



Measuring the Transverse Proton Structure at the LHC

QCD@LHC 2026, Oxford
Kyle Cormier, Sep 28

With thanks to many people

Why study the Proton Structure?

Well, It's Great Normal Science...

Okay, but what else?

Proton structure is important for:

Multiparton Interactions

Double Parton Scattering

Heavy Ion Reference

Precision Measurement (EW, α_s)

Disambiguating other soft effects

MinimumBias + Pileup

Underlying Event Activity

intrinsic k_T
PDFs

Colour Reconnection

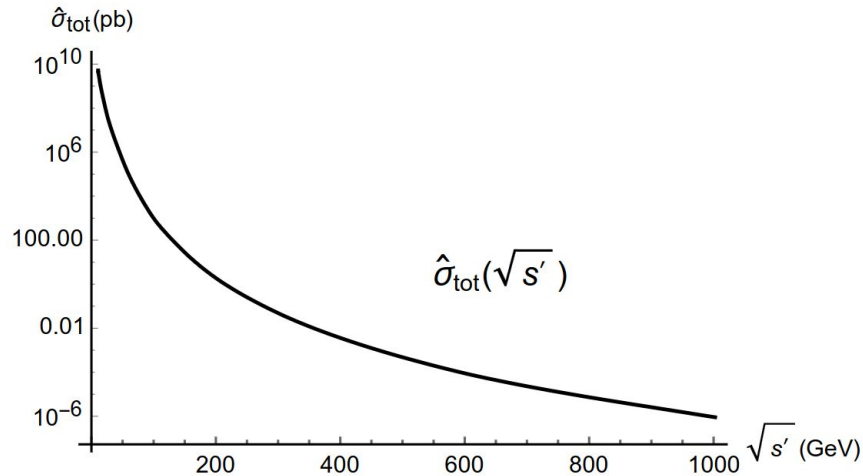
Hadronization Effects

Collective Effects

Why Proton Structure

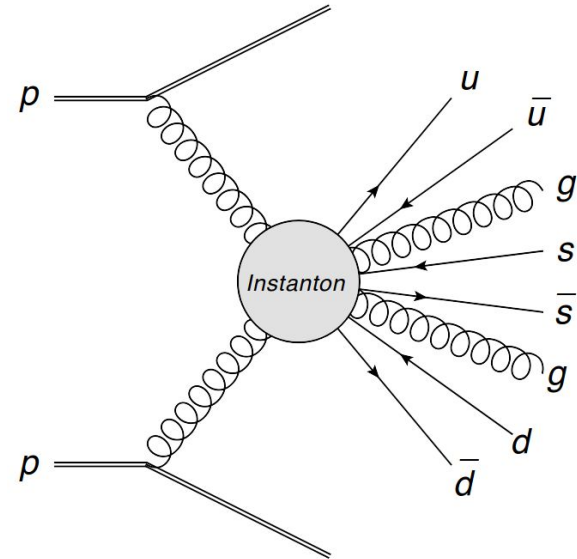
For me personally : Instanton Search

<https://arxiv.org/abs/1911.09726>



Instanton-induced processes
may have a large cross section
at the LHC

<https://arxiv.org/abs/2012.09120>

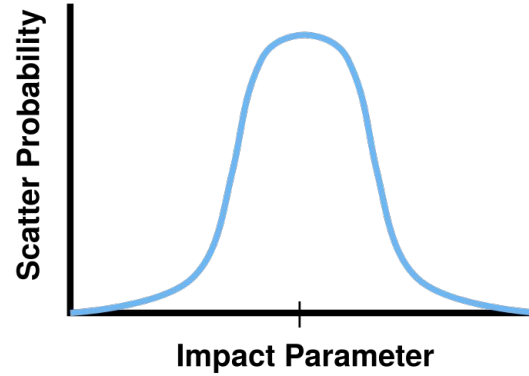
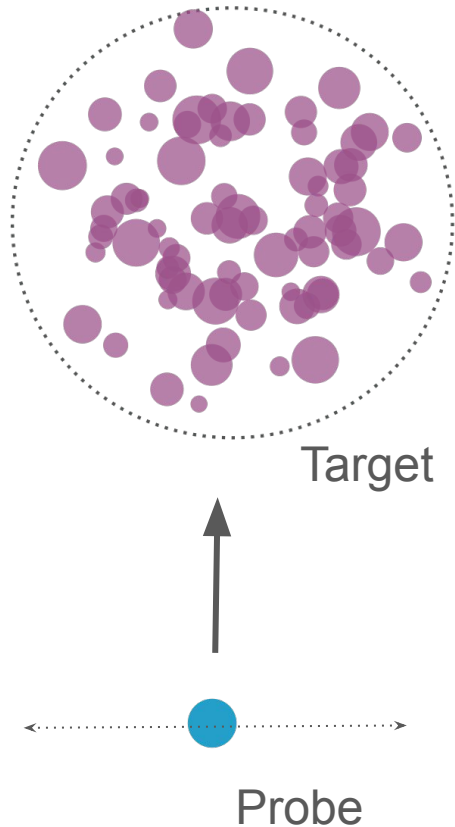


Their soft, many-particle signature
is hard to distinguish from
Multi-Parton Interactions

Measuring the transverse structure

Concepts and Toy Examples

How to measure transverse structure

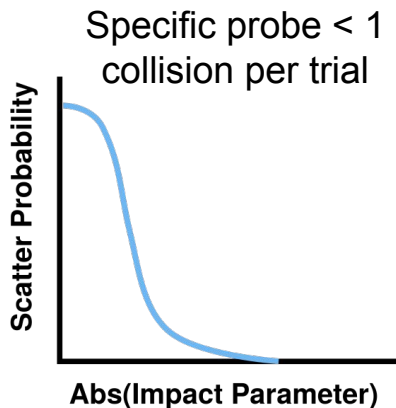
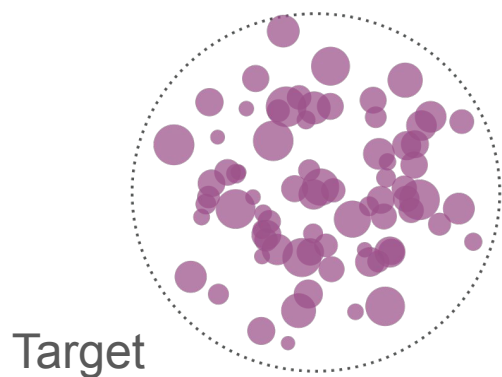


