Medal of the Mexican Society of Physics, Division of Particles and fields




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- Workshops in Guanajuato, Hermosillo, etc
- Reinforce collaborations in Mexico: CMS collaboration (Javier Murilo from Sonora,...), applications in medicine (Javier Murilo in Sonora, Arturo Tellez from Puebla,...), phenomenology (Martin Hentschinski, ...)

Physics with intact protons at the LHC: from the odderon discovery to the sensitivity to beyond standard model physics

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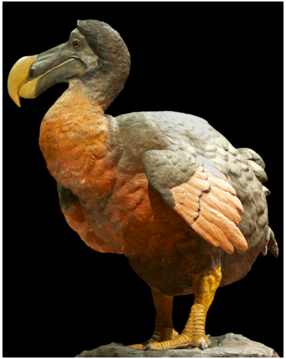
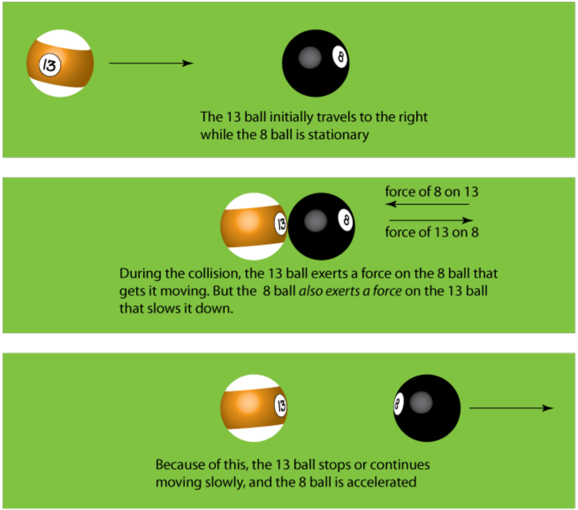


- Elastic interactions and introduction to the Odderon
- D0 $p\bar{p}$ and TOTEM pp data
- The odderon discovery
- Study of quartic anomalous couplings and search for axion-like particles
- Ultra Fast Silicon detectors

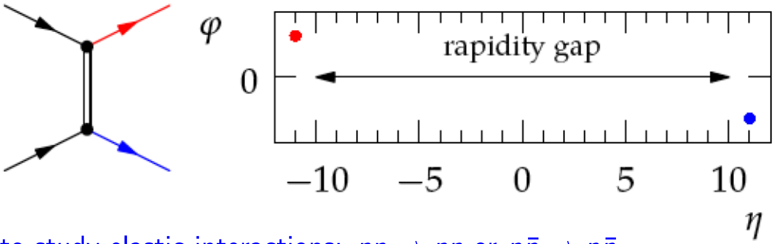
What is elastic scattering? The pool game...



- 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

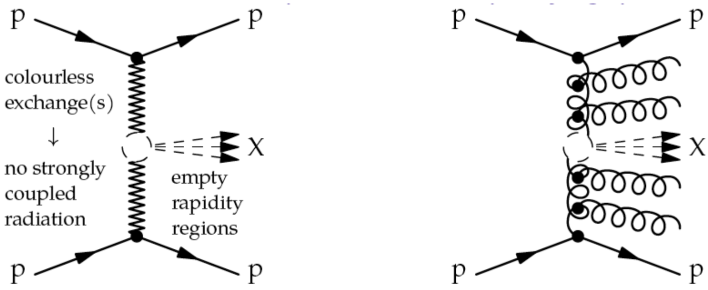
What do we want to study?

Elastic Scattering (ES), $\approx 30\,\text{mb}$



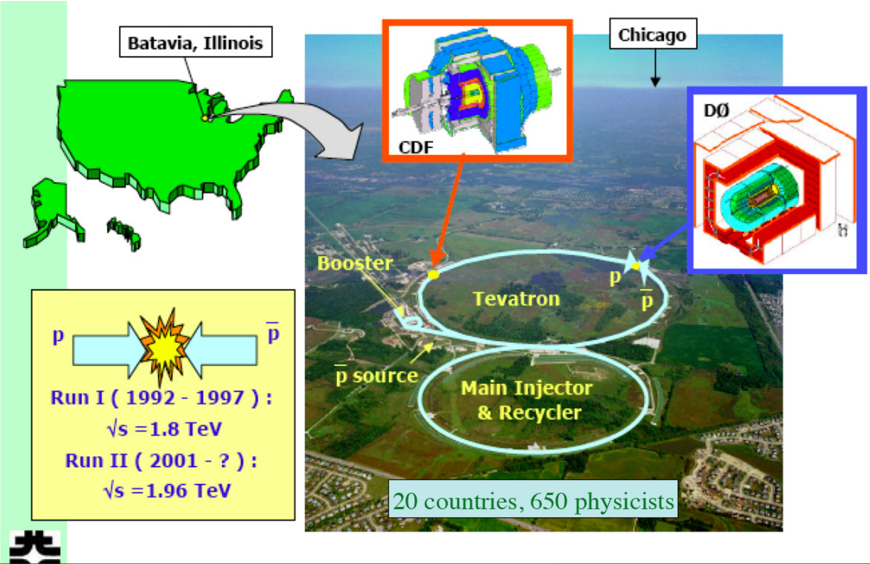
- We want to study elastic interactions: $pp \to pp$ or $p\bar{p} \to p\bar{p}$
- These are very clean events, where nothing is produced outside the two protons
- How to detect/measure these events? We need to detect the intact protons after interaction!
- Interactions explained by the exchange of a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

How to explain the fact that protons can be intact?



