Measuring intact protons at the LHC: from the odderon discovery to the search for axion-like particles

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DESY colloquium

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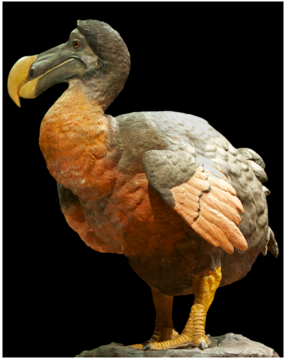
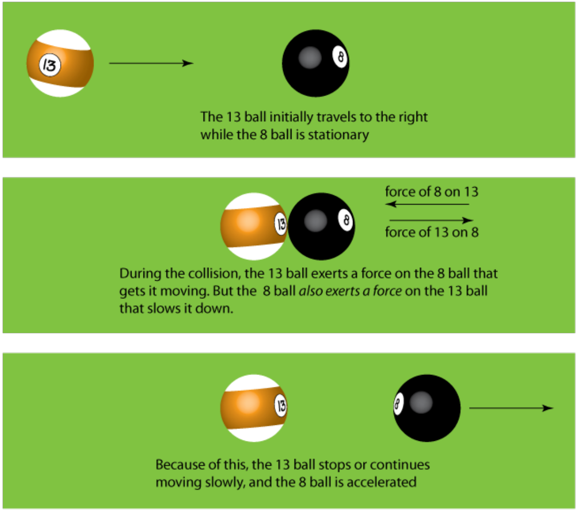


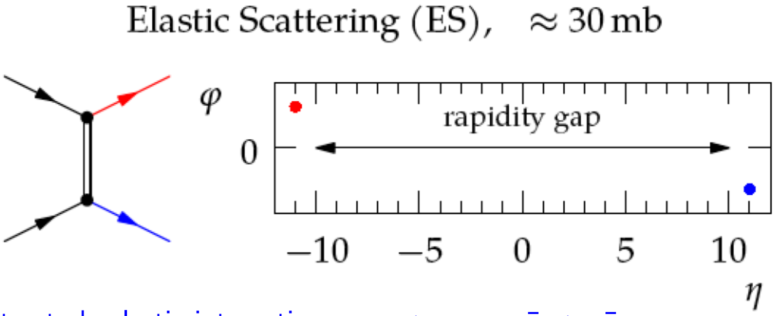
- Elastic interactions and introduction to the Odderon
- D0 $p\bar{p}$ and TOTEM pp data
- The odderon discovery
- Study of quartic anomalous couplings and search for axion-like particles
- Ultra Fast Silicon detectors

What is elastic scattering? The pool game...



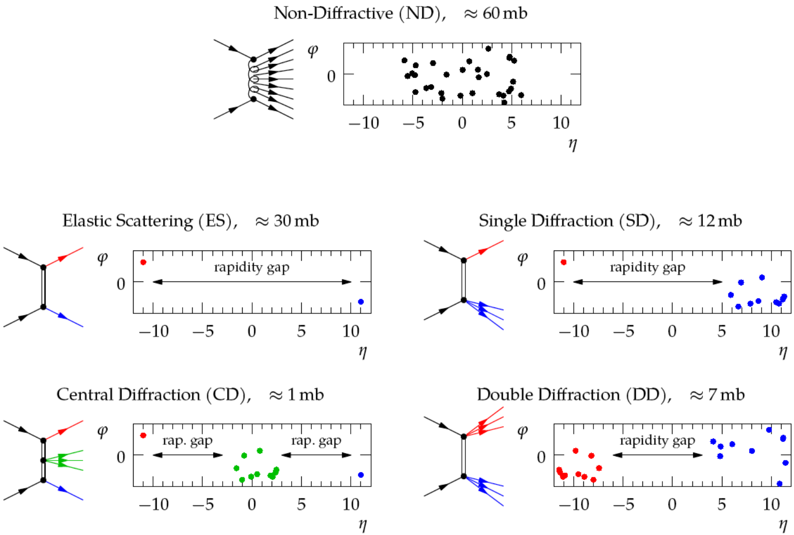
- We want to study "elastic" collisions between protons and proton-antiprotons
- In high energy physics: $pp \to pp$ and $p\bar{p} \to p\bar{p}$
- In these interactions, each proton/antiproton remains intact after interaction but are scattered at some angles and can lose/gain some momentum as in the pool game

What do we want to study?

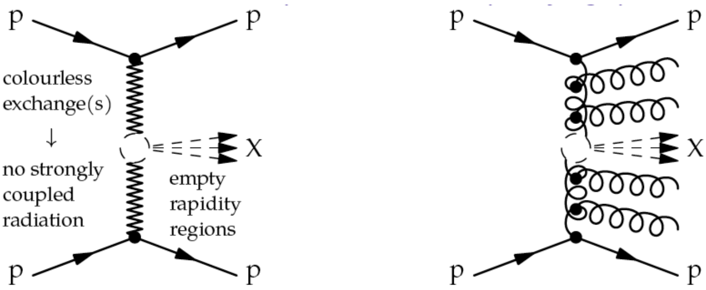


- We want to study elastic interactions: $pp \to pp$ or $p\bar{p} \to p\bar{p}$
- These are very clean events, where nothing is produced outside the two protons
- How to detect/measure these events? We need to detect the intact protons after interaction!
- Interactions explained by the exchange of a colorless object ($\geq$ 2 gluons, photon, etc...) between the two protons

Physics classification: what can we measure in *pp* interactions?

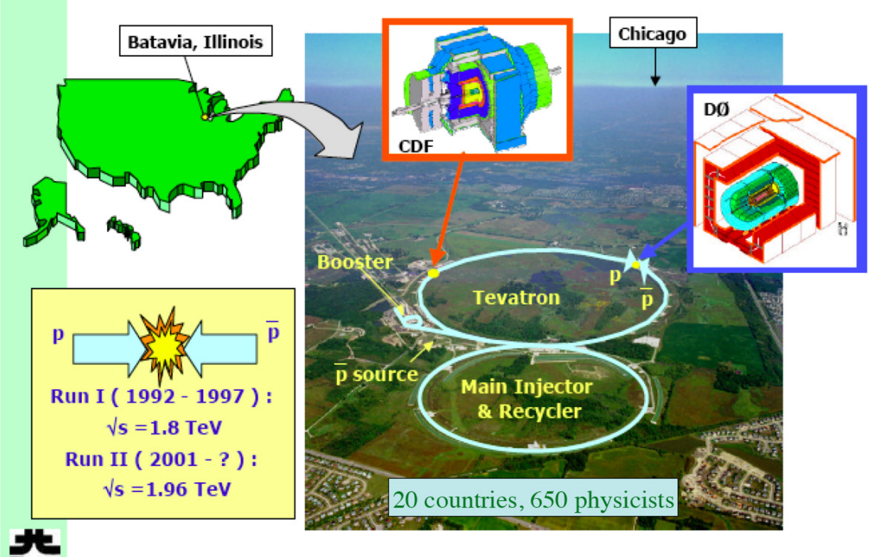


How to explain the fact that protons can be intact?



