Physics with tagged protons at the LHC

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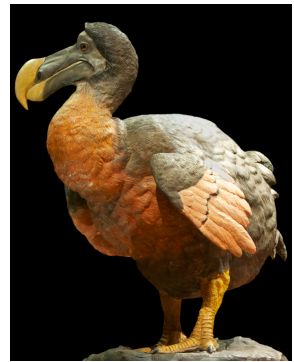
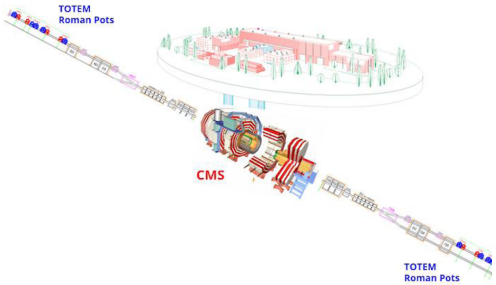


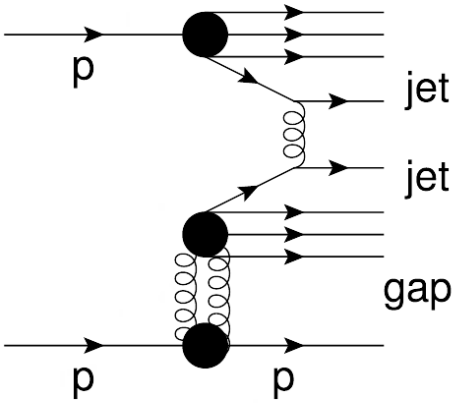
- Soft and low mass diffraction
- Hard diffraction at the LHC and the pomeron structure
- BFKL dynamics at the LHC
- Anomalous coupling studies at the LHC

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



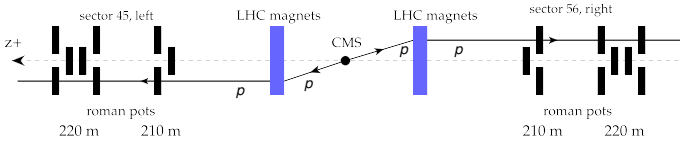
- TOTEM installed Roman Pot detectors to measure intact protons after collisions at the CMS interaction point on both sides of CMS
- CMS-TOTEM: Low-luminosity runs
- Proton Precision Spectrometer (PPS): High luminosity runs (115 fb^{-1} up to now)

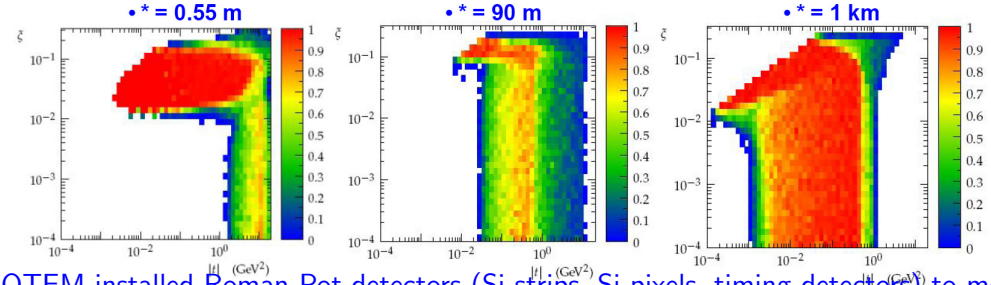
Kinematics: the example of single diffractive events



