Open Heavy Flavor Production at STAR

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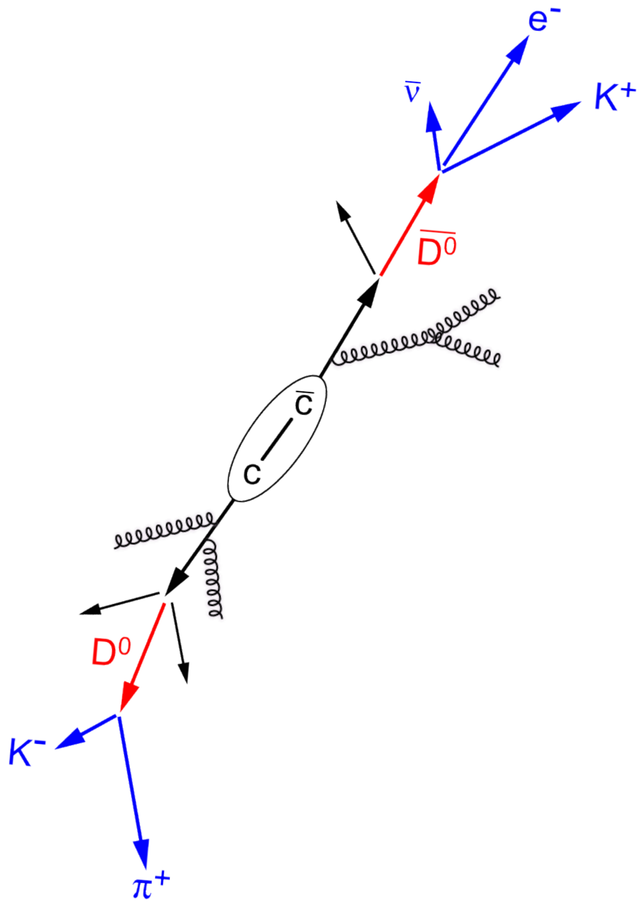
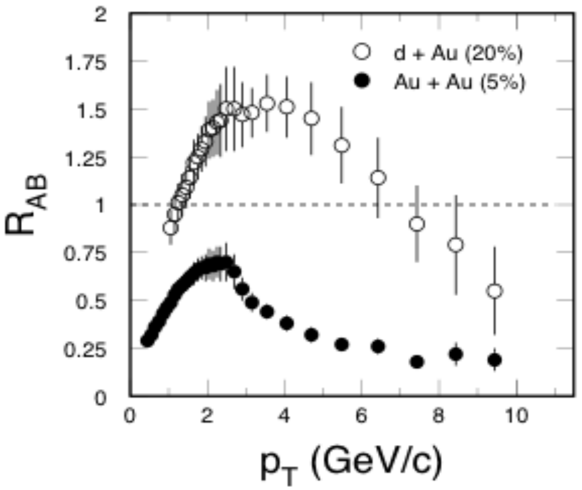
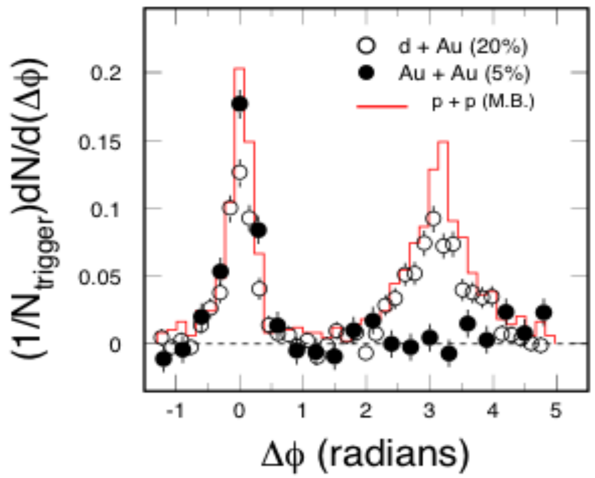


- ✧ Introductions
- ✧ Hadronic reconstruction
- ✧ Electron decay channel
- ✧ Near future HF program

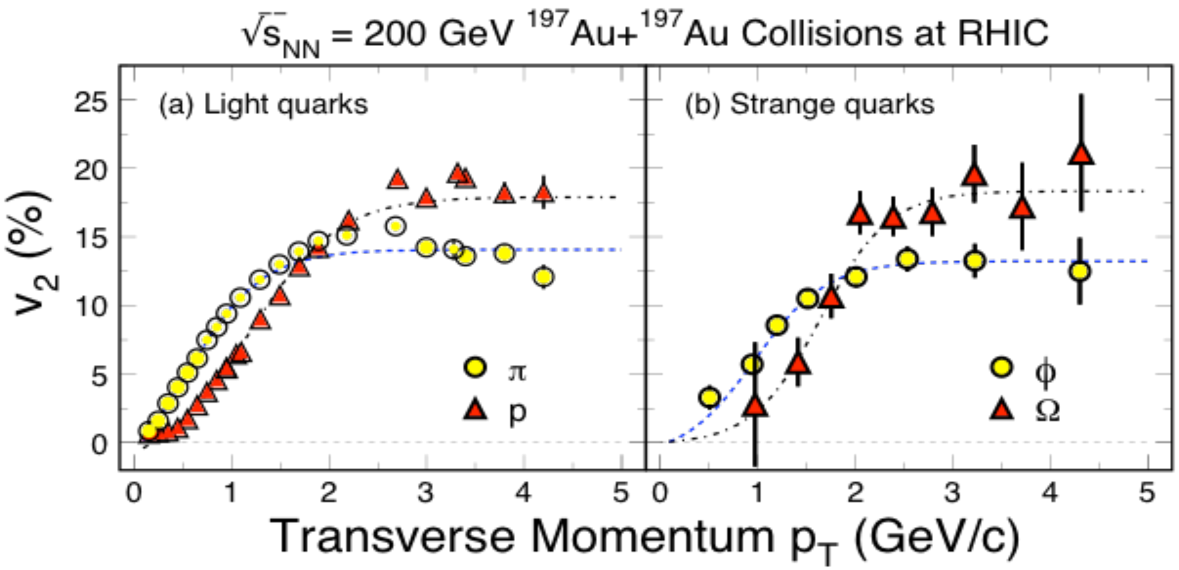
HPT2012 @ CCNU, Wuhan, 21-24 October 2012

Light flavor behavior in strong 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



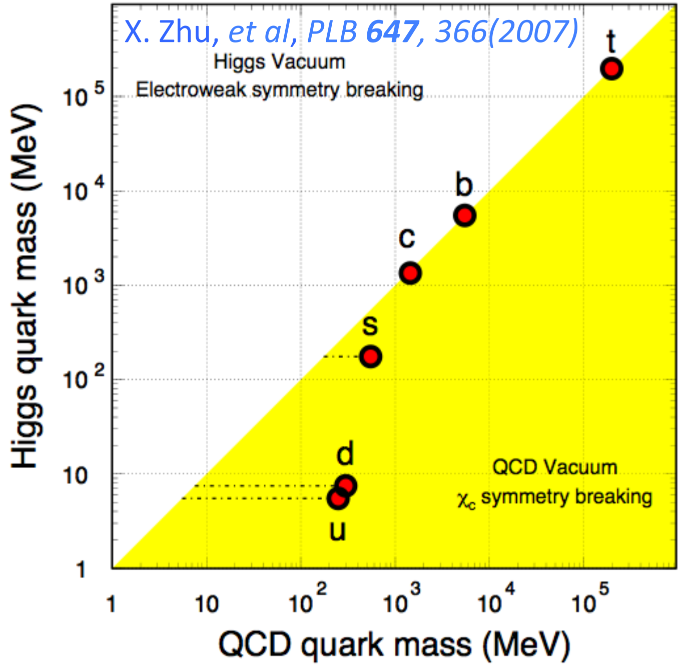
Large collective flow observed.
u, d, s quarks strongly interact with hot/dense medium.
What about heavy quarks?
Is the medium hot/dense enough to modify heavy quarks at RHIC energies?

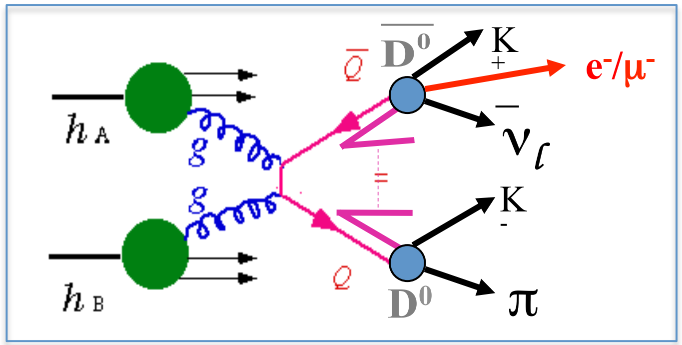
STAR: Nucl. Phys. ***A757***, 102(2005).

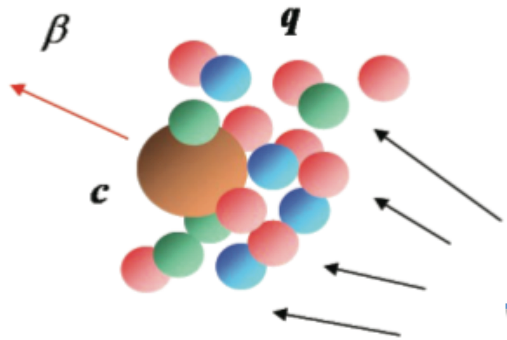
Why are heavy quarks important?

- Higgs mass: electro-weak symmetry breaking (current quark mass).
- QCD mass: Chiral symmetry breaking (constituent quark mass).
- Strong interactions impact little on heavy quark mass.

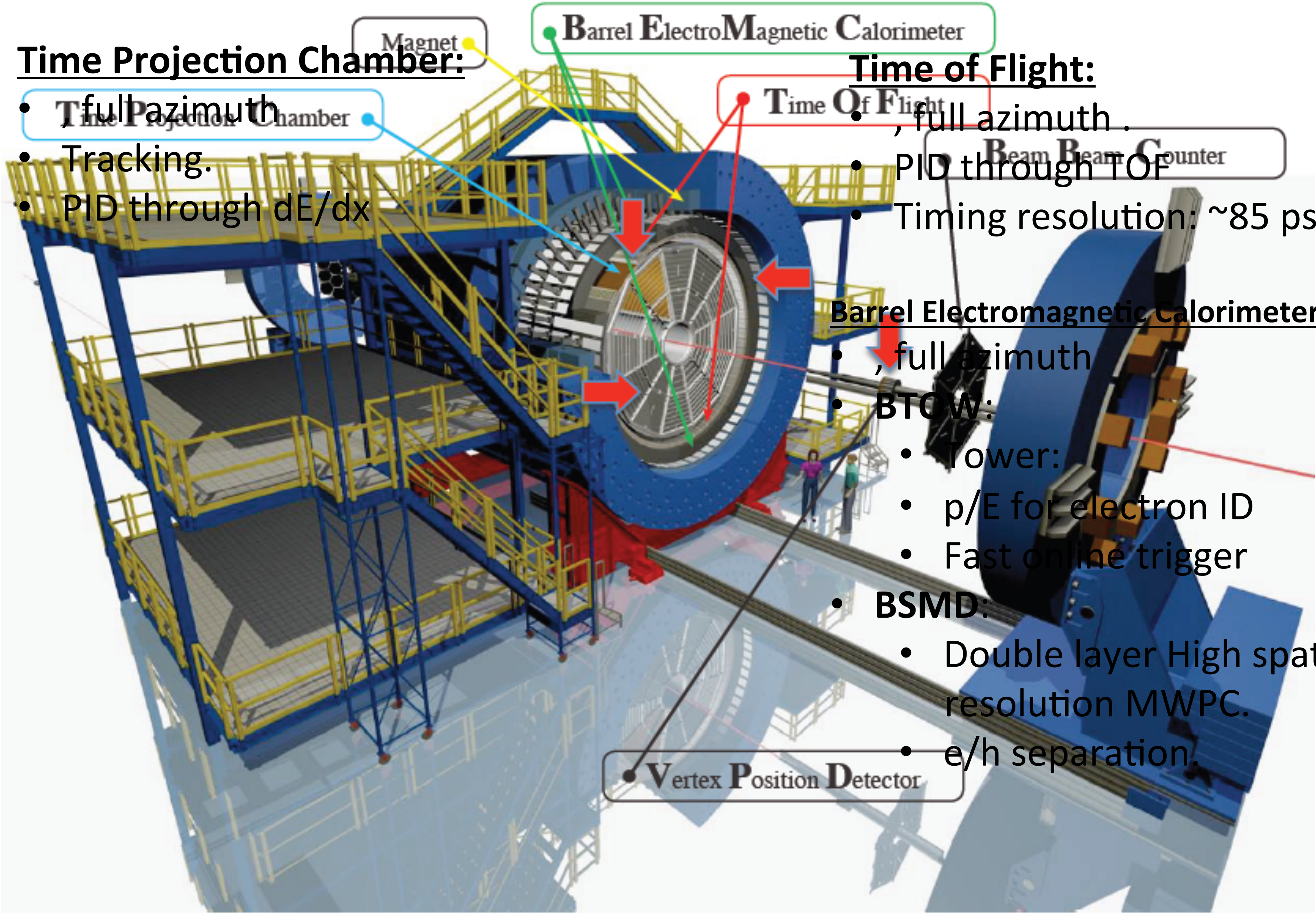
- Sensitive to initial gluon density and distribution.
- Production cross section can be evaluated by pQCD. Provide reference for charmonium calculations.
- Probe for studying medium properties.
- Charm collectivity => test light flavor thermalization.







The STAR detector for recent HF measurement



Time Projection Chamber:

- , full azimuth
- Tracking.
- PID through dE/dx

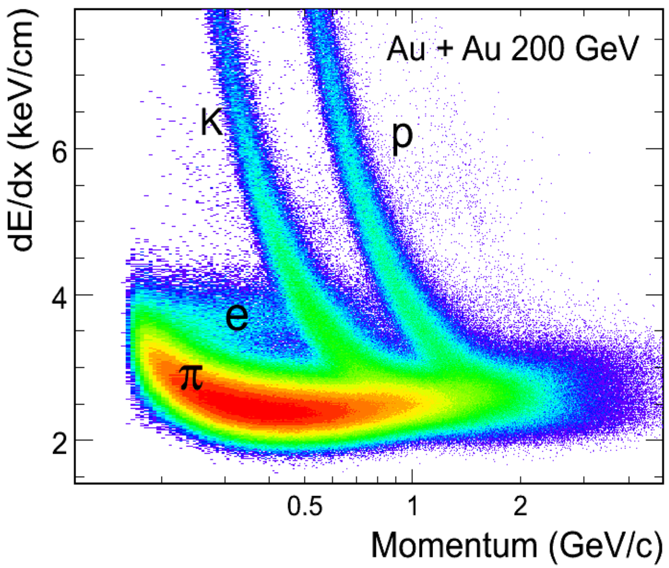
Time of Flight:

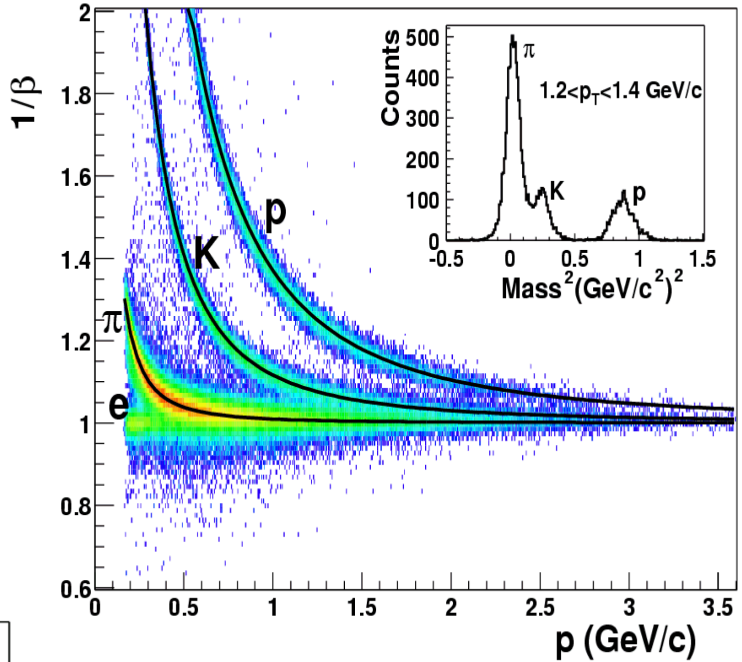
- , full azimuth .
- PID through TOF
- Timing resolution: ~85 ps.

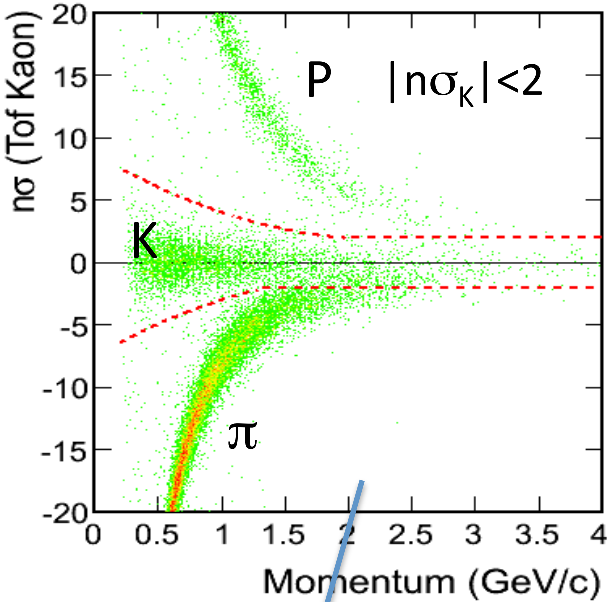
Barrel Electromagnetic Calorimeter

- , full azimuth
- **BTOW:**
  - Tower:
  - p/E for electron ID
  - Fast online trigger
- **BSMD:**
  - Double layer High spatial resolution MWPC.
  - e/h separation.

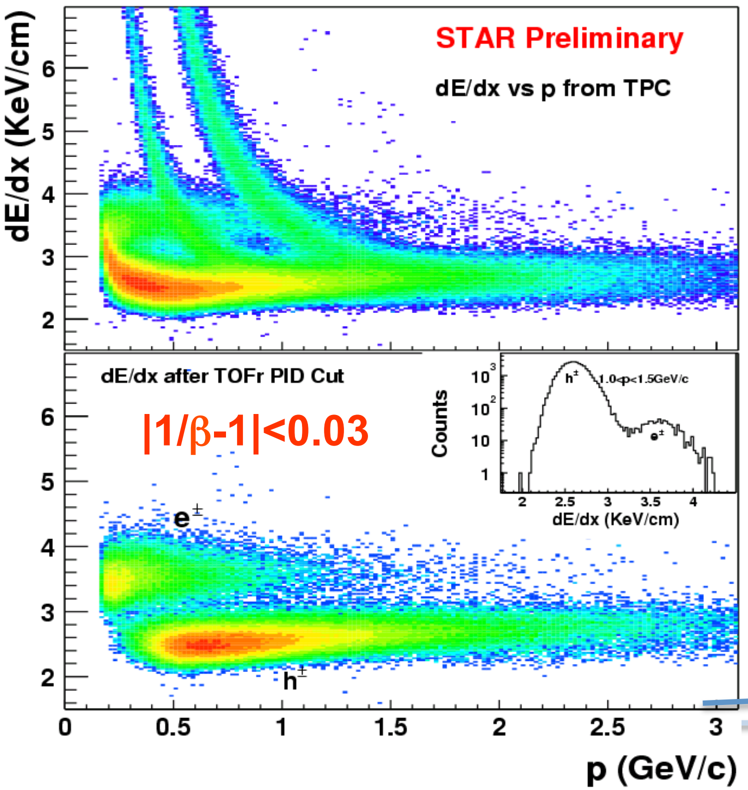
Particle Identification

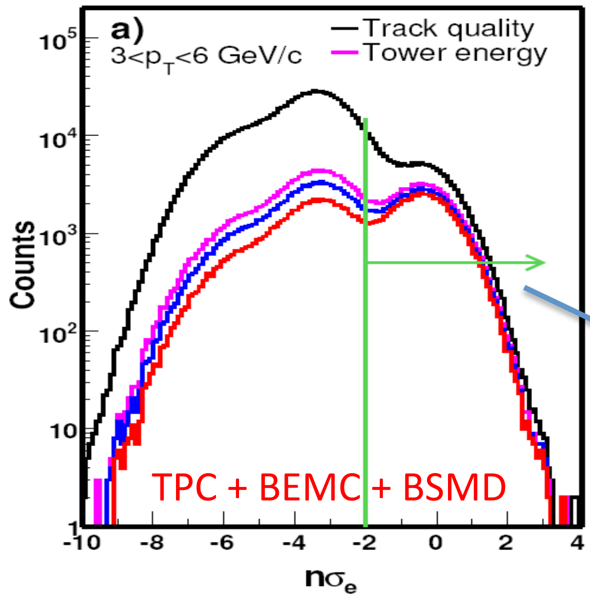






D meson hadronic daughter PID.

