Diffractive and photon-induced processes at the LHC: from the odderon discovery, the evidence for saturation to the search for axion-like particles

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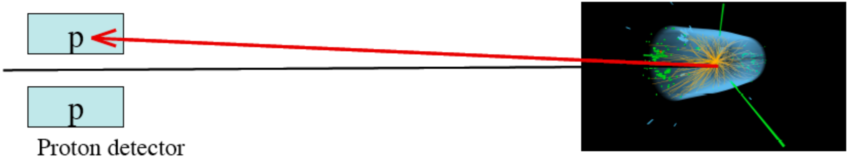
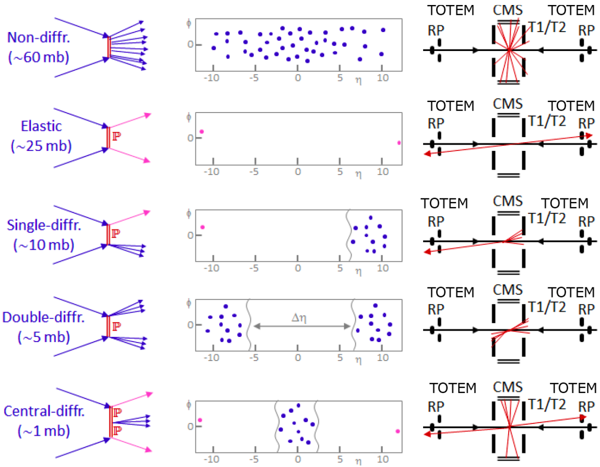
- Odderon discovery
- Diffractive physics
- Looking for saturation
- Quartic anomalous coupling studies and search for Axion-like particles

Strange events: intact protons after interaction



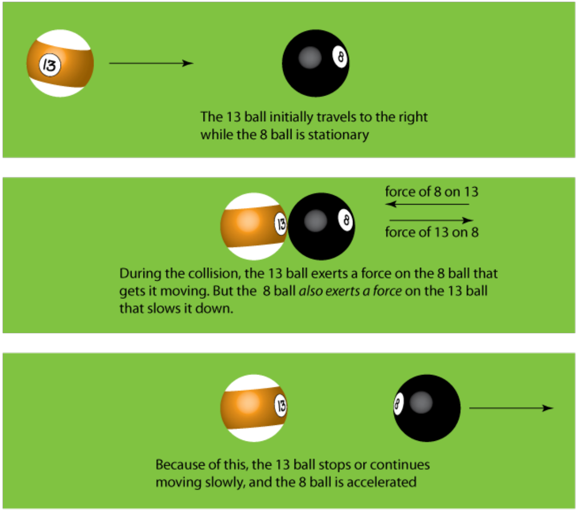
- Some unique events can be produced where the proton is not destroyed! The proton loses part of its energy
- These events can be produced via gluon or photon exchanges
- Consider clean method to detect and measure these events: tag intact protons after interaction

What do we want to measure? Diffractive events!



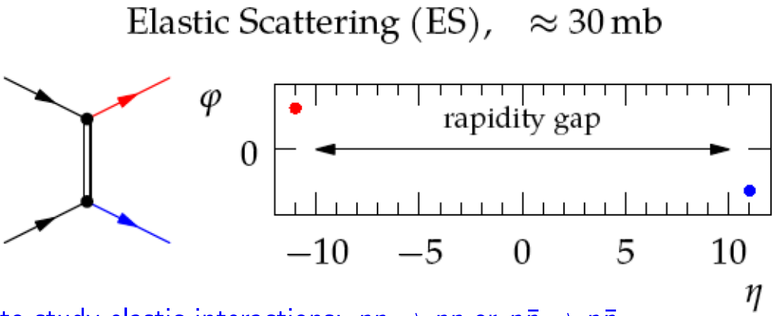
- Protons remain intact after interactions $pp \to pXp$ (central diffraction or double pomeron exchange) or $pp \to pXY$ (single diffraction)
- Non-diifractive interactions represent 60 *mb* out of 100 *mb* at LHC
- Intact protons can be detected using dedicated detectors
- Elastic interactions: $pp \to pp$

What is elastic scattering? The pool game...



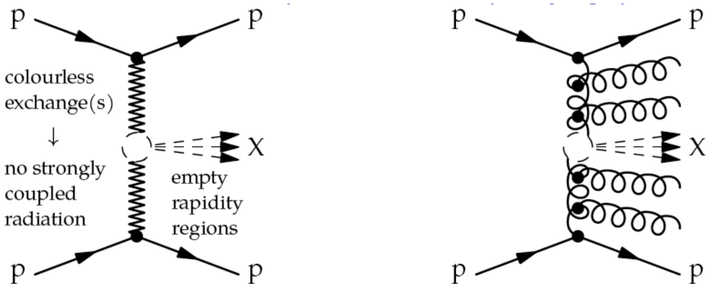
- We want to study "elastic" collisions between protons and proton-antiprotons
- In high energy physics: $pp \to pp$ and $p\bar{p} \to p\bar{p}$
- In these interactions, each proton/antiproton remains intact after interaction but are scattered at some angles and can lose/gain some momentum as in the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

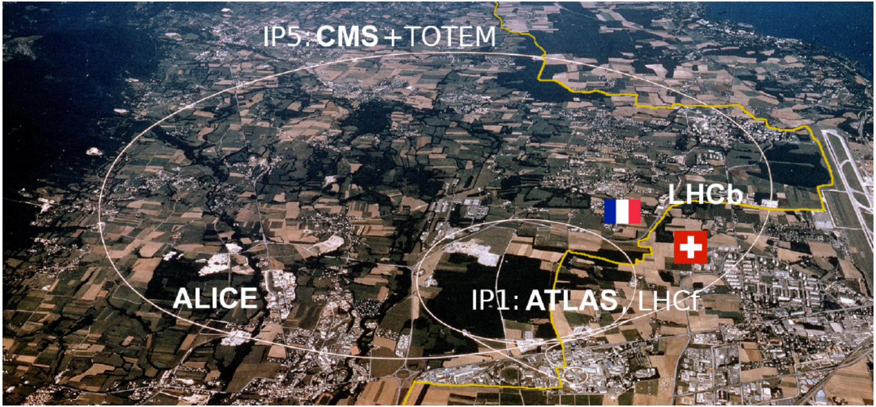
How to explain the fact that protons can be intact?



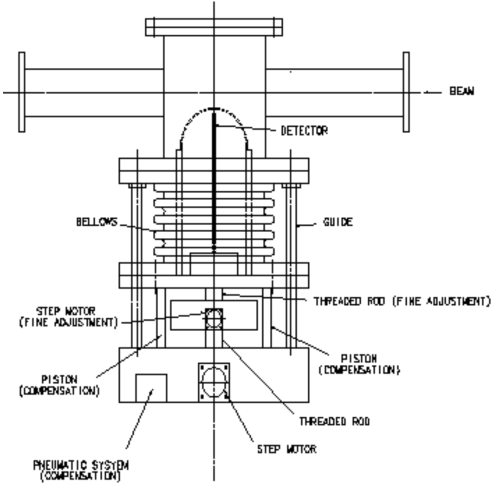
- Quarks/gluons radiate lots of gluons when one tries to separate them (confinement)
- Gluons exchange color, interact with other gluons in the proton and in that case protons are destroyed in the final state
- In order to explain how protons can remain intact: we need colorless exchanges, or at least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

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

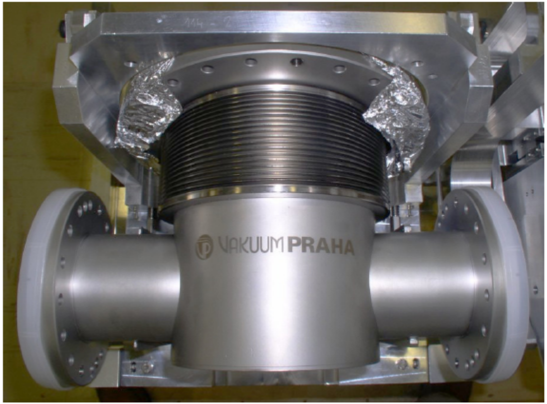


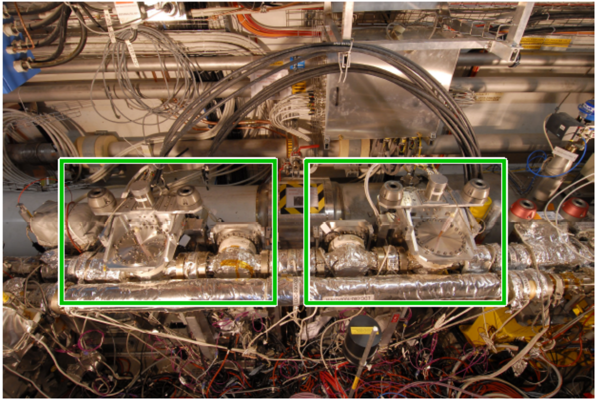
Which tools do we have? Roman Pot detectors



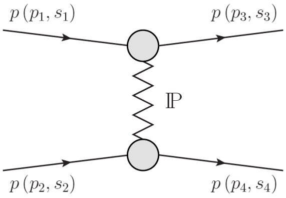
- We use special detectors to detect intact protons/ anti-protons called Roman Pots
- These detectors can move very close to the beam (up to 3σ) when beam are stable so that protons scattered at very small angles can be measured

Roman Pot detectors at the LHC





The odderon in a nutshell

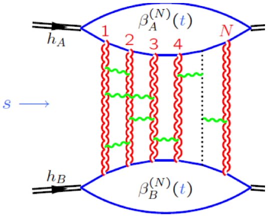


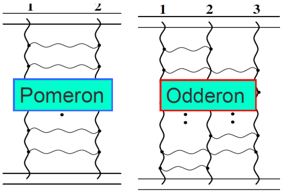
- Let us assume that elastic scattering can be due to exchange of colorless objects: Pomeron and Odderon
- Charge parity C: Charge conjugation changes the sign of all quantum charges
- Pomeron and Odderon correspond to positive and negative C parity: Pomeron is made of two gluons which leads to a $+1$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

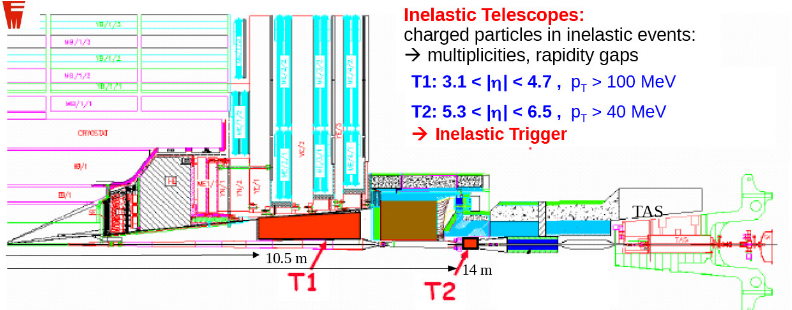
What is the odderon? The QCD picture





- 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

Forward coverage in CMS-TOTEM



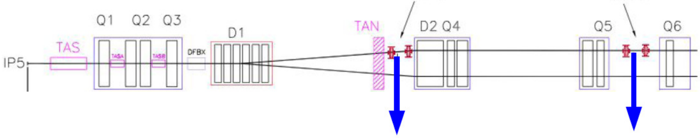
Inelastic Telescopes:
charged particles in inelastic events:
→ multiplicities, rapidity gaps

