Saturation effects in small *x* Physics

Gösta Gustafson

Department of Theoretical Physics
Lund University

Low-x Workshop, Sandomierz
1 – 6 Aug., 2015
Work in coll. with L. Lönnblad, C. Bierlich and ???

Questions:

- Multiple collisions give many overlapping strings

Can they interfere and form “ropes”?
How does this affect the hadronization?

- Conclusions about hydro expansion and plasma formation
depend strongly on the initial state

How do coherence effects influence the initial partonic state?

How can this be studied in inclusive cross sections?

Content

1. The Dipole Cascade model DIPSY

2. Rope formation in *pp* collisions

3. Initial state in *pA* and $\gamma^* A$ collisions
   a. General features of *pA* and $\gamma^* A$ collisions
   b. Colour interference between different nucleons
   c. Comparisons with Glauber model

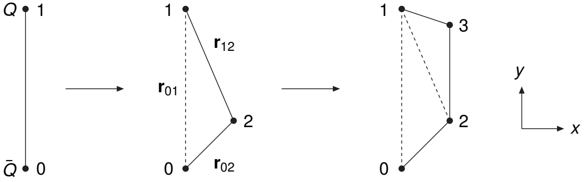
4. Conclusions

1. Dipole evolution

Mueller’s Dipol model:

LL BFKL evolution in transverse coordinate space

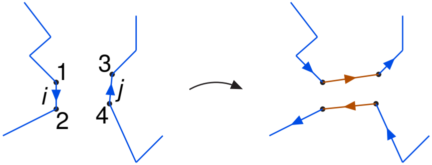
Gluon emission: dipole splits in two dipoles:



Emission probability: $\frac{d\mathcal{P}}{dy} = \frac{\bar{\alpha}}{2\pi} d^2\mathbf{r}_2 \frac{r_{01}^2}{r_{02}^2\, r_{12}^2}$

Dipole-dipole scattering

Single gluon exhange ⇒ Colour reconnection between projectile and target



Born amplitude:

$$f_{ij} = \frac{\alpha_s^2}{2} \ln^2 \left(\frac{r_{13} r_{24}}{r_{14} r_{23}} \right)$$

BFKL stochastic process with independent subcollisions:

Multiple subcollisions handled in eikonal approximation

The Lund cascade model, DIPSY

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

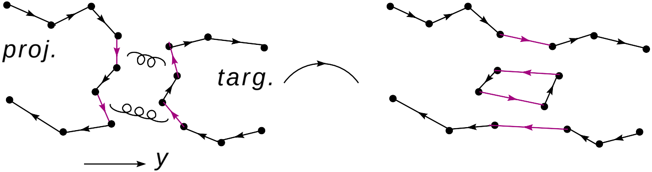
Based on Mueller's dipole model in transverse space

Includes also:

- Important non-leading effects in BFKL evol.
  (most essential rel. to energy cons. and running α_s)
- Saturation from pomeron loops in the evolution
  (Not included by Mueller or in BK)
- Confinement ⇒ t-channel unitarity
- MC DIPSY; includes also fluctuations and correlations
- Applicable to collisions between electrons, protons, and nuclei (proton $\sim$ 3 dipoles in a triangle)

Saturation within evolution

Multiple interactions ⇒ colour loops ∼ pomeron loops

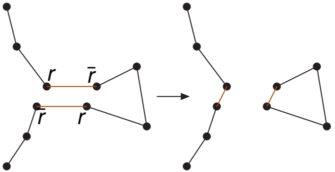


Gluon scattering is colour suppressed *cf* to gluon emission ⇒

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 $\Rightarrow$ quadrupole

May be better described by recoupled smaller dipoles

$\Rightarrow$ smaller cross section:
fixed resolution $\Rightarrow$ effective
$2 \rightarrow 1$ and $2 \rightarrow 0$ transitions

Is a form of colour reconnection

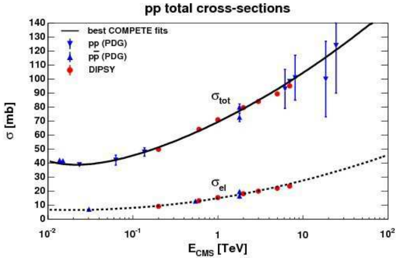
Including the "colour swing" makes the result almost frame independent

