The Angantyr model for heavy ion collisions

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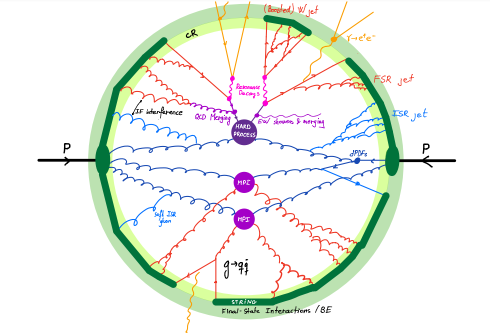
PYTHIA: Monte Carlo for e^+e^-, ep and pp

- General purpose event generator for pp collision physics and more.

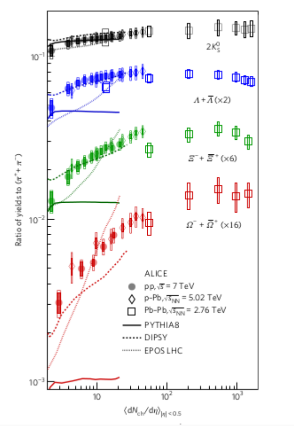


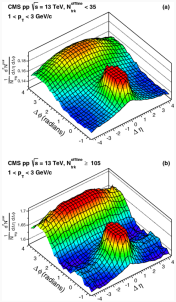
(Figure: Peter Skands)

- Focus on hard process + jets, parton showers, MPIs a sideshow, hadronization a necessity.
- *Jet universality* a cornerstone.

Collectivity in small systems (ALICE: 1606.07424, CMS: 1009.4122)

- LHC revealed that distinction between HI and pp is not simple.
- Probably most *surprising* discovery at LHC.





- Two paradigms at the prize of one!

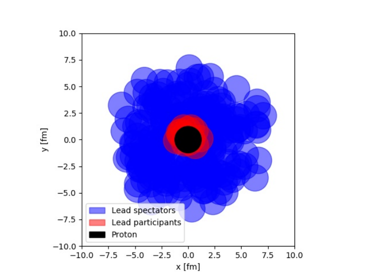
1. If QGP is produced in pp collisions, can general purpose Monte Carlos stay general purpose?
2. How “standard” is the standard model of heavy ion collisions, if QGP is not necessary for collectivity?

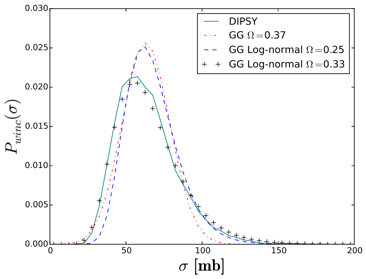
The motivation for "Angantyr"

- *How to reconcile* heavy ion effects in pp with jet universality?
  - Key idea: Let Lund strings interact with each other.
  - Possibly produce QGP features without a QGP, strangeness enhancement, flow, charm, jet quenching...
  - See talk by **Leif Lönnblad** earlier today.
- *What if* we could use this to construct QGP free heavy ion collisions as well?
  - The Angantyr heavy ion model extends the PYTHIA MPI picture.
  - "Clean slate" to add collective effects.
  - Cannot yet do *e*A collisions, but work is ongoing.

Heavy ion collisions: Angantyr (CB, Gustafson, Lönnblad, Shah: 1806.10820)

- Idea: Build a heavy ion collision by stacking nucleon–nucleon sub-collisions.
- Pay special attention to coherence effects.
- Step 1: Glauber calculation with fluctuating cross sections
  $\rightarrow$ ability to determine *type* of interaction

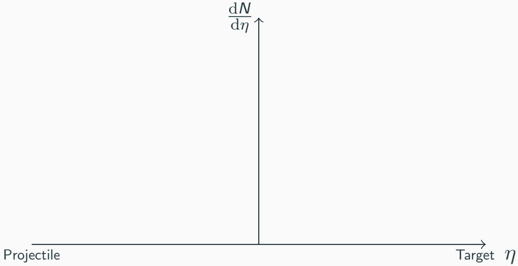




- Parameters fitted to pp cross sections
  $\rightarrow$ no AA input at this point.

