Forward physics using proton tagging at the LHC

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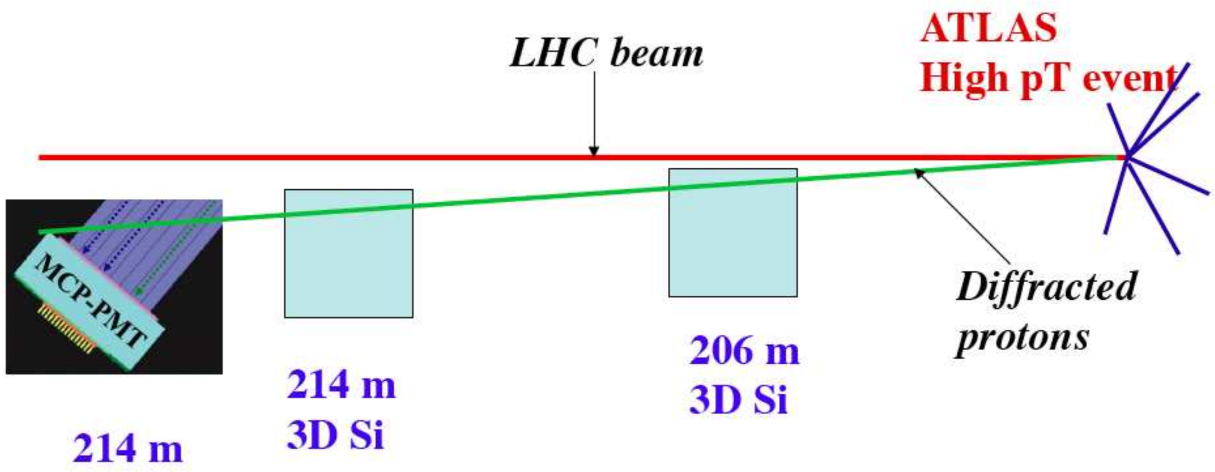
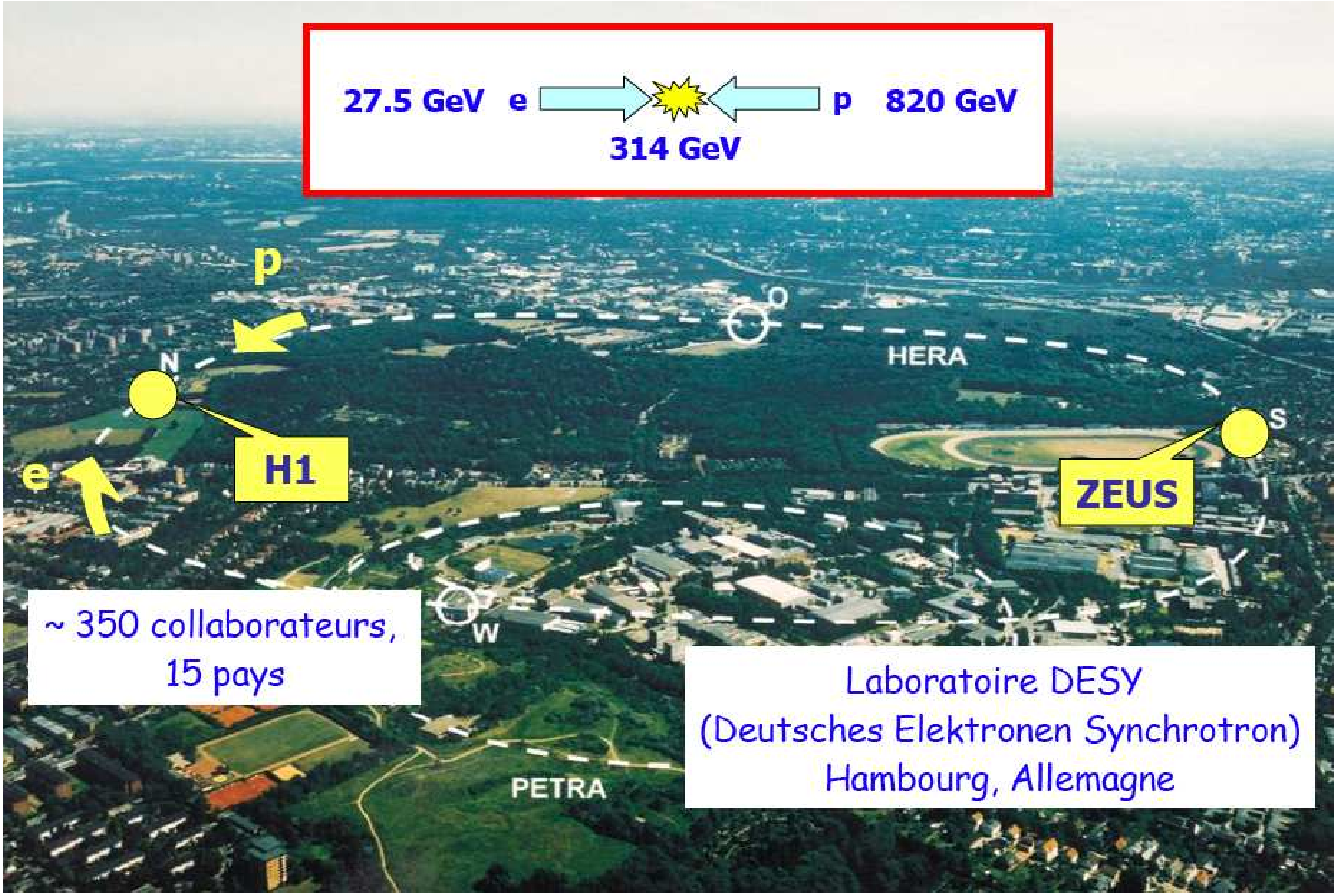
Contents:

- Pomeron structure: DPE dijets and γ+jet
- Soft colour interaction models
- BFKL tests: Jet gap jets
- Exclusive jets and Higgs
- Anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$
- An example: AFP project for ATLAS (SAMPIC chip)

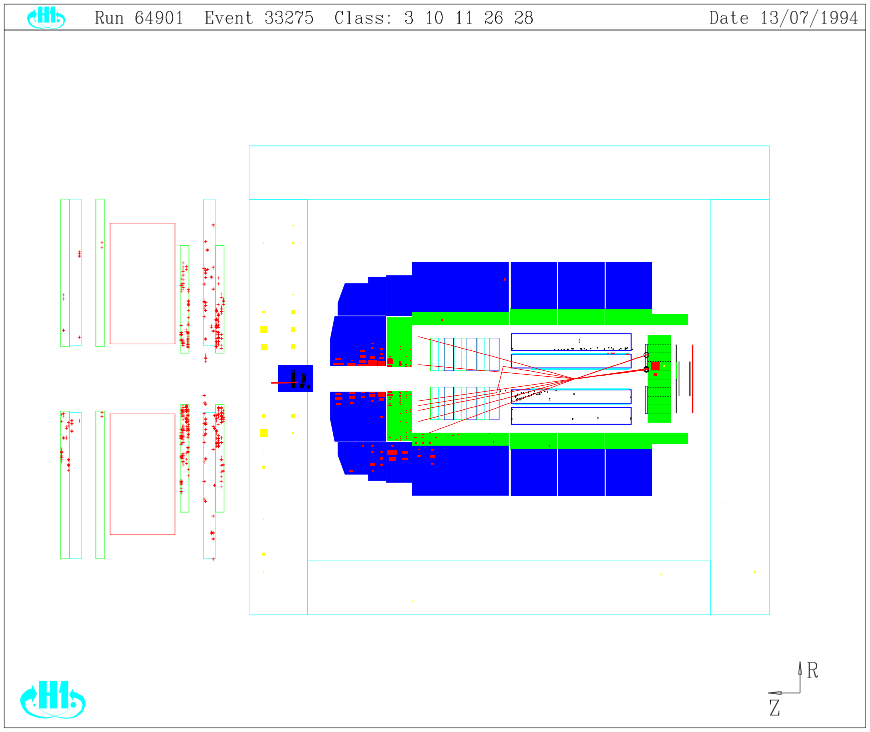


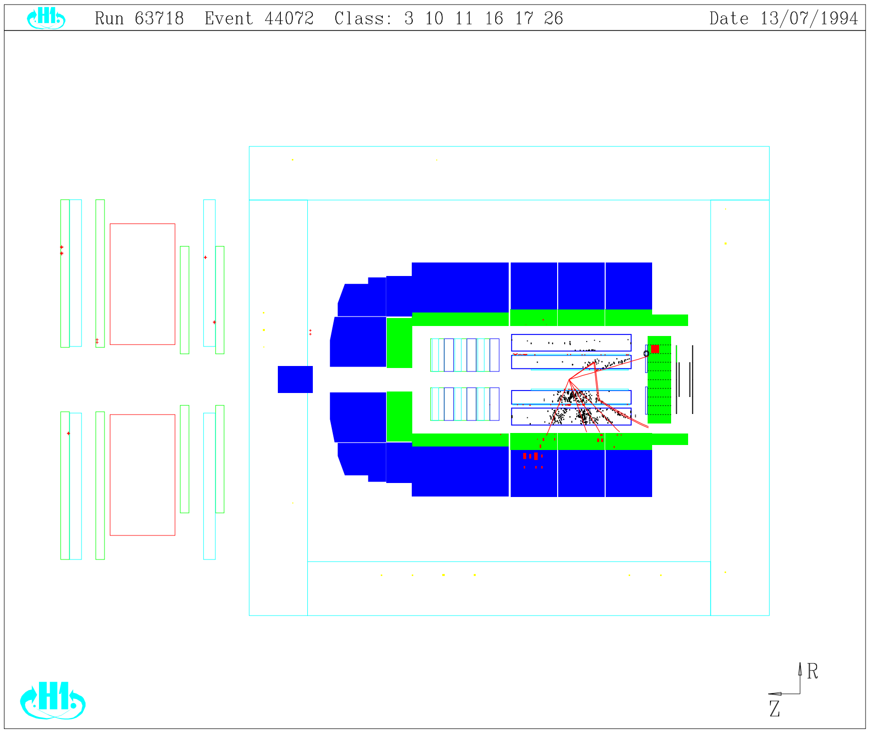
Definition of diffraction: example of HERA

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



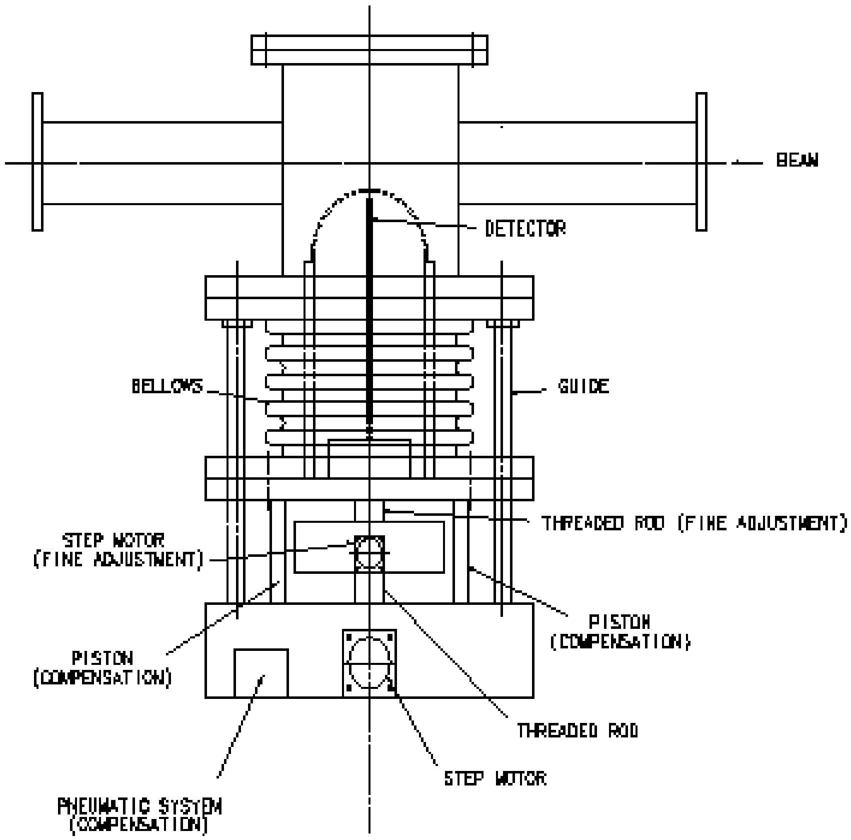
DIS and Diffractive event at HERA



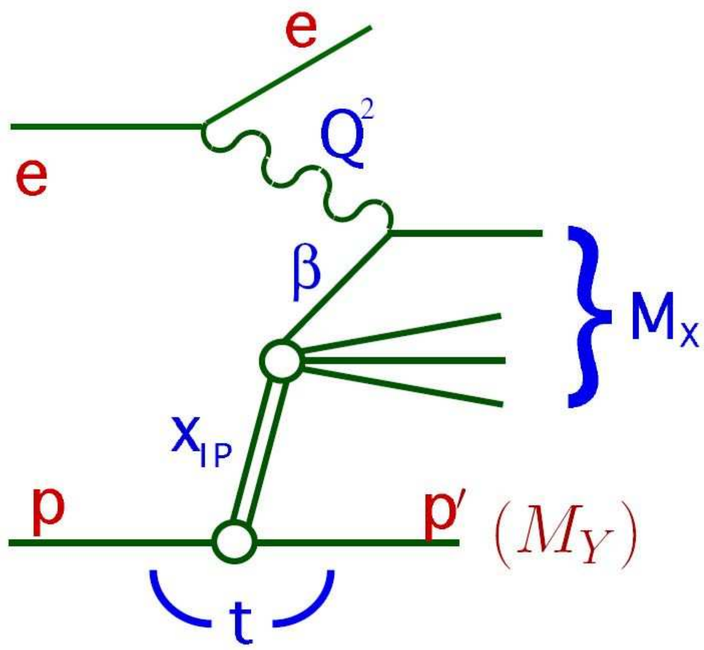


Definition of diffraction: example of HERA

- 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



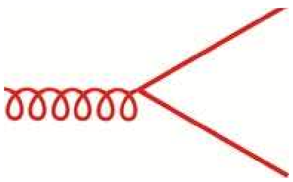
Invariant mass of the diffractive final state

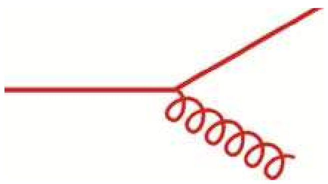
- Momentum fraction of the proton carried by the colourless object (pomeron): $x_p = \xi = \frac{Q^2+M_X^2}{Q^2+W^2}$
- Momentum fraction of the pomeron carried by the interacting parton if we assume the colourless object to be made of quarks and gluons: $\beta = \frac{Q^2}{Q^2+M_X^2} = \frac{x_{Bj}}{x_P}$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

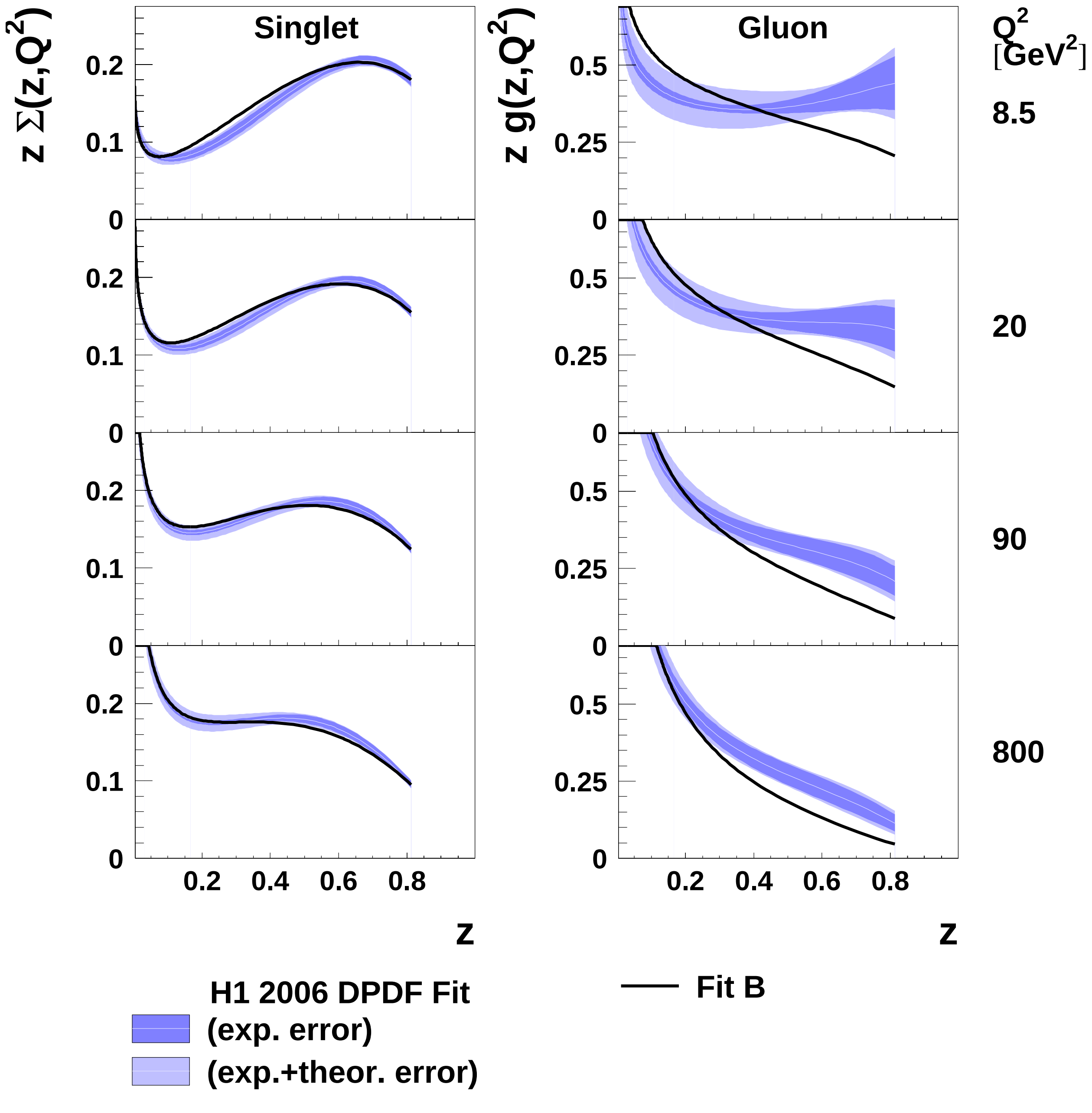
$$\frac{dF_2^D}{d\log Q^2} \sim \frac{\alpha_S}{2\pi}\left[P_{qg} \otimes g + P_{qq} \otimes \Sigma\right]$$





Parton densities in the pomeron (H1)

