

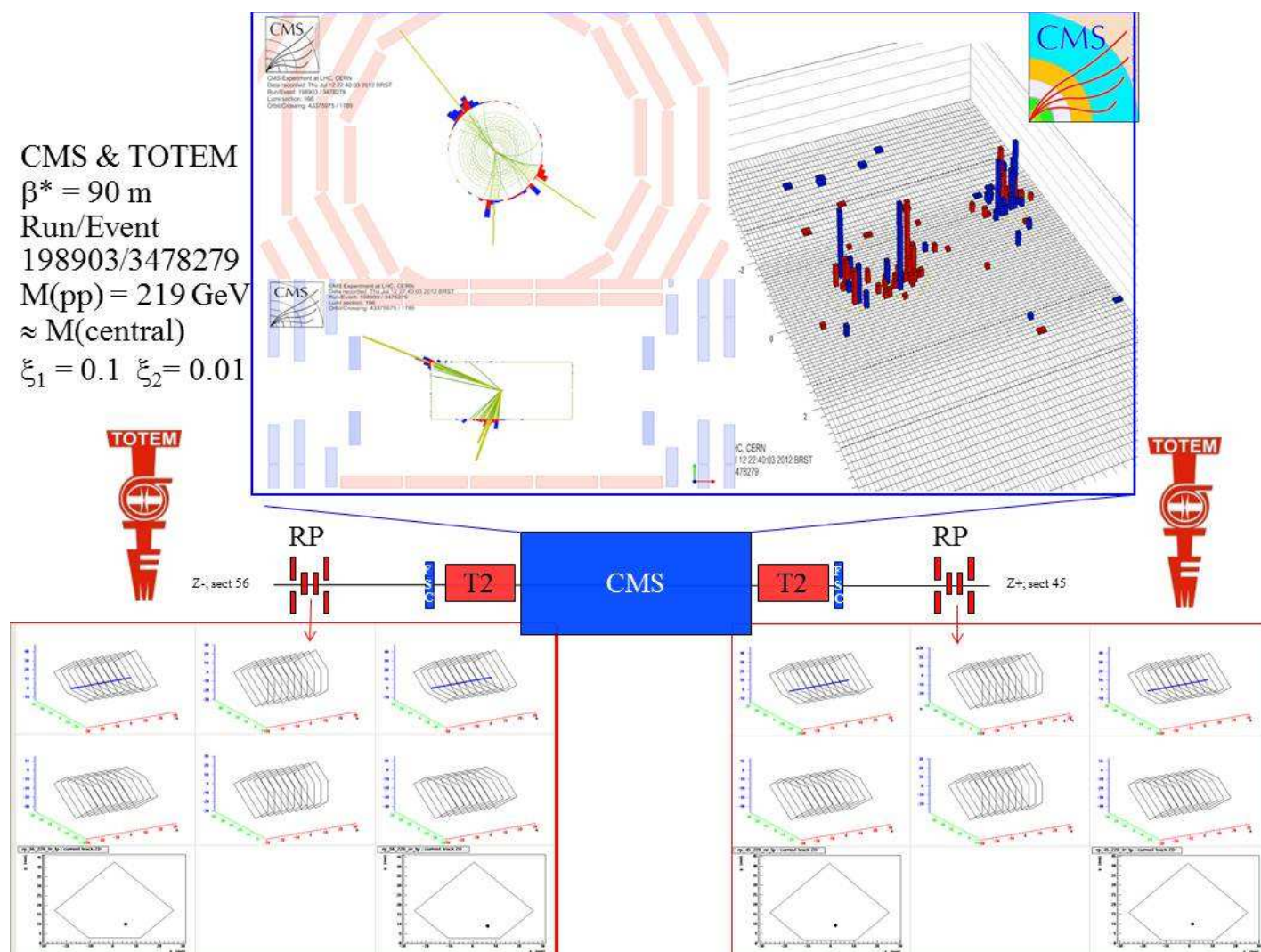
Forward physics with proton tagging at the LHC

Christophe Royon

Institute of Physics, Prague, Czech Republic
Nuclear Physics Institute, Cracow, Poland and CERN

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CMS & TOTEM
 $\beta^* = 90$ m
Run/Event
198903/3478279
 $M(pp) = 219$ GeV
 $\approx M(\text{central})$
 $\xi_1 = 0.1 \quad \xi_2 = 0.01$

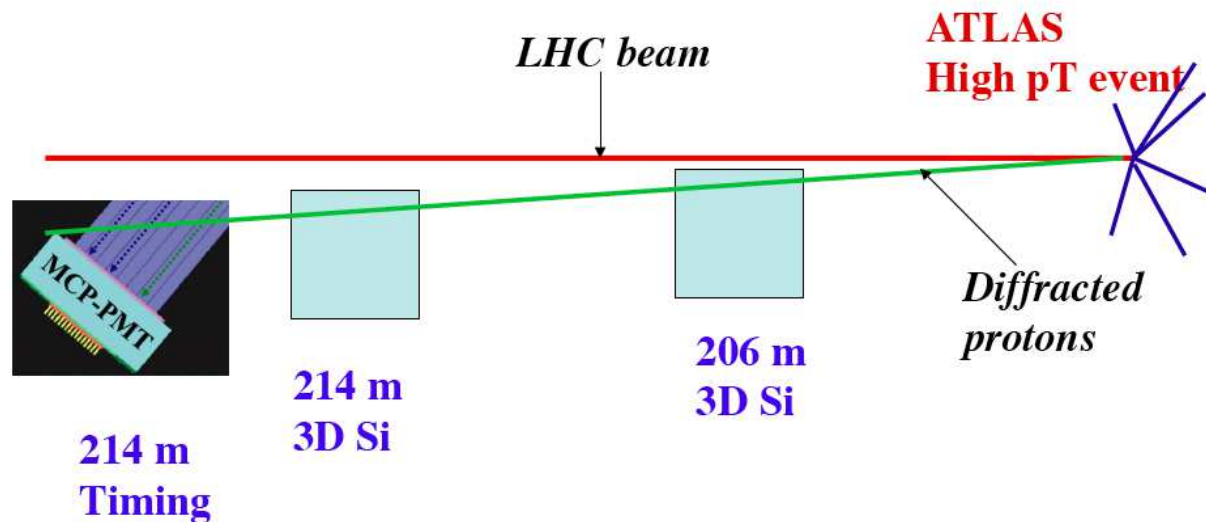


LHC: Exploration of a New Energy Frontier



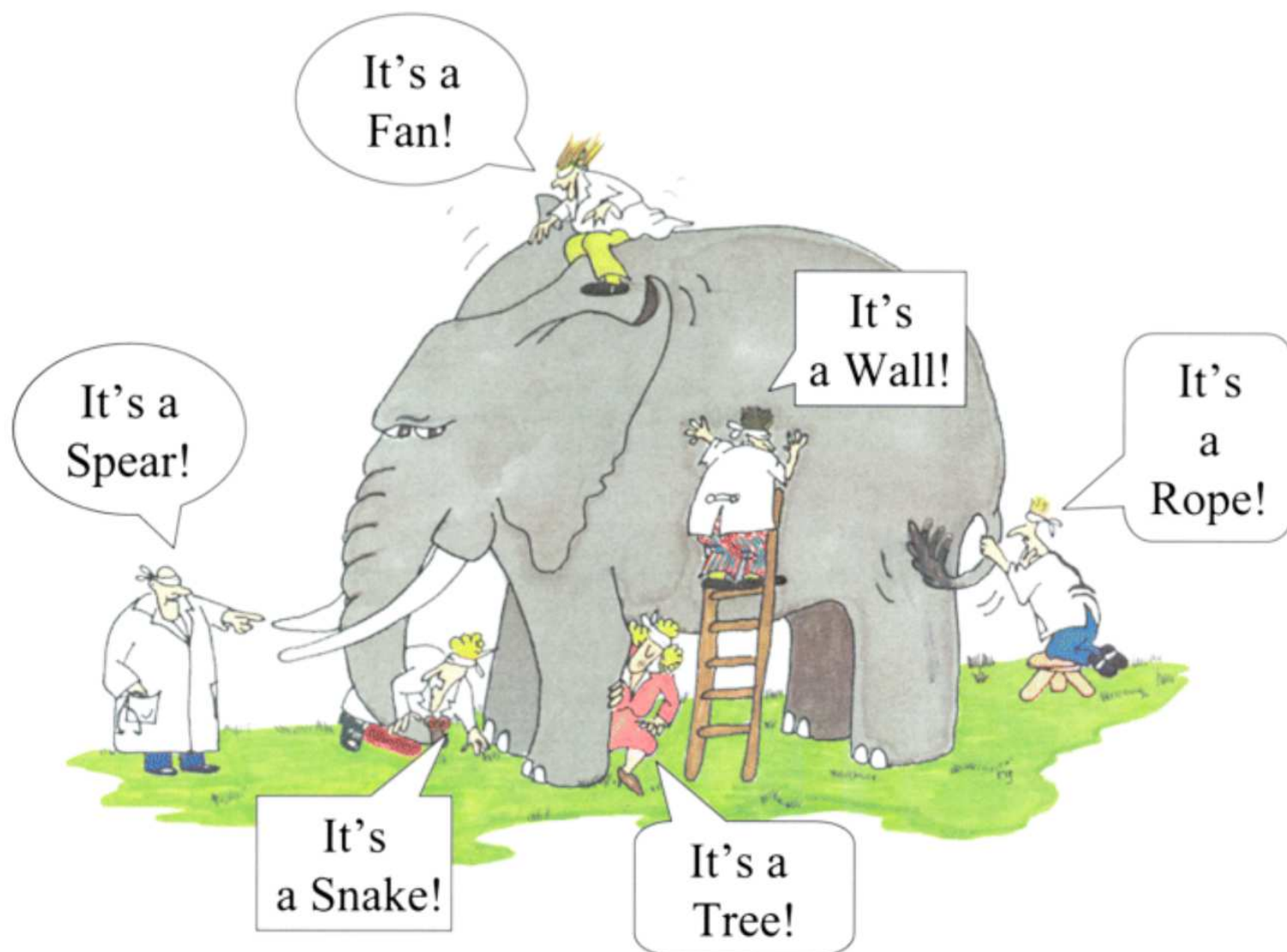
- **LHC** 13 TeV center-of-mass energy for 2015 (2011: 7 TeV, 2012: 8 TeV) (6.5 times more than the previous highest energy machine, the Tevatron, at Fermilab, Batavia, Illinois, USA)
- **LHC schedule**: data accumulated until 02/2013, shutdown until beginning of 2015, data for physics restarted in Spring 2015
- **LHC can accelerate protons and heavy ions**
- **Concentrate on Forward Physics**

Outline



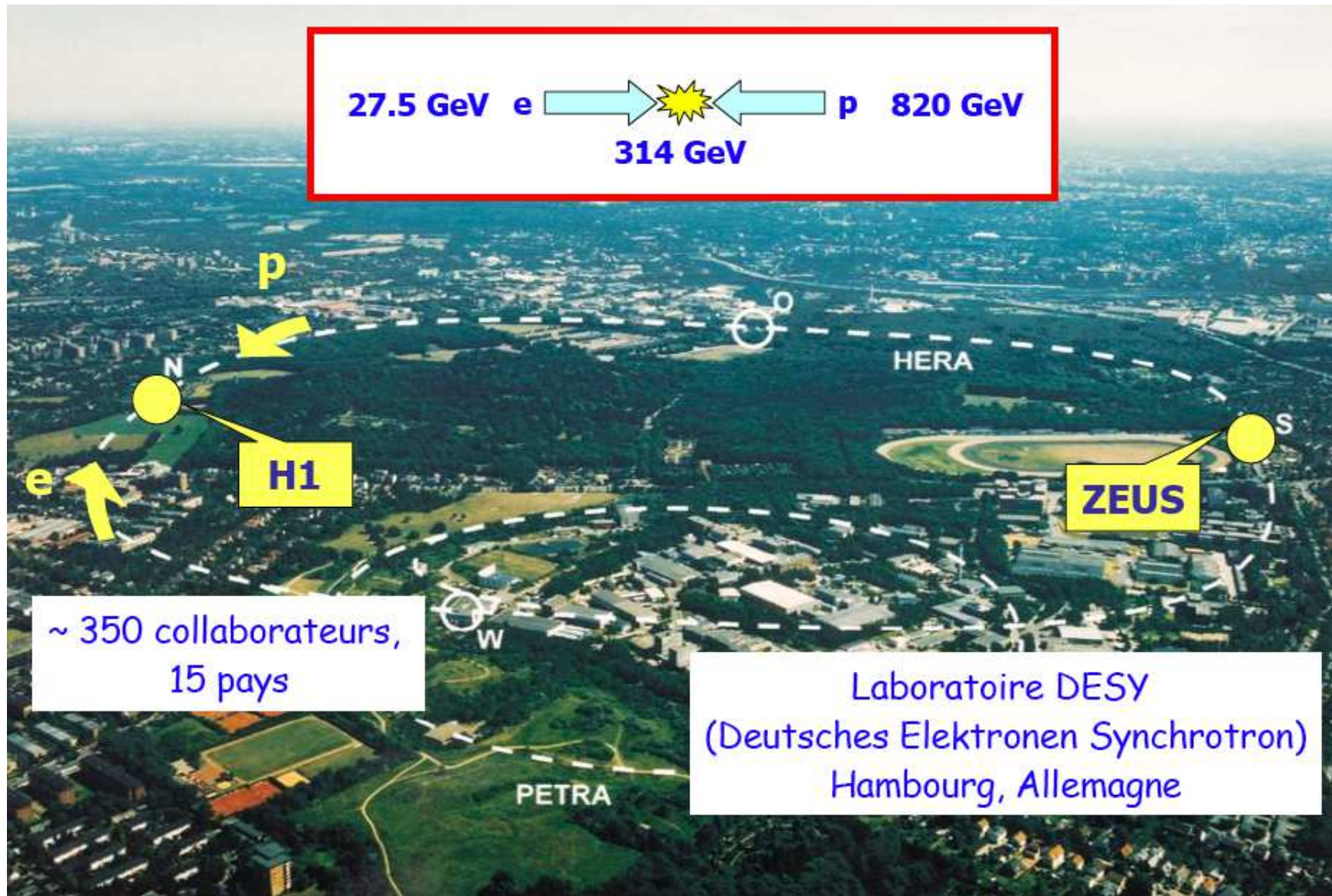
- Introduction: diffraction at HERA
- Hard diffraction and the Pomeron structure
- Exclusive diffraction: LHCb, ATLAS, CMS-TOTEM
- Photon exchanges processes and beyond standard model physics
- Detectors at LHC: AFP and CT-PPS projects in ATLAS/CMS-TOTEM
- Fast timing detectors: SAMPIC chip (Orsay/Saclay), Si, QUARTIC, Diamonds, GASTOF...

INTRODUCTION: DIFFRACTION AT HERA

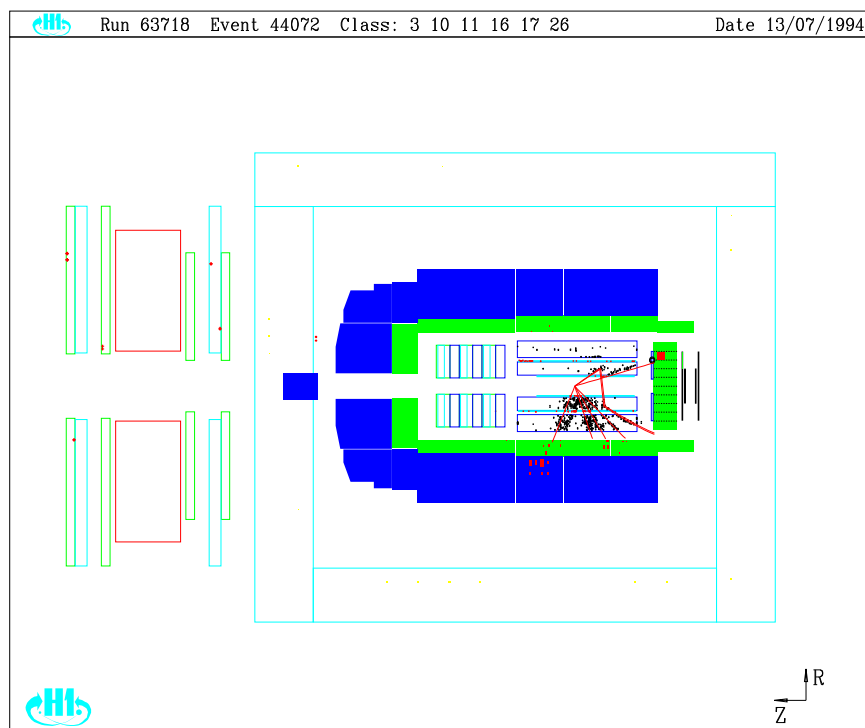
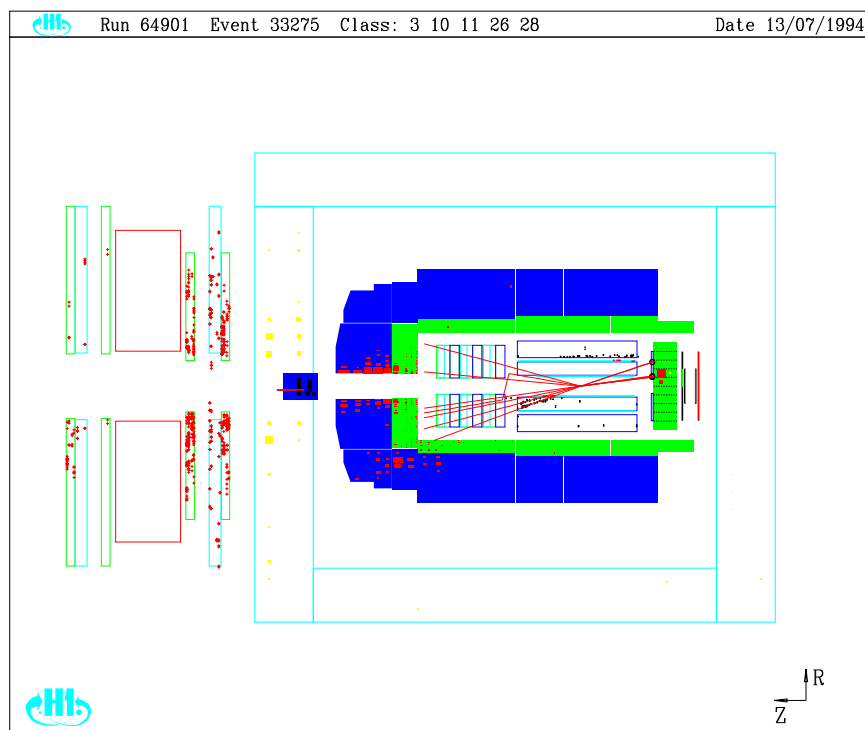


