PYTHIA and DIPSY

MPI, small x, correlations, and diffraction

in pp collisions

Gösta Gustafson

Department of Theoretical Physics
Lund University

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Content

1. PYTHIA MC (T. Sjöstrand):
Very good description of inelastic reactions in DIS and *pp*

Needs input structure functions determined by data

Simplified assumptions about correlations and diffraction

2. DIPSY (C. Flensburg, GG, L. Lönnblad):
Understand underlying dynamics in more detail
(at the cost of lower precision)

Evolution of parton densities to small x

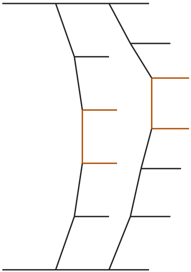
Correlations and fluctuations

Diffraction

(Nucleus coll.)

PYTHIA

Assume interaction dominated by perturbative parton-parton subcollisions



Color charge screened $\Rightarrow$
small $p_\perp$ suppressed in hard subcollisions

$$\frac{d\hat{\sigma}}{dp_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \rightarrow \frac{\alpha_s^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2}$$

Higher energy $\Rightarrow$ higher parton density
$\Rightarrow$ stronger screening

$$p_{\perp 0}(E_{\mathrm{CM}}) = p_{\perp 0}^{\mathrm{ref}} \times \left(\frac{E_{\mathrm{CM}}}{E_{\mathrm{CM}}^{\mathrm{ref}}}\right)^{\epsilon}$$

Matter profile in impact-parameter space

Simple Gaussian or more peaked variants

BFKL: random walk in transverse space:

x-dependent proton size

$$\rho(r,x) \propto \frac{1}{a^3(x)} \exp\left(-\frac{r^2}{a^2(x)}\right) \quad \text{with} \quad a(x) = a_0 \left(1 + a_1 \ln \frac{1}{x}\right)$$

a_1 and a_0 tuned to **rise** of σ_{ND}

$a_1 \approx 0.15 \Rightarrow a_0 \approx \mathit{constant}$, indep. of s

(Corke-Sjöstrand, JHEP 05 (2011) 009)

Convolution of two protons gives impact parameter shape

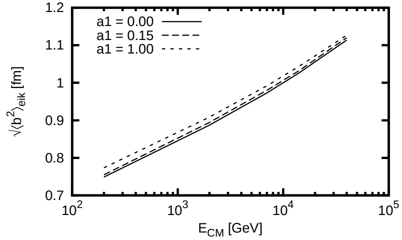
$$\tilde{\mathcal{O}}(b; x_1, x_2) = \frac{1}{\pi} \frac{1}{a^2(x_1) + a^2(x_2)} \exp\left(-\frac{b^2}{a^2(x_1) + a^2(x_2)} \right)$$

$\overline{n}(b) =$ average number of interactions for passage at b

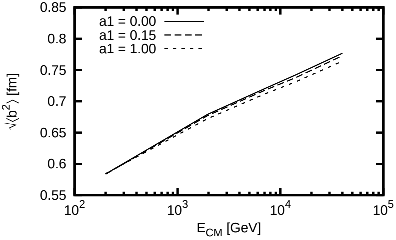
$$\overline{n}(b) = \sum_{i,j} \iiint \mathrm{d}x_1 \, \mathrm{d}x_2 \, \mathrm{d}p_\perp^2 \, f_i(x_1, p_\perp^2) \, f_j(x_2, p_\perp^2) \left. \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_\perp^2} \right|_{\mathrm{reg}} \tilde{\mathcal{O}}(b; x_1, x_2)$$

Gives $\sqrt{\langle b^2 \rangle}$ for σ_{ND} and for σ_{hard}

(b)



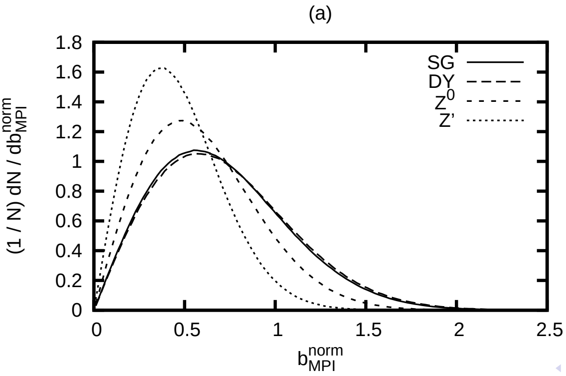
(a)



Consequence:

collisions at large x will have to happen at small b

$\Rightarrow$ further large-to-medium-x MPIs are enhanced,
while low-x partons are so spread out that it plays less role.



