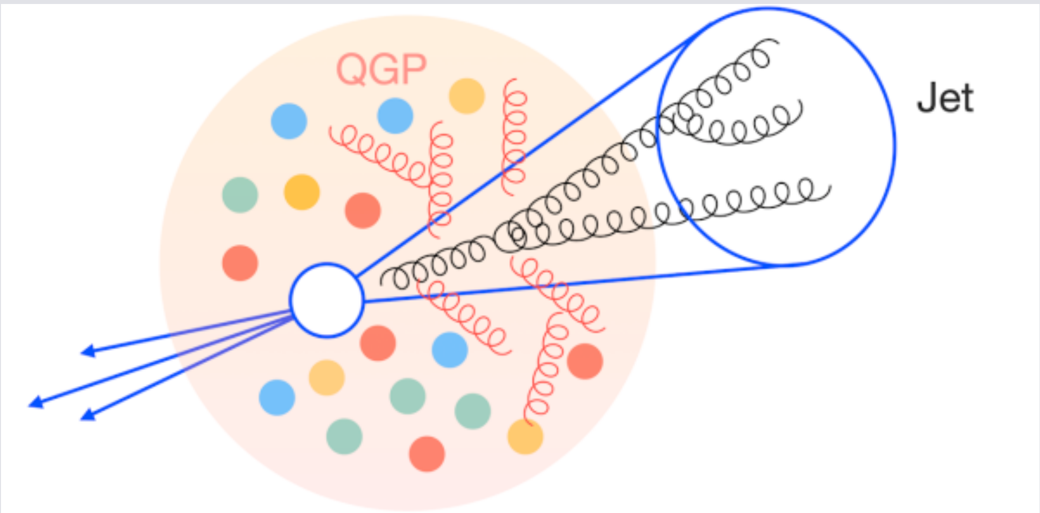


Azimuthal anisotropies at high-p_T in p-p and p-A collisions

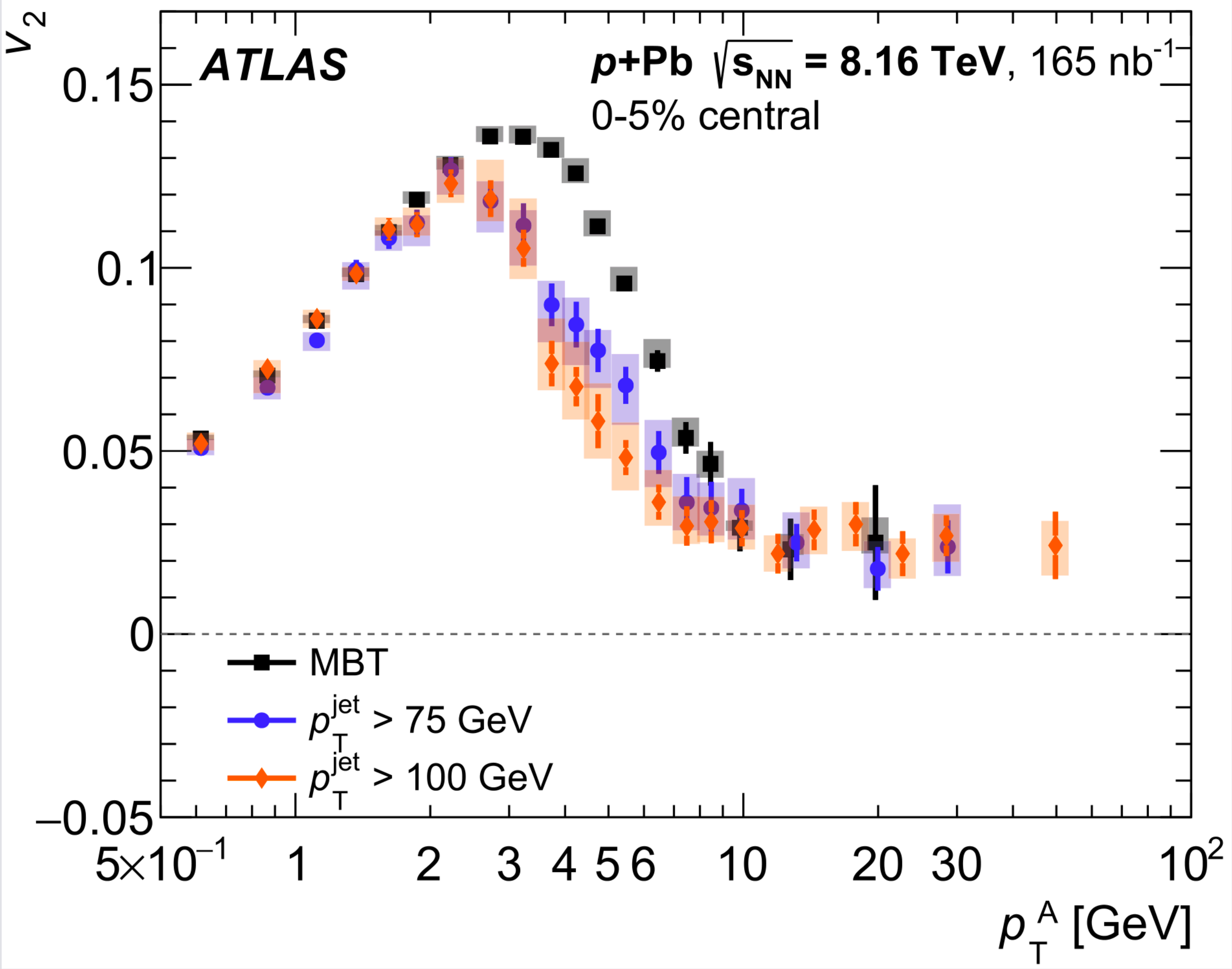
Ismail Soudi

Wayne State University

Based on IS and Abhijit Majumder ArXiv:2308.14702

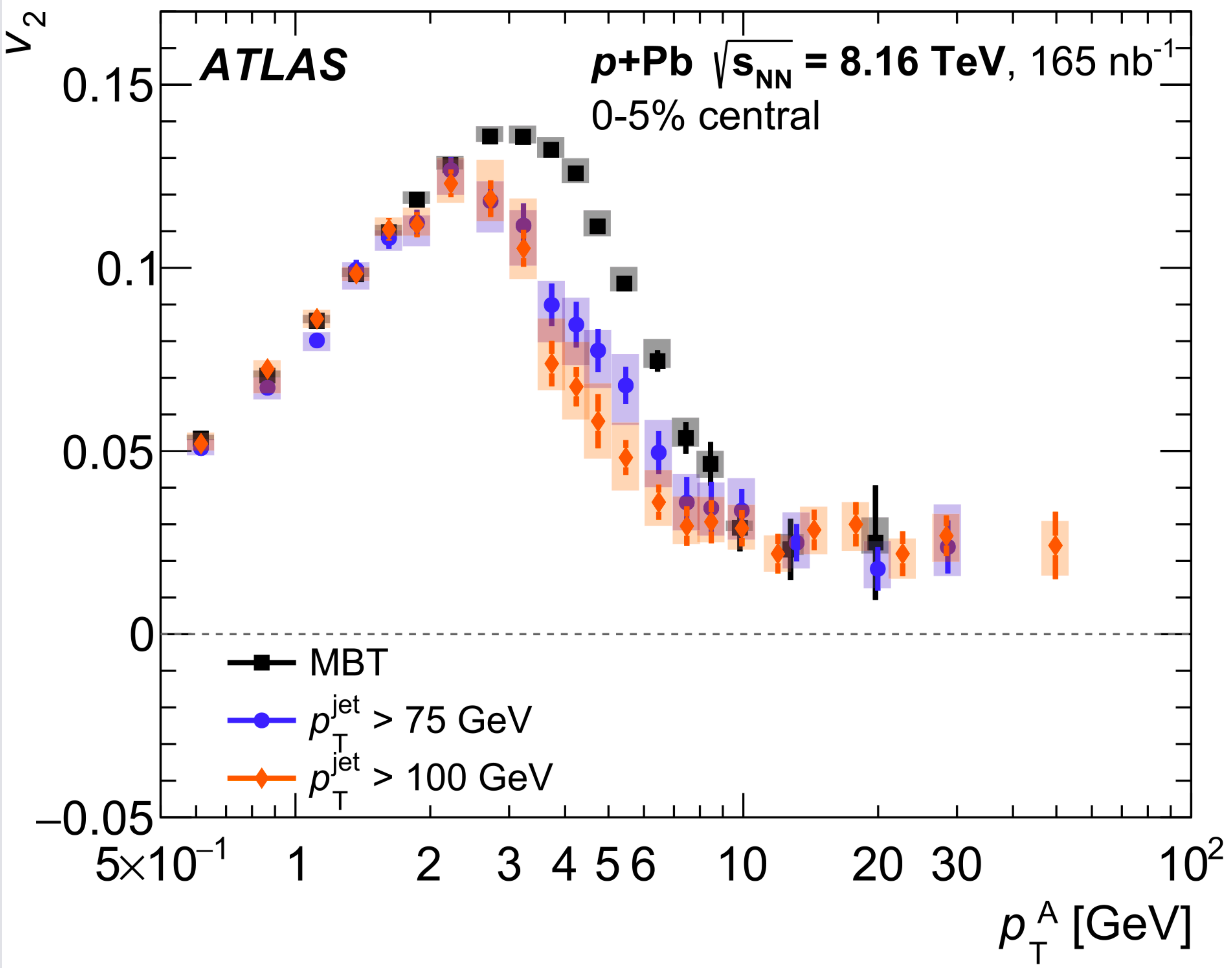
INSTITUTE for NUCLEAR THEORY, Seattle, WA

Small systems

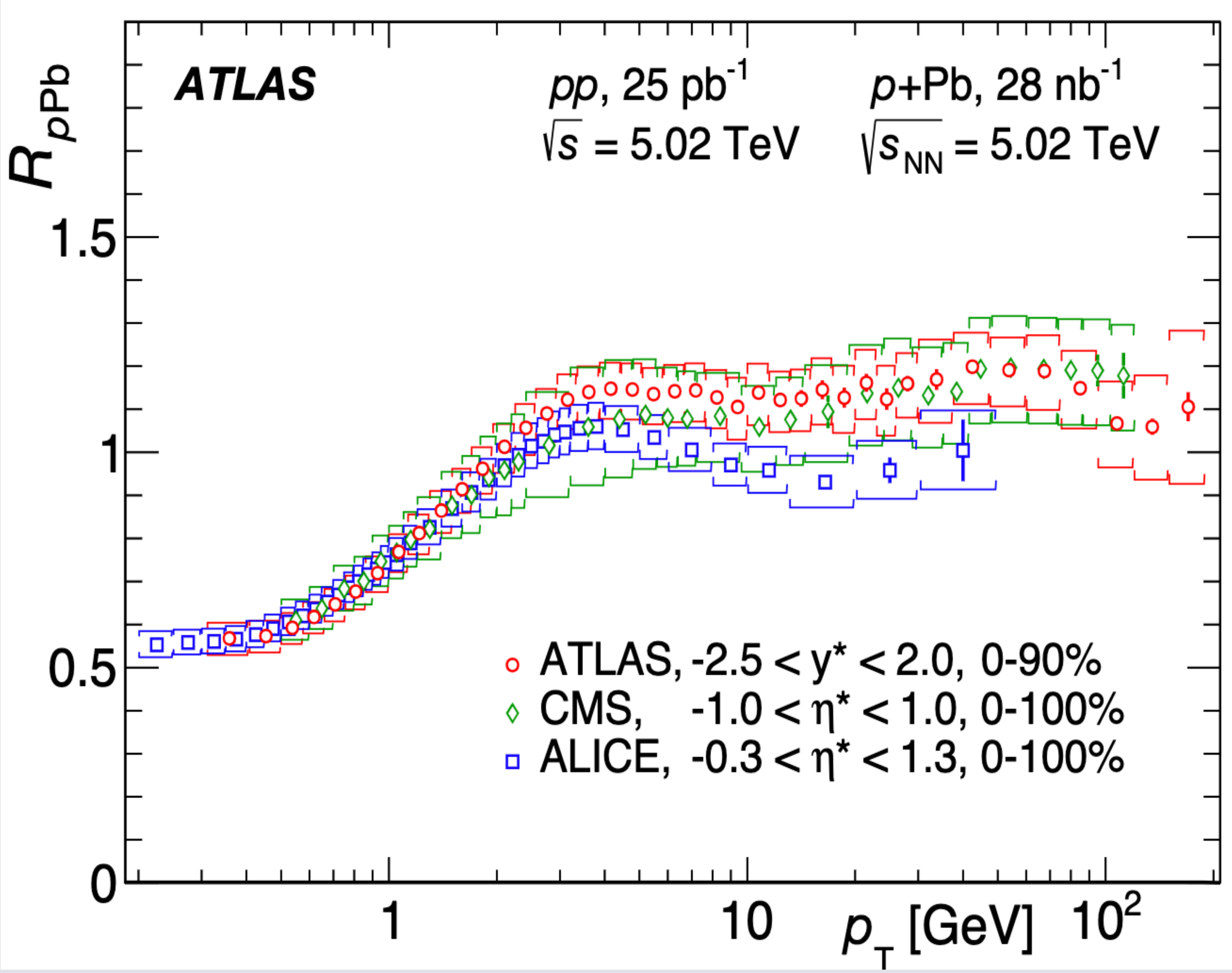


[ATLAS Eur. Phys. J. C 80 (2020) 73]

Small systems

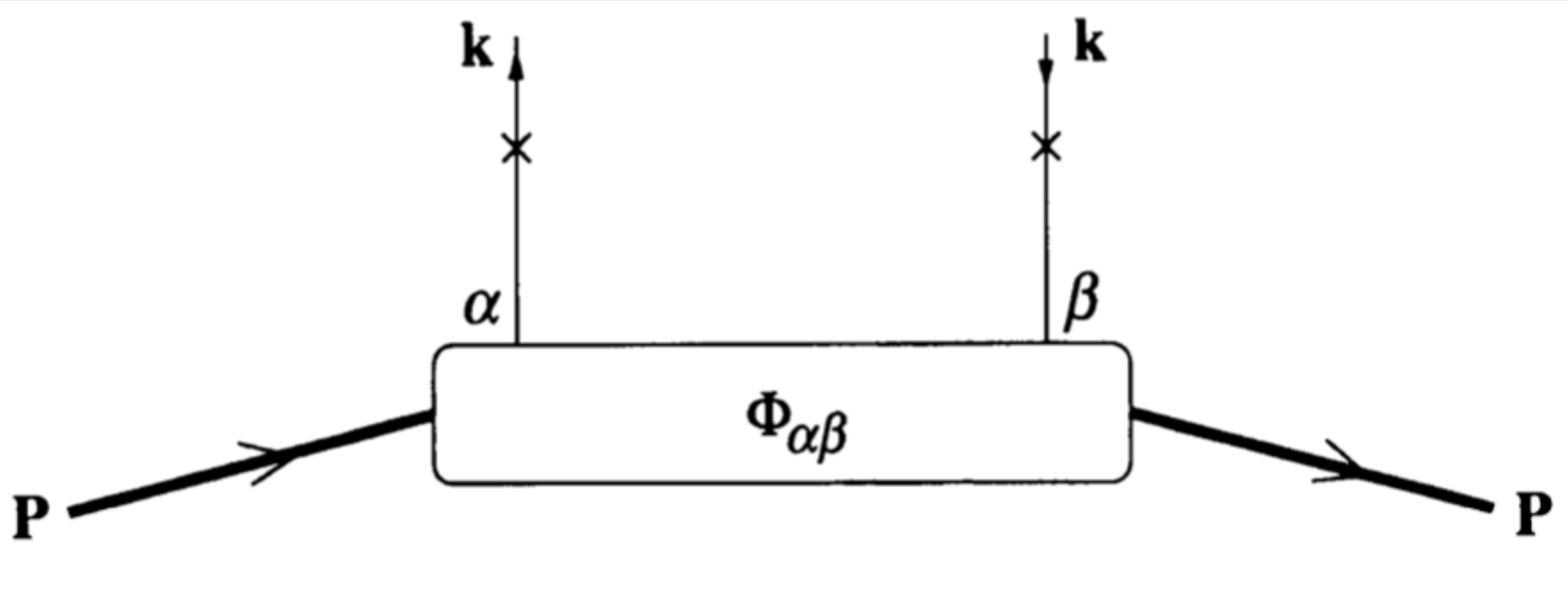


[ATLAS Eur. Phys. J. C 80 (2020) 73]



[ATLAS JHEP 07 (2023) 074]
[CMS JHEP 04 (2017) 039]
[ALICE JHEP 11 (2018) 013]

Collinear Factorization

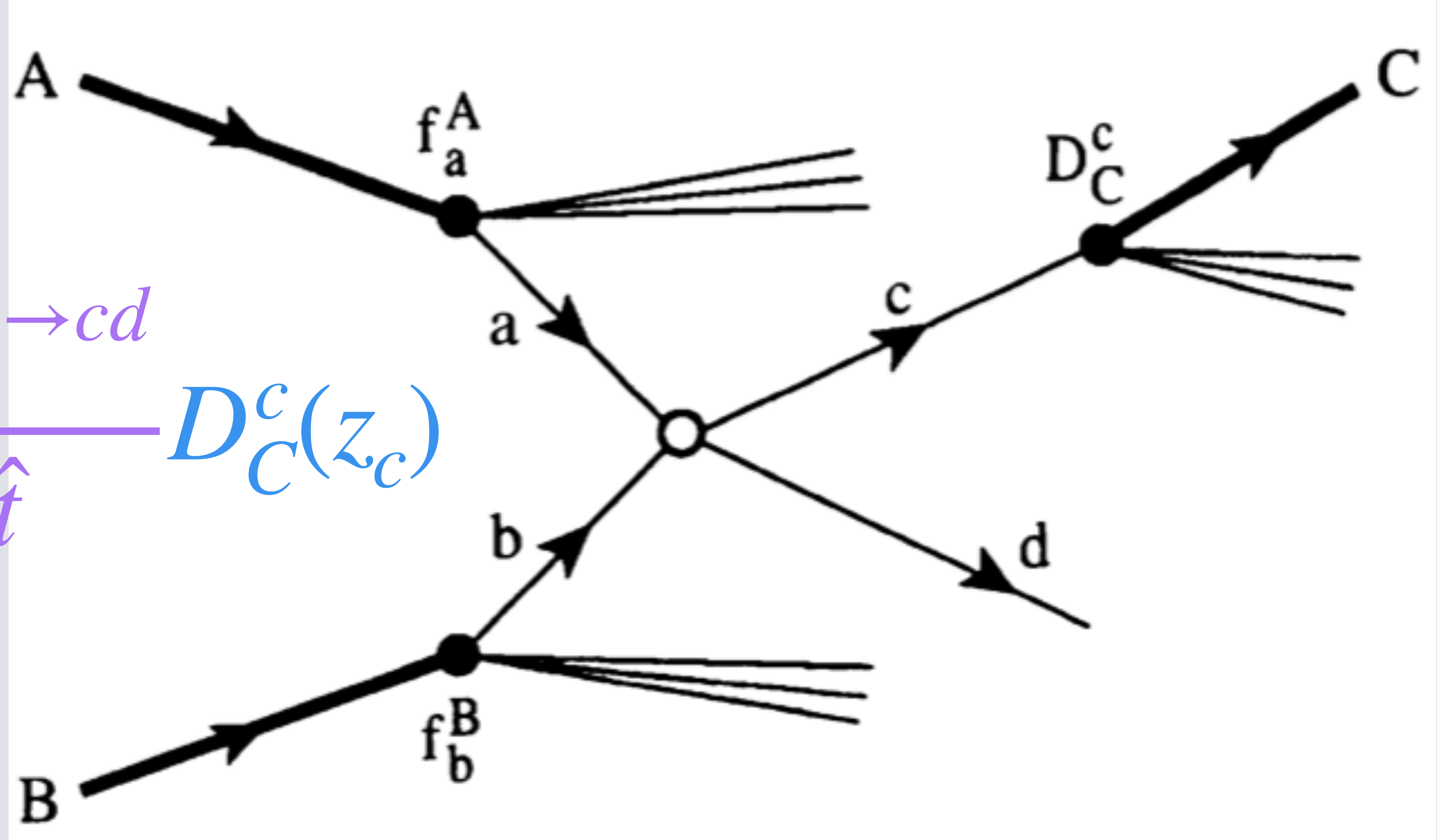


Partonic scattering

$$A^\alpha A^\beta \to \Phi_{\alpha\beta} \equiv \int d^3\xi \, \frac{e^{-ip\cdot\xi}}{(p^+)^2} \langle P, S \,|\, F^{-\mu}(\xi) F^{-\nu}(0) \,|\, P, S \rangle$$