- 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

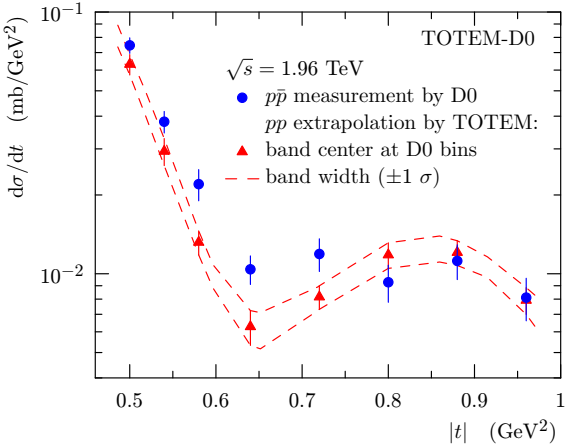




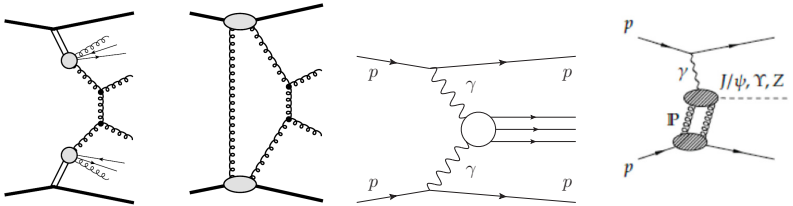
- TOTEM installed Roman Pot detectors (Si strips, Si pixels, timing detectors) to measure intact protons after collisions at the CMS interaction point on both sides of CMS
- High β^* (90 m for instance): good acceptance down to low ξ, low diffractive masses

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 (see Frici's talk)

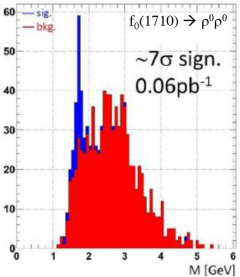


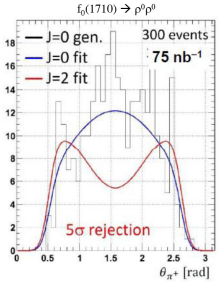
Exclusive diffraction



- 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



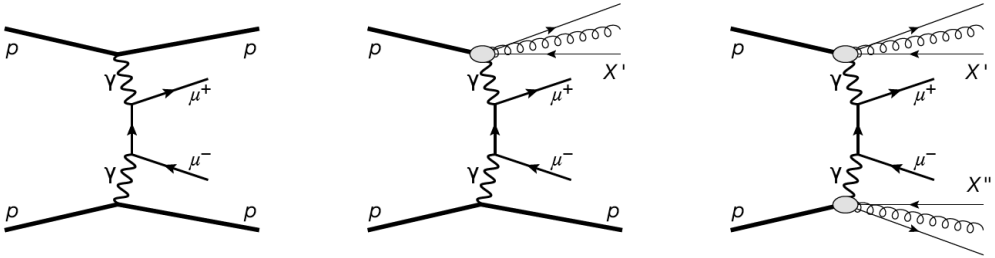


- 1-10 GeV masses can be probed diffractively ($\xi \sim 10^{-4} - 10^{-3}$), ensuring pure gluonic exchanges
- Check the $f_0(1500)$ or $f_0(1710)$ glueball candidates

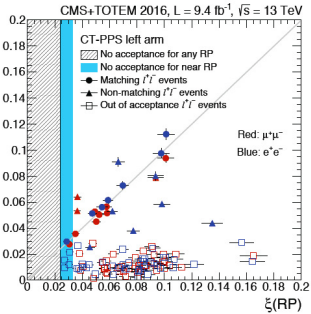
- Lattice calculations predict a $0++$ glueball at 1.7 GeV with a ~100 MeV uncertainty, favoring the $f_0(1710)$ candidate
- Simulation of signal ($f_0(1710) \to \rho^0\rho^0$ and non resonant $\rho^0\rho^0$ background including CMS tracker performance (20-30 MeV resolution): needs $\sim$ 0.06 pb^{-1} 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 $\sim$ 5 pb^{-1}

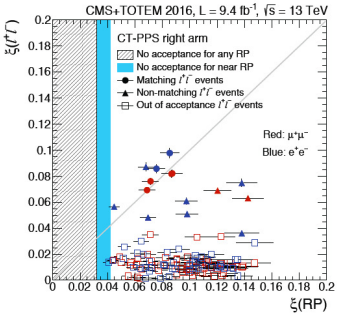
Low mass exclusive diffraction

- Measure exclusive production of low mass particles, π, K, etc, using special runs at low luminosity at the LHC at high β^* in order to detect intact protons in TOTEM roman pots
- Many million events collected in a few days at LHC, EIC
- Search for exclusive di-muon production: QED γ-exchange process



Quasi-exclusive dilepton production

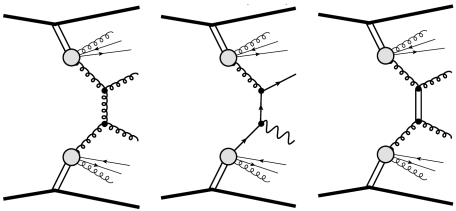




- First measurement of semi-exclusive dilepton process with proton tag by CMS-TOTEM: 12 (resp. 8) events with $< 2\sigma$ matching in the $\mu\mu$ (res. ee) channel

