Open Heavy Flavor Production at STAR

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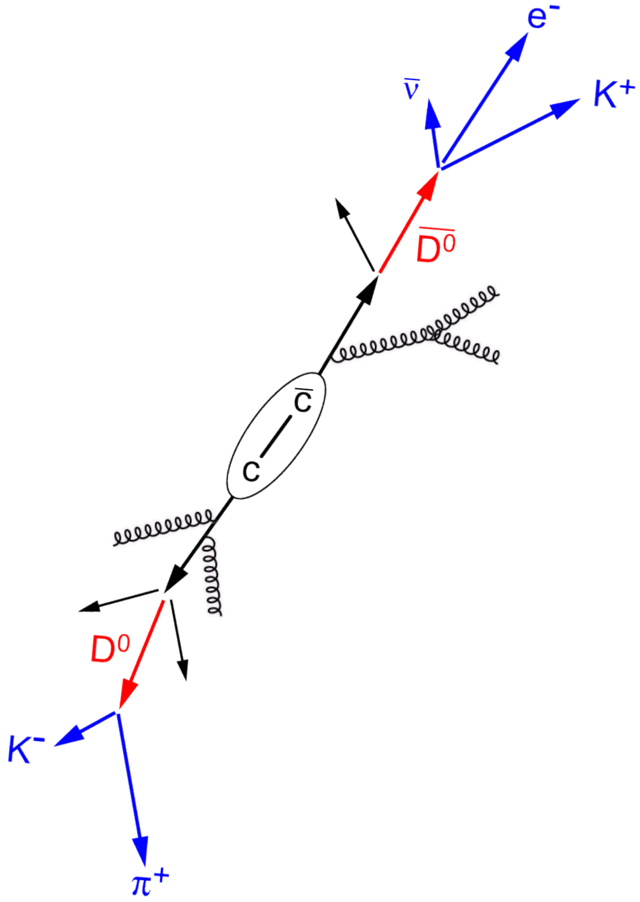
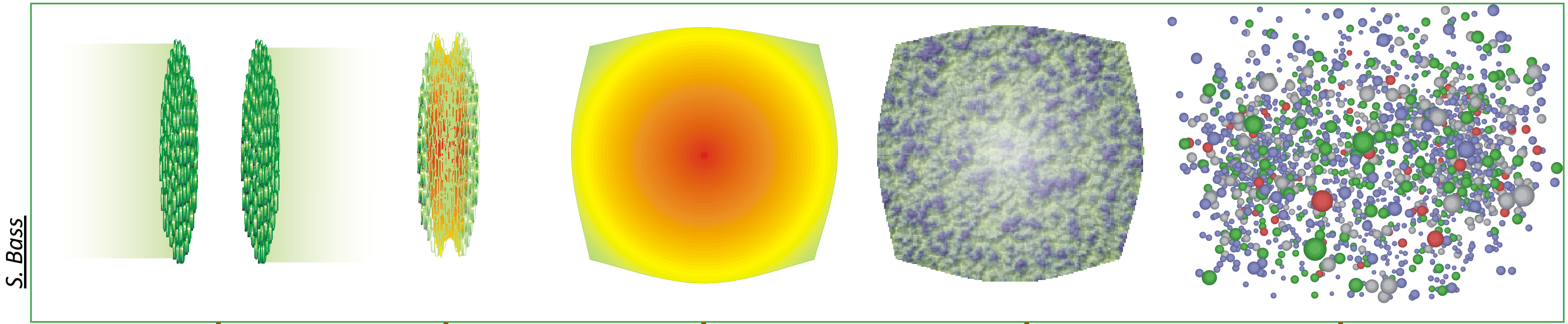


- ✧ Introductions
- ✧ Recent measurements
- ✧ STAR HFT performance
- ✧ What is next?
- ✧ Summary

U.S. DEPARTMENT OF ENERGY

QCD workshop @CCNU, Wuhan, 07/28/2015

The Quark-Gluon Plasma



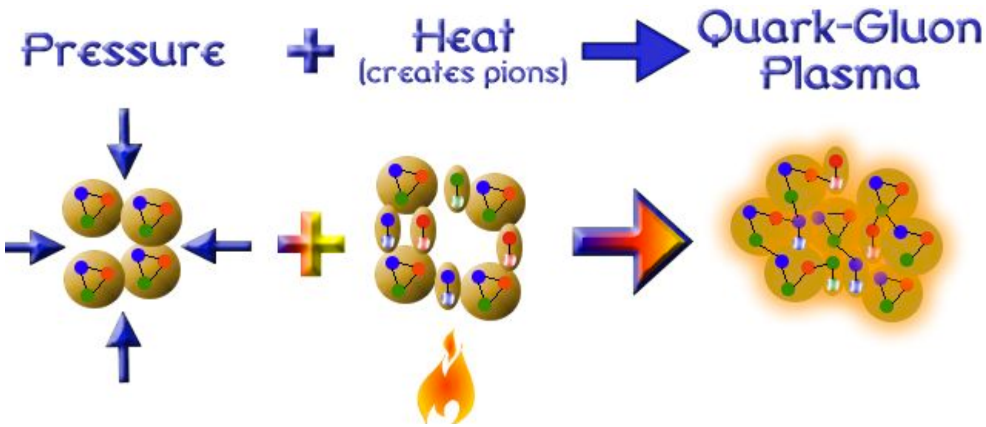
Initial conditions

Initial hard interactions

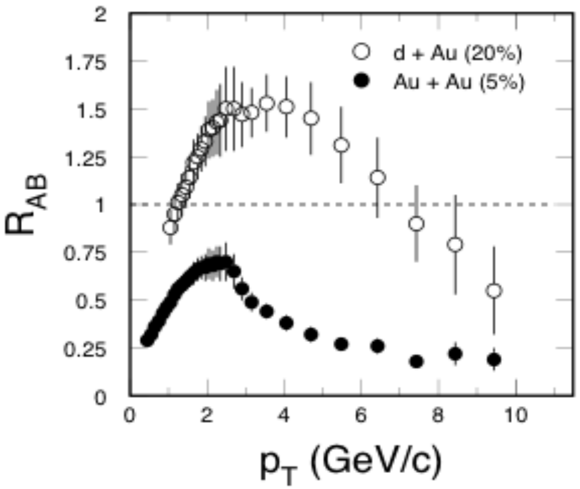
Partonic matter — QGP

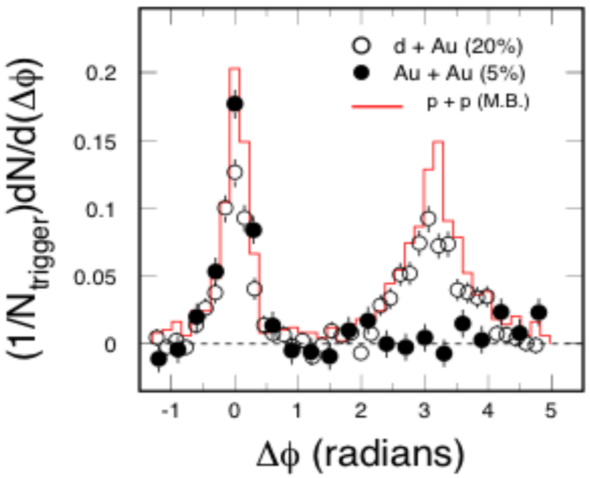
Hadronization and chemical freeze-out

Kinetic freeze-out

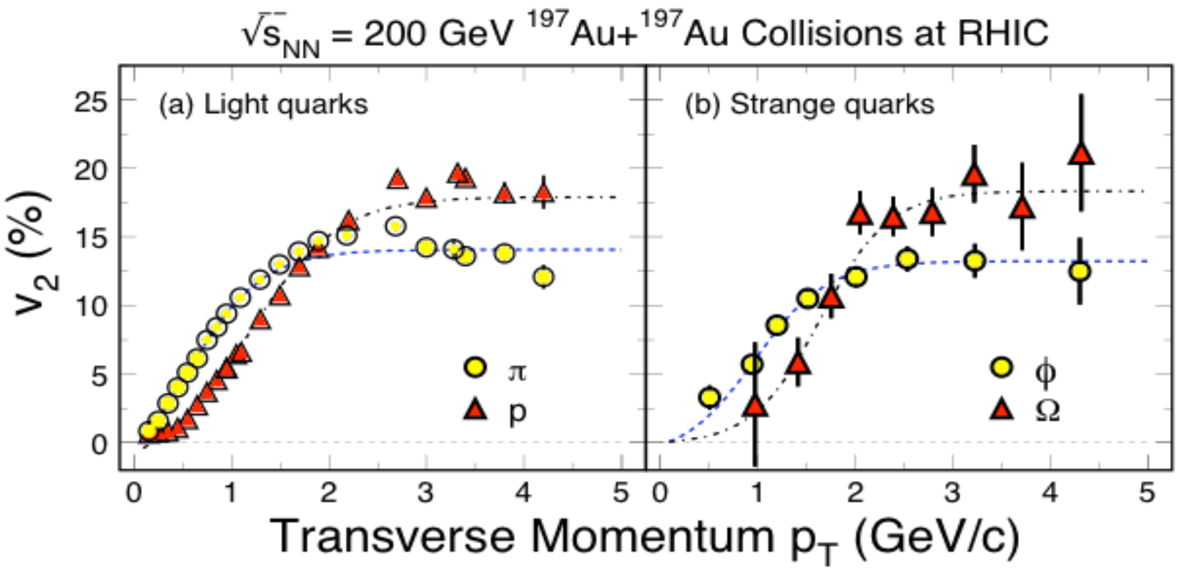


Light flavor behavior in strongly coupled medium



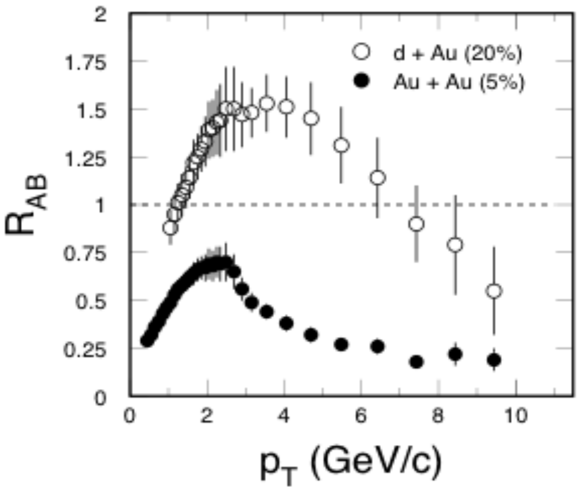


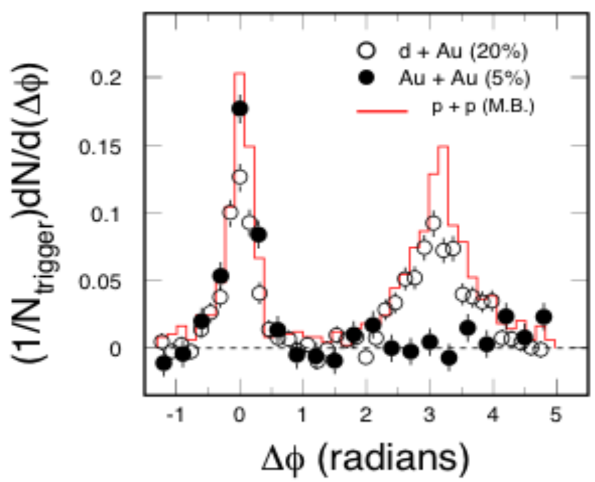
- High p_T:
  - Light quark e-loss, Jet quenching
- Low p_T:
  - Hydrodynamics works
  - Multi-strange hadrons flow
- Intermediate p_T:
  - Number of Constituent Quark scaling flow s ~ u,d

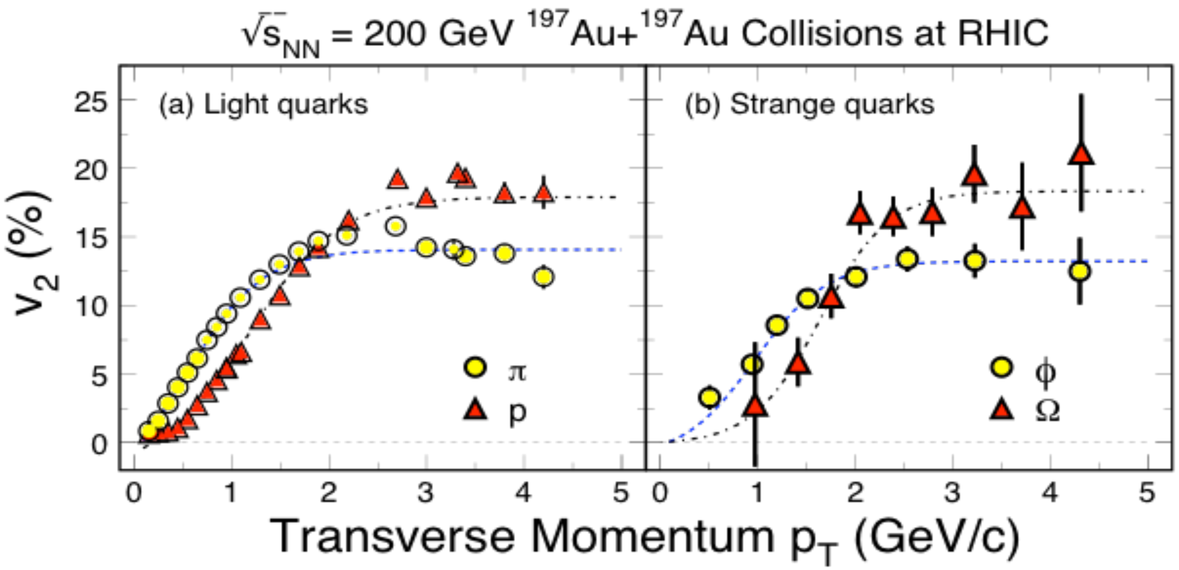


STAR: Nucl. Phys. ***A757***, 102(2005).
QM09

Light flavor behavior in strongly coupled medium







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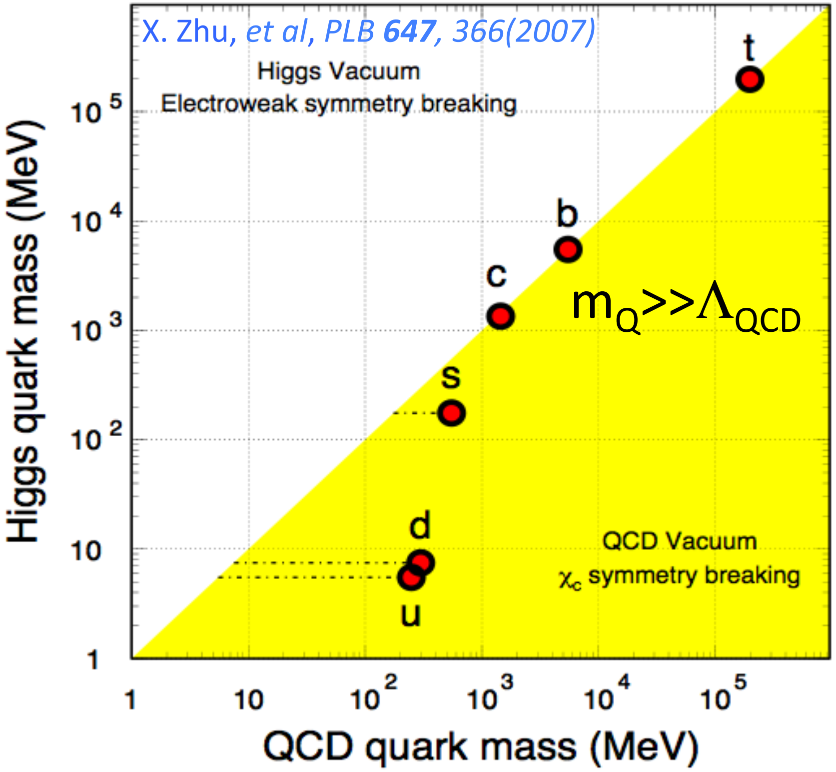
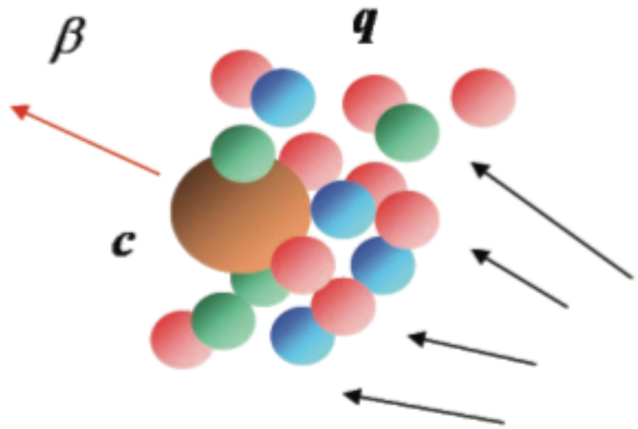
  - flow s ~ u,d

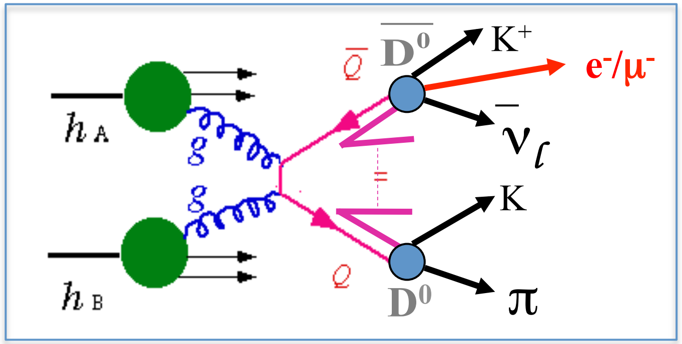
Large partonic collective flow observed. u, d, s quarks strongly interact with hot/dense medium.

What about heavy quarks?
Is the medium hot/dense enough to modify heavy quarks at RHIC energy?
And LHC energy?

Why are heavy quarks important?

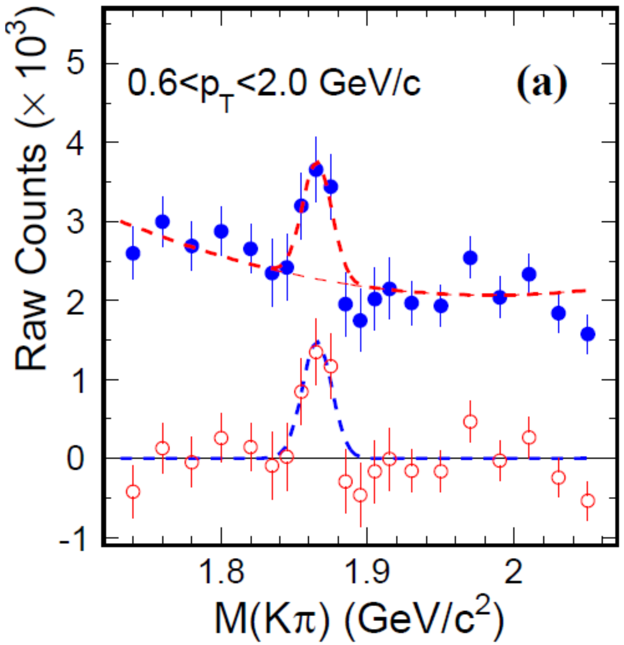


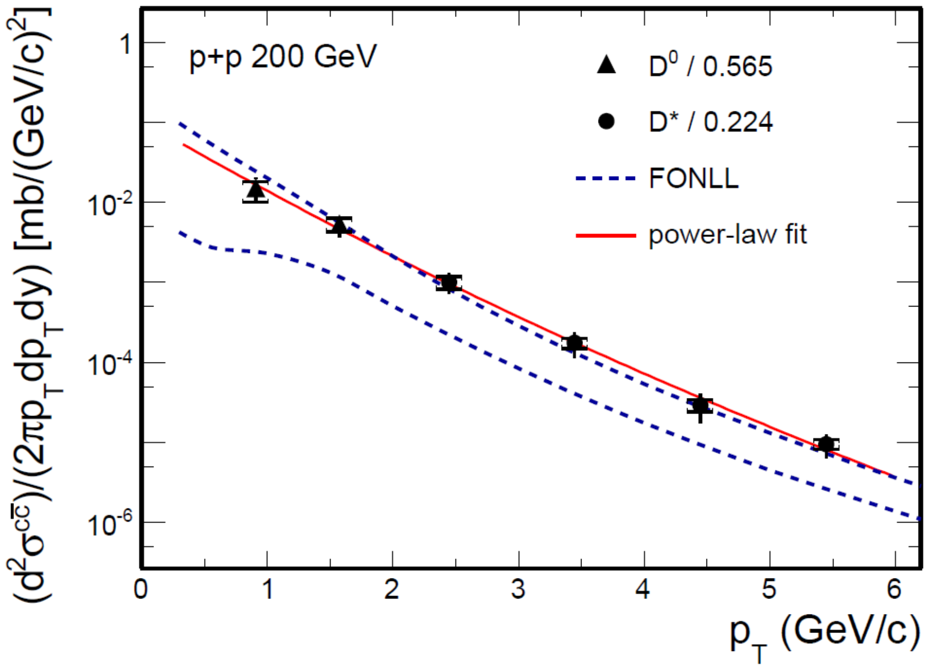


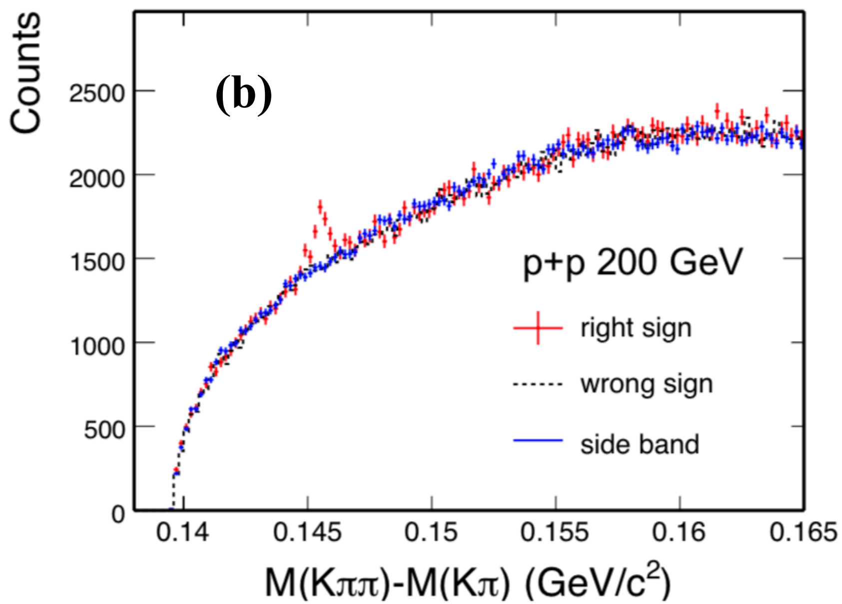


- Production cross section can be evaluated by pQCD. Provide reference for charmonium calculations.
- Sensitive to initial gluon density and distribution.
- Probe for studying medium properties.
- Charm collectivity => sensitive to the thermalization of the medium.

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







The charm cross section at mid-rapidity:

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

The total charm cross section:

$$\sigma^{pp}_{c\bar{c}} = 797 \pm 210^{+208}_{-295}\,\mu b$$

PRD 86, 072013 (2012)

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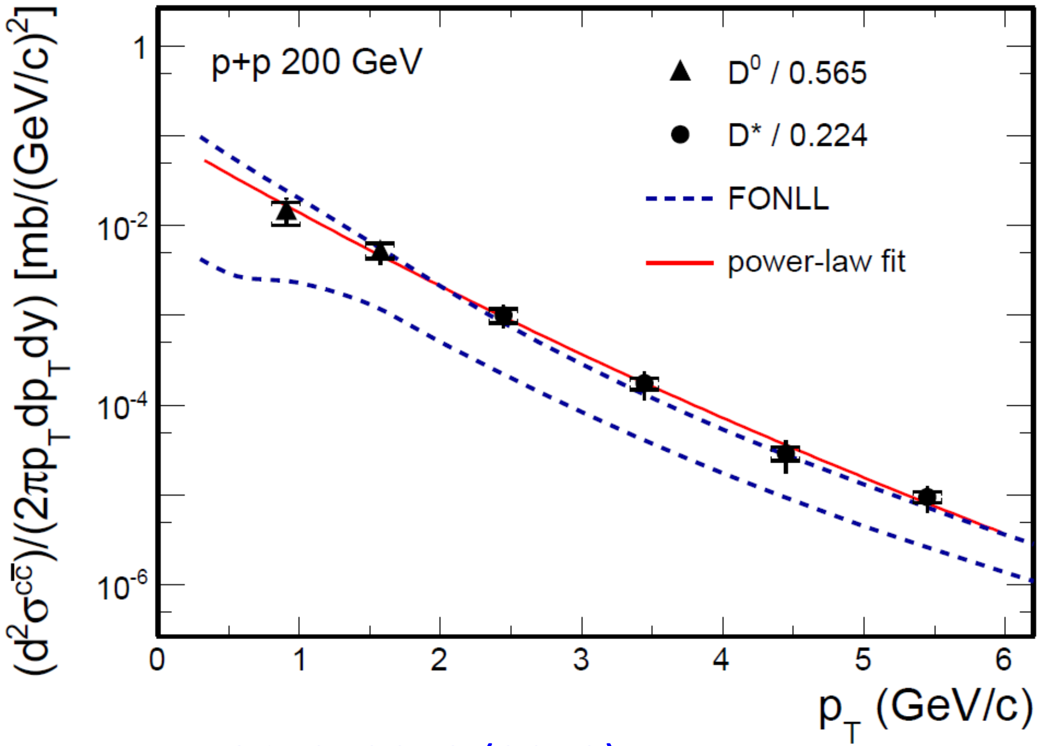
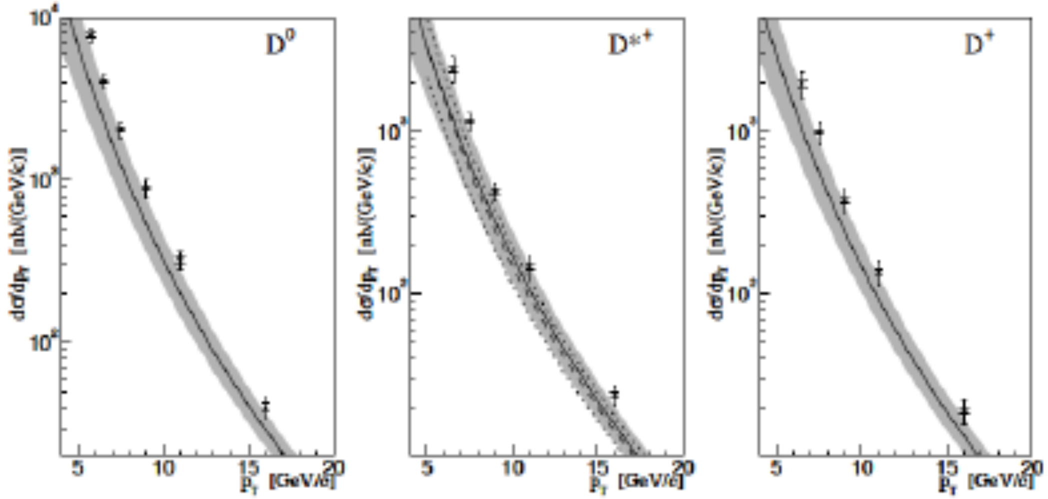
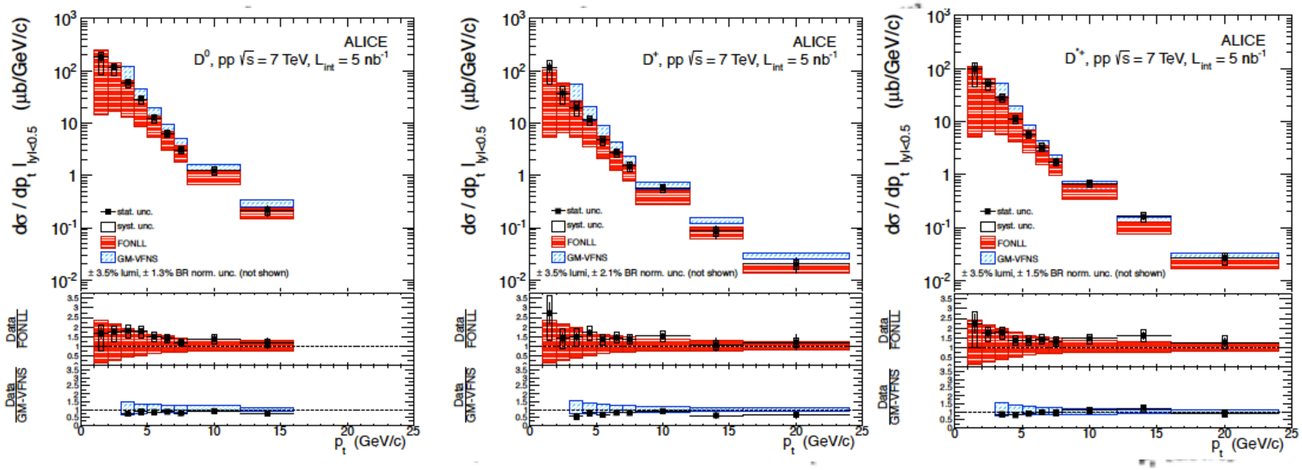


PRD 86, 072013 (2012)

CDF p+$\bar{p}$ @ 1.96 TeV *PRL 91 (2003) 241804*



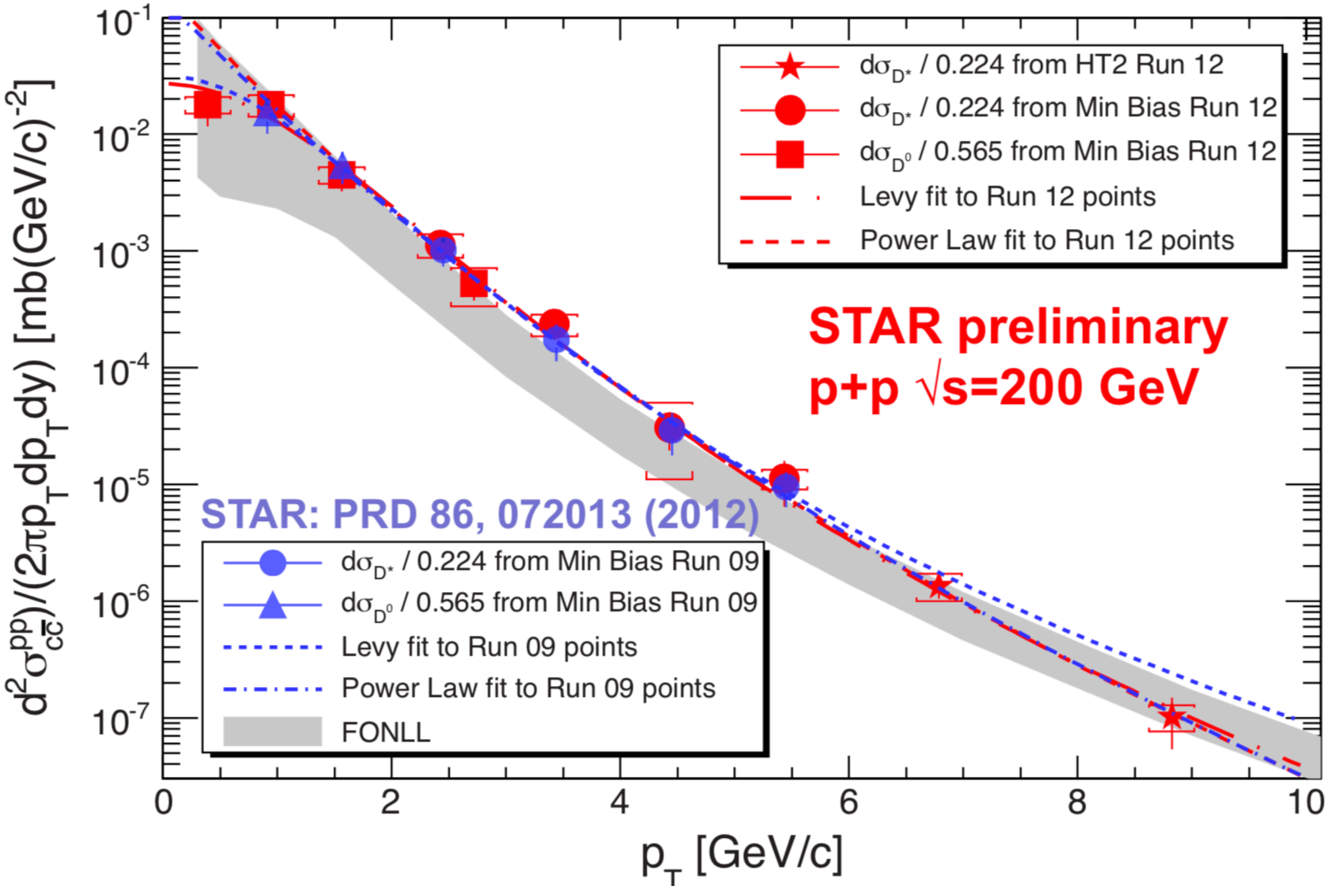
ALICE p+p @ 7 TeV *JHEP 1201 (2012) 128*



Consistent with FONLL upper limit.
Similar observations at CDF and ALICE.
Constraints to theory calculations.

