Mueller dipole evolution in PYTHIA 8

Christine O. Rasmussen
Dept. of Astronomy and Theoretical Physics

Outline:

- Mueller dipole formalism
- Matching to PY8 MPI framework
- Merging with Angantyr
- Collisions with photons

Based on C. Bierlich, COR JHEP 1910 (2019) 026 [arXiv:1907.12871 [hep-ph]]
In collaboration with C. Bierlich and I. Helenius

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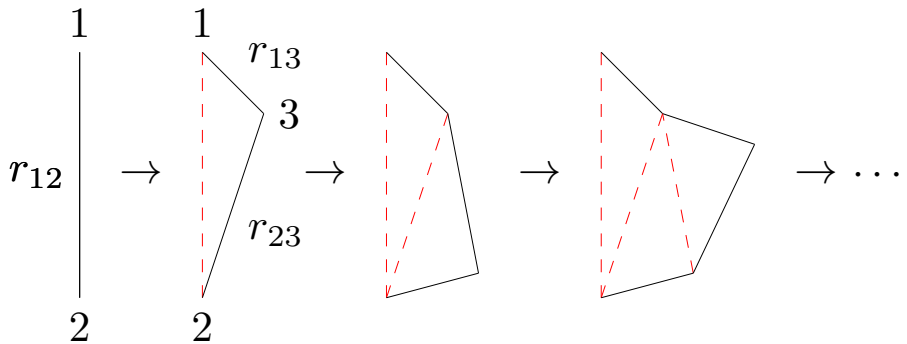
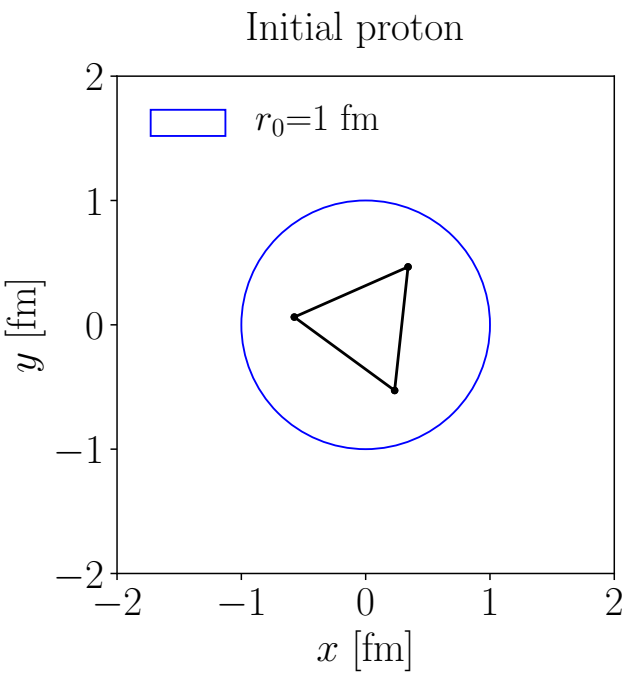
Mueller dipole formalism

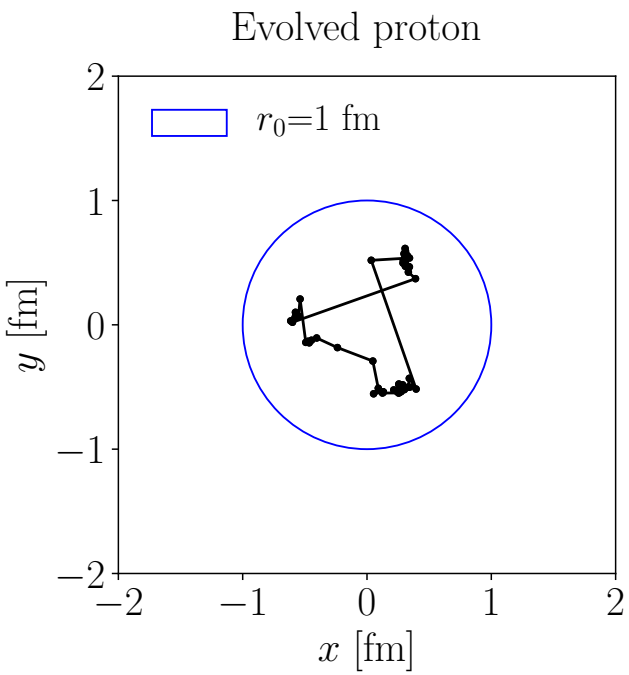
- Mueller dipole formalism describes evolution of a single dipole in rapidity.

