

Diffraction, saturation and gamma gamma physics at the LHC

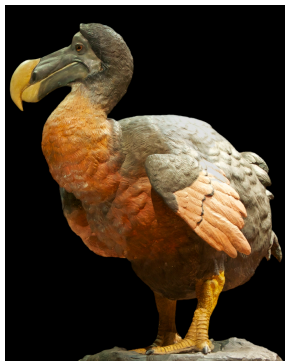
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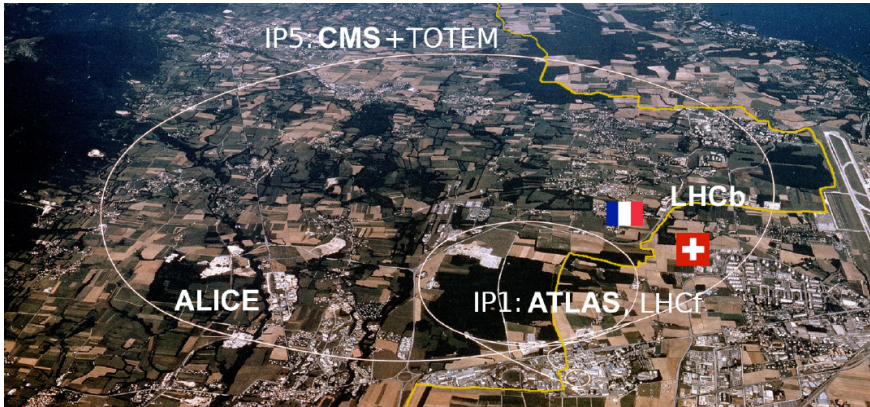
July 7 2026

- Elastic interactions and the Odderon discovery
- The high gluon regime: Jet gap jet events
- Looking for saturation at the LHC in Pb Pb collisions
- Photon-exchange processes and BSM physics
- Ultra-fast Silicon detectors and applications

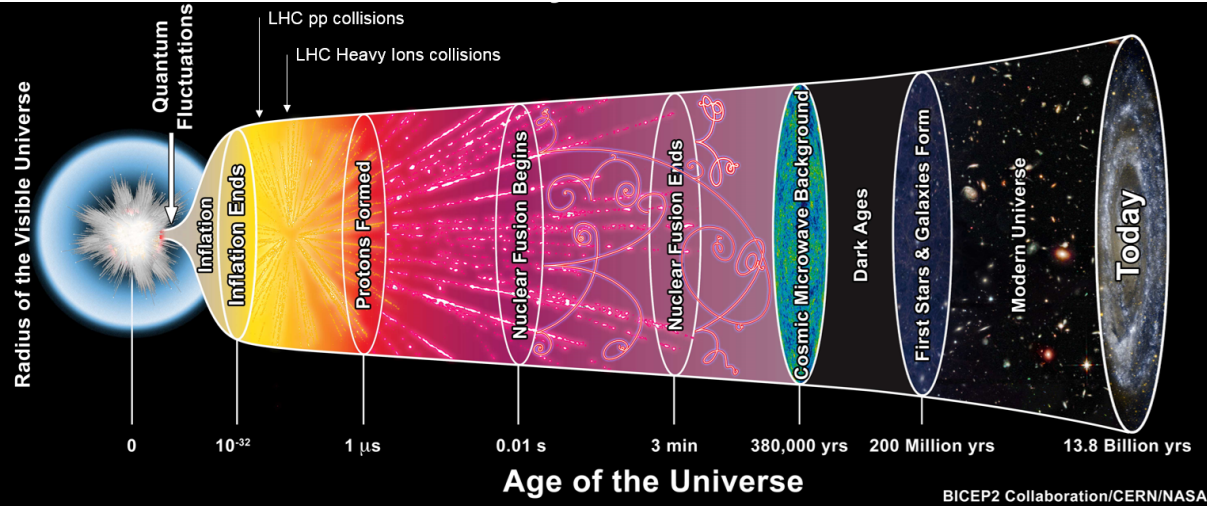


pp /heavy ion interactions: The Large Hadron Collider at CERN

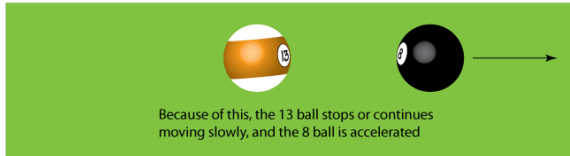
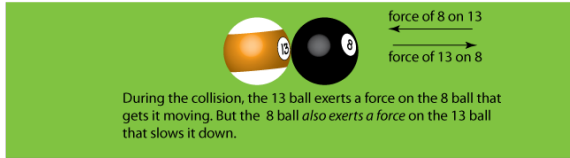
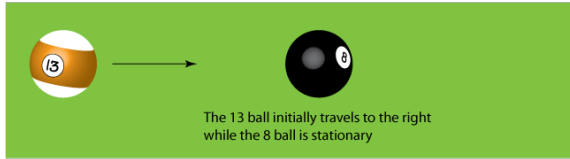
- Large Hadron Collider at CERN: proton proton collider with 2.76, 7, 8 and 13 TeV center-of-mass energy
- Circumference: 27 km; Underground: 50-100 m



Why the LHC? Going back in time....

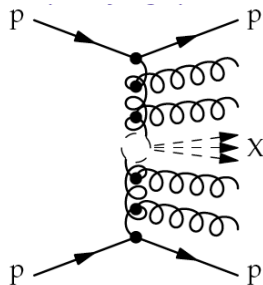
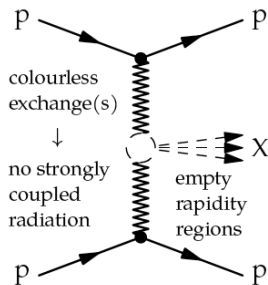


What is elastic scattering? The pool game...



