Forward physics with proton tagging at the LHC

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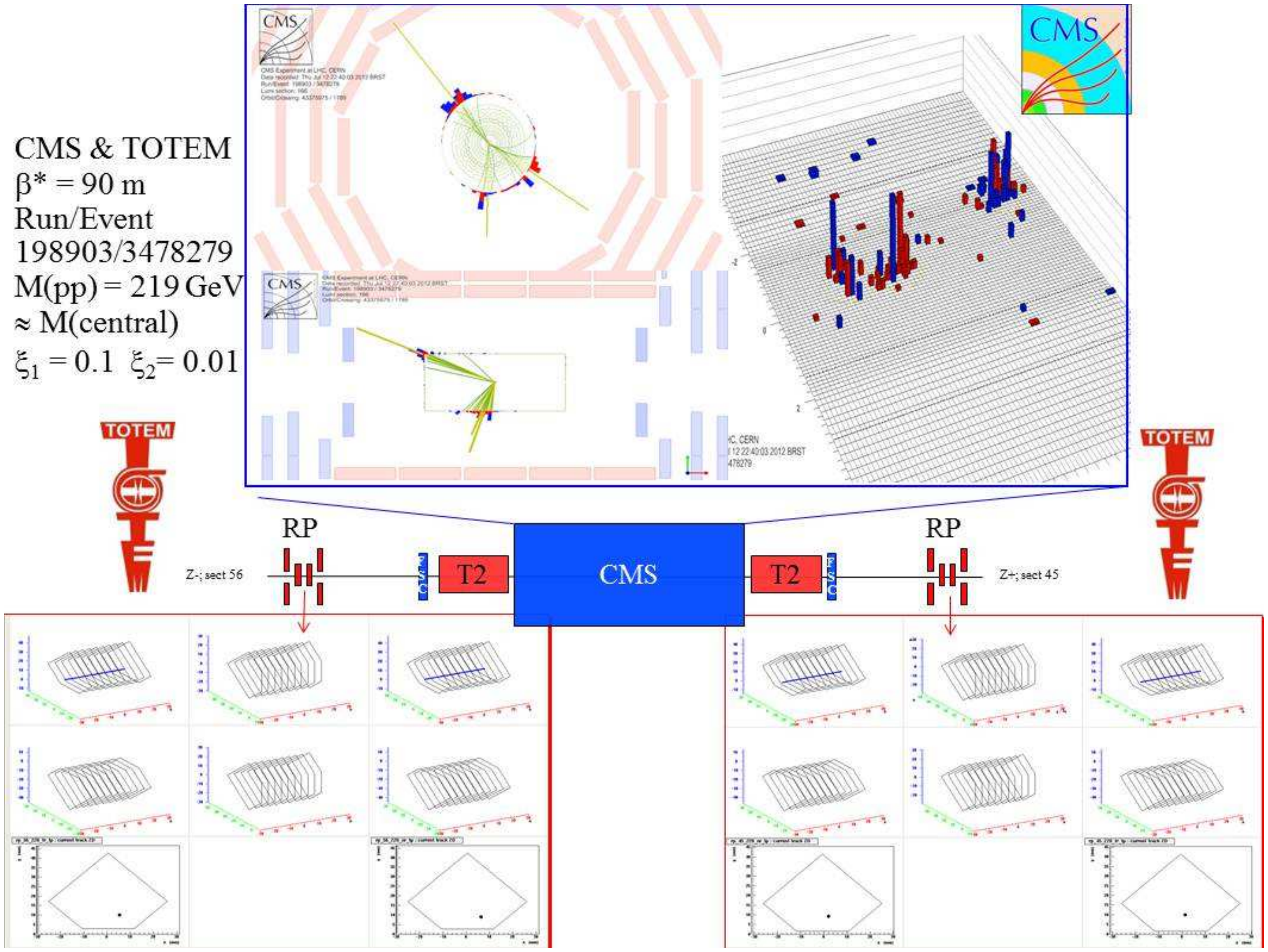
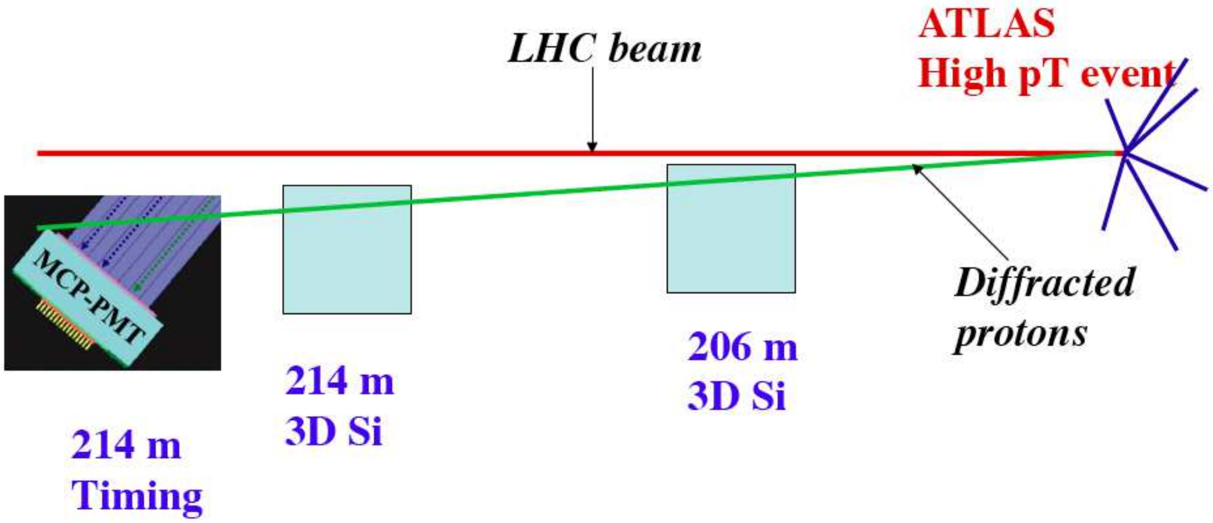
Workshop on forward physics and high energy scattering at zero degree
Nagoya, Japan, September 9-12 2015

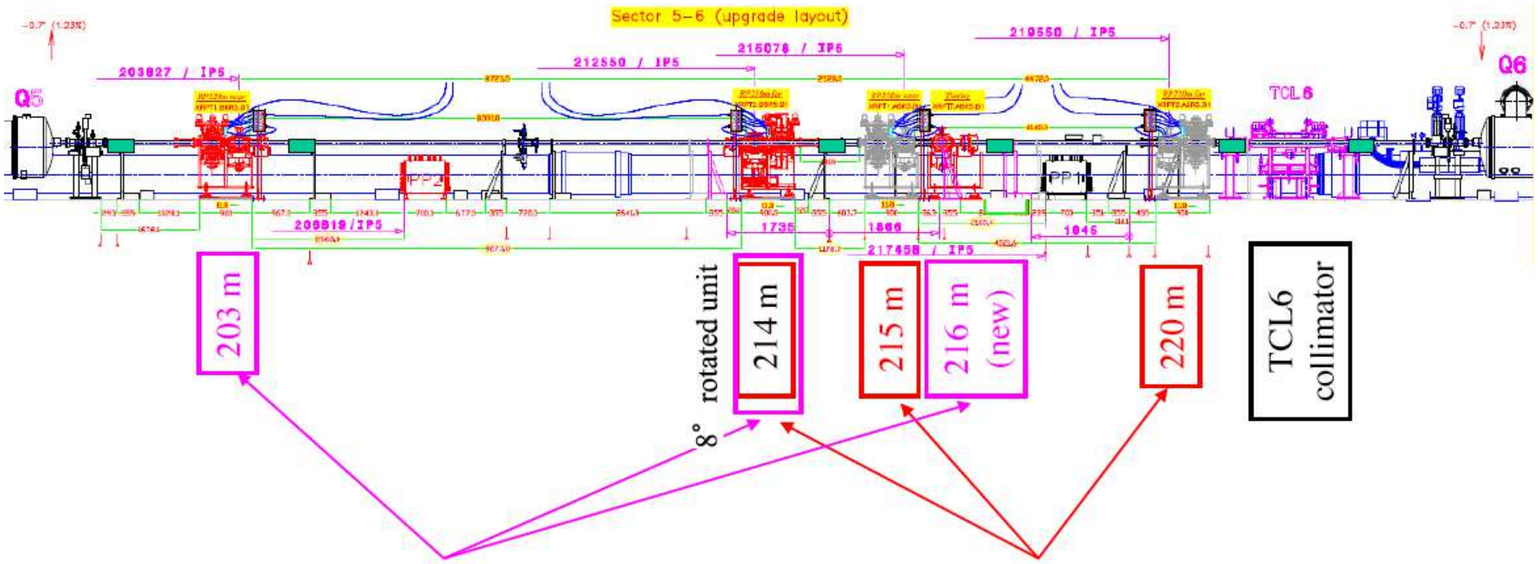


Outline



- CT-PPS, CMS-TOTEM and AFP/ALFA
- soft diffraction
- Hard diffraction and the Pomeron structure
- Exclusive diffraction
- Photon exchanges processes and beyond standard model physics
- Forward proton detectors at LHC

What is AFP/CMS-TOTEM/CT-PPS?



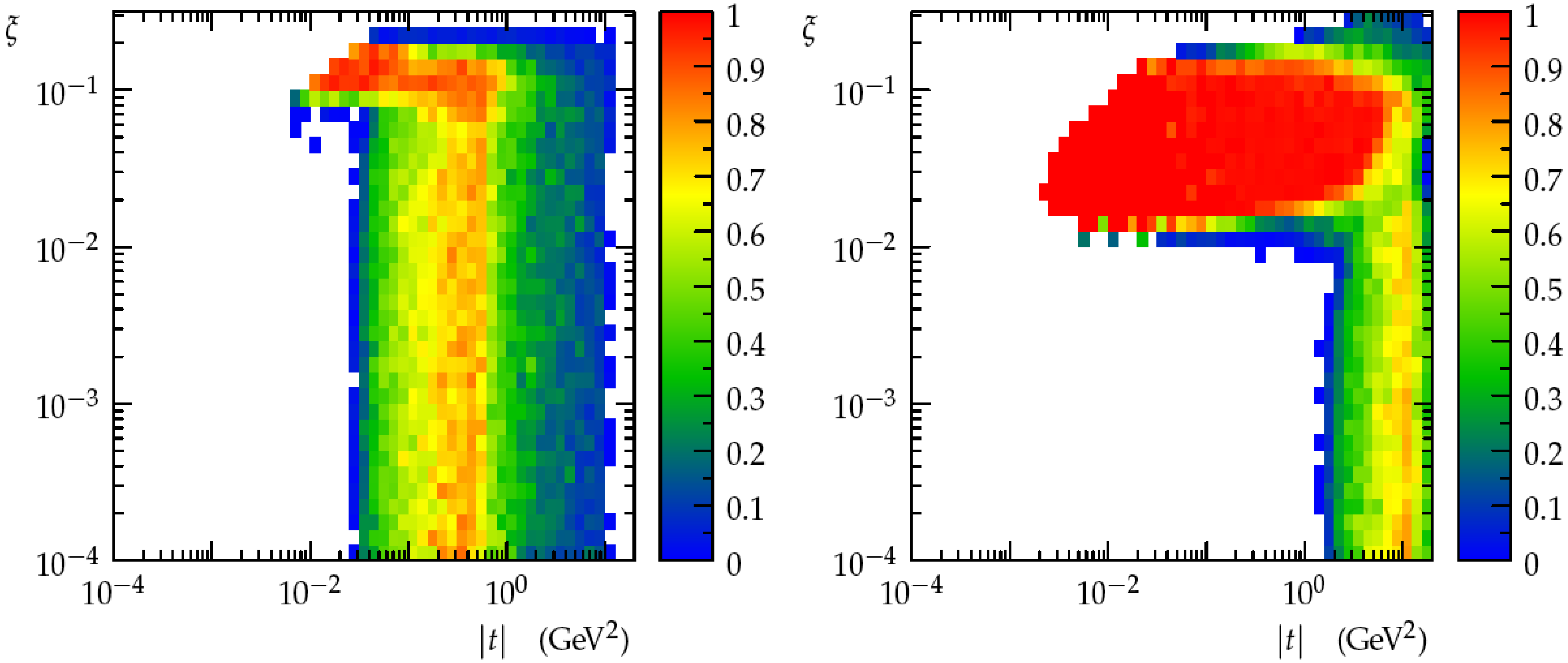
Operation at low β* (< 1 m),
high luminosity, standard runs

Operation at high β* (19 m, 90 m, > 1 km),
Low - medium luminosity, special runs

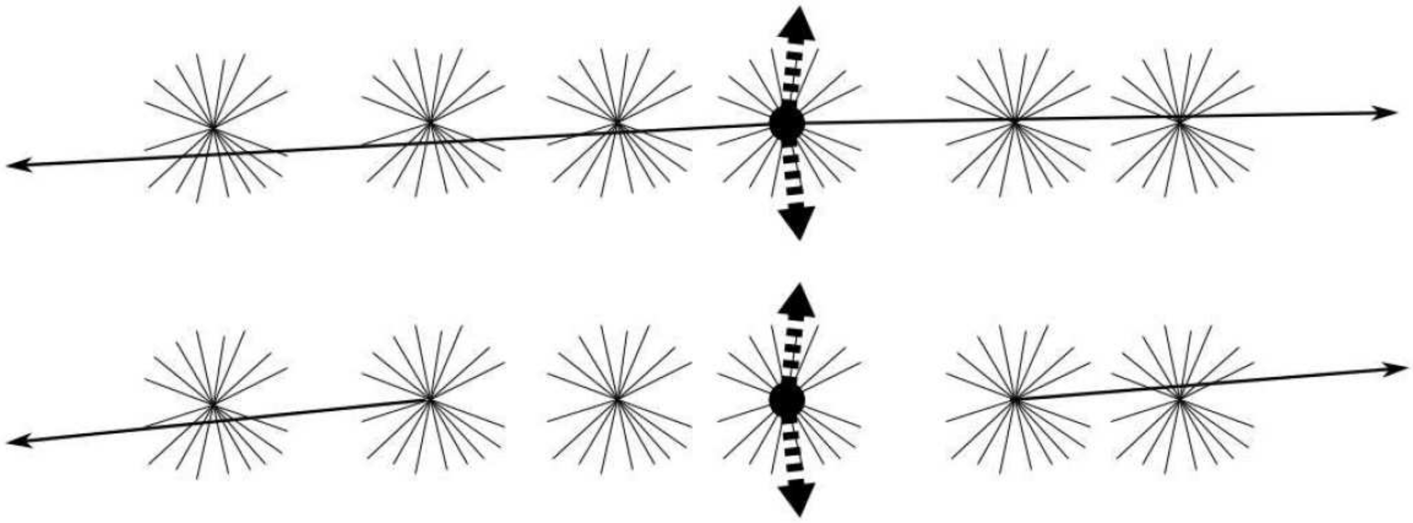
- TOTEM/ALFA only: Roman pots detecting intact protons at ± 200-220 m; in addition T1 and T2 forward stations in TOTEM in the very forward region of CMS ($3 < |\eta| < 6.5$) that are used as veto in total cross section and soft diffraction measurements
- Measure soft diffraction as well as total, elastic and inelastic cross section using TOTEM pots
- Tag and measure protons at ±200-220 m and measure global event in CMS/ATLAS: CMS-TOTEM/ALFA with vertical pots and CT-PPS/AFP (Precision Proton Spectrometer) for upgraded horizontal pots
- Different beam conditions allow sensitivities to different physics and kinematical domains

Running conditions: proton tagging

- Possibility to tag intact protons in the final state in CMS-TOTEM and in CT-PPS
- High β^* runnings using vertical pots mainly low mass diffraction (small luminosity, special runs, sensitivity to processes with high cross section)
- Low β^* runnings using horizontal pots: Standard high luminosity physics, sensitive to low cross sections and to new physics

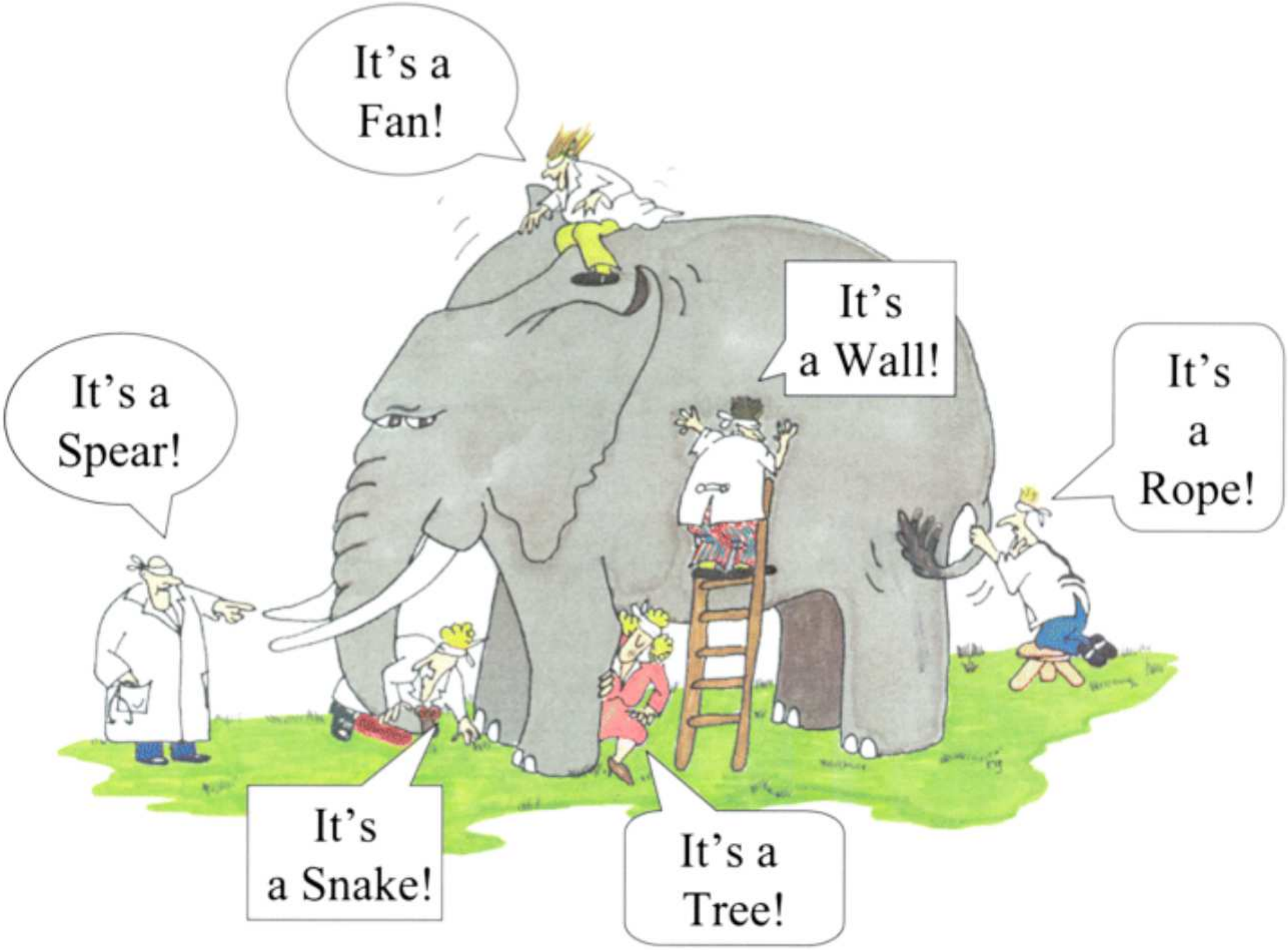


One aside: what is pile up at LHC?