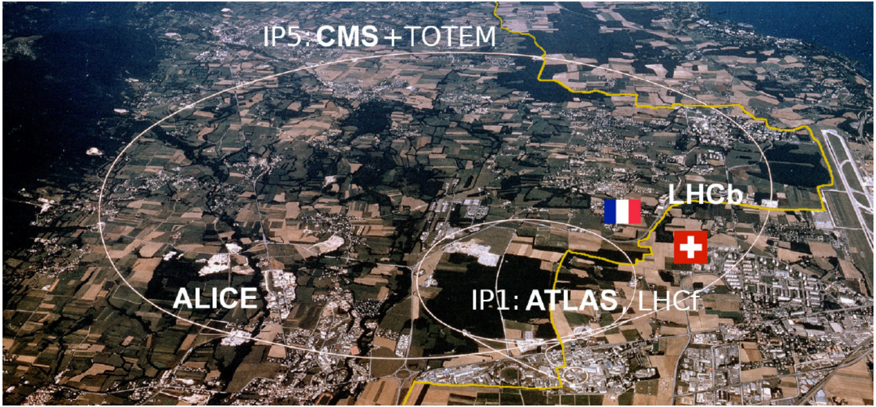
- Quarks/gluons radiate lots of gluons when one tries to separate them (confinement)
- Gluons exchange color, interact with other gluons in the proton and in that case protons are destroyed in the final state
- In order to explain how protons can remain intact: we need colorless exchanges, or at least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

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

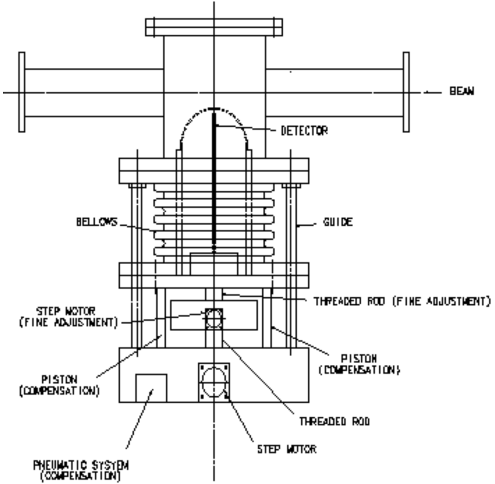


pp interactions: The Large Hadron Collider at CERN

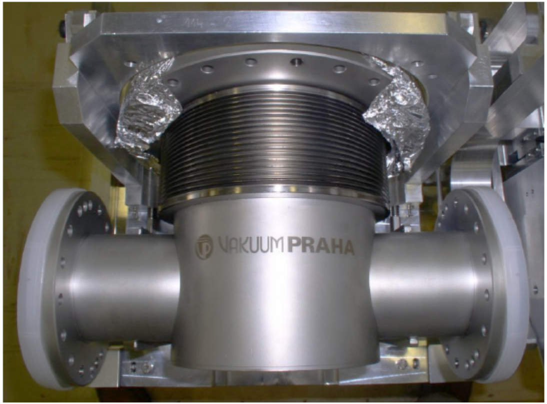
- Large Hadron Collider at CERN: proton proton collider with 2.76, 7, 8 and 13 TeV center-of-mass energy
- Circonference: 27 km; Underground: 50-100 m

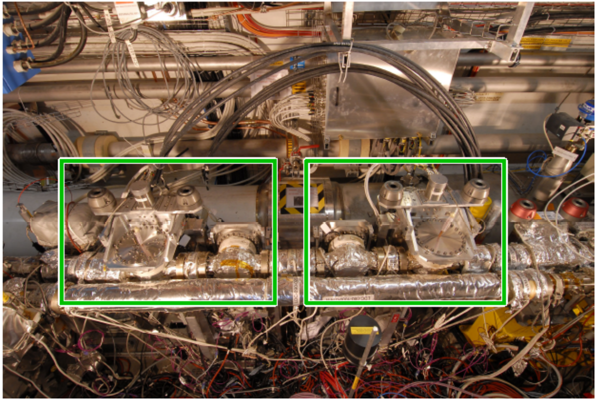


Which tools do we have? Roman Pot detectors

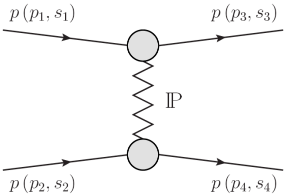


- We use special detectors to detect intact protons/ anti-protons called Roman Pots
- These detectors can move very close to the beam (up to 3σ) when beam are stable so that protons scattered at very small angles can be measured


VAKUUM PRAHA



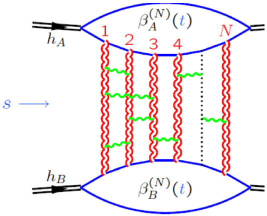
The odderon in a nutshell

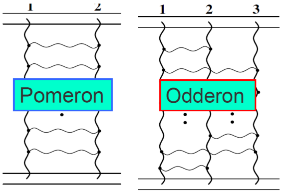


- Let us assume that elastic scattering can be due to exchange of colorless objects: Pomeron and Odderon
- Charge parity C: Charge conjugation changes the sign of all quantum charges
- Pomeron and Odderon correspond to positive and negative C parity: Pomeron is made of two gluons which leads to a $+1$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

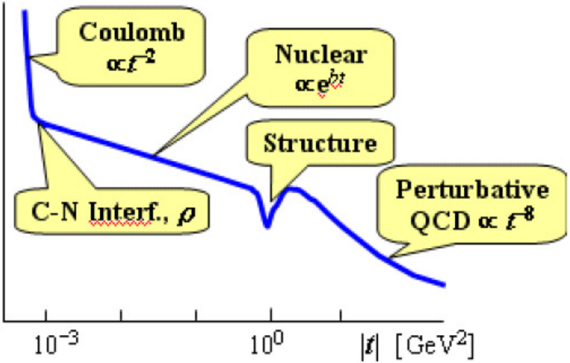




- Multi-gluon exchanges in hadron-hadron interactions in elastic *pp* interactions (Bartels-Kwiecinski-Praszalowicz)
- From B. Nicolescu: The Odderon is defined as a singularity in the complex plane, located at $J = 1$ when $t = 0$ and which contributes to the odd crossing amplitude

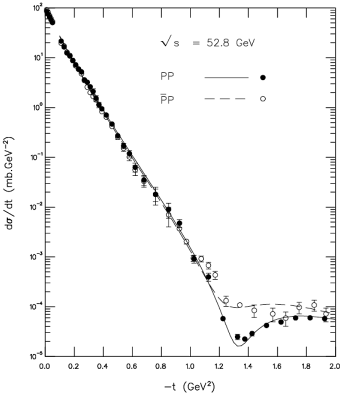
- Leads to contributions on 3,... gluon exchanges in terms of QCD for the perturbative odderon
- Colorless C-odd 3-gluon state (odderon) predicts differences in elastic $d\sigma/dt$ for pp and $p\bar{p}$ interactions since it corresponds to different amplitudes/ interferences

