HEP 2013
Stockholm
18-24 July 2013
( info@eps-hep2013.eu )

# Open Charm Hadron Production in p+p and Au+Au collisions at STAR

David Tlusty

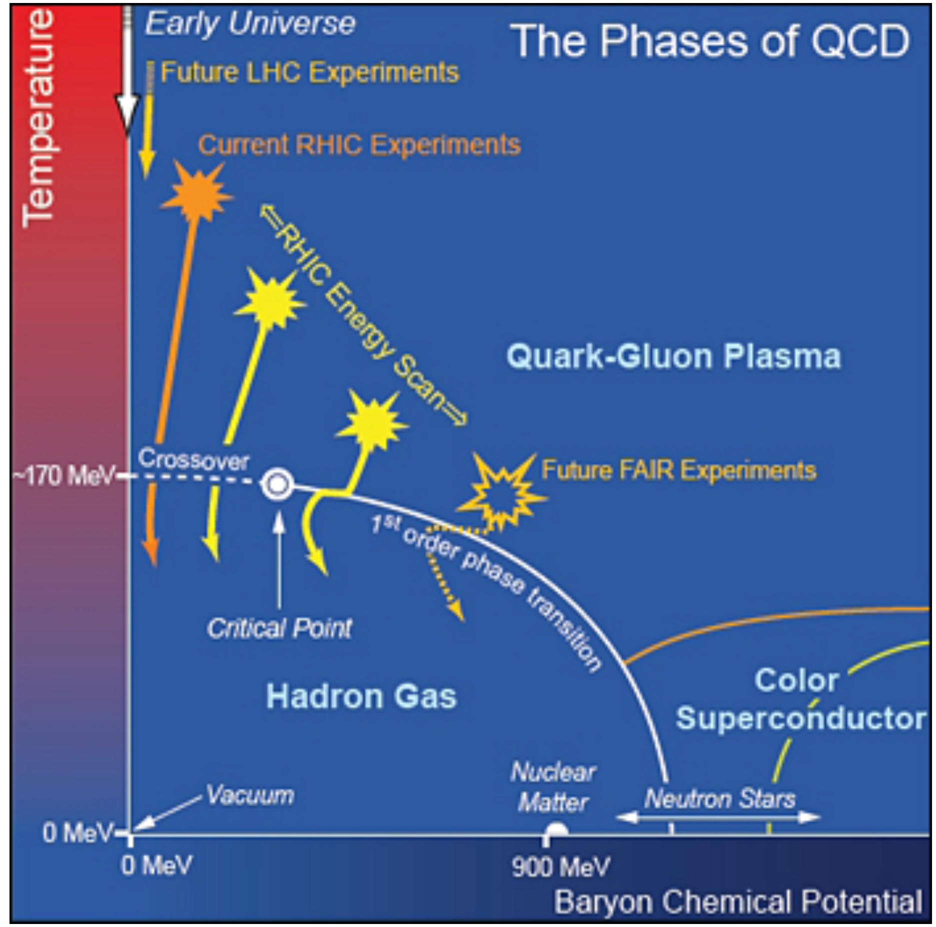
NPI ASCR, CTU Prague

for the STAR collaboration

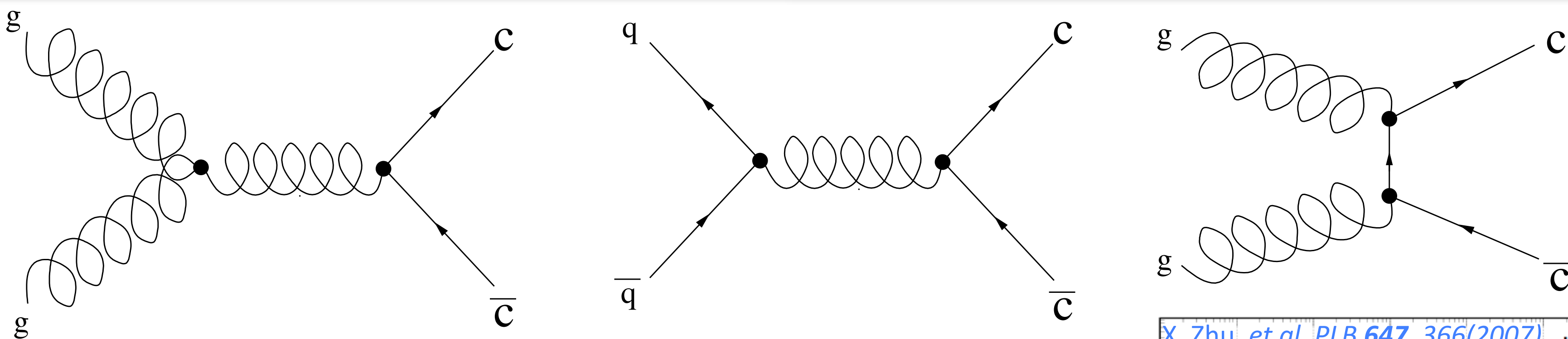
# Outline

1. Motivation
2. STAR detector and analysis
3. $D^0$ in Au+Au 200 GeV collisions
4. $D^0$ and D* in p+p 500 GeV collisions
5. Summary

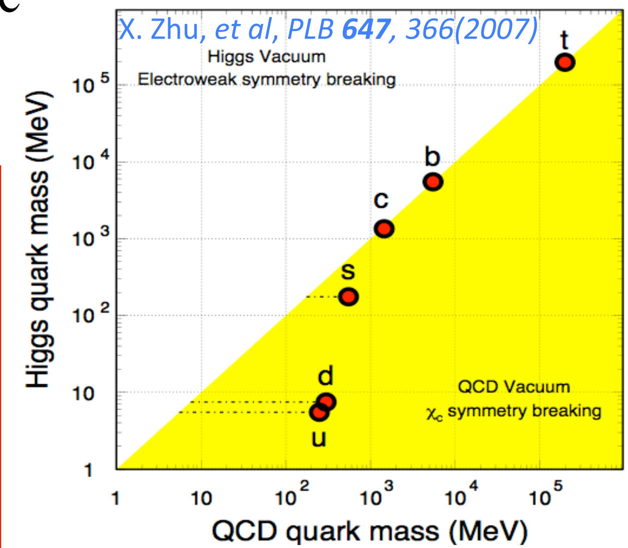
- Questions to be answered
    - Properties of the strongly-coupled system produced at RHIC, and how does it thermalize
    - weak or strong interactions of energetic partons with QCD matter?
    - detailed mechanism for partonic energy loss

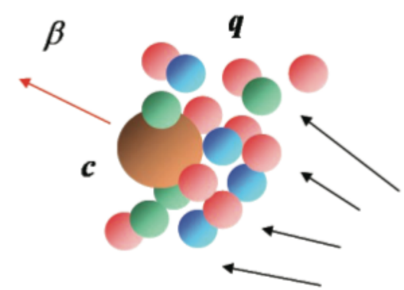


# Why to study heavy quarks

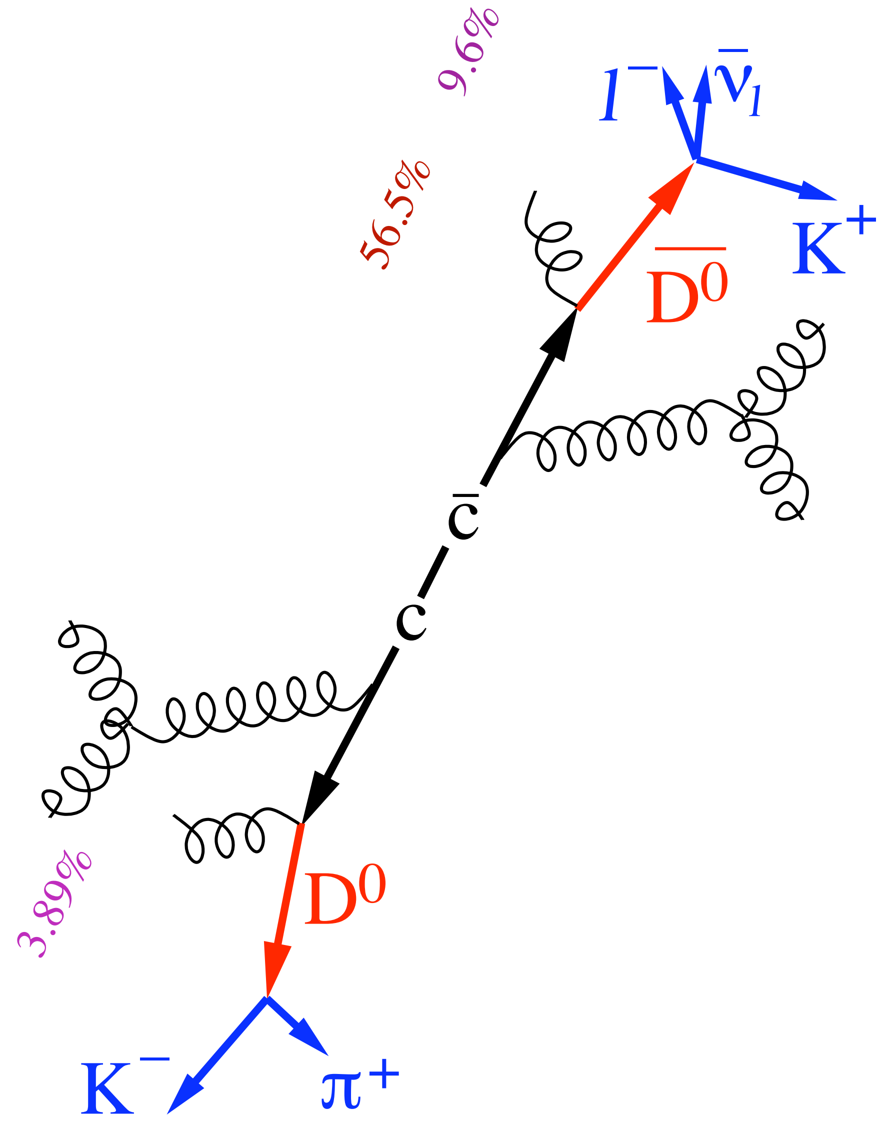



- Produced in initial hard partonic collisions (described well by pQCD) => $\sigma(c\bar{c})$ should follow number-of-binary-scaling
- Heavy quark mass not (significantly) modified in the QGP
- Reveal critical features of the medium



