Forward physics with tagged protons at the LHC

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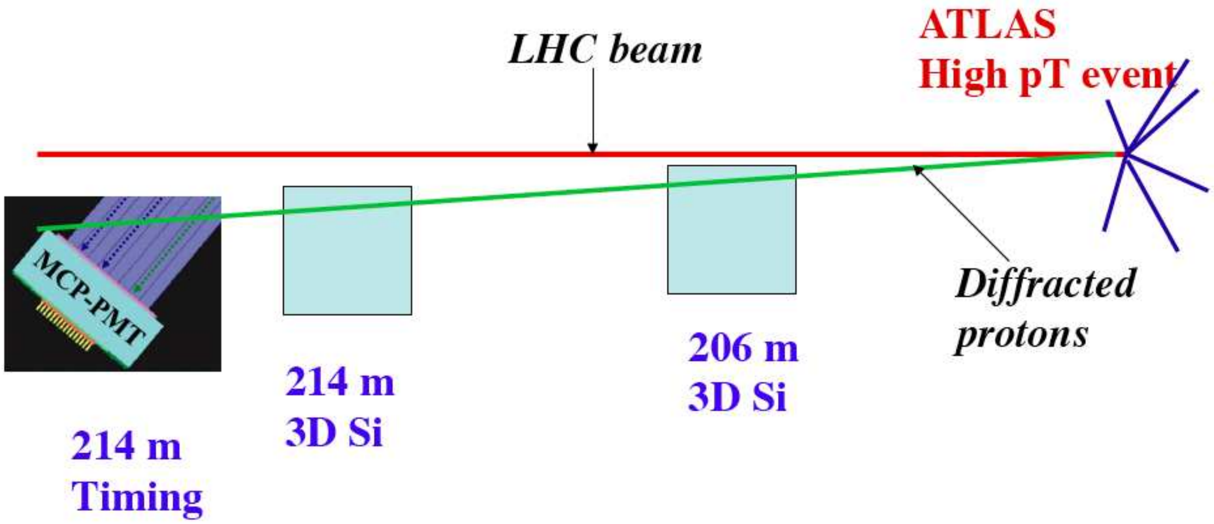
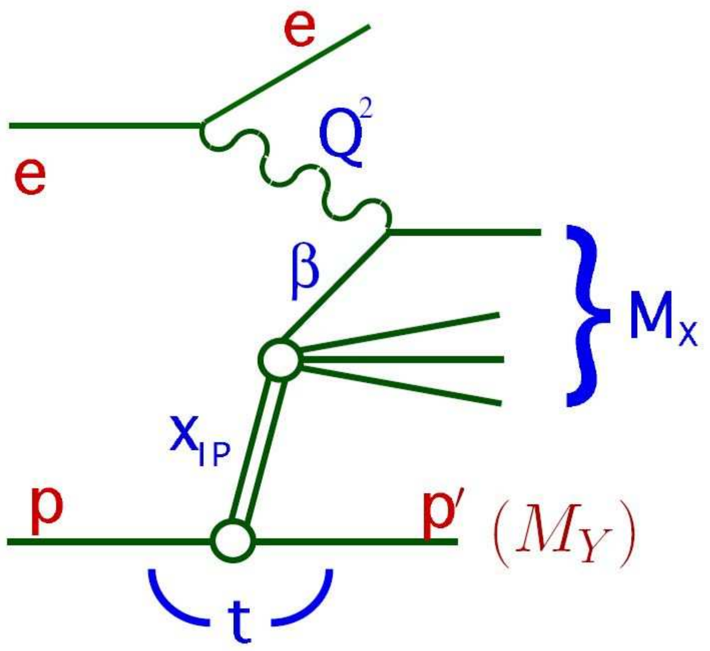
Contents:

- Constraining the Pomeron structure (DPE jets and γ+jet)
- Anomalous $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings
- Exclusive jets
- Exclusive diffractive Higgs: uncertainties
- AFP detectors



Diffractive kinematical variables

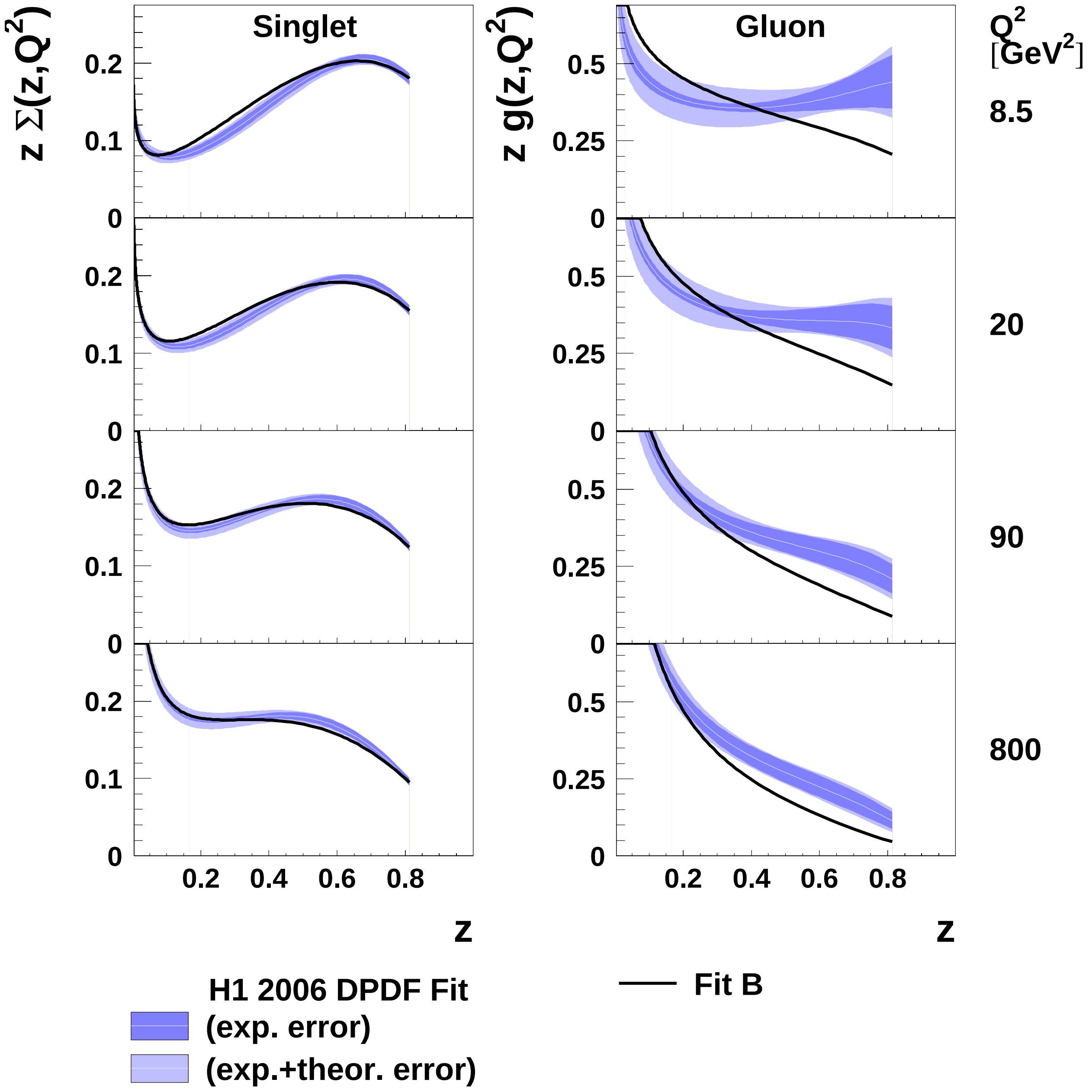


Invariant mass of the diffractive final state

- 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: $t = (p - p')^2$

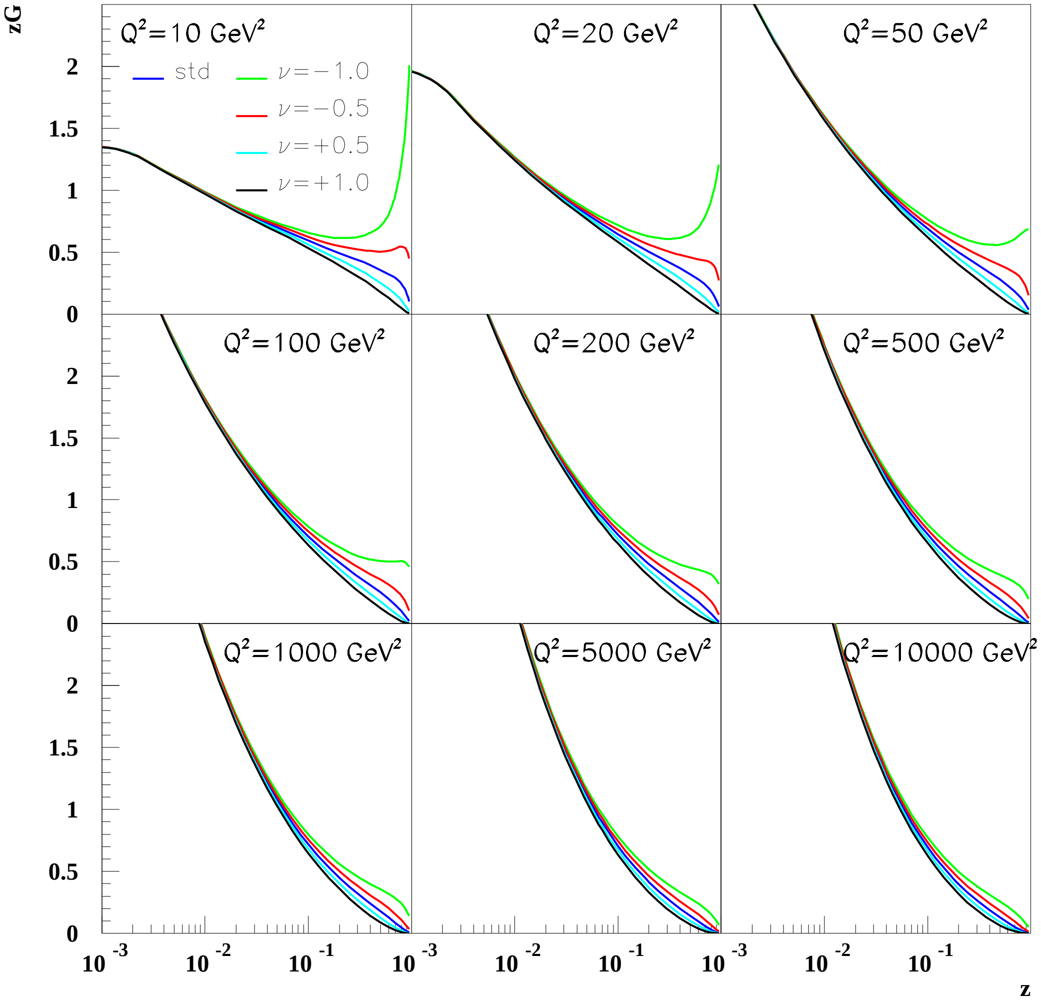
Parton densities in the pomeron (H1)

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



Uncertainty on high β gluon

- Important to know the high β gluon since it is a contamination to exclusive events
- Study coonstraints from LHC data to the Pomeron structure
- Uncertainty on gluon density at high β: multiply the gluon density by $(1-\beta)^{\nu}$ (fit: $\nu = 0.0 \pm 0.6$)
- See O. Kepka, C. Royon, Phys.Rev.D76 (2007) 034012; arXiv0706.1798