Splitting probability

$$\frac{\mathrm{d}P}{\mathrm{d}^2\mathbf{r}_3\mathrm{d}y} = \frac{3\alpha_S(Q^2)}{2\pi^2}\frac{r_{12}^2}{r_{13}^2 r_{23}^2}$$



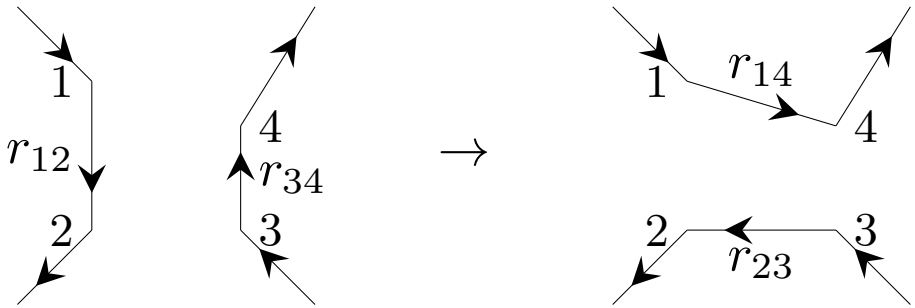




- After evolution the two chains of dipoles are allowed to interact.

Scattering probability

$$f_{ij} = \frac{\alpha_S^2(Q^2)}{2} \log^2\left[\frac{r_{14}r_{23}}{r_{24}r_{13}}\right]$$



- Measurable quantities obtained from unitarized dipole-dipole scattering amplitude:

$$T(\mathbf{b}) = 1 - \exp\left(-\sum_{i=1}^{N_A}\sum_{j=1}^{N_B} f_{ij}\right) = 1 - \exp(-F(\mathbf{b}))$$

- Good-Walker formalism used for cross sections:

$$\sigma_{\text{tot}} = \int \mathrm{d}^2\mathbf{b}\, 2\,\langle T(\mathbf{b})\rangle, \quad \sigma_{\text{el}} = \int \mathrm{d}^2\mathbf{b}\langle T(\mathbf{b})\rangle^2$$

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Previous implementations includes

- OEDIPUS by Mueller and Salam [arXiv:hep-ph/9601220]
- Unpublished MC by Kovalenko [arXiv:1212.2590[nucl-th]]
- DIPSY by Avsar et. al [arXiv:1103.4321 [hep-ph]]

New implementation in PY8 [arXiv:1907.12871 [hep-ph]]

- Includes energy and momentum conservation (k_+ and k_-)
- Includes confinement effects by adding gluon mass
- Includes recoil effects when new dipoles are created
- New! Running coupling constant

Contains four (tunable) parameters: Preliminary hand-set values

- Initial dipole size: $r_0 = 0.75$ fm
- Width of Gaussian fluctuations of r_0: $r_{\mathrm{width}} = 0.01$ fm
- Maximal dipole size in confinement: $r_{\mathrm{max}} = 0.75$ fm (fixed to r_0)
- $\Lambda_{\mathrm{QCD}} = 0.297$ (fixed to PDG 4-quark value)

