Hard/Soft Correlations in Small Systems

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Based on:

- IS, A. Majumder PRC 111 (2025)
- IS, A. Majumder PLB 859 (2024)
- IS, et al. arXiv:2407.17443

UNIVERSITY OF JYVÄSKYLÄ

HELSINKI INSTITUTE OF PHYSICS

Centre of Excellence in Quark Matter

Yocto/LHC

European Research Council
Established by the European Commission

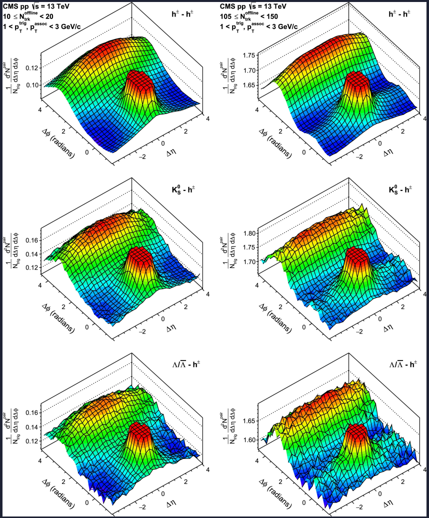
High energy probes of the initial stages 2025, CERN, Geneva

Apr 03, 2025

Introduction

"Evidence for collectivity in pp collisions at the LHC":

- Collective flow



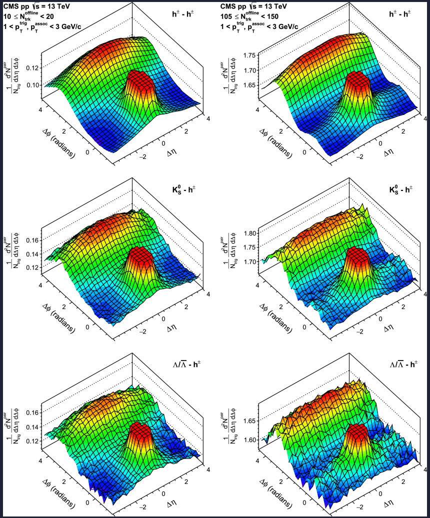
CMS *PLB*765 (2017)

Introduction

"Evidence for collectivity in pp collisions at the LHC":

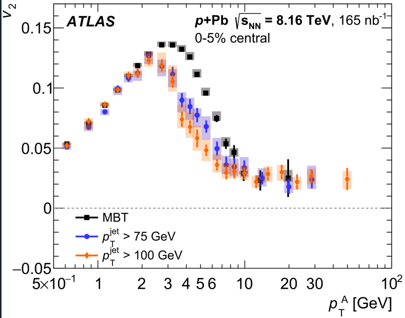
- Collective flow

⚠️ No Jet quenching observed



CMS *PLB765 (2017)*

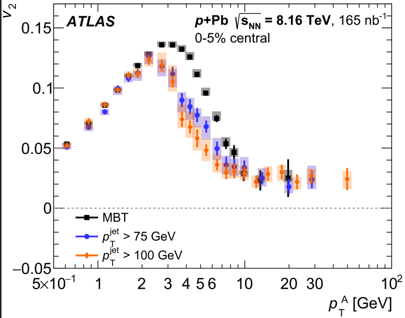
Jet quenching vs Flow

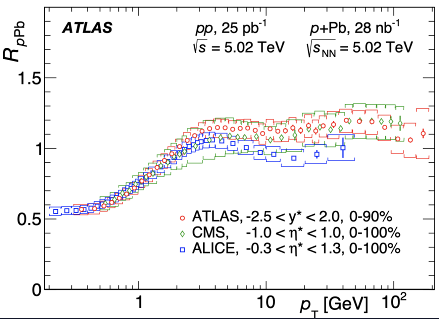


ATLAS *EPJ C80 (2020)*

Jet quenching vs Flow

- R_{pPb} vs v_2 puzzle



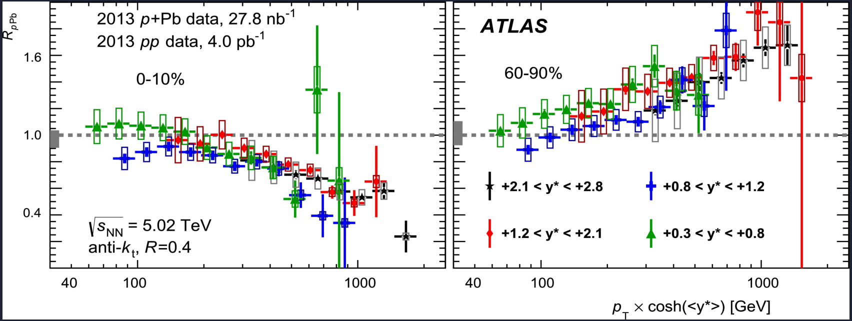


ATLAS *EPJ C80 (2020)*

ATLAS *JHEP07 (2023)*
CMS *JHEP04 (2017)*
ALICE *JHEP11 (2018)*

Jet quenching vs Flow

- R_{pPb} vs v_2 puzzle
- R_{pPb} vs centrality



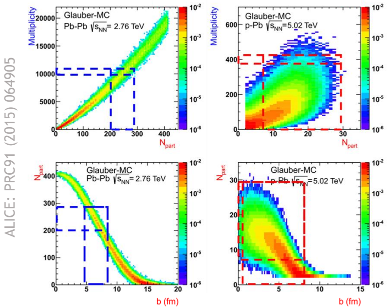
ATLAS *PLB748* (2015)

Multiplicity? I

Daniel Firak (for the PHENIX collaboration) - HP2024 PHENIX *Phys. Rev. Lett.*134 (2025)

Is the Glauber Model good both in small and large systems?

