Forward physics with proton tagging at the LHC: from QCD to extra-dimensions

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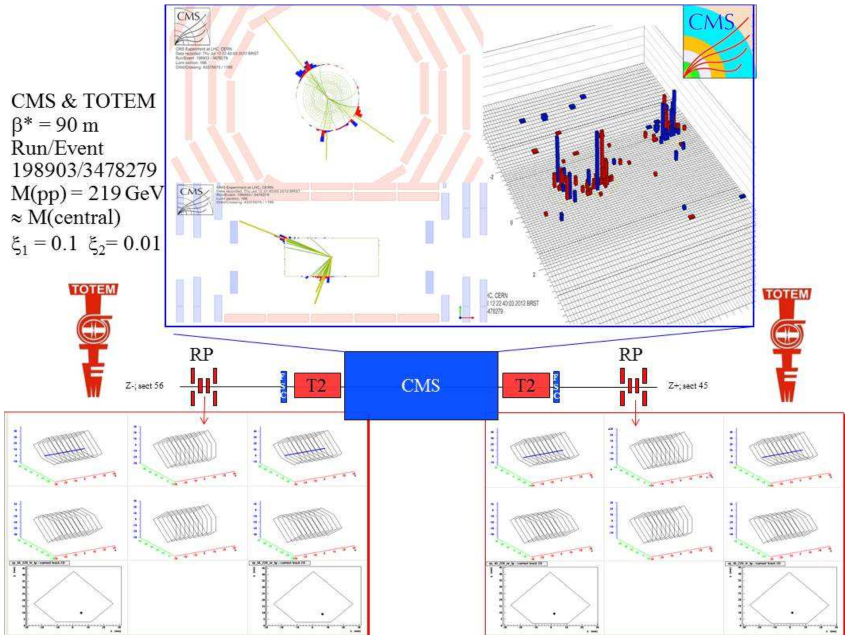
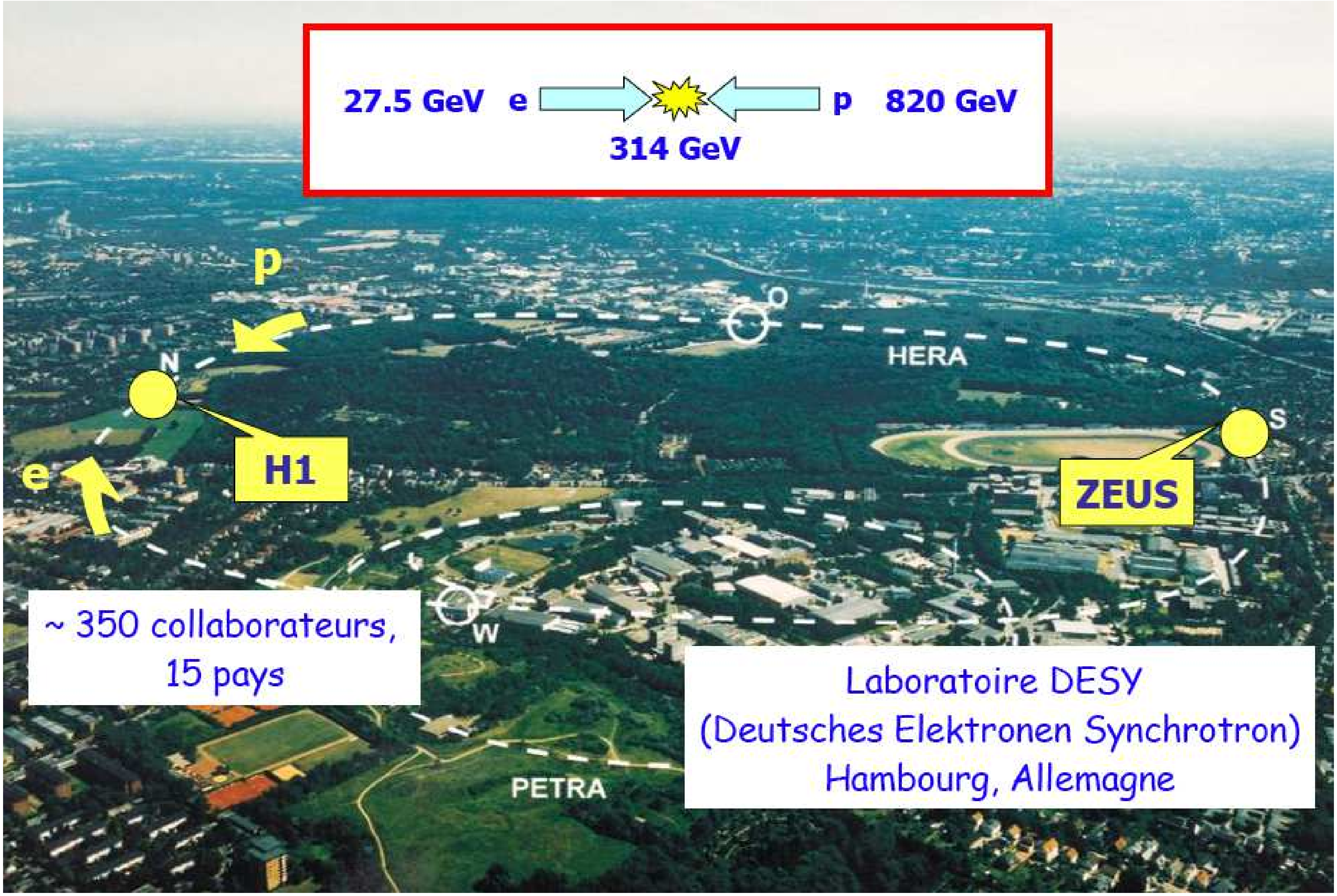


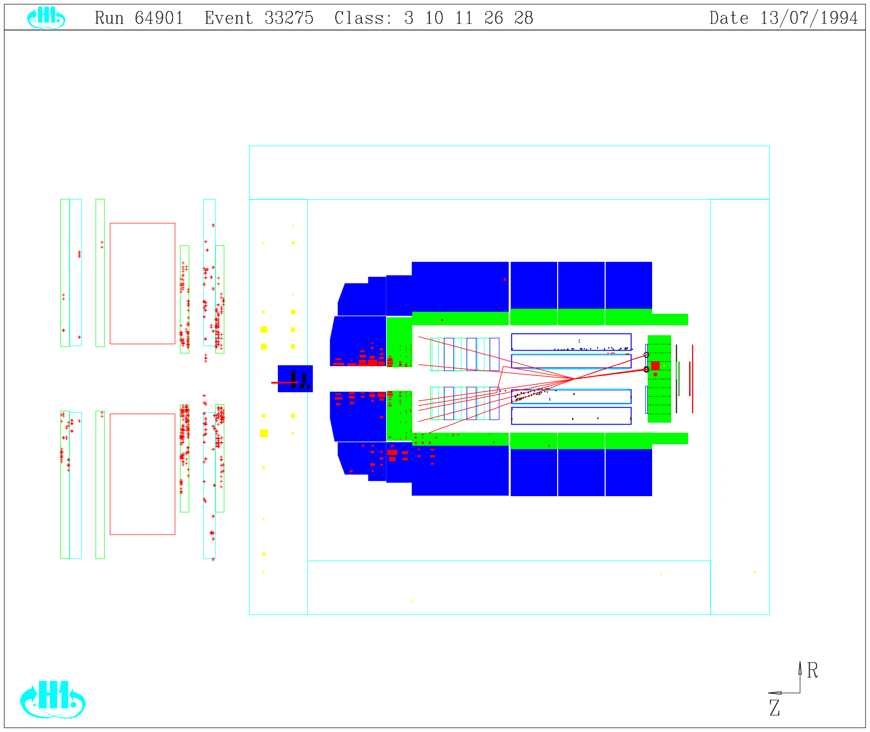
- Pomeron structure in terms of quarks/gluons
- Tests of BFKL resummation
- Photon exchanges processes and beyond standard model physics
- Anomalous quartic $\gamma\gamma\gamma\gamma$ couplings using intact protons
- Fast timing detectors: SAMPIC chip, Si, Diamonds...

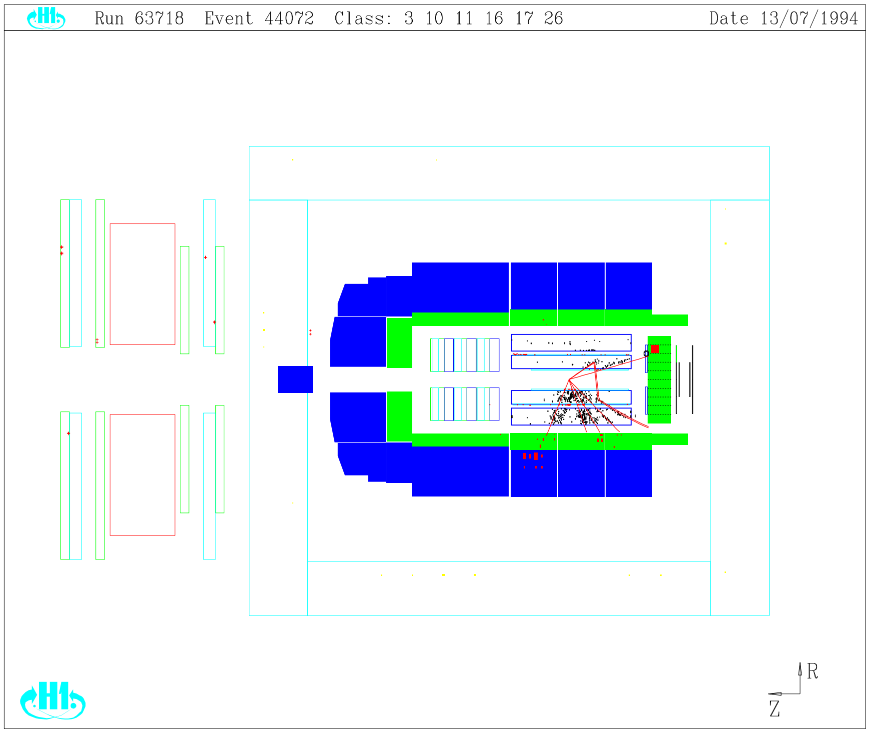
Definition of diffraction: example of HERA

HERA: ep collider who closed in 2007, about 1 fb^{-1} accumulated



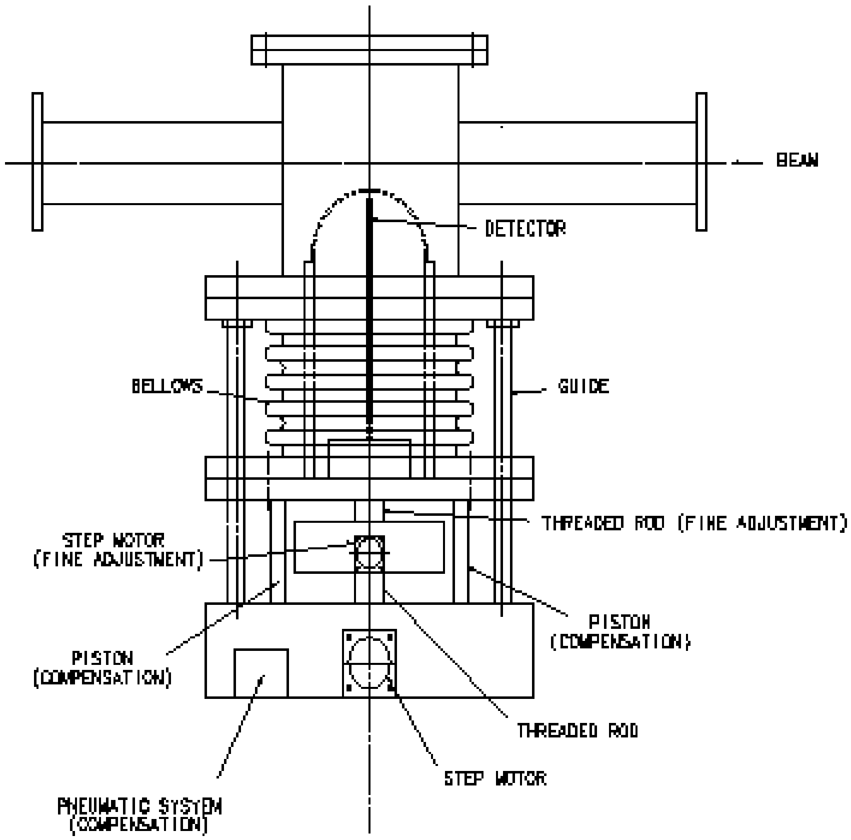
DIS and Diffractive event at HERA



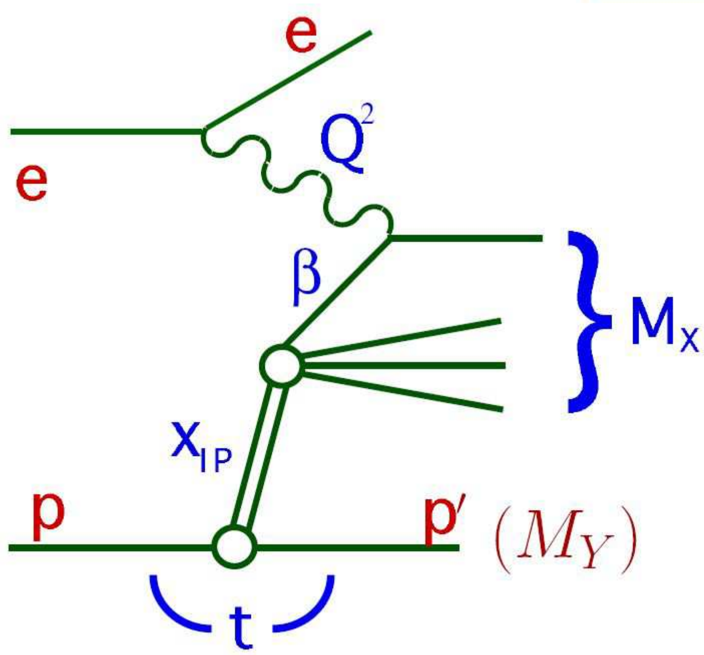


Definition of diffraction: example of HERA

- Typical DIS event: part of proton remnants seen in detectors in forward region (calorimeter, forward muon...)
- HERA observation: in some events, no energy in forward region, or in other words no colour exchange between proton and jets produced in the hard interaction
- Leads to the first experimental method to detect diffractive events: rapidity gap in calorimeter: difficult to be used at the LHC because of pile up events
- Second method to find diffractive events: Tag the proton in the final state, method to be used at the LHC (example of AFP project)



Diffractive kinematical variables



Invariant mass of the diffractive final state

- Momentum fraction of the proton carried by the colourless object (pomeron): $x_p = \xi = \frac{Q^2+M_X^2}{Q^2+W^2}$
- Momentum fraction of the pomeron carried by the interacting parton if we assume the colourless object to be made of quarks and gluons: $\beta = \frac{Q^2}{Q^2+M_X^2} = \frac{x_{Bj}}{x_P}$
- 4-momentum squared transferred: $t = (p - p')^2$