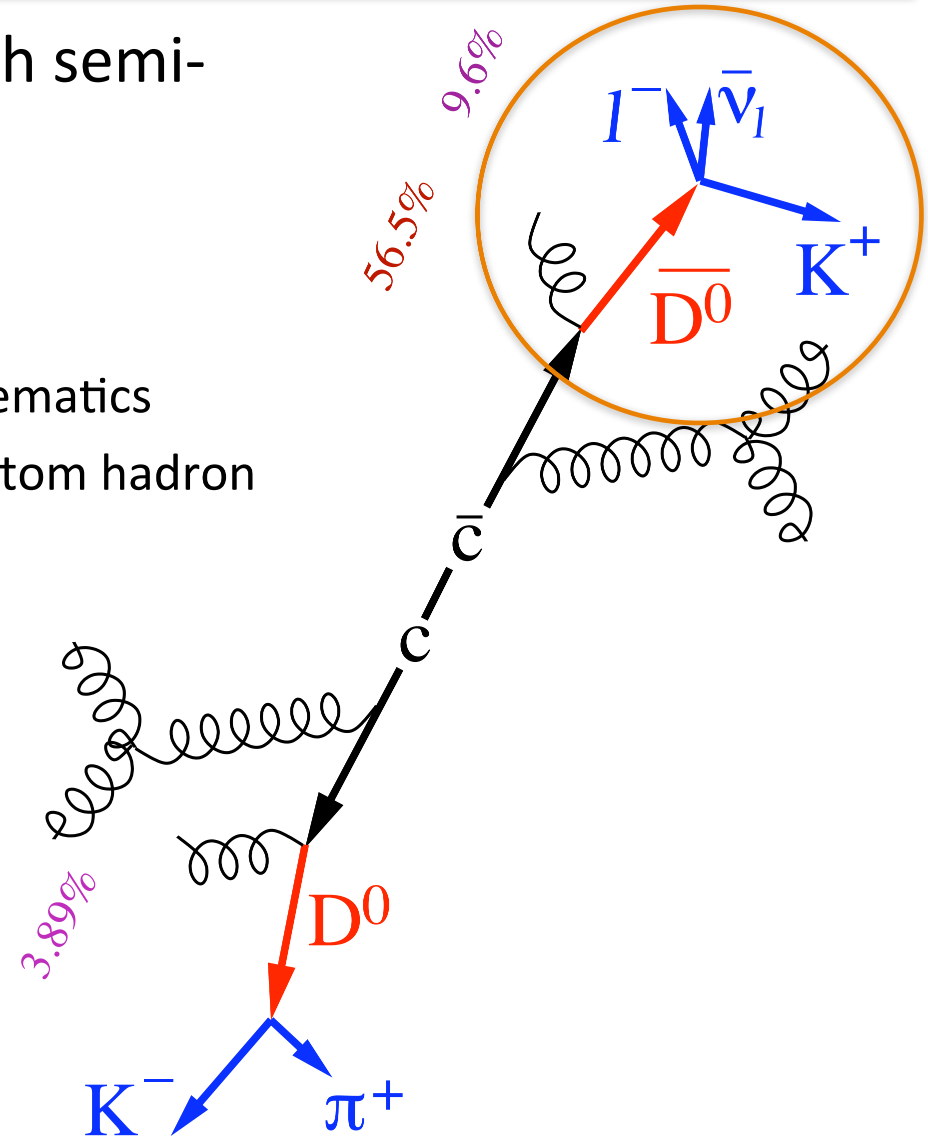



# How to Measure Charm Quarks



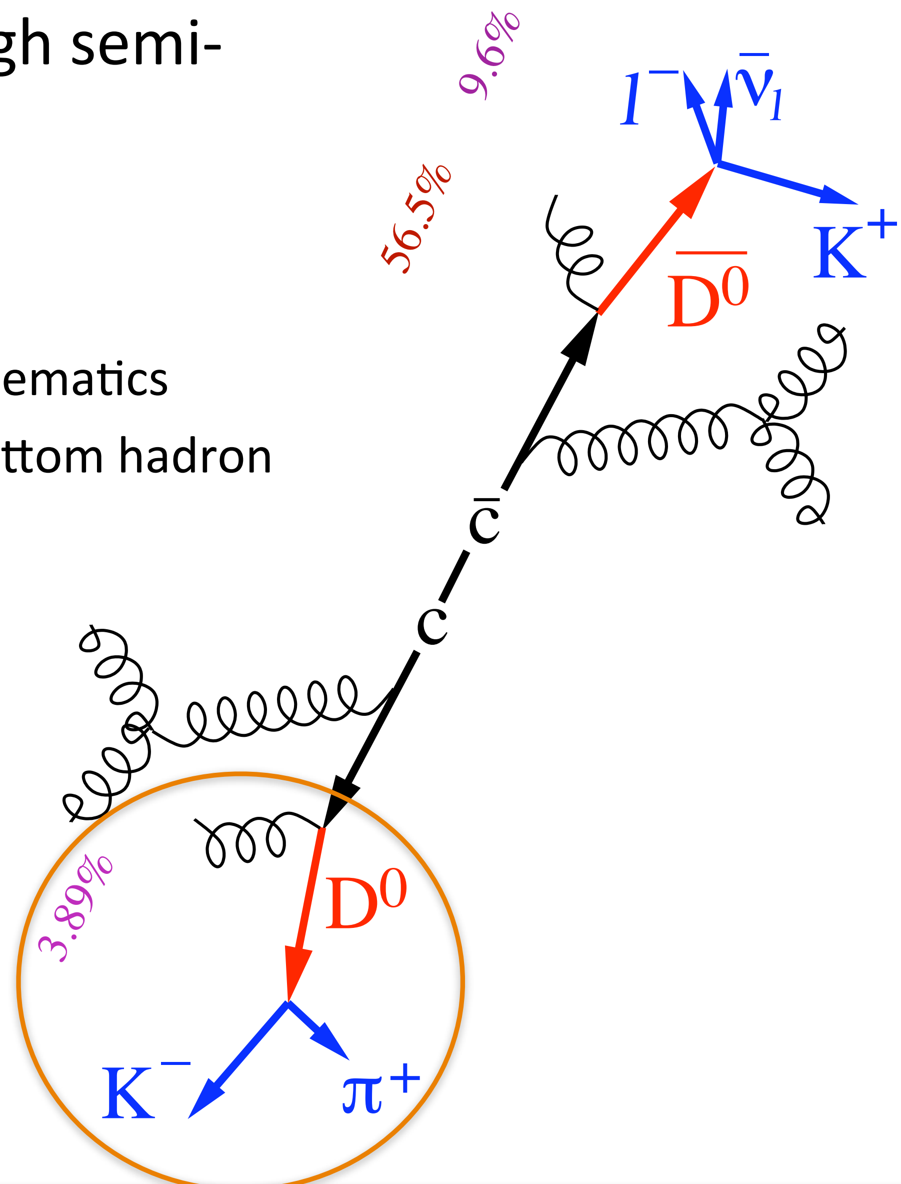
# How to Measure Charm Quarks

- ★ Indirect measurements through semi-leptonic decay
  - ★ can be triggered easily (high $p_T$)
  - ★ higher Branching Ratio
  - ★ indirect access to the heavy quark kinematics
  - ★ contribution from both charm and bottom hadron decays



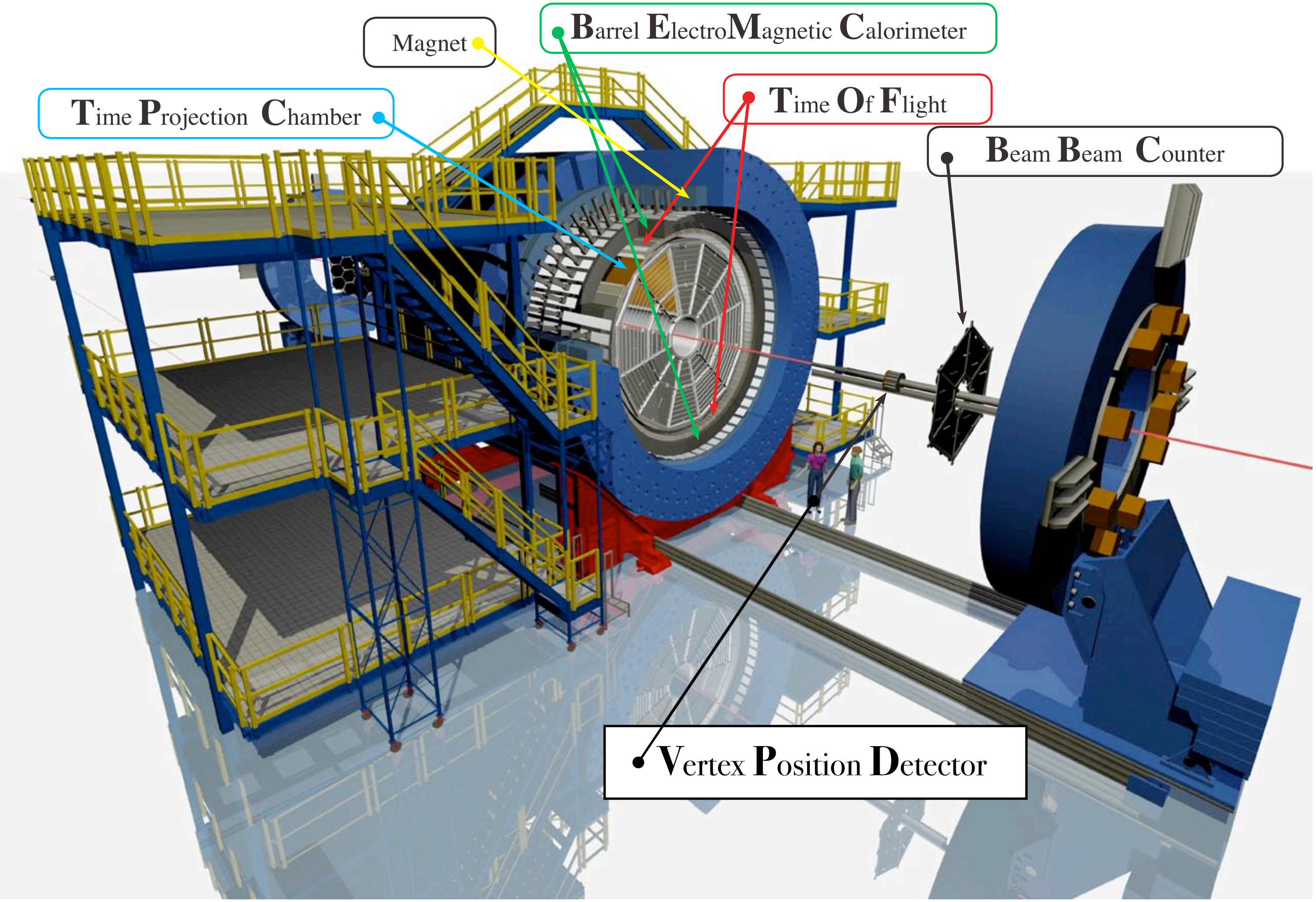
# How to Measure Charm Quarks

- ★ Indirect measurements through semi-leptonic decay
  - ★ can be triggered easily (high $p_T$)
  - ★ higher Branching Ratio
  - ★ indirect access to the heavy quark kinematics
  - ★ contribution from both charm and bottom hadron decays
- ★ Direct reconstruction
  - ★ direct access to heavy quark kinematics
  - ★ difficult to trigger (high energy trigger only for correlation measurements)
  - ★ smaller Branching Ratio
  - ★ large combinatorial background (need handle on decay vertex)