PHENIX



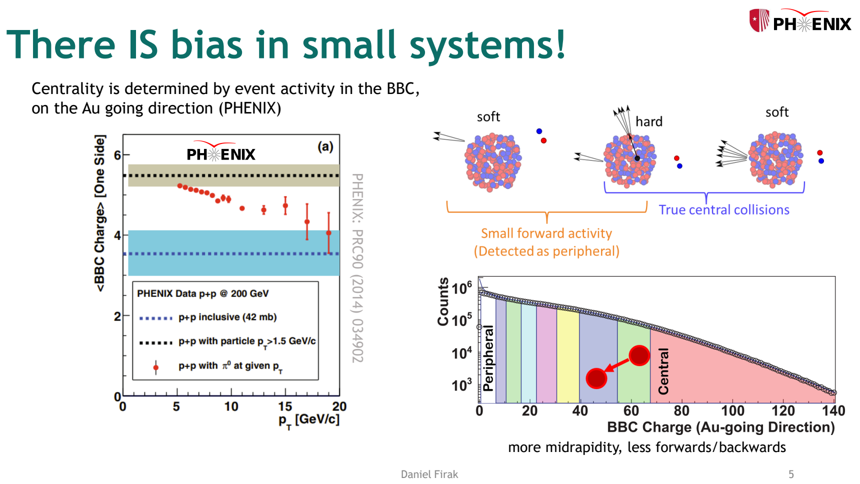
Red axis: theory / model calculations
Blue axis: experimentally measurable

$$\frac{dN_{ch}}{d\eta} \Rightarrow N_{coll} \underbrace{\Longrightarrow}_{Model/Theory} N_{par} \underbrace{\Longrightarrow}_{Theory} b$$

- Multiplicity window = centrality class
  - Measurable
- $N_{coll}^{GL} \propto \left(\frac{dN_{ch}}{d\eta}\right)^{a}$: Not directly measurable!
  - Obtained through Glauber model

Multiplicity? II

Daniel Firak (for the PHENIX collaboration) - HP2024 PHENIX *Phys. Rev. Lett.*134 (2025)

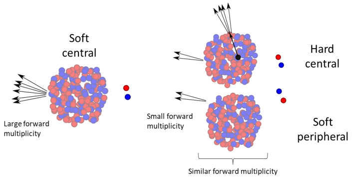


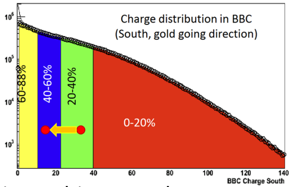
Multiplicity? III

Daniel Firak (for the PHENIX collaboration) - HP2024 PHENIX *Phys. Rev. Lett.*134 (2025)

PHENIX

Bias in Centrality determination

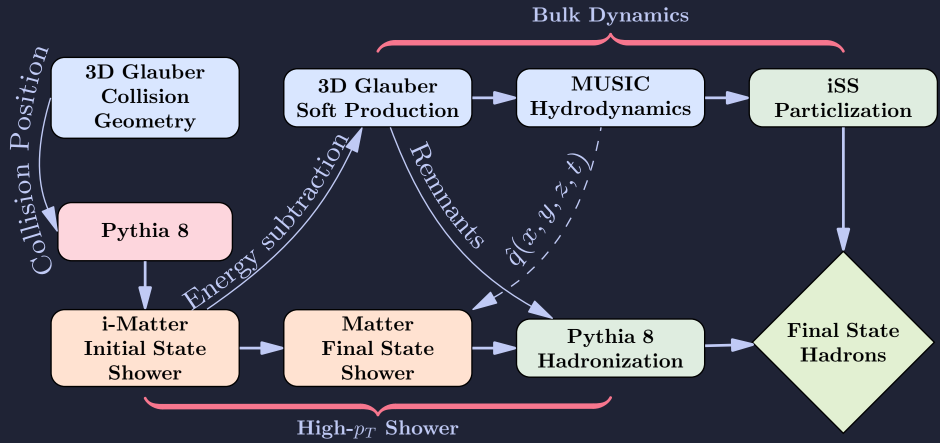




- Since the event activity is measured in the forward region of the detector, a hard event (think jets) can deplete the forward activity, and would have a high pT event on the central detectors
- This can drive central events to appear as peripheral, explaining a source of "peripheral enhancement" at high pT

