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

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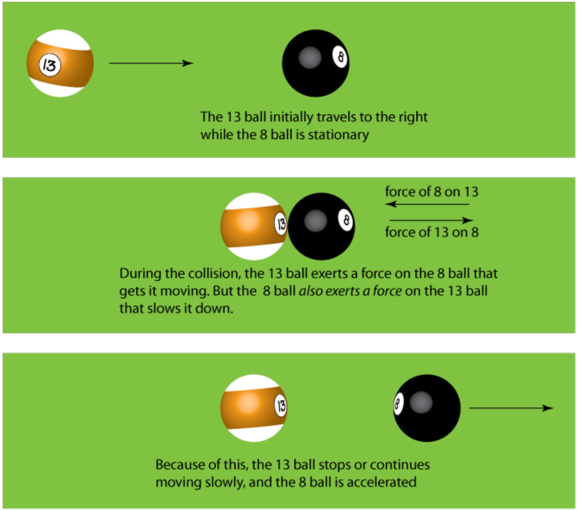
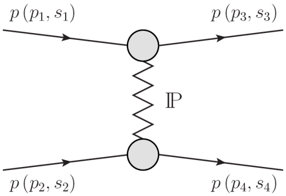
- Elastic interactions and the Odderon discovery
- Jet gap jet events and BFKL dynamics
- Looking for saturation at the LHC in vector meson production
- Photon-exchange processes and BSM physics
- Ultra-fast Silicon detectors and applications

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

The odderon in a nutshell

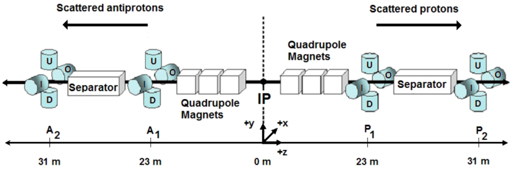


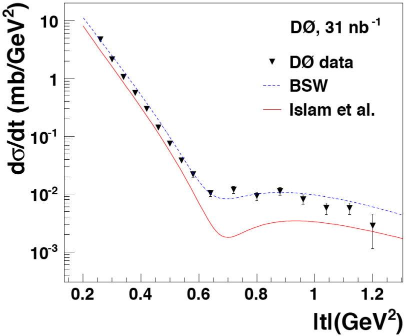
- Let us assume that elastic scattering can be due to exchange of colorless objects: Pomeron and Odderon
- Charge parity C: Charge conjugation changes the sign of all quantum charges
- Pomeron and Odderon correspond to positive and negative C parity: Pomeron is made of two gluons which leads to a $+1$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

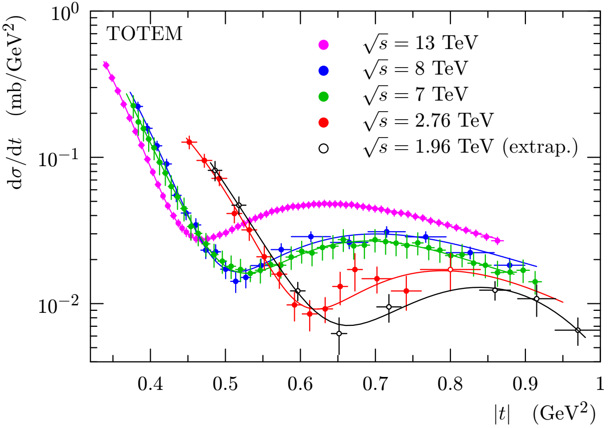
D0 elastic $p\bar{p}$ $d\sigma/dt$ cross section measurements





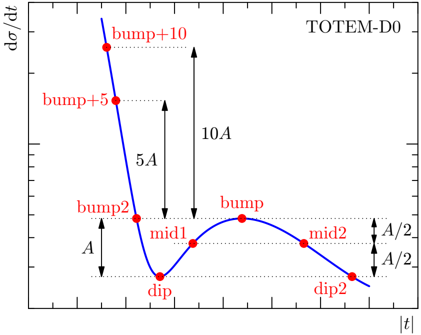
- D0 collected elastic $p\bar{p}$ data with intact p and $\bar{p}$ detected in the Forward Proton Detector with 31 nb^{-1} Phys. Rev. D 86 (2012) 012009
- Measurement of elastic $p\bar{p}$ $d\sigma/dt$ at 1.96 TeV for $0.26 < |t| < 1.2$ GeV^2

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

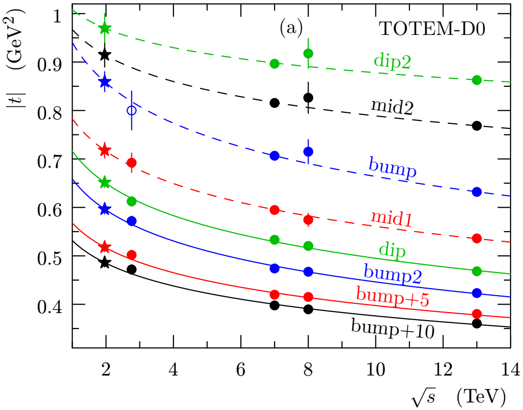
Reference points of elastic $d\sigma/dt$

