# Jets and Correlations: Highlights from STAR

Alán Dávila for the STAR Collaboration

RHIC/AGS Annual Users' meeting
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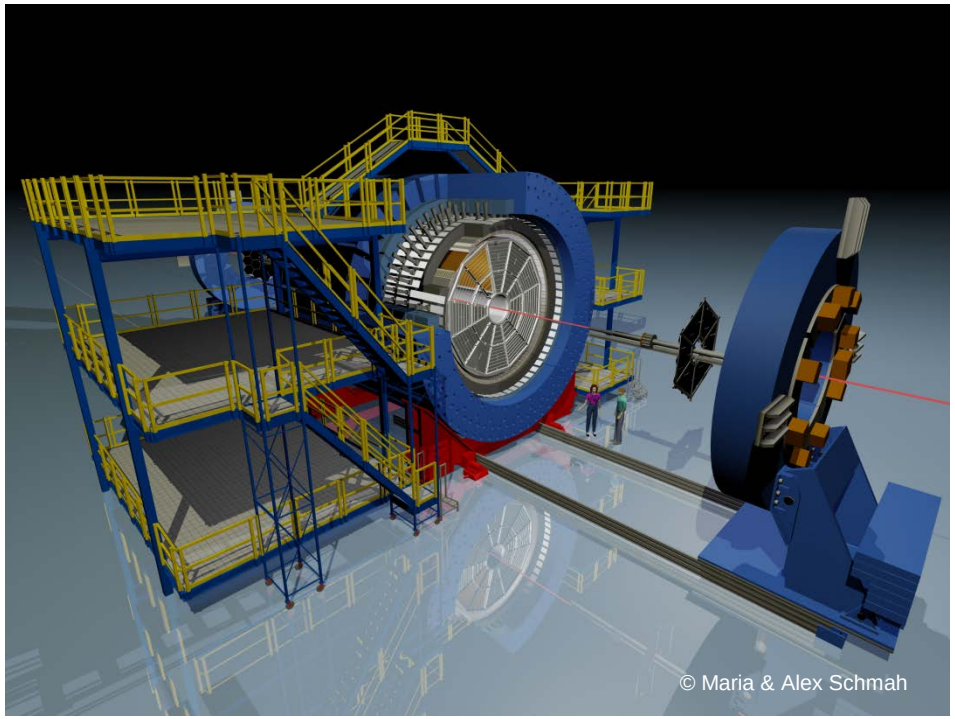
# outline




- 2+1 Correlations
- ♑+hadron Correlations
- 2D Correlations
- PID di-hadron Correlations
- Cold nuclear matter
- Full Jet reconstruction
- Jet+hadron correlations

# High $P_T$ probes

Parton kinematics are not directly measureable:

Use high $P_T$ particles as an approximation of the parton kinematics

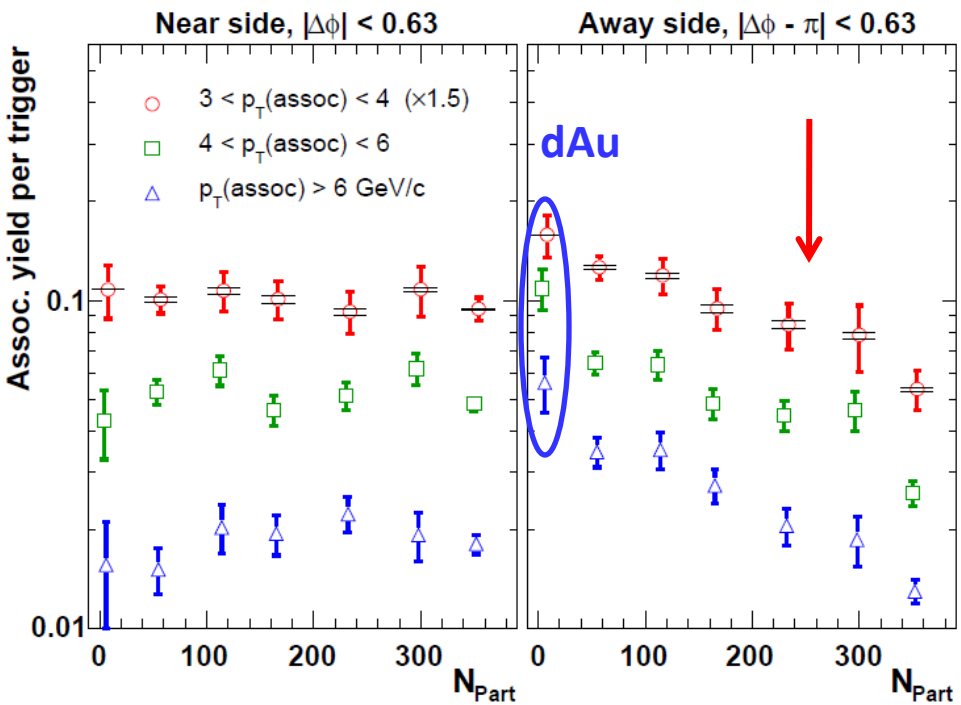
$$\sqrt{s_{NN}} = 200GeV$$

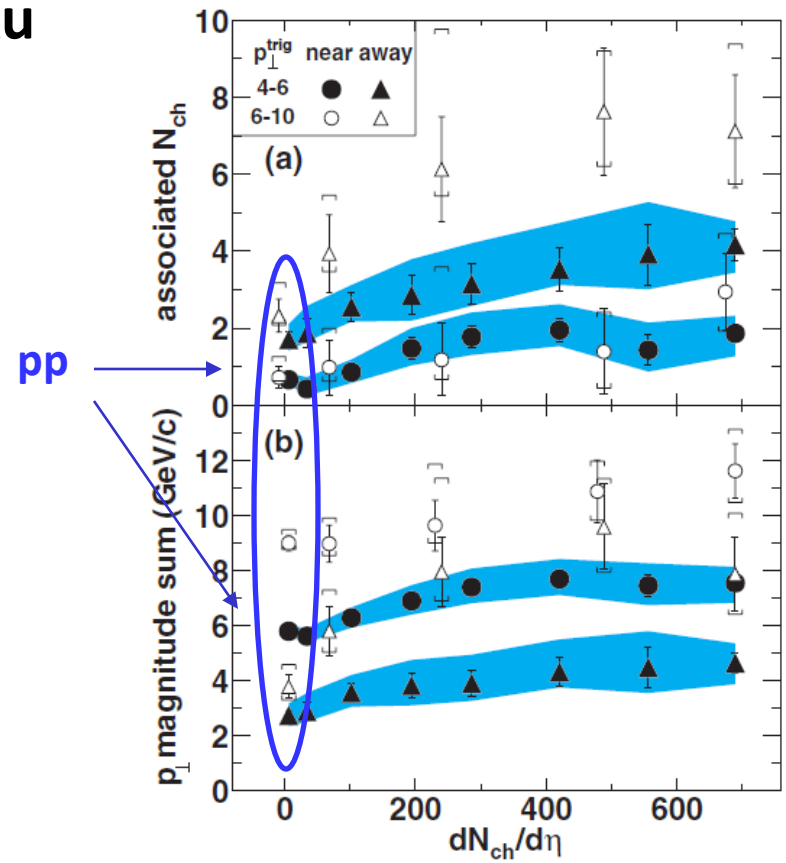
**Recoil low $P_T$ multiplicity and $P_T$ sum enhancement**

0.15 GeV/c < $p_T^{assoc}$ < 4GeV/c

**Au+Au**

**Recoil: high $P_T$ yield suppression**




**Possible explanation: softening of jet fragments**

J. Adams et al. (STAR), Phys. Rev. Lett. 97, 162301 (2006)

J. Adams et al. (STAR), Phys. Rev. Lett. 95, 152301 (2005)

# 2+1 Correlations

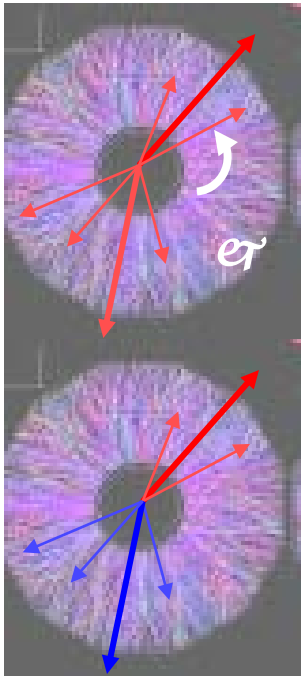
Di-hadron correlations use a single trigger ( away side is not identified EbyE)

correlations in away side are not accessed.

2+1 Correlations use two triggers as proxy of a di-jets:

Allow study of di-jet surface bias.

