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

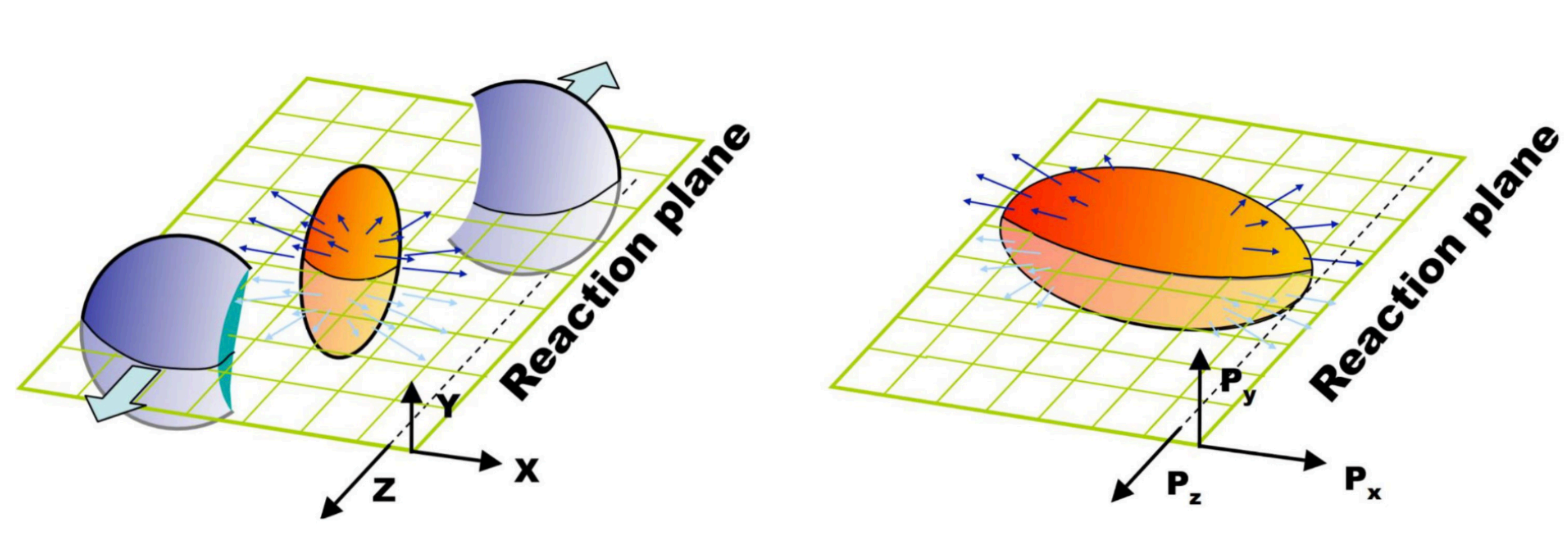
Ismail Soudi

Wayne State University

Based on IS and Abhijit Majumder ArXiv:2308.14702

SPIN 2023, Durham

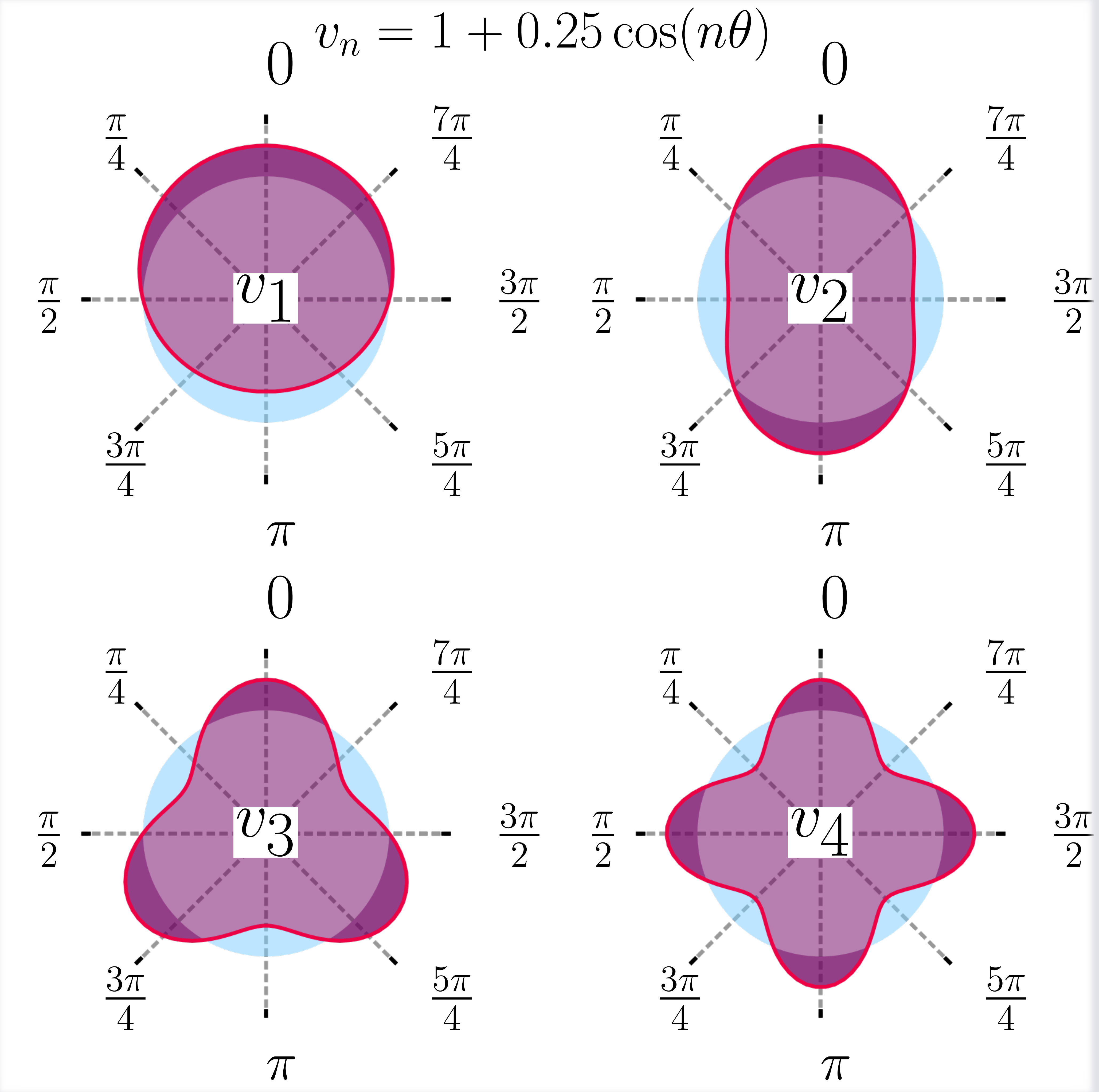
Elliptic Flow in Relativistic Heavy-Ion Collisions



v_n Azimuthal Anisotropies

Azimuthal momentum correlated with soft bulk (event plane)

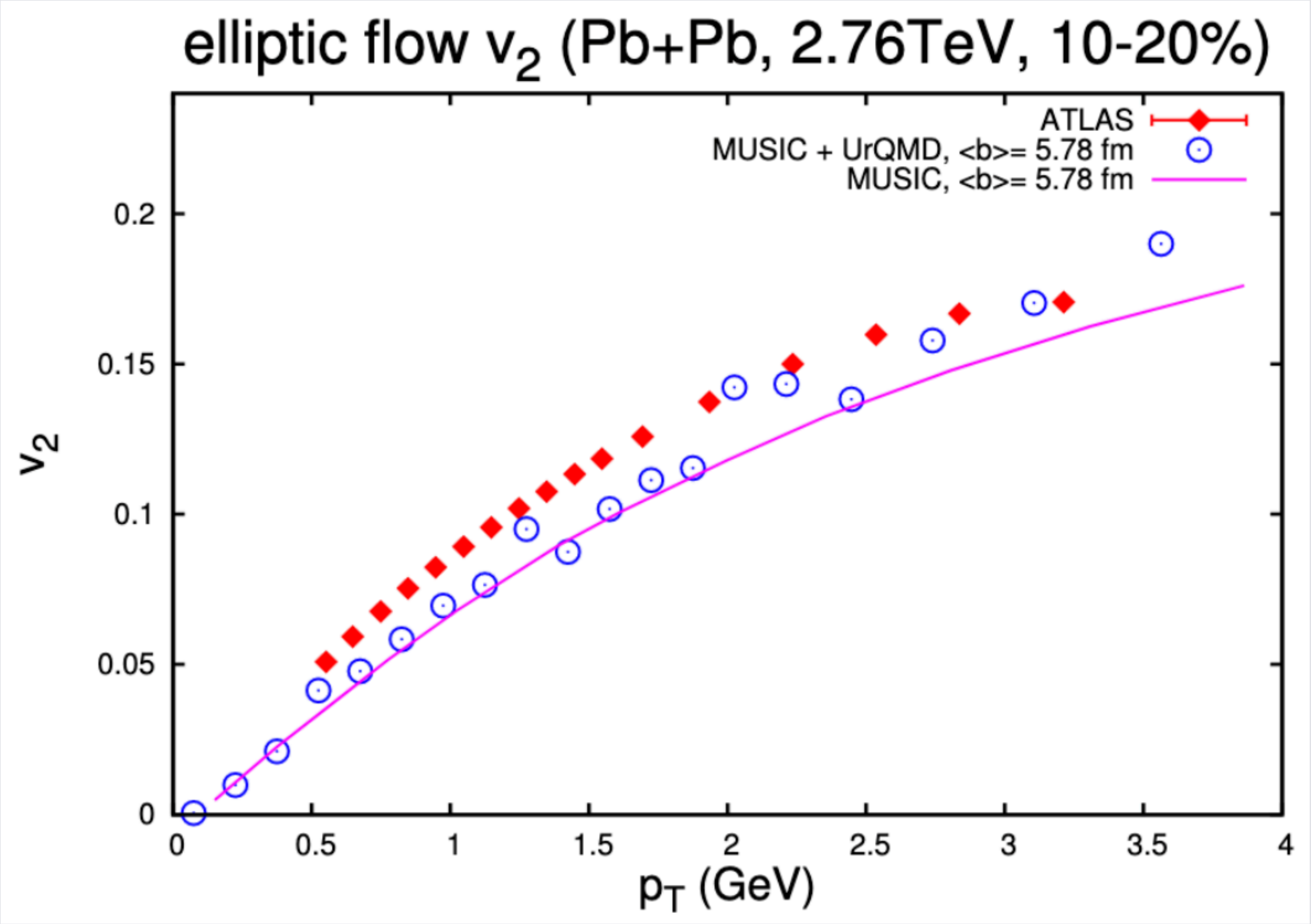
$$\frac{dN}{d\phi} \propto 1 + \sum_{1}^{\infty} 2v_n cos[n(\phi - \Psi_n)]$$



Signature of QGP formation

Measurement of elliptic flow v_2 one of the main signatures of the QGP

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

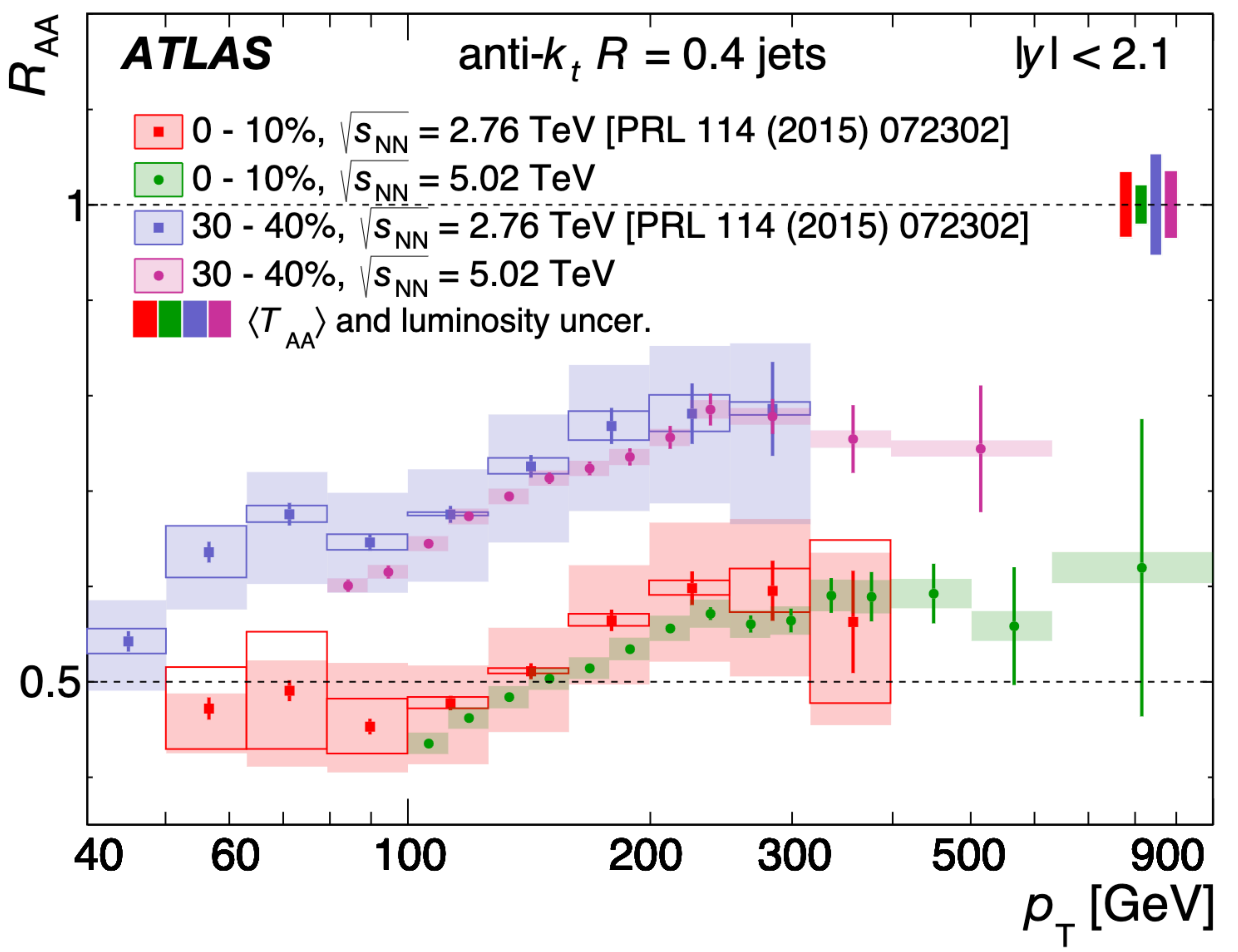


[Int. J. of Mod. Phys. A, Vol. 28, 1340011 (2013)]
[ATLAS Phys.Lett. B707, 330 (2012)]

Jet suppression: 2nd Signature of QGP formation

Energy loss leads to a suppression of jets

$$R_{AA} = \frac{\left.\frac{d^2N_{jet}}{dp_T dy}\right|_{PbPb}}{\langle T_{AA}\rangle \left.\frac{d^2N_{jet}}{dp_T dy}\right|_{pp}}$$

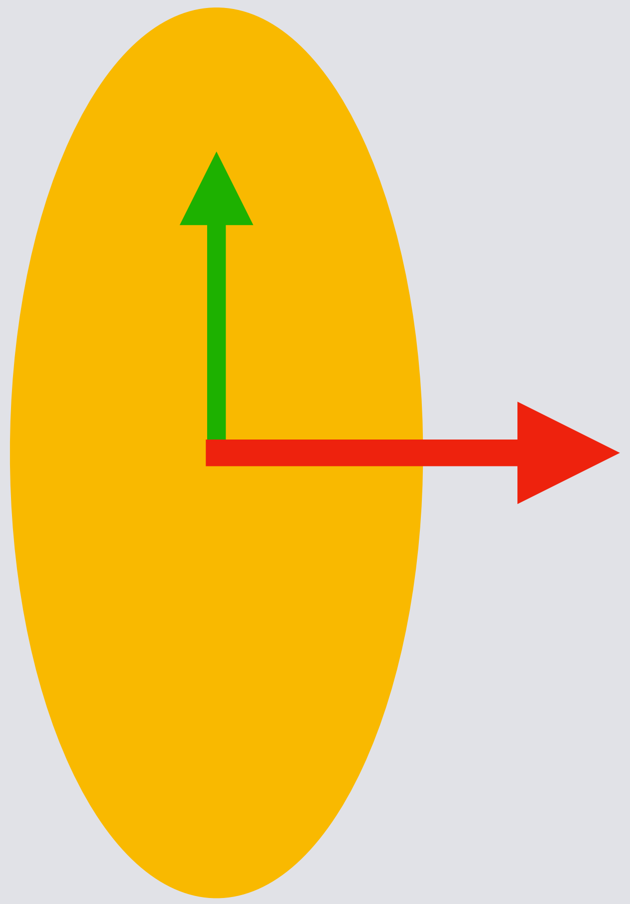


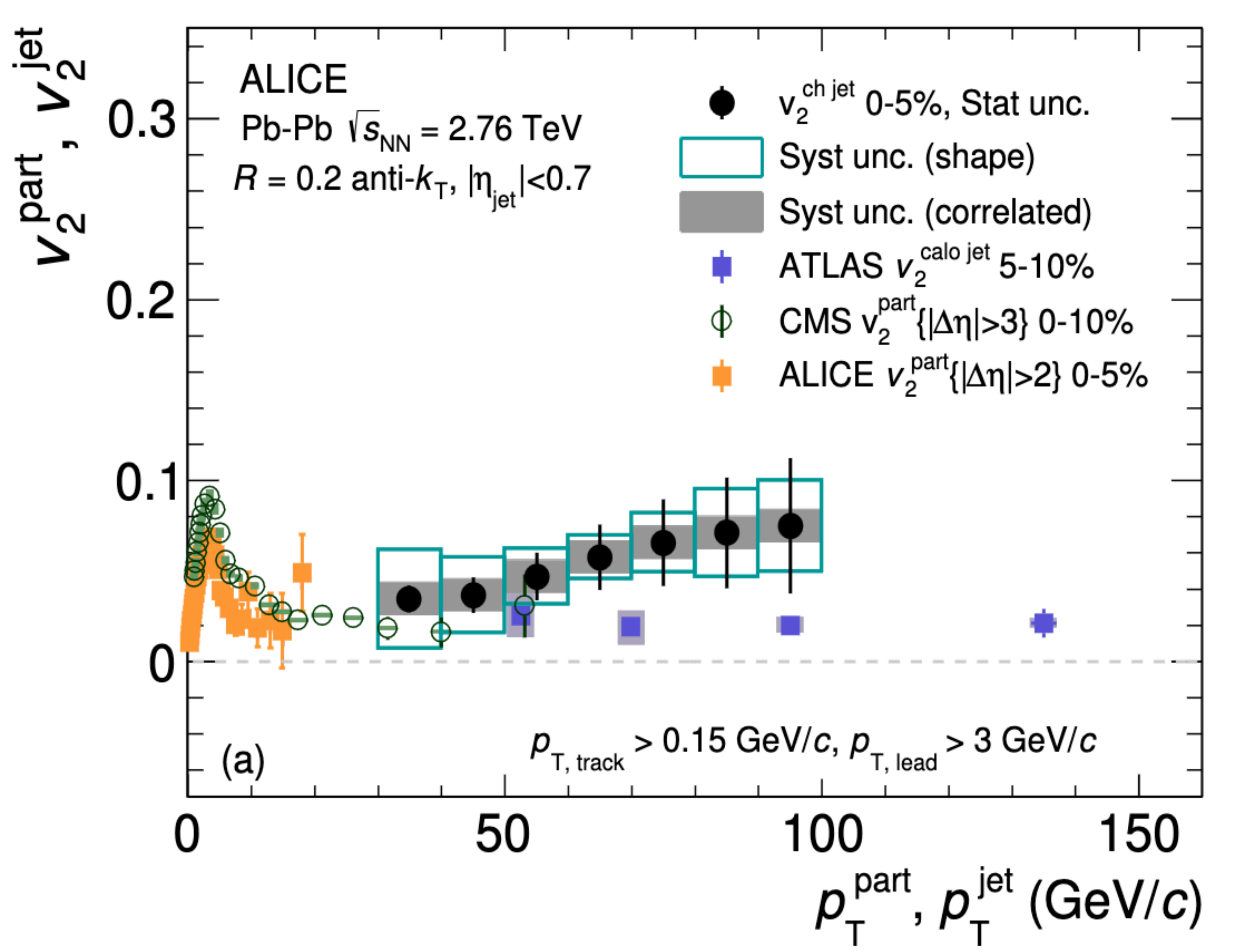
[ATLAS Phys. Lett. B 790 (2019) 108]

