k_T Asymmetry in Longitudinally Polarized $\vec{p}\vec{p}$ Collisions

Douglas Fields

University of New Mexico

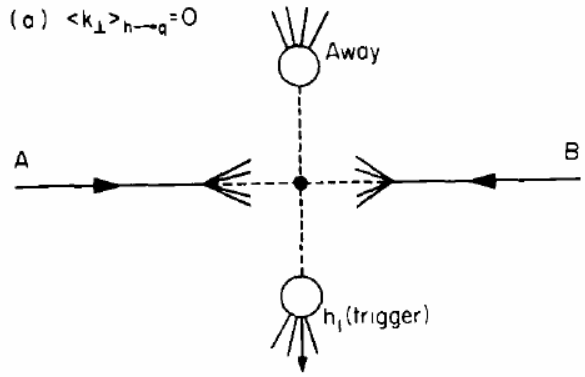
for PHENIX

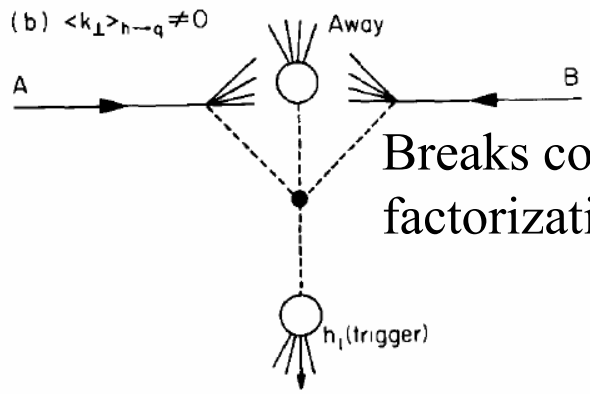
What is the origin of jet k_T?

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

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

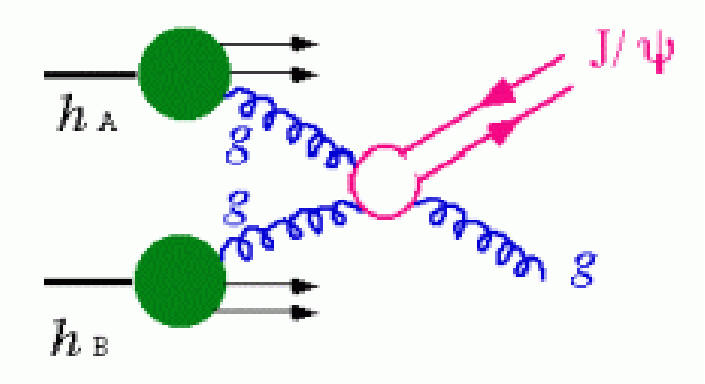
Soft QCD radiation.





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

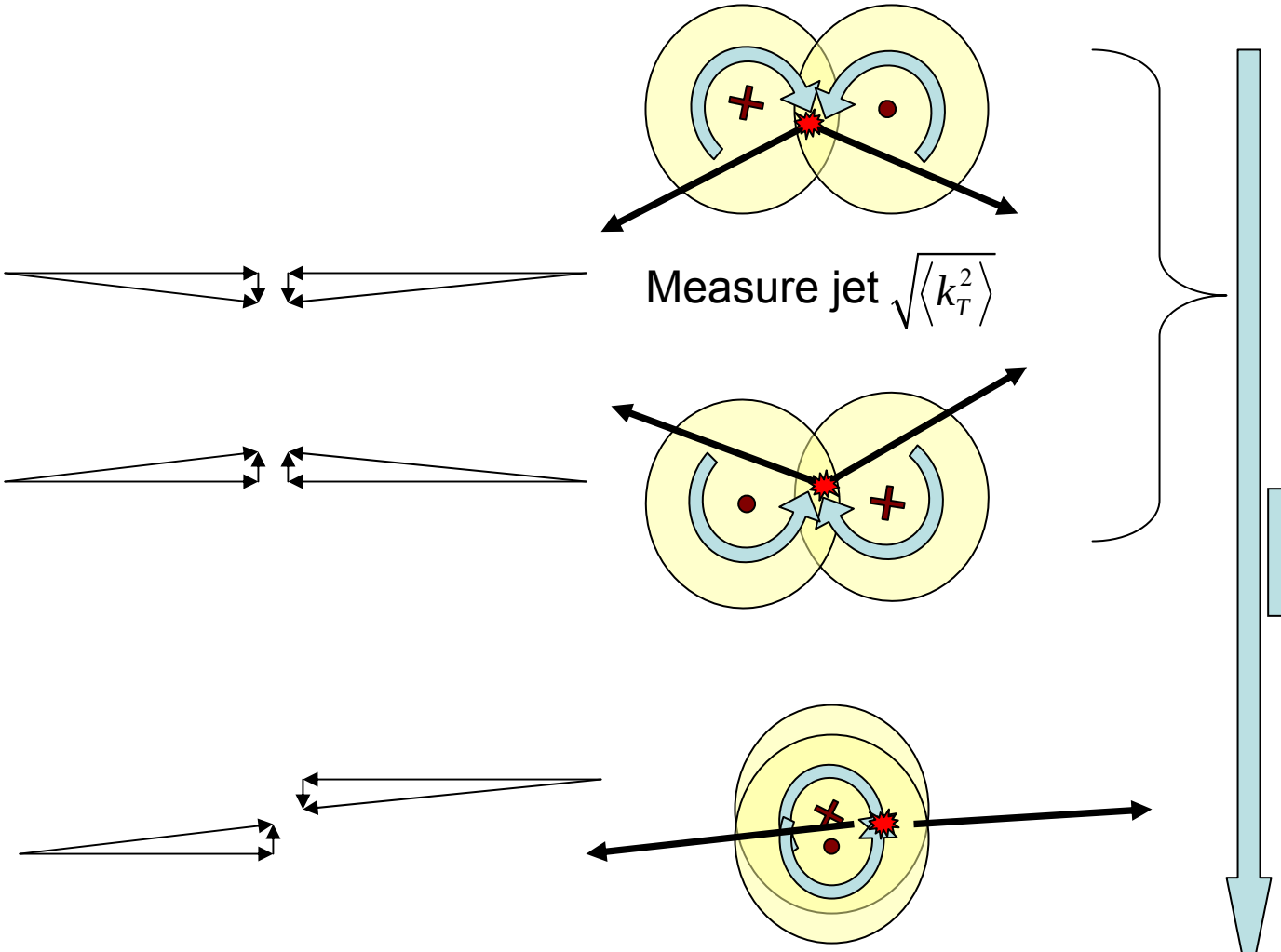
Phys. Rev. Lett. 92, 051802, (2004).

Another Possibility

- Spin-Correlated transverse momentum – partonic orbital angular momentum
- We can perhaps measure using jet k_T
- Sivers Effect in single transverse spin
  - Idea proposed by Boer and Vogelsang (Phys. Rev. D69 094025, 2004)
- Possible Effect in double longitudinal spin
  - Idea proposed for the Drell-Yan process by M.Ta-chung et. al. (Phys. Rev. D40 p.769, 1989)
  - Same idea for jets proposed by DF

Like Helicity

(Positive on Positive Helicity)



