Correlations and Fluctuations in High Energy Scattering

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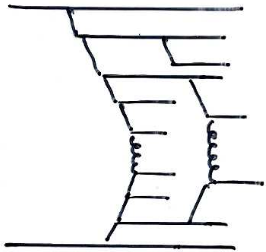
Work in coll. with C. Flensburg, L. Lönnblad, and A. Ster

High energy reactions:

Assumption: HE collisions driven by partonic subcollisions (cf. PYTHIA)

Small x: BFKL evolution



High parton density:
fluctuations, correlations
and saturation important

Observable effects:
- Multiple interactions
- Diffraction

Mult. int. more easily treated in impact parameter space

Study effects of correlations & fluctuations in a model based on BFKL evolution and saturation

Content

1. Double parton distributions
2. Diffractive excitation
3. Dipole cascade models
   a) Mueller's dipole cascade
   b) Lund dipole cascade model
4. Results
   a) Correlations in double parton distributions
   b) Diffractive excitation
5. Preliminary results for final states
   a) *pp* collisions
   b) Nucleus collisions
6. Summary

1. Double parton distribution

$\Gamma_{ij}(x_1, x_2, b; Q_1^2, Q_2^2)$

$$\sigma^D_{(A,B)} = \frac{m}{2} \sum_{i,j,k,l} \int \Gamma_{ij}(x_1, x_2, b; Q_1^2, Q_2^2)\, \hat{\sigma}^A_{ik}(x_1, x_1')\, \hat{\sigma}^B_{jl}(x_2, x_2')$$
$$\times \Gamma_{kl}(x_1', x_2', b; Q_1^2, Q_2^2)\, dx_1 dx_2 dx_1' dx_2' d^2b$$

MC: PYTHIA, HERWIG:

$$\Gamma_{ij}(x_1, x_2, b; Q_1^2, Q_2^2) = D^i(x_1, Q_1^2)\, D^j(x_2, Q_2^2)\, F(b),$$

+ adjustment from energy conservation

$$\Rightarrow \quad \sigma^D_{(A,B)} = \frac{1}{1+\delta_{AB}} \frac{\sigma_A^S \sigma_B^S}{\sigma_{\text{eff}}} \quad \text{with} \quad \sigma_{\text{eff}} = \left[\int d^2b (F(b))^2\right]^{-1}$$

Gaunt–Stirling: This violates DGLAP evolution

Propose ansatz:

$$\Gamma_{ij}(x_1, x_2, b; Q_1^2, Q_2^2) = D^{ij}(x_1, x_2; Q_1^2, Q_2^2) F_j^i(b)$$

More general: Define $F(b; x_1, x_2, Q_1^2, Q_2^2)$ by the relation

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

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

depends on x_1, x_2, Q_1^2, and Q_2^2

Correlation effects

Hot spots

Smaller regions with higher parton density expected for small x and/or large Q^2.

$\Rightarrow \sigma_{\rm eff} = \left[\int d^2b(F(b))^2\right]^{-1}$ is reduced and σ^D increases

But this effect is counteracted by the increase of F for more typical b-values.

Fluctuations

Without fluctuations F would be normalized to $\int F(b)\,d^2b = 1$

With fluctuations, but no other effects, F is normalized to

$\int F(b)\,d^2b = \frac{\langle n^2\rangle}{\langle n\rangle^2} > 1$ with $n = \#$ partons

This also enhances σ^D

2. Diffractive excitation

Eikonal approximation

Diffraction and saturation more easily described in impact parameter space

Scattering driven by absorption into inelastic states i, with weights $2f_i$

Structureless projectile

Optical theorem $\Rightarrow$

Elastic amplitude $T = 1 - e^{-F}$, with $F = \sum f_i$

$$\begin{cases} d\sigma_{tot}/d^2b \sim 2T \\ \sigma_{el}/d^2b \sim T^2 \\ \sigma_{inel}/d^2b \sim 1 - e^{-\sum 2f_i} = \sigma_{tot} - \sigma_{el} \end{cases}$$

Good – Walker

If the projectile has an internal structure, the mass eigenstates can differ from the eigenstates of diffraction

Diffractive eigenstates: Φ_n; Eigenvalue: T_n

Mass eigenstates: $\Psi_k = \sum_n c_{kn}\Phi_n$ $(\Psi_{in} = \Psi_1)$

Elastic amplitude: $\langle\Psi_1|T|\Psi_1\rangle = \sum c_{1n}^2 T_n = \langle T\rangle$