Access to in away side

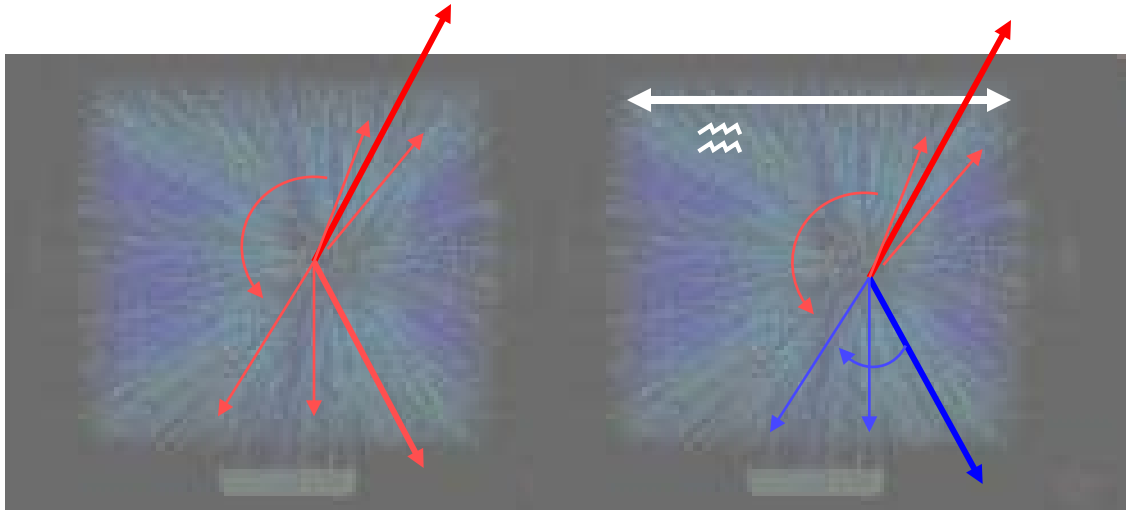



**Di-hadron**

**Trigger: $E_T$ > 10 GeV/c**

**2+1**

**Trigger2: 4 < $P_T$ < 10 GeV/c**



**Associated: 1.5 < $P_T$ < 10 GeV/c**

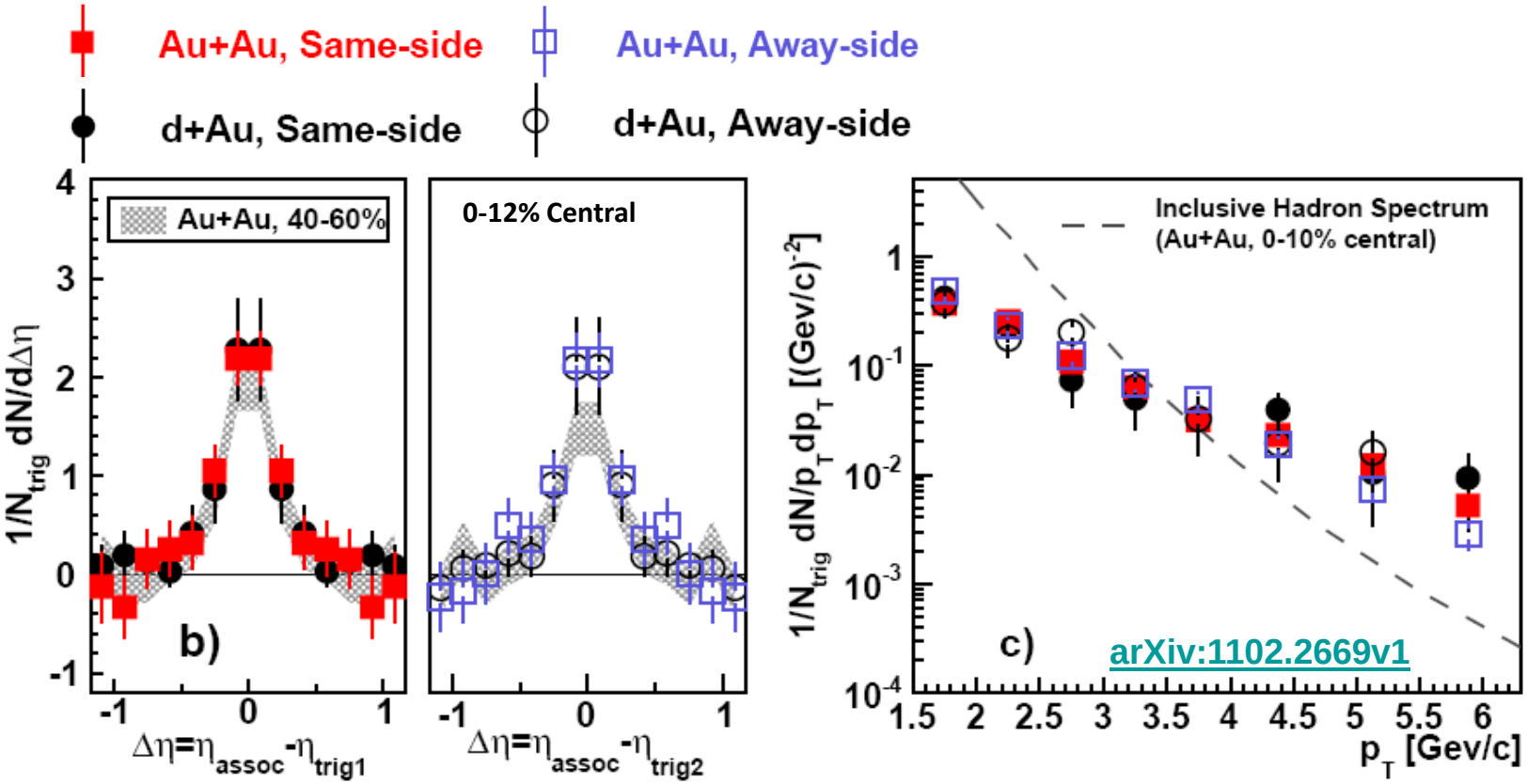
# 2+1 Correlations

$\sqrt{s_{NN}}$ = 200 GeV Au+Au and d +Au data

High $E_T$ trigger from EMCAL, second trigger from TPC

Di-jet proxy condition: $|\varphi_1 - \varphi_2 - \square| < 0.2$ (back to back hadrons)

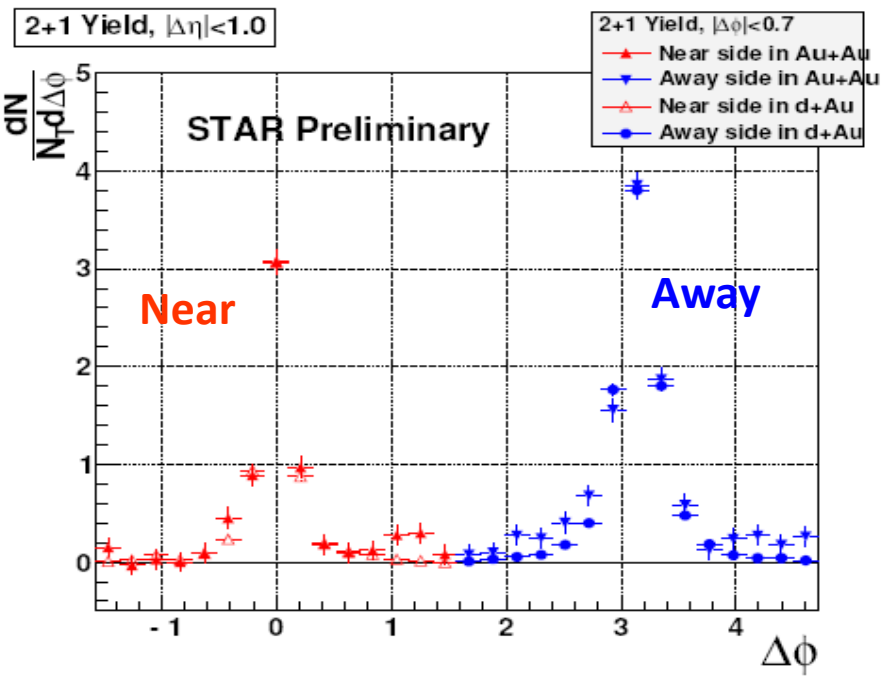
No difference found between d+Au and Au+Au correlations for symmetric trigger pairs

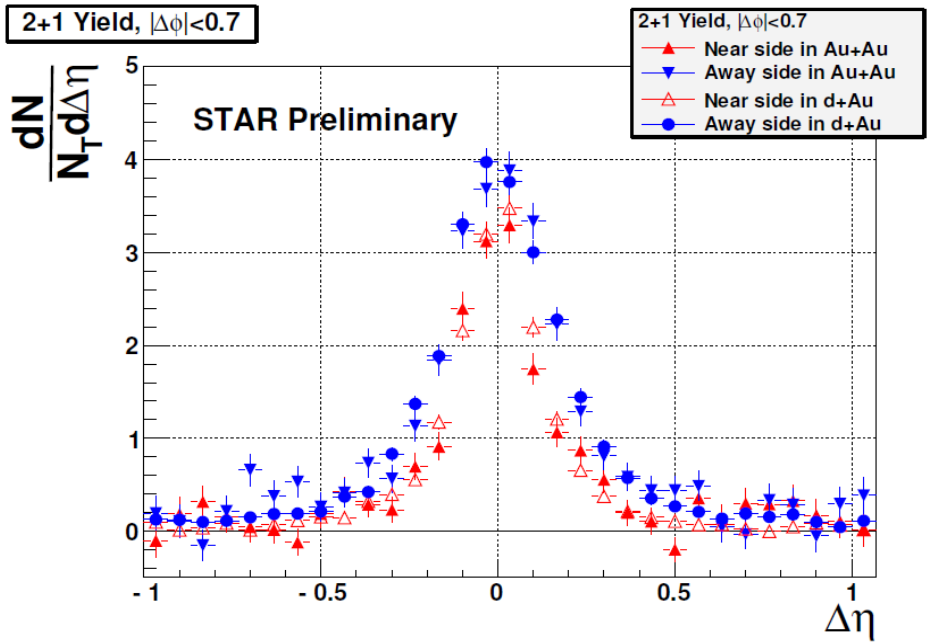


# 2+1 Correlations

$\sqrt{s_{NN}}$ = 200 GeV Au+Au and d +Au data

Using asymmetric trigger pairs



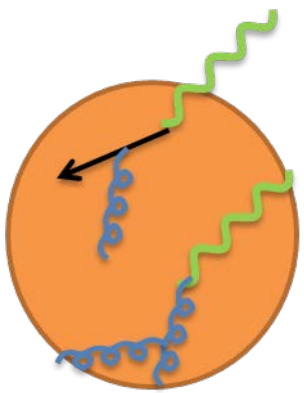

and correlations shapes and amplitudes look similar in central Au+Au and d+Au

Associated hadron $P_T$ spectra is similar in central Au+Au and d+Au

**No evidence of the di-jets proxy interacting with the medium**

Hua Pei WWND 2011

# Gamma + hadron correlations



$\gamma$ - jets do not suffer surface bias as the photon gets the original parton kinematics

Trigger $E_T$ > 8 GeV to reduce gammas from fragmentation

Compare $\pi^0$ and $\gamma$ –hadron correlation to look for E, path and color factor dependence of $\hat{q}$E