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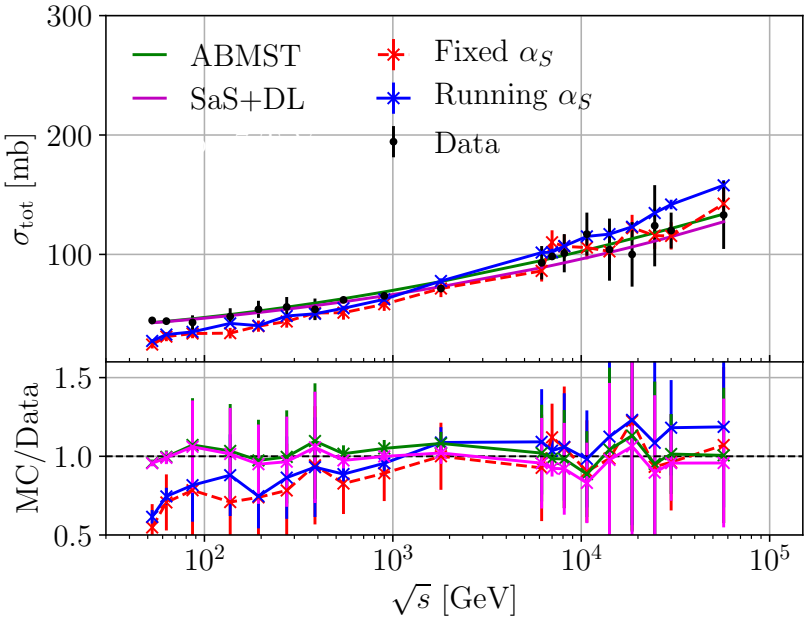
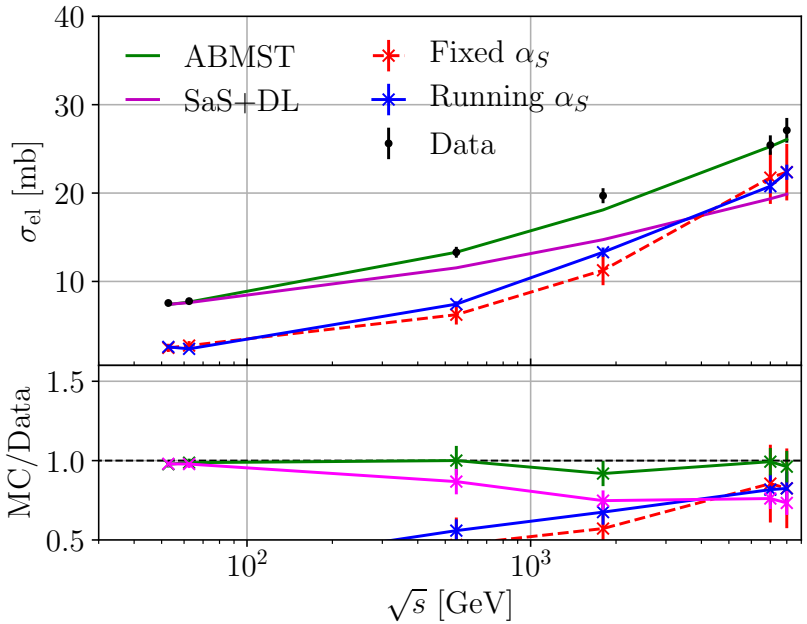
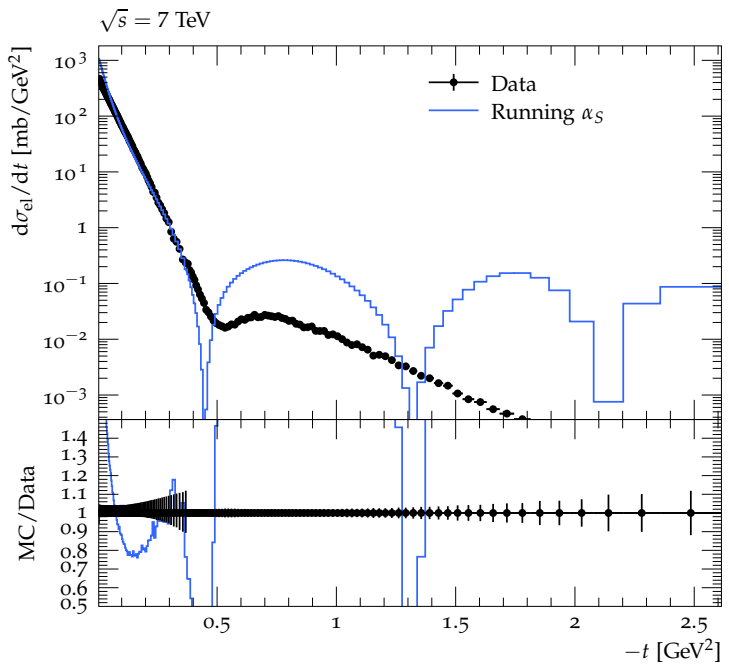
Preliminary pp cross sections:

- Overall agreement with data for $\sigma_{\text{tot}} > 10^2$ GeV
- σ_{el} too low
- Differential elastic cross section possible to describe with running coupling







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So where do we use this model in PY8:

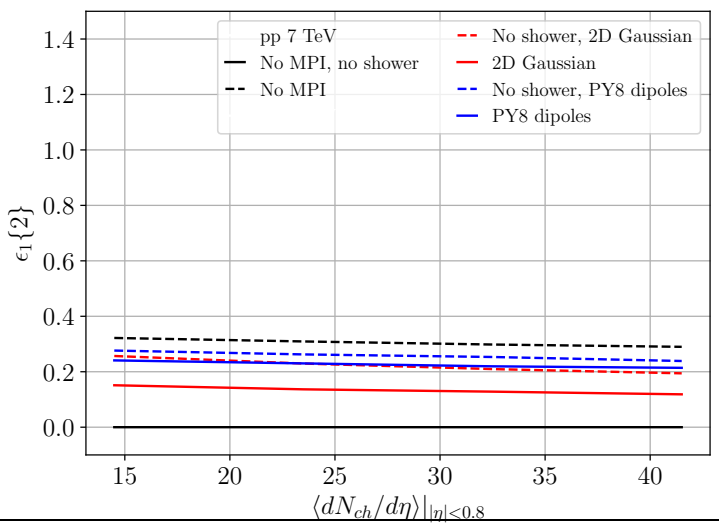
- In PartonVertex:
  - Used solely for assigning vertices for the MPIs
  - Needed for studies on geometry: eccentricities, flow coefficients etc.
  - Studied in C. Bierlich and COR [arXiv:1907.12871 [hep-ph]]
- In Angantyr:
  - Additional model for choosing subcollision type
  - Needed when extending Angantyr to photons
  - Ongoing work with C. Bierlich and I. Helenius

