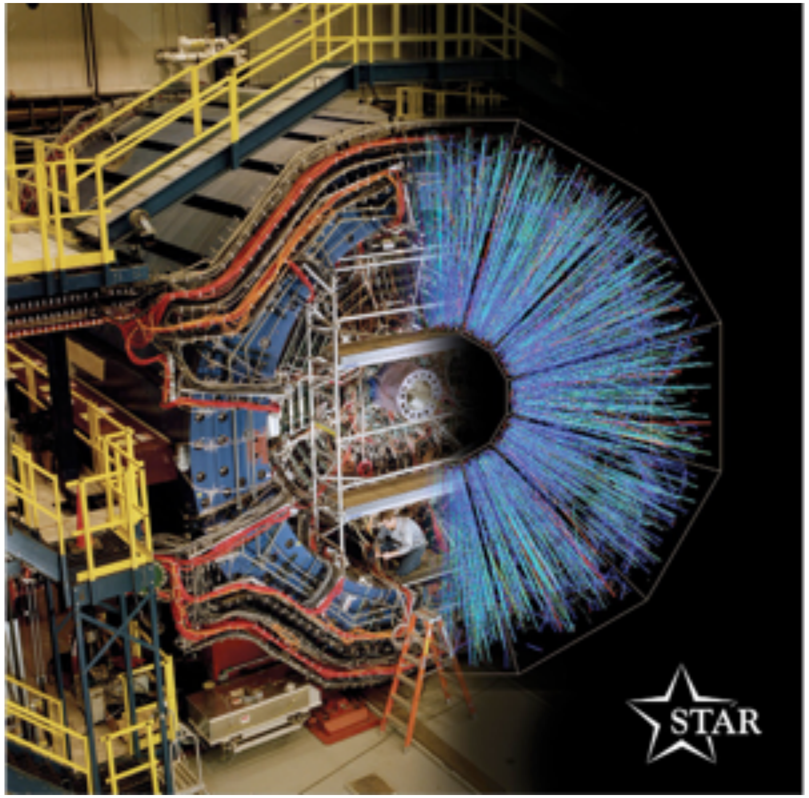
Probing the Initial Stages with STAR



All truth passes through three stages.
First, it is ridiculed.
Second, it is violently opposed.
Third, it is accepted as being self-evident.

- Arthur Schopenhauer (1788-1860)

Helen Caines - Yale University

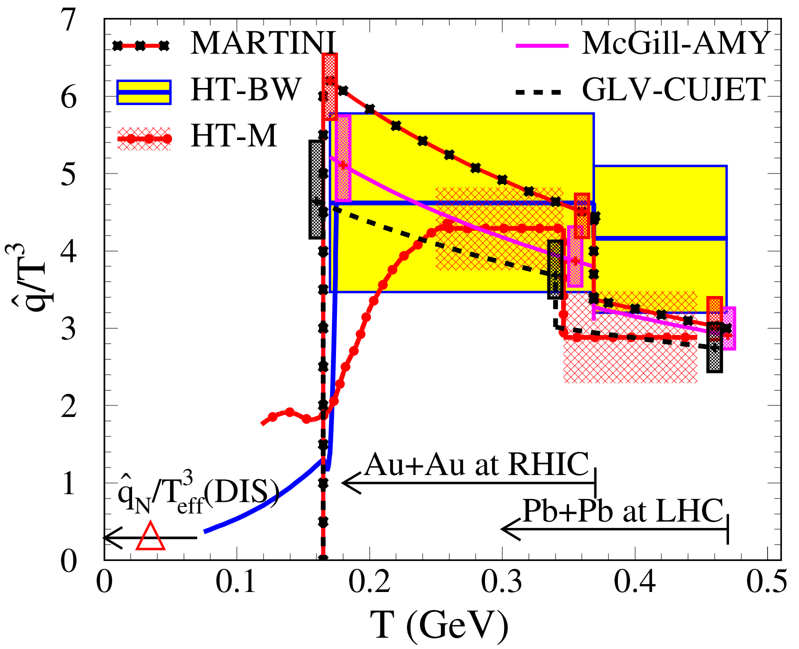
The 2nd International Conference on
the Initial Stages in High-Energy
Nuclear Collisions
Nappa Valley, Dec 3rd-7th 2014

RHIC/LHC complimentarity

Why should I care about RHIC now there's LHC?

Different initial conditions and evolutionary paths:

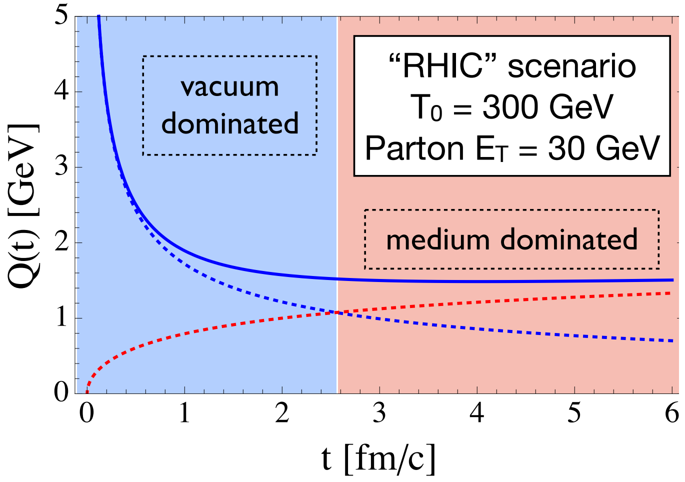
$$\hat{q} \sim \begin{matrix} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{matrix}\ \mathrm{GeV^2/fm}\quad \begin{matrix} T=370\ \mathrm{MeV} \\ T=470\ \mathrm{MeV} \end{matrix}$$

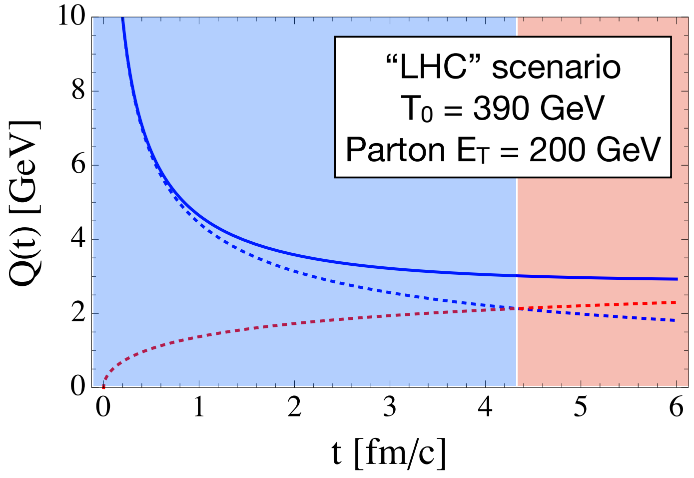


RHIC probes may behave differently to LHC probes and be in "different" medium

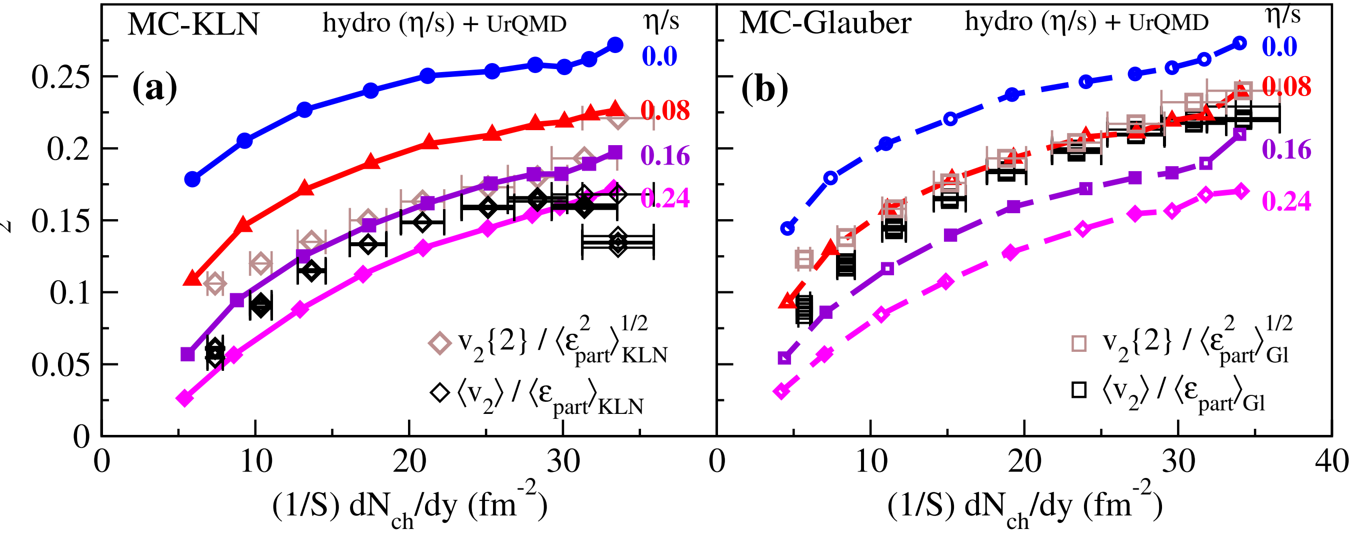
Different virtuality evolutions:

How/when does parton become "aware" of medium





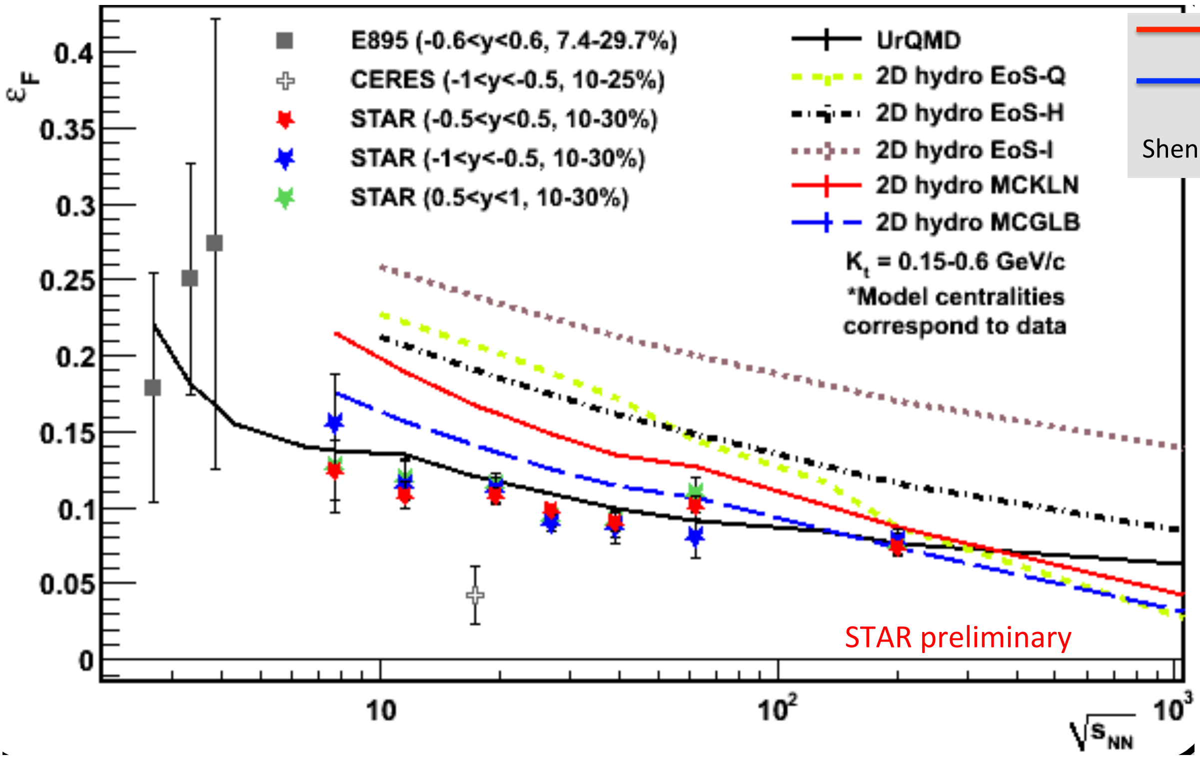
Initial conditions via v_n and HBT



Song et al. PRL 106 192301 (2011)

$$\frac{\eta}{s} = 0.08 \rightarrow 0.2$$

Details of initial configuration large source of uncertainty



MC-KLN η/s = 0.2

MC-Glauber η/s = 0.08

Shen and Heinz (PRC85 054902 (2012))

Reveals spatial anisotropy
after expansion

Azimuthal coordinate space measurement breaks degeneracy from azimuthal momentum space

Ultra-central geometry fluctuations

Fri: H. Wang

Probe correlation of multiplicity and v_n in very central ZDC selected data

v_3:

Au+Au and U+U:

Slope zero or slightly positive

Fluctuations dominate

v_2:

Au+Au:

Slope zero or slightly positive

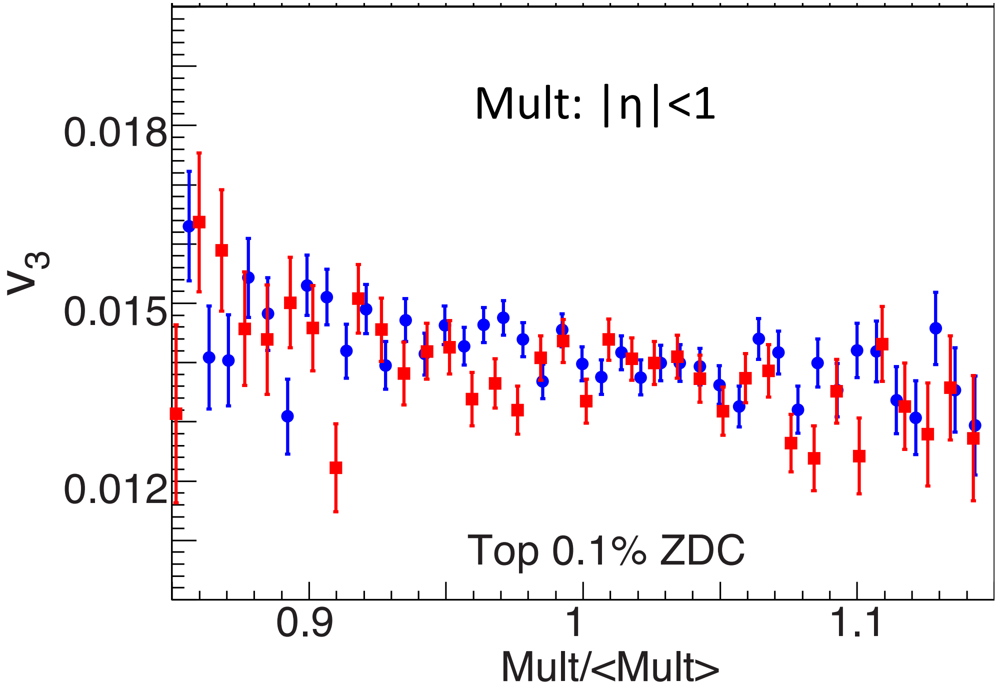
Fluctuations dominate

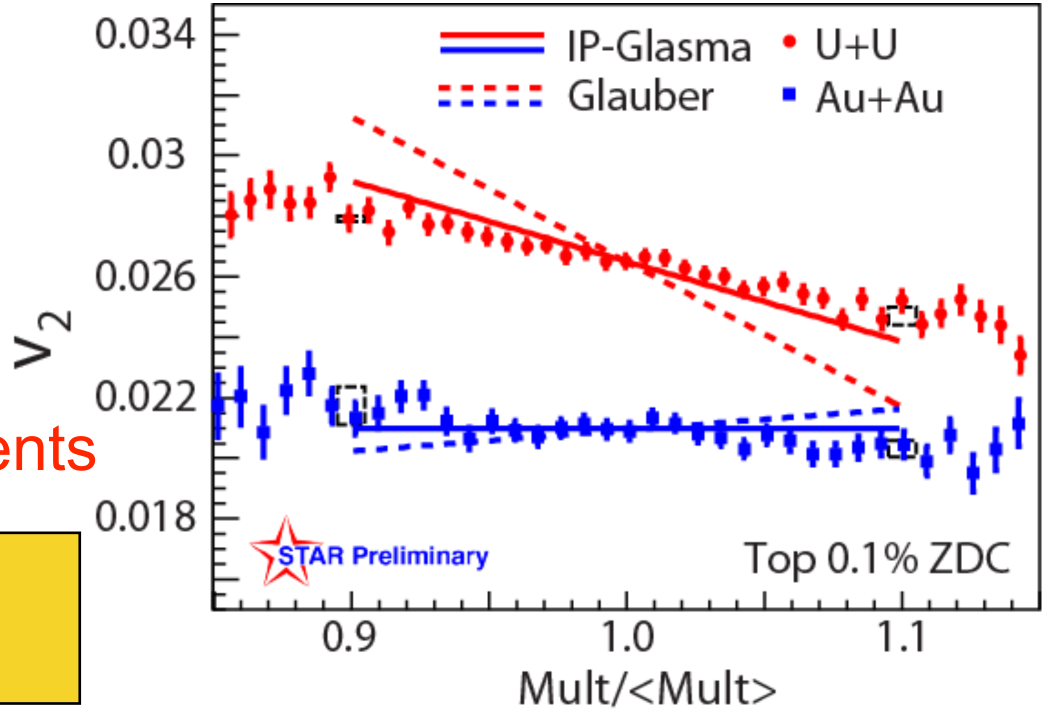
U+U:

Slope negative

Geometry also matters

Select tip-tip in high mult. events





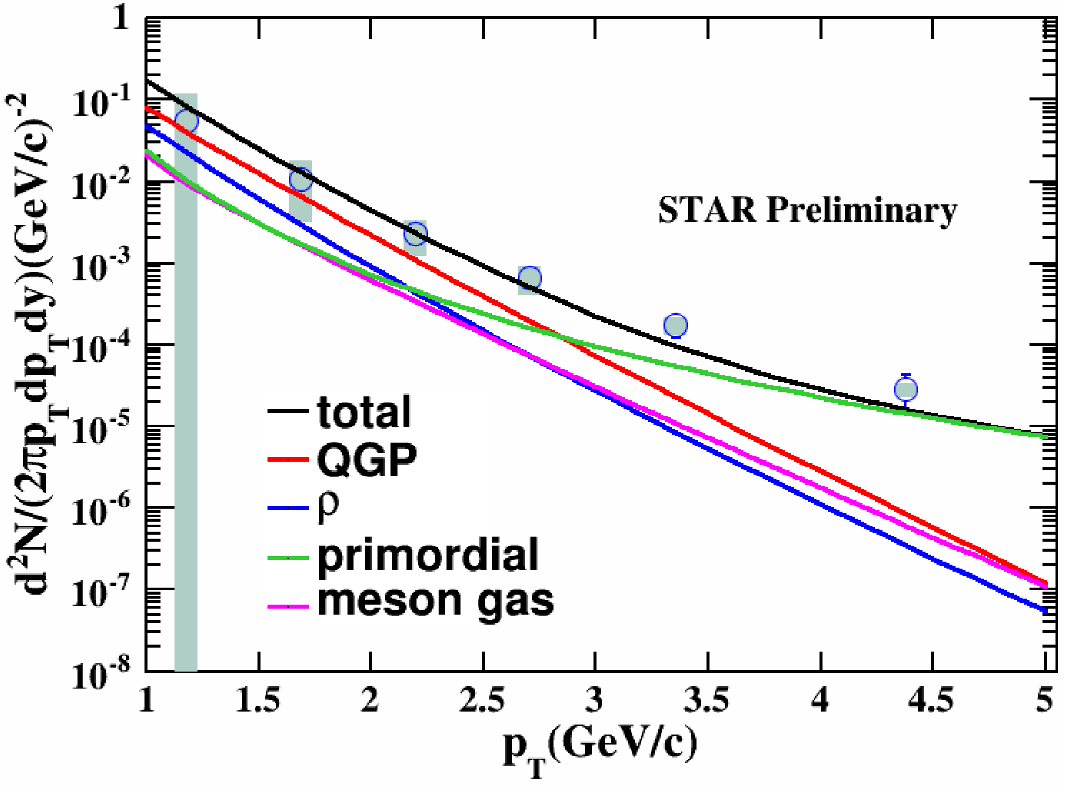
U+U very sensitive to Initial State
IP-Glasma better match to the data

Di-electrons & Direct Virtual Photons

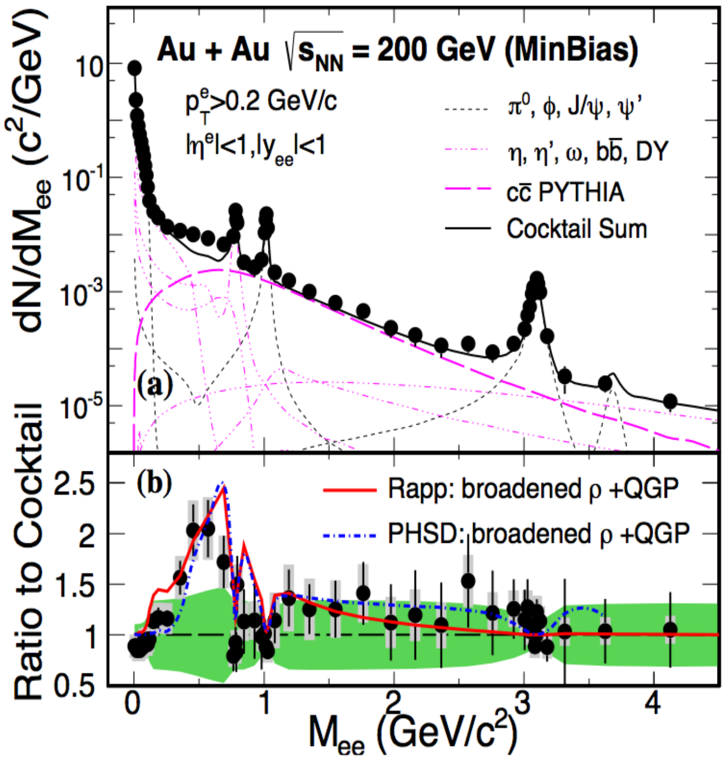
Fri: C. Yang

Rapp model prediction[3] including QGP, ρ, primordial and meson gas in good agreement with data

T = 320 MeV at 0.36 fm/c fireball lifetime ~10 fm/c



Phys. Rev. Lett. 113 (2014) 22301



Enhancement in ρ-like region

1.77 ± 0.11 (stat) ± 0.24 (sys) ± 0.33 (cocktail)

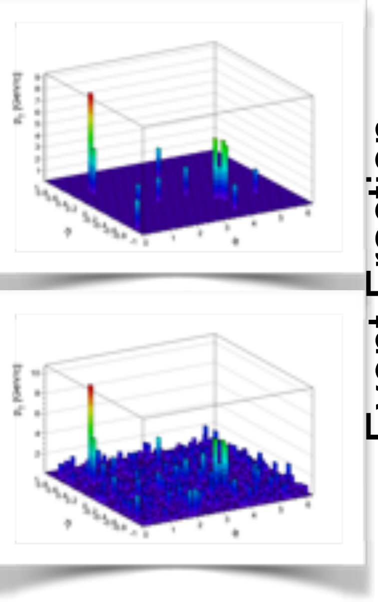
Broadened ρ models can explain data

Rapp[1]: Effective many-body model

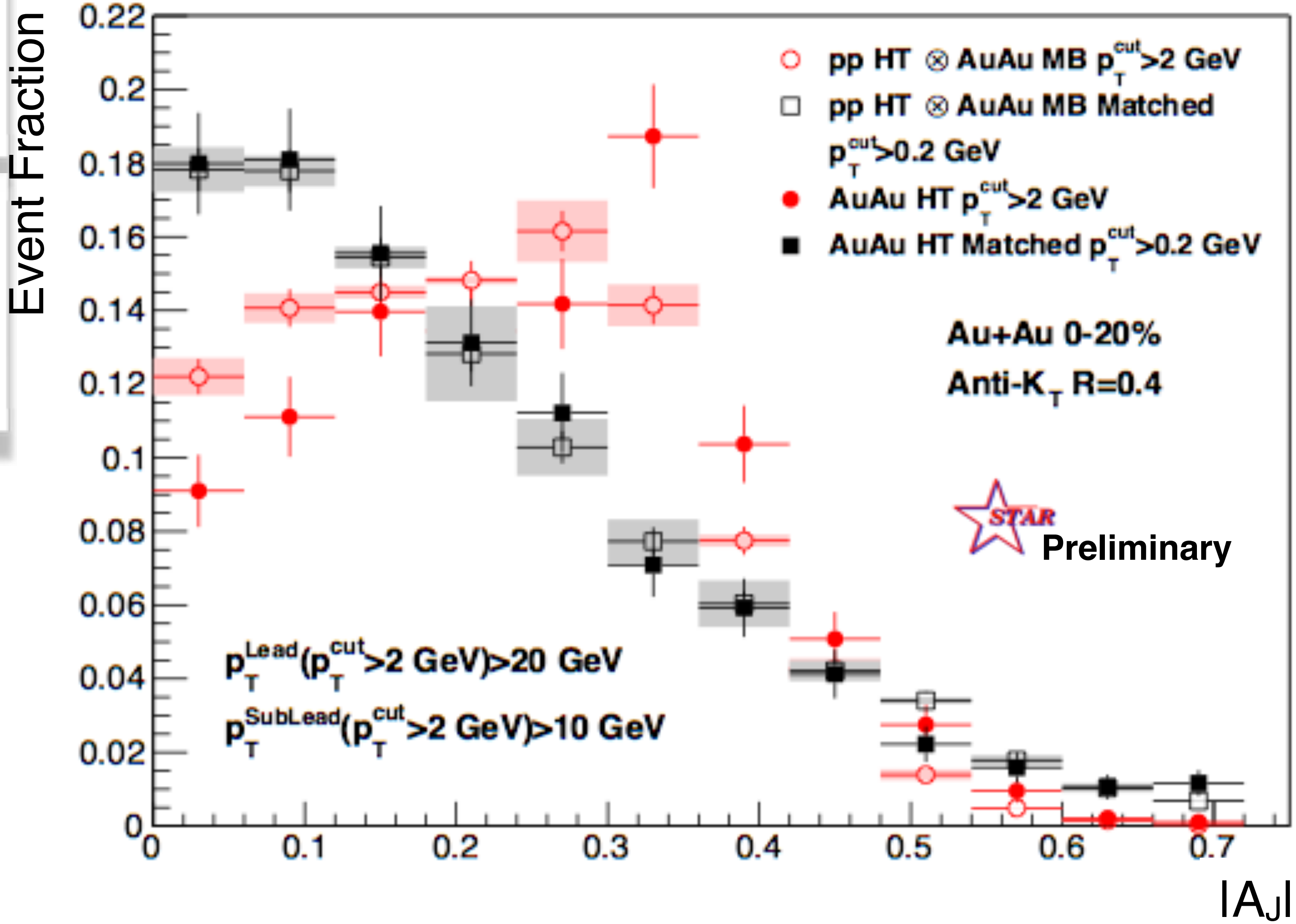
PHSD[2]: Parton-Hadron string dynamics

1:R.Rapp PoS CPOD2013, 008 (2013)
2: O.Linnyk et al. Phys. Rev. C 85, 024910 (2012)
3: Van Hees,Gale and Rapp, Phys. Rev. C 84, 054906

Di-jet imbalance A_J Au+Au 0-20% R=0.4



Anti-k_T R=0.4, $p_{T,1}$>20 GeV & $p_{T,2}$>10 GeV with p_T^{cut}>2 GeV/c



p-value<10^{-5}
(stat. error only)

p-value~0.8
(stat. error only)

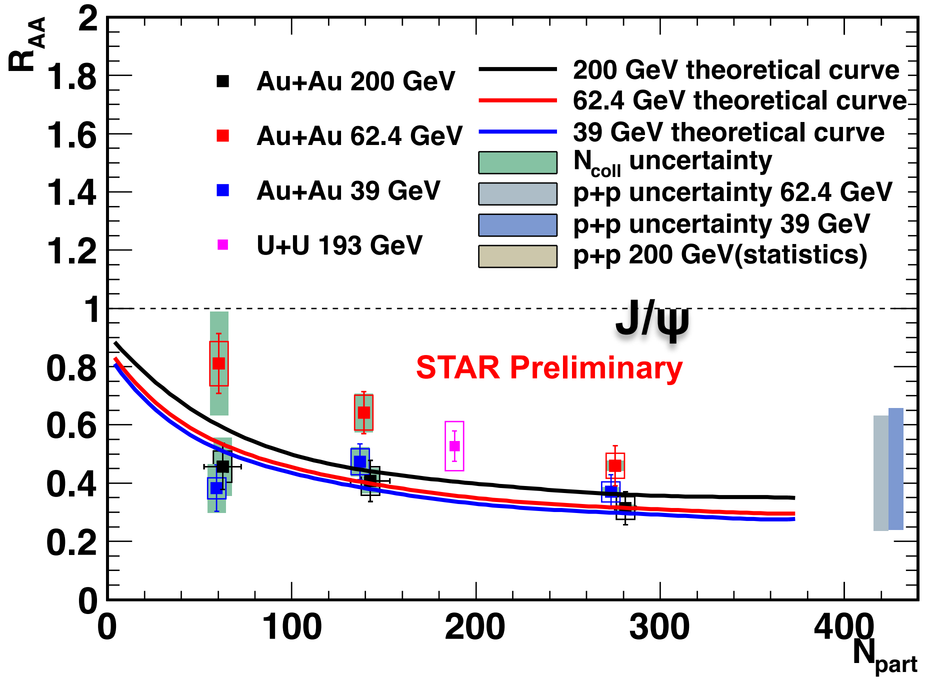
Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

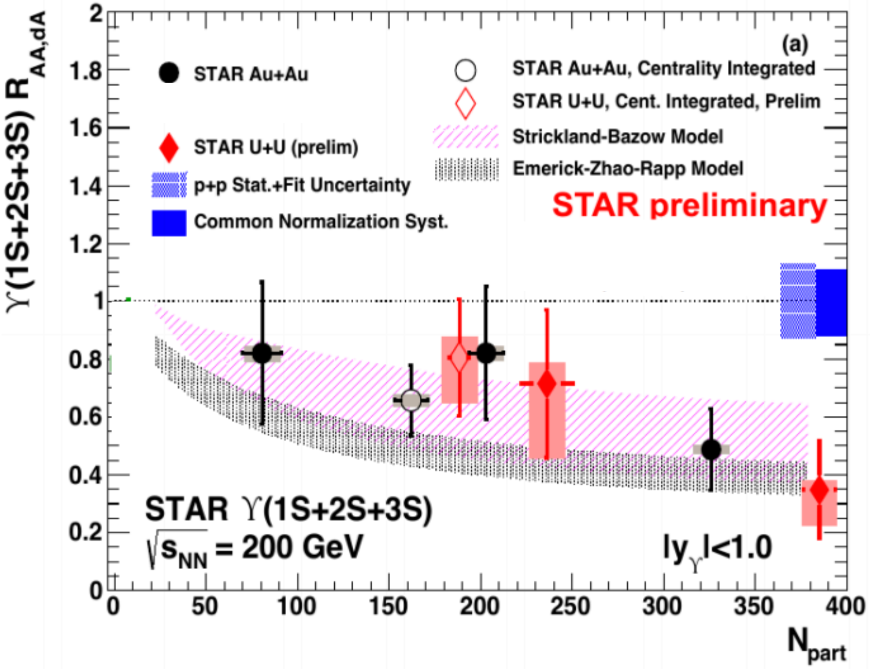
Au+Au di-jets more imbalanced than p+p for p_T^{cut}>2 GeV/c

Au+Au A_J ~ p+p A_J for matched di-jets R=0.4 (Not true when R = 0.2)

Different behavior to LHC?
but different jet p_T and biases

Quarkonia suppression in A+A



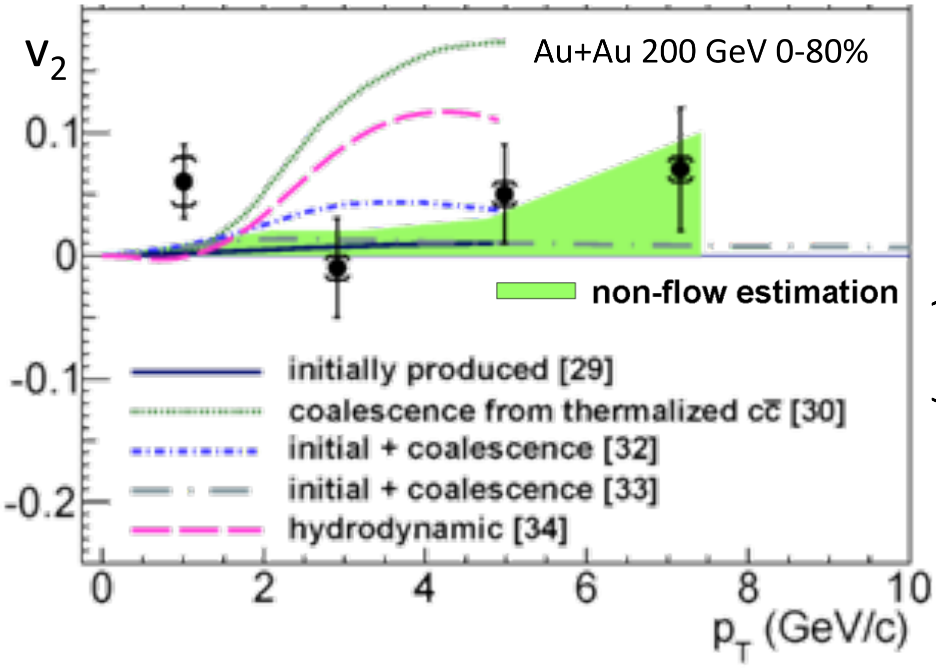


Similar suppression in U+U and Au+Au

Weak beam energy dependence
Some centrality dependence

v_2 consistent with no flow

Disfavors production from thermalized charm



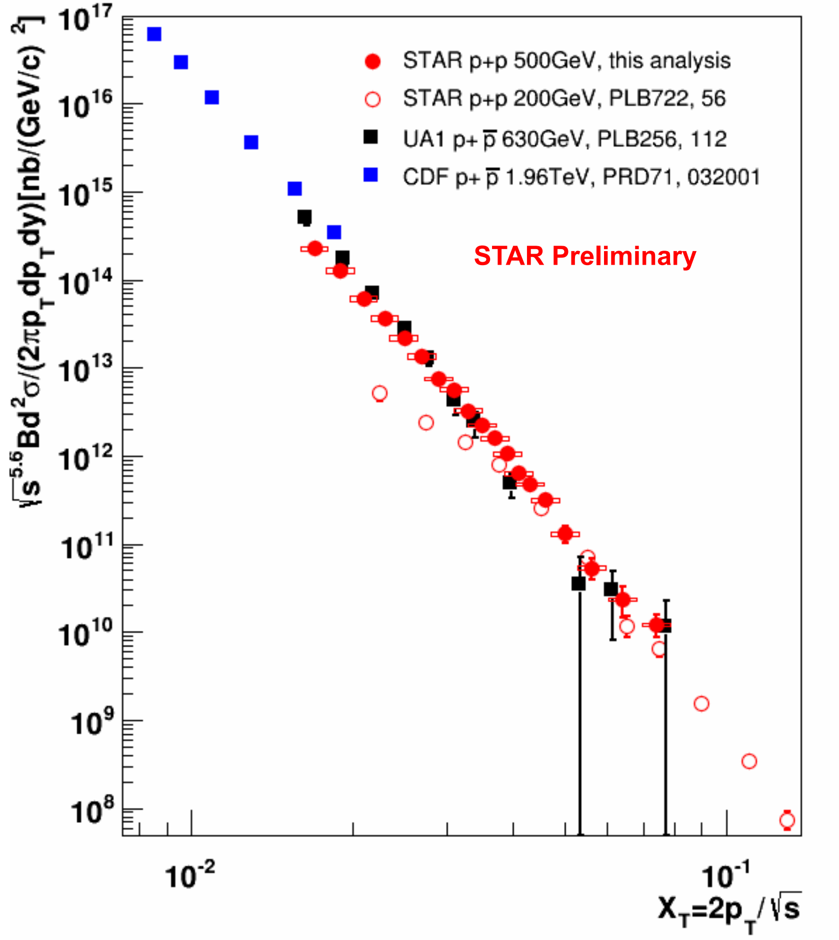
PRL 111 52301 (2013)