Daniel Firak 22

X-SCAPE

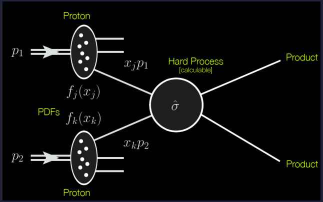


JETSCAPE arXiv:2407.17443

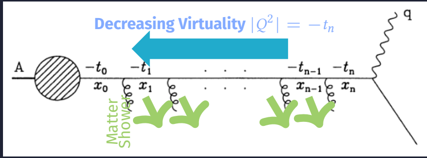
Hard/Soft

Hard

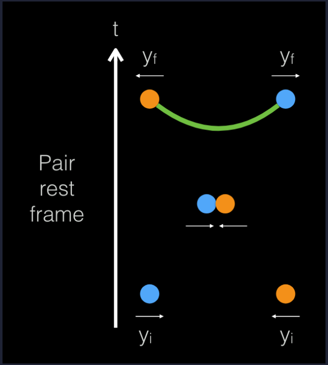
- Pythia Hard Process



- i-Matter ISR + Matter FSR

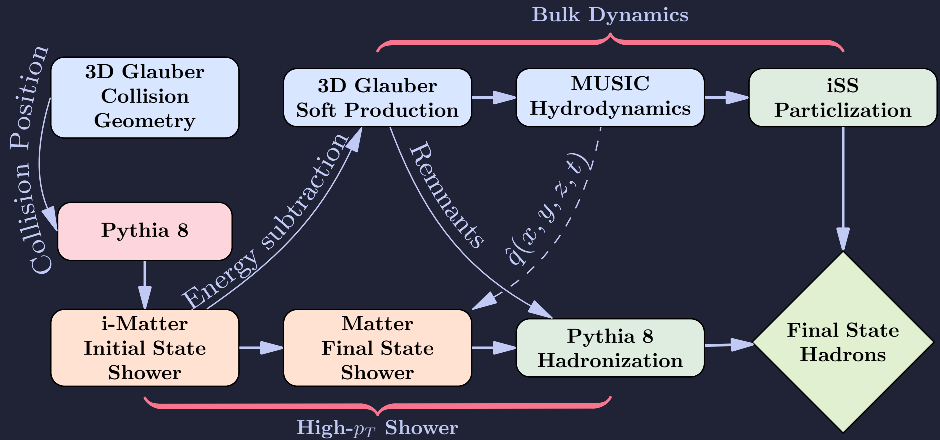


Soft



$$\frac{dE}{dz} = -\sigma \; , \qquad \frac{dp_z}{dt} = -\sigma \tag{1}$$

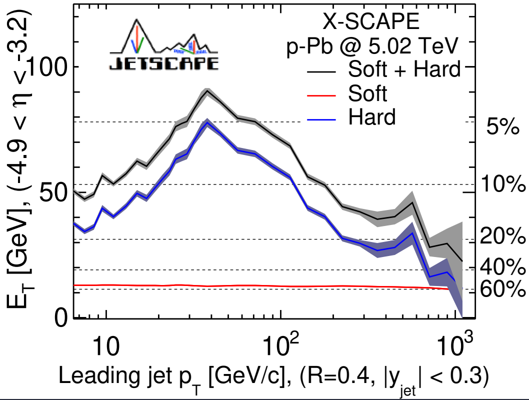
X-SCAPE

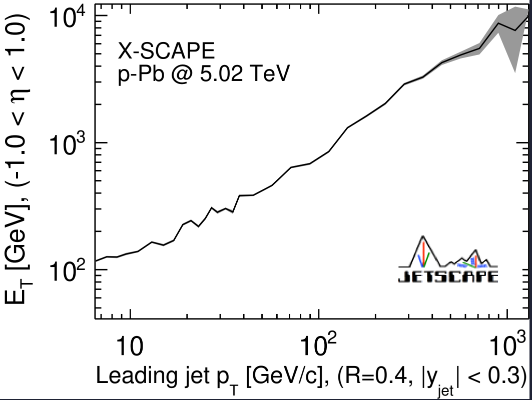


JETSCAPE arXiv:2407.17443

Correlations

Forward | Mid



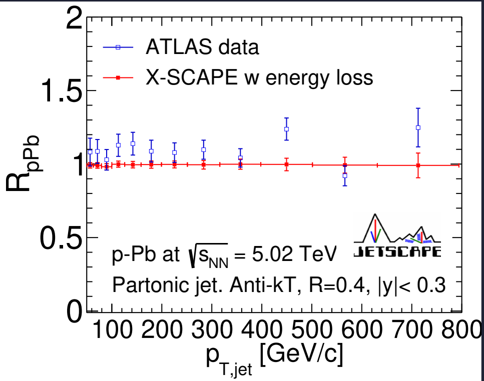


Competing effects

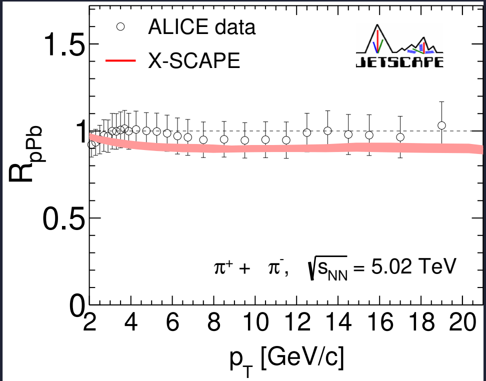
- » E_T increases with leading jet p_T
- » At higher p_T energy conservation leads to decrease in E_T

Energy Loss?

Jets



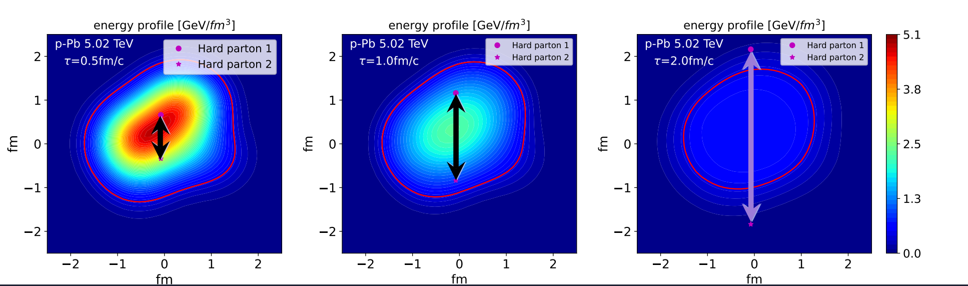
Pions



Matter Energy loss in p-Pb collisions

» No evidence for jet quenching

Energy Loss: Explanation

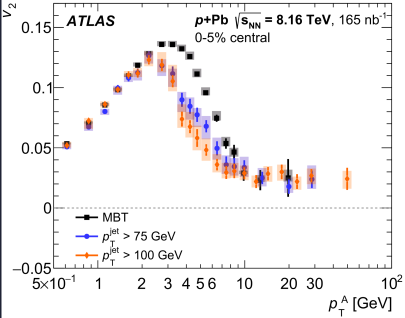


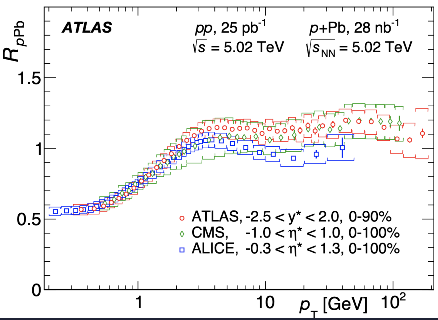
Medium extent small

» Hard partons spend limited time in medium

Jet quenching vs Flow

- R_{pPb} vs v_2 puzzle





ATLAS *EPJ C80* (2020)