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**

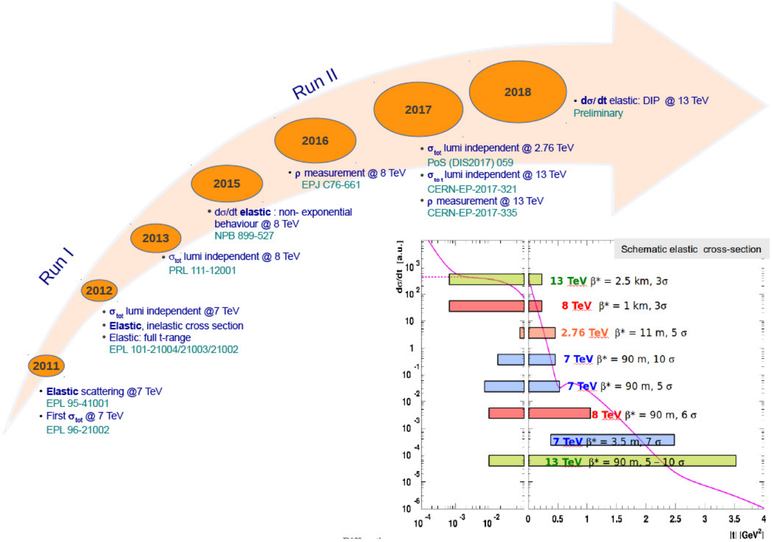


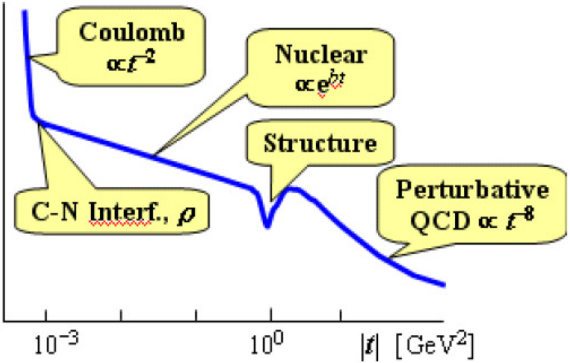
Roman Pot stations in the LHC tunnel (before LS1)

RP (147 m)

RP (220m)

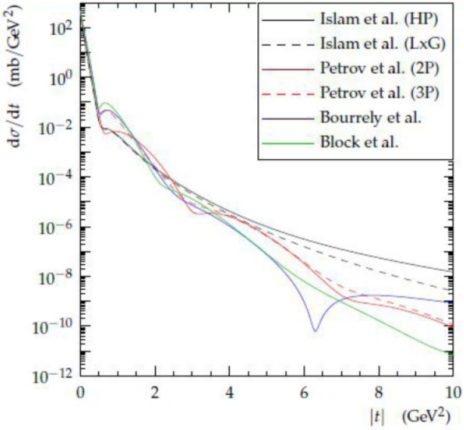
TOTEM cross section measurements





- 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 $d\sigma/dt$

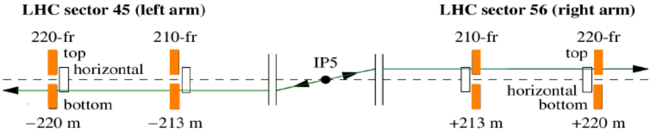
What is the expected situation at the LHC?

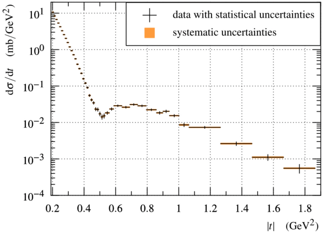


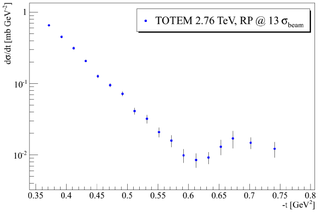
- Expected elastic $d\sigma/dt$ before LHC measurements
- Many different predictions including many possible contributions at high $|t|$, such as pomeron, reggeon, mesons (ω, ϕ) whereas other predictions mentioned that, at high energies, we should be more asymptotical and pomeron dominated
- Almost nobody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

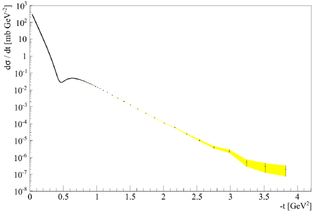
TOTEM elastic pp $d\sigma/dt$ cross section measurements

- 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

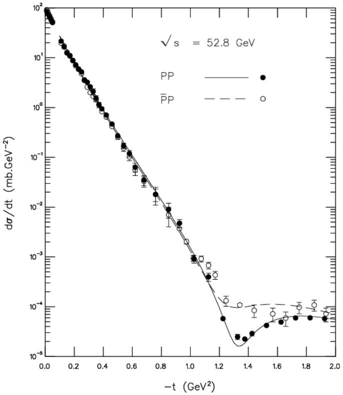






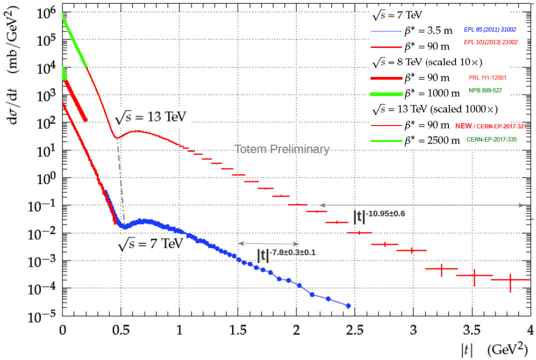


Why has the odderon not been observed yet? Why is it so elusive?

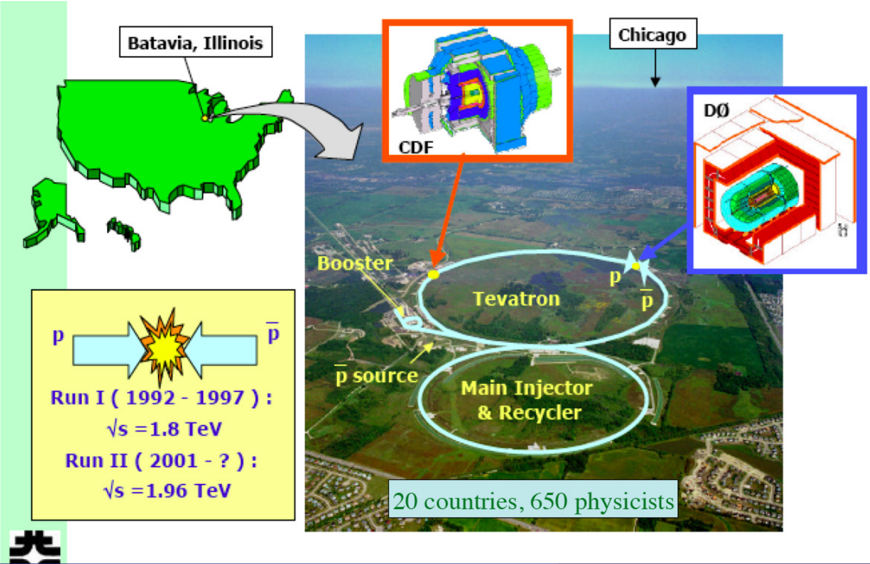


- The situation is not that simple: elastic scattering at low energies can be due to exchanges of additional particles to pomeron/odderon: ρ, ω, ϕ, reggeons...
- How to distinguish between all these exchanges? Not easy...
- At ISR energies, there was already some indication of a possible difference between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

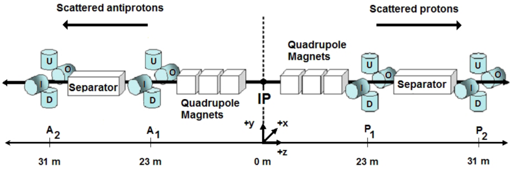
Are we in the asymptotic regime at the LHC?

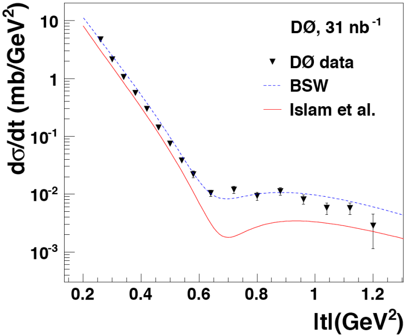


- Contrary to what some models expected before LHC, the elastic cross section is smooth: we do not see reggeons, mesons...!
- Effects of reggeon, meson exchanges are negligible at LHC energies: we can concentrate on pomeron/odderon studies!
- We can directly look for the existence of the odderon by comparing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


Batavia, Illinois
Chicago
CDF
DØ
Booster
Tevatron
p
p̄
p̄ source
Main Injector
& Recycler
p
p̄
Run I (1992 - 1997) :
√s =1.8 TeV
Run II (2001 - ?) :
√s =1.96 TeV
20 countries, 650 physicists

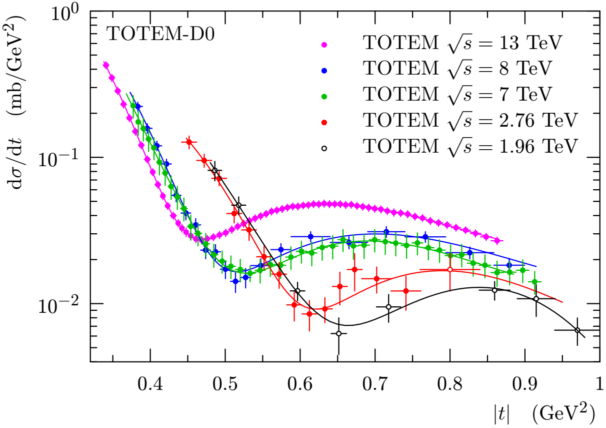
D0 elastic $p\bar{p}$ $d\sigma/dt$ cross section measurements





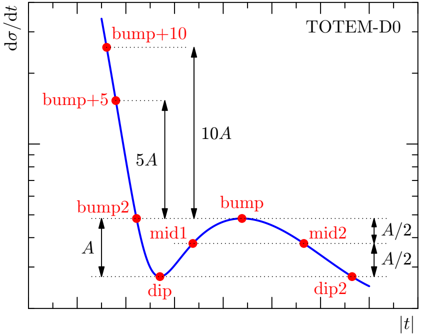
- D0 collected elastic $p\bar{p}$ data with intact p and $\bar{p}$ detected in the Forward Proton Detector with 31 nb^{-1} Phys. Rev. D 86 (2012) 012009
- Measurement of elastic $p\bar{p}$ $d\sigma/dt$ at 1.96 TeV for $0.26 < |t| < 1.2$ GeV^2

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

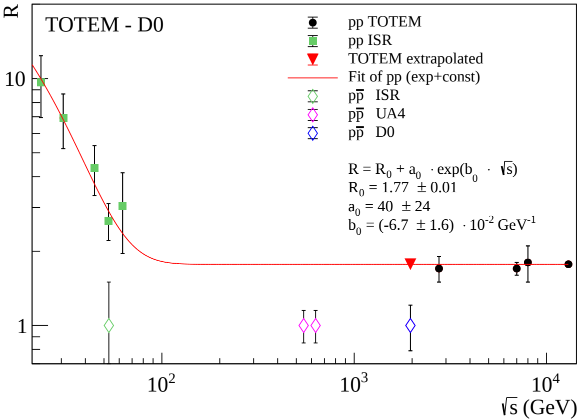
Reference points of elastic $d\sigma/dt$



