Initial state fluctuations in PYTHIA 8

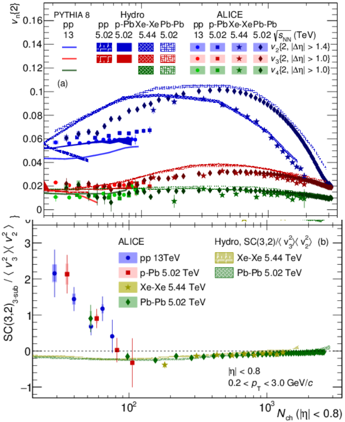
Christine O. Rasmussen
Dept. of Astronomy and Theoretical Physics

- Mueller dipole formalism
- Monte Carlo implementation
- Eccentricities for $\mathrm{pp}, \mathrm{pA}, \mathrm{AA}$
- Steps towards eA

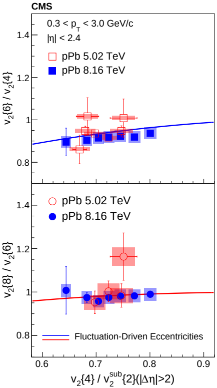
Based on the following work:
Christian Bierlich, Christine O. Rasmussen: *Probing the spatial structure of the proton at small and large scales*, In preparation.

Motivation

- Take pQCD model with event-by-event initial-state fluctuations
- Neglect any final-state effects (no hydro, no interacting strings etc.)
- Can we describe observables related to geometry with model tuned **only** to cross sections?



ALICE arXiv:1903.01790[nucl-ex]



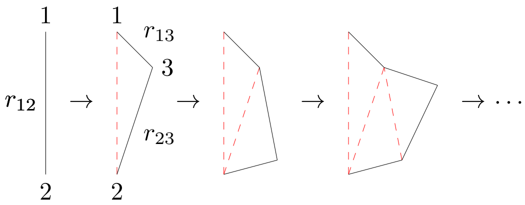
CMS arXiv:1904.11519[hep-ex]

Mueller dipole formalism

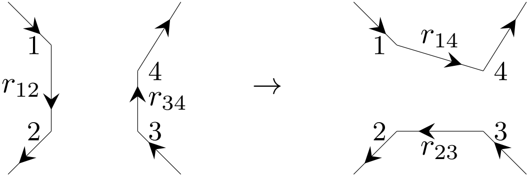
Mueller dipole formalism describes evolution of a single dipole in rapidity.

- Defined by the dipole 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.
- Frame choice for collision not obvious, we use "center-of-rapidity", where both beams are evolved equally in rapidity



- Interaction given by dipole-dipole 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 plus Good-Walker formalism,

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

$$\sigma_{\mathrm{tot}} = \int \mathrm{d}^2\mathbf{b} 2 \langle T(\mathbf{b}) \rangle, \quad \sigma_{\mathrm{el}} = \int \mathrm{d}^2\mathbf{b} \langle T(\mathbf{b}) \rangle^2, \quad B_{\mathrm{el}} = \frac{\int \mathrm{d}b b^3 \langle T(\mathbf{b}) \rangle}{2 \int \mathrm{d}b b \langle T(\mathbf{b}) \rangle}$$