J/Ψ in p+p and d+Au

J/Ψ in p+p exhibits x_T scaling

for p_T>4 GeV/c, n=5.6

Including new 500 GeV data

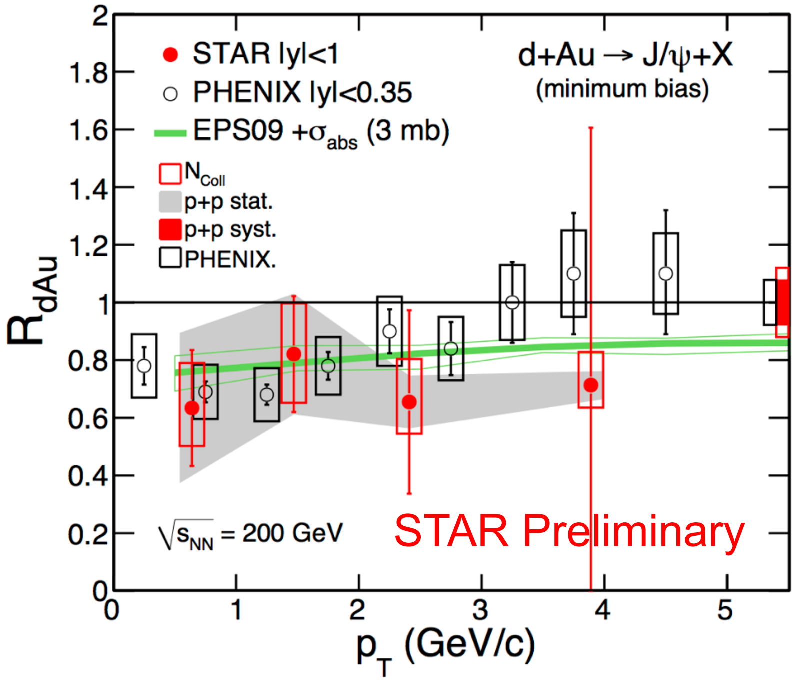


At 200 GeV:

prompt NLO CS+CO describes data

prompt CEM describes data at high p_T

direct NNLO CS under-predicts high p_T



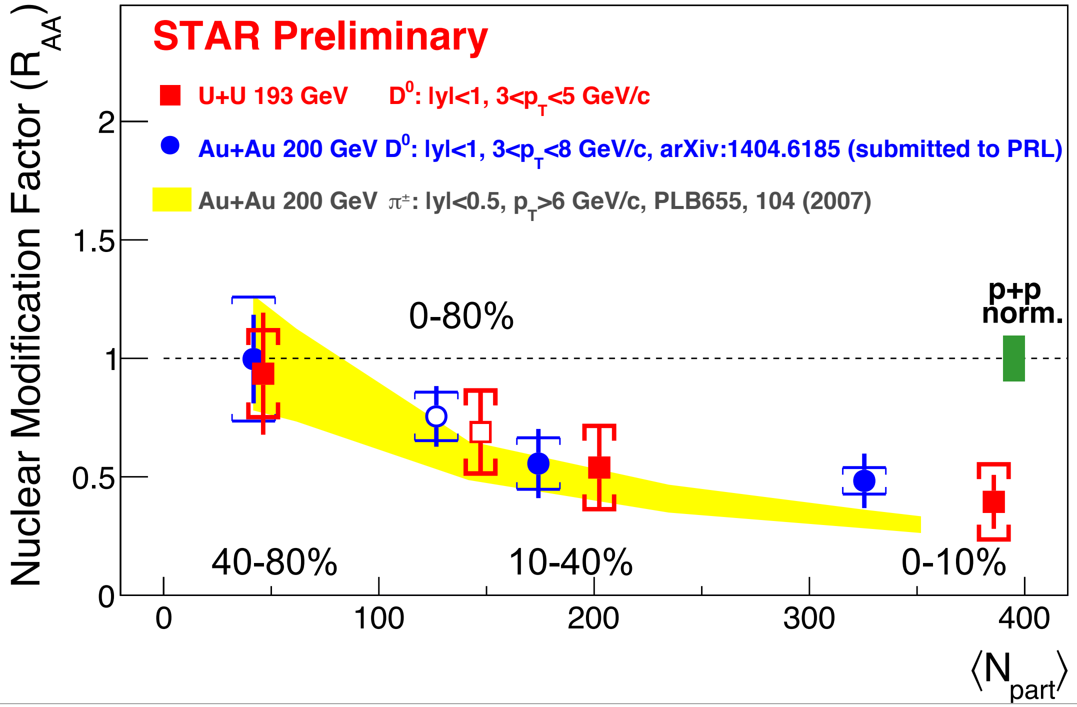
R_{dAu} consistent with model calculations

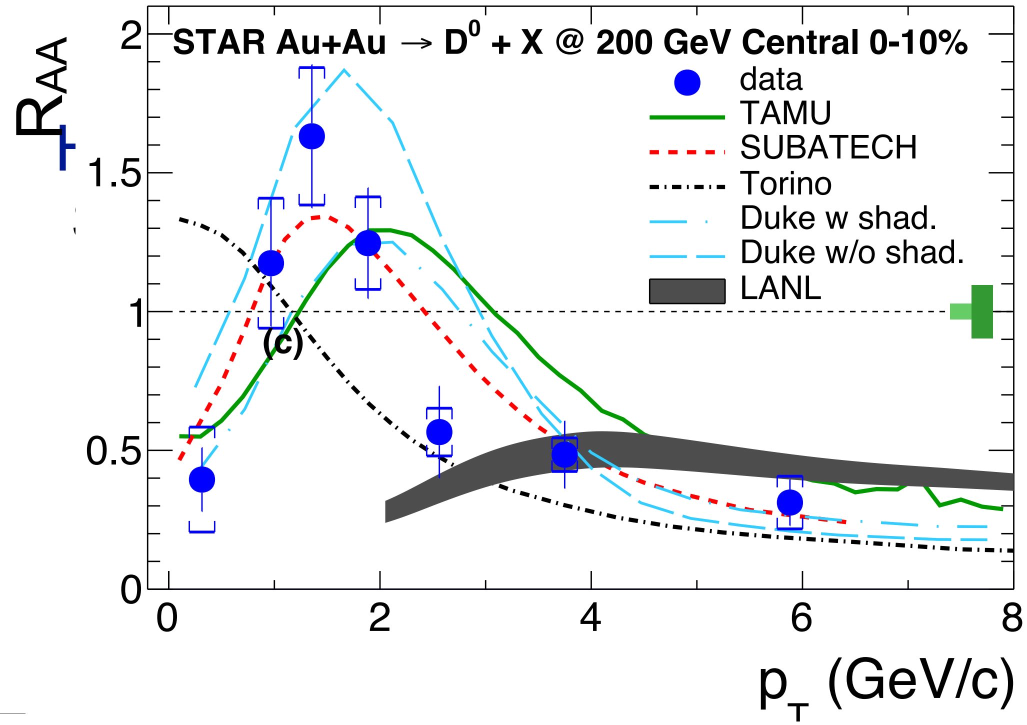
shadowing from EPS09 nPDF

nuclear absorption $\sigma_{abs}^{J/\Psi}$ ~ 3mb

Eskola et al. Nucl. Phys A 830, 599 (2009)

Direct charm suppression





Low p_T enhancement

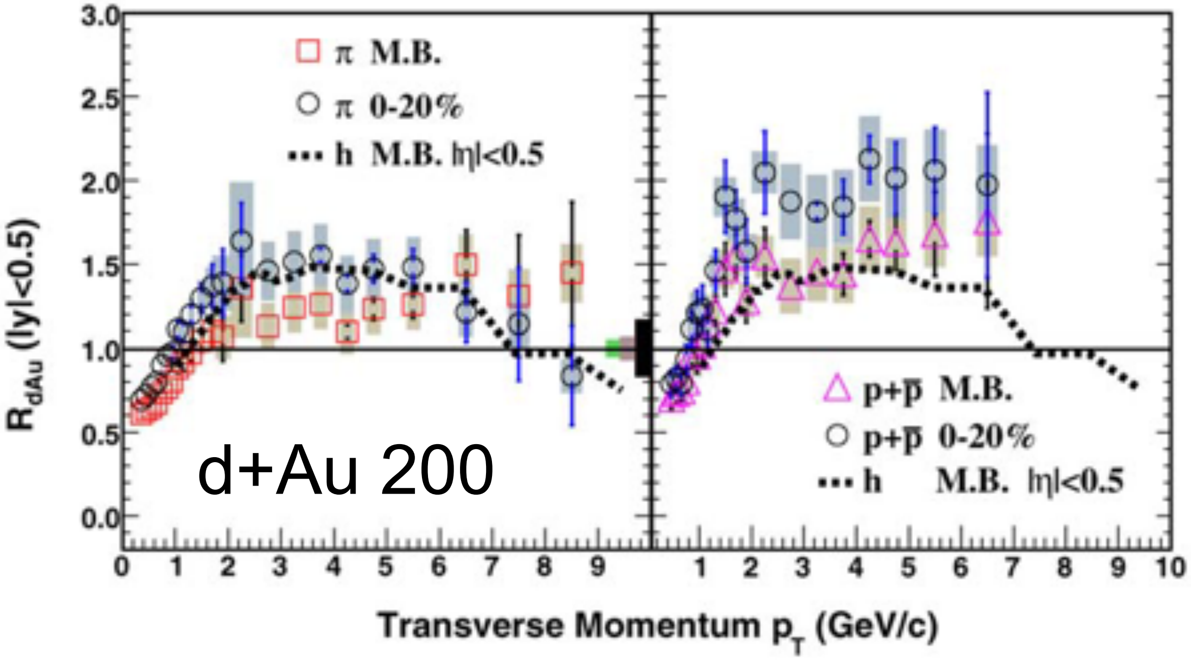
Described by models including coalescence of charm quarks

flow and/or shadowing?

CNM effects could be important

	TAMU	SUBATECH	Torino	Duke	LANL
HQ prod.	LO	FNOLL	NLO	LO	LO
QGP-Hydro	ideal	ideal	viscous	viscous	ideal
HQ eLoss	coll.	coll. +rad.	coll. +rad.	coll. +rad.	diss. +rad.
Coalescence	Yes	Yes	No	Yes	No
Cronin effect	Yes	Yes	No	No	Yes
Shadowing	No	No	Yes	Yes/No	Yes

Cronin at lower energies/smaller systems

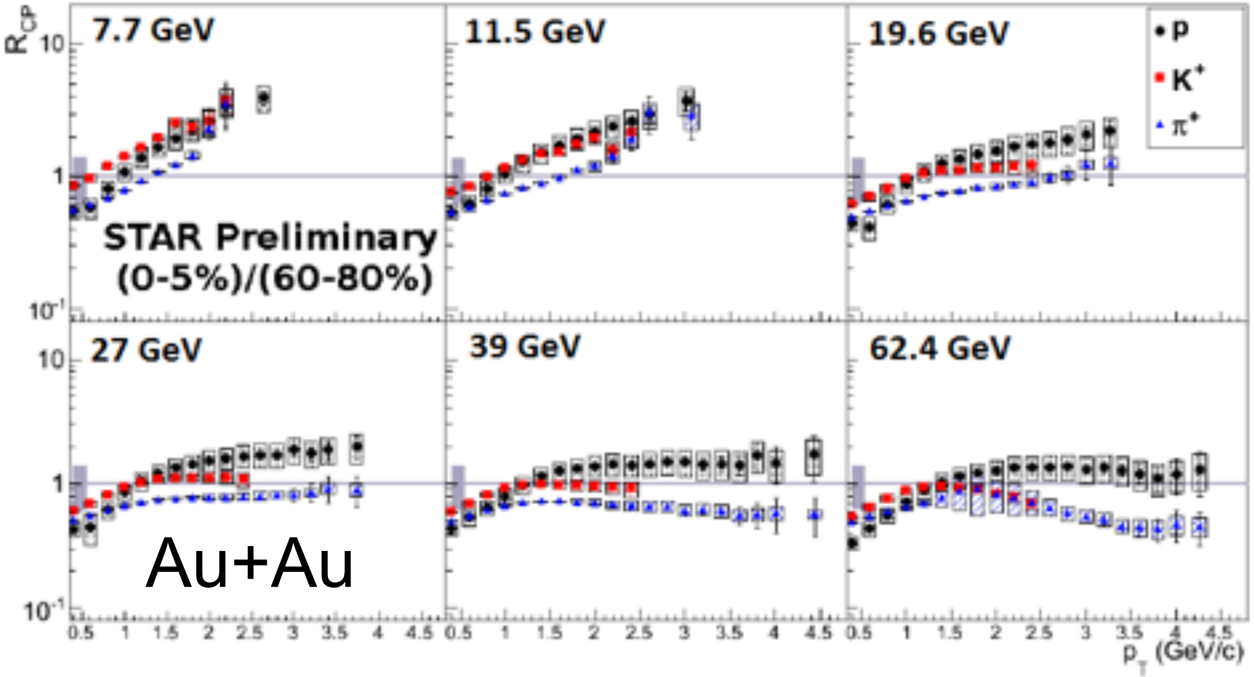


Species dependent effect seen as in original Cronin data

$R_{cp}^{p} > R_{cp}^{K} > R_{cp}^{\pi}$

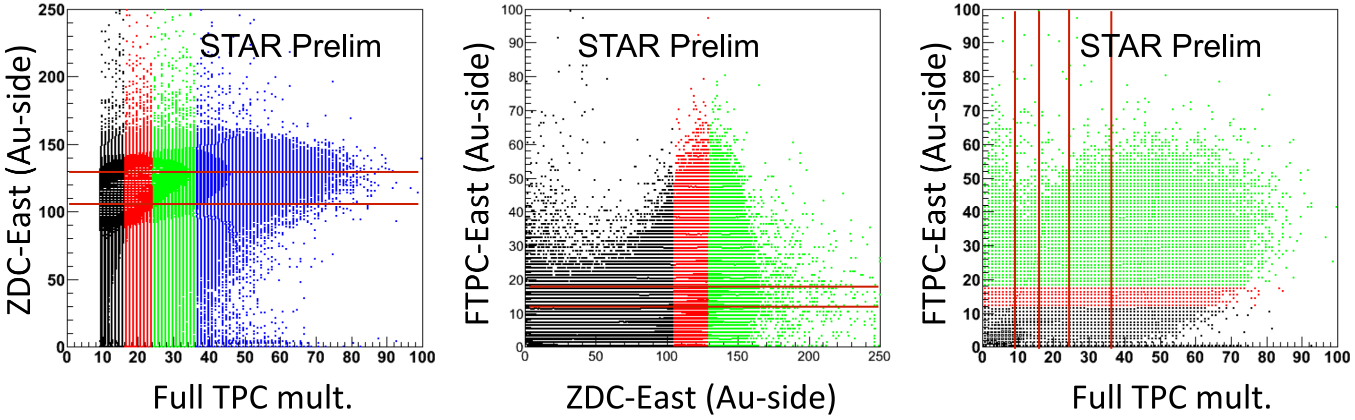
Compare:

d+Au √s=200		Au+Au √s=27
R_{dAu}	~	R_{cp}
$<p_T>$	~	$<p_T>$
μ_B	<	μ_B
dN/dy	<	dN/dy
$dN/dy/N_{part}$	>	dN/dy_{part}



Flow in both systems?

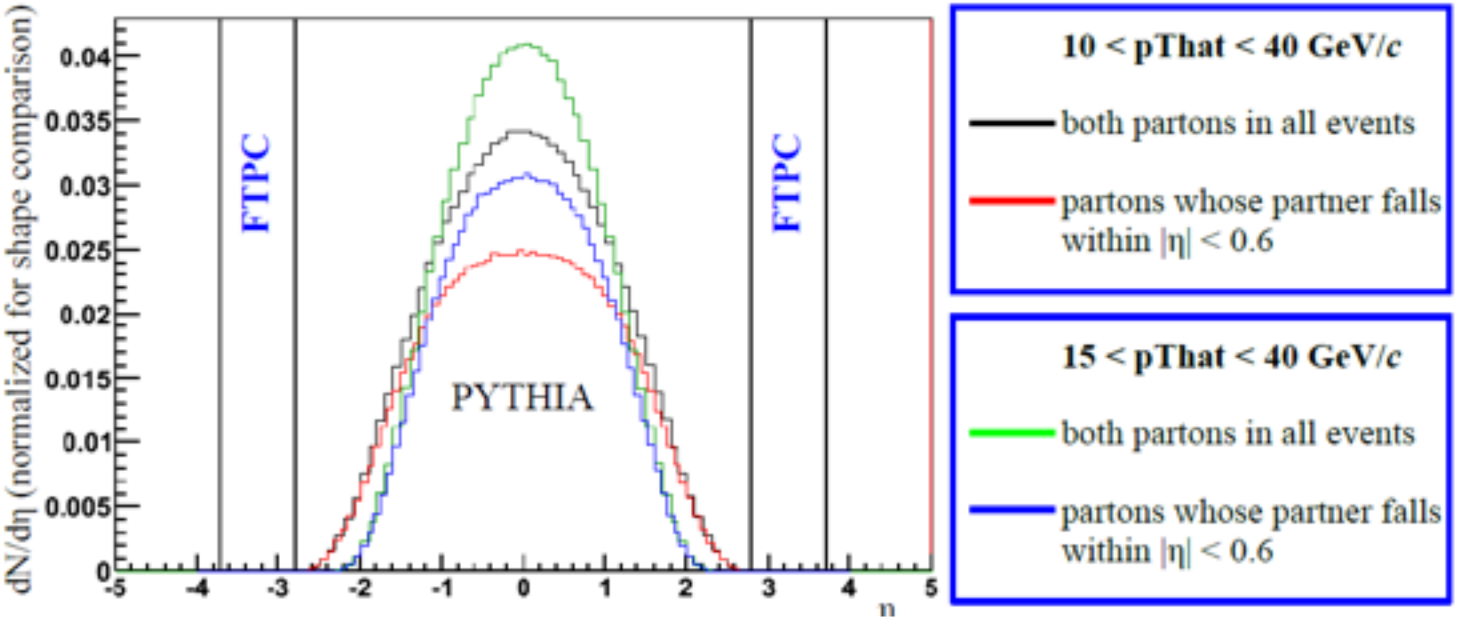
Centrality in d+Au



Different rapidity ranges to define centrality → different event samples

STAR TPC -1<η<1, FTPC 2.8<η<3.7, ZDC η>6

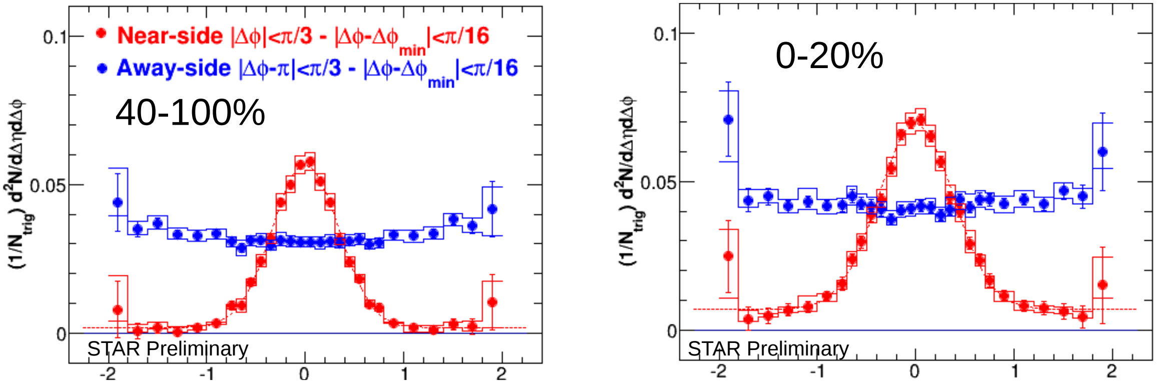
Different fluctuations/ jet contamination



