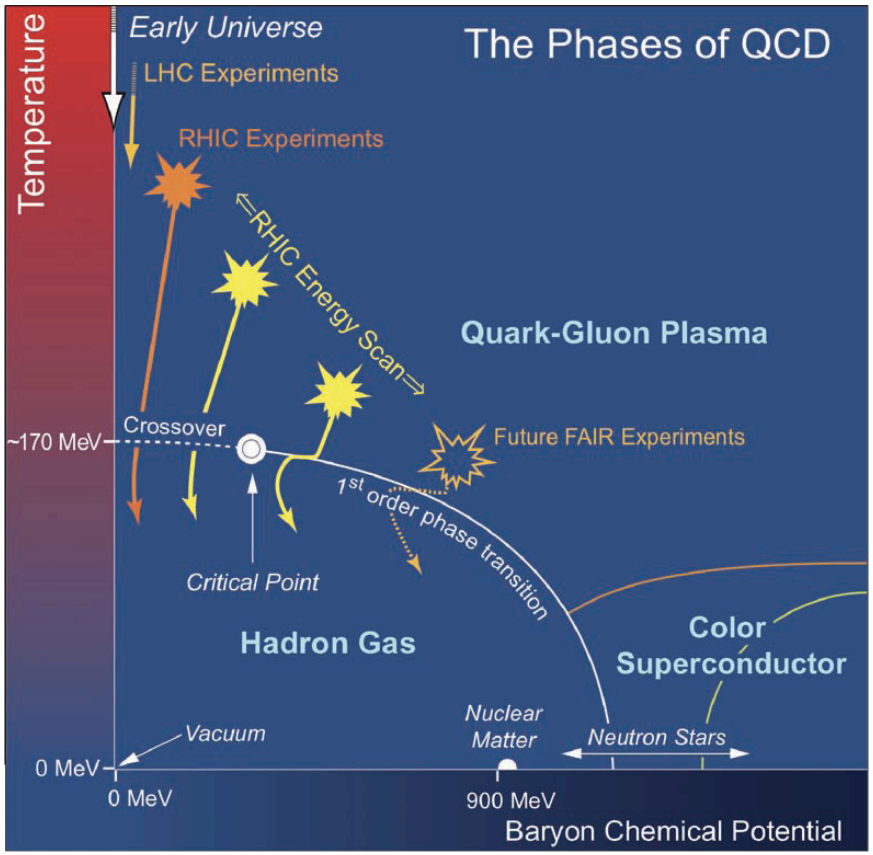
STAR Heavy Ion @ RNC

Xin Dong
Nuclear Science Division / LBNL



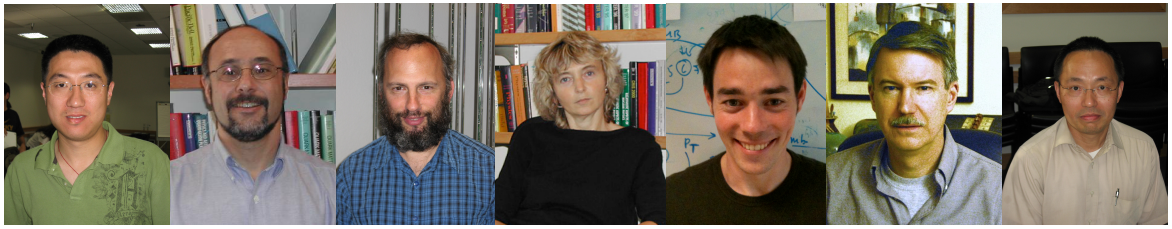
Structure and Dynamics of QCD Matter

- Study sQGP properties at RHIC top energy
- Study QCD phase structure through RHIC Beam Energy Scan

Well aligned with NSAC Long Range Plans 2007/2015

People (STAR HI Analyses)

Staffs

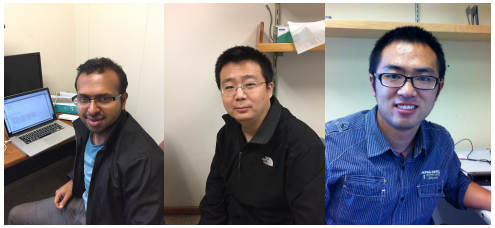


X. Dong P. Jacobs S. Klein G. Odyniec A. Schmah J. Thomas N. Xu

retirees

A. Poskanzer H.G. Ritter

Postdocs

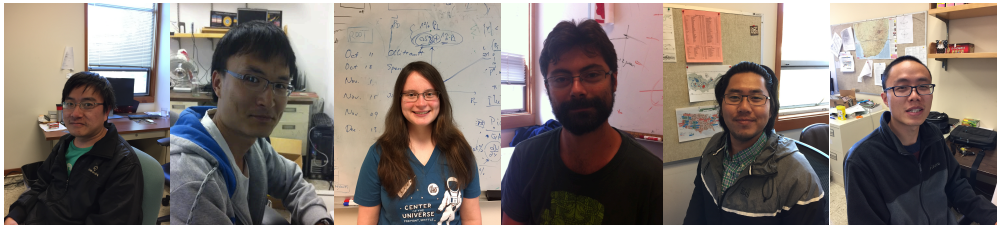


S. Radhakrishnan Y. Guo X. Sun

alumni

H. Masui S. Mizuno M.Mustafa H. Qiu S. Shi J. Thader Y. Zhang

Students

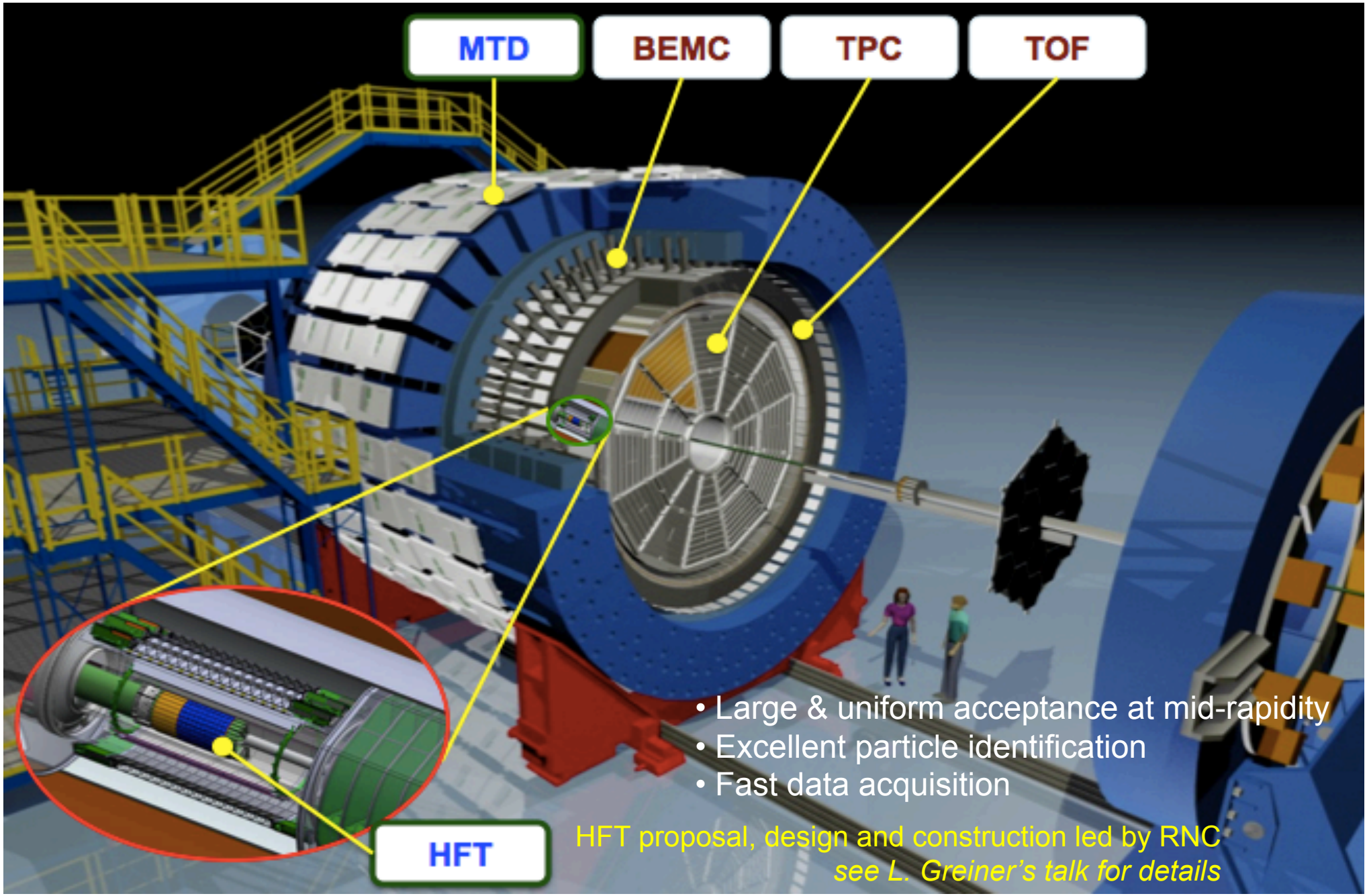


X. Chen G. Xie K. Meehan M. Lomnitz K. Oh J. Xu

alumni

P. Huck X. Luo L. Ma C. Powell E. Sangaline J. Zhao

Solenoidal Tracker at RHIC (STAR)



- Large & uniform acceptance at mid-rapidity
- Excellent particle identification
- Fast data acquisition

HFT proposal, design and construction led by RNC

see L. Greiner's talk for details

HI Physics Results Led by RNC

1) Study sQGP Properties

- Systematic investigation of partonic collectivity
  - *– Identified particle v_2*
- Thermalization
  - *– Heavy Quark Production (D-meson, J/ψ)* **- DM12**
- Chiral properties
  - *– Dielectron production (energy dependence)* **- DM13**
- Jet-medium interactions
  - *– Reconstructed jets, high p_T correlations* **- DM10**

Synergies with NSD Theory

NSAC milestones

2) Study QCD phase structure - Beam Energy Scan **- DM11**

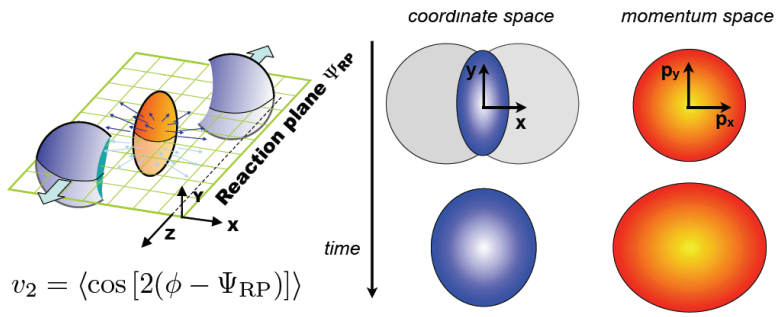
- Turn-off of sQGP signatures
  - *– elliptic flow of identified particles*
- Search for critical point
  - *– high moments of net-proton/net-charge/net-Kaon multiplicity*

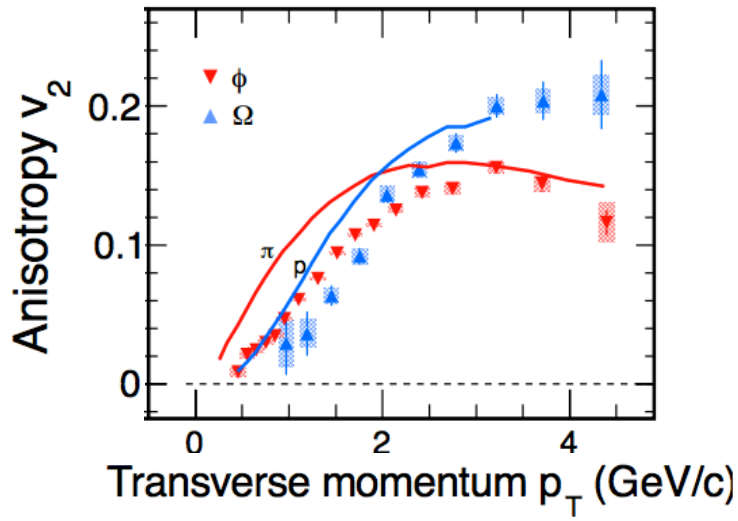
Synergies with NSD Theory

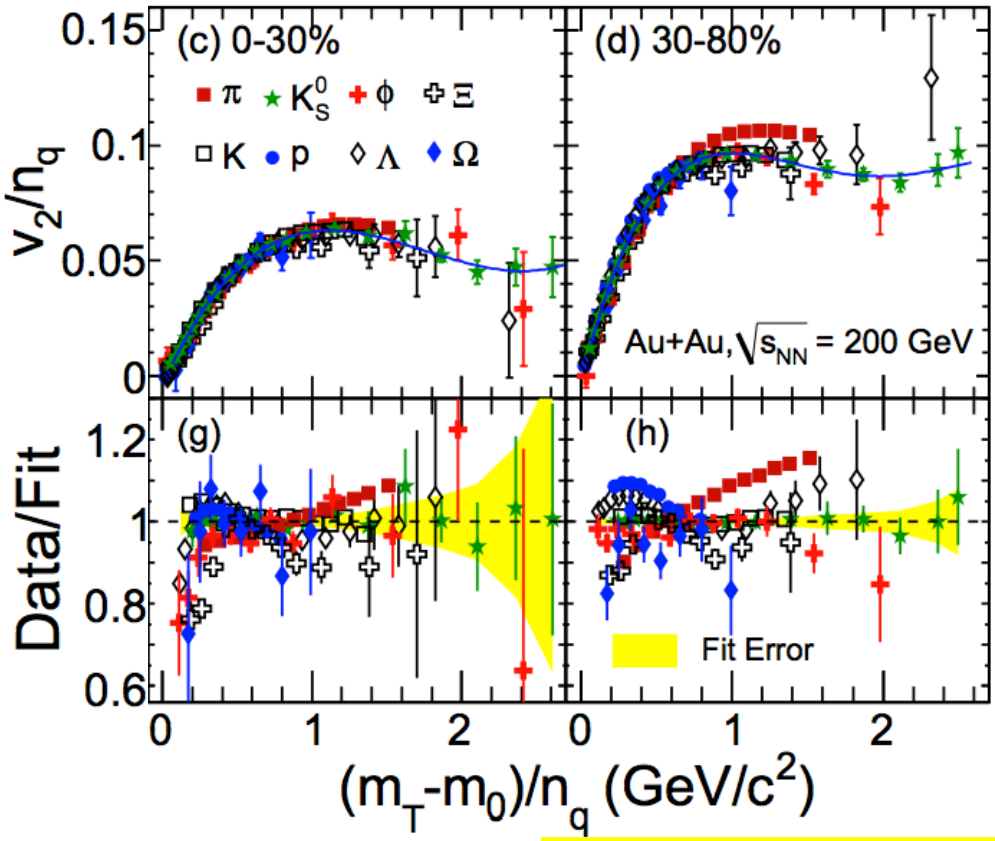
3) Photo-production in ultra-peripheral collisions

– ρ/ω photo-production

Partonic Collectivity







STAR, PRL 116 (2016) 062301

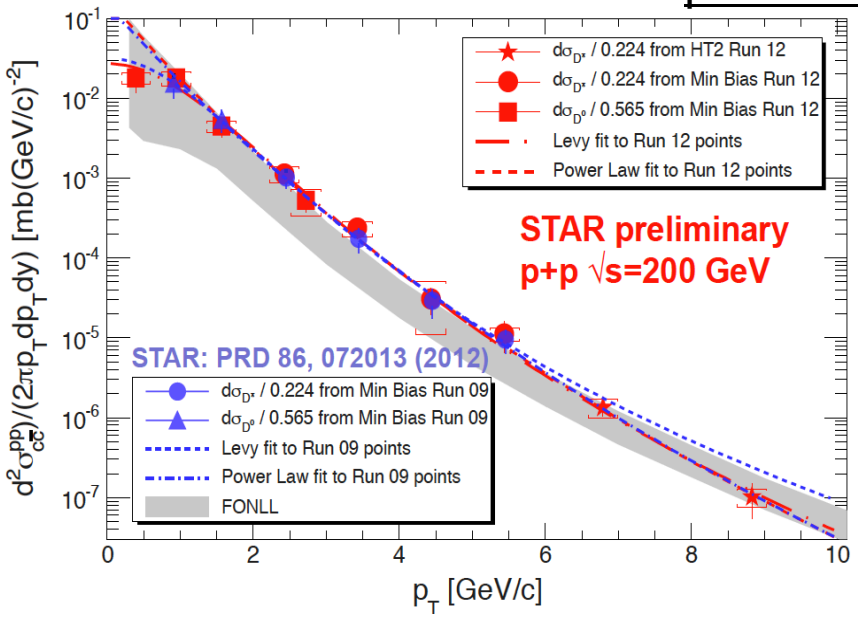
Hiroshi Masui, Shusu Shi

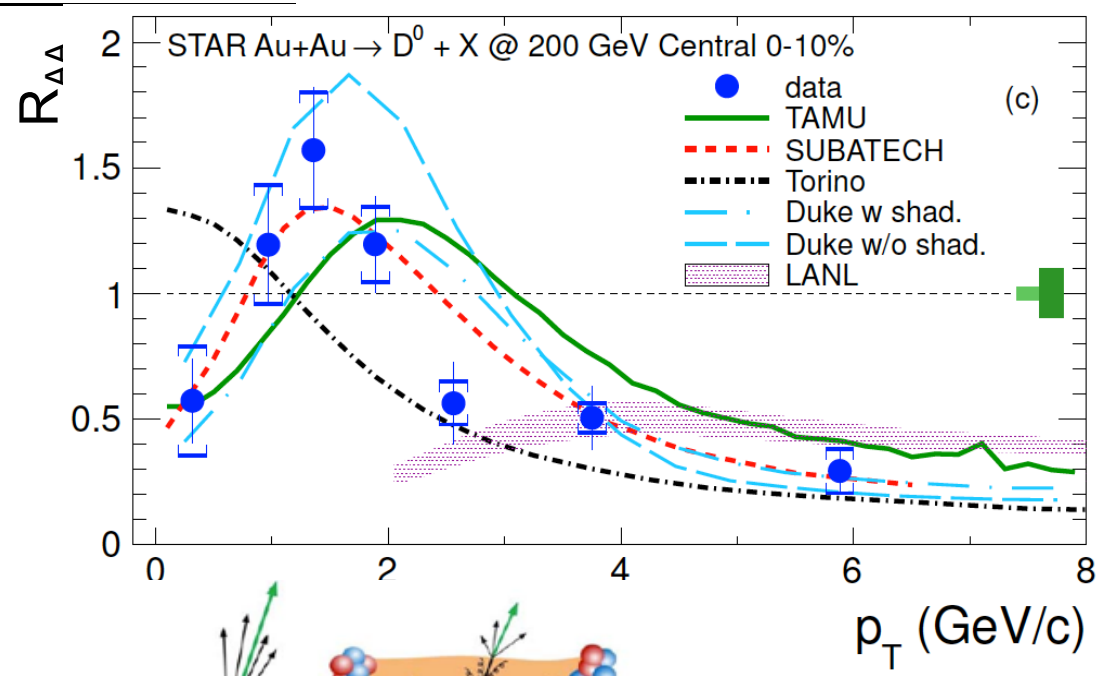
- Precision measurements of multi-strange (ϕ, Ξ, Ω) particles show
  $v_2(\Omega) \sim v_2(\Xi) \sim v_2(p)$, $v_2(\phi) \sim v_2(\pi)$
- Number-of-Constituent-Quark scaling holds within 10%
  strange quark: thermalized and flows!

