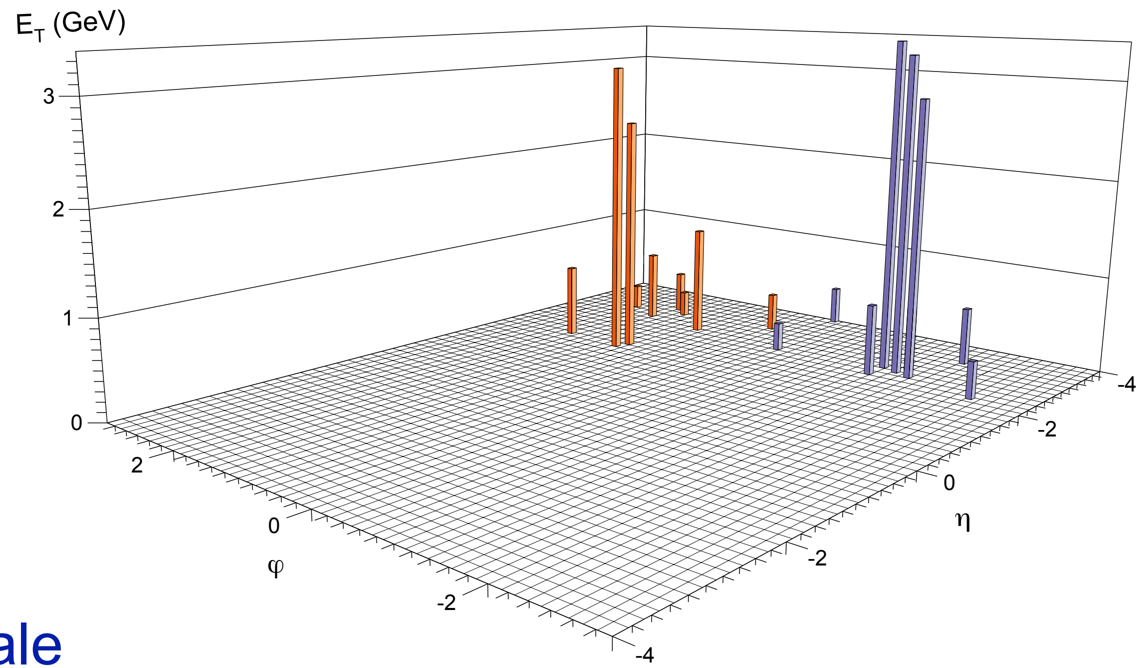
Elliptic Azimuthal Anisotropy in Dijet Production



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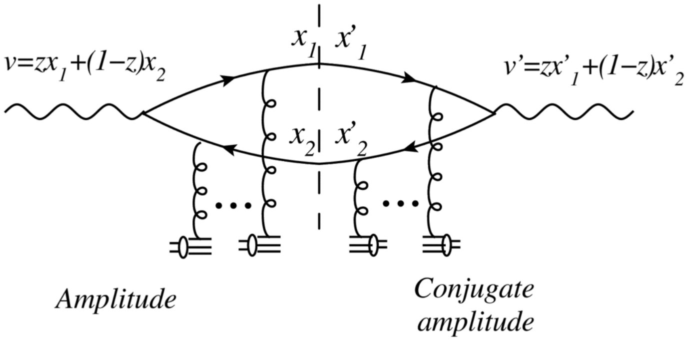
What Is It About?

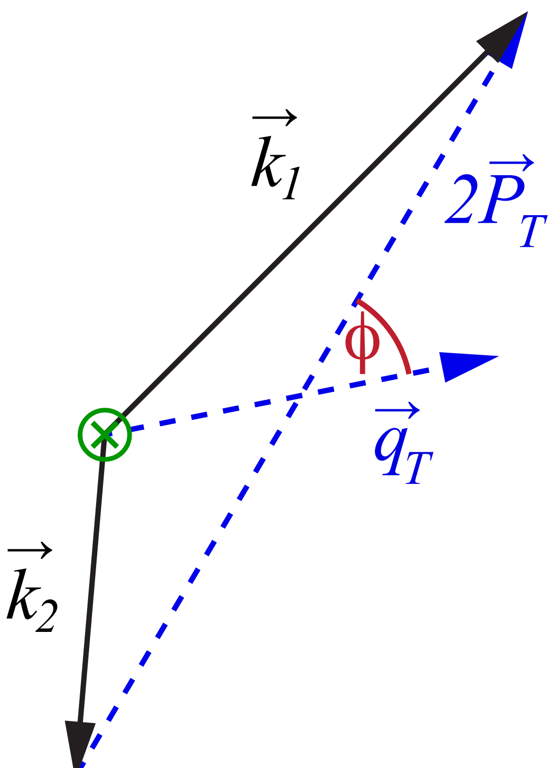
- Thus far, focus on quark TMDs while the available studies of gluon TMDs are sparse
- Of particular interest: WW distribution of linearly polarized gluons inside an unpolarized hadron, $\mathbf{h_T^{(1)}}$
- These gluon distributions play also central role in small-x saturation phenomena.

$h_T^{(1)}$ can be accessed through measuring azimuthal anisotropies in processes such as **jet pair (dijet) production** in e+p and e+A scattering.

A. Metz and J. Zhou, Phys. Rev. D84 , 051503 (2011), arXiv:1105.1991.
D. Boer, P. J. Mulders, and C. Pisano, Phys. Rev. D80 , 094017 (2009), arXiv:0909.4652
D. Boer, S. J. Brodsky, P. J. Mulders, and C. Pisano, Phys. Rev. Lett. 106 , 132001 (2011), arXiv:1011.4225.
F. Dominguez, J.-W. Qiu, B.-W. Xiao, and F. Yuan, Phys. Rev. D85 , 045003 (2012), arXiv:1109.6293.
A. Dumitru, L. McLerran, and V. Skokov, Phys. Lett. B743 , 134 (2015), arXiv:1410.4844.
A. Dumitru and V. Skokov, Phys. Rev. D91 , 074006 (2015), arXiv:1411.6630.
A. Dumitru, T. Lappi, and V. Skokov, Phys. Rev. Lett. 115 , 252301 (2015), arXiv:1508.04438.
A. Dumitru and V. Skokov, Phys. Rev. D94 , 014030 (2016), arXiv:1605.02739.