Monte Carlo implementation

Previous implementations includes

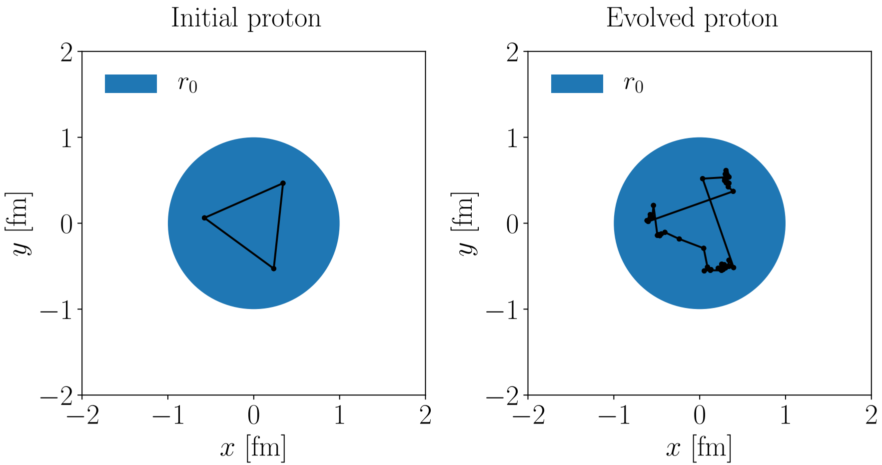
- OEDIPUS by Mueller and Salam (arXiv:hep-ph/9601220)
- Unpublished MC by Kovalenko (arXiv:1212.2590[nucl-th])
- DIPSY by Avsar et. al (arXiv:1103.4321 [hep-ph])

New implementation in PYTHIA 8 C. Bierlich, COR in prep.

- Includes energy and momentum conservation (k_+ and k_-)
- Includes confinement effects by adding gluon mass
- Includes recoil effects when new dipoles are created
- Possibility for collisions with γ^*- and p-beams
- Larger systems described with ANGANTYR model
- Available in upcoming PYTHIA 8.3 release

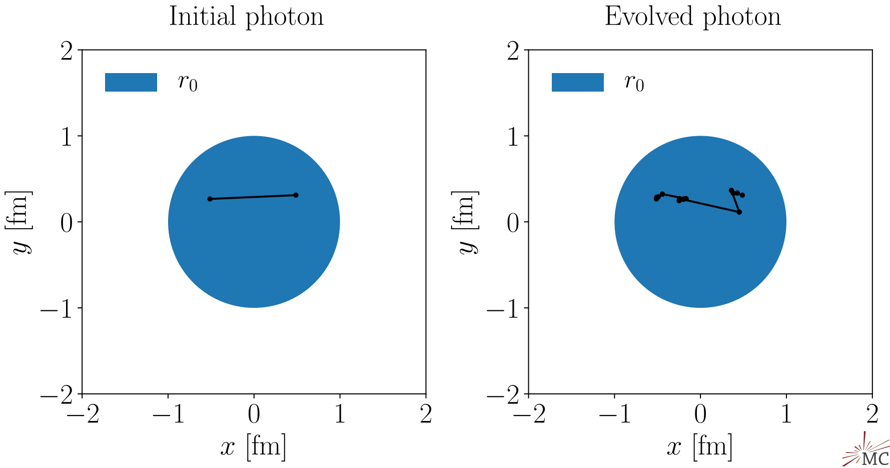
Framework requires assumption on initial dipole configuration

- Previous implementation showed reasonable agreement with data when using equilateral triangle



- Photon represented by single dipole with wavefunction using three lightest quarks,

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



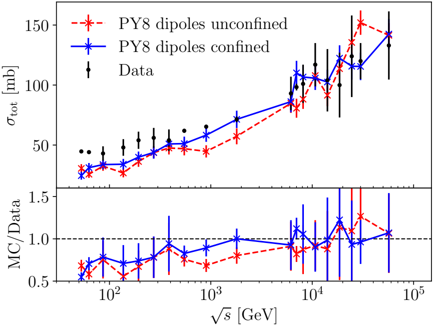
New model contains four tunable parameters

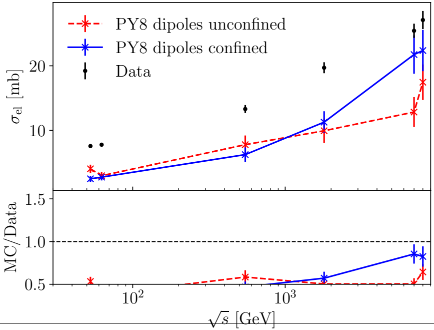
- Initial dipole size for protons: r_0
- Width of fluctuations around initial dipole size for protons: r_{width}
- Maximal dipole size used with confinement: r_{max}
- Fixed strong coupling: α_S

