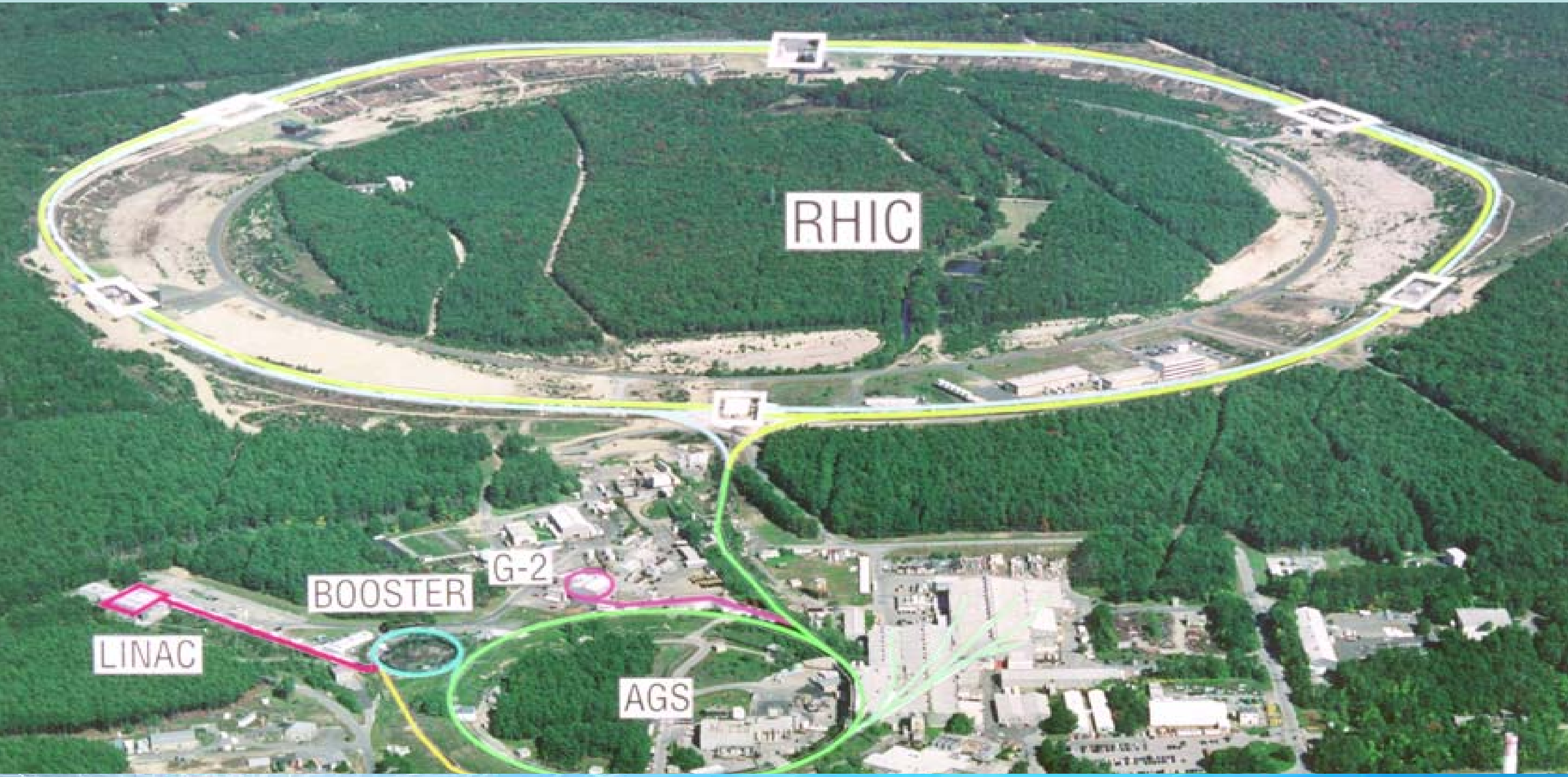
Jets at RHIC

Kirill Filimonov

Lawrence Berkeley National Laboratory



Quark Matter 2004
Oakland – January 11-17

Jets at RHIC

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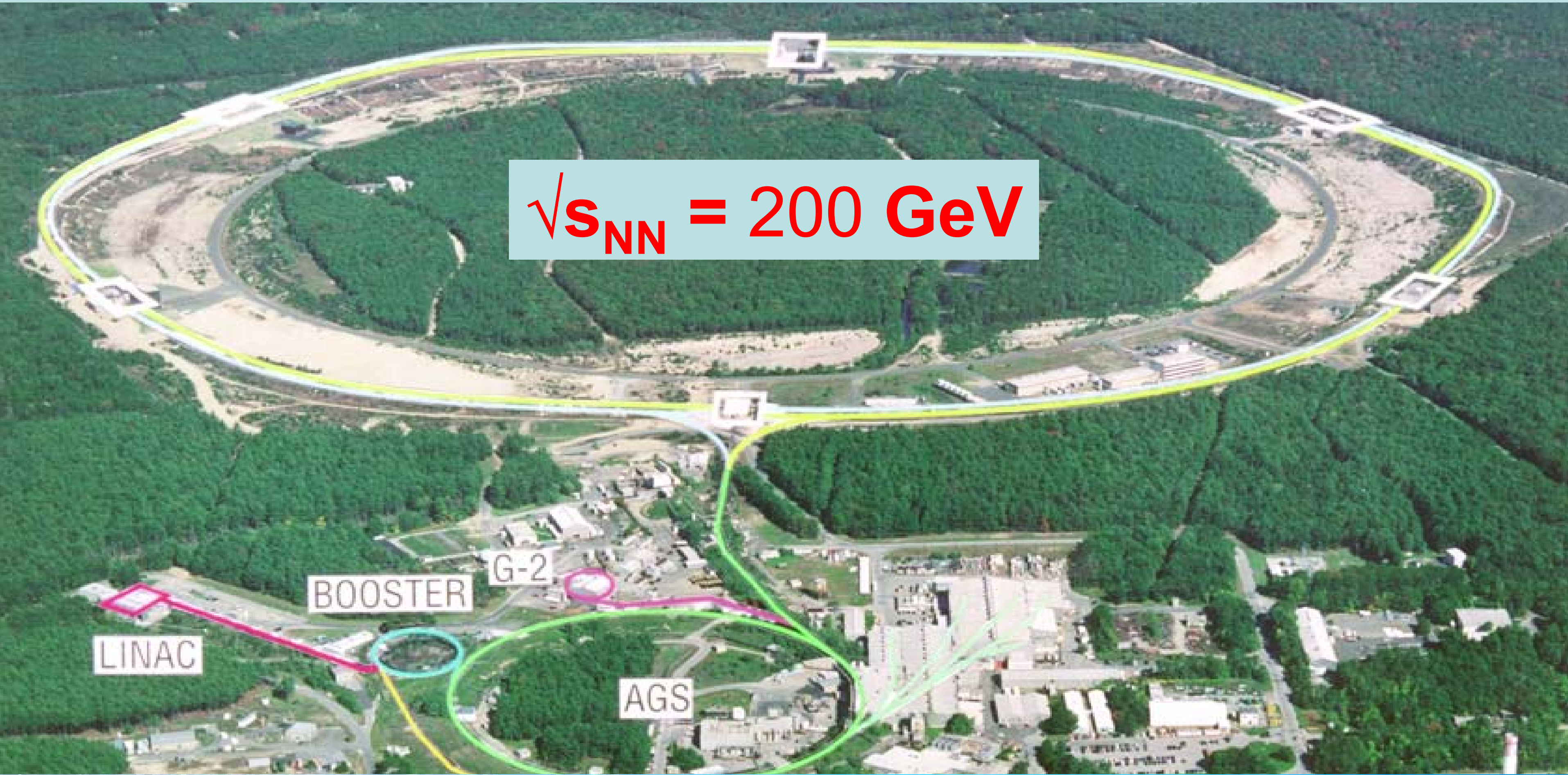

Quark Matter 2004
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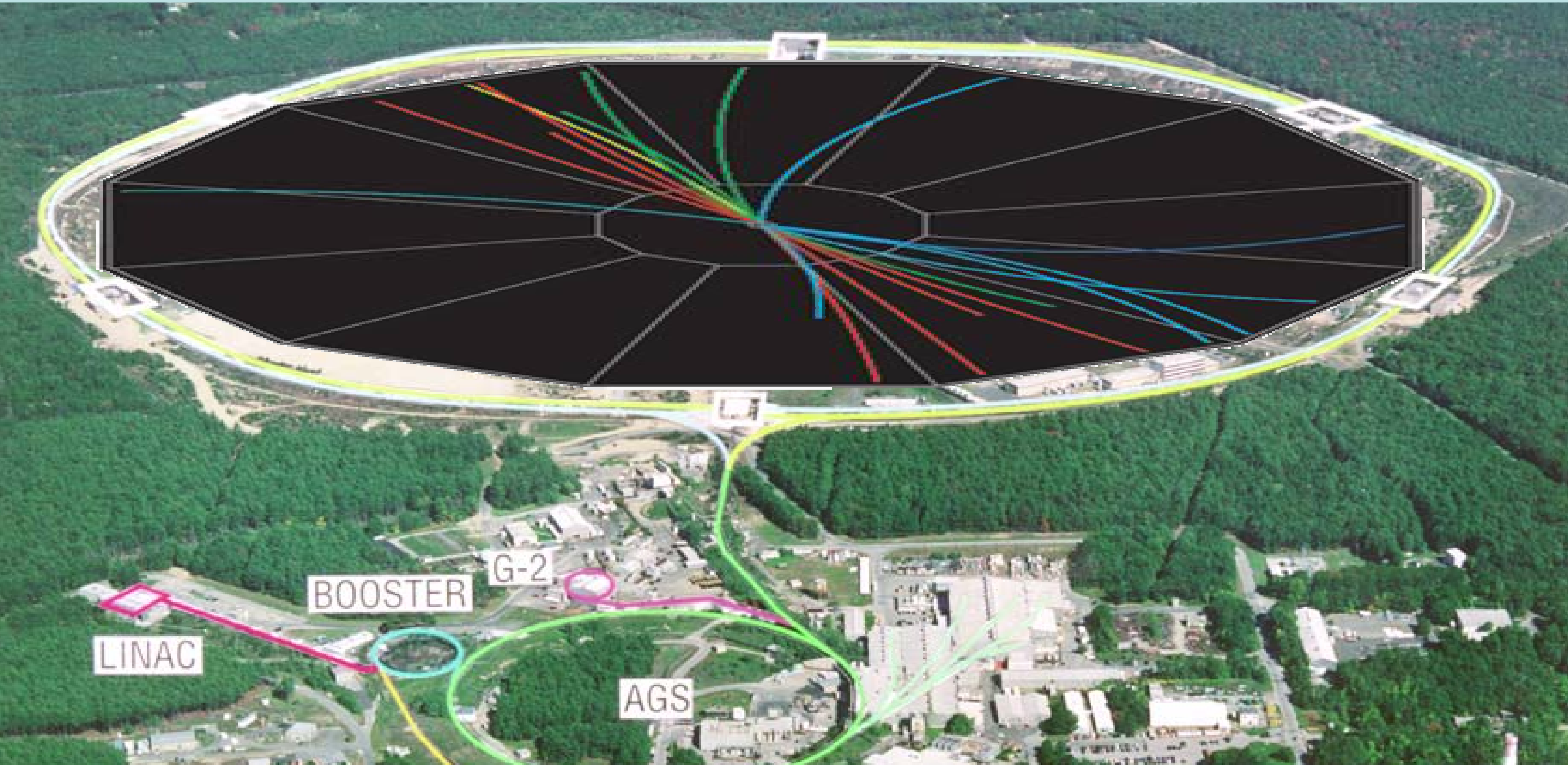
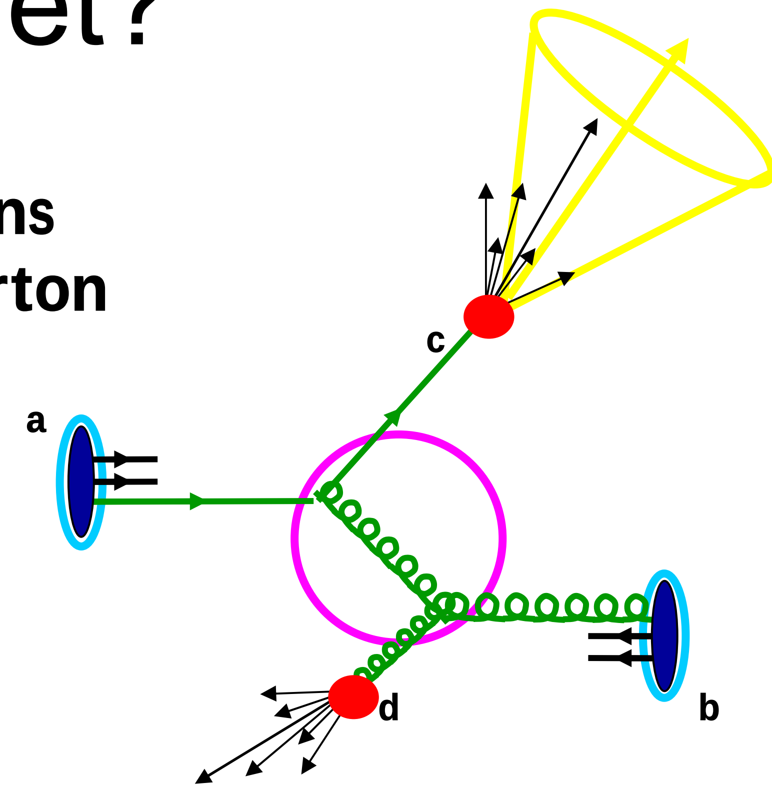


Quark Matter 2004

Oakland – January 11-17

What is a jet?

Jet: A <u>localized</u> collection of hadrons which come from a fragmenting parton



Parton distribution Functions

Hard-scattering cross-section

Fragmentation Function

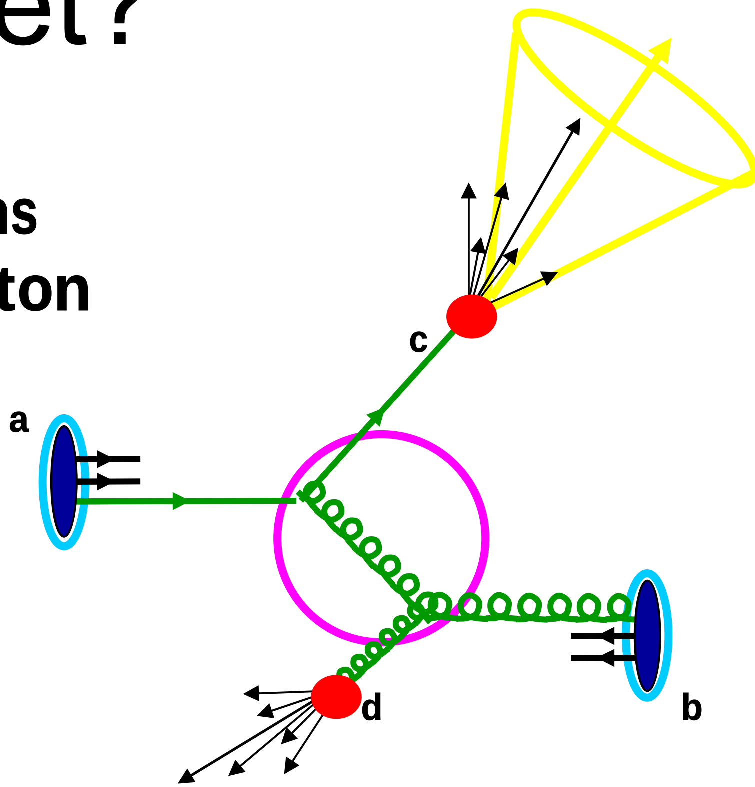
High p_T (> ~2.0 GeV/c) hadron production in pp collisions:

$$\frac{d\sigma_{pp}^{h}}{dy d^2 p_T} = K \sum_{abcd} \int dx_a dx_b f_a(x_a, Q^2) f_b(x_b, Q^2) \frac{d\sigma}{d\hat{t}}(ab \to cd) \frac{D_{h/c}^{0}}{\pi z_c}$$

What is a jet?

Jet: A localized collection of hadrons which come from a fragmenting parton

Parton distribution Functions
Hard-scattering cross-section
Fragmentation Function



High p_T (> ~2.0 GeV/c) hadron production in pp collisions:

Provides a well calibrated probe

High p_T Particle Production in A+A

(According to pQCD...)

$$\frac{dN^h_{AB}}{dy d^2 p_T} = K \sum_{abcd} \int dx_a dx_b \int d^2\mathbf{k}_a d^2\mathbf{k}_b$$

$$\times f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2)$$ **Parton Distribution Functions**

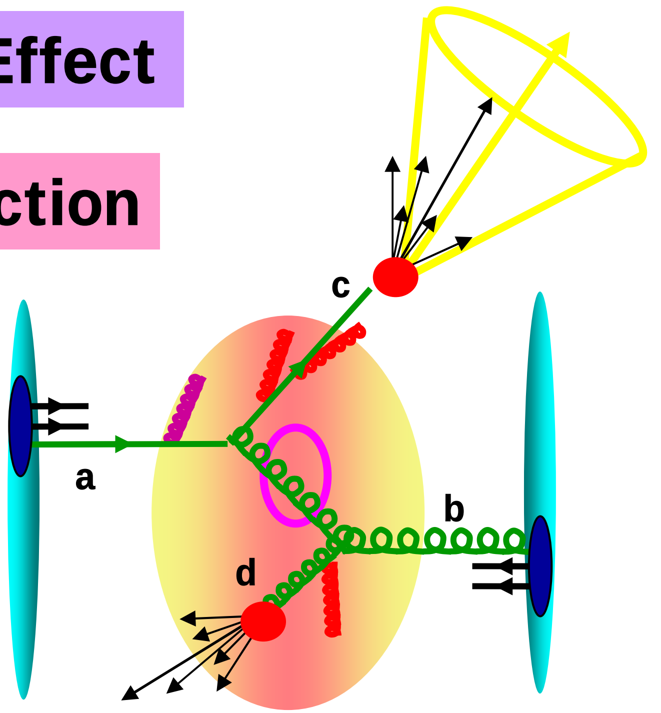
$$\times g(\mathbf{k}_a) g(\mathbf{k}_b)$$ **Intrinsic k_T , Cronin Effect**

$$\times S_A(x_a, Q_a^2) S_B(x_b, Q_b^2)$$ **Shadowing, EMC Effect**

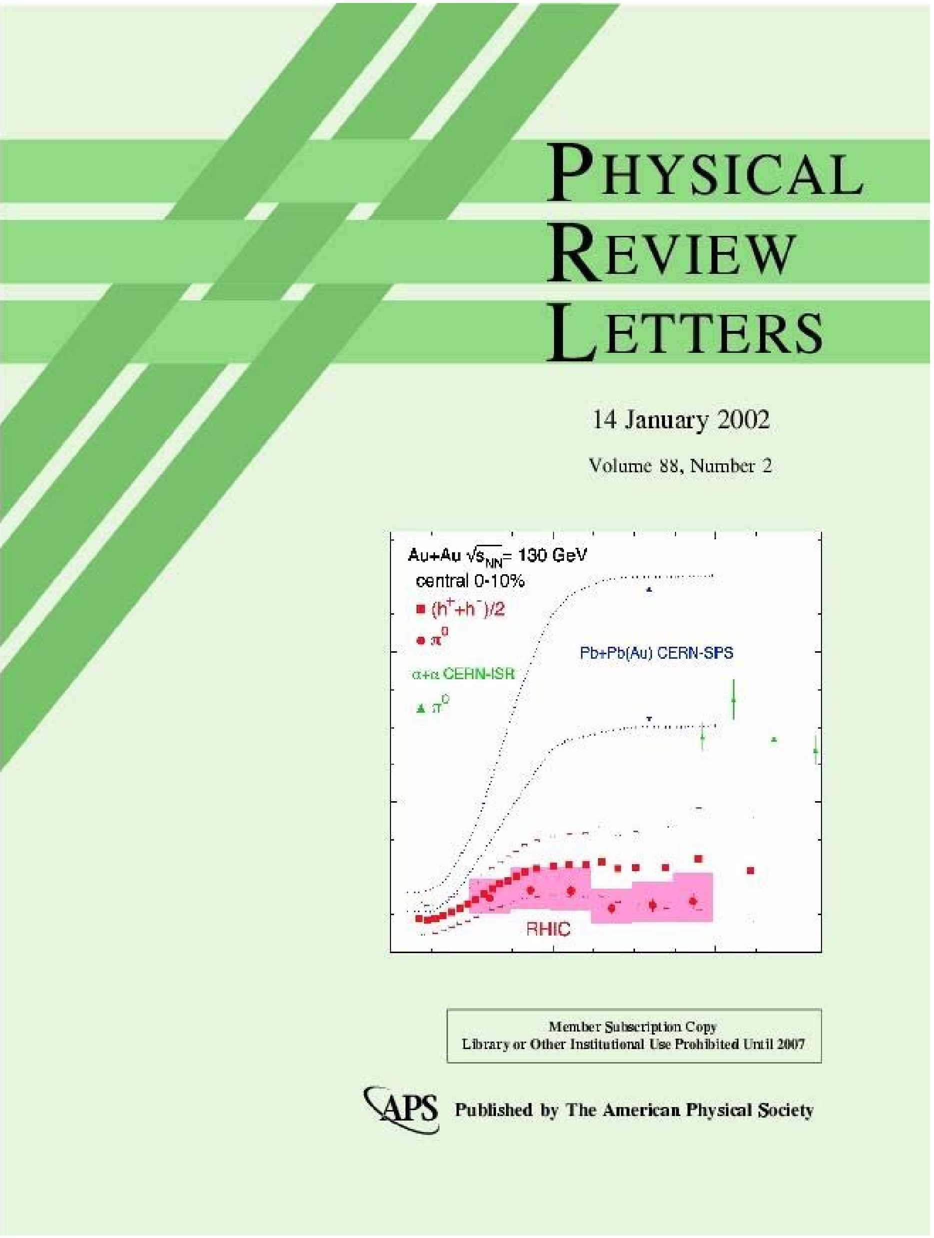
$$\times \frac{d\sigma}{d\hat{t}}(ab \rightarrow cd)$$ **Hard-scattering cross-section**