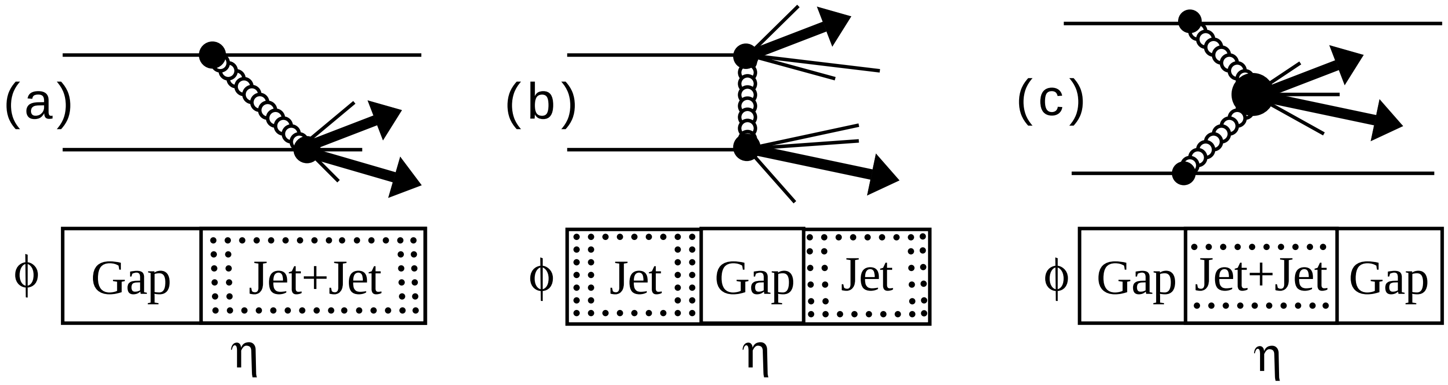
- Extraction of gluon and quark densities in pomeron: gluon dominated
- Gluon density poorly constrained at high β



Forward physics at LHC using proton tagging

- Present and discussion standard model and beyond standard model physics that can be accomplished using proton tagging at the LHC: AFP (ATLAS) and PPS (CMS/TOTEM)
- Soft diffraction and measurement of total cross section (TOTEM/ALFA) in addition, not mentionned in this talk

Diffraction at Tevatron/LHC

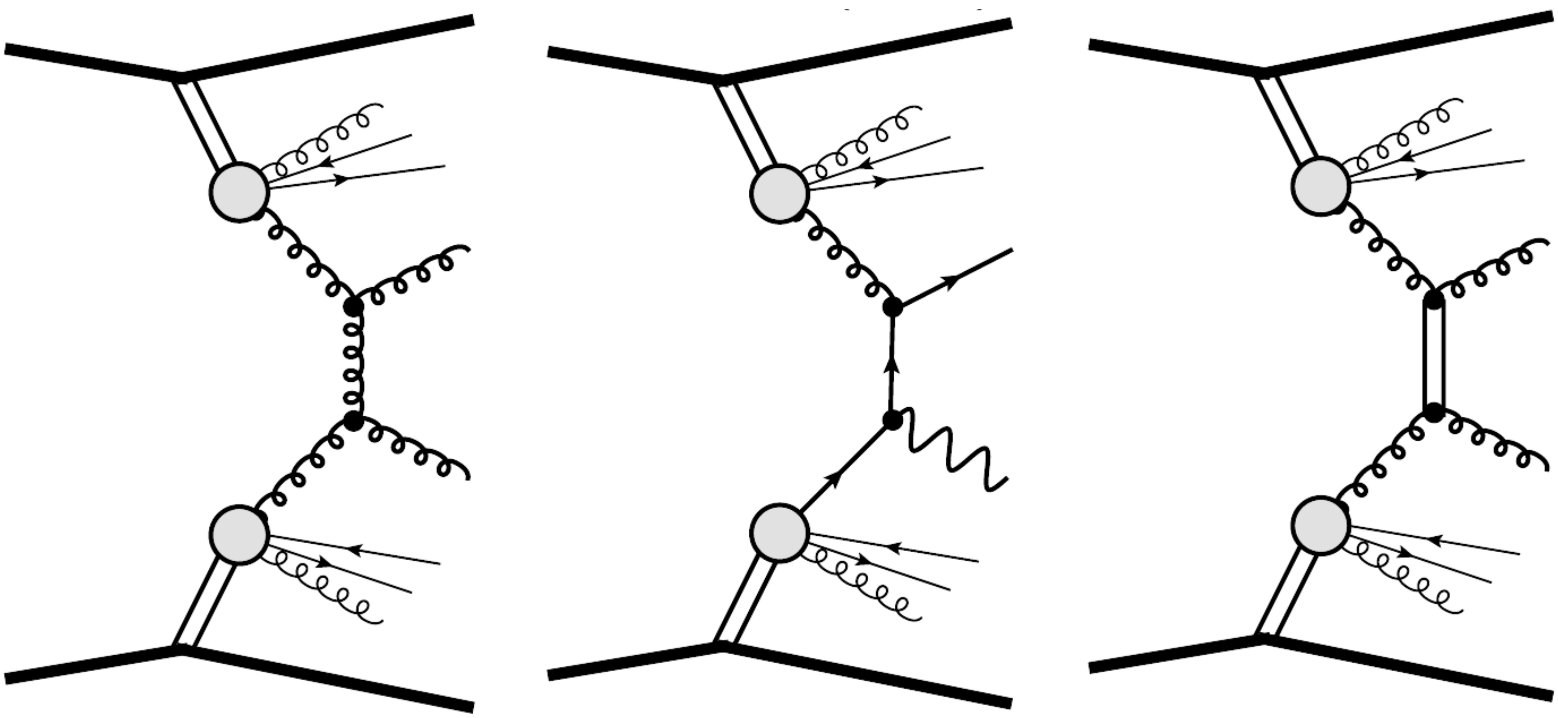


Kinematic variables

- 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

Inclusive diffraction at the LHC

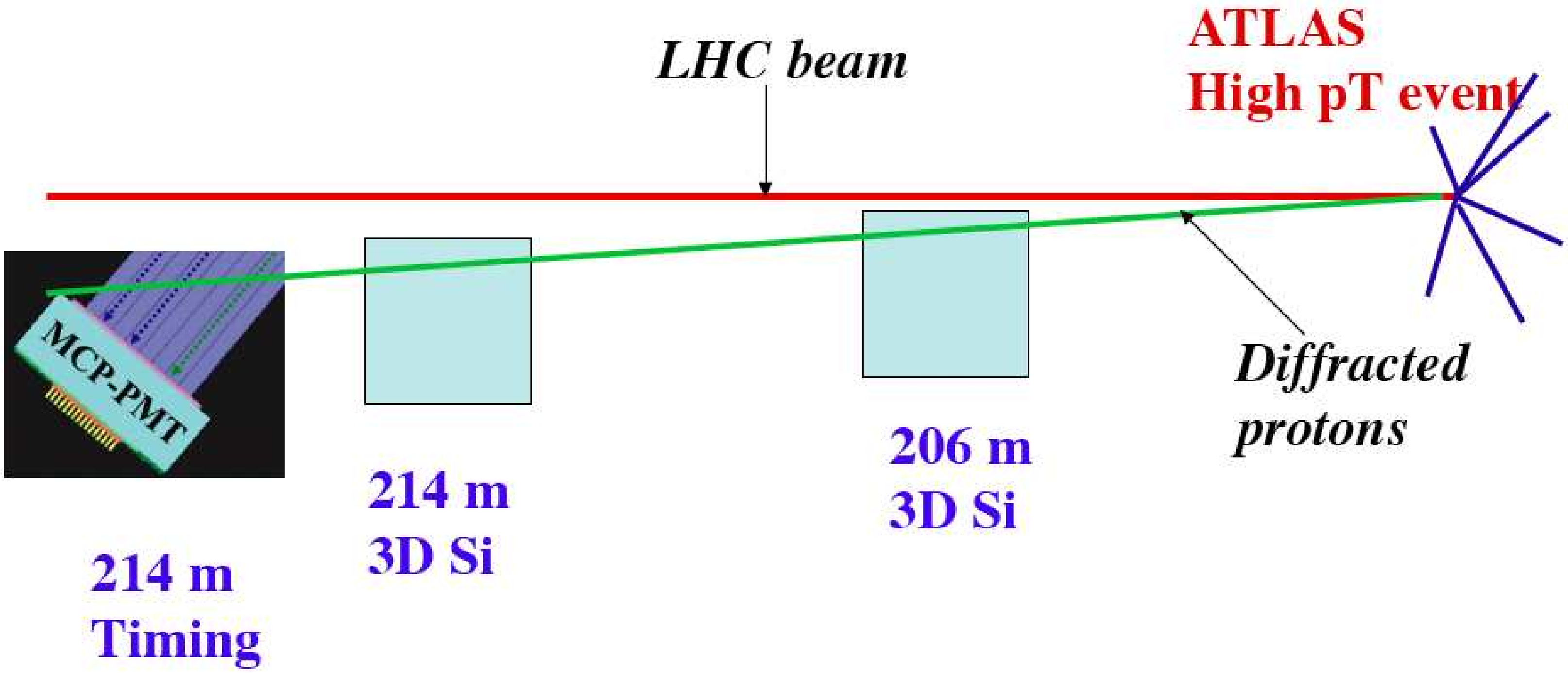
- Dijet production: dominated by gg exchanges
- γ+jet production: dominated by qg exchanges
- C. Marquet, C. Royon, M. Saimpert, D. Werder, arXiv:1306.4901
- Jet gap jet in diffraction: Probe BFKL
- C. Marquet, C. Royon, M. Trzebinski, R. Zlebcik, Phys. Rev. D 87 (2013) 034010; O. Kepka, C. Marquet, C. Royon, Phys. Rev. D79 (2009) 094019; Phys.Rev. D83 (2011) 034036
- Take quark and gluon density in Pomeron as measured at HERA to predict dijet and γ+jet cross sections



Forward Physics Monte Carlo (FPMC)

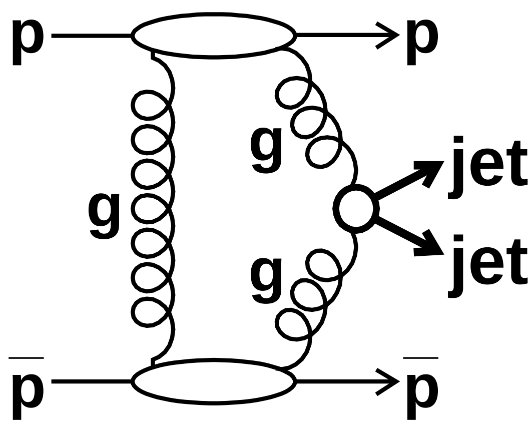
- FPMC (Forward Physics Monte Carlo): implementation of all diffractive/photon induced processes
- List of processes
  - two-photon exchange
  - single diffraction
  - double pomeron exchange
  - central exclusive production
- Inclusive diffraction: Use of diffractive PDFs measured at HERA, with a survival 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

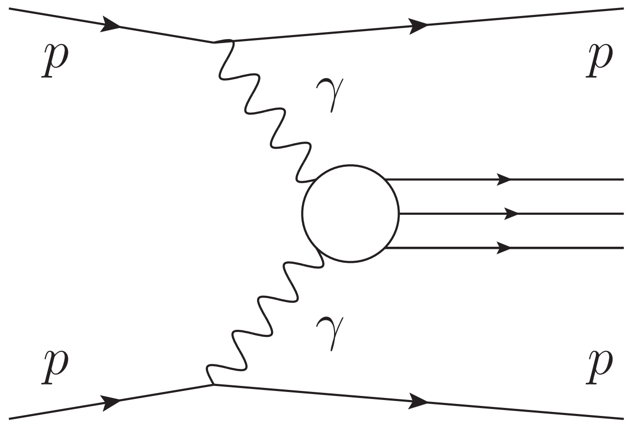
What is AFP/PPS?

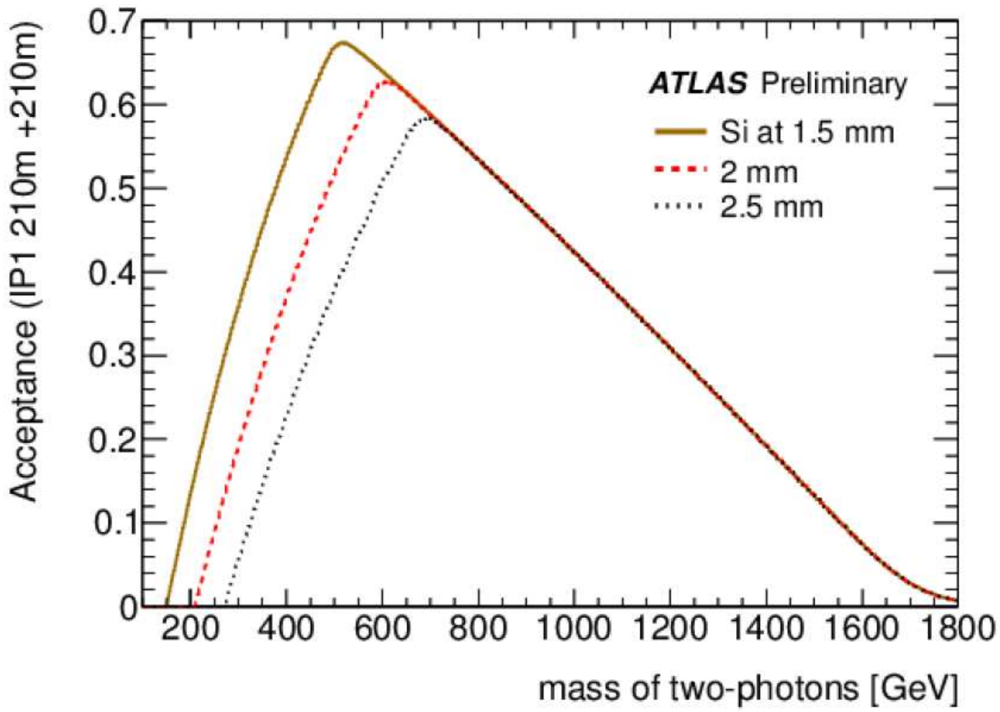


- Tag and measure protons at ±210 m: AFP in ATLAS, PPS in CMS/Totem
- AFP detectors: measure proton position (Silicon detectors) and time-of-flight (timing detectors)

AFP/PPS acceptance in total mass



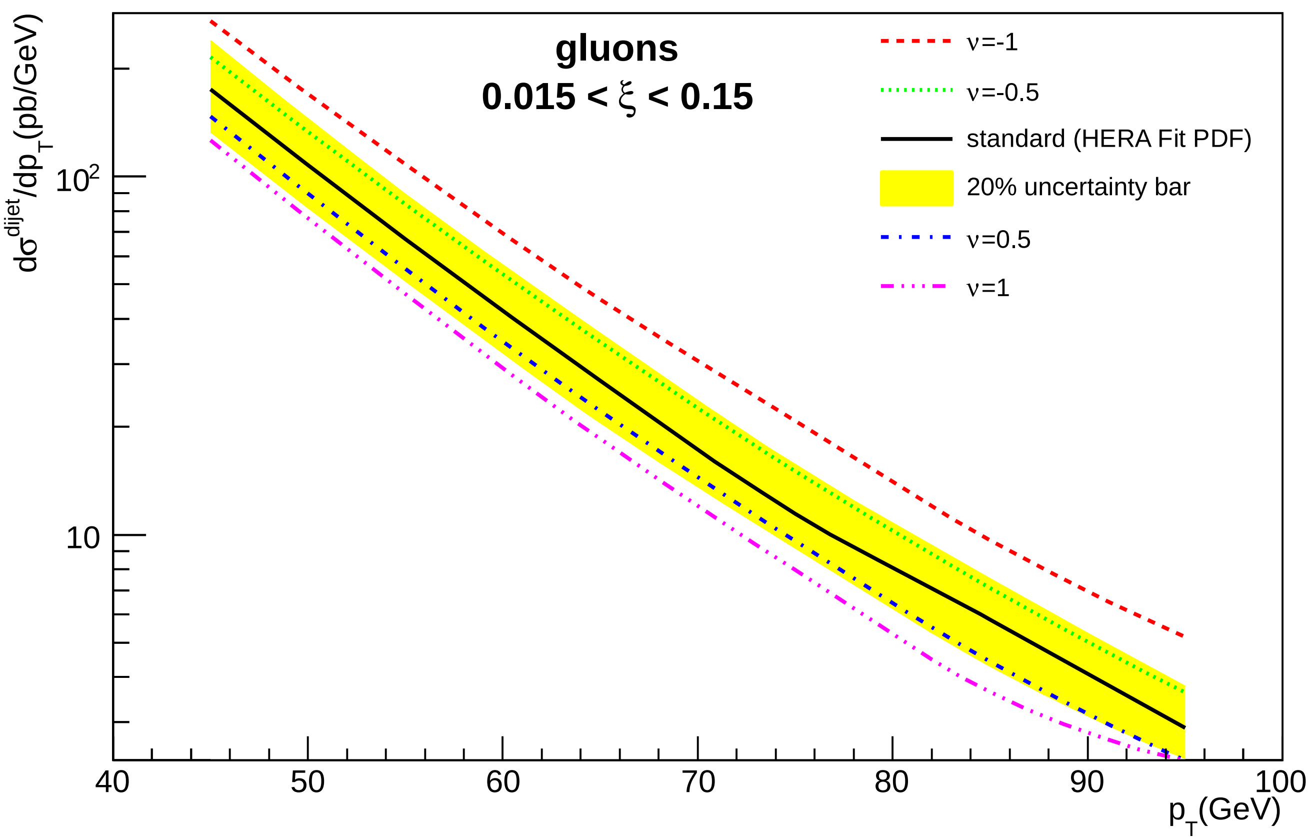




- Assume protons to be tagged at 210 m and/or 420 m
- Sensitivity to high mass central system, X, as determined using AFP
- Very powerful for exclusive states: kinematical constraints coming from AFP proton measurements

