Diffraction and forward physics in ATLAS

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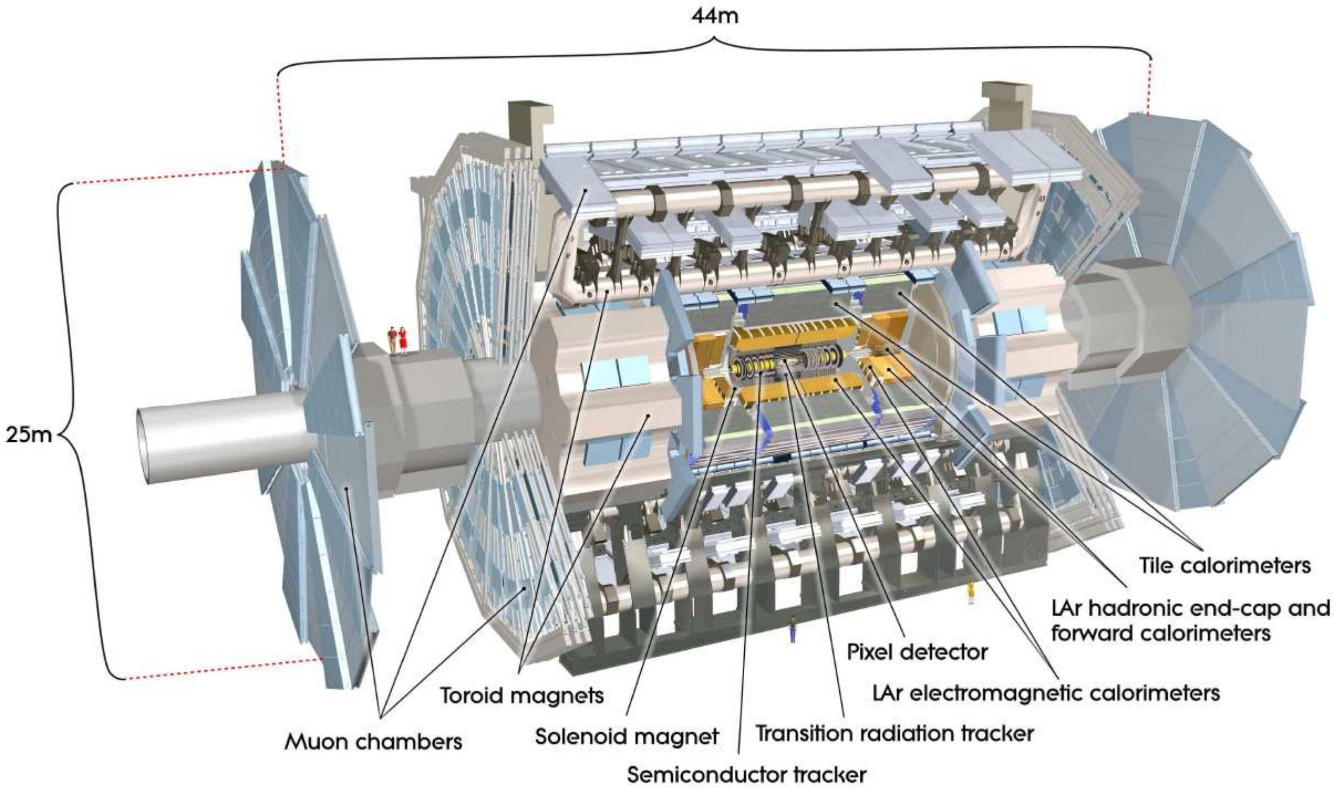
LHC: Exploration of a New Energy Frontier

- LHC 8 TeV center-of-mass energy (2011: 7 TeV) (4 times more than the previous highest energy machine, the Tevatron, at Fermilab, Batavia, Illinois, USA)
- Ultimate LHC energy: 14 TeV
- LHC schedule: data accumulated until 02/2013, shutdown until Autumn 2014, restarts with a center-of-mass energy of 13 TeV
- LHC can accelerate protons and heavy ions (last runs in Jan./Feb.)

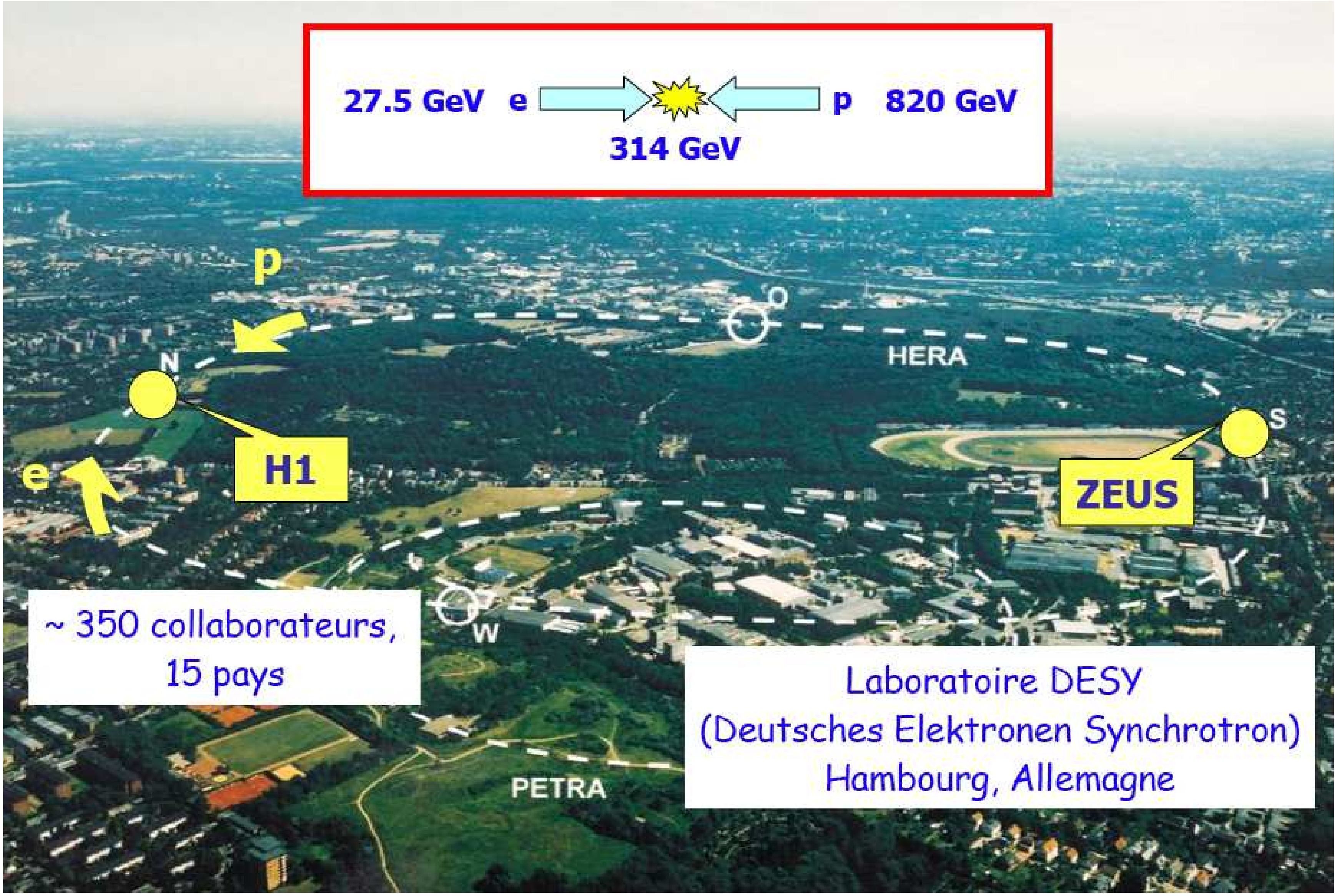
Outline



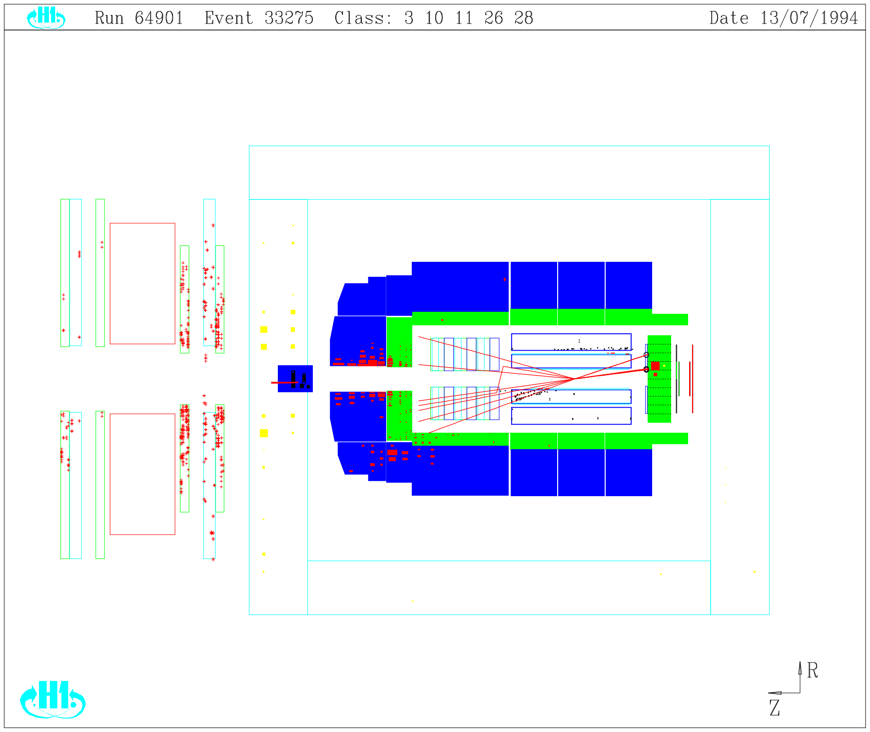
- Definition of diffraction: the example of HERA
- Rapidity gap method in ATLAS
- Total cross section: ALFA (proton tagging)
- Measurement of the pomeron structure in ATLAS (AFP)
- Jet gap jet events in diffraction at the LHC (AFP)
- Exclusive diffraction at the LHC)AFP)
- Anomalous quartic $W\gamma$ and $Z\gamma$ couplings at the LHC
- ATLAS Forward Physics (AFP) project (movable beam pipe, roman pots, Si and timing detectors)

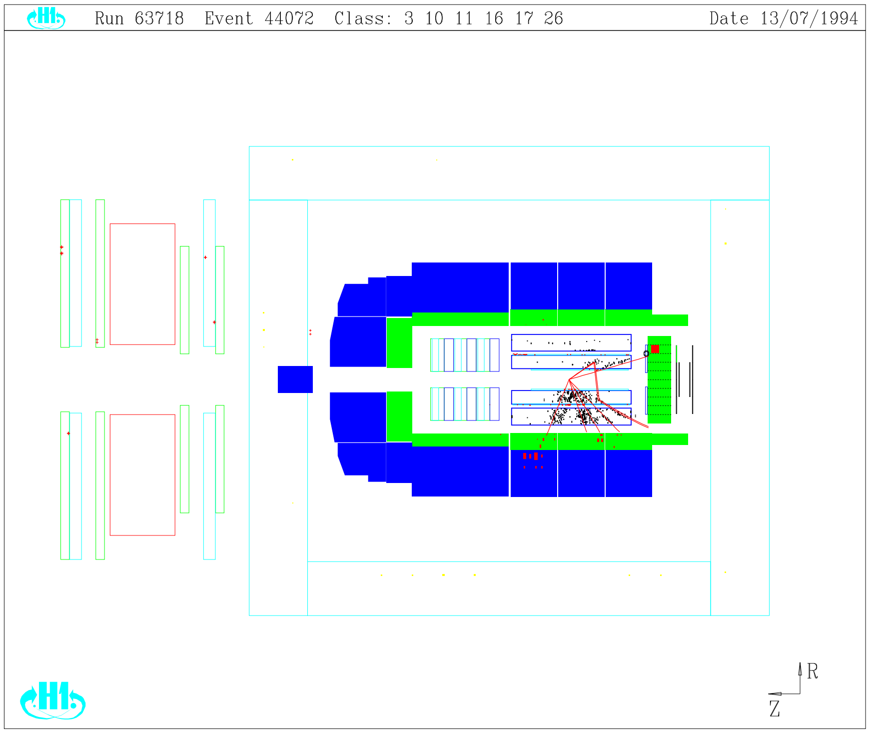
Definition of diffraction: example of HERA

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



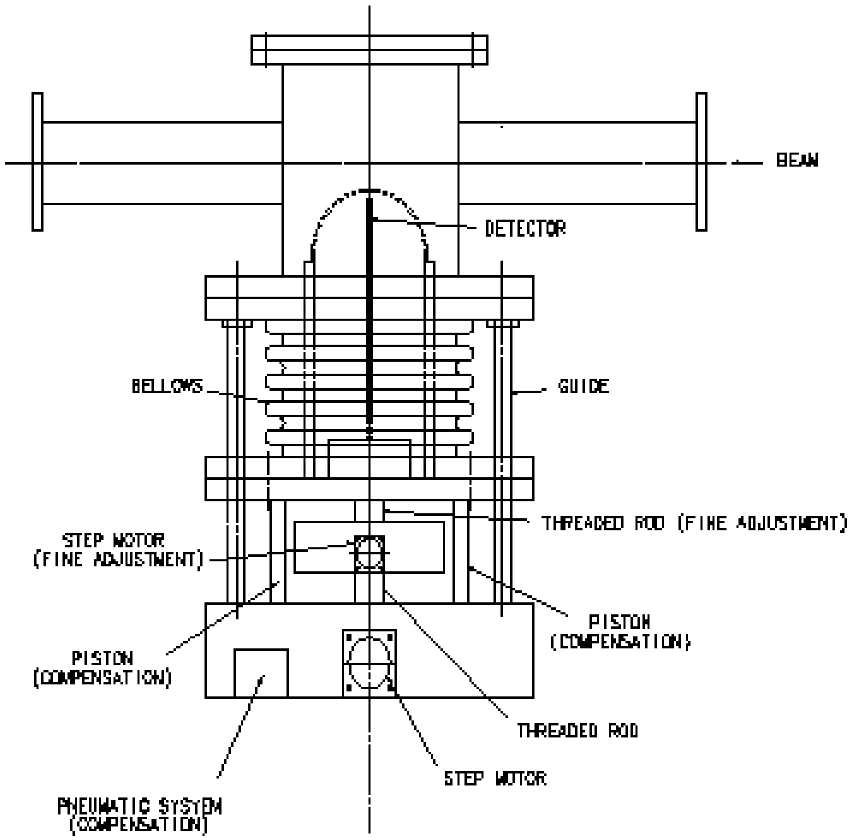
DIS and Diffractive event at HERA





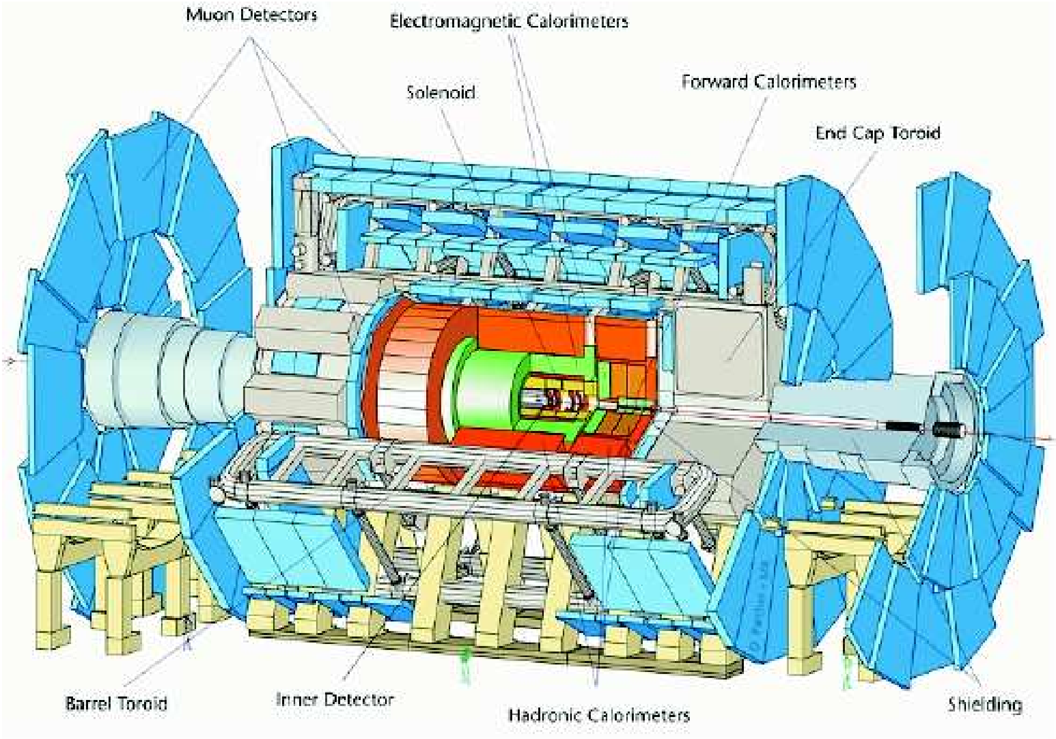
Definition of diffraction: example of HERA

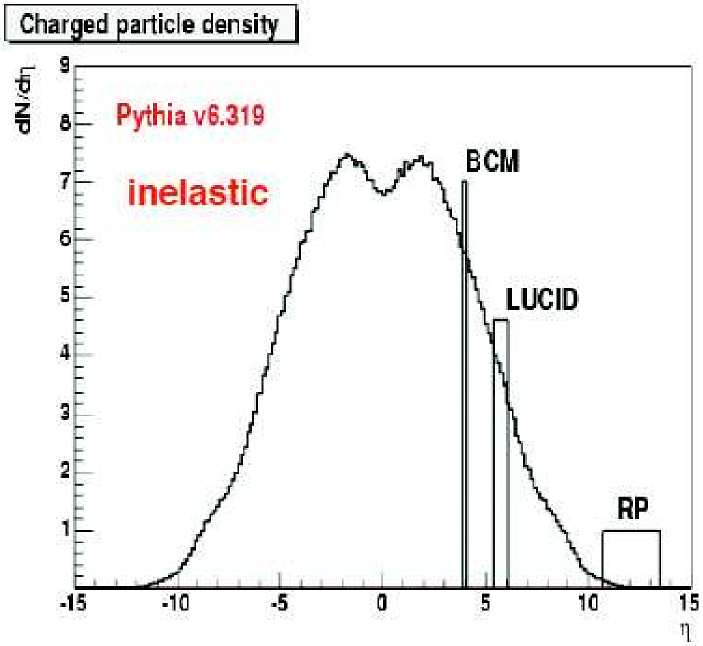
- Typical DIS event: part of proton remnants seen in detectors in forward region (calorimeter, forward muon...)
- HERA observation: in some events, no energy in forward region, or in other words no colour exchange between proton and jets produced in the hard interaction
- Leads to the first experimental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

