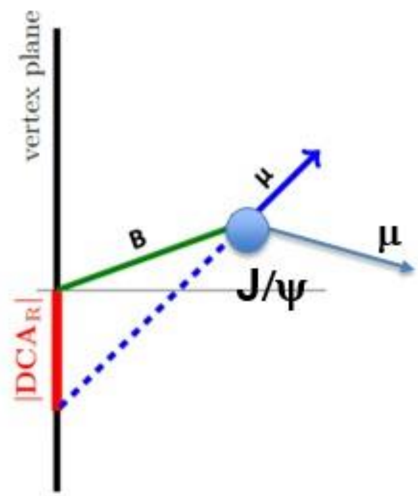
PHENIX: PRC 93, 034904 (2016)

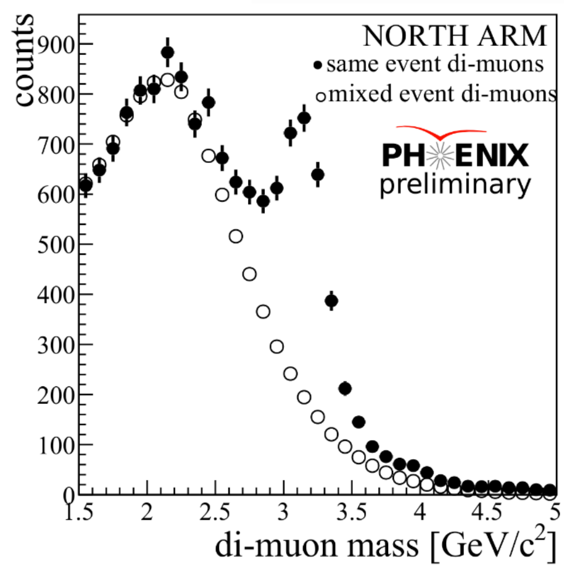
- Hint of R_{AA} (B→e) > R_{AA}(D→e) for p_T < 4 GeV/c
- Suggest the different in shape between R_{AA} (HF→e) and $R_{AA}(\pi^0)$ is mostly a mass effect.
- Similar dependence of R_{AA} (B→e) vs. p_T is observed in at LHC