Charm quark flows? More sensitivity to medium transport properties

Charm Production in p+p and Au+Au Collisions

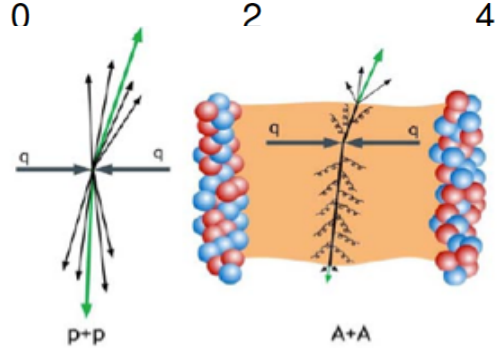
pre-HFT measurements





STAR, PRD 86 (2012) 072013,
PRL 113 (2014) 142301, QM2014

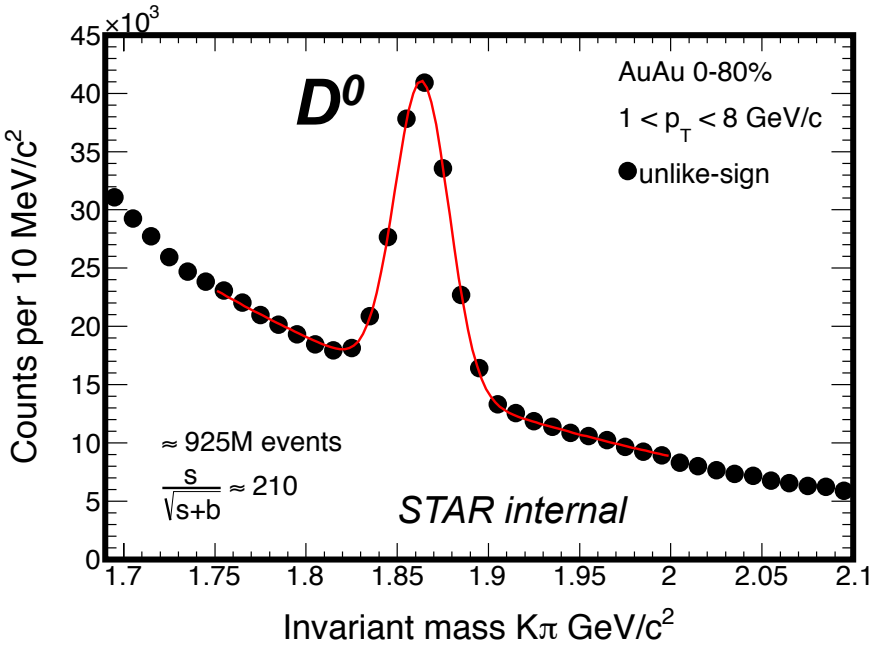
Mustafa Mustafa, Hao Qiu, Yifei Zhang



$$R_{AA} = \frac{d^2N^{AA}/dp_T dy}{N_{bin} d^2N^{pp}/dp_T dy}$$

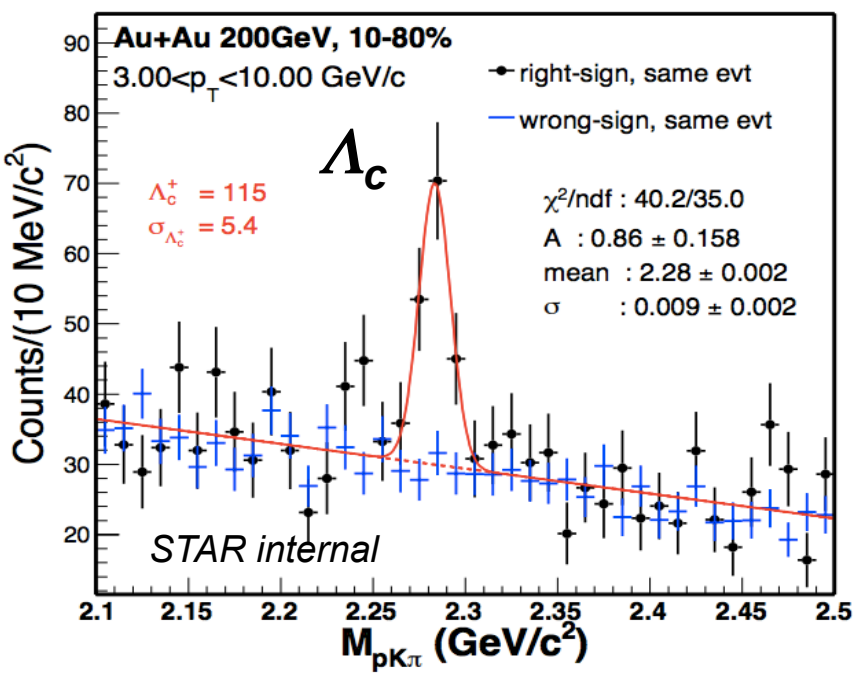
- Consistent with the pQCD calculation in p+p 200 GeV collisions
- Significant suppression at high p_T - $R_{AA}(D^0) \sim R_{AA}(e) \sim R_{AA}(h)$
- Coalescence for charm-hadron formation for low-intermediate p_T region
- Charm quark flows? - interplays between cold/hot nuclear effects
  need D^0 v_2 measurement -> HFT

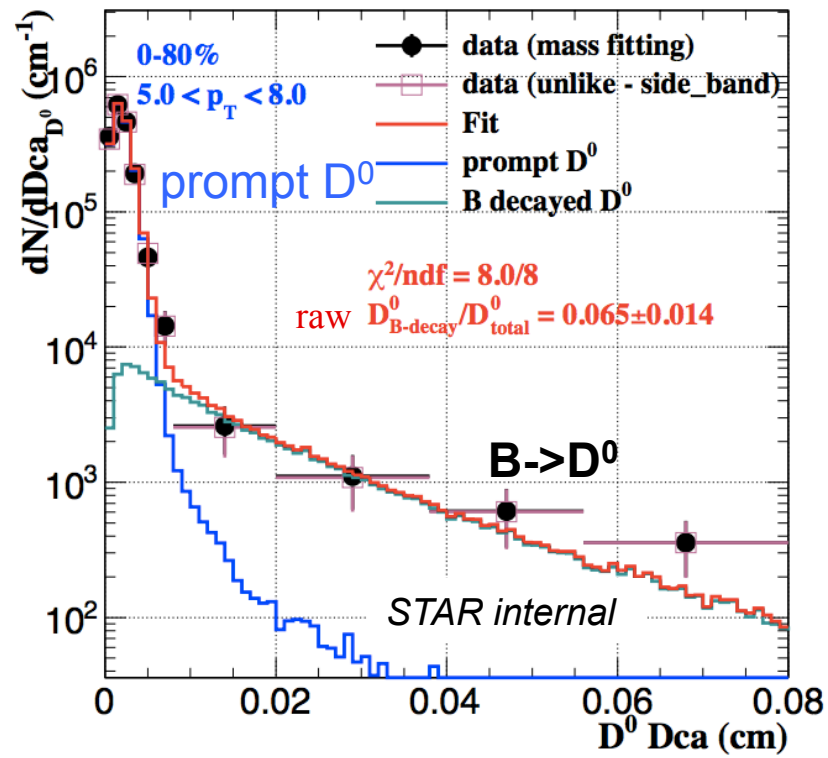
Heavy Flavor Tracker (HFT) Performance



HFT details – see L. Greiner's talk

	2010/2011	2014 w/ HFT
D^0 significance per billion events	13	~220



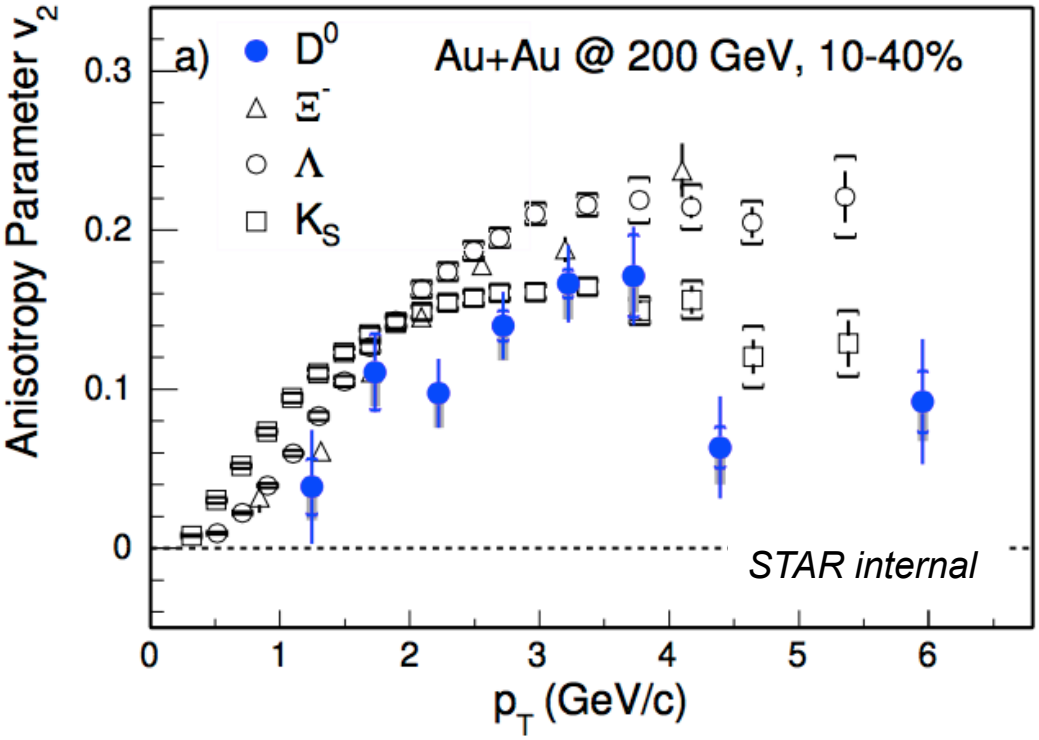


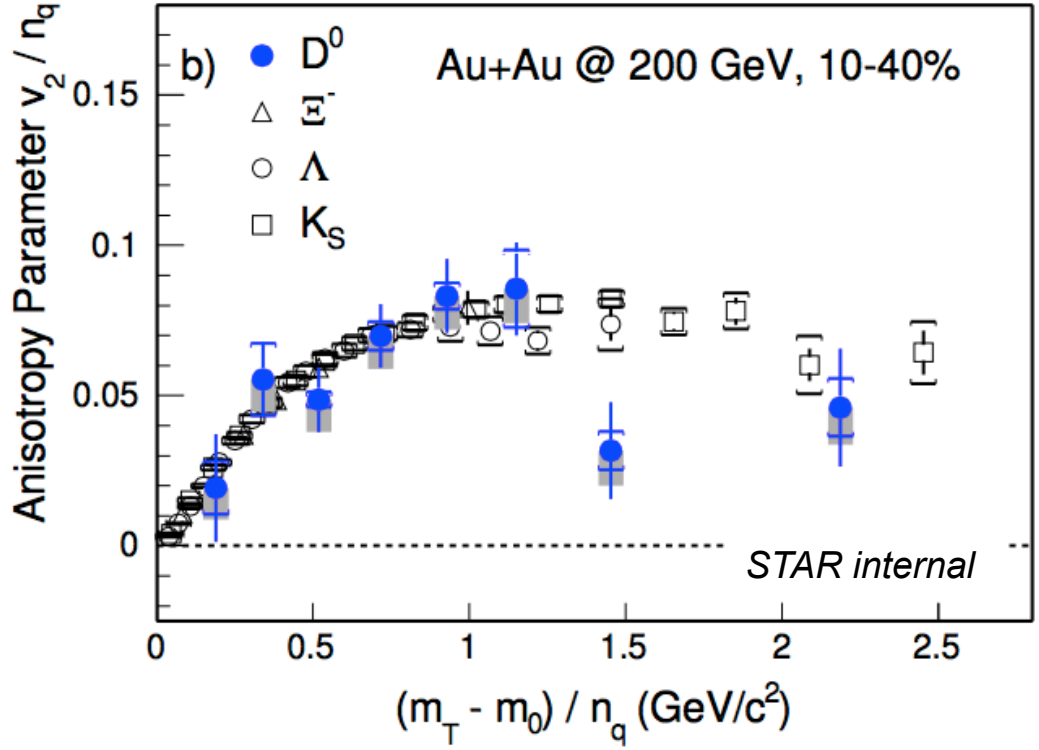
LDRD16 - Nu Xu

Xiaolong Chen, Michael Lomnitz, Mustafa Mustafa, Hao Qiu, *Guannan Xie*

D-meson v_2 at RHIC

70% of 2014 Au+Au 200 GeV Data



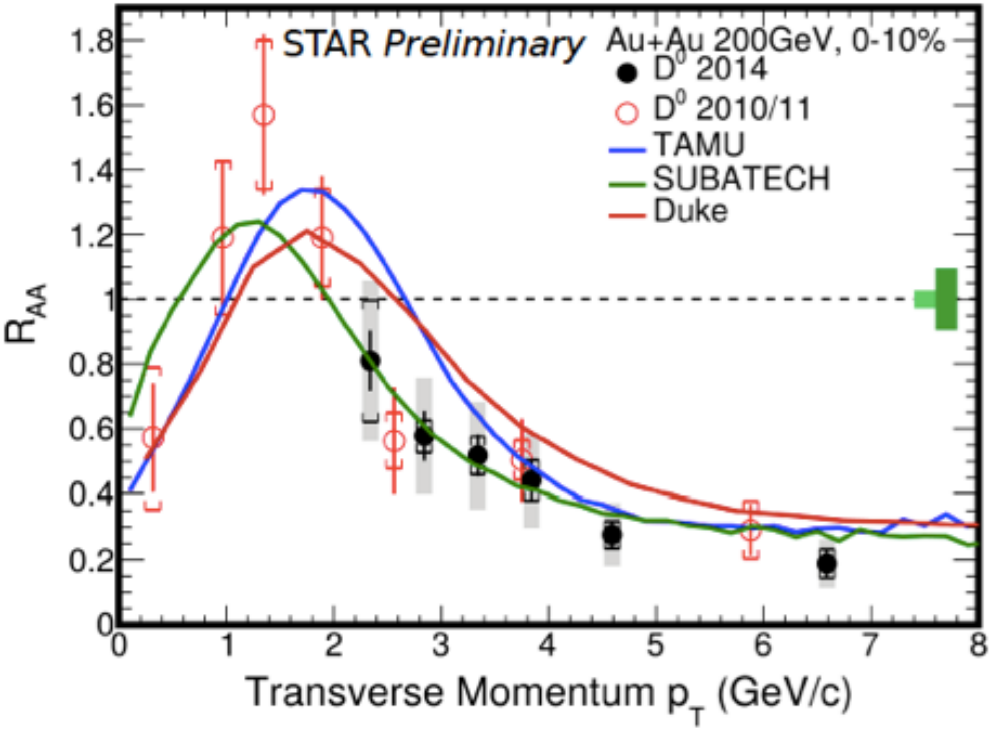


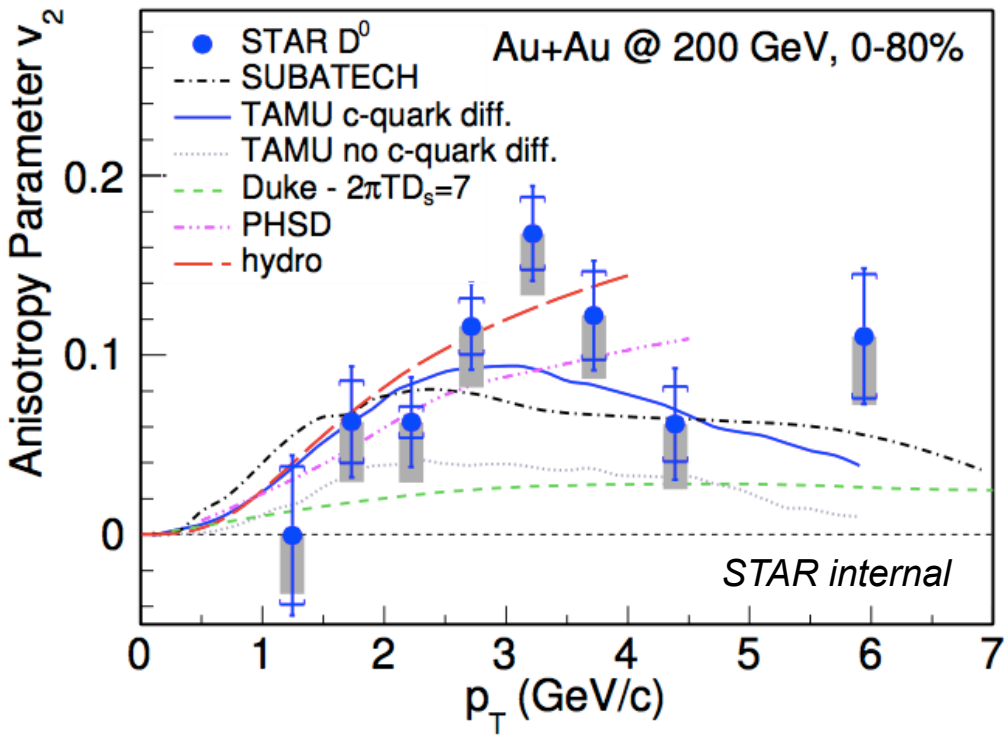
Paper in collaboration review

Michael Lomnitz, Hao Qiu

- Significant charm hadron v_2 at p_T>1.5 GeV/c
- v_2/n_q vs. $(m_T-m_0)/n_q$: D^0 mesons flow the same as light hadrons
  - charm quark thermalized in the medium !
  - similar observation at LHC energies

D-meson R_{AA} and v_2



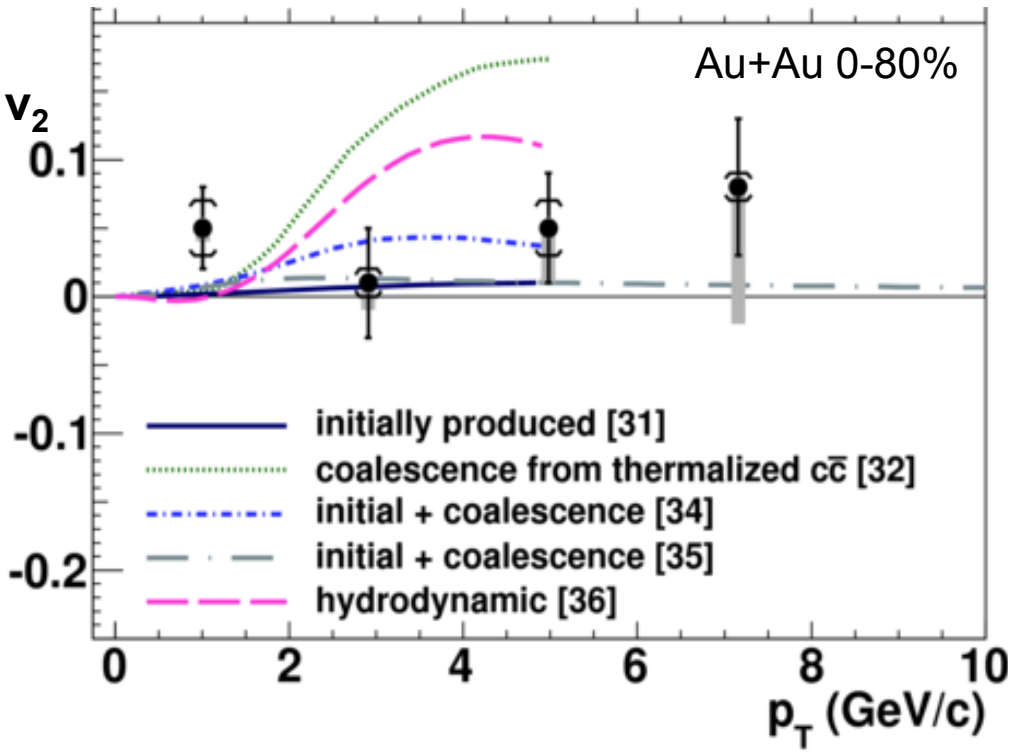


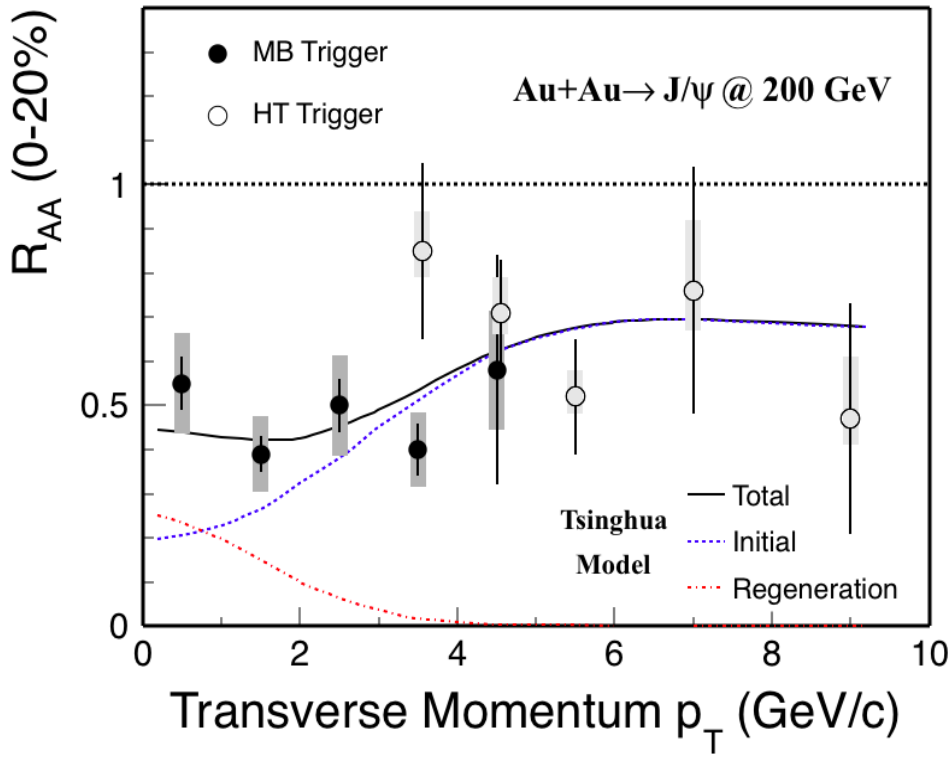
STAR, QM2015

Michael Lomnitz, Mustafa Mustafa, Hao Qiu, *Guannan Xie*

- Charm quarks at RHIC show
  - significant suppression at high p_T, $R_{AA}(D) \sim R_{AA}(h)$
  - significant flow at low-intermediate p_T, $v_2(D) \sim v_2(h)$ vs. m_T-m_0
- Models with a diffusion coefficient $2\pi T\boldsymbol{D_s} \sim$ 2-12 describe both D^0 R_{AA} and v_2
  - *differences between models to be settled*
- Future measurements:
  - Λ_c, D_s, bottom production