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

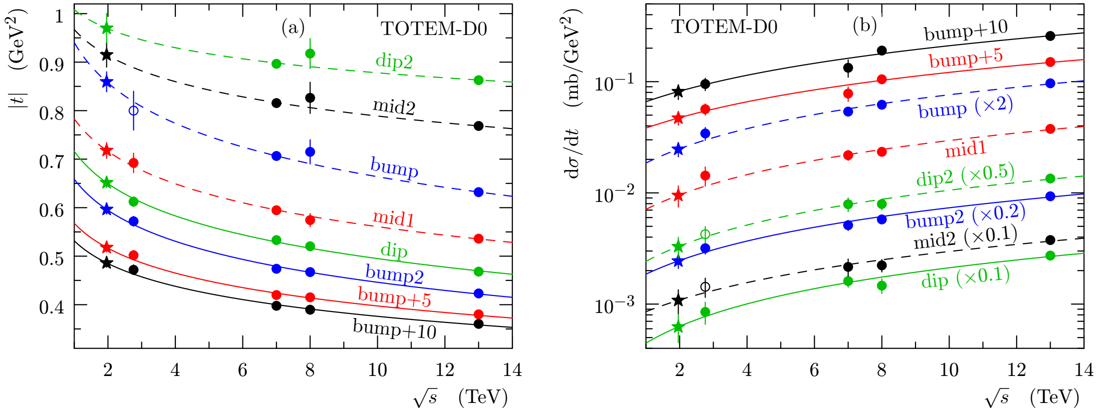
- Determine how the values of $|t|$ and $d\sigma/dt$ of characteristic points vary as a function of $\sqrt{s}$ in order to predict their values at 1.96 TeV
- We use data points closest to those characteristic points (avoiding model-dependent fits)
- Data bins are merged in case there are two adjacent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



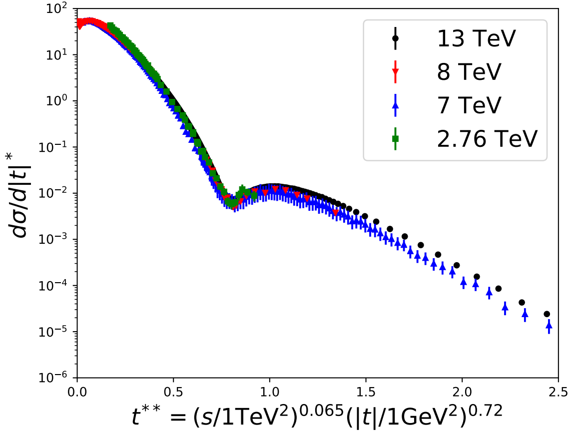
- Bump over dip ratio measured for *pp* interactions at ISR and LHC energies
- Bump over dip ratio in *pp* elastic collisions: decreasing as a function of $\sqrt{s}$ up to $\sim$ 100 GeV and flat above
- D0 $p\bar{p}$ shows a ratio of 1.00$\pm$0.21 given the fact that no bump/dip is observed in $p\bar{p}$ 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



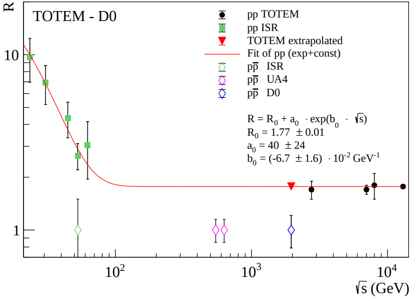
$$|t| = a\log(\sqrt{s}[\mathrm{TeV}]) + b \qquad (d\sigma/dt) = c\sqrt{s}\ [\mathrm{TeV}] + d$$

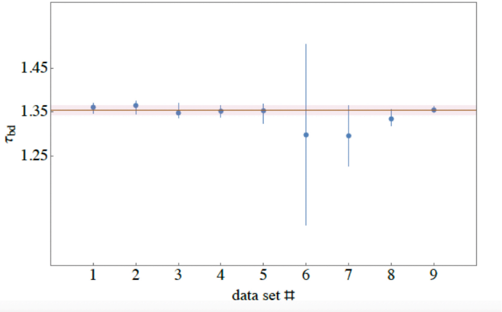
One aside: a new scaling in data



- We introduce the variable $t^* = (s/|t|)^A \times |t|$, inspired by geometric scaling in terms of saturation models
- $t^{**} = t^*/s^B$, A and B being parameters to be fitted to data
- $d\sigma/dt^*$ shows scaling as a function of t^{**}
- A and B are correlated: full valley of parameters leading to similar scalings: $B = A - 0.065 \to 1$ single parameter fit
- $A = 0.28$, C. Baldenegro, C. Royon, A. Stasto, Phys. Lett. B830 (2022) 137141

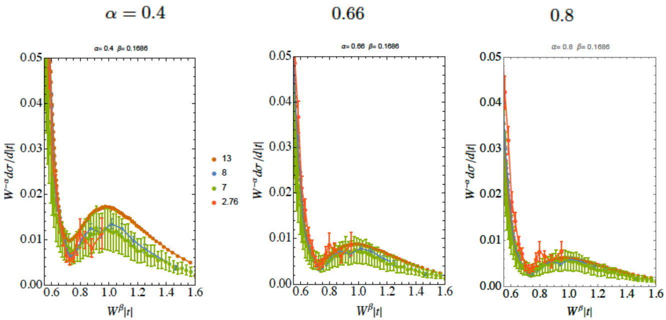
One aside: Scaling of the elastic proton-proton cross section





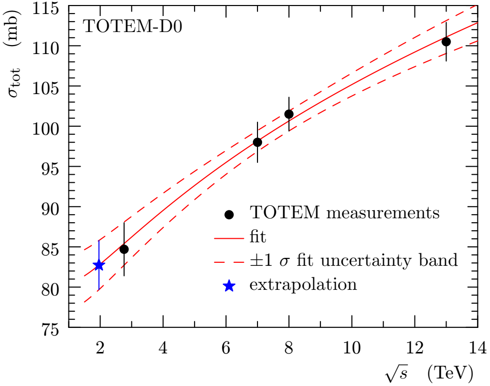
- Bump over dip cross section $d\sigma/dt$ ratio constant at high energies
- The position ratio in $|t|$ between the bump and the dip is also constant between ISR and LHC energies
- C. Baldenegro, M. Praszalowicz, C. Royon, A. Stasto, Phys. Lett. B 856 (2024) 13896

One aside: Scaling of the elastic proton-proton cross section



- $|t| \to \tau = W^{\beta}|t|$ with $\beta = 0.1686$
- $\frac{d\sigma_{el}}{dt}(\tau) \to W^{-\alpha}\frac{d\sigma_{el}}{dt}(\tau)$
- A family of scalings exists at high energy

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**

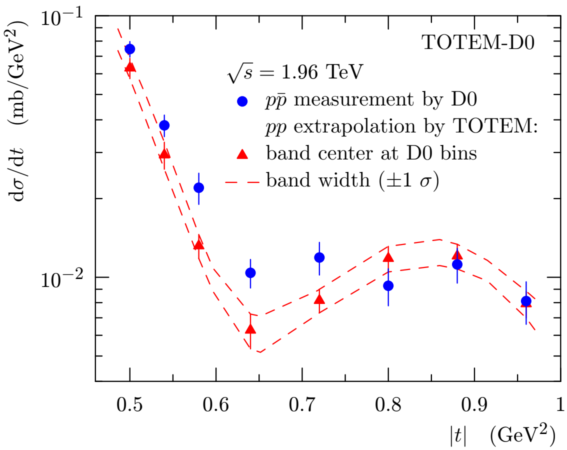
Relative normalization between D0 measurement and extrapolated TOTEM data: Rescaling TOTEM data

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

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

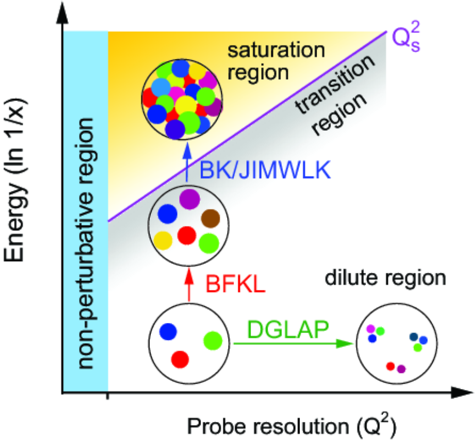
- Assuming $\rho = 0.145$, the ratio of the imaginary and the real part of the elastic amplitude, as taken from COMPETE extrapolation
- This leads to a TOTEM $d\sigma/dt(t=0)$ at the OP of 357.1 ± 26.4 mb/GeV^2
- D0 measured the optical point of $d\sigma/dt$ at small t: 341$\pm$48 mb/GeV^2
- TOTEM data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



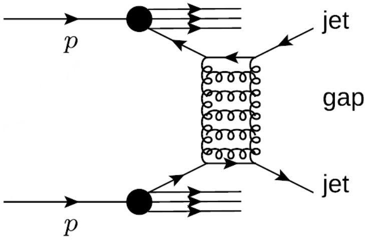
- Reference points at 1.96 TeV (extrapolating TOTEM data) and 1σ uncertainty band
- Comparison with D0 data: the χ^2 test with six degrees of freedom yields the **p-value of 0.00061, corresponding to a significance of 3.4σ**
- Combination with the independent evidence of the odderon found by TOTEM using ρ and total cross section measurements at low t leads to a 5.3 to 5.7σ discovery

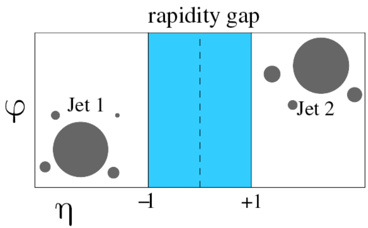
Looking for BFKL resummation / saturation effects



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

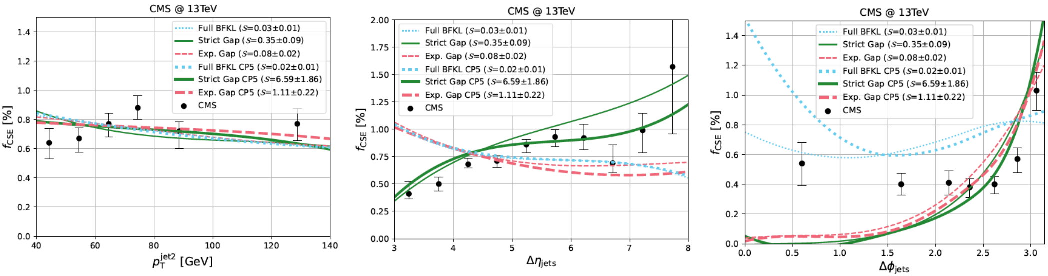
Mueller Tang: Gap between jets at the Tevatron and the LHC





