Mueller dipole evolution in PYTHIA 8

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- Mueller dipole formalism
- Eccentricities for $\mathrm{pp}, \mathrm{pA}, \mathrm{AA}$
- Steps towards UPCs and eA

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

Motivation

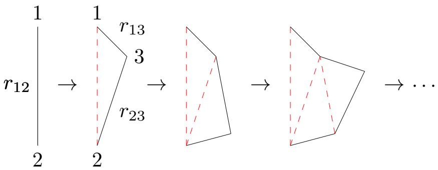
- Initial state fluctutations in pp collisions described with pQCD model (Mueller dipole formalism / BFKL evolution)
- Neglect any final-state effects (no hydro, no interacting strings etc.)
- Tune model to cross sections
- Predictions for pp, pA, AA observables related to geometry
- NEW! Include model in PY8 HI framework (Angantyr)
- NEW! Validation on pPb events
- NEW! Extend Angantyr to handle photons
- NEW! First steps towards UPCs and eA events

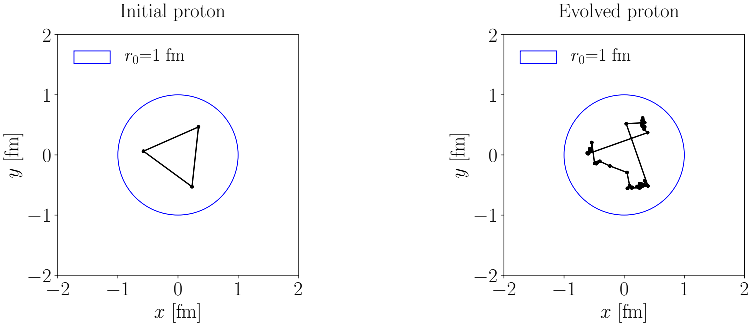
Mueller dipole formalism

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

Splitting probability

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

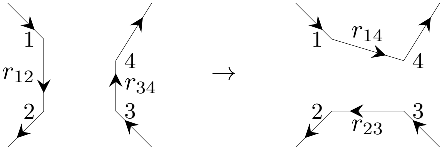




- After evolution the two chains of dipoles are allowed to interact.

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:

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

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- Unpublished MC by Kovalenko [arXiv:1212.2590[nucl-th]]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]]

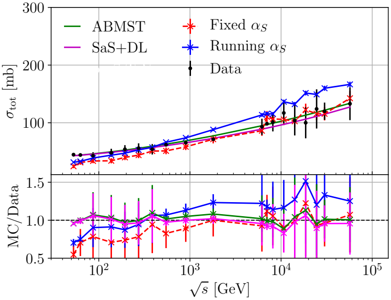
- Includes energy and momentum conservation (k_+ and k_-)
- Includes confinement effects by adding gluon mass
- Includes recoil effects when new dipoles are created
- New! Running coupling constant
- New! Fully integrated with ANGANTYR [JHEP 1810, 134 (2018)]

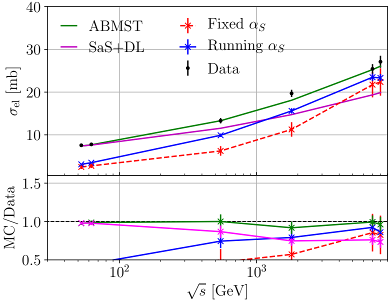
Contains four (tunable) parameters: Preliminary hand-set values

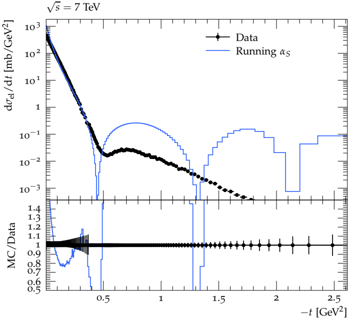
- Initial dipole size for protons: $r_0 = 0.78$ fm
- Width of fluctuations around initial dipole size for protons: $r_{\rm width} = 0.0$ fm (fixed)
- Maximal dipole size in confinement: $r_{\rm max} = 0.78$ fm (fixed to r_0)
- $\Lambda_{\rm QCD} = 0.297$ (PDG 4-quark value) (fixed)

Preliminary pp cross sections:

- Roughly 25% too high σ_{tot} at LHC and cosmic ray energies with these parameters
- Differential elastic cross section possible to describe with running coupling

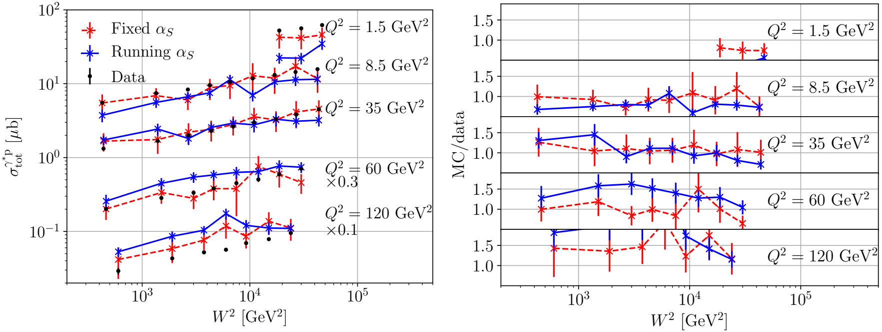






Preliminary γp cross sections:

- 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



Eccentricities

- Full space-time structure of partonic event comes **for free** with dipole model
- Space-time information used as input for PY8 MPI model
  - Default PY8: MPIs placed according to Gaussian – symmetric
  - Dipole model gives transverse location of MPIs – not symmetric