Measurement of elastic scattering at Tevatron and LHC



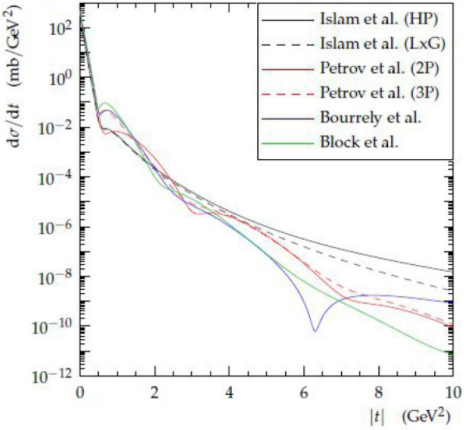
- Study of elastic $pp \rightarrow pp$ reaction: exchange of momentum between the two protons which remain intact
- Measure intact protons scattered close to the beam using Roman Pots installed both by D0 and TOTEM collaborations
- From counting the number of events as a function of $|t|$ (4-momentum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

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



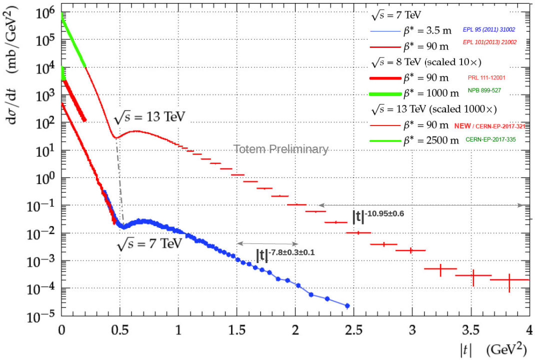
- The situation is not that simple: elastic scattering at low energies can be due to exchanges of additional particles to pomeron/odderon: ρ, ω, ϕ, reggeons...
- How to distinguish between all these exchanges? Not easy...
- At ISR energies, there was already some indication of a possible difference between 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?



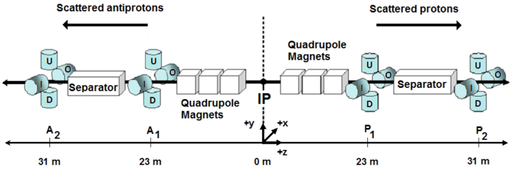
- Expected elastic $d\sigma/dt$ before LHC measurements
- Many different predictions including many possible contributions at high $|t|$, such as pomeron, reggeon, mesons (ω, ϕ) whereas other predictions mentioned that, at high energies, we should be more asymptotical and pomeron dominated
- Almost nobody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

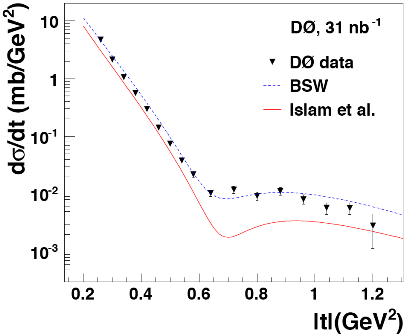
Are we in the asymptotic regime at the LHC?



- 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

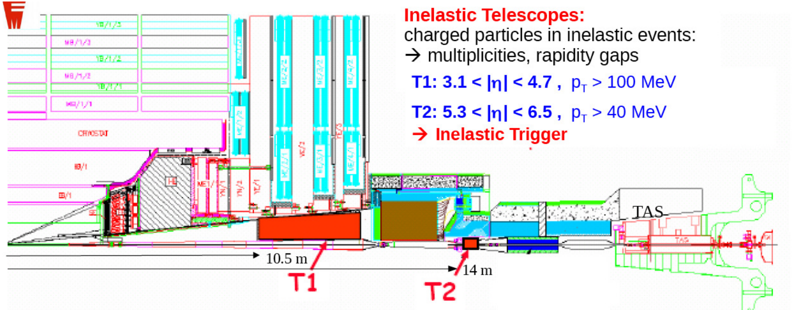
Elastic cross section at the LHC: Forward coverage in CMS-TOTEM

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

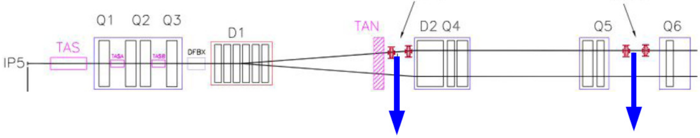
T1: $3.1 < |\eta| < 4.7$, $p_T > 100$ MeV

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

→ Inelastic Trigger



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

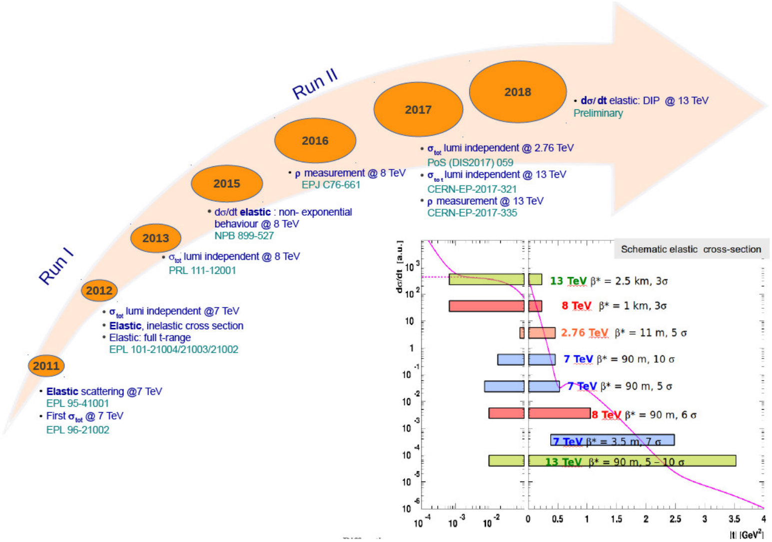


Roman Pot stations in the LHC tunnel (before LS1)

RP (147 m)

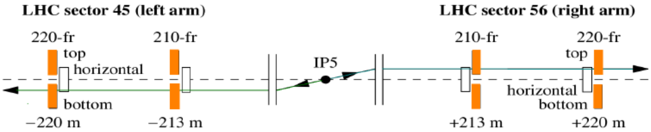
RP (220m)