- Looking for a gap between two jets: Region in rapidity devoid of any particle production, energy in detector
- Exchange of a BFKL Pomeron between the two jets: two-gluon exchange in order to neutralize color flow
- Method to test BFKL resummation: Implementation of BFKL NLL formalism in HERWIG/PYTHIA Monte Carlo

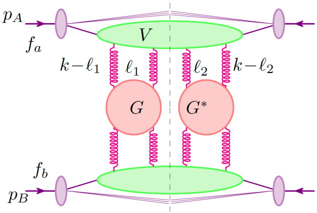
Jet gap jet measurements at the LHC (CMS@13 TeV)



- Measurement of fraction of jet gap jet events as a function of jet $\Delta\eta$, p_T, $\Delta\Phi$ (Phys.Rev.D 104 (2021) 032009)
- Implementation of BFKL NLL formalism in Pythia and compute jet gap jet fraction
- Dijet cross section computed using POWHEG and PYTHIA8
- Good agreement with theory with "strict" gap definition (C. Baldenegro, P. Gonzalez Duran, M. Klasen, C. Royon, J. Salomon, JHEP 08 (2022) 250)

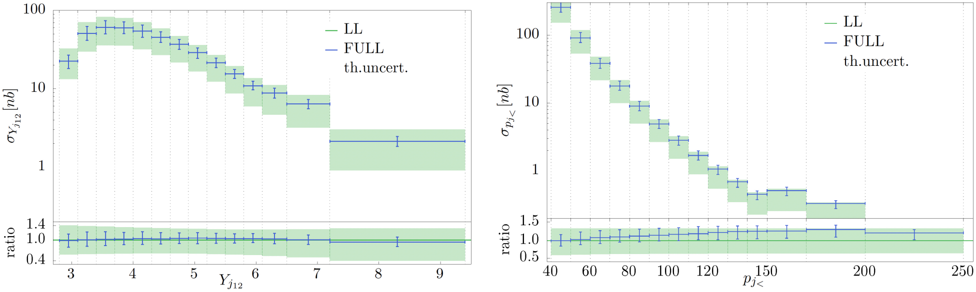
Jet gap jet: Full NLO BFKL calculation including NLO impact factor

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



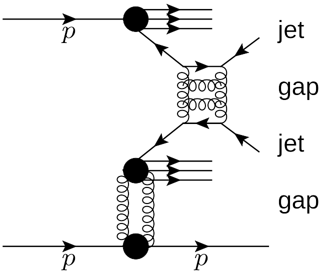
- Gluon Green functions in red
- Impact factors in green
- Will lead to an improved parametrisation to be implemented in HERWIG/PYTHIA
- D. Colferai, F. Deganutti, T. Raben, C. Royon, JHEP 06 (2023) 091

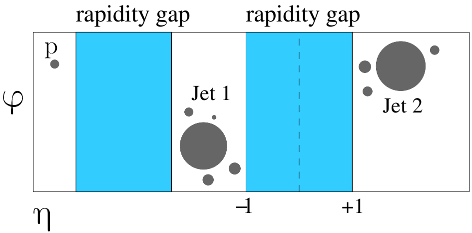
Effect of NLO impact factor on jet gap jet cross section: final results



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

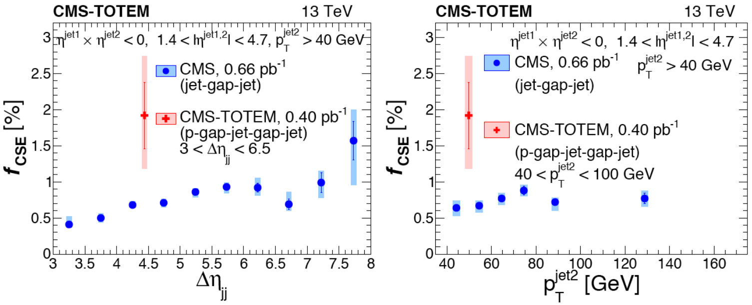
Jet gap jet events in diffraction (CMS/TOTEM)





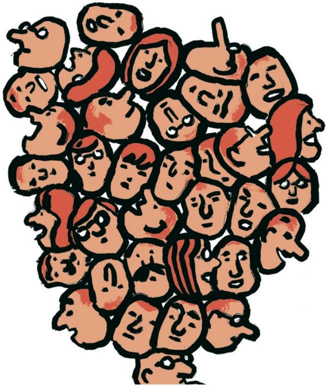
- Jet gap jet events: powerful test of BFKL resummation C. Marquet, C. Royon, M. Trzebinski, R. Zlebcík, Phys. Rev. D 87 (2013) 3, 034010
- Subsample of gap between jets events requesting in addition at least one intact proton on either side of CMS
- **Jet gap jet events were observed for the 1st time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

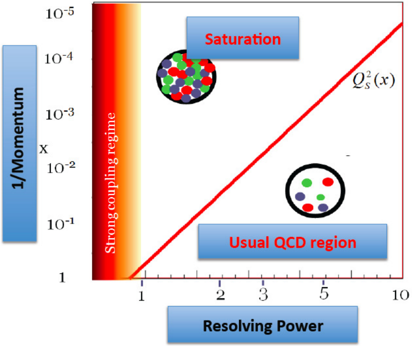
First observation of jet gap jet events in diffraction (CMS/TOTEM)



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

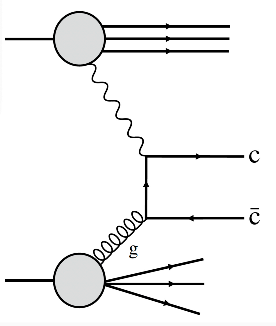
New kinematical domain: saturation





- Very small x Regions where the density of gluons is very large, "saturation"
- The usual QCD linear equations (BFKL/DGLAP) are no longer valid!
- Can be studied at the LHC and at the future Electron-Ion Collider in the US

J/Ψ, Υ, c and b productions: observables for saturation

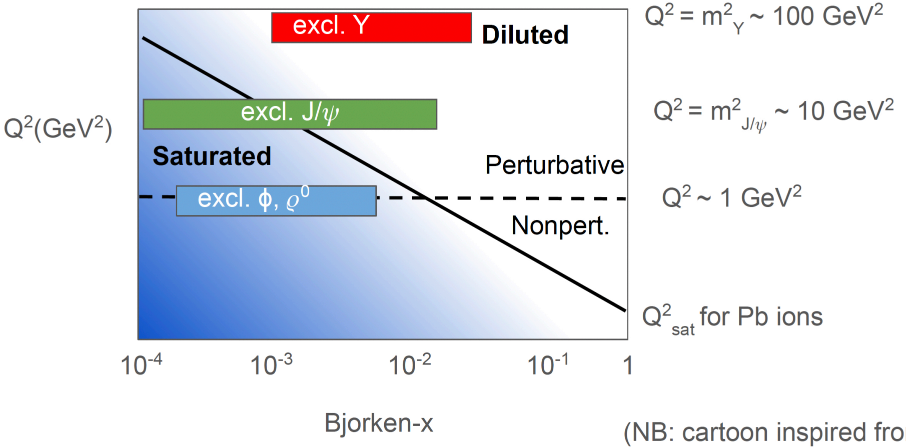


- What do we need to see saturation at the LHC?
- γPb c, b, J/Ψ are ideal probes for low-x physics

$$x = \frac{m_{c\bar{c}}}{\sqrt{s_{NN}}} \exp(-y_c)$$

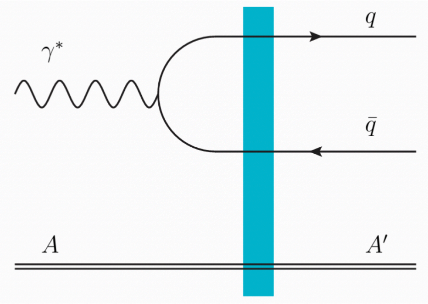
- We can reach low x values of 10^{-4} or smaller
- We need a low scale (to be below Q_S), and this is why c or b where one can go to very low p_T or J/Ψ (low mass vector mesons) are ideal while still being in the perturbative region
- $d\sigma/dW$ is the best observable while $d\sigma/dy$ presents the difficulties to mix up low and high x

Looking for saturation effects: vector meson channel



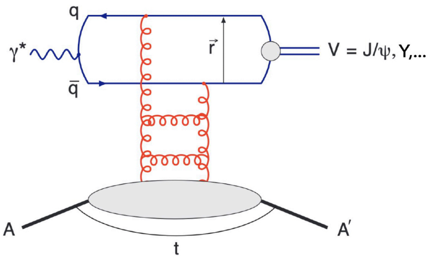
(NB: cartoon inspired from Wei's plot)

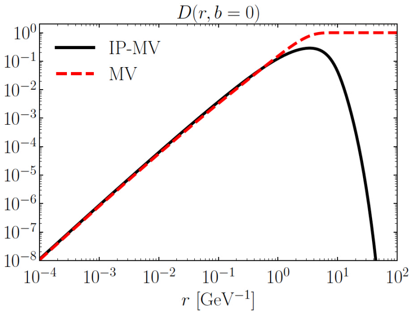
Cross section computation: the case of γPb



- The process can be factorized in two parts: 1. The photon fluctuates into a quark-antiquark pair; 2. The quark-antiquark pair interacts with the target hadron
- The first part is described by the light-cone wave function of the photon, calculable using perturbative QCD
- The second part of the process is given by the dipole scattering amplitude which is non-perturbative
- However, its energy dependence can be described using perturbative evolution equation (BFKL or BK) and the dipole amplitude must be fitted to measurement data at some initial energy scale

Looking for saturation: vector meson production

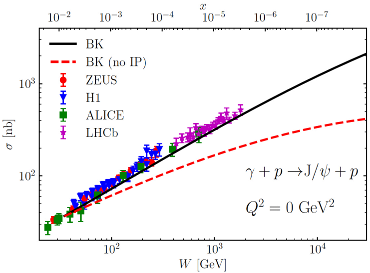


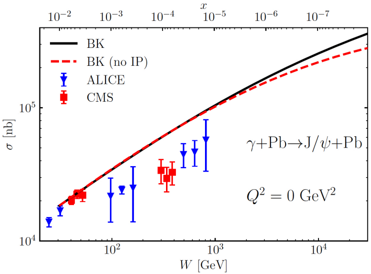


- Compute exclusive vector meson production in γp (HERA, EIC and pPb LHC) and γPb (EIC and Pb Pb LHC) where we probe the gluon density in p or Pb
- Saturation effects are expected to happen in Pb Pb, not in p Pb
- Computation: Factorize the $\gamma \to q\bar{q}$ part from the coupling to the proton: cross section proportional to $(xG)^2$ at LO
- Take into account b impact parameter dependence in dipole amplitude

High energy evolution

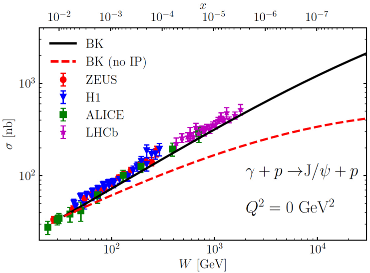
$$\partial_Y D(\mathbf{x}_0, \mathbf{x}_1, Y) = \int \mathrm{d}^2\mathbf{x}_2\, K_{\mathrm{BK}}(\mathbf{x}_0, \mathbf{x}_1, \mathbf{x}_2) \Big[D(\mathbf{x}_0, \mathbf{x}_2, Y) + D(\mathbf{x}_2, \mathbf{x}_1, Y) - D(\mathbf{x}_0, \mathbf{x}_1, Y) - D(\mathbf{x}_0, \mathbf{x}_2, Y) D(\mathbf{x}_2, \mathbf{x}_1, Y) \Big]$$

