High p_T hadron suppression and jet v_2 from STAR

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Introduction

Jet quenching: suppression of inclusive particle production relative to a binary scaled p+p result [M. Gyulassy, et al. (1992)]

Jet quenching in A+A collisions has been regarded as one of the most important discoveries at RHIC

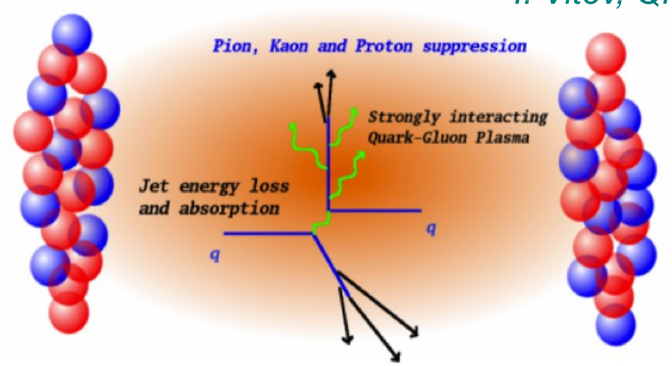
New observables or systematic measurements can be performed for detailed tomography study of properties of matter. [X.-N. Wang, PRC63]

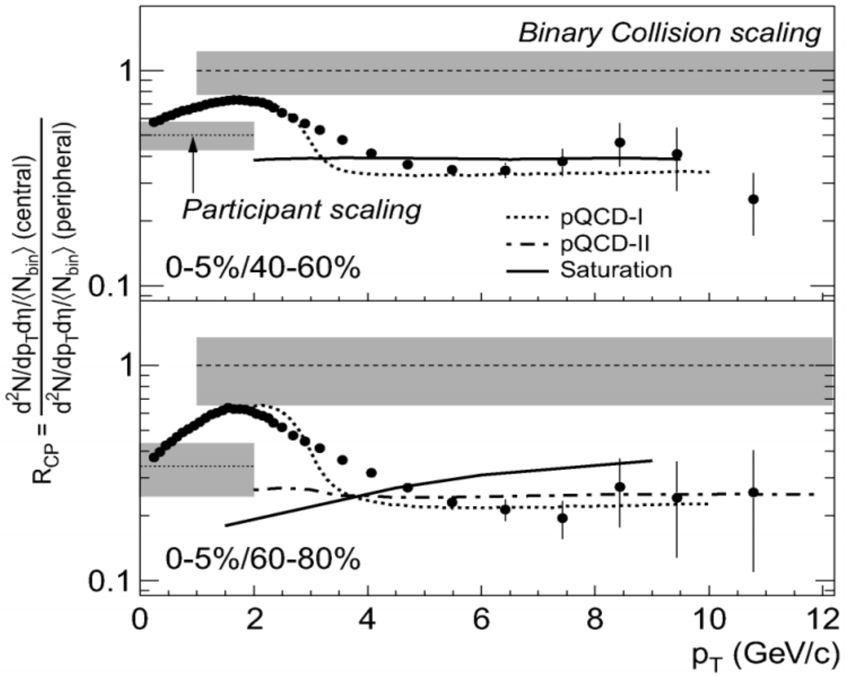
$\sqrt{s_{NN}}$ dependence: High p_T hadron suppression at RHIC beam energy scan

pathlength dependence: Jet v_2 at top RHIC energy

Sangaline, Horvat, Zhang, Ohlson, QM2012

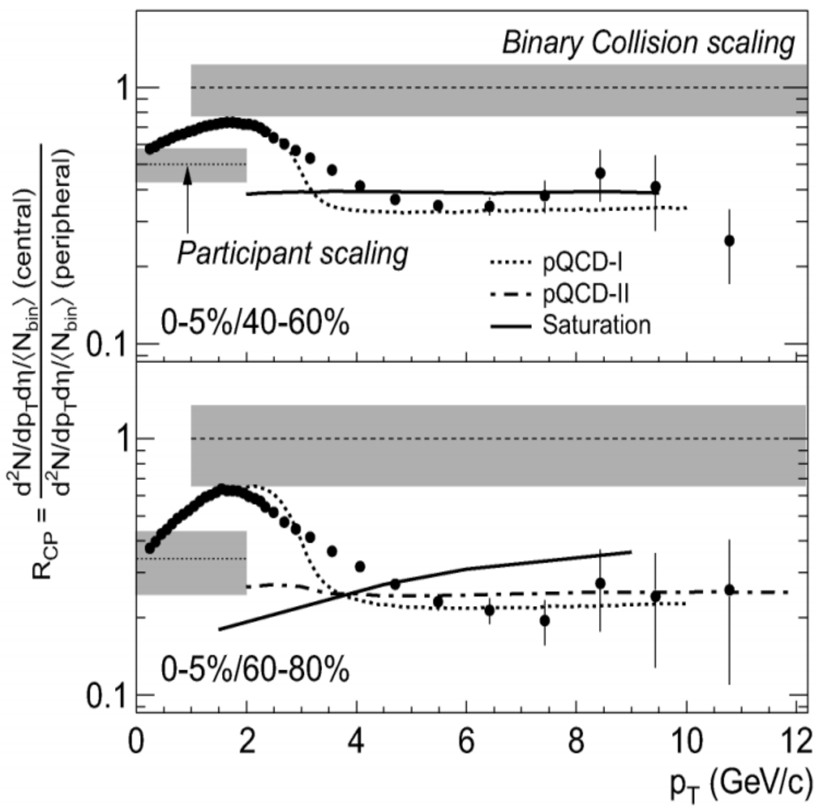
I. Vitev, QM2011





Phys. Rev. Lett. 91 172302

Previous R_{CP} (R_{AA}) Measurements at RHIC



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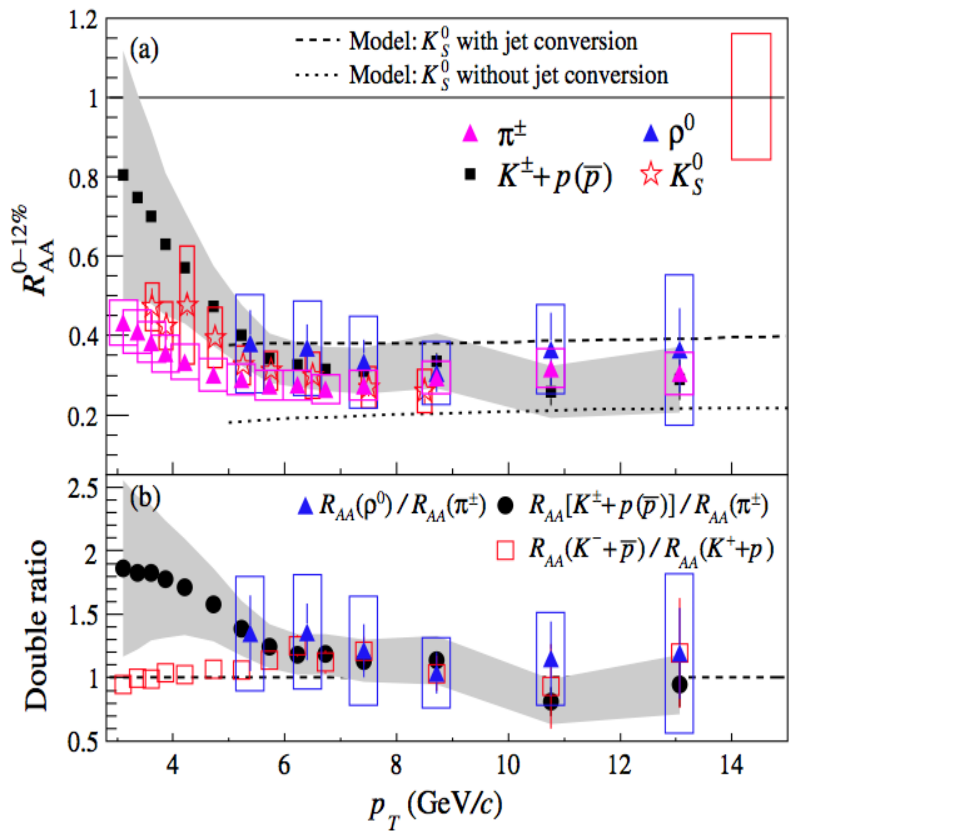
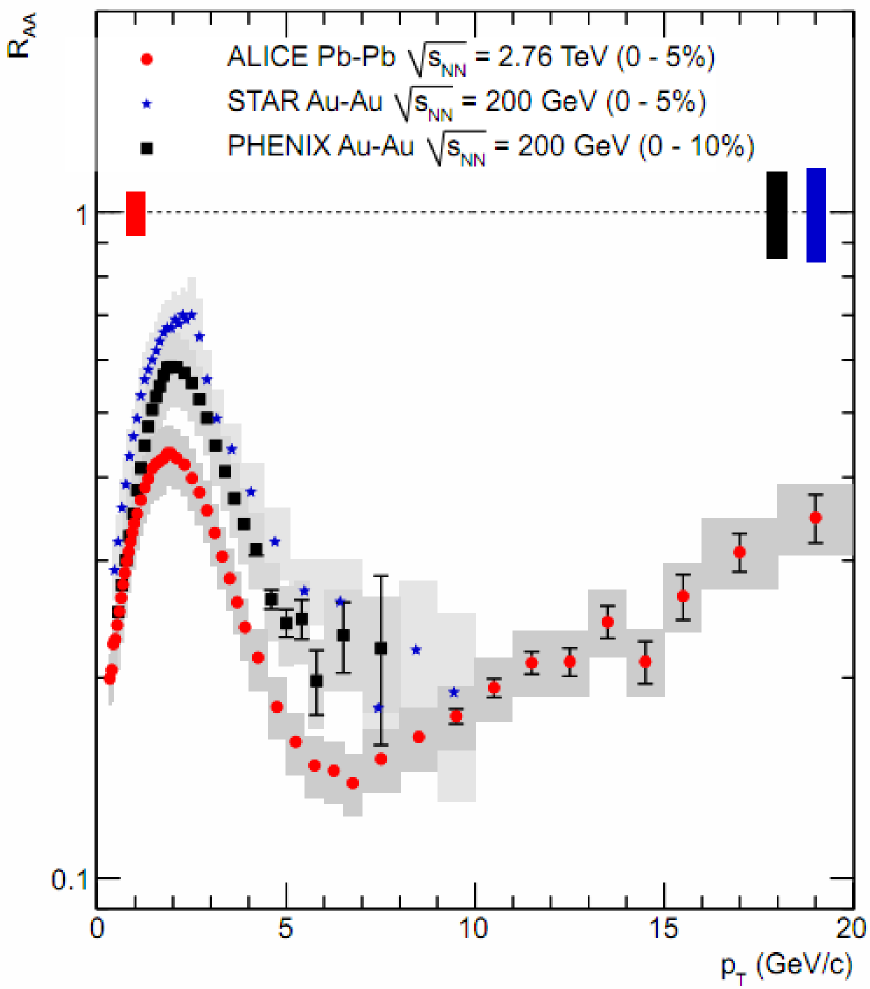


Phys. Rev. Lett. 108 072302

- Clear suppression of high p_T particles
- Common suppression patten for different particle species
- Consistent with partonic energy loss models
- Key signature of a dense colored medium

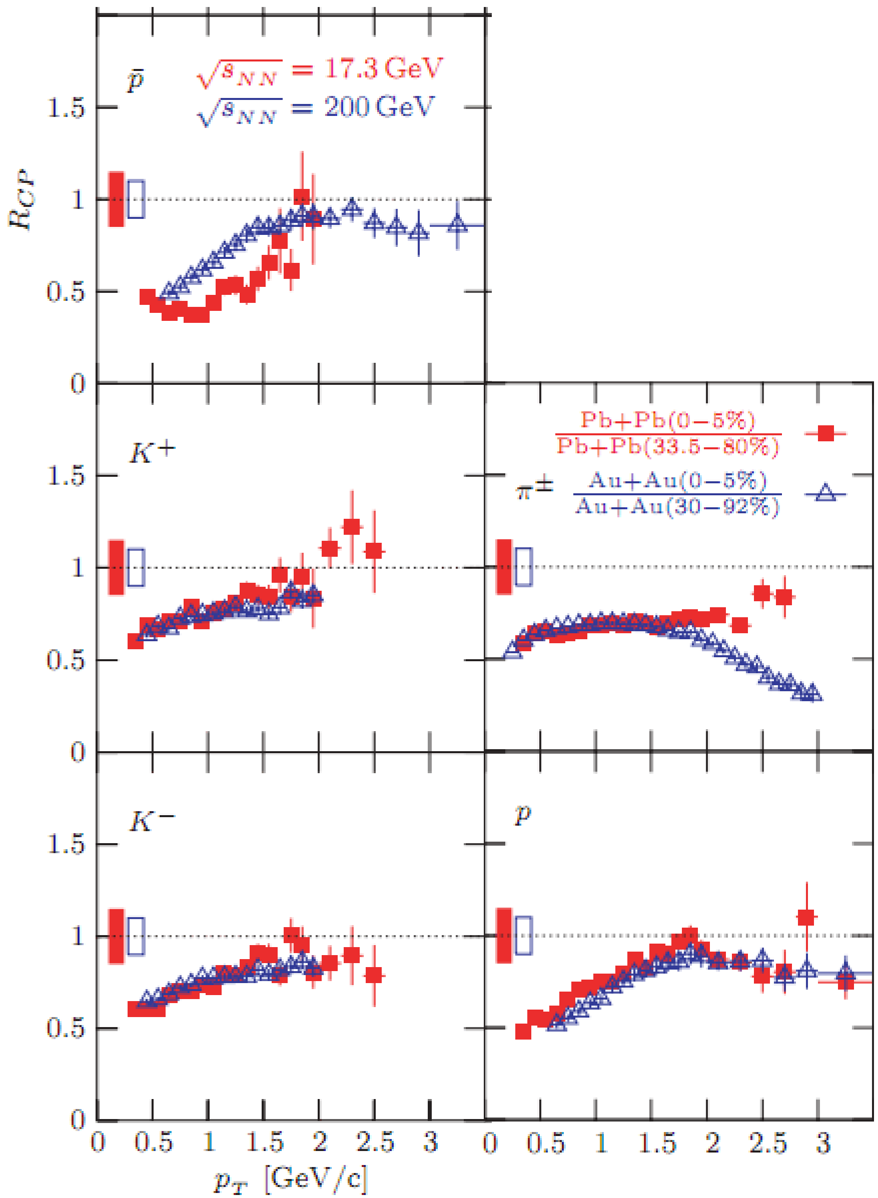
R_{AA} Measurements at LHC



arXiv:1012.1004v1

- Increased suppression at higher collision energies
- Suppression extends to higher transverse momentum

R_{CP} Measurements at SPS



Phys. Rev. C. 77 034906

- Attempted to measure R_{CP} at $\sqrt{s_{NN}} = 17.3$ GeV
- Statistics too limited to make a firm statement about the extent of suppression