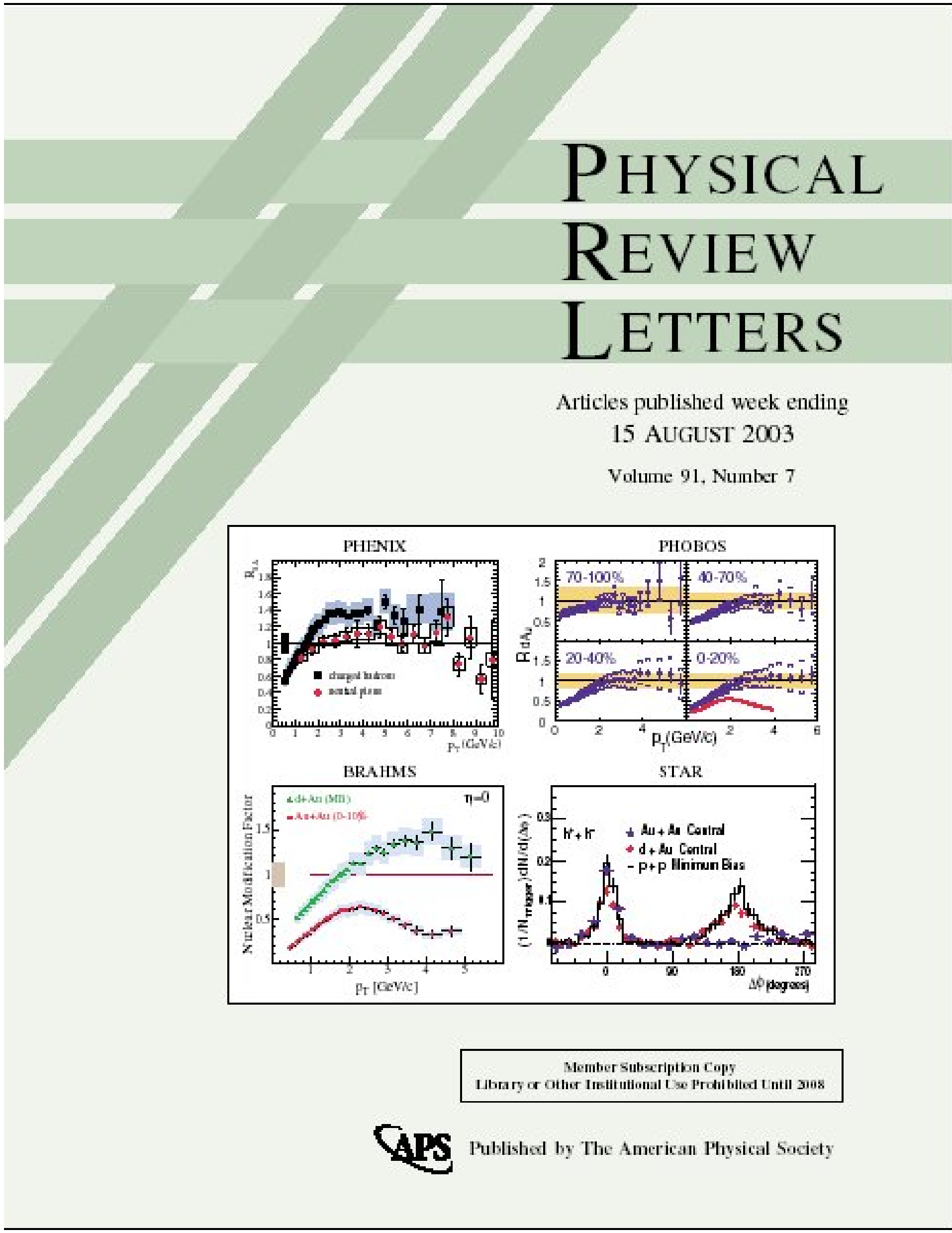
$$\times \int_0^1 d\varepsilon P(\varepsilon) \frac{z_c^*}{z_c}$$ **Partonic Energy Loss**

$$\frac{D^0_{h/c}(z_c^*, Q_c^2)}{\pi z_c}$$ **Fragmentation Function**



Suppresion is due to the final state





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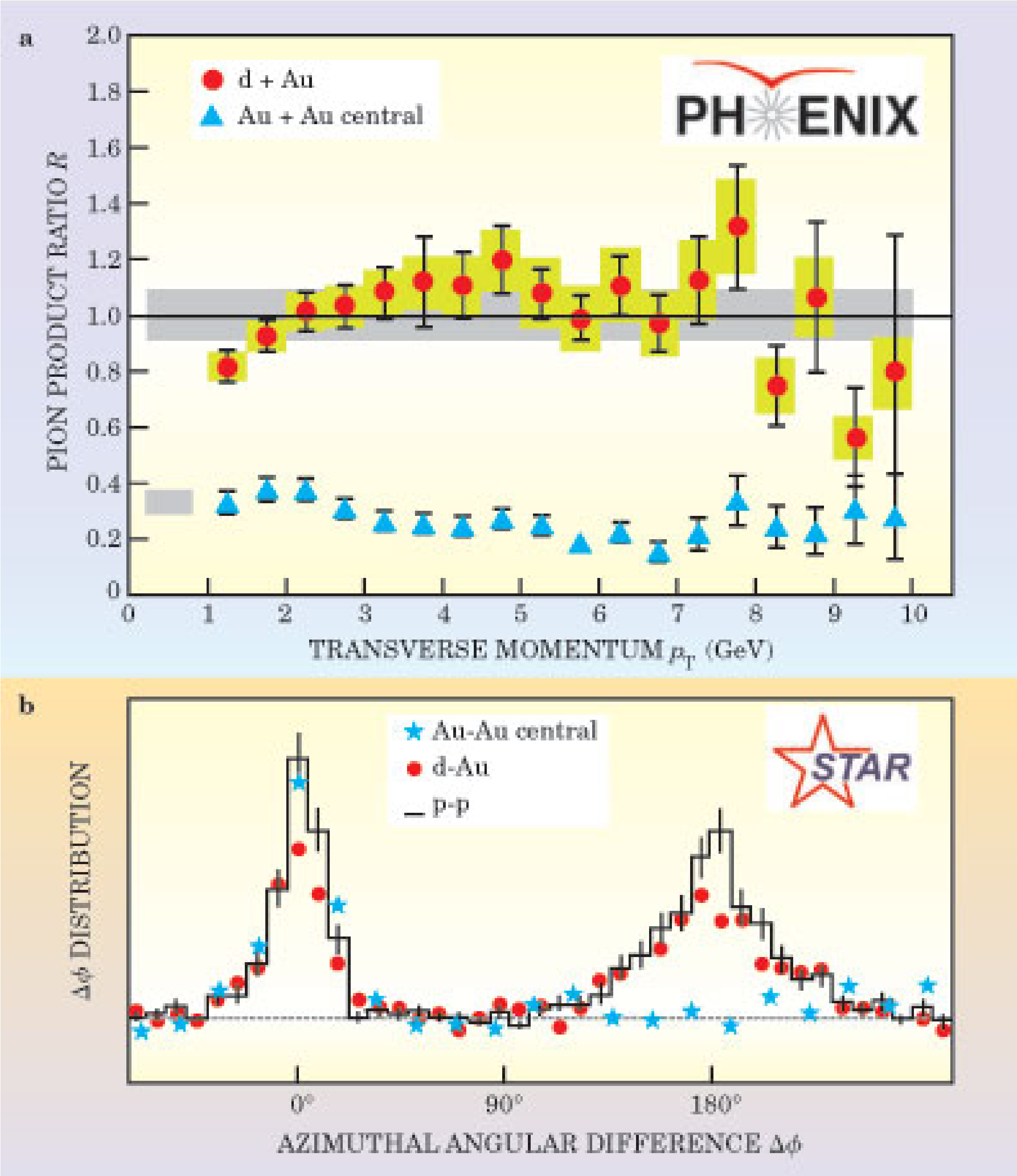
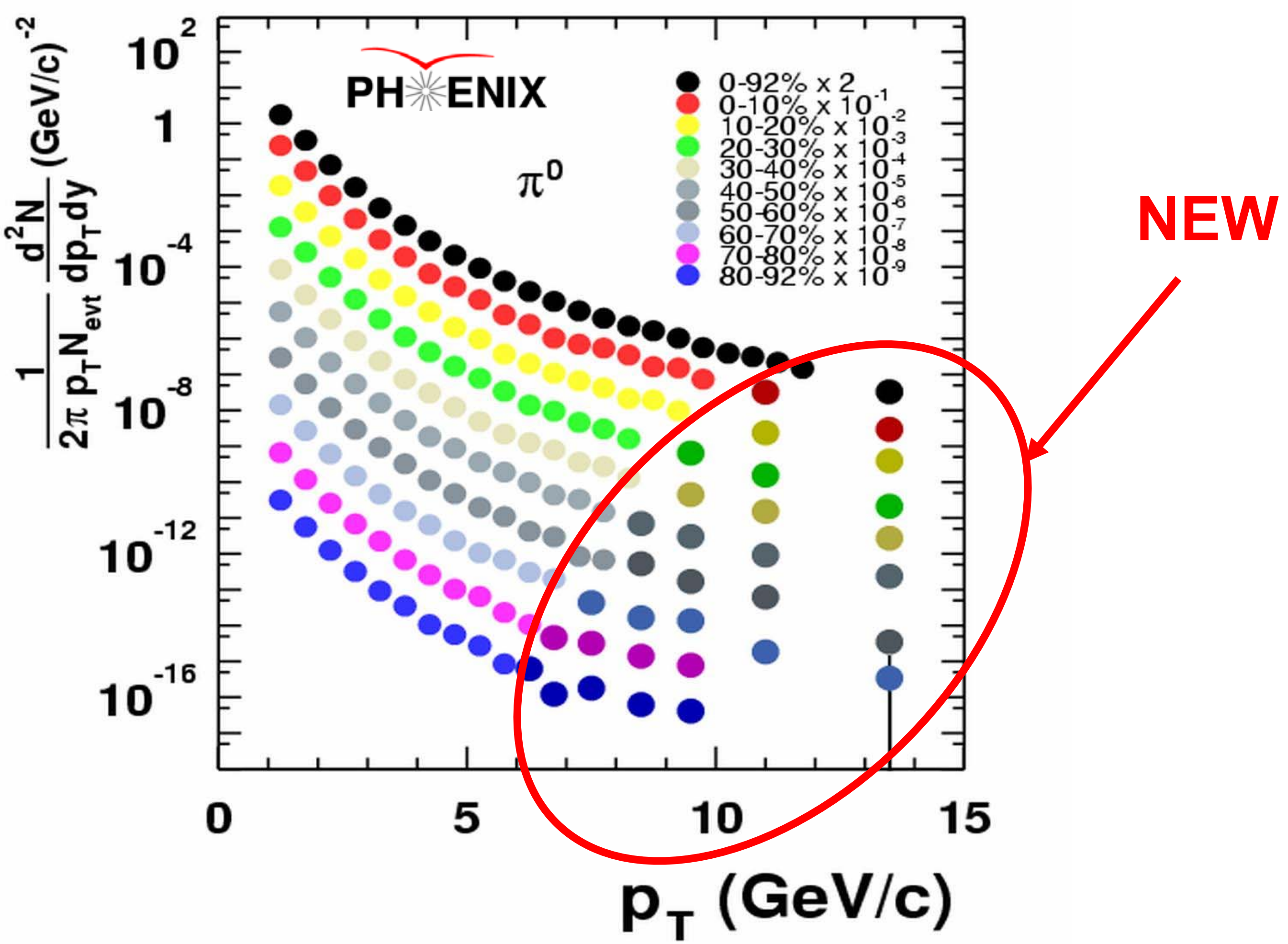


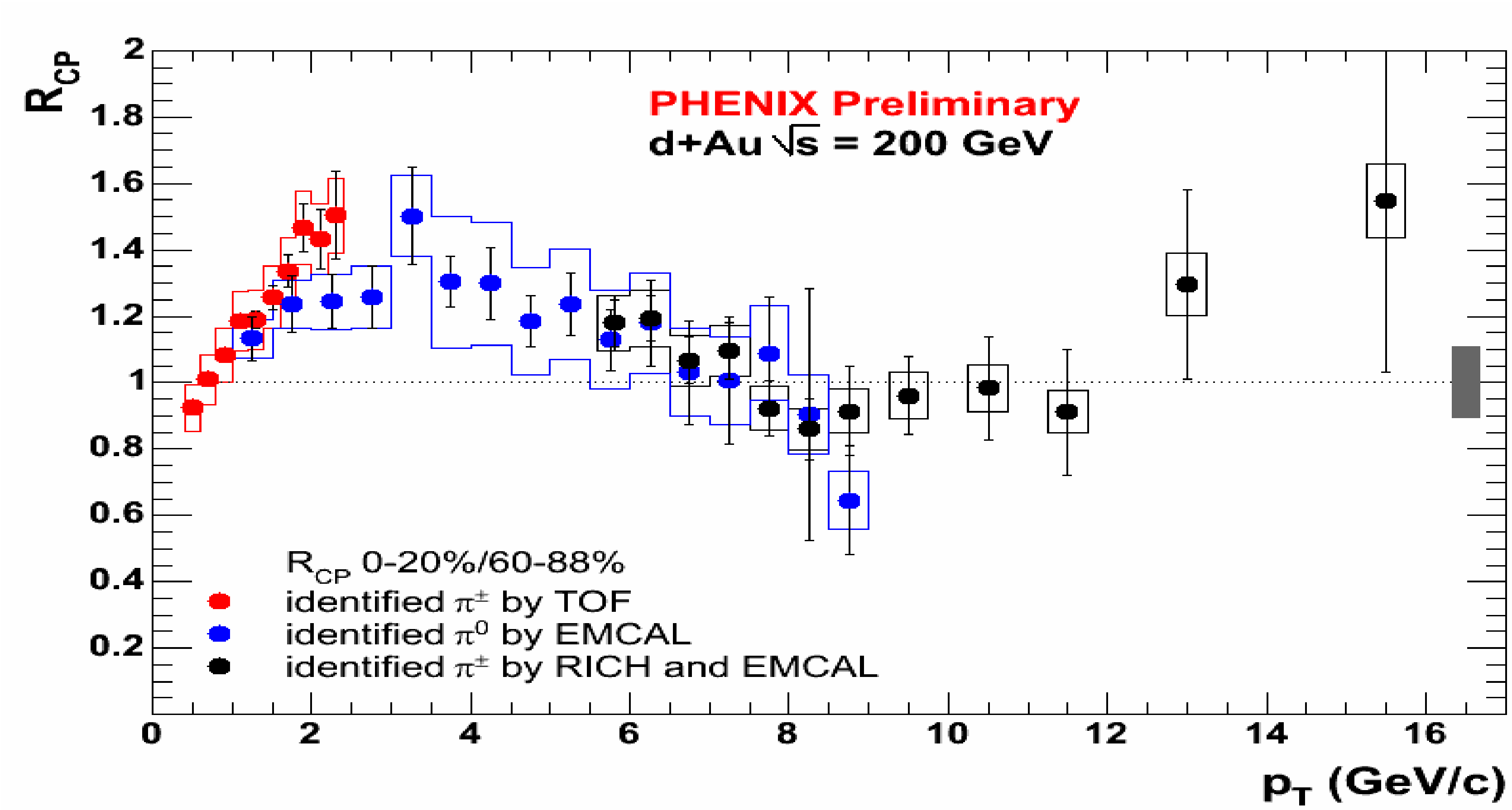
High pt Spectra

π^0's in Au+Au up to 15 GeV/c!



Cronin enhancement

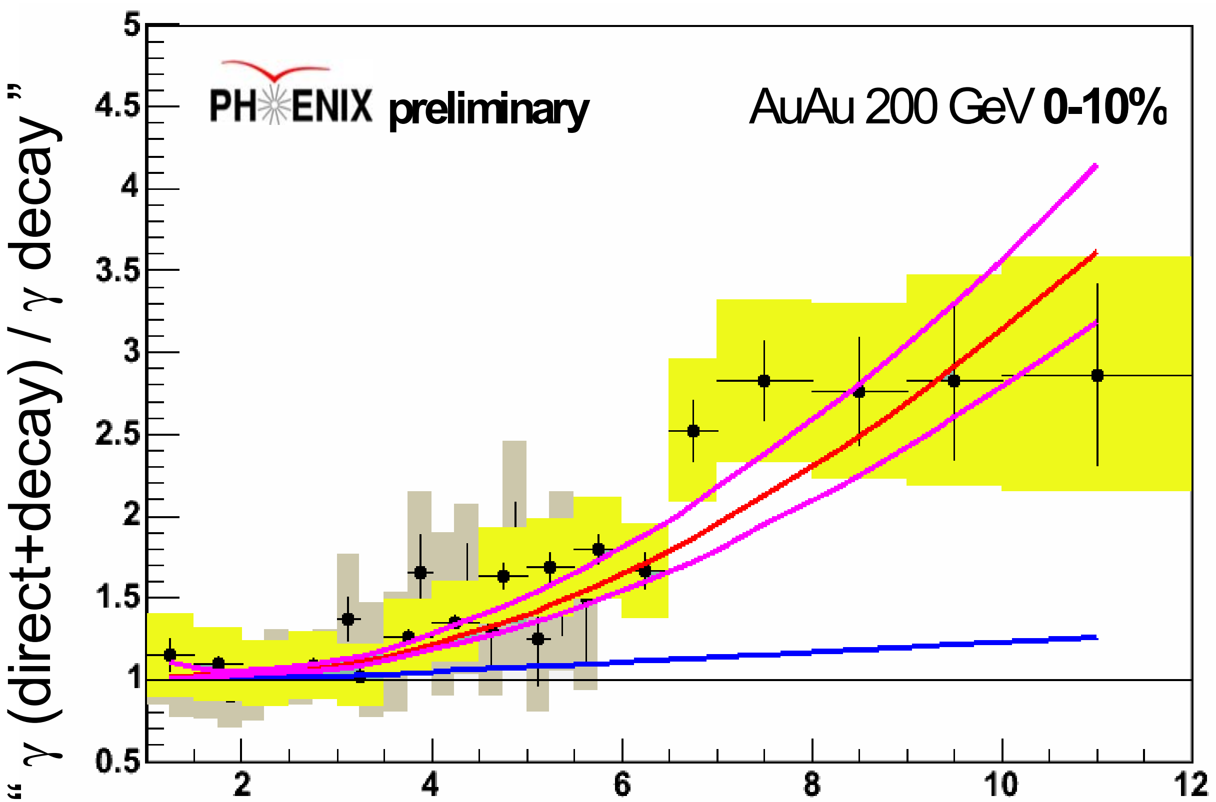
C. Klein-Boesing



Cronin Enhancement vanishes at high p_T

Perturbative QCD in Au+Au

Prompt γ's in Au+Au up to 12 GeV/c



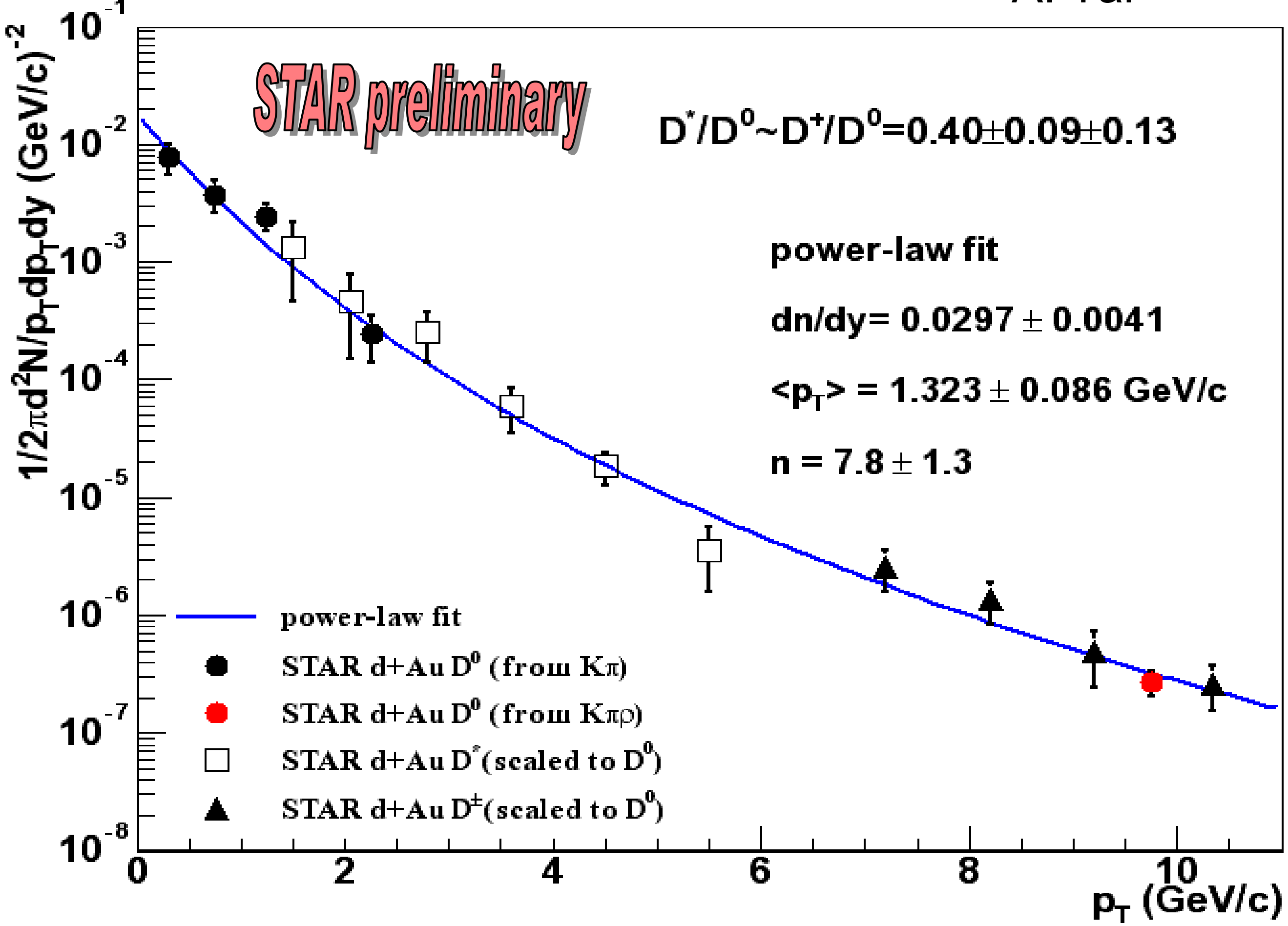
J. Frantz

Prompt γ's scale with N_{binary}

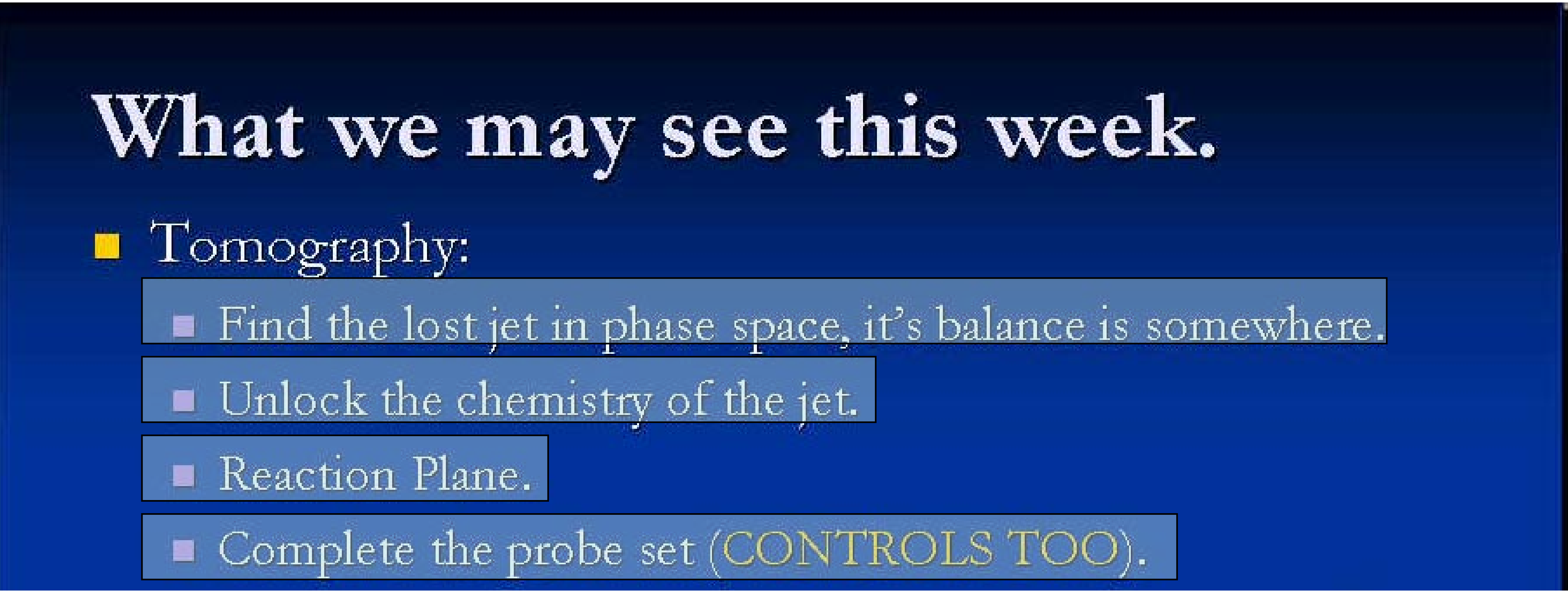
High pt Spectra

D's in d-Au up to 11 GeV/c!