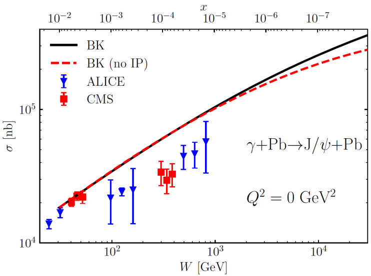




- Use Balitsky Kovchegov (BK) equation to describe the dipole evolution (so including saturation effects)

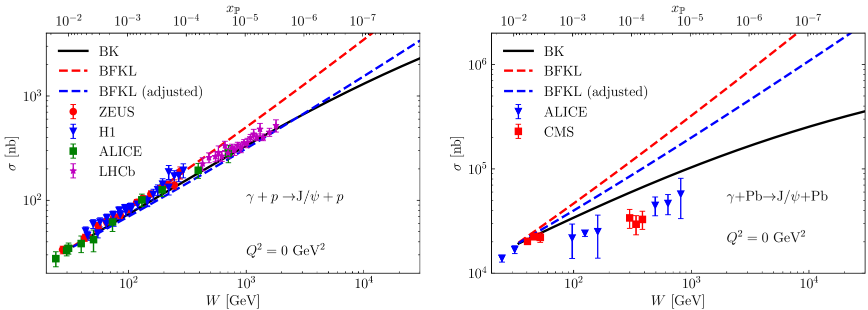
High energy evolution





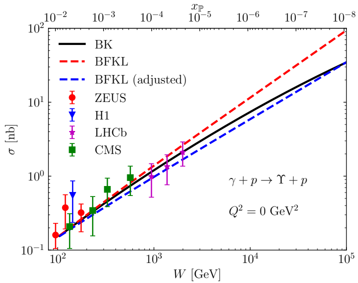
- Huge difference between taking into account b impact parameter dependence or not for γp (H. Mäntysaari, J. Penttala, F. Salazar, B. Schenke, Phys. Rev. D 111 (2025))
- Much smaller differences for γPb: nucleus much larger than proton and neglecting impact parameter dependence is more justified
- Possibility to determine effects of saturation by neglecting the gluon recombination term in BK: equivalent of linear BFKL equation

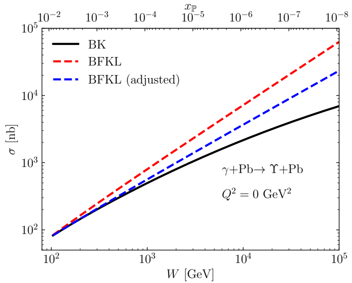
Looking for saturation: J/Ψ vector meson production

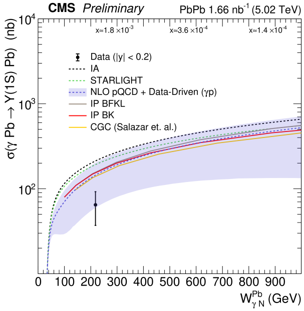


- BFKL and BK CGC predictions taking into account b-dependence (J. Penttala, C. R.)
- J/Ψ production in pPb: small differences between BK and BFKL, BK slightly favored
- Large differences between BK and BFKL in PbPb collisions

Looking for saturation: Υ vector meson production

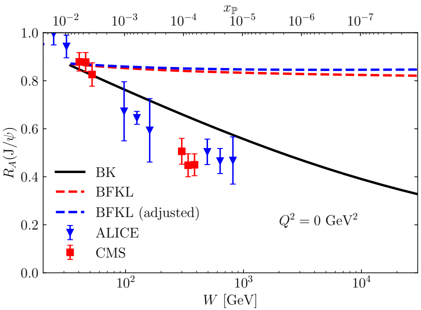


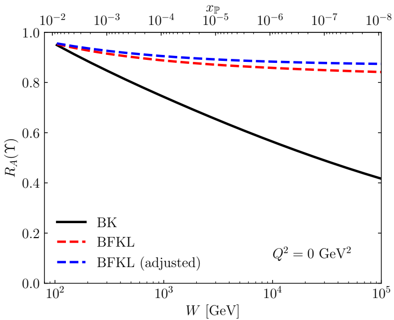




- Υ vector meson production: smaller differences between BFKL and BK in pPb or PbPb collisions
- Looking for additional observables: charm, etc

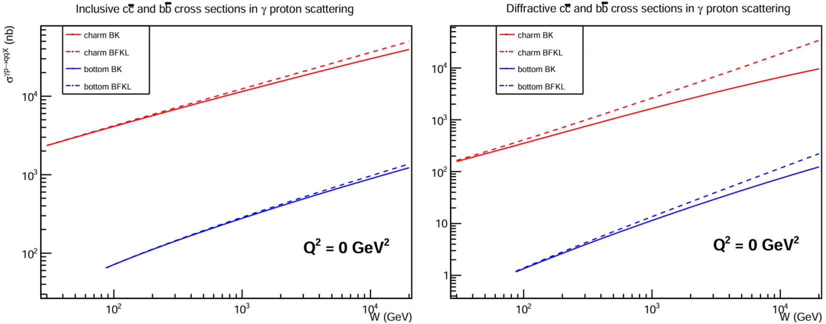
Looking for saturation: J/Ψ and Υ nuclear suppression factor





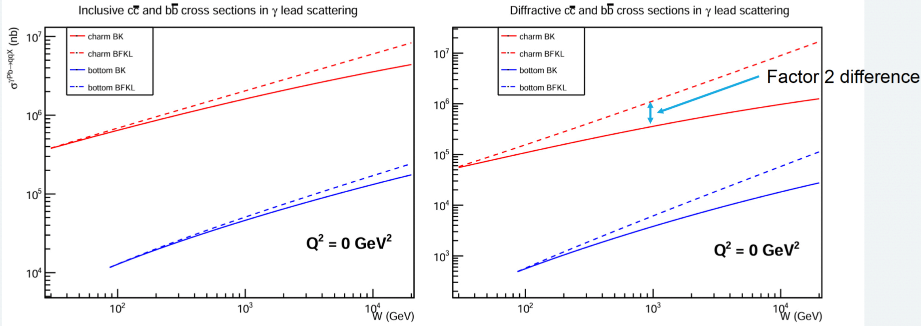
- Large nuclear suppression factor for J/Ψ in PbPb collisions
- Have we seen saturation in Pb Pb?
- Importance to have precise measurements of pp interactions as a reference at the same $\sqrt{s}$

$c\bar{c}$ and $b\bar{b}$ productions: pPb interactions



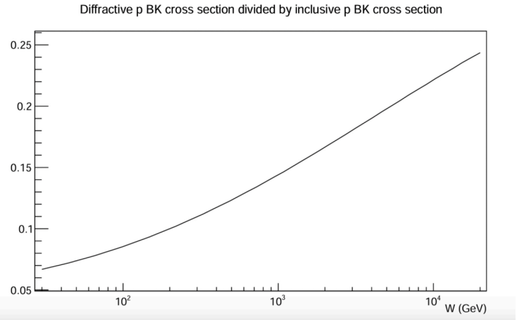
- Left: inclusive $c\bar{c}$ and $b\bar{b}$ production; Right: diffractive production
- As expected, small effect of saturation in p Pb
- Work done in collaboration with Jarno Vierros, Jani Penttala, CR

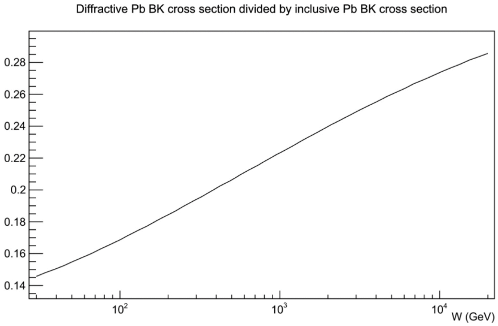
$c\bar{c}$ and $b\bar{b}$ productions: $PbPb$ interactions



- Left: inclusive $c\bar{c}$ and $b\bar{b}$ production; Right: diffractive production
- As expected, large effect of saturation in p Pb, especially for diffractive component
- Large diffractive component predicted: about 10 to 20% of cross section

$c\bar{c}$ and $b\bar{b}$ productions: diffractive contributions

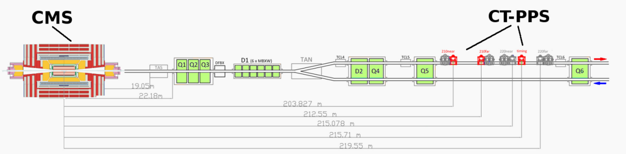


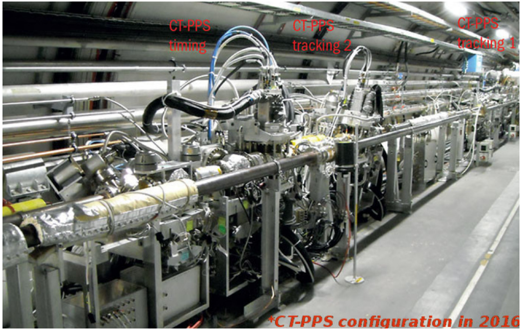


- Compute the ration of diffractive to total $c\bar{c}$ and $b\bar{b}$ productions when p, Pb is intact in pPb and $PbPb$ collisions
- Large diffractive component predicted: about 10 to 20% of cross section for $PbPb$ interactions

Searching for beyond standard model physics using intact protons

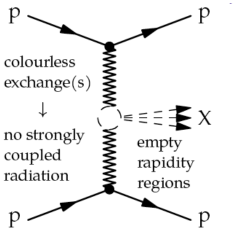
What is the CMS-TOTEM Precision Proton Spectrometer (CT-PPS)?

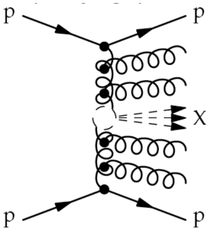


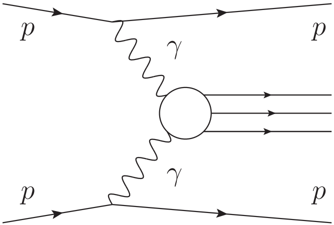


- Joint CMS and TOTEM project: https://cds.cern.ch/record/1753795
- LHC magnets bend scattered protons out of the beam envelope
- Detect scattered protons a few *mm* from the beam on both sides of CMS: 2016-2018, $\sim$ 115 fb^{-1} of data collected
- Similar detectors: ATLAS Forward Proton (AFP)

How to explain the fact that protons can be intact?

