Double Helicity Dependence of Jet Properties

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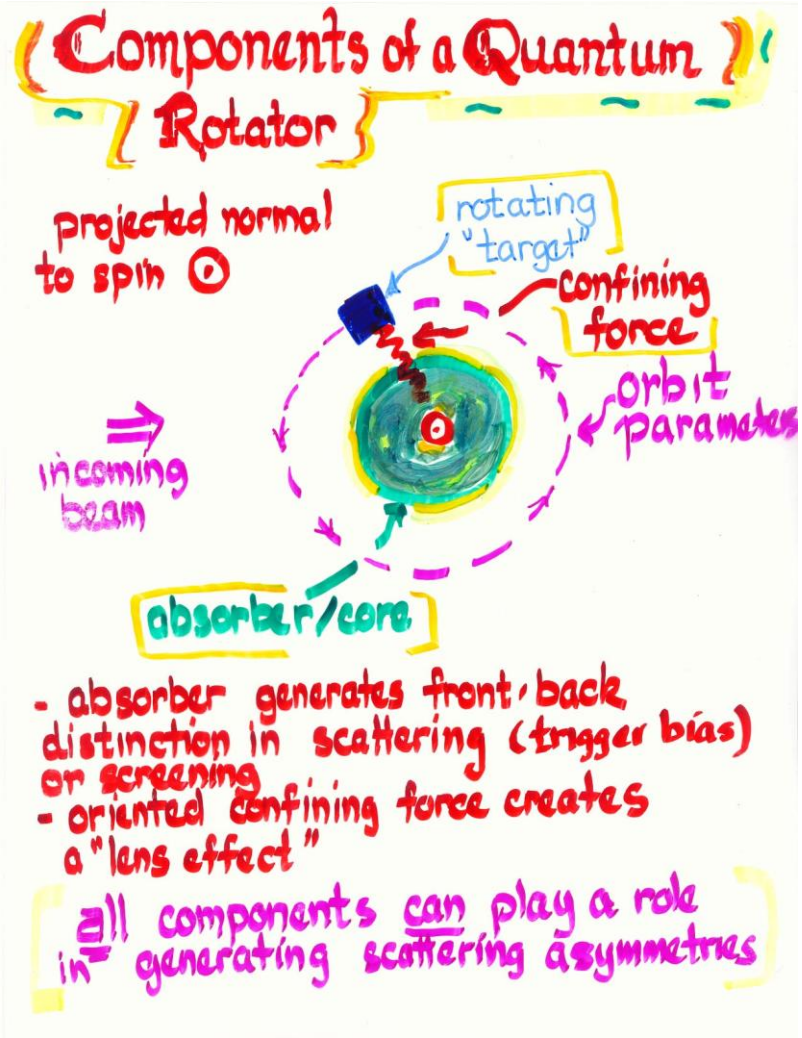
How can you get a net k_T?

- Nice conceptual picture from D. Sivers (talk given at UNM/RBRC Workshop on Parton Orbital Angular Momentum).
- Summary:
  - Sivers effect requires orbital motion.
  - Is process dependent.
- I would like to just follow this conceptual picture to see where it may lead.

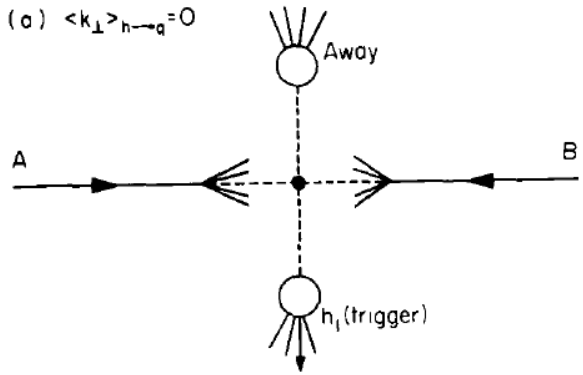


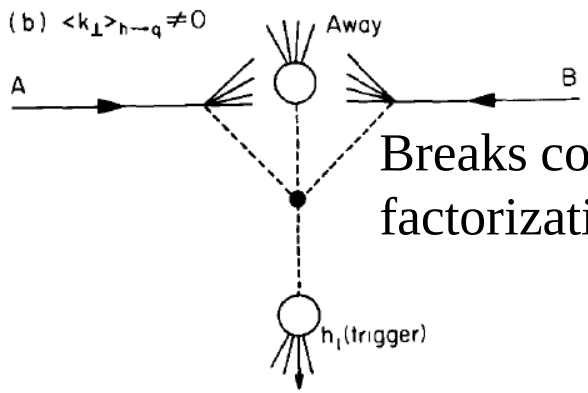
What is the origin of jet k_T?

$$\frac{\langle p_T^2 \rangle_{\text{pair}}}{2} = \langle k_T^2 \rangle = \langle k_T^2 \rangle_{\text{intrinsic}} + \langle k_T^2 \rangle_{\text{soft}} + \langle k_T^2 \rangle_{\text{NLO}}$$

Intrinsic (Confinement) $k_T \approx 200$ MeV/c

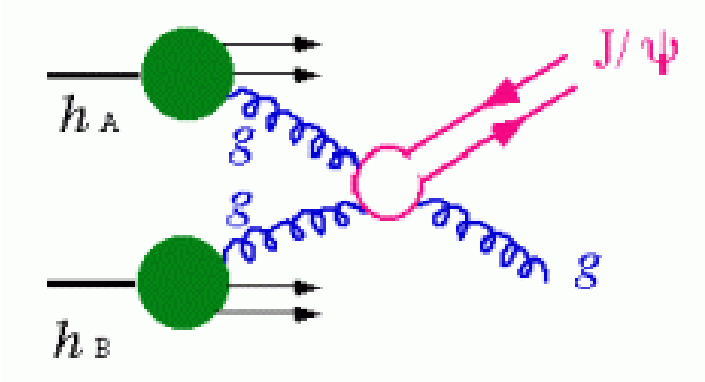
Soft QCD radiation.





Breaks collinear factorization

An example - J/ψ production.



Extra gluon kick

$\langle p_T \rangle_{J/\psi} = 1.8 \pm 0.23 \pm 0.16$ GeV/c

Phys. Rev. Lett. 92, 051802, (2004).

Origin of Jet k_T

Net transverse momentum of a di-hadron pair in a factorization ansatz

$$\frac{\langle p_T^2 \rangle_{\rm pair}}{2} = \langle k_T^2 \rangle = \langle k_T^2 \rangle^I \oplus \langle k_T^2 \rangle^S \oplus \langle k_T^2 \rangle^H$$

- *I* = *initial* – fermi motion of the confined partons, initial-state gluon radiation…
- *S* = *soft* – one or several soft gluons emitted
- *H* = *hard* – final-state radiation (three-jet)…

Another Possibility:

