



Azimuthal anisotropies at high- p_T from transverse momentum dependent (TMD) parton distribution and fragmentation functions

Ismail Soudi

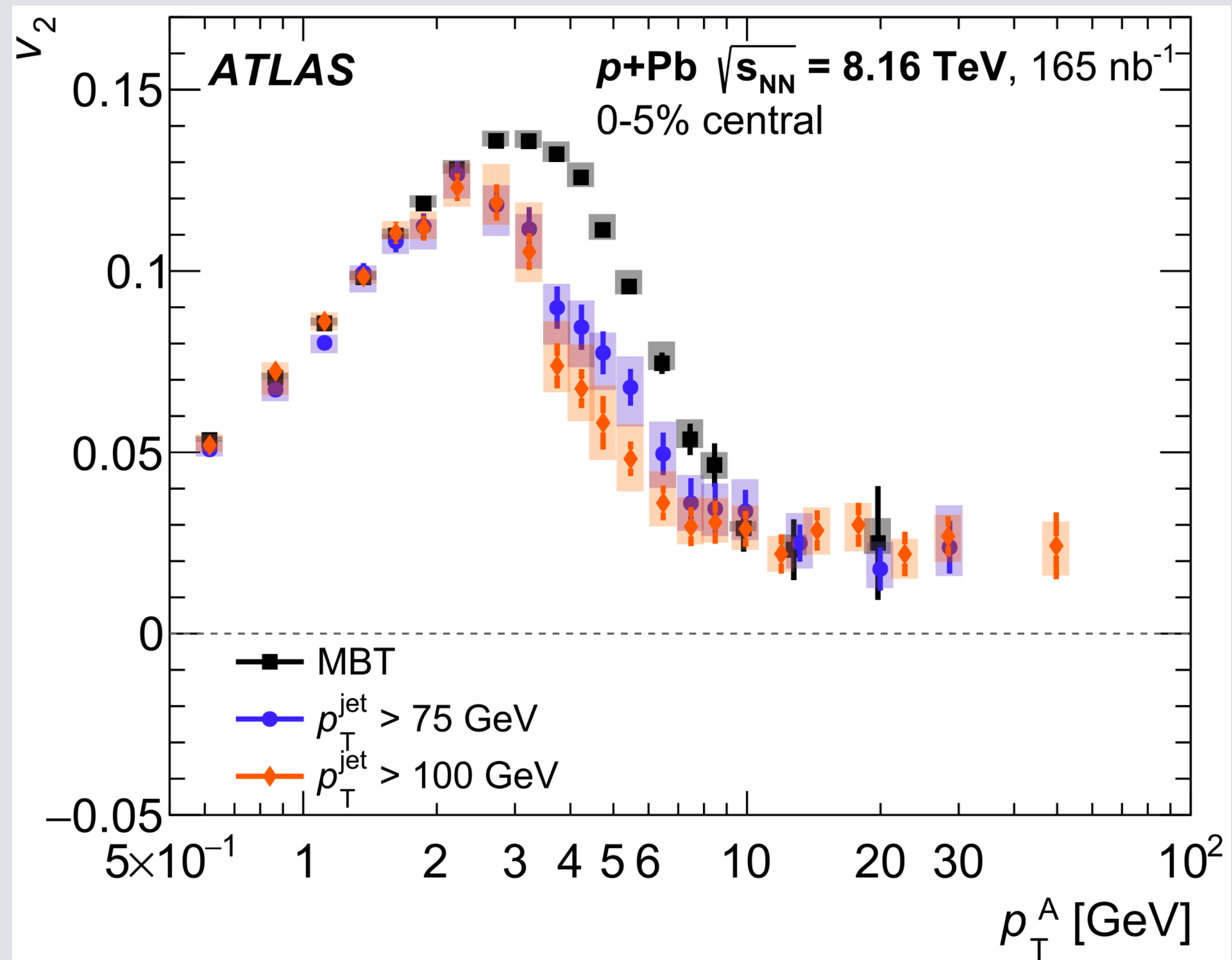
Wayne State University

Based on IS and Abhijit Majumder ArXiv:[2308.14702](https://arxiv.org/abs/2308.14702)

Quark Matter 2023, Houston

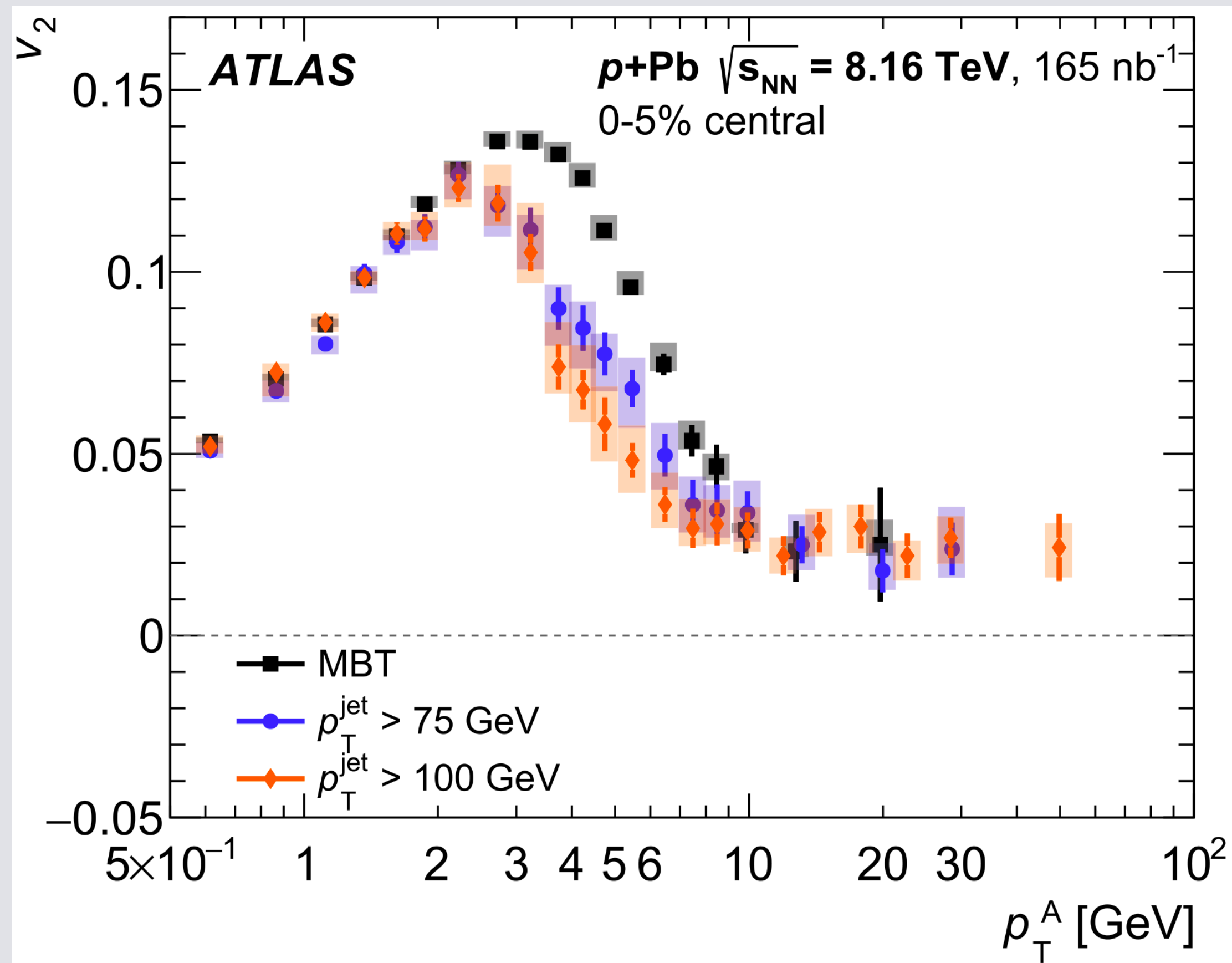


Small systems

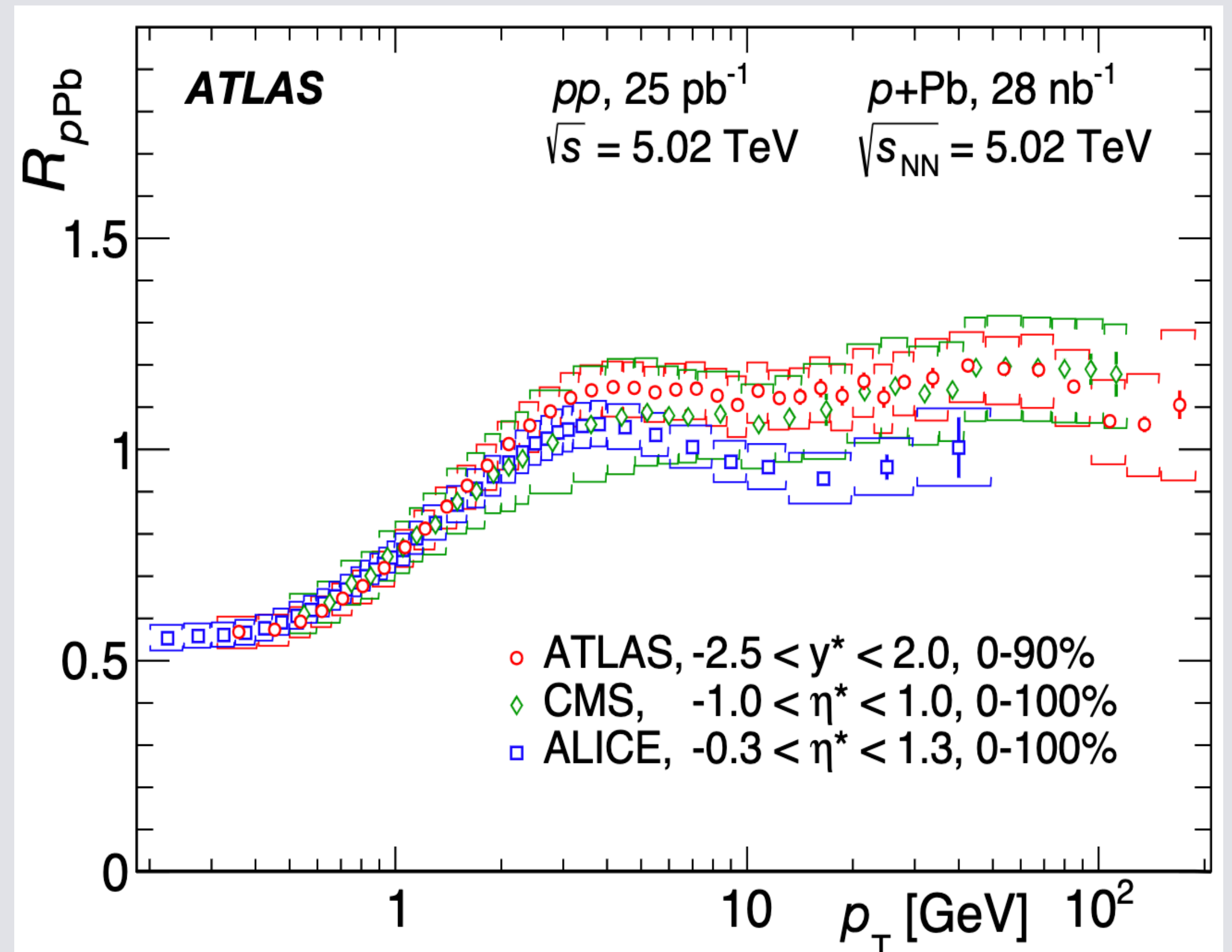


[ATLAS Eur. Phys. J. C 80 (2020) 73]

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]

Transverse Momentum Distributions

Table of TMD PDFs

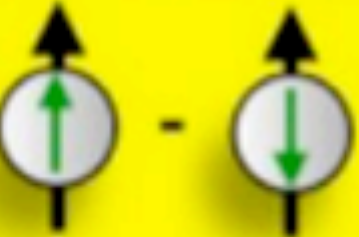
nucleon (N)

unpolarized quark (Q)

nucleon spin

quark spin

quark k_T

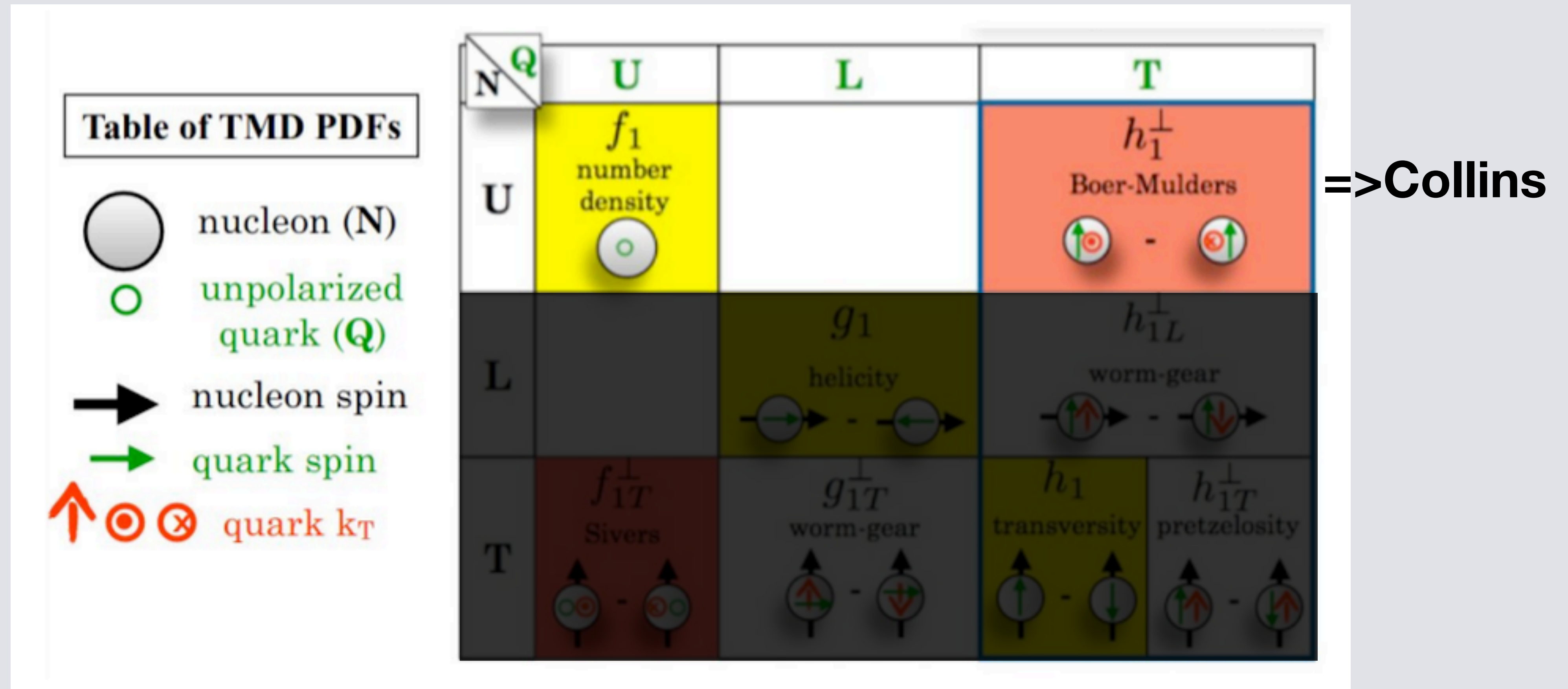
N \ Q	U	L	T	
U	f_1 number density 		$h_1^\perp$ Boer-Mulders 	
L		g_1 helicity 	$h_{1L}^\perp$ worm-gear 	
T	$f_{1T}^\perp$ Sivers 	$g_{1T}^\perp$ worm-gear 	h_1 transversity 	$h_{1T}^\perp$ pretzelosity 

=>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

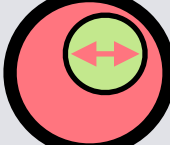


[Fig from PHENIX Spin Physics Overview]

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Transverse Momentum Distributions

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

-  Unpolarized gluon inside unpolarized hadron
-  Linearly polarized gluon inside unpolarized hadron