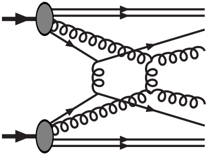
Other features

Further correlations

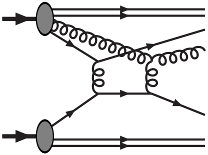
ISR and MPI compete for beam momentum $\rightarrow$ PDF rescaling
$+$ flavour effects (valence, $\mathrm{q\bar{q}}$ pair companions, ...)
$+$ correlated primordial $k_\perp$ and colour in beam remnant

Rescattering

Often assume that MPI =



...but should also include



Same order in α_s, $\sim$ same propagators, but small contribution to double scattering

Not included in default version

Interleaved evolution

Transverse-momentum-ordered parton showers for ISR, FSR, and MPI

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_\perp}\right) \times \exp\left(-\int_{p_\perp}^{p_{\perp\max}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p'_\perp}\right) \mathrm{d}p'_\perp\right)$$

Ordered in decreasing $p_\perp$ using “Sudakov” trick.

Affects the number of secondary interactions

Hard trigger

Theoretical trigger for hard interactions available in the MC

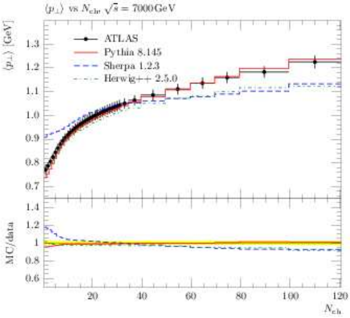
Final states: Add FSR and hadronization

Many partons close in space–time ⇒ colour rearrangement:

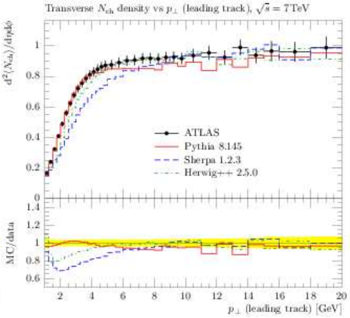
Reduction of total string length ⇒ steeper $\langle p_\perp \rangle (n_{\rm ch})$

Some results and comparisons with HERWIG++ and SHERPA:

$\langle P_\perp \rangle$ *vs* N_{ch}



Transverse $\langle N_{ch} \rangle$ *vs* $p_\perp^{lead}$



(A. Buckley et al., Phys. Rep. 504 (2011) 145 (MCnet/11/01, arXiv:1101.2599[hep-ph]))

DIPSY

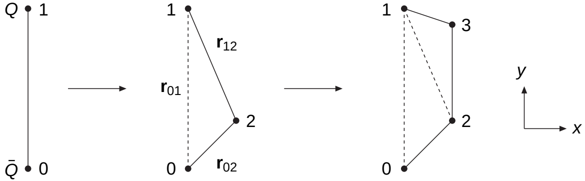
MC generator based on BFKL evolution and saturation

Based on Mueller's Dipol model:

LL BFKL evolution in transverse coordinate space

Colour charge always screened by accompanying anticharge

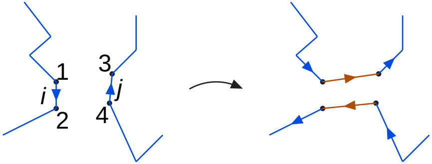
Gluon emission: dipole splits in two dipoles:



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 $\Rightarrow$ Colour reconnection between projectile and target



Born amplitude:

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

Multiple interactions:

Stochastic process $\Rightarrow$ Born ampl. $F = \sum_{ij} f_{ij}$

Unitarity: Eikonal approx. in imp. parameter space

Uniterized ampl.: $T = 1 - e^{-\sum f_{ij}}$ (neglecting fluctuations)

