Future diffractive measurements at the LHC

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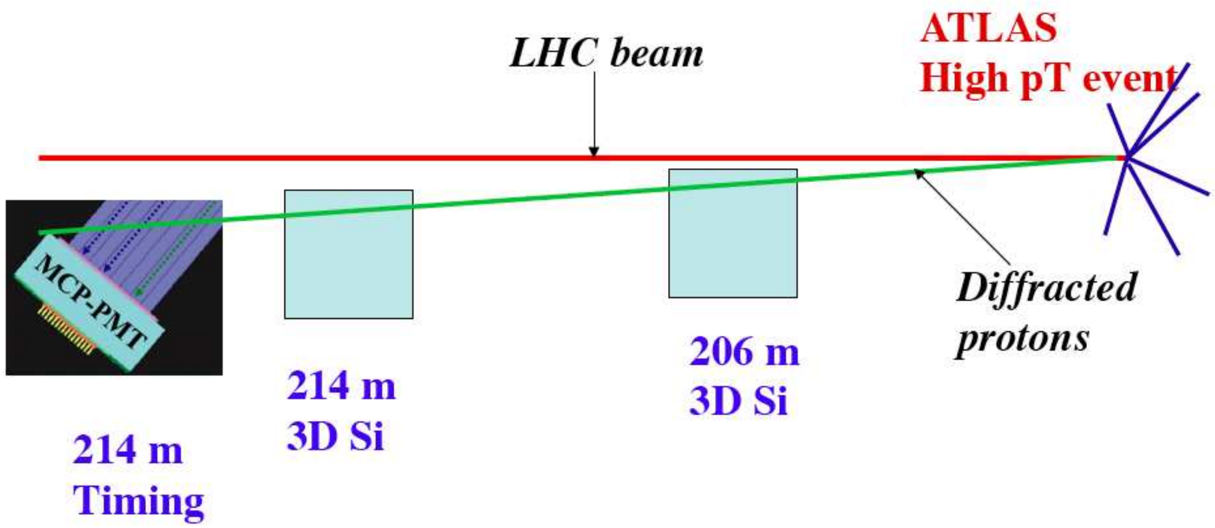
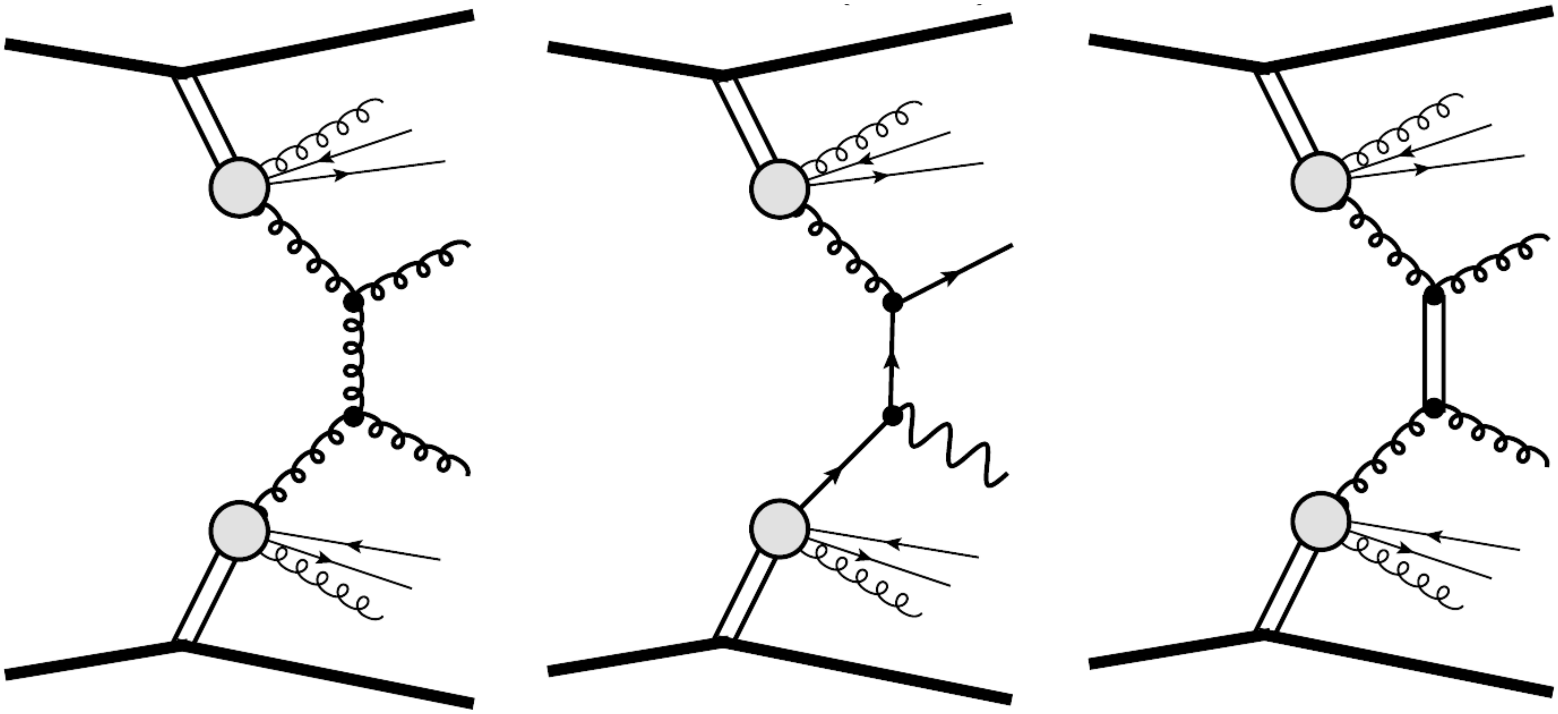
Contents:

- Pomeron structure: DPE dijets and γ+jet
- Soft colour interaction models
- BFKL tests: Jet gap jets
- Exclusive jets and Higgs
- Anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$