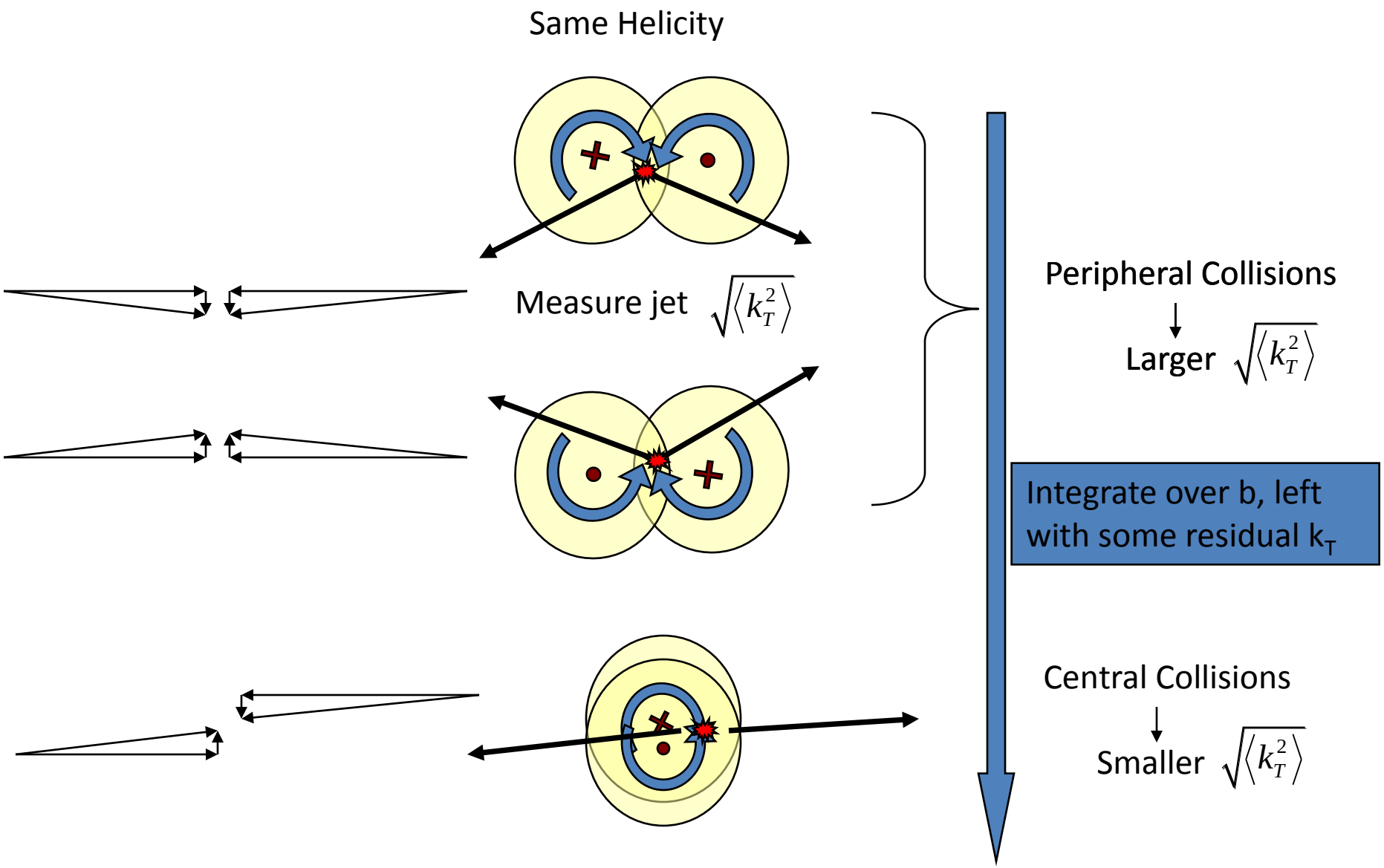
- Spin-correlated transverse momentum – partonic orbital angular momentum
- Can examine the helicity dependence of each term:

$$\Delta \left\langle k_T^2 \right\rangle_{initial} \neq 0?$$

$$\Delta \left\langle k_T^2 \right\rangle_{soft} = 0$$

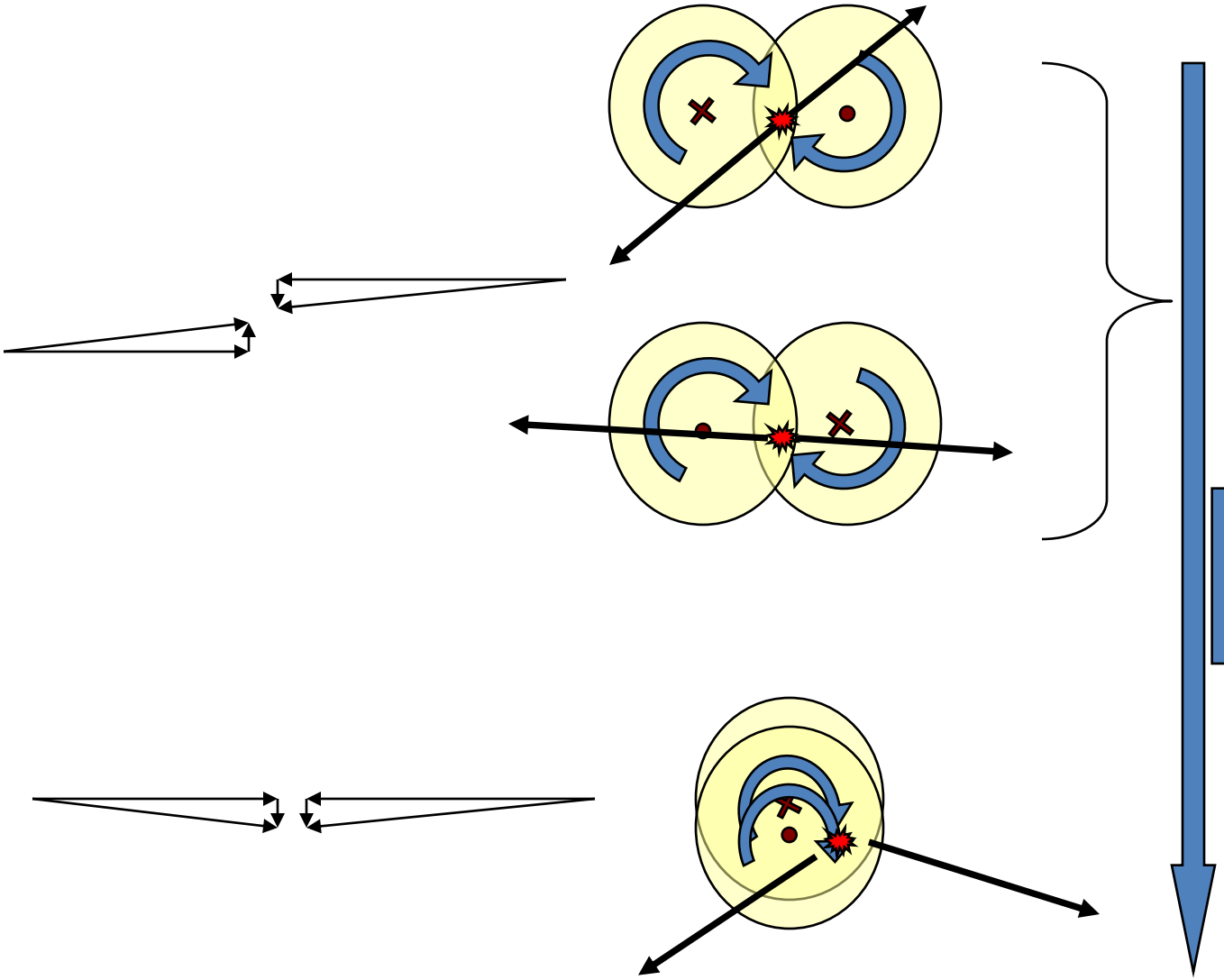
$$\Delta \left\langle k_T^2 \right\rangle_{hard} \neq 0?$$

Mechanism for $\Delta\left\langle k_T^2 \right\rangle_{initial} \neq 0$



Mechanism for $\Delta\left\langle k_T^2 \right\rangle_{initial} \neq 0$

Opposite Helicity



Peripheral Collisions

↓

Smaller $\sqrt{\left\langle k_T^2 \right\rangle}$

Integrate over b, left with some *different* residual k_T

Central Collisions

↓

Larger $\sqrt{\left\langle k_T^2 \right\rangle}$

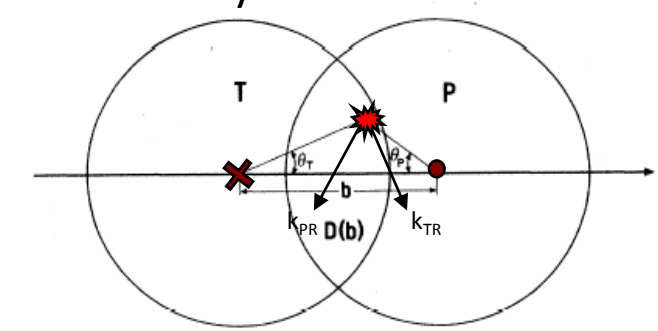
Integrating over Impact Parameter

Drell-Yan pair production in polarized *p+p* collisions.

