BFKL signatures at colliders

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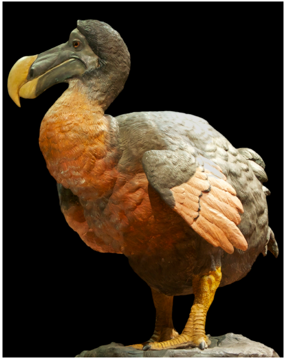
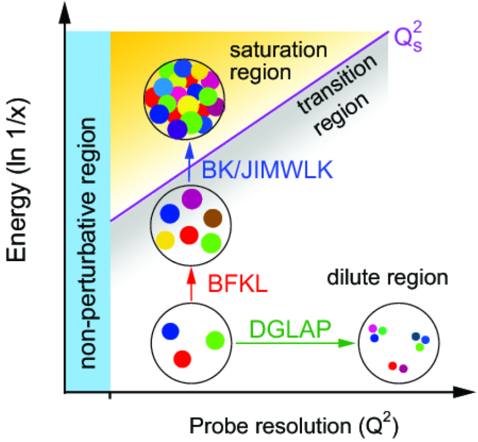


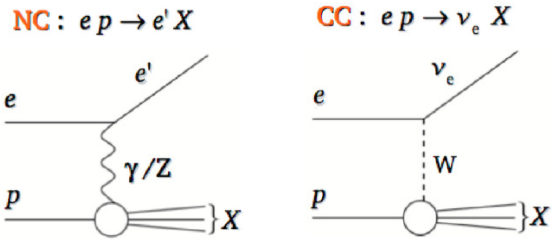
- BFKL dynamics
- Forward jet at HERA
- Mueller Navelet jets
- Jet gap jet

Looking for BFKL resummation /saturation effects



- DGLAP (Dokshitzer Gribov Lipatov Altarelli Parisi): Evolution in resolution Q^2, resums terms in $\alpha_S \log Q^2 \rightarrow$ resolving "smaller" partons at high Q
- BFKL (Balitski Fadin Kuraev Lipatov (BFKL): Evolution in energy x, resums terms in $\alpha_S \log 1/x \rightarrow$ Large parton densities at small x
- Saturation region at very small x
- Important to understand QCD evolution, parton densities
- Important for cosmic ray physics: understand forward physics

The starting point: the HERA *ep* collider



Kinematic variables:

- Virtuality exchanged boson

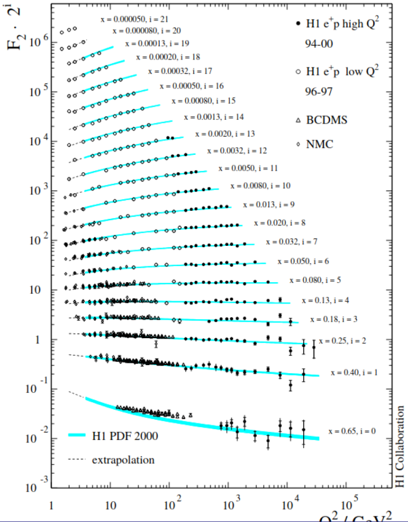
$$Q^2 = -q^2 = -(k - k')^2$$

- Bjorken scaling variable

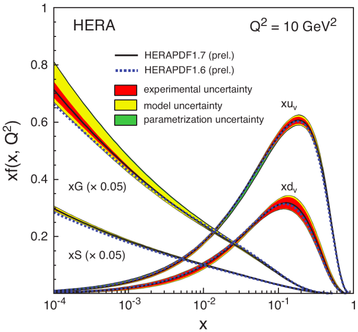
$$x = \frac{Q^2}{2p \cdot q}$$

- Measurement of the $ep \to eX$ cross section: as a function of two independent variables x and Q^2
- Many methods available to measure x (momentum fraction of the proton carried by the interacting quark), or Q^2 (transfered energy squared) using scattered electron or hadron information