If η>3 for centrality trigger di-jet partner not at mid-rapidity Fluctuations different

High vs Low mult. d+Au Correlations

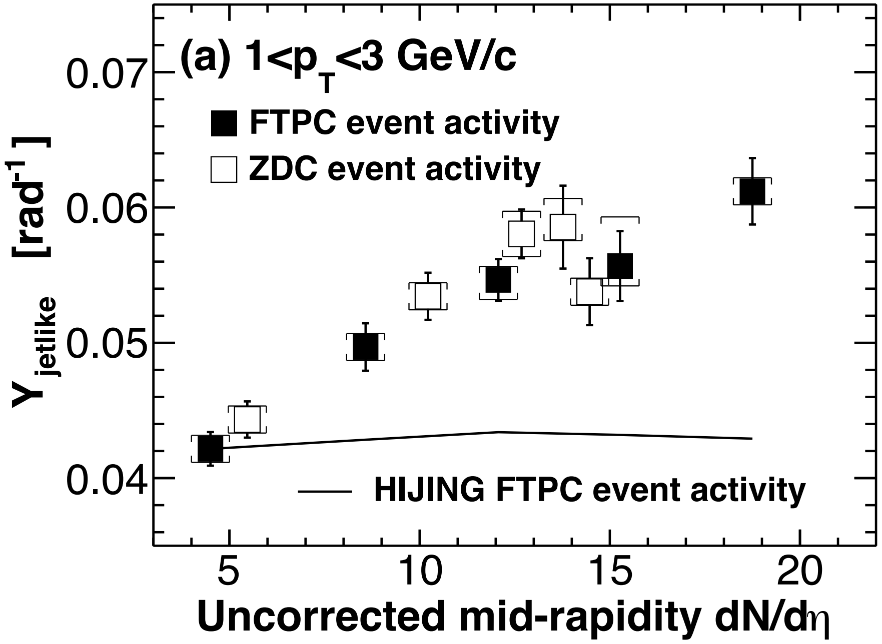
Fri: L. Yi

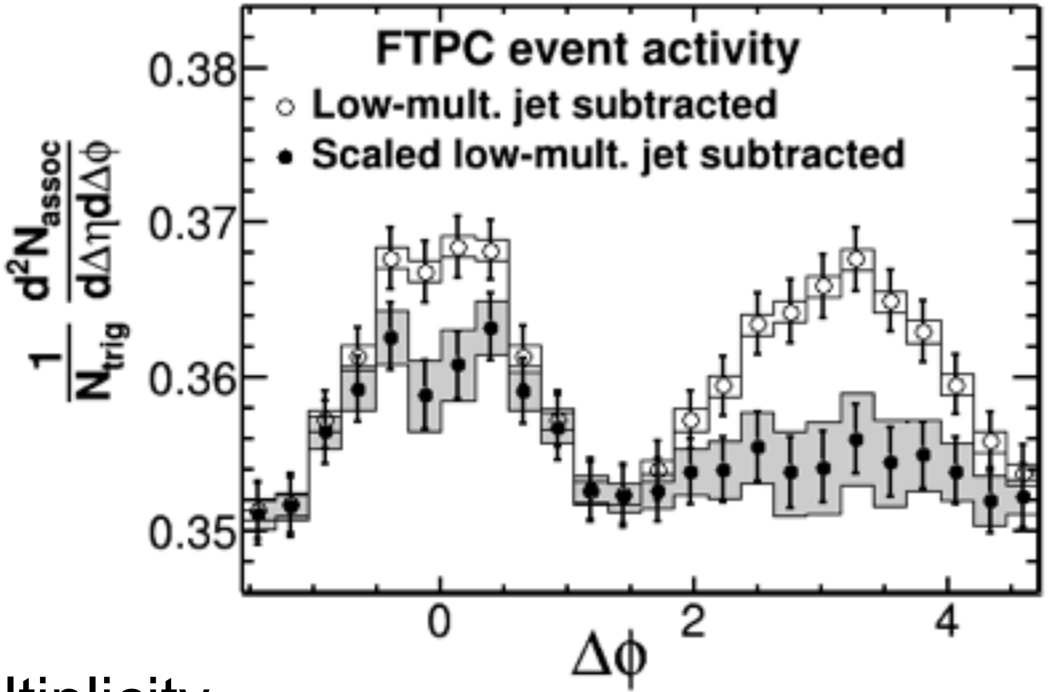


Near-side jet not the same in High and Low mult.

Yield Ratio = 1.29

Widths Ratio = 1.13





"Jet"-like yield increases with multiplicity

Increase not observed in Hijing

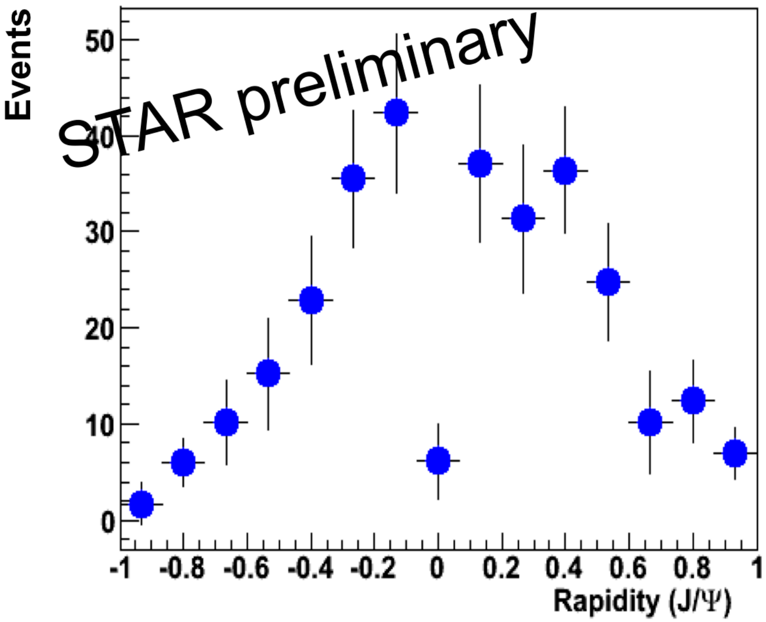
At RHIC high-low may not work to remove jet signals

After simple scaling:

Near-side	Away-side
High != Low	High = Low

Vector meson photo-production (UPC)

J/Ψ cross-section as function of rapidity can provide insight into gluon distribution in the nucleus. $d\sigma/dy \sim [g(x,Q^2)]^2$



J/Ψ production observed over 2 rapidity units

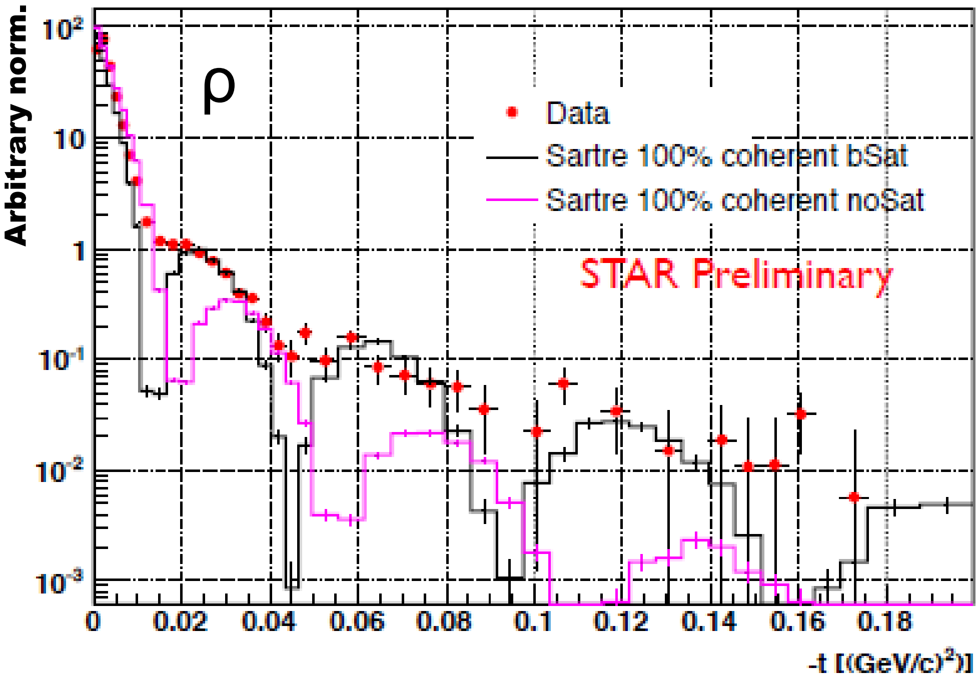
$3<M_{ee}<3.2$ GeV/c^2

Only preliminary acceptance applied

- dip at zero due to cuts

t = $-p_T^2$ distribution

(only preliminary corrections applied)



Diffraction pattern visible to "3rd dip"

Data consistent with coherent interactions with a nuclear size ~6.38 fm

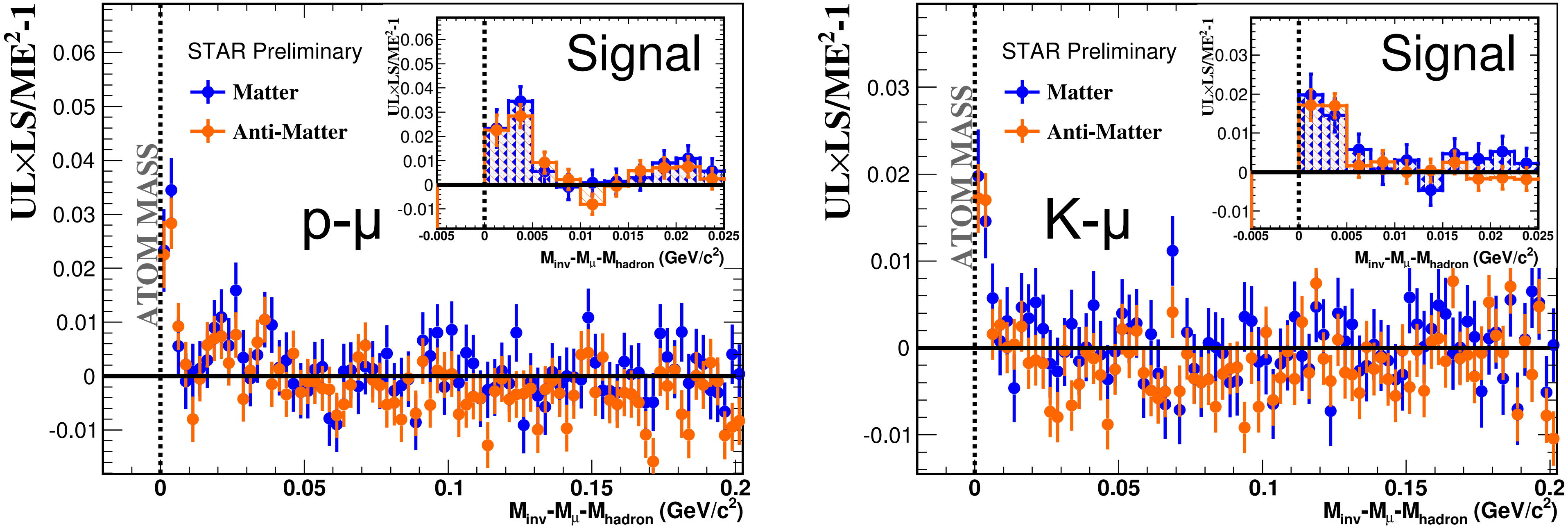
Muonic atoms

hadron-μ Coulomb bound state

- Formed in early dense part of collision from low p_T thermal μ

First observation of anti-matter and strange μ atoms

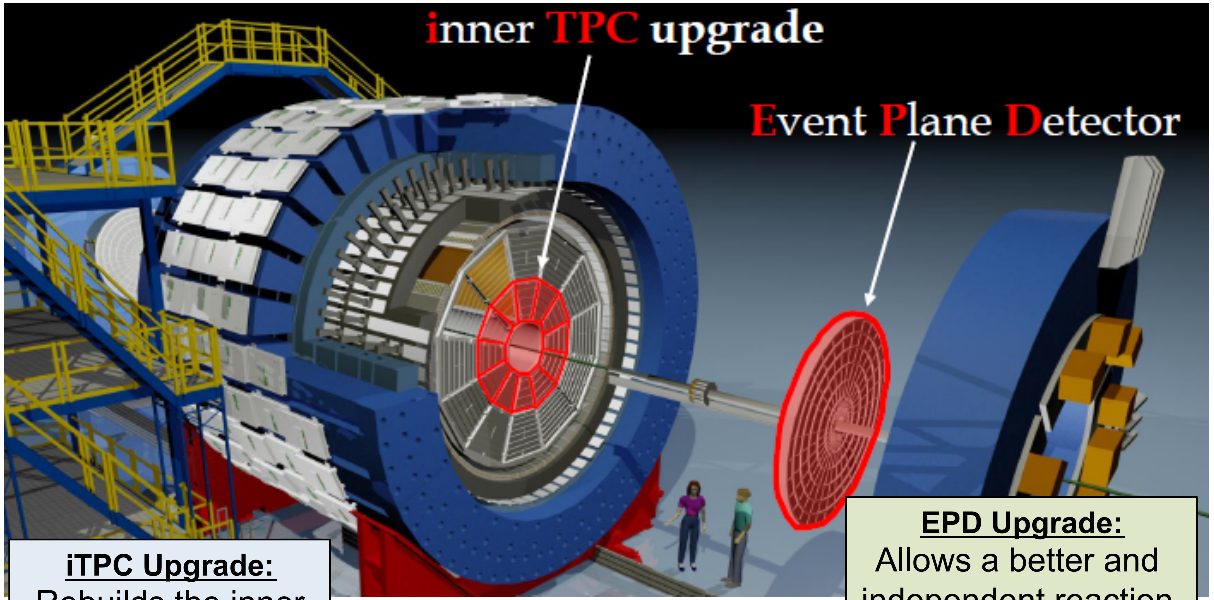
Au-Au 200 GeV



μ "Perfect" early time probe
- colorless, no interaction with QGP
- little background from later stages

Much to digest and more coming soon!