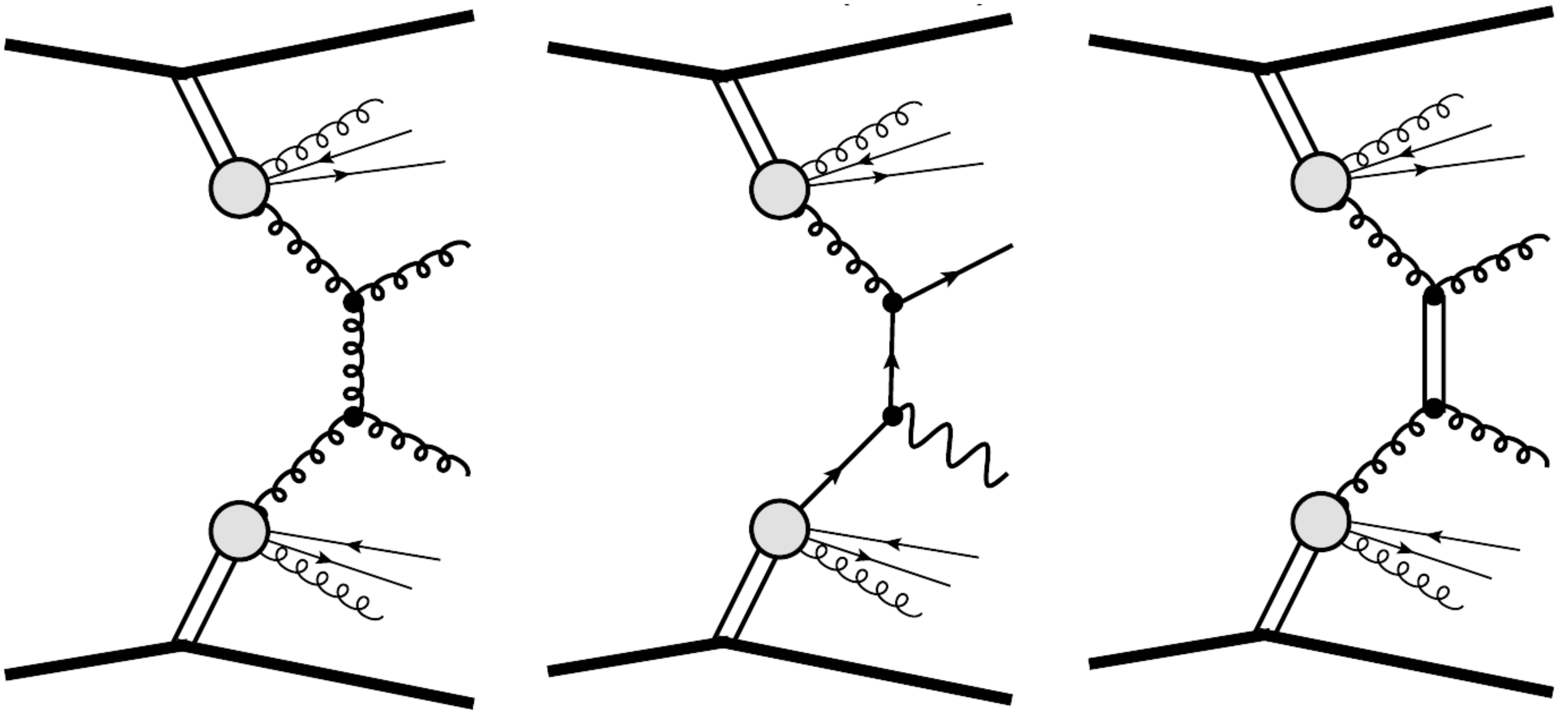


Forward Physics Monte Carlo (FPMC)

- 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

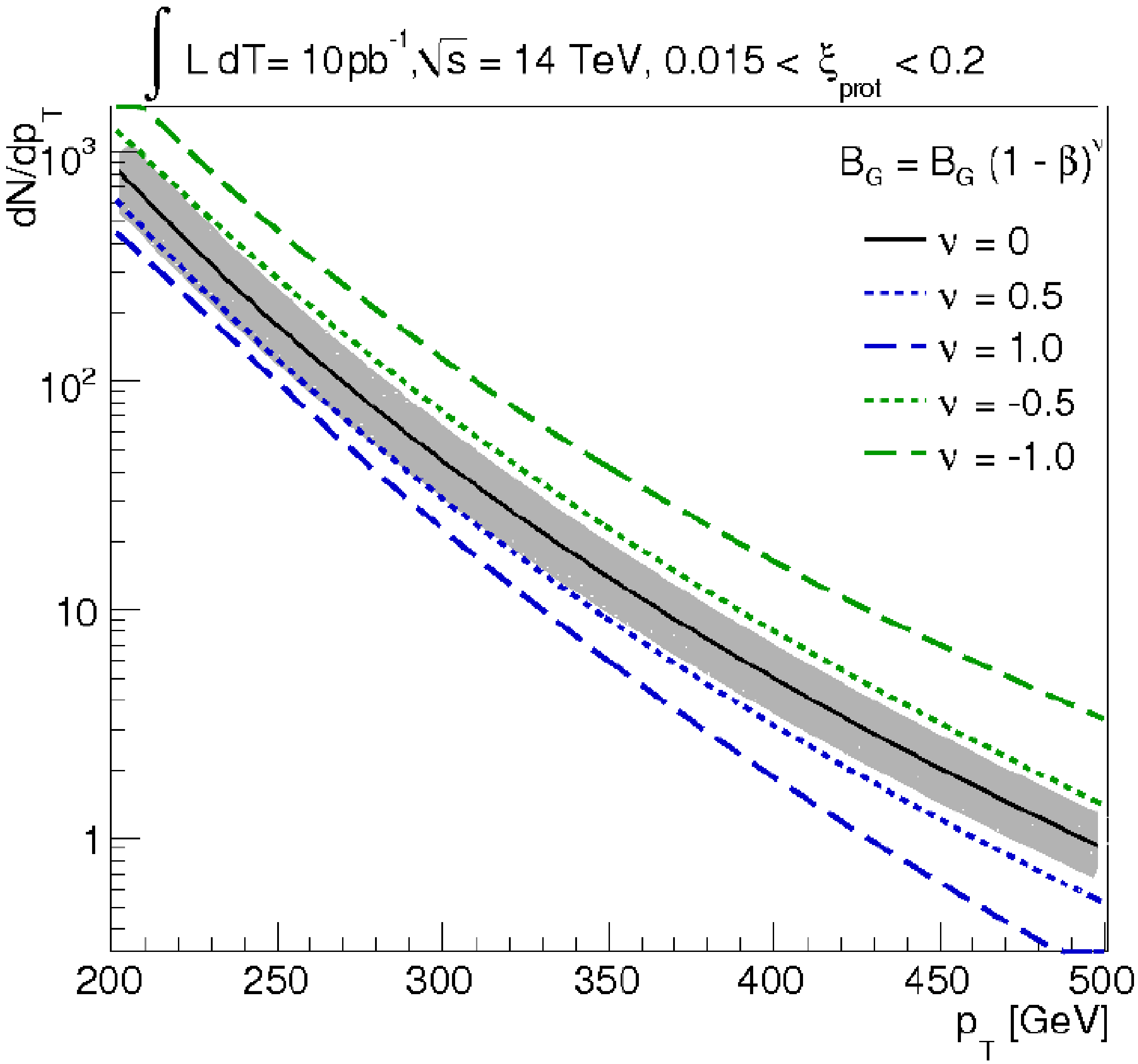
Inclusive diffraction at the LHC

- Dijet production: dominated by gg exchanges
- γ+jet production: dominated by qg exchanges
- Jet gap jet in diffraction: Probe BFKL (see talk by Maciej Trzebinski)



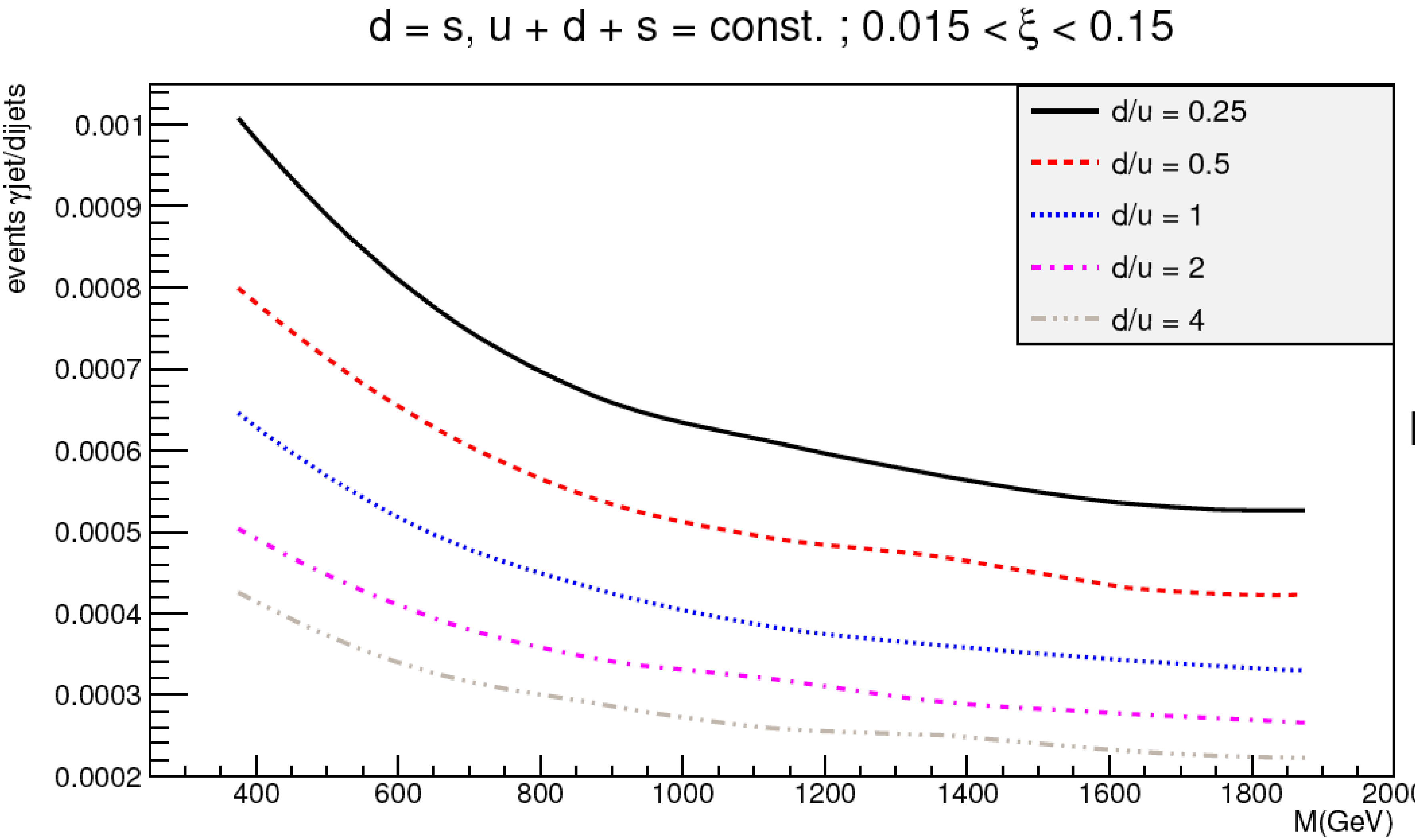
Inclusive diffraction at the LHC: sensitivity to gluon density

- Predict DPE dijet cross section at the LHC
- Sensitivity to gluon density in Pomeron