Not included in Mueller's model or in BK equation

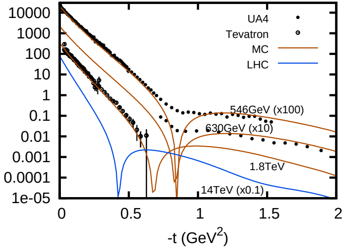
Some results from DIPSY

pp total and elastic cross sections

σ_{tot} and σ_{el}



$d\sigma/dt$



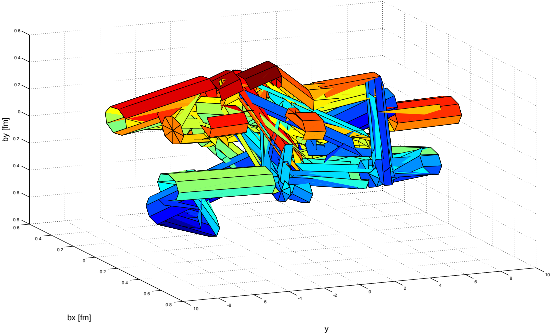
2. Final state saturation, Ropes

(C. Bierlich, GG, L. Lönnblad, A. Tarasov, arXiv:1412.6259, JHEP 2015)

Old problem: s/u ratio higher in pp than in e^+e^-
LHC: Higher fractions of strange particles and baryons

Old proposal (Biro-Nielsen-Knoll 1984):
Many strings close in transverse space may form "ropes"

DIPSY: Extension of strings in $(\mathbf{r}_\perp, y)$-space in *pp* at 7 TeV



Radius set to 0.1 fm for more clear picture

String diameter $\sim$ 1 fm $\Rightarrow$ a lot of overlap

Assume strings within a radius *R* interact coherently

Rope formation:

Add uncorrelated colour charges:
Random walk in 2-dim. colour space

Ends up in a SU(3) multiplet $\{p, q\}$:
p *coherent* triplets and q *coherent* antitriplets

Multiplicity: $\frac{1}{2}(p+1)(q+1)(p+q+2)$

Rope tension:

Lattice calc. ⇒ prop. to Casimir operator

$$C_2 \propto \frac{1}{4}(p^2 + pq + q^2 + 3p + 3q)$$

Rope fragmentation:

Assume: Stepwise break up by $q\bar{q}$ pair creation:

$$p \to p-1 \text{ or } q \to q-1 \quad \text{(in total } p+q \text{ steps)}$$

Energy released in one step gives "effective string tension"

$$\kappa_{eff}/\kappa_0 = C_2(\{p,q\}) - C_2(\{p-1,q\}) = \frac{1}{4}(2p+q+2)$$

$$\text{break up} \propto exp\left\{-\frac{\pi}{\kappa_{eff}}(\mu^2+p_\perp^2)\right\}$$

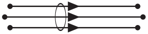
Result:

a) Fewer breaks needed to neutralize the colour charges.
(Effect similar to the recouplings in PYTHIA)

b) Higher effective string tension
⇒ more baryons – more strange particles – more $p_\perp$

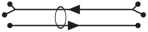
Ex.: 3 uncorrelated triplets

$\{3,0\} = 10$:



rope tension $4.5\kappa_0$; decays in 3 steps

$\{1,1\} = 8$:



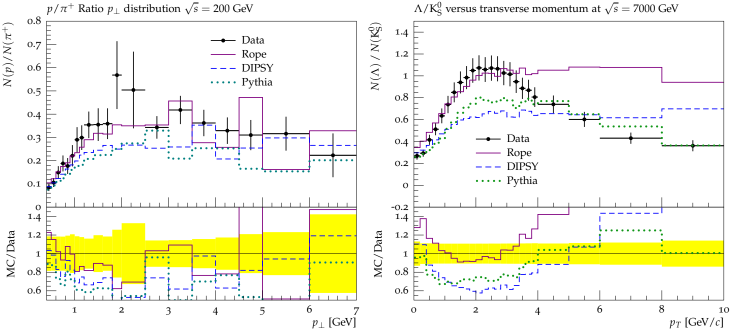
rope tension $2.25\kappa_0$; decays in 2 steps

$\{0,0\} = 1$:

no force field

Results

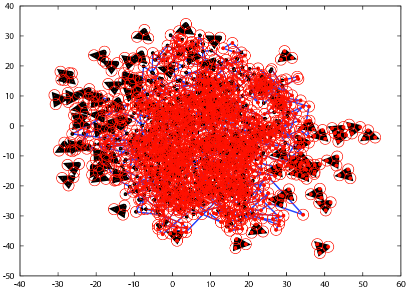
Ratios p/π and Λ/K_s^0 *vs* $p_\perp$ at 200 GeV. Data from STAR.