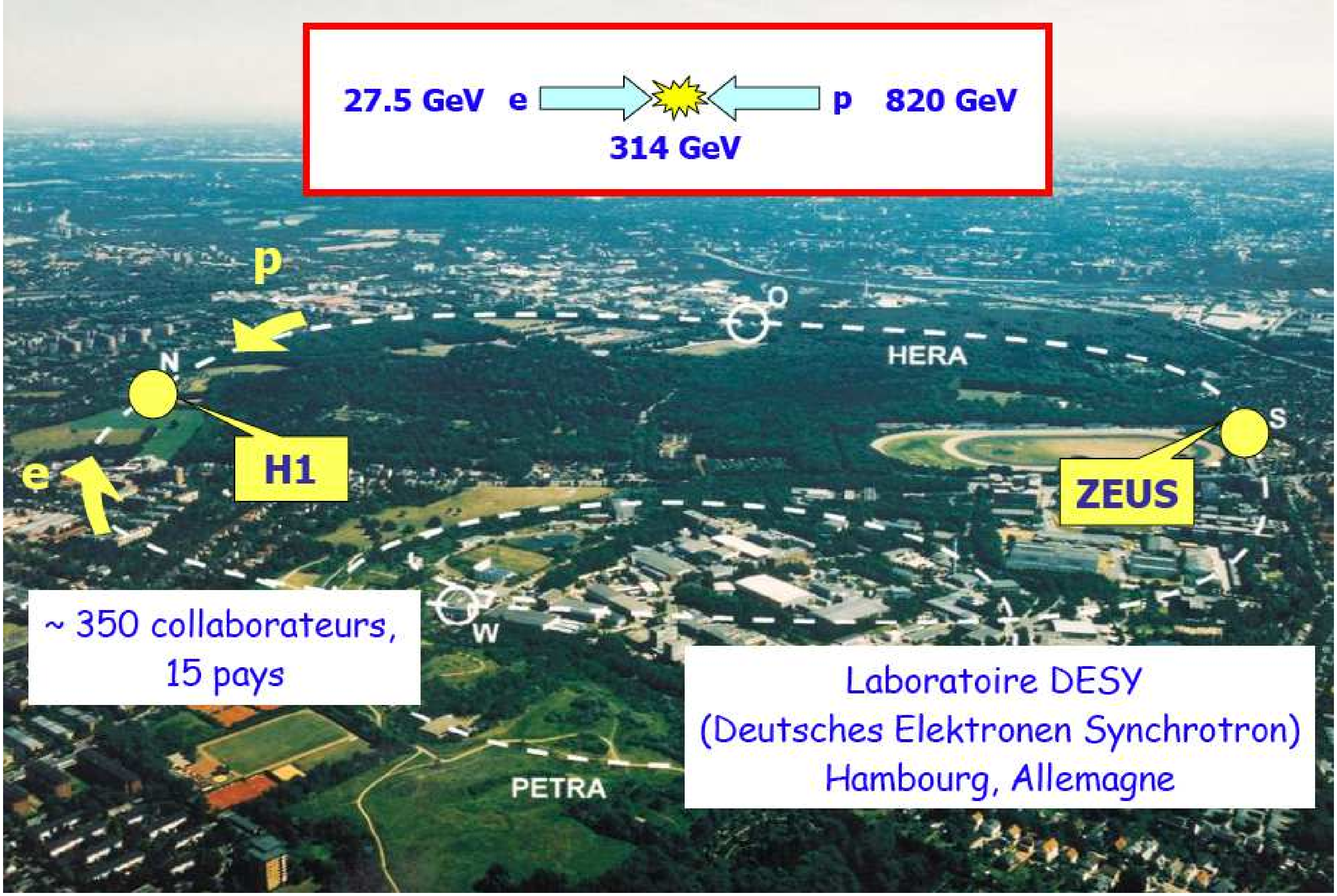
- High luminosity at the LHC to look for rare (non standard events): many protons in one bunch, many interactions within the same bunch crossing in ATLAS and CMS (LHCb is different)
- Hard interaction and pile up: one hard interaction (leading to a high p_T event with jets, W/Z, top...) and many additional 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

INTRODUCTION:
DIFFRACTION AT HERA



Definition of diffraction: example of HERA

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

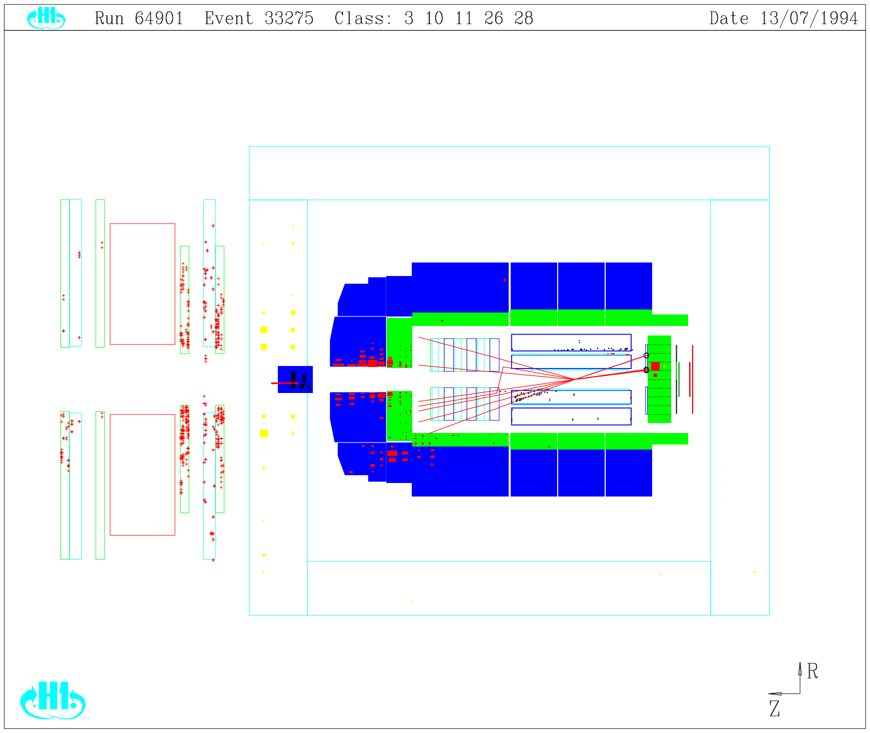


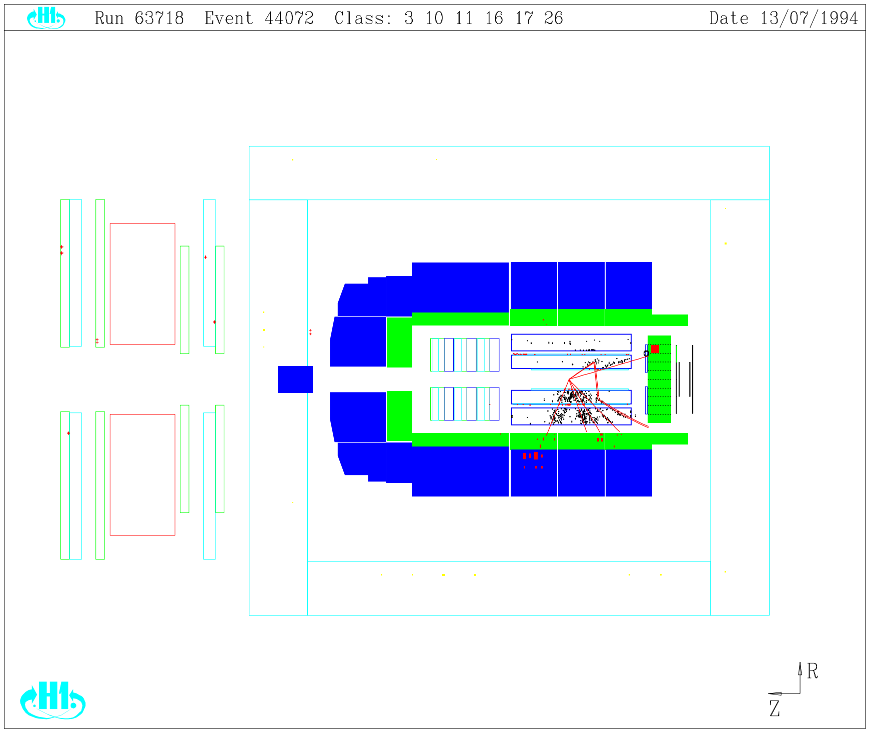
27.5 GeV e → ← p 820 GeV
314 GeV

~ 350 collaborateurs,
15 pays

Laboratoire DESY
(Deutsches Elektronen Synchrotron)
Hambourg, Allemagne

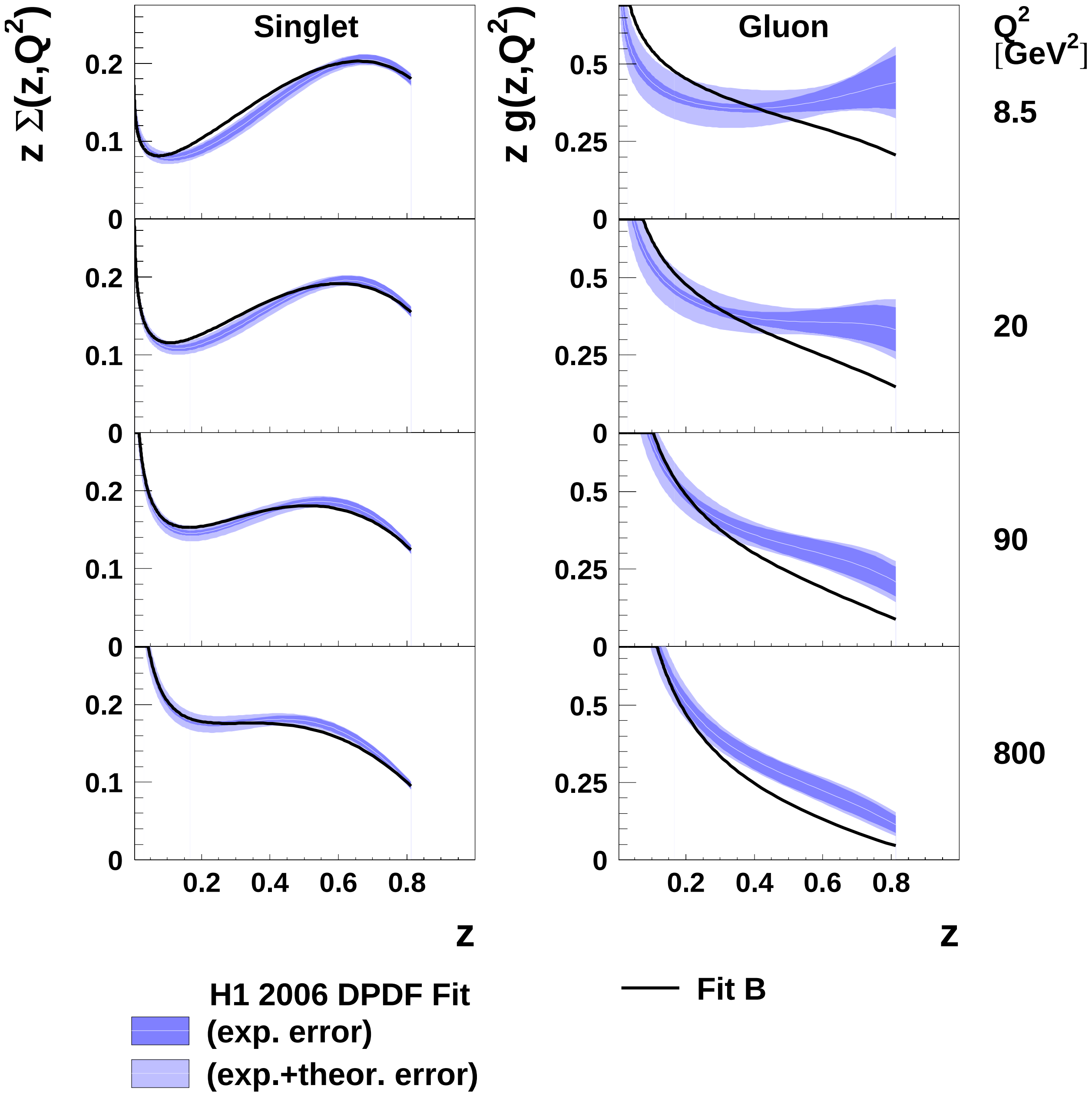
Diffraction at HERA: rapidity gap / proton tagging





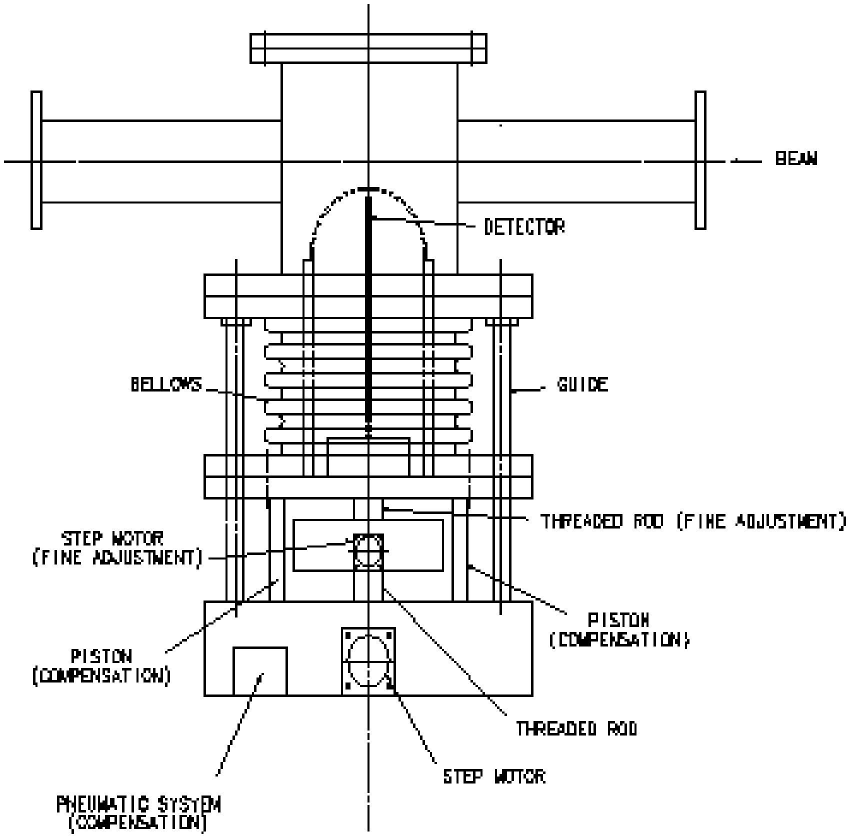
Parton densities in the pomeron (H1)

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



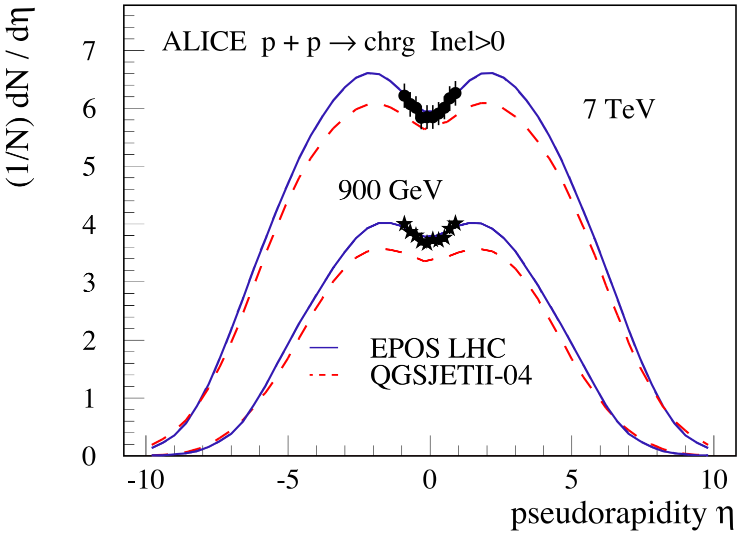
Definition of diffraction: example of HERA

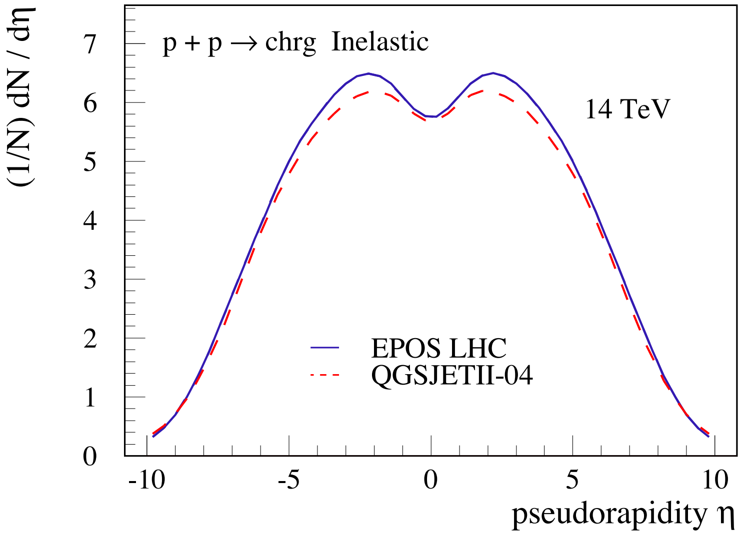
- Typical DIS event: part of proton remnants seen in detectors in forward region (calorimeter, forward muon...)
- HERA observation: in some events, no energy in forward region, or in other words no colour exchange between proton and jets produced in the hard interaction
- Leads to the first experimental 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)