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

Requires two flips for unpolarized pion production

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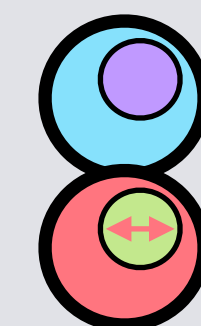
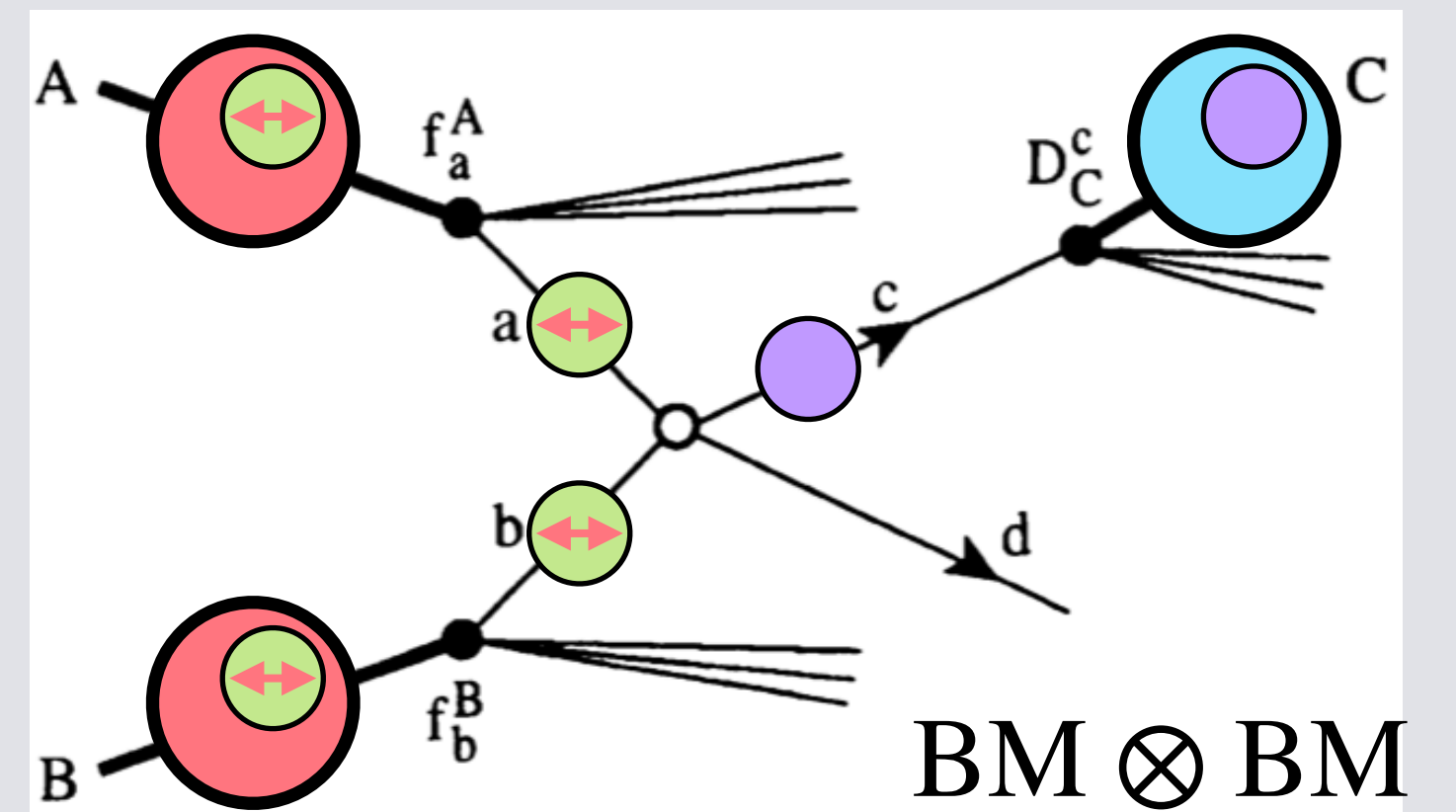
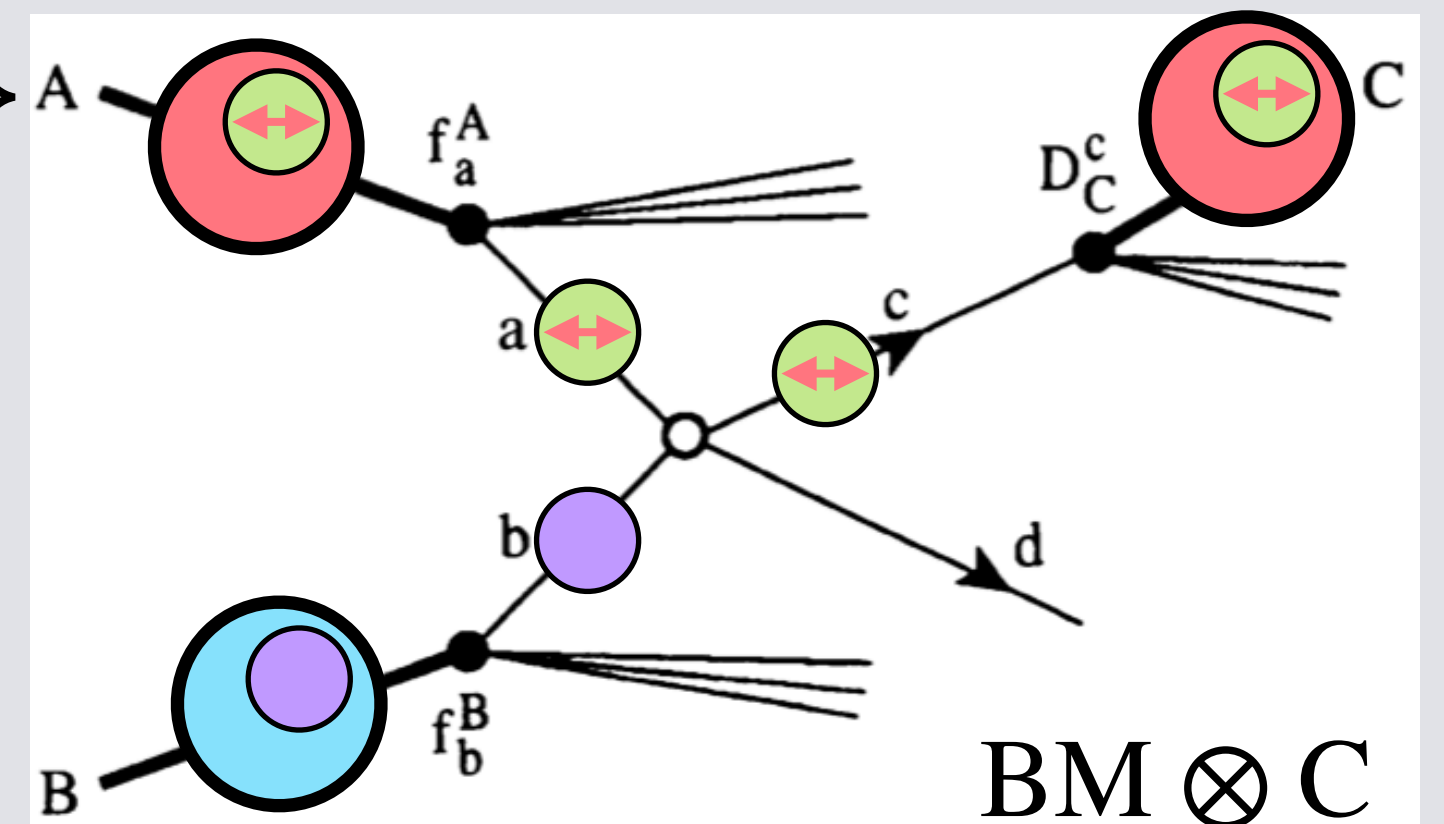
For $gg \longleftrightarrow gg$:

• $BM \otimes C$

$$\Rightarrow M_{\lambda,\lambda}^{\lambda,\lambda} \left(M_{-\lambda,\lambda}^{-\lambda,\lambda} \right)^*$$

• $BM \otimes BM$

$$\Rightarrow M_{-\lambda,\lambda}^{\lambda,-\lambda} \left(M_{-\lambda,\lambda}^{-\lambda,\lambda} \right)^*$$



Unpolarized gluon inside unpolarized hadron

Linearly polarized gluon inside unpolarized hadron

Spin-helicity formalism

Matrix element for $\text{BM} \otimes \text{C}$ Naturally contains asymmetries

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

with

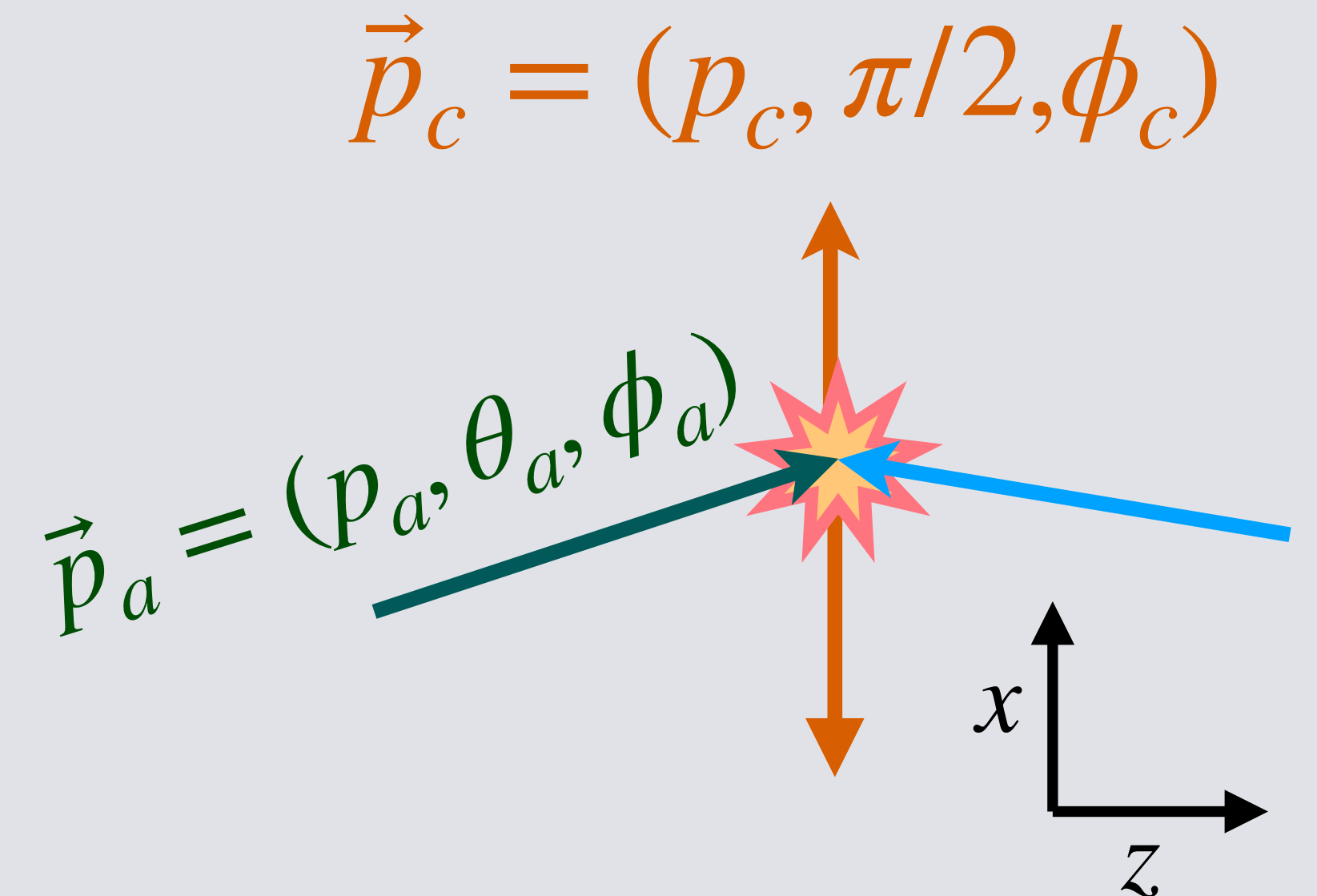
$$\hat{M}_1^0 \hat{M}_2^0 = \frac{9}{4} g_s^4 \frac{u^2 + tu + t^2}{t^2}, \quad \text{and} \quad \tan \phi_{ij} = \tan \frac{\phi_j - \phi_i}{2} \frac{\sin \frac{\theta_j + \theta_i}{2}}{\sin \frac{\theta_j - \theta_i}{2}}.$$
$$\hat{M}_1^0 \hat{M}_3^0 = \frac{9}{4} g_s^4 \frac{u^2 + tu + t^2}{u^2},$$

[I.S. A. Majumder [ArXiv:2308.14702](https://arxiv.org/abs/2308.14702)]

Spin Independent

TMD matrix element contains angular correlations as well

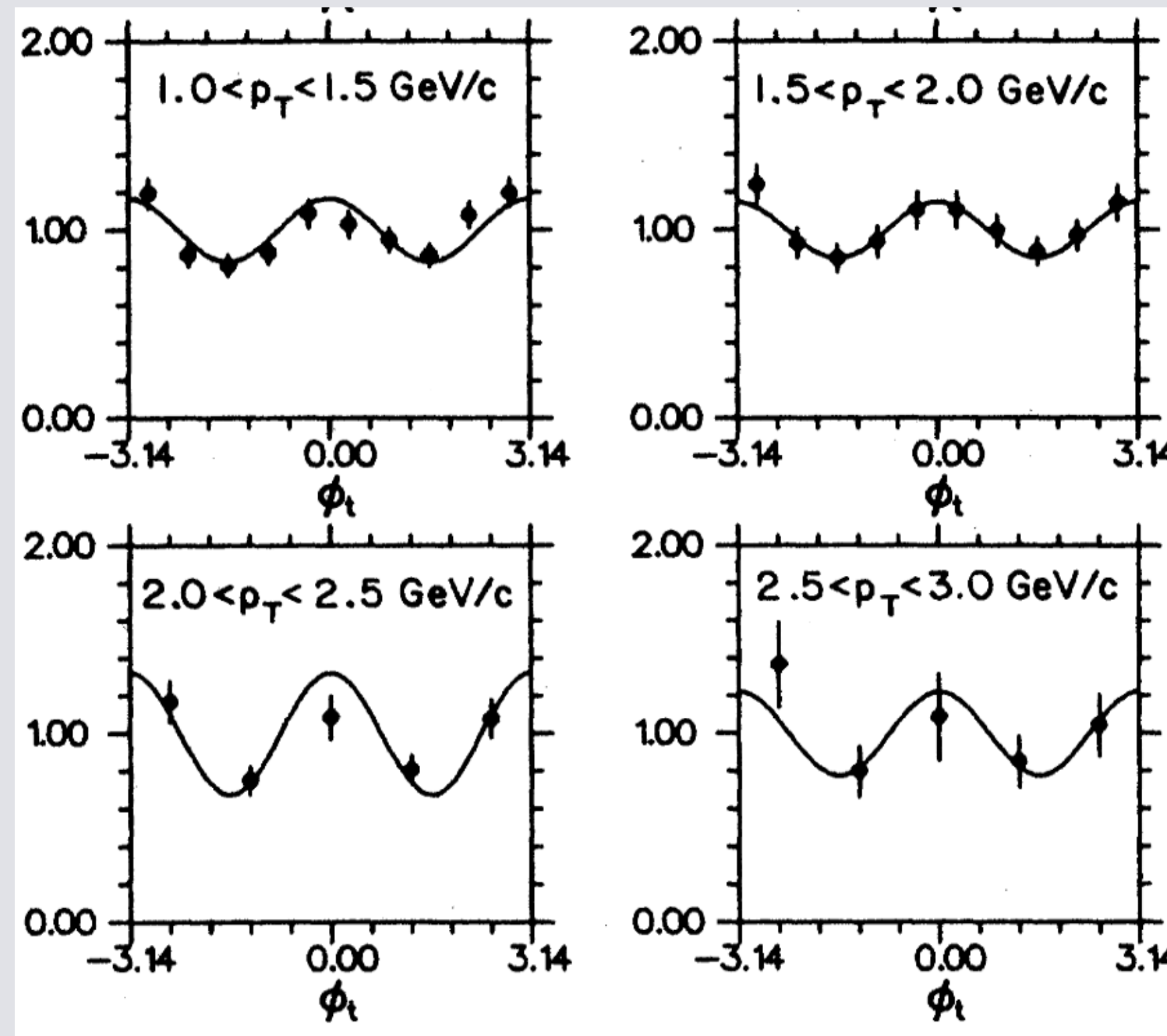
$$\begin{aligned} \frac{\hat{s}}{\hat{t}} &= \frac{-\hat{s}}{2p_c \cdot p_a} \stackrel{\theta_a \ll 1}{=} \frac{-\hat{s}}{2p_c p_a [1 - \theta_a \cos(\phi_a - \phi_c)]} \\ &= \frac{-\hat{s}}{2p_c p_a} \left[1 + \frac{\theta_a^2}{4} + \theta_a \cos(\phi_a - \phi_c) \right. \\ &\quad \left. + \frac{\theta_a^2 \cos(2(\phi_a - \phi_c))}{4} + \mathcal{O}(\theta_a^3) \right]. \end{aligned}$$



[I.S. A. Majumder [ArXiv:2308.14702](https://arxiv.org/abs/2308.14702)]