- Significance $> 5\sigma$ for observing 20 events for a background of 3.85
- Observation of quasi-exclusive di-lepton (e and μ) by ATLAS using 14.6 fb^{-1} at 13 TeV
- 57 (123) events are observed in ee ($\mu\mu$) channels $> 5\sigma$ evidence
- $\sigma_{ee+p} = 11.0 \pm 2.6$ (stat) ± 1.2 (syst) ± 0.3 (lumi) fb and $\sigma_{\mu\mu+p} = 7.2 \pm 1.6$ (stat) ± 0.9 (syst) ± 0.2 (lumi) fb
- Also important to check alignment of roman pots

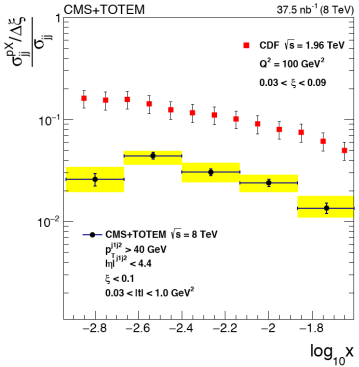
Hard diffraction at the LHC

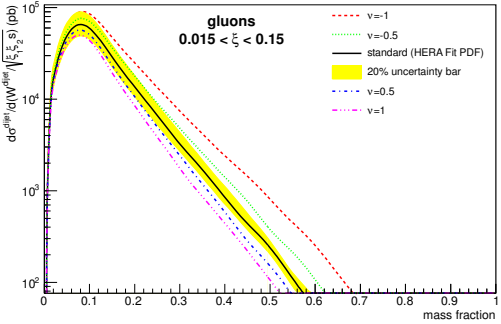


- Dijet production: dominated by gg exchanges
- γ+jet production and W production: dominated by qg exchanges
- Jet gap jet in diffraction: Probe BFKL

- **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

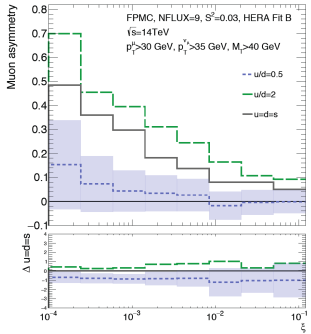
Inclusive diffractive jet measurements



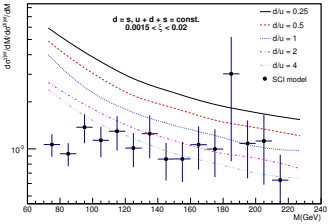


- CMS SD dijet studies at 8 TeV
- Measure SD and DPE dijets with protons in TOTEM in high β^* runs
- Sensitivity to gluon density in Pomeron especially the gluon density on Pomeron at high β: multiply the gluon density by $(1-\beta)^\nu$ with $\nu = -1, ..., 1$

Sensitivity to quark densities: W asymmetries and γ+jet measurement

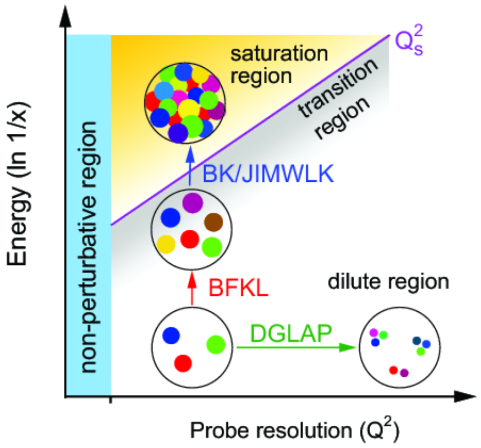


- Measure the average W charge asymmetry to probe the quark content of the proton:
  $A = (N_{W^+} - N_{W^-})/(N_{W^+} + N_{W^-})$