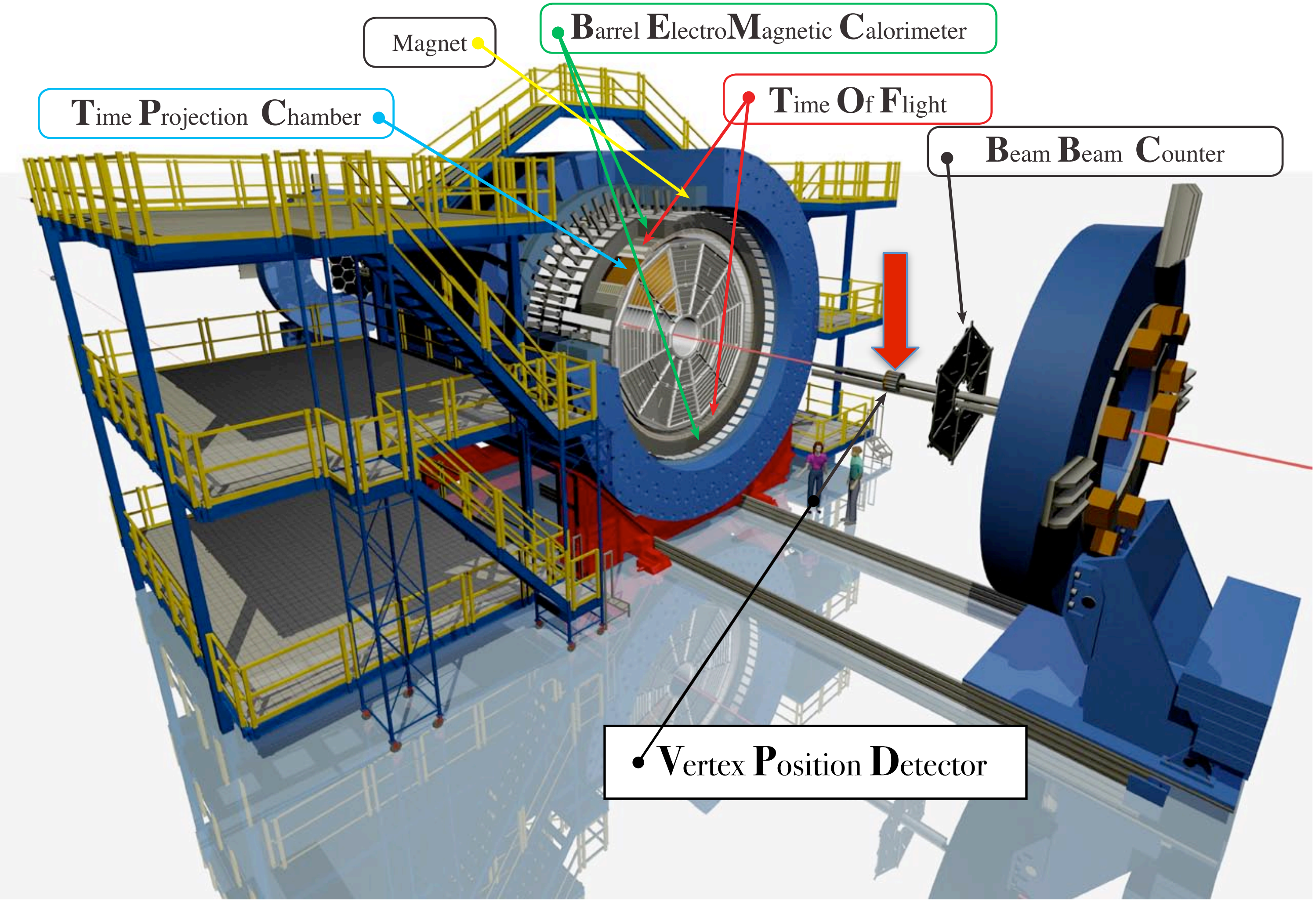
# The STAR Detector

Solenoidal Tracker At RHIC : $-1 < \eta < 1,\ 0 < \phi < 2\pi$



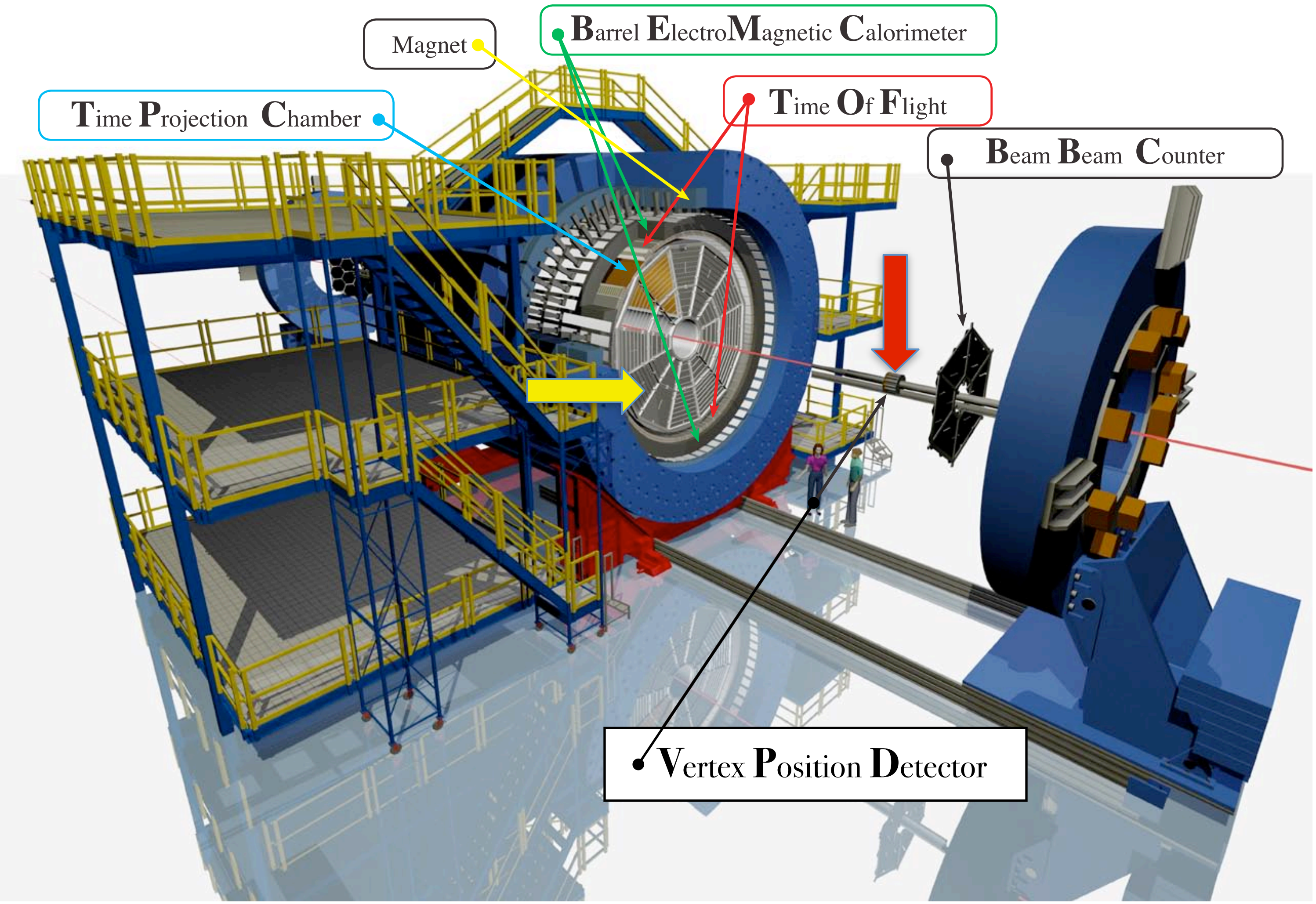
# The STAR Detector

## Solenoidal Tracker At RHIC : $-1 < \eta < 1$, $0 < \phi < 2\pi$



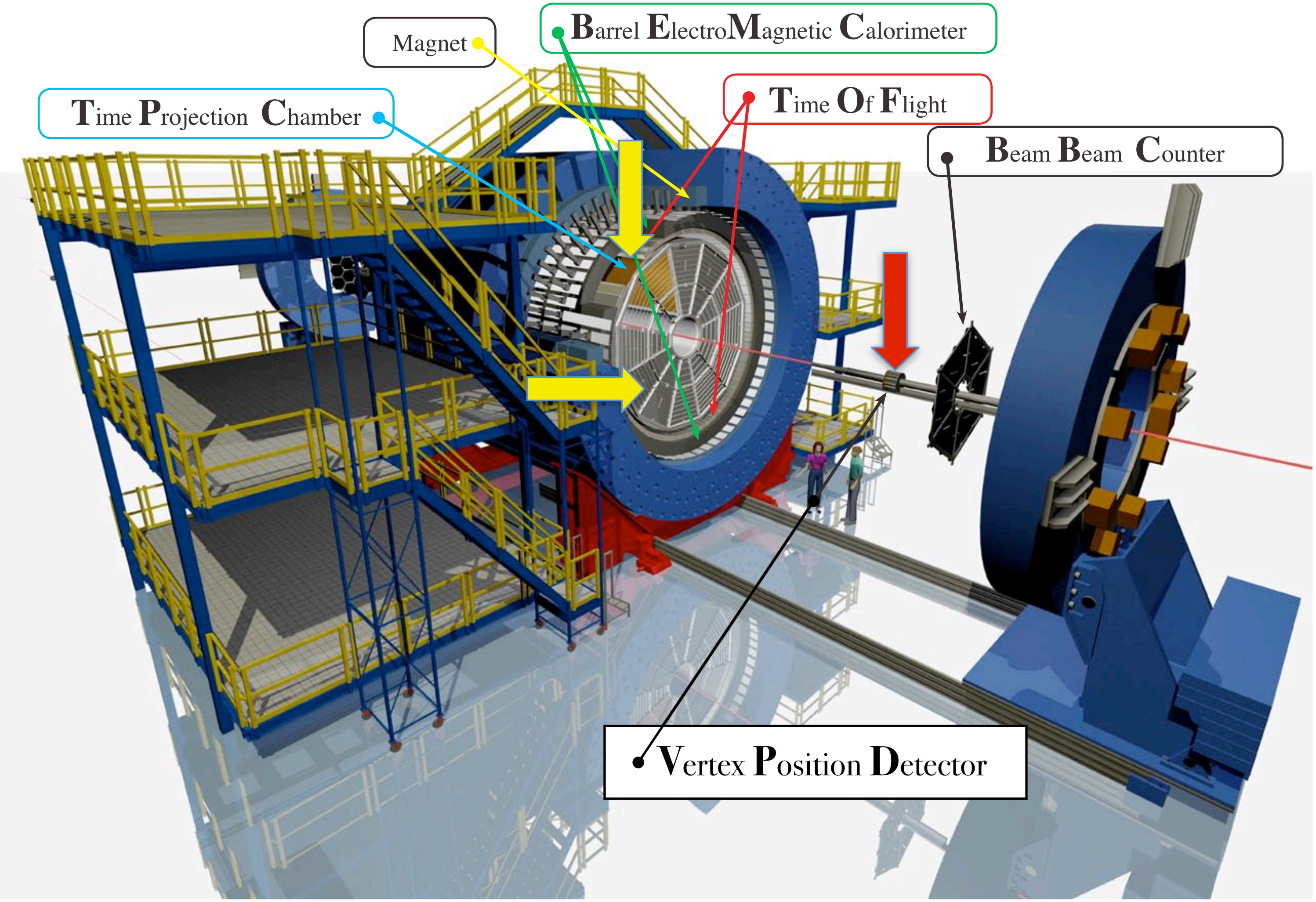

- ★ **VPD: minimum bias trigger**

# Solenoidal Tracker At RHIC : $-1 < \eta < 1$, $0 < \phi < 2\pi$




- ★ **VPD: minimum bias trigger**
- ★ **TPC: PID, tracking**

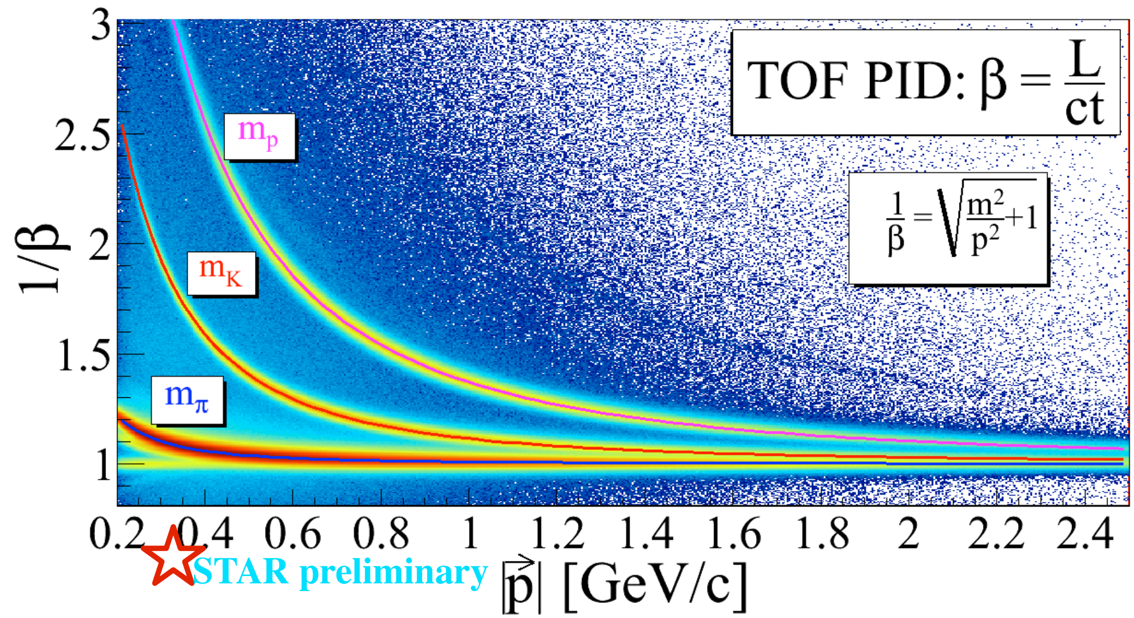
**S**olenoidal **T**racker **A**t **R**HIC : $-1 < \eta < 1$, $0 < \phi < 2\pi$