(Meng Ta-Chung et al. Phys. Rev. D 1989)

$$p_t^2(b,\theta_P,\theta_T;\pm) = \left|\vec{k}_{PR}\right|^2 + \left|\vec{k}_{TR}\right|^2 \pm \left|\vec{k}_{PR}\right|\left|\vec{k}_{TR}\right| \cos\left(\theta_P + \theta_T\right)$$

Like Helicity



Averaging over *D(b)*:

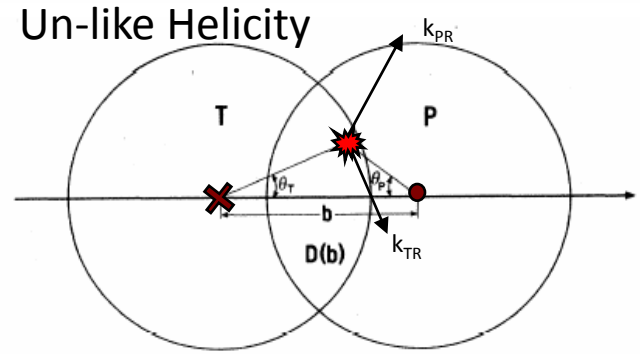
$$\Delta\left\langle p_t^2(b)\right\rangle = \left\langle p_t^2(b,+)\right\rangle - \left\langle p_t^2(b,-)\right\rangle$$

Integrating over impact parameter *b*:

$$\Delta\left\langle p_t^2\right\rangle \approx 1.9\left\langle k_R\right\rangle^2$$

$$\left\langle k_R\right\rangle \equiv \left\langle\left|\vec{k}_{PR}\right|\right\rangle = \left\langle\left|\vec{k}_{TR}\right|\right\rangle$$