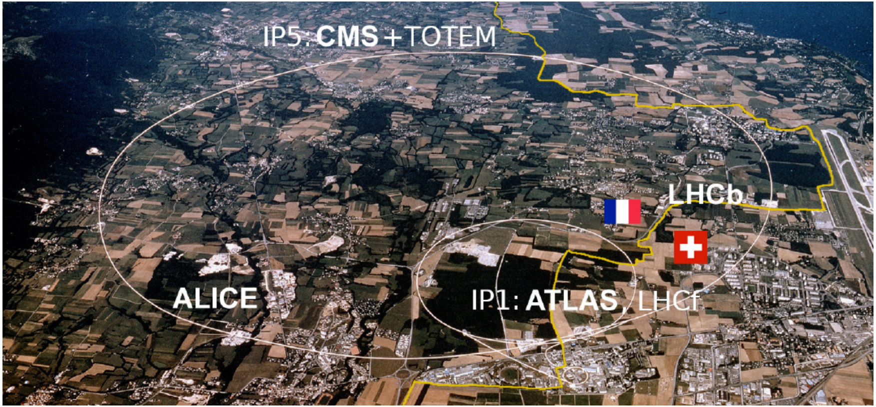
- Quarks/gluons radiate lots of gluons when one tries to separate them (confinement)
- Gluons exchange color, interact with other gluons in the proton and in that case protons are destroyed in the final state
- In order to explain how protons can remain intact: we need colorless exchanges, or at least 2 gluons to be exchanged

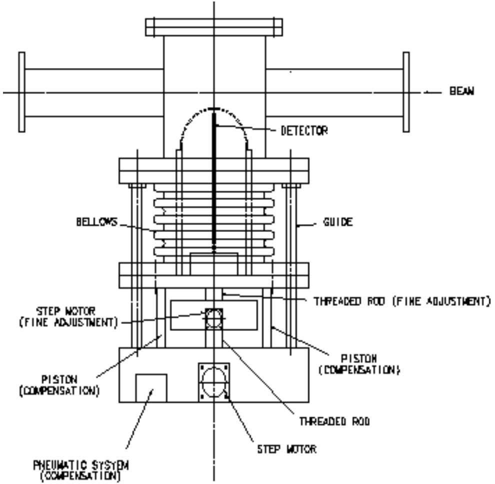
$p\bar{p}$ interactions: the Tevatron



pp interactions: The Large Hadron Collider at CERN

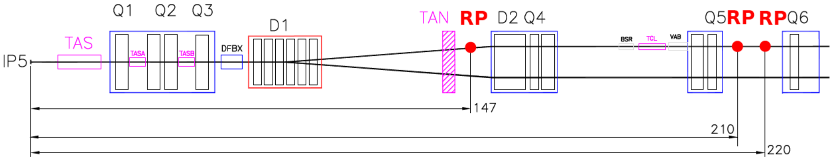
- Large Hadron Collider at CERN: proton proton collider with 2.76, 7, 8 and 13 TeV center-of-mass energy
- Circonference: 27 km; Underground: 50-100 m





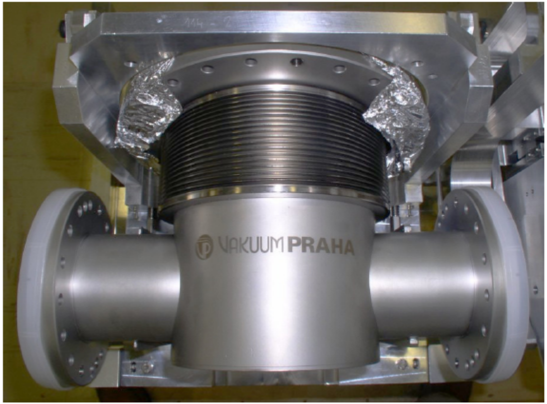
- We use special detectors to detect intact protons/ anti-protons called Roman Pots
- These detectors can move very close to the beam (up to 3σ) when beam are stable so that protons scattered at very small angles can be measured

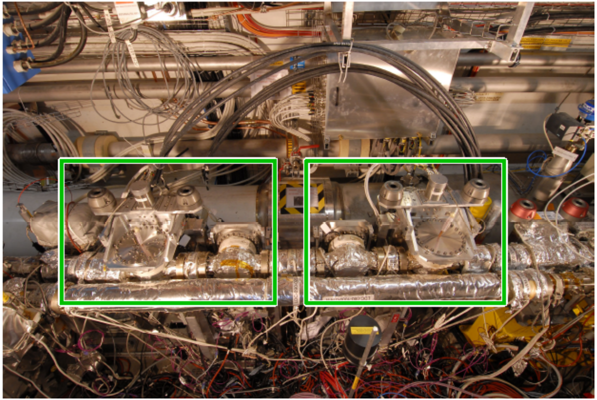
- dipoles (D): bending
- quadrupoles (Q): (de)focusing



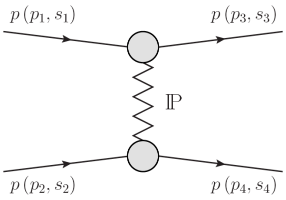
- But why are the protons/anti-protons not in the beam (which would prevent detection)?
- As we saw in the pool game, p or $\bar{p}$ are scattered at small angles and thus can be detected in the dedicated roman pot detectors
- NB: in non-elastic diffractive case with some particles produced in CMS $pp \to pXp$, p and $\bar{p}$ lose part of their energy and we use the LHC/Tevatron magnets as a spectrometer $p/\bar{p}$ at smaller v, so they have a smaller bending radius than the $p/\bar{p}$ from the beam

Roman Pot detectors at the LHC





The odderon in a nutshell

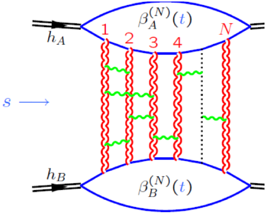


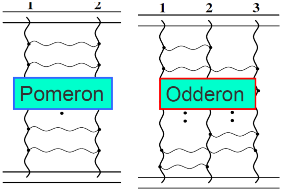
- Let us assume that elastic scattering can be due to exchange of colorless objects: Pomeron and Odderon
- Charge parity C: Charge conjugation changes the sign of all quantum charges
- Pomeron and Odderon correspond to positive and negative C parity: Pomeron is made of two gluons which leads to a $+1$ parity whereas the odderon is made of 3 gluons corresponding to a -1 parity
- Scattering amplitudes can be written as:

$$\begin{aligned} A_{pp} &= Even + Odd \\ A_{p\bar{p}} &= Even - Odd \end{aligned}$$

- From the equations above, it is clear that observing a difference between pp and $p\bar{p}$ interactions would be a clear way to observe the odderon

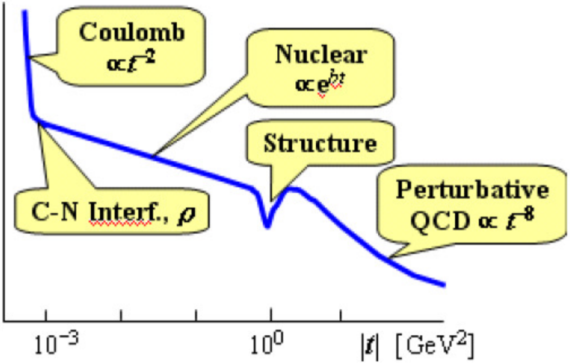
What is the odderon? The QCD picture





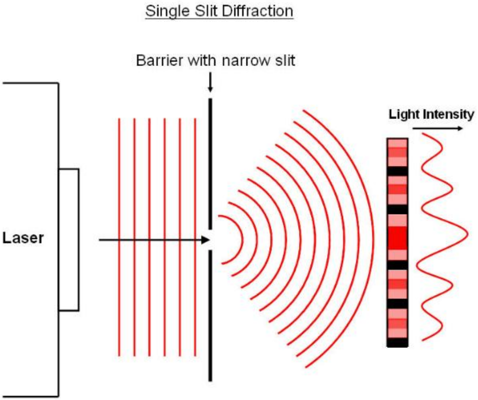
- Multi-gluon exchanges in hadron-hadron interactions in elastic *pp* interactions (Bartels-Kwiecinski-Praszalowicz)
- From B. Nicolescu: The Odderon is defined as a singularity in the complex plane, located at $J = 1$ when $t = 0$ and which contributes to the odd crossing amplitude
- Leads to contributions on 3,... gluon exchanges in terms of QCD for the perturbative odderon
- Colorless C-odd 3-gluon state (odderon) predicts differences in elastic $d\sigma/dt$ for pp and $p\bar{p}$ interactions since it corresponds to different amplitudes/ interferences