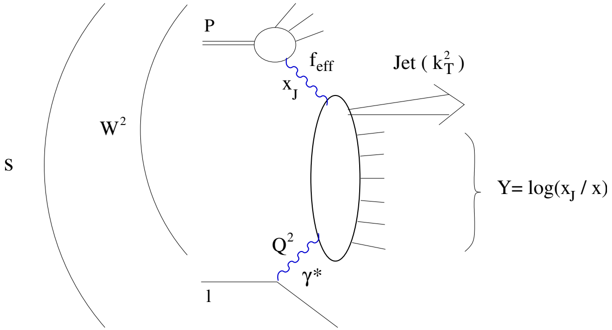
The starting point: the proton structure as seen at HERA



- Measurement of the proton structure function from H1/ZEUS at HERA
- Leads to the discovery of the rising gluon density at low x



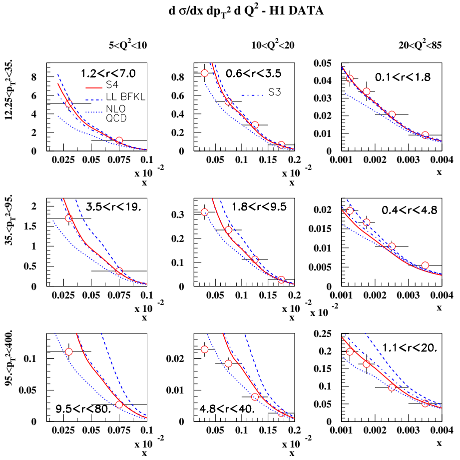
The starting point: Forward jet measurements at HERA



- Full BFKL NLL calculation used for the BFKL kernel

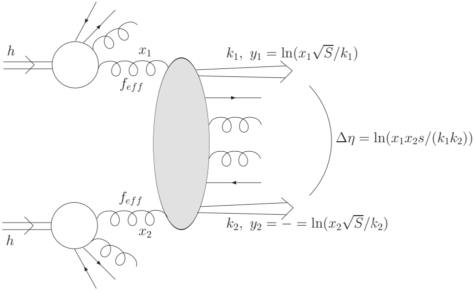
- when $Q^2 \sim k_T^2$ the phase space to emit gluons along the ladder predicted by DGLAP is low because of k_T ordering of different gluons
- When Y is large, possibility to emit lots of gluon due to BFKL evolution (no ordering on k_T)
- Forward jet production is an ideal observable to look for BFKL dynamics in a high gluon density regime

Forward jet measurements at HERA: comparison with H1 triple differential cross section



- NLO QCD: Fails at low jet p_T, low x, this is the BFKL domain where the gluon density in the proton gets very large
- BFKL LL: Fails at high jet p_T, this is the usual DGLAP domain, no Q^2 evolution for BFKL LL
- BFKL NLL: Good description everywhere, shows the relevance of BFKL dynamics and also the effect of Q^2 evolution given by renormalization group equation

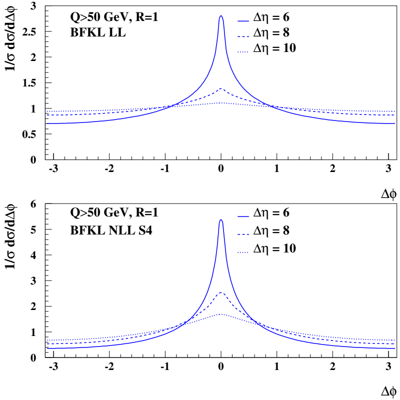
Looking for BFKL resummation effects at hadron colliders



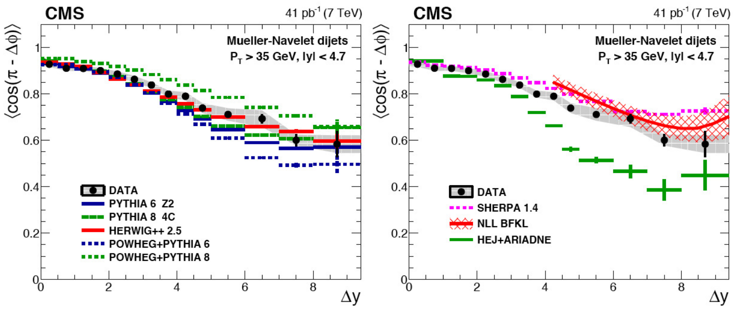
- Mueller Navelet jets: Look for dijet events separated by a large interval in rapidity
- If jets have similar p_T, DGLAP cross section suppressed because of the k_T ordering of the gluons emitted between the two jets
- BFKL cross section enhanced: gluon emissions possible because of large rapidity interval
- Study the $\Delta\Phi$ between jets dependence of the cross section as an example

