Effects of diffraction in pp and pA collisions in the dipole picture

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Coll. with L. Lönnblad, Ch. Bierlich, E. Avsar, Ch. Flensburg

Content

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   Dipole Cascade evolution
2. Diffraction in DIS and pp
   Good–Walker
3. Diffraction in collisions with nuclei
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4. Conclusions

1. BFKL evolution in impact param. space

High gluon density: Saturation

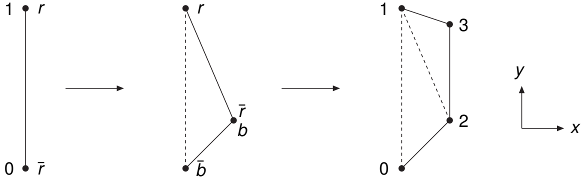
Most easily described in impact parameter space

$k_\perp < Q_s$ suppressed $\Rightarrow$ α_s small and pert. th. OK (*cf.* CGC)

a) Mueller's dipol cascade model

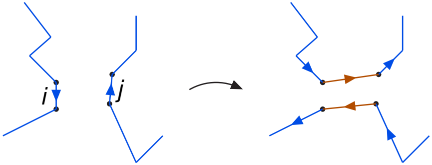
Gluon emission à la Weizsäcker–Williams:

A dipole splits in two dipoles:



Dipole-dipole scattering

Single gluon exhange ⇒ Colour reconnection



Born amplitude: F_{ij}

Reproduces LL BFKL evolution

Multiple subcollisions handled in eikonal approximation:

$$T(b) \equiv \mathrm{Im}\, A_{el}(b) = 1 - e^{-F(b)}, \qquad F(b) = \sum F_{ij}(b)$$

$$d\sigma_{el}/d^2b = T^2 = (1 - e^{-F})^2$$

$$d\sigma_{tot}/d^2b = 2T = 2(1 - e^{-F})$$

b) The Lund cascade model, DIPSY

(E. Avsar, GG, L. Lönnblad, Ch. Flensburg, Ch. Bierlich)

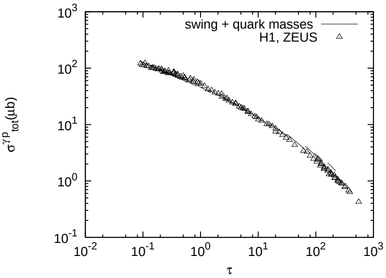
Includes also:

- Important non-leading effects in BFKL evol.
- Saturation from pomeron loops in the evolution
  Identical colours can reconnect
- Confinement ⇒ *t*-channel unitarity
- MC DIPSY; includes also fluctuations and correlations
- Applicable to collisions between electrons, protons, and nuclei

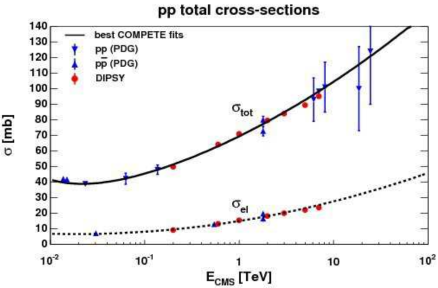
Total cross sections

DIS

Satisfies geometric scaling

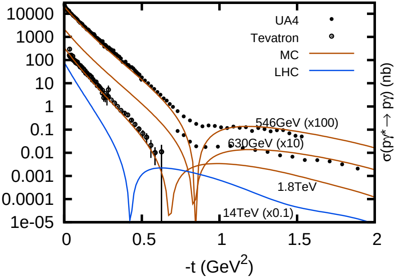


pp



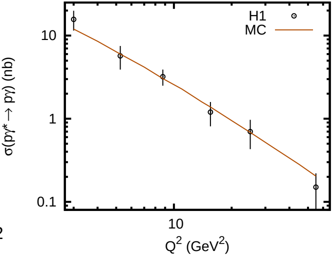
Elastic and quasi-elastic scattering

pp: $d\sigma/dt$



DVCS $\gamma^\star p \to \gamma p$

$W = 82$ GeV as function of Q^2



Data from H1

2. Diffractive excitation

Good–Walker formalism:

Projectile with a substructure:

Mass eigenstates Ψ_k can differ from
eigenstates of diffraction Φ_n (eigenvalues T_n)