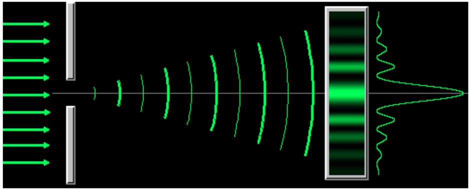
Measurement of elastic scattering at Tevatron and LHC



- Study of elastic $pp \to pp$ reaction: exchange of momentum between the two protons which remain intact
- Measure intact protons scattered close to the beam using Roman Pots installed both by D0 and TOTEM collaborations
- From counting the number of events as a function of $|t|$ (4-momentum transferred square at the proton vertex measured by tracking the protons), we get $d\sigma/dt$

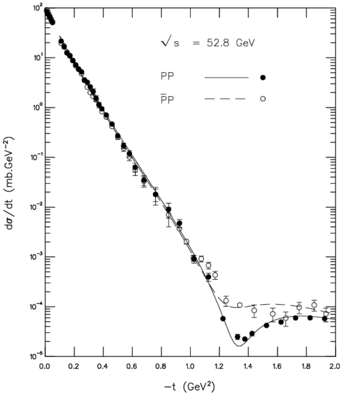
Why do we see maxima (bumps) and minima (dips): analogy with optics





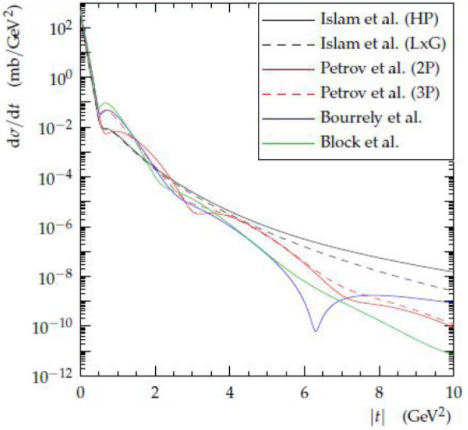
- $|t|$ distribution expected to show maxima (bump) and minima (dip)
- Analogy with optics: analogous to the pattern of dips and bumps that can be seen when shining light against a slit (diffraction)

Why has the odderon not been observed yet? Why is it so elusive?



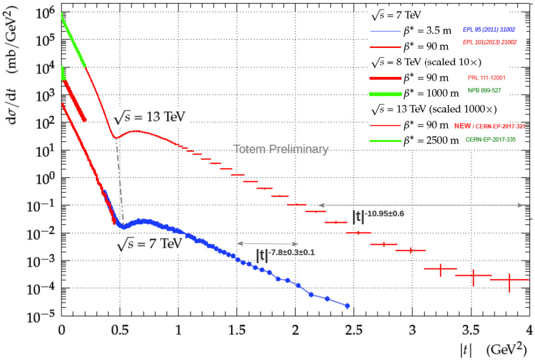
- The situation is not that simple: elastic scattering at low energies can be due to exchanges of additional particles to pomeron/odderon: ρ, ω, ϕ, reggeons...
- How to distinguish between all these exchanges? Not easy...
- At ISR energies, there was already some indication of a possible difference between pp and $p\bar{p}$ interactions, differences of about 3σ between pp and $p\bar{p}$ interactions but this was not considered to be a clean proof of the odderon because of these additional reggeon, meson exchanges at low $\sqrt{s}$

What is the expected situation at the LHC?



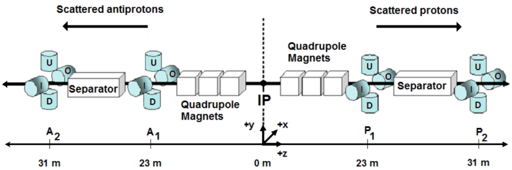
- Expected elastic $d\sigma/dt$ before LHC measurements
- Many different predictions including many possible contributions at high $|t|$, such as pomeron, reggeon, mesons (ω, ϕ) whereas other predictions mentioned that, at high energies, we should be more asymptotical and pomeron dominated
- Almost nobody thought about the odderon (except a few theorists such as Martynov, Nicolescu...)

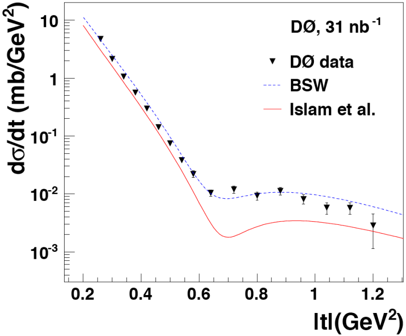
Are we in the asymptotic regime at the LHC?



- Contrary to what some models expected before LHC, the elastic cross section is smooth: we do not see reggeons, mesons...!
- Effects of reggeon, meson exchanges are negligible at LHC energies: we can concentrate on pomeron/odderon studies!
- We can directly look for the existence of the odderon by comparing pp and $p\bar{p}$ elastic cross sections at very high energies: 1.96 TeV (Tevatron), 2.76, 7, 8, 13 (LHC)

D0 elastic $p\bar{p}$ $d\sigma/dt$ cross section measurements

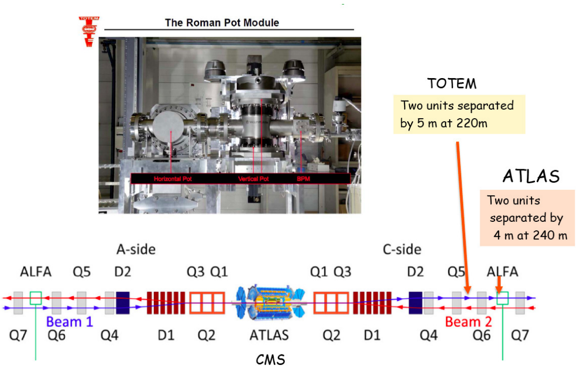




- D0 collected elastic $p\bar{p}$ data with intact p and $\bar{p}$ detected in the Forward Proton Detector with 31 nb^{-1} Phys. Rev. D 86 (2012) 012009
- Measurement of elastic $p\bar{p}$ $d\sigma/dt$ at 1.96 TeV for $0.26 < |t| < 1.2$ GeV^2

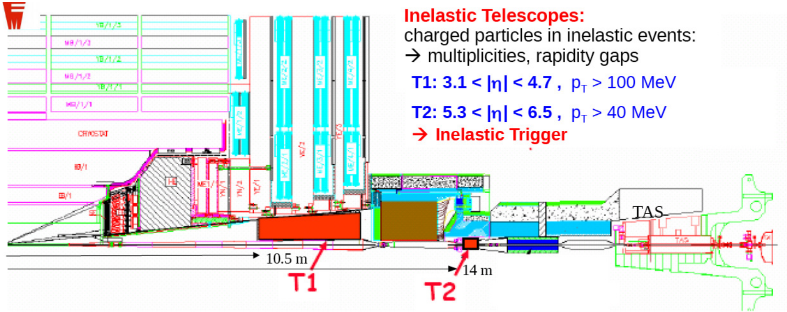
Elastic cross section measurements at the LHC: detecting protons!