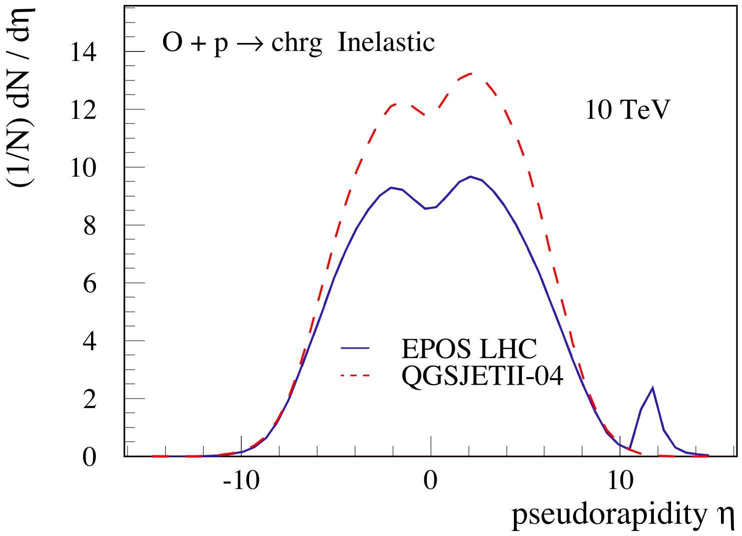


Very low lumi: Soft interactions

- Measure multiplicity, energy distribution in soft events: complementarity between rapidity reach in LHCf, ATLAS, Alice, CMS...
- Measurement of soft diffraction, total cross section: high β^* measurement in TOTEM, ATLAS-ALFA
- Constrain cosmic ray models
- Importance of measuring p-Oxygen: useful to tune cosmic-ray models

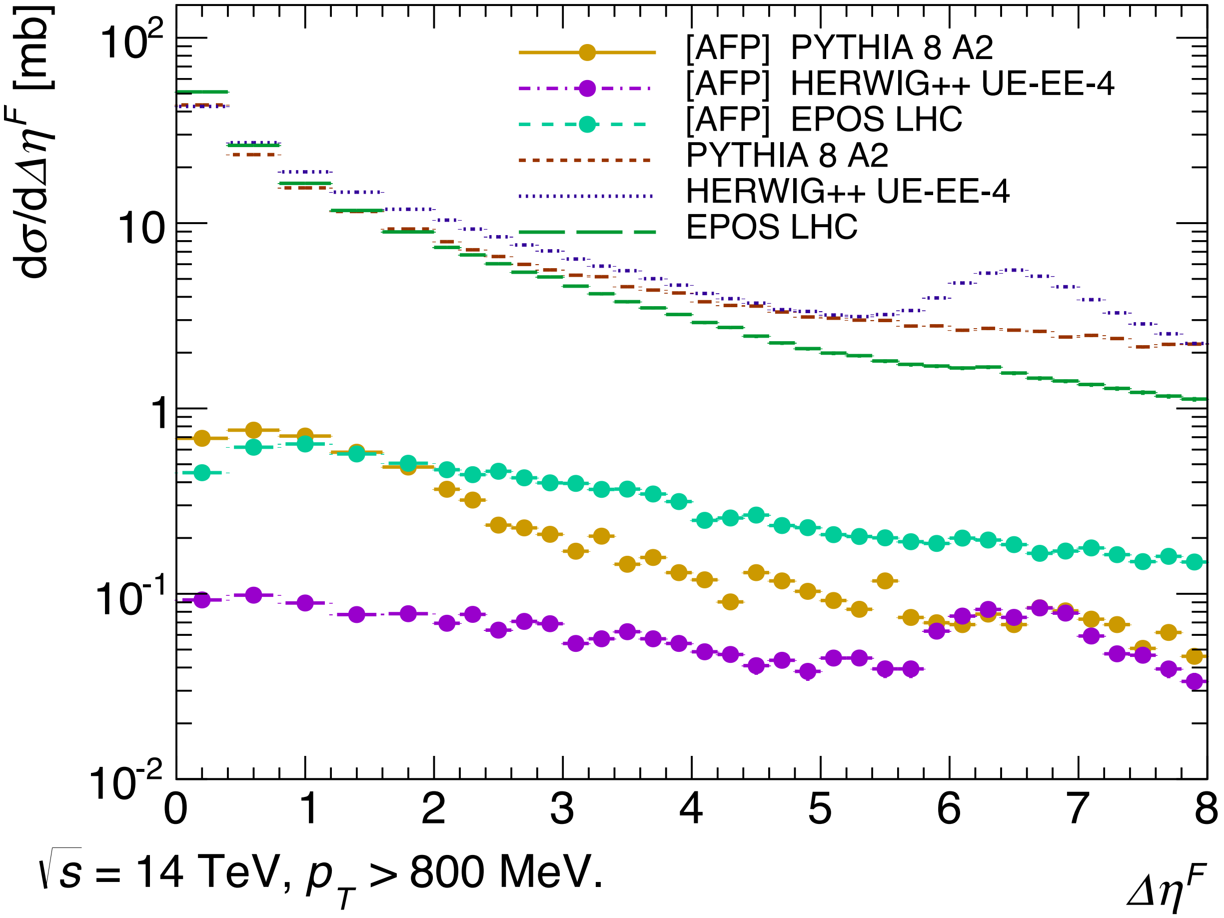






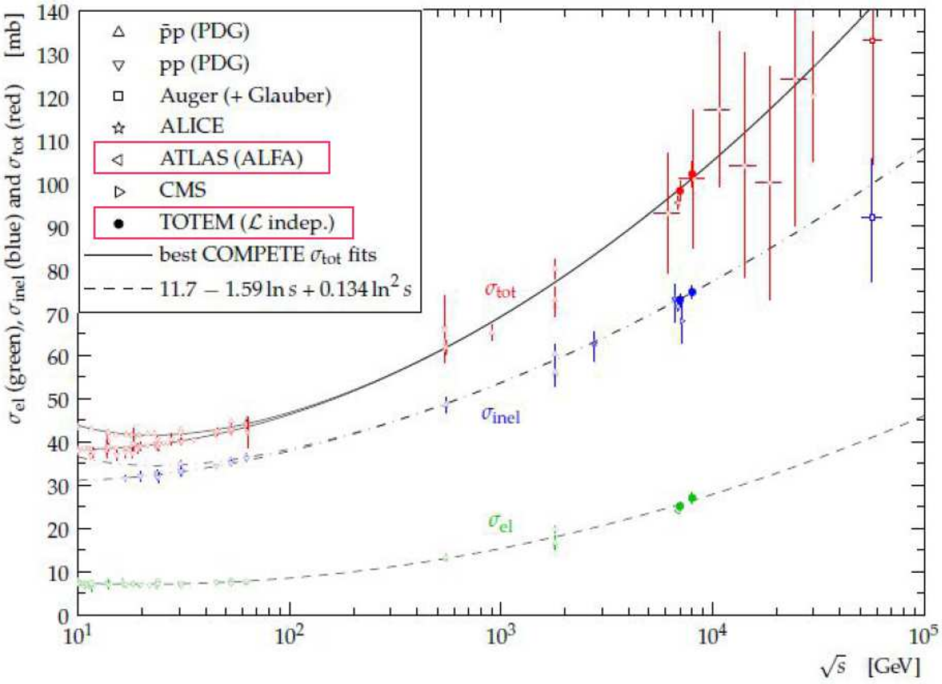
Very low lumi: Forward gap in soft diffraction

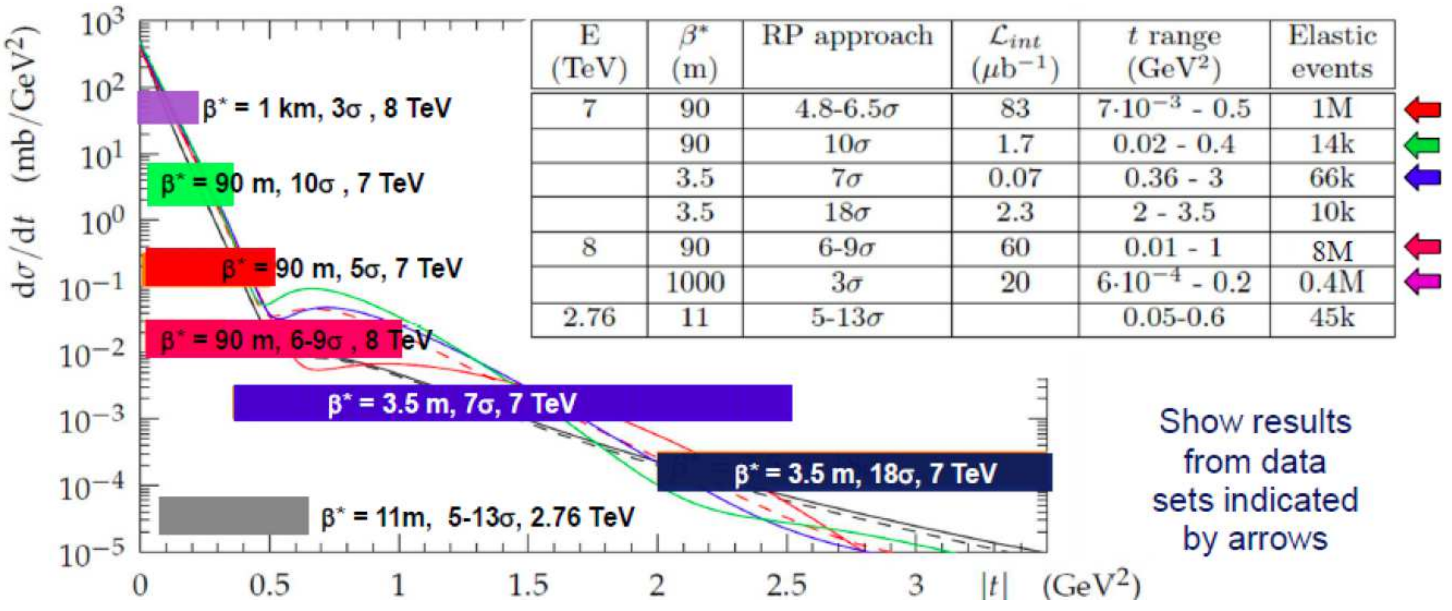
- Measure size of forward gap in diffractive events
- Measurement important to tune models (hadronisation...)
- Larger differences between models when proton is tagged in AFP or CMS/TOTEM



Low luminosity: soft diffraction measurement

- Perform measurements of total, elastic and inelastic cross section at 13 TeV: similarly to 7-8 TeV
- Need very high $\beta^* \sim$1 km optics in order to access very low $|t|$

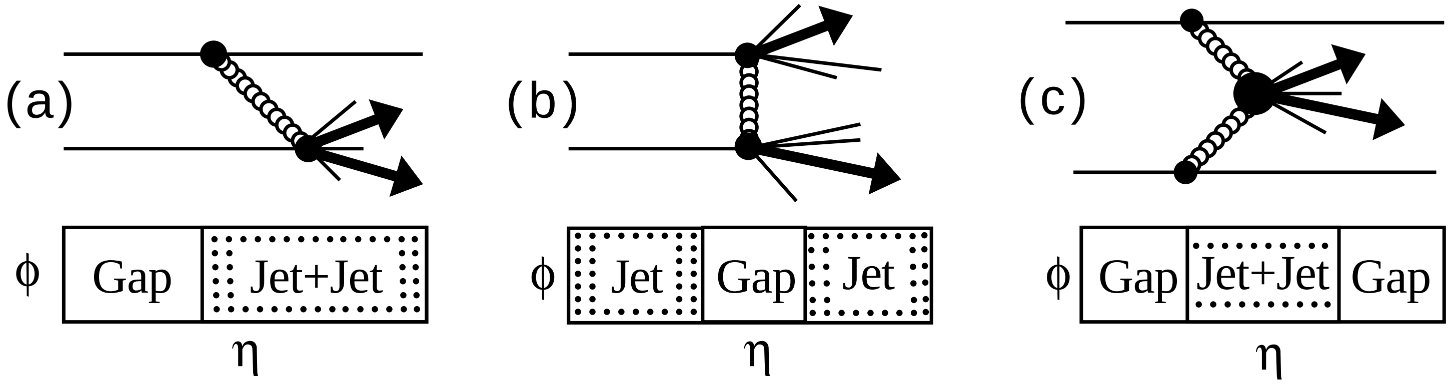




E (TeV)	β^* (m)	RP approach	$\mathcal{L}_{int}$ (μb^{-1})	t range (GeV^2)	Elastic events	
7	90	4.8-6.5σ	83	$7 \cdot 10^{-3}$ - 0.5	1M	⬅
	90	10σ	1.7	0.02 - 0.4	14k	⬅
	3.5	7σ	0.07	0.36 - 3	66k	⬅
	3.5	18σ	2.3	2 - 3.5	10k	
8	90	6-9σ	60	0.01 - 1	8M	⬅
	1000	3σ	20	$6 \cdot 10^{-4}$ - 0.2	0.4M	⬅
2.76	11	5-13σ		0.05-0.6	45k	

Show results
from data
sets indicated
by arrows

Diffraction at LHC: kinematical variables

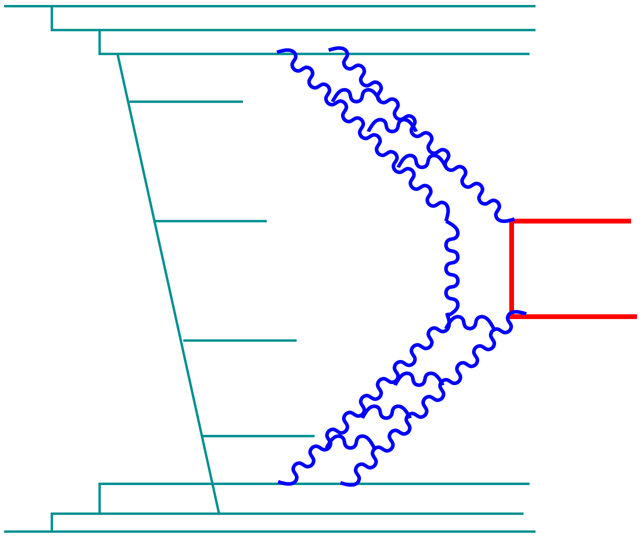


Kinematic variables

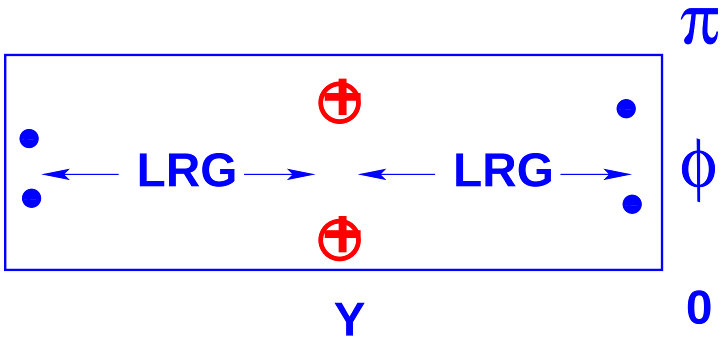
- t: 4-momentum transfer squared
- ξ_1, ξ_2: proton fractional momentum loss (momentum fraction of the proton carried by the pomeron)
- $\beta_{1,2} = x_{Bj,1,2}/\xi_{1,2}$: Bjorken-x of parton inside the pomeron
- $M^2 = s\xi_1\xi_2$: diffractive mass produced
- $\Delta y_{1,2} \sim \Delta\eta \sim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

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)



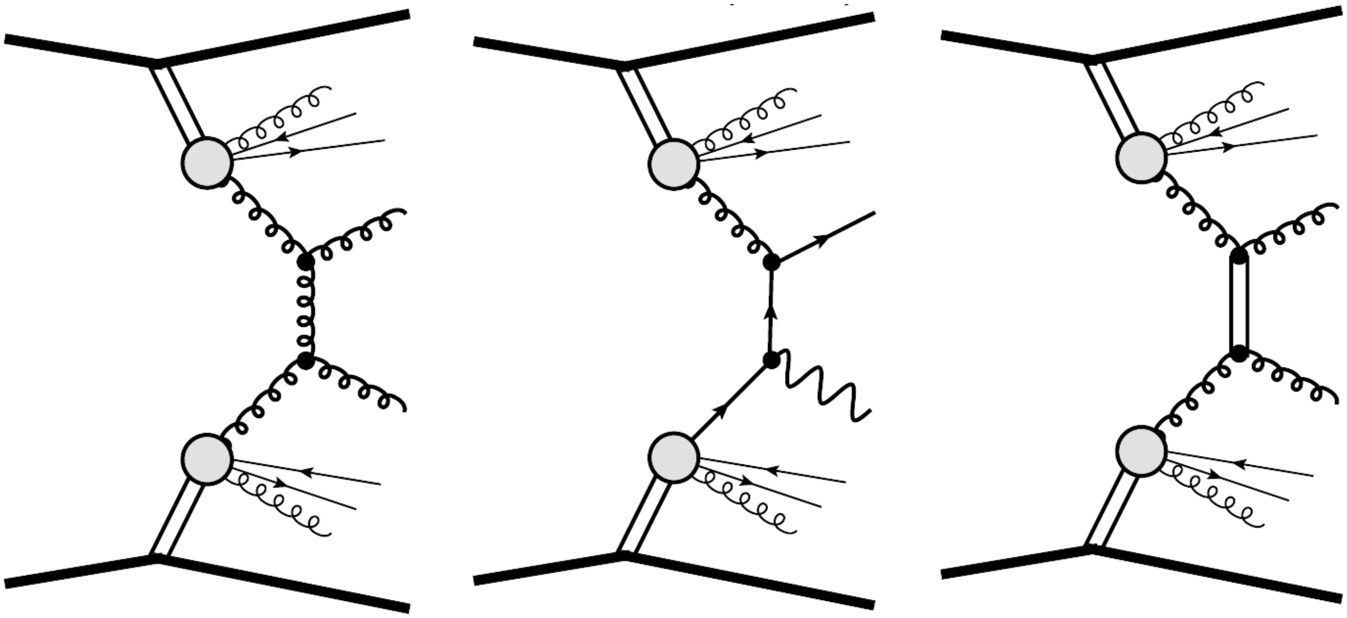
a)



b)