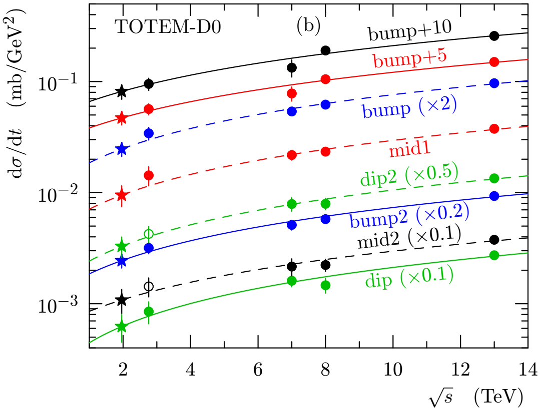


- Define 8 characteristic points of elastic *pp* $d\sigma/dt$ cross sections (dip, bump...) that are feature of elastic *pp* interactions

- 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

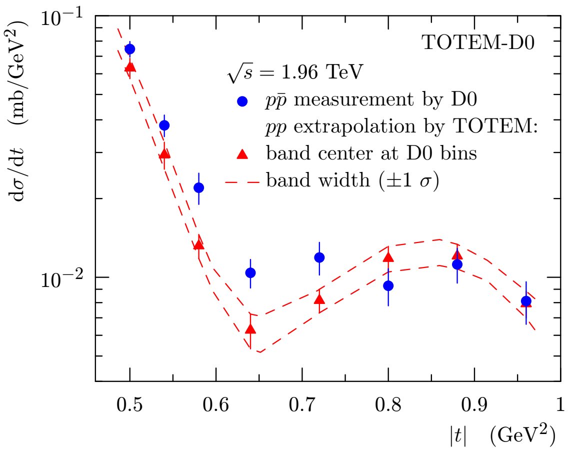
Variation of t and $d\sigma/dt$ values for reference points





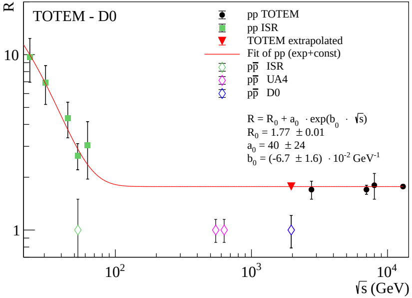
$$|t| = a\log(\sqrt{s}[\mathrm{TeV}]) + b \qquad (d\sigma/dt) = c\sqrt{s}\ [\mathrm{TeV}] + d$$

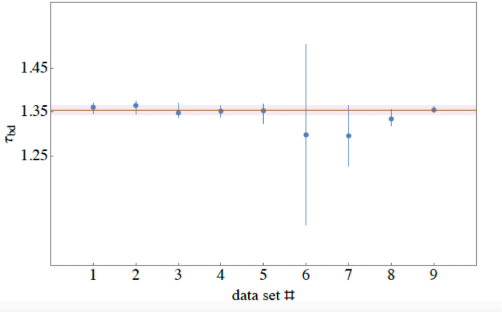
Predictions at $\sqrt{s} = 1.96$ TeV



- 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

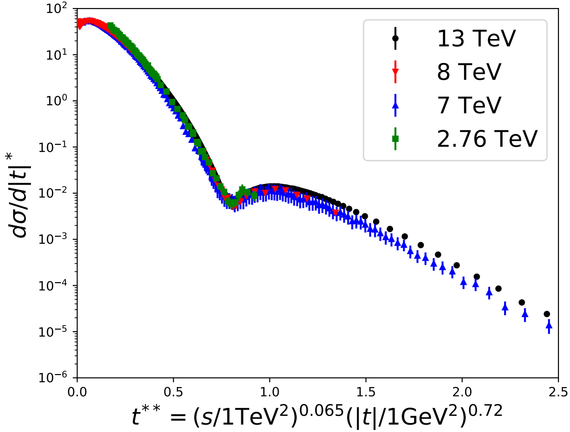
One aside: Scaling of the elastic proton-proton cross section





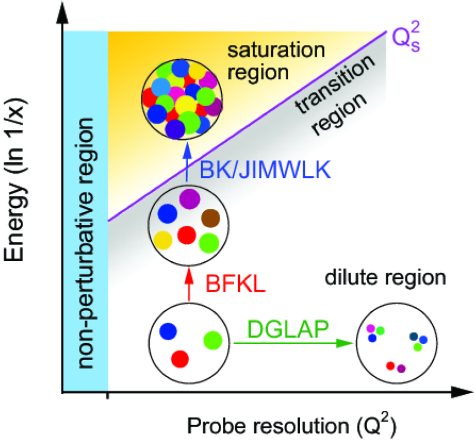
- Bump over dip cross section $d\sigma/dt$ ratio constant at high energies
- The position ratio in $|t|$ between the bump and the dip is also constant between ISR and LHC energies
- C. Baldenegro, M. Praszalowicz, C. Royon, A. Stasto, Phys. Lett. B 856 (2024) 13896