- Measurement of $pp \to pp$ elastic cross section by detecting intact protons and vetoing on activity in the main CMS detector
- TOTEM installed vertical Roman Pot detectors at 220 m from CMS



- Trigger on elastic collisions using proton in back-to-back configurations: Up (Down) on one side, Down (Up) on the other side

Forward coverage in CMS-TOTEM



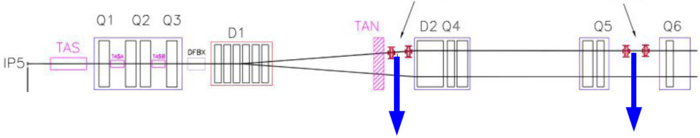
Inelastic Telescopes:
charged particles in inelastic events:
→ multiplicities, rapidity gaps

T1: $3.1 < |\eta| < 4.7$, $p_T > 100$ MeV

T2: $5.3 < |\eta| < 6.5$, $p_T > 40$ MeV

→ Inelastic Trigger

Roman Pots: elastic & diffractive protons close to outgoing beams **→ Proton Trigger**

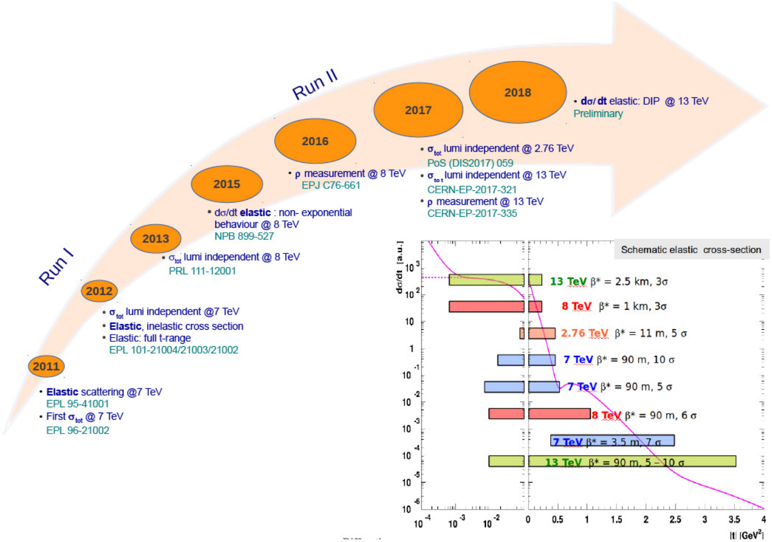


Roman Pot stations in the LHC tunnel
(before LS1)

RP (147 m)

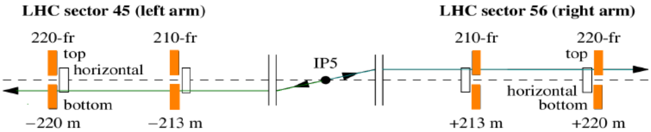
RP (220m)

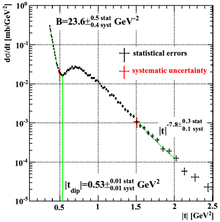
TOTEM cross section measurements

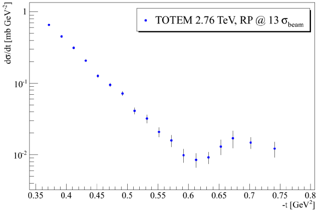


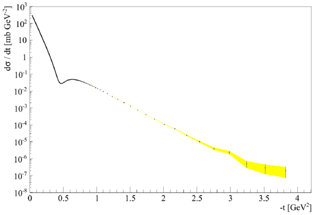
TOTEM elastic pp $d\sigma/dt$ cross section measurements

- Elastic pp $d\sigma/dt$ measurements: tag both intact protons in TOTEM Roman Pots 2.76, 7, 8 and 13 TeV
- Very precise measurements at 2.76, 7, 8 and 13 TeV: Eur. Phys. J. C 80 (2020) no.2, 91; EPL 95 (2011) no. 41004; Nucl. Phys. B 899 (2015) 527; Eur. Phys. J. C79 (2019) no.10, 861

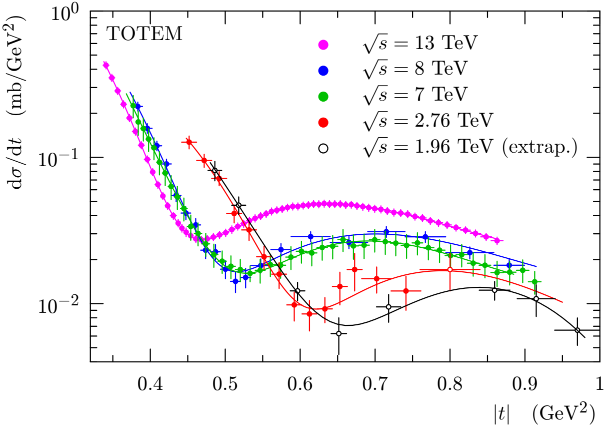






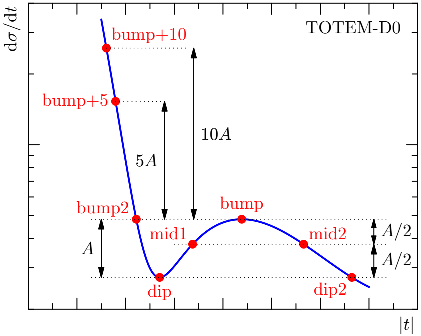


Strategy to compare pp and $p\bar{p}$ data sets



- In order to identify differences between pp and $p\bar{p}$ elastic $d\sigma/dt$ data, we need to compare TOTEM measurements at 2.76, 7, 8, 13 TeV and D0 measurements at 1.96 TeV
- All TOTEM $d\sigma/dt$ measurements show the same features, namely the presence of a dip and a bump in data, whereas D0 data do not show this feature

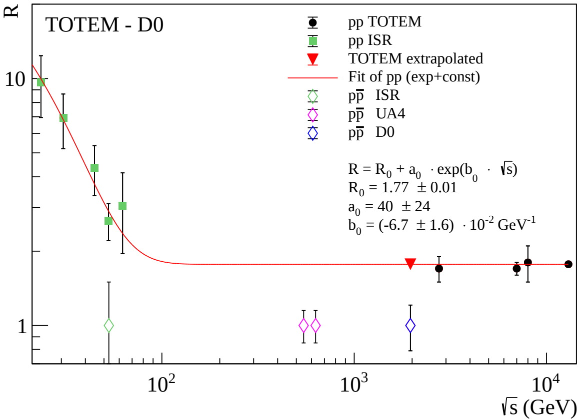
Reference points of elastic $d\sigma/dt$



- Define 8 characteristic points of elastic *pp* $d\sigma/dt$ cross sections (dip, bump...) that are feature of elastic *pp* interactions

- Determine how the values of $|t|$ and $d\sigma/dt$ of characteristic points vary as a function of $\sqrt{s}$ in order to predict their values at 1.96 TeV
- We use data points closest to those characteristic points (avoiding model-dependent fits)
- Data bins are merged in case there are two adjacent dip or bump points of about equal value
- This gives a distribution of t and $d\sigma/dt$ values as a function of $\sqrt{s}$ for all characteristic points

Bump over dip ratio



- Bump over dip ratio measured for *pp* interactions at ISR and LHC energies
- Bump over dip ratio in *pp* elastic collisions: decreasing as a function of $\sqrt{s}$ up to $\sim$ 100 GeV and flat above
- D0 $p\bar{p}$ shows a ratio of 1.00$\pm$0.21 given the fact that no bump/dip is observed in $p\bar{p}$ data within uncertainties: **more than 3σ difference between *pp* and $p\bar{p}$ elastic data** (assuming flat behavior above $\sqrt{s} = 100 GeV$)