J/ψ v_2 and R_{AA} at RHIC



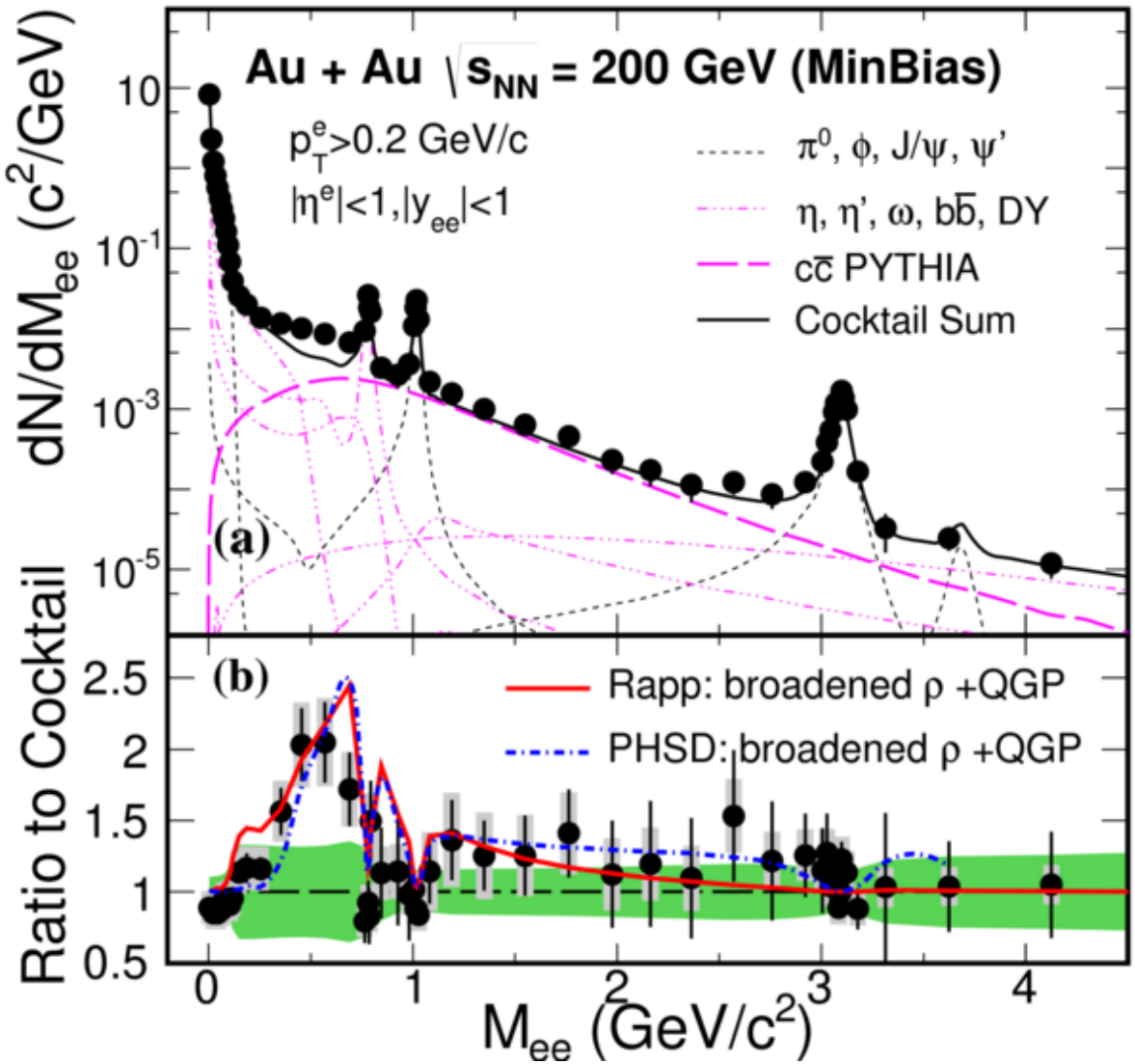


STAR, PRL 111 (2013) 052301, PLB 722 (2013) 55, PRC 90 (2014) 024906

Hao Qiu, *Chris Powell*

- J/ψ production
  - a mixture of initial production (high p_T) and charm quark coalescence (low p_T)
- Small v_2 + R_{AA} comparison to models - coalescence at RHIC is small
- High p_T J/ψ suppression - color screening signature at RHIC

Dielectrons at Au+Au 200 GeV

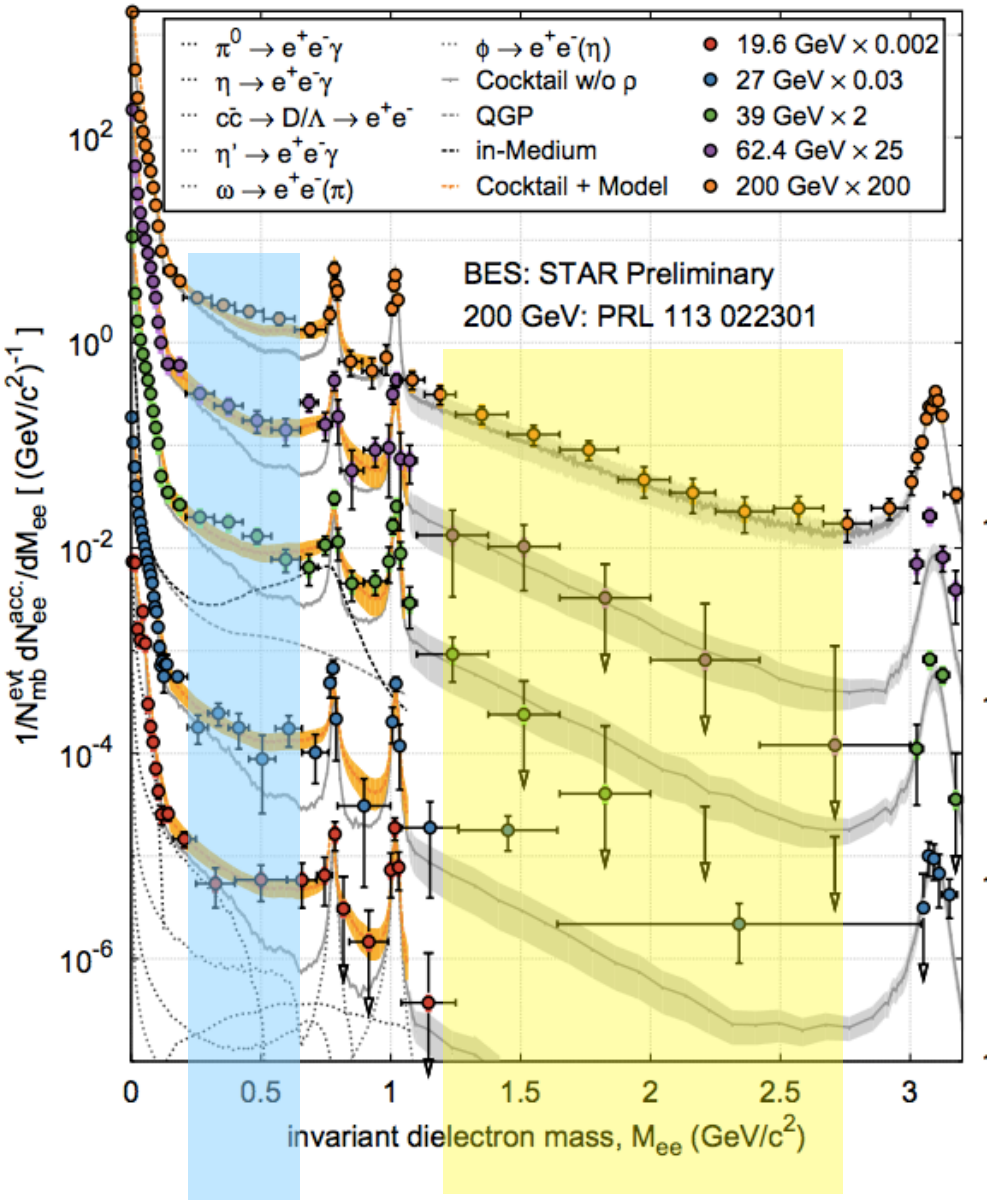


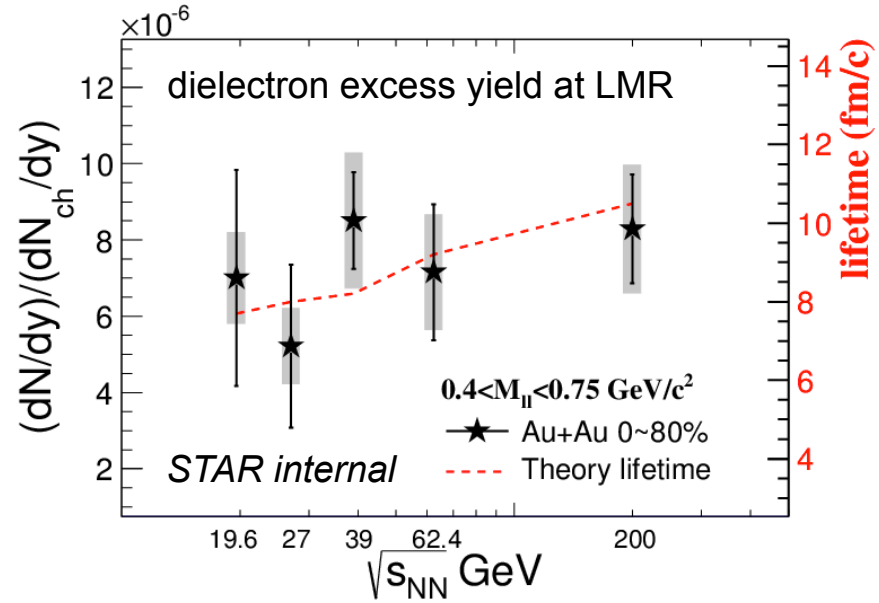
- **Clean penetrating probe** to study various stage of HI collisions
- Goals:
  - *In-medium vector mesons*
  - *Thermal radiation*
- Enhancement at 0.3-0.7 GeV/c^2 compared to the hadron cocktail.
- Vacuum ρ cannot reproduce the excess observed in data.
  - ρ in-medium modification
  - chiral property of the medium

Yi Guo, Jie Zhao

STAR PRL 113 (2014) 022301, PRC 92 (2015) 024912

Energy Dependence of Dielectron Production





- Low mass region (LMR) enhancement persists from 19.6 – 200 GeV
- In-medium ρ broadening reproduce LMR excesses consistently

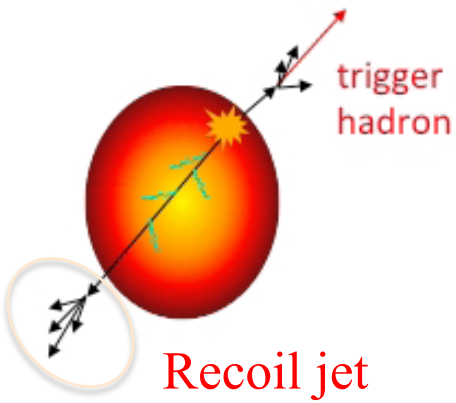
  R. Rapp, private communications

- Future measurements:
  - IMR: separate charm/QGP radiation
    - *direct measure of QGP temperature*
  - LMR: BES-II 7.7-20 GeV

paper in collaboration review *STAR, QM2014*

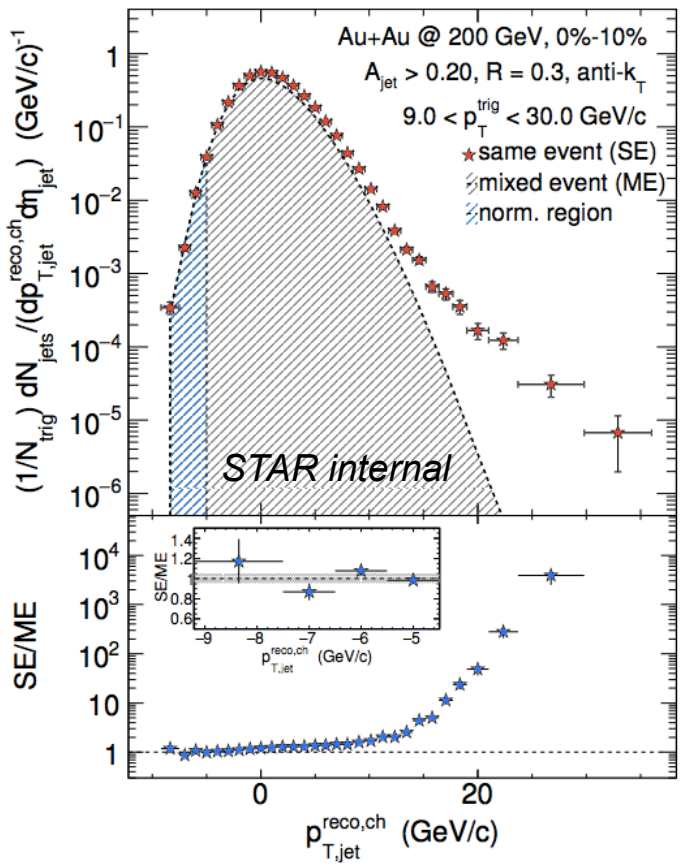
Yi Guo, Patrick Huck

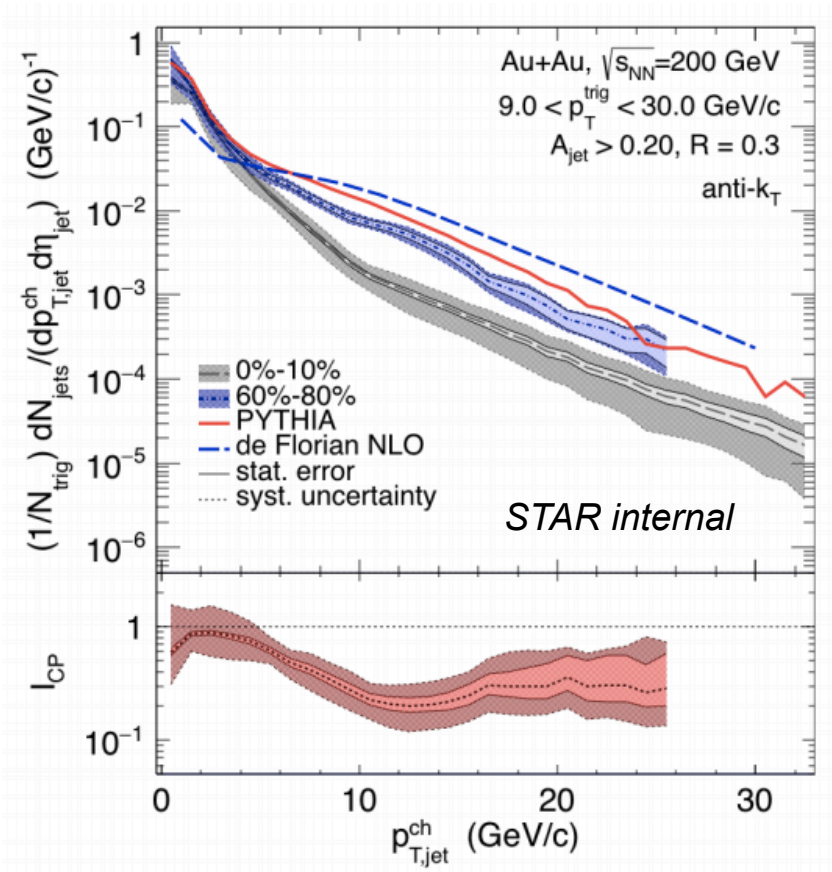
Semi-inclusive hadron+jet Measurement



STAR, QM15

Alex Schmah



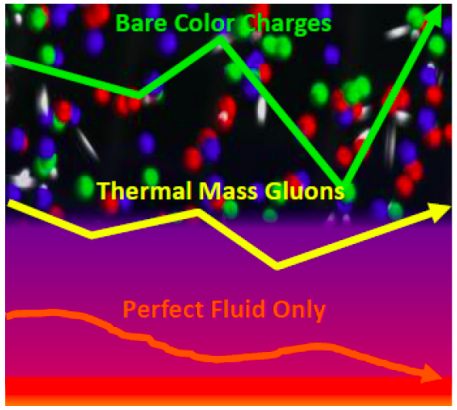


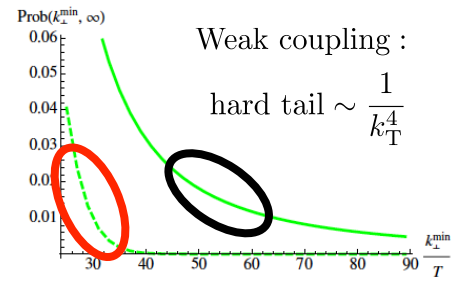
- Trigger: high p_T hadron; recoil: reconstructed charged jet, IRC-safe
  Semi-inclusive h+jet: calculable in vacuum via pQCD
- Clear jet signals at p_T above a few GeV/c
  - mixed event technique applied to remove uncorrelated background
- I_{CP} (central-to-peripheral ratio) significantly suppressed
  - Out-of-cone energy transfer = -5.0 ± 0.5(stat.) ± 1.2(syst.) GeV/c (R=0.3)

h-jet Δϕ Correlation Measurement

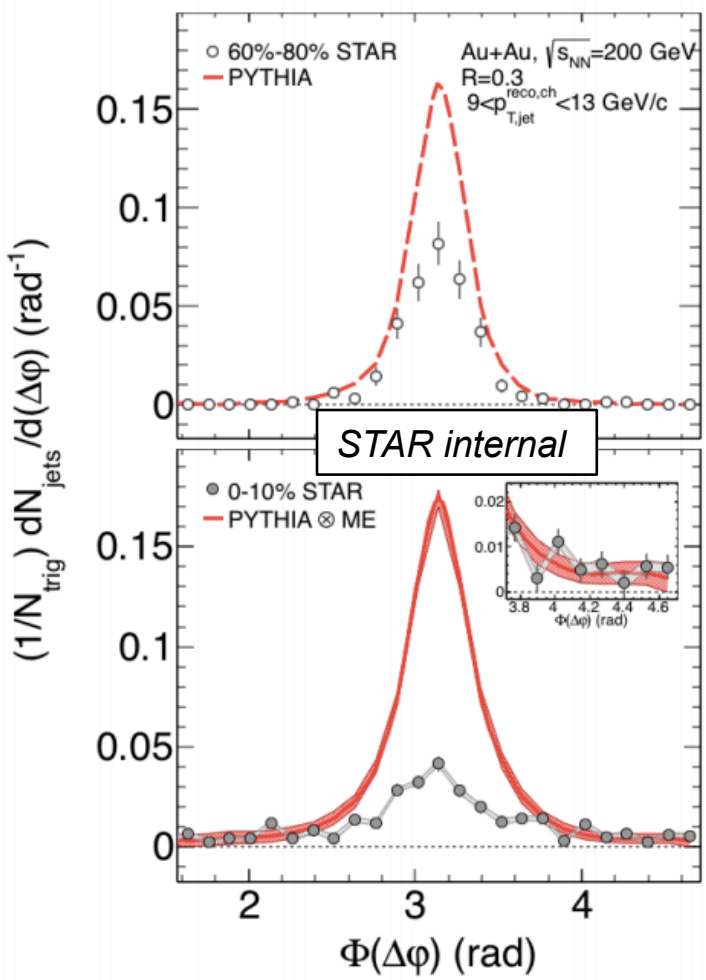
NSAC Long Range Plan 2015: key heavy ion jet measurement
- Large-angle Moliere scattering probes quasi-particles of medium

Low p_T jets have greatest sensitivity

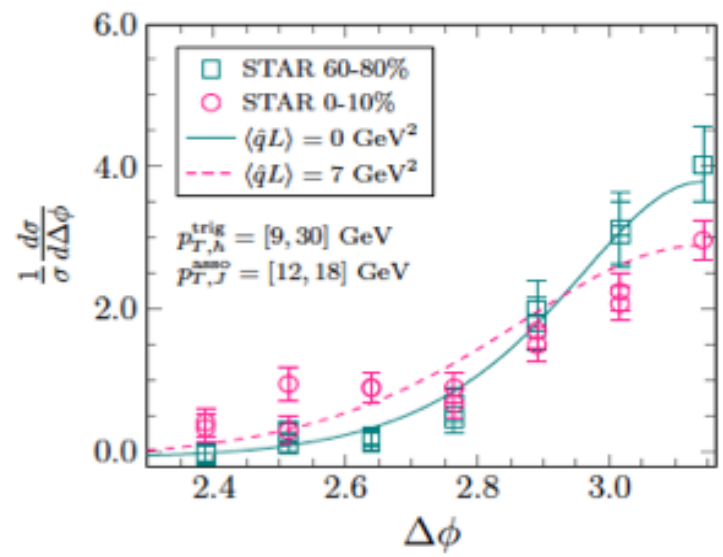




d'Eramo et al, JHEP 1305 (2013) 031



No evidence of large angle scattering within current uncertainties.