Jet v_2

Path length dependence of energy loss

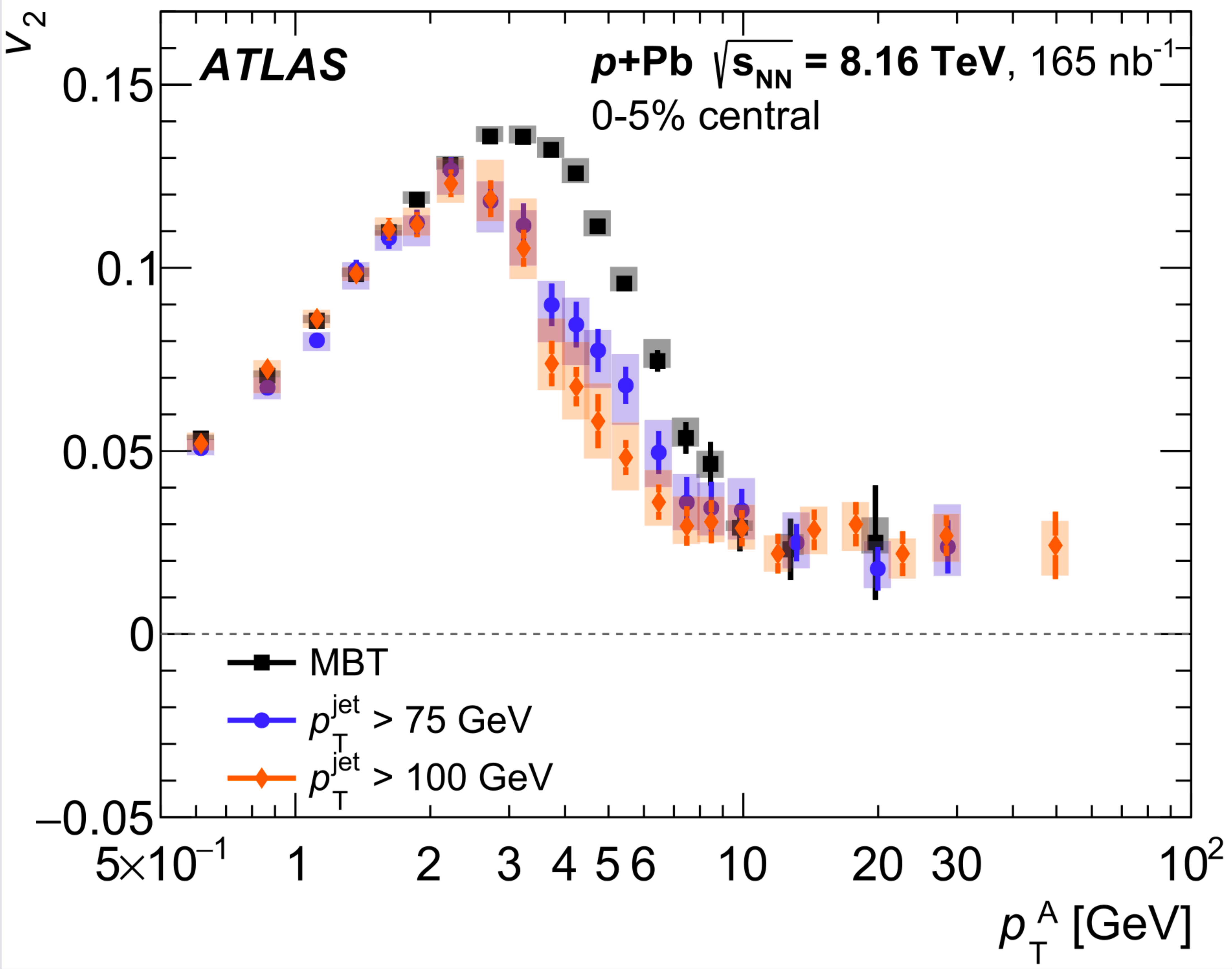
$$\frac{dN}{d\phi_{jet}} \propto 1 + \sum_{1}^{\infty} 2v_n^{jet} cos[n(\phi_{jet} - \Psi_n)]$$





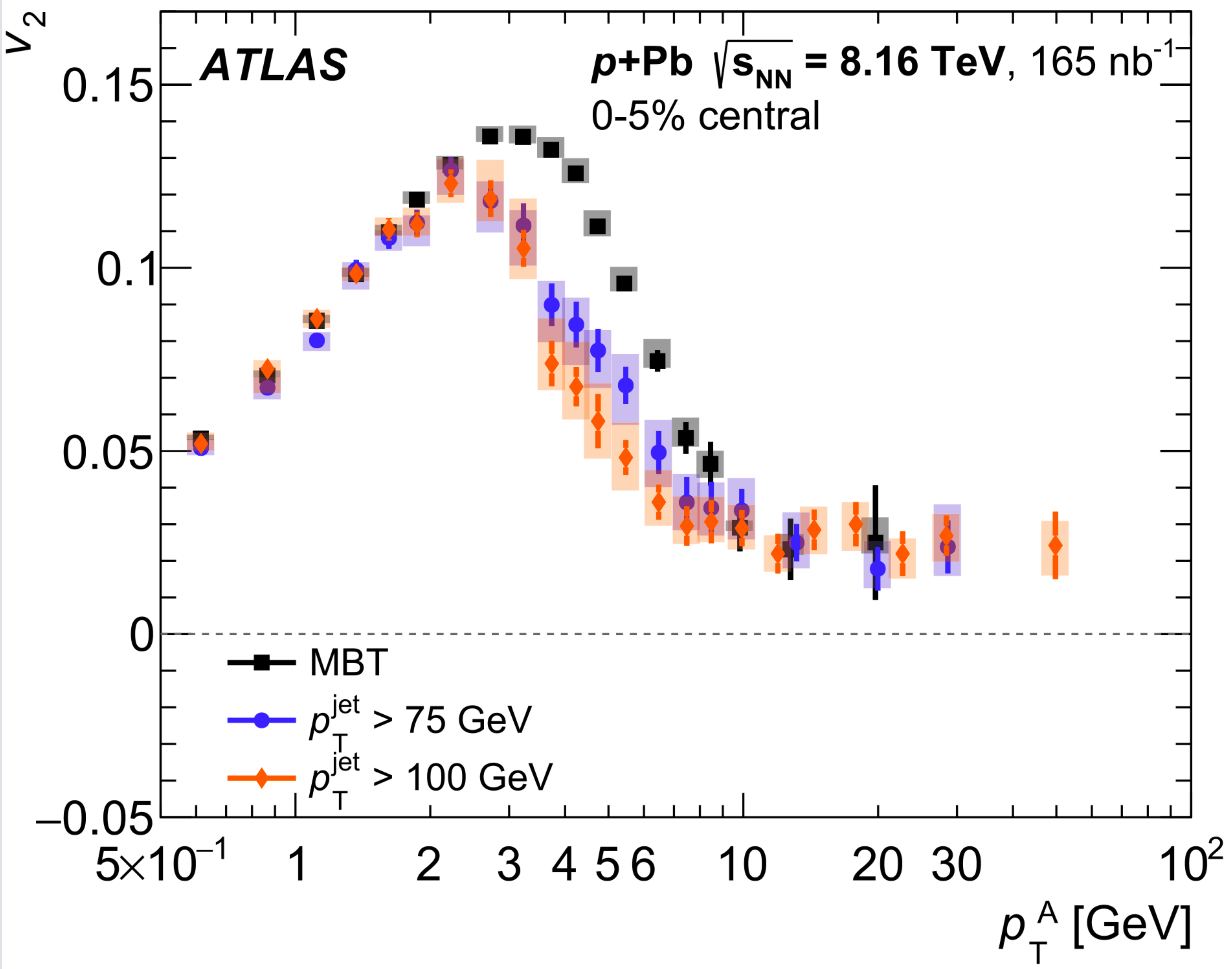
[ALICE Phys.Lett. B 753 (2016) 511-525]

Small systems



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

Small systems



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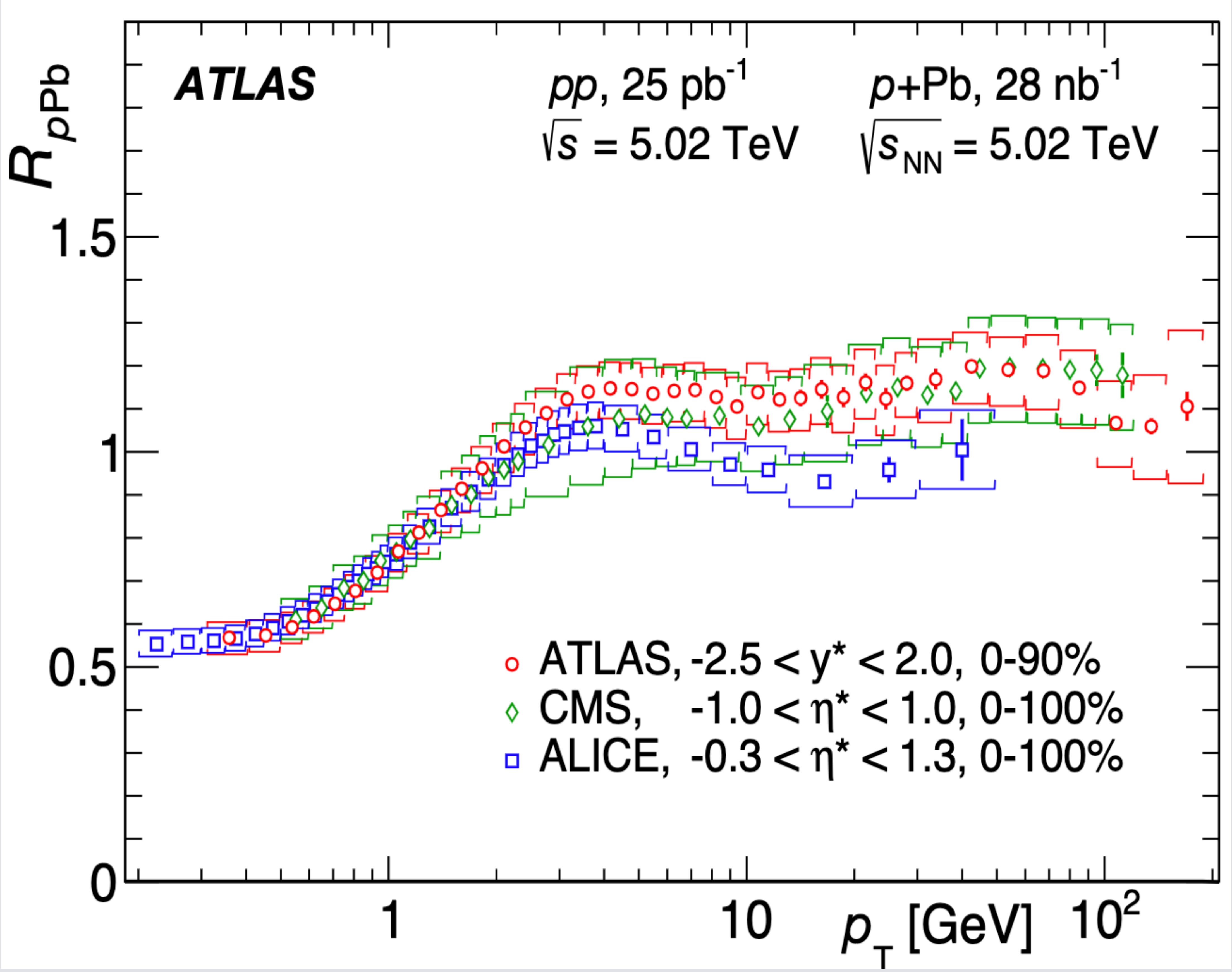
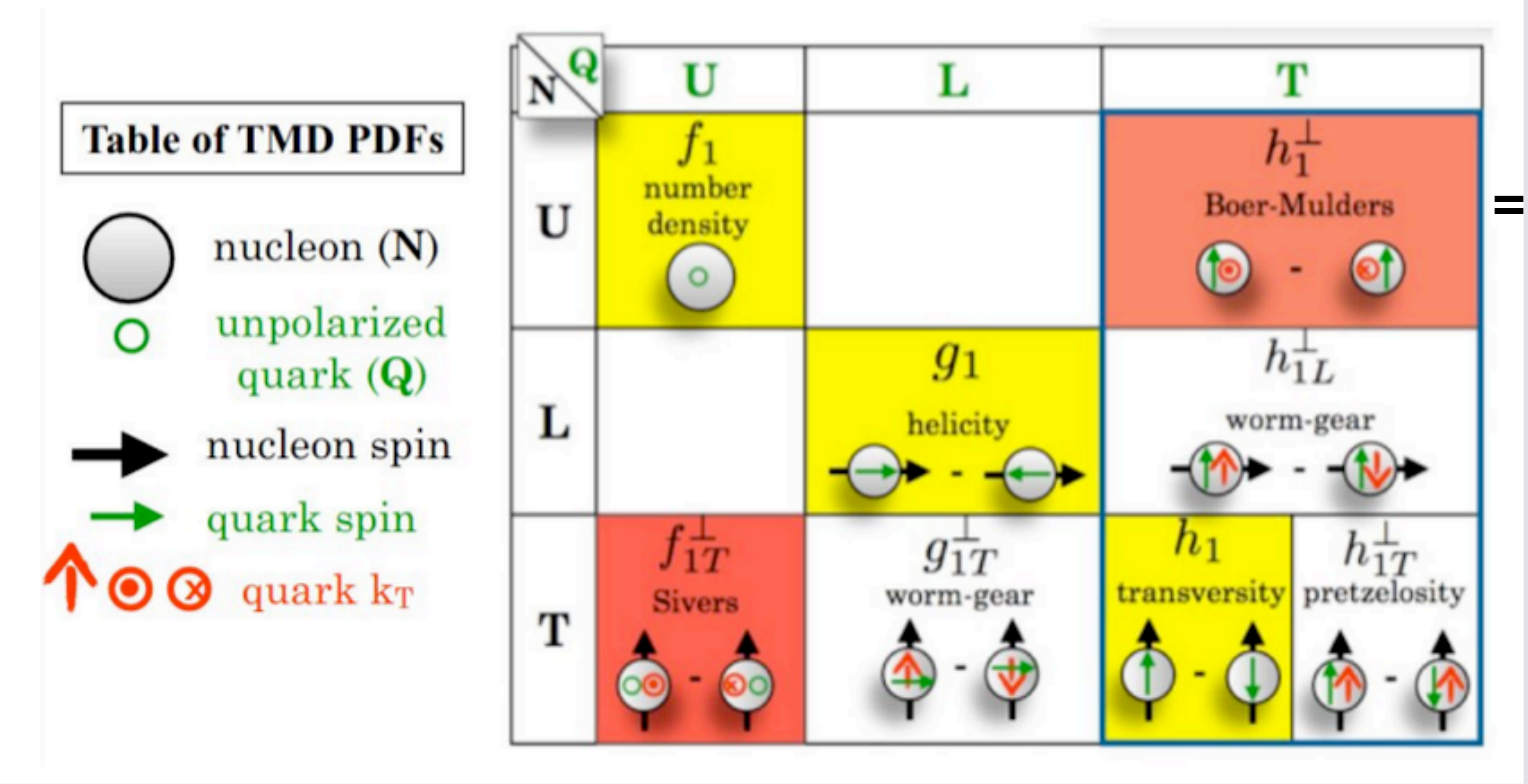


[ATLAS JHEP 07 (2023) 074]
[CMS JHEP 04 (2017) 039]
[ALICE JHEP 11 (2018) 013]

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…]

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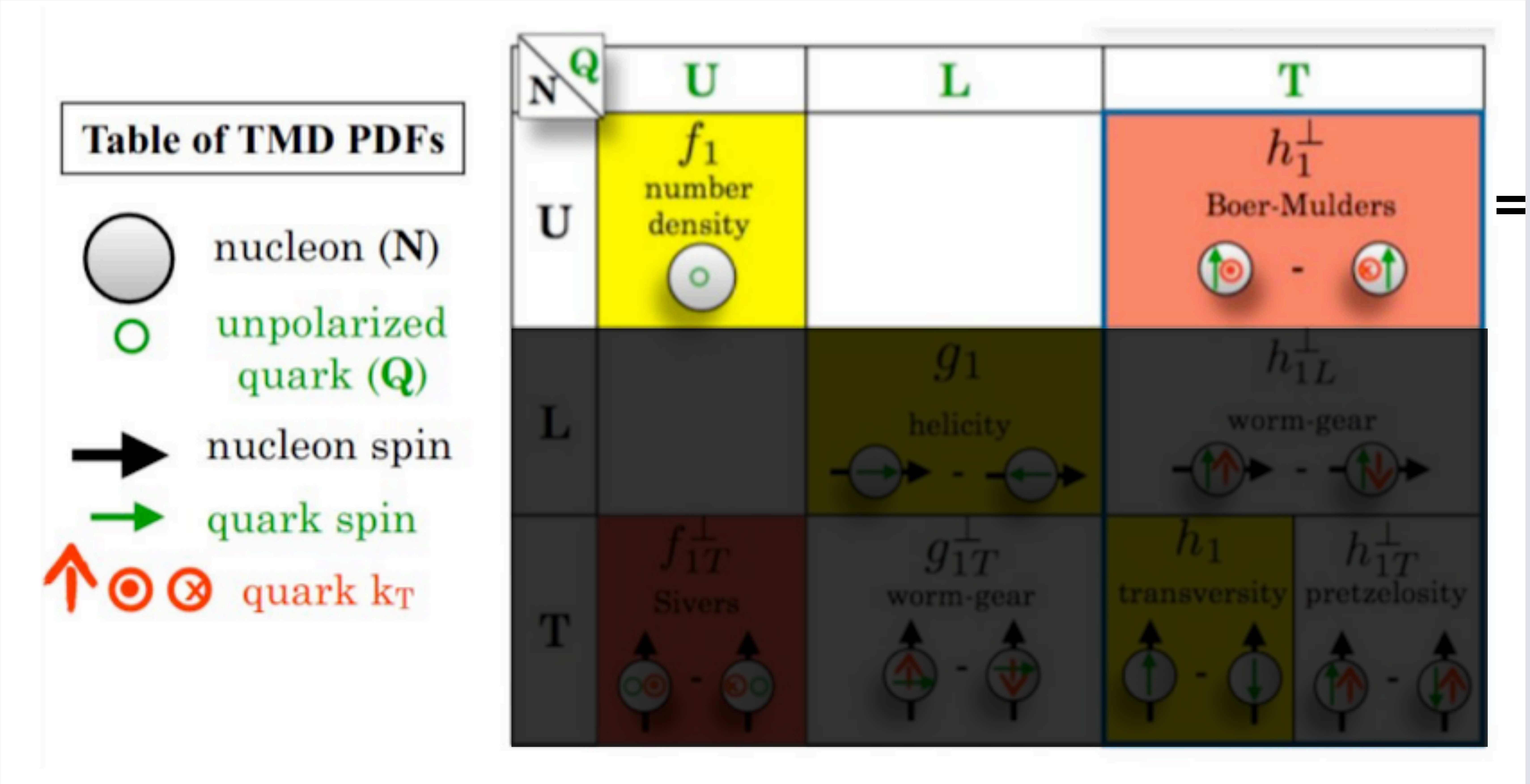