Probe the transverse density with a simple probe:

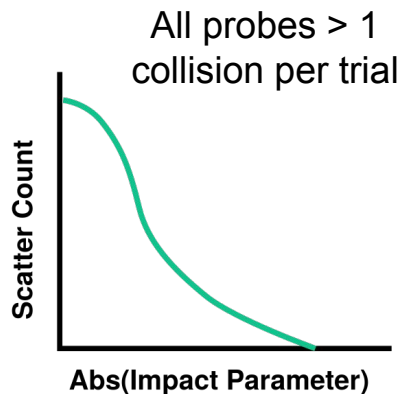
- Measure the scatter probability of the probe as a function of impact parameter

Using a proxy for the impact parameter

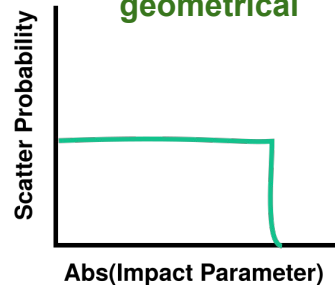
- Use a composite probe, which typically has multiple interactions/scatters with the target
- Approximate impact parameter based on total scattering activity



Specific probe rate is biased to central collisions

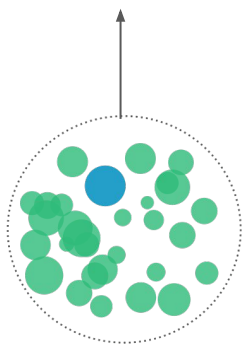


Composite probe cross section is purely geometrical



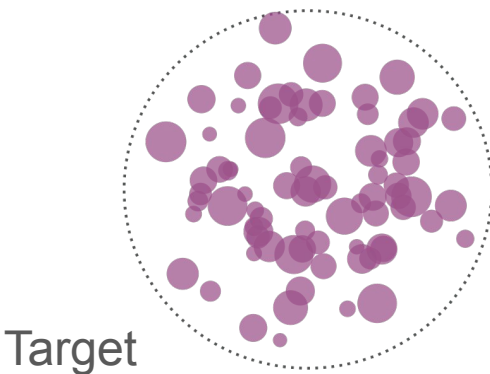
Here using
“hard sphere approximation”

$$p(n_{\text{scatter}} > 0) = \begin{cases} 1 & \text{if } b < R_{\text{target}} + r_{\text{probe}} \\ 0 & \text{otherwise} \end{cases}$$

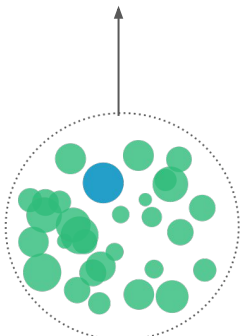


Using a proxy for the impact parameter

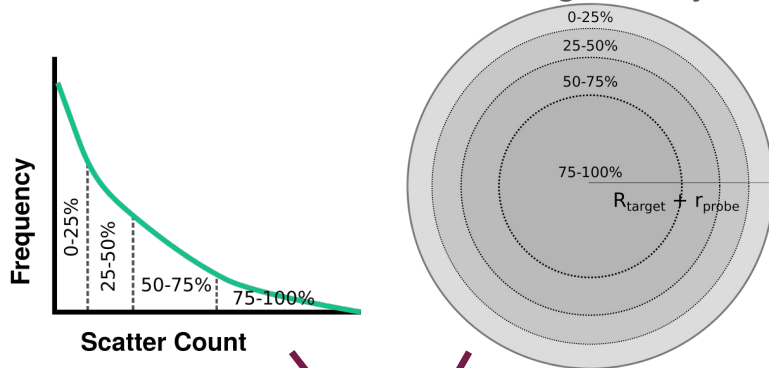
- Use a composite probe
- Approximate impact parameter based on total scattering activity



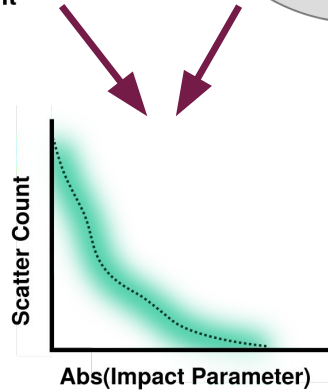
Target



Probe(s)



Use geometrical relationship to estimate impact parameter based on cross-section quantiles