Inclusive diffraction at the LHC

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

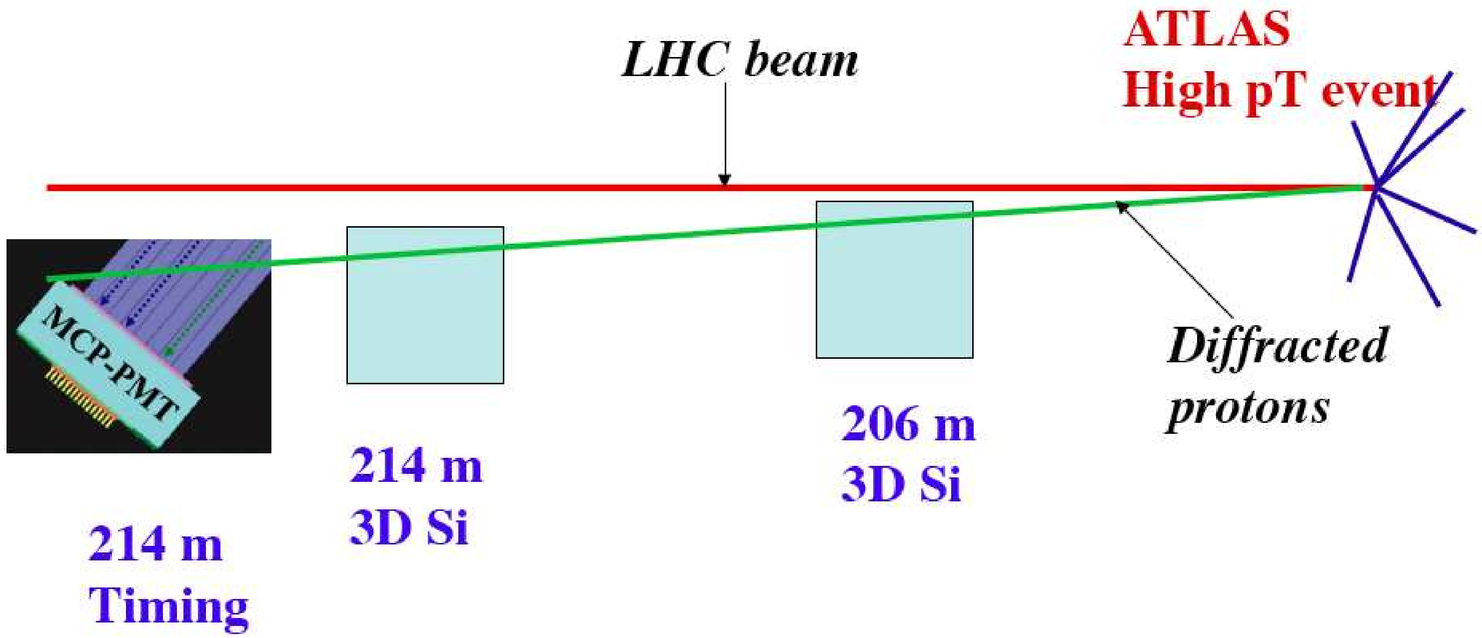


Forward Physics Monte Carlo (FPMC)

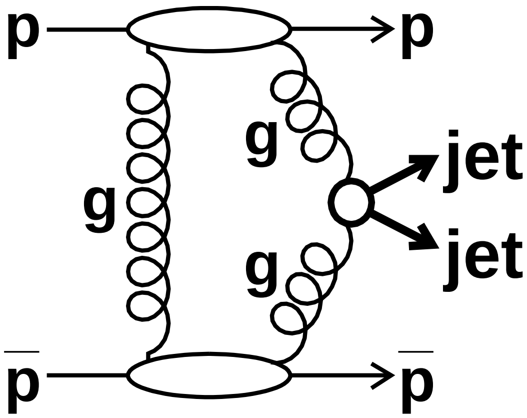
- FPMC (Forward Physics Monte Carlo): implementation of all diffractive/photon induced processes
- List of processes
  - two-photon exchange
  - single diffraction
  - double pomeron exchange
  - central exclusive production
- Inclusive diffraction: Use of diffractive PDFs measured at HERA, with a survival probability of 0.03 applied for LHC
- Central exclusive production: Higgs, jets...
- FPMC manual (see M. Boonekamp, A. Dechambre, O. Kepka, V. Juranek, C. Royon, R. Staszewski, M. Rangel, ArXiv:1102.2531)
- Survival probability: 0.1 for Tevatron (jet production), 0.03 for LHC, 0.9 for γ-induced processes
- Output of FPMC generator interfaced with the fast simulation of the ATLAS detector in the standalone ATLFast++ package

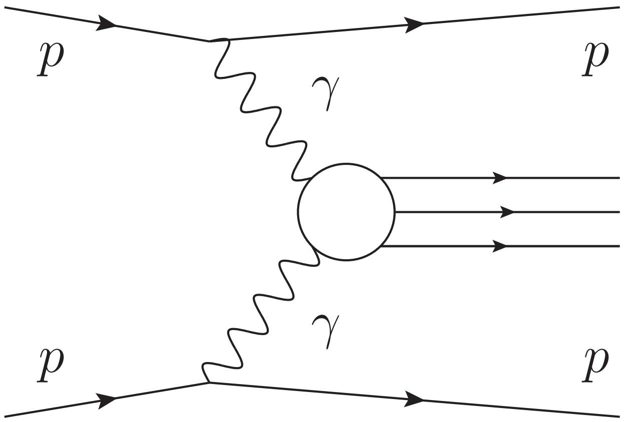
Forward proton detectors

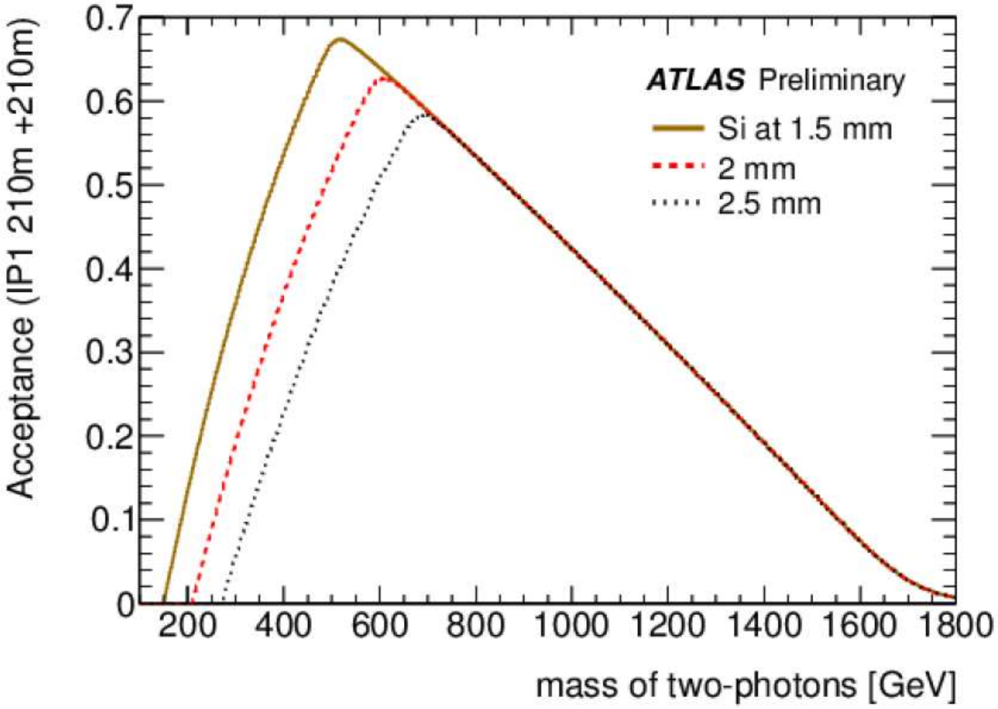
- In the following, we assume protons to be tagged in CMS/Totem or ATLAS, for AFP:
  - 210 m detectors: $0.015 < \xi < 0.15$
  - 210 and 420 m detectors: $0.0015 < \xi < 0.15$
- Measurement assumed to be performed at low luminosity, no pile up was introduced: possibility of using low pile up runs (3-5)