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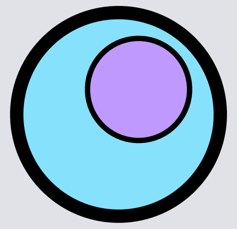
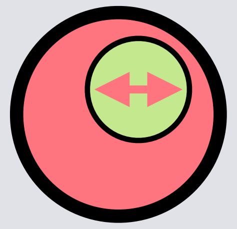
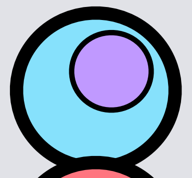
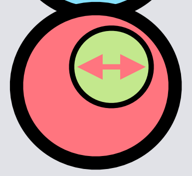
 

$$\Phi^{\alpha\beta}\epsilon_{\alpha}^{\lambda_1}(k)\epsilon_{\beta}^{\lambda_2 *}(k) = \frac{1}{2x}\left\{ \delta_{\lambda_1,\lambda_2} f^{g}(x, k_\perp) + \delta_{\lambda_1,-\lambda_2}\frac{k_\perp^2}{2M^2} h^{\perp g}(x, k_\perp) \right\}$$

 Unpolarized gluon inside unpolarized hadron

 Linearly polarized gluon inside unpolarized hadron

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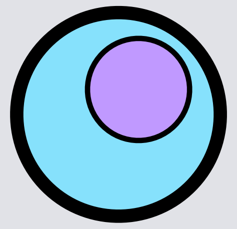
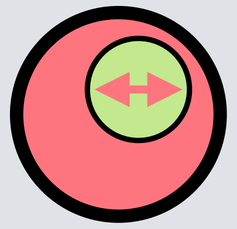

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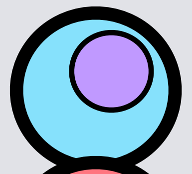
The Boer-Mulders/Collins flips helicity between amplitude and conjugate

Requires two flips for unpolarized pion production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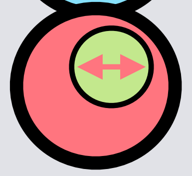
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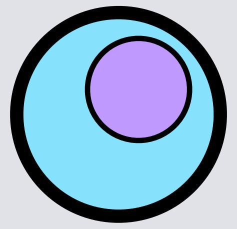 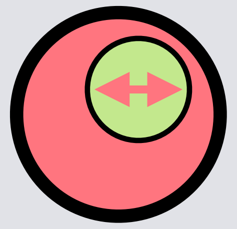

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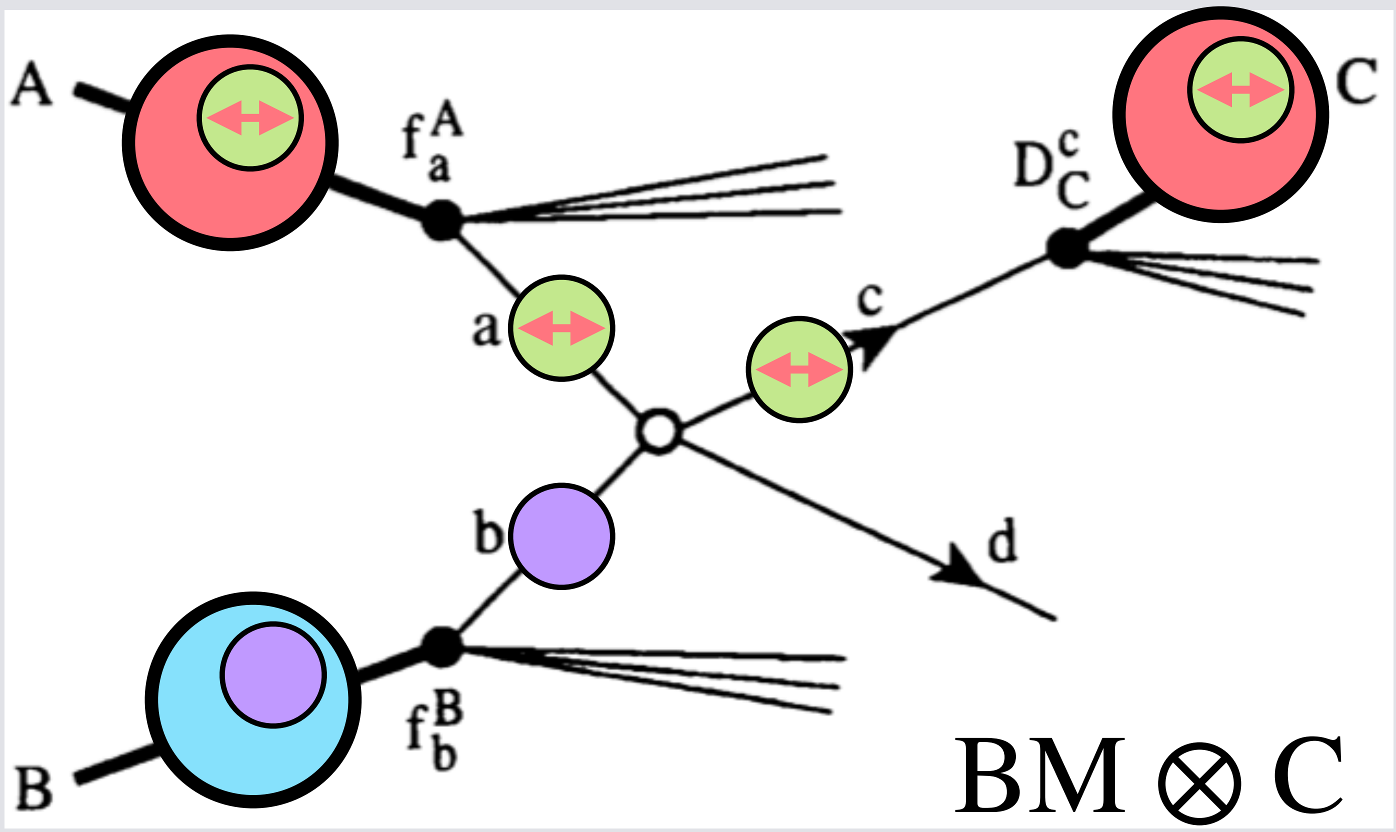

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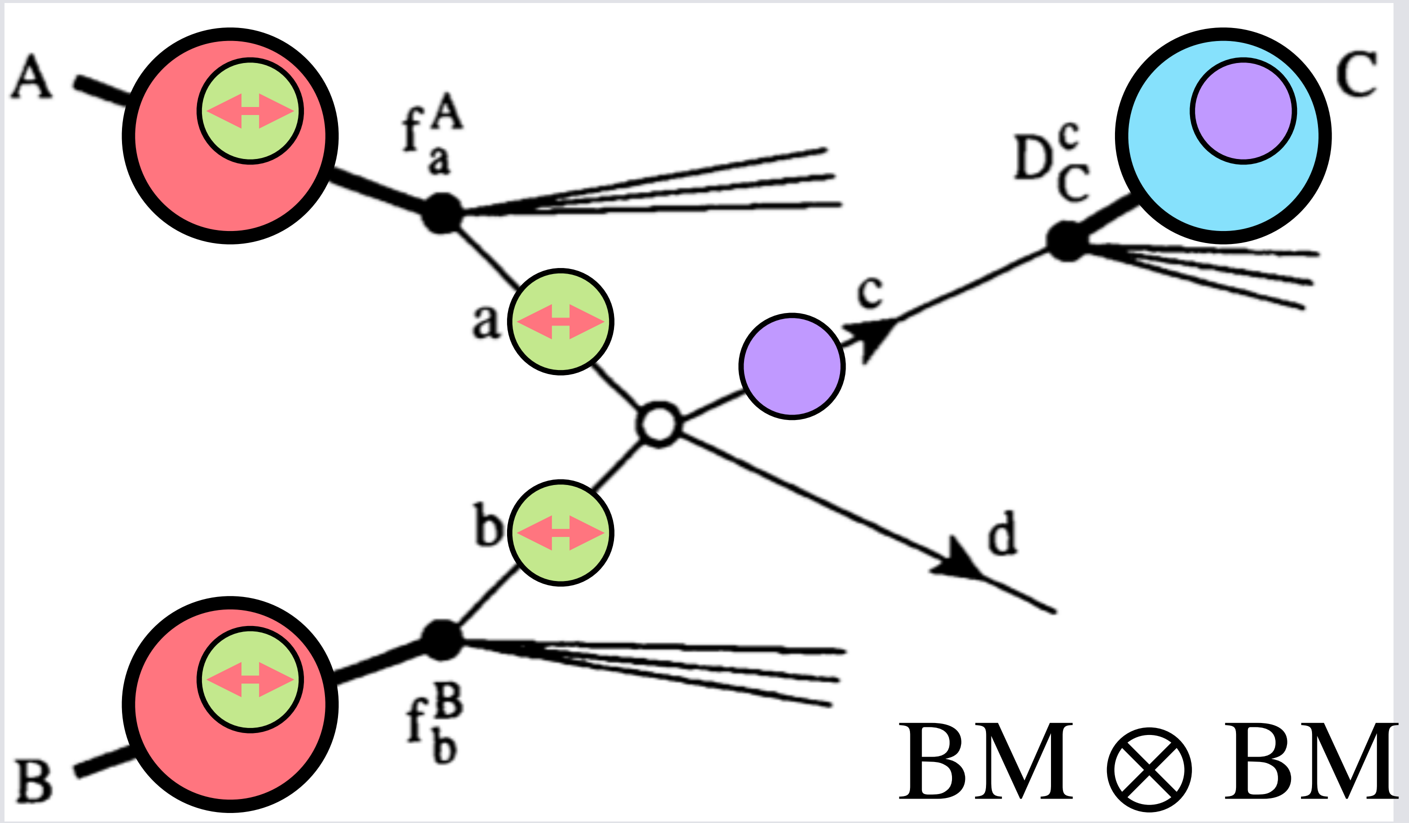
Requires two flips for unpolarized pion production

For gg⟷gg:

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

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

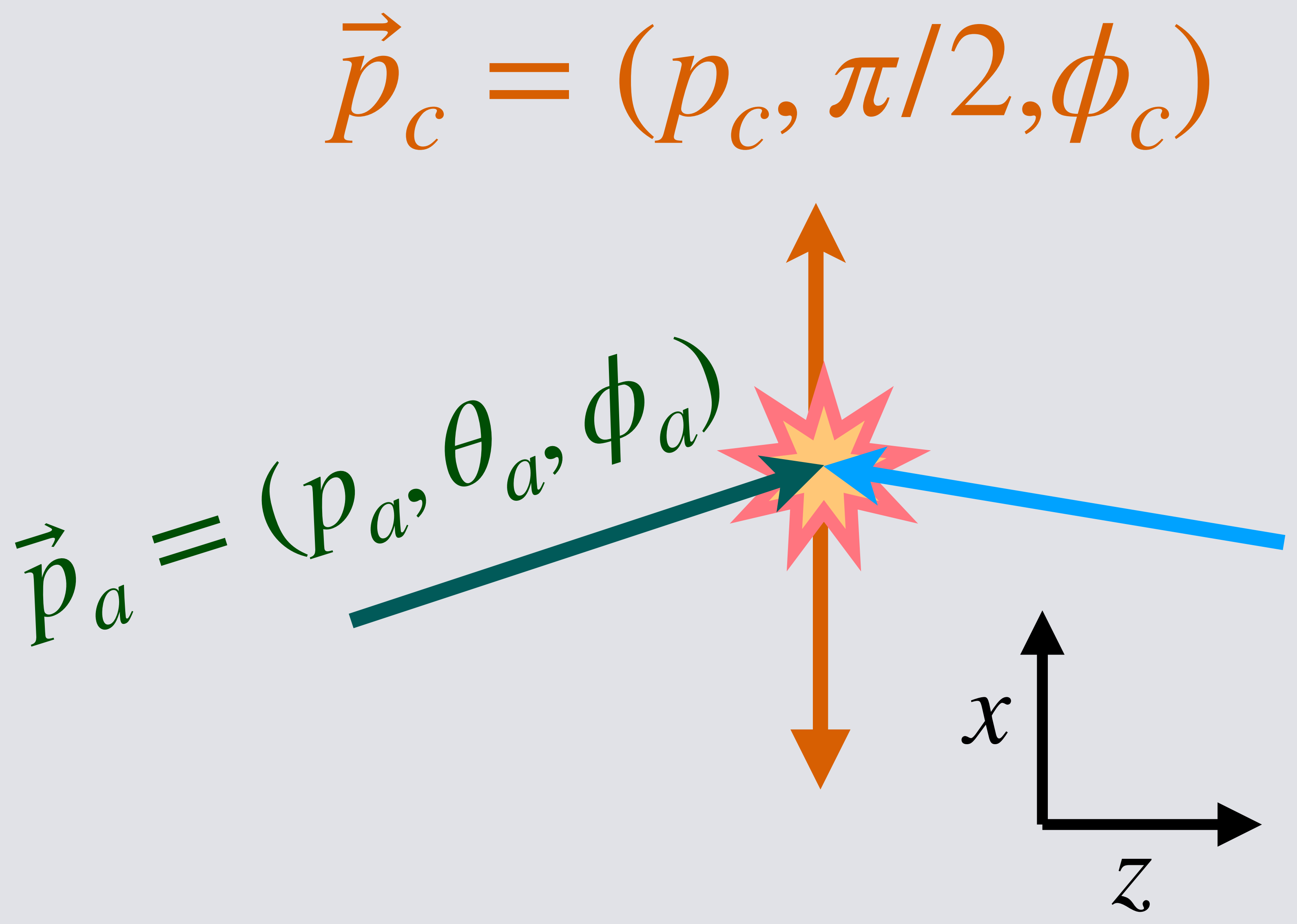
[I.S. A. Majumder ArXiv:2308.14702]

Spin Independent

TMD matrix element contains angular correlations as well

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

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



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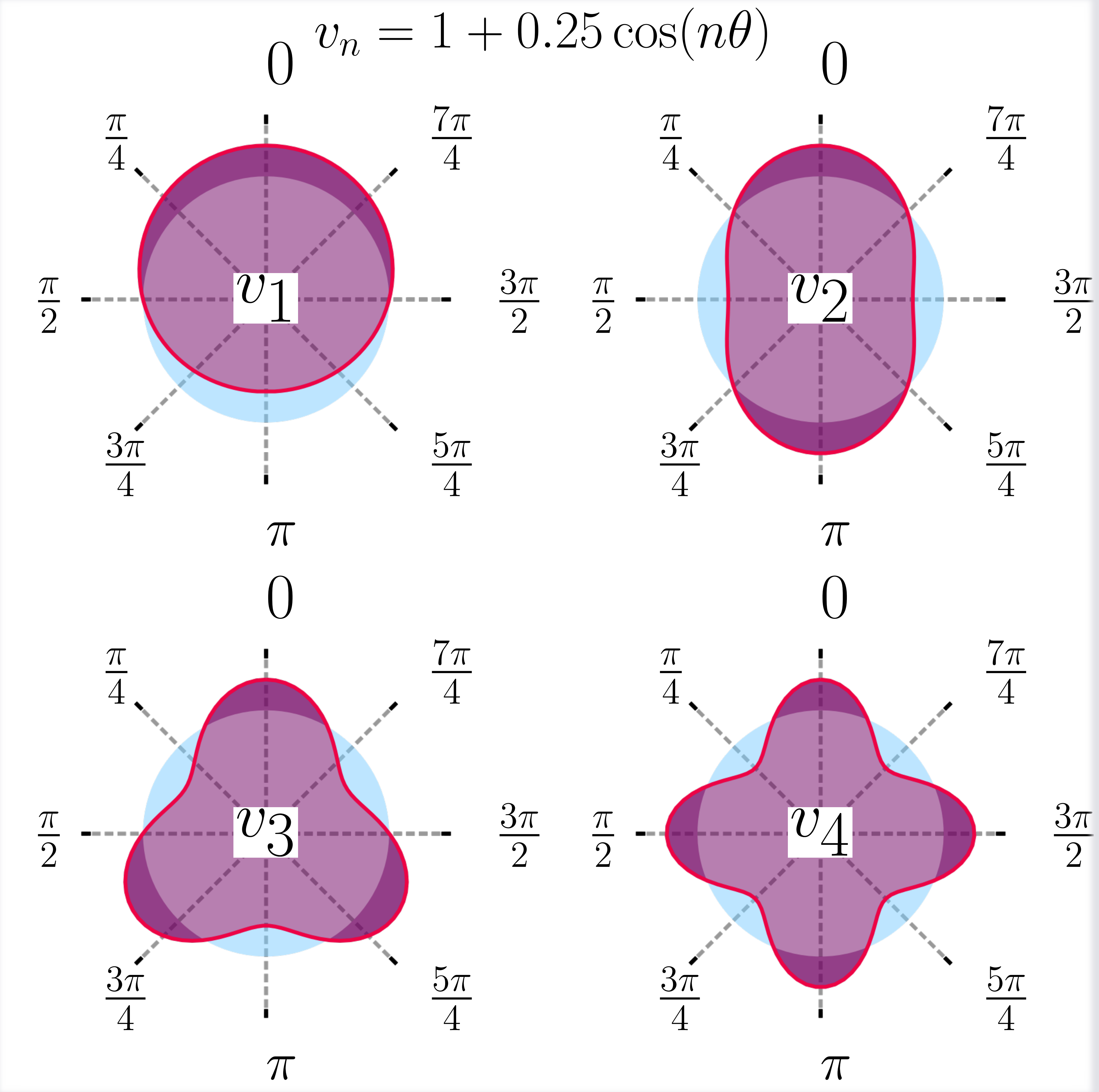
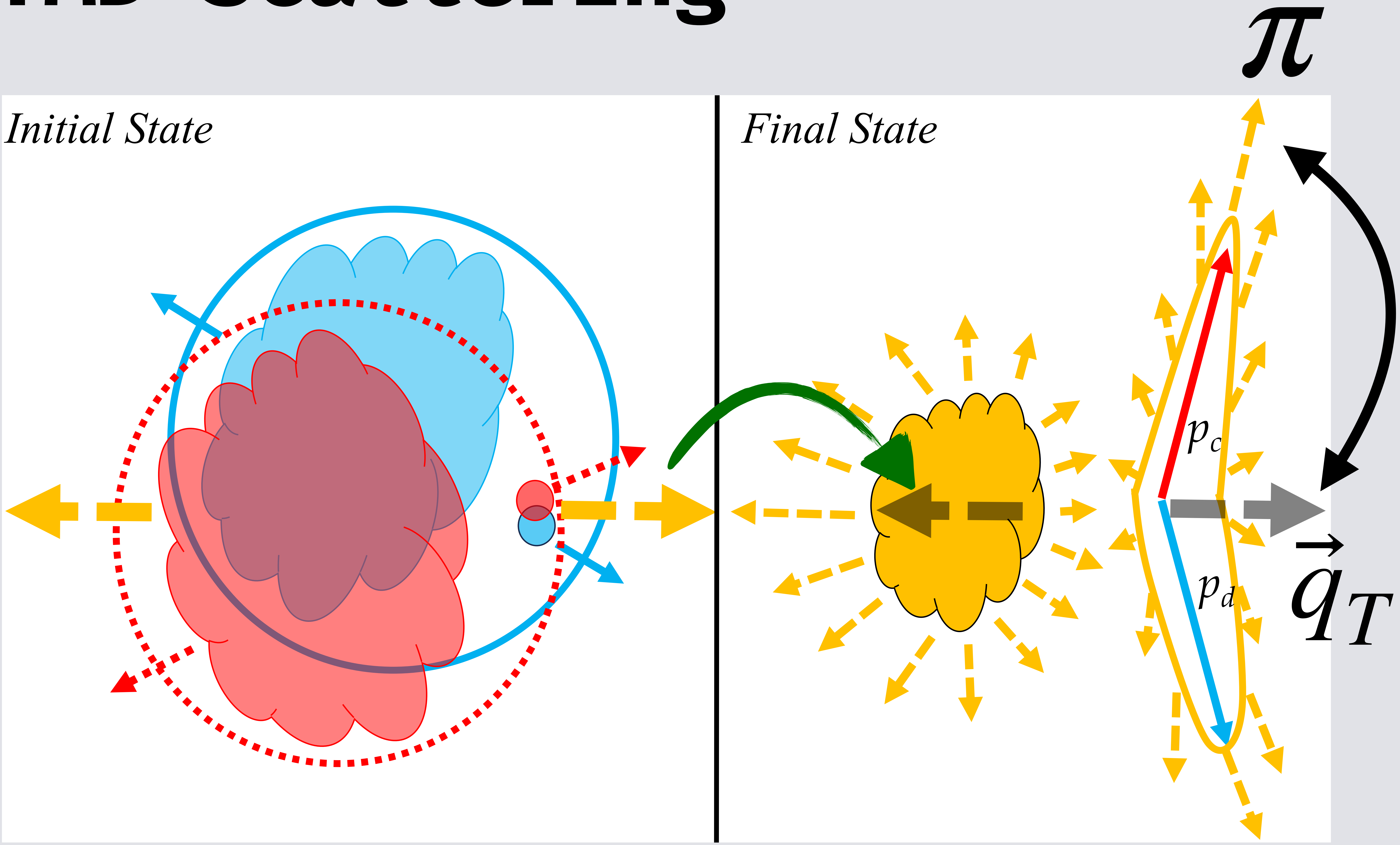
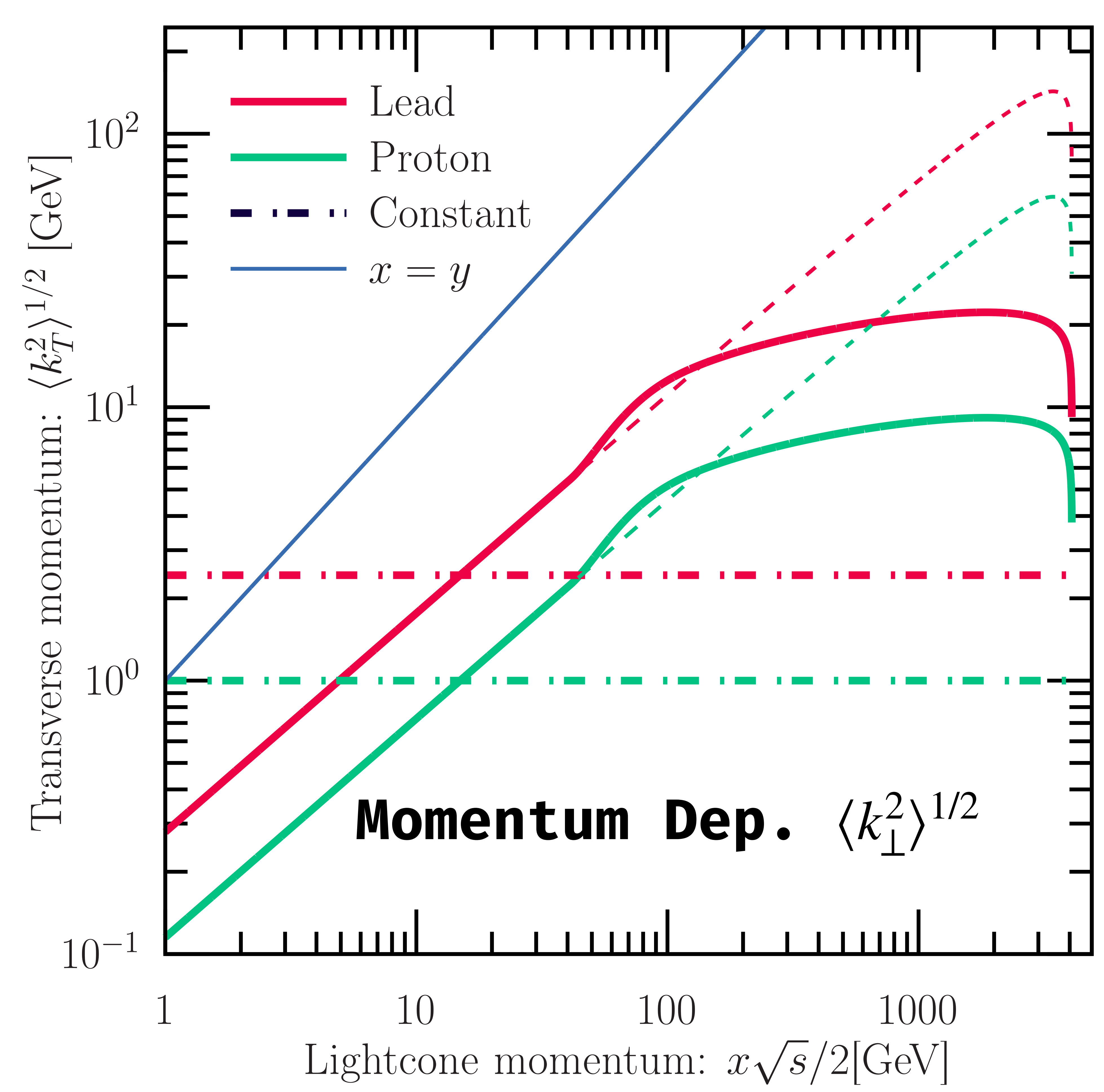