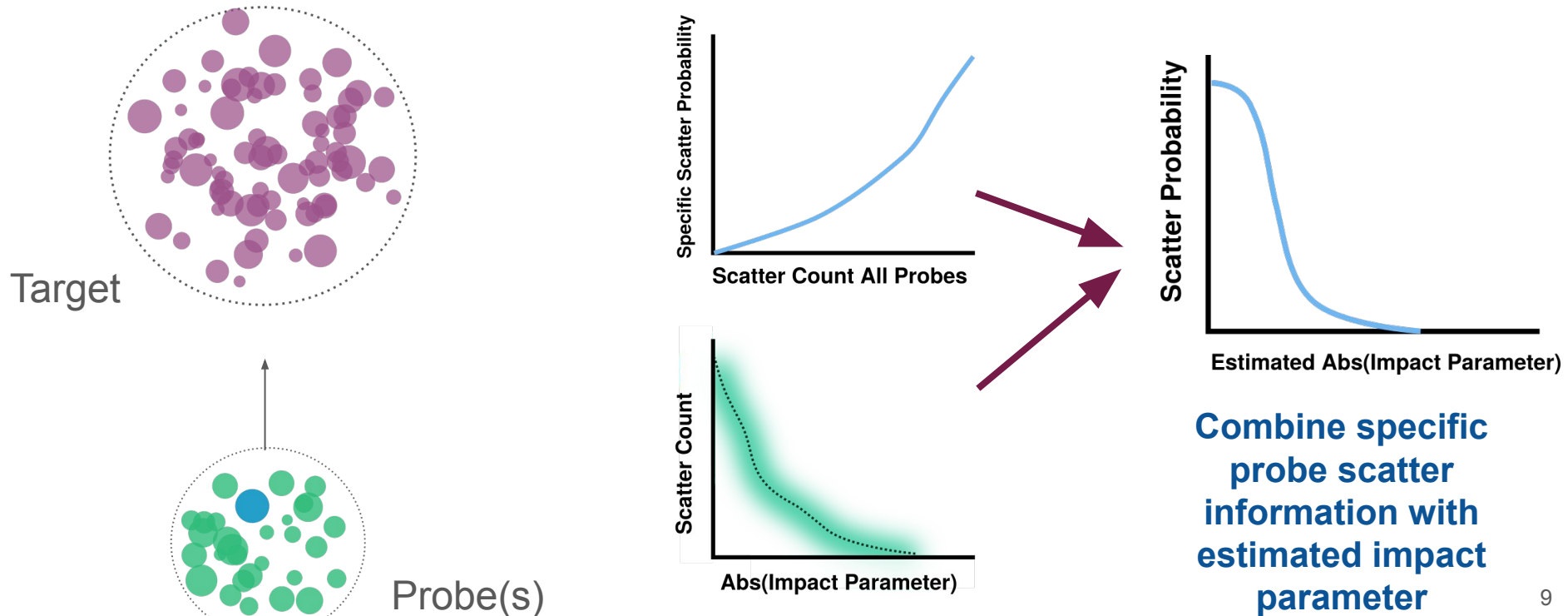


Here using "hard sphere approximation"

$$p(n_{\text{scatter}} > 0) = \begin{cases} 1 & \text{if } b < R_{\text{target}} + r_{\text{probe}} \\ 0 & \text{otherwise} \end{cases}$$

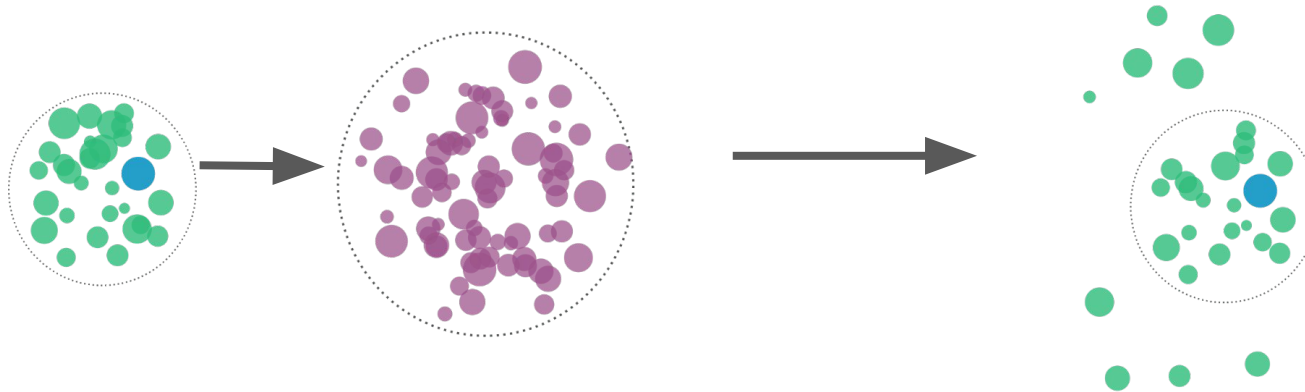
The Process-specific method

- Use a composite probe
- Approximate impact parameter based on total scattering activity



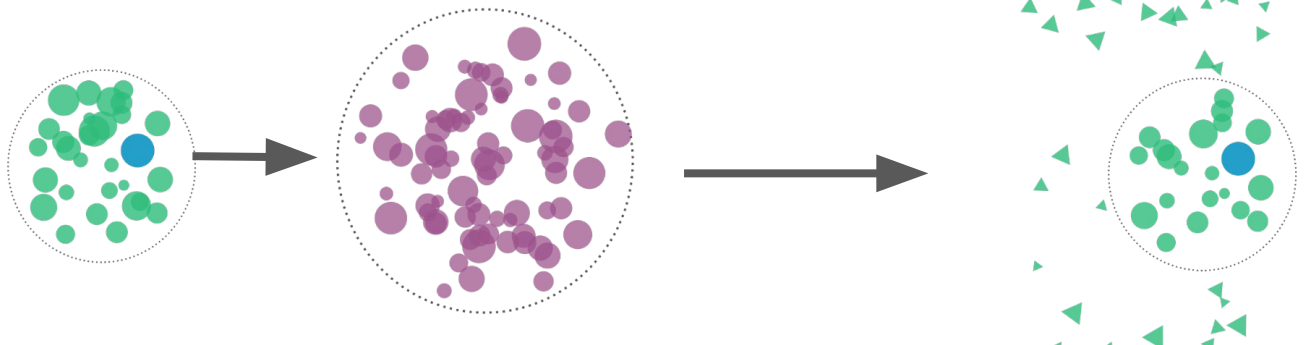
The difficulties of counting scatters

Individual Probe pieces stay in tact: Scatters easily countable



N_{scatters} is not necessary
for impact parameter
reconstruction, but still
might be valuable to
know

Individual Probe pieces transform or break apart: Scatters not easily countable

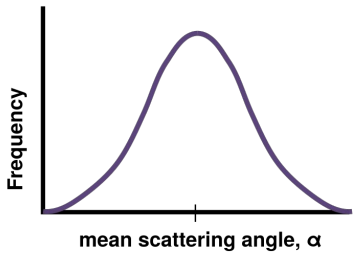
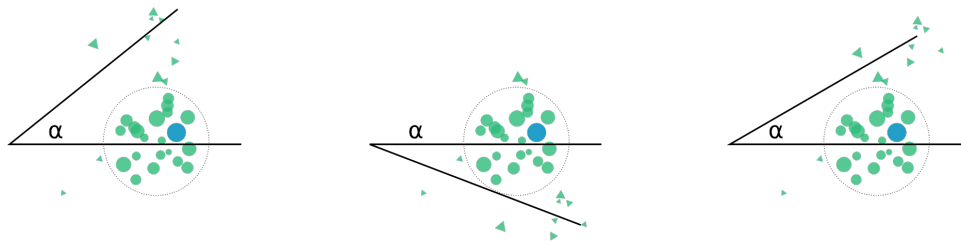


