Small systems: Theory overview – energy loss

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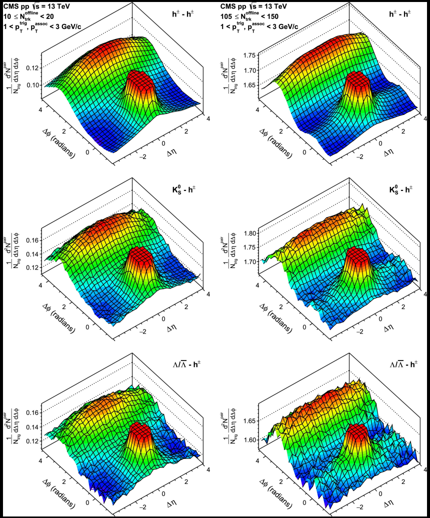
Introduction

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

- Collective flow



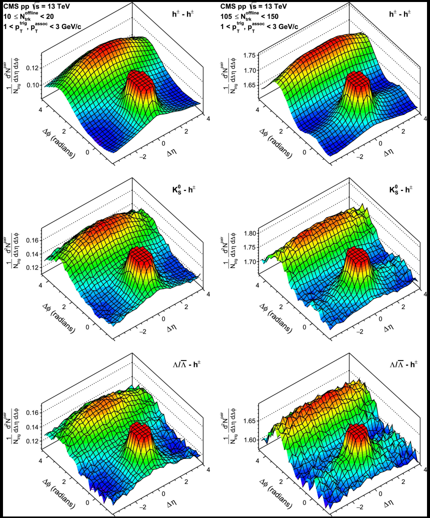
CMS:2016fnw

Introduction

“Evidence for collectivity in pp collisions at the LHC”:

- Collective flow

⚠️ No Jet quenching observed



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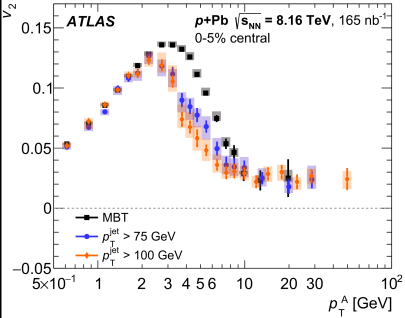
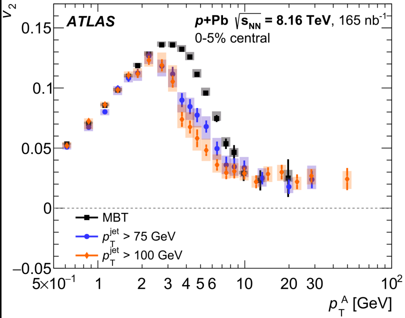
Jet quenching vs Flow

