Diffraction at the LHC: Theoretical Remarks

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Introduction

Diffraction at LHC: soft diffraction + rapidity gap physics.
The latter is a first step beyond fully inclusive measurement.

- experimentally cleaner, but theoretically more complicated:
  interface between pQCD and strong interactions
  - when thinking about the search for new physics
    may view this as a complication. But: Cannot escape strong interaction.
  - don't be afraid, accept the challenge to understand strong interactions
    Strong interactions - QCD - is the least understood part of the SM.
    Main task: determine the validity of pQCD, investigate the transiton to npQCD
- Recent boost of diffraction: discovery tool of new physics.
  Really clean measurement possible.
  Need to understand theory.

Plan of talk:

- soft diffraction
- diffraction with a hard scale
- multiple interactions, underlying event, saturation etc.
- discovery of new physics

Soft diffraction

1) Total cross section σ_{pp}: energy dependence
either (Regge)

$$\sigma_{pp} \sim s^{\alpha(0)-1)}, \ \alpha(0) - 1 \approx 0.08$$

or (geometric)

$$\sigma_{pp} \sim (\ln s/s_0)^2$$

or something else (threshold of new physics, critical behavior: $\sigma_{pp} \sim (\ln s/s_0)^\gamma$)

No theory.
Variety of predictions, uncertainty because of Tevatron.

Energy dependence changes with the transverse size of projectile/target:
- pp is nonperturbative, no first principle theory, only from data
- $\gamma^* p$ is semi-perturbative: $\sigma_{\gamma^* p} \sim (W^2)^{\lambda(Q^2)}$ (HERA)
- $\gamma^*\gamma^*$ is predicted to be perturbative: $\sigma_{\gamma^*\gamma^*} \sim (\hat{s})^{\omega_{BFKL}}$ (LEP)

2) Elastic scattering, t-dependence: from very small $|t|$ to large $|t|$.

Very small $|t|$ (O(0.001 Gev^2)): Coulomb phase
Medium $|t|$ (O(< 1 Gev^2)):

$$\frac{d\sigma}{dt} = \frac{1}{16\pi s}|T(s,t)|^2, \; T(s,t) = \beta_p(t)\xi(t)\,(s/s_0)^{\alpha(t)}\,\beta_p(t)$$

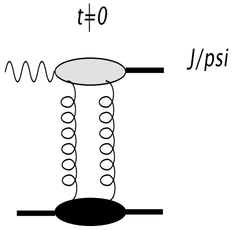
Transformation to impact parameter leads to a description of transverse extension:

$$f(s,\vec{b}) = \int \frac{d^2k}{16\pi^2 s} e^{-i\vec{k}\vec{b}} T(s,t,), \; t = -\vec{k}^2$$

$$< R^2_{int} >= B_0 + 2\alpha' \ln s/s_0$$

B_0 and α' ($\alpha(t) = \alpha(0) + \alpha' t$) are confinement parameter of 'QCD forces at high energies'.

In pQCD: radius grows with a power of s, very different diffusion pattern!
In reality: exponential shape in b, logarithmic growth of radius, diffusion in b

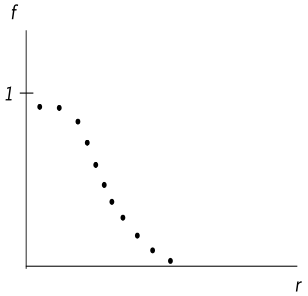


At HERA: $\gamma^* p$ system ('half-perturbative') looks different from pp

Larger $|t|$ (1 Gev$^2 < |t| < 10$ GeV^2): dip structure in $\frac{d\sigma}{dt}$?
Elements of pQCD might become visible: three gluon exchange model? Odderon?