$d\sigma_{el}/d^2b = T^2, \qquad d\sigma_{tot}/d^2b = 2T$

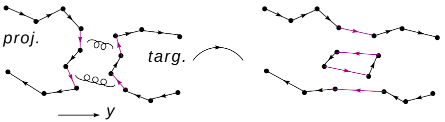
The Lund cascade model, DIPSY

Includes:

- 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 $\Rightarrow$ t-channel unitarity
- MC DIPSY
  gives also fluctuations and correlations
- Applicable to collisions between electrons, protons, and nuclei

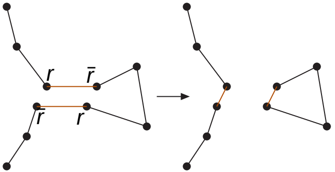
Saturation

Multiple interactions ⇒ colour loops ∼ pomeron loops



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

Gluon scattering is colour suppressed compared to gluon emission ⇒ Loop formation related to identical colors.



Same colour ⇒ quadrupole

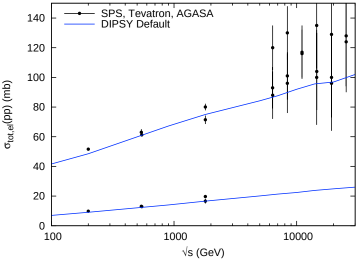
May be better described by recoupled smaller dipoles

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

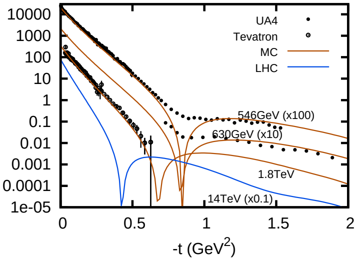
pp total and elastic cross sections

Initial proton wavefunction ∼ three dipoles in a triangle

σ_{tot} and σ_{el}

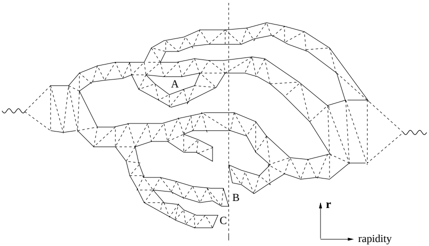


$d\sigma/dt$



Exclusive final states

Schematic picture: BFKL is a stochastic process:
independent dipole-dipole interactions



Non-interacting branches cannot come on shell.

To get final states:

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

Comparisons to ATLAS data

[JHEP 2011, arXiv:1103.4321]

Min bias

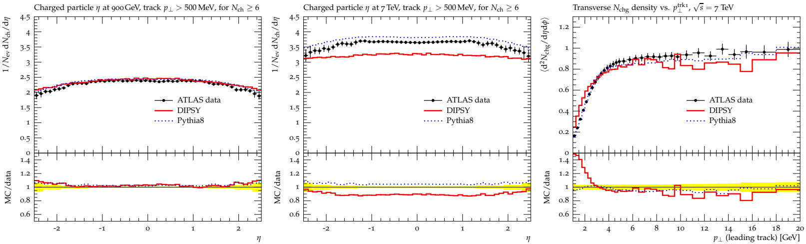
η distrib. charged particles

0.9 TeV   7 TeV

Underlying event

N_{ch} in transv. region

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



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

At present no quarks, only gluons

Correlations. Double parton distributions

Define double parton distribution and imp. param. profile F:

$$\Gamma(x_1, x_2, b; Q_1^2, Q_2^2) \equiv D(x_1, Q_1^2)\, D(x_2, Q_2^2)\;\; F(b; x_1, x_2, Q_1^2, Q_2^2),$$

and effective cross section: $\sigma^D_{(A,B)} \equiv \frac{1}{(1+\delta_{AB})} \frac{\sigma^S_A \sigma^S_B}{\sigma_{\text{eff}}}$

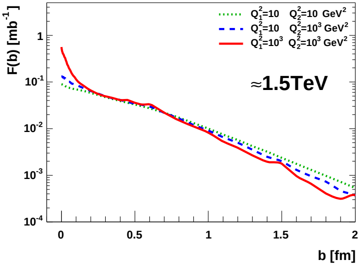
For double hard interactions at midrapidity this gives:

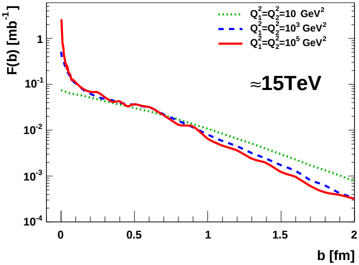
$$\sigma_{\text{eff}} = \left[\int d^2b (F(b))^2\right]^{-1}$$

F and σ_{eff} often assumed to depend only weakly on x_i and Q_i^2

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

[JHEP 2011, arXiv:1103.4320]

$\Rightarrow$ $\sigma_{\rm eff}$ depends strongly on Q^2 for fixed $\sqrt{s}$

Q_1^2	Q_2^2 [GeV^2]	x_1	x_2	$\sigma_{\rm eff}$ [mb]	$\int F$
1.5 TeV, midrapidity					
10	10	0.001	0.001	35.3	1.09
10^3	10^3	0.01	0.01	23.1	1.06
15 TeV, midrapidity					
10	10	0.0001	0.0001	40.4	1.11
10^3	10^3	0.001	0.001	26.3	1.07
10^5	10^5	0.01	0.01	19.6	1.03

Part of the correlations is due to fluctuations

No fluct. $\Rightarrow \int d^2b\, F(b) = 1$; the MC gives ~ 1.1

Fluctuations cause Diffractive excitation

Good–Walker formalism

Projectile with a substructure

The mass eigenstates, Ψ_k, can differ from
the eigenstates of diffraction, Φ_n (with eigenvalues T_n)

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

Ampl. for transition to state Ψ_k given by $\langle \Psi_k | T | \Psi_{in} \rangle$

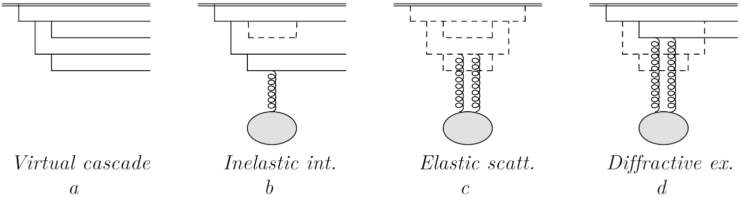
Total diffractive cross section (incl. elastic):

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

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

What are the diffractive eigenstates?

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



BFKL dynamics ⇒ Large fluctuations,

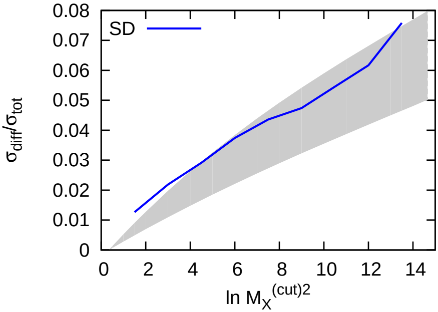
Continuous distrib. up to high masses

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

DIPSY: *pp* 1.8 TeV

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

Shaded area: Estimate of CDF result



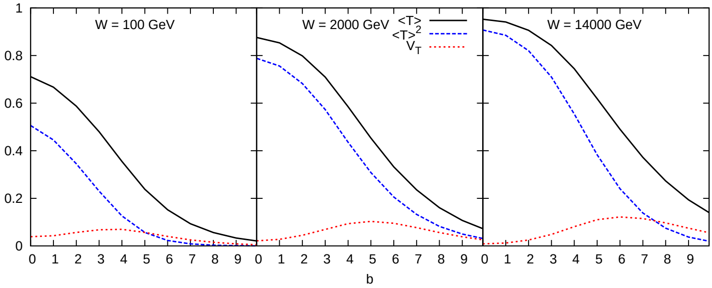
Note: Tuned only to $\sigma_{\rm tot}$ and $\sigma_{\rm el}$. No new parameter

Impact parameter profile

Saturation ⇒ Fluctuations suppressed in central collisions

Diffr. excit. largest in a circular ring,

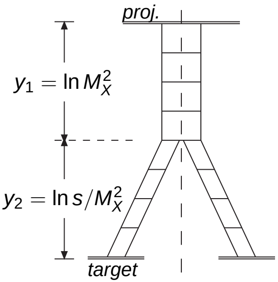
expanding to larger radius at higher energy