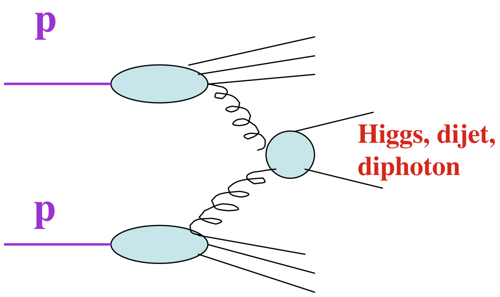


Inclusive diffraction at the LHC: sensitivity to quark densities

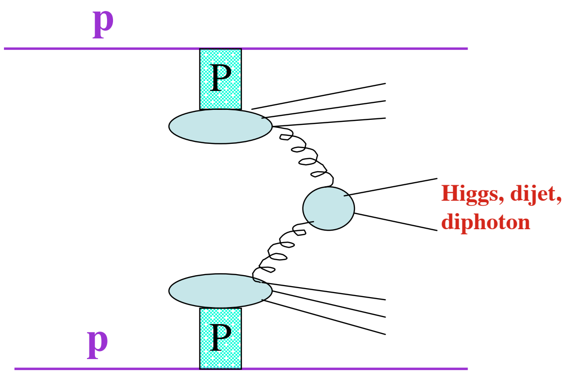
- Predict DPE γ+jet divided by dijet cross section at the LHC
- Sensitivity to universality of Pomeron model
- Sensitivity to gluon density in Pomeron, of assumption: $u = d = s = \bar{u} = \bar{d} = \bar{s}$ used in QCD fits at HERA
- C. Marquet, C. Royon, M. Saimpert, in preparation



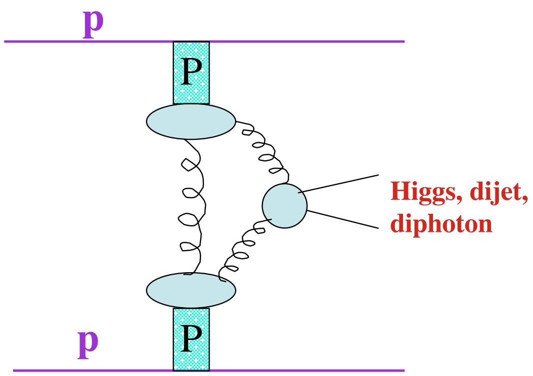
“Exclusive models” in diffraction



Inclusive non diffractive (1)



Inclusive Diffractive (2)

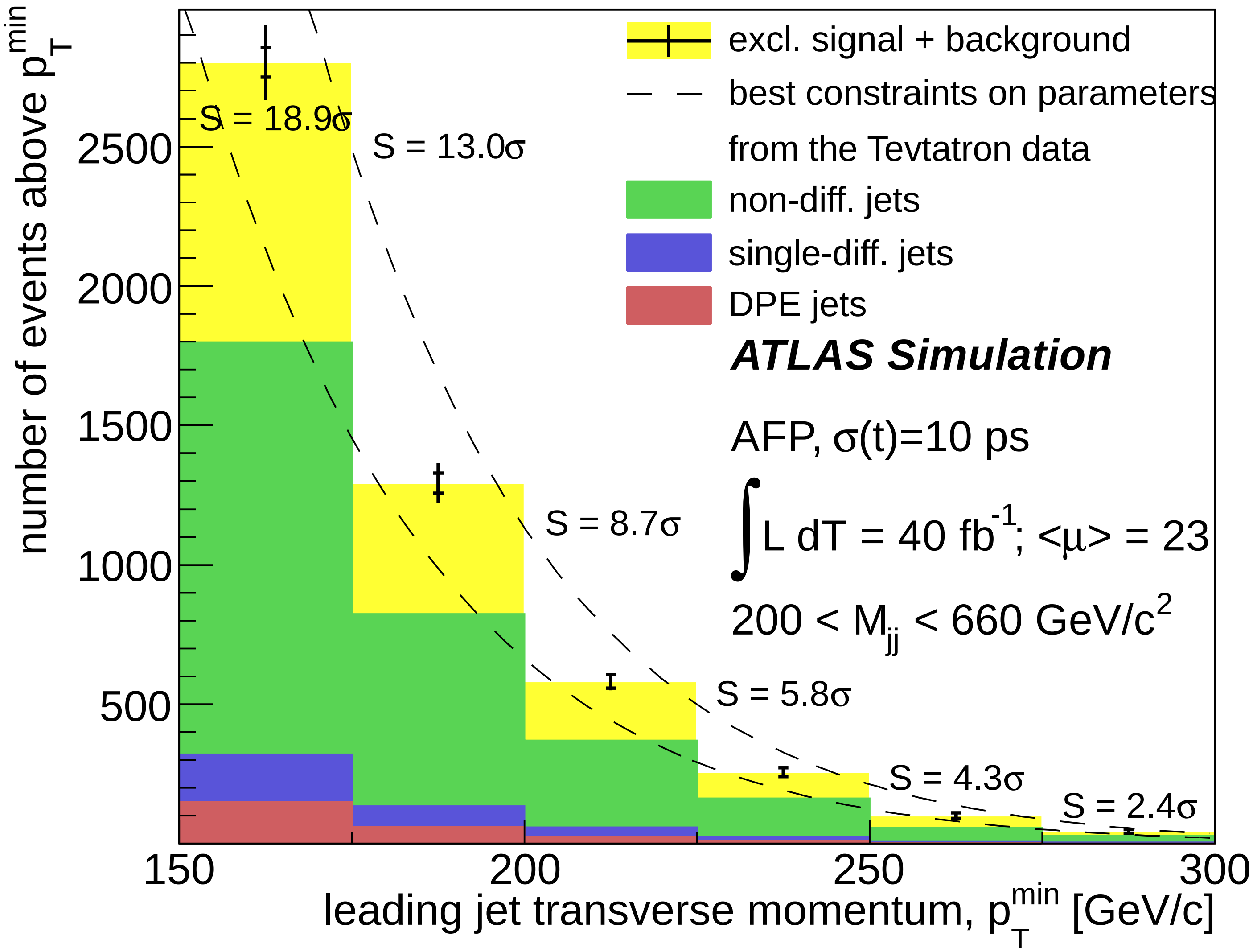


Exclusive Diffractive (3)

- 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

Exclusive jet production at the LHC

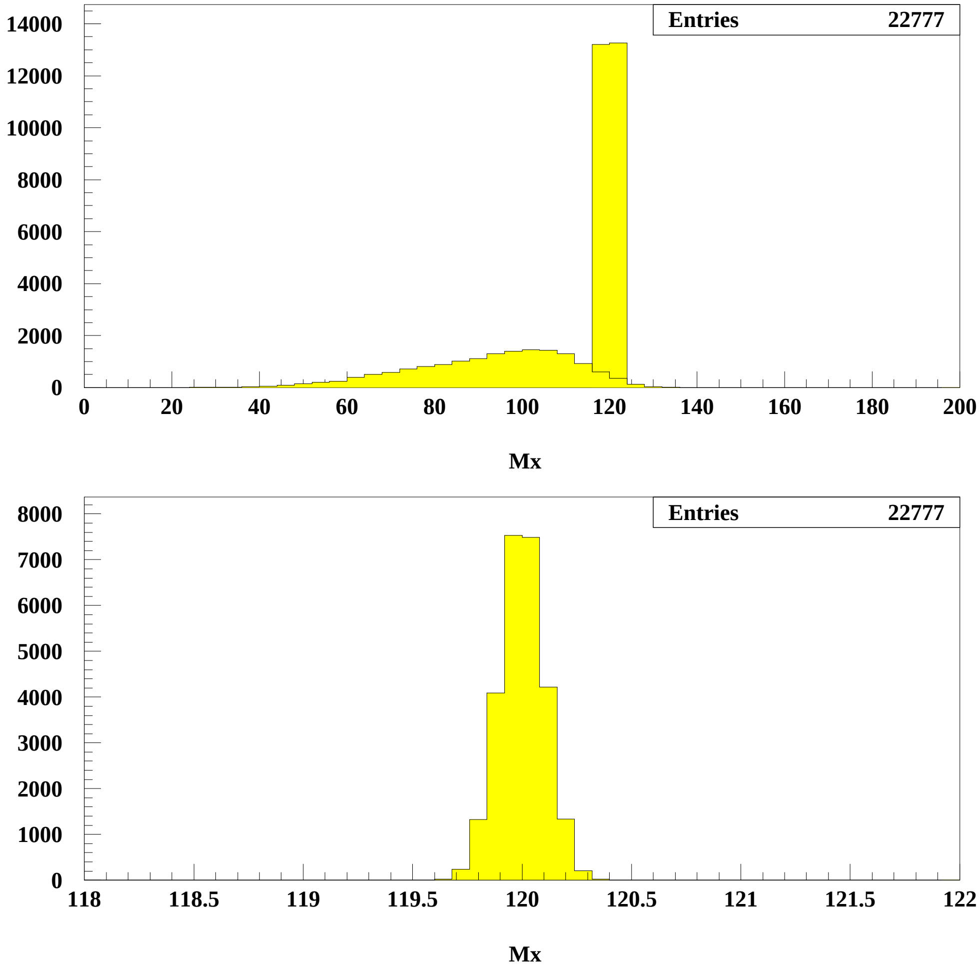
- Jet cross section measurements: up to 18.9 σ for exclusive signal with 40 fb^{-1} $(\mu = 23)$: highly significant measurement in high pile up environment, improvement over measurement coming from Tevatron (CDF) studies using $\bar{p}$ forward tagging by about one order of magnitude



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

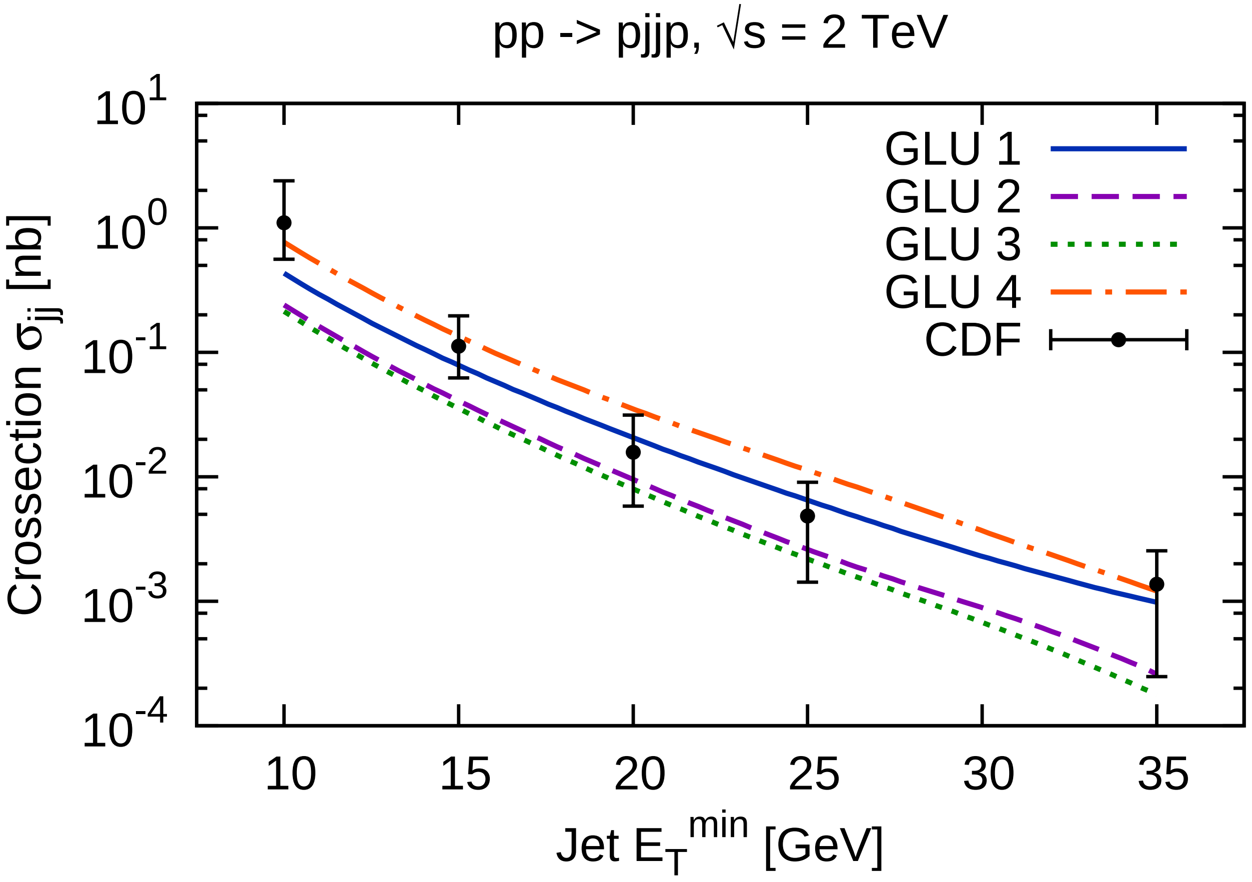
Advantage of exclusive production: Higgs boson?