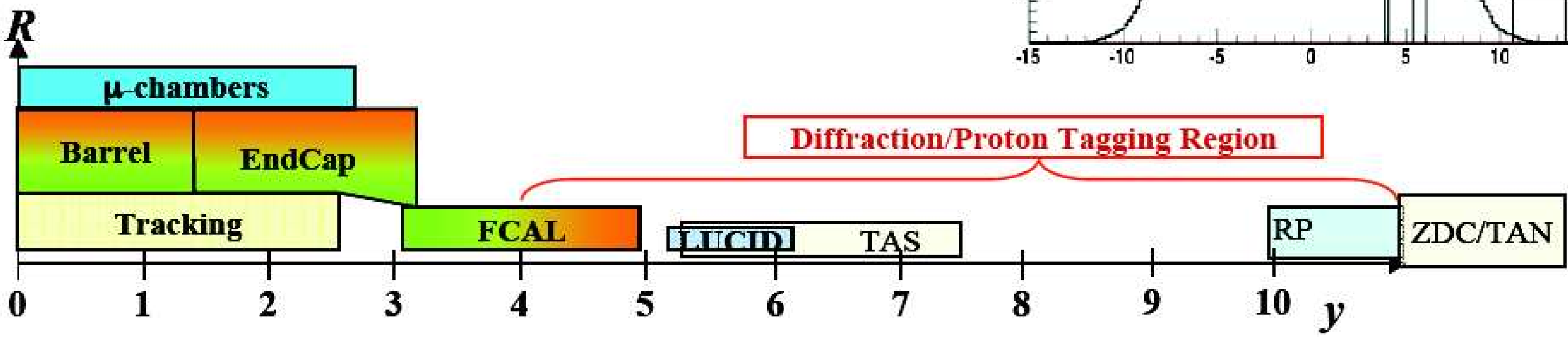


ATLAS detector

Forward region of ATLAS covered by LUCID, roman pot detectors

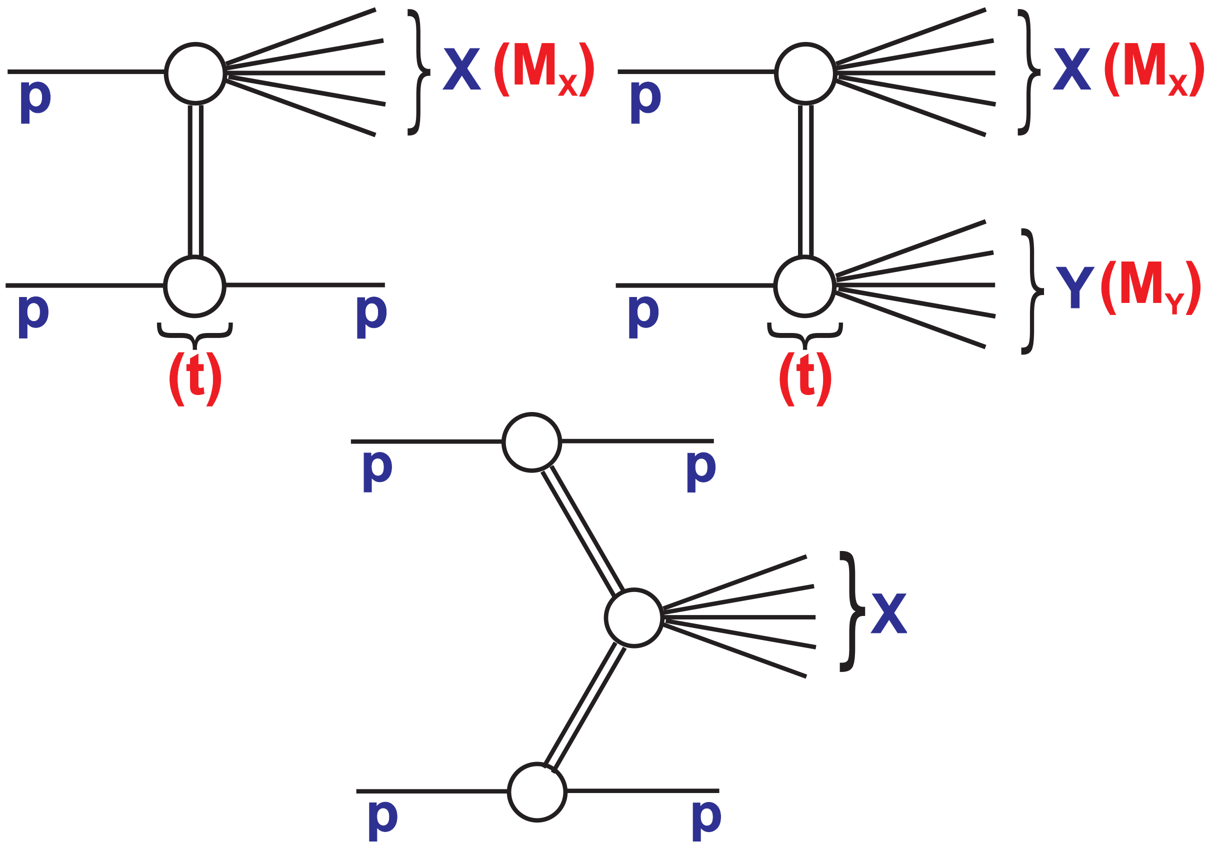






Rapidity gap method

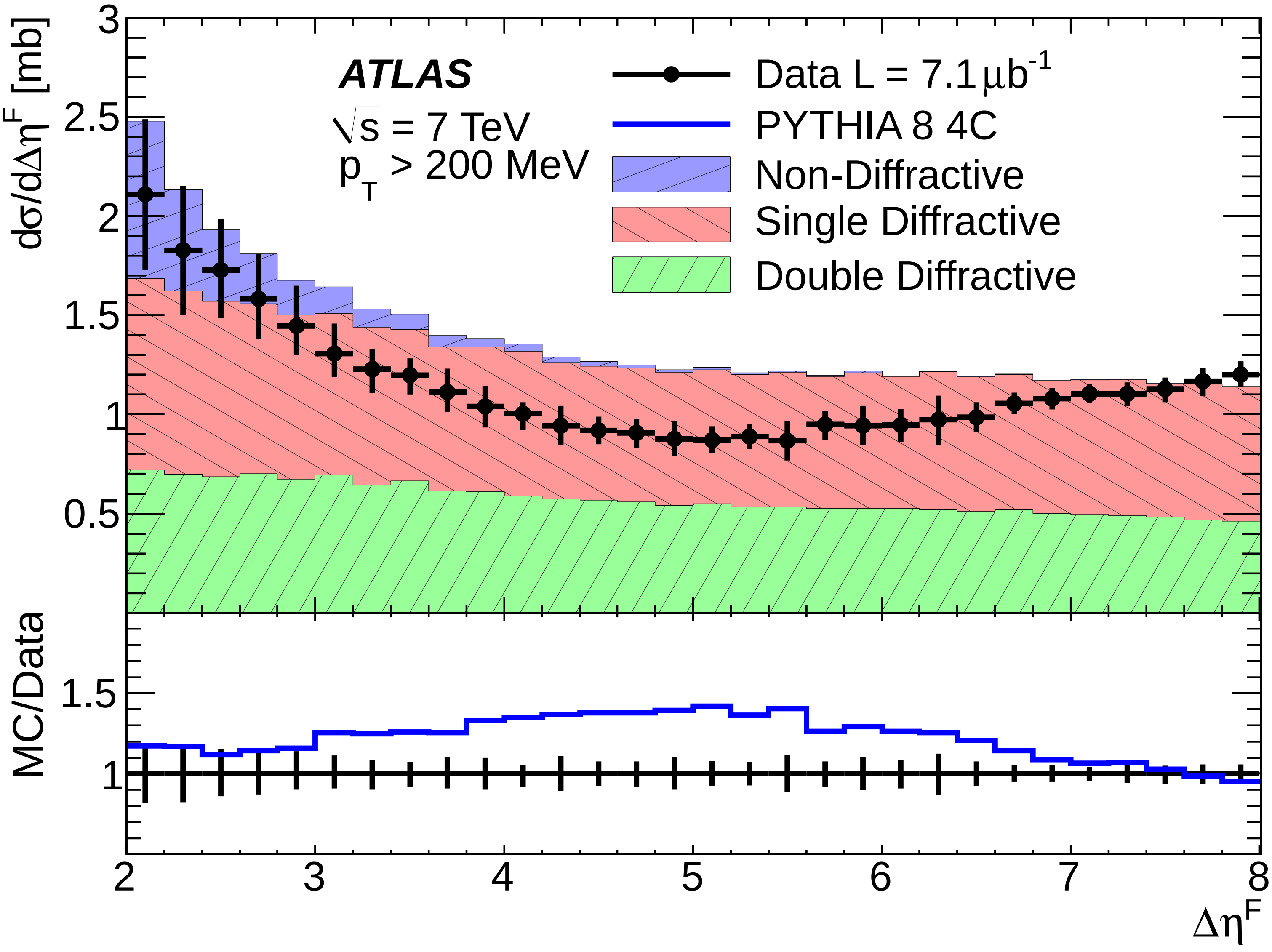
- Measure rapidity gap cross section as a function of the gap size at $\sqrt{S}$ =7 TeV and comparison with PYTHIA MC expectations
- Different components: non diffractive (not shown; due to gap size fluctation in hadronic final states), single diffractive, double diffractive, central diffraction



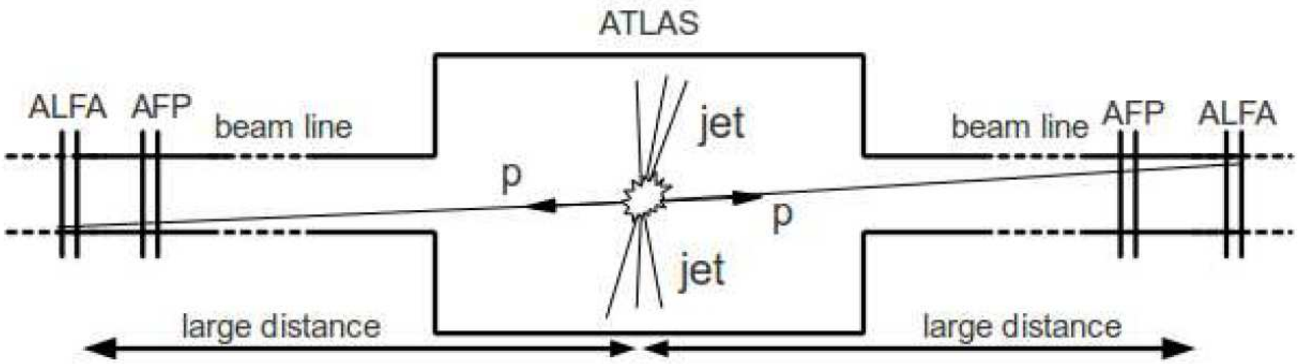
- Measurement of the rapidity gap cross section allows to tune MC predictions

Rapidity gap method

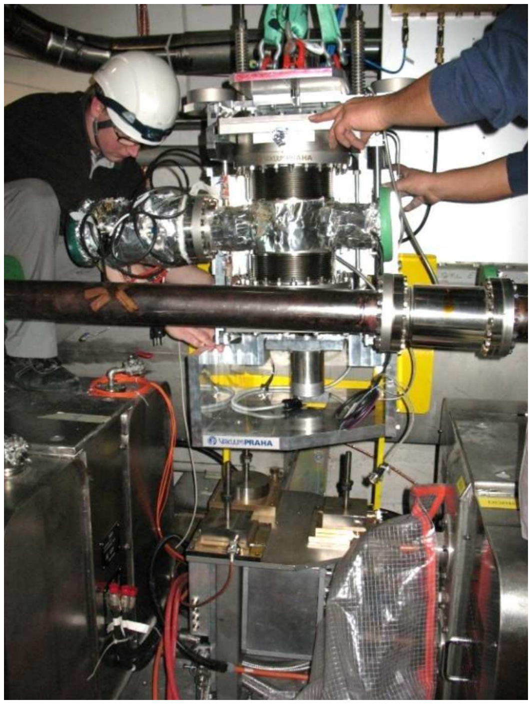
- To define the "gap", use particles with p_T >200 MeV
- MC (pythia for instance) needs to be tuned to data: No MC gives a correct description of data



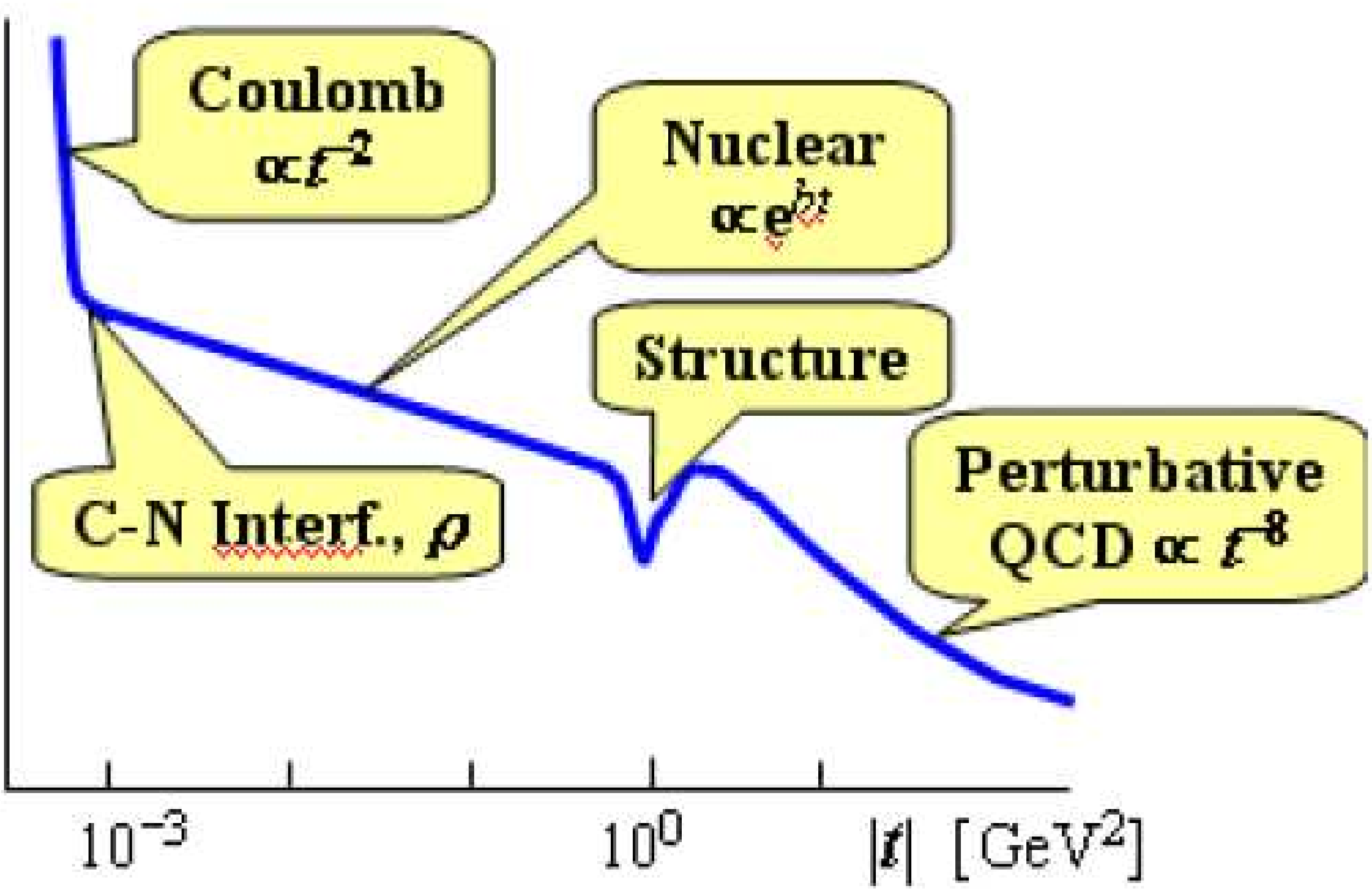
Detecting protons: The ALFA detector in ATLAS



- ALFA stands for Absolute Luminosity Measurement in ATLAS
- Tag and measure protons at ± 240 m from the ATLAS main detector
- ALFA detectors: measure proton position (silicon fibers)



Elastic scattering in the Coulomb region



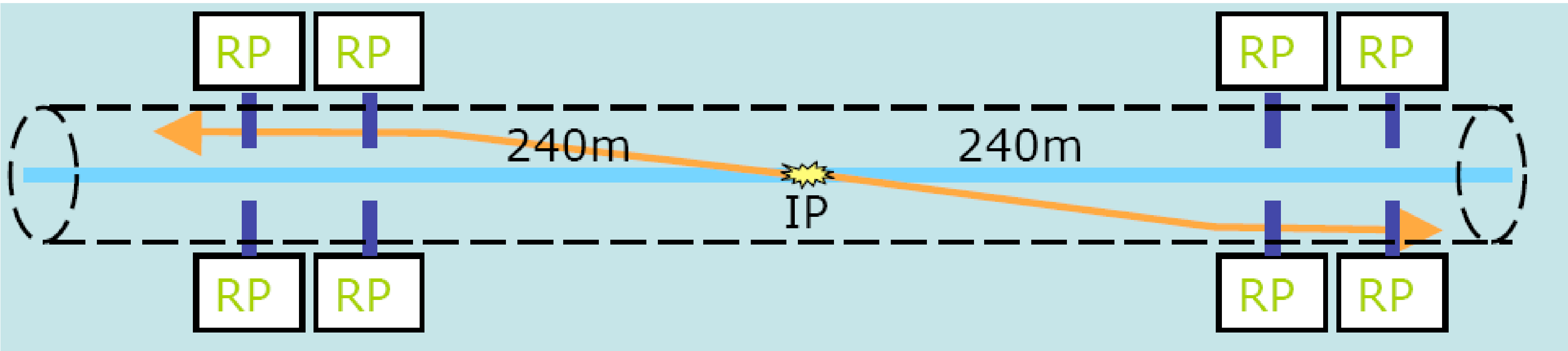
- Study of elastic $pp \to pp$ reaction: exchange of momentum between the two protons which remain intact
- Measurement of total cross section via dN/dt:

$$\frac{dN}{dt}(t \to 0) = L\pi \left(\frac{-2\alpha}{|t|} + \frac{\sigma_{tot}}{4\pi}(i+\rho)e^{-b|t|/2} \right)^2$$

- From the fit, we get σ_{tot}, ρ, b and L

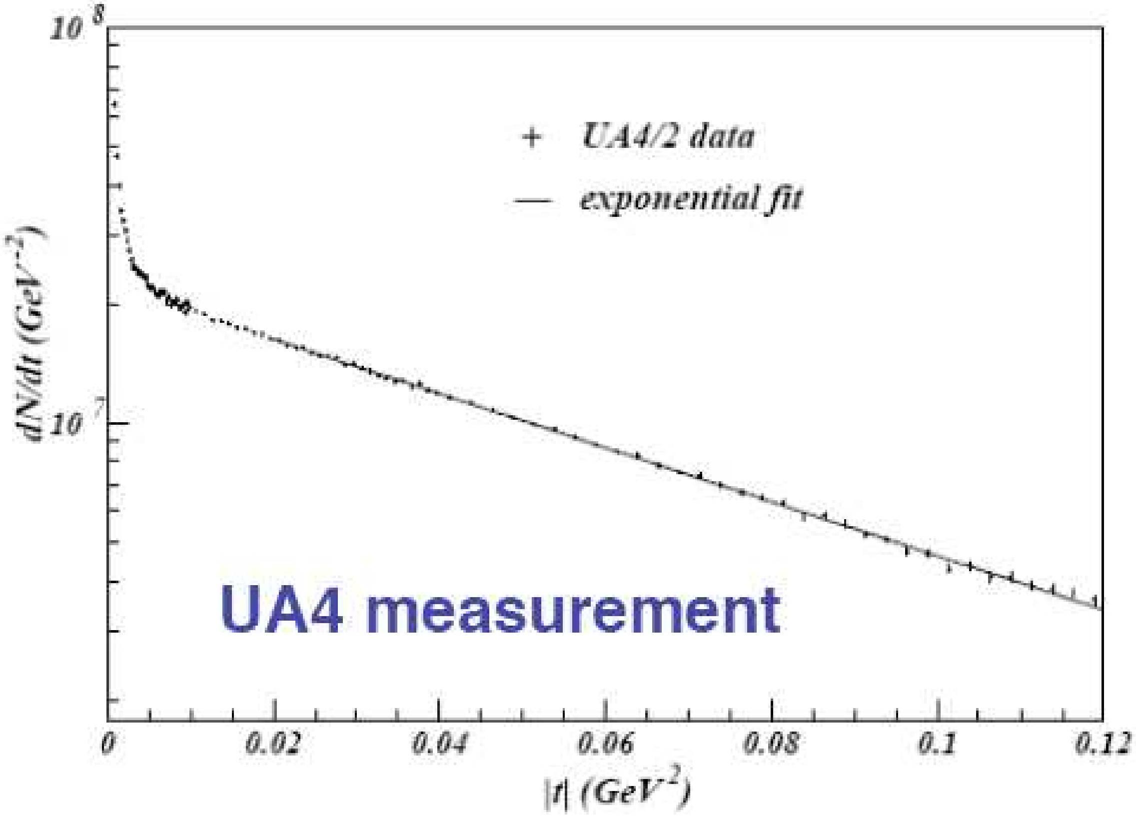
Elastic scattering in the Coulomb region: How technically?