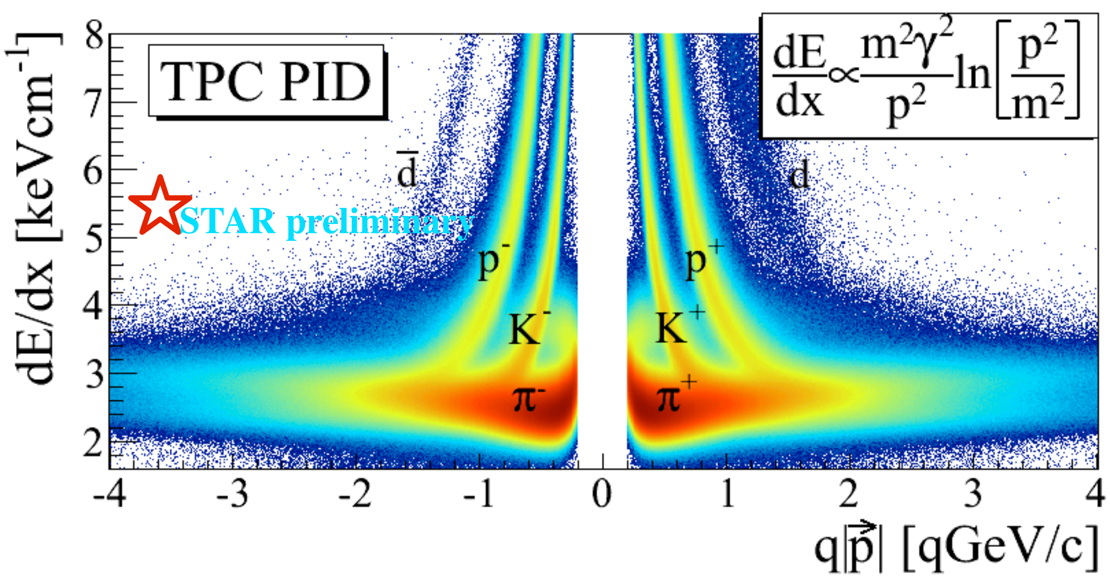



- ★ **VPD:** **minimum bias trigger**
- ★ **TPC:** **PID, tracking**
- ★ **TOF:** **PID** **(time resolution 110 ps in p+p, 87 ps in Au+Au)**

# Hadron Identification

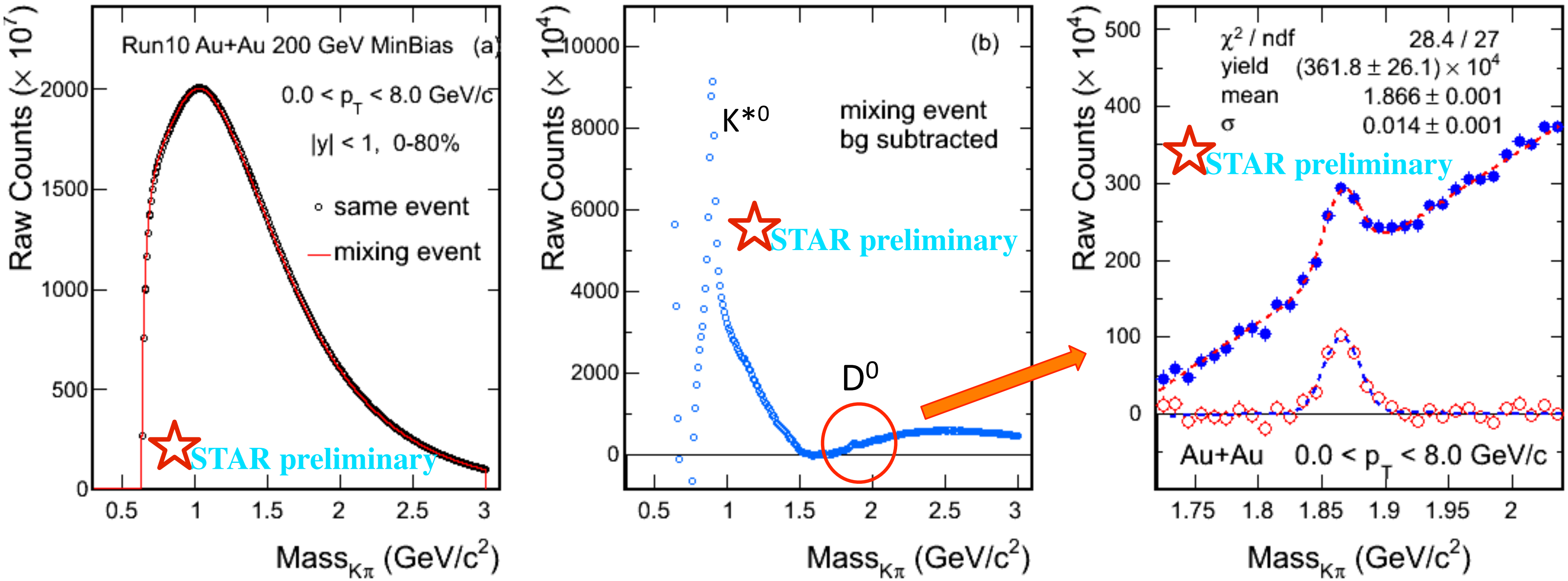
TOF provides clean sample of kaons with momentum up to ~1.6 GeV/c




TPC better than TOF for track with momentum above ~2.5 GeV/c

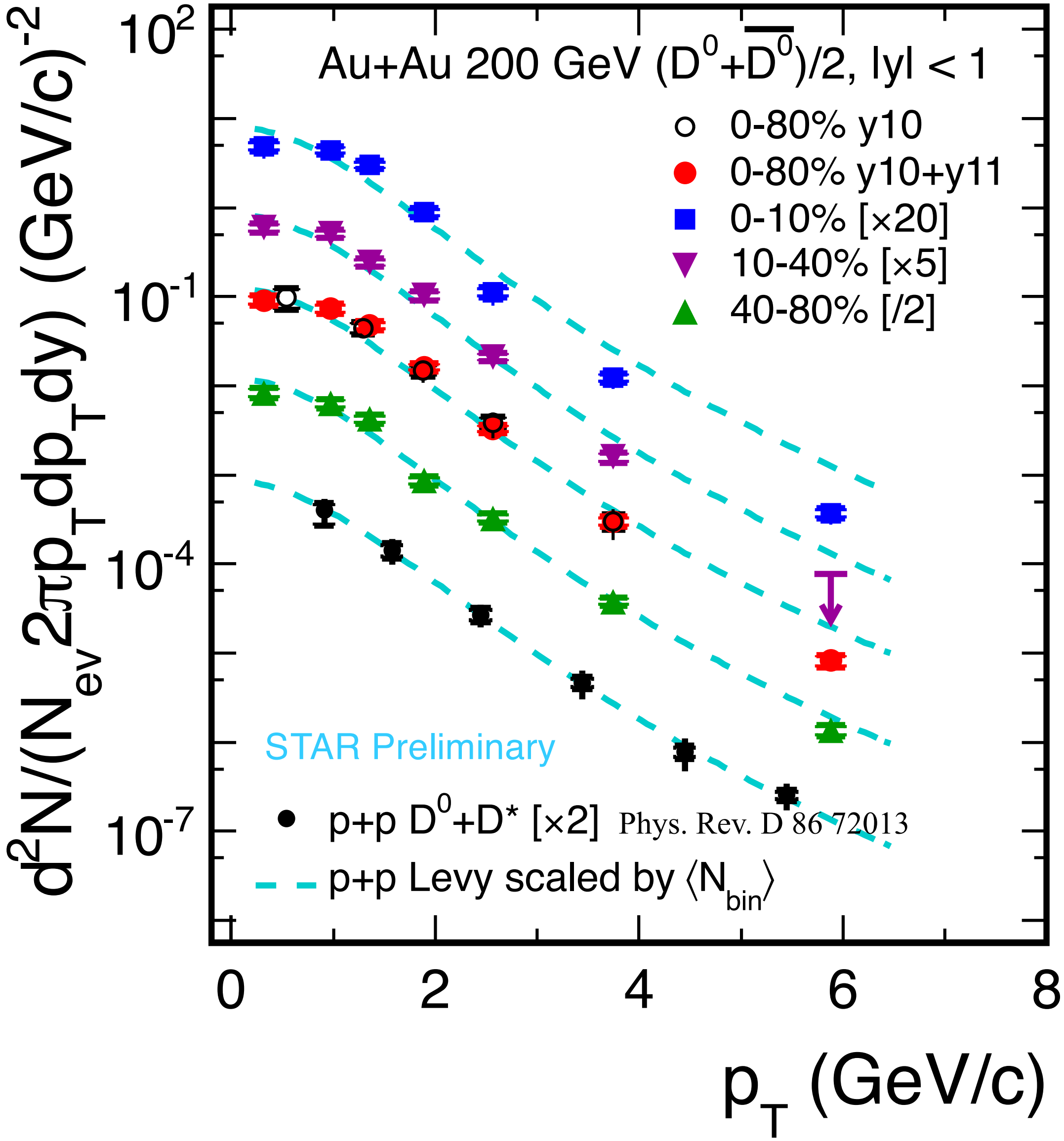
# $D^0$ in Au+Au 200 GeV (Run 10 & 11)

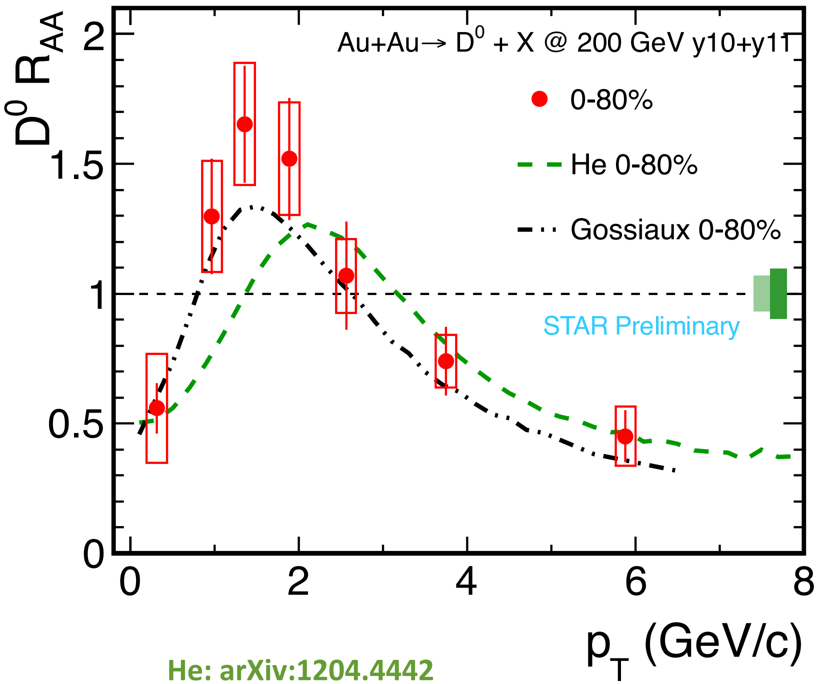



$S/\sqrt{(S+B)} \sim 14$; Mass = $1866 \pm 1$ MeV/$c^2$ (PDG: $1864.5 \pm 0.4$ MeV/$c^2$)