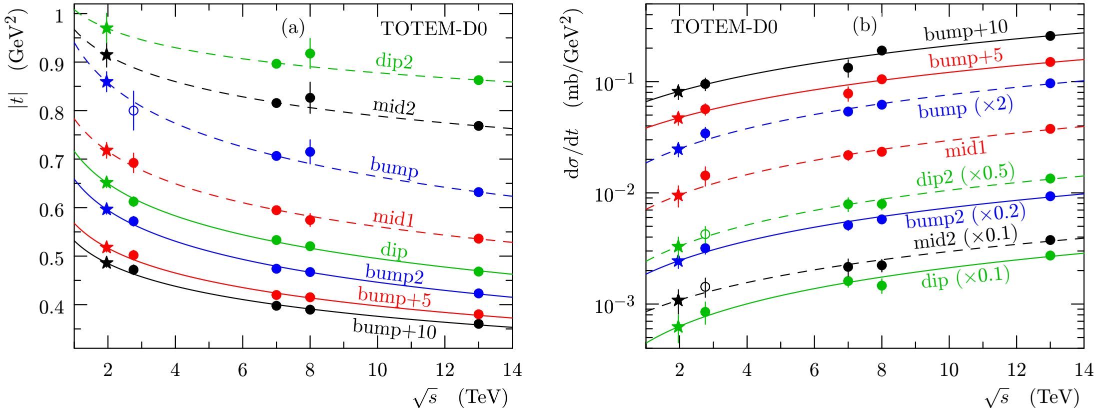
Fits of t and $d\sigma/dt$ values for reference points

- Fit of all reference points using the following formulae:

$$\begin{aligned} |t| &= a\log(\sqrt{s}[\mathrm{TeV}]) + b \\ (d\sigma/dt) &= c\sqrt{s}\ [\mathrm{TeV}] + d \end{aligned}$$

- The same form is used for the 8 reference points (this is an assumption and works to describe all characteristic points): this simple form is chosen since we fit at most 4 points, corresponding to $\sqrt{s} = 2.76$, 7, 8 and 13 TeV
- We also tried alternate parametrizations such as $|t| = e(s)^f$ leading to compatible results well within 1σ
- Leads to very good χ^2 per dof, better than 1 for most of the fits
- Extrapolating the fits leads to predictions for $|t|$ and $d\sigma/dt$ at 1.96 TeV for each characteristic point

Variation of t and $d\sigma/dt$ values for reference points

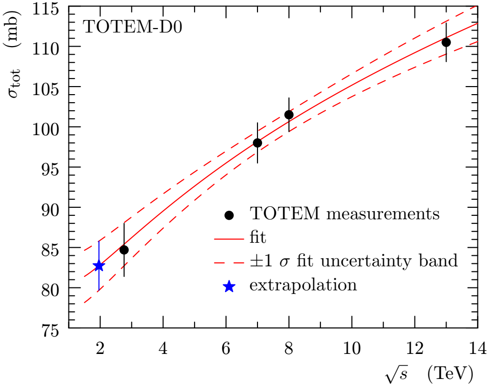


$$|t| = a\log(\sqrt{s}[\mathrm{TeV}]) + b \qquad (d\sigma/dt) = c\sqrt{s}\ [\mathrm{TeV}] + d$$

Fits of TOTEM extrapolated characteristic points at 1.96 TeV

- The last step is to predict the *pp* elastic cross sections at the same t values as measured by D0 in order to make a direct comparison
- Fit the reference points extrapolated to 1.96 TeV from TOTEM measurements using a double exponential fit ($\chi^2 = 0.63$ per dof): $h(t) = a_1 e^{-b_1|t|^2 - c_1|t|} + d_1 e^{-f_1|t|^3 - g_1|t|^2 - h_1|t|}$
  - This function is chosen for fitting purposes only
  - Low-t diffractive cone (1st function) and asymmetric structure of bump/dip (2nd function)
  - The two exponential terms cross around the dip, one rapidly falling and becoming negligible in the high t-range where the other term rises above the dip
- Systematic uncertainties evaluated from an ensemble of MC experiments in which the cross section values of the eight characteristic points are varied within their Gaussian uncertainties. Fits without a dip and bump position matching the extrapolated values within their uncertainties are rejected, and slope and intercept constraints are used to discard unphysical fits
- Such formula leads also to a good description of TOTEM data in the dip/bump region at 2.76, 7, 8 and 13 TeV

Relative normalization between D0 measurement and extrapolated TOTEM data: total *pp* cross section at 1.96 TeV



- Differences in normalization taken into account by adjusting TOTEM and D0 data sets to have the same cross sections at the optical point $d\sigma/dt(t=0)$ (NB: OP cross sections expected to be equal if there are only C-even exchanges)
- Predict the *pp* total cross section from extrapolated fit to TOTEM data (χ^2 =0.27)

$$\sigma_{tot} = a_2 \log^2 \sqrt{s}[\mathrm{TeV}] + b_2$$

Other parametrizations lead to same results

- Leads to estimate of *pp* σ_{tot} =**82.7 $\pm$ 3.1 mb at 1.96 TeV**

Relative normalization between D0 measurement and extrapolated TOTEM data: Rescaling TOTEM data

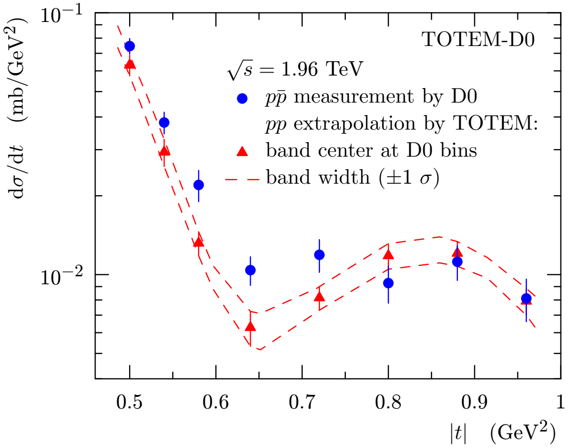
- Adjust 1.96 TeV $d\sigma/dt(t=0)$ from extrapolated TOTEM data to D0 measurement
- From TOTEM pp σ_{tot}, obtain $d\sigma/dt(t=0)$:

$$\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2}\left(\frac{d\sigma}{dt}\right)_{t=0}$$

- Assuming $\rho = 0.145$, the ratio of the imaginary and the real part of the elastic amplitude, as taken from COMPETE extrapolation
- This leads to a TOTEM $d\sigma/dt(t=0)$ at the OP of 357.1 ± 26.4 mb/GeV^2
- D0 measured the optical point of $d\sigma/dt$ at small t: 341$\pm$48 mb/GeV^2
- TOTEM data rescaled by 0.954 ± 0.071
- NB: We do not claim that we performed a measurement of $d\sigma/dt$ at the OP at $t=0$ (it would require additional measurements closer to $t=0$), but we use the two extrapolations simply in order to obtain a common and somewhat arbitrary normalization point

Predictions at $\sqrt{s} = 1.96$ TeV

- Reference points at 1.96 TeV (extrapolating TOTEM data) and 1σ uncertainty band
- Comparison with D0 data