Disentangle B→J/ψ from prompt J/ψ



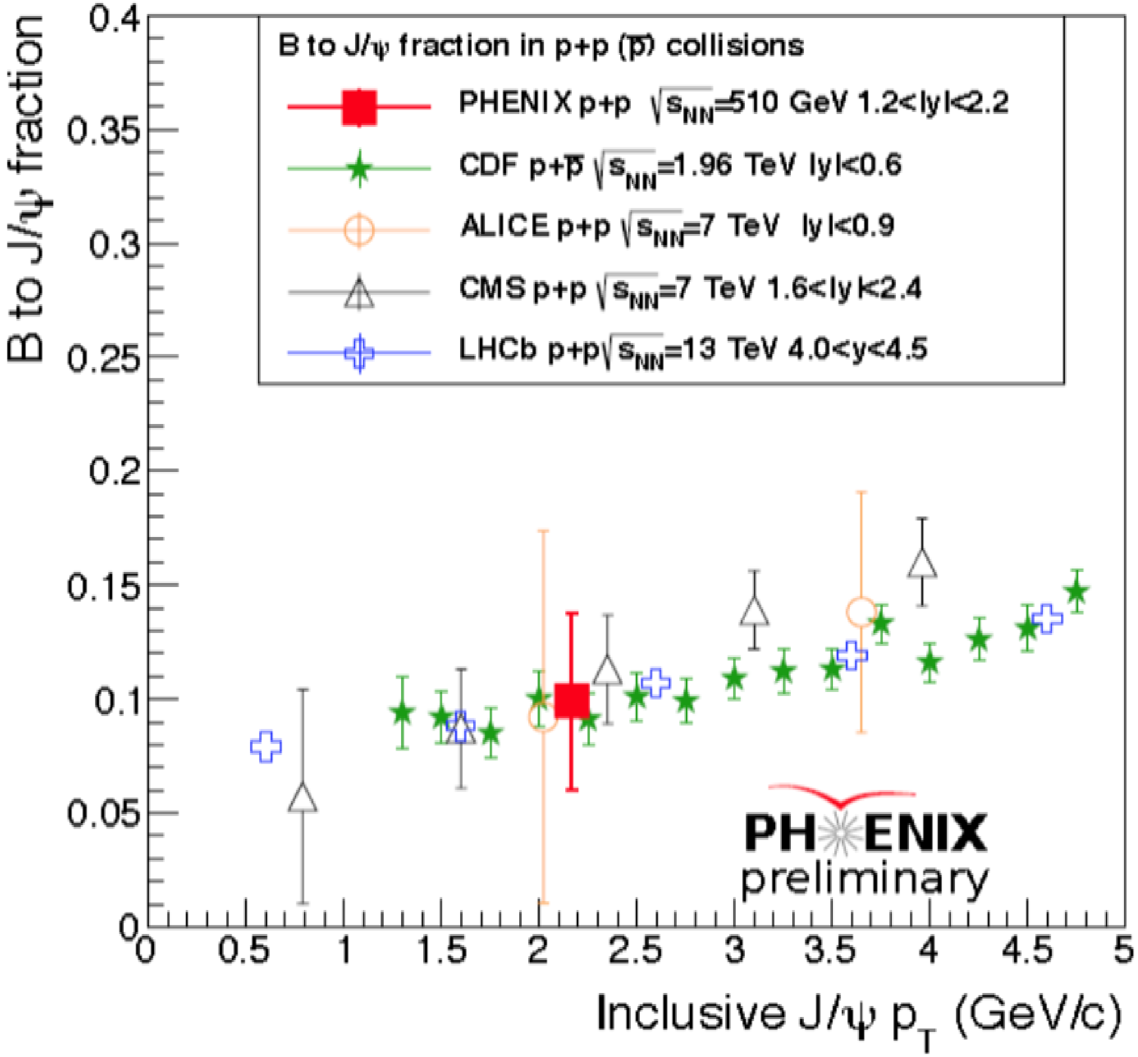






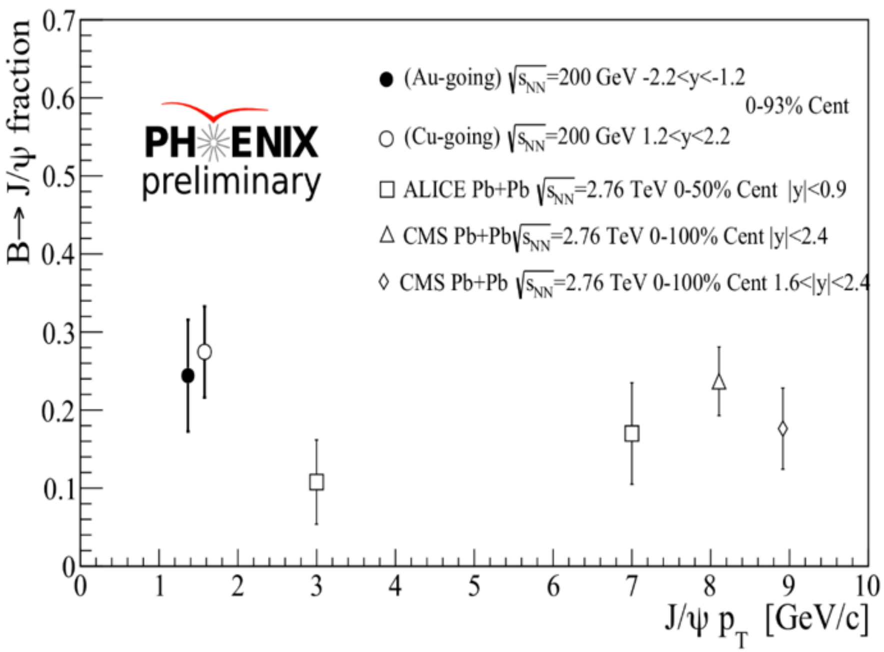
- MC template on B→J/ψ→μμ and prompt J/ψ→μμ.
- Large difference in shape between the templates.