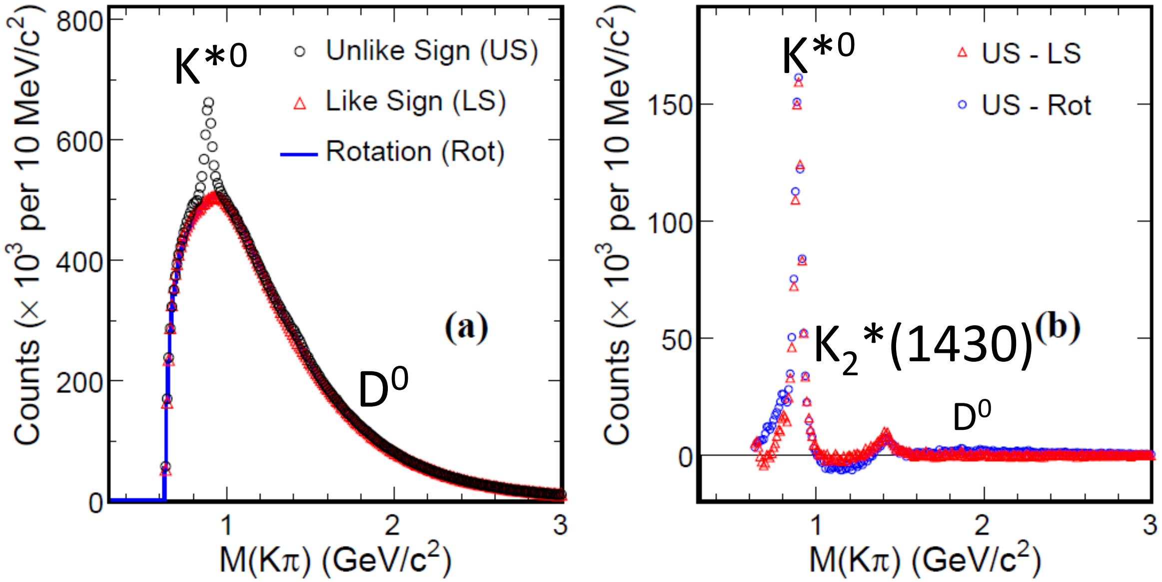


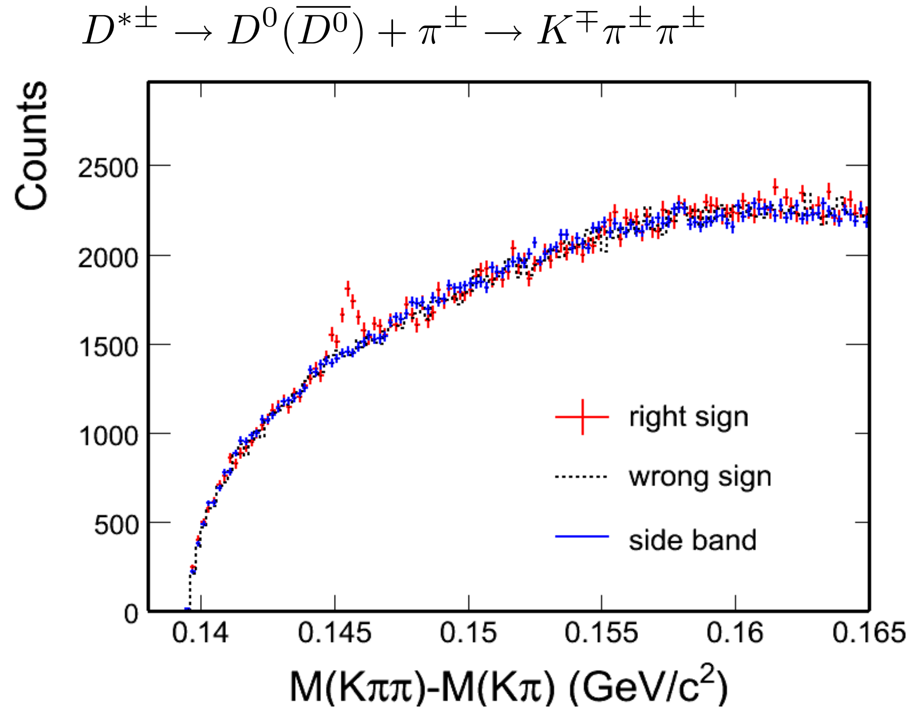


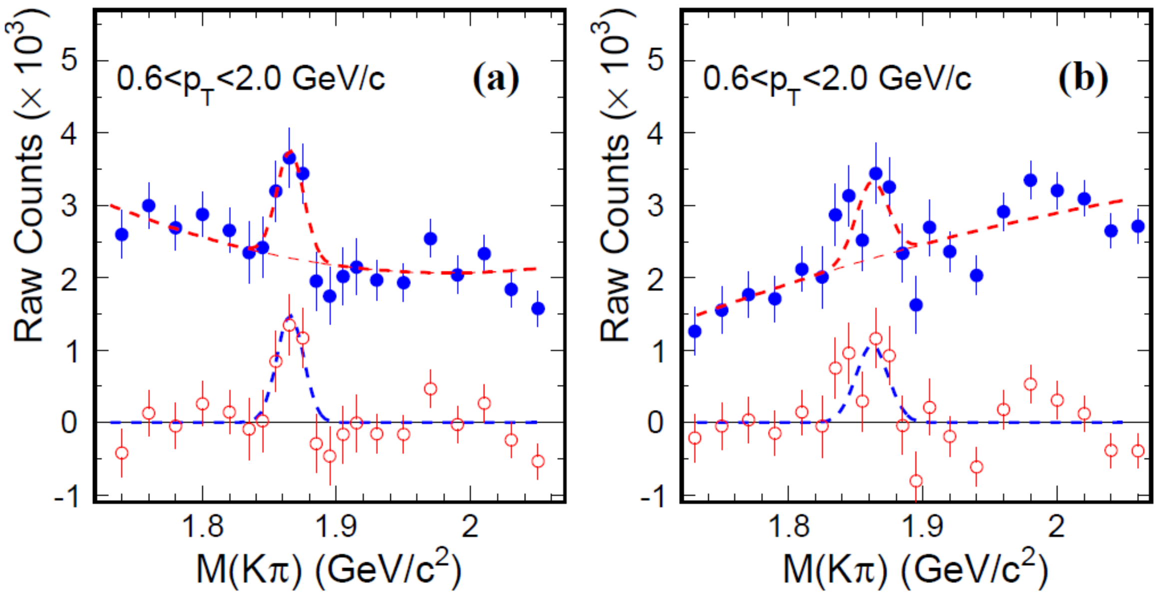
High p_T NPE

Low p_T NPE

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







p+p minimum bias 105 M

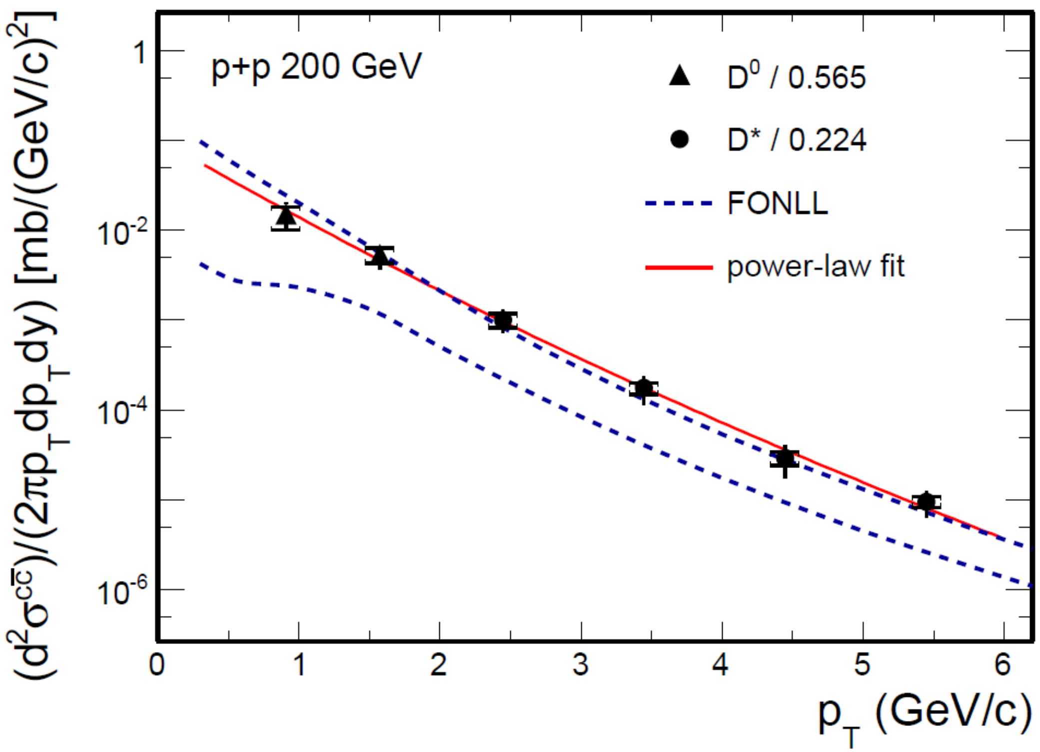
Different methods reproduce comb. background.

Consistent between two background methods.

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

arXiv: 1204.4244

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.

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

$F = 4.7 \pm 0.7$ scale to full rapidity.

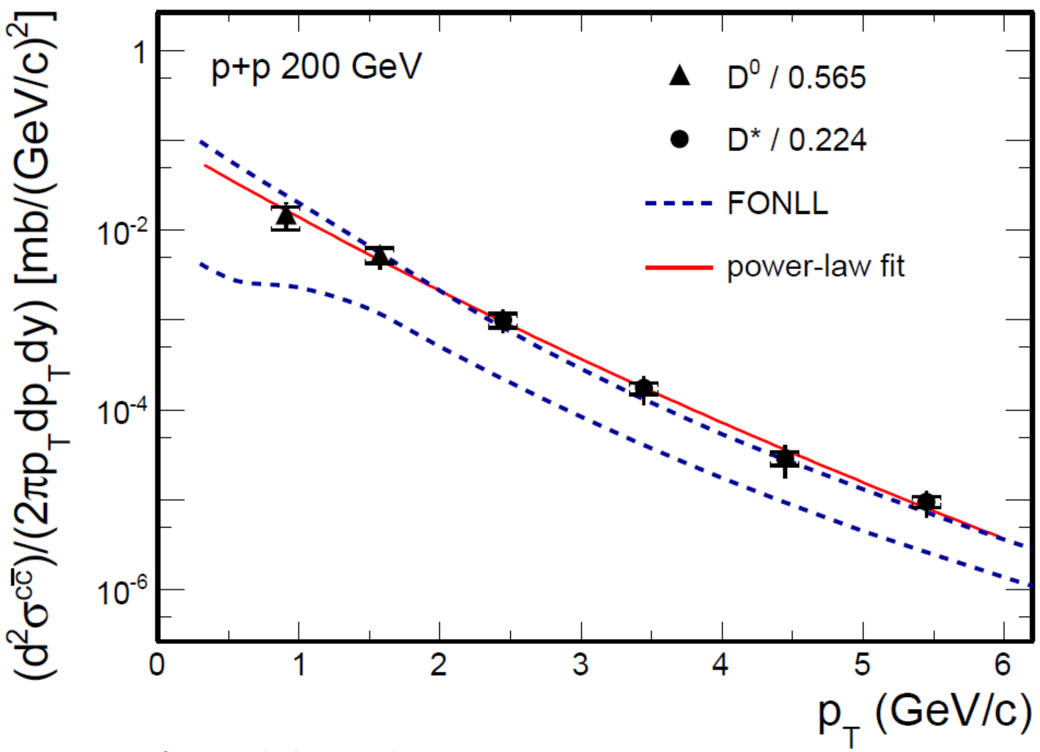
$\sigma_{pp}(NSD) = 30$ mb

The charm cross section at mid-rapidity is:
170 ± 45 (stat.) $^{+38}_{-59}$ (syst.) μb

The charm total cross section is extracted as:
797 ± 210 (stat.) $^{+208}_{-295}$ (syst.) μb

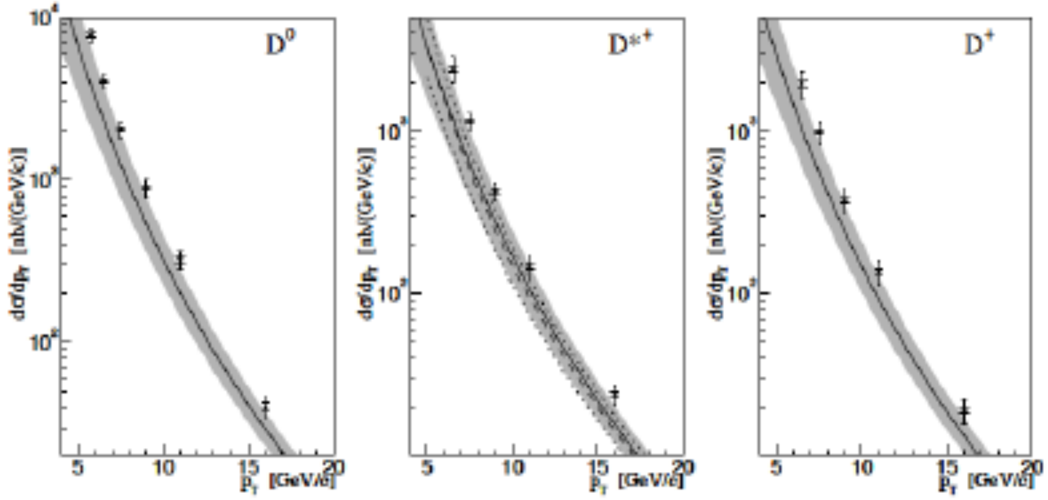
[1] C. Amsler et al. (Particle Data Group), PLB 667 (2008) 1.
[2] Fixed-Order Next-to-Leading Logarithm: M. Cacciari, PRL 95 (2005) 122001.

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

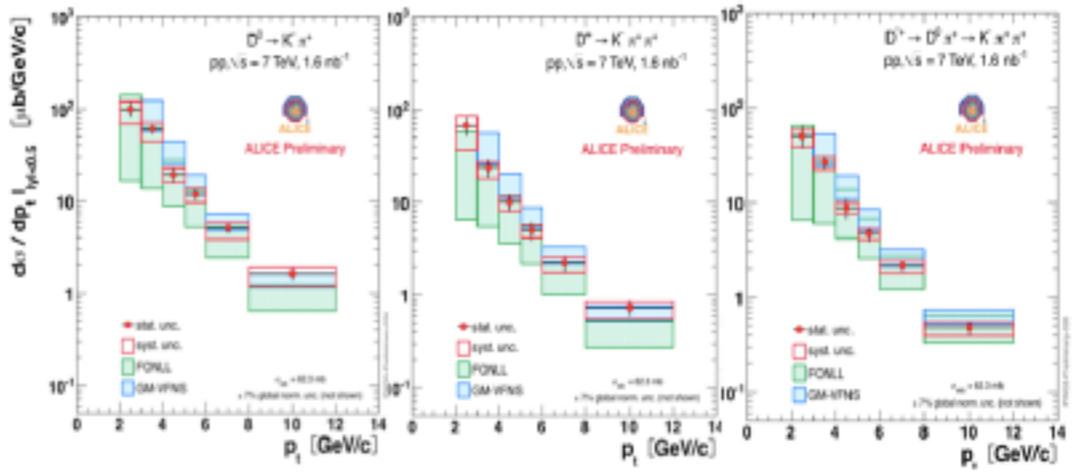


arXiv: 1204.4244.

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

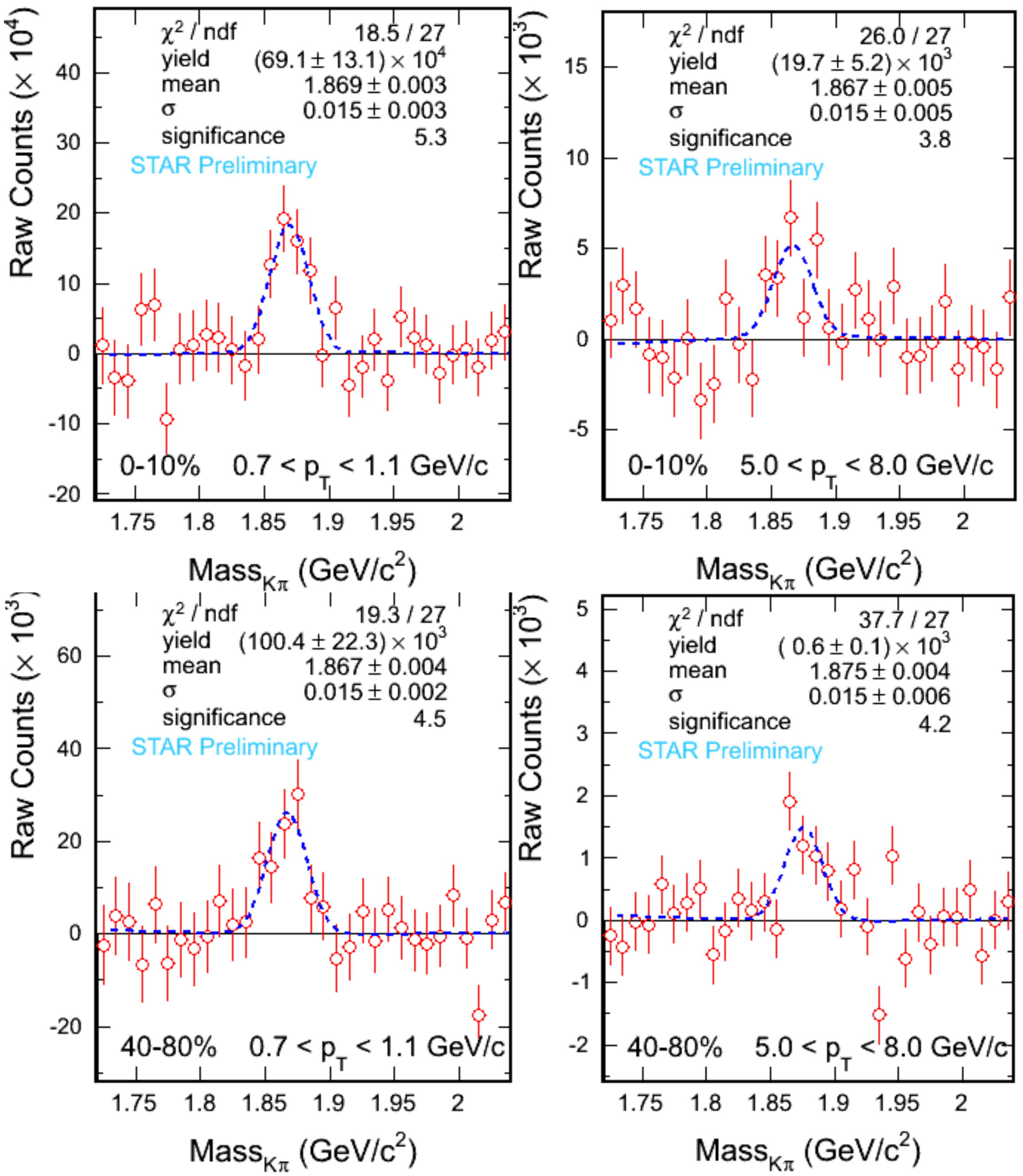


ALICE p+p @ 7 TeV *J. Shukraft, Alice QM11*



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

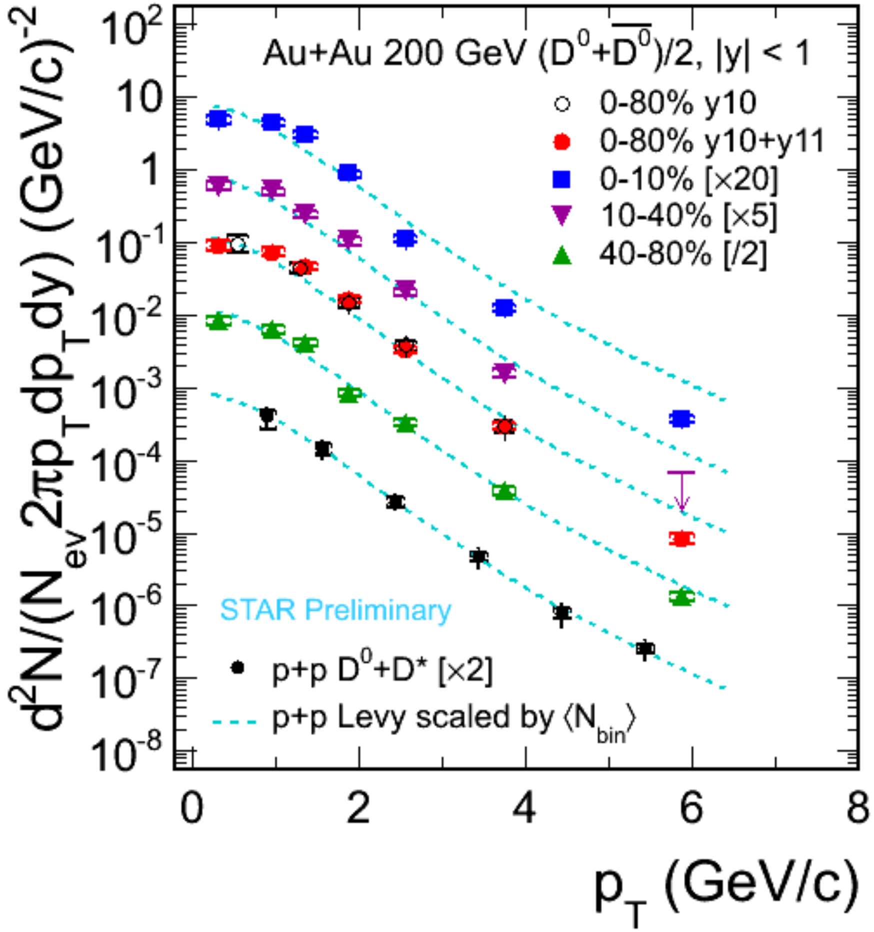
D^0 signals in Au+Au 200 GeV

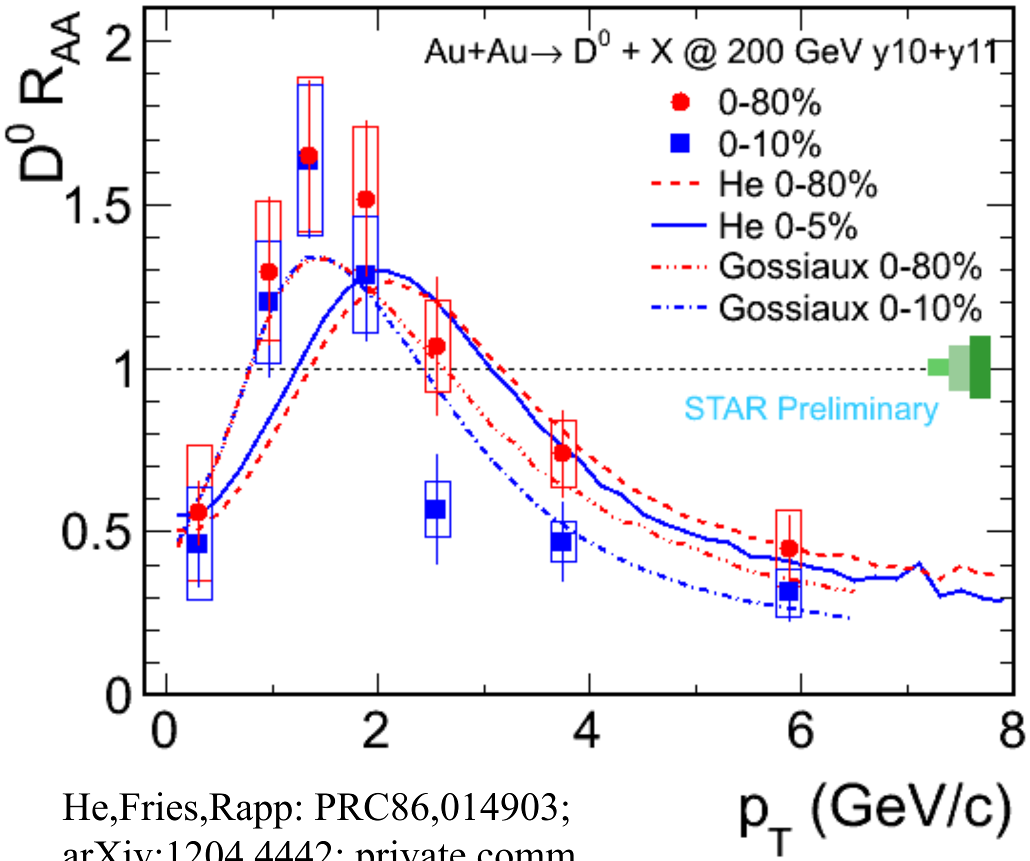


- Combining data from Year2010 & 2011.
- **Total: ~ 800 M Min.Bias events**
- **Significant signals are observed**
- **In collisions of all centralities**

W. Xie QM 2012

D^0 spectra in Au+Au 200 GeV

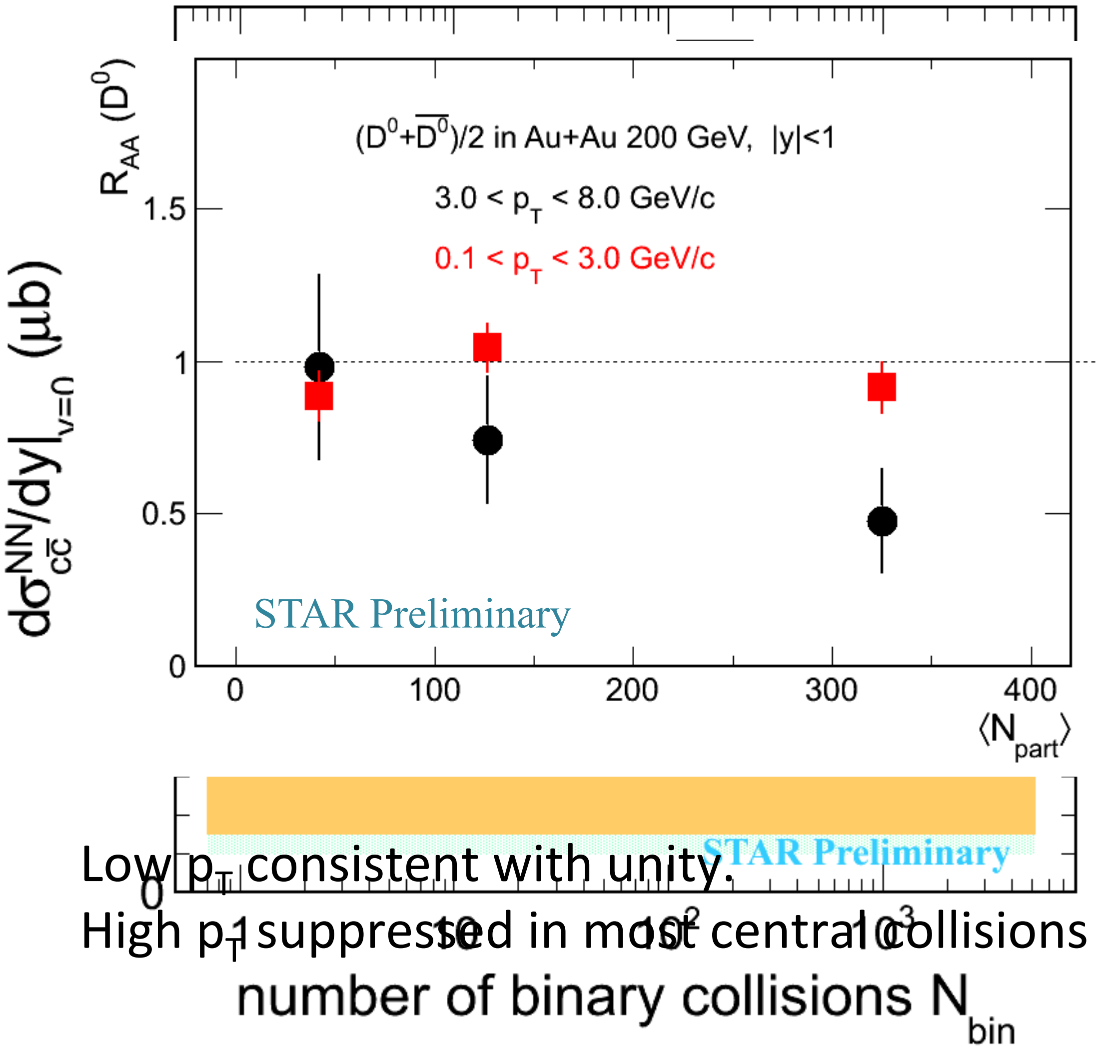




He,Fries,Rapp: PRC86,014903;
arXiv:1204.4442; private comm.