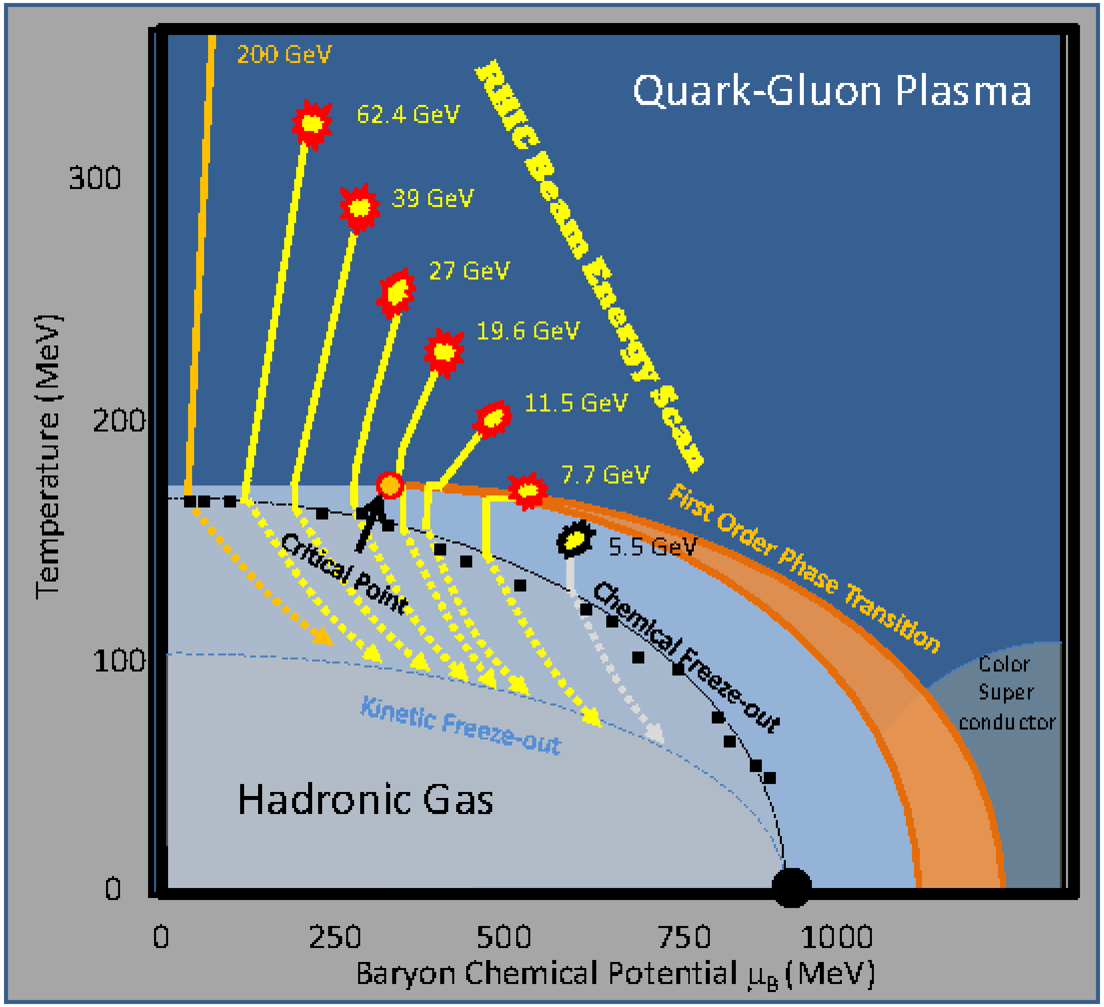
The RHIC Beam Energy Scan (BES)

Main Goals:

To search for...

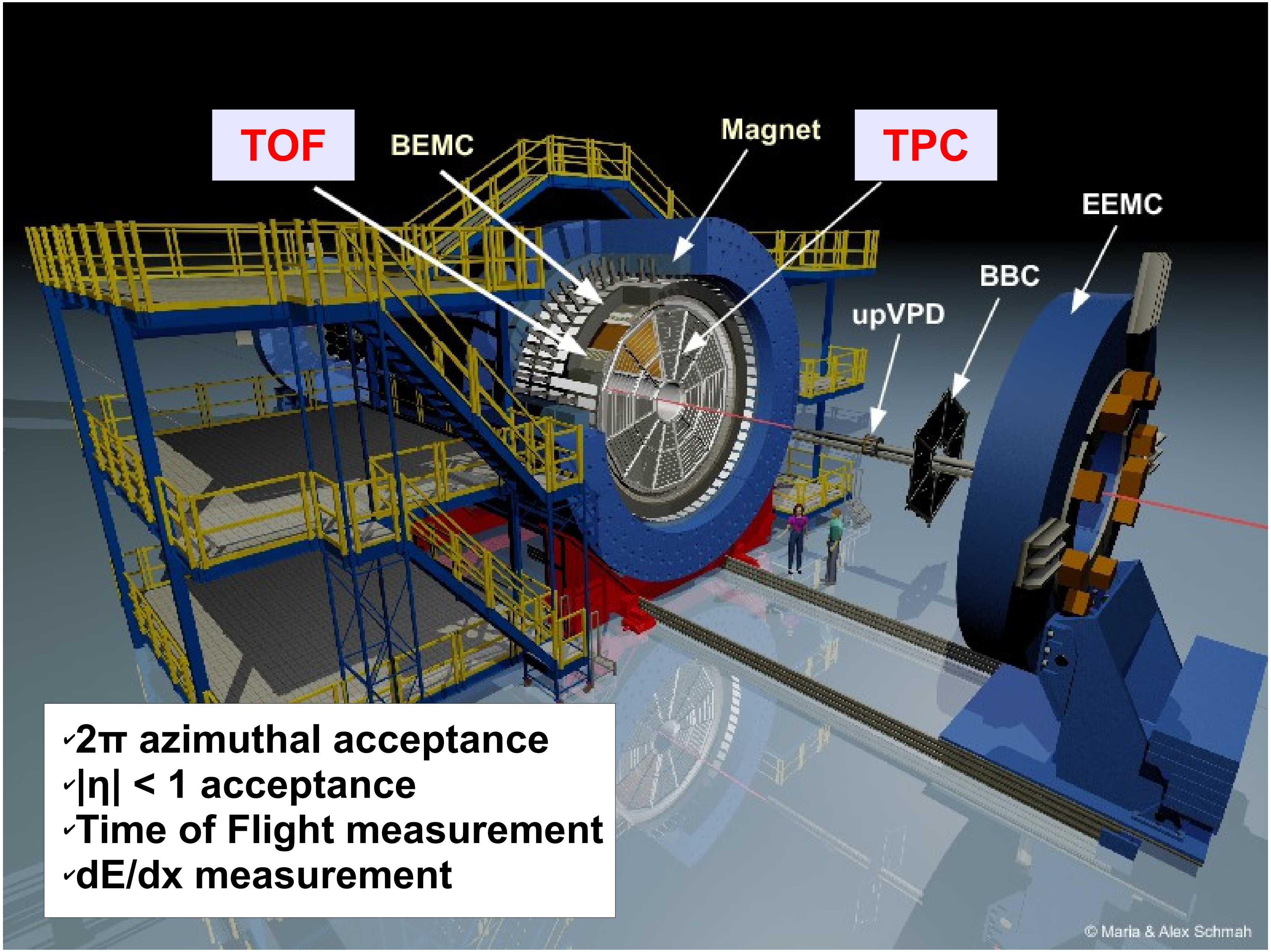
I. Critical point
II. Phase transition
III. Turn-off of QGP signatures

$\sqrt{s_{NN}}$ (GeV)	MB Events (10^6)
7.7	4.3
11.5	11.7
19.6	35.8
27	70.4
39	130.4
62.4	67.3

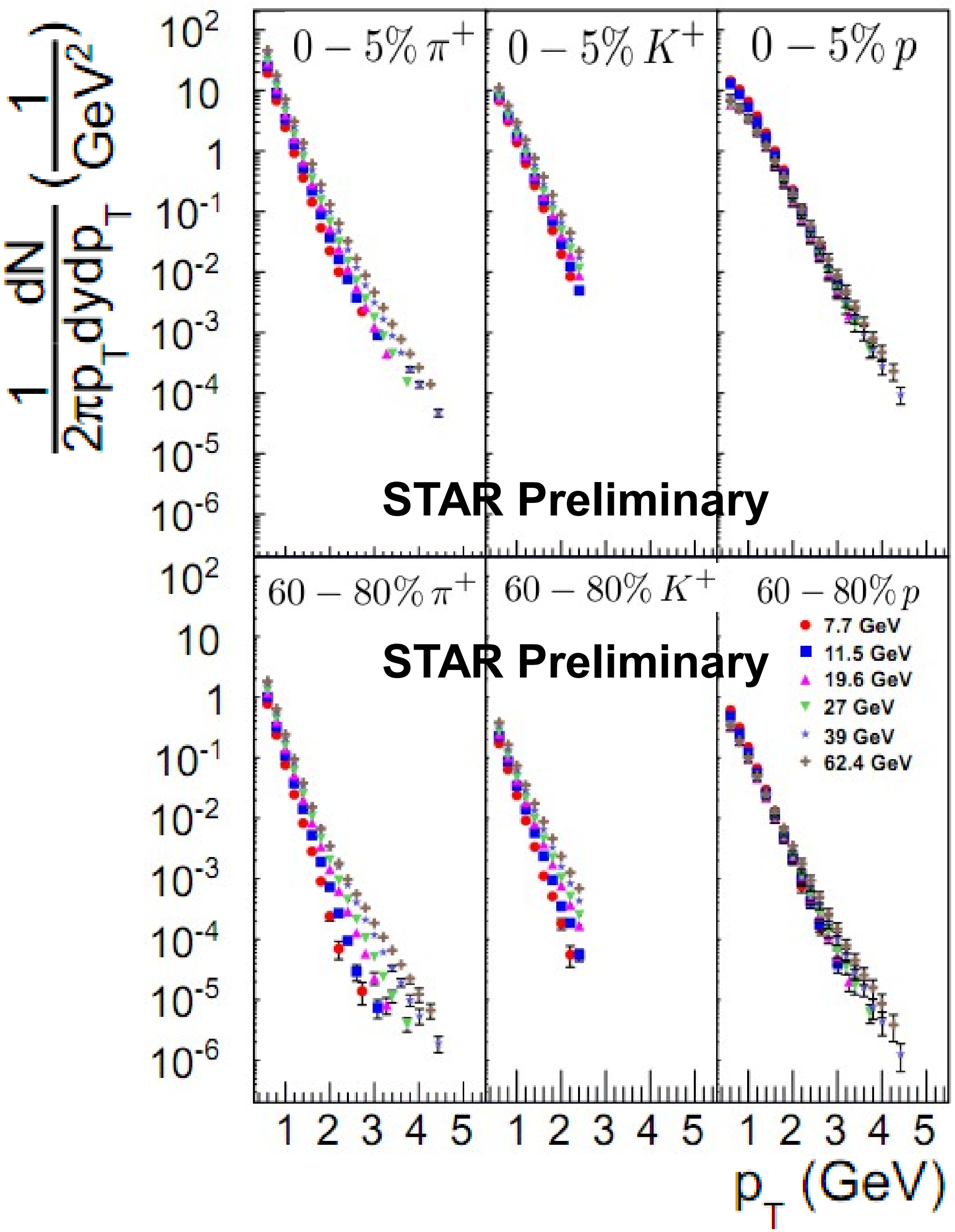


arXiv:1007.2613

The STAR Detector

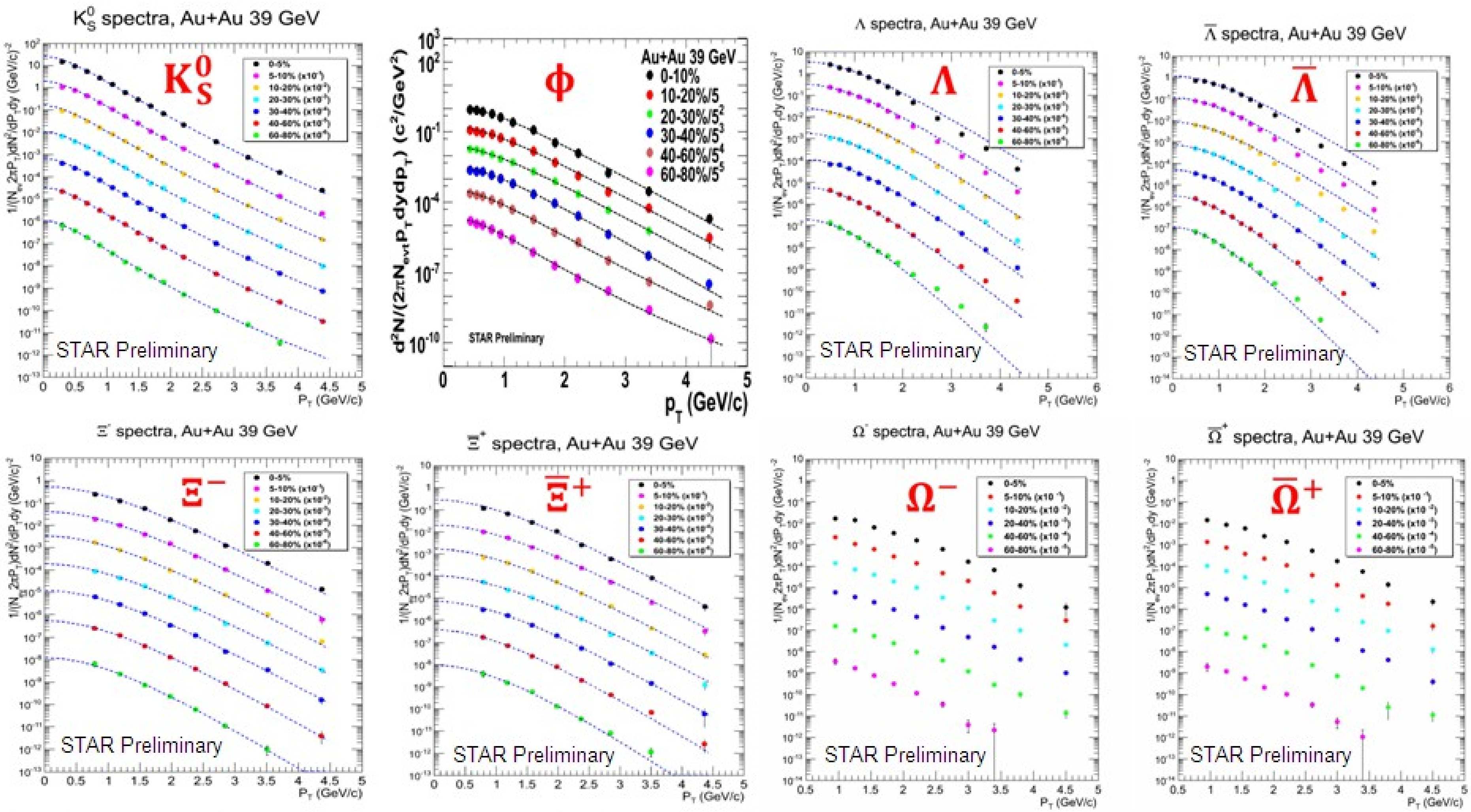


Charged Particle Spectra



- Spectra for identified charged particles is extracted at each collision energy
- Efficiency and energy loss corrections are applied