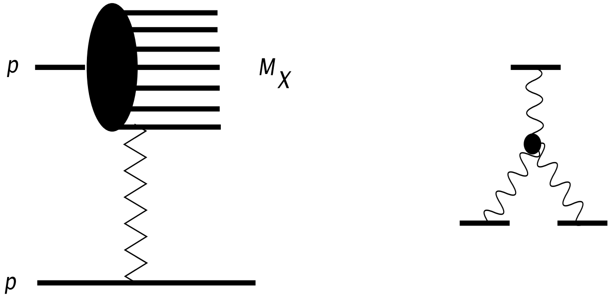
Current picture of pp scattering in transverse space (mainly ISR at $\sqrt{s} = 53$ GeV)

- pp system expands logarithmically (shrinkage): $\alpha' \approx 0.25$ Gev^{-2}
- (Amaldi et al.) proton is black at small $\vec{b}$, black region grows with energy (unitarity)

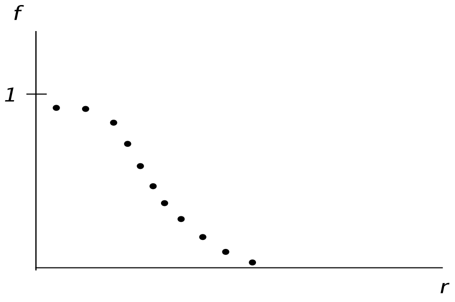


How does this picture look at much higher energies?

3) Inelastic diffraction: high mass diffaction
Long-lasting discussion,
potential inconsistency with Regge picture.
Mostly large b region.
Nonperturbative.



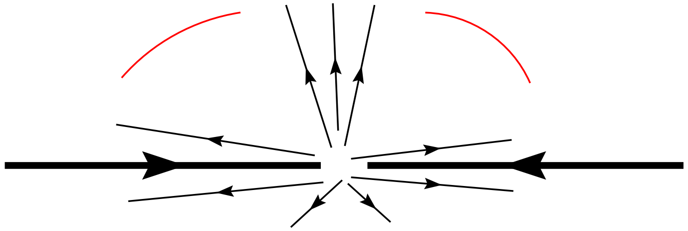
What are the prospects of making progress in the theory of high energy pp scattering?



- at small $\vec{b}$: dense gluon states, nonlinear evolution, saturation, unitarization ($\longrightarrow$ small-x community; heavy ion physics)
- at large $\vec{b}$: change (or breakdown?) of the present framework: major challenge in this field.

Diffraction with a hard scale

In contrast to completely inclusive measurements:
final states with empty regions (rapidity gaps). Attractive for experimentalists.

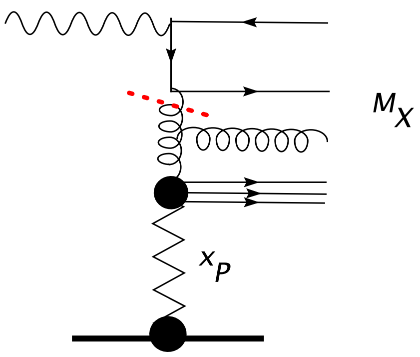


Theoretical status: interface between hard and soft QCD, no general theory.
No factorization between hard and soft physics.

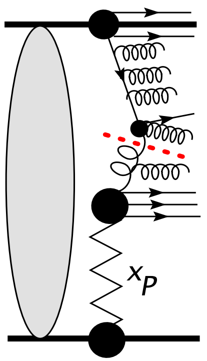
Common picture:
Either: single parton chain plus soft interactions (well-developed tool: survival factor).
But maybe: rescattering not completely soft.
Expand pQCD - multiple interactions (early stage).
In the following: illustrate and discuss a few cases.

1) Most interesting: double diffractive production of new physics (Higgs): clean! See later.

2) Diffractive parton densities: measured at HERA and at the Tevatron.