Kinematics: Dijets in γ*A



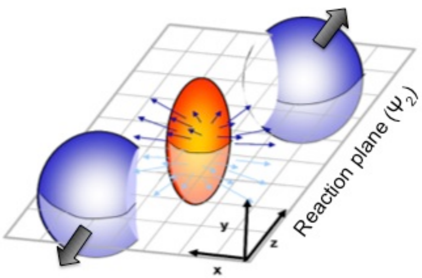


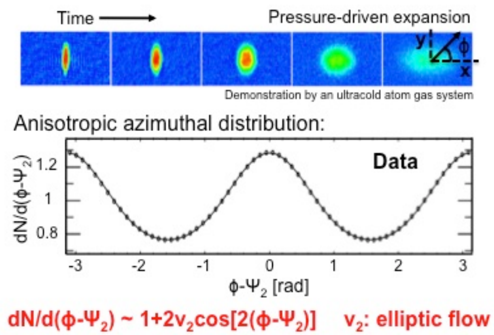
Key observables: P_T and q_T

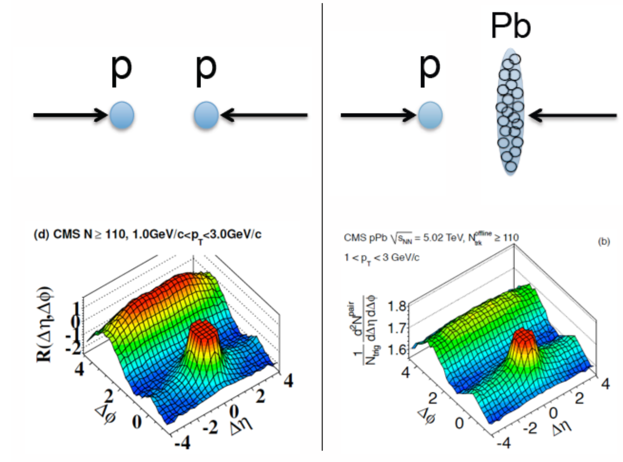
- the difference in momenta (imbalance)
  $$\vec{q}_T = \vec{k}_1 + \vec{k}_2$$
- the average transverse momentum of the jets
  $$\vec{P}_T = (1-z)\vec{k}_1 - z\vec{k}_2$$
- ϕ is angle between P_T and q_T
- This study: work in “correlation limit” $P_T >> q_T$

Dominguez, Marquet, Xiao, Yuan, PRD 2011

Anisotropy (v_2)

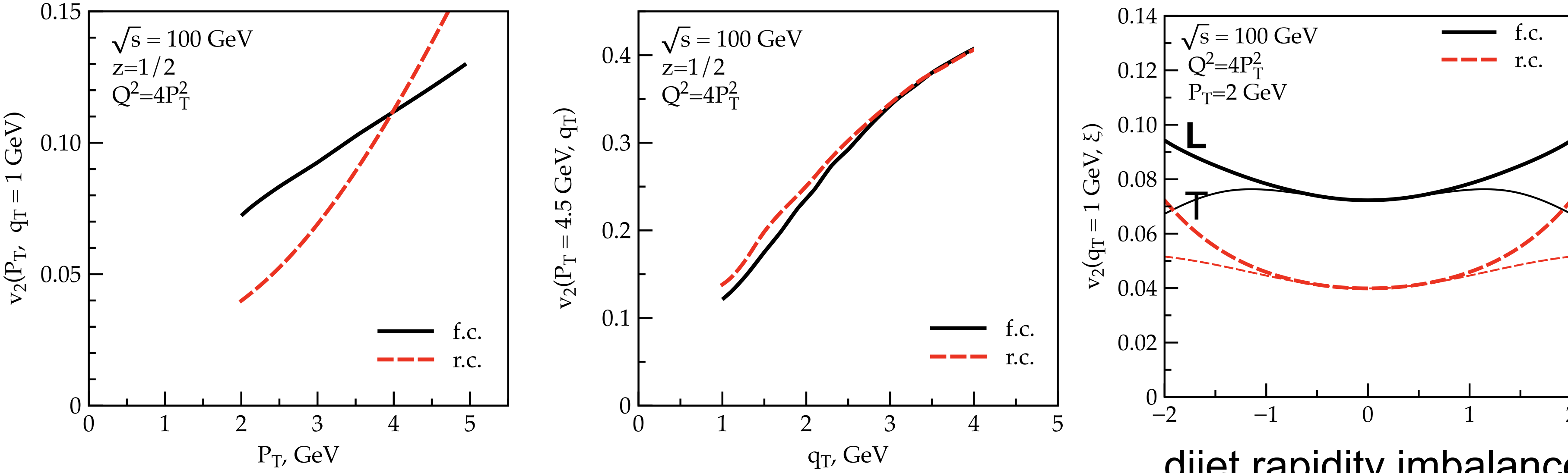






- RHIC: Strong elliptic flow in A+A established presence of QGP. LHC: p+p and p+Pb collisions revealed long-range near-side azimuthal angular correlations in high multiplicity events.
- They are quantified by $v_2 = \langle \cos 2\phi \rangle$
- Dijet production in e+A at high energies originates from long-ranged eikonal interactions ⇒ parameterizing the azimuthal structure arising from the linearly polarized gluon distribution also in terms of v_2

Theory Prediction: Substantial v_2



dijet rapidity imbalance
ξ = log(1-z)/z

- Studies on parton level
  - substantial v_2 (> 10%)
  - different v_2 for long. and trans. polarized γ^*
- Goal:

$$v_2^L = \frac{1}{2}\frac{h_\perp^{(1)}(x,q_\perp)}{G^{(1)}(x,q_\perp)} \quad , \quad v_2^T = -\frac{\epsilon_f^2 P_\perp^2}{\epsilon_f^4 + P_\perp^4}\frac{h_\perp^{(1)}(x,q_\perp)}{G^{(1)}(x,q_\perp)}$$