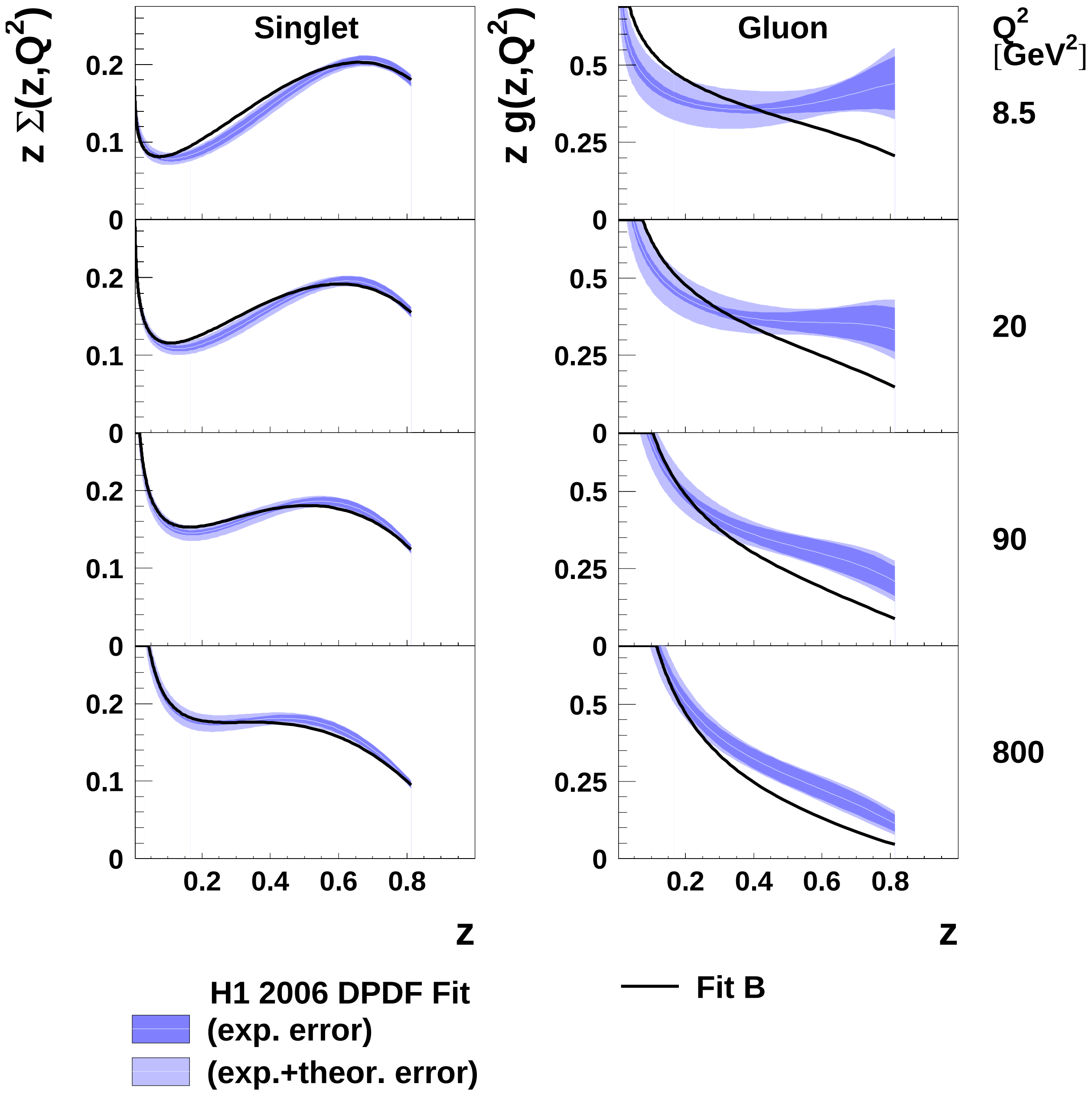
Measurement of the diffractive structure function F_2^D

- Measurement of the diffractive cross section using the rapidity gap selection over a wide kinematical domain in (x_P, β, Q^2) (same way as F_2 is measured, there are two additional variables for diffraction, t is not measured)
- Use these data to make QCD fits using NLO Dokshitzer Gribov Lipatov Altarelli Parisi evolution equation and determine the pomeron structure in quarks and gluons: $\rightarrow$ allows to predict inclusive diffraction at Tevatron/LHC
- At low β: evolution driven by $g \rightarrow q\bar{q}$, at high β, $q \rightarrow qg$ becomes important
- Take all data for $Q^2 > 8.5$ GeV^2, $\beta < 0.8$ to be in the perturbative QCD region and avoid the low mass region (vector meson resonances)

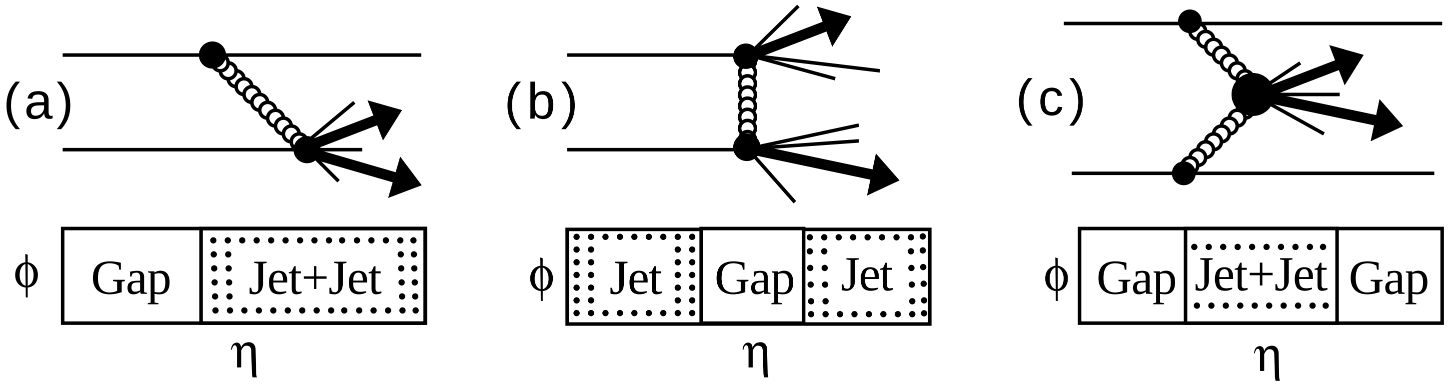
$$\frac{dF_2^D}{d\log Q^2} \sim \frac{\alpha_S}{2\pi}\left[P_{qg} \otimes g + P_{qq} \otimes \Sigma\right]$$

Parton densities in the pomeron (H1)

- Extraction of gluon and quark densities in pomeron: gluon dominated
- Gluon density poorly constrained at high β



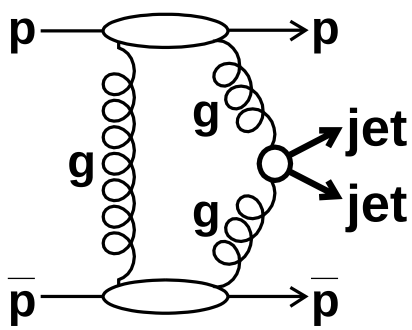
Diffraction at Tevatron/LHC

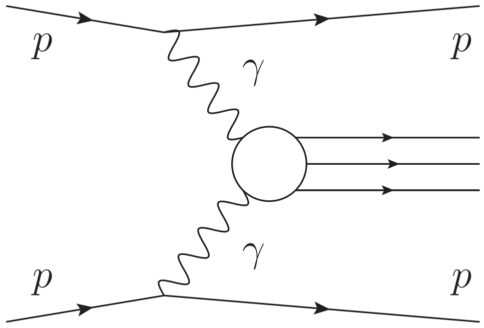


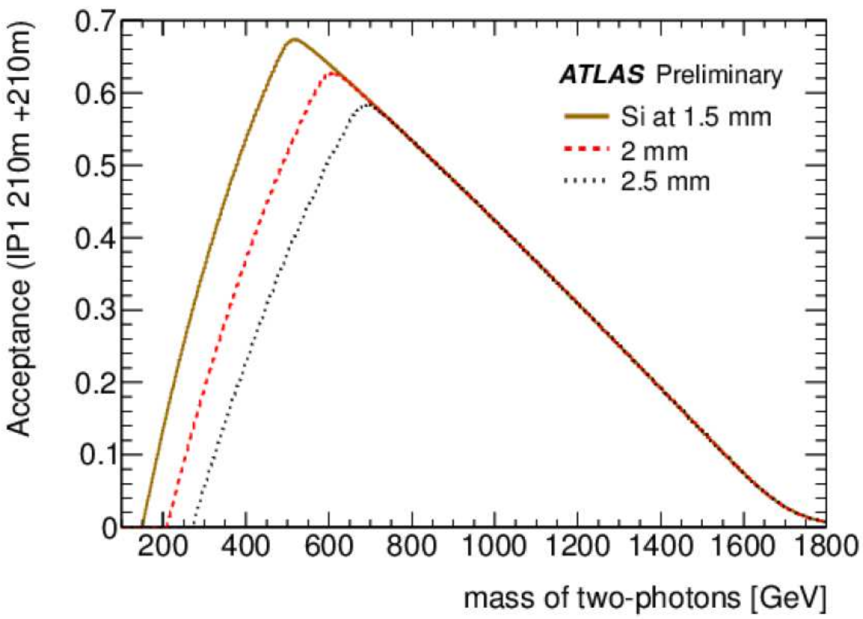
Kinematic variables

- t: 4-momentum transfer squared
- ξ_1, ξ_2: proton fractional momentum loss (momentum fraction of the proton carried by the pomeron)
- $\beta_{1,2} = x_{Bj,1,2}/\xi_{1,2}$: Bjorken-x of parton inside the pomeron
- $M^2 = s\xi_1\xi_2$: diffractive mass produced
- $\Delta y_{1,2} \sim \Delta\eta \sim \log 1/\xi_{1,2}$: rapidity gap
- See also the talks by Beatriz Gay-Ducati, Victor Goncalves, Sandro de Souza

What is AFP/CT-PPS?



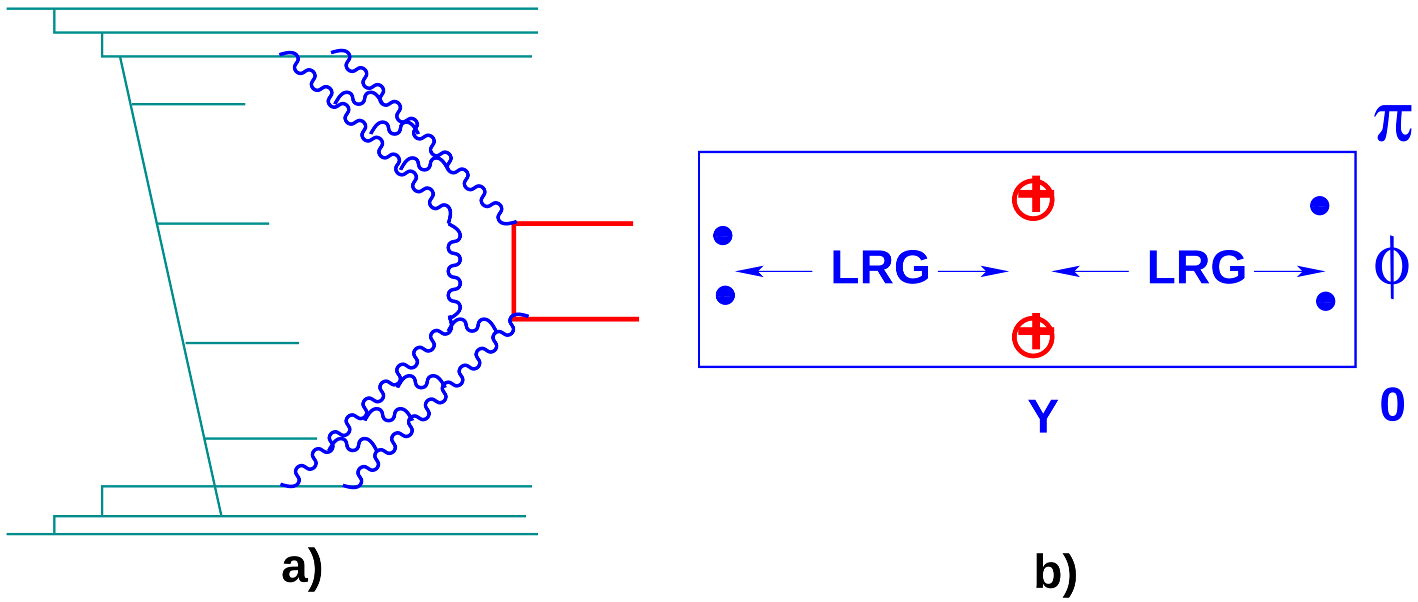




- Tag and measure protons at ± 210 m: AFP (ATLAS Forward Physics), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)
- All diffractive cross sections computed using the Forward Physics Monte Carlo (FPMC)
- Sensitivity to high mass central system, X, as determined using AFP/CT-PPS: Very powerful for exclusive states: kinematical constraints coming from AFP and CT-PPS proton measurements

Hard diffraction: A difficulty to go from HERA to LHC: survival probability

- Use parton densities measured at HERA to predict diffractive cross section at the LHC
- Factorisation is not expected to hold: soft gluon exchanges in initial/final states
- Survival probability: Probability that there is no soft additional interaction, that the diffractive event is kept
- Value of survival probability assumed in these studies: 0.1 at Tevatron (measured), 0.03 at LHC (extrapolated)

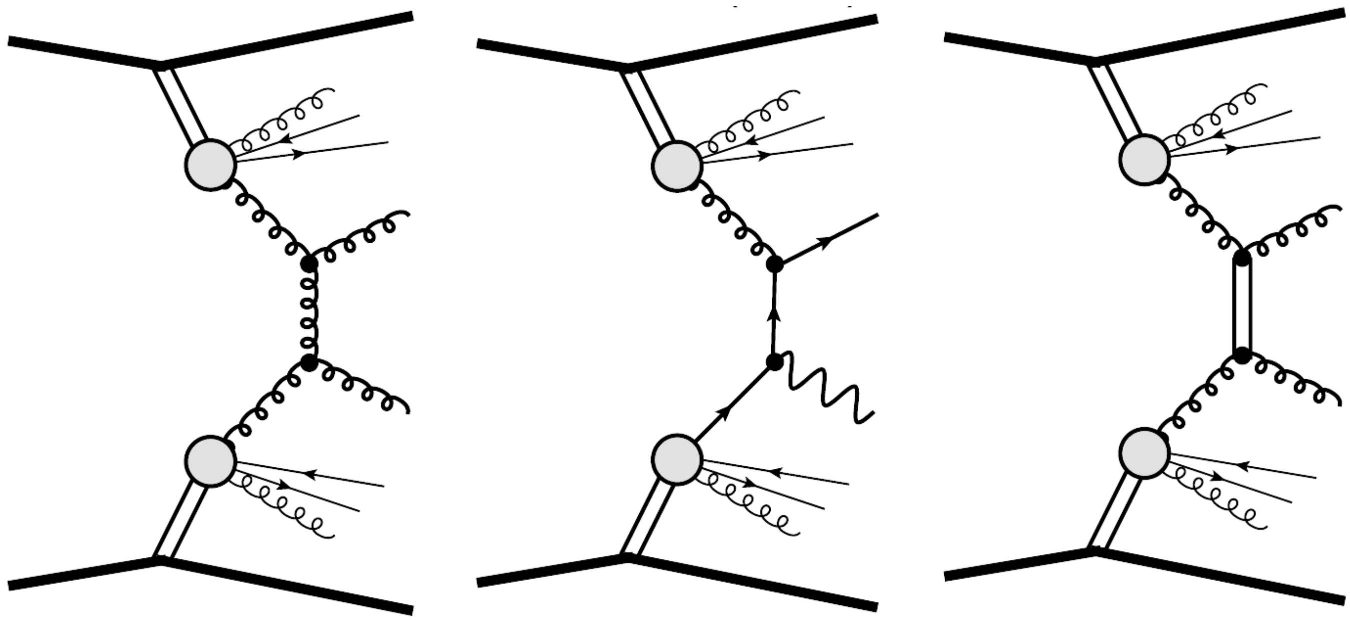


Forward Physics Monte Carlo (FPMC)

