Effects of diffraction in *pp* and *pA* collisions

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Work in coll. with L. Lönnblad, C. Bierlich and others

Content

1. The role of pertubation theory

DIS at Hera: High parton density at small x grows $\sim 1/x^{1.3}$

Predicted by pert. BFKL pomeron

pp coll.: Models based on multiple pert. parton-parton subcollisions very successful at high energies

PYTHIA (Sjöstrand–van Zijl 1987)
HERWIG also dominated by semihard subcollisions

May be understood from unitarity constraints:

Saturation $\Rightarrow$ suppression of partons with $k_\perp < Q_s^2$ (*cf.* CGC:

When perturbative physics dominates, can the result be calculated from basic principles, without input pdf's?

2. Unitarity constraints and Eikonal approximation

Saturation most easily described in impact parameter space

Rescattering $\sim$ convolution in $\mathbf{k}_\perp$-space $\to$ product in $\mathbf{b}$-space

$\mathrm{Re}\, A_{el}^{pp}$ small $\Rightarrow$ interaction driven by absorption

Absorption probability in Born approx. = $2F(b)$ $\Rightarrow$

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

If NO fluctuations:

Optical theorem $\Rightarrow \mathrm{Im}\, A_{el} \equiv T(b) = 1 - e^{-F}$

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

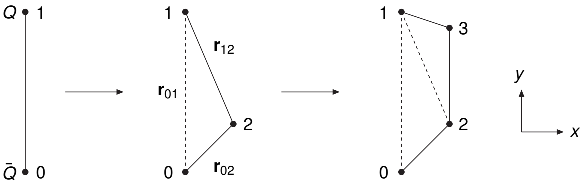
With fluctuations: $e^{-F} \to \langle e^{-F} \rangle$

3. BFKL evolution in impact param. space

a) Mueller's Dipol model:

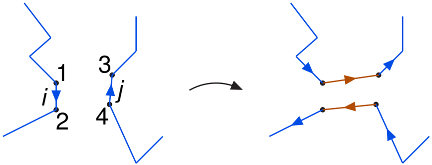
BFKL evolution in transverse coordinate space

Gluon emission: dipole splits in two dipoles:



Dipole-dipole scattering

Single gluon exhange ⇒ Colour reconnection between projectile and target



Reproduces LL BFKL evolution

BFKL stochastic process with independent subcollisions:

Multiple subcollisions handled in eikonal approximation

b) The Lund cascade model, DIPSY

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

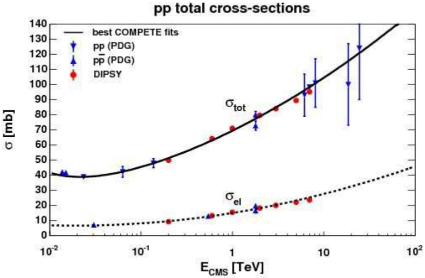
Based on Mueller's dipole model in transverse space

Includes also:

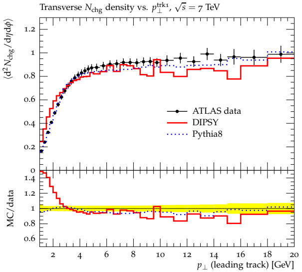
- Important non-leading effects in BFKL evol.
- Saturation from pomeron loops in the evolution
- Confinement $\Rightarrow$ t-channel unitarity
- MC DIPSY; includes also fluctuations and correlations
- Applicable to collisions between electrons, protons, and nuclei

Results *pp* scattering

Total and elastic cross sections



Underlying event:
N_{ch} in transv. region *vs* $p_\perp^{lead}$
Atlas data 7 TeV



4. Diffractive excitation

Example: A photon in an optically active medium:

Righthanded and lefthanded photons move with different velocity; they propagate as particles with different mass.

Study a beam of righthanded photons hitting a polarized target, which absorbs photons linearly polarized in the *x*-direction.