Particle production (Inspired by Białas and Czyz: Nucl.Phys.B 111 (1976))

- Emission $F(\eta)$ per wounded nucleon
$$\rightarrow \frac{\mathrm{d}N}{\mathrm{d}\eta} = n_t F(\eta) + n_p F(-\eta).$$
- $F(\eta)$ modelled with even gaps in rapidity, as diffraction.
- Tuned to reproduce pp in the $n_t = n_p = 1$ case.
- No tunable parameters for AA – though some freedom in choices along the way.



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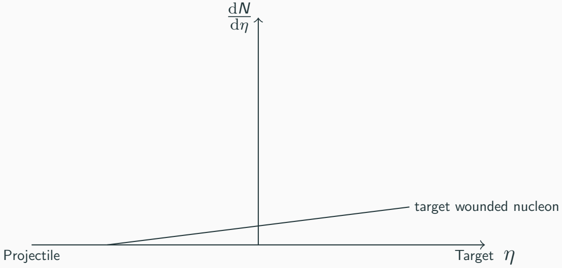

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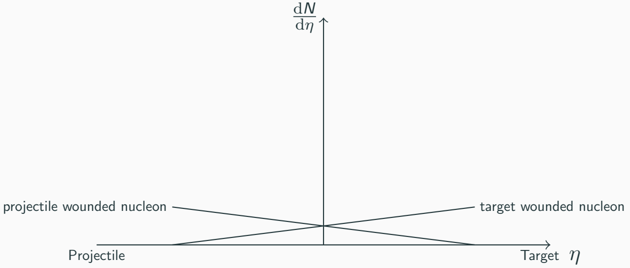

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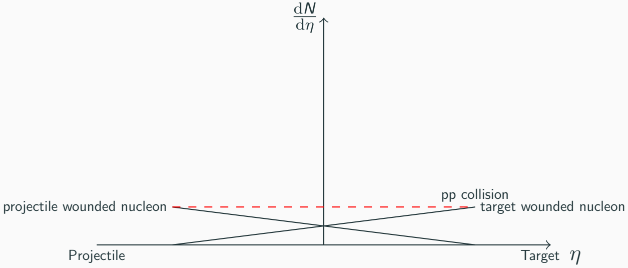

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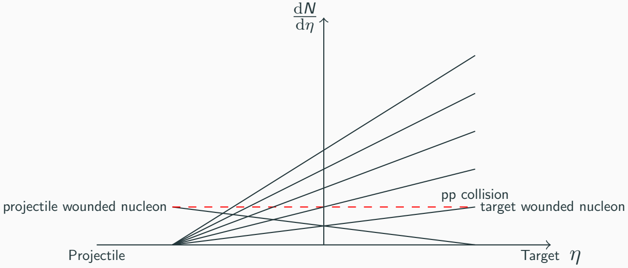

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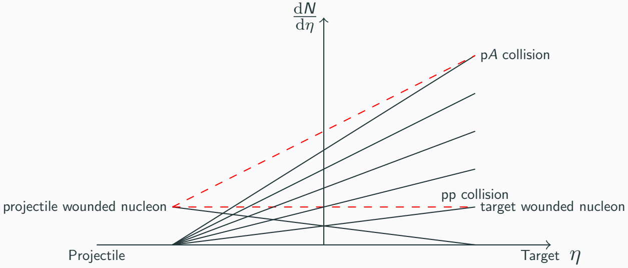