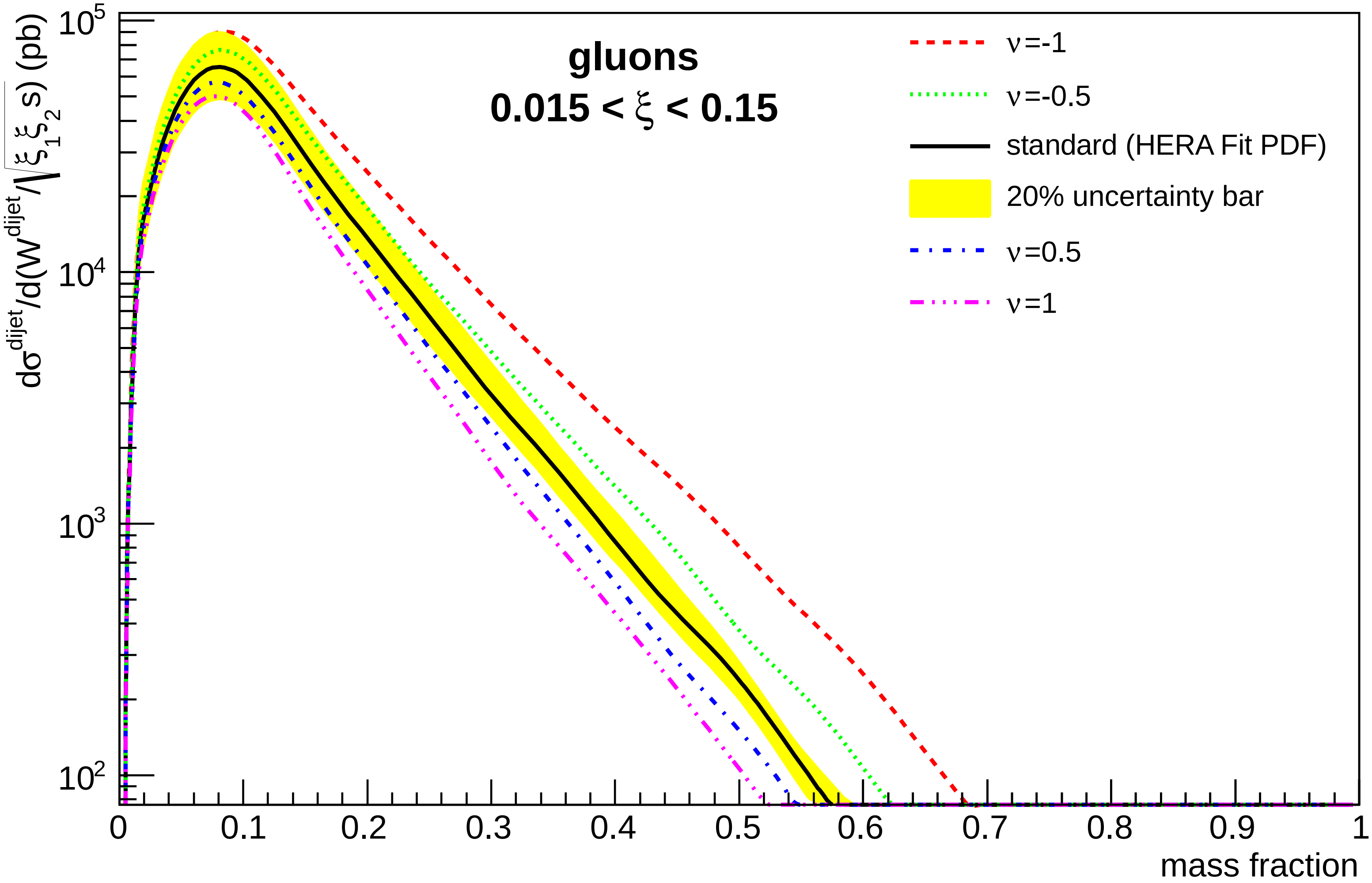
Inclusive diffraction at the LHC: sensitivity to gluon density

- 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)
- If a difference is observed, it will be difficult to know if it is related to the survival probability or different gluon density



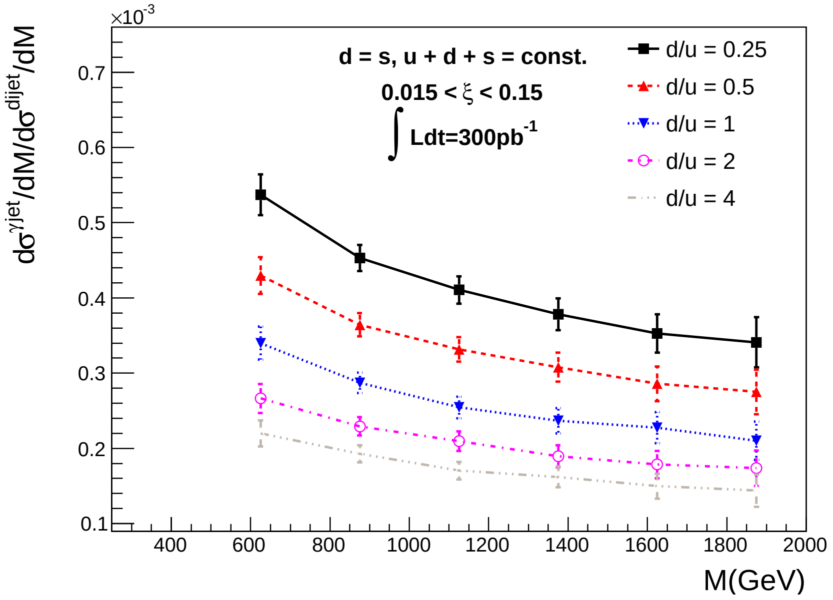
Dijet mass fraction: sensitivity to gluon density

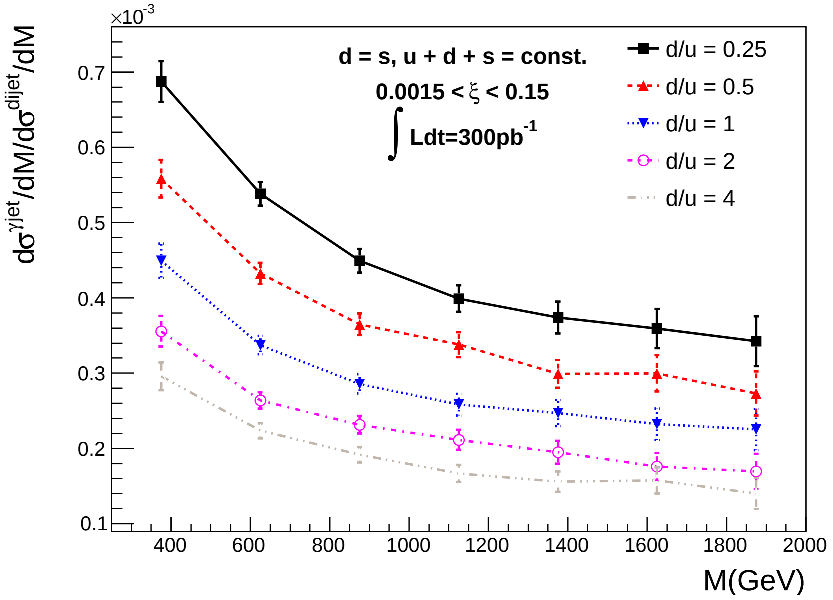
- Dijet mass fraction: dijet mass divided by total diffractive mass ($\sqrt{\xi_1 \xi_2 S}$)
- Sensitivity to gluon density in Pomeron especially the gluon density on Pomeron at high β
- Exclusive jet contribution will appear at high dijet mass fraction



Inclusive diffraction at the LHC: sensitivity to quark densities

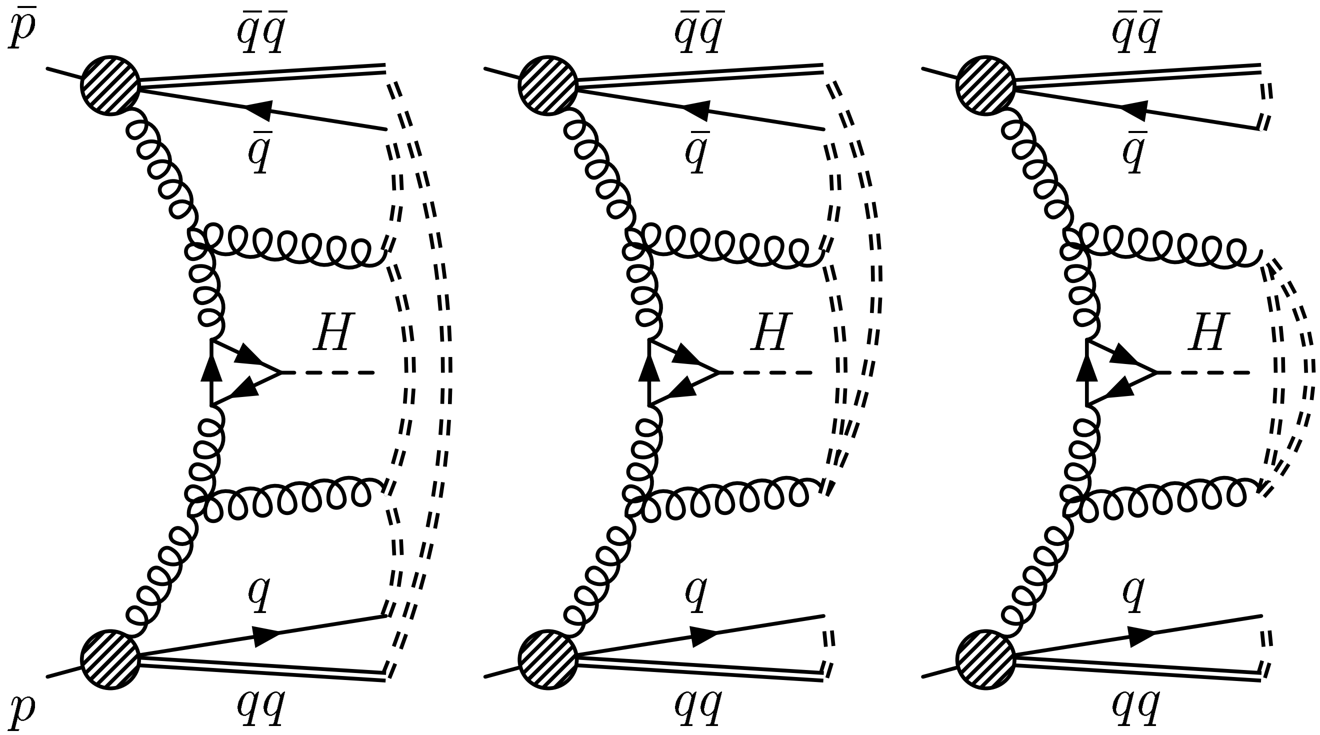
- Predict DPE γ+jet divided by dijet cross section at the LHC
- Sensitivity to universality of Pomeron model
- Sensitivity to quqrk density in Pomeron, and of assumption: $u = d = s = \bar{u} = \bar{d} = \bar{s}$ used in QCD fits at HERA





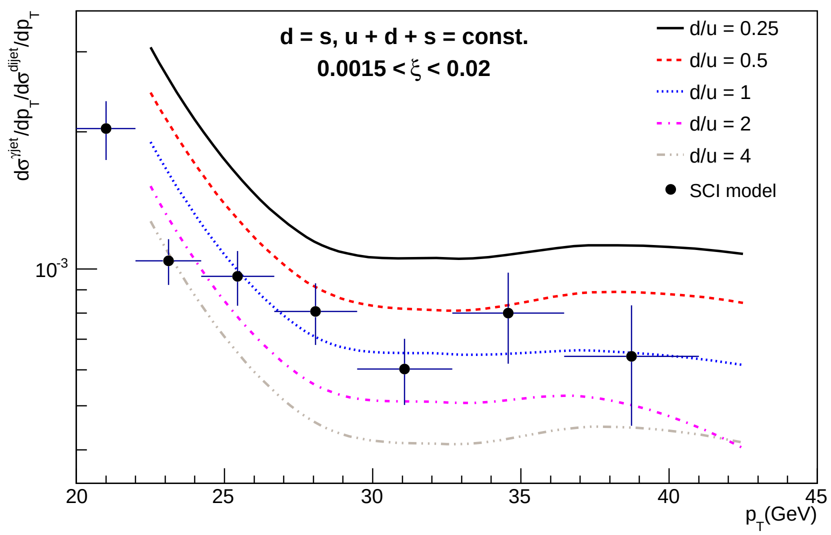
Soft Colour Interaction models

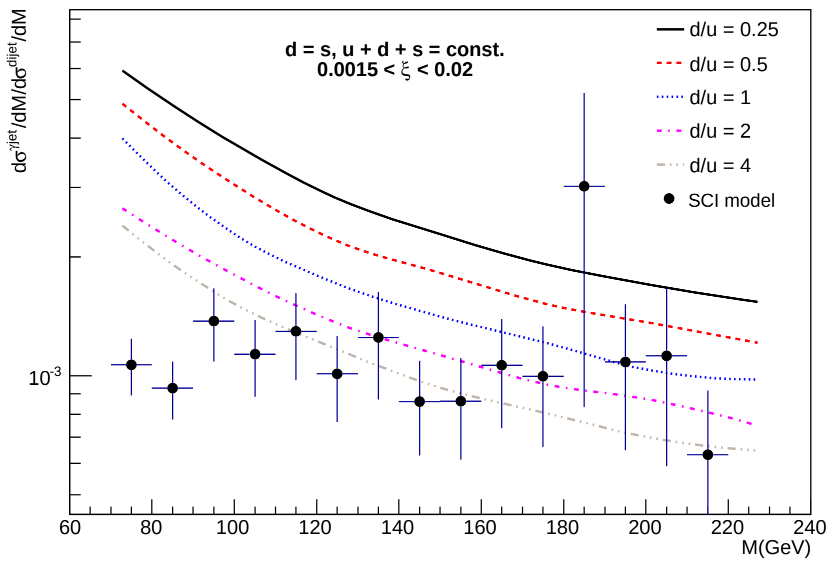
- A completely different model to explain diffractive events: Soft Colour Interaction (R.Enberg, G.Ingelman, N.Timneanu, hep-ph/0106246)
- Principle: Variation of colour string topologies, giving a unified description of final states for diffractive and non-diffractive events
- No survival probability for SCI models



Inclusive diffraction at the LHC: sensitivity to soft colour interaction m

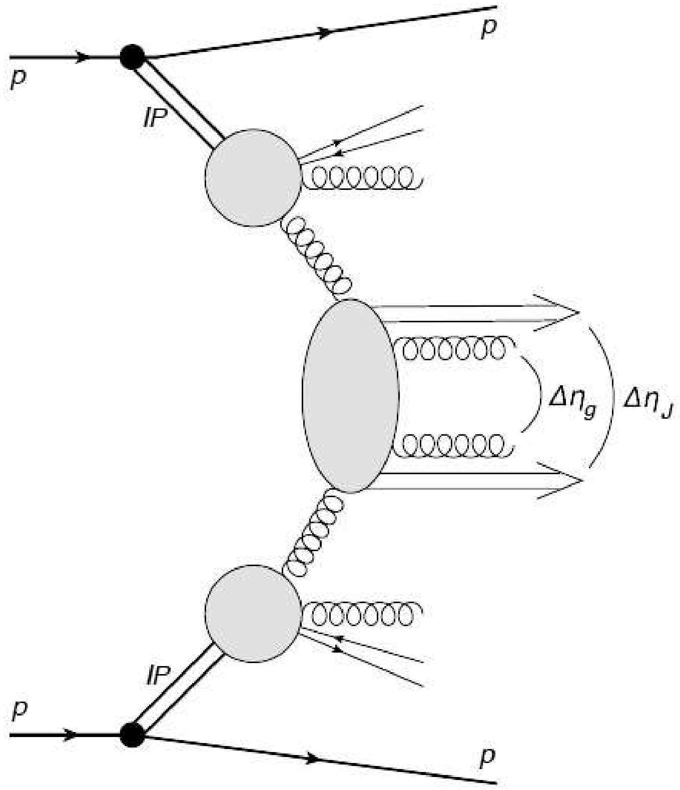
- Predict DPE γ+jet divided by dijet cross section at the LHC for pomeron like and SCI models
- In particular, the diffractive mass distribution (the measurement with lowest systematics) allows to distinguish between the two sets of models: flat distribution for SCI

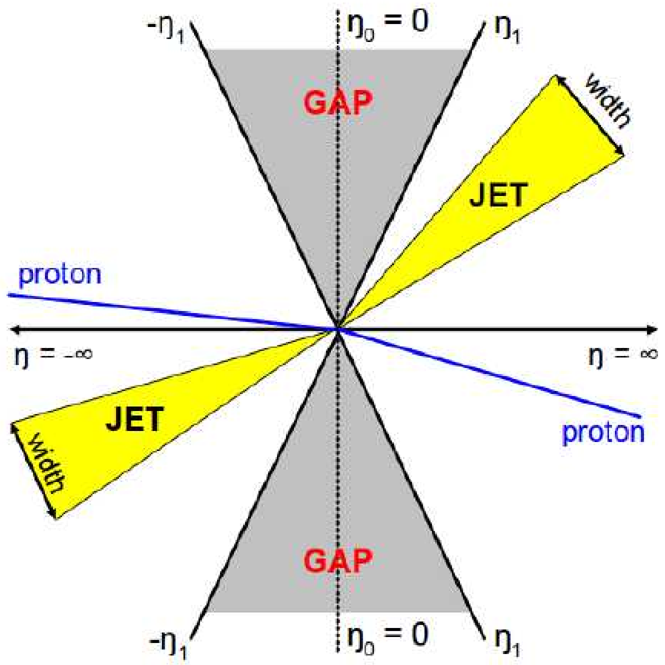




Jet gap jet events in diffraction

- 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

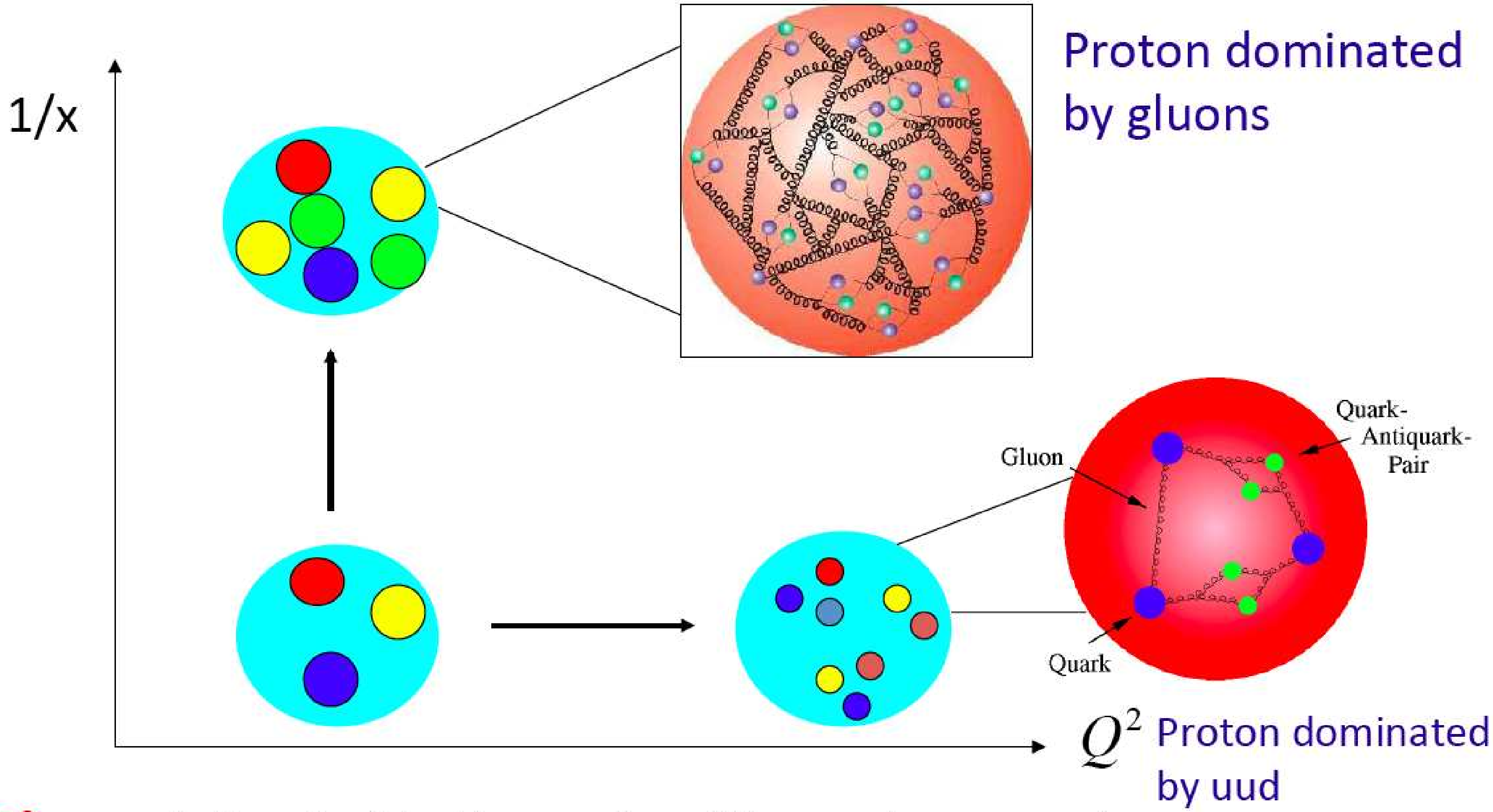




Looking for BFKL effects

- 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)