- FPMC (Forward Physics Monte Carlo): implementation of all diffractive/photon induced processes
- List of processes
  - two-photon exchange
  - single diffraction
  - double pomeron exchange
  - central exclusive production
- Inclusive diffraction: Use of diffractive PDFs measured at HERA, with a survival probability of 0.03 applied for LHC
- Central exclusive production: Higgs, jets...
- FPMC manual (see M. Boonekamp, A. Dechambre, O. Kepka, V. Juranek, C. Royon, R. Staszewski, M. Rangel, ArXiv:1102.2531)
- Survival probability: 0.1 for Tevatron (jet production), 0.03 for LHC, 0.9 for γ-induced processes
- Output of FPMC generator interfaced with the fast simulation of the ATLAS detector in the standalone ATLFast++ package

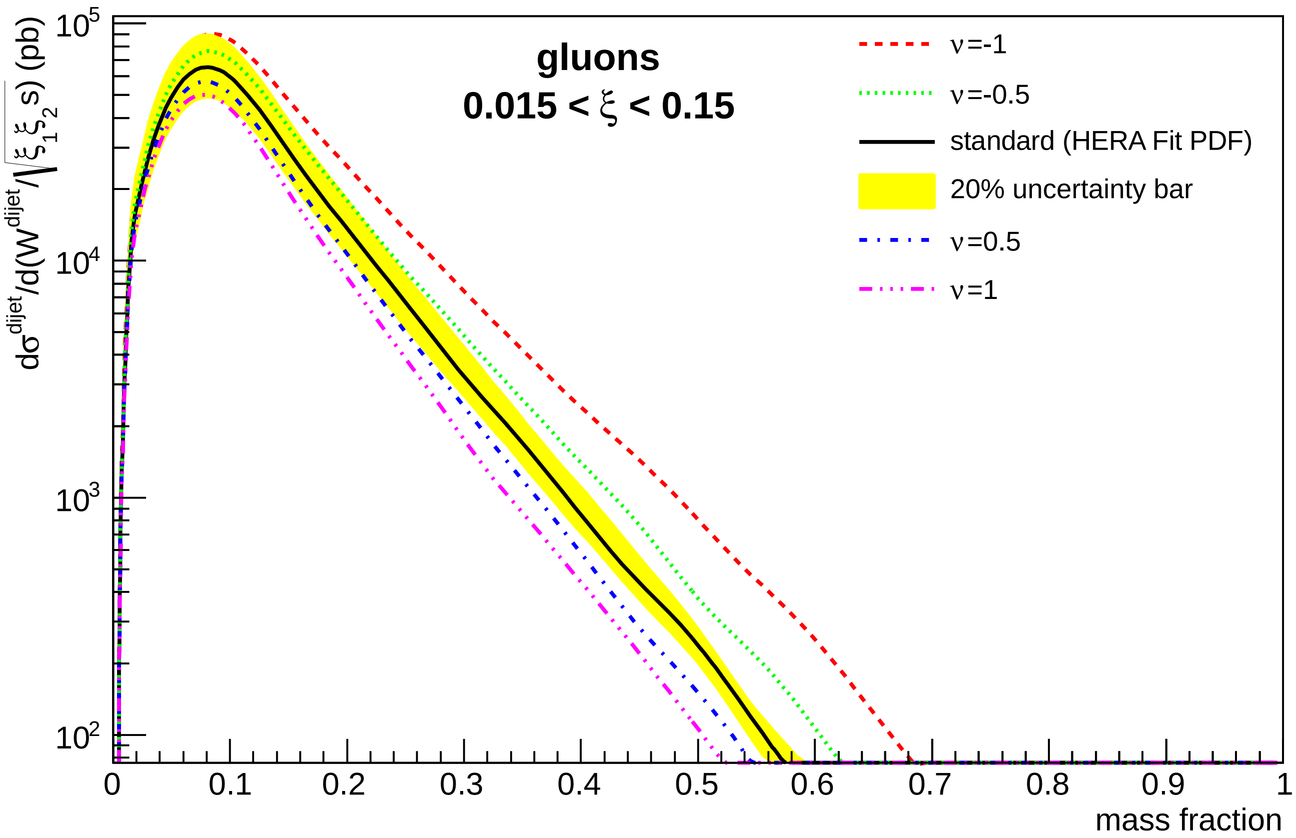
Hard diffraction at the LHC

- Dijet production: dominated by gg exchanges; γ+jet production: dominated by qg exchanges (C. Marquet, C. Royon, M. Saimpert, D. Werder, arXiv:1306.4901)
- Jet gap jet in diffraction: Probe BFKL (C. Marquet, C. Royon, M. Trzebinski, R. Zlebcik, Phys. Rev. D 87 (2013) 034010; O. Kepka, C. Marquet, C. Royon, Phys. Rev. D79 (2009) 094019; Phys.Rev. D83 (2011) 034036)
- Three aims
  - Is it the same object which explains diffraction in pp and ep?
  - Further constraints on the structure of the Pomeron as was determined at HERA
  - Survival probability: difficult to compute theoretically, needs to be measured, inclusive diffraction is optimal place for measurement



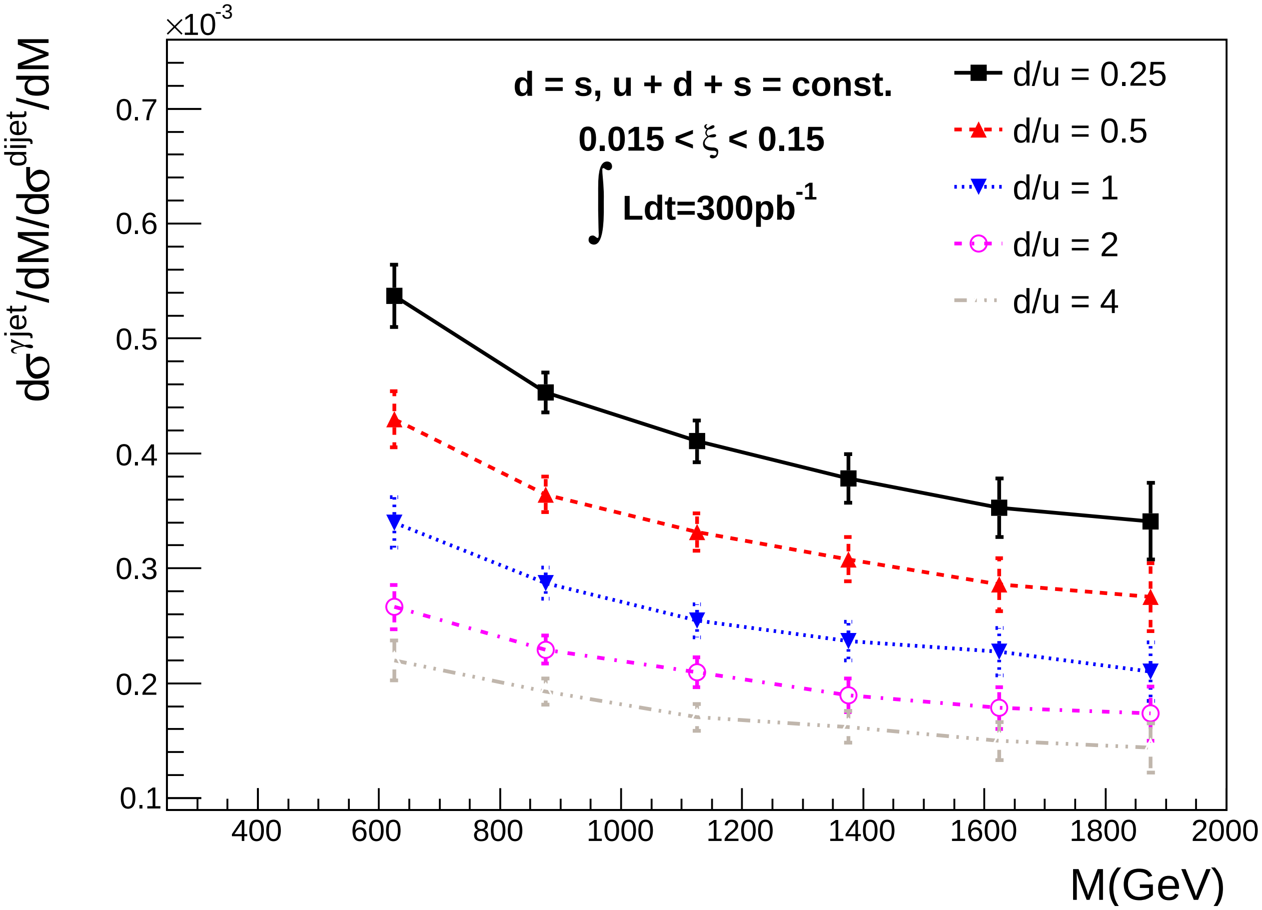
Inclusive diffraction at the LHC: sensitivity to gluon density

- Predict DPE dijet cross section at the LHC in AFP acceptance, jets with $p_T >$20 GeV, reconstructed at particle level using anti-k$_T$ algorithm
- Sensitivity to gluon density in Pomeron especially the gluon density on Pomeron at high β: multiply the gluon density by $(1-\beta)^\nu$ with $\nu = -1, ..., 1$
- Measurement possible with 10 pb^{-1}, allows to test if gluon density is similar between HERA and LHC (universality of Pomeron model)
- Dijet mass fraction: dijet mass divided by total diffractive mass ($\sqrt{\xi_1 \xi_2 S}$)



Inclusive diffraction at the LHC: sensitivity to quark densities

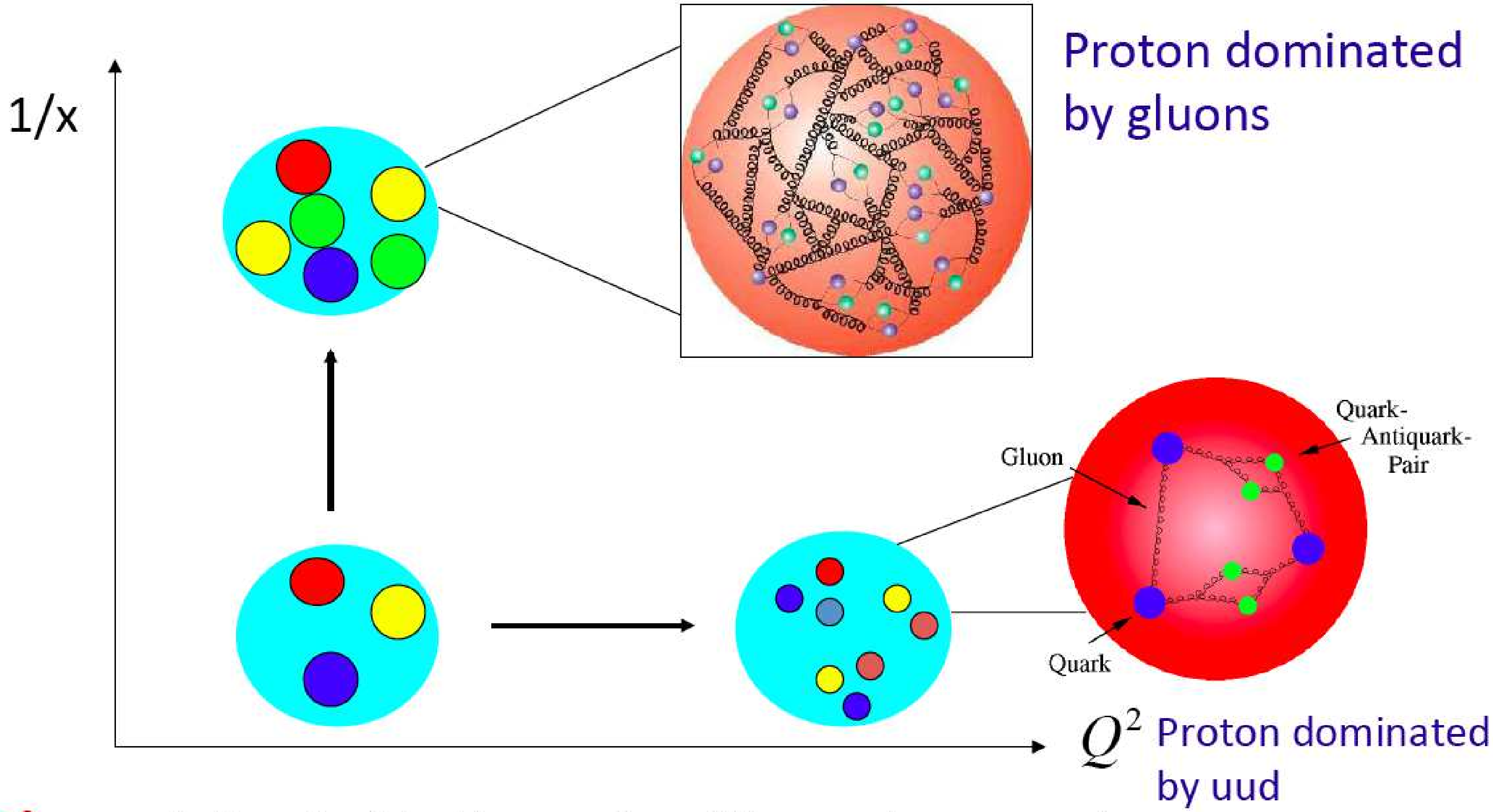
- Predict DPE γ+jet divided by dijet cross section at the LHC
- Sensitivity to universality of Pomeron model
- Sensitivity to quark density in Pomeron, and of assumption: $u = d = s = \bar{u} = \bar{d} = \bar{s}$ used in QCD fits at HERA
- Measurement of W asymmetry also sensitive to quark densities



Looking for BFKL effects

- Dokshitzer Gribov Lipatov Altarelli Parisi (DGLAP): Evolution in Q^2
- Balitski Fadin Kuraev Lipatov (BFKL): Evolution in x

Aim: Understanding the proton structure (quarks, gluons)