Comparison between D0 measurement and extrapolated TOTEM data

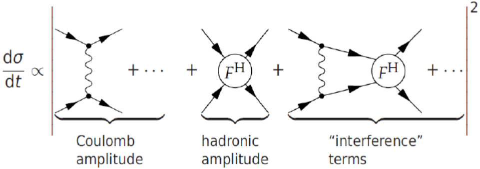
- χ^2 test to examine the probability for the D0 and TOTEM $d\sigma/dt$ to agree

$$\chi^2 = \Sigma_{i,j}[(T_i - D_i)C_{ij}^{-1}(T_j - D_j)] + \frac{(A - A_0)^2}{\sigma_A^2} + \frac{(B - B_0)^2}{\sigma_B^2}$$

where T_j and D_j are the j^{th} $d\sigma/dt$ values for TOTEM and D0, C_{ij} the covariance matrix, A (B) the nuisance parameters for scale (slope) with A_0 (B_0) their nominal values

- Slopes constrained to their measured values (pp to $p\bar{p}$ integrated elastic cross section ratio (dominated by the exp part) becomes 1 in the limit $\sqrt{s} \to \infty$ which means similar slopes at small $|t|$ as observed in data)
- Test using the difference of the integrated cross section in the examined $|t|$-range with its fully correlated uncertainty, and the experimental and extrapolated points with their covariance matrices
- Given the constraints on the OP normalization and logarithmic slopes of the elastic cross sections, the χ^2 test with six degrees of freedom yields the p**-value of 0.00061, corresponding to a significance of 3.4σ**

Combination with additional TOTEM measurement: ρ measurement

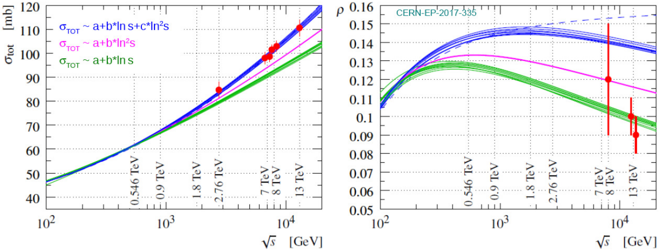


- Measure elastic scattering at very low t: Coulomb-Nuclear interference region

$$\frac{d\sigma}{dt} \sim |A^C + A^N(1 - \alpha G(t))|^2$$

- The differential cross section is sensitive to the phase of the nuclear amplitude
- In the CNI region, both the modulus and the phase of the nuclear amplitude can be used to determine $\rho = \frac{Re(A^N(0))}{Im(A^N(0))}$ where the modulus is constrained by the measurement in the hadronic region and the phase by the t dependence

A previous measurement by TOTEM: ρ and σ_{tot} measurements as an indication for odderon



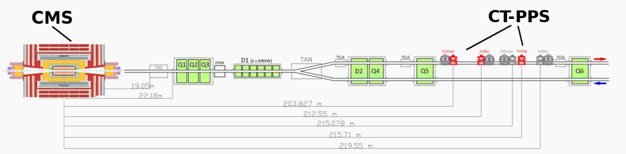
- ρ is the ratio of the real to imaginary part of the elastic amplitude at $t = 0$
- Using low $|t|$ data in the Coulomb-nuclear interference region, measurement of ρ at 13 TeV: $\rho = 0.09 \pm 0.01$ (EPJC 79 (2019) 785)
- Combination of the measured ρ and σ_{tot} values not compatible with any set of models without odderon exchange (COMPETE predictions above as an example)
- This result can be explained by the exchange of the Odderon in addition to the Pomeron

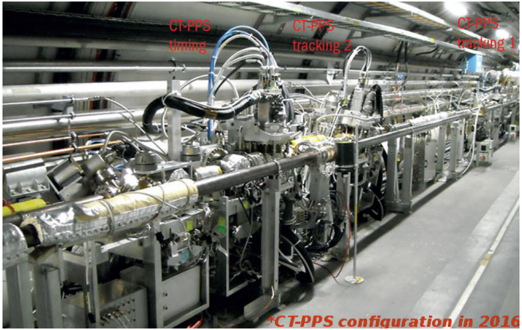
Comparison between D0 measurement and extrapolated TOTEM data

- Combination with the independent evidence of the odderon found by the TOTEM Collaboration using ρ and total cross section measurements at low t in a completely different kinematical domain
- For the models included in COMPETE, the TOTEM ρ measurement at 13 TeV provided a 3.4 to 4.6σ significance, to be combined with the D0/TOTEM result
- The combined significance ranges from **5.3 to 5.7σ depending on the model**
- Models without colorless C-odd gluonic compound are excluded including the Durham model and different sets of COMPETE models (blue, magenta and green bands on the previous slide)

Searching for beyond standard model physics using intact protons

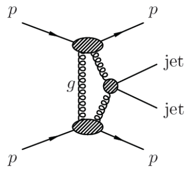
What is the CMS-TOTEM Precision Proton Spectrometer (CT-PPS)?

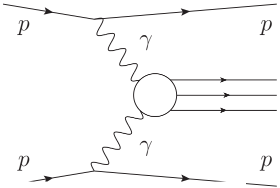


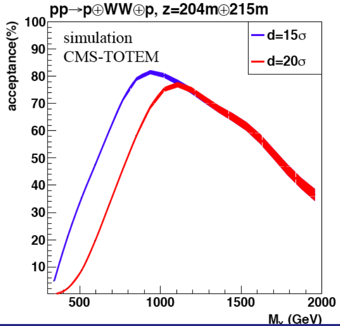


- Joint CMS and TOTEM project: https://cds.cern.ch/record/1753795
- LHC magnets bend scattered protons out of the beam envelope
- Detect scattered protons a few *mm* from the beam on both sides of CMS: 2016-2018, $\sim$ 115 fb^{-1} of data collected
- Similar detectors: ATLAS Forward Proton (AFP)

Detecting intact protons in ATLAS/CMS-TOTEM at the LHC

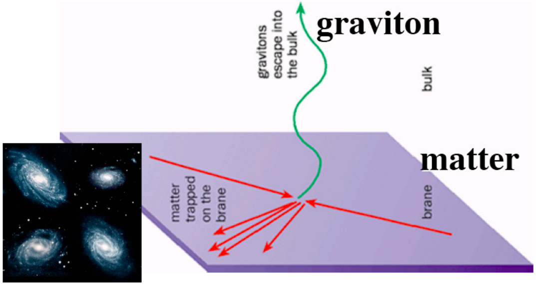






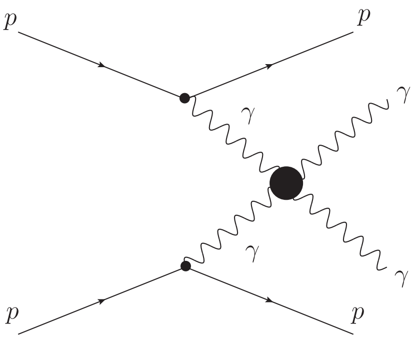
- Tag and measure protons at ± 210 m: AFP (ATLAS Forward Proton), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)
- All diffractive cross sections computed using the Forward Physics Monte Carlo (FPMC)
- Complementarity between low and high mass diffraction (high and low cross sections): special runs at low luminosity (no pile up) and standard luminosity runs with pile up

Looking for extra-dimensions in the universe



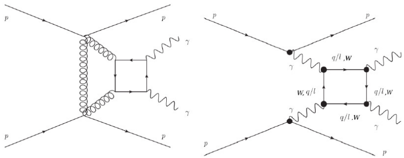
- We live in a 4-dimensional space: space-time continuum
- Gravity might live in extra-dimensions: this is idea is being explored at the LHC by looking for new couplings between particles and production of new particles
- If discovered at the LHC, this might lead to major changes in the way we see the world