- Goal: Measurement of dN/dt to understand the lumi with a precision better than 2-3%
- Measure elastic rate dN/dt in the Coulomb interference region: Necessity to go down to $t \sim 6.5\ 10^{-4}$ GeV^2, or $\theta \sim$ 3.5 μrad (when the strong amplitude equals the electromagnetic one)
- This requires:
  - Special high β^* beam optics
  - Detectors at $\sim$ 1.5 mm from LHC beam axis
  - Spatial resolution well below 100 μm
  - No significant inactive edge ($< 100\mu$m)
- Installation of two sets of roman pots at 240 m from the main ATLAS detector



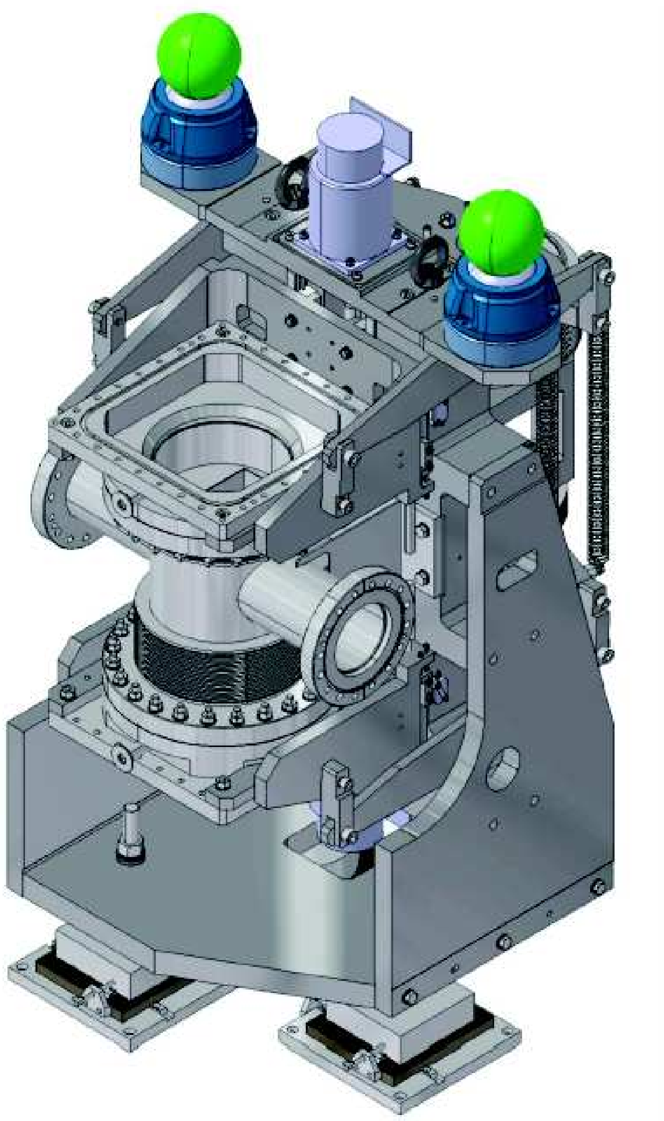
Elastic scattering in the Coulomb region: UA4 result

- Measurement of dN/dt from the UA4 collaboration: precision reached on absolute luminosity of the order of 3%
- Follow the same idea within the ATLAS collaboration (measurement going down to 120 μrad at UA4 whereas we need to go to 3.5 μrad at the LHC!): requires special beam optics (parallel-to-point optics from the interaction point to the roman pot), large β^*



Roman pots

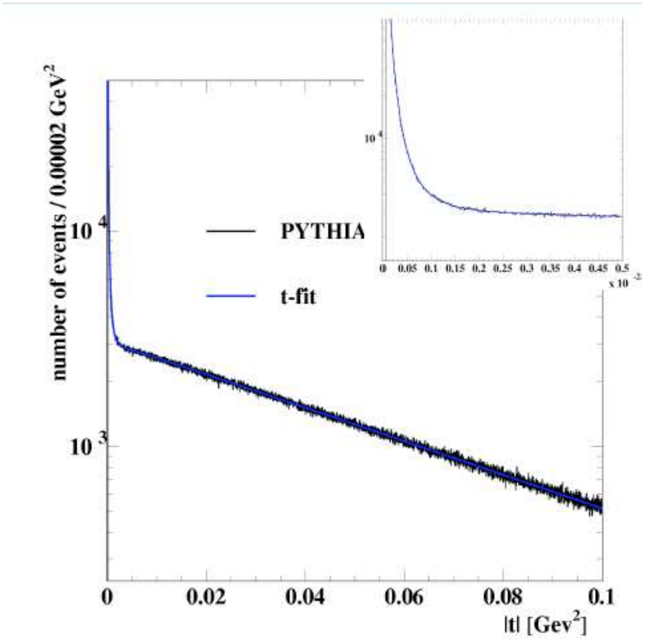
- Final roman pot design inspired by TOTEM roman pots
- Changes with respect to TOTEM: no horizontal pots, modify the geometry of flanges where pots are mounted, modify bases to allow different beam height
- Roman pots host a scintillating fiber detector



Luminosity extraction from a fit to the t-distribution

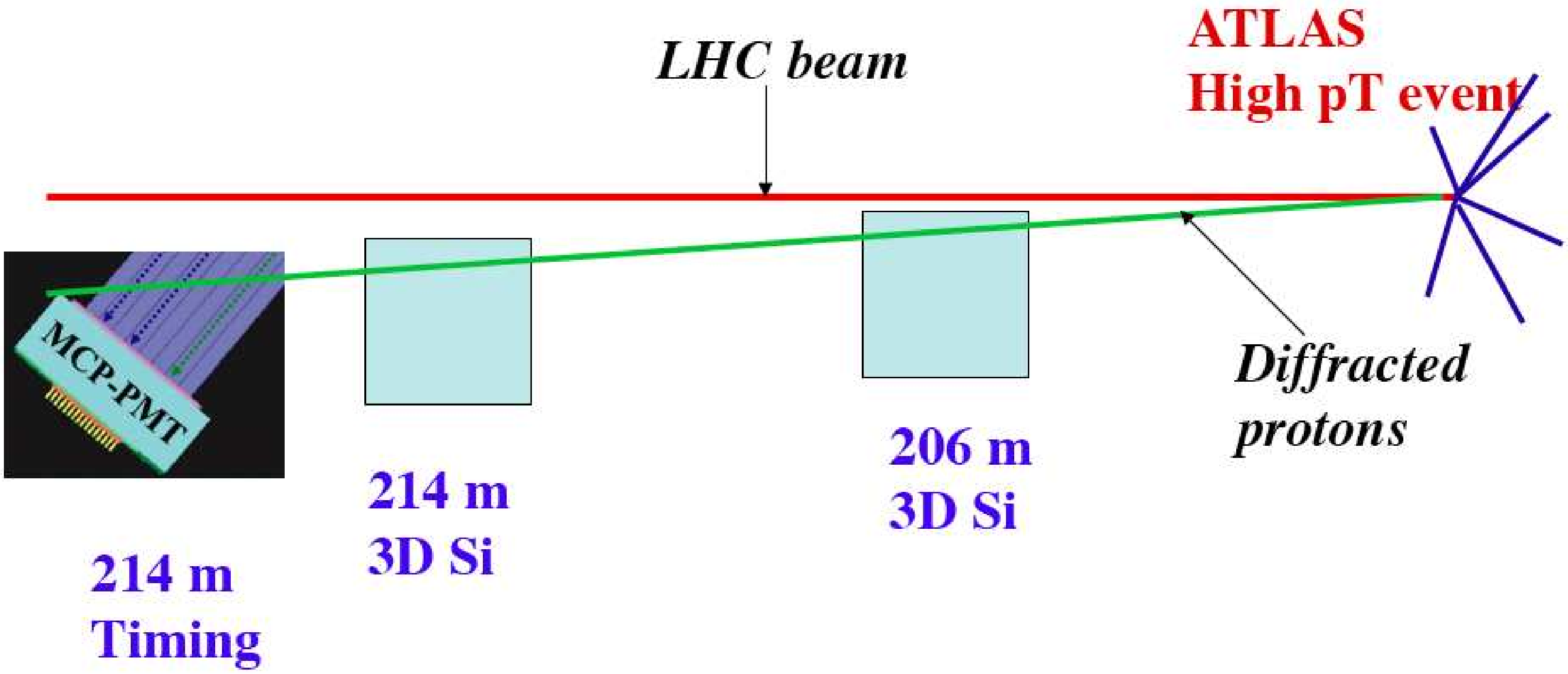
Aim: showing the feasibility of a fit to dN/dt to extract luminosity information after a full simulation of 10 million events

$$\frac{dN}{dt} = L\left(\frac{4\pi\alpha^2}{|t|^2} - \frac{\alpha\rho\sigma_{tot}e^{-b|t|/2}}{|t|} + \frac{\sigma_{tot}^2(1+\rho^2)e^{-b|t|}}{16\pi}\right)$$



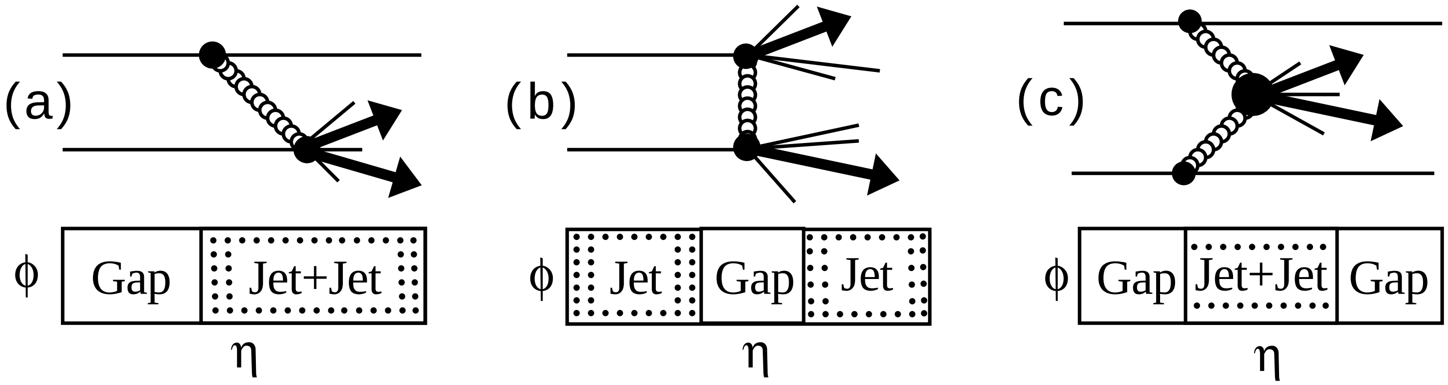
Parameters	input	fitted	error	correlation
L	8.124 10^{26}	8.162 10^{26}	1.5%	
σ_{tot}	100 mb	101.1 mb	0.74%	99%
b	18 GeV^{-2}	17.95 GeV^{-2}	0.59%	64%
ρ	0.15	0.1502	4.24%	92%

Hard diffraction: What is AFP?



- Tag and measure protons at ±210 m
- AFP detectors: measure proton position (Silicon detectors) and time-of-flight (timing detectors)

Diffraction at Tevatron/LHC

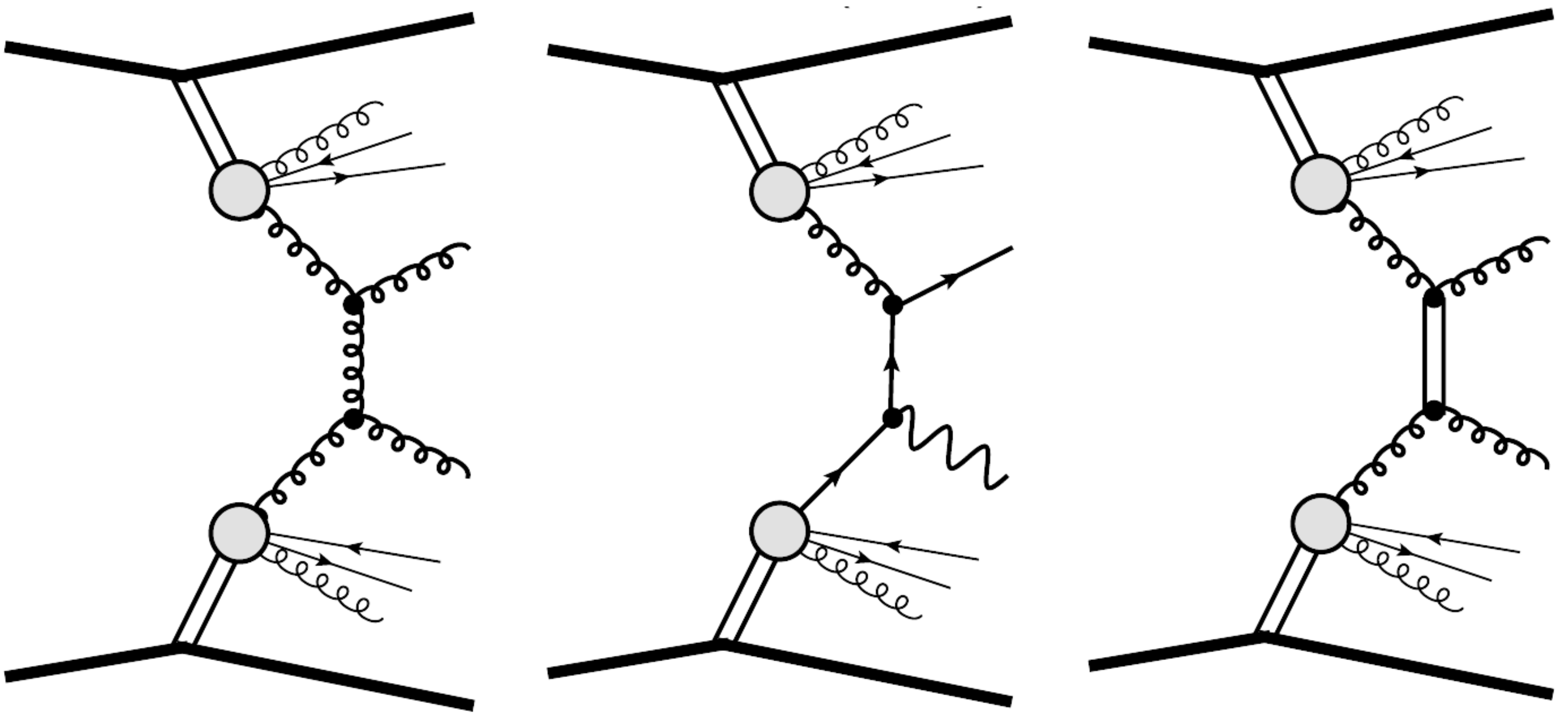


Kinematic variables

- 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

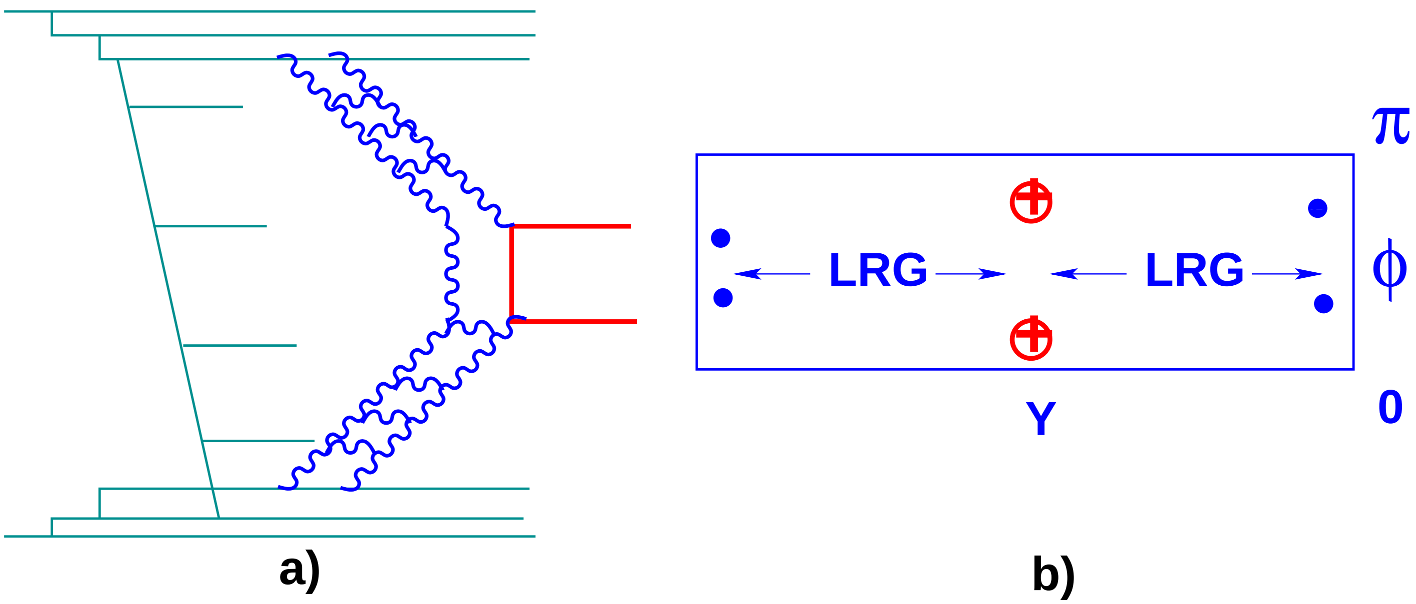
Inclusive diffraction at the LHC

- 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
- All processes produced using the Forward Physics Monte Carlo (FPMC) developed in Saclay, Prague, Cracow (see M. Boonekamp, A. Dechambre, O. Kepka, V. Juranek, C. Royon, R. Staszewski, M. Rangel, ArXiv:1102.2531)