Peripheral Collisions

↓

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

Integrate over b, left with some residual k_T

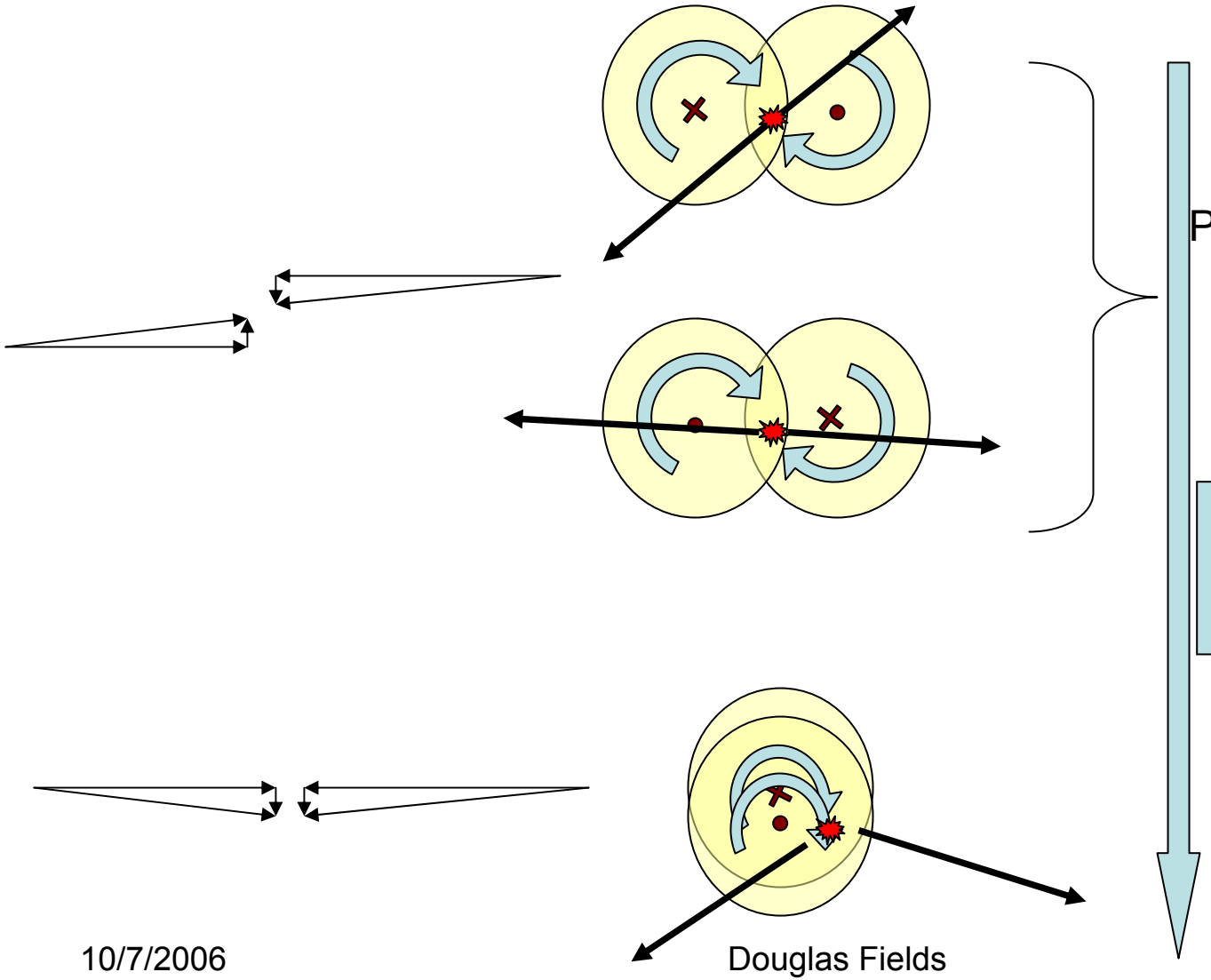
Central Collisions

↓

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

Un-like Helicity

(Positive On Negative Helicity)



Peripheral Collisions

↓

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

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

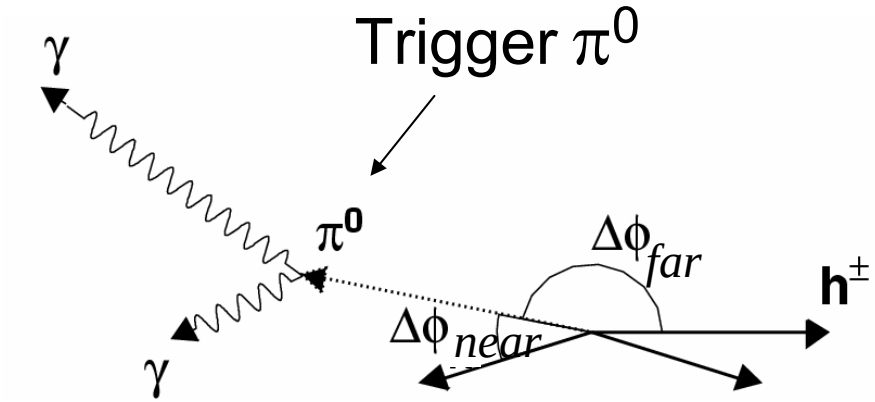
Central Collisions

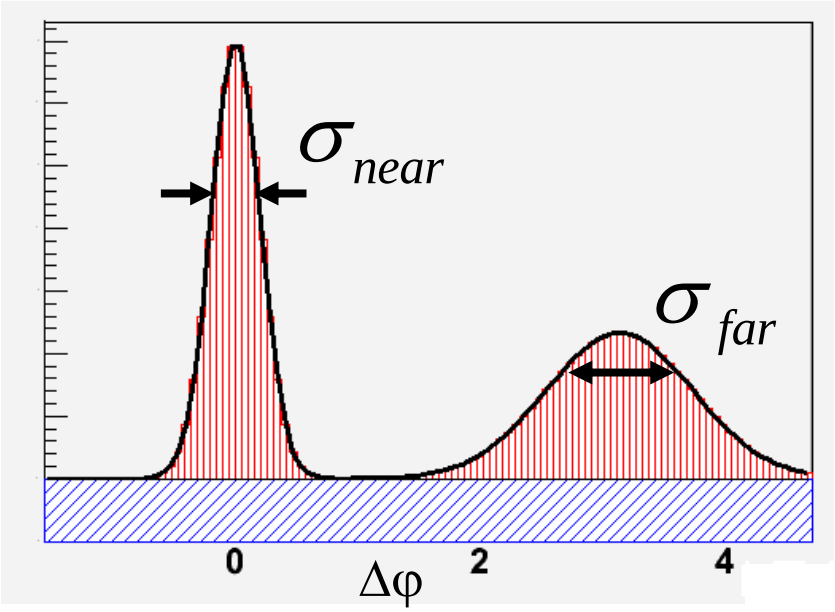
↓

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

How does PHENIX measure jet k_t?

- PHENIX doesn't measure jets, so…
- π^0 - $h^{\pm}$ azimuthal correlation functions



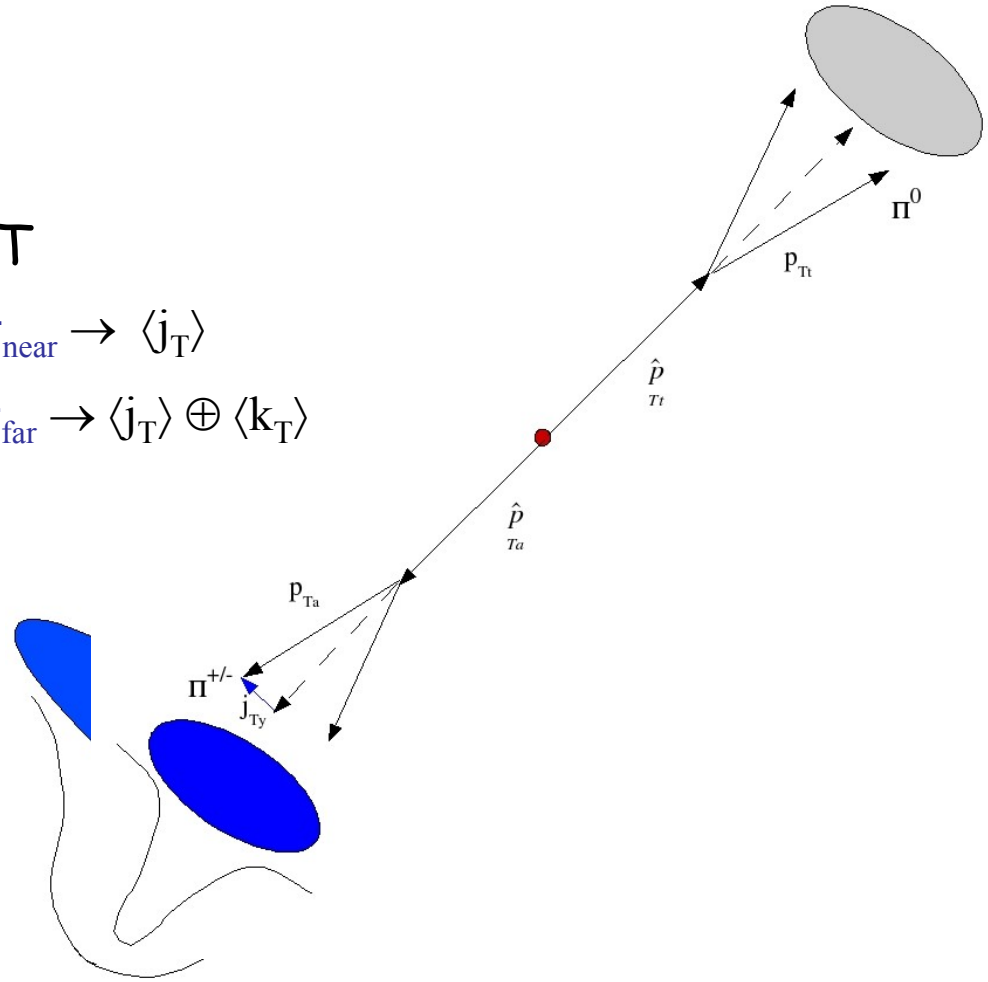


How does PHENIX measure k_+?