Factorization broken between *pp* and DIS

Relation Good–Walker *vs* triple-pomeron

Claim: Good–Walker and Triple-pomeron describe the same dynamics



Triple-pomeron:

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

Due to the stochastic nature of the BFKL cascade:

$\Rightarrow$ # dipoles satisfy approx. KNO scaling:

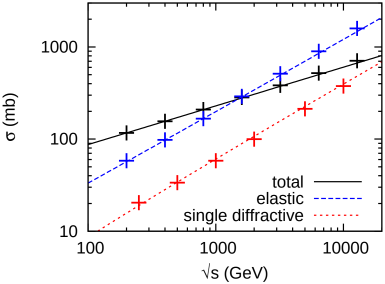
$$\sigma^2 \approx \langle n \rangle^2$$

(For more details see arXiv:1206.1733)

DIPSY results have the expected triple-regge form

BARE pomeron (Born amplitude without saturation effects)

Total, elastic and singel diffractive cross sections



Triple-Regge fit with a single pomeron pole

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

$g_{pP}(t) = (5.6\,\text{GeV}^{-1})\,e^{1.9t}, \;\; g_{3P}(t) \approx 1\text{GeV}^{-1}$ (dep. on def.)

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

[arXiv:1210.2407]

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

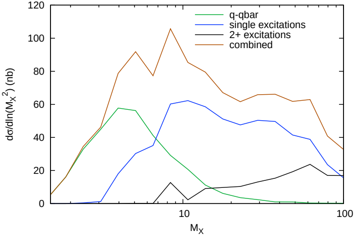
JHEP 1010, 014, arXiv:1004.5502)

Early results for DIS ($W = 120\,\mathrm{GeV},\ Q^2 = 24\,\mathrm{GeV}^2$):

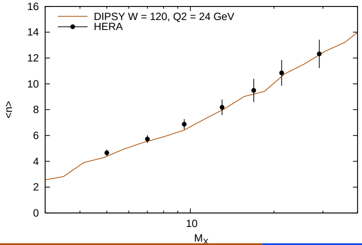
Distrib. in $\ln M_X^2$

separated in parton states with $q\bar{q} + 0$, 1, and ≥ 2 gluons

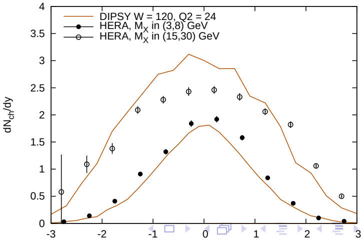
(cutoff for $M_X > 50$ GeV due to Lorentz frame used)



Hadronic state: $\langle n_{ch} \rangle$ vs M_X



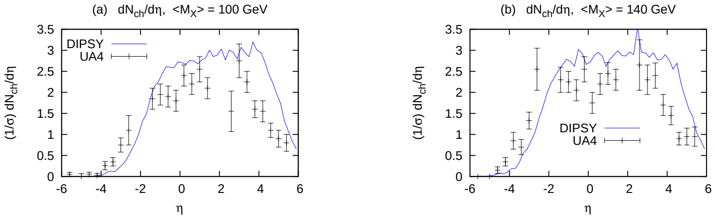
$dn_{ch}/d\eta$ in 2 M_X-bins



pp collisions:

Early result for $dn_{ch}/d\eta$ at $W = 546$ GeV,

$\langle M_X \rangle$= 100 GeV $\langle M_X \rangle$= 140 GeV



Too hard for large η. Due to lack of quarks in proton wavefunction; no forward baryon

Has to be added in future improvements

Note: Based purely on fundamental QCD dynamics

Conclusions:

1. Pythia

Recent developments related to MPI:

- x-dependent proton size
- rescattering
- Two hard trigger processes in MPI
- MPI framework for hard diffraction
- Central diffraction

Generally very good agreement with data

2. DIPSY

Can data be understood from QCD evolution and saturation?