A. Tai



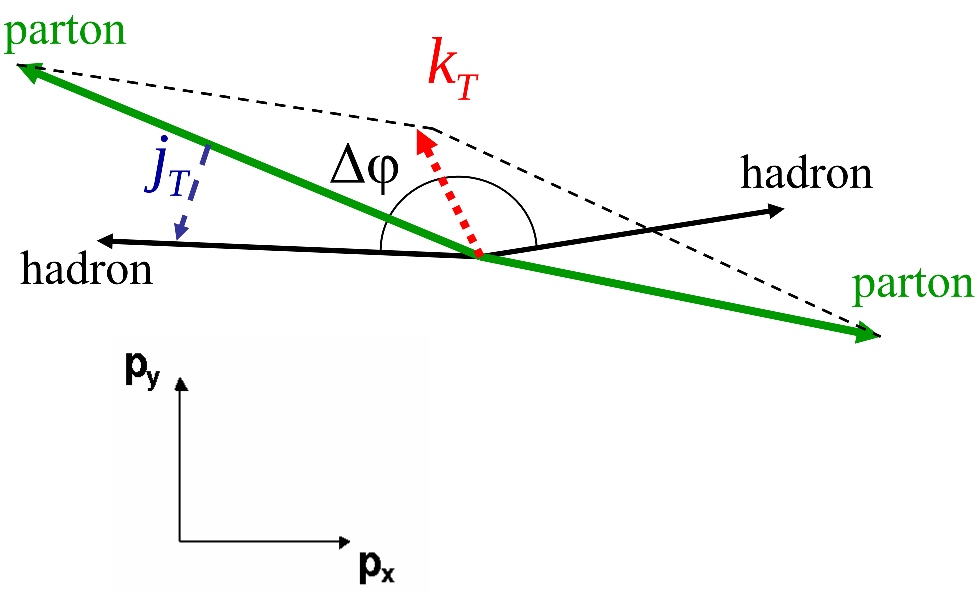
Opening Act from Tom Hemmick:



- Jet fragmentation in pp and d-Au: j_T, k_T
- v_2 at high pT in AuAu and di-hadron correlations w.r.t. reaction plane
- Baryon/meson ratios and R_{CP}, flavour-tagged correlations
- High p_T/low p_T di-hadron correlations

1. pp, dAu: Calibration of jets at RHIC

Jet Fragmentation “shape”



$\langle |k_{Ty}| \rangle$: $\langle \vec{p}_T^{\,a} + \vec{p}_T^{\,b} \rangle$ of colliding partons

$\langle |j_{Ty}| \rangle$: $\langle p_T \rangle$ of hadron $\perp$ to jet axis

di-hadron

$$\langle |j_{\perp y}| \rangle = \langle p_\perp \rangle \sin \frac{\sigma_{Near}}{\sqrt{\pi}}$$

$$\langle |k_{Ty}| \rangle \approx \frac{\langle p_T \rangle}{\langle z \rangle} \sqrt{\sigma^2_{Far} - \sigma^2_{Near}}$$

Jet “width”

Jet-coplanarity

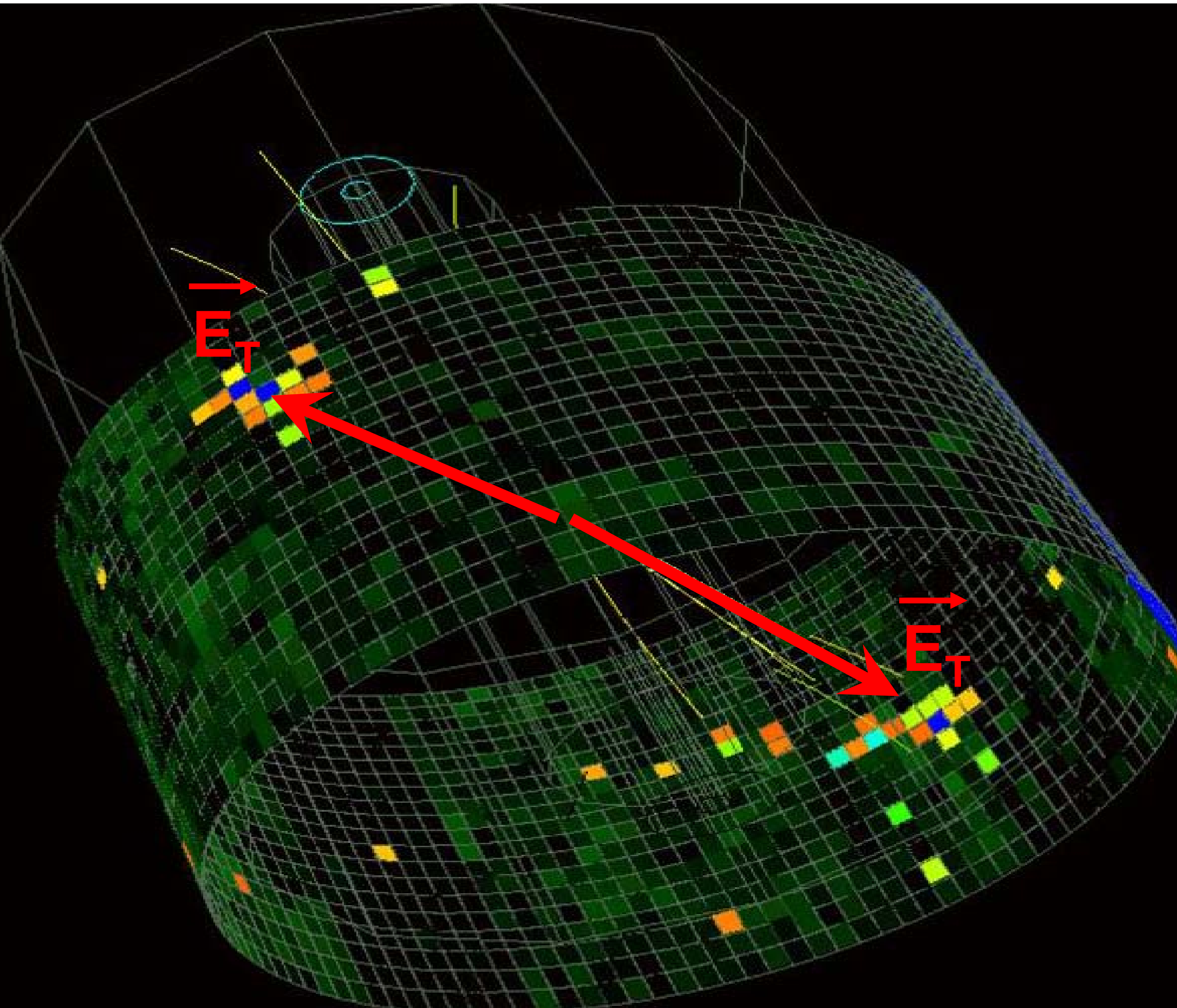
Reconstructed jets

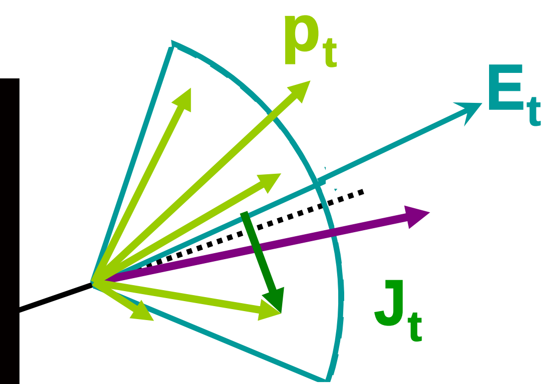
$$j_T = p_T^{hadron} \sin(\theta_{jet-had})$$

$$k_T = p_T^{jet} \sin(\Delta\phi_{jet-jet})$$

Full jet reconstruction in pp, dAu

T. Henry (STAR)





pp MinBias:

Corrected $\langle E_t \rangle$ = $11.3 \pm 0.7_{sys}$ GeV

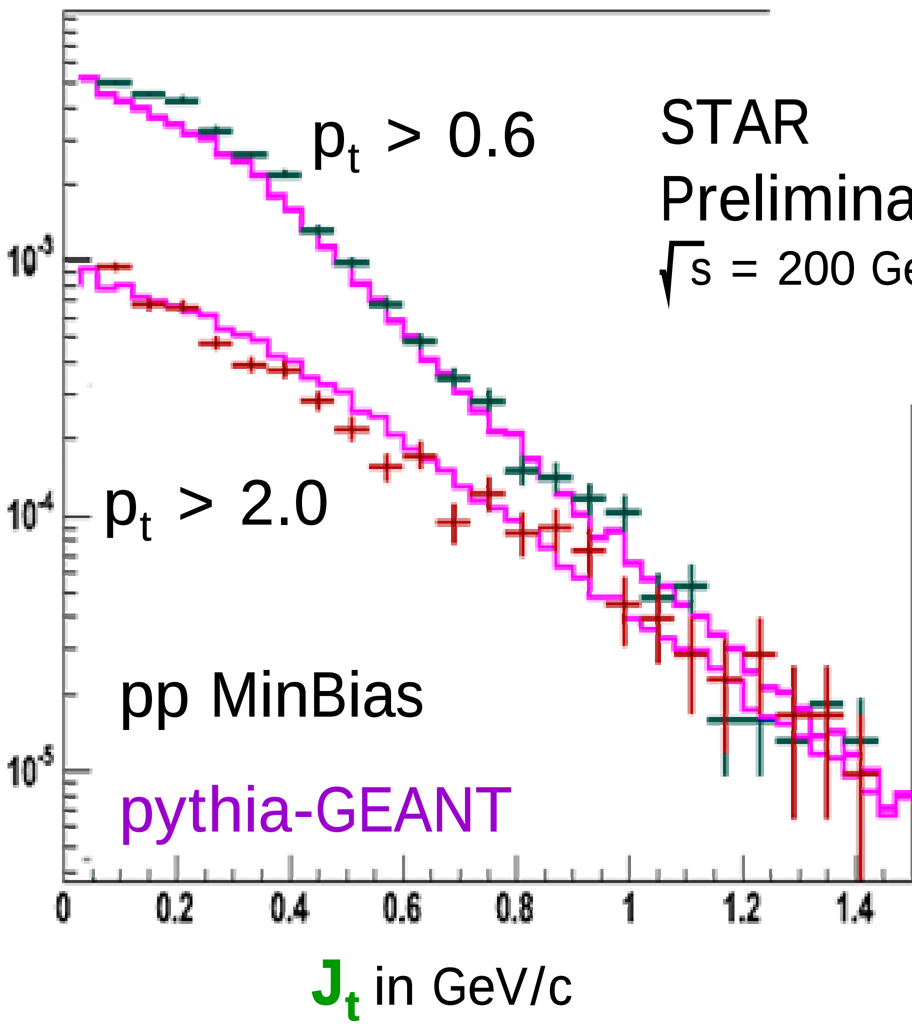
Jet "Width" (RMS J_t):

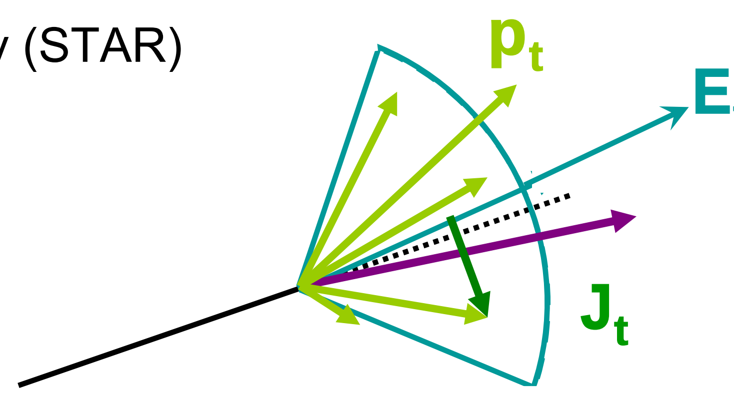
$p_t > 0.6$:
$490 \pm 50_{sys}$ MeV/c

$p_t > 2.0$:
$615 \pm 60_{sys}$ MeV/c

Full jet reconstruction in pp, dAu

T. Henry (STAR)





Agree within 4%

pp MinBias:

Corrected $\langle E_t \rangle$ = 11.3 ± 0.7_{sys} GeV

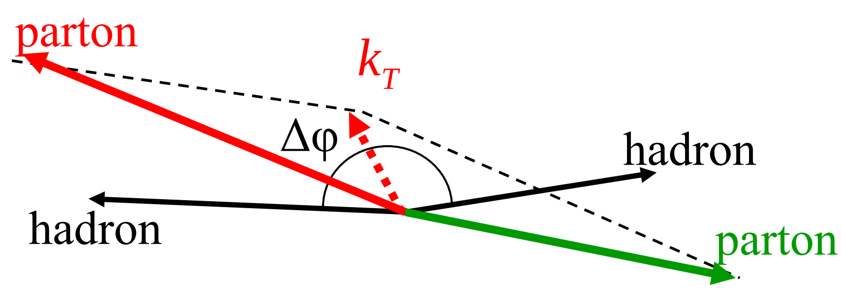
Jet "Width" (RMS J_t):

p_t>0.6:
490 ± 50_{sys} MeV/c

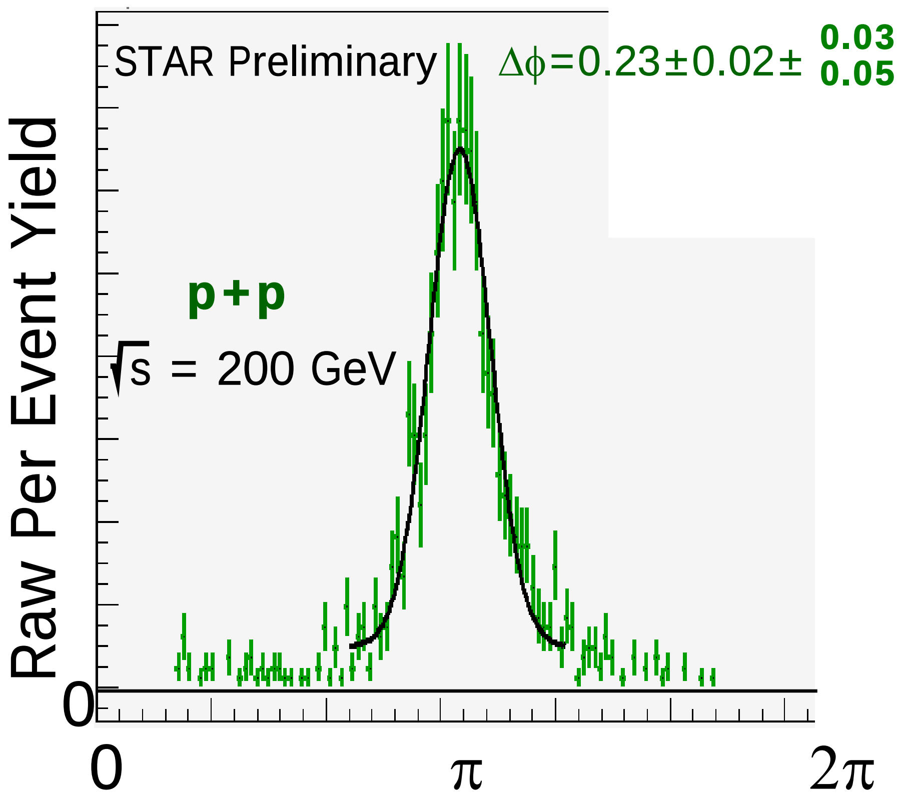
p_t>2.0:
615 ± 60_{sys} MeV/c

Di-Jet Reconstruction

Trigger Jet
TPC only
Determines first thrust axis



Away Jet
TPC only
Determines second thrust axis



- Dijet high tower corrected

$\langle E_t \rangle = 13.0 \pm 0.7(\text{sys})$ GeV

$k_t = 2.3 \pm 0.4 \pm ^{0.67}_{1.11}$ GeV/c

No correction for <z> needed!

T. Henry

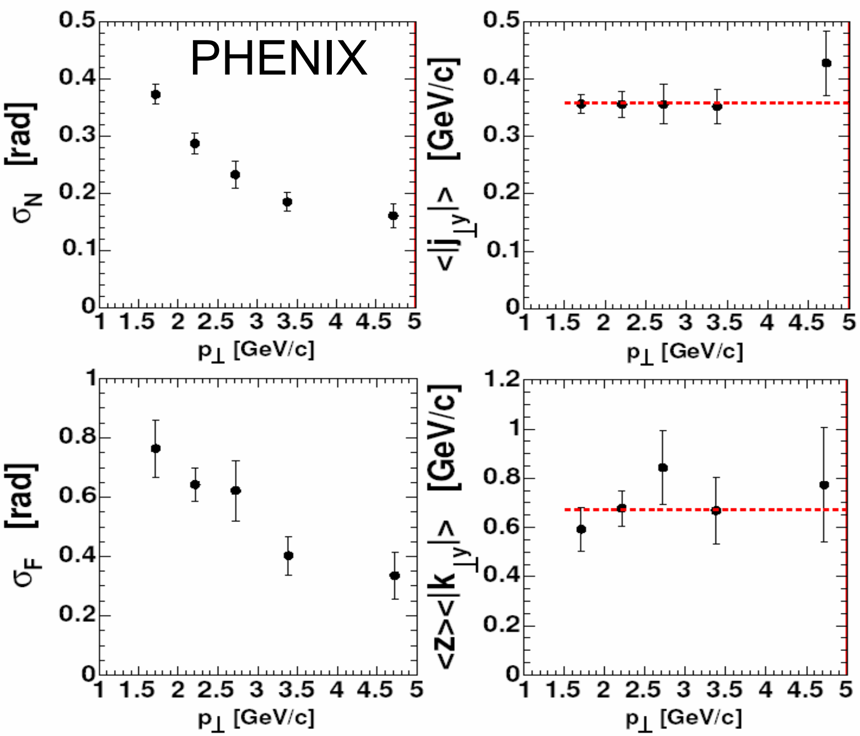
Di-hadron correlations

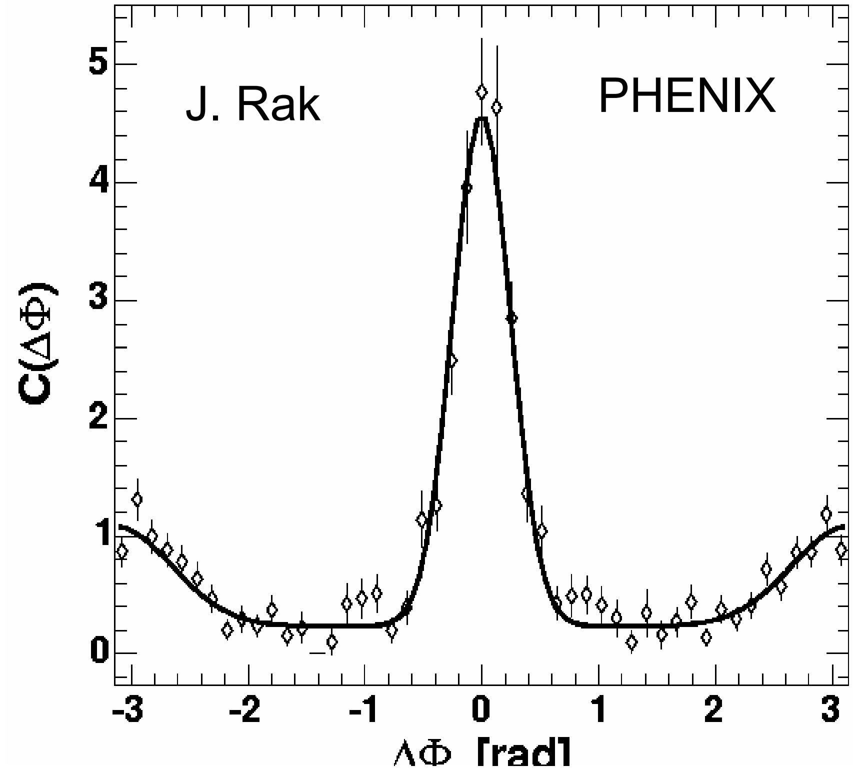
- Fragmentation function unknown: extract k_t*<z>, or infer <z> from the data

di-hadron

$$\langle|j_{\perp y}|\rangle = \langle p_{\perp}\rangle \sin\frac{\sigma_{Near}}{\sqrt{\pi}}$$

$$\langle|k_{Ty}|\rangle \approx \frac{\langle p_T\rangle}{\langle z\rangle}\sqrt{\sigma_{Far}^2 - \sigma_{Near}^2}$$