**Trigger**:

$\gamma_{dir}$

$$q + g \rightarrow q + \gamma$$
$$q + \bar{q} \rightarrow g + \gamma$$

$\pi^0$

$$\pi^0 \rightarrow \gamma + \gamma$$

**Recoil parton**:

$\pi^0$ : Longer L

$\pi^0$ : q/g mix

$\gamma_{dir}$ : q

Scattered parton energy of away side from $\pi^0$

**>**

Scattered parton energy of away side of $\gamma_{dir}$

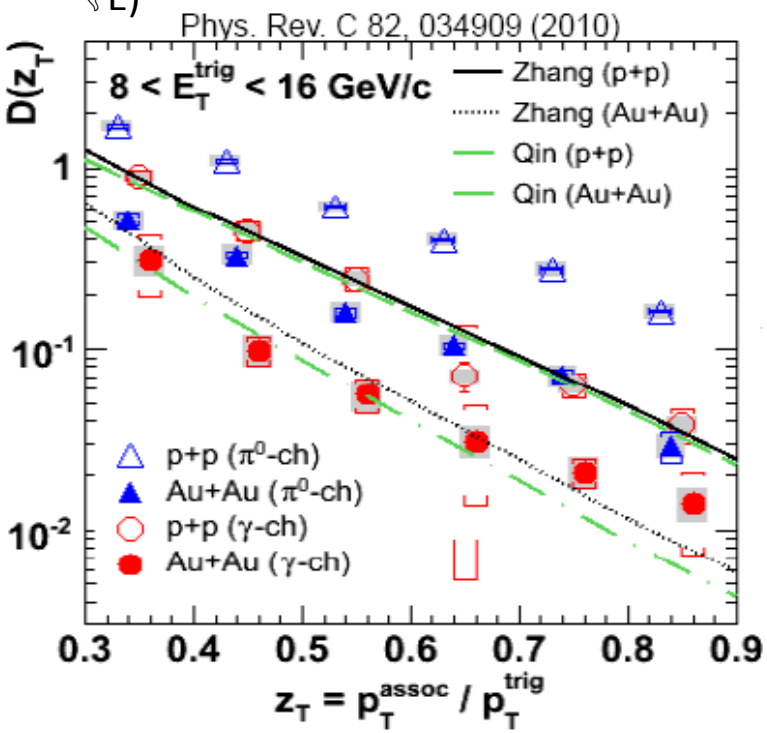
(At same trigger $P_T$)

# Gamma + hadron correlations

Away side

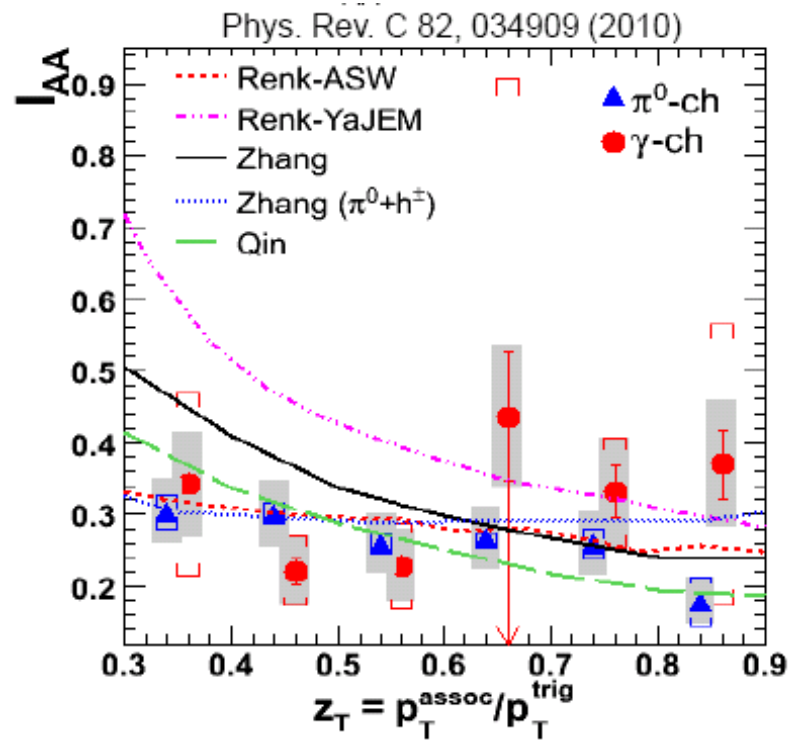
$D^{\pi^0}(Z_T) > D^{\gamma}(Z_T)$

(expected: $\eta_0$ has no E)




$I_{AA}^{\pi^0} = I_{AA}^{\gamma}$ , but $L^{\pi^0} \neq L^{\gamma}$

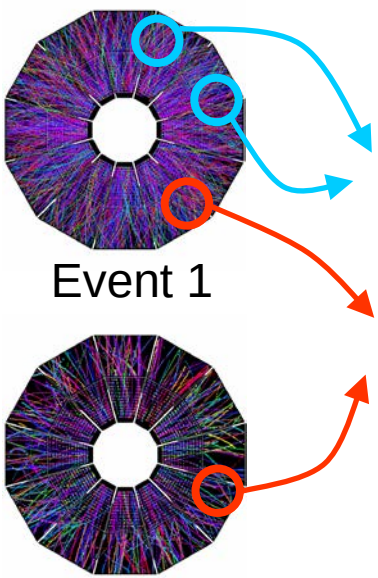
Combined effect of lost energy dependence on parton E?




No $P_T$ $\eta_0$ dependence (E-parton ), then no L or color factor energy loss in this kinematic region

**Measurements indicate path length independent parton energy loss at this $P_T$**

# 2D Correlations




$\rho(\vec{p_1},\vec{p_2})$ = 2 particle density

$$\rho_{sibling}(\vec{p}_1, \vec{p}_2)$$

$$\rho_{reference}(\vec{p}_1, \vec{p}_2)$$

Fill 2D histograms (a,b), e.g. ($\eta_1$,$\eta_2$), ($\phi_1$,$\phi_2$), ($\eta_1$-$\eta_2$,$\phi_1$-$\phi_2$), ($p_{t1}$,$p_{t2}$), etc.

$$\frac{\Delta\rho}{\sqrt{\rho_{ref}}} = \frac{dN_{ch}}{d\eta d\phi}\left[\frac{\rho_{sib}(a,b)}{\rho_{ref}(a,b)} - 1\right]$$

measures number of correlated pairs *per final state particle*

square-root of $r_{ref}(a,b)$; (for $\phi$,$\eta$ space)

normalized ratio of 2D binned histograms; acceptance cancellation; two-track ineff. corrections

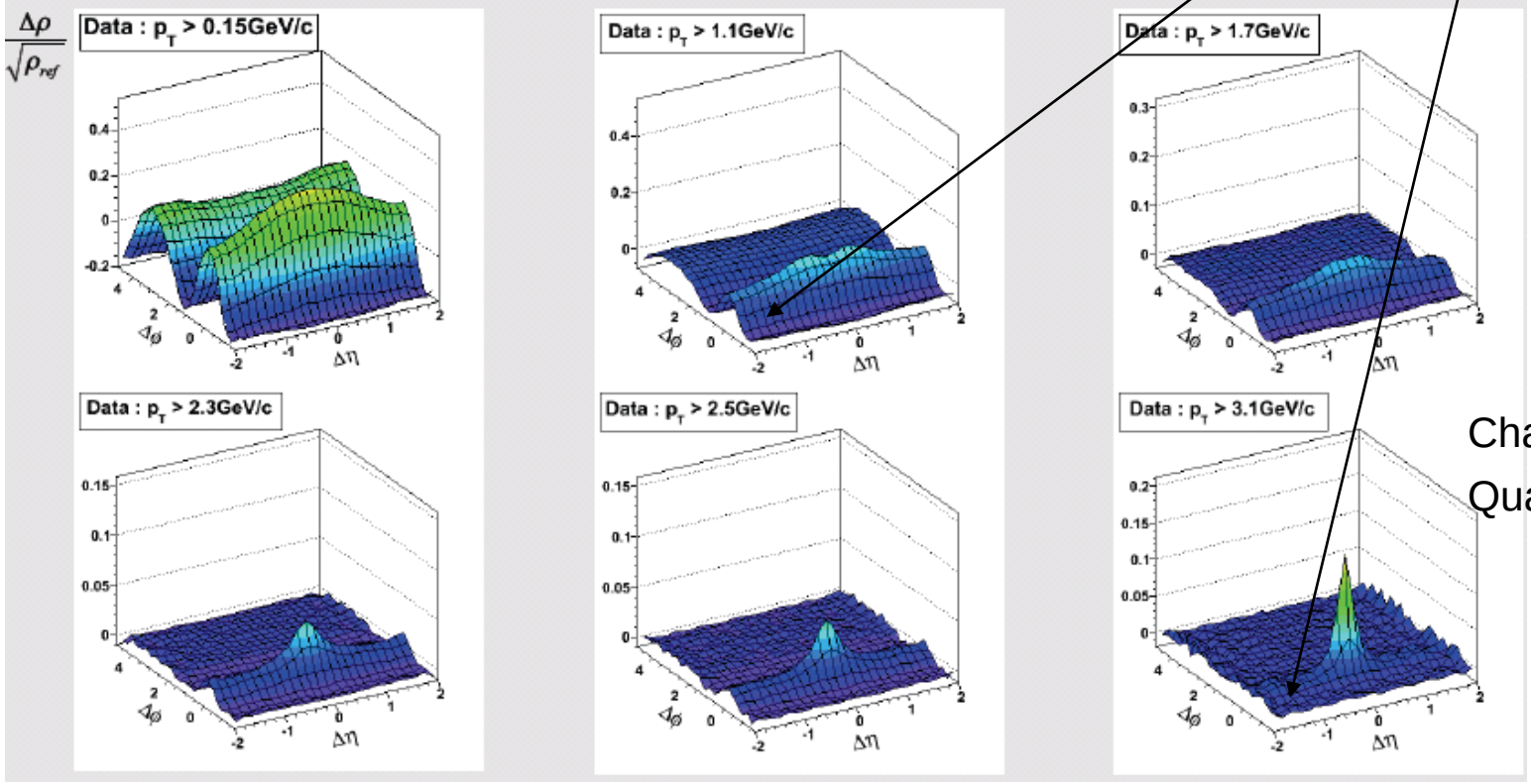
# 2D Correlations

**Momentum evolution**

**Fit function**

| | | |
|---|---|---|
| $f_1 = c_0$ | offset | |
| $f_2 = c_1 * \cos(\Delta\Phi)$ | $\cos(\Delta\Phi)$ | away side $p_T$ conservation |
| $f_3 = c_2 * \cos(2\Delta\Phi)$ | $\cos(2\Delta\Phi)$ | elliptic flow |
| $f_4 = c_3 * \exp(-0.5*((\Delta\eta/c_4)^2 + (\Delta\Phi/c_5)^2))$ | 2D asymmetric Gaussian | SS long range correlation |
| $f_5 = c_6 * \exp(-0.5*((\Delta\eta/c_7)^2 + (\Delta\Phi/c_7)^2))$ | 2D symmetric Gaussian | Jet fragmentation |
| $f_6 = c_8 * \exp(-1*\sqrt{(\Delta\eta/c_9)^2 + (\Delta\Phi/c_{10})^2})$ | 2D exponent | HBT & $e^+e^-$ |