Chen et al., arXiv:1607.01932

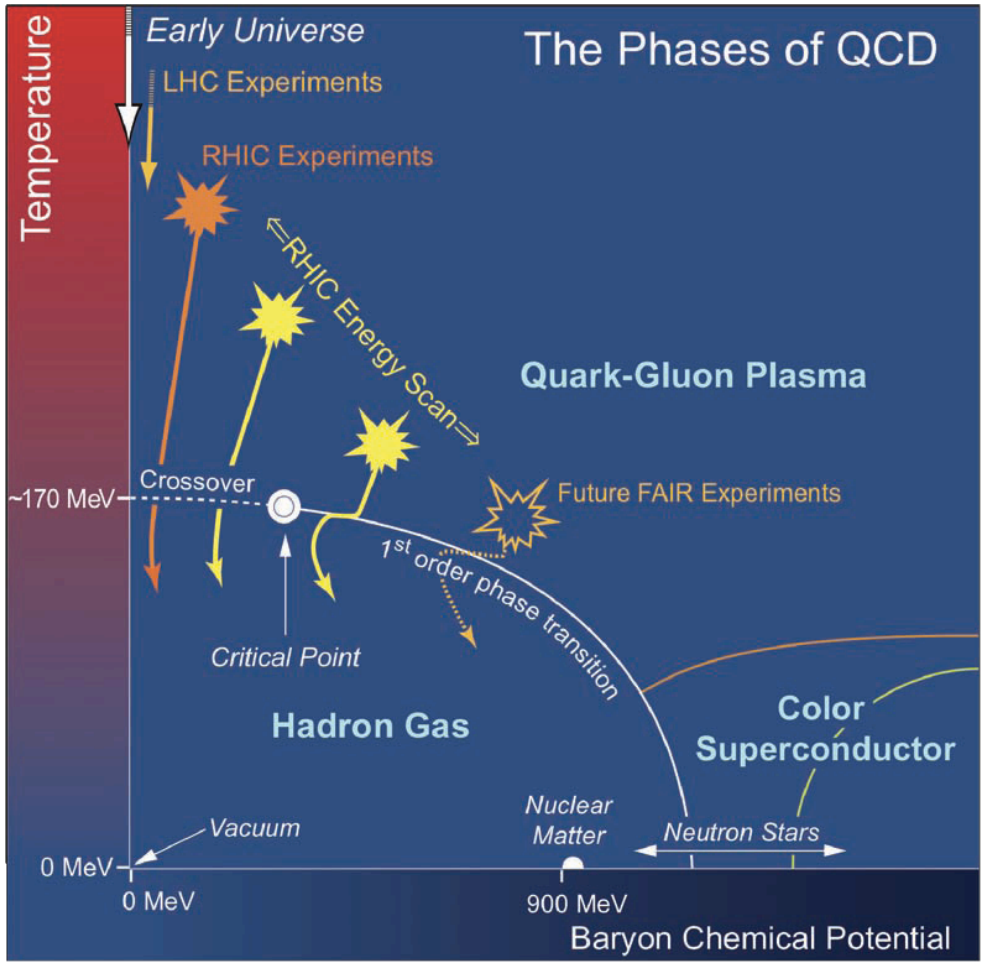
Main recoil peak broadened in central collisions:
Sensitive to $\langle \hat{q}L \rangle$

Alex Schmah

paper in collaboration review

Completion of Beam Energy Scan Phase I

NSAC Long Range Plan (LRP) 2007



RNC initiated and is now leading the BES program at RHIC

BES Phase-II endorsed by NSAC LRP 2015

0) Turn-off of sQGP signatures

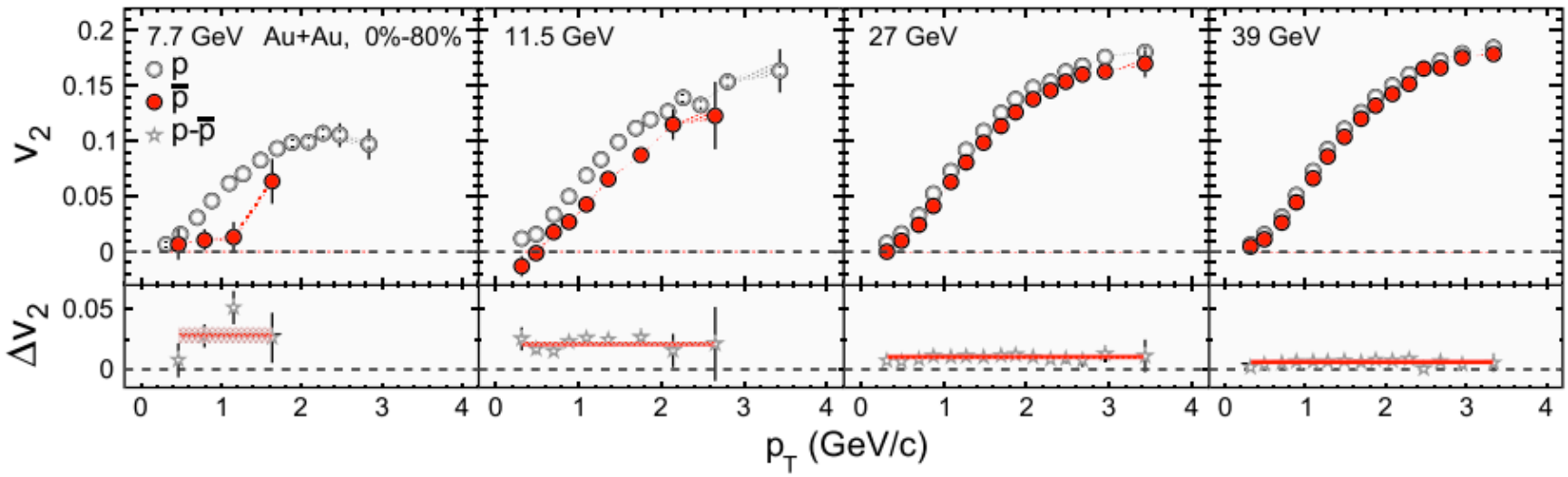
1) Search for the phase boundary

2) Search for the critical point

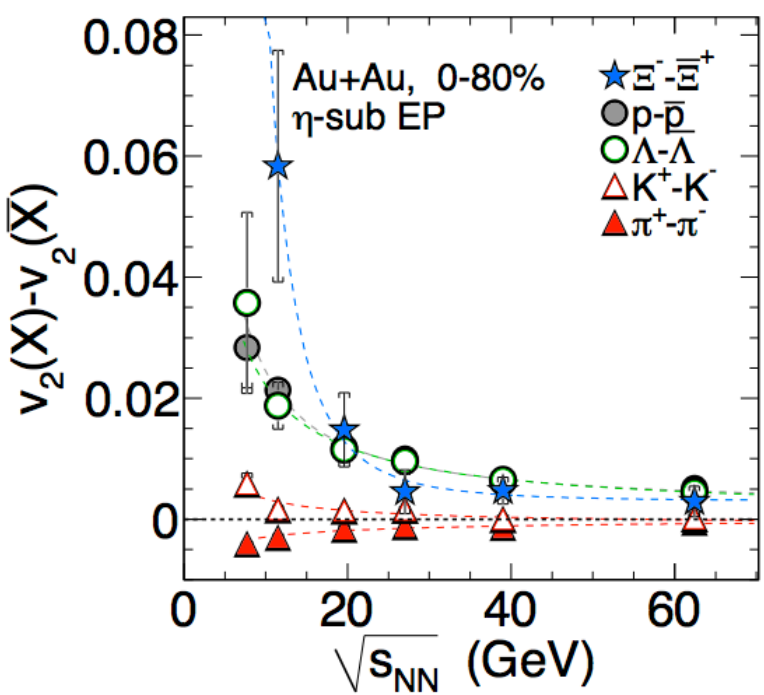
BES Phase-I

√s (GeV)	Statistics (Millions)	Year
7.7	~4	2010
11.5	~12	2010
14.5	~ 20	2014
19.6	~36	2011
27	~70	2011
39	~130	2010
62.4	~67	2010
200	~350	2010

v_2 Difference between Particles and Anti-particles



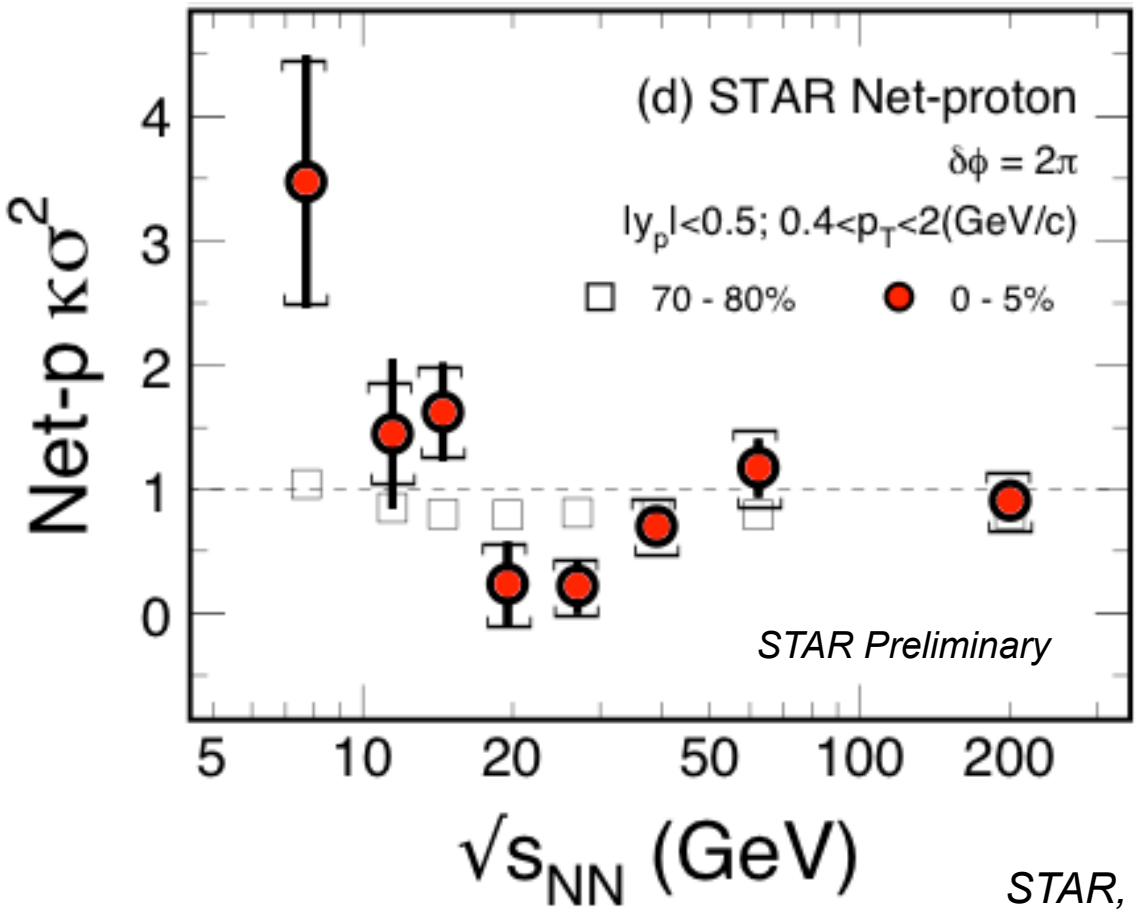
Alex Schmah



STAR, PRL 110 (2013) 142301,
PRC 88 (2013) 014902
PRC 93 (2016) 014907

- Significant difference between baryon-antibaryon v_2 at $\sqrt{s_{NN}}$<= 11.5 GeV
- Number-of-Constituent-Quark (NCQ) scaling between particles and anti-particles is broken

High Moments of Net-proton Multiplicity

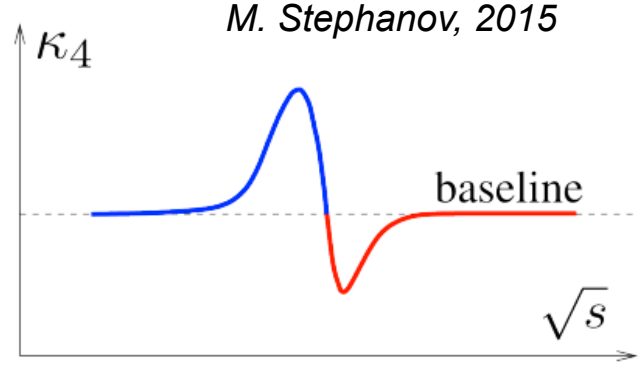


variance $\sigma^2 = \langle (N - \langle N \rangle)^2 \rangle$

skewness $S = \langle (N - \langle N \rangle)^3 \rangle / \sigma^3$

kurtosis $\kappa = \langle (N - \langle N \rangle)^4 \rangle / \sigma^4 - 3$

M. Stephanov, 2015

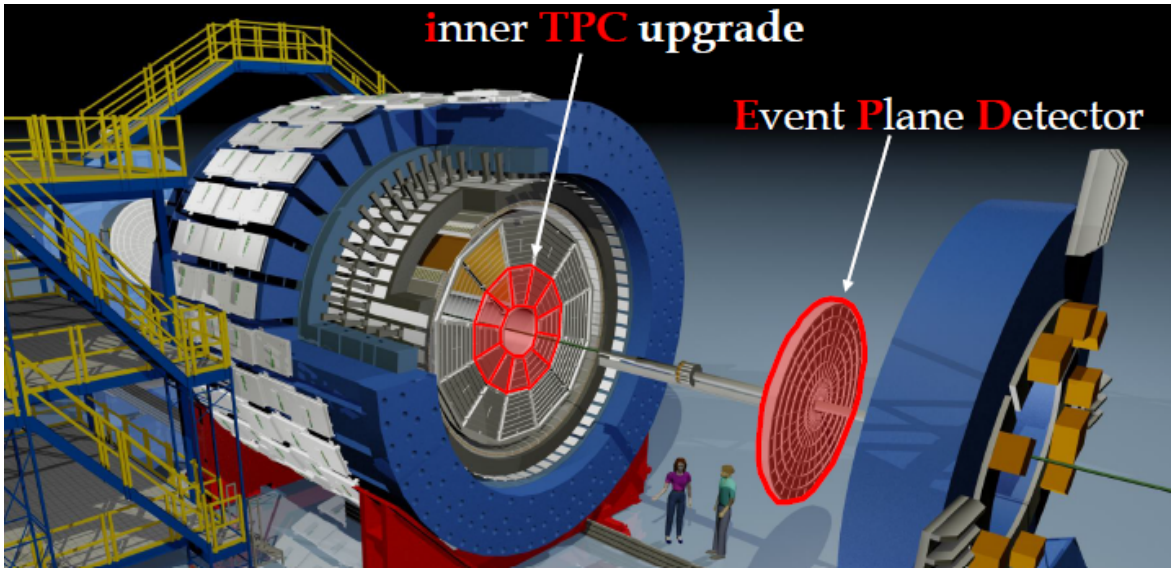


Xiaofeng Luo, Jochen Thader, Ji Xu

STAR, PRL 112 (2014) 032302, CPOD2014, QM2015

- Higher moments - more sensitive to Critical Point induced fluctuations
- A non-monotonic behavior observed for net-proton $\kappa^*\sigma^2$ vs. energy in central Au+Au collisions
  - connection to critical fluctuations?
- Future precision measurements at low energies with enlarged acceptance

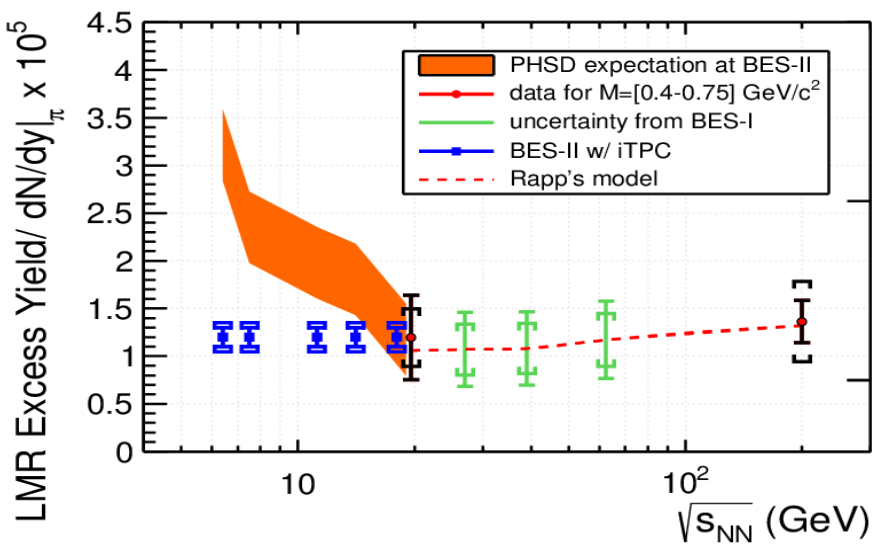
BES-II Physics with Detector Upgrades



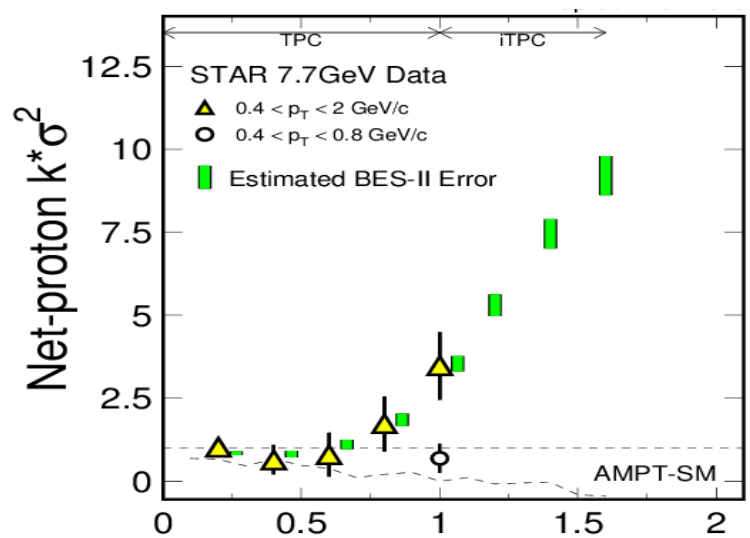
iTPC upgrade
- extended tracking η coverage
- improved momentum and dE/dx resolution

Event Plane Detector (EPD)
- improved event plane resolution
- independent centrality determination
  - *important for fluctuation analysis*

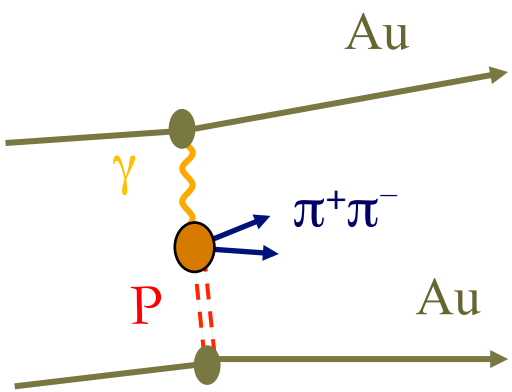
Low-mass dielectron excess



High moments of net-protons



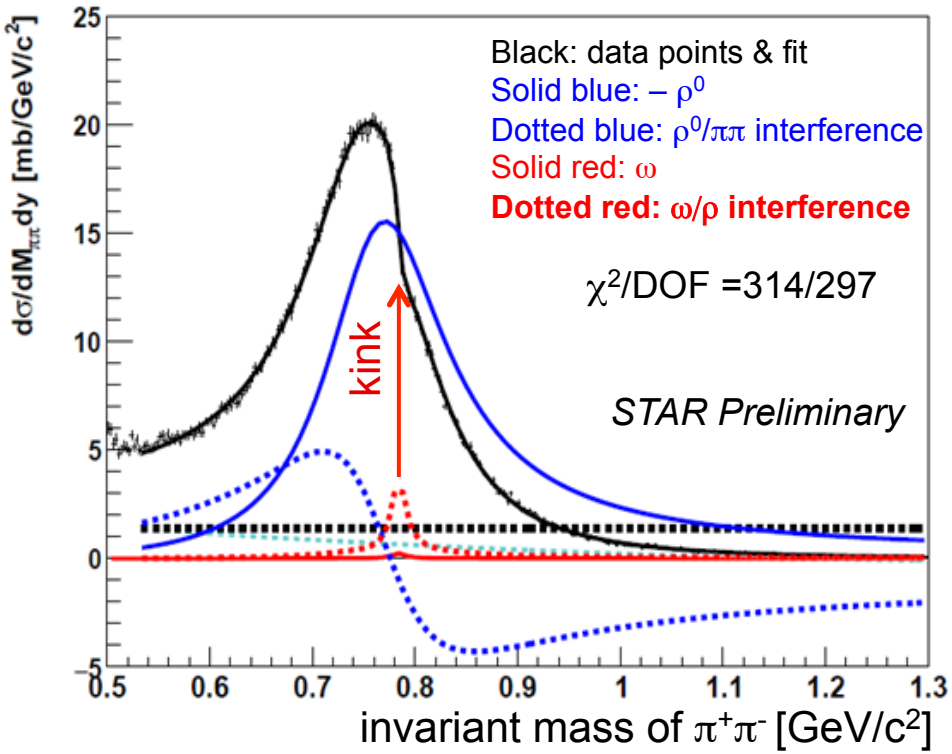
Ultra-peripheral Photonuclear Collisions