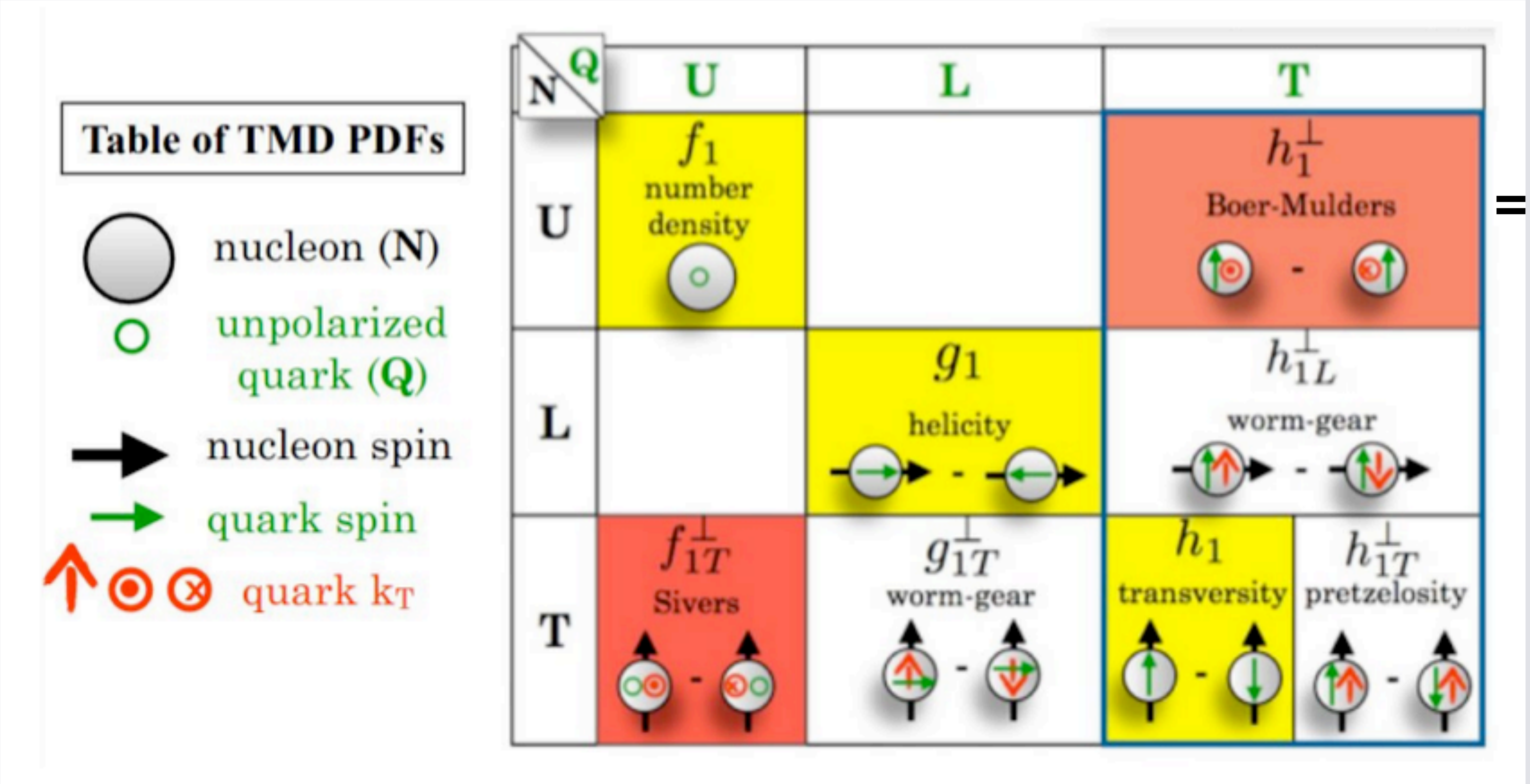
$\Rightarrow$ PDFs $\otimes$ FFs

$$E_C \frac{d^3\sigma}{d^3\mathbf{p}_C} = \frac{1}{\pi} \sum_{a,b,c,d} \int dx_a dx_b \, \hat{f}_a^A(x_a, Q^2) \hat{f}_b^B(x_b, Q^2) \frac{d\sigma^{ab\to cd}}{d\hat{t}} D_C^c(z_c)$$



[Fig from E. Leader(2011)]

Transverse Momentum Distributions

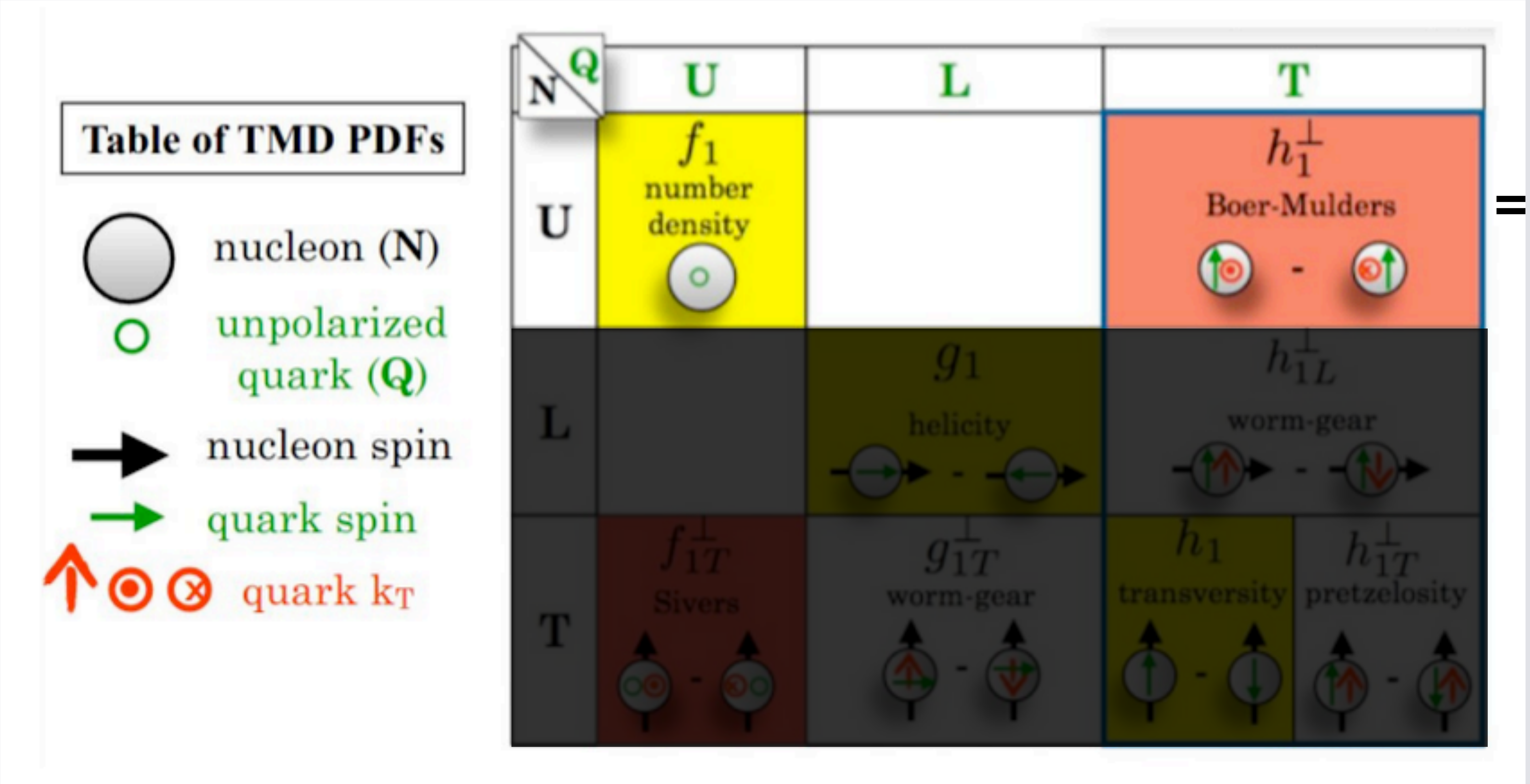


=>Collins

[Fig from PHENIX Spin Physics Overview]

[D. Boer, P. J. Mulders, J. C. Collins, J. Rodrigues, C. Pisano, S. J. Brodsky, M. Anselmino, M. Boglione, U. D'Alesio, E. Leader, D.W. Sivers, F. G. Celiberto…]

Transverse Momentum Distributions



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Transverse Momentum Distributions

Fierz decomposition of quark-quark correlator contains additional terms than the leading twist distributions

Γ_S	Γ_V^μ	$\Gamma_T^{\mu\nu}$	Γ_A^μ	Γ_P
I	γ^μ	$\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$	$\gamma^5\gamma^\mu$	$i\,\gamma^5$

$$X = x_\alpha \, \Gamma^\alpha = \frac{1}{4}\Gamma^\alpha \, \mathrm{Tr}\left(X\Gamma_\alpha\right)$$

Transverse Momentum Distributions

Unpolarized gluon inside unpolarized hadron

Linearly polarized gluon inside unpolarized hadron

Transverse Momentum Distributions

Gluon correlator

$$\Phi^{\alpha\beta} = \frac{1}{2x}\left\{ -g_T^{\alpha\beta} f^g(x, k_\perp) + \left(\frac{k_\perp^\alpha k_\perp^\beta}{M^2} + g_T^{\alpha\beta} \frac{k_\perp^2}{2M^2} \right) h^{\perp g}(x, k_\perp) \right\}$$

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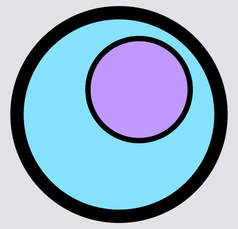
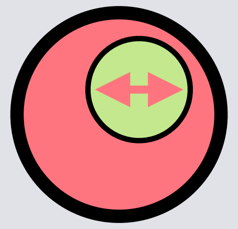
Linearly polarized gluon inside unpolarized hadron

Transverse Momentum Distributions

Gluon correlator





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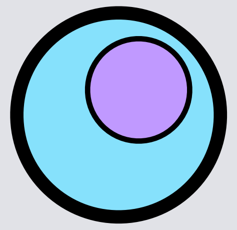
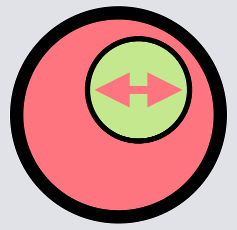
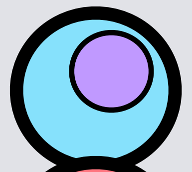
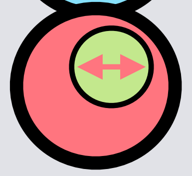
Unpolarized + Boer-Mulders/Collins





$$\Phi^{\alpha\beta}\epsilon_\alpha^{\lambda_1}(k)\epsilon_\beta^{\lambda_2 *}(k) = \frac{1}{2x}\left\{ \delta_{\lambda_1,\lambda_2} f^g(x, k_\perp) + \delta_{\lambda_1,-\lambda_2}\frac{k_\perp^2}{2M^2} h^{\perp g}(x, k_\perp) \right\}$$


Unpolarized gluon inside unpolarized hadron


Linearly polarized gluon inside unpolarized hadron

Ismail Soudi

Transverse Momentum Distributions

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$$\Phi^{\alpha\beta} = \frac{1}{2x}\left\{ -g_T^{\alpha\beta} f^g(x, k_\perp) + \left(\frac{k_\perp^\alpha k_\perp^\beta}{M^2} + g_T^{\alpha\beta} \frac{k_\perp^2}{2M^2} \right) h^{\perp g}(x, k_\perp) \right\}$$

Unpolarized + Boer-Mulders/Collins

$$\Phi^{\alpha\beta} \epsilon_\alpha^{\lambda_1}(k) \epsilon_\beta^{\lambda_2 *}(k) = \frac{1}{2x}\left\{ \delta_{\lambda_1,\lambda_2} f^g(x, k_\perp) + \delta_{\lambda_1,-\lambda_2} \frac{k_\perp^2}{2M^2} h^{\perp g}(x, k_\perp) \right\}$$

The Boer-Mulders/Collins flips helicity between amplitude and conjugate

Unpolarized gluon inside unpolarized hadron

Linearly polarized gluon inside unpolarized hadron

Spin-helicity formalism

Polarization sum

$$\sum_{\lambda} \epsilon_{\mu}^{\lambda}\epsilon_{\nu}^{\lambda *} \rightarrow -g_{\mu\nu}$$

$$\mathscr{M} \propto e^{i\lambda\phi}\,, \qquad \mathscr{M}^{\dagger} \propto e^{-i\lambda\phi}\,,$$

Phases drop-out of $|\mathscr{M}|^2$

Spin-Helicity flips

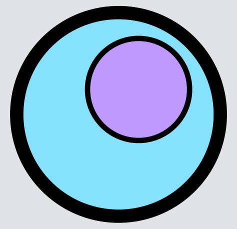
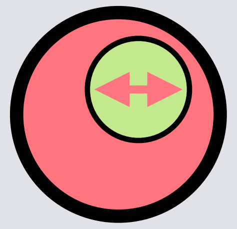
$$\sum_{\lambda_1\lambda_2} \epsilon_{\mu}^{\lambda_1}\epsilon_{\nu}^{\lambda_2 *} \rightarrow -g_{\mu\nu}$$

$$\mathscr{M} \propto e^{i\lambda_1\phi}\,, \qquad \mathscr{M}^{\dagger} \propto e^{-i\lambda_2\phi}\,,$$

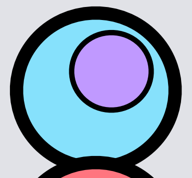
$$|\mathscr{M}|^2 \propto cos(\phi)$$

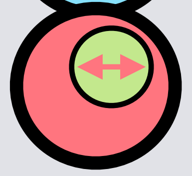
Only Maximum Helicity Violating (MHV) Amps are relevant

Transverse Momentum Distributions

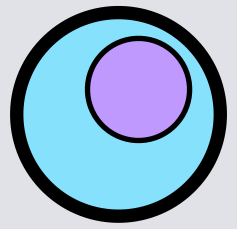
 

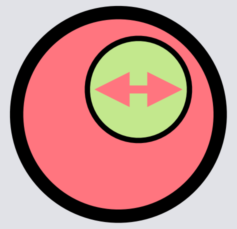
$$\Phi^{\alpha\beta}\epsilon_{\alpha}^{\lambda_1}(k)\epsilon_{\beta}^{\lambda_2 *}(k) = \frac{1}{2x}\left\{ \delta_{\lambda_1,\lambda_2} f^{g}(x, k_\perp) + \delta_{\lambda_1,-\lambda_2}\frac{k_\perp^2}{2M^2} h^{\perp g}(x, k_\perp) \right\}$$

 Unpolarized gluon inside unpolarized hadron

 Linearly polarized gluon inside unpolarized hadron

Transverse Momentum Distributions





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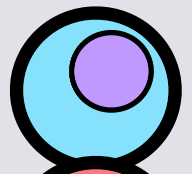
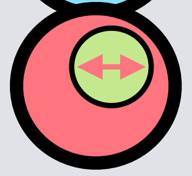
The Boer-Mulders/Collins flips helicity between amplitude and conjugate

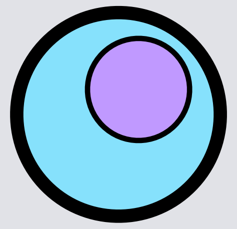
Requires two flips for unpolarized pion production

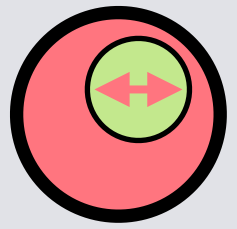

Unpolarized gluon inside unpolarized hadron


Linearly polarized gluon inside unpolarized hadron

Ismail Soudi

Transverse Momentum Distributions





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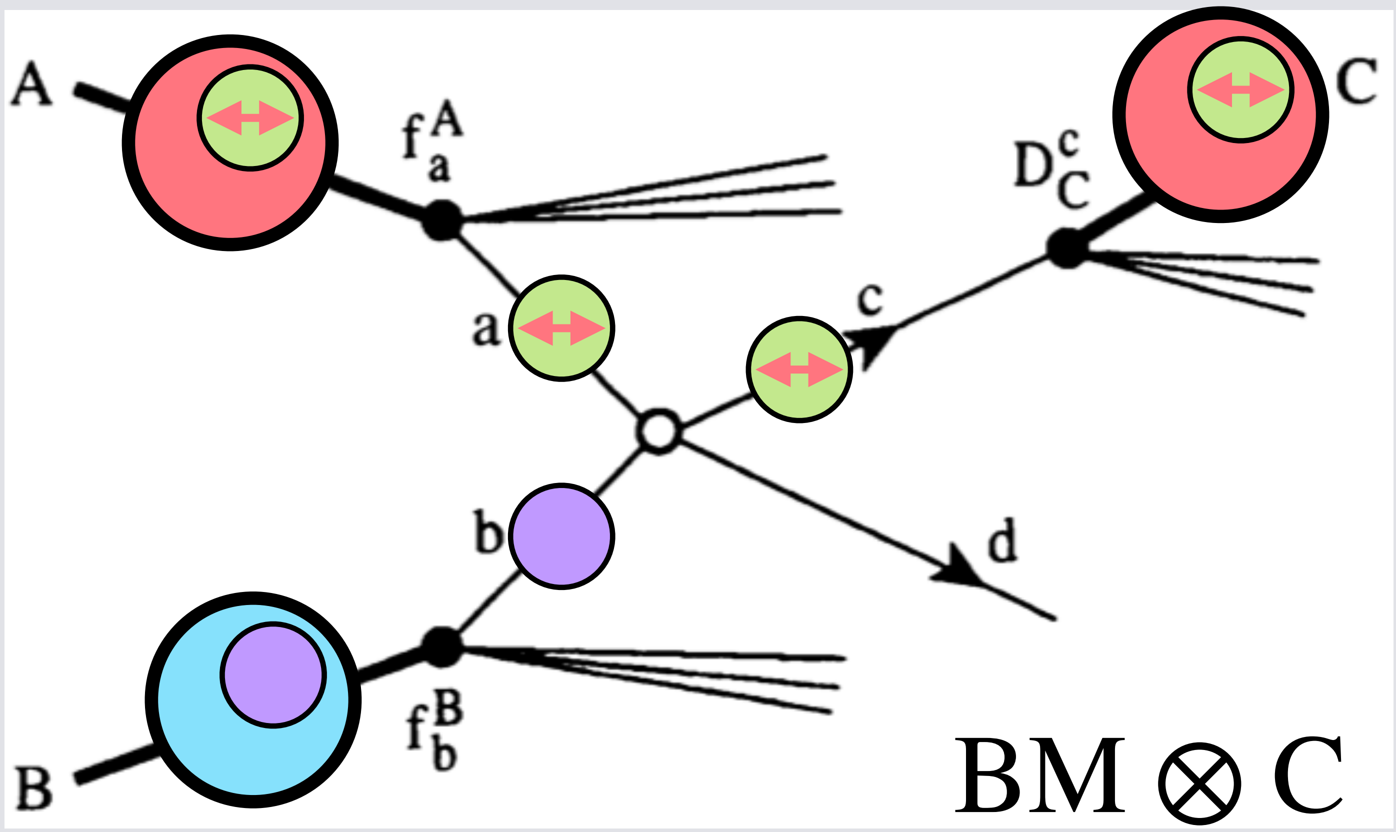
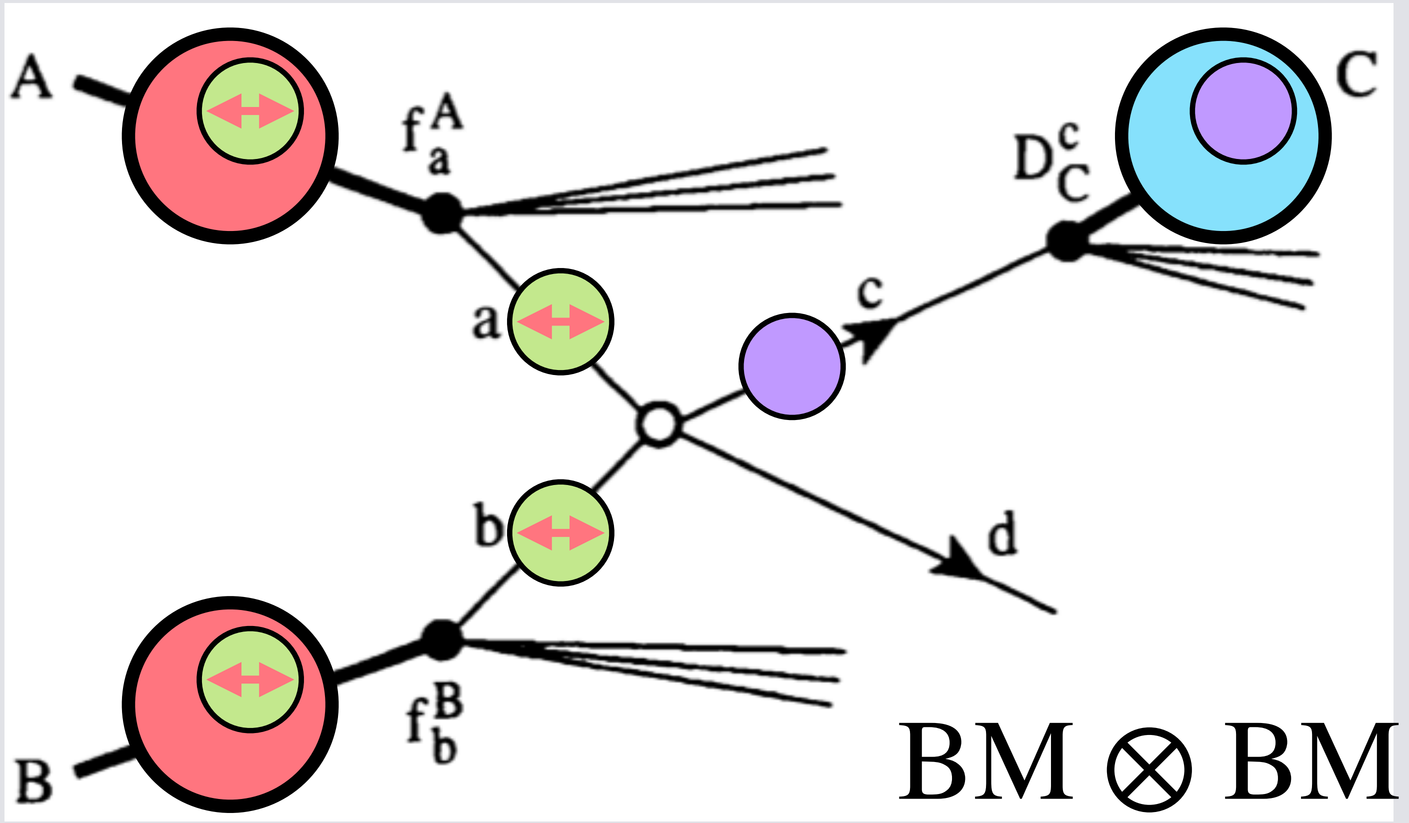