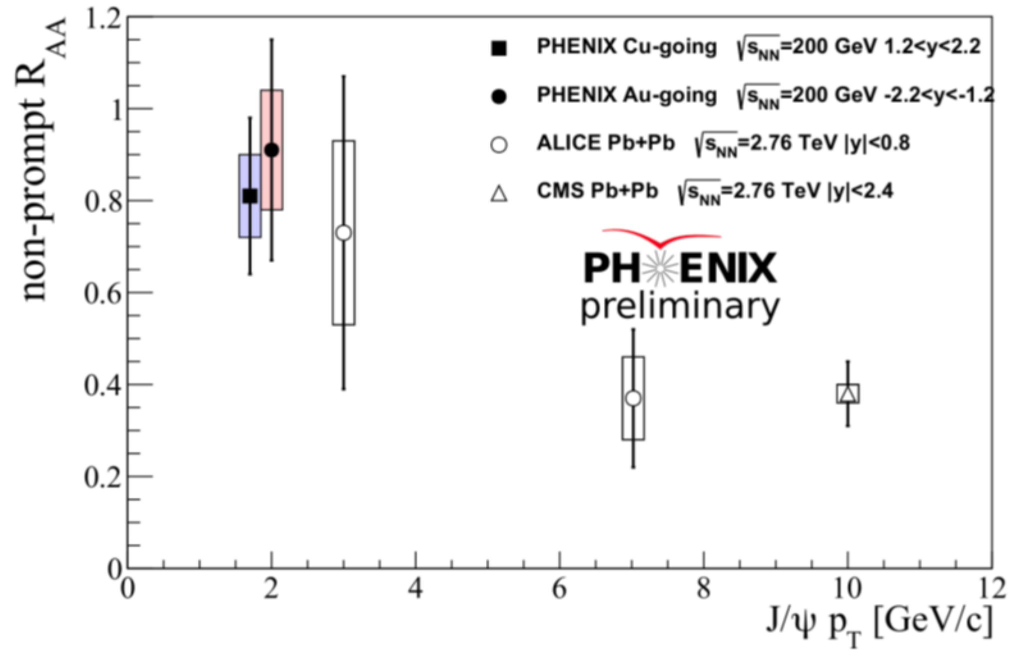
B→J/ψ in pp at 510 GeV



- No large collisions energy dependence for B→J/ψ fraction within uncertainties
- One **may assume** B→J/ψ fraction ~ 0.1 for p_T = 1-2 GeV/c in pp at 200 GeV

B→J/ψ R_{AA} in Cu+Au at 200 GeV

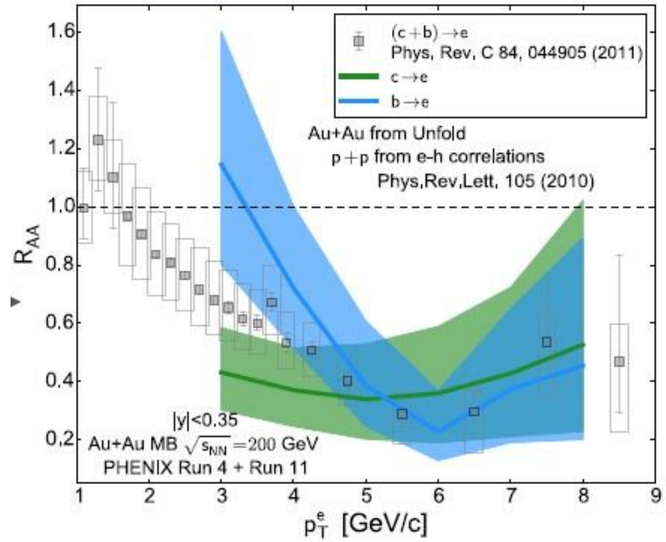




- Hint of larger B→J/ψ fraction in Cu+Au than p+p at 200 GeV
- **Assuming** B→J/ψ fraction = 0.1 at 200 GeV

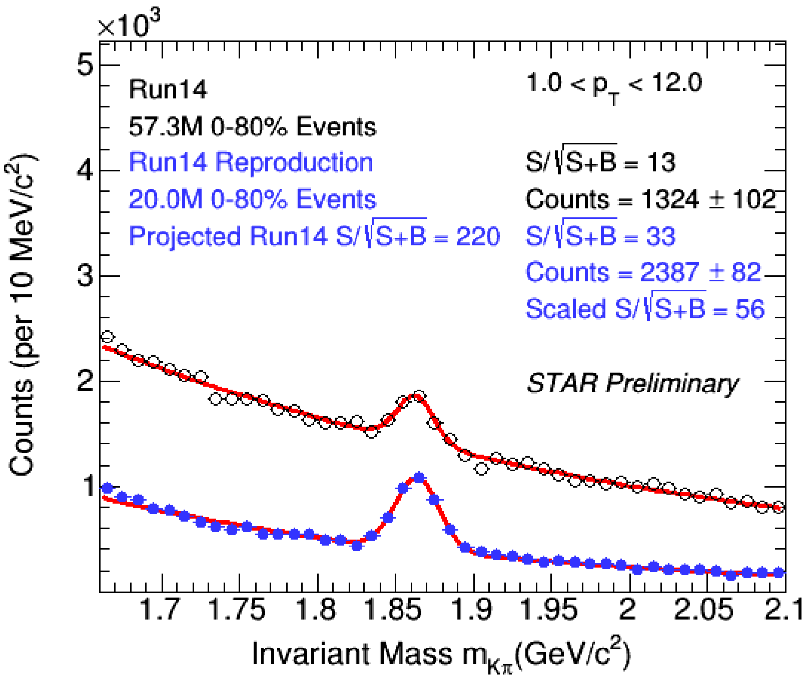
$$R_{CuAu}^{B\rightarrow J/\psi} = \frac{F_{CuAu}^{B\rightarrow J/\psi}}{F_{CuAu}^{B\rightarrow J/\psi}} R_{CuAu}^{inc.\, J/\psi}$$