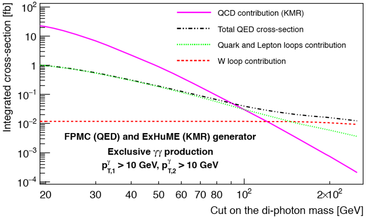
Search for new $\gamma\gamma\gamma\gamma$ couplings using $\gamma\gamma$ and two intact protons



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

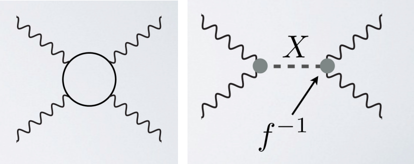
$\gamma\gamma$ exclusive production: SM contribution





- 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**

Motivations to look for quartic $\gamma\gamma$ anomalous couplings

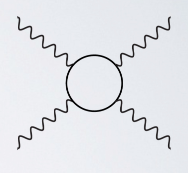


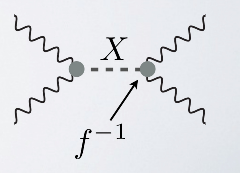
- Two effective operators and two different couplings at low energies ζ
- $\gamma\gamma\gamma\gamma$ couplings can be modified in a model independent way by loops of heavy charge particles

$$\zeta_1 = \alpha_{em}^2 Q^4 m^{-4} N c_{1,s}$$

where the coupling depends only on $Q^4 m^{-4}$ (charge and mass of the charged particle) and on spin, $c_{1,s}$ depends on the spin of the particle This leads to ζ_1 of the order of 10^{-14}-10^{-13}

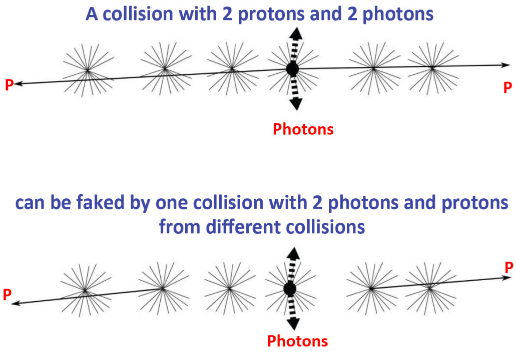
Motivations to look for quartic $\gamma\gamma$ anomalous couplings





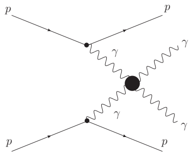
- Two effective operators at low energies
- ζ_1 can also be modified by neutral particles at tree level (extensions of the SM including scalar, pseudo-scalar, and spin-2 resonances that couple to the photon) $\zeta_1 = (f_s m)^{-2} d_{1,s}$ where f_s is the $\gamma\gamma X$ coupling of the new particle to the photon, and $d_{1,s}$ depends on the spin of the particle; for instance, 2 TeV dilatons lead to $\zeta_1 \sim 10^{-13}$

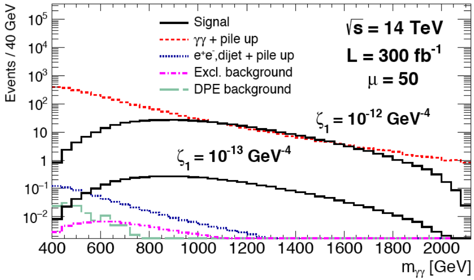
So what is pile up at LHC?



- 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

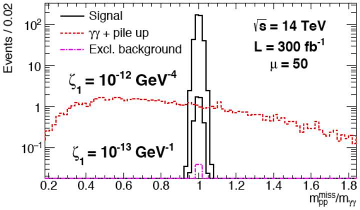
Search for quartic $\gamma\gamma$ anomalous couplings

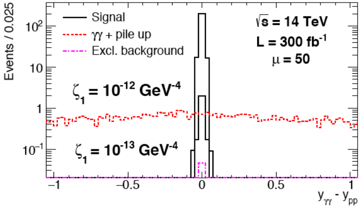




- Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- Analysis performed at hadron level including detector efficiencies, resolution effects, pile-up...
- Anomalous coupling events appear at high di-photon masses
- S. Fichet,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

Search for quartic $\gamma\gamma$ anomalous couplings

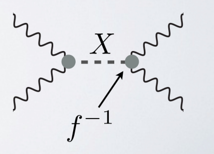


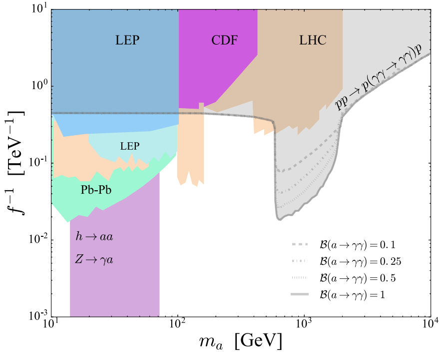


Cut / Process	Signal (full)	Signal with (without) f.f (EFT)	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15$, $p_{T1,(2)} > 200, (100)$ GeV$]$	65	18 (187)	0.13	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	64	17 (186)	0.10	0	0.2	1023
$[p_{T2}/p_{T1} > 0.95$, $\lvert\Delta\phi\rvert > \pi - 0.01]$	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})

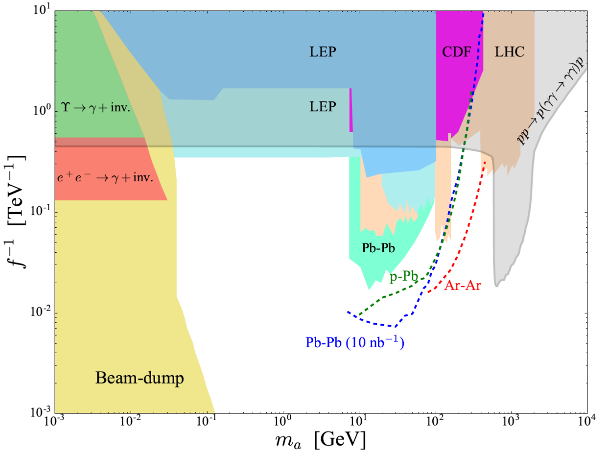
Search for axion like particles





- 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

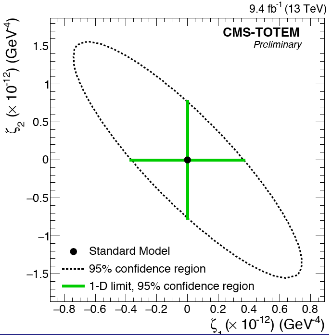
Search for axion like particles: complementarity with heavy ion runs

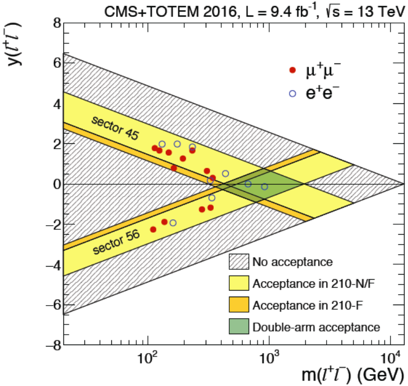


- Production of ALPs via photon exchanges in heavy ion runs: Complementarity to *pp* running
- Sensitivity to low mass ALPs: low luminosity but cross section increased by Z^4, C. Baldenegro, S. Hassani, C.R., L. Schoeffel, ArXiv:1903.04151
- Similar gain of three orders of magnitude on sensitivity for $\gamma\gamma\gamma Z$, $\gamma\gamma WW$, $\gamma\gamma ZZ$, etc, couplings in *pp* collisions