- Suppression at high p_T in central and mid-central collisions
- Enhancement at intermediate p_T.
- **D0 freeze out earlier than light hadron and/or**
- **D0 does not have much radial flow as light quarks**

Charm cross section versus N_{bin} in Au+Au 200 GeV



Low p_T consistent with unity.

High p_T suppressed in most central collisions

Year 2003 d+Au : D^0 + e

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

Year 2010 Au+Au: 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:

$$\left.\frac{d\sigma}{dy}\right|_{y=0}^{pp} = 797 \pm 210^{+208}_{-295}\,\mu b \qquad \left.\frac{d\sigma}{dy}\right|_{y=0}^{AuAu} = 822 \pm 62 \pm 192\,\mu b$$

[1] STAR d+Au: J. Adams, et al., PRL 94 (2005) 62301

[2] FONLL: M. Cacciari, PRL 95 (2005) 122001.

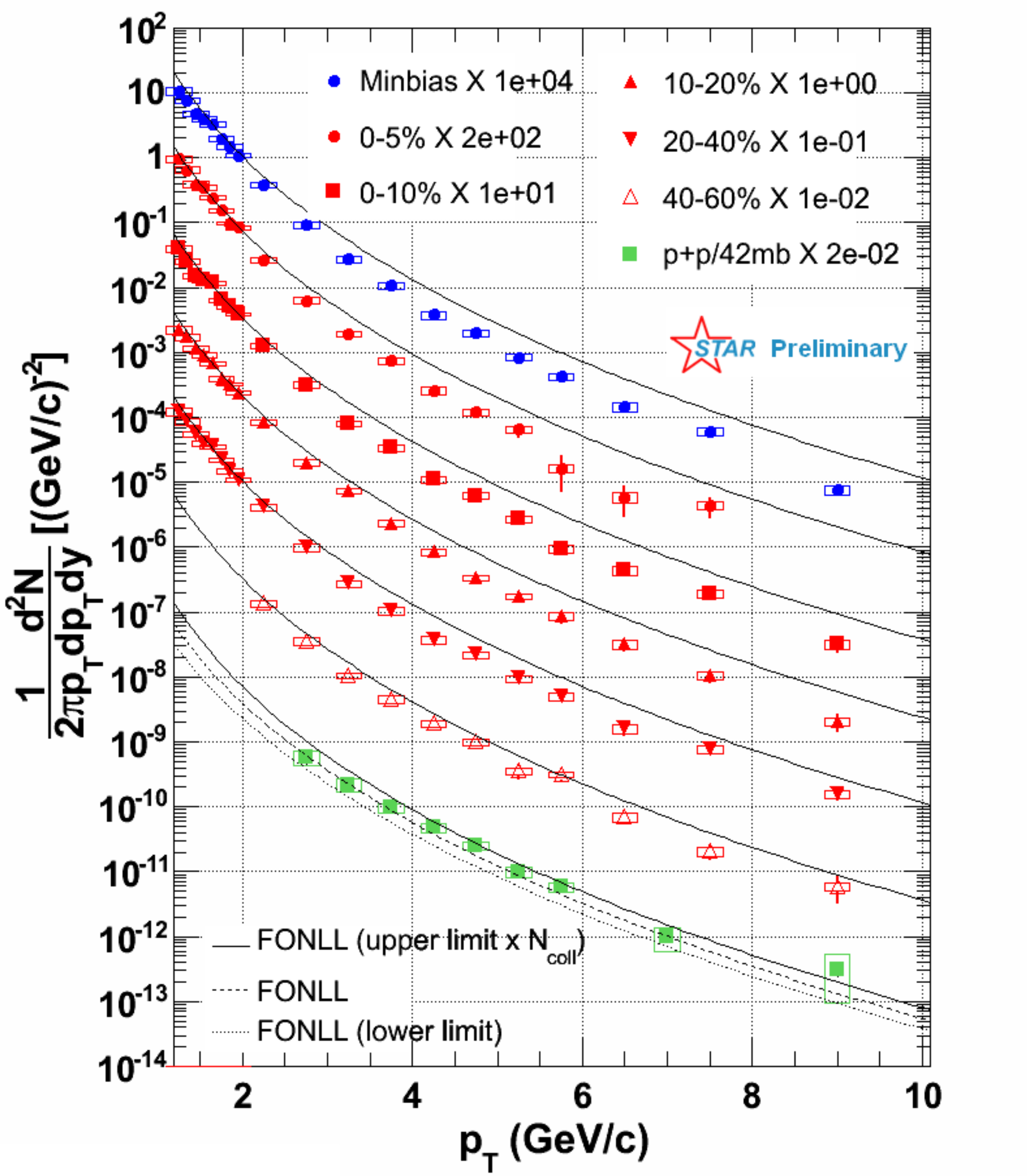
[3] NLO: R. Vogt, Eur.Phys.J.ST 155 (2008) 213

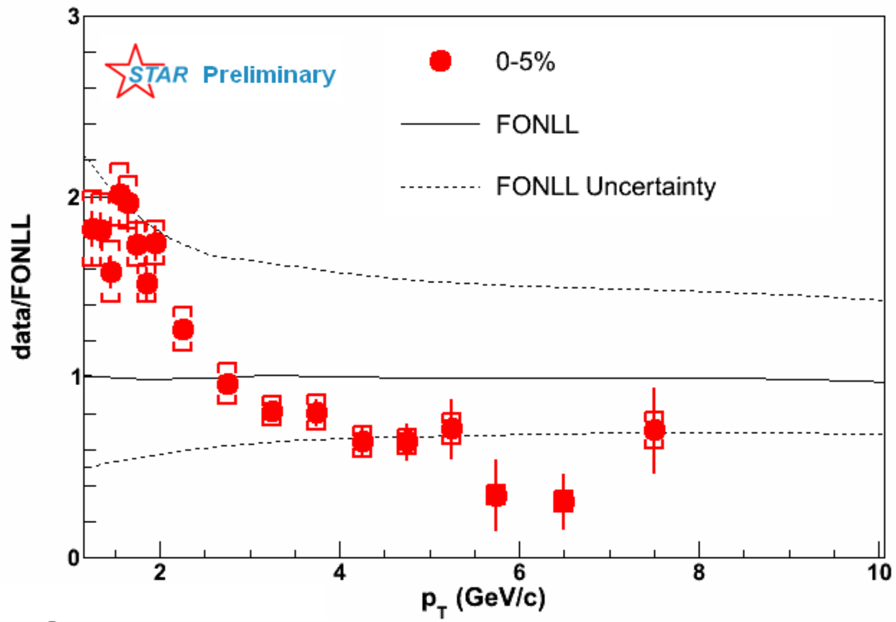
[4] PHENIX e: A. Adare, et al., PRL 97 (2006) 252002.

Charm cross section follows number of binary collisions scaling =>

Charm quarks are mostly produced via initial hard scatterings

Non-photonic electron spectra in Au+Au 200 GeV

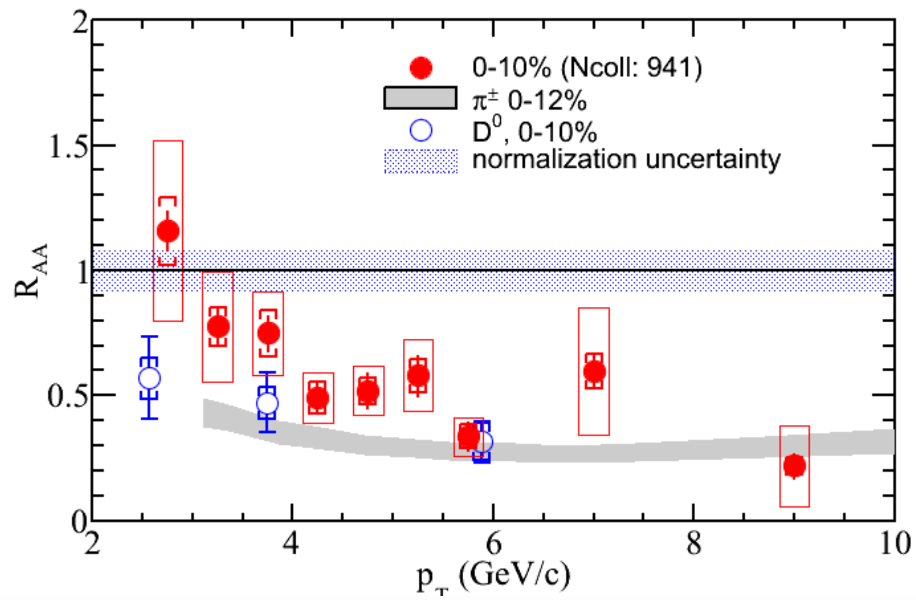


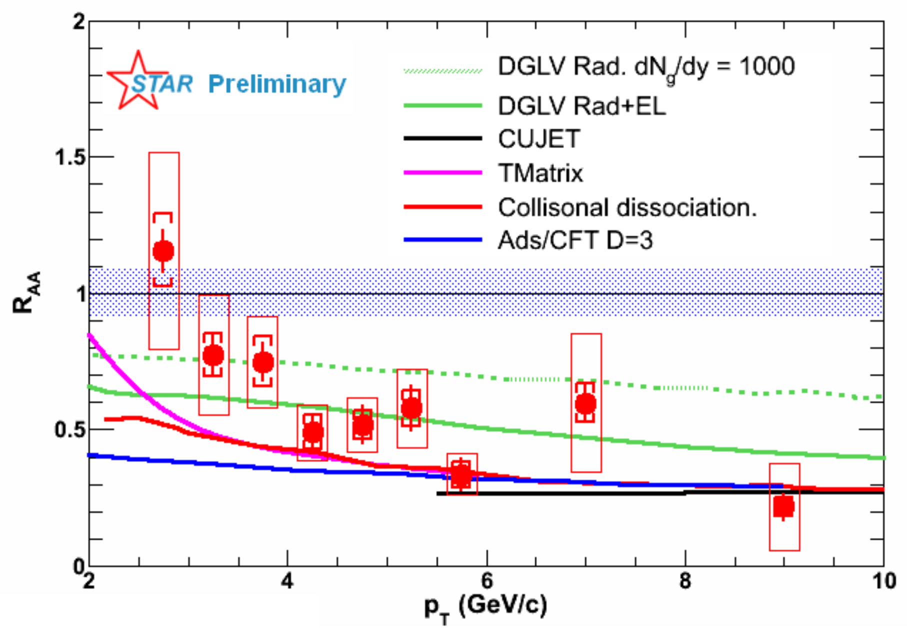


- ~1 nb^{-1} sampled luminosity in Run2010 Au+Au collisions.
- ~6 pb^{-1} sampled luminosity in Run2005 and Run2008 p+p collisions.

QM 2012

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

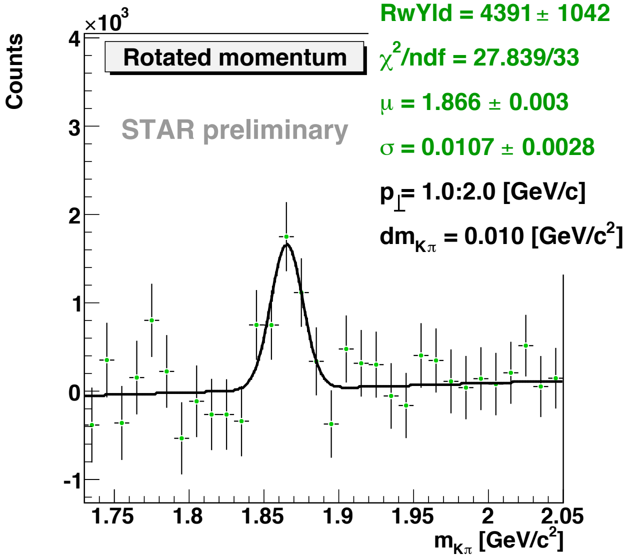


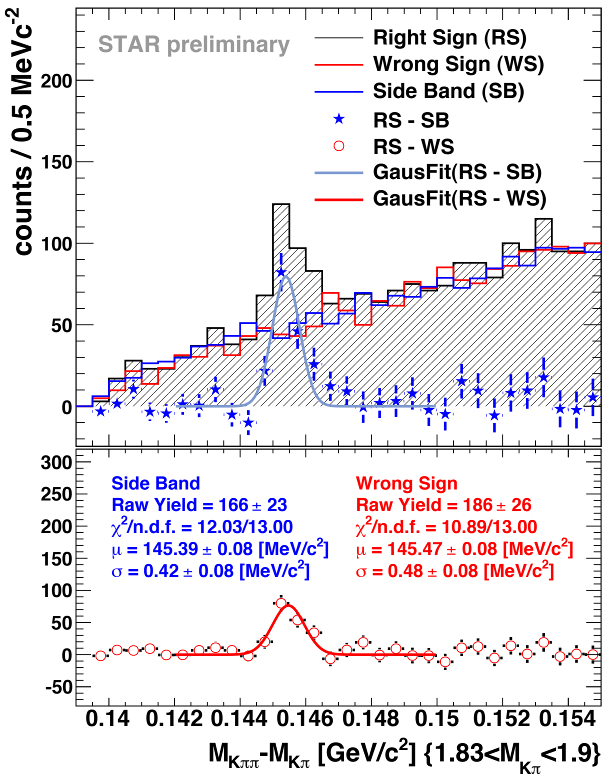


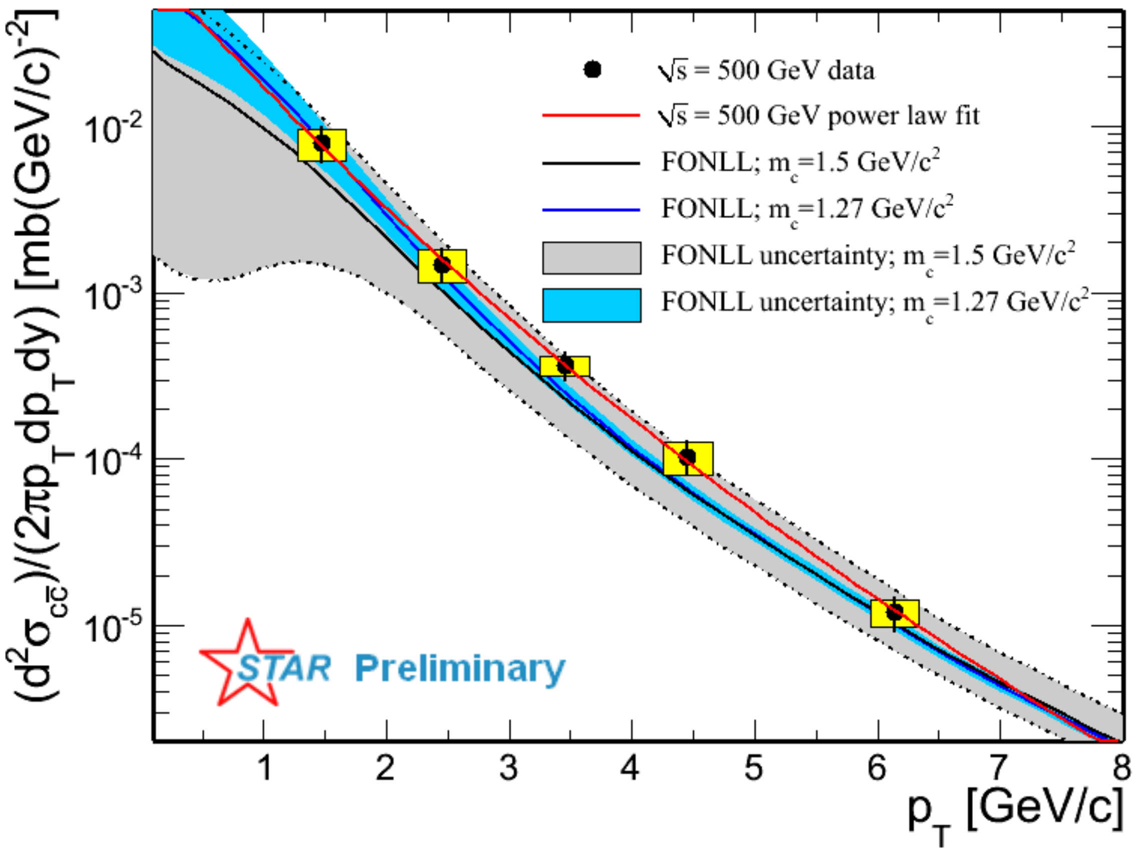
- Strong suppression at high p_T in central collisions
- D^0, NPE results seems to be consistent → kinematics smearing & charm/bottom mixing
- Models with radiative energy loss underestimate the suppression
- Uncertainty dominated by p+p result.
- Compare with Au+Au spectra directly, if possible.
- High quality p+p data from Run09 and Run12 are on disk.

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.

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



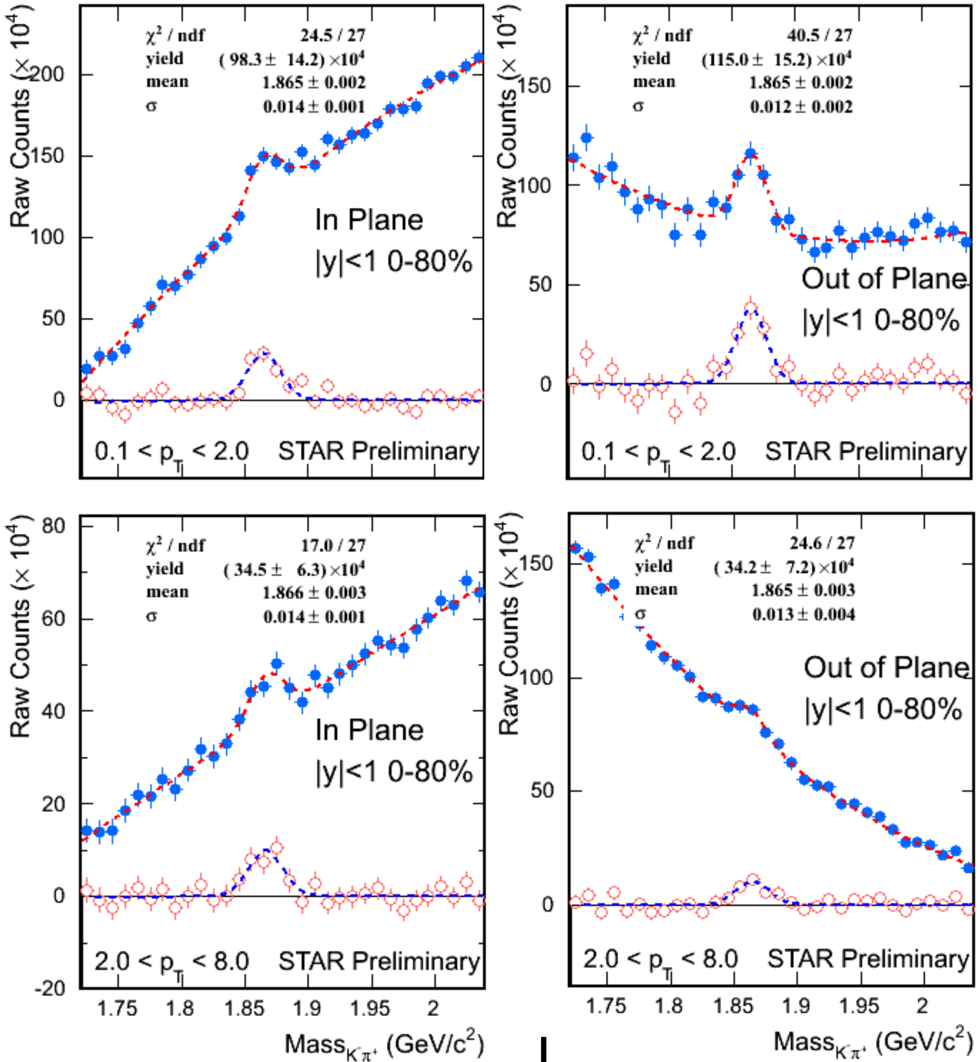


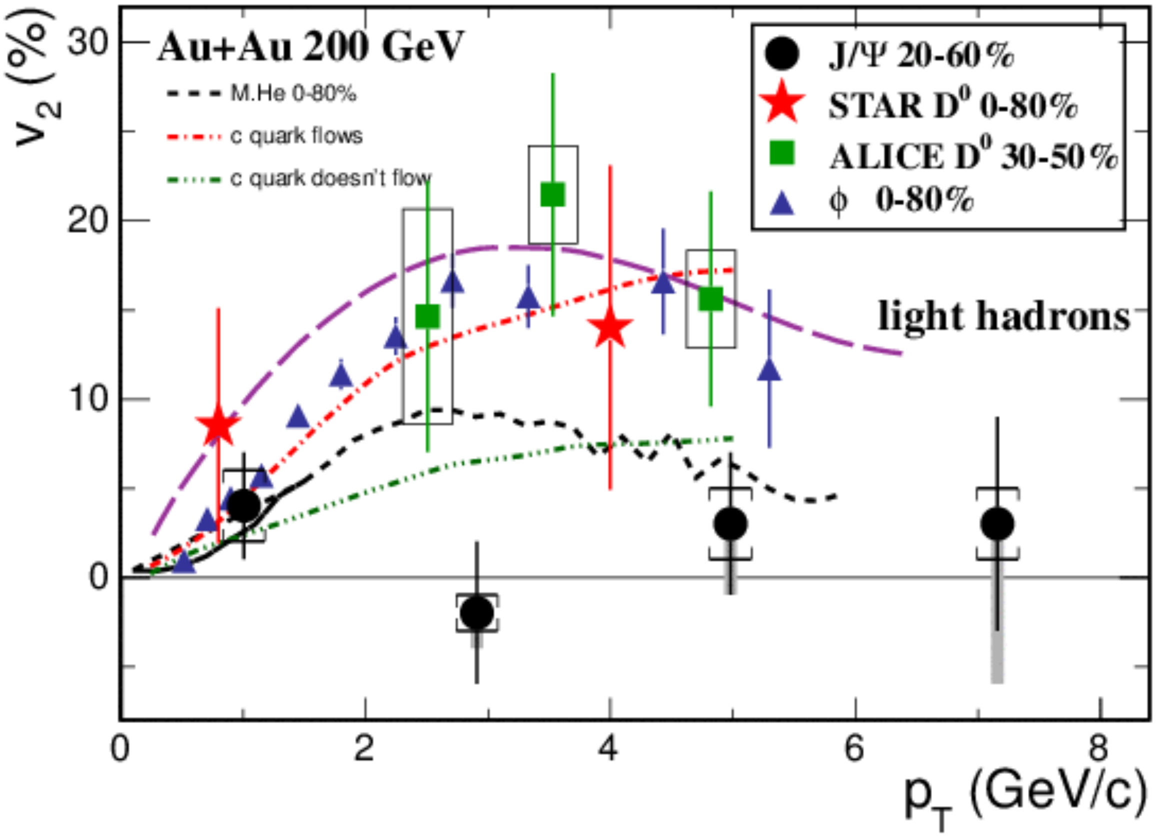


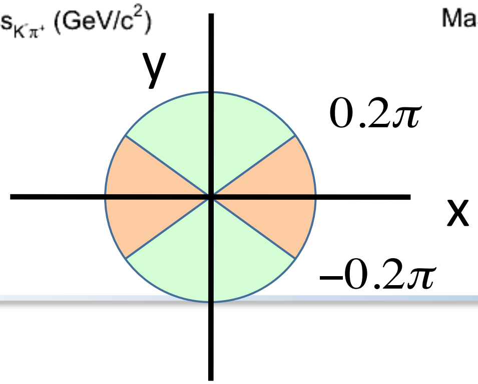
FONLL: R. Vogt, private communication

- **Data are consistent with FONLL prediction within uncertainties.**

D^0 v_2 measurement in Au+Au 200 GeV

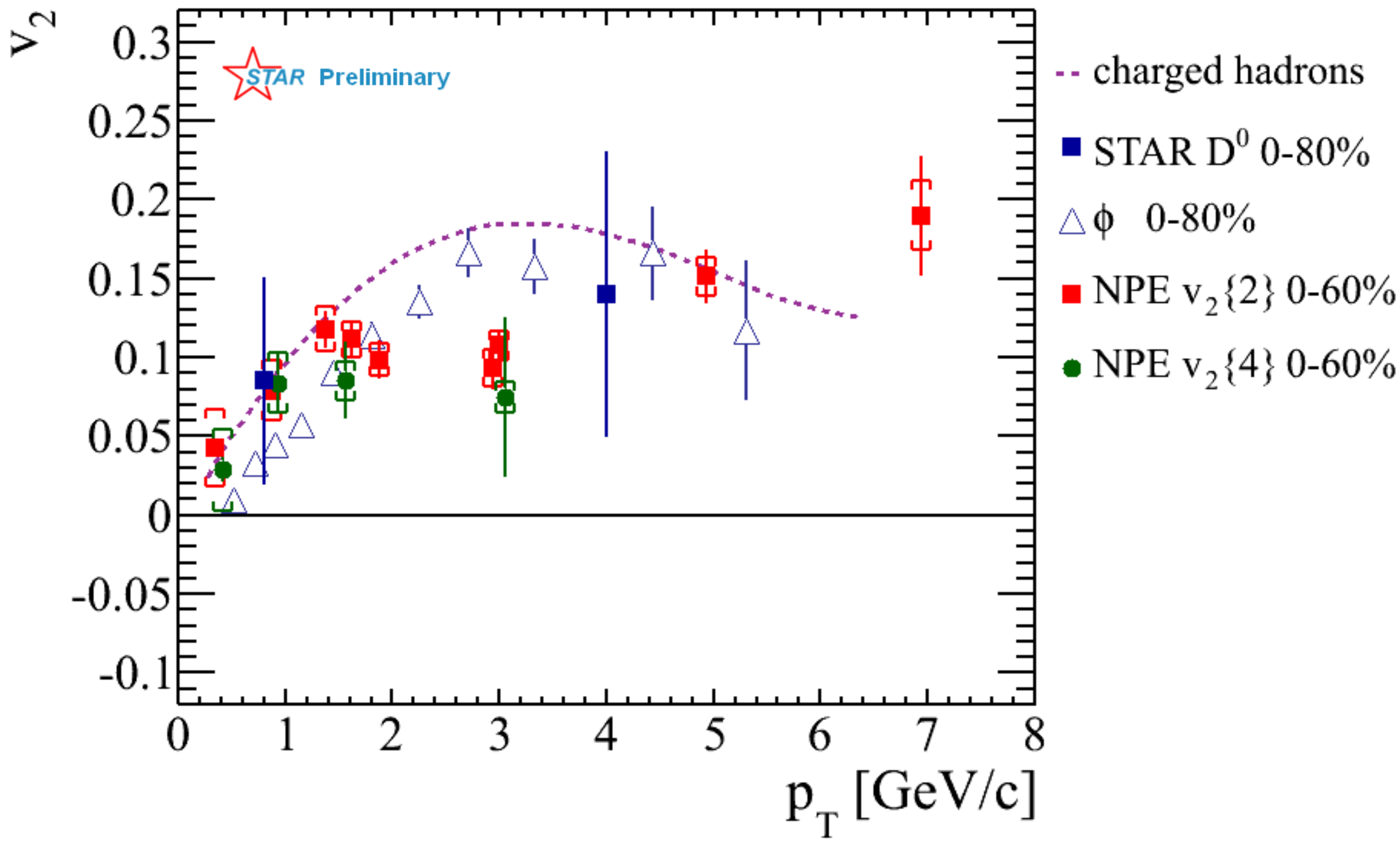






- ✧ **Finite v_2 observed with large errors.**
- ✧ **Need HFT for more precise measurement:**
  - **- to confirm the coalescence scenarios.**
  - **- to confirm the energy dependence.**
- ✧ **Different production mechanisms compared with hidden charm?**