R. Nelson, R. Vogt, A. D. Frawley, *arXiv: 1210.4610*

Further precise measurements in p+p collisions



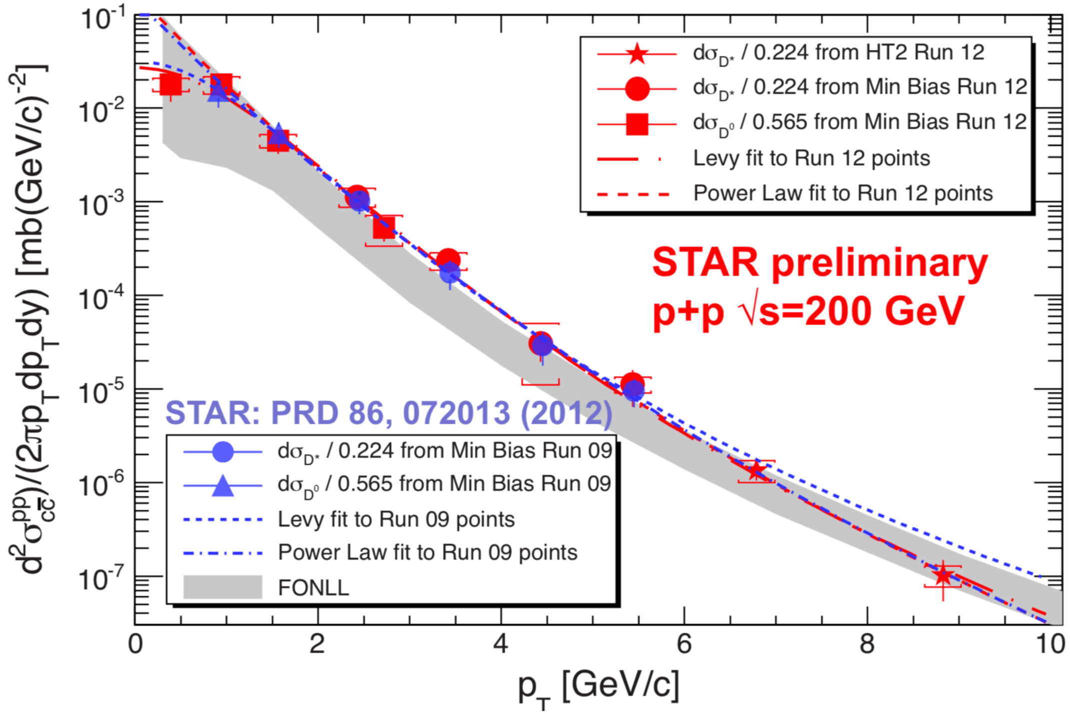
D^0 yield scaled by N_{D0}/N_{cc}= 0.565[1]

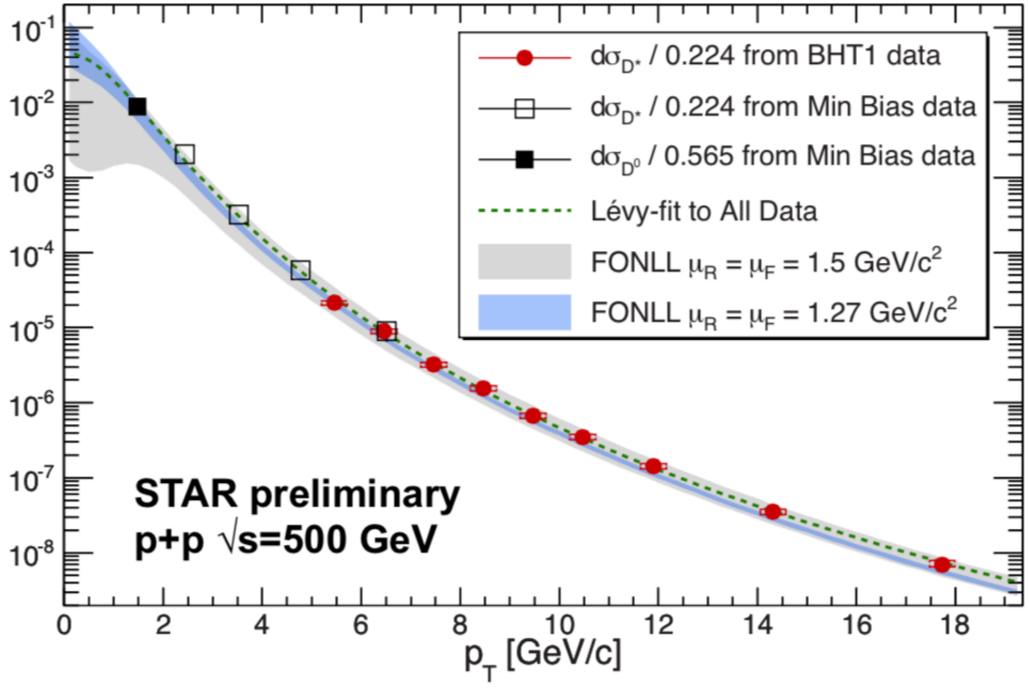
D^* yield scaled by N_{D*}/N_{cc}= 0.224[1]

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

Consistent with previous measurement.
Extended the p_T coverage down to p_T ~0.4 GeV/c and up to ~9 GeV/c.

Further precise measurements in p+p collisions

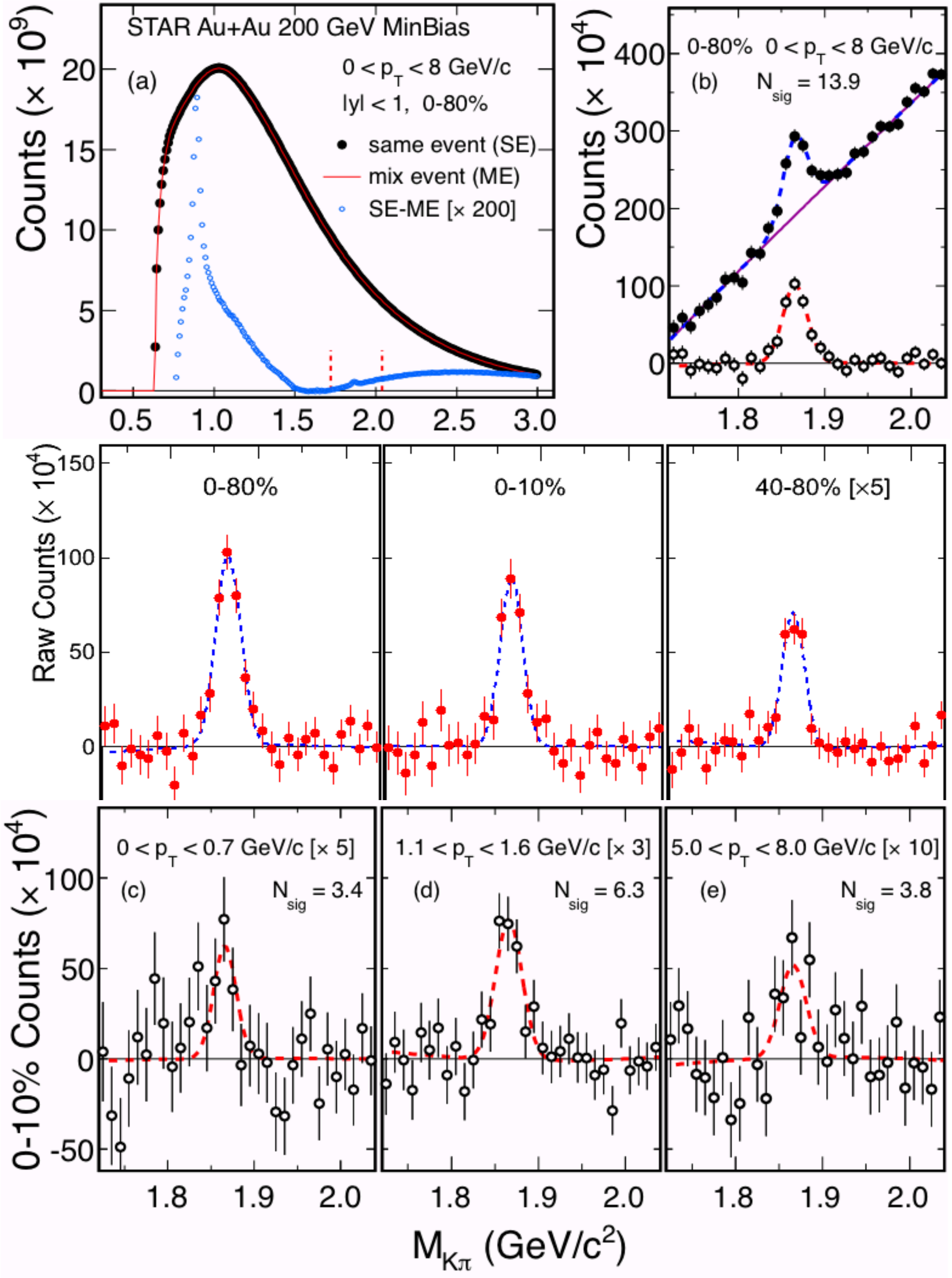




More statistics in 500 GeV, extended p_T up to 18 GeV/c.
Data consistent with FONLL calculation.

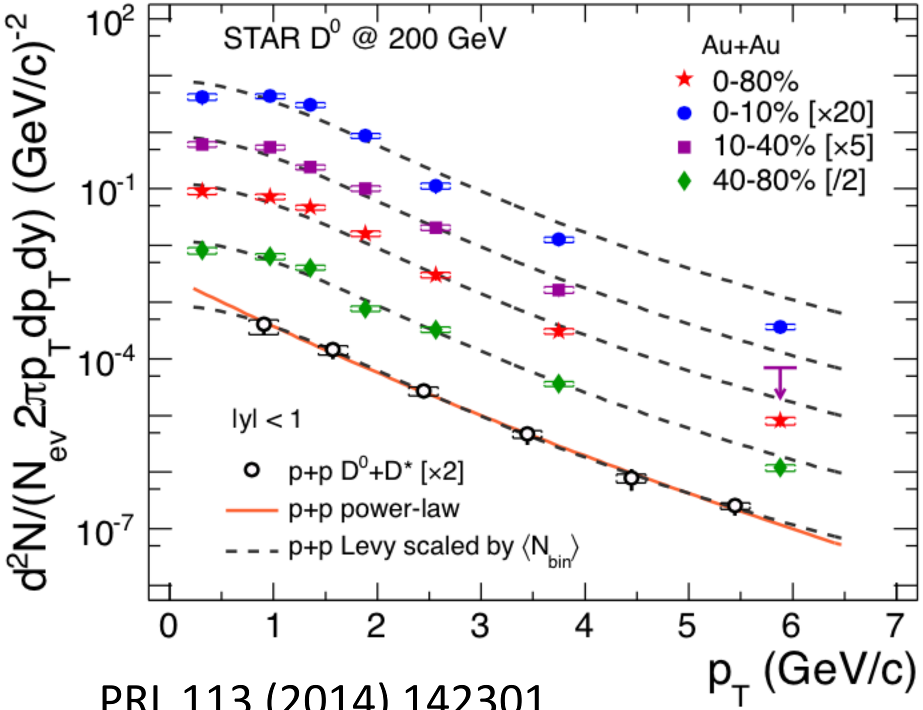
FONLL calculation:
R. Vogt
$\mu_F = \mu_R = m_c$, $|y| < 1$

D^0 signals in Au+Au 200 GeV



- Combining data from Year2010 & 2011.
- **Total: ~ 800M Min.Bias events**
- **Without HFT (no secondary vertices reconstructed)**
- **Significant signals are observed Total ~ 14σ**

Nuclear modification of D^0



PRL 113 (2014) 142301
pp reference:
PRD 86 (2012) 072013

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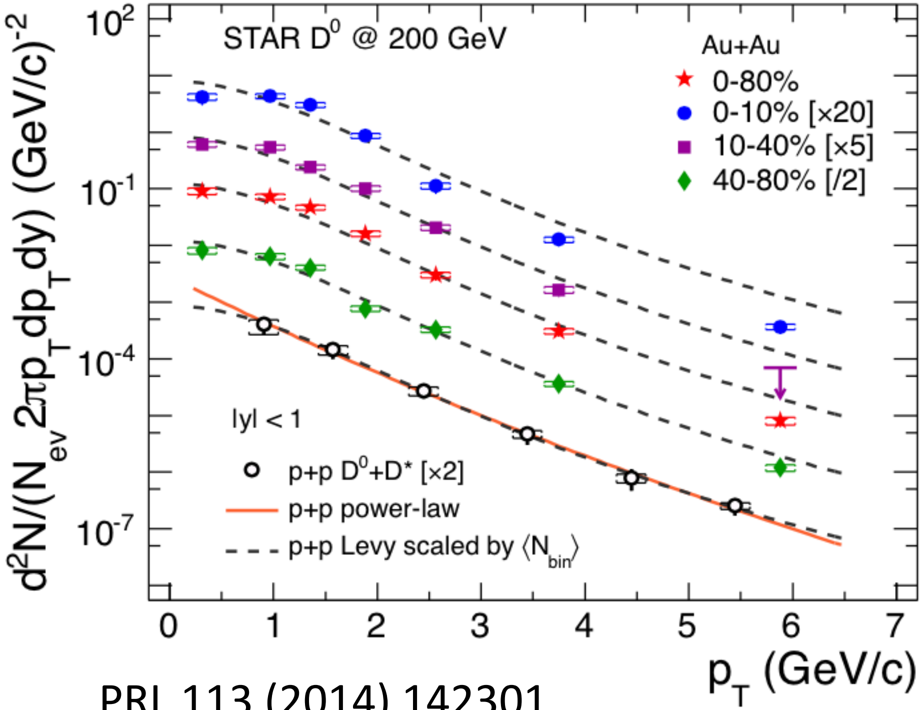

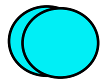

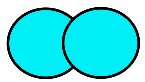

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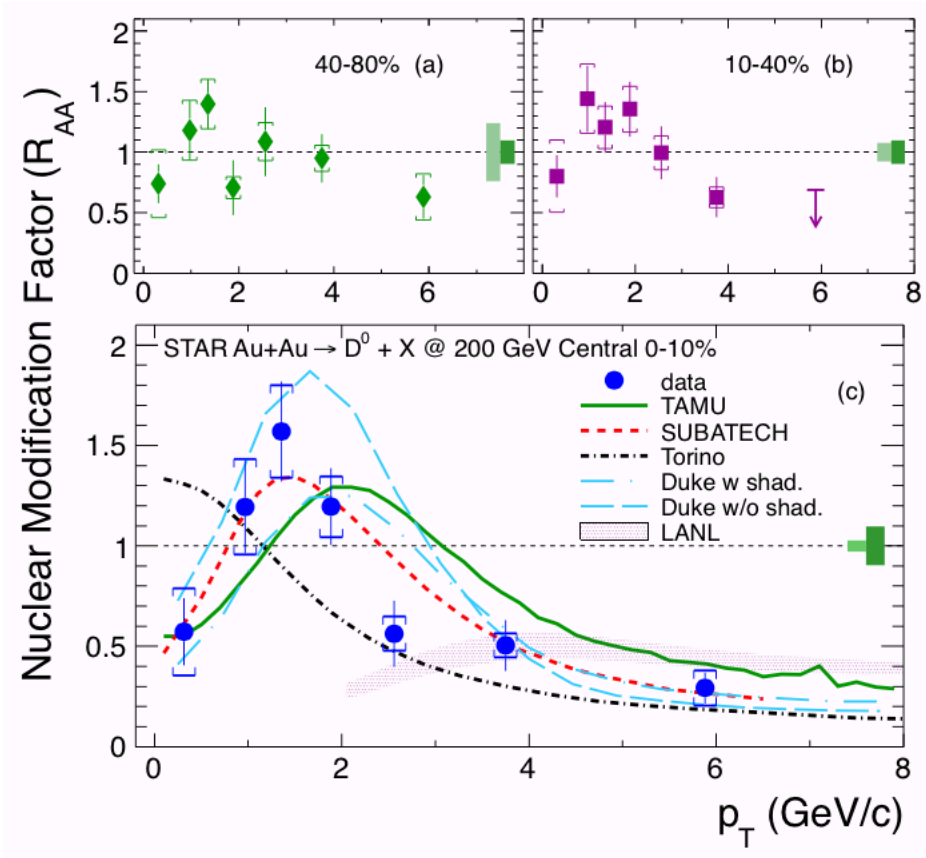
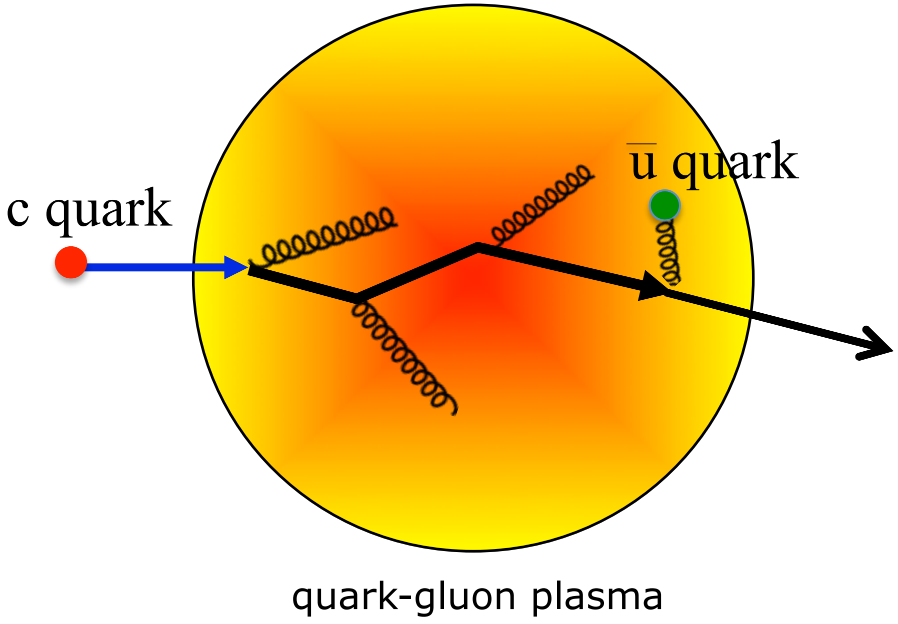
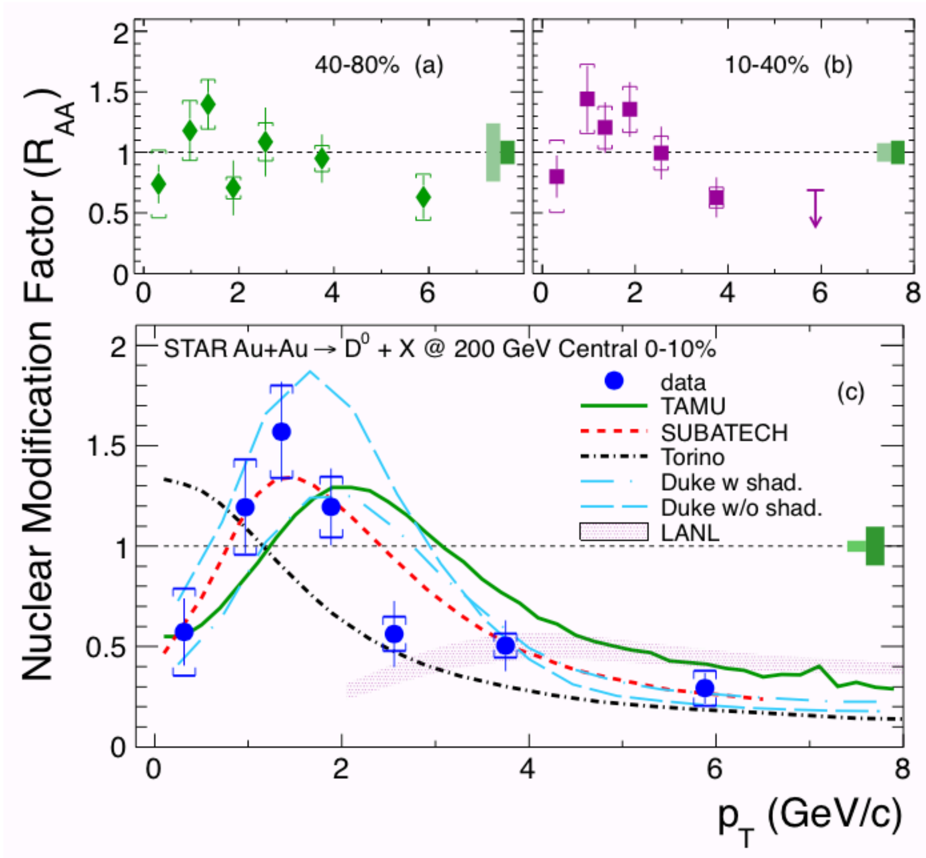


- No obvious suppression observed in peripheral collisions.
- Suppression at high p_T (> 3 GeV/c) in central and mid-central collisions.
- Low p_T enhancement, radial flow of light quarks coalescence with charm.

He,Fries,Rapp: PRC86,014903;
arXiv:1204.4442; private comm.
P. Gossiaux: arXiv: 1207.5445

Nuclear modification of D^0





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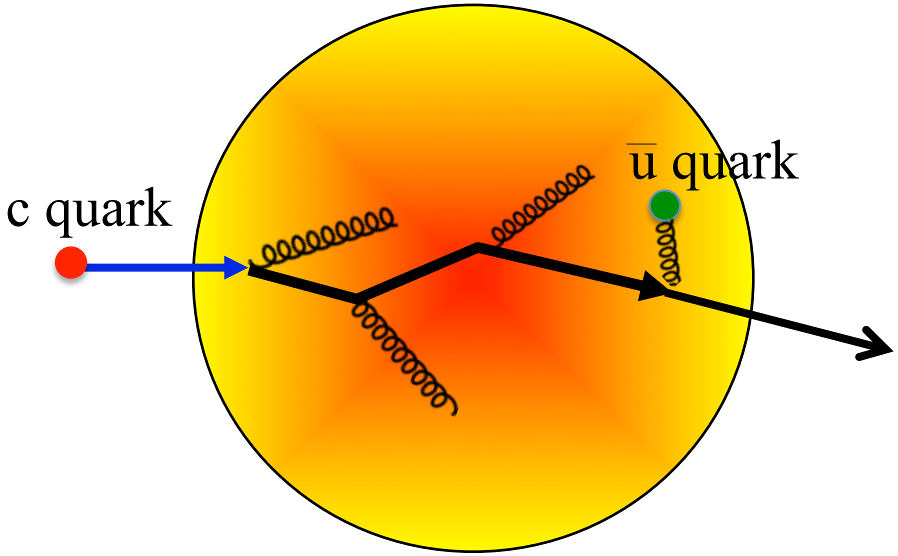
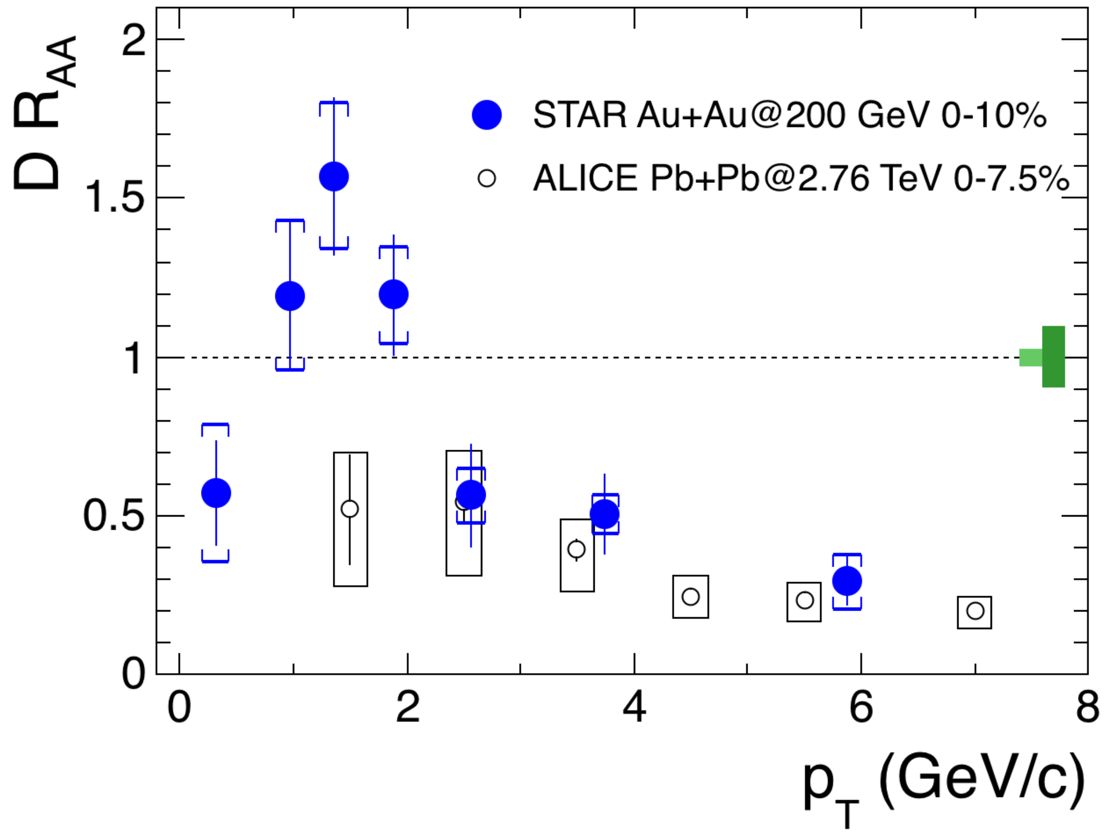
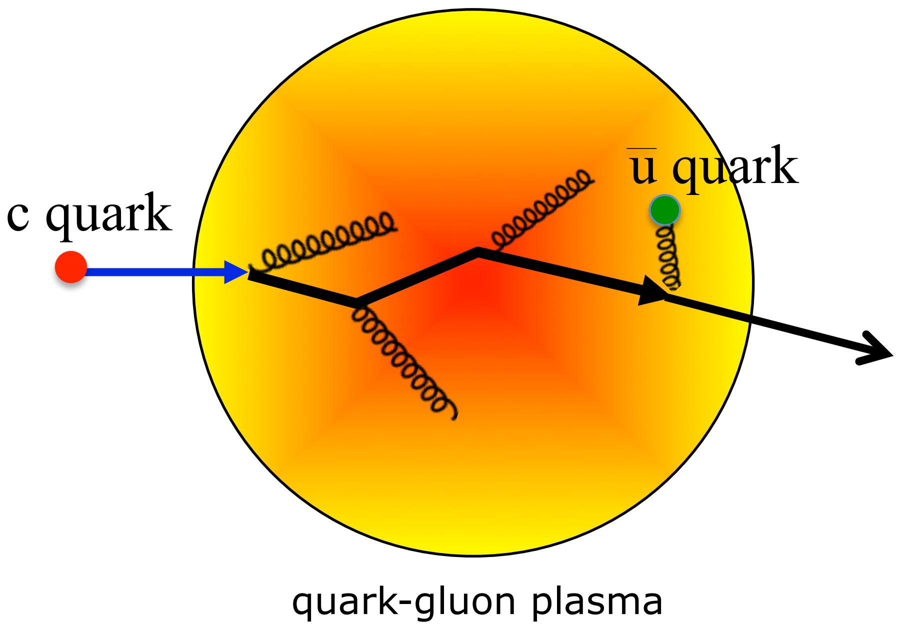
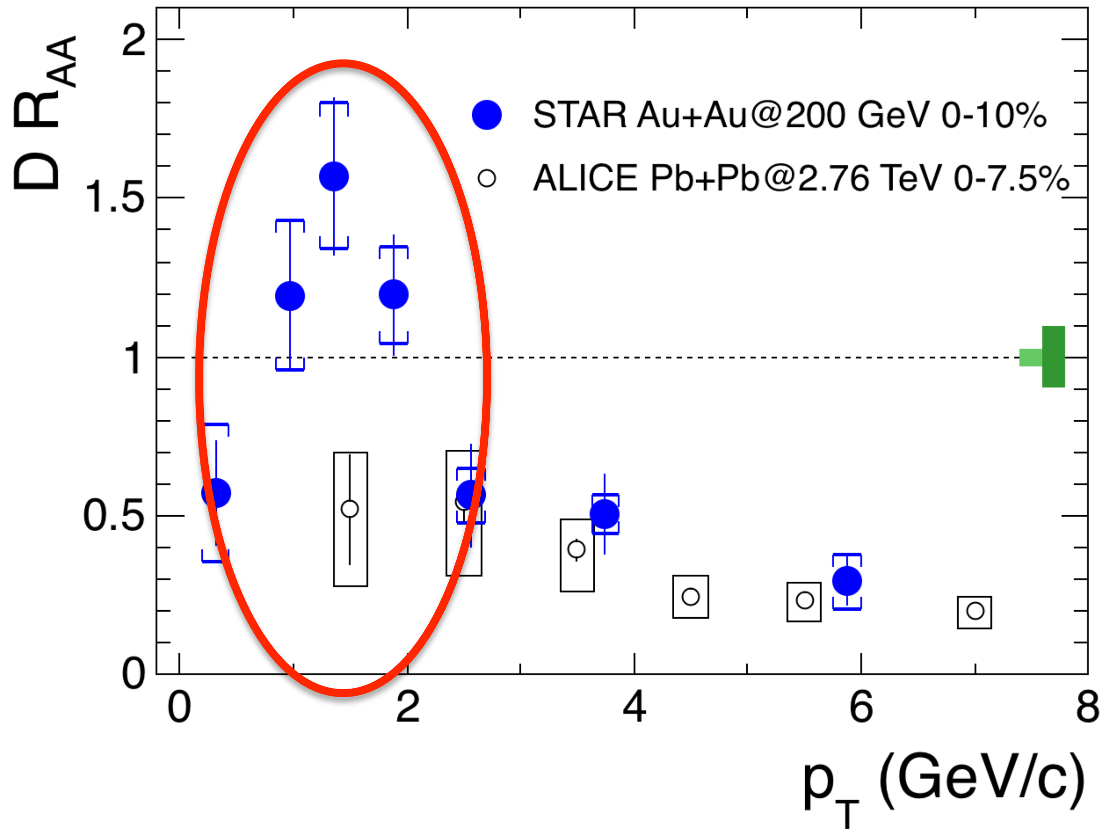




➢ Suppression at high p_T (> 3 GeV/c) in central collisions.
Consistent with ALICE result at high p_T.