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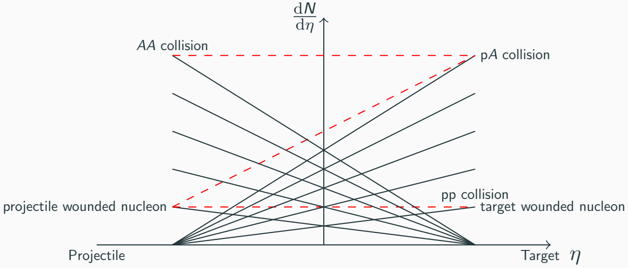
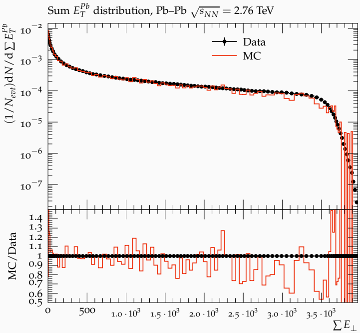
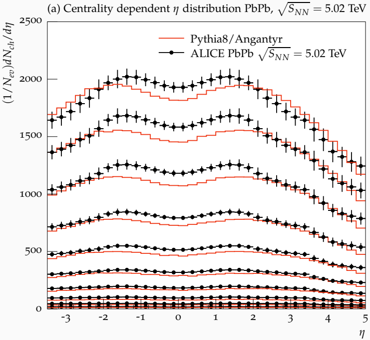


Angantyr particle production

- Reduces to normal Pythia in pp. In AA:
  1. Good reproduction of centrality measure (forward measurement ATLAS).
  2. Particle density at mid–rapidity.

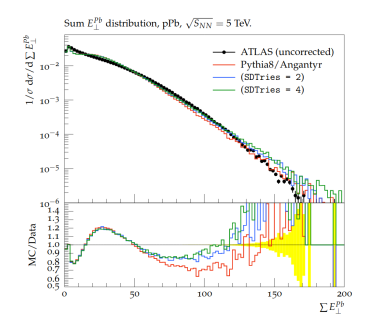


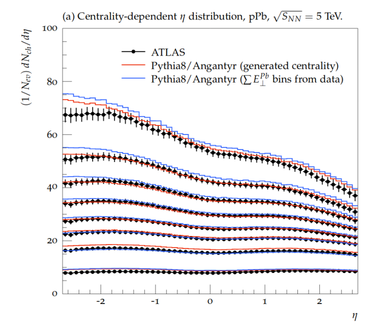


- Mostly PbPb collisions at LHC energies so far.
- RHIC: lower energy + geometry are good model tests.
- RIVET analyses crucial (See talks by **Vaibhavi Gawas** and **Andy Buckley** (1912.05451, 2001,10737))

Asymmetric collision systems

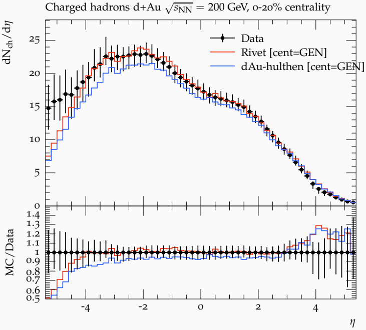
- Same type of measurements in pA equally well reproduced.
- Question of "centrality measure" more important here:
  Angantyr reproduces experimental curve well.

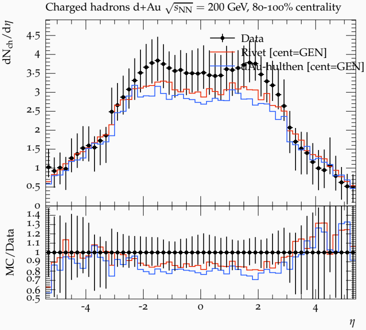




Other nucleus geometries

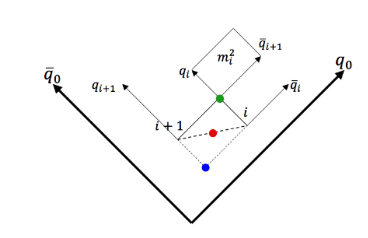
- Default nucleus geometry is Woods–Saxon, unsuitable for light nuclei.
- Nuclear geometries are easy to “plug and play”, improved infrastructure and more options in the pipeline.
- Input from EIC community welcome, already large effects for simple observables, here d-Au 200 GeV PHOBOS data.ls f





Hadronic rescattering (CB, Utheim, Sjöstrand, Ferreres-Solé: 2103.09665, 2005.05658, 1808.04619)