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



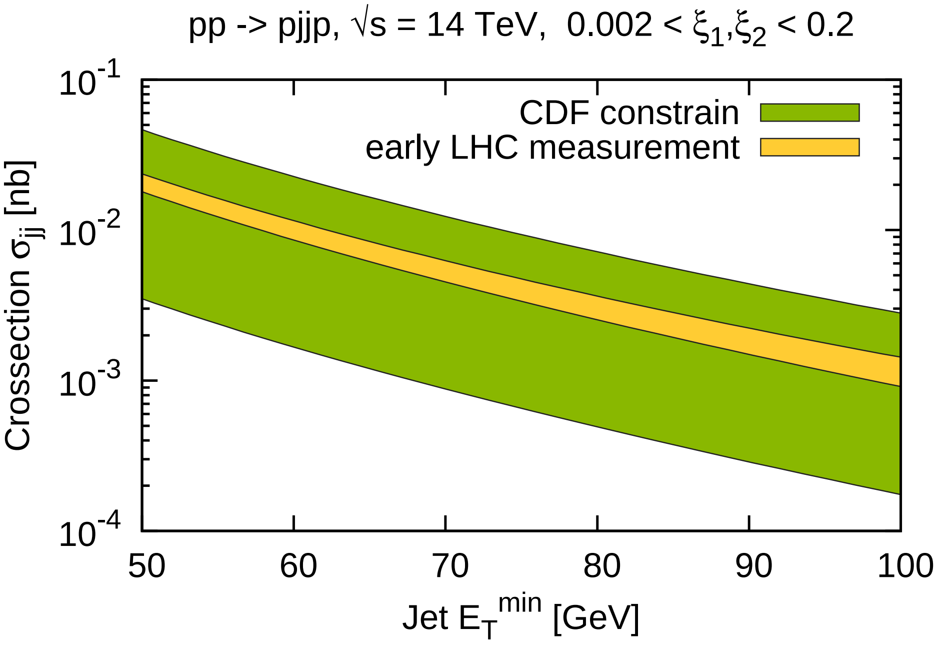
Exclusive model uncertainties - unintegrated gluon

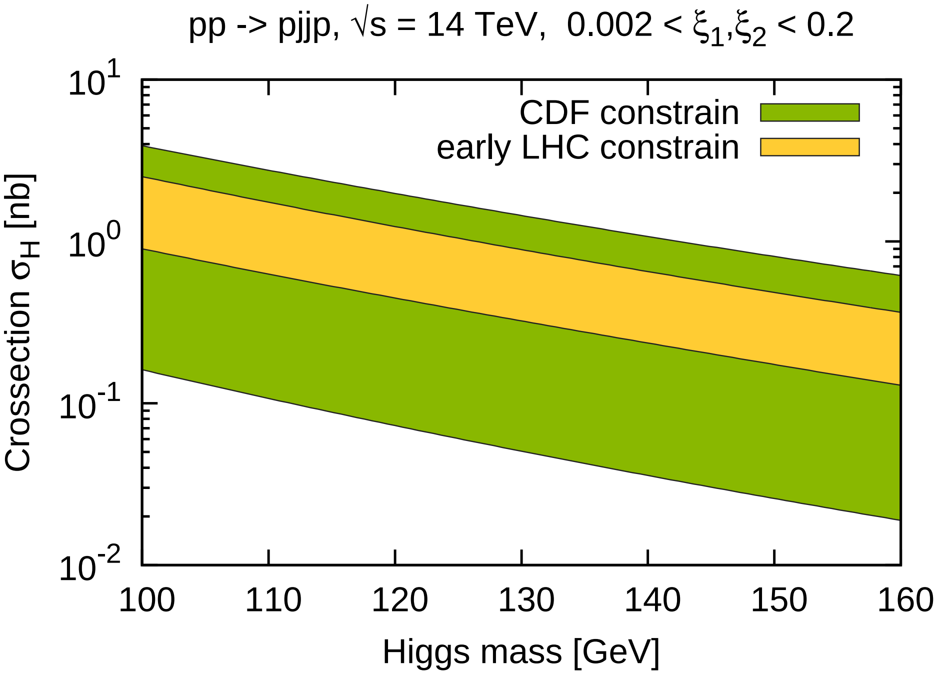
- Study model uncertainties by varying the parameters in CHIDe model
- Survival probability: 0.1 at Tevatron, 0.03 assumed at LHC (multiplication factor to exclusive cross sections, to be measured using diffractive LHC data)
- Uncertainty on unintegrated gluon densities: 4 different gluon densities with same known hard contribution (GRV98) and different assumptions on soft contribution (represent the present uncertainty on soft part)
- see: A. Dechambre, O. Kepka, C. Royon, R. Staszewski, Phys. Rev. D83 (2011) 054013



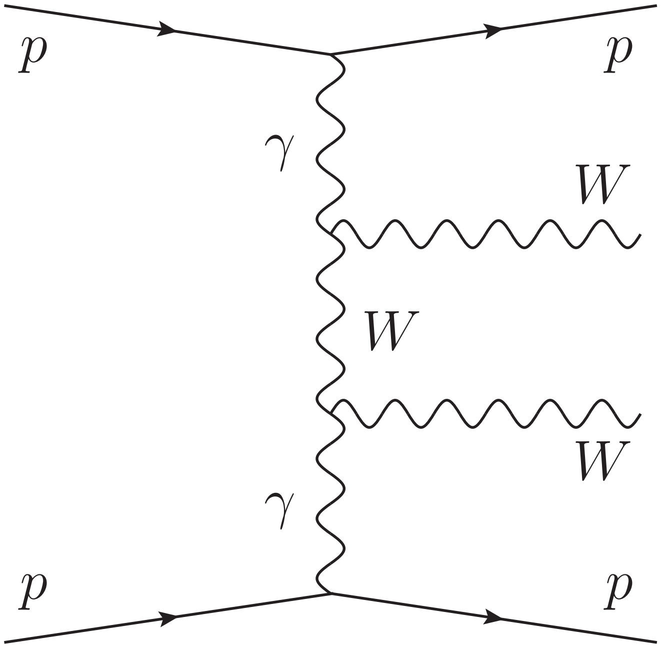
Impact of future LHC measurements on model uncertainty

- Study model uncertainties on exclusive Higgs production: unintegrated gluon distribution, Sudakov integration lower/upper limits
- Green error band: constraint from the CDF measurements
- Assume new measurement of exclusive jet production at the LHC: 100 pb^{-1}, precision on jet energy scale assumed to be $\sim$3% (conservative for JES, but takes into account other possible systematics)
- Possible constraints on Higgs production: about a factor 2 uncertainty
- Possible large enhancement of the Higgs production cross section in NMSSM models





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 anomalous couplings to be studied (dimension 6 and 8 operators) if Higgs boson is discovered; $\gamma\gamma$ specially interesting
- Rich $\gamma\gamma$ physics at LHC: see E. Chapon, O. Kepka, C. Royon, Phys. Rev. D78 (2008) 073005; Phys. Rev. D81 (2010) 074003

Quartic anomalous gauge couplings

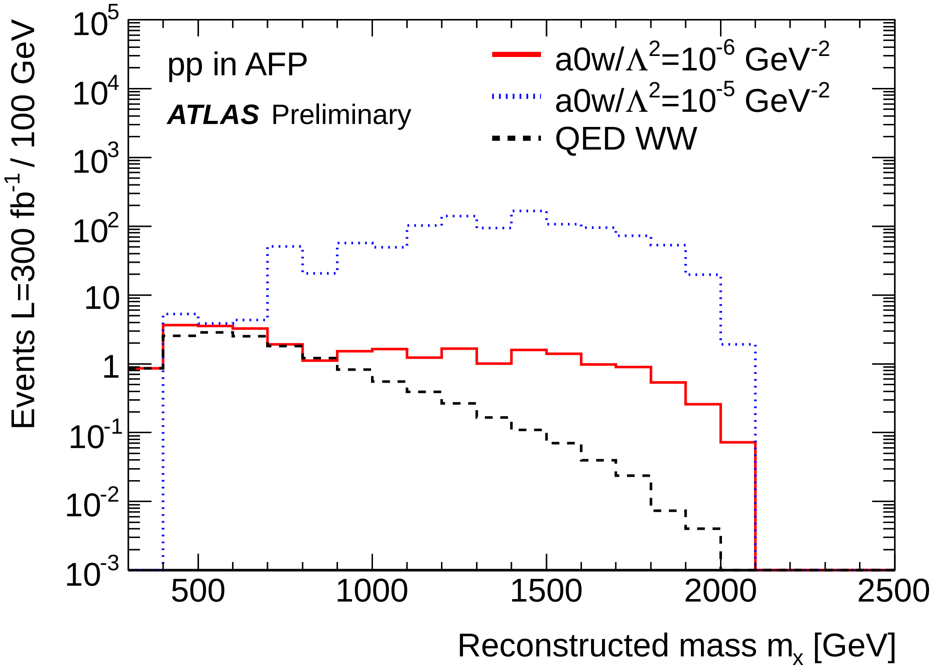
- Quartic gauge anomalous $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings parametrised by a_0^W, a_0^Z, a_C^W, a_C^Z

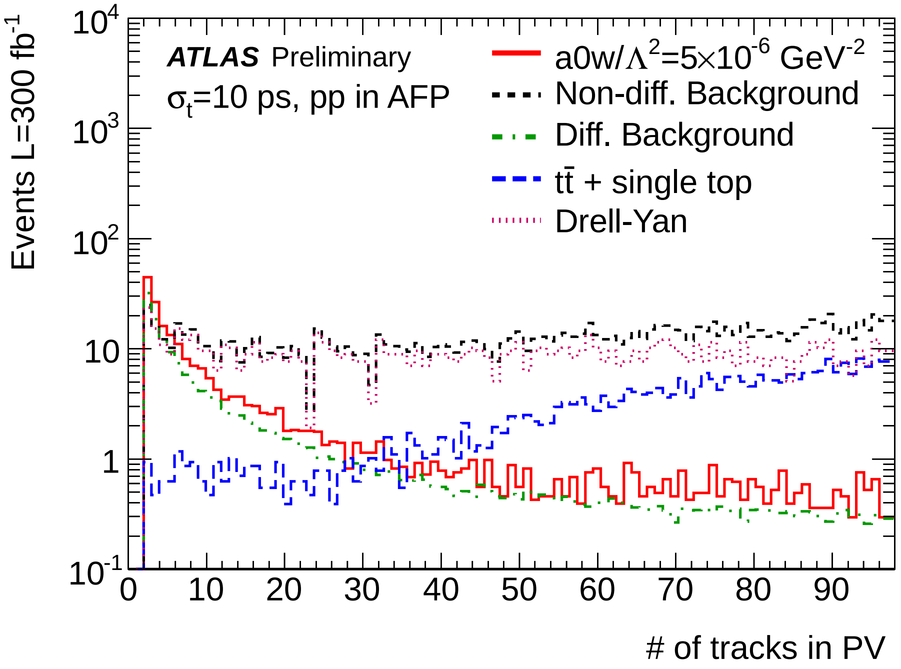
$$
\begin{aligned}
\mathcal{L}_6^0 &\sim \frac{-e^2}{8}\frac{a_0^W}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-_\alpha - \frac{e^2}{16\cos^2(\theta_W)}\frac{a_0^Z}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}Z^\alpha Z_\alpha \\
\mathcal{L}_6^C &\sim \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W^-_\beta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

- Anomalous parameters equal to 0 for SM
- Best limits 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}
- Dimension 6 operators → violation of unitarity at high energies