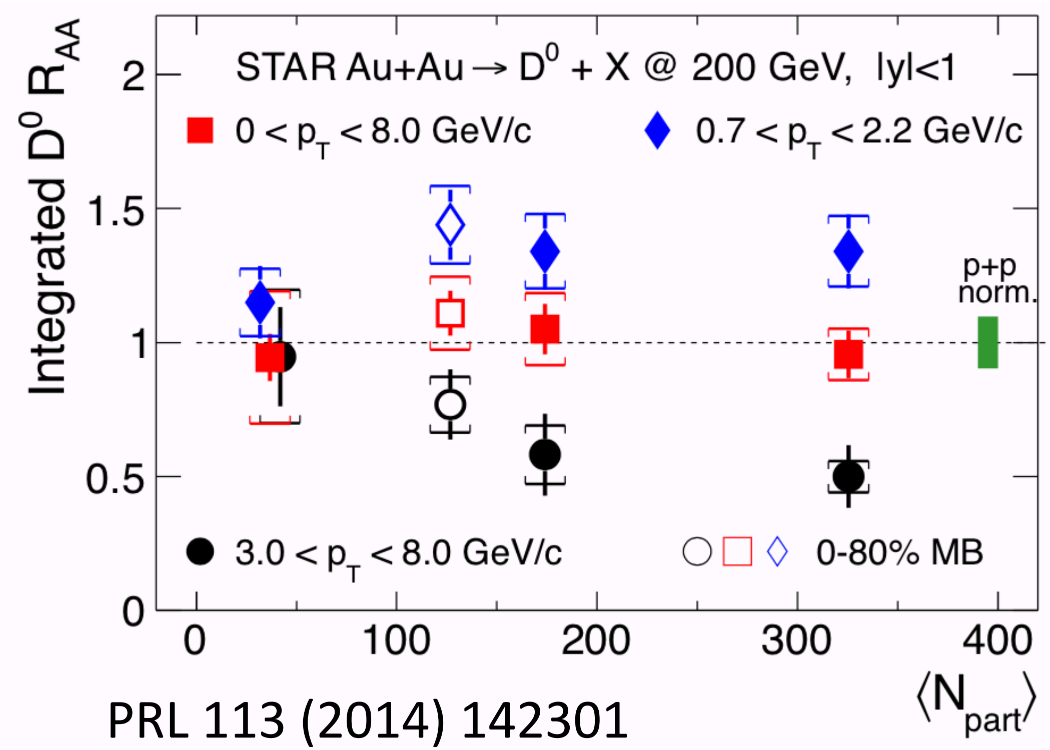
Nuclear modification of D^0





- Suppression at high p_T (> 3 GeV/c) in central collisions.
  Consistent with ALICE result at high p_T.
- Charm may not be heavy enough at LHC.

Nuclear modification of D^0



PRL 113 (2014) 142301

The charm cross section at mid-rapidity:

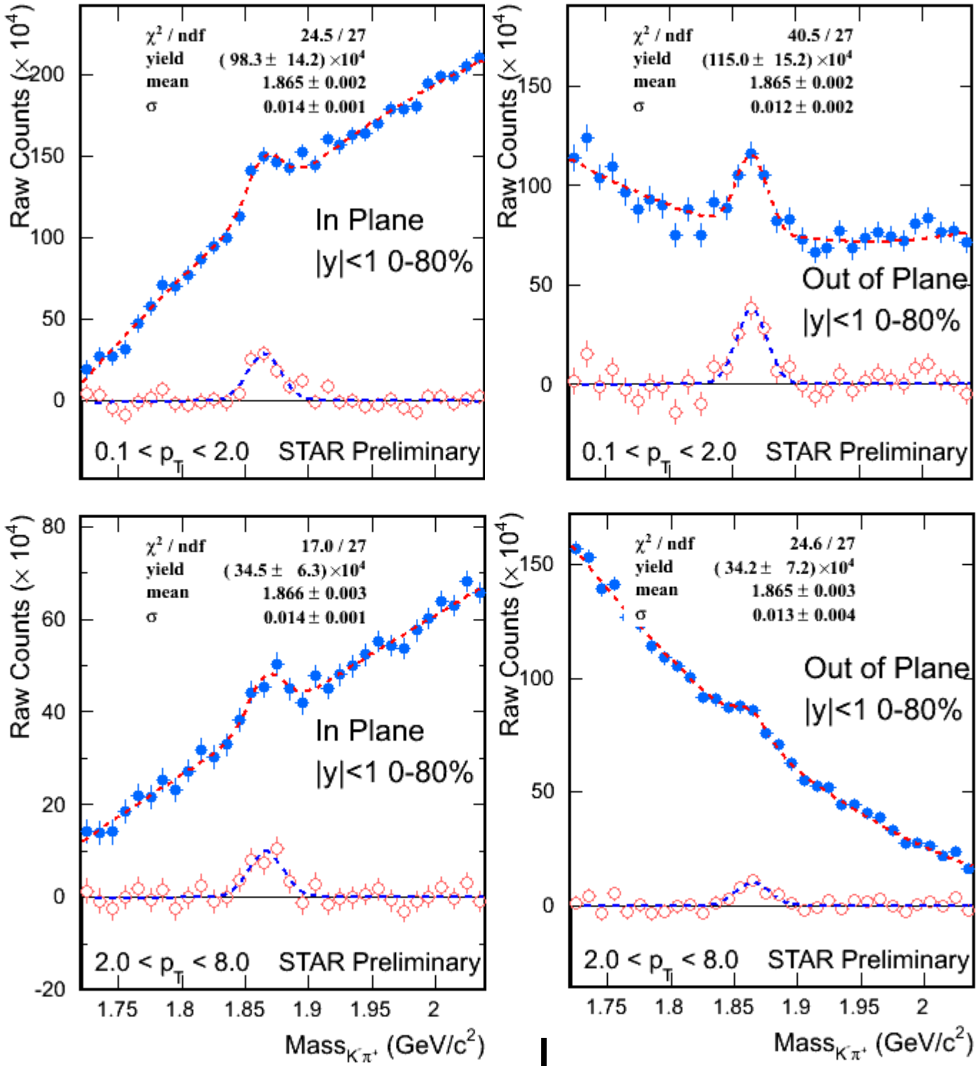
$$\left.\frac{d\sigma}{dy}\right|_{y=0}^{pp} = 170 \pm 45^{+38}_{-59}\,\mu b \qquad \left.\frac{d\sigma}{dy}\right|_{y=0}^{AuAu} = 175 \pm 13 \pm 23\,\mu b$$

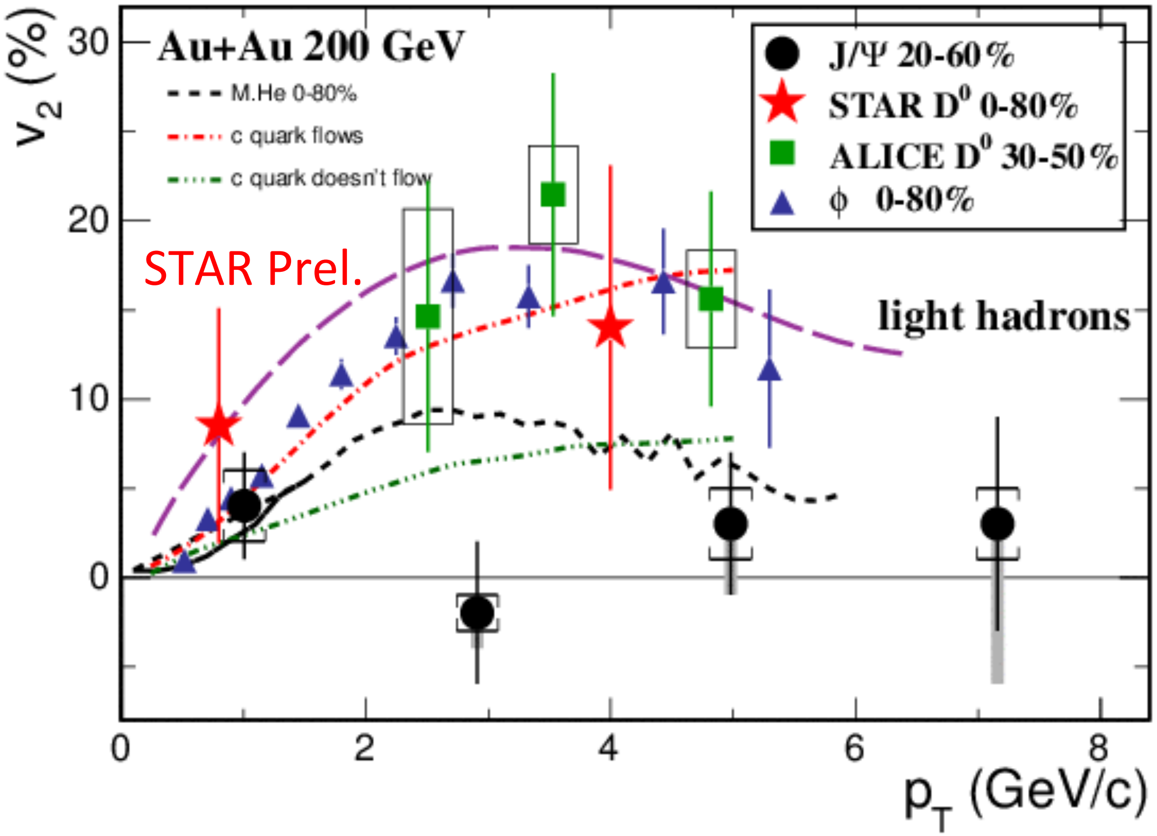
The total charm cross section (extrapolate from PYTHIA F~4.7):

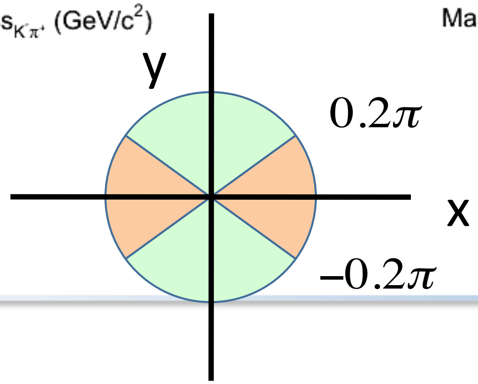
$$\sigma_{c\bar{c}}^{pp} = 797 \pm 210^{+208}_{-295}\,\mu b \qquad \sigma_{c\bar{c}}^{AuAu} = 822 \pm 62 \pm 192\,\mu b$$

- No obvious suppression observed in peripheral collisions.
- Suppression at high p_T (> 3 GeV/c) in central and mid-central collisions.
- Low p_T enhancement, radial flow of light quarks coalescence with charm.
- Integrated yields is number of binary scaled => charm is mainly produced via initial hard scatterings.

D^0 v_2 measurement in Au+Au 200 GeV

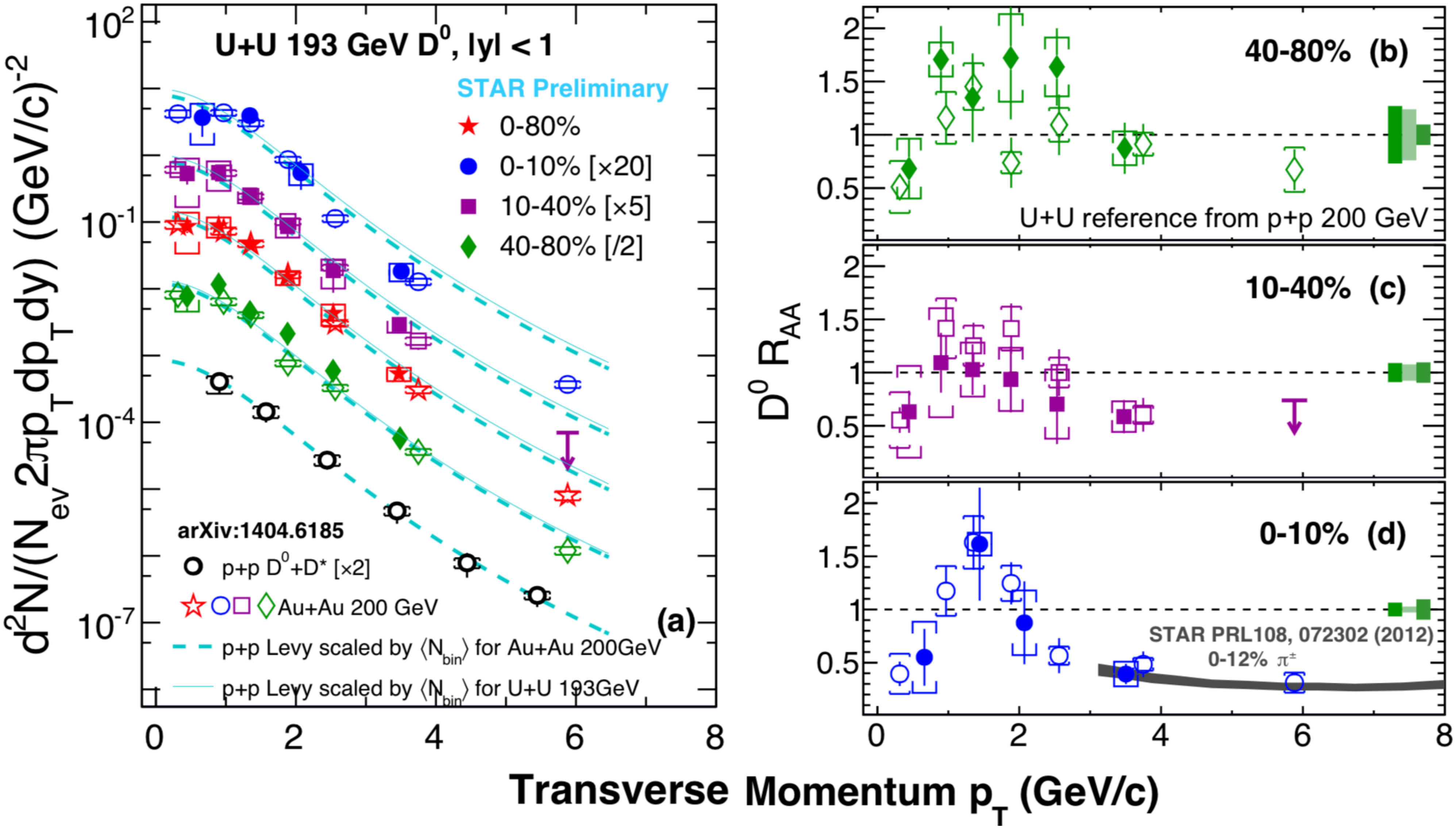






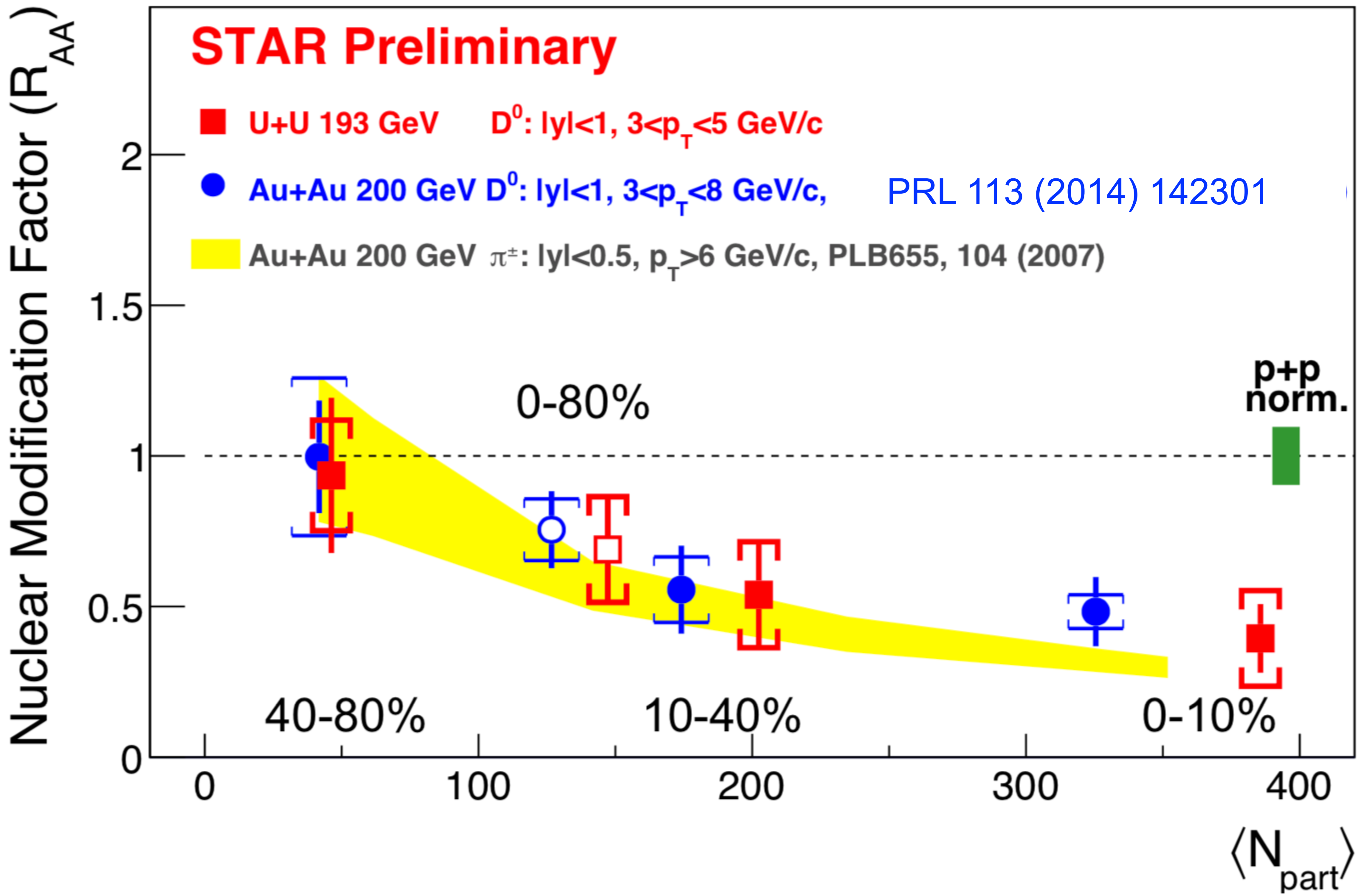
- ✧ Finite v_2 observed with large errors.
- ✧ Need HFT for more precise measurement:
  - to confirm the coalescence scenarios.
  - to confirm the energy dependence.
- ✧ Different production mechanisms compared with hidden charm?

OHF in U+U collisions



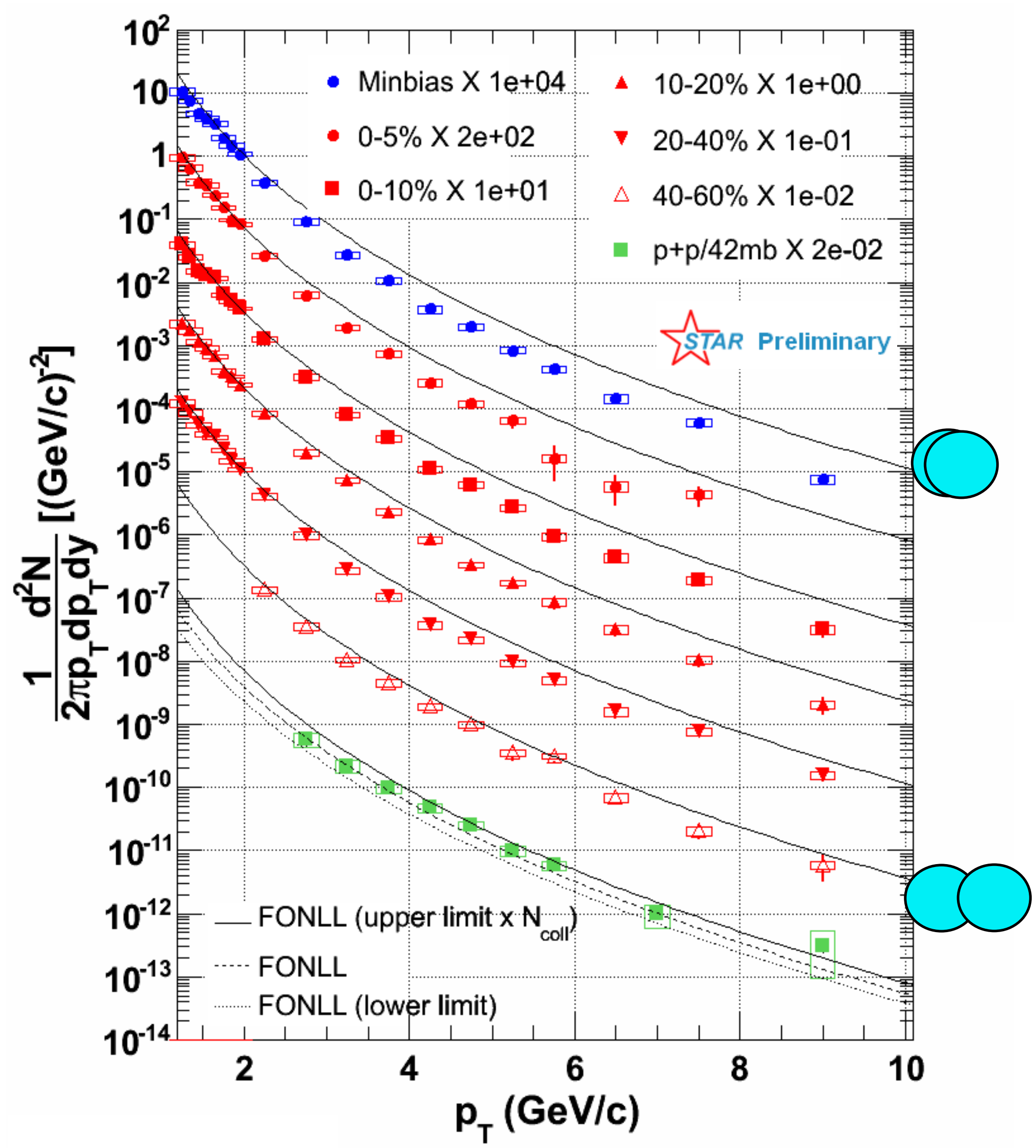
R_{AA} similar trend in U+U collisions as in Au+Au collisions.

OHF in U+U collisions



Suppression of open charm at high p_T in U+U collisions is similar to and extends the trend as that of open charm and pions in Au+Au collisions.

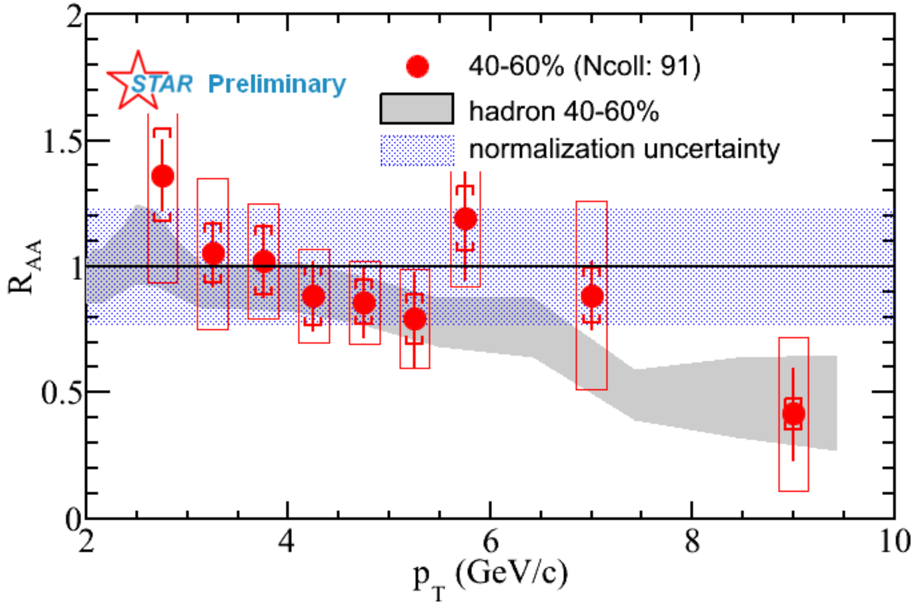
Non-photonic electron spectra in Au+Au 200 GeV



Non-photonic electron (NPE):
electron from HF decays

- ~1 nb^{-1} sampled luminosity in Run2010 Au+Au collisions.
- ~6 pb^{-1} sampled luminosity in Run2005 and Run2008 p+p collisions.