Un-like Helicity

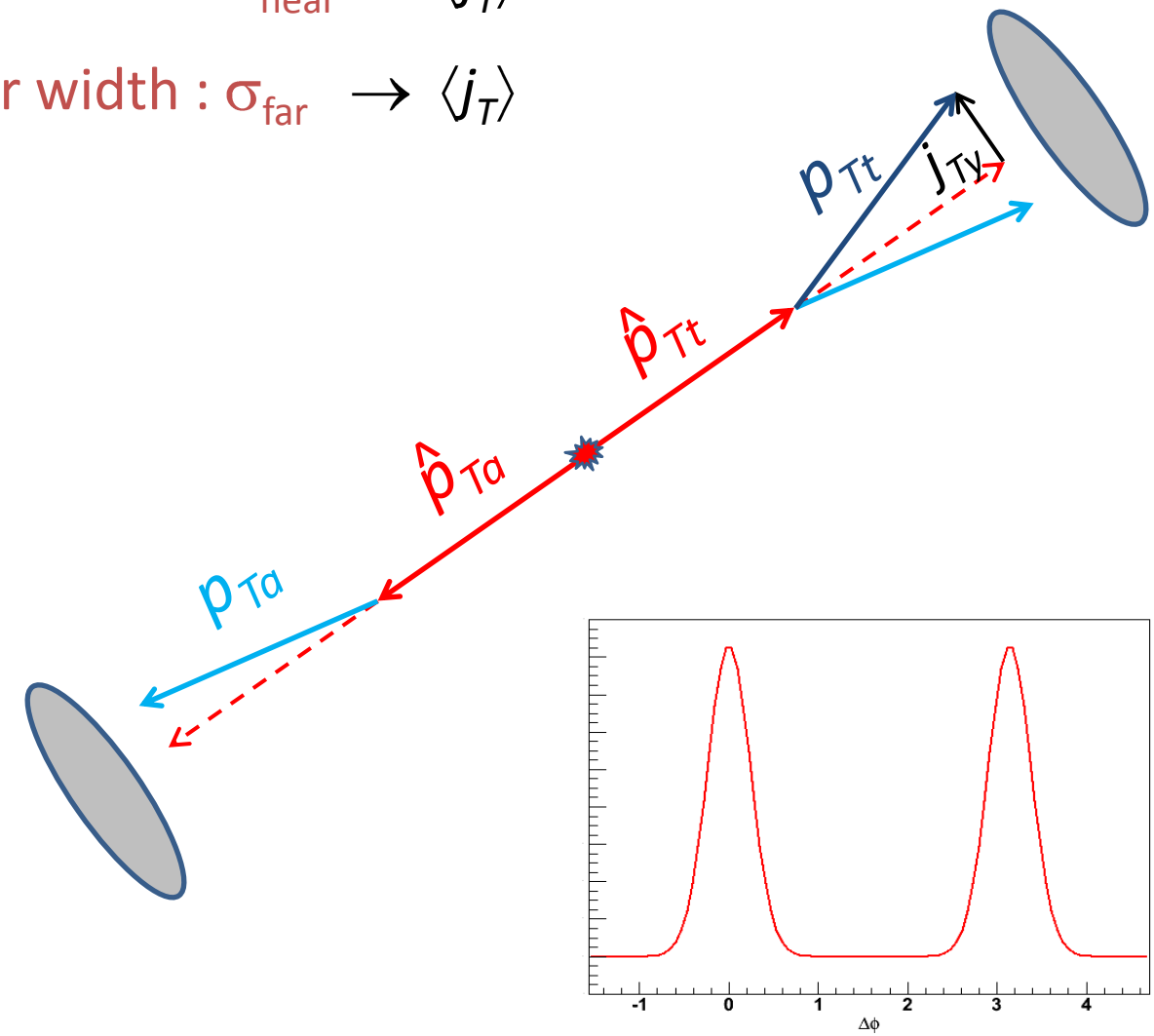


Measuring jet k_T – di-hadron correlation

Intra-jet pairs angular width : $\sigma_{near} \rightarrow \langle j_T \rangle$

Inter-jet pairs angular width : $\sigma_{far} \rightarrow \langle j_T \rangle$

- Zero k_T

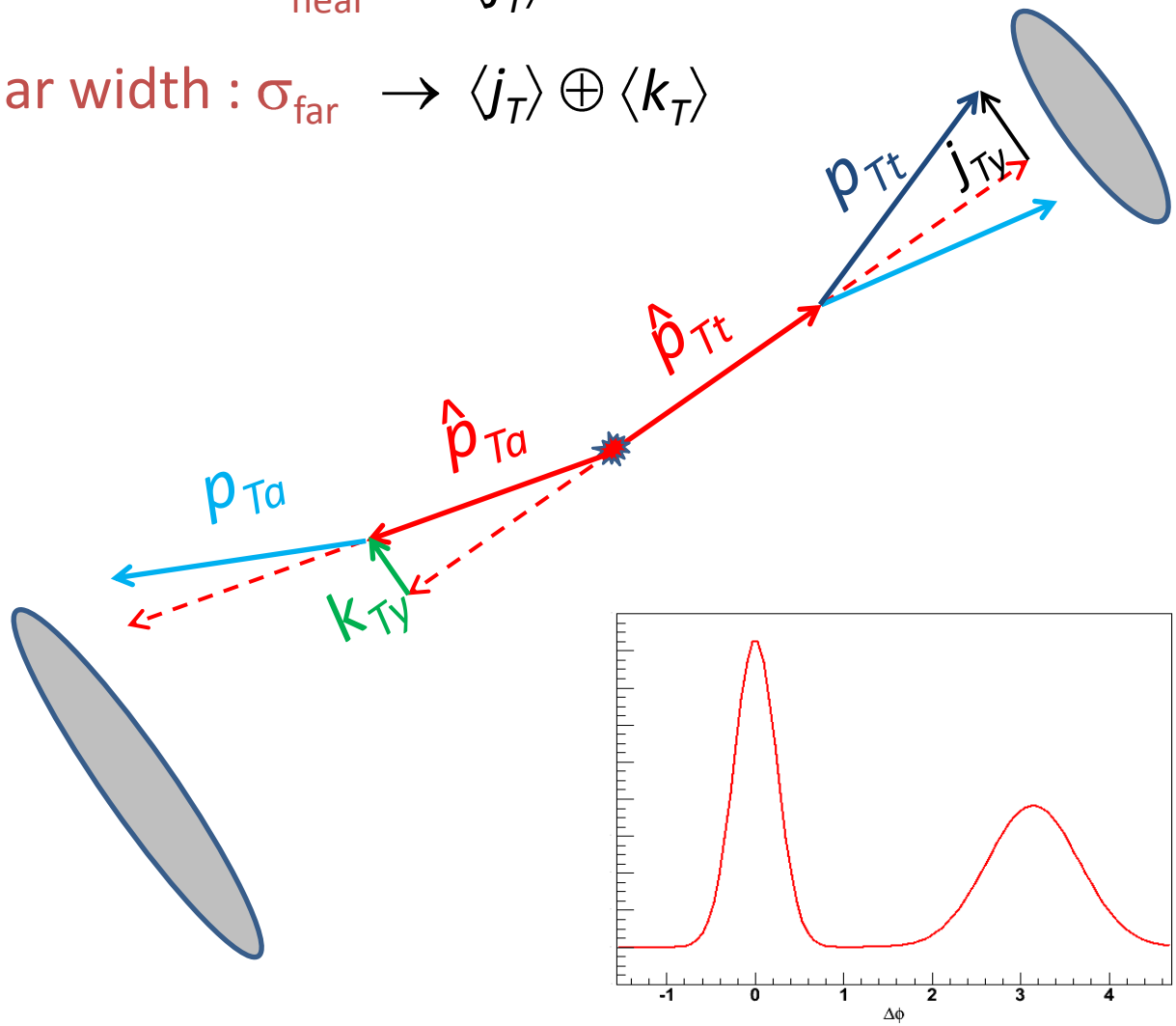


Measuring jet k_T – di-hadron correlation

Intra-jet pairs angular width : $\sigma_{near} \rightarrow \langle j_T \rangle$

Inter-jet pairs angular width : $\sigma_{far} \rightarrow \langle j_T \rangle \oplus \langle k_T \rangle$

- Non-Zero k_T



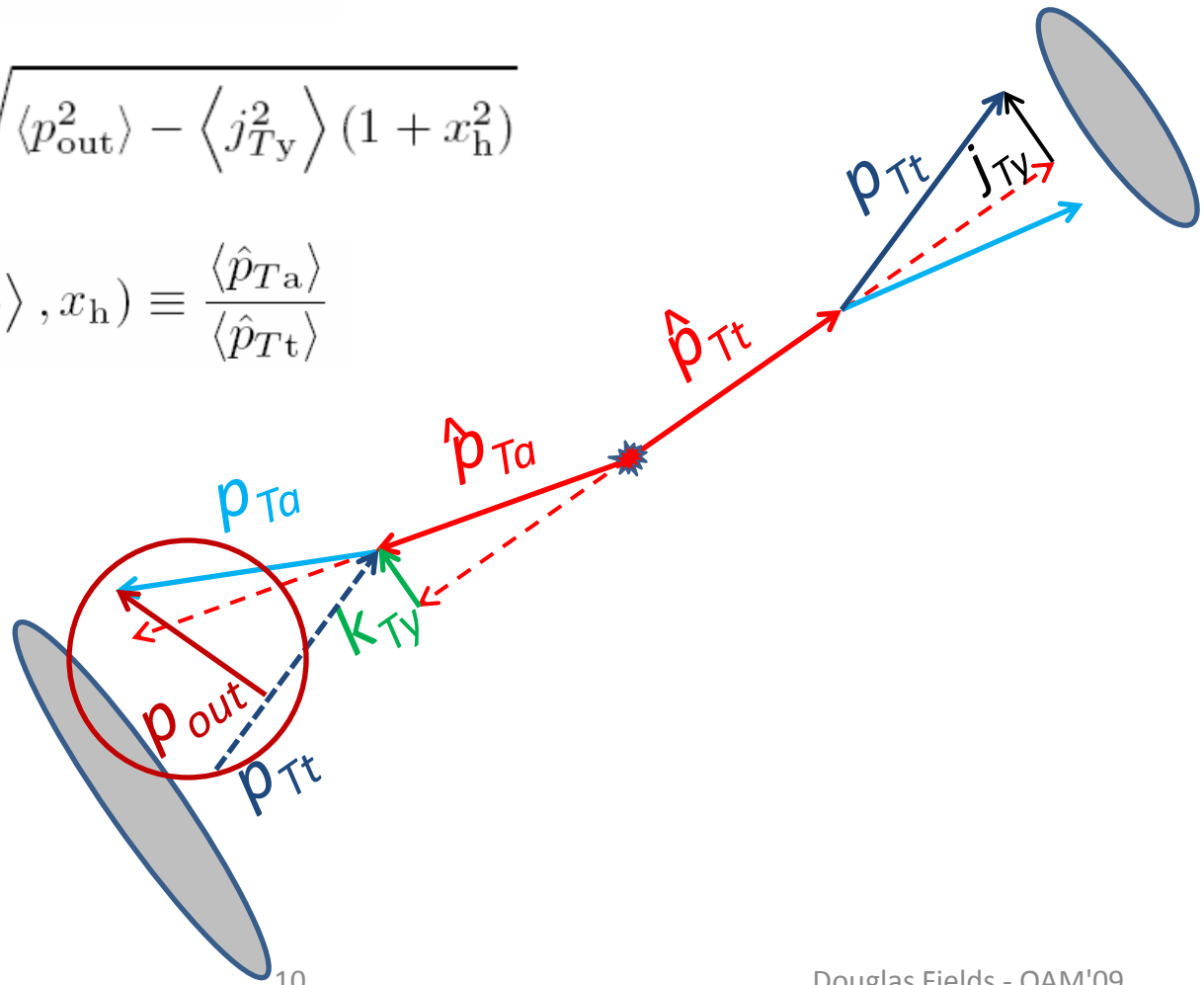
Jet Kinematics

$$\sqrt{\langle j_T^2 \rangle} = \sqrt{2\left\langle j_{T\mathrm{y}}^2 \right\rangle} \simeq \sqrt{2}\frac{p_{T\mathrm{t}} \cdot p_{T\mathrm{a}}}{\sqrt{p_{T\mathrm{t}}^2 + p_{T\mathrm{a}}^2}}\,\sigma_{\mathrm{N}}$$

$$\frac{\langle z_{\mathrm{t}}(k_T, x_{\mathrm{h}})\rangle \sqrt{\langle k_T^2 \rangle}}{\hat{x}_{\mathrm{h}}(k_T, x_{\mathrm{h}})} = \frac{1}{x_{\mathrm{h}}}\sqrt{\langle p_{\mathrm{out}}^2 \rangle - \left\langle j_{T\mathrm{y}}^2 \right\rangle (1 + x_{\mathrm{h}}^2)}$$

$$x_{\mathrm{h}} \equiv \frac{p_{T\mathrm{a}}}{p_{T\mathrm{t}}} \qquad \hat{x}_{\mathrm{h}} = \hat{x}_{\mathrm{h}}(\langle k_T^2 \rangle, x_{\mathrm{h}}) \equiv \frac{\langle \hat{p}_{T\mathrm{a}} \rangle}{\langle \hat{p}_{T\mathrm{t}} \rangle}$$