Strange Particle Spectra

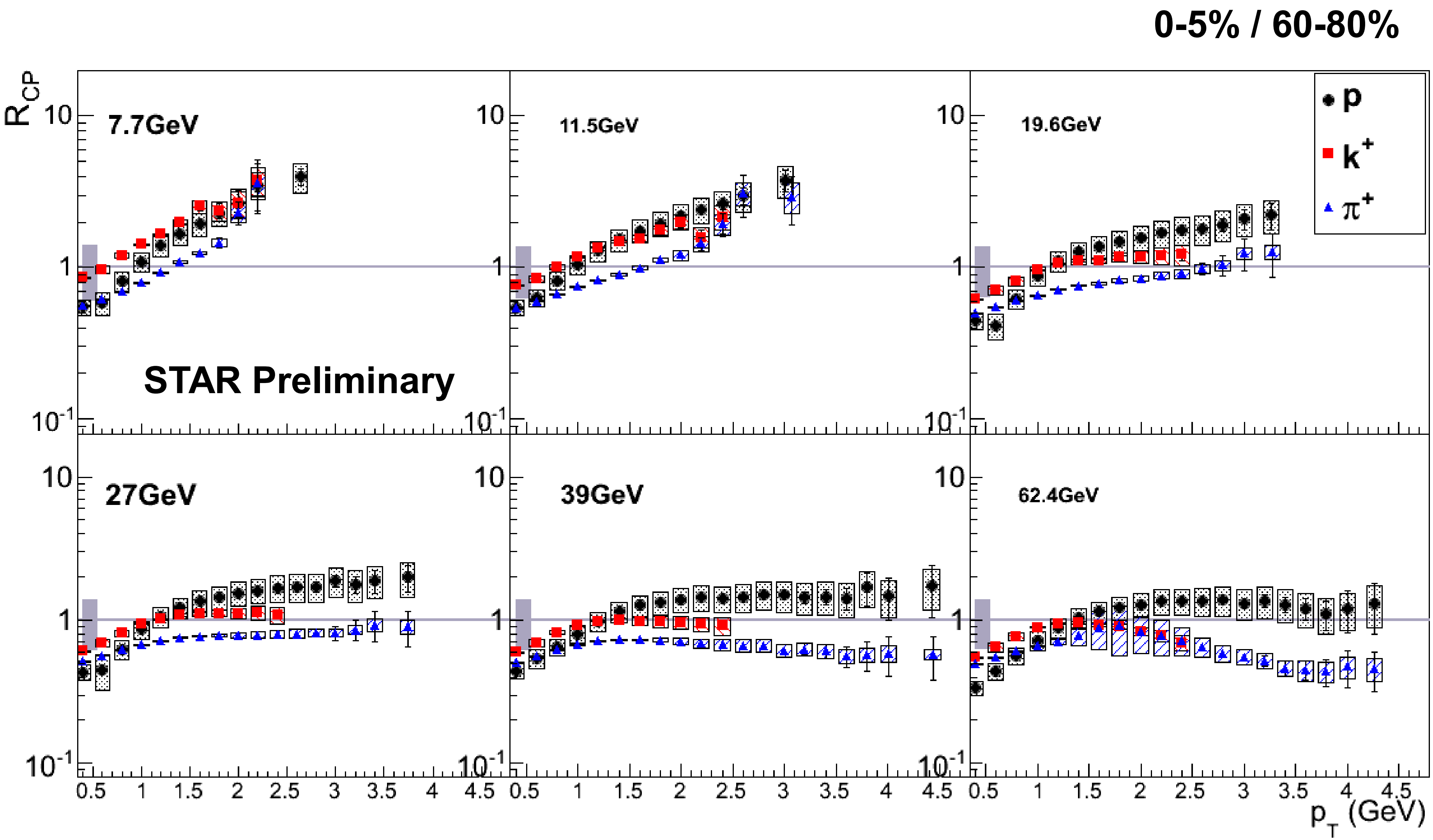


Statistical error

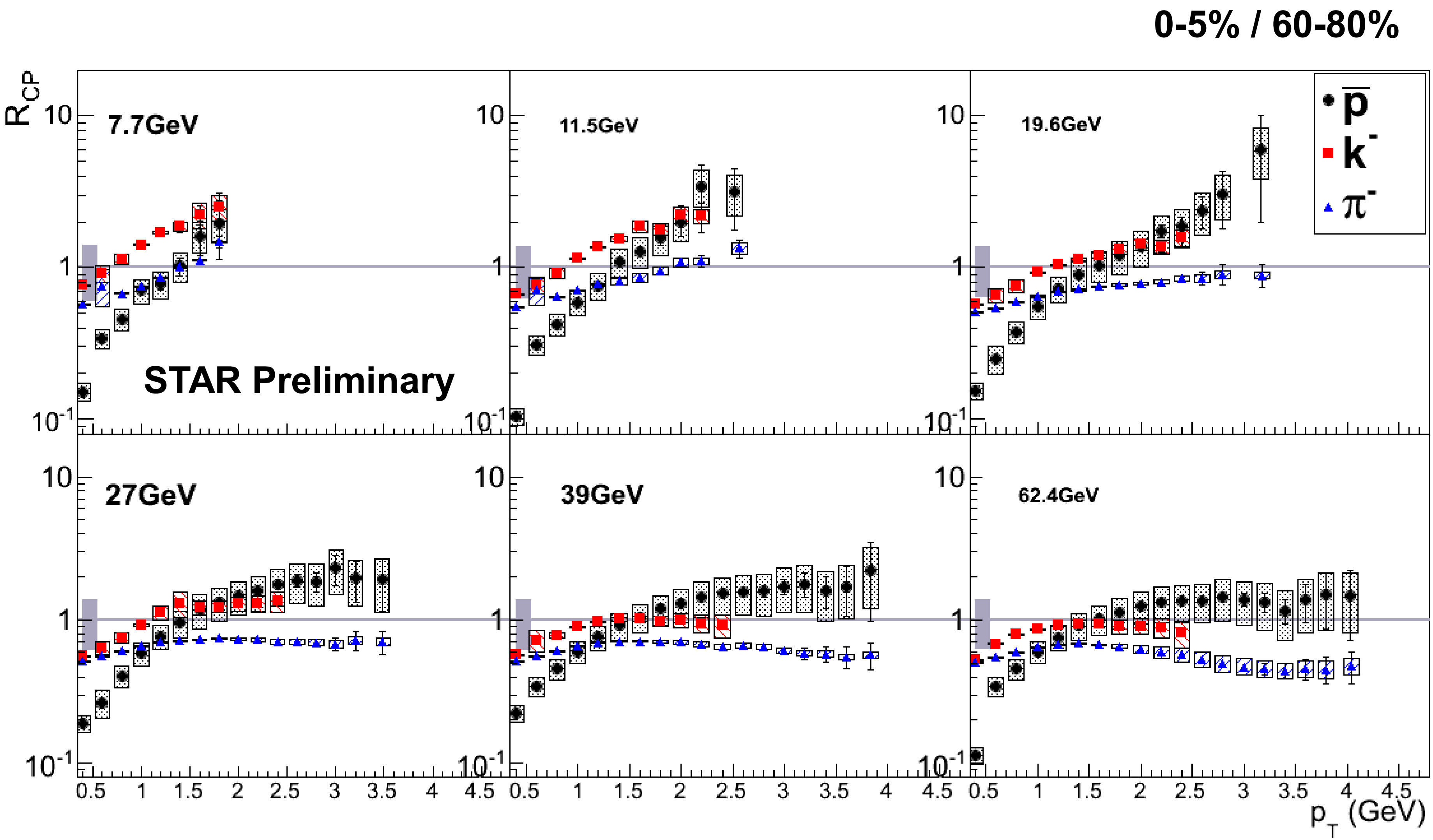
- Extensive strange particle spectra
- **$\Lambda(\bar{\Lambda})$ spectra are weak decay feed-down corrected**

  ~ 20% for Λ: ~ 25% for $\bar{\Lambda}$

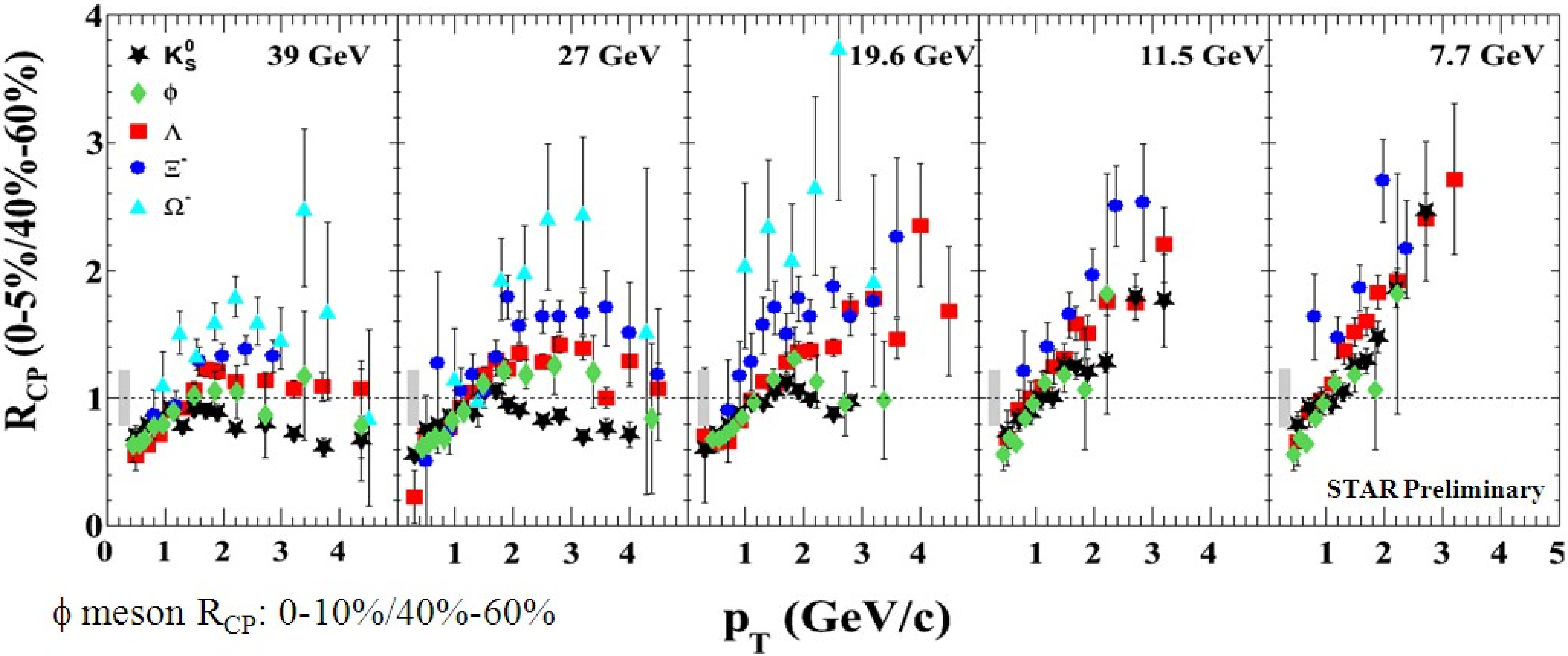
Positive Charge R_{CP}



Negative Charge R_{CP}



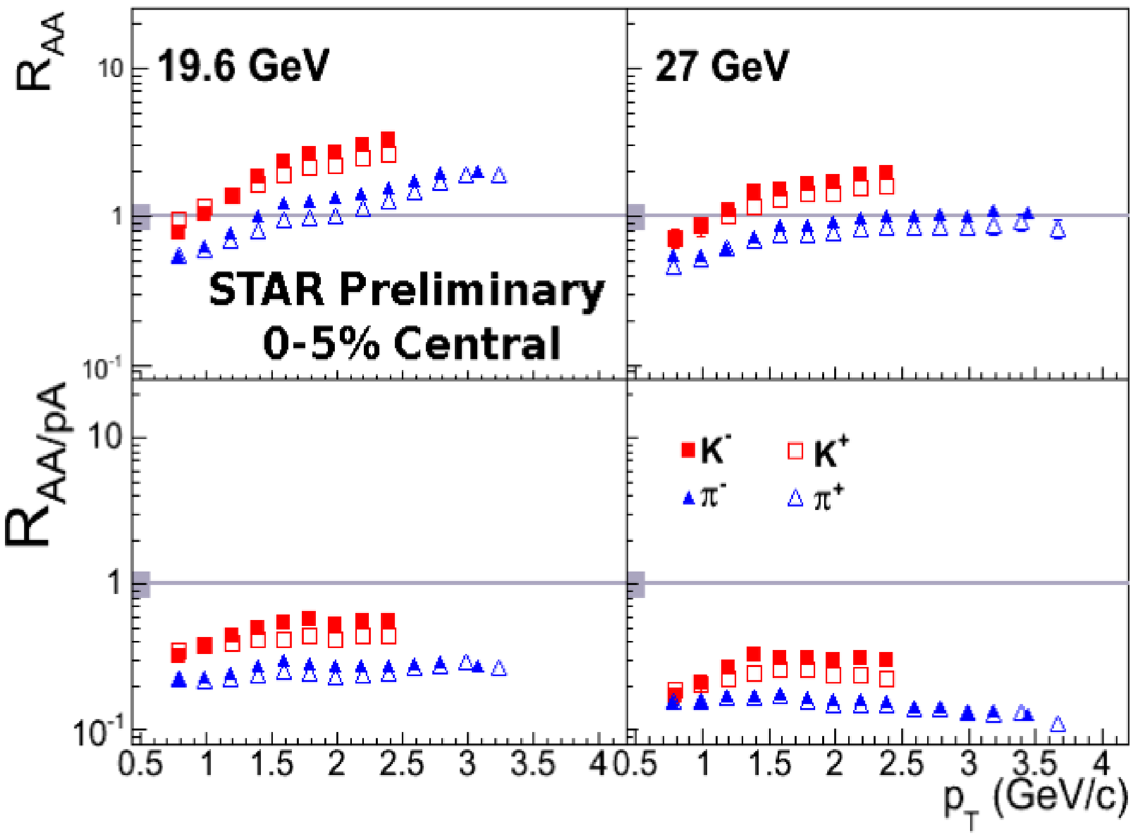
Strange Particle R_{CP}



φ meson R_{CP}: 0-10%/40%-60%

- No K^0_S suppression at lower energies
- Cronin effect takes over partonic rescatterings at lower energies

R_{AA} and $R_{AA/pA}$



- Cronin enhancement stronger at high p_T
- Impact on R_{CP} and R_{AA} would be a reduction of apparent suppression