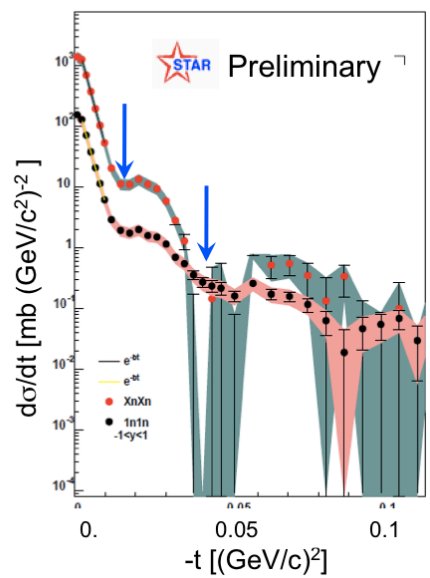


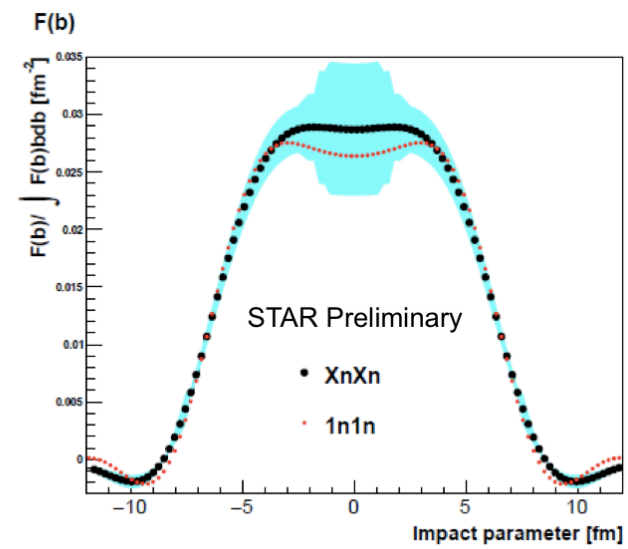
High statistics photoproduced $\pi^+\pi^-$ in UPC
- ρ^0, direct $\pi\pi$, ω, ***ρ/ω interference***
- ρ,ω magnitudes consistent with STARlight

- Multiple diffraction dips visible
  - expected as nucleus approaches "black disk"
- 2-d Fourier transformation $F(b) \propto \frac{1}{2\pi}\int_0^\infty dp_T\, p_T\, J_0(bp_T)\sqrt{\frac{d\sigma}{dt}}$

  FWHM = 2 * (6.17 ± 0.12) fm
- Lead-in physics in future EIC experiments



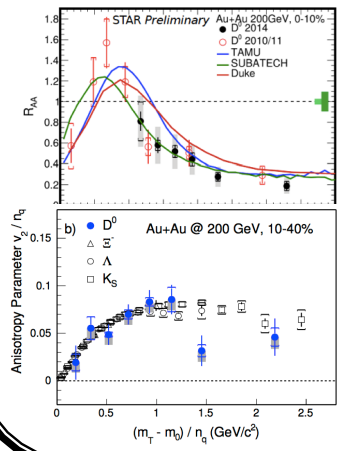


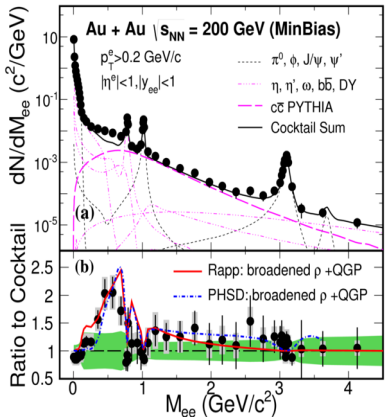


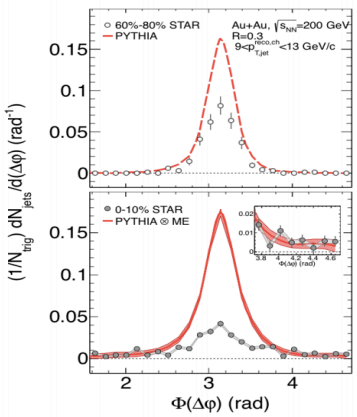
paper in collaboration review

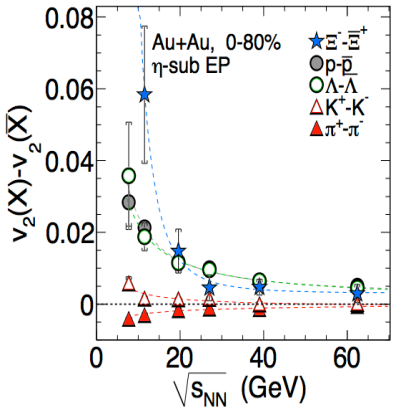
Summary - Accomplishments and Future Focus

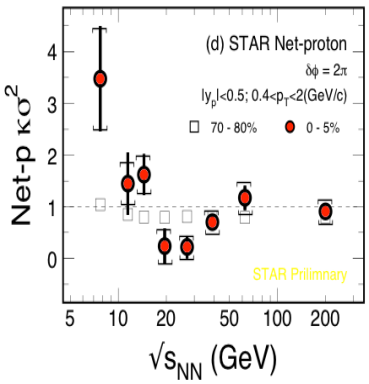
Accomplishments











Future Focus:

1) **Heavy quark production:**

   Charmed baryon Λ_c production, Open bottom production, Heavy quark correlations

2) **Di-lepton production**: intermediate mass region for QGP thermal radiation

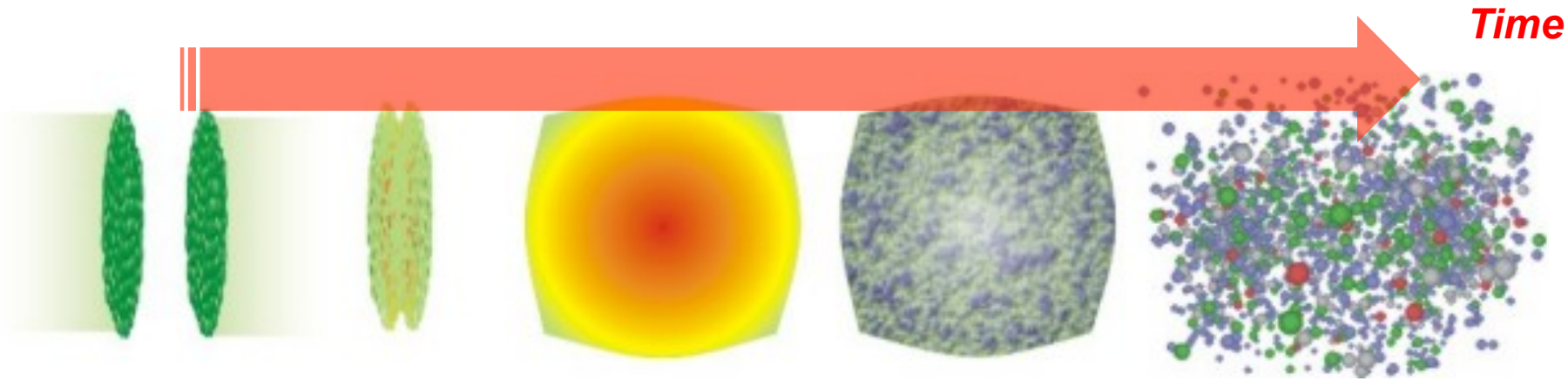
3) **Jet physics in heavy ion collisions:** micro-structure of the medium

4) **Ultra-peripheral collisions**

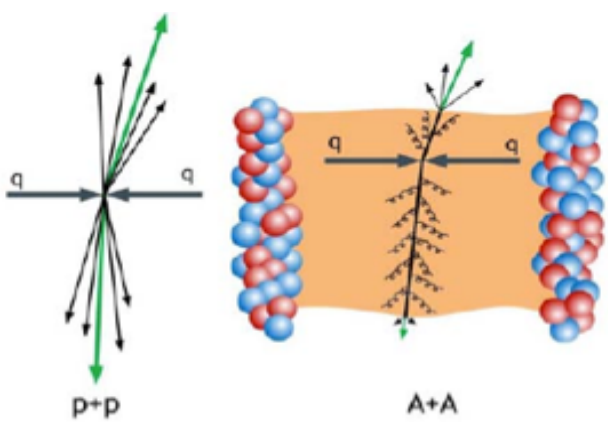
5) **Beam Energy Scan – II**

   Net-proton high moments, Beam energy dependence of di-electron production

High Energy Nucleus-Nucleus Collisions



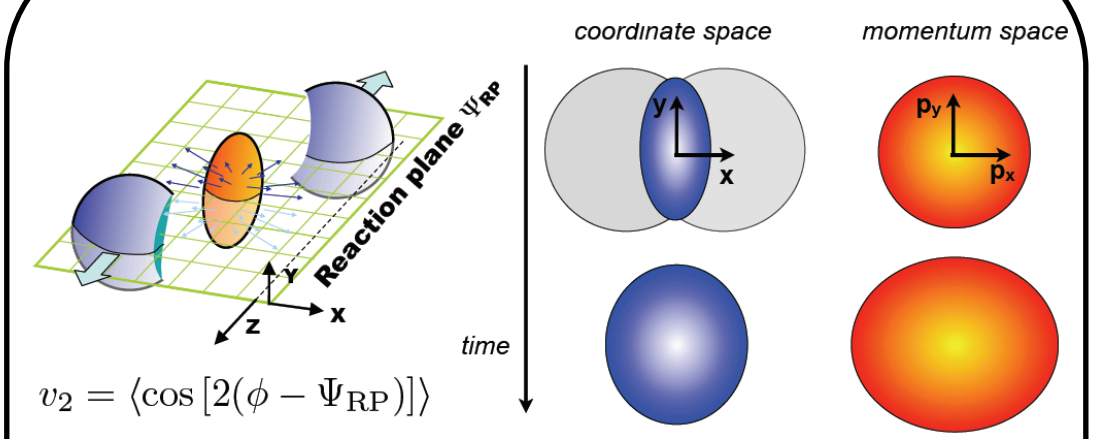
Initial hard scatterings | QGP phase | Hadron phase | Freeze-out



Nuclear modification factor (R_{AA})

$$R_{AA} = \frac{d^2N^{AA}/dp_T dy}{N_{bin} d^2N^{pp}/dp_T dy}$$

Characterize the medium effect

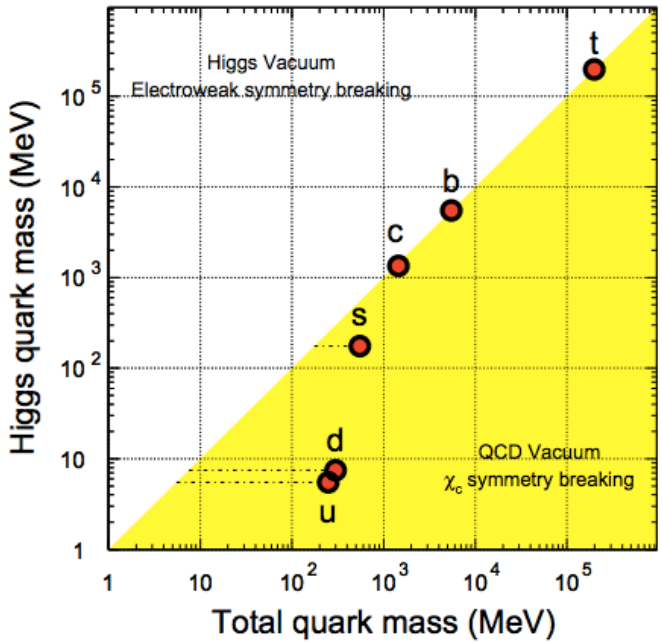


$$v_2 = \langle \cos[2(\phi - \Psi_{RP})] \rangle$$

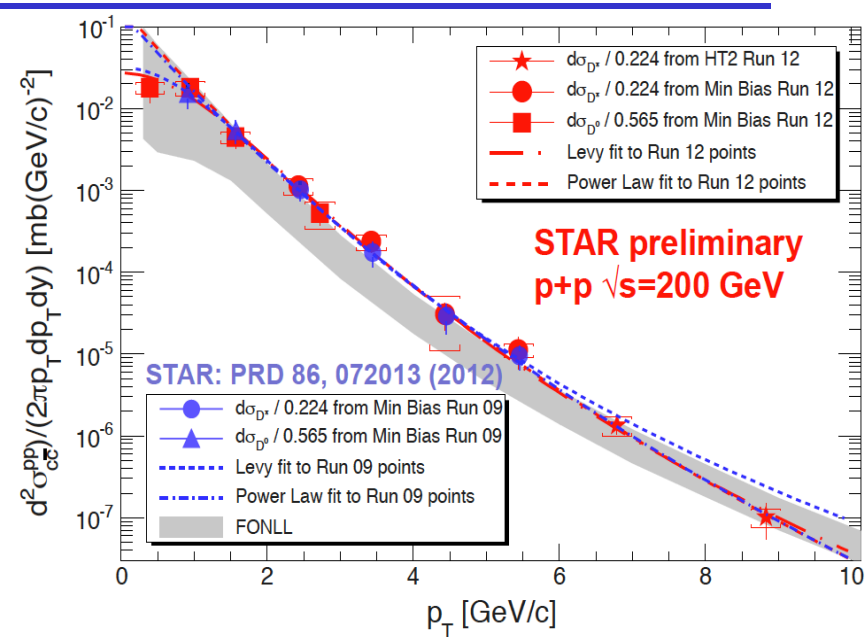
Elliptic flow (v_2) = 2nd Fourier coefficient

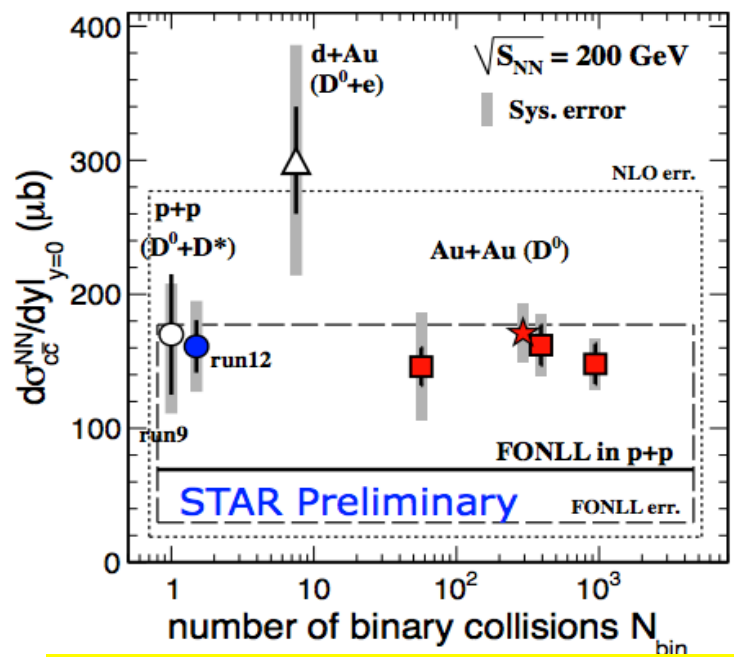
Sensitive to the early stage properties

Charm Production Cross Section



X. Zhu et al, PLB 647(2007)366





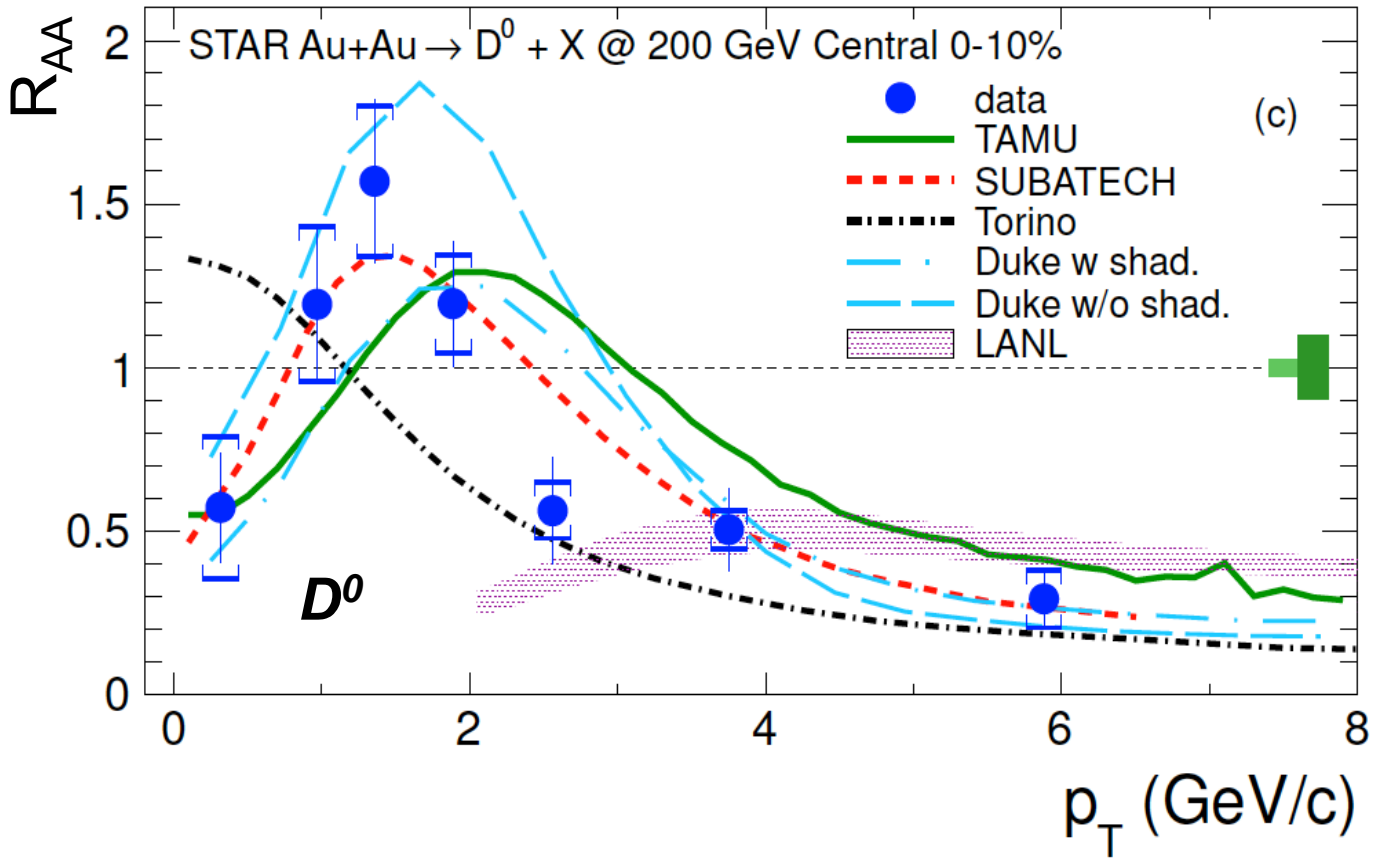
- Heavy quarks – sensitive to early dynamics
- consistent with the pQCD calculation in p+p
- predominantly created from initial hard scatterings in HI collisions
- pre-HF measurements, **HFT improves both stat. and sys. uncertainties**

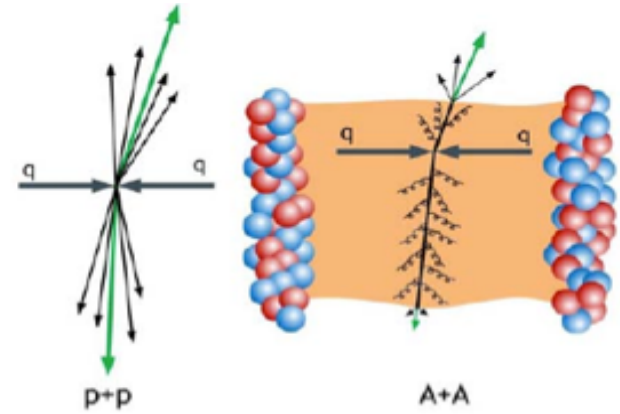
STAR, PRD 86 (2012) 072013, PRL 113 (2014) 142301, QM2014