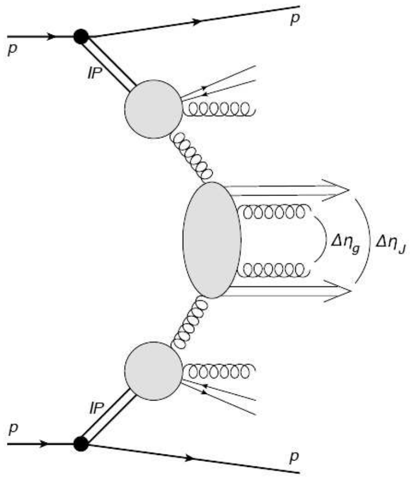


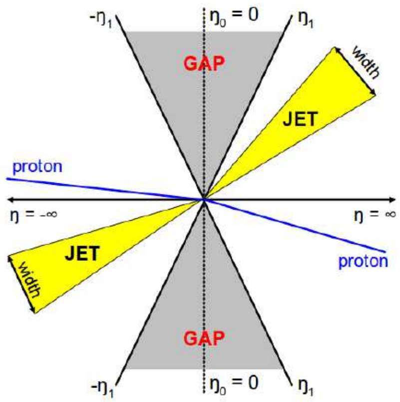
Q^2 : resolution inside the proton (like a microscope)

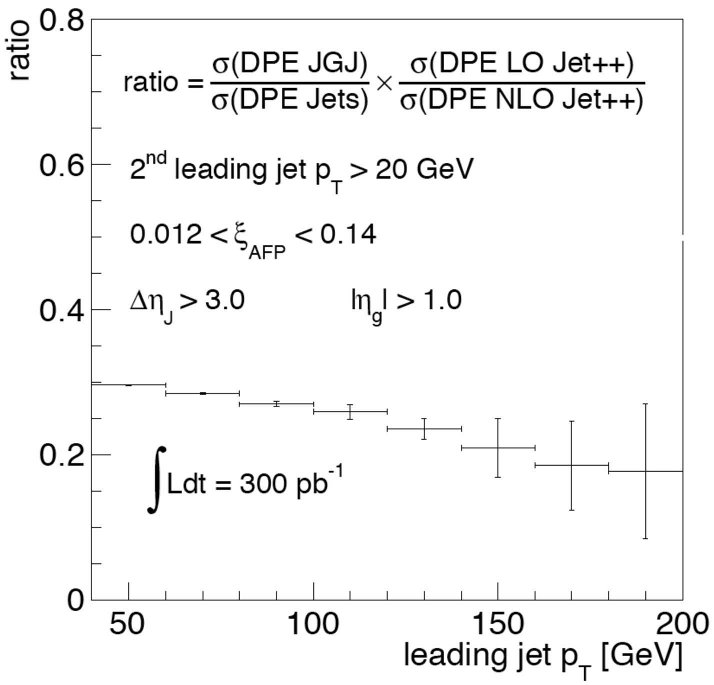
X :Proton momentum fraction carried away by the interacting quark

Jet gap jet events in diffraction

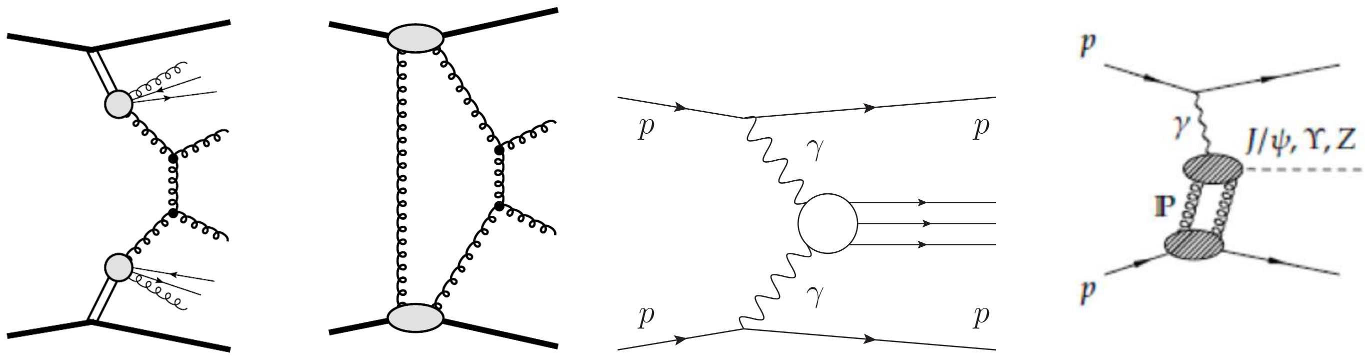
- Study BFKL dynamics using jet gap jet events in DPE
- See: C. Marquet, C. Royon, M. Trzebinski, R. Zlebcik, Phys. Rev. D 87 (2013) 034010



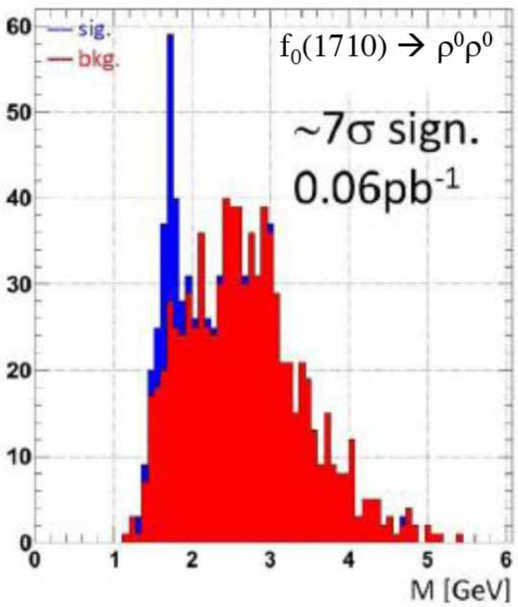


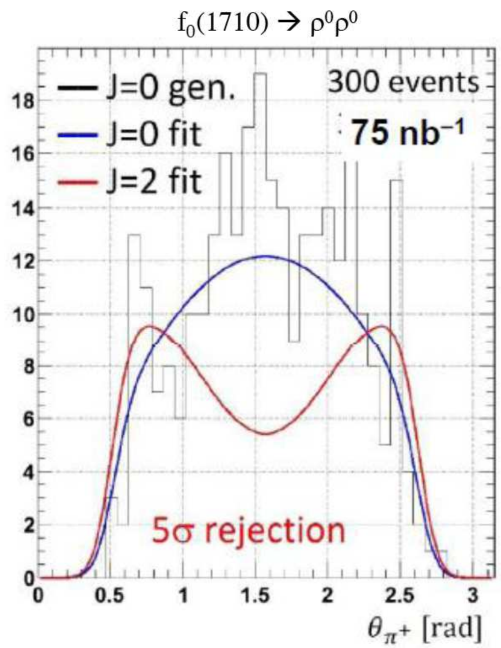


Exclusive diffraction

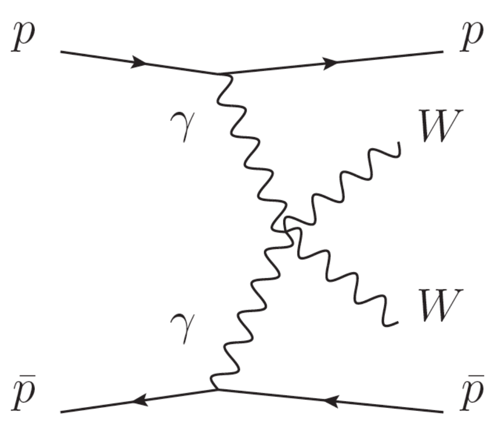


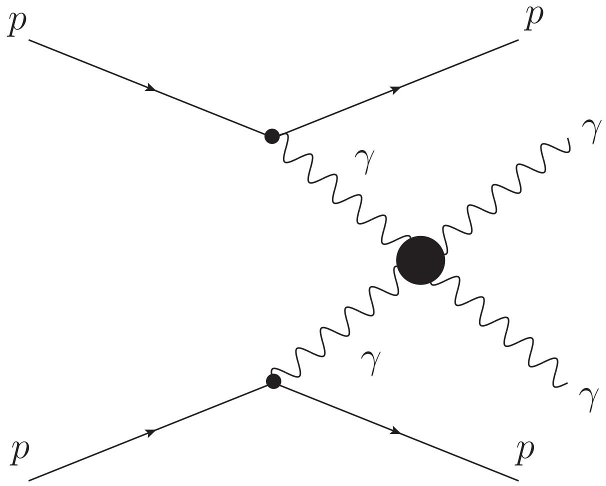
- Many exclusive channels can be studied: jets, χ_C, charmonium, J/Ψ....
- Possibility to reconstruct the properties of the object produced exclusively (via photon and gluon exchanges) from the tagged proton
- CMS/TOTEM has the possibility to discover/exclude glueballs at low masses: Check the $f_0(1500)$ or $f_0(1710)$ glueball candidates
- Simulation of signal $f_0(1710) \to \rho^0\rho^0$ and non resonant $\rho^0\rho^0$





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

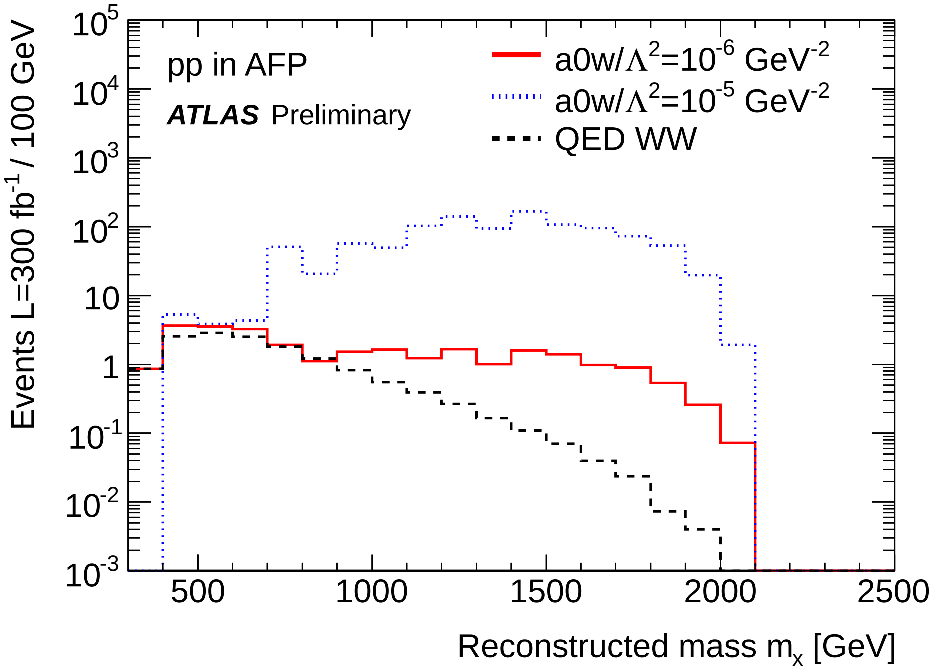


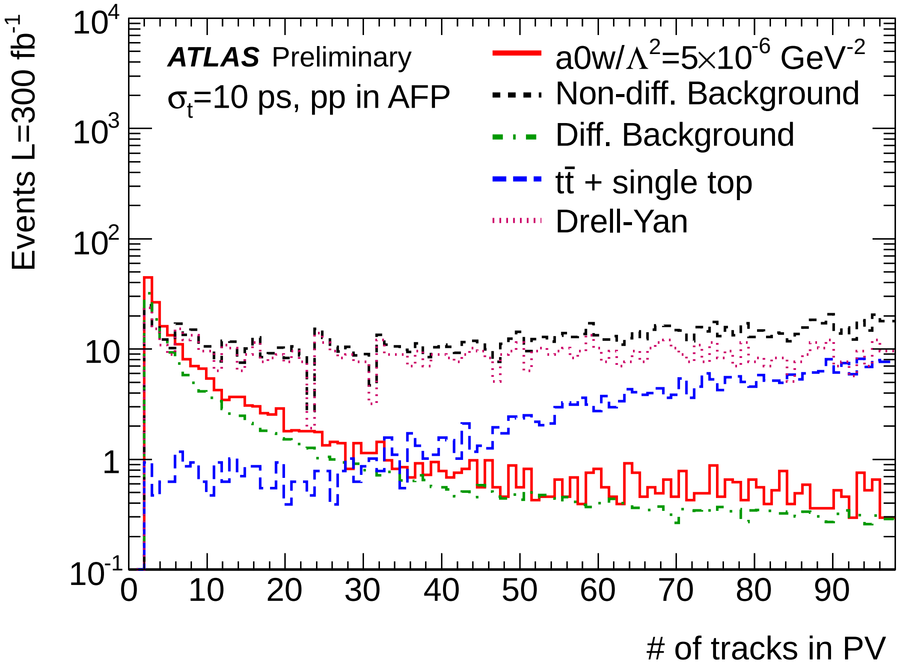


- Study of the process: $pp \to ppWW$, $pp \to ppZZ$, $pp \to pp\gamma\gamma$
- Standard Model: $\sigma_{WW} = 95.6$ fb, $\sigma_{WW}(W = M_X > 1TeV) = 5.9$ fb
- Process sensitive to anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$; motivated by studying in detail the mechanism of electroweak symmetry breaking, predicted by extradim. models
- Rich $\gamma\gamma$ physics at LHC: see papers by C. Baldenegro, E. Chapon, S. Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert: Phys. Rev. D78 (2008) 073005; Phys. Rev. D81 (2010) 074003; Phys.Rev. D89 (2014) 114004 ; JHEP 1502 (2015) 165; Phys. Rev. Lett. 116 (2016) no 23, 231801; Phys. Rev. D93 (2016) no 7, 075031; JHEP 1706 (2017) 142

Anomalous couplings studies in WW events

- Reach on anomalous couplings studied using a full simulation of the ATLAS detector, including all pile-up effects; only leptonic decays of Ws are considered
- Signal appears at high lepton p_T and dilepton mass (central ATLAS) and high diffractive mass (reconstructed using forward detectors)
- Cut on the number of tracks fitted to the primary vertex: very efficient to remove remaining pile-up after requesting a high mass object to be produced (for signal, we have two leptons coming from the W decays and nothing else)





Results from full simulation

- Effective anomalous couplings correspond to loops of charged particles, Reaches the values expected for extradim models (C. Grojean, J. Wells)

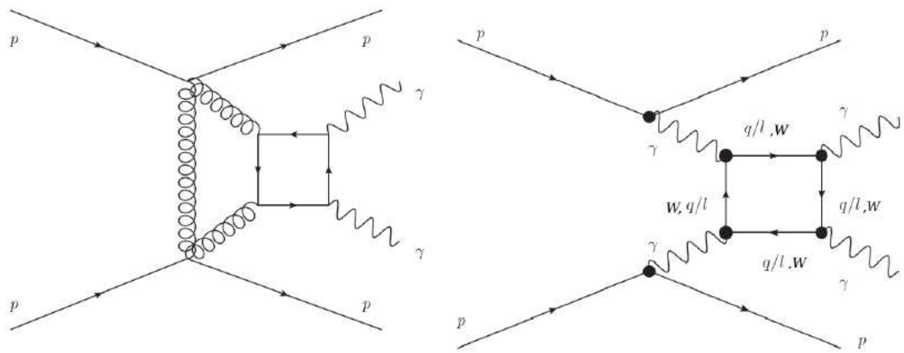
Cuts	Top	Dibosons	Drell-Yan	W/Z+jet	Diffr.	$a_0^W/\Lambda^2 = 5 \cdot 10^{-6}$ GeV^{-2}
timing < 10 ps, $p_T^{lep1} > 150$ GeV, $p_T^{lep2} > 20$ GeV	5198	601	20093	1820	190	282
M(ll)>300 GeV	1650	176	2512	7.7	176	248
nTracks ≤ 3	2.8	2.1	78	0	51	71
$\Delta\phi < 3.1$	2.5	1.7	29	0	2.5	56
$m_X > 800$ GeV	0.6	0.4	7.3	0	1.1	50
$p_T^{lep1} > 300$ GeV	0	0.2	0	0	0.2	35