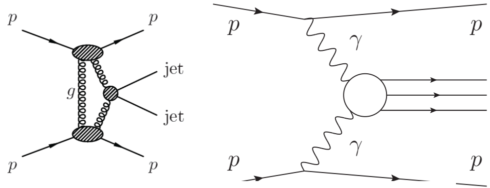


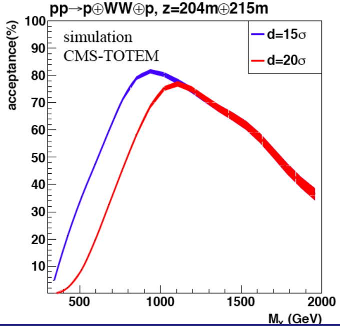




- Quarks/gluons radiate lots of gluons when one tries to separate them (confinement)
- Gluons exchange color, interact with other gluons in the proton and in that case protons are destroyed in the final state
- In order to explain how protons can remain intact: we need colorless exchanges, or at least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

Detecting intact protons in ATLAS/CMS-TOTEM at high luminosity

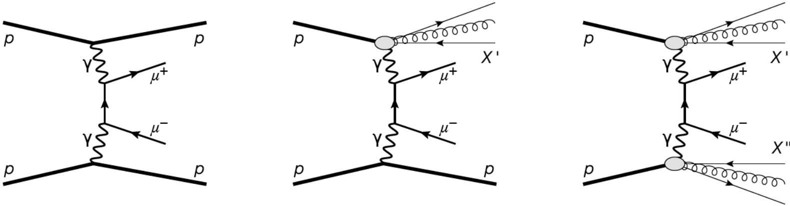




- Tag and measure protons at ± 210 m: AFP (ATLAS Forward Proton), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)
- All diffractive cross sections computed using the Forward Physics Monte Carlo (FPMC)
- Complementarity between low and high mass diffraction (high and low cross sections): special runs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

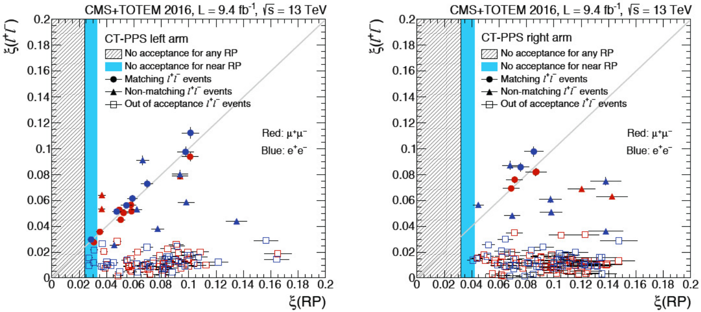
Quasi-exclusive $\mu\mu$ and *ee* production in PPS/AFP

- Turn the LHC into a $\gamma\gamma$ collider at high luminosity: flux of quasi-real photons under the Equivalent Photon Approximation, dilepton production dominated by photon exchange processes
- CMS TOTEM-Precision Proton Spectrometer: Tag one of the two protons
- The dilepton mass acceptance of PPS/AFP starts at about $\sim$400 GeV $\rightarrow$ expect very small number of double tagged events
- The two first diagrams are signal, the last one background (JHEP 1807 (2018) 153)

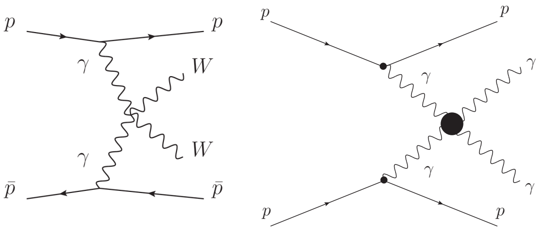


Observed signal

- First measurement of semi-exclusive dilepton process with proton tag
- PPS works as expected (validates alignment, optics determination...)
- 17 (resp. 23) events are found with protons in the PPS acceptance and 12 (resp. 8) $< 2\sigma$ matching in the $\mu\mu$ (resp. ee) channel (JHEP 1807 (2018) 153)
- Significance $> 5\sigma$ for observing 20 events for a background of 3.85 $(1.49 \pm 0.07(stat) \pm 0.53(syst)$ for $\mu\mu$ and $2.36 \pm 0.09(stat) \pm 0.47(syst)$ for $ee)$

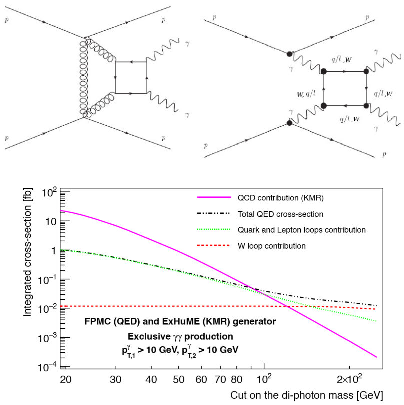


Search for $\gamma\gamma WW$, $\gamma\gamma\gamma\gamma$ quartic anomalous coupling



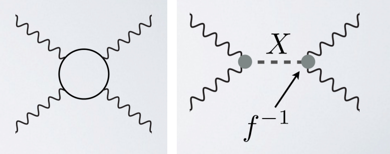
- Study of the process: $pp \rightarrow ppWW$, $pp \rightarrow ppZZ$, $pp \rightarrow pp\gamma\gamma$
- Standard Model: $\sigma_{WW} = 95.6$ fb, $\sigma_{WW}(W = M_X > 1 TeV) = 5.9$ fb
- Process sensitive to anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$; motivated by studying in detail the mechanism of electroweak symmetry breaking, predicted by extradim. models
- Rich $\gamma\gamma$ physics at LHC: see papers by C. Baldenegro, S. Fichet, M. Saimpert, G. Von Gersdorff, E. Chapon, O. Kepka, CR... Phys.Rev. D89 (2014) 114004 ; JHEP 1502 (2015) 165; Phys. Rev. Lett. 116 (2016) no 23, 231801; JHEP 1706 (2017) 142; JHEP 1806 (2018) 131

$\gamma\gamma$ 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

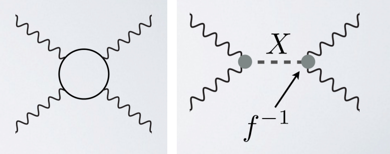


- Two effective operators at low energies

$$\mathcal{L}_{4\gamma} = \zeta_1^{\gamma} F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2^{\gamma} F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu}$$

- $\gamma\gamma\gamma\gamma$ couplings can be modified in a model independent way by loops of heavy charged 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

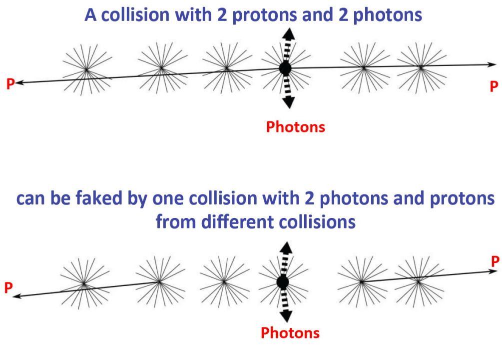


- Two effective operators at low energies

$$\mathcal{L}_{4\gamma} = \zeta_1^{\gamma} F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2^{\gamma} F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu}$$

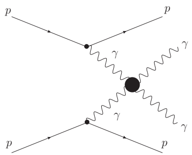
- ζ_1 can also be modified by neutral particles at tree level (extensions of the SM including scalar, pseudo-scalar, and spin-2 resonances that couple to the photon) $\zeta_1 = (f_s m)^{-2} d_{1,s}$ where f_s is the $\gamma\gamma X$ coupling of the new particle to the photon, and $d_{1,s}$ depends on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

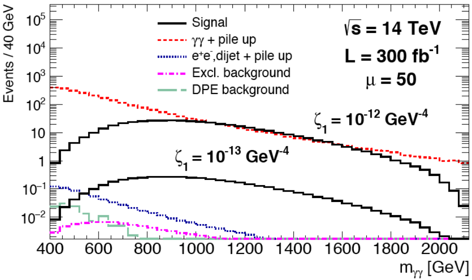
One aside: what is pile up at LHC?



- The LHC machine 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

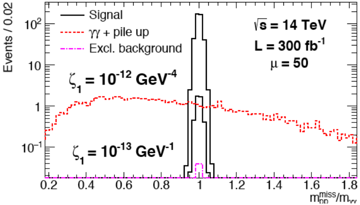
Search for quartic $\gamma\gamma$ anomalous couplings

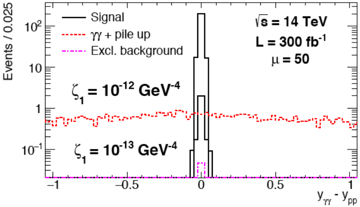




- Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- Analysis performed at hadron level including detector efficiencies, resolution effects, pile-up...
- Anomalous coupling events appear at high di-photon masses
- S. Fichet,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

Search for quartic $\gamma\gamma$ anomalous couplings

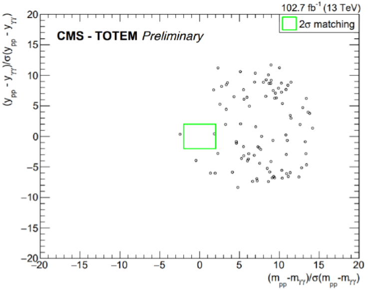


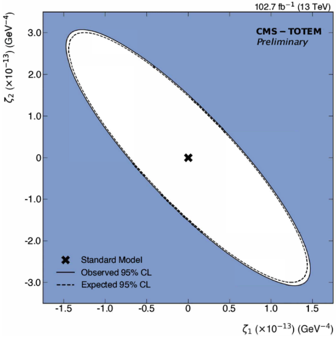


Cut / Process	Signal (full)	Signal with (without) f.f (EFT)	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15$, $p_{T1,(2)} > 200, (100)$ GeV$]$	65	18 (187)	0.13	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	64	17 (186)	0.10	0	0.2	1023
$[p_{T2}/p_{T1} > 0.95$, $\lvert\Delta\phi\rvert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

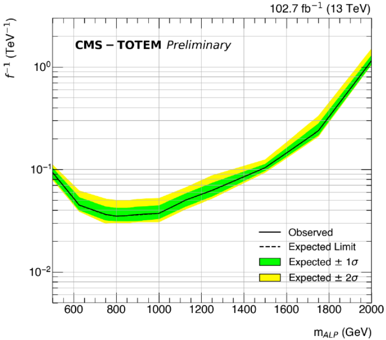
First search for high mass exclusive $\gamma\gamma$ production

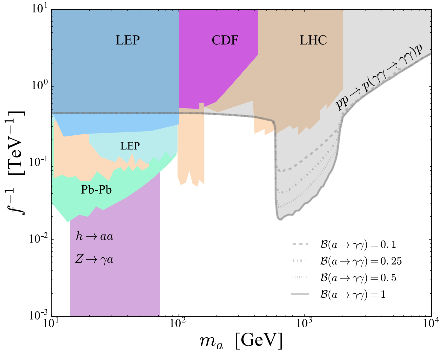


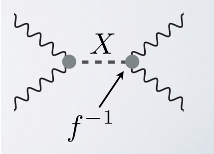


- Search for exclusive diphoton production: back-to-back, high diphoton mass ($m_{\gamma\gamma} > 350$ GeV), matching in rapidity and mass between diphoton and proton information
- First limits on quartic photon anomalous couplings: $|\zeta_1| < 2.9\ 10^{-13}$ GeV^{-4}, $|\zeta_2| < 6.\ 10^{-13}$ GeV^{-4} 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