- $J_t = 615 \pm 60_{sys}$ MeV/c
- $k_t = 2.3 \pm 0.4 \pm^{0.67}_{1.11}$ GeV/c

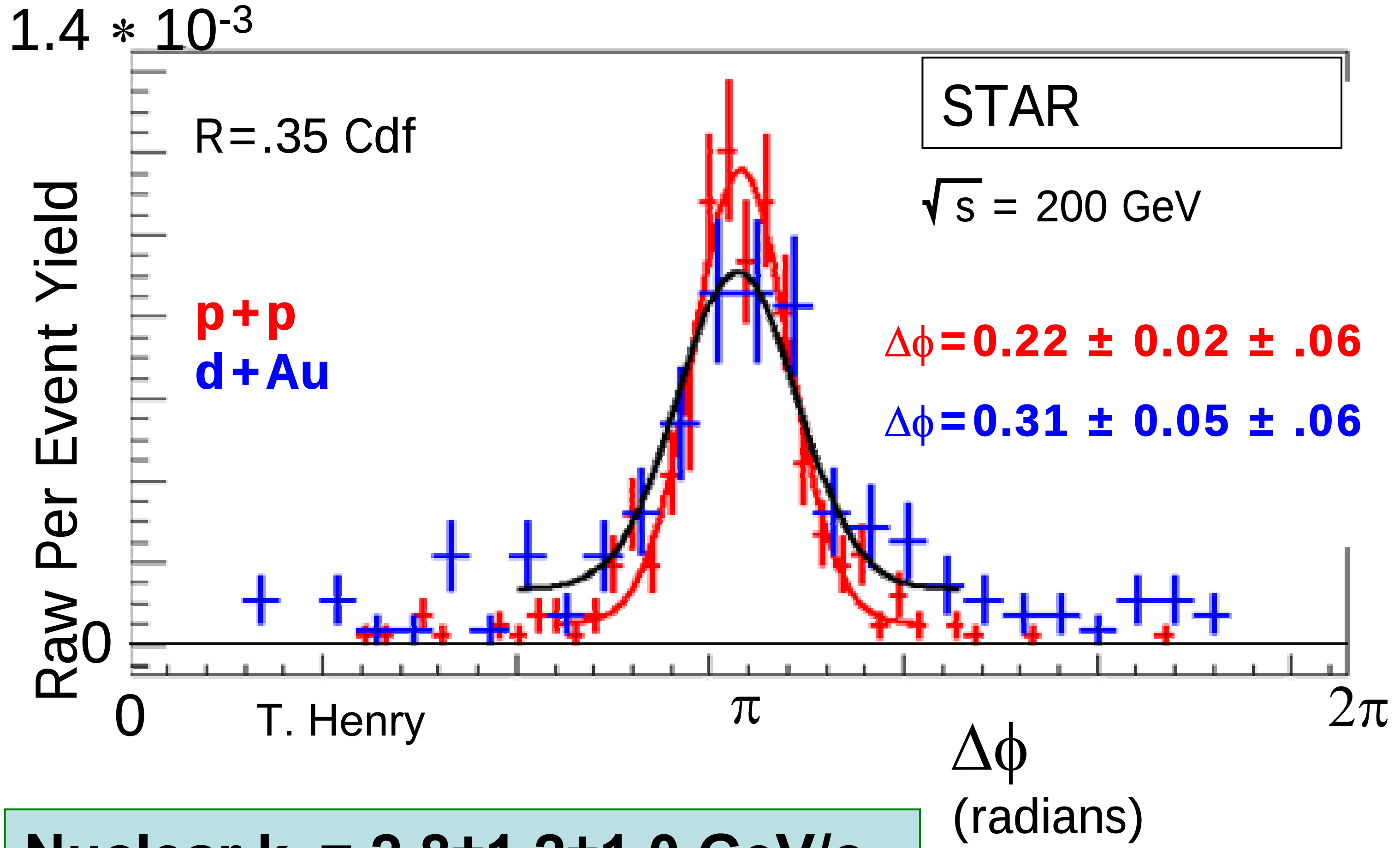
STAR

- $J_t = 636 \pm 20$ MeV/c
- $k_t = 1.7 \pm 0.1$ GeV/c

PHENIX

Extracting nuclear k_T from dAu

$$\langle k_\perp^{\,2} \rangle_{\mathrm{dAu}} = \langle k_\perp^{\,2} \rangle_{\mathrm{vac}} + \langle k_\perp^{\,2} \rangle_{\mathrm{IS\ nucl}}$$

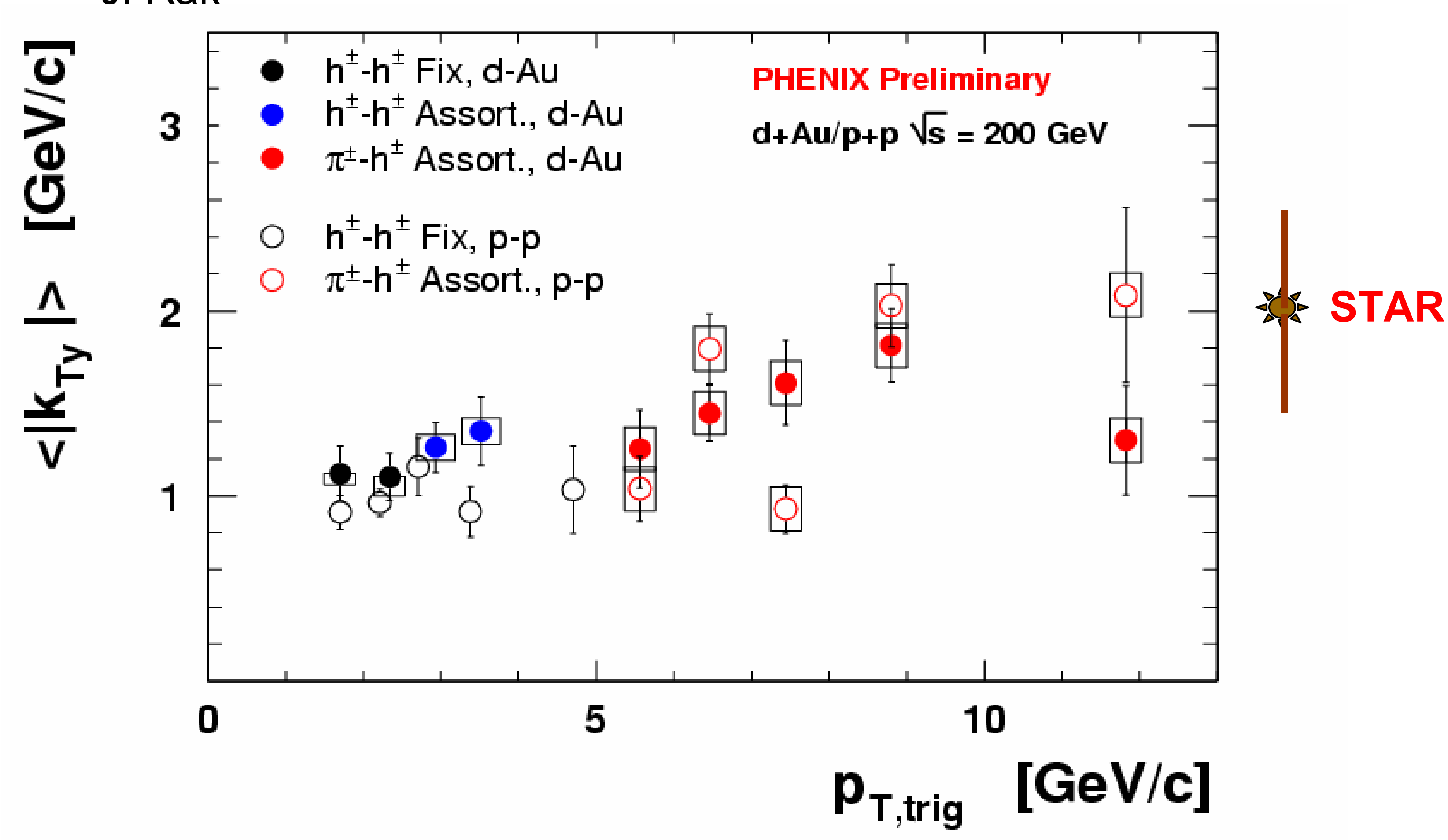


Nuclear k_t = 2.8±1.2±1.0 GeV/c

Extracting nuclear k_T from dAu

$$\langle k_\perp{}^2 \rangle_{\mathrm{dAu}} = \langle k_\perp{}^2 \rangle_{\mathrm{vac}} + \langle k_\perp{}^2 \rangle_{\mathrm{IS\ nucl}}$$

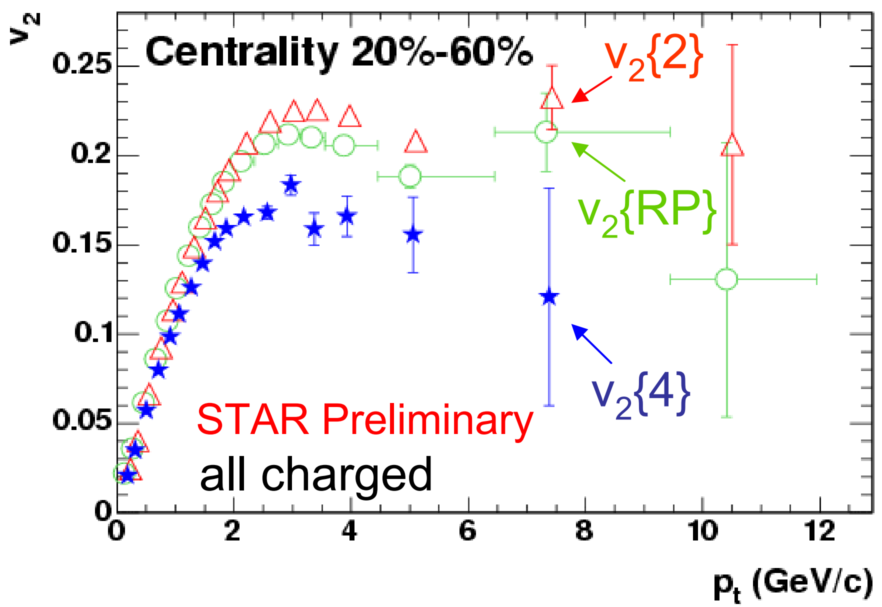
J. Rak



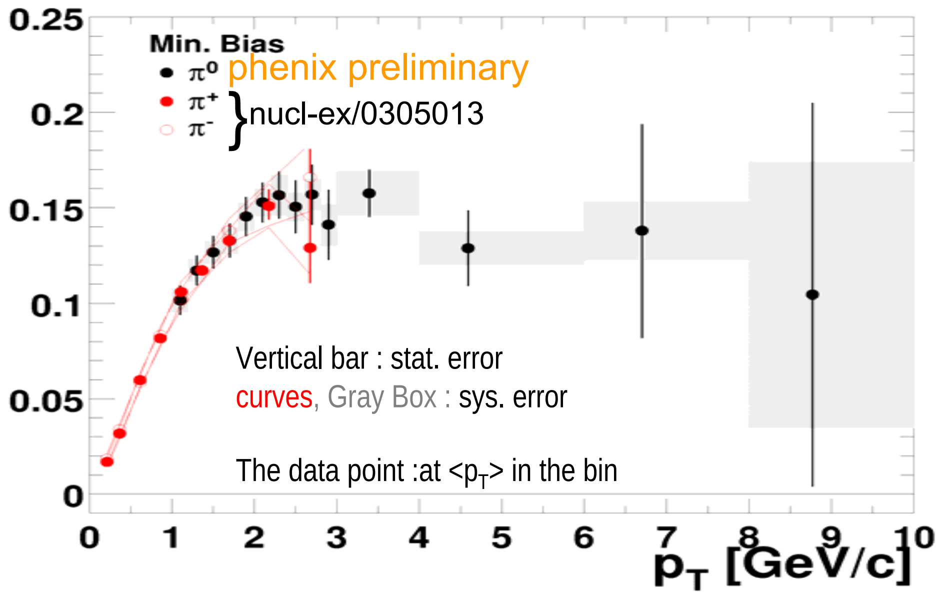
2. Au+Au: Azimuthal dependencies at high p_T

Azimuthal anisotropy v_2 at high p_T

A. Tang



M. Kaneta



Finite azimuthal anisotropy to the highest measured p_T

v_2 for p_T=3-6 GeV/c exceeds the maximum values from surface emission: quark coalescence?

Need reliable v_2 for p_T>7 GeV/c to test jet quenching

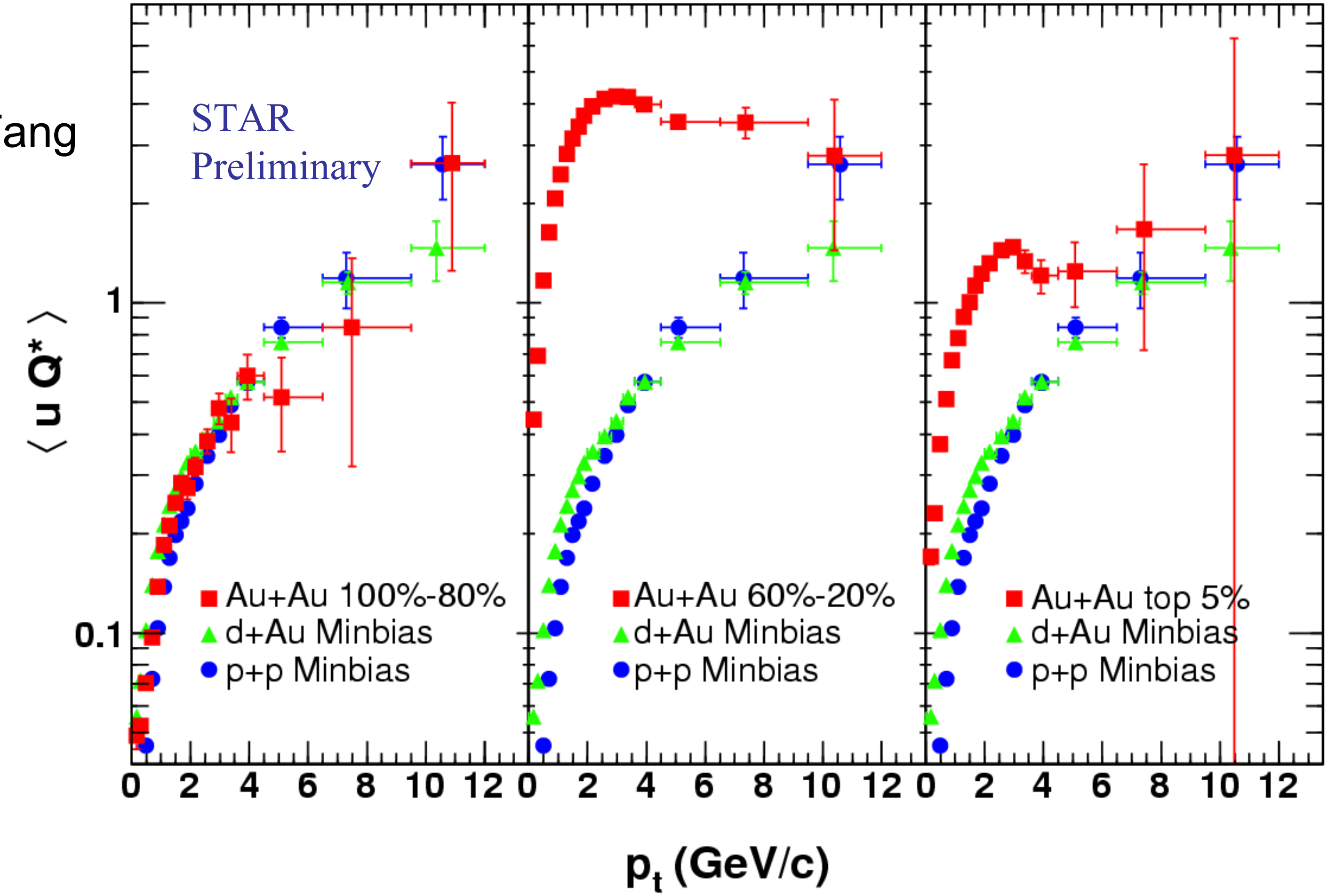
Azimuthal correlation in AuAu, dAu and pp

S. Voloshin:

$$\left\langle u_b Q^* \right\rangle^{AA} \approx v_b v_p M^{AA} + \left\langle u_b Q^* \right\rangle^{pp}$$

- multiplicity (or Nbinary) independent quantity
- compare azimuthal correlations in different systems

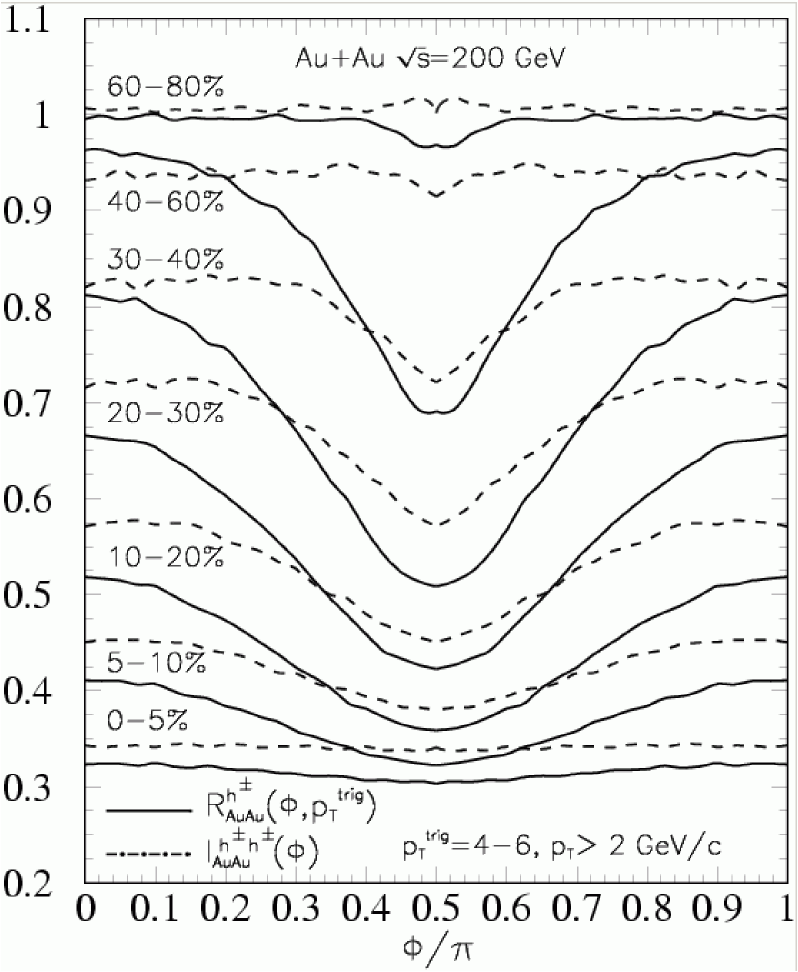
A. Tang

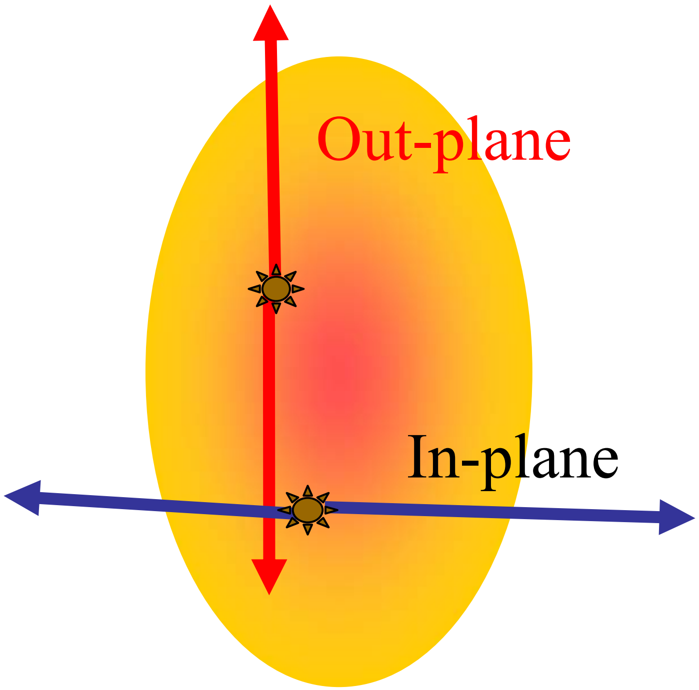


Strong real collective motion in Au+Au

Di-jet tomography: Predictions

X.N. Wang



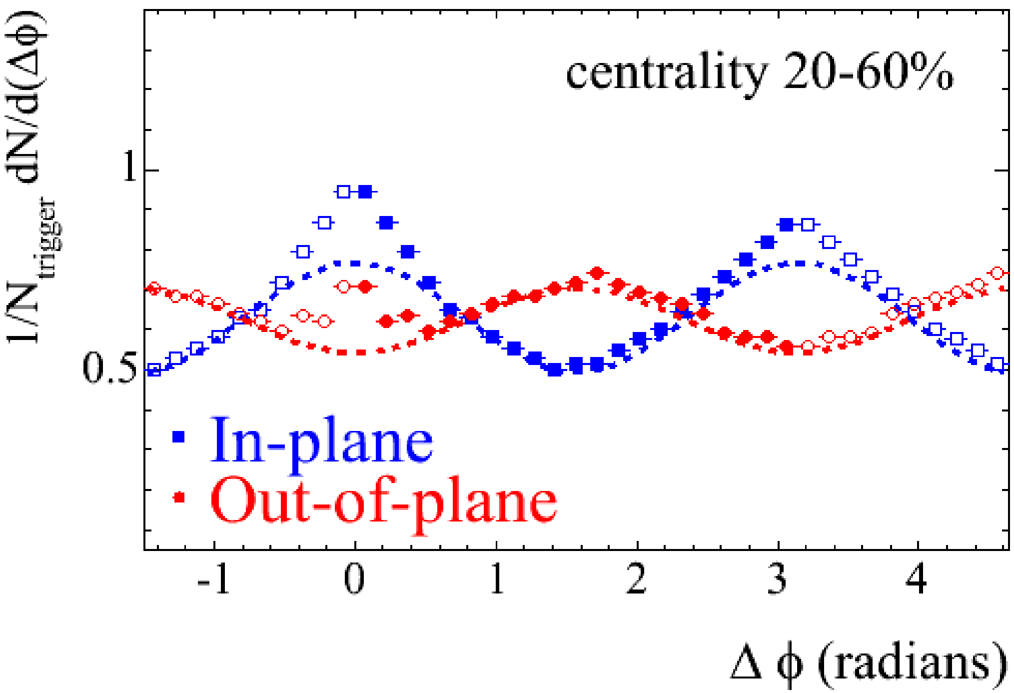


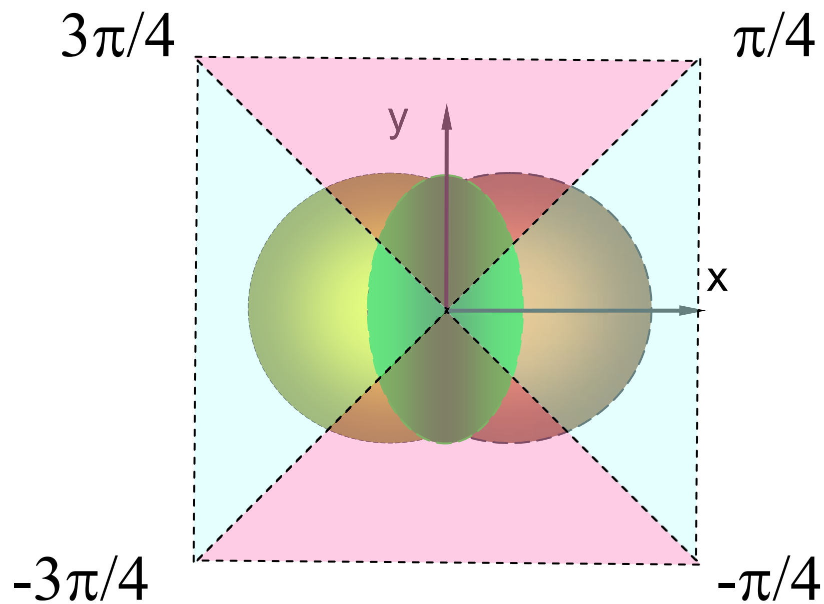
Path length dependence of energy loss leads to $I_{AA}(\varphi)$