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

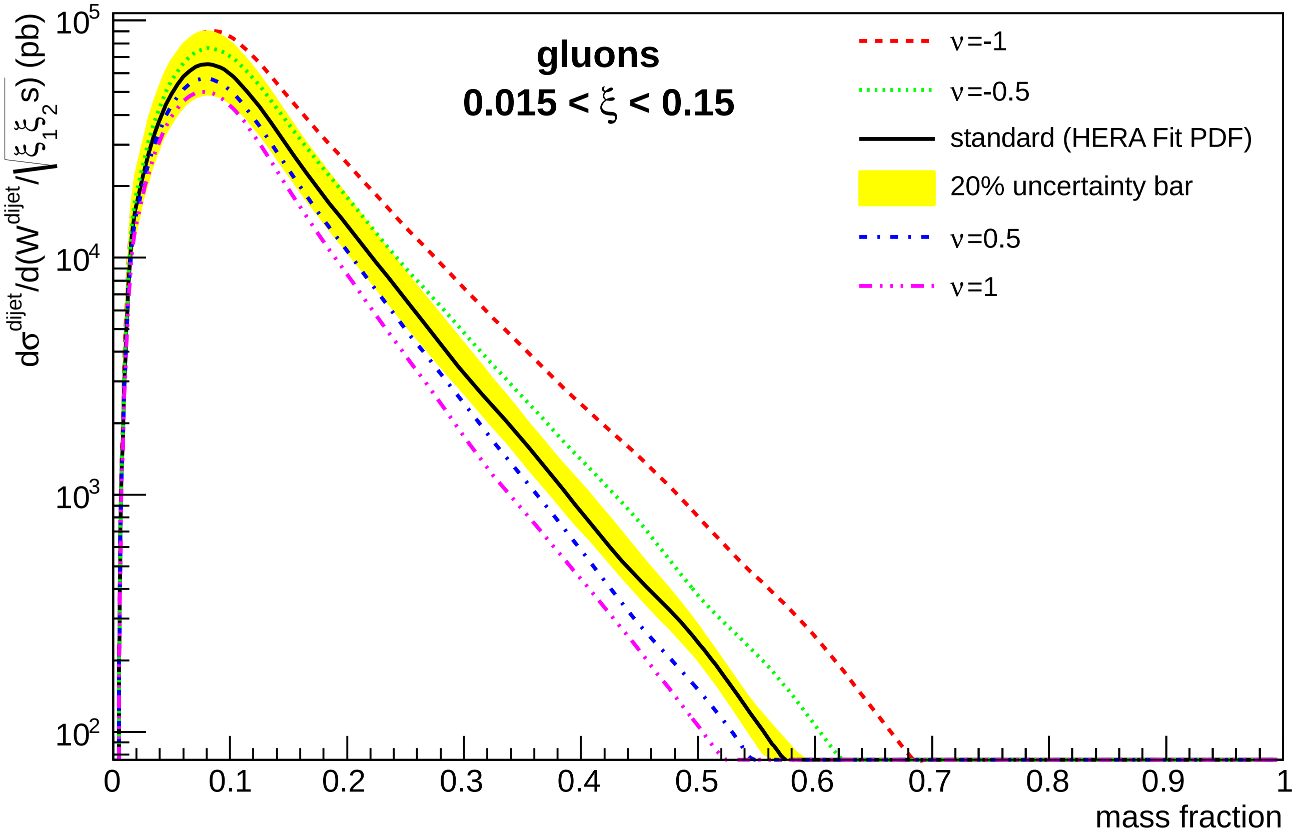


Forward Physics Monte Carlo (FPMC)

- 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

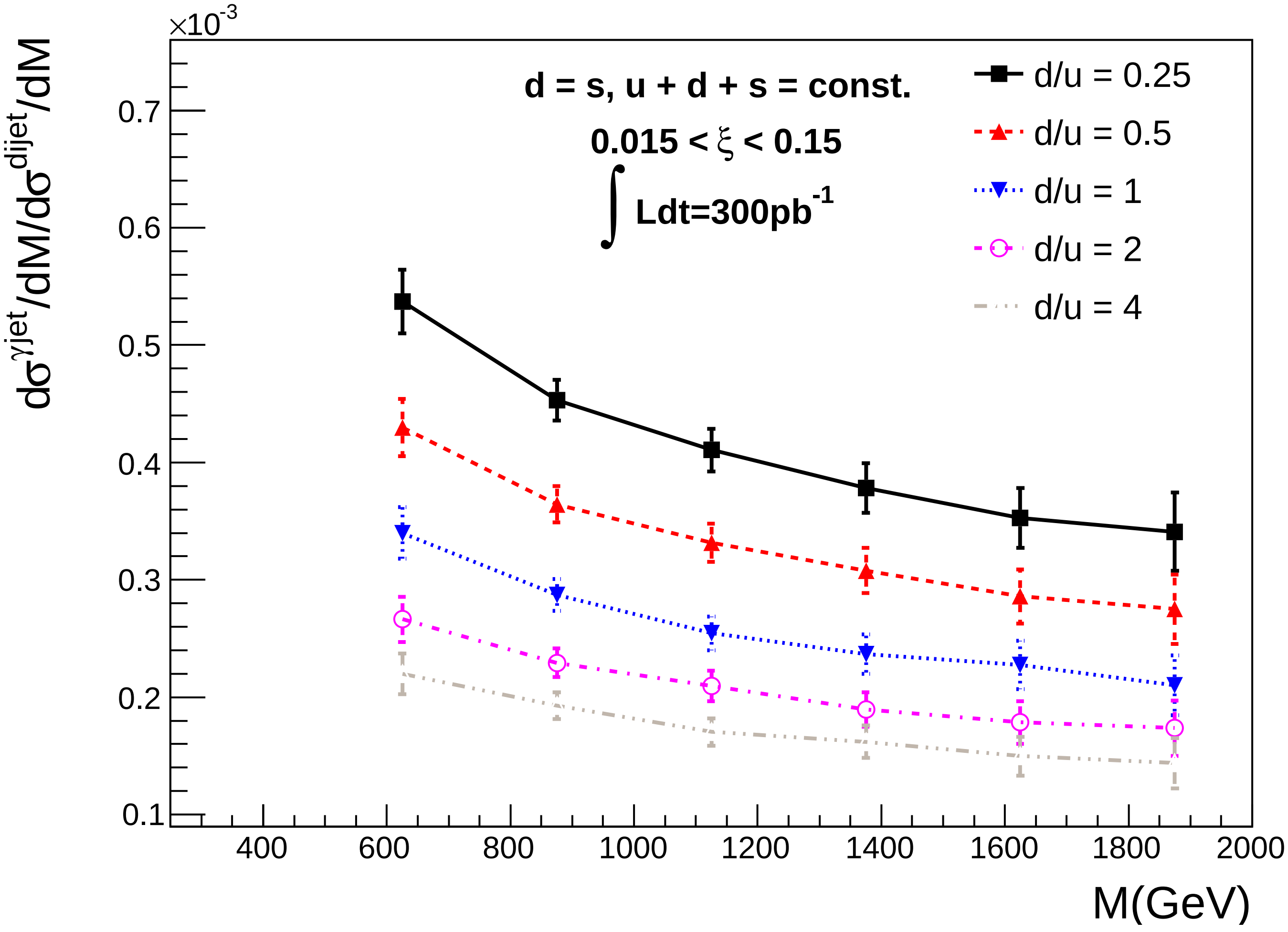
Inclusive diffraction at the LHC: sensitivity to gluon density

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

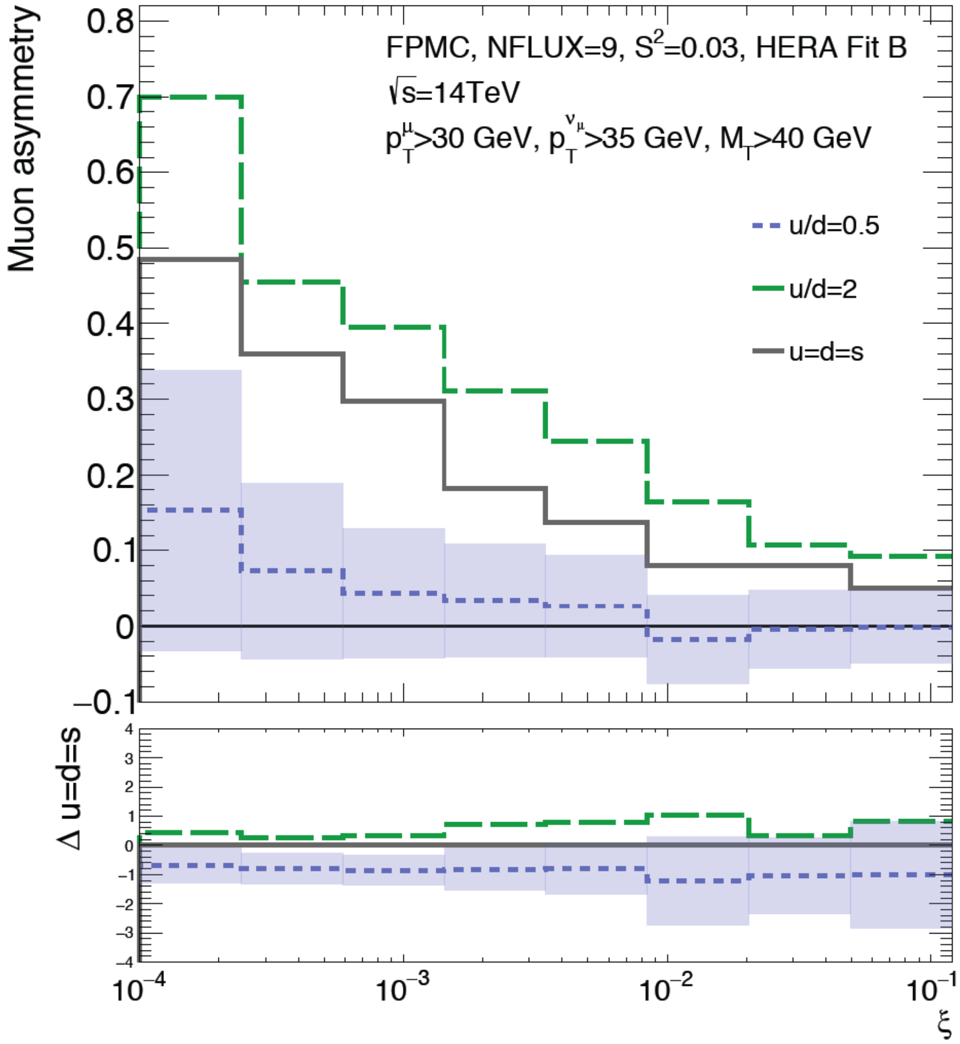


Inclusive diffraction at the LHC: sensitivity to quark densities

- 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



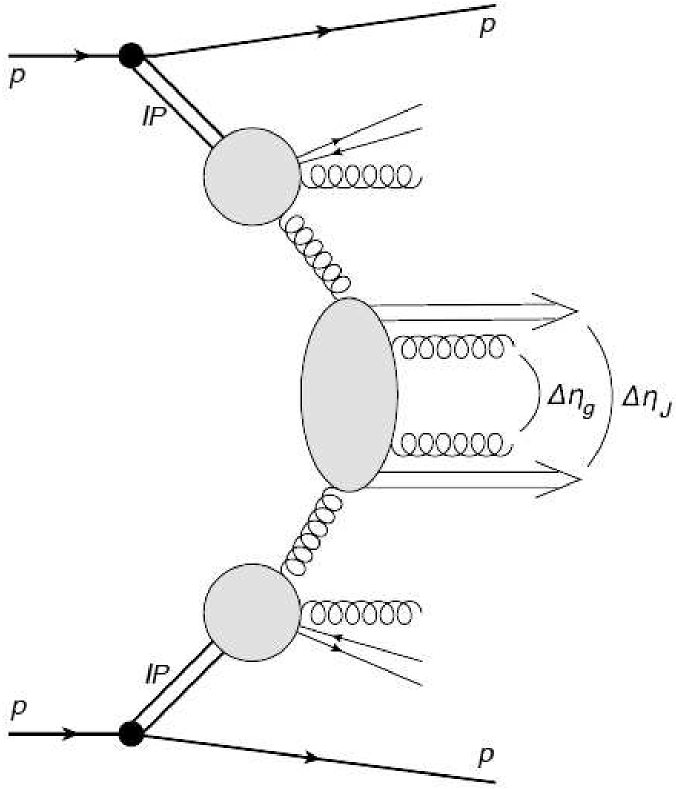
Medium lumi: W charge asymmetry
Sensitivity to quark densities

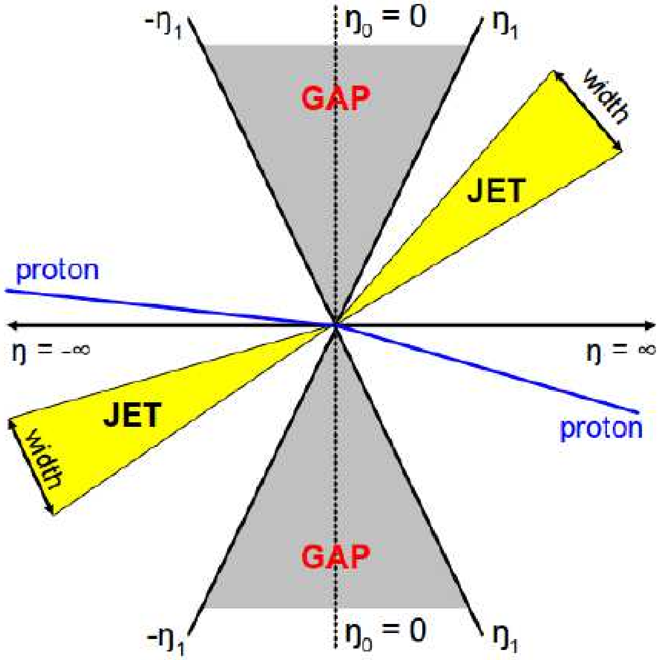


- Measure the average W charge asymmetry in ξ bins to probe the quark content of the proton: $A = (N_{W^+} - N_{W^-})/(N_{W^+} + N_{W^-})$
- Test if u/d is equal to 0.5, 1 or 2 as an example
- A. Chuinard, C. R..,R. Staszewski, to be published

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

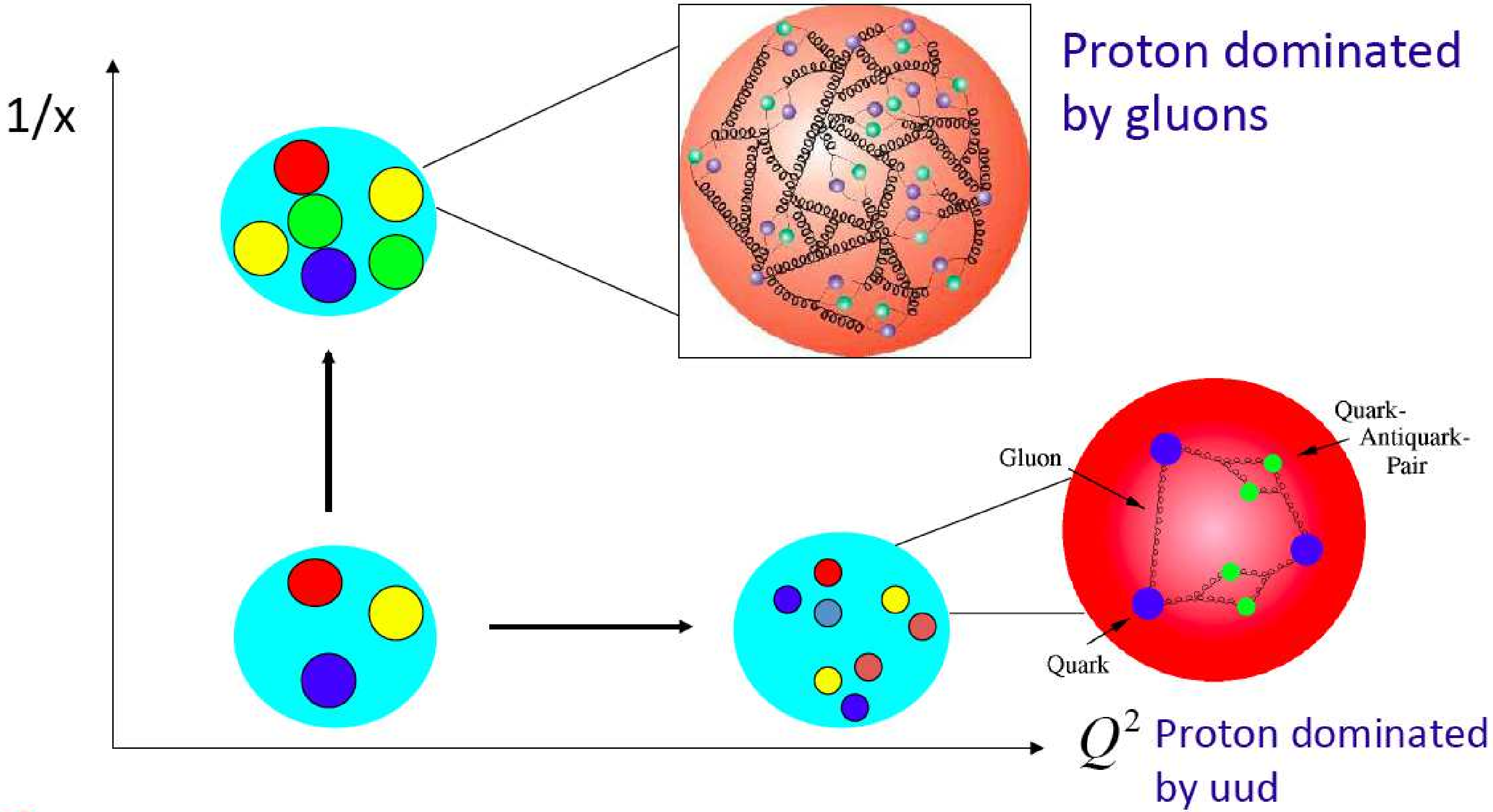




Looking for BFKL effects

- 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)