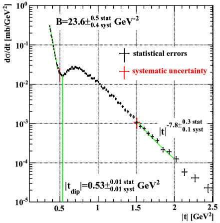
TOTEM cross section measurements

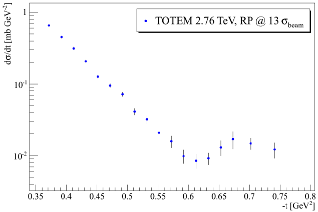


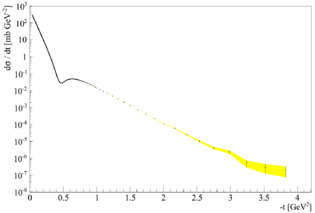
TOTEM elastic $pp\ d\sigma/dt$ cross section measurements

- 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

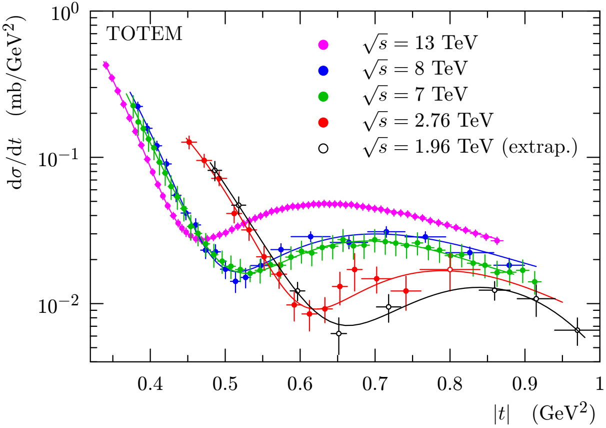






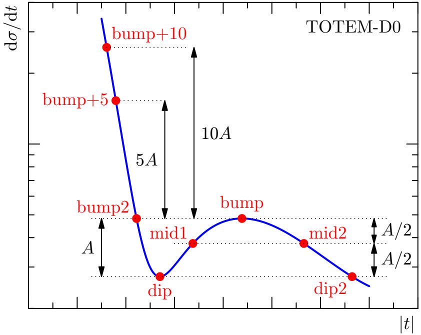


Strategy to compare pp and $p\bar{p}$ data sets



- 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

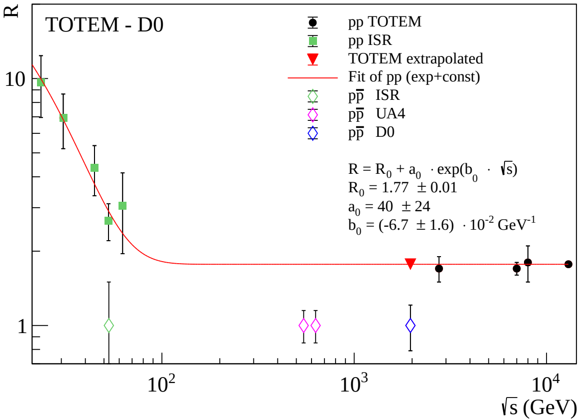
Reference points of elastic $d\sigma/dt$



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

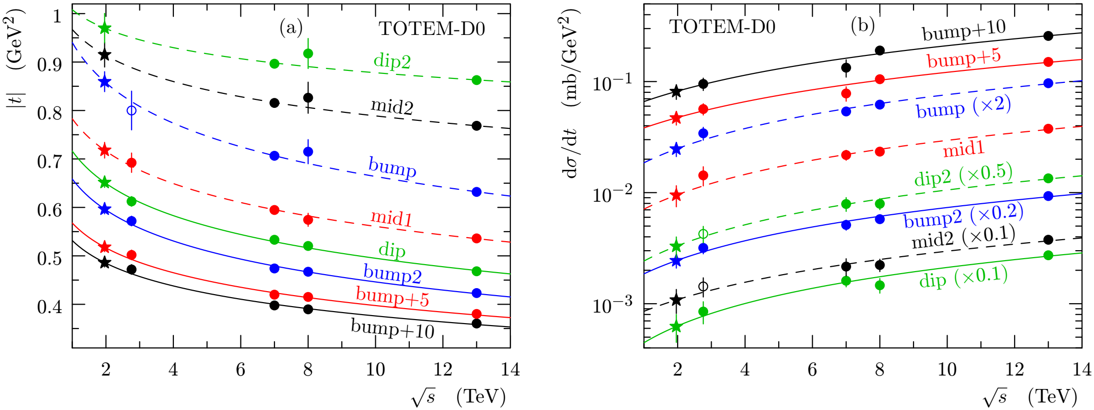
- Determine how the values of $|t|$ and $d\sigma/dt$ of characteristic points vary as a function of $\sqrt{s}$ in order to predict their values at 1.96 TeV
- We use data points closest to those characteristic points (avoiding model-dependent fits)
- Data bins are merged in case there are two adjacent 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 $\sqrt{s} = 100 GeV$)

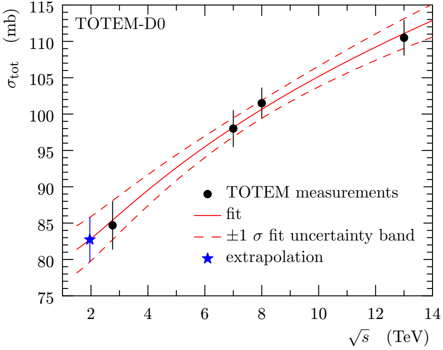
Variation of t and $d\sigma/dt$ values for reference points



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

Fits of TOTEM extrapolated characteristic points at 1.96 TeV

- Last step: 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): $h(t) = a_1 e^{-b_1|t|^2 - c_1|t|} + d_1 e^{-f_1|t|^3 - g_1|t|^2 - h_1|t|}$



- Differences in normalization taken into account by adjusting TOTEM and D0 data sets to have the same cross sections at the optical point $d\sigma/dt(t=0)$
- Predict the *pp* total cross section from extrapolated fit to TOTEM data (χ^2 =0.27): *pp* σ_{tot} =82.7 ± 3.1 mb at 1.96 TeV