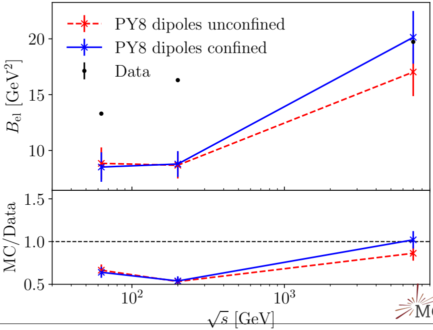
	pp		γ^*p	
Parameter	unconfined	confined	unconfined	confined
r_0 [fm]	0.53	0.70	1.08	1.15
r_{max} [fm]	-	3.00	-	3.50
r_{width} [fm]	0.17	0.27	0.10	0.10
α_S	0.24	0.22	0.21	0.22

pp cross sections:

- Confined model consistent with data on σ_{tot} for $\sqrt{s} \geq 10^2$ GeV
- Difficult to get both σ_{el} and B_{el} right w/o saturation
- $\mathrm{d}\sigma/\mathrm{d}t$ impossible w/o saturation effects

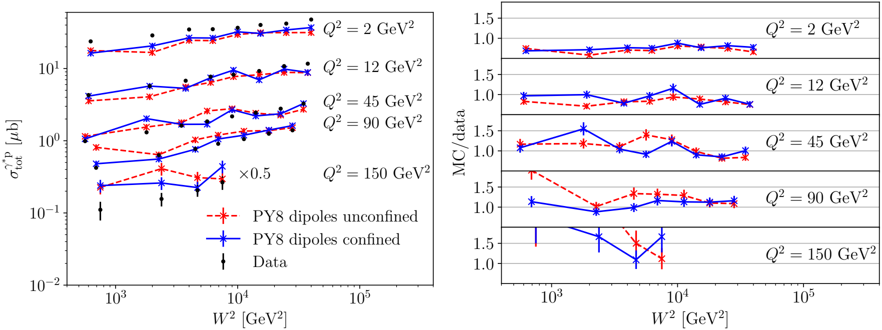






MCnet

γ^*p total cross section:



- Low Q^2: lacks vector meson contribution and light quark masses
- Intermediate Q^2: Good overall agreement
- Very high Q^2: overshoots data.

Model highlights:

- Dipole model describes energy dependence of total cross sections in pp as well as energy dependence of elastic slope at $t = 0$
- Dipole model describes energy dependence of total cross section for $\gamma^*\mathrm{p}$ well over a large range of virtualities
- Full space-time structure of partonic event comes **for free** with dipole model
- Use model to study collective effects in small and large systems
- Starting point for $\gamma^*\mathrm{A}$ exclusive final states

Eccentricities

Space-time information used as input for PYTHIA 8 MPI model

- Default: MPIs normal distributed around proton center – symmetric
- Dipole model gives transverse location of MPIs – not symmetric
- Study effects of asymmetry in partonic eccentricities ϵ_n and normalised symmetric cumulants in $\mathrm{pp}, \mathrm{pA}, \mathrm{AA}$
- **Note**: Initial state is everything **before hadronization**
- Parton shower adds a small ($p_\perp$-dependent) non-flow effect
- No response function added as no final-state effects are included