In typical
experiments
counting scatters is
not straightforward

Scaling, but not counting

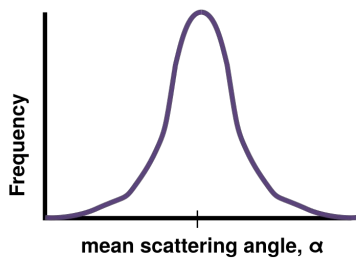
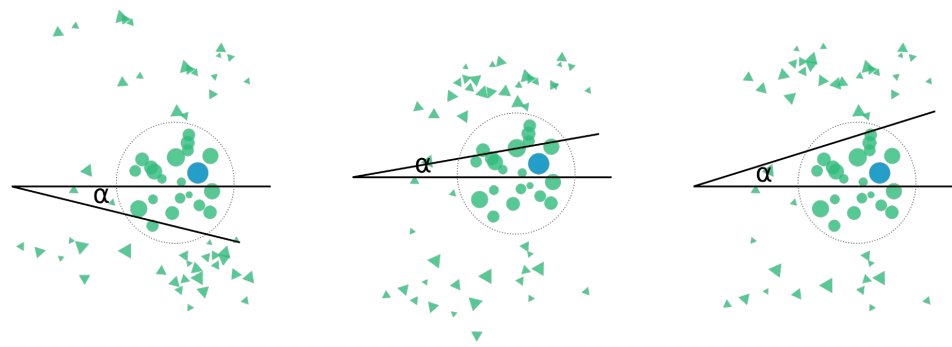
Small # of scatters

Larger variance of per-event scattering angle



Large # of scatters

Smaller variance of per-event scattering angle

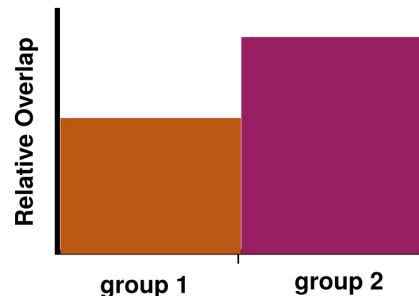
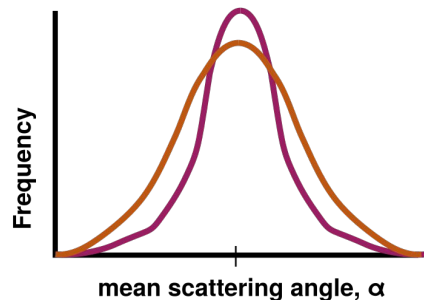
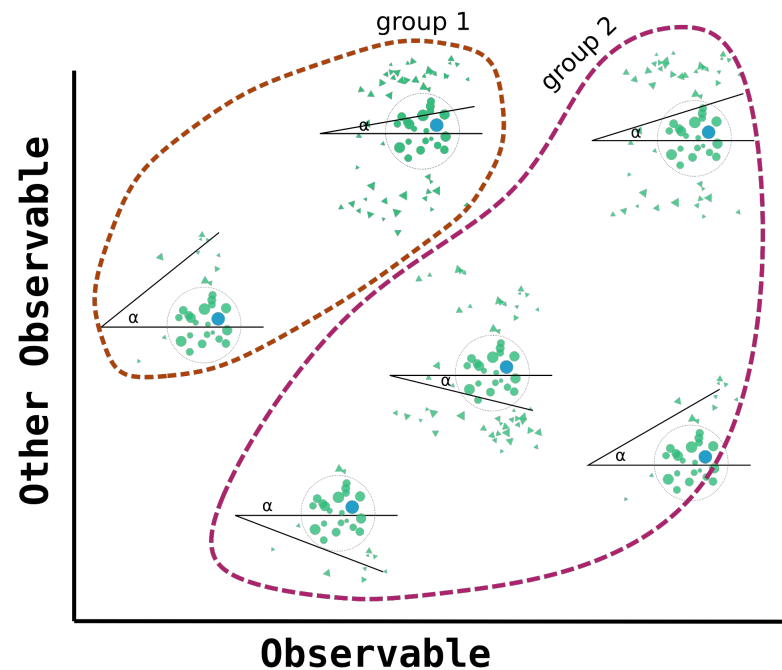


$$\text{Var}(\alpha) \cong k/N_{\text{scatter}}$$

Asymptotic
behaviour, assumes
independent
scatters

The Process-averaged Method

Estimate the number of (relative number) of Scatters in different event classes
E.g. – By event activity (N_{ch} , $\sum p_T$, ...) or by process (minimum bias, Z , J/Ψ)



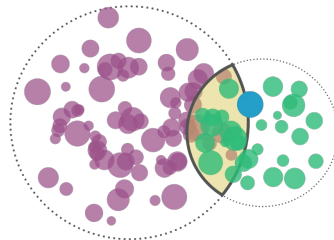
- Measure the mean opening angle differentially
- Calculate $1/\text{variance}$ in each category
- Proportional to (density-weighted) overlap of probe and target

Proton-Proton Studies

Applying the methods for proton-proton collisions

Overlap Function/Enhancement Factor

$$F(b) \propto \int \rho_1(x, y + \frac{b}{2}) \rho_2(x, y - \frac{b}{2}) dx dy$$



Enhancement factor is a dimensionless measure of the partonic overlap in the colliding protons

$$F(b) \propto \tilde{\mathcal{O}}^h(b) = \frac{\sigma_0}{2\pi b \sigma^h} \frac{d\sigma^h}{db}$$

Enhancement factor = 1 on average

Calculate Other quantities from the enhancement factor

$$\langle N_{\text{MPI}} \rangle_{b=b_0} \propto \frac{1}{2\pi b} \frac{d\sigma^H}{db} \bigg|_{b=b_0} \propto \tilde{\mathcal{O}}^h(b_0)$$