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

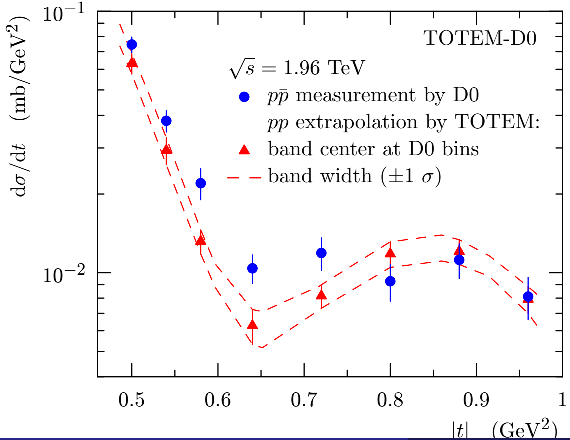
- Adjust 1.96 TeV $d\sigma/dt(t=0)$ from extrapolated TOTEM data to D0 measurement
- From TOTEM pp σ_{tot}, obtain $d\sigma/dt(t=0)$:

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

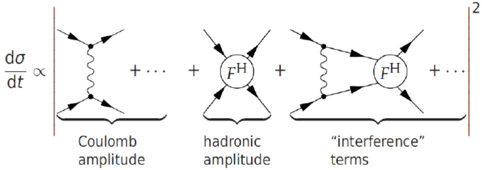
- Assuming $\rho = 0.145$, the ratio of the imaginary and the real part of the elastic amplitude, as taken from COMPETE extrapolation
- This leads to a TOTEM $d\sigma/dt(t=0)$ at the OP of 357.1 ± 26.4 mb/GeV^2
- D0 measured the optical point of $d\sigma/dt$ at small t: 341 ± 48 mb/GeV^2
- TOTEM data 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: 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

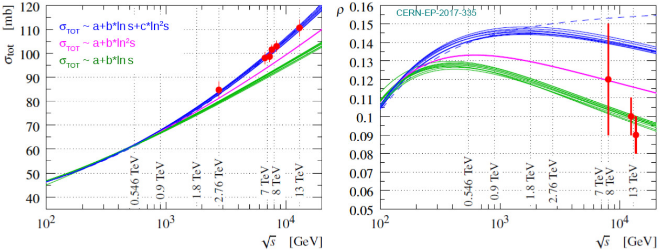


- Measure elastic scattering at very low t: Coulomb-Nuclear interference region

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

- 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



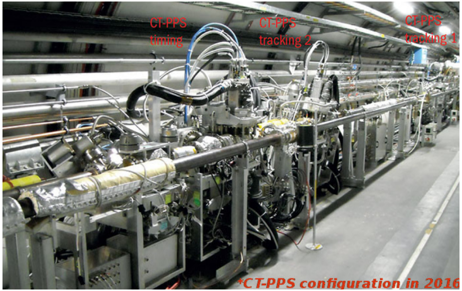
- ρ is the ratio of the real to imaginary part of the elastic amplitude at $t = 0$
- Using low $|t|$ data in the Coulomb-nuclear interference region, measurement of ρ at 13 TeV: $\rho = 0.09 \pm 0.01$ (EPJC 79 (2019) 785)
- Combination of the measured ρ and σ_{tot} values not compatible with any set 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

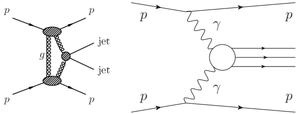
Comparison between D0 measurement and extrapolated TOTEM data

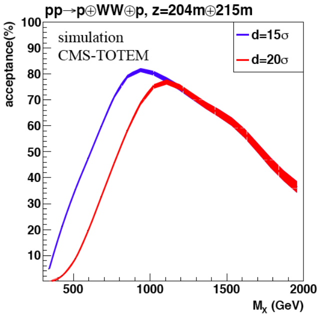
- Combination with the independent evidence of the odderon found by the TOTEM Collaboration using ρ and total cross section measurements at low t in a completely different kinematical domain
- For the models included in COMPETE, the TOTEM ρ measurement at 13 TeV provided a 3.4 to 4.6σ significance, to 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

Roman pot detectors from PPS installed in the tunnel

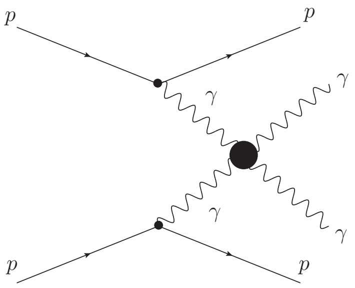






- Good acceptance at high mass in standard runs (PPS in CMS, AFP in ATLAS)
- >100 fb^{-1} collected in Run II

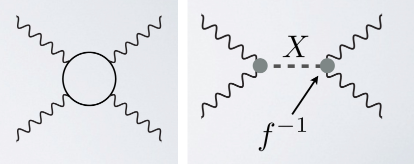
Search for quartic $\gamma\gamma\gamma\gamma$ anomalous coupling



- Search for production of two photons and two intact protons in the final state: $pp \to p\gamma\gamma p$

- Additional channels: WW, ZZ, γZ, $t\bar{t}$
- Possible larger number of events than expected in SM due to extra-dimensions, composite Higgs models, axion-like particles
- Anomalous couplings can appear via loops of new particles coupling to photons or via resonances decaying into two photons
- JHEP 1806 (2018) 131; JHEP 1502 (2015) 165; Phys.Rev. D89 (2014) 114004; Phys.Rev. D81 (2010) 074003; Phys.Rev. D78 (2008) 073005

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

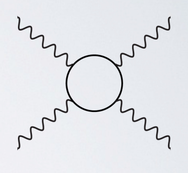


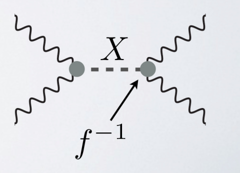
- Two effective operators and two different couplings at low energies ζ
- $\gamma\gamma\gamma\gamma$ couplings can be modified in a model independent way by loops of heavy charge particles

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

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}

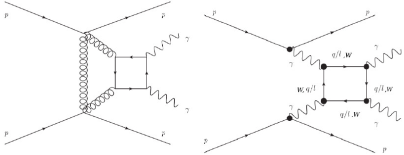
Motivations to look for quartic $\gamma\gamma$ anomalous couplings

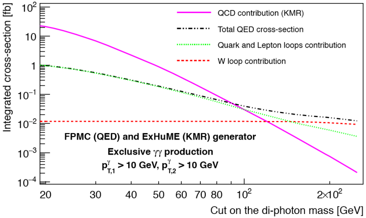




- Two effective operators at low energies
- ζ_1 can also be modified by neutral particles at tree level (extensions of the SM including scalar, pseudo-scalar, and spin-2 resonances that couple to the photon) $\zeta_1 = (f_s m)^{-2} d_{1,s}$ where f_s is the $\gamma\gamma X$ coupling of the new particle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