Model with no input pdf:s, no tunable soft cutoff for hard subcollisions, no input diffractive pdf:s or pomeron flux factors

- MC gives correlations, fluctuations, and expansion in b-space
- Double parton distr. strongly dependent on Q^2 and x
- Works well for inclusive observables
- Fair description of exclusive final states (also in diffraction)
- Diffraction described in Good–Walker formalism also for high masses
- Applicable for e, p, and A collisions

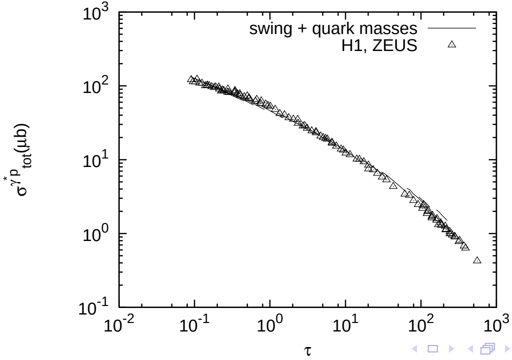
Extra slides

Structure functions

$F_2(x, Q^2) \sim \gamma^* p$ cross section

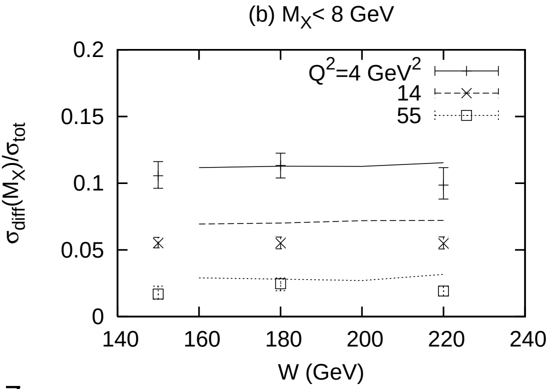
$\gamma^\star \to q\bar{q}$ dipole wavefunction from QED

Satisfies geometric scaling. $\tau = Q^2/Q_s^2(x)$, $Q_s^2 \propto x^{-0.3}$



Diffractive excitation in DIS

Example $M_X < 8$ GeV, $Q^2 = 4, 14, 55\,\mathrm{GeV}^2$.

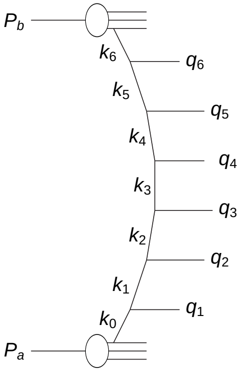


Data from Zeus

Exclusive final states

BFKL: Inclusive

In momentum space



Exclusive: CCFM

Inclusive:

Cross section determined by "back-bone" emissions, where $k_\perp$ gets a big kick: "$k_\perp$-changing emissions"

(either $k_{\perp i} \gg k_{\perp i-1}$; $q_{\perp i} \simeq k_{\perp i}$
or $k_{\perp i} \ll k_{\perp i-1}$; $q_{\perp i} \simeq k_{\perp i-1}$)
(Lund 1996, Salam 1999)

Exclusive:

Select backbone chains
Reabsorbe remaining gluons
add FSR & hadronization

Fluctuations

Fluctuations modify unitarization effects

Born ampl. $F \Rightarrow$ Uniterized ampl. $T = 1 - e^{-F}$

F fluctuates from event to event $\Rightarrow$

Elastic ampl. given by $\langle T \rangle = \langle 1 - e^{-F} \rangle \neq 1 - e^{-\langle F \rangle}$

Suppresses interaction for small b, and enhances it for larger b-values

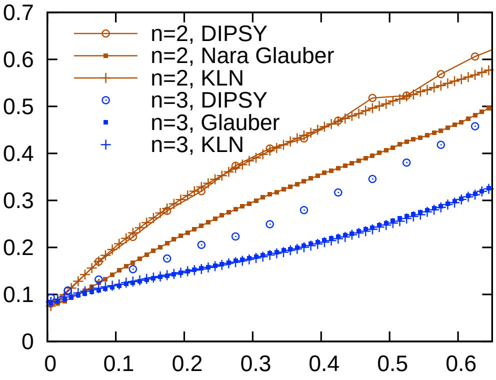
(Cf. “diffusive scaling”)