Matching to PY8 MPI model

- Original PY8 MPI does not give information on spatial location of MPIs
- Naive model implemented, which places MPIs according to 2D Gaussian – symmetric (Denoted default in the following)
- Full space-time structure of partonic event comes **for free** with dipole model – not symmetric
- Dipole model only used as input for vertex placement – PY8 MPI model left as is

Note: Initial state is everything **before hadronization**

- Parton shower adds a small ($p_\perp$-dependent) non-flow effect



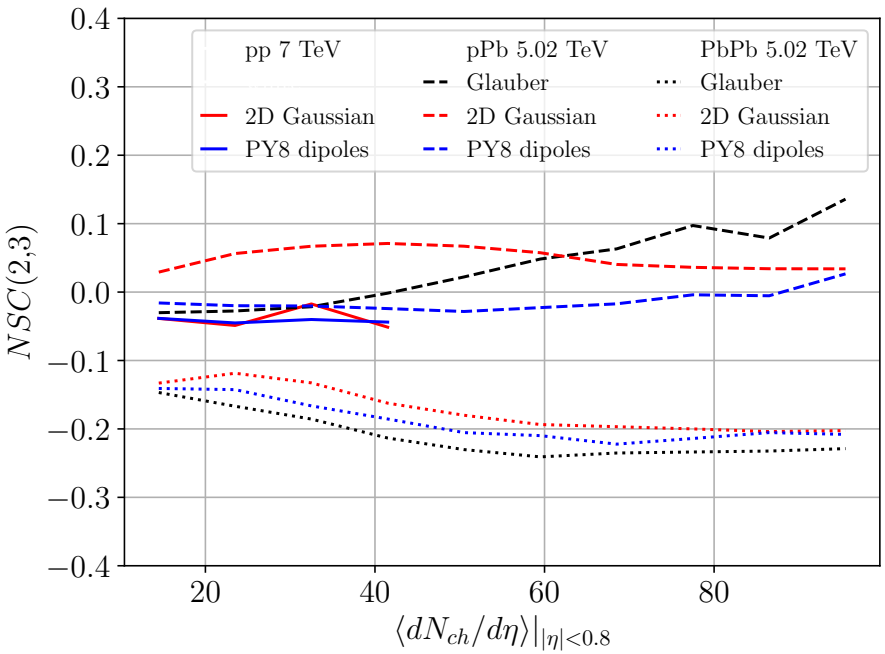
Dipole approach:

- For each event a single projectile and a single target is generated and f_{ij} is calculated using b from the PY8 MPI framework
- A list of possible MPIs from the dipole model is created with a weights $f_{ij}/\sum f_{ij}$
- The PY8 MPIs are assigned vertices according to this list such that the hardest MPI is associated to the dipole-dipole interaction with the largest f_{ij}
  - **Note**: Not the approach used in DIPSY, where the hardest MPIs are associated with the smallest f_{ij}
  - We argue that the largest dipoles give the largest contribution to the cross section, so we want to make sure that we include these in the MPI framework
- Vertex is simply the mean of the transverse coordinates of the dipoles in the interaction

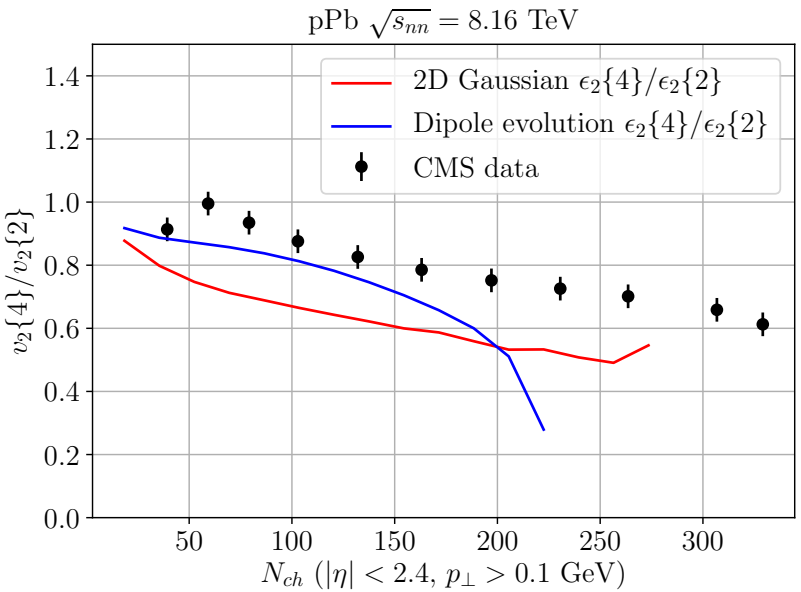
Results:

- **Note**: Currently no final-state effects, so we cannot describe flow coefficients, only ratios

ALICE [arXiv:1903.01790[nucl-ex]]



CMS [arXiv:1904.11519[hep-ex]]



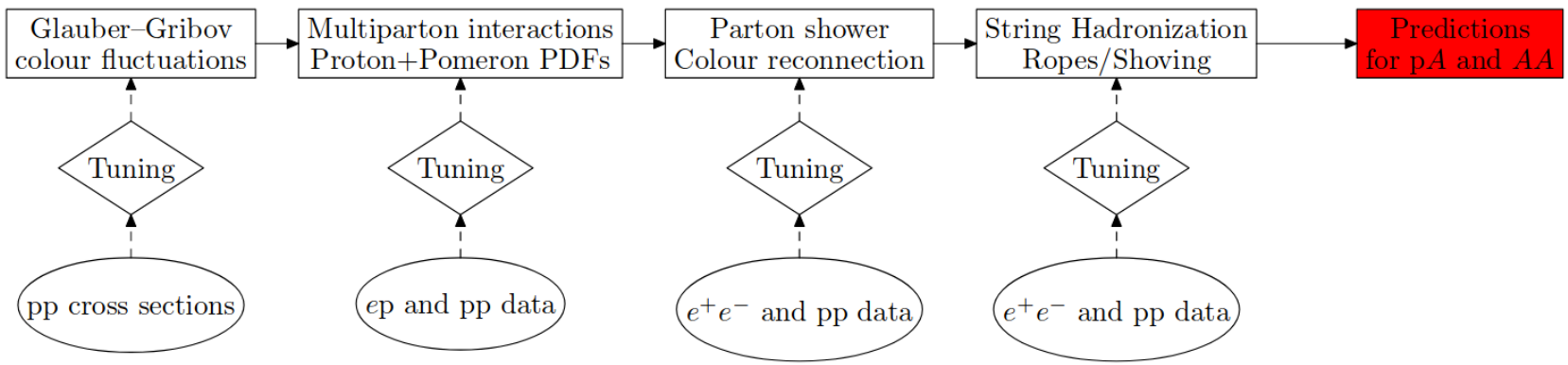
- Best discriminatory power in pPb
- Dipole model: Negative $NSC(2,3)$ in pPb!
- Flow ratios better described by dipole model

Merging with Angantyr

Angantyr in one slide:

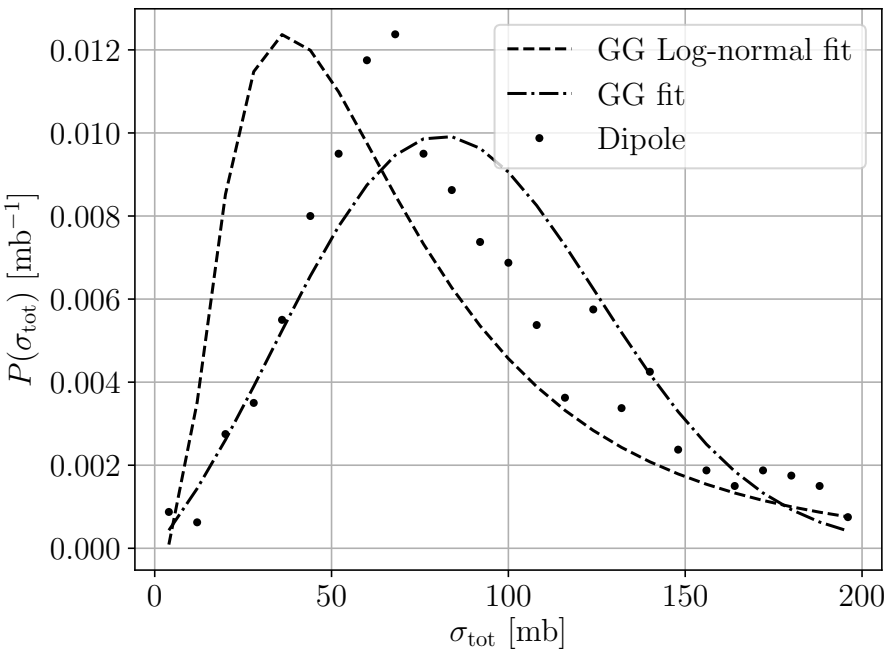
- Glauber-Gribov for number and types of collisions
- Wounded nucleons for particle production