3. Collisions with nuclei

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

Initial state in *pA* and γ^* *A* collisions

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

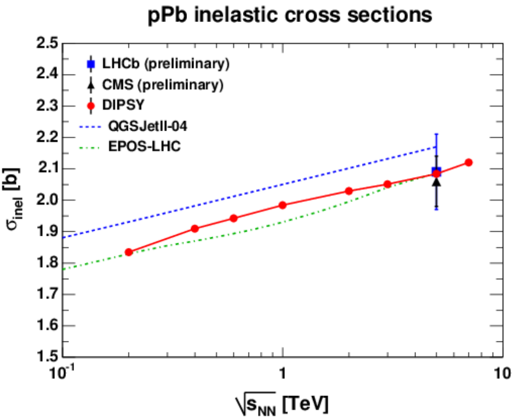
Essential for interpretation of collective final state effects

from plasma formation and hydro expansion

Study coherence effects in the initial state via

total, elastic, and diffractive cross sections

Test: DIPSY agrees with CMS and LHCb inelastic cross section

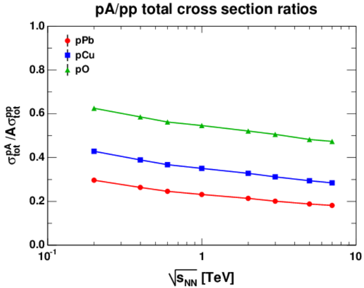


a. General features: *pA* collisions

Scaling features:

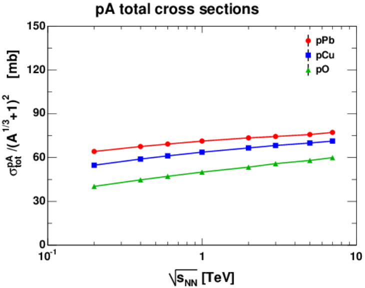
Transparent limit

$\sigma^{pA}_{tot} \approx A\,\sigma^{pp}_{tot}$



Black limit

$\sigma^{pA}_{tot} \propto (A^{1/3}+1)^2$

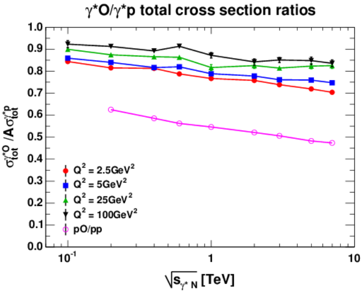


pp interaction rather close to black

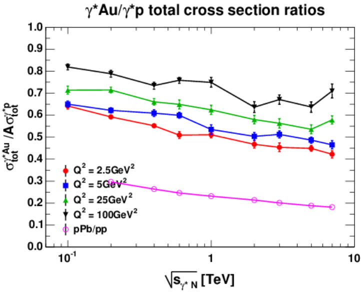
$\gamma^* A$ collisions

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

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



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



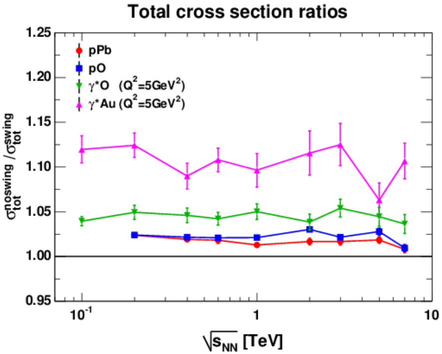
$\gamma^* p$ scaling closer to $\sim A\sigma_{tot}^{\gamma^*}$.