Mustafa Mustafa, Hao Qiu, Yifei Zhang

Charm Modification in Au + Au Collisions at RHIC

pre-HFT result





$$R_{AA} = \frac{d^2N^{AA}/dp_T dy}{N_{bin} d^2N^{pp}/dp_T dy}$$

STAR, PRL 113 (2014) 142301

Yifei Zhang

Significant charm energy loss in medium - $R_{AA}(D^0) \sim R_{AA}(e) \sim R_{AA}(h)$

Coalescence for charm-hadron formation

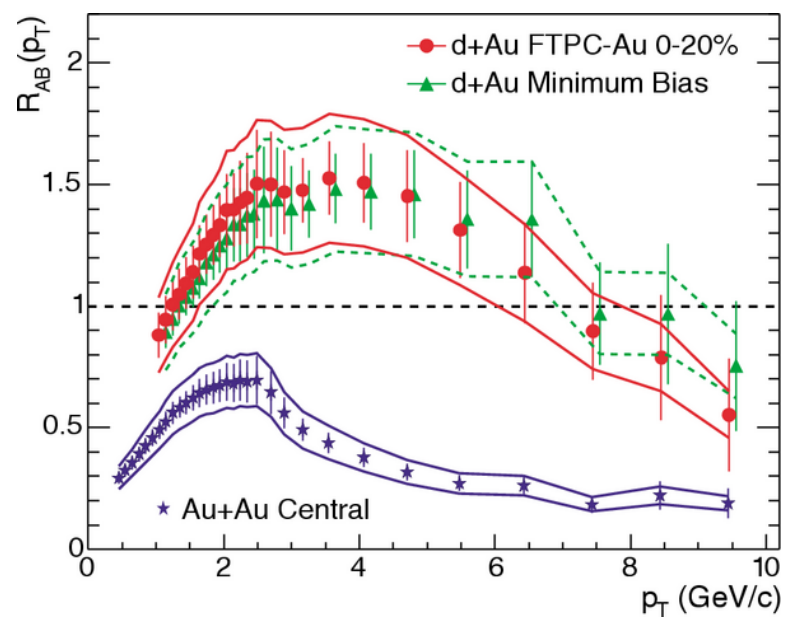
Charm quark flows? - interplays between cold/hot nuclear effects

RHIC Discoveries

Two most significant discoveries originated in RNC:

"Jet Quenching"

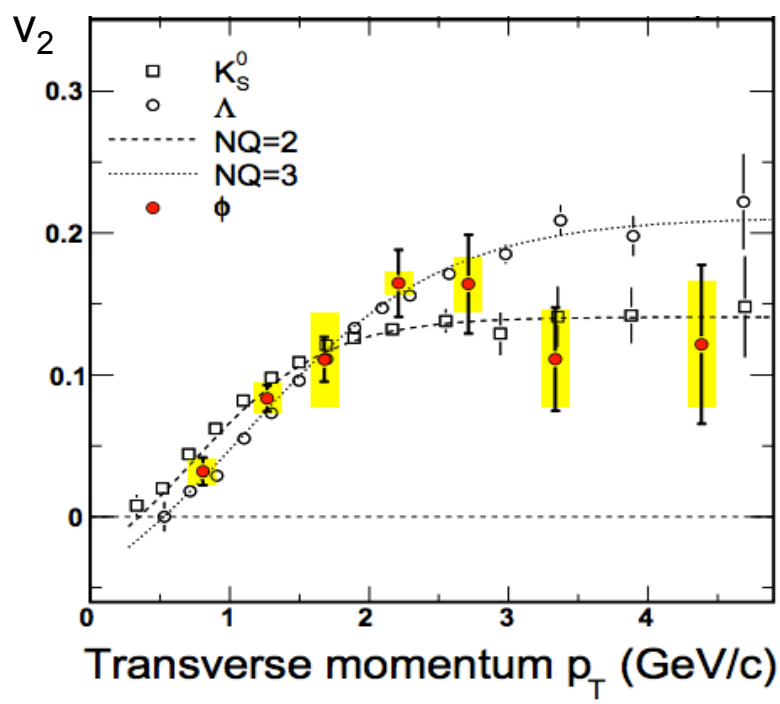
- Significant suppression in particle yield at high p_T in central heavy ion collisions



STAR: PRL. 91 (2003) 072304

"Partonic Collectivity"

- Strong collective flow, even for multi-strange hadrons (ϕ, Ω)
- Flow driven by Number-of-Constituent-Quark (NCQ) in hadrons



STAR: PRL. 99 (2007) 112301

Formation of strongly-coupled Quark Gluon Plasma (sQGP)!

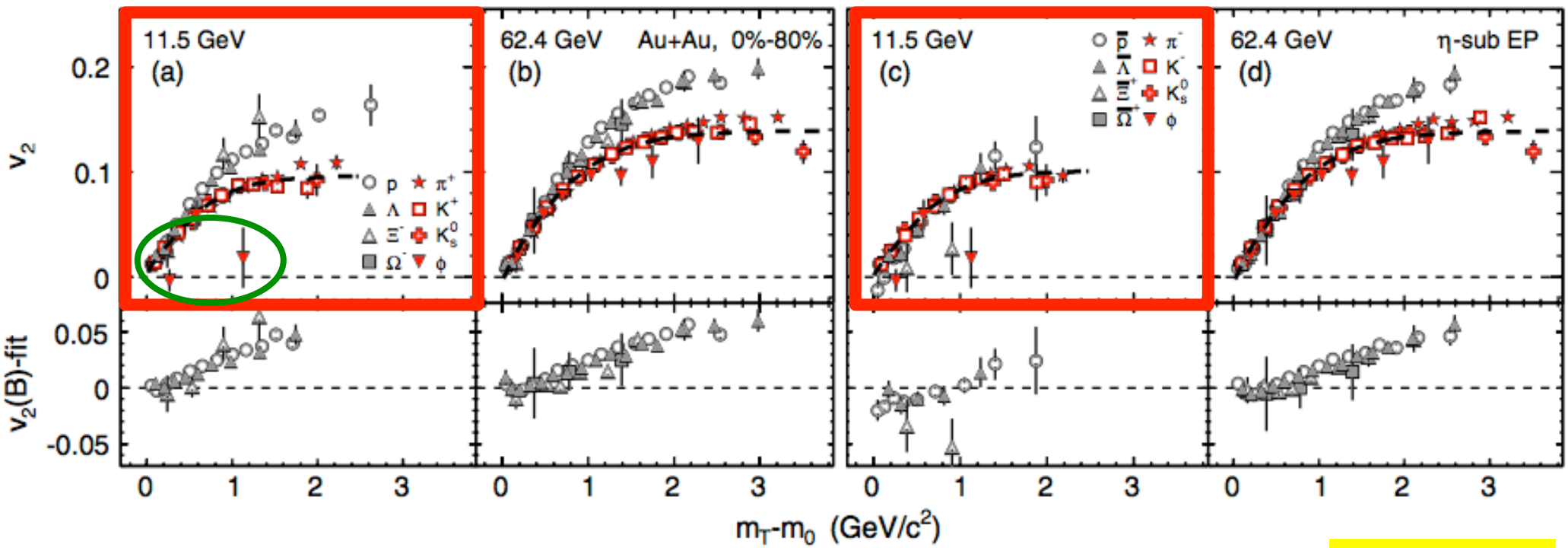
Relativistic Heavy Ion Collider

Heavy Ion Collisions:

Au + Au $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4, 130, 200 GeV

Baryon/Meson Splitting

Particles | Anti-particles

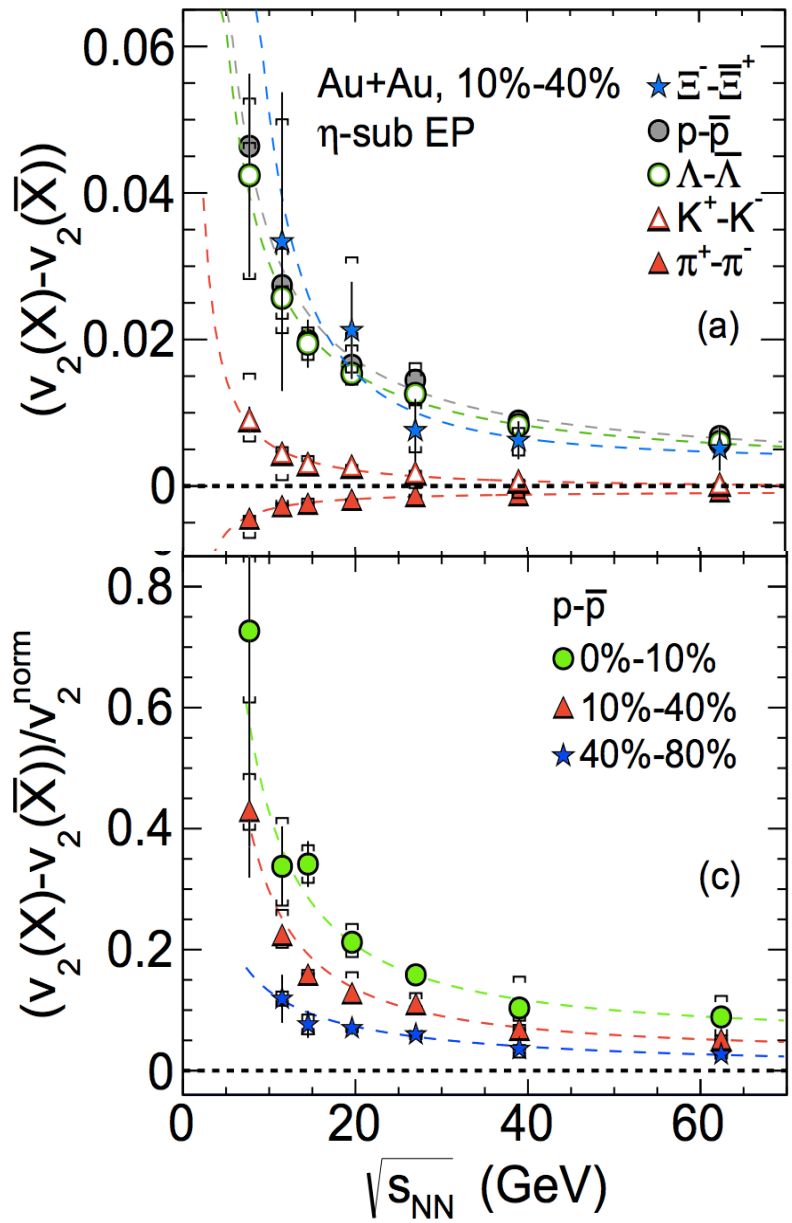


Alex Schmah

STAR, PRL 110 (2013) 142301, PRC 88 (2013) 014902, PRC 93 (2016) 014907

- No clear baryon/meson splitting for anti-particles at $\sqrt{s_{NN}}$<= 11.5 GeV
- Indication of ϕ–meson v_2 deviating from other hadrons at $\sqrt{s_{NN}}$<= 11.5 GeV

Centrality Dependence of Identified Particle v_2

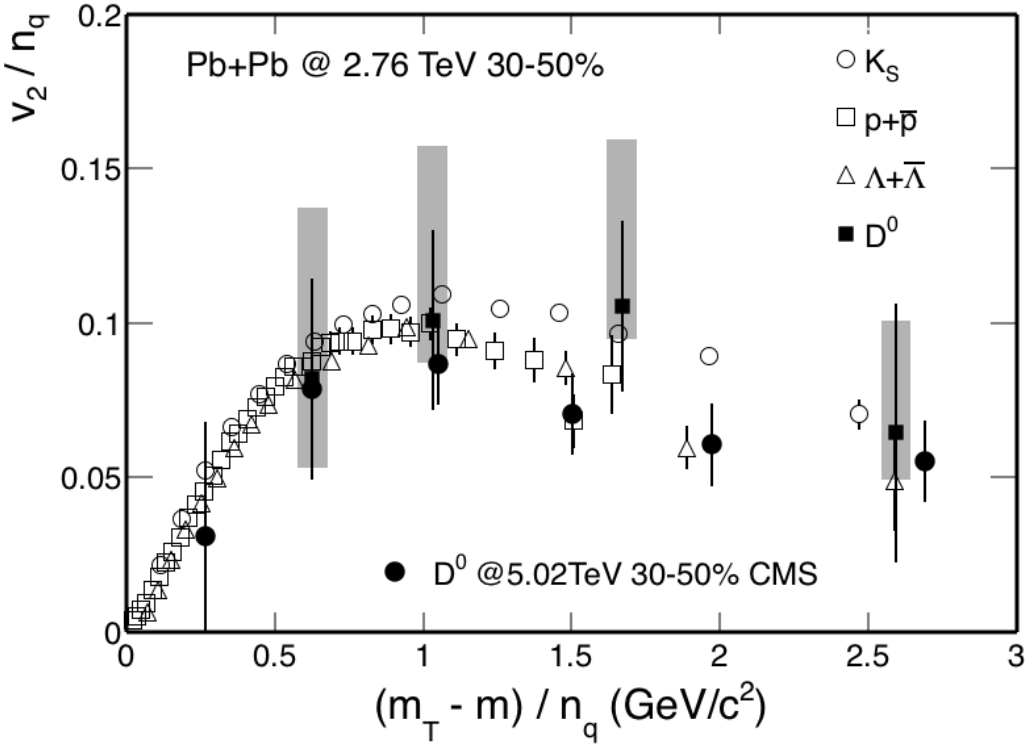


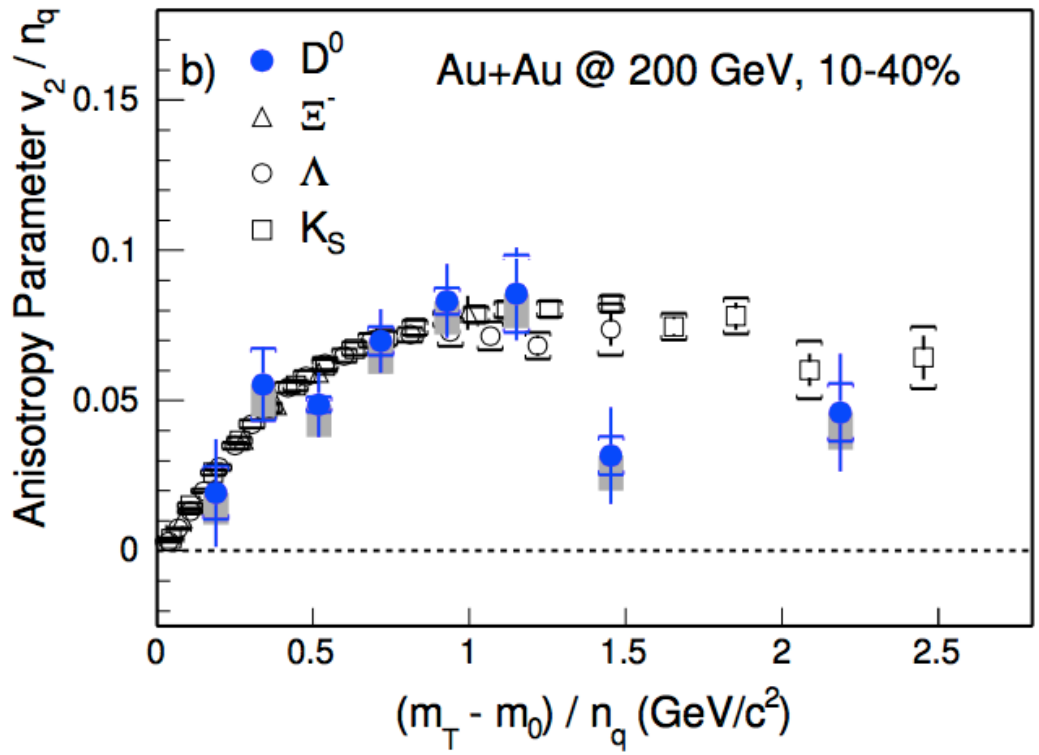
STAR, PRC 93 (2016) 014907

Alex Schmah

D-meson v_2 at RHIC

70% of 2014 Au+Au 200 GeV Data





Papers in the collaboration

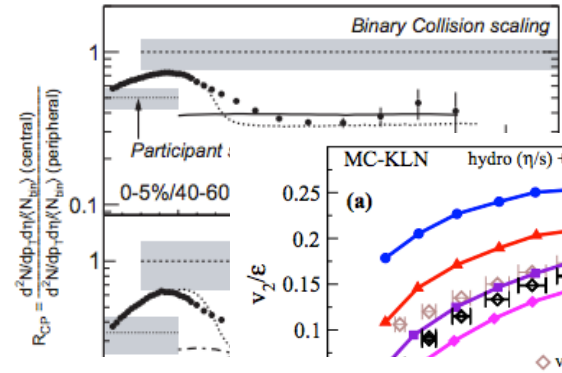
Michael Lomnitz, Hao Qiu

- Significant charm hadron v_2 at p_T>1.5 GeV/c
- v_2/n_q vs. $(m_T-m_0)/n_q$: D^0 mesons flow the same as light hadrons
  - charm quark thermalized in the medium !
  - similar observation at LHC energies

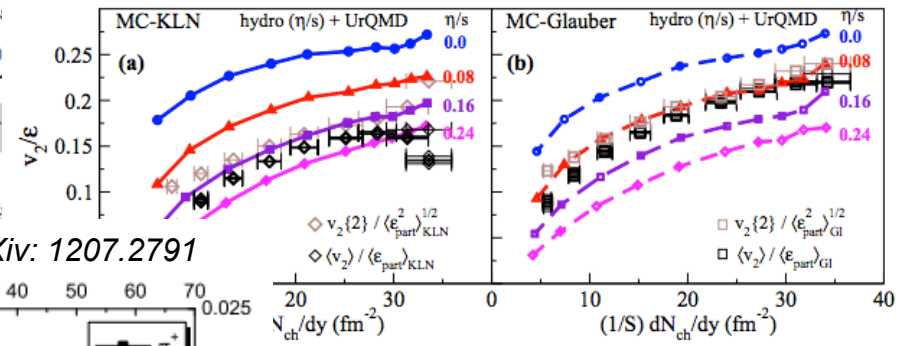
Synergies with Theory Group

- Jet quenching and partonic energy loss
- Hydrodynamic flow
- Correlation / fluctuation
- Heavy flavor
- Dileptons
- Spin

