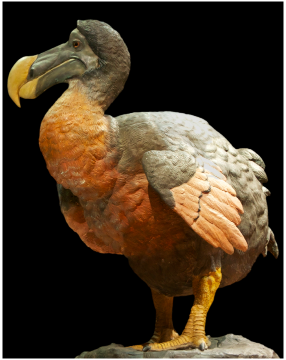
Low x and saturation at the LHC

Christophe Royon
University of Kansas, Lawrence, USA
Medical and HEP workshop, Sonora, Mexico

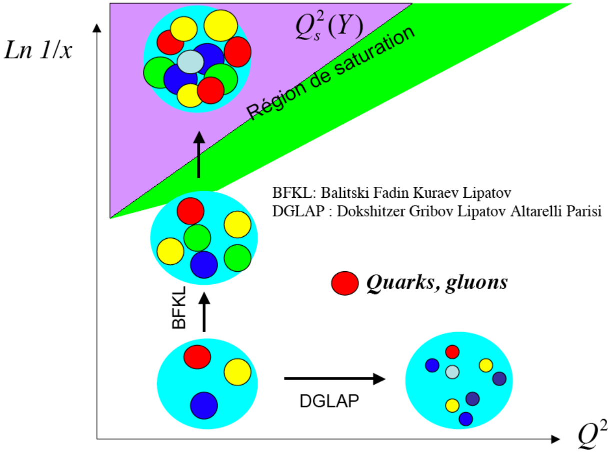


May 21-24 2024

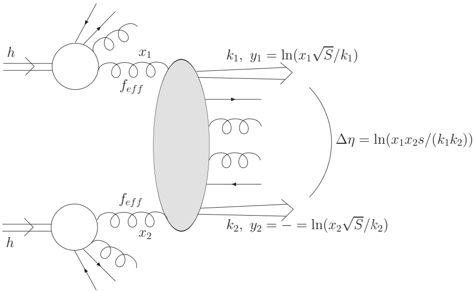
- Mueller Navelet processes at the LHC
- Jet gap jet measurements at the LHC
- Jet gap jet cross sections including NLO impact factors
- Diffraction at the LHC

Looking for BFKL/saturation effects

Looking for BFKL/CGC effects at LHC/EIC in dedicated final states



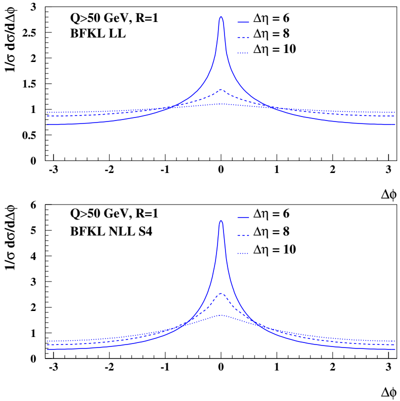
Looking for BFKL resummation effects at hadron colliders



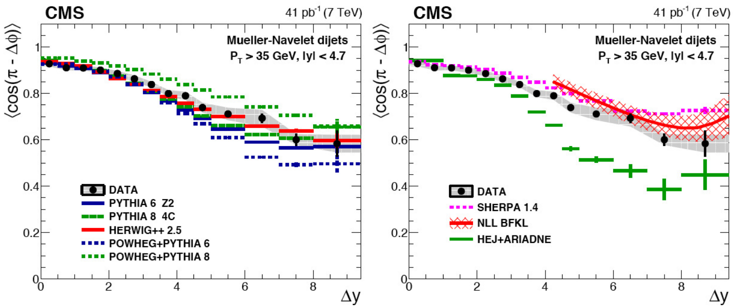
- Mueller Navelet jets: Look for dijet events separated by a large interval in rapidity
- If jets have similar p_T, DGLAP cross section suppressed because of the k_T ordering of the gluons emitted between the two jets
- BFKL cross section enhanced: gluon emissions possible because of large rapidity interval
- 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
- Implementation of NLL BFKL predictions in BFKL-Ex (A. Sabio Vera, G. Chachamis), allow to obtain gluon emission along the ladder, also to compare with NLO QCD (POWHEG+PYTHIA)

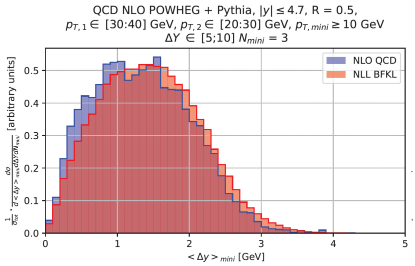


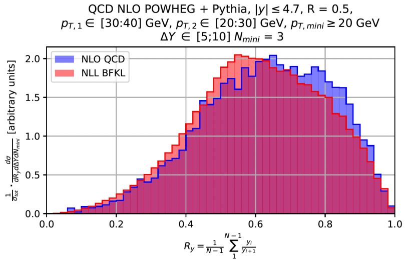
Mueller Navelet jets: ΔΦ dependence: CMS measurements