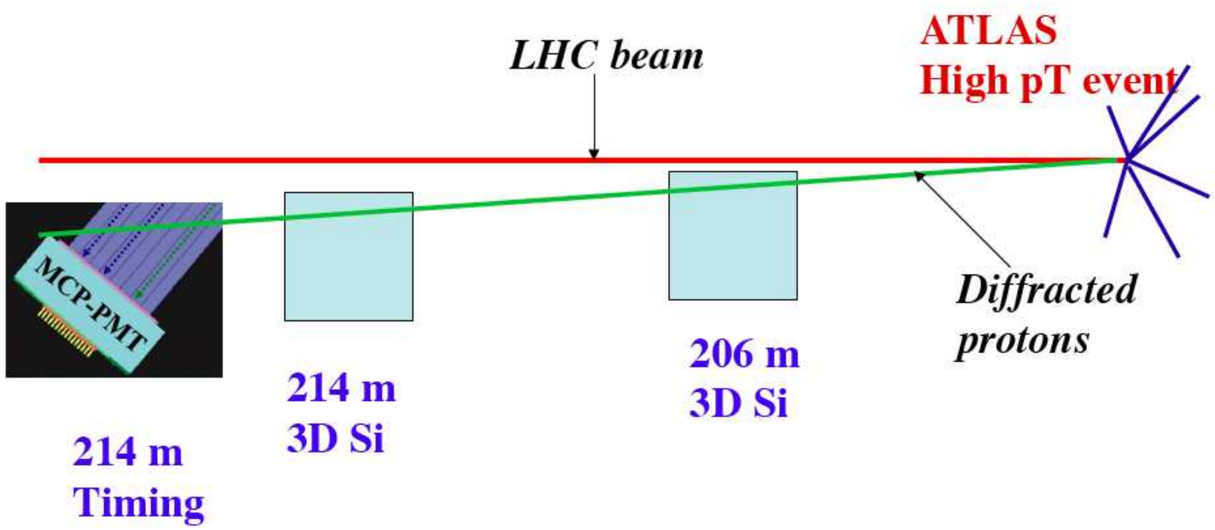
Factorisation at Tevatron/LHC?

- 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)



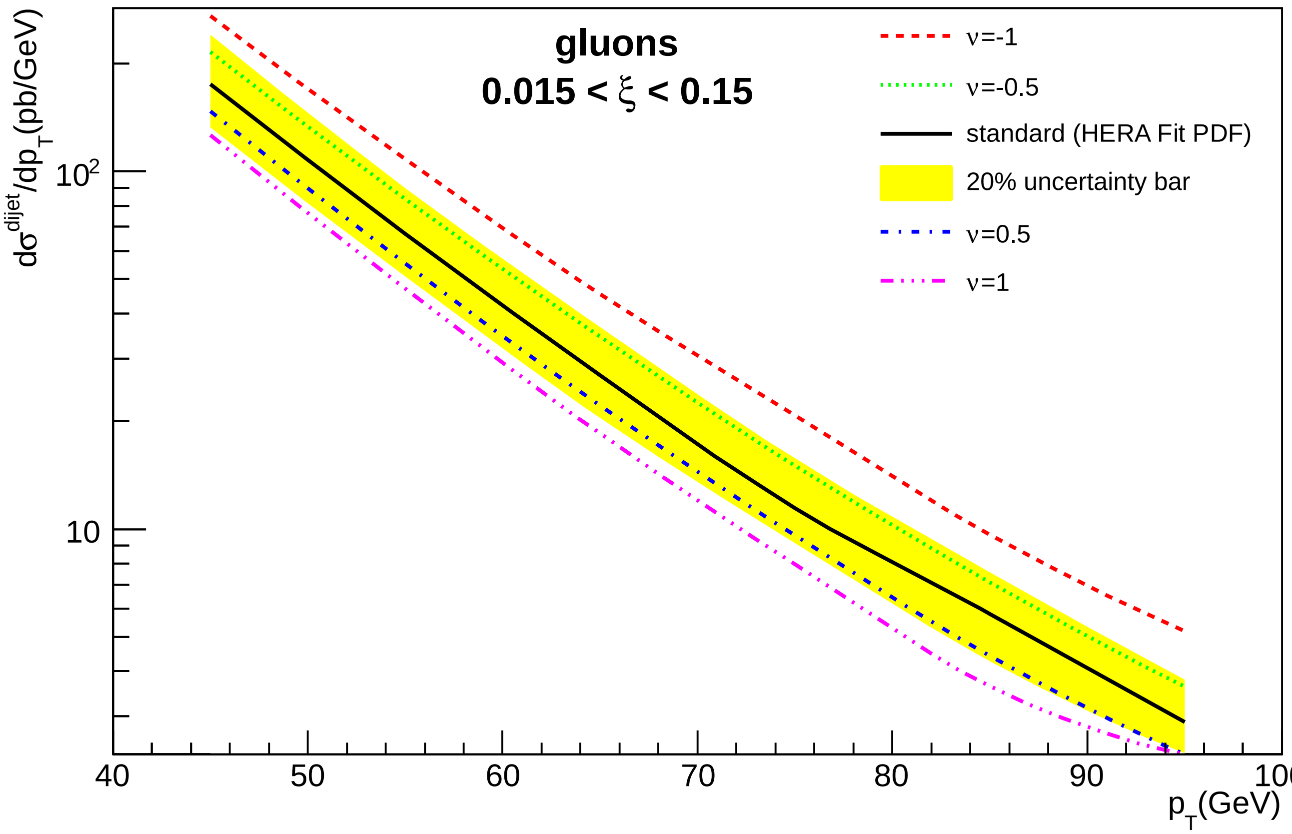
AFP detectors

- In the following, we assume protons to be tagged in AFP:
  - 210 m detectors: $0.015 < \xi < 0.15$
  - 210 and 420 m detectors: $0.0015 < \xi < 0.15$
- No reggeon exchange was introduced in this study, only Pomeron; Reggeons are assumed to dominate only above $\xi > 0.1$
- Measurements assumed to be performed at low luminosity, no pile up was introduced
- Trigger possibilities:
  - For $\gamma +$ jet, trigger on γ in central detector
  - For dijets, trigger on leading jet and on protons in AFP (timing detector gives the trigger)



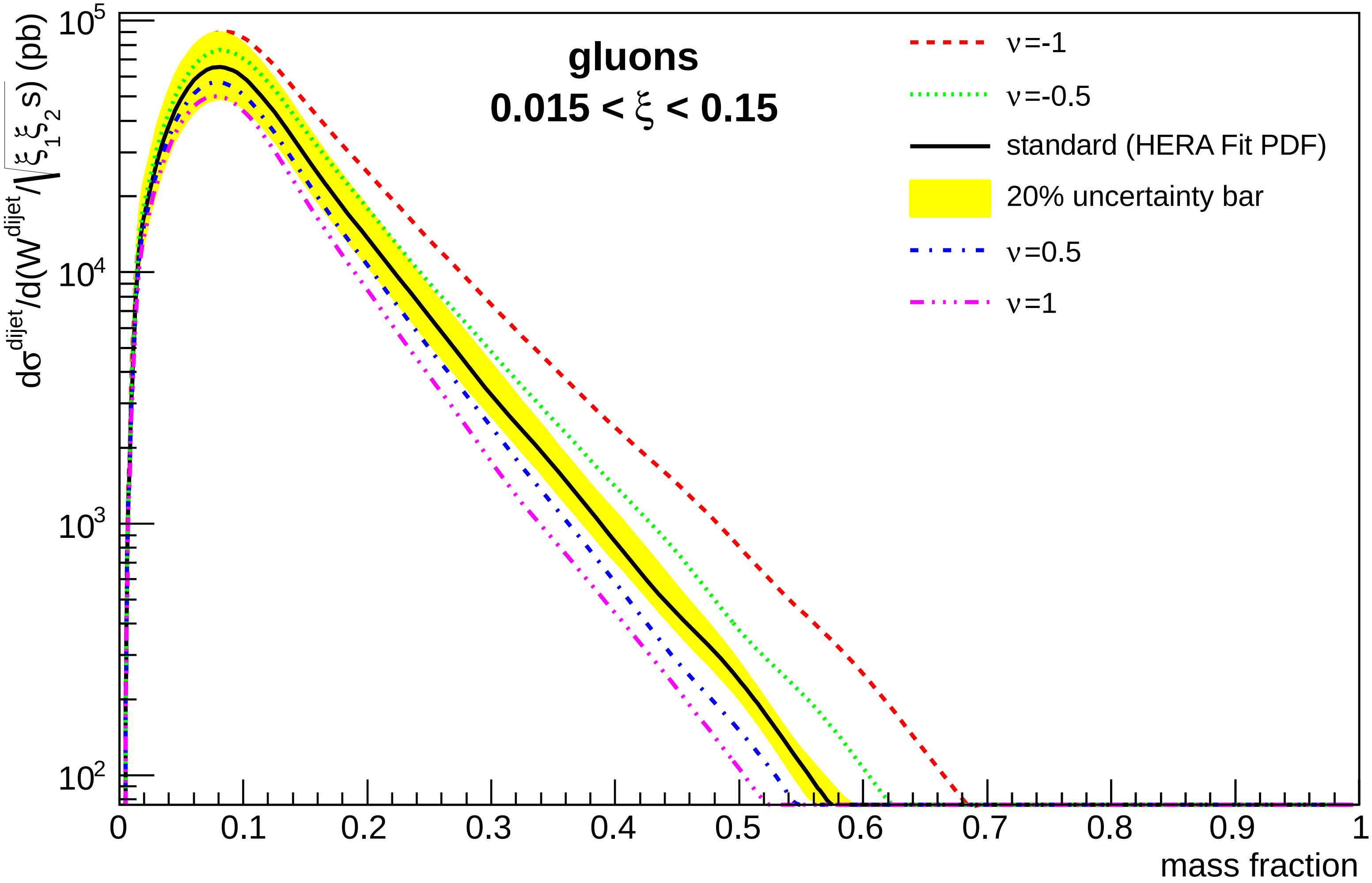
Inclusive diffraction at the LHC: sensitivity to gluon density

- 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



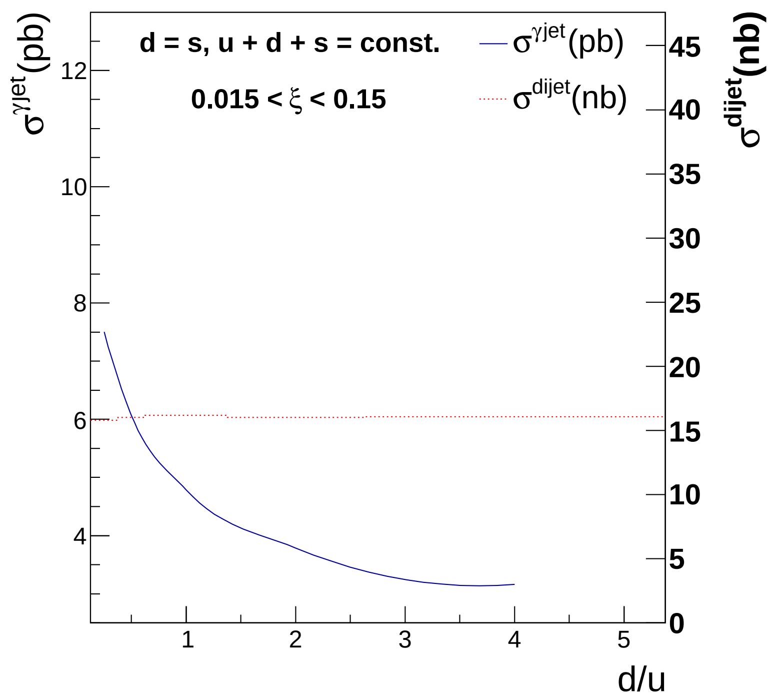
Dijet mass fraction: sensitivity to gluon density

- 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



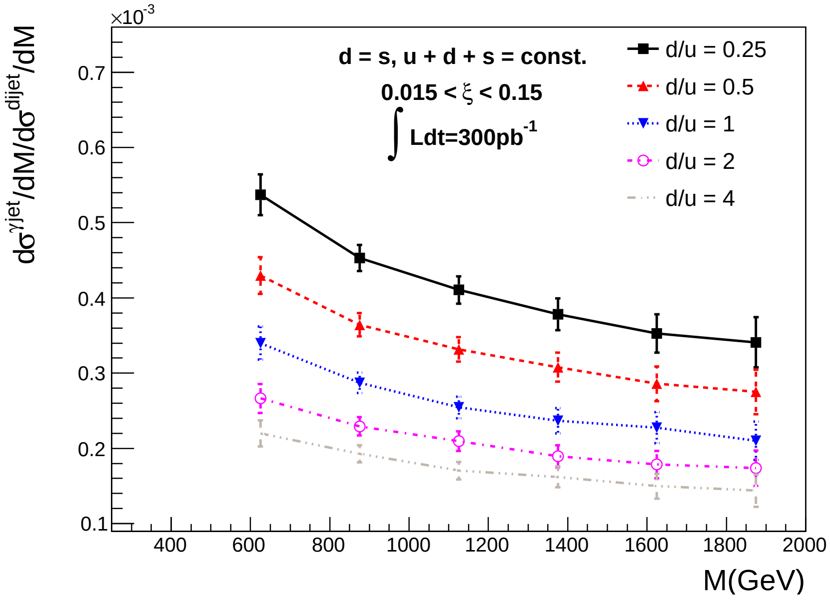
Inclusive diffraction at the LHC: sensitivity to quark densities

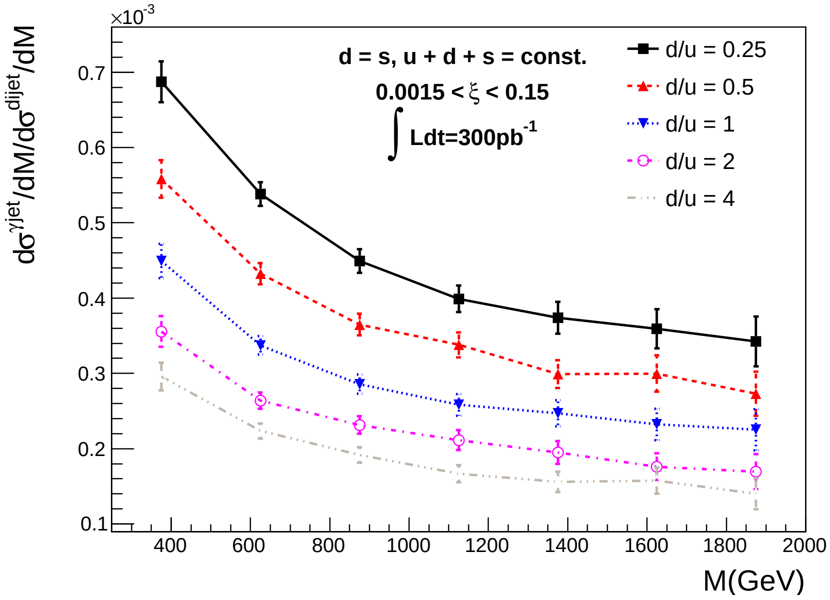
- γ+jet and dijet cross sections as a function of d/u in the acceptance of AFP (210 and 210+420 m detectors)
- As expected, the dijet cross section remains constant, whereas the $\gamma+$ jet cross section varies by a factor 2.5
- Jets and photon at particle level with p_T >20 GeV



Inclusive diffraction at the LHC: sensitivity to quark densities

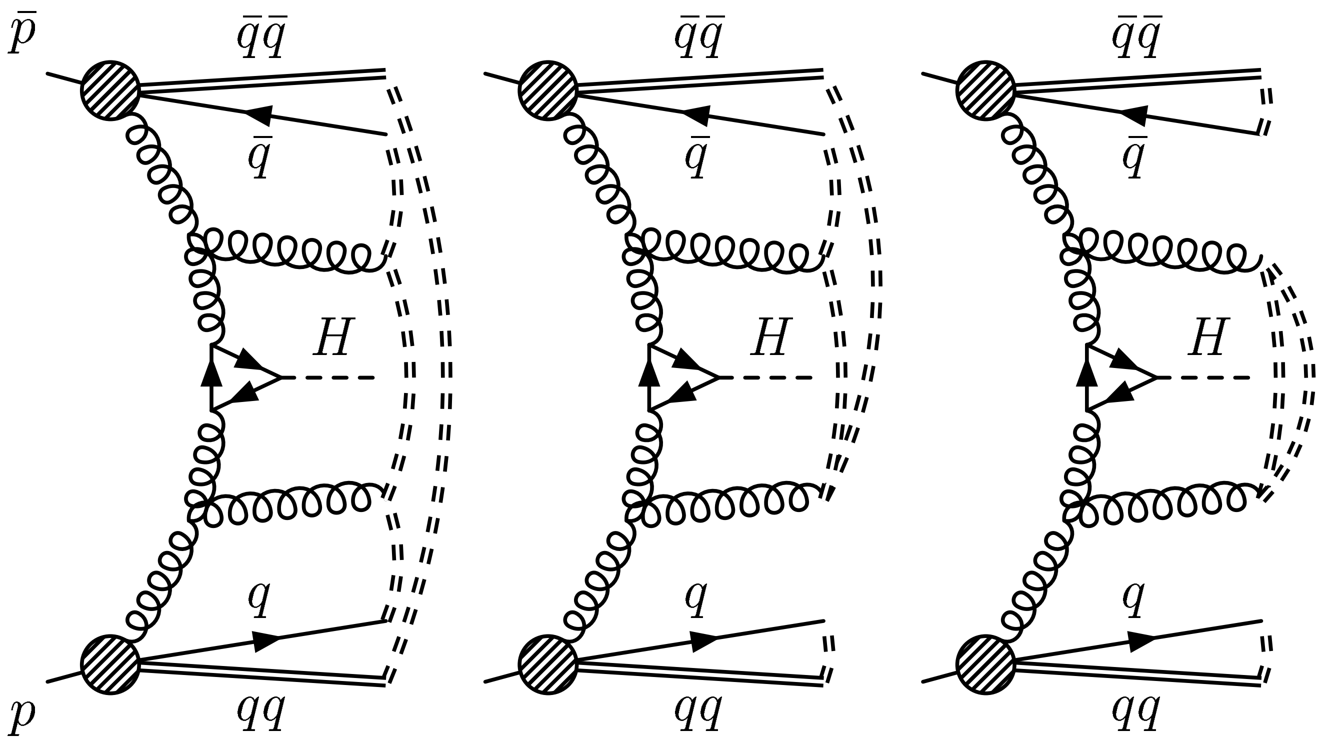
- Predict DPE γ+jet divided by dijet cross section at the LHC
- Sensitivity to universality of Pomeron model
- Sensitivity to gluon density in Pomeron, of assumption: $u = d = s = \bar{u} = \bar{d} = \bar{s}$ used in QCD fits at HERA