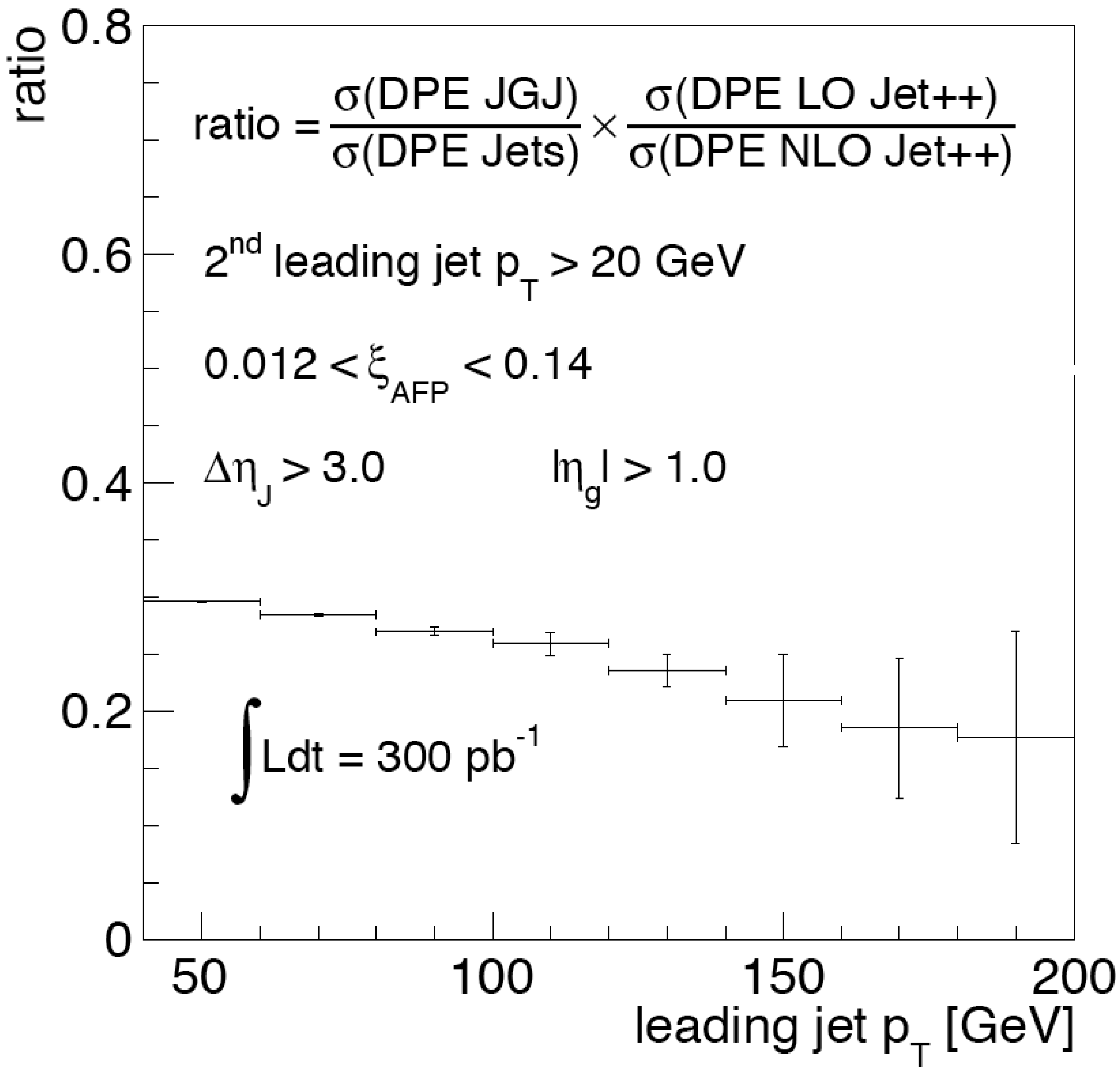


Q^2 : resolution inside the proton (like a microscope)

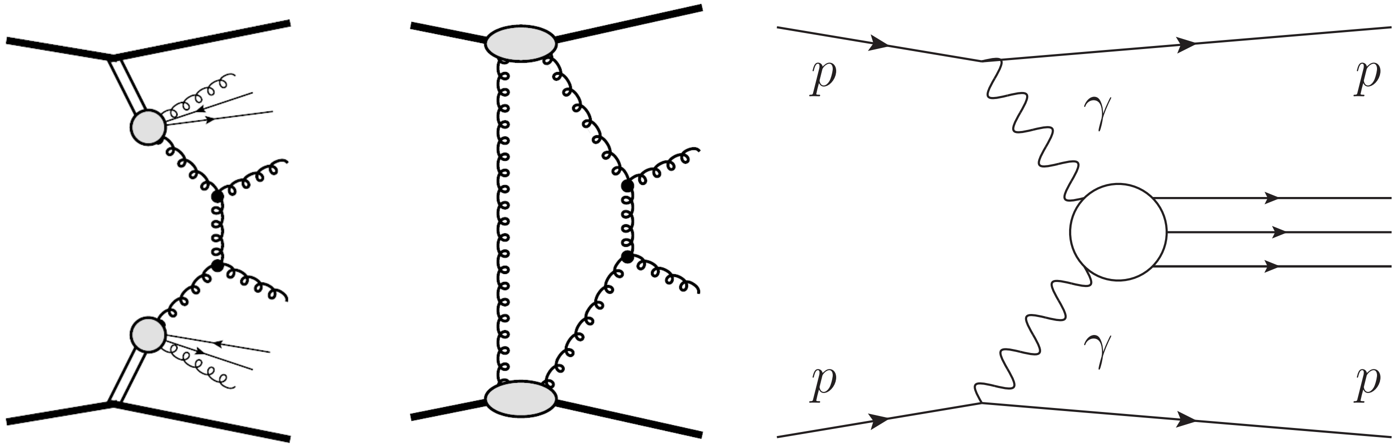
x :Proton momentum fraction carried away by the interacting quark

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



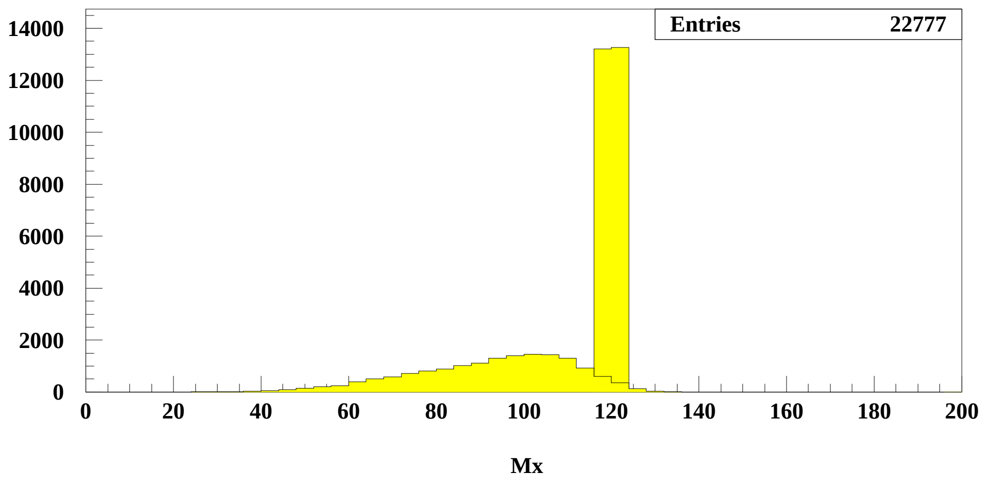
Exclusive and inclusive diffraction

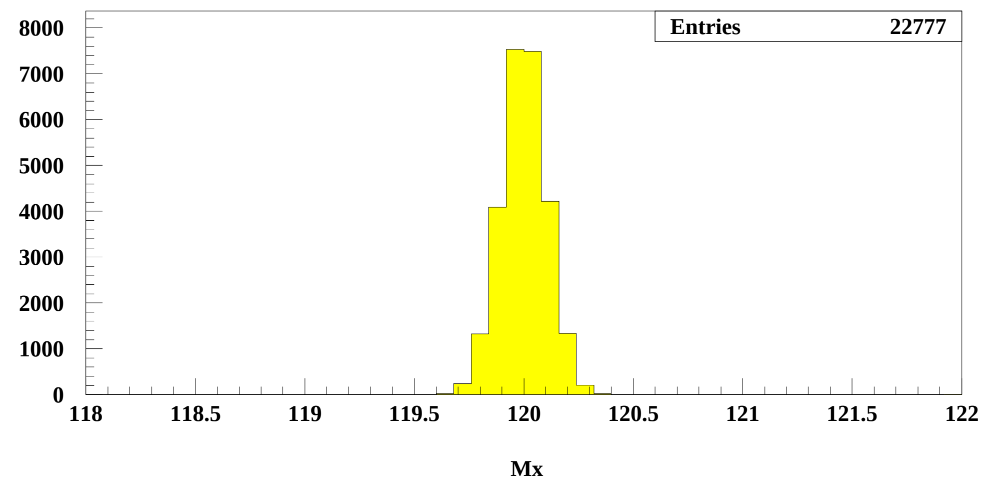


- Exclusive diffraction: All the energy is used to produce the dijets, namely $xG \sim \delta$
- Possibility to reconstruct the properties of the object produced exclusively (via photon and gluon exchanges) from the tagged proton: system completely constrained
- Possibility of constraining the background by asking the matching between the information of the two protons and the produced object

Advantage of exclusive production: Higgs boson?

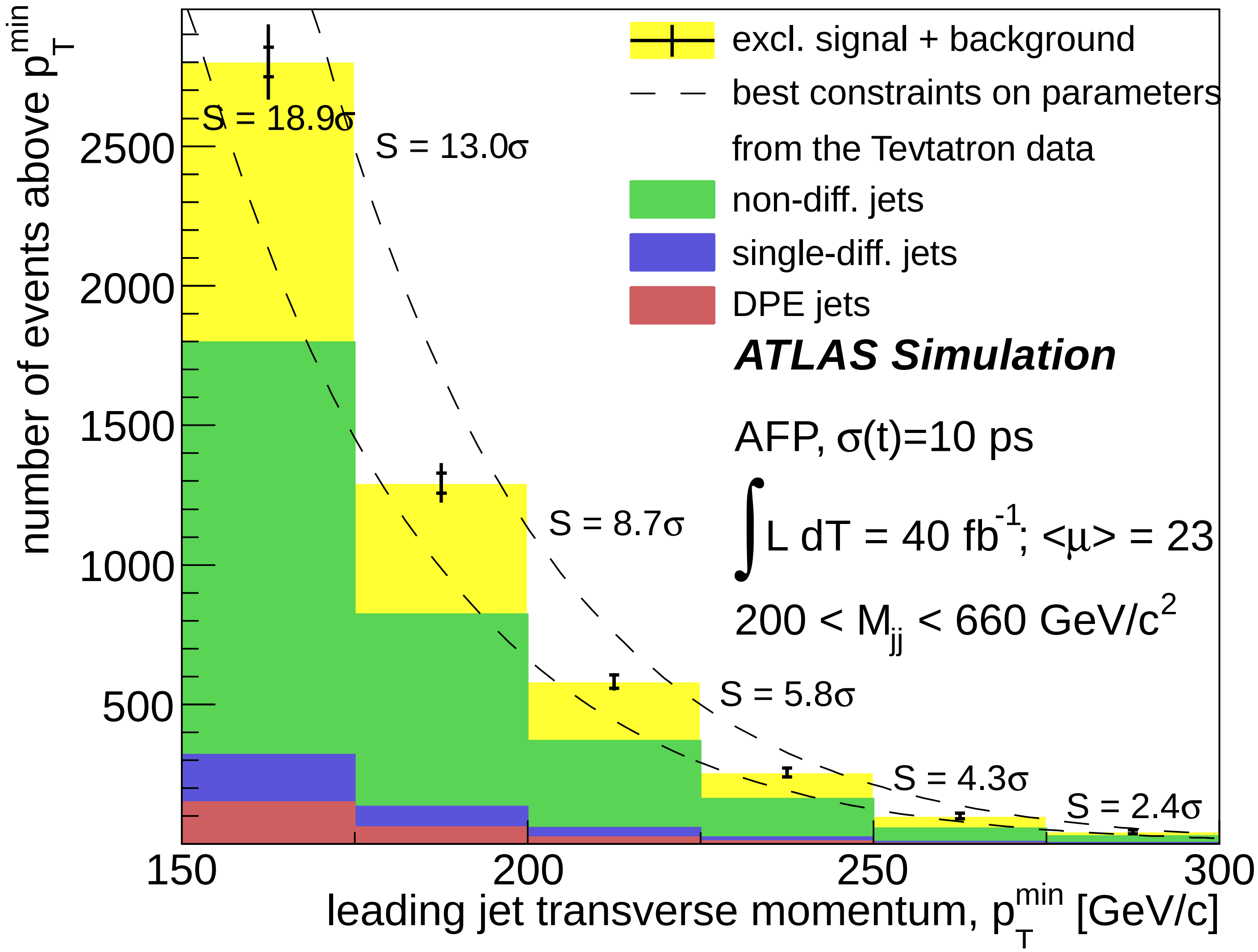
- Good Higgs mass reconstruction: fully constrained system, Higgs mass reconstructed using both tagged protons in the final state ($pp \to pHp$)
- Typical SM cross section: About 3 fb for a Higgs boson mass of 120 GeV (large uncertainty), strong increase in NMSSM models for instance
- No energy loss in pomeron "remnants"
- Mass resolution of the order of 2-3% after detector simulation





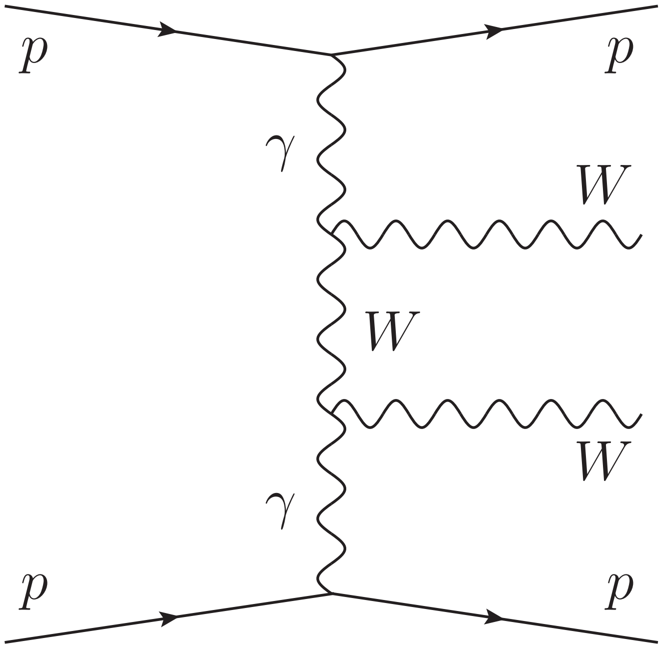
Exclusive jet production at the LHC

- Jet cross section measurements: up to 18.9 σ 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

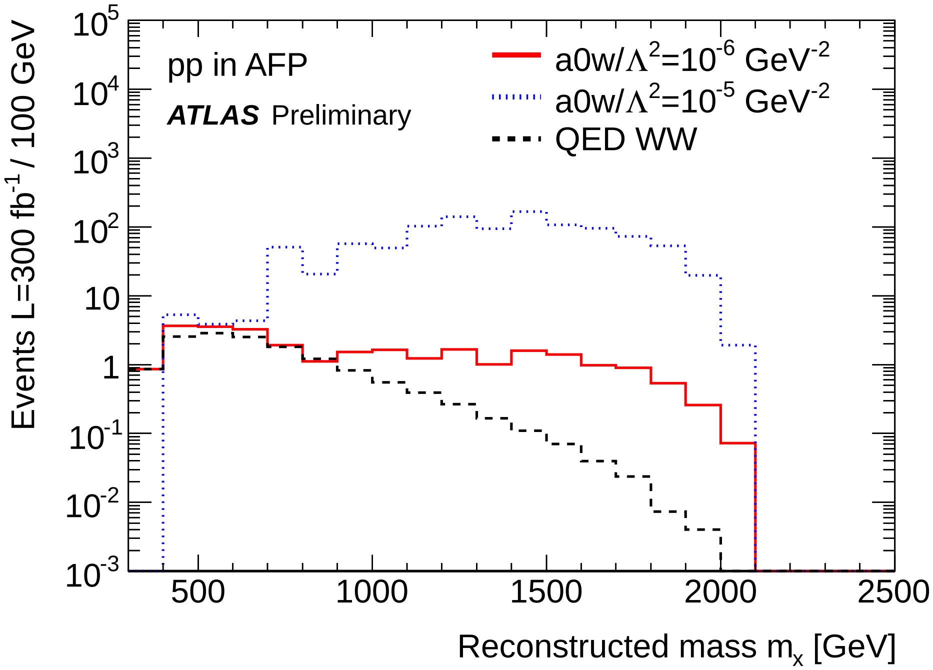
Search for $\gamma\gamma WW$ quartic anomalous coupling