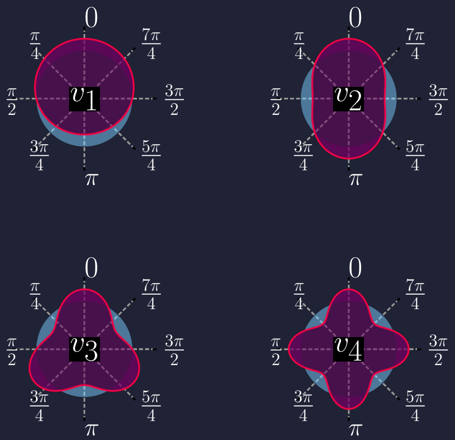
ATLAS *JHEP07* (2023)
CMS *JHEP04* (2017)
ALICE *JHEP11* (2018)

v_n Azimuthal Anisotropy

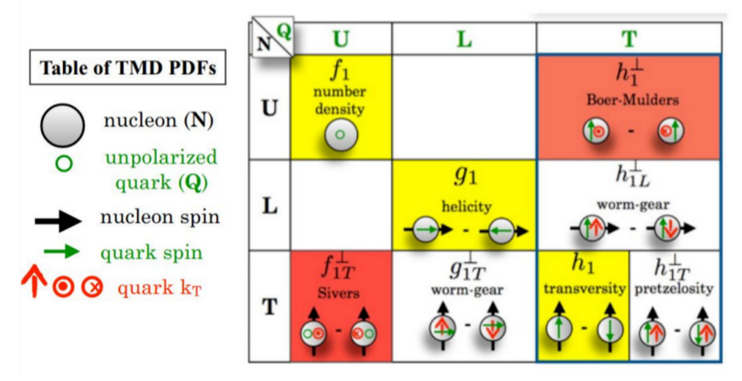
Azimuthal momentum correlated with soft bulk (event plane)

$$\frac{dN}{d\phi} \propto 1 + \sum_n 2 v_n \cos\left[n(\phi - \Psi_n)\right] \qquad (2)$$

$v_n = 1 + 0.25\cos(n\theta)$



Transverse Dependent Distributions

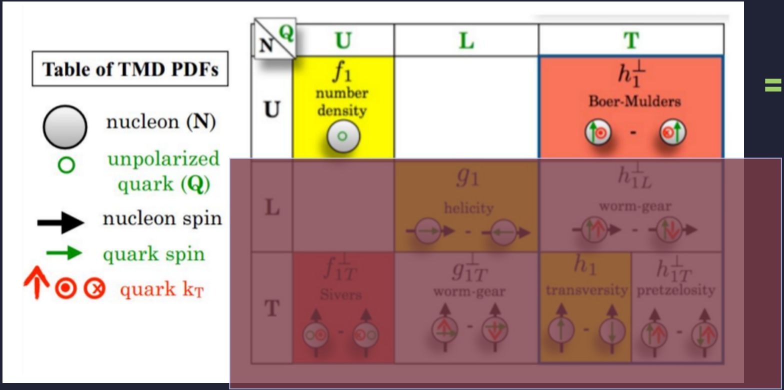


=> Collins

[1] Fig from PHENIX Spin Physics Overview

[0] 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 Dependent Distributions



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Cross Section

Cross section for[1] $p+p \to \pi + X$:

$$\frac{d\sigma}{dy d^2P_T} = \sum_{a,b,c,d} \int \frac{dx_a dx_b dz}{2\pi^2 z^3 s} d^2k_{\perp a} d^2k_{\perp b} d^3k_{\perp C} \delta(\boldsymbol{k}_{\perp C} \cdot \hat{p}_c) \mathcal{J}(\boldsymbol{k}_{\perp C}) \Gamma^{\sigma\mu}(x_a, k_{\perp a}) \Gamma^{\alpha\nu}(x_b, k_{\perp b})$$
$$\hat{M}_{\mu\nu\rho} \left(\hat{M}_{\sigma\alpha\beta}\right)^* \Delta^{\rho\beta}(z, k_{\perp C}) \delta(\hat{s} + \hat{t} + \hat{u}) \; , \tag{3}$$

With generalized correlators:

$$\Gamma_P^{\mu\nu}(x, k_\perp) = \int \frac{d(\xi \cdot P) d^2\xi_T}{(2\pi)^3} e^{i(p\cdot\xi)} \frac{\langle P|\mathrm{Tr}\left[F^{\mu\rho}(0)F^{\nu\sigma}(\xi)\right]|P\rangle n_\rho n_\sigma}{(p\cdot n)^2}$$
$$= \frac{-g_T^{\mu\nu} f_g(x, k_\perp) + \left(\frac{k_\perp^\mu k_\perp^\nu}{M_p^2} + g_T^{\mu\nu} \frac{k_\perp^2}{2M_p^2}\right) h_g^\perp(x, k_\perp^2)}{2x} \; , \tag{4}$$

[1] M. Anselmino et al. *PRD71 (2005)*, M. Anselmino et al. *PRD73 (2006)*

Transverse Momentum Dependent Distributions

 

$$\Phi^{\alpha\beta}\epsilon_{\alpha}^{\lambda_1}(k)\epsilon_{\beta}^{\lambda_2}(k) = \frac{1}{2x}\left\{\delta^{\lambda_1,\lambda_2} f_g(x, k_\perp) + \delta^{\lambda_1,-\lambda_2}\frac{k_\perp^2}{2M^2} h_g^\perp(x, k_\perp)\right\}$$

The Boer-Mulders/Collins flips helicity between amplitude and conjugate
Requires two flips for unpolarized pion production =>
For $gg \to gg$:

 : Unpolarized gluon/unpolarized hadron

 : Polarized gluon/unpolarized hadron

Transverse Momentum Dependent Distributions

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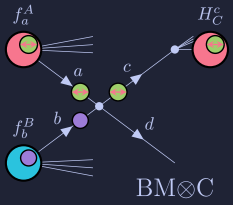

The Boer-Mulders/Collins flips helicity between amplitude and conjugate
Requires two flips for unpolarized pion production =>
For $gg \to gg$:

- $BM \otimes C$ => $M_{\lambda,\lambda}^{\lambda,\lambda}\left(M_{-\lambda,\lambda}^{-\lambda,\lambda}\right)$

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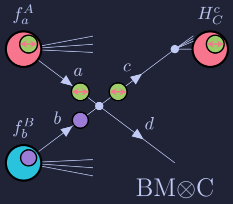