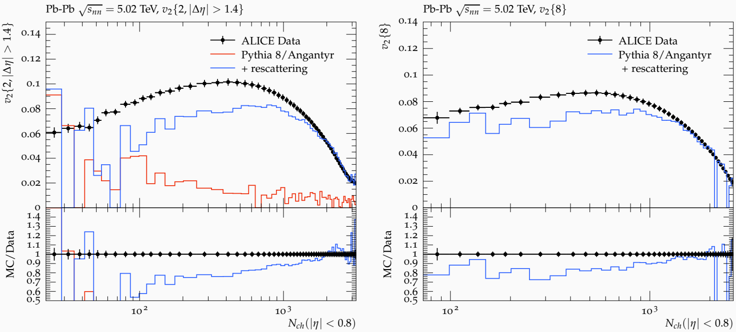
- Internal PYTHIA model plugs directly with Angantyr. Some advantages over eg UrQMD.
- Requires space–time vertices, calculable in string model.
- Momentum-space to space-time breakup vertices through string EOM: $v_i = \frac{\hat{x}_i^+ p^+ + \hat{x}_i^- p^-}{\kappa}$
- Hadron located between vertices: $v_i^h = \frac{v_i + v_{i+1}}{2} \left(\pm \frac{p_h}{2\kappa} \right)$



- Formalism also handles complex topologies.
- Hadron cross sections from Regge theory or data.
- Note recent extension for prompt pentaquark production (Ilten, Utheim: 2108.03479).

Hadronic rescattering, flow

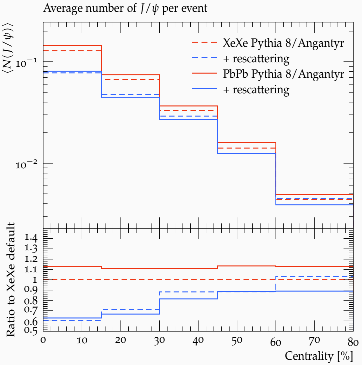
- Angantyr: String lifetime $\langle \tau^2 \rangle \approx 2$ fm $\rightarrow$ dense initial state for hadronic rescattering.
- Allows large v_2 to build up, multiparticle, long range in η.

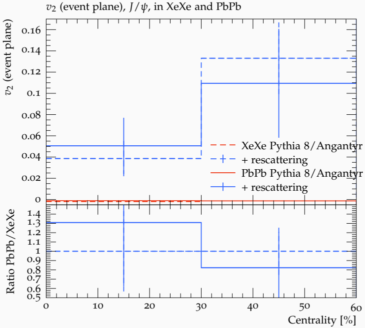


- Connecting with string dynamics in the pipeline.

Hadronic rescattering, closed charm

- Includes additive quark model for charm cross sections.
- Large effect for J/ψ (dissociation, flow). Early production.
- Full comparison to data needed, preferably RIVET.





The Angantyr commercial slide

- As easy to use as normal Pythia.
- Just specify your nuclear beam, and it works.
- HepMC output, pipe to eg. Rivet or write ROOT trees.
- Normal PYTHIA settings can be used.

```cpp
#include "Pythia8/Pythia.h"
#include "Pythia8/HeavyIons.h"

using namespace Pythia8;

// This is a one-slide example program demonstrating Heavy Ion
// functionality.
int main() {
  Pythia pythia;
  // Setup the beams.
  pythia.readString("Beams:idA = 1000822080");
  pythia.readString("Beams:idB = 1000822080"); // The lead ion.
  pythia.readString("Beams:eCM = 2760.0");
  // Sum up the weights of all generated events.
  double sumw = 0.0;
  // Count the number of charged particles.
  double ncEvent = 0.0;
  // Initialise Pythia.
  pythia.init();
  for ( int iEvent = 0; iEvent < 1000; ++iEvent ) {
    if ( !pythia.next() ) continue;
    double nc = 0.0;
    for (int i = 0; i < pythia.event.size(); ++i) {
      Particle & p = pythia.event[i];
      if ( p.isFinal() ) {
        if ( p.isCharged() && p.pT() > 0.1 && abs(p.eta()) < 0.5 ) ++nc;
      }
    }
    sumw += pythia.info.weight();
    ncEvent += nc * pythia.info.weight();
  }
  cout << "Charged multiplicity density at mid-eta: " << ncEvent / sumw << endl;
  return 0;
}
```

So... eA collisions?