TMD Scattering



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

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 $(x \otimes k_T)$

⇒ 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

⇒ 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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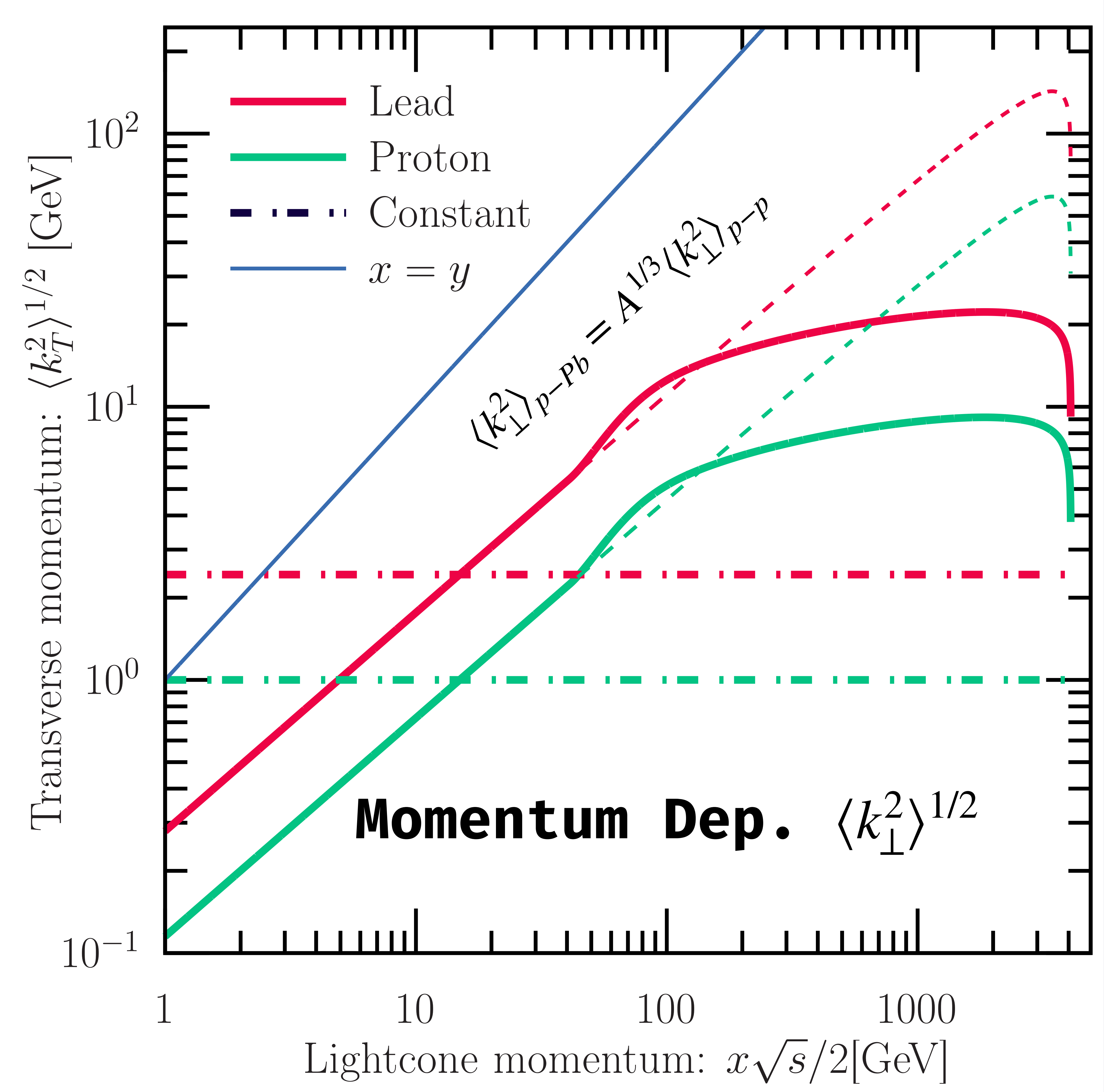

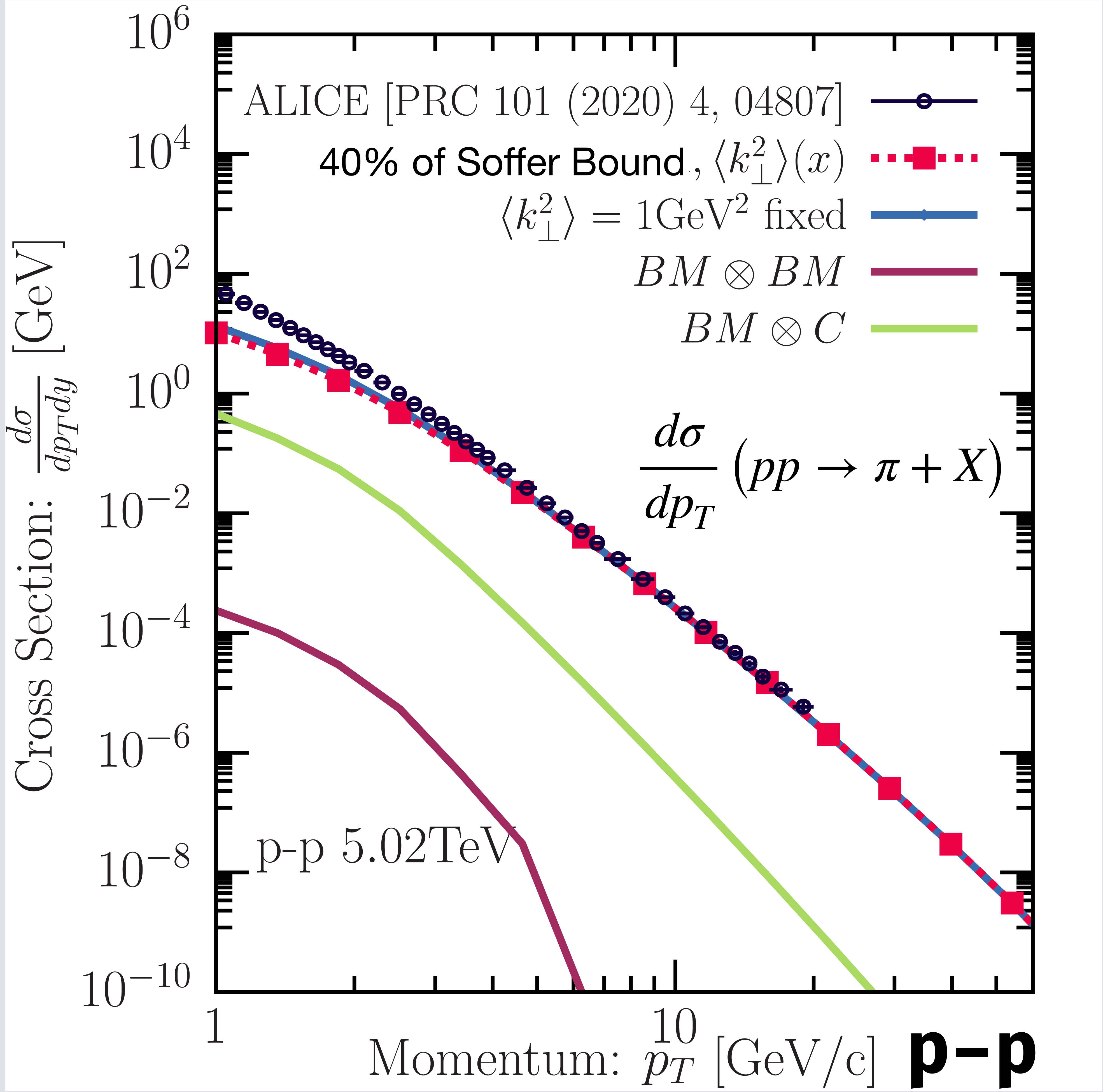

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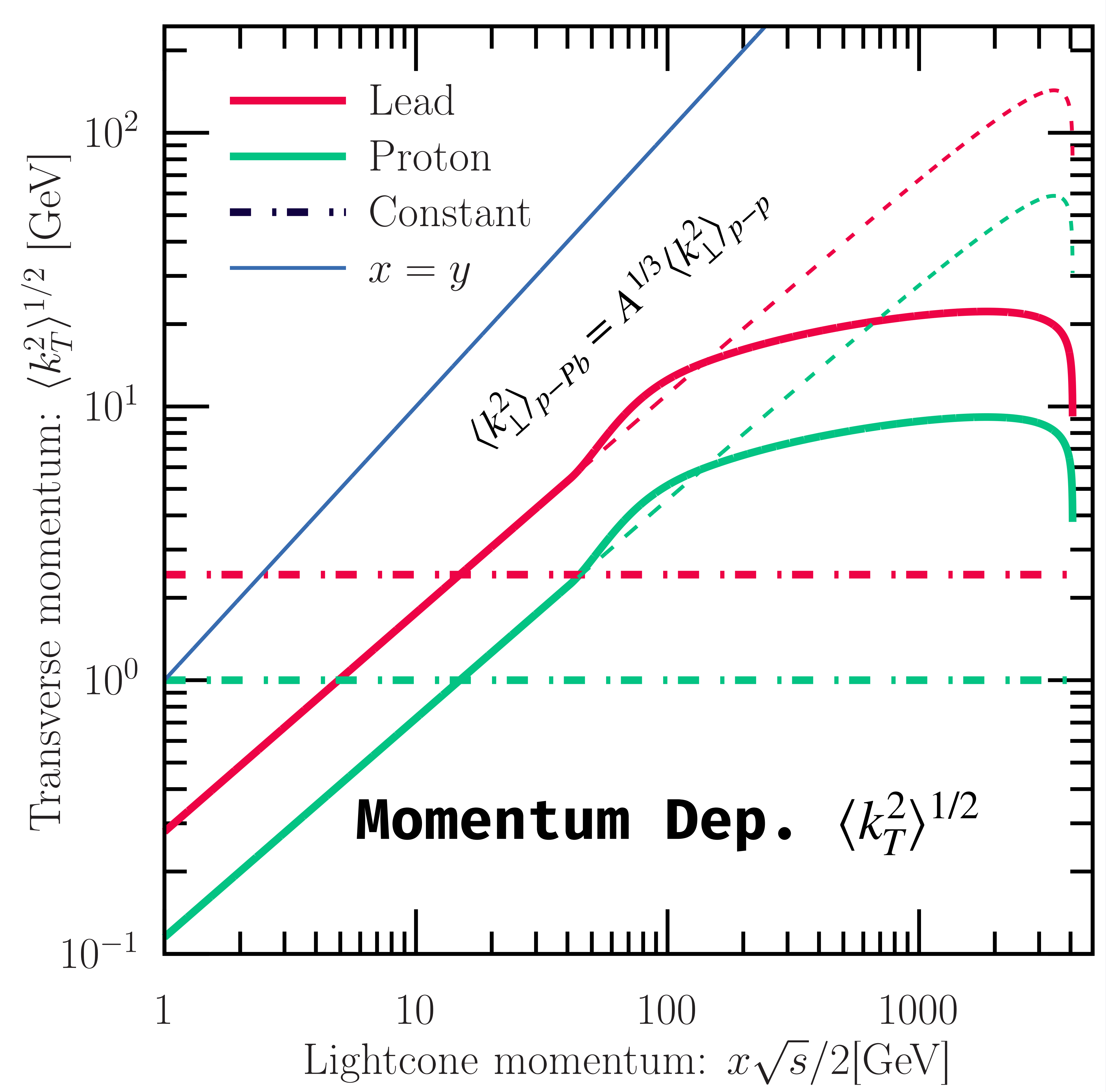