Proton dominated by gluons

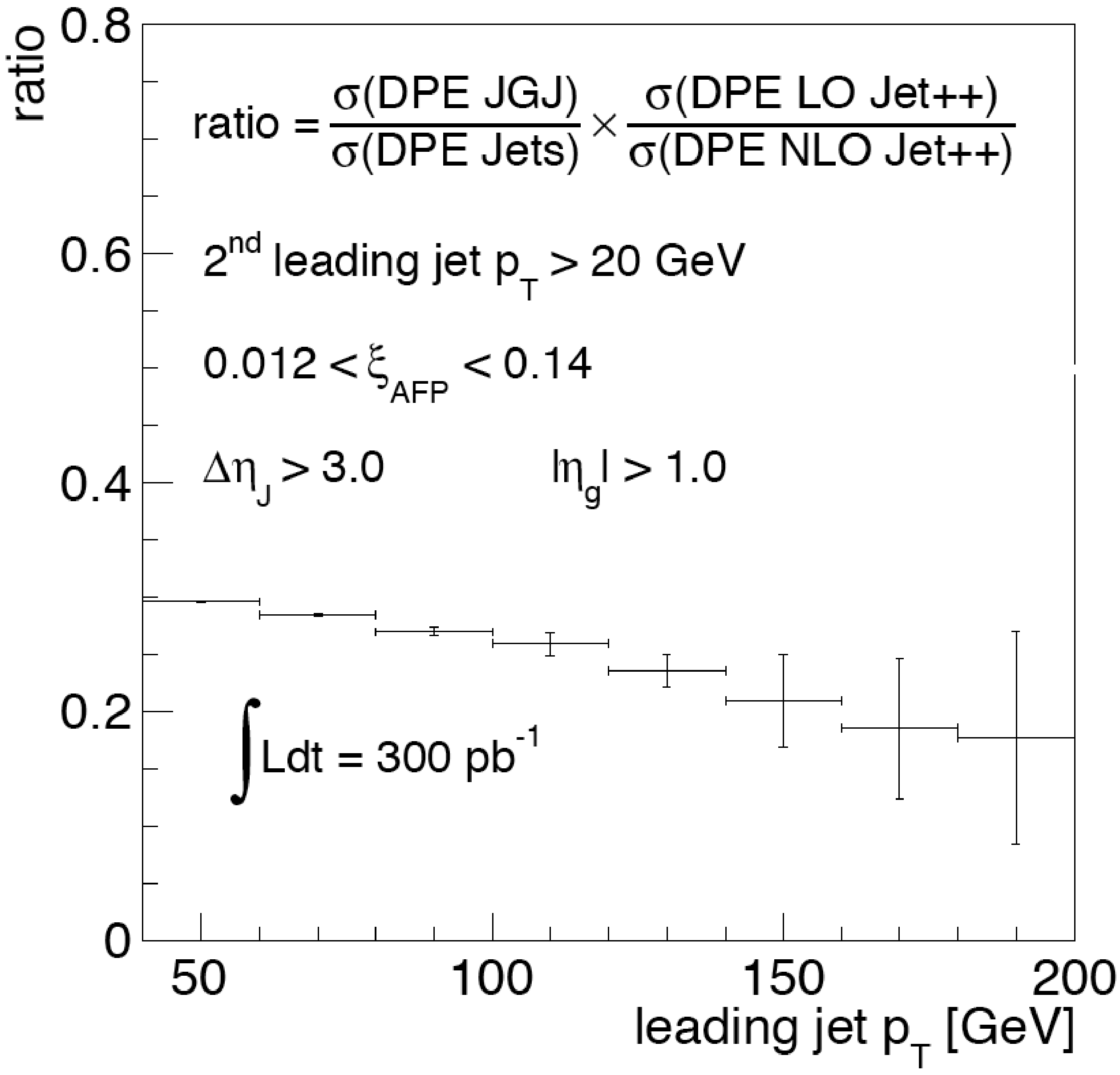
Proton dominated by uud

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

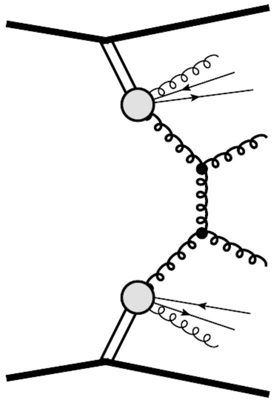
x :Proton momentum fraction carried away by the interacting quark

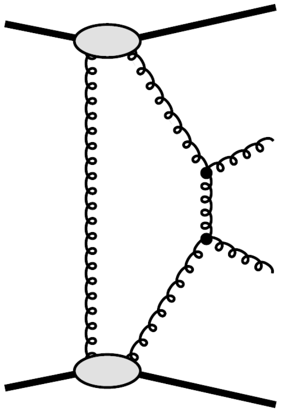
Jet gap jet events in diffraction

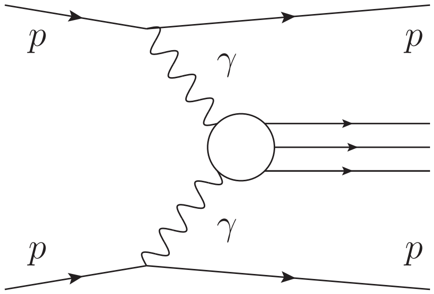
- Measure the ratio of the jet gap jet to the dijet cross sections: sensitivity to BFKL dynamics
- As an example, study as a function of leading jet p_T

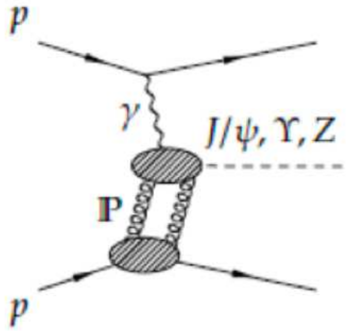


Exclusive diffraction





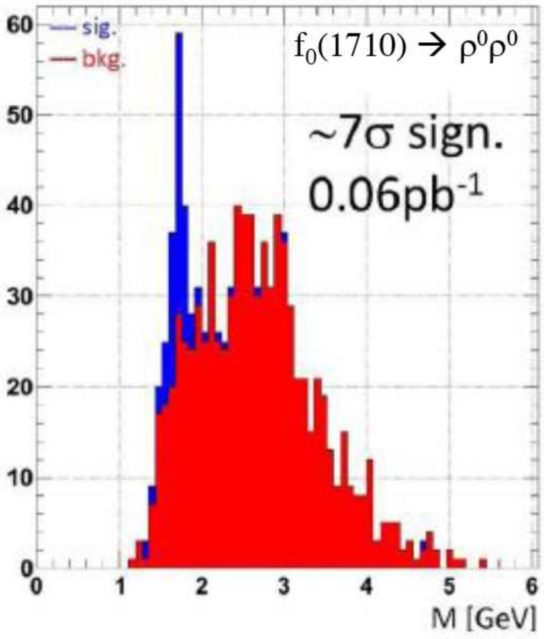


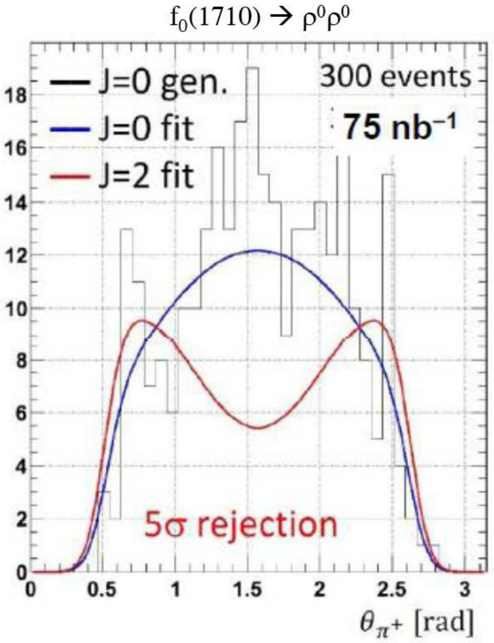


- Many exclusive channels can be studied at medium and high luminosity: jets, χ_C, charmonium, J/Ψ....
- Possibility to reconstruct the properties of the object produced exclusively (via photon and gluon exchanges) from the tagged proton: system completely constrained
- Possibility of constraining the 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
- 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)

Low-Medium Lumi: Glueball production

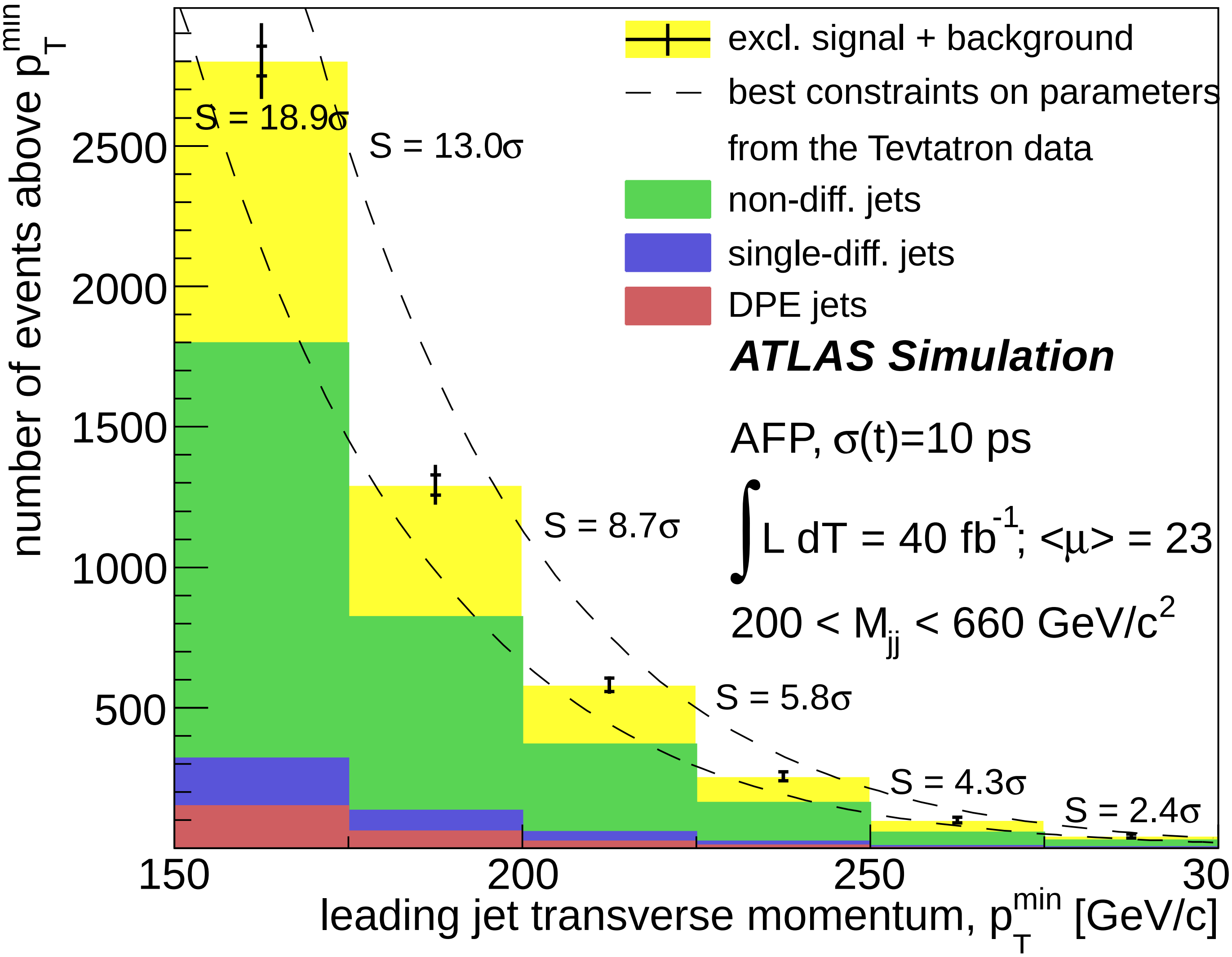
- CMS/TOTEM has the possibility to discover/exclude glueballs at low masses: 1-10 GeV masses can be probed diffractively ($\xi \sim 10^{-4} - 10^{-3}$), ensuring pure gluonic exchanges
- Check the $f_0(1500)$ or $f_0(1710)$ glueball candidates (Lattice calculations predict a $0++$ glueball at 1.7 GeV with a ~100 MeV uncertainty, favoring the $f_0(1710)$ candidate)
- Simulation of signal ($f_0(1710) \rightarrow \rho^0\rho^0$ and non resonant $\rho^0\rho^0$ background including CMS tracker performance (20-30 MeV resolution): needs $\sim$ 0.06 pb^{-1} for 7 σ signal; need about 0.6 pb^{-1} for decay characterisation
- Spin analysis of $f_0(1710) \rightarrow \rho^0\rho^0 \rightarrow 4\pi$ to dtermine $J = 0$ or 2: as an example polar angle of the $\pi^+\pi^-$ pair for the ρ candidate; spin analysis in mass bins $<$ 40 MeV needs $\sim$ 5 pb^{-1}





Exclusive jet production at the LHC

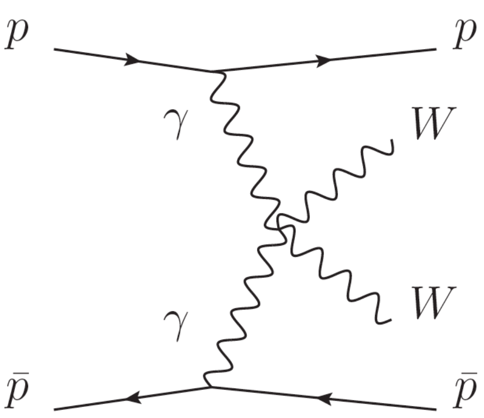
- Jet cross section measurements: up to 18.9 σ for exclusive signal with 40 fb^{-1} ($\mu = 23$): highly significant measurement in high pile up environment, improvement over measurement coming from Tevatron (CDF) studies using $\bar{p}$ forward tagging by about one order of magnitude

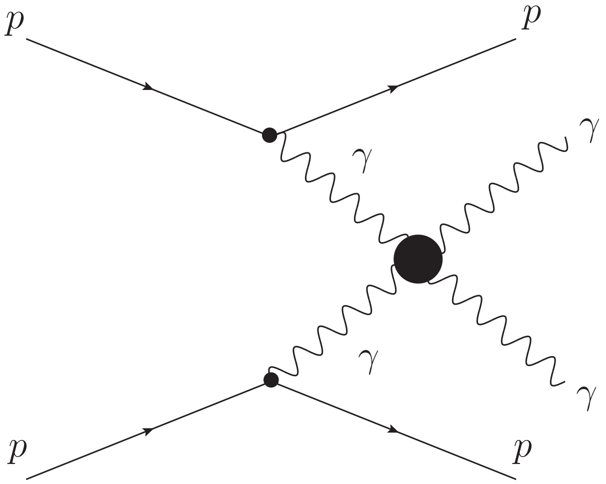


- Important to perform these measurements to constrain exclusive Higgs production: background/signal ratio close to 1 for central values at 120 GeV

PHOTON EXCHANGE PROCESSES : EXPLORATORY PHYSICS

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 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, JHEP 1502 (2015) 165; 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 $-0.02 < a_0^W < 0.02$ GeV^{-2}
- New limits from D0/CMS: 1.5 10^{-4} (2.5 10^{-3}), and 5 10^{-4} (9.3 10^{-3} for CMS (D0) for a_0^W and a_c^W with a form factor at 500 GeV
- Dimension 6 operators → violation of unitarity at high energies

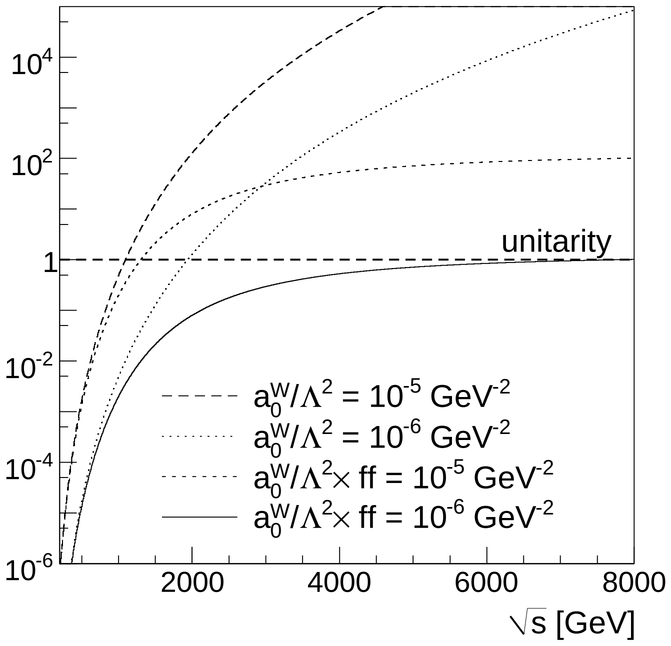
Quartic anomalous gauge couplings: form factors

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

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

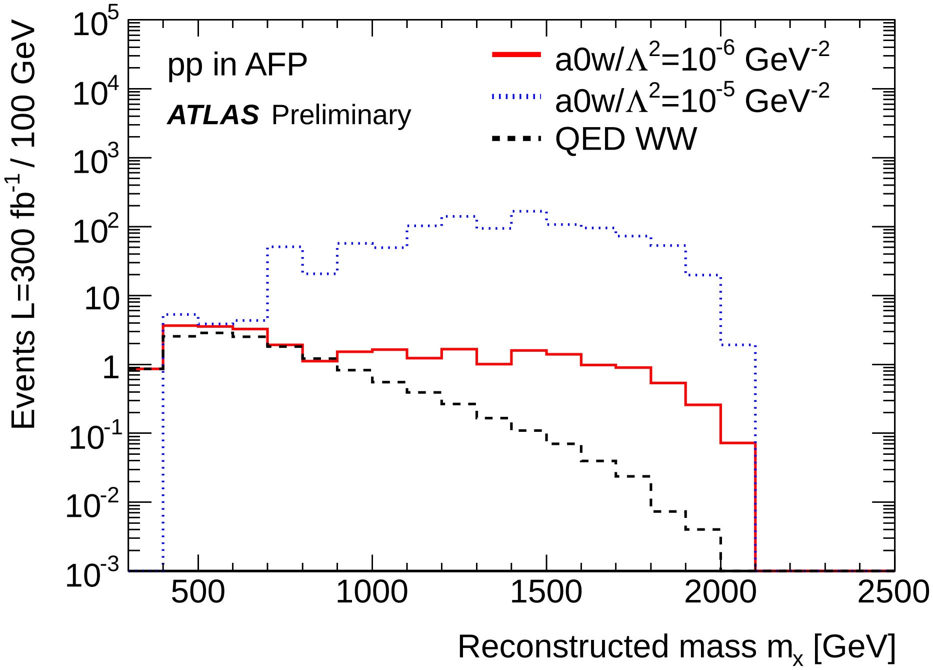
  where $a = a_0/\Lambda^2$

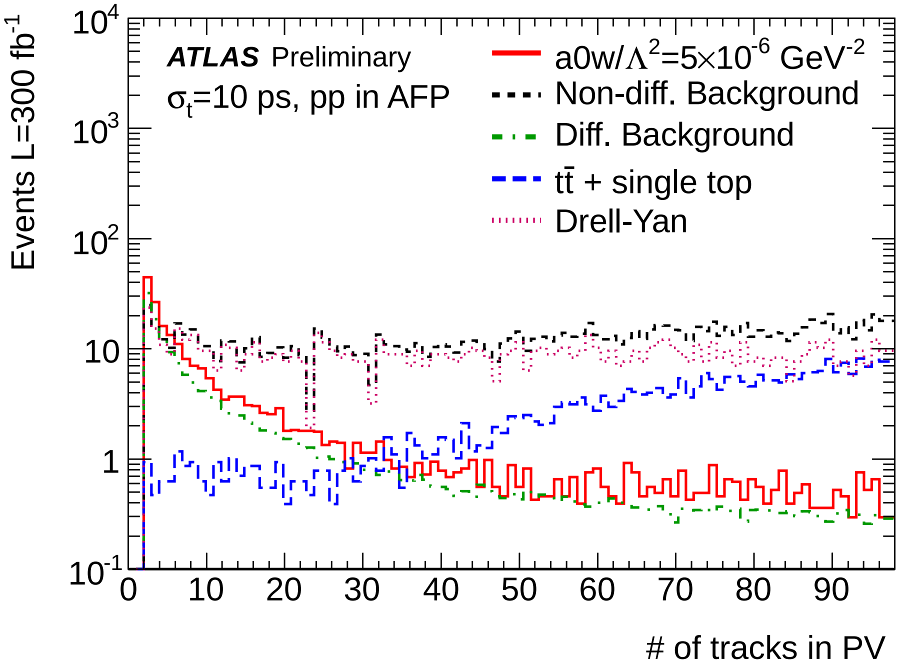
- Introducing form factors to avoid quadratical divergences of scattering amplitudes due to anomalous couplings in conventional way: $a_0^W/\Lambda^2 \to \frac{a_0^W/\Lambda^2}{(1+W\gamma\gamma/\Lambda_{cutoff})^2}$ with $\Lambda_{cutoff} \sim 2$ TeV, scale of new physics
- For $a_0^W \sim 10^{-6}$ GeV^{-2}, 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