Anomalous couplings studies in WW events

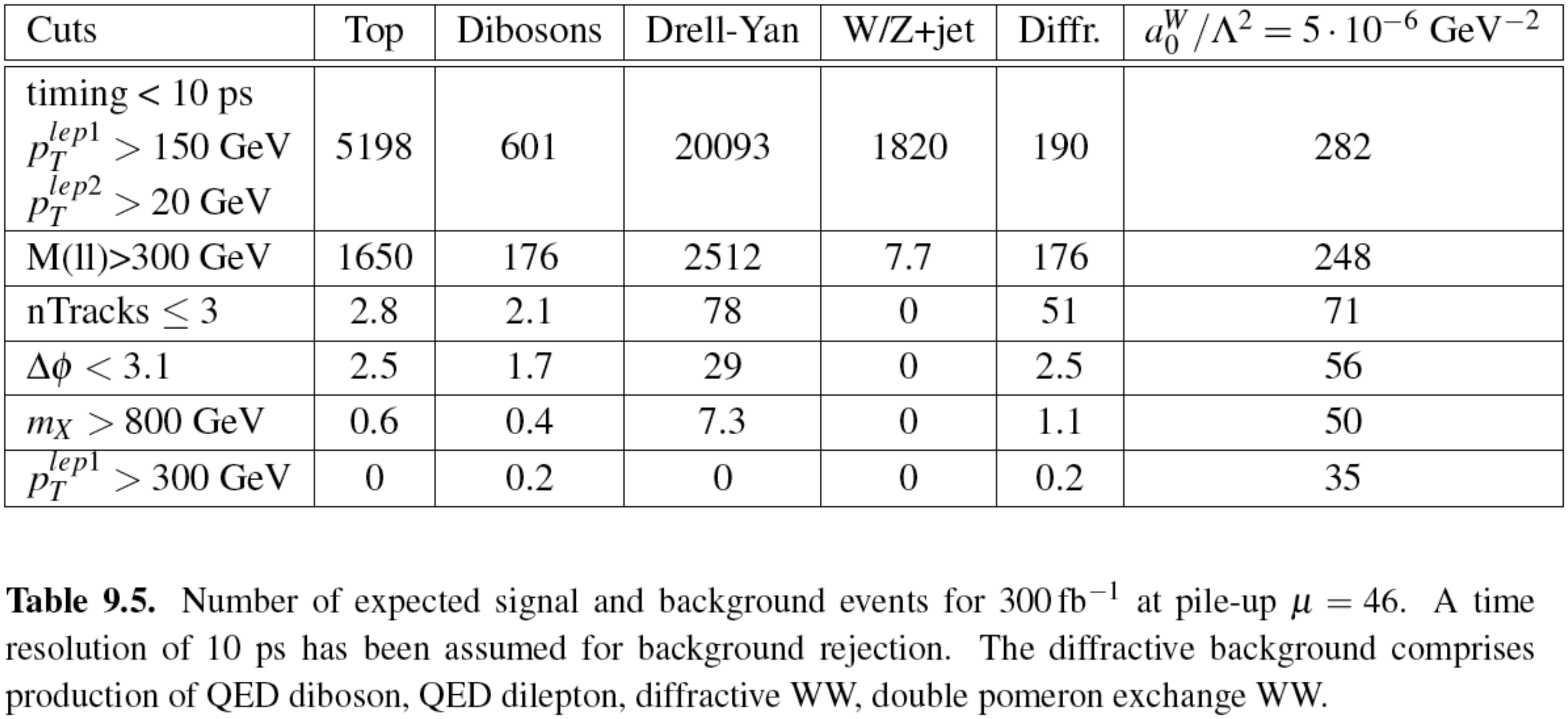
- Reach on anomalous couplings studied using a full simulation of the ATLAS detector, including all pile up effects; only leptonic decays of Ws are considered
- Signal appears at high lepton p_T and dilepton mass (central ATLAS) and high diffractive mass (reconstructed using forward detectors)
- Cut 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 $pp \to l^\pm \nu\gamma\gamma$ (see P. J. Bell, ArXiV:0907.5299) by more than 2 orders of magnitude with 40/300 fb^{-1} at LHC**

	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}	

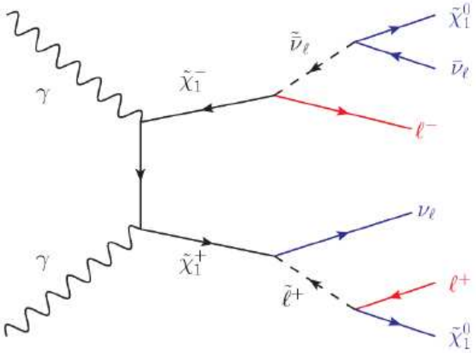
Reach at LHC

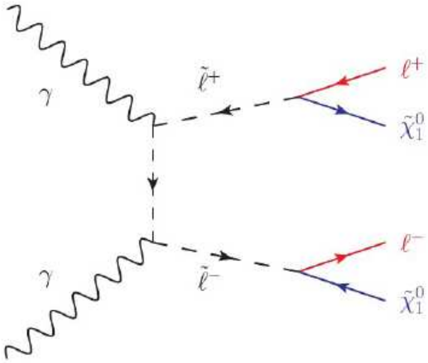
Reach at high luminosity on quartic anomalous coupling using fast simulation (study other anomalous couplings, ZZ...)

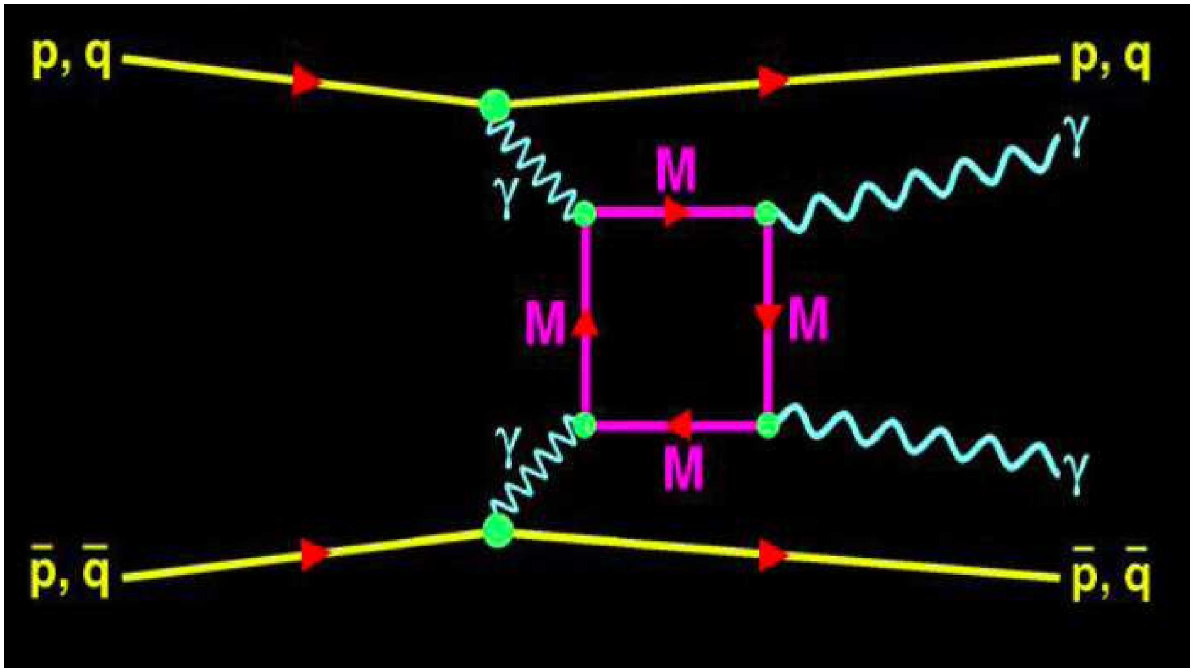
Couplings	OPAL limits [GeV^{-2}]	Sensitivity @ $\mathcal{L} = 30$ (200) fb^{-1} 5σ	95% CL
a_0^W/Λ^2	[-0.020, 0.020]	5.4 10^{-6} (2.7 10^{-6})	2.6 10^{-6} (1.4 10^{-6})
a_C^W/Λ^2	[-0.052, 0.037]	2.0 10^{-5} (9.6 10^{-6})	9.4 10^{-6} (5.2 10^{-6})
a_0^Z/Λ^2	[-0.007, 0.023]	1.4 10^{-5} (5.5 10^{-6})	6.4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

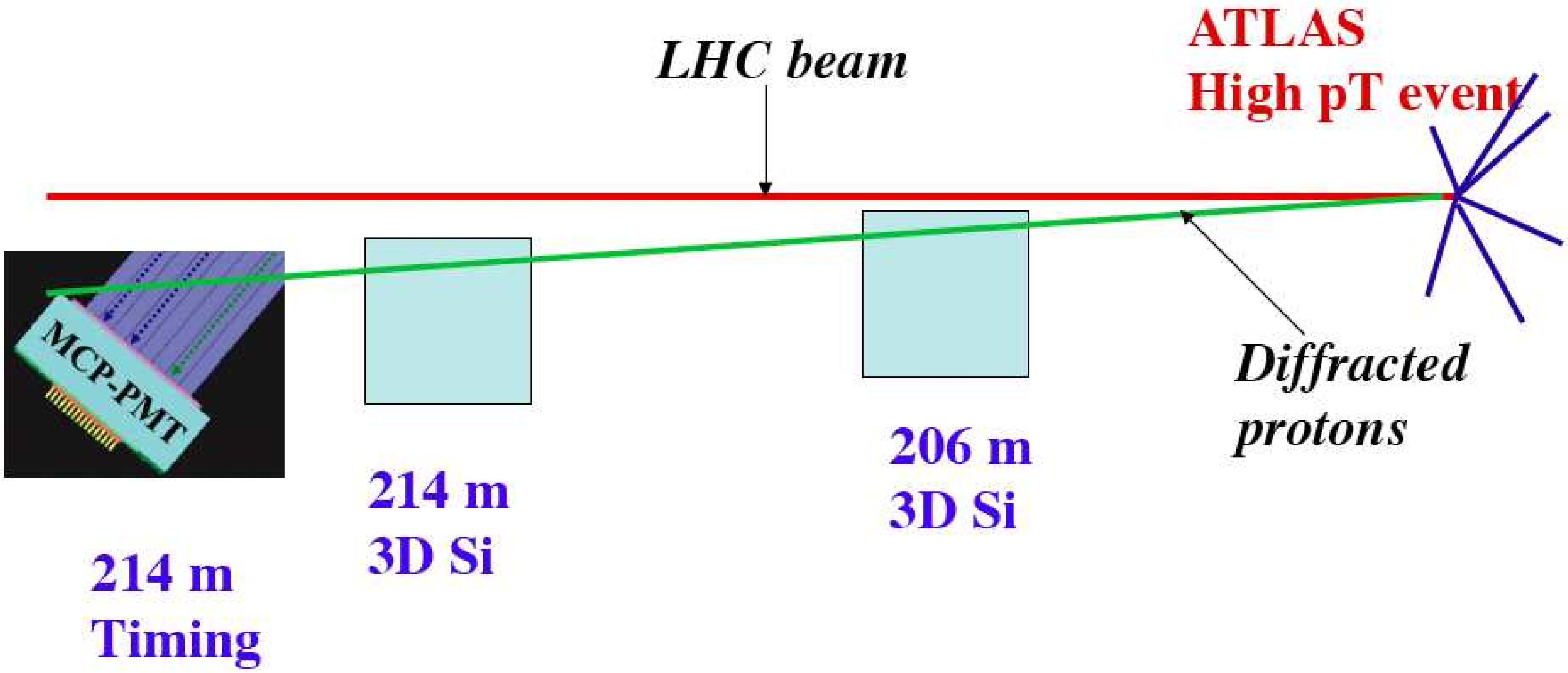






- Production of new objects (with mass up to 1.3 TeV) to be produced either by photon or gluon exchanges: magnetic monopoles, KK resonances, SUSY,... (which could be missed in central ATLAS if predominant decays are hadronic)
- Production of SUSY particles: Possibility of measuring the mass of sleptons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

What is AFP?