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

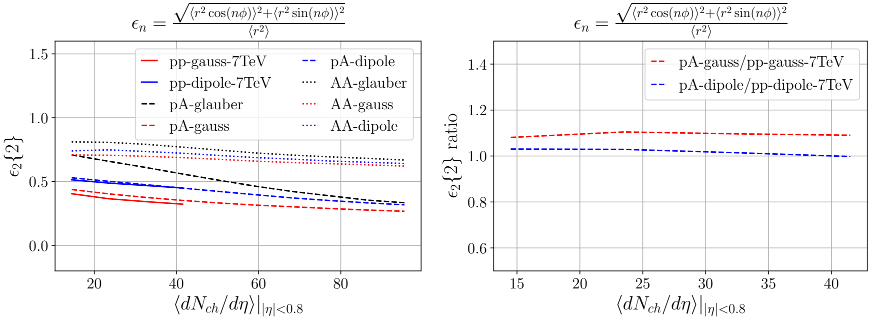
$$\epsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$$

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

Models for assigning coordinates to MPI vertices in transverse space:

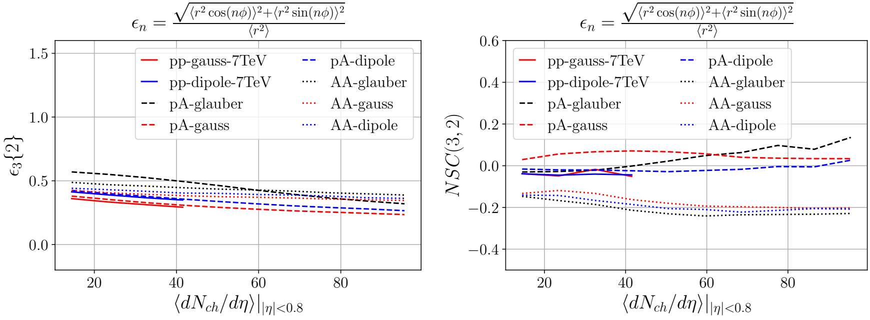
- Glauber: MPIs moved to nucleon position
- Gaussian model: x, y chosen from gaussian with $r_p = 0.7$ and $w_r = 0.1$
- Dipole model: x, y chosen w.r.t. dipole-dipole interaction strength f_{ij}

$\epsilon_2\{2\}$ as a function of average central multiplicity



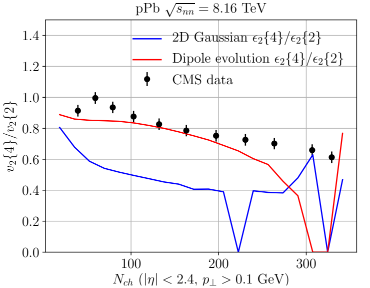
- Asymmetry gives rise to more eccentricity
- Initial state fluctuations important in AA at low multiplicity
- If response function for pA equals that of pp at same average multiplicity, then
  - Eccentricity ratio should be comparable to flow ratios measured in data
  - Dipole model predicts flat pA/pp ratio also seen in data

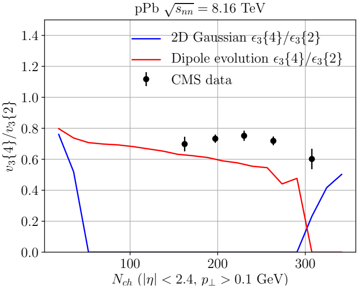
$\epsilon_3\{2\}$ and $NSC(2,3)$ as a function of average central multiplicity

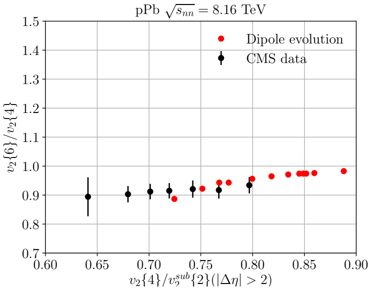


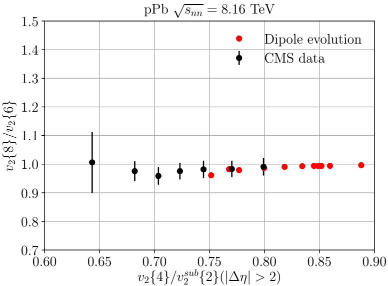
- ϵ_3 related to initial geometry
- Intial geometry not distinguishable in $NSC(3,2)$ for pp
- Very different behaviour in pA for symmetric and asymmetric initial states

Ratios of higher order eccentricities: CMS $\sqrt{s_{NN}} = 8.16$ TeV.