Definition of diffraction: example of HERA

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

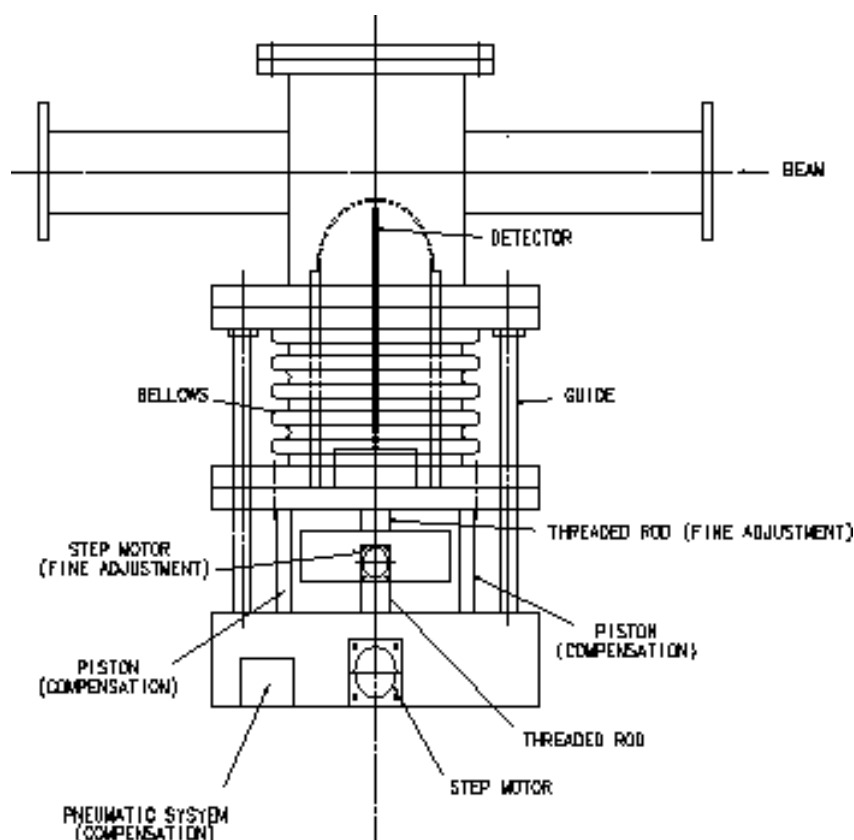


DIS and Diffractive event at HERA

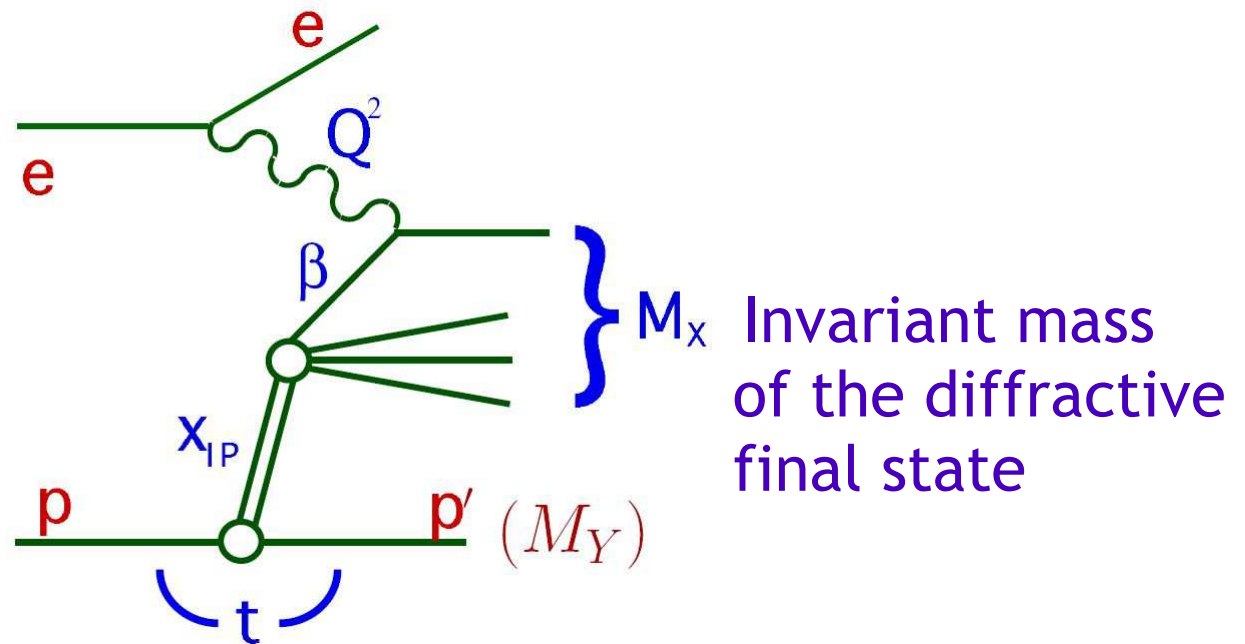


Definition of diffraction: example of HERA

- **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

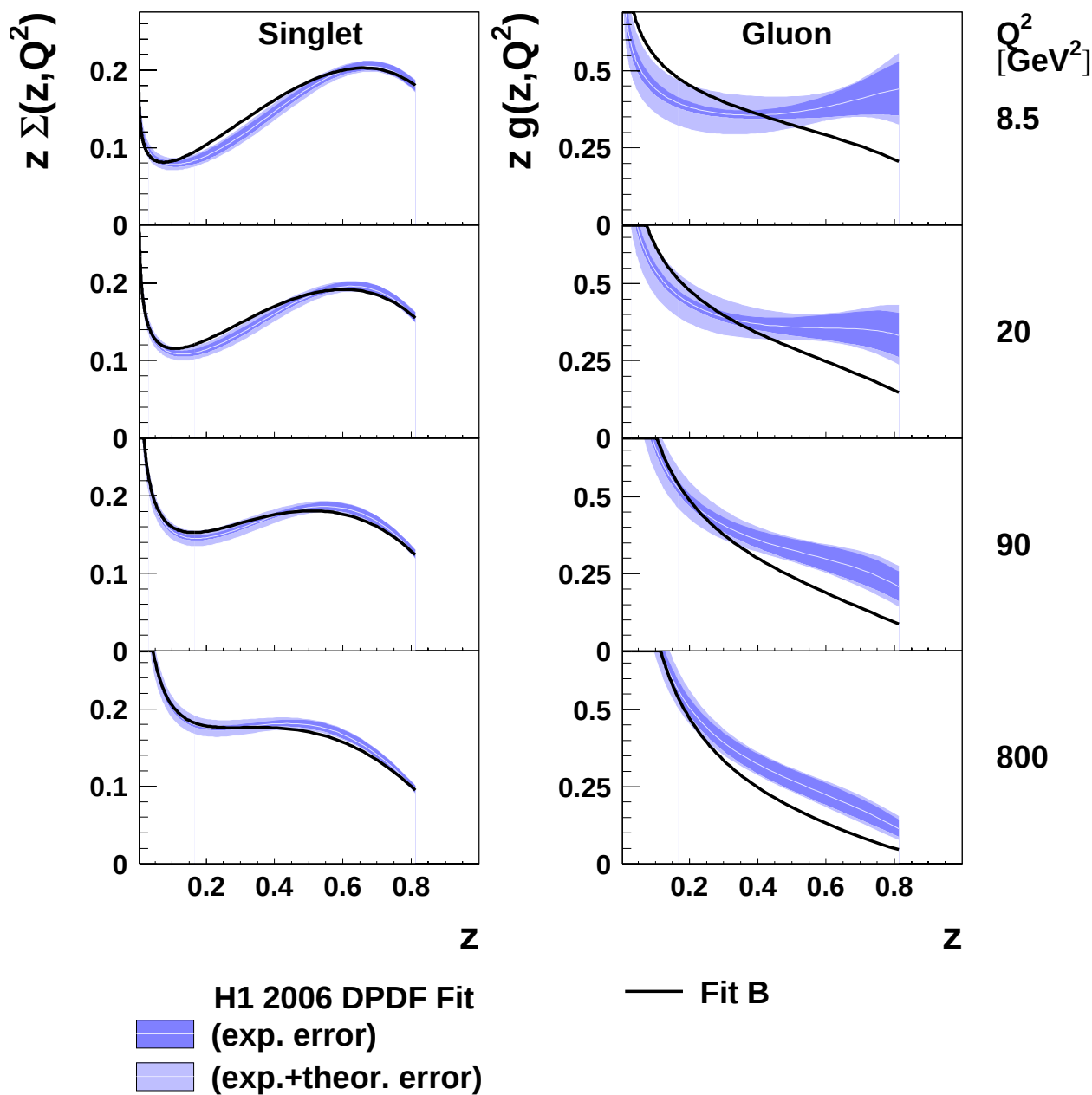


- Momentum fraction of the proton carried by the colourless object (pomeron): $x_p = \xi = \frac{Q^2 + M_X^2}{Q^2 + W^2}$
- Momentum fraction of the pomeron carried by the interacting parton if we assume the colourless object to be made of quarks and gluons:

$$\beta = \frac{Q^2}{Q^2 + M_X^2} = \frac{x_{Bj}}{x_P}$$
- 4-momentum squared transferred: $t = (p - p')^2$

Parton densities in the pomeron (H1)

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

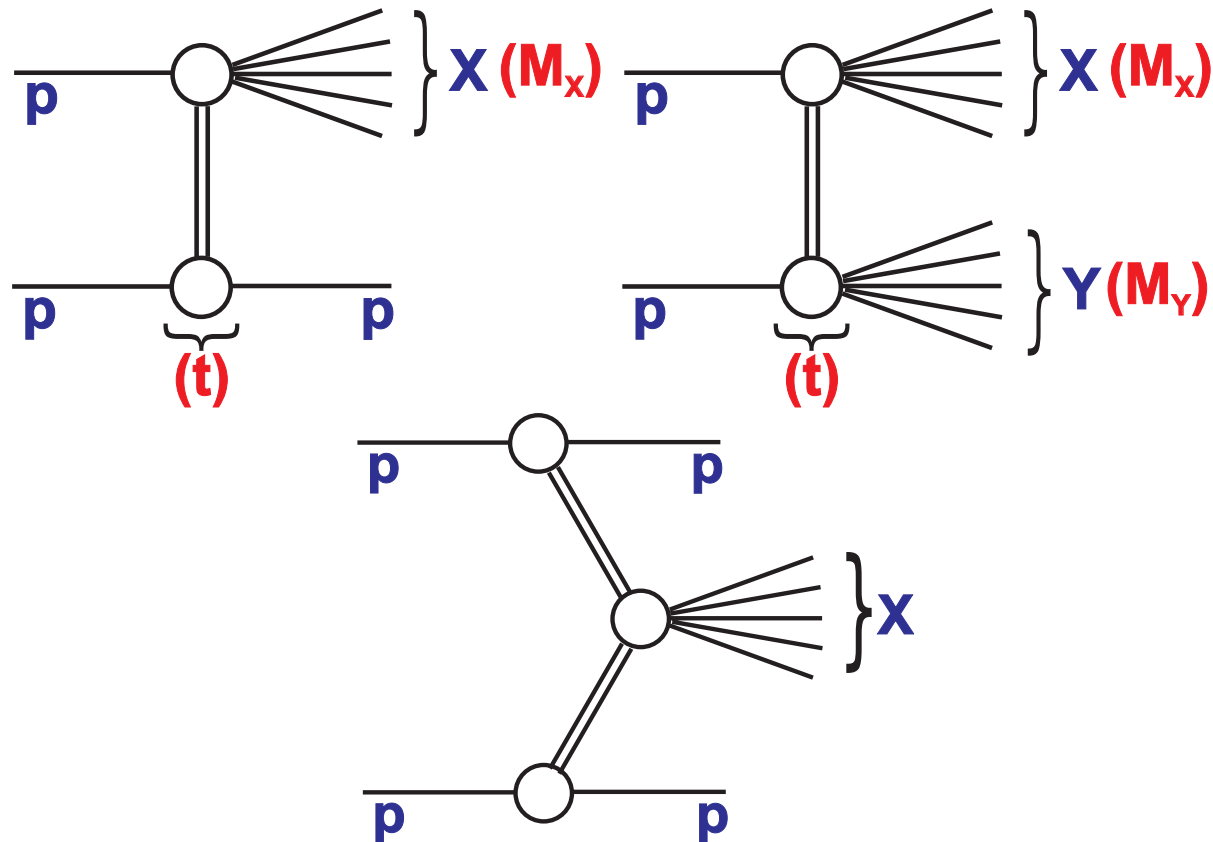


HARD DIFFRACTION : FROM HERA TO LHC (SD, DPE...)



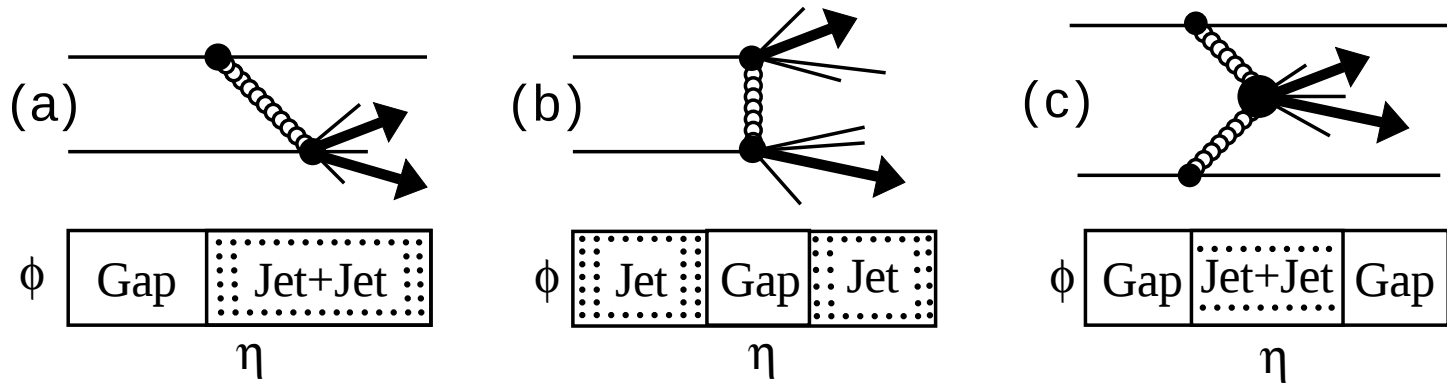
Diffractive components at the LHC

- Different components: non diffractive (not shown; due to gap size fluctuation in hadronic final states), single diffractive, double diffractive, central diffraction (double Pomeron exchange)



- Measurement of the rapidity gap cross section allows to tune MC predictions

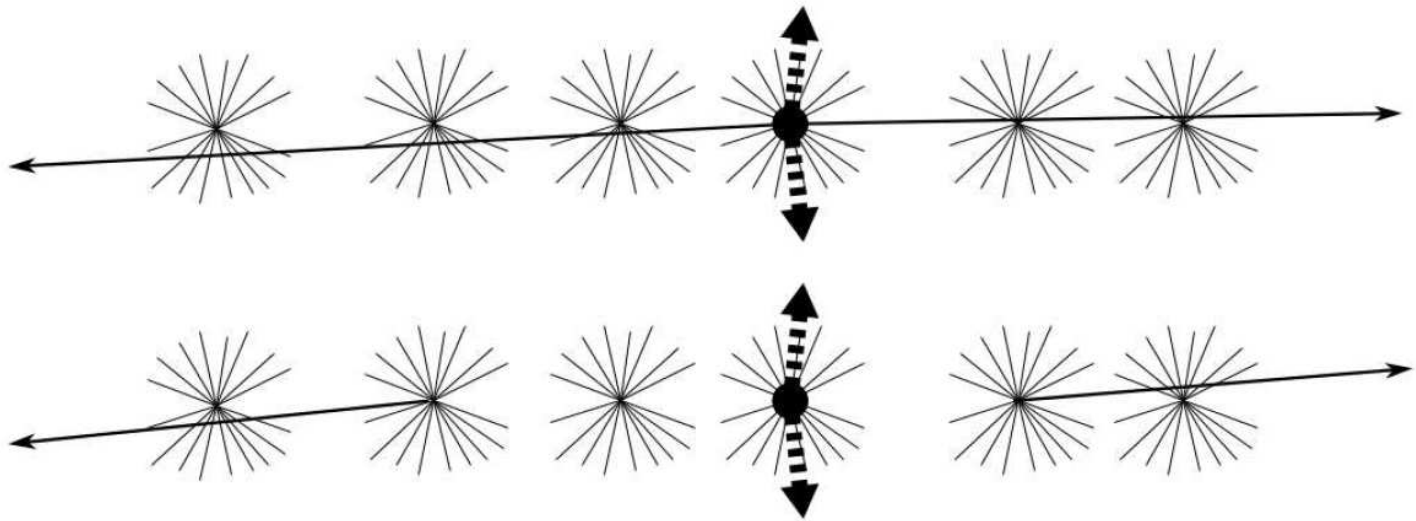
Diffraction at Tevatron/LHC



Kinematic variables

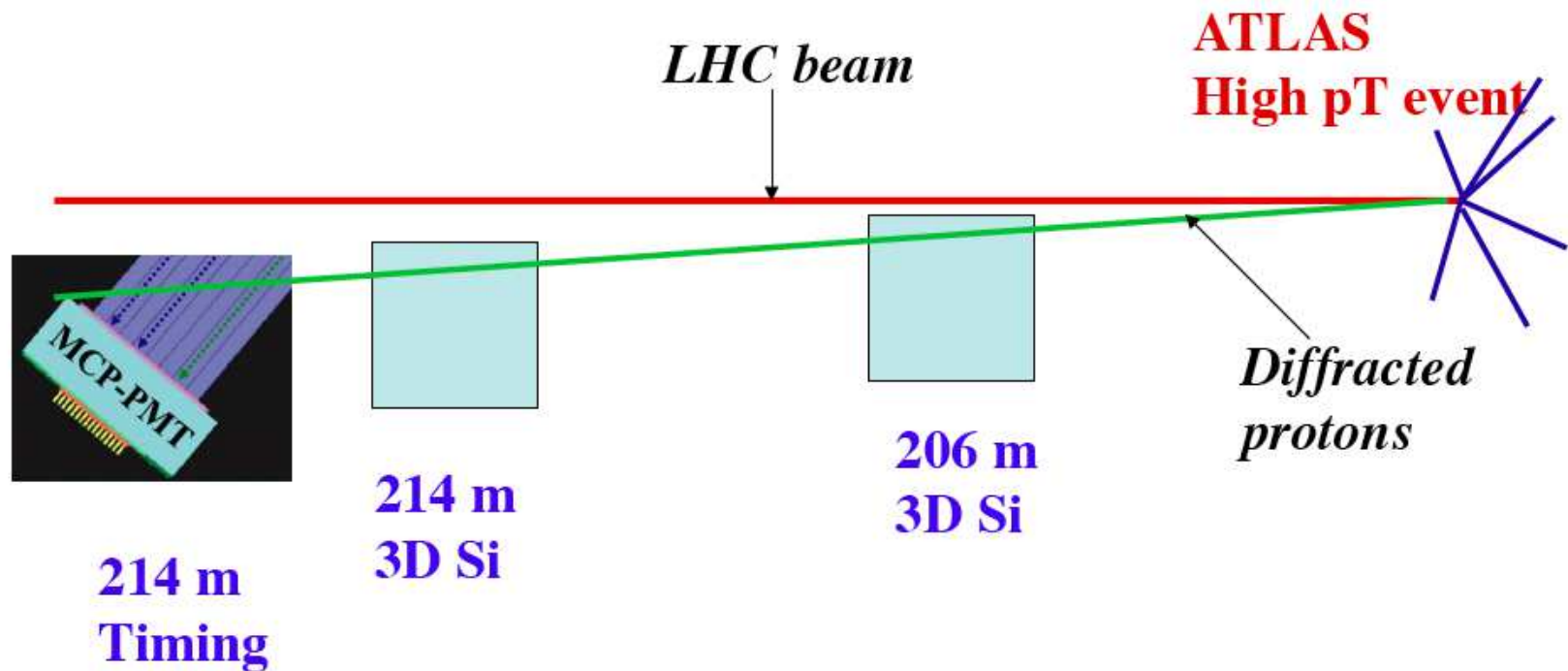
- t : 4-momentum transfer squared
- ξ_1, ξ_2 : proton fractional momentum loss (momentum fraction of the proton carried by the pomeron)
- $\beta_{1,2} = x_{Bj,1,2}/\xi_{1,2}$: Bjorken- x of parton inside the pomeron
- $M^2 = s\xi_1\xi_2$: diffractive mass produced
- $\Delta y_{1,2} \sim \Delta\eta \sim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

One parenthesis: what is pile up at LHC?