- CMS collaboration: Azimuthal decorrelation between jets at 7 TeV: J. High Energy Phys. 08 (2016) 139
- BFKL NLL leads to a good description of data but also PYTHIA/HERWIG after MPI tuning...
- More differential observables needed or completely new ones

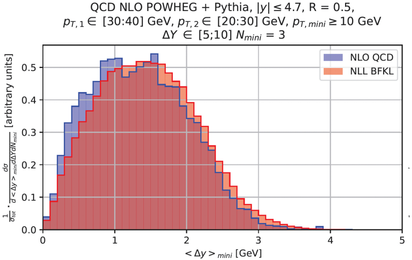
Mueller Navelet processes: Looking for less inclusive variables

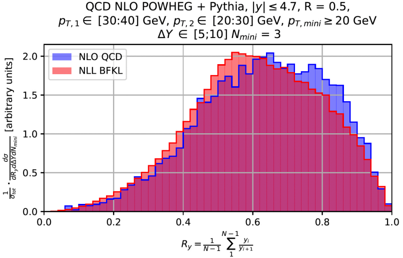




- Looking for multi-gluon emission along ladder, characteristic of BFKL NLL/DGLAP NLO
- Comparison between BFKL-ex MC and usual QCD NLO MC to compare both approaches (M. Kampshoff, A. Sabio Vera, G. Chachamis, C. Baldenegro, CR in preparation)
- We first require two forward jets with $5 < |\Delta Y| < 10$, $30 < p_{T_1} < 40$ GeV, $20 < P_{T_2} < 30$ GeV

Mueller Navelet processes: Looking for less inclusive variables





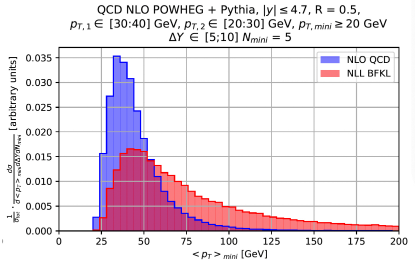
- We define as $y = 0$ the rapidity of the mini-jet closest to the MN jet and N is the number of mini-jets above 20 GeV (or 10 GeV) emitted between the two MN jets
- Rapidity of emitted mini-jets

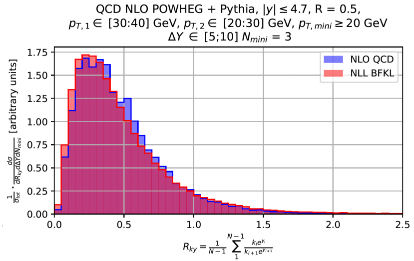
$$< \Delta y_{mini} > = \frac{1}{N-1}(y_N - y_1)$$

$$< R_y > = \frac{1}{N-1}\Sigma_1^{N-1}\frac{y_i}{y_{i+1}}$$

- Similar distributions for both approaches (R_y slightly higher for NLO QCD): test of gluon emission as predicted by QCD

Mueller Navelet processes: Looking for less inclusive variables





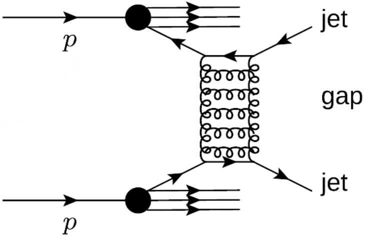
- We look for the average p_T of the emitted jets, as well as p_T weighted rapidity distrbutions

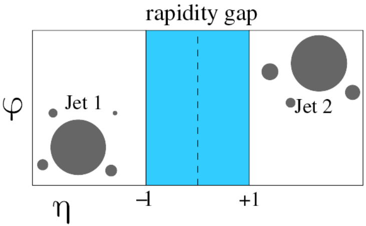
$$< p_T > = \frac{1}{N+} \Sigma_1^{N-1} p_{T_i}$$

$$< R_{ky} > = \frac{1}{N-1} \Sigma_1^{N-1} \frac{p_{T_i} e^{y_i}}{p_{T_{i+1}} e^{y_{i+1}}}$$

- Small differences, NLO QCD giving slightly higher values for R_{ky}
- $< p_T >$ is quite different but probably an artefact due to the fact there is no showering in BFKL-Ex and only conservation of transverse energy in the BFKL equation