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



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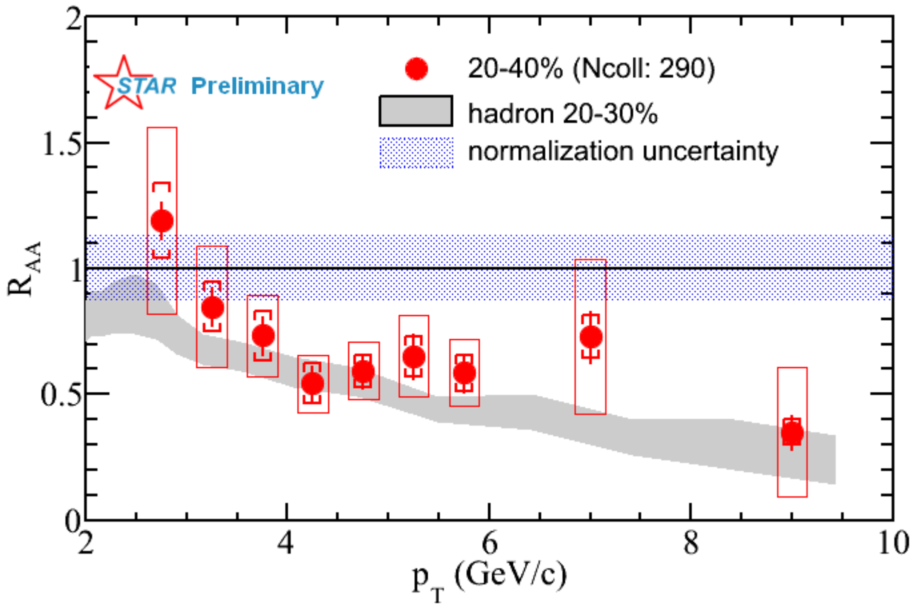

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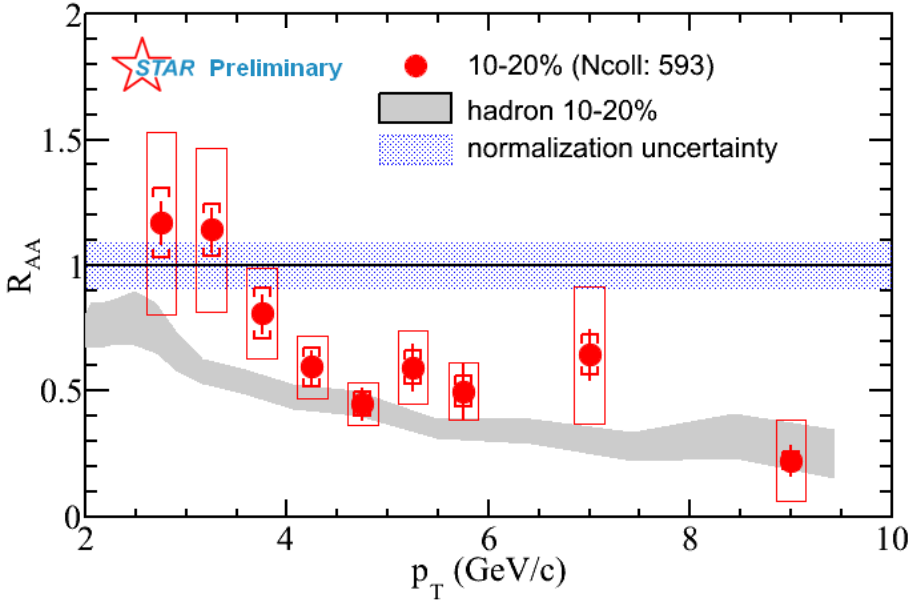

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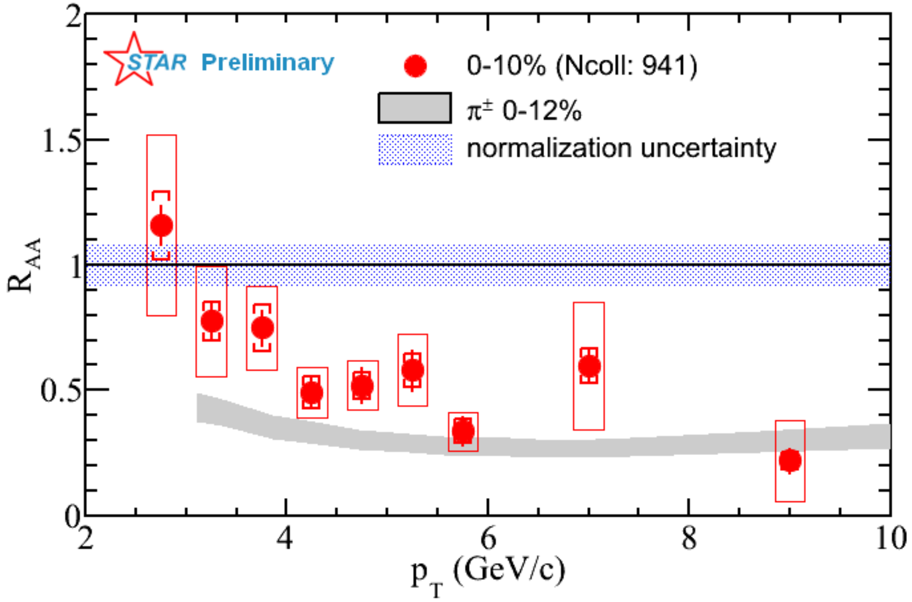
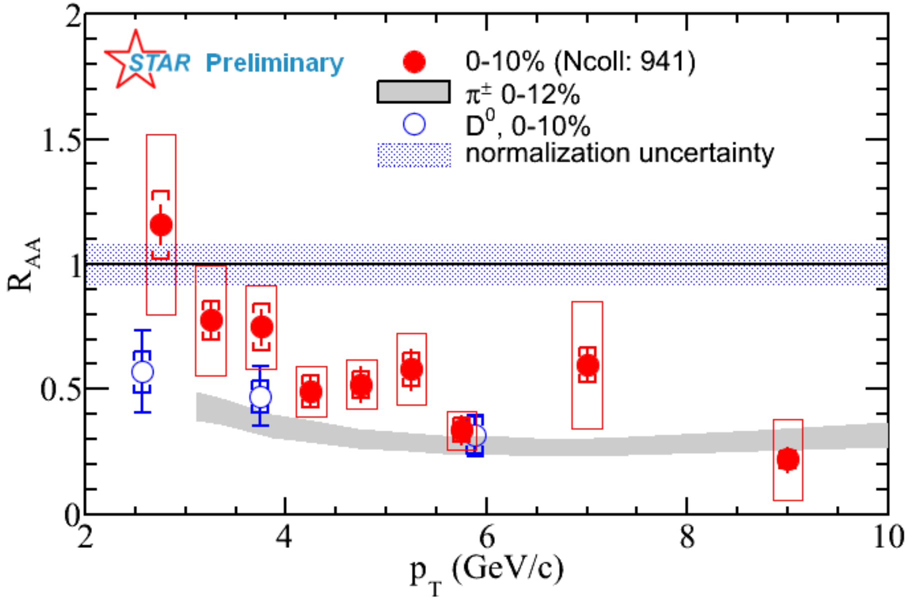


- Strong suppression at high p_T in central collisions

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



- Strong suppression at high p_T in central collisions
- D^0, NPE results seems to be consistent, in spite of kinematics smearing & charm/bottom mixing

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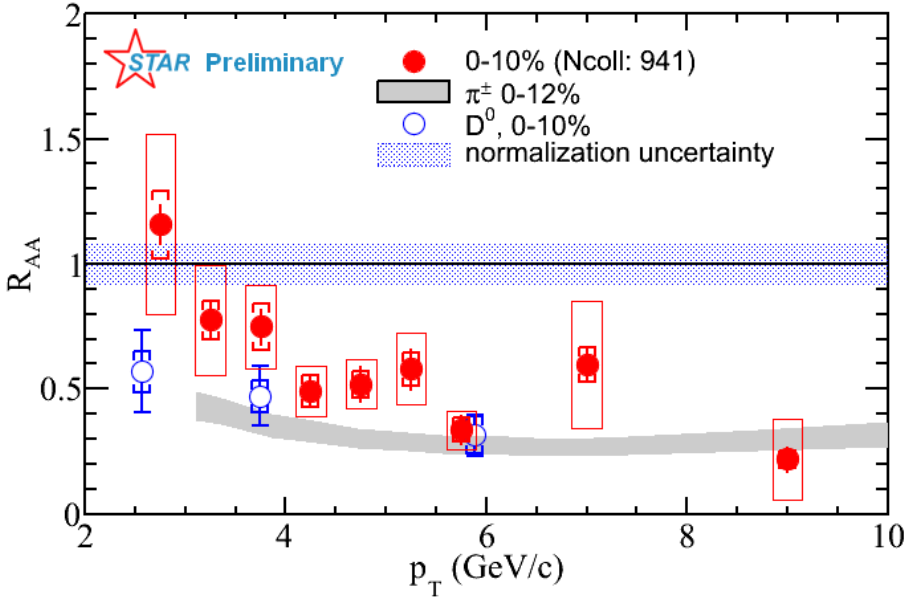
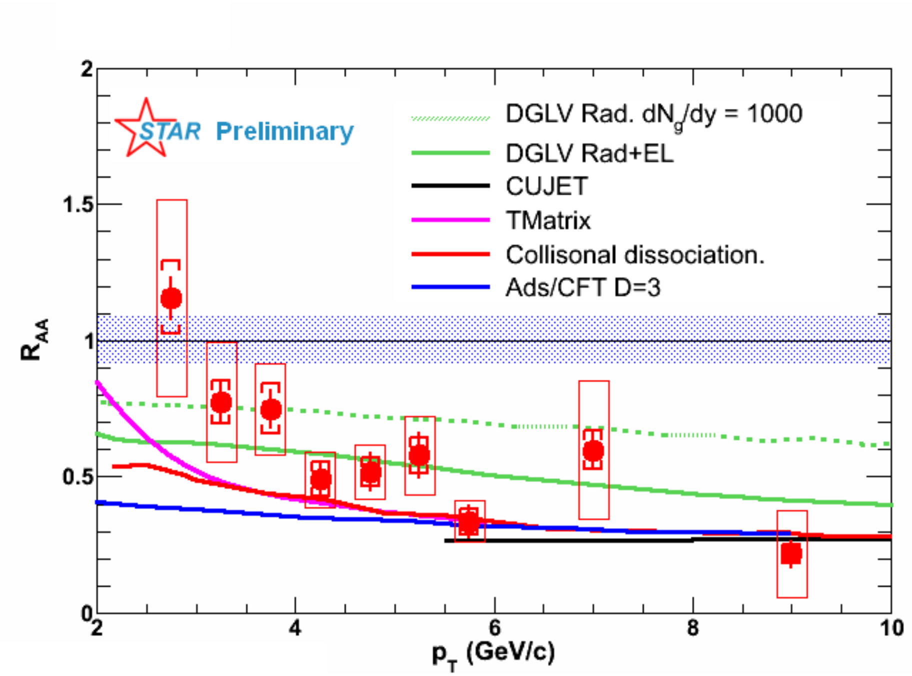
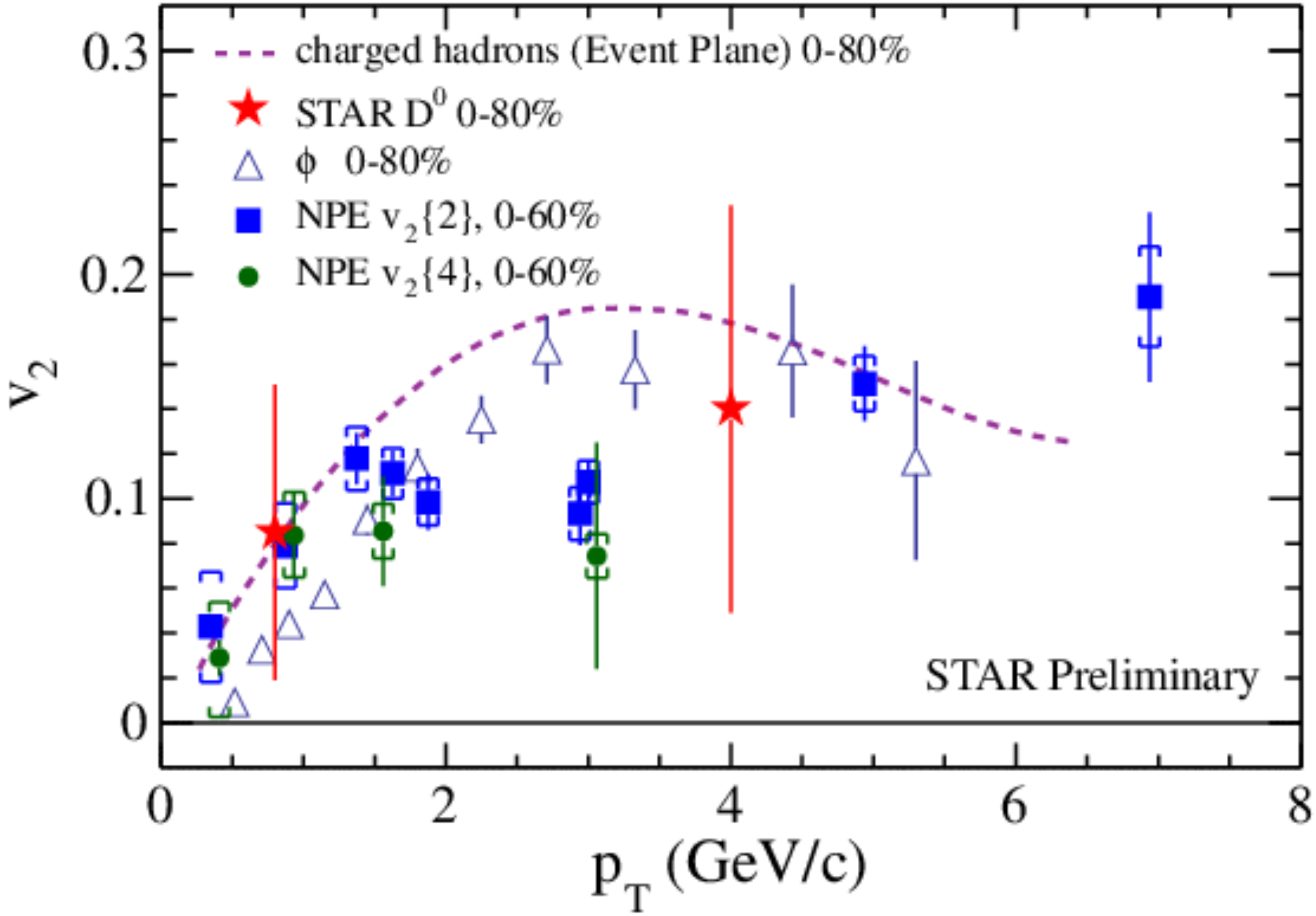




- Strong suppression at high p_T in central collisions
- D^0, NPE results seems to be consistent, in spite of kinematics smearing & charm/bottom mixing
- Models with radiative energy loss underestimate the suppression
- Uncertainty dominated by p+p result.
- Result with high quality p+p data from Run12 is on going.

DGLV: Djordjevic, PLB632, 81 (2006)
CUJET: 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.

NPE v_2 in Au+Au 200 GeV



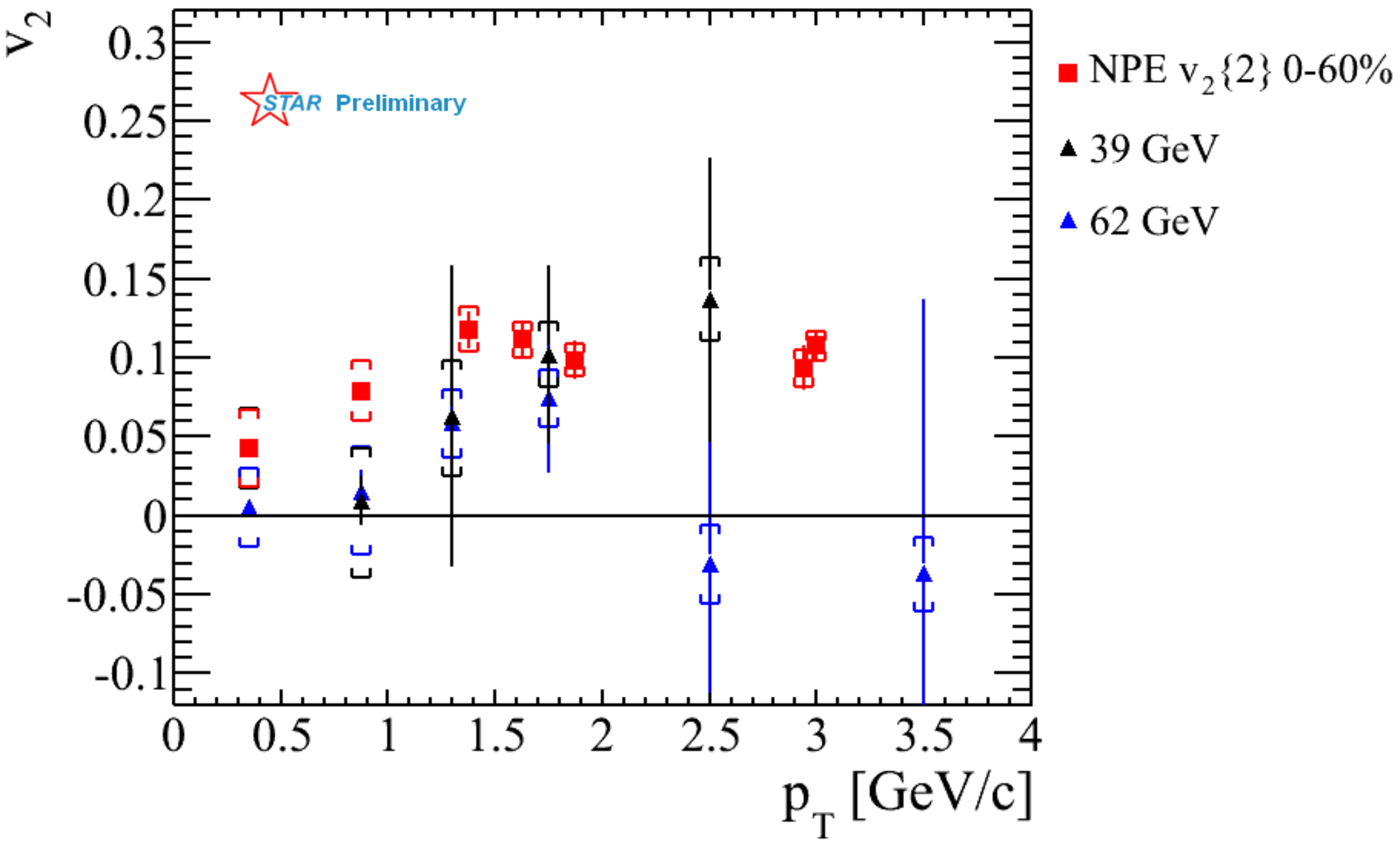
200 GeV Au+Au:

❑ **Large NPE v_2 observed at low p_T => strong charm-medium interaction**

❑ **v_2 increase at p_T > 3 GeV/c**

- path length of energy loss
- Jet-like correlation.

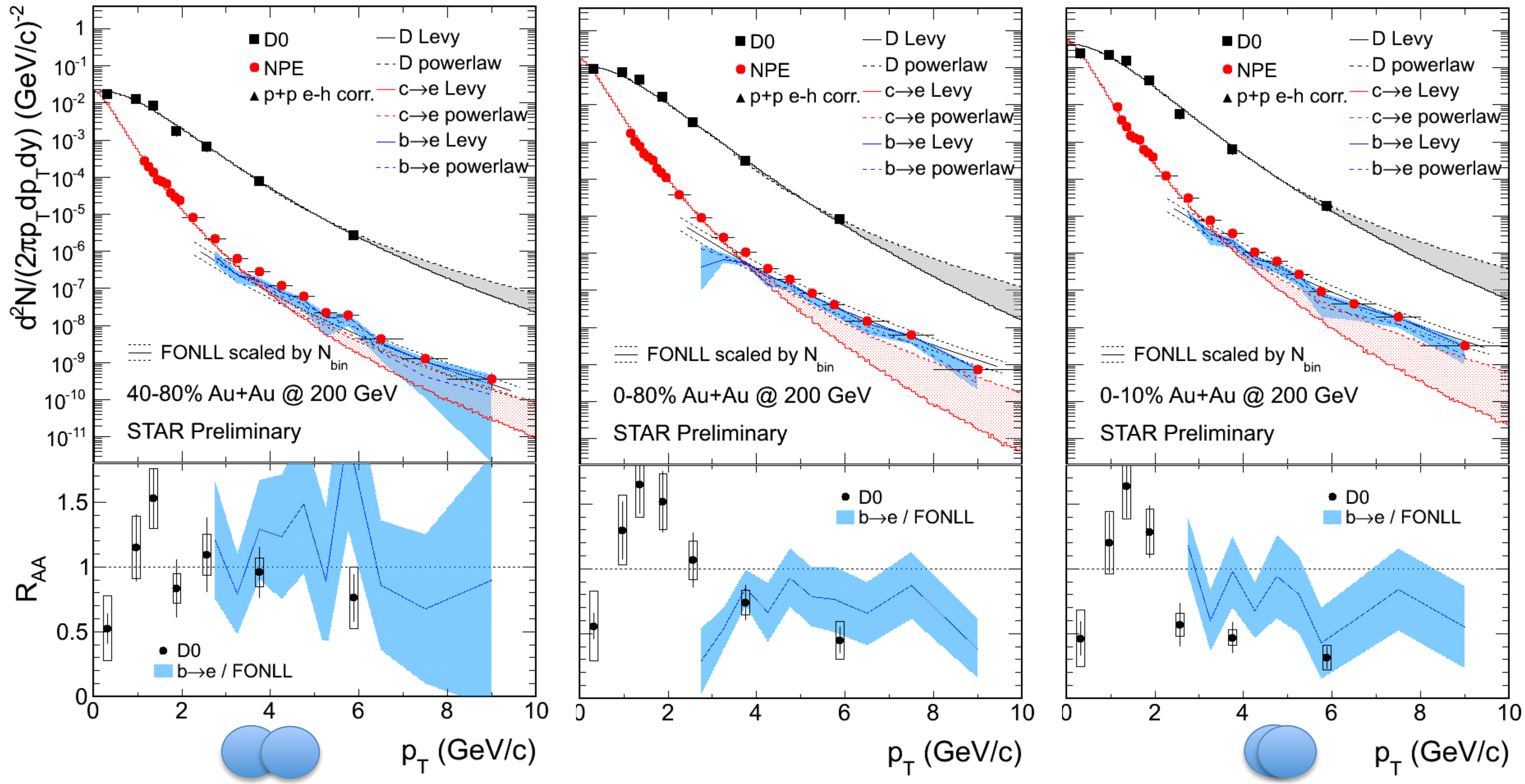
NPE v_2 in Au+Au 39 & 62 GeV



39 and 62.4 GeV Au+Au:

Low p_T v_2 consistent with zero => might suggest charm–medium interaction in lower energies is not as strong as in 200 GeV.

Bottom R_{AA}



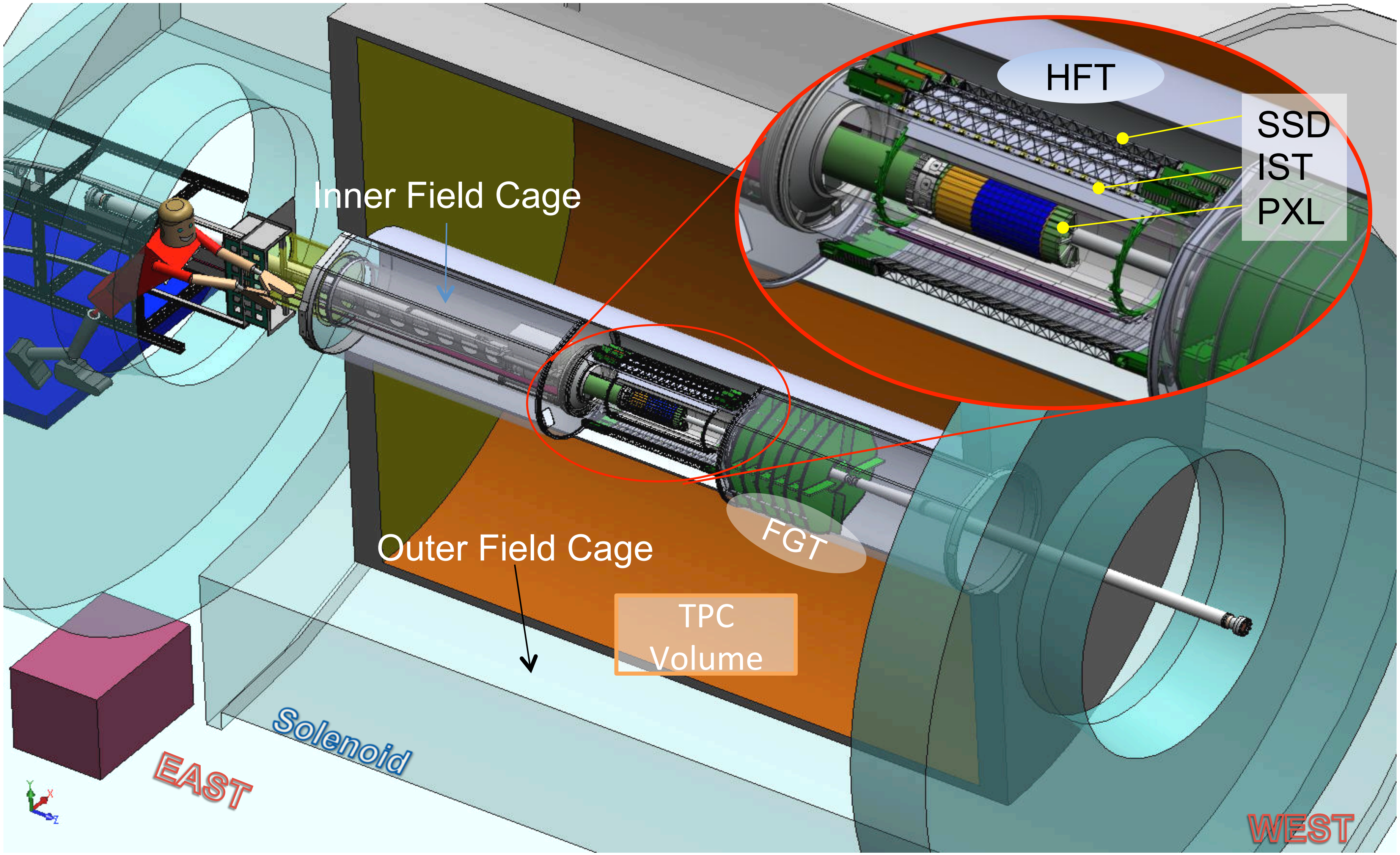
Peripheral is consistent with no suppression.

Minbias and central 0-10% show no obviously larger suppression compared with D^0 R_{AA}.

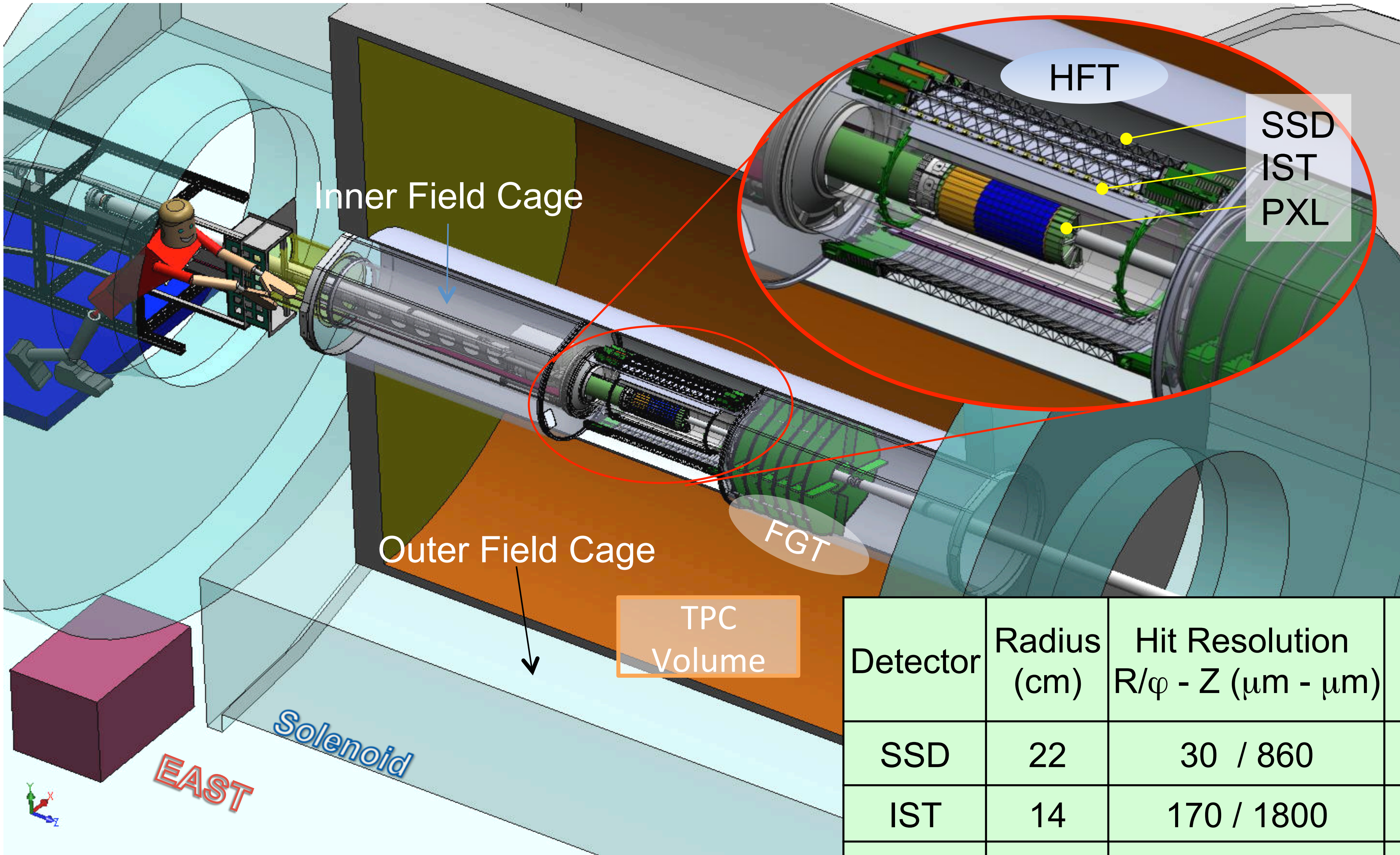
We expect more precise measurement with Heavy Flavor Tracker.

Now is HFT era …

Heavy Flavor Tracker

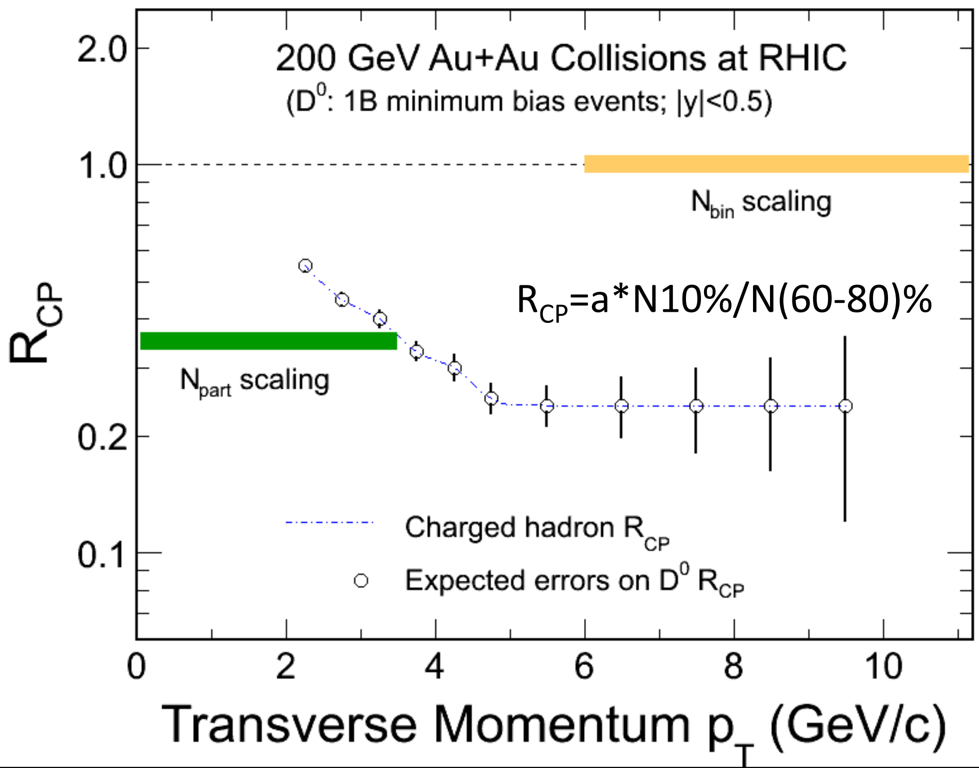


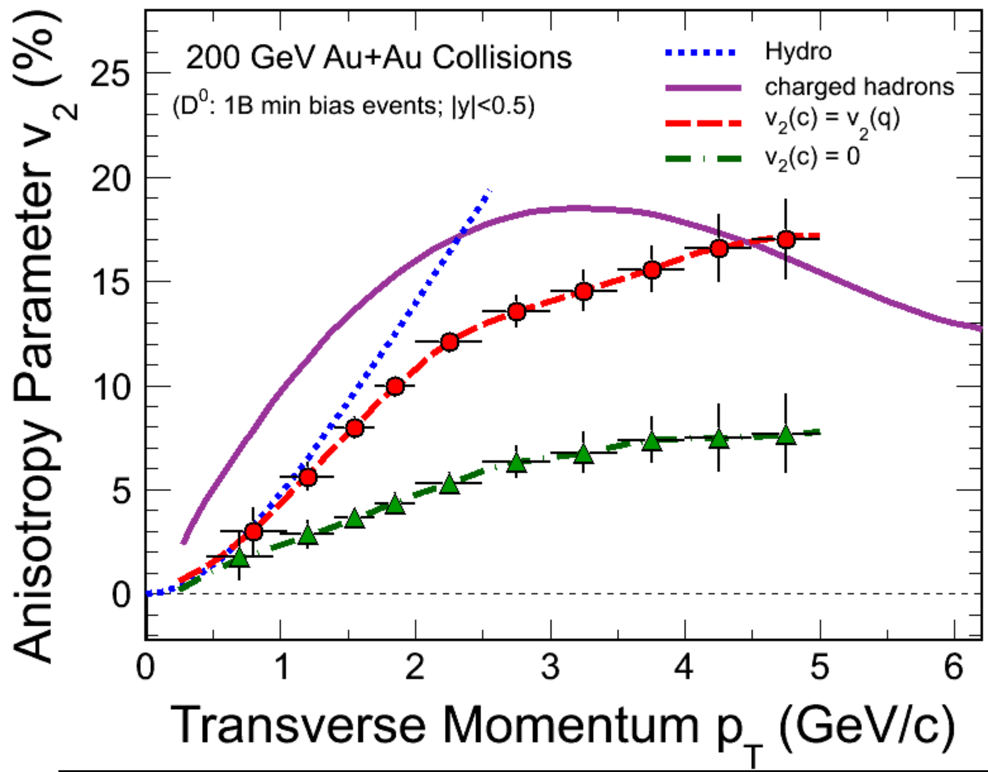
Heavy Flavor Tracker



Detector	Radius (cm)	Hit Resolution R/φ - Z (μm - μm)	Radiation length
SSD	22	30 / 860	1% X_0
IST	14	170 / 1800	1.32% X_0
PIXEL	8	6.2 / 6.2	~0.52% X_0
	2.8	6.2 / 6.2	~0.39% X_0

Physics projections with HFT





Assuming D^0 R_{cp} distribution as charged hadron.