Correlations w.r.t. reaction plane

STAR (A. Tang)

$p_T^{trigger}$=4-6 GeV/c, 2<$p_T^{associated}$<$p_T^{trigger}$, |η|<1





Flow pattern is shifted by π/2:

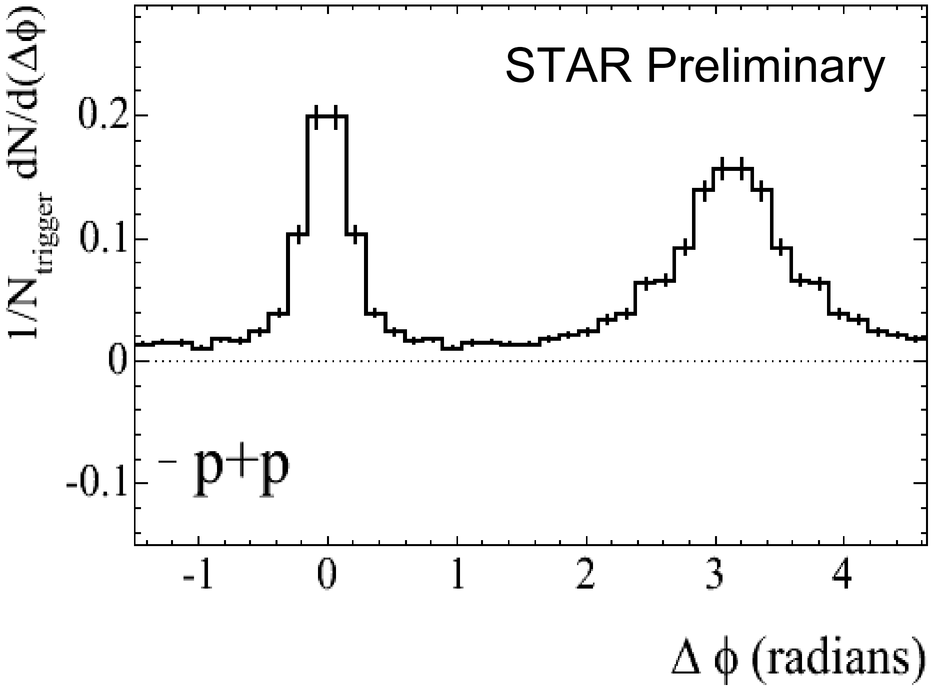
J. Bielcikova, S.Esumi, KF, S.Voloshin, and J.P.Wurm, nucl-ex/0311007, to appear in PRC(R).

$$\frac{dn^{\text{in}}}{d\Delta\phi} \propto 1 + 2v_2 \frac{\pi v_2 + 2\langle\cos 2\Delta\Psi\rangle}{\pi + 4v_2\langle\cos 2\Delta\Psi\rangle} \cos 2\Delta\phi;$$

$$\frac{dn^{\text{out}}}{d\Delta\phi} \propto 1 + 2v_2 \frac{\pi v_2 - 2\langle\cos 2\Delta\Psi\rangle}{\pi - 4v_2\langle\cos 2\Delta\Psi\rangle} \cos 2\Delta\phi,$$

Di-hardron tomography

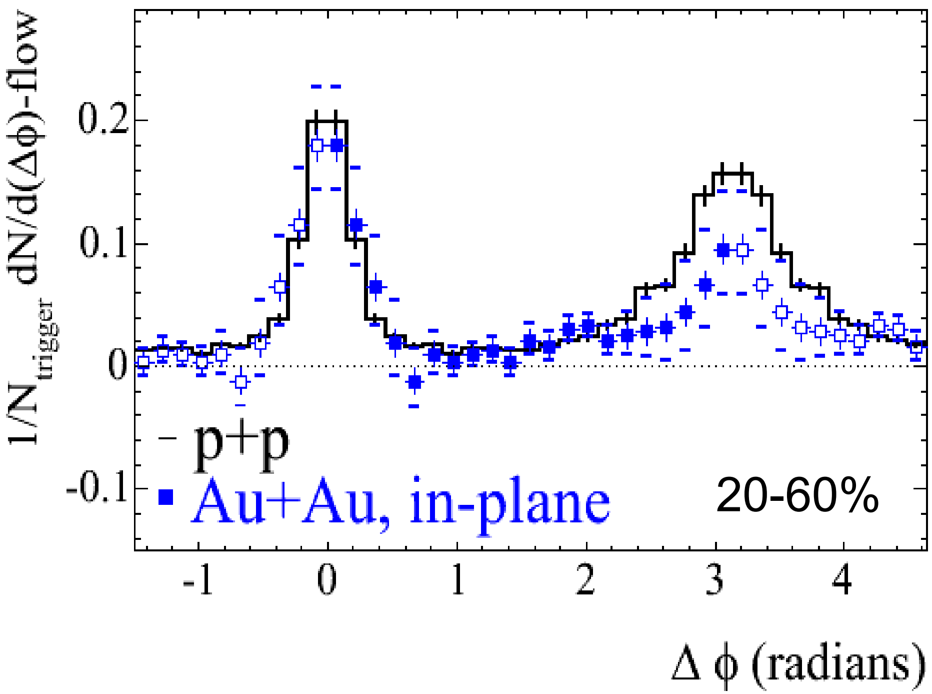
p_T^{trig}=4.0-6.0 GeV/c, |η|<1.0
2.0<p_T^{assoc}<p_T^{trig}



A. Tang

Di-hardron tomography

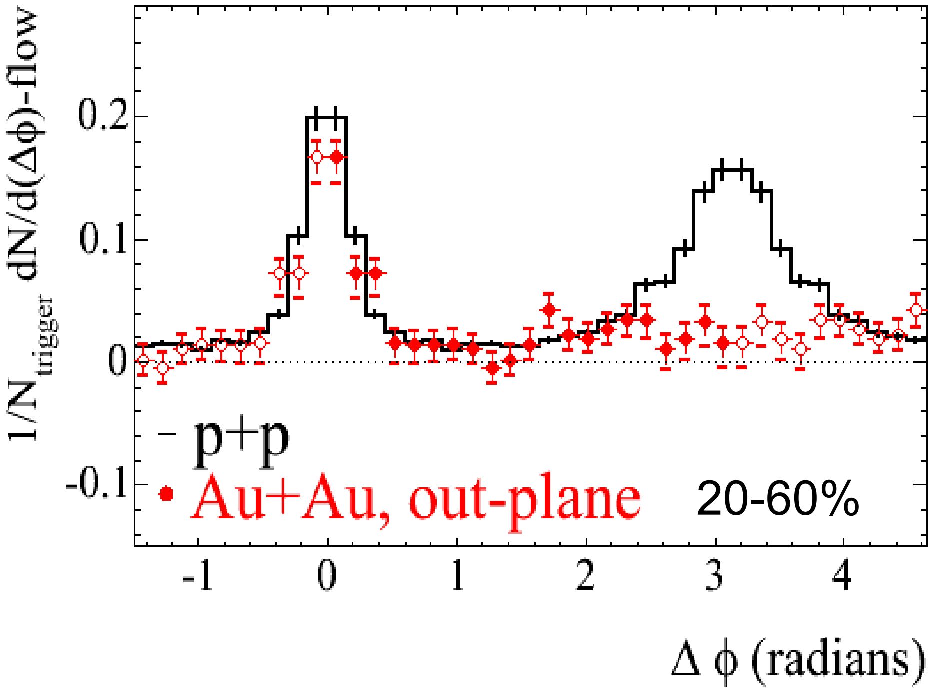
p_T^{trig}=4.0-6.0 GeV/c, |η|<1.0
$2.0<p_T^{assoc}<p_T^{trig}$



A. Tang

Di-hardron tomography

p_T^{trig}=4.0-6.0 GeV/c, $|\eta|$<1.0
2.0<p_T^{assoc}<p_T^{trig}



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Di-hardron tomography

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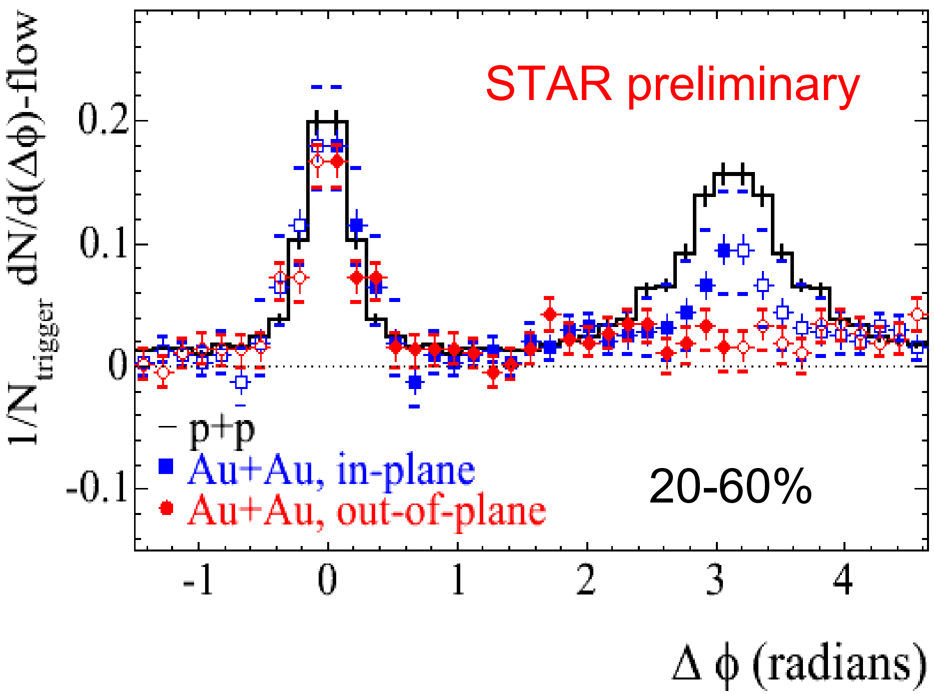
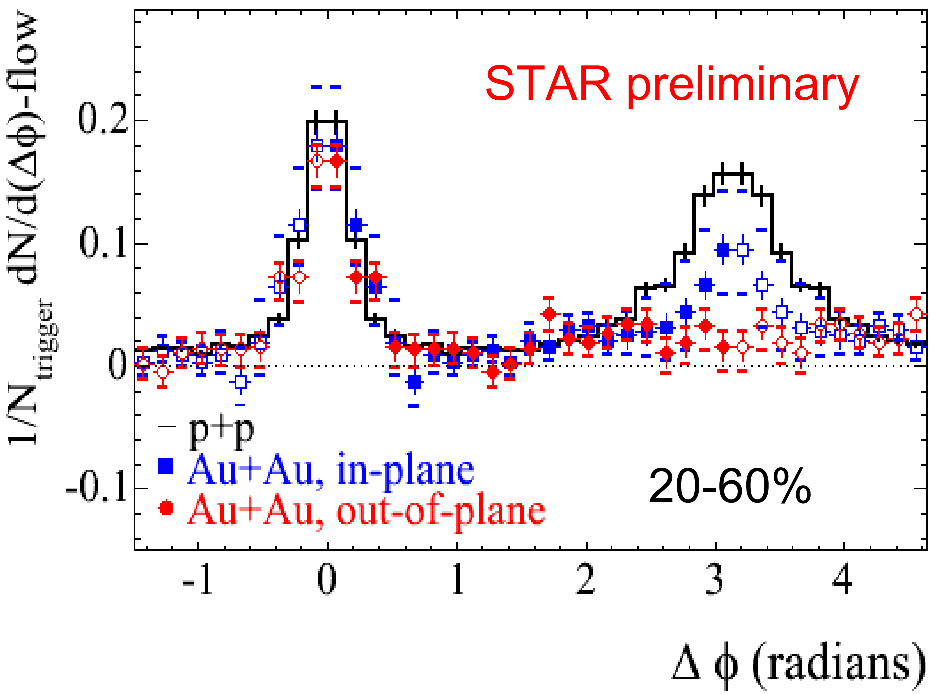


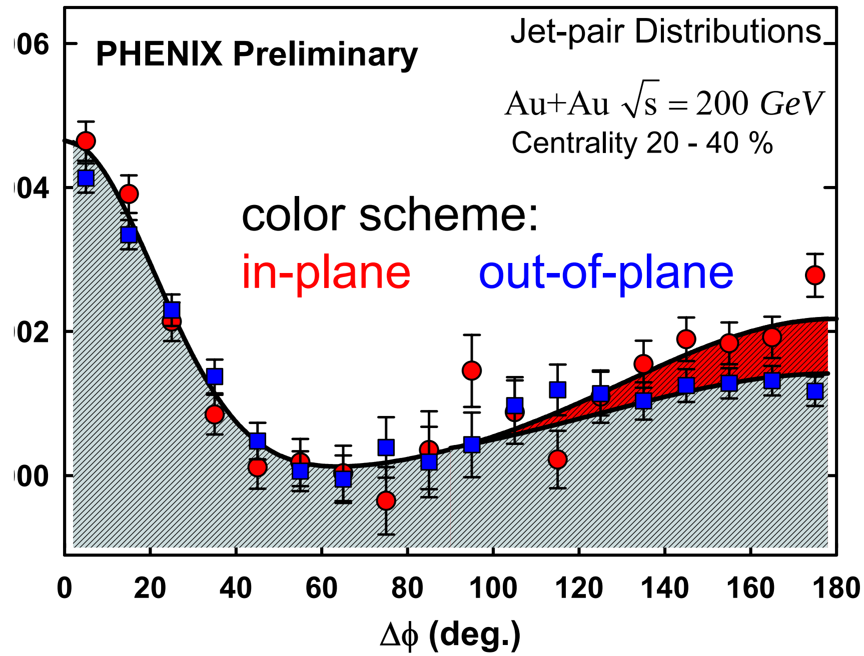
A. Tang

Di-hardron tomography

p_T^{trig}=4.0-6.0 GeV/c, |η|<1.0
2.0<p_T^{assoc}<p_T^{trig}



p_T^{trig}=2.5-4.0 GeV/c, |η|<0.35
1.0<p_T^{assoc}<2.5 GeV/c

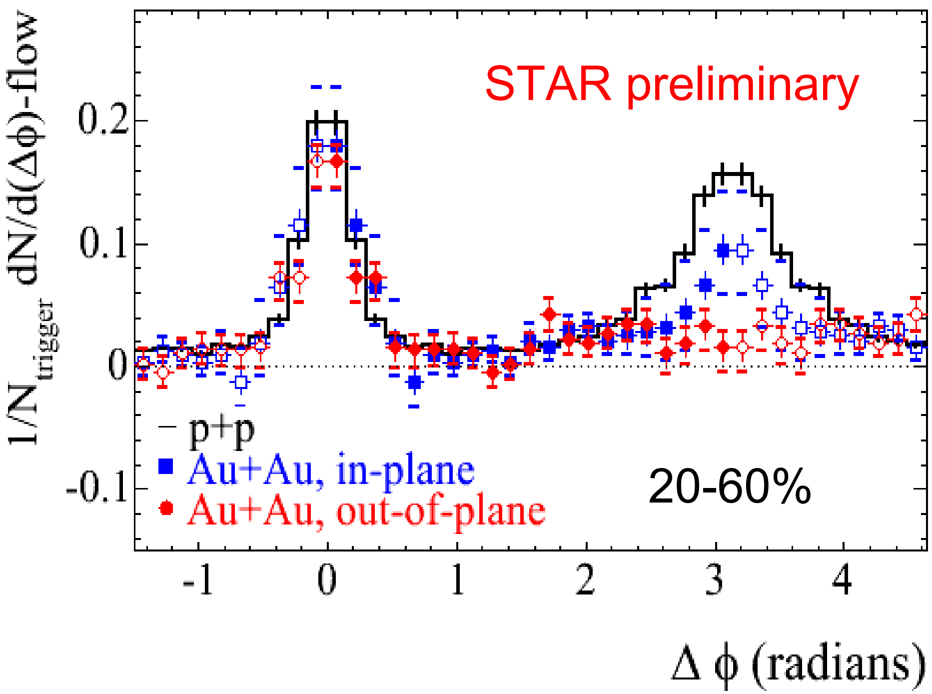


W. Holzmann

A. Tang

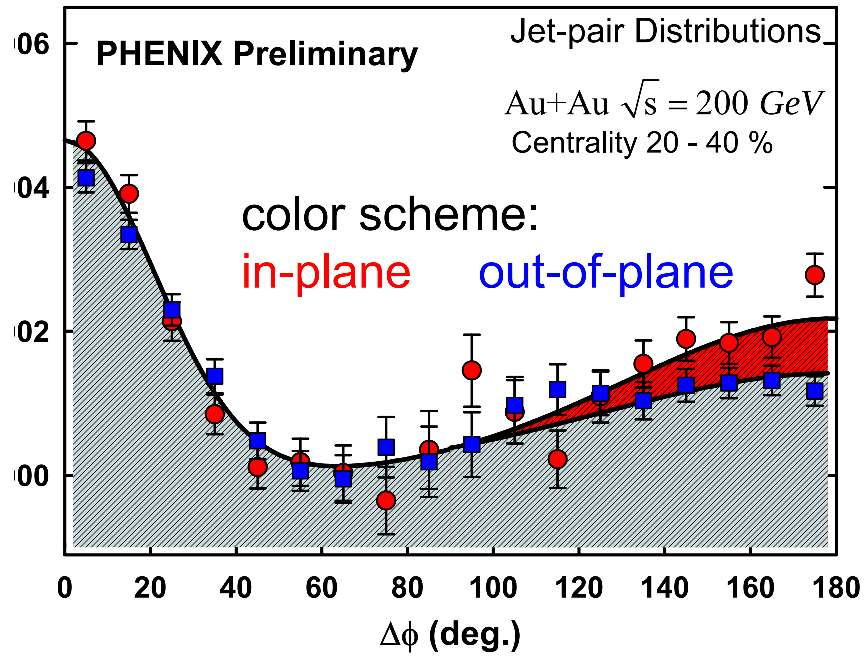
Di-hardron tomography

p_T^{trig}=4.0-6.0 GeV/c, |η|<1.0
2.0<p_T^{assoc}<p_T^{trig}



A. Tang

p_T^{trig}=2.5-4.0 GeV/c, |η|<0.35
1.0<p_T^{assoc}<2.5 GeV/c



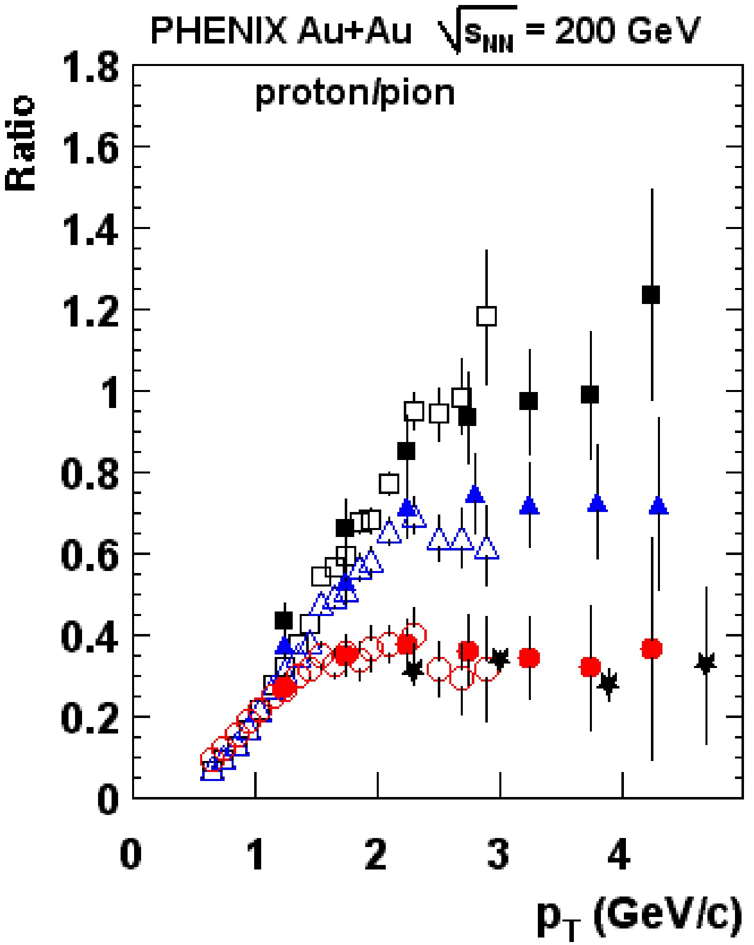
W. Holzmann

Back-to-back suppression depends on the reaction plane orientation:
energy loss dependence on the path length