split into 7 $p_T$ and 3 centrality bins

# $D^0$ Au+Au 200 GeV Invariant Yield Spectra & $R_{AA}$



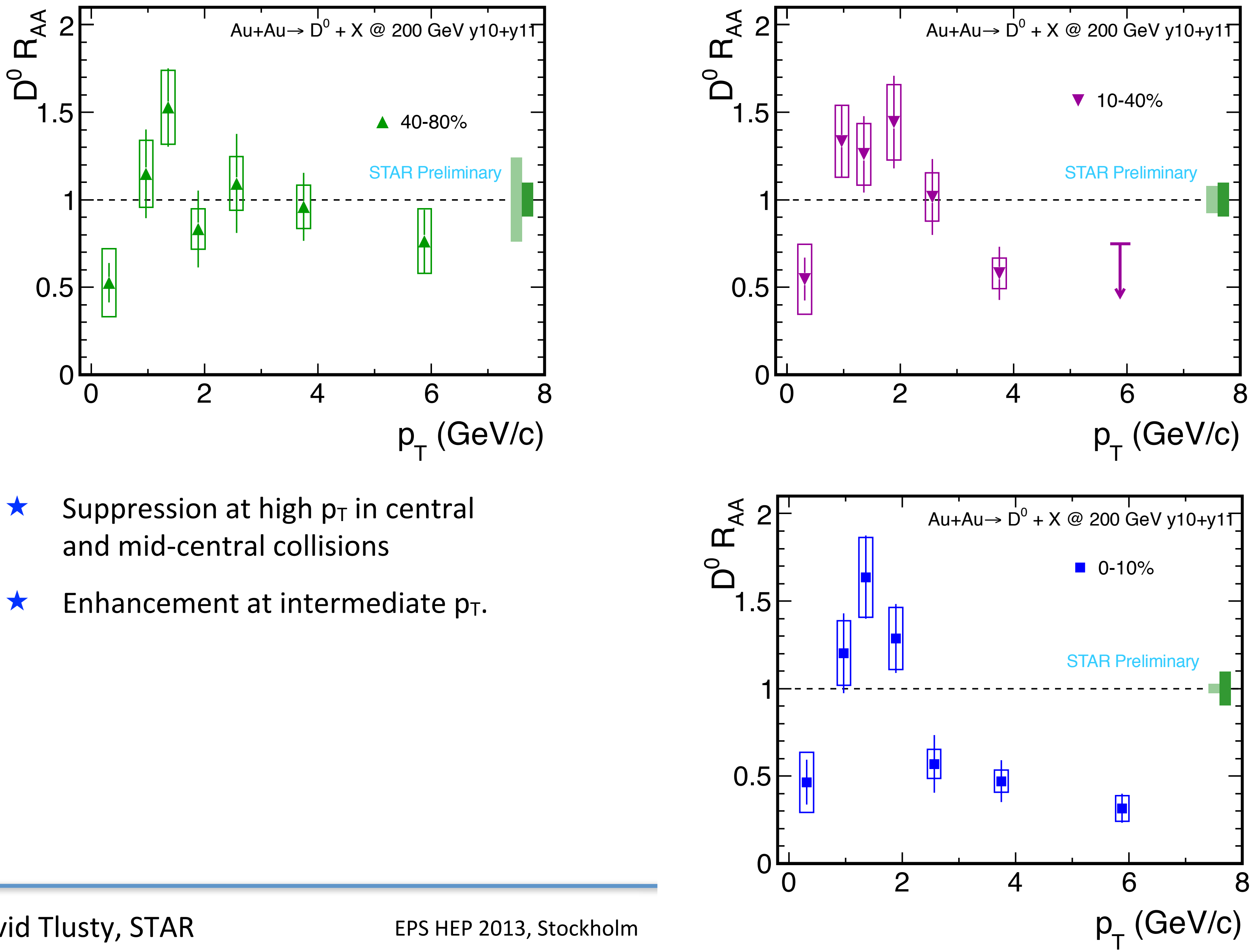

**He: arXiv:1204.4442**

Time evolution by Fokker-Planck
Langevin + Hydro simulation
coalescence for hadronization
collisional+radiative energy loss

**Gossiaux: arXiv:1207.5445**

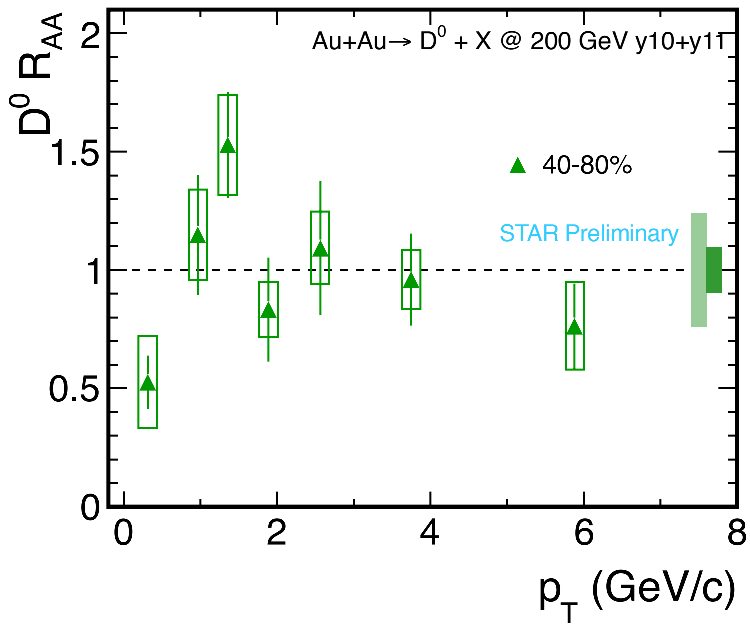
time evolution by Boltzmann
coalescence for hadronization
collisional energy loss only

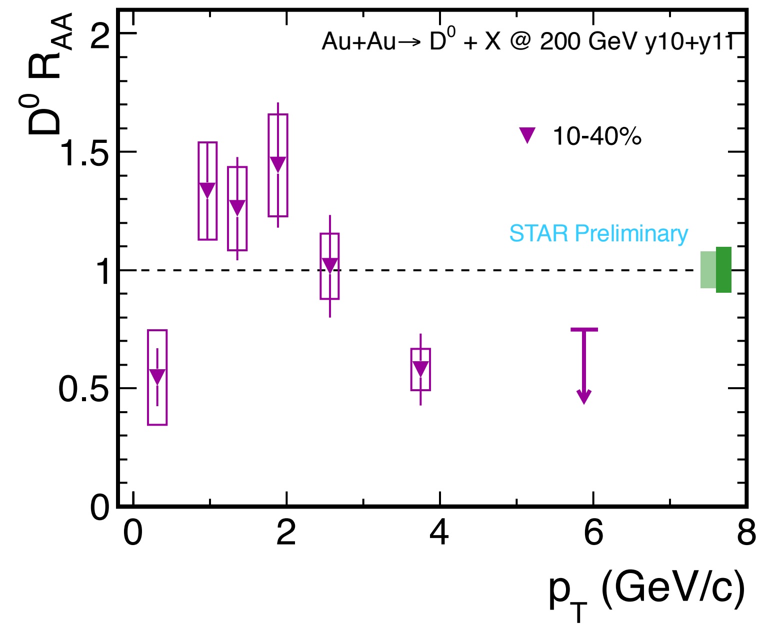
# $R_{AA}$ vs $p_T$ in centrality bins



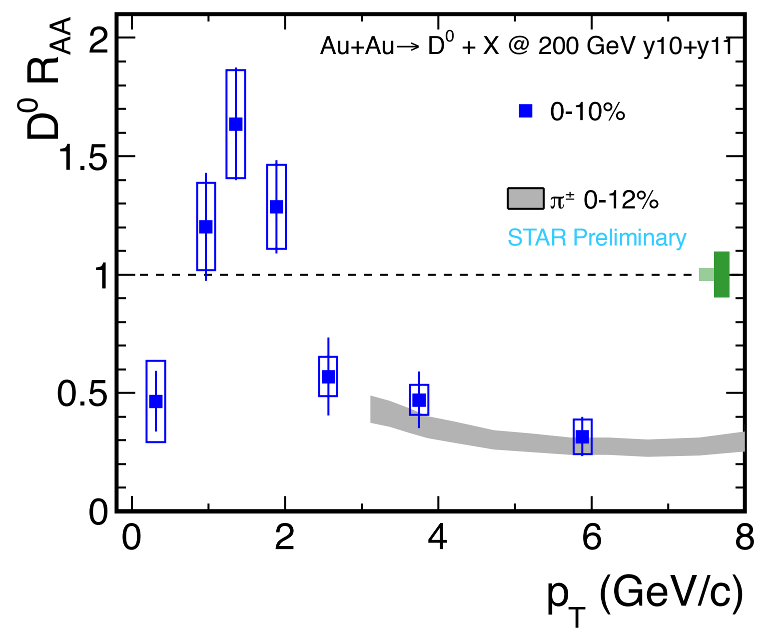

- ★ Suppression at high $p_T$ in central and mid-central collisions
- ★ Enhancement at intermediate $p_T$.

# $R_{AA}$ vs $p_T$ in centrality bins

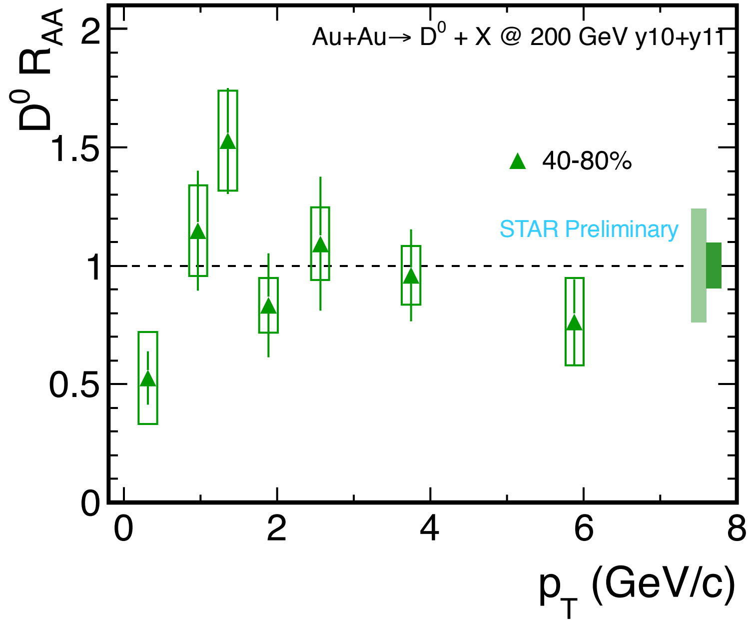


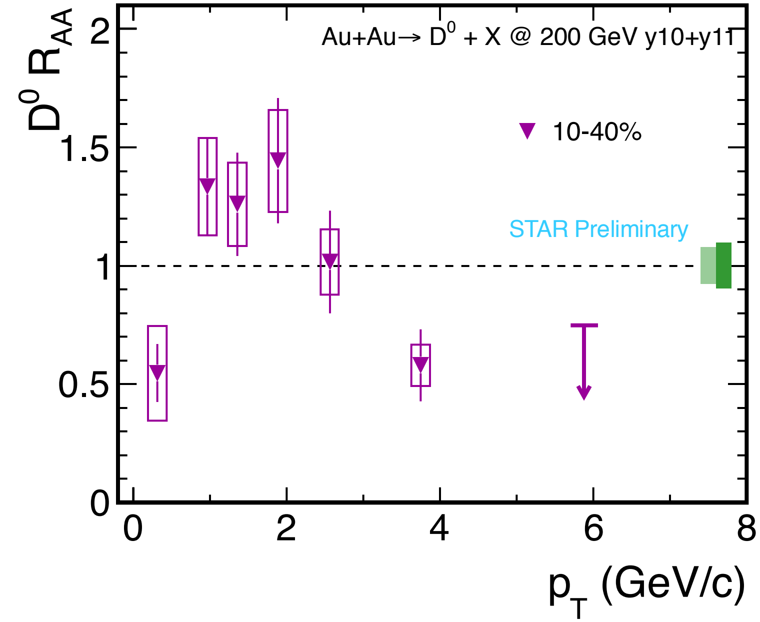




- ★ Suppression at high $p_T$ in central and mid-central collisions
- ★ Enhancement at intermediate $p_T$.