1B Au+Au m.b. events at 200 GeV.

- Charm R_{AA} ⇨

Energy loss mechanism!

Charm interaction with QCD matter!

Assuming D^0 v_2 distribution from quark coalescence.

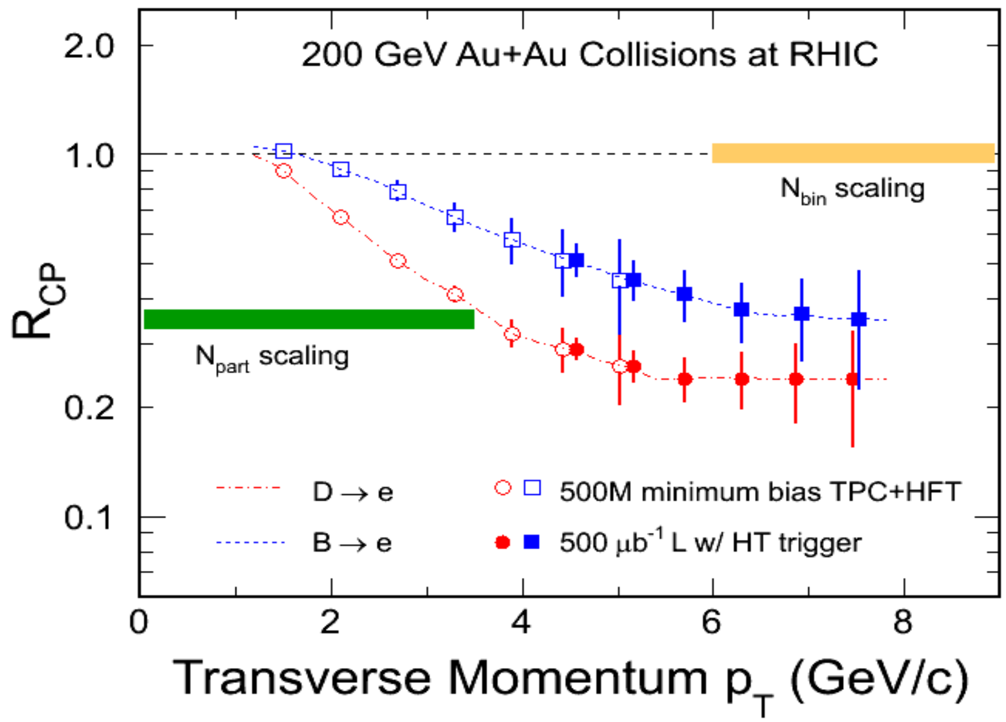
1B Au+Au m.b. events at 200 GeV.

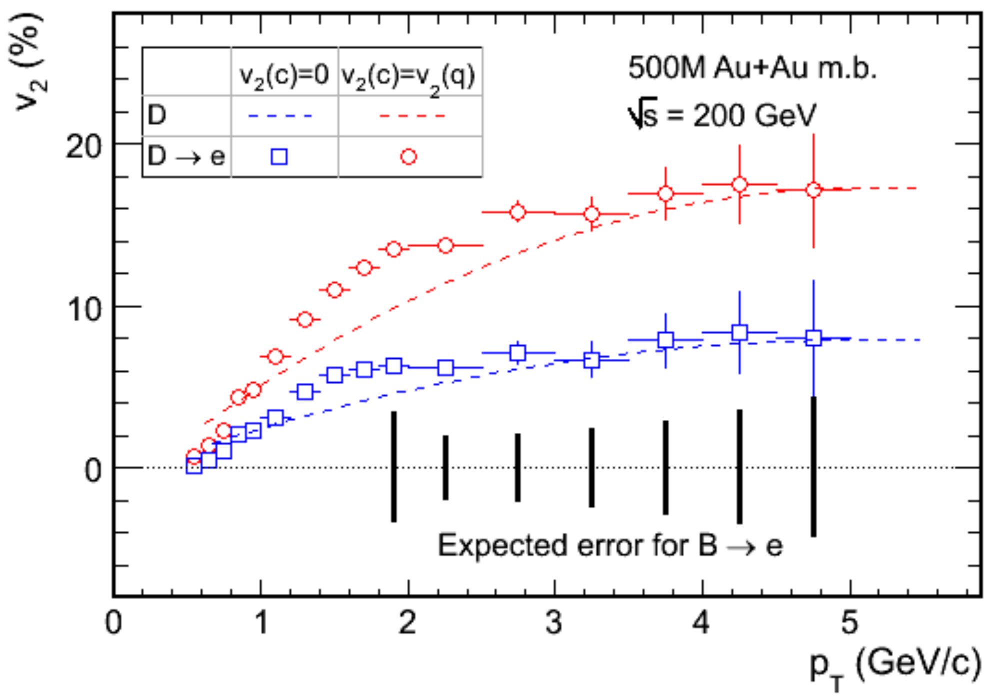
- Charm v_2 ⇨

Medium/light flavor thermalization

Drag coefficients!

Statistic projection of e_D, e_B R_{CP} & v_2

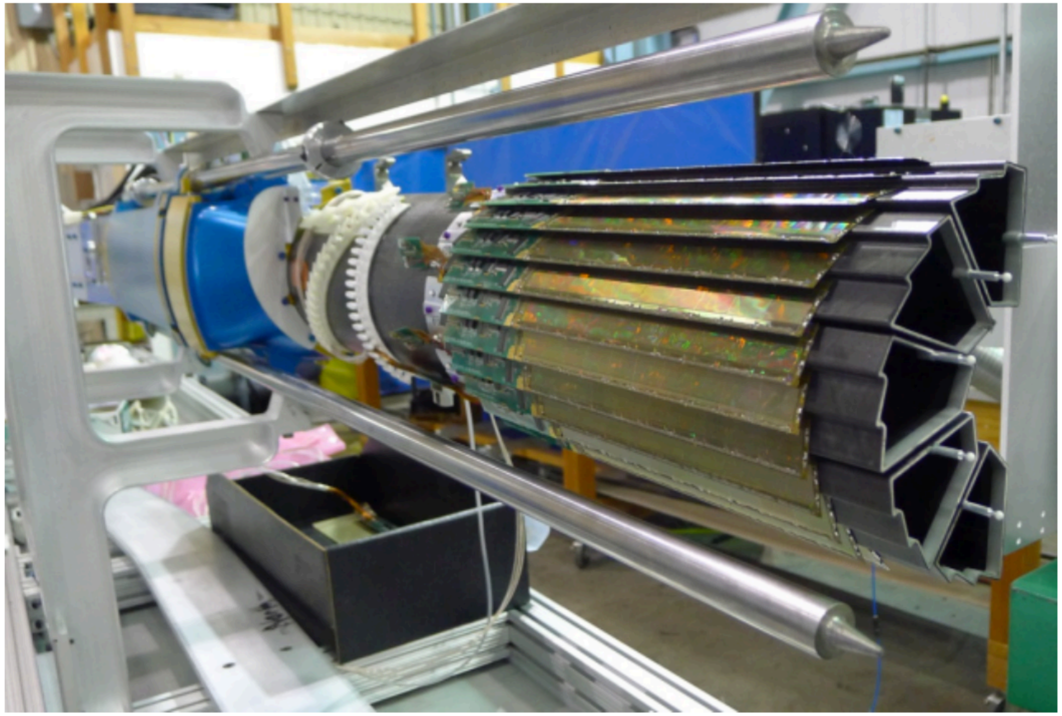


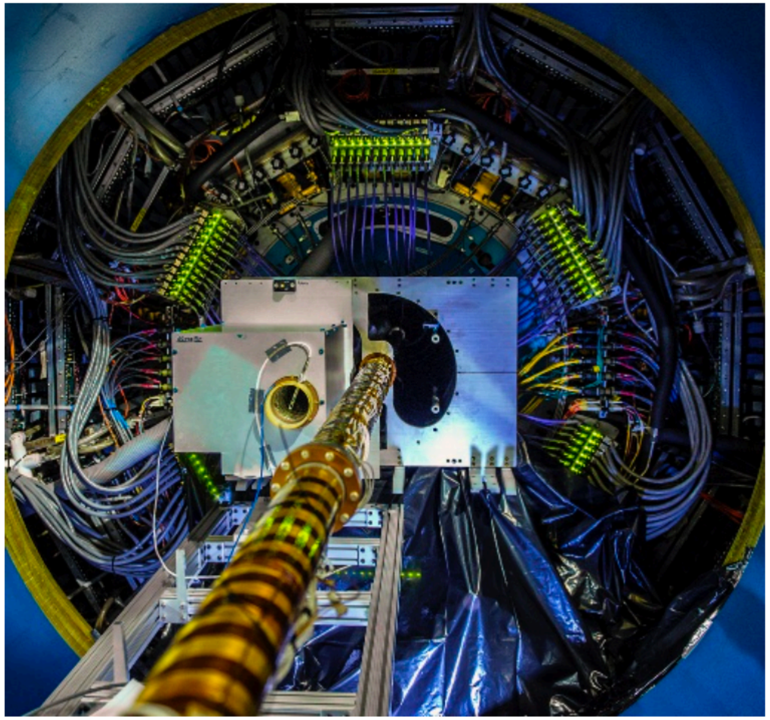


Curves: H. van Hees *et al*. Eur. Phys. J. **C61**, 799(2009).

- (B→e) spectra obtained via the subtraction of charm decay electrons from inclusive NPEs:
  - **- no model dependence, reduced systematic errors.**
- Unique opportunity for bottom e-loss and flow.
  - **- Charm may not be heavy enough at RHIC, but how is bottom?**

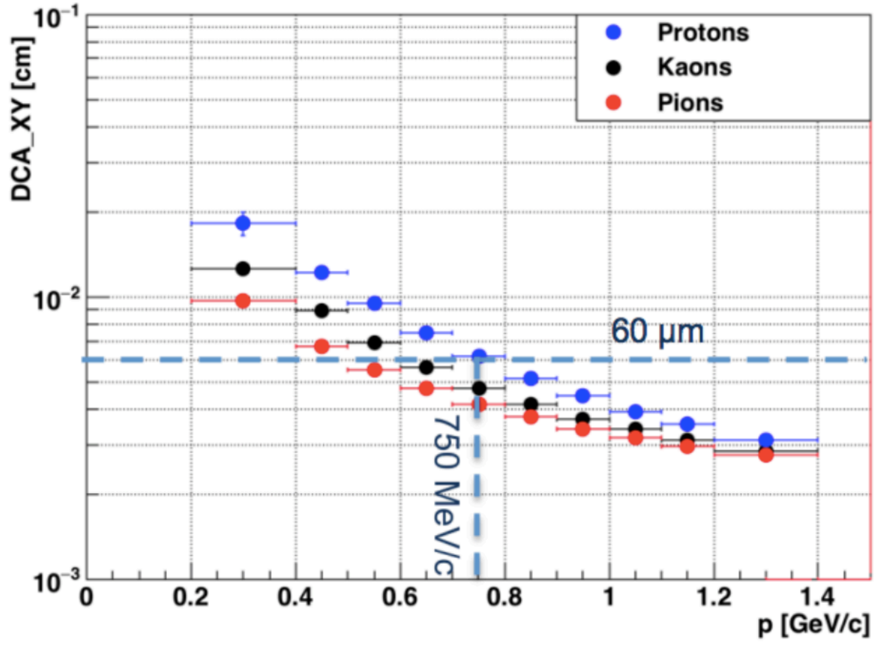
HFT Commission and Operation in STAR

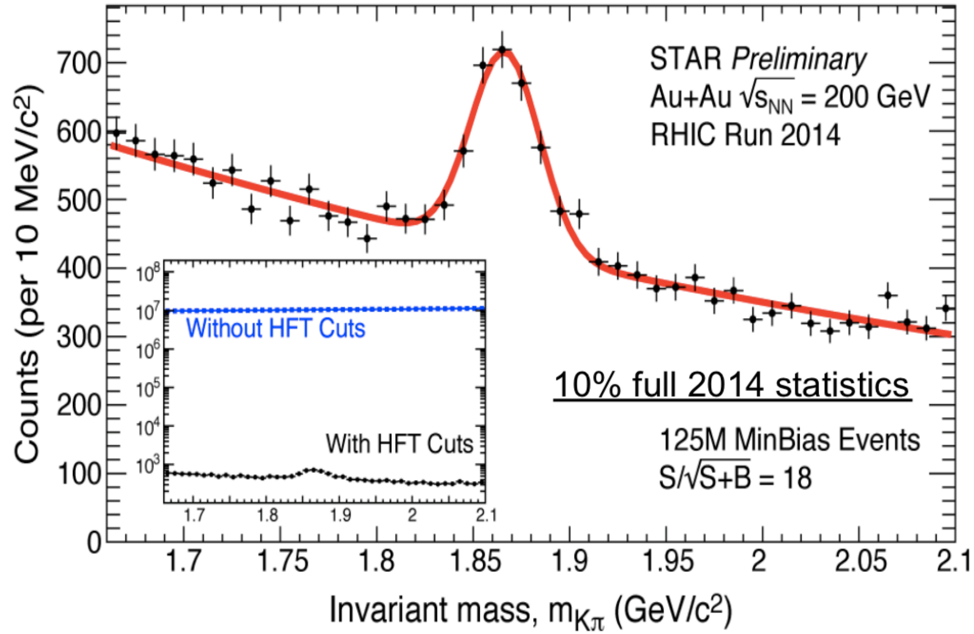




2013 May	– PXL prototype engineering run with 3 sectors (out of 10 in total)
2013 Sept	– IST, SSD fully installed into STAR
2014 Jan	– PXL fully installed into STAR (within 12 hours)
2014 Jan-Feb	– cosmic runs for detector commissioning, data for alignment calibration
2014 March	– Commissioning in Au+Au 200 GeV collisions. Physics mode since then
2014 Sept	– HFT project closeout. Project finished on time and under budget.

HFT performance at Au+Au 200 GeV



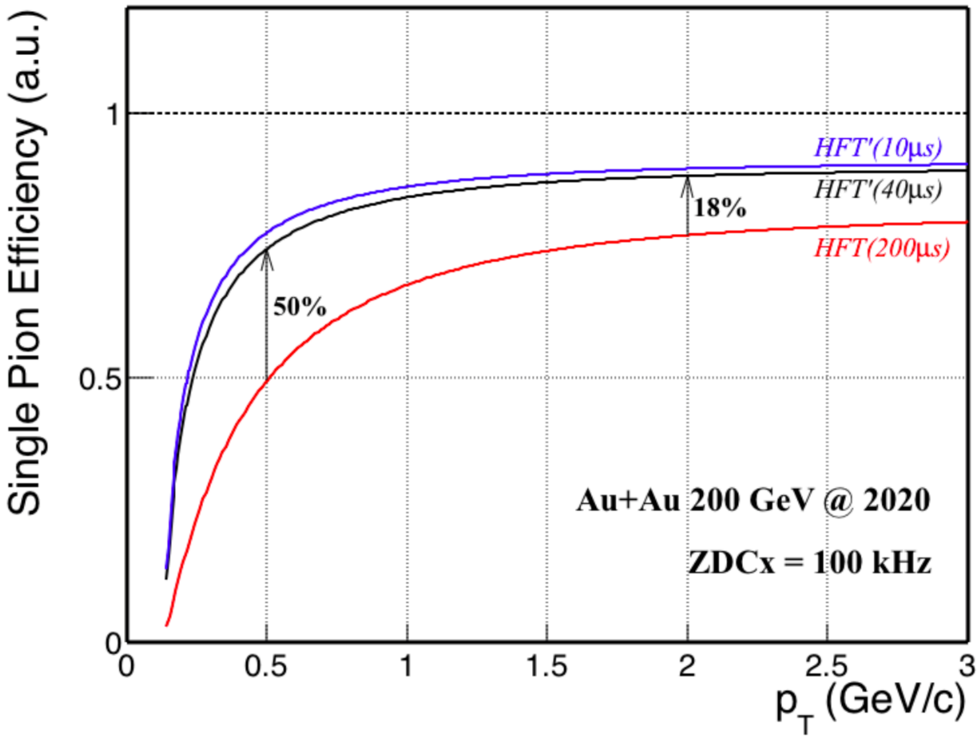


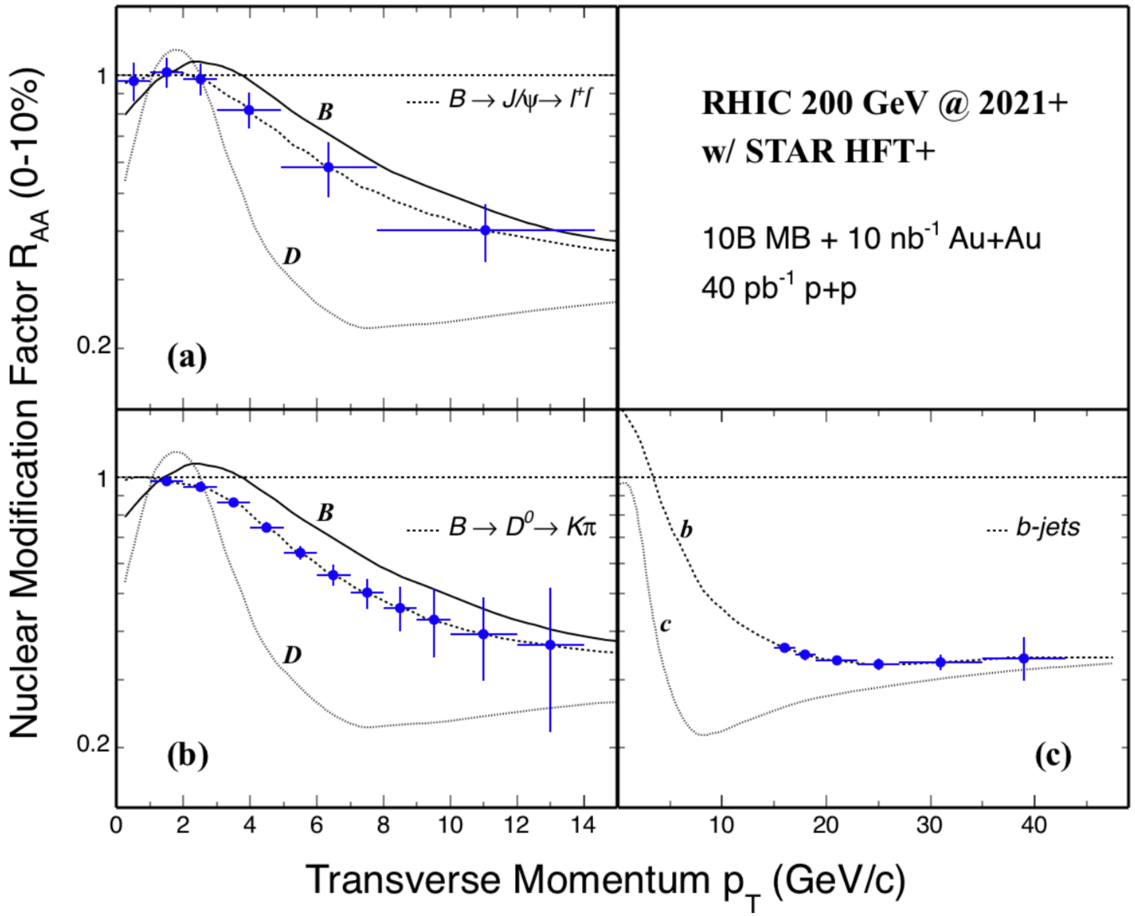
Physics datasets collected with STAR-HFT

	Beam Species	Data sets	Physics goals
2014	Au+Au 200 GeV	1.2B minbias	D-meson v_2, R_{cp}
2015 Al-cable	p+p 200 GeV	1.1B minbias, 12 pb^{-1}	D-meson R_{AA} baseline
	p+Au 200 GeV	0.5B minbias, 42 nb^{-1}	D-meson R_{pA}
2016* Al-cable	Au+Au 200 GeV	2B minbias, 1 nb^{-1}	Λ_c, bottom, D-meson v_2, R_{AA}
	Au+Au 62.4 GeV	1B minbias	√s dependent D-meson v_2, R_{cp}

* 2016 requests accommodated by the STAR Beam-Use-Request

HFT+ Upgrade



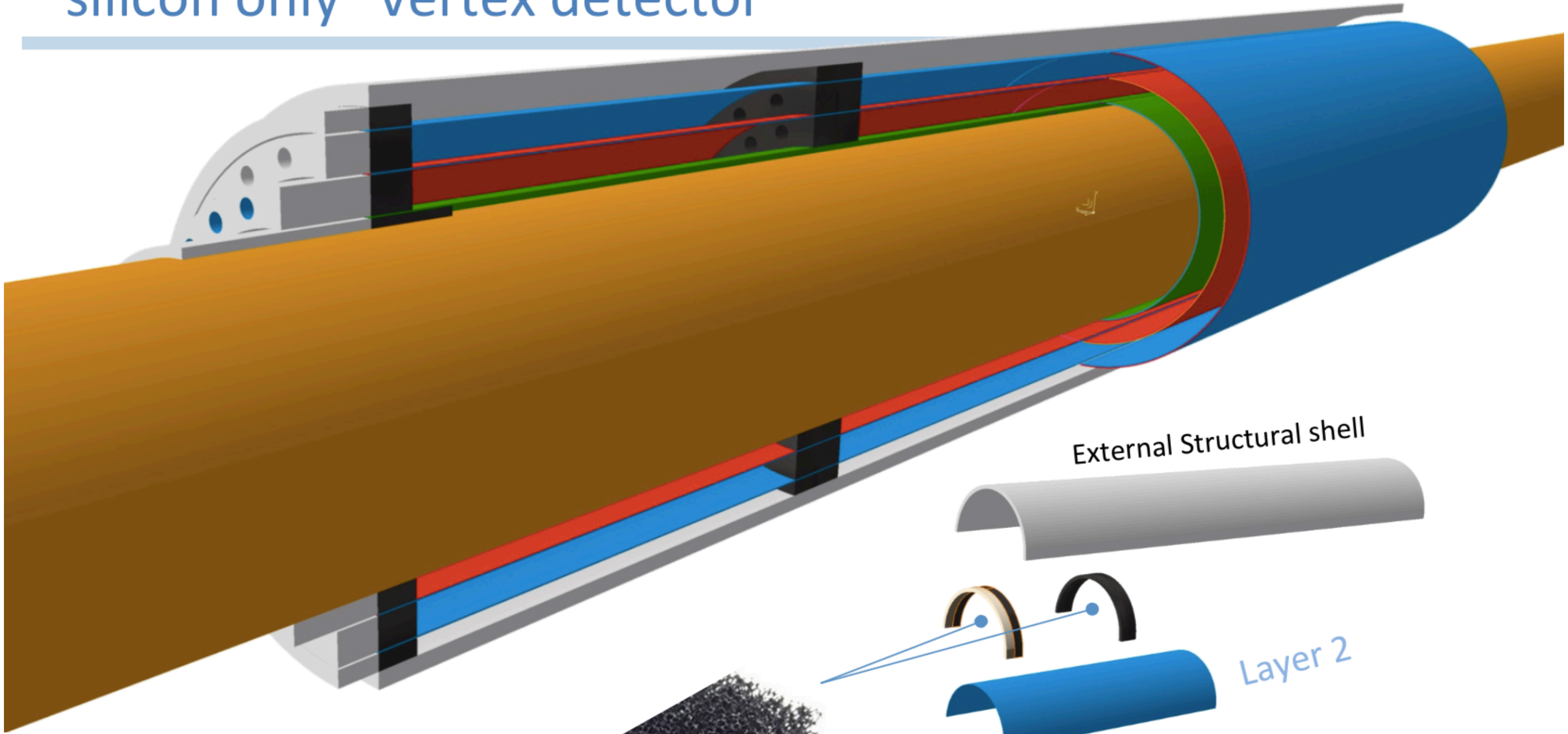


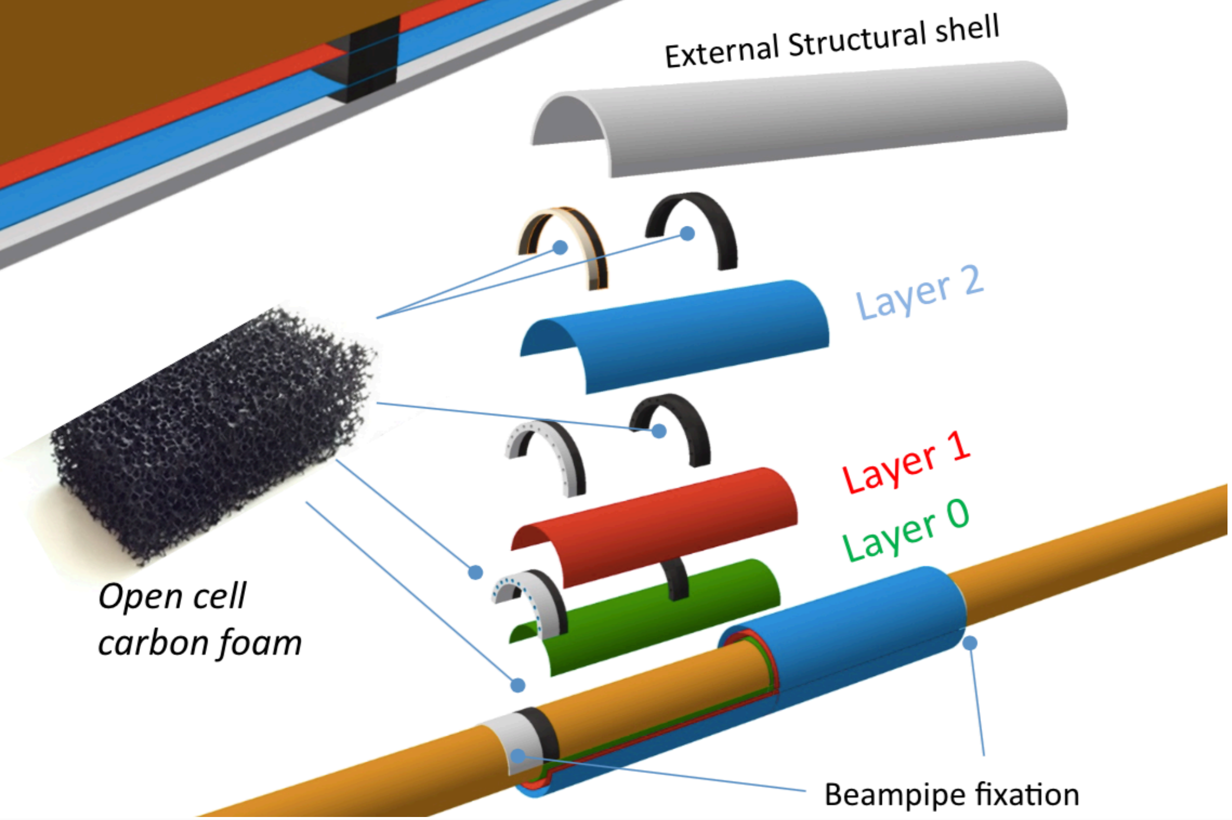
Aiming for open bottom measurements at 2020+.
Next generation MAPS sensors (x10 faster), R&D for ALICE ITS upgrade.
Preserve high detecting efficiency in high luminosity environment.

Ultra-light vertex detector

Courtesy of L. Musa

“silicon only” vertex detector





Layers supported in position by high thermal conductive carbon foam, half-ring.

Cooling is provided by air flow through the carbon foam.

Foam in thermal contact with silicon act as a radiator, a large radiative surface is provided by the foam open cell.

Summary

1) Charm cross sections at mid-rapidity follow number of binary collisions scaling, which indicates charm quarks are mostly produced via initial hard scatterings.

2) Observed large high-p_T suppression of heavy quark production via NPE and D^0 meson measurement in 200 GeV central Au+Au collisions.

3) Low-p_T enhanced structure of D^0 R_{AA} is consistent with coalescence picture that charm recombined with thermalized light quarks in the medium.

4) 2+3 together consistent with QGP formation picture.

5) Nice performance and convincing signal has been observed by current HFT data, expected more results shown at this QM.

6) Future program with HFT+ and ultra-light vertex detector is prospected.

Summary

1) Charm cross sections at mid-rapidity follow number of binary collisions scaling, which indicates charm quarks are mostly produced via initial hard scatterings.

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6) Future program with HFT+ and ultra-light vertex detector is prospected.

More exciting results are coming soon !