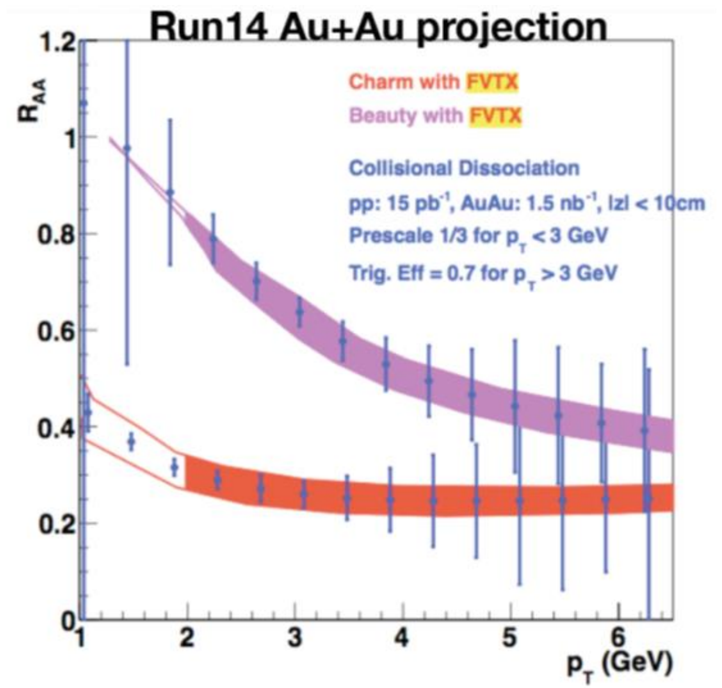
- Consistent with the large B→e R_{AA} at low p_T



Cesar Luiz @HF(II)

Expectations in the Near Future.





- **STAR**: Run14 (reproduction) + Run16 = 10 – 30 × Run14 (presented)
- **PHENIX**: Run14 + Run16 ≈ 30× Run14 (presented)
- List of expected measurements from the near future:
  - Precise R_{AA} of B→e, D→e, B→J/ψ
  - Precise D^0 v_2 in different centrality bin and good v_3.
  - First Λ_c in Au+Au collisions.

Guannan Xie @HF(I) Cesar Luiz @HF(II)

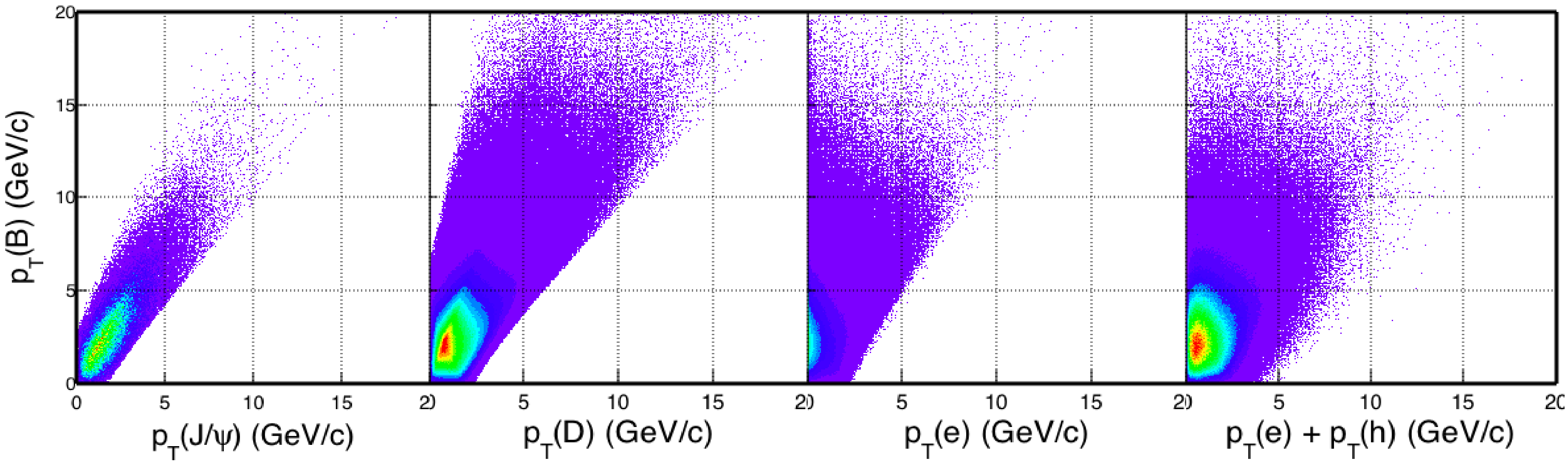
Summary

- **FONLL describe well the HF production in pp collisions from 62 GeV – 13 TeV.**
- **Large enhancement of HF→e observed in d+Au collision**
  - *CNM or/and small system sQGP effect?*
- **Indication of enhancement of HF→e in 62.4 GeV/c Au+Au collisions.**
  - *CNM or/and sQGP effect?*
- **Enhancement of D^0 production in intermediate p_T**
  - *Coalescence*
- **Large suppression of D^0 and HF→e at high p_T**
  - *Consistent with light hadrons.*
- **Indication of higher B→e/B→J/ψ R_{AA} than that of D→e R_{AA} at low p_T.**
  - *Mass ordering effect or/and p_T spectra.*
- **Significant D^0 v_2 as well as HF→e v_2 are observed.**
  - *More measurements in differential centrality bins.*