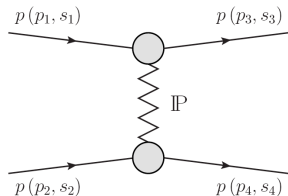
- We want to study “elastic” collisions between protons and proton-antiprotons
- In high energy physics: $pp \rightarrow pp$ and $p\bar{p} \rightarrow p\bar{p}$
- In these interactions, each proton/antiproton remains intact after interaction but are scattered at some angles and can lose/gain some momentum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

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

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

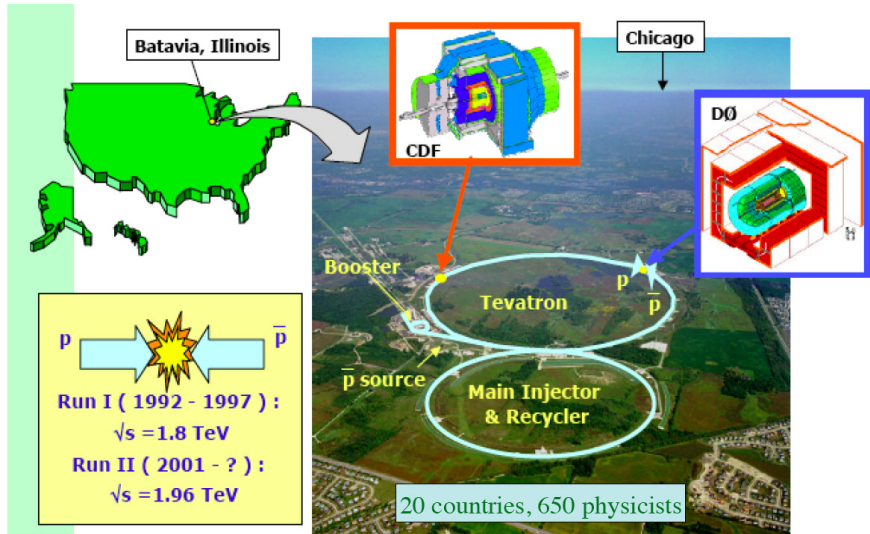
- Pomeron and Odderon correspond to positive and negative C parity
- Scattering amplitudes can be written as:

$$A_{pp} = \text{Even} + \text{Odd}$$

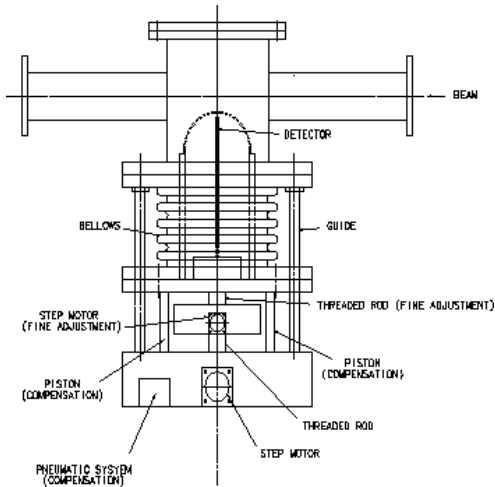
$$A_{p\bar{p}} = \text{Even} - \text{Odd}$$

- 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
- For a review, see C. Ewerz, hep-ph/0306137

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

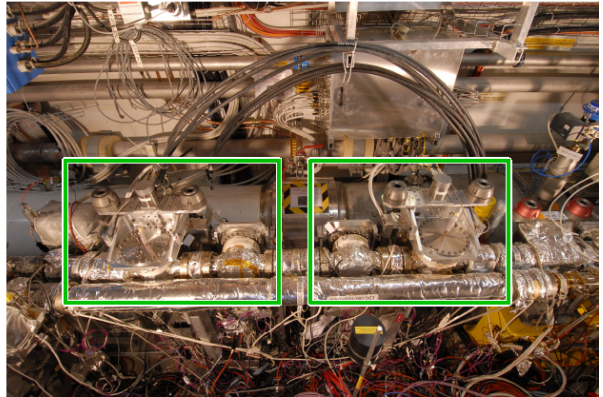
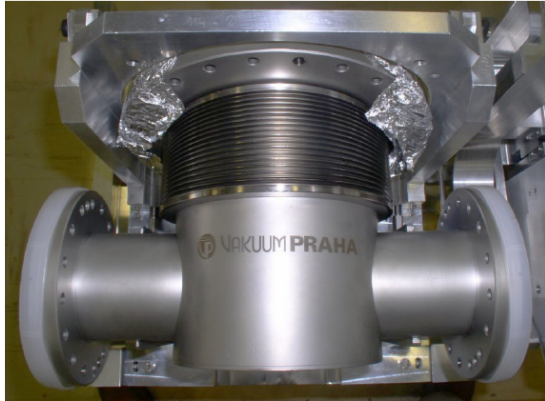


Which tools do we have? Roman Pot detectors

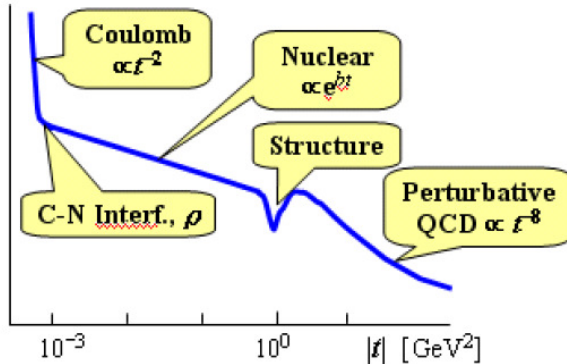


- We use special detectors to detect intact protons/ anti-protons called Roman Pots
- These detectors can move very close to the beam (up to 3σ) when beam are stable so that protons scattered at very small angles can be measured

Roman Pot detectors at the LHC

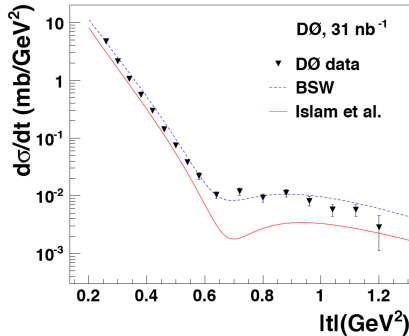
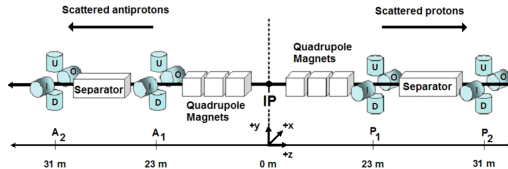


Measurement of elastic scattering at Tevatron and LHC



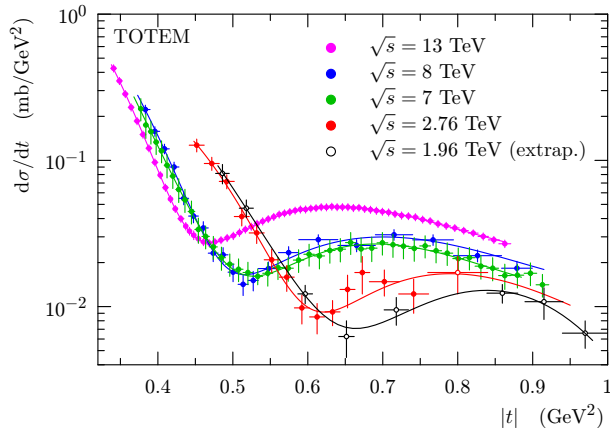
- Study of elastic $pp \rightarrow pp$ reaction: exchange of momentum between the two protons which remain intact
- Measure intact protons scattered close to the beam using Roman Pots installed both by D0 and TOTEM collaborations
- From counting the number of events as a function of $|t|$ (4-momentum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