NPE v_2 in Au+Au 200 GeV



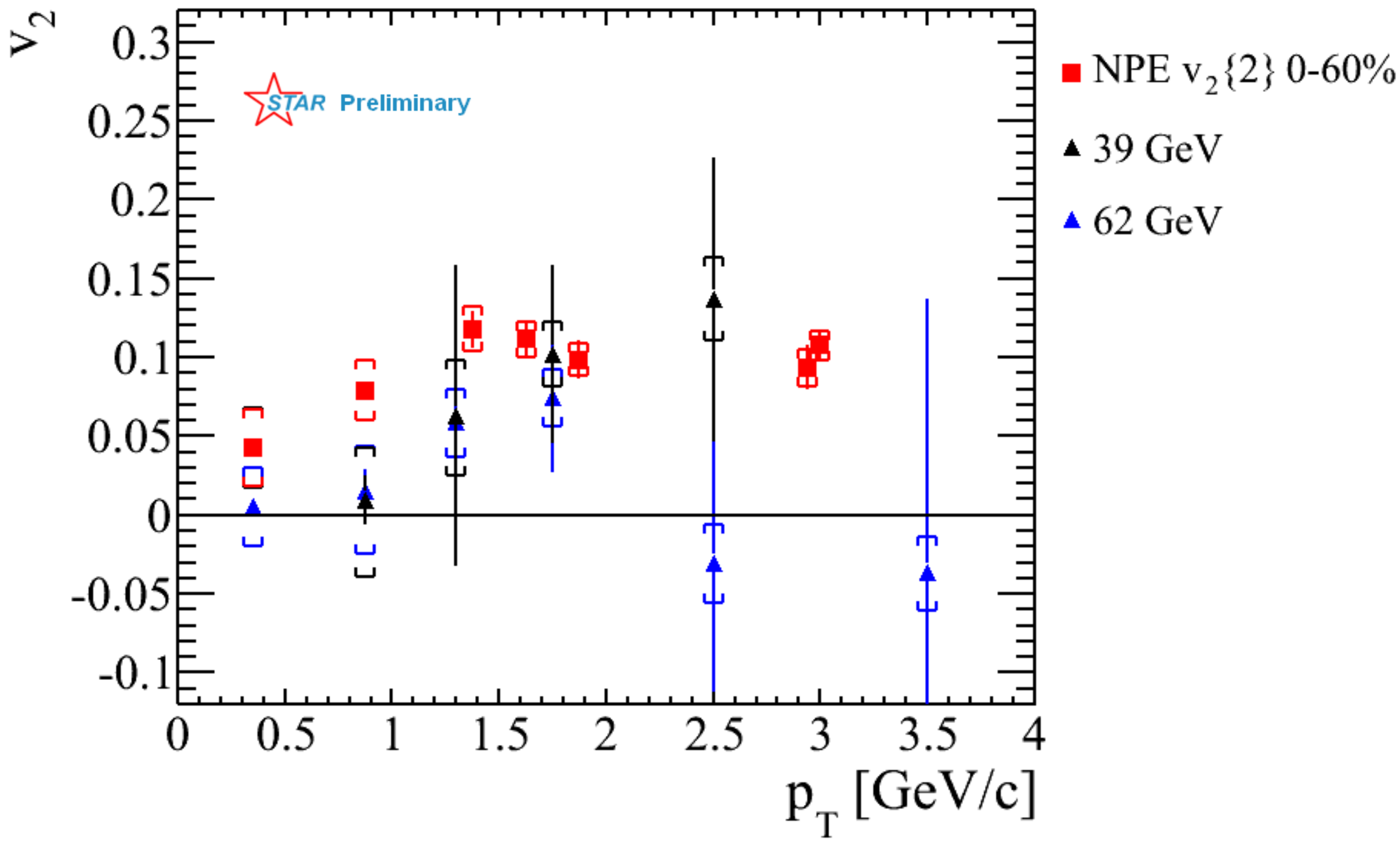
200 GeV Au+Au:

❑ **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.

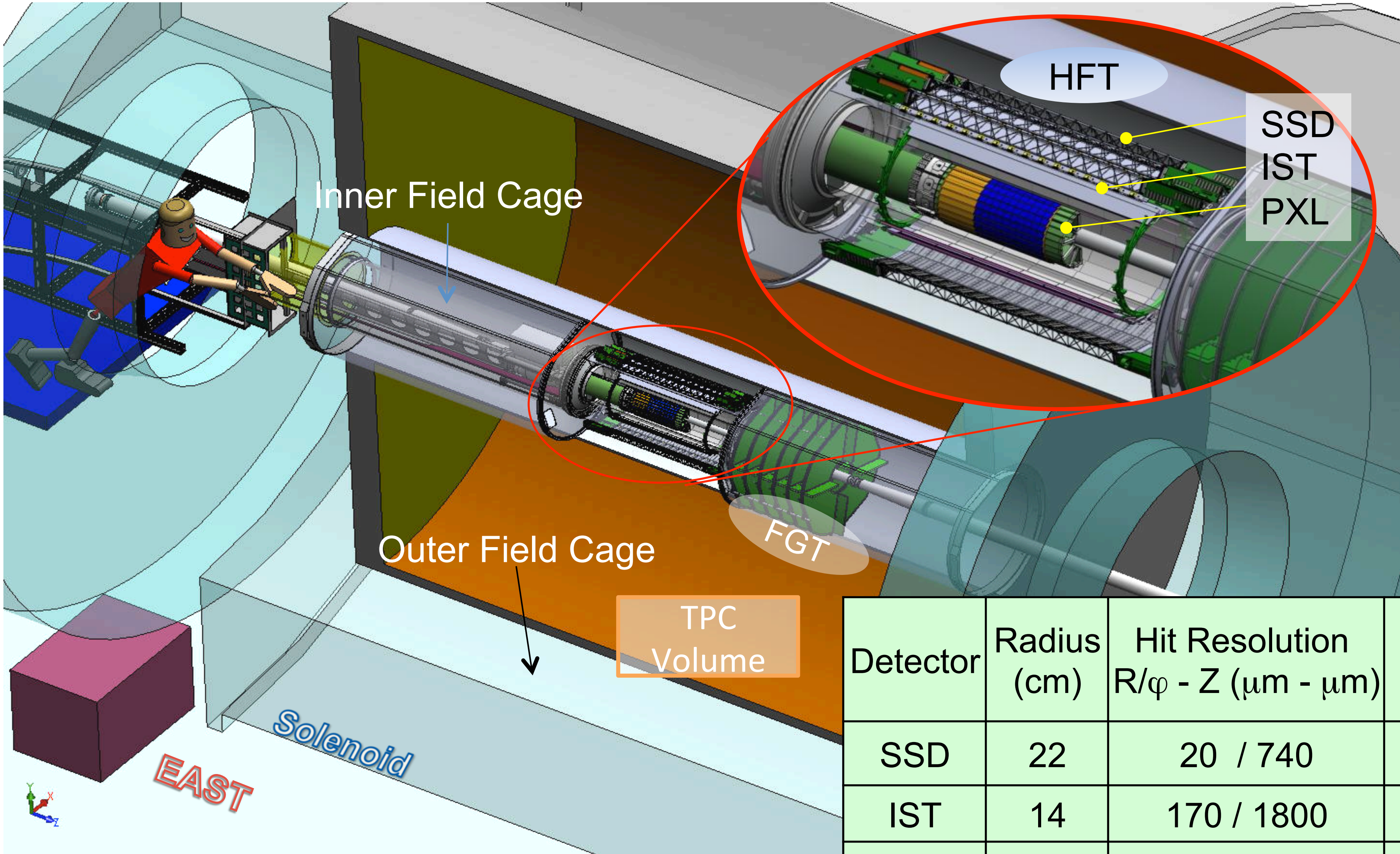
NPE v_2 in Au+Au 39 & 62 GeV



39 and 62.4 GeV Au+Au:

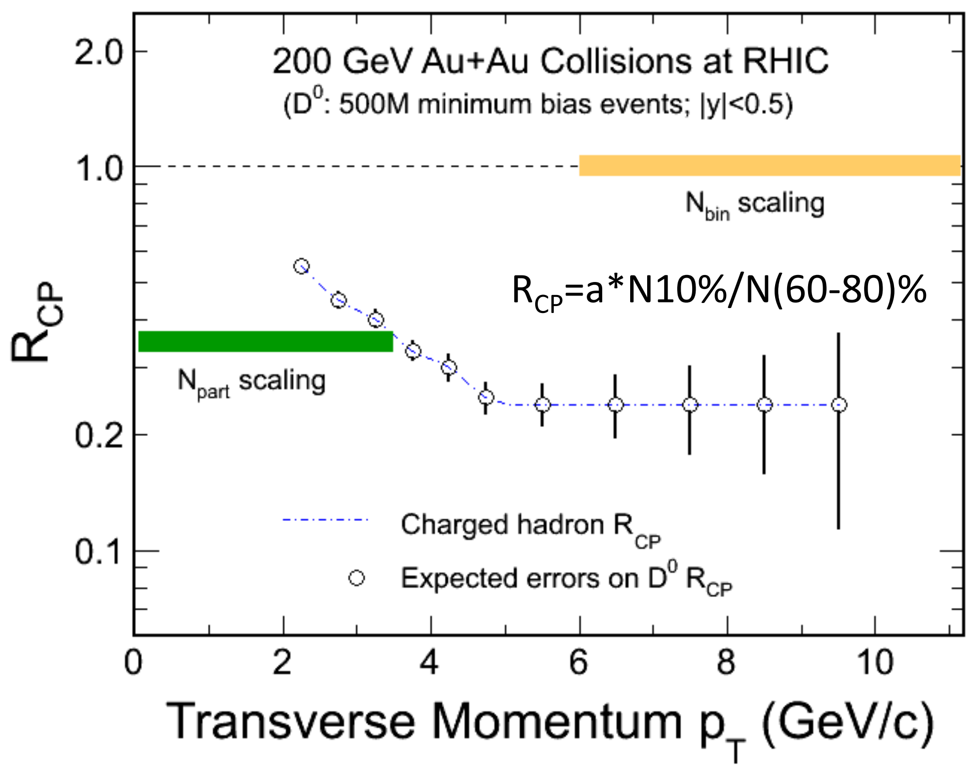
Low p_T v_2 consistent with zero => might suggest charm–medium interaction in lower energies is not as strong as in 200 GeV.

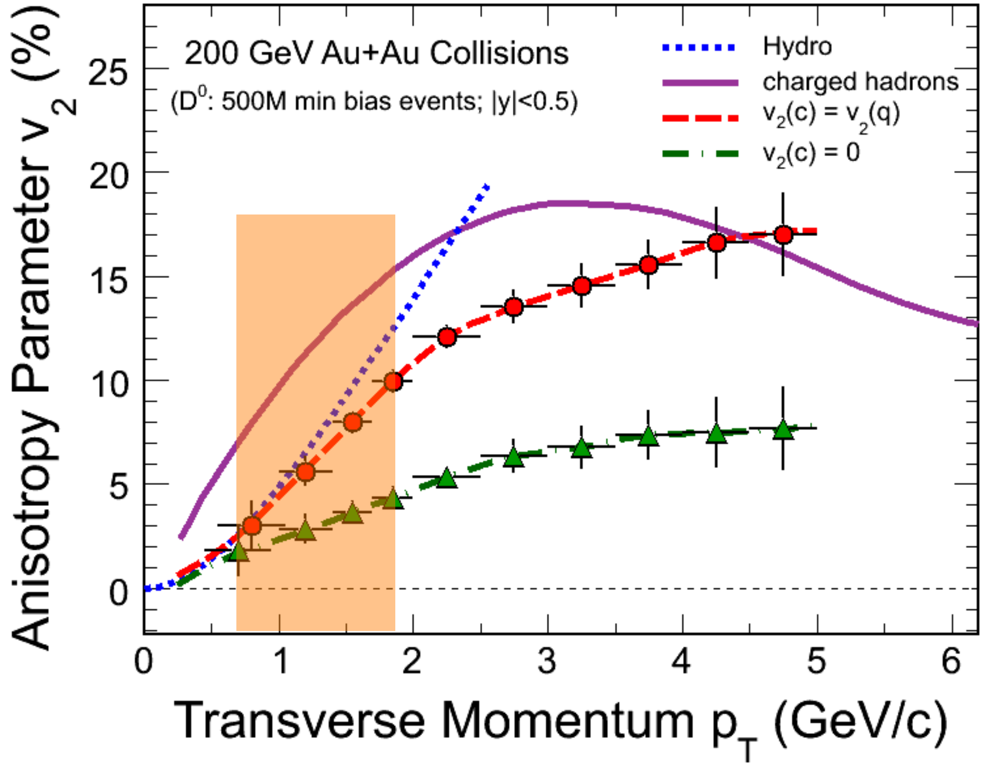
Heavy Flavor Tracker



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

Physics projections – punchline for Y13,14





Assuming D0 R_{cp} distribution as charged hadron.

500M Au+Au m.b. events at 200 GeV.

- Charm R_{AA} ⇨

Energy loss mechanism!
Color charge effect!
Interaction with QCD matter!

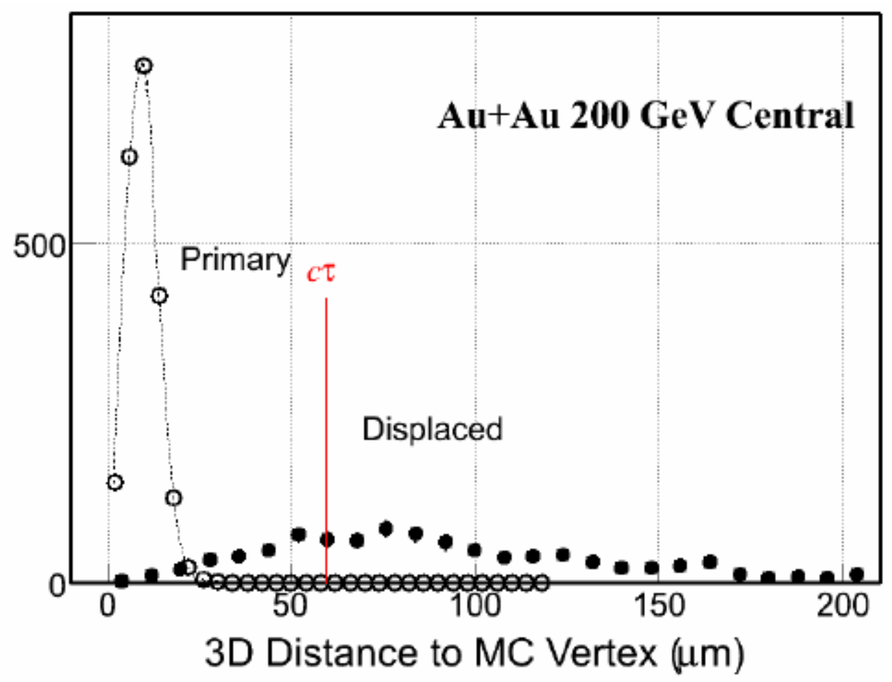
Assuming D0 v_2 distribution from quark coalescence.

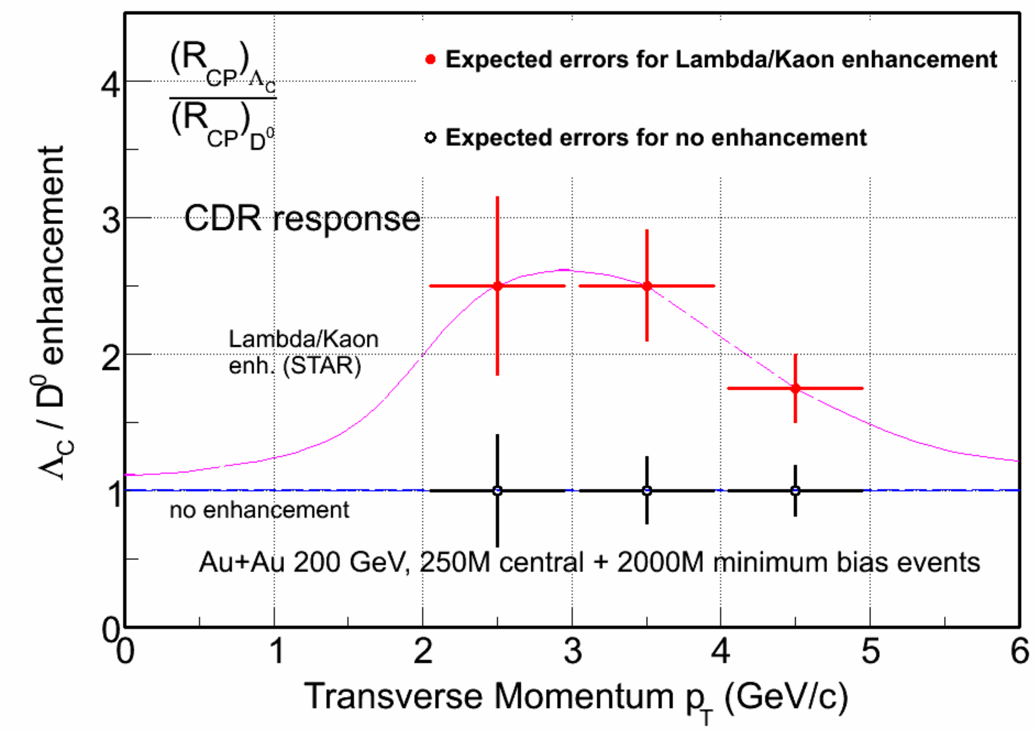
500M Au+Au m.b. events at 200 GeV.

- Charm v_2 ⇨

Medium thermalization degree
Drag coefficients!

Charmed baryons – Y14



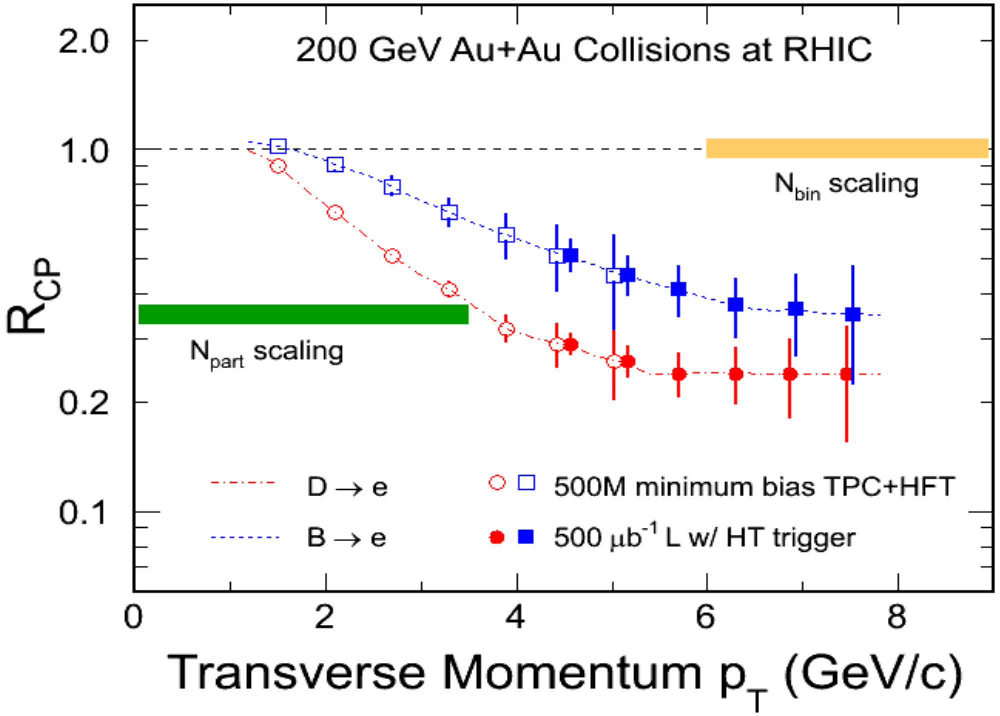


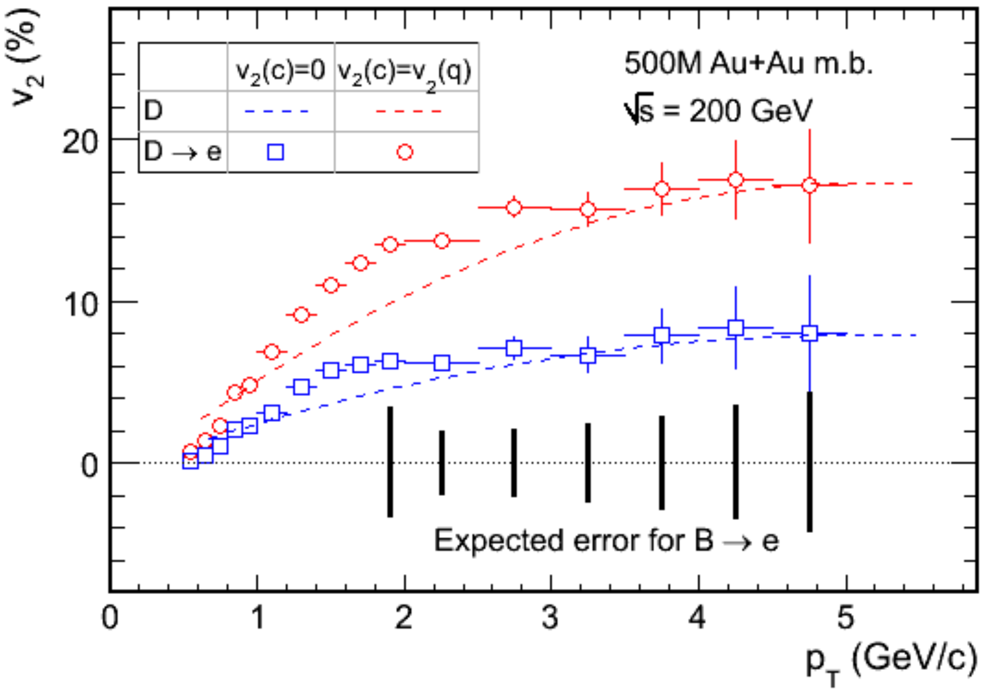
$\Lambda_c \rightarrow pK\pi$ Lowest mass charm baryons cτ = 60 μm

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

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?**

Summary

◆ The charm cross section per nucleon-nucleon collision in mid-rapidity is measured to be

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

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

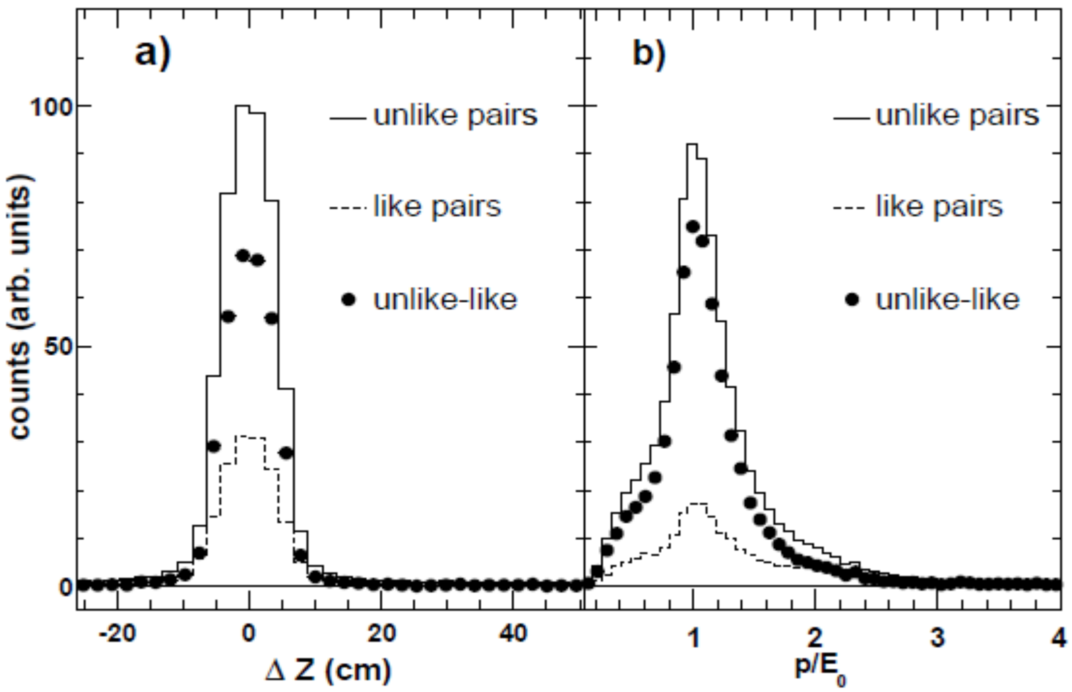
◆ Observed large high-p_T suppression of heavy quark production via NPE and D^0 meson measurement in 200 GeV central Au+Au collisions.