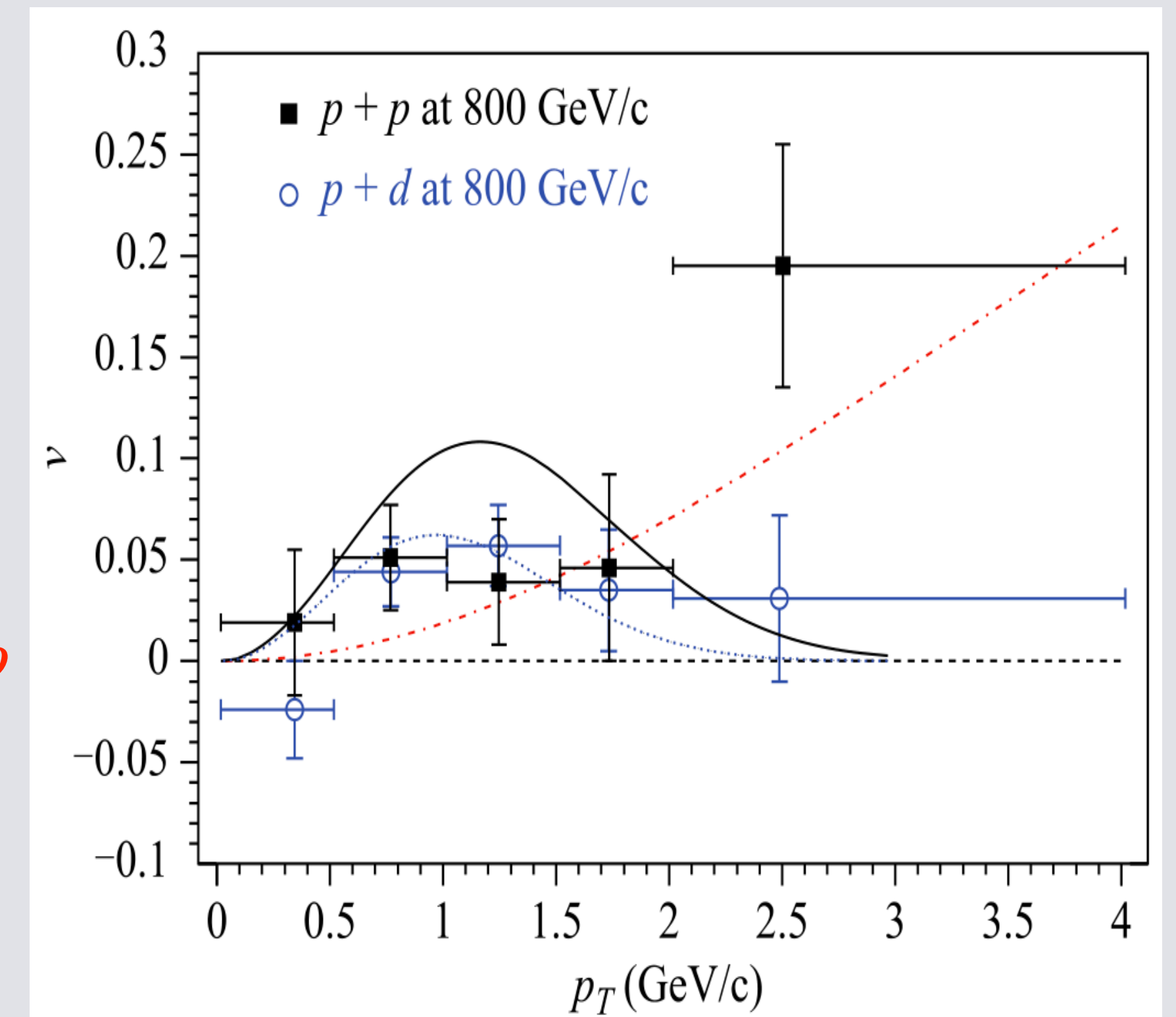
Anisotropies in Drell-Yann

Distribution



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

Average



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

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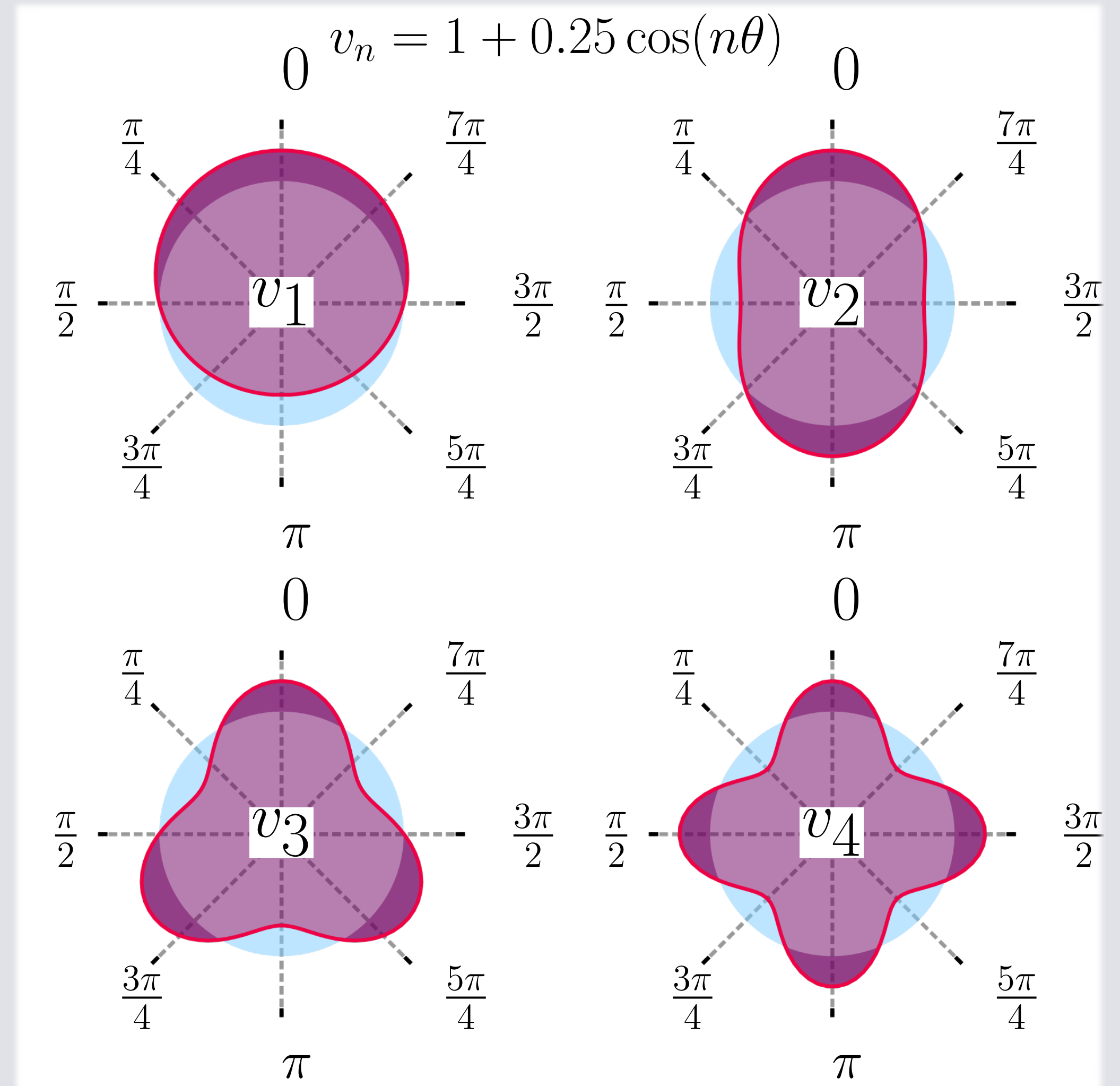
[B. Zhang et al., PRD 77, 054011]

[Z. Lu, FP 11 (2016) 1, 111204]

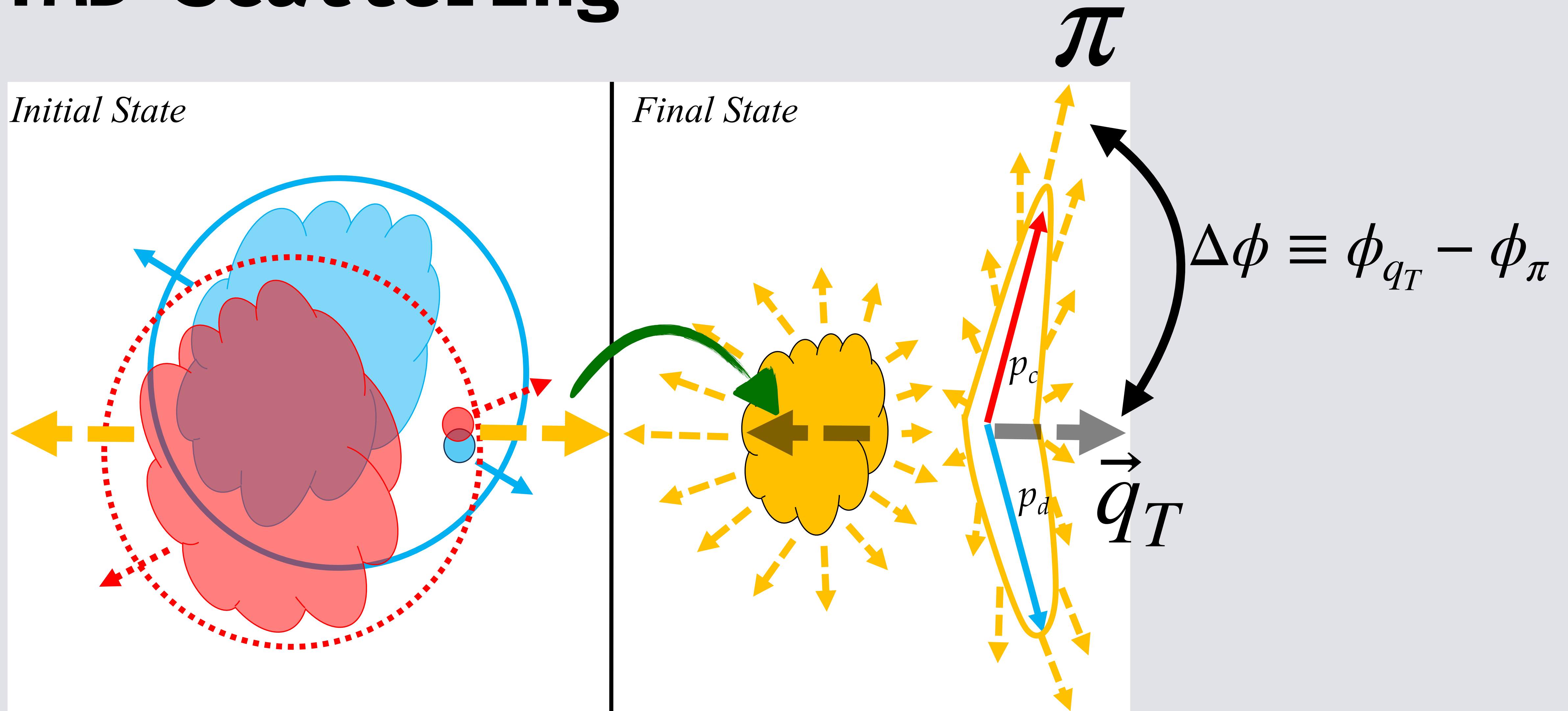
v_n Azimuthal Anisotropies

Azimuthal momentum correlated
with soft bulk (event plane)

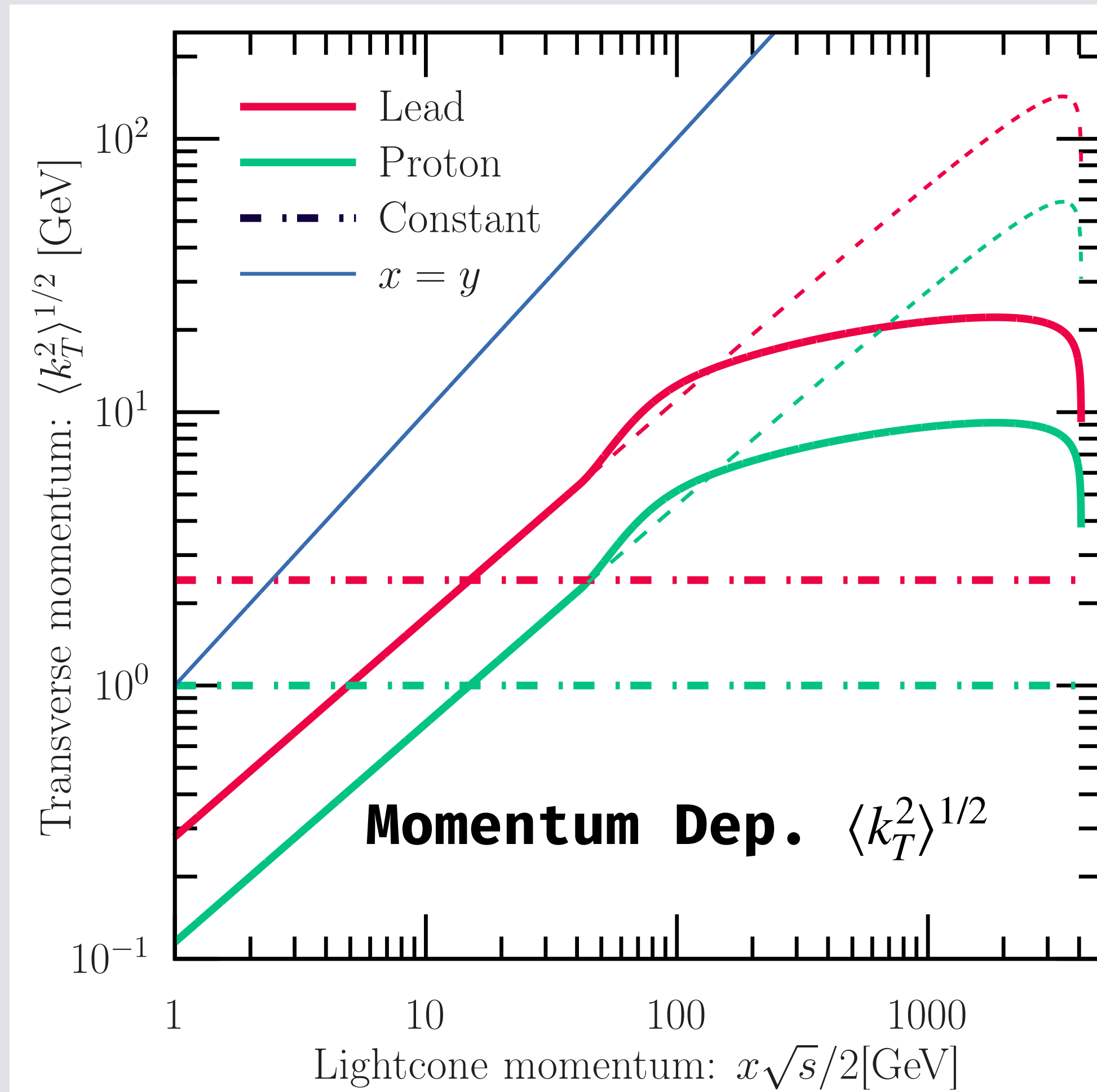
$$\frac{dN}{d\phi} \propto 1 + \sum_1^{\infty} 2v_n \cos[n(\phi - \Psi_n)]$$