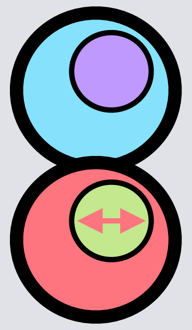


The Boer-Mulders/Collins flips helicity between amplitude and conjugate

Requires two flips for unpolarized pion production

For gg⟷gg:

- $BM \otimes C \quad \Rightarrow M_{\lambda,\lambda}^{\lambda,\lambda}\left(M_{-\lambda,\lambda}^{-\lambda,\lambda}\right)^*$
- $BM \otimes BM \quad \Rightarrow M_{-\lambda,\lambda}^{\lambda,-\lambda}\left(M_{-\lambda,\lambda}^{-\lambda,\lambda}\right)^*$



Unpolarized gluon inside unpolarized hadron

Linearly polarized gluon inside unpolarized hadron

Ismail Soudi

Spin-helicity formalism

Matrix element for BM $\otimes$ C Naturally contains asymmetries

$$\Sigma^{\mathrm{BM}\otimes\mathrm{C}} = H^{\perp(1)}(z, k_{\perp C})\Big\{h^{\perp(1)}(x_a, k_{\perp a}^2)f(x_b, k_{\perp b}^2)\hat{M}_1^0\hat{M}_2^0\cos\left(4(\phi_{ab}-\phi_{bc})\right)$$
$$+f(x_a, k_{\perp a}^2)h^{\perp}(x_b, k_{\perp b}^2)\hat{M}_1^0\hat{M}_3^0\cos\left(4(\phi_{ab}-\phi_{ac})\right)\Big\},$$

with

$$\hat{M}_1^0\hat{M}_2^0 = \frac{9}{4}g_s^4\frac{u^2+tu+t^2}{t^2},$$
$$\hat{M}_1^0\hat{M}_3^0 = \frac{9}{4}g_s^4\frac{u^2+tu+t^2}{u^2},$$

and

$$\tan\phi_{ij} = \tan\frac{\phi_j-\phi_i}{2}\,\frac{\sin\frac{\theta_j+\theta_i}{2}}{\sin\frac{\theta_j-\theta_i}{2}}.$$

[I.S. A. Majumder ArXiv:2308.14702]

Spin-helicity formalism

Matrix element for BM $\otimes$ BM Naturally contains asymmetries

$$\Sigma^{\mathrm{BM}\otimes\mathrm{BM}} = D(z, k_{\perp C}) h^{\perp(1)}(x_a, k_{\perp a}^2) h^{\perp(1)}(x_b, k_{\perp b}^2) \hat{M}_2^0 \hat{M}_3^0 \cos\left(4(\phi_{bc} - \phi_{ac})\right) ,$$

with $\hat{M}_2^0 \hat{M}_3^0 = \frac{9}{4} g_s^4 \frac{u^2 + tu + t^2}{s^2}$, and $\tan\phi_{ij} = \tan\frac{\phi_j - \phi_i}{2} \frac{\sin\frac{\theta_j + \theta_i}{2}}{\sin\frac{\theta_j - \theta_i}{2}}$.

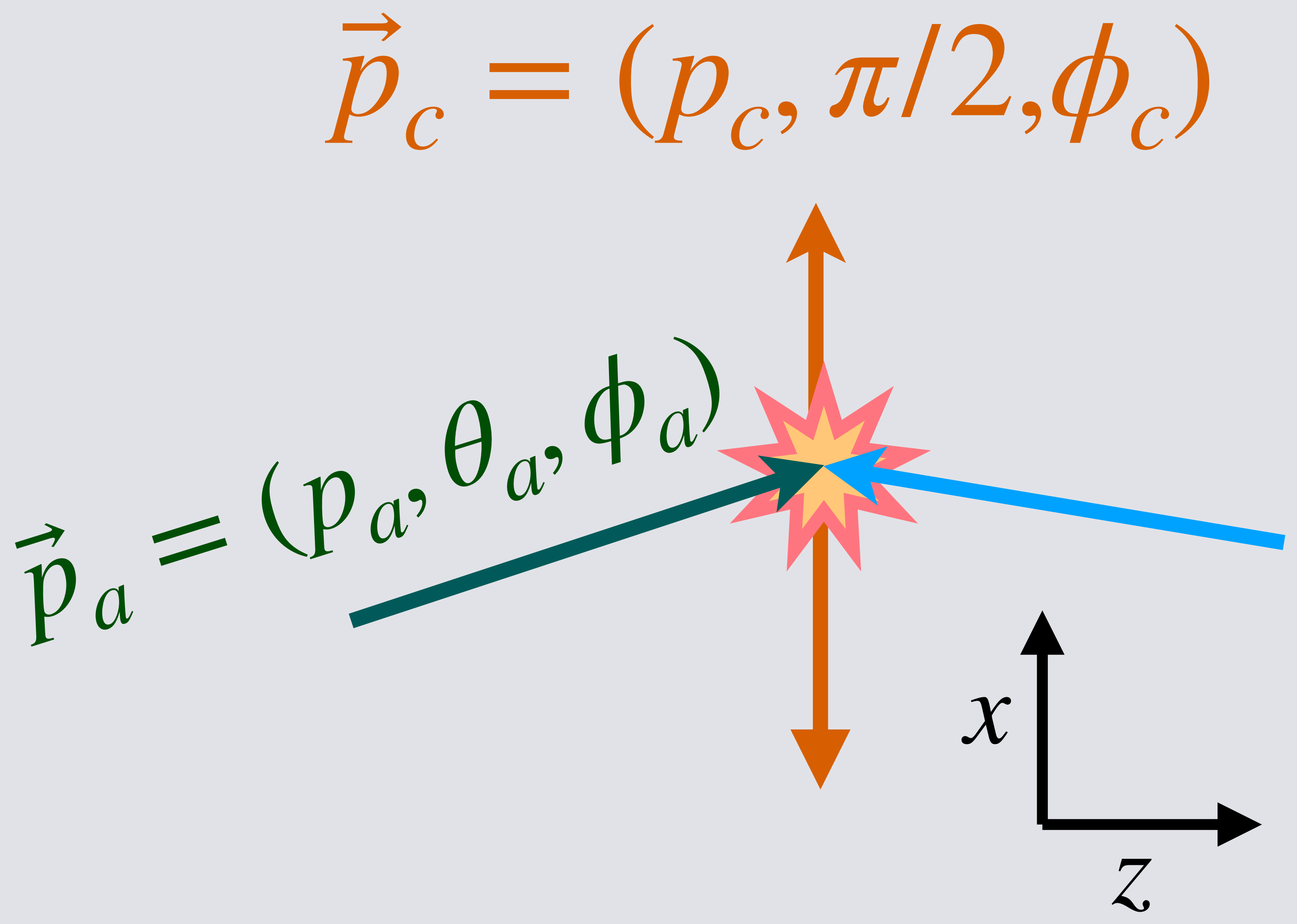
[I.S. A. Majumder ArXiv:2308.14702]

Spin Independent

TMD matrix element contains angular correlations as well

$$\frac{\hat{s}}{\hat{t}} = \frac{-\hat{s}}{2p_c \cdot p_a} \overset{\theta_a \ll 1}{=} \frac{-\hat{s}}{2p_c p_a[1-\theta_a\cos(\phi_a-\phi_c)]}$$

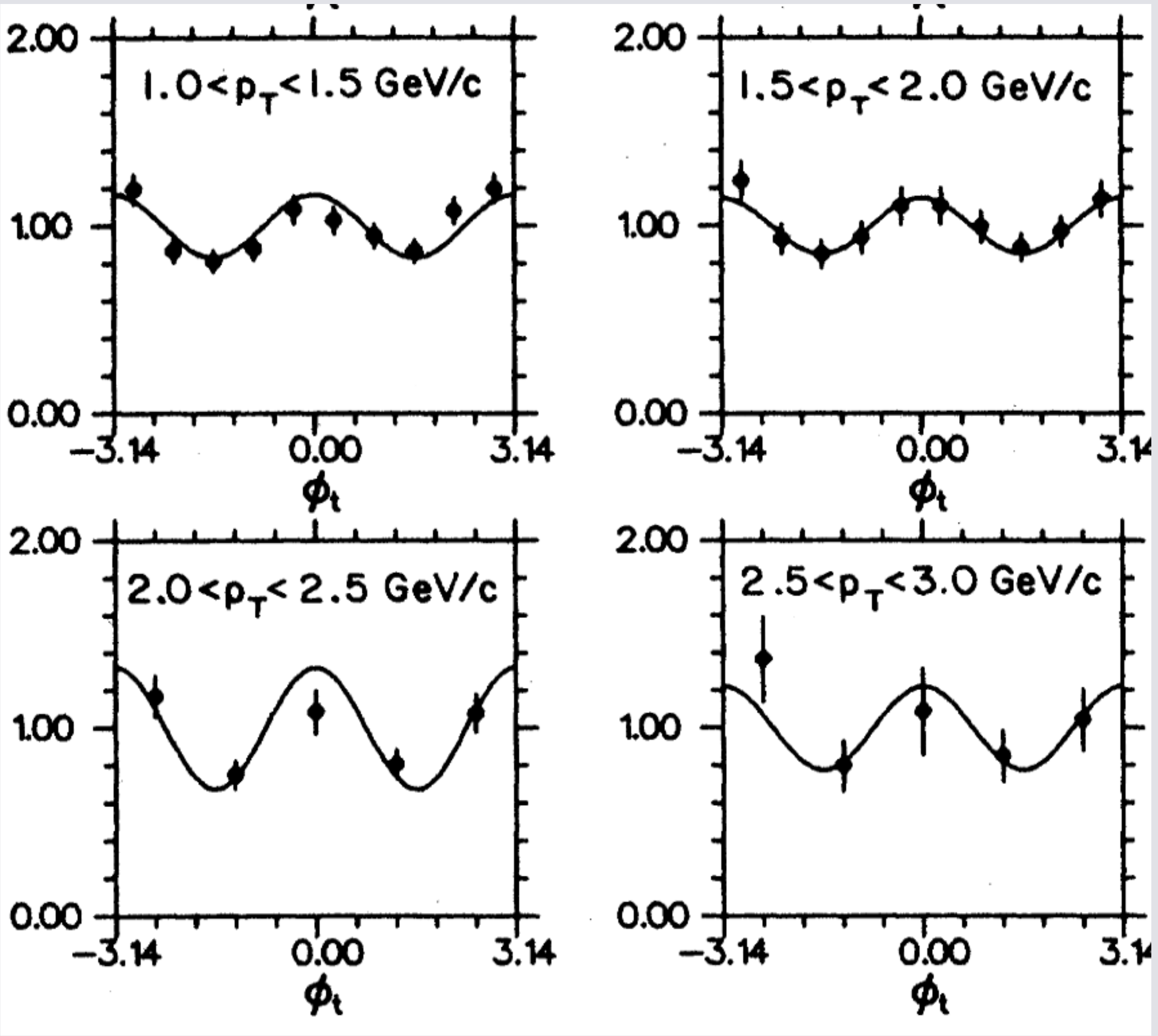
$$= \frac{-\hat{s}}{2p_c p_a}\left[1 + \frac{\theta_a^2}{4} + \theta_a\cos(\phi_a-\phi_c) + \frac{\theta_a^2\cos(2(\phi_a-\phi_c))}{4} + \mathcal{O}(\theta_a^3)\right].$$



[I.S. A. Majumder ArXiv:2308.14702]

Anisotropies in Drell-Yann

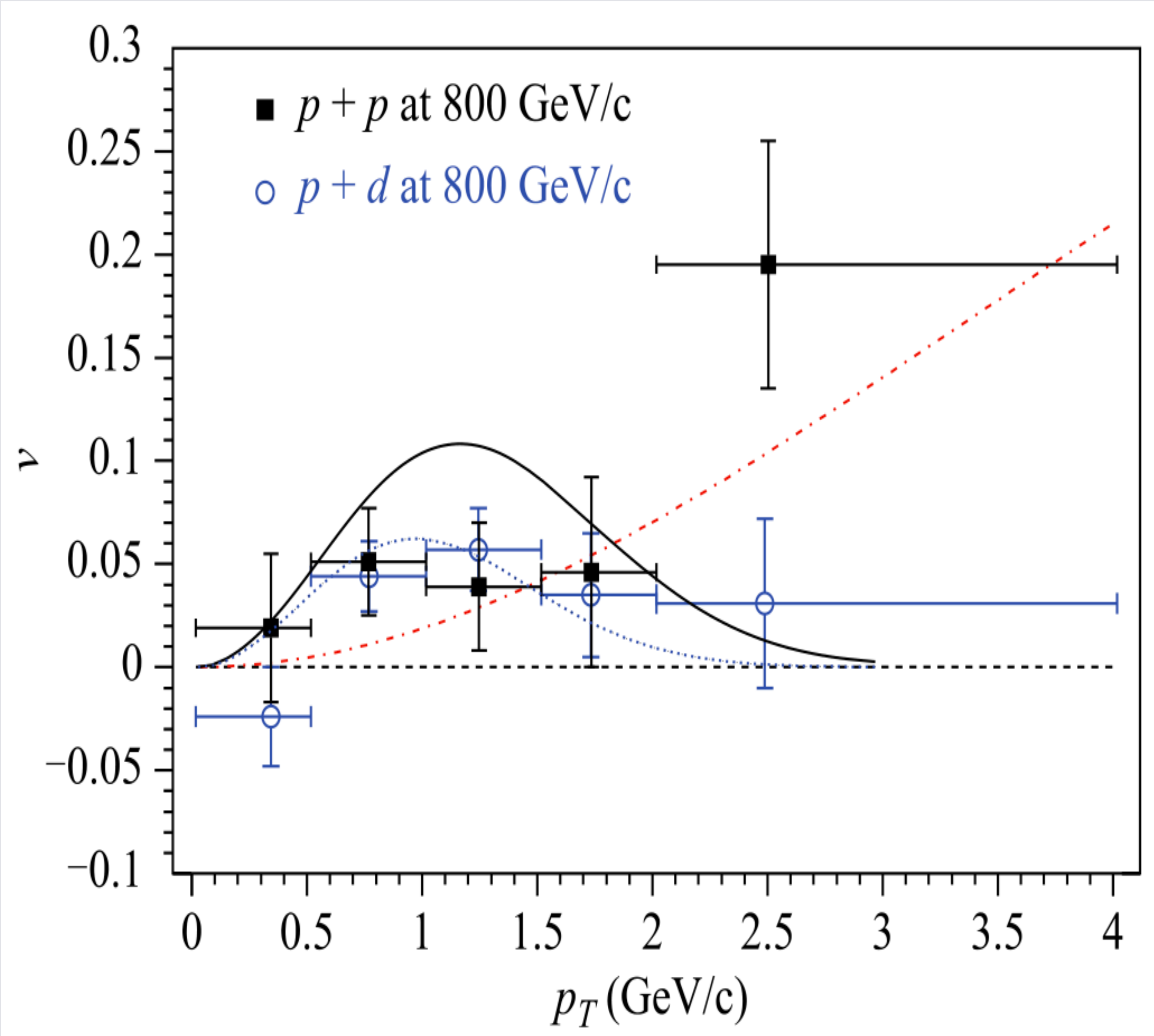
Distribution



[J. S. Conway et al., PRD 39, 92 (1989).]

$$\frac{d\sigma}{d\omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$

Average

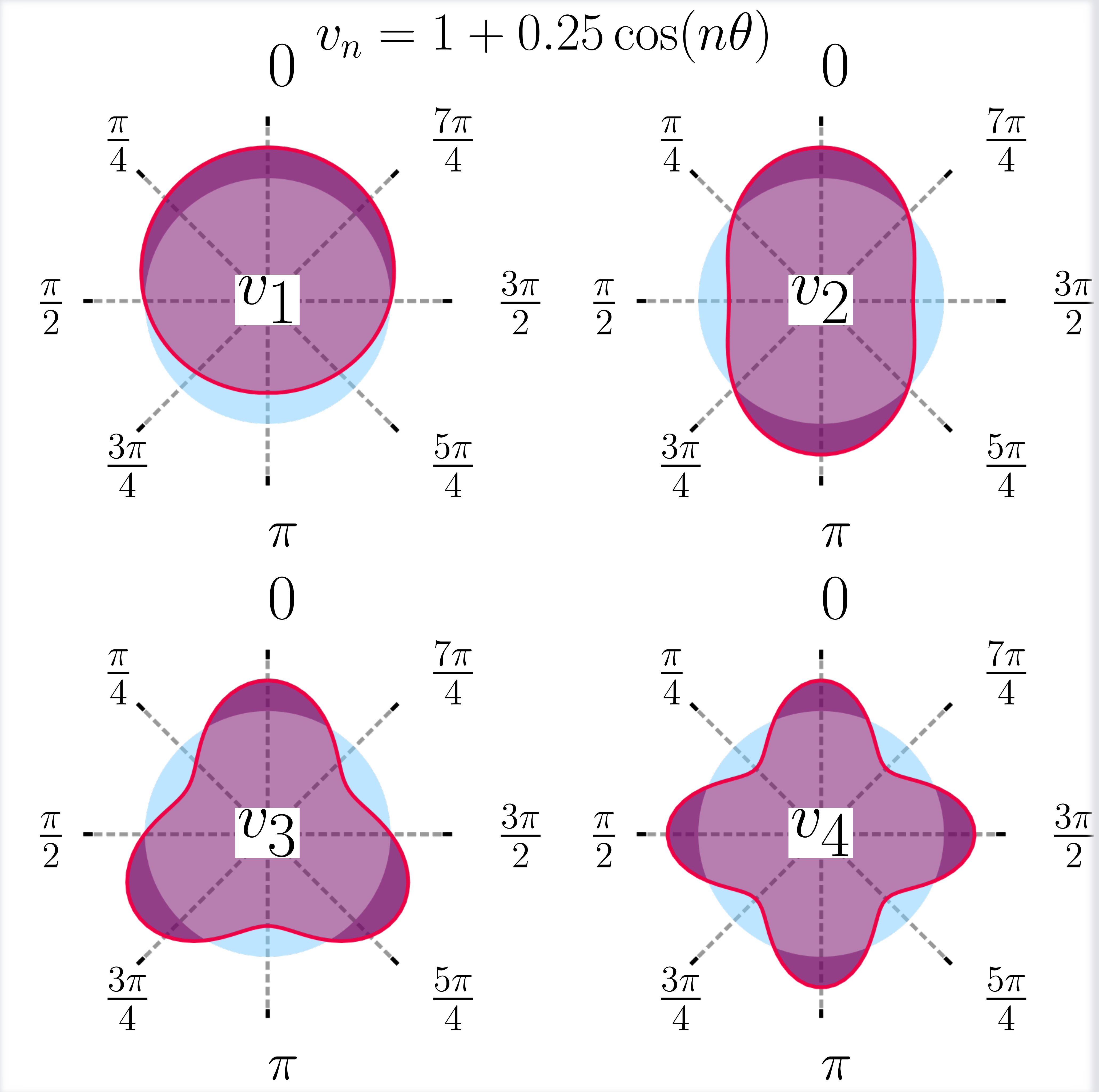


[B. Zhang et al., PRD 77, 054011]
[Z. Lu, FP 11 (2016) 1, 111204]