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

$\Rightarrow$ dynamic effects more visible

b. Colour interference between different nucleons

Ratio: $\frac{\textit{no colour interference between different nucleons}}{\textit{include colour interference}}$



Small effect for *pA*, which is close to black

$\sim$ 10% effect for $\gamma^* Au$, which is more transparent

Approximately independent of energy

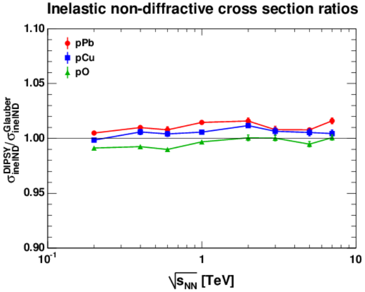
c. Comparison with Glauber model

"Black disc" approximation frequently used

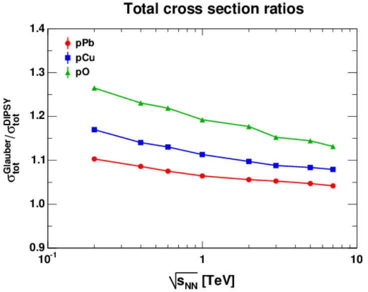
$\Rightarrow$ no diffr. excit.; $\sigma_{el} = \sigma_{inel} = \frac{1}{2}\sigma_{tot}$

Adjust disc radius to fit σ^{pp}_{inelND}:

$\sigma^{DIPSY}_{inelND} / \sigma^{Glauber}_{inelND}$



$\sigma^{DIPSY}_{tot} / \sigma^{Glauber}_{tot}$



DIPSY and Glauber agree for σ^{pA}_{inelND}, disagree for σ^{pA}_{tot}

Similarly: Glauber black disc adjusted to fit σ_{tot}^{pp}

$\Rightarrow$ agreement for σ_{tot}^{pA} but not for σ_{inelND}^{pA}

Ex.: Results for *pPb* at 5 TeV:

DIPSY: $\sigma_{tot} = 3.54$ b, $\sigma_{inelND} = 1.89$ b

Glauber: $\sigma_{tot} = 3.50$ b, $\sigma_{inelND} = 1.75$ b

Also more advanced Glauber models exist
(e.g. a gray disc or a Gaussian density distribution)

Important to know what kind of Glauber is used
How are diffractive events handled?

Conclusions

Final state interaction

Many overlapping strings also in *pp* coll. → rope formation

Random walk in colour space → random colour multiplet

Stepwise breakup by $q\bar{q}$ pairs
→ fewer breaks, higher effective string tension
(κ_{eff} given by reduction in rope tension caused by the break)
→ more strangness, more baryons

Nucleus interaction, saturation in initial state

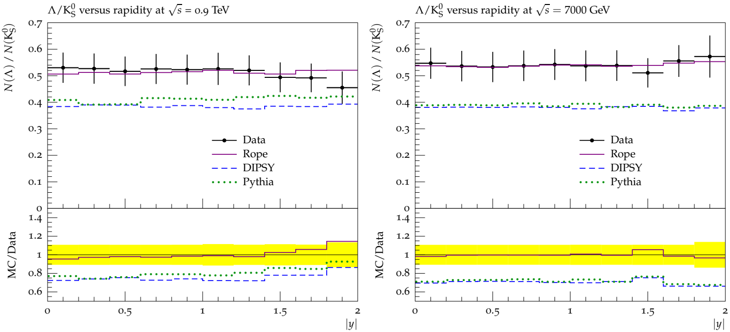
pA: rather black ⇒ small effects

$\gamma^* A$: more transparent ⇒ more clear signals

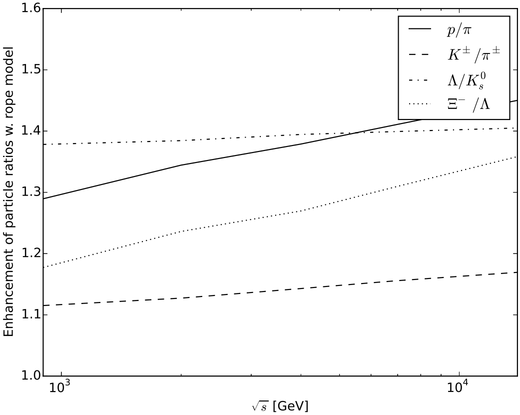
Cf with Glauber: Which Glauber version is very important, and how is diffraction handled?