TMD Scattering



p-p Results



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

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

Factorization of $(x \otimes k_T)$

⇒ 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 $gg \rightarrow gg$ only

⇒ Most relevant for kinematics

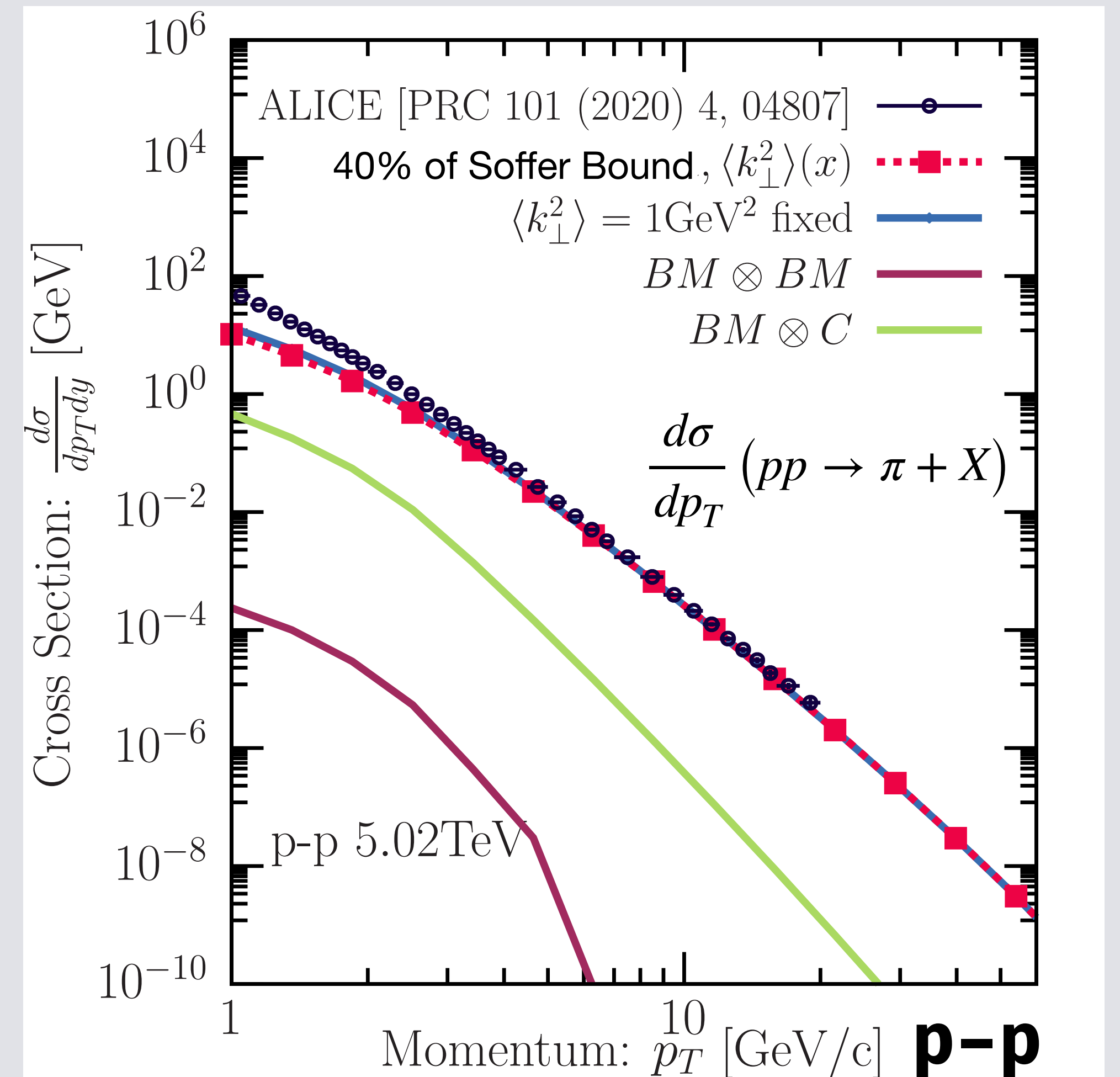
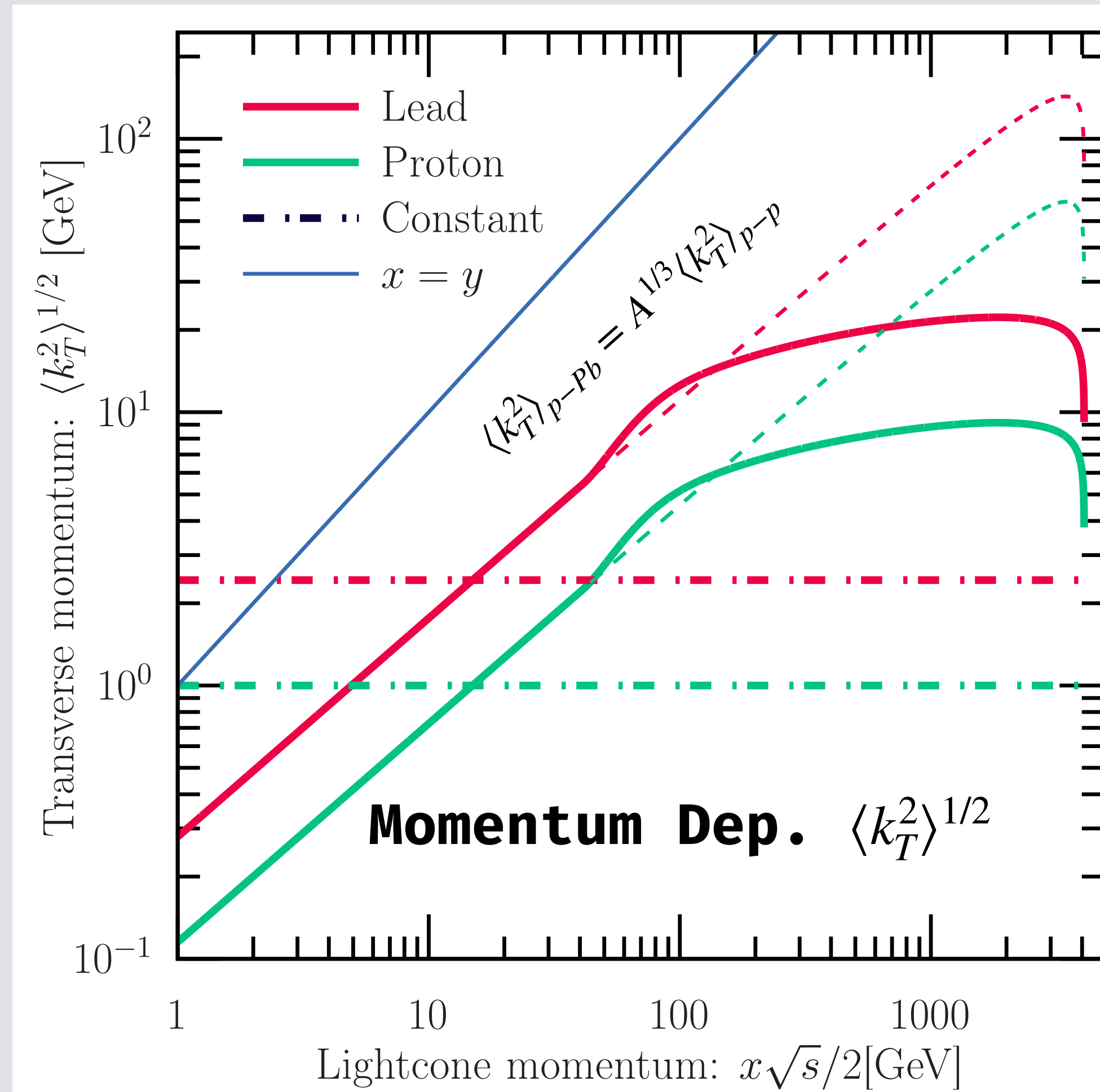
[X. Guo, Phys. Phys. Rev. D 58, 036001(1998)]

[R. J. Fries, Phys. Rev. D 68, 074013 (2003)]

[A. Majumder and B. Müller, Phys. Rev. C 77, 054903 (2008)]

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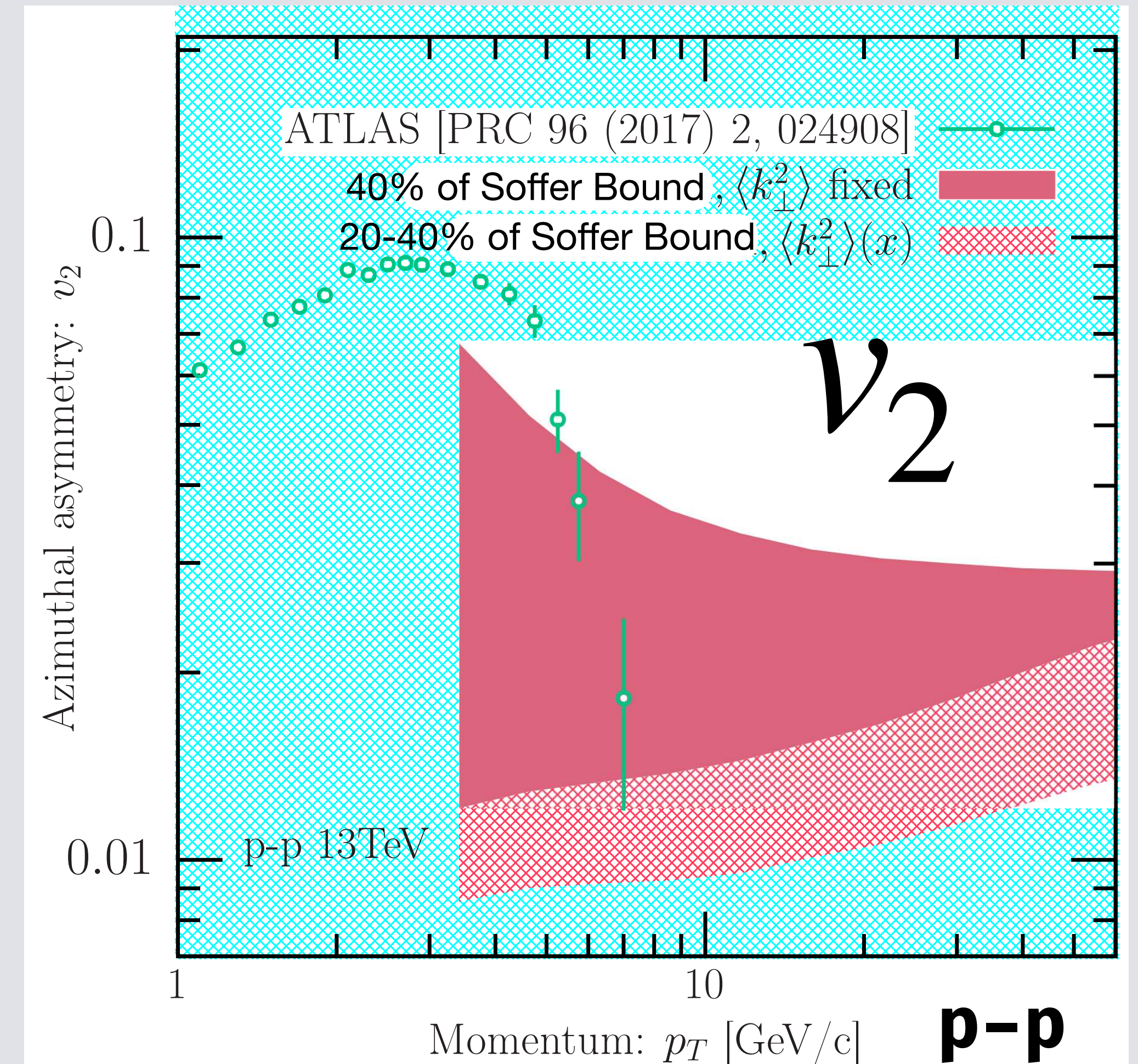
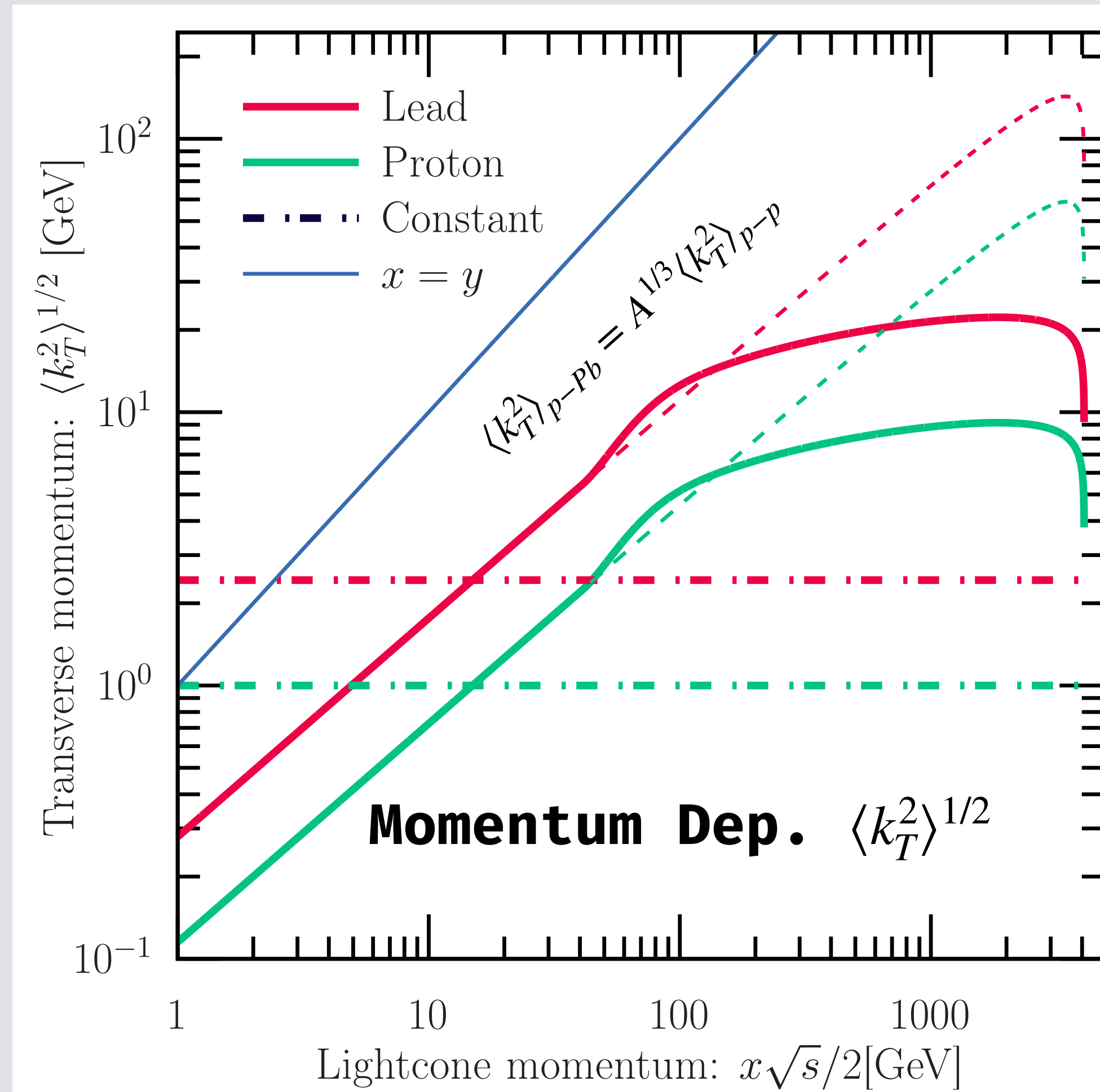
We use nCTEQ PDFs and KKP FFs

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

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

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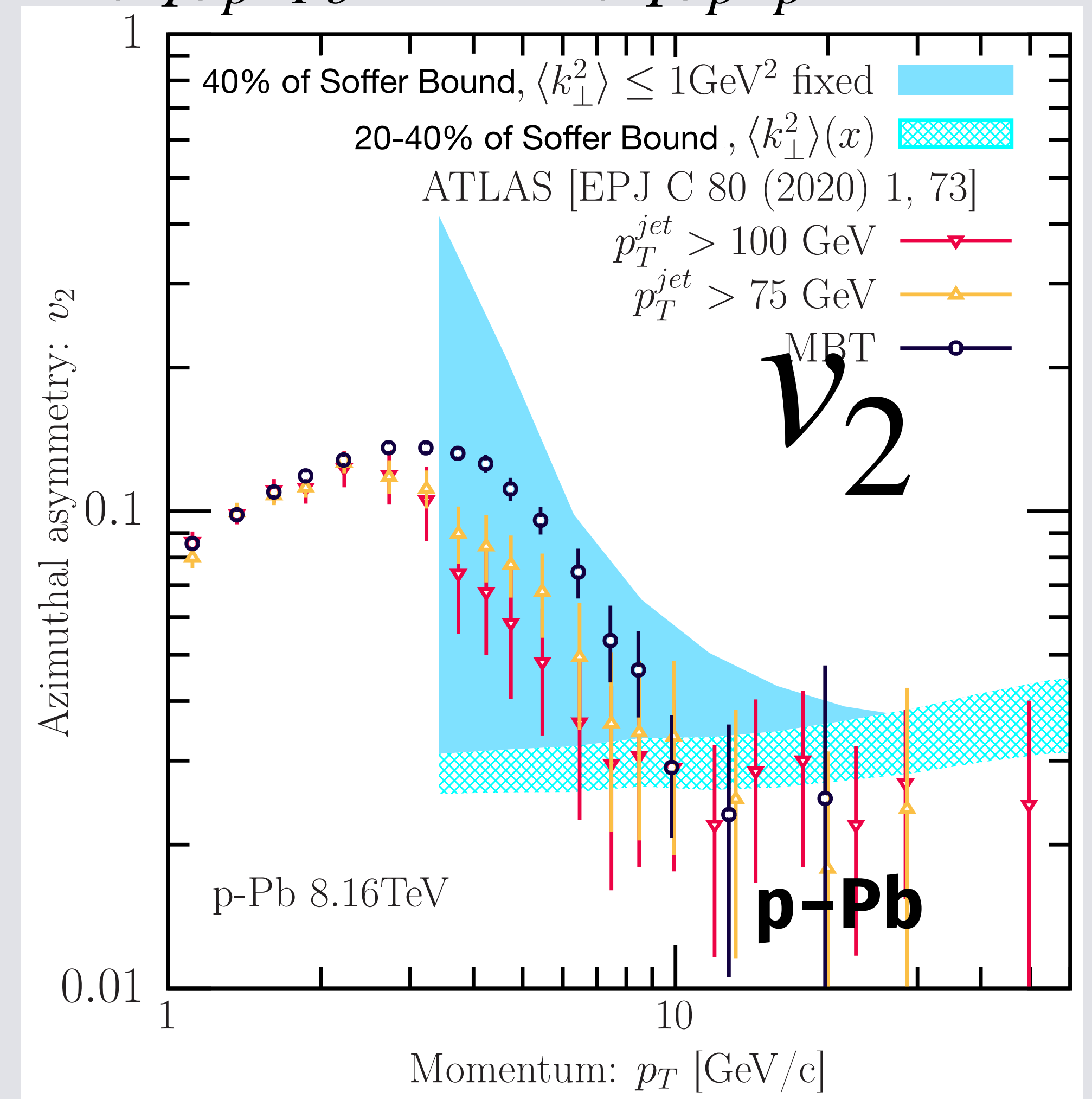


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[I.S. A. Majumder ArXiv:2308.14702]