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



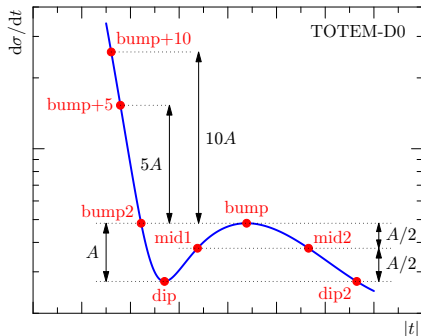
- D0 collected elastic $p\bar{p}$ data with intact p and $\bar{p}$ detected in the Forward Proton Detector with 31 nb⁻¹ Phys. Rev. D 86 (2012) 012009
- Measurement of elastic $p\bar{p}$ $d\sigma/dt$ at 1.96 TeV for $0.26 < |t| < 1.2$ GeV²

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

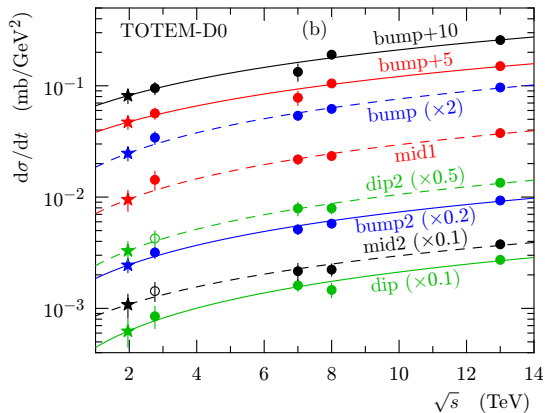
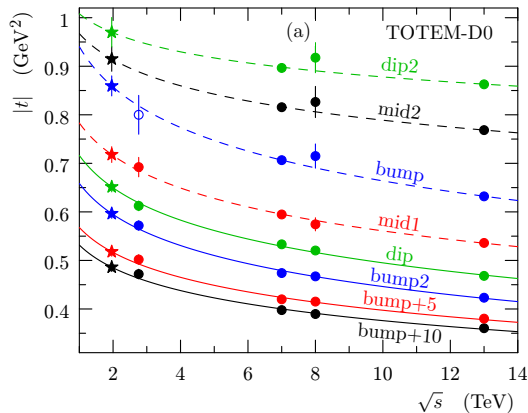
Reference points of elastic $d\sigma/dt$



- 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

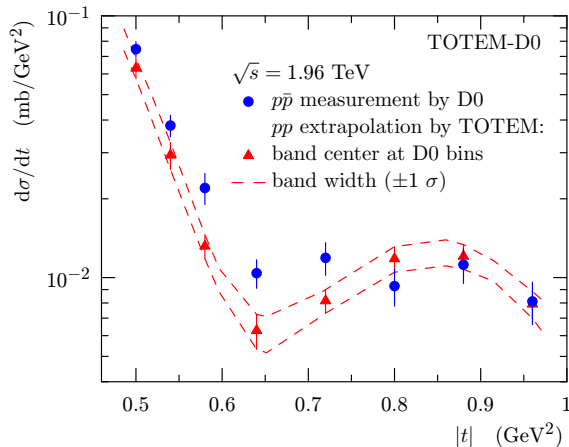
Variation of t and $d\sigma/dt$ values for reference points



$$|t| = a \log(\sqrt{s} [\text{TeV}]) + b$$

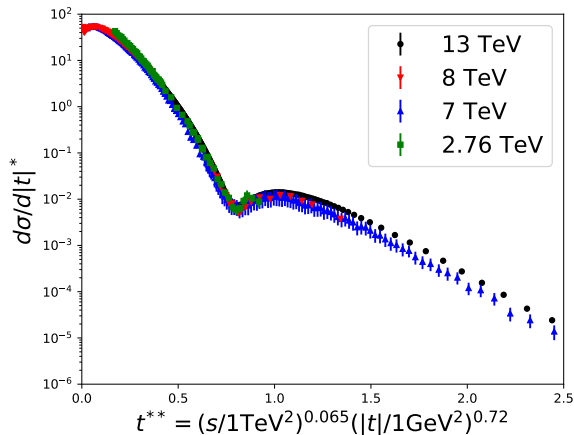
$$(d\sigma/dt) = c\sqrt{s} [\text{TeV}] + d$$

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



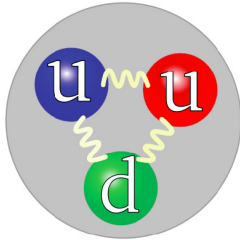
- Reference points at 1.96 TeV (extrapolating TOTEM data) and 1σ uncertainty band
- Comparison with D0 data: the χ^2 test with six degrees of freedom yields the **p -value of 0.00061, corresponding to a significance of 3.4σ**
- Combination with the independent evidence of the odderon found by TOTEM using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

One aside: a new scaling in data



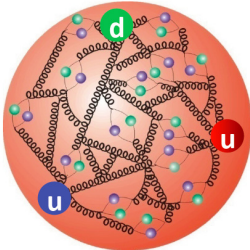
- We introduce the variable $t^* = (s/|t|)^A \times |t|$, inspired by geometric scaling in terms of saturation models
- $t^{**} = t^*/s^B$, A and B being parameters to be fitted to data
- $d\sigma/dt^*$ shows scaling as a function of t^{**}
- A and B are correlated: full valley of parameters leading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

What is a proton?



LHC is a proton-proton collider,
so what are protons?

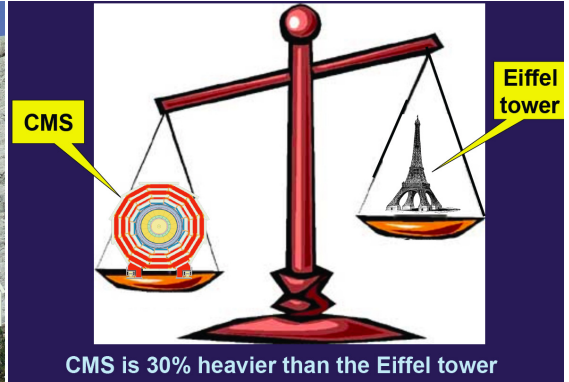
Protons are constituents of nuclei. They are small and have a size of $\sim 10^{-15}$ m (1 fermi) or about 1/1000 of the size of a hydrogen atom.