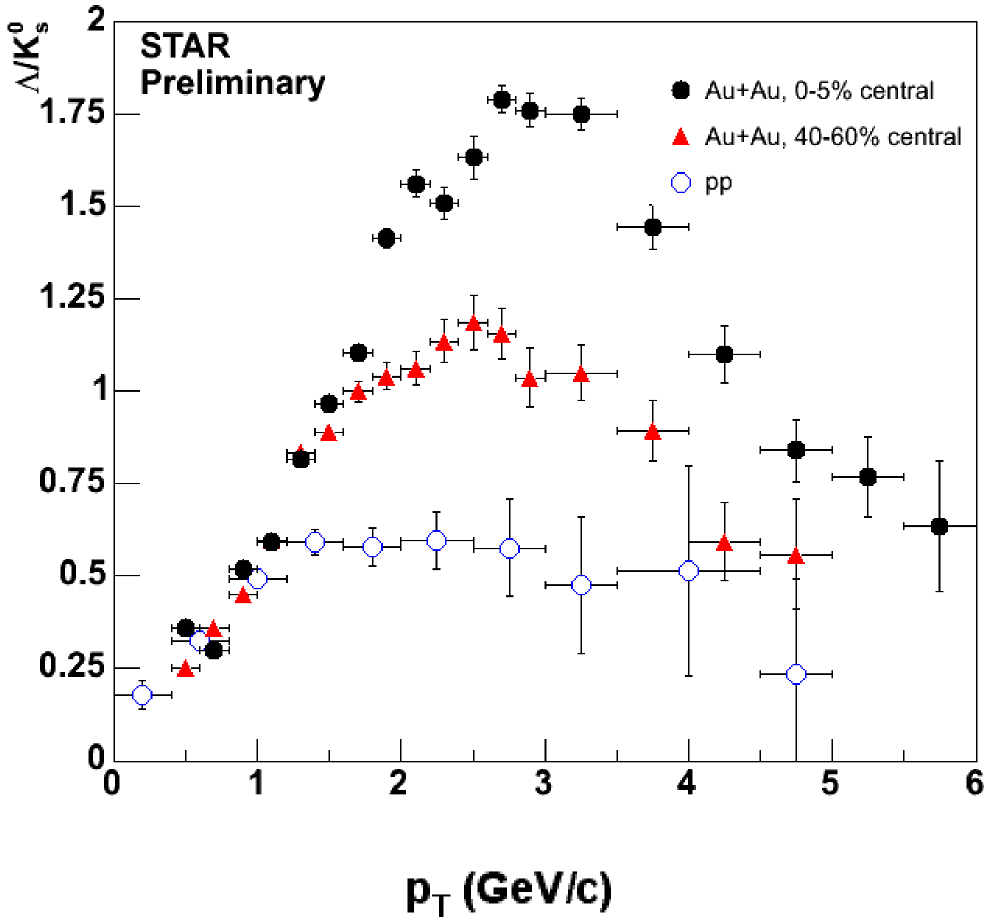
3. Unraveling flavor of jets

Baryon/Meson Ratios

F. Matathias

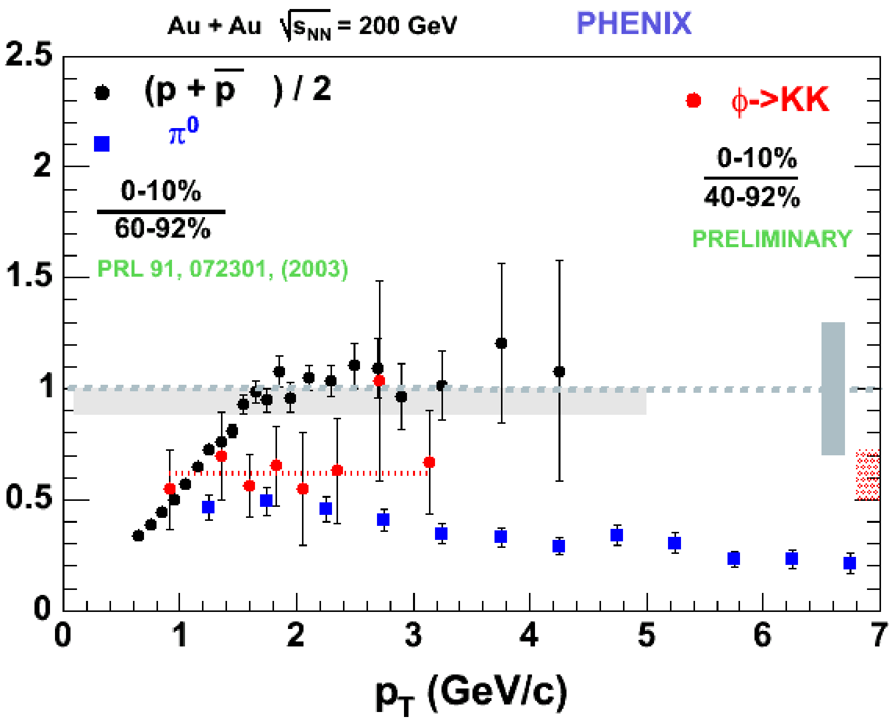


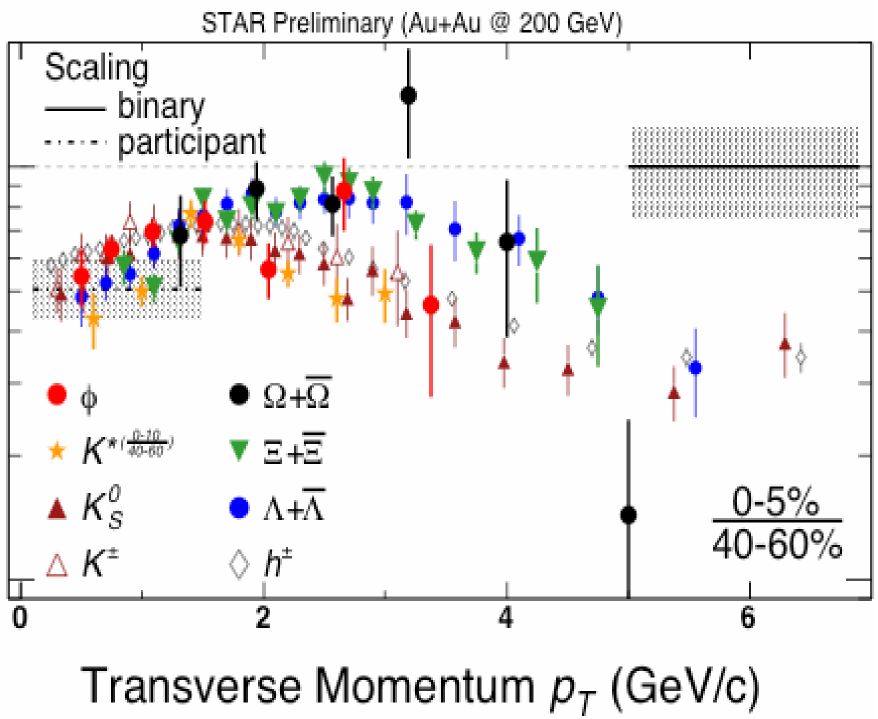
M. Lamont



Baryon/meson ratio “anomalous” for p_T<6-7 GeV/c

Identified particle R_{CP}



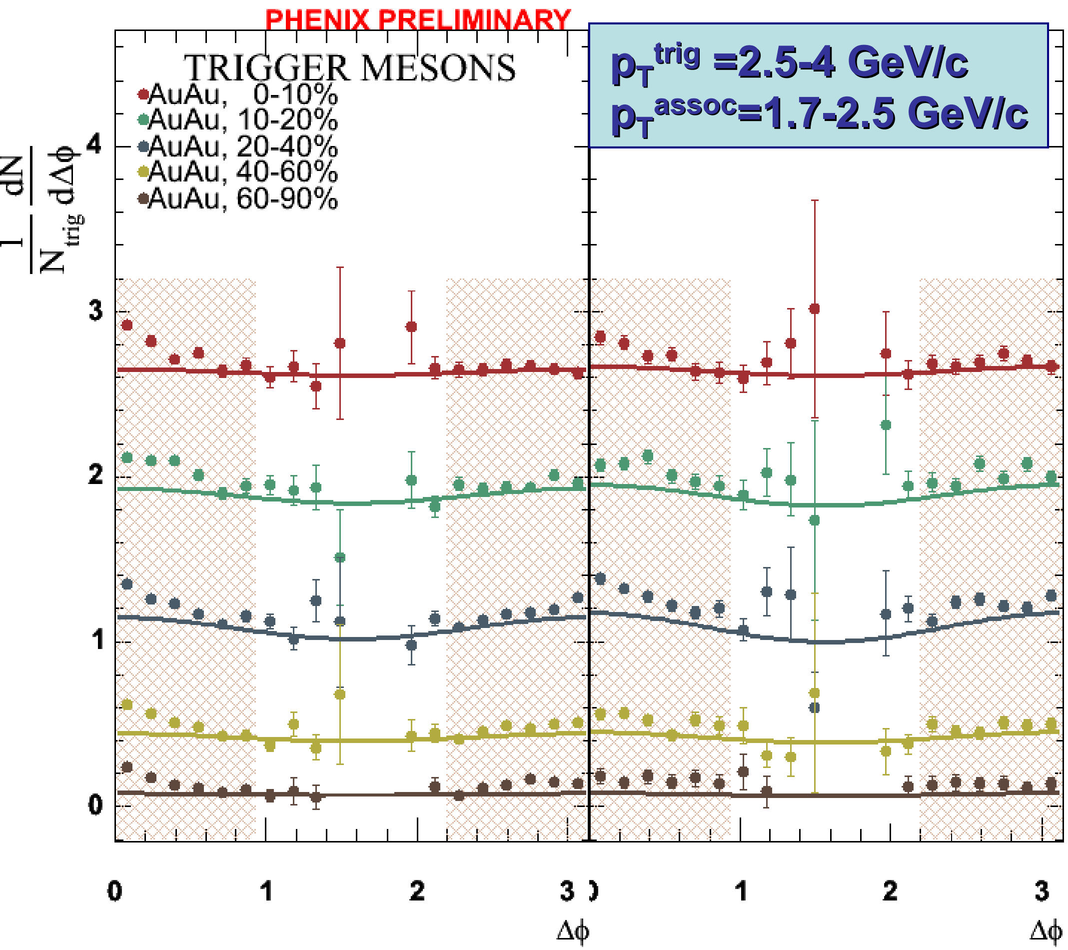


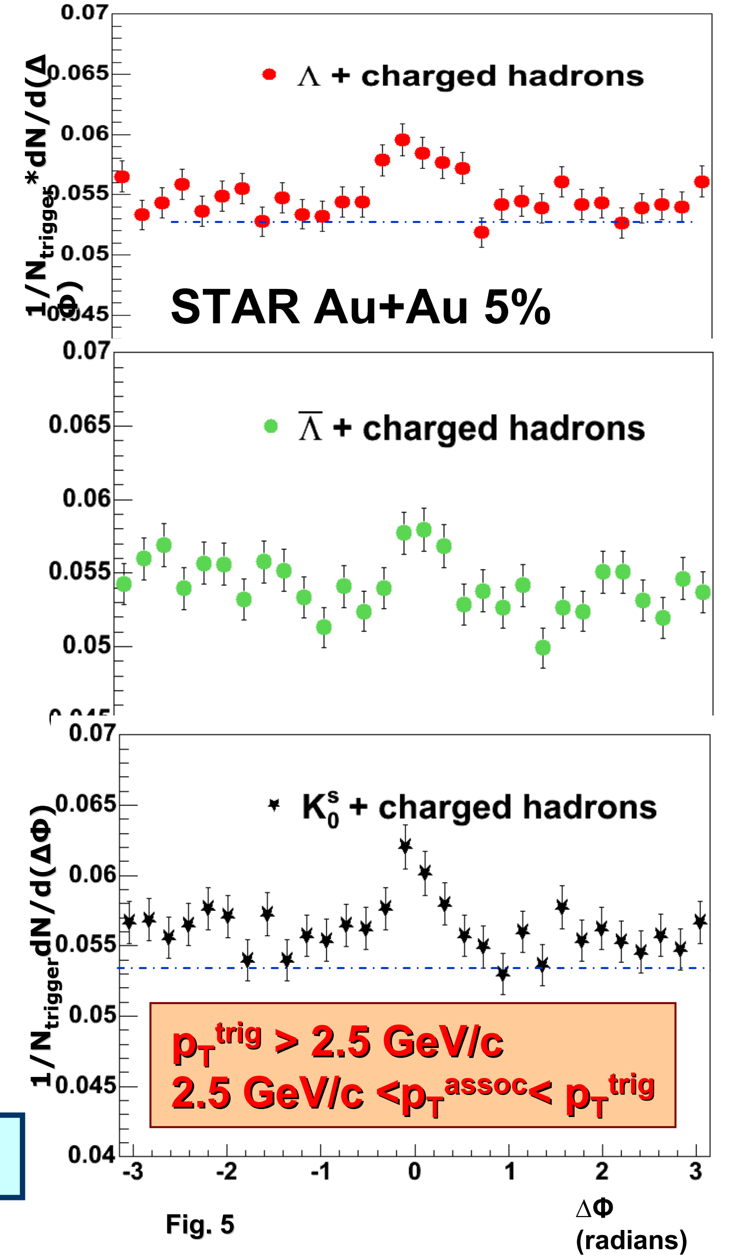
Baryon/meson effect!

Coalecence for p_T=2-6 GeV/c? v_2 says yes…

Flavor-tagged correlations M. Lamont

A. Sickles



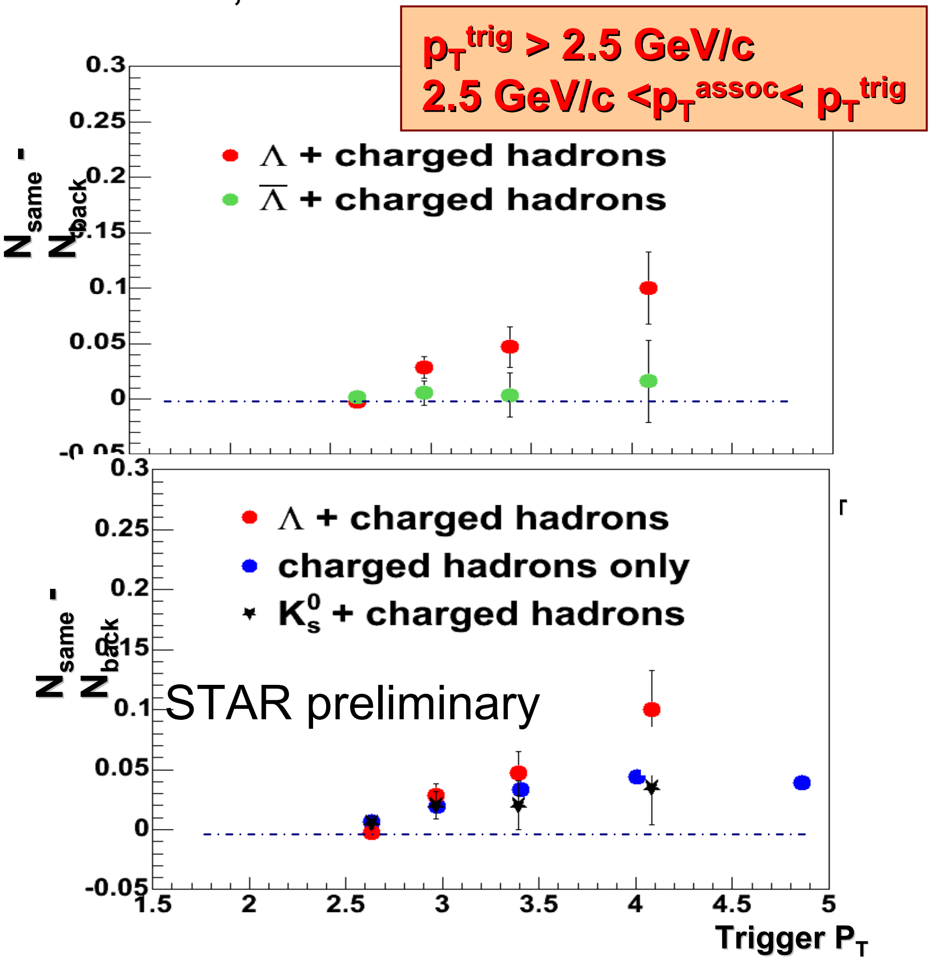


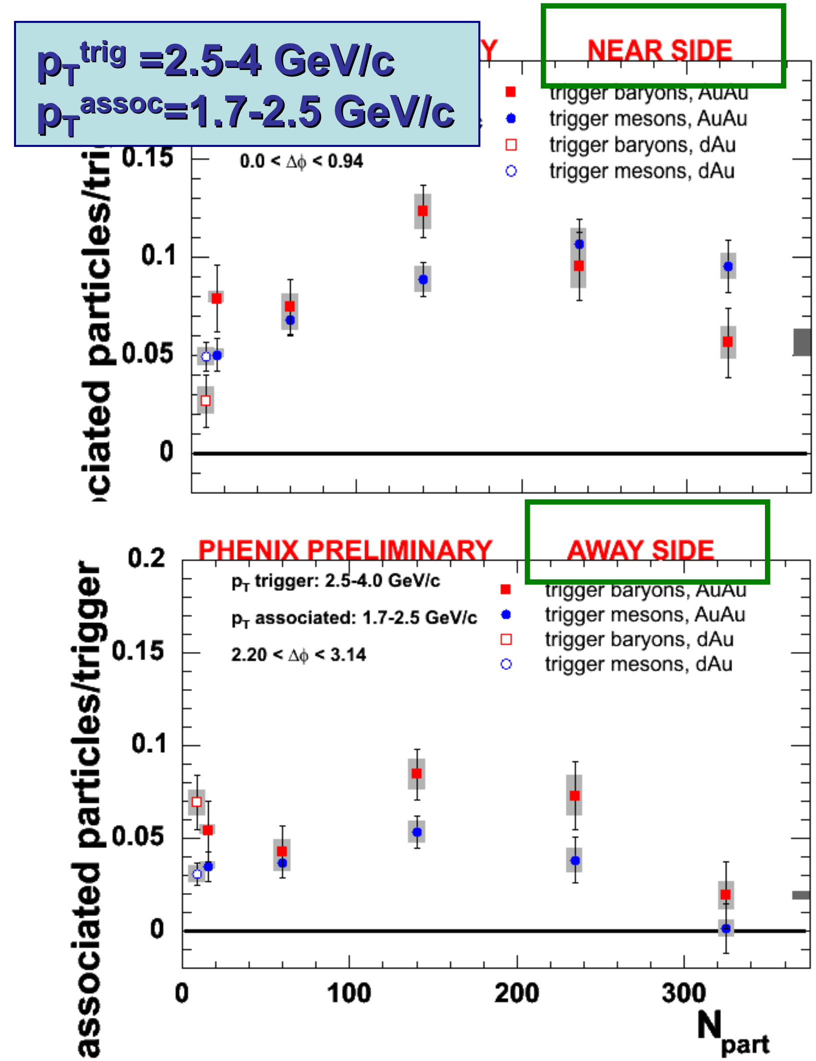
Note pt-range: right in the baryon/meson "anomaly"