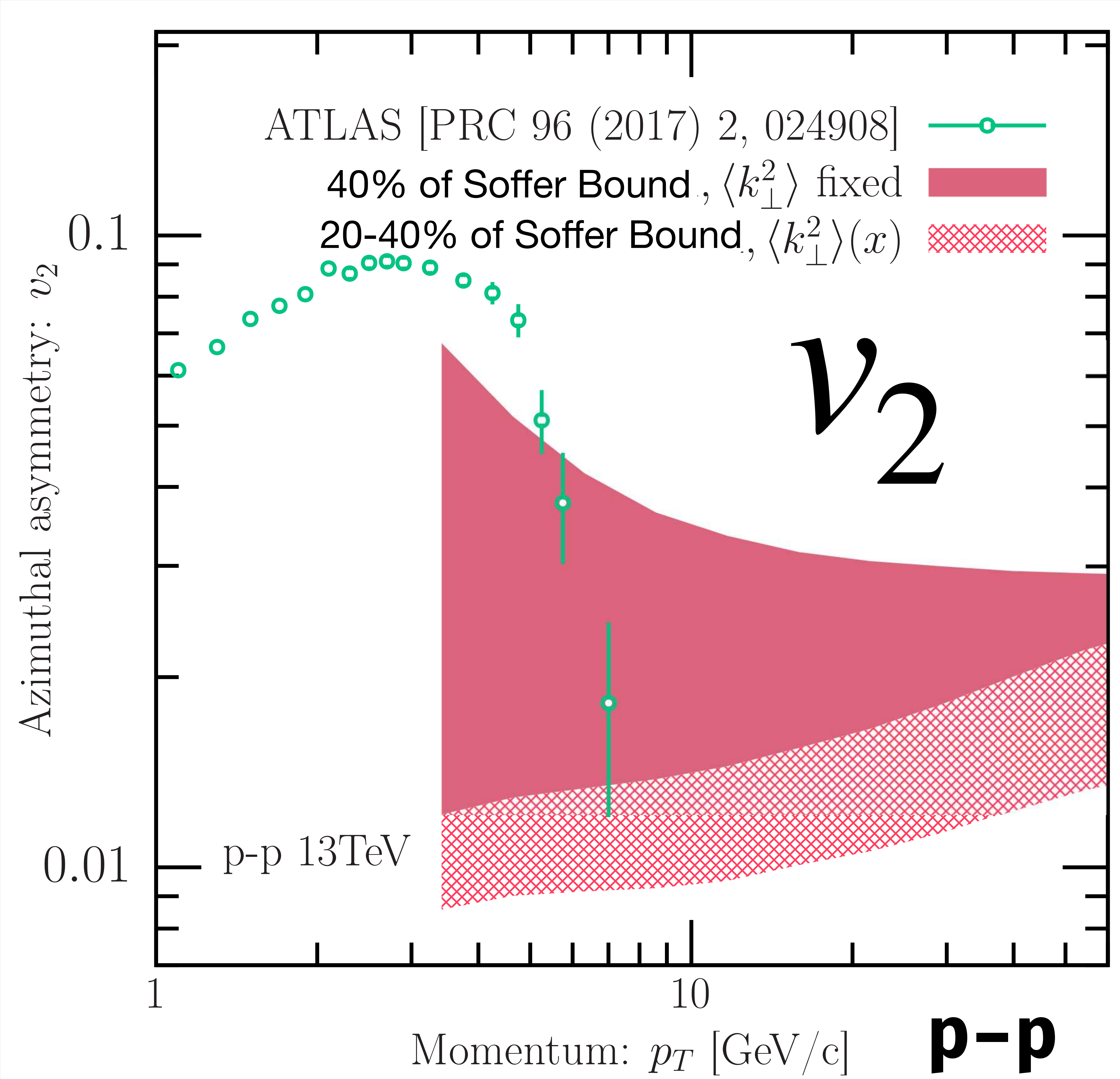

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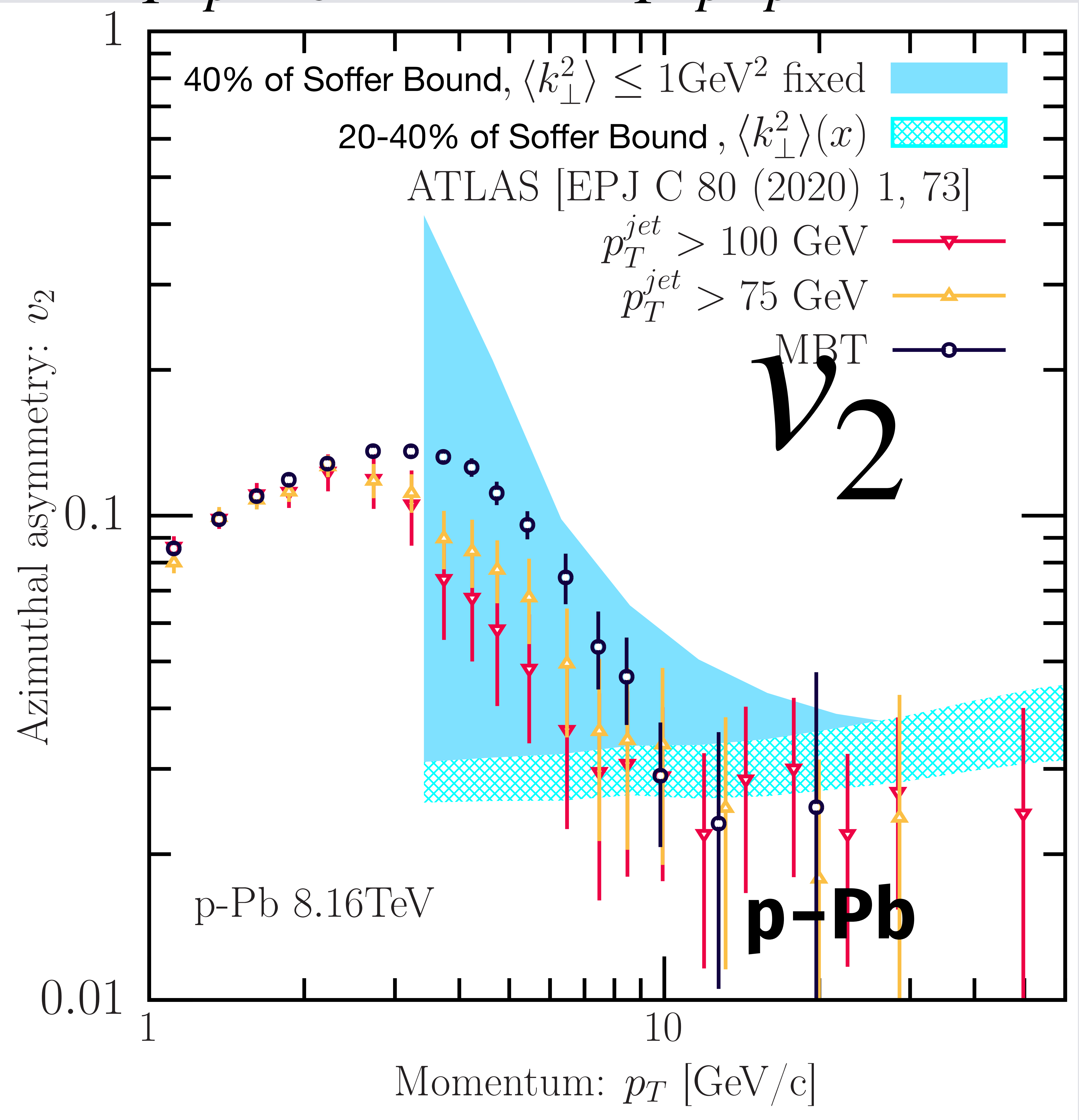
Ismail Soudi

Results

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



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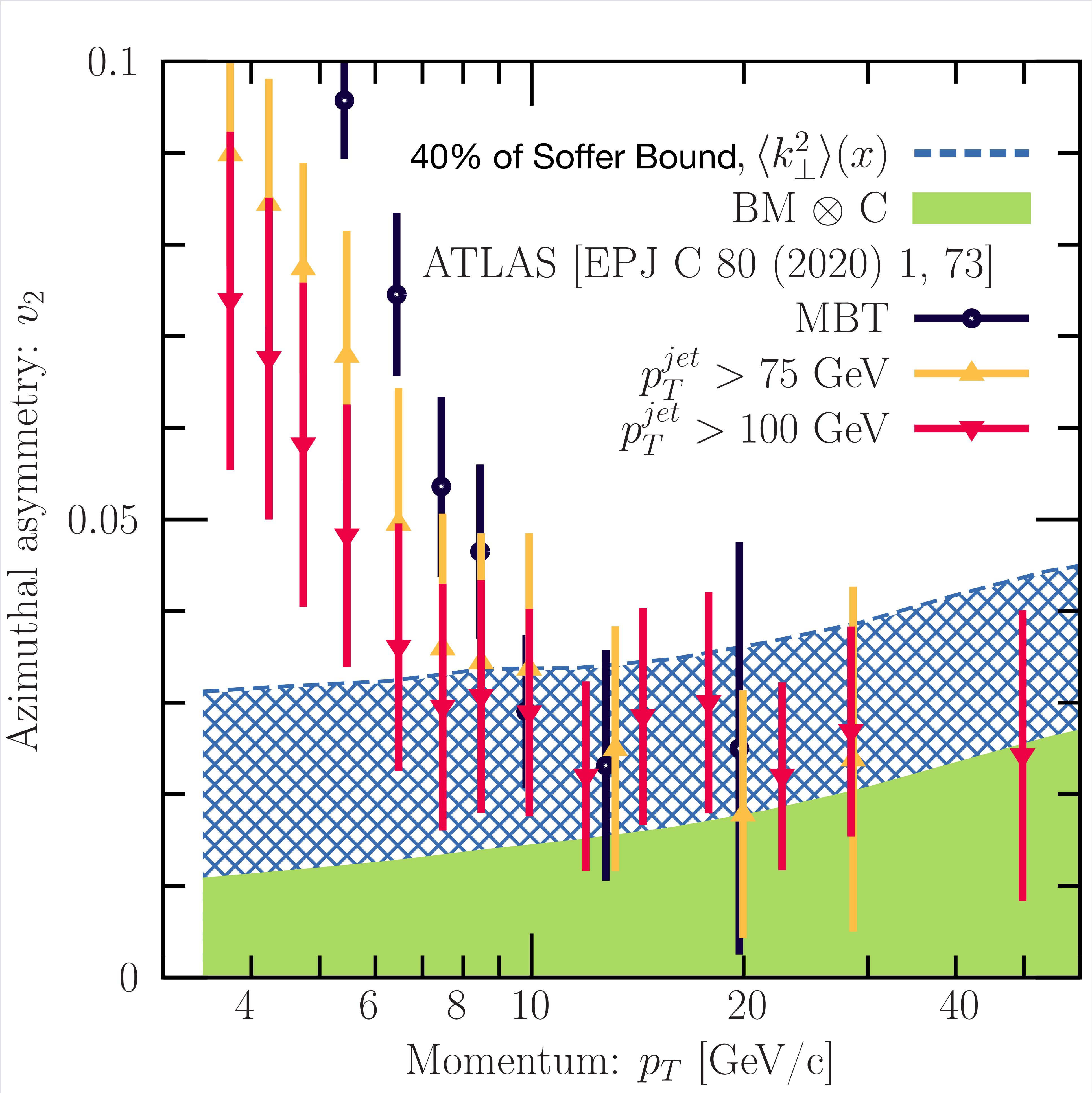

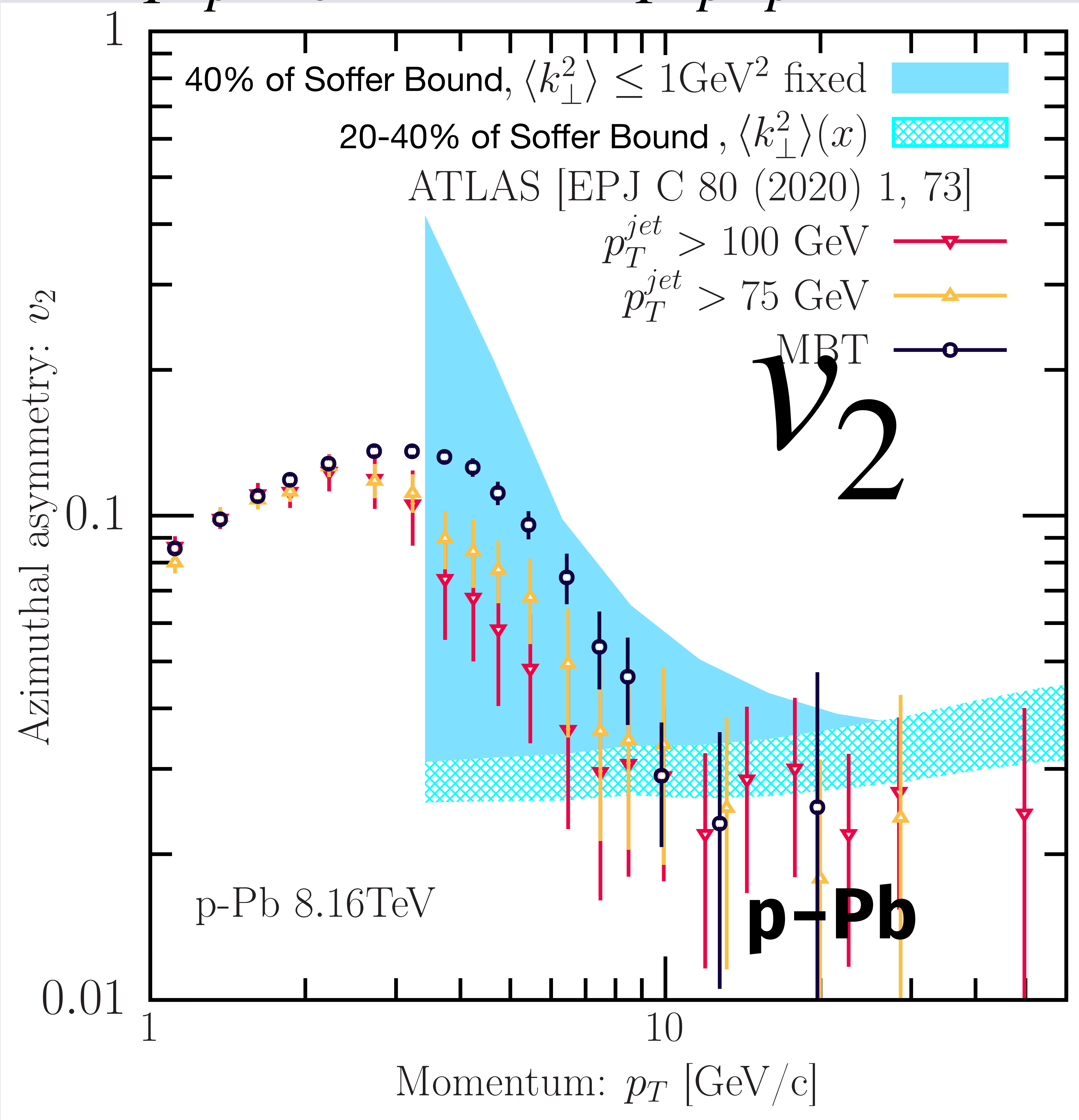

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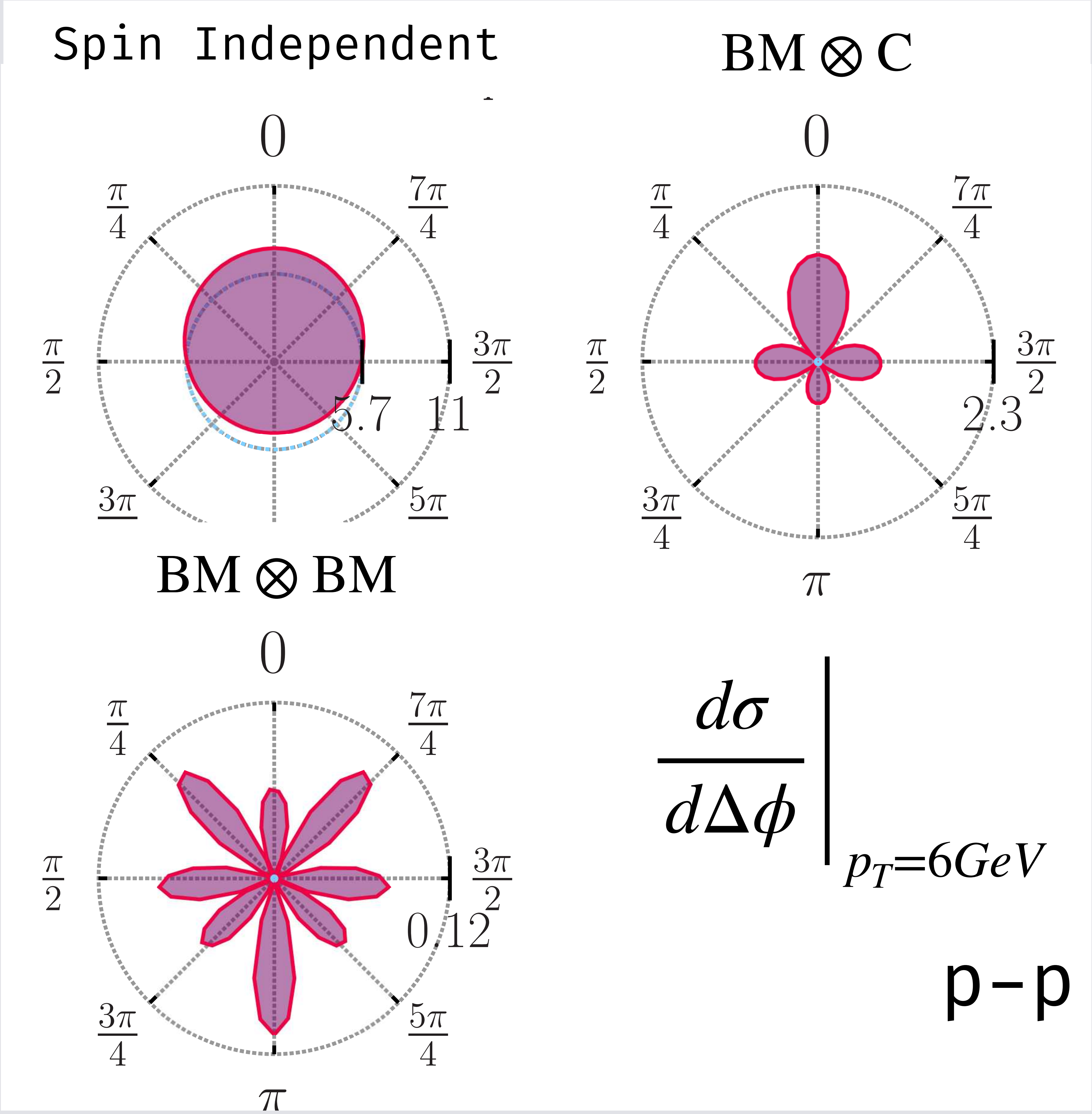
Angular Distribution $\Delta\phi \equiv \phi_{q_T} - \phi_\pi$



$p_T = 6\text{GeV}$

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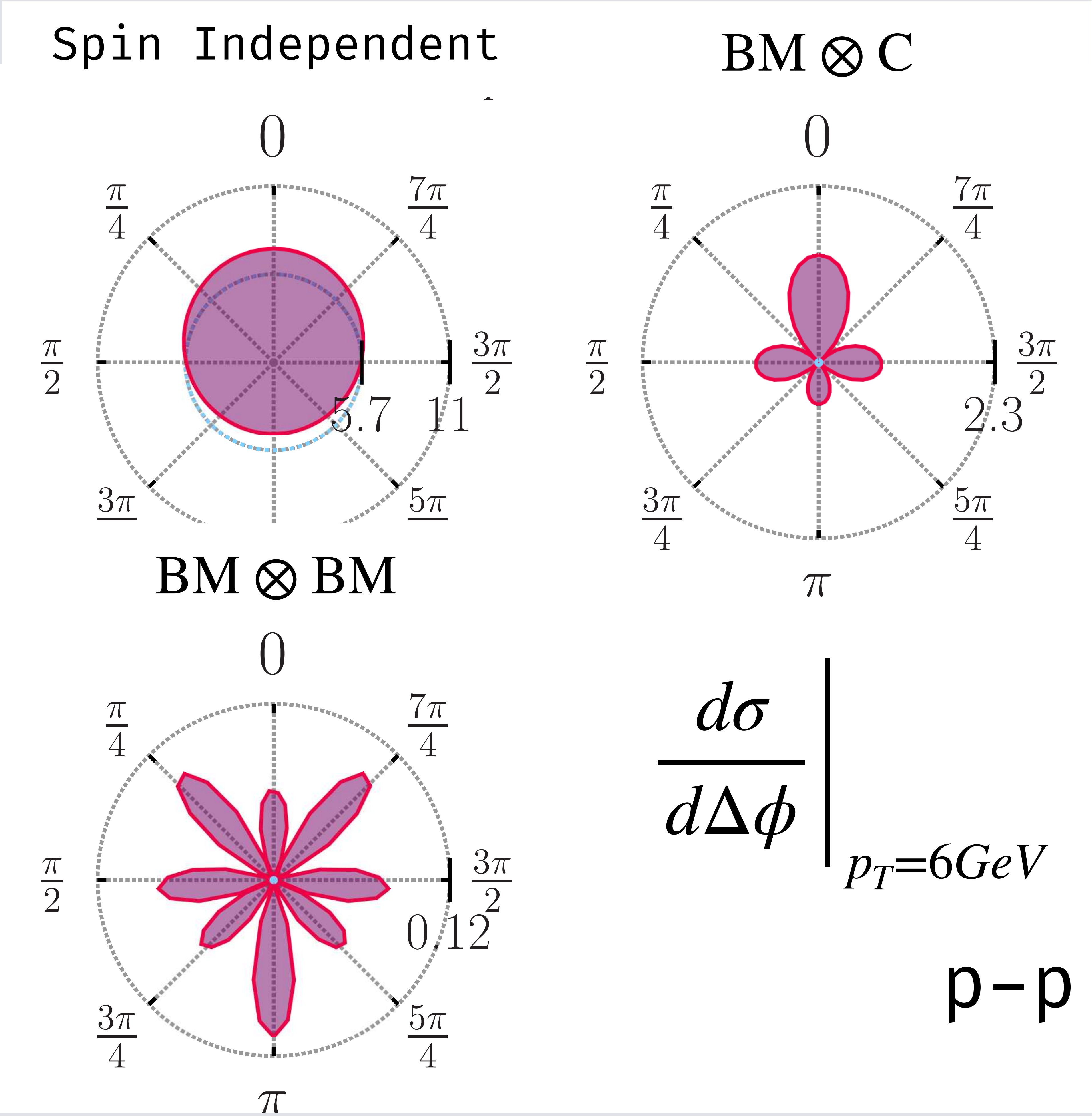