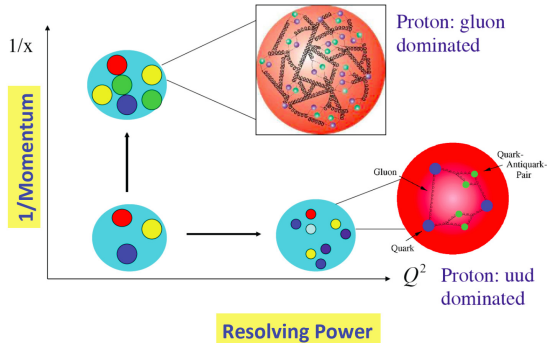
It “consists” three valence quarks and many gluons and sea quarks, bound together by nuclear (strong) interaction.

About half of the proton energy is carried by quarks while the other half by gluons.

Two general purpose experiments: ATLAS and CMS

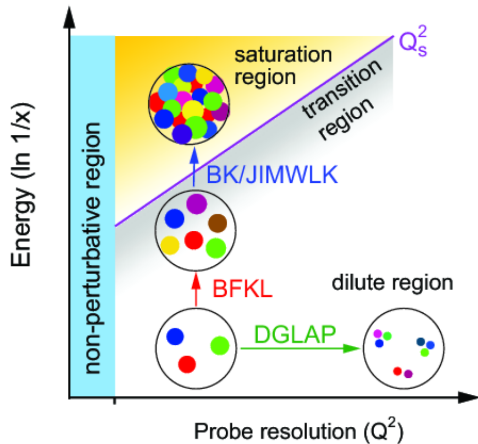


The proton structure



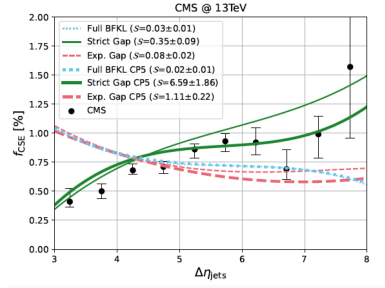
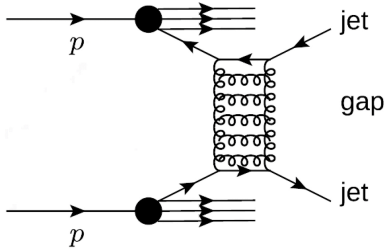
- The proton is a complicated object: it appears differently according to its energy (quantum object)
- Q^2 : Resolution power (like a microscope): *the higher the energy of an accelerator is (bigger machines), the higher values of Q^2 (the resolution) and the smaller distances that we can reach*
- x : momentum fraction of the proton possessed by the quark/gluon (proton constituent)

Looking for BFKL resummation /saturation effects



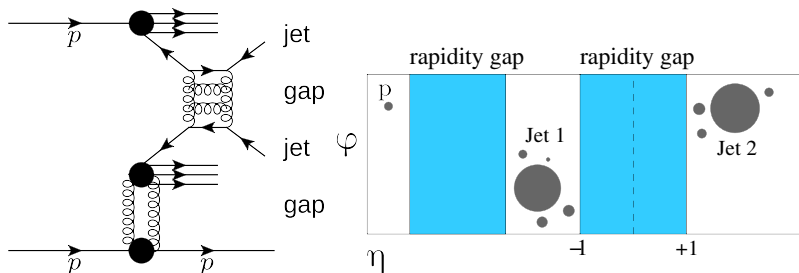
- DGLAP (Dokshitzer Gribov Lipatov Altarelli Parisi): Evolution in resolution Q^2 , resums terms in $\alpha_S \log Q^2 \rightarrow$ resolving "smaller" partons at high Q
- BFKL (Balitski Fadin Kuraev Lipatov (BFKL): Evolution in energy x , resums terms in $\alpha_S \log 1/x \rightarrow$ Large parton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

Jet gap jet measurements at the LHC



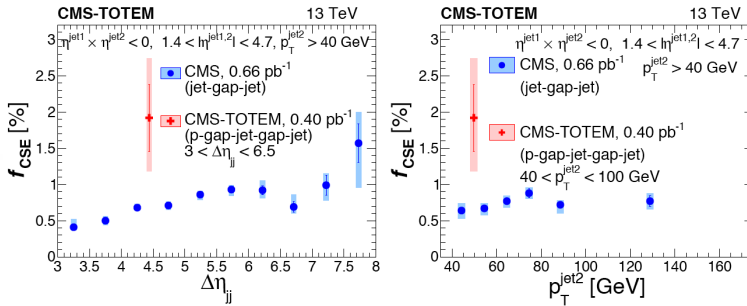
- Measurement of jet gap jet events as a test of high gluon regime
- Good agreement with theory (green curve)

Jet gap jet events in diffraction (CMS/TOTEM)



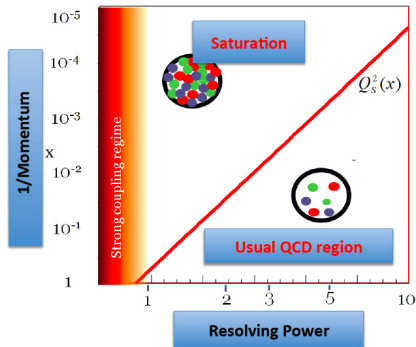
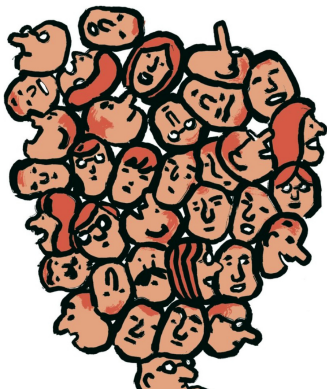
- Jet gap jet events: powerful test of BFKL resummation C. Marquet, C. Royon, M. Trzebinski, R. Zlebcík, Phys. Rev. D 87 (2013) 3, 034010
- Subsample of gap between jets events requesting in addition at least one intact proton on either side of CMS
- **Jet gap jet events were observed for the 1st time 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 $\sim 0.7 \text{ pb}^{-1}$
- 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 $>10 \text{ pb}^{-1}$ needed, 100 for DPE