AFP acceptance in total mass



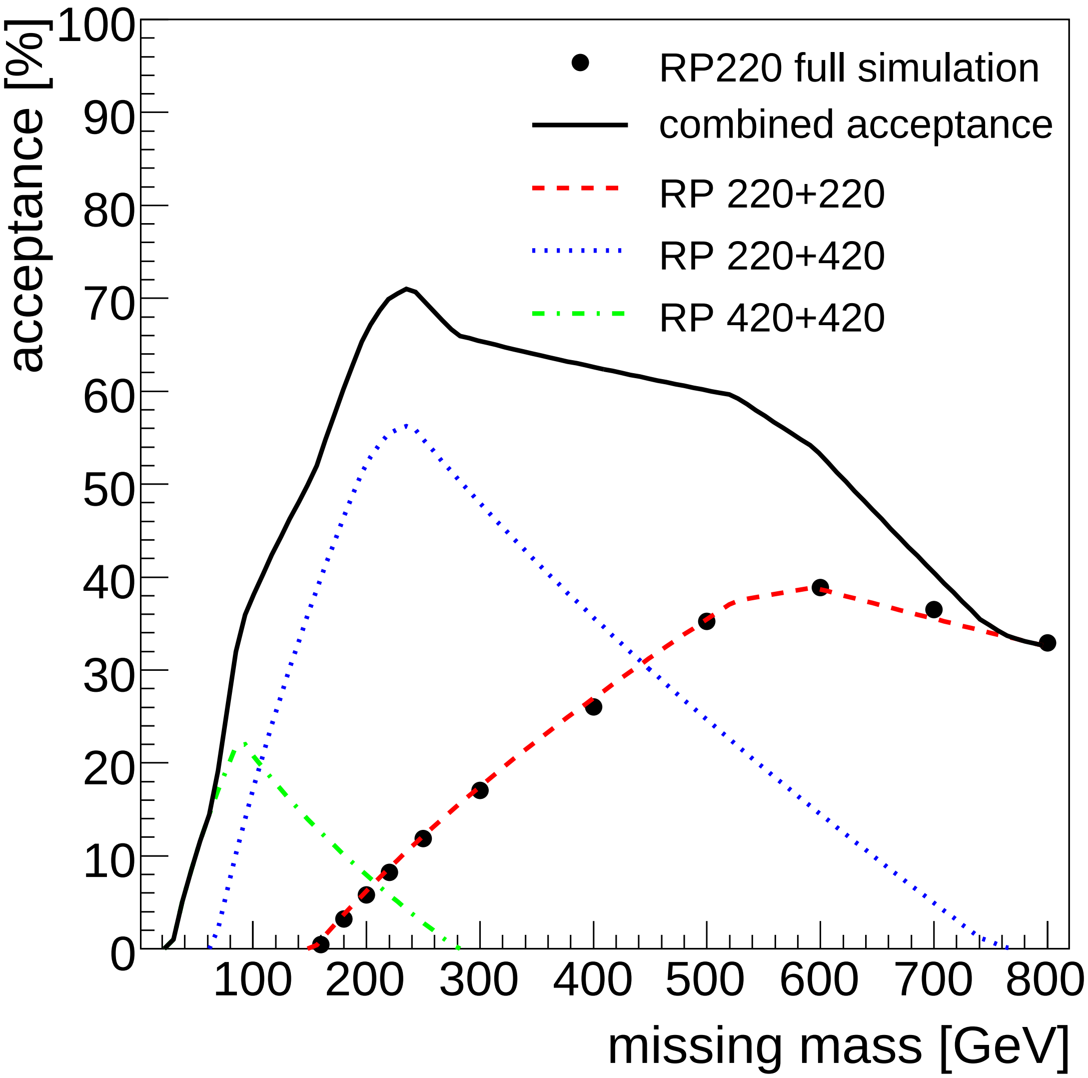




- Assume protons to be tagged at 210 m and/or 420 m
- Sensitivity to high mass central system, X, as determined using AFP
- Very powerful for exclusive states: kinematical constraints coming from AFP proton measurements

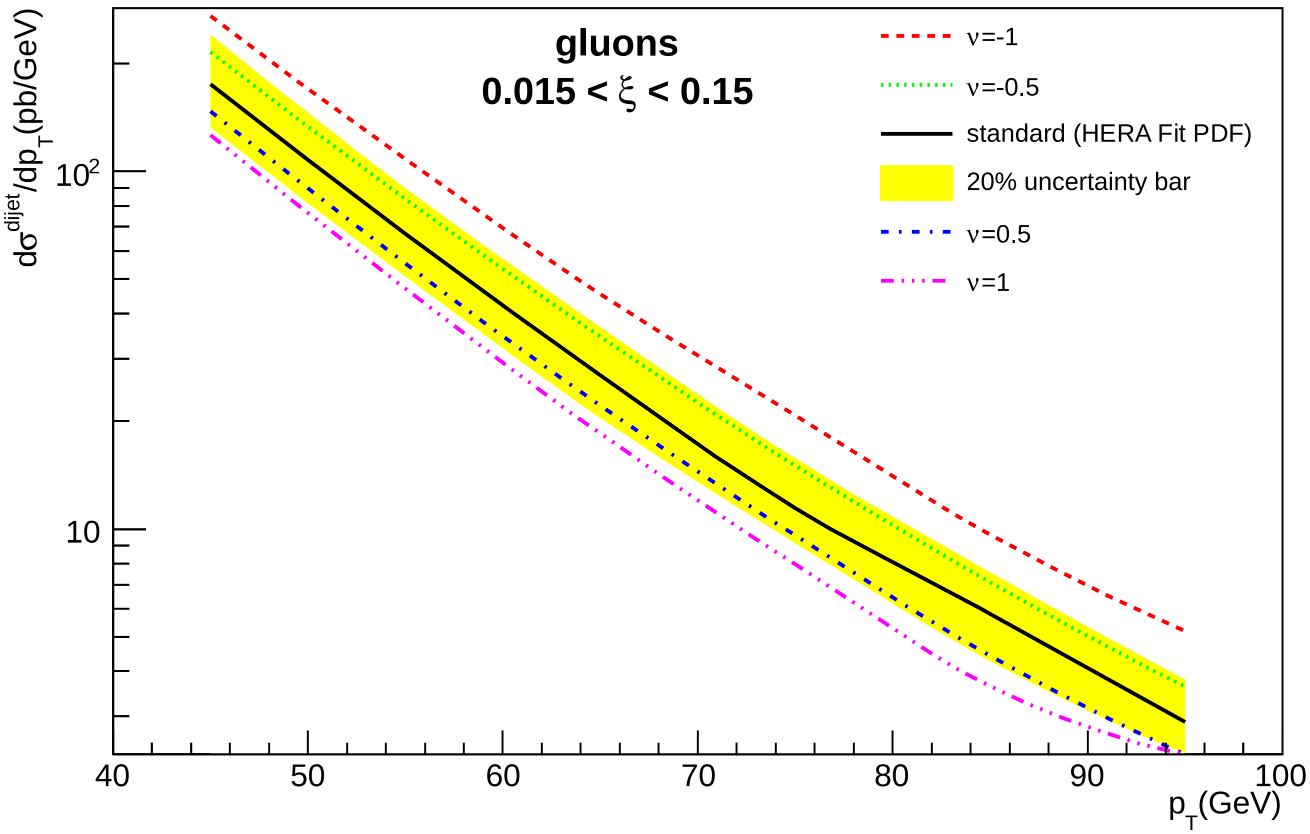
Possible upgrades of forward proton detectors