v_n Azimuthal Anisotropies

Azimuthal momentum correlated with soft bulk (event plane)

$$\frac{dN}{d\phi} \propto 1 + \sum_{1}^{\infty} 2v_n cos[n(\phi - \Psi_n)]$$



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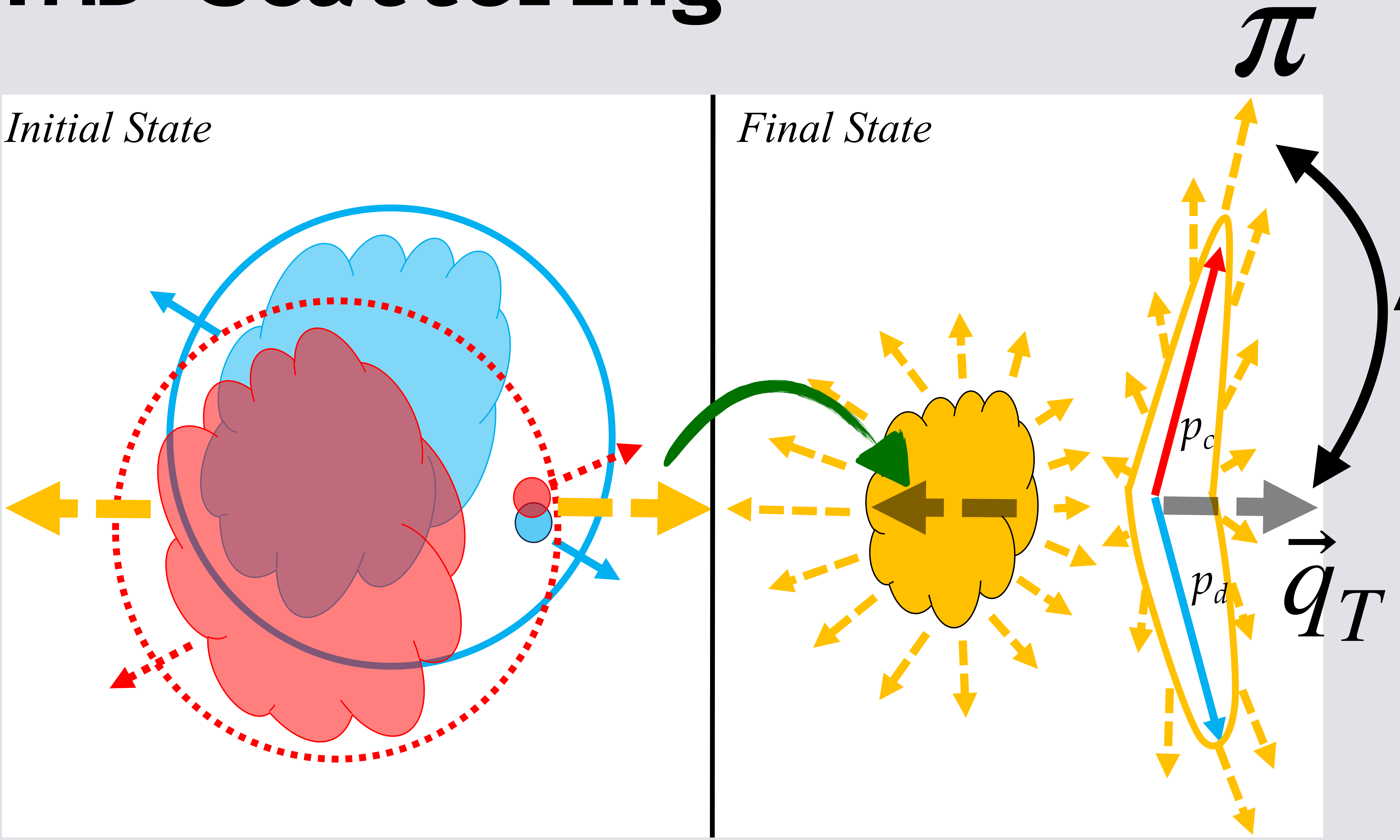
TMD Scattering

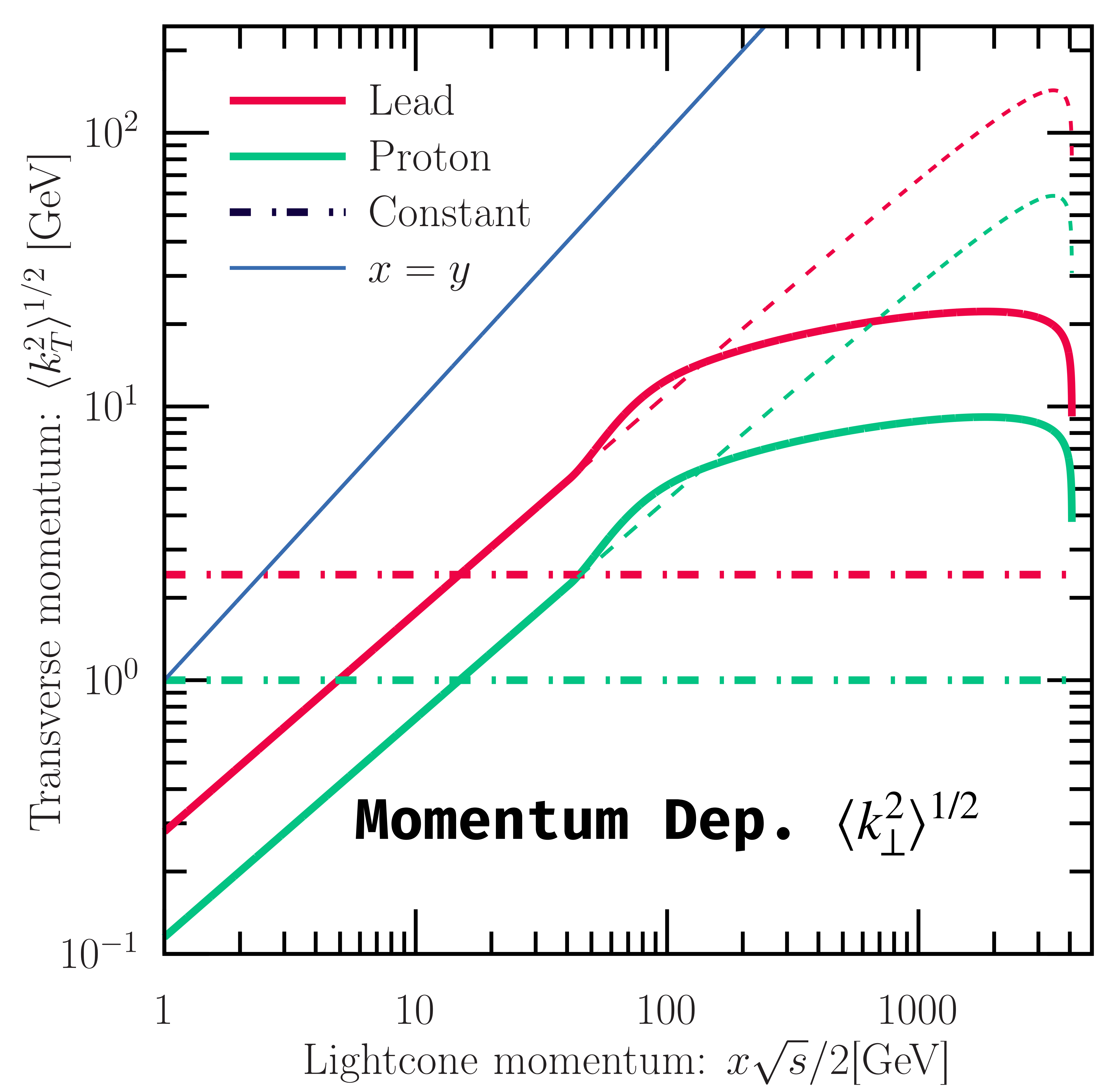


$$\Delta\phi \equiv \phi_{q_T} - \phi_{\pi}$$

p-p Results

$$f(x,k_\perp) = \frac{4\pi}{\langle k_\perp^2\rangle} e^{-\frac{k_\perp^2}{\langle k_\perp^2\rangle}} f(x)\,,$$

$$\langle k_\perp^2\rangle_{p-Pb} = A^{1/3}\langle k_\perp^2\rangle_{p-p}$$



Factorization of $(x \otimes k_T)$

$\Rightarrow$ Allows to approximate to p-A

Soffer Bound: $B \leq 1$ $b \leq 1$

$$\frac{k_\perp^2}{2M^2}|h^{\perp g}(x,k_\perp)| = b \cdot f^g(x,k_\perp)\,,$$

$$\frac{k_\perp^2}{2M^2}|H^{\perp g}(x,k_\perp)| = B \cdot D^g(x,k_\perp)\,,$$

Results gg→gg only

$\Rightarrow$ Most relevant for kinematics

[X. Guo, Phys. Phys. Rev. D 58, 036001(1998)]
[R. J. Fries, Phys. Rev. D 68, 074013 (2003)]
[A. Majumder and B. Müller, Phys. Rev. C 77, 054903 (2008)]

Ismail Soudi

p-p Results

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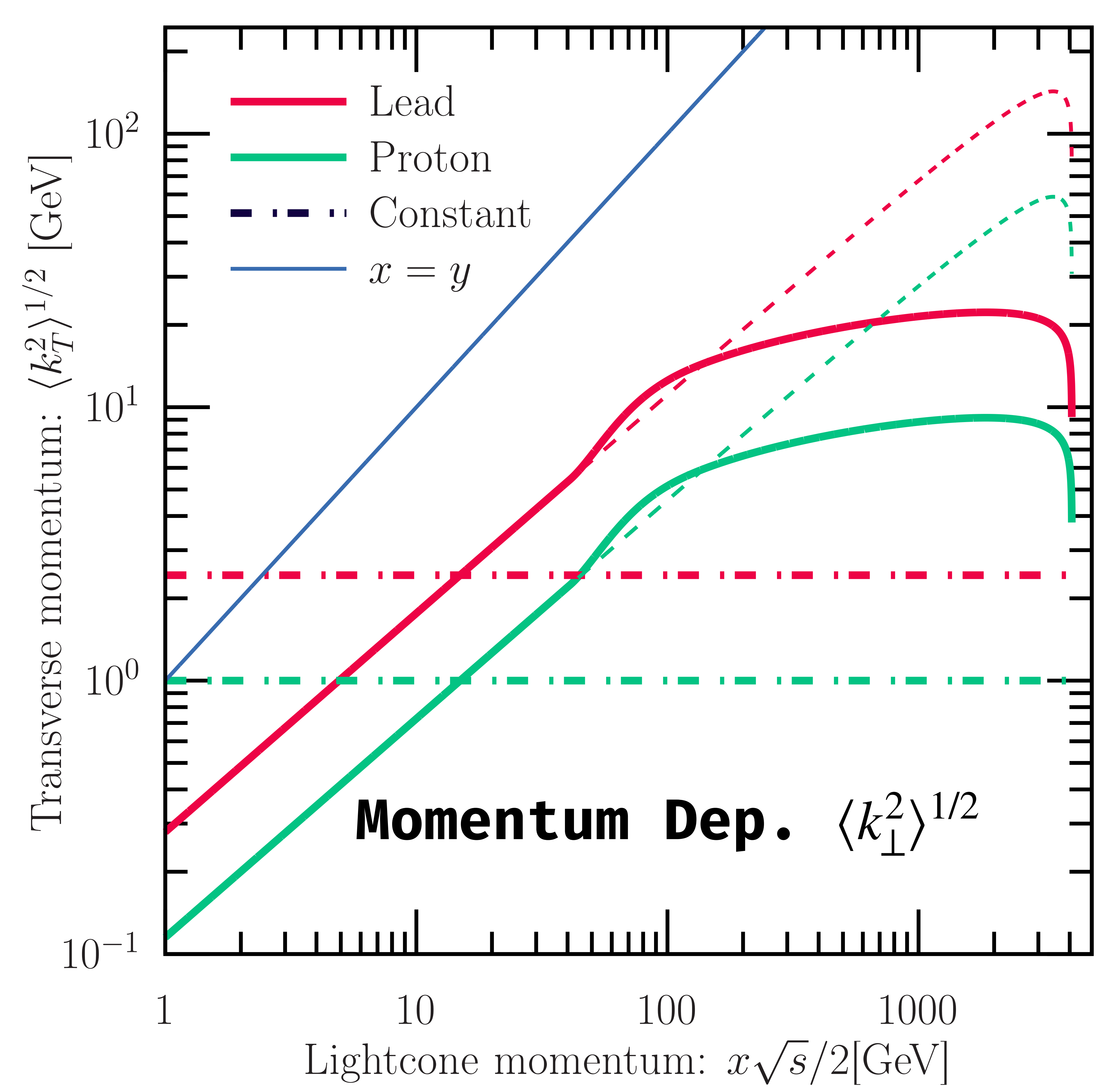

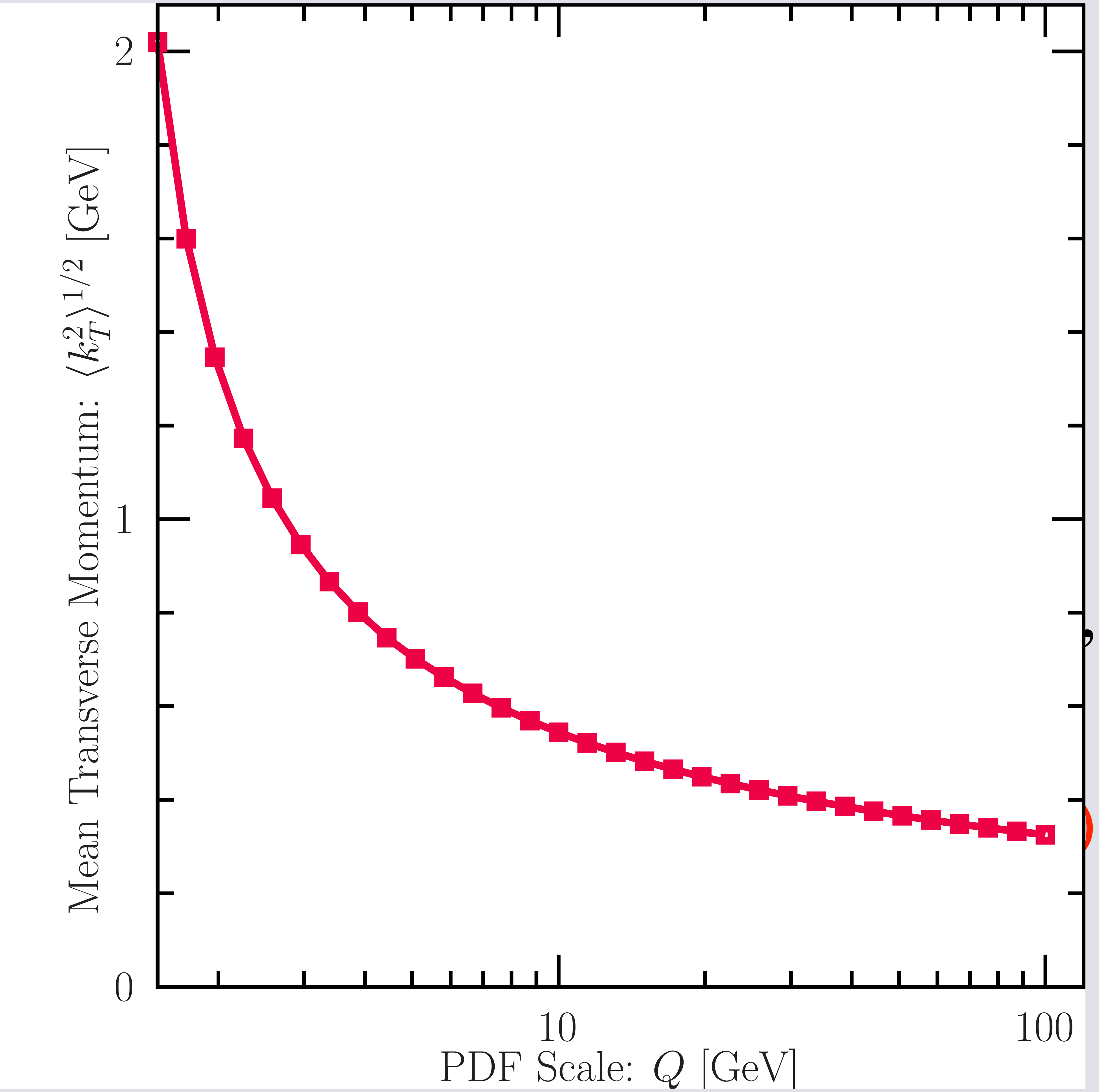

[X. Guo, Phys. Phys. Rev. D 58, 036001(1998)]
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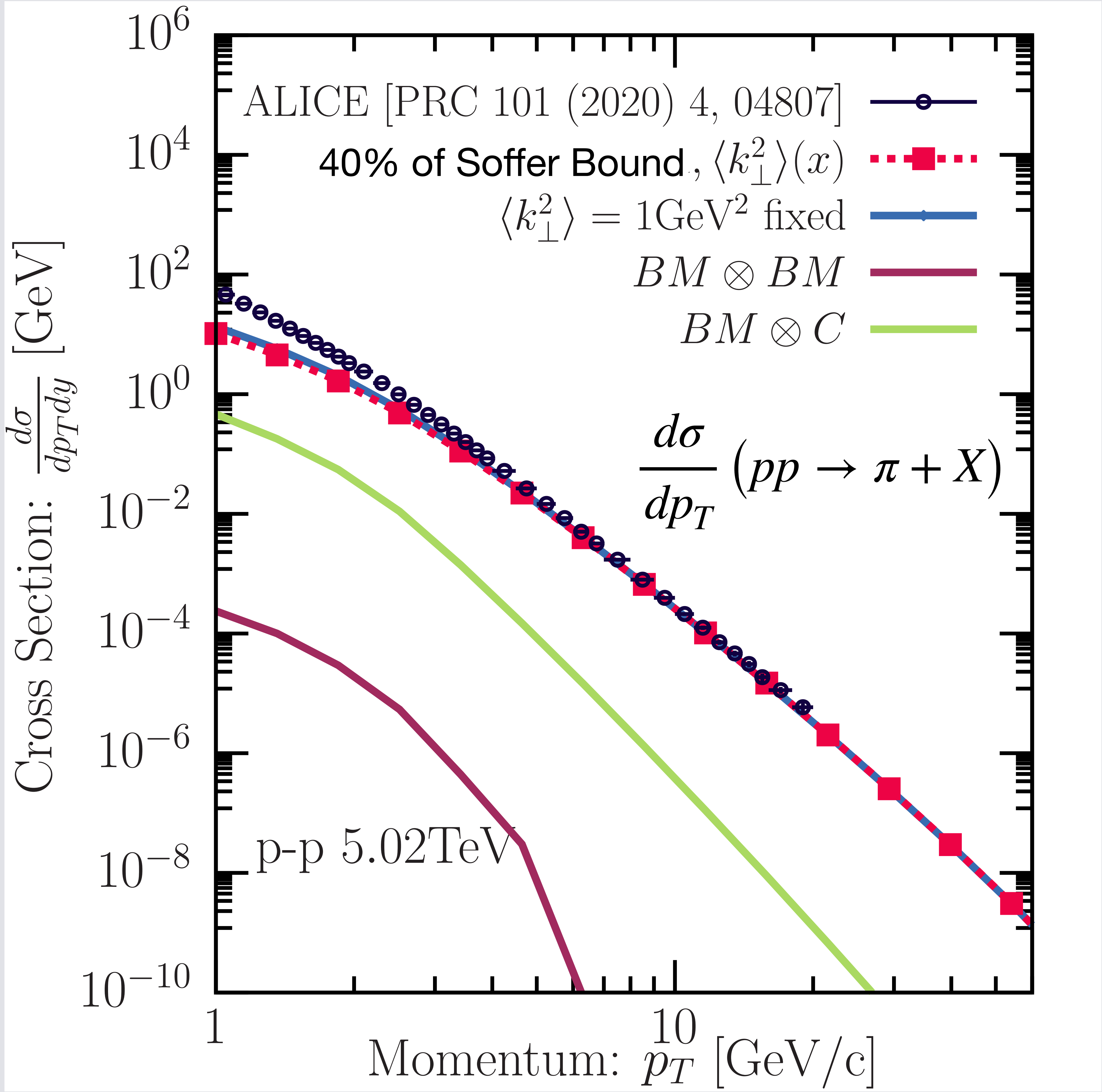

We use nCTEQ PDFs and KKP FFs

[K. Kovarik et al., Phys. Rev. D 93, 085037 (2016)]

[B. A. Kniehl et al., Nucl. Phys. B582, 514 (2000)]