One aside: a new scaling in data



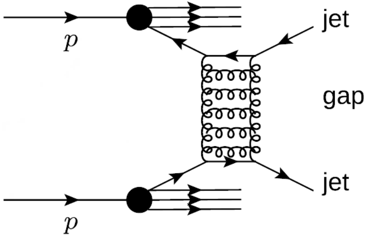
- We introduce the variable $t^* = (s/|t|)^A \times |t|$, inspired by geometric scaling in terms of saturation models
- $t^{**} = t^*/s^B$, A and B being parameters to be fitted to data
- $d\sigma/dt^*$ shows scaling as a function of t^{**}
- A and B are correlated: full valley of parameters leading 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

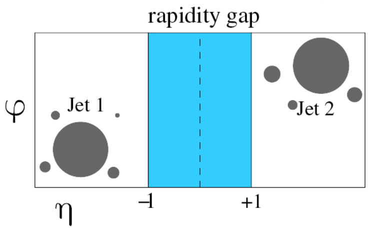
Looking for BFKL resummation /saturation effects



- 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

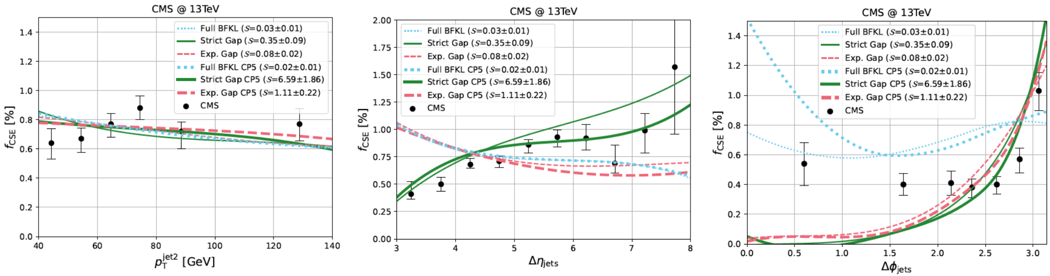
Mueller Tang: Gap between jets at the Tevatron and the LHC





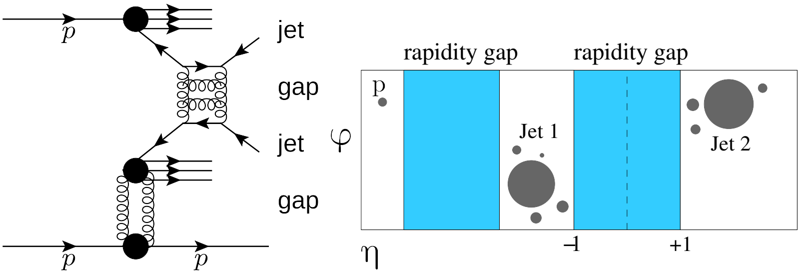
- Looking for a gap between two jets: Region in rapidity devoid of any particle production, energy in detector
- Exchange of a BFKL Pomeron between the two jets: two-gluon exchange in order to neutralize color flow
- Method to test BFKL resummation: Implementation of BFKL NLL formalism in HERWIG/PYTHIA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

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



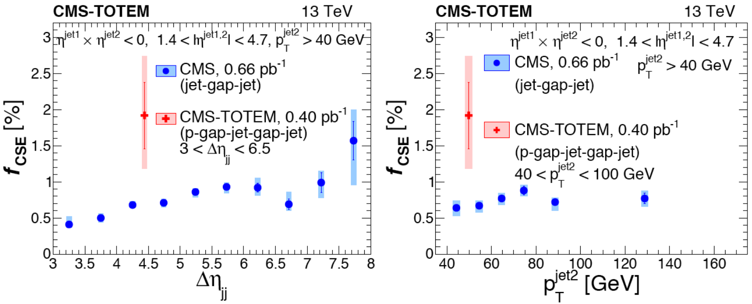
- Measurement of fraction of jet gap jet events as a function of jet $\Delta\eta$, p_T, $\Delta\Phi$ (Phys.Rev.D 104 (2021) 032009)
- Implementation of BFKL NLL formalism in Pythia and compute jet gap jet fraction
- Dijet cross section computed using POWHEG and PYTHIA8
- Good agreement with theory with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

Jet gap jet events in diffraction (CMS/TOTEM)



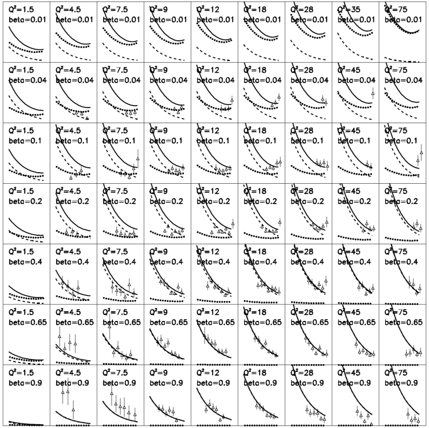
- Jet gap jet events: powerful test of BFKL resummation C. Marquet, C. Royon, M. Trzebinski, R. Zlebcík, Phys. Rev. D 87 (2013) 3, 034010
- Subsample of gap between jets events requesting in addition at least one intact proton on either side of CMS
- **Jet gap jet events were observed for the 1st time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