- Zero k_T
- Non-Zero k_T

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

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

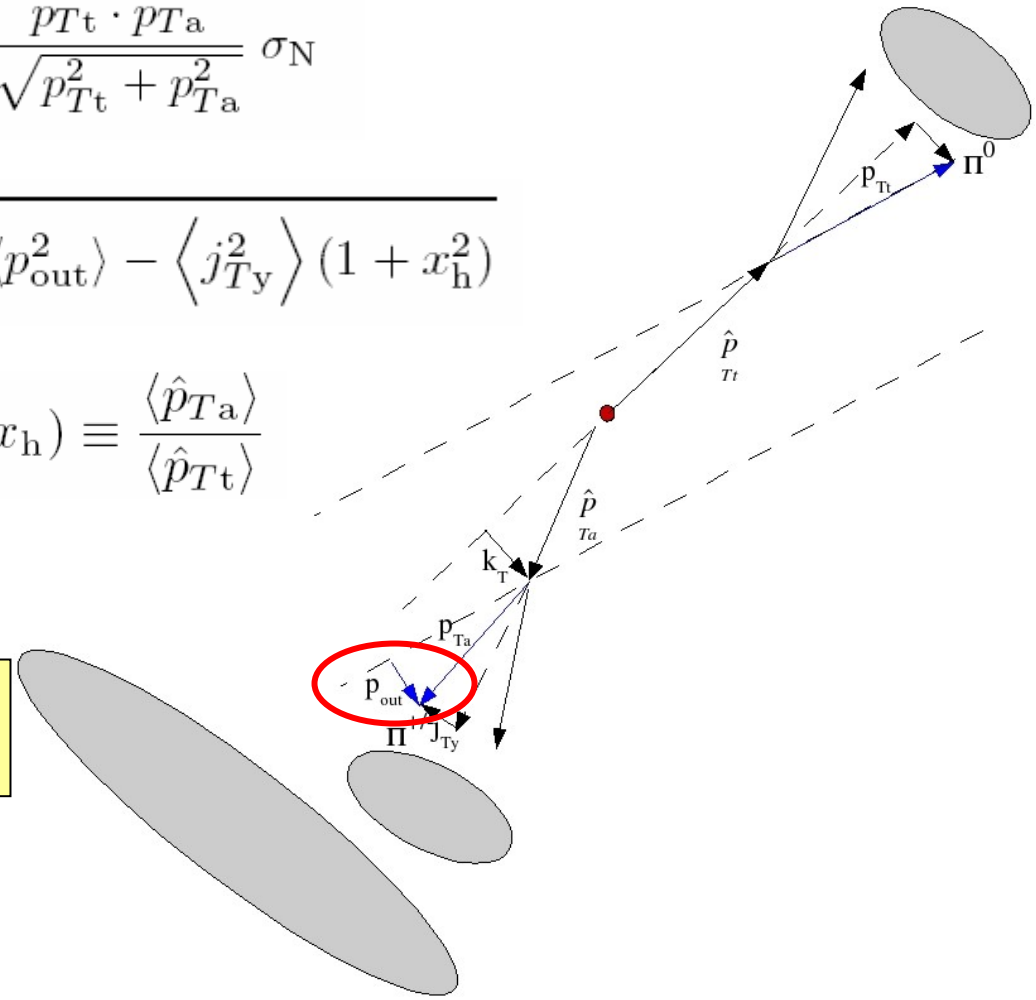


Jet Kinematics

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

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

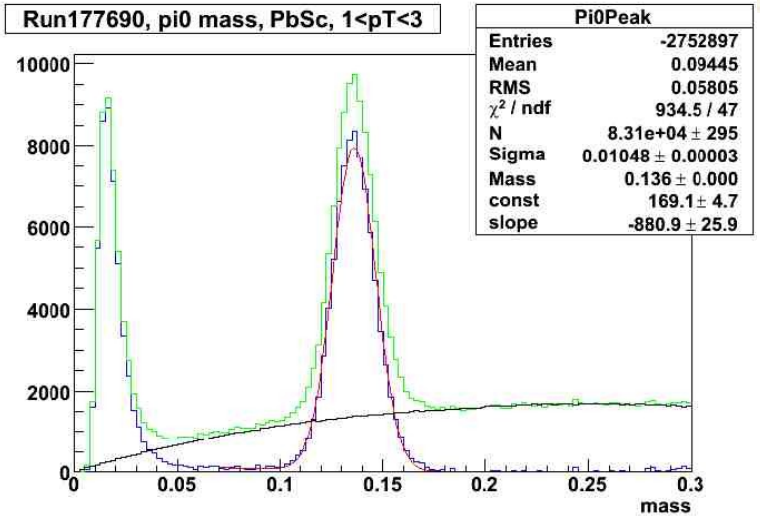
$$x_{\mathrm{h}} \equiv \frac{p_{T\mathrm{a}}}{p_{T\mathrm{t}}} \qquad \hat{x}_{\mathrm{h}} = \hat{x}_{\mathrm{h}}(\left\langle k_T^2 \right\rangle, x_{\mathrm{h}}) \equiv \frac{\langle \hat{p}_{T\mathrm{a}} \rangle}{\langle \hat{p}_{T\mathrm{t}} \rangle}$$

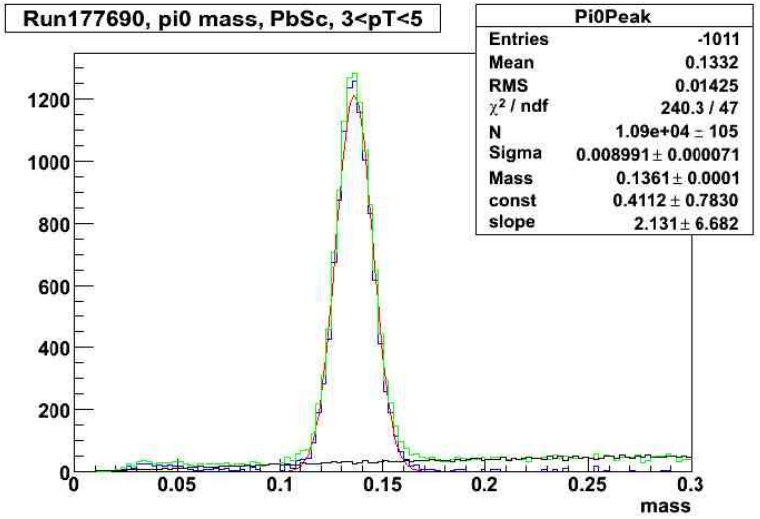


For details, see:
Phys. Rev. D **74**, 072002 (2006)

π^0 Identification

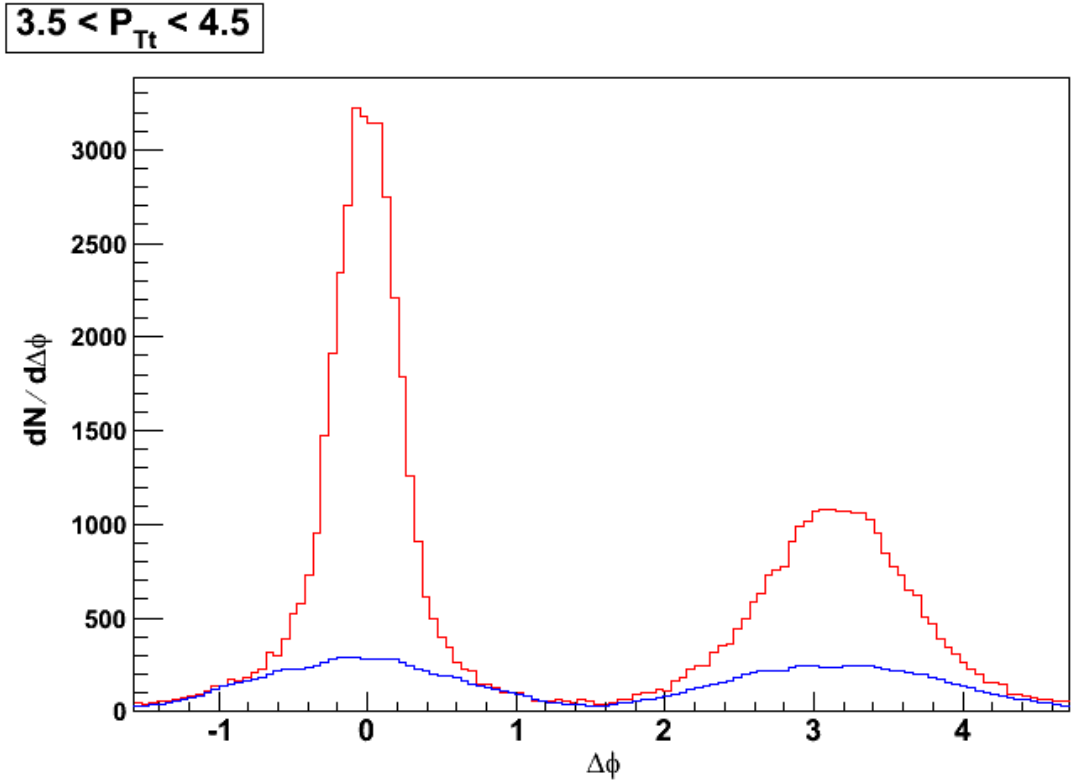
- Min photon energy > 0.2 GeV (for both PbSc and PbGl).
- Photon probability > 0.02.
- Two photon energy asymmetry < 0.8.
- Gamma3 trigger check for higher energy photon in the pair.





