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: $pp \rightarrow pp$ 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.
What do we want to study?

- We want to study elastic interactions: \( pp \rightarrow pp \) or \( p\bar{p} \rightarrow p\bar{p} \)
- 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

Batavia, Illinois

Chicago

Run I (1992 - 1997): $\sqrt{s} = 1.8$ TeV
Run II (2001 - ?): $\sqrt{s} = 1.96$ TeV

Tevatron

CDF

DØ

20 countries, 650 physicists
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 $3\sigma$) when beams are stable so that protons scattered at very small angles can be measured.
But why are the protons/anti-protons not in the beam (which would prevent detection)?

As we saw in the pool game, $p$ or $\bar{p}$ are scattered at small angles and thus can be detected in the dedicated roman pot detectors.

NB: in non-elastic diffractive case with some particles produced in CMS $pp \rightarrow pXp$, $p$ and $\bar{p}$ lose part of their energy and we use the LHC/Tevatron magnets as a spectrometer $p/\bar{p}$ at smaller $\nu$, so they have a smaller bending radius than the $p/\bar{p}$ from the beam.
Roman Pot detectors at the LHC
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:

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

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

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
What is the odderon? The QCD picture

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

- Study of elastic $pp \rightarrow pp$ 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 do we see maxima (bumps) and minima (dips): analogy with optics

- $|t|$ distribution expected to show maxima (bump) and minima (dip)
- Analogy with optics: analogous to the pattern of dips and bumps that can be seen when shining light against a slit (diffraction)
Why has the odderon not been observed yet? Why is it so elusive?

- The situation is not that simple: elastic scattering at low energies can be due to exchanges of additional particles to pomeron/odderon: \(\rho, \omega, \phi\), 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 3\(\sigma\) 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 ($\omega, \phi$) 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...)

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

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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 collected elastic $p\bar{p}$ data with intact $p$ and $\bar{p}$ detected in the Forward Proton Detector with 31 nb$^{-1}$ Phys. Rev. D 86 (2012) 012009

Measurement of elastic $p\bar{p}$ $d\sigma/dt$ at 1.96 TeV for $0.26 < |t| < 1.2$ GeV$^2$
Elastic cross section measurements at the LHC: detecting protons!

- Measurement of \( pp \rightarrow pp \) elastic cross section by detecting intact protons and vetoing on activity in the main CMS detector
- TOTEM installed vertical Roman Pot detectors at 220 m from CMS
- Trigger on elastic collisions using proton in back-to-back configurations: Up (Down) on one side, Down (Up) on the other side
Forward coverage in CMS-TOTEM

**Inelastic Telescopes:** charged particles in inelastic events:
- multiplicities, rapidity gaps
- \( T1: 3.1 < |\eta| < 4.7 \), \( p_T > 100 \text{ MeV} \)
- \( T2: 5.3 < |\eta| < 6.5 \), \( p_T > 40 \text{ MeV} \)
  → **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

Run I
- Elastic scattering @ 7 TeV
- First $\sigma_{el}$ @ 7 TeV
  EPL 96-21002
- $\sigma_{el}$ lumi independent @ 7 TeV
  PRL 111-12001

Run II
- $\sigma_{el}$ lumi independent @ 2.76 TeV
  PDS (C1352017) 069
- $\sigma_{el}$ lumi independent @ 13 TeV
- p measurement @ 13 TeV
- $d\sigma/dt$ elastic
- DIP @ 13 TeV
  Preliminary
- $p$ measurement @ 13 TeV

Schematic elastic cross-section

Measuring intact protons at the LHC: from the odderon discovery to the search for axion-like particles
TOTEM elastic $pp \frac{d\sigma}{dt}$ cross section measurements

- Elastic $pp \frac{d\sigma}{dt}$ measurements: tag both intact protons in TOTEM Roman Pots 2.76, 7, 8 and 13 TeV


Measuring intact protons at the LHC: from the odderon discovery to the search for axion-like particles
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.
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 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 3\( \sigma \) difference between \( pp \) and \( p\bar{p} \) elastic data (assuming flat behavior above \( \sqrt{s} = 100 \text{GeV} \))
Fits of $t$ and $d\sigma/dt$ values for reference points

- Fit of all reference points using the following formulae:

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

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

- The same form is used for the 8 reference points (this is an assumption and works to describe all characteristic points): this simple form is chosen since we fit at most 4 points, corresponding to $\sqrt{s} = 2.76, 7, 8$ and $13 \,$ TeV.