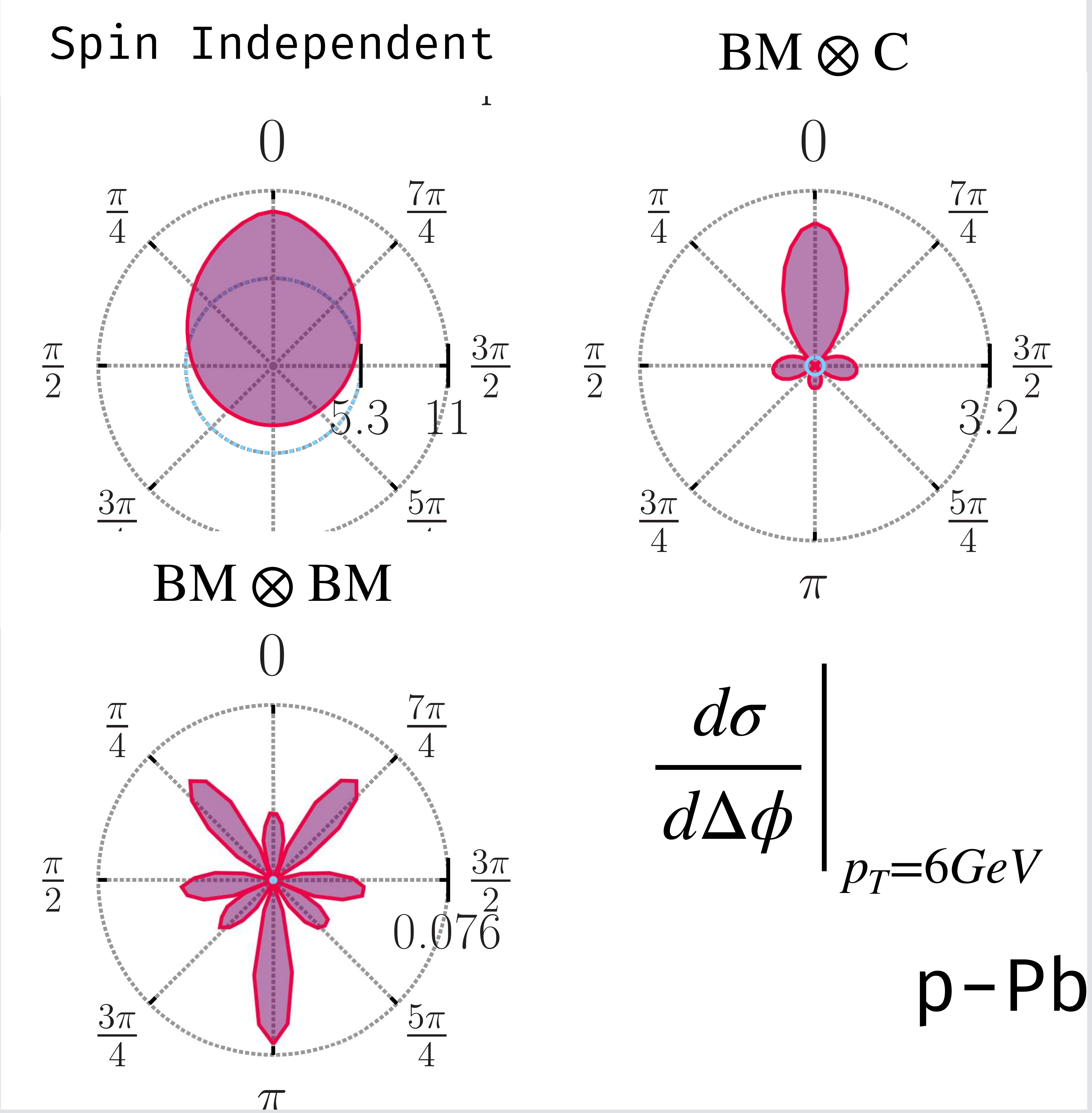

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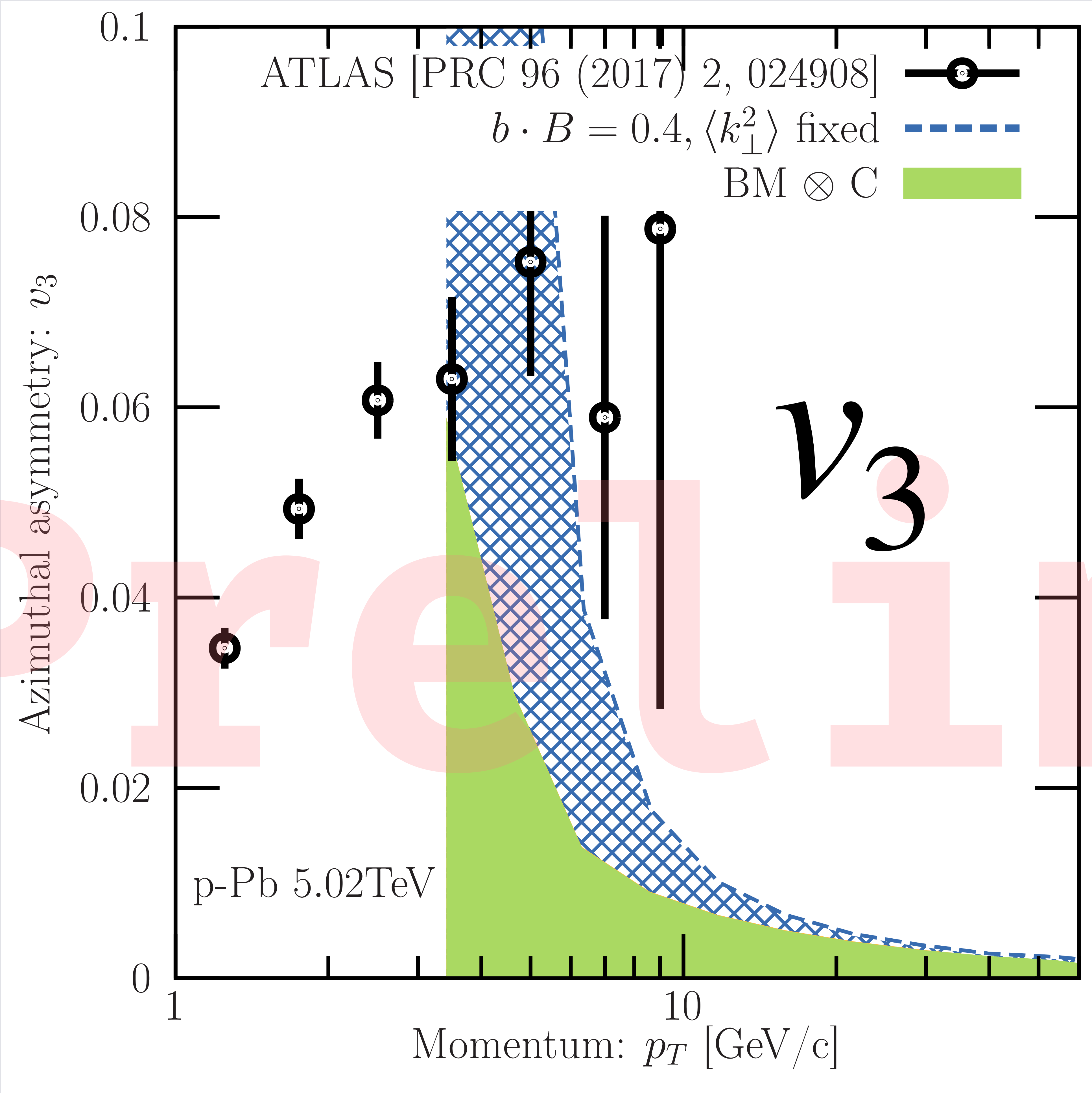
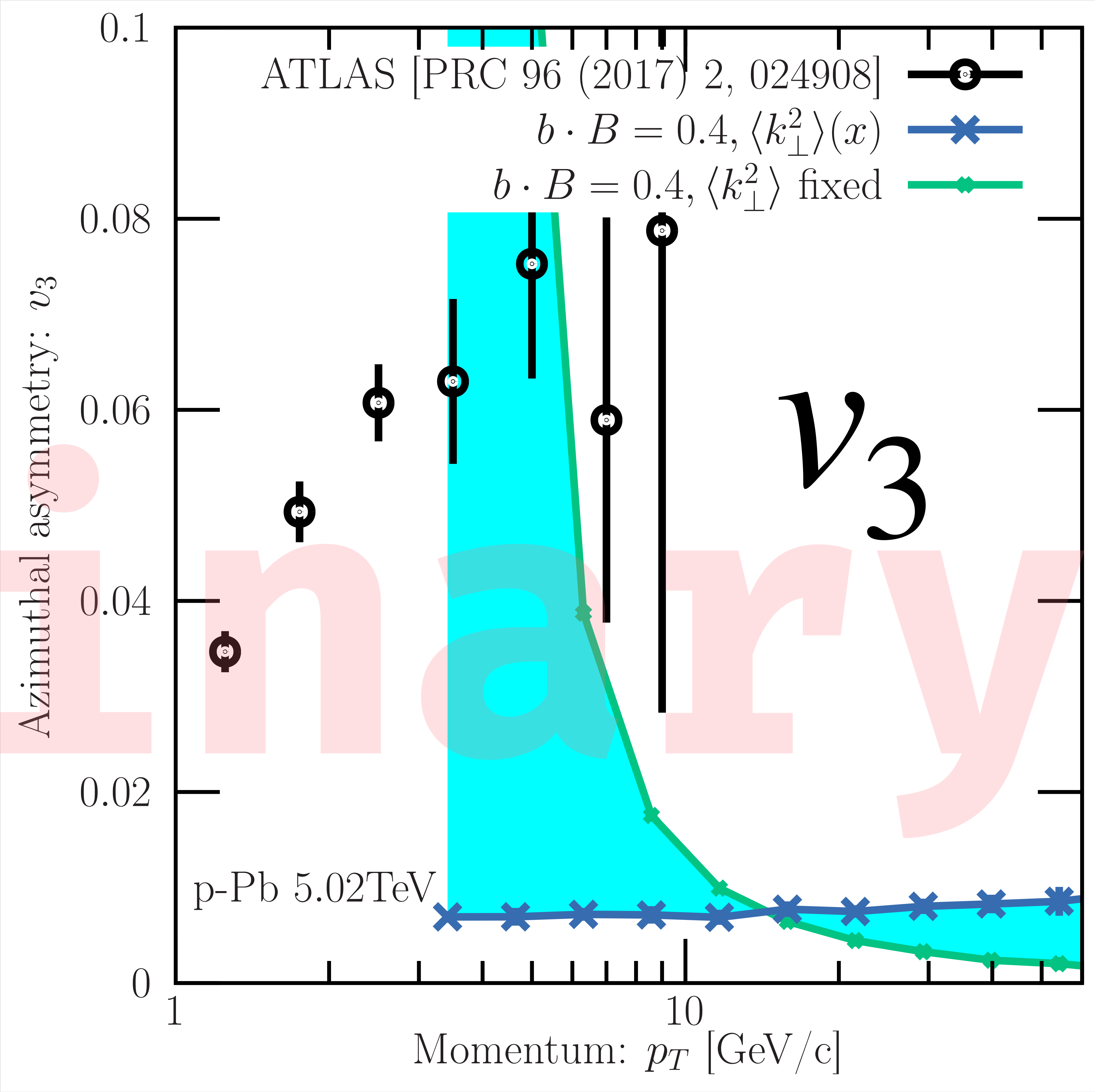
Preliminary results

p-Pb





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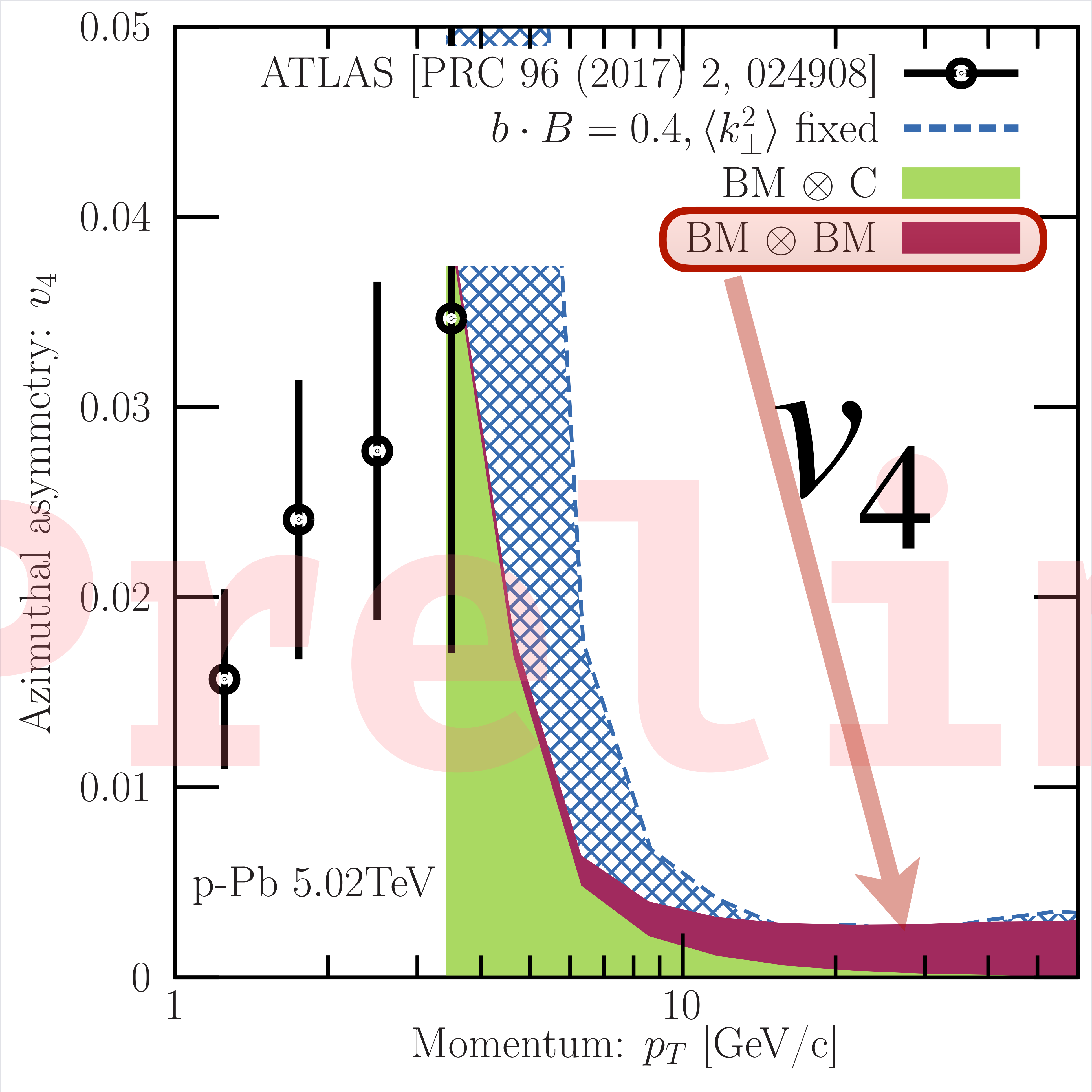

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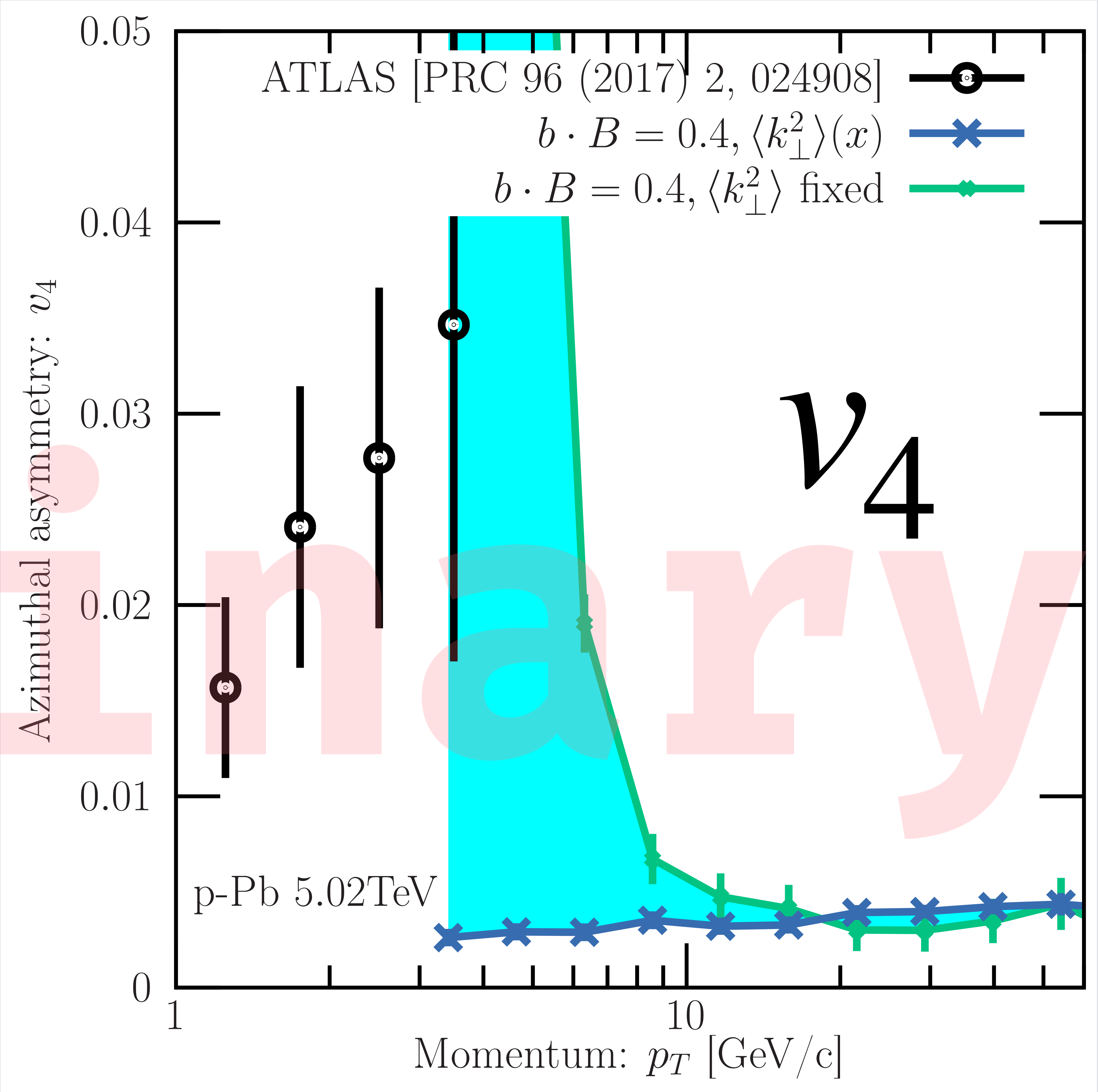
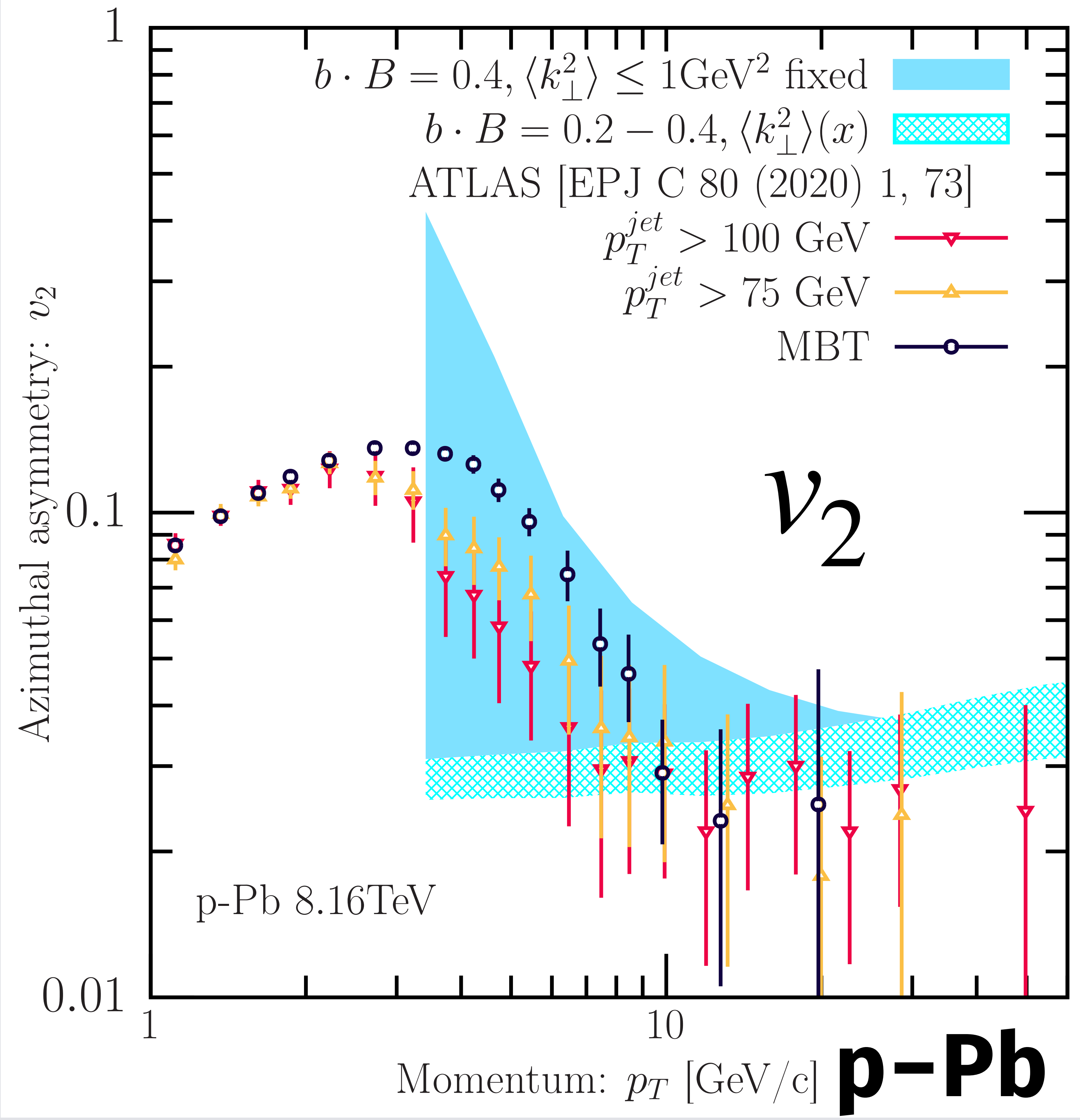