σ_{eff} for Double Parton Scattering

$$\sigma^{A,B} = \frac{m}{2} \frac{\sigma^A \sigma^B}{\sigma_{\text{eff}}}$$

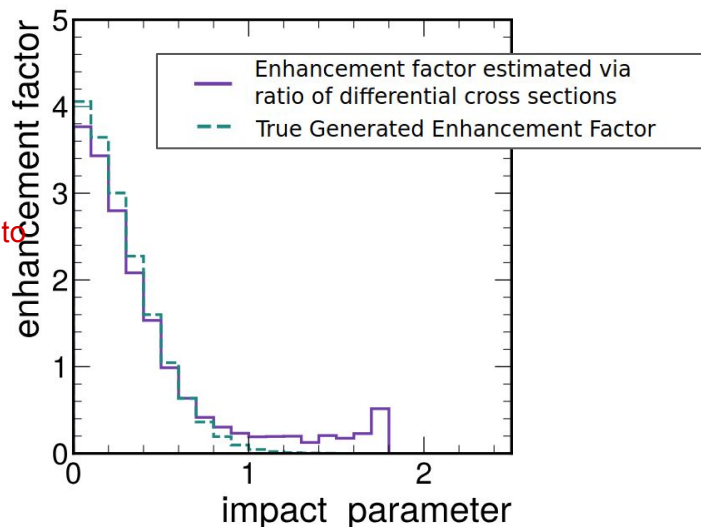
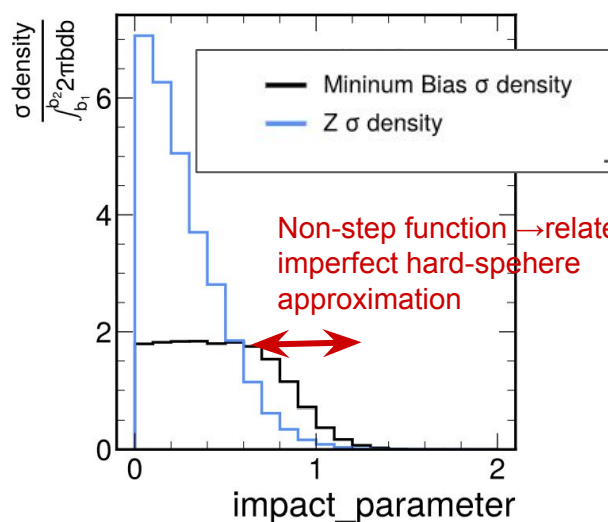
$$\sigma_{\text{eff}} = \frac{\sigma_0^2}{\int db^2 (\tilde{\mathcal{O}}(b))^2}$$

Process-specific method in pp

Use minimum bias collisions to estimate the geometric factors

$$\Omega^h(b) := \frac{\sigma_{\text{tot}}^{nd}}{\sigma_{\text{tot}}^h} \frac{\frac{d\sigma^h}{db}}{\frac{d\sigma^{nd}}{db}} = \frac{\sigma_{\text{nd}}}{2\pi p(\text{nd}|b)\sigma^h} \frac{d\sigma^h}{db} \approx \frac{\sigma_0}{2\pi b\sigma^h} \frac{d\sigma^h}{db} = \tilde{\mathcal{O}}^h(b)$$

“Proof of concept”: Simulated Example in impact parameter space



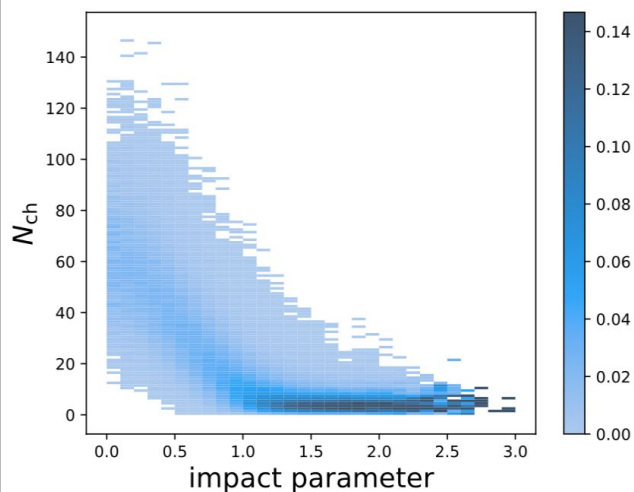
Next: Move to general observable space

$$\Omega^h(\mathcal{E}) = \frac{\sigma_{\text{tot}}^{nd}}{\sigma_{\text{tot}}^h} \frac{\frac{d\sigma^h}{d\mathcal{E}}}{\frac{d\sigma^{nd}}{d\mathcal{E}}}$$

Choice of proxy observable

1. High correlation with impact parameter

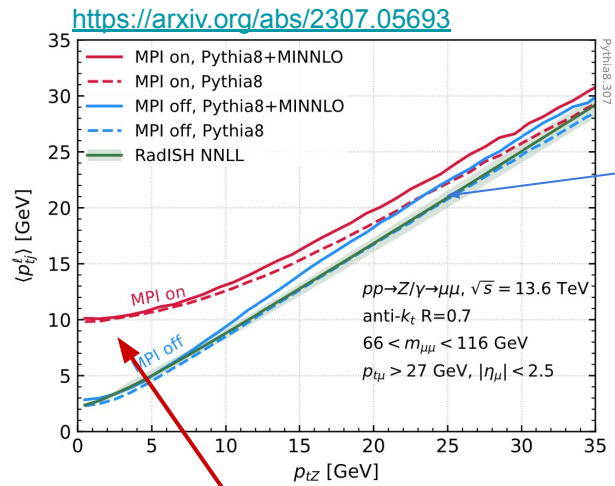
Always use charged particles in tracker acceptance
($p_T > 0.5, |\eta| < 2.5$)



- N_{ch}
- $H_T = \sum p_T$
- $\sum p_T$
- $\sum p_T^2$
- Inv. mass

2. Minimal contamination from the hard-scatter process

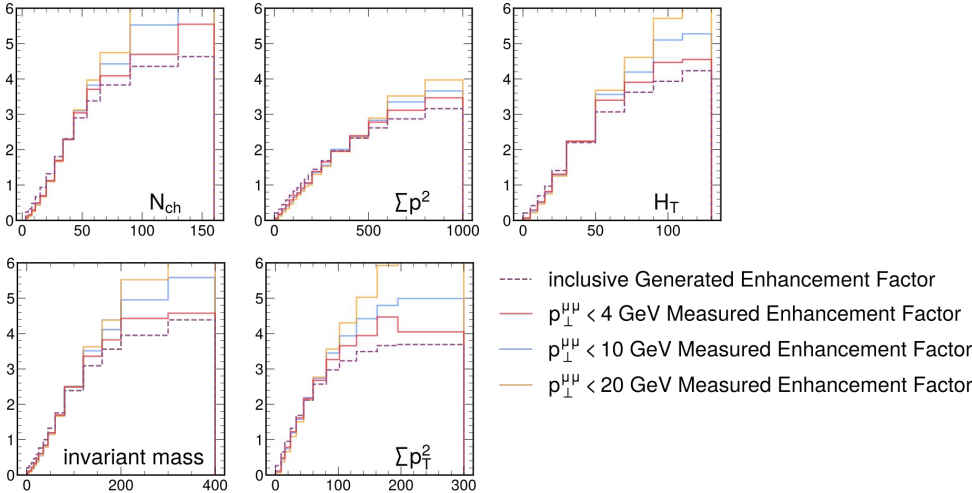
Dimuon production
Restricted to $p_T(\mu\mu) < 4$ GeV