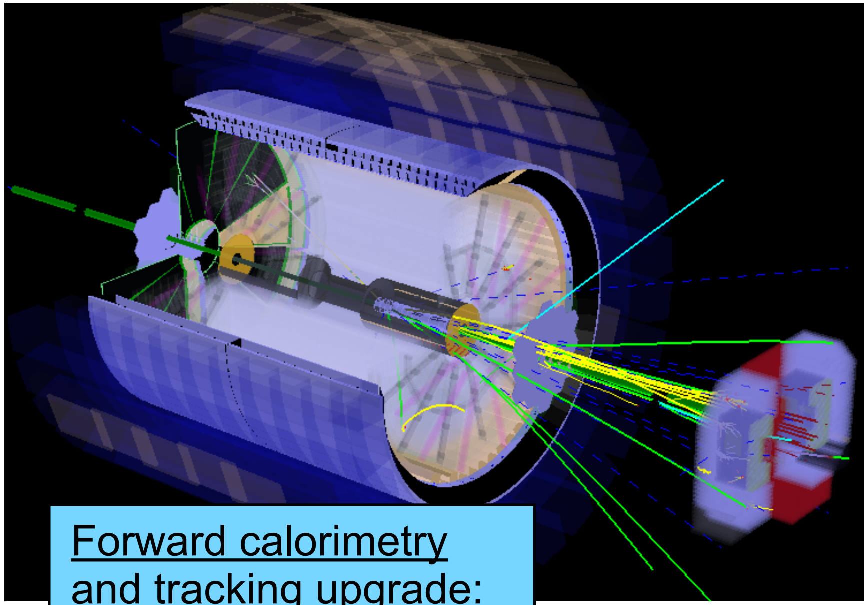
MTD and HFT - detailed heavy flavor measurements coming soon



iTPC Upgrade:
Rebuilds the inner sectors of the TPC

EndCap TOF Upgrade:
Rapidity coverage is critical for several proposed BES Phase II measurements

EPD Upgrade:
Allows a better and independent reaction plane measurement critical to BES physics



Forward calorimetry and tracking upgrade:
New forward coverage

Ultimately onto eSTAR

BES-II

detailed exploration of systems close to CP and smaller systems

p+Au, d+Au, and ^{3}He+Au collisions

test when and how “more” becomes “different”

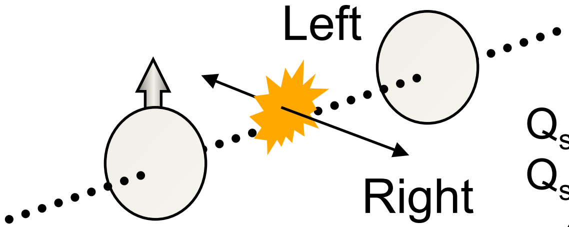
Polarized p+Au

unique RHIC capability single spin asymmetries probe saturation scale

Backup

Polarized pA

$$A_N = \frac{1}{P}\frac{\sigma_L^\pi - \sigma_R^\pi}{\sigma_L^\pi + \sigma_R^\pi}$$



$Q_{sp}^2 = (1.0\ \text{GeV})^2$
$Q_{sA}^2 = (2.5\ \text{GeV})^2$
$\delta = 0.16\ \text{GeV}$

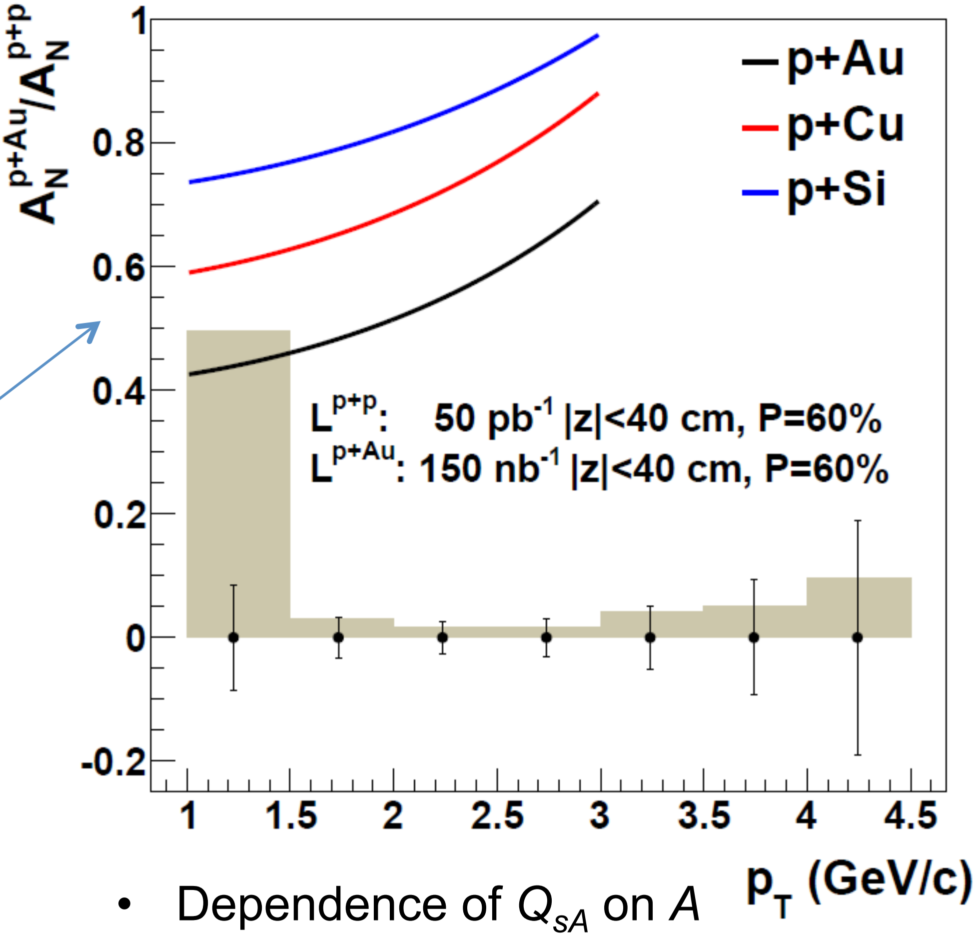
$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp}^2 \ll Q_{sA}^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2}\, e^{P_{h\perp}^2 \delta^2 / Q_{sp}^2}$$

Single spin asymmetries can act as a probe of the saturation scale – the p+p reference will also be better understood with new instruments.

A unique capability of RHIC!

Y. Kovchegov & M.D. Sievert: PRD 86, 034028 (2012)

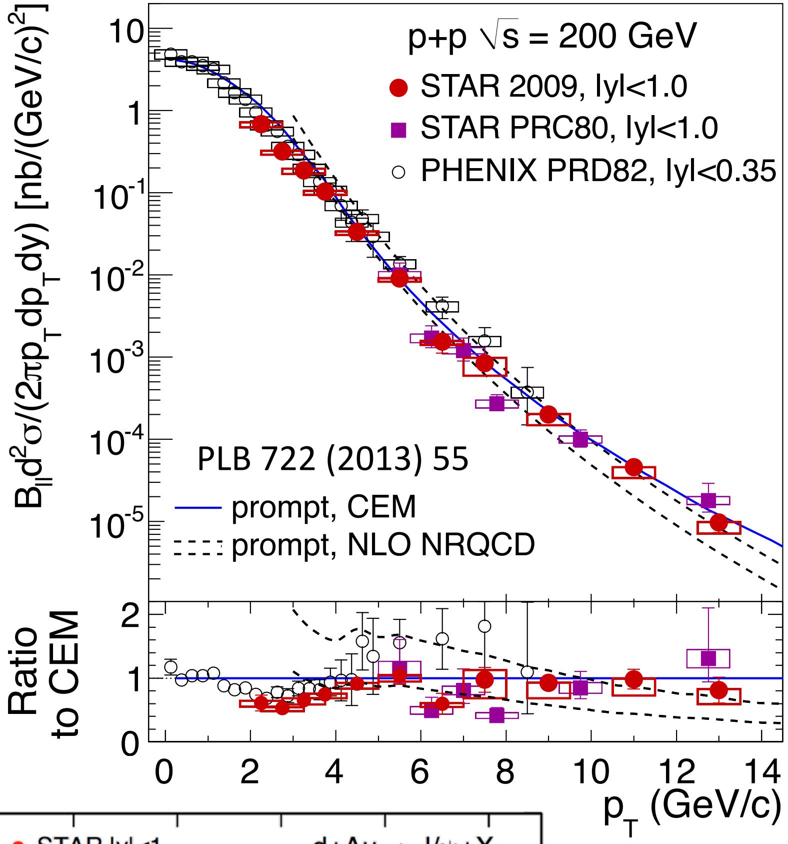
Kang, Yuan: PRD 84, 034019 (2011)

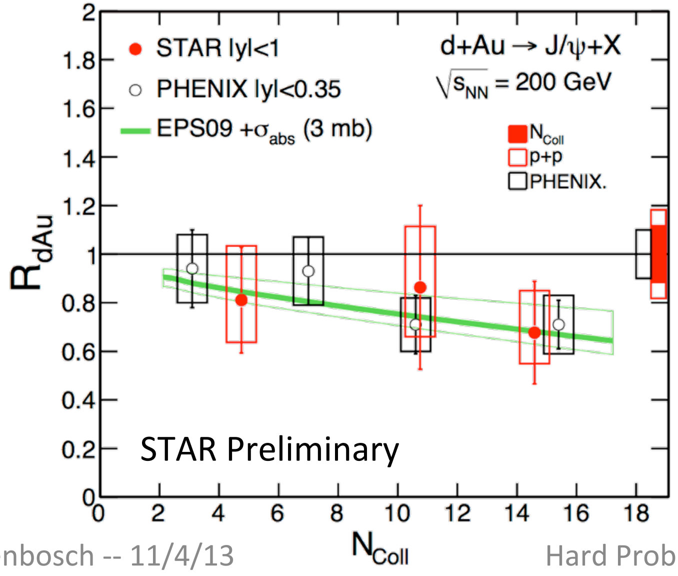


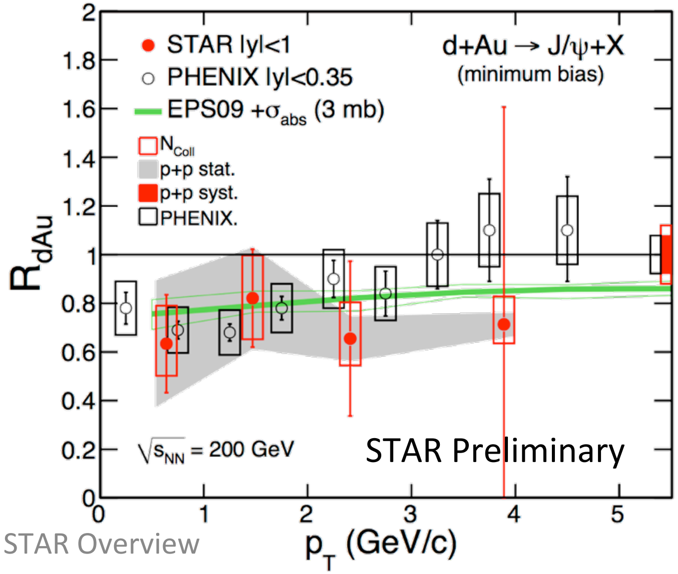
- Dependence of Q_{sA} on A
- Combined with other measurements this can estimate Q_{sp}

– J/Ψ in p+p and d+Au

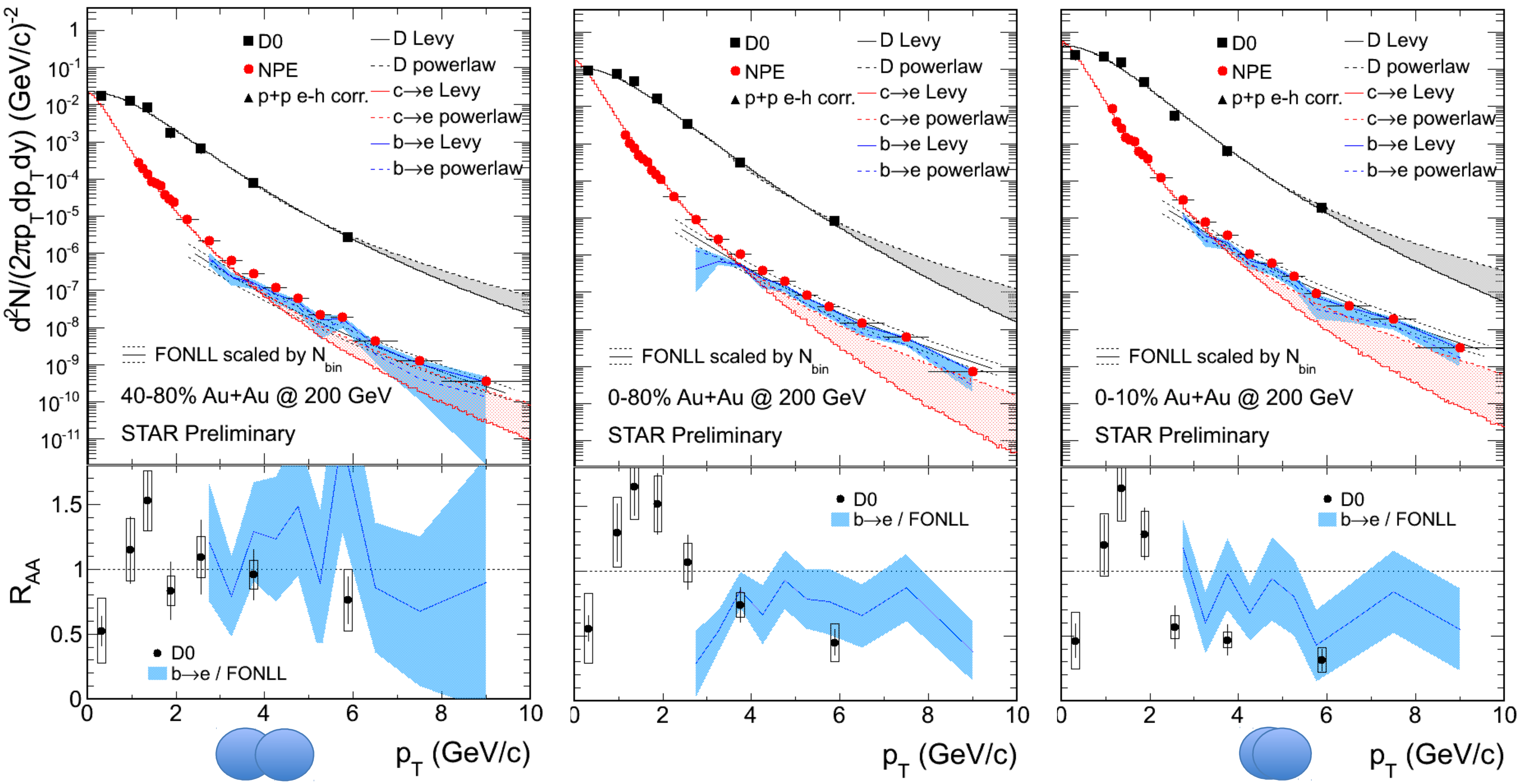
- p_T range in p+p extended to 14 GeV/c
  - prompt NLO CS+CO describes data
  - prompt CEM describes data at high p_T
  - direct NNLO CS underpredicts high p_T
- R_{dAU} consistent with model calculations
  - shadowing from EPS09 nPDF
  - nuclear absorption: $\sigma_{abs}^{J/\Psi}$=3mb







Bottom suppression



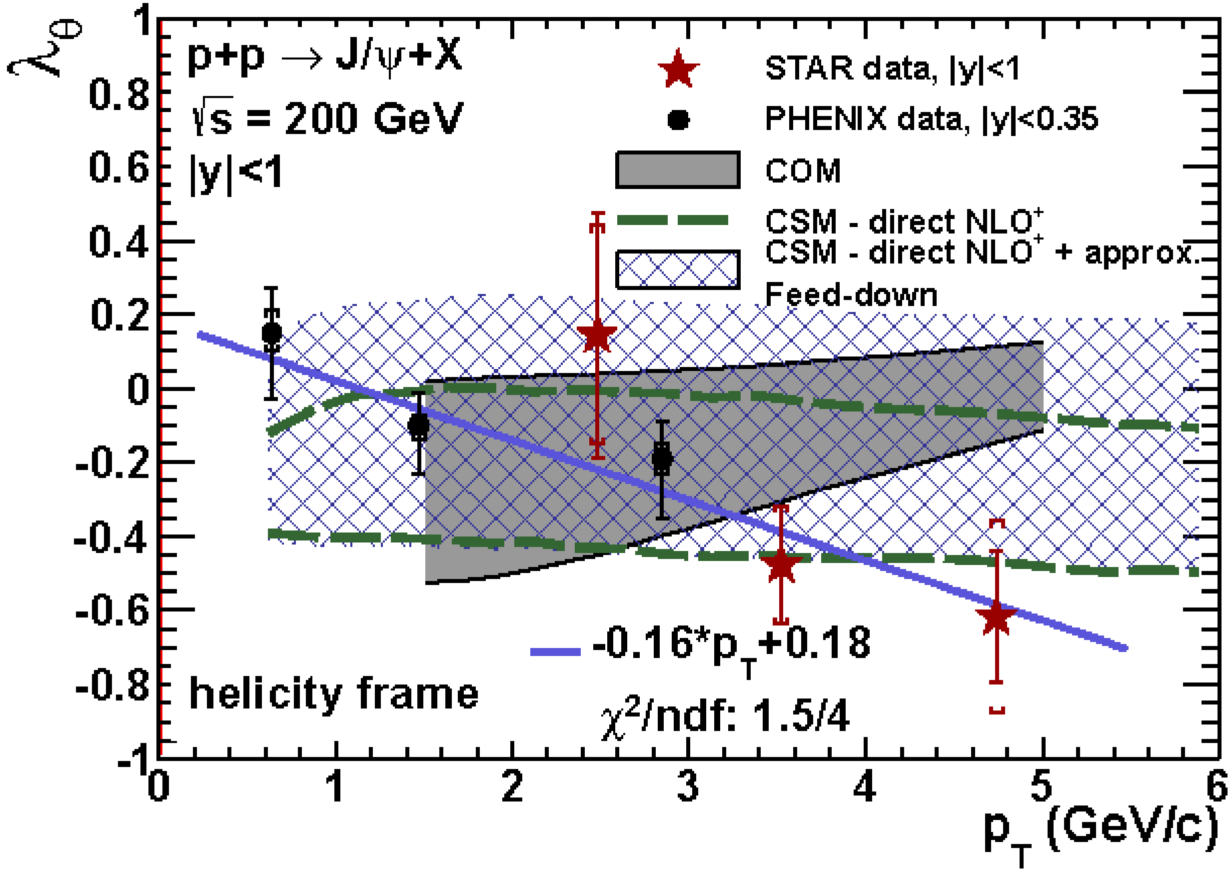
Given D and NPE can deduce B suppression

Hint that $R_{AA}^{D} < R_{AA}^{B}$

Does this mean less energy loss?

J/Ψ polarization

J/ψ polarization



- Polarization parameter λ_θ in helicity frame at $|y| < 1$ and $2 < p_T < 6$ GeV/c.
- λ_θ is consistent with NLO+ CSM.
- RHIC data indicates a trend towards longitudinal J/ψ polarization as p_T increases.
- More precise measurement from p+p 500 GeV expected.

PHENIX: Phys. Rev. D 82, 012001 (2010)
COM: Phys. Rev. D 81, 014020 (2010)
CSM NLO+: Phys. Lett. B, 695, 149 (2011)

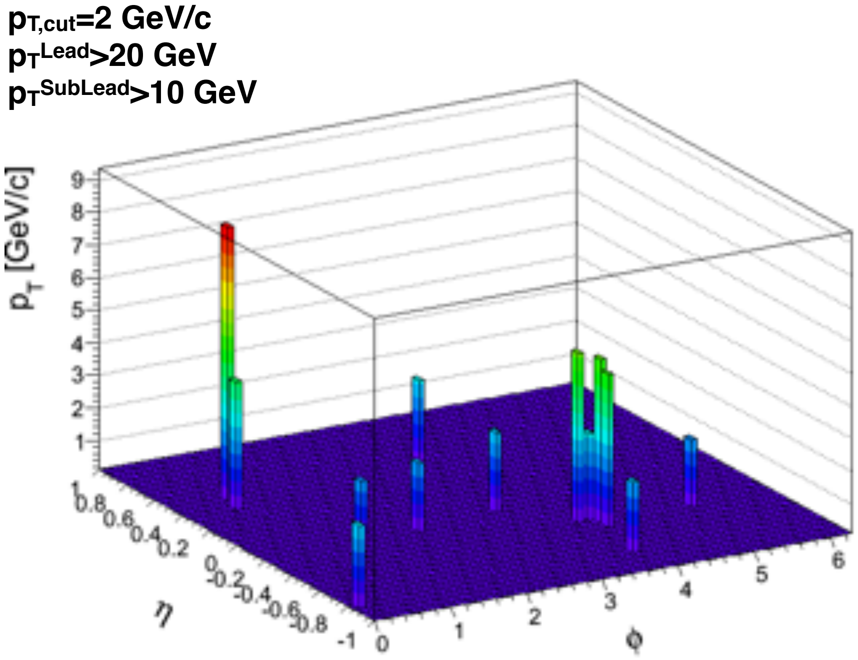
appeared on arXiv today
arXiv 1311.1621

Is this random background?