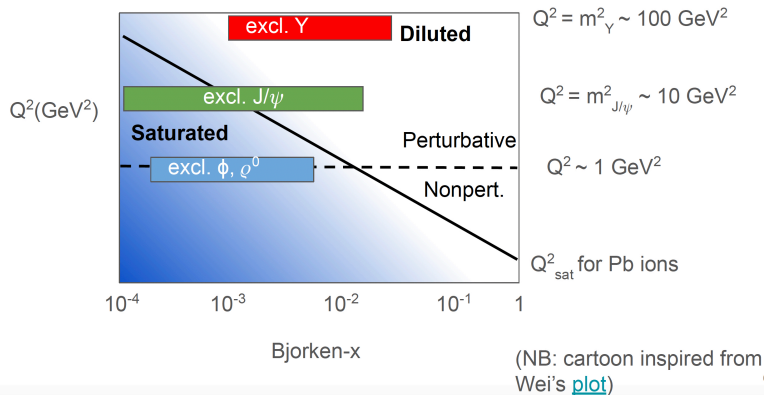
New kinematical domain: saturation



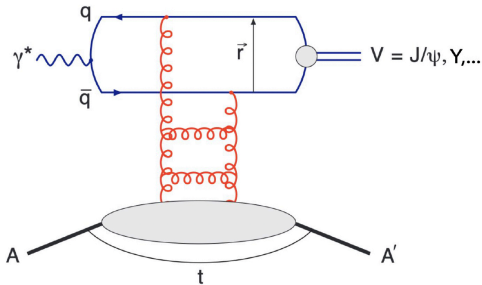
- Very small x Regions where the density of gluons is very large, “saturation”
- The usual QCD linear equations (BFKL/DGLAP) are no longer valid!
- Can be studied at the LHC and at the future Electron-Ion Collider in the US

What do we need to see saturation?

- We need low x , high W ; also a perturbative scale to perform QCD saturation
- Mesons such as J/ψ , Υ are ideal

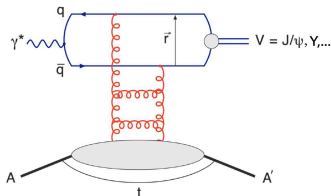
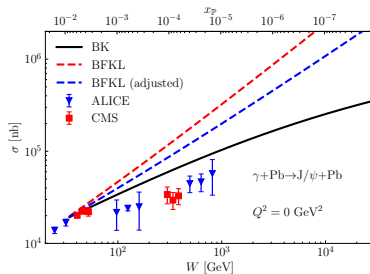
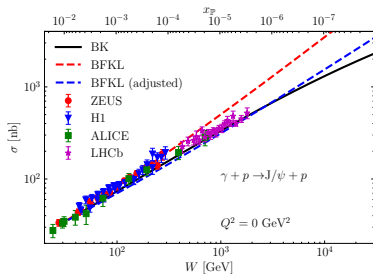


Looking for saturation effects: vector meson channel in Pb Pb interactions



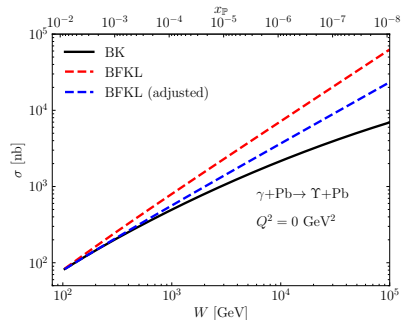
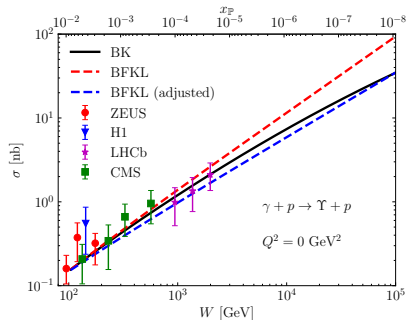
- Possibility to produce particles with different masses (ρ , J/ψ , Υ ...) that are usually made of different quarks such as charm, beauty
- The photon can be emitted by the Pb in case of pPb or $PbPb$ collisions
- The dipole ($q\bar{q}$ pair) couples with the gluon density in the proton or the Pb
- Saturation effects expected for the high gluonic object, so for Pb, not for proton

Looking for saturation: LHC J/ψ data in pPb and $PbPb$ collisions



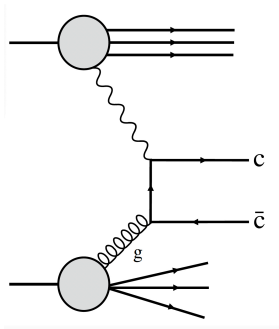
- Use dense objects to look for saturation: Pb instead of protons
- BFKL: no saturation, BK: saturation
- Study effects of saturation for vector meson, c , b quark

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

Forward jets, J/ψ , c and b productions: observables for saturation

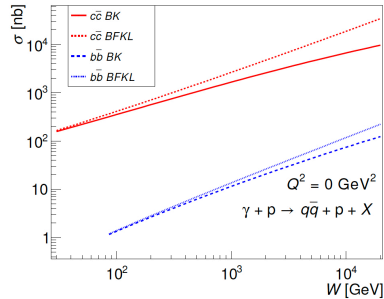
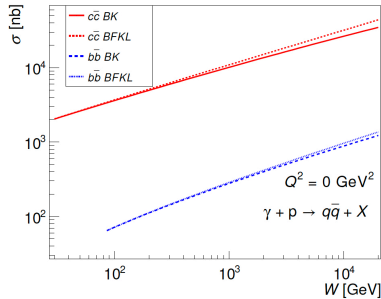


- What do we need to see saturation at the LHC?
- γPb c , b , J/ψ are ideal probes for low- x physics

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

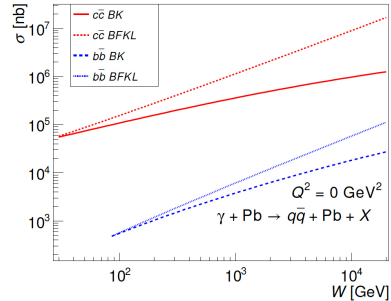
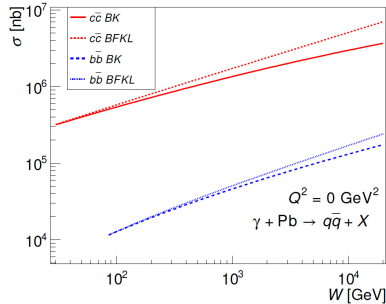
- We can reach low x values of 10^{-4} or smaller
- We need a low scale (to be below Q_S), and this is why c or b where one can go to very low p_T or J/ψ (low mass vector mesons) are ideal while still being in the perturbative region
- $d\sigma/dW$ is the best observable while $d\sigma/dy$ presents the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