HERA

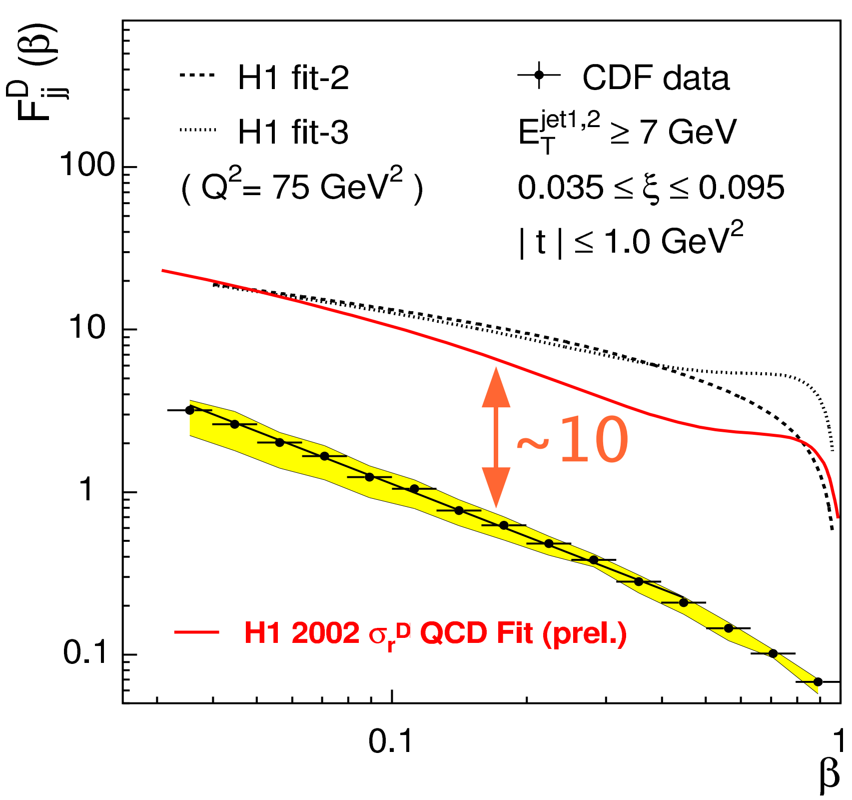


pp–scattering

Central tool in describing diffractive final states at LHC.
No universality:
diffractive parton densities from HERA cannot be transported to pp scattering:
there is always (soft) rescattering!

CDF F_{jj}^{D} from

QCD factorization breaks down



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Pomeron/Reggeon contributions

$$F_{jj}^{D}(\beta) \sim \sum_{i=IP,IR} \int dt \int d\xi \; C_i \cdot f_{i/\bar{p}}(\xi,t) \cdot F_{jj}^{i}(\beta)$$

Flux: $f_{i/\bar{p}}(\xi,t) = e^{b_i t} / \xi^{2\alpha_i(t)-1}$

$\alpha_{IP}(t) = 1.20+0.26t$, $\alpha_{IR}(t) = 0.57+0.9t$

$b_{IP} = 4.6$ GeV^{-2}, $b_{IR} = 2.0$ GeV^{-2}

$C_{IP} = 1$, $C_{IR} = 16.0$ (fit 2)

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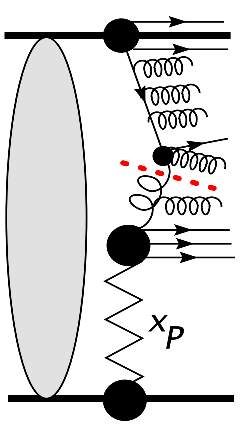
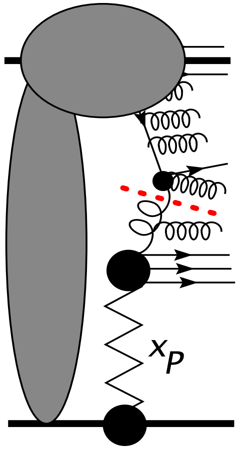
Results:

- HERA: strong gluon component
  $\alpha_{eff} > \alpha_{soft}$: 'Pomeron is harder'
- Tevatron: survival probability $\sim 10\%$.
- Is there a simple factorization of the (low mass) survival probability?
  Could there be 'hard rescattering' (multiple interaction)?
  Important tests: measure dependence upon x_P, k_t^2, t.

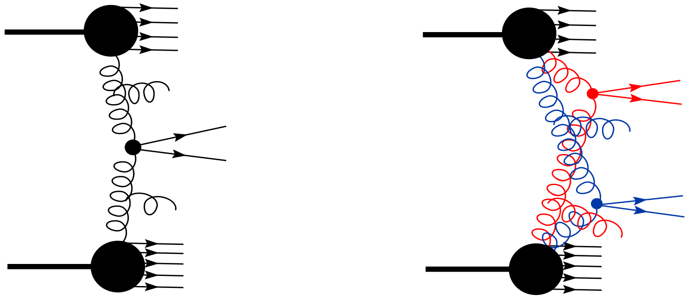




Digression on: multiple interactions, saturation (not diffraction, but forward physics)