# $R_{AA}$ vs $p_T$ in centrality bins



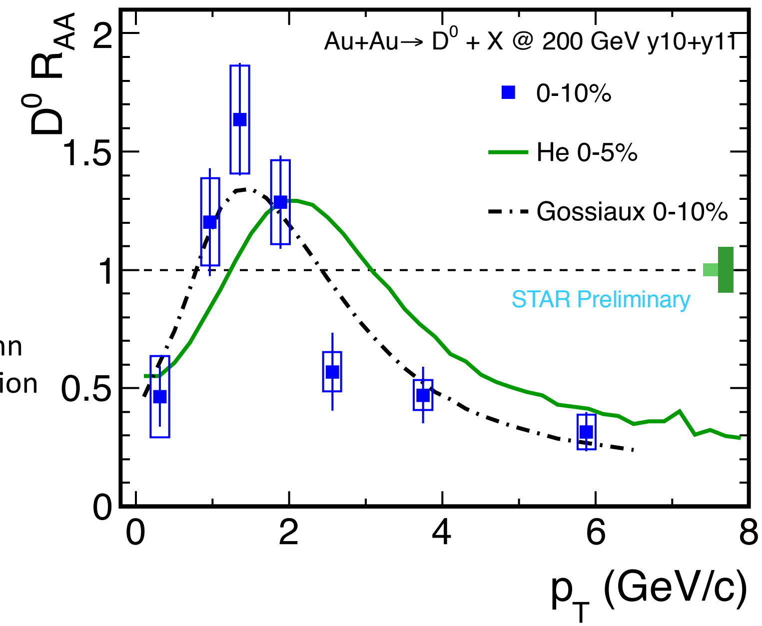

- Suppression at high $p_T$ in central and mid-central collisions
- Enhancement at intermediate $p_T$.

**He: arXiv:1204.4442**

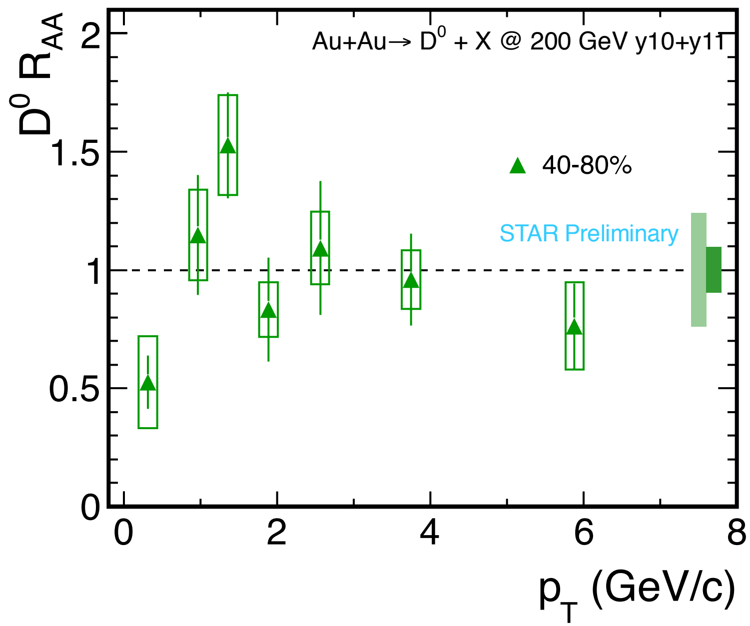
Time evolution by Fokker-Planck Langevin + Hydro simulation
coalescence for hadronization
collisional+radiative energy loss

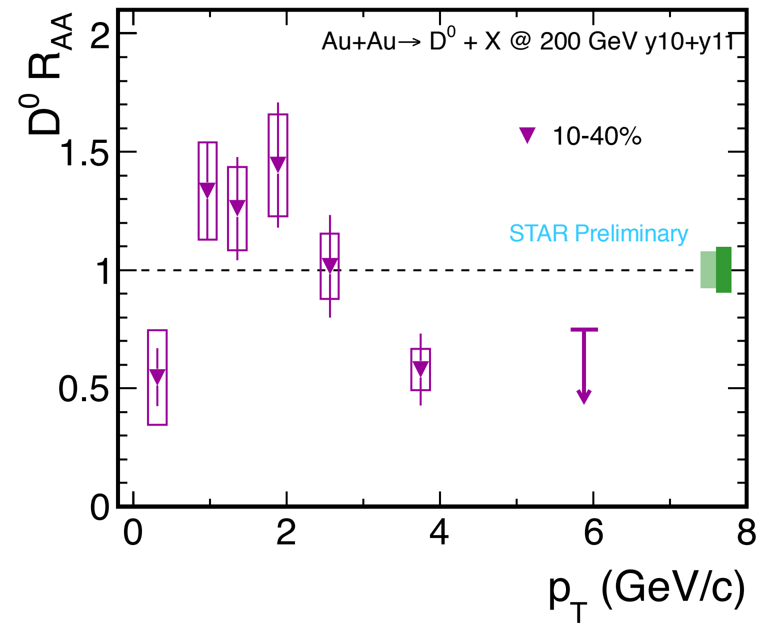
**Gossiaux: arXiv:1207.5445**

time evolution by Boltzmann
coalescence for hadronization
collisional energy loss only

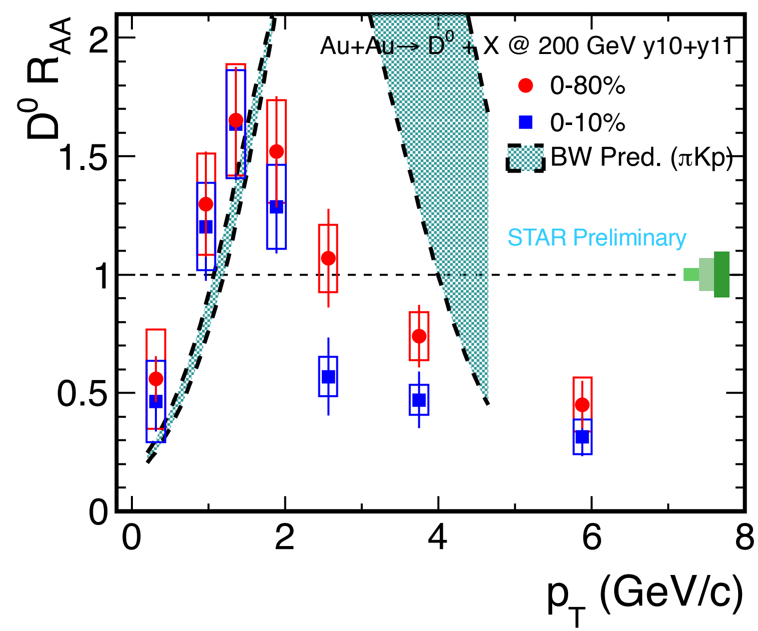


# $R_{AA}$ vs $p_T$ in centrality bins

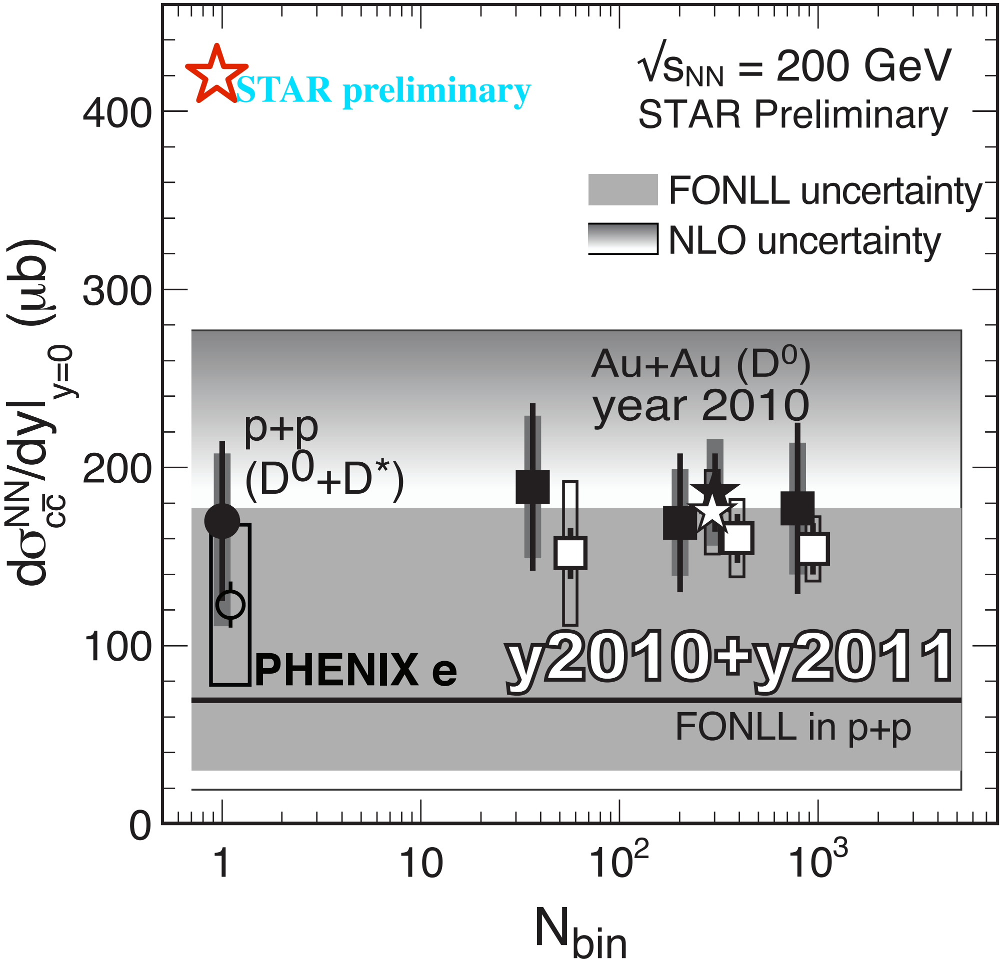


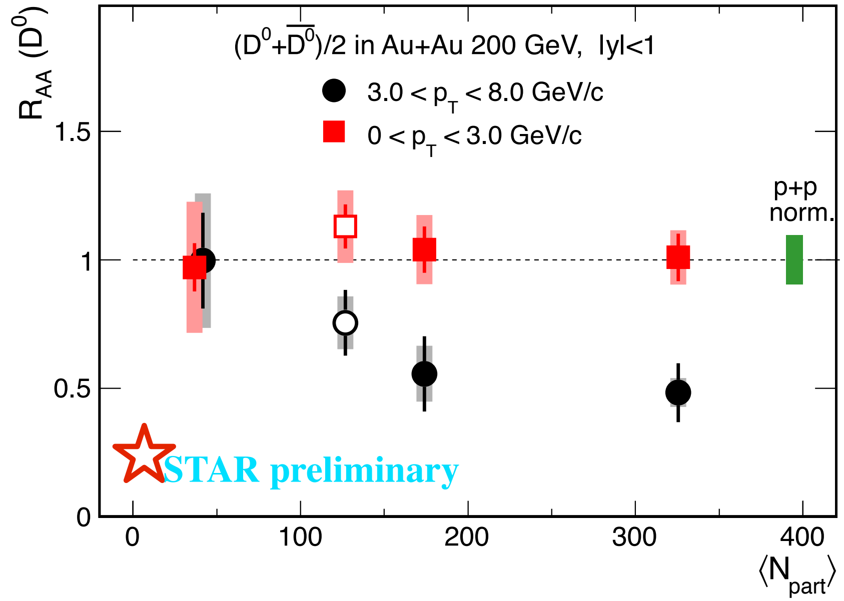




- ★ Suppression at high $p_T$ in central and mid-central collisions
- ★ Enhancement at intermediate $p_T$.
- ★ $D^0$ freeze out earlier than light hadron and/or does not have much radial flow as light quarks



# Number-of-binary-collisions Scaling




$$\left.\frac{d\sigma_{c\bar{c}}}{dy}\right|_{y=0}^{pp} = 170 \pm 45(\text{stat.})^{+38}_{-59}(\text{sys.})\ \mu b$$

Phys. Rev. D 86 72013

$$\left.\frac{d\sigma_{c\bar{c}}}{dy}\right|_{y=0}^{AuAu} = 175 \pm 13(\text{stat.}) \pm 23(\text{sys.})\ \mu b$$

Charm cross section follows number of binary collisions scaling =>
Charm quark produced at early stage of collisions.