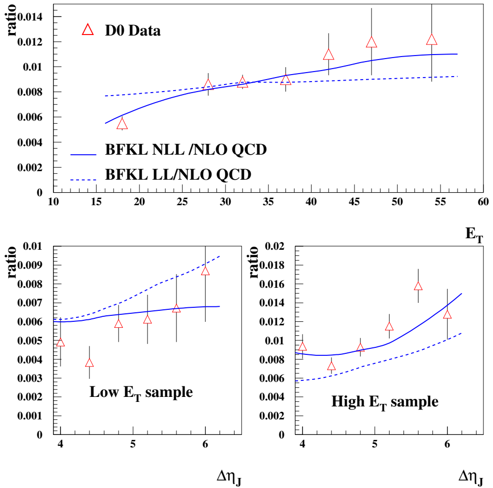
Mueller Tang: Gap between jets at the Tevatron and the LHC





- 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
- Method to test BFKL resummation: Implementation of BFKL NLL formalism in HERWIG/PYTHIA Monte Carlo

Comparison with D0 data

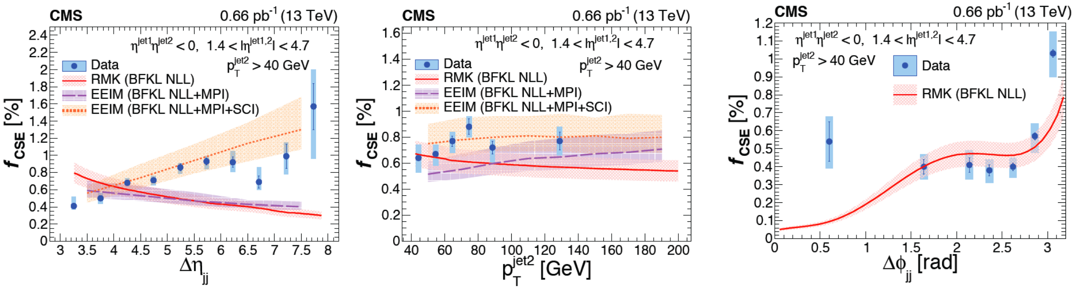


- D0 measurement: Jet gap jet cross section ratios, gap between jets being between -1 and 1 in rapidity
- Comparison with BFKL formalism:

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

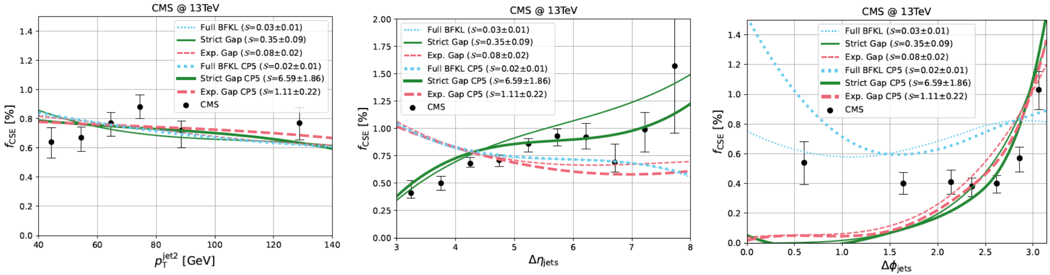
- Reasonable description using BFKL NLL formalism
- O. Kepka, C. Marquet, C. Royon, Phys. Rev. D 83 (2011) 034036

LHC: Measurement of jet gap jet fraction (CMS)



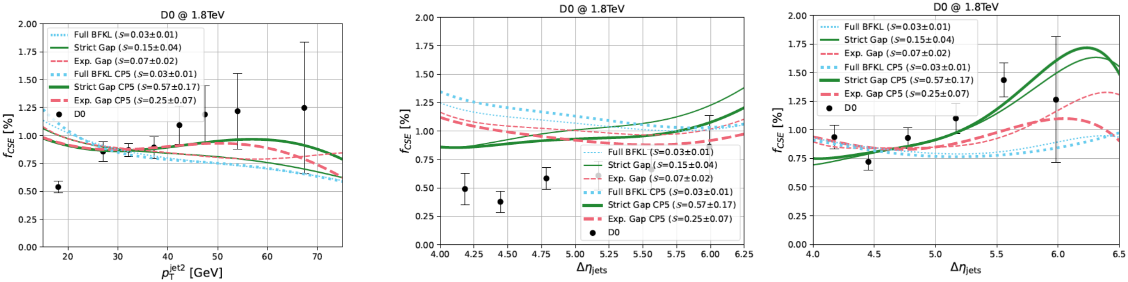
- Measurement of fraction of jet gap jet events as a function of jet $\Delta\eta$, p_T, $\Delta\Phi$ (Phys.Rev.D 104 (2021) 032009)
- Comparison with NLL BFKL (with LO impact factors) as implemented in PYTHIA, and soft color interaction based models (Ingelman et al.)
- Disagreement between BFKL and measurements ($\Delta\eta$ dependence): What is going on?