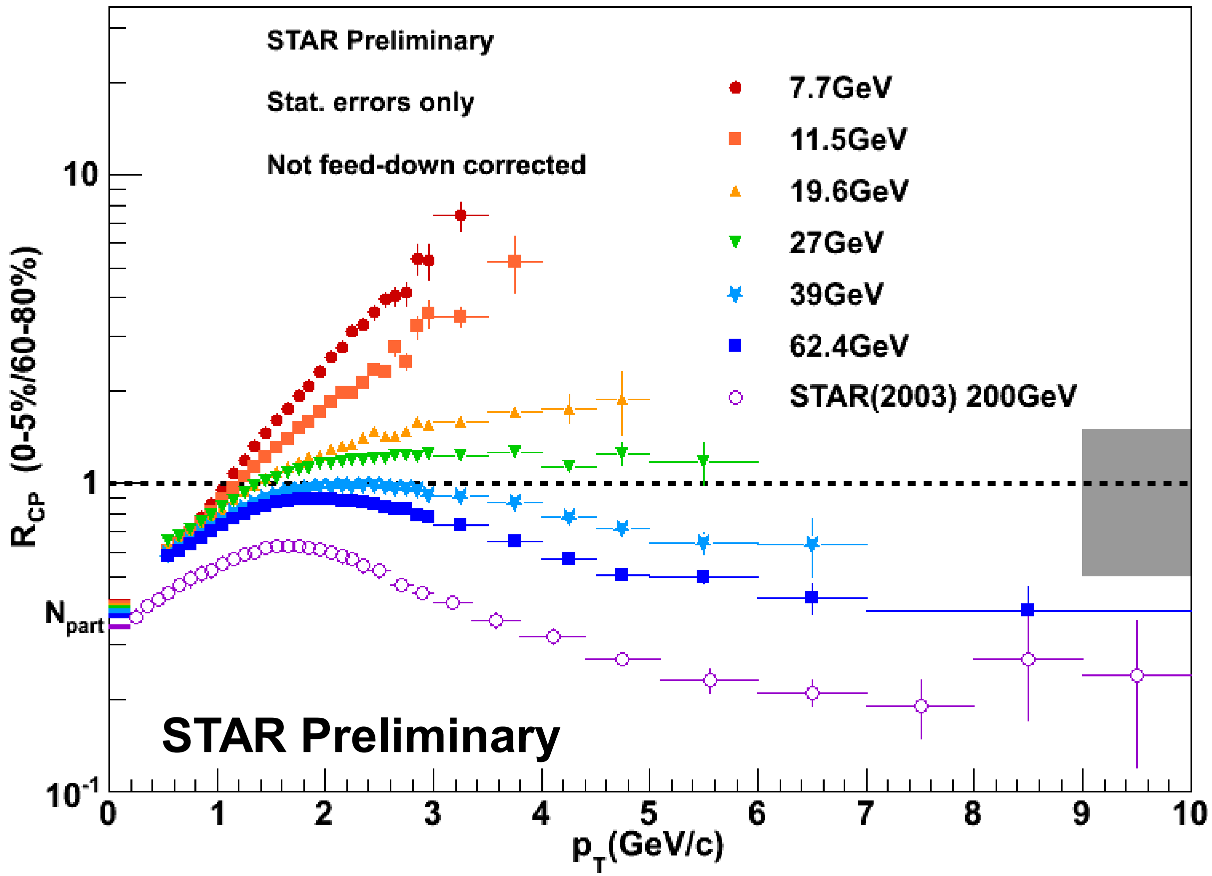
$$R_{AA/pA}(p_T) = \frac{\langle N_{coll}^{pA} \rangle}{\langle N_{coll}^{AA} \rangle_{0-5\%}} * \frac{d^2 N_{AA}^{0-5\%} / dy dp_T}{d^2 N_{pA} / dy dp_T}$$

p+W reference

Phys. Rev. D 19, 764–778 (1979)

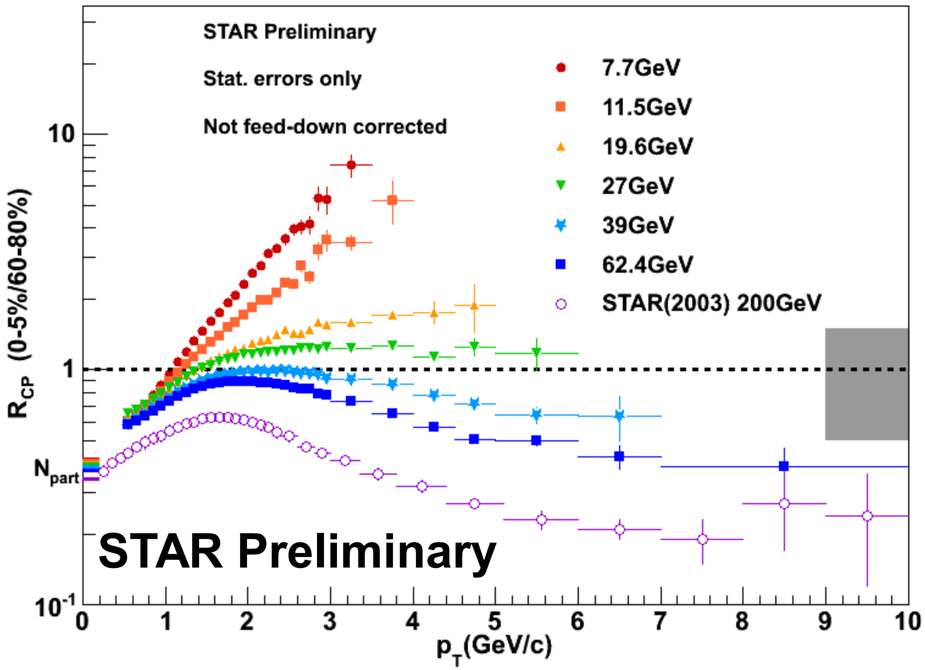
$R_{AA/pA}$ is meant to be qualitative, the Cronin effect scales in a more complicated way.

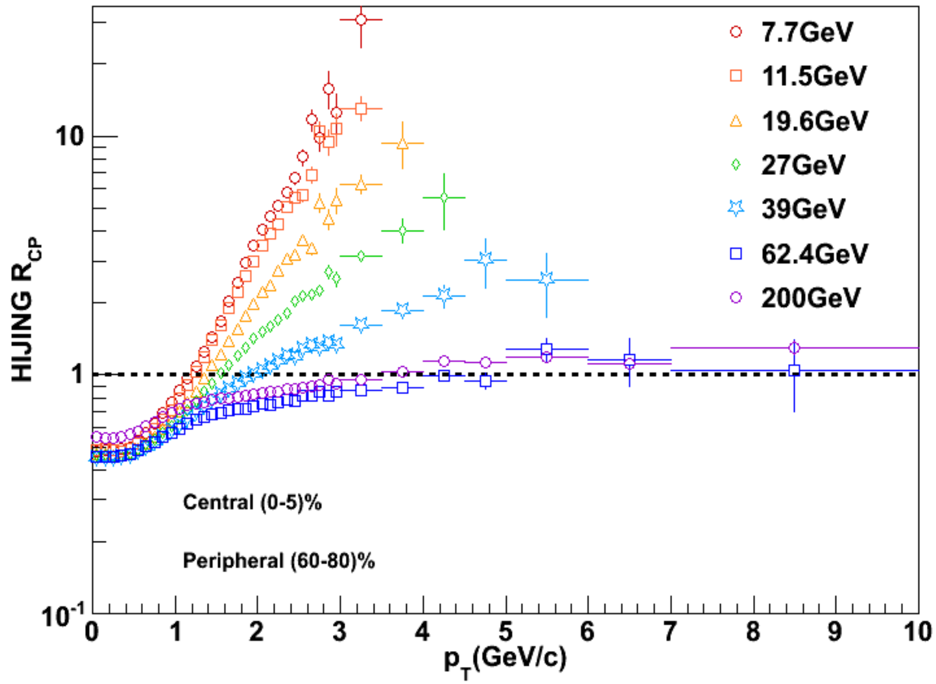
Unidentified R_{CP}



High p_T suppression turns off at lower collision energies.

HIJING Simulation



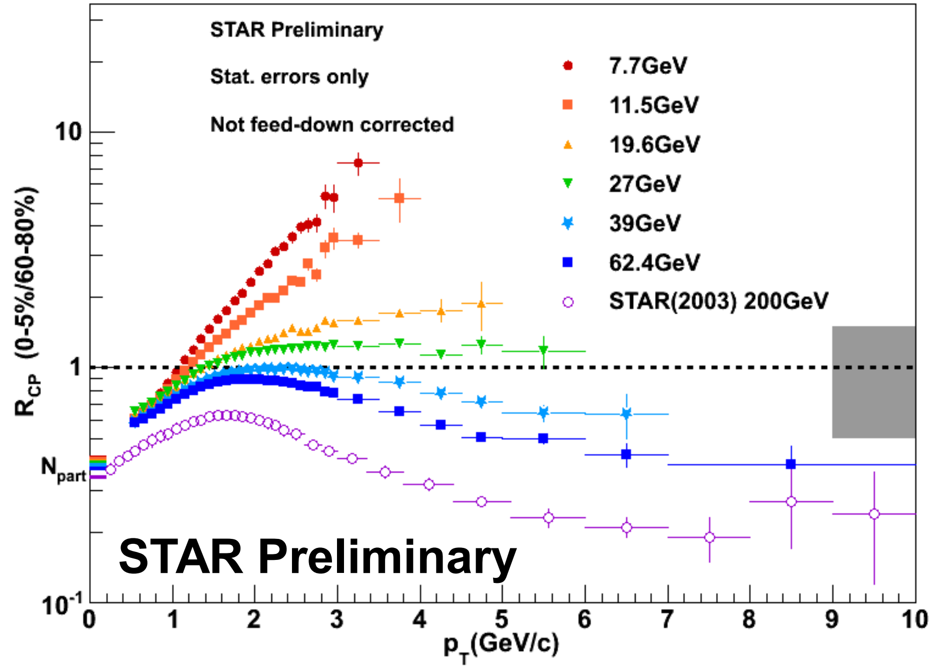


HIJING qualitatively describes trend between energies without jet quenching enabled.

Discussion

Suppression turns off at lower collision energies

- Possible disappearance of QGP?
- Cronin effect
- Relative contributions of soft physics and hard scattering



Model comparisons are necessary!

Summary for high p_T hadron suppression

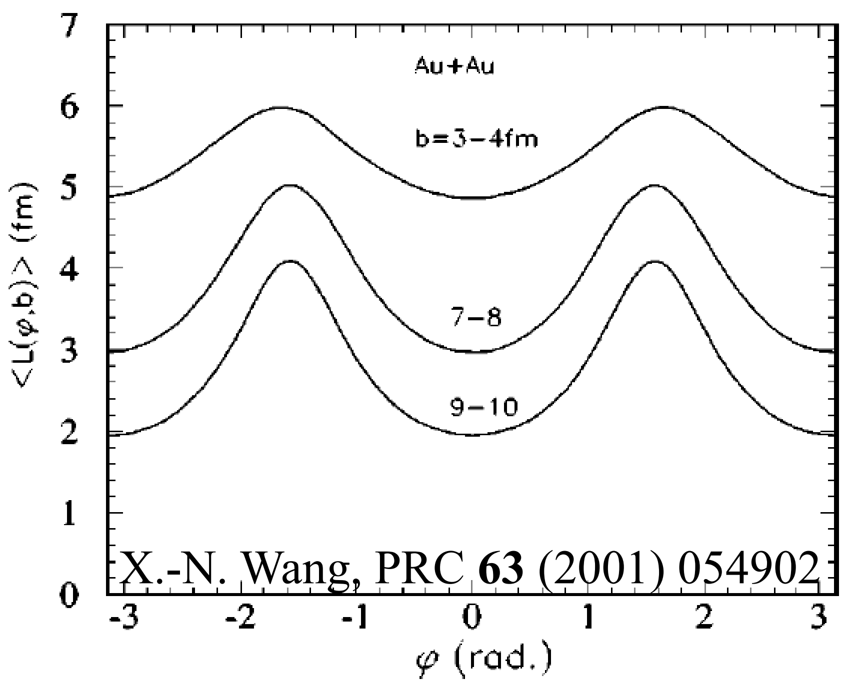
- Nuclear modification factors have been measured in RHIC beam energy scan
- Smooth transition in behavior between energies
- Clear turn off of suppression ($R_{CP} < 1$) has been observed at 27 GeV and below
  - R_{CP} has varying sensitivity to jet quenching at different collision energies
  - Further studies are ongoing to disentangle effects

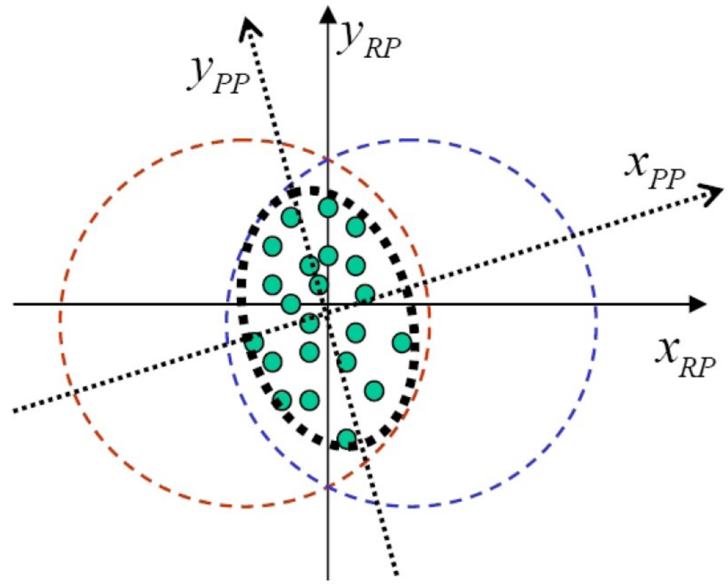
What is Jet v_2?

In-medium pathlength depends on orientation to reaction plane

Pathlength-dependent jet quenching →

Energy/number of reconstructed jets may depend on orientation to reaction plane.





- "Jet v_2" → correlation between *reconstructed* jets and the reaction plane (or 2nd -order participant plane)
- "Jet v_2" ≠ "Jet flow"

Measuring Jet v_2

- Why measure Jet v_2?
  → Information about pathlength-dependent parton energy loss
  → Information about jet-finding techniques and biases
  → Necessary for background subtraction in jet-hadron correlations

- How to measure jet v_2:

$$v_2^{\mathrm{jet}} = \frac{\left\langle \cos\left(2(\phi_{\mathrm{jet}} - \Psi_{\mathrm{EP}})\right)\right\rangle}{Res}$$

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1) Angle of reconstructed jet axis

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1) Angle of reconstructed jet axis
2) Azimuthal angle of event plane

$$\Psi_{\mathrm{EP}} = \frac{1}{2}\tan^{-1}\left(\frac{\sum_i w_i \sin(2\phi_i)}{\sum_i w_i \cos(2\phi_i)}\right)$$

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3) Event plane resolution

Jets at STAR

Run 7 Au+Au $\sqrt{s_{NN}}$ = 200 GeV

High Tower (HT) Trigger → Online Trigger

$E_T > 5.4$ GeV in one tower

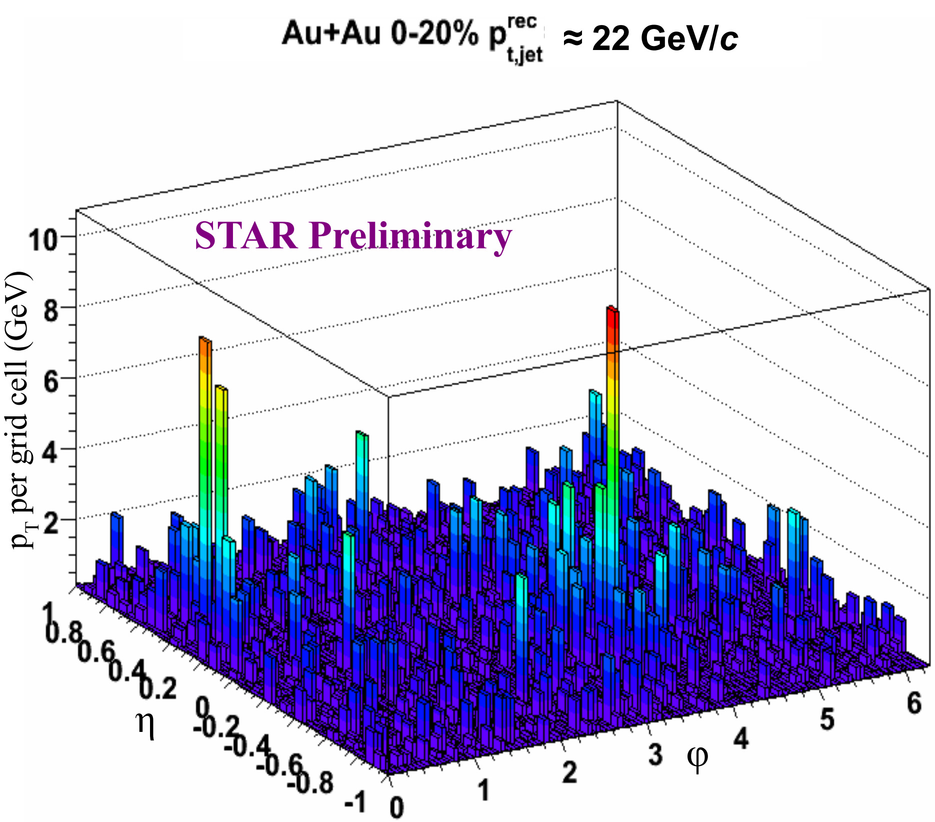
$\Delta\varphi \times \Delta\eta = 0.05 \times 0.05$