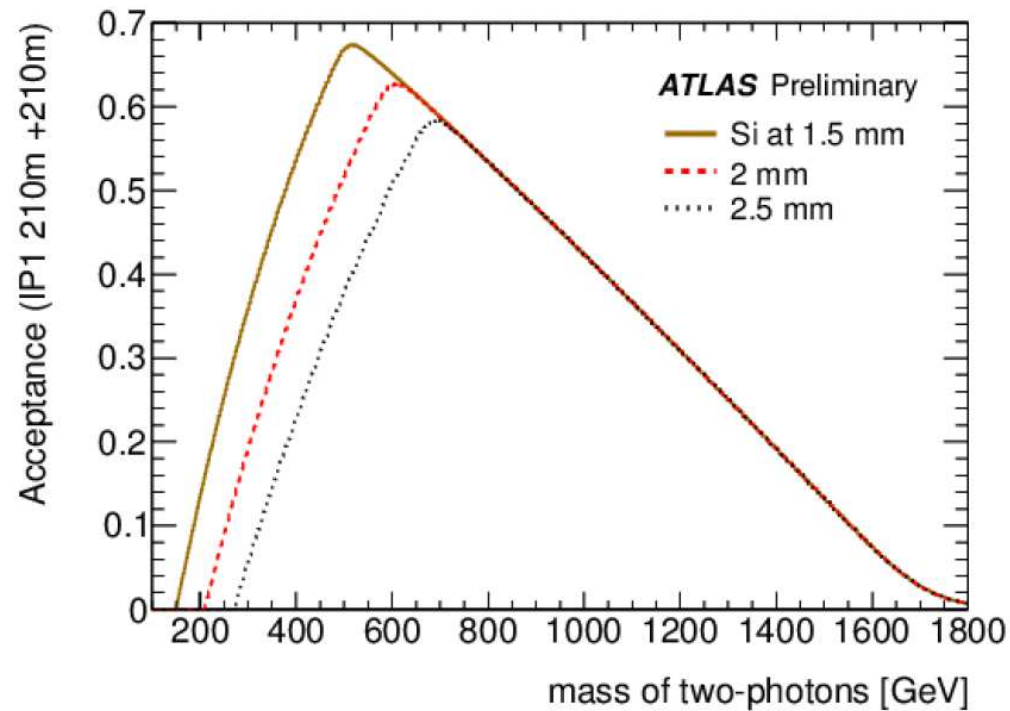
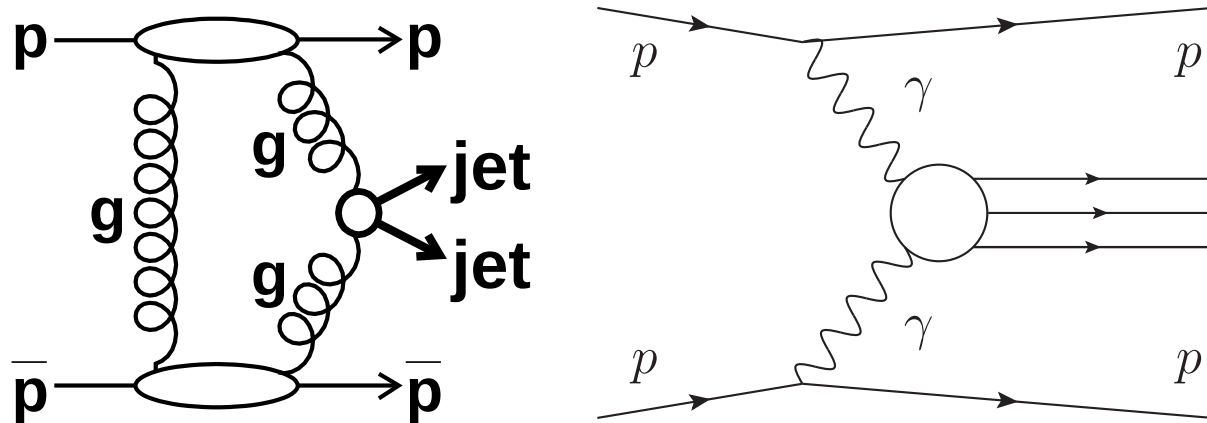
- High luminosity at the LHC to look for rare (non standard events): many protons in one bunch, many interactions within the same bunch crossing in ATLAS and CMS (LHCb is different)
- Hard interaction and pile up: one hard interaction (leading to a high p_T event with jets, W/Z , top...) and many additional soft events in the detectors
- Energy flow everywhere in the event due to pile up: rapidity gap measurement works only at very low pile up (“special runs”) at the LHC
- Intact protons can originate from hard events (hard diffractive production of jets for instance with intact protons) or also from additional soft interaction
- Typically 20-25 pile up events per interaction at 8 TeV, between 25 and 50 next year at 13 TeV, and 200 for the high luminosity LHC

What is AFP/CT-PPS?



- Tag and measure protons at ± 210 m: AFP (ATLAS Forward Physics) in ATLAS, CT-PPS (CMS TOTEM - Precision Proton Spectrometer) in CMS/Totem
- **AFP detectors:** measure proton position (Silicon detectors) and time-of-flight (timing detectors)

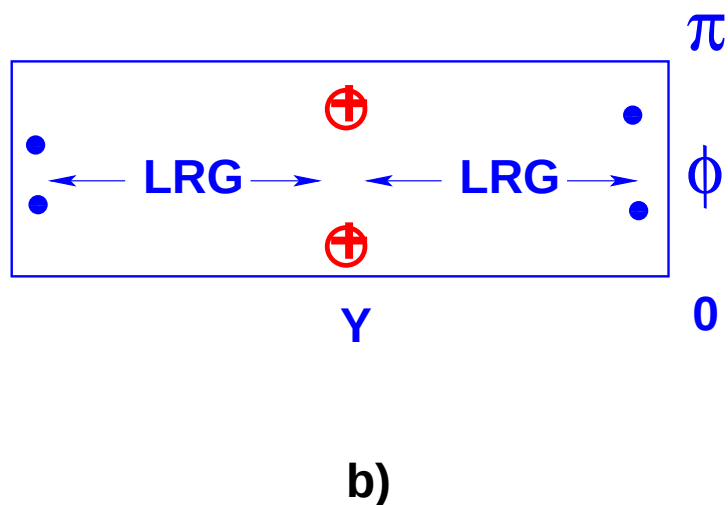
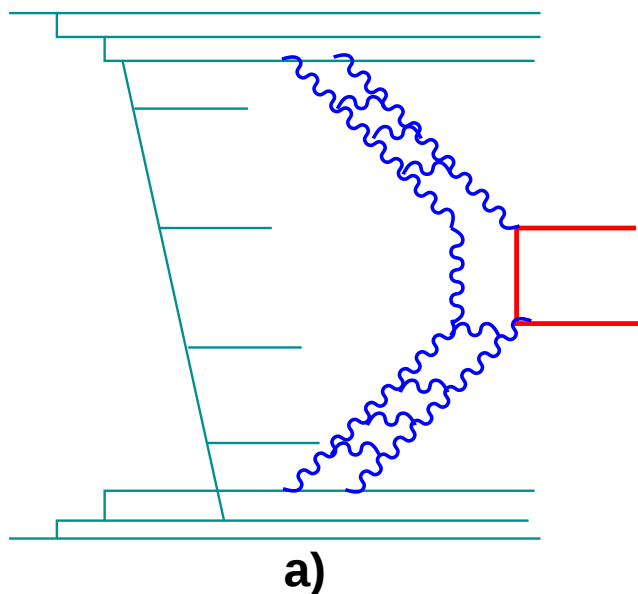
AFP/CT-PPS acceptance in total mass



- Protons are tagged at 210 m
- Sensitivity to high mass central system, X, as determined using AFP
- Very powerful for exclusive states: kinematical constraints coming from AFP proton measurements

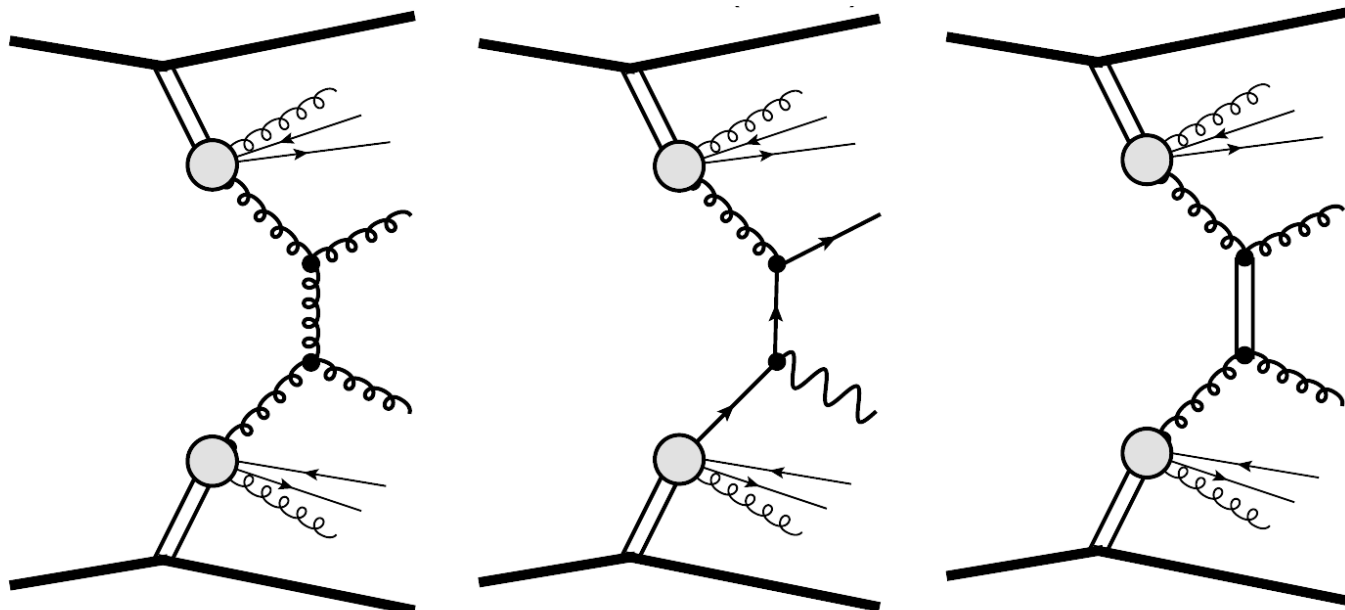
Another difficulty to go from HERA to Tevatron: survival probability

- 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)



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

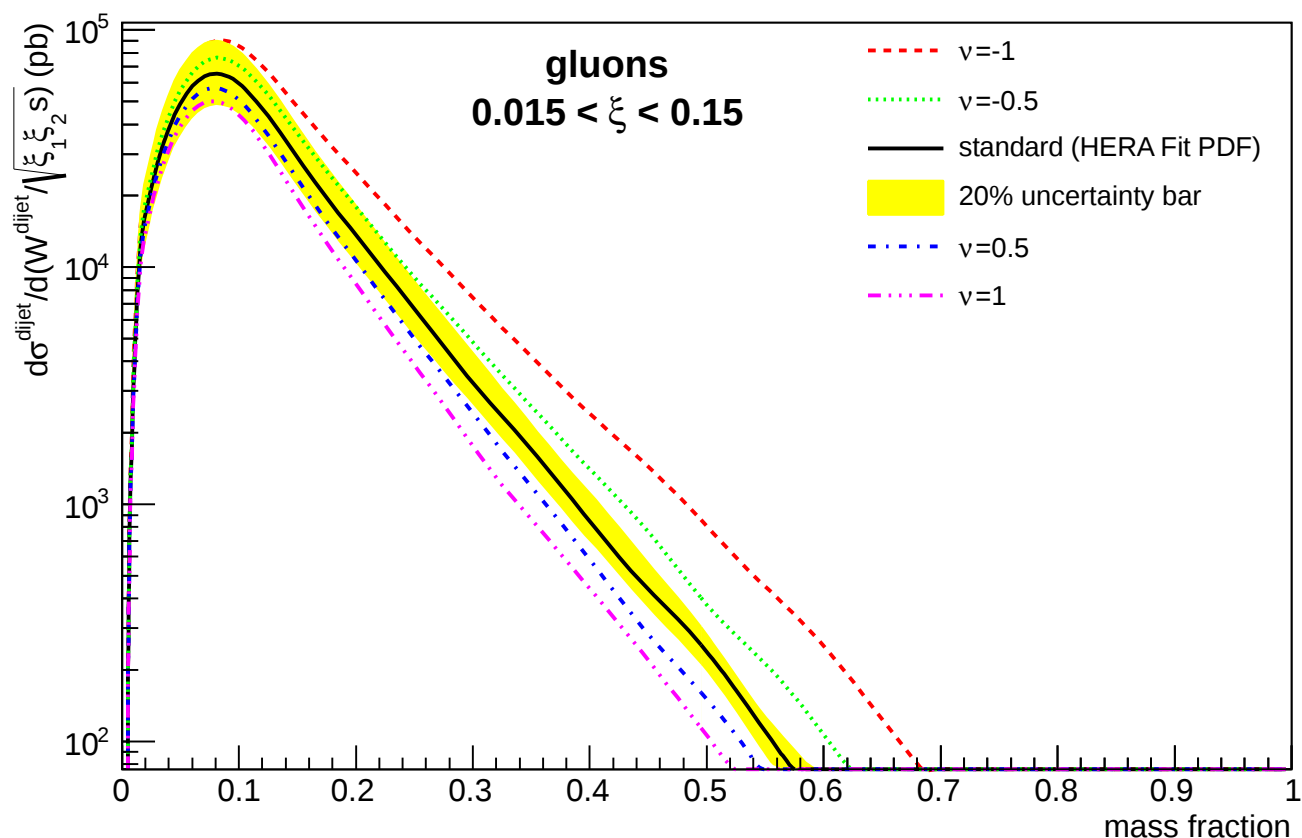


Forward Physics Monte Carlo (FPMC)

- 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

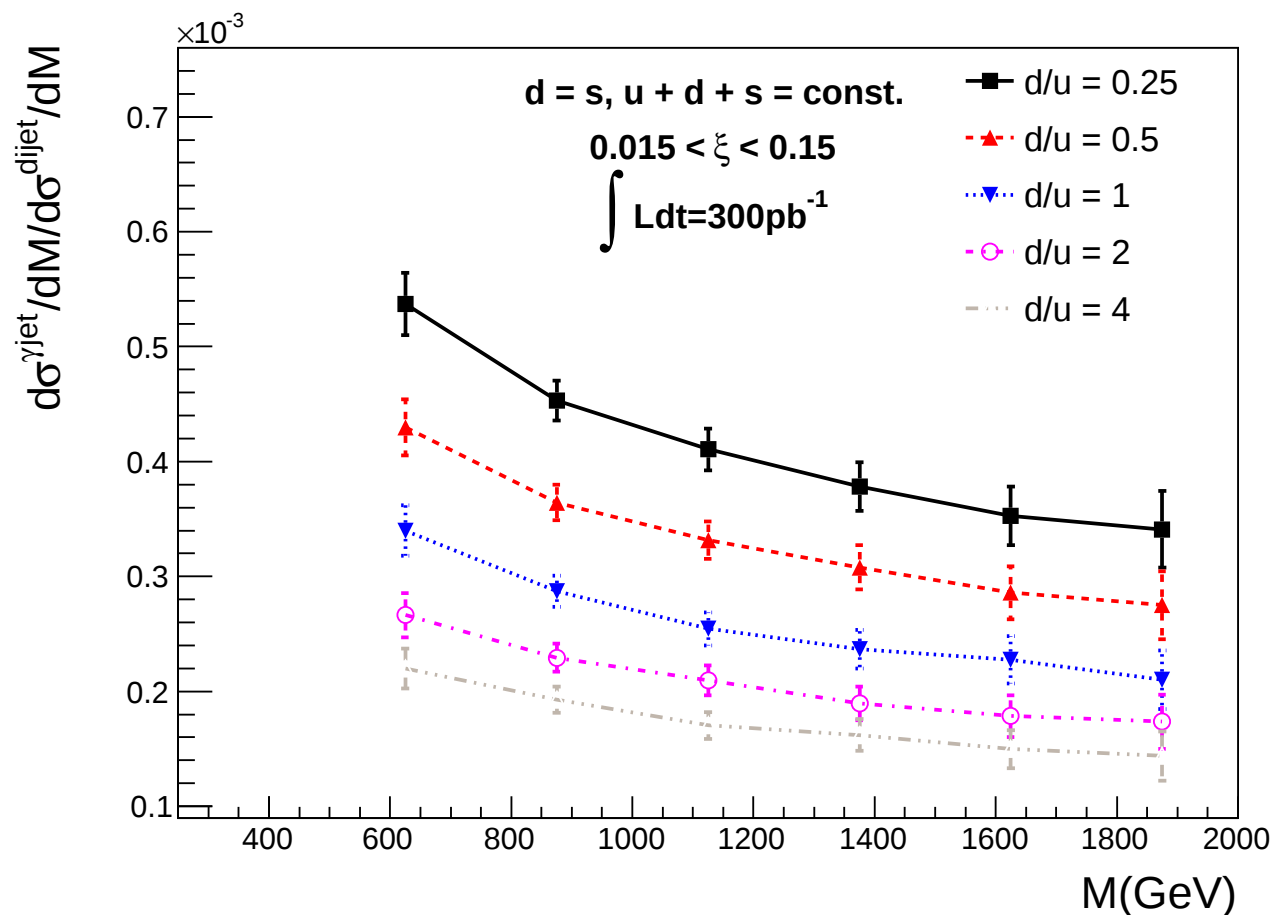
Inclusive diffraction at the LHC: sensitivity to gluon density

- 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 $\nu = -1, \dots, 1$
- 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 ($\sqrt{\xi_1 \xi_2 S}$)



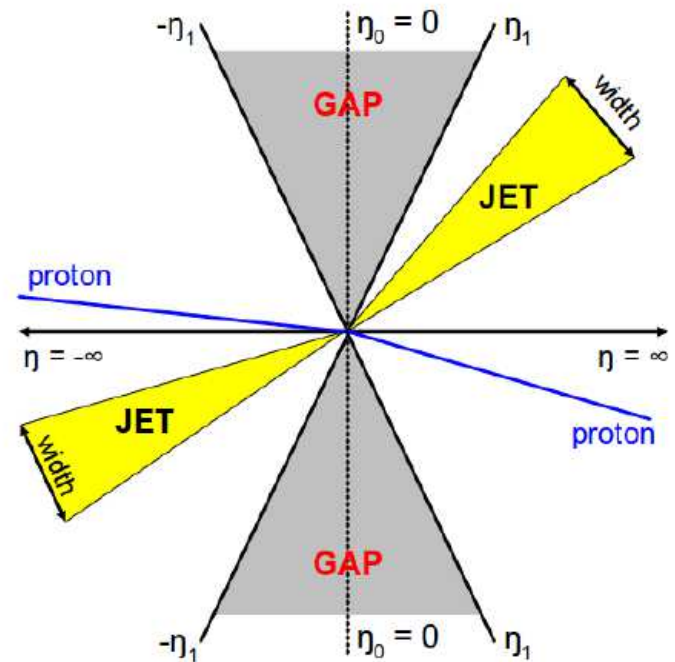
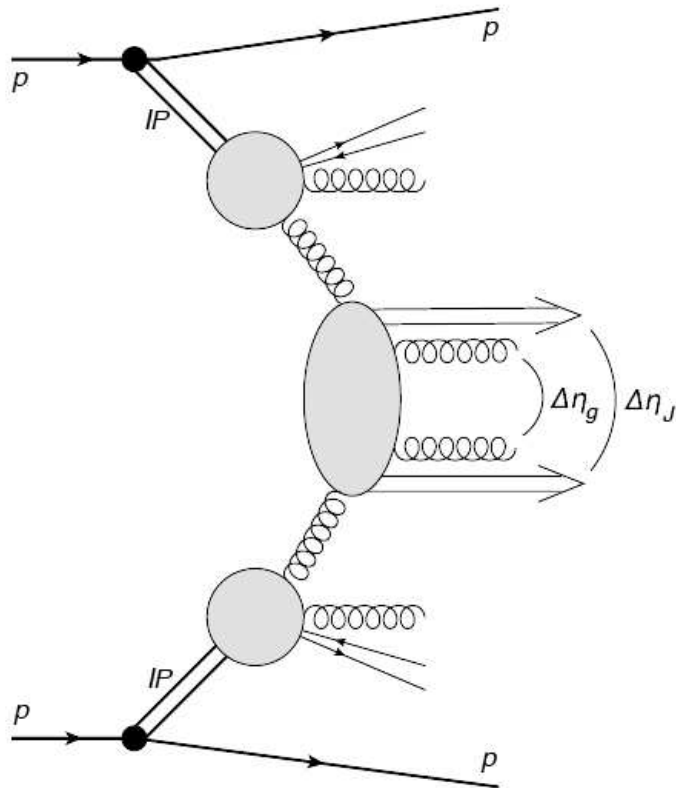
Inclusive diffraction at the LHC: sensitivity to quark densities

- 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
- Possibility to use the W charge asymmetry to be sensitive on quark densities (A. Chuinard, C. Royon, R. Staszewski, work in progress)