Extra slides

Λ/K_s^0 ratio *vs* rapidity at 0.9 and 7 TeV. Data from CMS



Enhancement of particle ratios *vs* $\sqrt{s}$.



Final states

cf. ATLAS data

Min bias

Underlying event

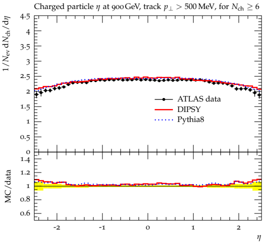
η distrib. charged particles

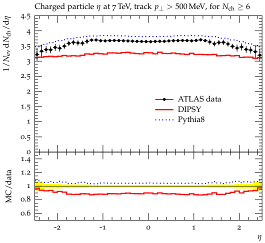
0.9 TeV

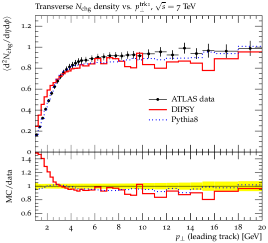
7 TeV

N_{ch} in transv. region

vs $p_\perp^{lead}$, 7 TeV


Charged particle η at 900 GeV, track $p_\perp > 500$ MeV, for $N_{ch} \geq 6$


Charged particle η at 7 TeV, track $p_\perp > 500$ MeV, for $N_{ch} \geq 6$


Transverse N_{chg} density vs. $p_\perp^{trk1}$, $\sqrt{s} = 7$ TeV

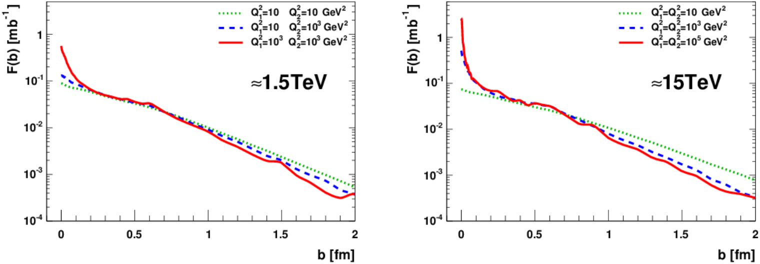
Our aim to get dynamical insight, not to give precise predictions

At present no quarks, only gluons

Correlations

Double parton distributions

Correlation function $F(b)$. Depends on both x and Q^2



Spike (hotspot) developes for small b at larger Q^2

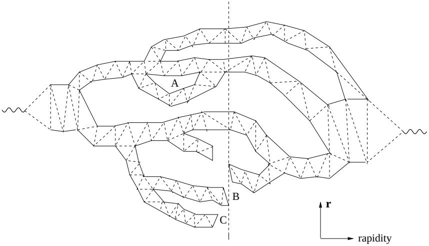
Fourier transform: $D(x_1, x_2, Q_1^2, Q_2^2; \vec{\Delta})$ (Blok *et al.*)

Spike for small $b \Rightarrow$ tail for large momentum imbalance Δ

Saturation in final state interaction

Exclusive final states

BFKL is a stochastic process:
Independent dipole-dipole interactions



Non-interacting branches cannot come on shell

have to be removed

To get final states:

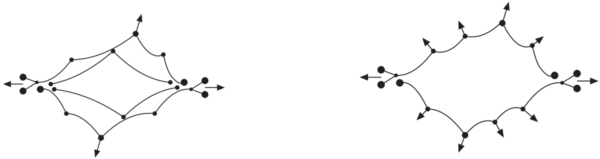
- Determine which dipoles interact
- Absorbe non-interacting chains
- Determine final state radiation

Hadronization

Multiple collisions gives many gluons connected by strings.