- 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



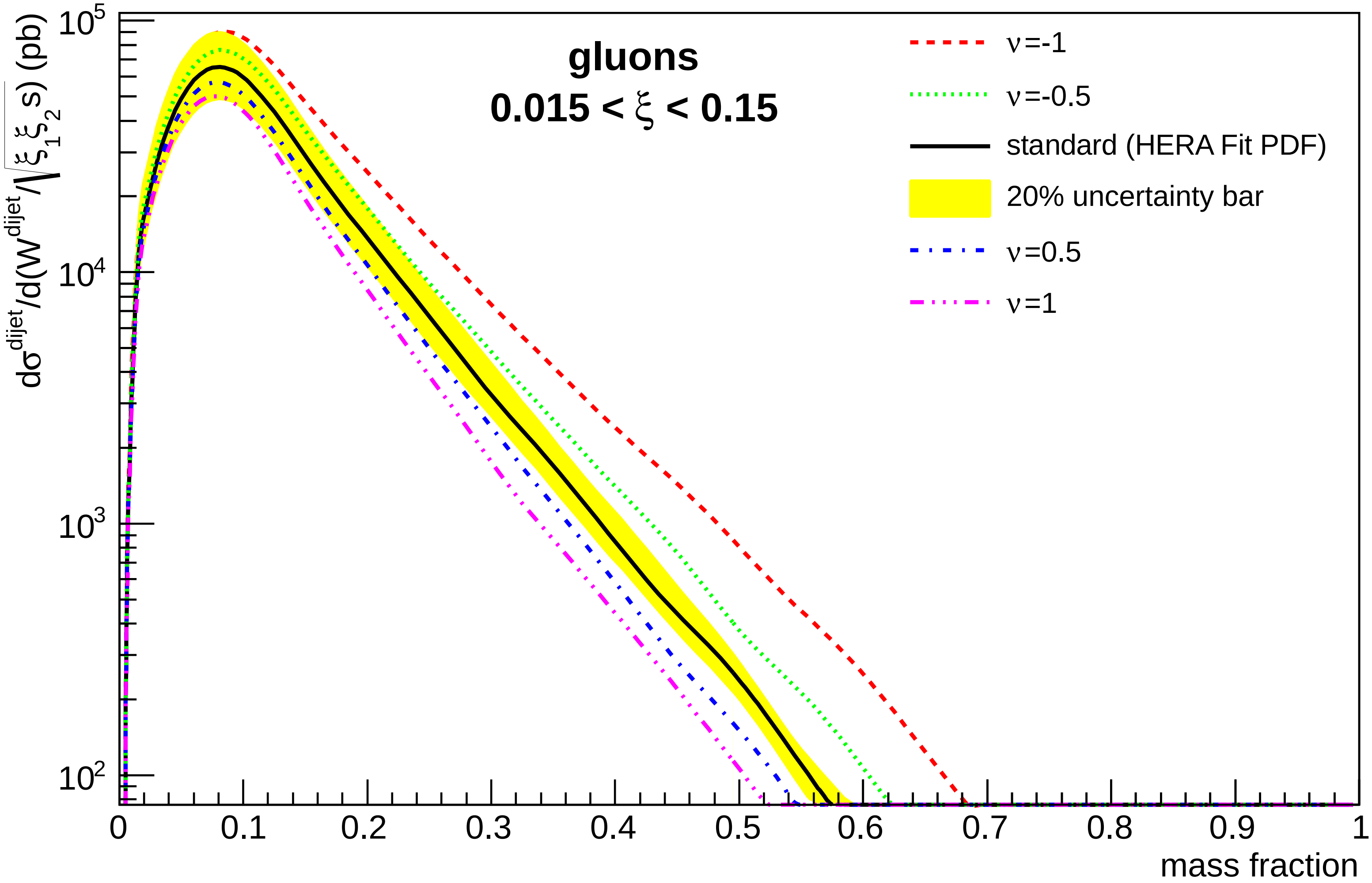
Inclusive diffraction at the LHC: sensitivity to gluon density

- 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



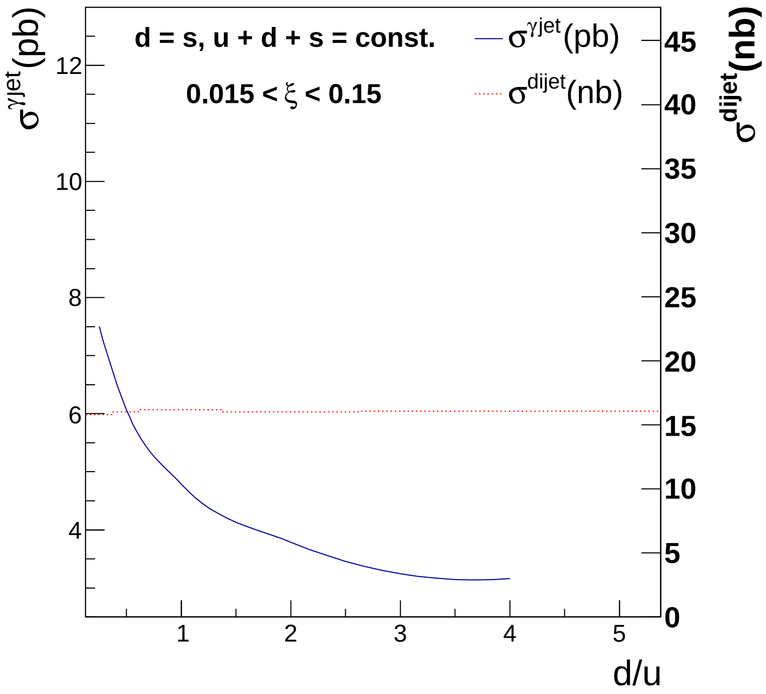
Dijet mass fraction: sensitivity to gluon density