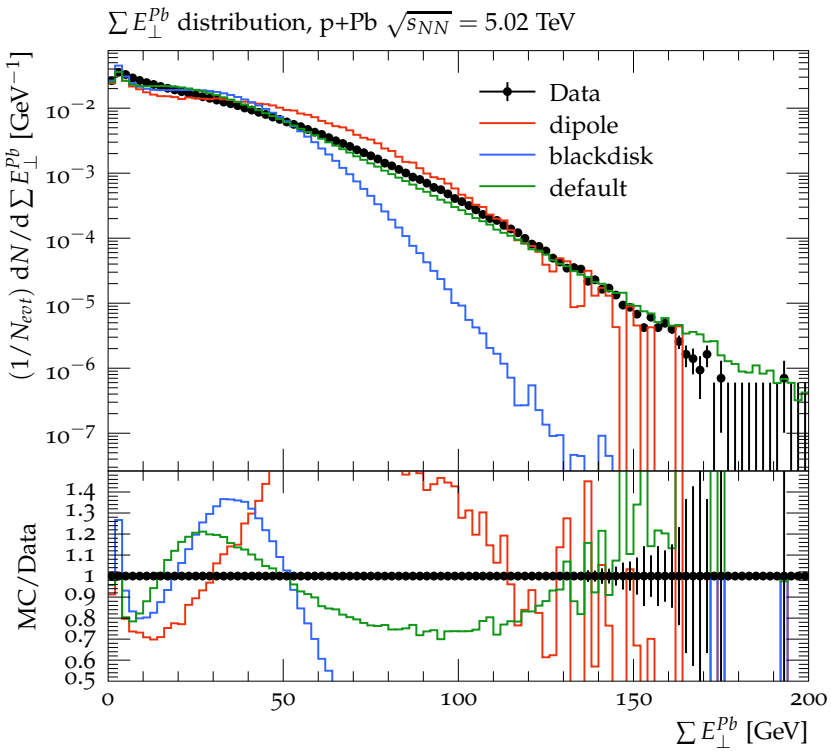
Only tuning to small systems.



Nucleon-nucleon interactions can be calculated from several models:

- Black disk approximation (no diffraction)
- Naive model based on Schuler-Sjostrand pp cross sections
- "Double Strikman" model including fluctuating cross sections (default Angantyr): Cross sections parametrized from DIPSY MC
- Mueller dipole formulation (also including fluctuating cross sections)





ATLAS [arXiv:1508.00848 [hep-ex]]

Collisions with photons

Photon wave function has to be taken into account

$$\sigma_{\mathrm{tot}}^{\gamma^* \mathrm{p}}(W^2, Q^2) = \int \mathrm{d}z \int \mathrm{d}^2\mathbf{r} \left(|\psi_L(Q^2, z, r)|^2 + |\psi_T(Q^2, z, r)|^2\right) \int \mathrm{d}^2\mathbf{b} 2 \left\langle T(W^2, z, r, \mathbf{b})\right\rangle_t$$

For each event with fixed Q^2 we sample z, r according to $|\psi|$, where

$$|\psi_L(z, r)|^2 = \frac{6\alpha_{\mathrm{em}}}{\pi^2} \sum_q e_q^2 Q^2 z^2 (1-z)^2 K_0^2\left(\sqrt{z(1-z)}Qr\right)$$