The diffractively scattered beam is now a mixture of right- and lefthanded photons.

If the righthanded photons have lower mass:

The diffractive beam contains also photons excited to a state with higher mass

pp coll.: Diffract. exc. is large $\approx 1/3\ \sigma_{inel}$ at LHC

Good–Walker formalism:

Projectile with a substructure:

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

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

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

Total diffractive cross section (incl. elastic):

$$d\sigma_{diff\ tot}/d^2b = \sum_k \langle \Psi_{in} | T | \Psi_k \rangle \langle \Psi_k | T | \Psi_{in} \rangle = \langle T(b)^2 \rangle$$

Diffractive excitation determined by the fluctuations:

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

Scattering against a fluctuating target

Total diffractive excitation:

$$d\sigma_{tot.diffr.exc.}/d^2b = \langle\, T^2 \,\rangle_{p,t} - \langle T\rangle^2_{p,t}$$

$$d\sigma_{el}/d^2b = \langle T\rangle^2_{p,t}$$

Averageing over target states before squaring

$\Rightarrow$ elastic interaction for the target.

Subtract σ_{el} $\rightarrow$ single diffr. excit.:

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

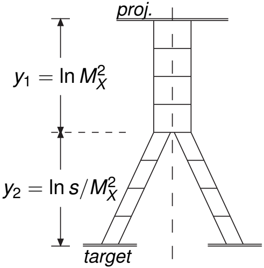
Relation Good–Walker *vs* triple-pomeron

Diffractive excitation in *pp* coll. commonly described by Mueller's triple-pomeron formalism

Stochastic nature of the BFKL cascade ⇒

Good–Walker and Triple-pomeron describe the same dynamics

(PL B718 (2013) 1054)

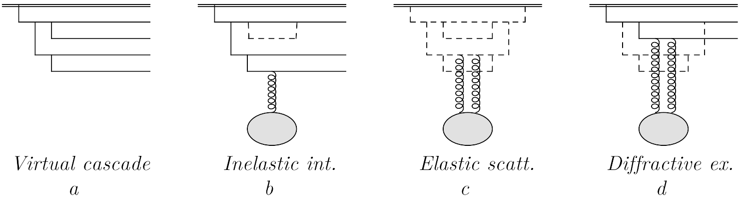


But: Saturation is easier treated in the Good–Walker formalism; in particular for collisions with nuclei

Fluctuations and diffraction

What are the diffractive eigenstates?

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



BFKL dynamics ⇒ Large fluctuations,

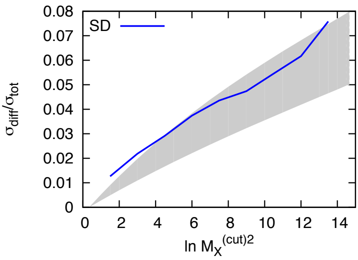
Continuous distrib. up to high masses

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

Single diffraction in *pp*

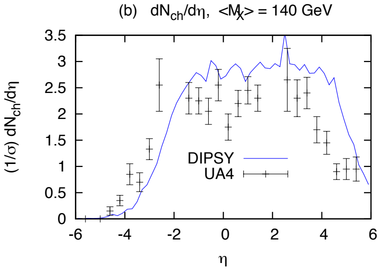
Inclusive $M_X < M_X^{(cut)}$

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

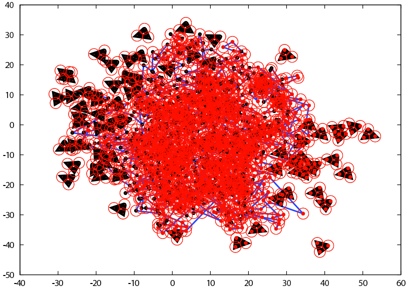
Tuned only to total and elastic cross sections

5. Collisions with nuclei

Initial state:

DIPSY gives full partonic picture, dense gluon soup.