Multiple interactions are present and need to be taken into account.
Underlying event structure. They are related to diffraction.

a) cancellation of multiple interactions in unsual inclusive jet cross section. But what is dangerous: multijet final states, e.g. two pairs of $b\bar{b}$ jets (background to new physics):

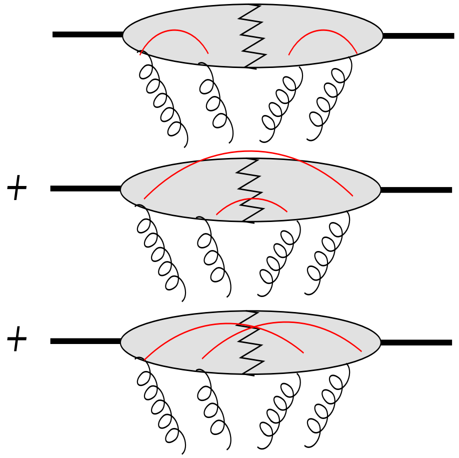


Intense work in Monte Carlo development (tests at Tevatron and at HERA).

Key questions: how large are 'double parton densities', what is the x dependence?

Any help from theory?

Theory: constraints from AGK rules in pQCD, e.g. symmetry in color connection.

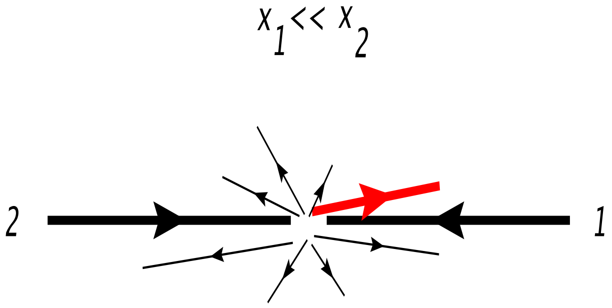


First line: diffraction! Needs to be consistent.

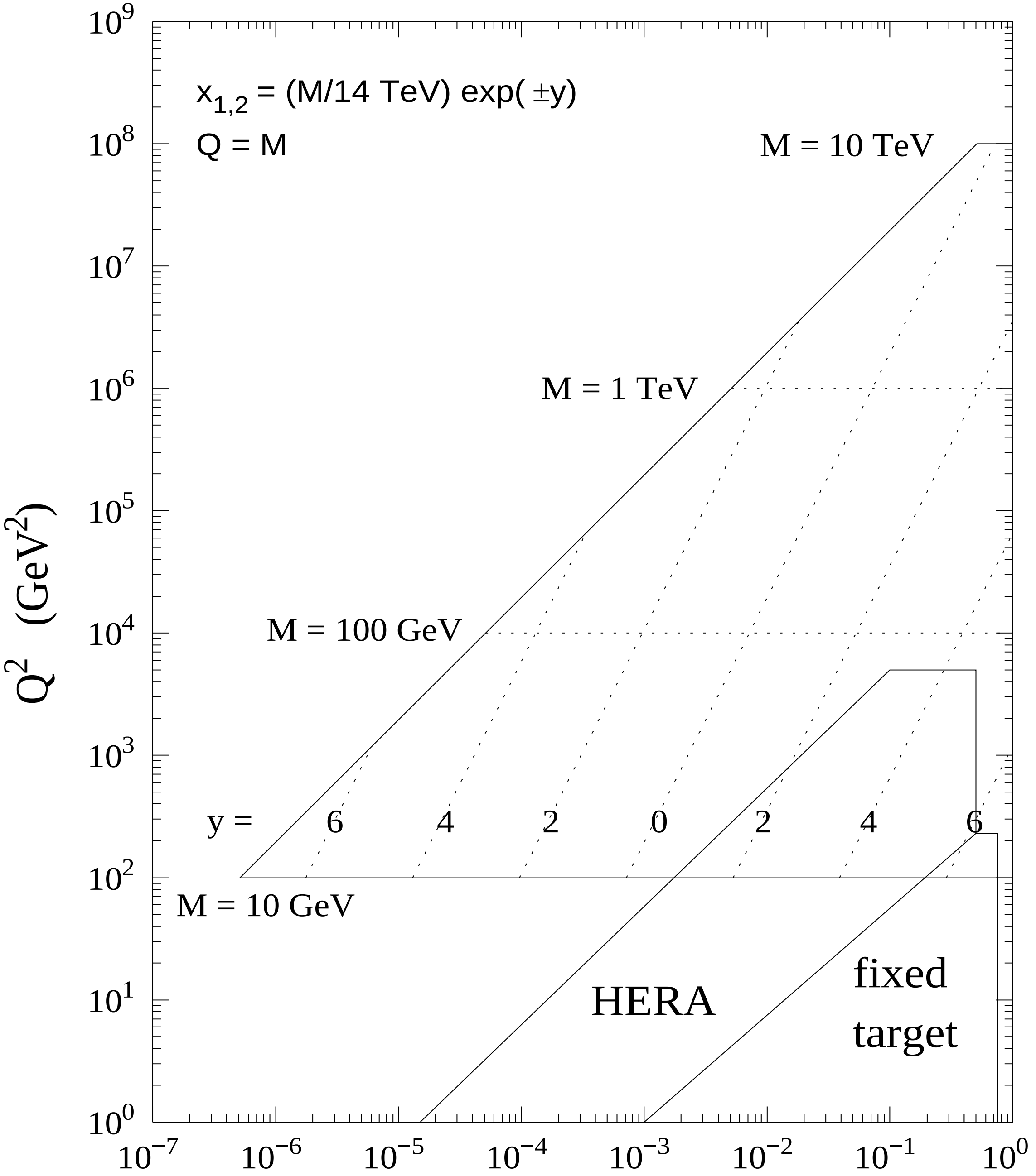
b) saturation: at small x, Q^2 expect to see, in $xg(x, Q^2)$, deviations from DGLAP.