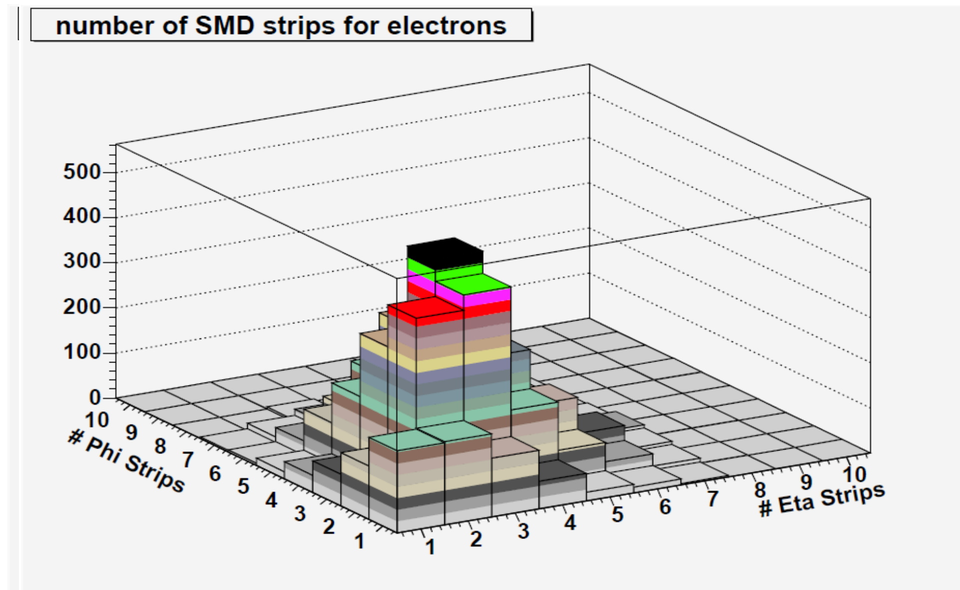
◆ Finite v_2 observed for both NPE and D^0. Observe larger NPE v_2 in 200 GeV than in 39 and 62.4 GeV Au+Au collisions, suggesting the strength of charm-medium interaction increase with energy.

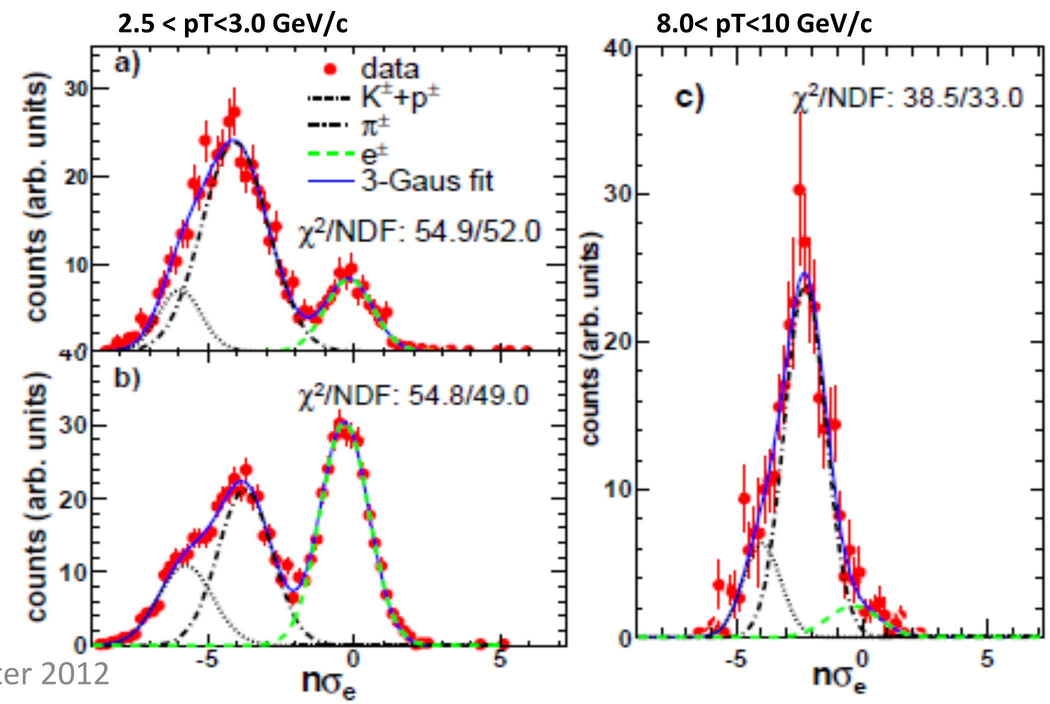
◆ HFT upgrade with increasing RHIC luminosity is expected to provide much more precise measurement on open heavy flavors.

Backup Slides

Electron Identification from TPC + BEMC



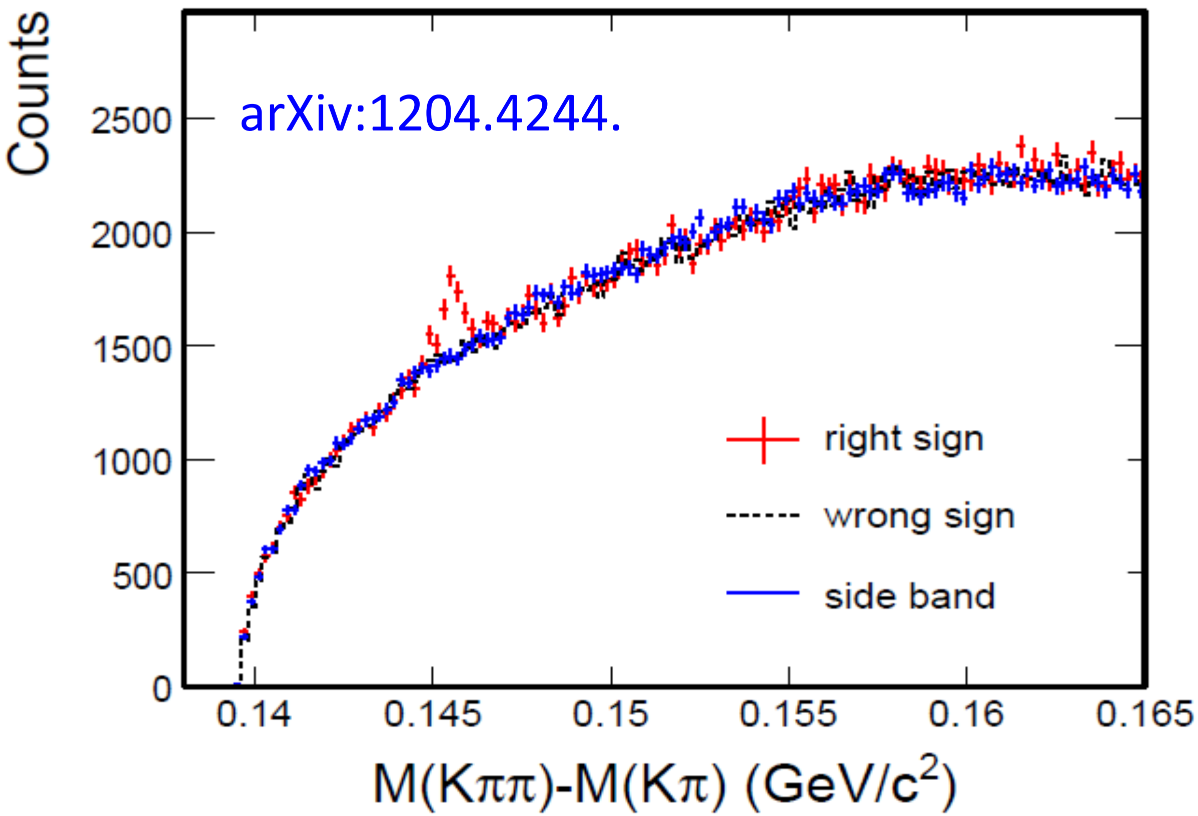


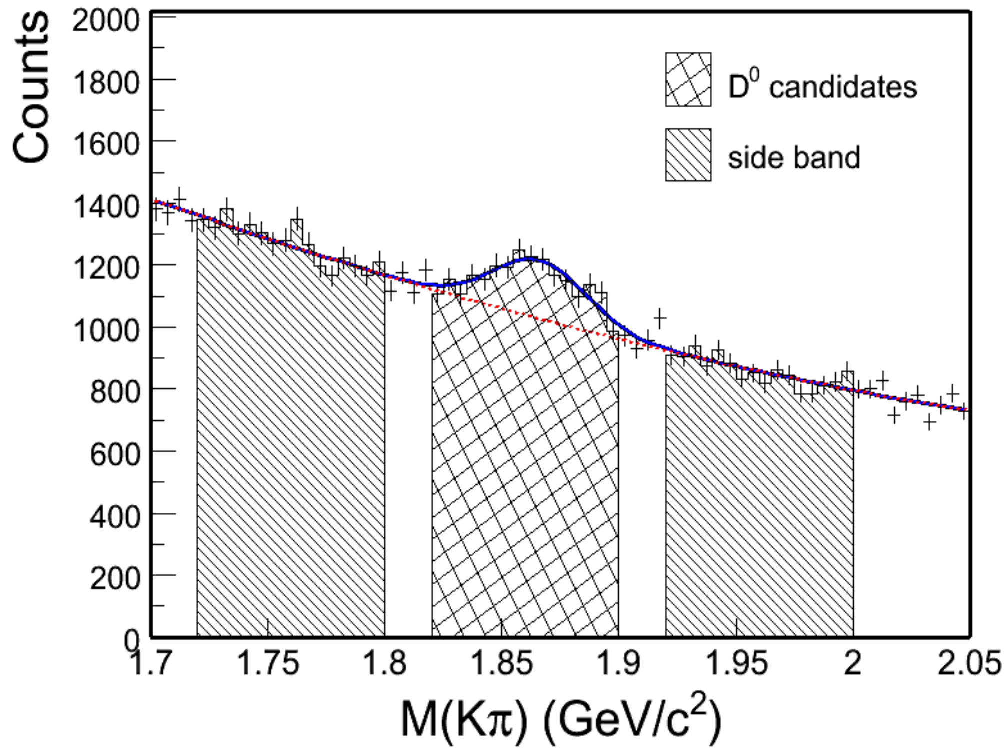


<u>High pT electron PID:</u>

- TPC+BTOW:
  - Associate TPC tracks with BTOW clusters.
  - cut p/E ~1.0
- Cut on number of BSMD strips per cluster:
  - Associate TPC tracks with BSMD clusters.
  - Higher for electron.

D* signal in p+p 200 GeV



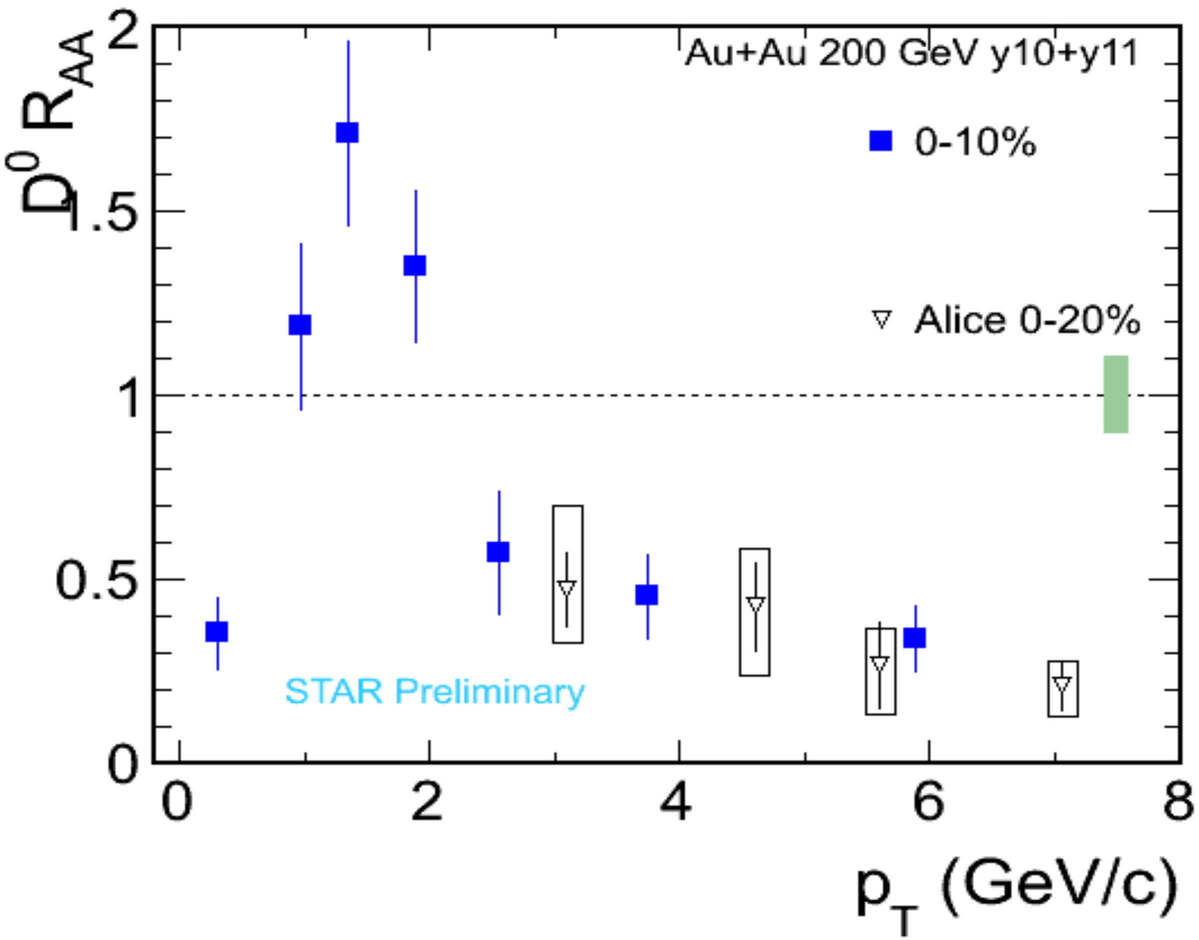


- Minimum bias 105M events in p+p 200 GeV collisions.
- Two methods to reconstruct combinatorial background: wrong sign and side band.
- 8-σ signal observed.

Background recomstruction:

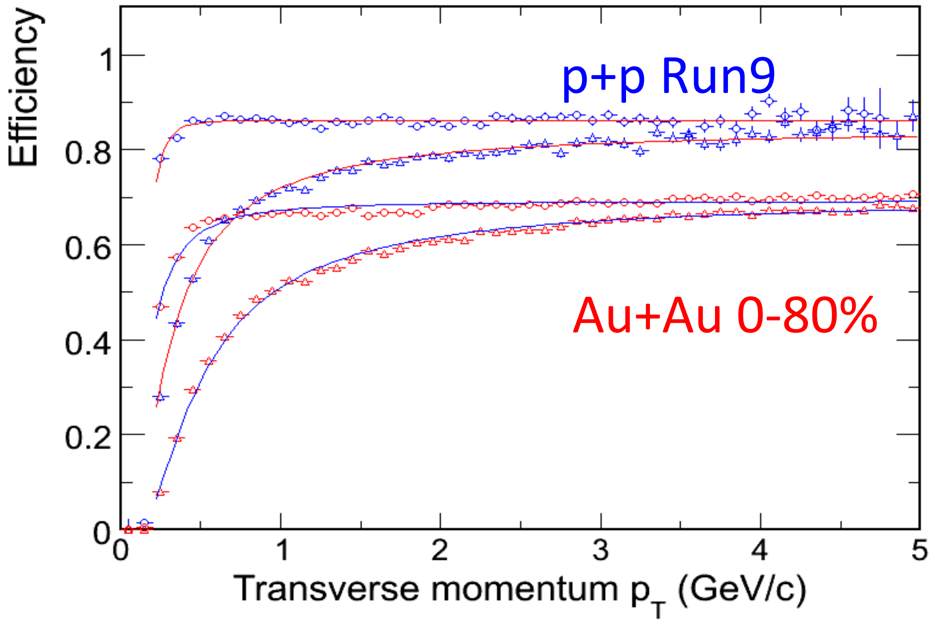
- Wrong sign:
  - D^0 and π^-, and π^+
- Side band:
  - $1.72 < M(K\pi) < 1.80$ or
  - $1.92 < M(K\pi) < 2.0$ GeV/c^2

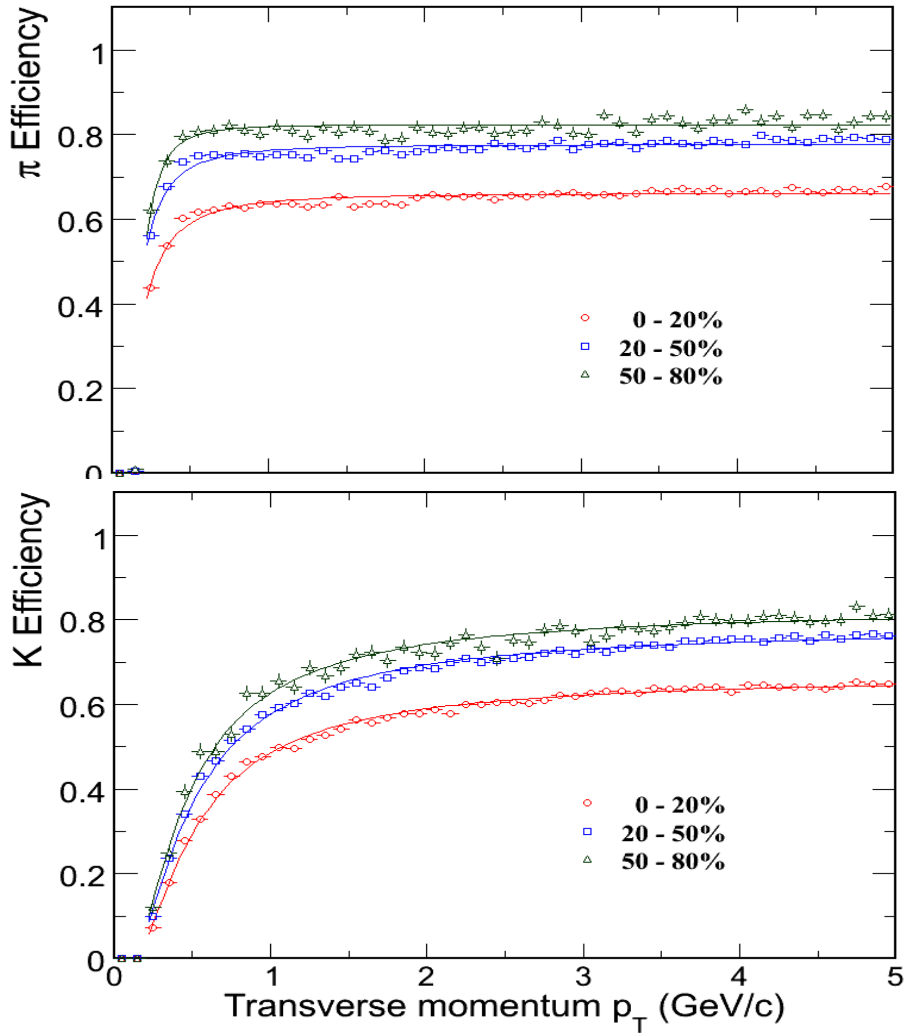
R_{AA} vs p_T



Peripheral seems no suppression above 1 GeV/c.
Semi-central seems suppressed, but do not trust the last pT bin for this centrality.
Strong suppression above 2 GeV/c has been observed in central collisions.
Consistent with Alice R_{AA} 0-20% in the overlap region.