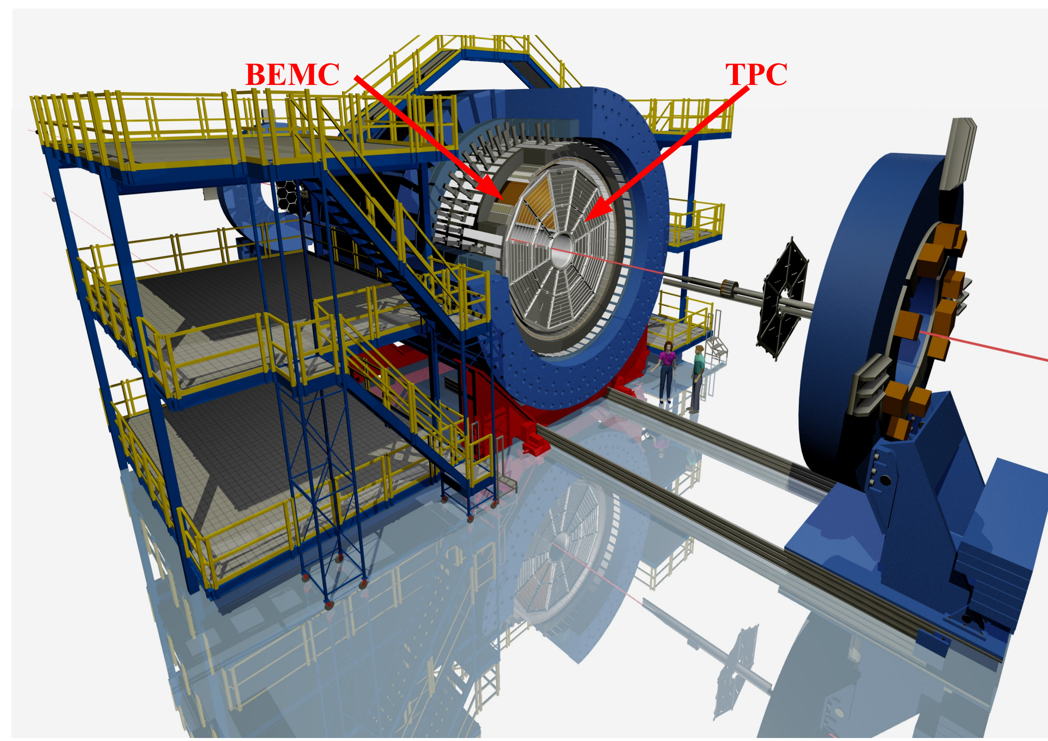
Offline cut: $E_T > 5.5$ GeV

Trigger Jets found with Anti-k_T algorithm [1]

($R = 0.4$, $p_T^{track,tower} > 2$ GeV/c).

[1] M. Cacciari and G. Salam, Phys. Lett. B **641,** 57 (2006)





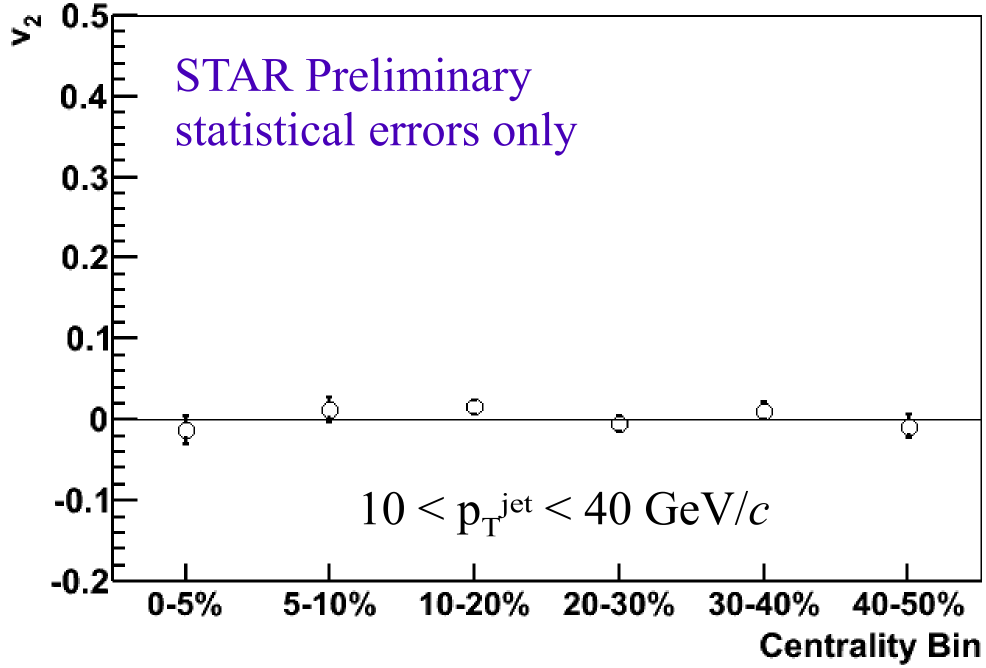
Artificial Sources of Anisotropy

- **Background Fluctuations and the Jet Energy Scale**
  Background particles (with $p_T > 2$ GeV/c) with significant v_2 are more likely to be clustered into the jet cone in-plane versus out-of-plane
  → more low-p_T jets reconstructed with a higher p_T
  → increased number of in-plane jets in a fixed reconstructed jet p_T range

- **Biased Event Plane**
  Jet fragments included in event plane calculation
  → event plane pulled towards jet

Background Fluctuations

- Embed p+p HT jets isotropically into Au+Au minimum bias events
- Reconstruct p_T of p+p jet before and after embedding
- Correlate reconstructed jet axis with event plane of Au+Au event
- Calculate jet v_2 for a given range in jet p_T



Jet Definition:
HT trigger $E_T > 5.5$ GeV
constituent $p_T^{cut} = 2$ GeV/c

○ jet p_T calculated before embedding

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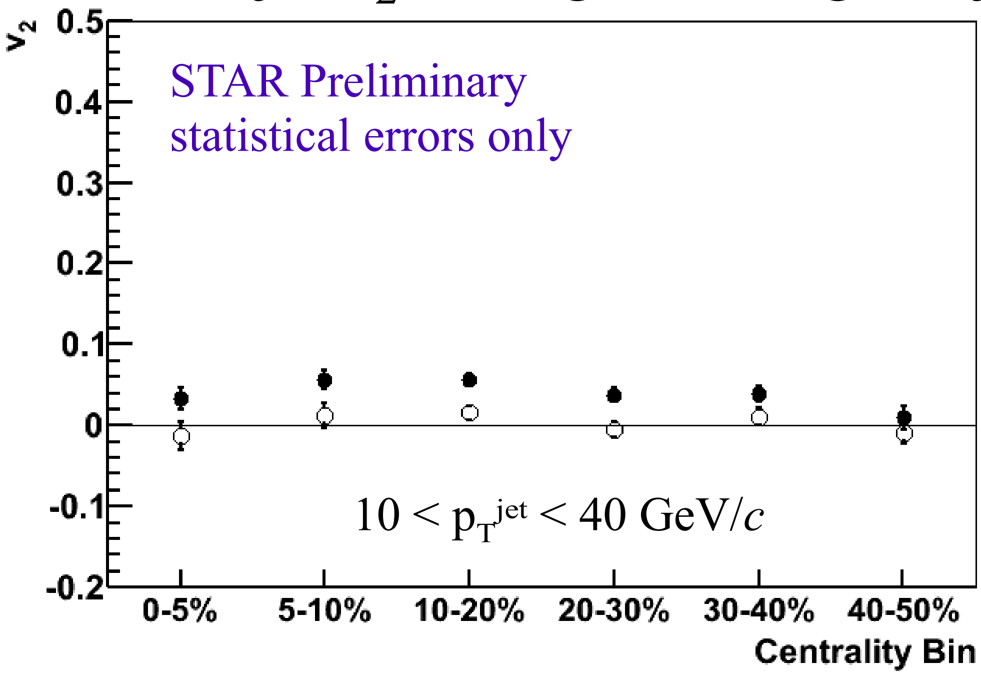

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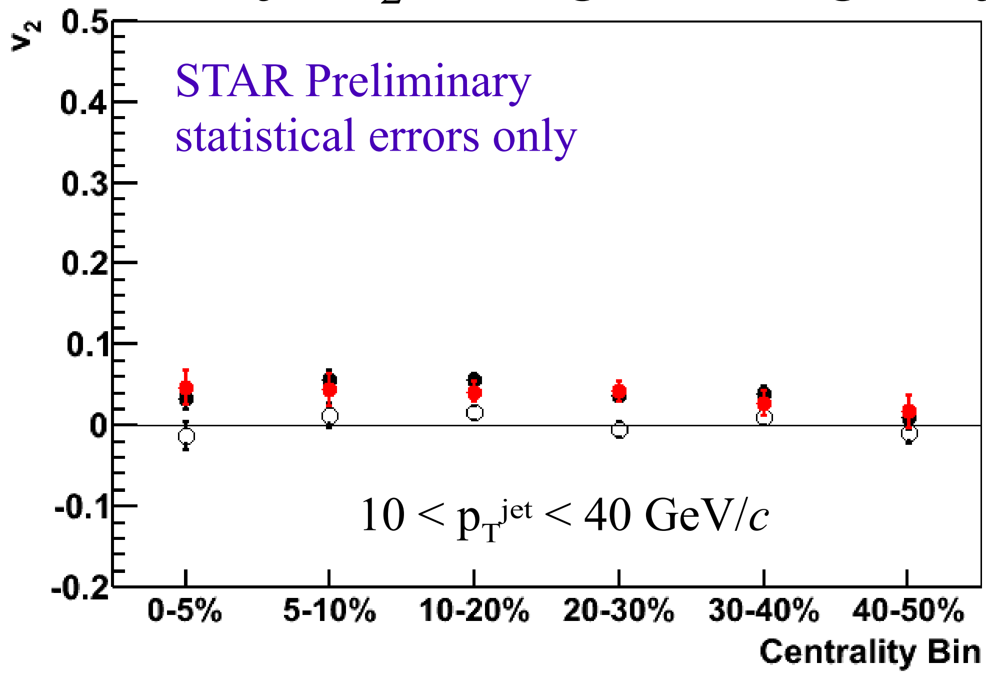
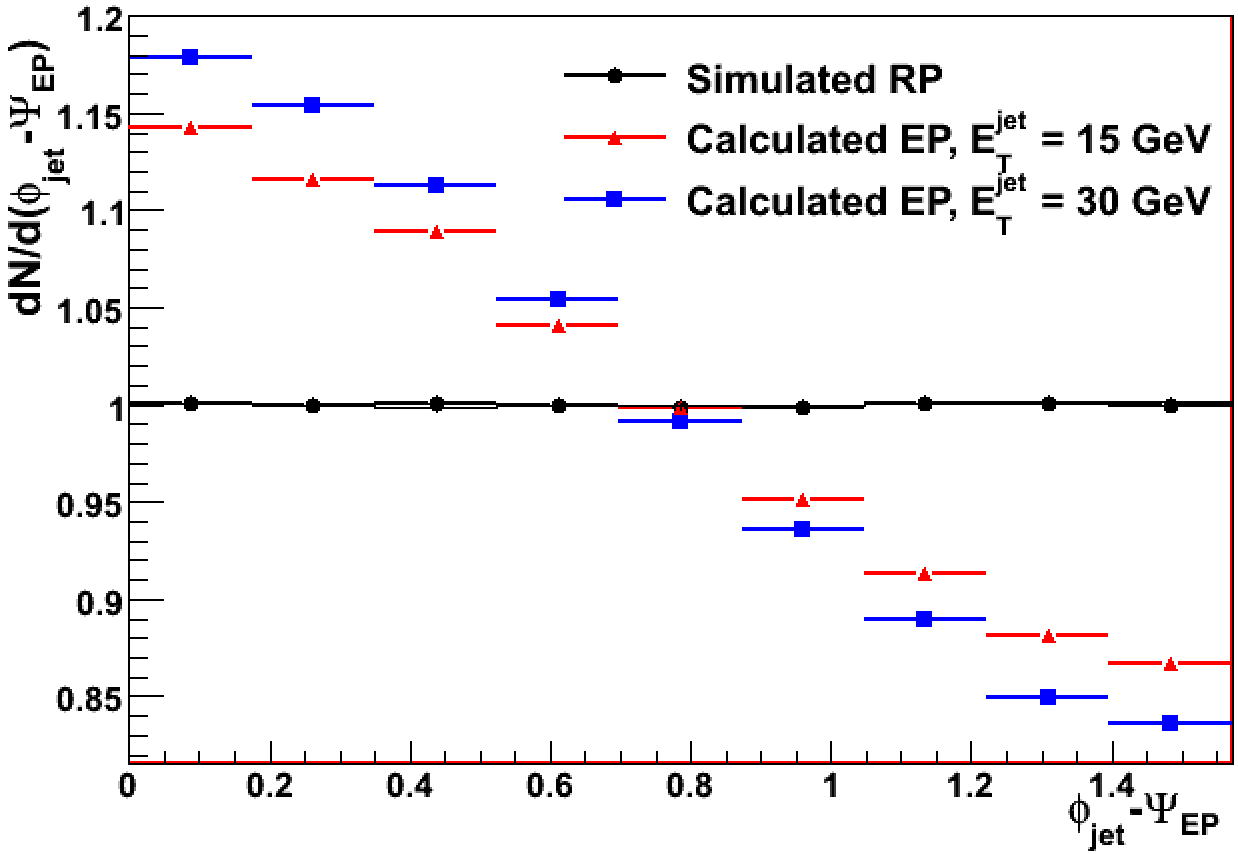


Jet Definition:
HT trigger $E_T > 5.5$ GeV
constituent $p_T^{cut} = 2$ GeV/c

○ jet p_T calculated before embedding
● jet p_T calculated after embedding
● difference

- Artificial jet v_2 caused by background fluctuations is ~ 4%
- Subtract from measured jet v_2 values.