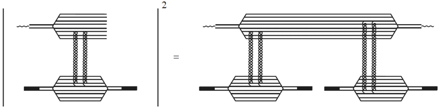
First observation of jet gap jet events in diffraction (CMS/TOTEM)



- 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

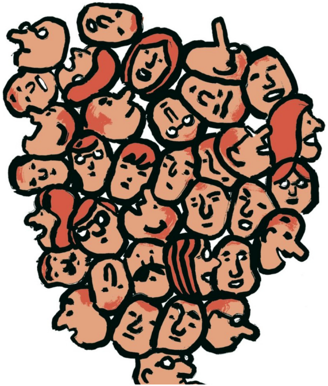
One aside: description of HERA diffractive data using dipole model

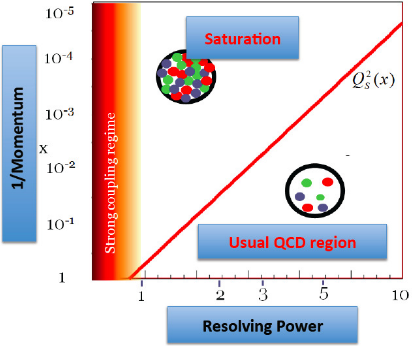




- Description of HERA diffractive F_2^D measurement using the dipole model
- 2 components: Inelastic diffraction (left), Quasi-elastic diffraction (right), both longitudinal and transverse
- Leads to a fair description of data (dotted line: Inelastic, dashed line: Quasi-elastic, A. Bialas, R. Peschanski, C.Royon, Phys. Rev. D 57 (1998) 6899

New kinematical domain: saturation

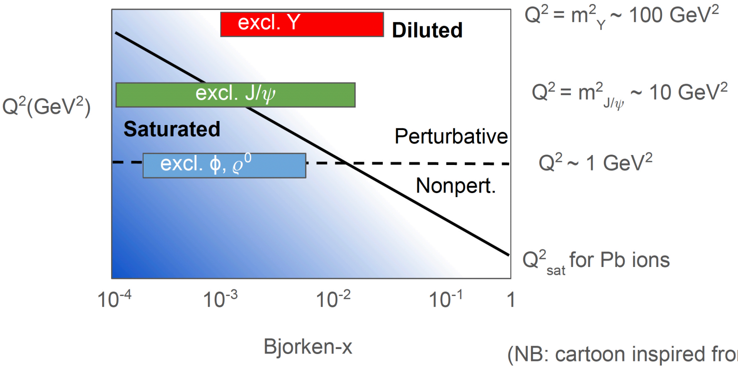




- Very small x Regions where the density of gluons is very large, "saturation"
- The usual QCD linear equations (BFKL/DGLAP) are no longer valid!
- Can be studied at the LHC and at the future Electron-Ion Collider in the US

What do we need to see saturation?

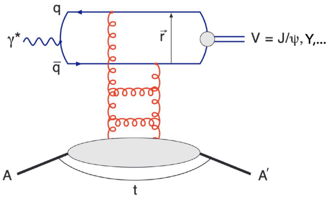
- We need low x, high W; also a perturbative scale to perform QCD saturation
- Mesons such as J/Ψ, Υ are ideal

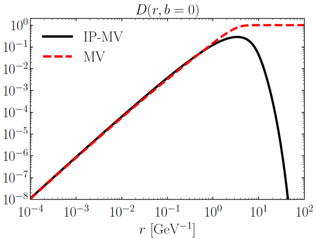


(NB: cartoon inspired from Wei's plot)

Looking for saturation: vector meson production

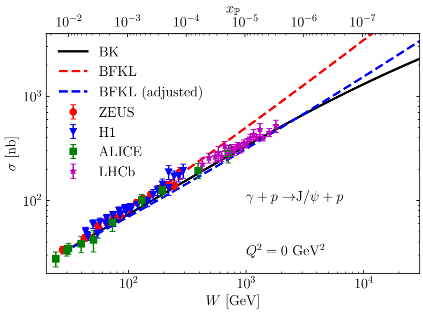
$$\partial_Y D(\mathbf{x}_0, \mathbf{x}_1, Y) = \int \mathrm{d}^2\mathbf{x}_2\, K_{\mathrm{BK}}(\mathbf{x}_0, \mathbf{x}_1, \mathbf{x}_2) \Big[D(\mathbf{x}_0, \mathbf{x}_2, Y) + D(\mathbf{x}_2, \mathbf{x}_1, Y) - D(\mathbf{x}_0, \mathbf{x}_1, Y) - D(\mathbf{x}_0, \mathbf{x}_2, Y) D(\mathbf{x}_2, \mathbf{x}_1,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