A. Dumitru, T. Lappi, V. Skokov, Phys. Rev. Lett. 115 (2015) no.25, 252301

Theory → Experiment (EIC)

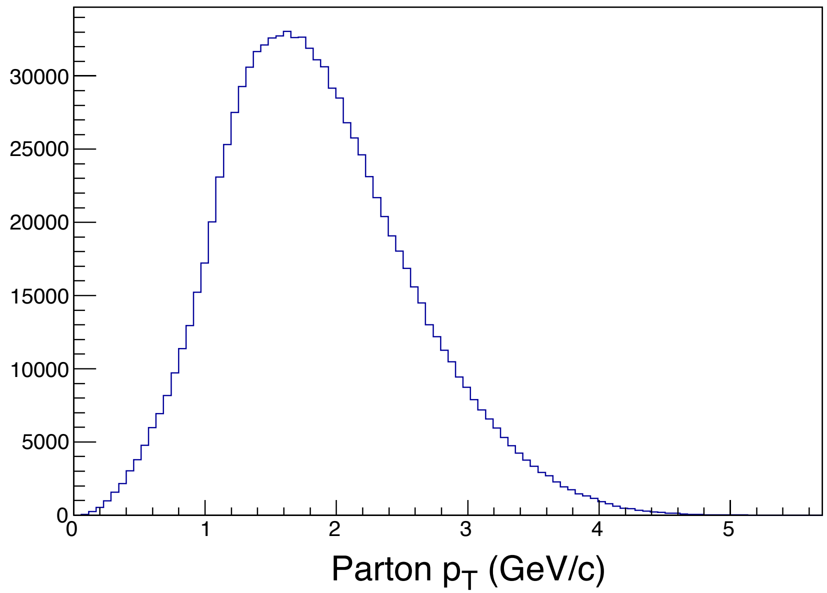
Theory	Experiment
parton level	jets does v_2 survive showering and jet finding?
no backgrounds	various background sources, does signal survive?
γ^*: L and T distinguished	Cannot experimentally distinguish L and T
both partons $\eta > 0$	Does jet kinematics reflect original parton directions

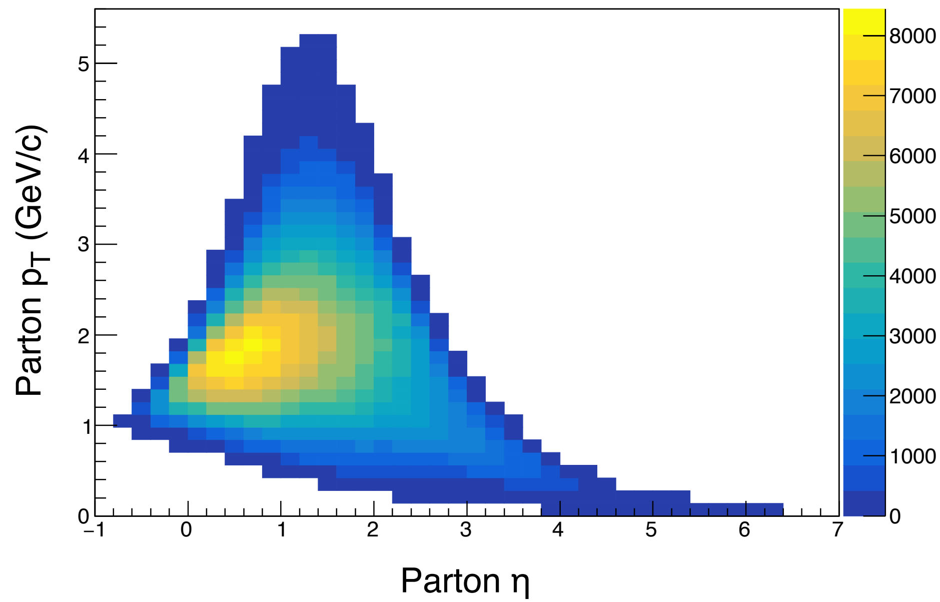
Exciting theory but need to show that measurement is feasible

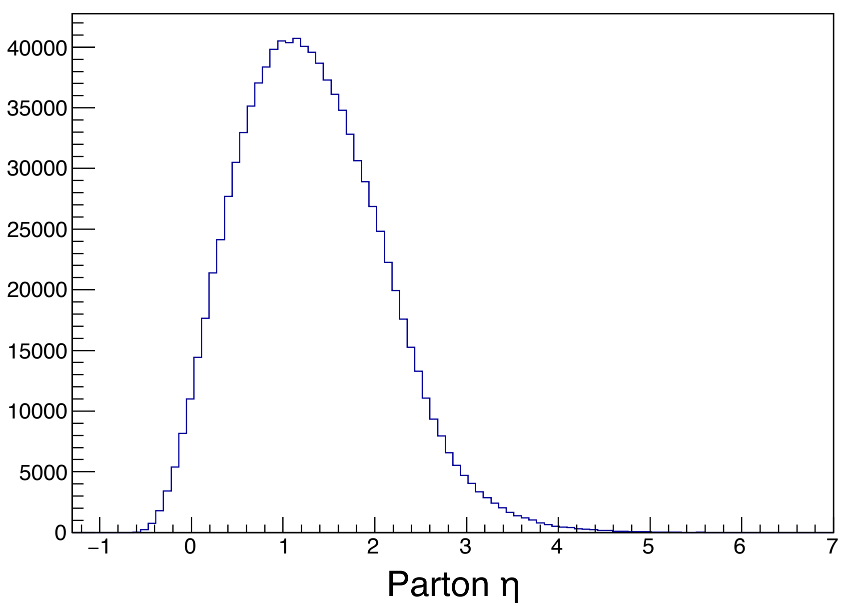
Simulations: Event Generation

- Event generator: MCDijet
  - V. Skokov, A. Dumitru, TU, https://github.com/vskokov/
  - $q\bar{q}$ dijet at LO in eA collisions
  - Determines the distribution of linearly polarized gluons of a dense target at small-x by solving the B-JIMWLK renormalization evolution equation
  - Output:
    - x, Q^2, ….
    - partons $\mathbf{p}_1$, $\mathbf{p}_2$
- Parton showering → Jets: Pythia8
  - input: $q\bar{q}$ pair
  - output: Pythia event record