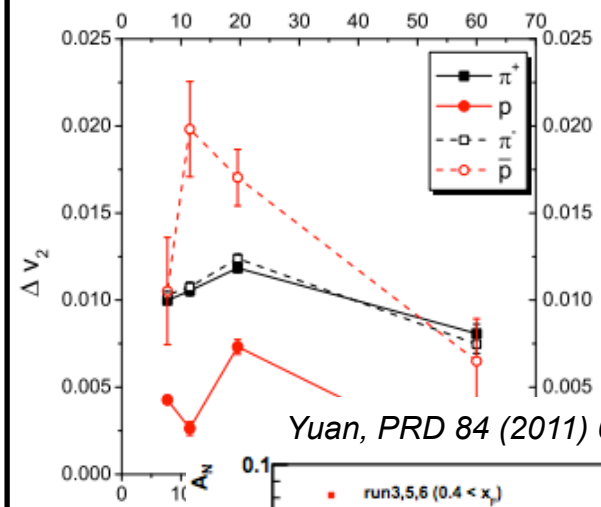
STAR, PRL 91 (2003) 172302



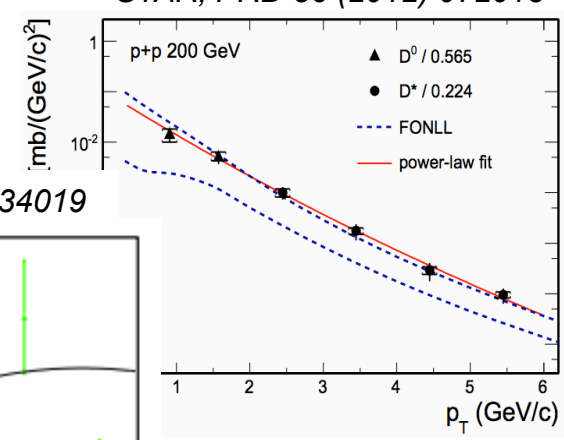
Song, PRL 106 (2011) 192301



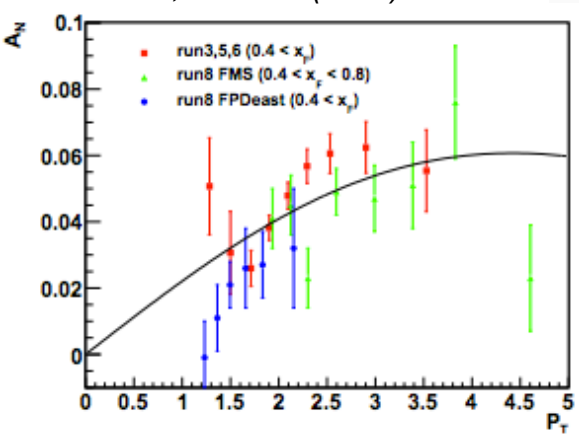
Steinheimer, arXiv: 1207.2791



STAR, PRD 86 (2012) 072013



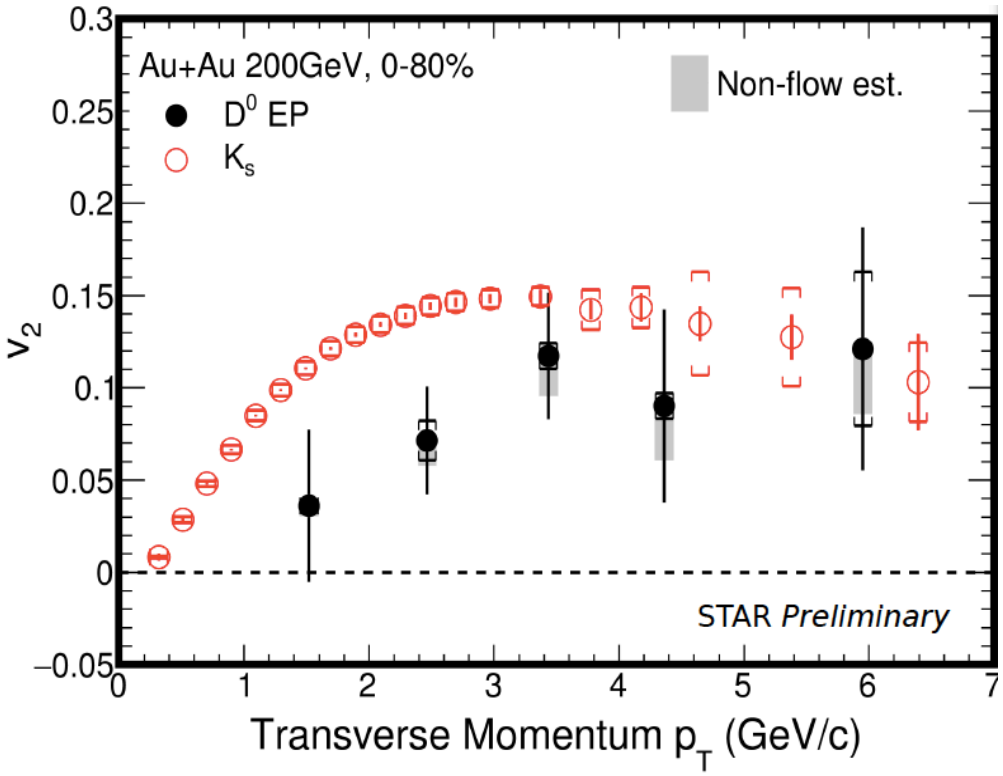
Yuan, PRD 84 (2011) 034019

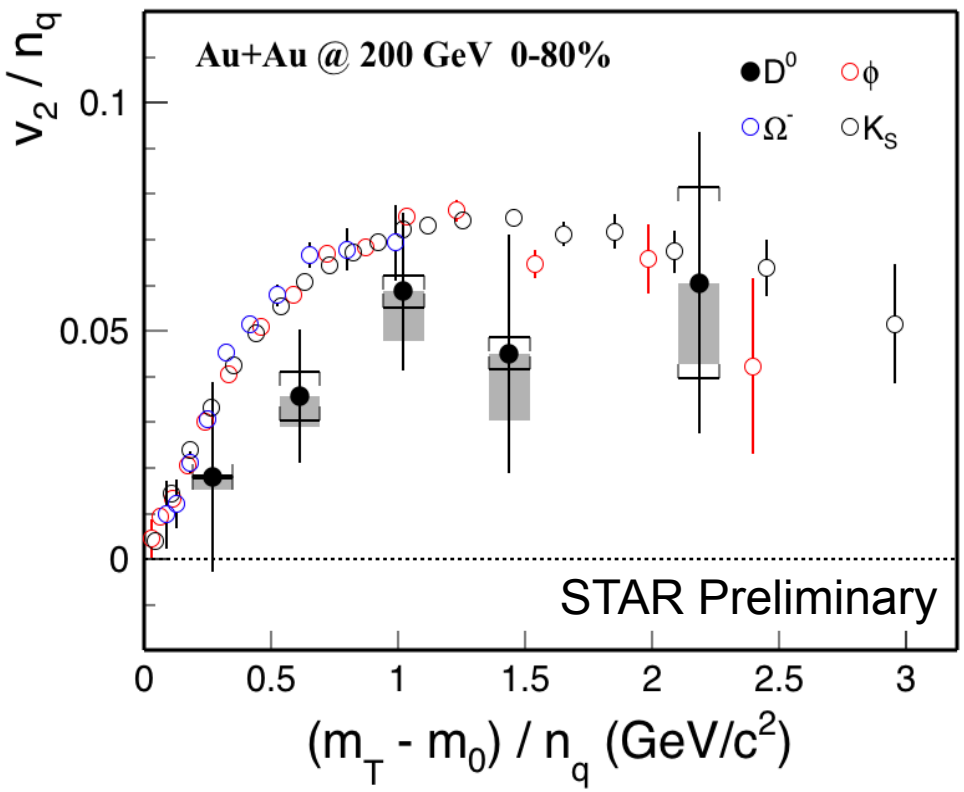


D-meson v_2 at RHIC

70% of 2014 Au+Au 200 GeV Data

M. Lomnitz, H. Qiu
QM2015



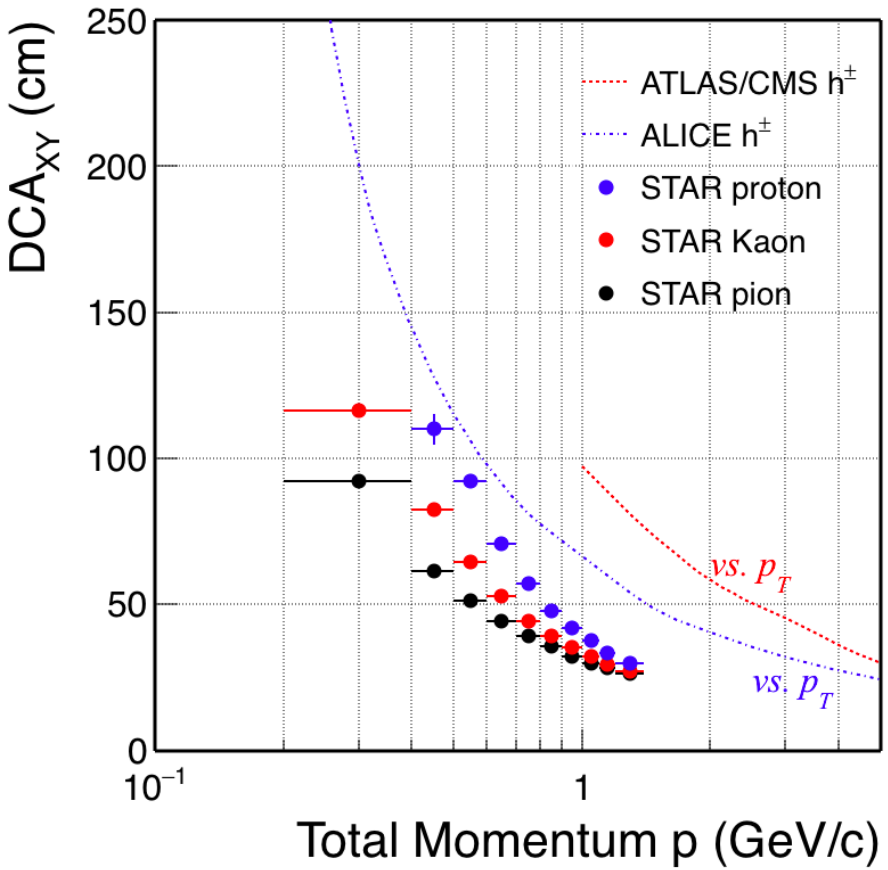


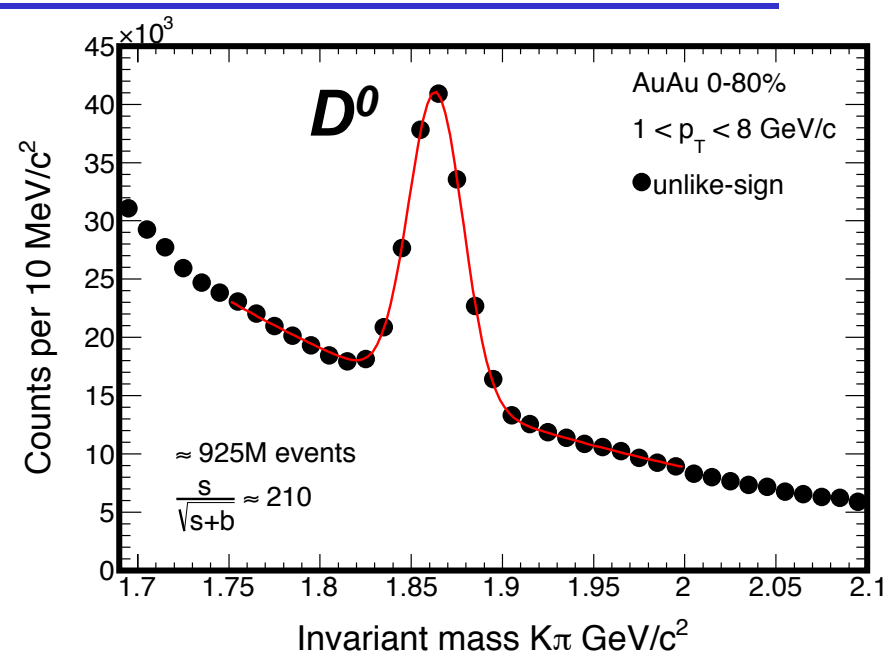
Significant charm hadron v_2 at p_T>2 GeV/c

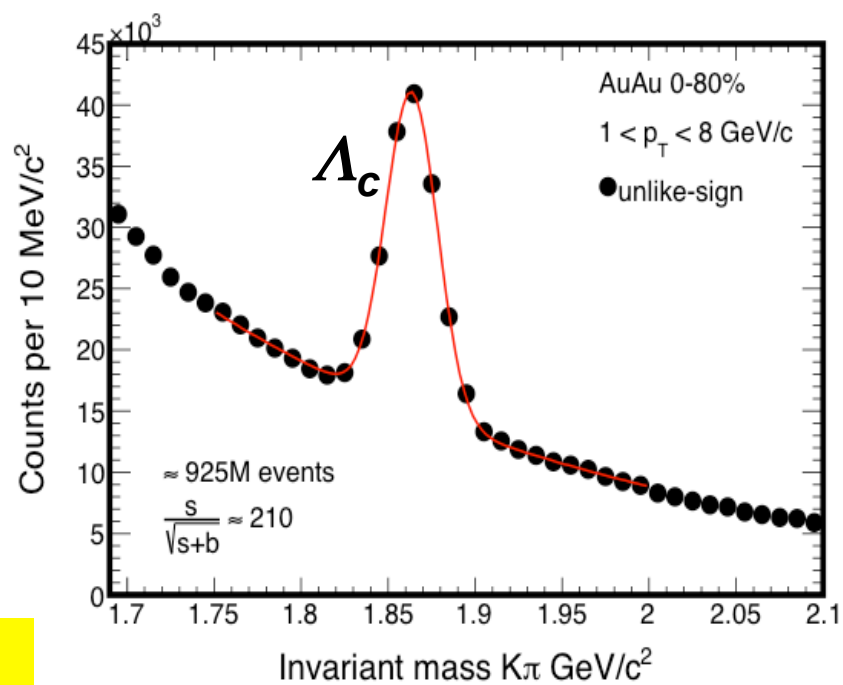
v_2/n_q vs. $(m_T-m_0)/n_q$: indication of D-meson lower than Ks, ϕ, Ω

- caveat: centrality bias (D ~ N_{bin} scaling, light hadrons ~ N_{part} scaling)

Heavy Flavor Tracker (HFT) Performance







See L. Greiner's Talk

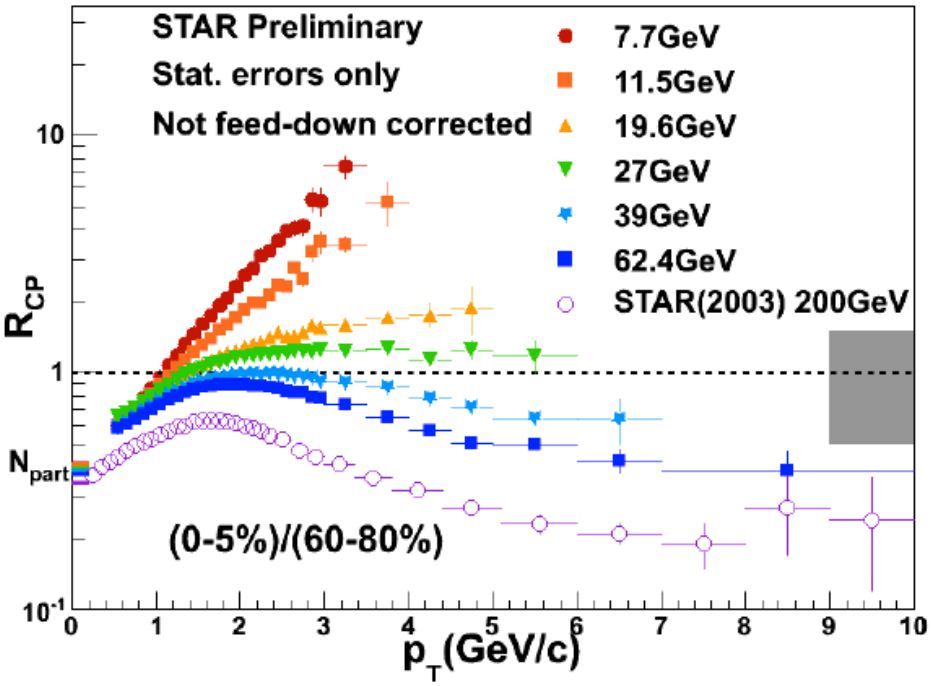
	2010/2011	2014 w/ HFT
D^0 significance per billion events	13	~220

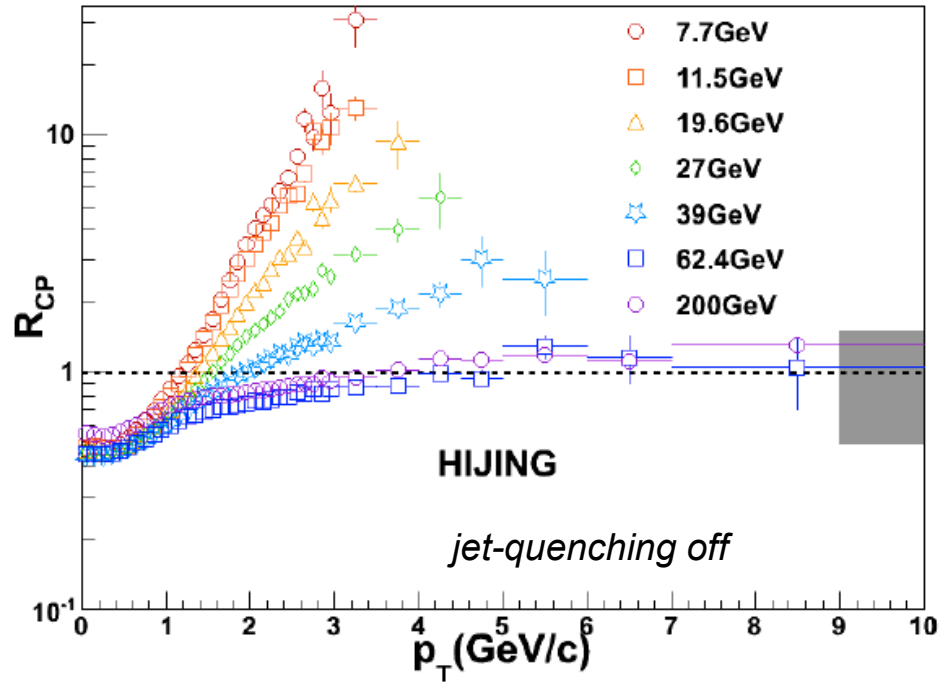
Michael Lomnitz, Mustafa Mustafa, Hao Qiu, *Guannan Xie*

R_{cp} of Charged Hadrons

STAR, QM 2012

$$R_{CP} = \frac{\left(dN/dp_T/N_{bin}\right)_{0-5\%}}{\left(dN/dp_T/N_{bin}\right)_{60-80\%}}$$





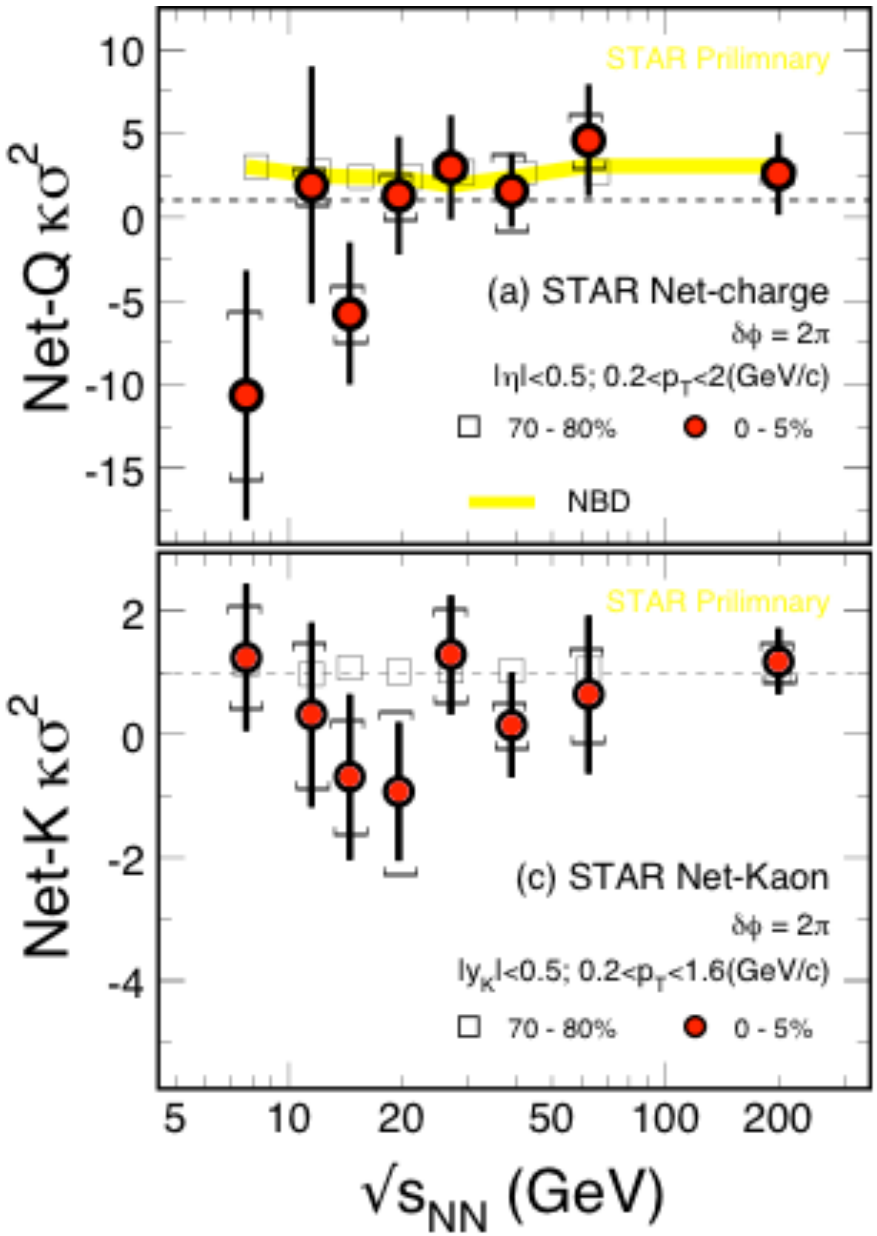
paper in collaboration review

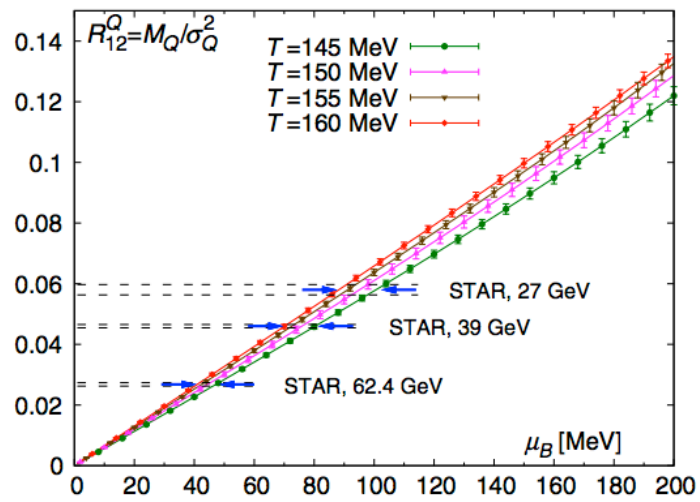
Evan Sangaline

- Significant change in the charged hadron R_{cp} at low energies
- Similar behavior in HIJING with no partonic energy loss at low energies
  - suppression at 200 GeV – partonic energy loss