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



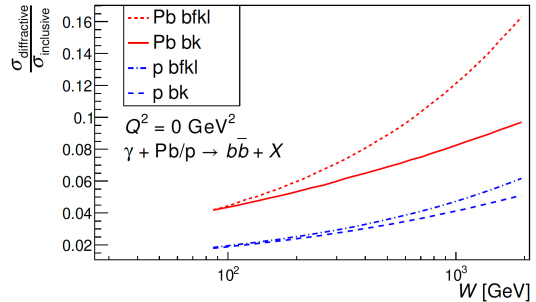
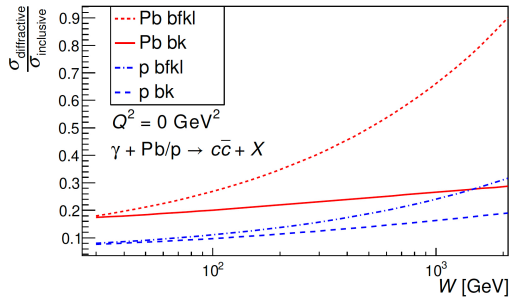
- Left: inclusive $c\bar{c}$ and $b\bar{b}$ production; Right: diffractive production
- As expected, small effect of saturation in p Pb
- Work done in collaboration with Jarno Vierros, Jani Penttala, CR

$c\bar{c}$ 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

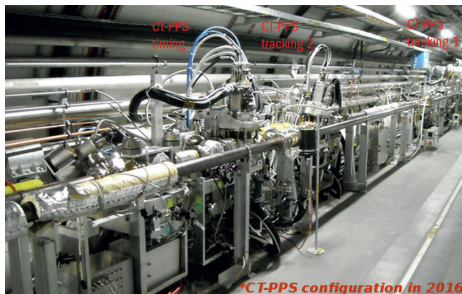


- Compute the ratio of diffractive to total $c\bar{c}$ and $b\bar{b}$ productions when p , Pb is intact in pPb and $PbPb$ collisions
- Large diffractive component predicted: about 10 to 20% of cross section for $PbPb$ interactions

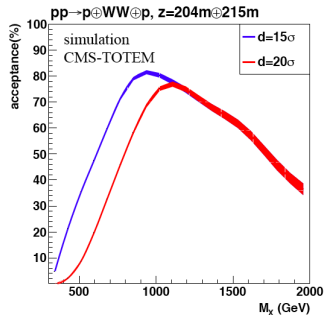
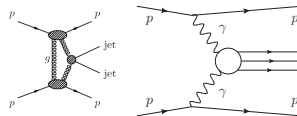
Searching for beyond standard model physics using intact protons



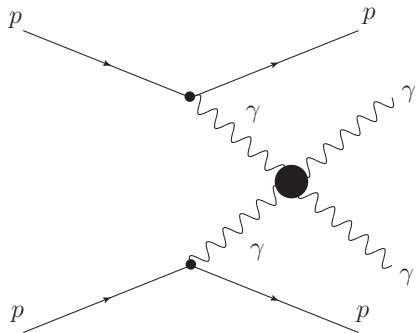
Roman pot detectors from PPS installed in the tunnel



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

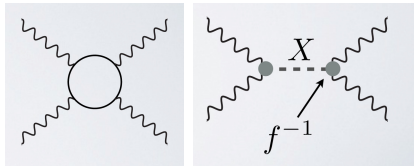


Search for extra dimensions in the universe and axion-like particles using $\gamma\gamma$ and two intact protons



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

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

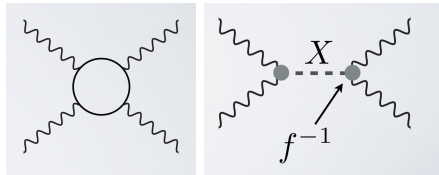


- Two effective operators and two different couplings at low energies ζ
- $\gamma\gamma\gamma\gamma$ couplings can be modified in a model independent way by loops of heavy charge particles

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

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

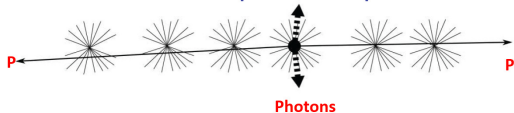
Motivations to look for quartic $\gamma\gamma$ anomalous couplings



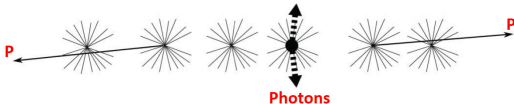
- Two effective operators at low energies
- ζ_1 can also be modified by neutral particles at tree level (extensions of the SM including scalar, pseudo-scalar, and spin-2 resonances that couple to the photon) $\zeta_1 = (f_s m)^{-2} d_{1,s}$ where f_s is the $\gamma\gamma X$ coupling of the new particle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

So what is pile up at LHC?

A collision with 2 protons and 2 photons



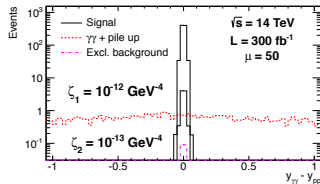
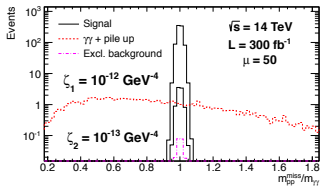
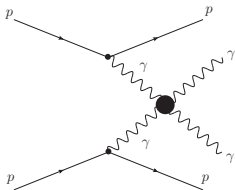
can be faked by one collision with 2 photons and protons from different collisions



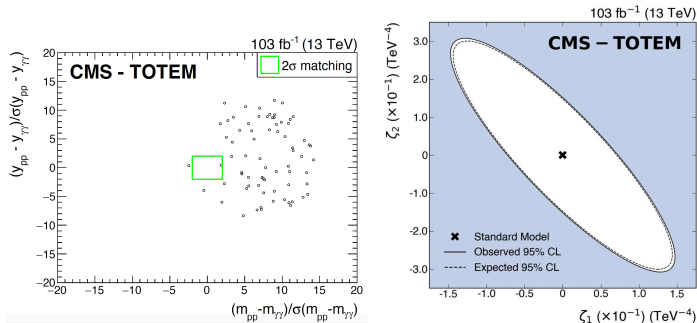
- The LHC collides packets of protons
- Due to high number of protons in one packet, there can be more than one interaction between two protons when the two packets collide
- Typically up to 50 pile up events