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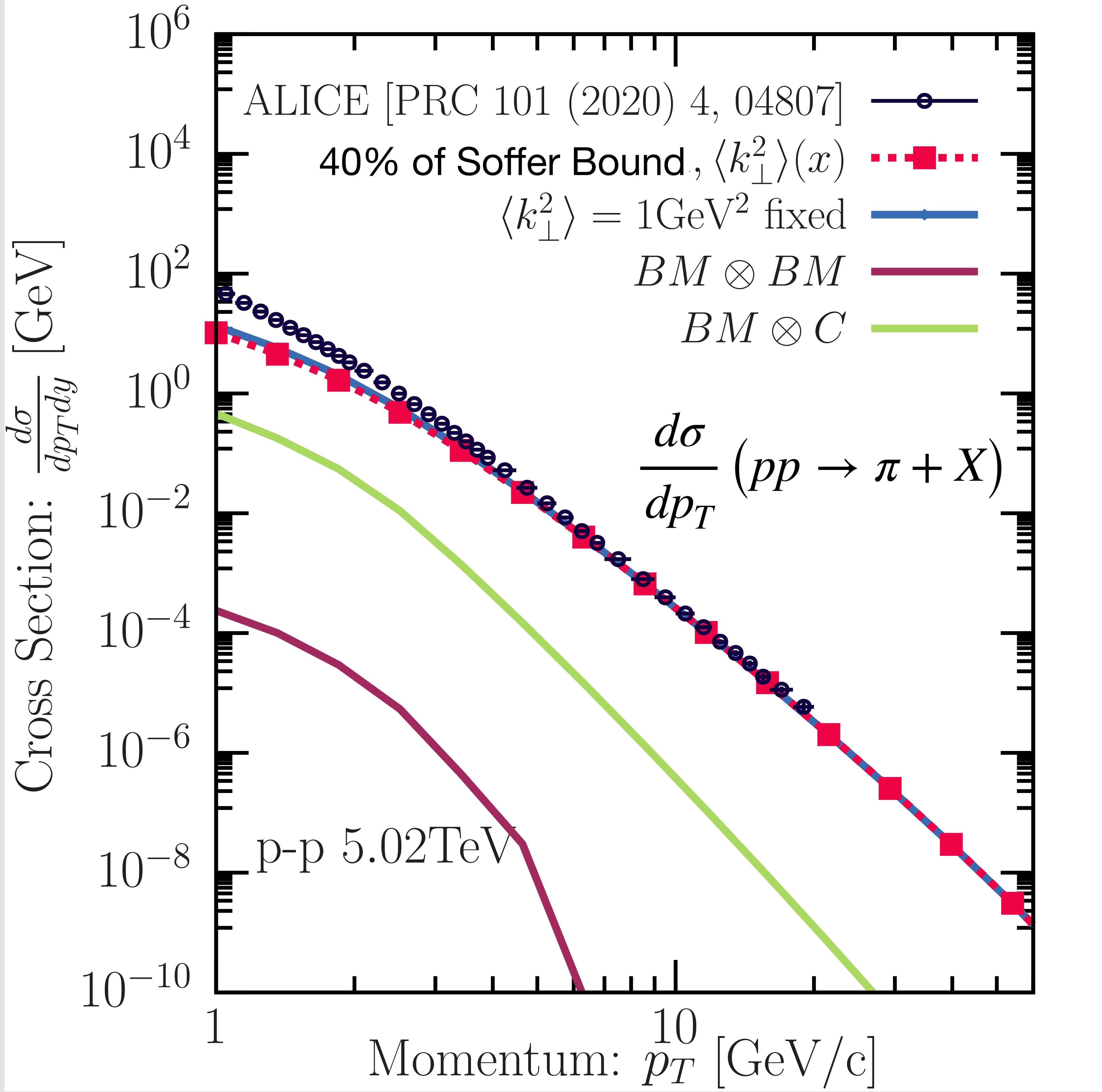

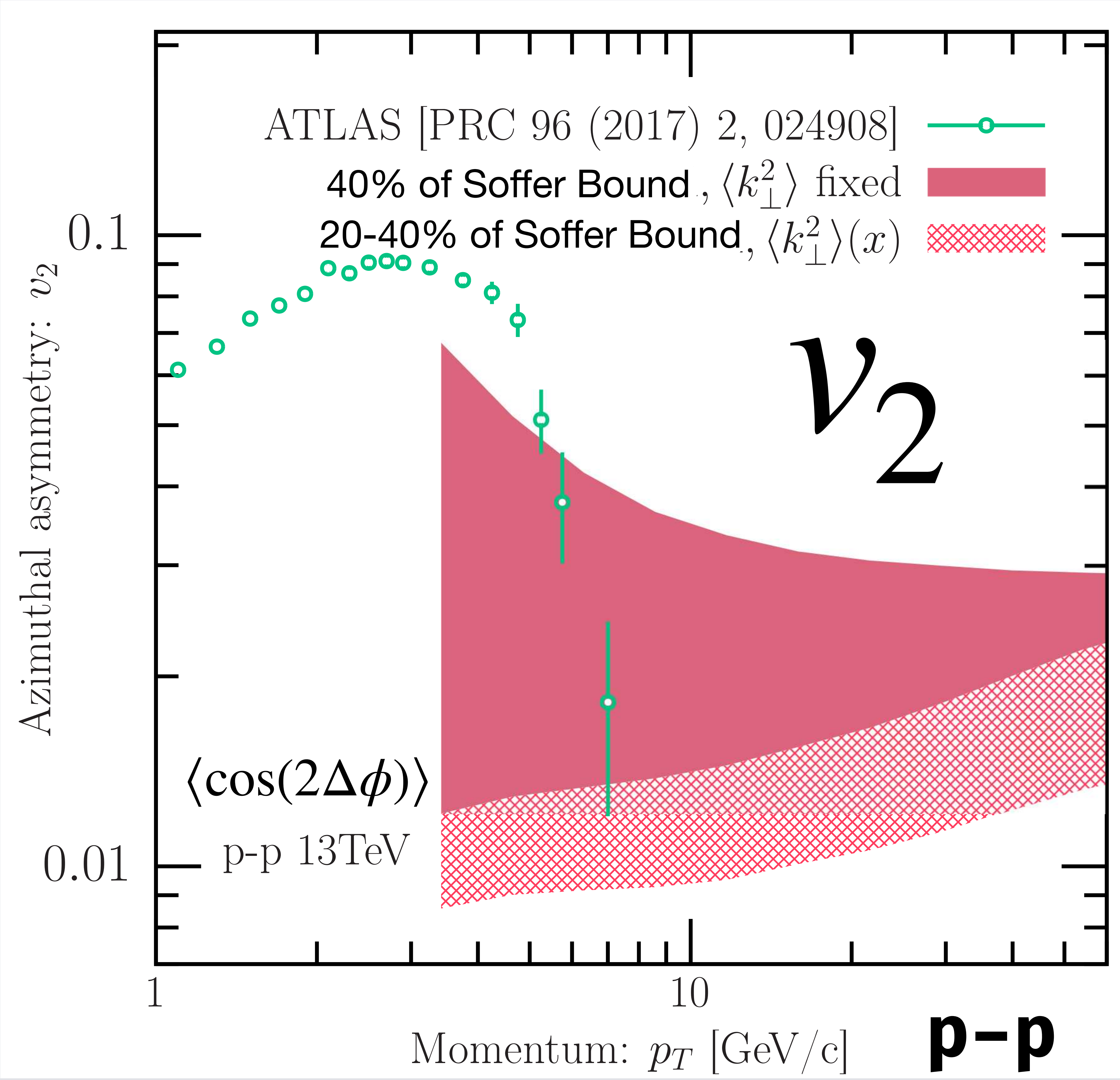

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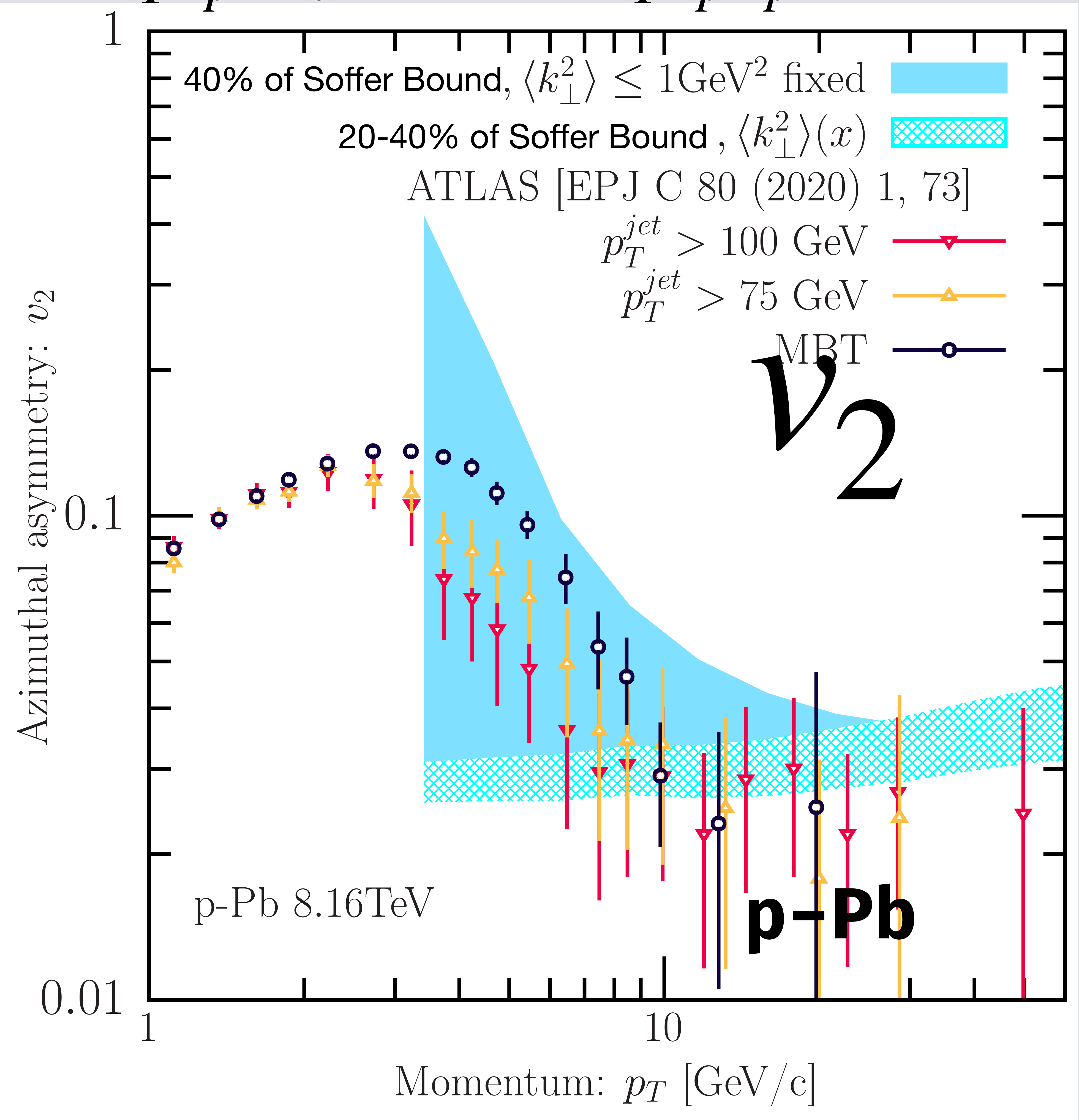
[B. A. Kniehl et al., Nucl. Phys. B582, 514 (2000)]

[I.S. A. Majumder ArXiv:2308.14702]

Results

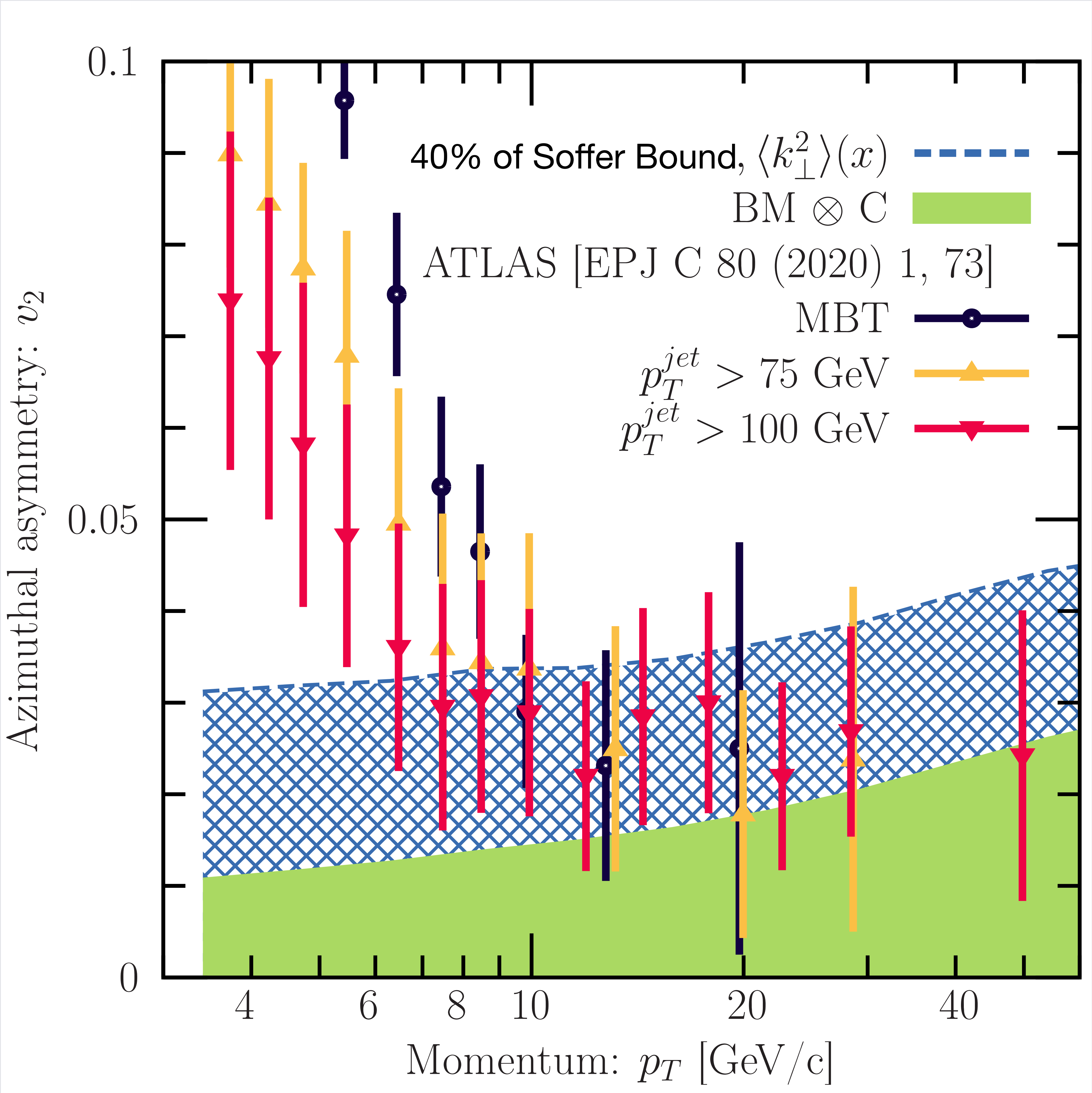
Approximation $\Rightarrow \langle k_T^2\rangle_{p-Pb} = A^{1/3}\langle k_T^2\rangle_{p-p}$

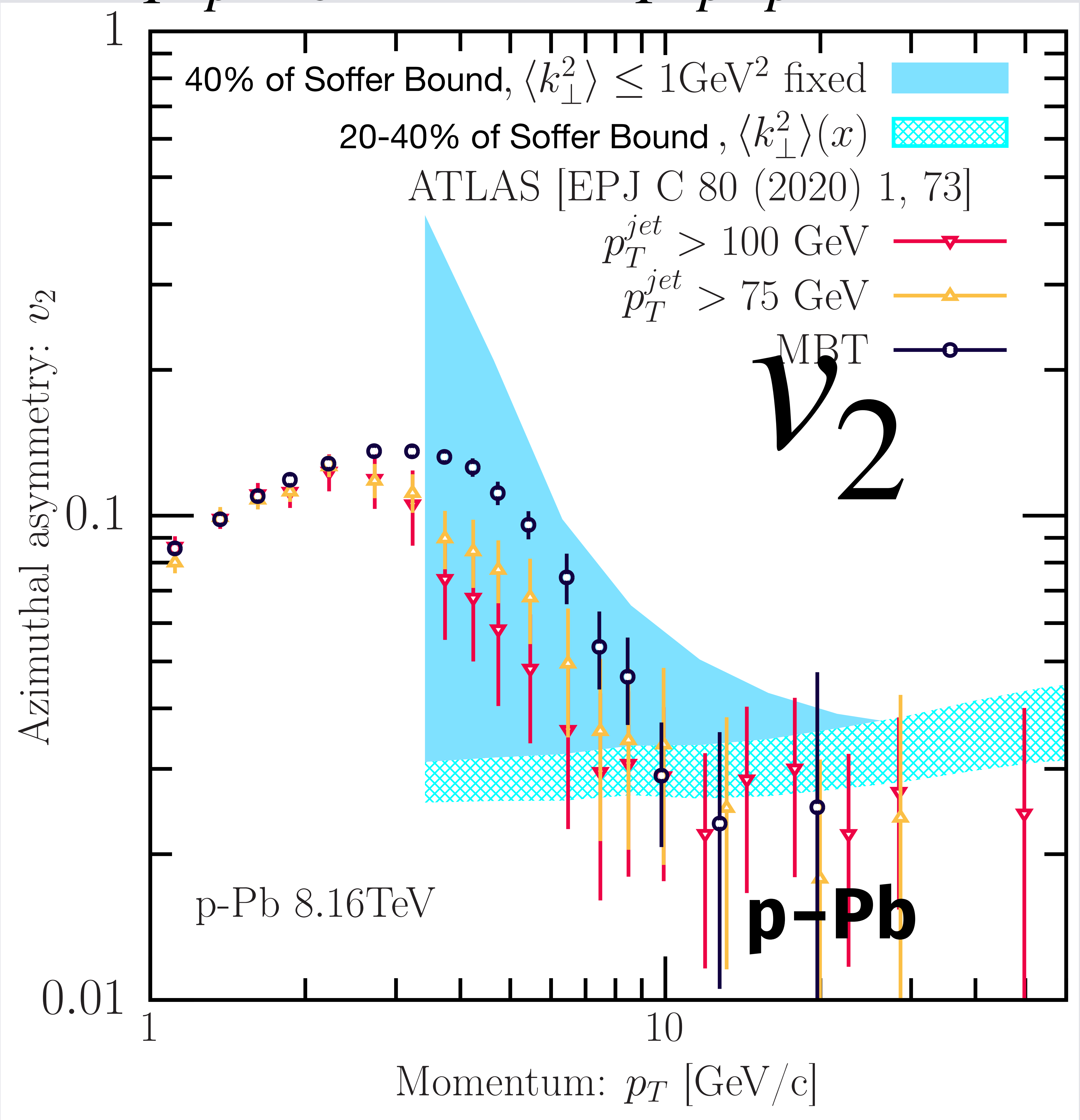


[I.S. A. Majumder ArXiv:2308.14702]