Correlation Function

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



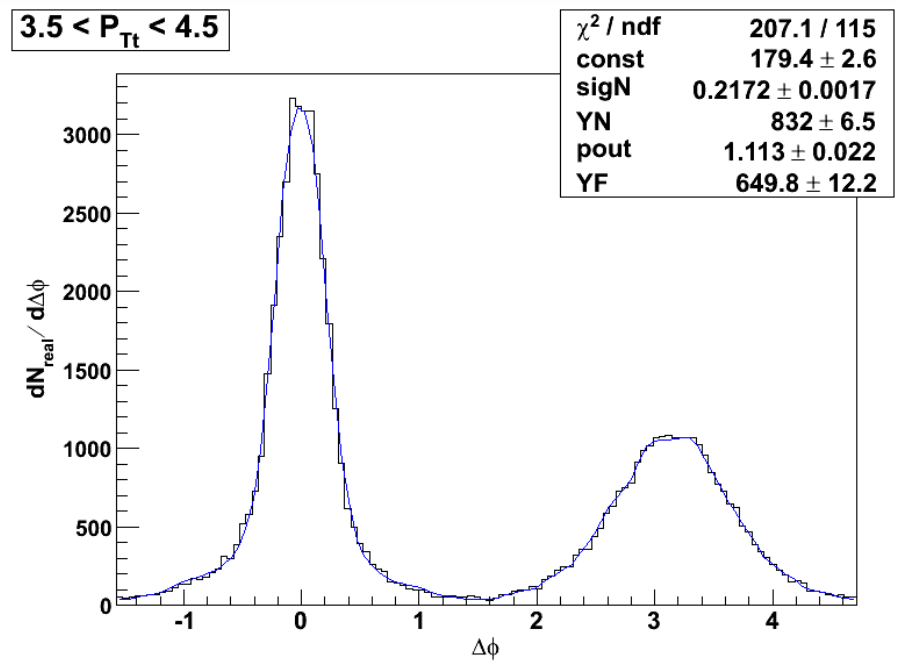
Fit Function

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

where

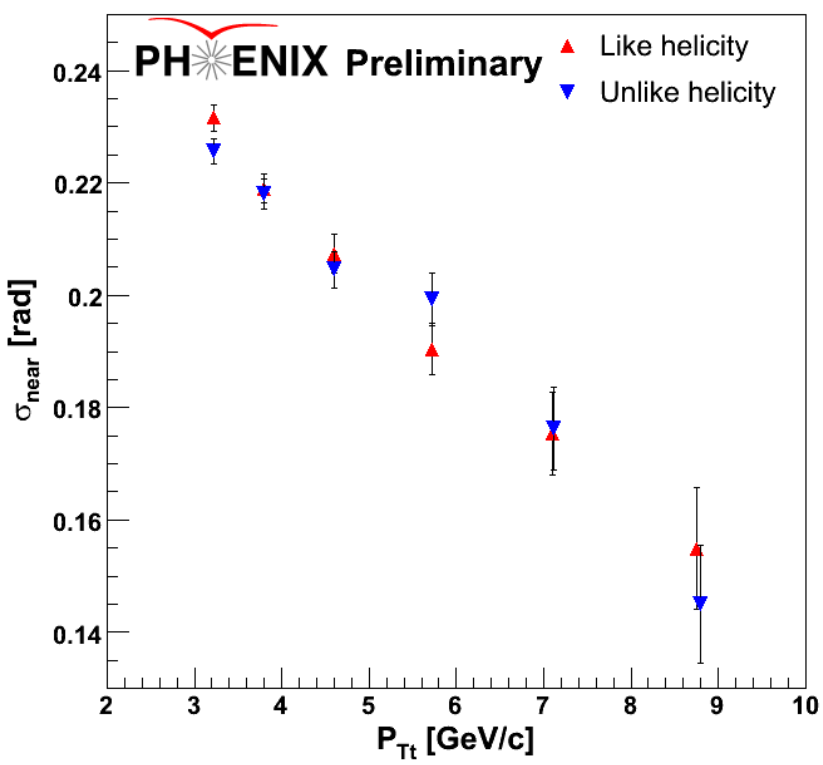
$$\frac{dN_{away}}{d\Delta\phi}\Big|_{\pi/2}^{3\pi/2} = \frac{-p_{Ta}\cos\Delta\phi}{\sqrt{2\pi\langle p_{out}^2\rangle}\, Erf\left(\sqrt{2}p_{Ta}/\sqrt{\langle p_{out}^2\rangle}\right)} exp\left(-\frac{p_{Ta}^2\sin^2\Delta\phi}{2\langle p_{out}^2\rangle}\right) \quad (3)$$

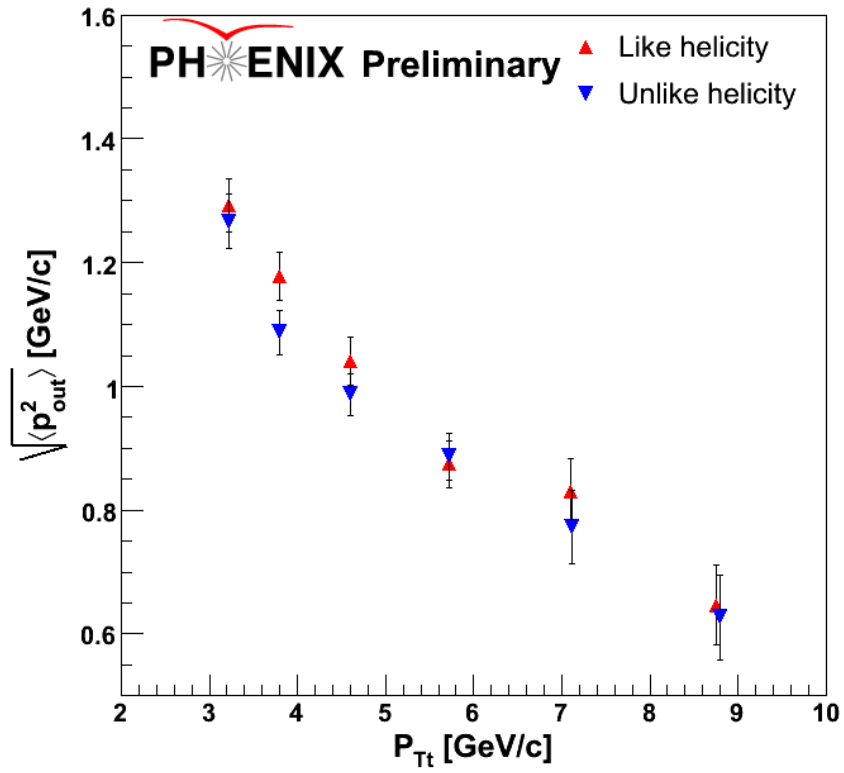
- Black – real (raw Δφ)
- Blue – Fit from above equation



Fit Results

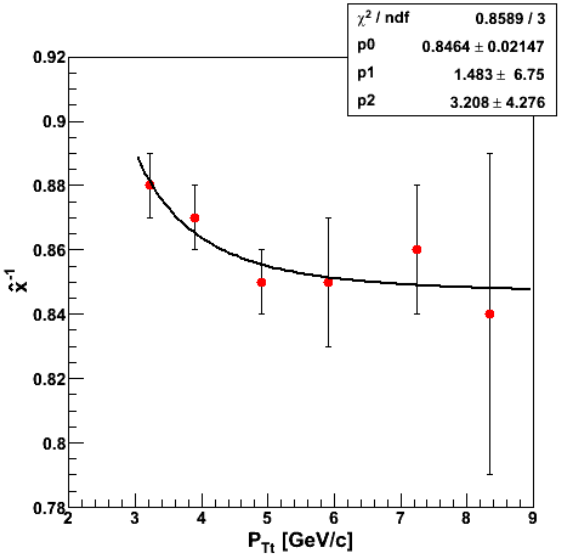
- Red ▲ - Like helicity (++ & --)
- Blue ▼ - Unlike helicity (+- & -+)