$d\sigma_{el}/d^2b \sim (\sum c_{1n}^2 T_n)^2 = \langle T\rangle^2$

Amplitude for diffractive transition to mass eigenstate Ψ_k:

$\langle\Psi_k|T|\Psi_1\rangle = \sum_n c_{kn} T_n c_{1n}$

$d\sigma_{diff}/d^2b = \sum_k \langle\Psi_1|T|\Psi_k\rangle\langle\Psi_k|T|\Psi_1\rangle = \langle T^2\rangle$

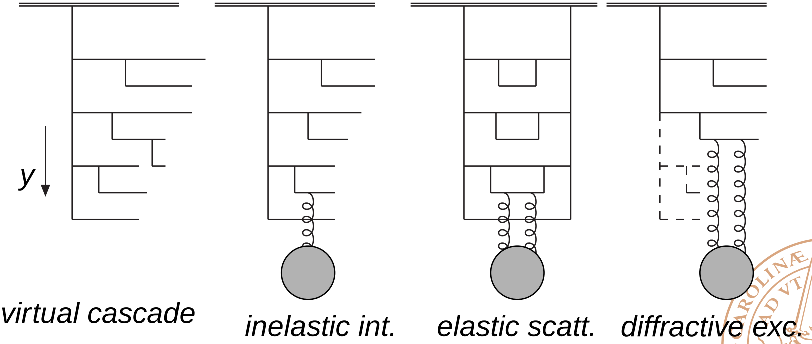
Diffractive excitation determined by the fluctuations:

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

Proton substructure: parton cascade

Depends on energy, *i.e.* on Lorentz frame

Can fill a large rapidity range ⇒ high mass excitation possible



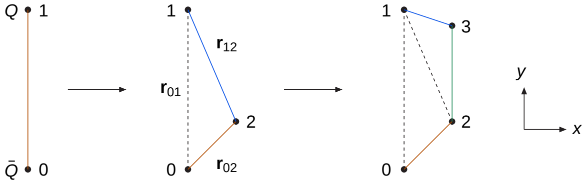
Cf. Miettinen–Pumplin (1978), Hatta *et al.* (2006)

3. Dipole cascade models

a. Mueller Dipole Model:

A color charge is always associated with an anticharge

Formulation of LL BFKL in transverse coordinate space



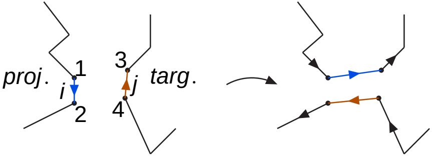
Emission probability: $\frac{d\mathcal{P}}{dy} = \frac{\bar{\alpha}}{2\pi} d^2\mathbf{r}_2 \frac{r_{01}^2}{r_{02}^2 r_{12}^2}$

Color screening: Suppression of large dipoles

$\sim$ suppression of small $k_\perp$ in BFKL

Dipole-dipole scattering

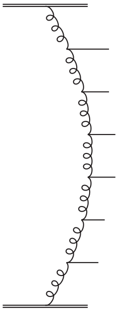
Gluon exchange
⇒ Color connection
projectile–target



Interaction probability:

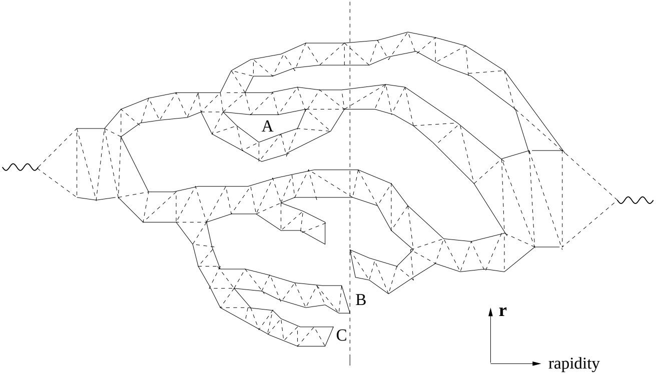
$$2f_{ij} = \alpha_s^2 \ln^2\left(\frac{r_{13}r_{24}}{r_{14}r_{23}}\right)$$

BFKL evol.:
frame independent



Largest $k_\perp$ can be anywhere in the evolution

Multiple interactions ⇒ Dipole chains and color loops



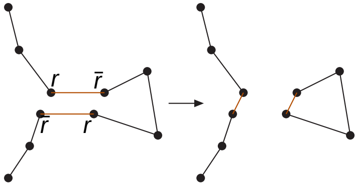
Frame independent formalism ⇒ dipole loops in the evolution

Note that

Gluon emission $\sim \bar{\alpha} = \frac{N_C}{\pi}\alpha_s$

Gluon exchange $\sim \alpha_s$. Color suppressed
$\Rightarrow$ Also loop formation color suppressed $\sim \alpha_s$

Related to identical colors.