Jet gap jet measurements at the LHC (CMS@13 TeV)



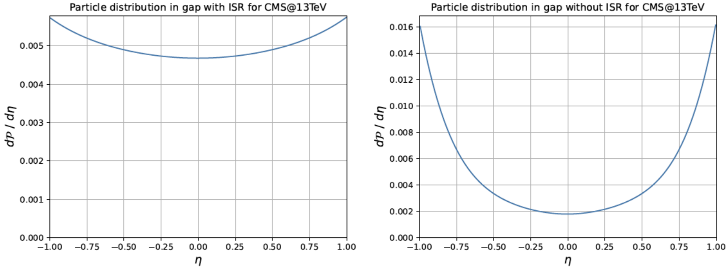
- Implementation of BFKL NLL formalism in Pythia and compute jet gap jet fraction
- Dijet cross section computed using POWHEG and PYTHIA8
- Three definitions of gap: theory (pure BFKL), experimental (no charged particle above 200 MeV in the gap $-1 < \eta < 1$) and strict gap (no particle above 1 MeV in the gap region) (C. Baldenegro, P. Gonzalez Duran, M. Klasen, C. Royon, J. Salomon, JHEP 08 (2022) 250)
- Two different CMS tunes: CP1 without MPI, CP5 with MPI

Jet gap jet measurements at the Tevatron (D0)

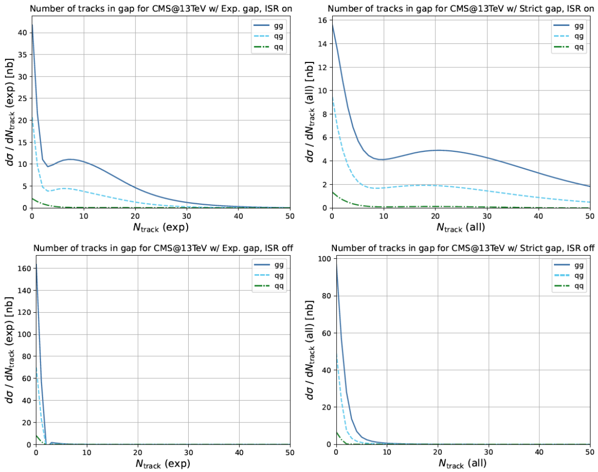


- Better agreement with the strict gap definition
- Fair agreement with the experimental gap definition since the differences between strict and experimental predictions are now that large compared to results at LHC energies
- Why such a large difference at the LHC?

Charged particle distribution



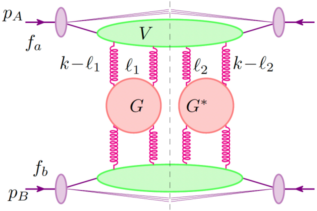
- Disitribution of charged particles from PYTHIA in the gap region $-1 < \eta < 1$ with ISR ON (left) and OFF (right)
- Particles emitted at large angle with $p_T > 200$ MeV from initial state radiation have large influence on the gap presence or not, and this on the gap definition (experimental or strict)



- Number of particles emitted in the gap region $-1 < \eta < 1$ with $p_T > 200$ MeV from PYTHIA with ISR ON (top) and OFF (bottom)
- Number of particles much larger for gg processes, gluons radiate more
- Tevatron/LHC energies: mainly quark gluon/gluon gluon induced processes, so more radiation at LHC
- ISR emission from PYTHIA too large at high angle and must be further tuned for jet gap jet events: Use for instance J/Ψ-gap-J/Ψ events which is a gg dominated process

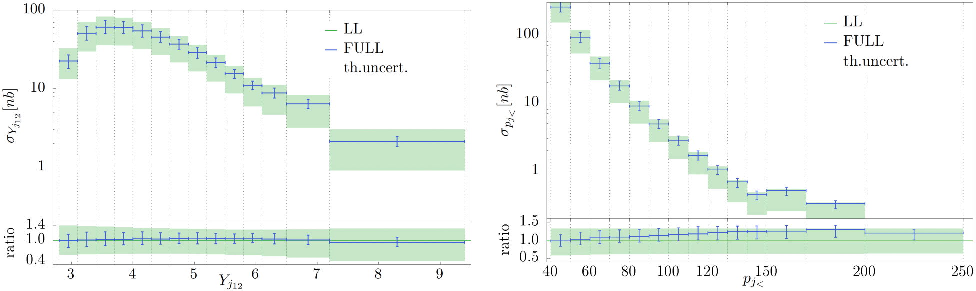
Jet gap jet: Full NLO BFKL calculation including NLO impact factor