Results

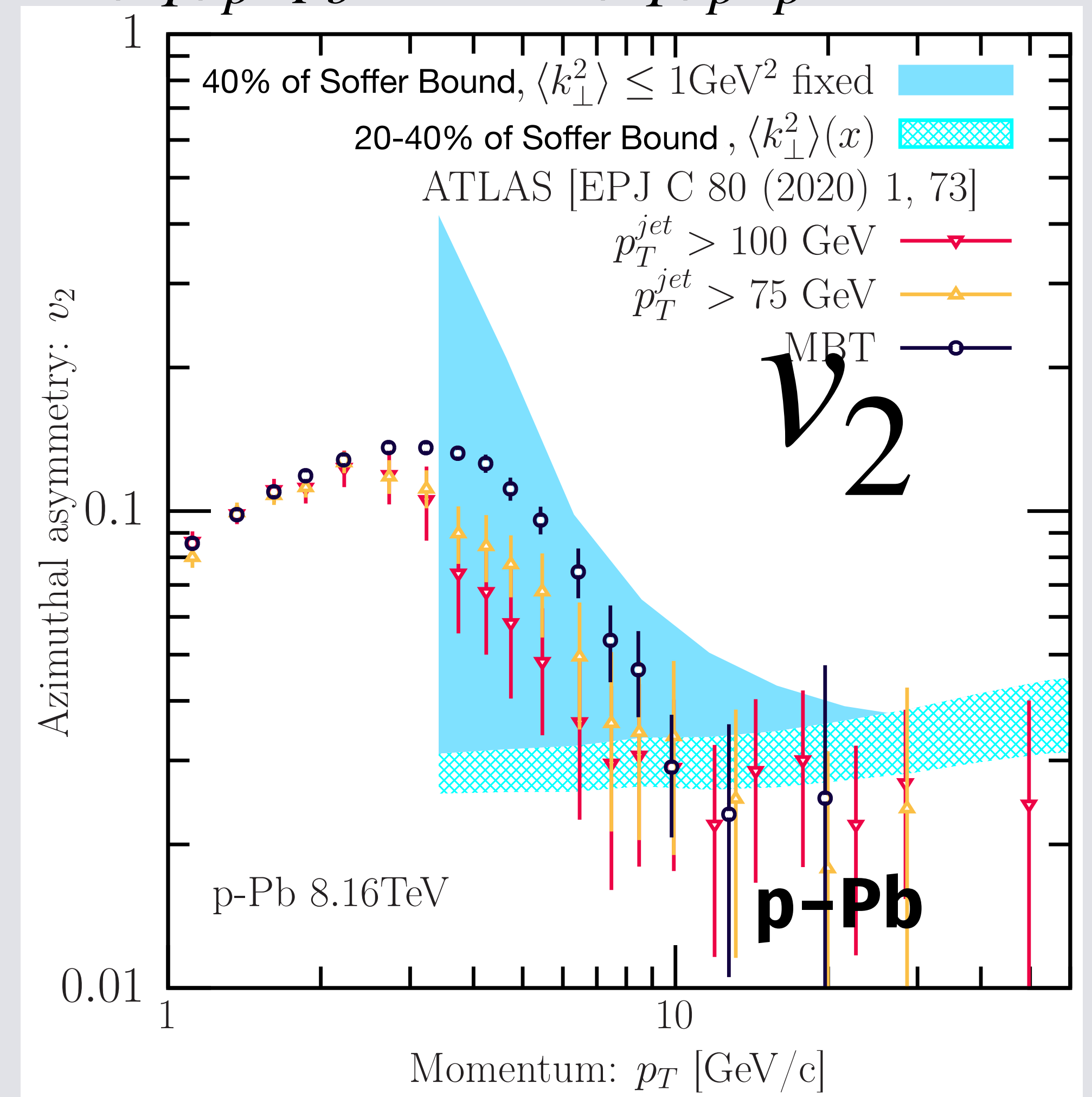
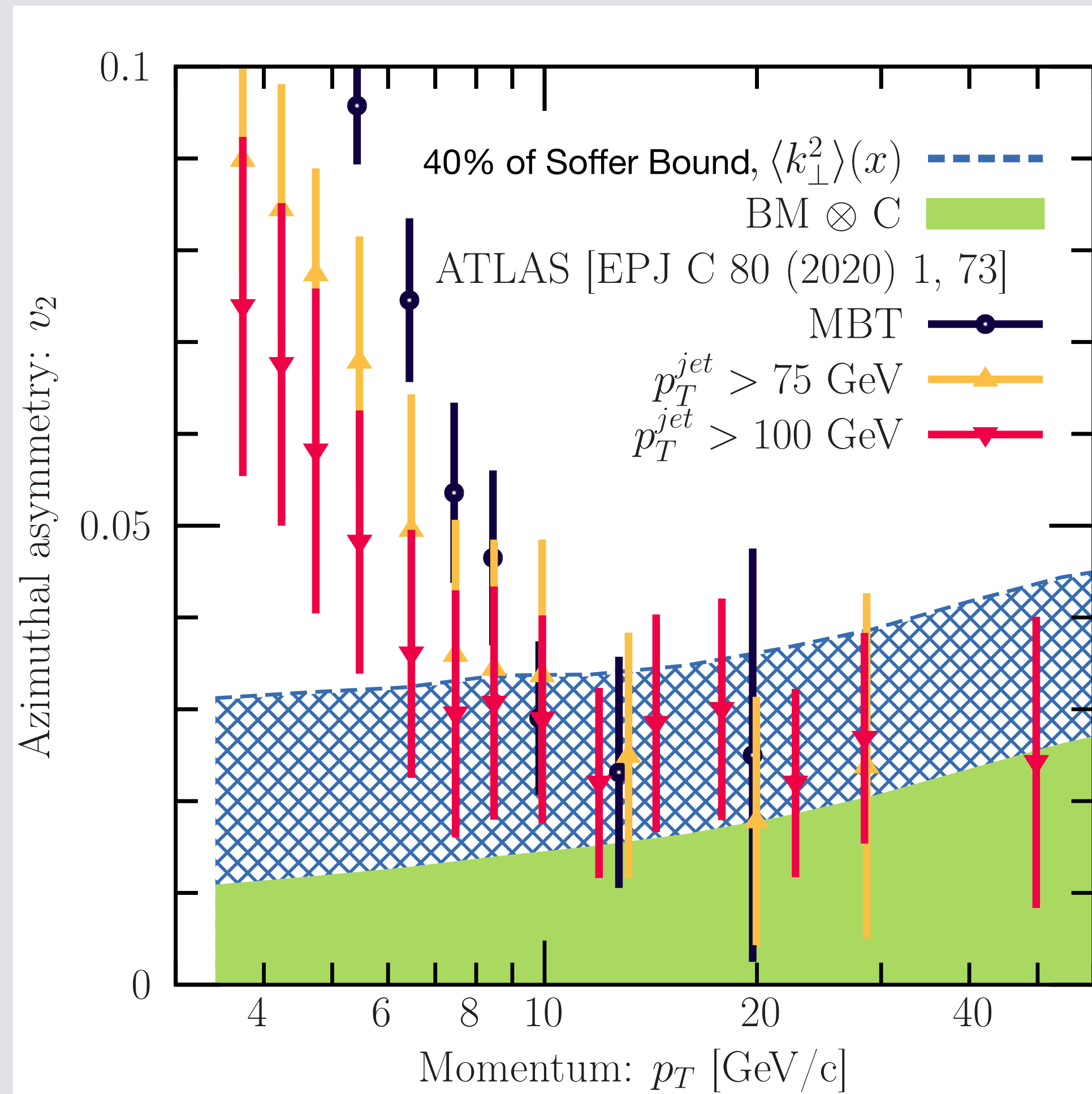
$$\text{Approximation} \Rightarrow \langle k_T^2 \rangle_{p-Pb} = A^{1/3} \langle k_T^2 \rangle_{p-p}$$



[I.S. A. Majumder [ArXiv:2308.14702](https://arxiv.org/abs/2308.14702)]

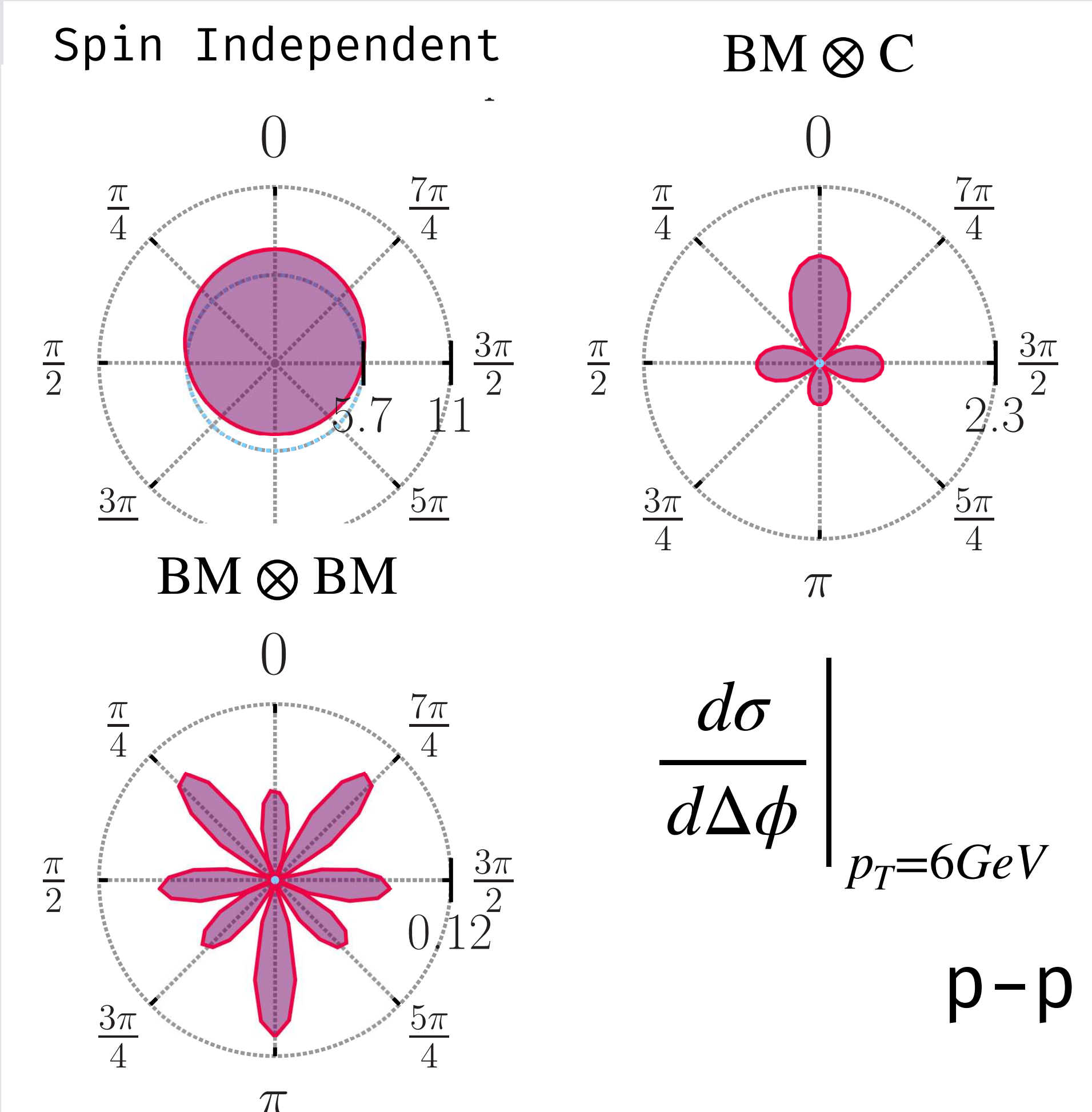
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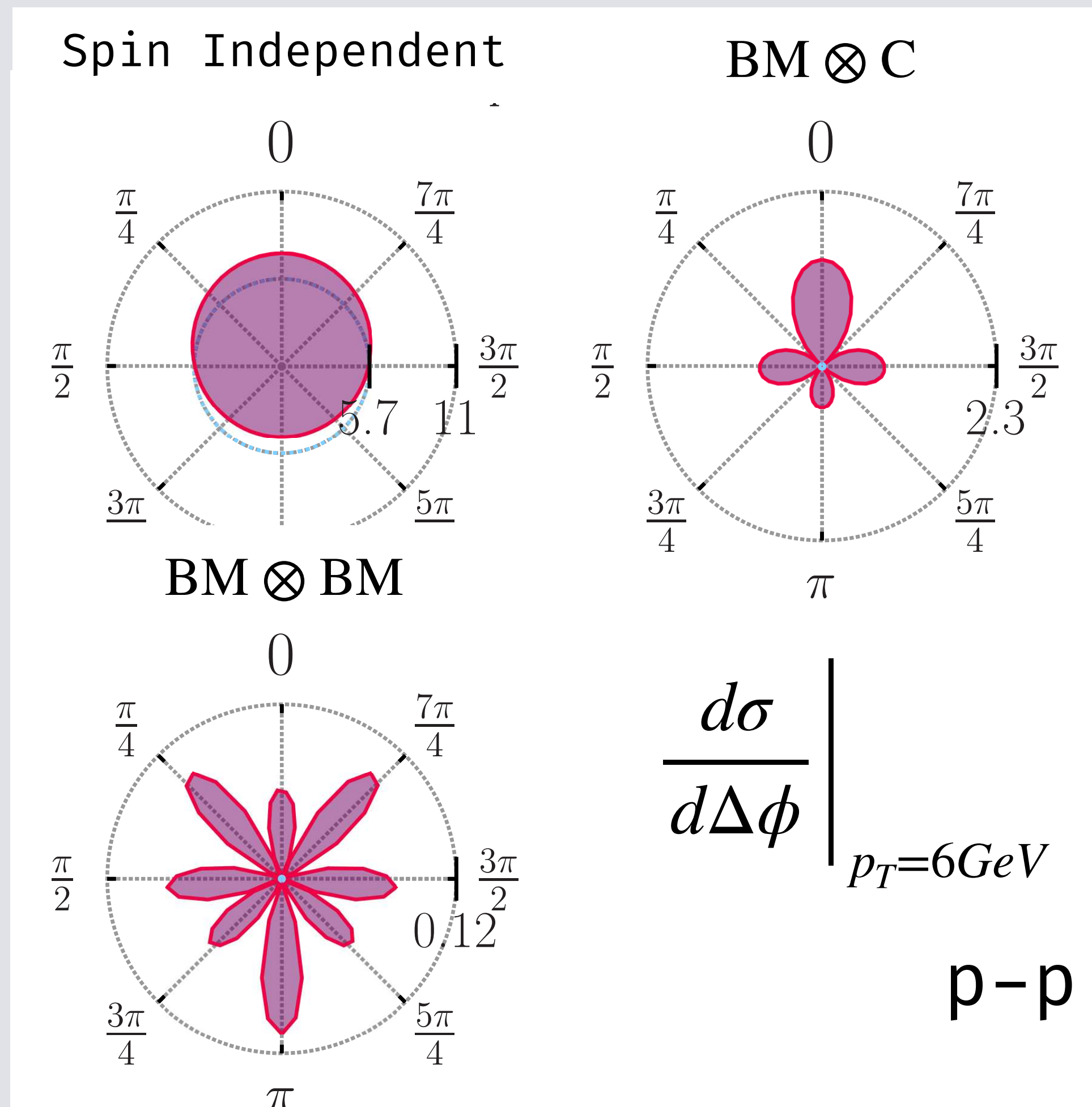
[I.S. A. Majumder ArXiv:2308.14702]