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Requires two flips for unpolarized pion production =>

For $gg \to gg$:

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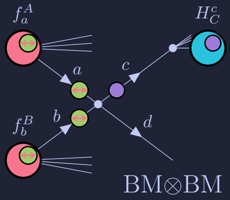


 : Unpolarized gluon/unpolarized hadron

 : Polarized gluon/unpolarized hadron

Spin-Helicity Formalism

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

$$\begin{aligned}\Sigma^{\mathrm{BM}\otimes\mathrm{C}} =& \hat{H}^{\perp(1)}(z, k_{\perp C}) 2 \Big[\hat{h}^{\perp(1)}_{g/A}(x_a, k_{\perp a}) \hat{f}_{g/B}(x_b, k_{\perp b}) \hat{M}_1^0 \hat{M}_2^0 \cos\left(4(\phi_{ab} - \phi_{bc})\right) \\ &+ \hat{f}_{g/A}(x_a, k_{\perp a}) \hat{h}^{\perp(1)}_{g/B}(x_b, k_{\perp b}) \hat{M}_1^0 \hat{M}_3^0 \cos\left(4(\phi_{ab} - \phi_{ac})\right) \Big] \ , \end{aligned} \tag{5}$$

with $\hat{M}_1^0 \hat{M}_2^0 = g_s^4 \dfrac{N_c^2}{N_c^2 - 1} \dfrac{t^2 + tu + u^2}{t^2}$,

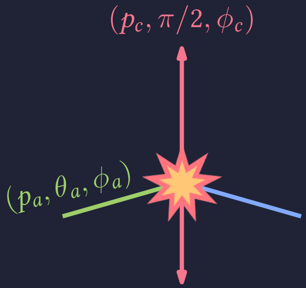
$\hat{M}_1^0 \hat{M}_3^0 = g_s^4 \dfrac{N_c^2}{N_c^2 - 1} \dfrac{t^2 + tu + u^2}{u^2}$,

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

Spin Independent

TMD matrix element contains angular correlations as well

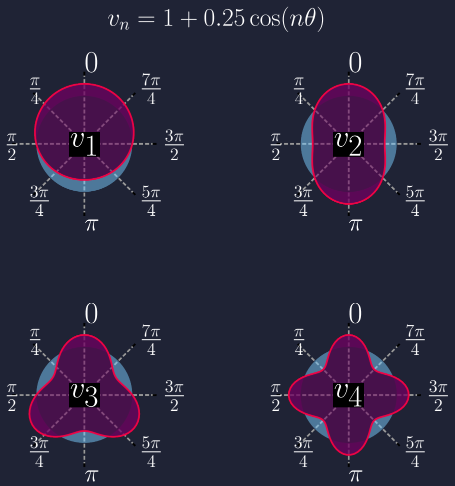
$$\begin{aligned}\frac{\hat{s}}{\hat{t}} &\overset{\theta_1 \ll 1}{\simeq} \frac{-\hat{s}}{2p_a p_c(1-\theta_a\cos(\phi_a-\phi_c))} \\ &\simeq \frac{-\hat{s}}{4p_a p_c}\left[2+\theta_a^2+2\theta_a\cos(\phi_a-\phi_c)+\theta_a^2\cos[2(\phi_a-\phi_c)]\right] \ .\end{aligned}$$



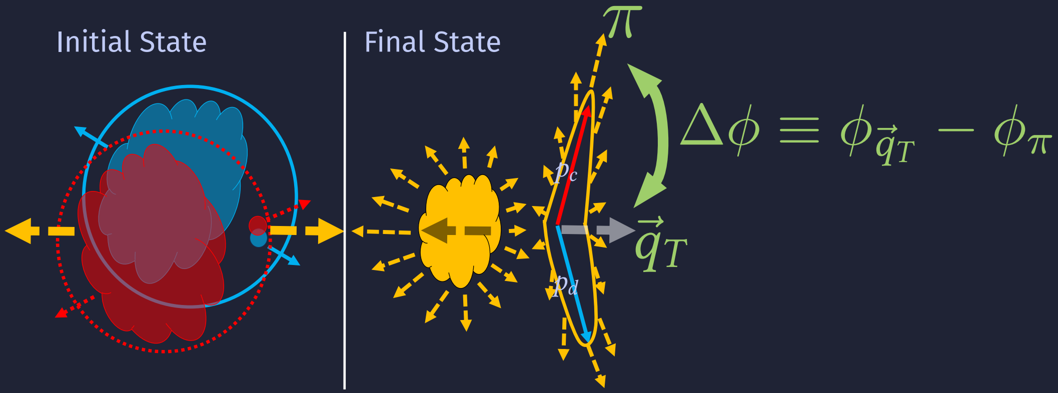
v_n Azimuthal Anisotropy

Azimuthal momentum correlated with soft bulk (event plane)

$$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos\left[n(\phi - \Psi_n)\right] \quad (6)$$



TMD Scattering



Pythia Simulation

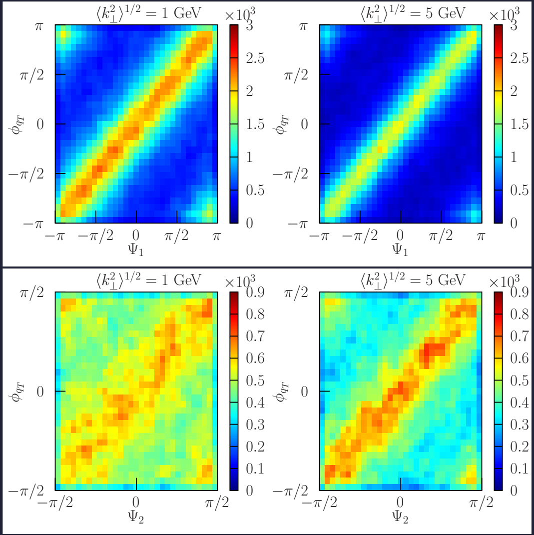
Simple Pythia Simulation:

- Single Hard Scattering => 2 initiating partons $+ 2$ remnants
- Generate k_T for each initiating parton => Each balanced by its remnant
- Lund String Hadronization connects final parton to remnant

Pythia Simulation

Correlation:

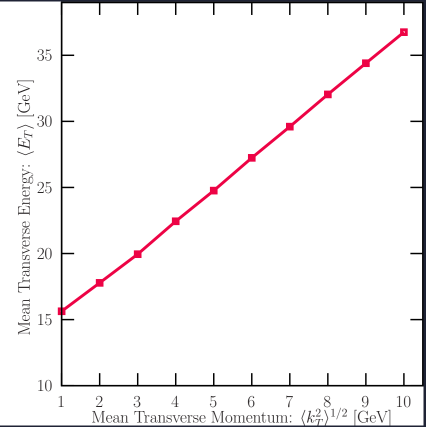
- Event plane $\Psi = \frac{1}{n}\arg[Q]$ with $Q_n = \frac{1}{\sqrt{M}}\sum_j^M e^{in\phi_j}$,
- Balance momentum $\phi_{\vec{q}}$.



Pythia Simulation

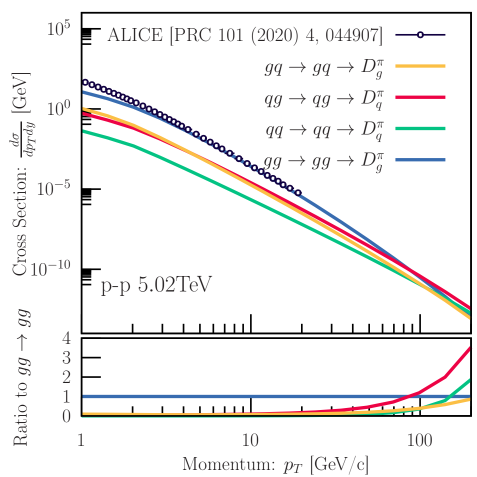
Correlation:

- $\langle E_T \rangle$ at FoCal $3.9 \leq \eta \leq 5.0$
- Mean transverse momentum $\langle k_T^2 \rangle$ of hard parton



Setup

$gg \rightarrow gg$ => Most relevant for kinematics



0 X. Guo *PRD58 (1998)*, R. J. Fries *PRD68 (2003)*, A. Majumder and B. Muller *PRC77 (2008)*

Setup

Factorization $x \otimes k_\perp$ => Approximate to $p - A$

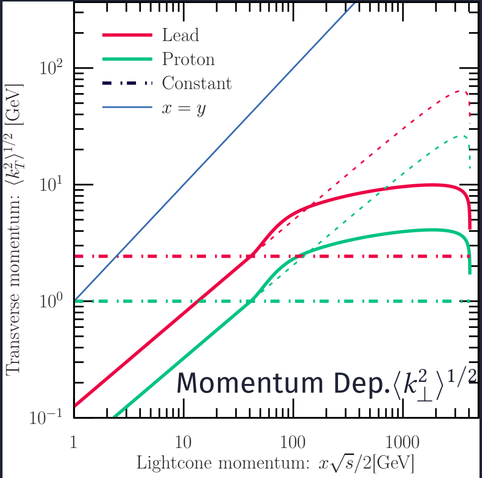
$$f(x,k_\perp) = \frac{4\pi}{\langle k_\perp^2 \rangle} e^{-k_\perp^2/\langle k_\perp^2 \rangle} f(x)\,, \qquad (7)$$

$$\langle k_\perp^2 \rangle_{p-Pb} = A^{1/3} \langle k_\perp^2 \rangle_{p-p}\,. \qquad (8)$$

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

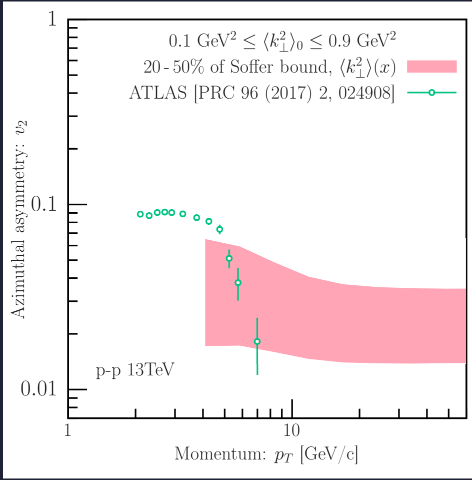
$$\frac{k_\perp^2}{2M^2} \left| h^{\perp g}(x,k_\perp) \right| = b \cdot f(x,k_\perp)\,, \qquad (9)$$

$$\frac{k_\perp^2}{2M^2} \left| H^{\perp g}(x,k_\perp) \right| = B \cdot D(x,k_\perp)\,. \qquad (10)$$

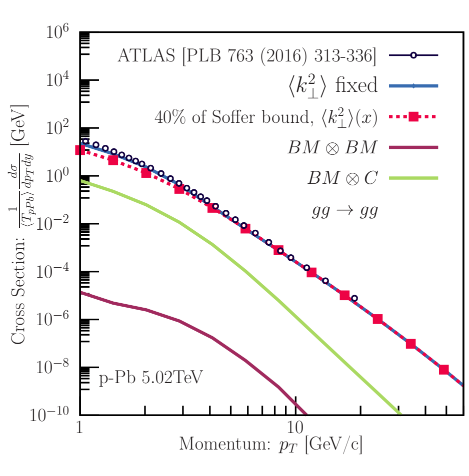


[0] X. Guo PRD58 (1998), R. J. Fries PRD68 (2003), A. Majumder and B. Muller PRC77 (2008)