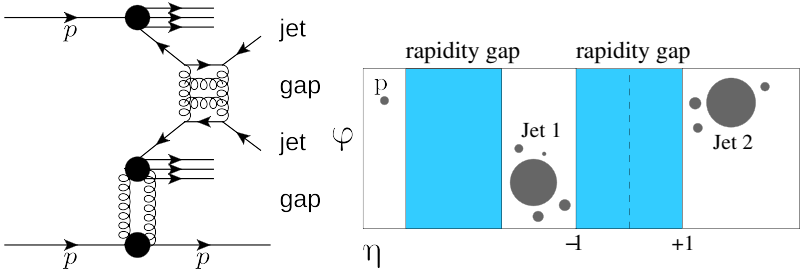
- Measure SD and DPE γ+jet divided by dijet cross section at the LHC
- Soft models predict different ratios from pomeron models
- Sensitivity to quark density, and of assumption: $u = d = s = \bar{u} = \bar{d} = \bar{s}$ used in QCD fits at HERA

Looking for BFKL resummation effects



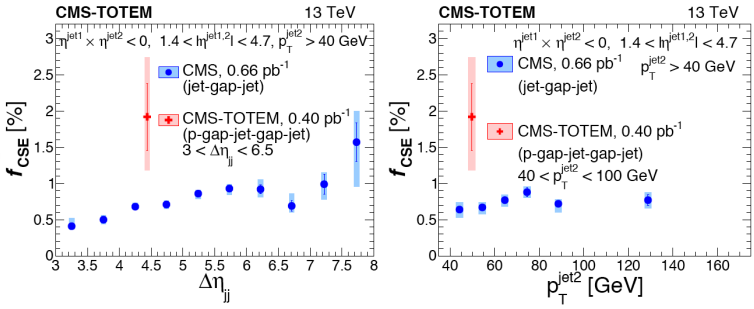
- DGLAP (Dokshitzer Gribov Lipatov Altarelli Parisi): Evolution in resolution Q^2, resums terms in $\alpha_S \log Q^2 \rightarrow$ resolving "smaller" partons at high Q
- BFKL (Balitski Fadin Kuraev Lipatov (BFKL): Evolution in energy x, resums terms in $\alpha_S \log 1/x \rightarrow$ Large parton densities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

Jet gap jet events in diffraction



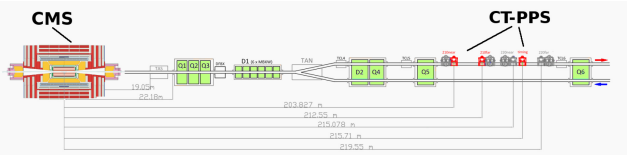
- TOTEM roman pots detectors on both sides of CMS allow to measure intact protons in the final state
- Subsample of gap between jets events requesting in addition at least one intact proton on either side of CMS
- **Jet gap jet events in diffraction were observed for the 1st time by CMS!**

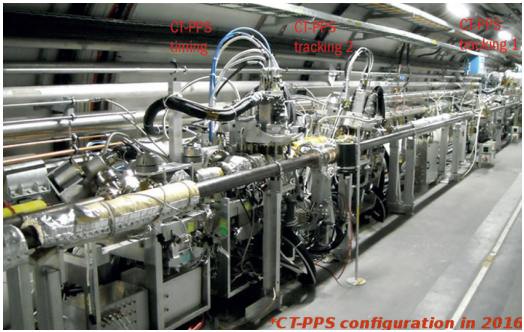
First observation of jet gap jet events in diffraction



- 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

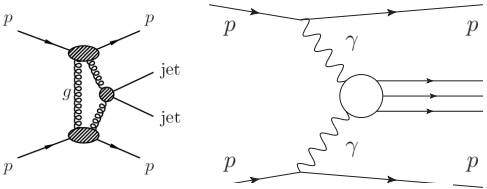
PPS: Detecting intact protons at high luminosity

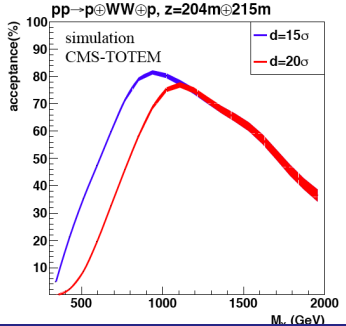




- Joint CMS and TOTEM project: https://cds.cern.ch/record/1753795
- LHC magnets bend scattered protons out of the beam envelope
- Detect scattered protons a few *mm* from the beam on both sides of CMS: 2016-2018, $\sim$ 115 fb^{-1} of data collected