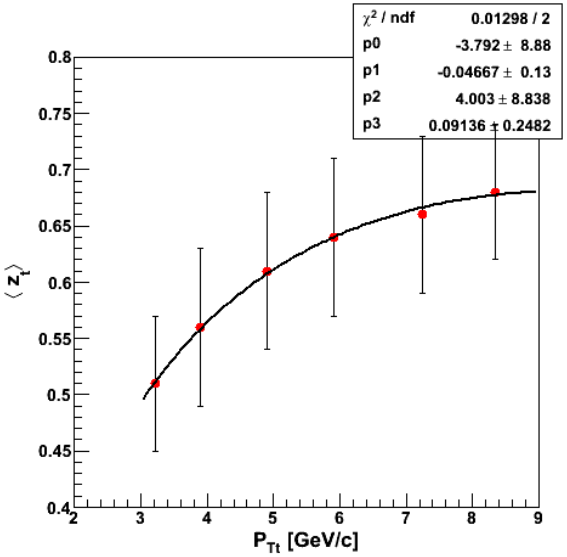




Need z_t and x_h

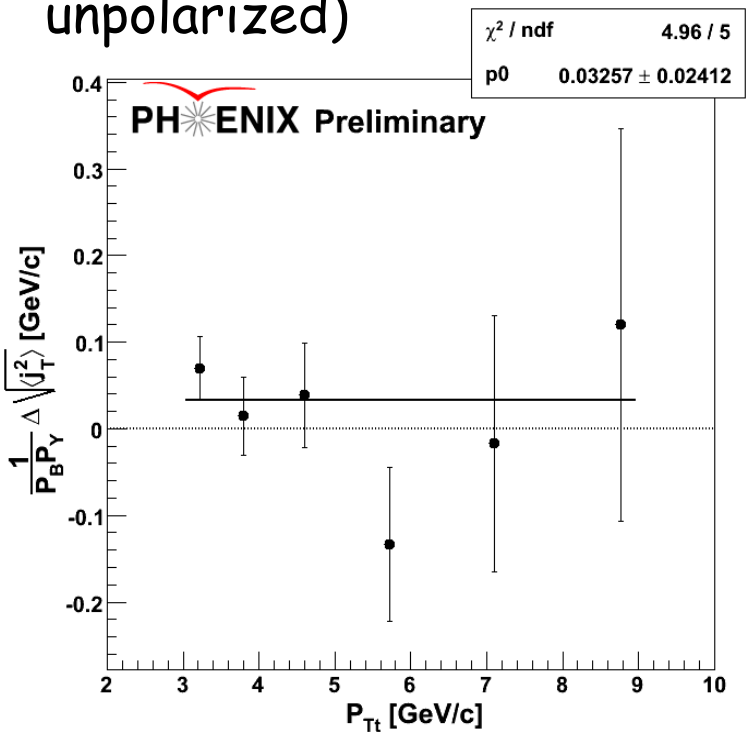
- Go from $p_{out} \rightarrow \quad x_h^{-1} \langle z_t \rangle \sqrt{\langle k_T^2 \rangle}$
- Simple parameterizations of z_t and x_h taken from Phys. Rev. D 74, 072002 (2006)
- Our results are not sensitive to this parameterization – only needed to set the scale
- Use these parameterizations to estimate $\sqrt{\langle k_T^2 \rangle}$

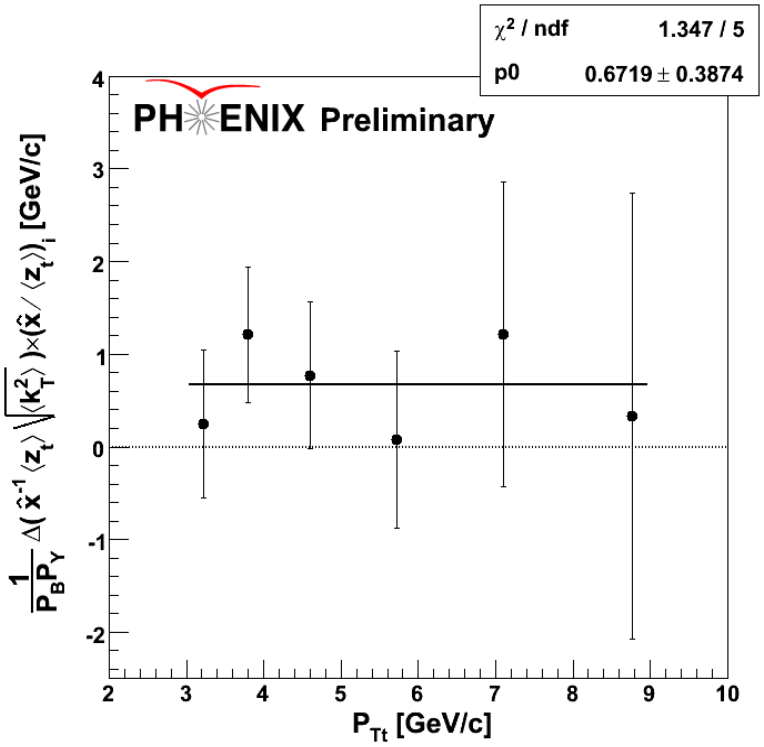




Preliminary Results

- Take the difference Like – Unlike helicities
- Normalized by beam polarizations
- j_T asymmetry small (32 ± 24MeV/c out of ~580MeV/c for unpolarized)
- k_T asymmetry not small (672 ± 387MeV/c out of ~3GeV for unpolarized)





Summary

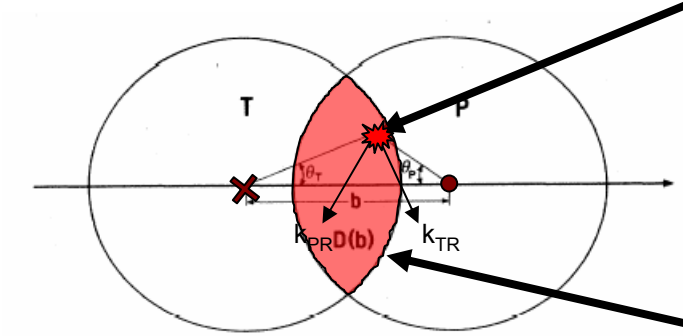
- Many more things to do:
  - Can attempt to sort on "impact parameter" by looking at multiplicities in forward and central rapidities (Done, but not yet PRELIMINARY – very interesting…).
  - Sort by hadron charge to change mix of interacting partons (PYTHIA MC).
  - All of above with π^0 in forward rapidities (MPC).
- Need theoretical guidance on how to interpret in terms of connection to orbital angular momentum.
- Look forward to Run6 data analysis (~ x3 in F.O.M.) soon!

Backups

- Think of rotating (longitudinal) water balloons, or…

From Meng Ta-Chung *et al.*

Phys Rev. D40, p769, (1989)



Total transverse momentum squared of partons

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

For a particular impact parameter, b, the average transverse momentum

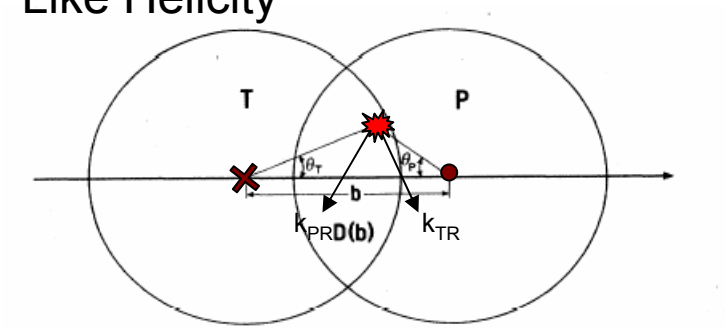
$$\langle p_t^2(b,\pm)\rangle = \frac{\int_{D(b)} \langle p_t^2(b,\theta_P,\theta_T;\pm)\rangle F(b,\theta_P,\theta_T)\,d\theta_P\,d\theta_T}{\int_{D(b)} F(b,\theta_P,\theta_T)\,d\theta_P\,d\theta_T}$$

Where, $F(b,\theta_P,\theta_T)$ is the product of the Jacobian and the density profile of partons, and D(b) is the overlap region.

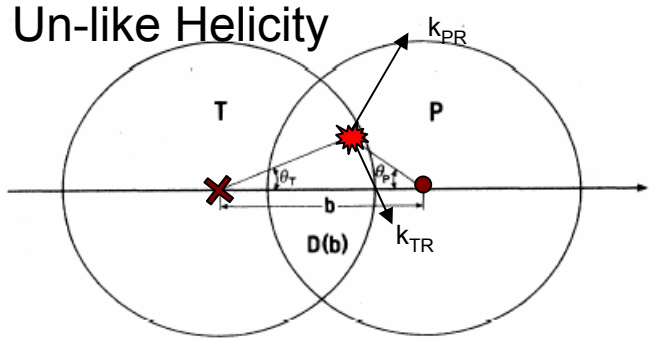
From Meng Ta-Chung *et al.*

Phys Rev. D40, p769, (1989)

Like Helicity



Un-like Helicity



We can now helicity separate:

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

The constant terms in p_t cancel and we have

$$\Delta\langle p_t^2(b)\rangle = \frac{4\int_{D(b)} |\mathbf{k}_{PR}||\mathbf{k}_{TR}|\cos(\theta_P+\theta_T)F(b,\theta_P,\theta_T)\,d\theta_P\,d\theta_T}{\int_{D(b)} F(b,\theta_P,\theta_T)\,d\theta_P\,d\theta_T}$$

We can then average over the impact parameter

$$\Delta\langle p_t^2\rangle = \int_0^{2R} \Delta\langle p_t^2(b)\rangle\, b\, db/(2R^2)$$

From Meng Ta-Chung *et al.*

Phys Rev. D40, p769, (1989)

This paper makes the following assumptions:

1) Uniform spherical density $F(b,\theta_P,\theta_T)$
2) $k_{PR} \sim k_{TR} \sim k_R$ (no dependence on b, θ_P, θ_T.)