$p-p$ Results

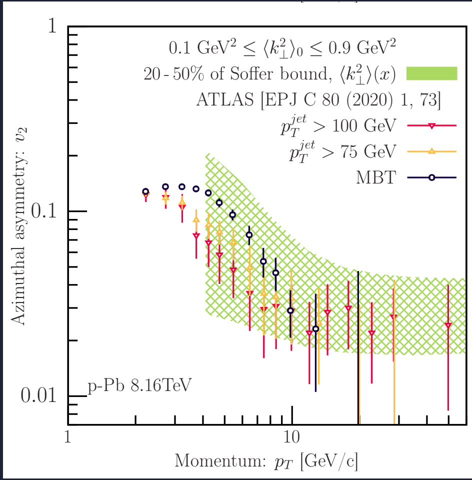


0.1 GeV^2 ≤ $\langle k_\perp^2 \rangle_0$ ≤ 0.9 GeV^2
20 - 50% of Soffer bound, $\langle k_\perp^2 \rangle(x)$
ATLAS [PRC 96 (2017) 2, 024908]
Azimuthal asymmetry: v_2
p-p 13TeV
Momentum: p_T [GeV/c]

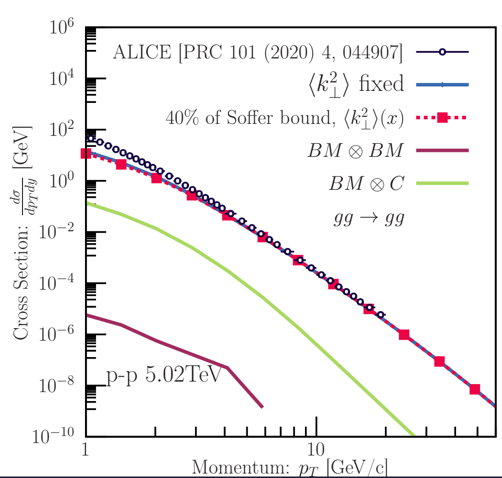


ATLAS [PLB 763 (2016) 313-336]
$\langle k_\perp^2 \rangle$ fixed
40% of Soffer bound, $\langle k_\perp^2 \rangle(x)$
$BM \otimes BM$
$BM \otimes C$
$gg \to gg$
Cross Section: $\frac{1}{\langle T_{pPb} \rangle} \frac{d\sigma}{dp_T dy}$ [GeV]
p-Pb 5.02TeV
Momentum: p_T [GeV/c]

$p - Pb$ Results

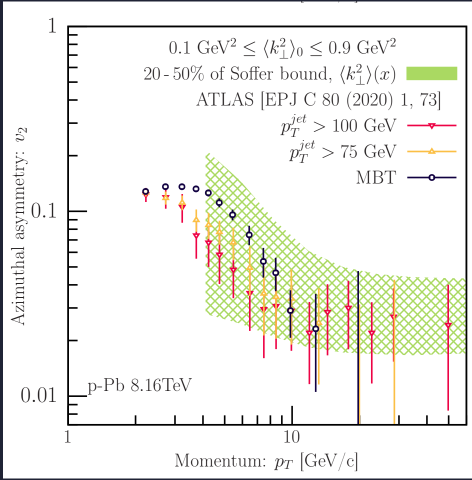


0.1 GeV$^2 \leq \langle k_\perp^2 \rangle_0 \leq$ 0.9 GeV^2
20 - 50% of Soffer bound, $\langle k_\perp^2 \rangle(x)$
ATLAS [EPJ C 80 (2020) 1, 73]
$p_T^{jet} > 100$ GeV
$p_T^{jet} > 75$ GeV
MBT
p-Pb 8.16TeV
Azimuthal asymmetry: v_2
Momentum: p_T [GeV/c]
1
0.1
0.01
1
10

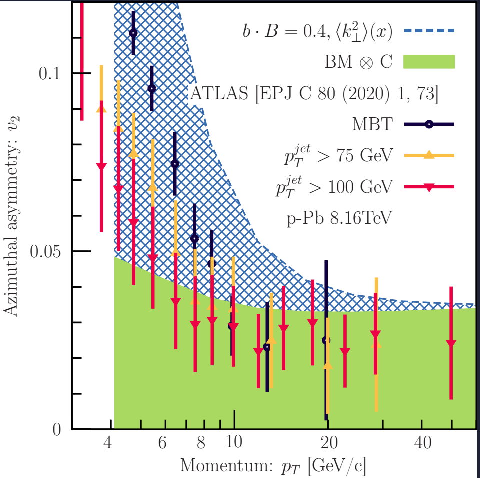


ALICE [PRC 101 (2020) 4, 044907]
$\langle k_\perp^2 \rangle$ fixed
40% of Soffer bound, $\langle k_\perp^2 \rangle(x)$
$BM \otimes BM$
$BM \otimes C$
$gg \to gg$
p-p 5.02TeV
Cross Section: $\frac{d\sigma}{dp_T dy}$ [GeV]
Momentum: p_T [GeV/c]
10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
1
10

$p - Pb$ Results

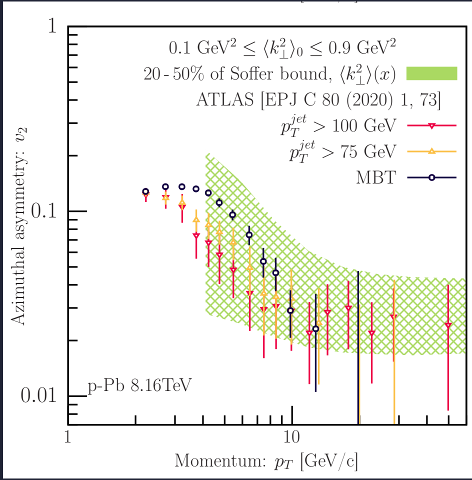


$0.1 \text{ GeV}^2 \leq \langle k_\perp^2 \rangle_0 \leq 0.9 \text{ GeV}^2$
20 - 50% of Soffer bound, $\langle k_\perp^2 \rangle(x)$
ATLAS [EPJ C 80 (2020) 1, 73]
$p_T^{jet} > 100$ GeV
$p_T^{jet} > 75$ GeV
MBT
p-Pb 8.16TeV
Azimuthal asymmetry: v_2
Momentum: p_T [GeV/c]