$\gamma\gamma$ exclusive production: SM contribution

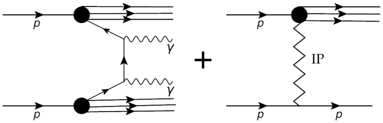


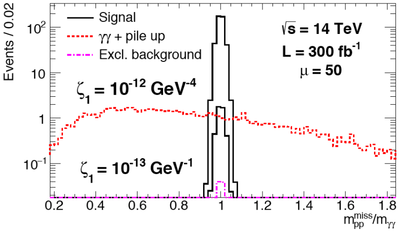


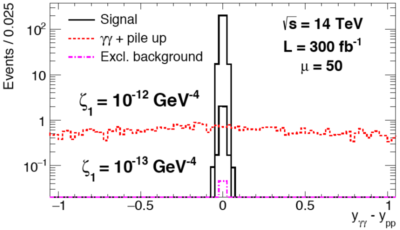
- QCD production dominates at low $m_{\gamma\gamma}$, QED at high $m_{\gamma\gamma}$
- Important to consider W loops at high $m_{\gamma\gamma}$
- At high masses ($>$ 200 GeV), the photon induced processes are dominant
- **Conclusion: Two photons and two tagged protons means photon-induced process**

Removing pile up at the LHC

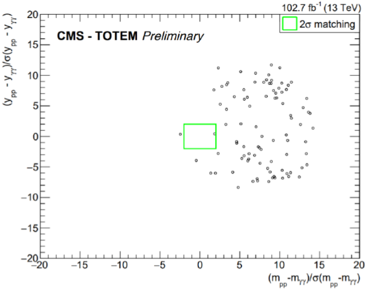
- Advantage of tagging protons: negligible background after matching mass/rapidity of photon and proton systems (JHEP 1502 (2015) 165; Phys.Rev. D89 (2014) 114004)
- Possibility to use fast timing detectors to measure proton time of flights

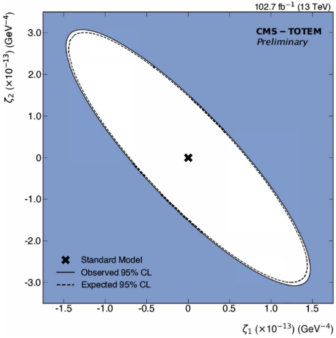






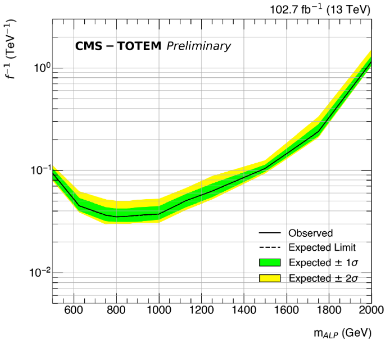
First search for high mass exclusive $\gamma\gamma$ production (CMS/TOTEM)

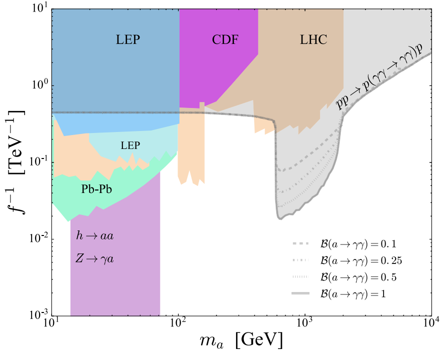


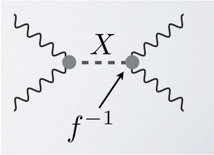


- Search for exclusive diphoton production: back-to-back, high diphoton mass ($m_{\gamma\gamma} > 350$ GeV), matching in rapidity and mass between diphoton and proton information
- First limits on quartic photon anomalous couplings: $|\zeta_1| < 2.9\ 10^{-13}$ GeV^{-4}, $|\zeta_2| < 6.\ 10^{-13}$ GeV^{-4} with about 10 fb^{-1}, accepted by PRL (2110.05916)
- Limit updates with 102.7 fb^{-1}: $|\zeta_1| < 7.3\ 10^{-14}$ GeV^{-4}, $|\zeta_2| < 1.5\ 10^{-13}$ GeV^{-4}

First search for high mass production of axion-like particles (CMS/TOTEM)

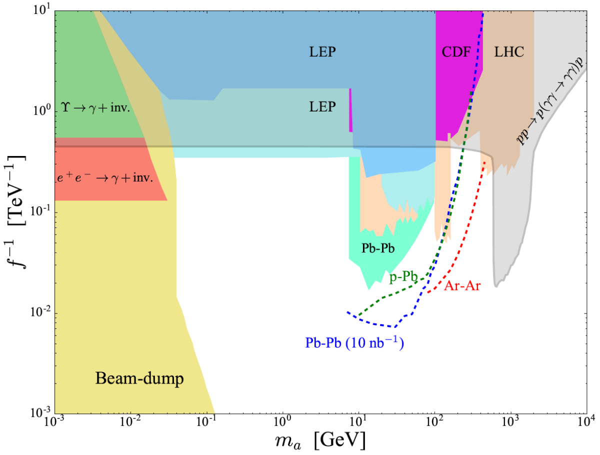






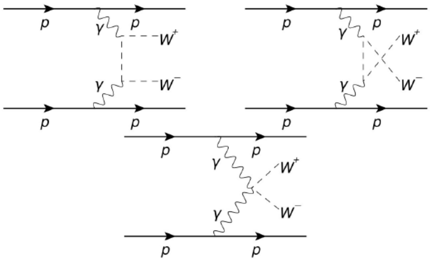
- First limits on ALPs at high mass (CMS-PAS-EXO-21-007)
- Sensitivities projected with 300 fb^{-1} (C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1806 (2018) 13)