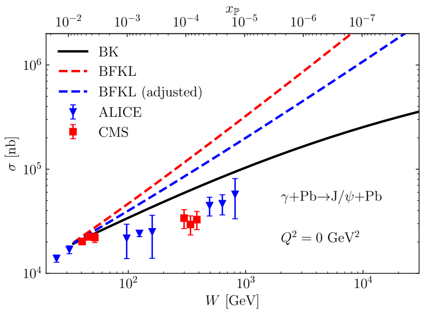




- Compute exclusive vector meson production in γp (HERA, EIC and pPb LHC) and γPb (EIC and Pb Pb LHC) where we probe the gluon density in p or Pb
- Saturation effects are expected to happen in Pb Pb, not in p Pb
- Use the BFKL linear or the BK non-linear evolution equation to quantify saturation effects
- Take into account b impact parameter dependence in dipole amplitude

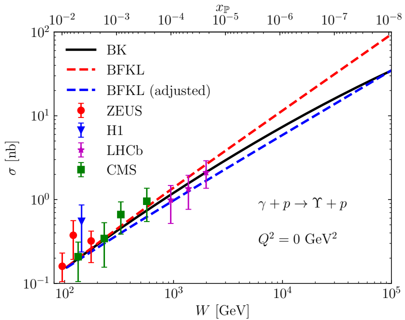
Looking for saturation: J/Ψ vector meson production

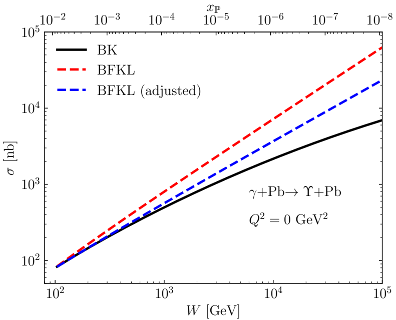




- BFKL and BK CGC predictions after taking into account b-dependence (J. Penttala, C. R., ArXiv 2411.14815)
- J/Ψ production in *pPb*: small differences between BK and BFKL, BK slightly favored
- Large differences between BK and BFKL in PbPb collisions

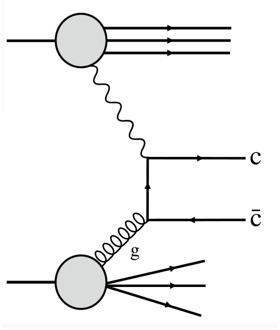
Looking for saturation: Υ vector meson production





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

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

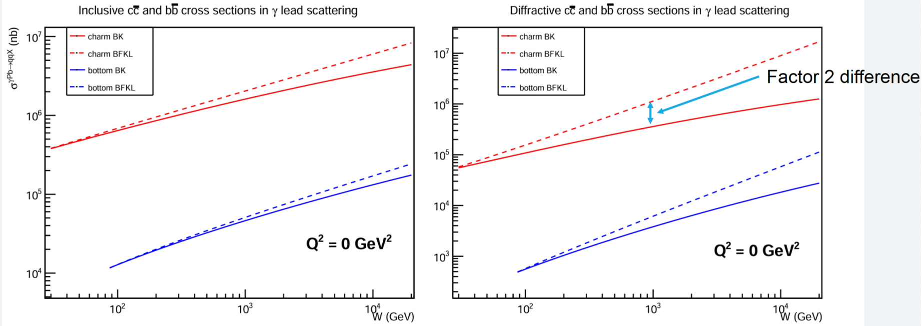


- What do we need to see saturation at the LHC?
- γPb c, b, J/Ψ are ideal probes for low-x physics

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

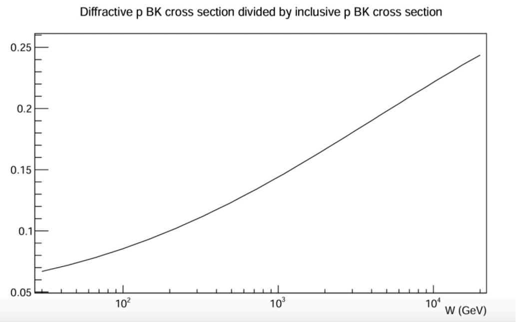
- We can reach low x values of 10^{-4} or smaller
- We need a low scale (to be below Q_S), and this is why c or b where one can go to very low p_T or J/Ψ (low mass vector mesons) are ideal while still being in the perturbative region
- $d\sigma/dW$ is the best observable while $d\sigma/dy$ presents the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

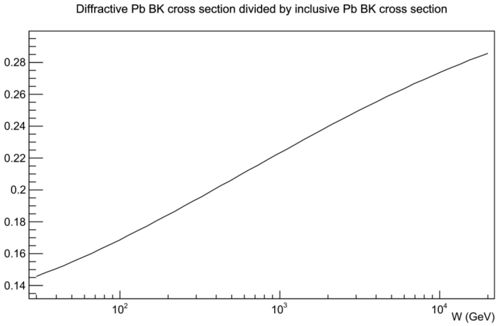
$c\bar{c}$ and $b\bar{b}$ productions: $PbPb$ interactions