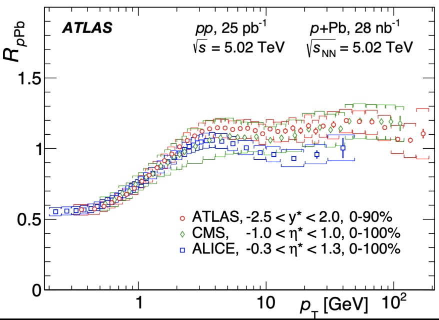


ATLAS:2019vcm

Jet quenching vs Flow

- R_{pPb} vs v_2 puzzle



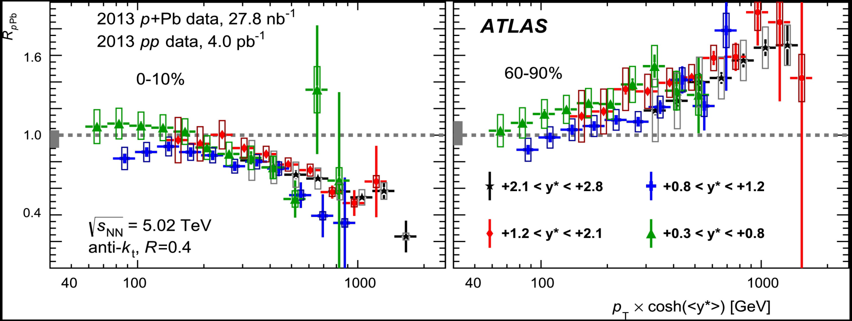


ATLAS:2019vcm

ATLAS:2022kqu
CMS:2016xef
ALICE:2018vuu

Jet quenching vs Flow

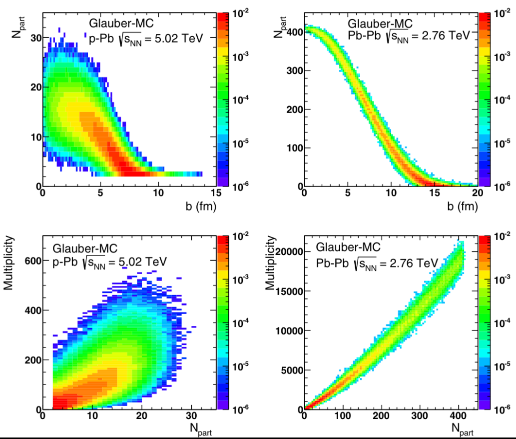
- R_{pPb} vs v_2 puzzle
- R_{pPb} vs centrality