Mueller Navelet jets: $\Delta\Phi$ dependence

- $1/\sigma d\sigma/d\Delta\Phi$ spectrum for BFKL NLL as a function of $\Delta\Phi$ for different values of $\Delta\eta$, scale dependence: $\sim$20%
- Stronger decorrelation for BFKL prediction than for DGLAP
- C. Marquet, C.Royon, Phys. Rev. D79 (2009) 034028

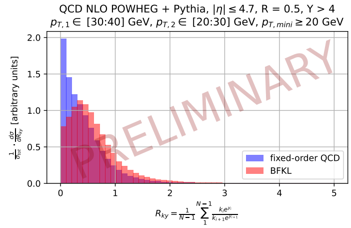


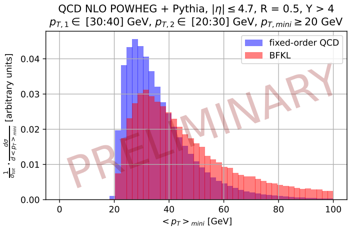
Mueller Navelet jets: ΔΦ dependence: CMS measurements



- CMS measurement: Azimuthal decorrelation between jets at 7 TeV: JHEP 08 (2016) 139
- BFKL NLL leads to a good description of data but also PYTHIA/HERWIG after MPI tuning...: Redo measurement at 13 TeV, and measure ratio of 13 to 7 TeV
- More differential observables needed or completely new ideas

Mueller Navelet processes: Looking for less inclusive variables



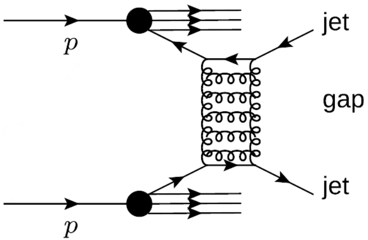


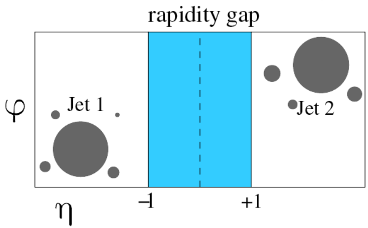
- Looking for multiple gluon emission along ladder characteristic of BFKL
- Comparison between BFKL-ex MC (Sabio Vera, Chachamis) and usual QCD MC to find best possible variables (Mats Kampshoff, Michael Klasen, Jens Salomon, Cristian Baldenegro, CR)
- As example:

$$< p_T > \; = \; \frac{1}{N} \Sigma_1^N p_{T_i}$$

$$< R_{ky} > \; = \; \frac{1}{N+1} \Sigma_1^{N+1} \frac{k_i e^{y_i}}{k_{i-1} e^{y_{i-1}}}$$

Another observable: Gap between jets

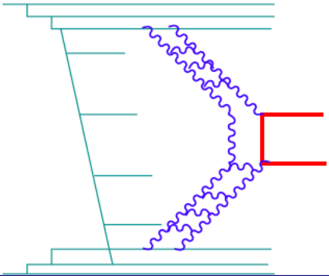


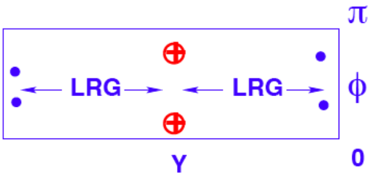


- Looking for a gap between two jets: Region in rapidity devoid of any particle production, energy in detector
- Exchange of a BFKL Pomeron between the two jets: two-gluon exchange in order to neutralize color flow
- In practice, we request no track between the two jets

One aside: survival probability

- Gaps can be suppressed by additional soft gluon emissions in initial/final states (MPI for instance)
- Survival probability: Probability that there is no soft additional interaction, that the diffractive event is kept
- We assume that the survival probability does not depend much on kinematics with respect to BFKL cross section (exponential $\Delta\eta$ dependence between jets dependence for instance): taken as a constant