Jet gap jet events in diffraction

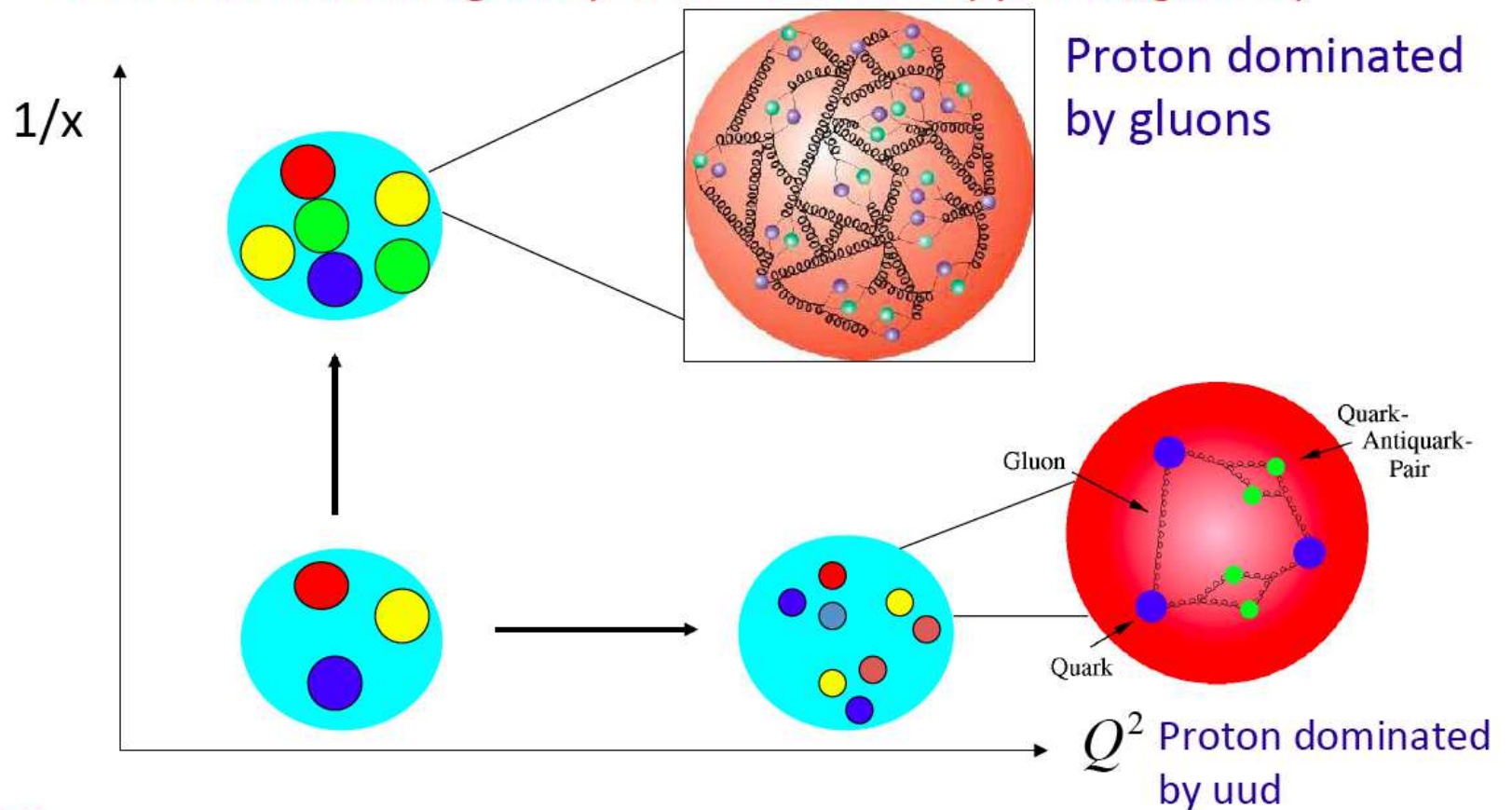
- Study BFKL dynamics using jet gap jet events
- Jet gap jet events in DPE processes: clean process, allows to go to larger $\Delta\eta$ between jets
- See: Gaps between jets in double-Pomeron-exchange processes at the LHC, C. Marquet, C. Royon, M. Trzebinski, R. Zlebcik, Phys. Rev. D 87 (2013) 034010



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)

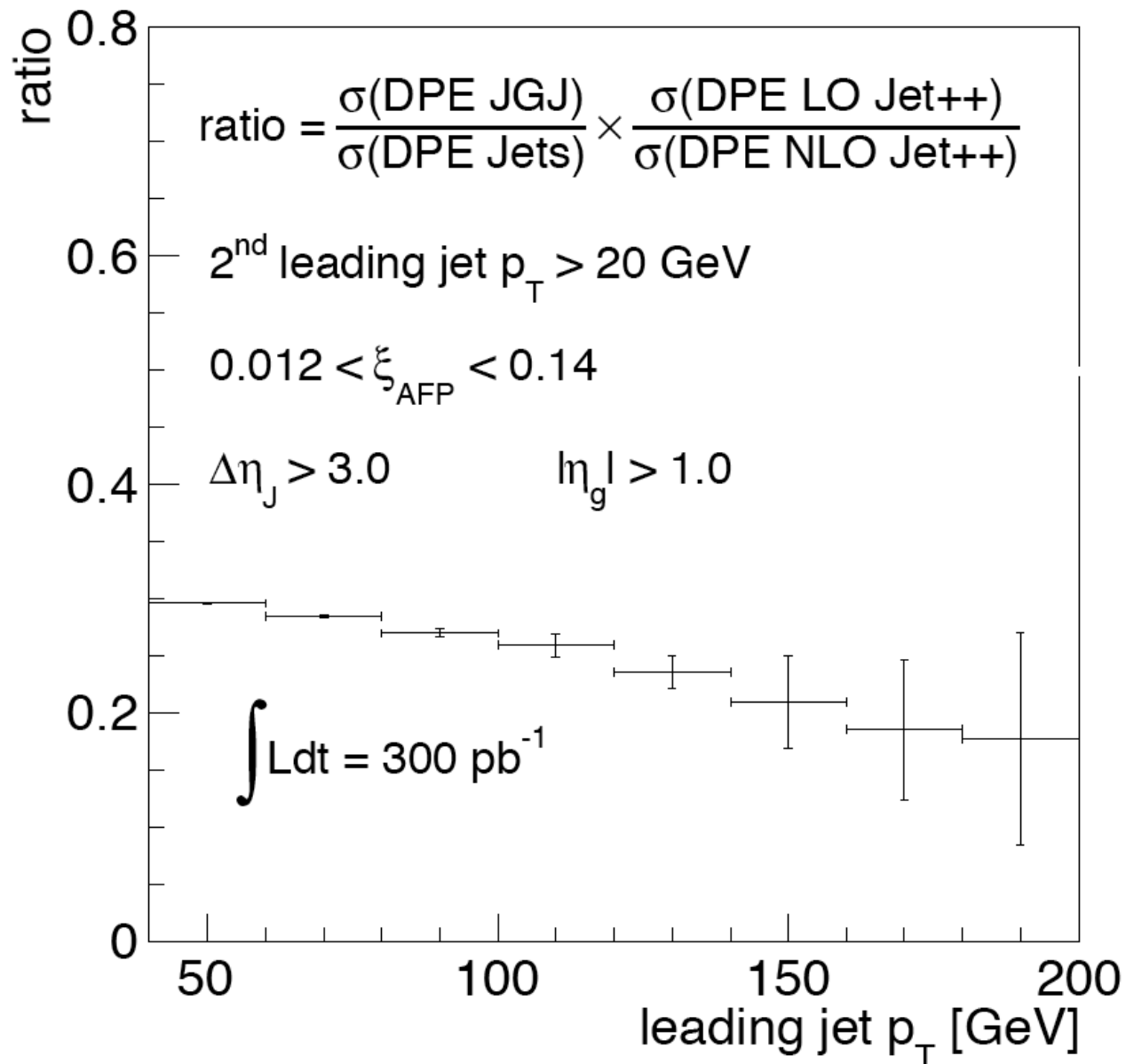


Q^2 : resolution inside the proton (like a microscope)

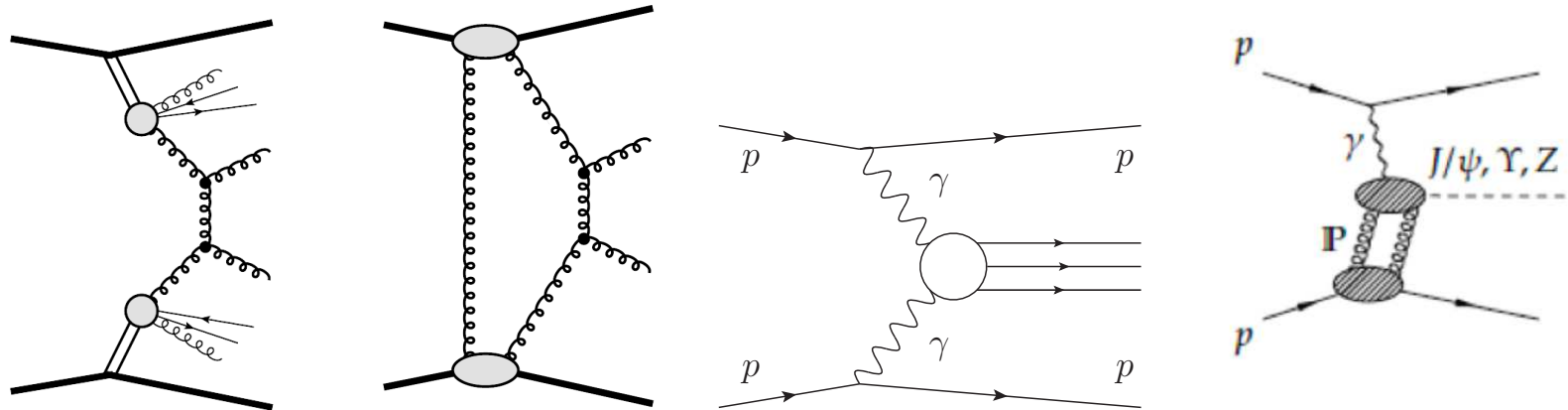
x : Proton momentum fraction carried away by the interacting quark

Jet gap jet events in diffraction

- Measure the ratio of the jet gap jet to the dijet cross sections: sensitivity to BFKL dynamics
- As an example, study as a function of leading jet p_T



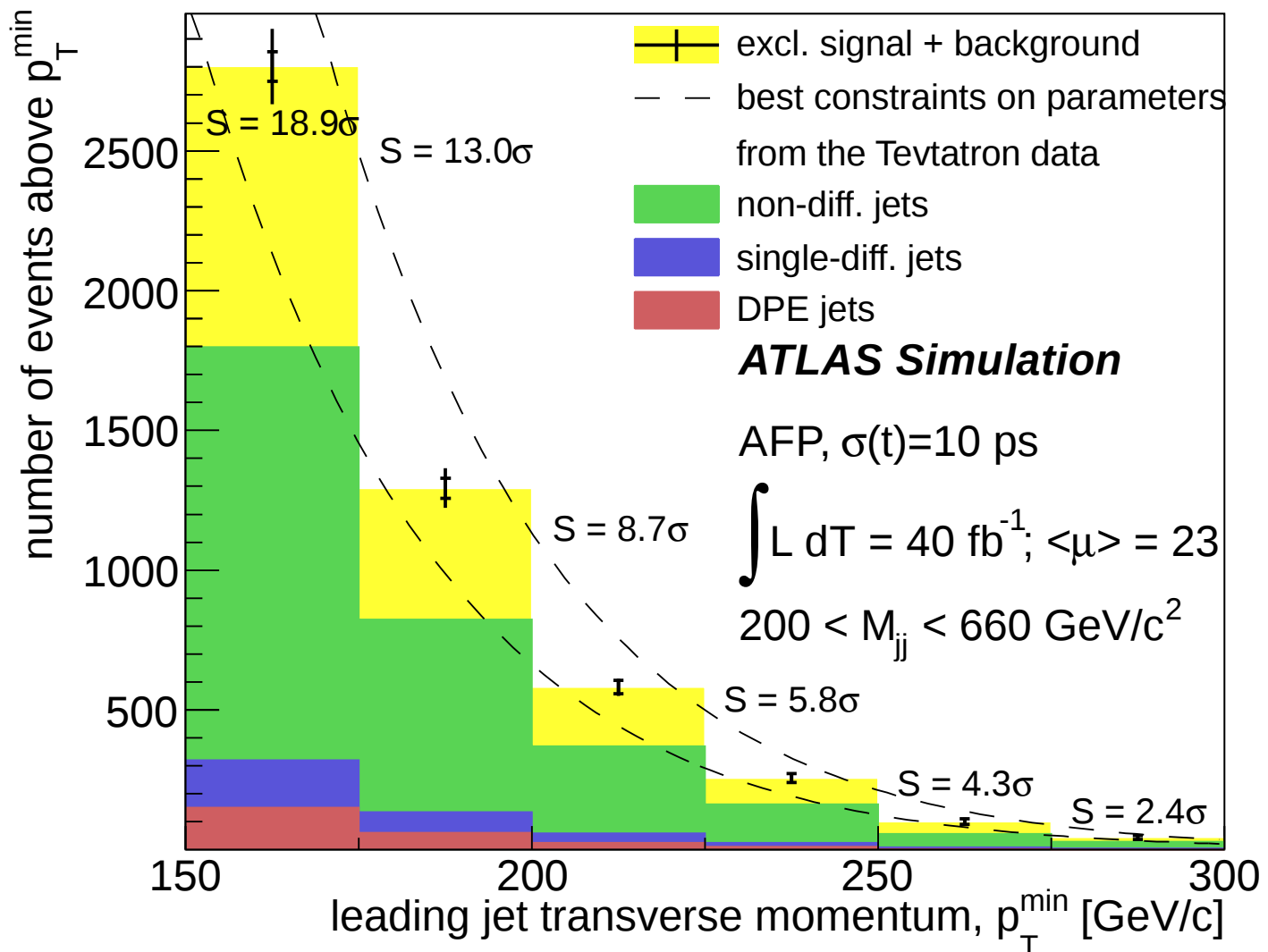
Exclusive diffraction



- Many exclusive channels can be studied at medium and high luminosity: 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: system completely constrained
- Possibility of constraining the background by asking the matching between the information of the two protons and the produced object
- Check the $f_0(1500)$ or $f_0(1710)$ glueball candidates (in excess of the meson SU(3) multiplet and resonances compatible with glueball in terms of mass, spin, parity, decay channels)
- Lattice calculations predict a 0^{++} glueball at 1.7 GeV with a ~ 100 MeV uncertainty, favoring the $f_0(1710)$ candidate
- Central exclusive production is a potential channel for BSM physics: sensitivity to high masses up to 1.8 TeV (masses above 400 GeV, depending how close one can go to the beam)

Exclusive jet production at the LHC

- Jet cross section measurements: up to 18.9σ for exclusive signal with 40 fb^{-1} ($\mu = 23$): highly significant measurement in high pile up environment, improvement over measurement coming from Tevatron (CDF) studies using $\bar{p}$ forward tagging by about one order of magnitude

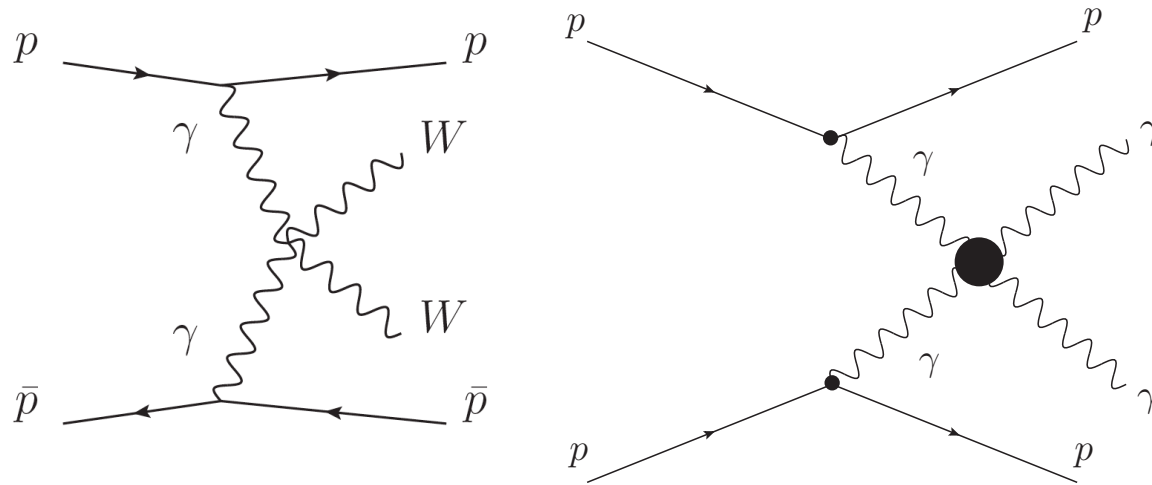


- Important to perform these measurements to constrain exclusive Higgs production: background/signal ratio close to 1 for central values at 120 GeV

PHOTON EXCHANGE PROCESSES : EXPLORATORY PHYSICS



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



- Study of the process: $pp \rightarrow ppWW$, $pp \rightarrow ppZZ$, $pp \rightarrow pp\gamma\gamma$
- Standard Model: $\sigma_{WW} = 95.6 \text{ fb}$, $\sigma_{WW}(W = M_X > 1\text{TeV}) = 5.9 \text{ fb}$
- 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 E. Chapon, O. Kepka, C. Royon, Phys. Rev. D78 (2008) 073005; Phys. Rev. D81 (2010) 074003; S.Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert, Phys.Rev. D89 (2014) 114004 ; S.Fichet, G. von Gersdorff, B. Lenzi, C. Royon, M. Saimpert, ArXiv:1411.6629; J. de Favereau et al., arXiv:0908.2020.

Quartic anomalous gauge couplings

- Quartic gauge anomalous $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings parametrised by $a_0^W, a_0^Z, a_C^W, a_C^Z$

$$\begin{aligned}\mathcal{L}_6^0 &\sim \frac{-e^2}{8} \frac{a_0^W}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W_{\alpha}^{-} - \frac{e^2}{16 \cos^2(\theta_W)} \frac{a_0^Z}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} Z^{\alpha} Z_{\alpha} \\ \mathcal{L}_6^C &\sim \frac{-e^2}{16} \frac{a_C^W}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} (W^{+\alpha} W_{\beta}^{-} + W^{-\alpha} W_{\beta}^{+}) \\ &\quad - \frac{e^2}{16 \cos^2(\theta_W)} \frac{a_C^Z}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} Z^{\alpha} Z_{\beta}\end{aligned}$$

- Anomalous parameters equal to 0 for SM
- Best limits before LHC from LEP, OPAL (Phys. Rev. D 70 (2004) 032005) of the order of 0.02-0.04, for instance $-0.02 < a_0^W < 0.02 \text{ GeV}^{-2}$
- New limits from D0/CMS: $1.5 \cdot 10^{-4}$ ($2.5 \cdot 10^{-3}$), and $5 \cdot 10^{-4}$ ($9.3 \cdot 10^{-3}$) for CMS (D0) for a_0^W and a_c^W with a form factor at 500 GeV
- Dimension 6 operators $\rightarrow$ violation of unitarity at high energies

Quartic anomalous gauge couplings: form factors

- Unitarity bounds can be computed (Eboli, Gonzales-Garcia, Lietti, Novaes):

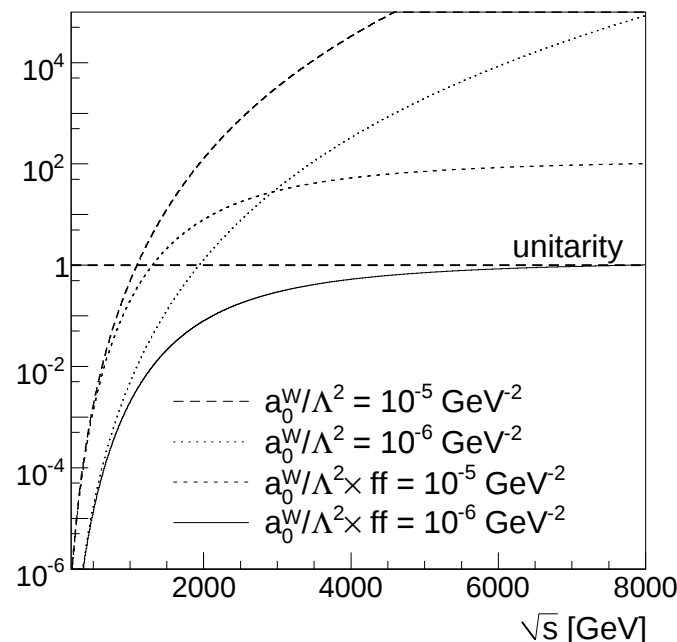
$$4 \left(\frac{\alpha a s}{16} \right)^2 \left(1 - \frac{4M_W^2}{s} \right)^{1/2} \left(3 - \frac{s}{M_W^2} + \frac{s^2}{4M_W^4} \right) \leq 1$$

where $a = a_0/\Lambda^2$

- Introducing form factors to avoid quadratical divergences of scattering amplitudes due to anomalous couplings in conventional way:

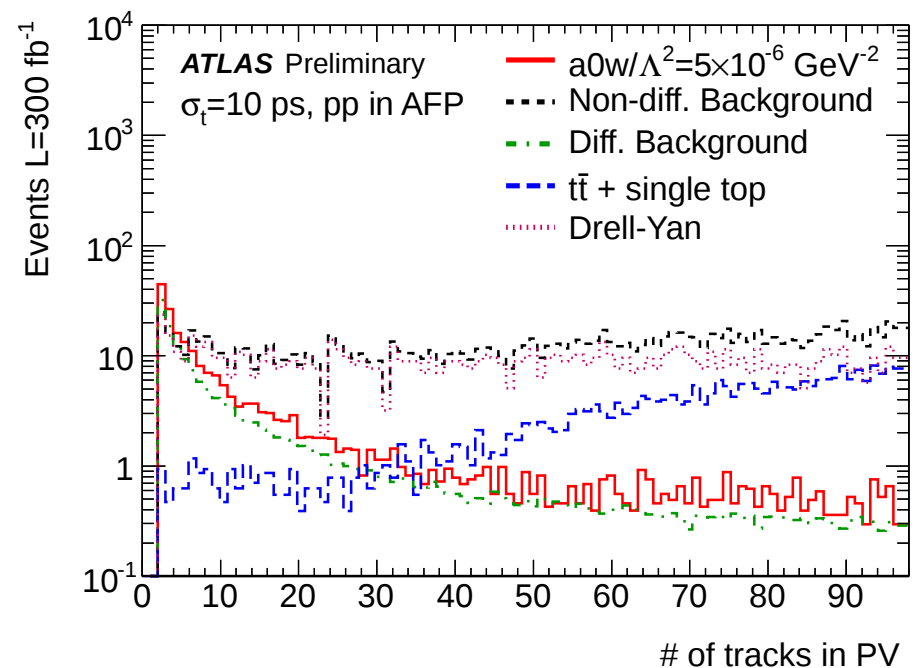
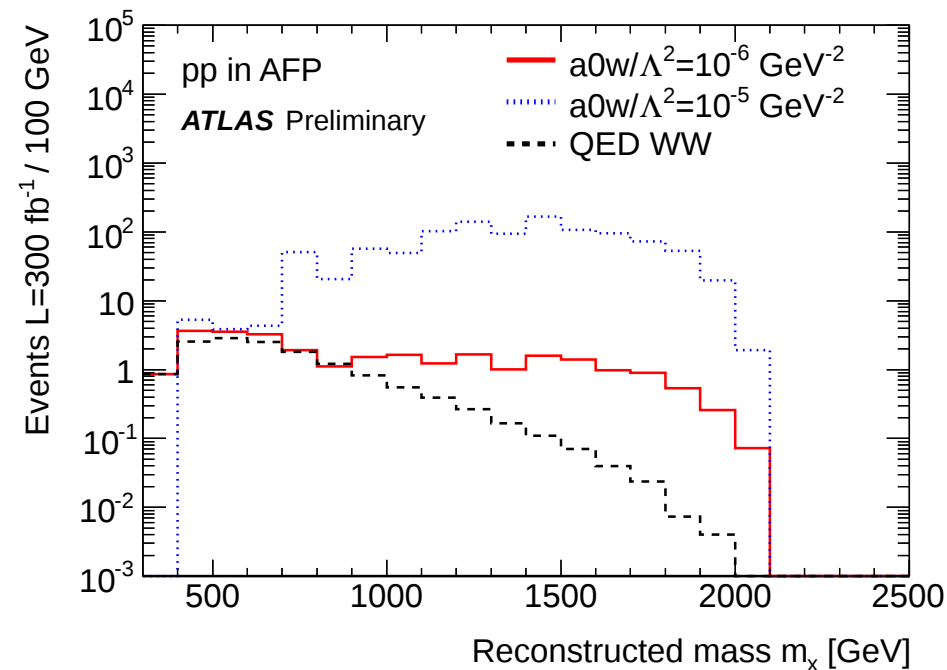
$$a_0^W/\Lambda^2 \rightarrow \frac{a_0^W/\Lambda^2}{(1+W\gamma\gamma/\Lambda_{cutoff})^2} \text{ with } \Lambda_{cutoff} \sim 2 \text{ TeV, scale of new physics}$$

- For $a_0^W \sim 10^{-6} \text{ GeV}^{-2}$, no violation of unitarity, but results depend on value of Λ_{cutoff} if new particle masses are of the same order as the LHC center-of-mass energy



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 W s 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	Diff.	$a_0^W/\Lambda^2 = 5 \cdot 10^{-6} \text{ GeV}^{-2}$
timing < 10 ps $p_T^{lep1} > 150 \text{ GeV}$ $p_T^{lep2} > 20 \text{ GeV}$	5198	601	20093	1820	190	282
$M(l\bar{l}) > 300 \text{ GeV}$	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
$m_X > 800 \text{ GeV}$	0.6	0.4	7.3	0	1.1	50
$p_T^{lep1} > 300 \text{ GeV}$	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 $pp \rightarrow l^\pm \nu \gamma \gamma$ (see P. J. Bell, ArXiv:0907.5299) by more than 2 orders of magnitude with $40/300 \text{ fb}^{-1}$ at LHC (CMS mentions that their exclusive analysis will not improve very much at high lumi because of pile-up)

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

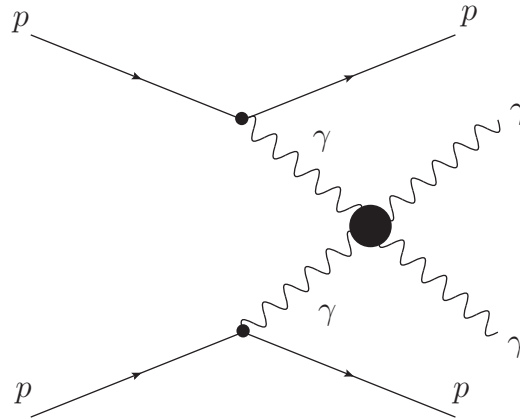
Reach at LHC

Reach at high luminosity on quartic anomalous coupling using fast simulation (study other anomalous couplings such as $\gamma\gamma ZZ\dots$)

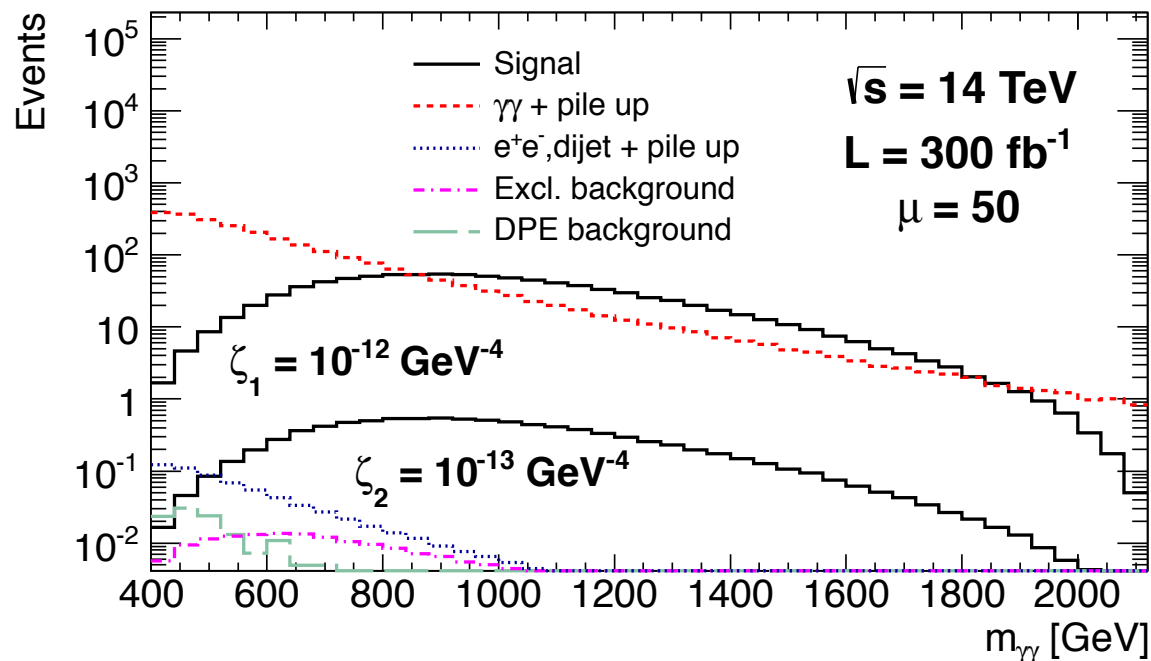
Couplings	OPAL limits [GeV ⁻²]	Sensitivity @ $\mathcal{L} = 30$ (200) fb ⁻¹	
		5 σ	95% CL
a_0^W/Λ^2	[-0.020, 0.020]	5.4 10 ⁻⁶ (2.7 10 ⁻⁶)	2.6 10 ⁻⁶ (1.4 10 ⁻⁶)
a_C^W/Λ^2	[-0.052, 0.037]	2.0 10 ⁻⁵ (9.6 10 ⁻⁶)	9.4 10 ⁻⁶ (5.2 10 ⁻⁶)
a_0^Z/Λ^2	[-0.007, 0.023]	1.4 10 ⁻⁵ (5.5 10 ⁻⁶)	6.4 10 ⁻⁶ (2.5 10 ⁻⁶)
a_C^Z/Λ^2	[-0.029, 0.029]	5.2 10 ⁻⁵ (2.0 10 ⁻⁵)	2.4 10 ⁻⁵ (9.2 10 ⁻⁶)

- Improvement of LEP sensitivity by more than 4 orders of magnitude with 30/200 fb⁻¹ at LHC, and of D0/CMS results by $\sim$ two orders of magnitude (only $\gamma\gamma WW$ couplings)
- Reaches the values predicted by extra-dimension models

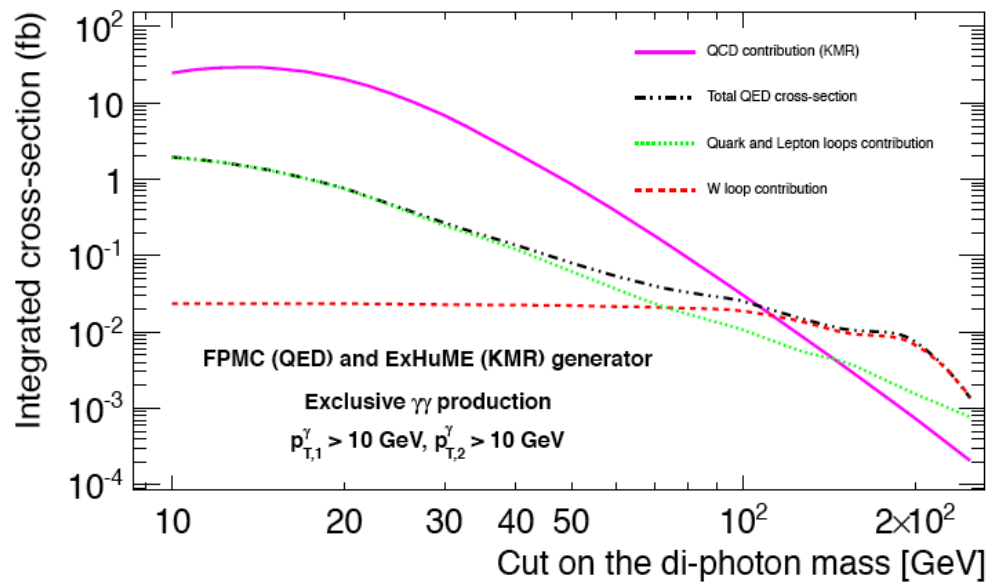
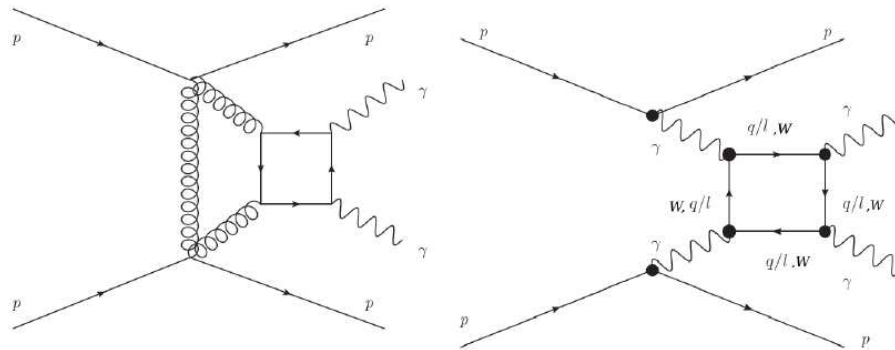
Search for quartic $\gamma\gamma$ anomalous couplings



- 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...

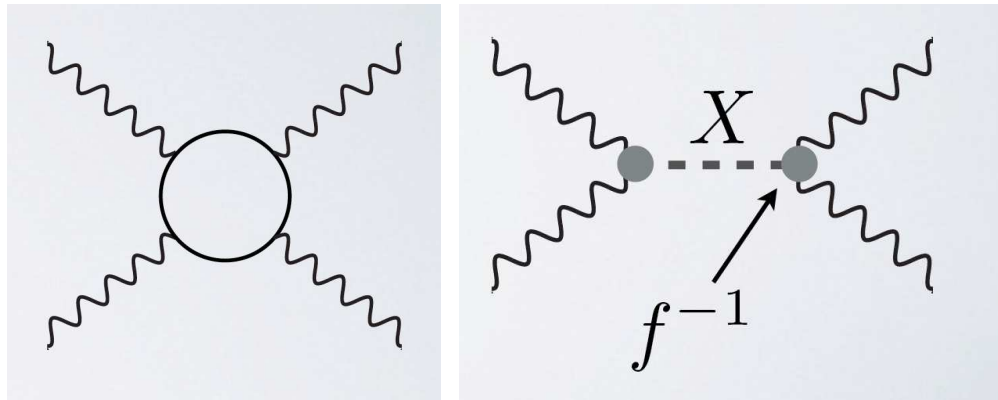


SM $\gamma\gamma$ exclusive production



- QCD production dominates at low $m_{\gamma\gamma}$, QED at high $m_{\gamma\gamma}$
- Important to consider W loops at high $m_{\gamma\gamma}$
- Possibility to measure KMR contribution at low $m_{\gamma\gamma}$ in high β^* runs: with two protons tagged in TOTEM/ALFA, $\sigma \sim 372 \text{ fb}$ for $m_{\gamma\gamma} > 10 \text{ GeV}$, $p_T^\gamma > 5 \text{ GeV}$

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

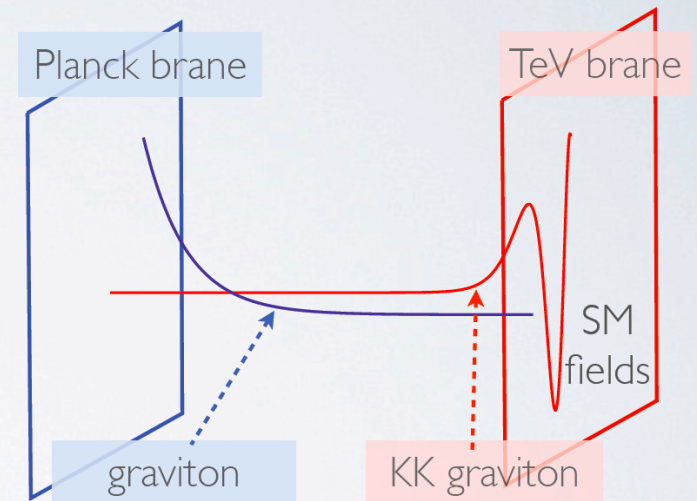
- ✗ Warped Extra Dimensions **solve hierarchy problem** of SM
- ✗ 5th dimension bounded by two branes
- ✗ SM on the visible (or TeV) brane

- ✗ The **Kaluza Klein** modes of the graviton couple with **TeV** strength

$$\mathcal{L}^{\gamma\gamma h} = f^{-2} h_{\mu\nu}^{\text{KK}} \left(\frac{1}{4} \eta_{\mu\nu} F_{\rho\lambda}^2 - F_{\mu\rho} F_{\rho\nu} \right)$$

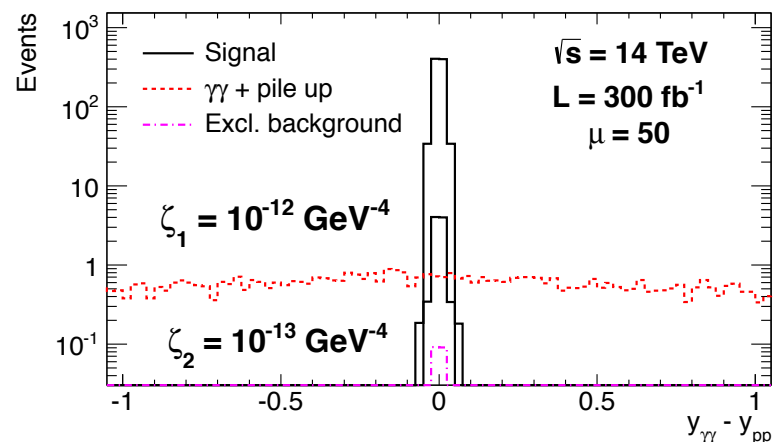
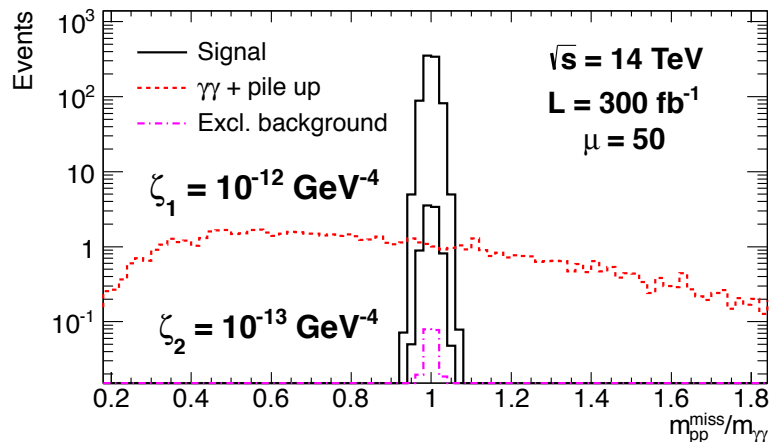
$$f \sim \text{TeV} \quad m_{\text{KK}} \sim \text{few TeV}$$

- ✗ 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 Gehrdsdorff

Search for quartic $\gamma\gamma$ anomalous couplings



- **Trigger:** 2 high p_T central photons, $P_{T_1} > 200$ GeV, no special AFP trigger needed
- **Protons are detected in AFP at high $\xi > \sim 0.04$:** massive objects are produced, we do not need to be very close to the beam
- **Exclusivity cuts:** diphoton mass compared from missing mass computed using protons, rapidity difference between diphoton and proton systems: suppresses all pile-up backgrounds
- **For 300 fb^{-1} and a pile-up of 50:** 0.2 background event for 32 signal events for an anomalous coupling of $2 \cdot 10^{-13}$
- **Exclusivity cuts are fundamental to suppress all background and increase the sensitivity**
- **NB:** theoretical uncertainties are larger in the case of non-exclusive production (usual study in ATLAS) since it is sensitive to the poorly known photon structure function at high energy

Search for quartic $\gamma\gamma$ anomalous couplings: Results

Cut / Process	Signal (full)	Signal with (without) f.f (EFT)	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15,$ $p_{T1,(2)} > 200, (100) \text{ GeV}]$	130.8	36.9 (373.9)	0.25	0.2	1.6	2968
$m_{\gamma\gamma} > 600 \text{ GeV}$	128.3	34.9 (371.6)	0.20	0	0.2	1023
$[p_{T2}/p_{T1} > 0.95,$ $ \Delta\phi > \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
$ y_{\gamma\gamma} - y_{pp} < 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 needed to suppress backgrounds:
 - Without exclusivity cuts using AFP: background of 80.2 for 300 fb^{-1} for a signal of 34.9 events ($\zeta_1 = 2 \cdot 10^{-13}$)
 - With exclusivity cuts: 0.18 background for 31.8 signal
- String theory/grand unification models predict couplings via radions/heavy charged particles/dilatons for instance up to 10^{-14} - 10^{-13}

Luminosity	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
pile-up (μ)	50	50	50	200
coupling (GeV^{-4})	$\geq 1 \text{ conv. } \gamma$ 5σ	$\geq 1 \text{ conv. } \gamma$ 95% CL	all γ 95% CL	all γ 95% CL
$\zeta_1 \text{ f.f.}$	$8 \cdot 10^{-14}$	$5 \cdot 10^{-14}$	$3 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$
$\zeta_1 \text{ no f.f.}$	$2.5 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$	$9 \cdot 10^{-15}$	$7 \cdot 10^{-15}$
$\zeta_2 \text{ f.f.}$	$2 \cdot 10^{-13}$	$1 \cdot 10^{-13}$	$6 \cdot 10^{-14}$	$4.5 \cdot 10^{-14}$
$\zeta_2 \text{ no f.f.}$	$5 \cdot 10^{-14}$	$4 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$