- Combine NLL kernel with NLO impact factors (Hentschinski, Madrigal, Murdaca, Sabio Vera 2014)



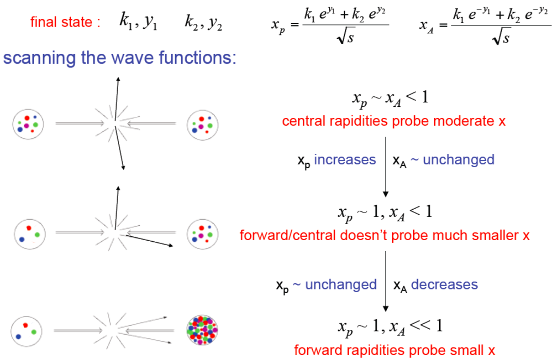
- Gluon Green functions in red
- Impact factors in green
- Will lead to an improved parametrisation to be implemented in HERWIG/PYTHIA
- D. Colferai, F. Deganutti, T. Raben, C. Royon, ArXiv 2304.09073

Effect of NLO impact factor on jet gap jet cross section: final results



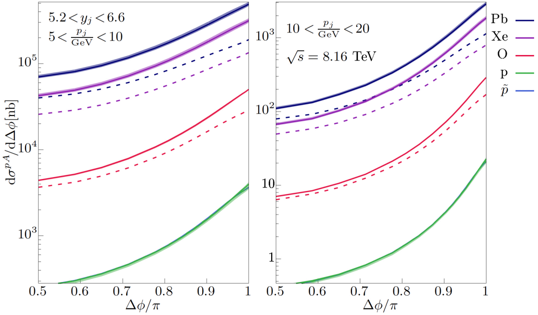
- Higher cross section by 20% at high p_T and small effect on the y dependence
- Total uncertainties are much smaller at NLO: 15-20%

Saturation at the LHC: Use pA data



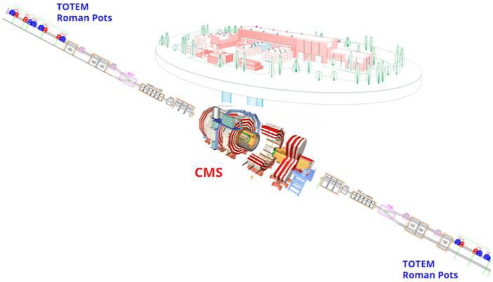
- If we want to see saturation effects, we need a dense object (Pb) and to go to very low x: measure jets in very forward direction
- Saturation effects: Measure two jets in very forward calorimeter (CASTOR in CMS, FOCAL project in ALICE)
- Compare pp and pA runs in order to remove many systematics
-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

Looking for saturation



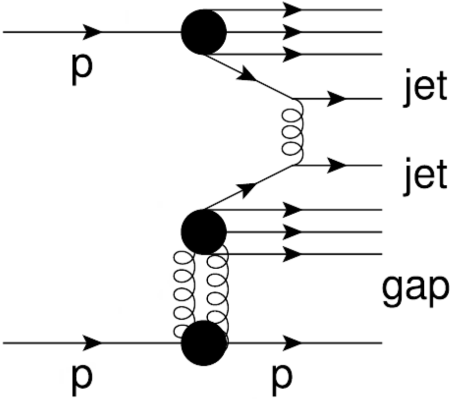
- Use dense objects to look for saturation: Pb instead of protons
- Dedicated observables to look for saturation: particle production in the forward region (F. Deganutti, C. Royon, S. Schlichting, JHEP 01 (2024) 159)
- Study effects of saturation for vector meson, c, b quark production

Diffraction and γ-exchange processes: Measuring intact protons in CMS-TOTEM and PPS