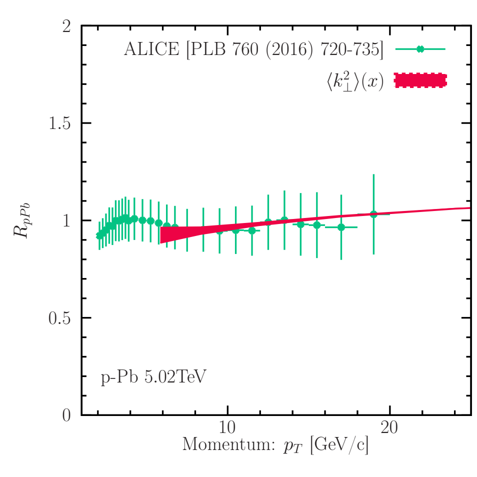


$b \cdot B = 0.4, \langle k_\perp^2 \rangle(x)$
BM ⊗ C
ATLAS [EPJ C 80 (2020) 1, 73]
MBT
$p_T^{jet} > 75$ GeV
$p_T^{jet} > 100$ GeV
p-Pb 8.16TeV
Azimuthal asymmetry: v_2
Momentum: p_T [GeV/c]

$p - Pb$ Results



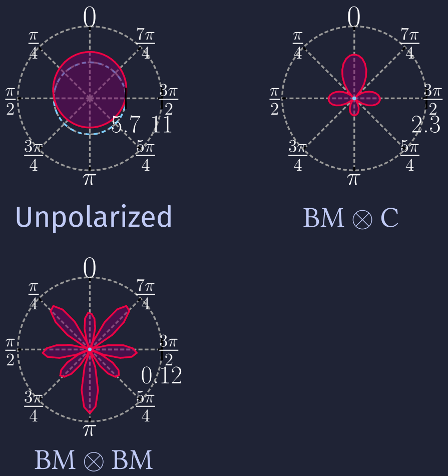
0.1 GeV² ≤ ⟨k⊥²⟩₀ ≤ 0.9 GeV²
20 - 50% of Soffer bound, ⟨k⊥²⟩(x)
ATLAS [EPJ C 80 (2020) 1, 73]
p_T^jet > 100 GeV
p_T^jet > 75 GeV
MBT
p-Pb 8.16TeV
Azimuthal asymmetry: v₂
Momentum: p_T [GeV/c]
1
0.1
0.01
1
10



ALICE [PLB 760 (2016) 720-735]
⟨k⊥²⟩(x)
p-Pb 5.02TeV
R_pPb
Momentum: p_T [GeV/c]
2
1.5
1
0.5
0
10
20

Angular Distribution $\Delta\phi = \phi_q - \phi_\pi$

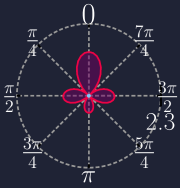
pp



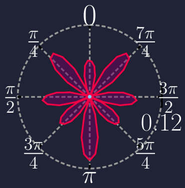
Angular Distribution $\Delta\phi = \phi_q - \phi_\pi$

pp

Unpolarized



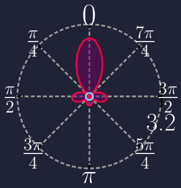
$\mathrm{BM} \otimes \mathrm{C}$



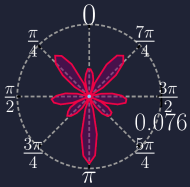
$\mathrm{BM} \otimes \mathrm{BM}$

pPb

Unpolarized

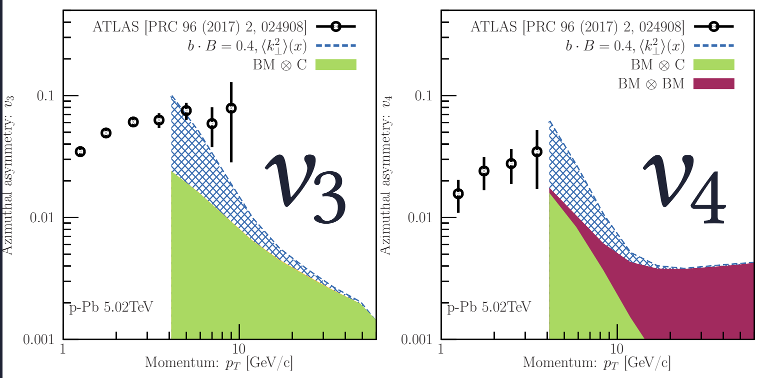


$\mathrm{BM} \otimes \mathrm{C}$



$\mathrm{BM} \otimes \mathrm{BM}$

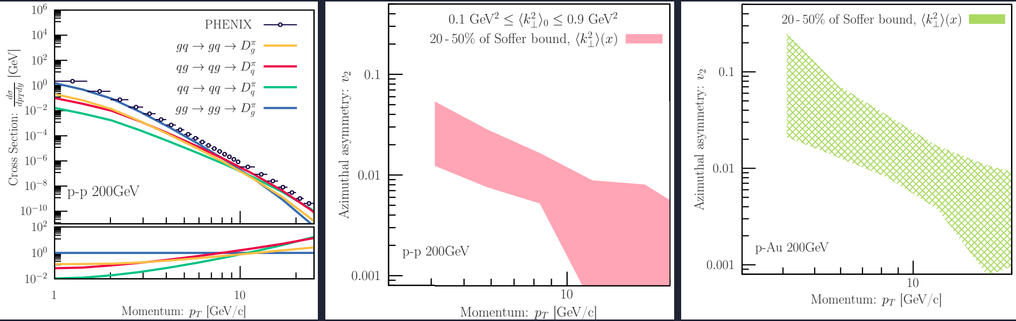
Higher Harmonics: v_3 & v_4



Non-zero v_3 and v_4 at high-p_T

- BM $\otimes$ C important for v_3
- BM $\otimes$ BM becomes more important for v_4

RHIC Predictions



- Quark becomes more important at RHIC
- Contributions from $\mathrm{BM} \otimes \mathrm{BM}$ for quarks

Conclusions

- Small systems constitute a unique opportunity to understand hard/soft correlation in the initial state
- Initial state correlations can allow for access to TMDs
- Going beyond simple $A^{1/3}$ approximation => Compute Spin-Dependent rescatterings