Quadrupole $\sim$ recoupled dipole chains

Gluon exchange $\rightarrow$ same effect

b. Lund Dipole Cascade model

(Avsar–Flensburg–GG–Lönnblad)

The Lund model is a generalization of Mueller’s dipole model, with the following improvements:

- Include NLL BFKL effects
- Include Nonlinear effects in evolution (loop formation)
- Include Confinement effects

MC: DIPSY (CF, LL)

Initial state wavefunctions:

γ^*: Given by perturbative QCD. $\Psi_{T,L}(r, z; Q^2)$

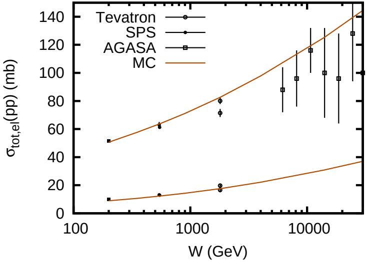
proton: Dipole triangle

2 tunable parameters: proton size and Λ_{QCD}

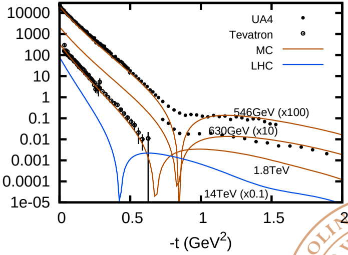
Total and elastic cross sections

pp

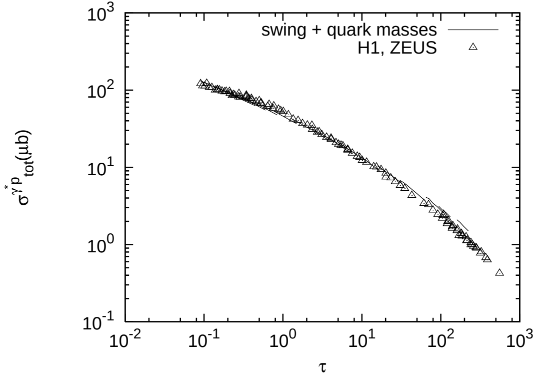
σ_{tot} and σ_{el}



$d\sigma/dt$



$\gamma^* p$

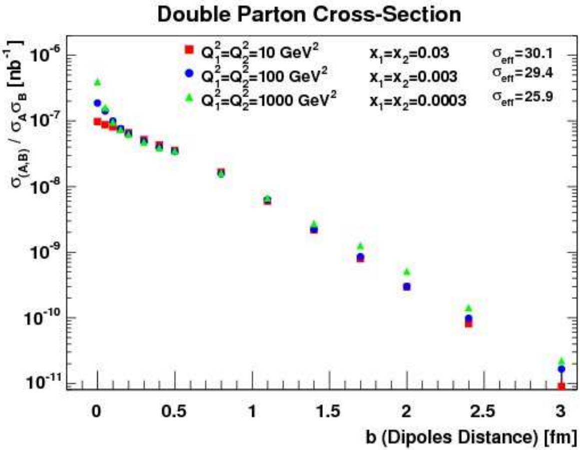


Satisfies geometric scaling

4. Results

a. Correlations in double parton distributions

$F(b)$



Spike develops at $b = 0$, for smaller x and larger Q^2

And longer tail

$x_1 = x_2 = 0.03, \quad Q_1^2 = Q_2^2 = 10$: $\quad \sigma_{\rm eff} = 30.1$ mb
$x_1 = x_2 = 0.003, \quad Q_1^2 = Q_2^2 = 100$: $\quad \sigma_{\rm eff} = 29.4$ mb
$x_1 = x_2 = 0.0003, \quad Q_1^2 = Q_2^2 = 1000$: $\quad \sigma_{\rm eff} = 25.9$ mb

$\sigma_{\rm eff}$ decreases: stronger correlations

$\int F d^2 b = 1.10, 1.08, 1.15$

Cf. $\sigma_{\rm eff} \sim 15$ mb for 3jet+γ at CDF and D0

This is sensitive to quark-gluon correlations

Stronger than gluon-gluon correlations?