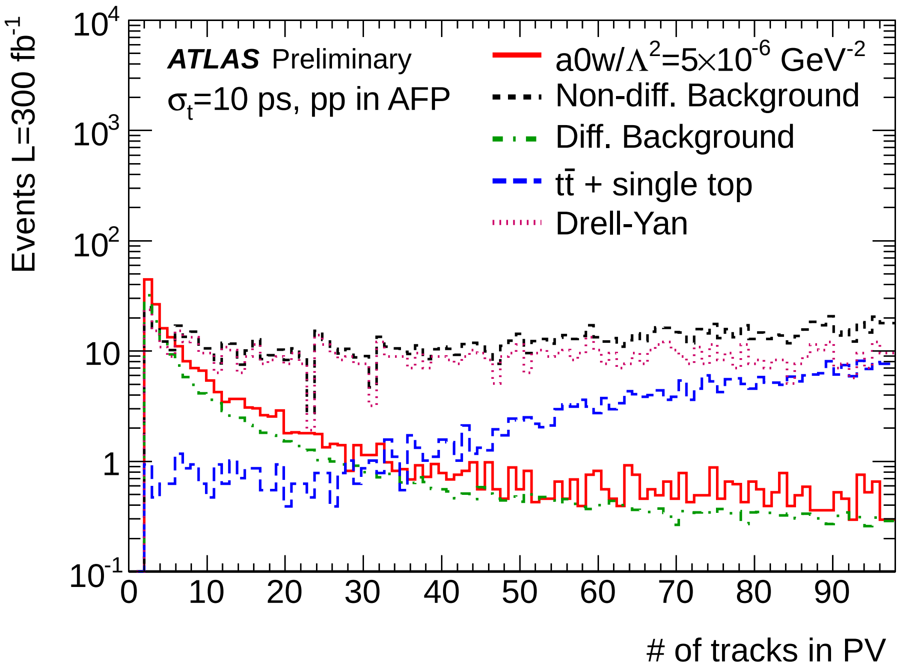


- Study of the process: $pp \to ppWW$
- Standard Model: $\sigma_{WW} = 95.6$ fb, $\sigma_{WW}(W = M_X > 1TeV) = 5.9$ fb
- Process sensitive to anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$; motivated by studying in detail the mechanism of electroweak symmetry breaking, predicted by extradim. models
- Many additional anomalous couplings to be studied involving Higgs bosons (dimension 8 operators); $\gamma\gamma$ specially interesting (C. Grojean, S. Fichet, G. von Gersdorff)
- 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, ArXiv 1312.5153

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}

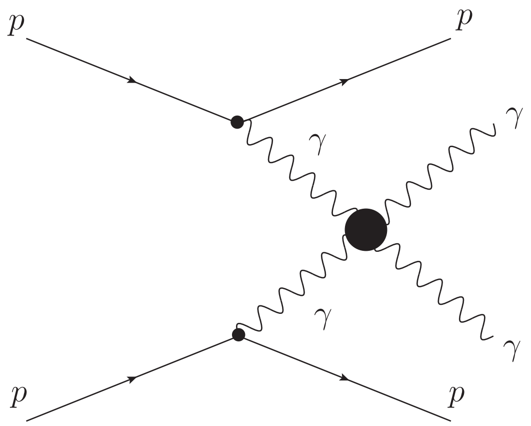
Reach at LHC

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

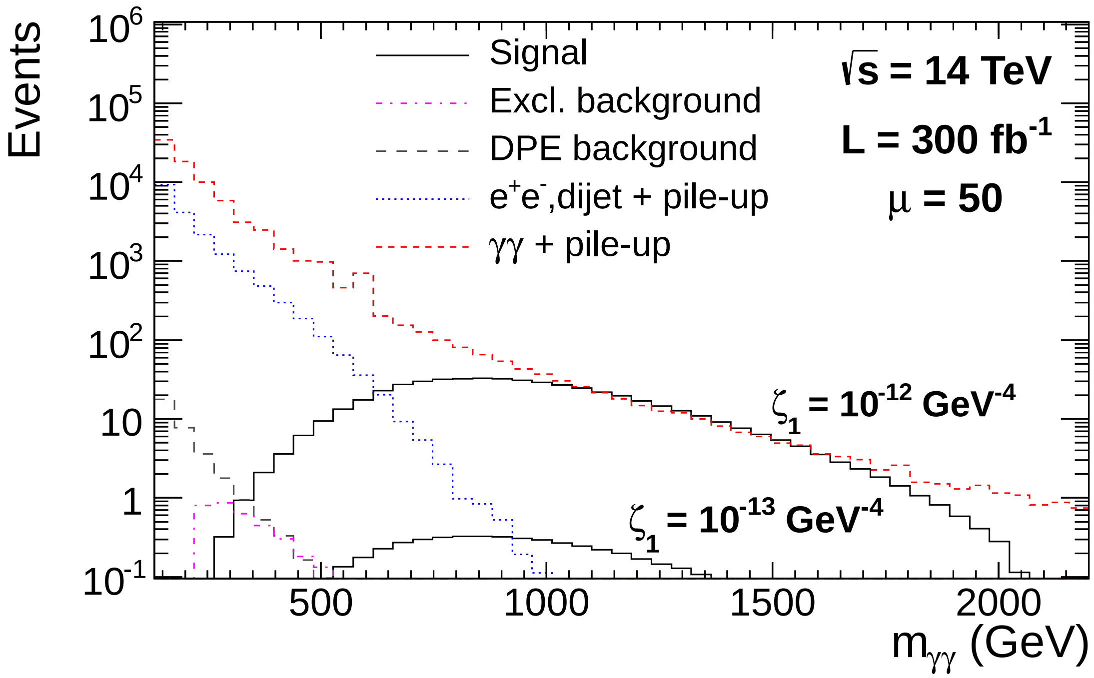
Couplings	OPAL limits [GeV^{-2}]	Sensitivity @ $\mathcal{L} = 30$ (200) fb^{-1} 5σ	95% CL
a_0^W/Λ^2	[-0.020, 0.020]	5.4 10^{-6} (2.7 10^{-6})	2.6 10^{-6} (1.4 10^{-6})
a_C^W/Λ^2	[-0.052, 0.037]	2.0 10^{-5} (9.6 10^{-6})	9.4 10^{-6} (5.2 10^{-6})
a_0^Z/Λ^2	[-0.007, 0.023]	1.4 10^{-5} (5.5 10^{-6})	6.4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

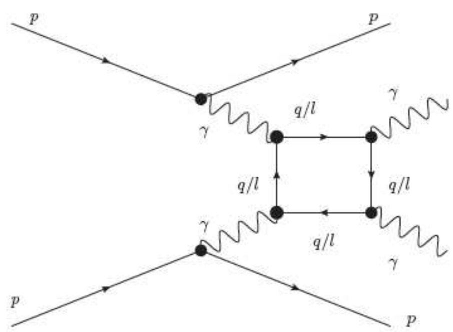
Search for quartic $\gamma\gamma$ anomalous couplings



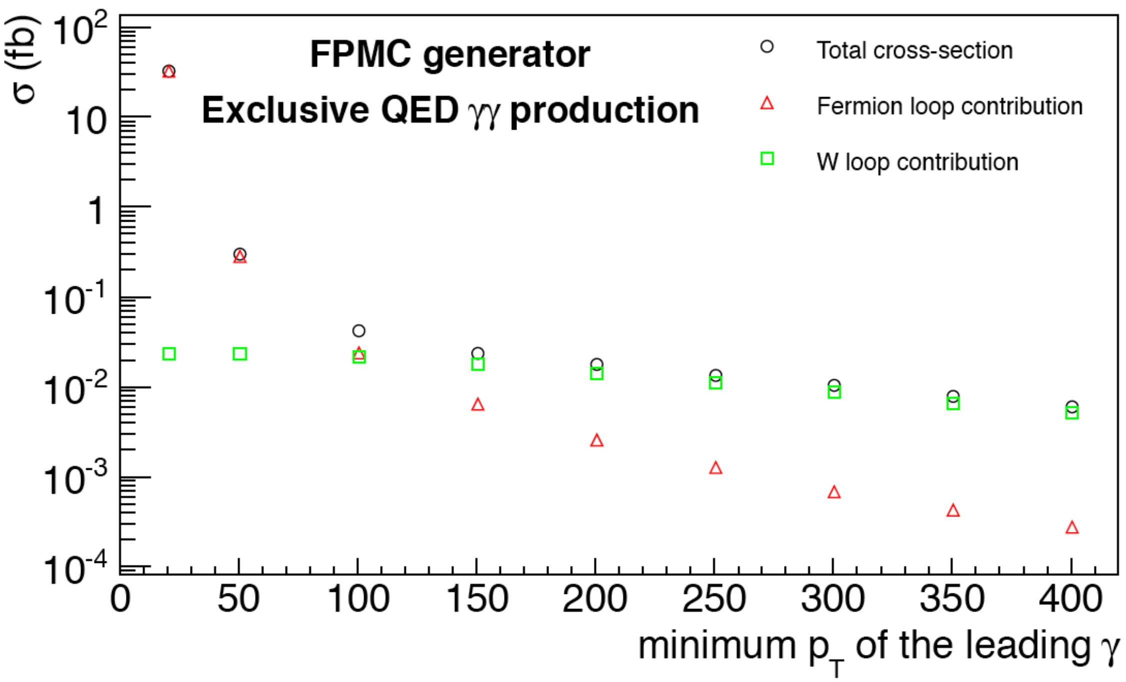
- Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- Analysis performed at hadron level including detector efficiencies, resolution effects, pile-up...



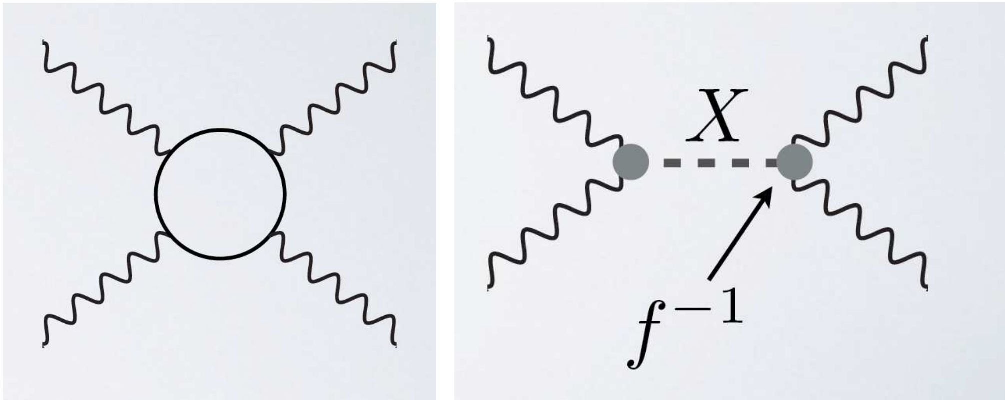
SM QED exclusive $\gamma\gamma$ production



- Different loop contributions: fermions (quarks, leptons), vectors (W bosons)
- W loop contributions and massive fermions added in the calculation, together with interferences SM/exotics
- W loop non negligible for $p_{T,\gamma} > 50$ 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}

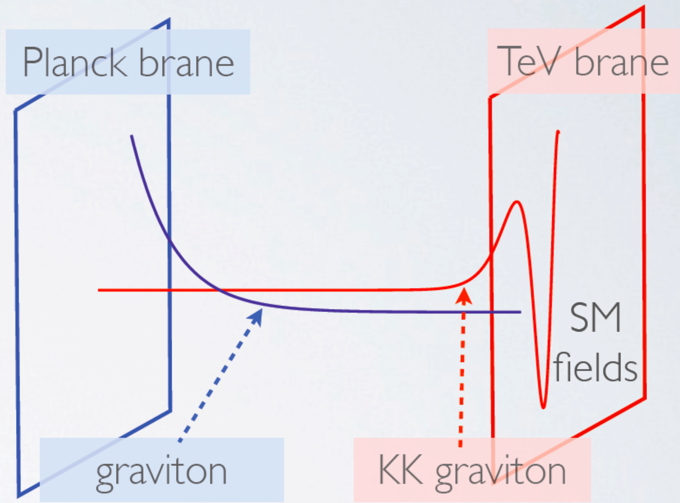
- ζ_1 can also be modified by neutral particles at tree level (extensions of the SM including scalar, pseudo-scalar, and spin-2 resonances that couple to the photon) $\zeta_1 = (f_s m)^{-2} d_{1,s}$ where f_s is the $\gamma\gamma X$ coupling of the new particle to the photon, and $d_{1,s}$ depends on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

Warped extra-dimensions (Gero von Gersdorff)

✘ Warped Extra Dimensions solve hierarchy problem of SM

✘ 5^{th} 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

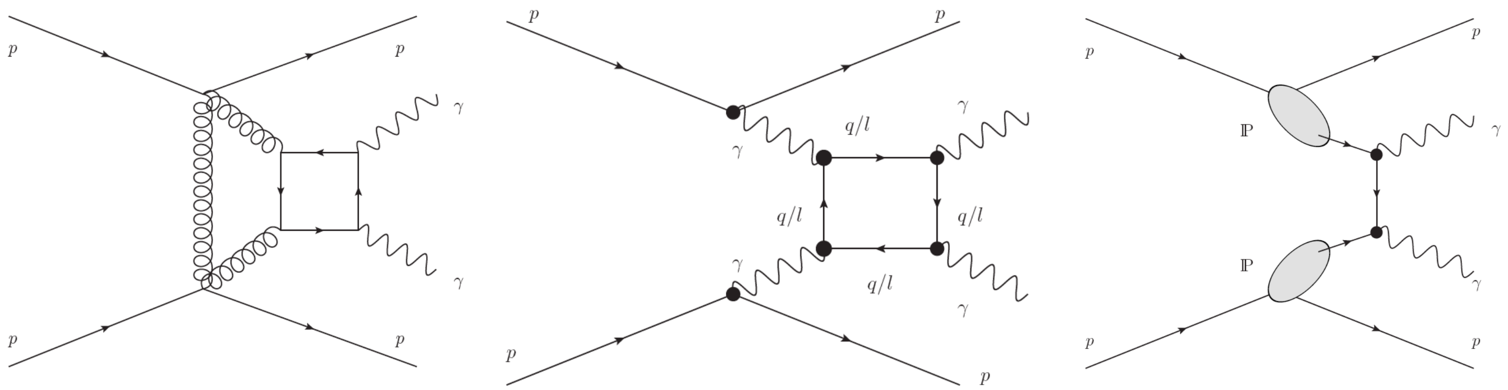
- Which models/theories are we sensitive to using AFP/PPS
- Beyond standard models predict anomalous couplings of $\sim 10^{-14}$-10^{-13}
- Work in collaboration with Sylvain Fichet, Gero von Gehrsdorff

Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings: Analysis flow

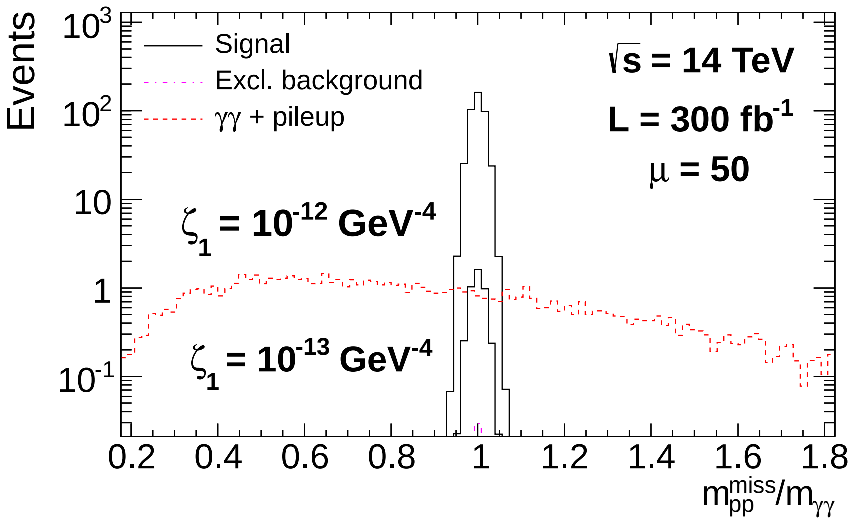
- Studies performed at hadron level but taking into account the main detector/pile-up effects
- By default, $> 1\gamma$ converted is requested (1 mm resolution), but all γ are also considered, and can handle pile-up thanks to the "pointing" ATLAS calorimeter (contrary to CMS...)
- pile-up simulated in AFP: 50, 100, 200 pile-up events per bunch crossing are considered
- Exclusive diffractive /DPE/ND backgrounds are considered and the largest one is pile-up
- Main detector effects are included (from ATLAS ECFA studies ATL-PHYS-PUB-2013-009), for instance:
  - Photon conversion probability: 15% in barrel, 30% in the end-caps; γ rapidity, Φ, and p_T resolutions taken into account as well as the reconstruction efficiency
  - Misidentification of electron as a γ: 1%
  - Misidentification of jet as a γ: 1/4000,
  - See: S.Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert, ArXiv 1312.5153, accepted in Phys. Rev. D

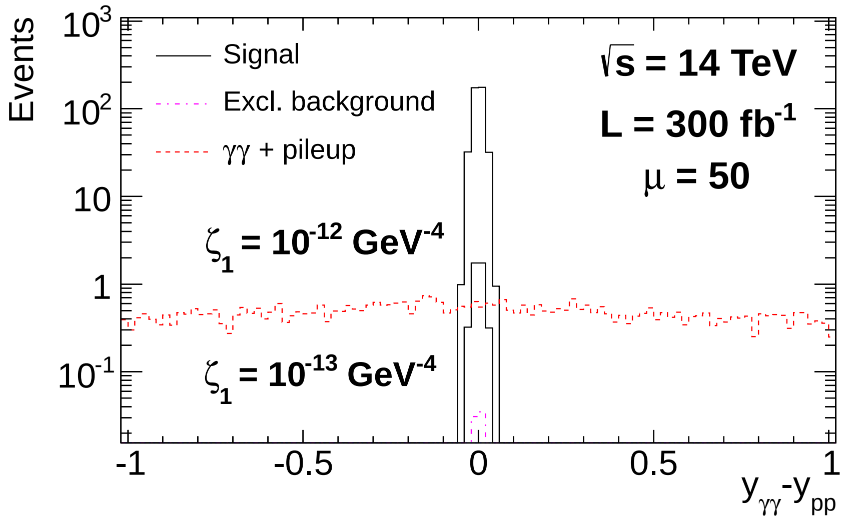
Considered background

- Background leading to two photons in the final state: DPE diphoton production, exclusive diphotons (quark box, exclusive KMR), DPE Higgs decaying into $\gamma\gamma$
- Background related to misidentification: Exclusive dilepton production, dijet production, same for DPE (using misidentification probanilities in ATLAS)
- Pile up background: Non diffractive production and pile up (50, 100, 200), Drell-Yan, dijet, diphoton
- Assume at least 1 photon to be converted, high p_T photons (above 200 GeV)
- Further reduction using timing detectors: Reject background by a factor 40 for a pile up of 50 (10 ps resolution assumed)



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 background event for 15.1 (3.8) signal events for an anomalous coupling of 2 10^{-13} (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

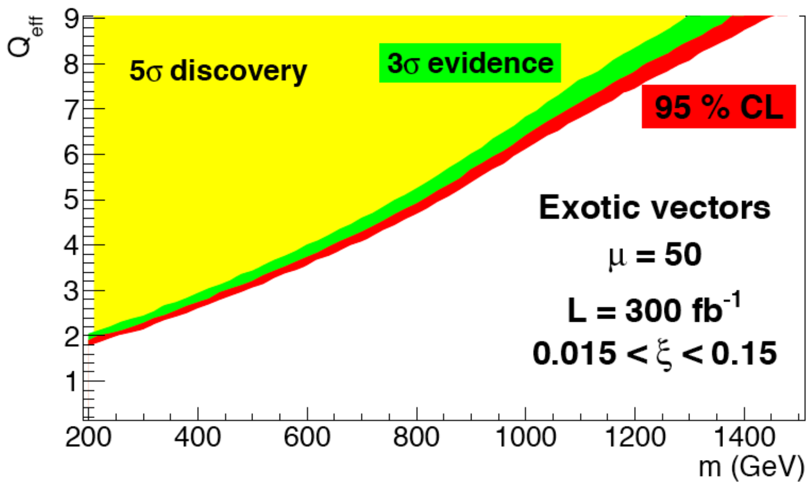
Cut / Process	Signal	Excl.	DPE	e^+e^-, dijet + pile-up	$\gamma\gamma$ + pile-up
$0.015 < \xi < 0.15$, $p_{T1,2} > 50$ GeV	20.8	3.7	48.2	$2.8\ 10^4$	$1.0\ 10^5$
$p_{T1} > 200$GeV, $p_{T2} > 100$ GeV	17.6	0.2	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	16.6	0.1	0.	0.2	1023
$p_{T2}/p_{T1} > 0.95$, $\|\Delta\phi\| > \pi - 0.01$	16.2	0.1	0.	0.	80.2
$\sqrt{\xi_1\xi_2 s} = m_{\gamma\gamma} \pm 3\%$	15.7	0.1	0.	0.	2.8
$\|y_{\gamma\gamma} - y_{pp}\| < 0.03$	15.1	0.1	0.	0.	0.