Then,

$$\Delta\langle p_t^2\rangle = \frac{4\langle k_R\rangle^2}{\pi(2R)^2}\int_0^{2R} W(b)\,db$$

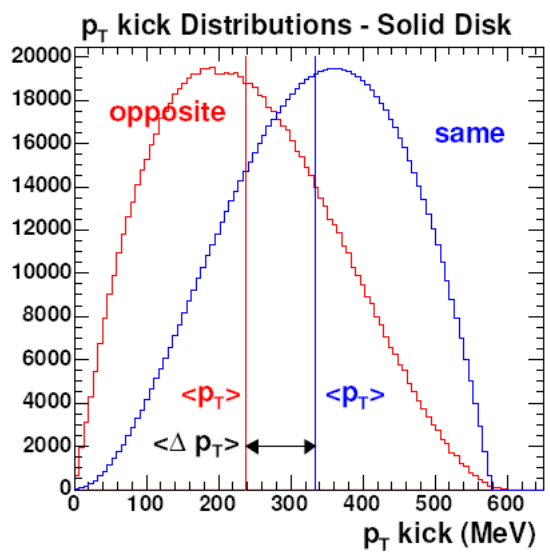
Evaluated numerically

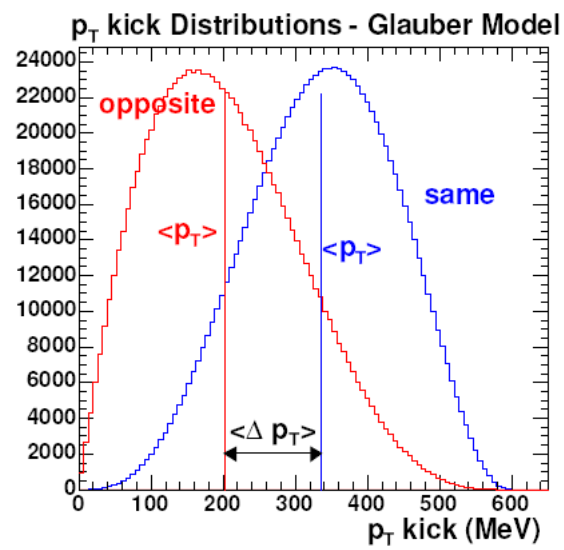
$$W(b) = \frac{2\pi b\int_D \cos(\theta_P+\theta_T)F(b,\theta_P,\theta_T)\,d\theta_P\,d\theta_T}{\int_D F(b,\theta_P,\theta_T)\,d\theta_P\,d\theta_T}$$

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

Our Model

- Use different transverse density distributions to get p_t kick from coherent spin-dependent motion:



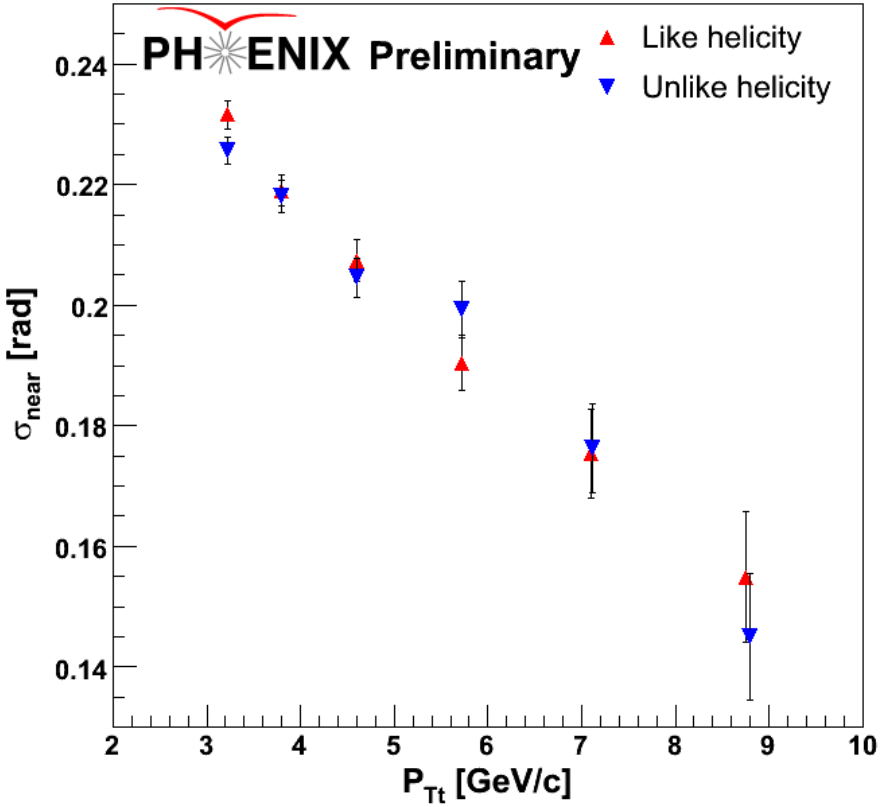


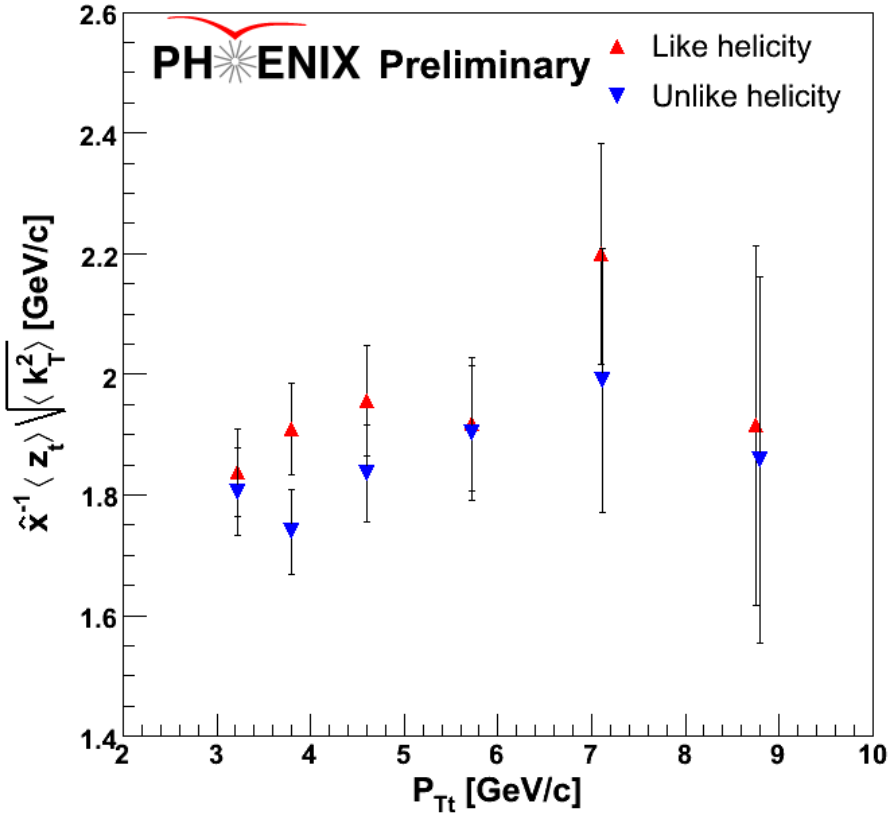
Our Model Results

- Basically independent of transverse density distribution.
- Ranges from 0.3 to 0.6 times the initial momentum.
- Very crude – would like suggestions to improve.