Search for axion like particles: complementarity with heavy ion runs



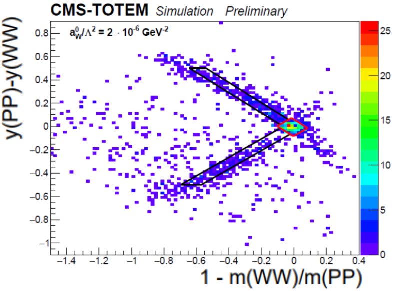
- Production of ALPs via photon exchanges in heavy ion runs: Complementarity to *pp* running
- Sensitivity to low mass ALPs: low luminosity but cross section increased by Z^4, C. Baldenegro, S. Hassani, C.R., L. Schoeffel, ArXiv:1903.04151
- Similar gain of three orders of magnitude on sensitivity for $\gamma\gamma\gamma Z$ couplings in *pp* collisions: C. Baldenegro, S. Fichet, G. von Gersdorff, C. R., JHEP 1706 (2017) 142

Exclusive production of W boson pairs (CMS/TOTEM)

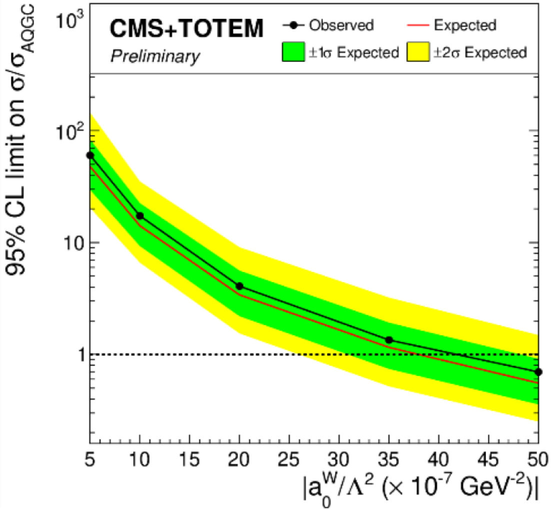


- Search with fully hadronic decays of W bosons: anomalous production of WW events dominates at high mass with a rather low cross section

- 2 “fat” jets (radius 0.8), jet $p_T > 200$ GeV, 1126$< m_{jj} <$2500 GeV, jets back-to-back ($|1-\phi_{jj}/\pi| < 0.01$)
- Signal region defined by the correlation between central WW system and proton information

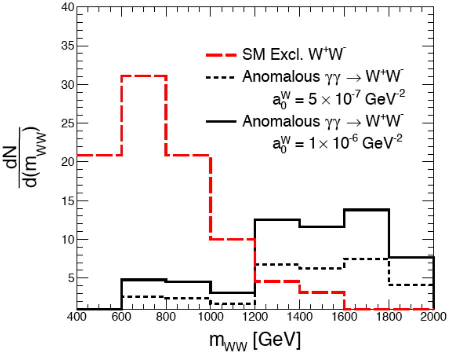


WW and ZZ exclusive productions (CMS/TOTEM)



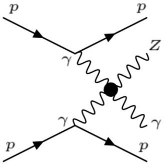
- Searches performed in full hadronic decays of W bosons (high cross section) with AK8 jets
- SM cross section is low
- Limits on SM cross section $\sigma_{WW} < 67$fb, $\sigma_{ZZ} < 43$fb for $0.04 < \xi < 0.2$ (CMS-PAS-EXO-21-014)
- New limits on quartic anomalous couplings: $a_0^W/\Lambda^2 < 4.3\ 10^{-6}$ GeV^{-2}, $a_C^W/\Lambda^2 < 1.6\ 10^{-5}$ GeV^{-2}, $a_0^Z/\Lambda^2 < 0.9\ 10^{-5}$ GeV^{-2}, $a_C^Z/\Lambda^2 < 4.\ 10^{-5}$ GeV^{-2} with 52.9 fb^{-1}

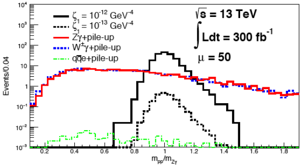
The future: Observation of exclusive *WW* production

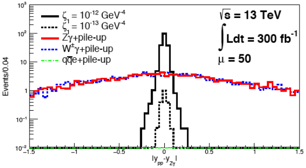


- SM contributiona appears at lower *WW* masses compared to anomalous couplings
- Use purely leptonic channels for *W* decays (the dijet background is too high at low masses for hadronic channels)
- SM prediction on exclusive WW (leptonic decays) after selection: about 50 events for 300 fb^{-1} (2 background)
- JHEP 2012 (2020) 165, C. Baldenegro, G. Biagi, G. Legras, C.R.

$\gamma\gamma\gamma Z$ quartic anomalous coupling: leptonic and hadronic decays of Z boson



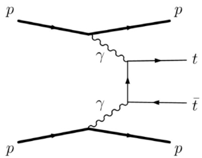




Coupling (GeV^{-4})	ζ ($\tilde{\zeta}=0$)		$\zeta=\tilde{\zeta}$	
Luminosity	300 fb^{-1}		300 fb^{-1}	
Pile-up (μ)	50		50	
Channels	5 σ	95% CL	5 σ	95% CL
$\ell\bar{\ell}\gamma$	$2.8\cdot10^{-13}$	$1.8\cdot10^{-13}$	$2.5\cdot10^{-13}$	$1.5\cdot10^{-13}$
$jj\gamma$	$2.3\cdot10^{-13}$	$1.5\cdot10^{-13}$	$2\cdot10^{-13}$	$1.3\cdot10^{-13}$
$jj\gamma\bigoplus\ell\bar{\ell}\gamma$	$1.93\cdot10^{-13}$	$1.2\cdot10^{-13}$	$1.7\cdot10^{-13}$	$1\cdot10^{-13}$

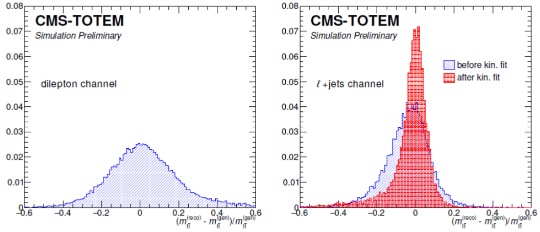
- C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1706 (2017) 142
- Best expected reach at the LHC by about three orders of magnitude
- Sensitivity to wide/narrow resonances, loops of new particles