Parton Kinematics

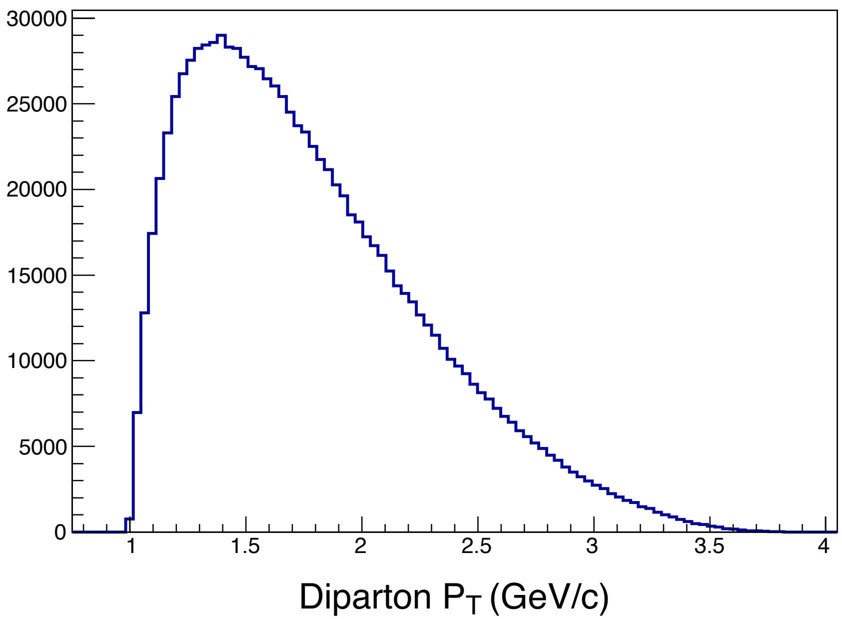


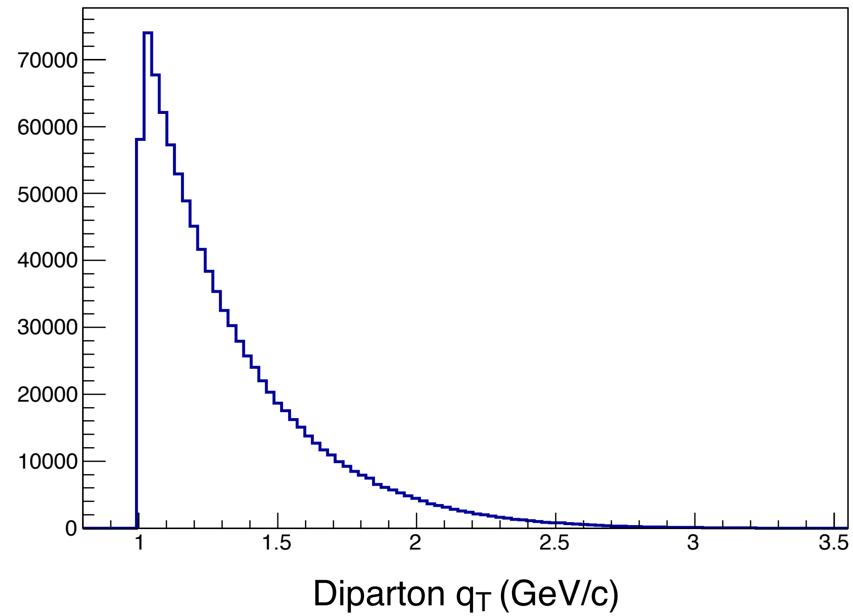




- Here: $\sqrt{s}$ = 90 GeV e+Au
- $4 < Q^2 < 81$ GeV^2
- Partons
  - $p_T < 5$ GeV/c, $\langle p_T \rangle \sim 1.8$ GeV/c
  - $0 < \eta < 3$
- Not optimal for jet finding