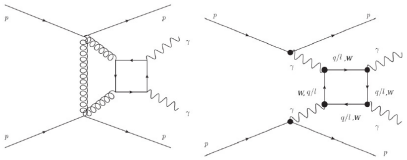
Detecting intact protons in PPS at high luminosity (low β^*)

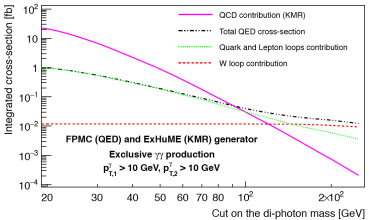




- Tag and measure protons in PPS
- All diffractive/ photon-induced cross sections computed using the Forward Physics Monte Carlo (FPMC)
- Acceptance in mass shown for standard low β^* running at the LHC: complementarity with high β^* running
- Possibility of detecting "invisible" objects using the missing mass of the protons? High missing mass, nothing in CMS, needs some ZDC detector at high rapidity with timing detectors to veto very forward low p_T particles emitted from main interaction, not easy!

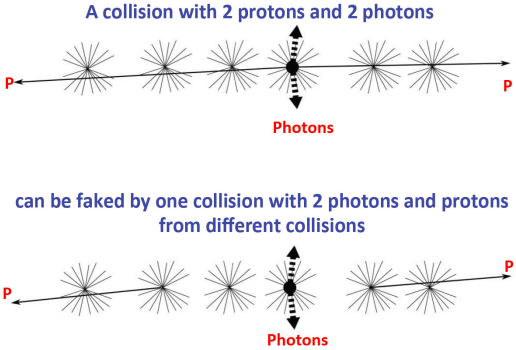
$\gamma\gamma$ exclusive production: SM contribution





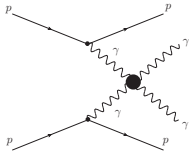
- QCD production dominates at low $m_{\gamma\gamma}$, QED at high $m_{\gamma\gamma}$
- Important to consider W loops at high $m_{\gamma\gamma}$
- At high masses (> 200 GeV), the photon induced processes are dominant
- **Conclusion: Two photons and two tagged protons means photon-induced process**

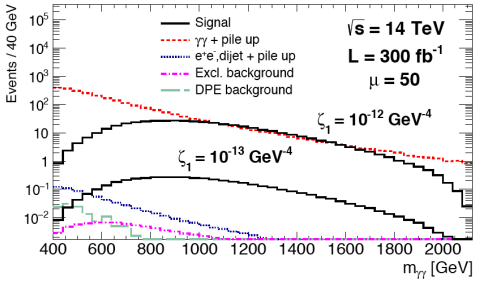
So what is pile up at LHC?



- 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

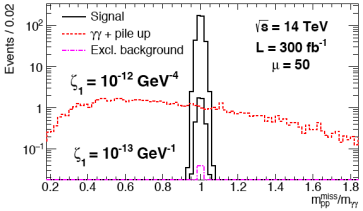
Search for quartic $\gamma\gamma$ anomalous couplings

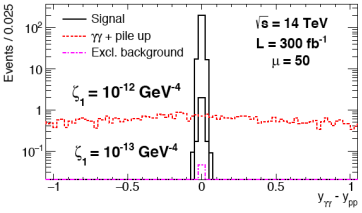




- Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- Analysis performed at hadron level including detector efficiencies, resolution effects, pile-up...
- Anomalous coupling events appear at high di-photon masses
- S. Fichet, G. von Gersdorff, B. Lenzi, C.R., M. Saimpert ,JHEP 1502 (2015) 165

Search for quartic $\gamma\gamma$ anomalous couplings

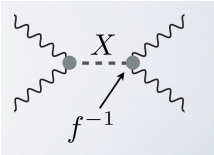


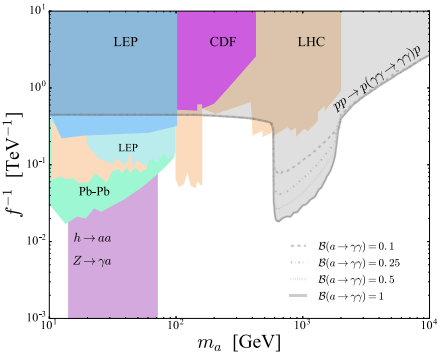


Cut / Process	Signal (full)	Signal with (without) f.f (EFT)	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15,$ $p_{T1,(2)} > 200, (100)$ GeV]	65	18 (187)	0.13	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	64	17 (186)	0.10	0	0.2	1023
$[p_{T2}/p_{T1} > 0.95,$ $\lvert\Delta\phi\rvert > \pi - 0.01]$	64	17 (186)	0.10	0	0	80.2
$\sqrt{\xi_1\xi_2 s} = m_{\gamma\gamma} \pm 3\%$	61	16 (175)	0.09	0	0	2.8
$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	60	12 (169)	0.09	0	0	0