ATLAS:2014cpa

Multiplicity? I

- Large fluctuations in p-Pb => Biased multiplicity selection



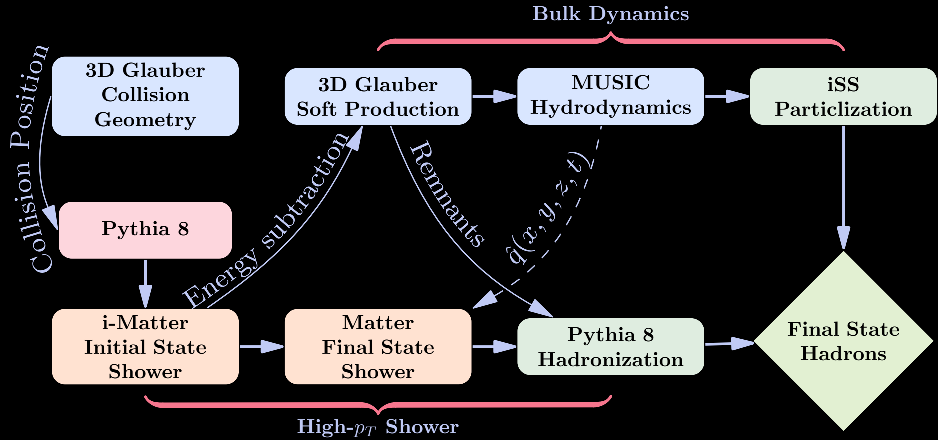
ALICE:2014xsp

Introduction

Correlation due to Energy Conservation

Transverse Momentum Correlations

X-SCAPE

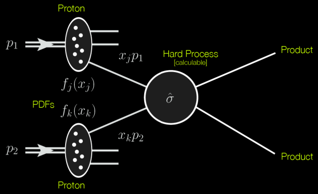


JETSCAPE:2024dgu

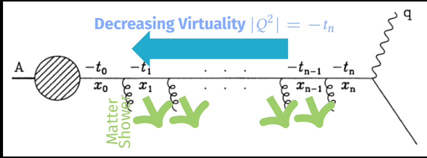
Hard/Soft

Hard

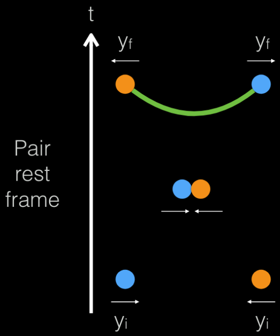
- Pythia Hard Process



- i-Matter ISR + Matter FSR

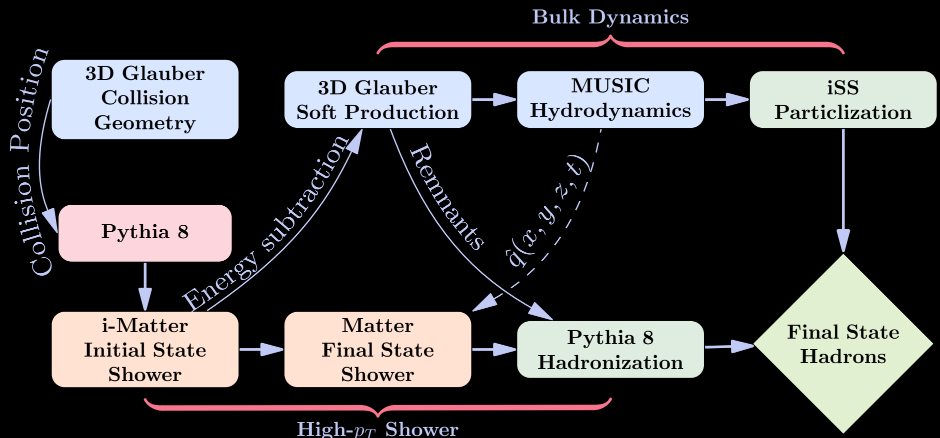


Soft



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

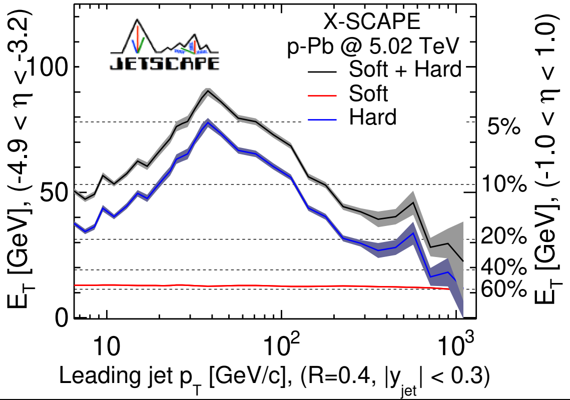
X-SCAPE



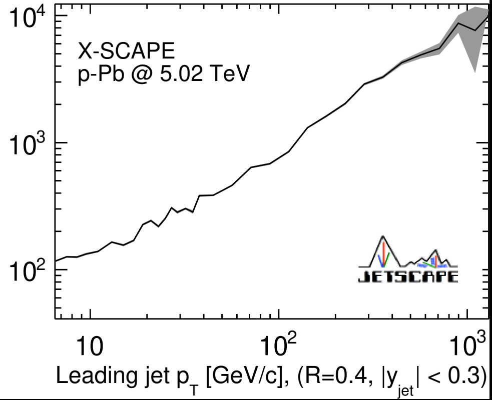
JETSCAPE:2024dgu

Correlations

Forward



Mid

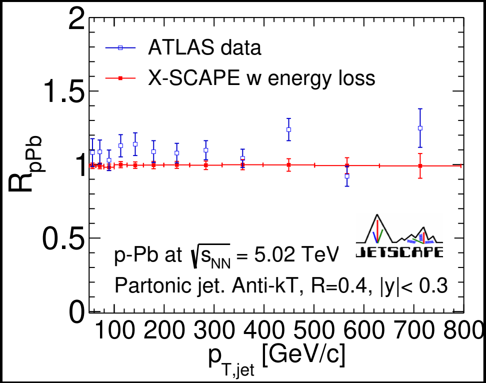


Competing effects

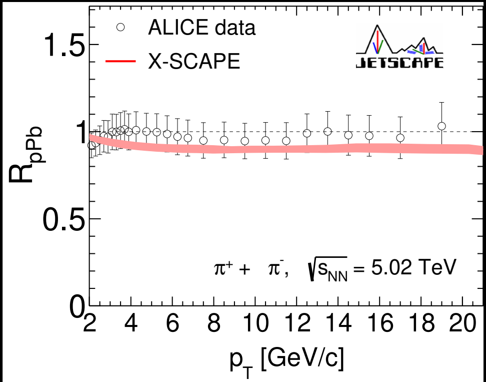
- E_T increases with leading jet p_T
- At higher p_T energy conservation leads to decrease in E_T

Energy Loss?

Jets



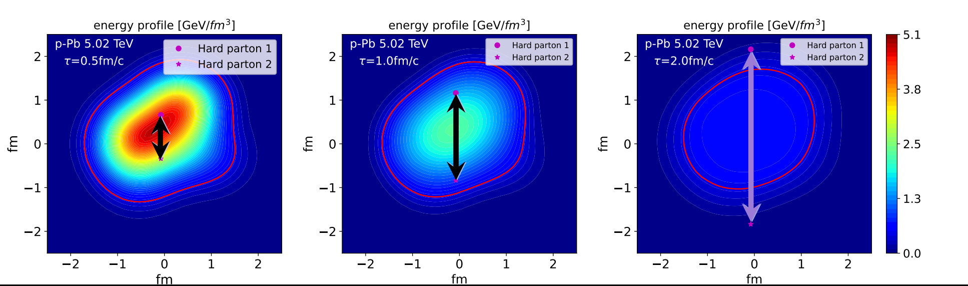
Pions



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

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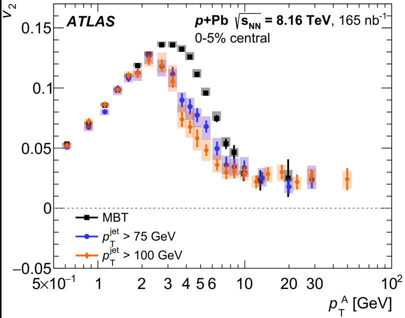