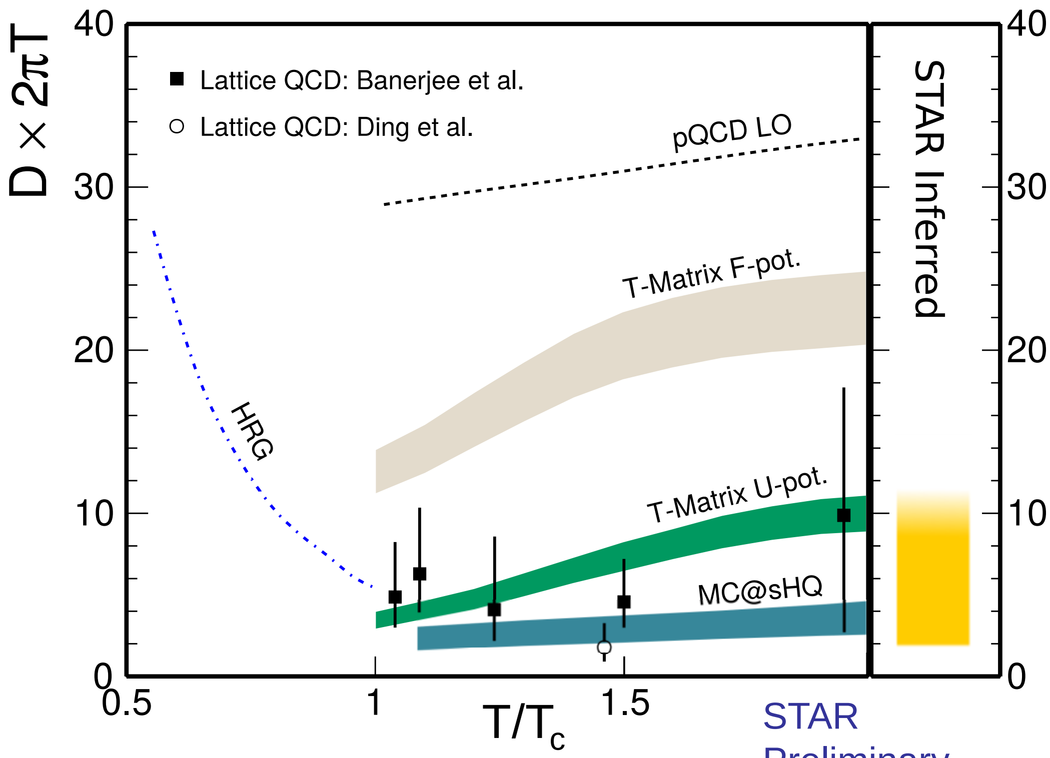
Expecting New and Precision Measurements Soon!

Backup

Kinematical correlation between B-decay daughters and B meson



Diffusion Coefficient



- D^0 v_2 and R_{AA} can be described by models with values of 2πTxD between 2 and ~12
- Lattice calculations, although with large uncertainties, are consistent with values inferred from data
- Differences between models need to be resolved