LHC beam

ATLAS
High pT event

Diffracted protons

MCP-PMT

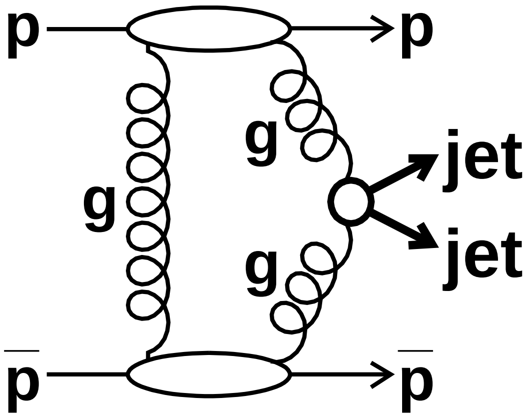
214 m
Timing

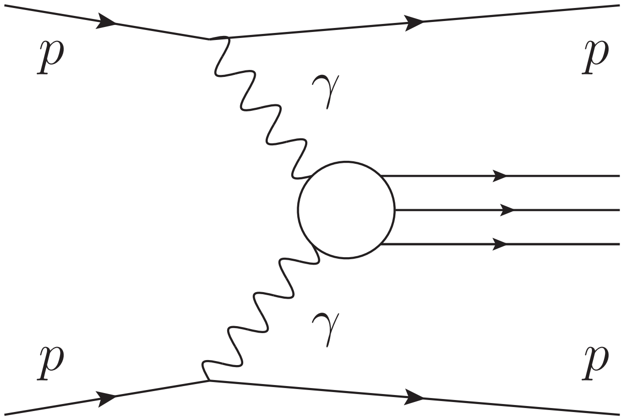
214 m
3D Si

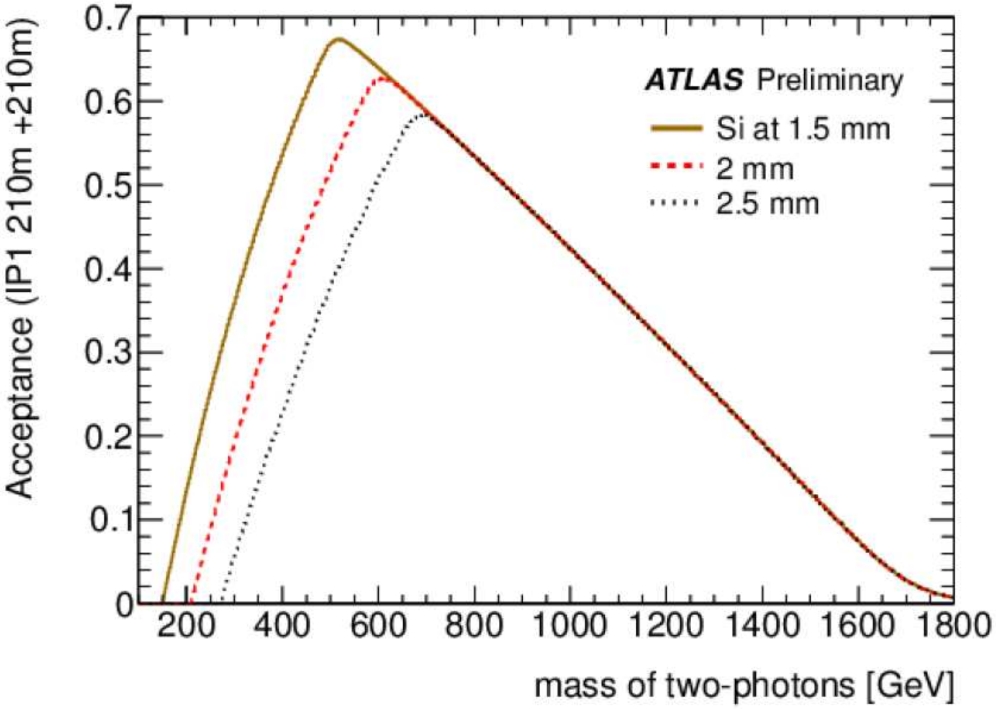
206 m
3D Si

- 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 acceptance in total mass



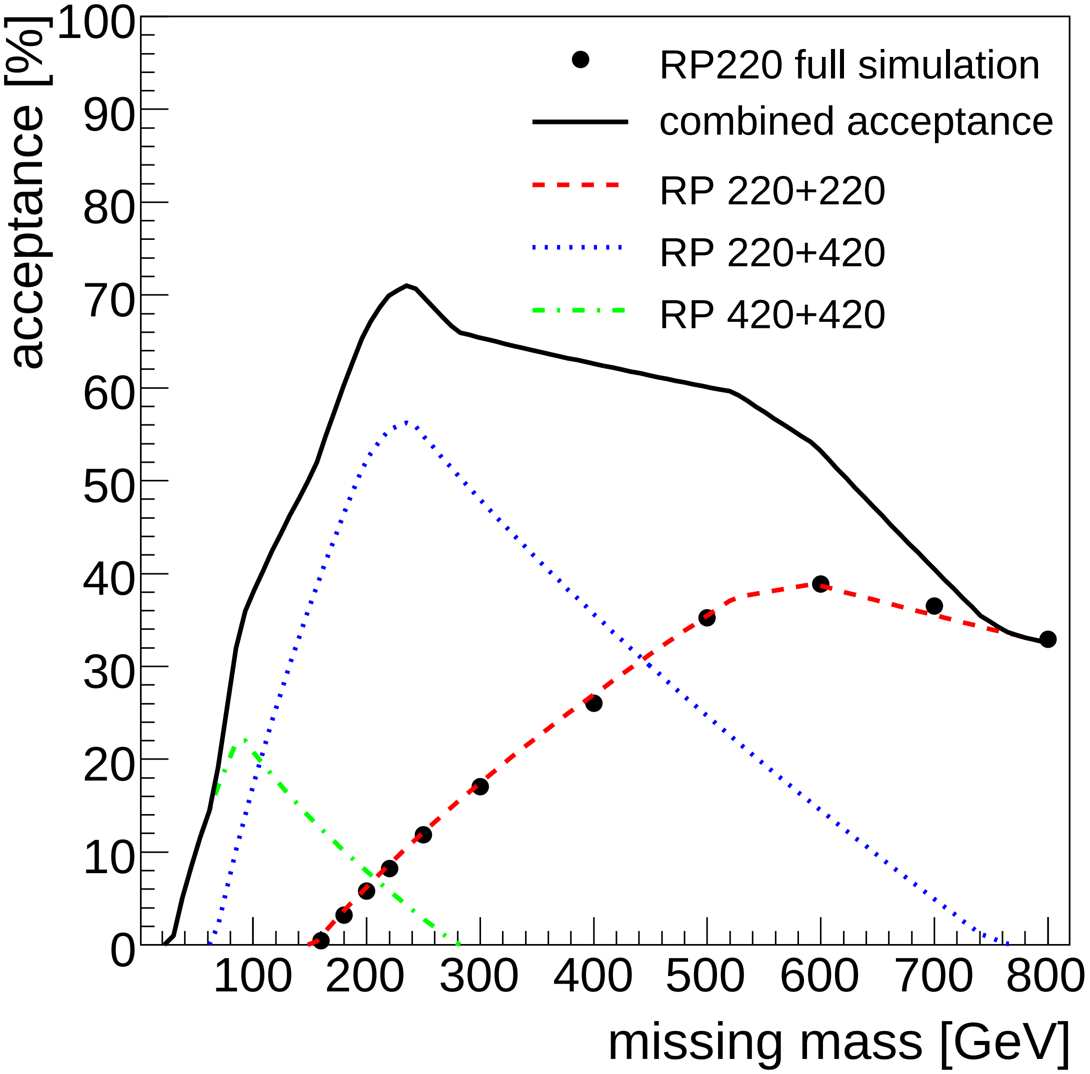




- Increase sensitivity to (new) physics in ATLAS due to color singlet or photon exchanges
- Sensitivity to high mass central system, X, as determined using AFP
- Very powerful for exclusive states: kinematical constraints coming from AFP proton measurements