Simulated Results

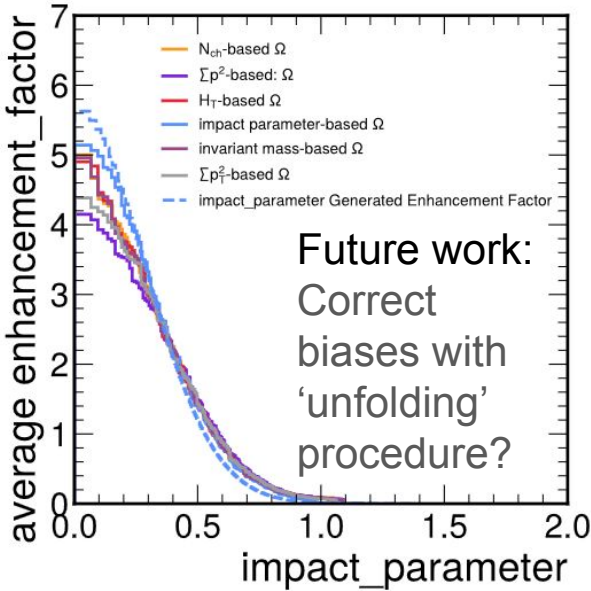
$p_T(\mu\mu)$ cut crucial for ensuring good estimates of enhancement factor

Dashed line: Generator-level truth (target)
Solid lines: Estimate via cross section ratio



Enhancement Factor in estimated impact parameter space

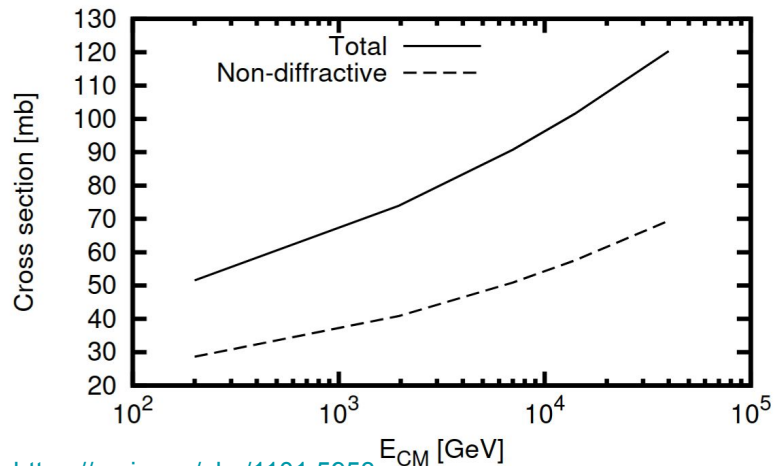
Dashed line: Generator-level truth (target)
Solid lines: Estimates with different observables



Flavour And Kinematic Dependence

The proton structure should depend on the parton kinematics and flavour being probed

Growth of total inelastic cross section with $E_{\text{CM}} \leftrightarrow$ Growth of proton size at low x



<https://arxiv.org/abs/1101.5953>

x-dependent proton structure implemented in pythia since 2011

- Tuned using total cross section growth

Enhancement factor dependence parameterized:

$$\tilde{O}(b, x_1, x_2) = \frac{1}{\pi} \frac{1}{a^2(x_1) + a^2(x_2)} \exp\left(-\frac{b^2}{a^2(x_1) + a^2(x_2)}\right)$$

$$a(x) = a_0 \left(1 + a_1 \ln \frac{1}{x}\right)$$

Studies shown here done with this model + tune

We can use the methods here to probe x- and flavour-dependence!

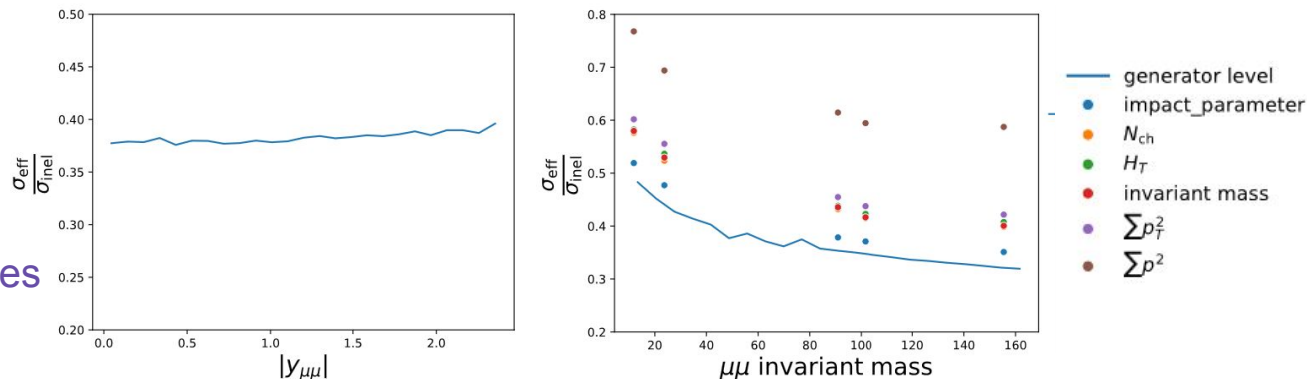
Simulated Results: σ_{eff} for DPS

Different dimuon kinematics can be targeted for differential measurements

Differential estimates of σ_{eff}
As a function of dimuon
mass, rapidity

Blue line: theory prediction

Points: Reconstructed estimates
from different observables



- Observables show large-ish, varying bias for absolute value of σ_{eff} inherited from imperfect resolution
- Biases largely disappear from differential results
 - Kinematic + flavour dependence of σ_{eff} can be probed with higher accuracy