$$\langle z_t \rangle = \left\langle \frac{p_{Tt}}{\hat{p}_{Tt}} \right\rangle$$

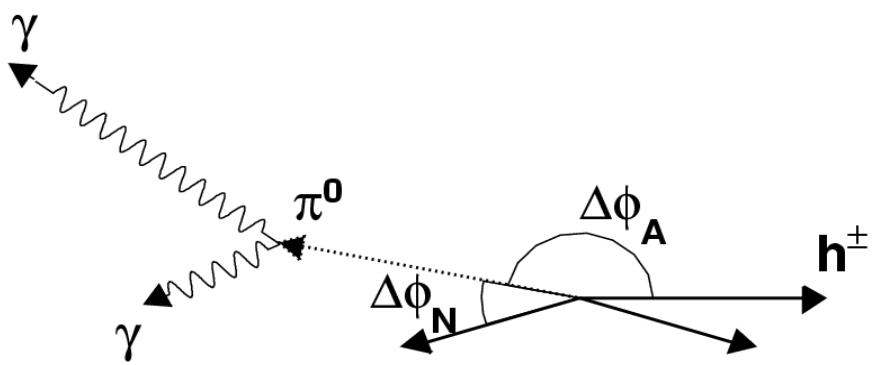


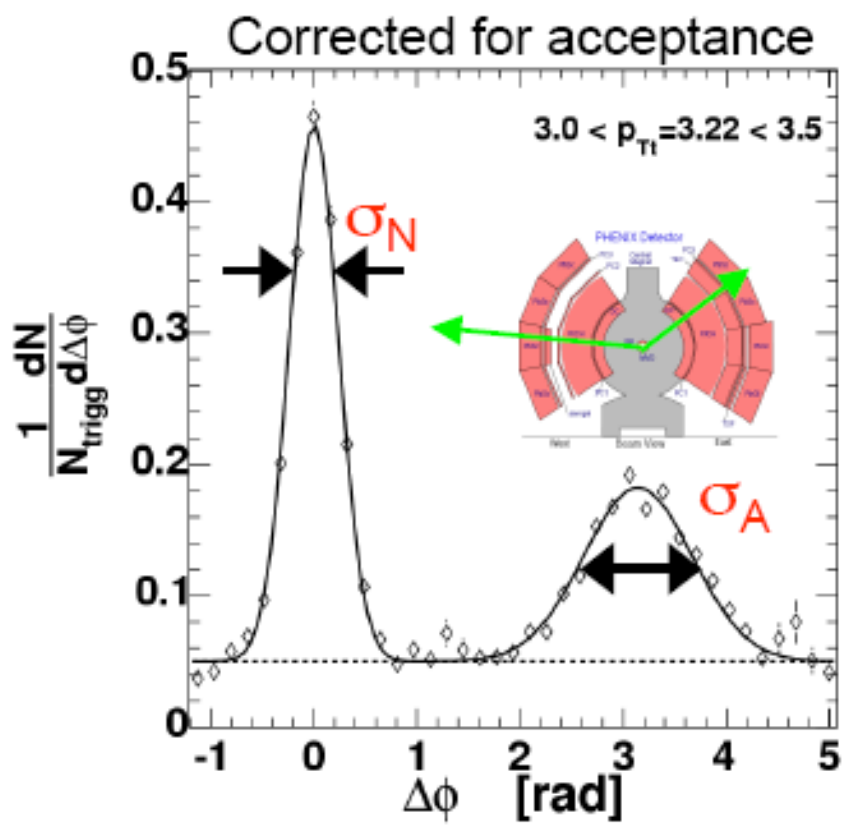
For details, see PRD 74, 072002 (2006)

Measuring jet k_T – di-hadron correlation

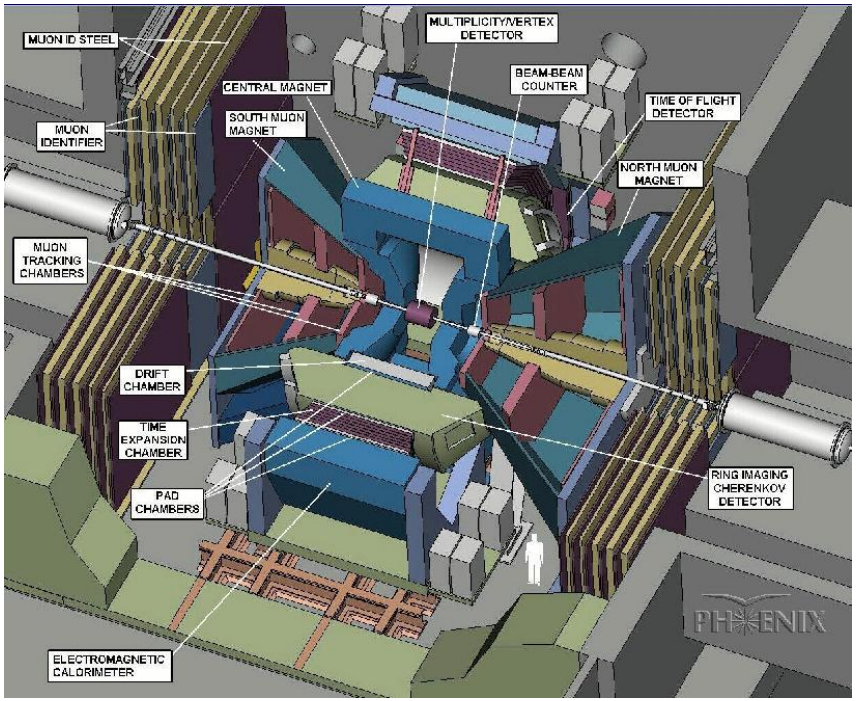
π^0- $h^\pm$ azimuthal correlation

Trigger on a particle, e.g. π^0, with transverse momentum p_{Tt}. Measure azimuthal angular distribution *w.r.t.* the azimuth of associated (charged) particle with transverse momentum p_{Ta}. The strong ***same*** and ***away*** **side peaks** in p-p collisions indicate di-jet origin from hard scattering partons.

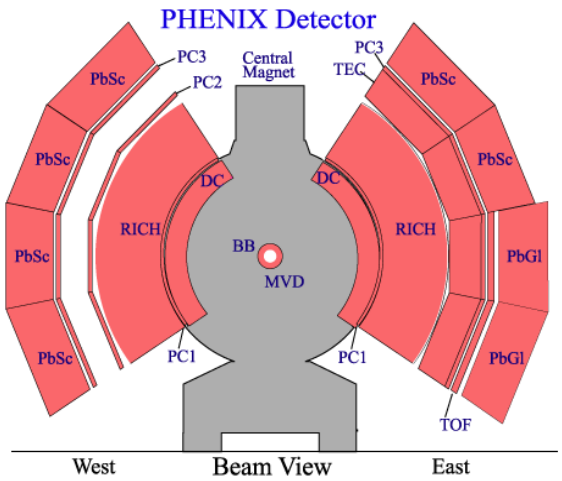


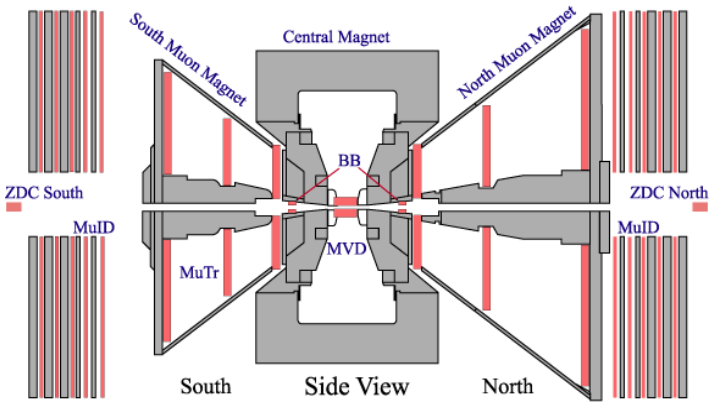


PHENIX Detector



- **Philosophy:**
  - **High resolution** at the cost of acceptance
  - **High rate** capable DAQ
  - Excellent **trigger capability** for rare events





- **Central Arms:**
  $|\eta|<0.35$, $\Delta\varphi=2\times90^0$
  Charged particle ID and tracking; photon ID. EM Calorimetry.
- **Muon Arm:**
  $1.2<|\eta|<2.4$
  Muon ID and tracking.