**HBT subtracted 2D data (0 – 10%)**




**Ridge weakens at sufficiently high $P_T$**

Chanaka De Silva

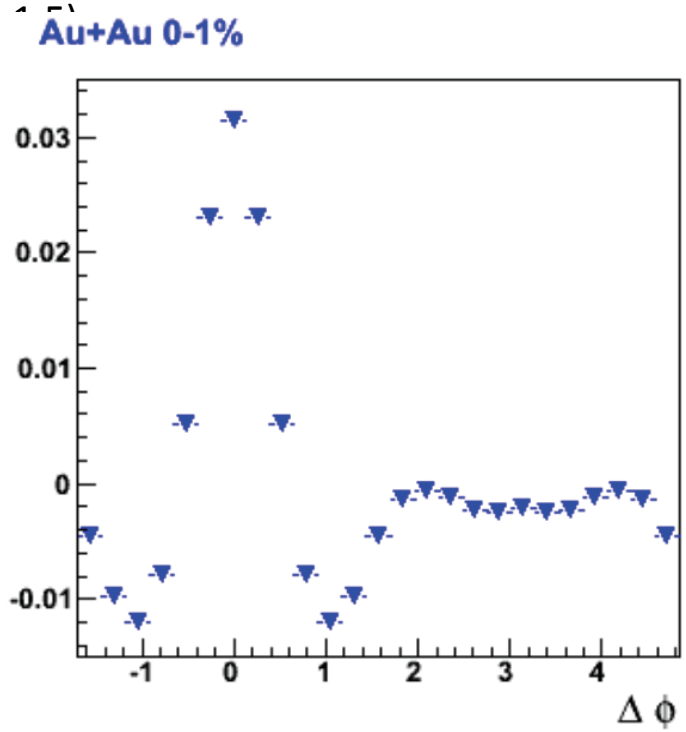
Quark Matter 2011

# 2D Correlations

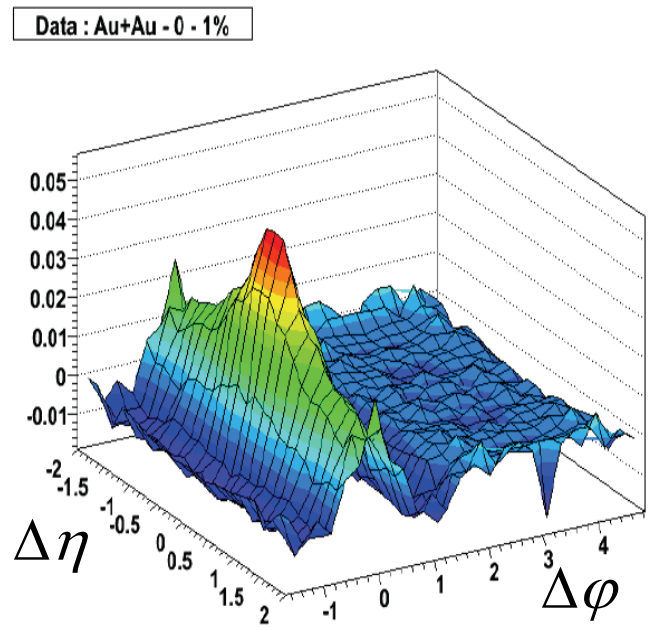
Exploring ◆$_3$ with different fit function…

1D Projection of 👎𝑒𝒯 (2 < $P_T$ < 5 GeV/c: |👎〰| < 1.5)

| | | |
|---|---|---|
| $f_1 = c_0$ | offset | |
| $f_2 = c_1 * \cos(\Delta\Phi)$ | $\cos(\Delta\Phi)$ | away side $p_T$ conservation |
| $f_3 = c_2 * \cos(2\Delta\Phi)$ | $\cos(2\Delta\Phi)$ | elliptic flow |
| $f_4 = c_3 * \cos(3\Delta\Phi)$ | $\cos(3\Delta\Phi)$ | triangular flow |
| $f_5 = c_3 * \exp(-0.5*((\Delta\eta/c_4)^2 + (\Delta\Phi/c_5)^2))$ | 2D asymmetric Gaussian | SS long range correlation |




$$\frac{\Delta\rho}{\sqrt{\rho_{ref}}}$$




The very central high $P_T$ data indicates the necessity of higher order Fourier harmonics (◆$_3$ ) to interpret 2D two particle correlations in Au+Au.

**Ridge is consistent with coexistence of jet + non jet contributions**

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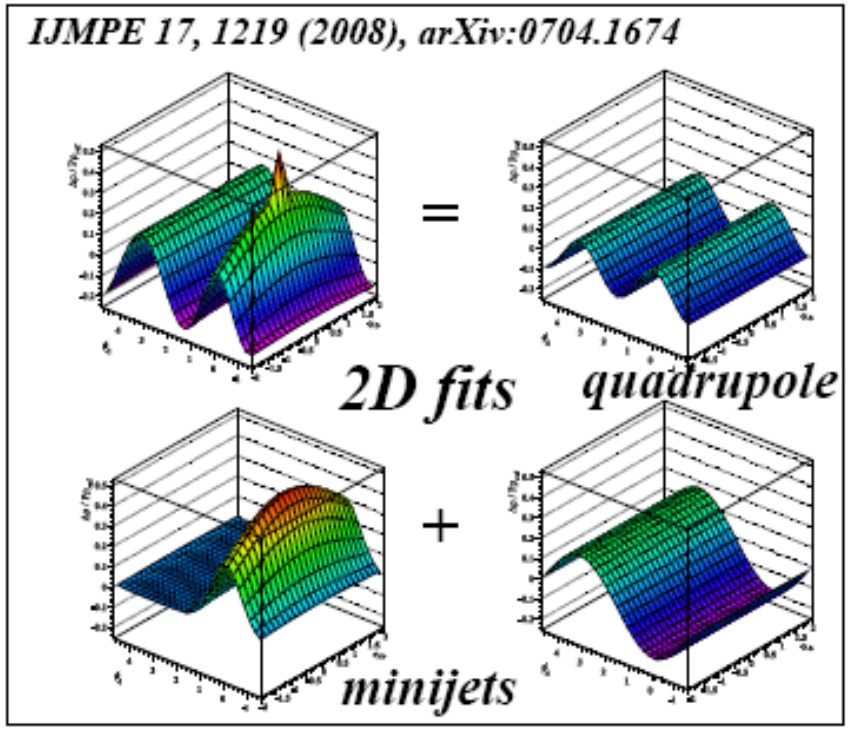
# 2D Correlations




Excluding HBT and e+e- bins

All tracks above $P_T$ = 0.15 GeV/c used

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

2D Correlations -> Disentangle jet-related and nonjet contributions to the azimuth quadrupole assuming a jet model

$$2\upsilon_2^2\{2D\} \equiv A_{2\varphi_\Delta}$$

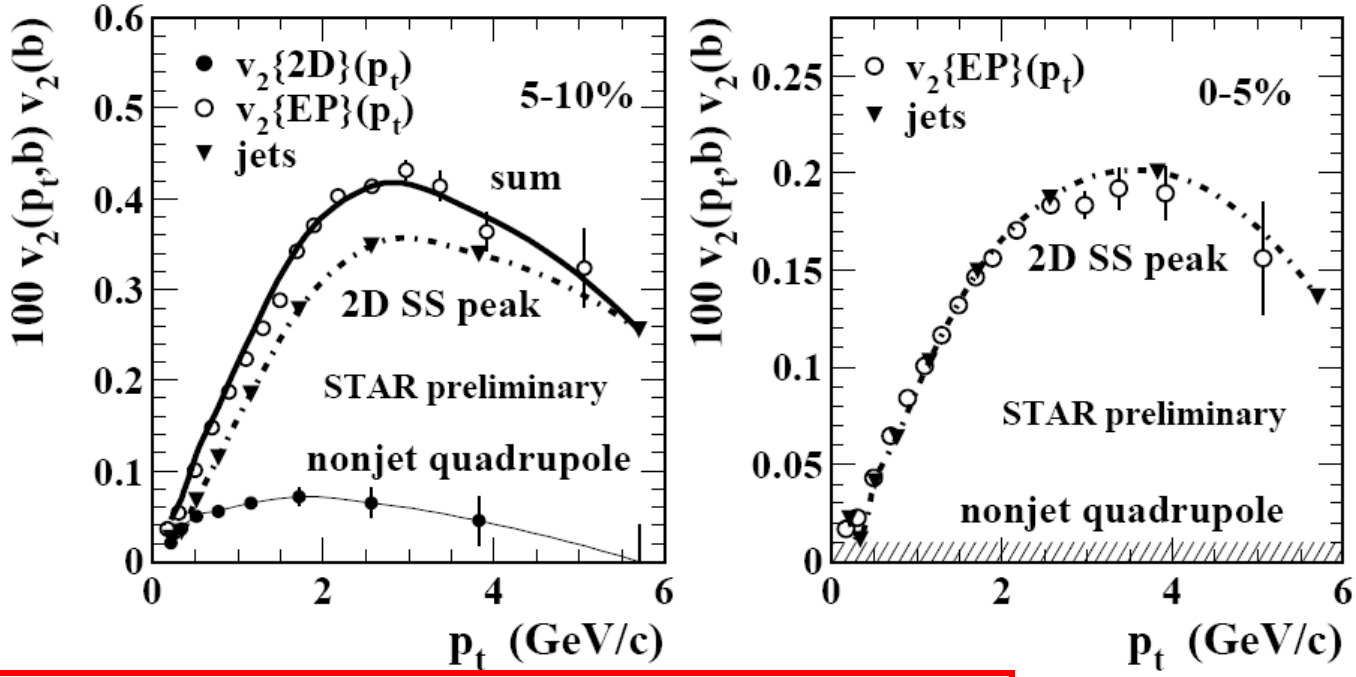
$$F = A_{\phi_\Delta}\cos(\phi_\Delta) + A_{2\phi_\Delta}\cos(2\phi_\Delta) + A_0 e^{-\frac{1}{2}\left(\frac{\eta_\Delta}{\sigma_0}\right)^2} + A_1 e^{-\frac{1}{2}\left\{\left(\frac{\phi_\Delta}{\sigma_{\phi_\Delta}}\right)^2 + \left(\frac{\eta_\Delta}{\sigma_{\eta_\Delta}}\right)^2\right\}} + A_2$$