- Angantyr currently cannot do electron–Ion collisions.
- ...but it is possible to work from what we have!
    1. Focus on forward production.
    2. Made with asymmetric systems in mind.
    3. Easy to specify hard/trigger processes.
    4. Hadronization/rescattering/string collectivity built-in.
- The hairs in the soup:
    1. Now γ^*p cross section fluctuations (Q^2) must be considered.
    2. Inheriting interaction model(s) from ep, will inherit its VMD problems.
- I will talk about the first issue now.

Tell me more about cross section fluctuations...

- Cross sections from $T(\vec{b})$ with normalizable particle wave functions:

$$\sigma_{\mathrm{tot}} = 2\int \mathrm{d}^2\vec{b}\Gamma(\vec{b}) = 2\int \mathrm{d}^2\vec{b}\ \langle T(\vec{b})\rangle_{p,t}$$

$$\sigma_{\mathrm{el}} = \int \mathrm{d}^2\vec{b}|\Gamma(\vec{b})|^2 = \int \mathrm{d}^2\vec{b}\ \langle T(\vec{b})\rangle_{p,t}^2$$

$$B_{\mathrm{el}} = \frac{\partial}{\partial t}\log\left(\frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}t}\right)\Big|_{t=0} = \frac{\int \mathrm{d}^2\vec{b}\ b^2/2\ \langle T(\vec{b})\rangle_{p,t}}{\int \mathrm{d}^2\vec{b}\ \langle T(\vec{b})\rangle_{p,t}}$$

- Or with photon wave function:

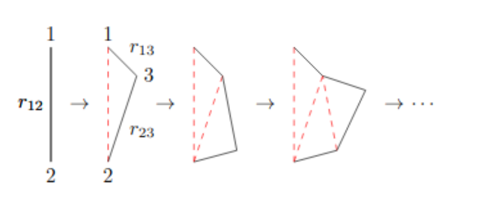
$$\sigma^{\gamma^* \mathrm{p}}(s) = \int_0^1 \mathrm{d}z \int_0^{r_{\mathrm{max}}} r\mathrm{d}r \int_0^{2\pi} \mathrm{d}\phi \left(|\psi_L(z,r)|^2 + |\psi_T(z,r)|^2\right)\sigma_{\mathrm{tot}}(z,\vec{r})$$

- Requiring us to know $T(\vec{b})$ for every state (p,t) combination.

Enter the dipole formalism

- Start with Mueller dipole branching probability:

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}y} = \mathrm{d}^2\vec{r}_3\ \frac{N_c\alpha_s}{2\pi^2}\frac{r_{12}^2}{r_{13}^2 r_{23}^2} \equiv \mathrm{d}^2\vec{r}_3\ \kappa_3.$$



- Evolve any observable $O(y) \to O(y + \mathrm{d}y)$ in rapidity:

$$\bar{O}(y+\mathrm{d}y) = \mathrm{d}y \int \mathrm{d}^2\vec{r}_3\ \kappa_3 \left[O(r_{13}) \otimes O(r_{23})\right] + O(r_{12}) \left[1 - \mathrm{d}y \int \mathrm{d}^2\vec{r}_3\ \kappa_3\right]$$

$$\to \frac{\partial \bar{O}}{\partial y} = \int \mathrm{d}^2\vec{r}_3\ \kappa_3 \left[O(r_{13}) \otimes O(r_{23}) - O(r_{12})\right].$$

A powerful formalism!