Eccentricities highlights:

- Not possible to describe flow coefficients with current implementation
- We can describe ratios, where response function does not appear
- Good agreement with pA/pp ratio from ALICE
- Good agreement with higher order eccentricities from CMS
- Dipole model is distinguishable wrt. symmetric model and pure glauber (initial states matter!)

Steps towards eA

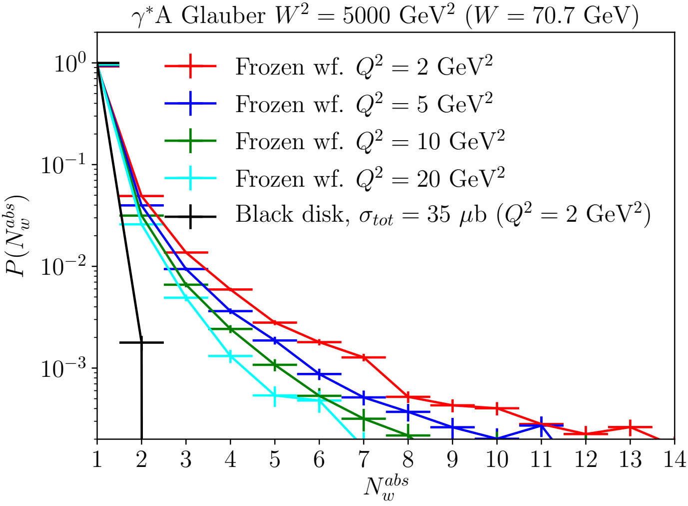
First steps towards $\gamma^* \mathrm{A}$ and eA in PYTHIA 8:

- Use Glauber-Gribov to calculate number of interacting nucleons
- Event-by-event colour fluctuations on total $\gamma^* \mathrm{p}$ cross section with dipole model
- Wounded nucleon model for particle production
- GG: Colour fluctuations studies with projectile frozen in some state k while target configuration is averaged

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

- 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

- '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 PYTHIA 8
- Promising results when comparing to integrated cross sections in pp and $\gamma^*\mathrm{p}$
- Asymmetric initial state show overall trends in eccentricities and normalised symmetric cumulants measured at ALICE
- First results presented for $\gamma^*\mathrm{A}$ exclusive final states

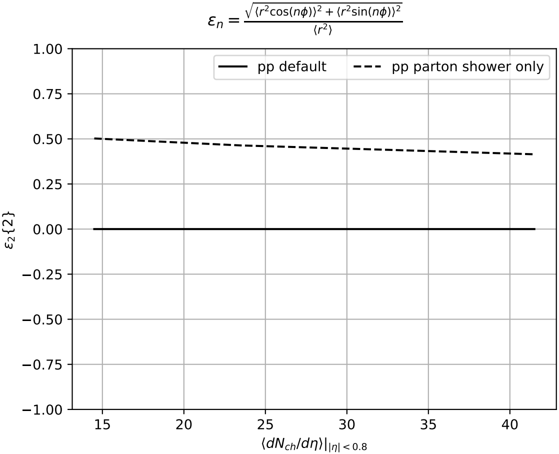
Future work:

- Running strong coupling, new initial proton configurations and saturation to go in next
- Extension to low-Q^2 photons (VMD contribution and quark masses)
- Combination with final-state effects expected using string-string interaction models

Thank you!