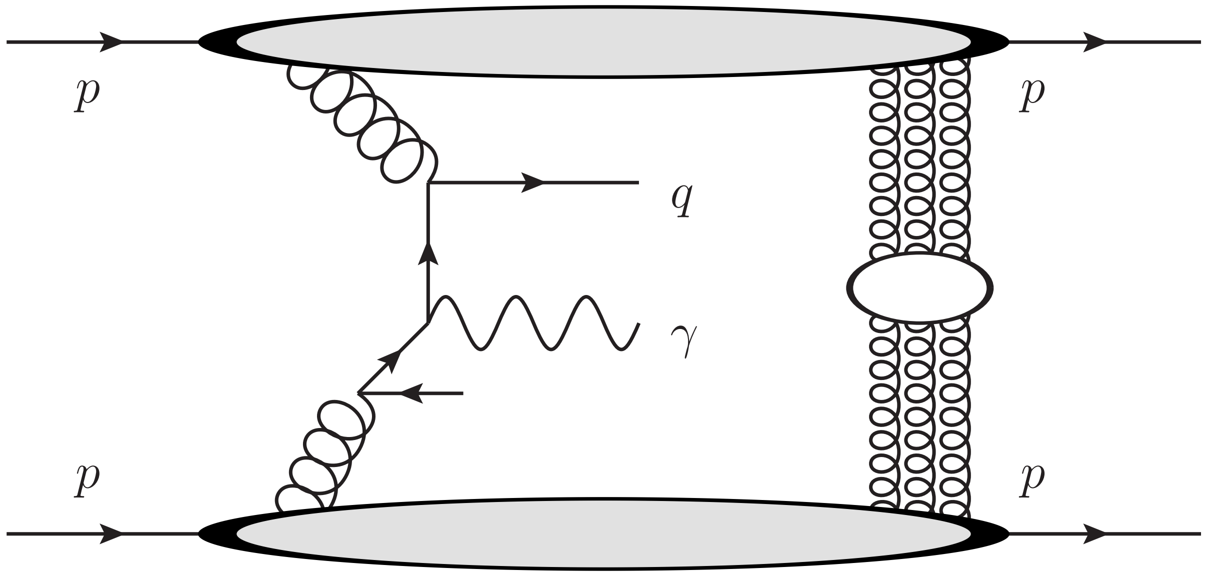
Soft Colour Interaction models

- 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



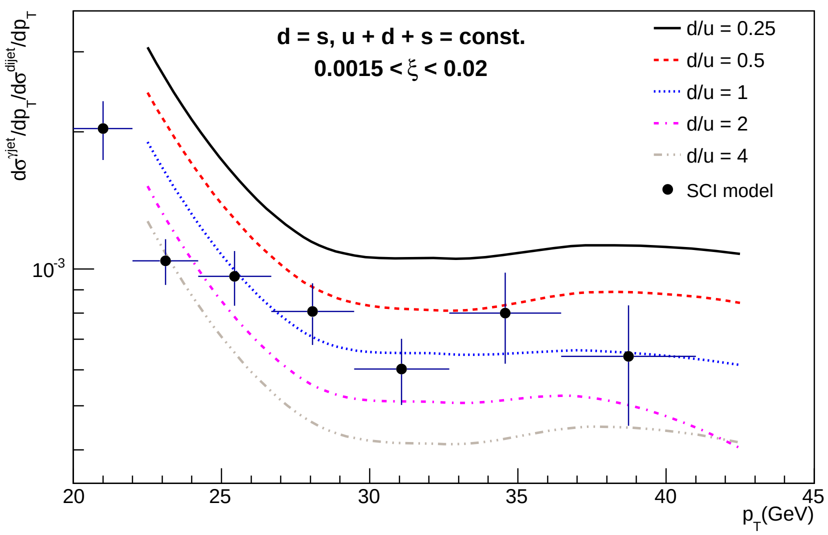
Soft colour interaction

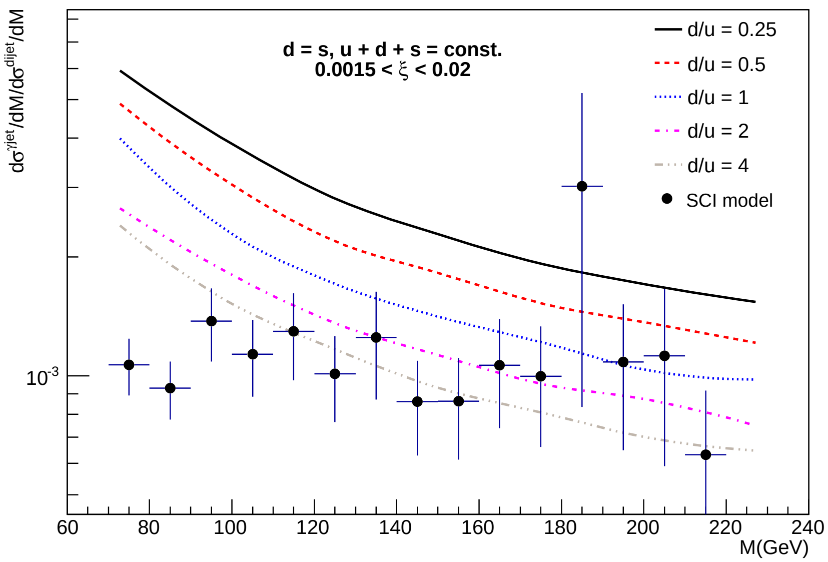
- Scheme of SCI production of γ+jet event as an example
- The advantage of SCI events is that they do not have any additional factors such as survival probability to explain the differences between HERA and Tevatron/LHC
- Very interesting to know if some observables allow to distinguish between both models at the LHC



Inclusive diffraction at the LHC: sensitivity to soft colour interaction

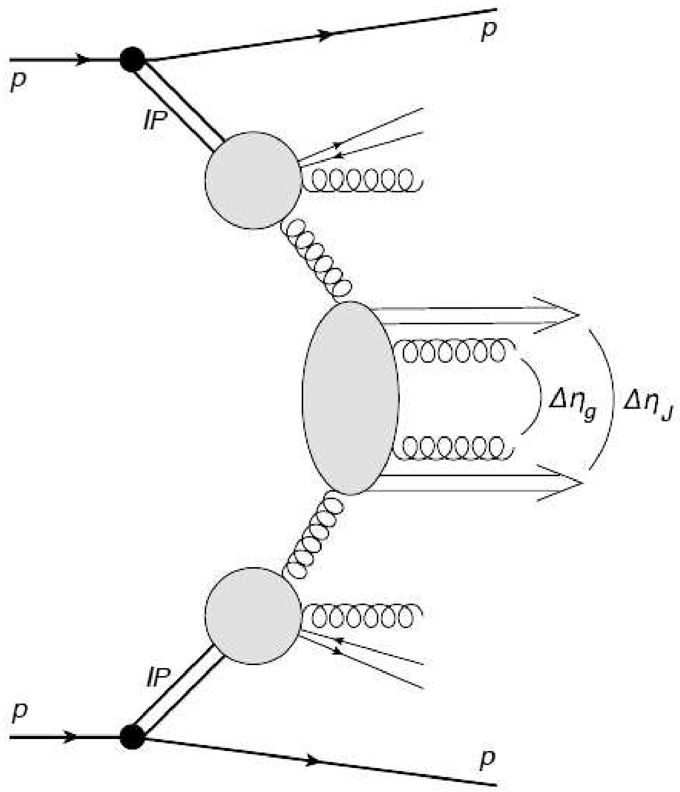
- Predict DPE γ+jet divided by dijet cross section at the LHC for pomeron like and SCI models
- In particular, the diffractive mass distribution (the measurement with lowest systematics) allows to distinguish between the two sets of models: flat distribution for SCI

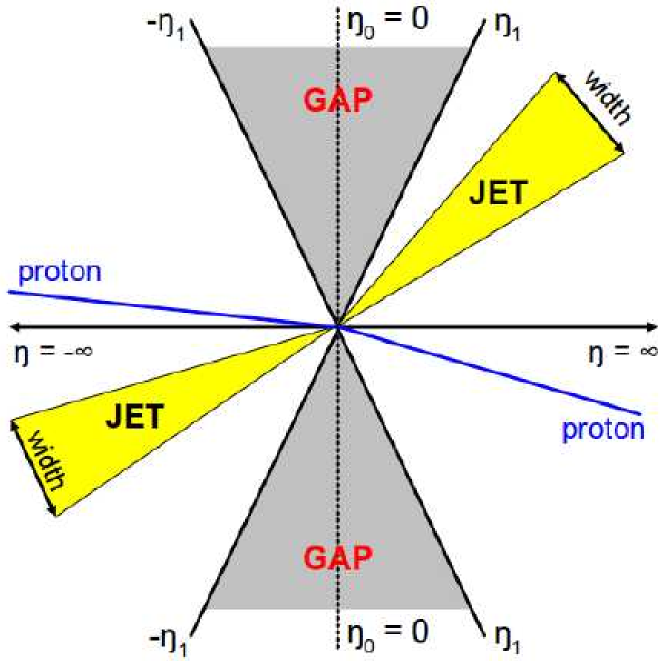




Jet gap jet events in diffraction

- 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, ArXiv:1212:2059, accepted by Phys. Rev. D

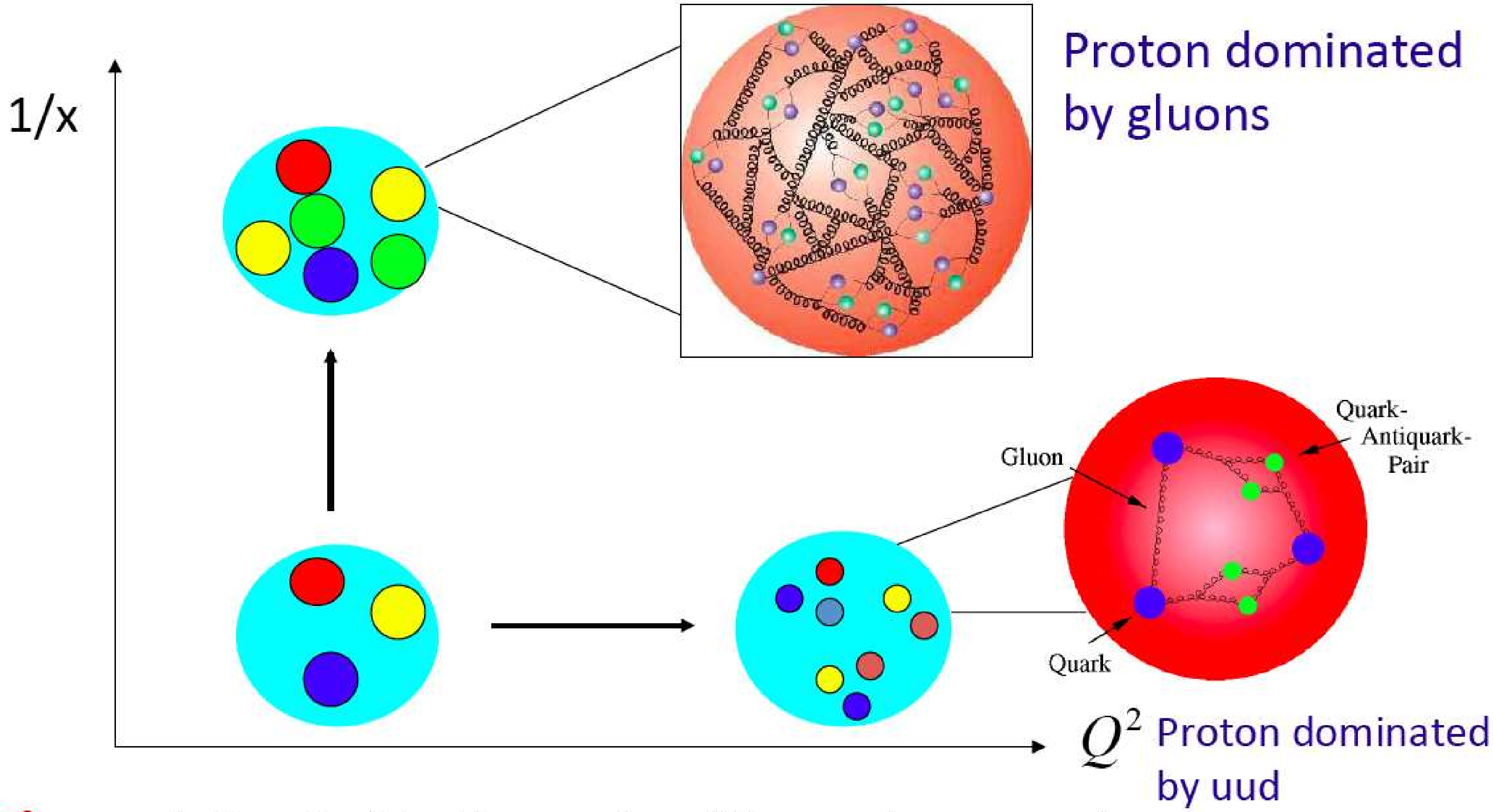




Looking for BFKL effects

- 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)

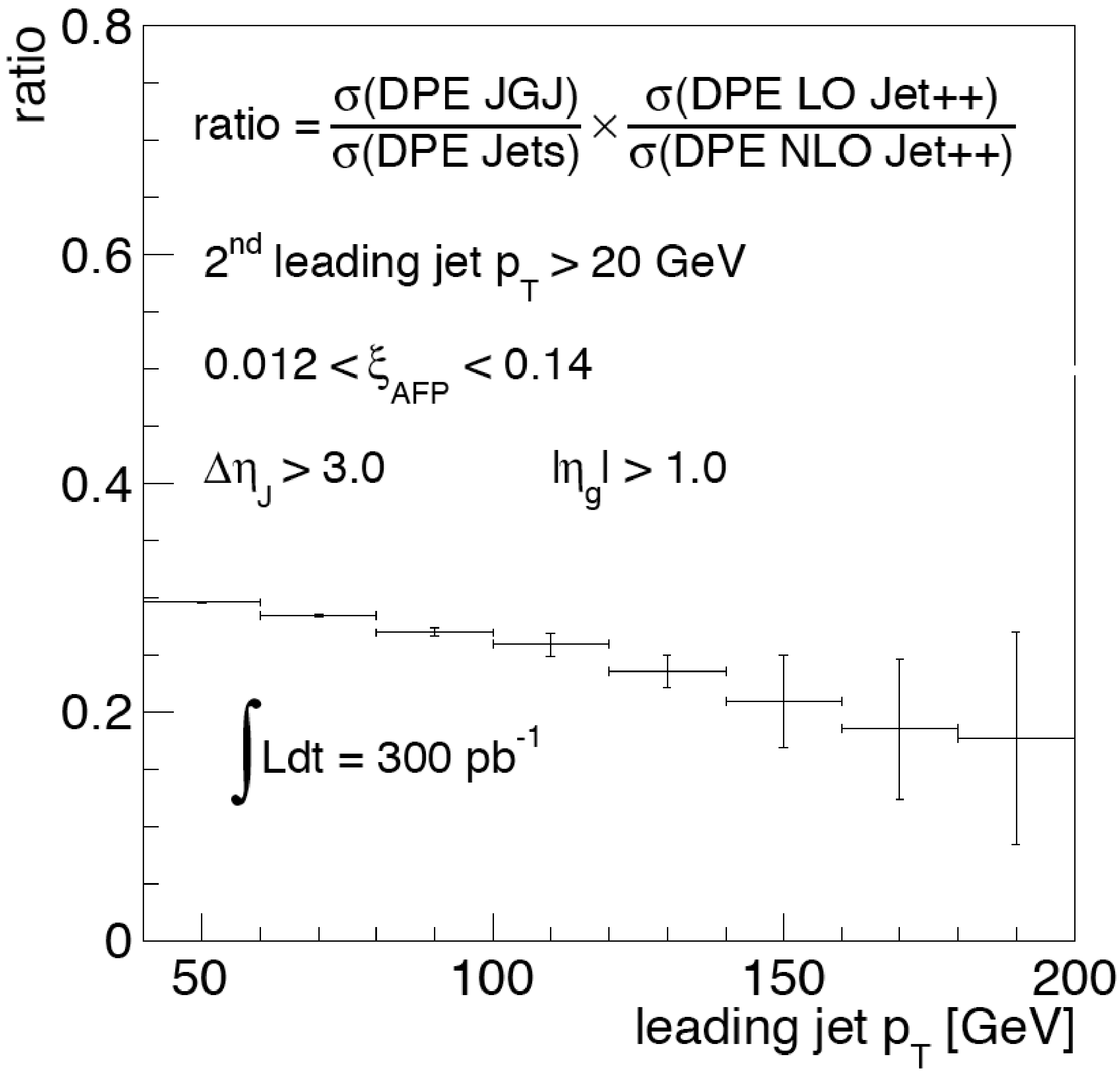


Q^2 : resolution inside the proton (like a microscope)