At HERA: some hints (F_2-fit (GBW model), geometric scaling, energy dependence of $\sigma^{\gamma^*}_{diff}/\sigma^{\gamma^*}_{tot}$).

LHC has new kinematic region: need to check consistency of parton densities. Small-x region is near forward direction.



Need to get close to forward direction.


$x_{1,2} = (M/14\ \text{TeV}) \exp(\pm y)$
$Q = M$
M = 10 TeV
M = 1 TeV
M = 100 GeV
M = 10 GeV
y =
6
4
2
0
2
4
6
HERA
fixed
target
Q^2 (GeV^2)
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{-7}
10^{-6}
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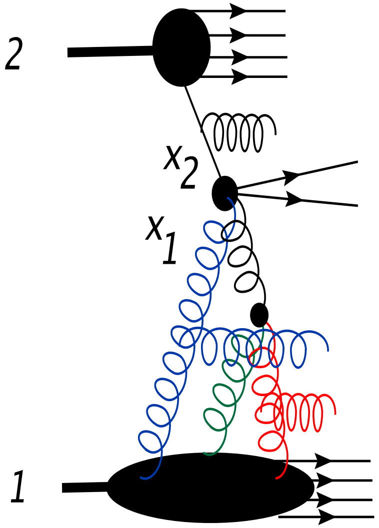
If there is saturation near the forward direction: what is the physics, what is the signature?
Multiple interactions on the small-x side:



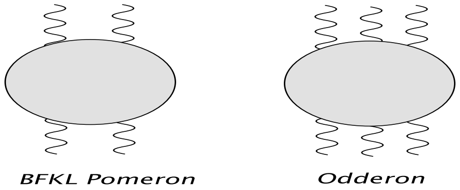
Signature: dependence upon x_1 (smaller cross section), enhanced multiplicities.
Geometric scaling? Dipole picture?
Diffractive parton densities in this region?

Connection with heavy ion physics (color glass condensate): check consistency at LHC!

Finally: the Odderon:
Has been invented more than 40 years ago (pre-QCD), as $C = -$ partner of the (vacuum quantum number) Pomeron:
distinguishes between pp and $p\bar{p}$ scattering.

Strongest experimental evidence for the existence of an Odderon:
difference in $d\sigma/dt$ between pp and $p\bar{p}$ (ISR); 3 gluon exchange at large t.
Then forgotten: CERN and Tevatron had only $p\bar{p}$; RHIC could measure pp and compare with Tevatron.