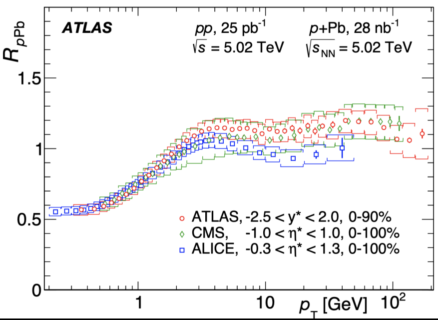

ATLAS:2019vcm

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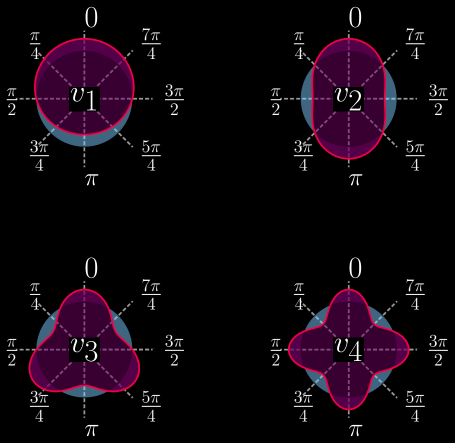
v_n Azimuthal Anisotropy

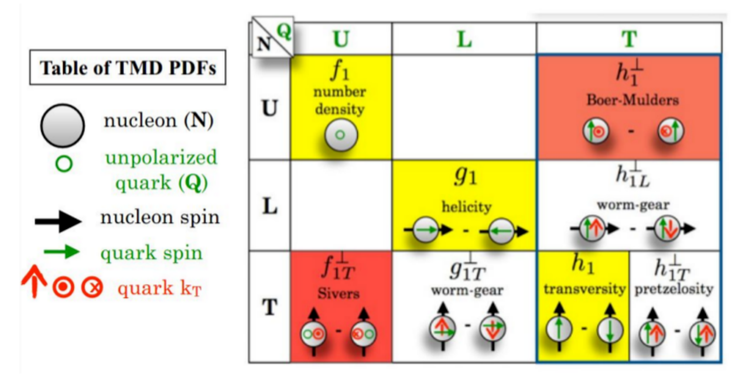
Azimuthal momentum correlated with soft bulk (event plane)

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

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



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...

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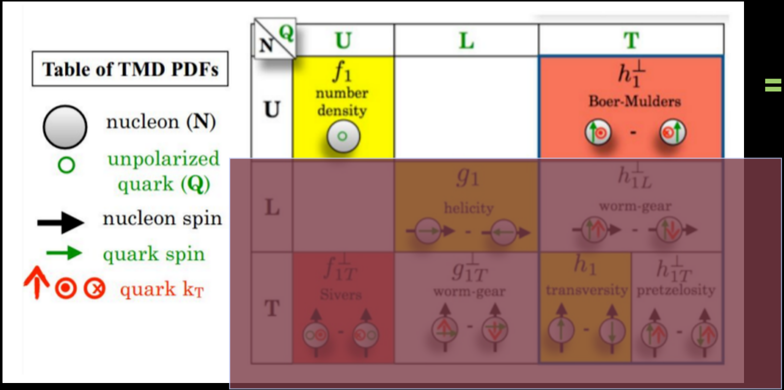

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Cross Section

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

$$\frac{d\sigma}{dy d^2 P_T} = \sum_{a,b,c,d} \int \frac{dx_a dx_b dz}{2\pi^2 z^3 s} d^2 k_{\perp a} d^2 k_{\perp b} d^3 k_{\perp C} \delta(\boldsymbol{k}_{\perp C} \cdot \hat{p}_c) \mathcal{J}(\boldsymbol{k}_{\perp C}) \Gamma^{\sigma\mu}(x_a, k_{\perp a}) \Gamma^{\alpha\nu}(x_b, k_{\perp b})$$

$$\hat{M}_{\mu\nu\rho} \left(\hat{M}_{\sigma\alpha\beta}\right)^* \Delta^{\rho\beta}(z, k_{\perp C}) \delta(\hat{s} + \hat{t} + \hat{u}) , \tag{3}$$

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] Anselmino:2004ky, Anselmino:2005sh

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

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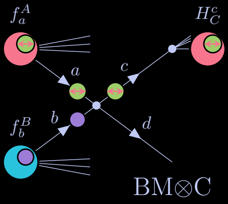

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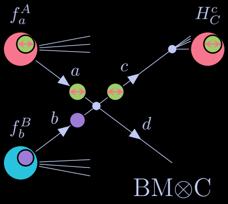