- 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

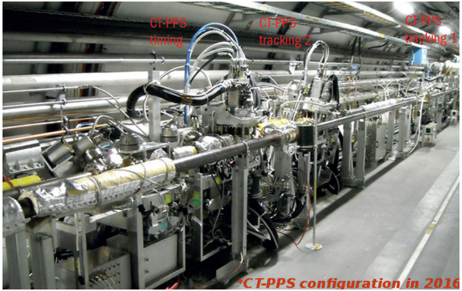
$c\bar{c}$ and $b\bar{b}$ productions: diffractive contributions

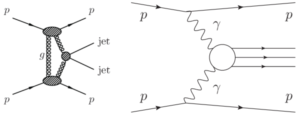


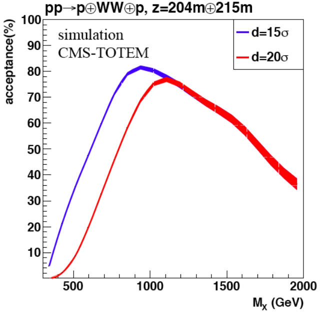


- Compute the ration of diffractive to total $c\bar{c}$ and $b\bar{b}$ productions when p, Pb is intact in pPb and $PbPb$ collisions
- Large diffractive component predicted: about 10 to 20% of cross section for $PbPb$ interactions

Roman pot detectors from PPS installed in the tunnel

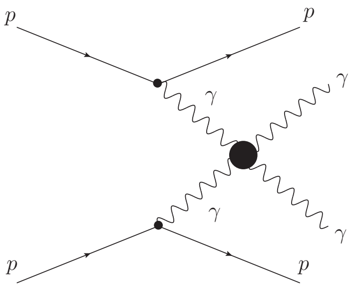






- Good acceptance at high mass in standard runs (PPS in CMS, AFP in ATLAS)
- >100 fb^{-1} collected in Run II

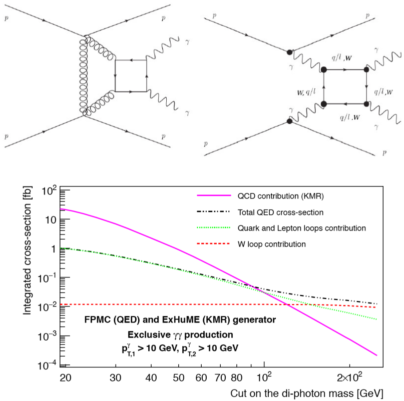
Search for quartic $\gamma\gamma\gamma\gamma$ anomalous coupling



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

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

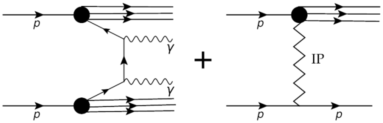
$\gamma\gamma$ exclusive production: SM contribution

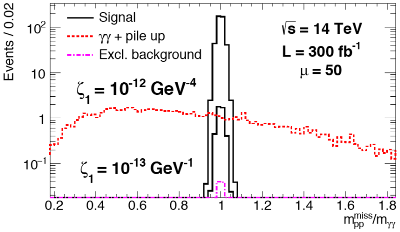


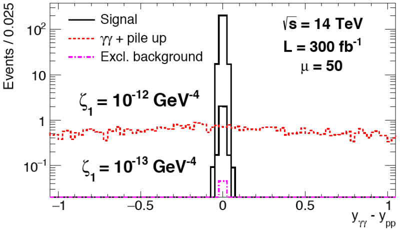
- QCD production dominates at low $m_{\gamma\gamma}$, QED at high $m_{\gamma\gamma}$
- Important to consider W loops at high $m_{\gamma\gamma}$
- At high masses (> 200 GeV), the photon induced processes are dominant
- **Conclusion: Two photons and two tagged protons means photon-induced process**

Removing pile up at the LHC

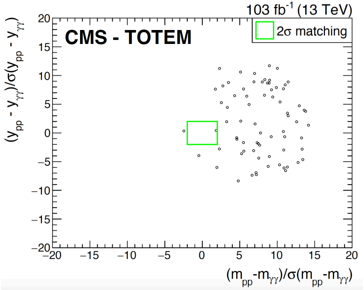
- Advantage of tagging protons: negligible background after matching mass/rapidity of photon and proton systems (JHEP 1502 (2015) 165; Phys.Rev. D89 (2014) 114004)
- Possibility to use fast timing detectors to measure proton time of flights

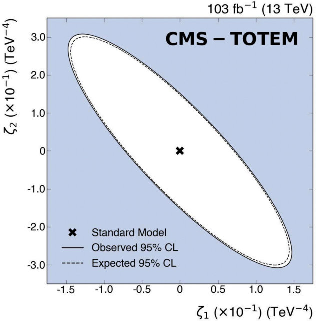






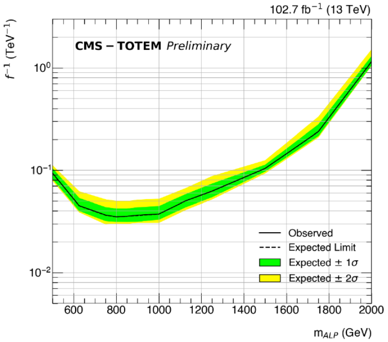
First search for high mass exclusive $\gamma\gamma$ production (CMS/TOTEM)