Identified particle angular distributions

M. Lamont, Y. Guo

A. Sickles



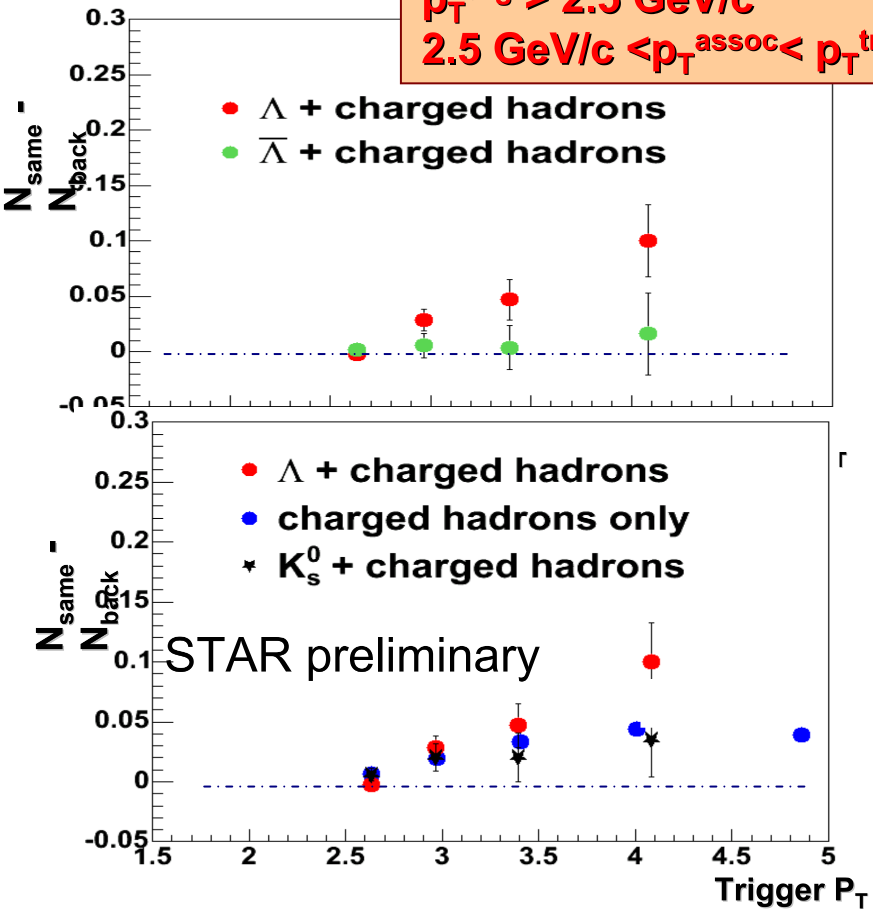


So far, more questions than answers…

Identified particle angular distributions

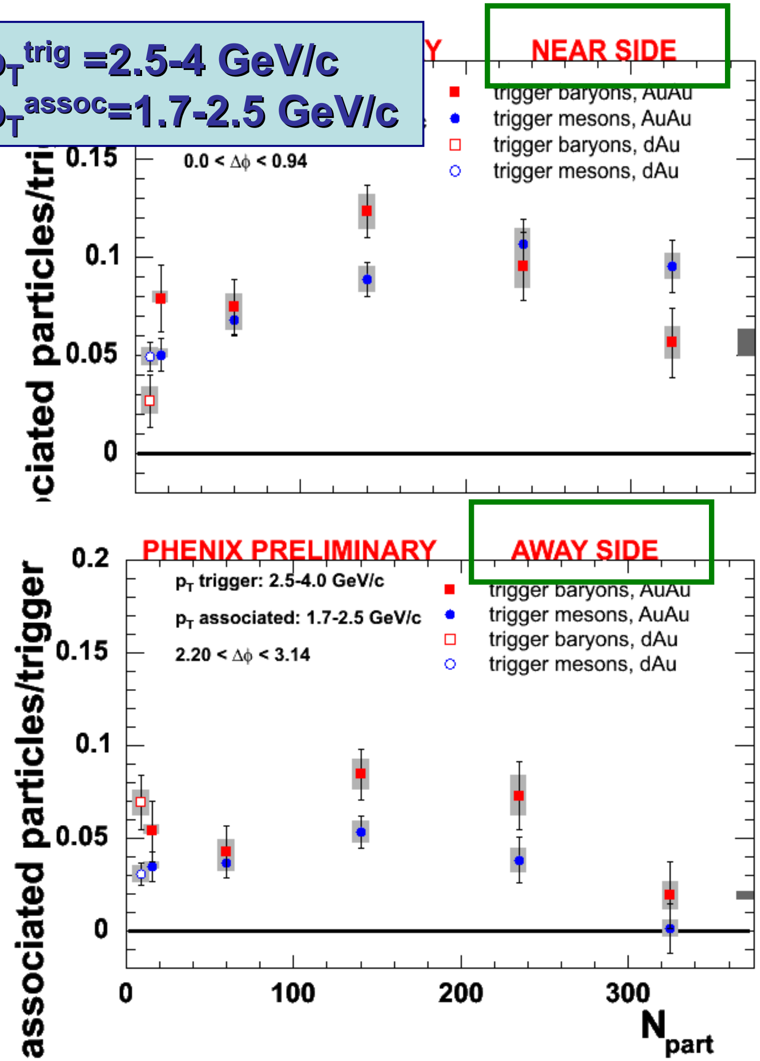
M. Lamont, Y. Guo

$p_T^{trig} > 2.5$ GeV/c
2.5 GeV/c $< p_T^{assoc} < p_T^{trig}$



A. Sickles

p_T^{trig} =2.5-4 GeV/c
p_T^{assoc}=1.7-2.5 GeV/c

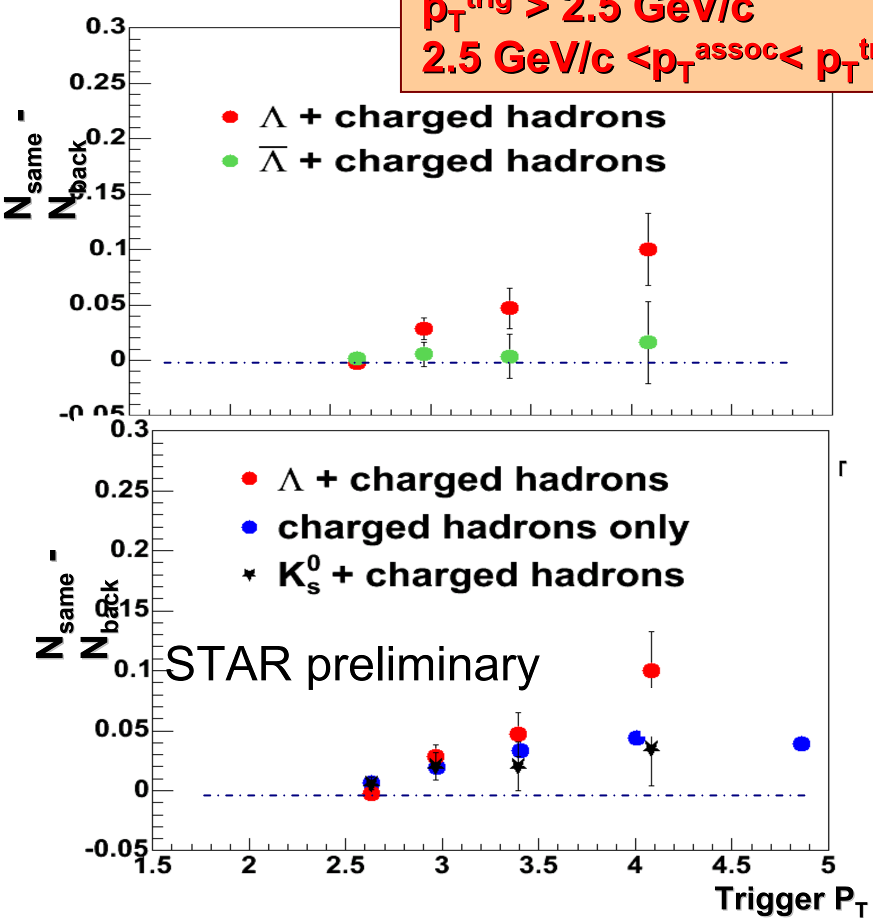


Why would Λ and anti-Λ be different?

Identified particle angular distributions

M. Lamont, Y. Guo

$p_T^{trig} > 2.5$ GeV/c
2.5 GeV/c $< p_T^{assoc} < p_T^{trig}$



A. Sickles

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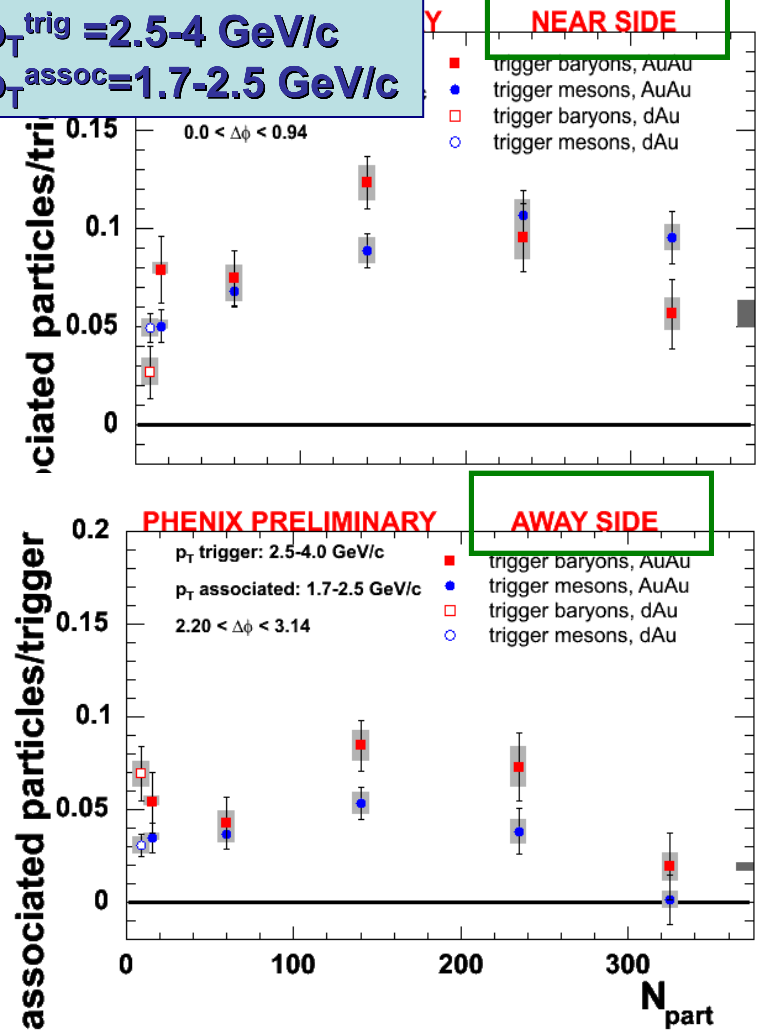

More associated particles on the away side for trigger baryons?

Identified particle angular distributions

M. Lamont, Y. Guo

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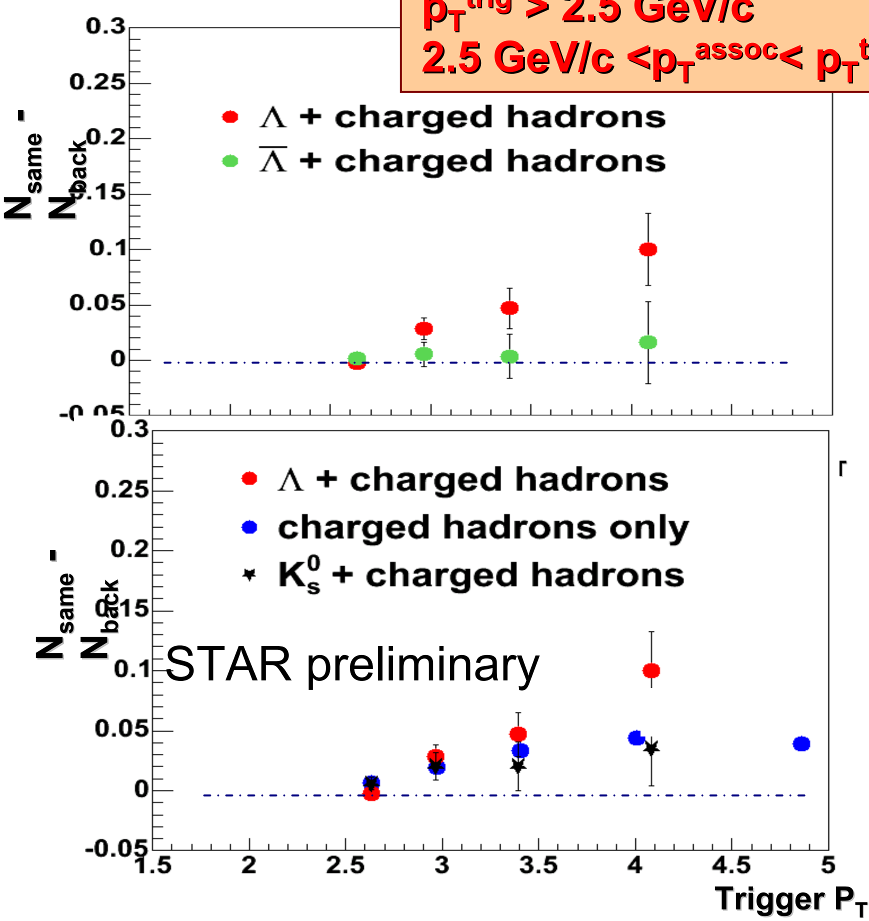

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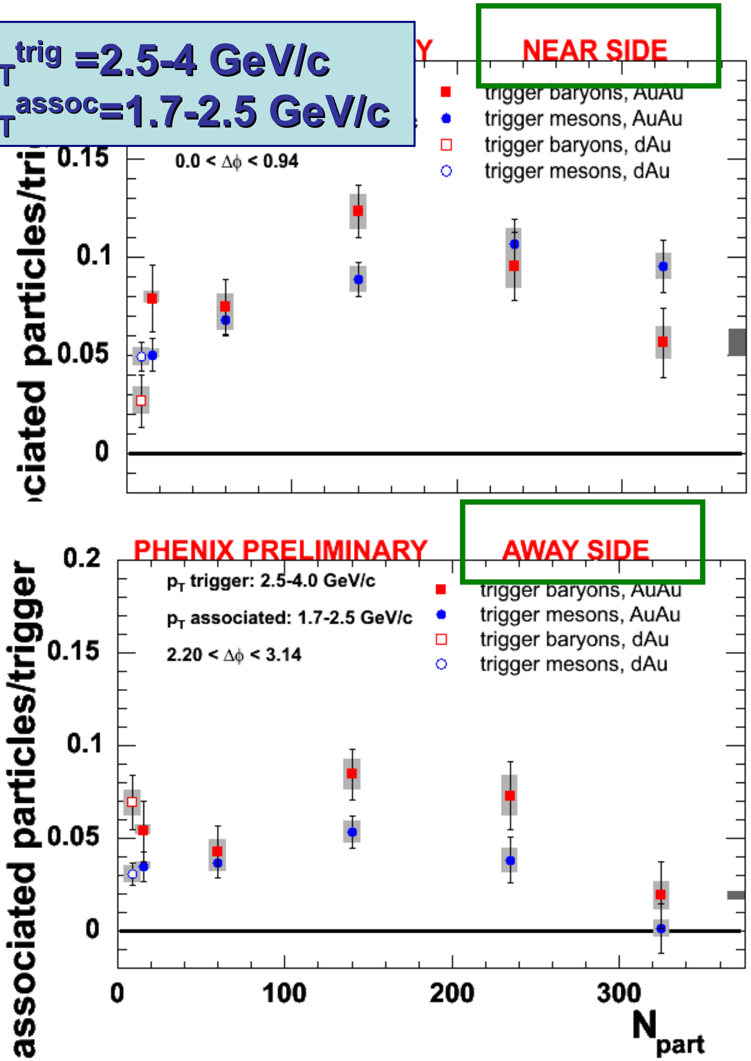
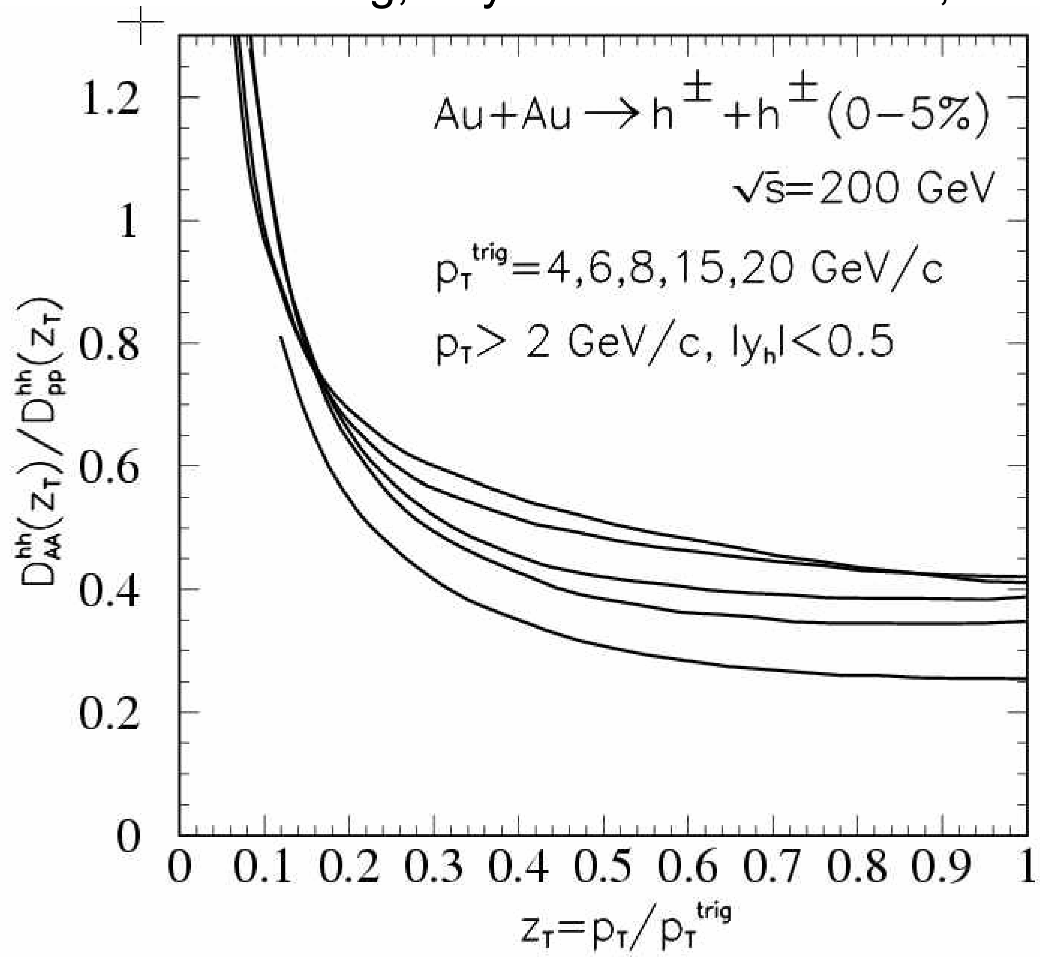


To test the coalescence, choose p_T^{trig}(baryon)=3/2*p_T^{trig}(meson)

4. Search for the lost energy

Medium Modification of FF

X.N. Wang, Phys.Lett.B579:299-308,2004

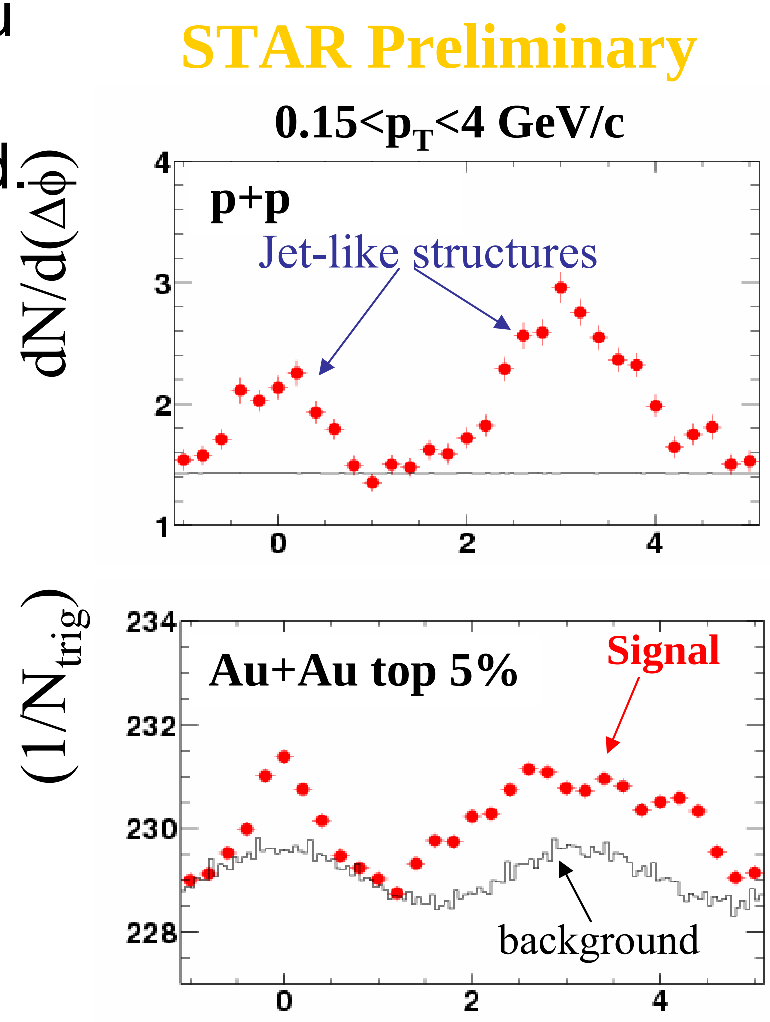


- Softening of fragmentation function due to energy loss
- Enhancement of soft hadrons from emitted gluons at low z

Di-hadron correlations at "all" p_T's

- Trigger on leading particle pT=4-6 GeV/c, $|\eta|<0.75$
- Associate "all" particles (pT=0.15-4.0 GeV/c, $|\eta|<1.1$)
- Form $\Delta\varphi$, $\Delta\eta$ correlation in pp, Au+Au
- Background from mixed events.
- Au+Au: v_2 modulation on background.