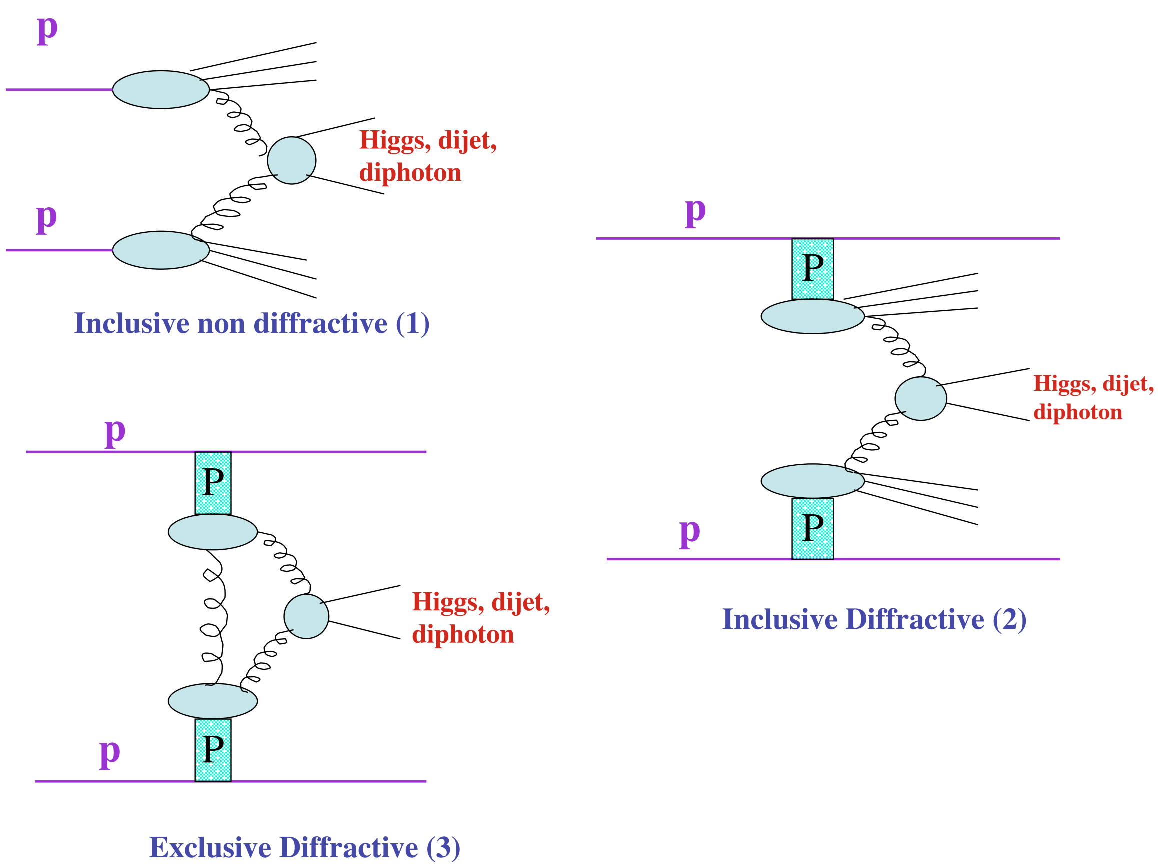
X :Proton momentum fraction carried away by the interacting quark

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



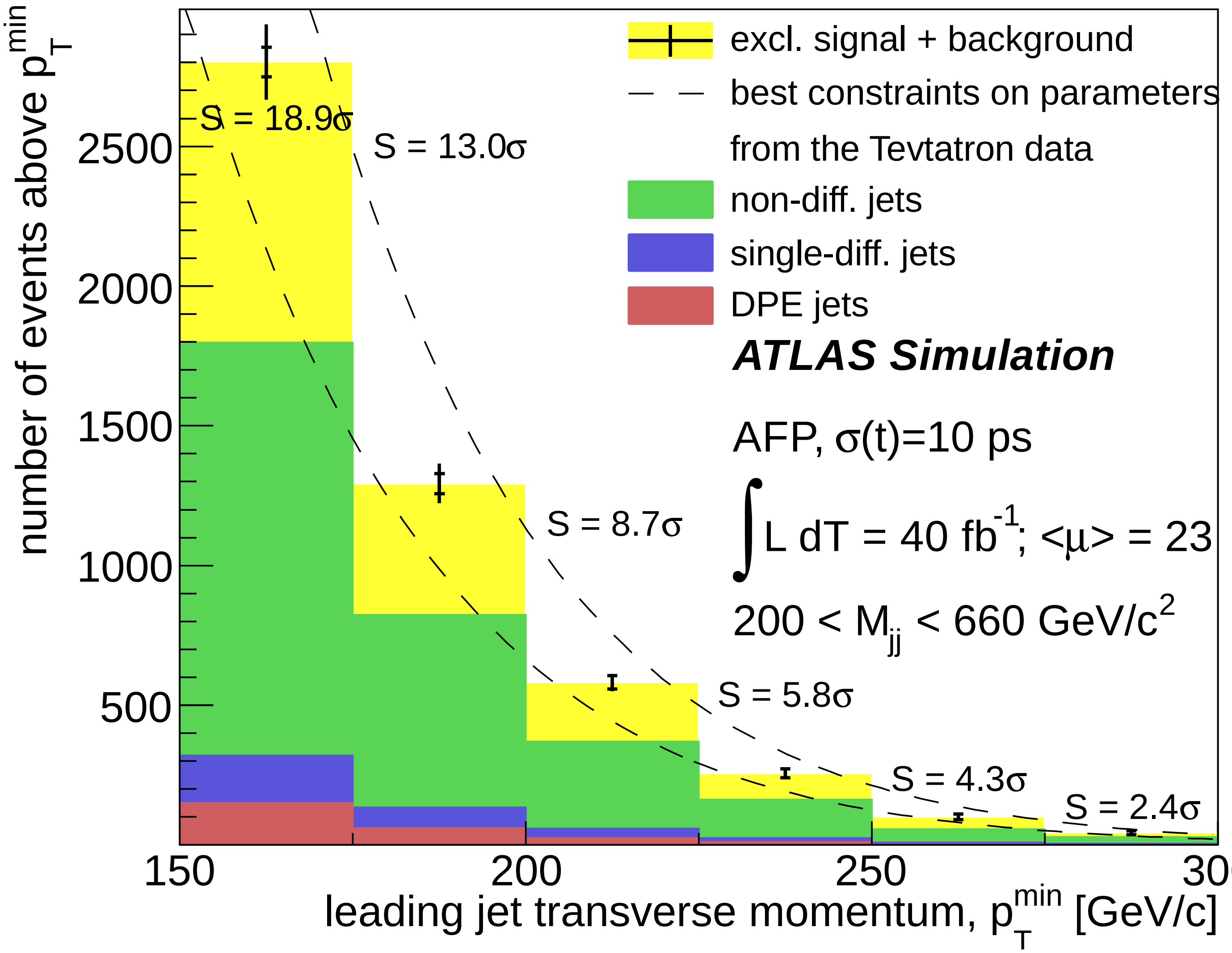
"Exclusive models" in diffraction



- All the energy is used to produce the Higgs (or the dijets), namely $xG \sim \delta$
- Possibility to reconstruct the properties of the object produced exclusively from the tagged proton: system completely constrained
- Possibility of studying any resonant production provided the cross section is high enough
- See papers by Khoze, Martin, Ryskin, Szczurek, Gay-Ducatti, Peschanski, Royon...

Exclusive jet production at the LHC

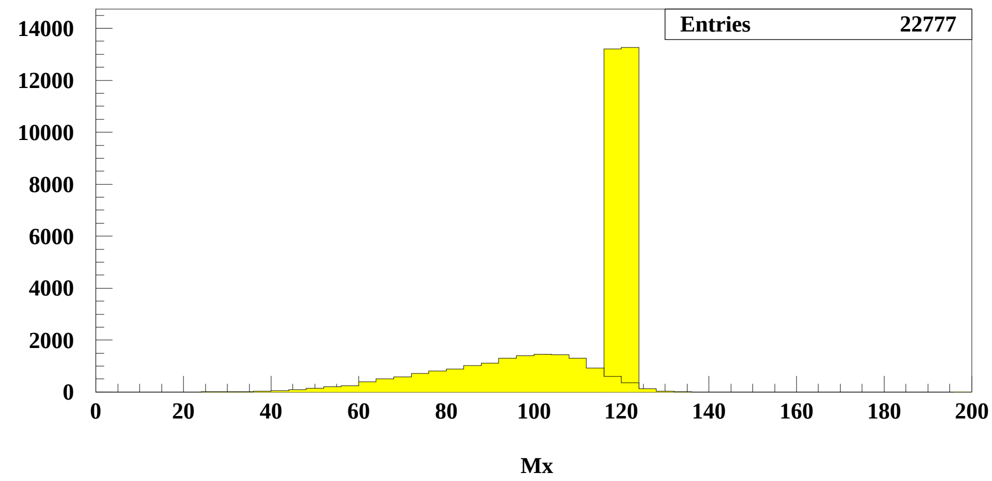
- Jet cross section measurements: up to 18.9 σ for exclusive signal with 40 fb^{-1} ($\mu = 23$): highly significant measurement in high pile up environment, improvement over measurement coming from Tevatron (CDF) studies using $\bar{p}$ forward tagging by about one order of magnitude

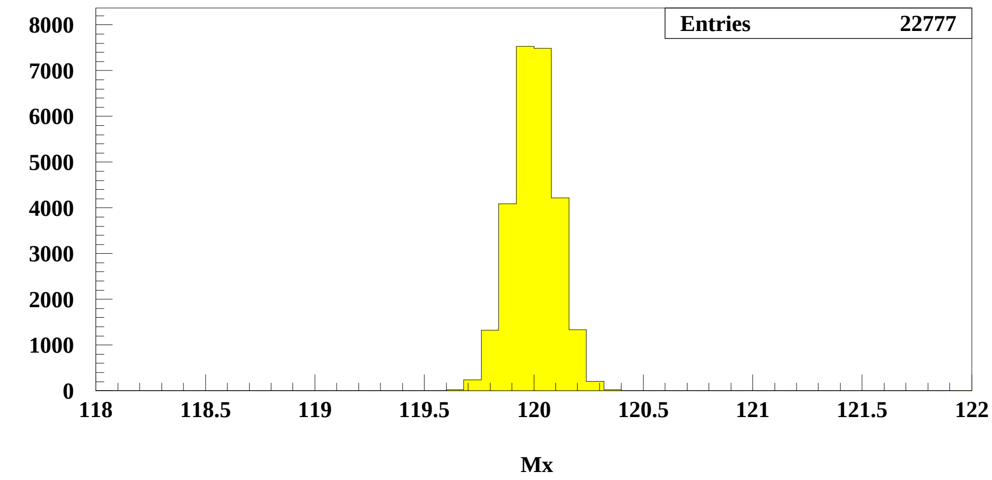


- Important to perform these measurements to constrain exclusive Higgs production: background/signal ratio close to 1 for central values at 120 GeV

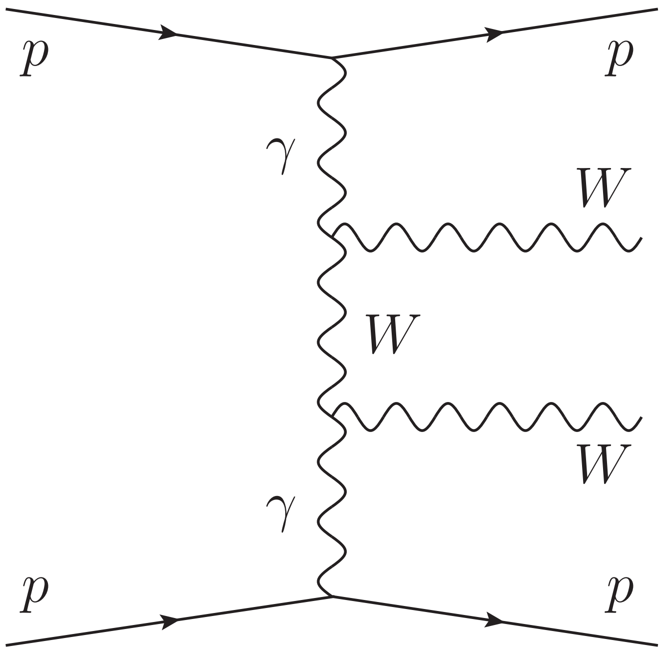
Advantage of exclusive production: Higgs boson?

- Good Higgs mass reconstruction: fully constrained system, Higgs mass reconstructed using both tagged protons in the final state ($pp \rightarrow pHp$)
- 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





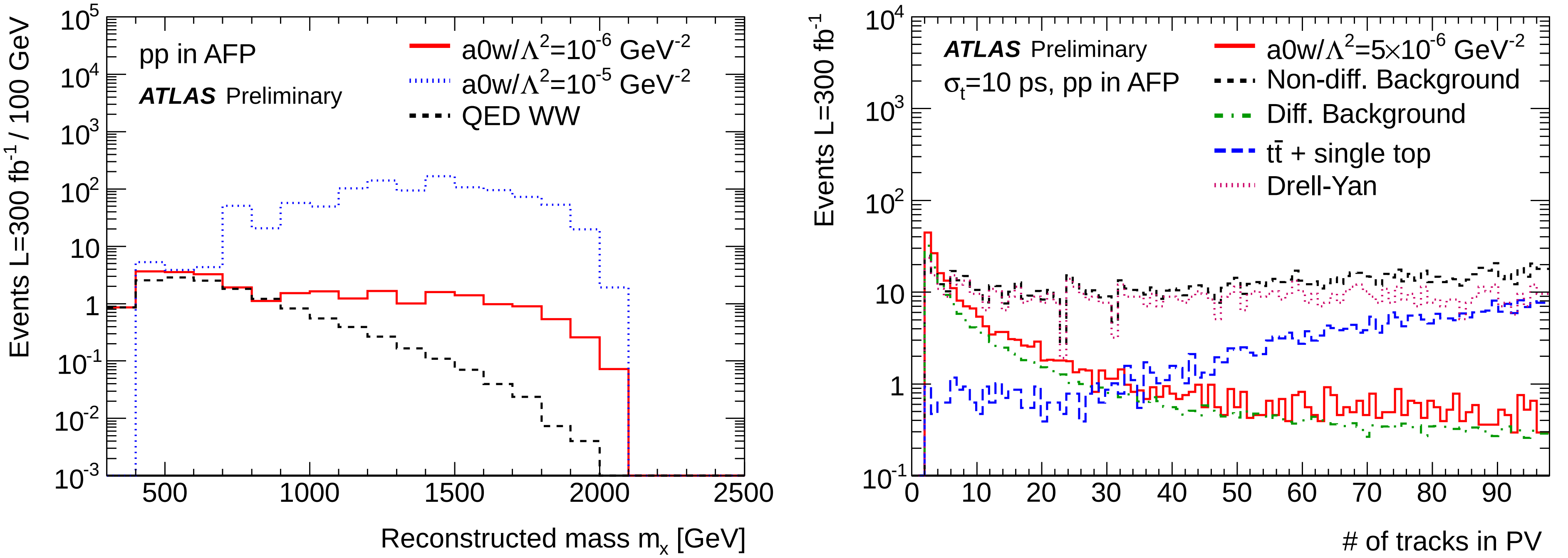
Search for $\gamma\gamma WW$ quartic anomalous coupling



- 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) if Higgs boson is discovered; $\gamma\gamma$ specially interesting (Christophe Grojean)
- Rich $\gamma\gamma$ physics at LHC: see E. Chapon, O. Kepka, C. Royon, Phys. Rev. D78 (2008) 073005; Phys. Rev. D81 (2010) 074003

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

- 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 $pp \rightarrow l^{\pm}\nu\gamma\gamma$ (see P. J. Bell, ArXiV:0907.5299) by more than 2 orders of magnitude with 40/300 fb^{-1} at LHC**

	5σ	95% CL	LEP limit
$\mathcal{L} = 40\ fb^{-1}, \mu = 23$	5.5 10^{-6}	2.4 10^{-6}	0.02
$\mathcal{L} = 300\ fb^{-1}, \mu = 46$	3.2 10^{-6}	1.3 10^{-6}	

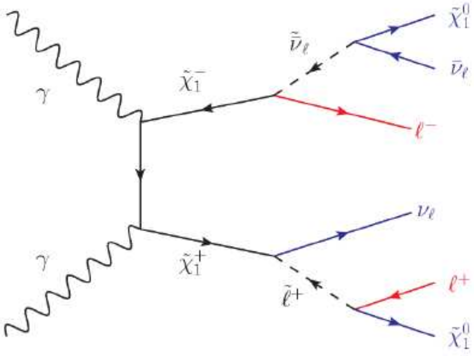
Reach at LHC

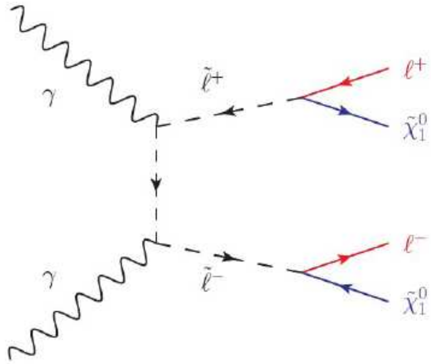
Reach at high luminosity on quartic anomalous coupling using fast simulation (study other anomalous couplings, ZZ...)