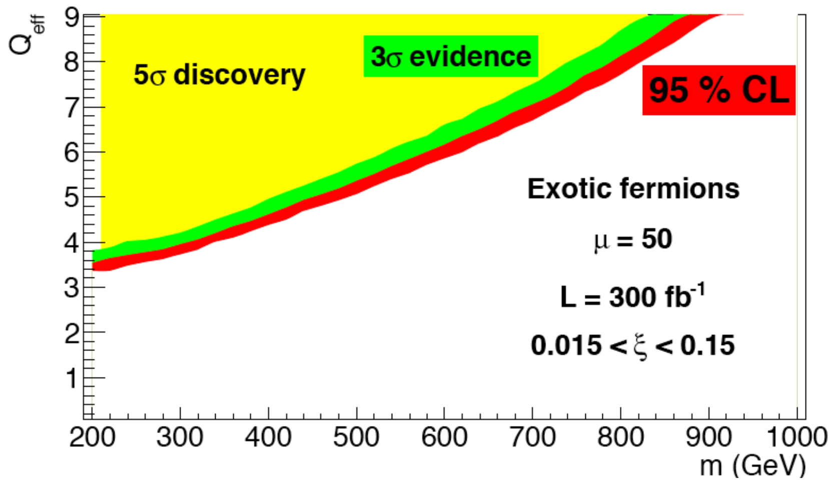
- No background after cuts for 300 fb^{-1} **without needing timing detector information**
- Exclusivity cuts needed to suppress backgrounds:
  - Without exclusivity cuts using AFP: background of 80.2 for 300 fb^{-1} for a signal of 16.2 events ($\zeta_1 = 2\ 10^{-13}$)
  - With exclusivity cuts: 0 background for 15,1 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})	≥ 1 conv. γ 5 σ	≥ 1 conv. γ 95% CL	all γ 95% CL	all γ 95% CL
ζ_1 f.f.	$1 \cdot 10^{-13}$	$9 \cdot 10^{-14}$	$5 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$
ζ_1 no f.f.	$3.5 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$	$7 \cdot 10^{-15}$
ζ_2 f.f.	$2.5 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$1 \cdot 10^{-13}$	$4.5 \cdot 10^{-14}$
ζ_2 no f.f.	$7.5 \cdot 10^{-14}$	$5.5 \cdot 10^{-14}$	$3 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$

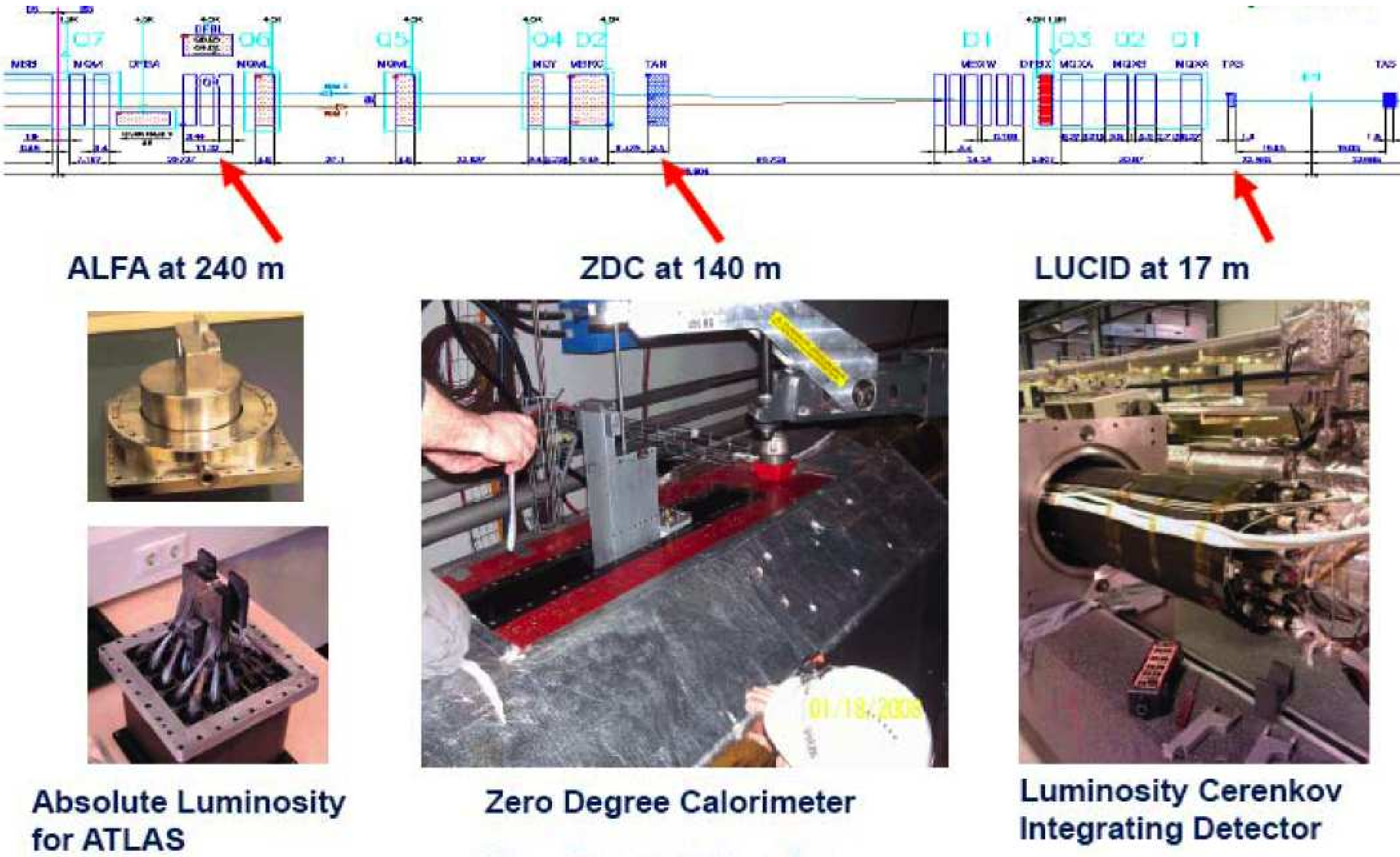
Full amplitude calculation

- 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 independant way
- Enhancement parametrised with particle mass and effective charge $Q_{eff} = QN^{1/4}$ where N is the multiplicity
- Publication in preparation with G. von Gehrsdorff, S. Fichet, M. Saimpert, O. Kepka, B. Lenzi, C. Royon
- Unprecedented sensituvites at hadronic colliders reaching the values predicted by extra-dim models



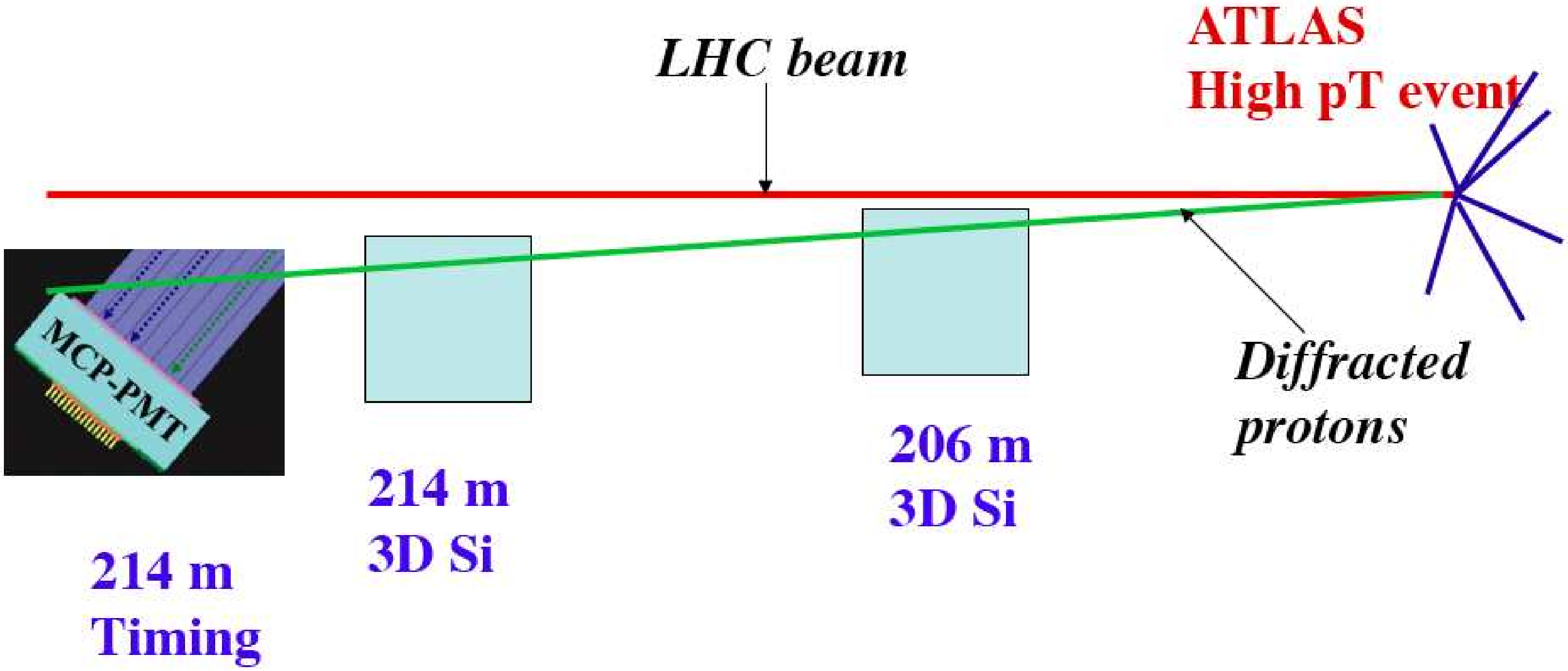


Forward detectors in ATLAS



- ALFA
- ZDC
- LUCID

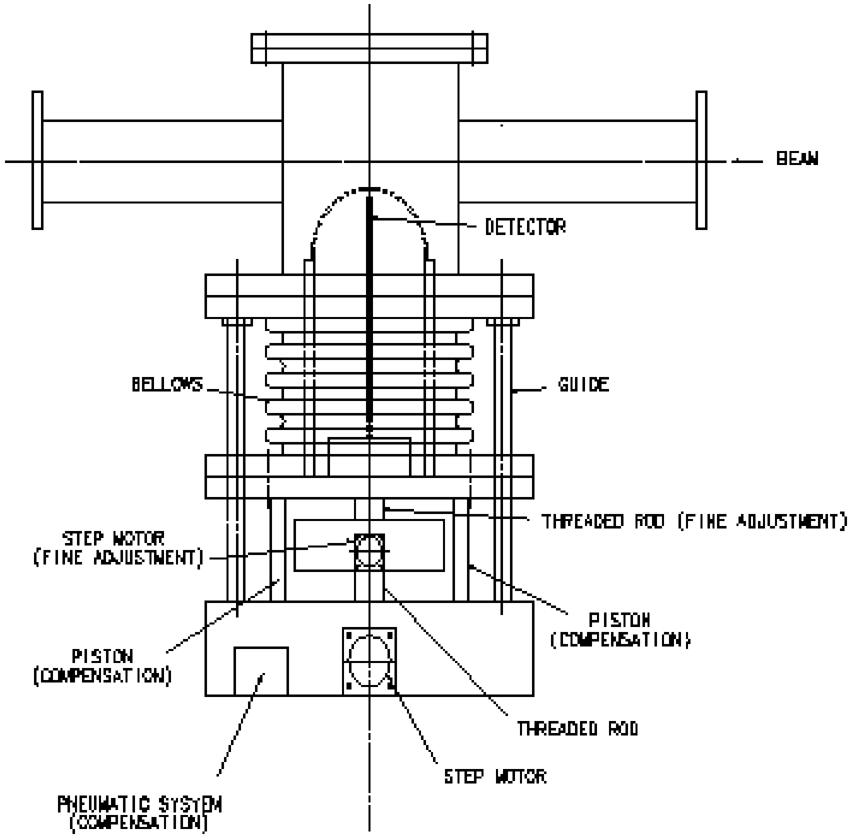
What is AFP/PPS?



- Tag and measure protons at ± 210 m
- 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

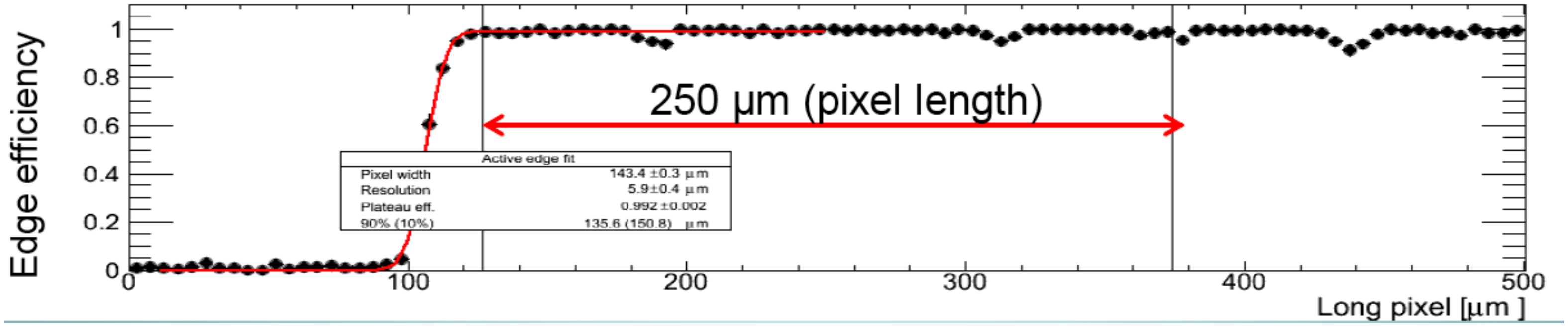
Roman pots

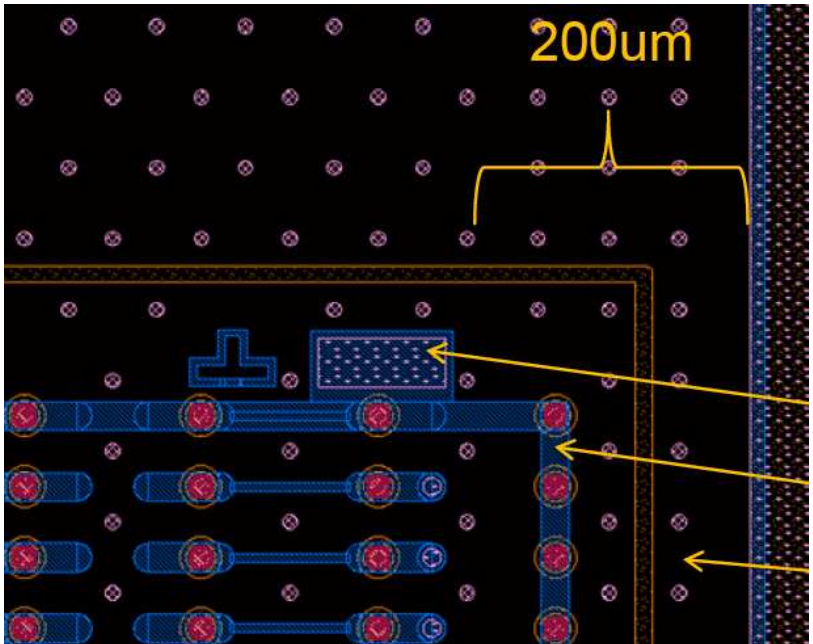
- Method to find diffractive events: Tag the proton in the final state
- Install roman pot detectors: by default solution at 210 m (2 roman pots with Si detectors, 1 with timing)



Detector I: 3D Si detector

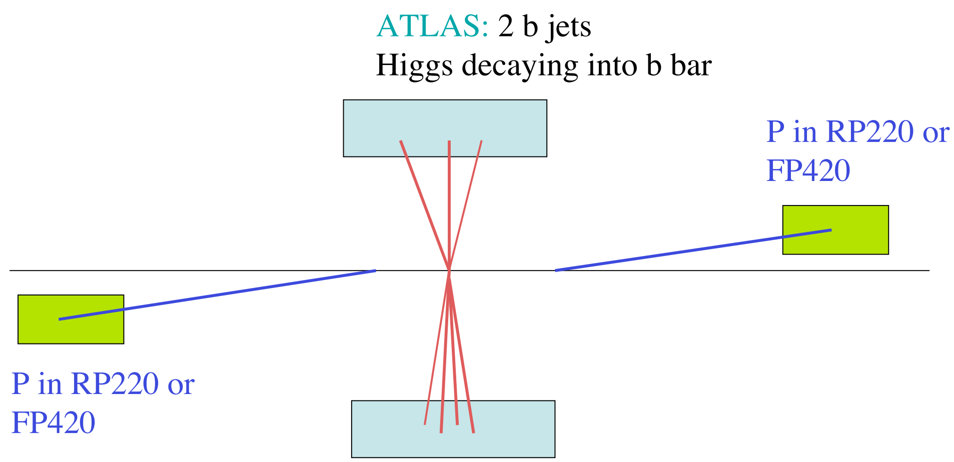
- Key requirements for the Si detector
  - Spatial resolution of 10 (30) μm in x (y) direction over the full detector coverage (2 cm $\times$ 2 cm); Angular resolution of 1 μrad
  - Minimal dead space at the edge and radiation hardness
- Sensors: double-sided 3D 50$\times$250 micron pixel detectors (FBK) 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...