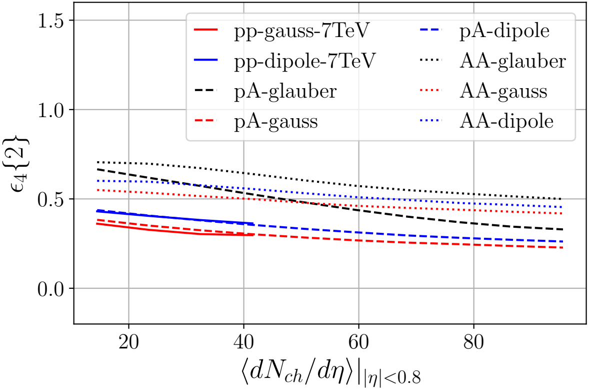
Backup slides

Eccentricities:



Eccentricities:

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



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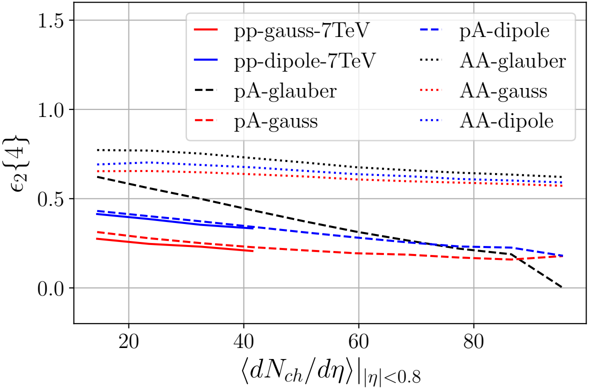

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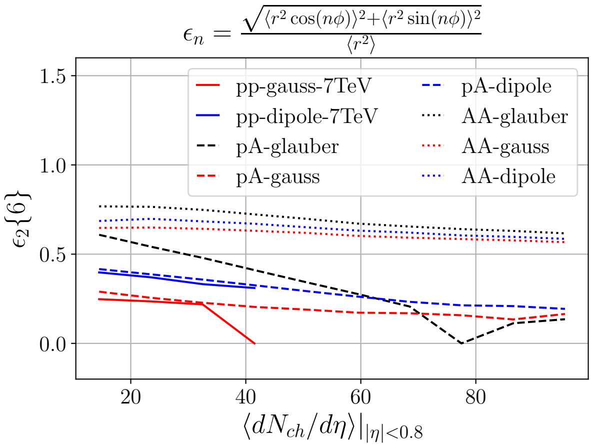

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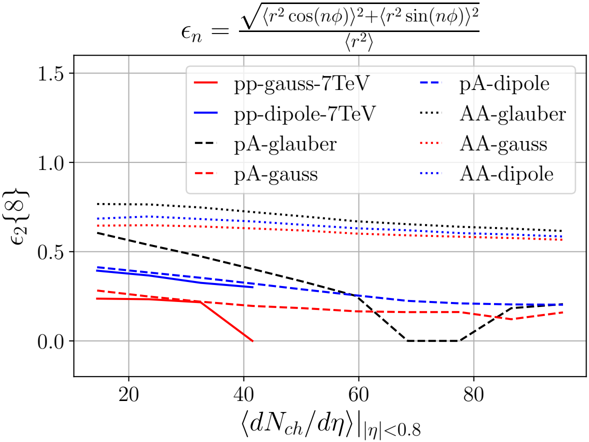

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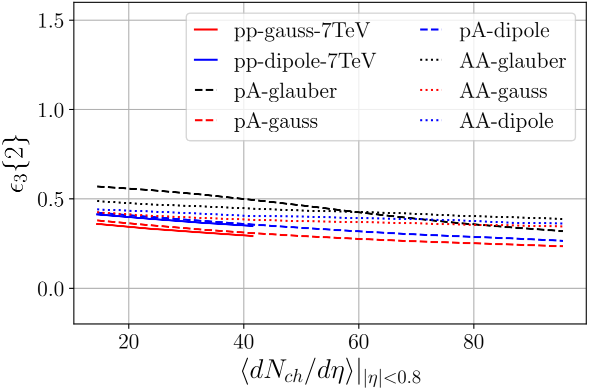