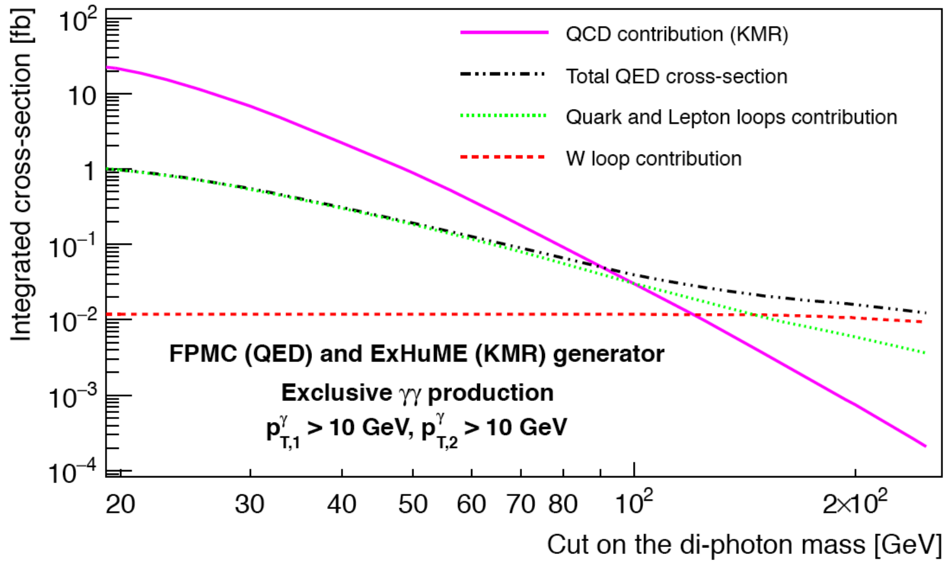
Table 9.5. Number of expected signal and background events for 300 fb^{-1} at pile-up $\mu = 46$. A time resolution of 10 ps has been assumed for background rejection. The diffractive background comprises production of QED diboson, QED dilepton, diffractive WW, double pomeron exchange WW.

- **Improvement of "standard" LHC methods by studying $pp \to l^\pm \nu \gamma\gamma$ (see P. J. Bell, ArXiV:0907.5299) by more than 2 orders of magnitude with 40/300 fb^{-1} at LHC (CMS mentions that their exclusive analysis will not improve very much at high lumi because of pile-up)**

	5σ	95% CL
$\mathcal{L} = 40\ fb^{-1}, \mu = 23$	5.5 10^{-6}	2.4 10^{-6}
$\mathcal{L} = 300\ fb^{-1}, \mu = 46$	3.2 10^{-6}	1.3 10^{-6}

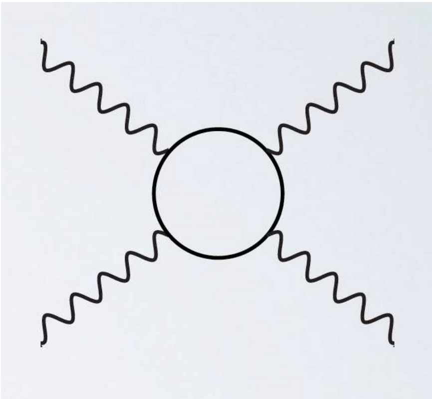
$\gamma\gamma$ exclusive production: SM contribution

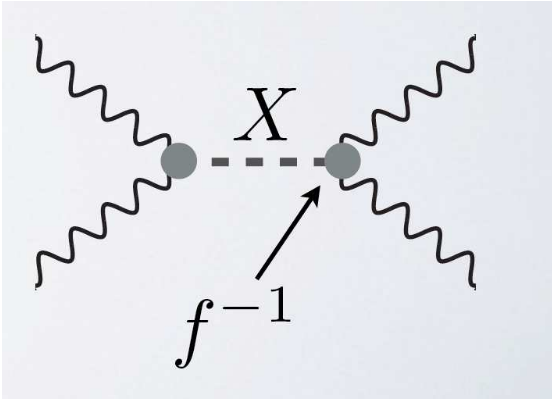




- QCD production dominates at low $m_{\gamma\gamma}$, QED at high $m_{\gamma\gamma}$
- Important to consider W loops at high $m_{\gamma\gamma}$
- At high masses (~ 750 GeV), the photon induced processes are dominant
- **Conclusion: Two photons and two tagged protons means photon-induced process**

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 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}

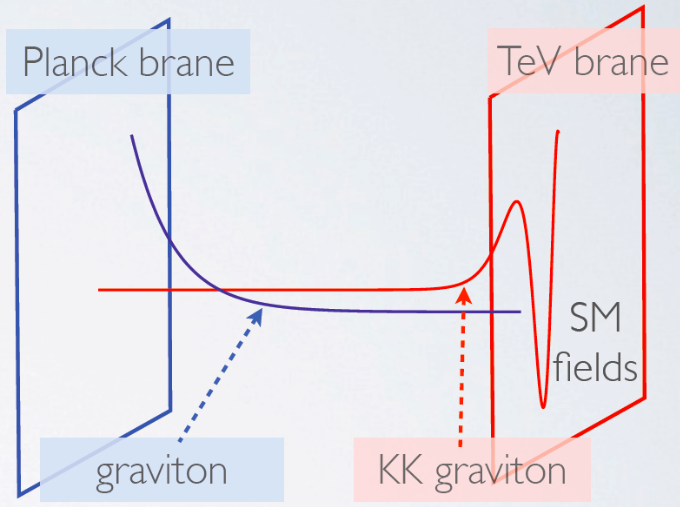
- ζ_1 can also be modified by neutral particles at tree level (extensions of the SM including scalar, pseudo-scalar, and spin-2 resonances that couple to the photon) $\zeta_1 = (f_s m)^{-2} d_{1,s}$ where f_s is the $\gamma\gamma X$ coupling of the new particle to the photon, and $d_{1,s}$ depends on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

Warped extra-dimensions

✘ Warped Extra Dimensions solve hierarchy problem of SM

✘ 5th dimension bounded by two branes

✘ SM on the visible (or TeV) brane



✘ The Kaluza Klein modes of the graviton couple with TeV strength

$$\mathcal{L}^{\gamma\gamma h} = f^{-2}\, h^{\rm KK}_{\mu\nu}\, \left(\tfrac{1}{4}\eta_{\mu\nu}F^2_{\rho\lambda} - F_{\mu\rho}F_{\rho\nu}\right)$$

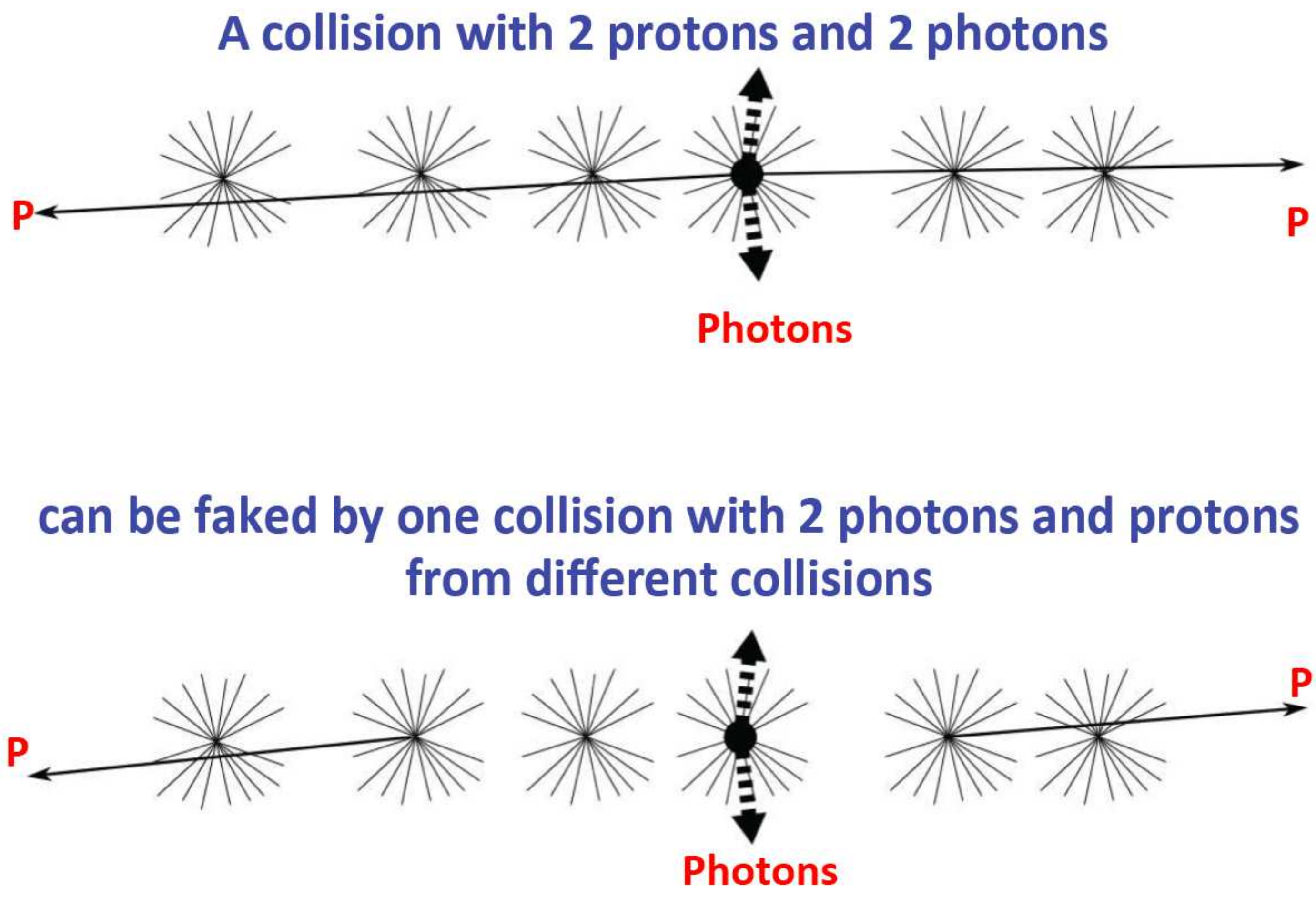
$$f \sim \text{TeV} \qquad m_{\rm KK} \sim \text{few TeV}$$

✘ Effective 4-photon couplings $\zeta_i \sim 10^{-14} - 10^{-13}\ \text{GeV}^{-2}$ possible

✘ The radion can produce similar effective couplings

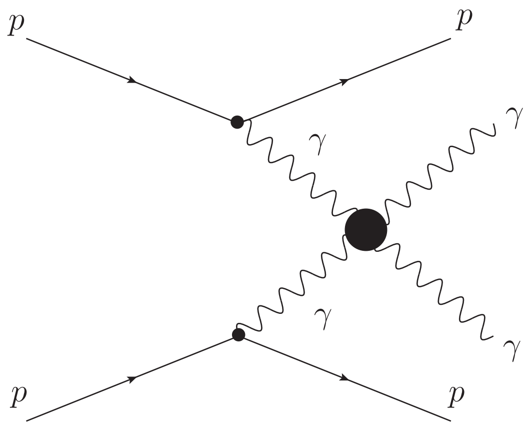
- Which models/theories are we sensitive to using AFP/CT-PPS
- Beyond standard models predict anomalous couplings of $\sim 10^{-14}$-10^{-13}
- Work in collaboration with Sylvain Fichet, Gero von Gersdorff

One aside: what is pile up at LHC?

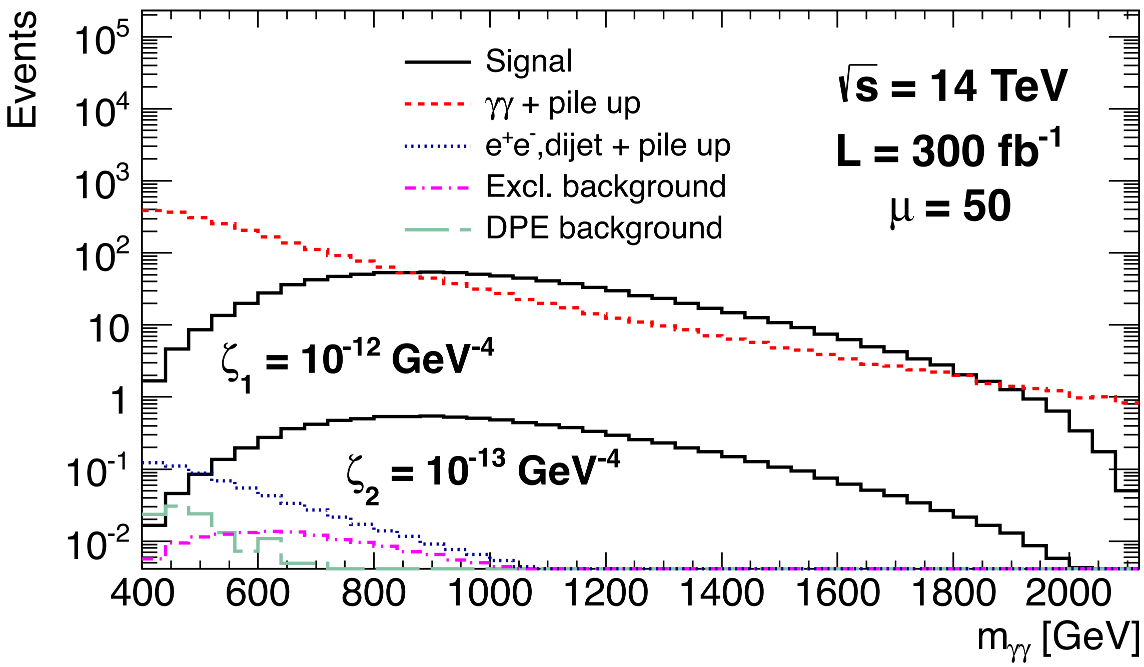


- The LHC machine collides packets of protons
- Due to high number of protons in one packet, there can be more than one interaction between two protons when the two packets collide
- Typically up to 50 pile up events

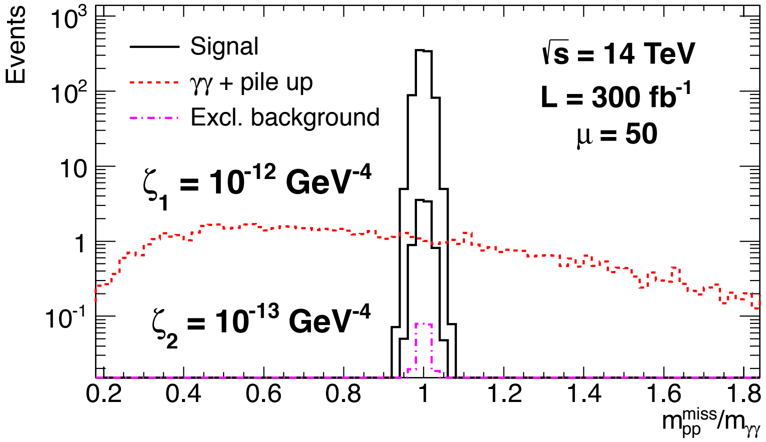
Search for quartic $\gamma\gamma$ anomalous couplings

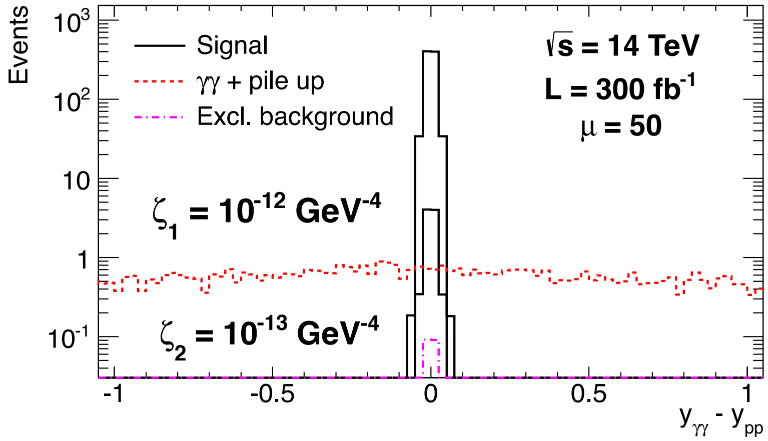


- Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- Analysis performed at hadron level including detector efficiencies, resolution effects, pile-up...