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

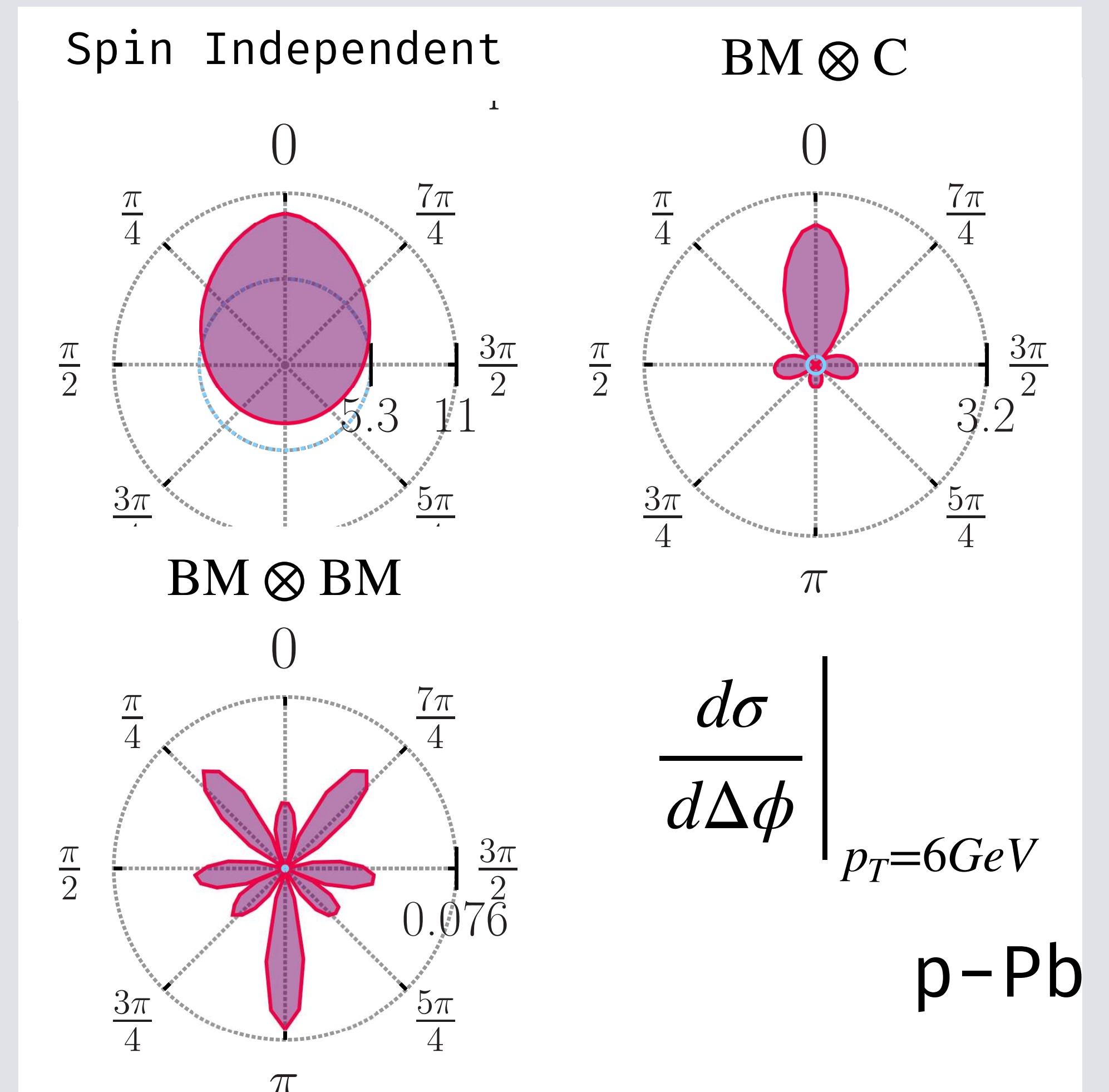


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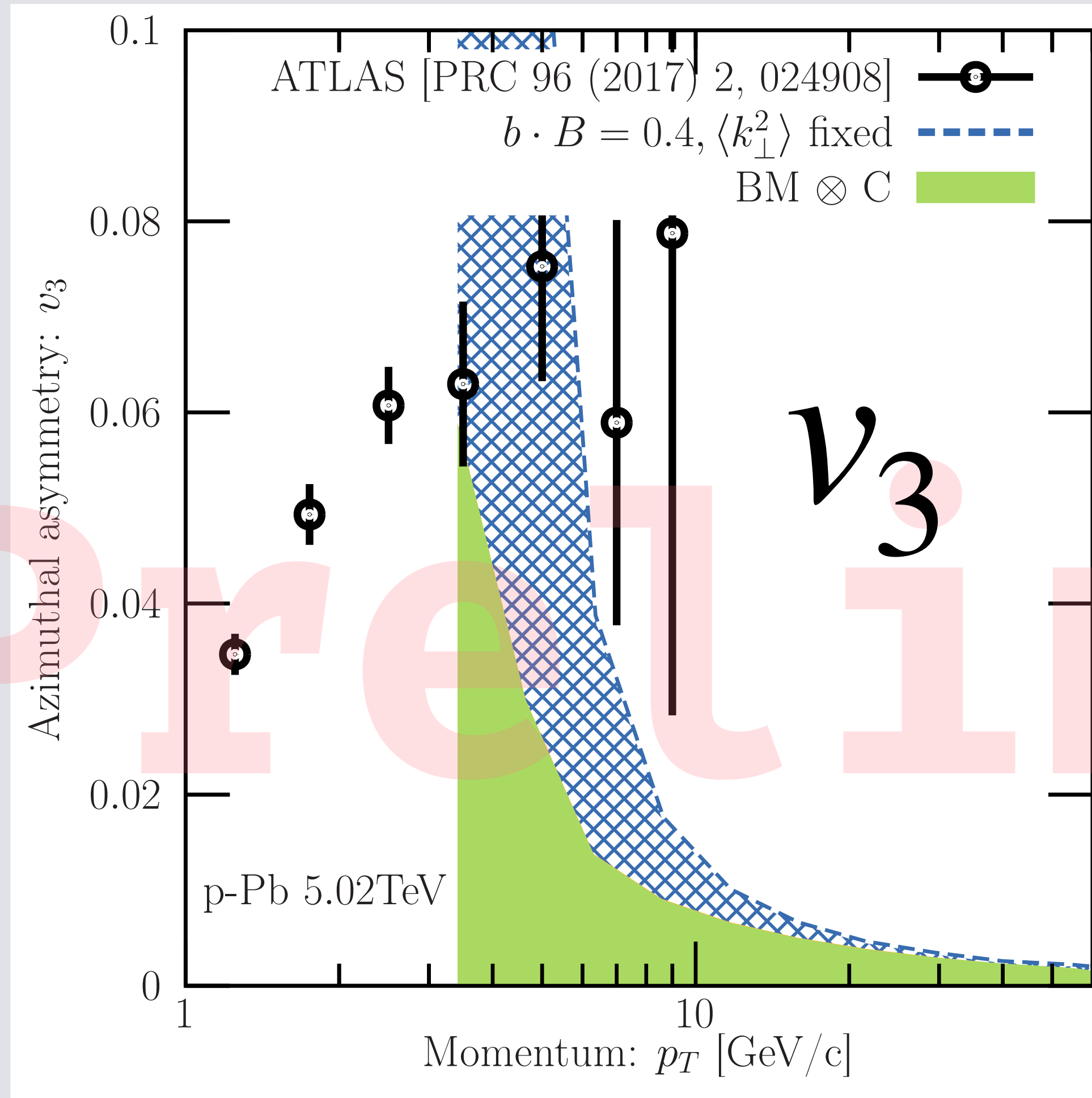


$p_T = 6\text{GeV}$

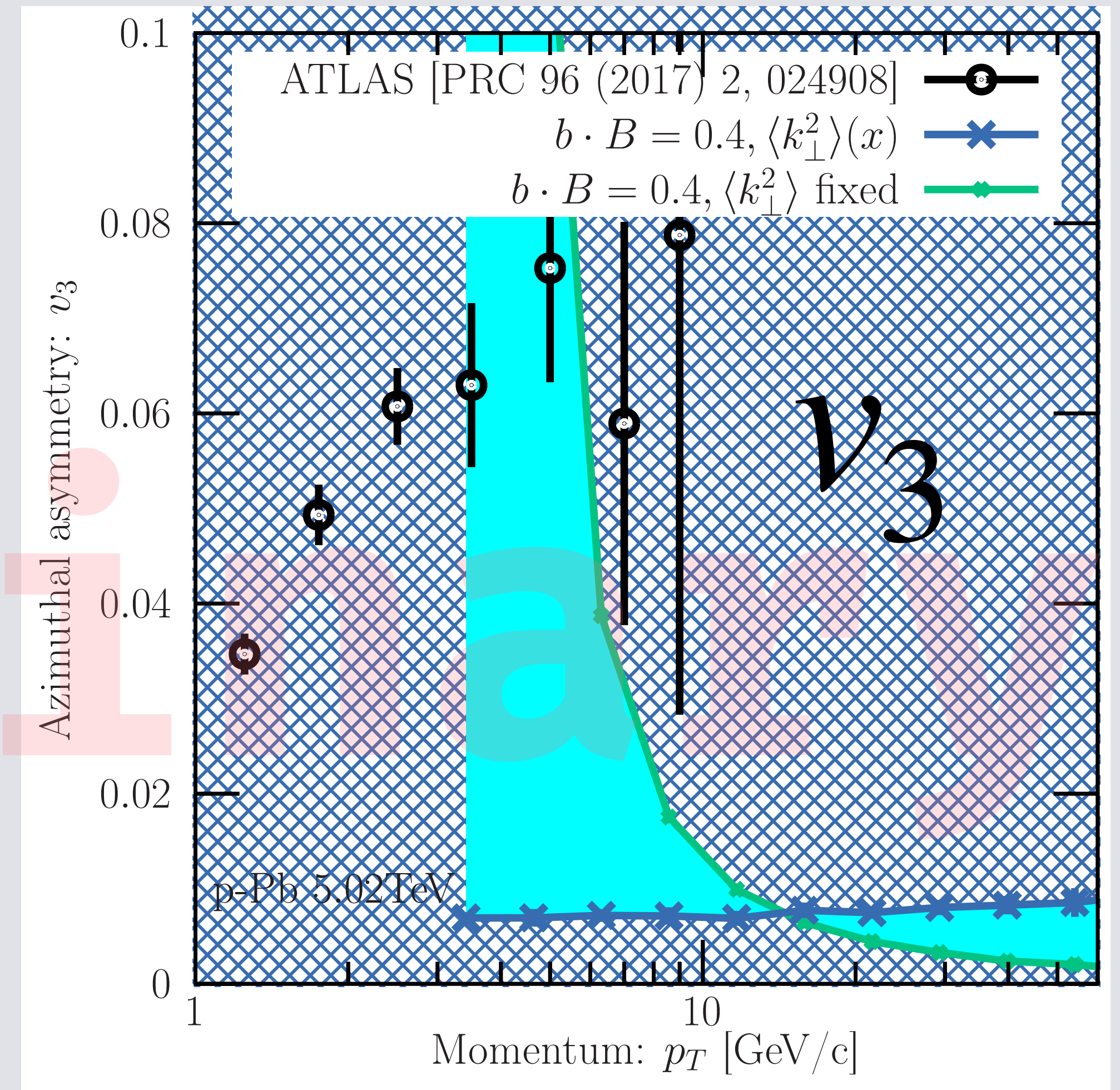


Ismail Soudi Approximation $\Rightarrow \langle k_T^2 \rangle_{p-Pb} = A^{1/3} \langle k_T^2 \rangle_{p-p}$

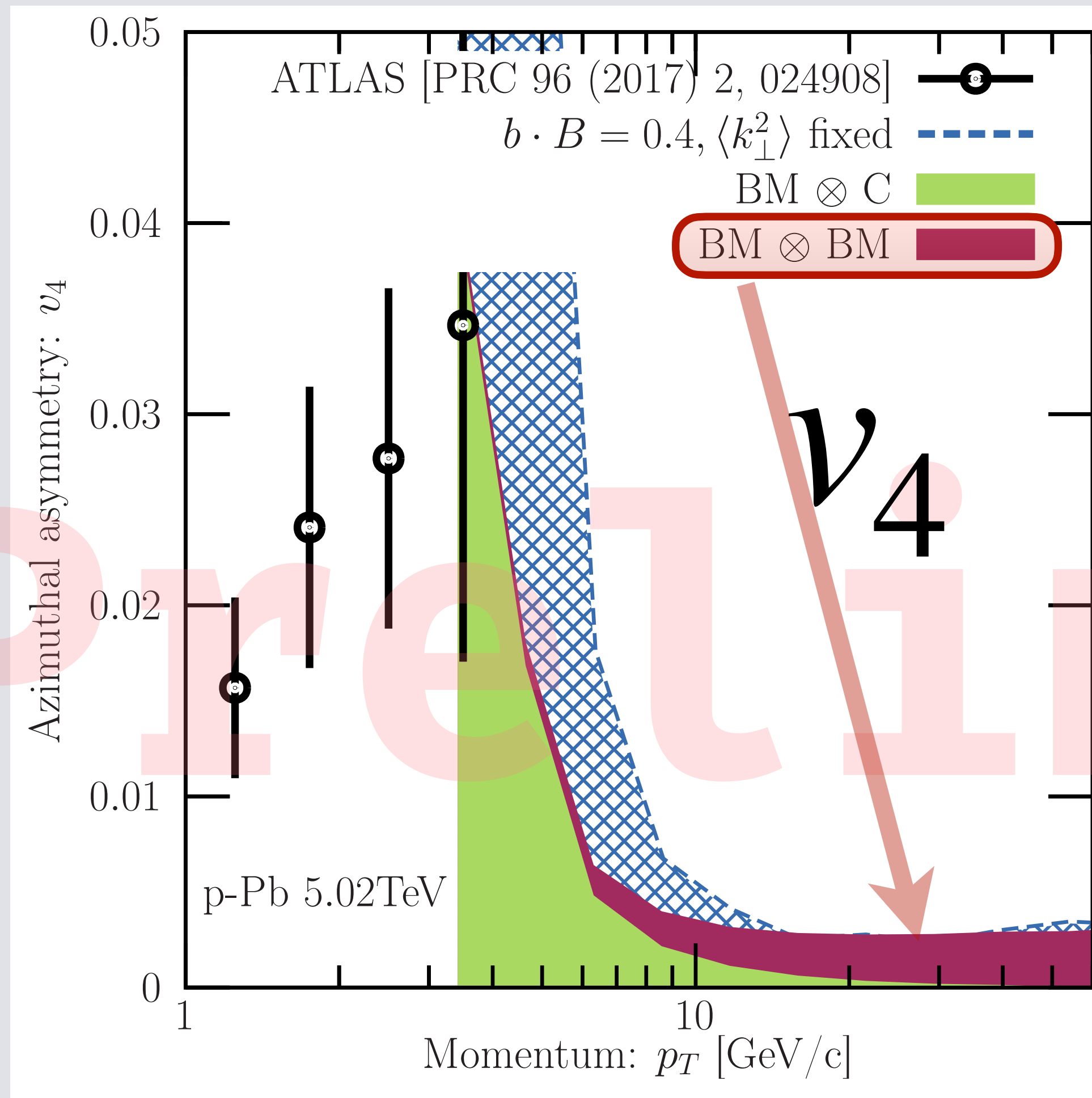
Preliminary results



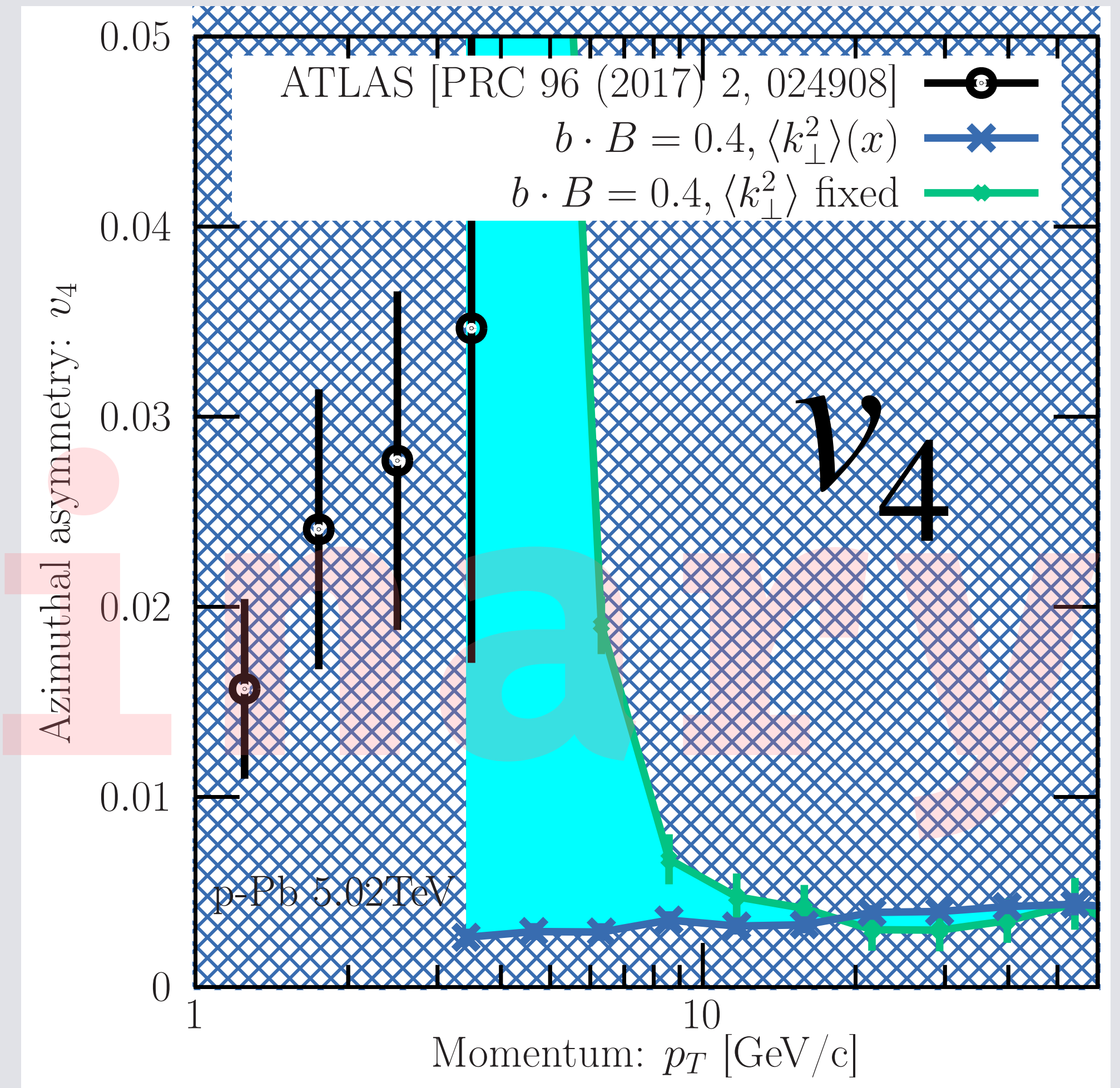
p-Pb



Preliminary results

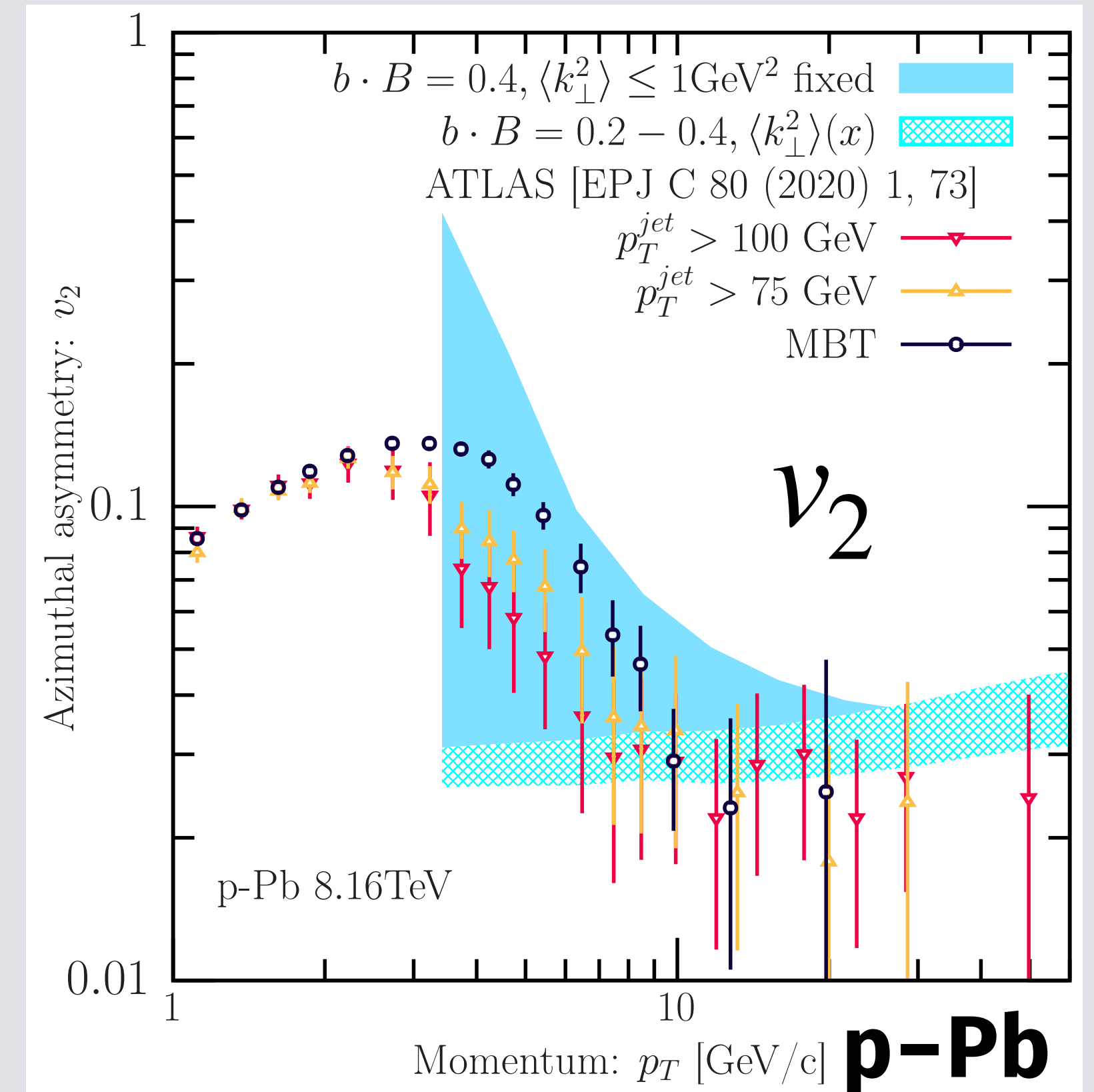


p-Pb



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 $qg \longleftrightarrow qg$ / $qq \longleftrightarrow qq$: important at higher p_T
- Beyond the $A^{1/3} \Rightarrow$ Compute Spin-dependent rescattering in p-A