- **Global Detectors**
  Collision trigger
  Collision vertex characterization
  Relative luminosity
  Local Polarimetry

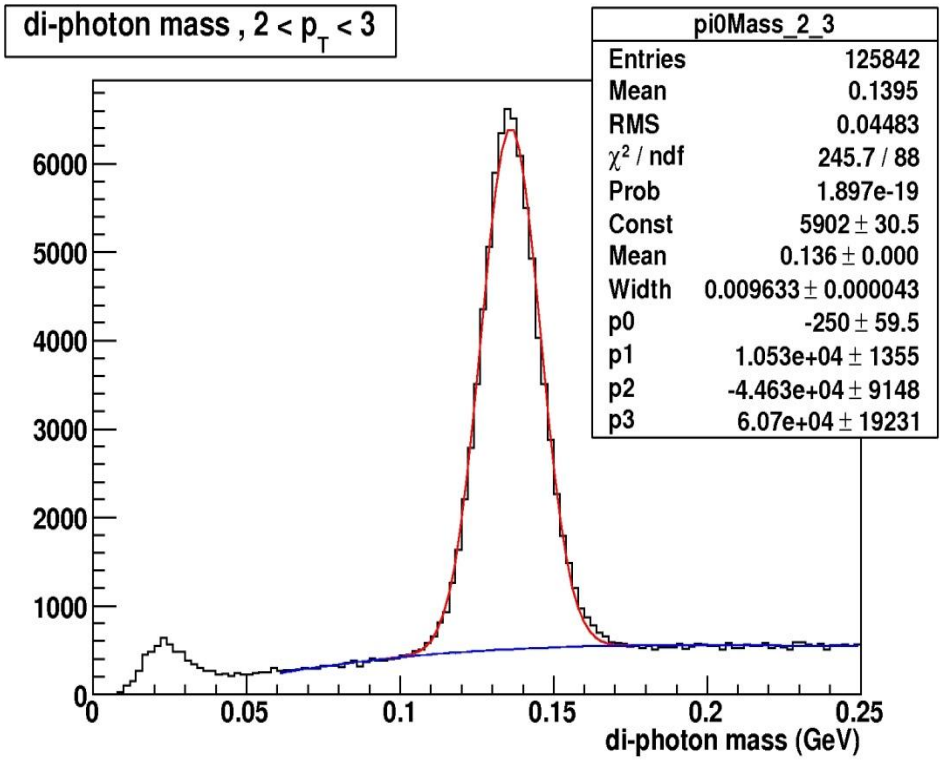
π° Identificaton

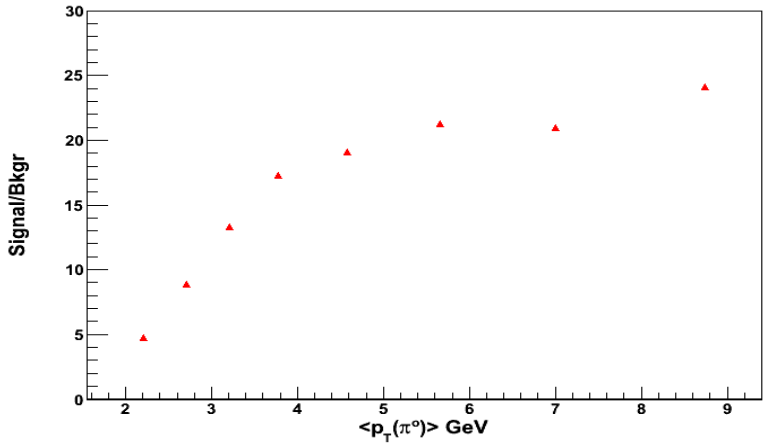
$\pi^\circ \rightarrow \gamma+\gamma$

The pions are selected within
$M_{\pi^\circ} \pm 2.0\sigma_{\pi^\circ}$

Photon trigger:
EMCal cluster energy > 1.4 GeV

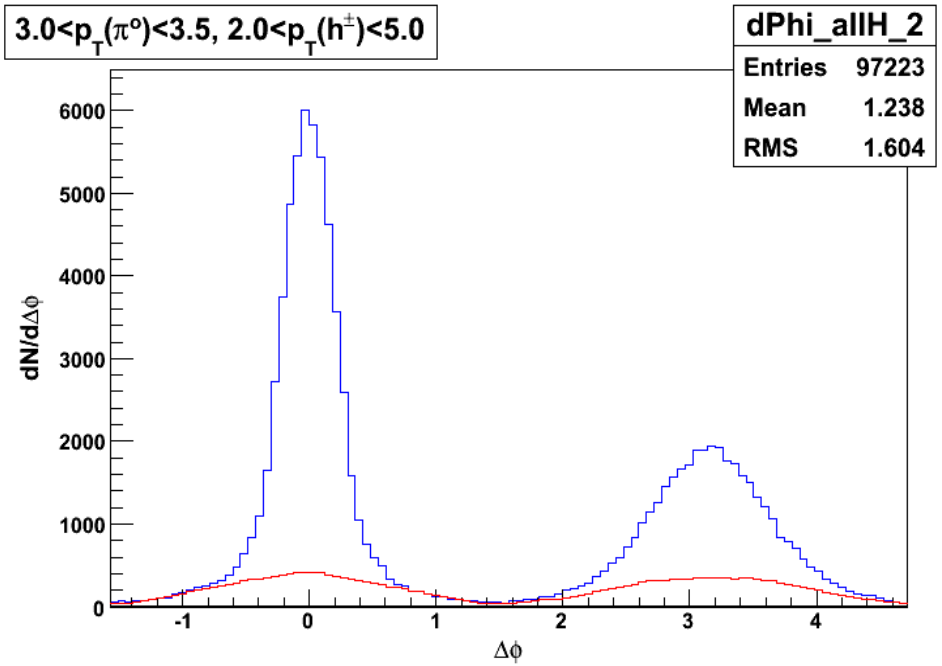
The mass, M_{π°, and the width, σ_{π°, are determined by fitting the di-photon mass spectrum with ***gaus+pol3***.

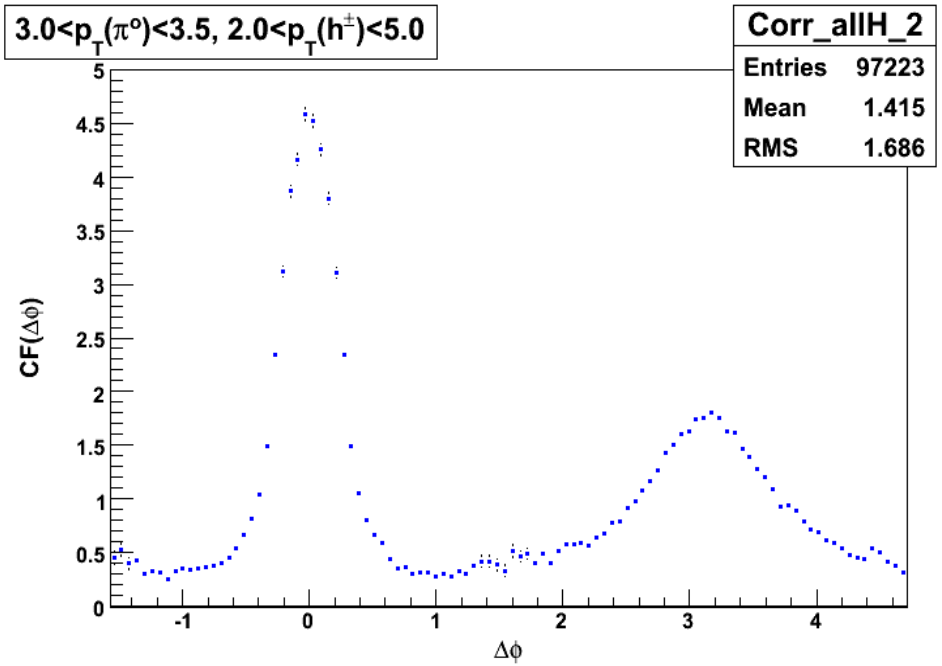




Correlation Function

- Blue – real (raw Δϕ)
- Red – background (mixed events)