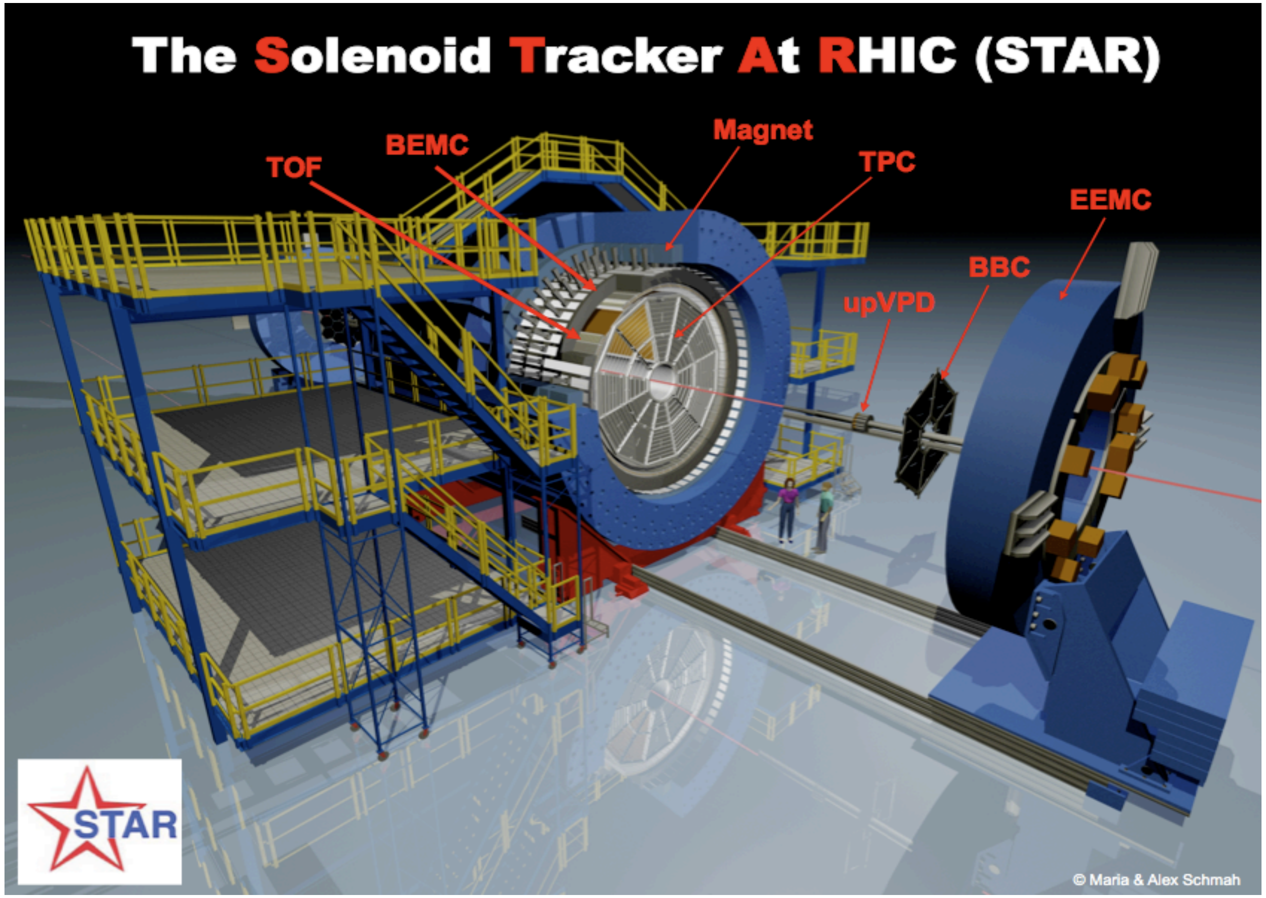
Thank you for your attention !

Backup Slides

The STAR detector for open HF measurement

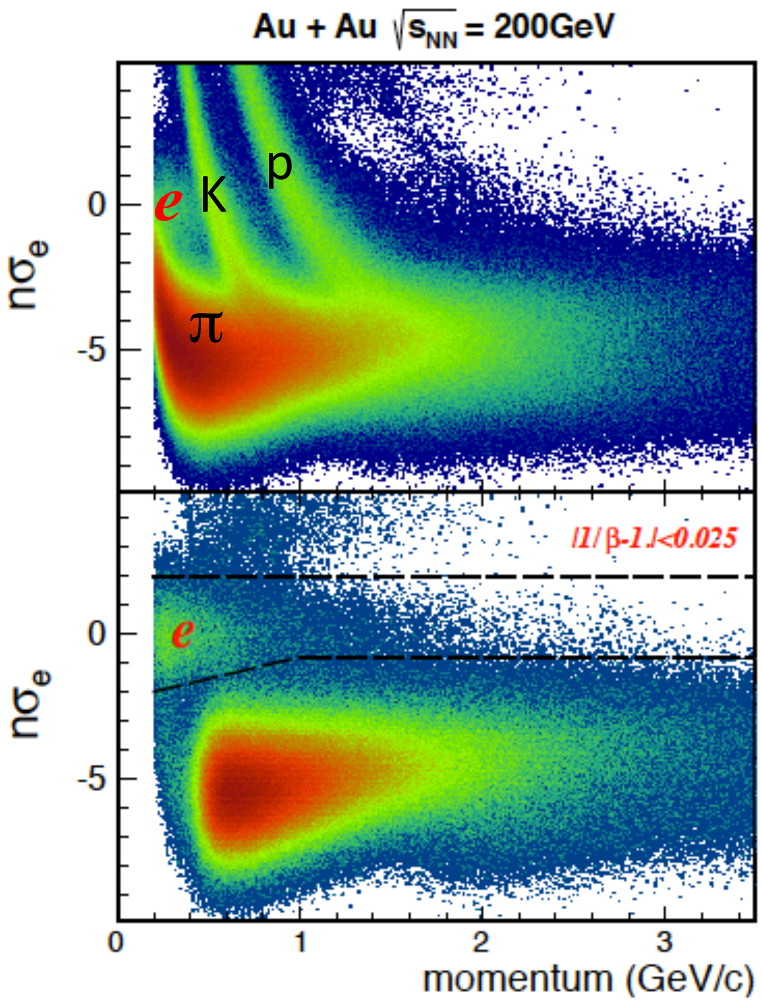
Time Projection Chamber:
- |eta|<1, full azimuth
- Tracking.
- PID through dE/dx

Time of Flight:
- |eta|<1, full azimuth .
- PID through TOF
- Timing resolution: ~85 ps.



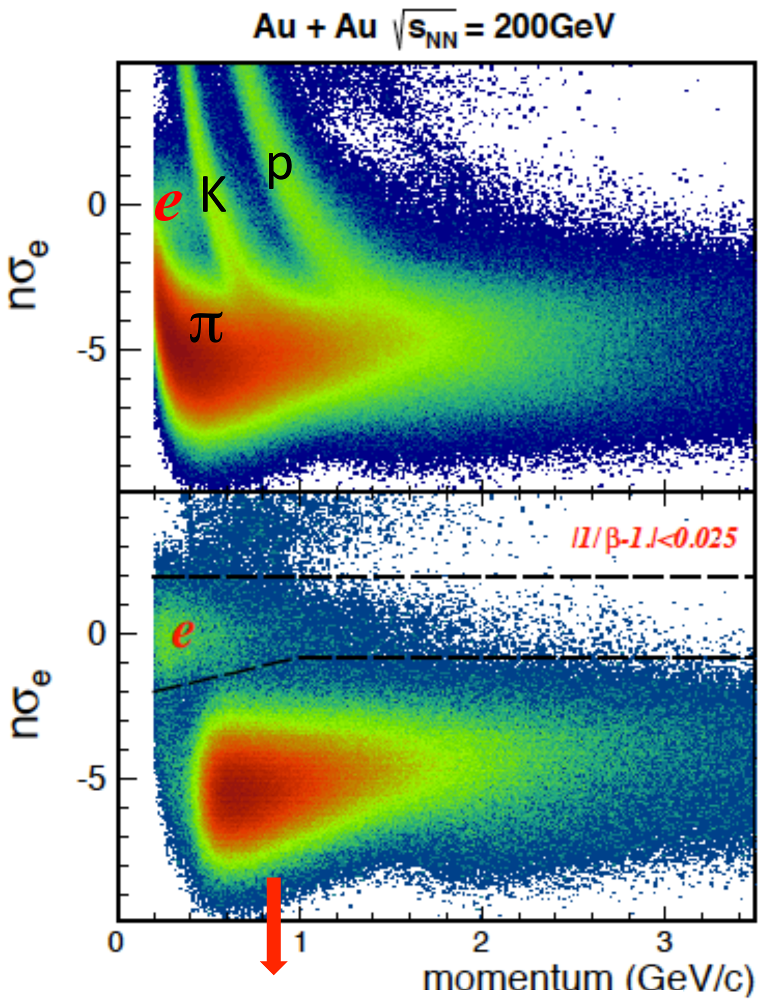
Barrel Electromagnetic Calorimeter
- |eta|<1, full azimuth
- **BTOW**:
  - Tower matching
  - p/E for electron ID
  - Fast online trigger
- **BSMD**:
  - Double layer High spatial resolution MWPC.
  - e/h separation.

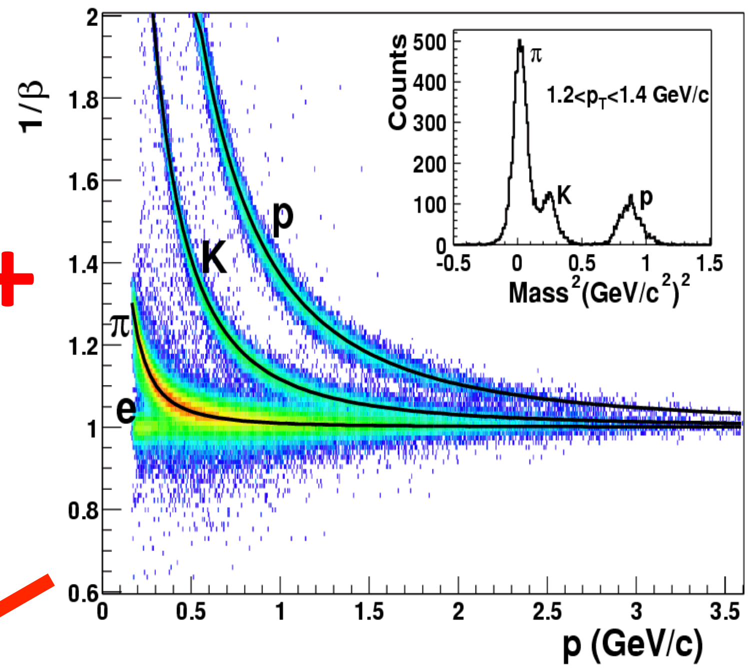
Particle Identification



$$n\sigma = \ln(dE^{Measured} / dx - dE^{Exp} / dx) / \sigma$$

Particle Identification





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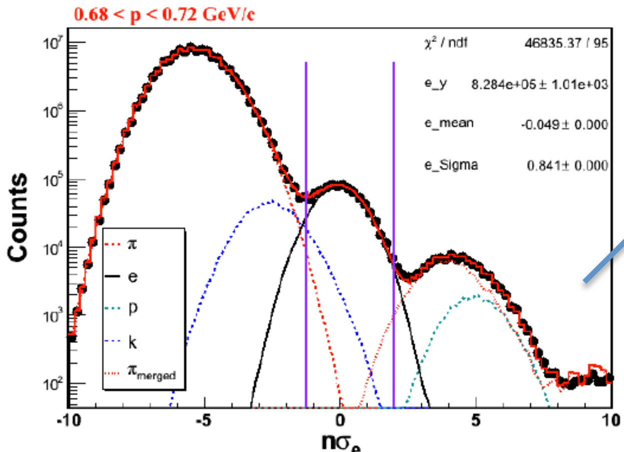
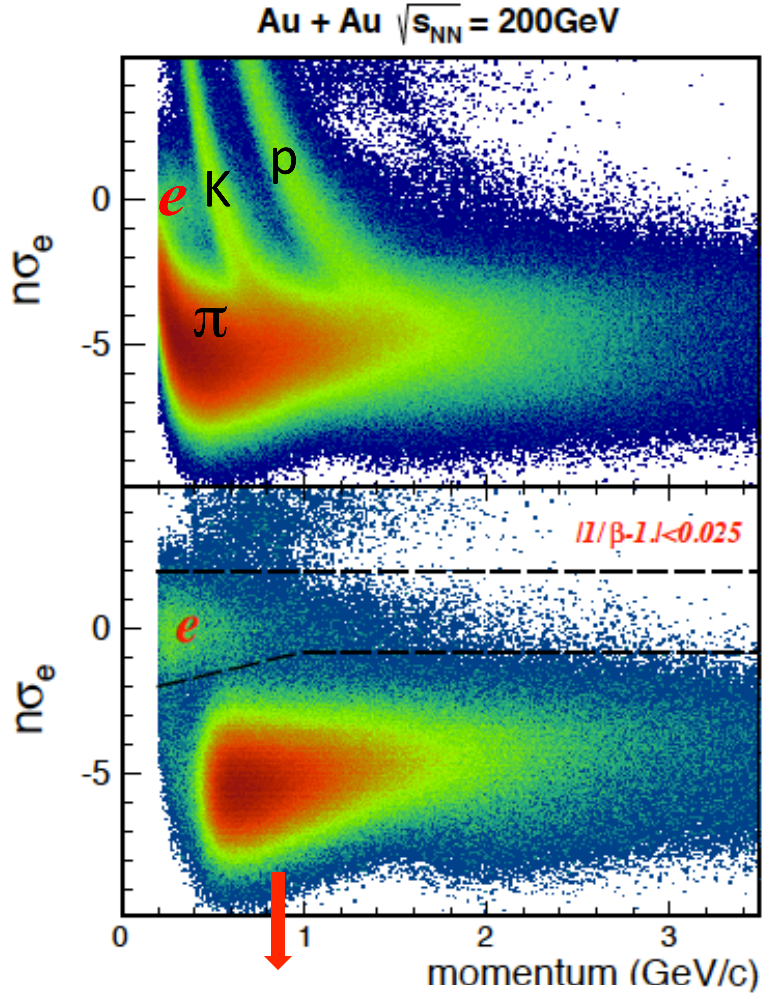
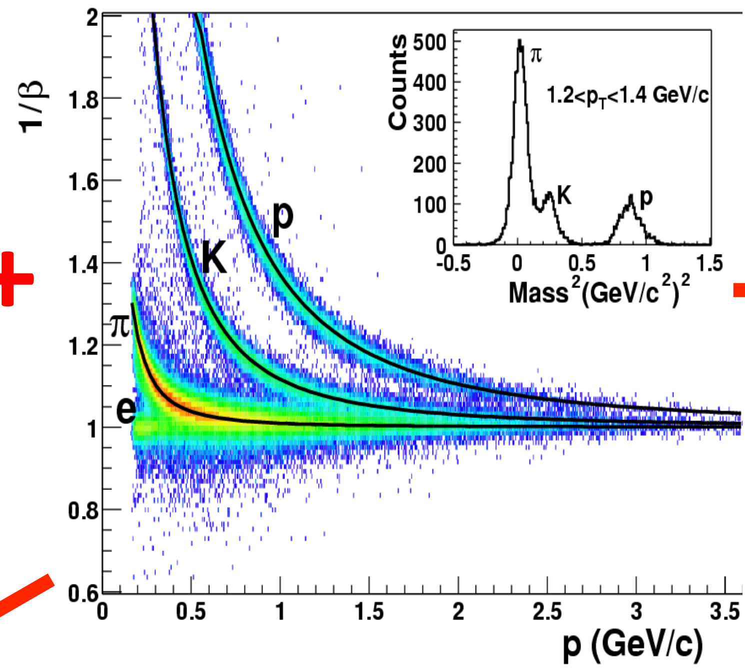
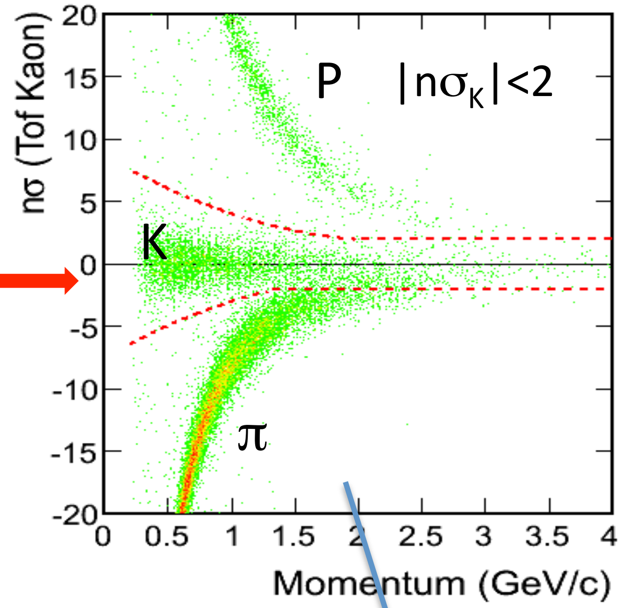


Low p_T e

Particle Identification

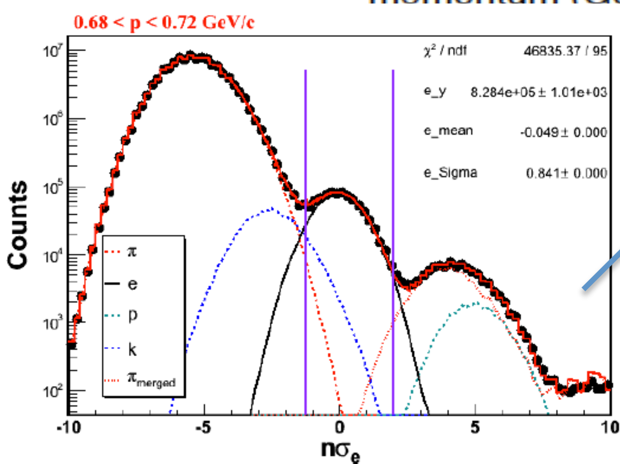






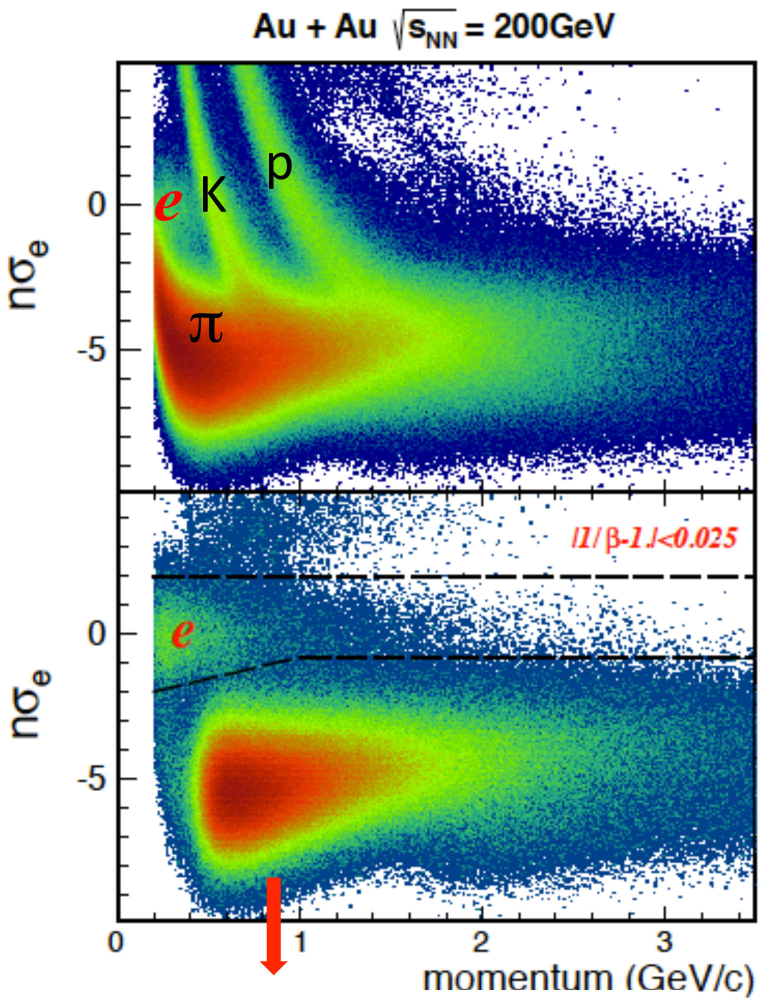
$$n\sigma = \ln(dE^{Measured} / dx - dE^{Exp} / dx) / \sigma$$

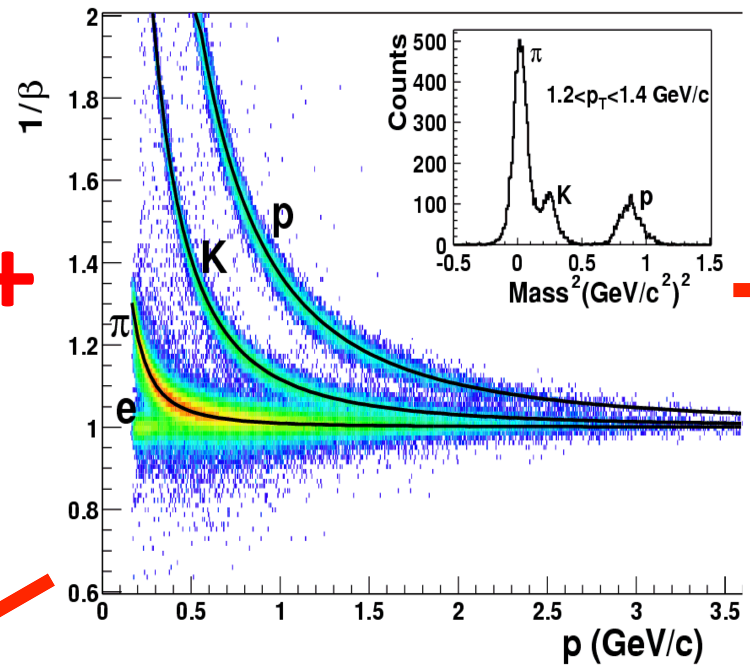
D meson hadronic daughter ID.

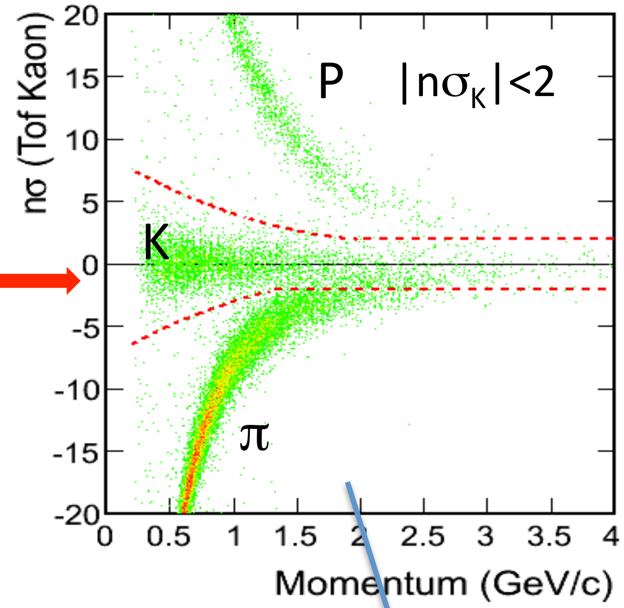


Low p_T e

Particle Identification







D meson hadronic daughter ID.

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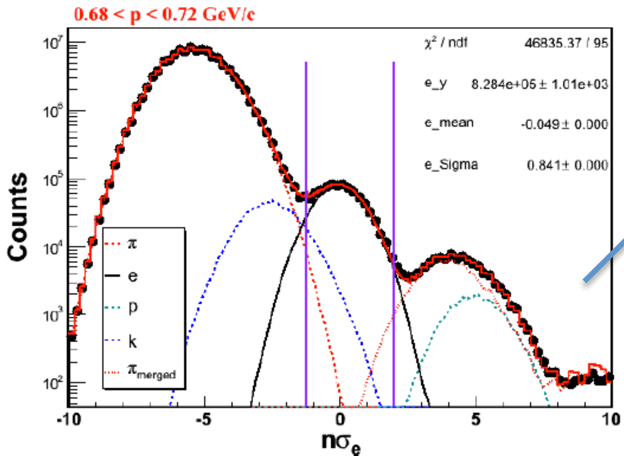
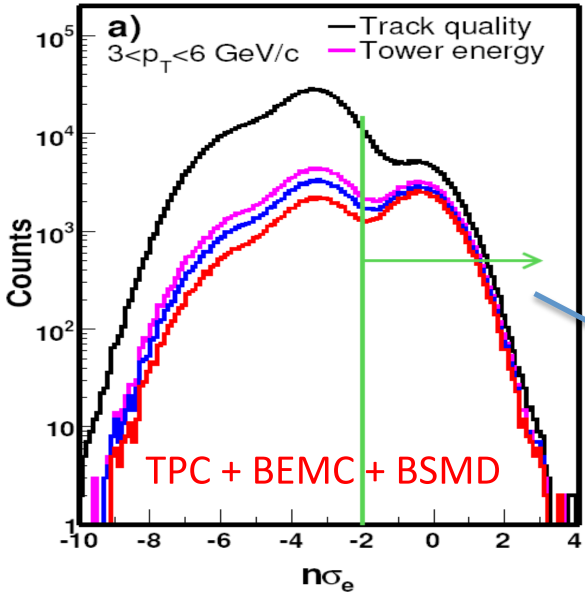
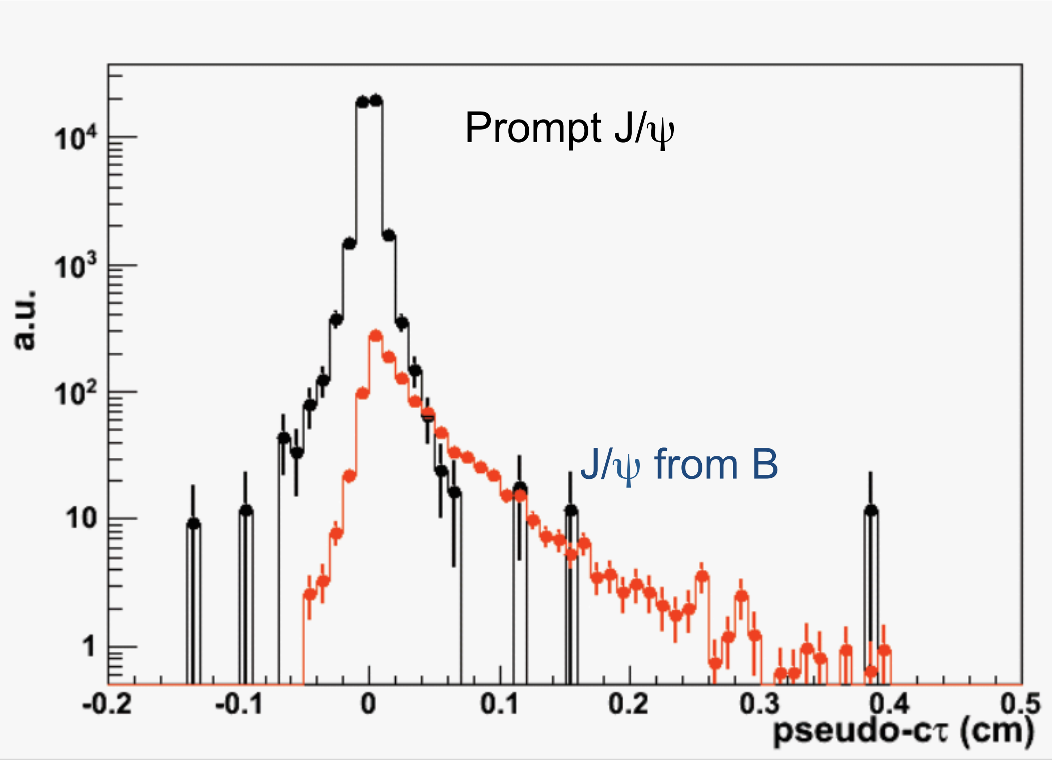


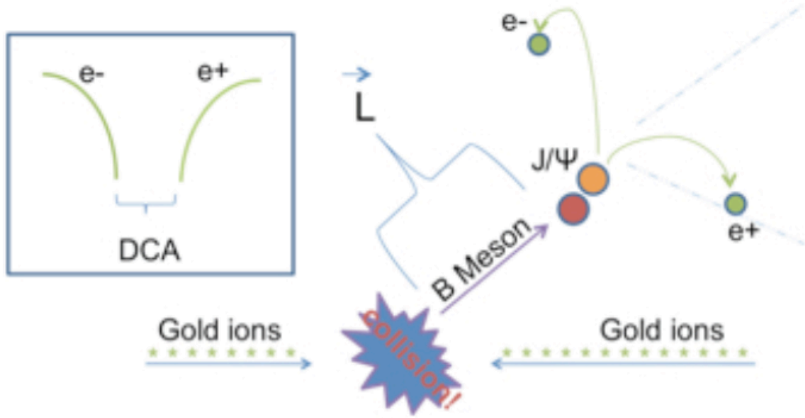
Low p_T e



High p_T e

B→J/ψ + X

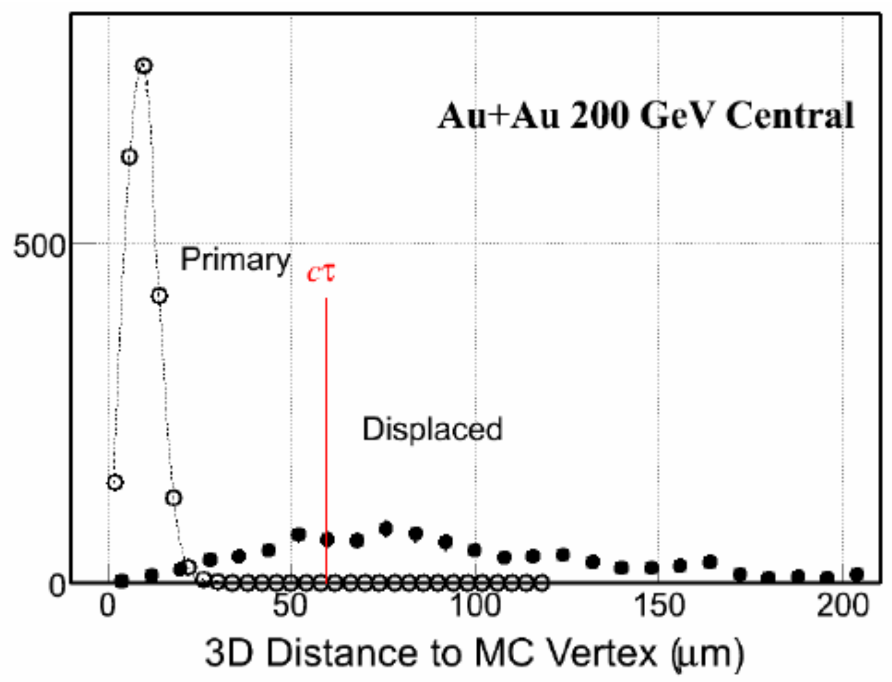


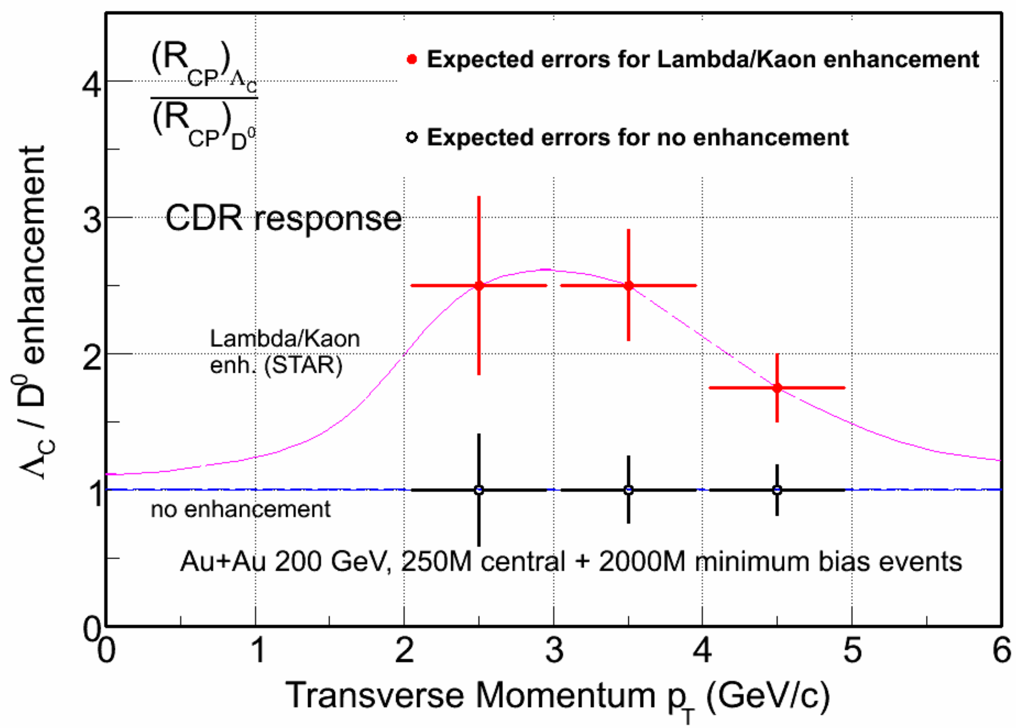


$$c\tau' = \vec{L} \cdot \frac{p_T^{\psi}}{|p_T^{\psi}|} \cdot \frac{M_{\psi}}{p_T^{\psi}}$$

- HFT precision should have no problem in separating B decay J/ψ from prompt J/ψ.
- Statistic limited analysis !
- Efficient J/ψ trigger for STAR needed.