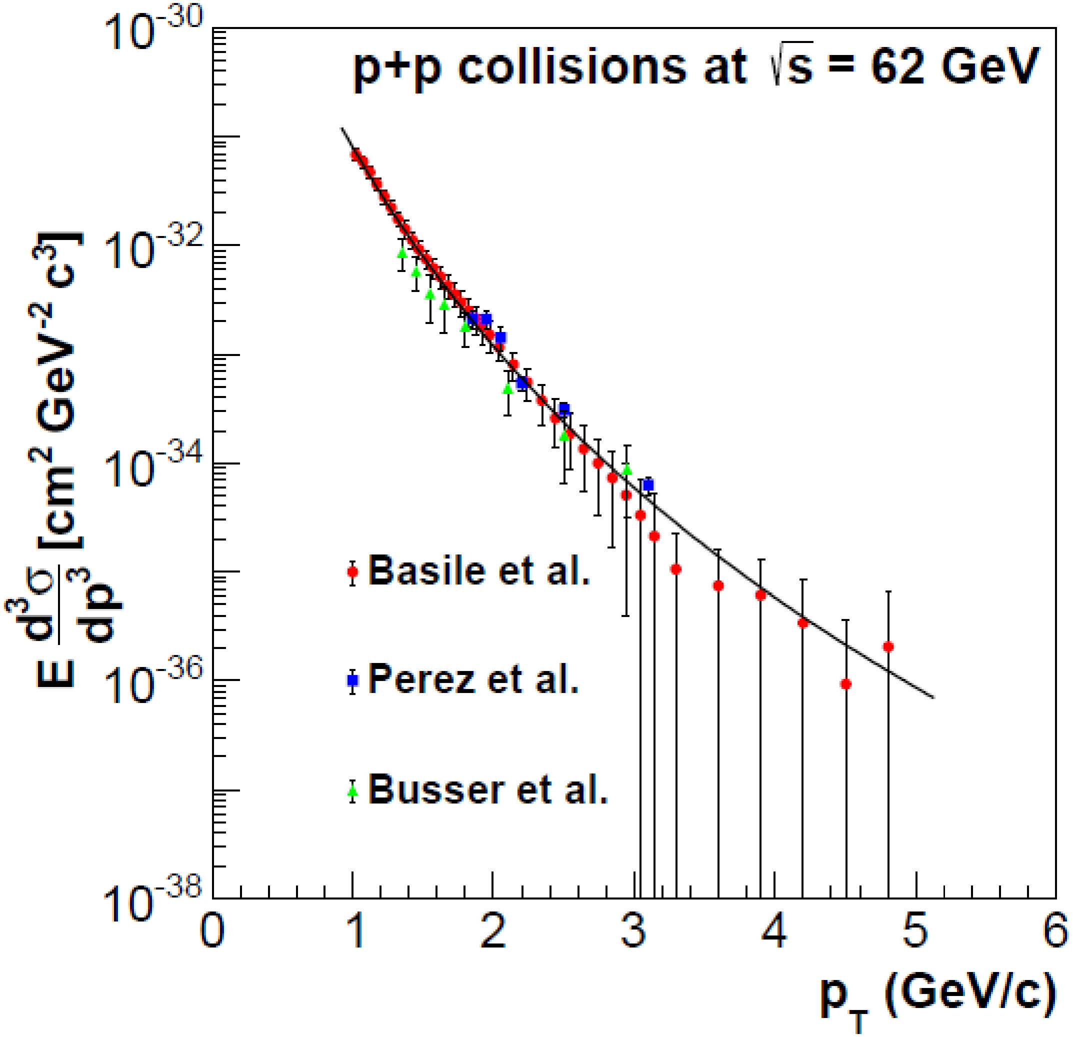
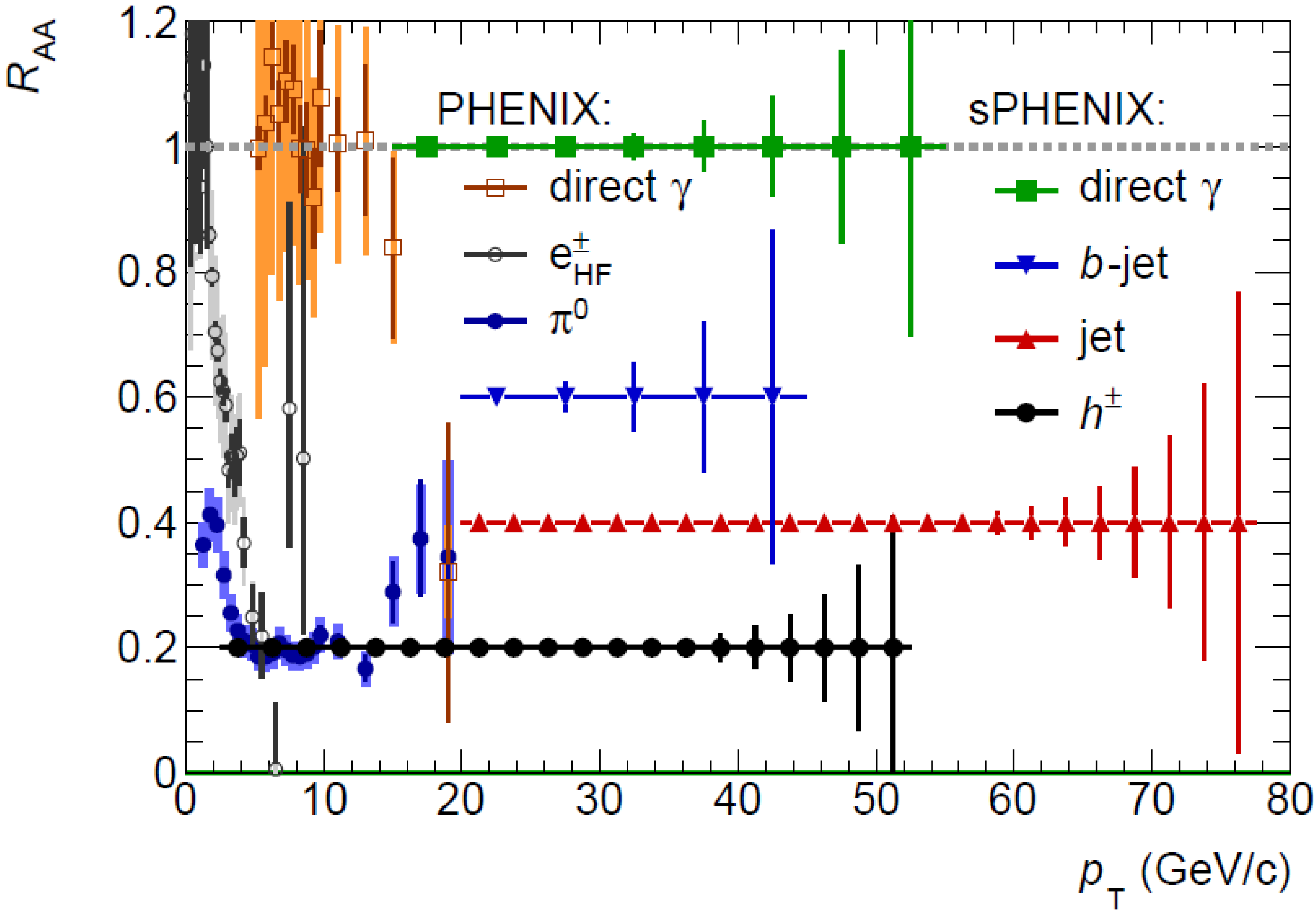