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



Accounts for:

saturation within the cascades,

correlations and fluctuations in partonic state,

finite size effects

Understanding the initial state essential for

interpretation of collective final state effects

Models for initial state in *AA* collisions can be tested in *pA*

Study coherence effects in total, elastic,

and diffractive cross sections

Glauber model

The Glauber model is frequently used in analyses of experimental data, for estimating centrality or the initial state

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

Study a projectile proton at impact param. **b**, hitting a nucleus with nucleon positions $\mathbf{b}_\nu$ $(\nu = 1, \ldots, A)$

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

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

$\Rightarrow$ Elastic amplitude:

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

Gribov corrections

A proton may fluctuate between different diffractive eigenstates

$\Rightarrow$ diffractive excitation

- 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:

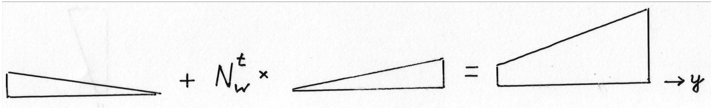
$$\langle\, T^{(pA)}(\mathbf{b})\,\rangle = 1 - \langle\, \langle\, \prod_\nu \,\langle\, \{1 - T^{(pp,\nu)}_{k,l_\nu}(\mathbf{b} - \mathbf{b}_\nu)\}\,\rangle_{l_\nu}\,\rangle_{\mathbf{b}_\nu}\,\rangle_k$$

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: High powers of pp amplitudes

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 = absorbed nucleons (inel. non diffr.)

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

S^2 also factorizes

Absorptive cross section:

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

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

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

b) Inclusively wounded nucleons

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

Only first power of T in target average

Simple approximations

Frequently used in exp. analyses

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

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

$\Rightarrow$ Diffraction completely negected

R reprod. $\sigma^{pp}_{inel,tot} \Rightarrow \sigma^{pA}_{tot}$ overestimated

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

(ii) Gray disc model:

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

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

pPb cross sections at 5 TeV (barn)

	DIPSY,	bl.d.(σ_{tot}^{pp}),	bl.d.(σ_{in}^{pp}),	gr.d.$(\sigma_{tot}^{pp}, \sigma_{el}^{pp})$
σ_{tot}	3.54	3.50	3.88	3.69
σ_{inel}	2.04	1.95	2.14	2.07
σ_{el}	1.51	1.55	1.73	1.62

Different approximations give very different results

(GG, L Lönnblad, A Ster, T Csörgő, JHEP 1510 (2015) 022, 1506.09095)

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

Ω is a parameter determining the fluctuations, related to $\sigma_{SD}^{(PP)}$

σ_0^{tot} is fixed from $\sigma_{tot}^{(pp)}$; ρ is a normalization constant.

Wounded nucleon cross section

1) Absorptive cross section

Def. $\hat{\sigma}_{abs} = \int d^2b \, \langle \{2T^{(pp)}(b) - T^{(pp)2}(b)\} \rangle_{targ}$ (*)

$\sigma_{abs}^{(pp)} = \langle \hat{\sigma}_{abs} \rangle_{proj}$

The same form is used, but Ω need not be the same:

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

Note: σ_0^{abs} ought to be adjusted to reproduce $\sigma_{inel\,ND}^{pp}$, but is often tuned to $\sigma_{inel\,tot}^{pp}$!