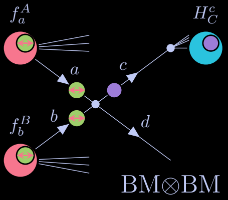

 : Unpolarized gluon/unpolarized hadron

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

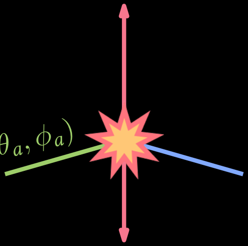
$\hat{M}_1^0 \hat{M}_3^0 = g_s^4 \dfrac{N_c^2}{N_c^2 - 1} \dfrac{t^2 + tu + u^2}{u^2}$,

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

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



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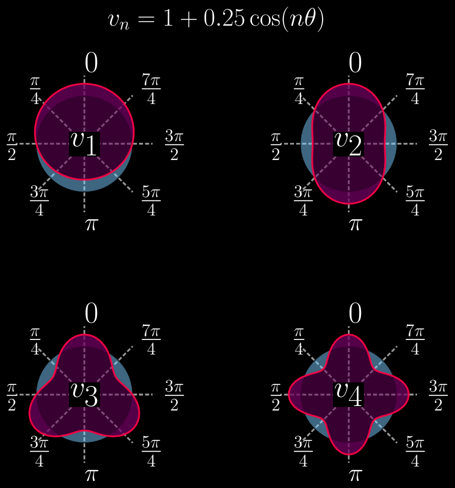
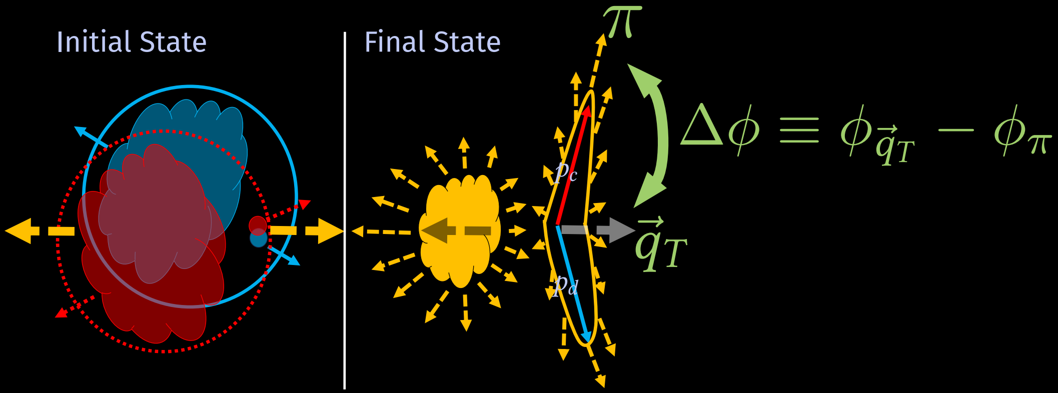


TMD Scattering



Pythia Simulation

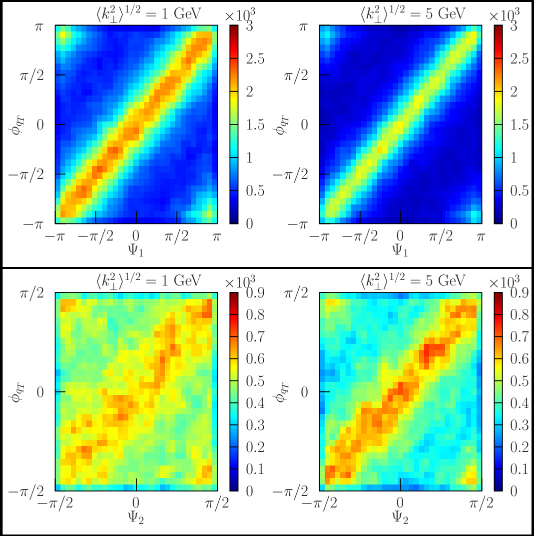
Simple Pythia Simulation:

- 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:

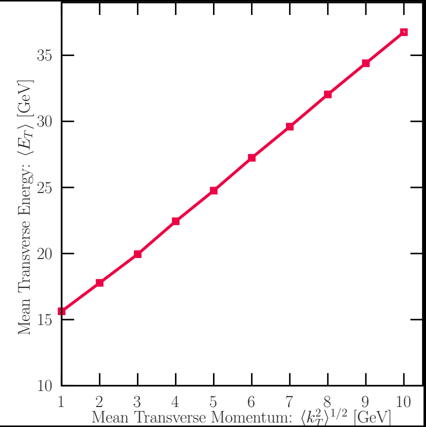
- Event plane $\Psi = \frac{1}{n}\arg[Q]$ with $Q_n = \frac{1}{\sqrt{M}}\sum_j^M e^{in\phi_j}$,
- Balance momentum $\phi_{\vec{q}}$.