- We also tried alternate parametrizations such as $|t| = e(s)^f$ leading to compatible results well within $1\sigma$.

- Leads to very good $\chi^2$ per dof, better than 1 for most of the fits.

- Extrapolating the fits leads to predictions for $|t|$ and $d\sigma/dt$ at 1.96 TeV for each characteristic point.
Variation of $t$ and $d\sigma/dt$ values for reference points

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

$$(d\sigma/dt) = c\sqrt{s} [\text{TeV}] + d$$
Fits of TOTEM extrapolated characteristic points at 1.96 TeV

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

- Differences in normalization taken into account by adjusting TOTEM and D0 data sets to have the same cross sections at the optical point $d\sigma/dt(t = 0)$ (NB: OP cross sections expected to be equal if there are only C-even exchanges)

- Predict the $pp$ total cross section from extrapolated fit to TOTEM data ($\chi^2 = 0.27$)

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

Other parametrizations lead to same results

- Leads to estimate of $pp \sigma_{tot} = 82.7 \pm 3.1$ 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 $pp \sigma_{tot}$, 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 $357.1 \pm 26.4$ 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 $0.954 \pm 0.071$
- 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 $1\sigma$ uncertainty band
- Comparison with D0 data

![Graph showing TOTEM-D0 data comparison]

$\sqrt{s} = 1.96$ TeV

- $p\bar{p}$ measurement by D0
- $pp$ extrapolation by TOTEM:
  - band center at D0 bins
  - band width ($\pm 1\sigma$)
Comparison between D0 measurement and extrapolated TOTEM data

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

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

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

- Slopes constrained to their measured values (pp to $p\bar{p}$ integrated elastic cross section ratio (dominated by the exp part) becomes 1 in the limit $\sqrt{s} \to \infty$ which means similar slopes at small $|t|$ as observed in data)

- Test using the difference of the integrated cross section in the examined $|t|$-range with its fully correlated uncertainty, and the experimental and extrapolated points with their covariance matrices

- Given the constraints on the OP normalization and logarithmic slopes of the elastic cross sections, the $\chi^2$ test with six degrees of freedom yields the $p$-value of 0.00061, corresponding to a significance of 3.4$\sigma$
Combination with additional TOTEM measurement: $\rho$ 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 $\rho = \frac{\text{Re}(A^N(0))}{\text{Im}(A^N(0))}$ where the modulus is constrained by the measurement in the hadronic region and the phase by the $t$ dependence
A previous measurement by TOTEM: $\rho$ and $\sigma_{tot}$ measurements as an indication for odderon

- $\rho$ 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 $\rho$ at 13 TeV: $\rho = 0.09 \pm 0.01$ (EPJC 79 (2019) 785)
- Combination of the measured $\rho$ and $\sigma_{tot}$ 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 $\rho$ and total cross section measurements at low $t$ in a completely different kinematical domain
- For the models included in COMPETE, the TOTEM $\rho$ measurement at 13 TeV provided a 3.4 to 4.6$\sigma$ significance, to be combined with the D0/TOTEM result
- The combined significance ranges from 5.3 to 5.7$\sigma$ depending on the model
- Models without colorless $C$-odd gluonic compound are excluded including the Durham model and different sets of COMPETE models (blue, magenta and green bands on the previous slide)
Searching for beyond standard model physics using intact protons
What is the CMS-TOTEM Precision Proton Spectrometer (CT-PPS)?