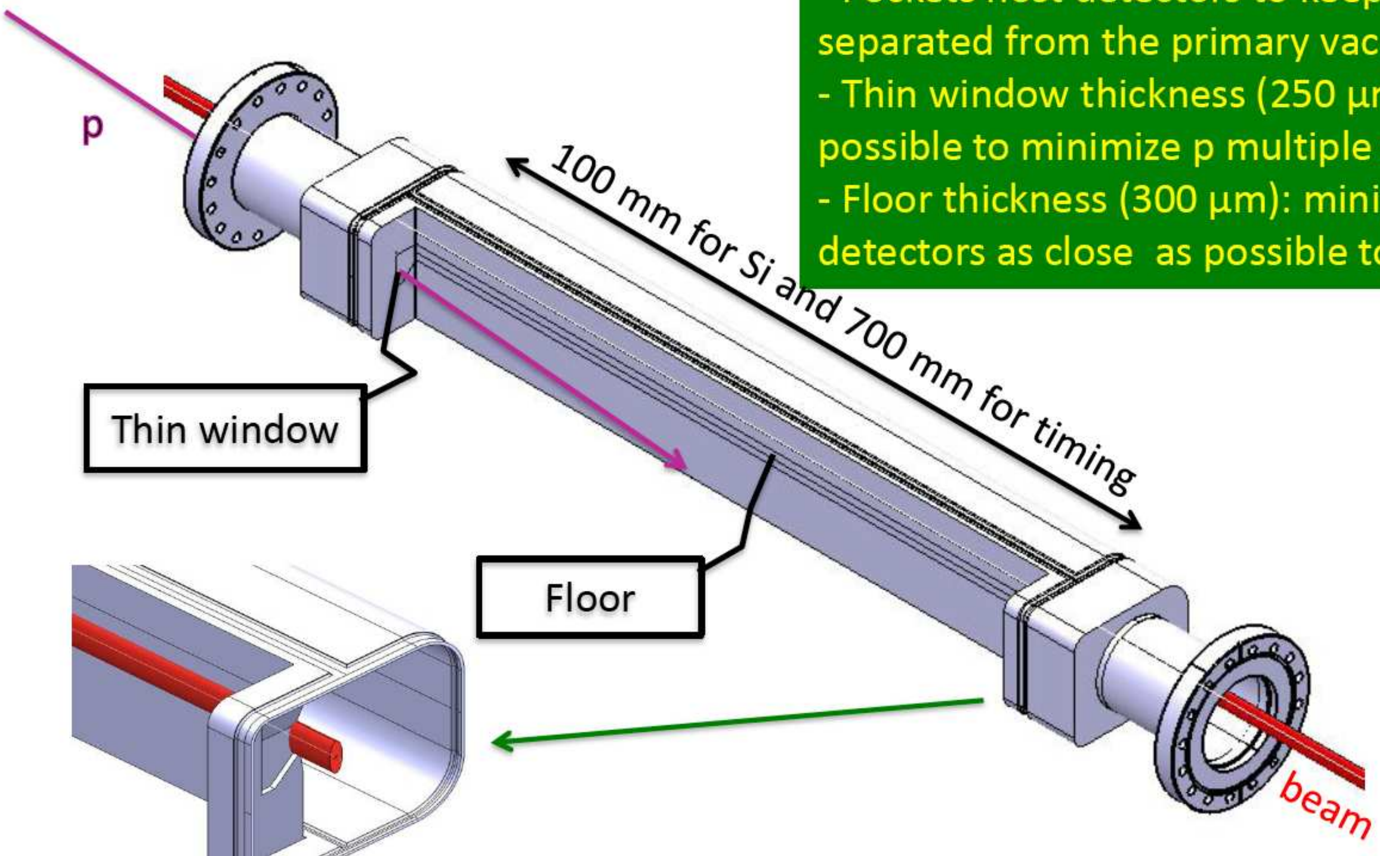
Possible upgrades of AFP

- 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

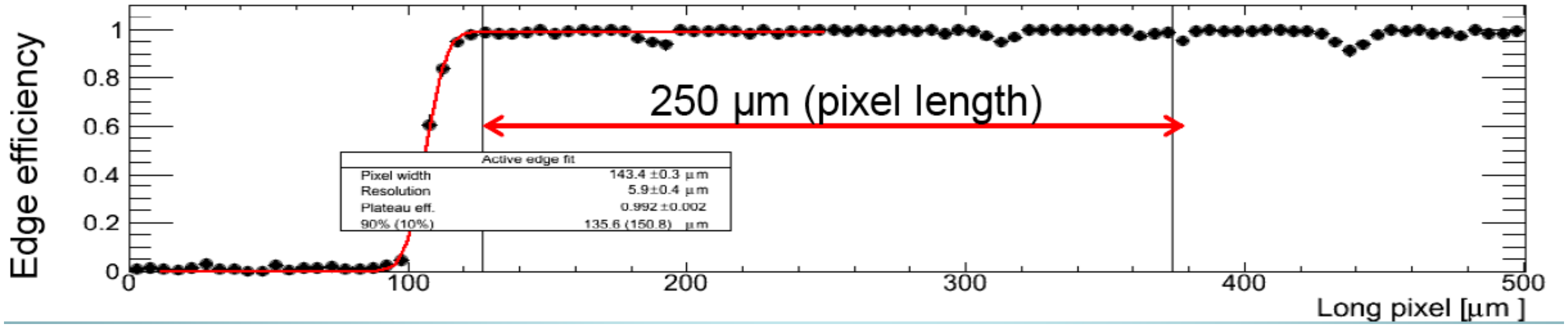
- allow precise and repeatable movement of detectors close to the beam by $\sim$ 25 mm (HERA, Louvain, CERN)
- minimum deformation, thin vacuum window (detector a few mm from the beam), small RF impact
- use standard LHC components (bellows...)
- Choose movable beam pipe technique: less mechanical stress 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

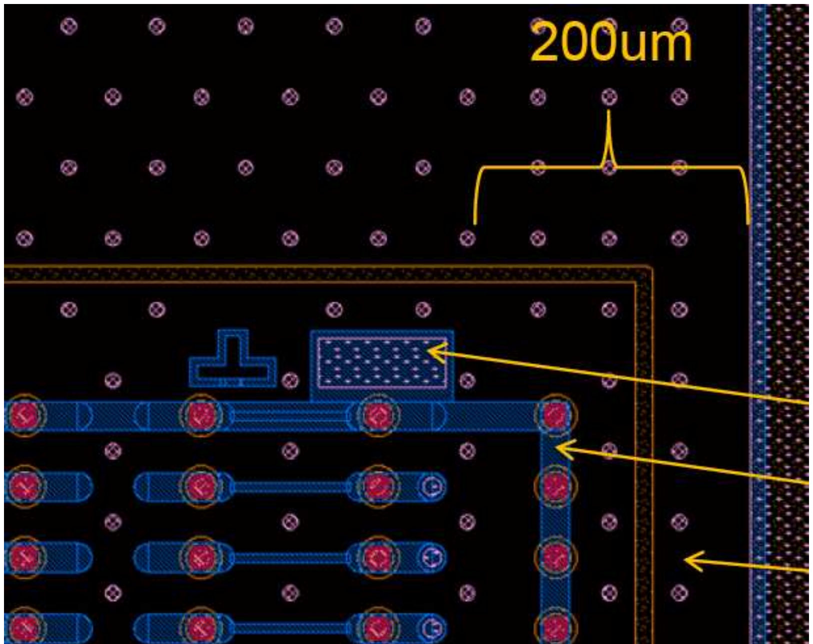


- Pockets host detectors to keep them separated from the primary vacuum
- Thin window thickness (250 µm): as thin as possible to minimize p multiple scattering
- Floor thickness (300 µm): minimized to get the detectors as close as possible to the beam

Detector I: 3D Si detector

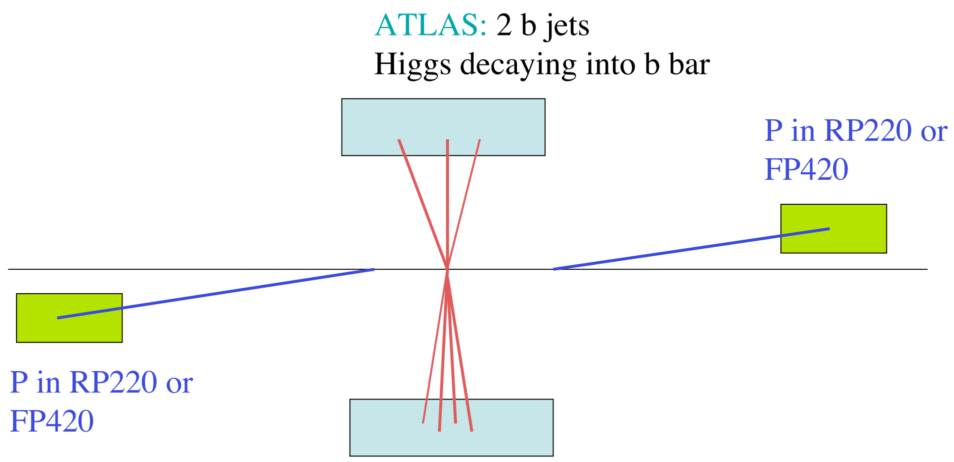
- Key requirements for the Si detector
  - Spatial resolution of 10 (30) μm in x (y) direction over the full detector coverage (2 cm × 2 cm); Angular resolution of 1 μrad
  - Minimal dead space at the edge and radiation hardness
- Sensors: double-sided 3D 50×250 micron pixel detectors (FBK) with slim-edge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





Why do we need timing detectors?

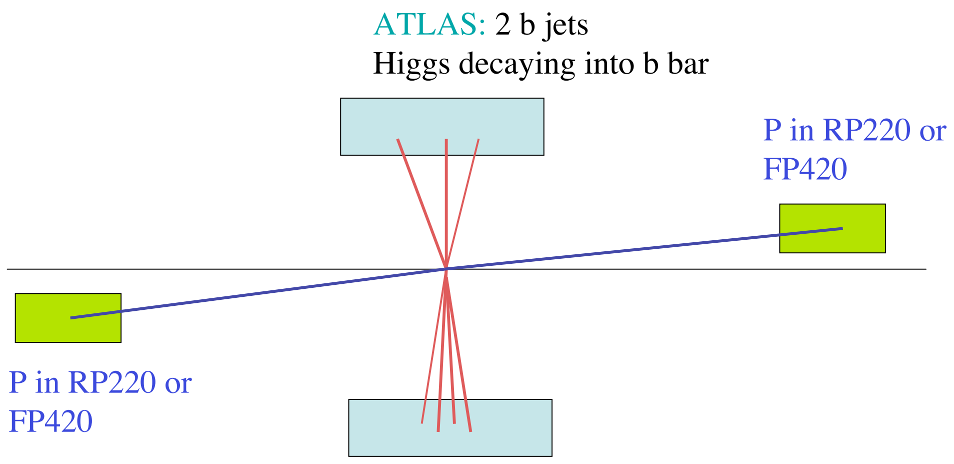
We want to find the events where the protons are related to Higgs production and not to another soft event (up to 35 events occuring at the same time at the LHC!!!!)



ATLAS: 2 b jets
Higgs decaying into b bar

P in RP220 or FP420

P in RP220 or FP420



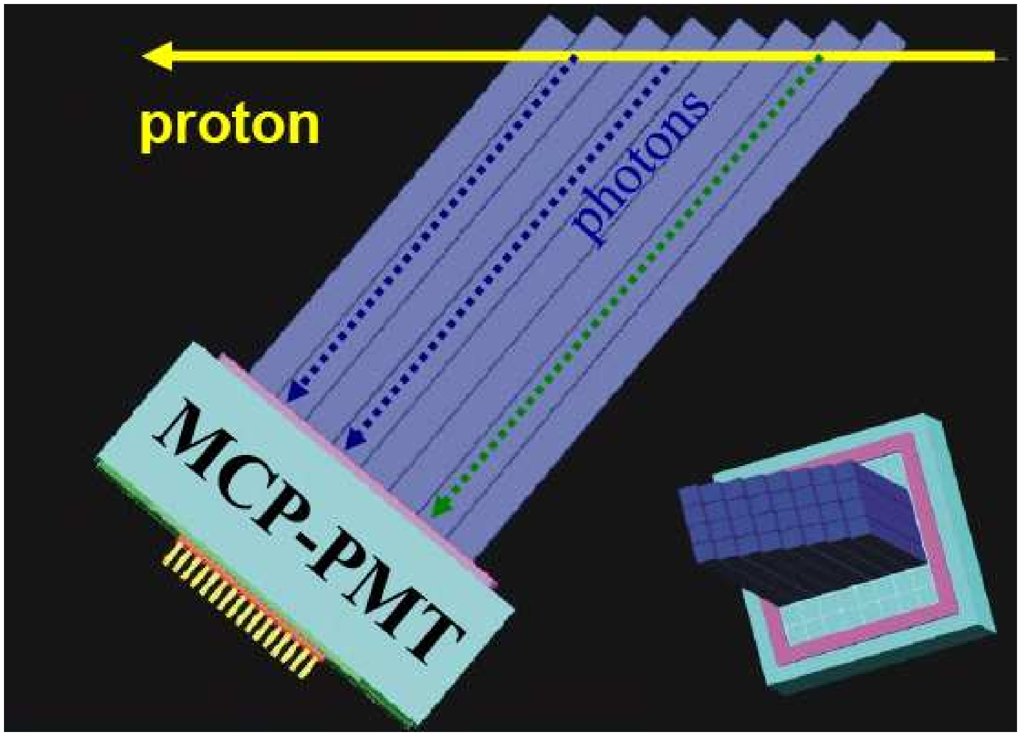
ATLAS: 2 b jets
Higgs decaying into b bar