Pythia Simulation

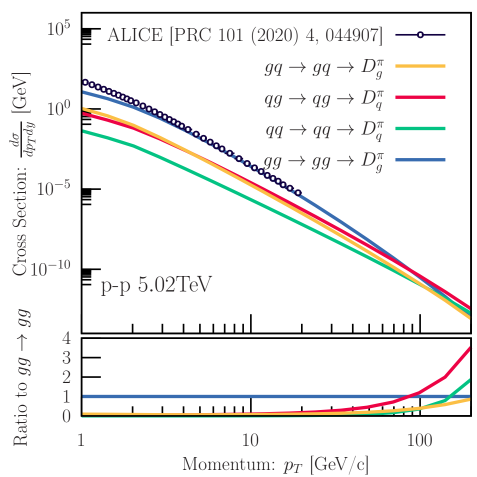
Correlation:

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



Setup

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



[0]Guo:1997it, Fries:2002mu, Majumder:2007hx

Setup

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

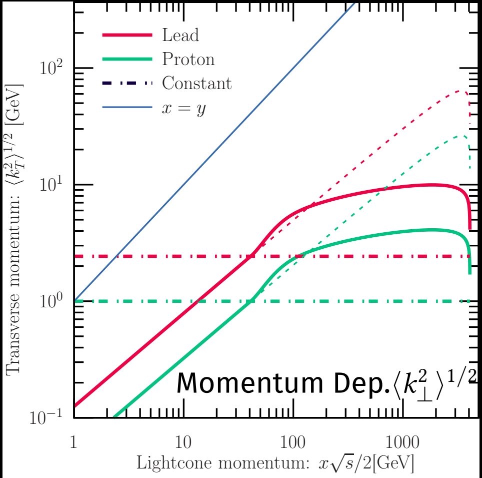
$$f(x,k_\perp) = \frac{4\pi}{\langle k_\perp^2 \rangle} e^{-k_\perp^2/\langle k_\perp^2 \rangle} f(x) \, , \tag{7}$$

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

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

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

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



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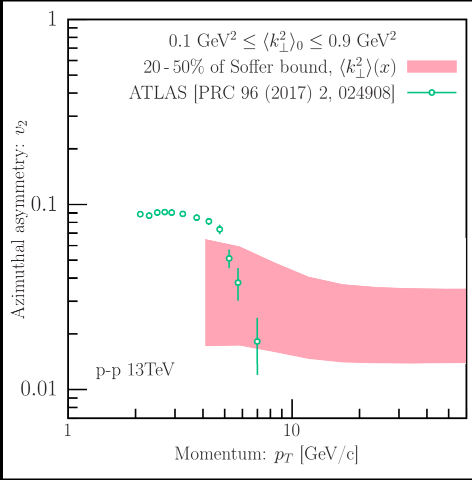
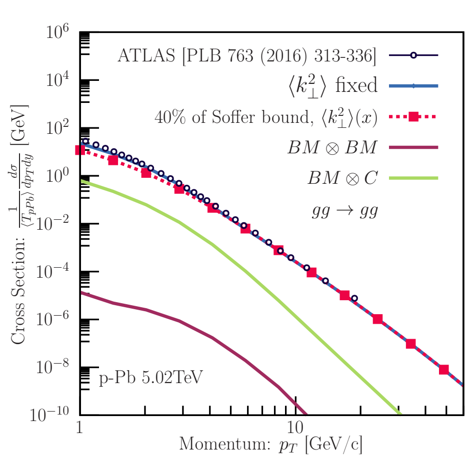
$p-p$ Results

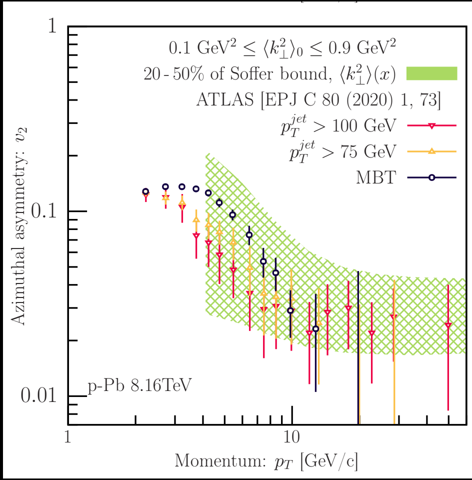


$0.1\ \mathrm{GeV}^2 \leq \langle k_\perp^2 \rangle_0 \leq 0.9\ \mathrm{GeV}^2$
20 - 50% of Soffer bound, $\langle k_\perp^2 \rangle(x)$
ATLAS [PRC 96 (2017) 2, 024908]
p-p 13TeV
Azimuthal asymmetry: v_2
Momentum: p_T [GeV/c]