- No background after cuts for 300 fb^{-1}: sensitivity up to a few 10^{-15}, better by 2 orders of magnitude with respect to "standard" methods
- Exclusivity cuts using proton tagging needed to suppress backgrounds (Without exclusivity cuts using CT-PPS: background of 80.2 for 300 fb^{-1})

Search for axion like particles

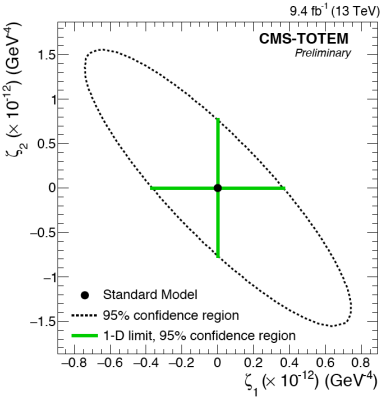




- Production of ALPs via photon exchanges and tagging the intact protons in the final state complementary to the usual search at the LHC (Z decays into 3 photons): sensitivity at high ALP mass, C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, ArXiv 1803.10835, JHEP 1806 (2018) 131
- Complementarity with Pb Pb running: sensitivity to low mass diphoton, low luminosity but cross section increased by Z^4

First search for quartic $\gamma\gamma\gamma\gamma$ anomalous couplings (CMS)

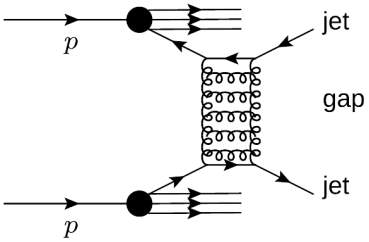
- 1st search for quartic $\gamma\gamma\gamma\gamma$ anomalous couplings in CMS with 9.2 fb^{-1}
- First limits on quartic anomalous couplings:
- Analysis with more than 100 fb^{-1} in progress
- Analysis in many different exclusive channels in progress: $\gamma\gamma$, $Z\gamma$, WW, ZZ, $t\bar{t}$, etc...

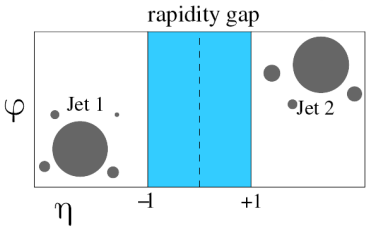


Conclusion

- Many physics results performed and in progress at the LHC in diffraction and γ-exchange events
- Low mass diffraction: discovery of the odderon, looking for low mass particle production including glueballs
- Low mass QED dilepton production: to be also used for calibration
- First observation of jet gap jet events in diffraction
- High mass exclusive $\gamma\gamma$, $Z\gamma$, WW, ZZ, $t\bar{t}$ production and sensitivity to new physics

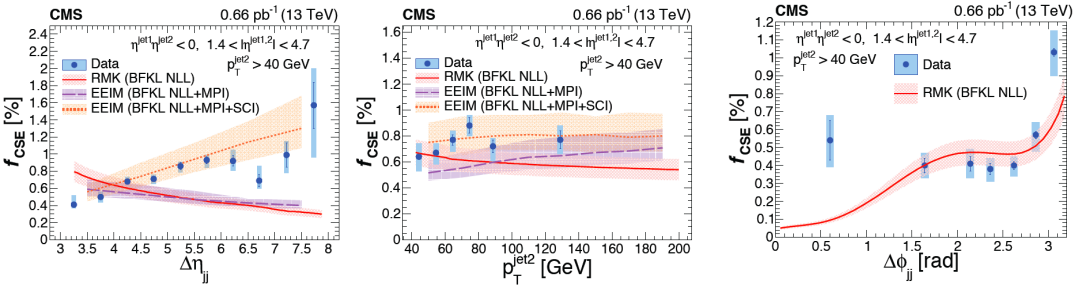
Looking for BFKL resummation effects: Gap between jets





- 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

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)