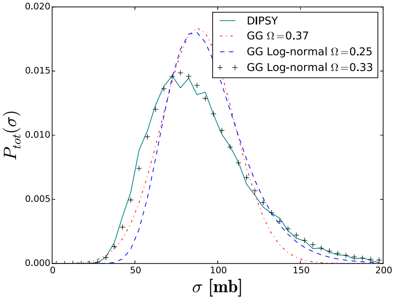
2) Wounded incl. target exc. $\Rightarrow \hat{\sigma}_{abs} \to \hat{\sigma}_w$

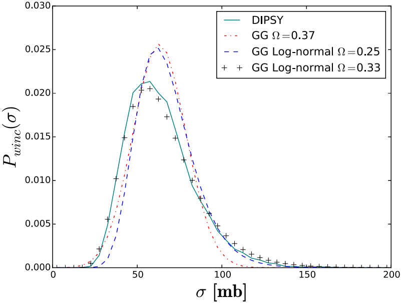
where $\langle T^{(pp)2}(b) \rangle_{targ} \to \langle T^{(pp)}(b) \rangle_{targ}^2$ in eq. (*)

DIPSY results compared with GG

(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)

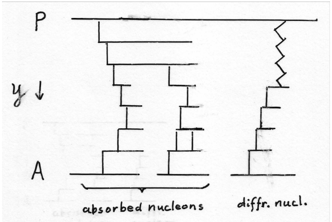
Final states

Old Fritiof model inspired by the wounded nucleon idea.
Worked well in fixed target region

Model "FritiofP8"

Secondary absorbed nucleons generated by PYTHIA8

Diffr. target nucl.: similar contrib. if $d\sigma/dM_X^2 \sim 1/M_X^2$



Compared with model called "Absorptive"

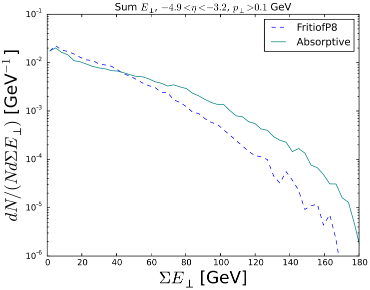
assuming all wounded target nucleons contribute like a *pp* collision at full energy. (*Cf* G-Pythia used by ALICE)

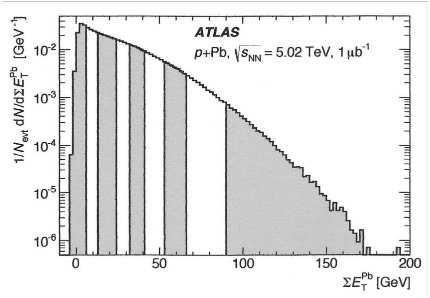
Expected to be better for high $p_\perp$ particles originating from hard parton interactions.

Results

Comparisons to ATLAS data

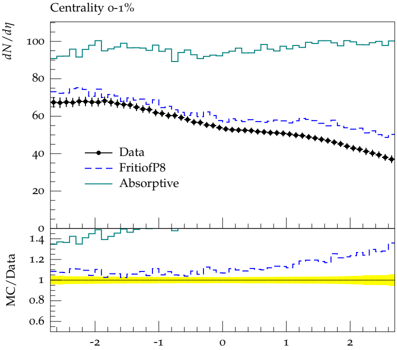
$\sum E_\perp$ in forward (nucleus) direction

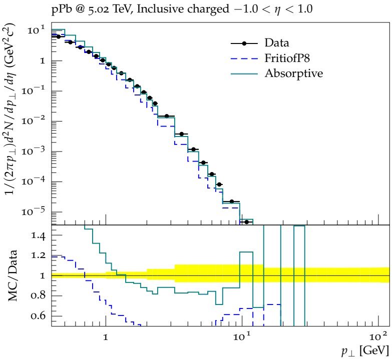




“FritiofP8” (- -) agrees well with data. “Absorptive” (—) too high.