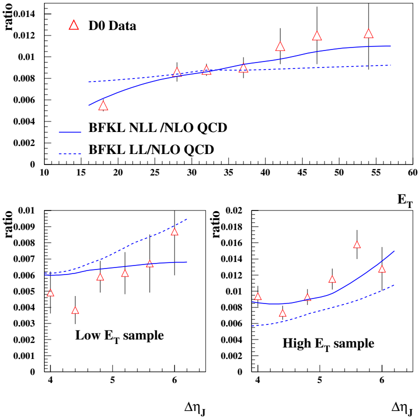


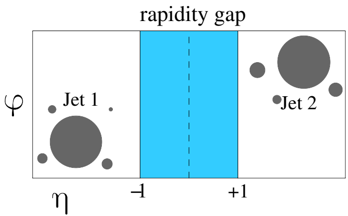
Comparison with D0 data

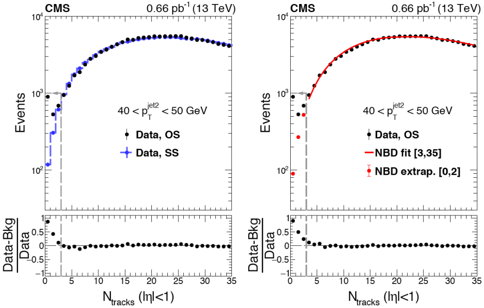
- D0 measurement: Jet gap jet cross section ratios as a function of second highest E_T jet, or $\Delta\eta$ for the low and high E_T samples, the gap between jets being between -1 and 1 in rapidity
- Comparison with BFKL formalism:

$$R = \frac{BFKL\ NLL\ Herwig}{Dijet\ Herwig} \times \frac{LO\ QCD\ NLOJet}{NLO\ QCD\ NLOJet}$$

- Reasonable description using BFKL NLL formalism

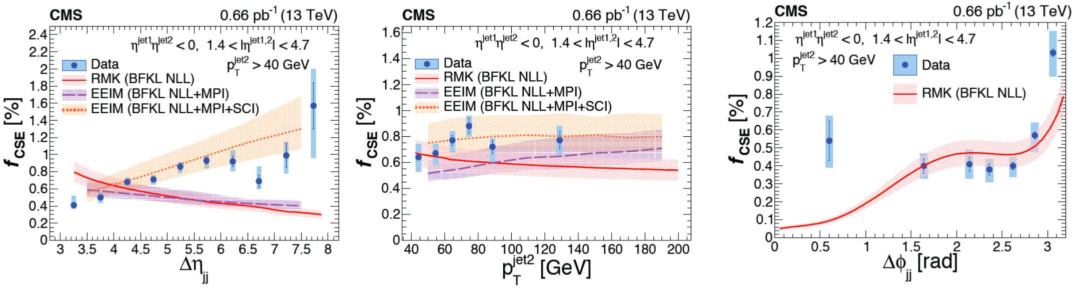






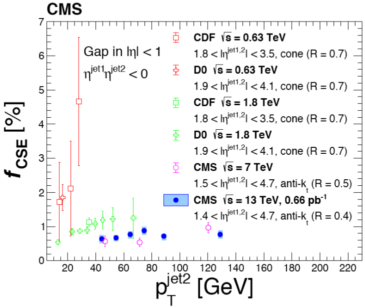
- 2015 *pp* collisions at 13 TeV, at low luminosity (pile up $\sim$ 0.05-0.1; 0.66 pb^{-1}): trigger $p_T^{jet} > 32$ GeV in $|\eta| < 4.7$ unprescaled
- Jet selection: anti-k_T algorithm ($R = 0.4$), jet $P_T > 40$ GeV, $1.4 < \eta_{jet} < 4.7$, jets in opposite hemisphere, 362,915 events
- **Clear signal of jet gap jet, the gap being in $-1 < \eta < 1$**
- Two methods to measure background:
  - Method 1: fit number of tracks in the gap region using a negative binomail distribution (NBD) for $3 \leq N_{tracks} \leq 35$ and extrapolate to 0
  - Method 2: use same side jet events