Results

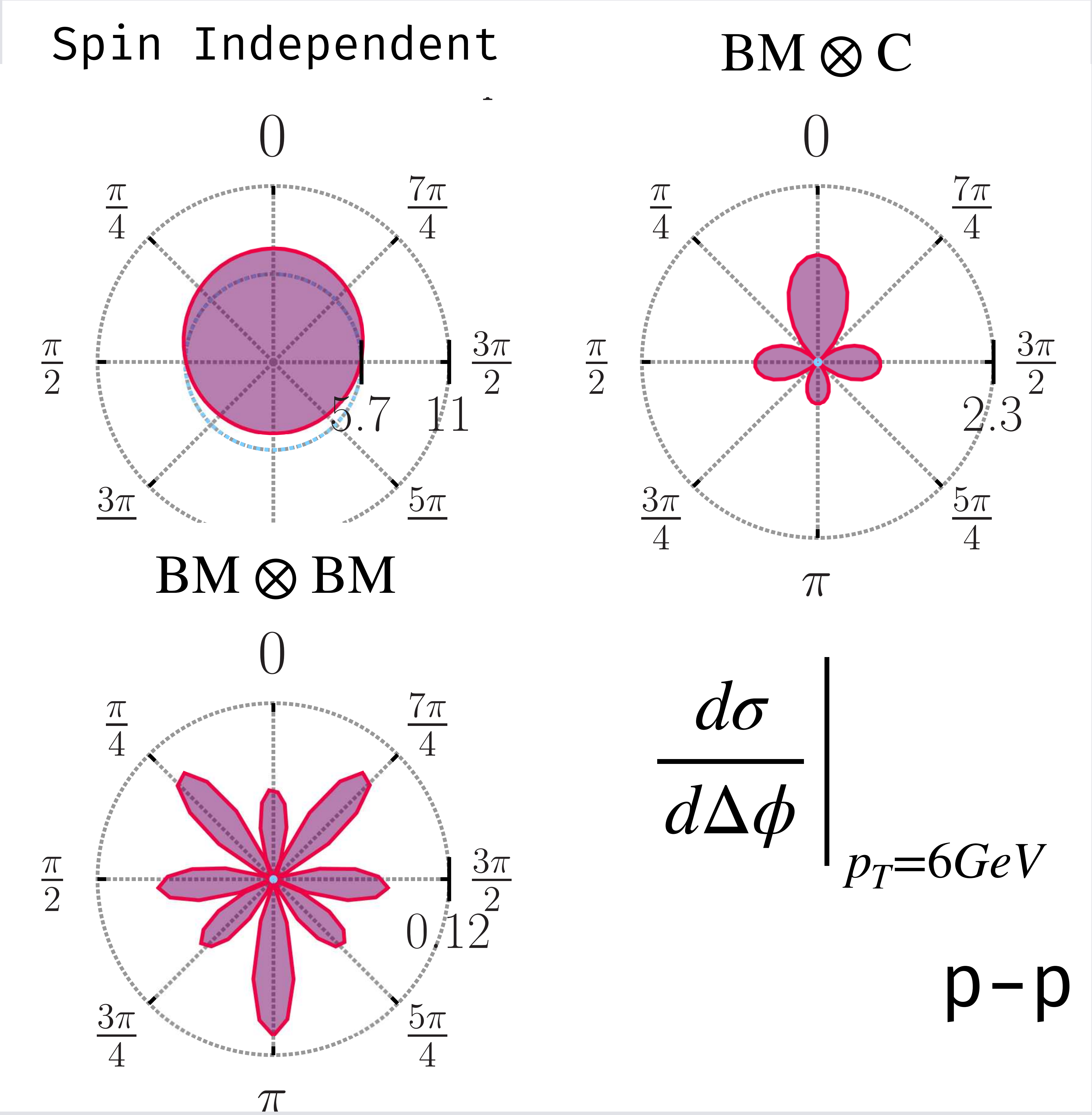
Approximation $\Rightarrow \langle k_T^2 \rangle_{p-Pb} = A^{1/3} \langle k_T^2 \rangle_{p-p}$





[I.S. A. Majumder ArXiv:2308.14702]

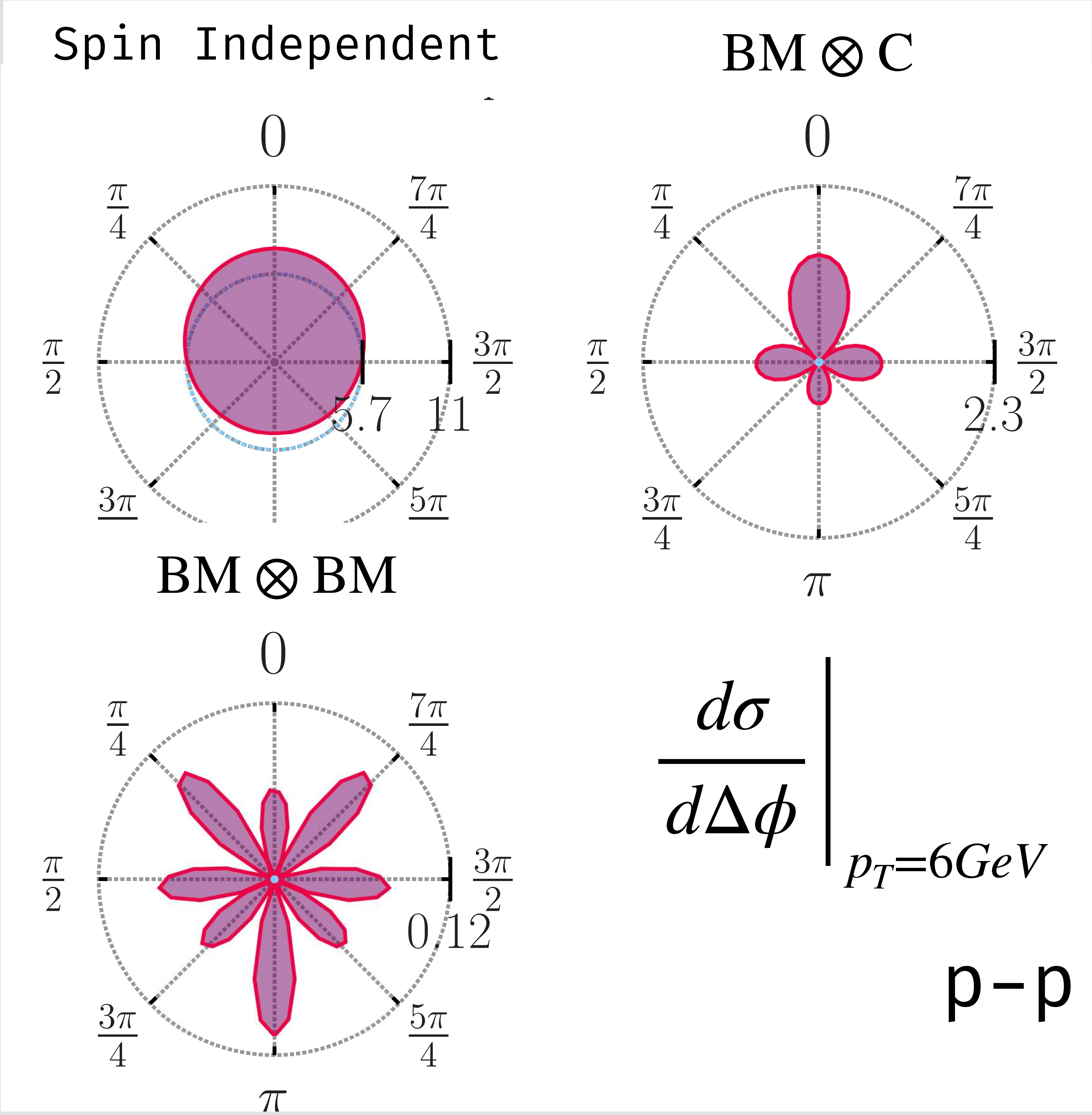
Angular Distribution $\Delta\phi \equiv \phi_{q_T} - \phi_\pi$

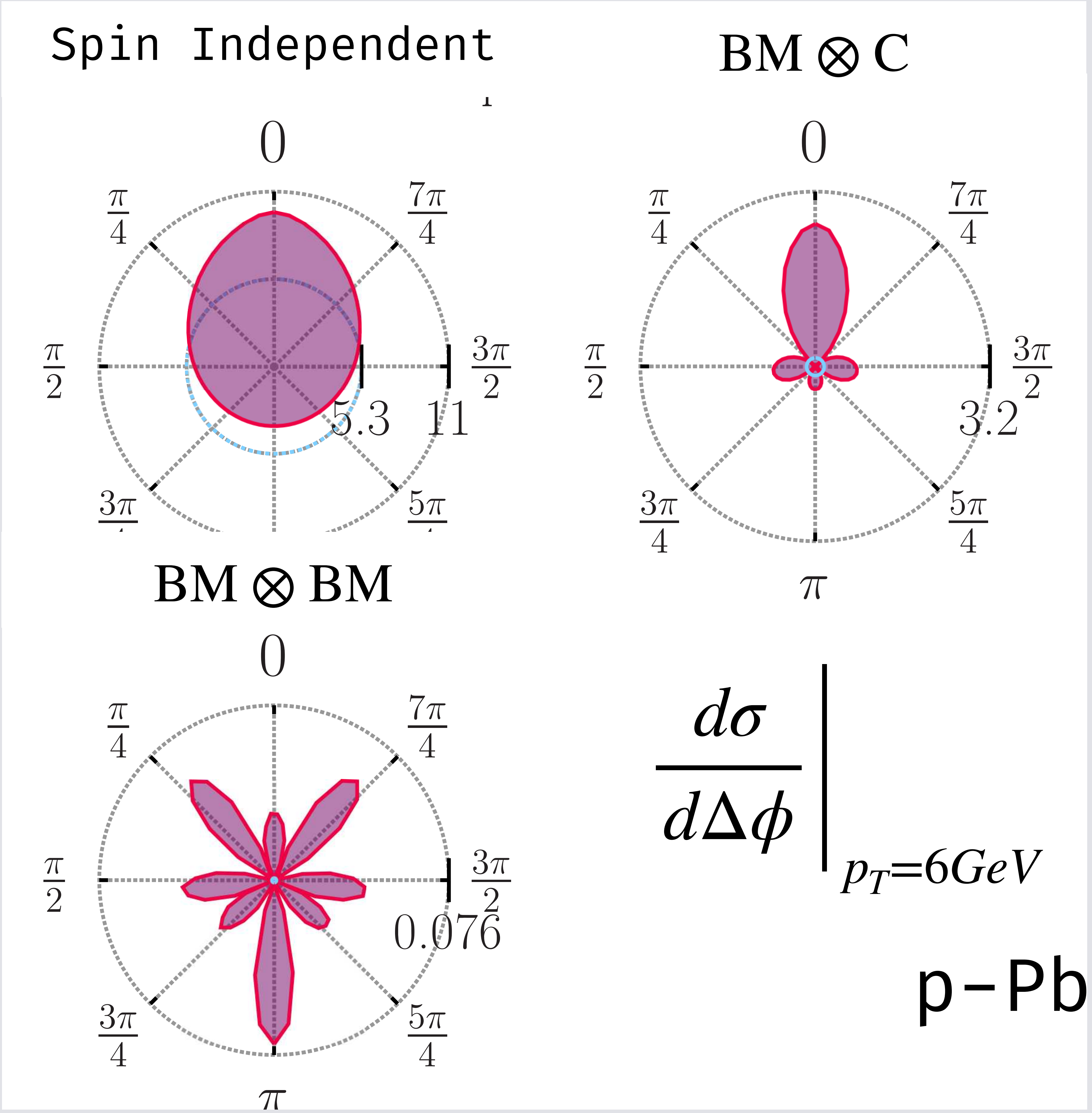


$p_T = 6\text{GeV}$

Approximation $\Rightarrow \langle k_T^2 \rangle_{p-Pb} = A^{1/3} \langle k_T^2 \rangle_{p-p}$

Angular Distribution $\Delta\phi \equiv \phi_{q_T} - \phi_\pi$

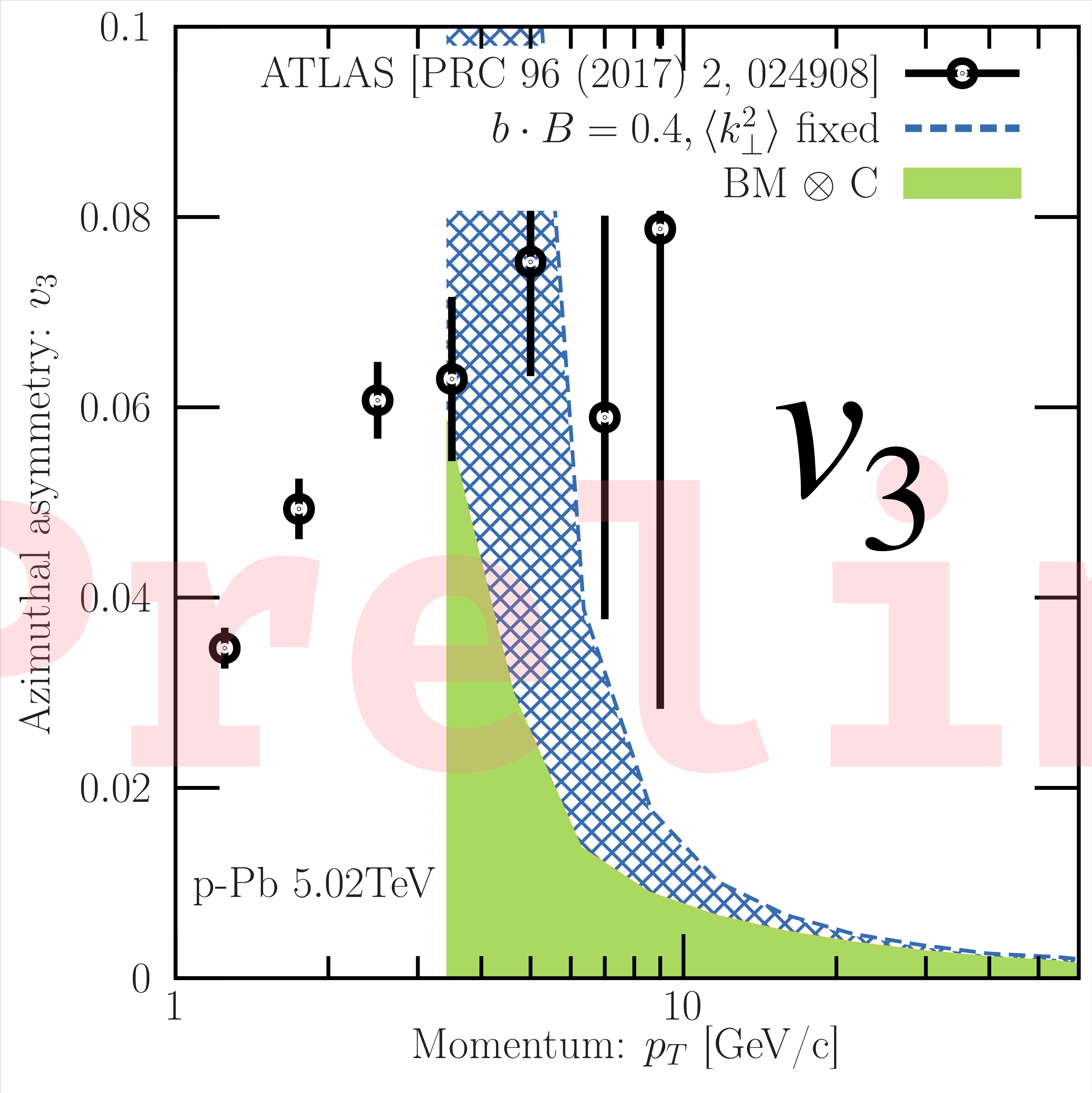




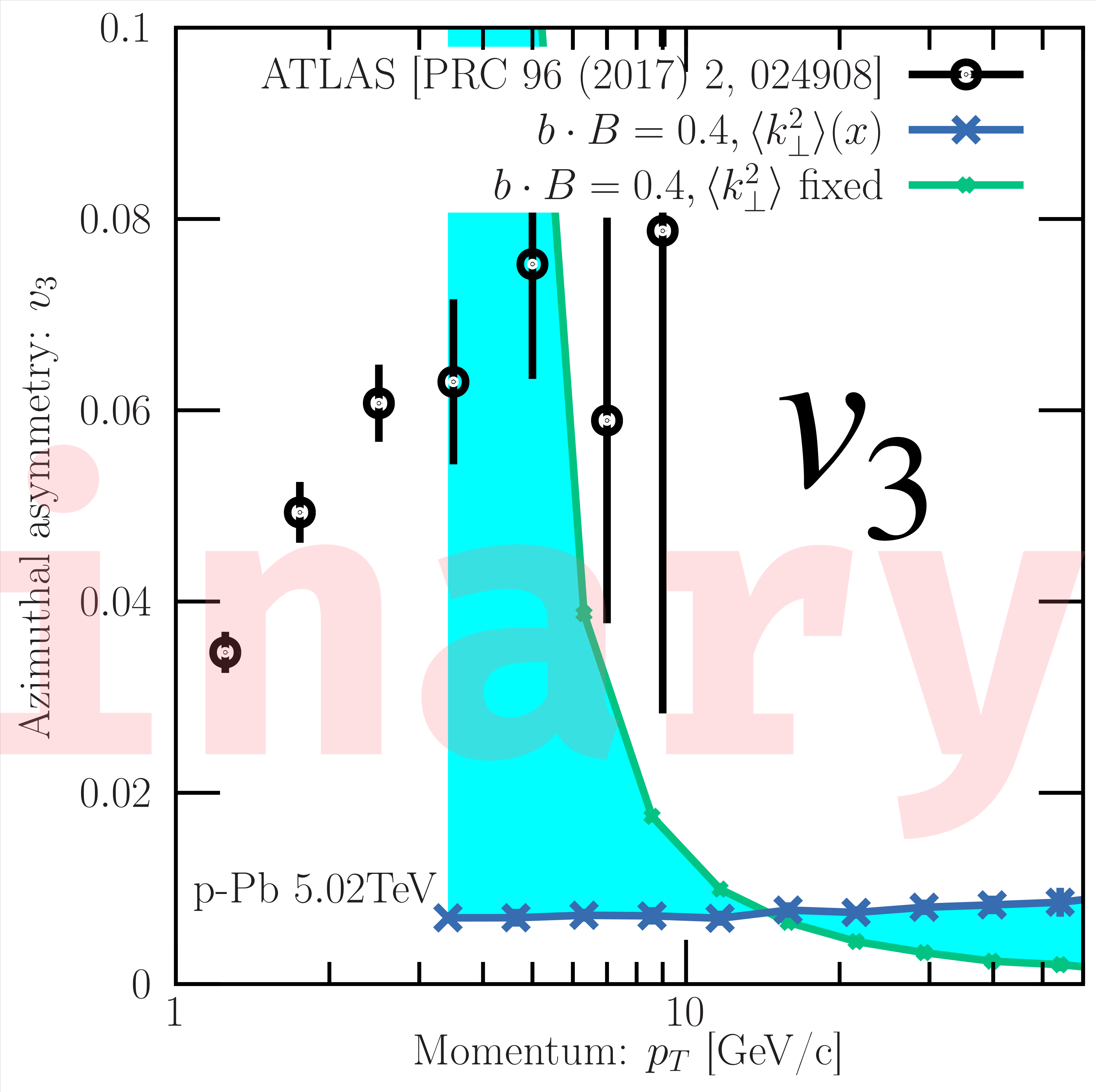
$p_T = 6\text{GeV}$

Approximation $\Rightarrow \langle k_T^2 \rangle_{p-Pb} = A^{1/3} \langle k_T^2 \rangle_{p-p}$