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
$[0.015 < \xi_{1,2} < 0.15$, $p_{\mathrm{T}1,(2)} > 200, (100)$ GeV]	130.8	36.9 (373.9)	0.25	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	128.3	34.9 (371.6)	0.20	0	0.2	1023
$[p_{\mathrm{T}2}/p_{\mathrm{T}1} > 0.95$, $\lvert\Delta\phi\rvert > \pi - 0.01]$	128.3	34.9 (371.4)	0.19	0	0	80.2
$\sqrt{\xi_1\xi_2 s} = m_{\gamma\gamma} \pm 3\%$	122.0	32.9 (350.2)	0.18	0	0	2.8
$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	119.1	31.8 (338.5)	0.18	0	0	0

- No background after cuts for 300 fb^{-1} **without needing timing detector information**
- Exclusivity cuts using proton tagging needed to suppress backgrounds (Without exclusivity cuts using CT-PPS: background of 80.2 for 300 fb^{-1})

High lumi: Search for quartic $\gamma\gamma$ anomalous couplings: Results from effective theory

Luminosity	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
pile-up (μ)	50	50	50	200
coupling (GeV^{-4})	$\geq$ 1 conv. γ 5 σ	$\geq$ 1 conv. γ 95% CL	all γ 95% CL	all γ 95% CL
ζ_1 f.f. ζ_1 no f.f.	$8 \cdot 10^{-14}$ $2.5 \cdot 10^{-14}$	$5 \cdot 10^{-14}$ $1.5 \cdot 10^{-14}$	$3 \cdot 10^{-14}$ $9 \cdot 10^{-15}$	$2.5 \cdot 10^{-14}$ $7 \cdot 10^{-15}$
ζ_2 f.f. ζ_2 no f.f.	$2. \cdot 10^{-13}$ $5 \cdot 10^{-14}$	$1. \cdot 10^{-13}$ $4 \cdot 10^{-14}$	$6 \cdot 10^{-14}$ $2 \cdot 10^{-14}$	$4.5 \cdot 10^{-14}$ $1.5 \cdot 10^{-14}$

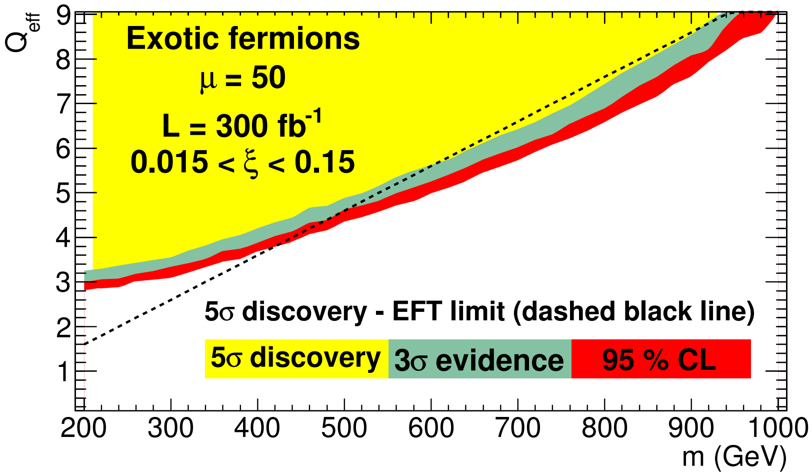
- Unprecedented sensitivities at hadronic colliders: no limit exists presently on $\gamma\gamma\gamma\gamma$ anomalous couplings
- Reaches the values predicted by extra-dim or composite Higgs models
- Introducing form factors to avoid quadratical divergences of scattering amplitudes due to anomalous couplings in conventional way: $a \rightarrow \frac{a}{(1+W_{\gamma\gamma}/\Lambda_{cutoff})^2}$ with $\Lambda_{cutoff} \sim 2$ TeV, scale of new physics
- Full amplitude calculation leads to similar results: avoids using a form factor and parameters dependence of the results
- **Conclusion: background free experiment**

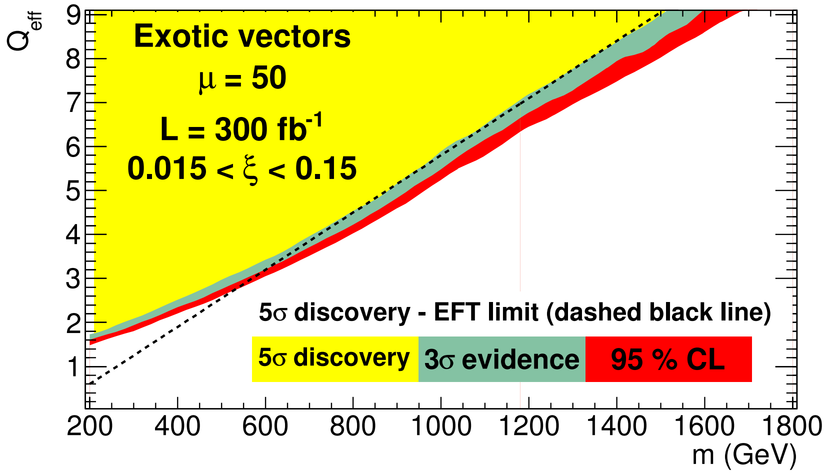
Full amplitude calculation

- 5 σ discovery sensitivity on the effective charge of new charged fermions and vector boson for various mass scenarii for 300 fb^{-1} and $\mu = 50$

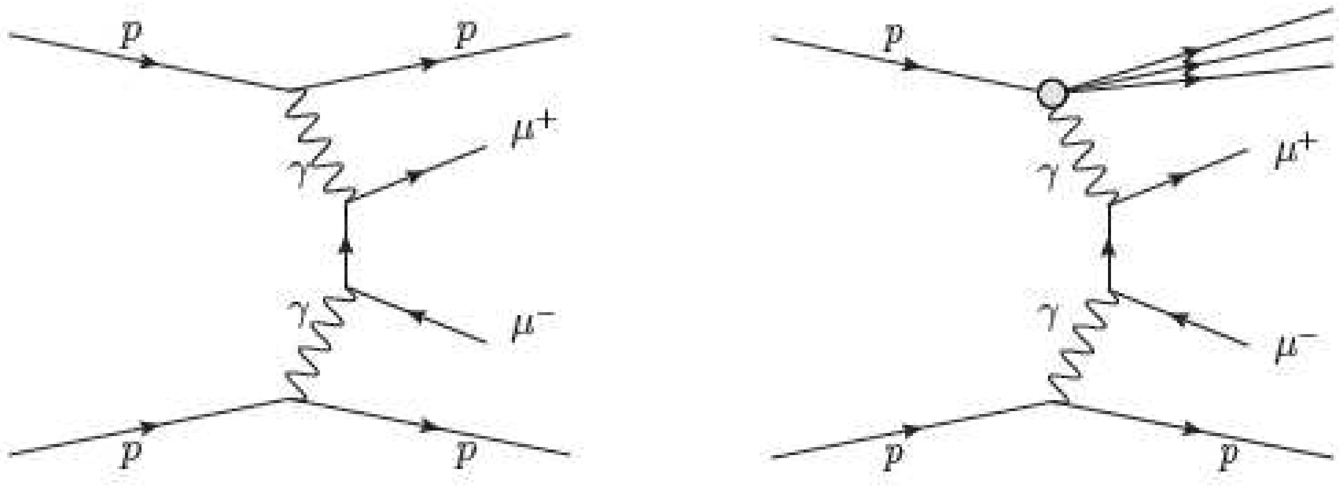
Mass (GeV)	300	600	900	1200	1500
Q_{eff} (vector)	2.2	3.4	4.9	7.2	8.9
Q_{eff} (fermion)	3.6	5.7	8.6	-	-

- Unprecedented sensitivites at hadronic colliders reaching the values predicted by extra-dim models - For reference, we also display the result of effective field theory (without form factor) which deviates at low masses from the full calculation
- For $Q_{Jeff} = QN^{1/4} = 4$, we are sensitive to new vectors (fermions) up to 700 (370) GeV for a luminosity of 300 fb^{-1}





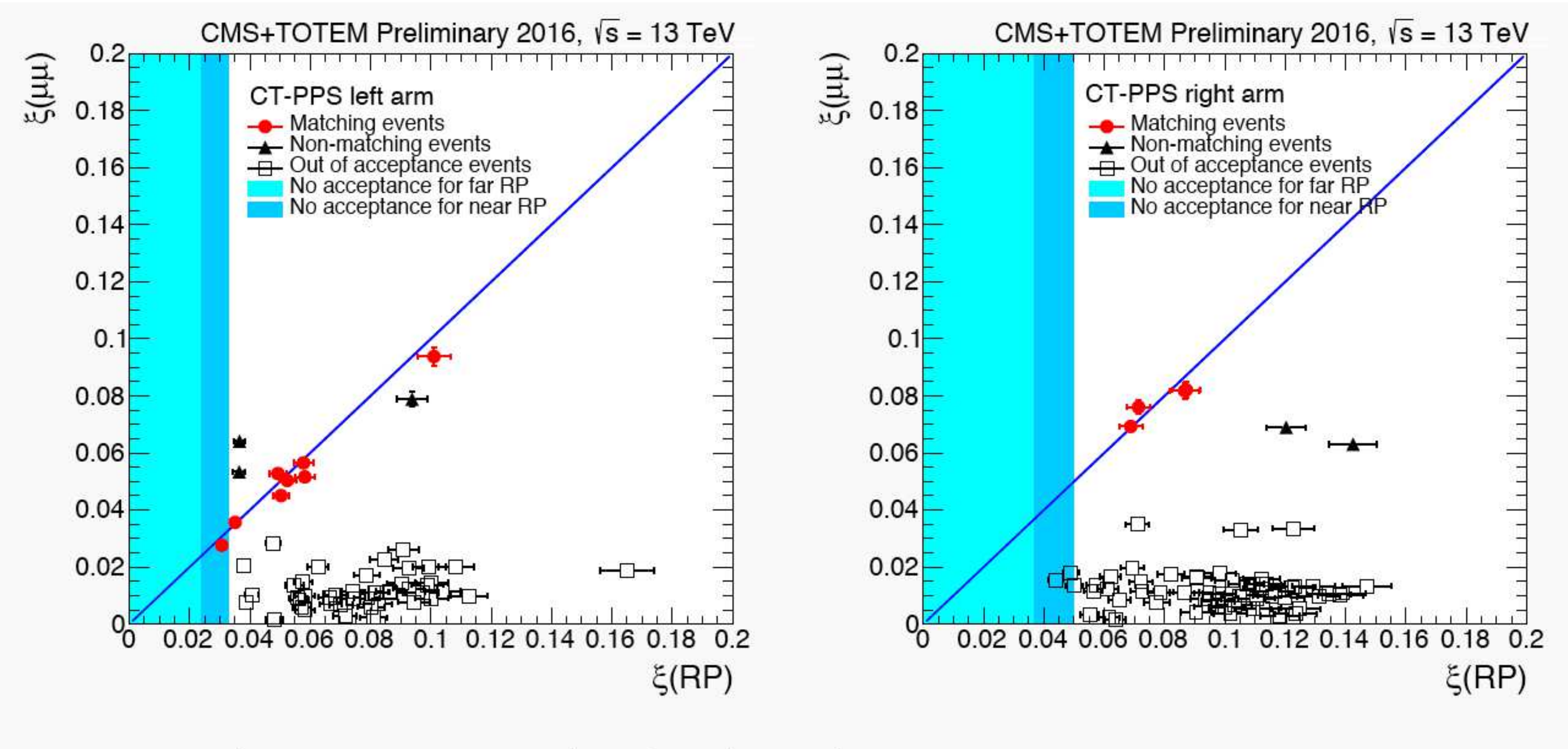
Observation of semi-exclusive dimuon production in CT-PPS



- Observation of exclusive dimuon production in CT-PPS
- First time a near-beam detector operates t a hadron collider at high luminosity (single tag events), < 1 event expected for a mass larger than 350-400 GeV for $\sim$ 15 fb^{-1}) $\rightarrow$ Request only one proton tagged
- Data-driven background estimate: Use sample of background protons from Z-peak events as example for Drell Yan contribution, Count number of Z-peak events with $\xi(\mu\mu)$ and ξ(proton) correlated within 2σ and use MC to extrapolate from Z-peak region to signal region