Preliminary

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



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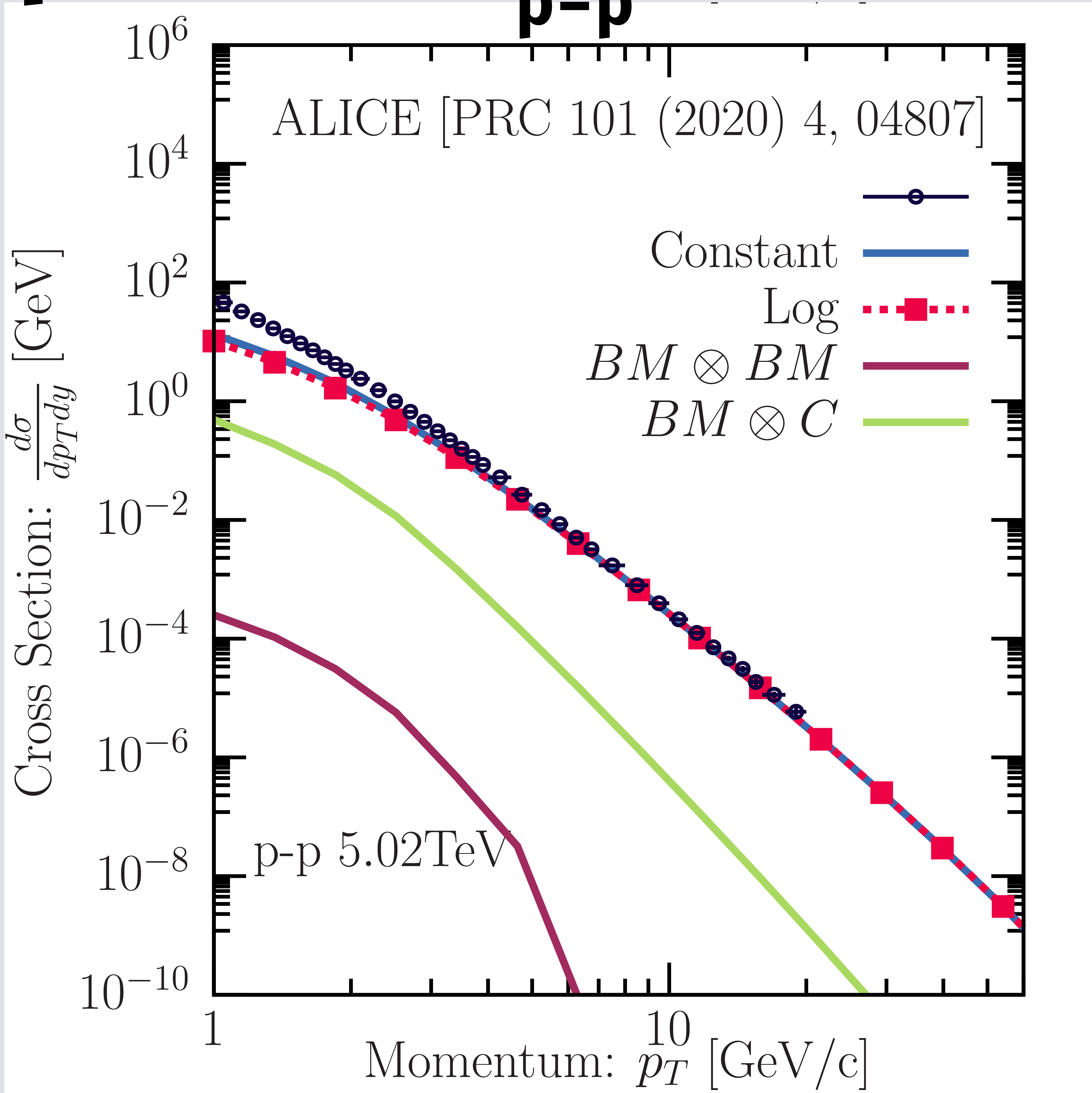
\o/ Thank you for listening!

Backup

Spectrum

p-p



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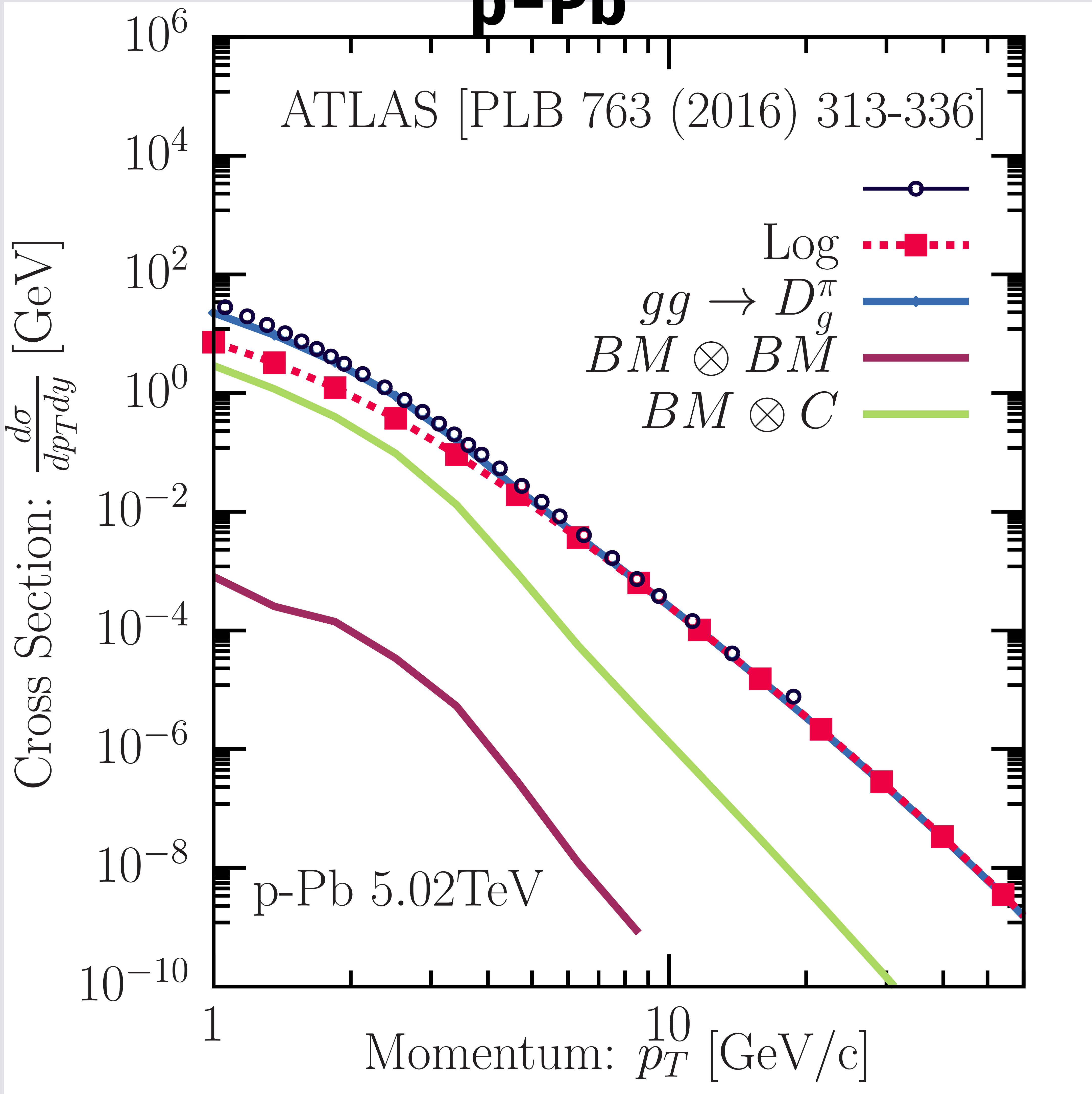
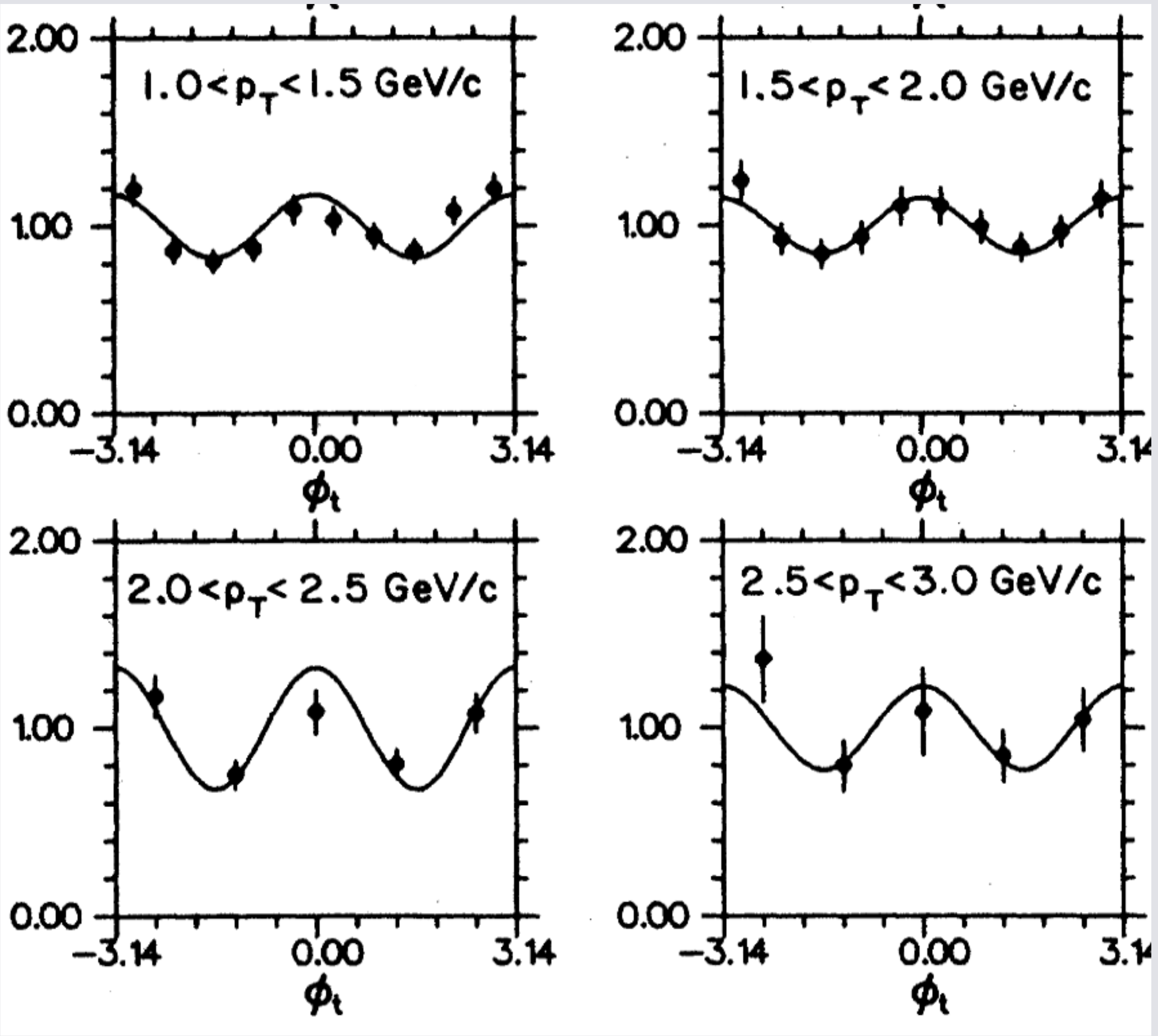


Anisotropies in Drell-Yann

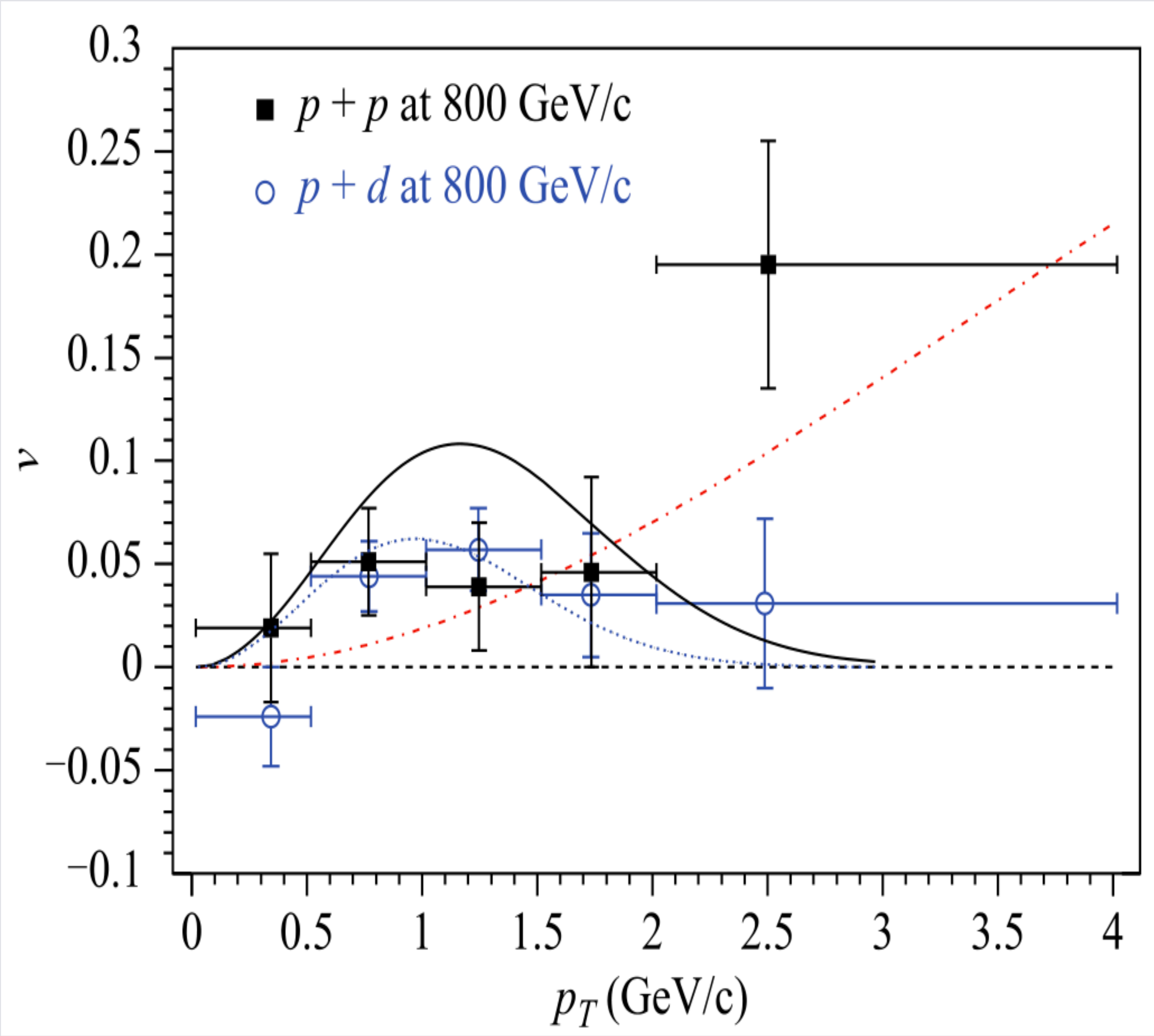
Distribution



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

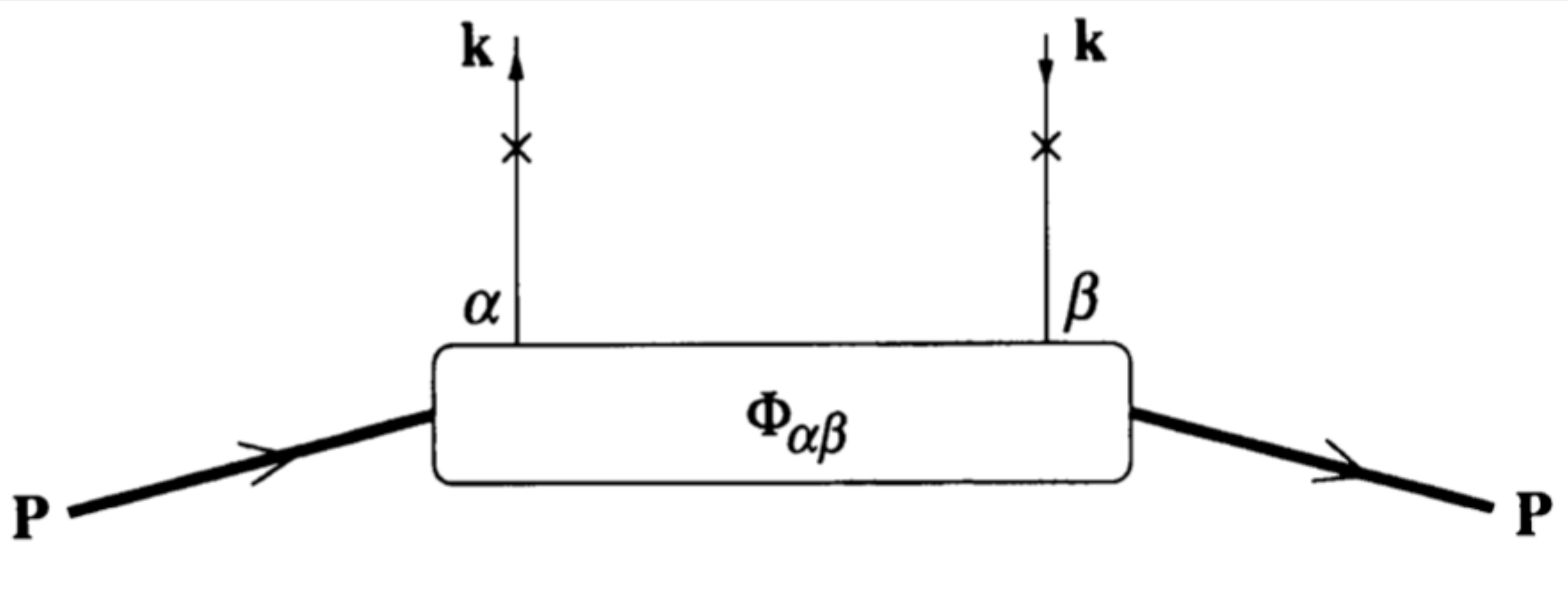
$$\frac{d\sigma}{d\omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$