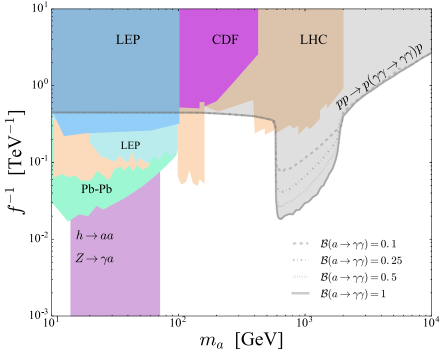


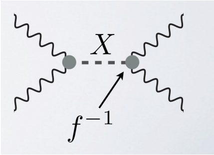


- Search for exclusive diphoton production: back-to-back, high diphoton mass ($m_{\gamma\gamma} > 350$ GeV), matching in rapidity and mass between diphoton and proton information
- 1st limits on $|\zeta_1| < 2.9\ 10^{-13}$ GeV^{-4}, $|\zeta_2| < 6.\ 10^{-13}$ GeV^{-4} ($\sim$10 fb^{-1}), PRL 129 (2022)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

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

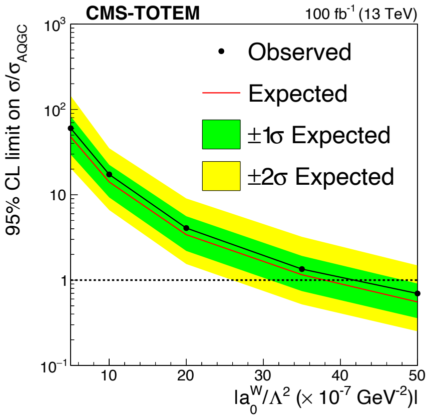






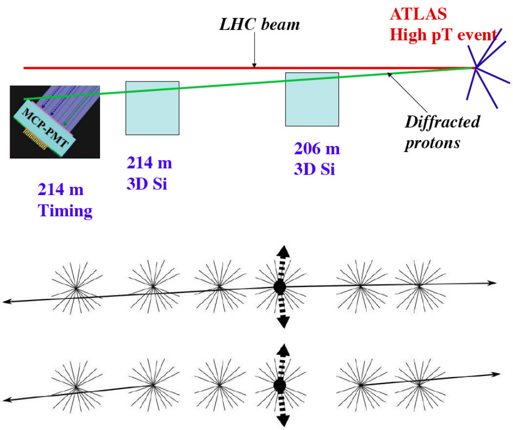
- First limits on ALPs at high mass (CMS-PAS-EXO-21-007)
- Sensitivities projected with 300 fb^{-1} (C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1806 (2018) 13)

WW and ZZ exclusive productions

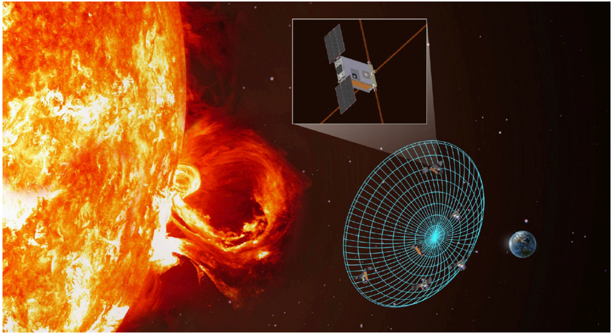


- Searches performed in full hadronic decays of W bosons (high cross section) with AK8 jets
- SM cross section is low
- Limits on SM cross section $\sigma_{WW} < 67$fb, $\sigma_{ZZ} < 43$fb for $0.04 < \xi < 0.2$ (JHEP 07 (2023) 229)
- New limits on quartic anomalous couplings (events violating unitarity 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}

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



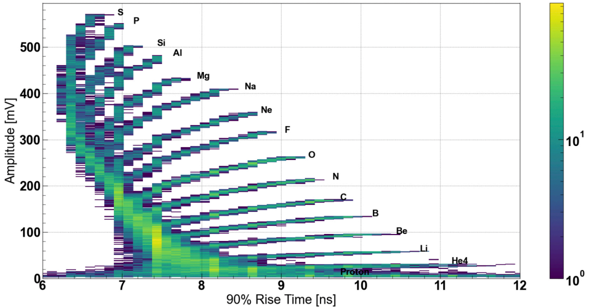
- Measure the proton time-of-flight in order to determine if they originate from the same interaction as the selected photon
- Typical precision: 10 ps means 2.1 mm
- Idea: use ultra-fast Si Low Gain Avalanche Detectors (signal duration of $\sim$few ns and possibility to use fast sampling to reconstruct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