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

$p - Pb$ Results



1
0.1
0.01
1
10
Azimuthal asymmetry: v_2
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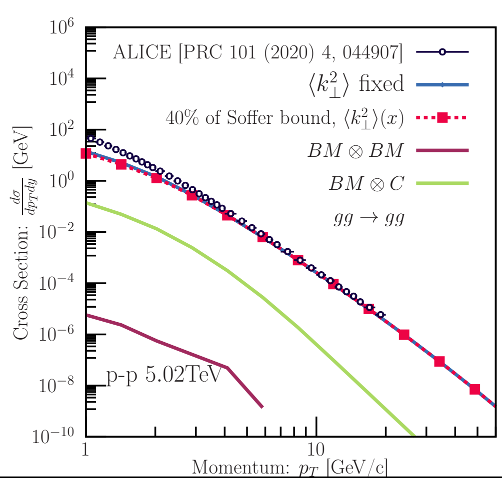
ATLAS [EPJ C 80 (2020) 1, 73]
$p_T^{jet} > 100$ GeV
$p_T^{jet} > 75$ GeV
MBT
p-Pb 8.16TeV



10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
1
10
Cross Section: $\frac{d\sigma}{dp_T dy}$ [GeV]
Momentum: p_T [GeV/c]
ALICE [PRC 101 (2020) 4, 044907]
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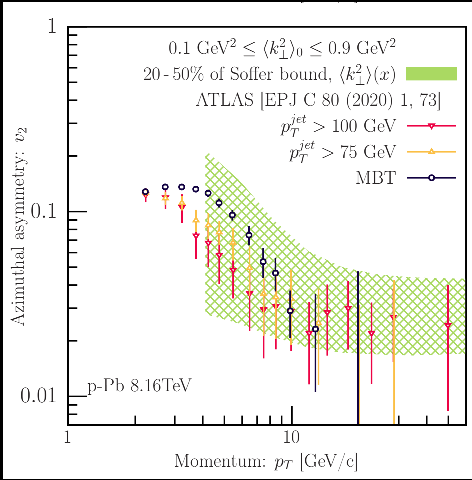
$p - Pb$ Results



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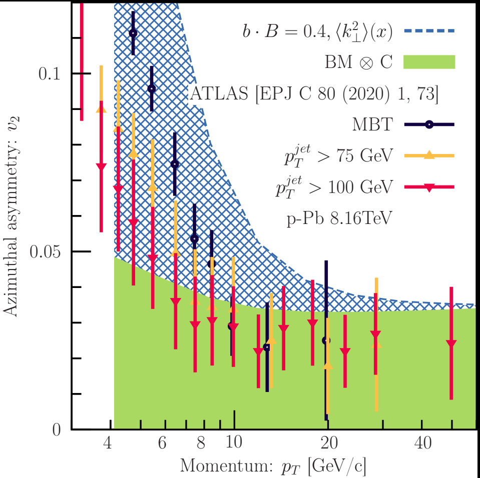

$b \cdot B = 0.4, \langle k_\perp^2 \rangle(x)$
BM ⊗ C
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MBT
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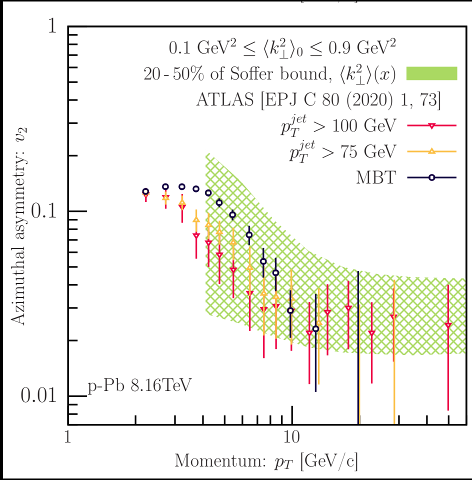
$p - Pb$ Results