# 2D Correlations

Choose $y_T$ bins and get 2D correlation fits with function to extract non flow ◆$_2$ from Same Side (SS) Gaussian parameters

◆$_2${EP} has high contributions at 5-10 % most central collisions

◆$_2${EP} is due to SS at 0-5% most central collisions



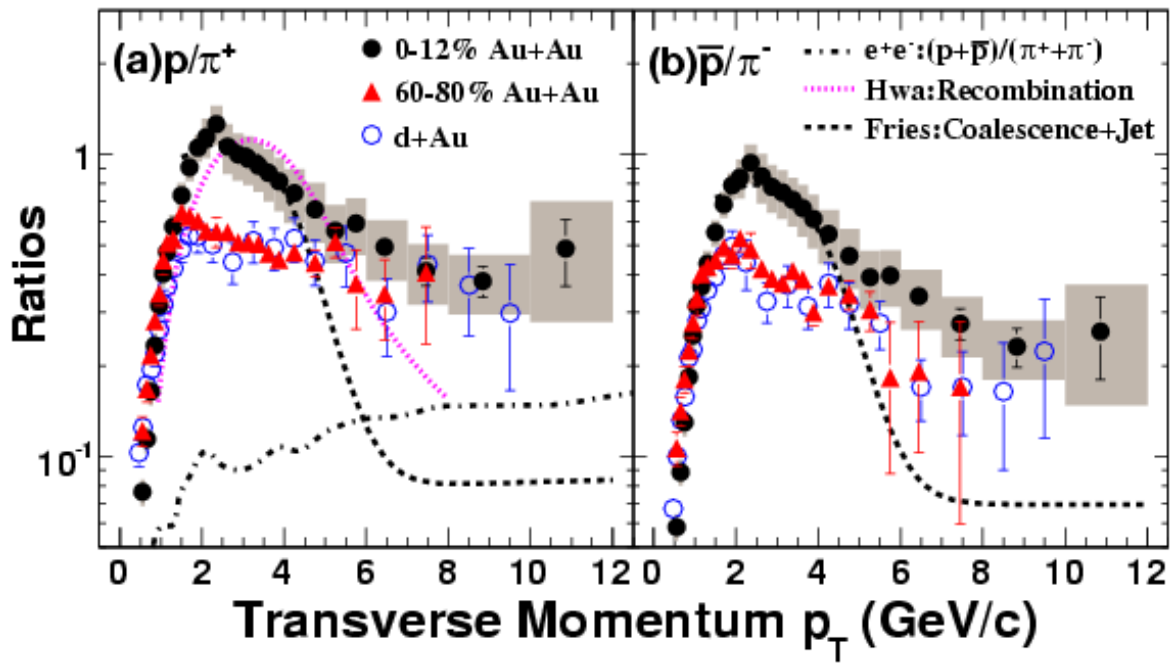

**◆$_2${EP} contains significant non-flow contributions for some centrality bins at ⌧S$_{NN}$ 200 GeV Au+Au collisions**

arXiv:1008.4793v1

# PID Di-hadron Correlations

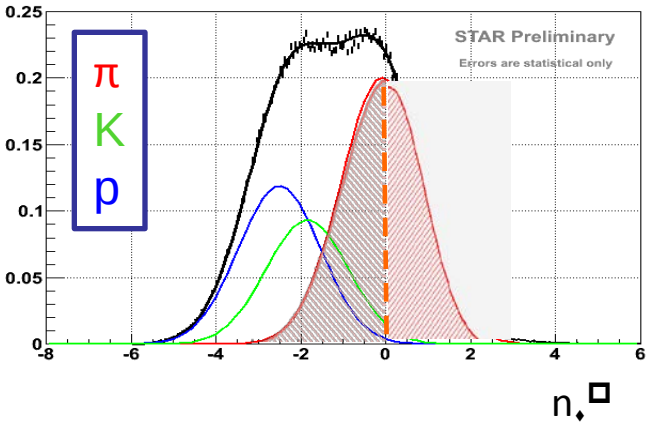
Looking for signs of dilution in azimuth correlations at mid $P_T$, the region of baryon/meson enhancement in Au+Au compared to d+Au

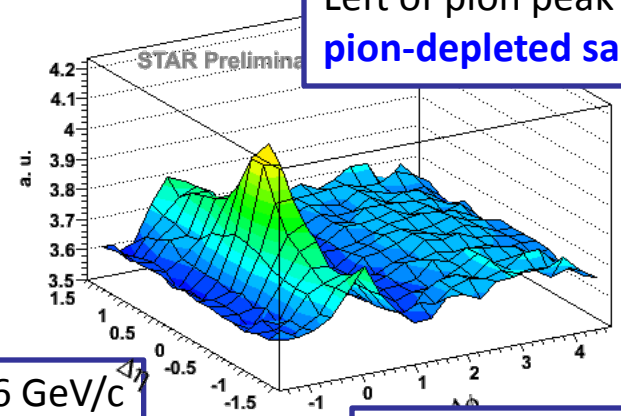
Hard to extract conclusions since bremsstrahlung from gluon jets could increase the correlation yield in azimuth correlations too... (higher contributions from baryons)




STAR, PRL 97 (2006) 152301

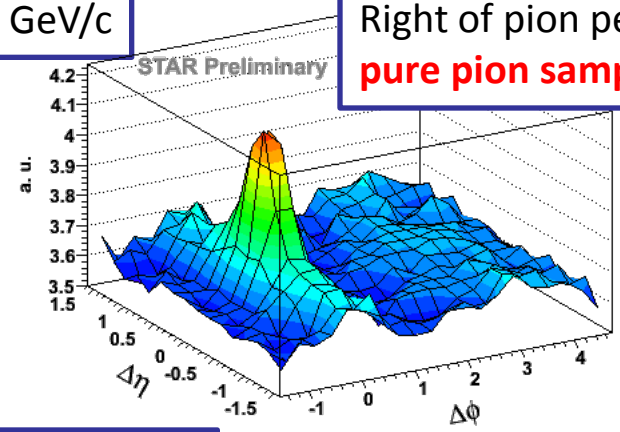
# PID Di-hadron Correlations



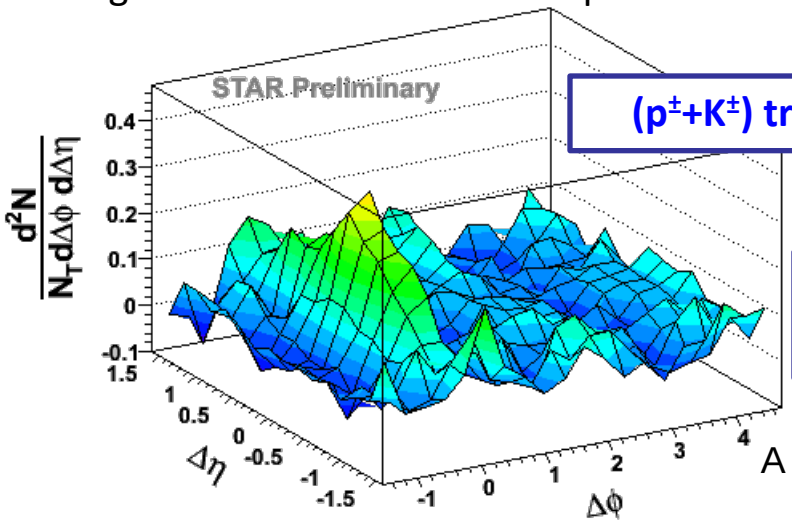

Left of pion peak
**pion-depleted sample**

$4 < p_{T,trigger} < 6$ GeV/c
$p_{t,assoc.} > 1.5$ GeV/c




Right of pion peak
**pure pion sample**

Charged hadrons for associated particles




**$(p^{\pm}+K^{\pm})$ trigger**

0-10% central, Trigger is highest $p_T$ track

A Dávila U of Texas

Kolja Kauder

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# PID Di-hadron Correlations

- **Jet cone:** Get background + flow + ridge from **raw signal** at 0.7<|Δφ|<1.5

→ Drastically reduced systematic uncertainties

| Au+Au | d+Au | Au+Au |
|---|---|---|

| Trigger PID | Pure cone yield | Pure cone yield | Ridge yield per unit Δφ |
|---|---|---|---|
| $\pi^{\pm}$ trigger | **0.22 ± 0.01** | **0.19 ± 0.01** | **0.057 ± 0.005** |
| $p^{\pm}+K^{\pm}$) trigger | **0.12 ± 0.01** | **0.14 ± 0.02** | **0.118 ± 0.007** |
| Charged hadron | 0.173 ± 0.005 | 0.168 ± 0.007 | 0.097 ± 0.003 |