Elastic amplitude $= \langle \Psi_{in} | T(b) | \Psi_{in} \rangle$

$\Rightarrow$ Elastic and total cross sections

$$d\sigma_{el}/d^2b = \langle T(b) \rangle^2$$

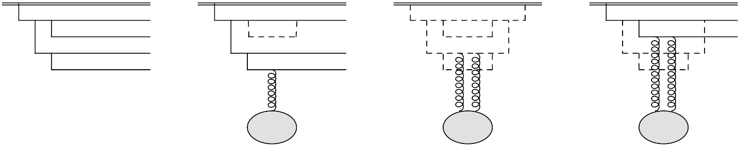
$$d\sigma_{tot}/d^2b = 2\,\langle T \rangle$$

Diffractive excitation determined by the fluctuations:

$$d\sigma_{diff\ ex}/d^2b = d\sigma_{diff} - d\sigma_{el} = \langle T^2 \rangle - \langle T \rangle^2$$

What are the diffractive eigenstates?

Parton cascades, which can come on shell through interaction with the target.



Virtual cascade *a* — *Inelastic int.* *b* — *Elastic scatt.* *c* — *Diffractive ex.* *d*

BFKL dynamics ⇒ Large fluctuations,

Continuous distrib. up to high masses

(Also Miettinen–Pumplin (1978), Hatta *et al.* (2006))

Scattering against a fluctuating target

Separate averages over target and projectile states

$$
\begin{aligned}
d\sigma_{el}/d^2b &= \langle T\rangle_{t,p}^2 \\
d\sigma_{SD,p}/d^2b &= \langle\,\langle T\rangle_t^2\,\rangle_p - \langle T\rangle_{t,p}^2 \\
d\sigma_{SD,t}/d^2b &= \langle\,\langle T\rangle_p^2\,\rangle_t - \langle T\rangle_{t,p}^2 \\
d\sigma_{DD}/d^2b &= \langle\,T^2\,\rangle_{t,p} - \langle\,\langle T\rangle_t^2\,\rangle_p - \langle\,\langle T\rangle_p^2\,\rangle_t + \langle T\rangle_{t,p}^2.
\end{aligned}
$$

Good–Walker agrees with the triple-pomeron formalism,

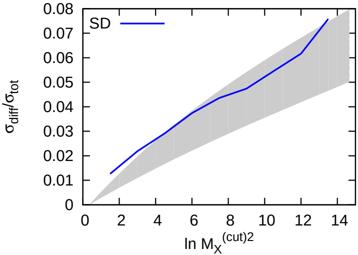
(PL B718 (2013) 1054)

but saturation is much easier in Good–Walker

Single diffraction in *pp*

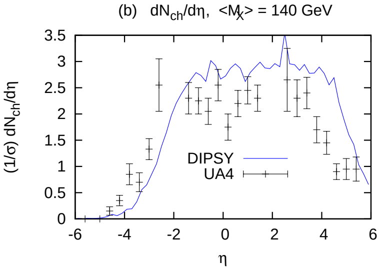
Inclusive $M_X < M_X^{(cut)}$

1.8 TeV,   Shaded: CDF



Final state

UA4: $W = 546$ GeV $\langle M_X \rangle = 140$



(JHEP(2012), arXiv:1210.2407)

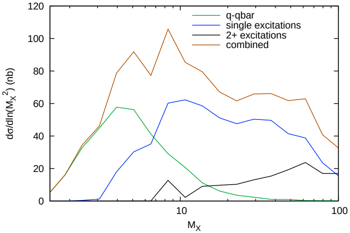
Note: Calculated directly fron pert. QCD
Tuned only to total and elastic cross sections

Diffraction in DIS

The photon splits in a $q\bar{q}$ pair, which starts a cascade

Single diffraction $W = 120\,\mathrm{GeV}, \quad Q^2 = 24\,\mathrm{GeV}^2$

$$\frac{d\sigma}{d\ln M_X^2}$$



Curves show contrib. from $q\bar{q}$ state plus 0, 1, and ≥ 2 gluons

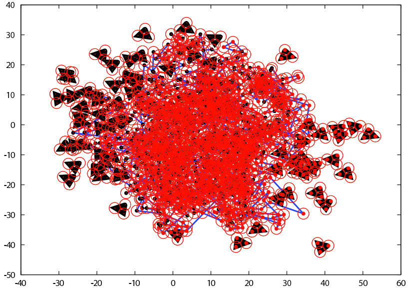
Rather small contribution from ≥ 2 gluons. (*Cf* GBW)

(Cutoff for $M_X > 50\,\mathrm{GeV}$ from the Lorentz frame used.)