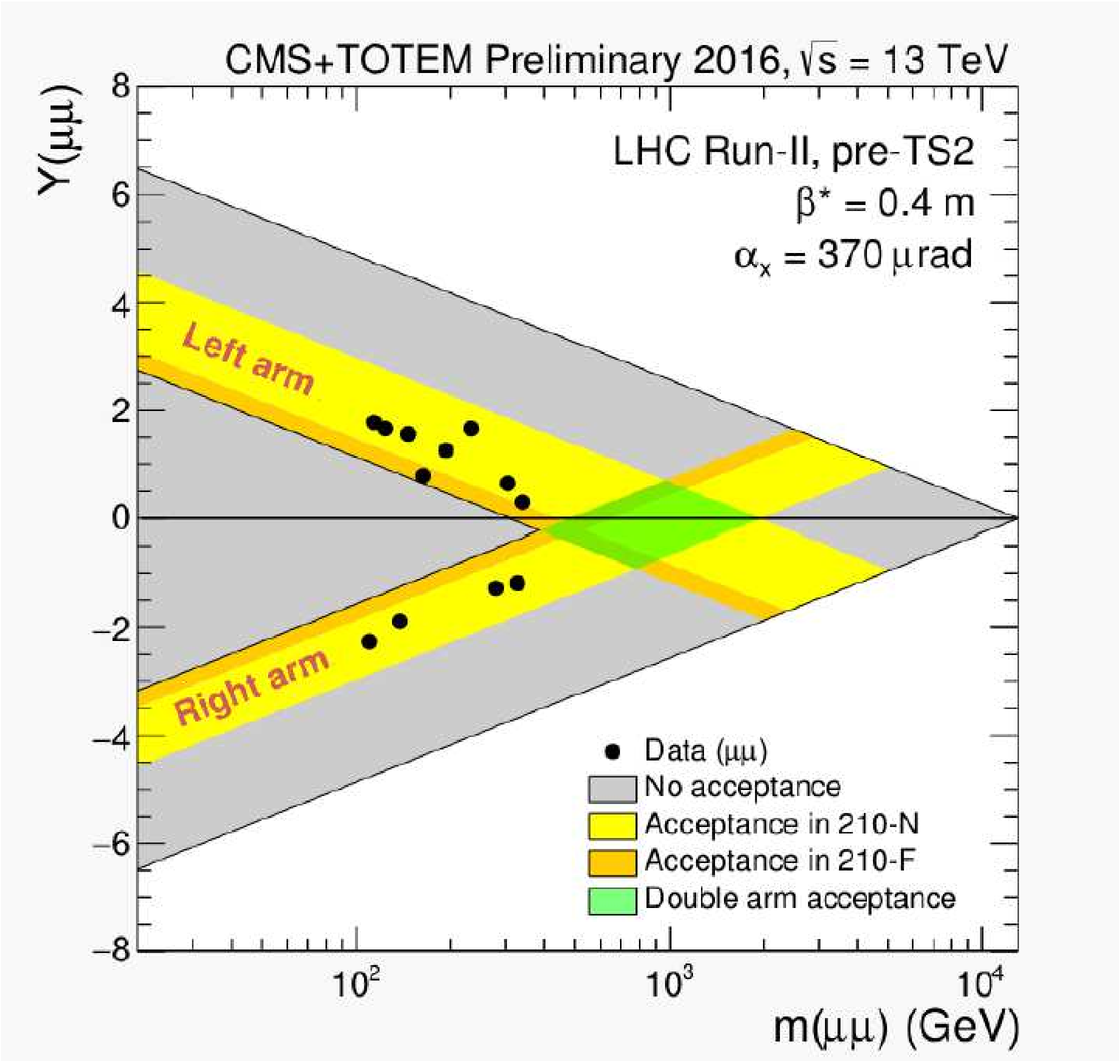
Observed signal (CT-PPS)

- First measurement of exclusive di-muon process with proton tag
- CT-PPS works as expected (validates alignment, optics determination...)
- 17 events are found with protons in the CT-PPS acceptance and 12 $< 2\sigma$ matching
- Significance for observing 12 events for a background of $1.47 \pm 0.06(stat) \pm 0.52(syst)$: 4.3 σ

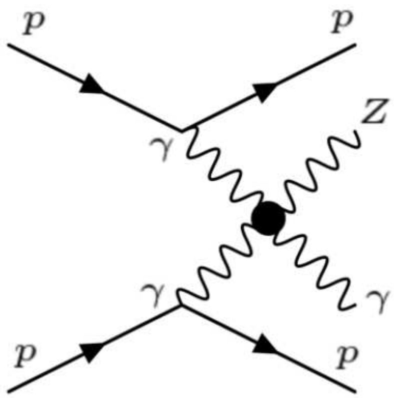


Summary of 12 candidate properties

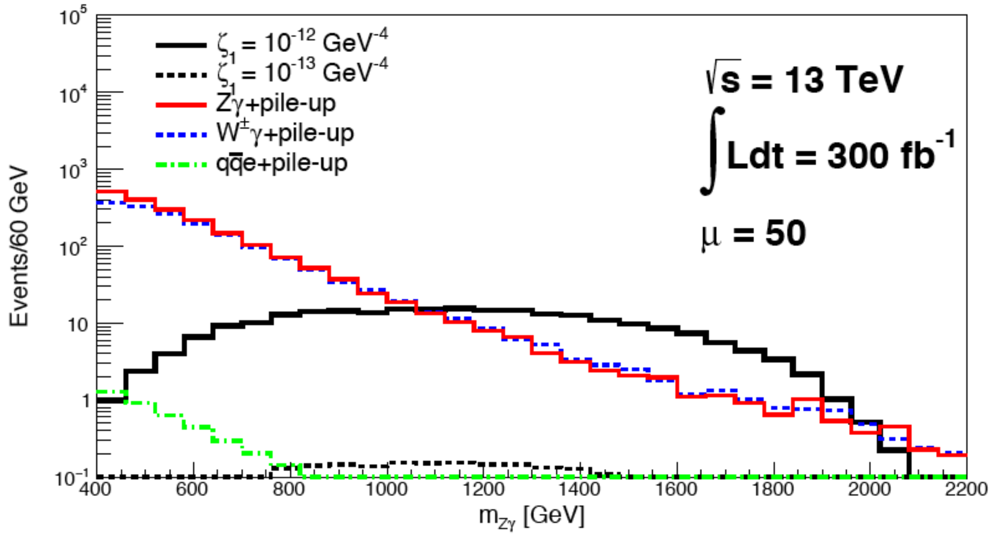
- Dimuon invariant mass vs rapidity distributions in the range expected for single arm acceptance
- No event at higher mass that would be in the acceptance for double tagging
- Highest mass event: 341 GeV
- CMS-PAS-PPS-17-001



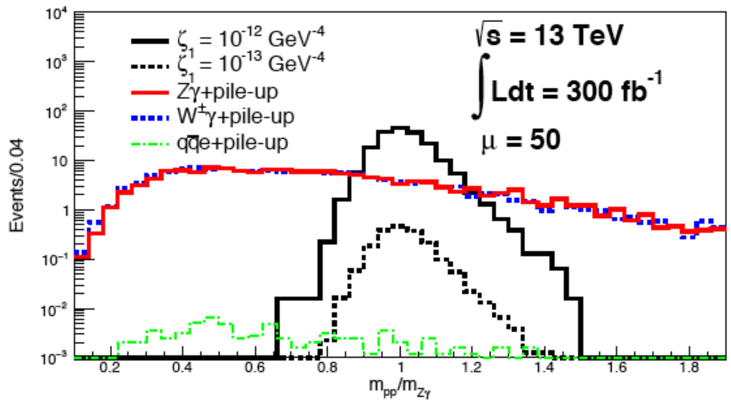
$\gamma\gamma\gamma Z$ quartic anomalous coupling

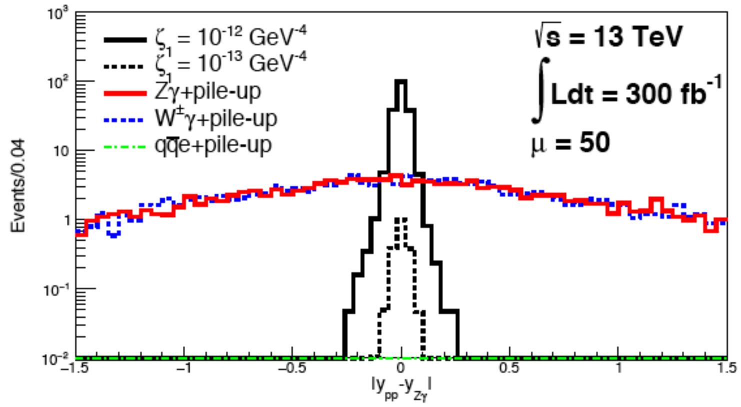


- Look for $Z\gamma$ anomalous production
- Z can decay leptonically or hadronically: the fact that we can control the background using the mass/rapidiy matching technique allows us to look in both channels (very small background)



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





Cut/Process	Signal ζ $(\tilde{\zeta}=0)$	Signal $\zeta=\tilde{\zeta}$	γZ +pile-up	$W^{\pm}\gamma$ +pile-up	$jje^{\pm}$ +pile-up
$0.015 < \xi_{1,2} < 0.15$, $p_{T\gamma} > 150$ GeV $p_{Tjj} > 100$ GeV]	38.6	51.4	1951.8	1631	8.47
$m_{\gamma Z} > 700$ GeV	37	49.5	349.8	358.9	1.3
$p_{T\gamma}/p_{Tjj} > 0.90$, $\lvert\Delta\phi - \pi\rvert < 0.02$	33.8	45.1	144.7	145.4	0.54
$\sqrt{\xi_1\xi_2 s} = m_{\gamma Z} \pm 10\%$	28.2	35.7	19.7	19.3	0.1
$\lvert y_{pp} - y_{\gamma Z}\rvert < 0.05$	25.5	32.7	1.5	1.6	0

- Background of about 3.1 events for 300 fb-1, and about 25 events of signal for a coupling of 4 10^{-13} GeV^{-4}
- C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1706 (2017) 142

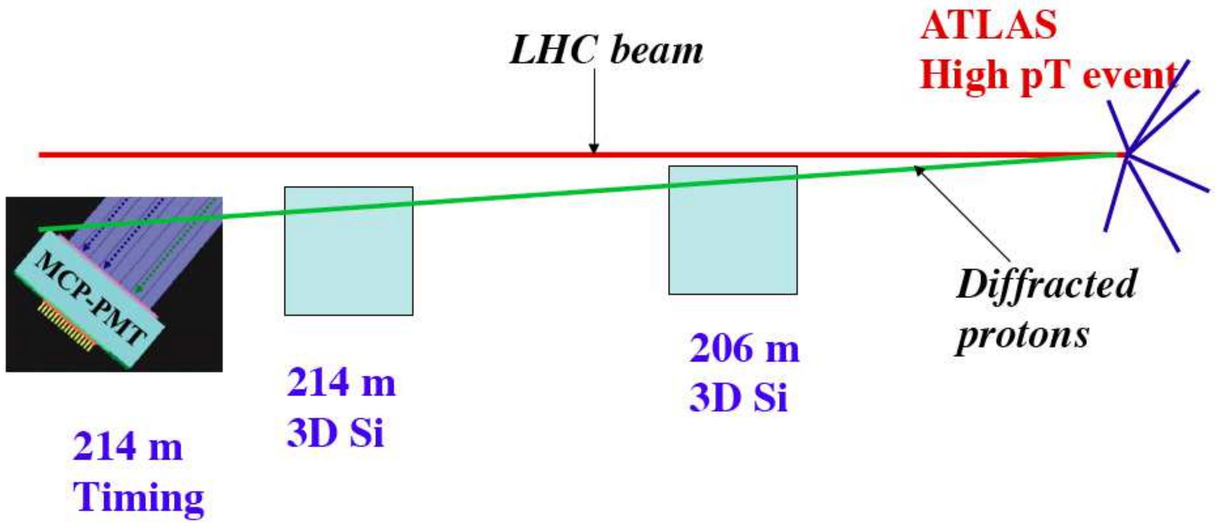
$\gamma\gamma\gamma Z$ quartic anomalous coupling

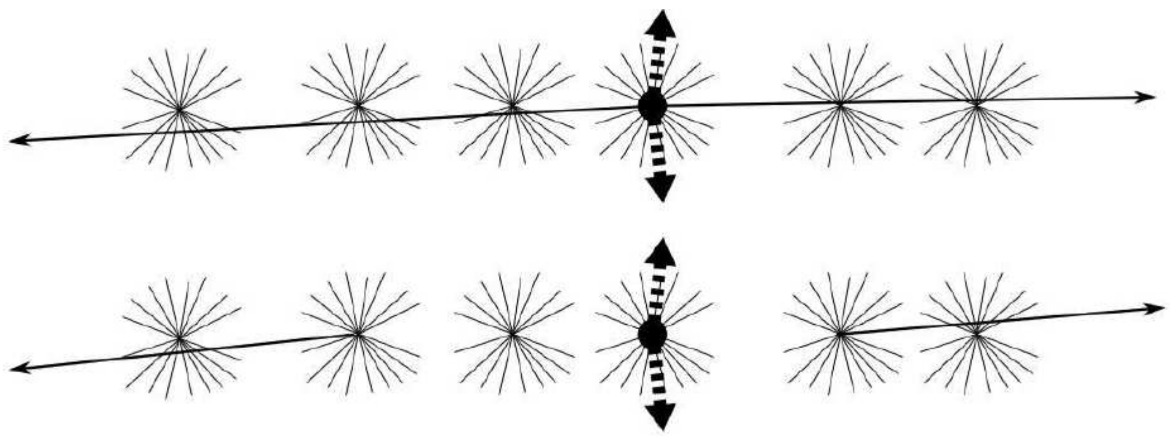
- Reach on $\gamma\gamma\gamma Z$ anomalous coupling

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
$\ell\bar{\ell}\gamma$	$2.8 \cdot 10^{-13}$	$1.8 \cdot 10^{-13}$	$2.5 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$
$jj\gamma$	$2.3 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$2 \cdot 10^{-13}$	$1.3 \cdot 10^{-13}$
$jj\gamma \bigoplus \ell\bar{\ell}\gamma$	$1.93 \cdot 10^{-13}$	$1.2 \cdot 10^{-13}$	$1.7 \cdot 10^{-13}$	$1 \cdot 10^{-13}$

- Best expected rach at the LHC by about two 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

Removing pile up: measuring proton time-of-flight

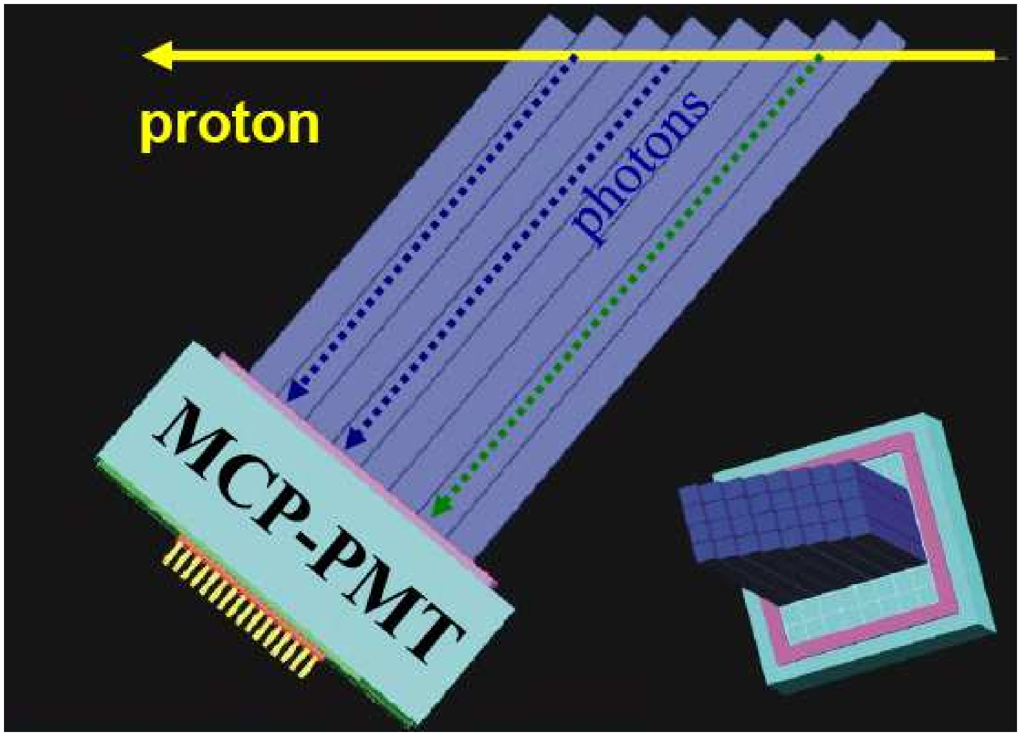




- Measure the proton time-of-flight in order to determine if they originate from the same interaction as our photon
- Typical precision: 10 ps means 2.1 mm