Fourier transform $\Rightarrow$

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

$\vec{\Delta}$ = momentum imbalance

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

Can be important for multiple interactions at LHC.

Should be further studied

b. Diffraction à la Good–Walker

(C. Flensburg-GG: JHEP 1010, 014, arXiv:1004.5502)

Fluctuations in $\gamma^* p$

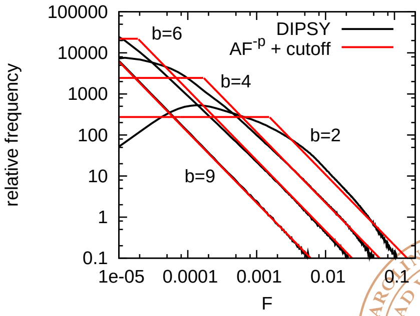
Prob. distrib. for
Born ampl. $F = \sum f_{ij}$

$dP/dF \approx A\,F^{-p}$

Wide distribution

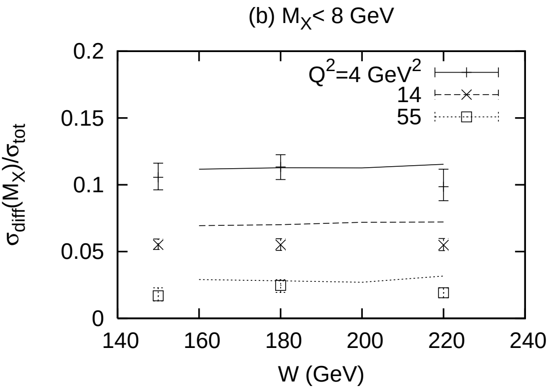
$\langle F \rangle$ small
$\Rightarrow T = 1 - e^{-F} \approx F$

$W = 220 \; Q^2 = 14$



$d\sigma_{diff.ex.}/d\sigma_{tot} \sim 10\%$, decreasing with Q^2

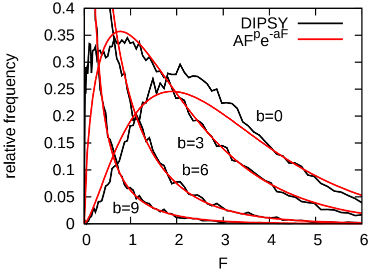
Example $M_X < 8$ GeV, $\quad Q^2 = 4, 14, 55\,\mathrm{GeV}^2$.

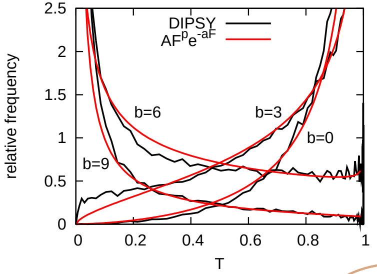


pp: Born approximation: large fluctuations

$$dP/dF \approx A\,F^p\,e^{-aF}$$

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





$\langle F \rangle$ is large: Unitarity important $\Rightarrow$ fluctuations suppressed

($\sim$ enhanced diagrams in multi-regge formalism)

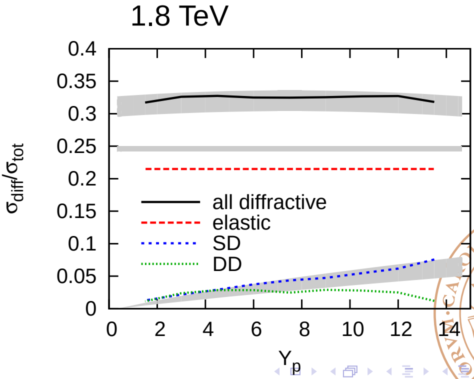
Factorization broken between DIS and *pp*

pp

Only events with a rapidity gap at $y = 0$, in the frame used for the calculation, are treated as diffractive.

In other frames they are classified as inelastic.