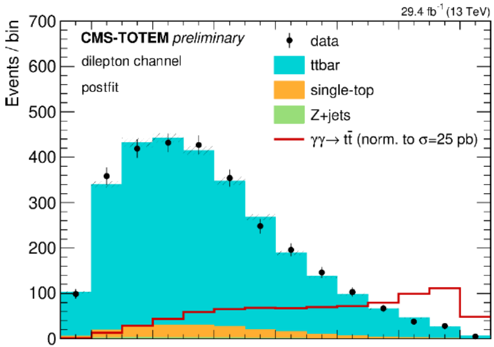
Exclusive $t\bar{t}$ production (CMS/TOTEM)



dilep channel ($\bar{t}t \to l\nu b + l\nu\bar{b}$)	Semilep channel ($\bar{t}t \to l\nu b + jj\bar{b}$)
Object selection	
Leptons: pT>30(20)GeV, |η|<2.1 Jets: pT>30GeV, |η|<2.4, ΔR(j,l)>0.4	Leptons: pT>30GeV, |η|<2.1(2.4) for e(μ) Jets: pT>25GeV, |η|<2.4, ΔR(j,l)>0.4
Event selection	
≥2 leptons (OS pair),|m(ll)-m(Z)|>15GeV ≥2 b-jets 1 proton / side	=1 lepton ≥2 b-jets, ≥2 non b-jets 1 proton / side

Exclusive $t\bar{t}$ production (CMS/TOTEM)





- Kinematic fitter based on W and t mass constraints to reduce background

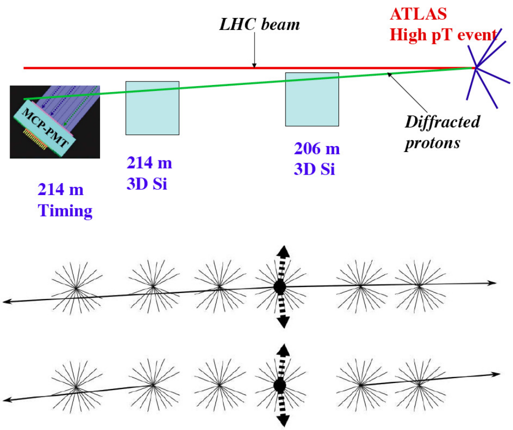
- Search for exclusive $t\bar{t}$ production in leptonic and semi-leptonic modes
- $\sigma_{t\bar{t}}^{excl.} < 0.6$ pb (CMS-PAS-TOP-21-007)

Exclusive $t\bar{t}$ production: the future

- Search for $\gamma\gamma t\bar{t}$ anomalous coupling in semi-leptonic decays with 300 fb^{-1}
- Use similar selection: high $t\bar{t}$ mass, matching between pp and $t\bar{t}$ information
- Use fast timing detectors to suppress further the pile up background
- C. Baldenegro, A. Bellora, S. Fichet, G. von Gersdorff, M. Pitt, CR arXiv:2205.01173

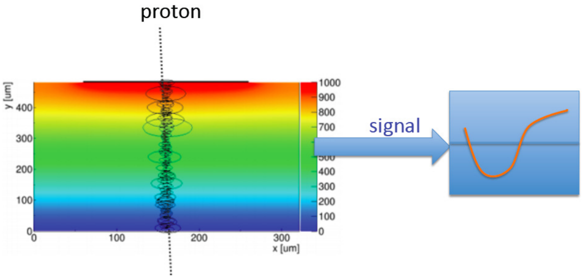
Coupling [10^{-11} GeV^{-4}]	95% CL	5σ	95% CL (60 ps)	5σ (60 ps)	95% CL (20 ps)	5σ (20 ps)
ζ_1	1.5	2.5	1.1	1.9	0.74	1.5
ζ_2	1.4	2.4	1.0	1.7	0.70	1.4
ζ_3	1.4	2.4	1.0	1.7	0.70	1.4
ζ_4	1.5	2.5	1.0	1.8	0.73	1.4
ζ_5	1.2	2.0	0.84	1.5	0.60	1.2
ζ_6	1.3	2.2	0.92	1.6	0.66	1.3

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



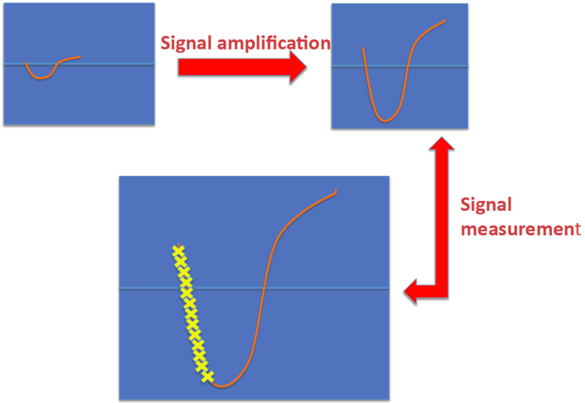
- Measure the proton time-of-flight in order to determine if they originate from the same interaction as the selected photon
- Typical precision: 10 ps means 2.1 mm
- Idea: use ultra-fast Si detectors (signal duration of ∼few ns and possibility to use fast sampling to reconstruct full signal)

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

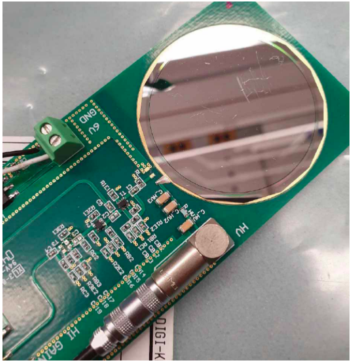
Signal analysis



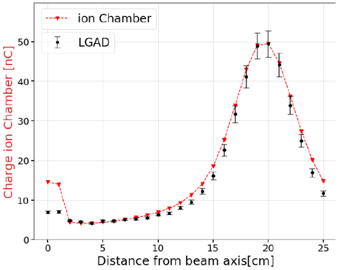
- Amplify the signal
- Very fast digitization of the signal: measure many points on the fast increasing signal as an example
- Allows reconstructing both the shape and amplitude of signal
- Leads to precise timing measurements (using for instance time when signal starts), and energy/type of particle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

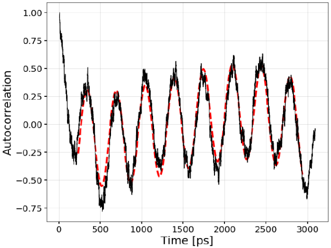
Measuring cosmic ray in space: the AGILE project

- 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 2022, https://arxiv.org/abs/2103.00613



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 ∼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, accepted in PRL
- **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...