Hadronic interactions play a significant role at $\sqrt{s_{NN}}$<= 11.5 GeV

High Moments of Net-Charge and Net-Kaon





WB group, PRL 111 (2013) 062005

High moments of conserved quantities (net-B, net-S, net-Q) – experimental

⬍

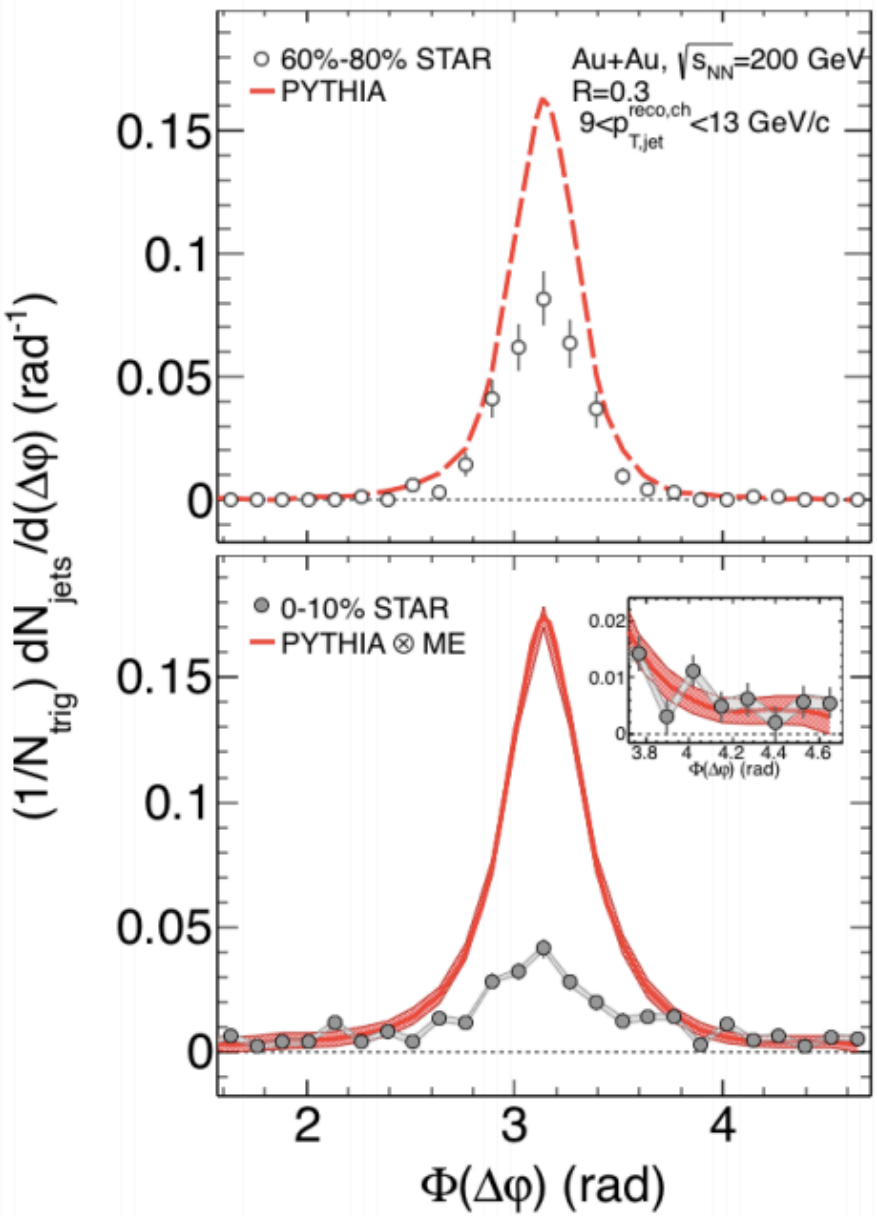
susceptibilities of thermdynamic quantities – calculable on Lattice QCD

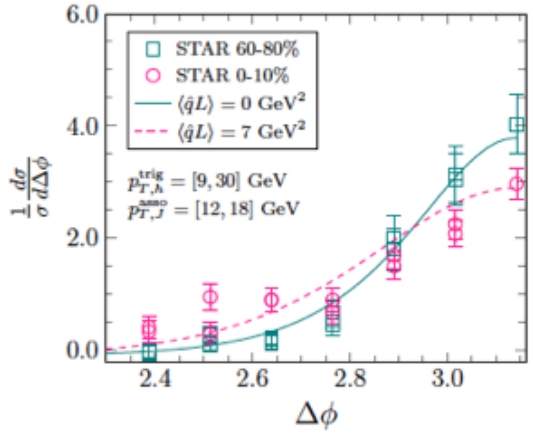
- Net-Q and Net-K $\kappa^*\sigma^2$ vs. energy show no significant deviation from Poisson expectations within current uncertainties

- Future BES-II improvements
  - higher statistics (machine upgrade)
  - higher efficiency, larger acceptance
    - iTPC, EPD upgrades

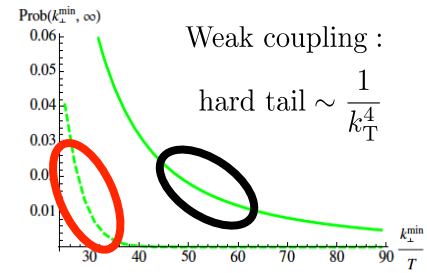
QM2015 Jochen Thaeder, *Ji Xu*

h-jet Δϕ Correlation Measurement





Chen et al., arXiv:1607.01932



Strong coupling:
Gaussian distribution

d'Eramo et al, JHEP 1305 (2013) 031

Away side modification - sensitive to <qhat*L>
Large angle Moliere scattering
- sensitive to weakly/strongly coupling nature
Low p_T jets have more sensitivity

- Broadening of away side peak in central heavy ion collisions

PYTHIA & 60-80%	0.24 ± 0.01
PYTHIA+ME(0-10%)	0.34
0-10% data	0.50 ± 0.05

- No clear evidence of large angle scattering with current uncertainties.

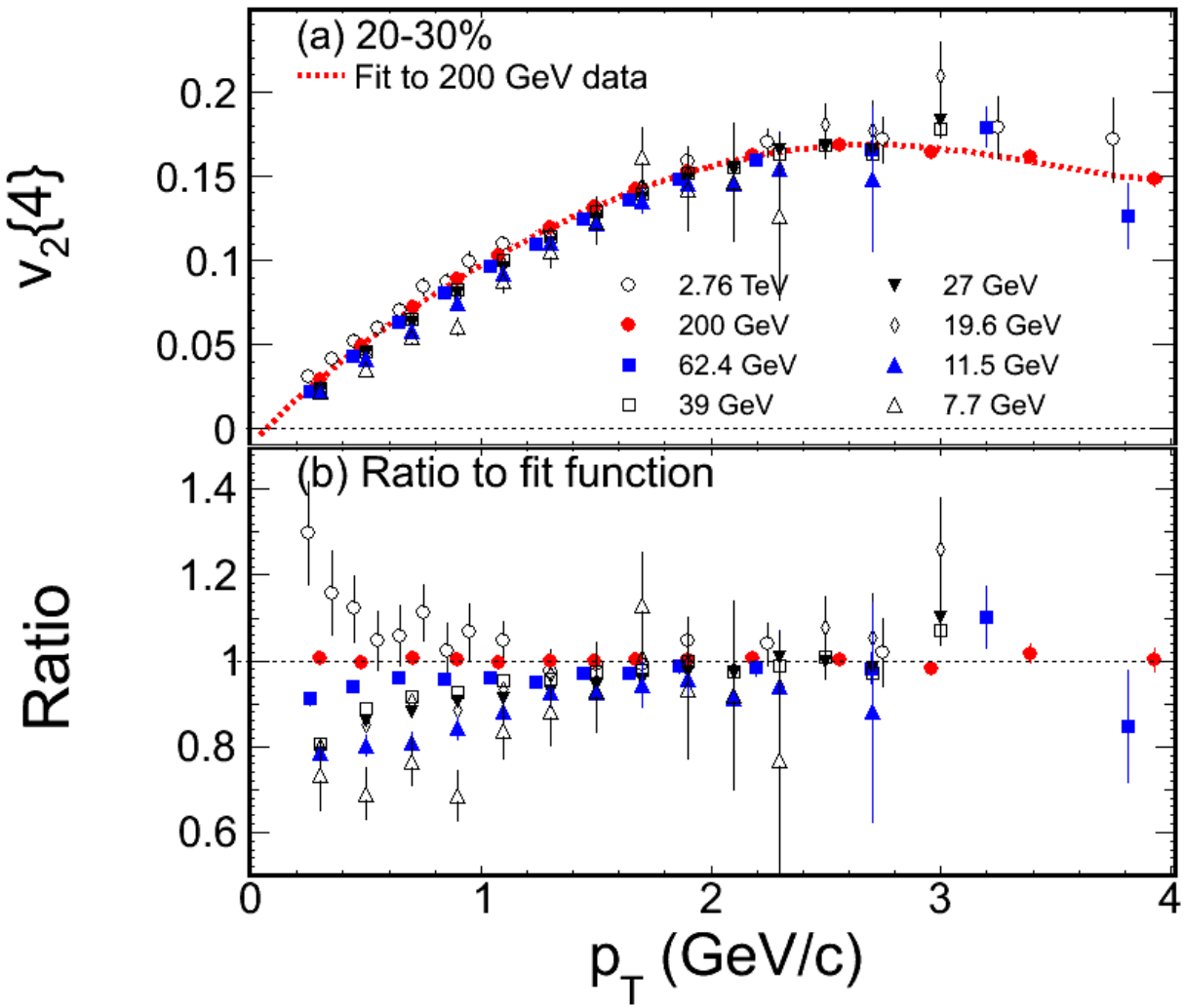
Papers in the collaboration
To be released soon

Alex Schmah

Inclusive Charged Hadron v_2

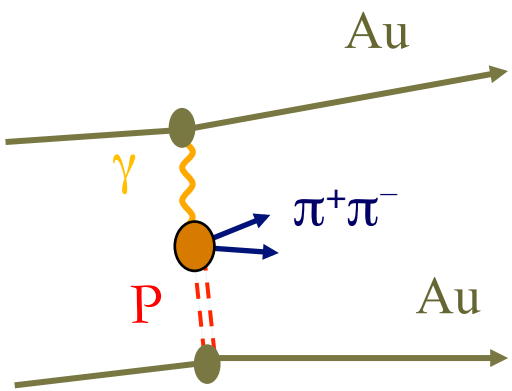
STAR, PRC 86 (2012) 054908

Hiroshi Masui, Alex Schmah, Shusu Shi



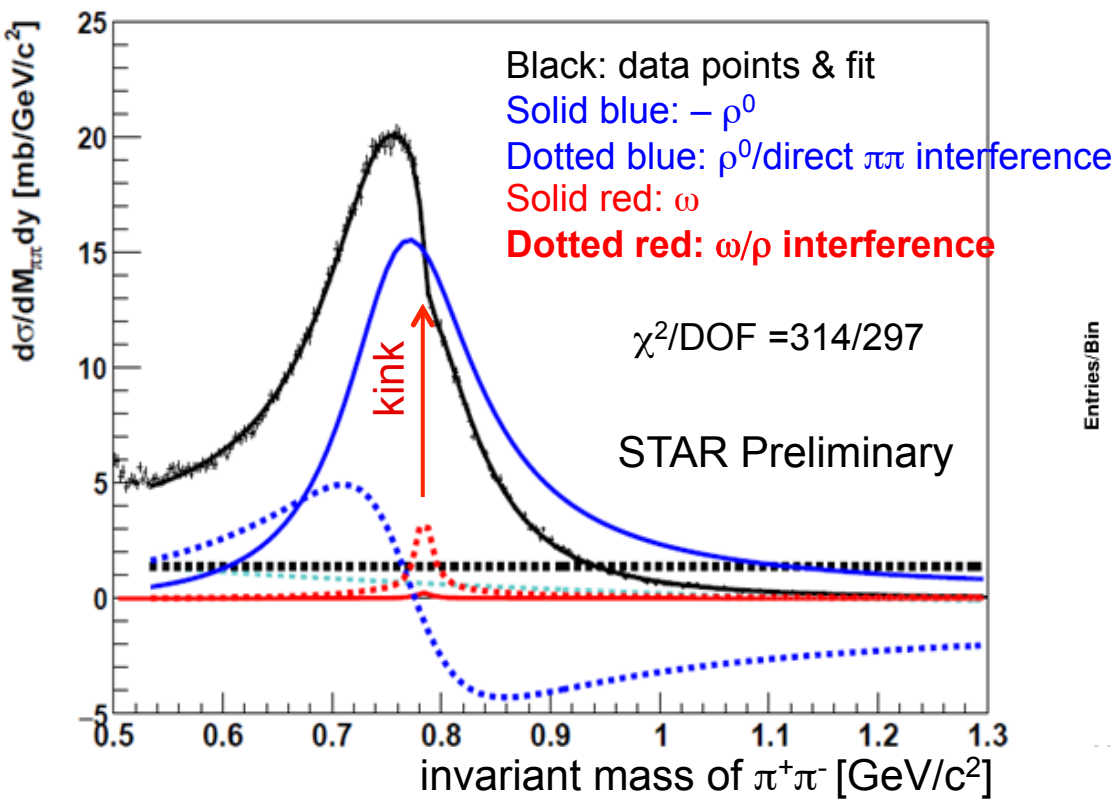
- Similar v_2 behavior over a wide energy range from 7.7 GeV – 2.76 TeV

Ultra-peripheral Photonuclear Collisions

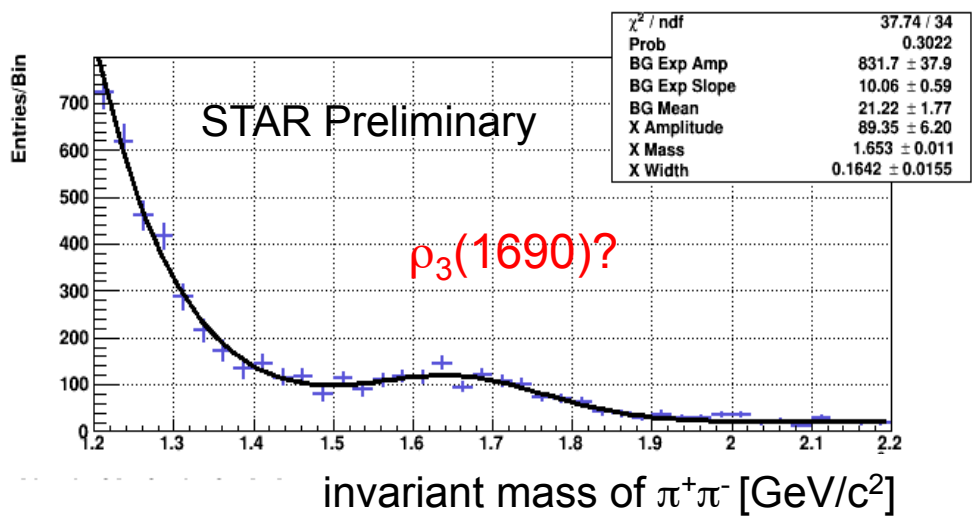


High statistics photoproduced $\pi^+\pi^-$ in UPC
- ρ^0, direct $\pi\pi$, ω
- ρ/ω interference
- ρ,ω magnitudes consistent with STARlight

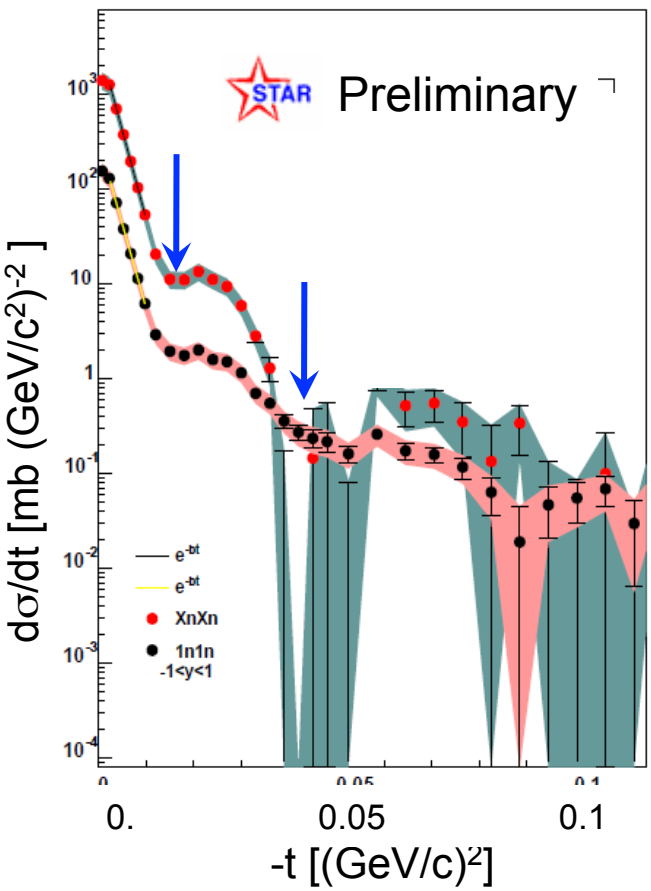
A clear high mass state
- consistent with $\rho_3(1690)$

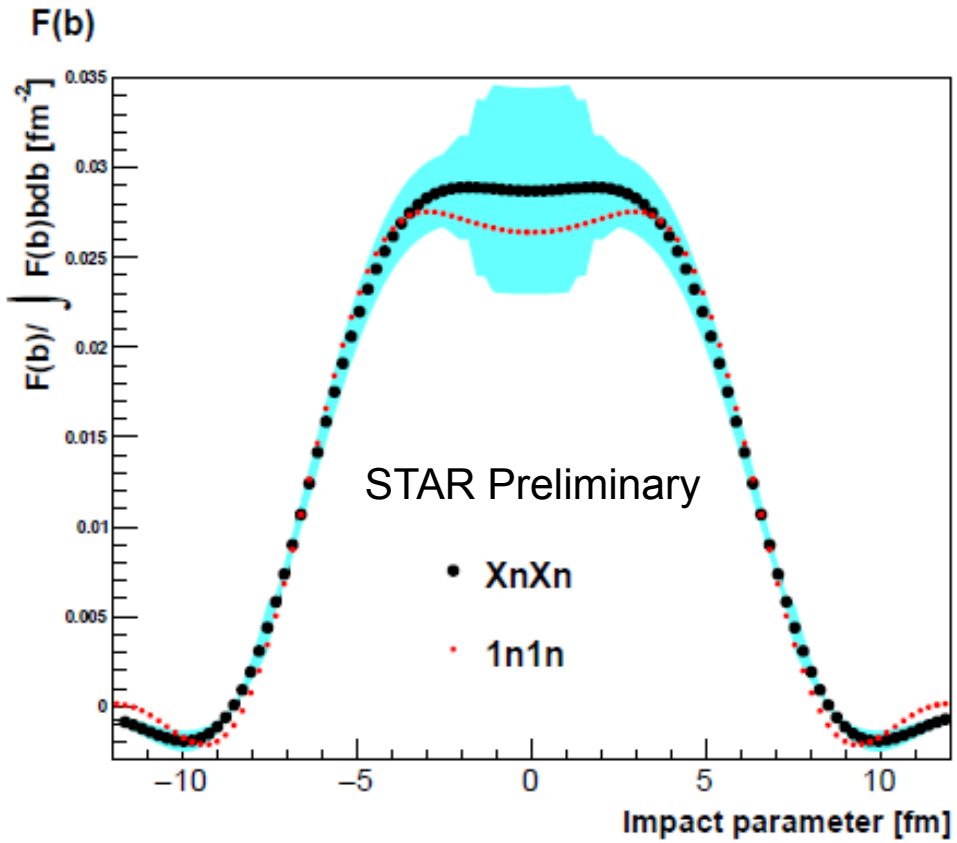


Papers in the collaboration
To be released soon



Coherent Production and "Imaging" the Nucleus





- Multiple diffraction dips visible
  - expected as nucleus approaches "black disk"
- 2-d Fourier transformation $F(b) \propto \frac{1}{2\pi}\int_0^\infty dp_T\, p_T\, J_0(bp_T)\sqrt{\frac{d\sigma}{dt}}$

  FWHM = 2 * (6.17 ± 0.12) fm
- Lead-in physics in future EIC experiments

STAR Physics Focus in Future

2014	2015	2016	2017	2018	2019	2020	2021+
BES-I					BES-II ($\sqrt{s_{NN}} \leq 20$GeV)		
HFT: Open charm/Dileptons							HFT+
			Spin	Chirality			pp/pA

Precision measurements on HF and dileptons:
Quantify the sQGP properties (hot QCD)

Precision measurements on focused energies
Map out the QCD phase structure

Precision measurements on pp and pA
Study QCD in cold matter