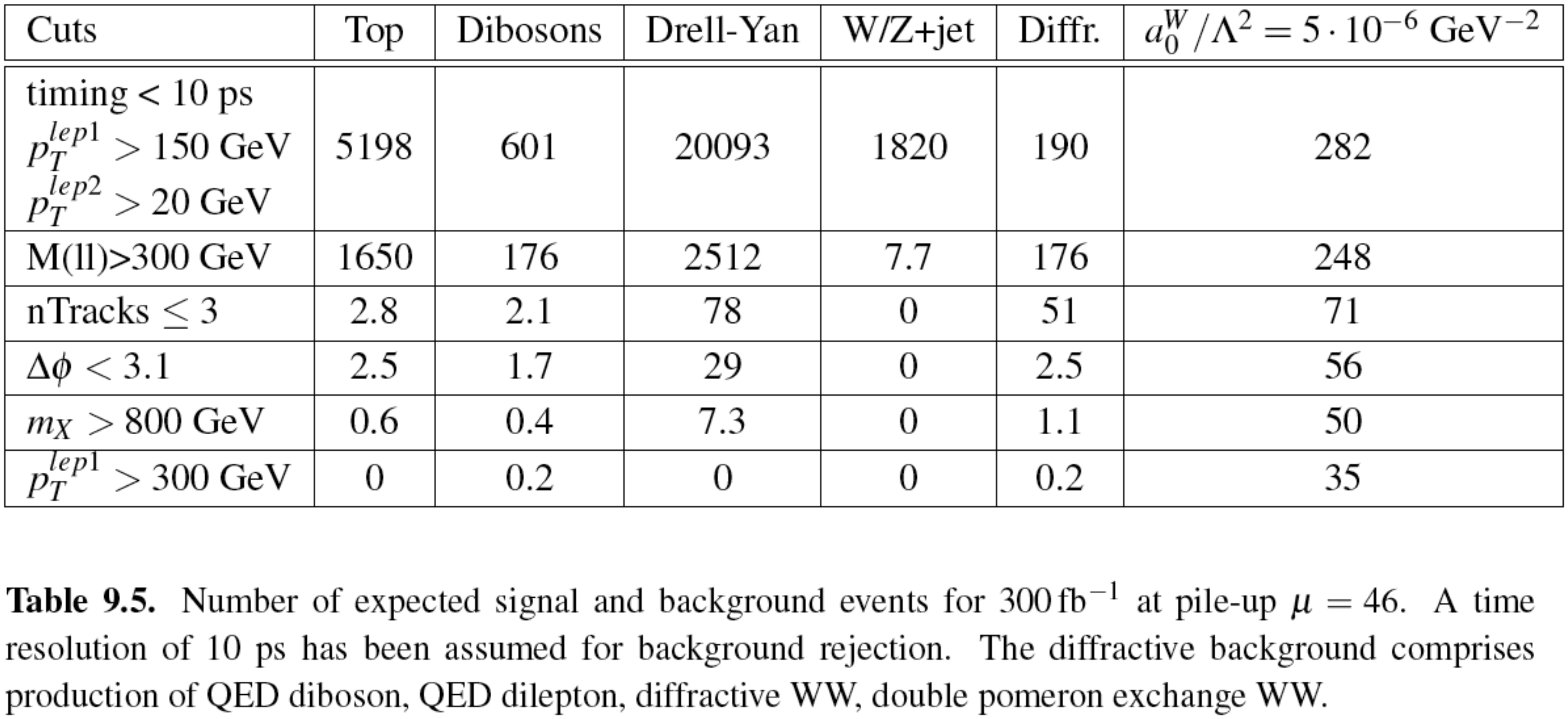
- Reach on anomalous couplings studied using a full simulation of the ATLAS detector, including all pile-up effects; only leptonic decays of Ws are considered
- Signal appears at high lepton p_T and dilepton mass (central ATLAS) and high diffractive mass (reconstructed using forward detectors)
- Cut 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}

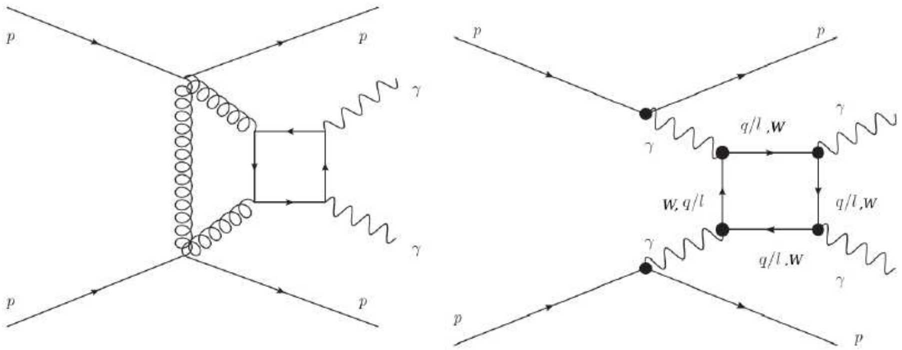
Reach at LHC

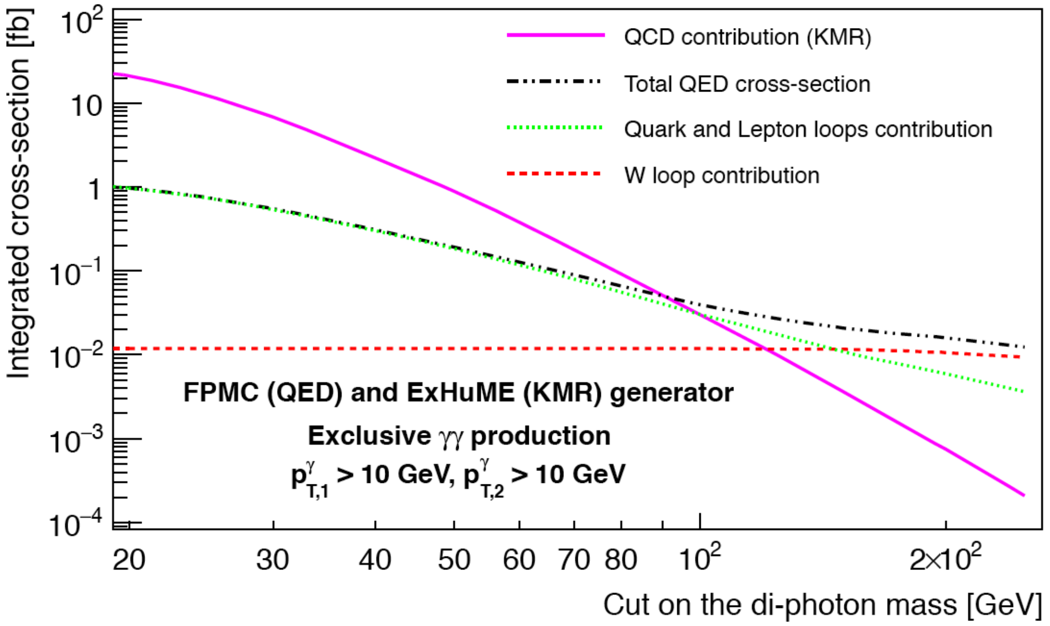
Reach at high luminosity on quartic anomalous coupling using fast simulation (study other anomalous couplings such as $\gamma\gamma ZZ$...)

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 ~two orders of magnitude (only $\gamma\gamma WW$ couplings)
- Reaches the values predicted by extra-dimension models

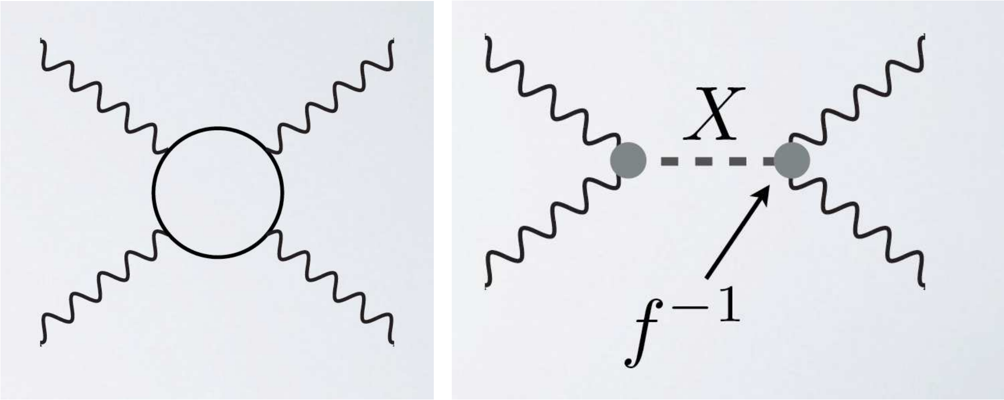
SM $\gamma\gamma$ exclusive production





- 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

Motivations to look for quartic $\gamma\gamma$ anomalous couplings



- Two effective operators at low energies

$$\mathcal{L}_{4\gamma} = \zeta_1^{\gamma} F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2^{\gamma} F_{\mu\nu}F^{\nu\rho}F_{\rho\lambda}F^{\lambda\mu}$$

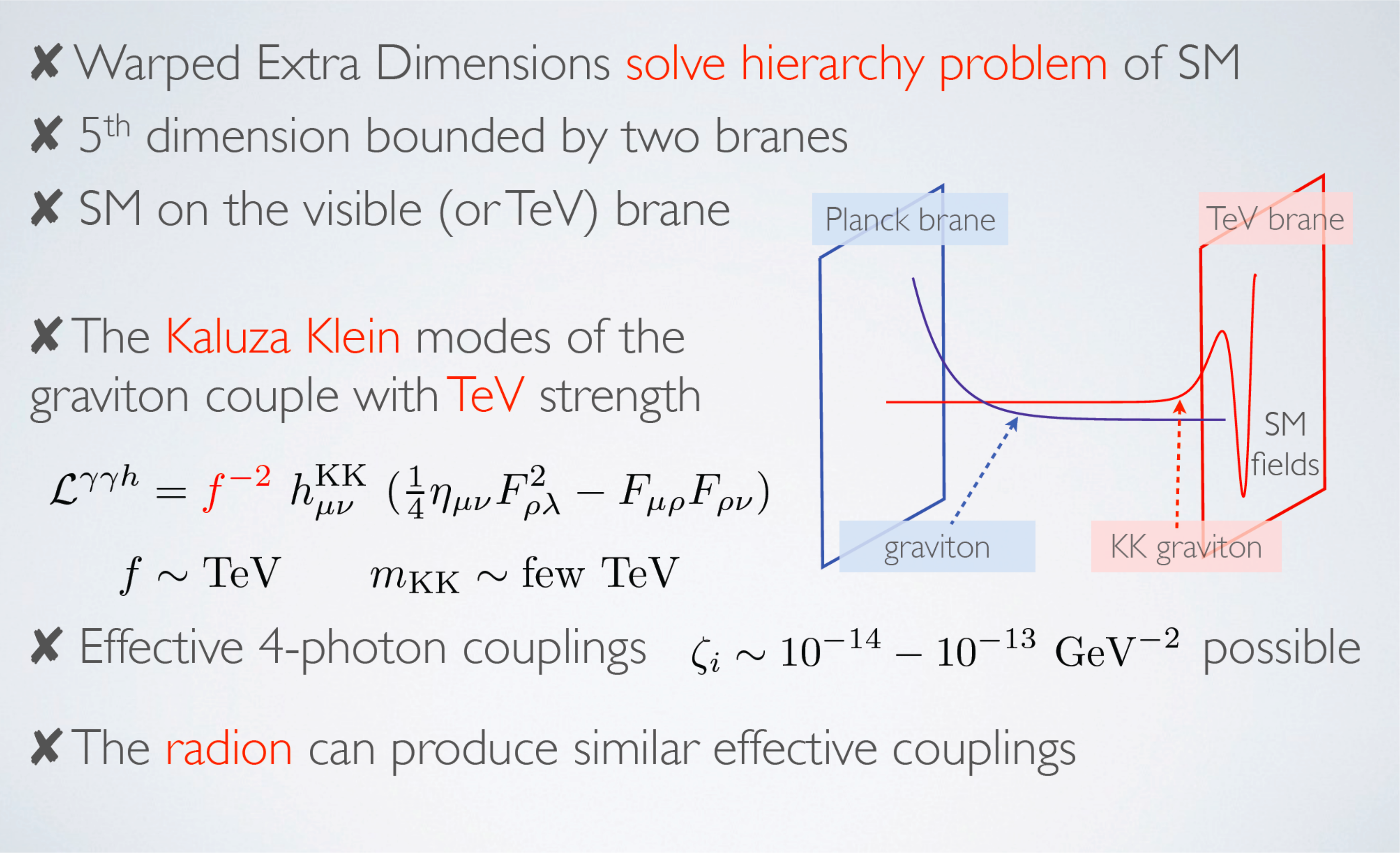
- $\gamma\gamma\gamma\gamma$ couplings can be modified in a model independent way by loops of heavy charge particles

$$\zeta_1 = \alpha_{em}^2 Q^4 m^{-4} N c_{1,s}$$

  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

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

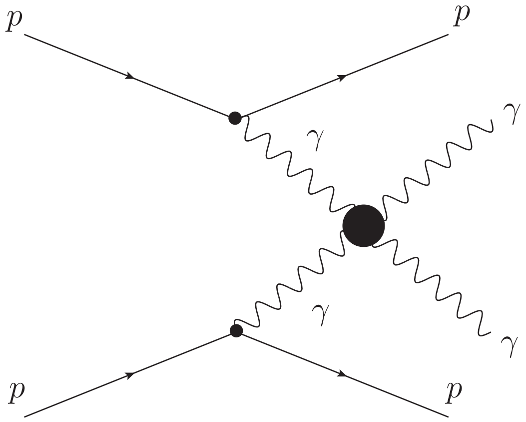
$$f \sim \mathrm{TeV} \qquad m_{\rm KK} \sim \text{few TeV}$$

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

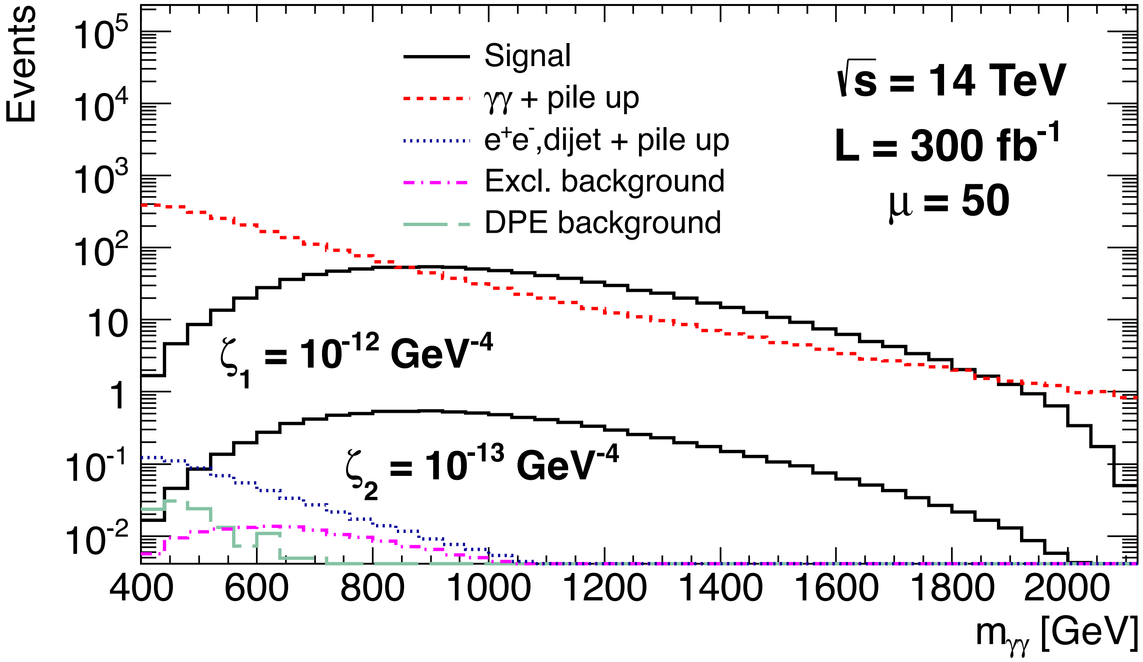
✘ The radion can produce similar effective couplings

- 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

Search for quartic $\gamma\gamma$ anomalous couplings

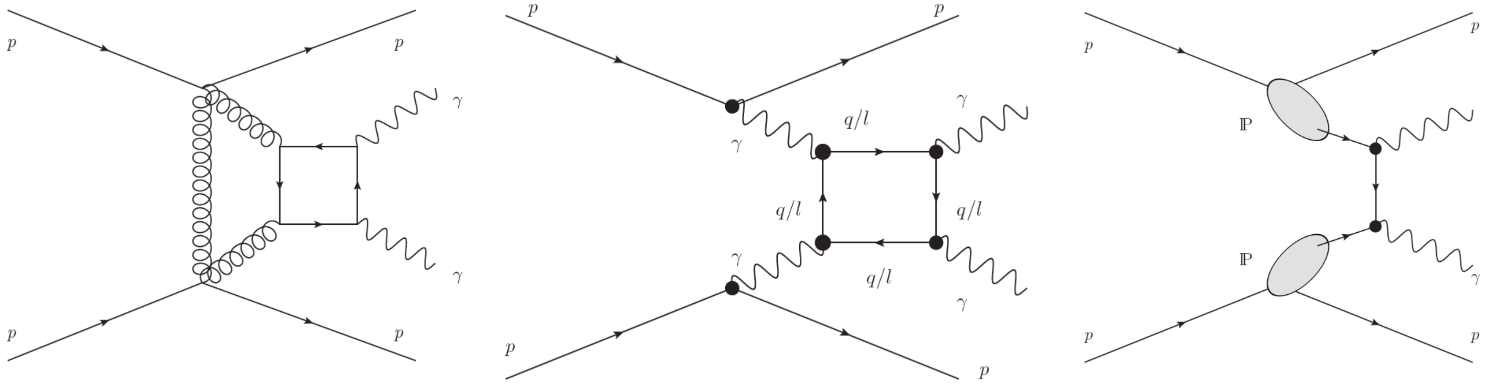


- Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- Analysis performed at hadron level including detector efficiencies, resolution effects, pile-up...