Example of an analysis

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

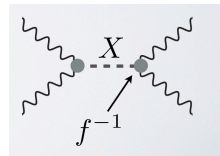
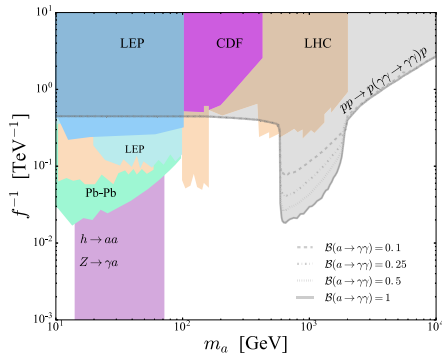
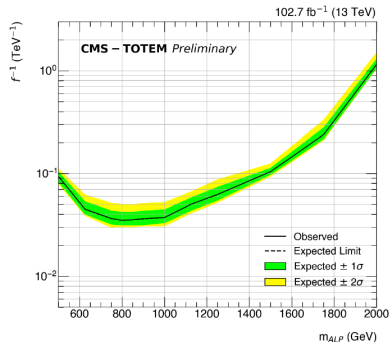


First search for high mass exclusive $\gamma\gamma$ production (CMS/TOTEM)



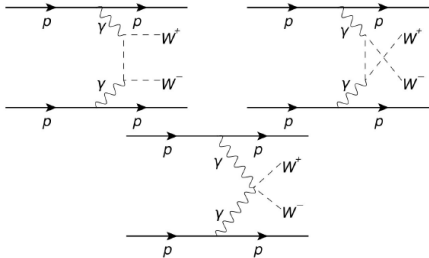
- Search for exclusive diphoton production: back-to-back, high diphoton mass ($m_{\gamma\gamma} > 350$ GeV), matching in rapidity and mass between diphoton and proton information
- 1st limits on $|\zeta_1| < 2.9 \cdot 10^{-13} \text{ GeV}^{-4}$, $|\zeta_2| < 6 \cdot 10^{-13} \text{ GeV}^{-4}$ ($\sim 10 \text{ fb}^{-1}$), PRL 129 (2022) 1, 011801
- Limit updates with 102.7 fb^{-1} : $|\zeta_1| < 7.3 \cdot 10^{-14} \text{ GeV}^{-4}$, $|\zeta_2| < 1.5 \cdot 10^{-13} \text{ GeV}^{-4}$ (Phys. Rev. D 110 (2024) 1, 012010)

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



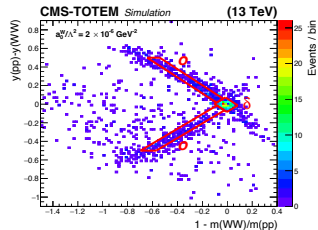
- First limits on ALPs at high mass (CMS-PAS-EXO-21-007)
- Sensivities projected with 300 fb⁻¹ (C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1806 (2018) 13)

Exclusive production of W boson pairs: sensitivity to anomalous coupling

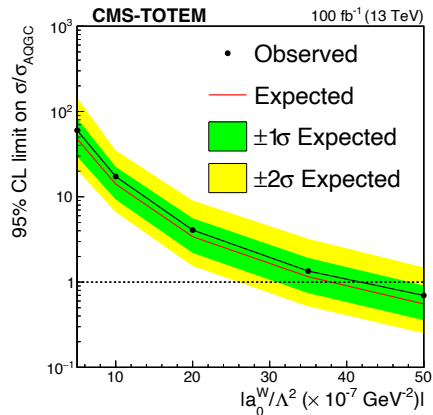


- Search with fully hadronic decays of W bosons: anomalous production of WW events dominates at high mass with a rather low cross section

- 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

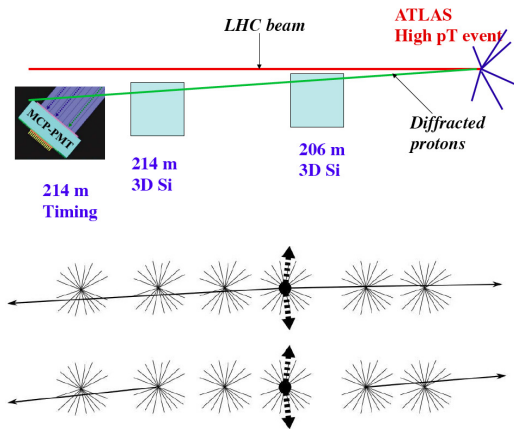


WW and ZZ exclusive productions



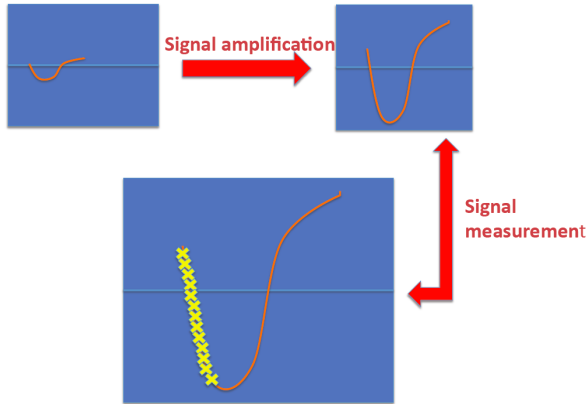
- Searches performed in full hadronic decays of W bosons (high cross section) with AK8 jets
- SM cross section is low
- Limits on SM cross section
 $\sigma_{WW} < 67\text{fb}$, $\sigma_{ZZ} < 43\text{fb}$ for $0.04 < \xi < 0.2$ (JHEP 07 (2023) 229)
- New limits on quartic anomalous couplings (events violating unitarity removed) : $a_0^W/\Lambda^2 < 4.3 \cdot 10^{-6} \text{ GeV}^{-2}$,
 $a_C^W/\Lambda^2 < 1.6 \cdot 10^{-5} \text{ GeV}^{-2}$,
 $a_0^Z/\Lambda^2 < 0.9 \cdot 10^{-5} \text{ GeV}^{-2}$,
 $a_C^Z/\Lambda^2 < 4. \cdot 10^{-5} \text{ GeV}^{-2}$ with 52.9 fb⁻¹