3. Is diffraction important in collisions with nuclei?

DIPSY gives full partonic picture for the initial state: a dense gluon soup.

Ex.: $Pb-Pb$ 200 GeV/N



Accounts for:

- saturation within the cascades,
- correlations and fluctuations in partonic state,
- coherence effects between nucleons,
- finite size effects

pA collisions

Glauber model:

Frequently used in analyses of experimental data

e.g. # “wounded” nucleons and # binary *NN* collisions

Projectile proton at impact param. **b**, hitting

Nucleus target with nucleon positions $\mathbf{b}_\nu$ $(\nu = 1,\ \ldots,\ A)$

In **b**-space rescattering is given by a product:

⇒ S-matrix factorizes: $S^{(pA)}(\mathbf{b}) = \prod_{\nu=1}^{A} S^{(pp,\nu)}(\mathbf{b}-\mathbf{b}_\nu)$

⇒ Elastic amplitude:

$$T^{(pA)}(\mathbf{b}) = 1 - S^{(pA)}(\mathbf{b}) = 1 - \prod_\nu \{1 - T^{(pp,\nu)}(\mathbf{b}-\mathbf{b}_\nu)\}$$

Gribov corrections

A proton may fluctuate between different diffractive eigenstates

- The projectile is frozen in the *same state*, k, during the passage through the nucleus

- The target nucleons are in *different*, uncorrelated states l_ν.

$\Rightarrow$ Elastic pA scattering amplitude:

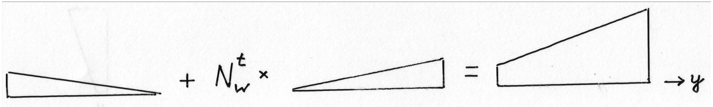
$$\langle\, T^{(pA)}(\mathbf{b})\,\rangle = 1 - \langle\,\langle\,\prod_\nu\,\langle\,\{1 - T^{(pp,\nu)}_{k,l_\nu}(\mathbf{b}-\mathbf{b}_\nu)\}\,\rangle_{l_\nu}\,\rangle_{\mathbf{b}_\nu}\,\rangle_k$$

with $\quad d\sigma^{pA}_{tot}/d^2b = 2\,\langle T^{(pA)}(\mathbf{b})\rangle, \quad d\sigma^{pA}_{el}/d^2b = \langle T^{(pA)}(\mathbf{b})\rangle^2$

Note: Only first power of T in average over target states,
but high powers in average over projectile states

Specification of wounded nucleons

Wounded nucleon model (Białas *et al.*)



Central particle density $\frac{dN^{pA}}{d\eta} \approx \frac{1+N_w^t}{2}\frac{dN^{pp}}{d\eta}$

Should diffractively excited target nucleons count as wounded?

Yes, for forward observables

and centrally if $\sigma_{SD}/dM_X^2 \sim dM_X^2/(M_X^2)^{1+\epsilon}$, with $\epsilon \approx 0$

No for central observables, if ϵ is large ($\sim$ 0.2)

Wounded nucleon cross sections

a) Wounded nucleons = inel. non diffr. (absorbed) nucleons

Absorption probability: $d\sigma_{abs}/d^2b = 1 - S^2$

S^2 also factorizes

Absorptive cross section:

$$d\sigma^{pA}_{abs}/d^2b = \langle 1 - \prod_\nu (S^{(pp,\nu)})^2 \rangle =$$

$$= 1 - \langle \prod_\nu \langle \{1 - T^{(pp,\nu)}(\mathbf{b} - \mathbf{b}_\nu)\}^2 \rangle_{l_\nu} \rangle_k$$

Involves target average of $T^{(pp)}$ squared: $\langle T^{(pp)2} \rangle_{targ}$

b) Inclusively wounded nucleons

$$d\sigma^{pA}_{winc}/d^2b = 1 - \langle \prod_\nu \{1 - \langle T^{(pp,\nu)}(\mathbf{b} - \mathbf{b}_\nu) \rangle^2_{l_\nu} \} \rangle_k$$

Only first power of T in target average

Frequently used approximations

(i) Black disk model: $T^{pp}(b) = \theta(R - b)$

Single parameter R $\Rightarrow$ $\sigma^{pp}_{abs} = \sigma^{pp}_{el} = \sigma^{pp}_{tot}/2$

$\Rightarrow$ Diffraction completely neglected

R chosen to reproduce $\sigma^{pp}_{inel,tot}$ $\Rightarrow$ σ^{pA}_{tot} overestimated

R reproducing σ^{pp}_{tot} $\Rightarrow$ σ^{pA}_{inel} underestimated

(ii) Gray disk model:

Projectile absorbed with prob. a, for $b < R$

Somewhat better,
but not possible to distinguish SD_{target}, SD_{proj}, and DD

The model by Strikman and coworkers

Blättel *et al.* 1993, sometimes called the GG model; often used in LHC exp.