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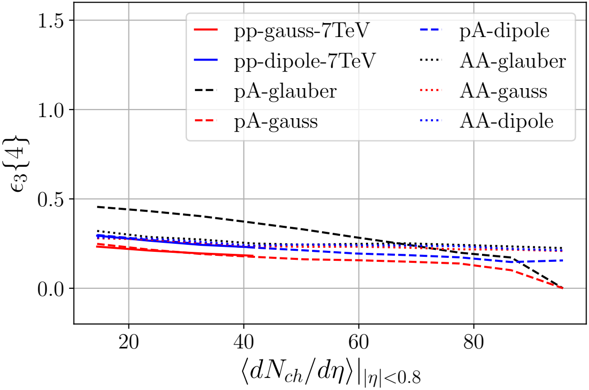

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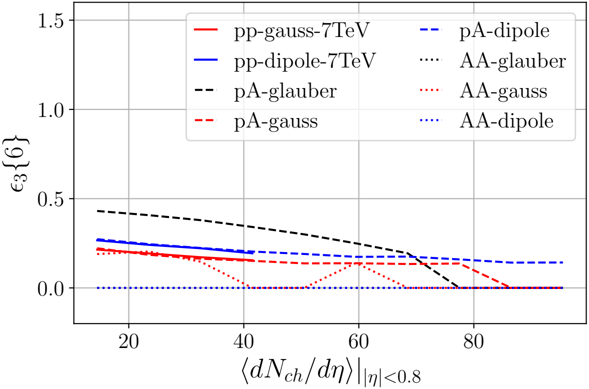

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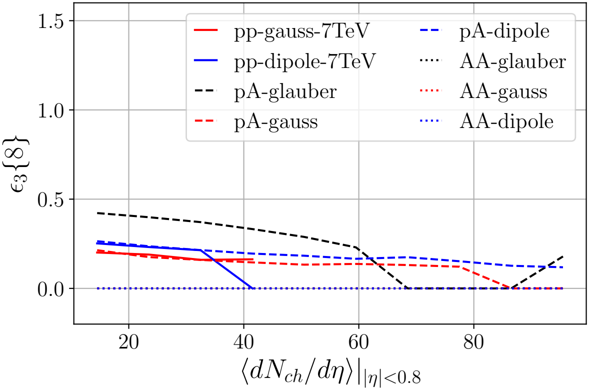

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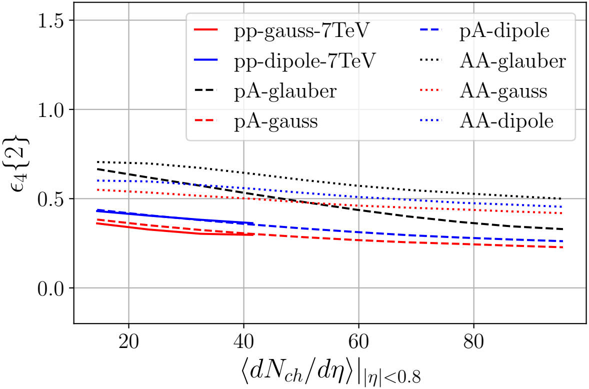

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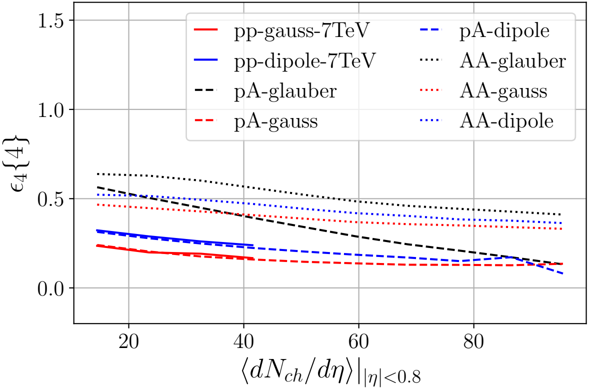