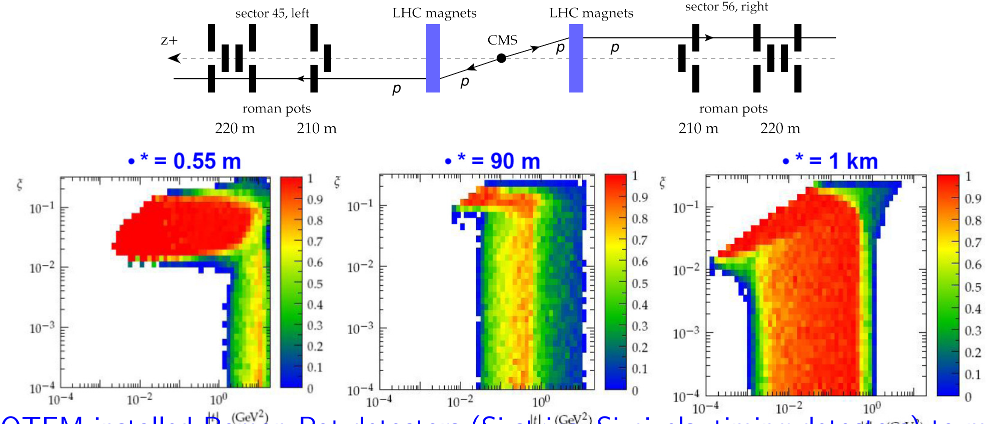
- TOTEM installed Roman Pot detectors to measure intact protons after collisions at the CMS interaction point on both sides of CMS
- CMS-TOTEM: Low-luminosity runs
- Proton Precision Spectrometer (PPS): High luminosity runs (115 fb^{-1} up to now)

Kinematics: the example of single diffractive events



- t: 4-momentum transfer squared
- ξ: proton fractional momentum loss (momentum fraction of the proton carried by the pomeron)
- $\beta = x_{Bj}/\xi$: Bjorken-x of parton inside the pomeron
- $M^2 = s\xi$: diffractive mass produced ($M^2 = s\xi_1\xi_2$ in case of double pomeron exchange)
- $\Delta y_{1,2} \sim \Delta\eta \sim \log 1/\xi_{1,2}$: rapidity gap

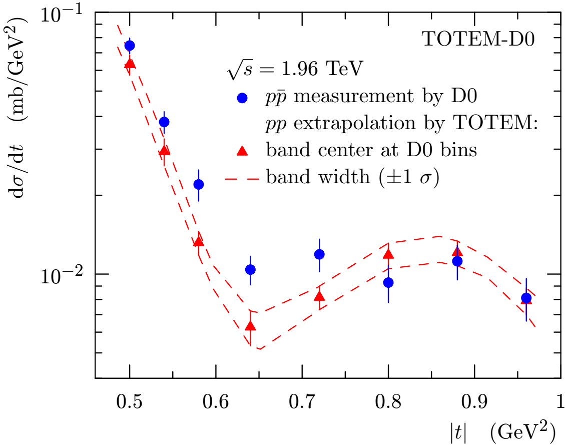
Different beam configurations at the LHC



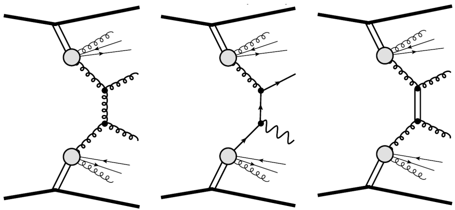
- TOTEM installed Roman Pot detectors (Si strips, Si pixels, timing detectors) to measure intact protons after collisions at the CMS interaction point on both sides of CMS
- High β^* (90 m for instance): good acceptance down to low ξ, low diffractive masses

Elastic D0 pp and TOTEM $p\bar{p}$ data: The odderon discovery

- Comparison between extrapolated TOTEM data and D0 measurement
- σ_{tot} and ρ measurements from TOTEM at 13 TeV $\rightarrow$ Odderon discovery



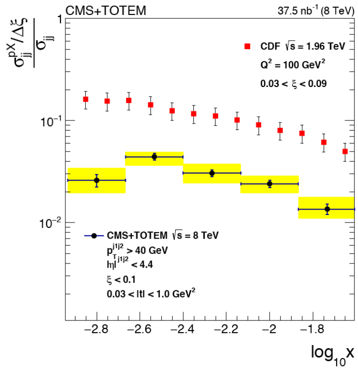
Hard diffraction at the LHC

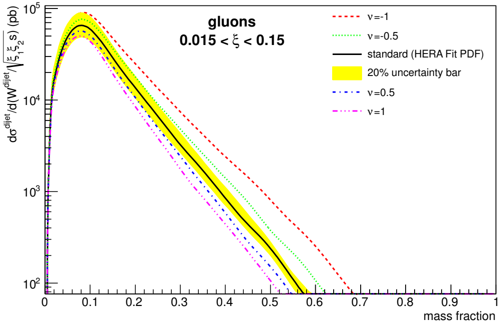


- Dijet production: dominated by gg exchanges
- γ+jet production and W production: dominated by qg exchanges
- Jet gap jet in diffraction: Probe BFKL