Accounts for a fluctuating projectile
but not fluctuating target nucleons

Notation:
Fluctuating *pp* total cross section, averaged over target states:

$$\hat{\sigma}_{tot} = 2\int d^2b \, \langle \, T^{(pp)}(b) \, \rangle_{targ}$$

Average also over projectile states $\Rightarrow \sigma_{tot}^{(pp)} = \langle \hat{\sigma}_{tot} \rangle_{proj}$

Ansatz: $$\frac{dP}{d\,\hat{\sigma}_{tot}} = \rho \, \frac{\hat{\sigma}_{tot}}{\hat{\sigma}_{tot} + \sigma_0^{tot}} \exp\left\{ -\frac{(\hat{\sigma}_{tot}/\sigma_0^{tot} - 1)^2}{\Omega^2} \right\}$$

Two parameters, σ_0 and Ω fix the average and width

Wounded nucleon cross sections

1) Wounded inclusive target excitations

Determined by distribution of

$$\hat{\sigma}_{inel} = \int d^2b\{\,\langle T^{(pp)(b)}\rangle_t - \langle T^{(pp)}(b)\rangle_t^2\,\}$$

The same form is used, normalized to $\sigma_{inel}^{(pp)}$

Commonly used in experiments, with tuned width parameters

Overestimates effect of wounded nucleons

2) Absorptive cross section

Depends also on the second moment over target states:

$\hat{\sigma}_{abs}$ obtained by $\langle T^{(pp)}\rangle_t^2 \rightarrow \langle T^{(pp)2}\rangle_t$

Should be normalized to the smaller absorptive cross section

Comparison with DIPSY

- DIPSY has a longer tail to large no. of wounded nucleons

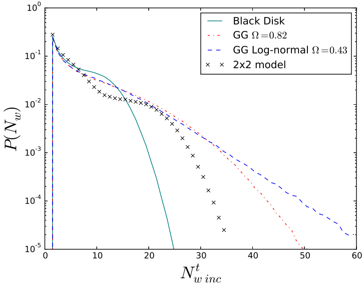
  Well fitted by a log-normal distribution

- Similar width parameter for all three distributions

  $\hat{\sigma}_{tot}, \hat{\sigma}_{inel}, \hat{\sigma}_{abs}$

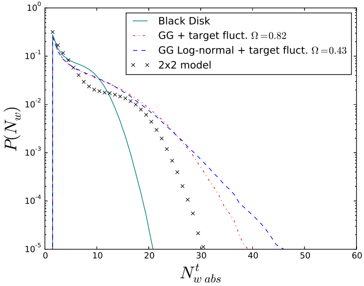
No. wounded target nucleons in pPb at 5 TeV

Inclusively wounded



$\langle N^t_{w\ incl} \rangle = 6.6$

Absorbed



$\langle N^t_{w\ abs} \rangle = 5.2$

Log-normal distr. à la DIPSY give larger tails (when tuned to same cross sections)

× ×: Simple gray disk model including also exitation of target nucleons

(C. Bierlich, GG, L. Lönnblad, arXiv:1607.04434)

Scaling by no. of wounded nucleons

$$R_{pA} = \frac{d\sigma^{pA}}{N_w\, d\sigma^{pp}}$$

often used to estimate collective effects

Normalization to σ_{inel} overestimates the no. of wounded nucleons!

4. Conclusions

The DIPSY dipole cascade model is based on BFKL dynamics with non-leading corrections and saturation.