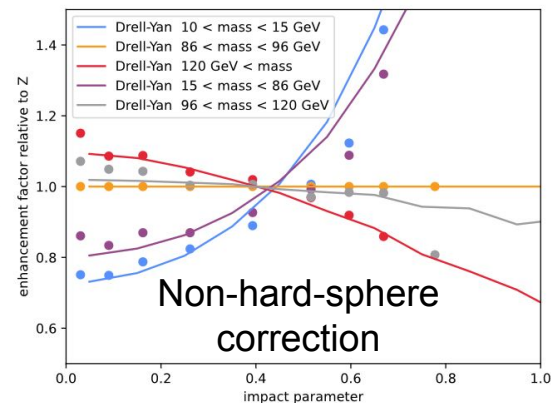
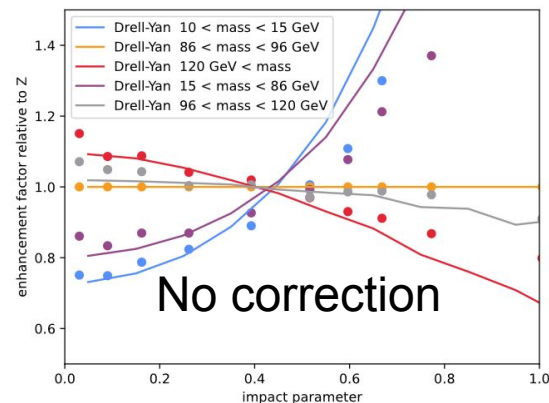
Simulated Results: Differential Enhancement Factor Map

- σ_{eff} is useful for DPS and comparisons
 - But it is derived from full enhancement factor
- Can provide differential map of enhancement factor as function of $(b, m_{\mu\mu}, y_{\mu\mu})$

Corrections to hard-sphere approximation can be calculated from the enhancement factor itself

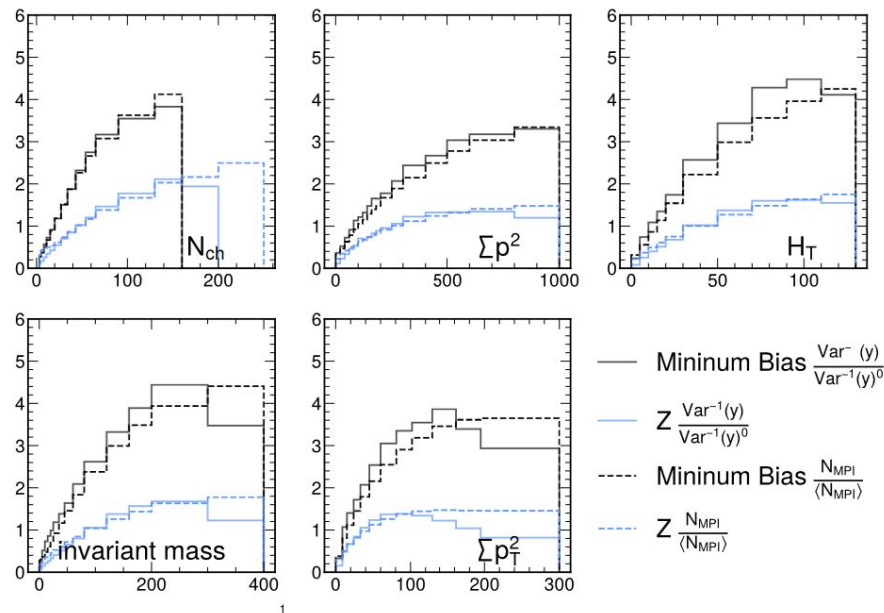
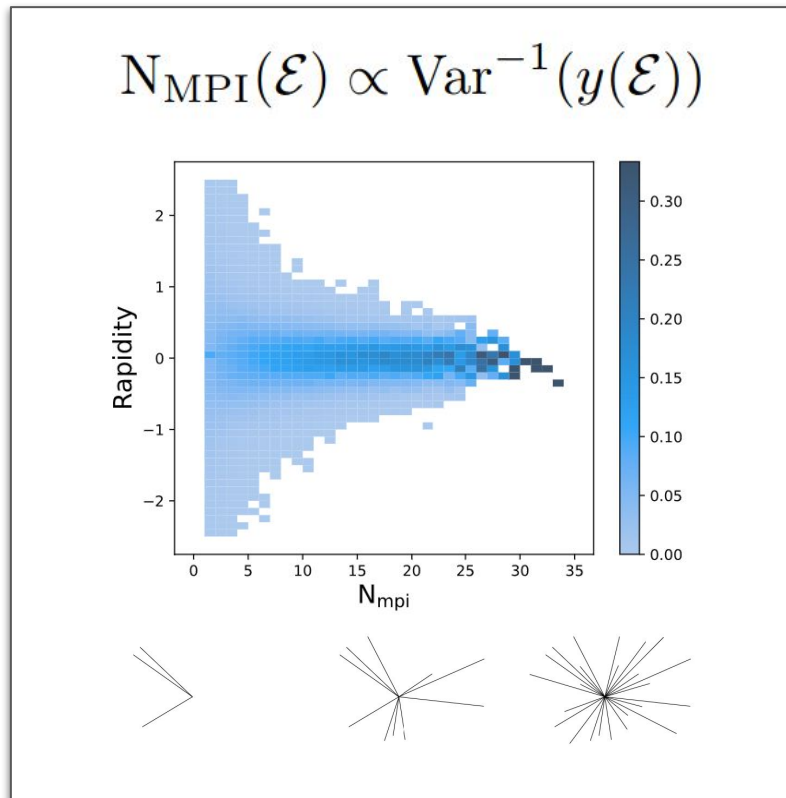
Relative change of enhancement factor in $(b, m_{\mu\mu})$

Lines: true generated relative enhancement factor
Points: Estimated relative enhancement factor



Process-averaged Method

Use the variance of the rapidity of all charged particles to estimate the number of MPI



Inverse Variance (Solid lines) provides a good estimate of generated MPI (dashed lines) in **Minimum Bias** and **Z boson** events