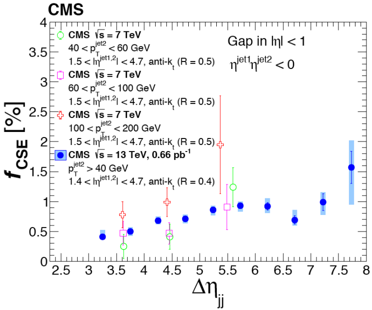
Jet gap jet fraction



- Measurement of fraction of jet gap jet events as a function of jet $\Delta\eta$, p_T
- Comparison with BFKL NLL calculation (including LO coupling to protons (impact factor) (Kepka, Marquet, Royon, Phys. Rev. D83 034036): Differences between prediction and measurement in $\Delta\eta$ observable
- Full NLO calculation in progress (F. Deganutti, D. Colferai, C. Royon)

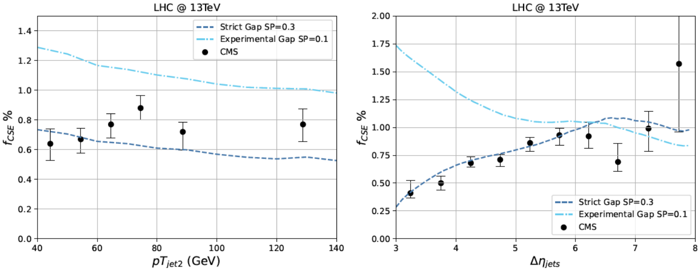
Comparison with previous experiments





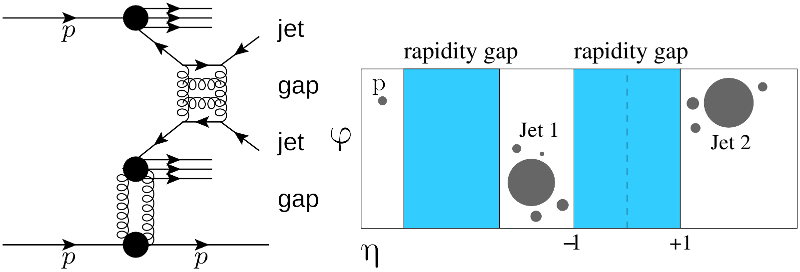
- Jet gap jet measurements at 4 different $\sqrt{S}$: 0.63 TeV, 1.8 TeV, 7 TeV, 13 TeV
- For the first time, measurement at high $\Delta\eta_{jj}$, important to probe BFKL
- Usually suppression of cross section as a function of $\sqrt{S}$ (survival probability): **No further suppression within uncertainties between 7 and 13 TeV!**

Jet gap jet fraction: sensitivity to gap definition



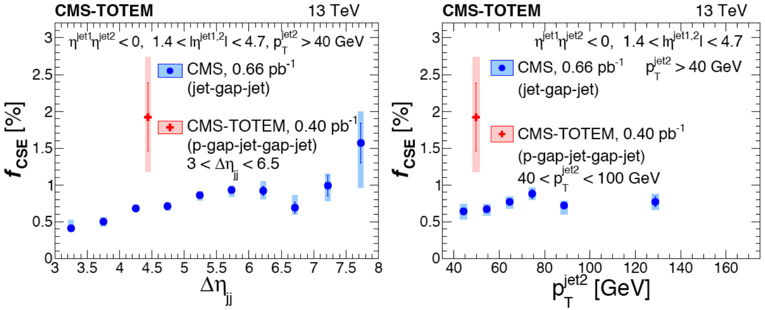
- Difference between "theory" gap definition (no particle above 5 MeV in the gap + ISR from pythia) and "experimental" (no charged particle agove 200 MeV)
- Theory gap prediction agrees with data
- Probably too much radiation generated by MC
- Work done in collaboration with Muenster group