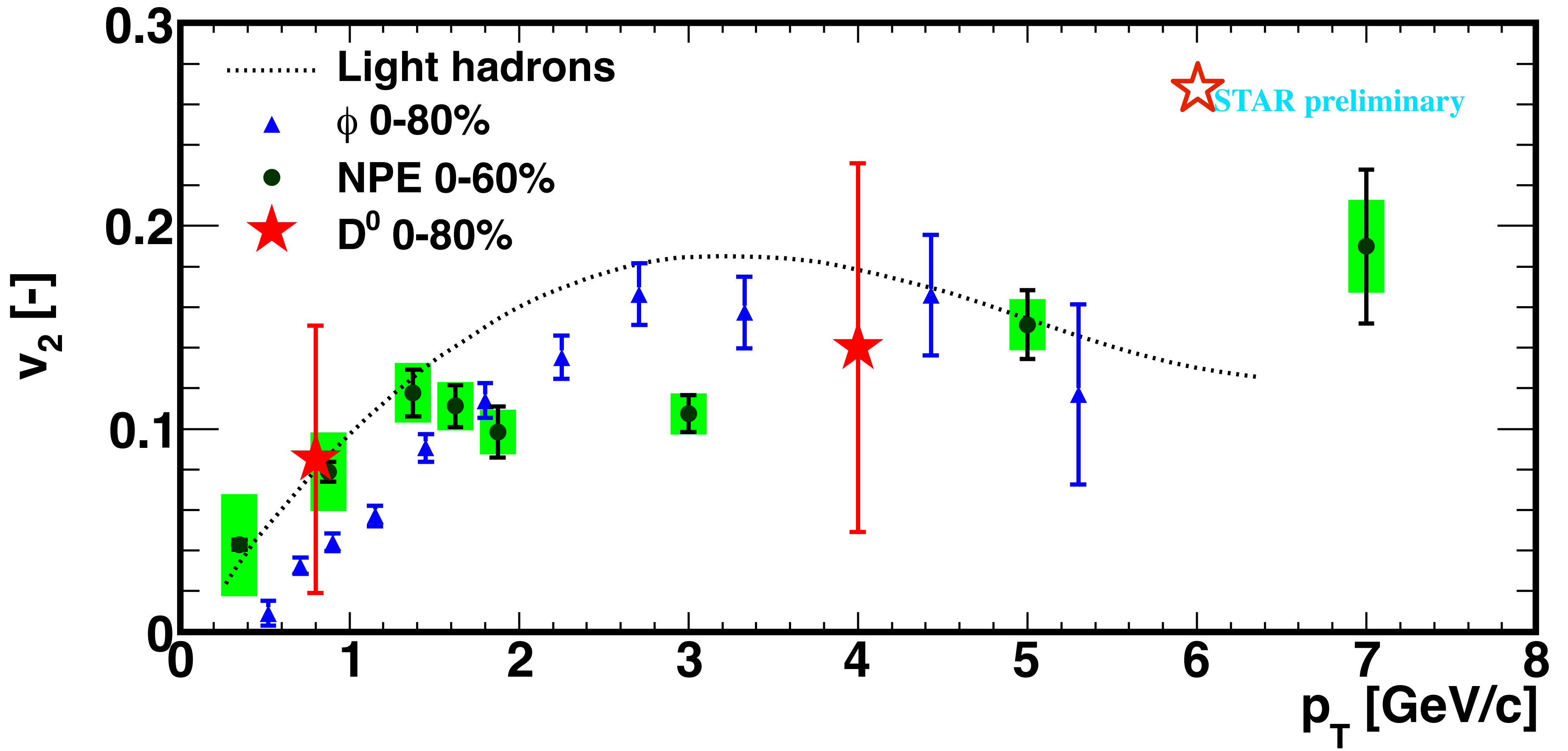

[1] FONLL: M. Cacciari, PRL 95 (2005) 122001.
[2] NLO: R. Vogt, Eur.Phys.J.ST 155 (2008) 213
[3] PHENIX e: A. Adare, et al., PRL 97 (2006) 252002.

# $D^0$ Au+Au 200 GeV Elliptic Flow

$$E\frac{d^3N}{d\mathbf{p}^3} = \frac{1}{N_{ev}}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_{RP})]\right)$$

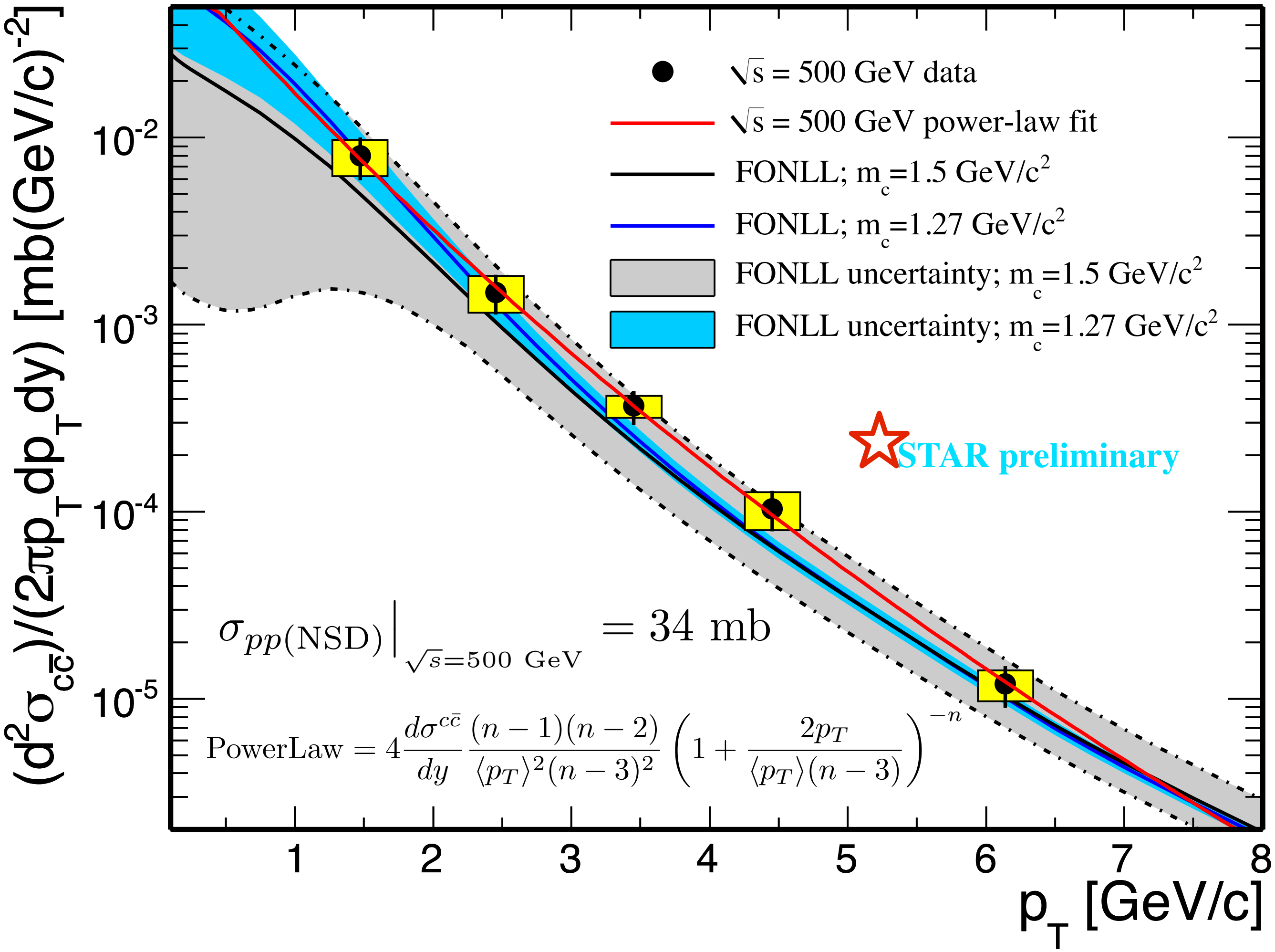
$$v_n(p_T, y) = \langle\cos[n(\phi - \Psi_{RP})]\rangle$$

probing the degree of thermalization of the light quarks



# $D^0$ and D* $p_T$ Spectra in p+p 500 GeV






D$^0$ yield scaled by $N_{D0}/N_{cc}$ = 0.565[1]

D$^*$ yield scaled by $N_{D*}/N_{cc}$ = 0.224[1]

[1] C. Amsler et al. (Particle Data Group), PLB 667 (2008) 1.

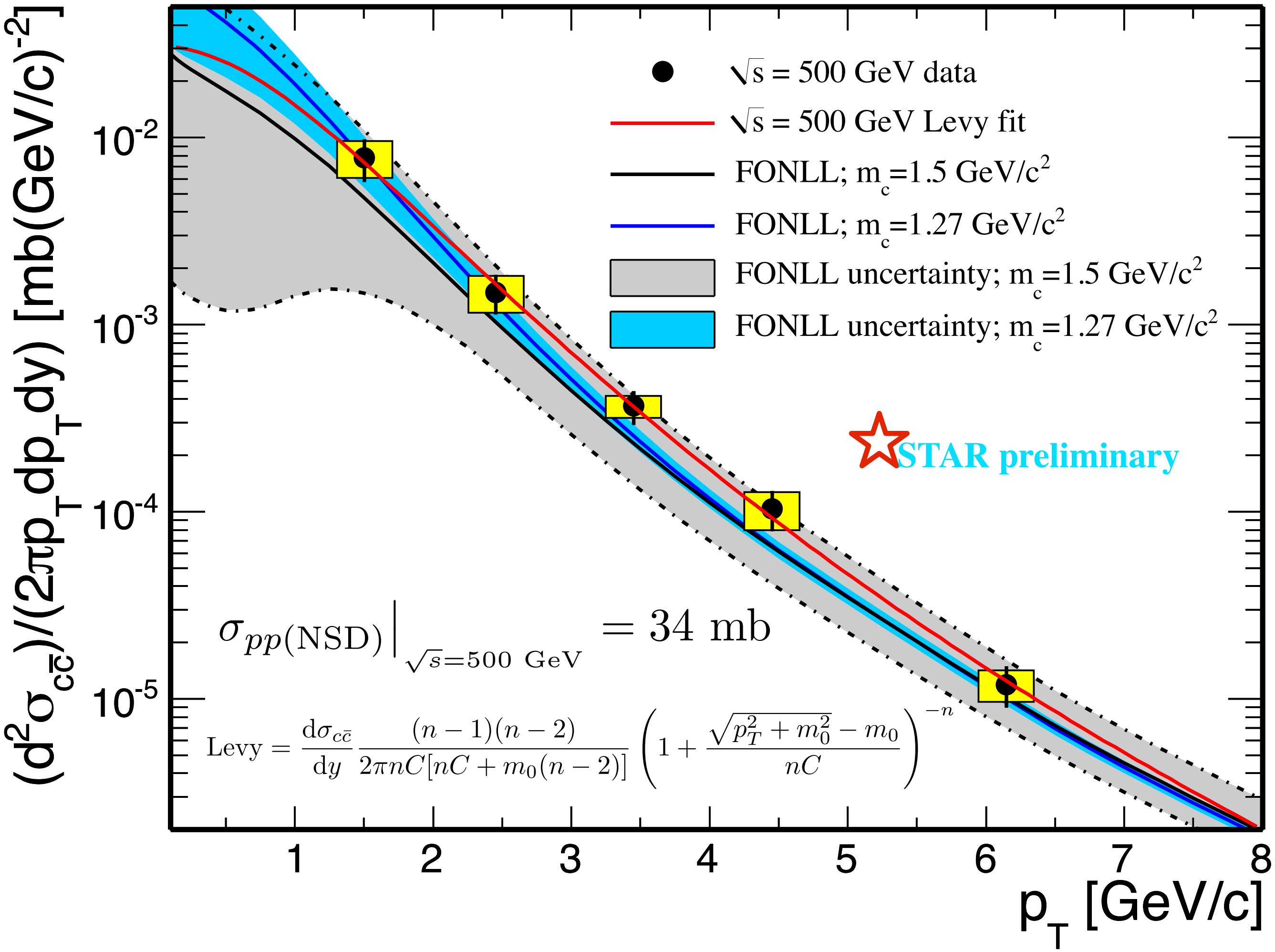
[2] FONLL calculation: Ramona Vogt

**$\mu_F = \mu_R = m_c$, |y| < 1**

$$\left.\frac{d\sigma_{c\bar{c}}}{dy}\right|_{y=0}^{\sqrt{s}=500\mathrm{GeV}} = 217 \pm 86(\mathrm{stat.}) \pm 73(\mathrm{sys.})\ \mu\mathrm{b}$$

$$\left.\frac{d\sigma_{c\bar{c}}}{dy}\right|_{y=0} = \left.\frac{dN_{c\bar{c}}}{dy}\right|_{y=0} \sigma_{pp(NSD)}$$

# $D^0$ and D* $p_T$ Spectra in p+p 500 GeV




$D^0$ yield scaled by $N_{D0}/N_{cc}$= 0.565[1]

$D^*$ yield scaled by $N_{D*}/N_{cc}$= 0.224[1]

[1] C. Amsler et al. (Particle Data Group), PLB 667 (2008) 1.