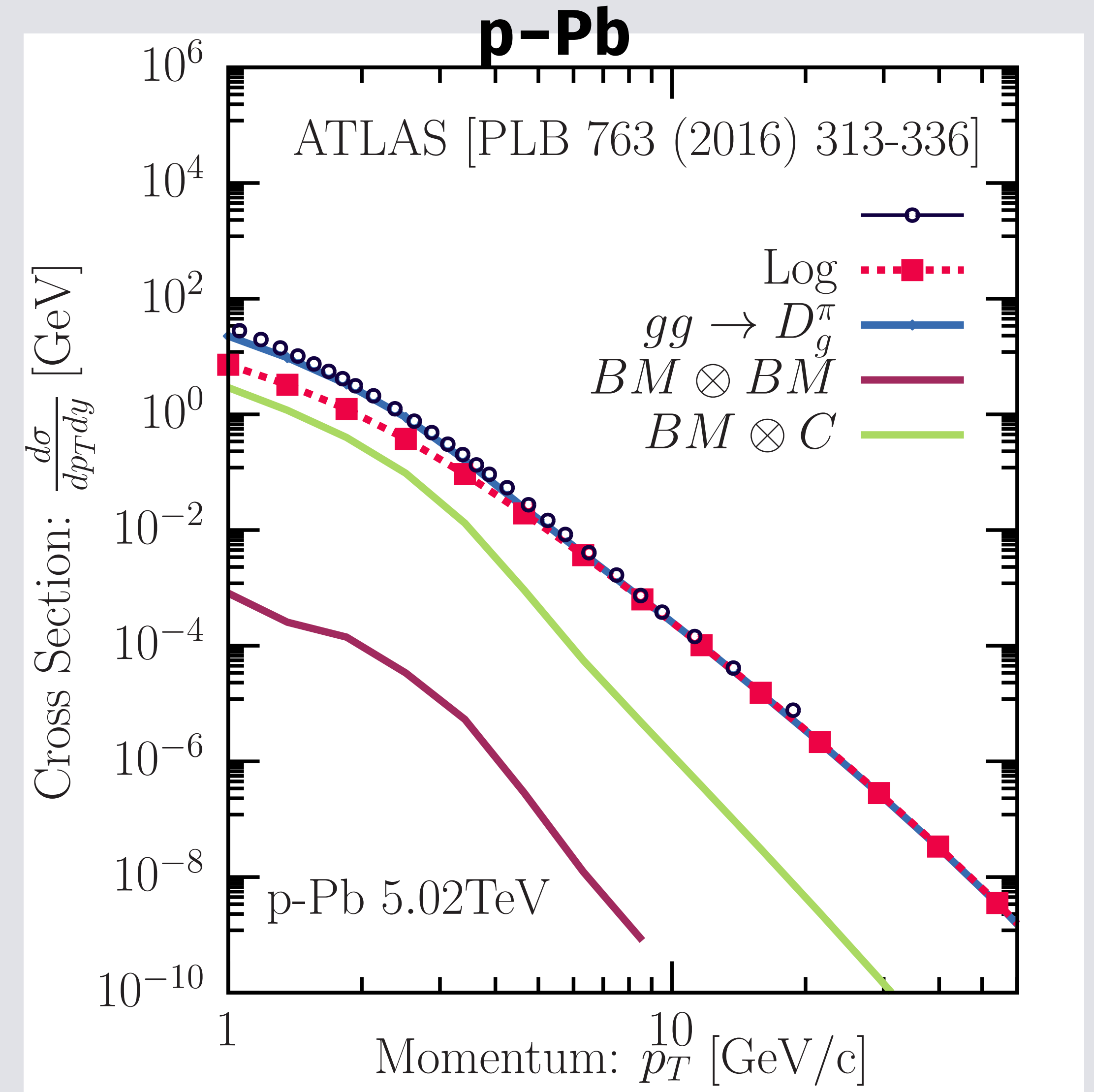
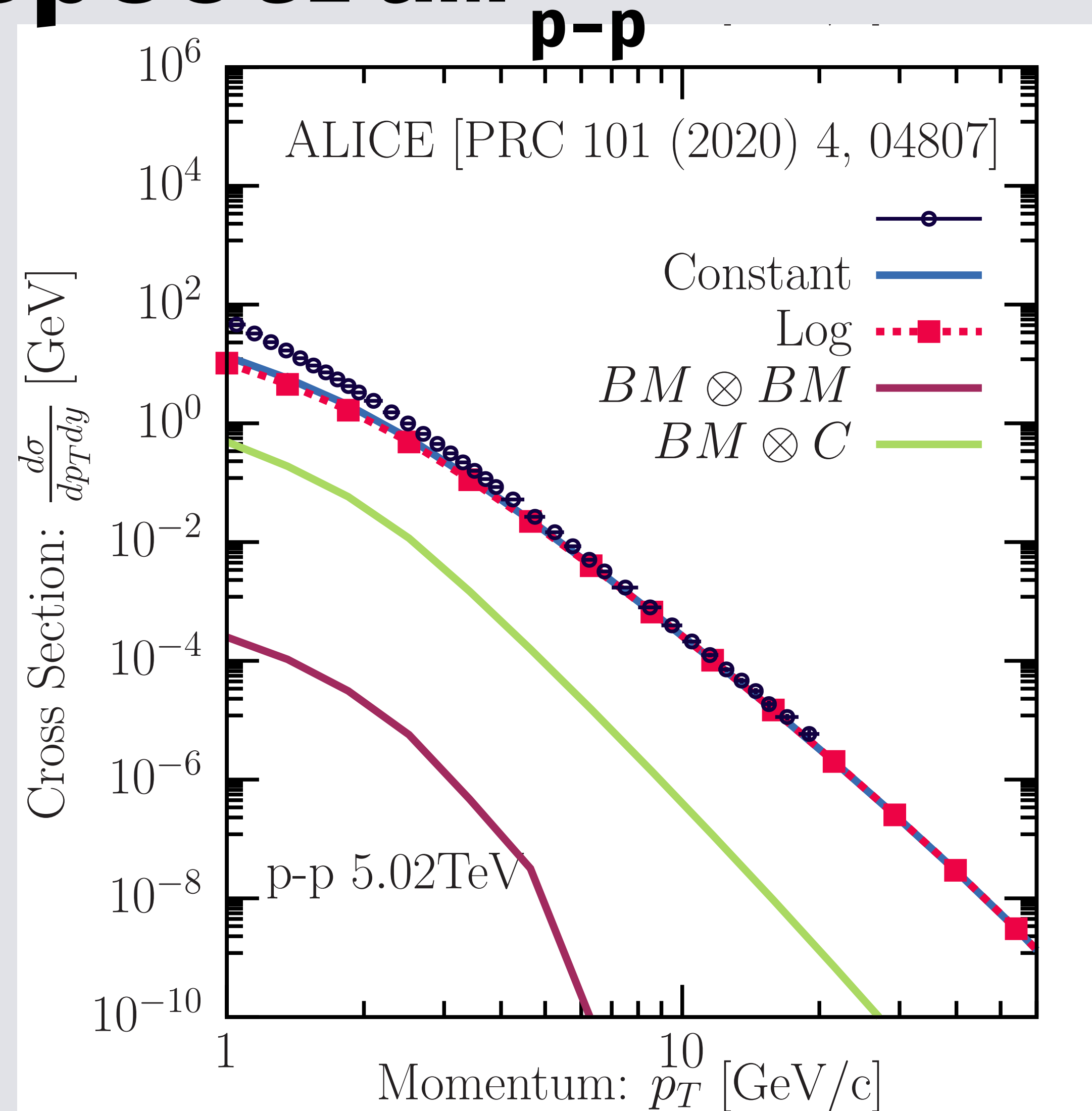


[I.S. A. Majumder [ArXiv:2308.14702](https://arxiv.org/abs/2308.14702)]

\o/ Thank you for listening!