- Example: S-matrix (eikonal approximation, b-space):

$$O(r_{13}) \otimes O(r_{23}) \rightarrow S(r_{13})S(r_{23})$$

- Change to $T \equiv 1 - S$:

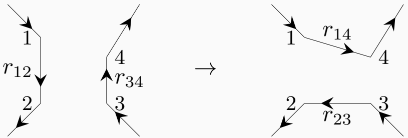
$$\frac{\partial \overline{\langle T \rangle}}{\partial y} = \int \mathrm{d}^2 \vec{r}_3 \ \kappa_3 \left[\langle T_{13} \rangle + \langle T_{23} \rangle - \langle T_{12} \rangle - \langle T_{13} T_{23} \rangle \right].$$

- B-JIMWLK equation, but could be written with other observables.
- Example: Average dipole coordinate ($\langle z \rangle$):

$$\frac{\partial \overline{\langle z \rangle}}{\partial y} = \int \mathrm{d}^2 \vec{r}_3 \kappa_3 \left(\frac{1}{3} z_3 - \frac{1}{6}(z_1 + z_2) \right).$$

Colliding dipole chains & unitarity

- Have: Evolved dipole chain á la BFKL.
- Dipole cross section in large-N_c limit (consistency with evolution):

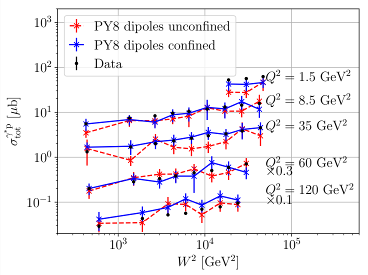


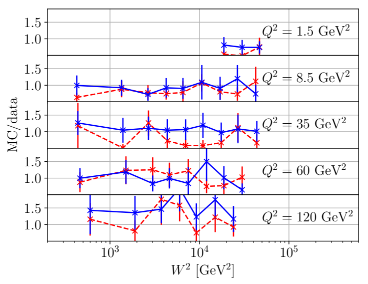
$$\frac{\mathrm{d}\sigma_{\mathrm{dip}}}{\mathrm{d}^2\vec{b}} = \frac{\alpha_s^2 C_F}{N_c} \log^2\left[\frac{r_{13} r_{24}}{r_{14} r_{23}}\right]$$
$$\rightarrow \frac{\alpha_s^2}{2} \log^2\left[\frac{r_{13} r_{24}}{r_{14} r_{23}}\right] \equiv f_{ij}$$

- Unitarized scattering amplitude: $T(\vec{b}) = 1 - \exp\left(-\sum_{ij} f_{ij}\right)$

Model parameters (CB, Rasmussen: 1907.12871)

- This means that all parameters (4) can be tuned to cross sections

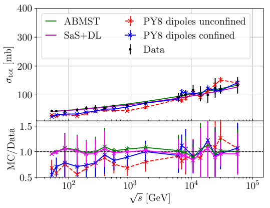


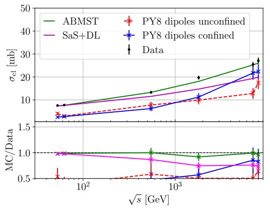


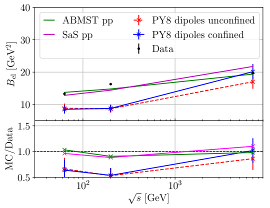
- Could constrain better in *ep* with eg. vector meson production.

Model parameters II

- Same parameters should describe pp, adds more data to the tuning.







- Not as good as dedicated (Regge-based) models.
- Accuracy not the point, control of physics features is!