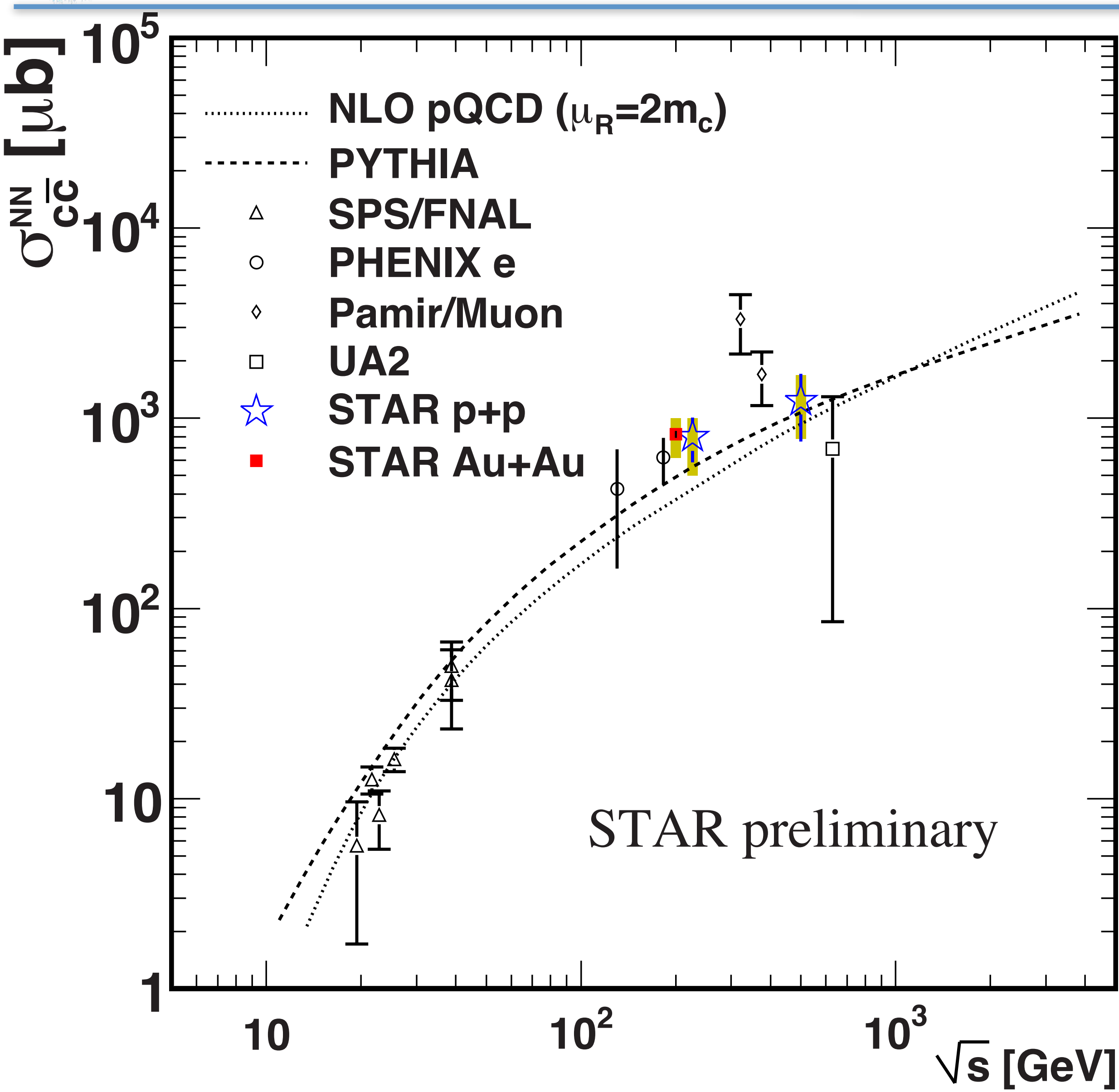
[2] FONLL calculation: Ramona Vogt

**$\mu_F = \mu_R = m_c$, $|y| < 1$**

$$\left.\frac{d\sigma_{c\bar{c}}}{dy}\right|_{y=0}^{\sqrt{s}=500\mathrm{GeV}} = 174 \pm 55(\mathrm{stat.}) \pm 47(\mathrm{sys.})\ \mu\mathrm{b}$$

$$\left.\frac{d\sigma_{c\bar{c}}}{dy}\right|_{y=0} = \left.\frac{dN_{c\bar{c}}}{dy}\right|_{y=0} \sigma_{pp(NSD)}$$

# Total Charm Cross Section




$$\sigma_{c\bar{c}} = F \left. \frac{dN_{c\bar{c}}}{dy} \right|_{y=0}$$

$$F \equiv \text{mid } y \rightarrow \text{full } y$$

**500 GeV, F = 5.6**

$$\sigma_{c\bar{c}} = 1215 \pm 482(\text{stat.}) \pm 409(\text{sys.})\ \mu b$$

**200 GeV, F = 4.7**

$$\sigma_{c\bar{c}} = 797 \pm 210(\text{stat.})\ ^{+208}_{-295}(\text{sys.})\ \mu b$$

Phys. Rev. D 86 72013

# Summary

★ $D^0$ are measured in Au+Au 200 GeV up to 6 GeV/c for 3 centrality bins.

➡ Charm cross sections at mid-rapidity follow number of binary collisions scaling

➡ Strong suppression above 2.2 GeV/c in central collisions, consistent with resonance recombination model; the $R_{AA}$ shape consistent with prediction from the SUBATECH group

★ $D^0$ observation might indicate non-zero $v_2$

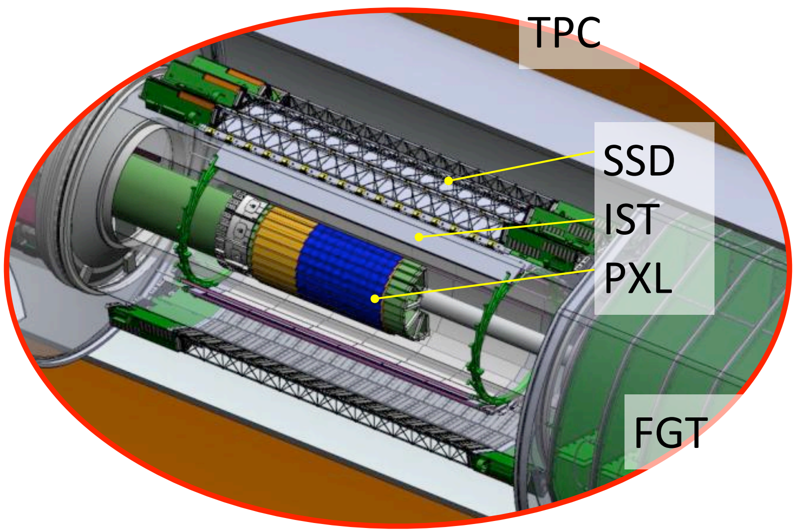
★ $D^0$ and $D^*$ are measured in p+p 500 GeV up to 6 GeV/c

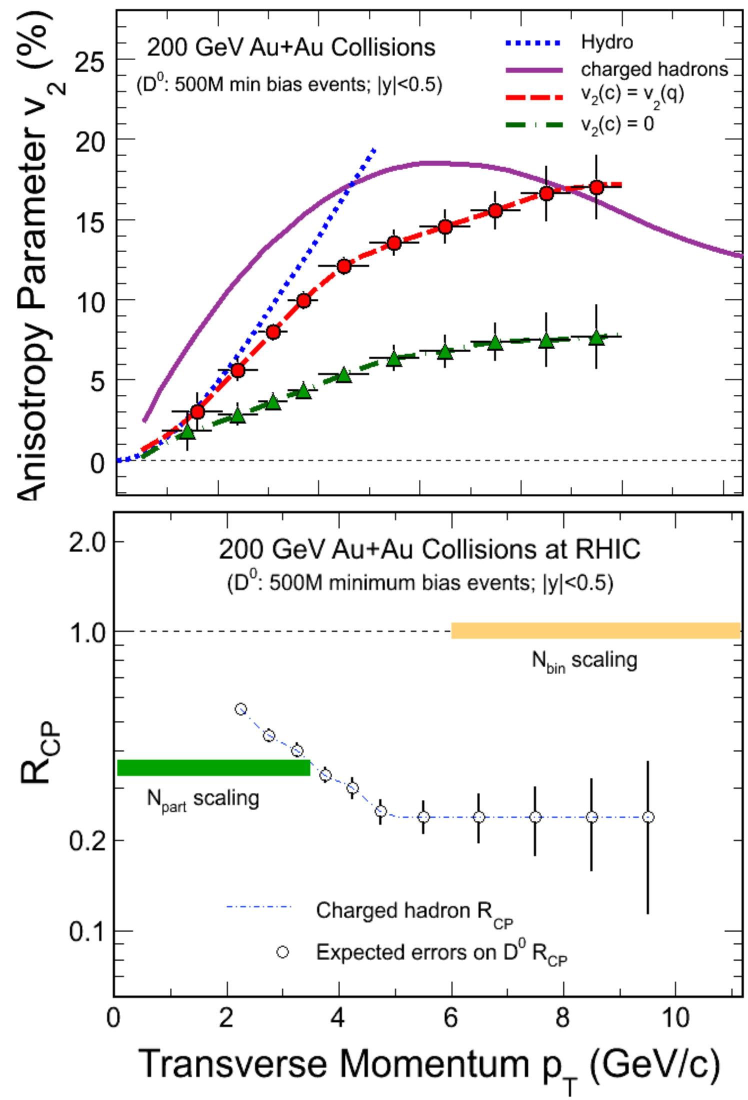
➡ $\mathrm{d}^2\sigma^{c\bar{c}}/p_T\mathrm{d}p_T\mathrm{d}y$ consistent with FONLL upper limit.

★ Further improvement with Heavy Flavor Tracker

# Thank you

# Heavy Flavor Tracker




STAR Heavy Flavor Tracker Project.

- ✓ Reconstruct secondary vertex.
- ✓ Dramatically improve the precision of measurements.
- ✓ Address physics related to heavy flavor.

$v_2$ : thermalization

$R_{CP}$: charm quark energy loss mechanism.

# Systematic error study

1) Raw Counts – Difference between methods
2) nFitPoints - difference between MC(nFitPts>25)/MC(nFitPts>15) and Data(nFitPts>25)/Data(nFitPts>15)
3) DCA - difference between MC(dca<1)/MC(dca<2) and Data(dca<1)/Data(dca<2)