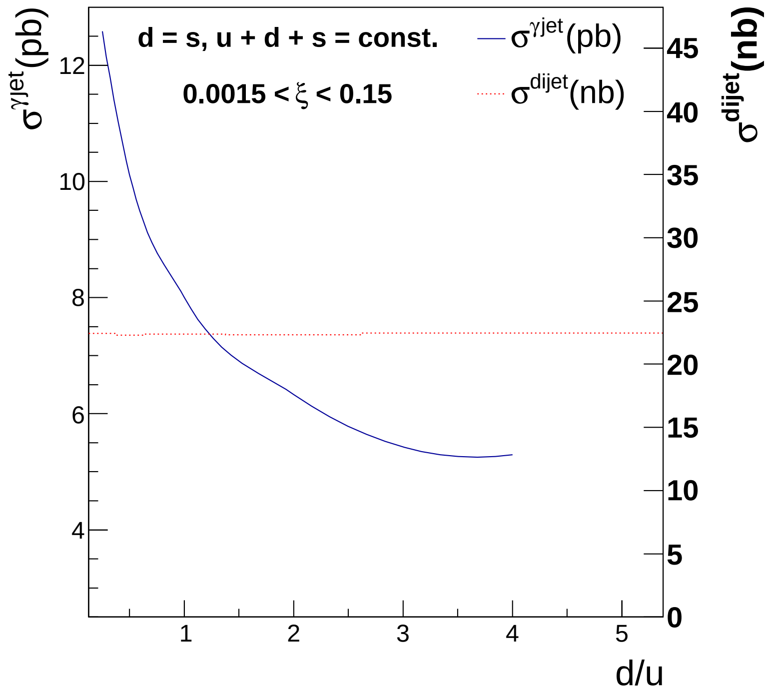
- Dijet mass fraction: dijet mass divided by total diffractive mass ($\sqrt{\xi_1 \xi_2 S}$)
- Sensitivity to gluon density in Pomeron especially the gluon density on Pomeron at high β
- Exclusive jet contribution will appear at high dijet mass fraction



Inclusive diffraction at the LHC: sensitivity to quark densities

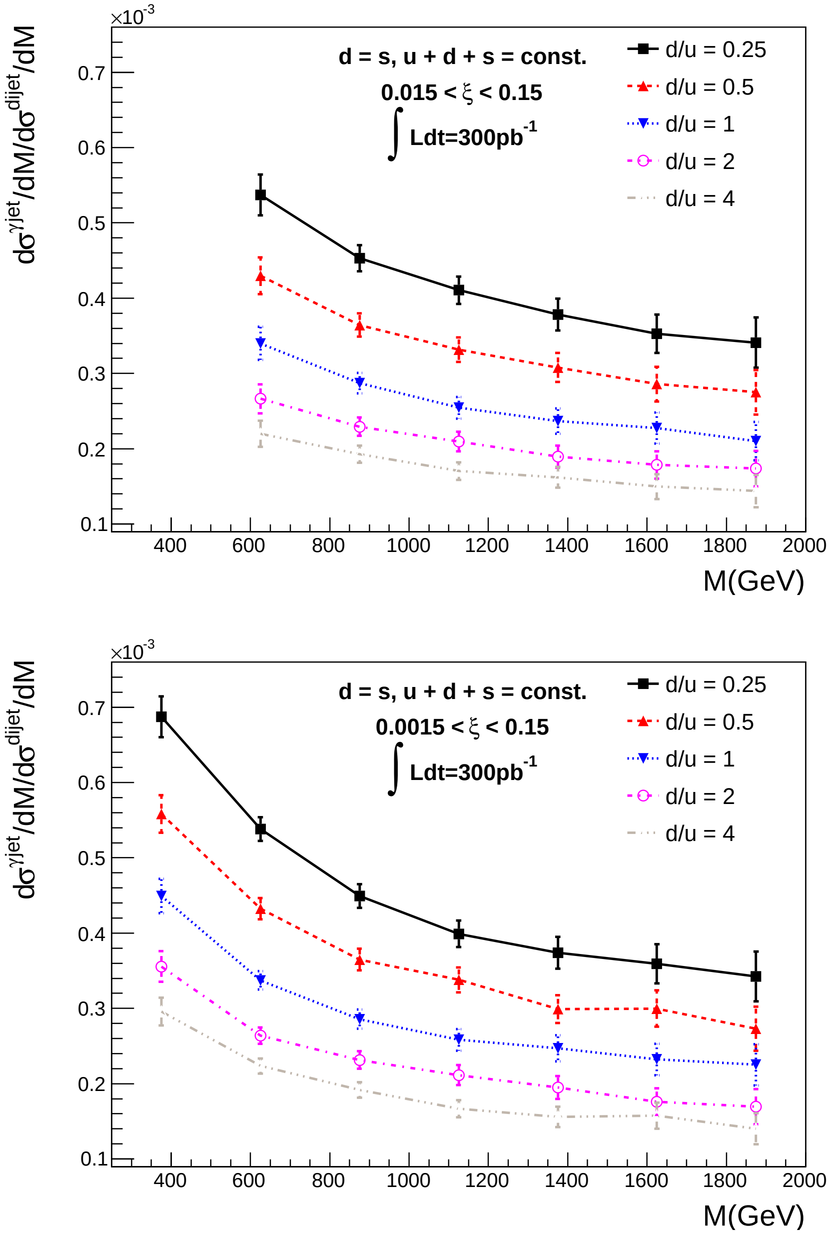
- γ+jet and dijet cross sections as a function of d/u in the acceptance of AFP (210 and 210+420 m detectors)
- As expected, the dijet cross section remains constant, whereas the $\gamma+$ jet cross section varies by a factor 2.5
- Jets and photon at particle level with p_T >20 GeV