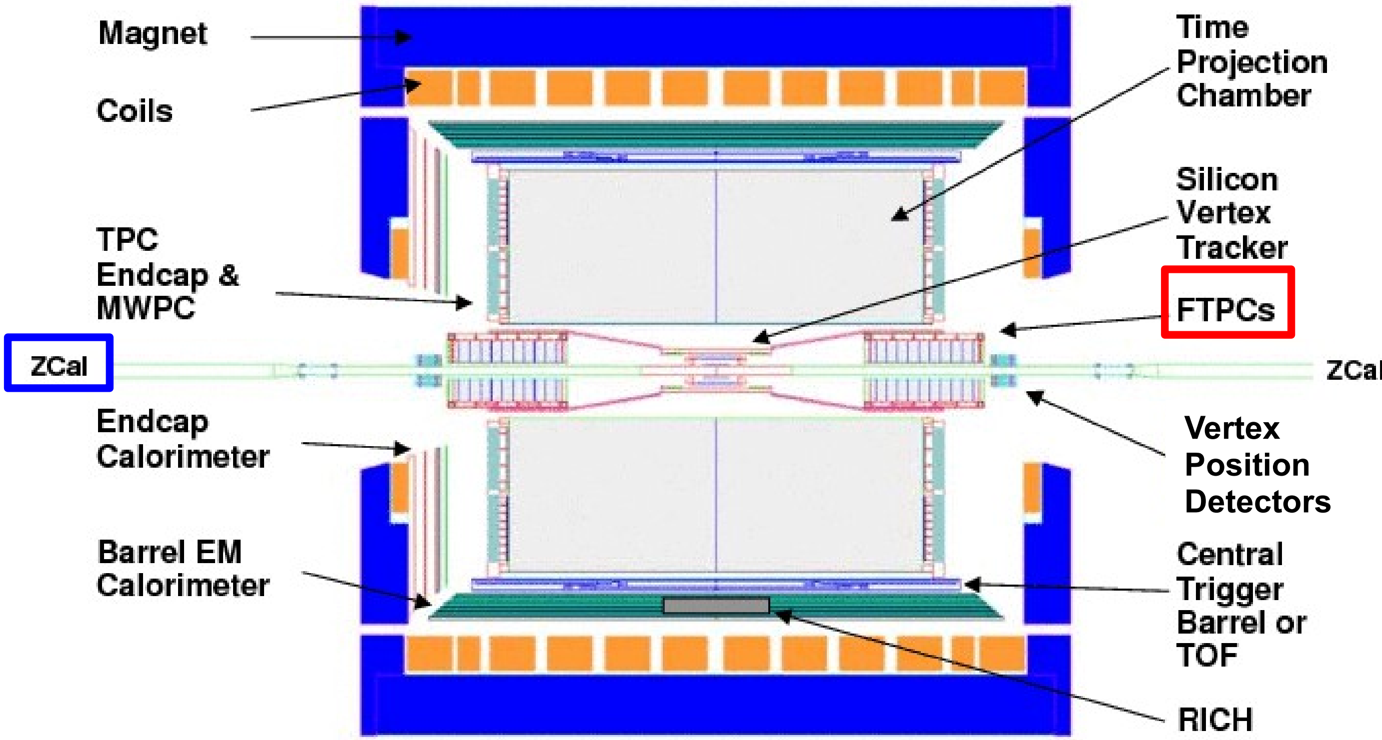
Jet – Event Plane Bias



Simulation:
PYTHIA jets embedded in thermal background

- Calculating the event plane at mid-rapidity leads to significant jet – event plane bias!
- Need to determine event plane at forward rapidities to measure jet v_2 at mid-rapidity...

STAR Forward Capabilities



Zero Degree Calorimeter – Shower Maximum Detectors

→ Spectator neutrons

$|\eta| > 6.3$

Forward Time Projection Chambers

→ Charged particle tracks

$2.8 < |\eta| < 3.7$

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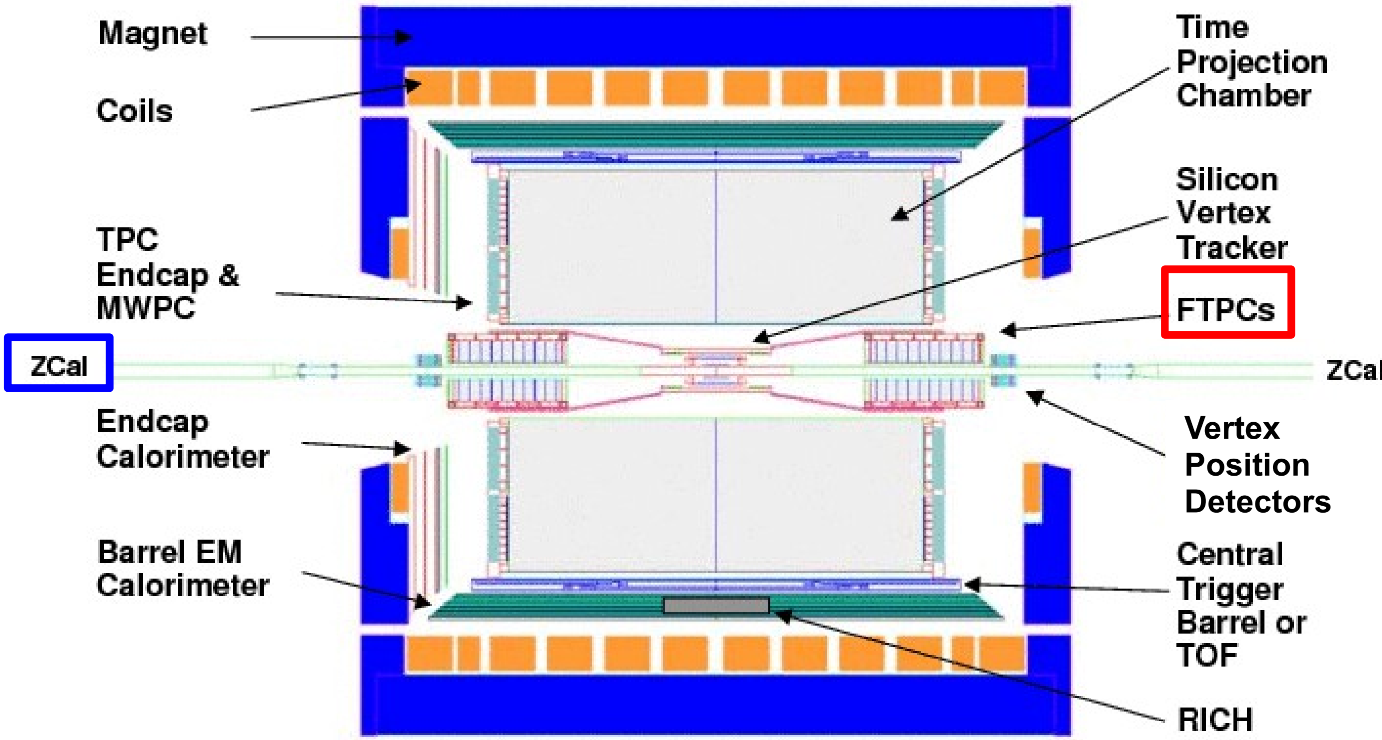

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→ Spectator neutrons

$|\eta| > 6.3$

Forward Time Projection Chambers

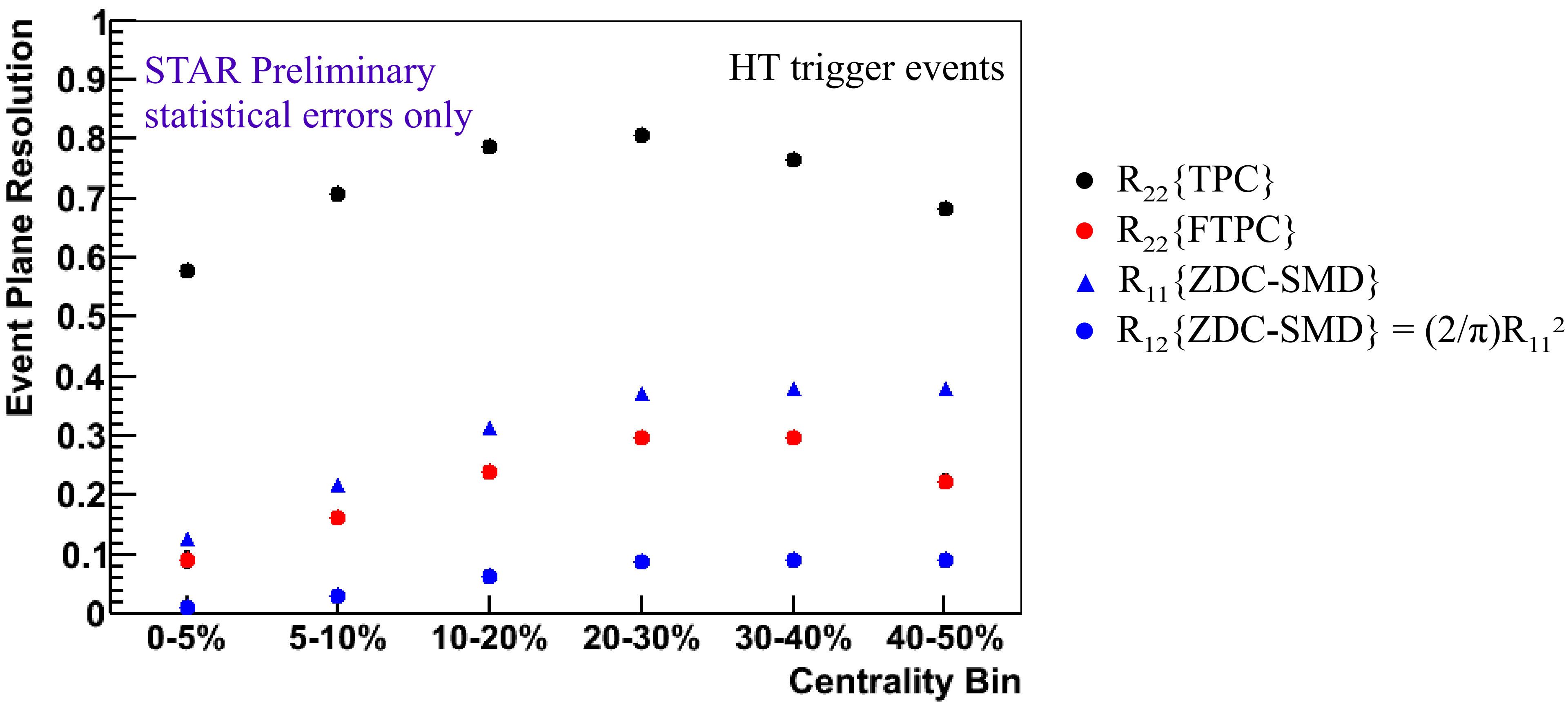
→ Charged particle tracks

$2.8 < |\eta| < 3.7$

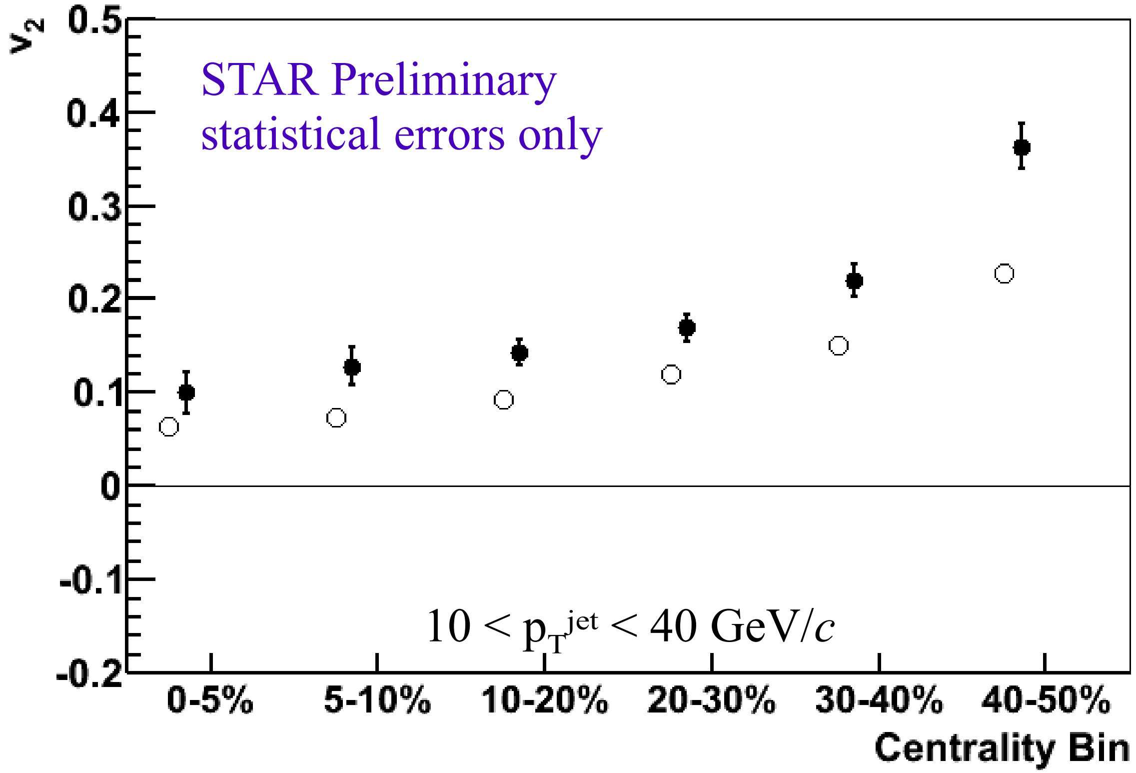
$|\Delta\eta| > 5.7$ $|\eta_{jet}| < 0.6$ $|\Delta\eta| > 2.2$

Event Plane Resolution

- Resolution determined from sub-event plane method
- Mixed harmonics: measure v_2{ZDC-SMD} with respect to Ψ_1



Jet v_2 and Trigger v_2



Jet Definition:
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● Jet v_2\{TPC EP\}

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- Jet v_2\{TPC\} > HT v_2\{TPC\} → Jet – event plane bias is more significant when jets have additional high-p_T fragments

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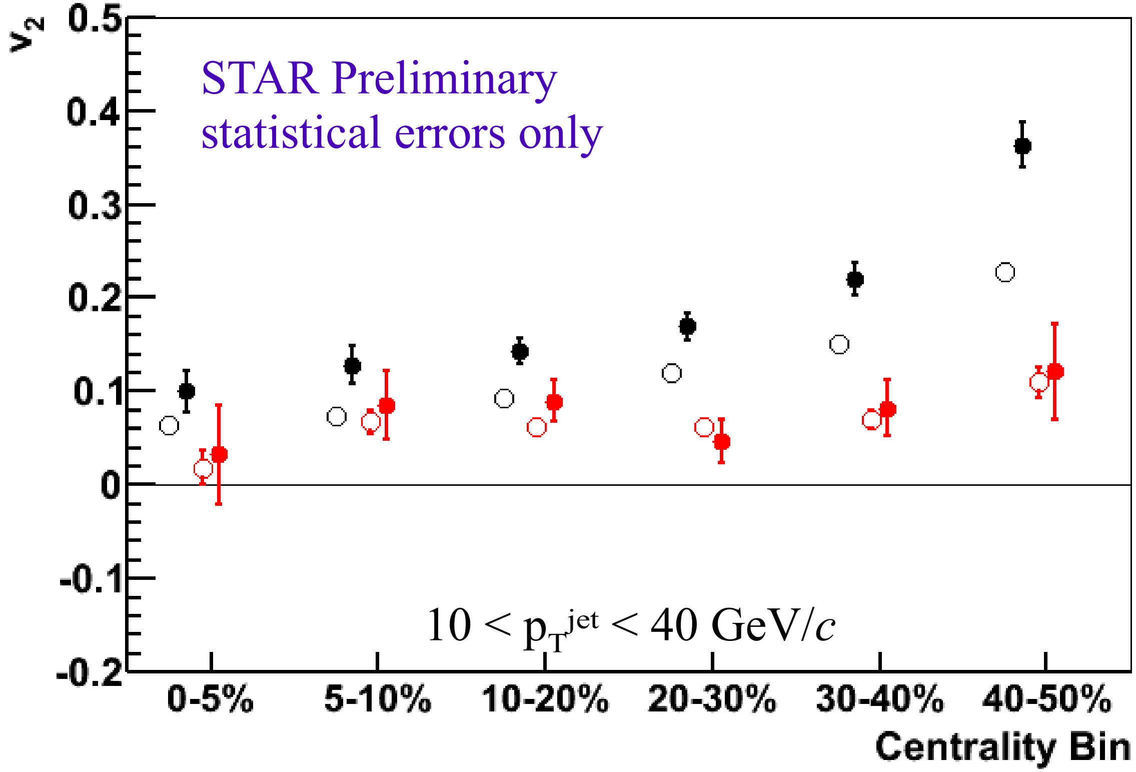