K pi efficiency study

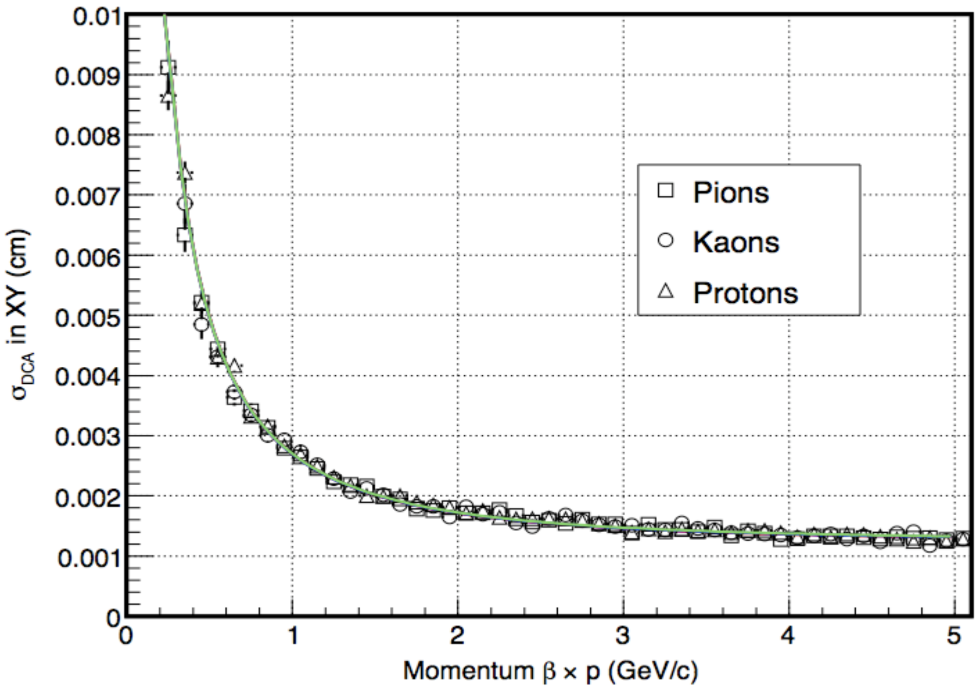


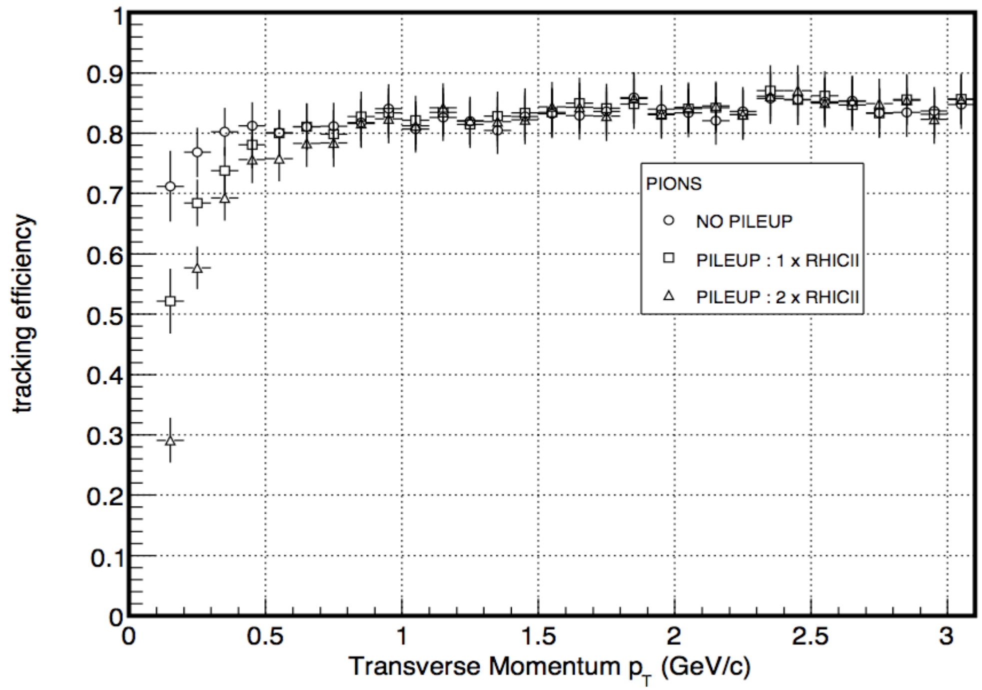


9 centrality bins studied, the 3 bins are weighted by Nbin, since D^0 events favor central collisions and Nbin scaled.
Minbias is also weighted from 9 centrality bins.
Propagate to D^0 decay using the efficiency for weight.
Much lower than p+p.
Au+Au central is only ~ 60% for p.

Embedding QA: http://www.star.bnl.gov/protected/heavy/yfzhang/Run10/
PiPlus_Run10AuAu_Qa.pdf, PiMinus_Run10AuAu_Qa.pdf
KPlus_Run10AuAu_Qa.pdf, KMinus_Run10AuAu_Qa.pdf

Simulation Performance

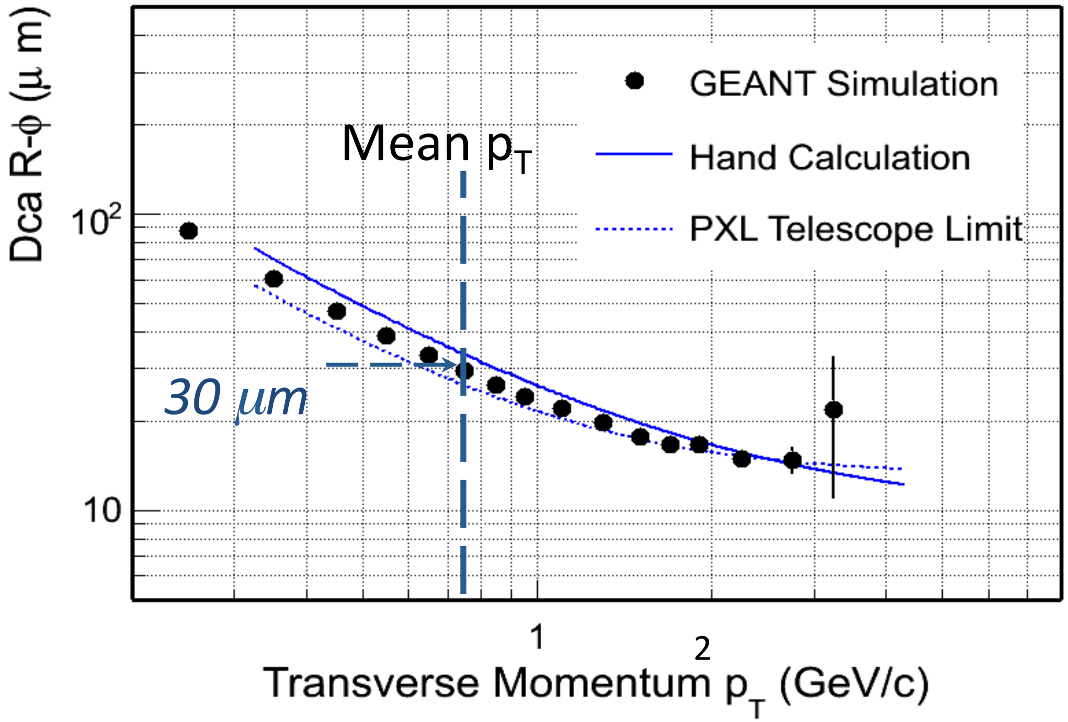


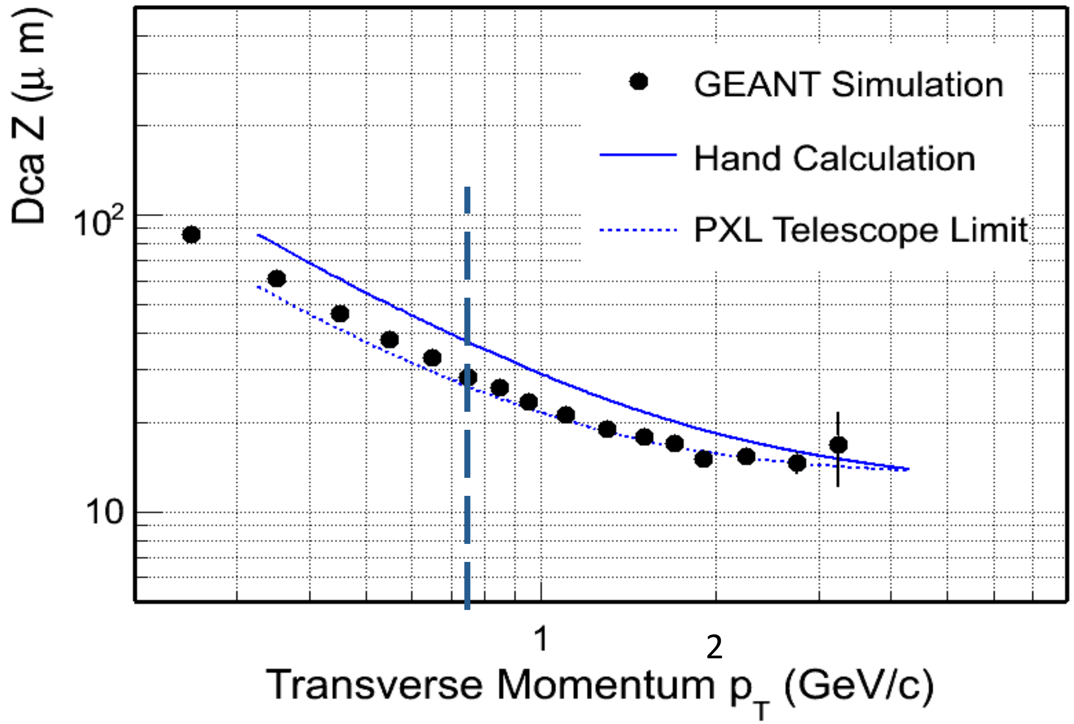


pointing resolution in r-φ to primary vertex for single particles (of K, π+, p.) including all hits in HFT.
< 20 μm at high p_T.

Tracking efficiency of single π+ for 3 pileup hits densities.
1xRICHII pile up effect was included in the simulation.

Dca resolution performance



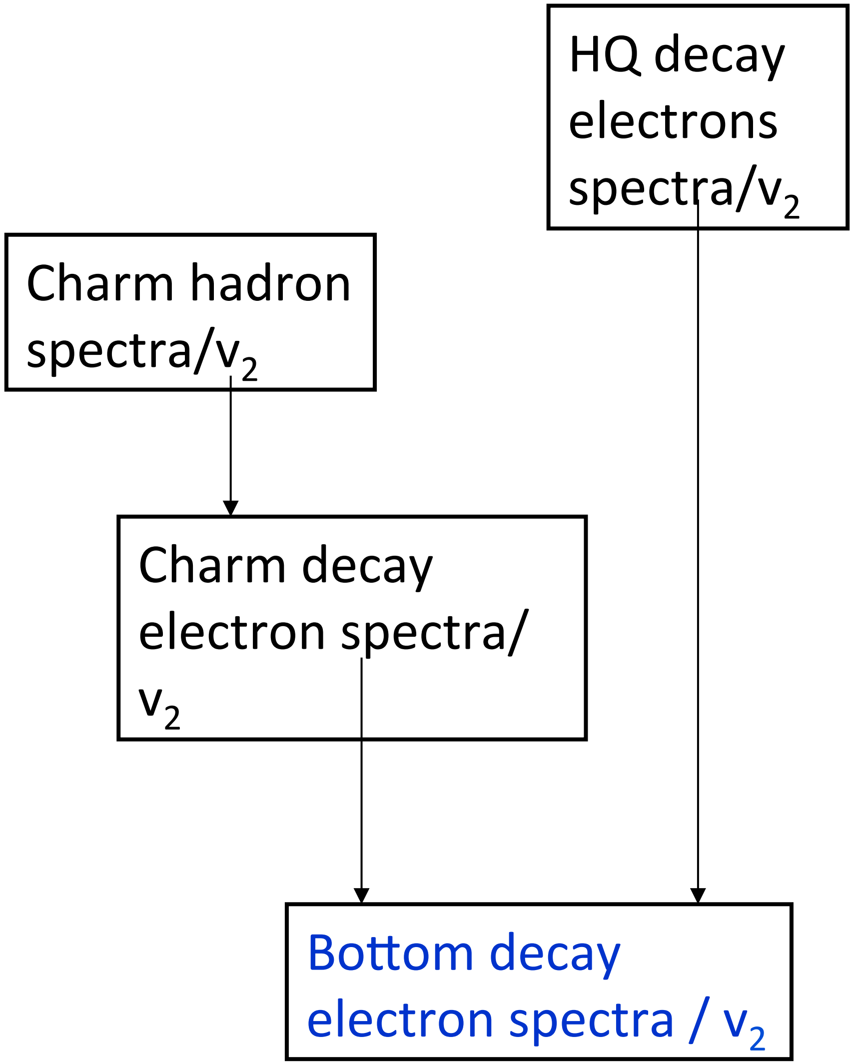


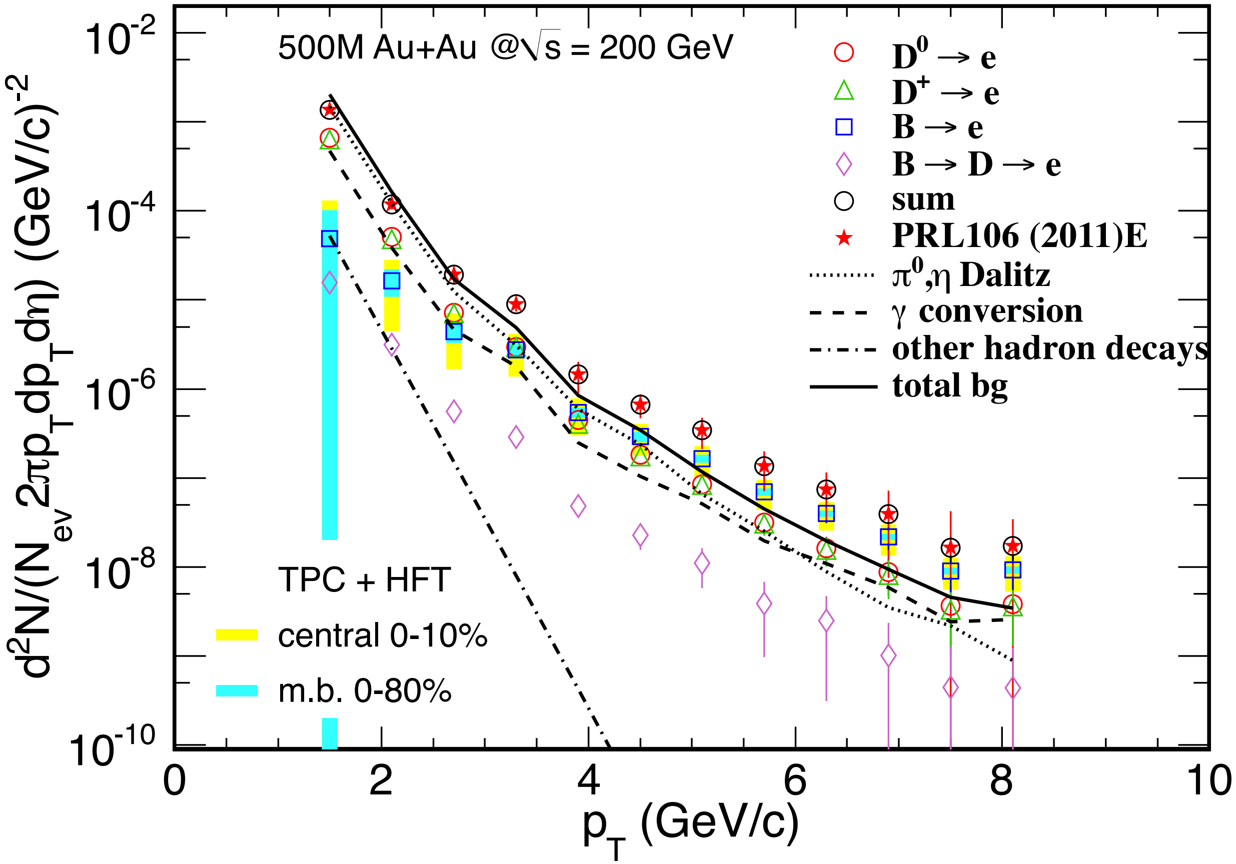
GEANT: Realistic detector geometry + Standard STAR tracking including the pixel pileup hits at RHIC-II luminosity

Hand Calculation: Multiple Coulomb Scattering + Detector hit resolution

PXL telescope limit: Two PIXEL layers only, hit resolution only

Access Bottom Production via Electrons

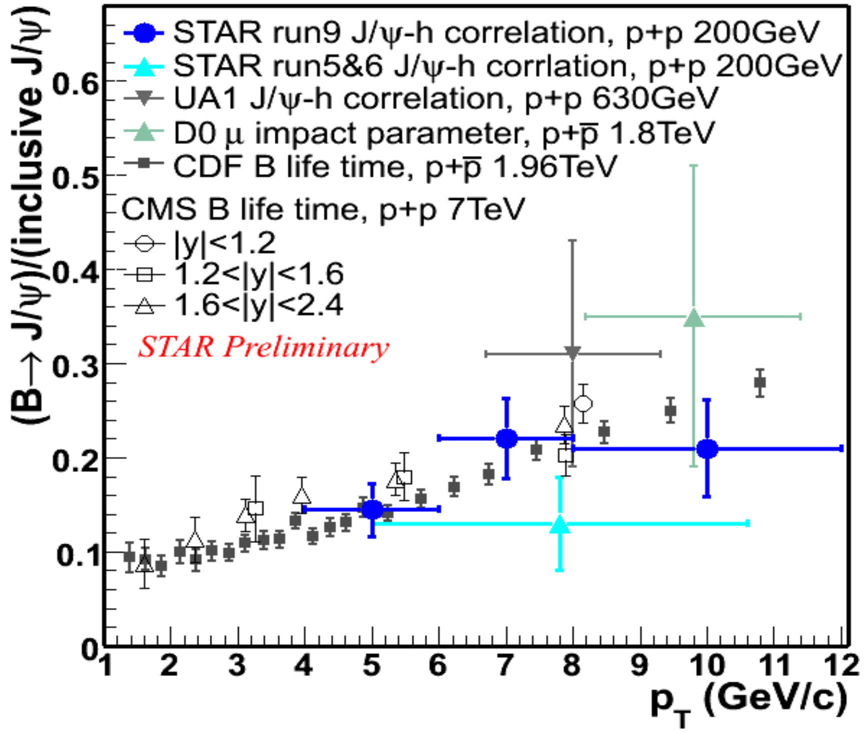


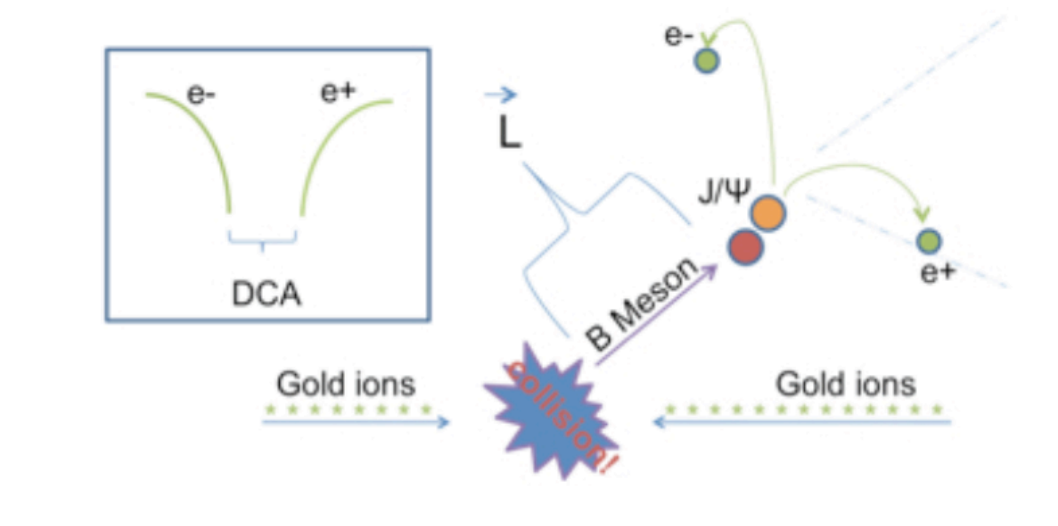


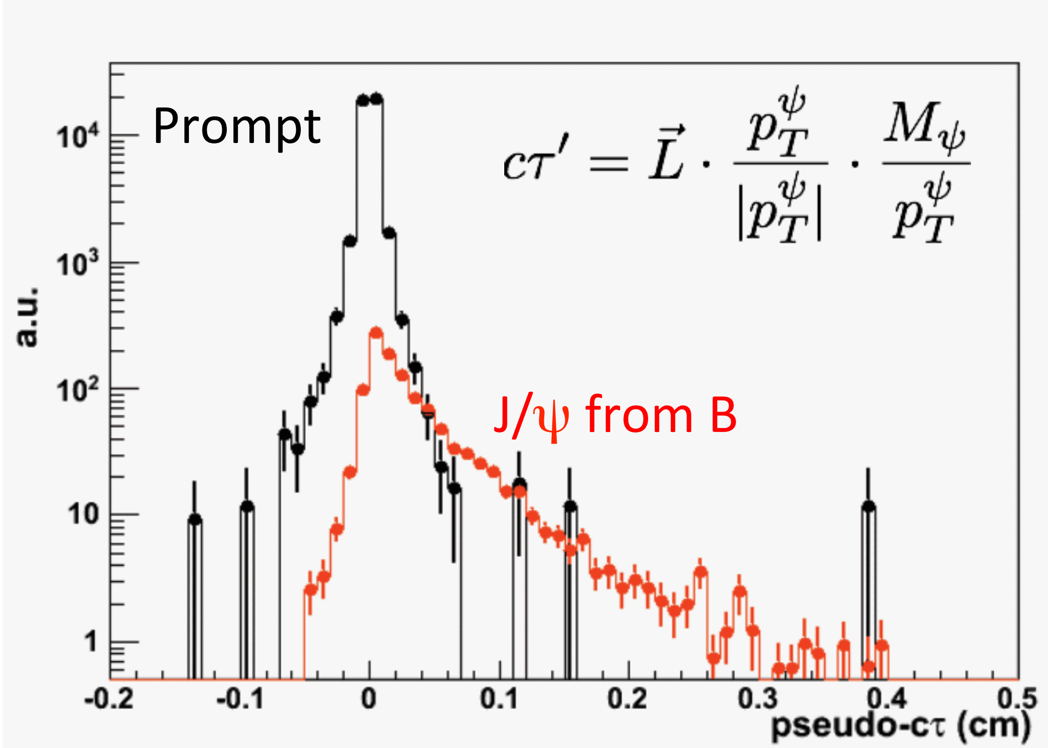
Bands: Uncertainty sources on e_B spectrum

- D-spectra shape
- Charm hadron chemistry difference

B tagged J/ψ





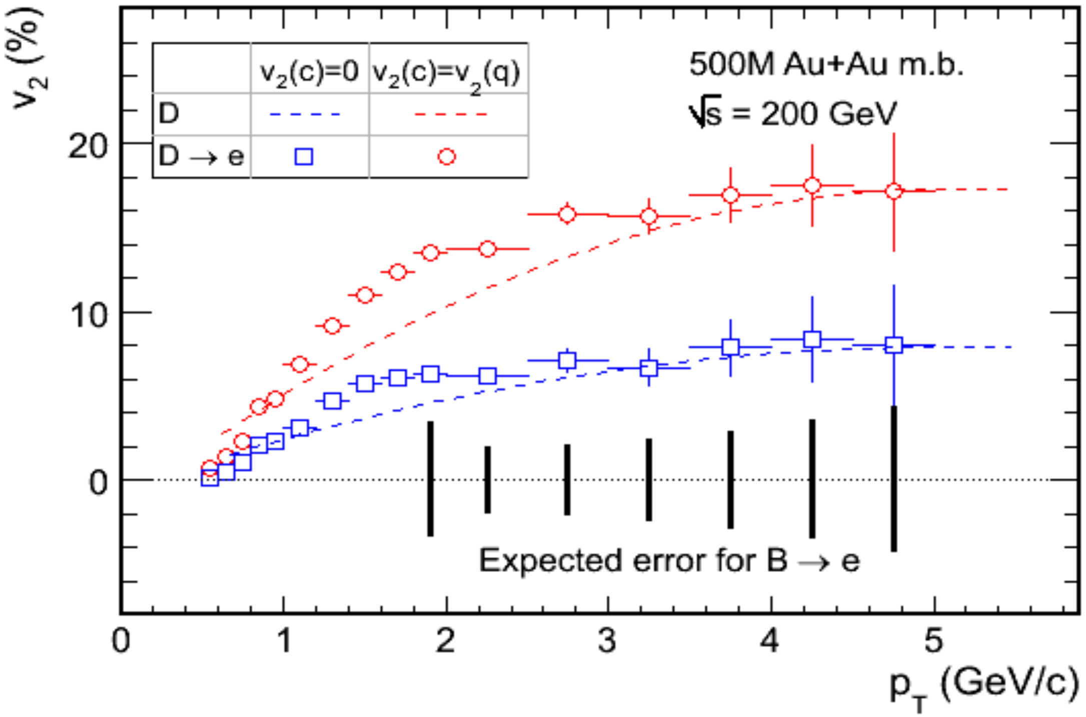


- Current measurement via *J/ψ*-hadron correlation with large uncertainties.

- Combine HFT+MTD on di-muon channel
  - Separate secondary *J/ψ* from prompt *J/ψ*
  - Constrain the bottom production at RHIC

Statistical Projections on e_B v_2

Need update



Assuming D meson v_2 from quark coalescence (curves).

$r * v_2(e_B) + (1-r) * v_2(e_D) = v_2(NPE)$
r is the $e_B/(e_D+e_B)$ ratio
$v_2(e_D)$ is D → e v_2
$v_2(e_B)$ is B → e v_2 , which can be extracted from this equation.