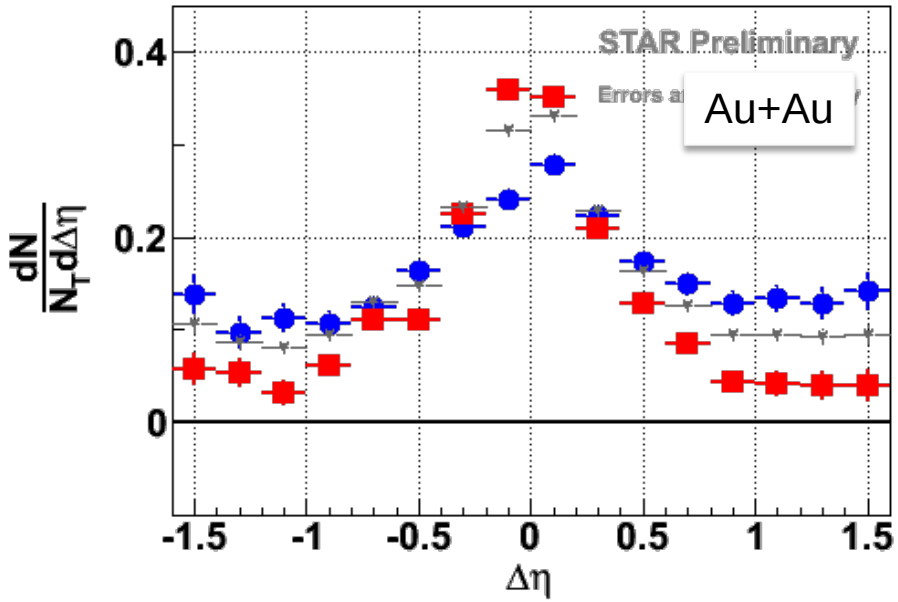
**Au+Au similar to d+Au: It challenges simple recombination expectations.**

**Cone yield is higher in pions**

**Proton+kaon have the largest ridge contribution**

**Trigger:**
- pion$^{\pm}$
- ($P^{\pm}+K^{\pm}$)
- Charged h

|Δφ|<0.73




$4 < p_{T,trigger} < 6$ GeV/c
$p_{t,assoc.} > 1.5$ GeV/c

Kolja Kauder

# Cold Nuclear Matter

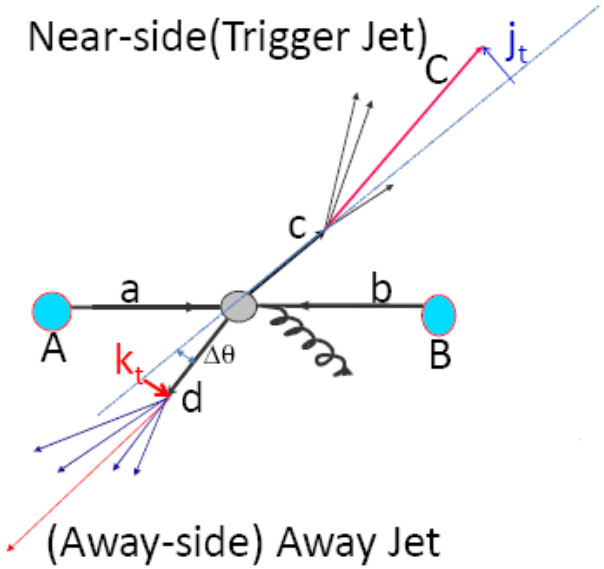
⌧ $S_{NN}$ 200 GeV p+p and d+Au

Azimuthal di-jet acoplanarity ($k_T$) due to scattering of partons in cold nuclear matter is studied with jets and di-hadron correlations in d+Au

**Di-hadron**

Trigger: $\pi^0$ $E_T$: 6.5-18.5 GeV

Charged hadron $P_T$: 4-8.5 GeV/c




**Jets**

Anti-kt jet algorithm

R = 0.4,0.5

Choose two highest PT jets in event

Background : $\rho = median\left\{\frac{P_T^i}{A^i}\right\}$

$$p_{Tjet} = p_{Tjet}^{meas} - \rho Area_{jet}$$

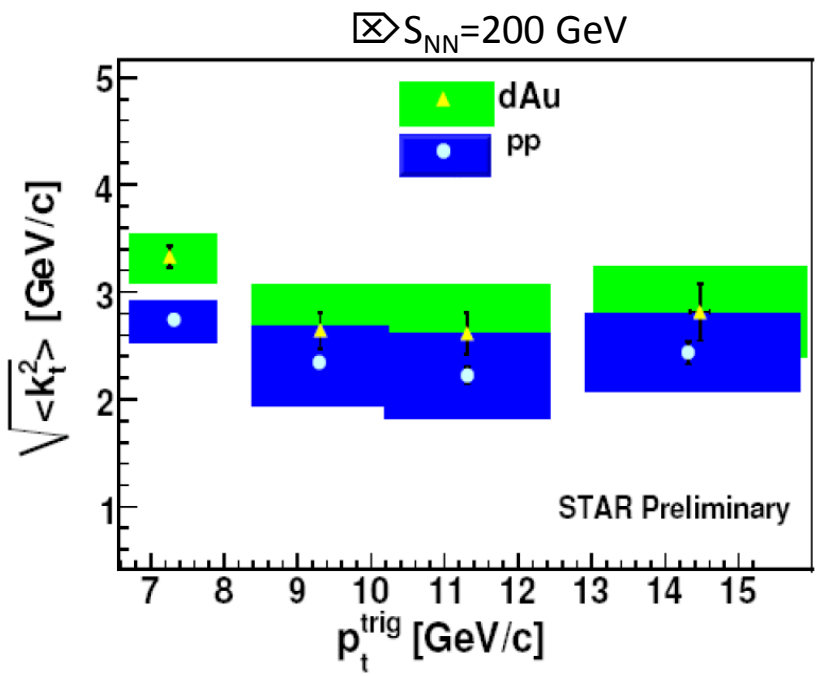
JHEP 0804 (2008) 063

JHEP 0804 (2008) 005

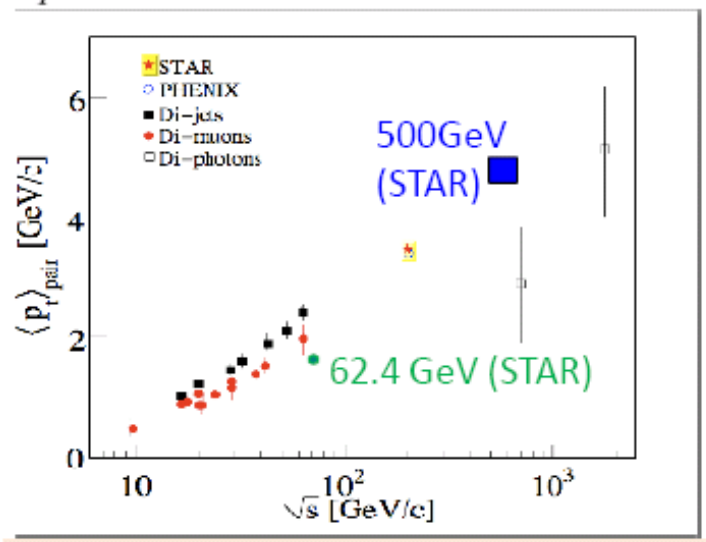
# Cold Nuclear Matter

**$k_T$ is mostly independent of trigger $P_T$ in both p+p and d+Au at $\sqrt{s_{NN}}$ 200 GeV**

**$k_T$ increases with $\sqrt{s_{NN}}$**




$$\langle p_t \rangle_{pair} = \sqrt{2} \times \langle k_t \rangle = \sqrt{\pi/2} \times \langle k_t^2 \rangle$$




$3.5<p_t^{trig}<8.5$ for $\sqrt{s}$ =62.4 GeV
$6.5<p_t^{trig}<18.5$ for $\sqrt{s}$ =200 GeV

Mriganka Mouli Mondal

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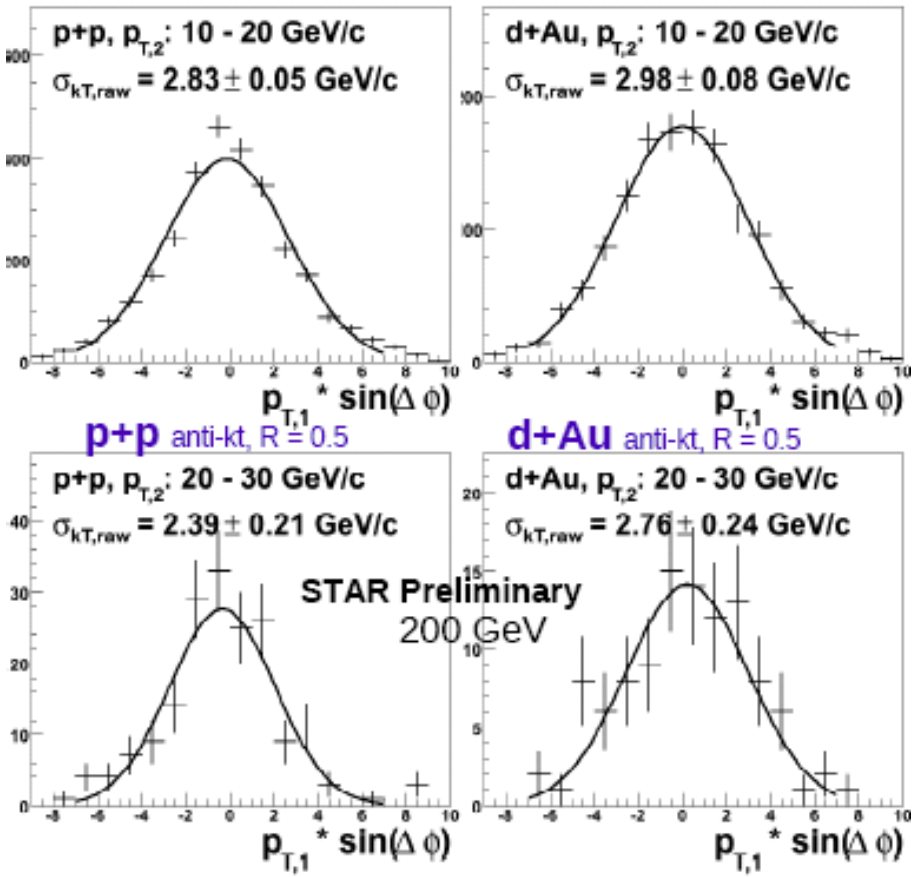
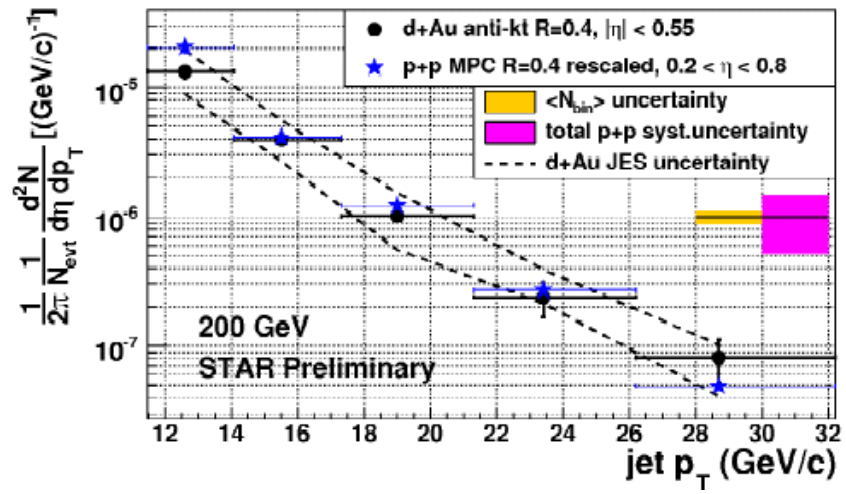
# Cold Nuclear Matter