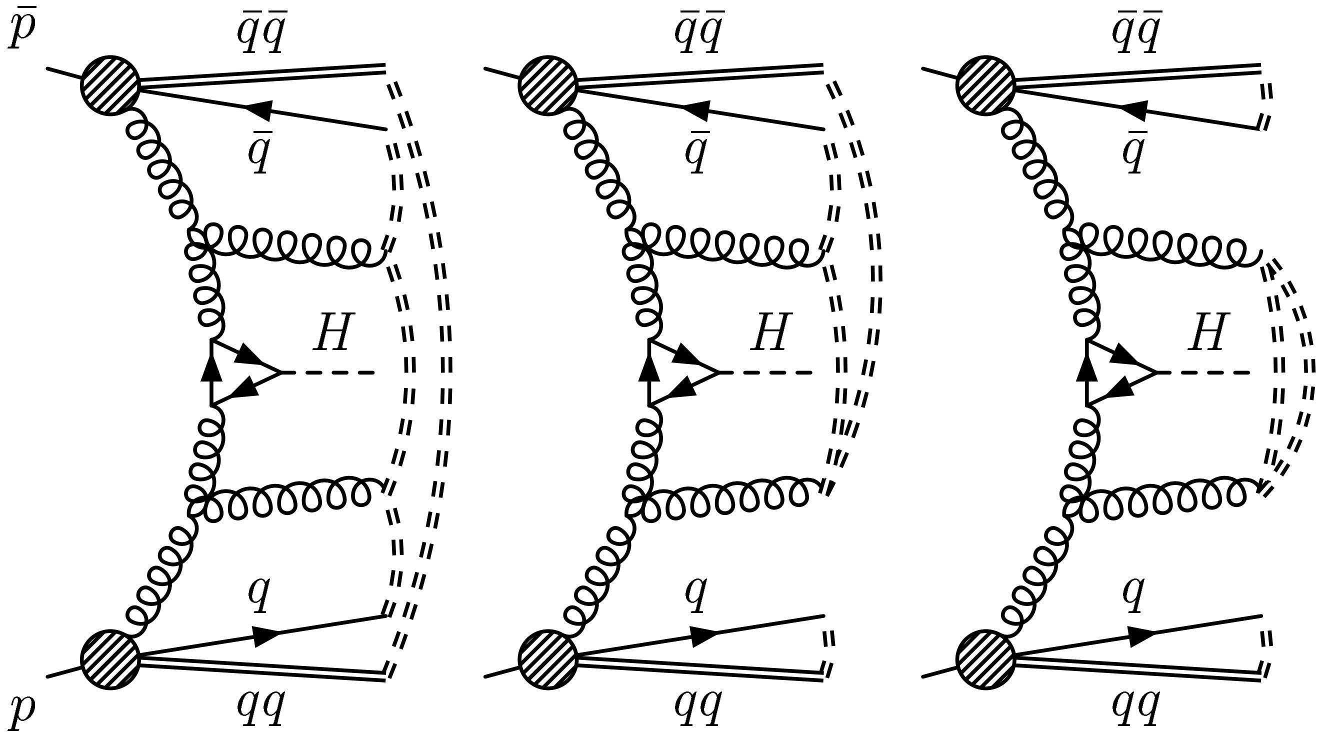
Inclusive diffraction at the LHC: sensitivity to quark densities

- 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



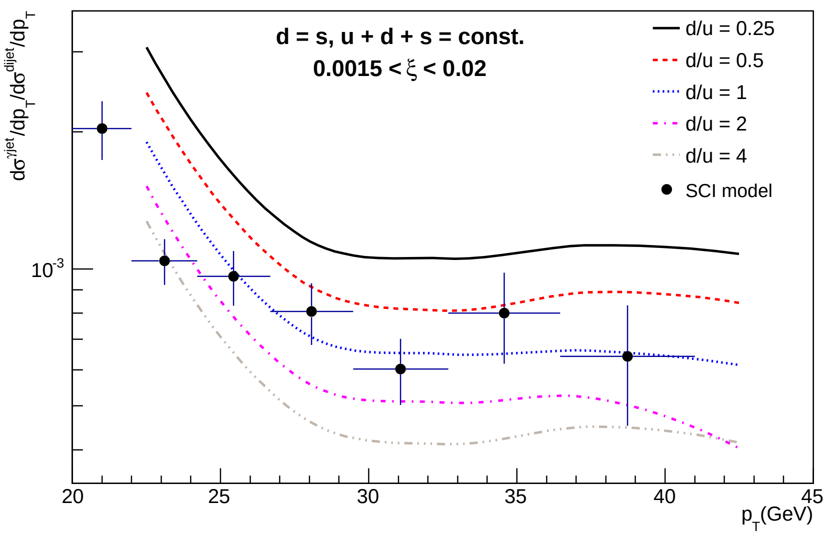
Soft Colour Interaction models

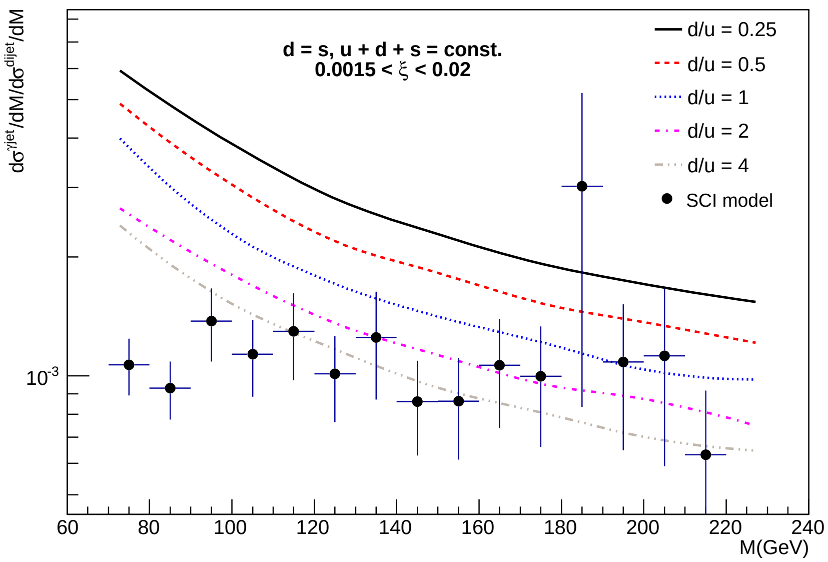
- A completely different model to explain diffractive events: Soft Colour Interaction (R.Enberg, G.Ingelman, N.Timneanu, hep-ph/0106246)
- Principle: Variation of colour string topologies, giving a unified description of final states for diffractive and non-diffractive events
- No survival probability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



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

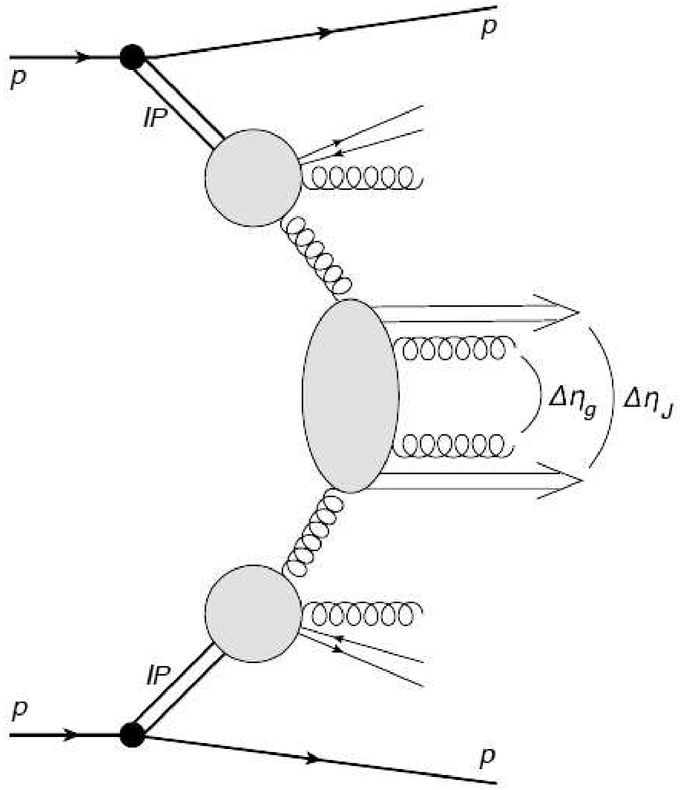
- Predict DPE γ+jet divided by dijet cross section at the LHC for pomeron like and SCI models
- In particular, the diffractive mass distribution (the measurement with lowest systematics) allows to distinguish between the two sets of models: flat distribution for SCI