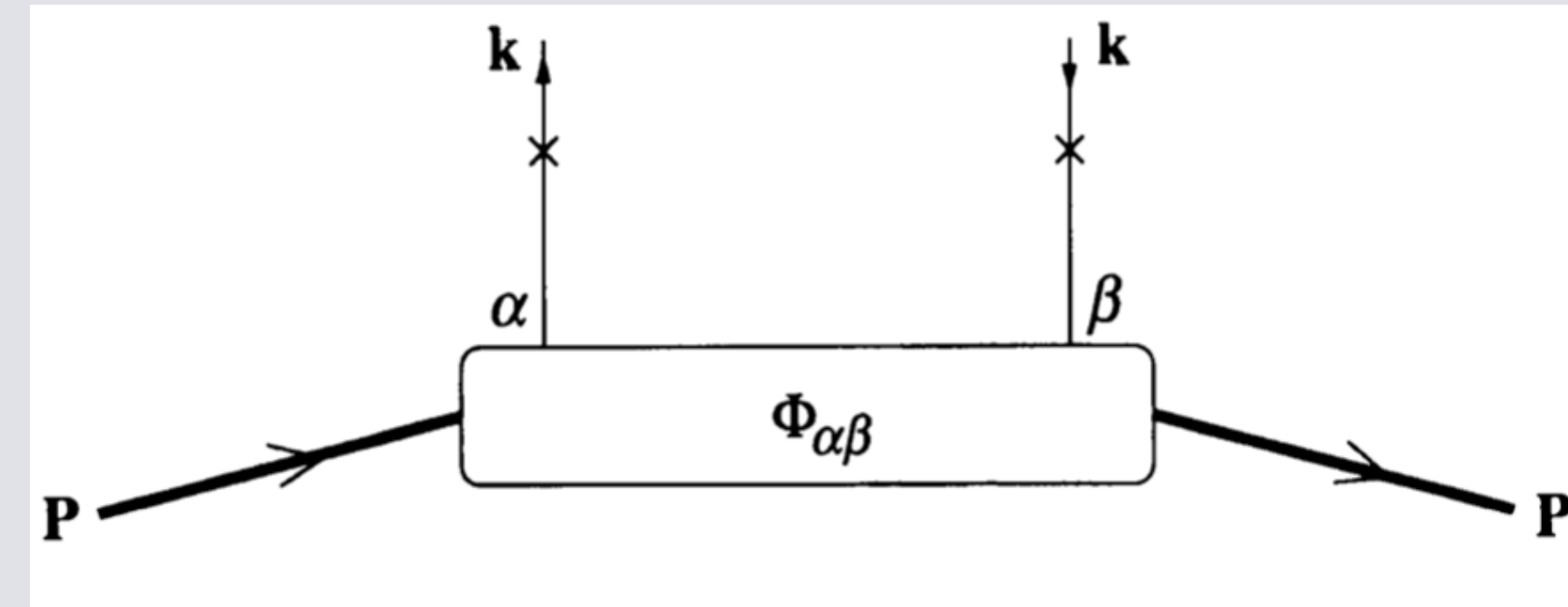
Backup

Spectrum



Collinear Factorization

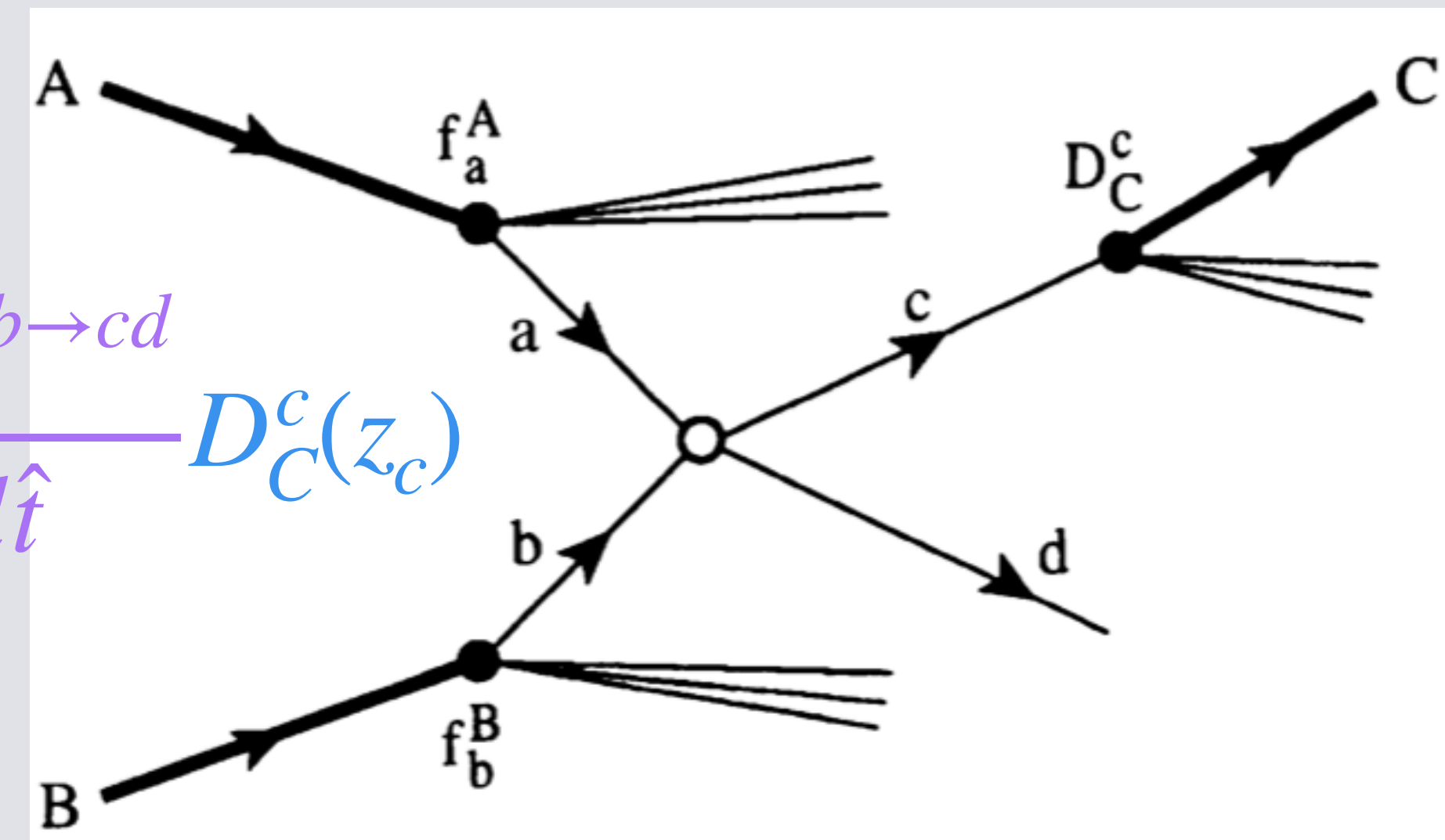
Partonic scattering



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

$\Rightarrow$ PDFs $\otimes$ FFs

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



Transverse Momentum Distributions

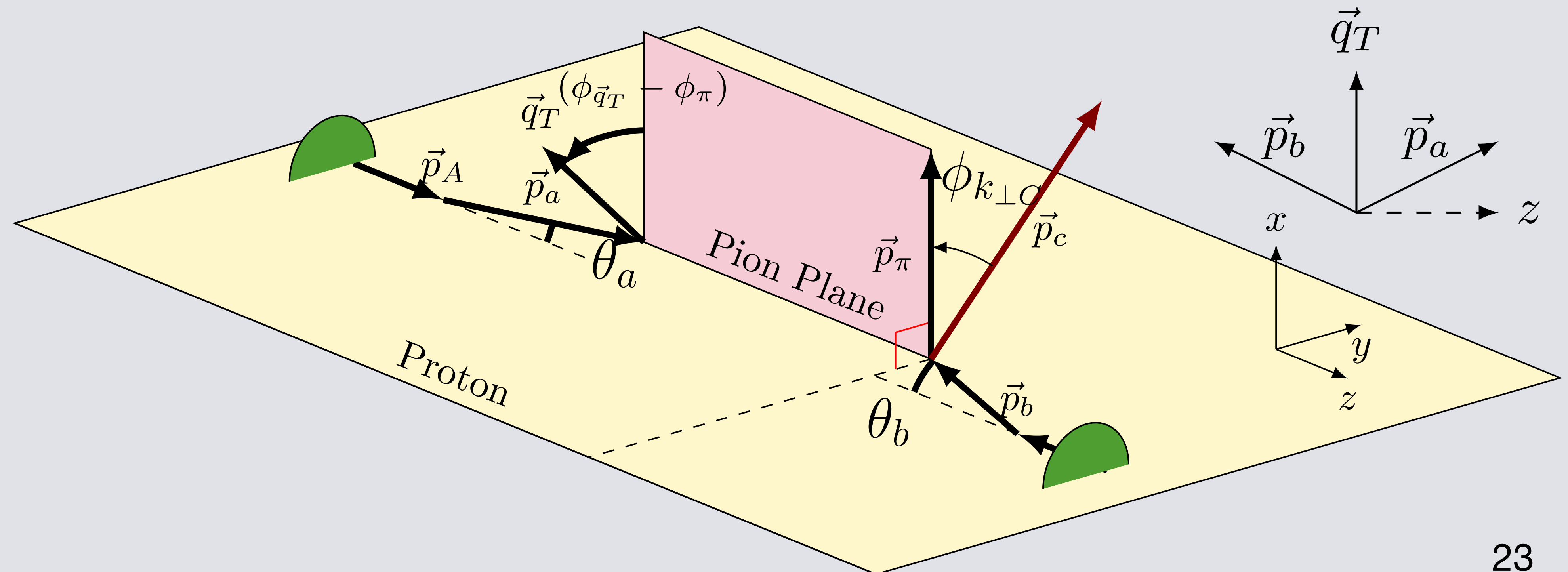
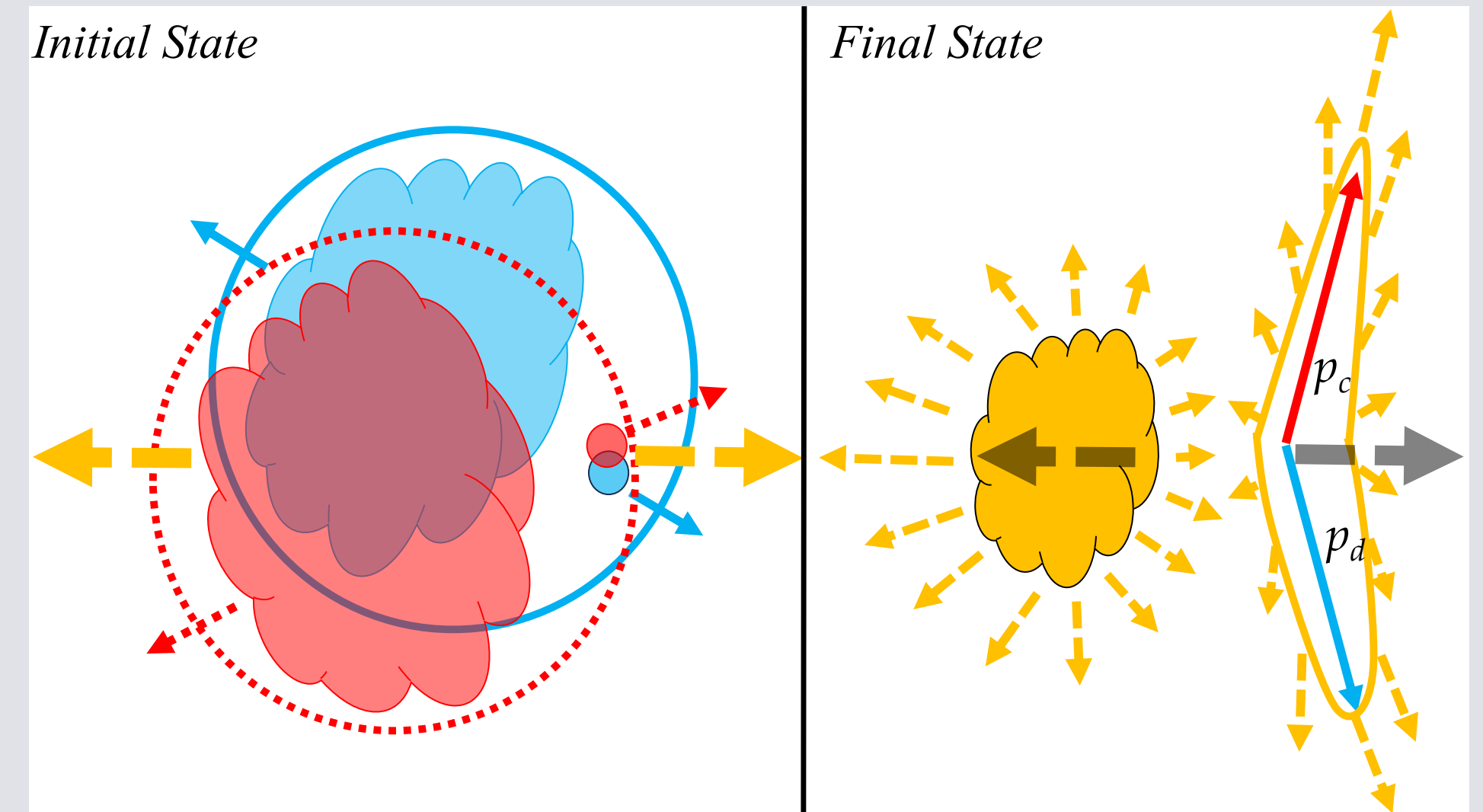
Fierz decomposition of quark-quark correlator contains additional terms than the leading twist distributions

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

$$X = x_\alpha \Gamma^\alpha = \frac{1}{4} \Gamma^\alpha \text{Tr} (X \Gamma_\alpha)$$

TMD Scattering

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



Transverse Momentum Distributions

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

For unpolarized hadrons

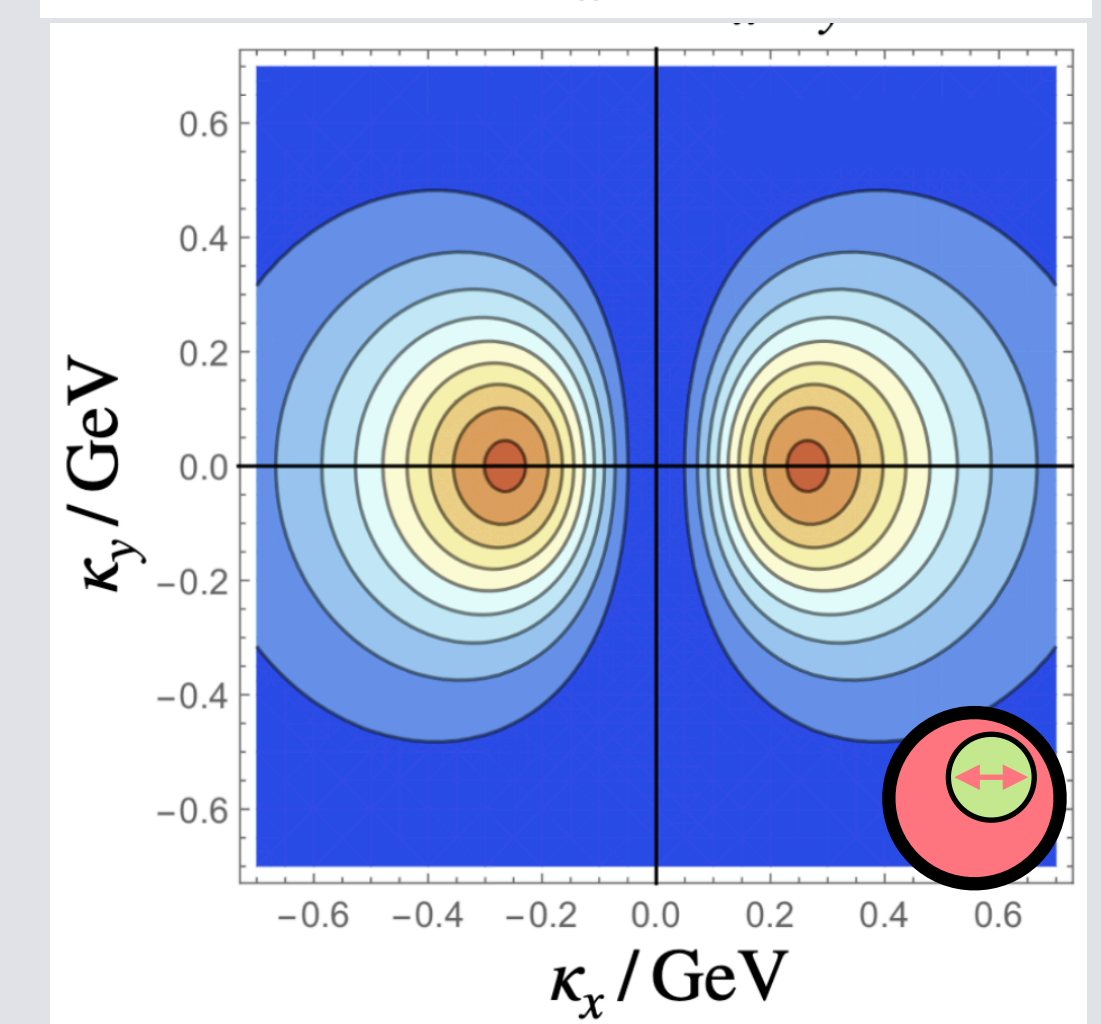
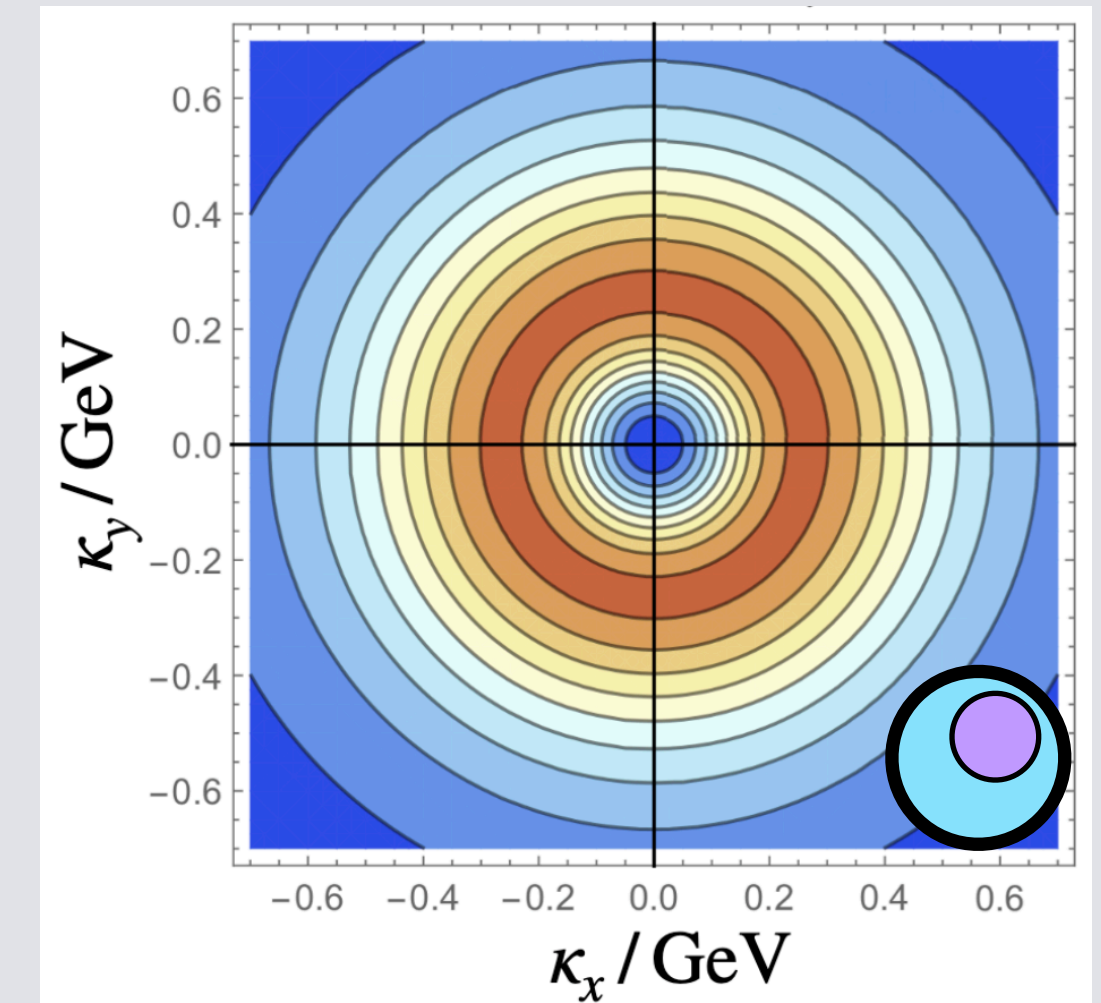
⇒ Gluon correlator

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

Unpolarized + Boer-Mulders/Collins

Soffer Bound:

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



kT Dist

$$\langle k_{\perp}^2 \rangle^{1/2}(x) = \langle k_{\perp}^2 \rangle_0^{1/2} \left((1-x) \sqrt{\frac{s}{s_0}} \right)^{0.15} A^{1/3} \\ \times \begin{cases} \left(\frac{x}{x_0} \sqrt{\frac{s}{s_0}} \right)^{0.8}, & \text{if } x \leq x_0 \\ \left[1 + b_0 \log \left(\frac{x}{x_0} \sqrt{\frac{s}{s_0}} \right) \right]^{1/2}, & \text{if } x > x_0 \end{cases}$$

Transverse Momentum Distributions

For unpolarized hadrons

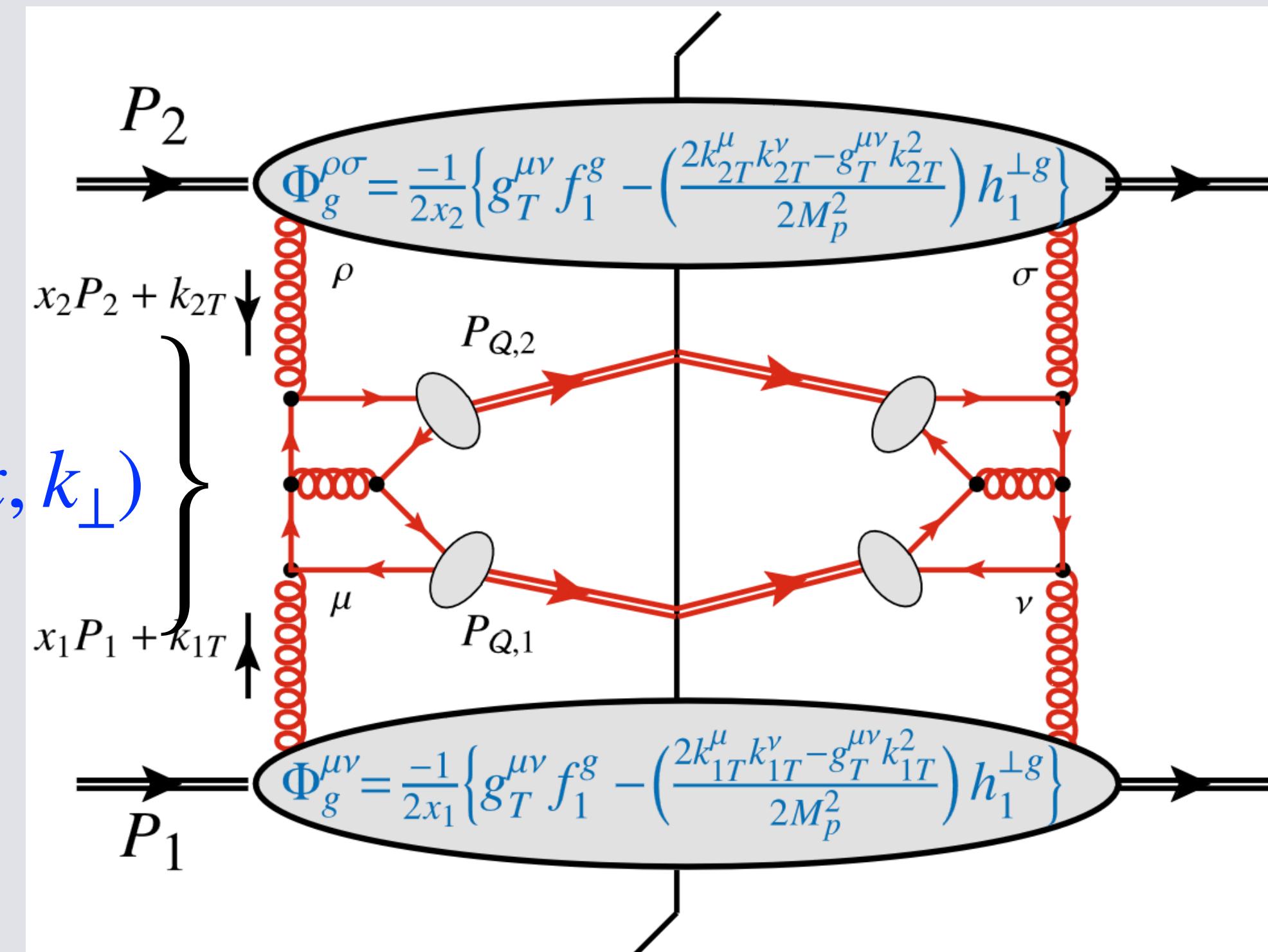
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[F. Scarpa et al., Eur.Phys.J.C 80 (2020) 2, 87]

Centrality