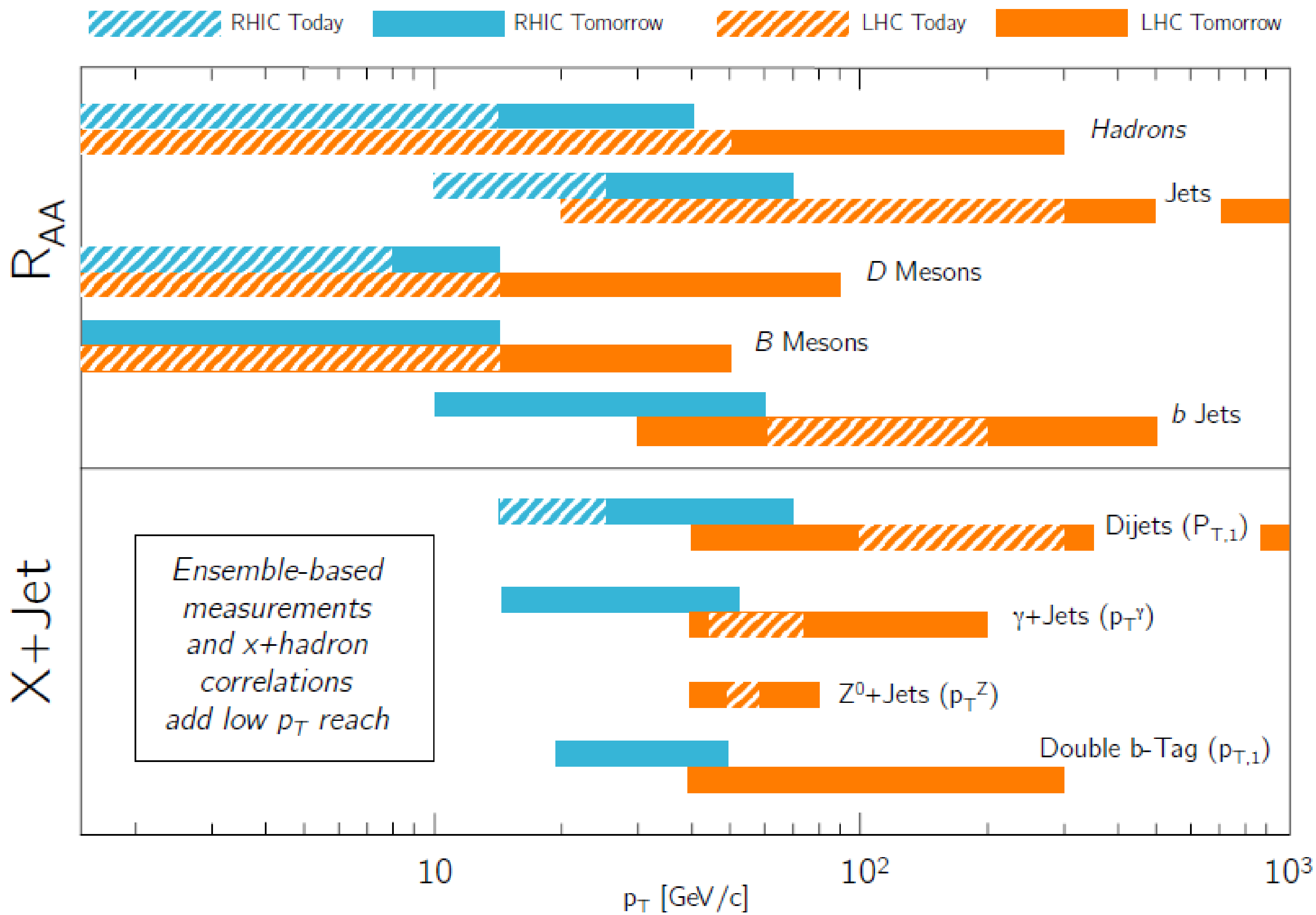