Includes correlations and fluctuations

Gives a fair description of DIS and *pp* data, with no input pdf's

Can give the initial condition in *pA* and *AA* collisions *pA* scattering intermediate step between *pp* and *AA*

Glauber model frequently used in experimental analyses
Gribov pointed out importance of diffractive scattering
Frequently not taken into account or treated in an improper way

Diffractively excited target nucleons are important
Contribute more or less depending on the observable

If small contributions from diffractive target nucleons:
the distribution in the GG model should be normalized to
$\sigma_{inel,ND}$ and not σ_{inel}

$\Rightarrow N_w$ reduced by factor $\approx 3/4$

Extra slides

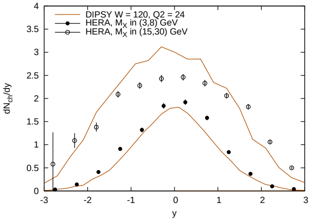
Diffractive final states in DIS and *pp*

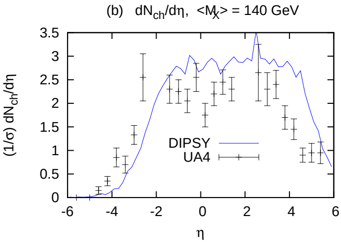
H1: $W = 120$, $Q^2 = 24$

$dn_{ch}/d\eta$ in 2 M_X-bins

UA4: $W = 546$ GeV

$\langle M_X \rangle = 140$ GeV





Too hard in proton fragmentation end. Due to lack of quarks in proton wavefunction

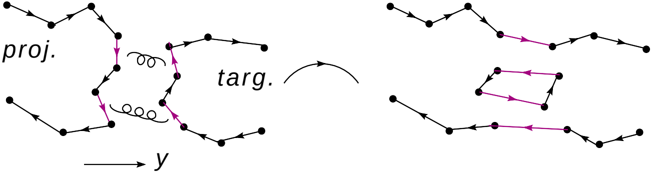
Has to be added in future improvements

Note: Based purely on fundamental QCD dynamics

(JHEP 1212 (2012) 115, arXiv:1210.2407)

Saturation within evolution

Multiple interactions ⇒ colour loops ∼ pomeron loops

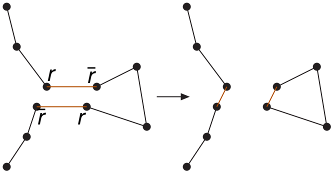


Gluon scattering is colour suppressed *cf* to gluon emission ⇒

Loop formation related to identical colours.

Multiple interaction in one frame ⇒
colour loop within evolution in another frame

Colour loop formation in a different frame



Same colour ⇒ quadrupole

May be better described by recoupled smaller dipoles

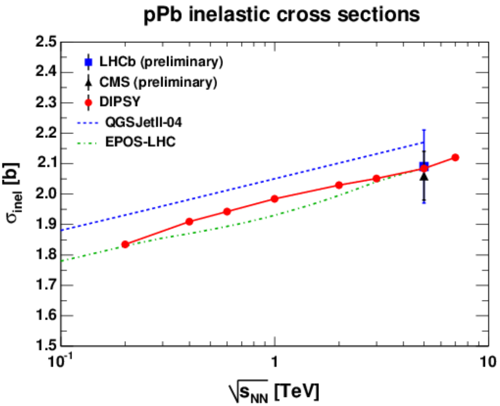
⇒ smaller cross section: fixed resolution ⇒ effective $2 \to 1$ and $2 \to 0$ transitions

Is a form of colour reconnection

Not included in Mueller's model or in BK equation

pA collisions

Test: DIPSY agrees with CMS and LHCb inelastic cross section



(GG, L. Lönnblad, A. Ster, T. Csörgő, arXiv:1506.09095)

Results for *pPb* at 5 TeV

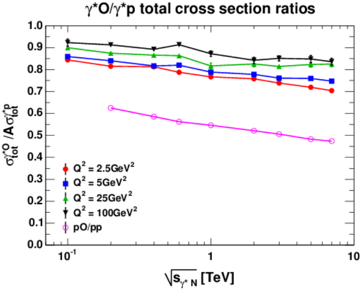
Model	DIPSY	Black disc (σ_{tot})	Black disc (σ_{in})	Black disc ($\sigma_{\text{in,ND}}$)	Grey disc ($\sigma_{\text{tot}}, \sigma_{\text{el}}$)	New disc ($\sigma_{\text{tot}}, \sigma_{\text{el}}, \sigma_{\text{DD}}, \sigma_{\text{SD}}$)
σ_{tot} (b)	3.54	3.50	3.88	3.73	3.69	3.54
σ_{in} (b)	2.04	1.95	2.14	2.06	2.07	2.02
$\sigma_{\text{in,ND}}$ (b)	1.89	1.75	1.94	1.86	1.84	1.89
σ_{el} (b)	1.51	1.55	1.73	1.66	1.62	1.55
$\sigma_{\text{SD,A}}$ (b)	0.085	0.198	0.204	0.200	0.083	0.086
$\sigma_{\text{SD,p}}$ (b)	0.023	-	-	-	-	0.031
σ_{DD} (b)	0.038	-	-	-	0.142	0.038
$\sigma_{\text{el}*}$ (b)	1.59	1.75	1.94	1.86	1.70	1.64
$\sigma_{\text{el}*}/\sigma_{\text{in}}$	0.78	0.90	0.91	0.90	0.82	0.79
$\sigma_{\text{in,ND}}/\sigma_{\text{tot}}$	0.53	0.50	0.50	0.50	0.50	0.53