Diparton Kinematics



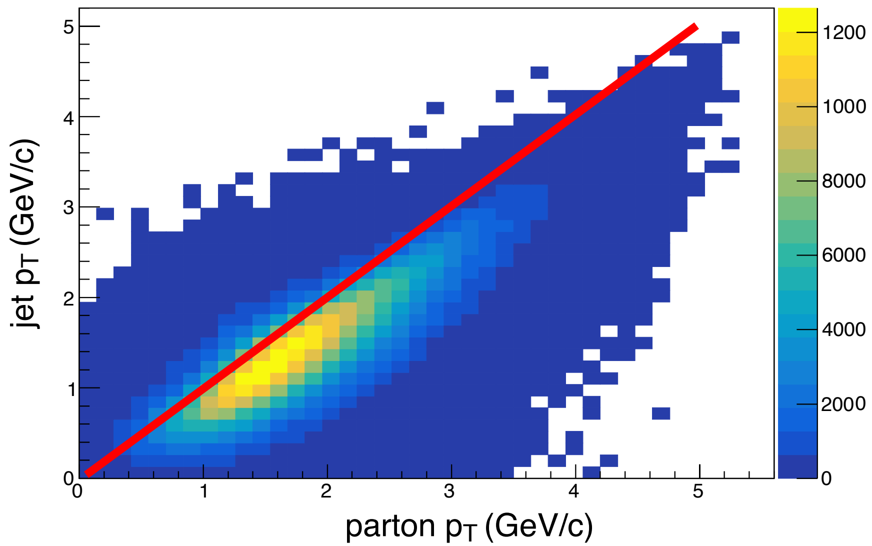


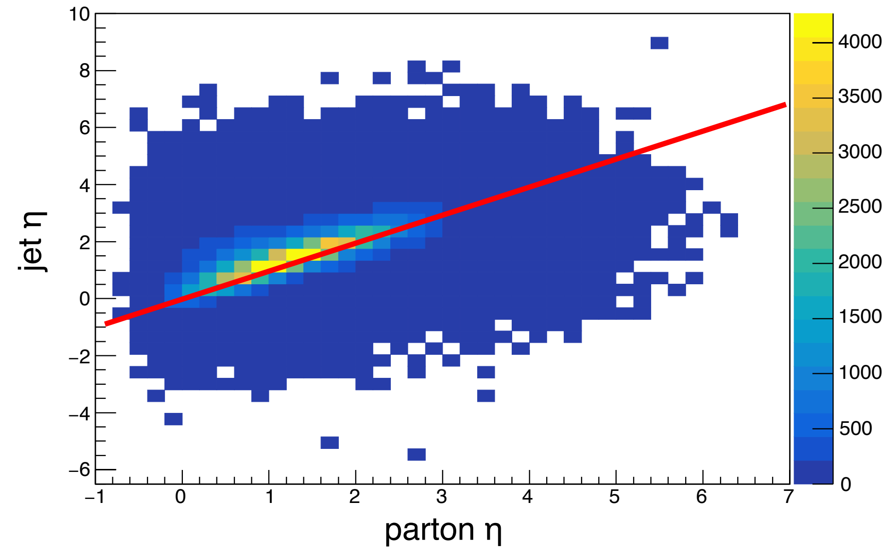
- Bulk $P_T < 3.5$ GeV/c and $q_T < 2$ GeV/c
- Correlation limit $P_T \gg q_T$ does cost lots of signal
- Note, cross-section and efficiencies do not matter (to some extent) only anisotropy

Jet Finding

- Standard jet finding package: FastJet
- Clean environment ⇒ R_{jet}=1
- Accept hadrons, p_T > 250 MeV/c
- Problem: two forward jets with low-moderate p_T
- Anti-kt algorithm **not** the right choice
  - ⟨#jets/event⟩ ~ 4.7
  - Comparison of parton with jet p_T, dijet q_T, P_T shows the algorithm is not up to the task
- ee-kt seems best of all available algorithms
  - Fixed number of jets, here 2
  - Future: combination of ee-kt and anti-kt with detailed comparison and QA

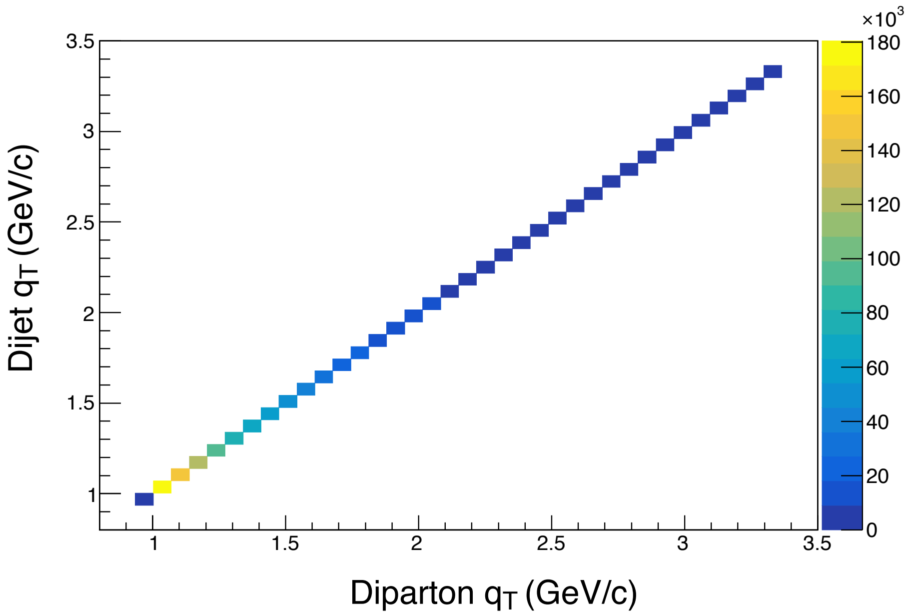
Jet - Parton Comparison

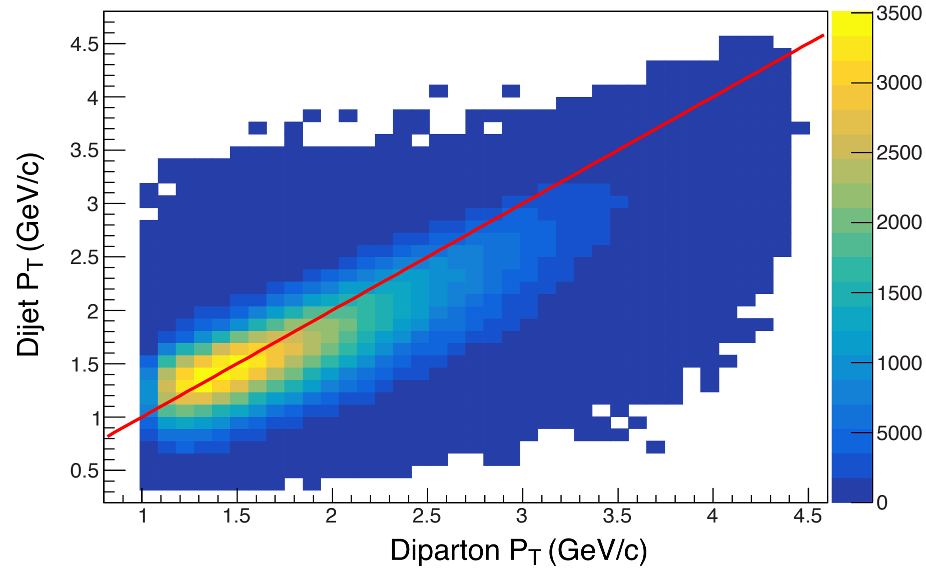




- Ok η match
- Obvious lower jet p_T than original parton
- Shift needs to be corrected by usual unfolding in “real” analysis. Beyond scope here.
- Poor man’s correction: add average E-loss to compensate