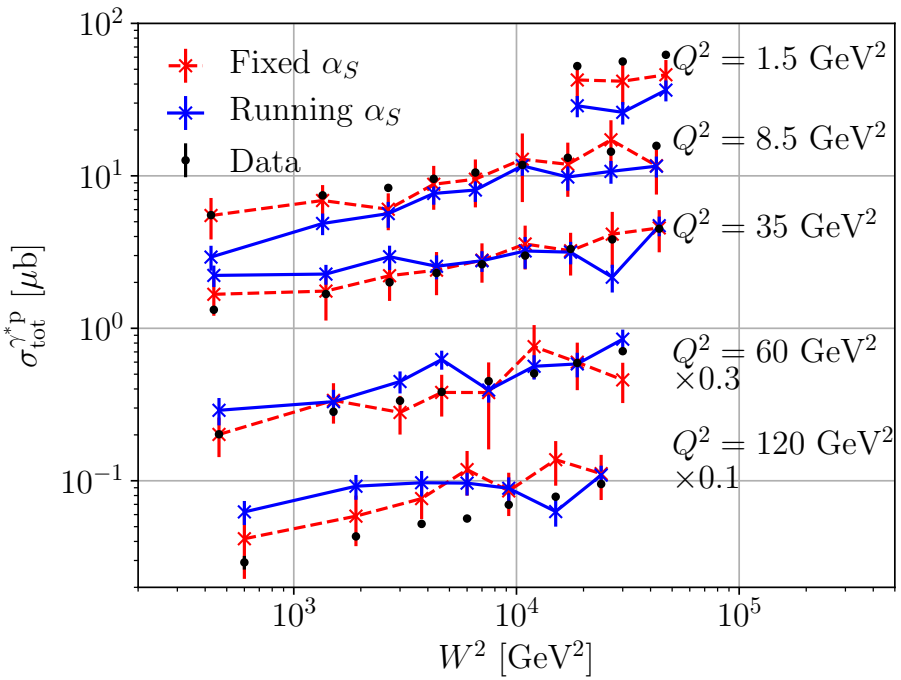
$$|\psi_T(z, r)|^2 = \frac{3\alpha_{\mathrm{em}}}{2\pi^2} \sum_q e_q^2 Q^2 \left[z^2 + (1-z)^2\right] z(1-z) K_1^2\left(\sqrt{z(1-z)}Qr\right),$$

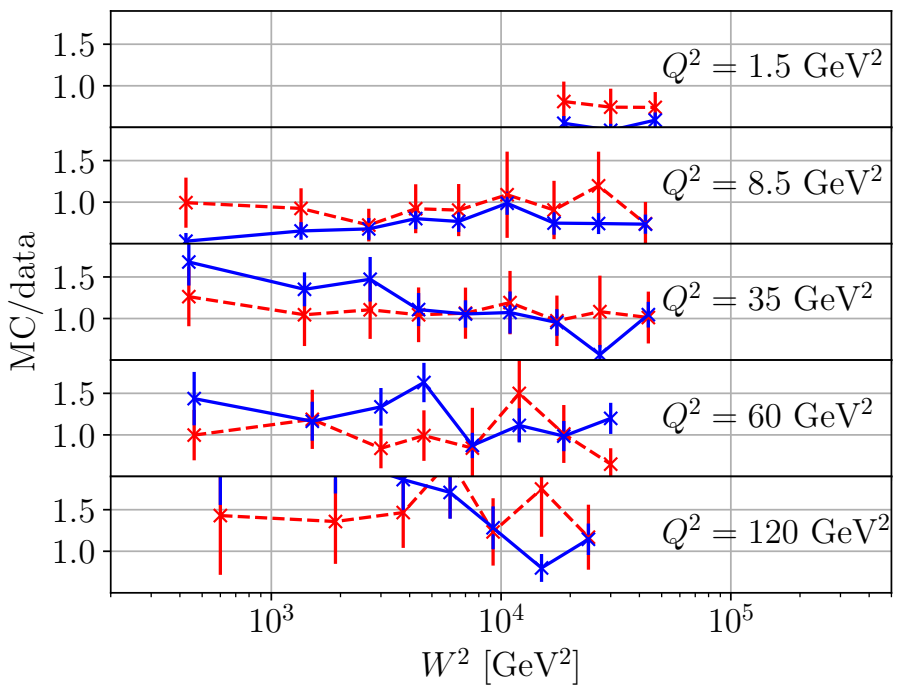
Current implementation:

- Three massless quarks
- No VMDs
- No confinement effects in photon wave function

Preliminary γp cross sections:

- No VMD contribution, so expect to undershoot at low Q^2.
- Reasonable agreement with intermediate Q^2 values with hand-set parameters
- Overshooting of very high Q^2 for both fixed and running couplings





NEW! Angantyr can now handle γ states!

Strategy for collisions with photons:

- First interaction selects specific dipole with a given (z_1, r_1)
- Dipole is then frozen in this state
- Secondary interactions described as dipole-proton interactions
- Currently only available for fixed user-defined Q^2
- Extension to photon-from-beam collisions ongoing using photon flux from beam to sample Q^2