- **Question 1**: Is it the same object which explains diffraction in pp and ep? What is the role of MPI, soft interactions?
- **Question 2**: Further constraints on the structure of the Pomeron as was determined at HERA
- **Question 3**: Survival probability: difficult to compute theoretically, needs to be measured, inclusive diffraction is optimal place for measurement

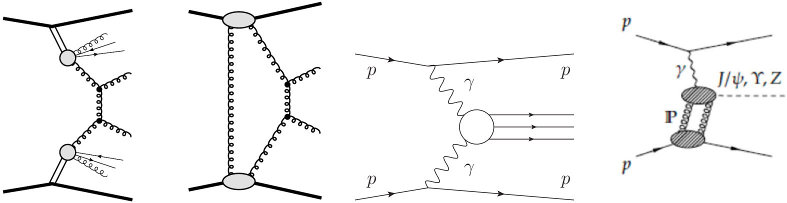
Inclusive diffractive jet measurements





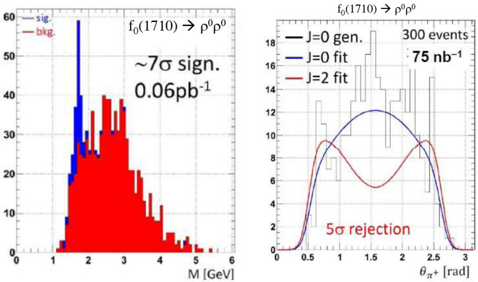
- CMS SD dijet studies at 8 TeV
- Measure SD and DPE dijets with protons in TOTEM in high β^* runs
- Sensitivity to gluon density in Pomeron especially the gluon density on Pomeron at high β: multiply the gluon density by $(1-\beta)^\nu$ with $\nu = -1, ..., 1$

Exclusive diffraction



- 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

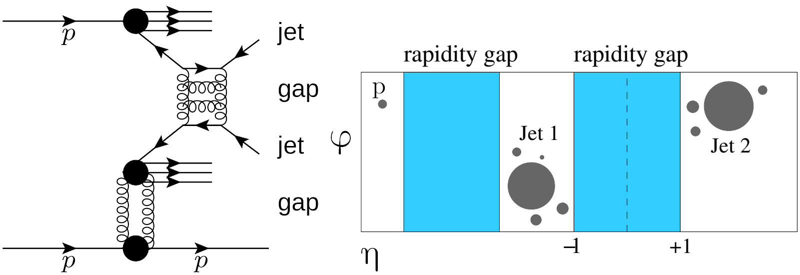
Low mass diffraction: search for glueballs



- 1-10 GeV masses can be probed diffractively ($\xi \sim 10^{-4} - 10^{-3}$), ensuring pure gluonic exchanges
- Check the $f_0(1500)$ or $f_0(1710)$ glueball candidates

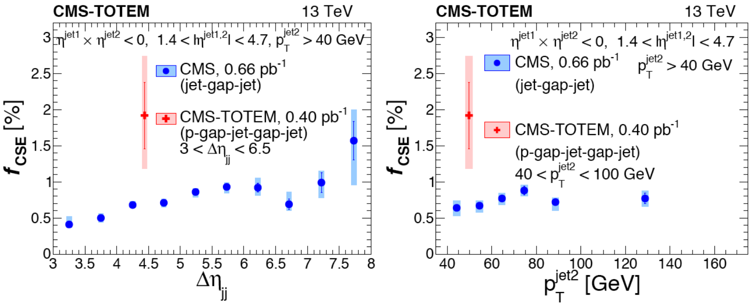
- Lattice calculations predict a $0++$ glueball at 1.7 GeV with a ∼100 MeV uncertainty, favoring the $f_0(1710)$ candidate
- Simulation of signal ($f_0(1710) \to \rho^0\rho^0$ and non resonant $\rho^0\rho^0$ background including CMS tracker performance (20-30 MeV resolution): needs ~ 0.06 pb^{-1} for 7 σ signal; need about 0.6 pb^{-1} for decay characterisation
- Spin analysis of $f_0(1710) \to \rho^0\rho^0 \to 4\pi$ to determine $J = 0$ or 2: as an example polar angle of the $\pi^+\pi^-$ pair for the ρ candidate; spin analysis in mass bins < 40 MeV needs ~ 5 pb^{-1}

Jet gap jet events in diffraction (CMS/TOTEM)