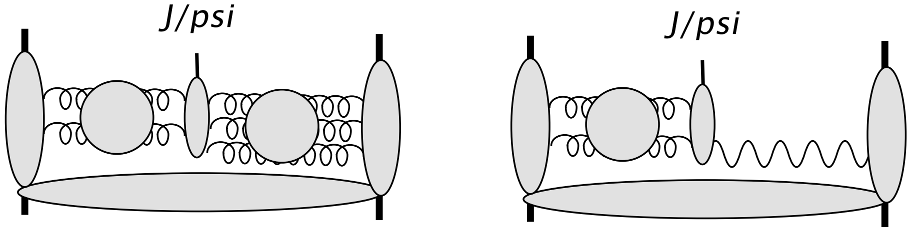
Recent interest: high energy (small x) limit of pQCD contains two fundamental gluonic configurations:
BFKL has been searched for at several places,
Odderon much less



BFKL Pomeron and Odderon - belong to the two Casimirs of QCD

Candidate:

Double diffractive J/ψ production:



Cross section has been estimated (Bzdak et al):

need t dependence in order to separate from γ exchange.

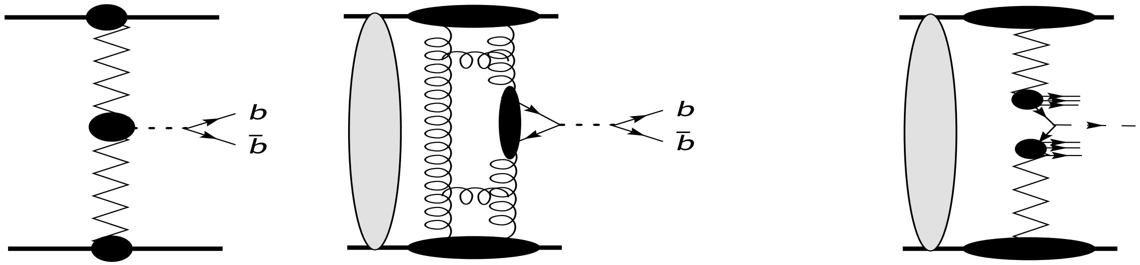
Photon - integrated: $\int d\sigma/dt \approx 12$ n b

Odderon - integrated: $\int d\sigma \approx 0.3 - 5$ nb

Diffraction: clean channel for new Physics

Hot topic, will have more discussion. Interesting for details of new physics.

Most interesting: (light) Higgs. Mass resolution = O(1) GeV.



Durham model: Sudakov suppression; $b\bar{b}$ background ($J_z = 0$ selection rule); survival probability.
Cross section: 3 fb ($m_H = 120$ GeV), $S/B = 1$.

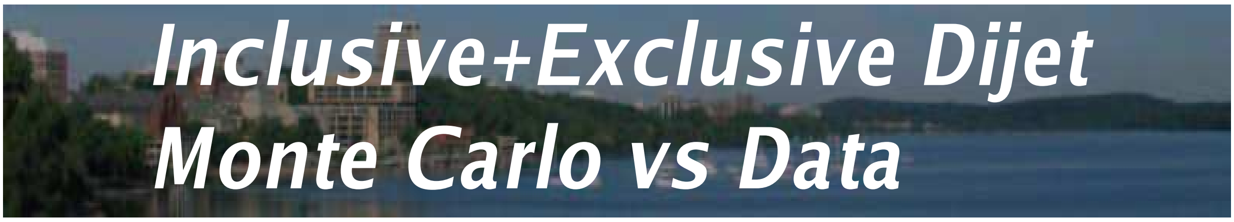
Other models (Saclay): slightly higher cross section, differences (dependence upon m_H, energy).

Needs very good forward detector (420 m).

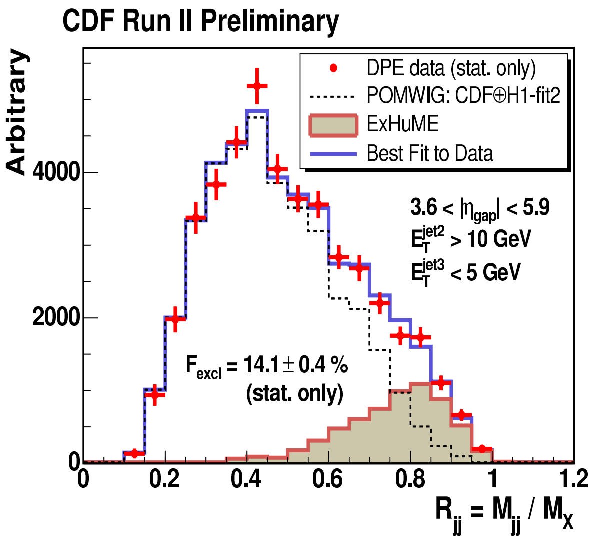
Double diffractive states are also interesting for other production processes (SUSY, χ_c, etc.).