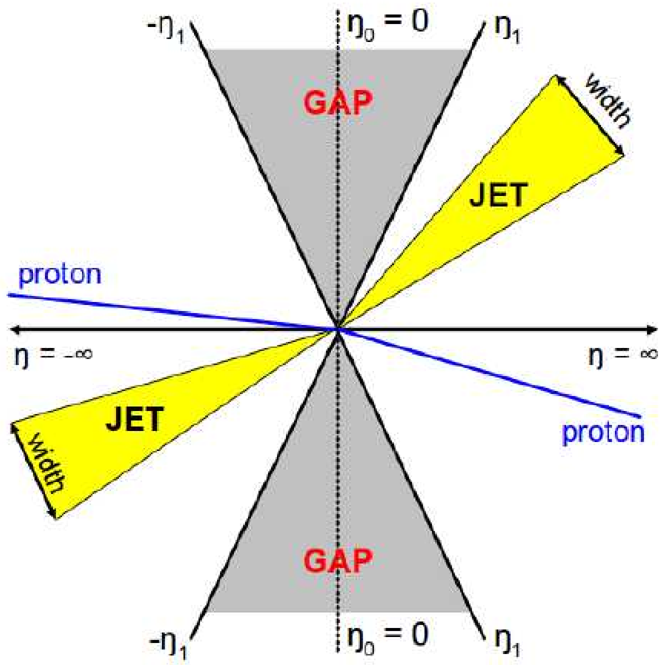




Jet gap jet events in diffraction

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

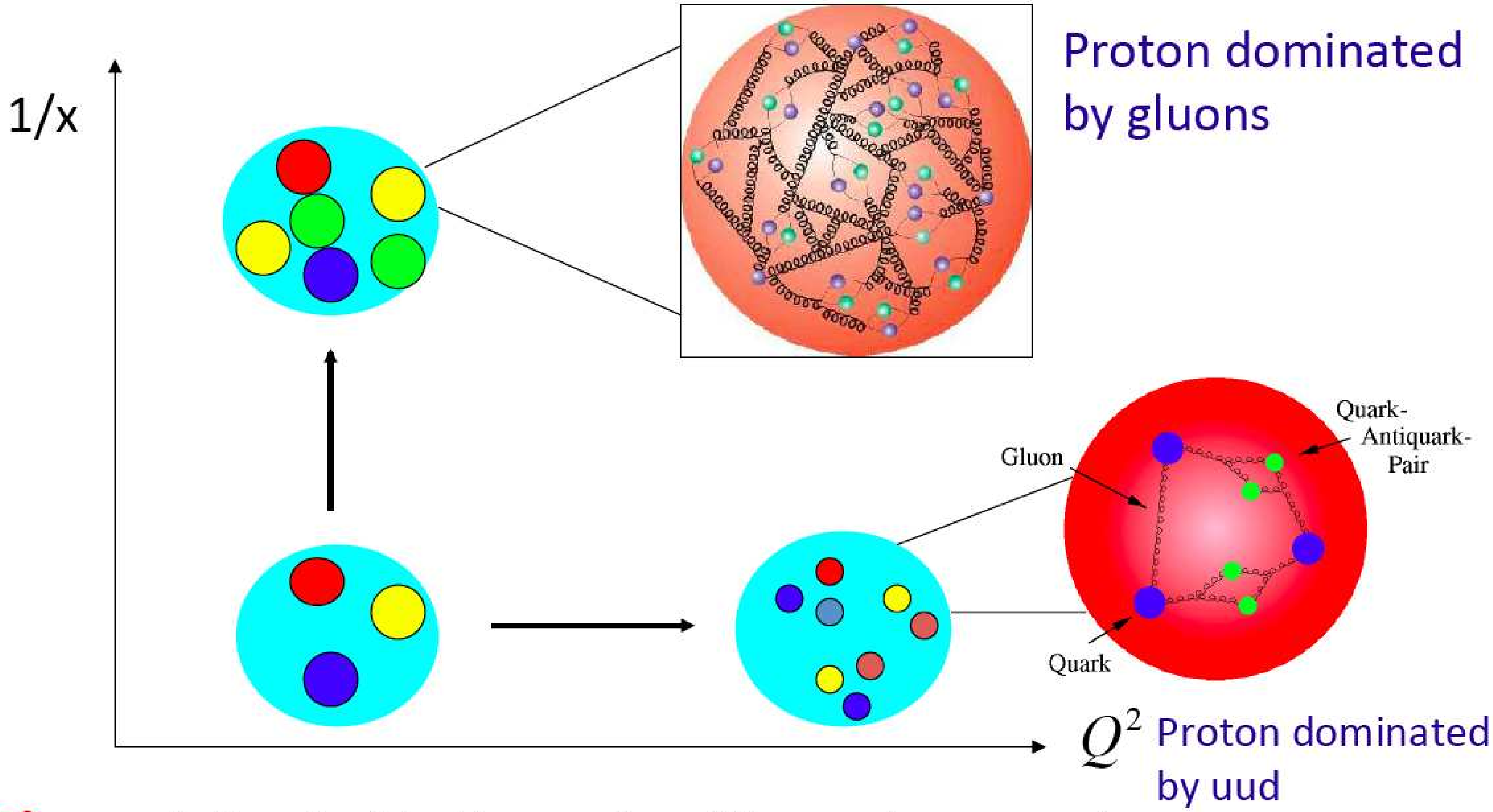




Looking for BFKL effects

- Dokshitzer Gribov Lipatov Altarelli Parisi (DGLAP): Evolution in Q^2
- Balitski Fadin Kuraev Lipatov (BFKL): Evolution in x

Aim: Understanding the proton structure (quarks, gluons)