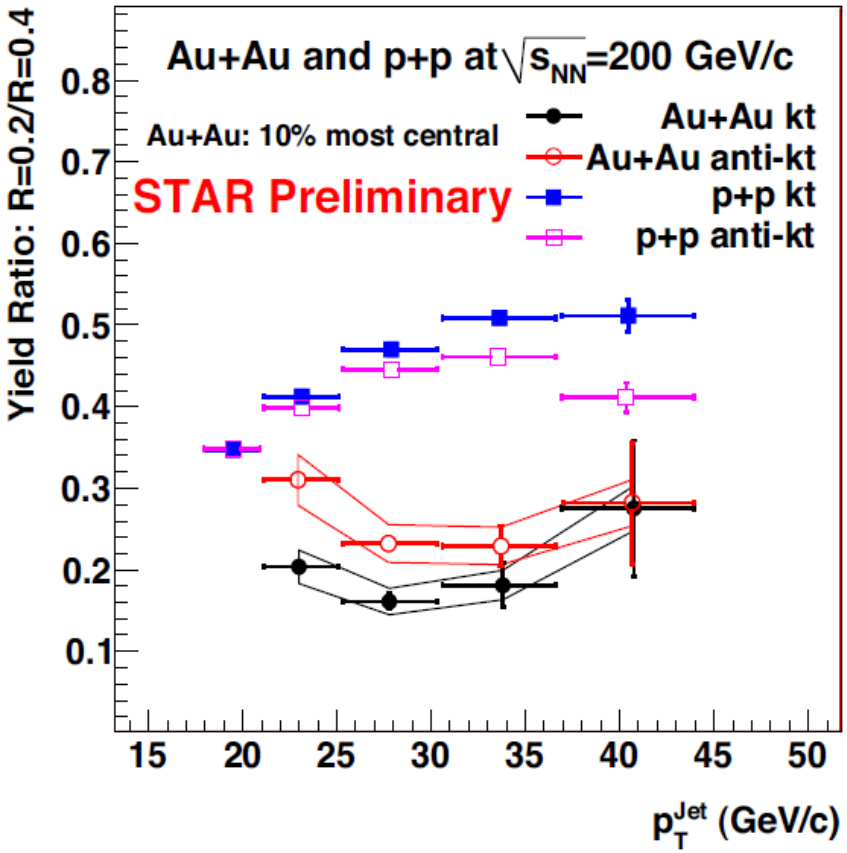

**No strong CNM effects found in $k_T$ measurement**

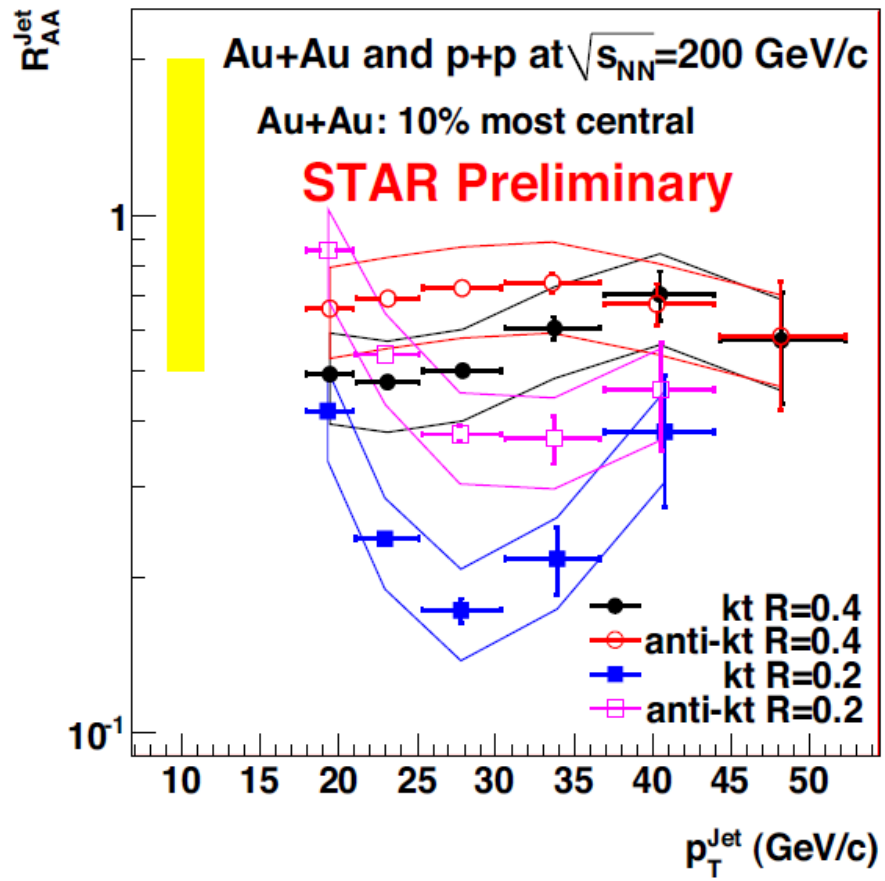
**Jet spectrum similar to Nbin scaled p+p**

# Full jet reconstruction

Ratio of R = 0.4/R = 0.2 shows an increased suppression in Au+Au compared to p+p

$R_{AA}$ consistent with one for R = 0.4, smaller for R = 0.2
The jet spectrum is not completely recovered




**This is suggestive of a broadening of jets in Au+Au collisions**

# Full jet reconstruction

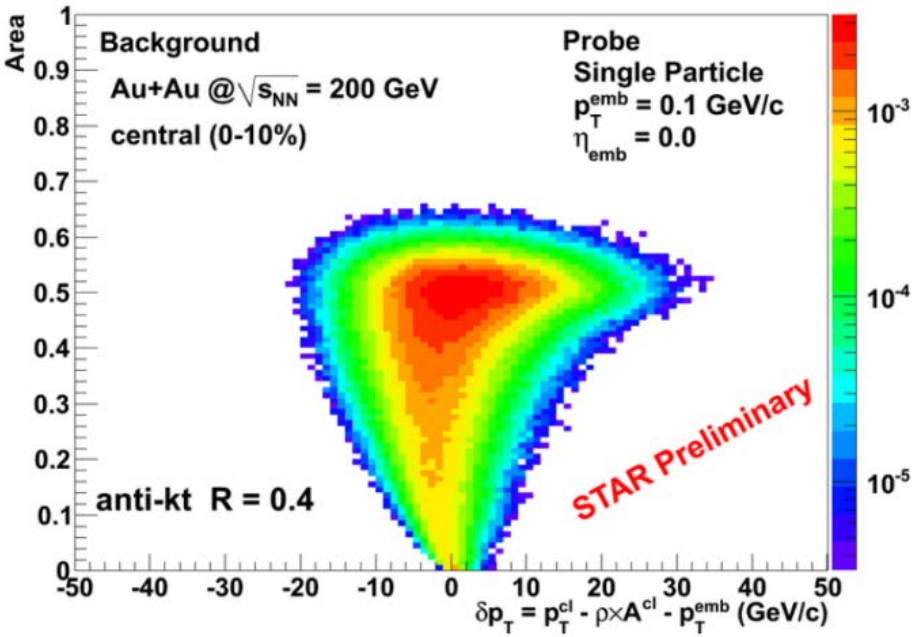
**(Background fluctuations)**

Generalized probe embedding

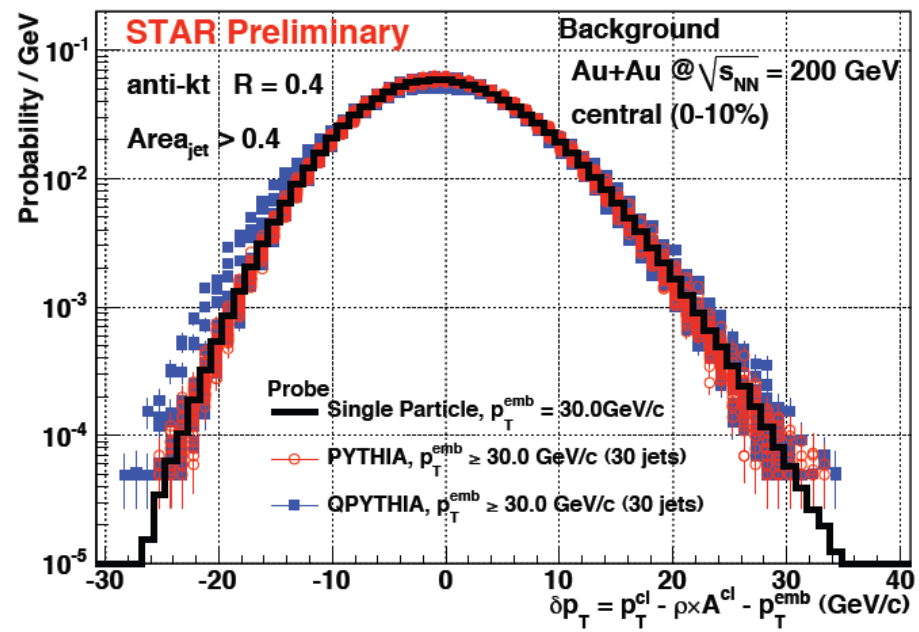
✓Embed a known probe in a AuAu central event

✓Reconstruct the jet that contains the probe in it

✓Calculate irresolution:




$\delta p_T$ does vary with jet area.