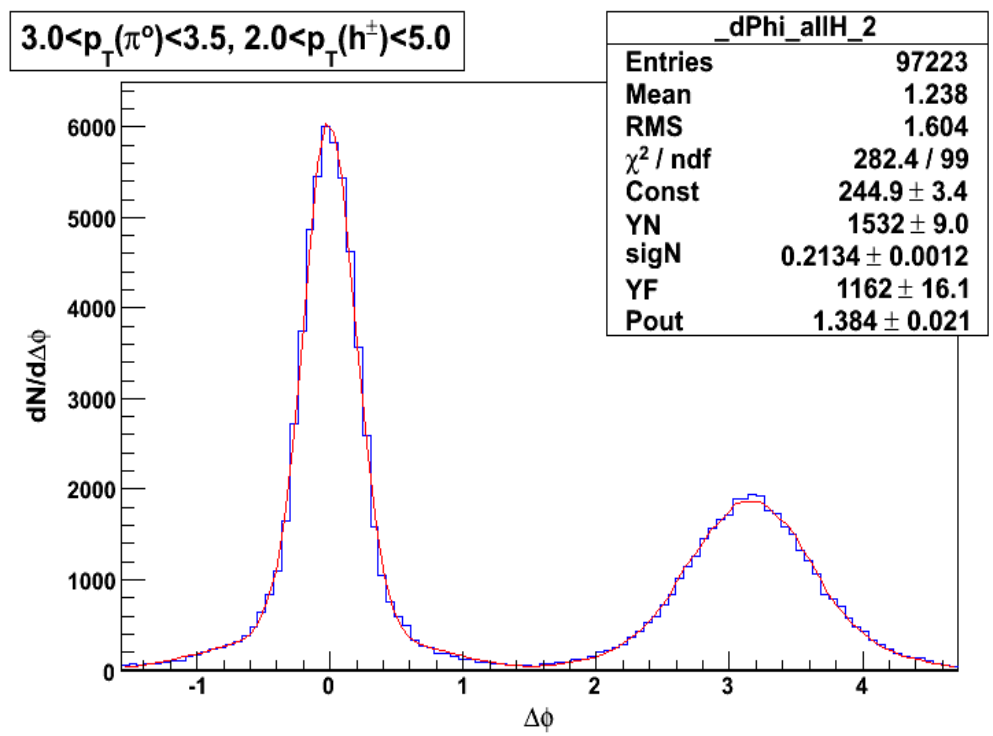


Fit Function

$$\frac{dN_{real}}{d\Delta\phi} = \frac{1}{N}\frac{dN_{mix}}{d\Delta\phi}\cdot\left(C_o + C_1\cdot Gaus(0) + C_2\cdot\left.\frac{dN_{away}}{d\Delta\phi}\right|_{\pi/2}^{3\pi/2}\right)$$

$$\left.\frac{dN_{away}}{d\Delta\phi}\right|_{\pi/2}^{3\pi/2} = \frac{-p_{Ta}\cos\Delta\phi}{\sqrt{2\pi\langle p_{out}^2\rangle}\,Erf\left(\sqrt{2}\,p_{Ta}/\sqrt{\langle p_{out}^2\rangle}\right)}\exp\left(-\frac{p_{Ta}^2\sin^2\Delta\phi}{2\langle p_{out}^2\rangle}\right)$$

- Blue – real (raw Δϕ)
- Red – Fit from above equation

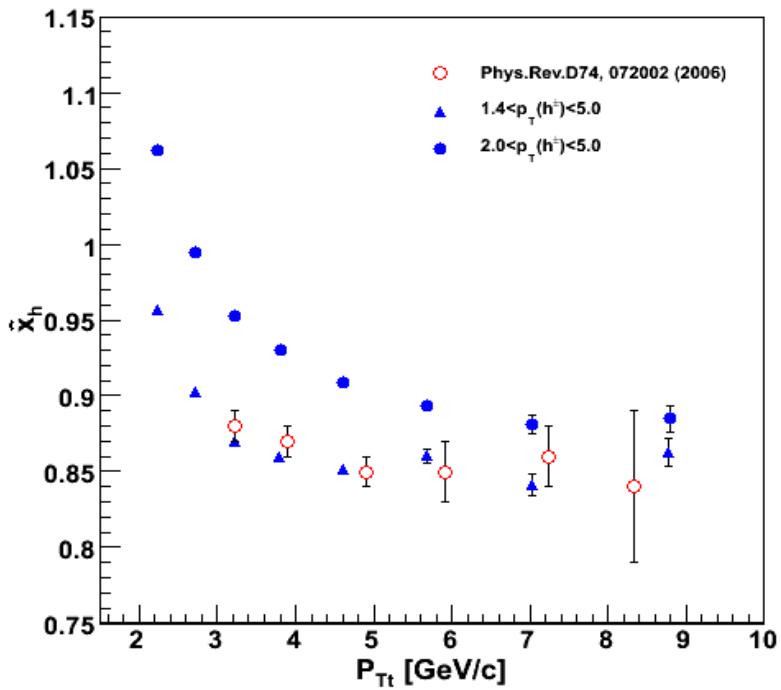


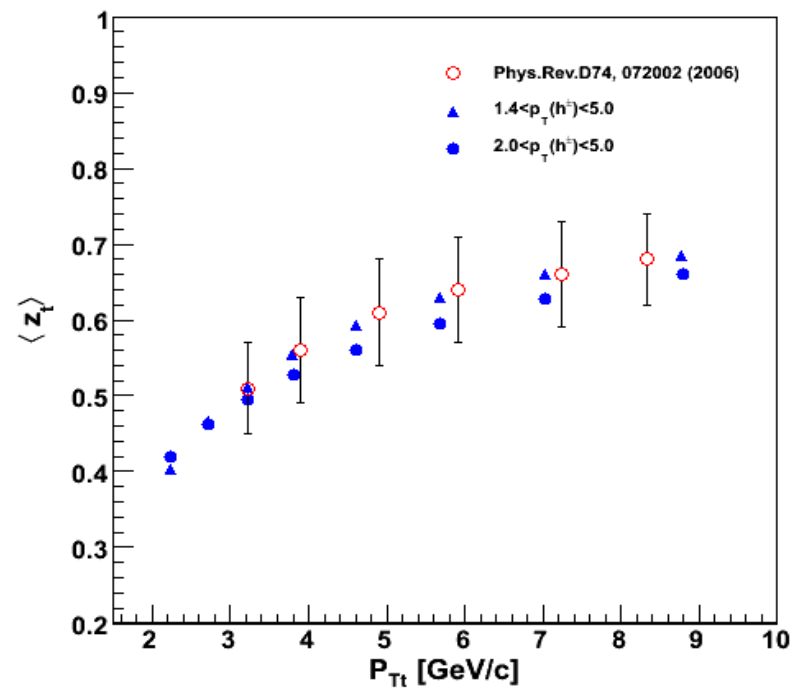
Need $\langle z_t \rangle$ and x_h

$$\frac{\langle z_{\rm t}(k_T, x_{\rm h})\rangle \sqrt{\langle k_T^2\rangle}}{\hat{x}_{\rm h}(k_T, x_{\rm h})} = \frac{1}{x_{\rm h}}\sqrt{\langle p_{\rm out}^2\rangle - \left\langle j_{T{\rm y}}^2\right\rangle (1+x_{\rm h}^2)}$$