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- Jet v_2\{TPC EP\}
- Jet v_2\{FTPC EP\}
- HT trigger v_2\{TPC EP\}
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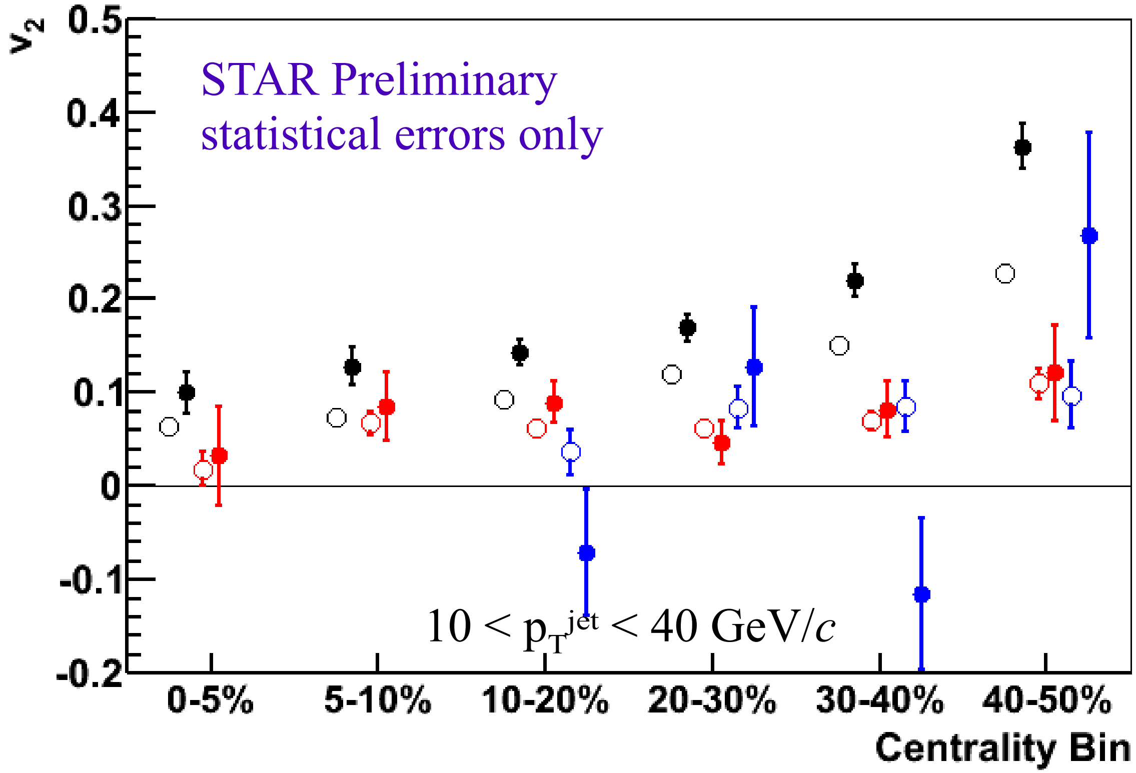
- Jet v_2\{TPC\} > HT v_2\{TPC\} → Jet – event plane bias is more significant when jets have additional high-p_T fragments
- Jet v_2\{FTPC\} ~ HT v_2\{FTPC\} → Surface bias / bias towards unmodified jets is largely driven by high-p_T trigger requirement

Jet v_2 and Trigger v_2



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- Jet v_2{TPC EP}
- Jet v_2{FTPC EP}
- Jet v_2{ZDC-SMD EP}
- HT trigger v_2{TPC EP}
- HT trigger v_2{FTPC EP}
- HT trigger v_2{ZDC-SMD EP}

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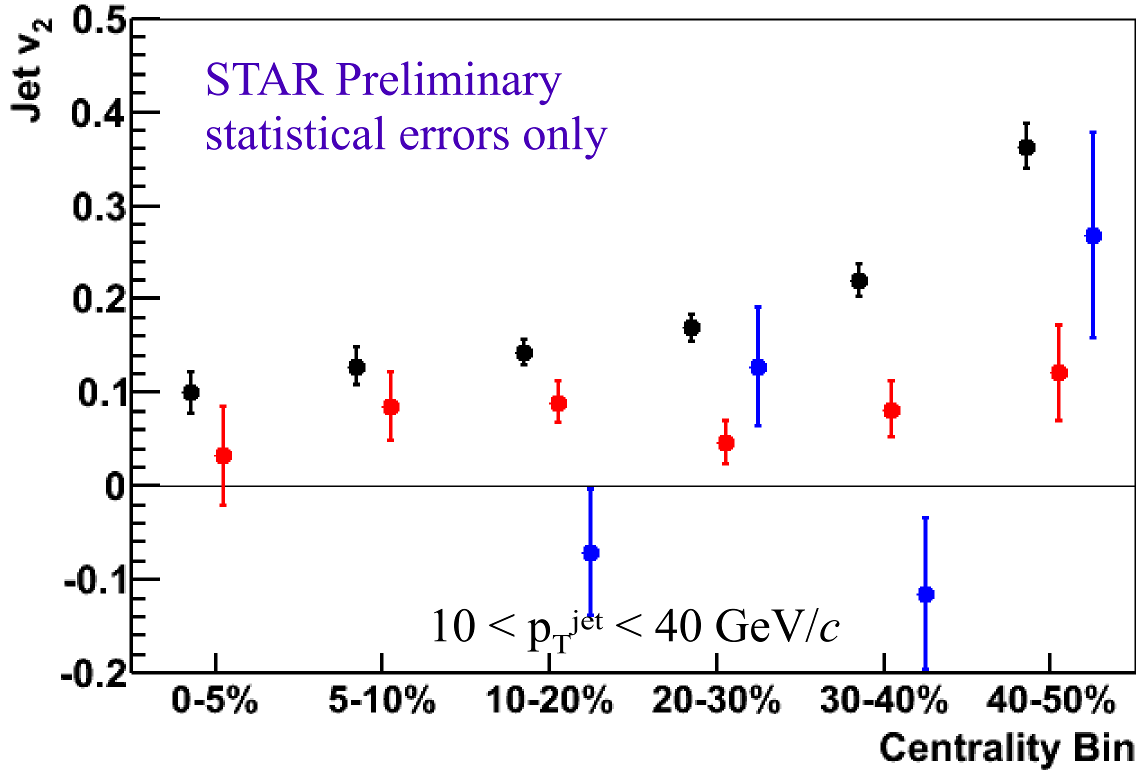
- Jet v_2{FTPC} ~ HT v_2{FTPC} → Surface bias / bias towards unmodified jets is largely driven by high-p_T trigger requirement
- HT v_2{ZDC-SMD EP} > 0

Jet v_2 vs Centrality



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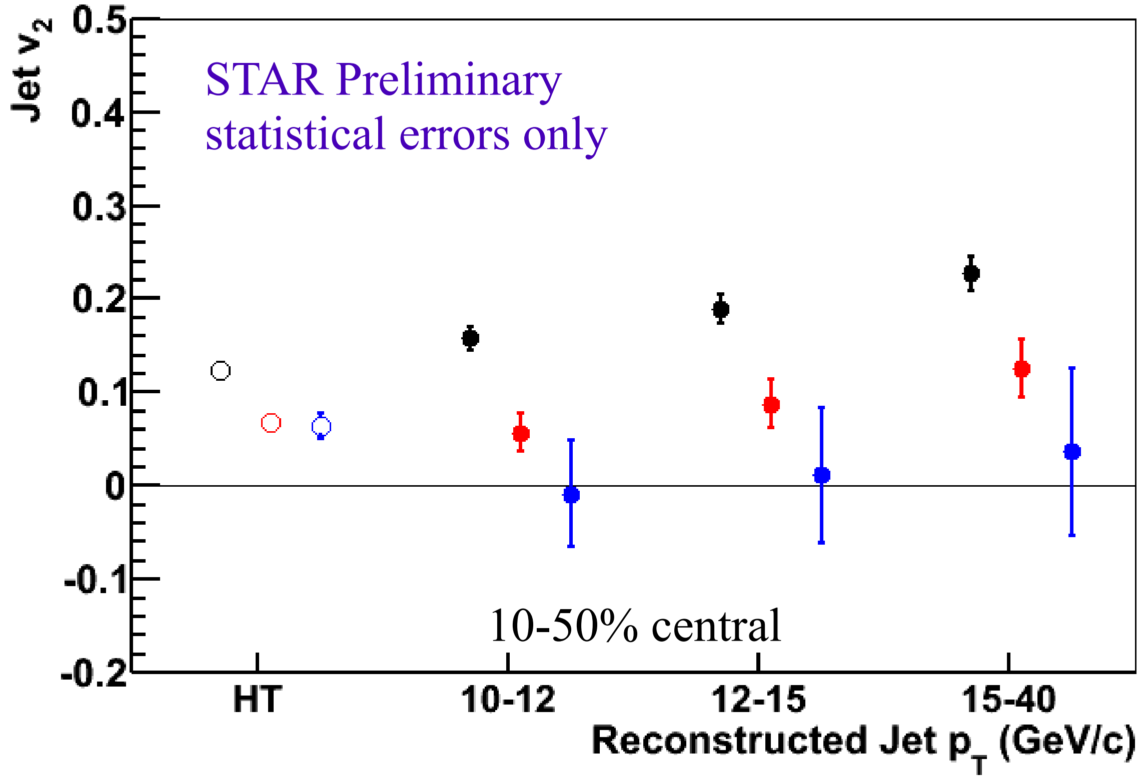
- Jet v_2\{TPC EP\}
- Jet v_2\{FTPC EP\}
- Jet v_2\{ZDC-SMD EP\}

- Jet v_2\{FTPC\} is non-zero.

  → Pathlength-dependent parton energy loss

- No clear centrality dependence outside statistical uncertainties.
- Caveat: Reconstructed jet energy has slight dependence on centrality

Jet v_2 vs Reconstructed Jet p_T



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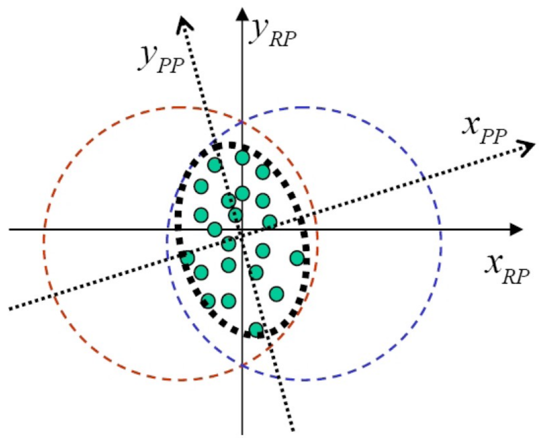


- Jet v_2{FTPC} increases slightly with jet p_T
- Jet v_2{FTPC} > Jet v_2{ZDC-SMD}
  → In single-particle v_2 measurements, this difference is attributed to flow in participant plane vs. reaction plane, v_2(PP) > v_2(RP)
  → Jet energy loss sensitive to geometry in participant frame?

Jet v_2 summary

- The correlation between reconstructed jets and the reaction plane / 2nd-order participant plane has been measured.
- Jet – event plane bias is reduced by using detectors at forward rapidities for event plane determination.
- **Non-zero reconstructed jet v_2{FTPC} is observed.**

  → Indicative of pathlength-dependent parton energy loss.
- Measurements of jet v_2 with respect to the event plane measured at forward rapidities show...

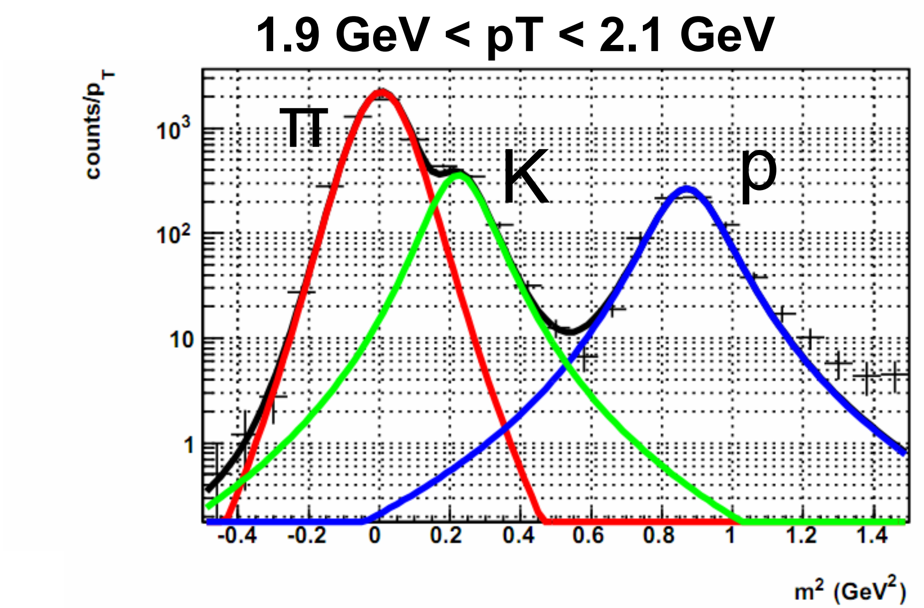
  → The bias towards unmodified jets is largely due to the trigger requirement.