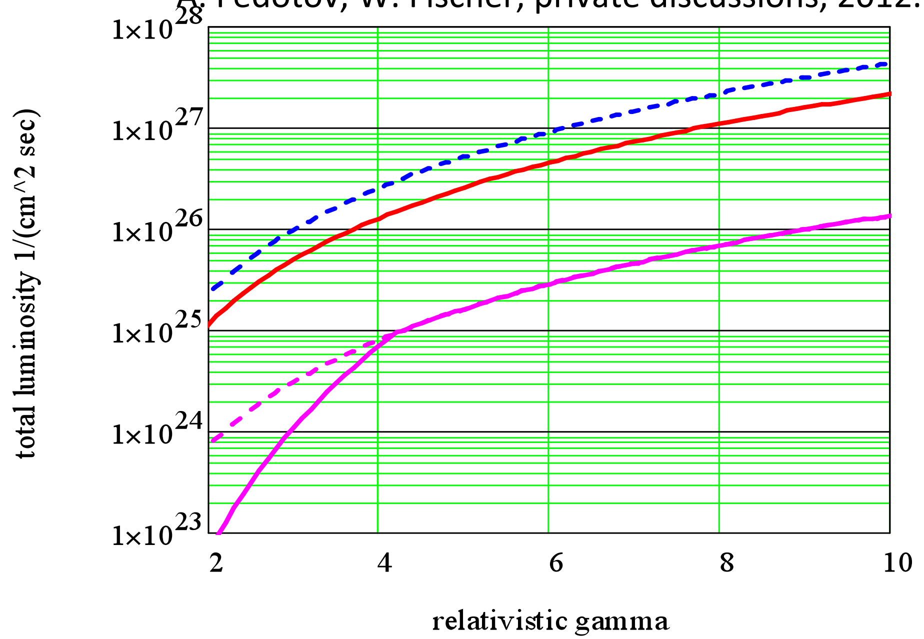
Dashed-curves: Assumed D0-mesom $v_2(p_T)$
- in coalescence model

Symbols: *D decay e* $v_2(p_T)$

Vertical bars: errors for *b decay e* $v_2(p_T)$ from 200 GeV 500M minimum bias Au + Au events

- ✧ Electron cooling will provide increased luminosity ~ 10 times
- ✧ Enables increased statistics for the BES energies
- ✧ Statistics enriched data for rare probes e.g. di-lepton, hypernuclei measurements

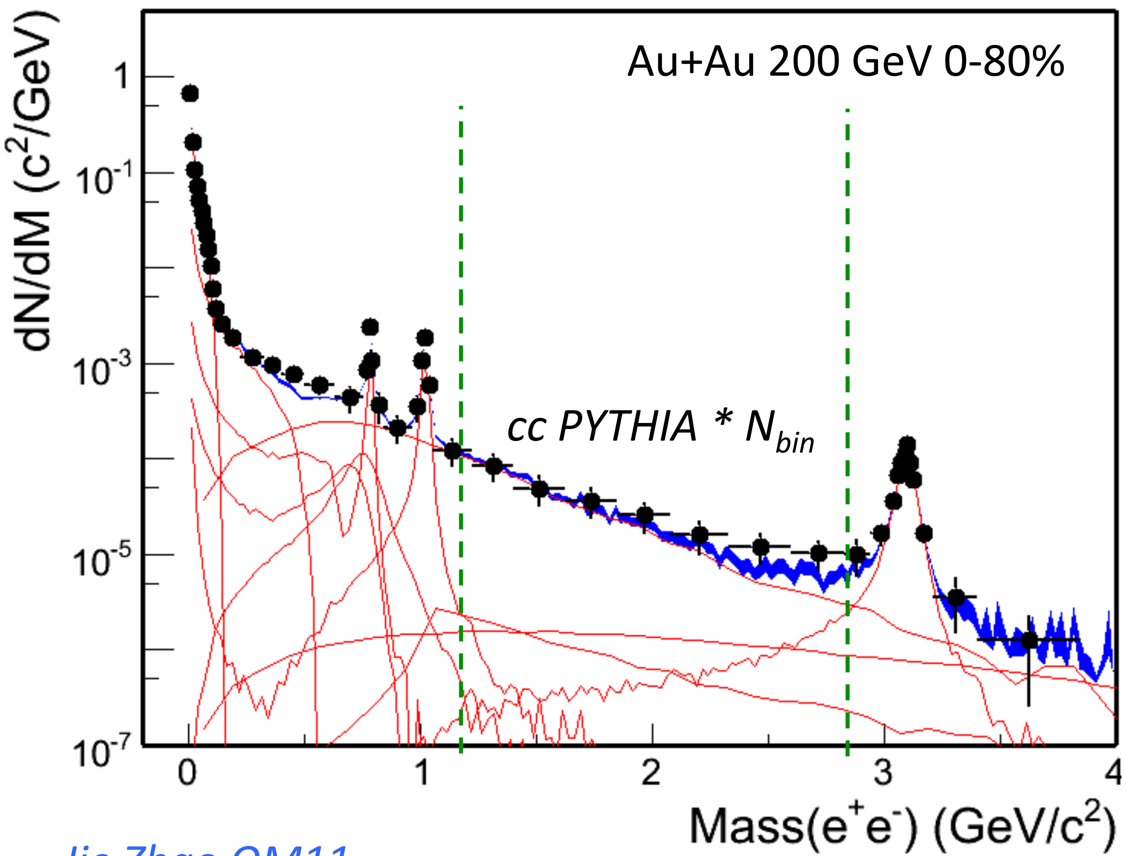
A. Fedotov, W. Fischer, private discussions, 2012.



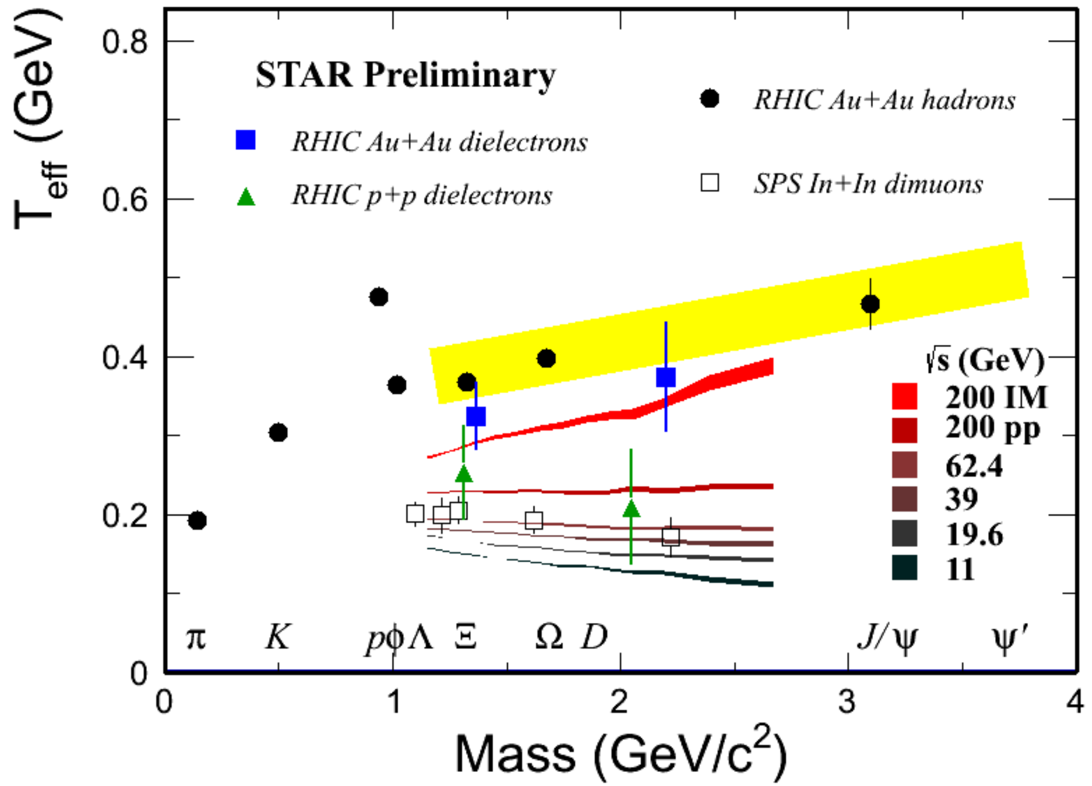
Proposed energies for BES-II (Years 2015-2017):

$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Requested Events(10^6)
Au+Au 19.6	206	150
Au+Au 15	256	150
Au+Au 11.5	316	50
Au+Au 7.7	420	70
U+U: ~20	~200	100

Charm correlation in di-lepton production



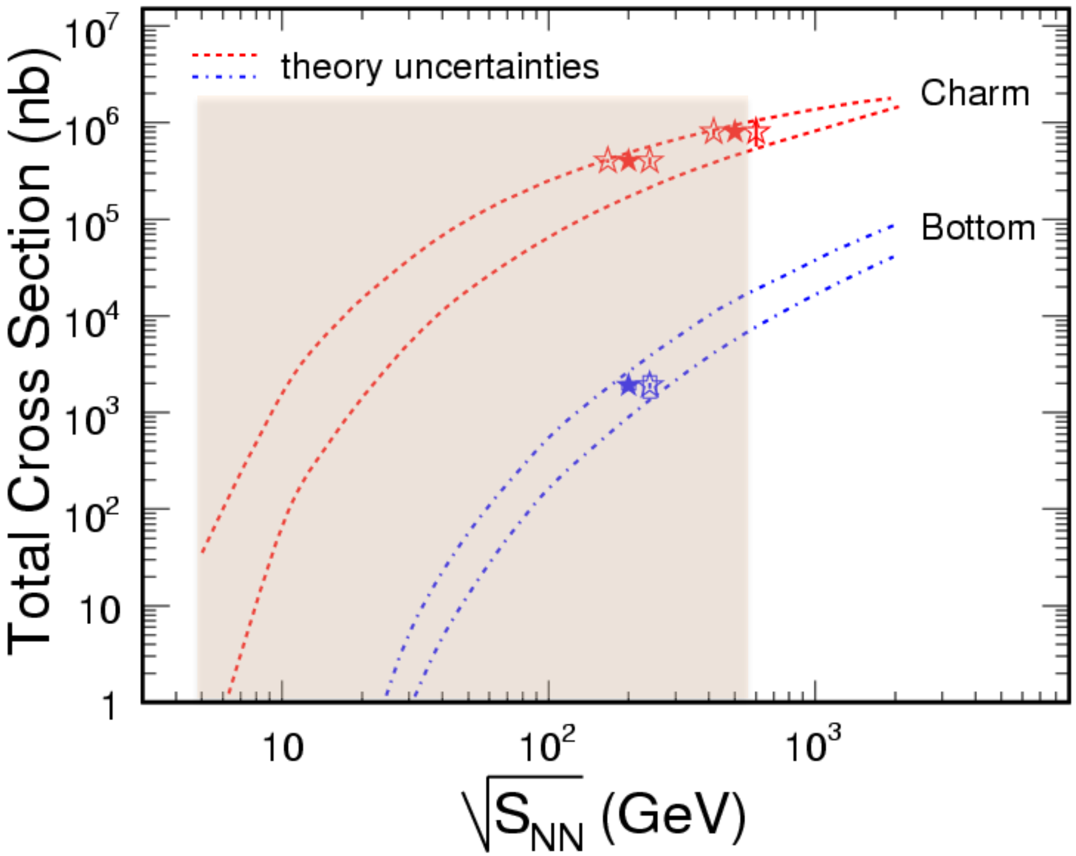
Jie Zhao QM11

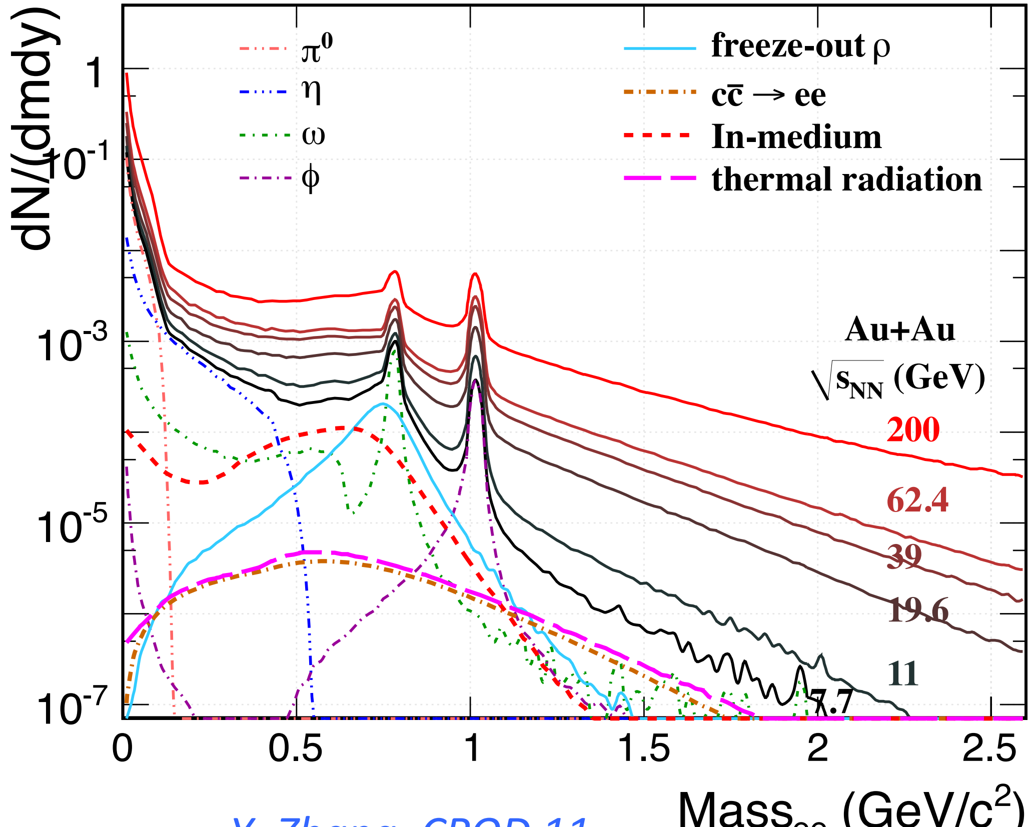


Y. Zhang, CPOD 11

IMR => QGP radiation + Correlated charm decays.
- Precise measurement to constrain the charm contribution.
- Slope of correlated charm changes sign from low to high energies.
- Impact parameter cut will help.

Charm production in BES program

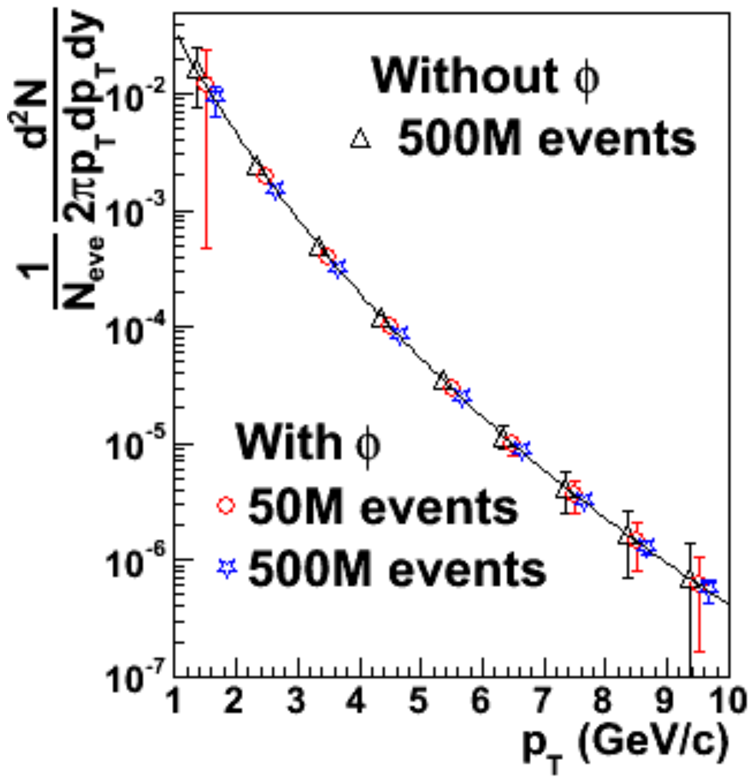


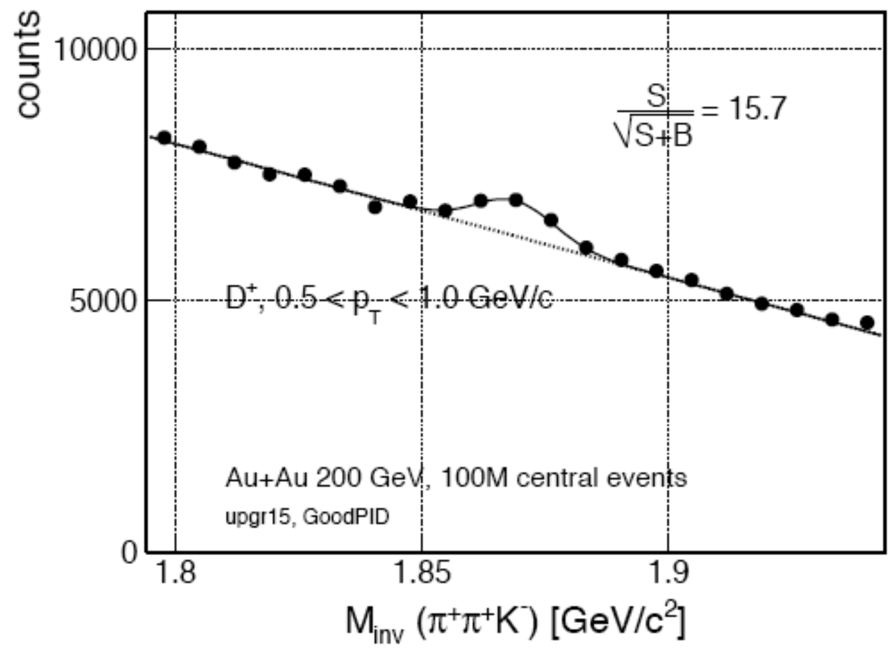


Y. Zhang, CPOD 11

- Precisely measure charm cross section at top energy.
- Measure charm cross section in RHIC BES phase-II program.
- Not only direct QGP radiation, but also charm correlation itself: expect a different slope evolution of the di-lepton at IMR.
- Test thermalization degree in BES energies.

Charm fragmentation: more channels





$D^+ \rightarrow K\pi\pi$

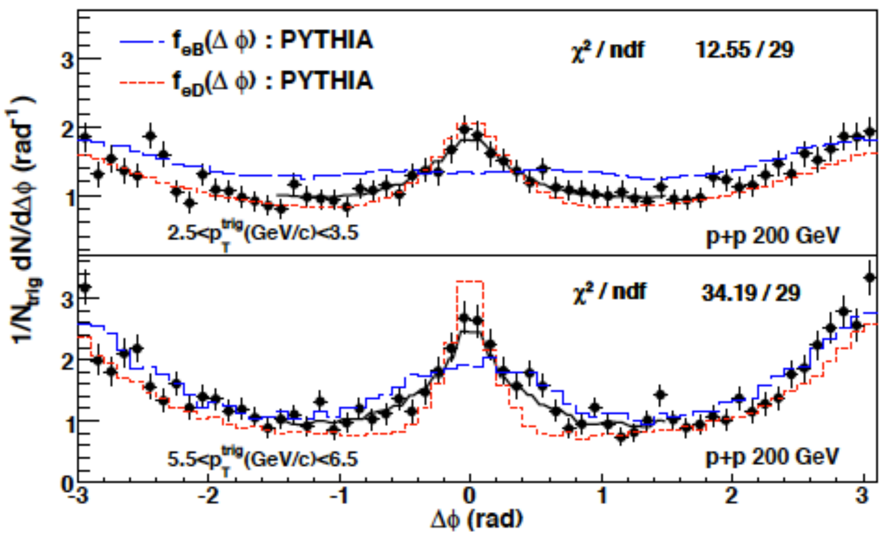
mass = 1.869 MeV $c\tau$=312μm

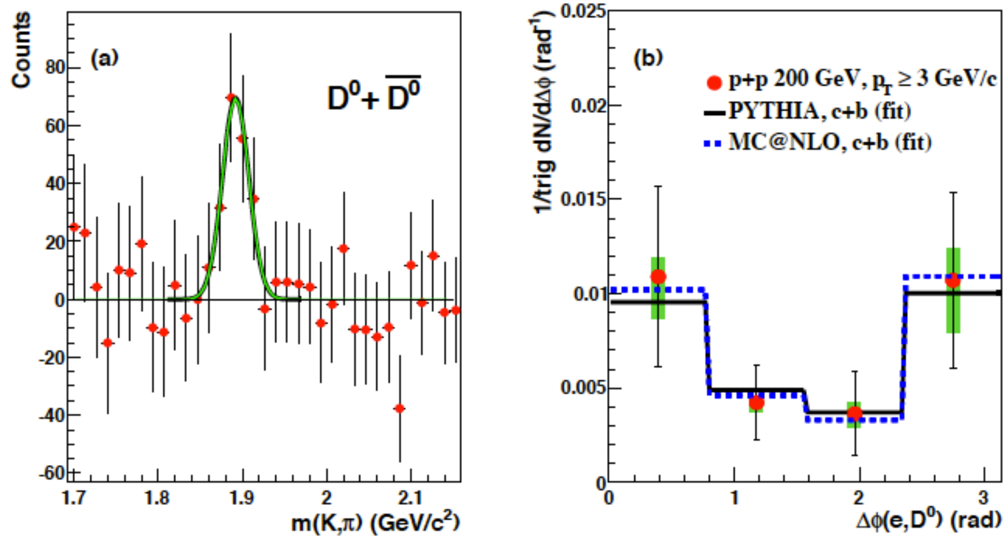
- $D_s \rightarrow K^+K^-\pi$ (BR 5.5%)
- $D_s \rightarrow \varphi\pi \rightarrow K^+K^-\pi$ (BR 2.2%)
- mass = 1968.49 ± 0.34 MeV
- **decay length** ~ 150 μm

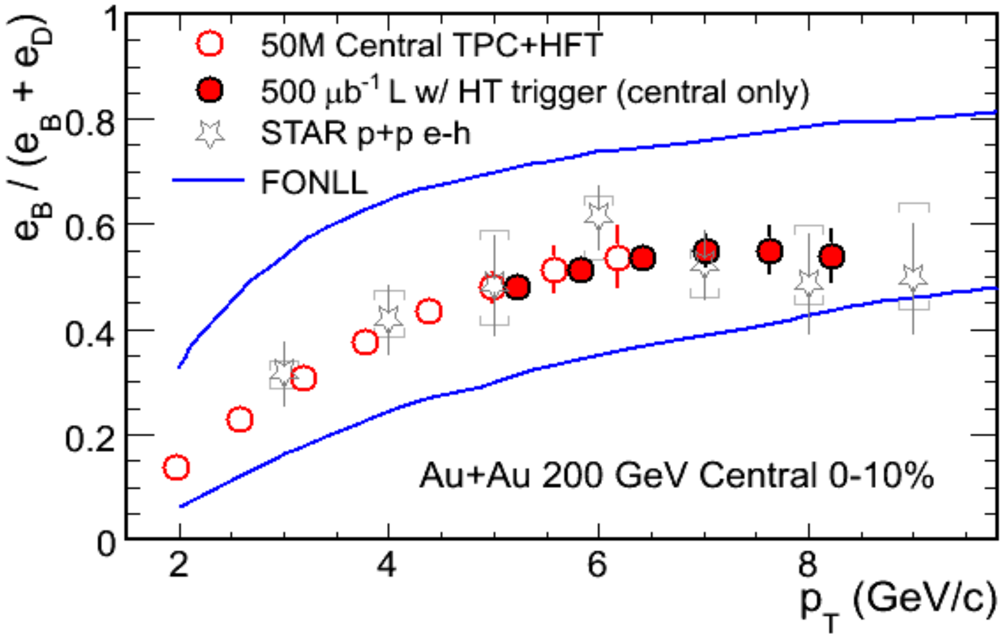
$D^+ \rightarrow K_S^0 + \pi^+$	$BR = 1.49\%$
$D_S^+ \rightarrow K_S^0 + K^+$	$BR = 1.49\%$
$D^0 \rightarrow K_S^0\pi^+\pi^-$	$BR = 2.94\%$
$D^0 \rightarrow K^-\pi^+\pi^0$	$BR = 13.9\%$
$D^0 \rightarrow K_S^0\pi^0$	$BR = 1.22\%$

Important for charm total cross section and fragmentation ratio measurements.

e-h, e-D correlations in p+p







Measure bottom fraction in NPE =>

Before:
Model dependent, large uncertainties.