Model	$< \Delta p_T >$
Solid Disk	96 MeV
Glauber Model	135 MeV
2D Saxon-Woods, a=0.2	168 MeV
2D Saxon-Woods, a=0.5	196 MeV
3D Saxon-Woods, a=0.2	154 MeV
3D Saxon-Woods, a=0.5	198 MeV

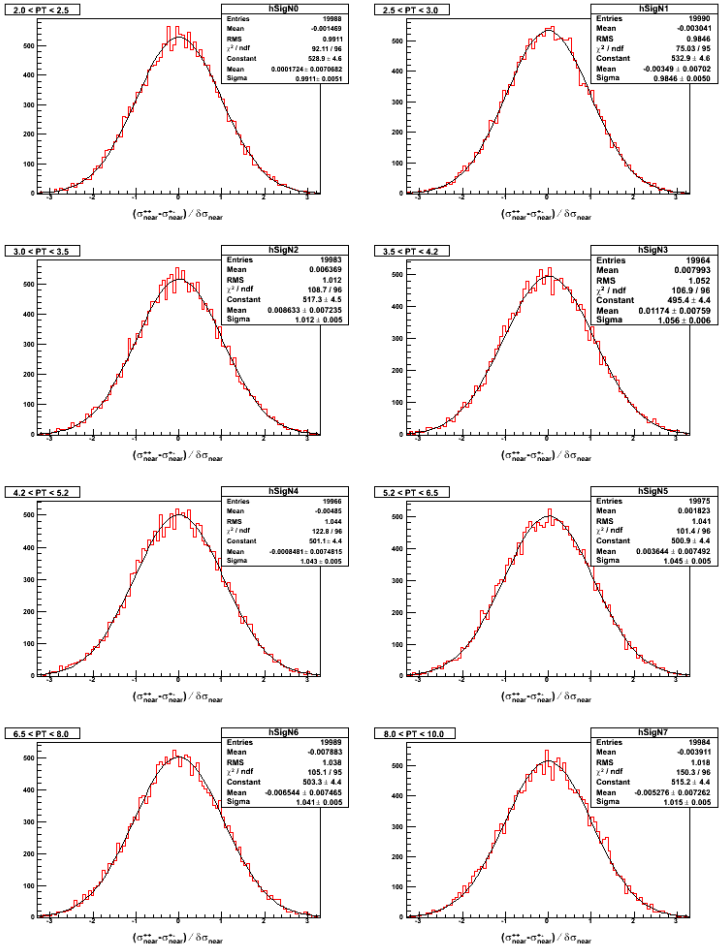
$\text{Sigma}_{\text{Near}}$ and xzkt





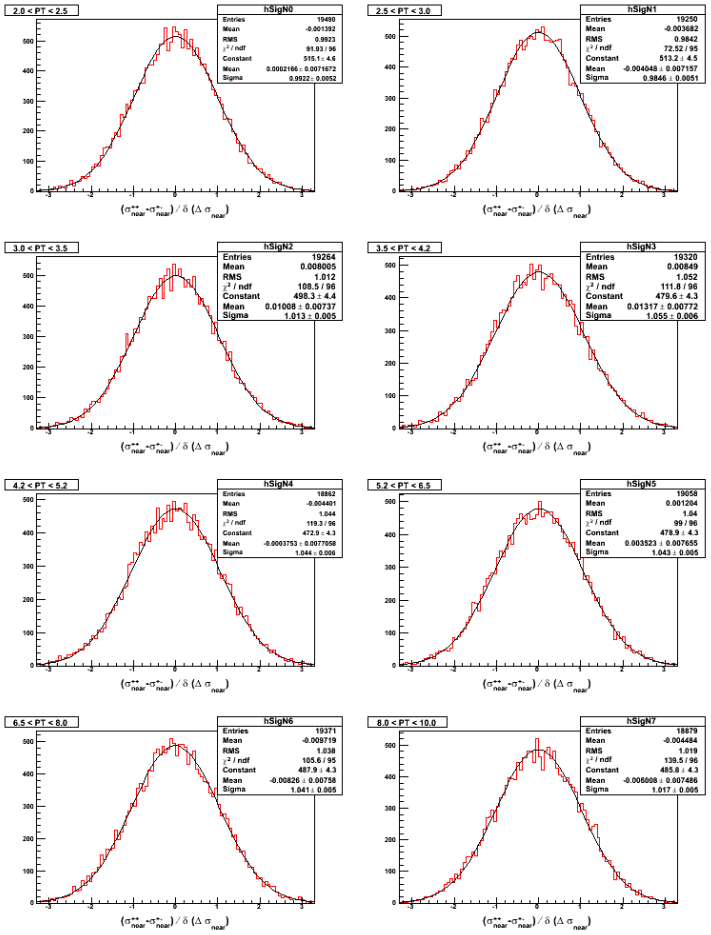
Bunch Shuffling (σ_{near})

- σ_{near}/ $\delta\sigma_{near}$
- Mean consistent with zero and width consistent with 1.

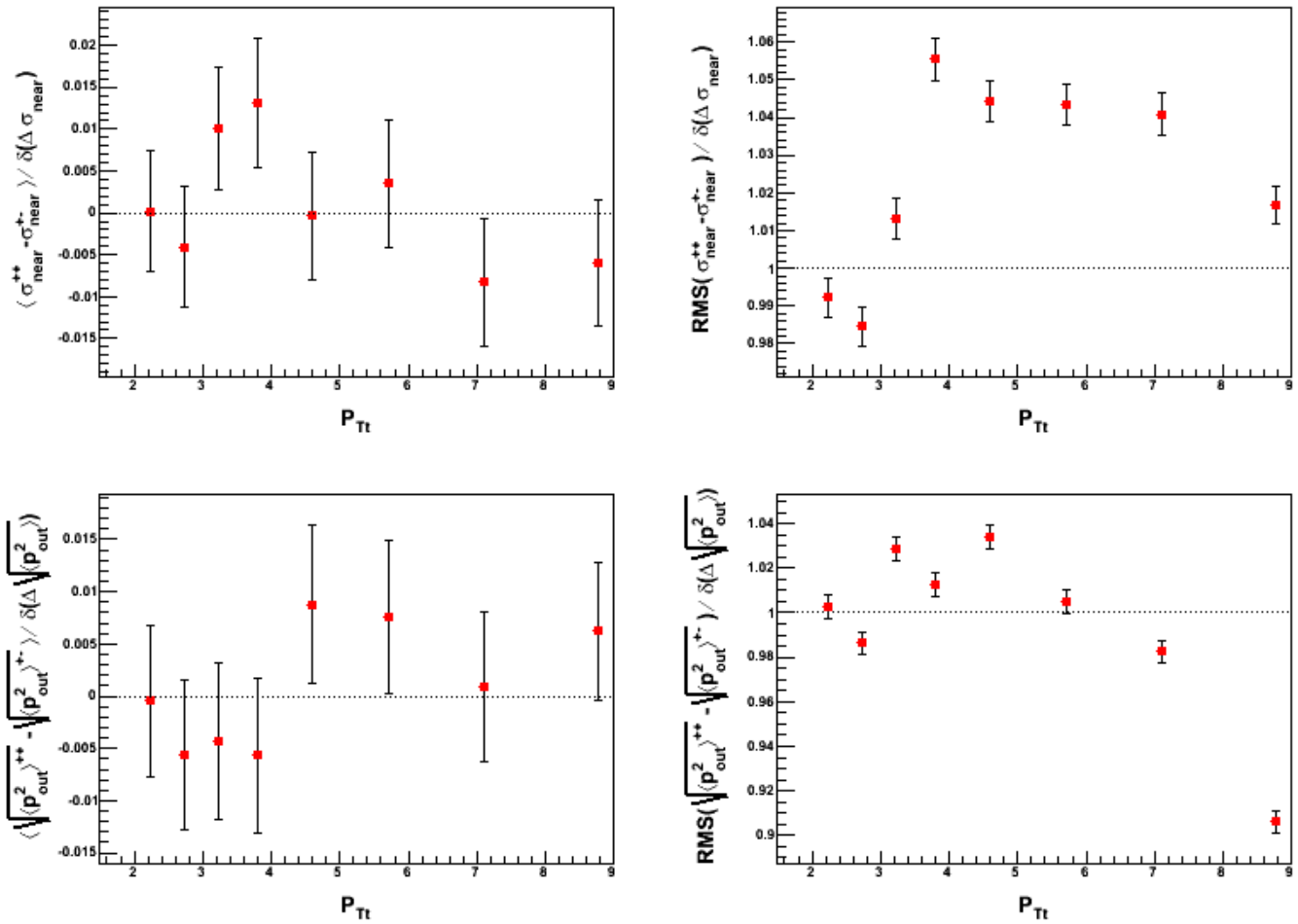


Bunch Shuffling (p_{out})

- $p_{out} / \delta p_{out}$
- Mean consistent with zero and width consistent with 1.