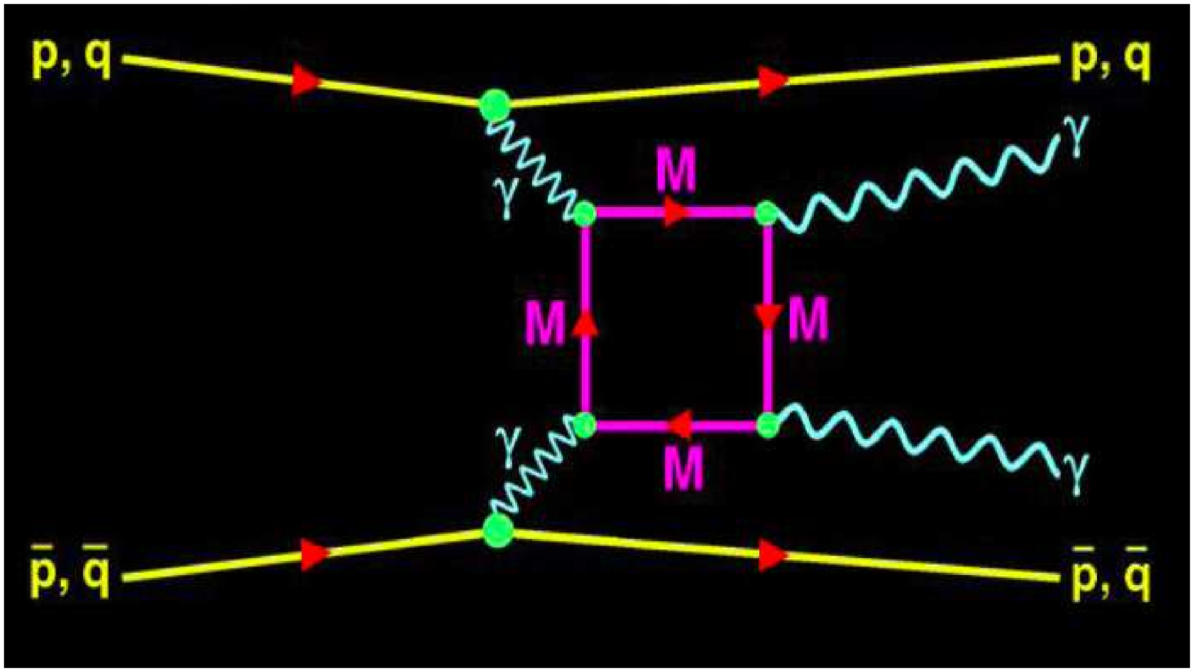
Couplings	OPAL limits [GeV^{-2}]	Sensitivity @ $\mathcal{L} = 30$ (200) fb^{-1} 5σ	95% CL
a_0^W/Λ^2	[-0.020, 0.020]	5.4 10^{-6} (2.7 10^{-6})	2.6 10^{-6} (1.4 10^{-6})
a_C^W/Λ^2	[-0.052, 0.037]	2.0 10^{-5} (9.6 10^{-6})	9.4 10^{-6} (5.2 10^{-6})
a_0^Z/Λ^2	[-0.007, 0.023]	1.4 10^{-5} (5.5 10^{-6})	6.4 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
- Reaches the values predicted by Higgsless/extradimension models
- Semic leptonic decays under study: looks promising, 1 order of magnitude gain with respect to pure leptonic decays, full simulation study under progress

Additional exclusive event production







- Production of new objects (with mass up to 1.3 TeV) to be produced either by photon or gluon exchanges: magnetic monopoles, KK resonances, SUSY,... (which could be missed in central ATLAS if predominant decays are hadronic)
- Production of SUSY particles: Possibility of measuring the mass of sleptons if cross section high enough

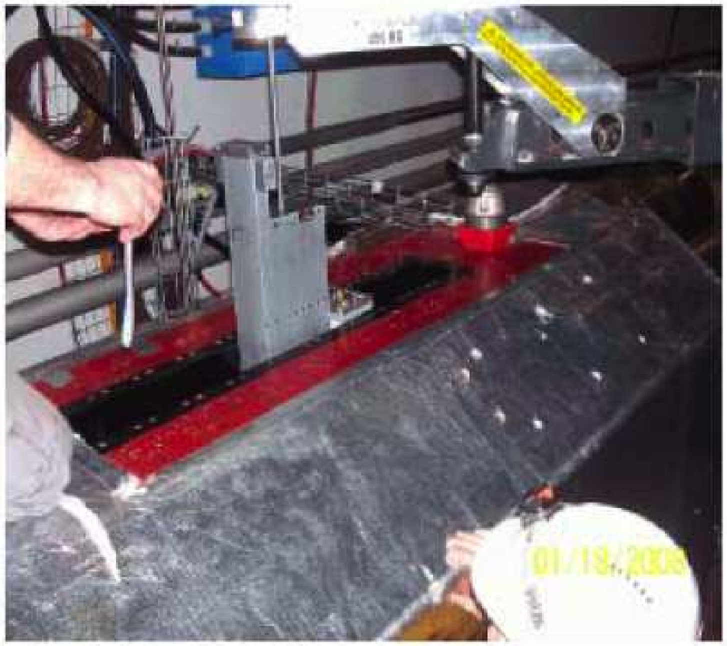
Forward detectors in ATLAS

ALFA at 240 m

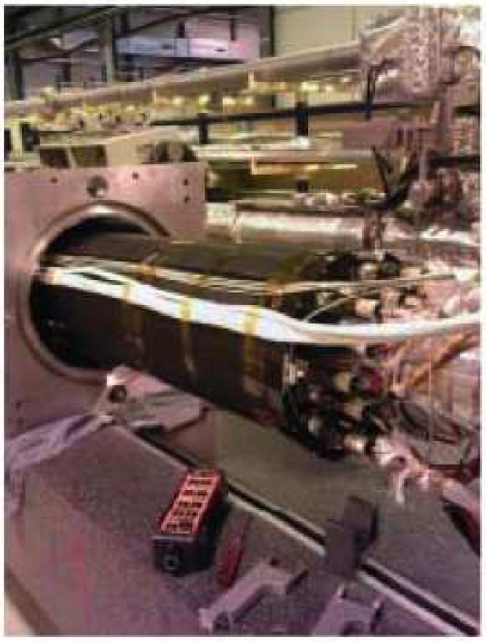
ZDC at 140 m

LUCID at 17 m

Absolute Luminosity for ATLAS



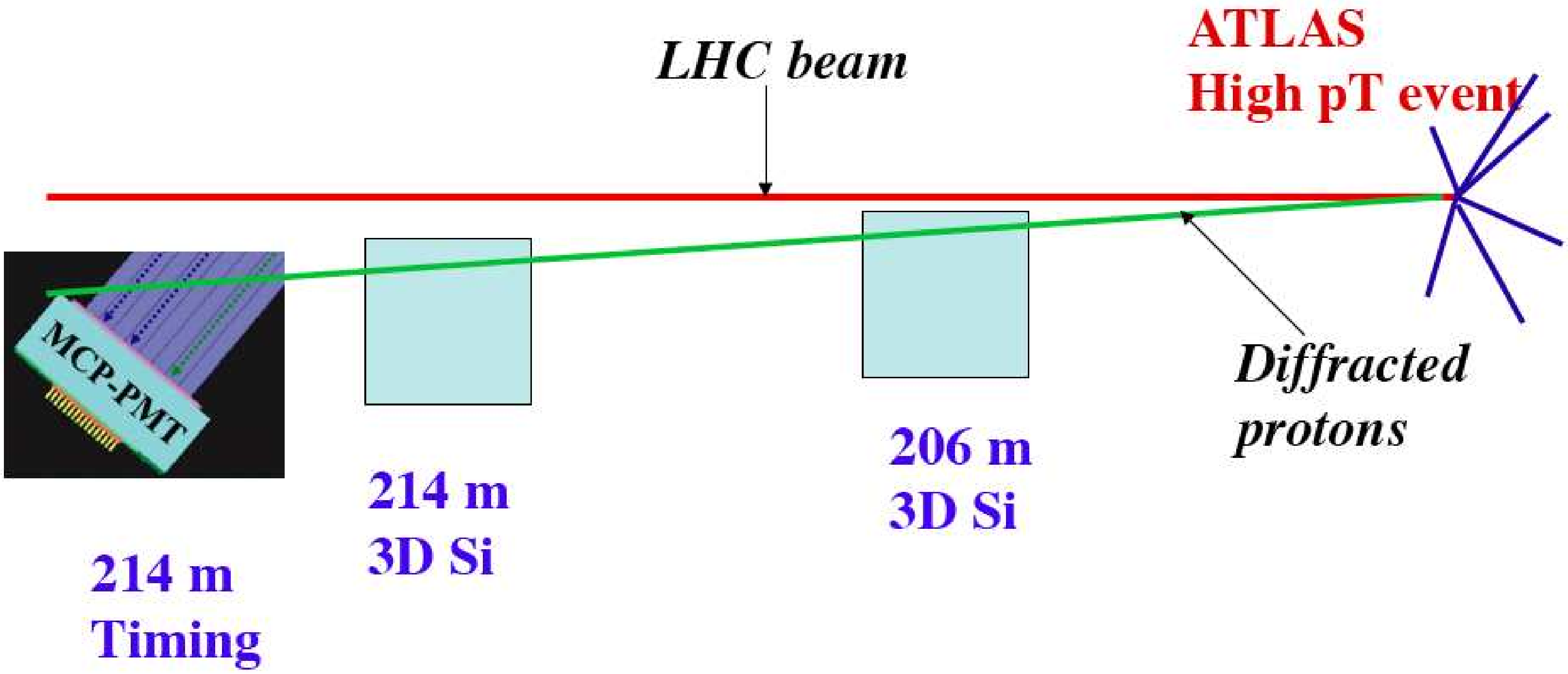
Zero Degree Calorimeter



Luminosity Cerenkov Integrating Detector

- ALFA
- ZDC
- LUCID

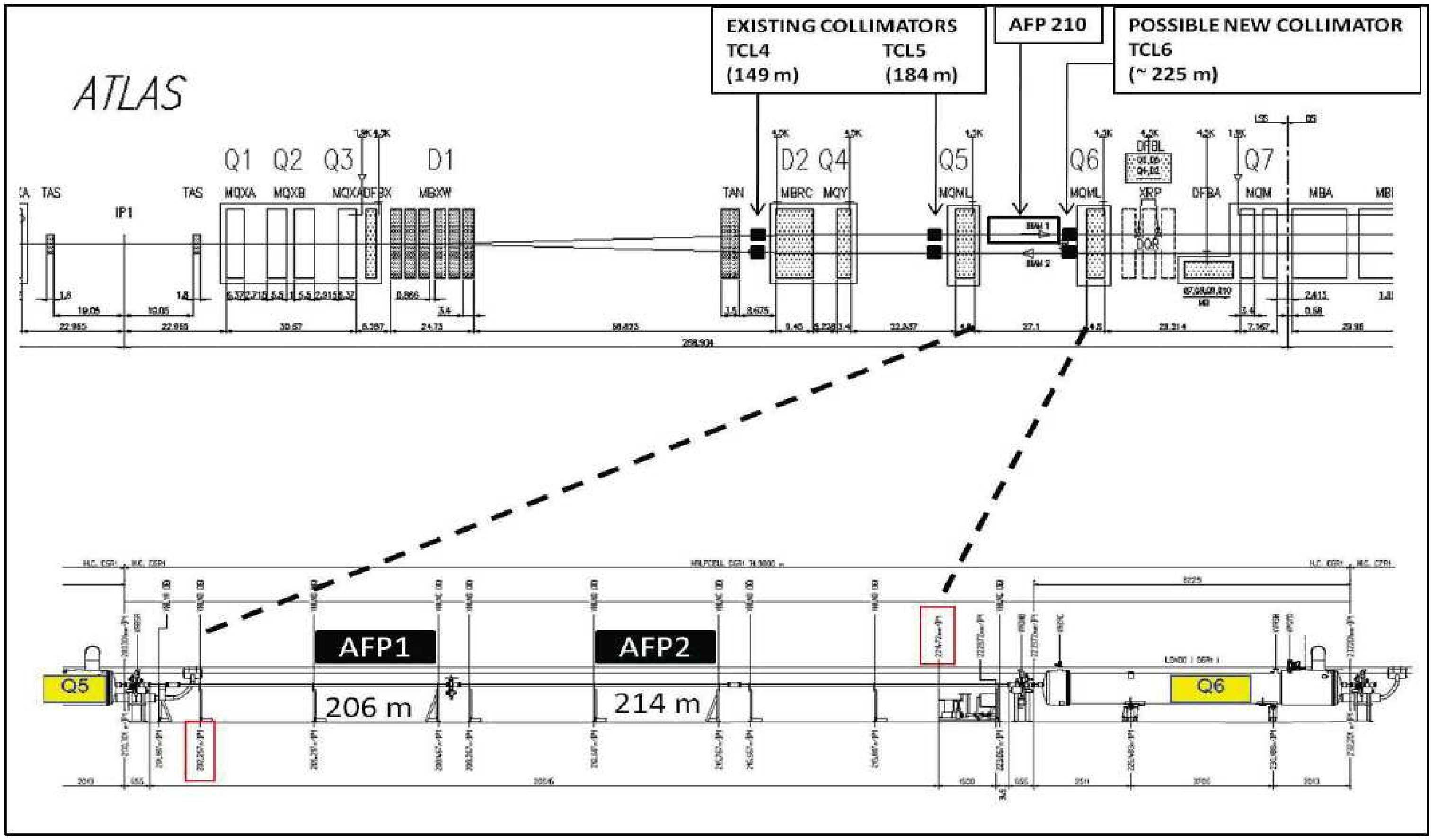
What is AFP?



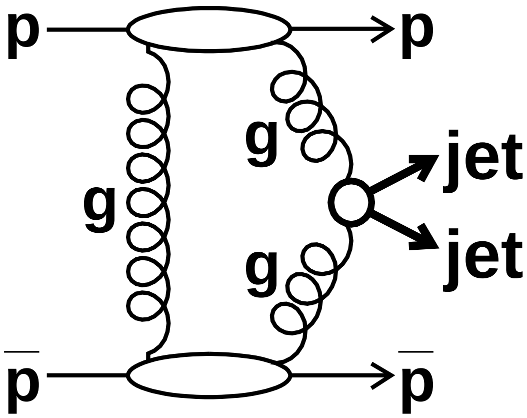
- Tag and measure protons at ± 210 m
- Trigger: Rely on ATLAS high p_T L1 trigger for high p_T events; AFP trigger for lower masses
- AFP detectors: Radiation hard "edgeless" 3D Silicon detectors, 10 ps timing detectors
- Allows running in high pile up conditions by association with correct primary vertex: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

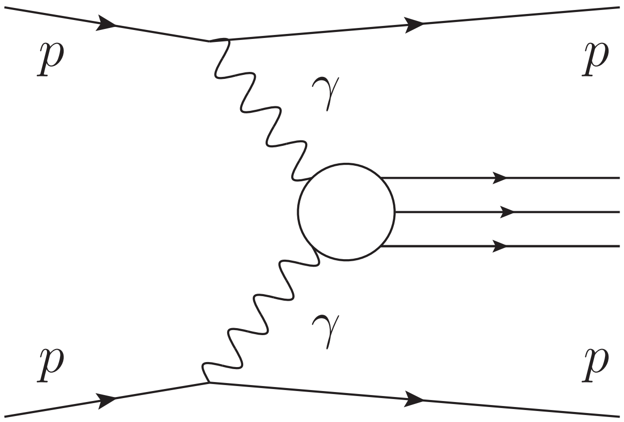
AFP location (phase I)

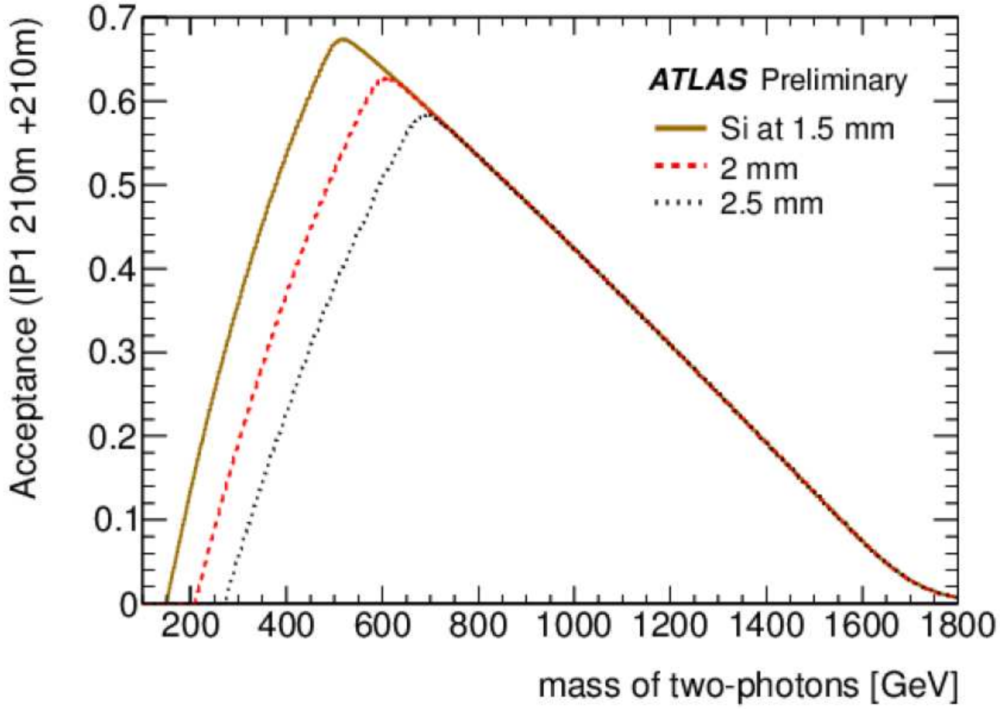
- AFP: two stations at 206 and 214 m
- Movable bea pipes host Si and timing detectors



AFP acceptance in total mass



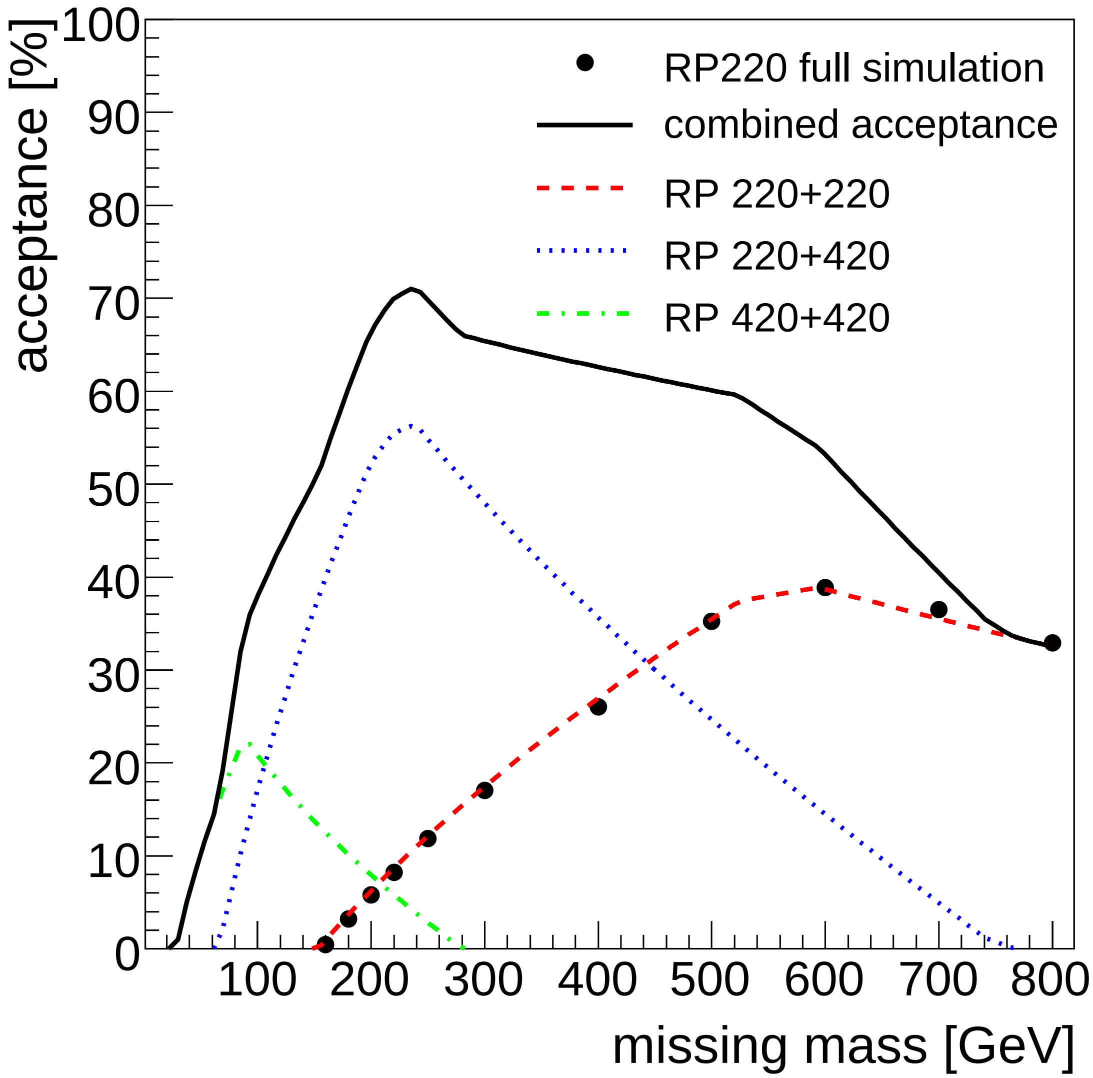




- Increase sensitivity to (new) physics in ATLAS due to color singlet or photon exchanges
- Sensitivity to high mass central system, X, as determined using AFP
- Very powerful for exclusive states: kinematical constraints coming from AFP proton measurements