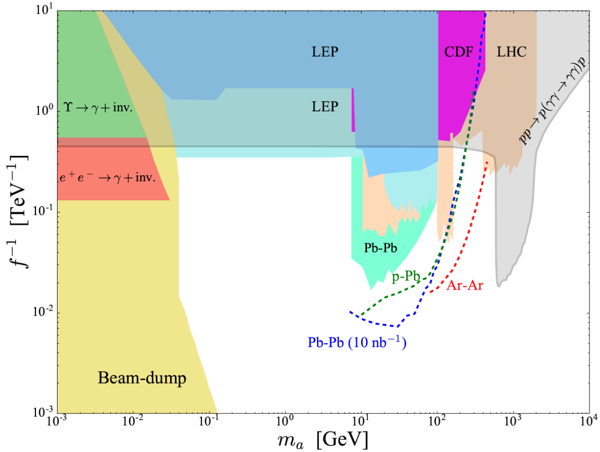






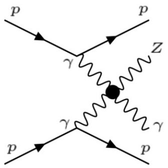
- First limits on ALPs at high mass (CMS-PAS-EXO-21-007)
- Sensitivities projected with 300 fb^{-1} (C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1806 (2018) 13)

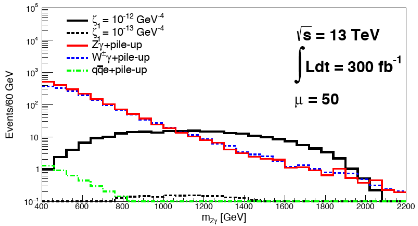
Search for axion like particles: complementarity with heavy ion runs



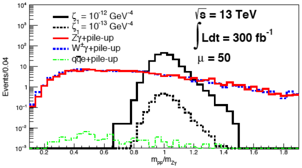
- Production of ALPs via photon exchanges in heavy ion runs: Complementarity to *pp* running
- Sensitivity to low mass ALPs: low luminosity but cross section increased by Z^4, C. Baldenegro, S. Hassani, C.R., L. Schoeffel, Phys. Lett. B795 (2019) 339; D. d'Enterria et al., PRL 111 (2013) 080405

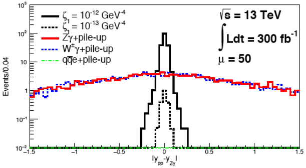
$\gamma\gamma\gamma Z$ quartic anomalous coupling





- Look for $Z\gamma$ anomalous production
- Z can decay leptonically or hadronically: the fact that we can control the background using the mass/rapidiy matching technique allows us to look in both channels (very small background)
- Leads to a very good sensitivity to $\gamma\gamma\gamma Z$ couplings

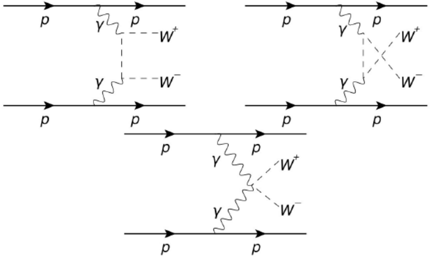




Coupling (GeV^{-4})	ζ ($\tilde{\zeta}=0$)		$\zeta=\tilde{\zeta}$	
Luminosity	300 fb^{-1}		300 fb^{-1}	
Pile-up (μ)	50		50	
Channels	5 σ	95% CL	5 σ	95% CL
$\ell\bar{\ell}\gamma$	$2.8\cdot10^{-13}$	$1.8\cdot10^{-13}$	$2.5\cdot10^{-13}$	$1.5\cdot10^{-13}$
$jj\gamma$	$2.3\cdot10^{-13}$	$1.5\cdot10^{-13}$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

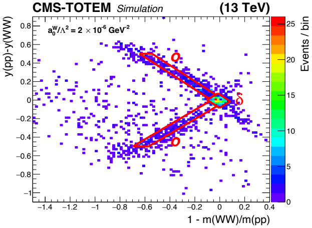
- C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1706 (2017) 142
- Best expected reach at the LHC by about three orders of magnitude
- Advantage of this method: sensitivity to anomalous couplings in a model independent way: can be due to wide/narrow resonances, loops of new particles as a threshold effect

Exclusive production of W boson pairs

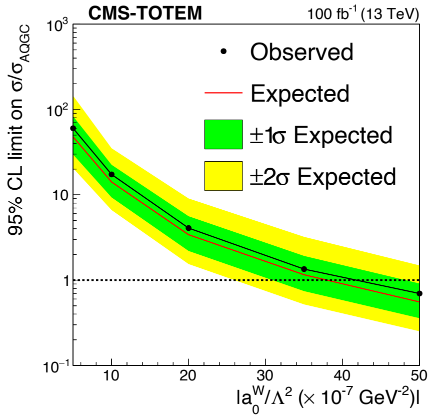


- Search with fully hadronic decays of W bosons: anomalous production of WW events dominates at high mass with a rather low cross section

- 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

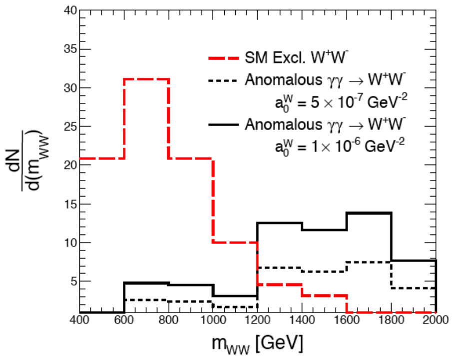


WW and ZZ exclusive productions



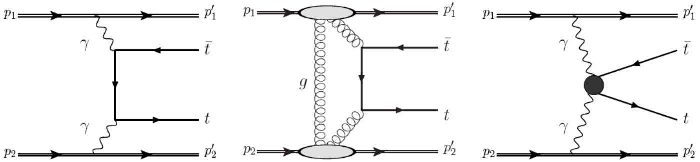
- Searches performed in full hadronic decays of W bosons (high cross section) with AK8 jets
- SM cross section is low
- Limits on SM cross section $\sigma_{WW} < 67$fb, $\sigma_{ZZ} < 43$fb for $0.04 < \xi < 0.2$ (CMS-PAS-EXO-21-014)
- New limits on quartic anomalous couplings (events violating unitarity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



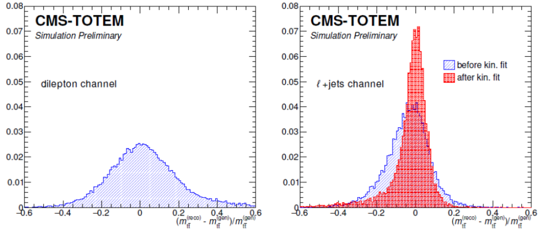
- SM contribution appears at lower WW masses compared to anomalous couplings
- Use purely leptonic channels for W decays (the dijet background is too high at low masses for hadronic channels)
- SM prediction on exclusive WW (leptonic decays) after selection: about 50 events for 300 fb^{-1} (2 background)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

Exclusive $t\bar{t}$ production

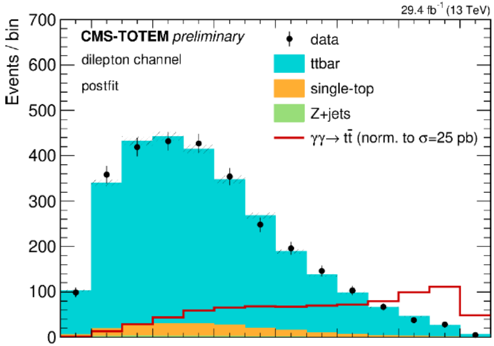


dilep channel ($\bar{t}t \to l\nu b + l\nu\bar{b}$)	Semilep channel ($\bar{t}t \to l\nu b + jj\bar{b}$)
Object selection	
Leptons: pT>30(20)GeV, |η|<2.1 Jets: pT>30GeV, |η|<2.4, ΔR(j,l)>0.4	Leptons: pT>30GeV, |η|<2.1(2.4) for e(μ) Jets: pT>25GeV, |η|<2.4, ΔR(j,l)>0.4
Event selection	
≥2 leptons (OS pair),|m(ll)-m(Z)|>15GeV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

Exclusive $t\bar{t}$ production

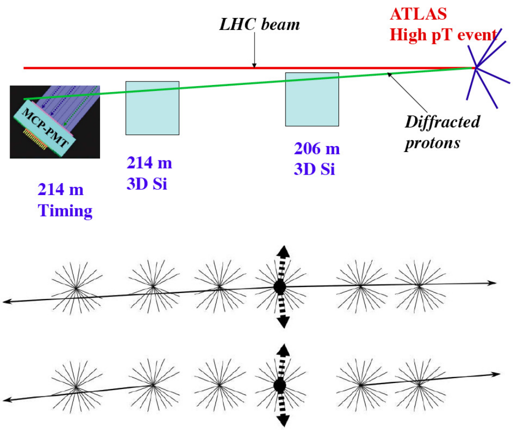


- Kinematic fitter based on W and t mass constraints to reduce background



- Search for exclusive $t\bar{t}$ production in leptonic and semi-leptonic modes
- $\sigma_{t\bar{t}}^{excl.} < 0.59$ pb (CMS-PAS-TOP-21-007)

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



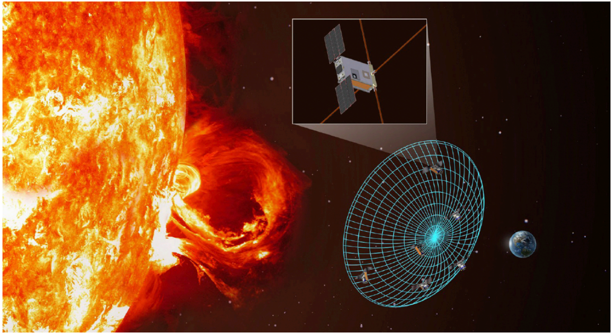
- Measure the proton time-of-flight in order to determine if they originate from the same interaction as the selected photon
- Typical precision: 10 ps means 2.1 mm
- Idea: use diamond, quartz bar, ultra-fast Si Low Gain Avalanche Detectors (signal duration of ∼few ns and possibility to use fast sampling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

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, JHEP 08 (2022) 021

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

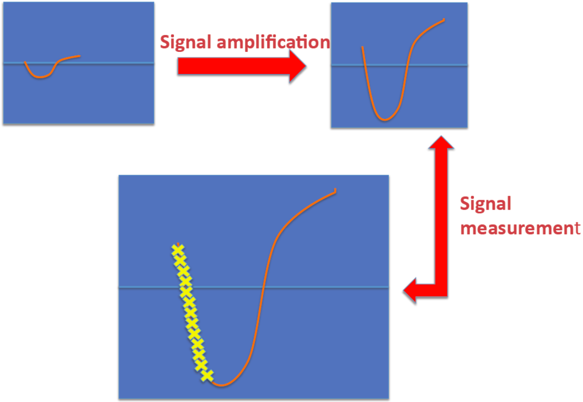
Goals of AGILE (Advanced Energetic Ion Electron Telescope)



- Build a compact low power and low cost instrument for characterization of solar energetic (SEP) and anomalous cosmic ray (ACR) particles