Assumption: balancing for jets with low p_T constituents **only** due to background fluctuations, **not** correlated signal yield!

Method 1: Random Cone (RC):

Take di-jet pair p_T^{Cut}>2 GeV/c (w/o low p_T)

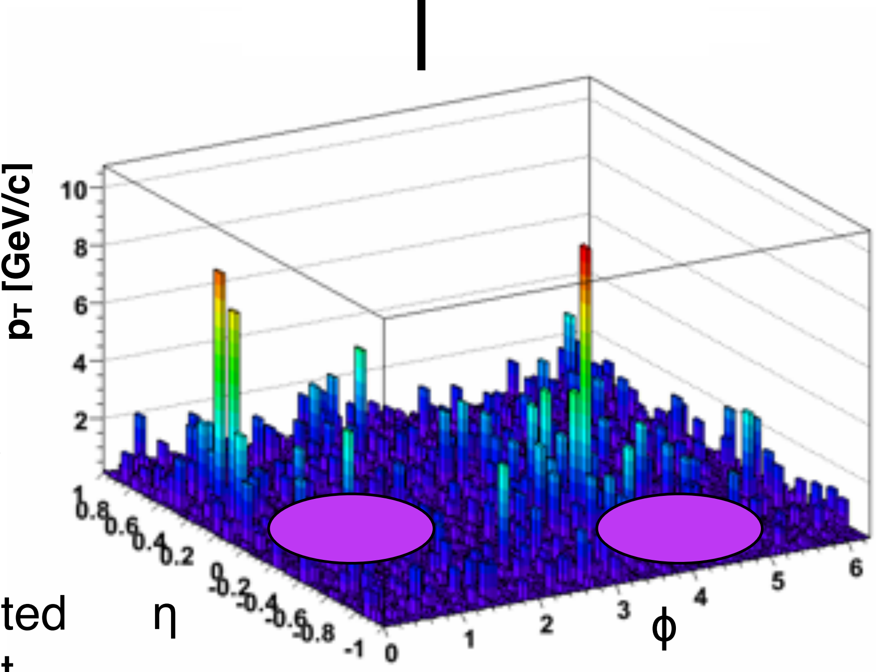


$p_{T,cut}$=2 GeV/c
p_T^{Lead}>20 GeV
$p_T^{SubLead}$>10 GeV

Embed randomly

the 2 Jet vectors into a Au+Au 0-20% Minimum Bias event

Calculate |A_J| with p_T^{Cut}>0.2 GeV/c using cone of R



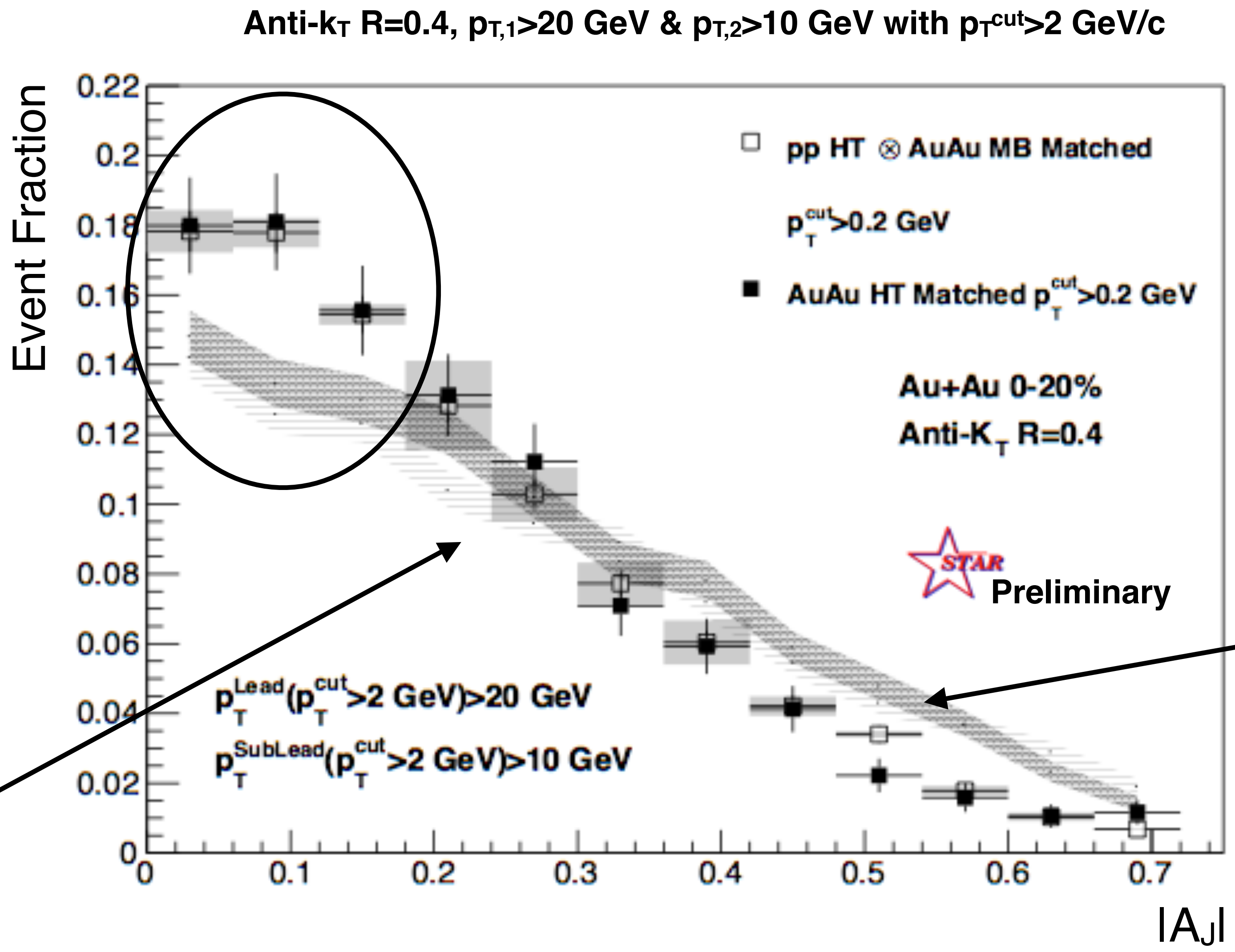
Method 2: EtaCone (EC):

Take di-jet pair p_T^{Cut}>2 GeV/c (w/o low p_T)

Embed the two Jet

vectors into 0-20% Au+Au HT event 2*R away from reconstructed di-jet pair in that event

Null-hypothesis



Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

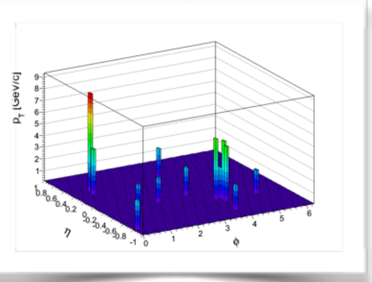
Method 1 (RC)

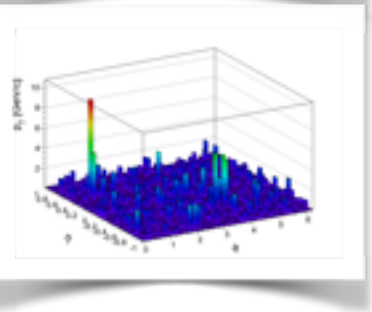
Method 2 (EC)

Balancing of Au+Au matched di-jets due to correlated signal yield in a cone of R=0.4

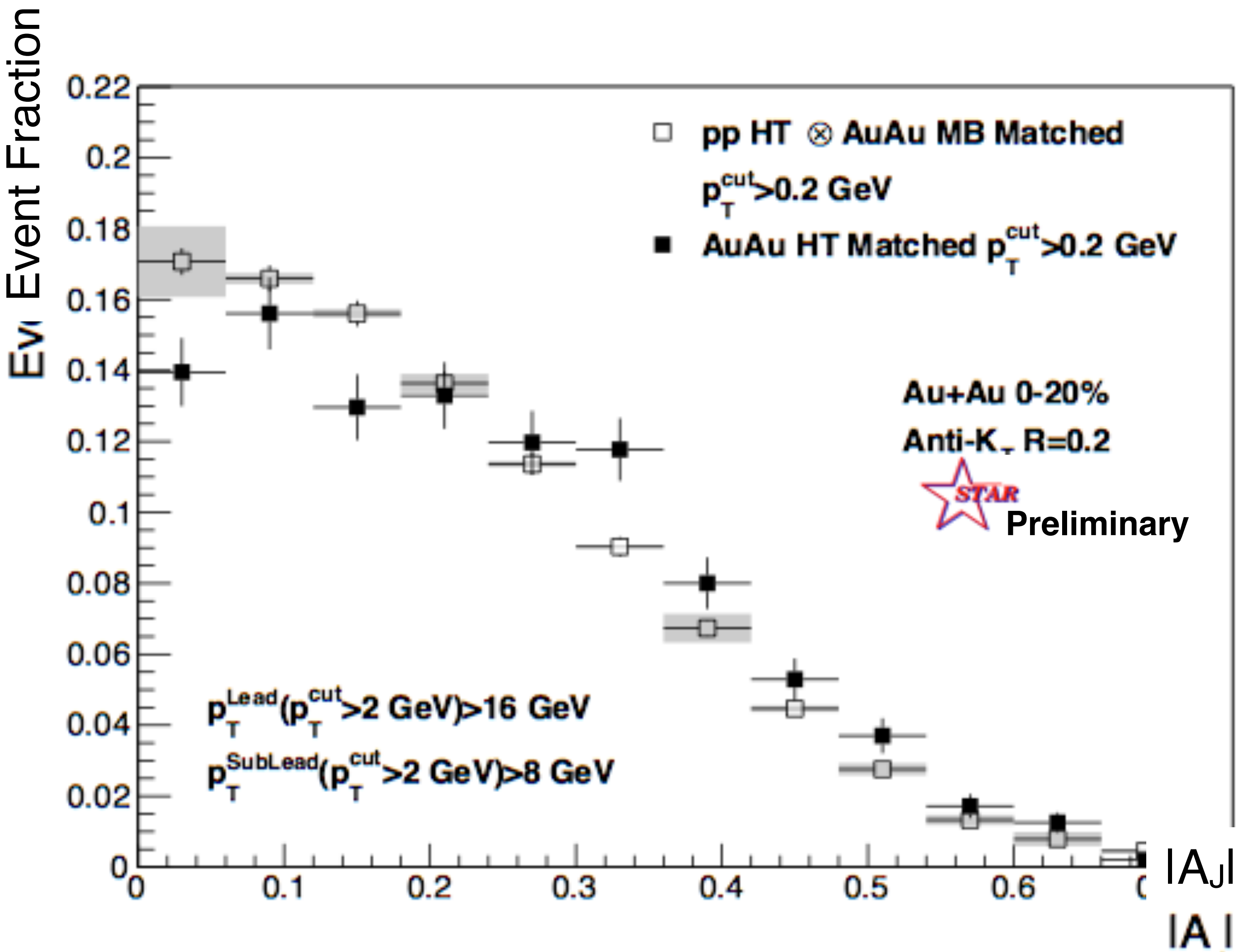
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

Di-jet imbalance A_J Au+Au 0-20% R=0.2





Anti-k_T R=0.2, $p_{T,1}$>16 GeV & $p_{T,2}$>8 GeV with p_T^{cut}>2 GeV/c



p-value<10^{-10}
(stat. error only)

p-value<10^{-4}
(stat. error only)

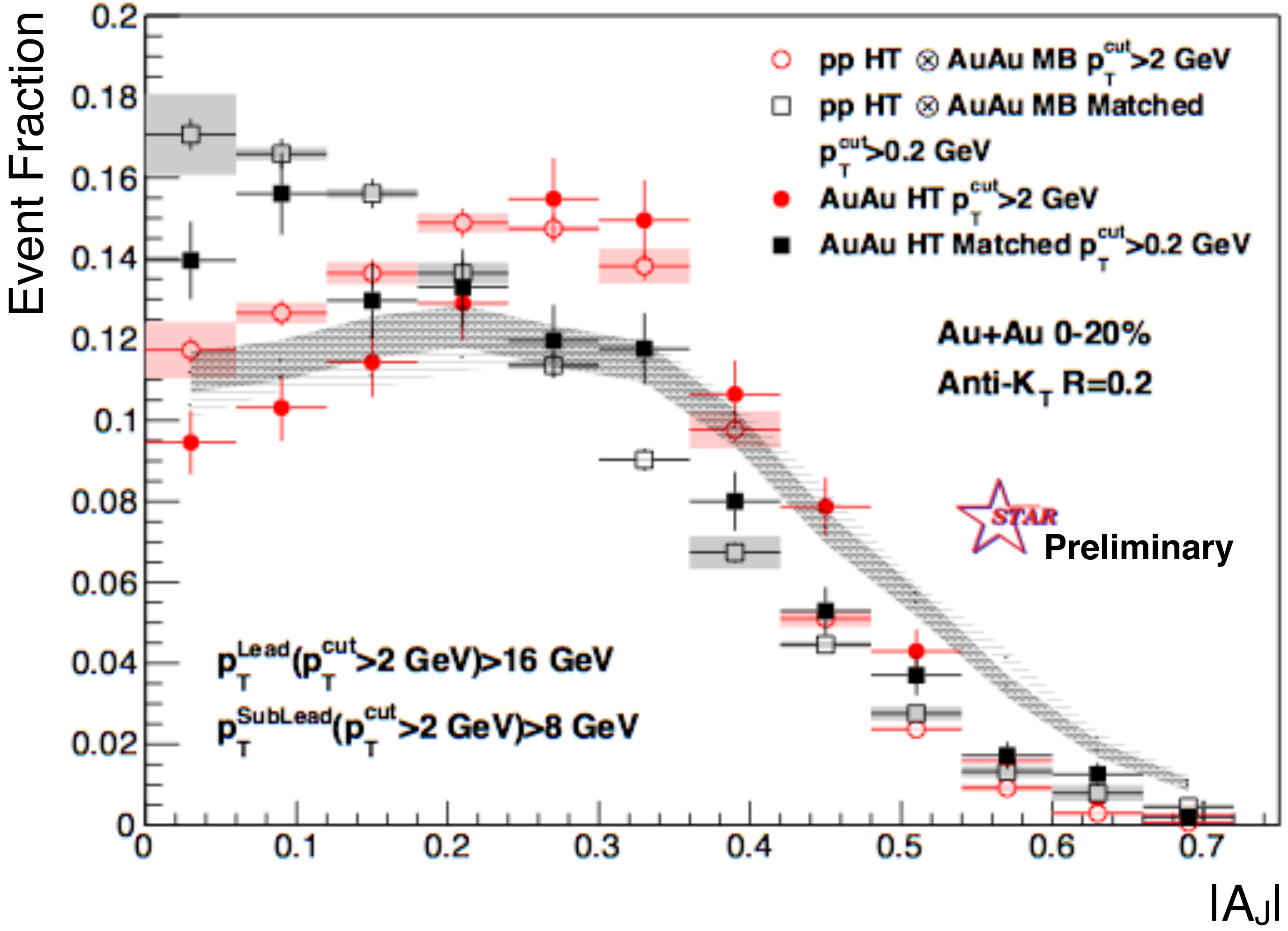
Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

Matched Au+Au $A_J \neq$ p+p A_J for R=0.2
→ (recoil) Jet broadening in 0.2 – 0.4

Di-Jet Imbalance A_J Au+Au 0-20% R=0.2 (I)

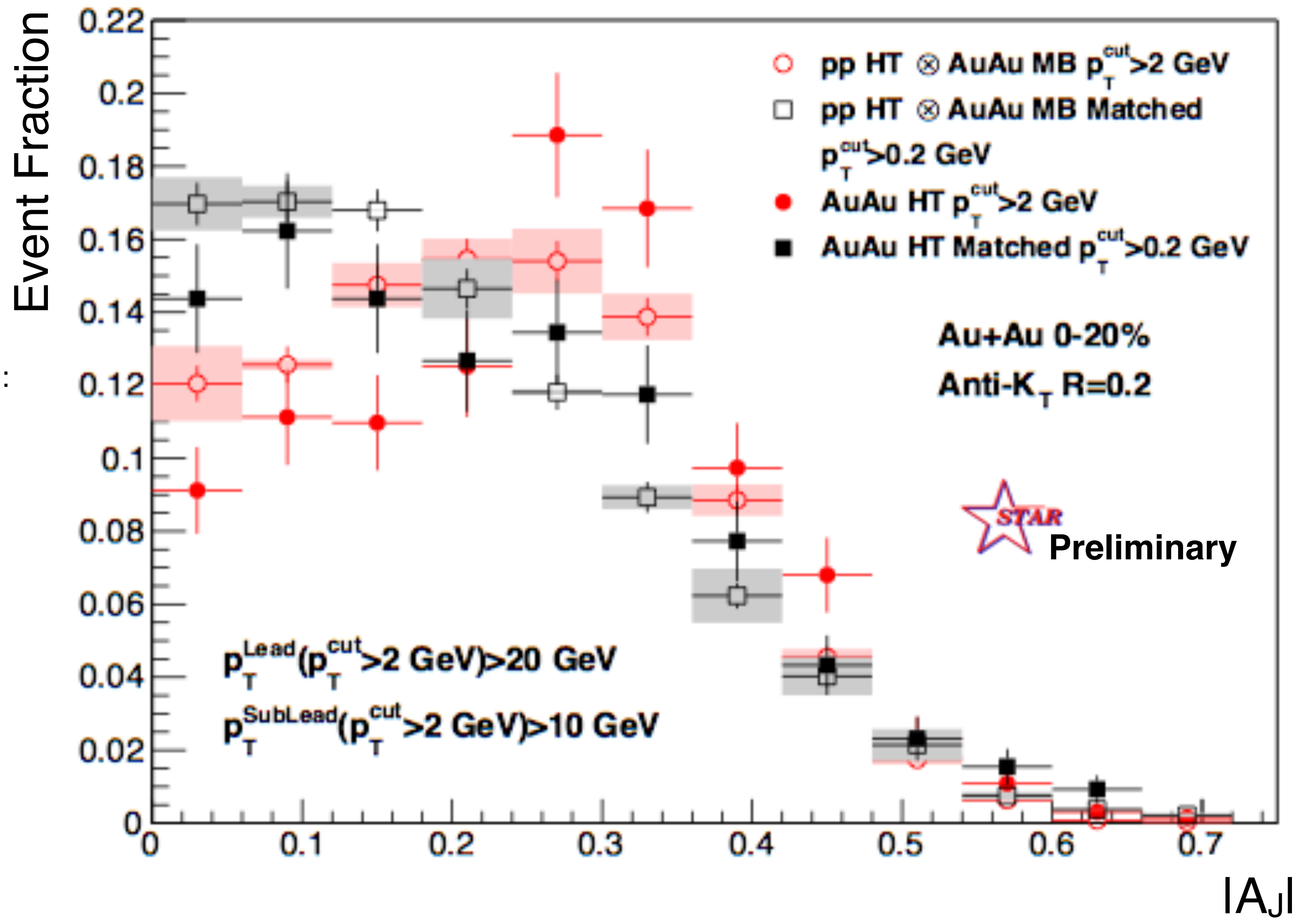
Anti-k_T R=0.2, $p_{T,1}$>16 GeV & $p_{T,2}$>8 GeV with p_T^{cut}>2 GeV/c



Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

Di-Jet Imbalance A_J AuAu 0-20% R=0.2 (II)

Anti-k_T R=0.2, $p_{T,1}$>20 GeV & $p_{T,2}$>10 GeV with p_T^{cut}>2 GeV



Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

Quick summary of A_J measurements

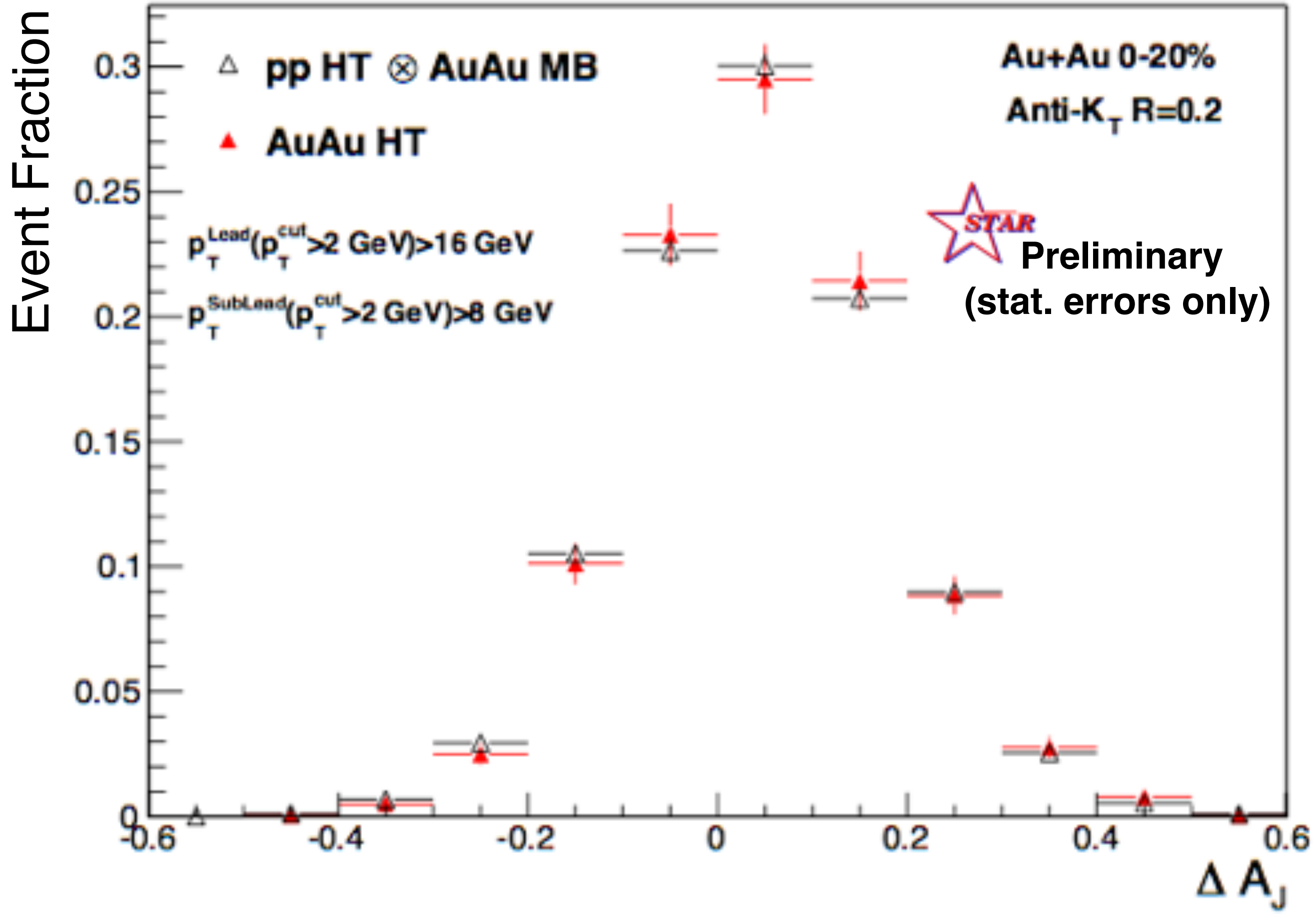
	R=0.4	R=0.2
Au+Au vs. p+p **p**	**X**	**X**
Matched **Au+Au vs. p+p** **(p**	**O**	**X**

X = "*Non-identical*" A_J distribution (Au+Au vs. p+p)

O = "*Identical*" A_J distribution (Au+Au vs. p+p)

E-by-E A_J difference: ΔA_J Au+Au 0-20%

$\Delta A_J = A_J(p_T^{cut} > 2\text{GeV}) - A_J(p_T^{cut} > 0.2\text{GeV})$



Behavior changing from R=0.2 to R=0.4

Need to probe this further!

R=0.4: ΔA_J larger for Au+Au than p+p

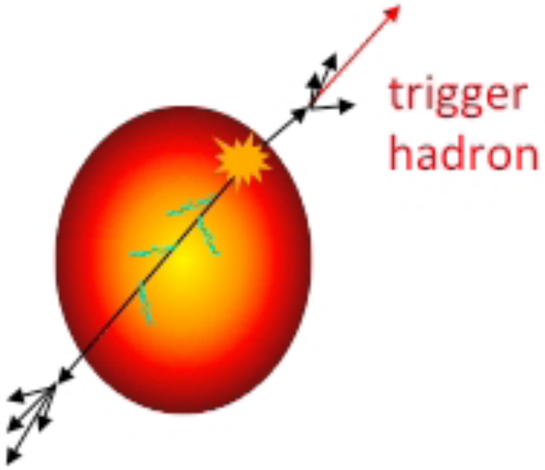
→ more energy recovered at low p_T

R=0.2: ΔA_J Au+Au ~ ΔA_J p+p

→ similar energy recovered at low p_T

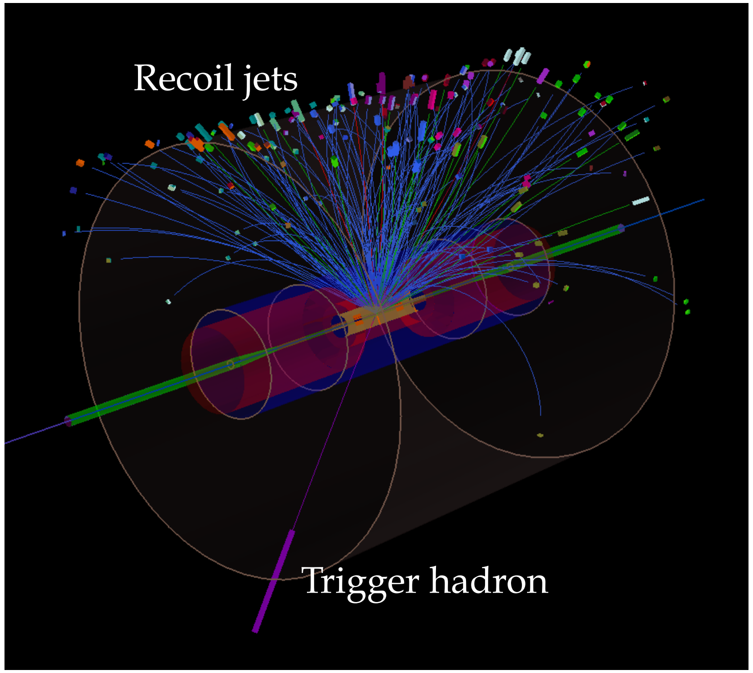
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

Semi-inclusive recoil jets



Semi-inclusive Observable:

Recoil jets per trigger



Trigger: Charged hadron $9<p_T<19$ GeV/c

Recoil: Charged particle jet:

Anti-k_T R=0.3

Constituent tracks: $p_T > 0.2$ GeV/c

Recoil jet azimuth: $|\varphi-\pi|<\pi/4$

Ensemble-averaged analysis:

No rejection of jet candidates on jet-by-jet basis

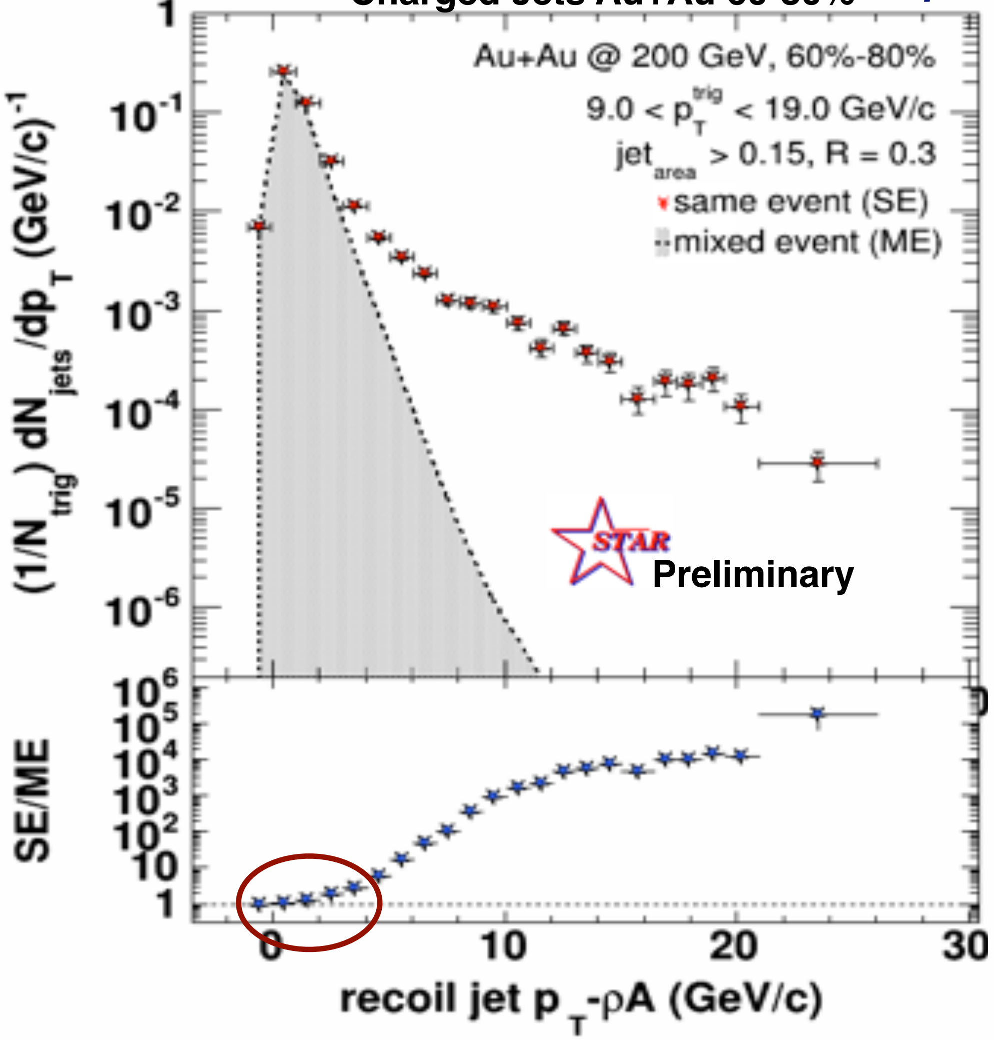
No bias on recoil jet

Jet measurement is collinear-safe with low infrared cutoff (0.2 GeV/c)

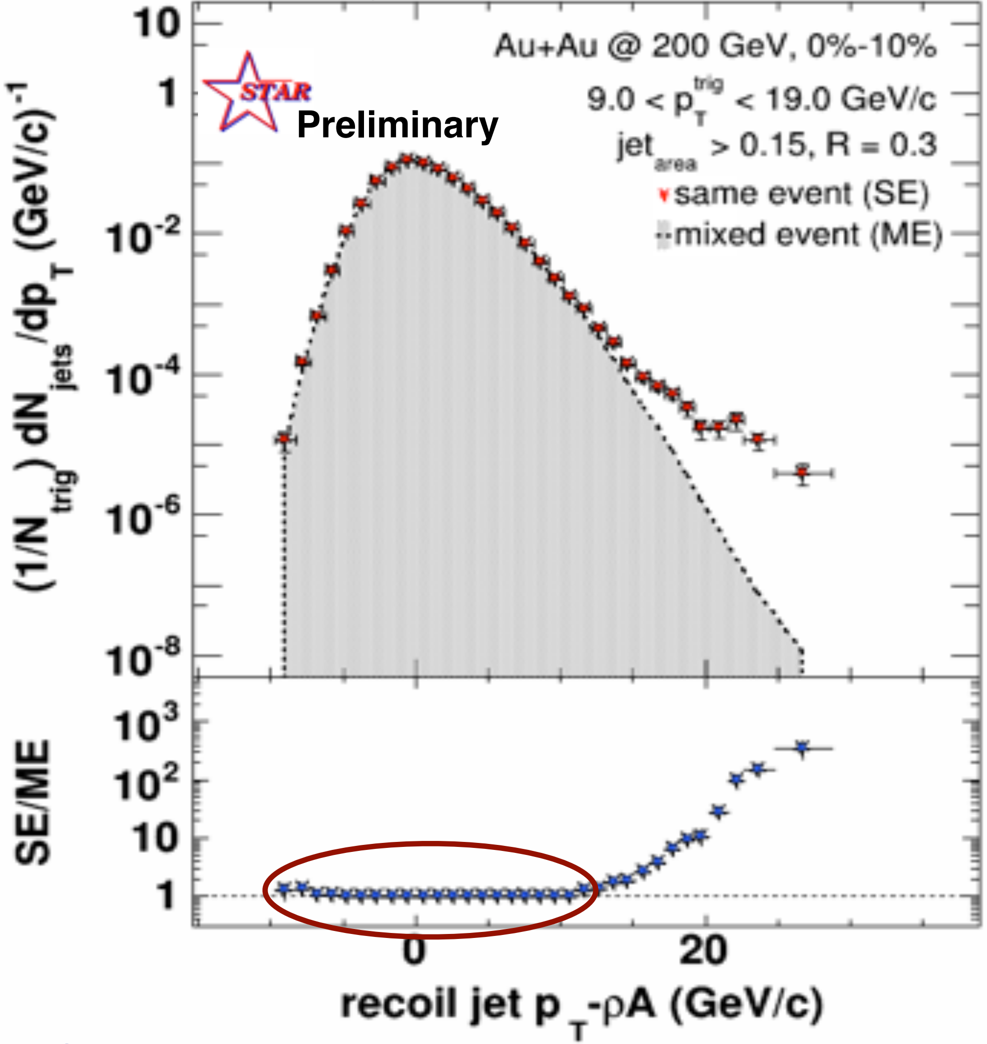
Semi-inclusive recoil jet spectrum

p_T^{trig}>9 GeV/c

Charged Jets Au+Au 60-80%



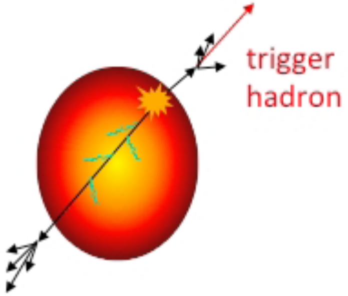
Charged Jets Au+Au 0-10%



Event mixing gives good description of combinatorial jet background

→ Triggered Recoil jet distribution:
Same Event (SE) - Mixed Event (ME)

Semi-inclusive recoil jets



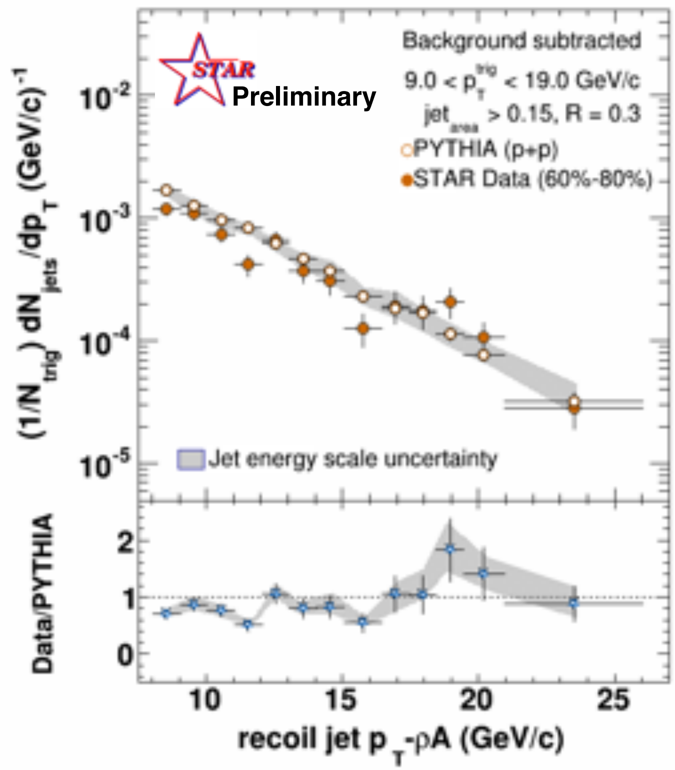
Au+Au background subtracted distributions (SE-ME):