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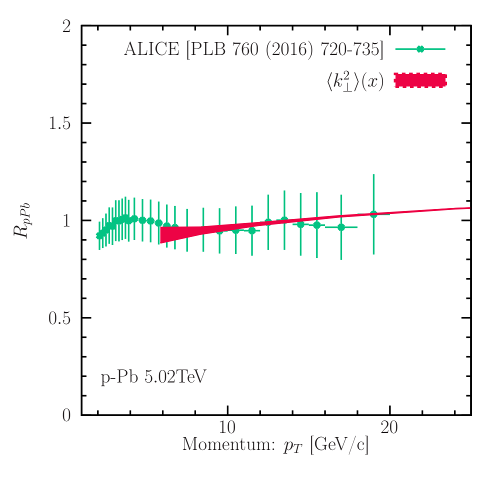
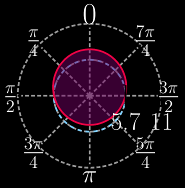
1
0.1
0.01
1
10



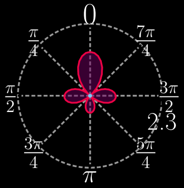
ALICE [PLB 760 (2016) 720-735]
$\langle k_\perp^2 \rangle(x)$
p-Pb 5.02TeV
R_{pPb}
Momentum: p_T [GeV/c]
2
1.5
1
0.5
0
10
20

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

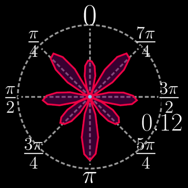
pp



Unpolarized



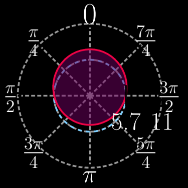
$\mathrm{BM} \otimes \mathrm{C}$



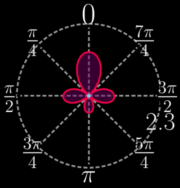
$\mathrm{BM} \otimes \mathrm{BM}$

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

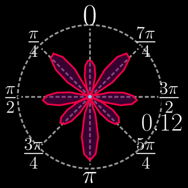
pp



Unpolarized

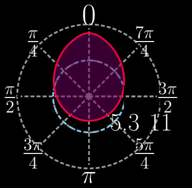


$\mathrm{BM} \otimes \mathrm{C}$

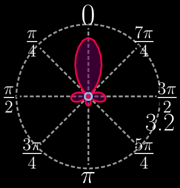


$\mathrm{BM} \otimes \mathrm{BM}$

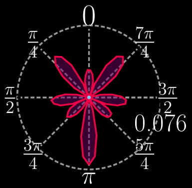
pPb



Unpolarized

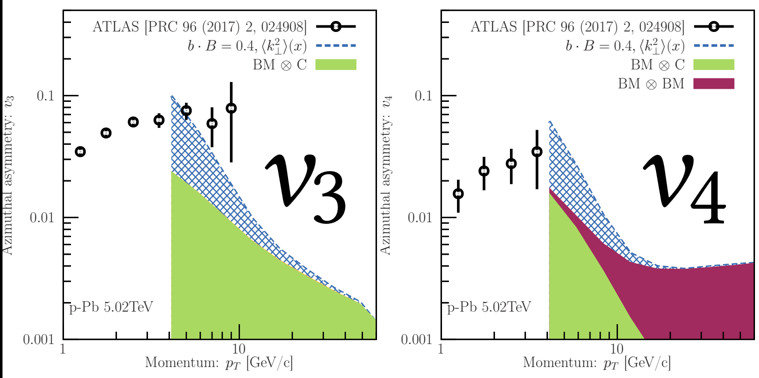


$\mathrm{BM} \otimes \mathrm{C}$



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

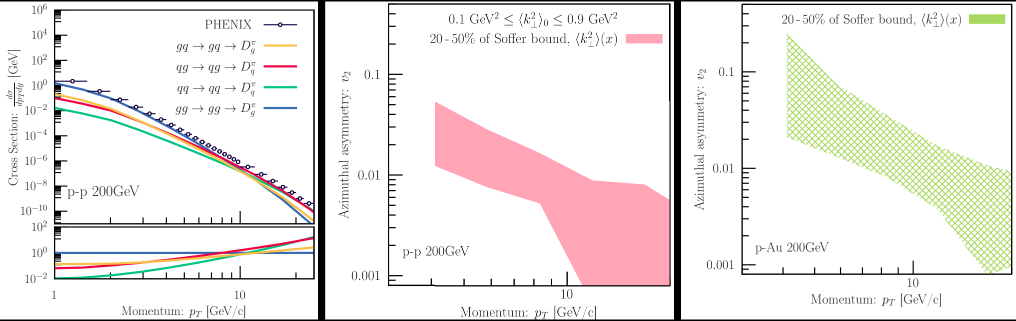
Higher Harmonics: v_3 & v_4



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