Full amplitude calculation

- Effective field theory valid if $S \ll 4m^2$, S smaller than the threshold production of real particles
- Since the maximum proton missing mass is ~ 2 TeV at the 14 TeV LHC, the effective theory needs to be corrected for masses of particles below ~ 1 TeV $\rightarrow$ use of form factor which creates an uncertainty on the results (depends on the exact value of form factors)
- Solution: compute the full momentum dependence of the 4 photon amplitudes: computed for fermions and bosons
- Full amplitude calculation for generic heavy charged fermion/vector contribution
- Existence of new heavy charged particles enhances the $\gamma\gamma\gamma\gamma$ couplings in a model independent way
- Enhancement parametrised with particle mass and effective charge $Q_{eff} = QN^{1/4}$ where N is the multiplicity

Search for quartic $\gamma\gamma$ anomalous couplings: Results from full theory

Cut / Process	Signal (full)	Signal with (without) f.f (EFT)	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15,$ $p_{T1,(2)} > 200, (100) \text{ GeV}]$	130.8	36.9 (373.9)	0.25	0.2	1.6	2968
$m_{\gamma\gamma} > 600 \text{ GeV}$	128.3	34.9 (371.6)	0.20	0	0.2	1023
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$ y_{\gamma\gamma} - y_{pp} < 0.03$	119.1	31.8 (338.5)	0.18	0	0	0

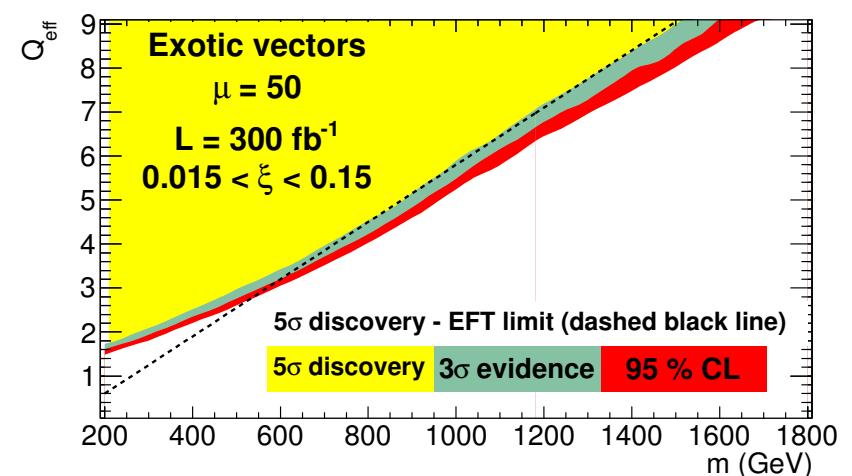
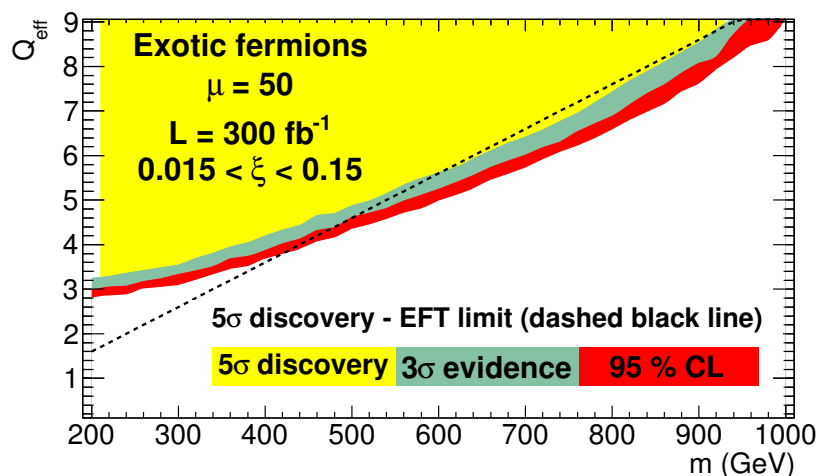
- No background after cuts for 300 fb^{-1} **without needing timing detector information**
- For signal: 119.1 events for $Q_{eff} = 4$, $m = 340 \text{ GeV}$
- Results for full calculation lay between the effective field result with/without form factor as expected since effective calculation not valid in the region of $S \sim m^2$

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	-	-

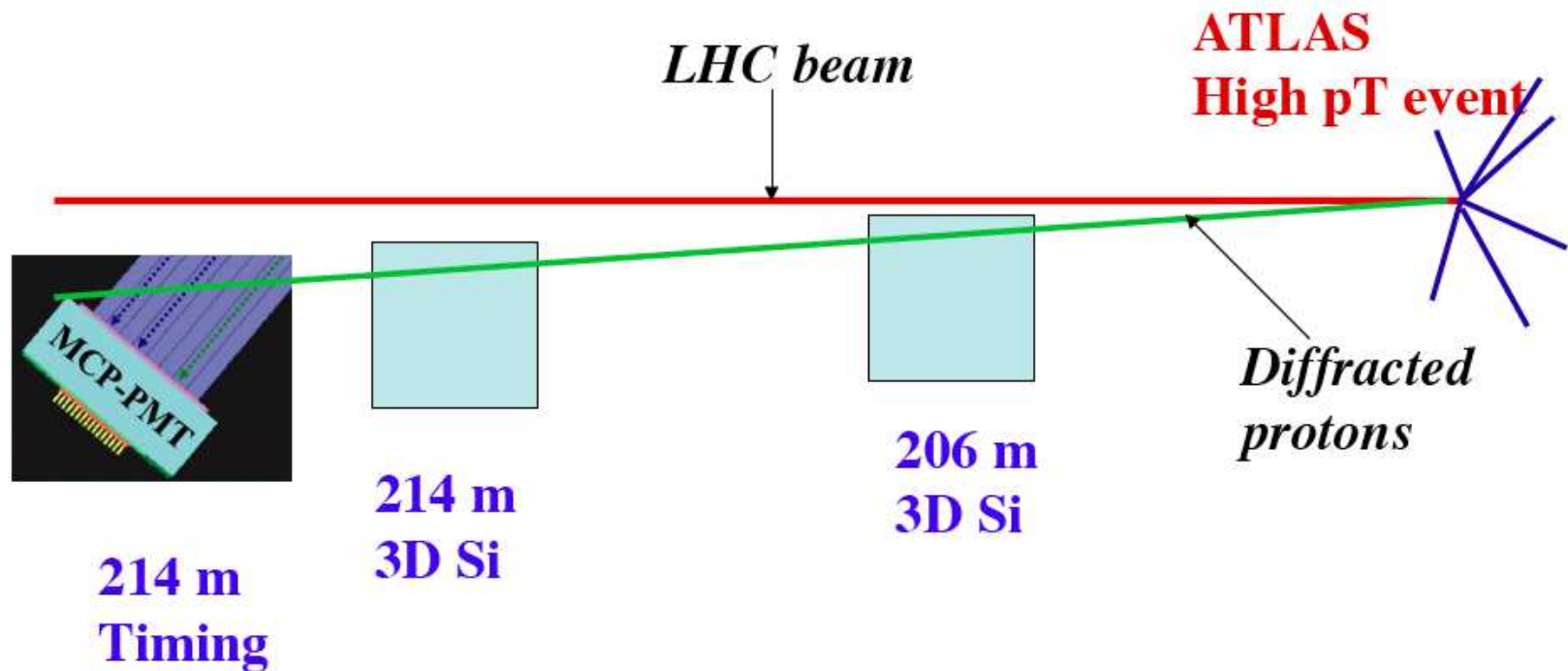
- Unprecedented sensitivities at hadronic colliders reaching the values predicted by extra-dim models - For reference, we also display the result of effective field theory (without form factor) which deviates at low masses from the full calculation
- For $Q_{\text{eff}} = 4$, we are sensitive to new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



FORWARD DETECTORS : AFP AND CT-PPS (ATLAS/CMS-TOTEM)

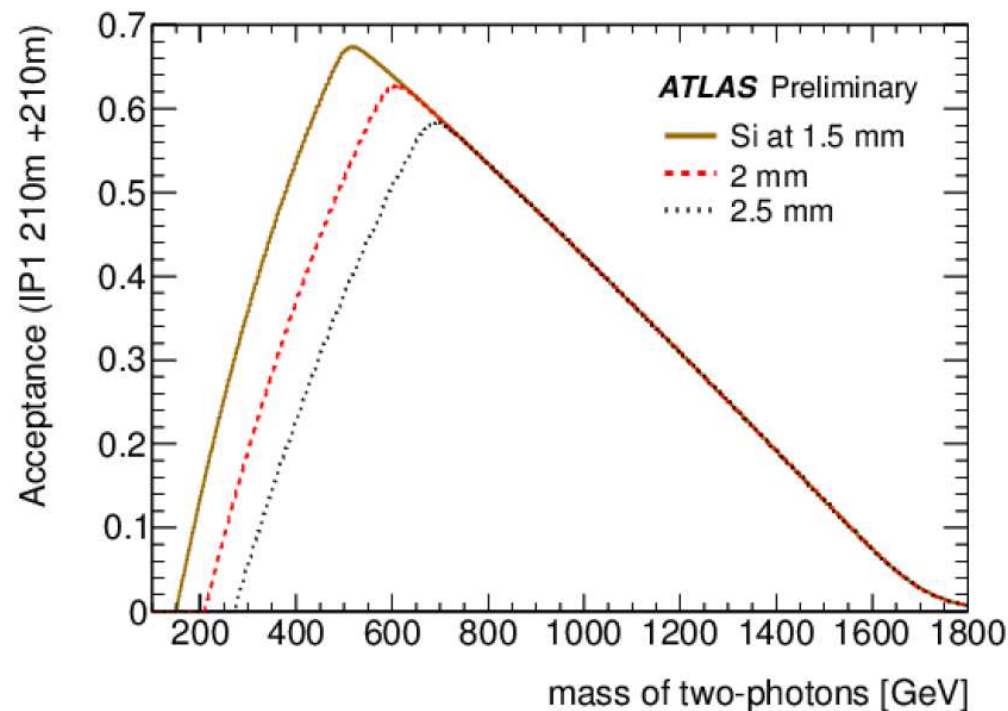
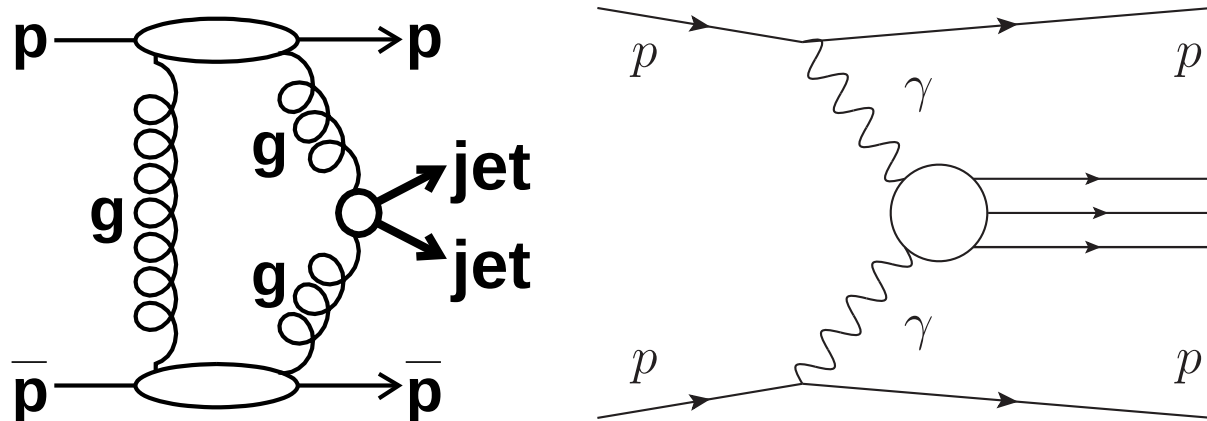


What is AFP/CT-PPS?



- Tag and measure protons at ± 210 m using roman pots
- **Trigger**: Rely on ATLAS high p_T L1 trigger for high p_T events; AFP trigger for lower masses
- **AFP detectors**: Radiation hard “edgeless” 3D Silicon detectors, 10 ps timing detectors
- **Allows running in high pile up conditions by association with correct primary vertex**: Access to rare processes
- **Allows running in low pile up special runs for QCD measurements**

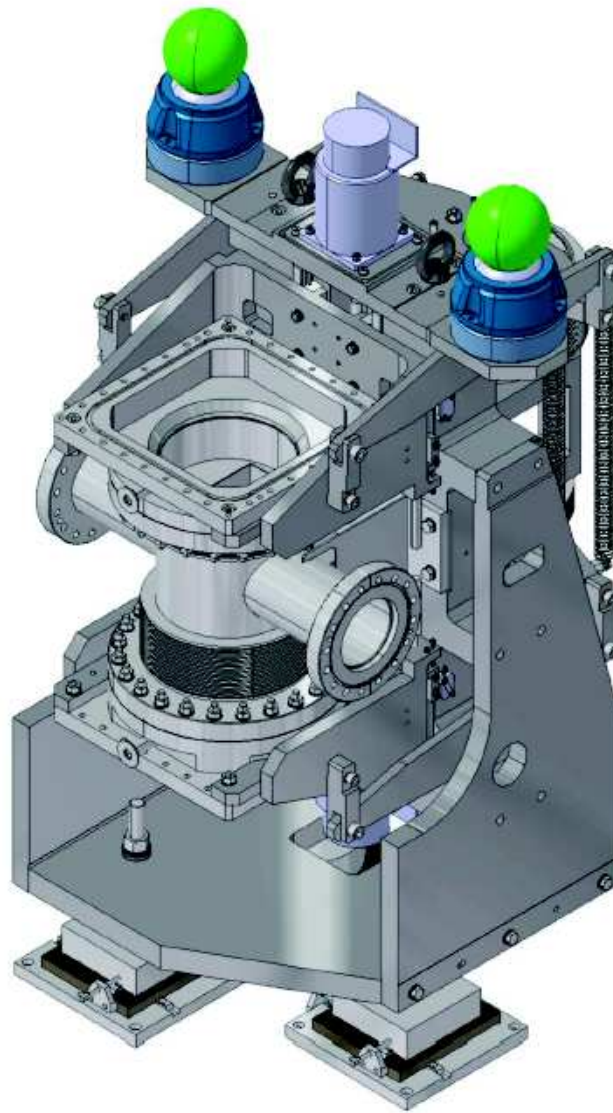
AFP/CT-PPS acceptance in total mass



- Increase sensitivity to (new) physics in ATLAS due to color singlet or photon exchanges
- Sensitivity to high mass central system, X, as determined using AFP
- Very powerful for exclusive states: kinematical constraints coming from AFP proton measurements

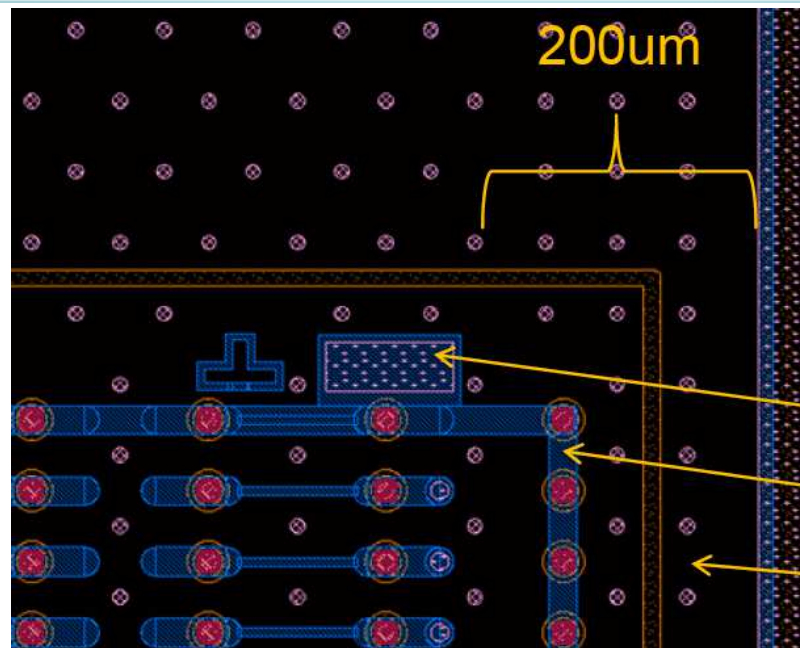
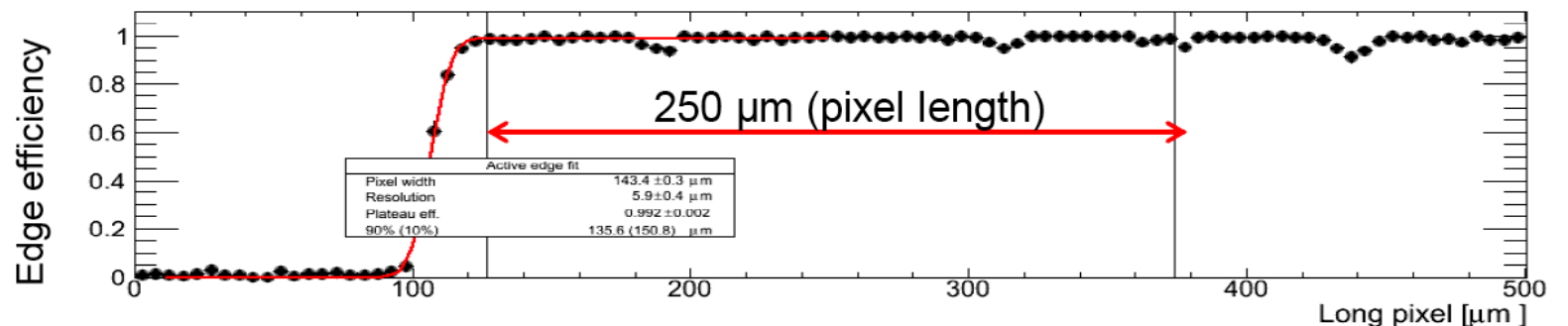
Roman pots

- Method to find diffractive events: Tag the proton in the final state
- Install roman pot detectors: by default solution at 210 m (2 roman pots with Si detectors, 1 with timing)



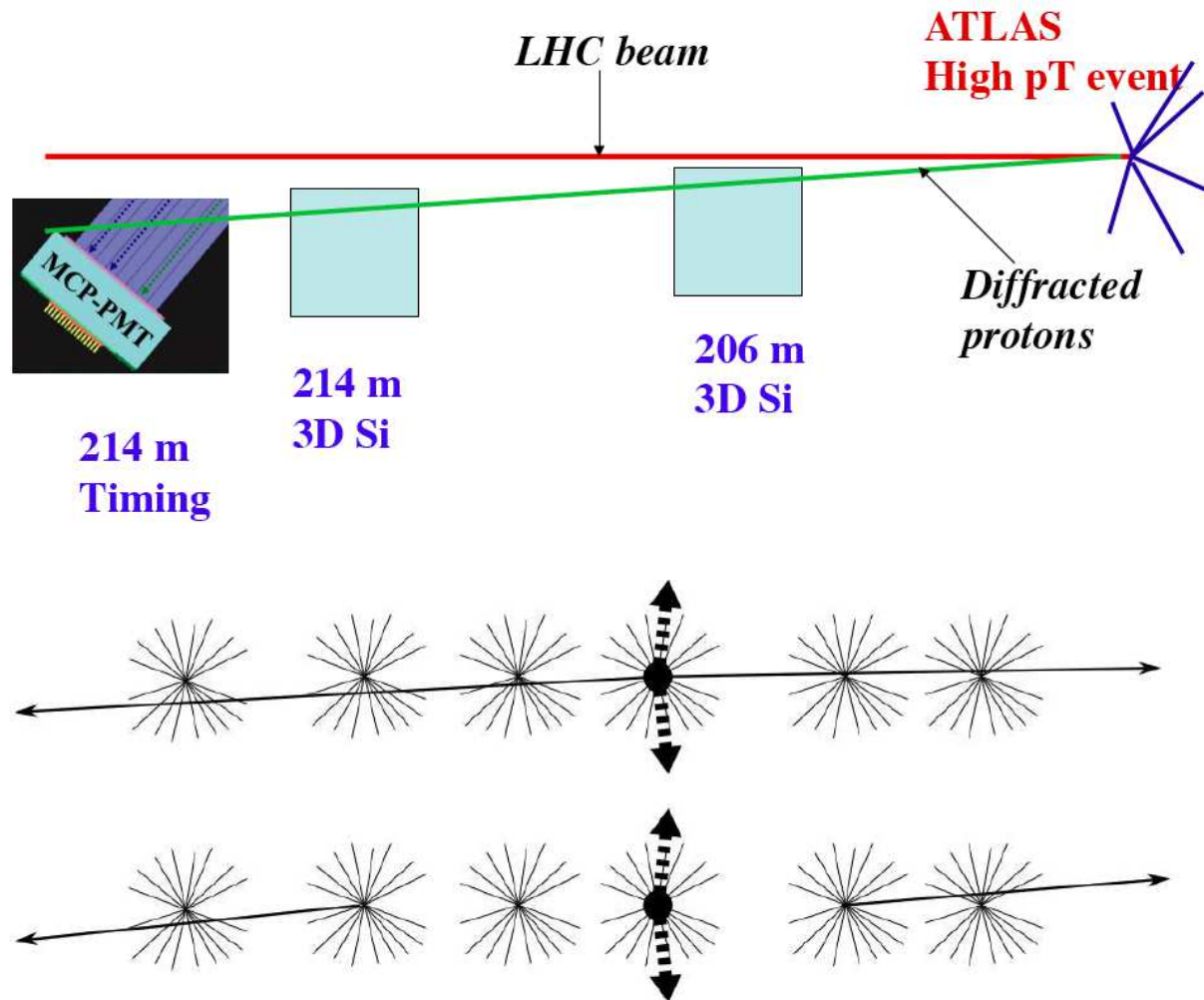
Detector I: 3D Si detector

- Key requirements for the Si detector
 - Spatial resolution of 10 (30) μm in x (y) direction over the full detector coverage ($2\text{ cm} \times 2\text{ cm}$); Angular resolution of $1\text{ }\mu\text{rad}$
 - Minimal dead space at the edge and radiation hardness
- **Sensors:** double-sided 3D 50×250 micron pixel detectors (FBK) with slim-edge dicing (Trento) and CNM 3D pixel detectors with slim-edge dicing (dead zone of 80 microns instead of 250)
- **Upgrade with 3D edgeless detectors by 2020:** SLAC, Manchester, Oslo, Bergen...