- 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

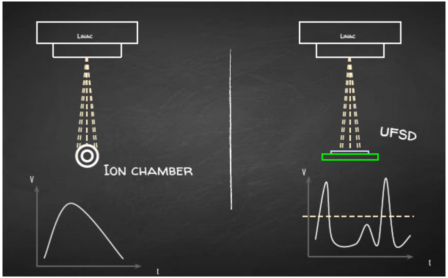
Particle identification with AGILE



- 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

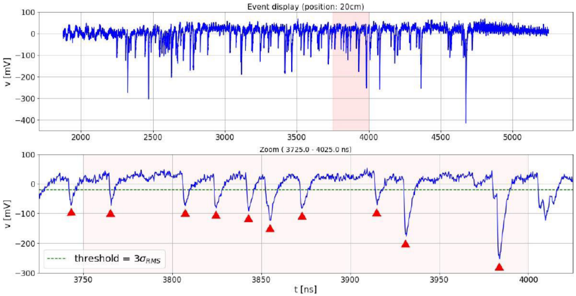
Measuring radiation in cancer treatment

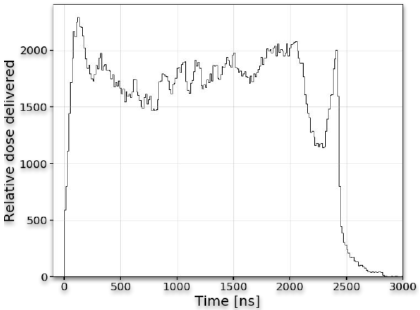
- Ultra fast silicon detectors and readout system were put in an electron beam used in the past for photon therapy at St Luke Hospital, Dublin, Ireland
- Precise and instantaneous measurements of dose during cancer treatment (especially for flash proton beam treatment)
- Develop a fast and efficient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

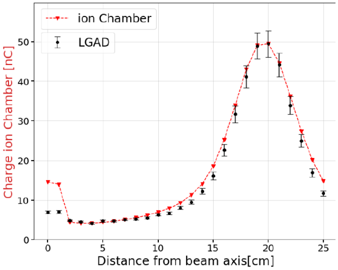
- Use UFSD and their fast signal in order to identify and measure spikes in signal due to particles passing by
- Allows measuring doses almost instantaneously

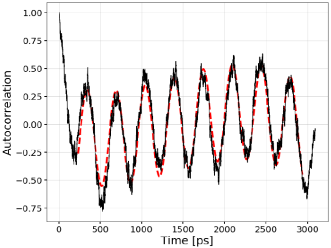




- Very precise dose measurement allowing to adapt better treatment to patients especially for flash dose treatments (brain cancer for instance)

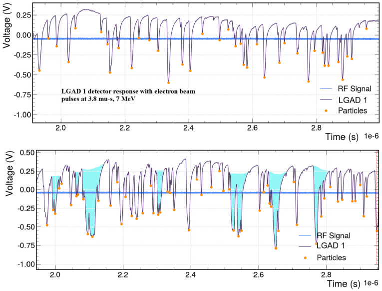
Tests performed at St Luke hospital, University of Dublin, Ireland

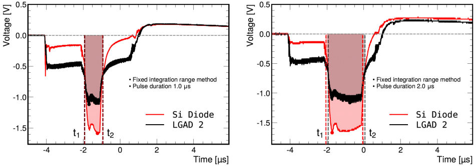




- Measurement of charge deposited in Si detector compared to standard measurement using an ion chamber: good correlation
- Our detectors see in addition the beam structure (periodicity of the beam of ∼330 ps, contrary to a few seconds for the ion chamber): measure single particles from the beam
- Fundamental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

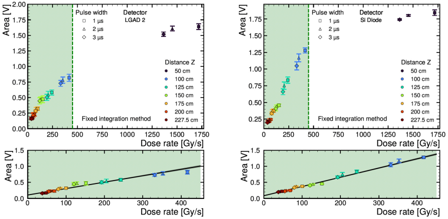
Going to cancer flash beam therapy: Tests at MD Anderson, Texas

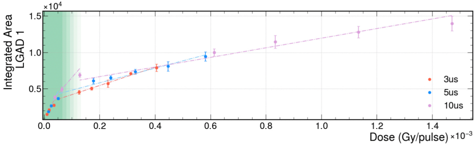




- High instantaneous doses in electron and proton cancer therapy, delivered in ms or shorter
- Issue to measure instantaneous doses and check machine quality
- Count number of particles going through LGADs (signal duration of $\sim$ 1 ns, electronics time resolution of a few ps: limited to many particles every ns
- Modify the method by measuring the area every μs or so
- Work performed in collaboration with Mexico, Puebla (Arturo, Tonatiuh, Saul), Sonora (Javier, Antonio)

Going to cancer flash beam therapy





- Comparison between our LGAD mesurement 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 μs or 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
- Happy birthday, Andrzej, and thanks for all the collaboration with Robi, exchanged ideas....