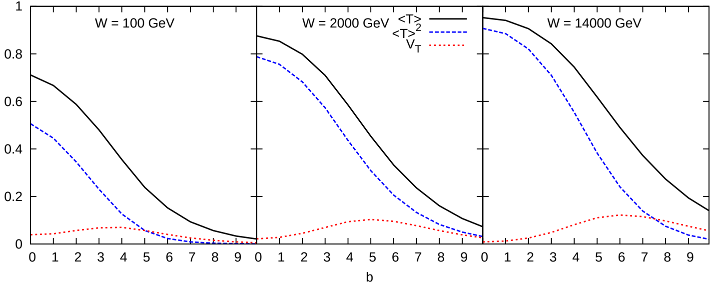
pp coll. in a frame, where the projectile is evolved Y_p rapidity units



Impact parameter profile

Central collisions: $\langle T \rangle$ large $\Rightarrow$ Fluctuations small

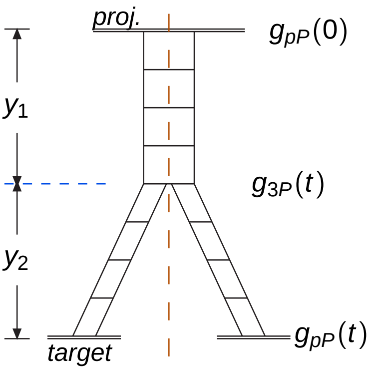
Peripheral collisions: $\langle T \rangle$ small $\Rightarrow$ Fluctuations small



Largest fluctuations when $\langle T \rangle \sim 0.5$

Circular ring expanding to larger radius at higher energy

Triple-Regge parameters



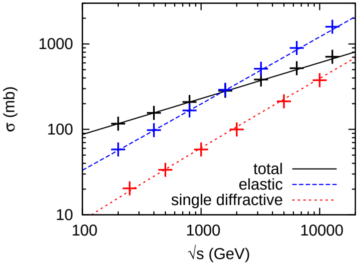
Traditionally fluctuations not taken into account

Reggeon parameters and couplings fitted to data

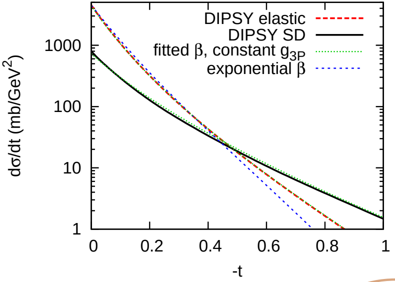
Bare pomeron

Born amplitude without saturation effects

$\sigma_{\rm tot}, \sigma_{\rm el}, \sigma_{\rm SD}$



$d\sigma_{\rm el}/dt, d\sigma_{\rm SD}dt$



Agrees with triple-regge form, with a single pomeron pole

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

$$g_{pP}(t) = (5.6\,\text{GeV}^{-1})\, e^{1.9t}, \quad g_{3P}(t) = 0.31\,\text{GeV}^{-1}$$

Compare with multi-regge analyses:

$$\alpha(0) = 1.21, \quad \alpha' = 0.2\,\text{GeV}^{-2}$$
$$g_{\text{pP}}(t) = (5.6\,\text{GeV}^{-1})\,e^{1.9t}, \quad g_{3\text{P}}(t) = 0.31\,\text{GeV}^{-1}$$

Ryskin *et al.*: $\alpha(0) = 1.3, \quad \alpha' \leq 0.05\,\text{GeV}^{-2}$

Kaidalov *et al.*: $\alpha(0) = 1.12, \quad \alpha' = 0.22\,\text{GeV}^{-2}$

Note:

Fit $\sim$ single pomeron pole (not a cut or a series of poles)

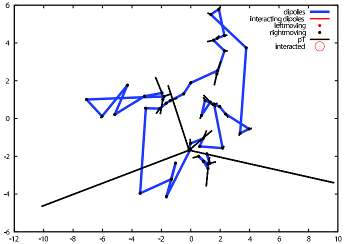
$g_{3\text{P}}$ approx. constant (*cf* LL BFKL $\sim 1/\sqrt{|t|}$),

6. Preliminary final state results

1. Remove virtual emissions, which do not come on shell in the interaction
(preliminary results, due to technical problems in the MC)

2. Add final state radiation

3. Hadronize (no color recon.)



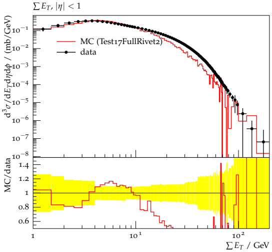
Note: No input structure fcns. No quarks, only gluons

No precision results should be expected

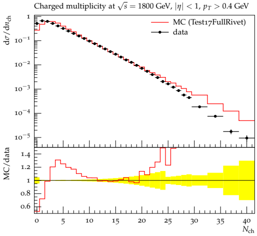
We hope to reproduce the qualitative features, and get insight into the basic mechanisms