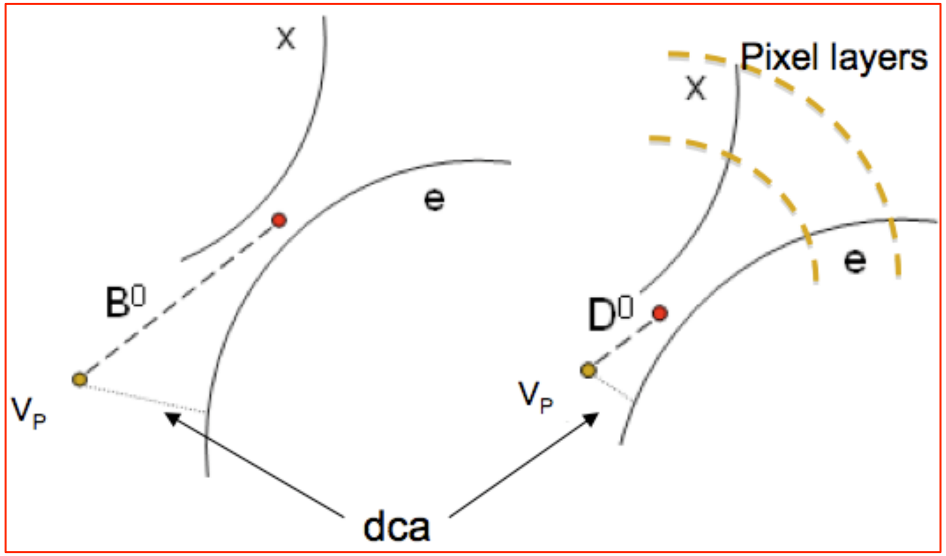
After:
No model dependence, precise measurement.

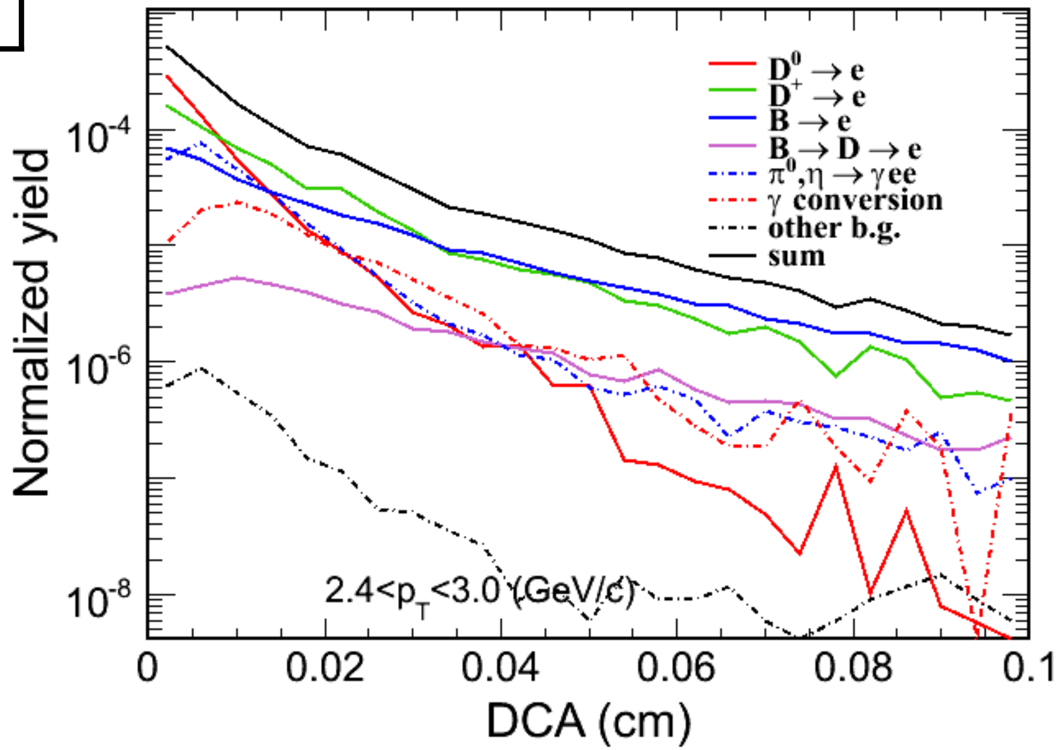
Access bottom production via electrons

particle	cτ (μm)	Mass	$q_{c,b} \rightarrow x$ (F.R.)	$x \rightarrow e$ (B.R.)
D^0	123	1.865	0.54	0.0671
$D^\pm$	312	1.869	0.21	0.172
B^0	459	5.279	0.40	0.104
$B^\pm$	491	5.279	0.40	0.109

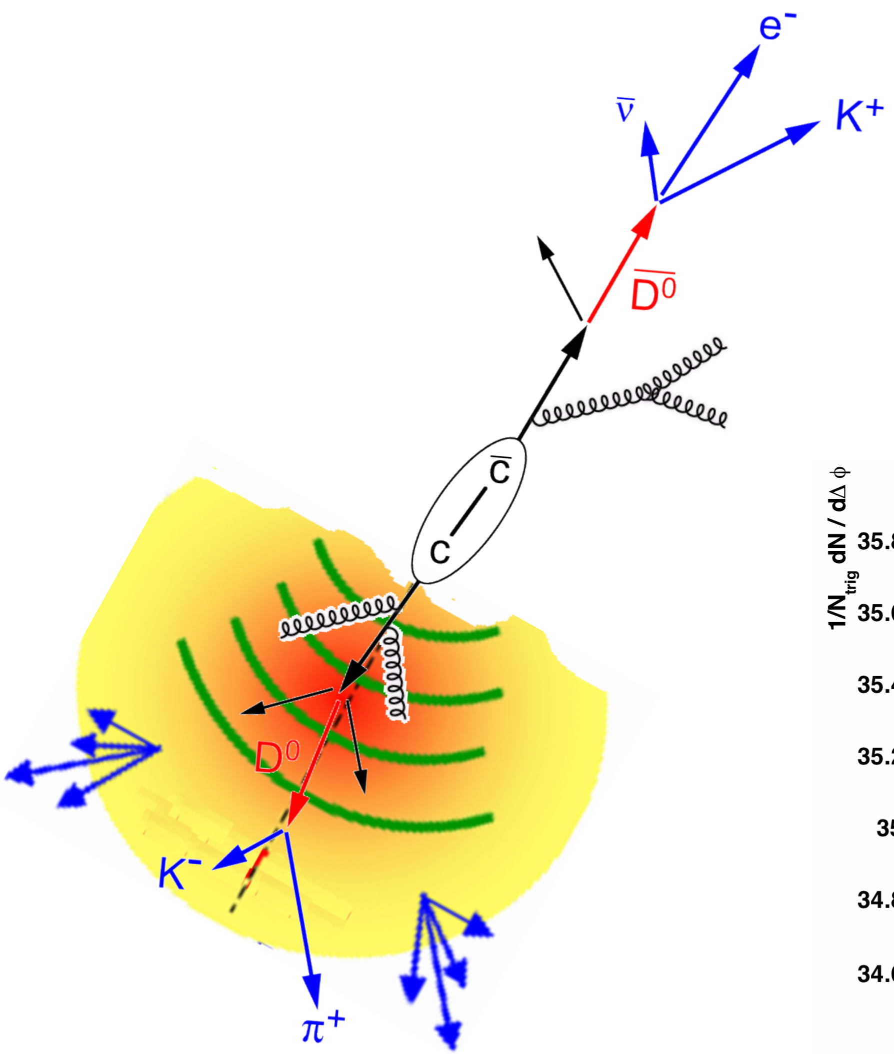
Two approaches:

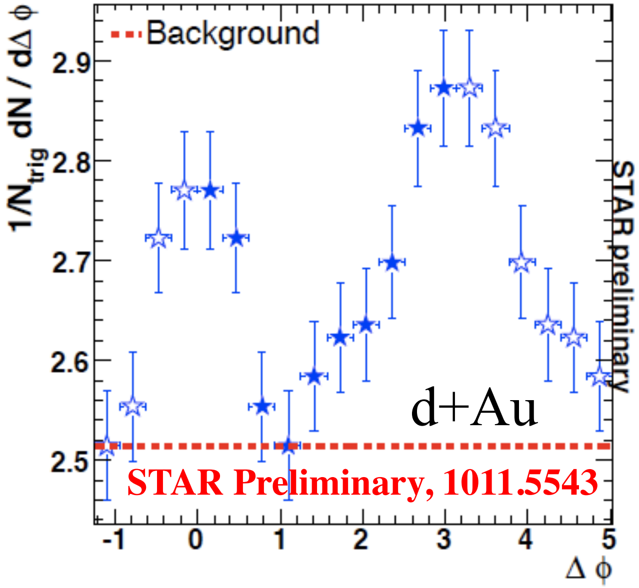
- Statistical fit with model assumptions
  Large systematic uncertainties
- With known charm hadron spectrum to constrain or be used in subtraction

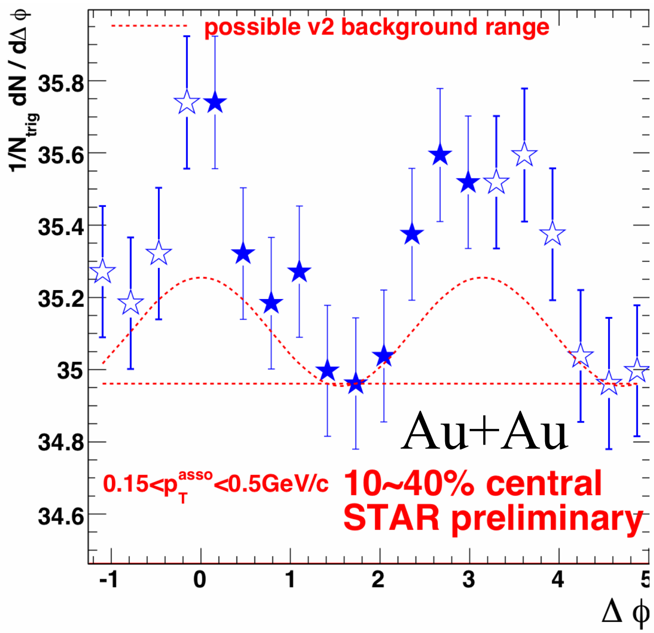


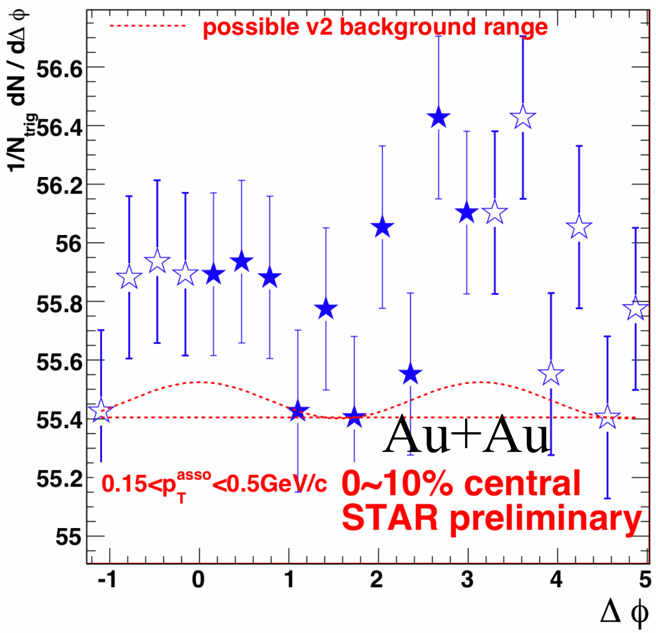


Heavy flavor tagged e-h correlations in AA

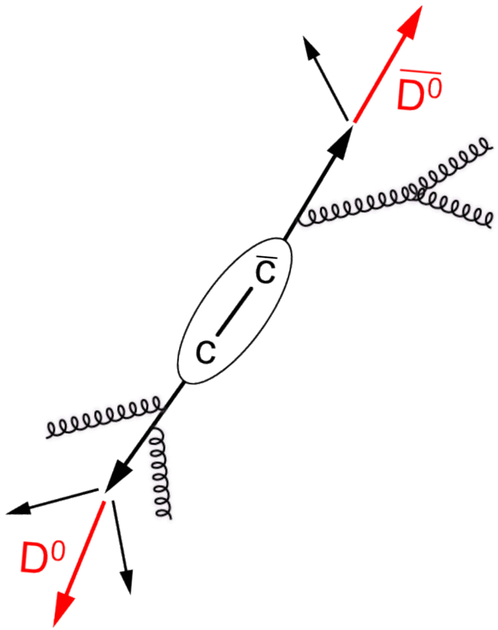




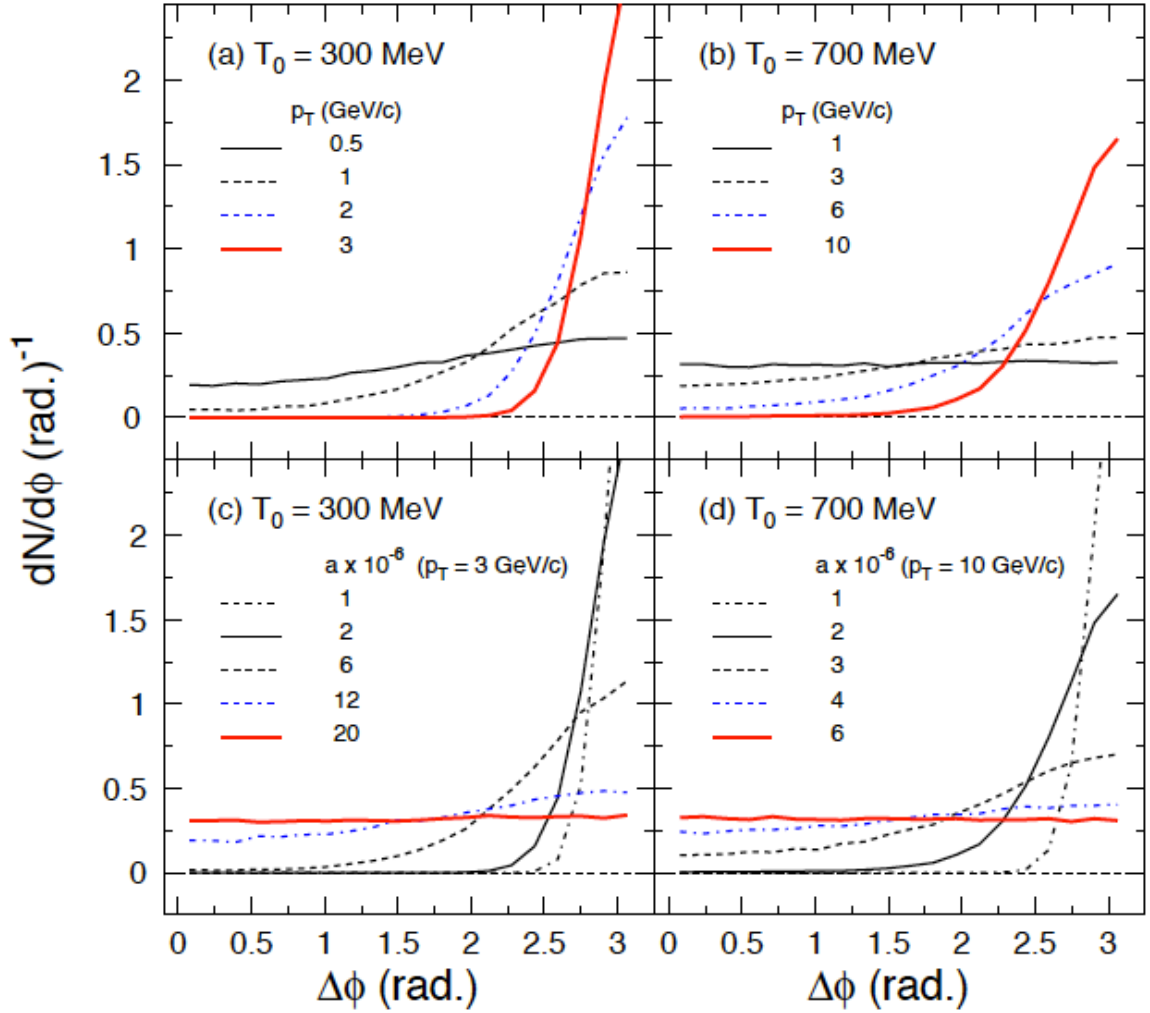




D-Dbar correlations

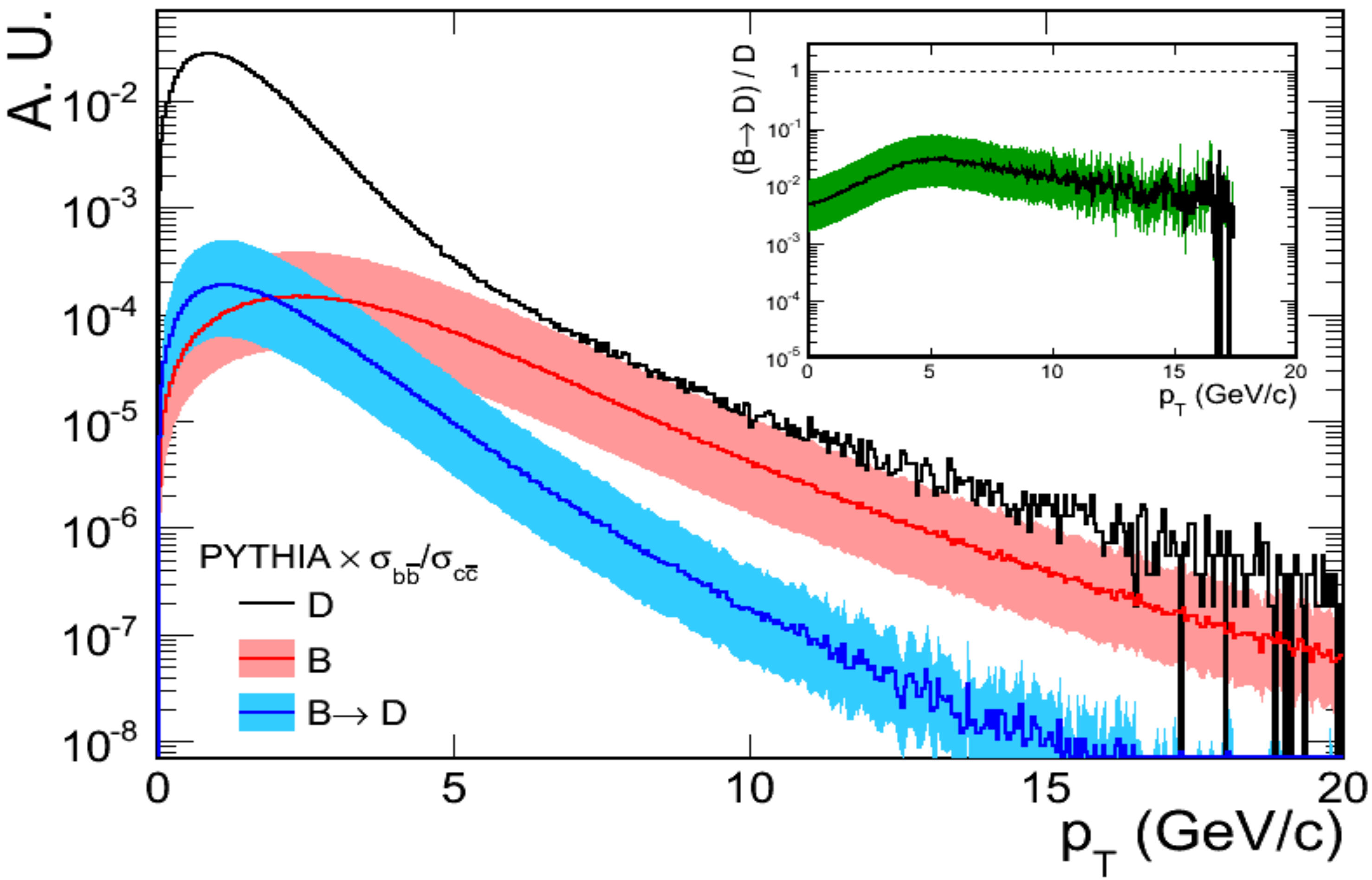


X. Zhu, et. al., PLB647 (2007) 366



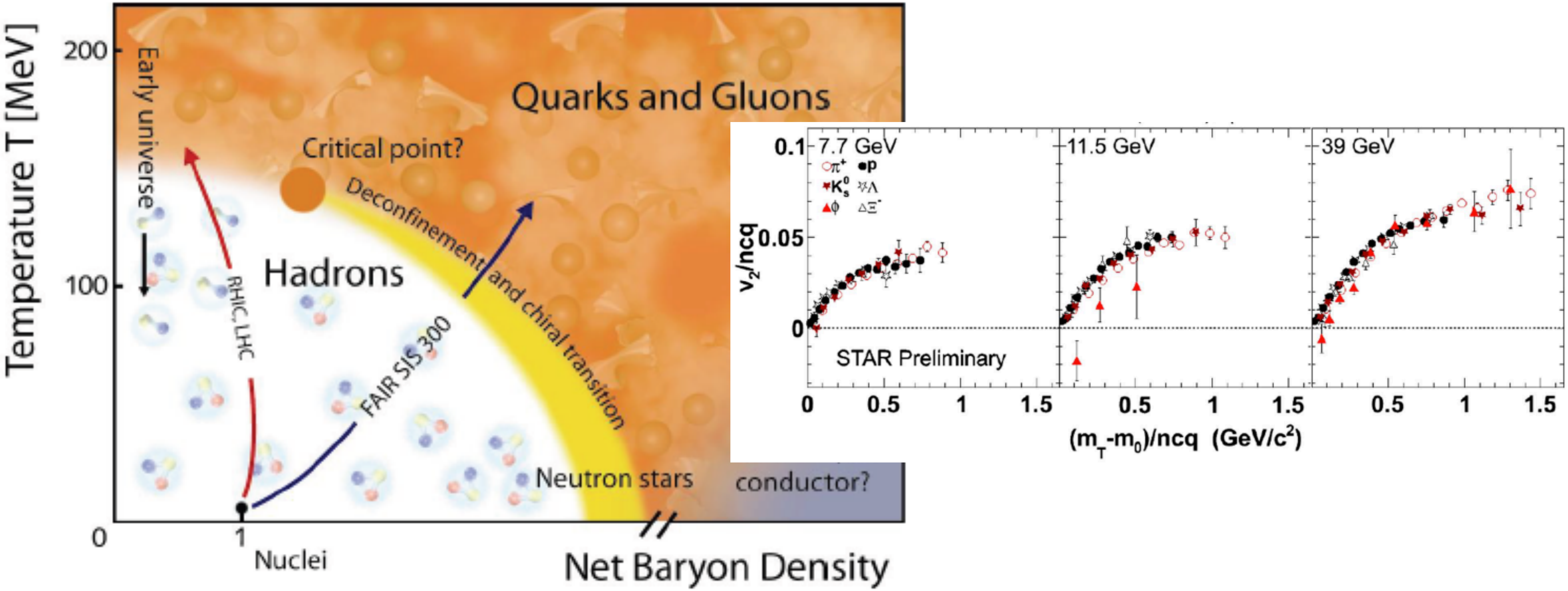
D-Dbar correlation is sensitive to medium interactions, constrains drag coefficient.

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.

QCD phase diagram



- QGP turn-off signature has been observed by STAR BES experiment.
- Thermalization at top energy is still an unsolved issue.
- Heavy quark may be sensitive to EoS, thermalization degree, drag coefficient?

Physics capability of HFT

1)The STAR HFT measurements (p+p and Au+Au)

(1) Heavy-quark cross sections: D0,±,*, D_S, Λ_C , B…

(2) Both spectra ($R_{AA,}$ R_{CP}) and v_2 in a wide p_T region

(3) Charm hadron correlation functions

(4) Full spectrum / v_2 of the heavy quark hadron (separated) decay electrons

(5) dependence versus collision energies.

2) Compelling Physics

(1) Establish elementary charm and bottom cross sections

(2) Characterize the medium through parton energy loss

(3) Determine the degree of thermalization via heavy quark flows

(4) Analyze hadro-chemistry in the charm sector

(5) Study the bottom behavior in medium via the separation of charm contributions

(6) BES program. Constrain pQCD calculations. Sensitive to thermalization degree.

Physics run plan

1) HFT 3 sectors in Y13: Au+Au 200 GeV

Detector engineering run.

First look at v_2 and R_{cp} of D/e.

2) Full HFT in Y14: >10 weeks Au+Au 200 GeV and p+p 200 GeV

a) v_2 and R_{cp} of D/e with high precision. R_{AA} of D/e.

b) Correlations: e-D, e-μ.

c) B->J/ψ

3) Y15 … Au+Au 200 GeV and pp 200 GeV high statistics, BES Phase-II …

a) Systematic studies of v_2 and R_{AA}, centrality, path length, $\sqrt{S}$, etc…

b) Λ_c baryon with sufficient statistics.

c) Correlations: e-D, e-μ, D-Dbar.

d) Di-lepton, top energy, BES.