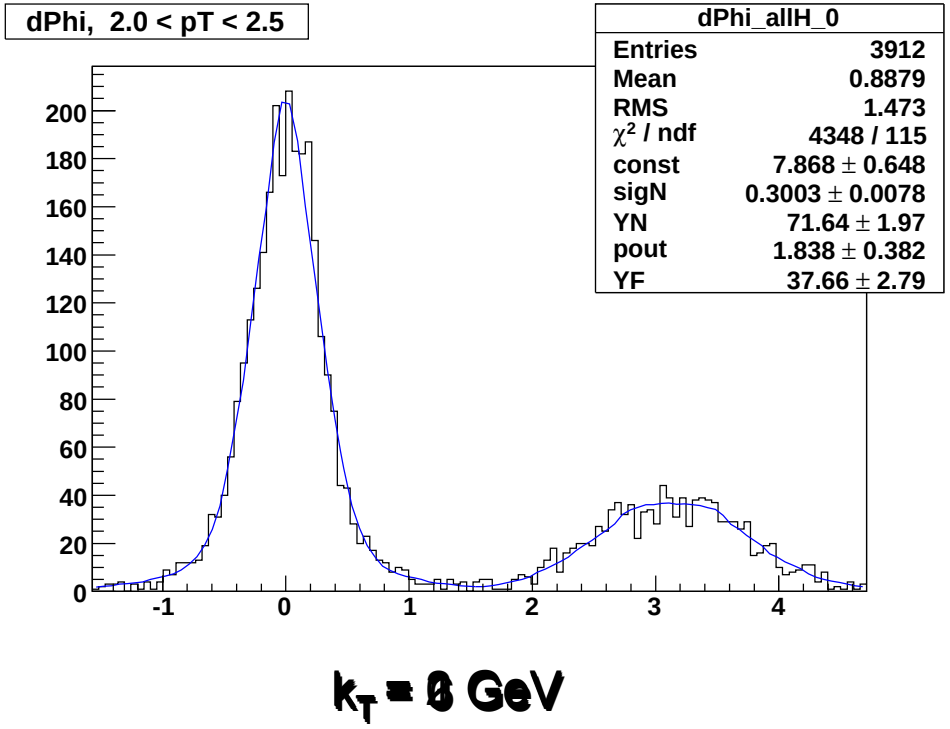
Bunch Shuffling Summary



p_{out} as a Function of k_T

- Can see the trend of the far-side width becoming larger with input k_T.
- At the largest k_T, the method may become unreliable since the two gaussians begin to overlap.

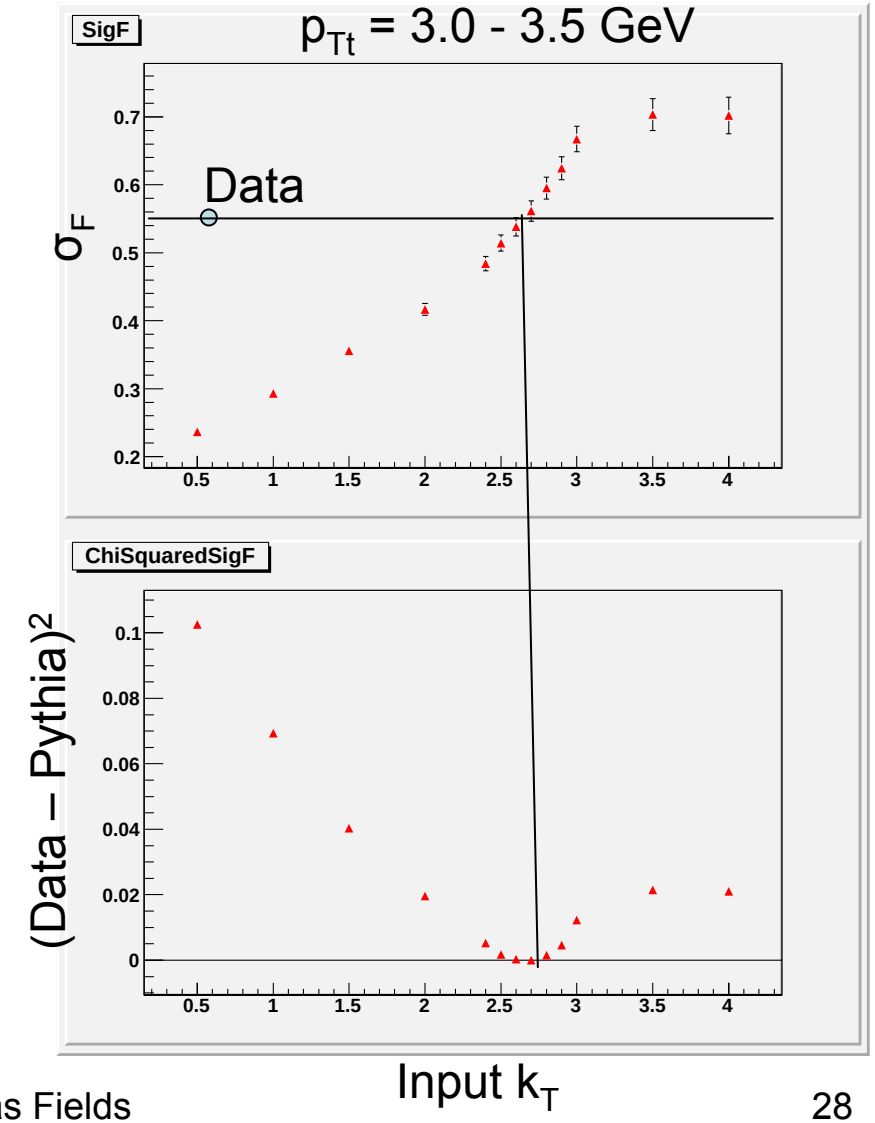
p_{Tt} = 2.0 - 2.5 GeV



k_T = 0 GeV

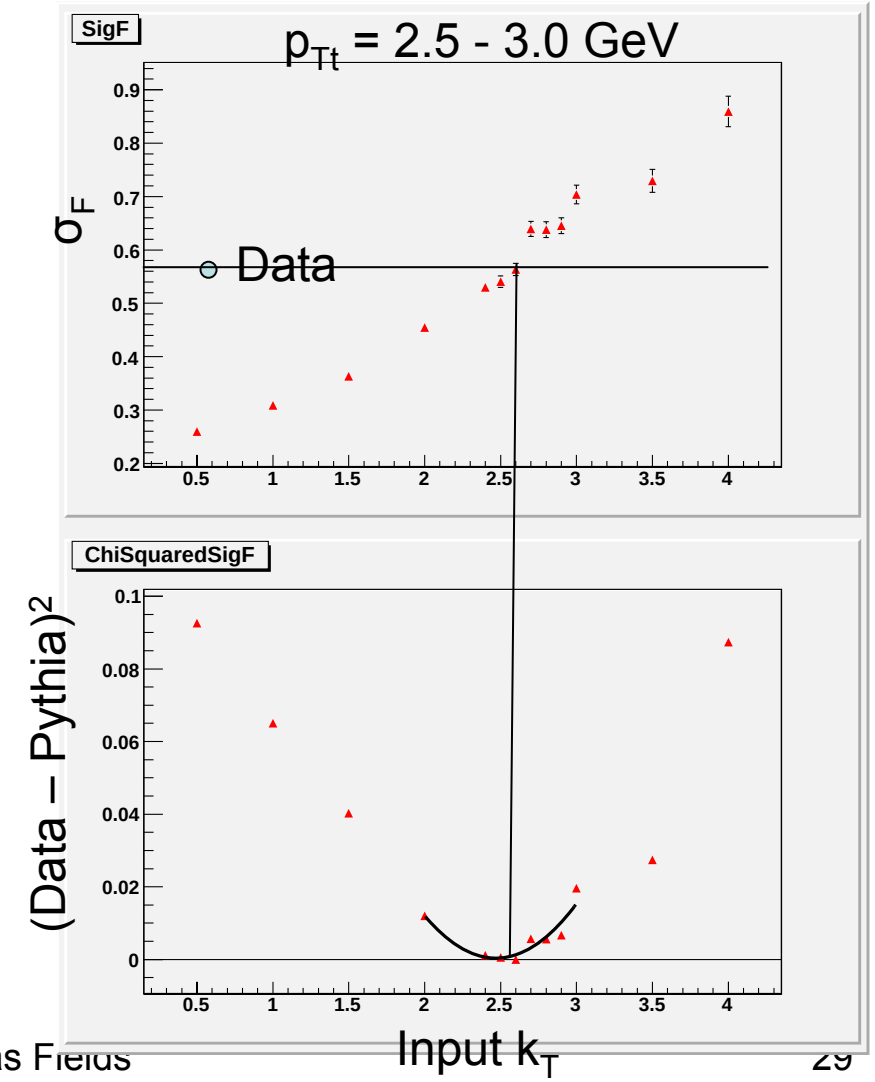
Compare to Data

- Plot of values of σ_F as k_T varies. There are eight such plots, each for a different range of p_{Tt}.
- Below, a comparison of σ_F from the simulation to σ_F of run 5 data. The minimum corresponds to the input k_T that best matches the data σ_F.



Compare to Data

- To find the minimum, each plot was fitted with a second order polynomial: $a + bx + cx^2$
- Here the fit can be seen between values of $k_T = 2$ GeV and $k_T = 3$ GeV.



Comparison to Data Results

- The final results are eight minima, one for each range of p_{Tt}.
- The mean of these minima gives a k_T of about 2.60 +/- .150 GeV, which is consistent with the k_T result extracted directly from the data (ppg029).

Pt bin	Minimum
2.0-2.5	2.659
2.5-3.0	2.469
3.0-3.5	2.6164
3.5-4.5	2.414
4.5-5.5	2.5828
5.5-6.5	2.5408
6.5-7.5	2.646
7.5-9.0	2.8427

Mean = 2.596 +/- * ~.150GeV
Data mean ~ 2.68GeV (ppg029)

* Estimated, not calculated