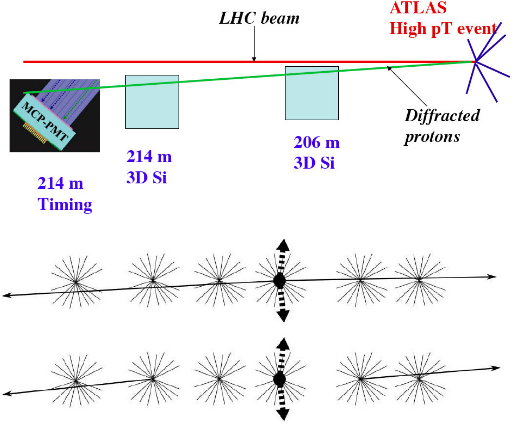
Evidence for quasi-exclusive dilepton production and 1st search for quartic $\gamma\gamma\gamma\gamma$ anomalous couplings (CMS)

- 20 quasi-exclusive dilepton production in CMS with one tagged proton
- 1st search for quartic $\gamma\gamma\gamma\gamma$ anomalous couplings in CMS



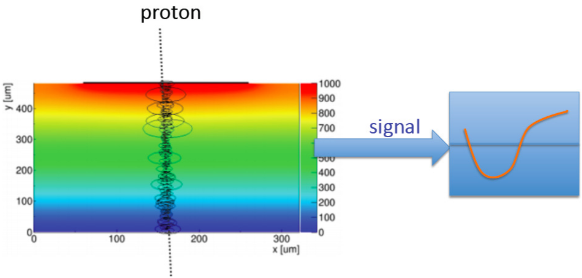


Additional method to remove pile up: Measuring proton time-of-flight



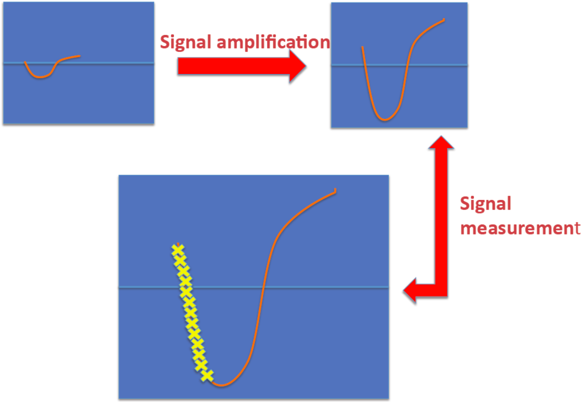
- Measure the proton time-of-flight in order to determine if they originate from the same interaction as the selected photon
- Typical precision: 10 ps means 2.1 mm
- Idea: use ultra-fast Si detectors (signal duration of $\sim$few ns and possibility to use fast sampling to reconstruct full signal)

Timing measurements in Particle Physics



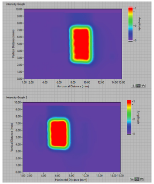
- Proton going through a detector (for instance scintillator, Silicon) emits a signal
- Measure this signal using an oscilloscope, or some electronics

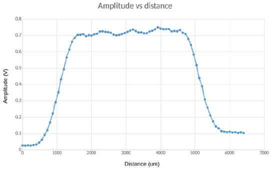
Signal analysis

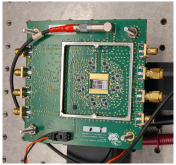


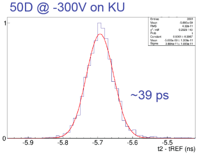
- Amplify the signal
- Very fast digitization of the signal: measure many points on the fast increasing signal as an example
- Allows reconstructing both the shape and amplitude of signal
- Leads to precise timing measurements (using for instance time when signal starts), and energy/type of particle measurements

Example of fast timing measurements using lasers





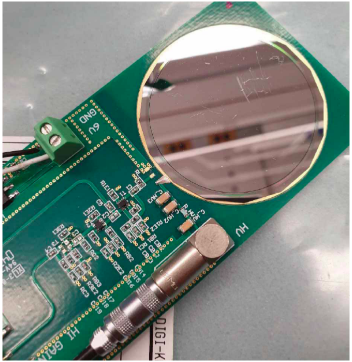




- Visualize pixels from Si detectors: Pixel size: $\sim$3 mm
- Test timing detectors at Fermilab: Timing resolution per layer of Si detector: $\sim$ 39 ps
- The main idea is to reconstruct the full signal by performing very fast sampling $\rightarrow$ Many applications

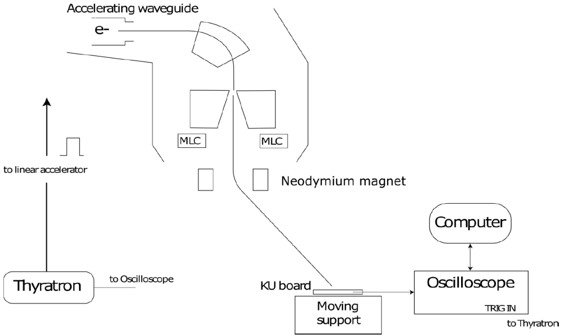
Measuring cosmic ray in space: the AGILE project

- We want to measure the type of particles (*p*, *He*, *Fe*, *Pb*, ...) and at the same time their energies
- Analysis of cosmic ray particles: using a cube sat, cheap to be sent into space
- Use similar technics: measure the signal (Bragg peak) where the particle stops in a ultra-fast Si detector
- Allows extracting type/energy of particles: project in collaboration with NASA, to be launched in Spring 2021, https://arxiv.org/abs/2103.00613

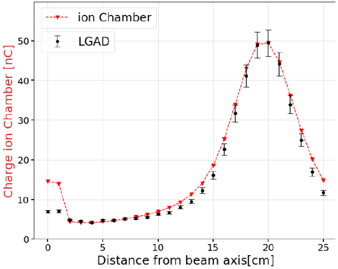


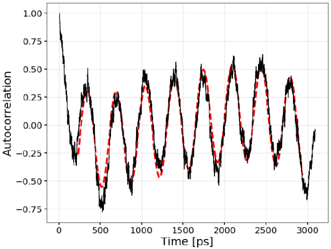
Measuring radiation is cancer treatment

- Utra fast silicon detectors and readout system were put in an electron beam used in the past for photon therapy at St Luke Hospital, Dublin, Ireland
- Precise and instantaneous measurements of dose during cancer treatment (especially for flash proton beam treatment)



Tests performed at St Luke hospital, University of Dublin, Ireland





- Measurement of charge deposited in Si detector compared to standard measurement using an ion chamber: good correlation
- Our detectors see in addition the beam structure (periodicity of the beam of $\sim$330 ps, contrary to a few seconds for the ion chamber): measure single particles from the beam
- Fundamental to measure instantaneous doses for high intensity proton therapy as example
- For more details: https://arxiv.org/abs/2101.07134

Conclusion

- Detailed comparison between $p\bar{p}$ (1.96 TeV from D0) and pp (2.76, 7, 8, 13 TeV from TOTEM) elastic $d\sigma/dt$ data - FERMILAB-PUB-20-568-E; CERN-EP-2020-236
- **pp and $p\bar{p}$ cross sections differ with a significance of 3.4σ in a model-independent way and thus provides evidence that the Colorless C-odd gluonic compound i.e. the odderon is needed to explain elastic scattering at high energies**
- **When combined with the ρ and total cross section result at 13 TeV, the significance is in the range 5.3 to 5.7σ and thus constitutes the first experimental observation of the odderon: Major discovery at CERN/Tevatron**
- PPS allows probing quartic anomalous couplings with unprecedented precision: sensitivity to composite Higgs, extra-dimension models, axion-like particles
- Development of fast timing detectors for HEP and applications in medicine, cosmic-ray physics

We need to look everywhere! For instance using intact protons...