GG, L Lönnblad, A Ster, T Csörgő, JHEP 1510 (2015) 022

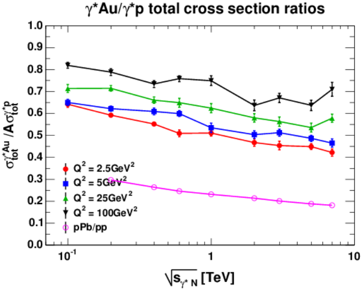
$\gamma^* A$ collisions

(Note: $\gamma^* \to q\bar{q}$ frozen during passage through nucleus)

$\gamma^* O/(A \cdot \gamma^* p)$



$\gamma^* Au/(A \cdot \gamma^* p)$



$\gamma^* A$ scales closer to $A \cdot \gamma^* p$ than pA to $A \cdot pp$

More transparent (and more so for high Q^2)

$\Rightarrow$ dynamic effects more visible

Final states in pp coll.

Comparisons to ATLAS data at 7 TeV

Min bias

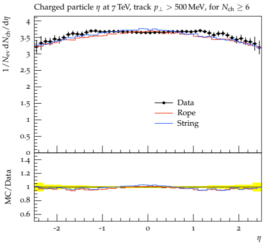
Charged particles

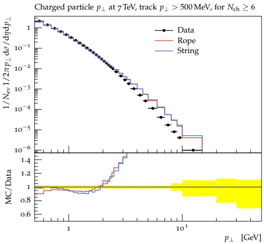
η-distrib.

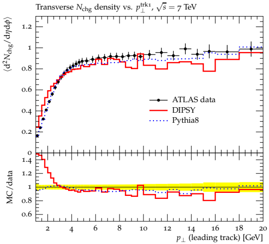
p_T-distrib.

Underlying event

N_{ch} in transv. region vs $p_\perp^{lead}$





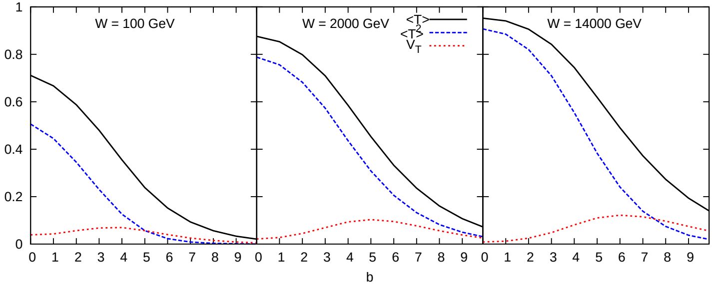


Impact parameter profile

Saturation ⇒ Fluctuations suppressed in central collisions

Diffr. excit. largest in a circular ring,

expanding to larger radius at higher energy

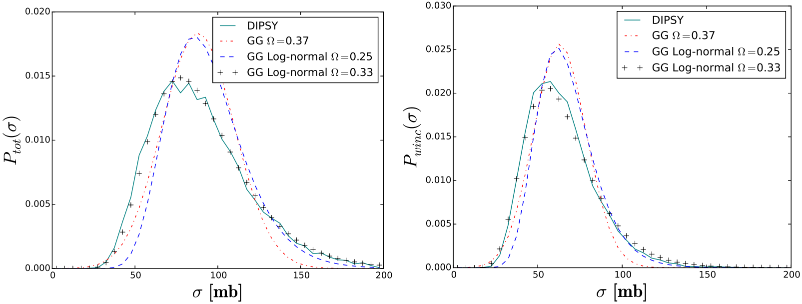


Factorization broken between *pp* and DIS

Results

(tuned to the DIPSY cross sections)

Prob. distrib. in *total* and *wounded*$_{incl}$ cross sects.



DIPSY have larger tails to large cross sections.

Well fitted by the GG formalism with a log-normal distrib.

(C. Bierlich, GG, L. Lönnblad, arXiv:1607.04434)