Average



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

Collinear Factorization

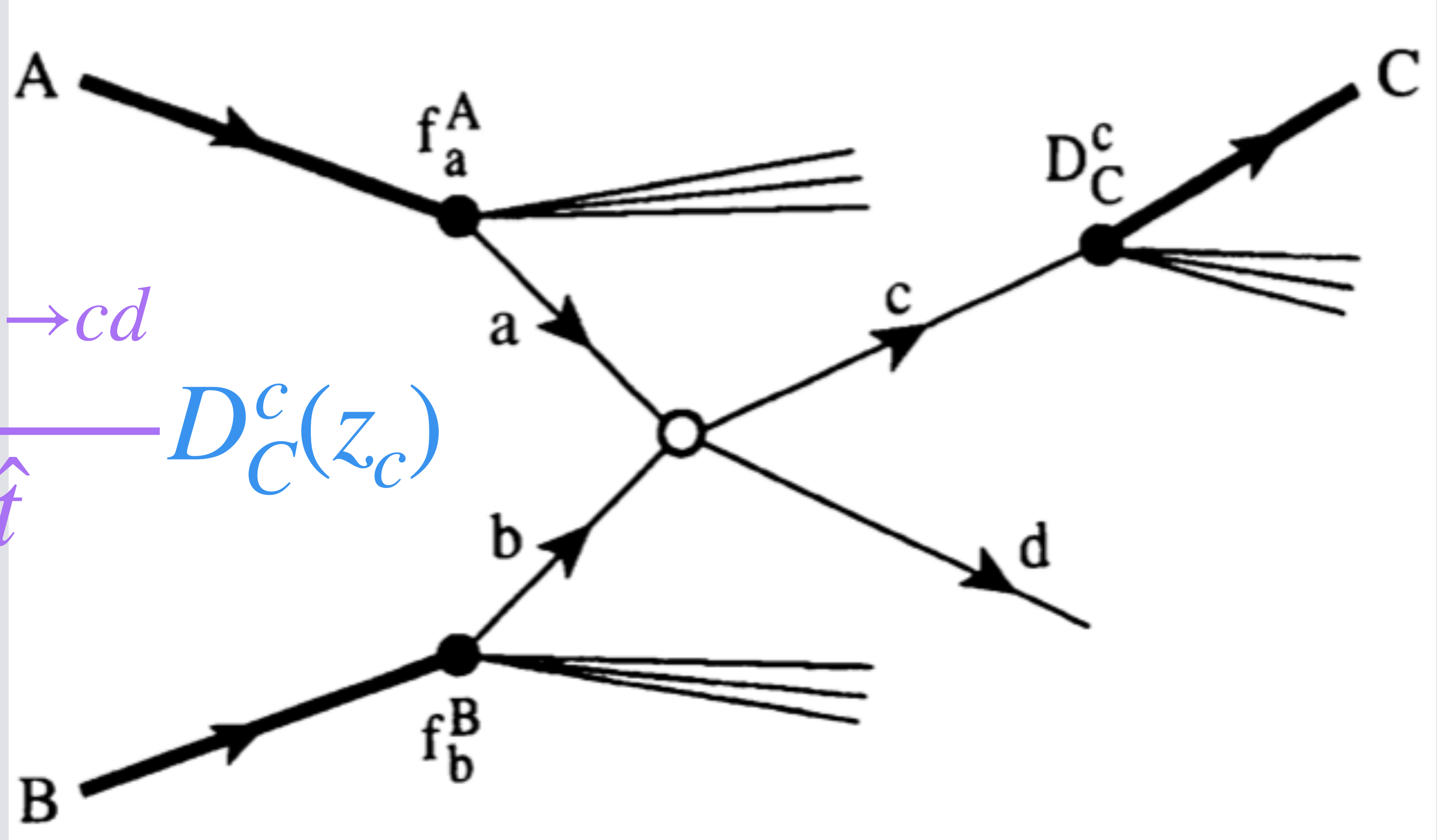


Partonic scattering

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

$\Rightarrow$ 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

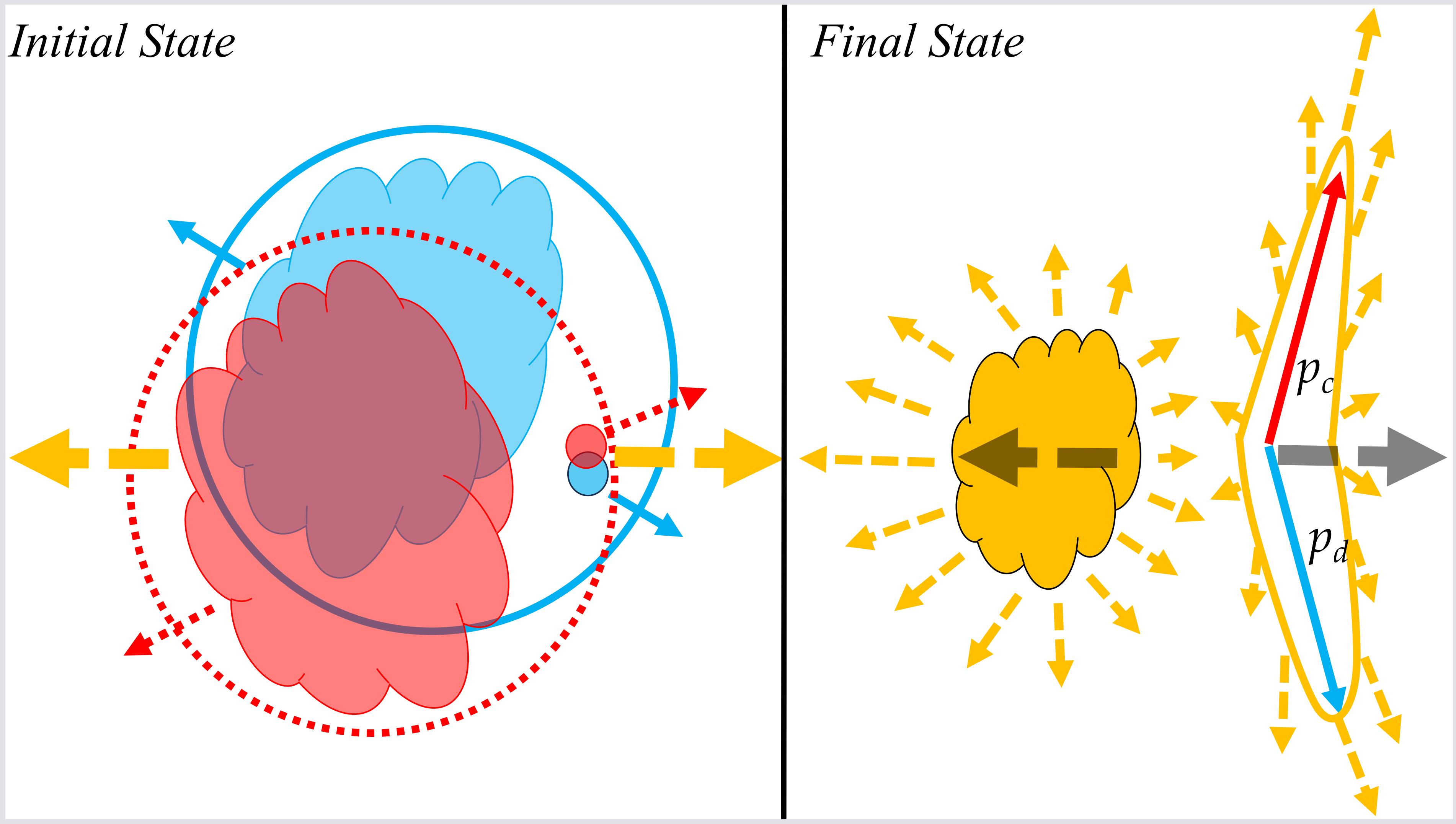
Fierz decomposition of quark-quark correlator contains additional terms than the leading twist distributions

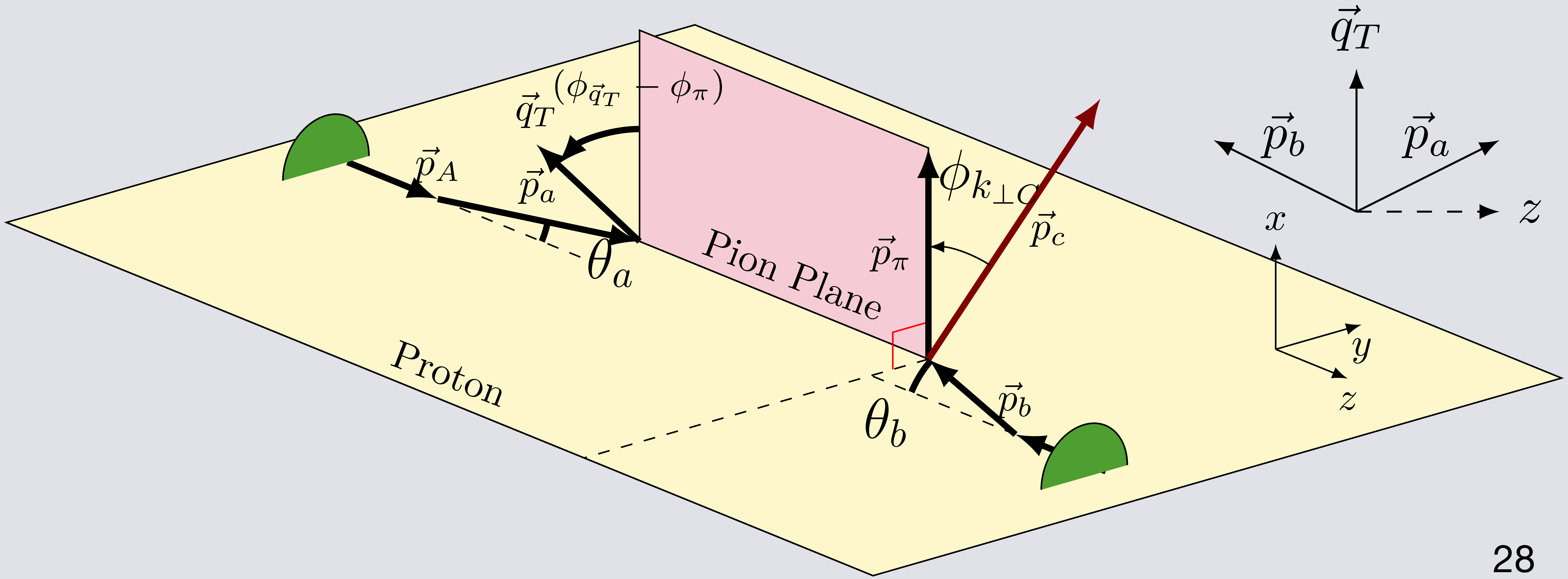
Γ_S	Γ_V^μ	$\Gamma_T^{\mu\nu}$	Γ_A^μ	Γ_P
I	γ^μ	$\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$	$\gamma^5\gamma^\mu$	$i\,\gamma^5$

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

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

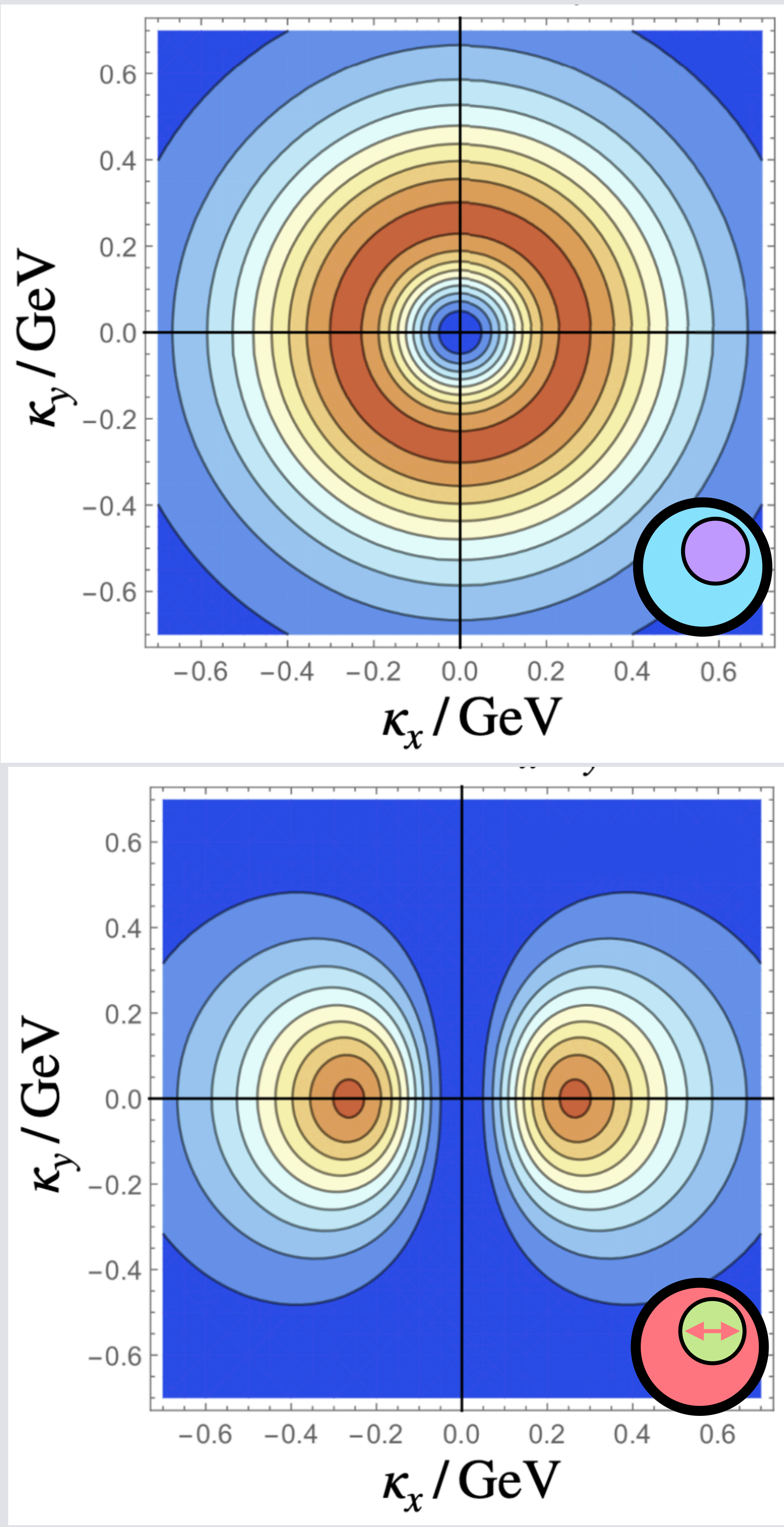
⇒ Gluon correlator

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

Unpolarized + Boer-Mulders/Collins

Soffer Bound:

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



kT Dist

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

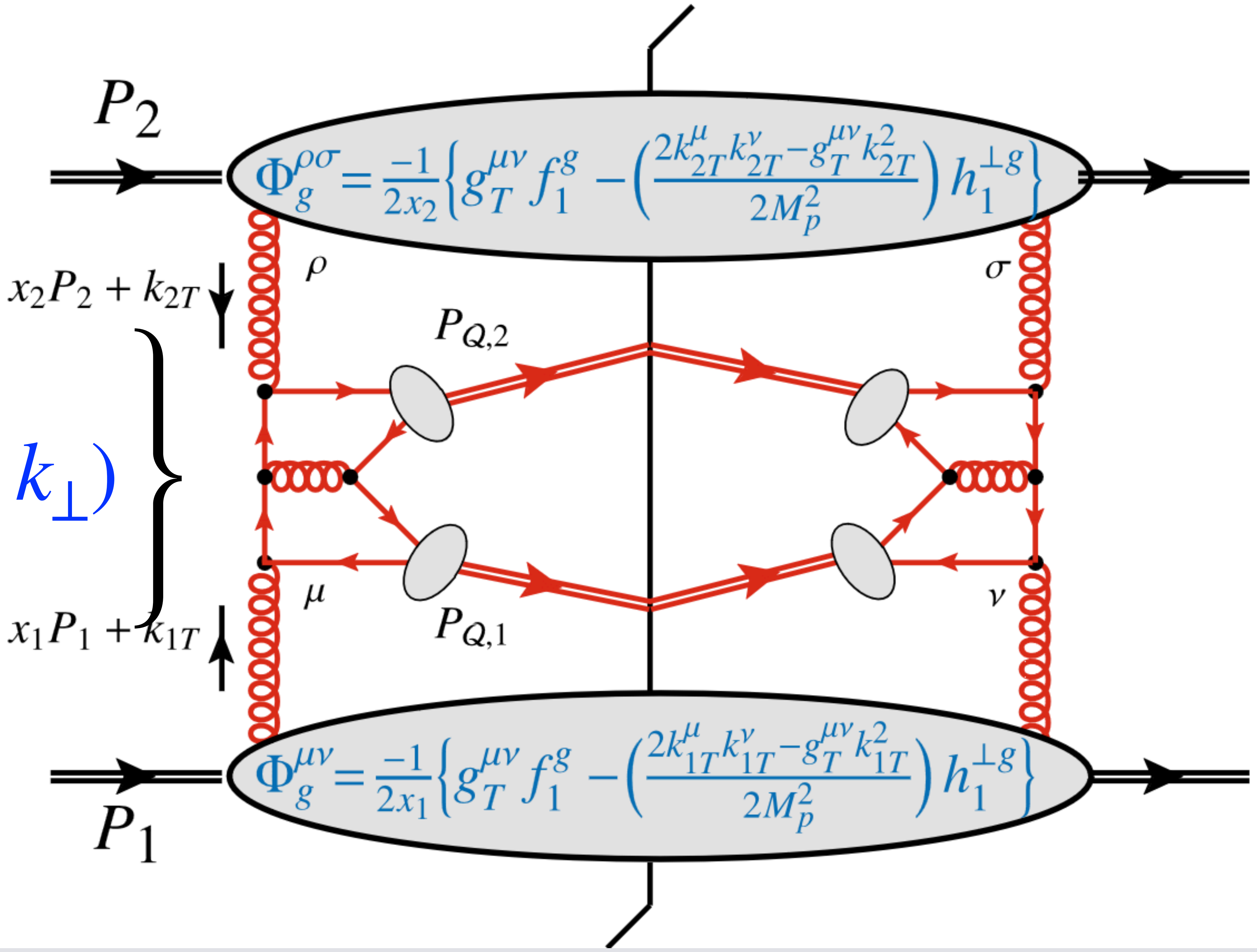
$$\times \begin{cases} \left(\frac{x}{x_0}\sqrt{\frac{s}{s_0}} \right)^{0.8}, & \text{if } x \leq x_0 \\ \left[1 + b_0 \log\left(\frac{x}{x_0}\sqrt{\frac{s}{s_0}} \right) \right]^{1/2}, & \text{if } x > x_0 \end{cases}$$

Transverse Momentum Distributions

For unpolarized hadrons

⇒ Gluon correlator

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



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

Unpolarized + Boer-Mulders/Collins

Soffer Bound:

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

Centrality