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



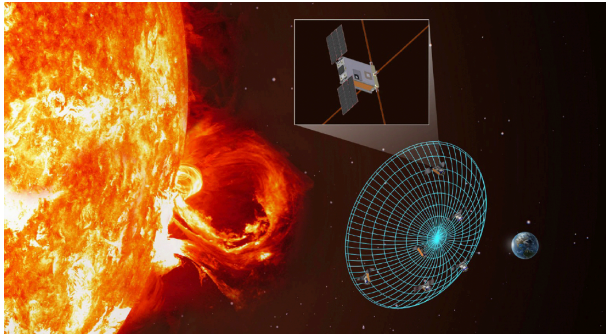
- Measure the proton time-of-flight in order to determine if they originate from the same interaction as the selected photon
- Typical precision: 10 ps means 2.1 mm
- Idea: use ultra-fast Si Low Gain Avalanche Detectors (signal duration of $\sim$ few ns and possibility to use fast sampling to reconstruct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

Signal amplification and measurement



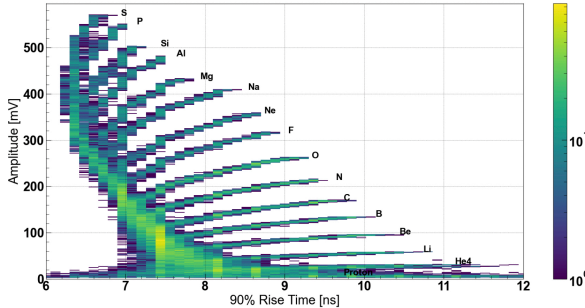
- Signal originating from a Si detector: signal duration of a few nanoseconds (fast detector)
- 1st step: Amplify the signal using an amplifier designed at KU using standard components (price: a few 10's of Euros per channel)
- 2nd step: Very fast digitization of the signal: measure many points on the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

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/nuc, 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

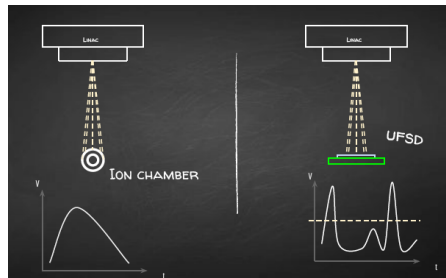
Particle identification with AGILE



- 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 ^3He , and ^4He !
- Launch is foreseen by the end of this year

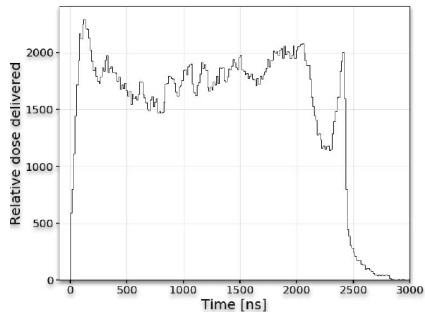
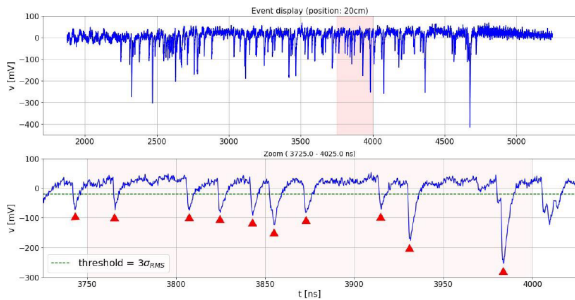
Measuring radiation in cancer treatment

- 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)



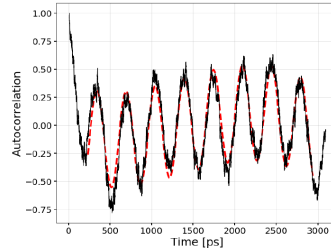
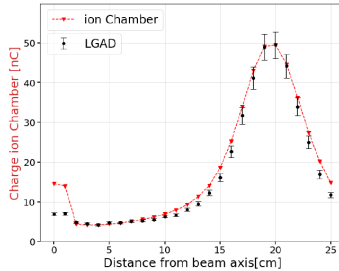
What Si detector can do better: Single particle Id in Dublin hospital

- 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



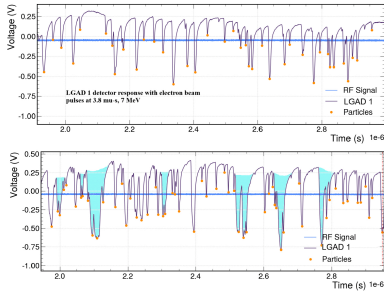
- Very precise dose measurement allowing to adapt better treatment to patients especially for flash dose treatments (brain cancer for instance)

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

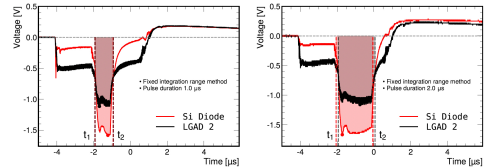


- Measurement of charge deposited in Si detector compared to standard measurement using an ion chamber: good correlation
- Our detectors see in addition the beam structure (periodicity of the beam of ~ 330 ps, contrary to a few seconds for the ion chamber): measure single particles from the beam
- Fundamental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

Going to cancer flash beam therapy: Tests at MD Anderson, Texas

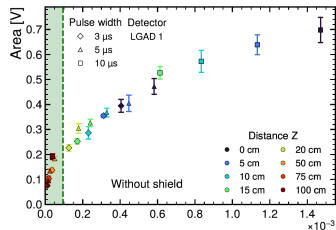
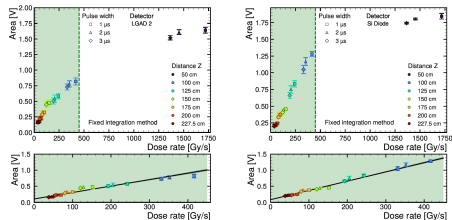


- High instantaneous doses in electron and proton cancer therapy, delivered in ms or shorter
- Issue to measure instantaneous doses and check machine quality



- Count number of particles going through LGADs (signal duration of ~ 1 ns, electronics time resolution of a few ps: limited to many particles every ns)
- Modify the method by measuring the area every μ s or so
- Work performed in collaboration with Mexico (Puebla/Hermosillo) and USA/Texas Houston

Going to cancer flash beam therapy



- Comparison between our LGAD measurement and with ion chamber: linear at lower doses, modification of slope at higher doses
- After calibration, possibility to measure doses higher than 2000 Gy/s for electrons and 1500 Gy/s for protons
- The advantage of our method is that we can perform measurements every 0.1 μs !
- Further tests using different detectors (size of mm^2) and electronics and higher proton/electron fluxes
- Publication being finalized between HEP/NP and medical physicists

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...