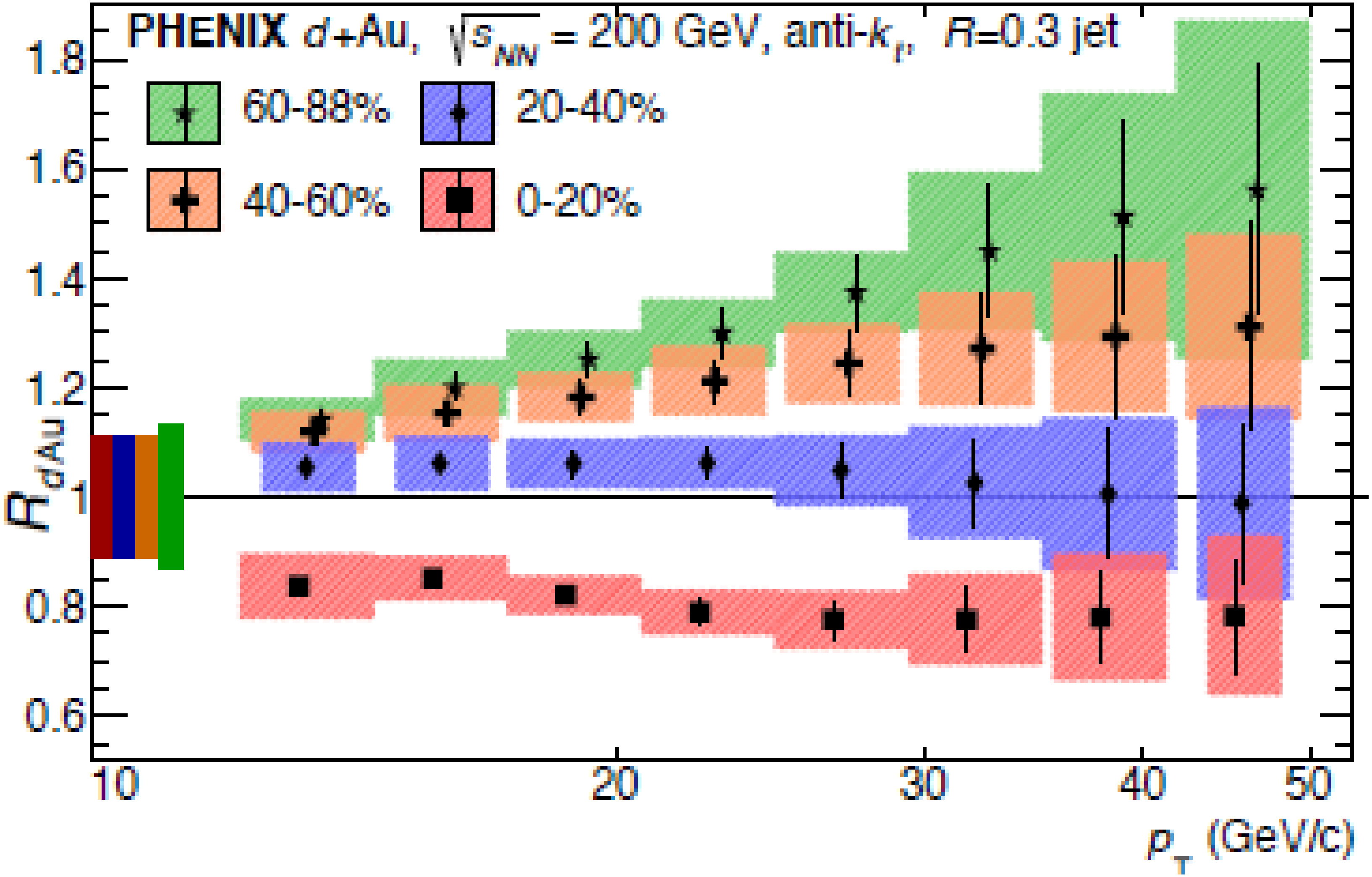
FIG. 13. (Color online) Invariant cross section of heavy-flavor electrons in p+p collisions at $\sqrt{s_{NN}} = 62.4$ GeV [38–40]. The curve is a combined power-law fit (see Table III.



Statistics uncertainty after 2 years of data taking.



RHIC Today
RHIC Tomorrow
LHC Today
LHC Tomorrow
R_{AA}
Hadrons
Jets
D Mesons
B Mesons
b Jets
X+Jet
Ensemble-based measurements and x+hadron correlations add low p_T reach
Dijets ($P_{T,1}$)
γ+Jets (p_T^{γ})
Z^0+Jets (p_T^Z)
Double b-Tag ($p_{T,1}$)
10
10^2
10^3
p_T [GeV/c]


PHENIX d+Au, $\sqrt{s_{NN}}$ = 200 GeV, anti-k_t, R=0.3 jet
60-88%
20-40%
40-60%
0-20%
R_{dAu}
1.8
1.6
1.4
1.2
1
0.8
0.6
10
20
30
40
50
p_T (GeV/c)