Jet gap jet events in diffraction

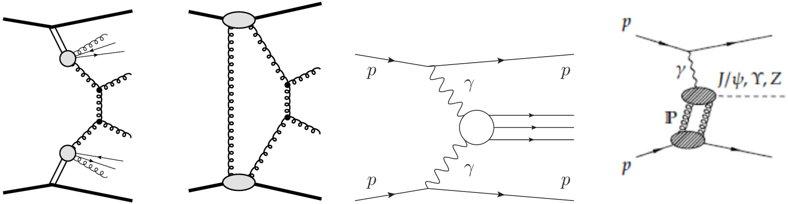


- TOTEM roman pots detectors on both sides of CMS allow to measure intact protons in the final state
- Subsample of gap between jets events requesting in addition at least one intact proton on either side of CMS
- **Jet gap jet events in diffraction were observed for the 1st time by CMS!**

First observation of jet gap jet events in diffraction

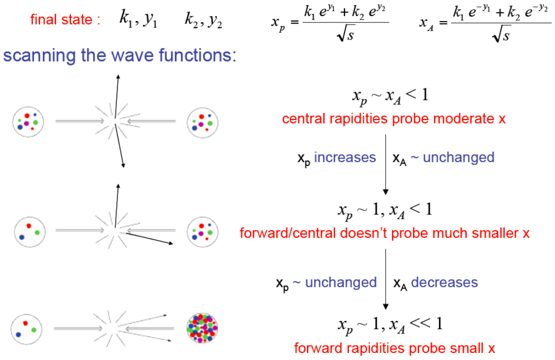


- First observation: 11 events observed with a gap between jets and at least one proton tagged with ~ 0.7 pb^{-1}
- Leads it very clean events for jet gap jets since MPI are suppressed and might be the "ideal" way to probe BFKL
- Would benefit from more stats and a dedicated trigger requesting an intact proton in the final state, probably $>$10 pb^{-1} needed, 100 for DPE



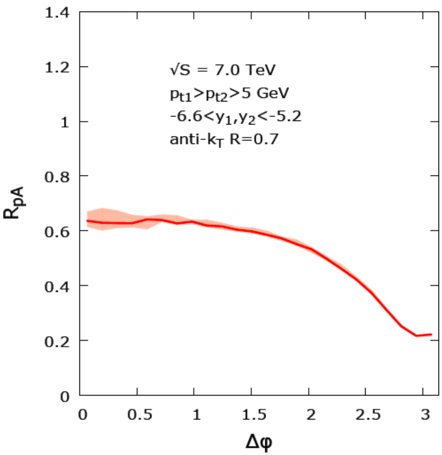
- Many exclusive channels can be studied: jets, χ_C, charmonium, J/Ψ....; many low mass data taken already by CMS-TOTEM, being analyzed
- Possibility to reconstruct the properties of the object produced exclusively (via photon and gluon exchanges) from the tagged proton
- Search for glueball production at low masses: related to the odderon discovery by D0 and TOTEM collaborations

Saturation at the LHC: Use pA data



- If we want to see saturation effects, we need a dense object (Pb) and to go to very low x: measure jets in very forward direction
- Saturation effects: Measure two jets in very forward calorimeter (CASTOR in CMS, FOCAL project in ALICE)
- Compare pp and pA runs in order to remove many systematics
- Possibility to look for quark gluon plasma formation using $t\bar{t}$ production in PbPb

Saturation effects at the LHC



- Suppression factor between pp and pA runs: estimated to be 1/2 in CASTOR (CMS) acceptance, similar for FOCAL
- Important to get a good understanding of JES in very forward region to measure jet energy: quite difficult
- FOCAL in Alice will be the ideal tool for those studies

Conclusion

- Mueller Navelet jets: Larger decorrelation expected for BFKL formalism
- Mueller Navelet jets: not enough discrimination to observe clearly BFKL resummation effects $\rightarrow$ Looking for less inclusive variables more sensitive to BFKL dynamics
- Jet gap jets:
  - NLL BFKL cross section implemented in HERWIG (Kernel), LO impact factors
  - Fair description of D0 (and CDF) data
  - Full NLL calculation including impact factors in progress
  - Small changes due to NLO impact factors
- Jet gap jet events in diffraction: clean tests of BFKL, modulo the survival probability (and its dependence on kinematics)