Timing measurements in particle physics

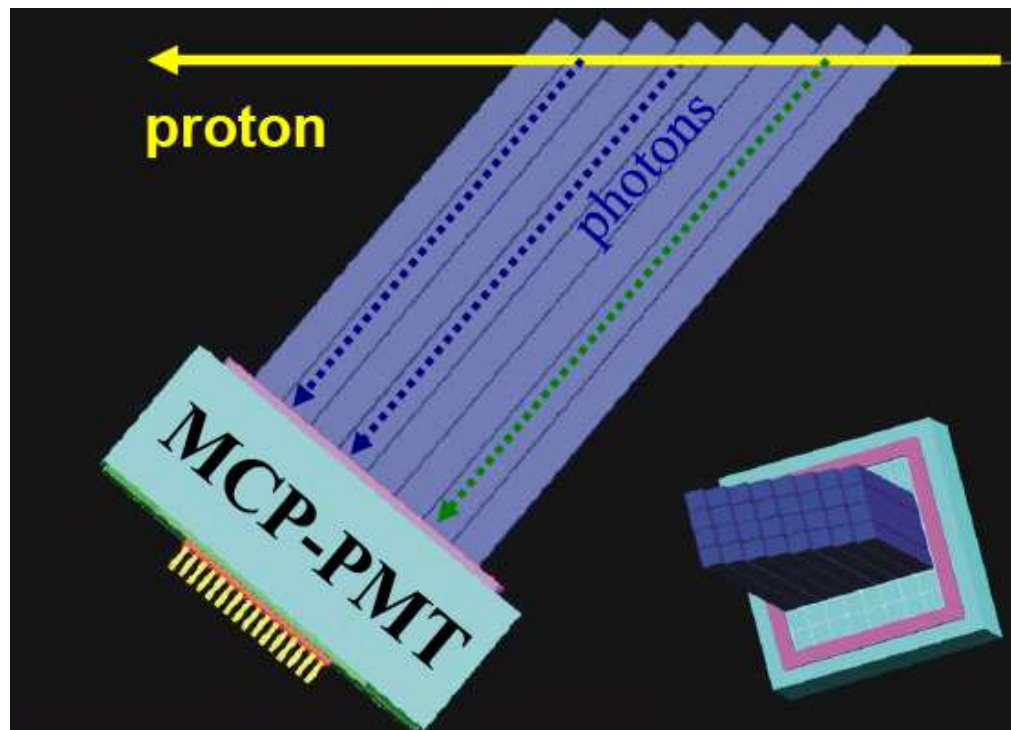
- Proton time-of-flight measurements at the LHC in ATLAS (AFP), and CMS/TOTEM (CT-PPS): $pp \rightarrow pXp$



- Determine if intact protons originate from main interaction in the events or from secondary ones (there are between 20-100 interactions per bunch crossing at the LHC)
- Ultimate goal of ~ 5 -10 ps resolution which means 1-2 mm in vertex position

Detector II: 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)



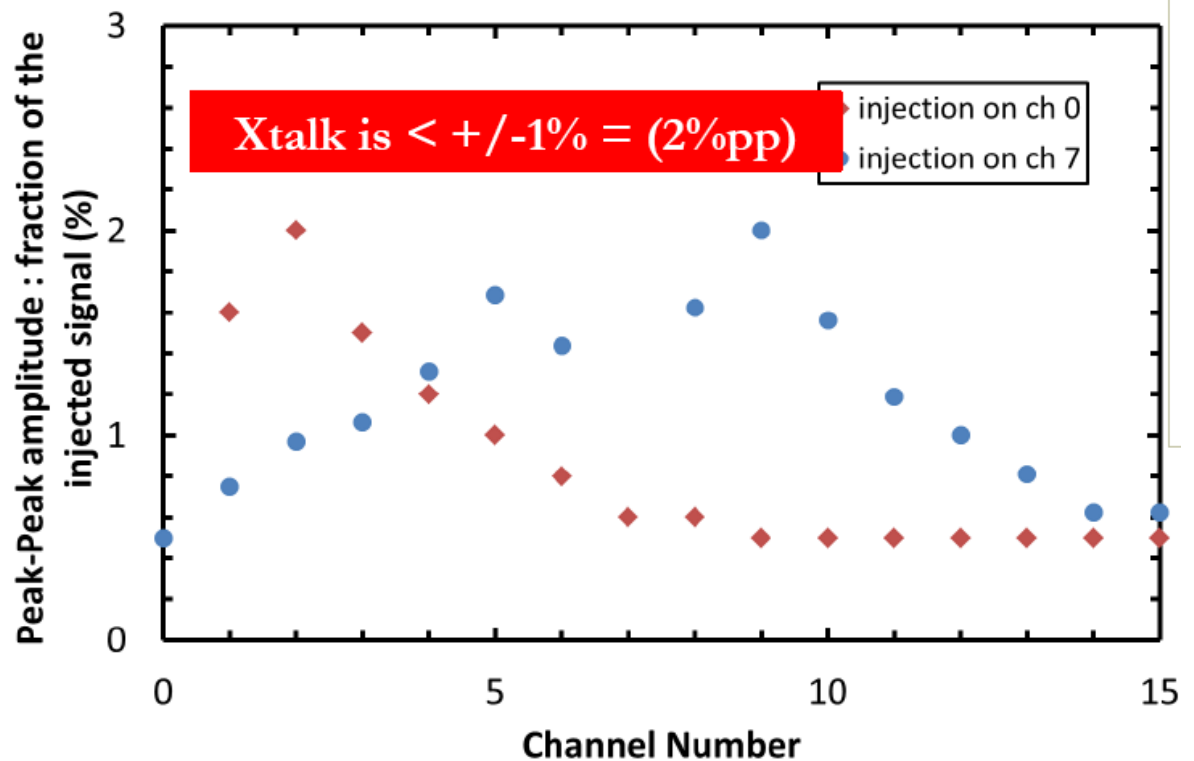
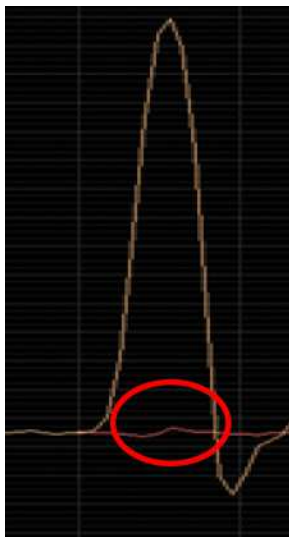
Measuring the proton time-of-flight: the SAMPIC concept

- 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 (~ 10 Euros per channel) (compared to a few 1000 Euros for previous technologies)



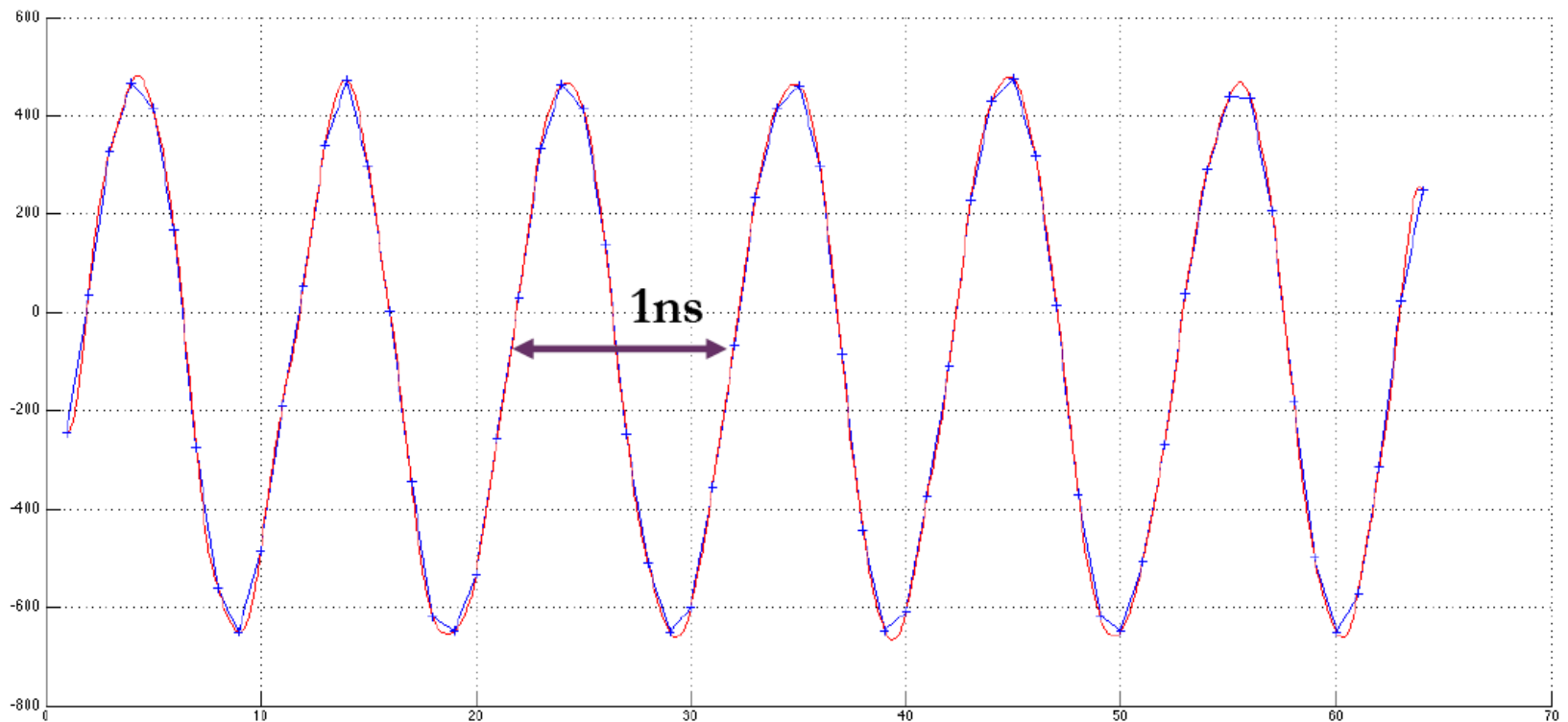
SAMPIC cross talk measurement

- Signal of 800 mV, 300 ps rise time injected on channel 0 or 7 of SAMPIC
- Signal measured on other channel
- Cross talk is less than 1%



Quality of sampling

- Sample speed from 3 to 8.2 Giga-sample per second on 16 channels (up to 10 GSPS on 8 channels)
- **Already very good sampling quality:** example of sampling of a sinus without corrections at 10 GSPS

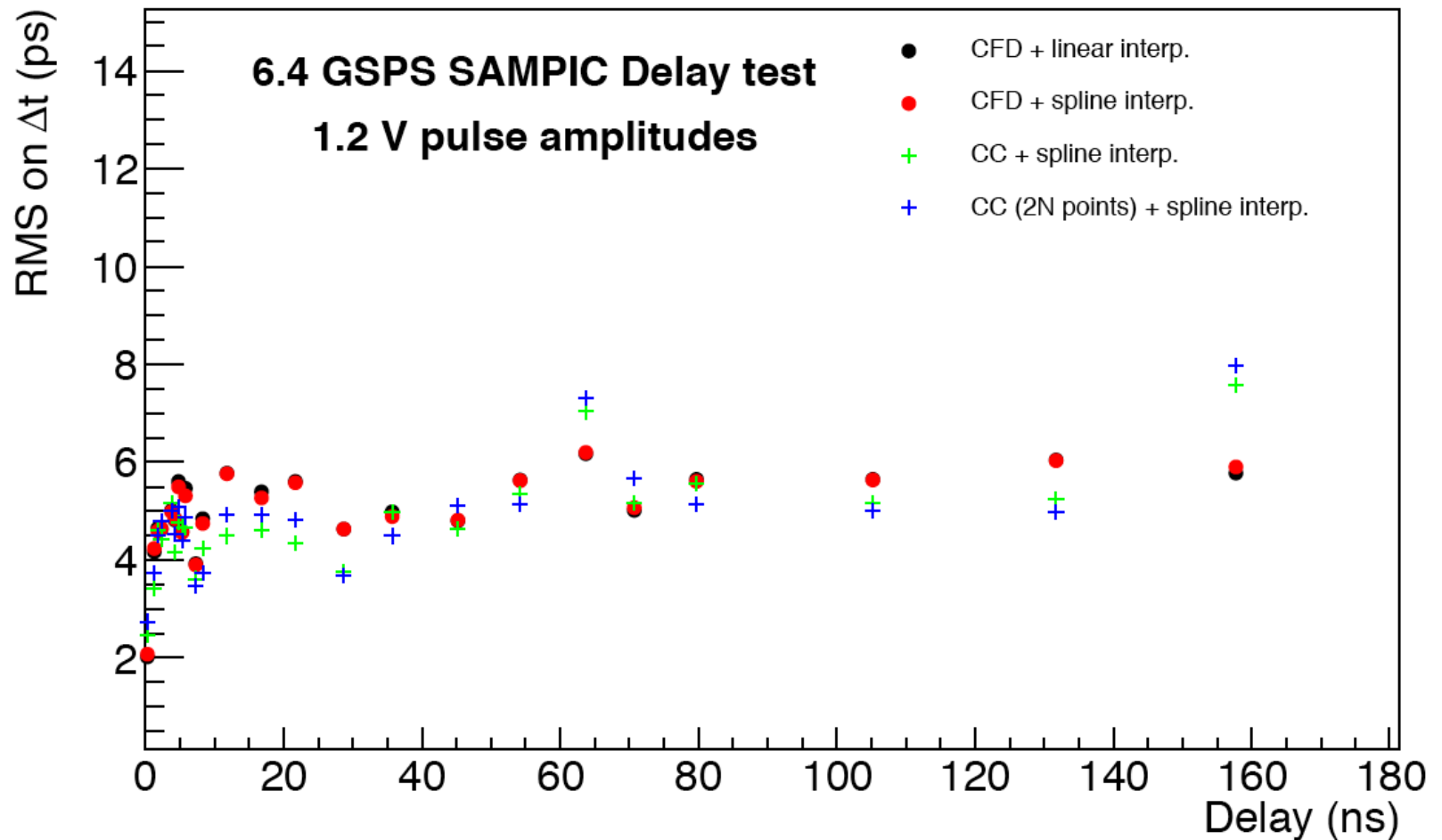


Timing resolution vs delay



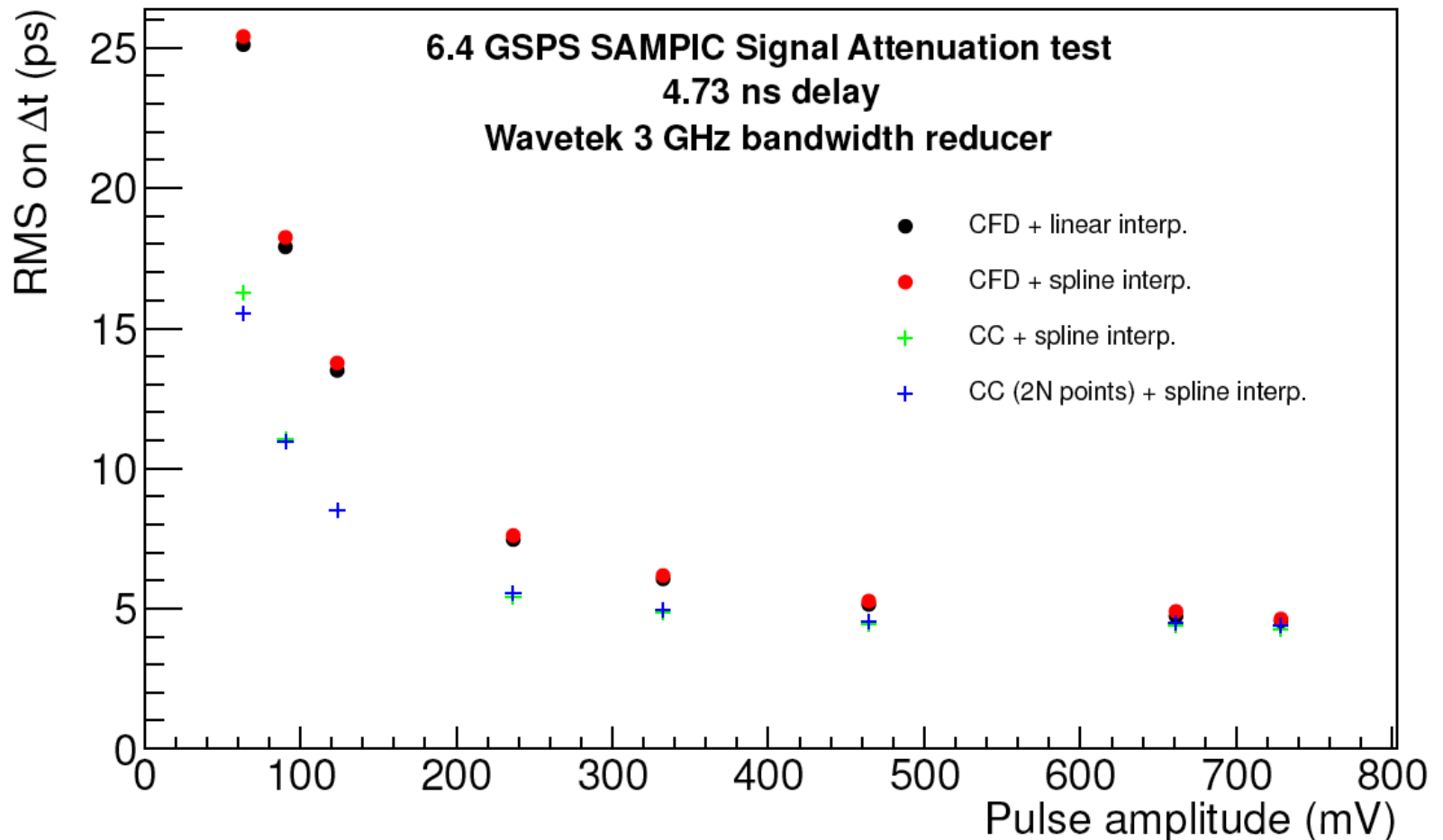
- Use two different channels of SAMPIC
- Send two times the same signal, one being delayed (delay box or longer cable)
- Measure the time difference and its RMS as a function of delay between 0 and μs
- check SAMPIC stability as a function of delay

Timing resolution vs delay



- Measure the RMS of the time difference between two pulses sent to SAMPIC vs delay using a pulse generator
- Different methods used: CFD (constant fraction discriminator), CC (cross correlation)
- Flat resolution of ~ 5 ps vs delay: time resolution per channel of ~ 3 ps