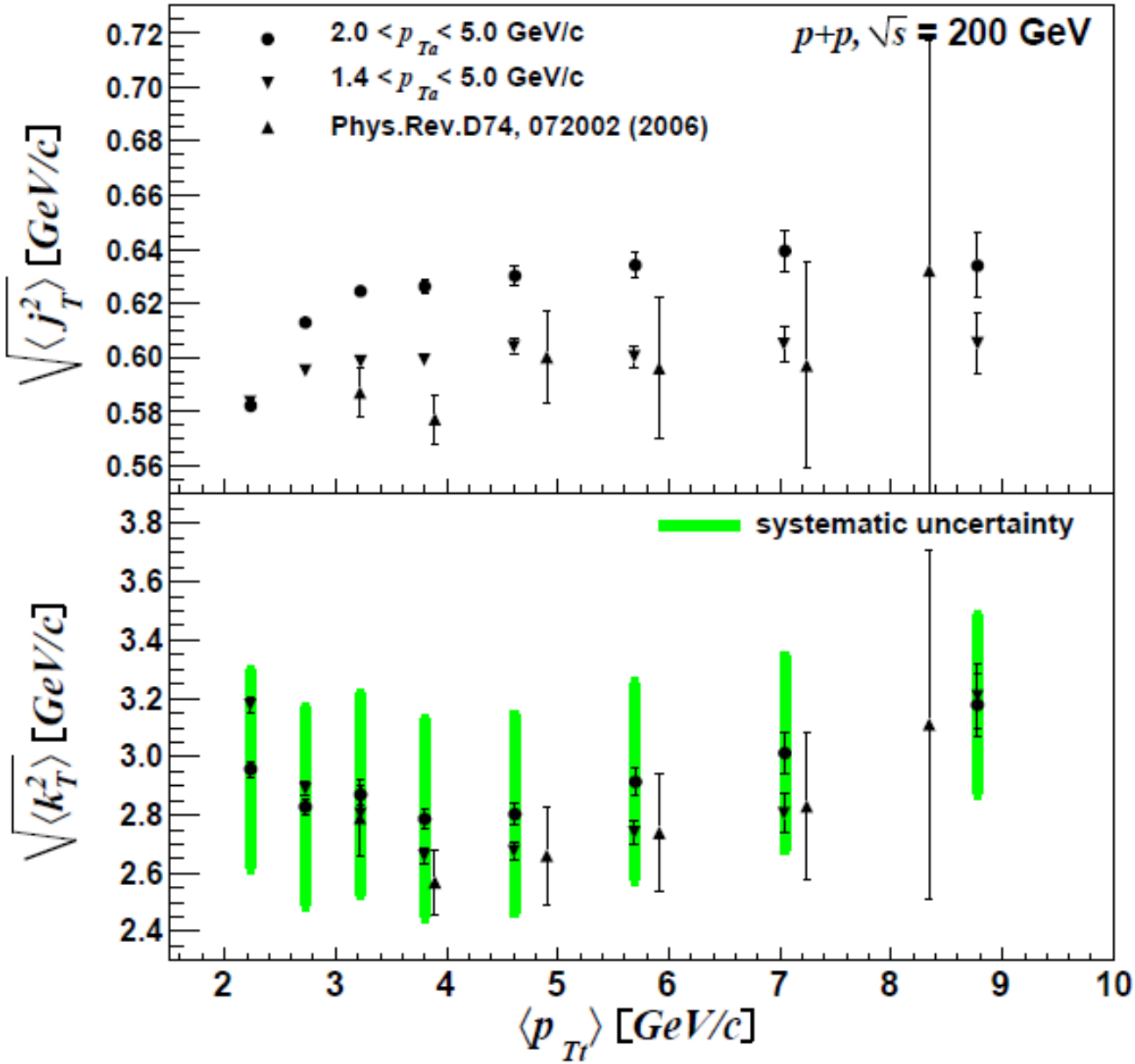
$\hat{x}_h$ and $\langle z_t \rangle$ are determined through a combined analysis of the π° inclusive cross section and using jet fragmentation function measured in e^+e^- collisions. *Ref*. PRD 74, 072002 (2006)

$\langle k^2_T \rangle$ asymmetry results are not sensitive to this $\hat{x}_h$ and $\langle z_t \rangle$ values – only needed to set the scale.



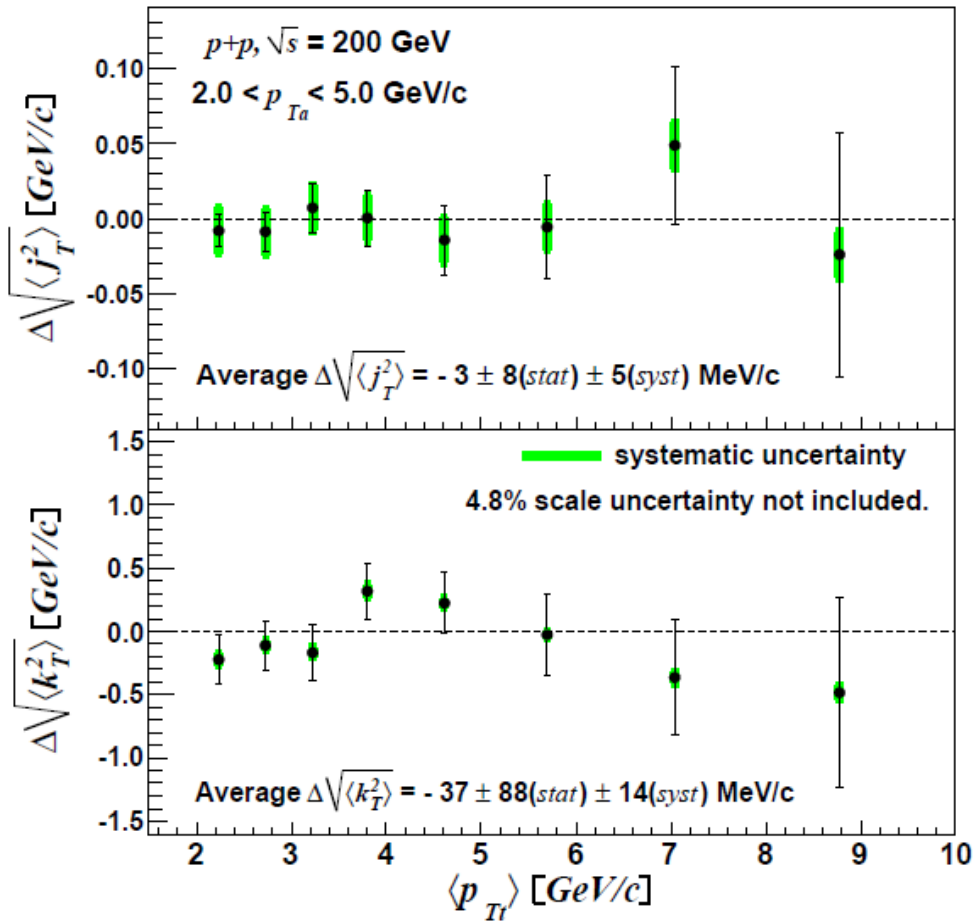


k_T results for unpolarized case



Preliminary Results

- Take the difference Like – Unlike helicities
- Normalized by beam polarizations
- $<j^2_T>$ asymmetry (-3 ± 8(stat) ± 5(syst) MeV out of ~630 MeV unpolarized)
- $<k^2_T>$ asymmetry also small (-37 ± 88(stat) ± 14(syst) MeV out of ~2.8 GeV unpolarized).



Interpretation

- The first term can be related in the "Meng conjecture" to partonic transverse momentum:

$$\Delta\langle k_T^2\rangle^I = \sum_{i,j} c^{ij} W^{ij} \left\{ \langle \vec{k}_T^i \cdot \vec{k}_T^j \rangle^{++} - \langle \vec{k}_T^i \cdot \vec{k}_T^j \rangle^{+-} \right\}$$

  where c^{ij} give the initial state weights and W^{ij} give the impact parameter weighting.
- Since PYTHIA studies show that the final state studied here is dominated by gg scattering (~50%),
- We can interpret this as a constraint on the gluon orbital angular momentum.
- Consistent with previous (Sivers) measurements, and complimentary, since one naïvely needs no initial or final state interactions (although Sivers measures orbital in *transversely* polarized proton).

Relating to Meng…

$$\Delta\langle p_T^2\rangle \approx 1.9\langle k_\phi\rangle^2$$

yields:

$$\langle k_\phi\rangle \approx \Delta\sqrt{\langle k_T^2\rangle} = -37 \pm 88^{\mathrm{stat}} \pm 14^{\mathrm{syst}}\ \mathrm{MeV}/c,$$

Summary

- We have an analysis tool – di-hadron azimuthal correlations - that allows us to measure k_T.
- We are studying this in helicity-sorted collisions to see if there is a spin-dependent, coherent component of k_T.
- In our kinematic range, we find $\Delta j_T^{\,RMS}$ = -3 ± 8(stat) ± 5(syst) MeV, and $\Delta k_T^{\,RMS}$ = -37 ± 88 ± 14(syst) MeV.
- While this is consistent with other measurements related to gluon OAM, the connection to parton OAM needs theoretical guidance!