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

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

Linear response function often assumed in AA: $v_n = f(\epsilon_n) \approx a\epsilon_n$

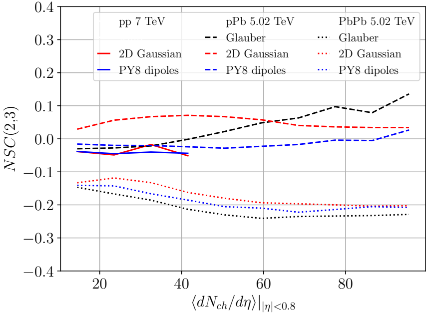
- No response function defined currently
- Study effects of asymmetry in ratios of partonic eccentricities ϵ_n and normalised symmetric cumulants in $\mathrm{pp}, \mathrm{pA}, \mathrm{AA}$

Eccentricities

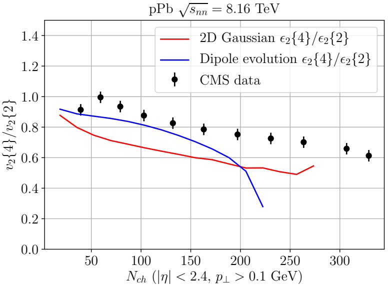
$$\epsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$$

$$NSC(n,m) = \frac{\langle v_n^2 v_m^2\rangle - \langle v_n^2\rangle\langle v_m^2\rangle}{\langle v_n^2\rangle\langle v_m^2\rangle} \approx \frac{\langle \epsilon_n^2 \epsilon_m^2\rangle - \langle \epsilon_n^2\rangle\langle \epsilon_m^2\rangle}{\langle \epsilon_n^2\rangle\langle \epsilon_m^2\rangle}$$

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

Steps towards UPCs and eA

- In general elastic amplitude calculated from average over target (t) and projectile (p) states $A_{el} = \langle T_{tp} \rangle_{tp}$
- Simplifying case: single projectile (e.g. p, γ) colliding with nucleus
- Projectile must remain in same state throughout passage of nucleus implying fixed projectile state k
- Nucleon states (N_i) within nucleus assumed uncorrelated and can be averaged
- Elastic amplitude for projectile-nucleon collision is then

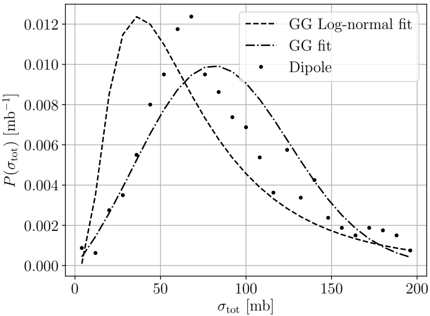
$$A_k^{pN_i}(\vec{b}_i) = \langle T_{t_i k}^{pN_i}(\vec{b}_i) \rangle_t,$$

- Giving total projectile-nucleus expression

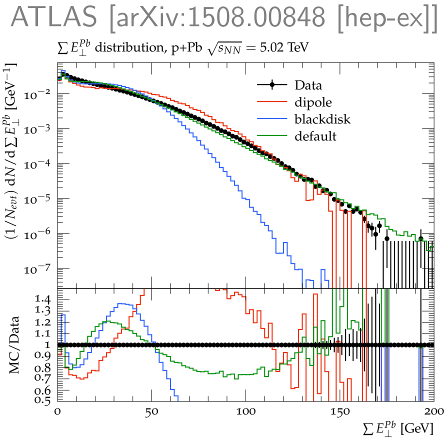
$$T^{(nA)}(\vec{b}) = 1 - \prod_{i=1}^{A} (1 - T^{(nN_i)}(\vec{b}_{ni})).$$

MCnet

- Nucleon-nucleon interactions (obtained from T^{nN_i}) 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)



Validation on pPb:



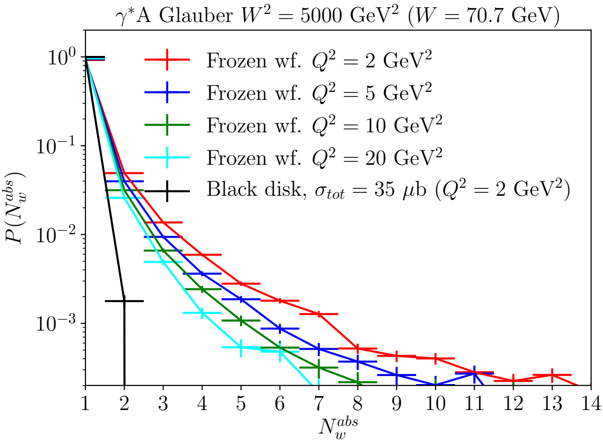
- Excess at 50 GeV $< \sum E_\perp <$ 100 GeV caused by underestimation of diffractive components leading to too many absorbtive events

- Considering photon-nucleon collisions requires photon wave function

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

- Photon is a superposition of all (z, r)
- At first interaction wavefunction collapses to 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

Predictions for EIC:



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

Conclusions and outlook

- 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
- Asymmetric initial state predicted by dipole model show overall trends in normalised symmetric cumulants and ratios of flow coefficients
- Angantyr with dipole evolution validated against $\sum E_\perp$ data from ATLAS
- Fully exclusive final states with photon collisions in Angantyr for user-defined fixed Q^2
- Predictions for $P(N_w^{abs})$ for EIC

Future work:

- Internal Q^2-sampling from photon flux already coded, needs to be tested
- 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!