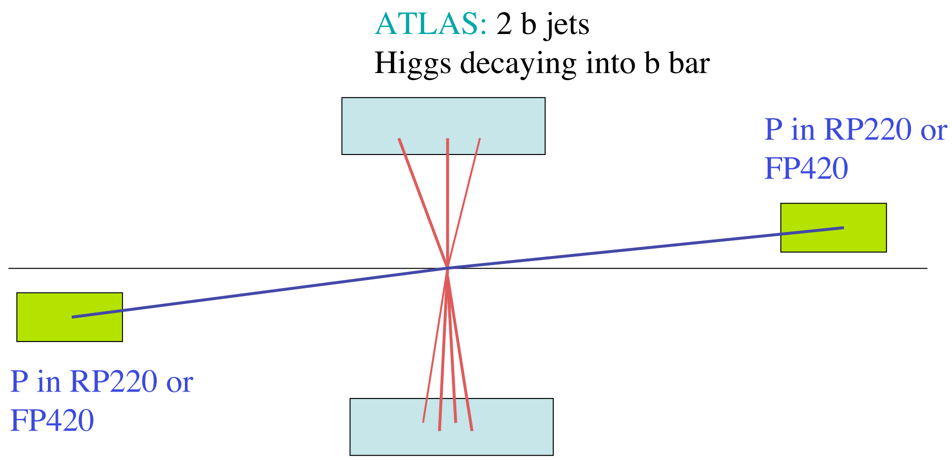




Detector II: Why do we need timing detectors?

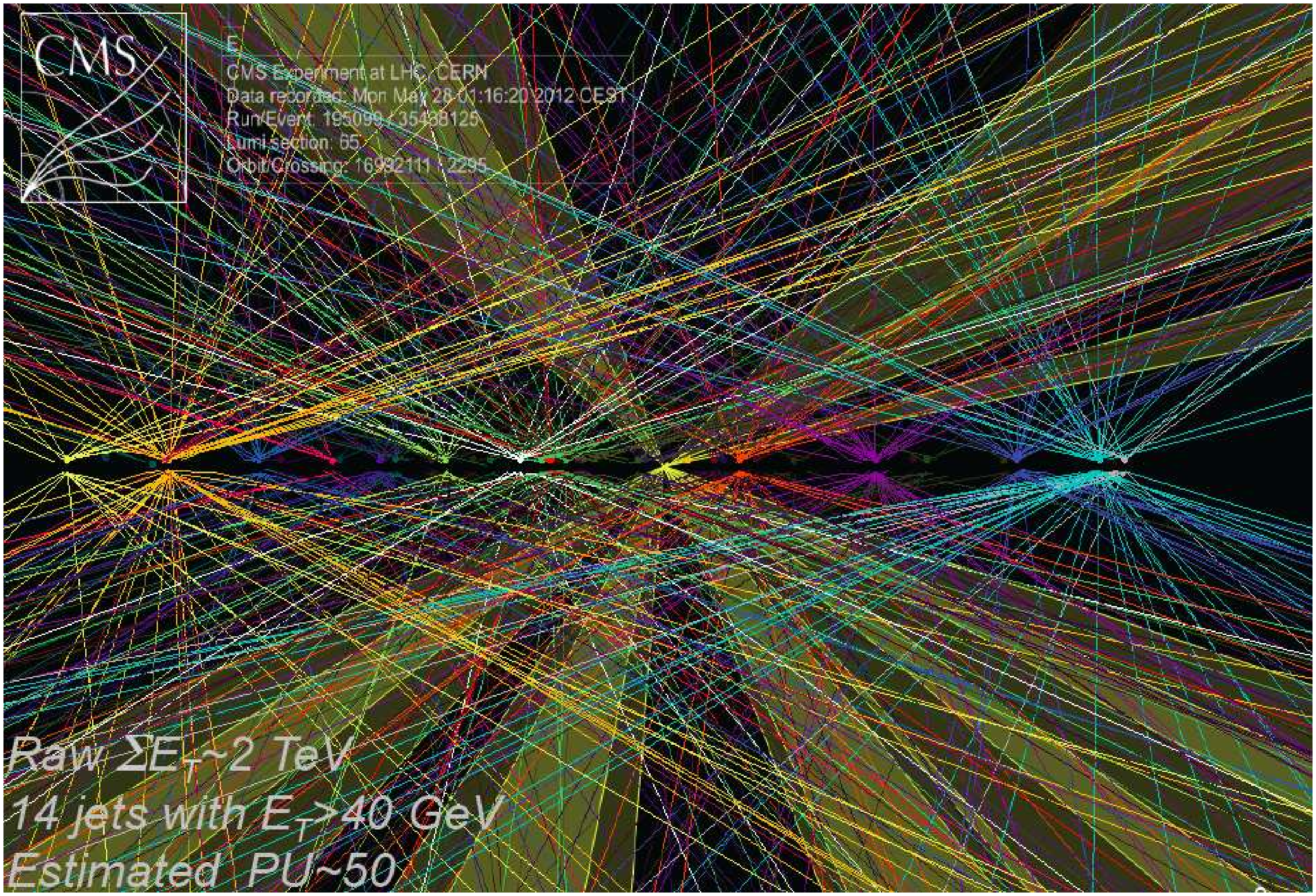
We want to find the events where the protons are related to Higgs production and not to another soft event (up to 35 events occuring at the same time at the LHC!!!!)





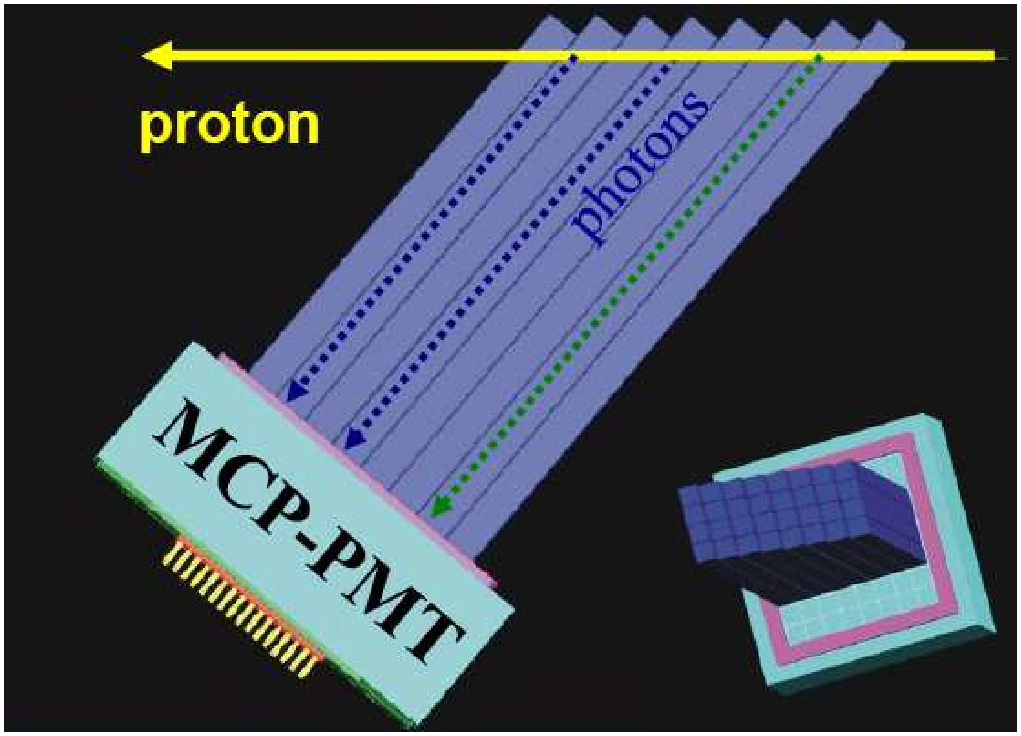
Pile up!

Many interactions occur in the same bunch crossing



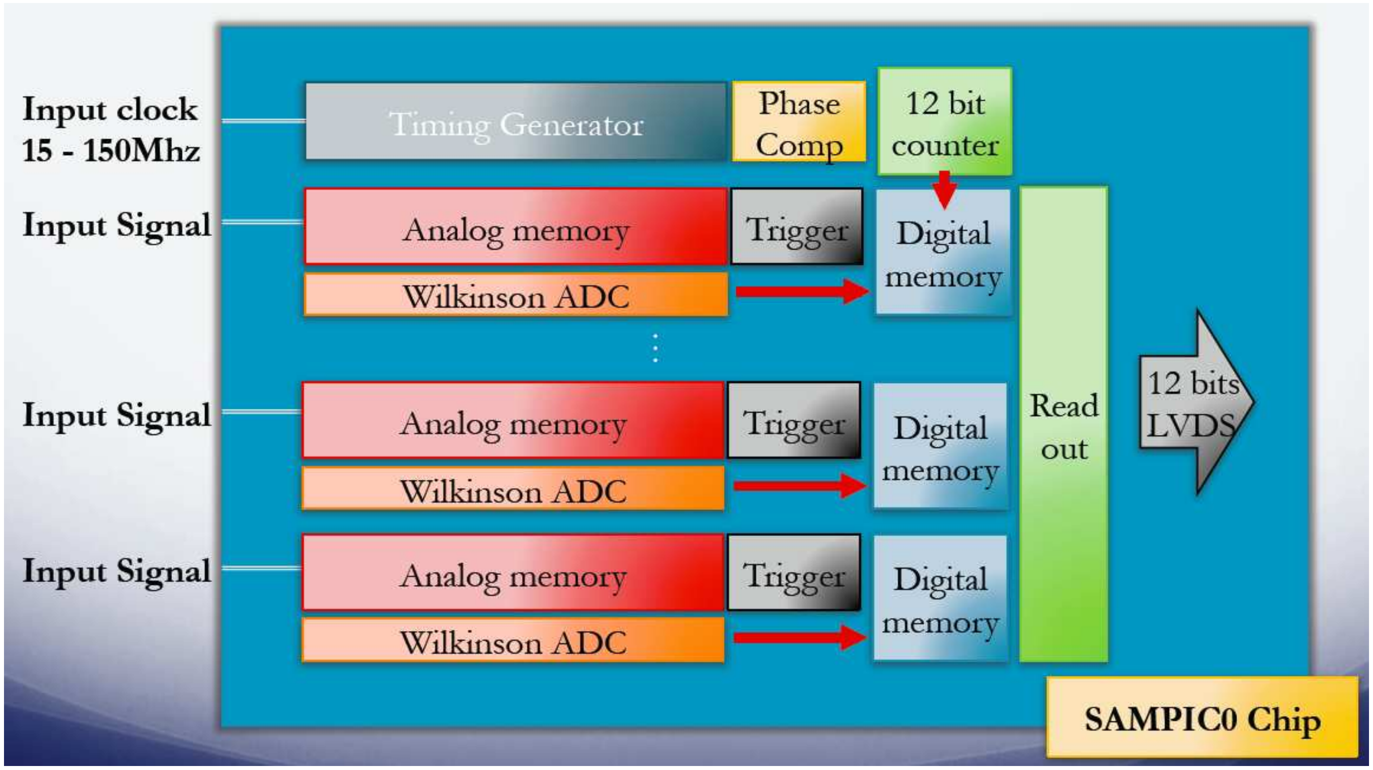
Detector II: timing detectors

- 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 or Silicon detectors



Saclay: Going beyond the present chip

- Development of a fast timing chip in Saclay SAMPIC:
  - Uses waveform sampling method
  - Sub 10 ps timing, 1GHz input bandwidth, low dead time for targeted data taking; Serial readout at 2 Gbit/s
  - 10 bit Wilkinson on chip for analog to digital conversion; Wilkinson diitisation at 2 Gsamples/s
  - Low cost: 10 $ per channel
- Chip being tested in stand-alone mode, with laser (Si detectors), beam tests

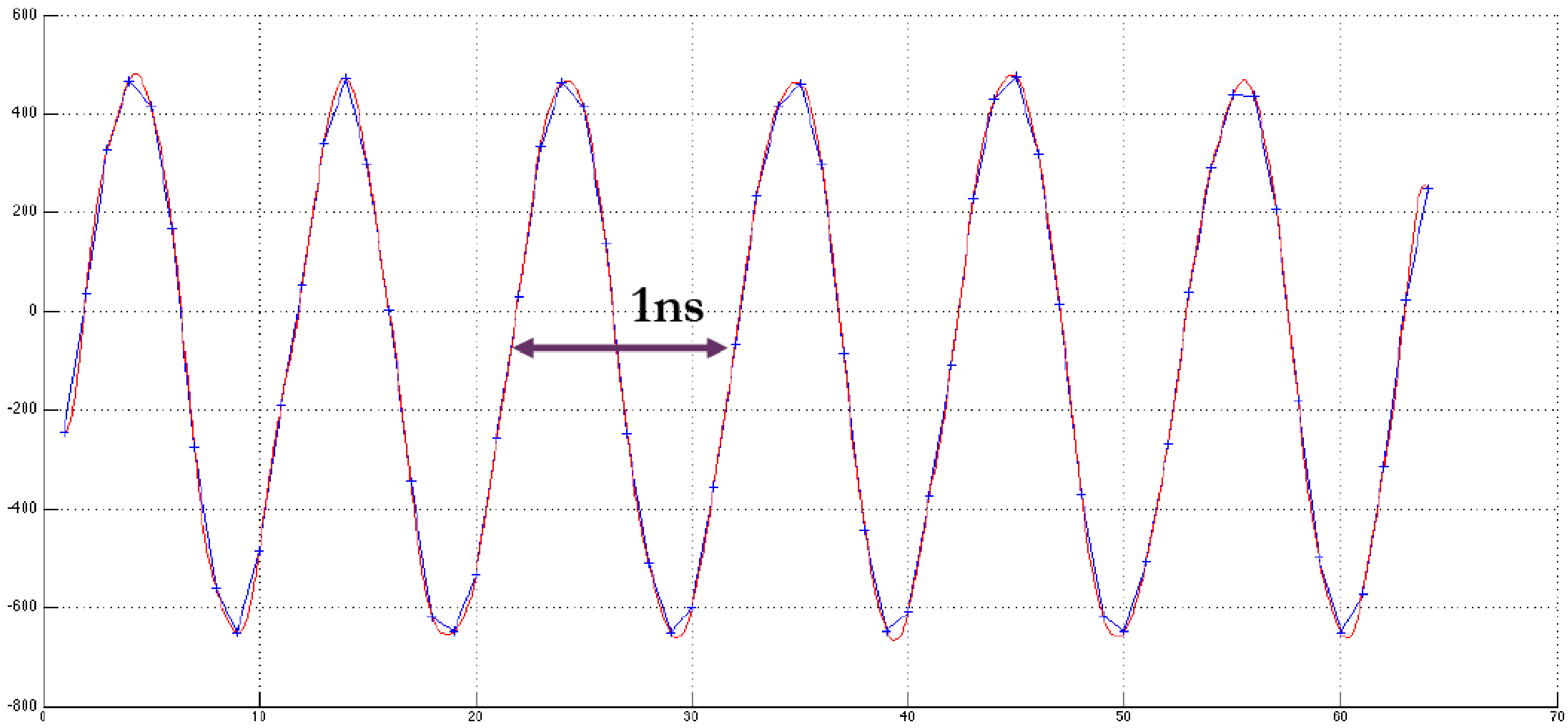


SAMPIC status and tests

- First prototype built and first tests give satisfactory results (3-4 ps RMS) - tests performed with a pulser
- 6 mezzanine boards integrating SAMPIC are available with 16 acquisition channels (1 is permanently at CERN for tests with CMS-Totem)
- USB, ethernet and Fiber optic read out

Quality of sampling

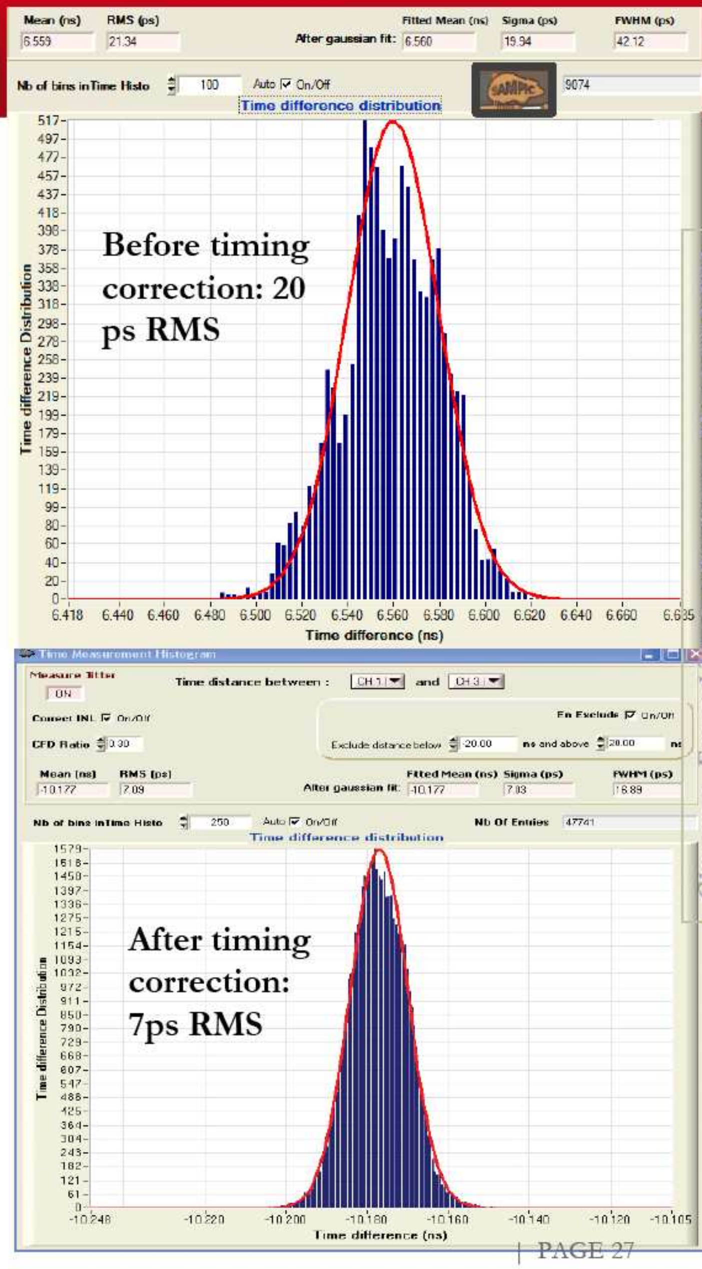
- Sample speed from 3 to 8.2 Gigasample per second on 16 channels (up to 10 GSPS on 8 channels)
- Already very good sampling quality: example of sampling of a sinus without corrections at 10 GSPS