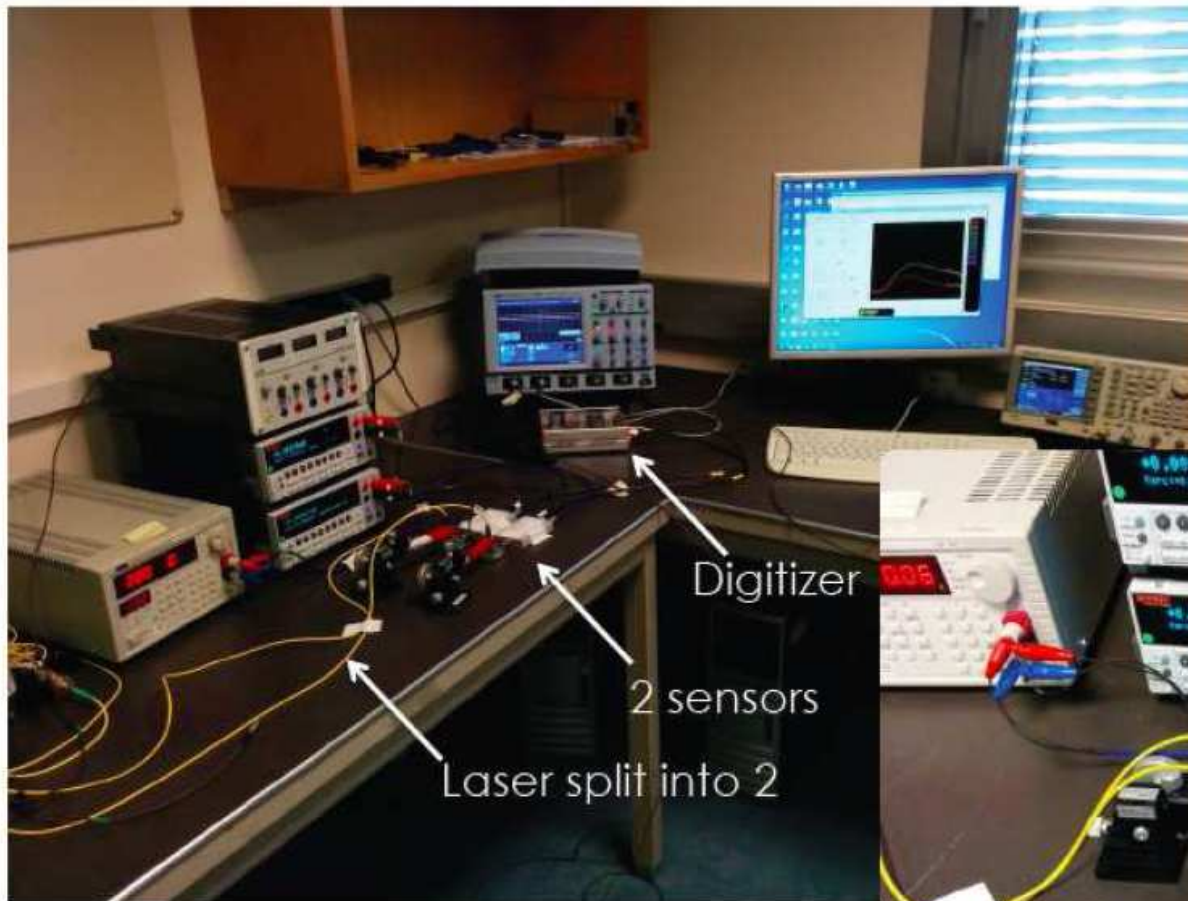
Timing resolution vs signal amplitude



- Measure the RMS of the time difference between two pulses sent to SAMPIC vs the pulse amplitude using a pulse generator
- Different methods used: CFD (constant fraction discriminator), CC (cross correlation)
- Best time resolution if the signal is above 450 mV

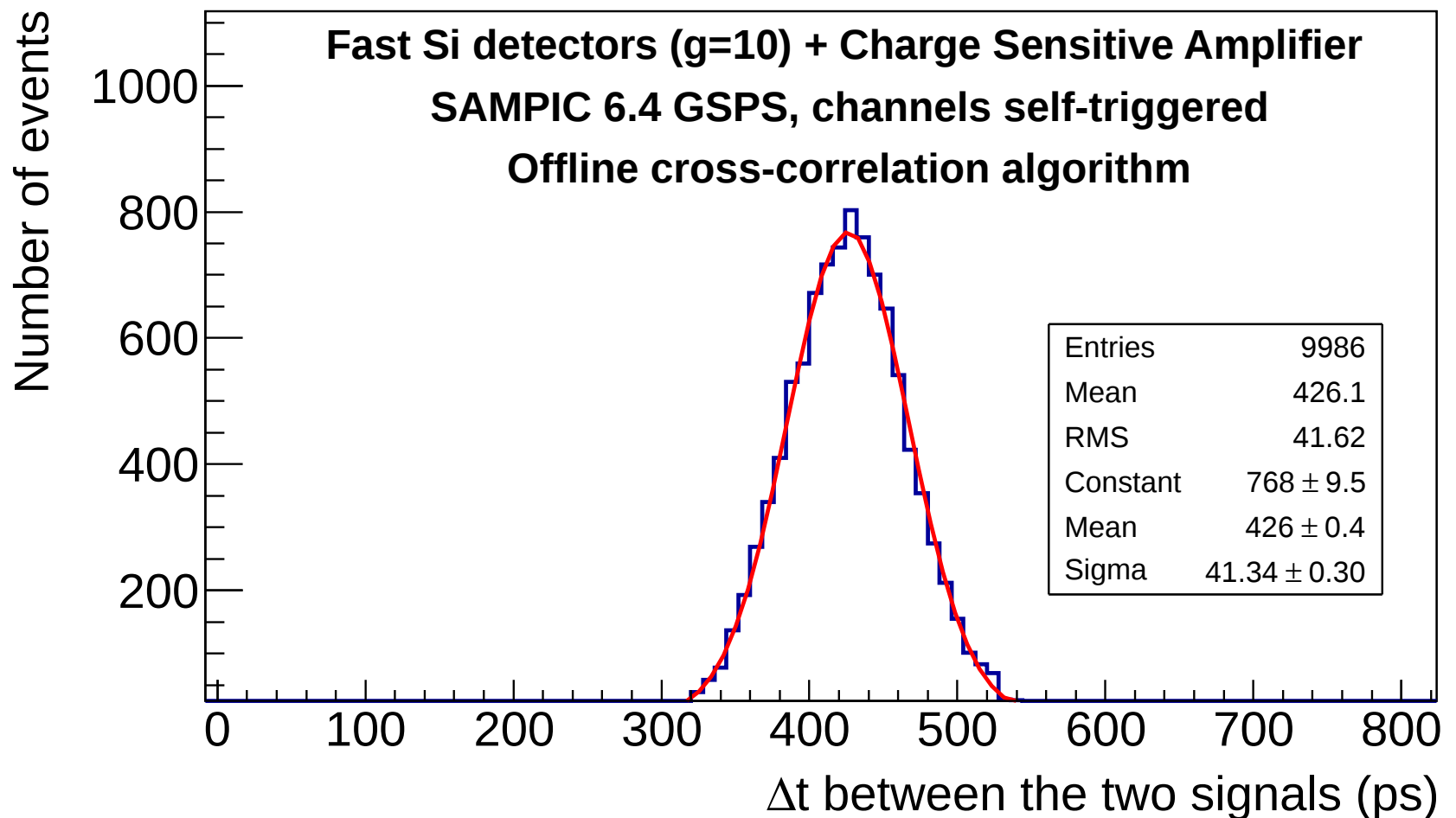
Time resolution using Si detectors

- Test setup using a laser signal splitted in 2 read out by fast Si detector
- Time difference and RMS measured by SAMPIC



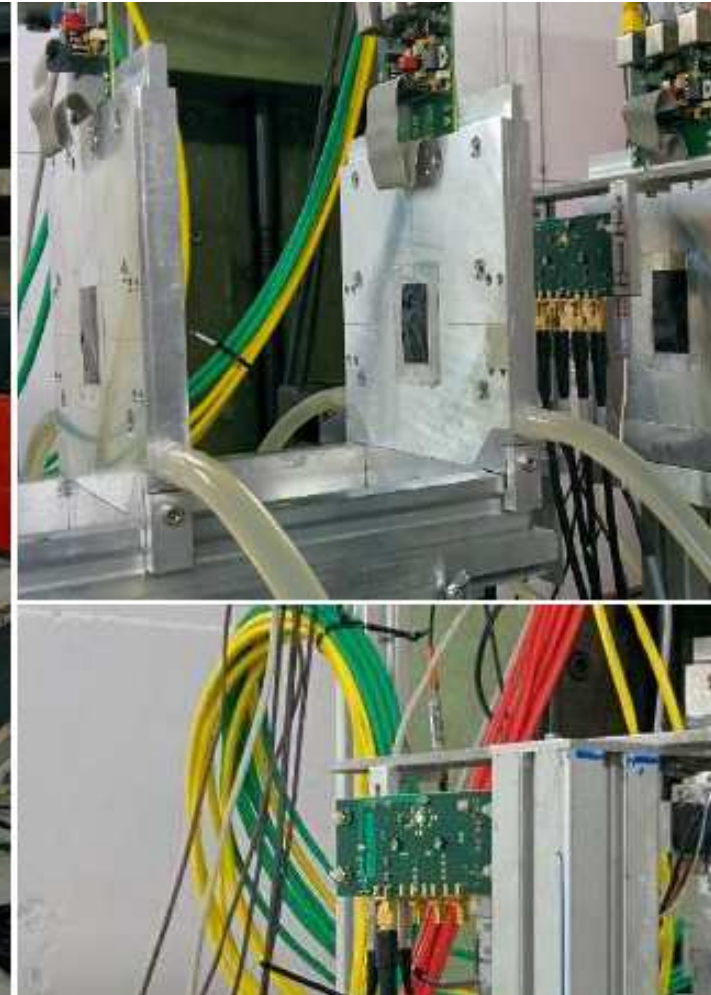
Time resolution using Si detectors

- Time resolution using sampic and fast Si detectors: measure the time difference between two channels
- Time resolution: (dominated by detector): ~ 30 ps



Beam tests in TOTEM using diamond detectors (I)

- Beam tests performed at DESY and CERN by TOTEM using diamonds detectors and SAMPIC

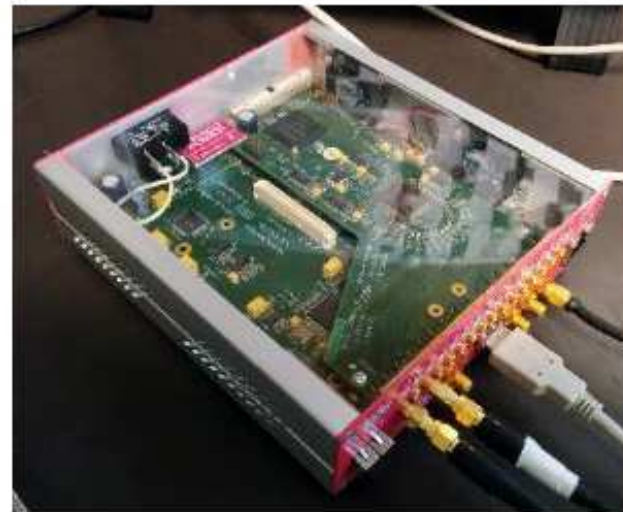


Beam tests in TOTEM using diamond detectors (II)

- Beam tests performed at DESY and CERN by TOTEM using diamonds detectors and SAMPIC



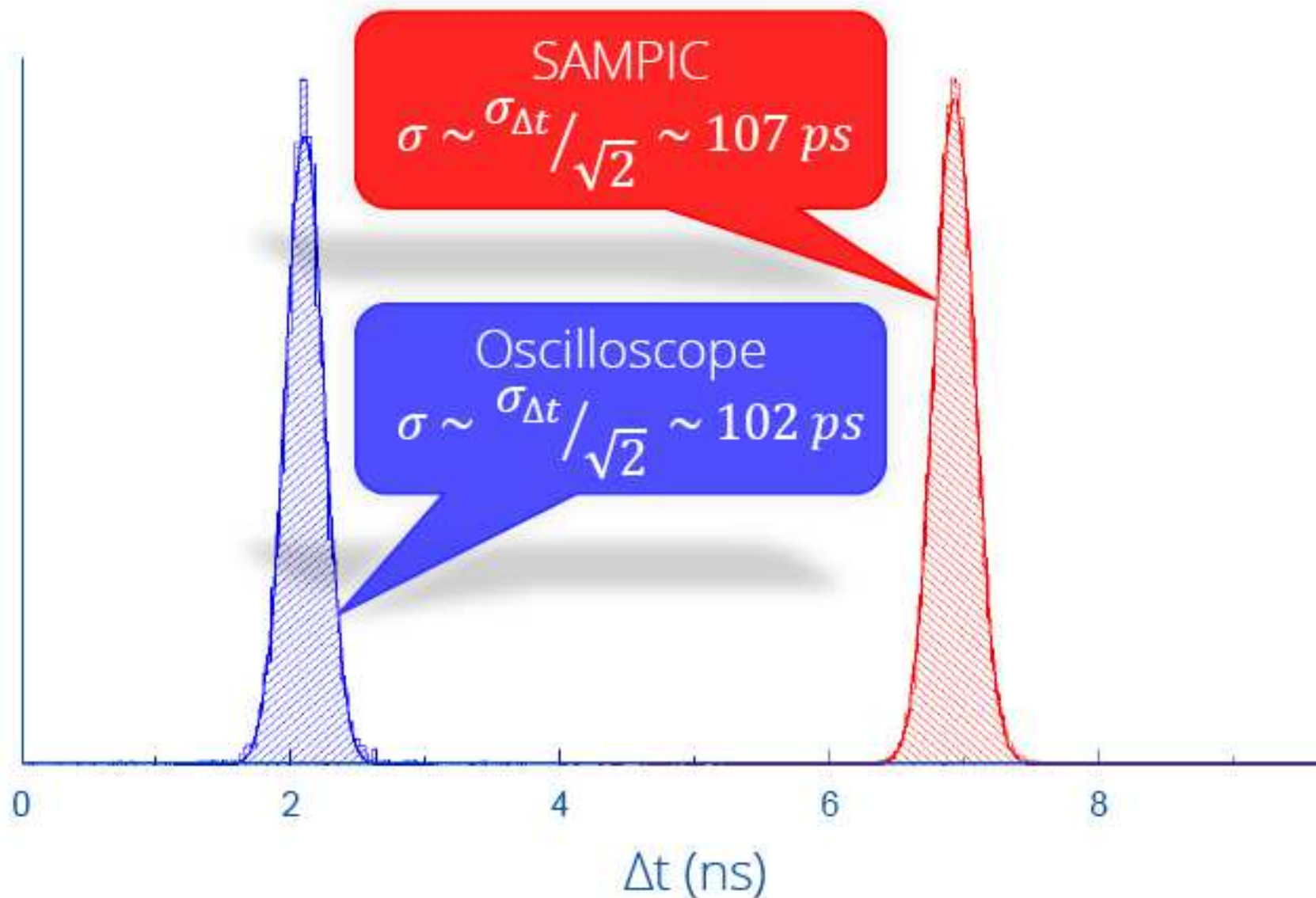
Agilent DSO 9254A
2.5 GHz bandwidth
10 Gs/s
8 bit
> 1000 samples
4 channels
Maximum rate ~100 Hz



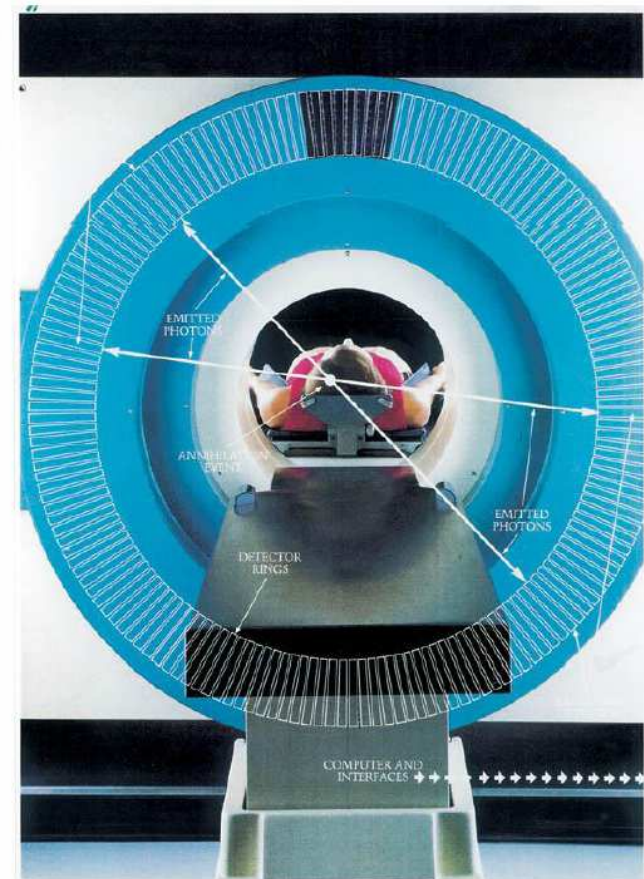
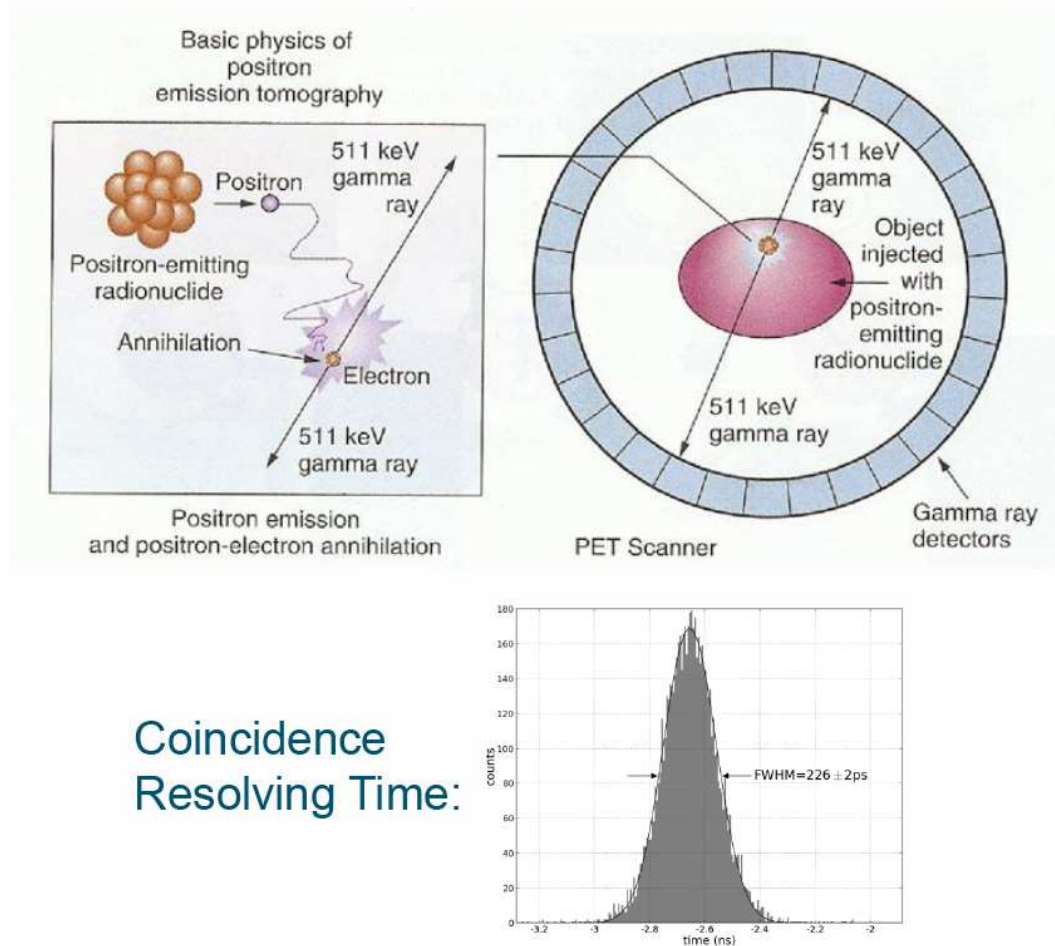
SAMPIC
2.5 GHz bandwidth
10 Gs/s (used at 6.4 Gs/s)
11 bit
64 samples
16 channels
Maximum rate ~500 kHz

Beam tests in TOTEM using diamond detectors (III)

- Measure the resolution on the time difference between two channels



The future: Application: Timing measurements in Positron Emission Tomography



- 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
- Other possible application in drone technology: fast decision taking and distance measurement using laser

Conclusion

- Detecting intact protons in ATLAS/CMS-TOTEM: increases the physics potential of ATLAS/CMS (QCD: understanding the Pomeron structure in terms of quarks and gluon, universality of Pomeron, jet gap jets, search for extra-dimensions in the universe via anomalous couplings between γ , W , Z , for magnetic monopoles...)
- Many applications especially in PET imaging (Manjit Dosanjh)

The holy grail: “10-picosecond PET”

With a CRT less than ~ 20 ps events can be localized directly:

- image reconstruction no longer necessary!
- only attenuation correction
- real-time image formation