$\delta p_T$ is independent of fragmentation pattern

**Irresolution independent on fragmentation pattern**
**Necessary to reconstruct quenched and unquenched jets alike**

# Jet + hadron correlations

Anti kt algorithm R=0.4

$P_{Tcut}$ >2 GeV/c

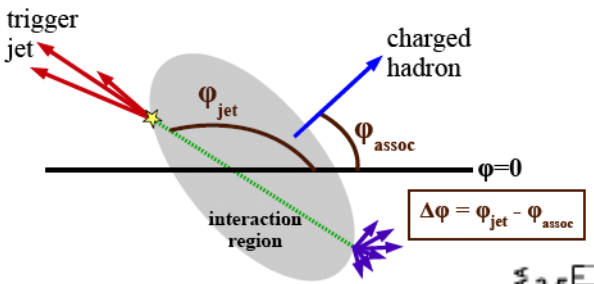
JHEP 0804 (2008) 063

⌧ $S_{NN}$ 200 GeV Au+Au and p+p

High Tower Trigger $E_T$ > 5.4 GeV

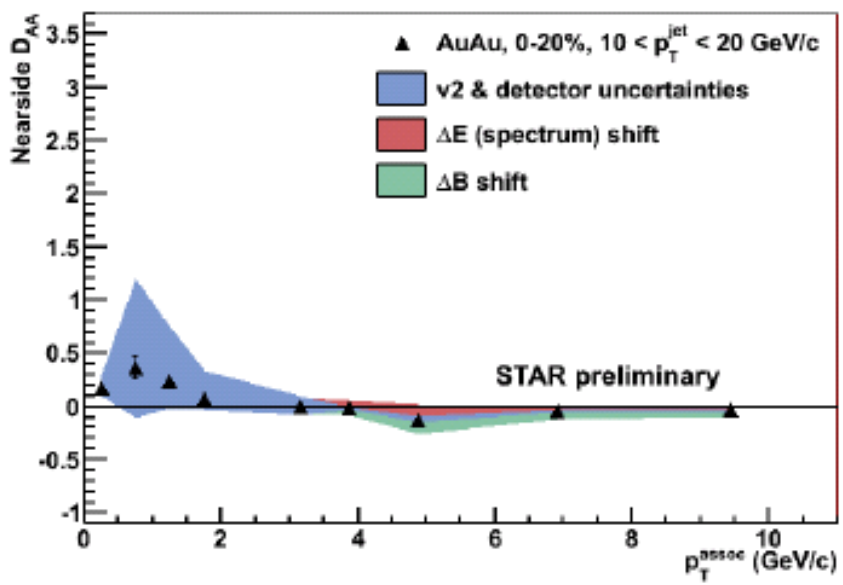
$$D_{AA}(p_T^{assoc}) = Y_{AA}(p_T^{assoc}) \cdot p_{T,AA}^{assoc} - Y_{pp}(p_T^{assoc}) \cdot p_{T,pp}^{assoc}$$

$$\Delta B = \int dp_T^{assoc} D_{AA}(p_T^{assoc})$$




One has to match pp and AuAu jet energies correctly on the Near Side

Background estimated by fitting offset +2 Gaussians + elliptic flow term



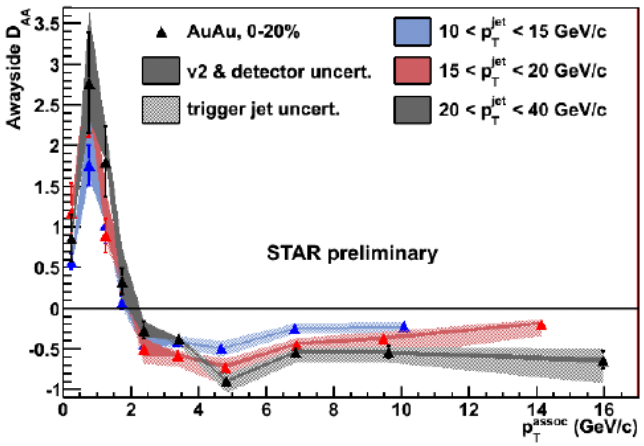

Alice Ohlson

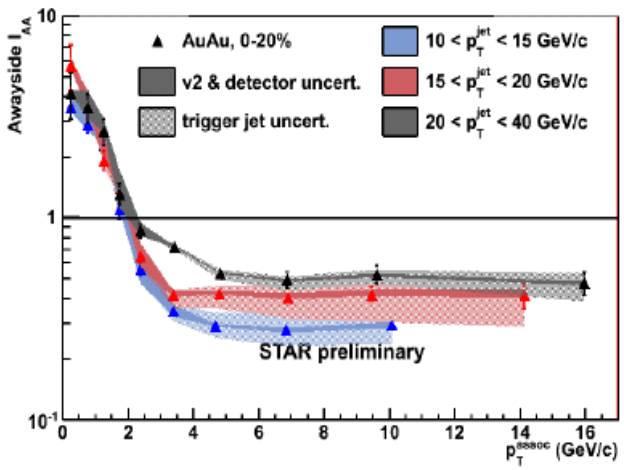
Quark Matter 2011

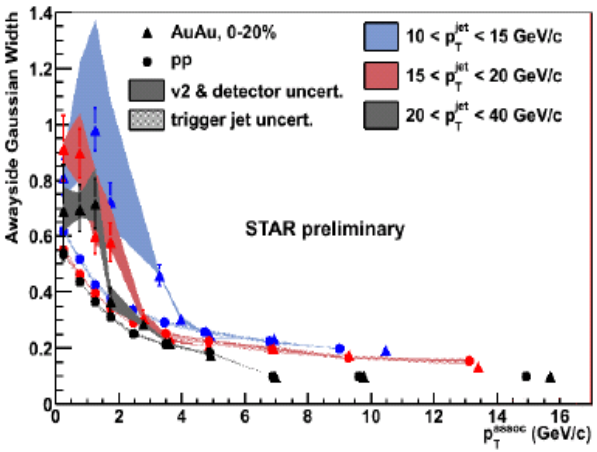
# Jet + hadron correlations

**High $P_T$ suppression gets balanced by low $P_T$ enhancement**

**Broadening of the azimuth correlation width at low $P_T$**




**Consistent with radiative energy loss (no black and white scenario)**

Alice Ohlson

Quark Matter 2011

# Conclusions

**2+1**: No evidence of dijet proxy interaction with the medium in ⌧SNN = 200 GeV Au+Au collisions at the given trigger $P_T$ kinematics

♑**+hadron**: Neither path nor color factor dependence of energy loss

**2D Correlations**: Ridge correlation signal weakens at high $P_T$ cut from below. Ridge consistent with coexistence of jet + non jet contributions. The very central high $P_T$ data requires third Fourier harmonic (◆$_3$) . ◆$_2${EP} contains significant (dominant) non-flow contributions at 5-10% (0-5%) most central ⌧$S_{NN}$ = 200 GeV Au+Au collisions.

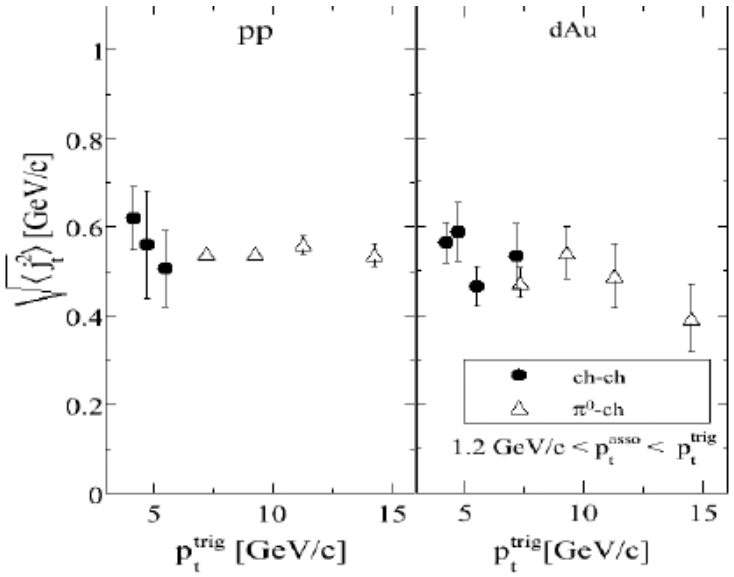
**PID di-hadron**: Cone yield in the 👎♒-👎♐ correlations is higher in ◻ than in (K+p). The cone yield is similar in d+Au and Au+Au at the studied kinematics. K+P have the largest ridge contribution.

**CNM**: Studied with jets and di-hadron correlations in ⌧$S_{NN}$ = 200 GeV d+Au. $k_T$ is mostly independent of trigger $P_T$. No strong CNM effects found. Jet spectrum similar to Nbin scaled p+p spectrum. Also, di-hadron results for ⌧$S_{NN}$ = 62 GeV d+Au and ⌧$S_{NN}$ = 500 in p+p. $k_T$ increases with collision energy.

**Full jet reconstruciton**: Broadening of jets in central Au+Au collisions, improvement in background fluctuations characterization. The jets transverse momentum irresolution is independent of fragmentation pattern.

**Jet+hadron**: In ⌧$S_{NN}$ = 200 GeV Au+Au events high $P_T$ suppression of associated hadrons gets balanced with low $P_T$ enhancement. 👎♐ correlation broadens at low $P_T$ . These results are consistent with a radiative energy loss mechanism – disfavoring a black and white picture.

# extras


pp
dAu
$\sqrt{\langle j_t^2 \rangle}$ [GeV/c]
ch-ch
$\pi^0$-ch
1.2 GeV/c < $p_t^{asso}$ < $p_t^{trig}$
$p_t^{trig}$ [GeV/c]
$p_t^{trig}$[GeV/c]