How to check: reference process.
Double diffractive dijet-production, $\gamma\gamma$ production.

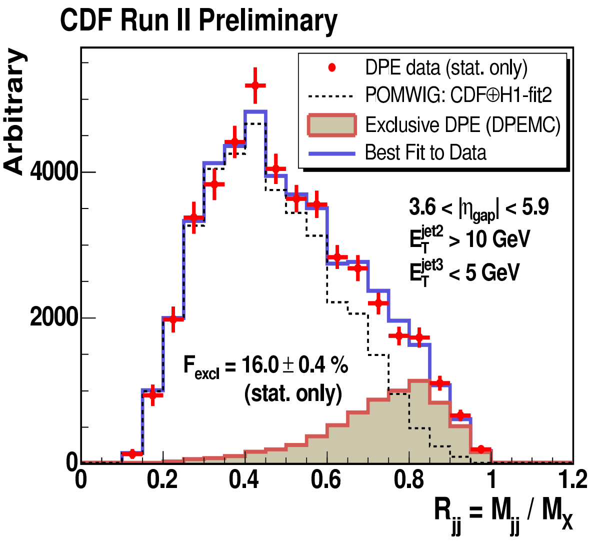
Recent CDF report on dijet cross section (→ De Roeck's talk)
(curves are Monte Carlo):



Inclusive+Exclusive Dijet Monte Carlo vs Data



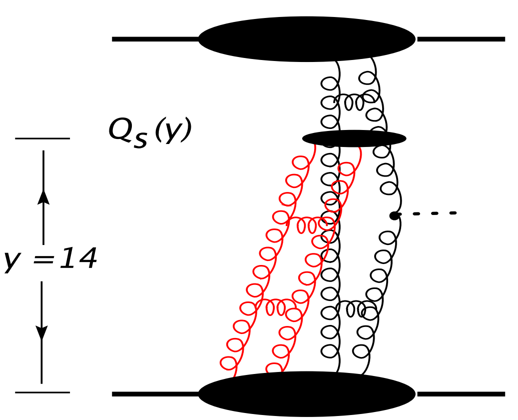
ExHuME (KMR) : ***gg* → *gg***

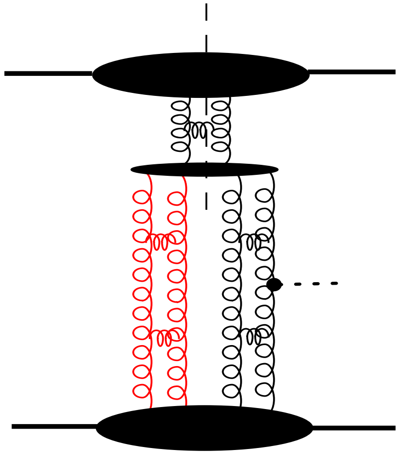


Exclusive DPE (in DPEMC) : ***IP* + *IP* → *2 jets***

The excess at high R_{jj} is well described by both exclusive dijet production models

Coming back to the survival probability: (JB,Bondarenko,Kutak, Motyka)
LHC offers a huge rapidity span for rescattering ($y > 14$):





high mass diffraction

Ongoing debate.
Might affect diffractive parton densitites (see above).

Conclusions

- Diffraction at the LHC:
  - Diffraction is developing as a valuable tool in searching for new physics
  - Diffraction with a hard scale: lives on the interface between hard and soft physics, theory requires special attention (pQCD and nonperturbative methods)
  - cross sections which belong to nonperturbative strong interactions (σ_{tot} etc): must be measured, and theorists should be challenged to develop methods
- Diffraction needs forward detectors.
- Strong interactions are the least understood part of SM,
  they are part of the search for new physics.