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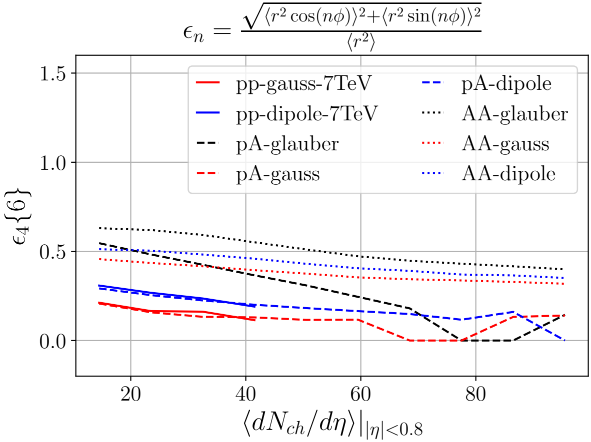

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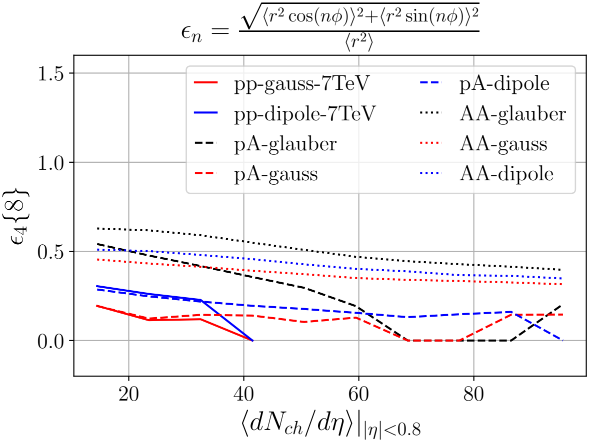
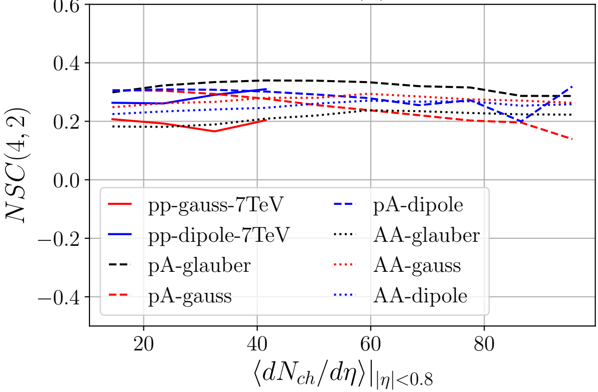
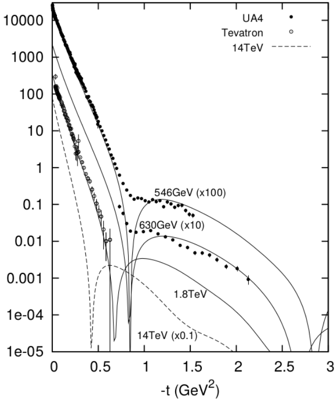


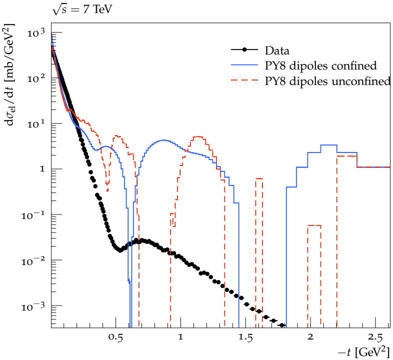
Normalised symmetric cumulants:

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



Saturation





Dipoles in PY8: cannot describe $\mathrm{d}\sigma/\mathrm{d}t$ w/o saturation, but DIPSY MC can (w/ dipole swing)