F.Wang



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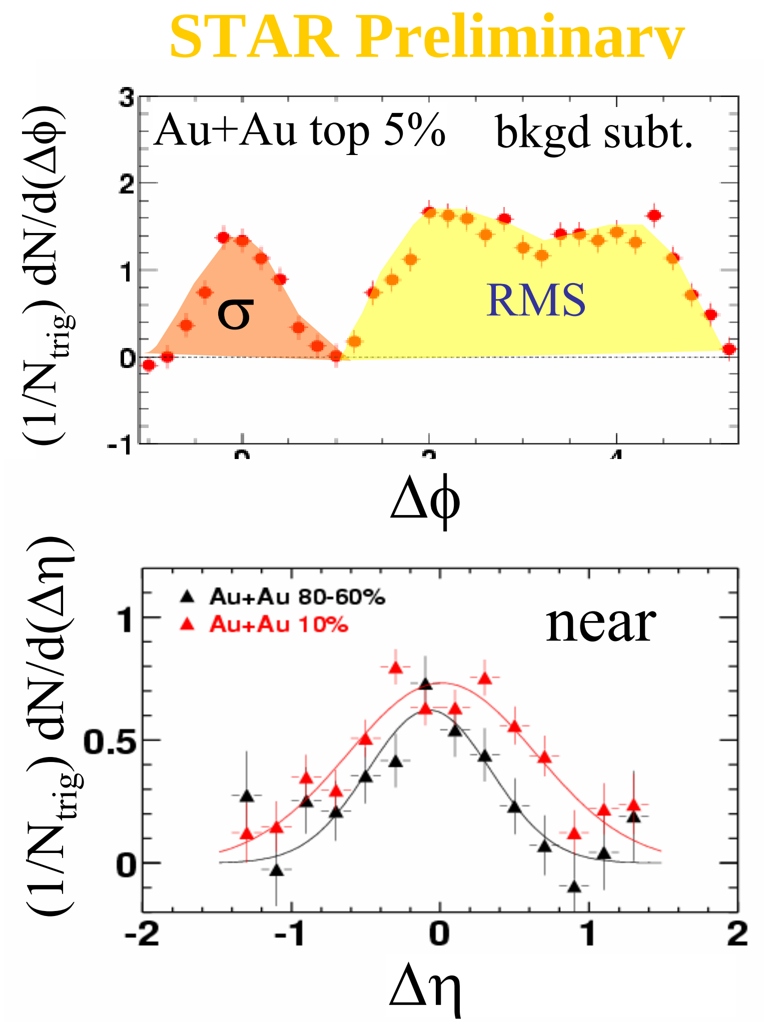

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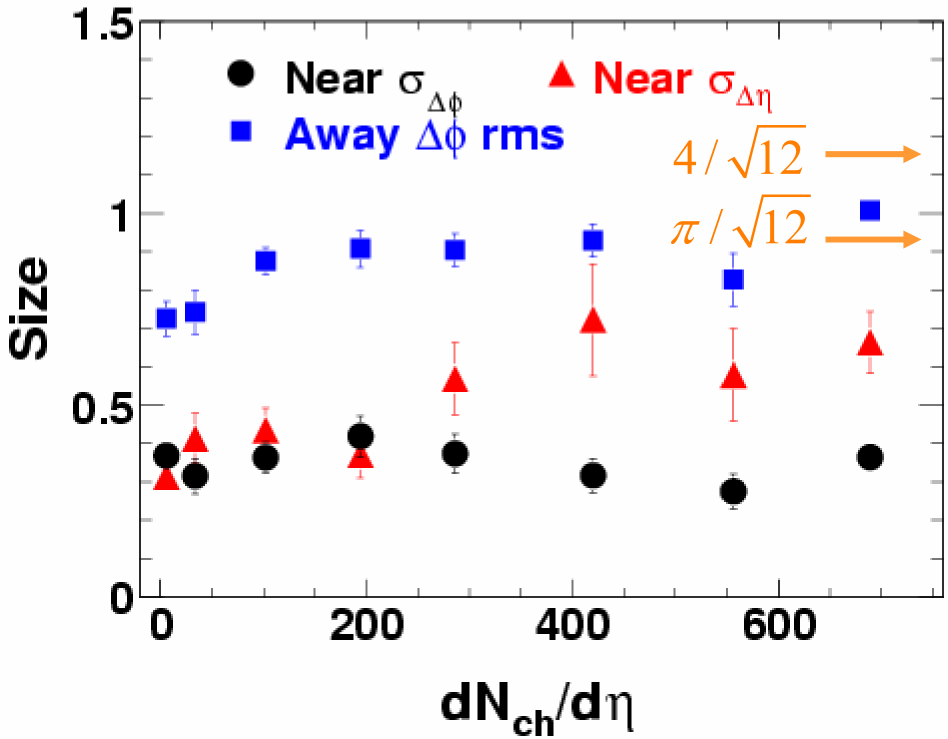
STAR Preliminary



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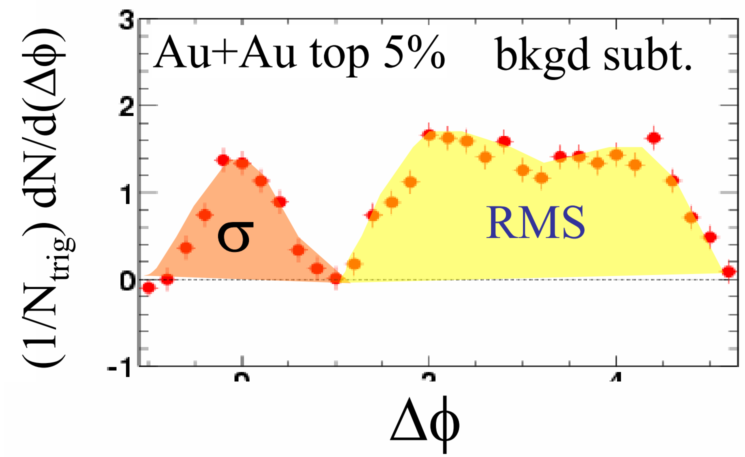
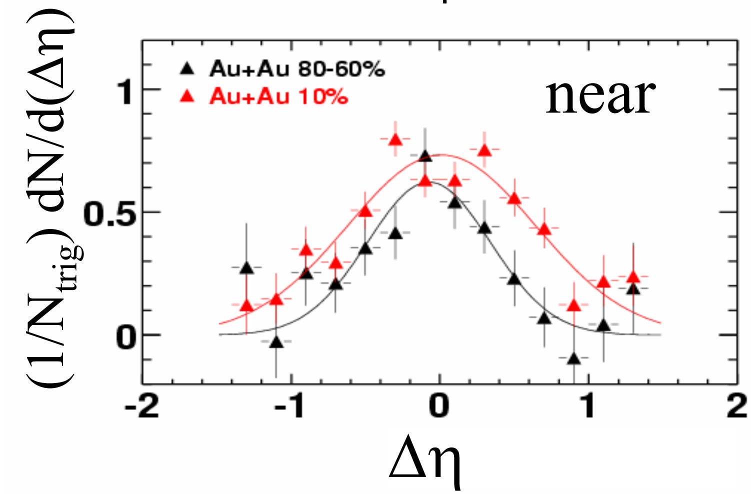


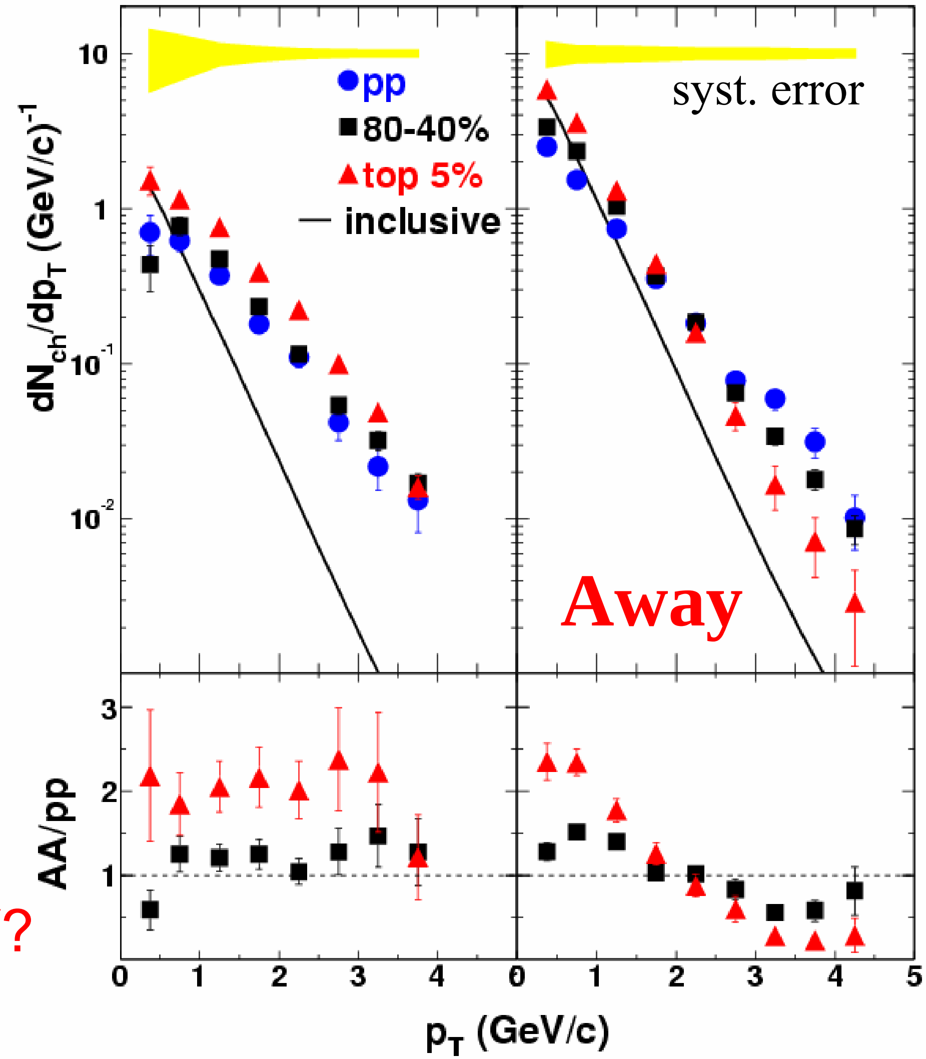


p_T distributions on near and away side

Near side:

Overall enhancement from pp to AA

Trigger bias in Au+Au? Coalescence effects at 4 GeV?



Away side:

energy from initial parton seems to be converted to lower p_T particles

reminiscent of energy loss predictions

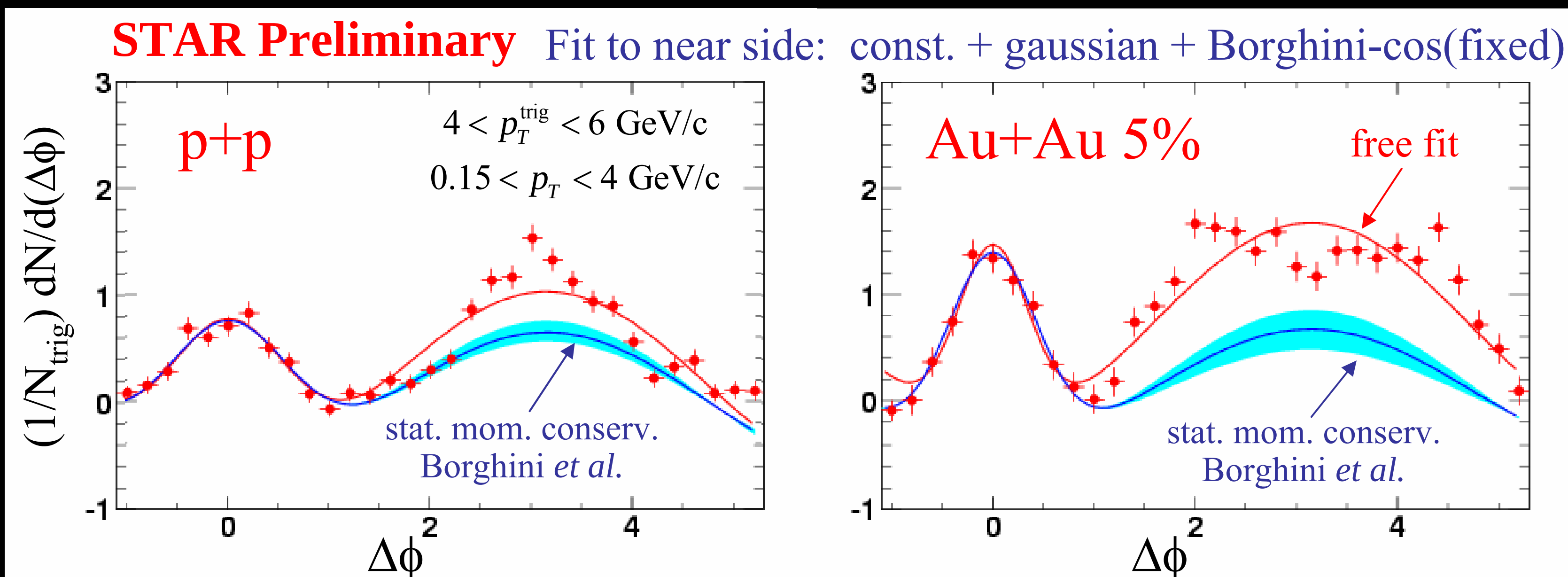
What about other explanations? Do we really know if it is a jet on away side?

e.g. a thermal fluctuated large p_T particle (or a mono-jet) would produce an away side excess due to momentum conservation.

Borghini *et al.* PRC 62, 034902 (2000):

$$C^{\Sigma p_T} = -\frac{2\vec{p}_{T1}\cdot\vec{p}_{T2}}{N_{\text{all}}\left\langle p_T^2\right\rangle_{\text{all}}} \rightarrow \frac{dN}{d(\Delta\phi)} = -\frac{N_{\text{meas}}}{2\pi}\frac{2P_T^{\text{jet}}\left\langle p_T\right\rangle_{\text{meas}}}{N_{\text{all}}\left\langle p_T^2\right\rangle_{\text{all}}}\cos(\Delta\phi)$$

$\left\langle p_T^2\right\rangle$ [GeV/c]^2	HIJING all η	STAR $\lvert\eta\rvert < 0.5$
p+p	0.23	0.26
Au+Au 5%	0.31	0.50



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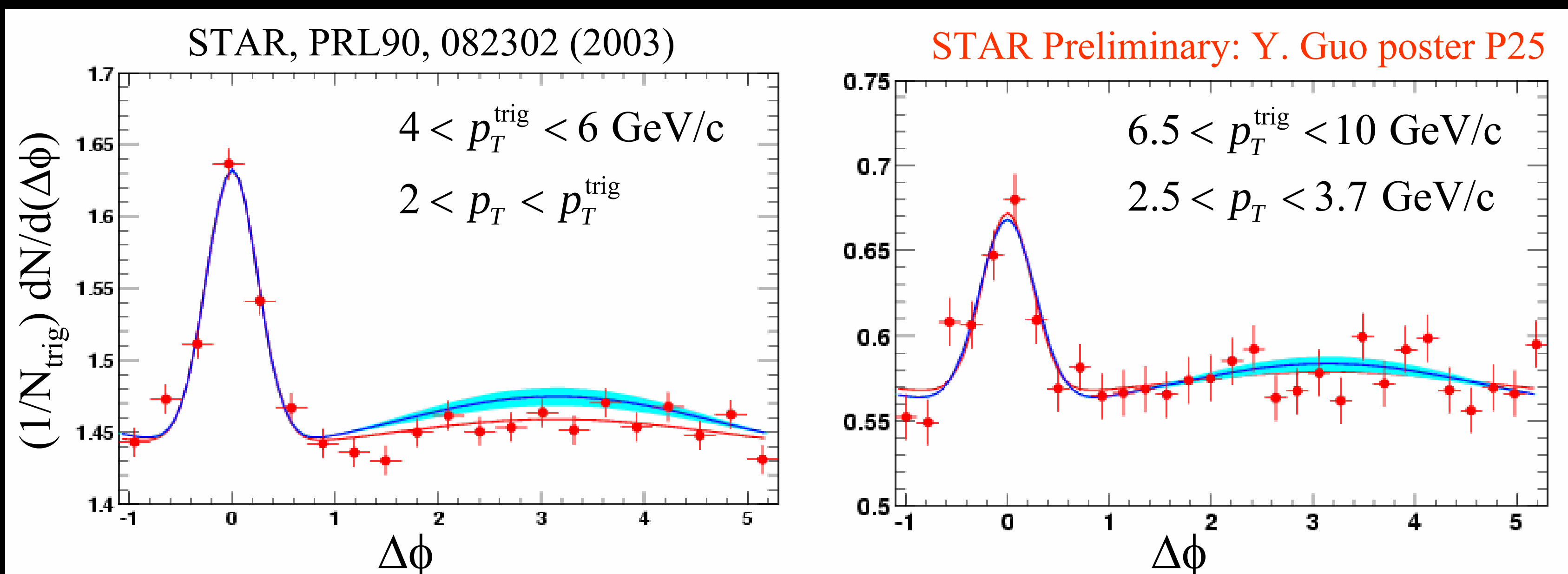

No punch-through for $6 < p_T^{trig} < 10$ GeV/c.

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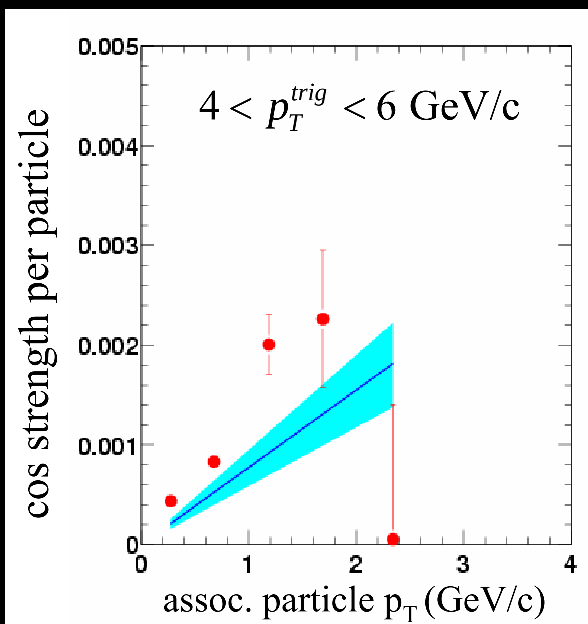
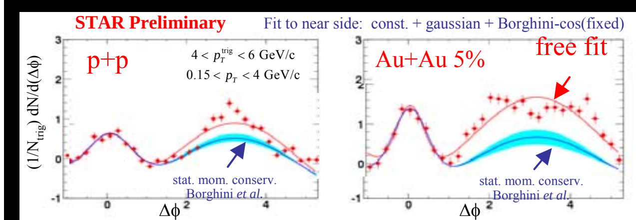
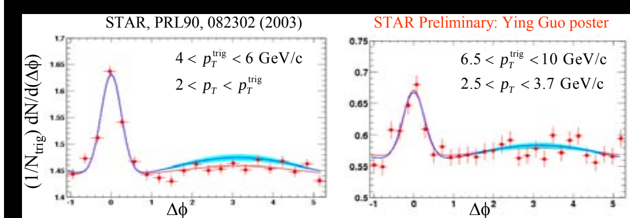
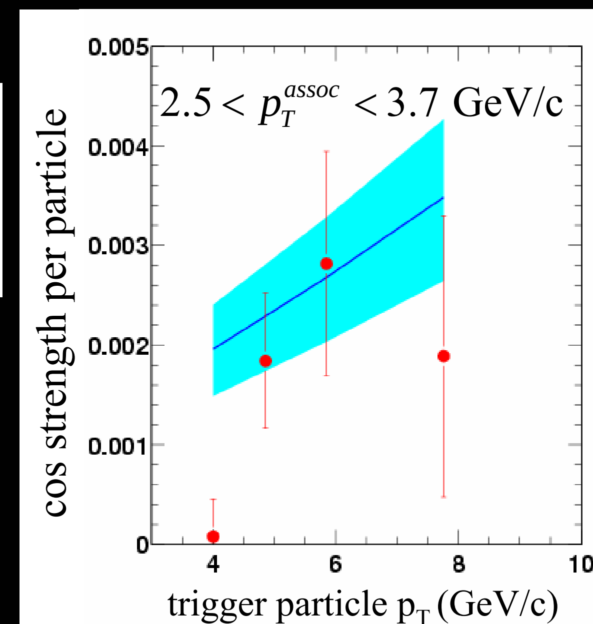






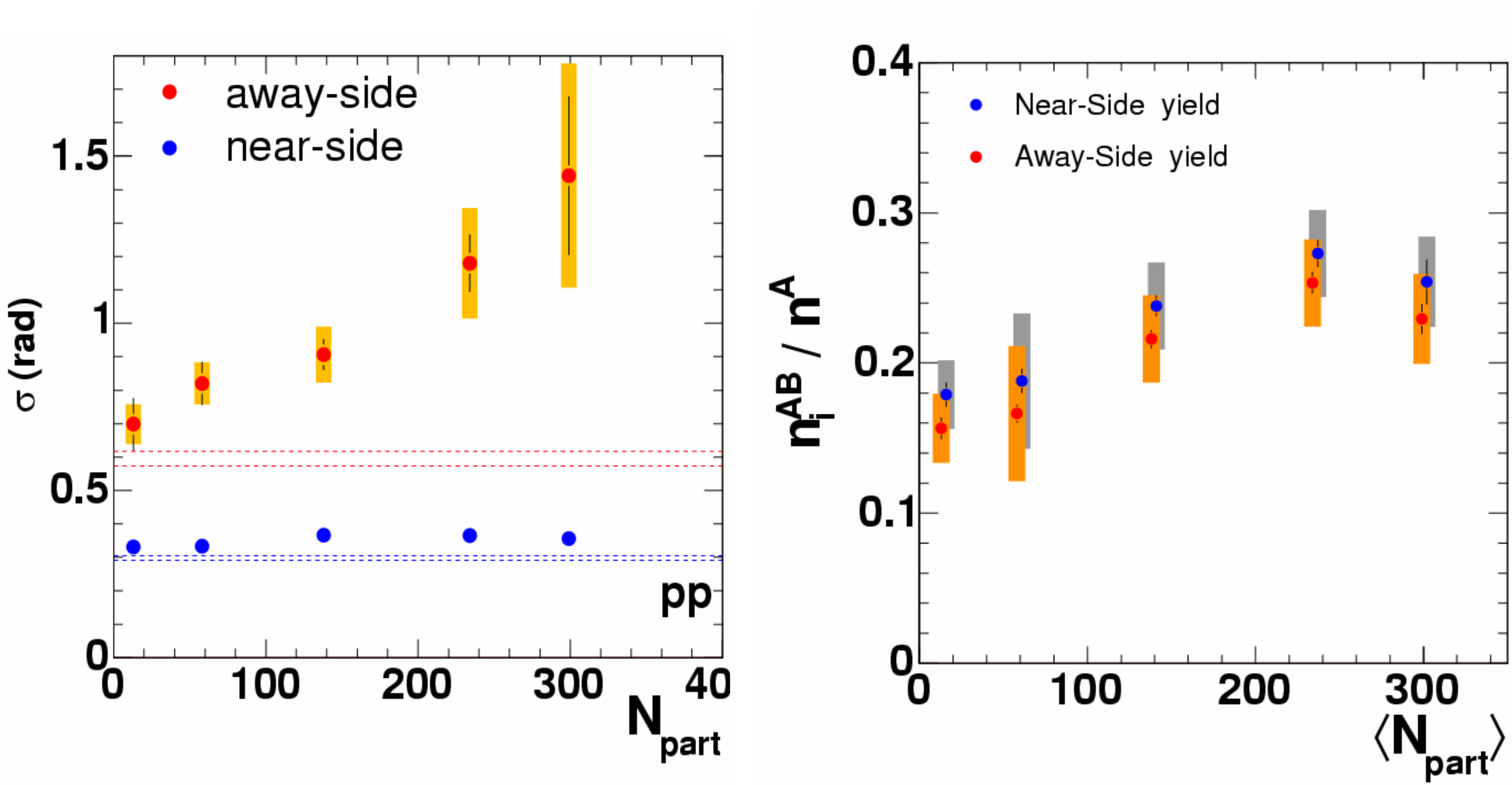


- the final state away excess has a similar shape to a stat. distr. from momentum conservation.
- near side is mostly a jet, and initially no mono-jet at mid-rapidity.

→ the away side excess is approaching equilibration with the medium, consistent with the p_T spectra results.

Broadening of di-hadron correlations

Trigger and associated particles: $(2.5<p_{Ttrigg}<4.0)\otimes(1.0<p_{Tassoc}<2.5)$ J. Rak



Most likely consistent with STAR, easy to check!

Summary

Inclusive spectra:

- very nice confirmation of R(dAu)~1>6-8 GeV
- at higher p_T most likely be boring (according to I. Vitev & Co)

Jet calibration: Finalize analysis, get solid numbers on k_T^{vac}, k_T^{nuc}

v_2 at high p_T: It'd better start going down with p_T! ☺

Di-jets with respect to reaction plane:

- Test dE/dx(L)-dependence soon

Jet chemistry: flavor-tagged correlations

- Potentially extremely interesting! More statistics is needed…
- More methods to disentangle jets and flow to come soon...

Search for lost energy: Very promising

- Higher trigger pT! Low z-region (not necessarily low p_T)
- Medium reaction to fast parton & thermalization

Thanks for the data and discussions!!!

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Be at lab by Monday and take data!!!