Dijet - Diparton Comparison

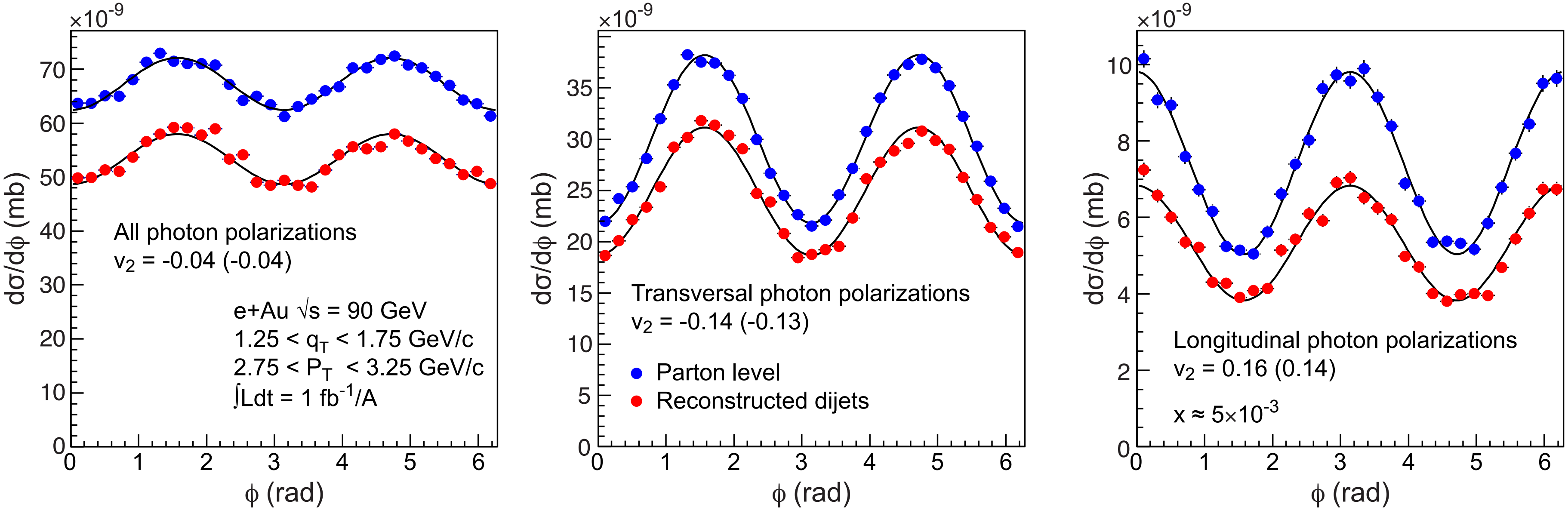




- Perfect q_T match due to ee-kt
- P_T matches quite well (unfolding would improve)

Elliptic Anisotropy

All polarizations | Trans. γ^* | Long. γ^*



- Here: eA $\sqrt{s}$=90 GeV, 1.25 < q_T < 1.75 GeV/c, 2.75 < P_T < 3.25 GeV/c
- Error bars scaled to 1 fb^{-1}/A, fluctuations due to limited MC stats
- Dijets recover the anisotropy (v_2) quite well
- Lower yield of jets due to uncorrected jet finding efficiency
  - doesn't matter as long it doesn't effect anisotropy
- NOTE: phase shift between long. and trans. γ^* (dominated by T)

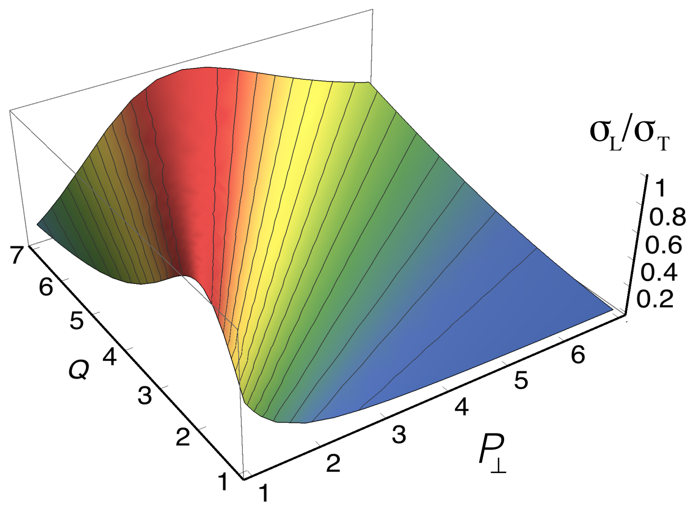
Disentangling L and T (I)

- Other than in diffractive exclusive J/ψ production, L and T cannot be separated easily
- However, essential to extract $h_T^{(1)}/G^{(1)}$

$$v_2^L = \frac{1}{2}\frac{h_\perp^{(1)}(x,q_\perp)}{G^{(1)}(x,q_\perp)} \quad , \quad v_2^T = -\frac{\epsilon_f^2 P_\perp^2}{\epsilon_f^4 + P_\perp^4}\frac{h_\perp^{(1)}(x,q_\perp)}{G^{(1)}(x,q_\perp)}$$

Several Methods available:

1. Using Q^2 and P_T dependence of L and T



- σ_L is negligible at small Q^2
- Bin data in Q^2 and P_T and study dependence

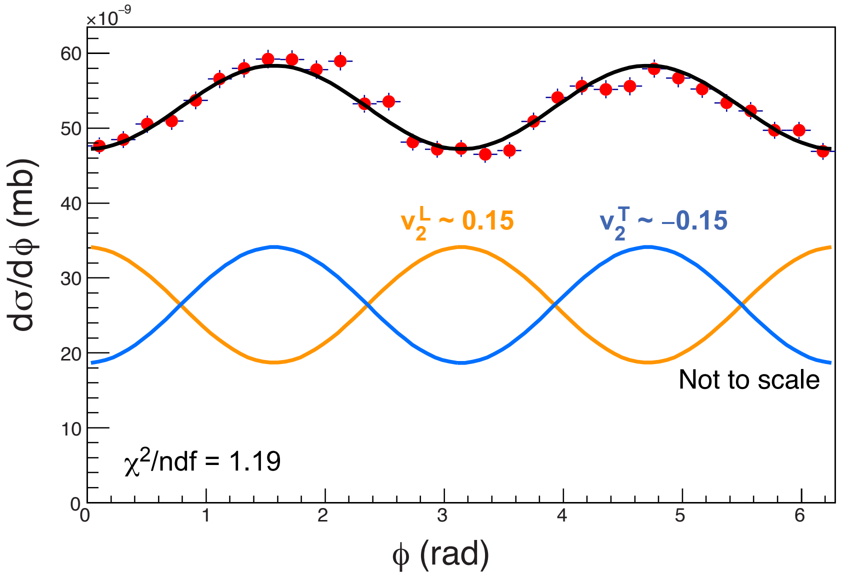
Disentangling L and T (II)

2. Use kinematic relation:

$$v_2^{\text{unpol.}} = \frac{R v_2^L + v_2^T}{1+R} \quad \text{where}$$

$$R = \frac{4z^2(1-z)^2\epsilon_f^2 P_T^2}{z(1-z)(z^2+(1-z)^2)(\epsilon_f^4 + P_T^4)} \quad \text{with} \quad \epsilon_f^2 = z(1-z)Q^2$$

Proof of principle from generated jet data:



- Fit dN/dφ with v_2^L and v_2^T as free parameter tied together by variable R
- Here no P_T, Q^2 binning, use average for proof of principle
- Sufficient leverage to disentangle L and T (true: $v_2^L \sim 0.14$ and $v_2^T \sim -0.14$)

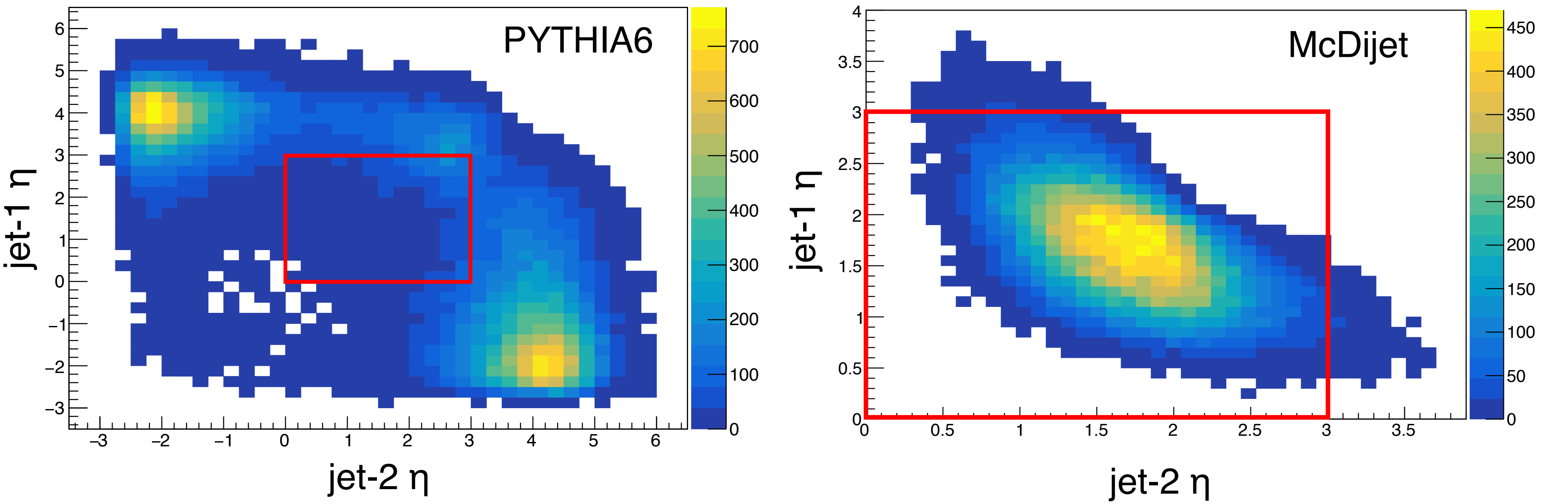
Background (I)

- Sources
  - physical background
  - artifacts by using *ee_kt* jet finder and enforcing two jets (fake jets)

- PYTHIA6 Simulations
  - Generate events with full suite of processes switched on
  - Same kinematic limits (Q^2, W,…) as McDijet (source generator)
  - Run through exactly same chain as McDijet

Background (II)

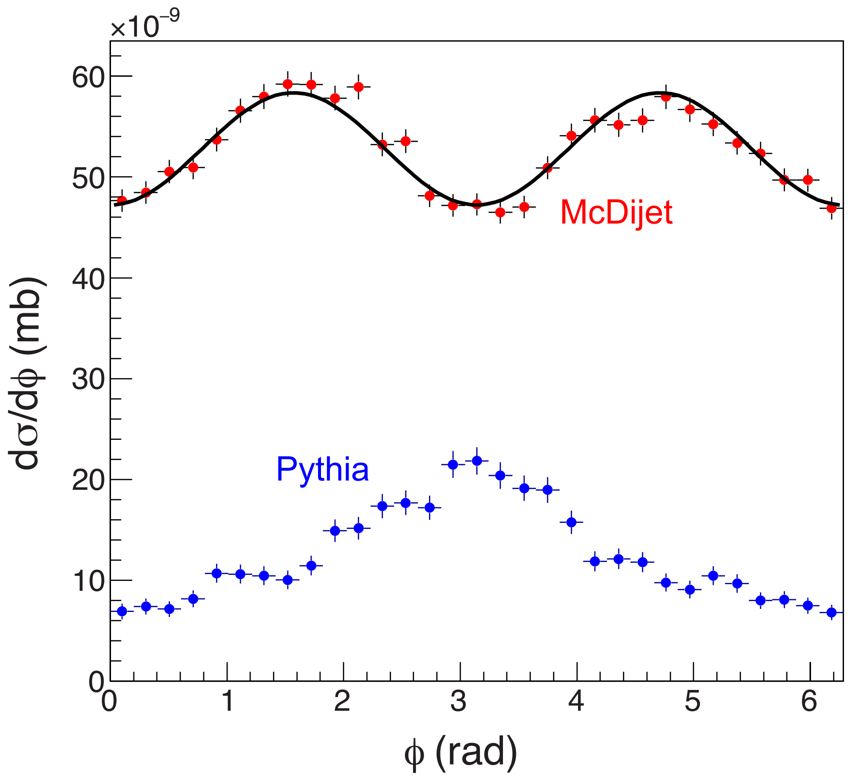
- Studying Background
  - Dijet distributions offer no obvious cuts in P_T, q_T
  - Key difference: rapidity dependence