P in RP220 or FP420

P in RP220 or FP420

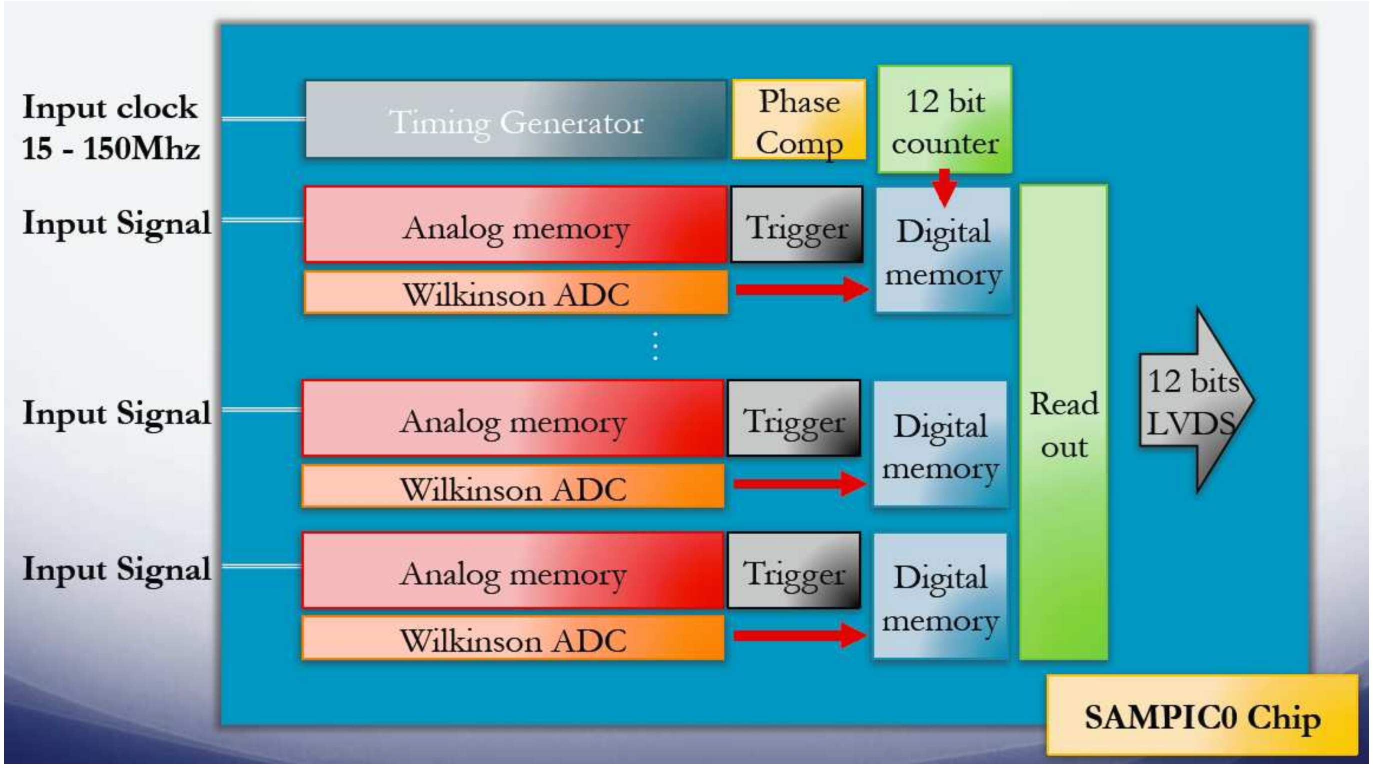
Detector II: timing detectors

- 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



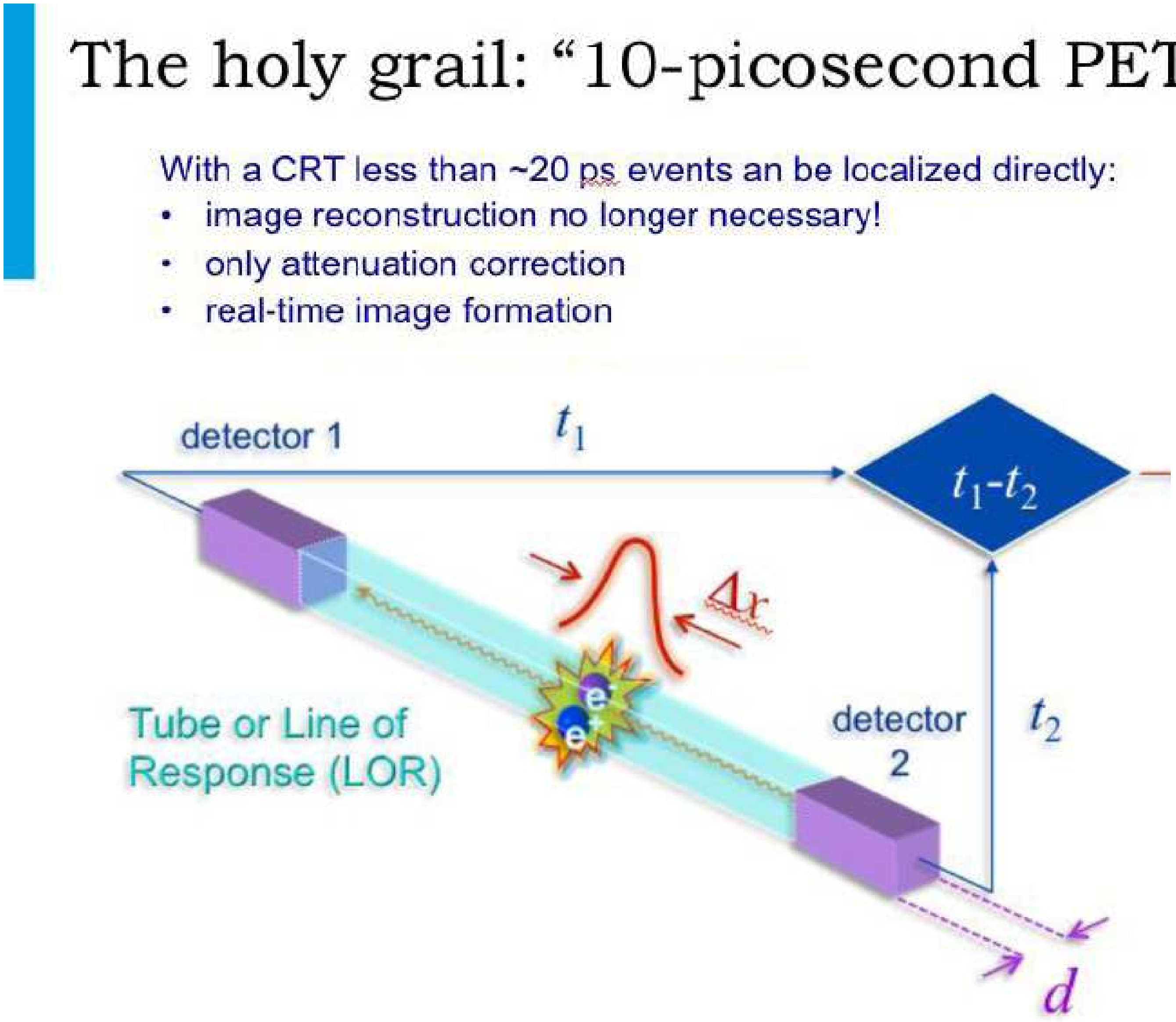
Saclay: Going beyond the present chip

- 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

- 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)



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

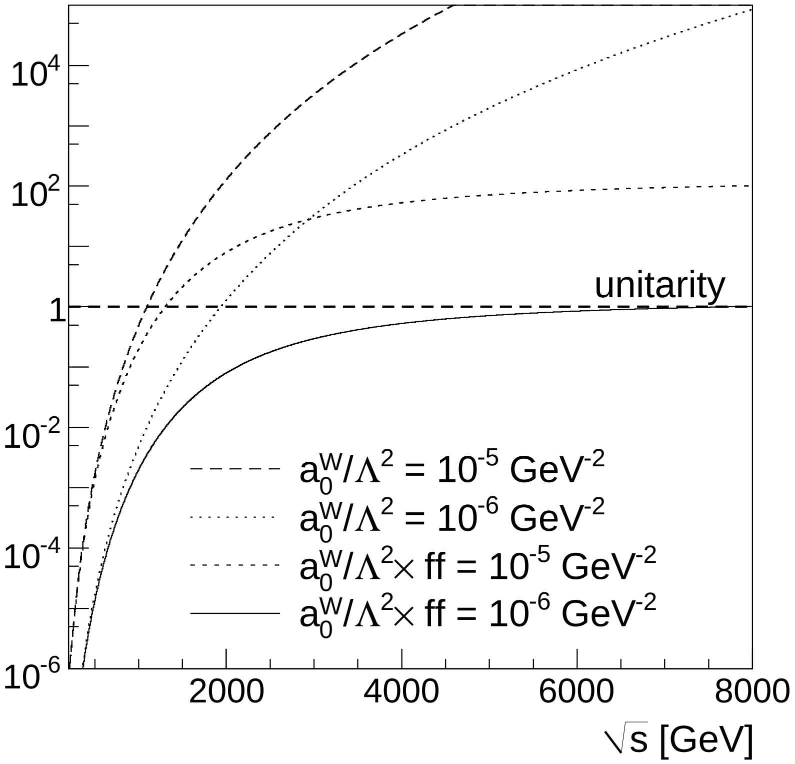
Quartic anomalous gauge couplings: form factors

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

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

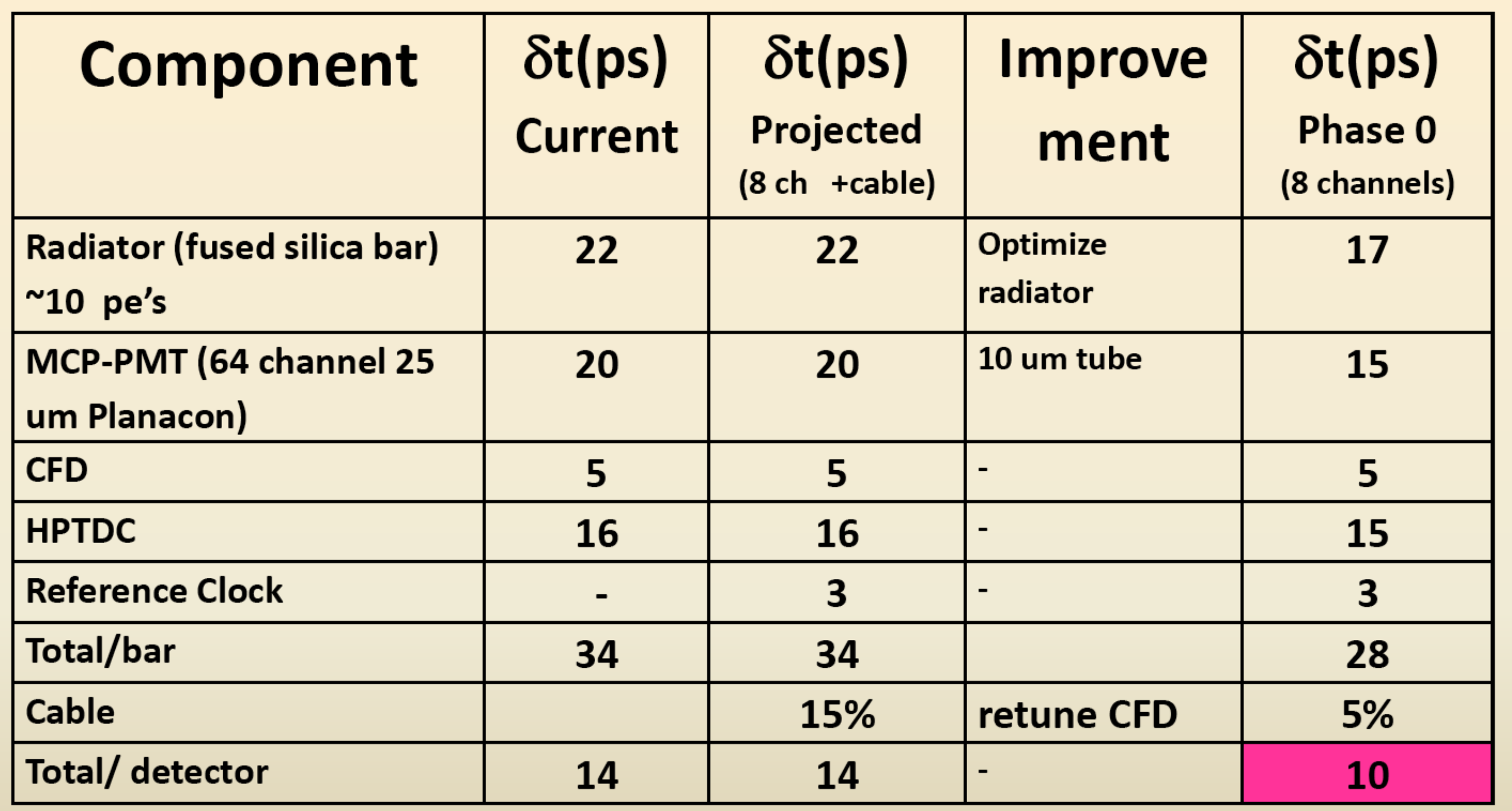
  where $a = a_0/\Lambda^2$

- Introducing form factors to avoid quadratical divergences of scattering amplitudes due to anomalous couplings in conventional way: $a_0^W/\Lambda^2 \rightarrow \frac{a_0^W/\Lambda^2}{(1+W\gamma\gamma/\Lambda_{cutoff})^2}$ with $\Lambda_{cutoff} \sim 2$ TeV, scale of new physics
- For $a_0^W \sim 10^{-6}$ GeV^{-2}, no violation of unitarity



How to achieve 10-20 ps timing resolution?

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