Preliminary results

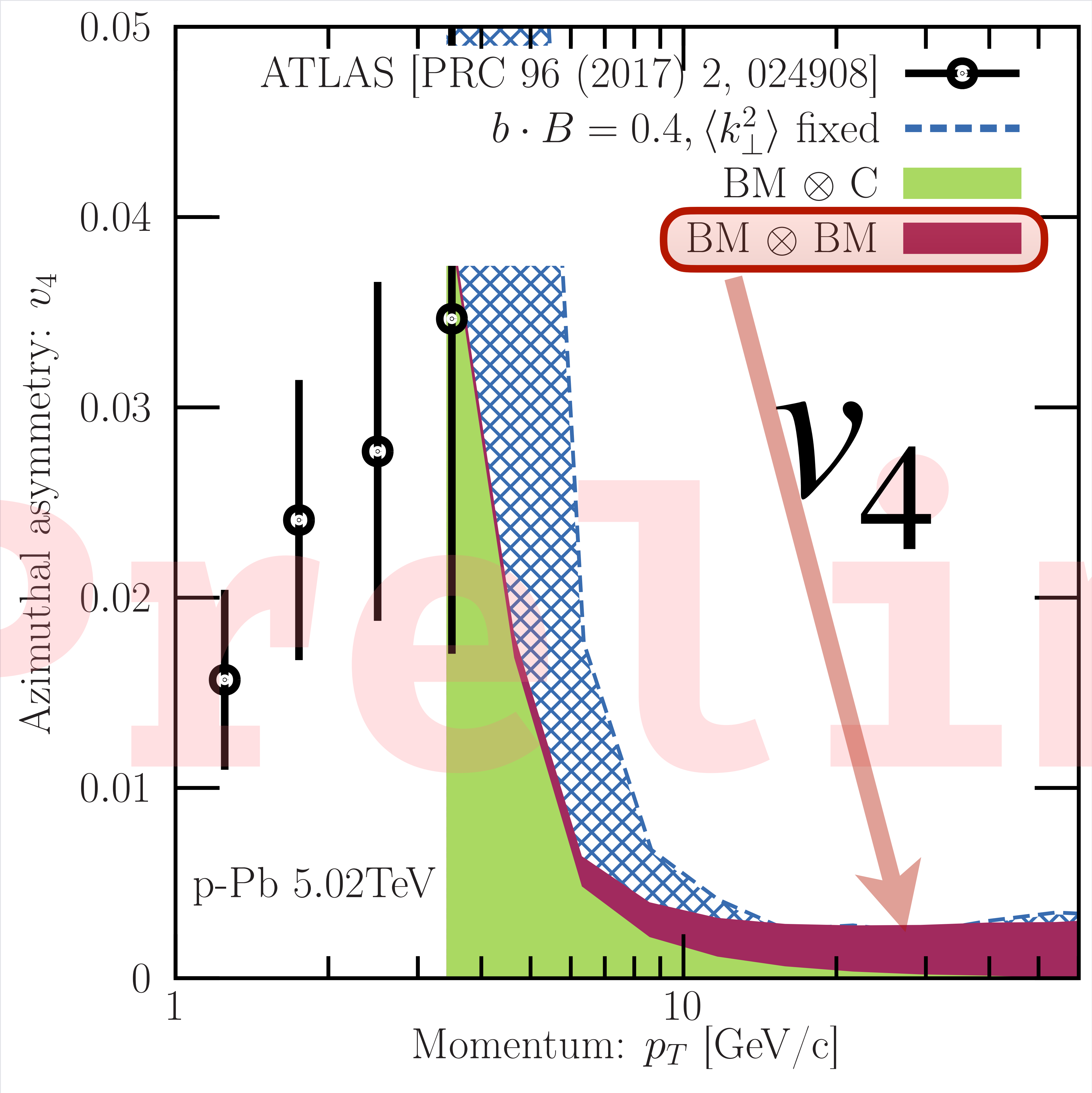


p-Pb

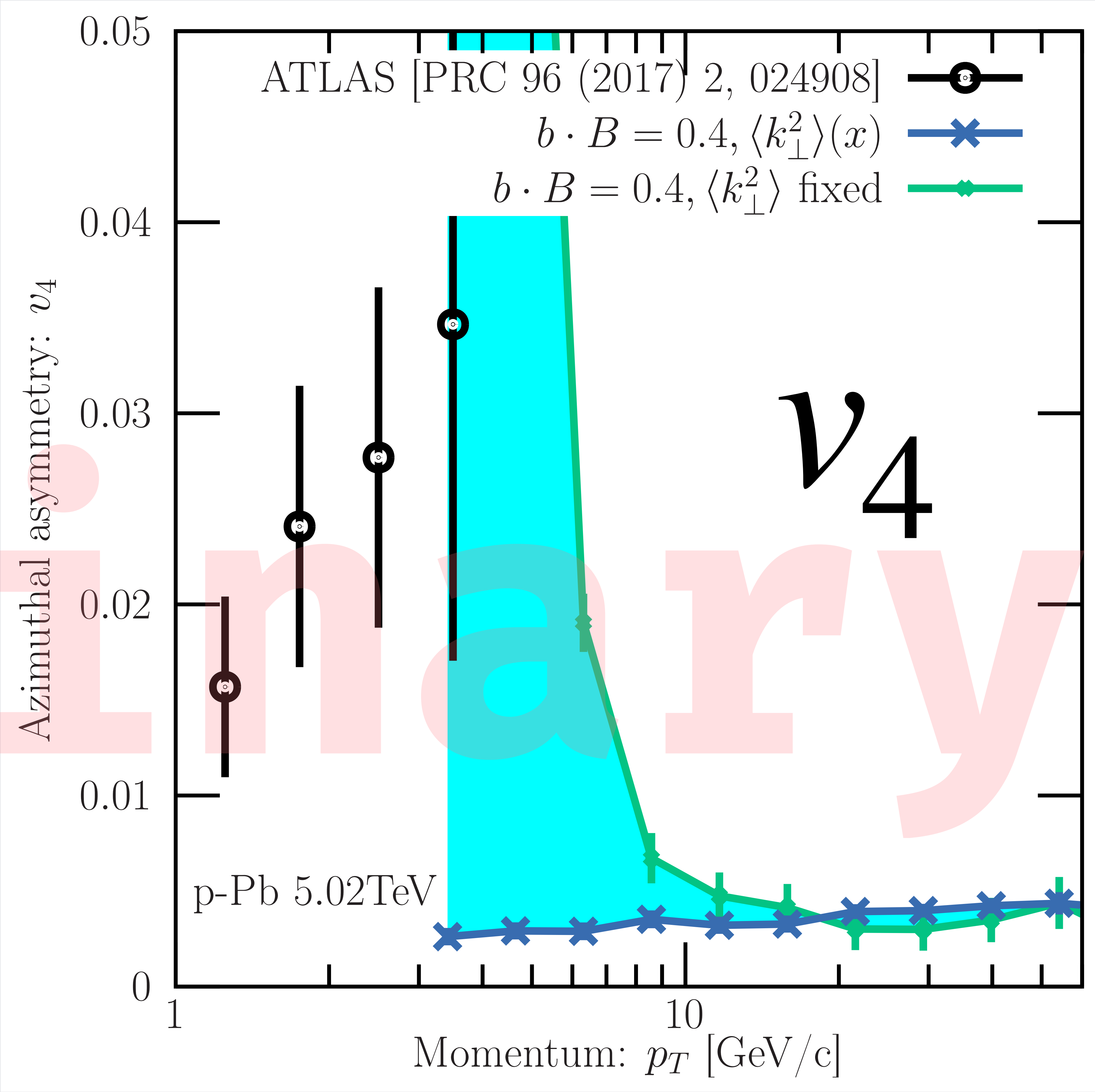


Preliminary

Preliminary results



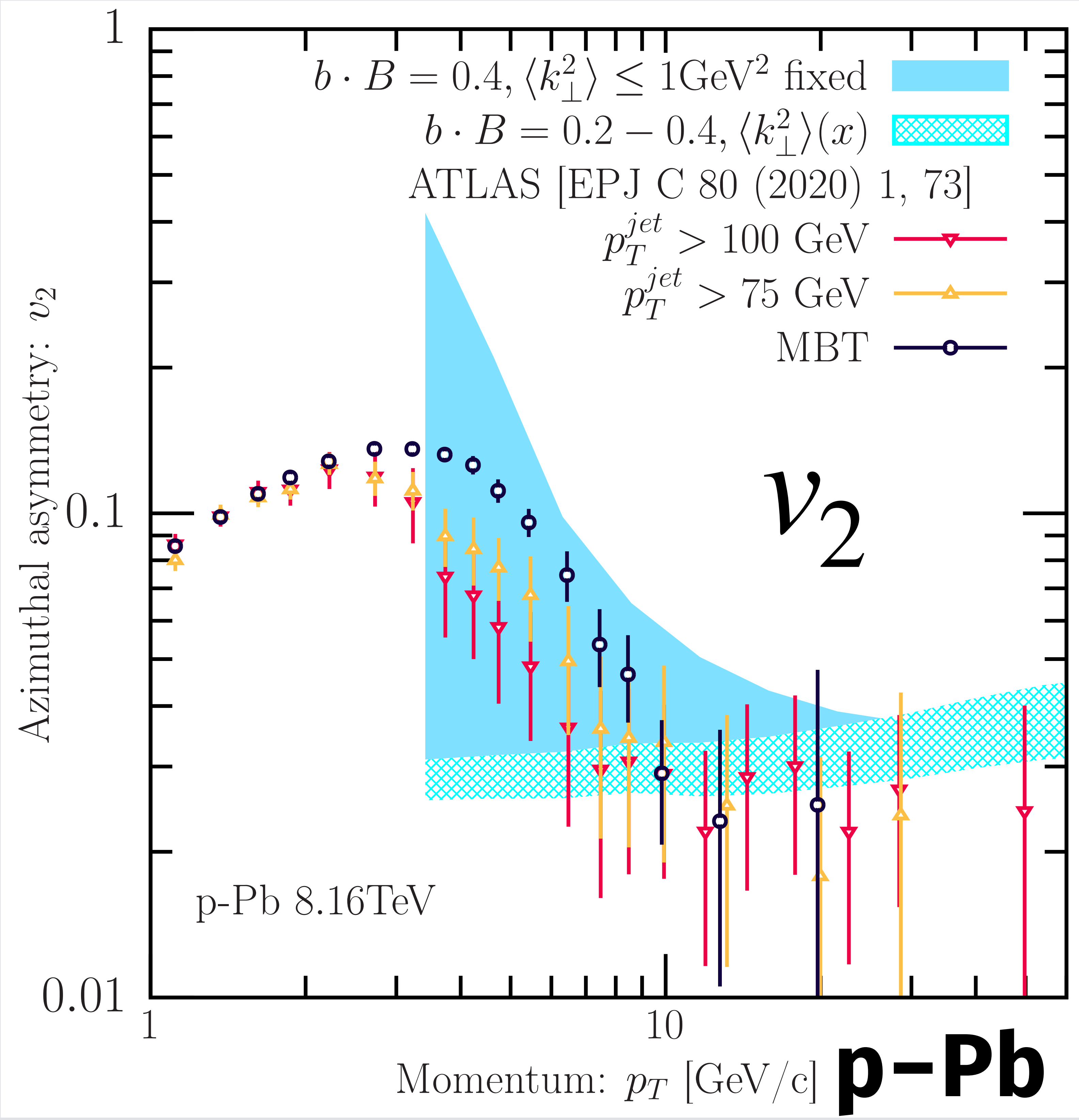
p-Pb



Preliminary

Conclusion

- High-p_T azimuthal correlations can be explained using TMD PDF/FF
- Heavy-ion studies provide a new approach to understand (T-even/T-odd) TMDs
- Include qg⟷qg / qq⟷qq: important at higher p_T
- Beyond the $A^{1/3}$ ⇒ Compute Spin-dependent rescattering in p-A

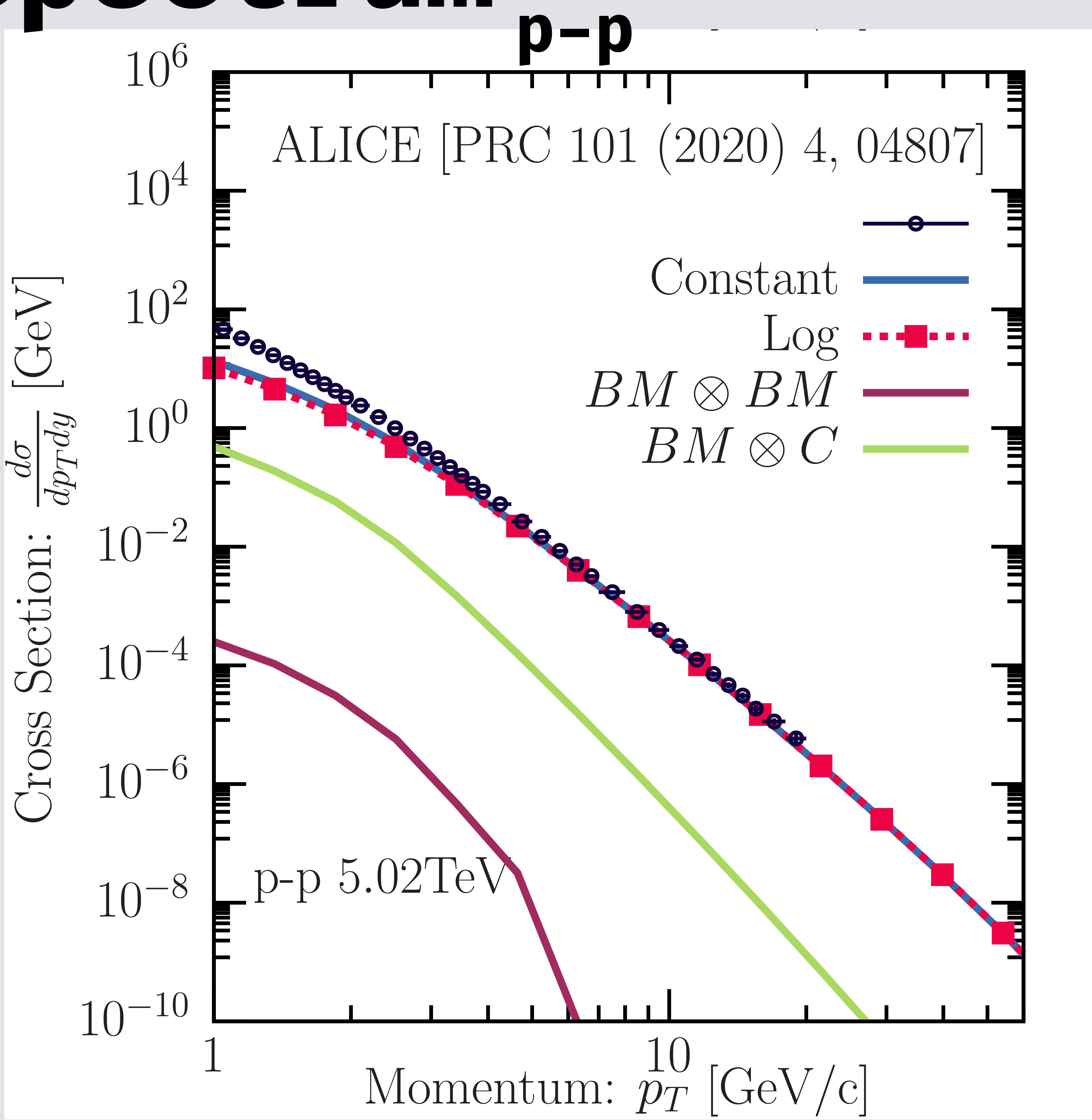


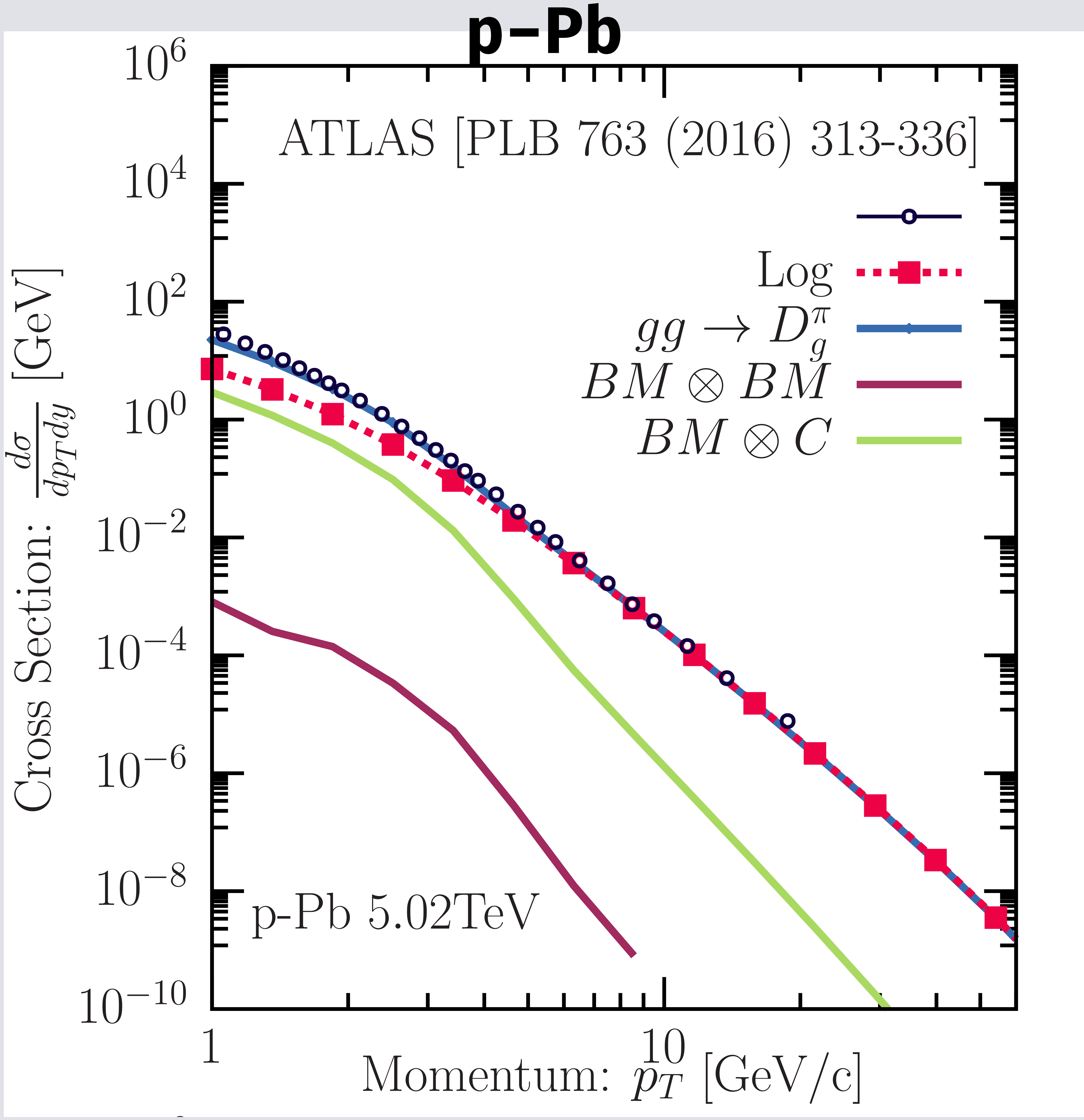
[I.S. A. Majumder ArXiv:2308.14702]

\o/ Thank you for listening!