- Pythia jets are more forward and dominantly $\eta_1 \cdot \eta_2 < 0$
- Require jets to be $0 < \eta < 3$
  - Signal loss 1-2%
  - Background reduction by factor 5

Factor 5 improvement in S/B

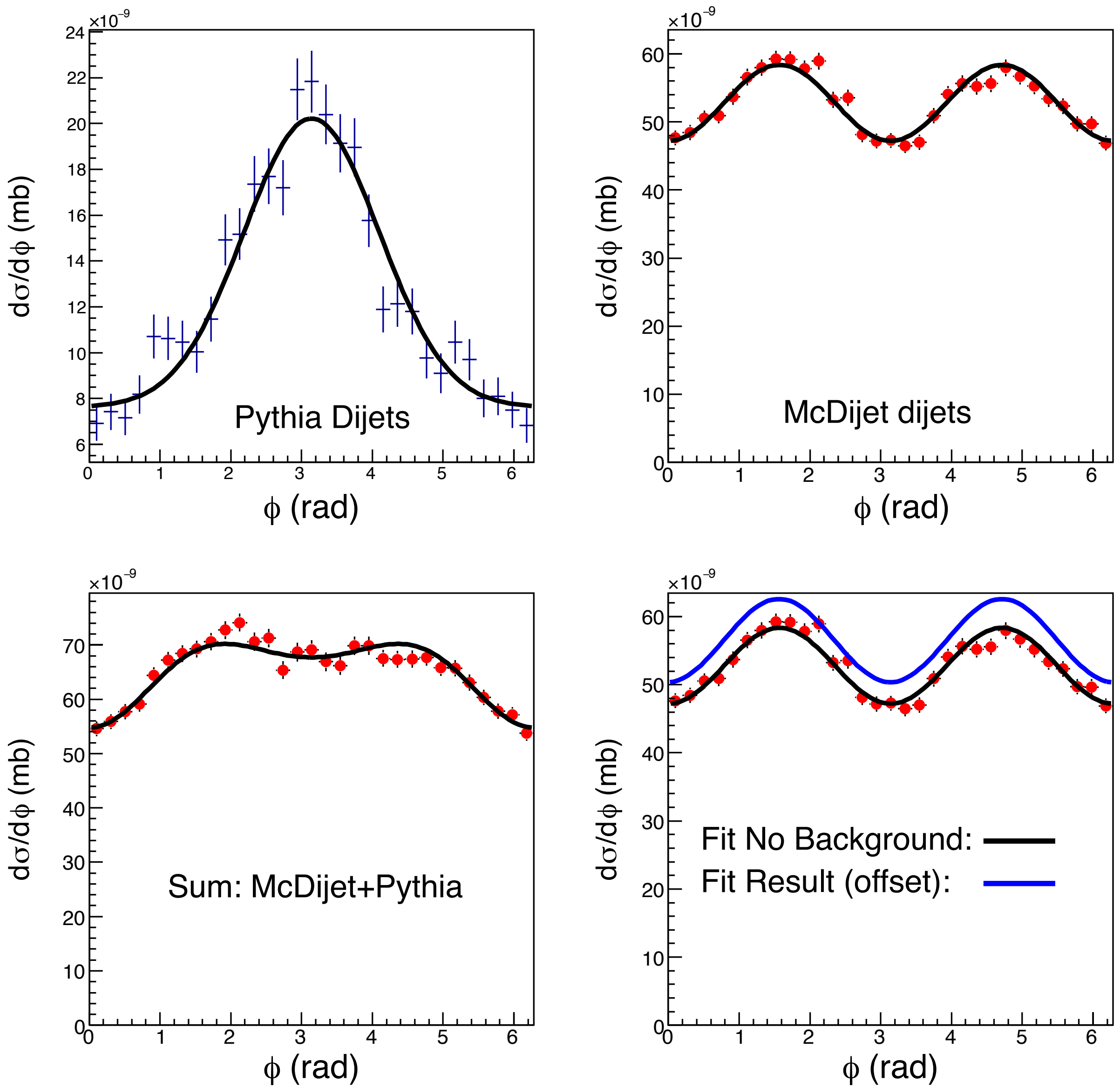
Background (III)



- Pythia & fake jet background is ~ 0.25 of that of signal.
- background shows no modulation but a broadened away-site peak
- Further QA cuts on jets may reduce the background further (to be checked)

- To subtract background need to know the shape quite well
  - simulations
  - ep events
- Proof of principle: assume Gaussian + const as free fit parameters

Background (IV)



- Fit works well
- v_2 within < 15%
- χ^2/ndf ~ 1.2

- Sufficient leverage to deal with backgrounds
- Further reduction of background through jet Q&A cuts and shape control

Summary

- Transverse momentum dependent (TMD) factorization in DIS predicts a distribution for linearly polarized gluons in an unpolarized target, $h_T^{(1)}$. This is reflected in an azimuthal anisotropy in dijet production, measured via v_2.
- Anisotropy is different for transverse (T) and longitudinal (L) polarized virtual photons
- First simulations show that the in eA an EIC can perform this challenging measurement
  - Can separate background from signal jet pairs
  - Can extract v_2^L and v_2^T

Measurement of v2 of dijets will give us this new TMD gluon distribution function which has not been measured so far.