η distrib. for central collisions $\quad$ $p_\perp$ distrib. at central rapidity





Atlas data, - - - : "FritiofP8", —: "Absorptive"

FritiofP8 works well for $p_\perp$-integrated data and for low $p_\perp$;
Absorptive better for higher $p_\perp$

7. Conclusions

Saturation suppresses low-$p_\perp$ gluons
$\Rightarrow$ high energy hadronic collisions dominantly perturbative

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 a significant fraction
Contributes more or less depending on the observable

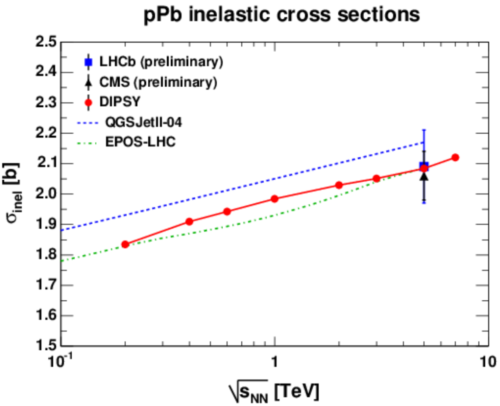
For observables not obtaining contribution from diffractive target nucleons, the distribution in the GG model should be normalized to $\sigma_{inel.ND} \approx 2/3\,\sigma_{inel}$

Simple model based on Fritiof works rather well
for min bias final states in *pA*

Extra slides

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

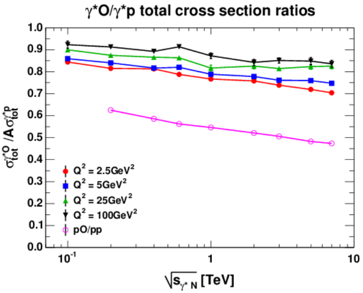
Model		DIPSY	Black disc (σ_{tot})	Black disc (σ_{in})	Black disc ($\sigma_{in,ND}$)	Grey disc ($\sigma_{tot}, \sigma_{el}$)	New disc ($\sigma_{tot}, \sigma_{el}, \sigma_{DD}, \sigma_{SD}$)
σ_{tot}	(b)	3.54	3.50	3.88	3.73	3.69	3.54
σ_{in}	(b)	2.04	1.95	2.14	2.06	2.07	2.02
$\sigma_{in,ND}$	(b)	1.89	1.75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

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

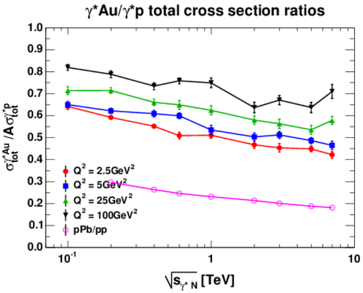
$\gamma^* A$ collisions

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

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



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



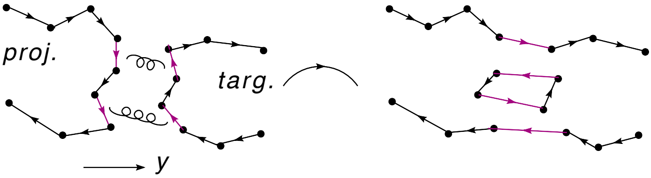
$\gamma^* p$ scaling closer to $\sim A\sigma_{tot}^{\gamma^*}$.

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

$\Rightarrow$ dynamic effects more visible

Saturation within evolution

Multiple interactions ⇒ colour loops ∼ pomeron loops

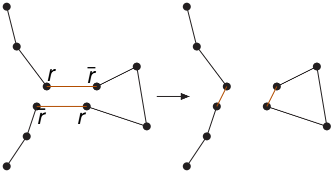


Gluon scattering is colour suppressed *cf* to gluon emission ⇒

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

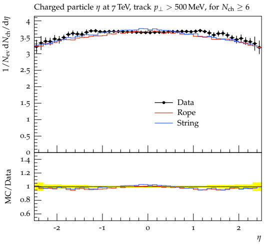
Not included in Mueller's model or in BK equation

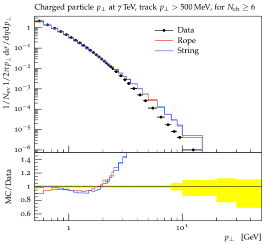
Final states

Comparisons to ATLAS data at 7 TeV

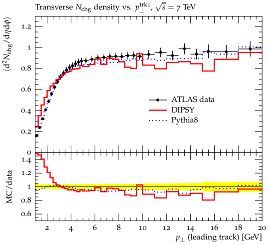
Min bias — Charged particles

η-distrib. p_T-distrib.