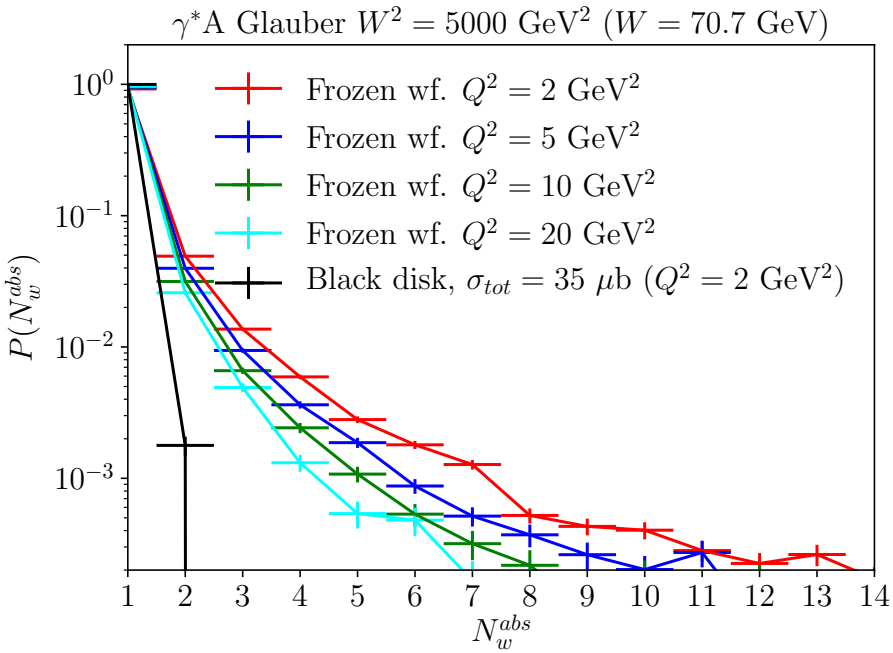
Predictions for UPCs:

Predictions for UPCs:

(almost there)

Predictions for EIC:

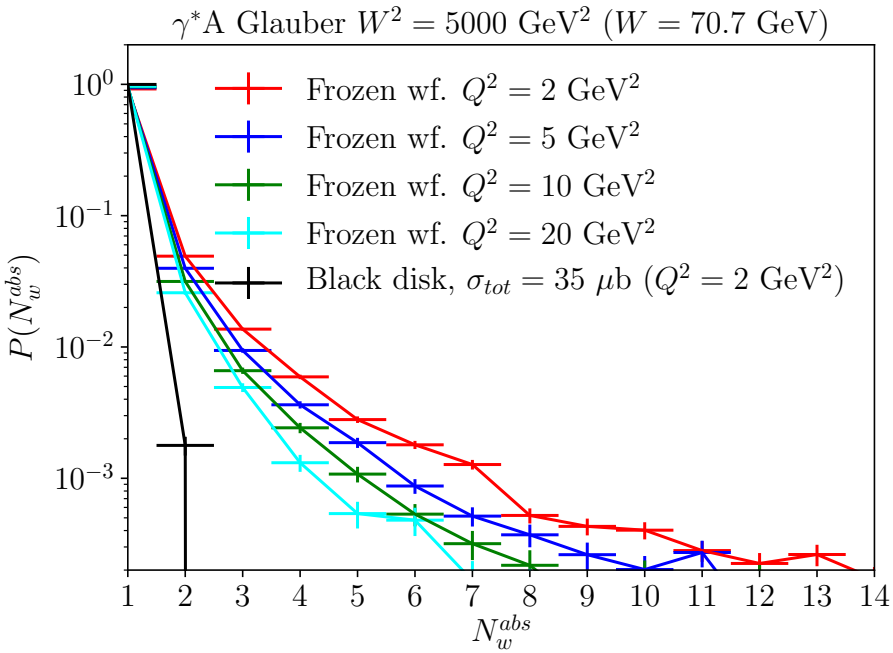
Number of collisions at EIC energies:



- 'Frozen': Secondaries found from dipole-proton cross sections
- Black disk: Full photon wavefunction used for both primary and secondary interactions

Predictions for EIC:

Number of collisions at EIC energies:



- 'Frozen': Secondaries found from dipole-proton cross sections
- Black disk: Full photon wavefunction used for both primary and secondary interactions
- Next step: Press enter and let Angantyr do its magic

Conclusions and outlook

Conclusions:

- New model for dipole evolution and dipole-dipole scatterings implemented in PY8
- Model has been updated since publication with running coupling
- Model fully integrated with Angantyr HI framework
- Good agreement with integrated pp and $\gamma^*\mathrm{p}$ cross sections
- Dipole model show overall trends in $NSC(2,3)$ and flow ratios
- Dipole model validated against $\sum E_\perp$ data from ATLAS
- Predictions for $P(N_w^{abs})$ for EIC

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Future work:

- Q^2-sampling from photon requires further testing
- Eccentricity study on UPCs and predictions for EIC expected within the next few weeks
- Extension to low-Q^2 photons (VMD contribution and quark masses) expected next
- Combination with final-state effects expected using string-string interaction models in future

Thank you!