Charmed baryons – Y14



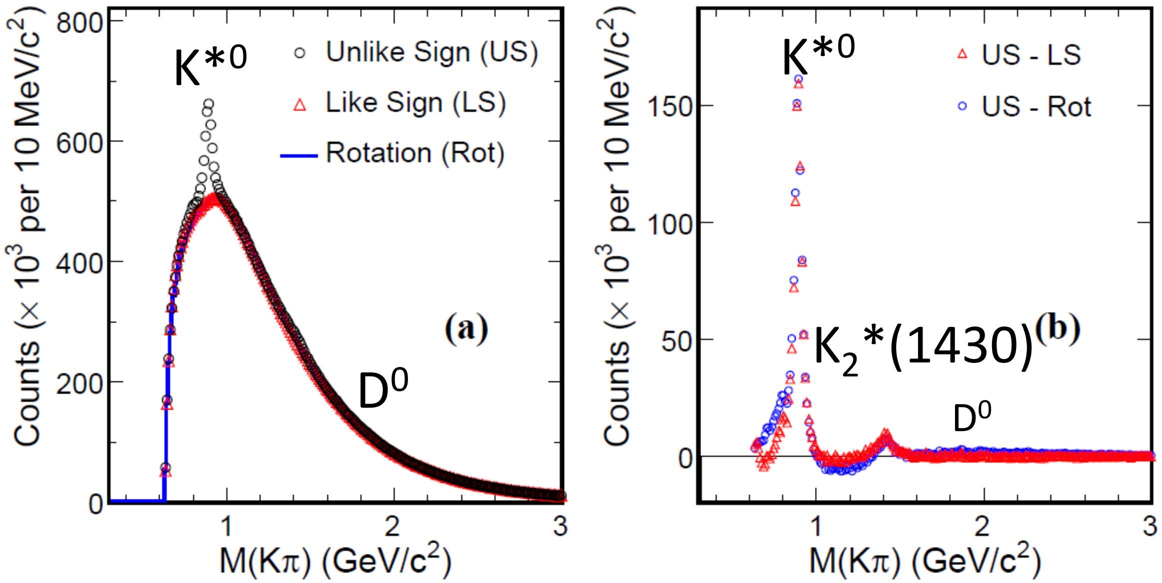


$\Lambda_c \to pK\pi$ Lowest mass charm baryons cτ = 60 μm

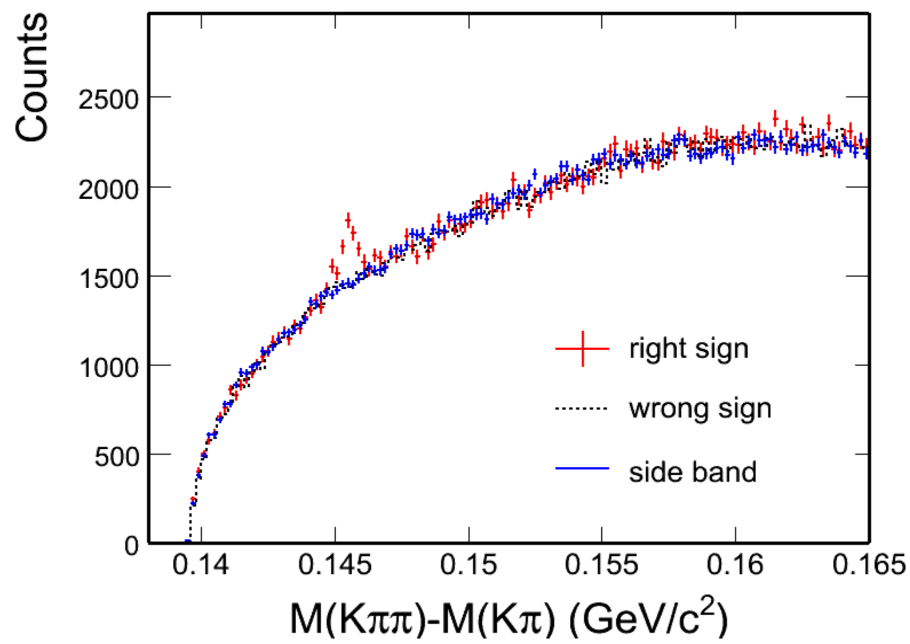
Λ_c/D enhancement?

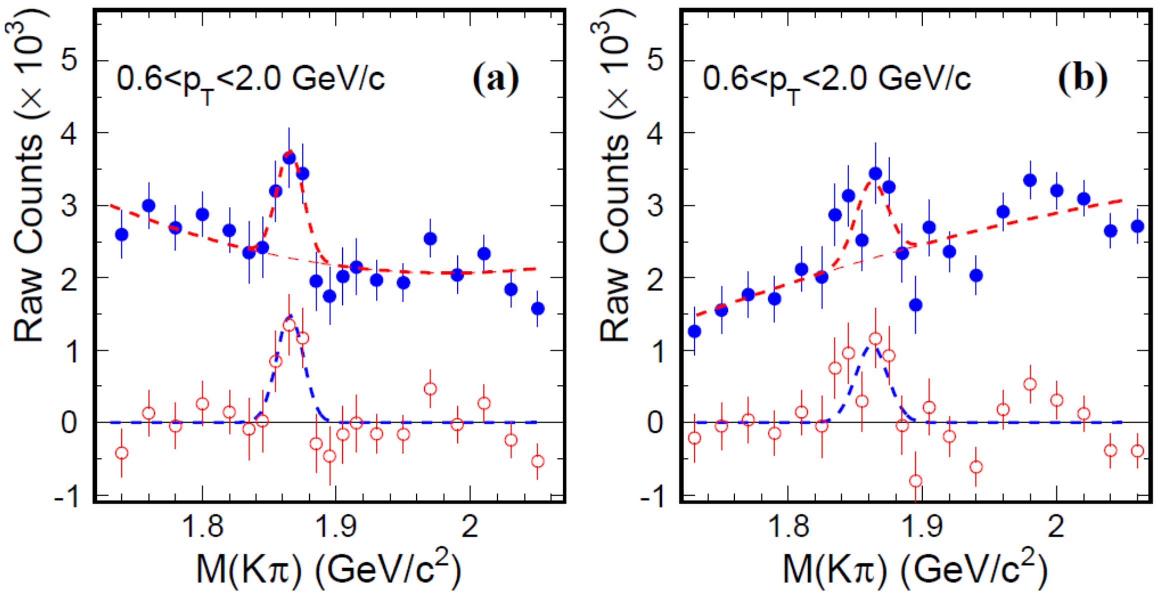
- 0.11 (pp PYTHIA) → 0.4-0.9 (Di-quark correlation in QGP)
  S.H. Lee etc. PRL 100, 222301 (2008)
- Total charm yield in heavy ion collisions

D^0 and D* signals in p+p 200 GeV



$D^{*\pm} \rightarrow D^0(\overline{D^0}) + \pi^{\pm} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}$





p+p minimum bias 105 M

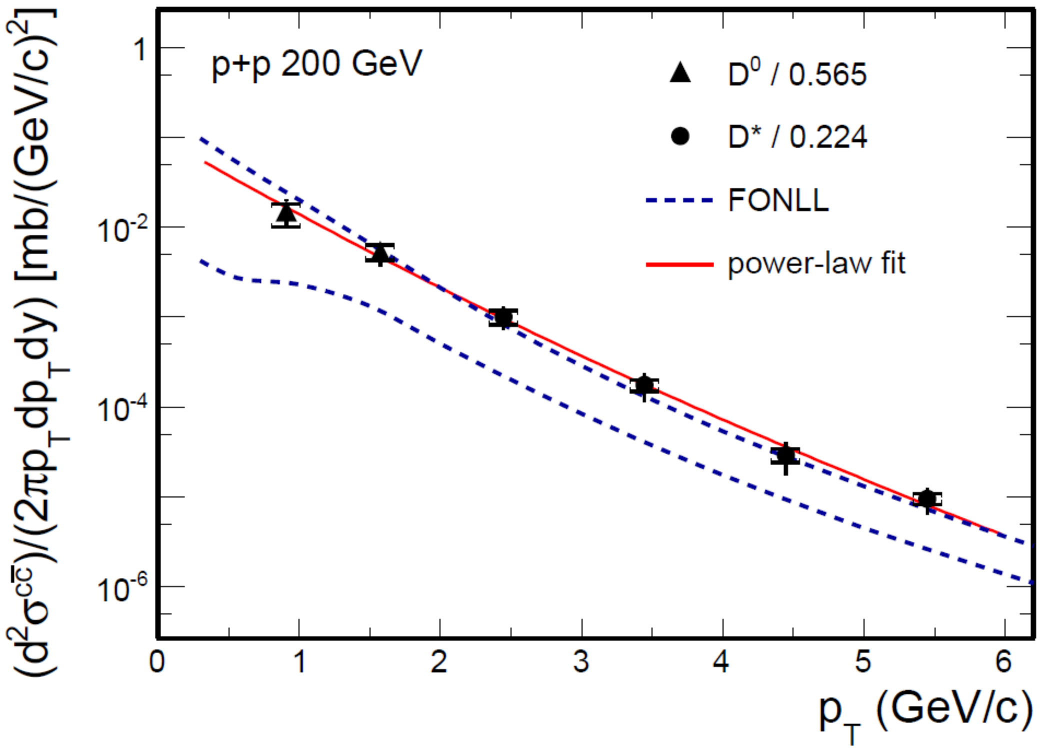
Different methods reproduce comb. background.

Consistent between two background methods.

- No secondary vertex reconstruction so far.
- STAR took advantage of the large acceptance, and beat combinatorial background with statistics

PRD 86, 072013 (2012)

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



arXiv: 1204.4244.

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

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

Consistent with FONLL[2] upper limit.

Xsec = $dN/dy|^{cc}_{y=0} \times F \times \sigma_{pp}$

F = 4.7 ± 0.7 scale to full rapidity.

σ_{pp}(NSD) = 30 mb

The charm cross section at mid-rapidity:

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

The total charm cross section:

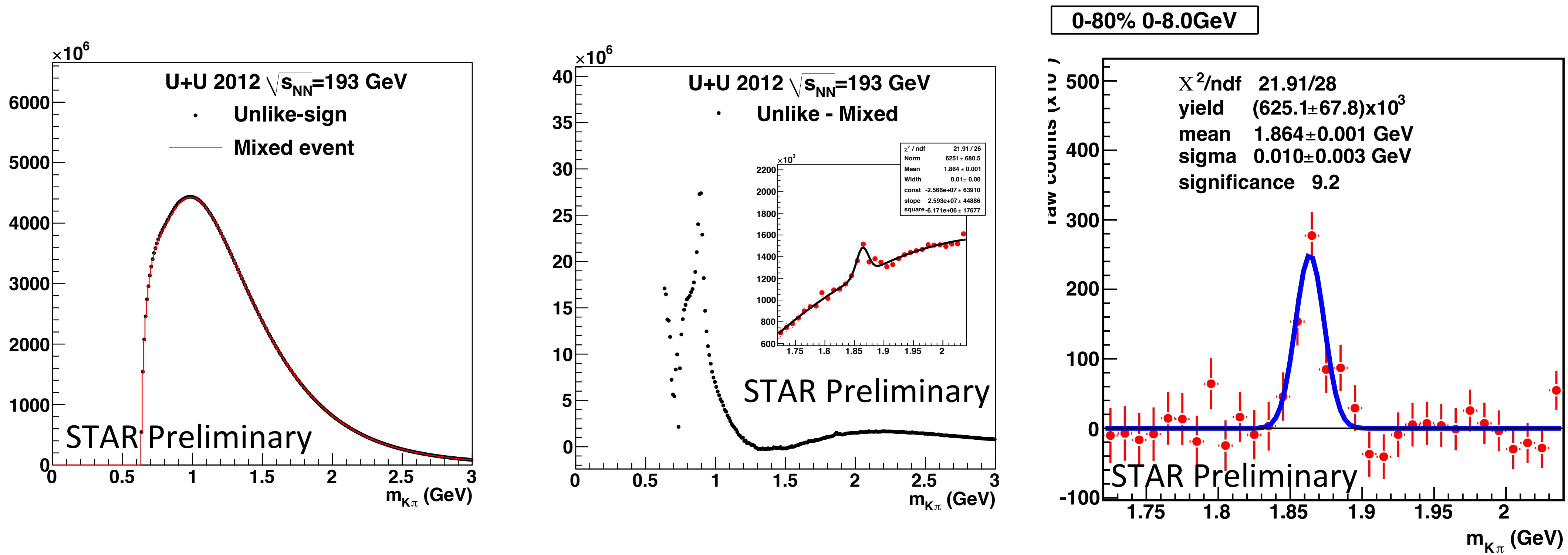
$$\sigma^{pp}_{c\bar{c}} = 797 \pm 210^{+208}_{-295}\,\mu b$$

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

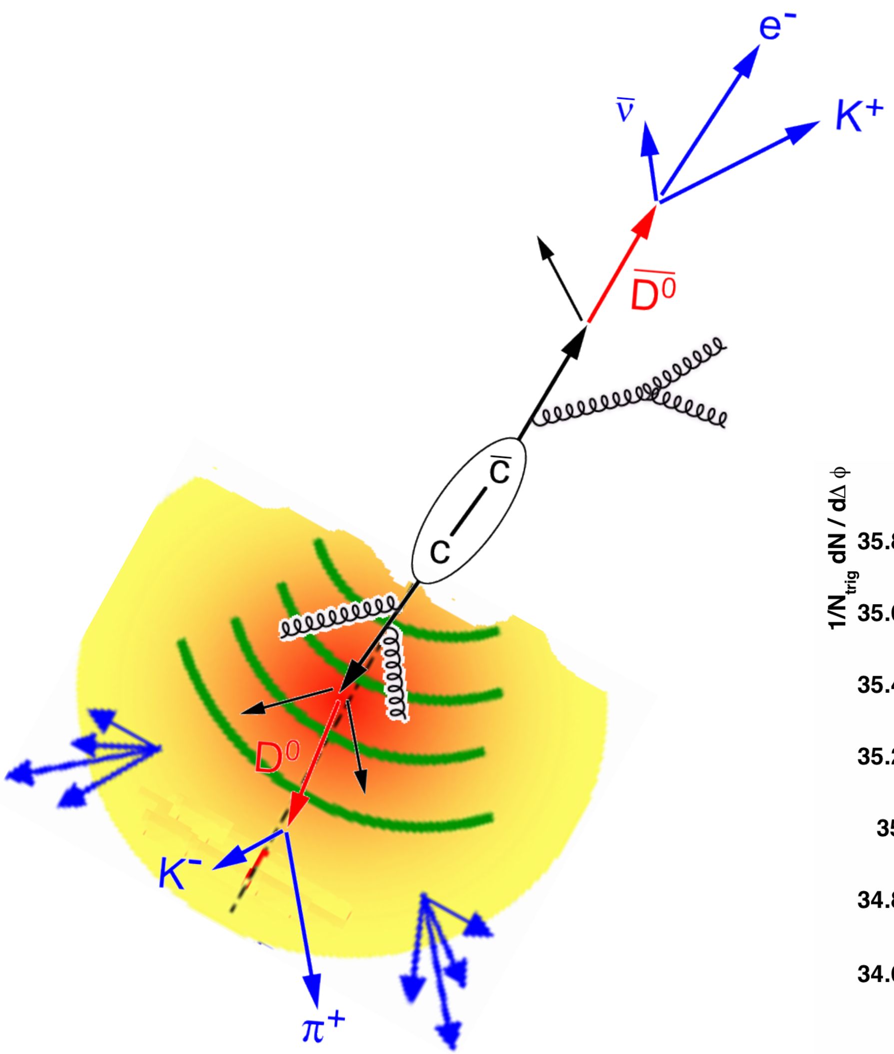
[2] Fixed-Order Next-to-Leading Logarithm: M. Cacciari, PRL 95 (2005) 122001.

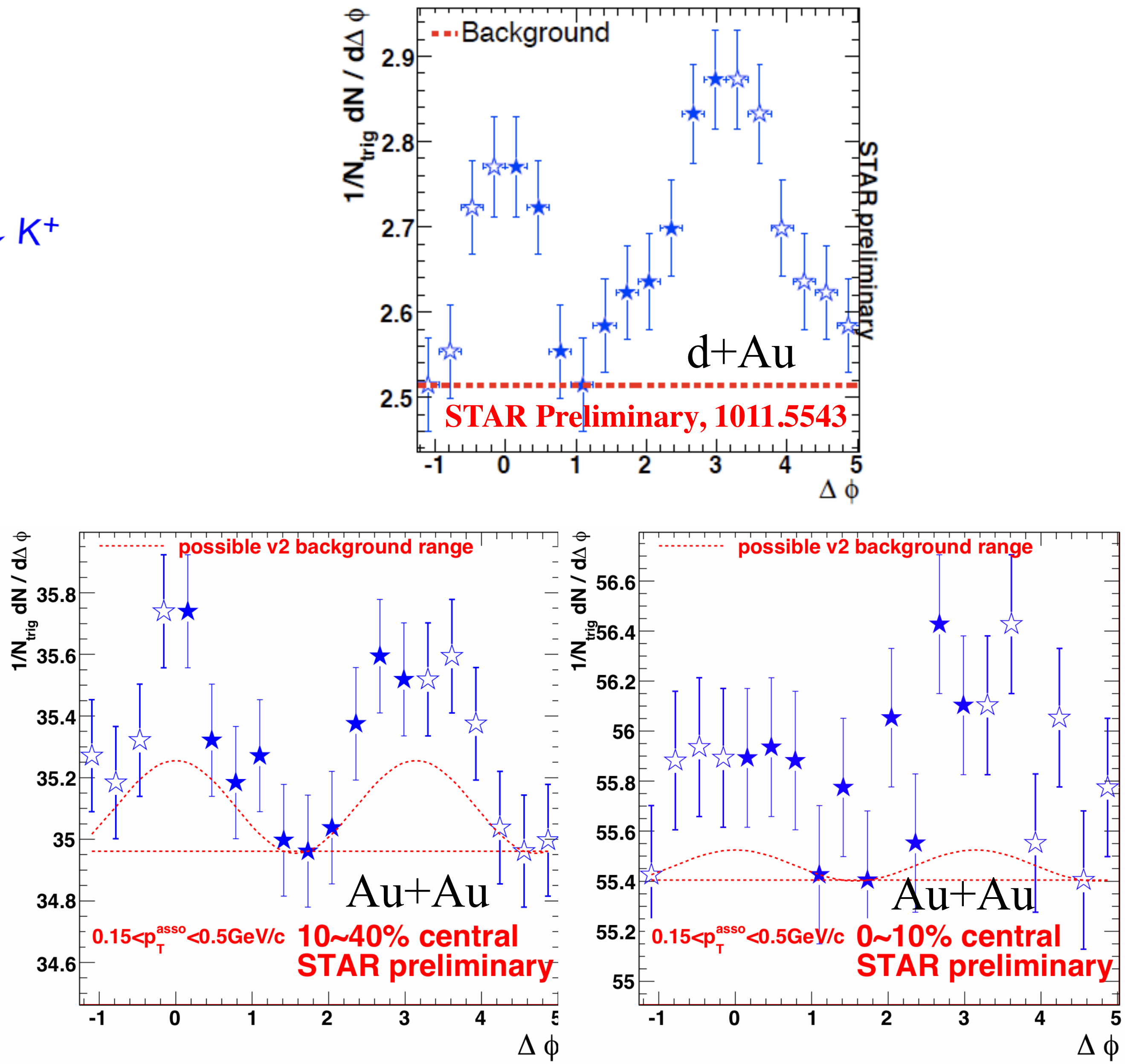
D^0 in U+U 193 GeV

- Background is estimated with a mixed event method.
- Significant signal (9.2σ) from U+U run 12.

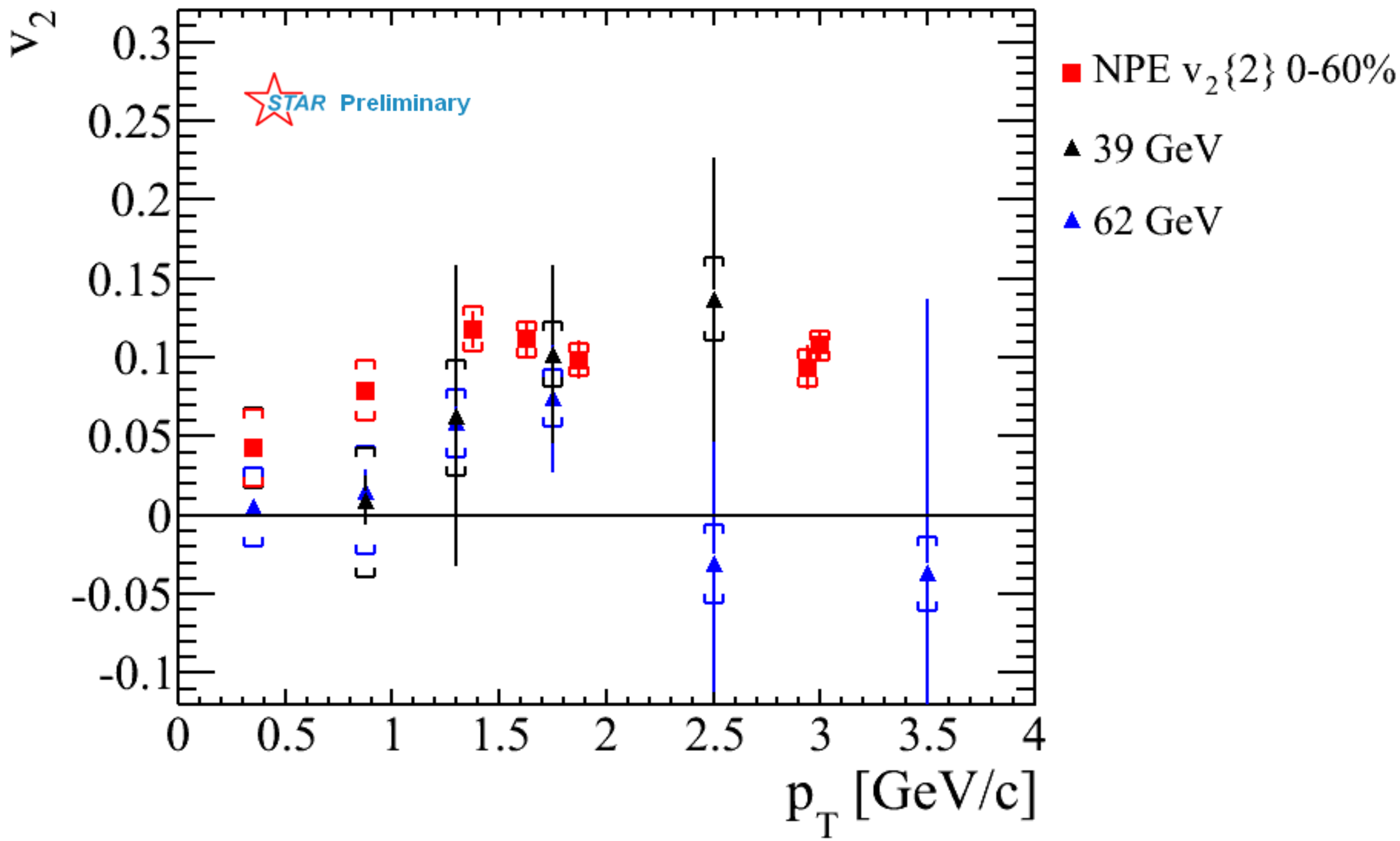


Heavy flavor tagged e-h correlations in AA



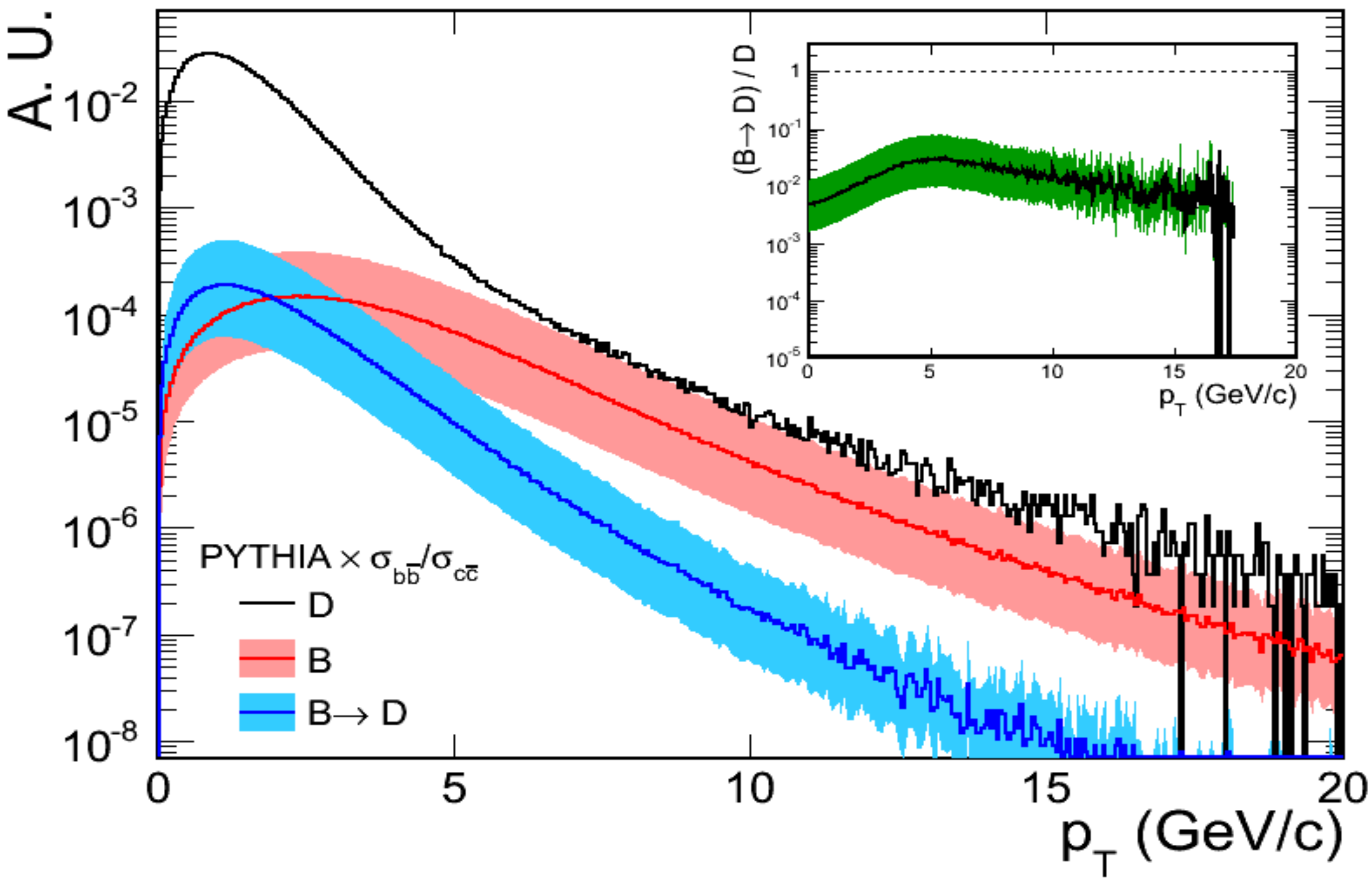


NPE v_2 in Au+Au 39 & 62 GeV



39 and 62.4 GeV Au+Au:
Low p_T v_2 consistent with zero => might suggest charm–medium interaction in lower energies is not as strong as in 200 GeV.

B feeddown



D, B and B->D are generated from PYTHIA.

Normalized by FONLL cross section, the band indicate uncertainty of

Strong pT dependence, but contribution is small, less than 10%.

Low pT only contributes a few percent, which will not affect cross section result.

Assuming B feeddown fraction is the same for p+p and Au+Au, then RAA will not be affected.

The B feeddown will be in the systematic uncertainty.