⇒ Saturation effects before hadronization

PYTHIA: Colour reconnection gives gluons connected by "short strings"



DIPSY: Reconnections in final state similar to the swing in initial cascade

Finally adding hadronization gives final states

Diffraction

Fluctuations cause Diffractive excitation
Good–Walker formalism

Projectile with a substructure

Mass eigenstates, Ψ_k, can differ from
the eigenstates of diffraction, Φ_n

Elastic amplitude: $\langle \Psi_{in} | T | \Psi_{in} \rangle = \langle T \rangle$, $\quad d\sigma_{el}/d^2b = \langle T \rangle^2$

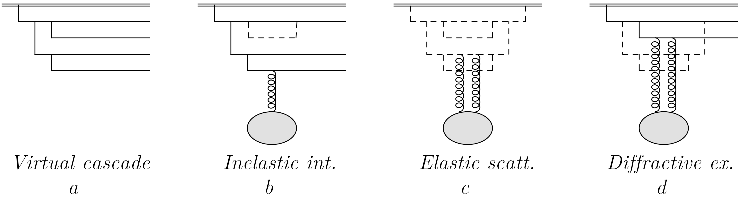
Total diffractive cross section (incl. elastic):

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

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

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

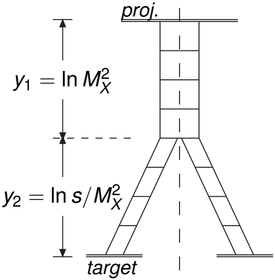
(Also Miettinen–Pumplin (1978), Hatta *et al.* (2006))

Relation Good–Walker *vs* triple-pomeron

Stochastic nature of the BFKL cascade $\Rightarrow$

Good–Walker and Triple-pomeron describe the same dynamics

(PL B718 (2013) 1054)



Without saturation:
DIPSY results have the expected triple-regge form

$$\frac{d\sigma_{SD}}{d\ln M^2} \sim g_{pP}^3 g_{3P} \left(\frac{s}{M^2}\right)^{2(\alpha_P-1)} (M^2)^{\alpha_P-1}$$

Born amplitude reproduced with single pomeron pole

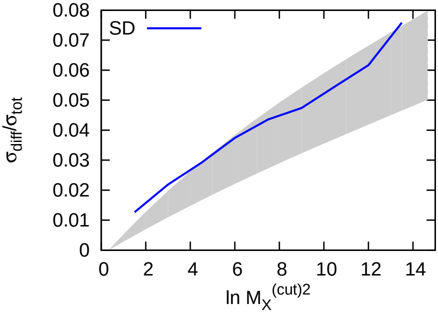
$$\alpha(0) = 1.21, \quad \alpha' = 0.2\,\text{GeV}^{-2}$$

Include saturation in the MC

pp 1.8 TeV

Single diffractive cross section for $M_X^2 < M_{max}^2$

Shaded area: Estimate of CDF result



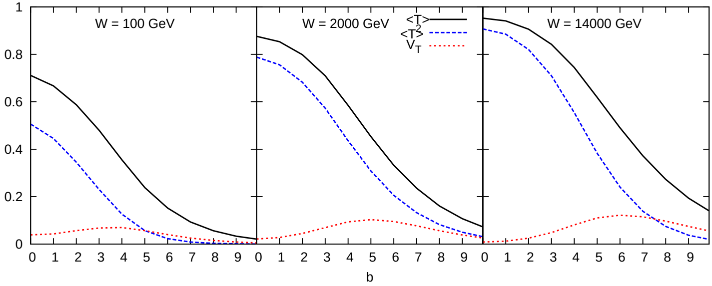
Note: Tuned only to $\sigma_{\rm tot}$ and $\sigma_{\rm el}$. No new parameter

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 ⇒

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. ⇒ all contributions real

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

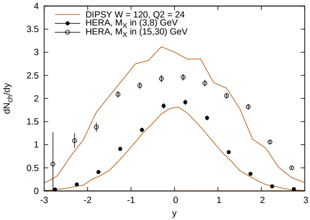
(Makes it also possible to take Fourier transform and get $d\sigma/dt$.

JHEP 1010, 014, arXiv:1004.5502)

Early results for DIS and *pp*

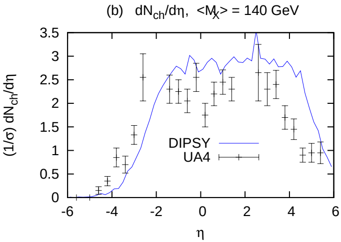
H1: $W = 120$, $Q^2 = 24$

$dn_{ch}/d\eta$ 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)