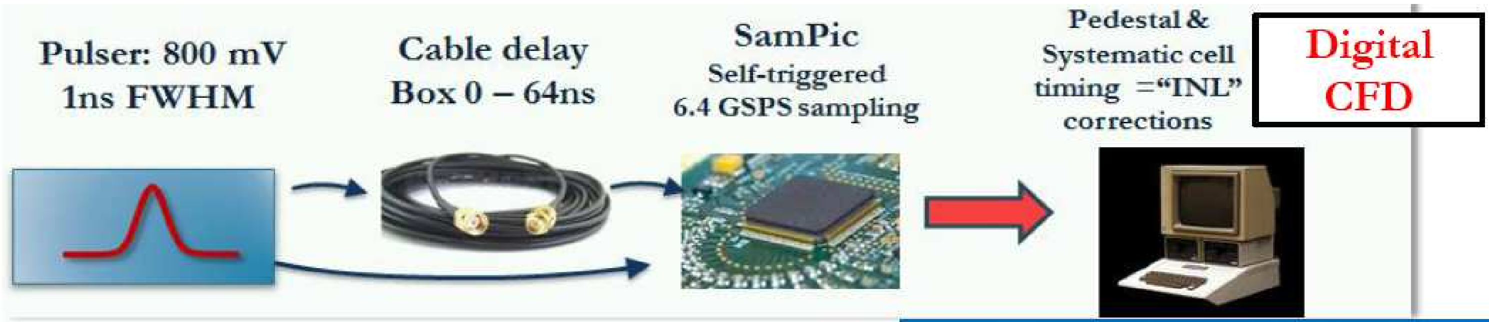
Timing resolution: SAMPIC alone

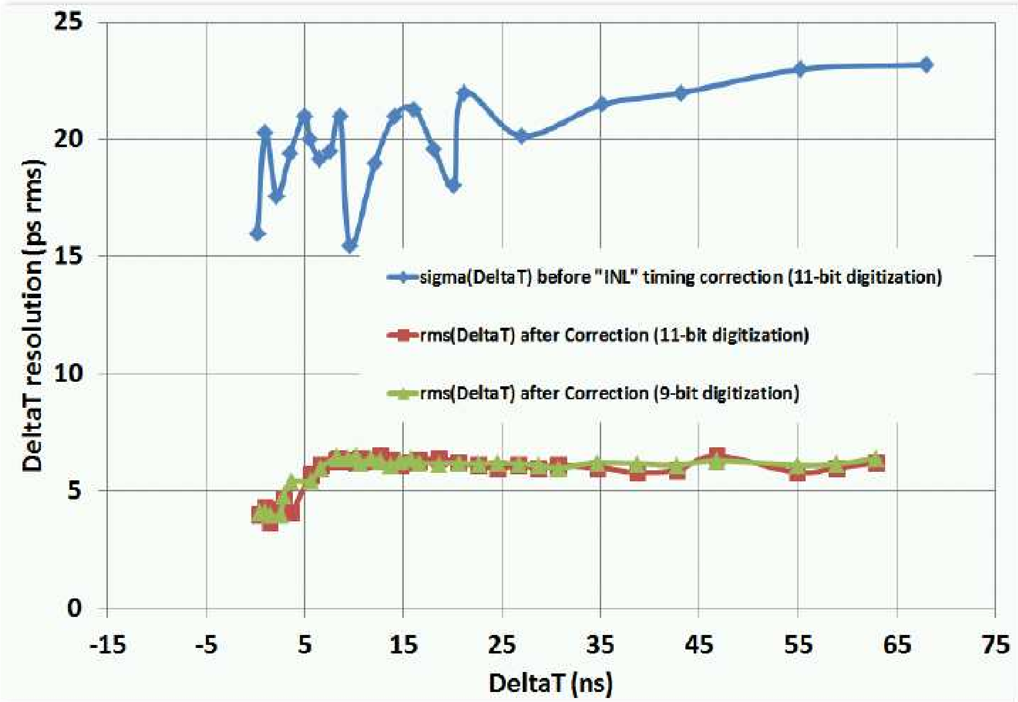
TIMING RESOLUTION (PEDESTAL CORRECTED ONLY)

- First measurement: 2 pulses with 10ns distance. ,1Ns FWHM, 800mV, 3 kHz rate
- Measurement performed for 6.4 GPSPS sampling
- **20 ps rms ΔT resolution before any correction => already not so bad.**
- **7 ps rms ΔT resolution after INL timing correction**
- No tail in the distribution.
- **No hit "out of time" due to metastabilities, problem of boundaries between ranges, …**



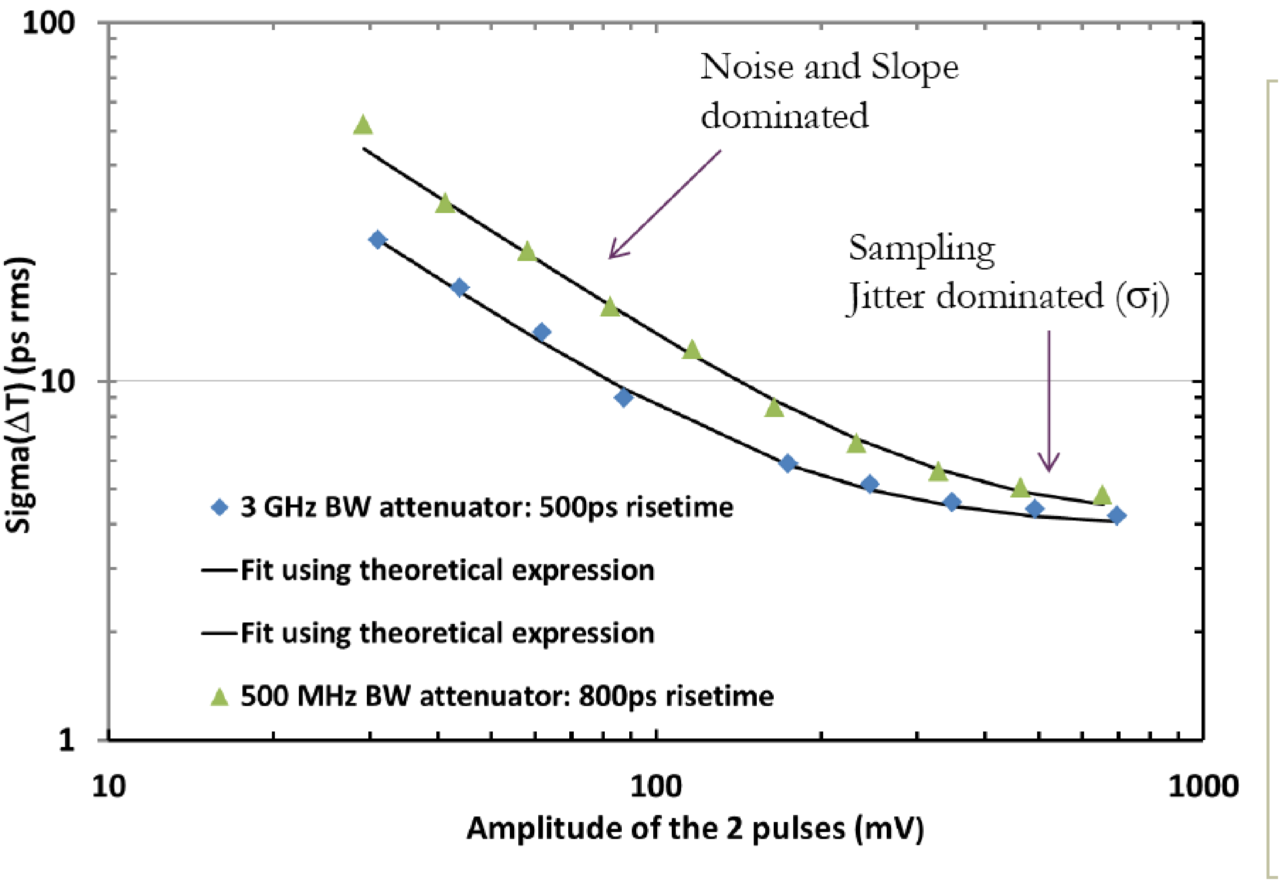
ΔT measurements, only pedestal corrected





- <15 ps RMS = (22/√2) single pulse timing resolution without any timing calibration (short DLLs)
- <5 ps RMS timing resolution on single pulse after timing "INL" correction
- Resolution vs ΔT is FLAT after 10ns
- Same results in 9-bit/400ns mode
- Correction of ADC gain spread and non-linearity not applied yet

Timing resolution vs amplitude and rise time

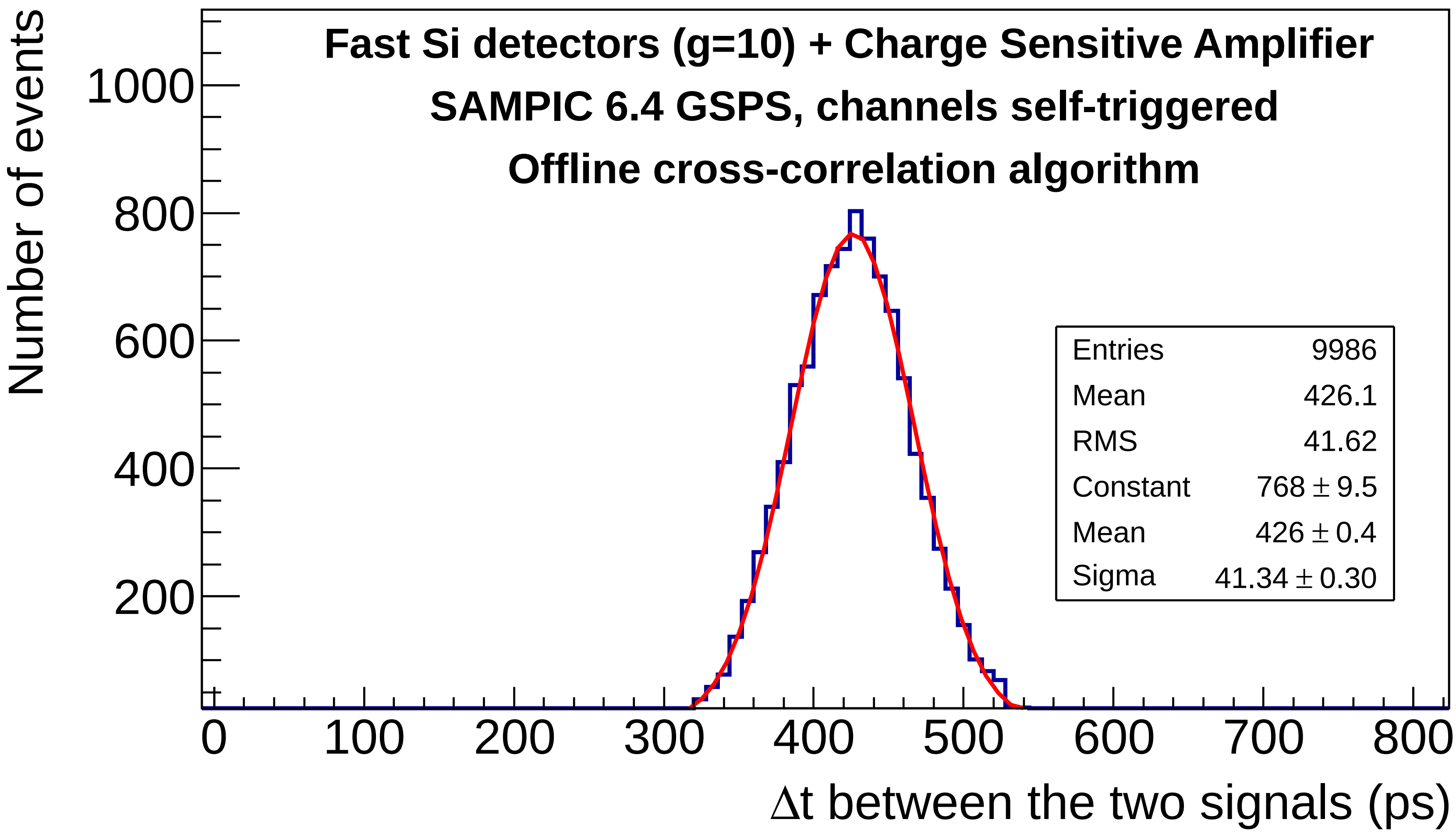


Atten. BW (GHz)	σj fit (ps rms)	α fit (ps.mV)	Nslope (ns^{-1})	Calc σn (mV rms)
500	2.82	919	1.33	1.2
3	2.76	538	1.88	1.0

$$\sigma(\Delta t) = \sqrt{2}\sqrt{\sigma_j^2 + \left(\frac{\sigma_n}{N_{slope}Amp}\right)^2} \quad \alpha = \frac{\sigma_n}{N_{slope}}$$

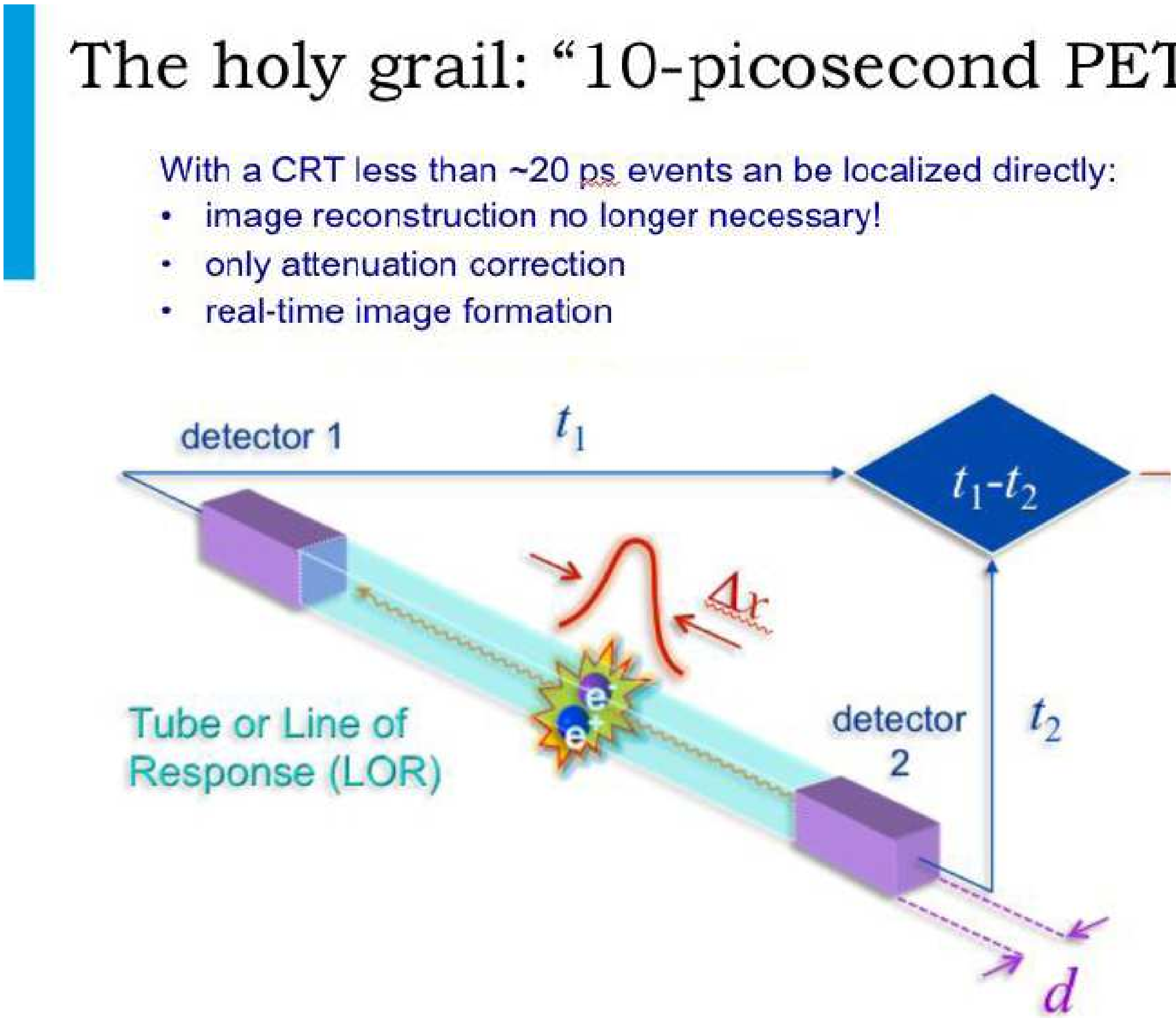
Time resolution using Si detectors

- Time resolution using sampic and Si detectors: measure the time difference between two channels
- Time reolution: (dominated by detector): $\sim$ 30 ps



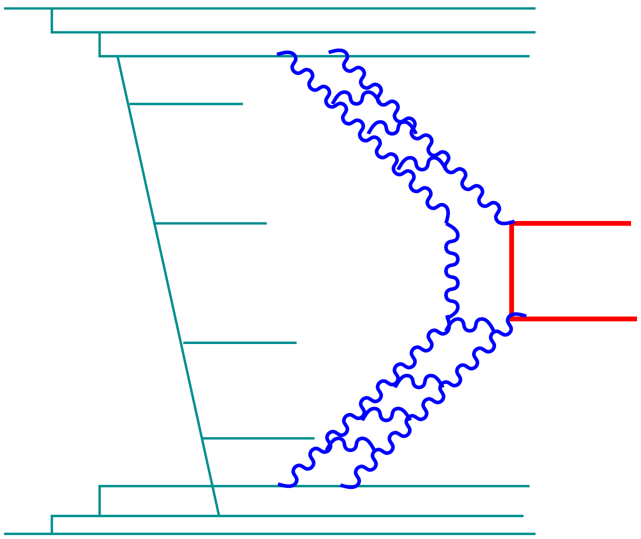
Conclusion

- AFP aims at detecting intact protons in ATLAS: increases the physics potential of ATLAS (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)

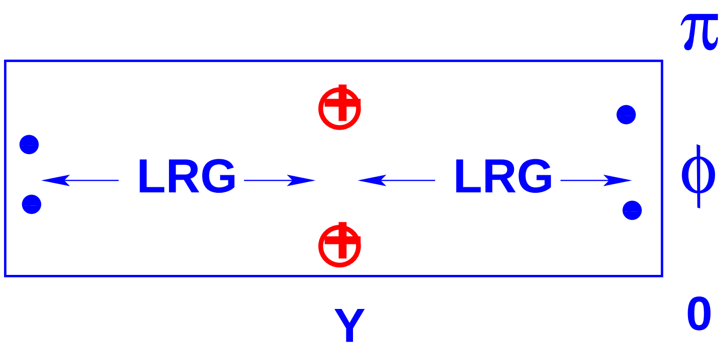


Factorisation at Tevatron/LHC?

- Is factorisation valid at Tevatron/LHC? Can we use the parton densities measured at HERA to use them at the Tevatron/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)



a)



b)