CDF 1.8 TeV

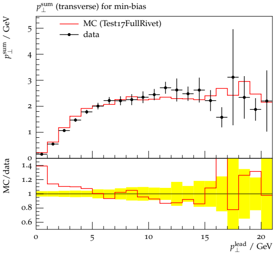
$$\frac{d\sigma}{dE_t d\phi}$$



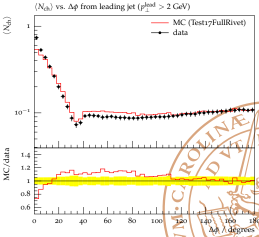
$$\frac{d\sigma}{dN_{ch}}$$



$\langle p_\perp \rangle$ vs $p_\perp^{lead}$

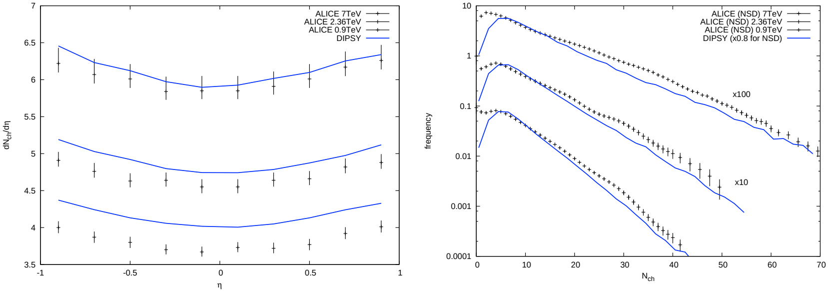


$$\frac{dN_{ch}}{d\Delta\phi}$$ from jet



ALICE

Rapidity distribution and multiplicity frequency.



$dN/d\eta$ varies somewhat too slowly with energy

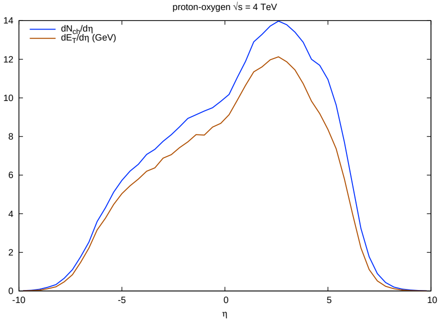
BFKL evolution $\Rightarrow$ more activity for large $|\eta|$ than PYTHIA

(Note also enhanced production of strangeness and baryons

$\Rightarrow$ hadronization modified in high density environment?)

Generalization to nucleus collisions

pO collision $\sqrt{s_{NN}} = 1$ TeV. $dN_{ch}/d\eta$, $dE_\perp/d\eta$

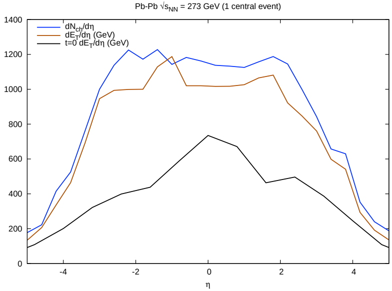


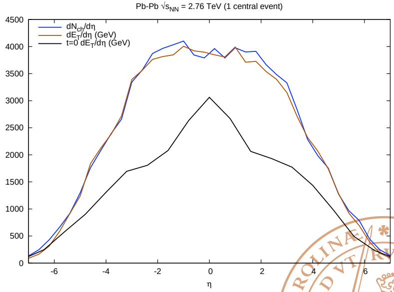
Pb Pb collision

Calculate energy and momentum densities for initial gluons

$\Rightarrow$ Initial condition for hydrodynamic evolution [— $dE_T/d\eta$]

$\sqrt{s_{NN}} = 273$ GeV (central) 2.76 TeV (1 central event)





Hadron distribution if NO plasma or hydrodynamic expansion

$dN_{ch}/d\eta$, $dE_T/d\eta$ (at 2.76 TeV 10,000$\times$10,000 dipoles)

Summary

- Correlations and fluctuations studied in a model based on BFKL evolution and saturation.
- Impact parameter dependence of double parton distributions depend on x_i and Q_i^2.
  Peak at small b for small x and large Q^2
  $\Rightarrow$ larger $p_\perp$ imbalance in multiple subcollisions.
- Fluctuations in BFKL evolution can describe diffractive excitation in *pp* collisions and DIS (with no extra parameters.)
  Reproduces triple-regge form, with simple pomeron pole.
- Preliminar results for final states.
- Generalization to nucleus collisions.