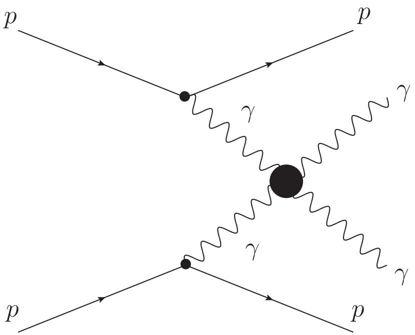
- Jet gap jet events: powerful test of BFKL resummation C. Marquet, C. Royon, M. Trzebinski, R. Zlebcík, Phys. Rev. D 87 (2013) 3, 034010
- Subsample of gap between jets events requesting in addition at least one intact proton on either side of CMS
- **Jet gap jet events were observed for the 1st time by CMS!** (Phys.Rev.D 104 (2021) 032009)

First observation of jet gap jet events in diffraction (CMS/TOTEM)



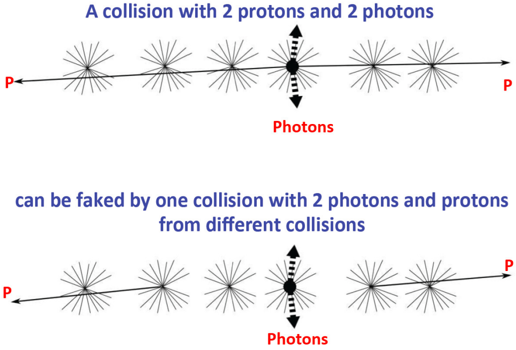
- First observation: 11 events observed with a gap between jets and at least one proton tagged with ~ 0.7 pb^{-1}
- Leads to very clean events for jet gap jets since MPI are suppressed and might be the "ideal" way to probe BFKL
- Would benefit from more stats $>$10 pb^{-1} needed, 100 for DPE

Search for extra dimensions in the universe using $\gamma\gamma$ and two intact protons



- Search for production of two photons and two intact protons in the final state: $pp \rightarrow p\gamma\gamma p$
- Number of events predicted to be increased by extra-dimensions, dark matter particles...
- Discovering those extra-dimensions would be a very fundamental discovery in physics
- Look in other channels: WW, ZZ, $Z\gamma$..

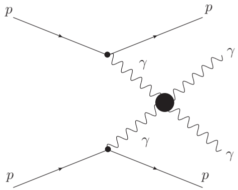
So what is pile up at LHC?

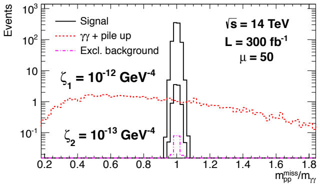


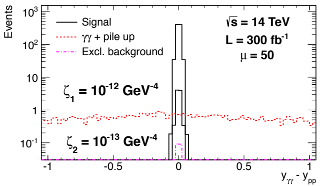
- The LHC collides packets of protons
- Due to high number of protons in one packet, there can be more than one interaction between two protons when the two packets collide
- Typically up to 50 pile up events

Example of an analysis

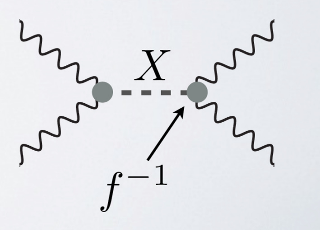
- We detect all produced particles after interaction: two intact protons and two photons
- Any observation would be a discovery!: no background by requesting same energy balance between the two photons and the two protons

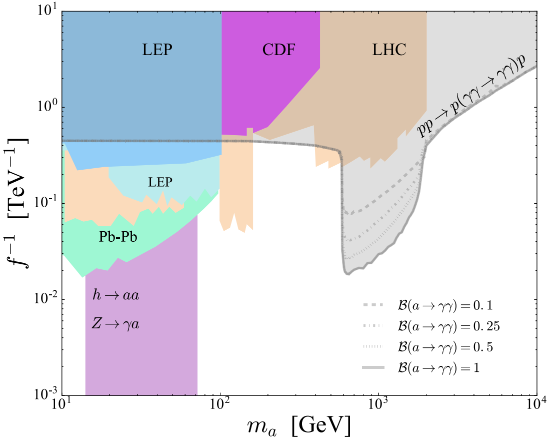






Looking for example for axion-like particles candidates decaying into two photons





Conclusion

- Mini-jets emission between Mueller Navelet jets: New variables to probe QCD dynamics
- Measurement of jet gap jet fraction at Tevatron and LHC
- BFKL predictions very sensitive to Initial State Radiation as described in PYTHIA especially for gg interaction processes: Too much ISR at high angle predicted by PYTHIA, should be tuned further using for instance J/Ψ-gap-J/Ψ events
- First calculation of Mueller Tang processes including NLO impact factors
- Diffractive and photon-exchange processes at the LHC