PYTHIA smeared using response matrix

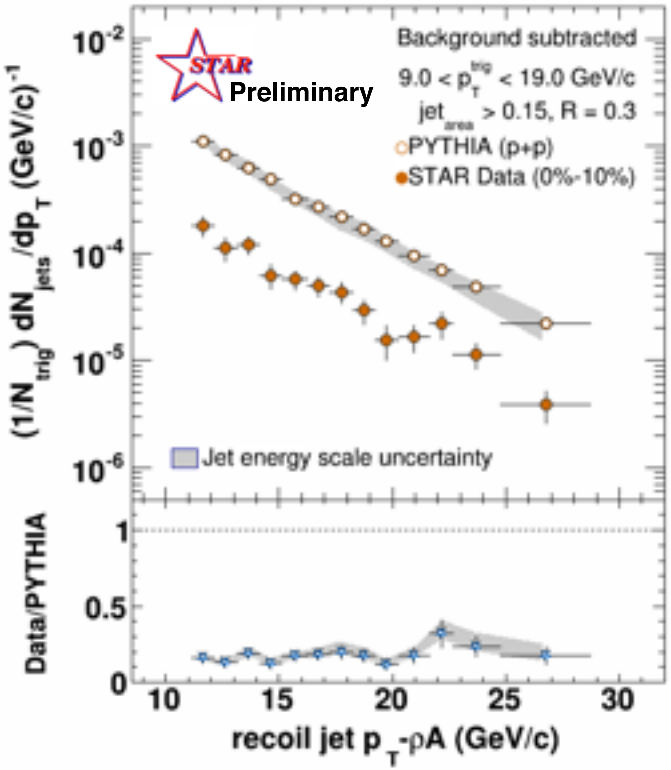
includes fluctuations and detector effects measured for Au+Au

(Aim to correct to particle level via unfolding)

Charged Jets Au+Au 60-80%



Charged Jets Au+Au 0-10%



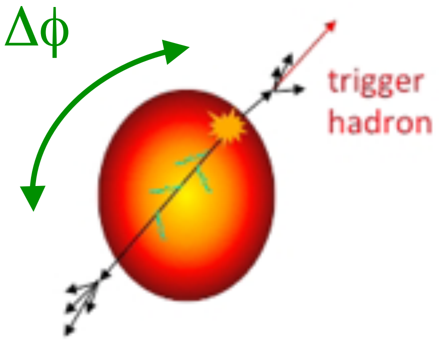
Dominant sys uncertainty:
Tracking eff. → Jet energy scale (JES) uncertainty ~7%

Peripheral Au+Au: Good agreement between data and PYTHIA

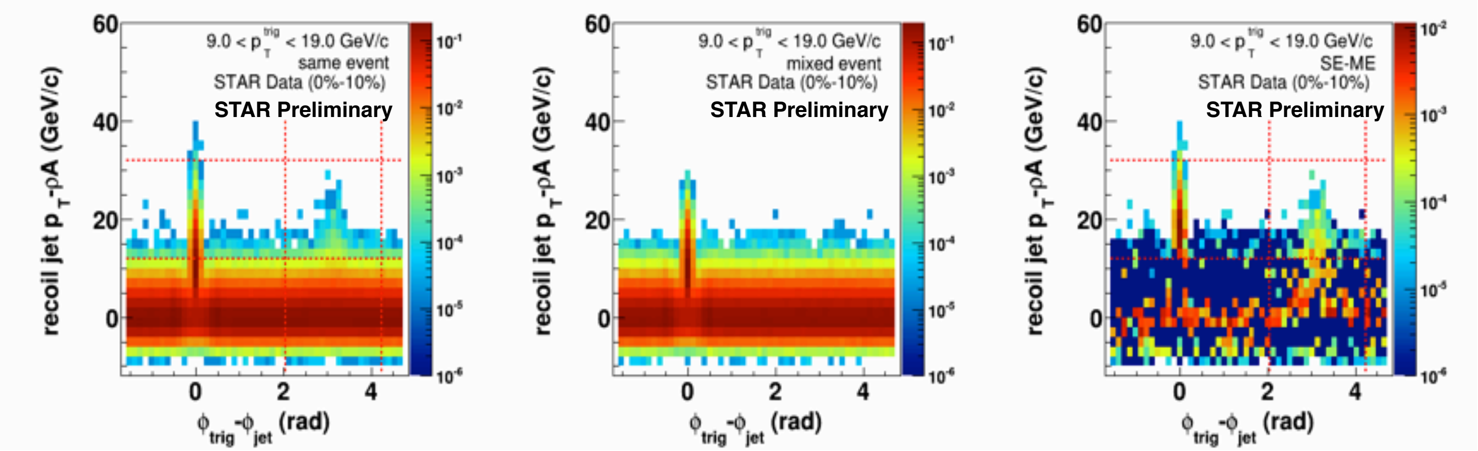
Central Au+Au: Strong suppression (relative to PYTHIA)

Medium induced acoplanarity?

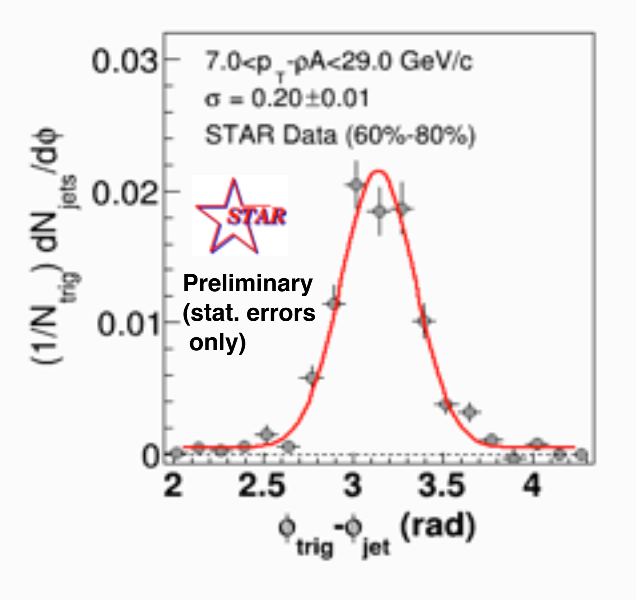
Charged Jets Au+Au 0-10%



SE **ME** **SE-ME**

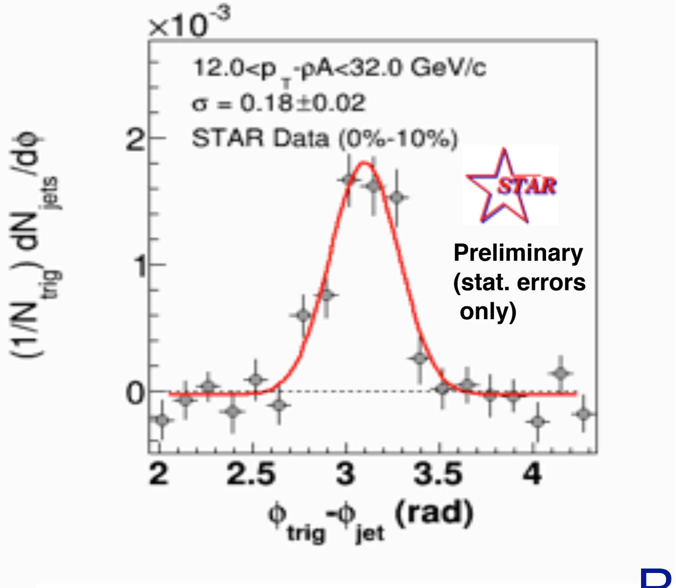


Charged Jets Au+Au 60-80%



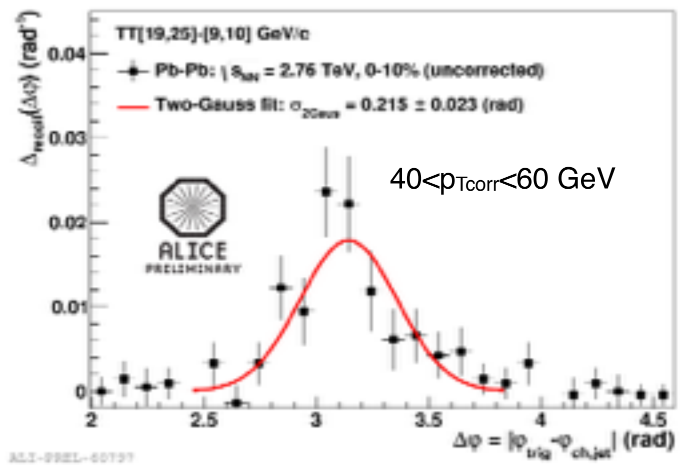
Preliminary (stat. errors only)

Charged Jets Au+Au 0-10%



Preliminary (stat. errors only)

Pb+Pb 2.76 TeV 0-10%



Au+Au central vs peripheral: Similar widths

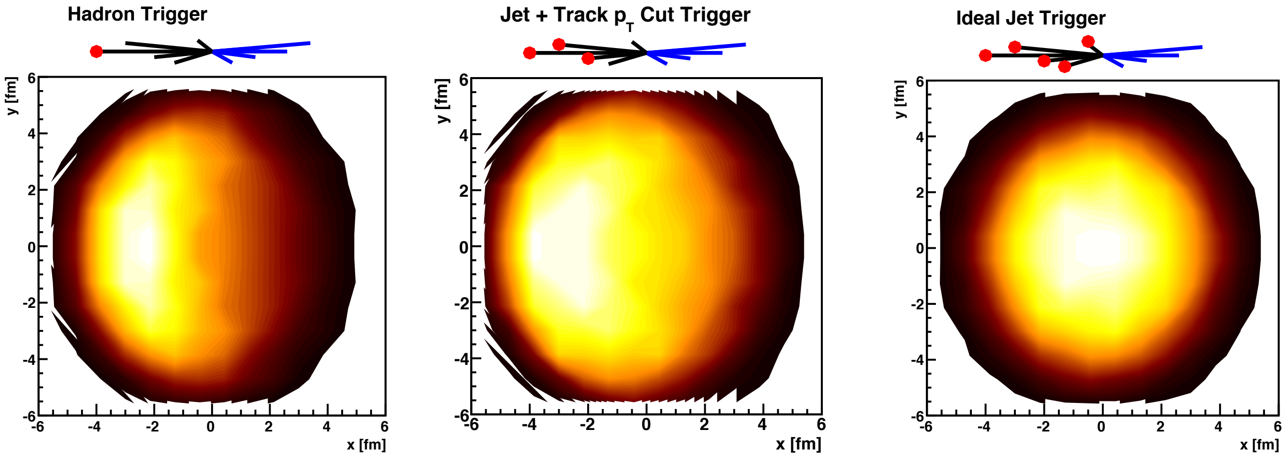
RHIC vs LHC: Comparable widths

Future: probe large angle radiation

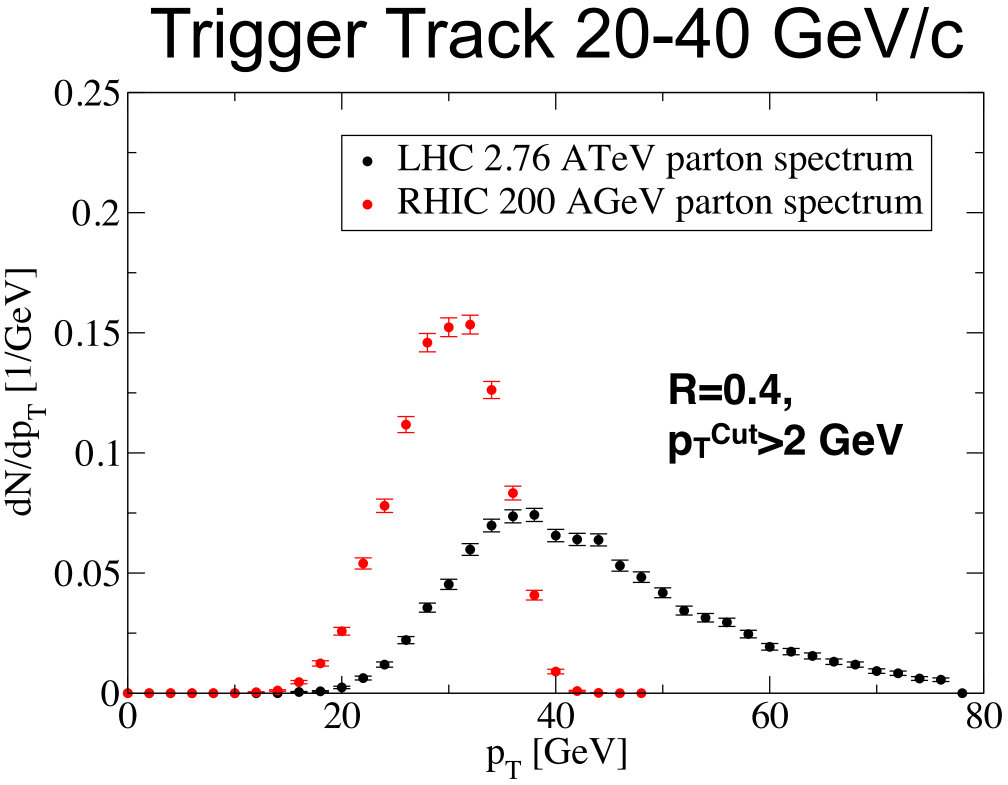
d'Erramo et al. ArXiv:1211:1922

Biases - taking control at RHIC!

T. Renk, Phys.Rev. C87 (2013) 024905



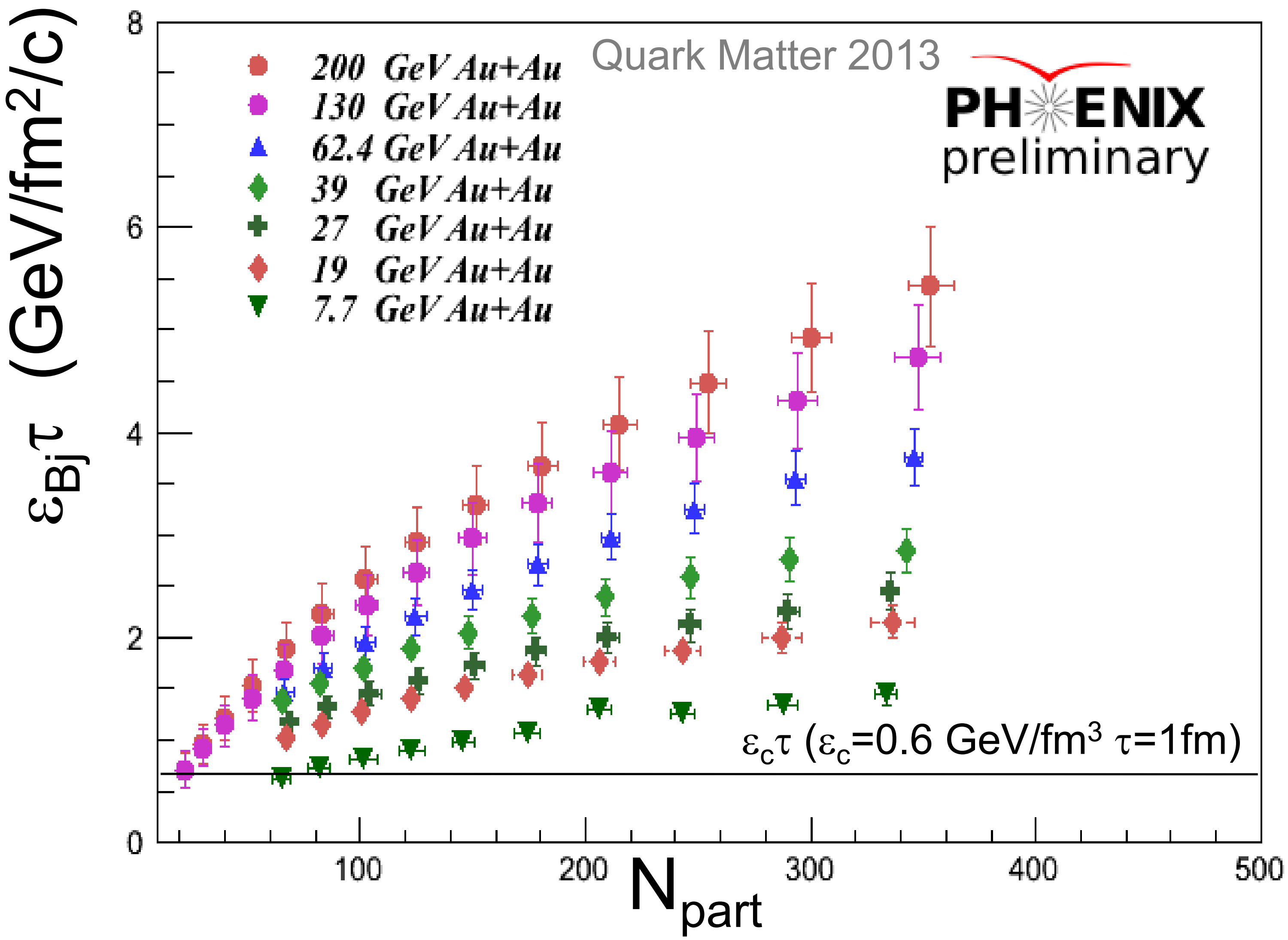
Trigger types, p_T^{Cut}, R, can be used to change *systematically pathlength* of recoil jet



Can also potentially be used to bias parton type

RHIC's steeply falling spectrum means good correlation to initial parton energy remains even after threshold cut

Generic features of A-A collisions - III



Lattice:

$\varepsilon_c \sim 0.6$ GeV/fm^3

Above critical density for all collision energies and centralities

QGP at all energies?