Heavy Flavor Tracker

- HFT consists of 3 sub-detector systems inside the STAR Inner Field Cage (IFC)

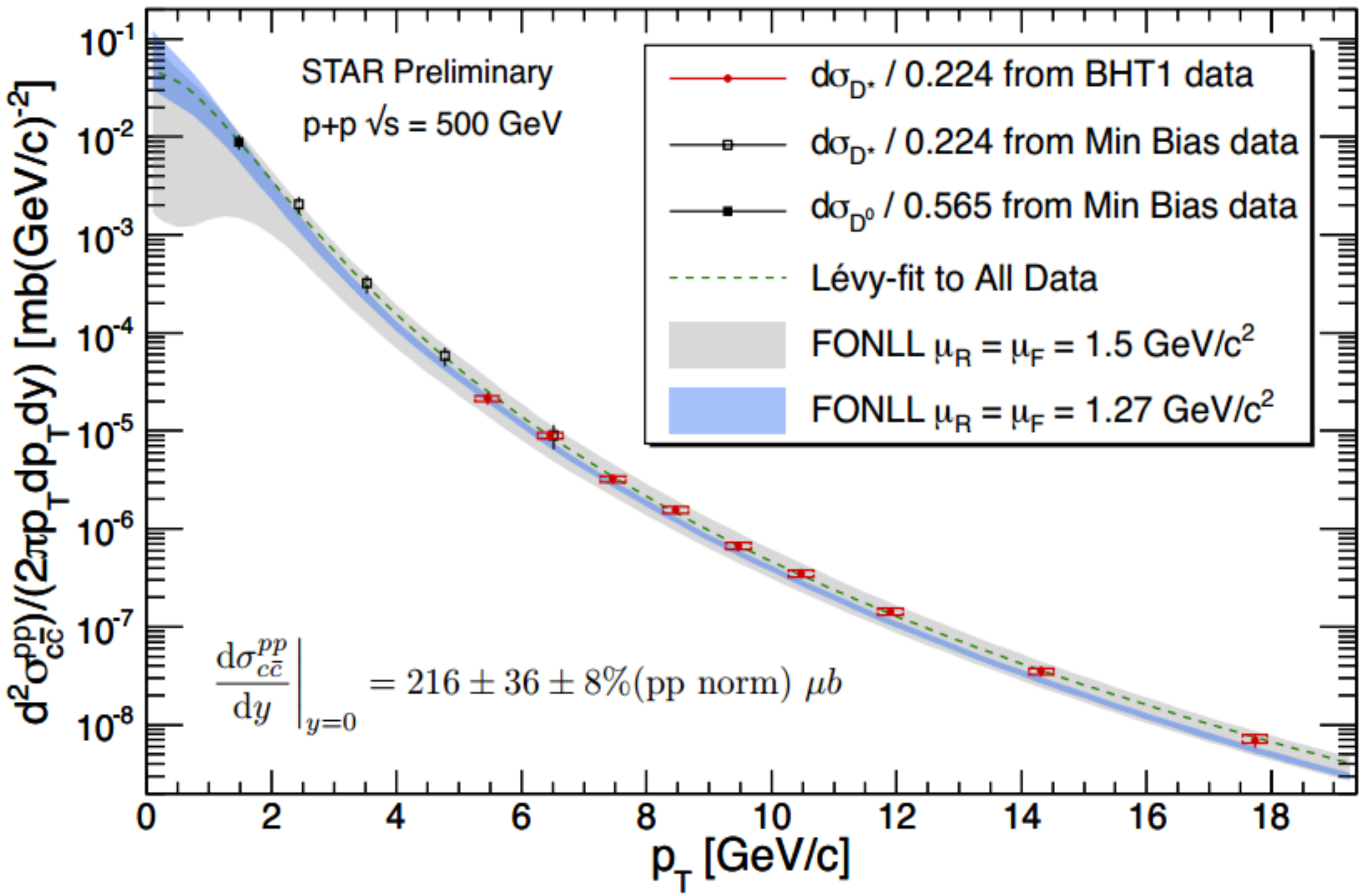
Detector	Radius (cm)	Hit Resolution R/φ - Z (μm - μm)	Radiation length
SSD	22	30 / 860	1% X_0
IST	14	170 / 1800	1.32 %X_0
PIXEL	8	12 / 12	~0.37 %X_0
	2.5	12 / 12	~0.37% X_0

➢ **SSD** existing single layer detector, double side strips (electronic upgrade)

➢ **IST** one layer of silicon strips along beam direction, guiding tracks from the SSD through PIXEL detector. **- proven strip technology**

➢ **PIXEL** double layers, 20.7x20.7 mm pixel pitch, 2 cm x 20 cm each ladder, 10 ladders, delivering ultimate pointing resolution. **- new active pixel technology**

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]

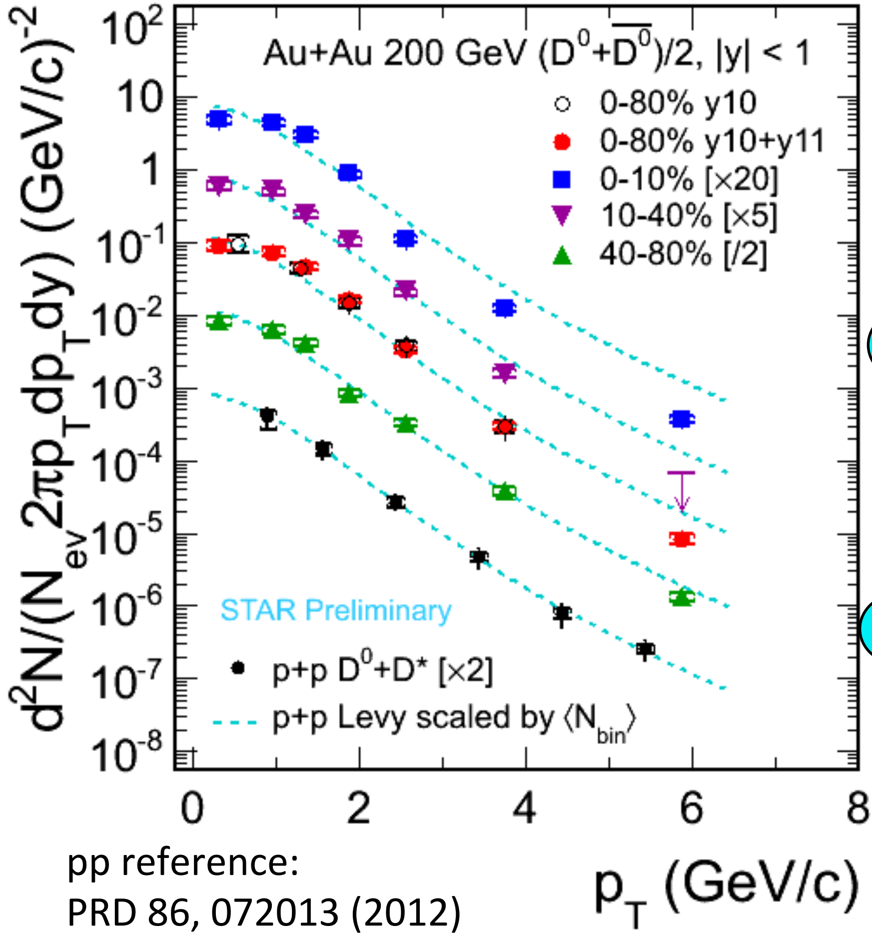
[1] C. Amsler et al. (Particle Data Group), PLB 667 (2008) 1.

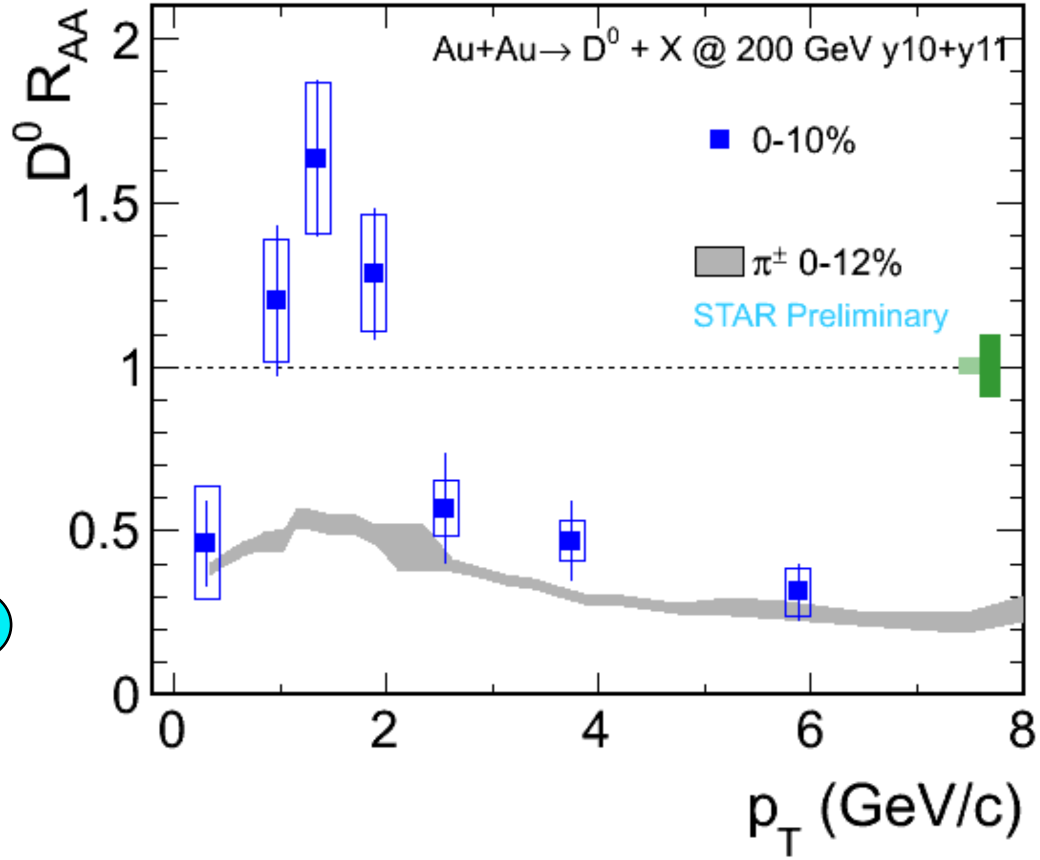
[2] FONLL calculation:
Ramona Vogt

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

FONLL upper band consistent with 500GeV (200GeV) charm spectra.

Nuclear modification of D^0

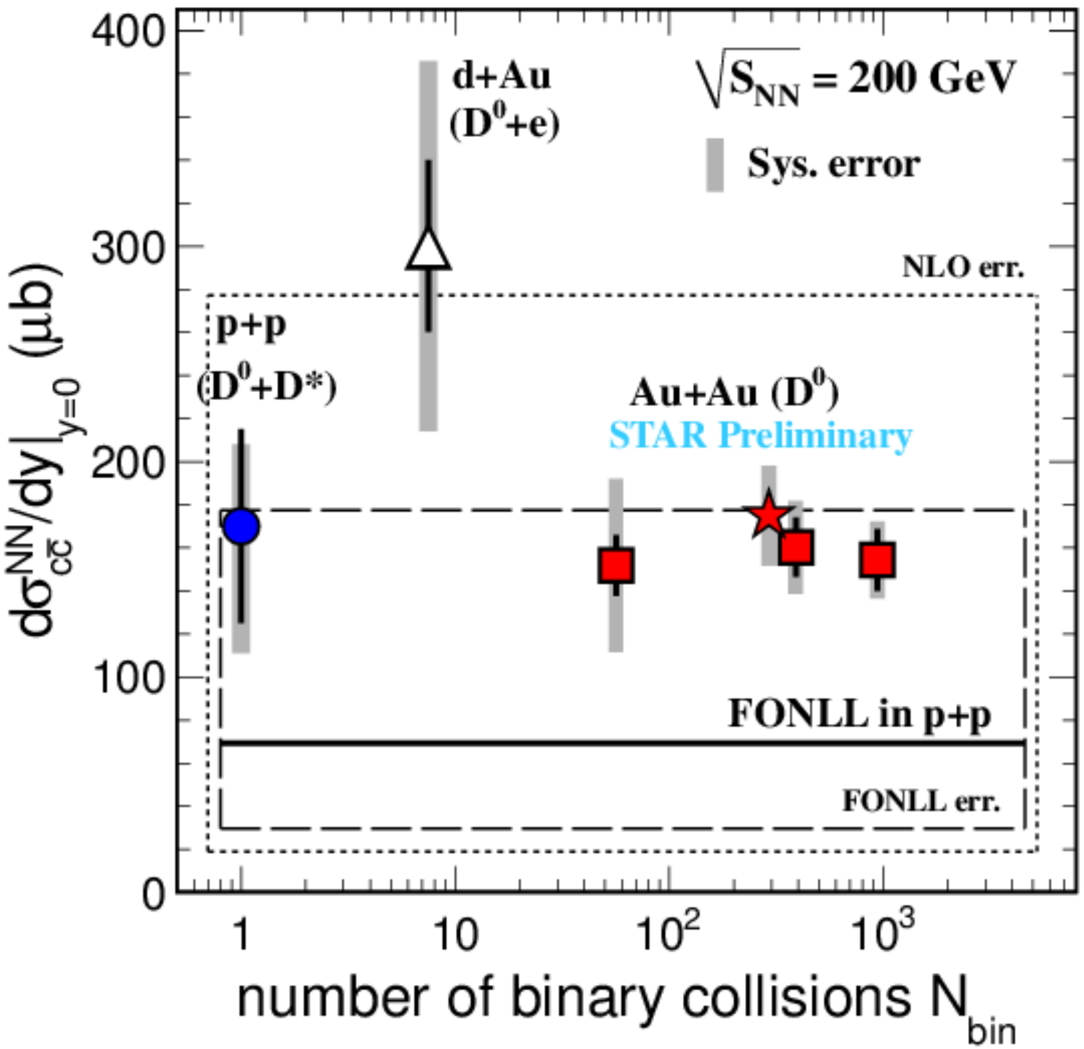




pp reference:
PRD 86, 072013 (2012)

- No obvious suppression observed in peripheral collisions.
- Suppression at high p_T (> 3 GeV/c) in central and mid-central collisions. Suppression level is consistent with pions.

Charm cross section versus N_{bin} at 200 GeV



Year 2003 d+Au 16M : D^0 + e

Year 2009 p+p 105M : D^0 + D*

Year 2010 + 2011 Au+Au 800M : D^0

Assuming N_{D0} / N_{cc} = 0.56 does not change for total cross section.

The charm cross section at mid-rapidity:

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

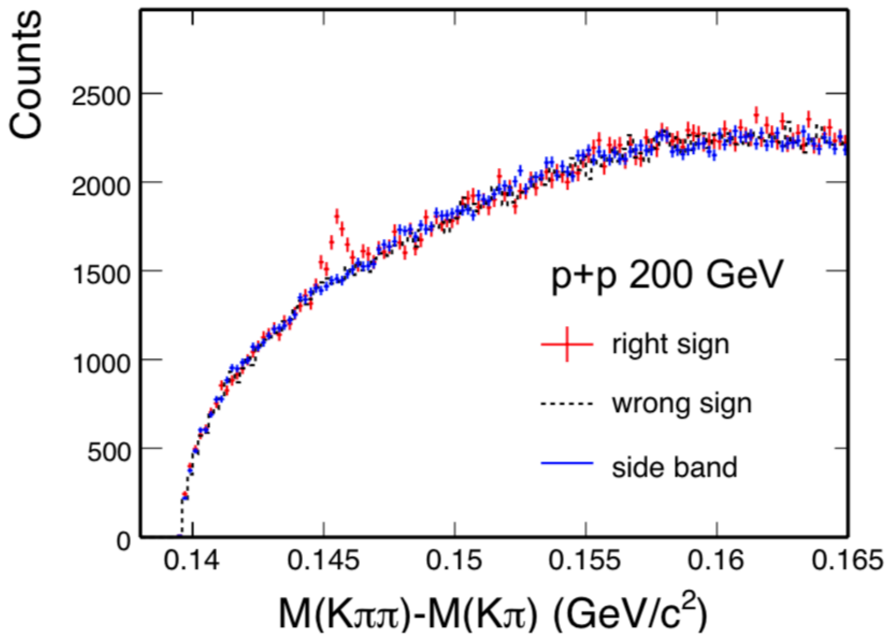
The total charm cross section（extrapolate from PYTHIA F~4.7）:

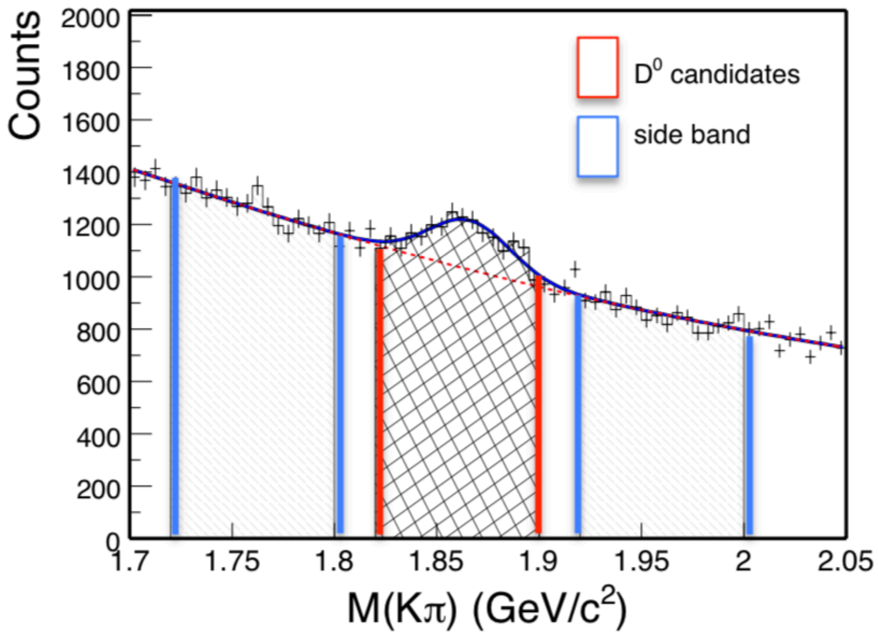
$$\sigma_{c\bar{c}}^{pp} = 797 \pm 210^{+208}_{-295}\mu b \qquad \sigma_{c\bar{c}}^{AuAu} = 822 \pm 62 \pm 192\mu b$$

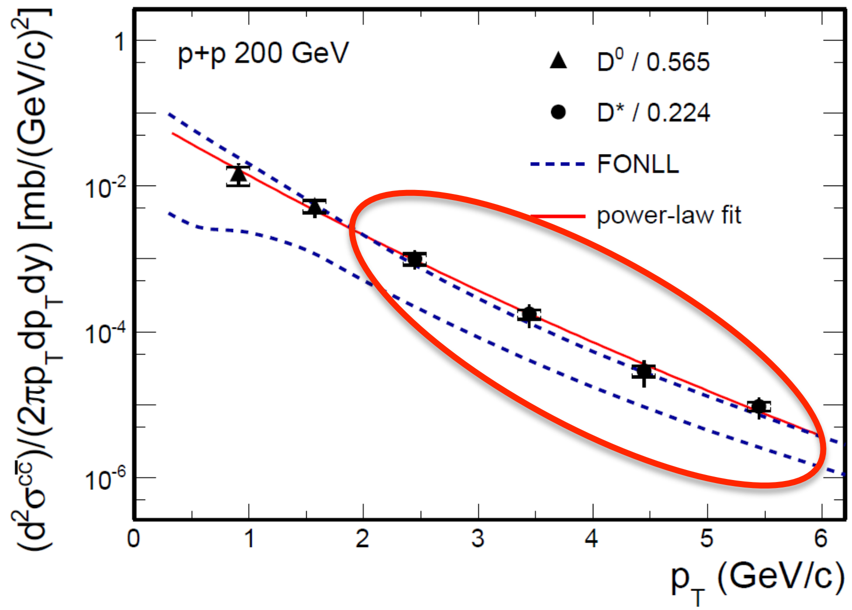
[1] STAR d+Au: J. Adams, et al., PRL 94 (2005) 62301
[2] STAR p+p: PRD 86 (2012) 072013.
[3] FONLL: M. Cacciari, PRL 95 (2005) 122001.
[4] NLO: R. Vogt, Eur.Phys.J.ST 155 (2008) 213

Charm cross section follows number of binary collisions scaling =>
Charm quarks are mostly produced via initial hard scatterings

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

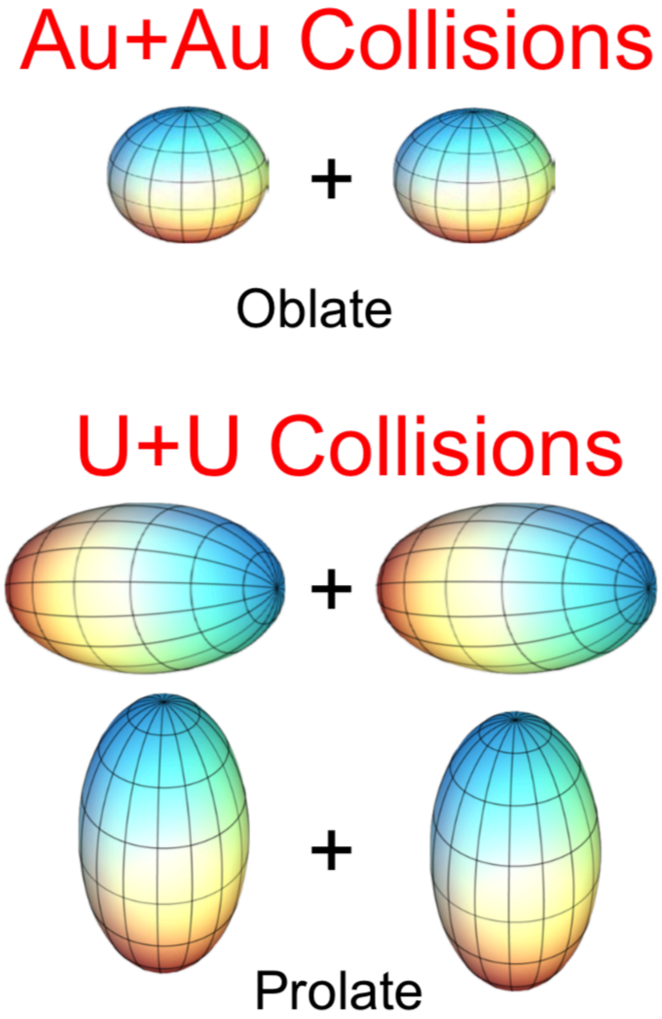


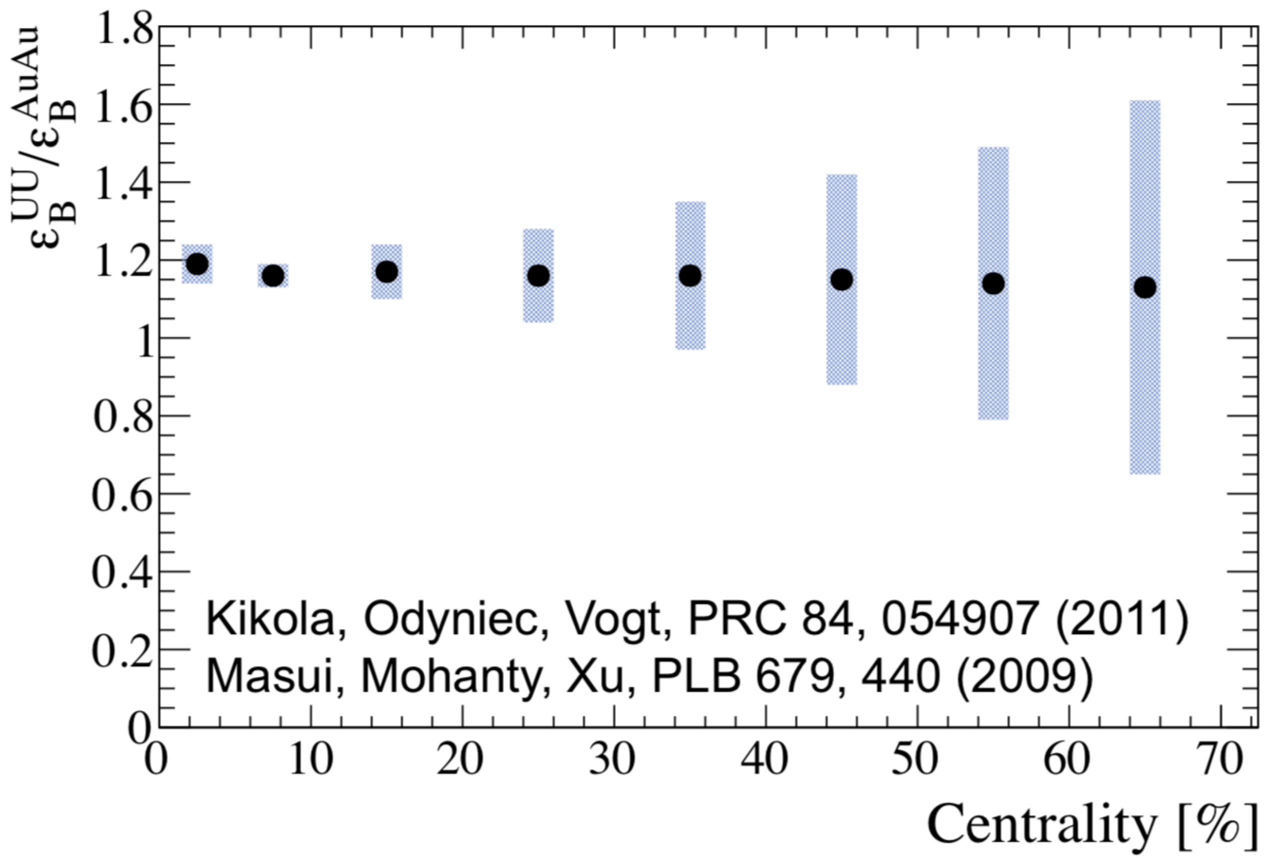




PRD 86, 072013 (2012)

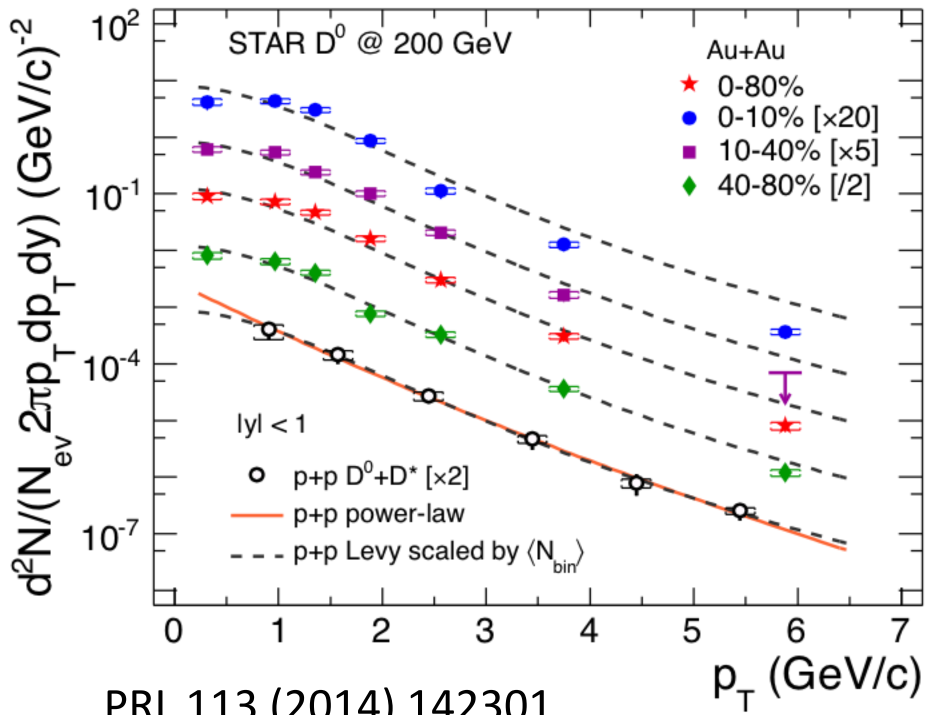
OHF in U+U collisions



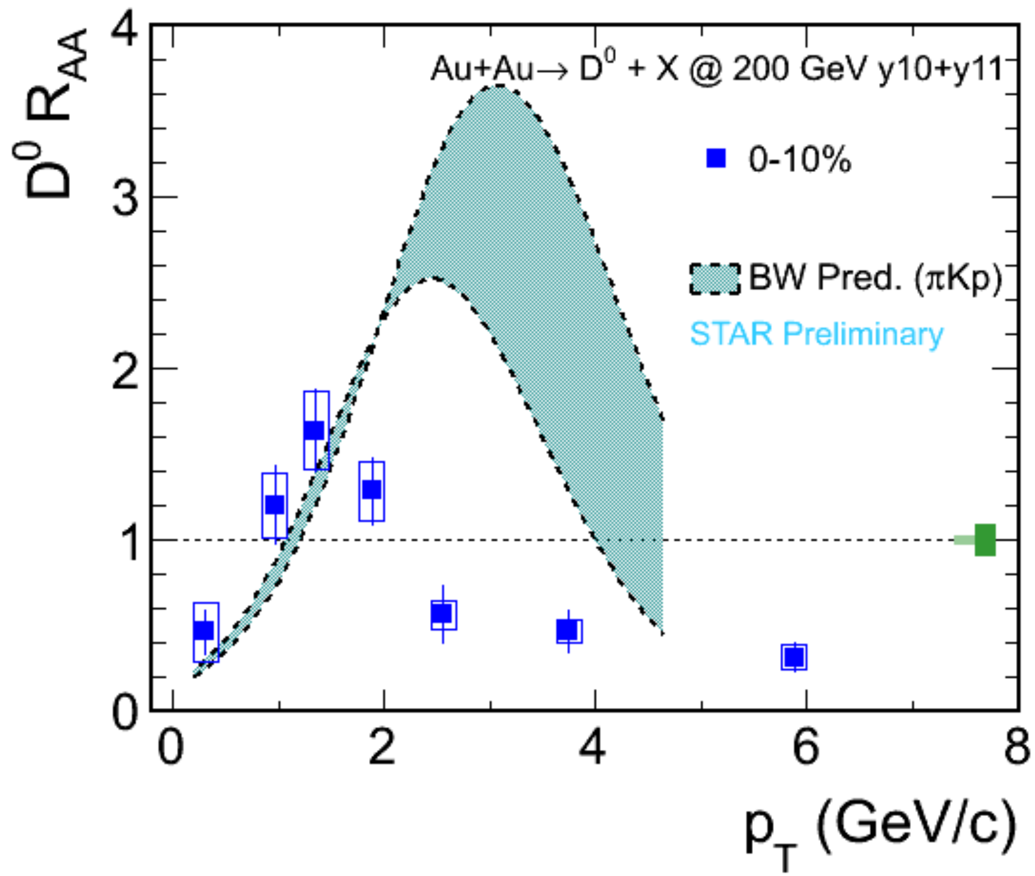


U+U collisions could have 20% higher energy density than Au+Au.

Nuclear modification of D^0



PRL 113 (2014) 142301
pp reference:
PRD 86 (2012) 072013



- No obvious suppression observed in peripheral collisions.
- Suppression at high p_T (> 3 GeV/c) in central and mid-central collisions.
- Low p_T enhancement, radial flow of light quarks coalescence with charm.
- D^0 may freeze out earlier and/or charm does not have much radial flow as light quarks.