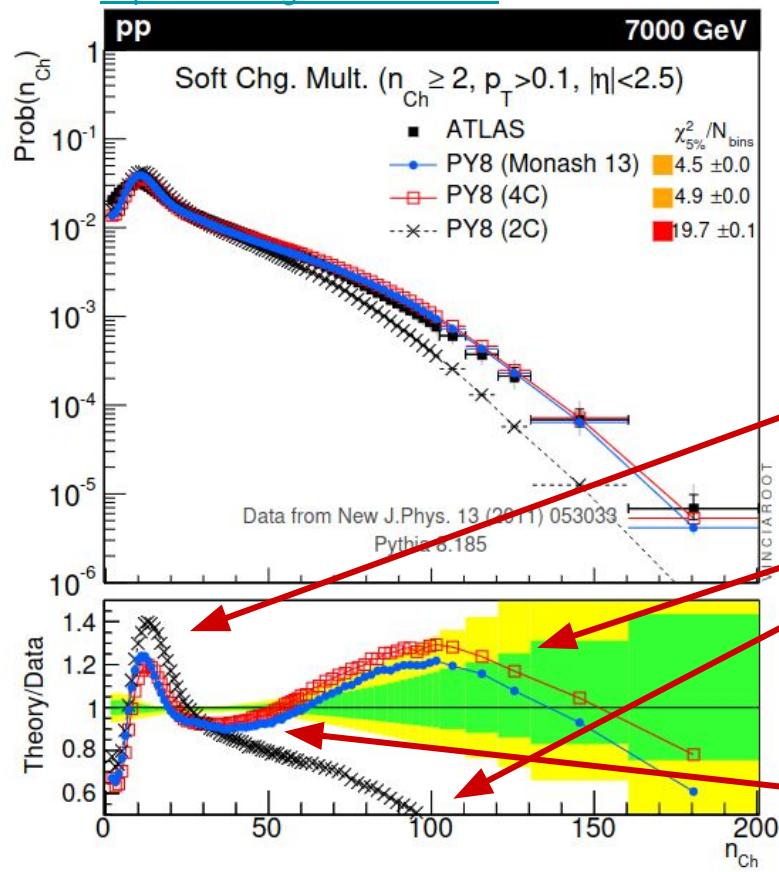
Summary

- Proton Structure is still only poorly understood, we have much to learn
 - Just to understand this important building block of our universe
 - To help enable more good science
- Two Methods for probing the overlap function/enhancement factor of protons at the LHC
 - Process-specific method → Highly target to specific partonic kinematics and flavours
 - Process-averaged method → Averaged over processes according to their cross-section + acceptance
- Can provide detailed information complementary to DPS measurements
 - Highly differential exploration of overlap functions
 - Near-direct determination of N_{MPI}

Bonus

How well do we understand QCD really?

<https://arxiv.org/abs/1404.5630>



There's a lot we do understand, but...

We really don't understand typical pp collisions in detail

We are not able to correctly describe basic quantities of common collisions

Need to isolate and understand effects!

Mis-described diffraction?

Missing higher orders?

Collective Effects?

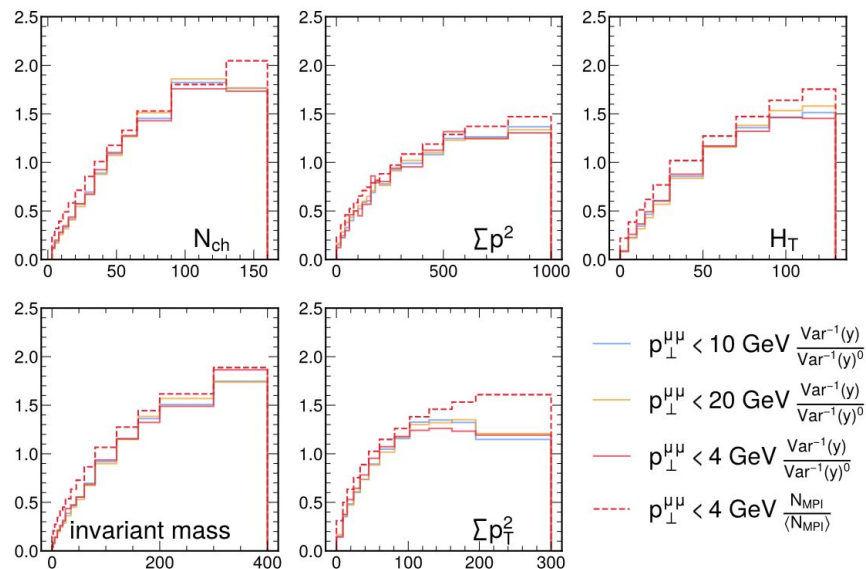
Incorrect Fragmentation?

Incorrect parton correlations?

...

Wrong proton shape?

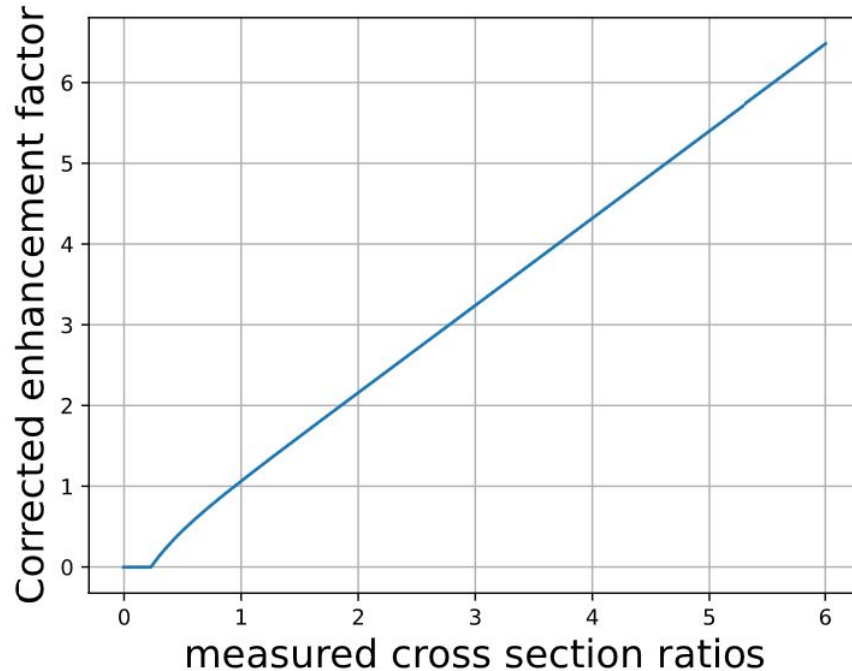
Process-averaged Method Results



Rapidity-variance based estimate shows little dependence on additional activity from the hard scatter

→ **Complementary to process-specific method**

Non-hard sphere corrections



$$\tilde{O}^h(b) = C(b) + \frac{W_0(-\alpha C(b)e^{-\alpha C(b)})}{\alpha}$$

$$\alpha \approx \frac{\sigma_0}{\sigma_{\text{nd}} \Omega^h(b \gg p_r)}$$

$$C(b) = \Omega(b) \frac{\sigma_0}{\sigma_{\text{nd}}}$$