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

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

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

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

- QCD production dominates at low $m_{\gamma \gamma}$, QED at high $m_{\gamma \gamma}$
- Important to consider $W$ loops at high $m_{\gamma \gamma}$
- At high masses (> 200 GeV), the photon induced processes are dominant

**Conclusion:** Two photons and two tagged protons means photon-induced process
Motivations to look for quartic $\gamma\gamma$ anomalous couplings

- Two effective operators and two different couplings at low energies $\zeta$

- $\gamma\gamma\gamma\gamma$ 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 $\zeta_1$ of the order of $10^{-14}$-$10^{-13}$
Motivations to look for quartic $\gamma\gamma$ anomalous couplings

- Two effective operators at low energies

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

- The LHC collides packets of protons
- Due to high number of protons in one packet, there can be more than one interaction between two protons when the two packets collide
- Typically up to 50 pile up events
Search for quartic $\gamma \gamma$ anomalous couplings

- Search for $\gamma \gamma \gamma \gamma$ quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- Analysis performed at hadron level including detector efficiencies, resolution effects, pile-up...
- Anomalous coupling events appear at high di-photon masses
Search for quartic $\gamma \gamma$ anomalous couplings

- 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$^{-1}$)

<table>
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<th>Cut / Process</th>
<th>Signal (full)</th>
<th>Signal with (without) f.f (EFT)</th>
<th>Excl.</th>
<th>DPE</th>
<th>DY, di-jet + pile up</th>
<th>$\gamma \gamma$ + pile up</th>
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<td>0.015 &lt; \xi_{1,2} &lt; 0.15,$ $pT_{L(2)} &gt; 200, (100)$ GeV]</td>
<td>65</td>
<td>18 (187)</td>
<td>0.13</td>
<td>0.2</td>
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<tr>
<td>$m_{\gamma \gamma} &gt; 600$ GeV</td>
<td>64</td>
<td>17 (186)</td>
<td>0.10</td>
<td>0</td>
<td>0.2</td>
<td>1023</td>
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<tr>
<td>$p_{T2}/p_{T1} &gt; 0.95,$ $</td>
<td>\Delta \phi</td>
<td>&gt; \bar{\pi} - 0.01]</td>
<td>64</td>
<td>17 (186)</td>
<td>0.10</td>
<td>0</td>
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<tr>
<td>$\sqrt{\xi_1 \xi_2} = m_{\gamma \gamma} \pm 3%</td>
<td>61</td>
<td>16 (175)</td>
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<td>0</td>
<td>0</td>
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<td>$</td>
<td>y_{\gamma \gamma} - y_{pp}</td>
<td>&lt; 0.03</td>
<td>60</td>
<td>12 (169)</td>
<td>0.09</td>
<td>0</td>
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Production of ALPs via photon exchanges and tagging the intact protons in the final state complementary to the usual search at the LHC ($Z$ decays into 3 photons): sensitivity at high ALP mass, C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, ArXiv 1803.10835, JHEP 1806 (2018) 131

Complementarity with Pb Pb running: sensitivity to low mass diphoton, low luminosity but cross section increased by $Z^4$
Search for axion like particles: complementarity with heavy ion runs

- Production of ALPs via photon exchanges in heavy ion runs: Complementarity to $pp$ running
- Similar gain of three orders of magnitude on sensitivity for $\gamma\gamma Z$, $\gamma\gamma WW$, $\gamma\gamma ZZ$, etc, couplings in $pp$ collisions

Measuring intact protons at the LHC: from the odderon discovery to the search for axion-like particles
Evidence for quasi-exclusive dilepton production and 1st search for quartic $\gamma\gamma\gamma\gamma$ anomalous couplings (CMS)

- 20 quasi-exclusive dilepton production in CMS with one tagged proton
- 1st search for quartic $\gamma\gamma\gamma\gamma$ anomalous couplings in CMS
Additional method to remove pile up: Measuring proton time-of-flight

Measure the proton time-of-flight in order to determine if they originate from the same interaction as the selected photon.

- Typical precision: 10 ps means 2.1 mm
- Idea: use ultra-fast Si detectors (signal duration of ~few ns and possibility to use fast sampling to reconstruct full signal)
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
Test stand at the University of Kansas

Example of fast timing measurements using lasers

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

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

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

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

- Detailed comparison between $p\bar{p}$ (1.96 TeV from D0) and $pp$ (2.76, 7, 8, 13 TeV from TOTEM) elastic $d\sigma/dt$ data - FERMILAB-PUB-20-568-E; CERN-EP-2020-236

- $pp$ and $p\bar{p}$ cross sections differ with a significance of 3.4$\sigma$ 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 $\rho$ and total cross section result at 13 TeV, the significance is in the range 5.3 to 5.7$\sigma$ 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...