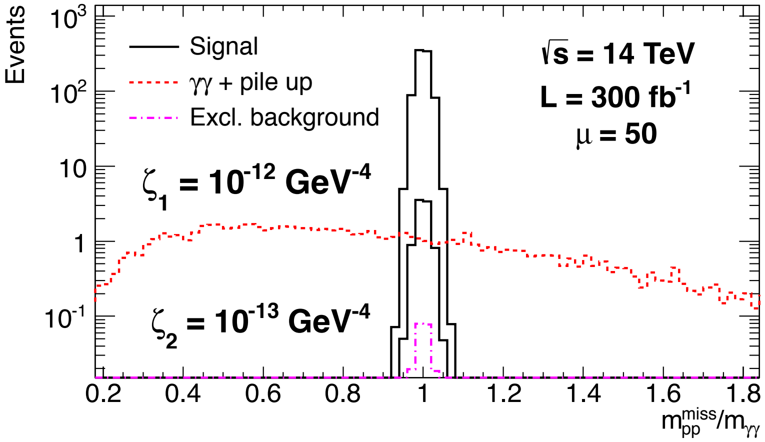


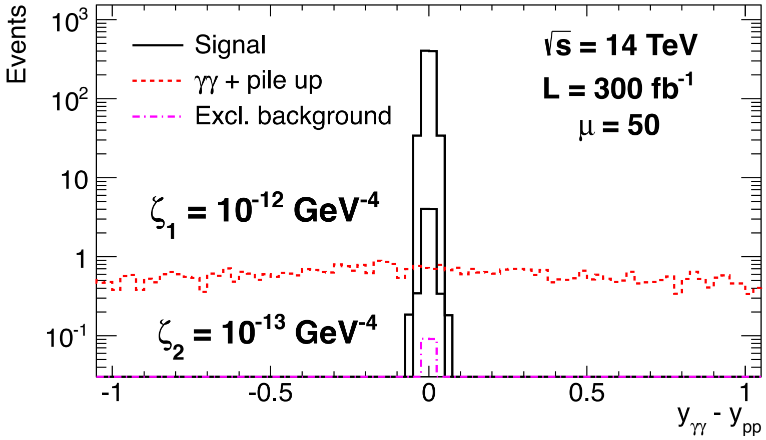
Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings: Analysis flow

- 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
- pile-up simulated in AFP/CT-PPS: 50, 100, 200...
- 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,
- All backgrounds were considered: DPE diphoton production, Higgs decaying into photons, exclusive production of diphtoon, dilepton, dijet with lepton/jet misidentified, pile up (ND production of Drell-Yan, dijet, diphoton...)



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
$[0.015 < \xi_{1,2} < 0.15,$ $p_{T1,(2)} > 200, (100)$ 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
$[p_{T2}/p_{T1} > 0.95,$ $\lvert\Delta\phi\rvert > \pi - 0.01]$	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
- Pile up background rejected using exclusivity cuts: timing detectors not used in this analysis
- Introducing form factors to avoid quadratical divergences of scattering amplitudes due to anomalous couplings in conventional way: $a \to \frac{a}{(1+W\gamma\gamma/\Lambda_{cutoff})^2}$ with $\Lambda_{cutoff} \sim 2$ TeV, scale of new physics

Full amplitude calculation

- Effective field theory valid if $S << 4m^2$, S smaller than the threshold production of real particles
- Since the maximum proton missing mass is $\sim$ 2 TeV at the 14 TeV LHC, the effective theory needs to be corrected for masses of particles below $\sim$ 1 TeV → 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 independant 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
$[0.015 < \xi_{1,2} < 0.15,$ $p_{\mathrm{T1,(2)}} > 200, (100)$ 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
$[p_{\mathrm{T2}}/p_{\mathrm{T1}} > 0.95,$ $\lvert\Delta\phi\rvert > \pi - 0.01]$	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

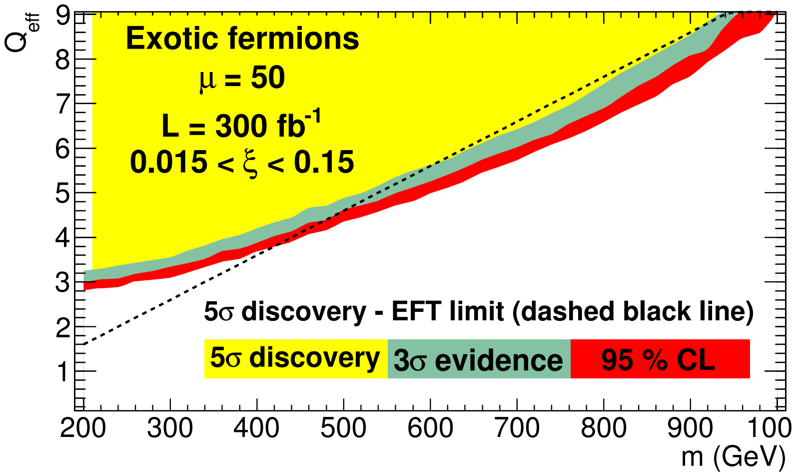
- No background after cuts for 300 fb^{-1} **without needing timing detector information**
- For signal: 119.1 events for $Q_{eff} = 4$, $m =$340 GeV
- Results for full calculation lay between the effective field result with/without form factor as expected since effective calculation not valid in the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

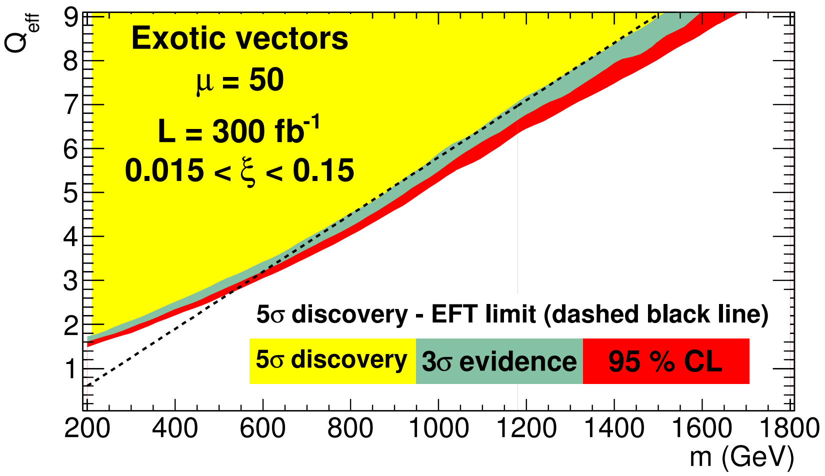
Full amplitude calculation

- 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
$Q_{\rm eff}$ (vector)	2.2	3.4	4.9	7.2	8.9
$Q_{\rm eff}$ (fermion)	3.6	5.7	8.6	-	-

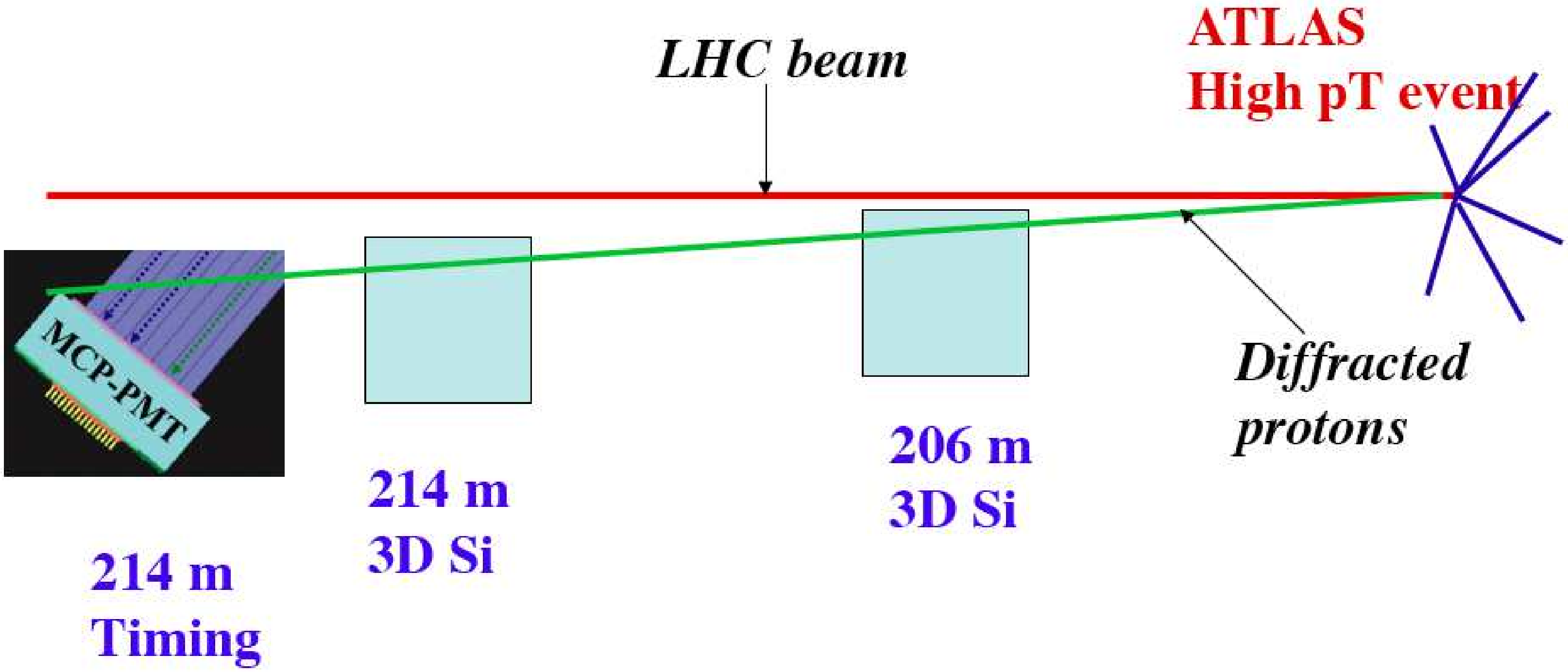
- Unprecedented sensitivites at hadronic colliders reaching the values predicted by extra-dim models - For reference, we also display the result of effective field theory (without form factor) which deviates at low masses from the full calculation
- For $Q_{Jeff} = 4$, we are sensitive to new vectors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





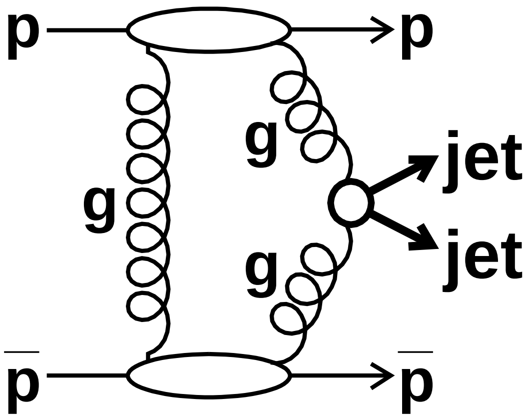
FORWARD DETECTORS : AFP AND CT-PPS (ATLAS/CMS-TOTEM)

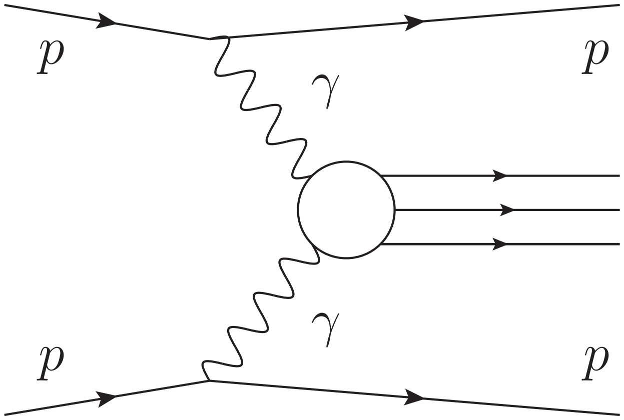
What is AFP/CT-PPS?

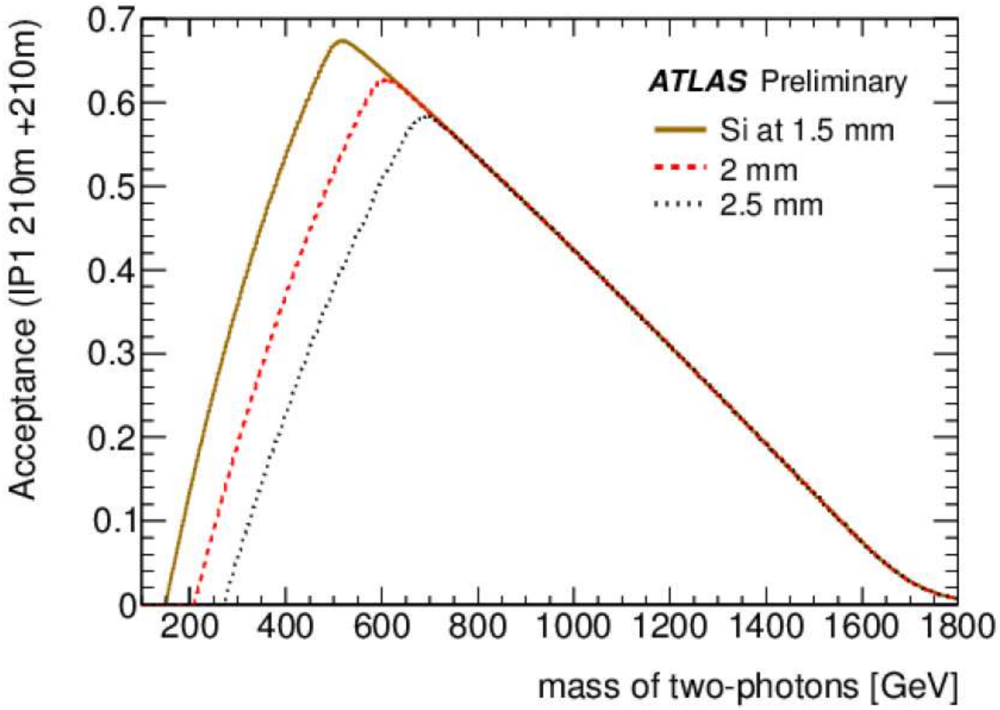


- Tag and measure protons at ±210 m using roman pots
- Trigger: Rely on ATLAS high p_T L1 trigger for high p_T events; AFP trigger for lower masses
- AFP detectors: Radiation hard "edgeless" 3D Silicon detectors, 10 ps timing detectors
- Allows running in high pile up conditions by association with correct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

AFP/CT-PPS acceptance in total mass



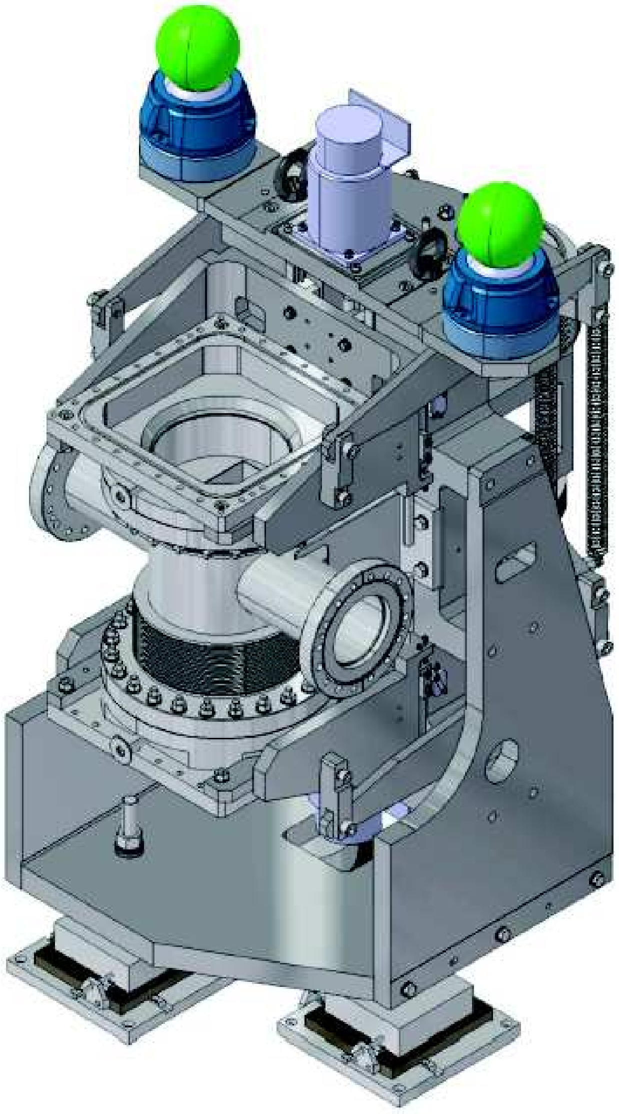




- Increase sensitivity to (new) physics in ATLAS due to color singlet or photon exchanges
- Sensitivity to high mass central system, X, as determined using AFP
- Very powerful for exclusive states: kinematical constraints coming from AFP proton measurements