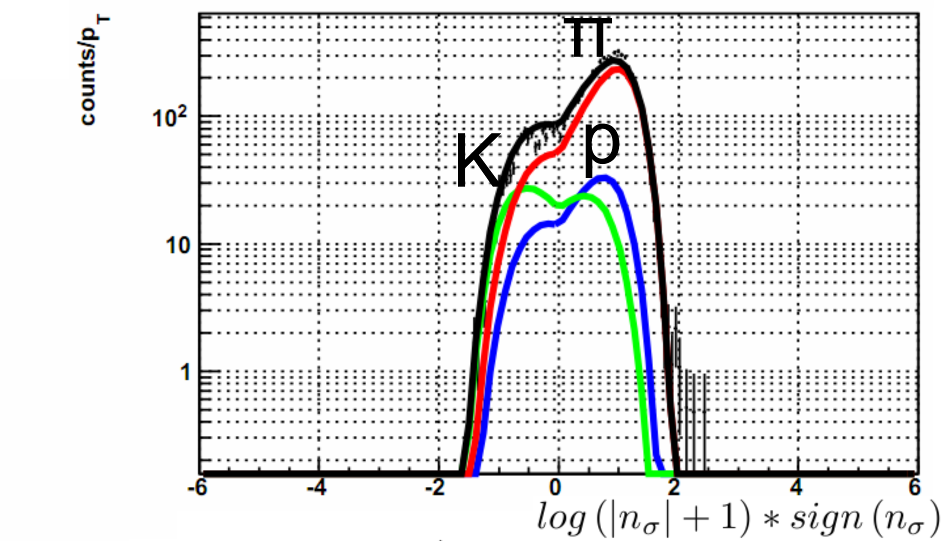
  → Within the kinematic regions studied, jet v_2 increases with p_T and is roughly independent of centrality.
- Can be used to further constrain theories of pathlength-dependent parton energy loss and parton-medium interactions.

Thanks!

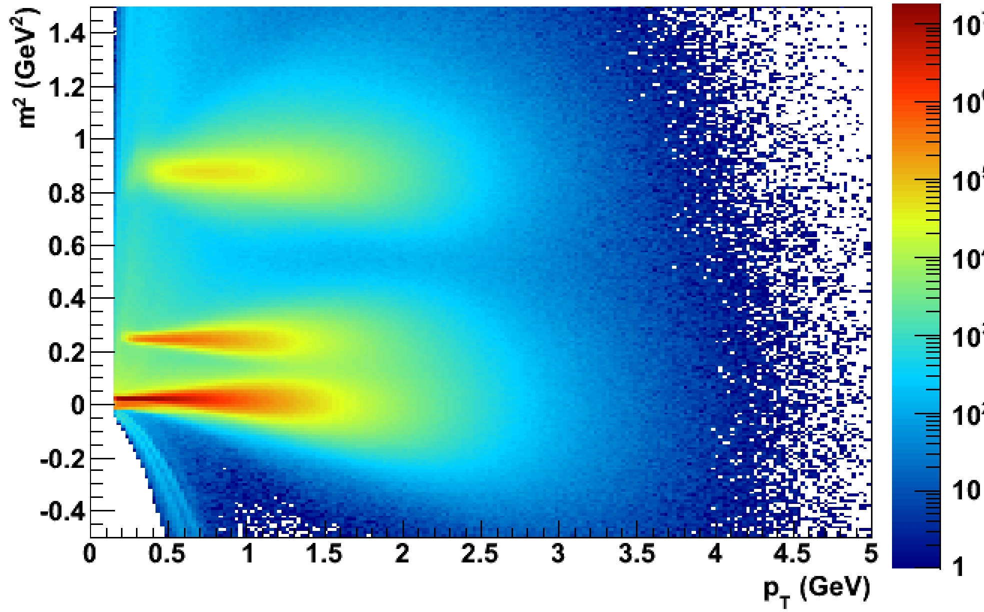
Backup

Particle Identification





where n_σ is dE/dx after being shifted and scaled such that $\mu \approx 0$ and $\sigma \approx 1$ for protons



Particle identification is performed using simultaneous TOF (m^2) and TPC (dE/dx) fits

Event Plane Calculations

- TPC: $0.2 < p_T^{track} < 2.0$, p_T-weighting

  Corrections: φ-weighting

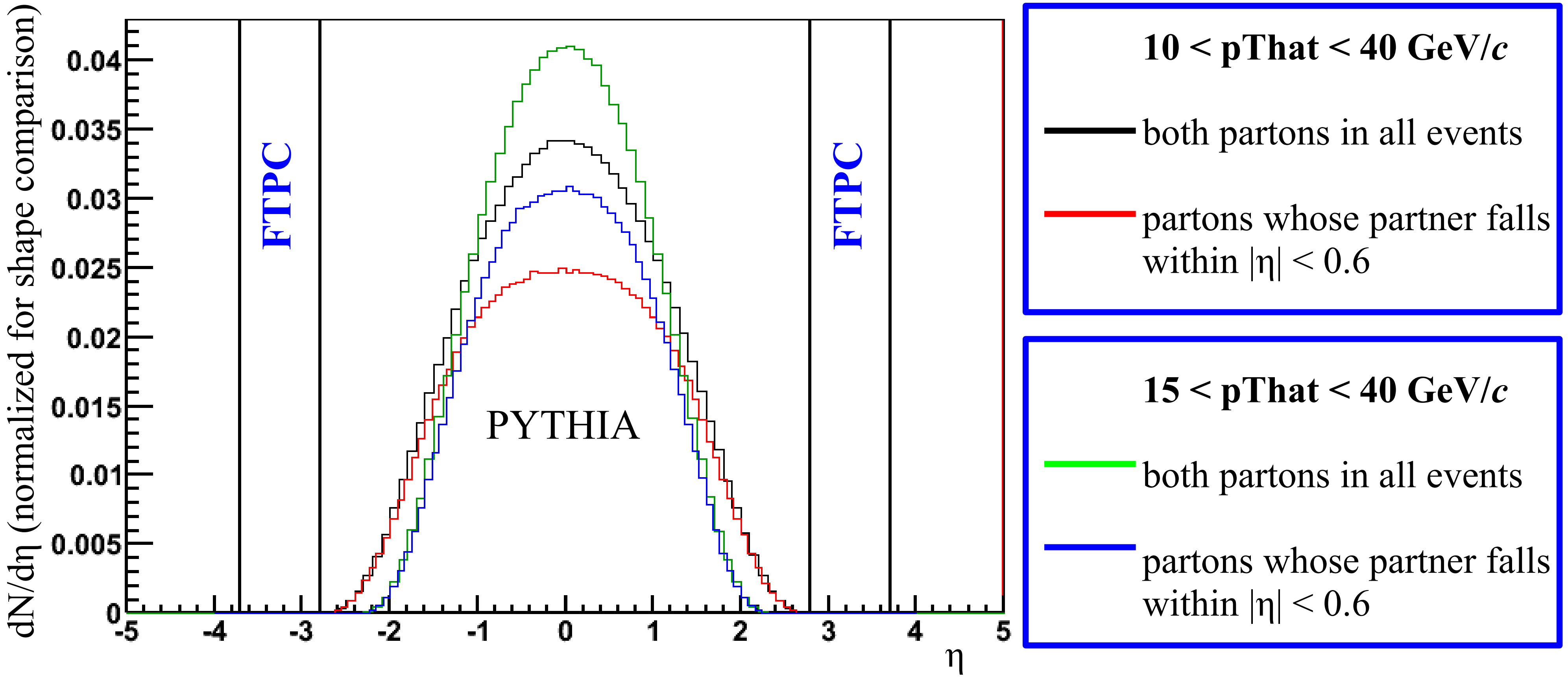
- FTPC: $0.2 < p_T^{track} < 2.0$, p_T-weighting

  Corrections: recentering, shifting

- ZDC-SMD

  Corrections: recentering, shifting

Does the recoil jet hit the FTPC?



- For pThat > 10 GeV/*c*, in 2M events, < 10 partons point towards the η region covered by the FTPC
- For pThat > 15 GeV/*c*, in 2M events, 0 partons point towards the η region covered by the FTPC

Participant vs. Reaction Plane

- $v_2\{PP\} > v_2\{RP\}$

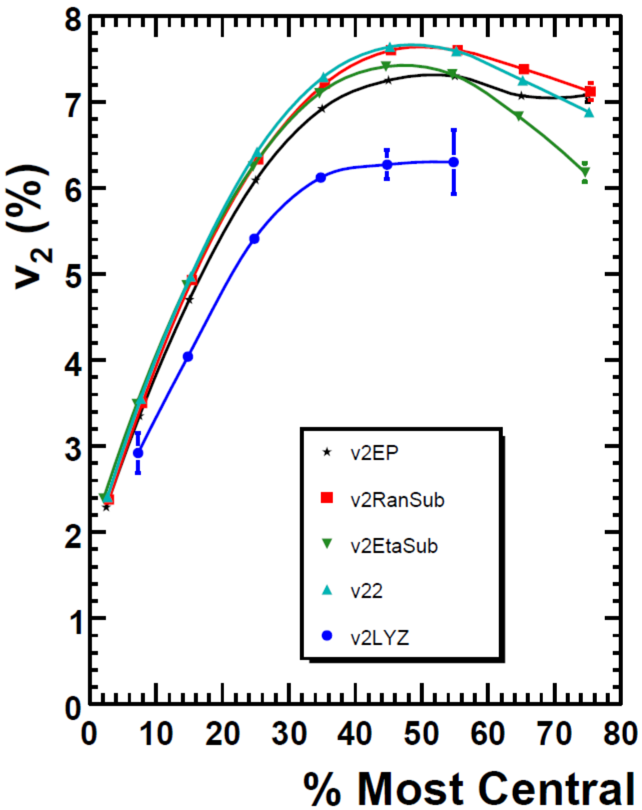


FIG. 6: (Color online) The values of v_2 from various analysis methods vs centrality. Both the upper lines [3] and the lower line [25] are STAR data.

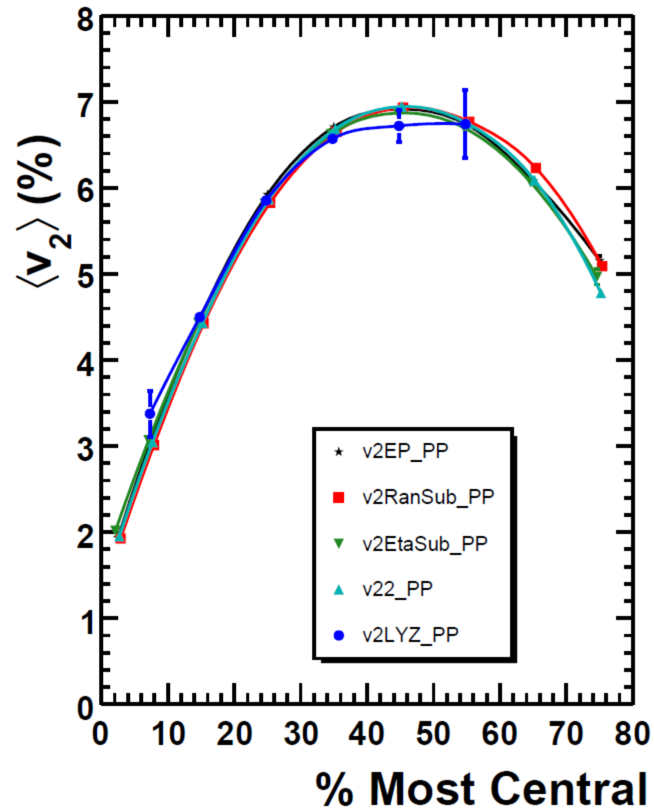


FIG. 7: (Color online) The data from Fig. 6 corrected to $\langle v_2 \rangle$ in the participant plane.

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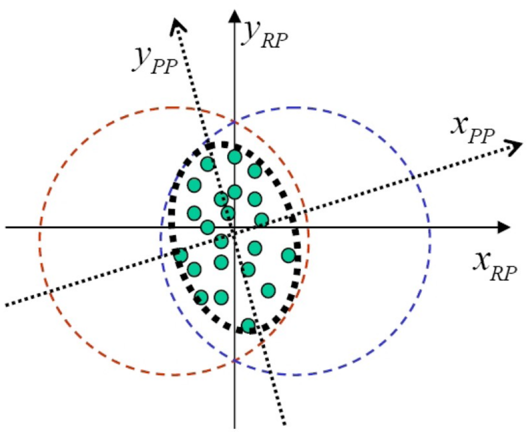
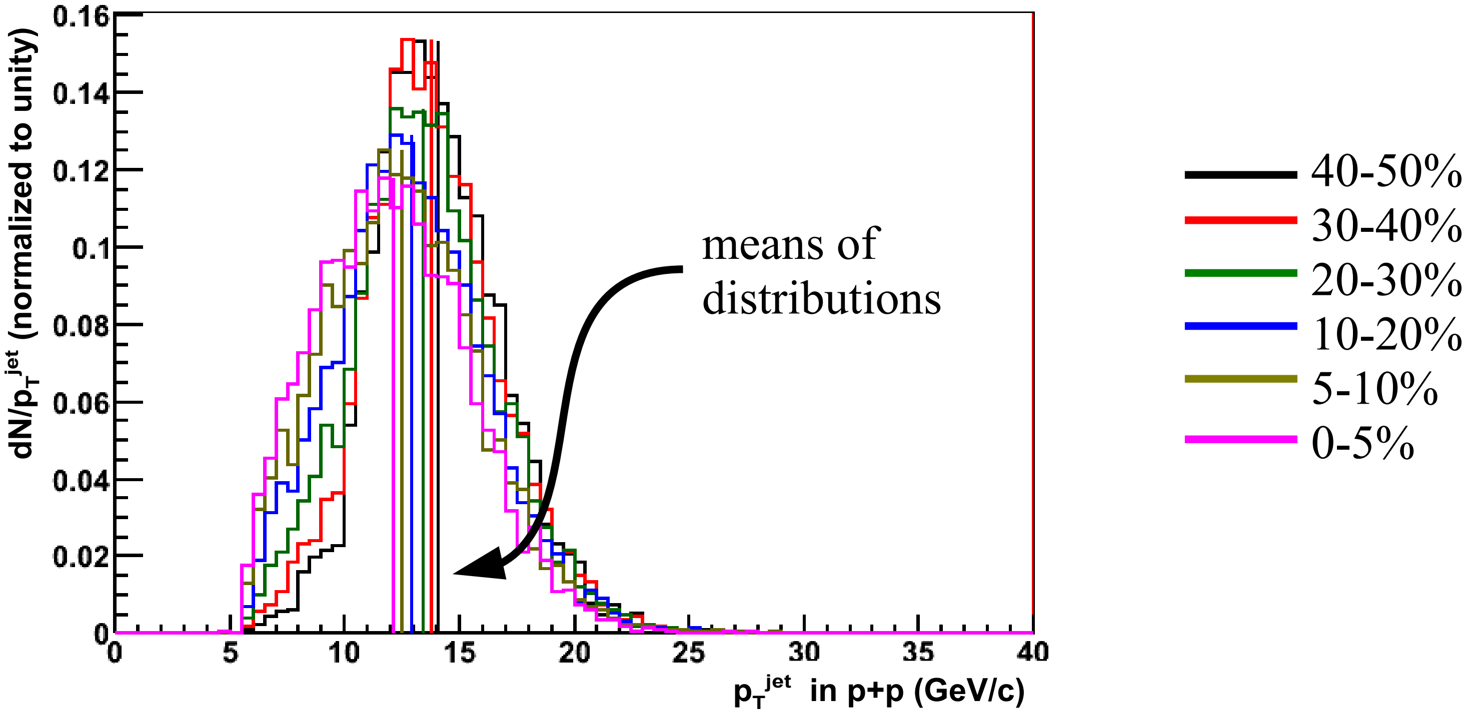


Reco. Jet p_T vs. Centrality

- Embed p+p HT trigger jets into Au+Au minimum bias events
- Reconstructed jet energy of embedded jets: $10 < p_T^{jet} < 15$ GeV/c
- Distribution of p+p jet energies (reconstructed before embedding, with $p_T^{cut} = 0.2$ GeV/c):



- Reconstructing jets in Au+Au samples slightly higher parton energies in peripheral events than in central (by ~2-5 GeV)