Timing detectors

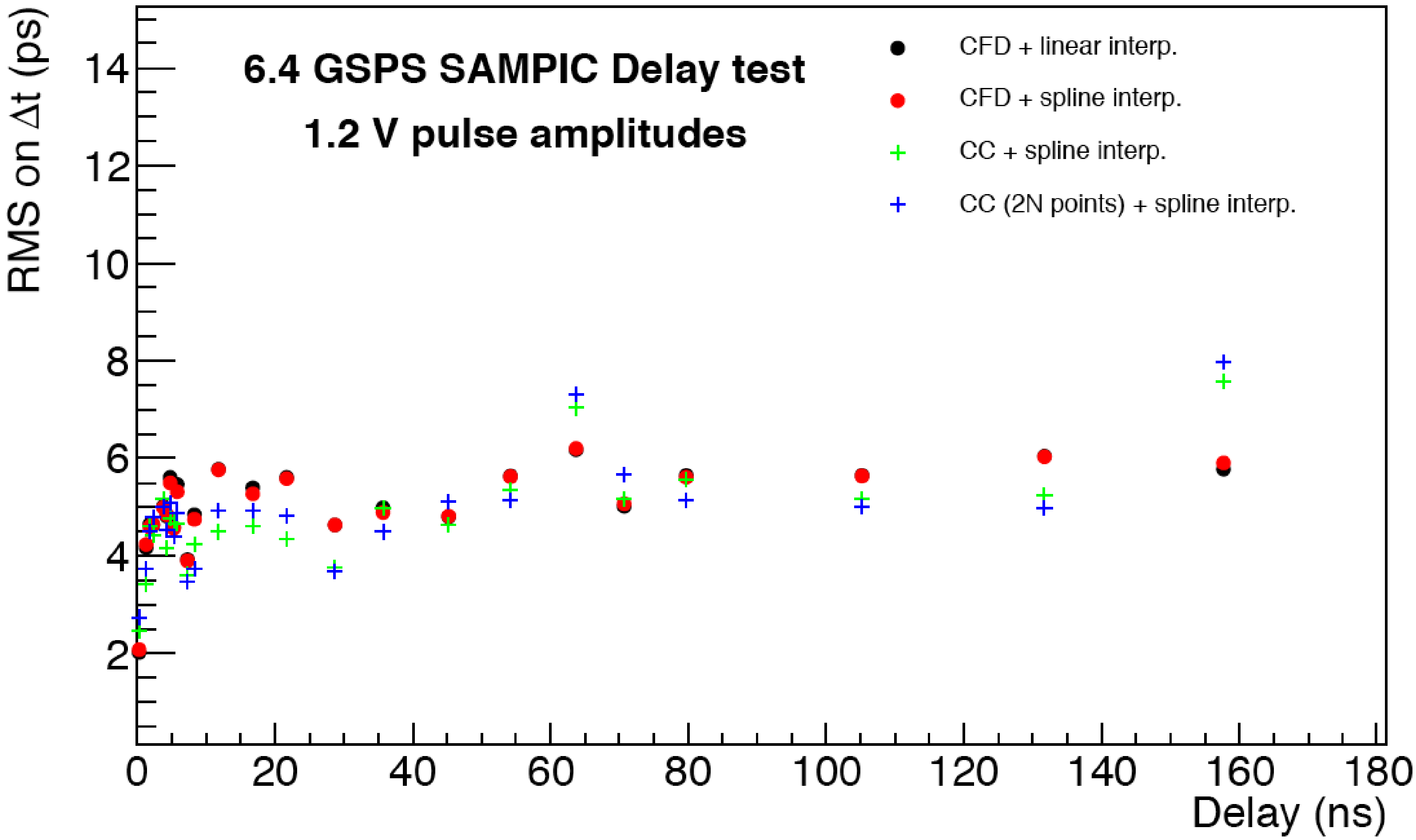
- Measure the vertex position using proton time-of-flight: suppresses high pile up events at the LHC (50 events in the same bunch crossing), allows to determine if protons originate from main interaction vertex
- Requirements for timing detectors
  - 10 ps final precision (factor 40 rejection on pile up)
  - Efficiency close to 100% over the full detector coverage
  - High rate capability (bunch crossing every 25 ns)
  - Segmentation for multi-proton timing
  - level 1 trigger capability
- Utilisation of quartz, diamond, gas or Silicon detectors (here focus on SAMPIC)



Measuring the proton time-of-flight: the SAMPIC concept

- The general idea is to measure the signal created by the protons inside a quartz, diamond or Silicon detector
- New electronics developed in Saclay/Orsay called SAMPIC that acquires the full waveform shape of the detector signal: about 3 ps precision!
- SAMPIC is cheap ($\sim$ 10 Euros per channel) (compared to a few 1000 Euros for previous technologies)

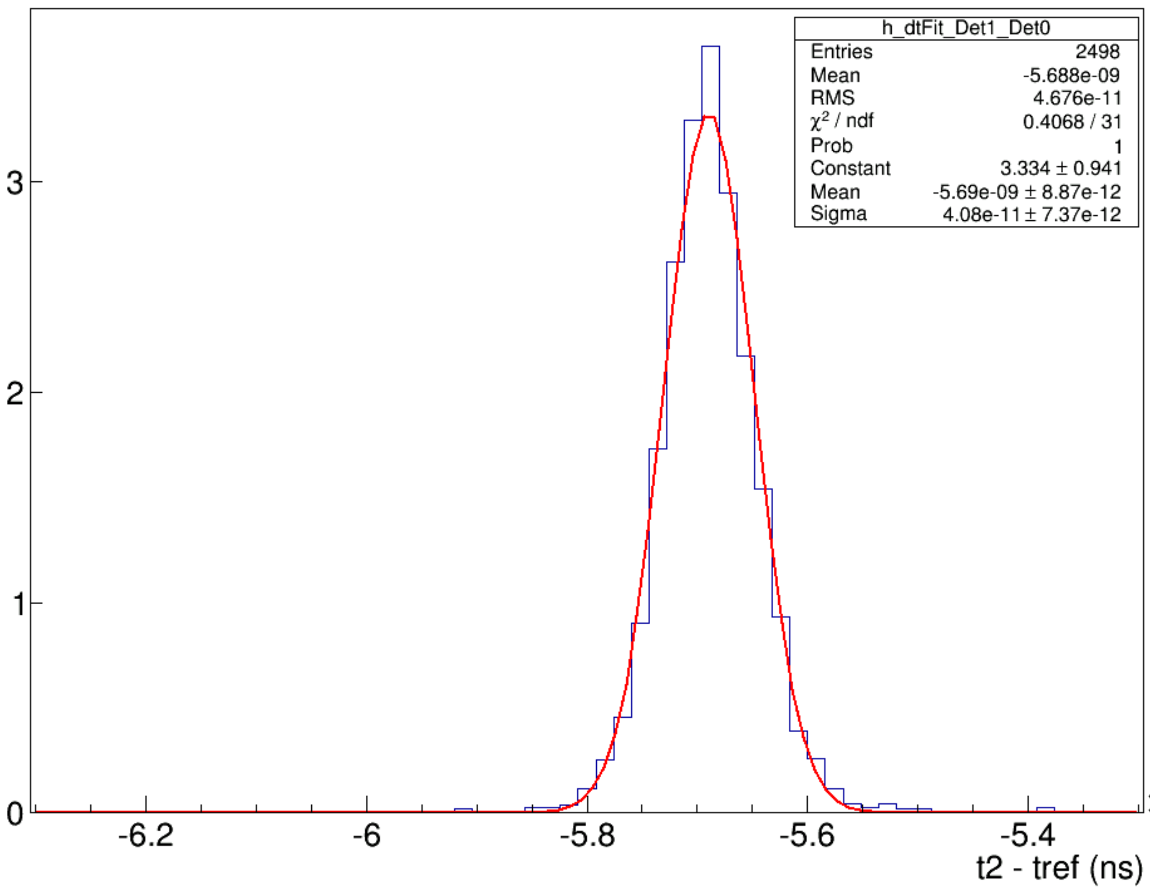
Timing resolution vs delay



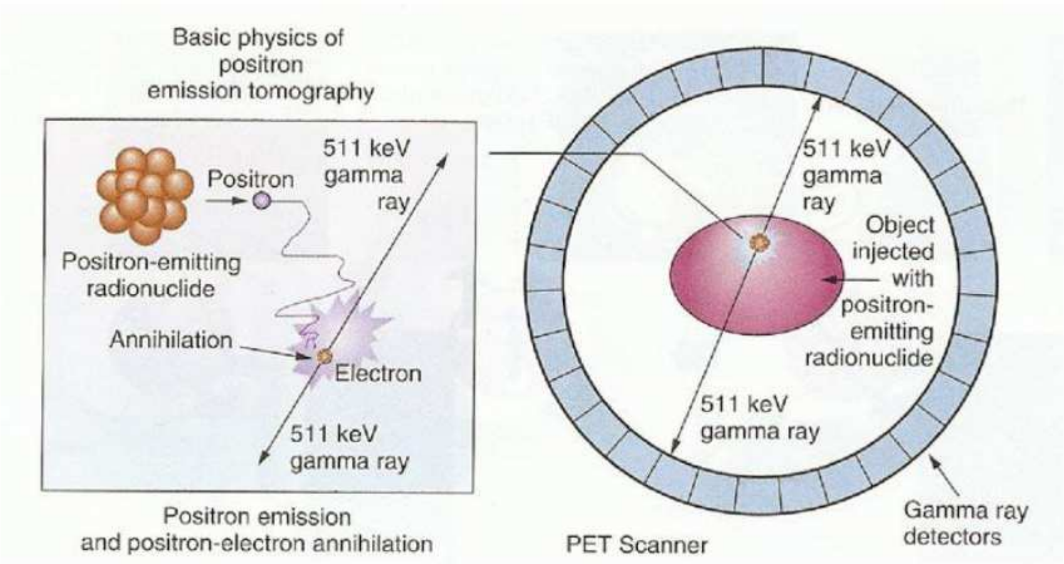
- Measure the RMS of the time difference between two pulses sent to SAMPIC vs delay using a pulse generator
- Flat resolution of ∼5 ps vs delay: time resolution per channel of ∼3 ps

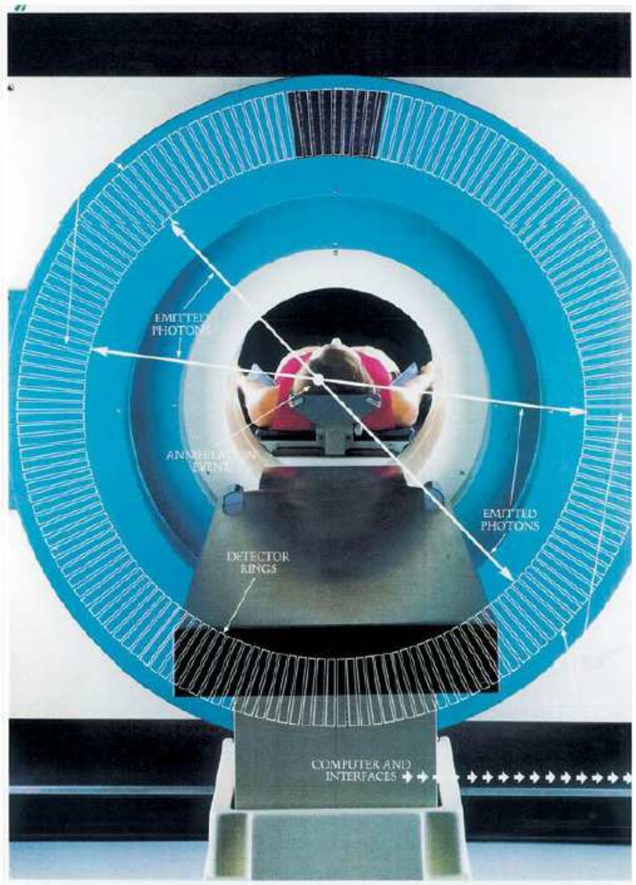
Time resolution using Si detectors

- Time resolution using fast Si detectors (3×3 mm^2): measure the time difference between one channel and a time reference (beam tests at Fermilab with protons at 120 GeV
- Time resolution: (dominated by detector): $\sim$ 40 ps (SAMPIC and amplifier alone give $\sim$3 ps)

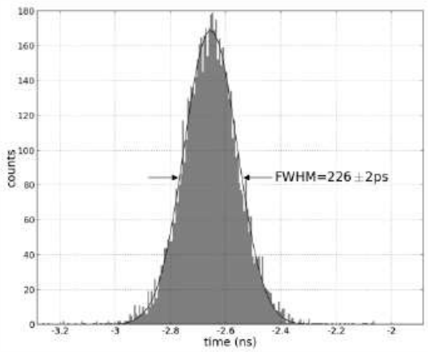


The future: Application: Timing measurements in Positron Emission Tomography





Coincidence Resolving Time:



- The holy grail: 10 picosecond PET (3 mm resolution)
- What seemed to be a dream a few years ago seems now to be closer to reality: Project that could benefit from the synergy between the different disciplines at the University of Kansas (physics, medicine, engineering, computing)
- Other possible application in drone technology: fast decision taking and distance measurement using laser

Conclusion

- Better constraints on gluon distribution in Pomeron, sensitivity to differences in quark distributions
- Jet gap jet events in diffraction: sensitivity to BFKL resummation effects, $\sim$15-20% of DPE jets are jet gap jet events!
- $\gamma\gamma\gamma\gamma$, $\gamma\gamma ZZ$, $\gamma\gamma WW$, $\gamma\gamma\gamma Z$ anomalous coupling studies
  - Exclusive process: **photon-induced processes** $pp \to p\gamma\gamma p$ (gluon exchanges suppressed at high masses):
  - Theoretical calculation in better control (QED processes with intact protons), not sensitive to the photon structure function
  - **"Background-free" experiment** and any observed event is signal
  - NB: Survival probablity in better control than in the QCD (gluon) case
- CT-PPS/AFP allows to probe BSM diphoton production in a model independent way: sensitivities to values predicted by extradim or composite Higgs models
- Search for invisible objects