Fluctuations give also odd eccentricity moments

triangular flow in pp and AA collisions

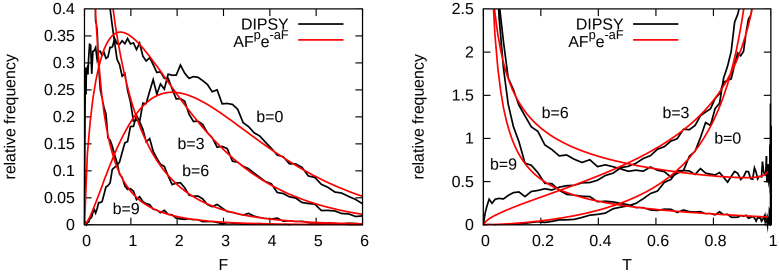
Eccentricities in PbPb coll. at $\sqrt{s_{NN}}$ = 2.76 GeV

for n = 2,3 from DIPSY, MC-KLM, and Glauber MC



Fluctuations in *pp* amplitudes

Born ampl. F $\qquad W = 2\,TeV$ $\qquad$ Uniterized ampl. $T = 1 - e^{-F}$



Born approximation: large fluctuations

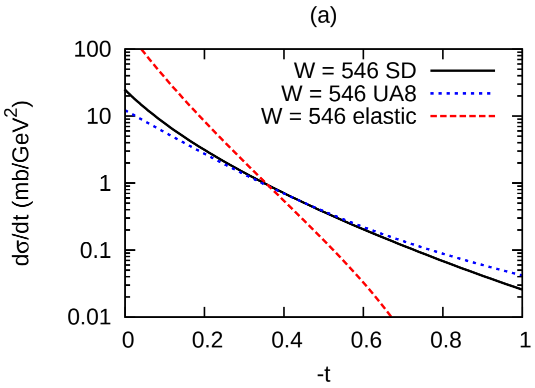
$\langle F \rangle$ is large $\Rightarrow$ Unitarity effects important

$\sim$ enhanced diagrams in triple-regge formalism

Fluctuations strongly reduced for central collisions

t-dependence

Single diffractive and elastic cross sections



Agrees with fit to UA8 data

Nonleading effects in the BFKL evolution

- Energy conservation ($\sim$ non-sing. terms in $P(z)$)

  small dipole — high $p_\perp \sim 1/r$

  Cascade ordered in p_+

  $\Rightarrow$ small dipoles suppressed for small δy

- "Energy scale terms" $\sim$ "consistency constraint"

  $\Rightarrow$ Cascade ordered in p_-

  A single chain is left-right symmetric

- Running α_s

Exclusive diffractive states

Diffraction is a quantum effect $\Rightarrow$ interference is important $\Rightarrow$ no probabilistic picture

But: positive and negative contributions to the amplitude can be generated by DIPSY, added, and squared.

Toy model example

System with a valence particle, which can emit a single gluon

2 states: valence only $\Psi_0 = |1, 0\rangle$

valence + gluon $\Psi_1 = |1, 1\rangle$

Probability for emission: β^2 prob. for no em.: $\alpha^2 = 1 - \beta^2$

General state $\Psi = a\Psi_0 + b\Psi_1 \equiv \begin{pmatrix} a \\ b \end{pmatrix}$

Assume an initial state Ψ which evolves to a cascade Φ at the time of interaction with the target

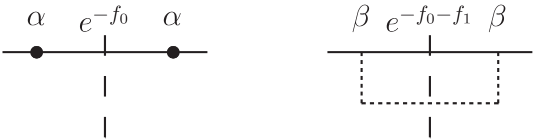
$$\Phi = U_{\mathrm{evol}}\Psi$$

Evolution operator U_{evol} is a unitary matrix $= \begin{pmatrix} \alpha & -\beta \\ \beta & \alpha \end{pmatrix}$

Eikonal interaction operator $U_{\mathrm{int}} = \begin{pmatrix} e^{-f_0} & 0 \\ 0 & e^{-f_0-f_1} \end{pmatrix}$

$$\Psi_{out} = S\Psi_{in} = U^{\dagger}_{\mathrm{evol}} U_{\mathrm{int}} U_{\mathrm{evol}} \Psi_{in}$$

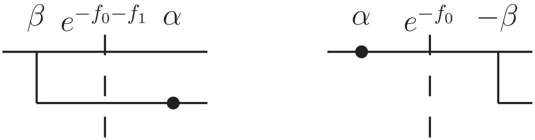
Elastic scattering:



Elastic amplitude

$$T_{11} = 1 - S_{11} = 1 - \alpha^2 e^{-f_0} - \beta^2 e^{-f_0-f_1} =$$
$$\alpha^2(1 - e^{-f_0}) + \beta^2(1 - e^{-f_0-f_1})$$

Diffractive excitation:

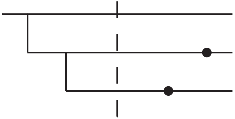


$$T_{21} = -S_{21} = -\alpha\beta e^{-f_0-f_1} - \alpha(-\beta)e^{-f_0} = \alpha\beta e^{-f_0}(1 - e^{-f_1})$$

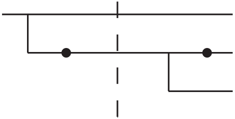
Cascade with 2 possible emissions

Ex.: Final state with both emissions

$\beta_1 \beta_2 e^{-f_0-f_1-f_2} \alpha_2 \alpha_1$

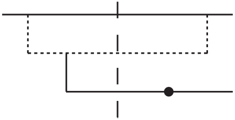


$\beta_1 \alpha_2 e^{-f_0-f_1} - \beta_2 \alpha_1$

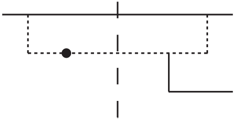


Final state with only the second emission

$\beta_1 \beta_2 e^{-f_0-f_1-f_2} \alpha_2 \beta_1$



$\beta_1 \alpha_2 e^{-f_0-f_1} - \beta_2 \beta_1$



Generalizations:

Continuous cascades

Independent gluon emissions $\rightarrow$ dipole cascade

Include target cascade

Calculations:

Collide many similar real cascades (emissions before and after interaction) which interfer

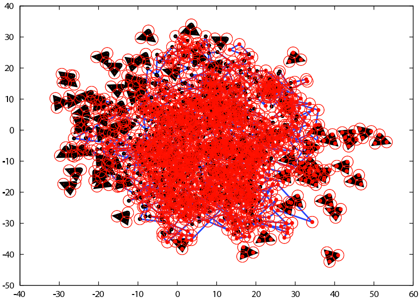
Collide with large no. of target cascades

Computationally demanding, but still possible in the MC

Nucleus collisions

Gives full partonic picture:

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



Accounts for:

saturation within the cascades,

correlations and fluctuations (gives e.g. triangular flow),

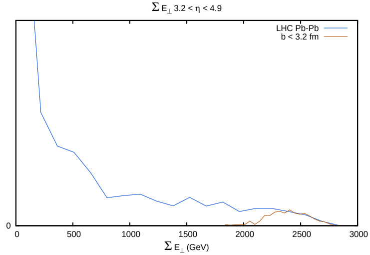
finite size effects

The interaction gives a dense gluon soup

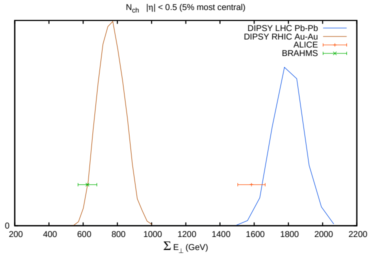
Independent FSR and hadronization $\Rightarrow$ too many particles

Toy model “thermalization”:
allow gluons within 1 fm to interact and reconnect

Forward $E_\perp$ at LHC PbPb



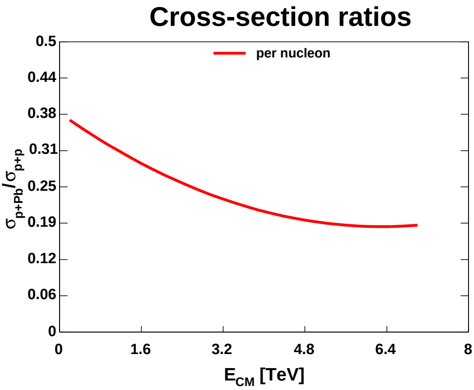
n_{ch} in $|\eta| < 0.5$ at RHIC and LHC



Future: Energy & momentum density as input for hydro expansion

pA collisions

Shadowing: $R = \sigma_{pA}/A\sigma_{pp}$



Eccentricities in PbPb coll. at $\sqrt{s_{NN}}$ = 2.76 GeV

for n = 2,3 from DIPSY, MC-KLM, and Glauber MC