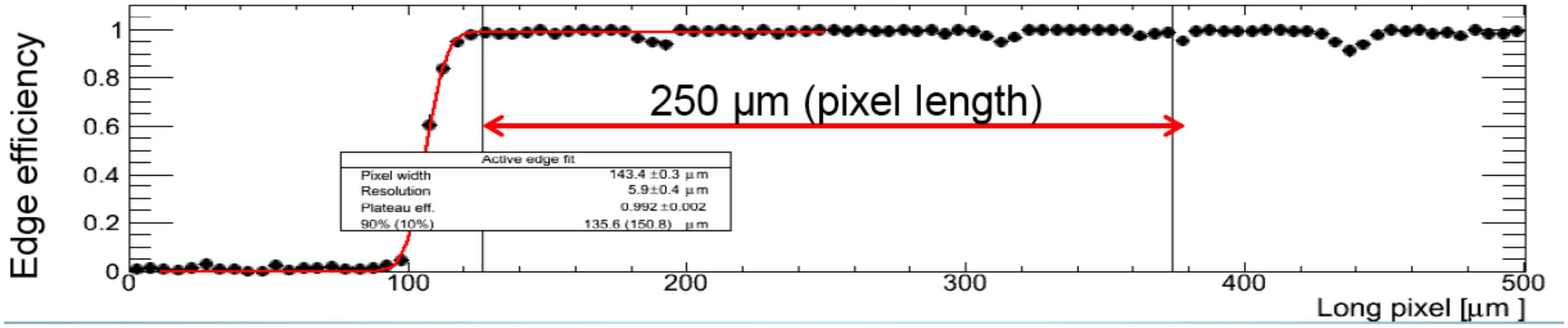
Roman pots

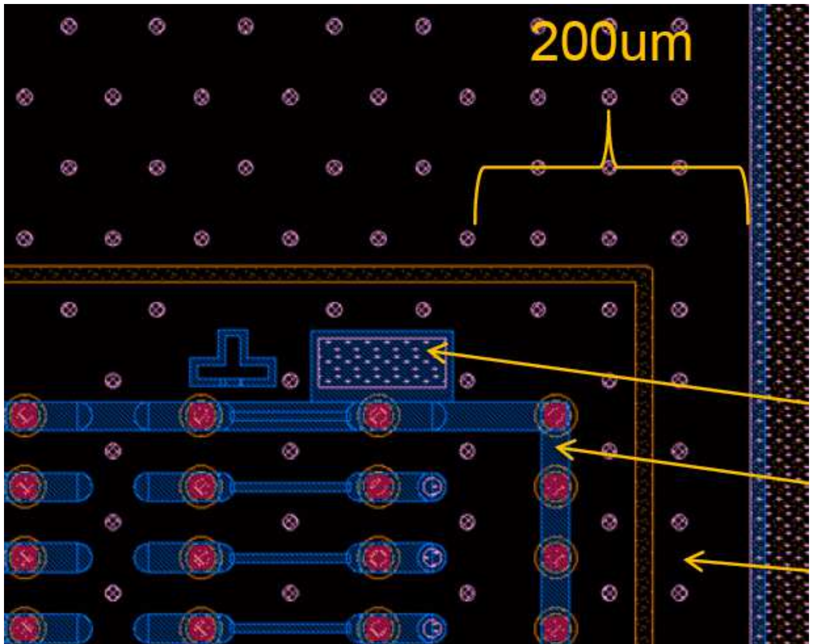
- Method to find diffractive events: Tag the proton in the final state
- Install roman pot detectors: by default solution at 210 m (2 roman pots with Si detectors, 1 with timing)



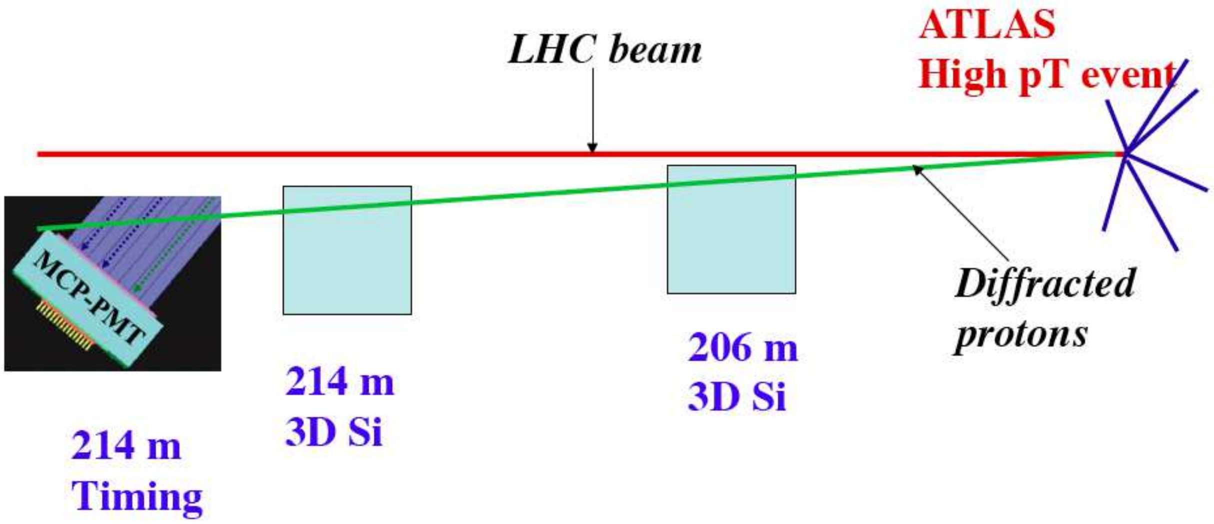
Detector I: 3D Si detector

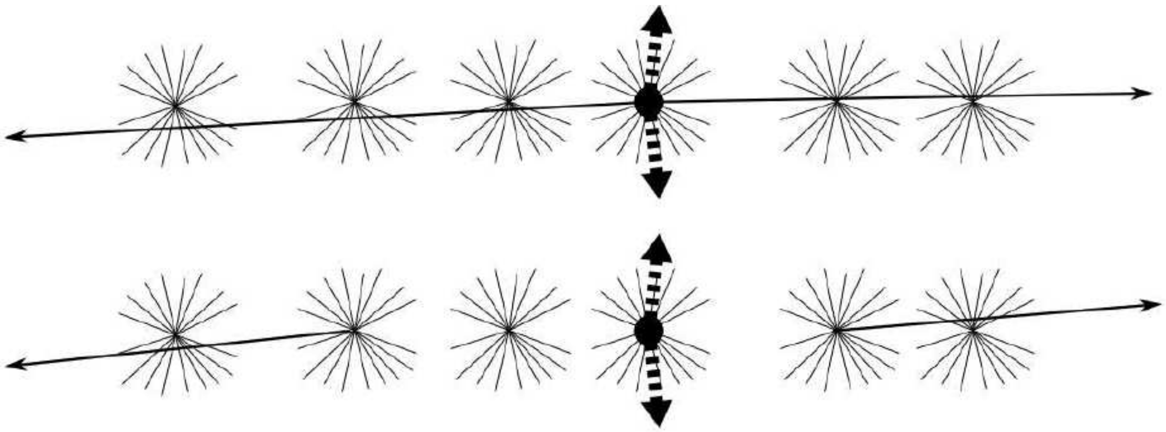
- Key requirements for the Si detector
  - Spatial resolution of 10 (30) μm in x (y) direction over the full detector coverage (2 cm × 2 cm); Angular resolution of 1 μrad
  - Minimal dead space at the edge and radiation hardness
- Sensors: double-sided 3D 50×250 micron pixel detectors (FBK) with slim-edge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





Removing pile up: measuring proton time-of-flight

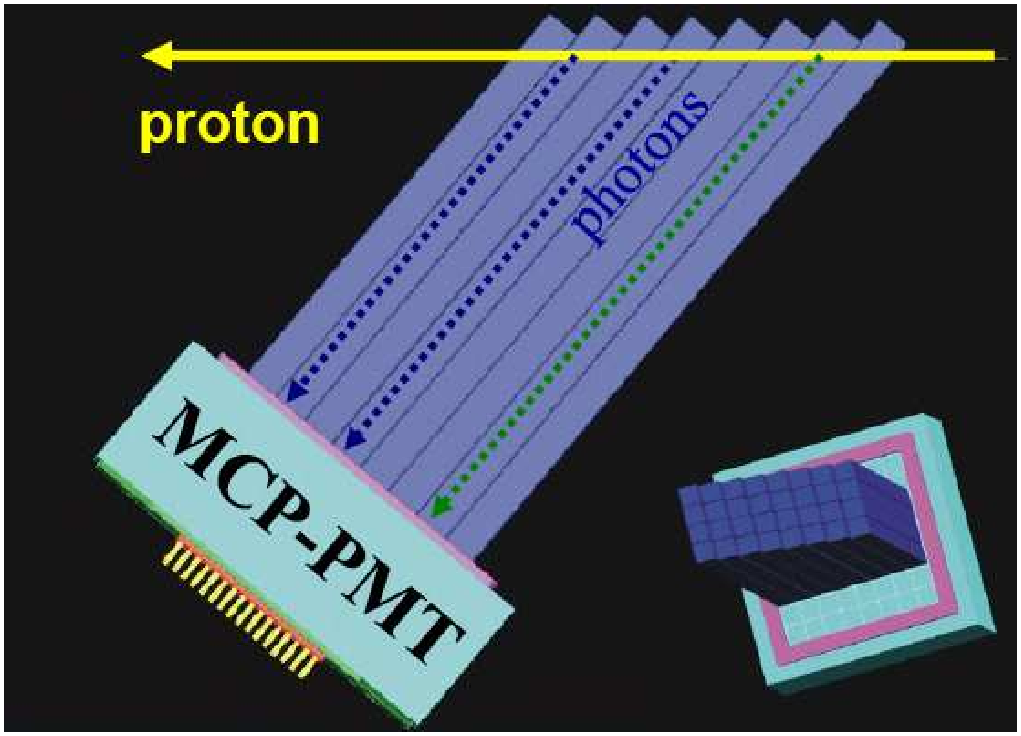




- Measure the proton time-of-flight in order to determine if they originate from the same interaction as our photon
- Typical precision: 10 ps means 2.1 mm

Detector II: timing detectors

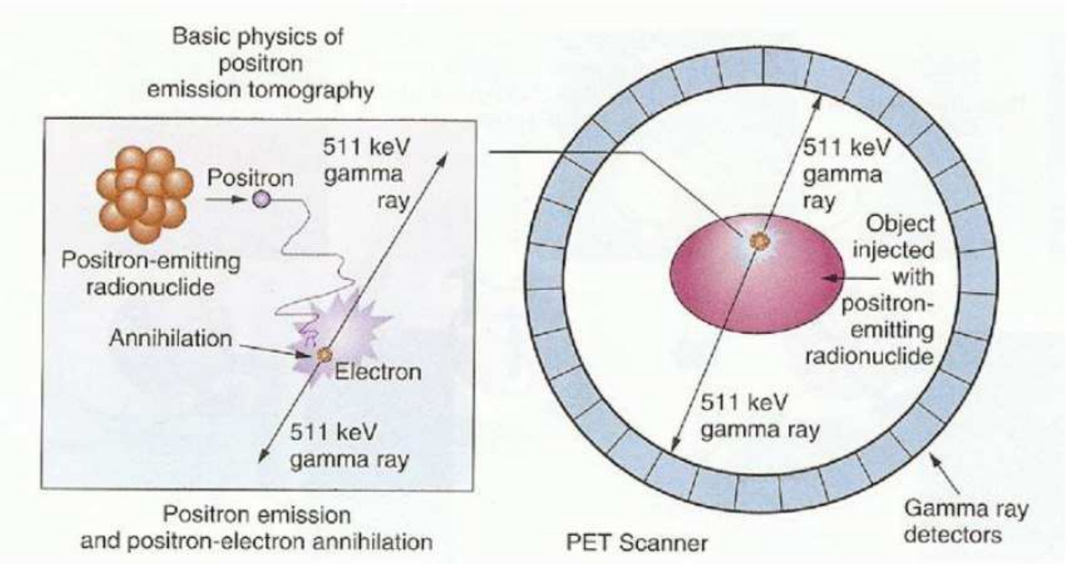
- Measure the vertex position using proton time-of-flight: suppresses high pile up events at the LHC (50 events in the same bunch crossing), allows to determine if protons originate from main interaction vertex
- Requirements for timing detectors
  - 10 ps final precision (factor 40 rejection on pile 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

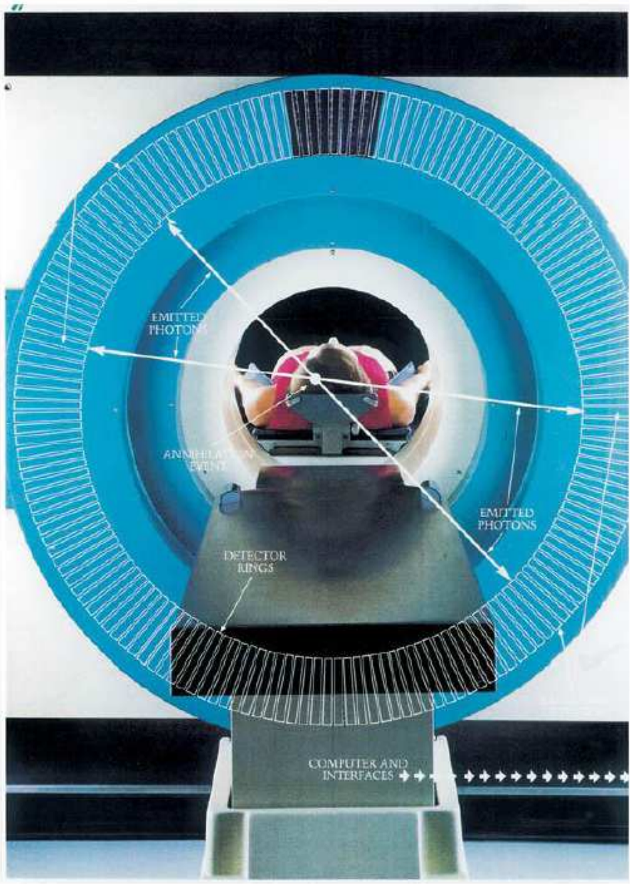


Measuring the proton time-of-flight: the SAMPIC concept

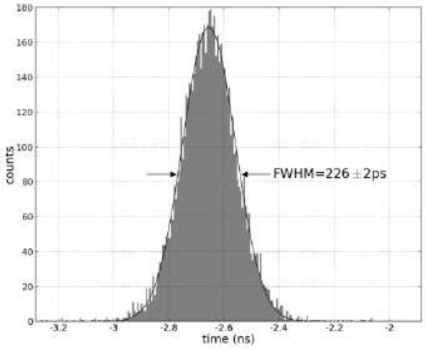
- The general idea is to measure the signal created by the protons inside a quartz, diamond or Silicon detector
- New electronics developed in Saclay/Orsay called SAMPIC that acquires the full waveform shape of the detector signal: about 3 ps precision!
- SAMPIC is cheap ($\sim$ 10 Euros per channel)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

The future: Application: Timing measurements in Positron Emission Tomography





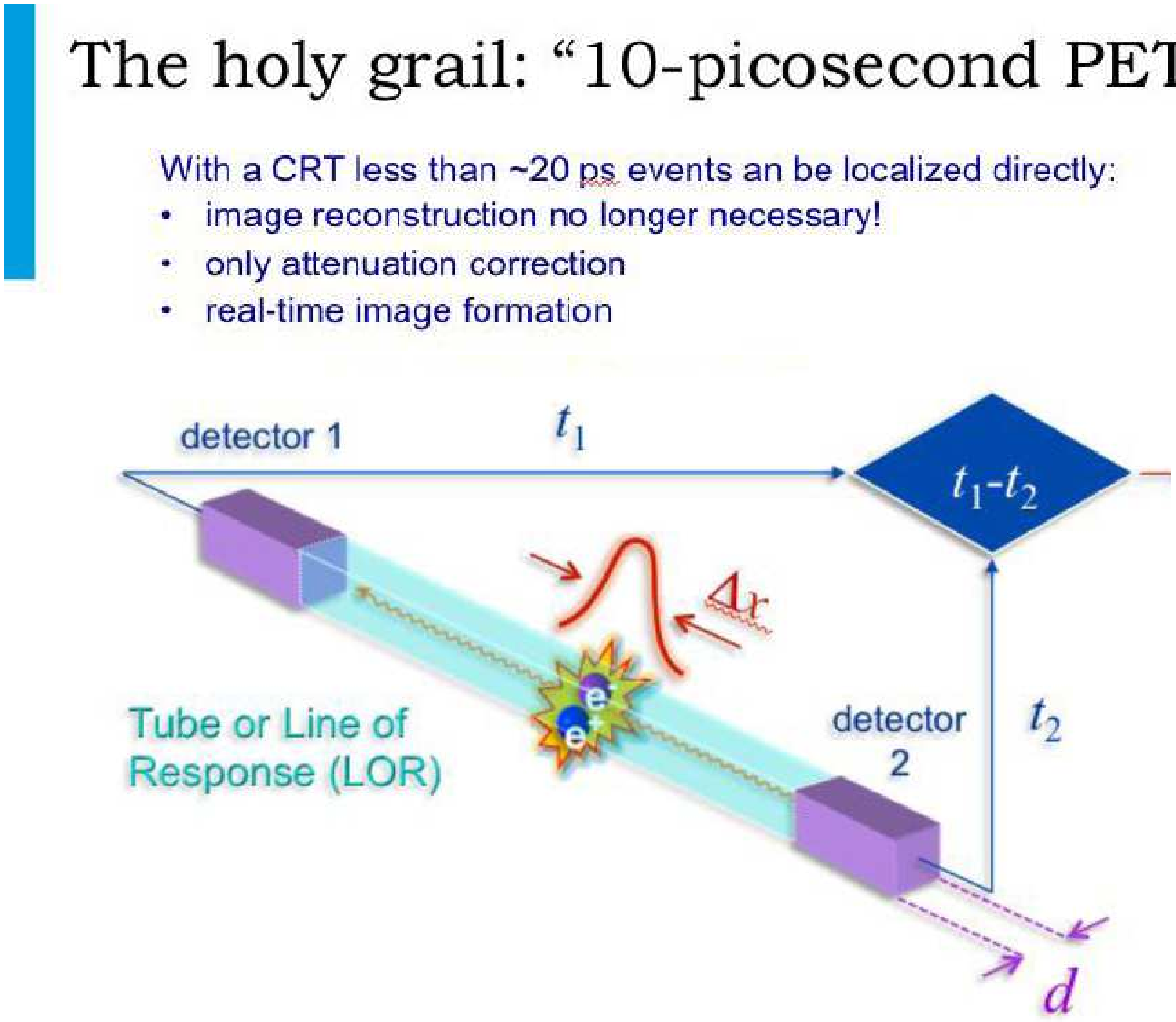
Coincidence Resolving Time:



- 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
- 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 an be localized directly:

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