Cross section colour fluctuations

- Cross section fluctuates event by event: important for pA, $\gamma^* A$ and less AA.
- Projectile remains frozen through the passage of the nucleus.
- Consider fixed state (k) projectile scattered on single target nucleon:

$$\Gamma_k(\vec{b}) = \langle \psi_S | \psi_I \rangle = \langle \psi_k, \psi_t | \hat{T}(\vec{b}) | \psi_k, \psi_t \rangle =$$

$$(c_k)^2 \sum_t |c_t|^2 T_{tk}(\vec{b}) \langle \psi_k, \psi_t | \psi_k, \psi_t \rangle =$$

$$(c_k)^2 \sum_t |c_t|^2 T_{tk}(\vec{b}) \equiv \langle T_{tk}(\vec{b}) \rangle_t$$

- And the relevant amplitude becomes $\langle T^{(nN_i)}_{t_i,k}(\vec{b}_{ni}) \rangle_t$

Fluctuating nucleon-nucleon cross sections

- Let nucleons collide with total cross section $2\langle T \rangle_{p,t}$
- Inserting frozen projectile recovers total cross section.
- Consider instead inelastic collisions only (color exchange, particle production):

$$\frac{\mathrm{d}\sigma_{\mathrm{inel}}}{\mathrm{d}^2\vec{b}} = 2\langle T(\vec{b})\rangle_{p,t} - \langle T(\vec{b})\rangle_{p,t}^2.$$

- Frozen projectile will not recover original expression, but requre target average first.

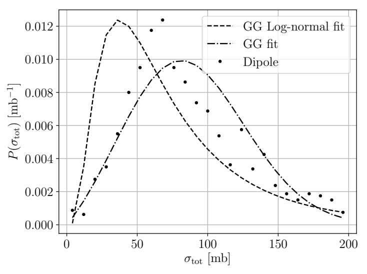
$$\frac{\mathrm{d}\sigma_w}{\mathrm{d}^2\vec{b}} = 2\langle T_k(\vec{b})\rangle_p - \langle T_k^2(\vec{b})\rangle_p = 2\langle T(\vec{b})\rangle_{t,p} - \langle\langle T(\vec{b})\rangle_t^2\rangle_p$$

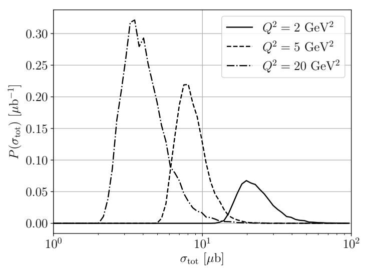
- Increases fluctuations! But pp can be parametrized.

EIC adds more complications

- For $\gamma^* A$ collisions the trick can be repeated.
- But photon wave function collapse to previous result at first hit.

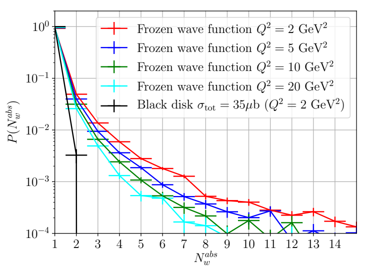
$$\frac{\mathrm{d}\sigma_w}{\mathrm{d}^2\vec{b}} = \int \mathrm{d}z \int \mathrm{d}^2\vec{r}\,(|\psi_L(z,\vec{r})|^2 + |\psi_T(z,\vec{r})|^2)(2\langle T(\vec{b})\rangle_{t,p} - \langle\langle T(\vec{b})\rangle_t^2\rangle_p).$$

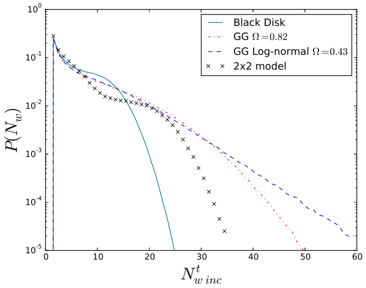




Drastic for number of wounded nucleons

- More multi-hit events, meaning more background.
- Clearly non-negligible, lesson already learned in p-Pb at LHC.





This is where the story ends...

- Angantyr exists and works for pA and AA collisions.
- Plug your favorite geometry, and use Pythia features.
- Hadronic rescattering can be directly enabled.
- Support for *e*A collisions not there yet.
  1. Cross section fluctuations tricky, but mostly in place.
  2. Would be nice with a fast parametrization!
  3. Frozen projectile states clearly important!
  4. A common MPI model including vector meson states wanted.
  5. Progress slow on this part, interfacing properly with string collectivity is current priority.

Thank you for the invitation!