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

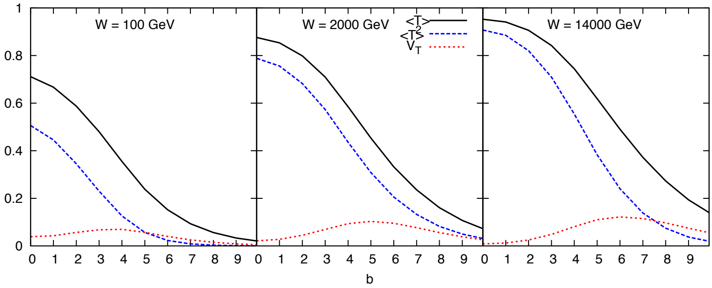


Impact parameter profile

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

Exclusive final states in diffraction

If gap events are analogous to diffraction in optics $\Rightarrow$

Diffractive excitation fundamentally a quantum effect

Different contributions interfere destructively,
no probabilistic picture

Still, different components can be calculated in a MC,
added with proper signs, and squared

Possible because opt. th. $\Rightarrow$ all contributions real

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

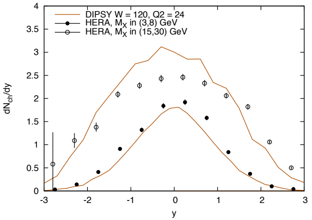
(Makes it also possible to take Fourier transform and get $d\sigma/dt$.

JHEP 1010, 014, arXiv:1004.5502)

Early results for DIS and *pp*

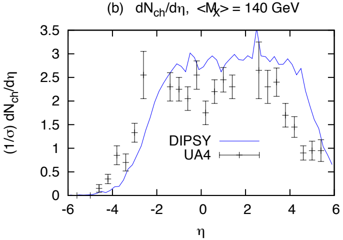
H1: $W = 120$, $Q^2 = 24$

$dn_{ch}/d\eta$ 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)

For a deuteron target this involves the averages

$$\langle\, \langle\, T^{(pp)} \,\rangle_{targ} \,\rangle_{proj} \quad \text{and} \quad \langle\, \langle\, T^{(pp)} \,\rangle^2_{targ} \,\rangle_{proj}$$

Note: The second average can be determined from

single diffractive excitation in *pp* scattering,

once the space distribution in the deuteron is known

Heavier targets involve higher moments $\langle\, \langle\, T^{(pp)} \,\rangle^n_{targ} \,\rangle_{proj}$

Can be calculated if the full distribution

$$dP/d\,\langle T^{(pp)}(b)\,\rangle_{targ}$$

is known, for all possible projectile states

Wounded nucleon distributions

a) Wounded nucleons = absorbed nucleons (not incl. diffr.)

$(S^{(pp,\nu)})^2$ = probability that target nucleon ν is not absorbed

Prob. for target nucleon ν to be absorbed by a proj. in state k:

$$1 - \langle (S_{k,l_\nu}^{pp,\nu})^2 \rangle_{l_\nu} = \langle\, 2T_{k,l_\nu}^{pp,\nu} - (T_{k,l_\nu}^{pp,\nu})^2 \,\rangle_{l_\nu}$$

b) Inclusively wounded nucleons

Prob. for target nucleon ν to be inclusively wounded:

$$1 - \langle (S_{k,l_\nu}^{pp,\nu})^2 \rangle_{k,l_\nu} = \langle\, 2T_{k,l_\nu}^{pp,\nu} \rangle_{l_\nu} - \langle T_{k,l_\nu}^{pp,\nu} \rangle_{l_\nu}^2$$