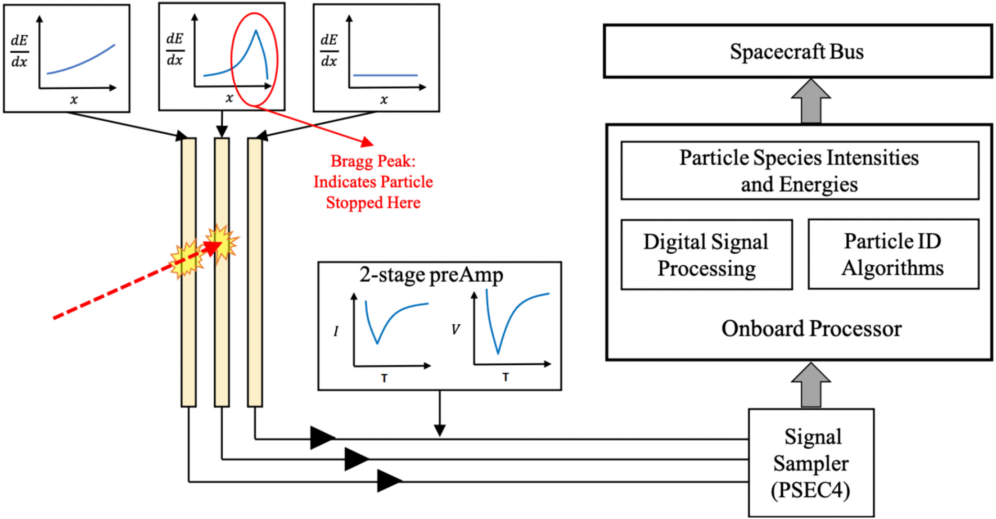
- Focus on Ions (H-Fe), $E = (1- 100)$ MeV/nucl, Electrons, $E = (1 - 10)$MeV, upgradable to higher energy ranges
- AGILE will perform robust real-time particle identification and energy measurement in space
- Solution: use multiple layers of fast Si detector (with or without absorbers) and measure the signal in stopping layer using the fast sampling technique
- Characteristics aspects of the signal (amplitude and duration) allow particle Id and energy measurement

Signal amplification and measurement

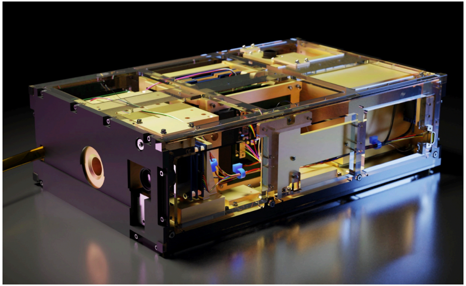


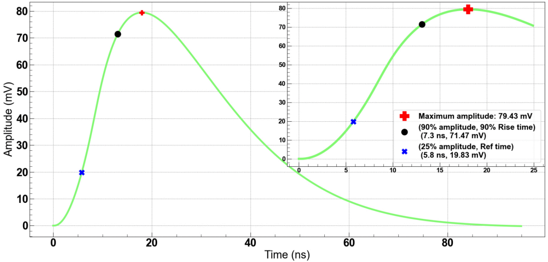
- Signal originating from a Si detector: signal duration of a few nanoseconds (fast detector)
- 1st step: Amplify the signal using an amplifier designed at KU using standard components (price: a few 10's of Euros per channel)
- 2nd step: Very fast digitization of the signal: measure many points on the fast increasing signal as an example
- Allows to measure simultanously time-of-flight, pulse amplitude and shape

AGILE schematic principle



Method developed for AGILE: signal measurement

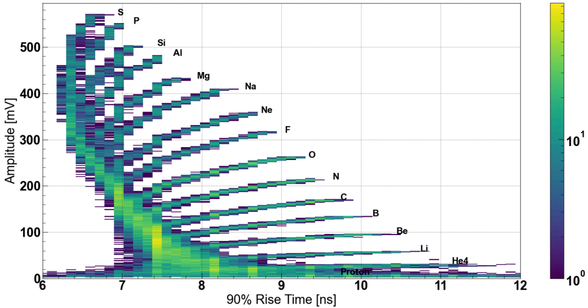




- 3 layers of fast Si detectors as a prototype
- Identification of ion type (*p*, *He*, *Au*, *Pb*, etc) and energy measurement by measuring the signal amplitude and duration

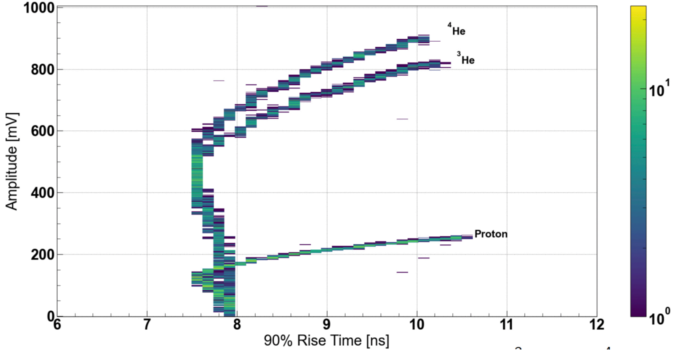
- Simulated signals of a 14 MeV/n oxygen ion that stopped in 2nd layer of AGILE
- Key characteristics: Maximum Amplitude and time to reach 90% of maximum

Particle identification with AGILE



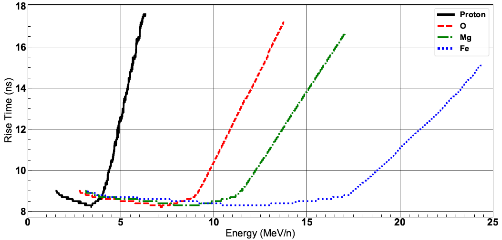
- Maximum amplitude vs time needed to reach 90% of maximum of amplitude (rise time) for p-Fe ions stopping in the detector
- Allows to obtain Particle Id since curves do not overlap for many values of rise time
- Allows even to distinguish between ^{3}He, and ^{4}He!
- Launch is foreseen by the end of this year

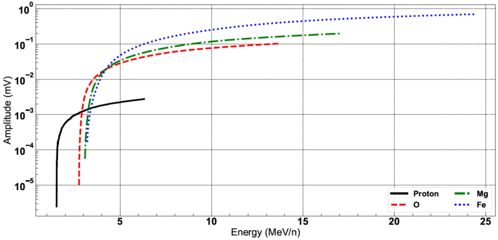
Particle identification with AGILE



- Maximum amplitude vs Rise time for Protons, ^{3}He, and ^{4}He ions
- We can distinguish ^{3}He, and ^{4}He!

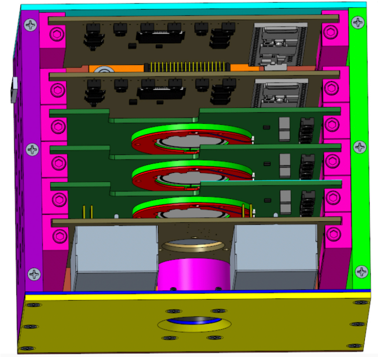
AGILE: Measuring energy of particles





- Rise time vs energy (or amplitude vs energy) allows to measure particle energy once the particle Id is known with high precision
- The energy reach depends obviously on the number of Si layers
- Launch by NASA foreseen for this year: first time we will do particle Id and energy measurement using the fast sampling technique in space!

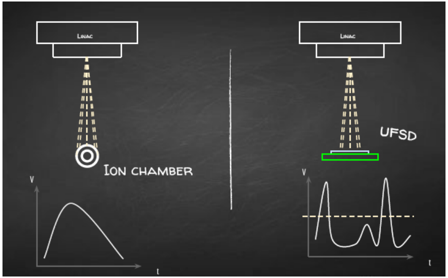
AGILE mockup: the first prototype



- 3 layers of 300 μm Si detectors
- Dimensioned to fit a CubeSat (10 cm$\times$10 cm)
- Flying in end of 2024 for a 1 year mission
- Focus on ions at lower energy range (40 MeV/n)
- A further upgrade will be to add more layers (increase the energy range) and launch a network of satellites (large coverage of space)

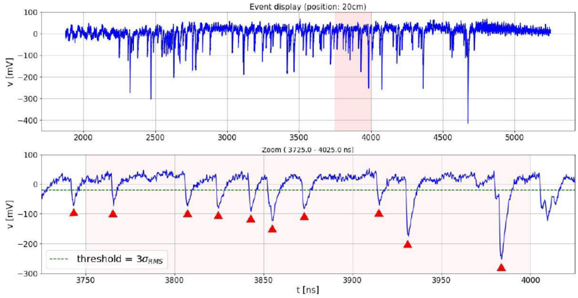
Measuring radiation in cancer treatment

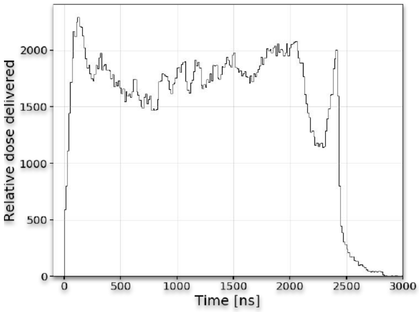
- Ultra fast silicon detectors and readout system were put in an electron beam used in the past for photon therapy at St Luke Hospital, Dublin, Ireland
- Precise and instantaneous measurements of dose during cancer treatment (especially for flash proton beam treatment)
- Develop a fast and efficient detector to count the particles up to a high rate: very precise instantaneous dose measurement, no need of calibration, high granularity (mm^2)



What Si detector can do better: Single particle Id in Dublin hospital

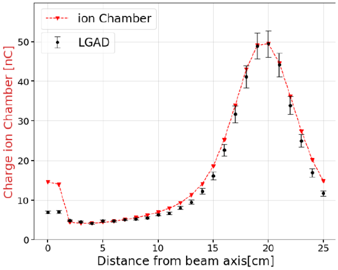
- Use UFSD and their fast signal in order to identify and measure spikes in signal due to particles passing by
- Allows measuring doses almost instantaneously

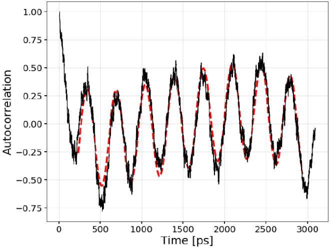




- Very precise dose measurement allowing to adapt better treatment to patients especially for flash dose treatments (brain cancer for instance)

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





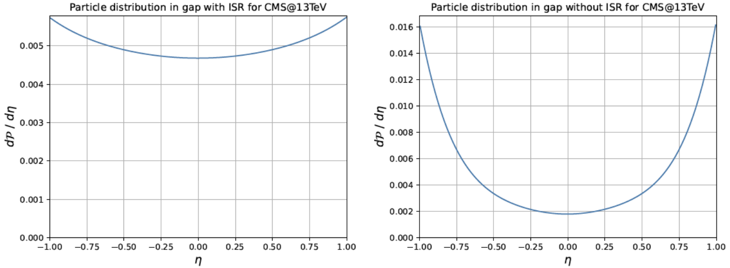
- Measurement of charge deposited in Si detector compared to standard measurement using an ion chamber: good correlation
- Our detectors see in addition the beam structure (periodicity of the beam of ∼330 ps, contrary to a few seconds for the ion chamber): measure single particles from the beam
- Fundamental to measure instantaneous doses for high intensity proton therapy as example
- For more details: Arxiv 2101.07134, Phys. Med. Biol. 66 (2021) 135002

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: odderon discovery
- Study of BFKL dynamics and saturation at the LHC
- 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...

Charged particle distribution



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