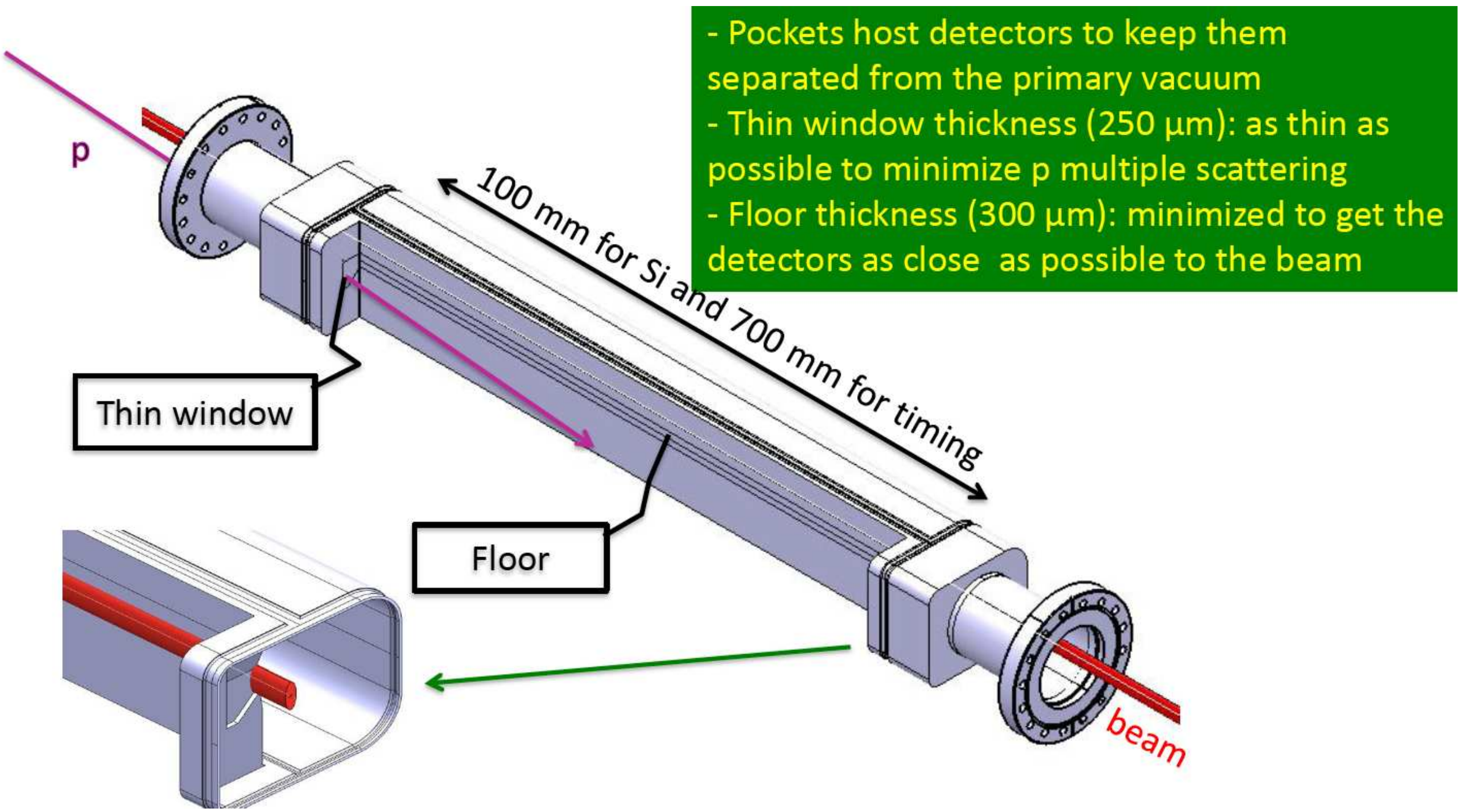
Possible upgrades of AFP

- Detectors at 420 and 220 allow to increase the acceptance at low masses (NB: acceptance slightly smaller in CMS than in ATLAS)
- Possibility to increase the acceptance at high mass by having additional detectors close to ATLAS



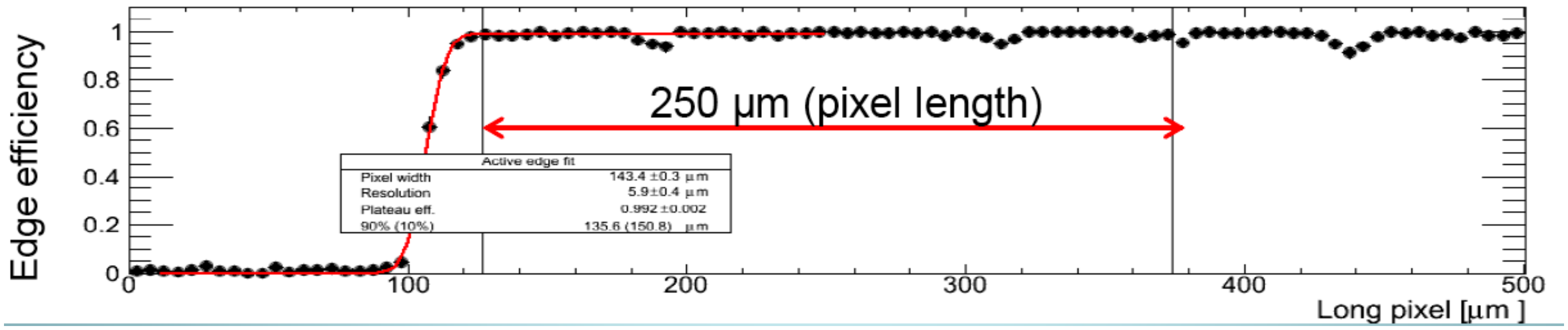
Movable beam pipes and roman pots

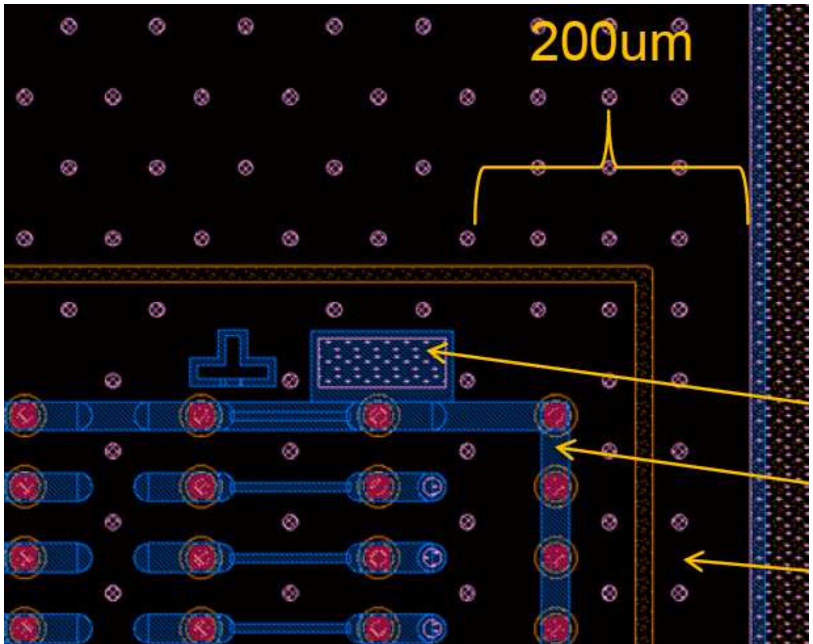
- Possibility to use either roman pots or movable beam pipes to detect protons
- Movable beam pipes allow precise and repeatable movement of detectors close to the beam by $\sim$ 25 mm (HERA, Louvain, CERN)
- Movable beam pipe technique: less mechanical stress than roman pots since a fixed vacuum volume is maintained
- The movable beam pipe is treated as an instrumented collimator from the LHC point of view which does not go as close to the beam as the collimator, uses same motors



Detector I: 3D Si detector

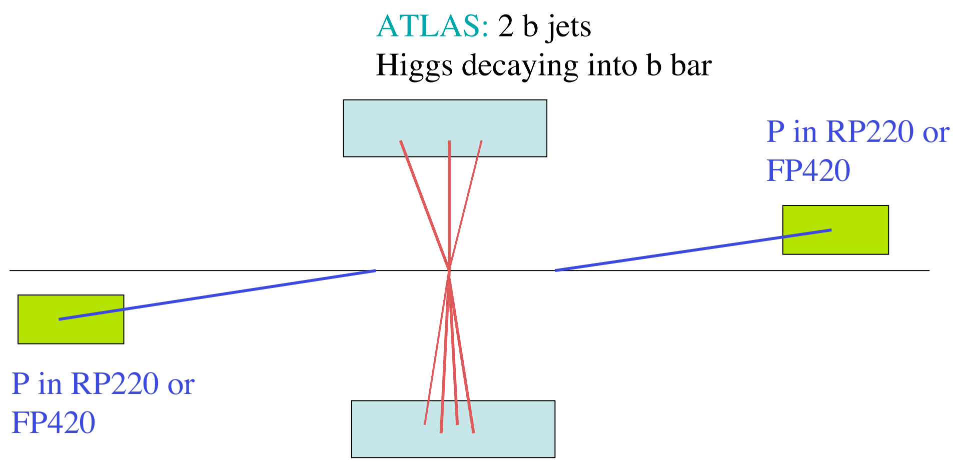
- Key requirements for the Si detector
  - Spatial resolution of 10 (30) μm in x (y) direction over the full detector coverage (2 cm $\times$ 2 cm); Angular resolution of 1 μrad
  - Minimal dead space at the edge and radiation hardness
- Sensors: double-sided 3D 50$\times$250 micron pixel detectors (FBK)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

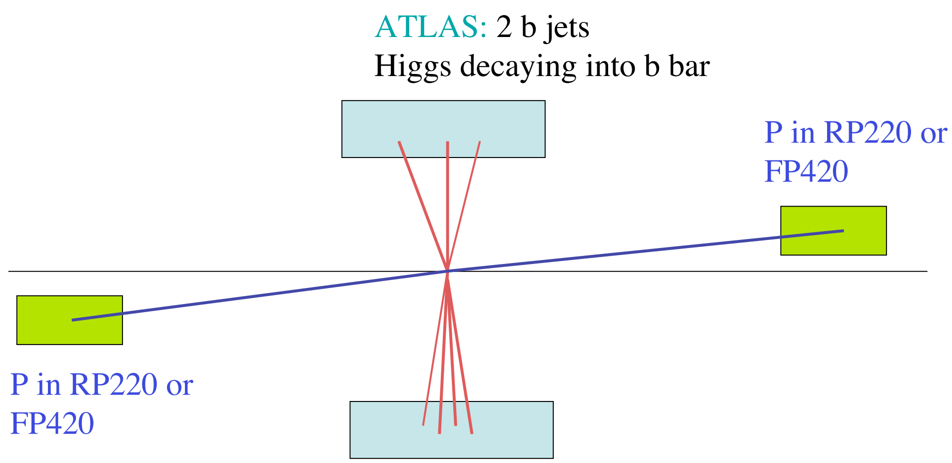




Why do we need timing detectors?

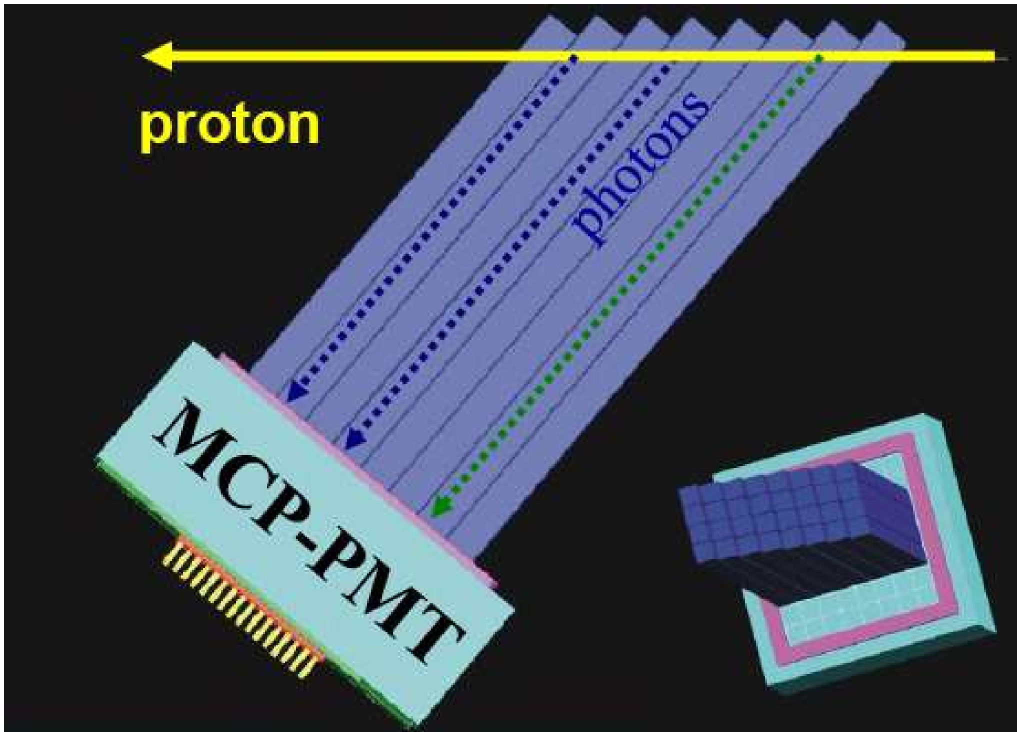
We want to find the events where the protons are related to Higgs production and not to another soft event (up to 35 events occuring at the same time at the LHC!!!!)





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
- QUARTIC has 4×8 array of quartz bars; Each proton passes through eight bars in one of the four rows and one only needs a 30-40 ps measurement/bar since one can do it 8 times



How to achieve 10-20 ps timing resolution?

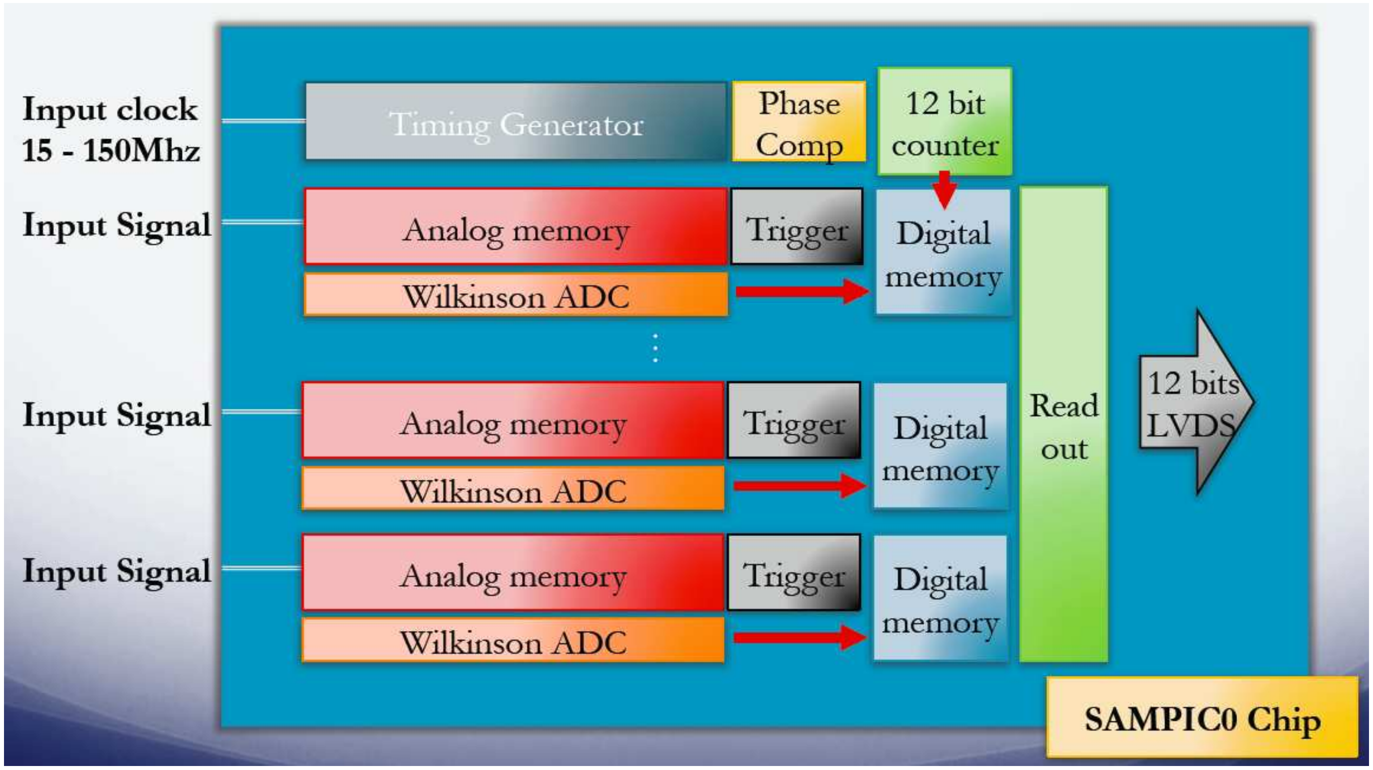
- Present achievement: ∼14 ps with one QUARTIC (8 times the same measurement with 8 bars)
- Future achievement (minor modifications) ∼ 7 ps with two QUARTICS
- Longer term achievements: 1 ps for readout Chip, better spatial resolution (∼ 1 mm^2)

Component	δt(ps) Current	δt(ps) Projected (8 ch +cable)	Improvement	δt(ps) Phase 0 (8 channels)
Radiator (fused silica bar) ~10 pe's	22	22	Optimize radiator	17
MCP-PMT (64 channel 25 um Planacon)	20	20	10 um tube	15
CFD	5	5	-	5
HPTDC	16	16	-	15
Reference Clock	-	3	-	3
Total/bar	34	34		28
Cable		15%	retune CFD	5%
Total/ detector	14	14	-	10

Possibility of using cheaper new chips to be built in Saclay with a preicison of about 1 ps

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, no 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
- New ideas for pixelisation (Saclay, Lecce, Roma, Bologna...): APDs, SiPM, Diamonds...



Conclusion

- Many topics about diffraction in ATLAS: rapidity gaps, total cross section, AFP (Better understanding the Pomeron structure, universality of Pomeron, jet gap jets, anomalous couplings between γ, W, Z, magnetic monopoles...)
- Many applications especially in PET imaging (Manjit Dosanjh)