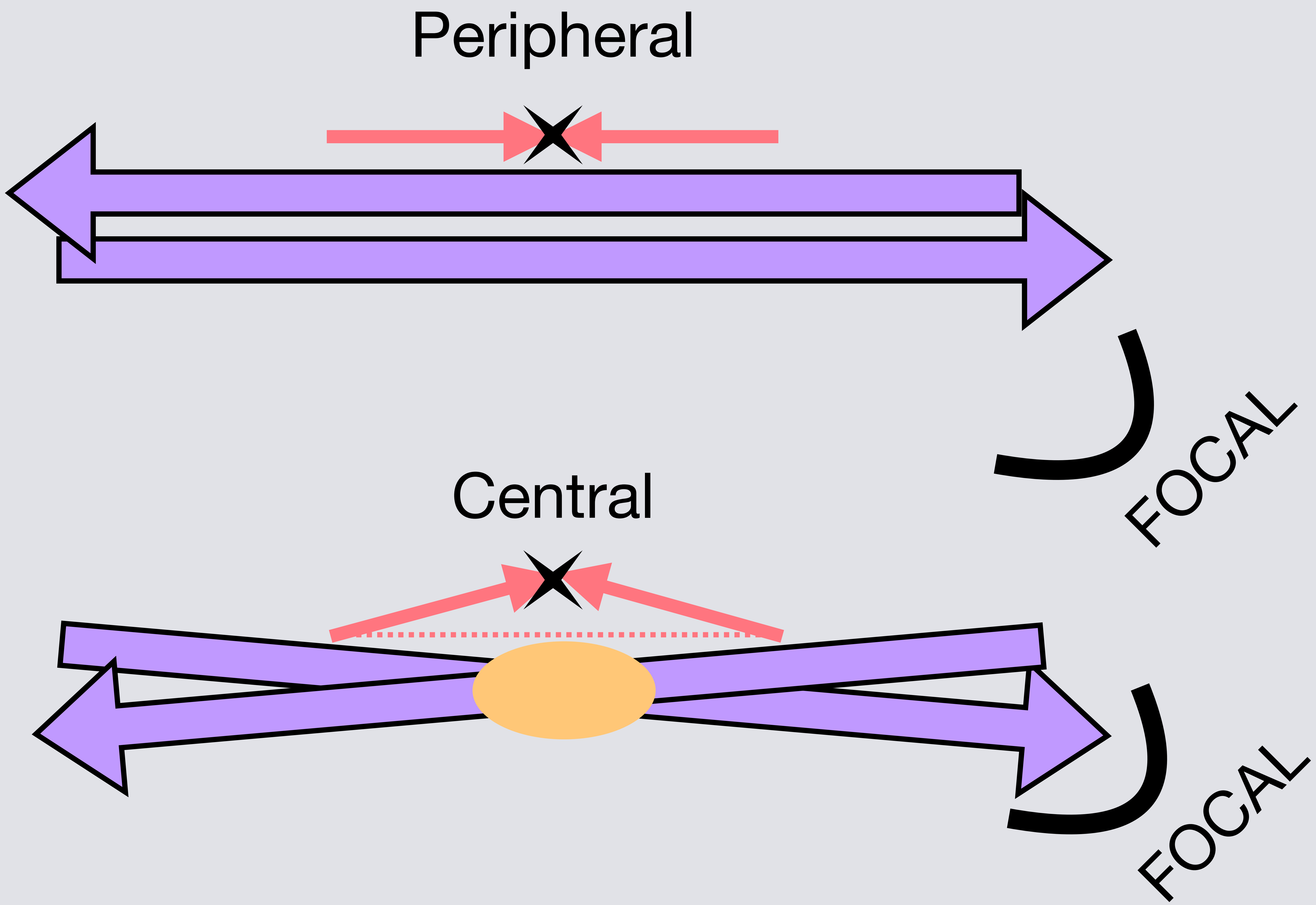
Backup

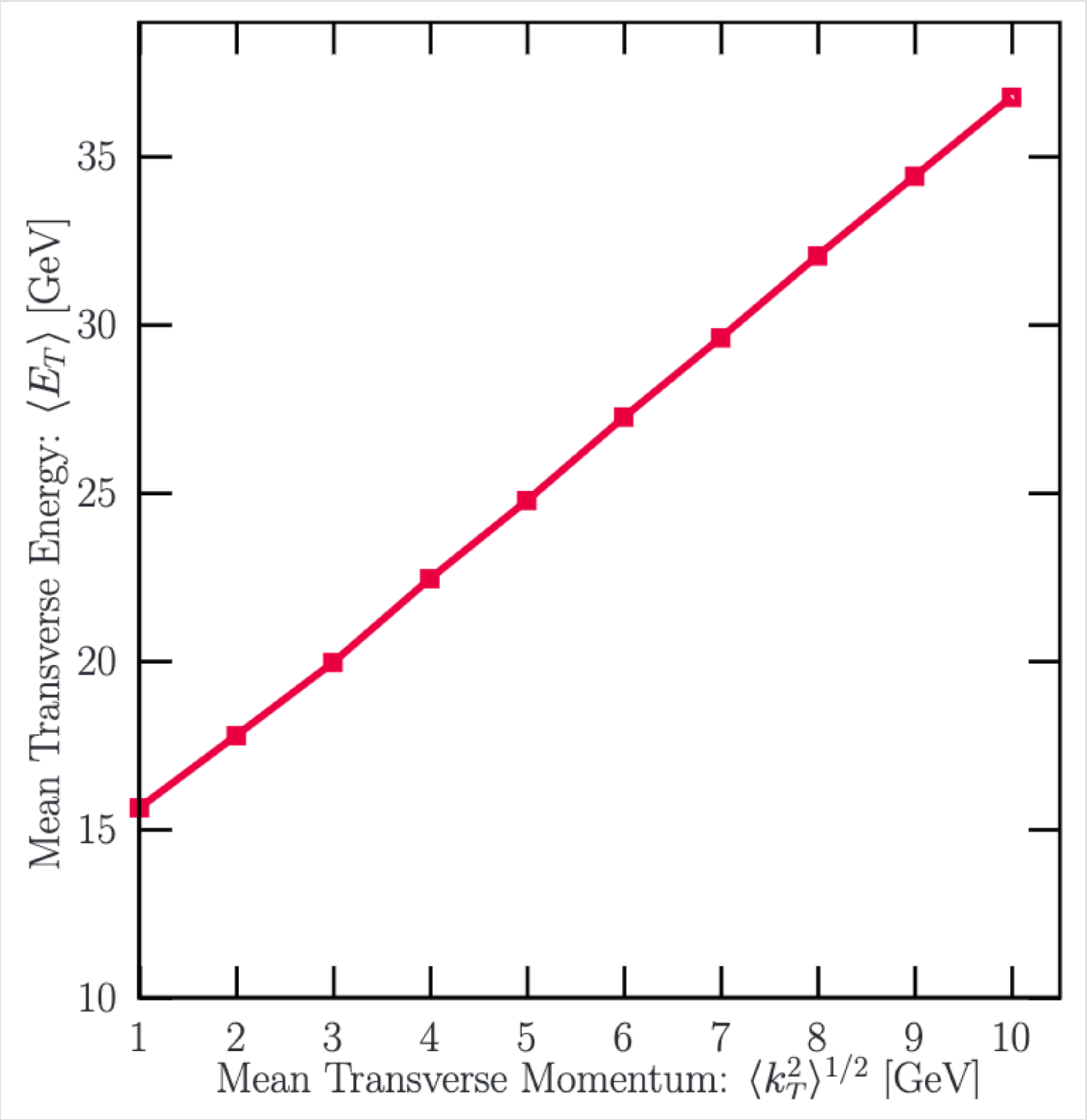
Spectrum


p-p
ALICE [PRC 101 (2020) 4, 04807]
Constant
Log
$BM \otimes BM$
$BM \otimes C$
p-p 5.02TeV
Cross Section: $\frac{d\sigma}{dp_T dy}$ [GeV]
Momentum: p_T [GeV/c]
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
1
10

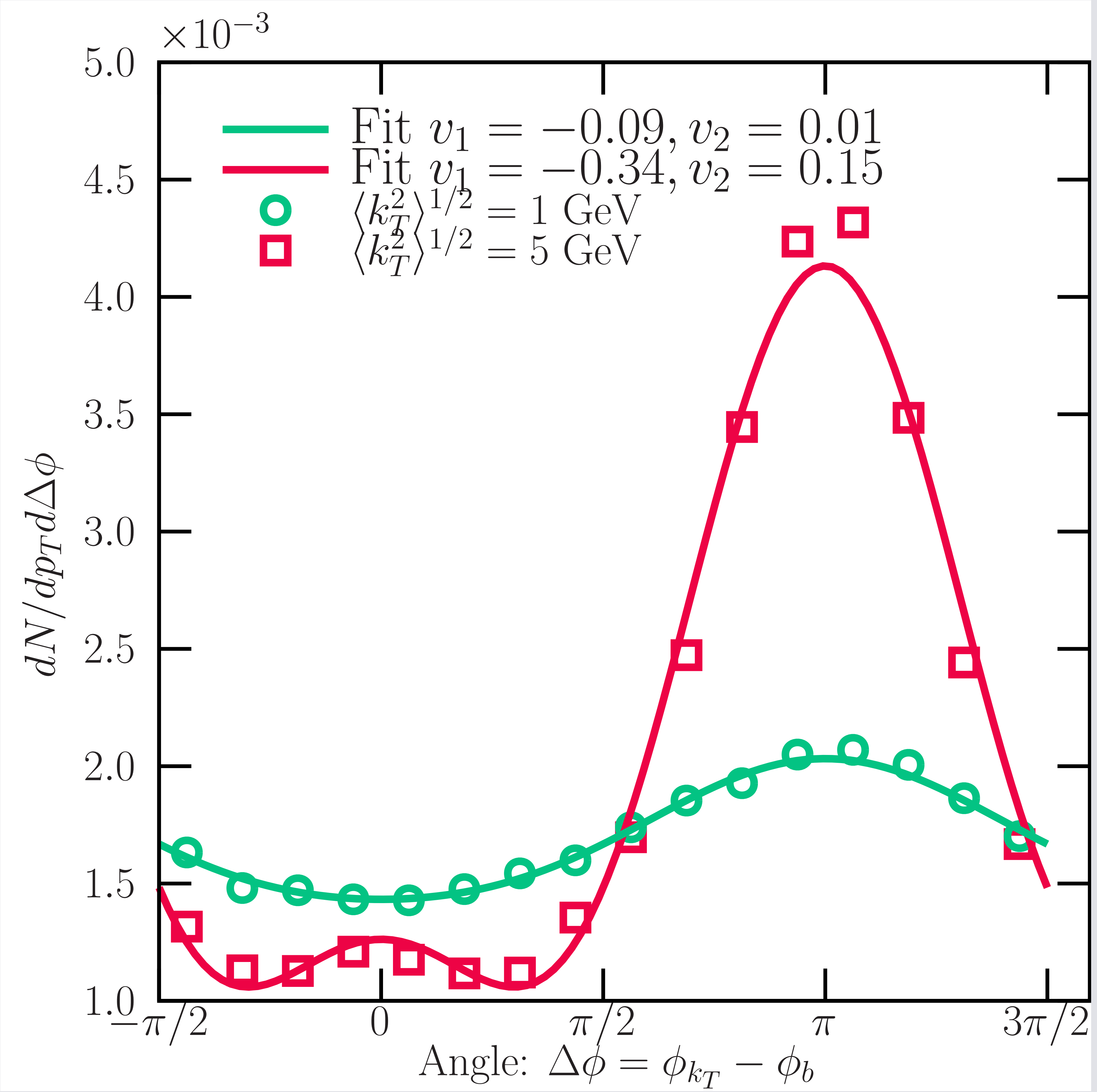

p-Pb
ATLAS [PLB 763 (2016) 313-336]
Log
$gg \to D_g^\pi$
$BM \otimes BM$
$BM \otimes C$
p-Pb 5.02TeV
Cross Section: $\frac{d\sigma}{dp_T dy}$ [GeV]
Momentum: p_T [GeV/c]
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
1
10

Centrality


Peripheral
Central
FOCAL
FOCAL


Mean Transverse Energy: $\langle E_T \rangle$ [GeV]
Mean Transverse Momentum: $\langle k_T^2 \rangle^{1/2}$ [GeV]
10
15
20
25
30
35
1
2
3
4
5
6
7
8
9
10

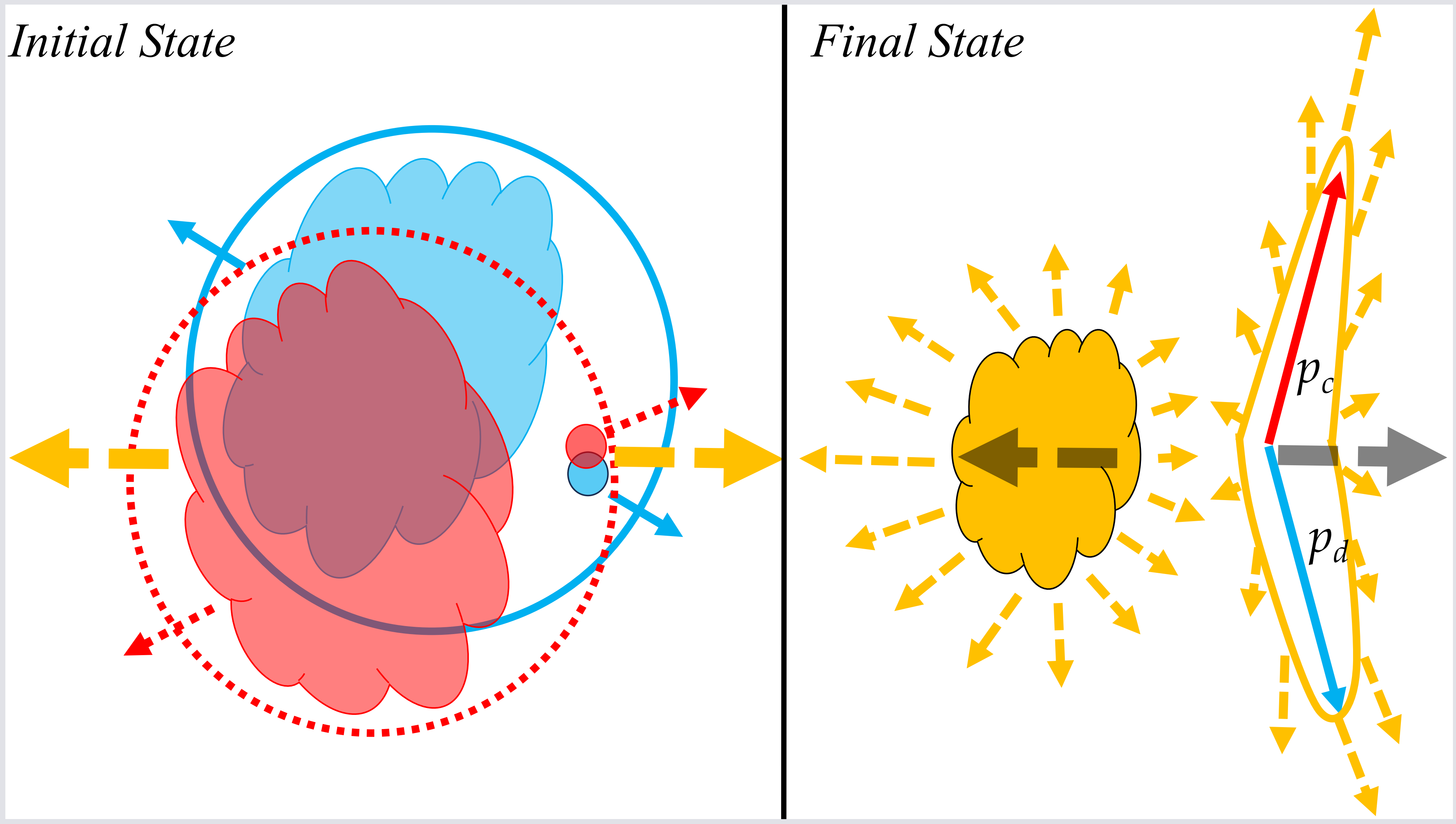
PYTHIA 8

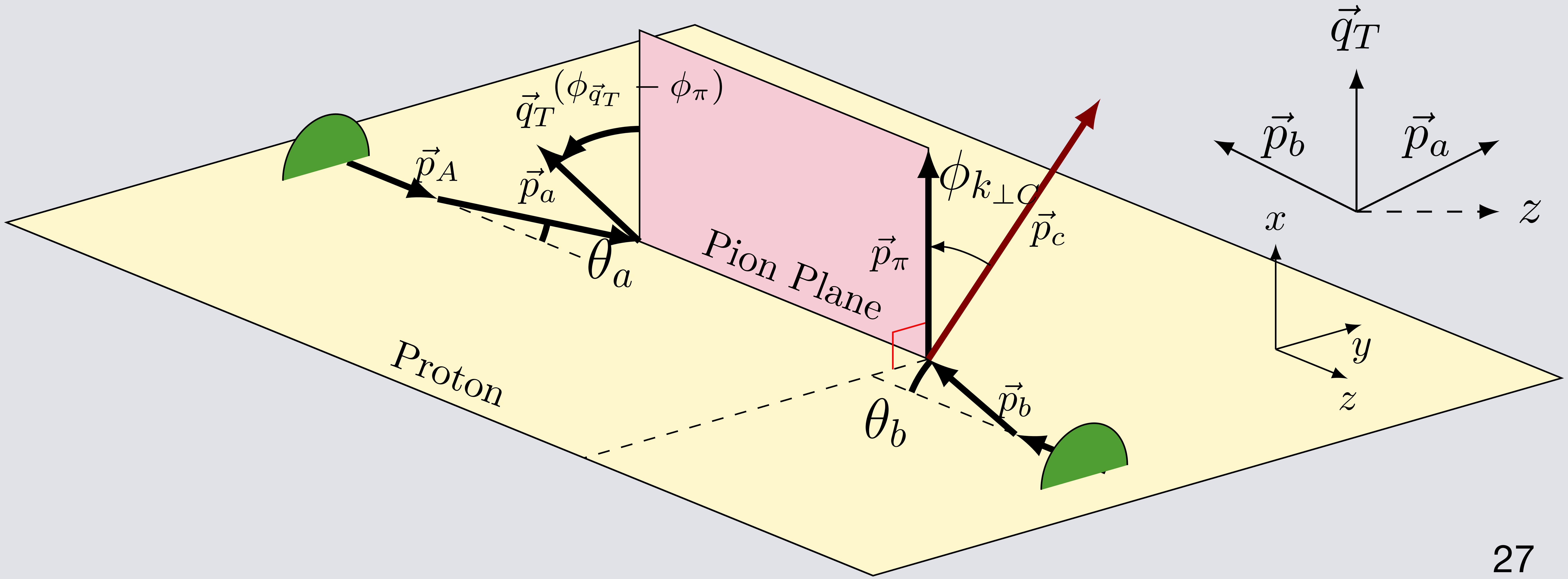


Ismail Soudi

TMD Scattering

In hadronic C.M.:
Due to momentum conservation
$\Rightarrow$ Direction of bulk given by $\vec{q}_T$





kT Dist

$$\langle k_\perp^2 \rangle^{1/2}(x) = \langle k_\perp^2 \rangle_0^{1/2} \left((1-x)\sqrt{\frac{s}{s_0}} \right)^{0.15} A^{1/3}$$

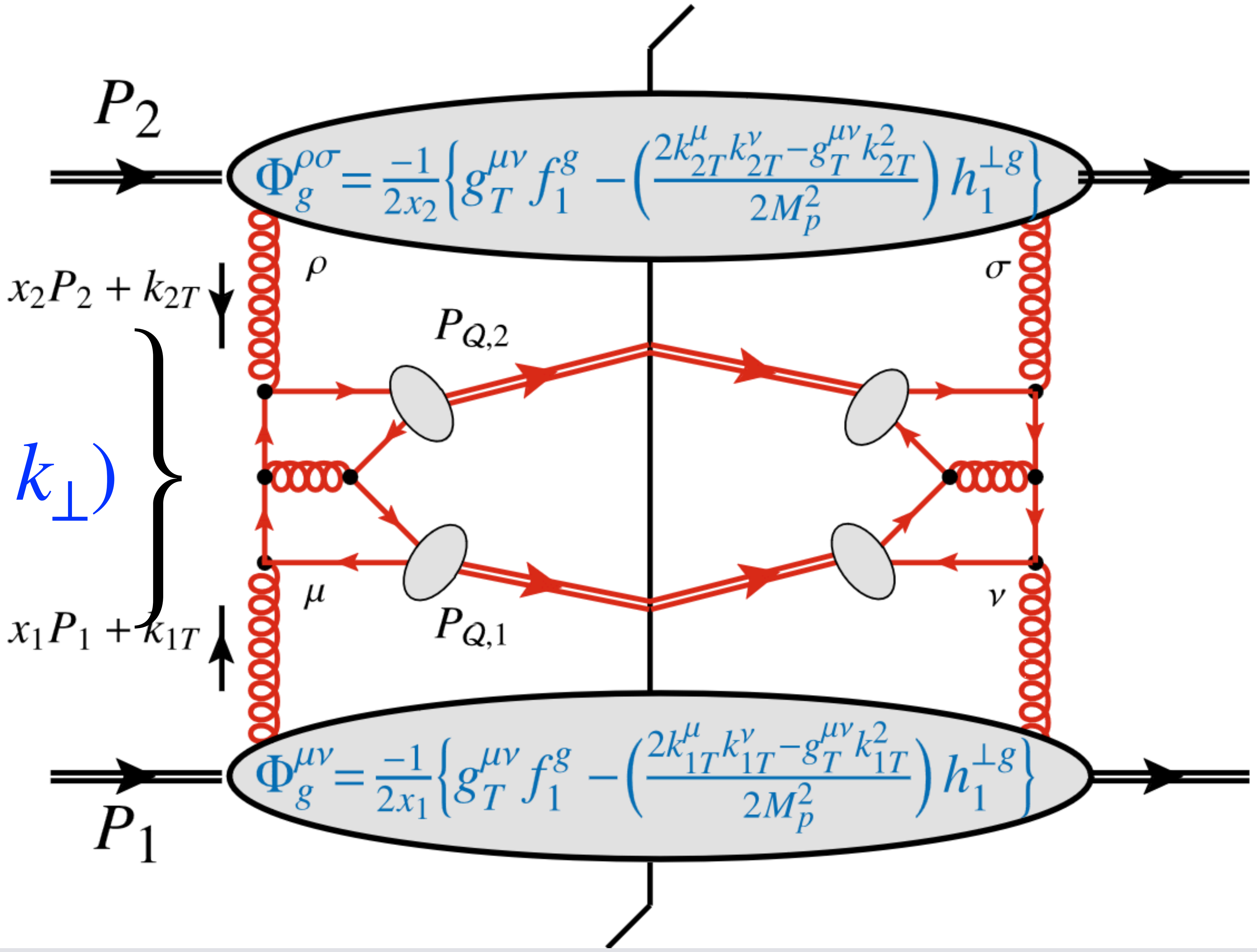
$$\times \begin{cases} \left(\frac{x}{x_0}\sqrt{\frac{s}{s_0}} \right)^{0.8}, & \text{if } x \le x_0 \\ \left[1 + b_0 \log\left(\frac{x}{x_0}\sqrt{\frac{s}{s_0}} \right) \right]^{1/2}, & \text{if } x > x_0 \end{cases}$$

Transverse Momentum Distributions

For unpolarized hadrons

⇒ Gluon correlator

$$\Phi^{\alpha\beta} = \frac{1}{2x}\left\{ -g_T^{\alpha\beta} f^g(x, k_\perp) + \left(\frac{k_\perp^\alpha k^\beta}{M^2} + g_T^{\alpha\beta} \frac{k_\perp^2}{2M^2} \right) h^{\perp g}(x, k_\perp) \right\}$$



[F. Scarpa et al., Eur.Phys.J.C 80 (2020) 2, 87]

Unpolarized + Boer-Mulders/Collins

Soffer Bound:

$$\frac{k_\perp^2}{2M^2} \left| h^{\perp g}(x, k_\perp) \right| \leq f^g(x, k_\perp)$$

Transverse Momentum Distributions

[F. G. Celiberto Universe 8 (2022) 12]

For unpolarized hadrons

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$$\Phi^{\alpha\beta} = \frac{1}{2x}\left\{ -g_T^{\alpha\beta} f^g(x, k_\perp) + \left(\frac{k_\perp^\alpha k_\perp^\beta}{M^2} + g_T^{\alpha\beta} \frac{k_\perp^2}{2M^2} \right) h^{\perp g}(x, k_\perp) \right\}$$

Unpolarized + Boer-Mulders/Collins

Soffer Bound:

$$\frac{k_\perp^2}{2M^2} \left| h^{\perp g}(x, k_\perp) \right| \leq f^g(x, k_\perp)$$