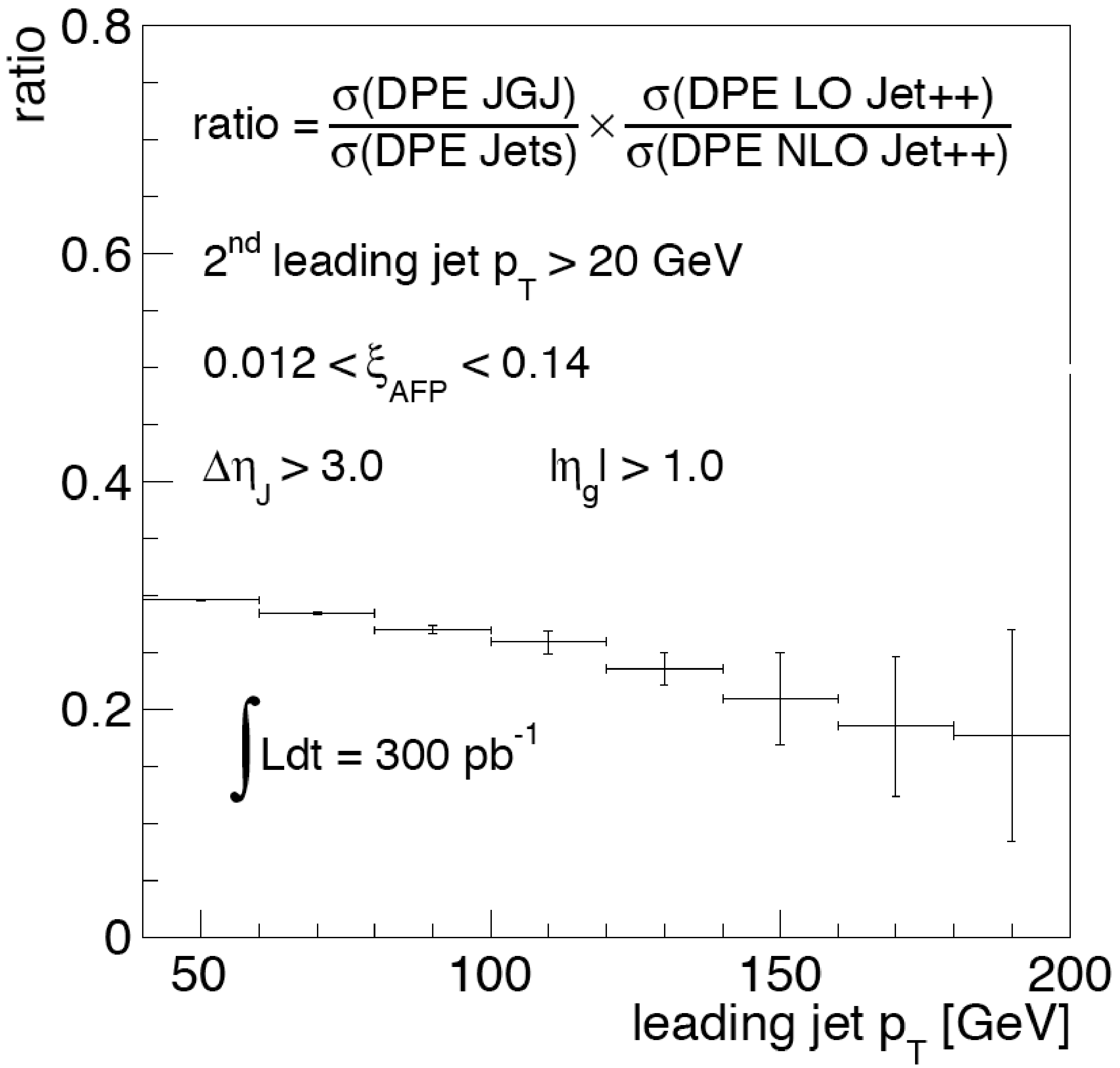


Q^2 : resolution inside the proton (like a microscope)

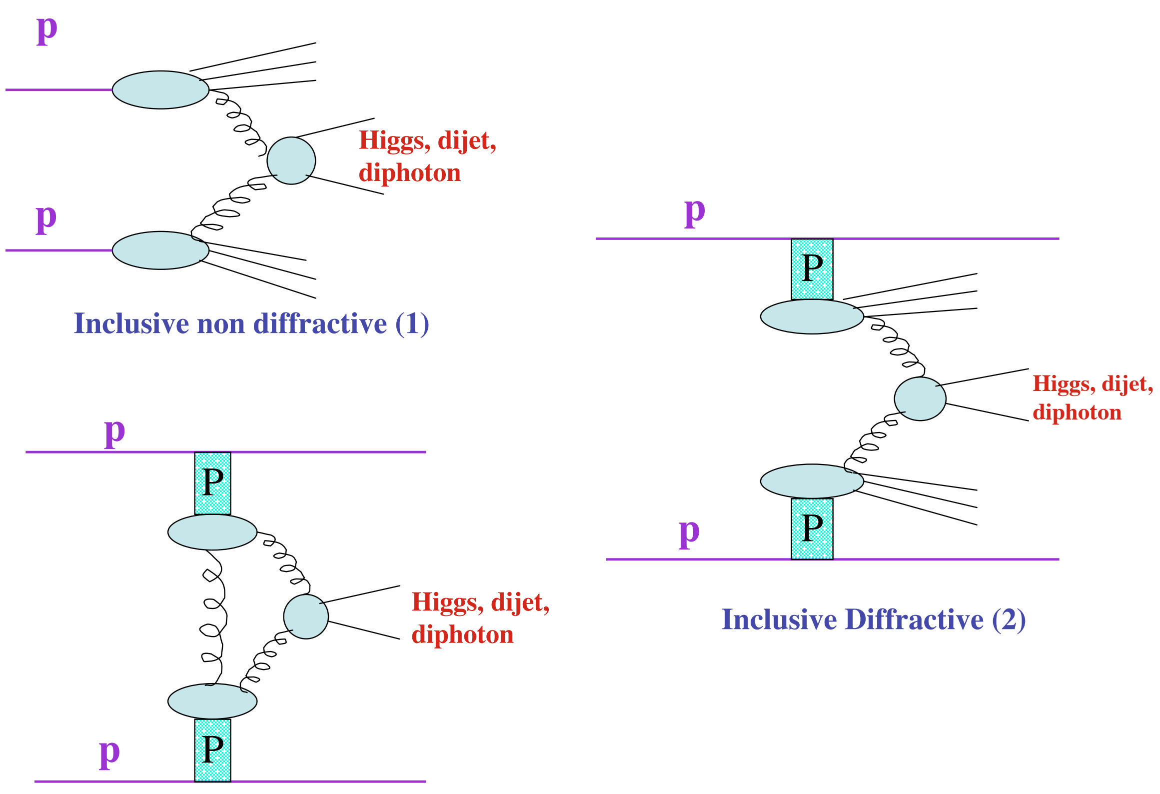
X :Proton momentum fraction carried away by the interacting quark

Jet gap jet events in diffraction

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



“Exclusive models” in diffraction



Inclusive non diffractive (1)

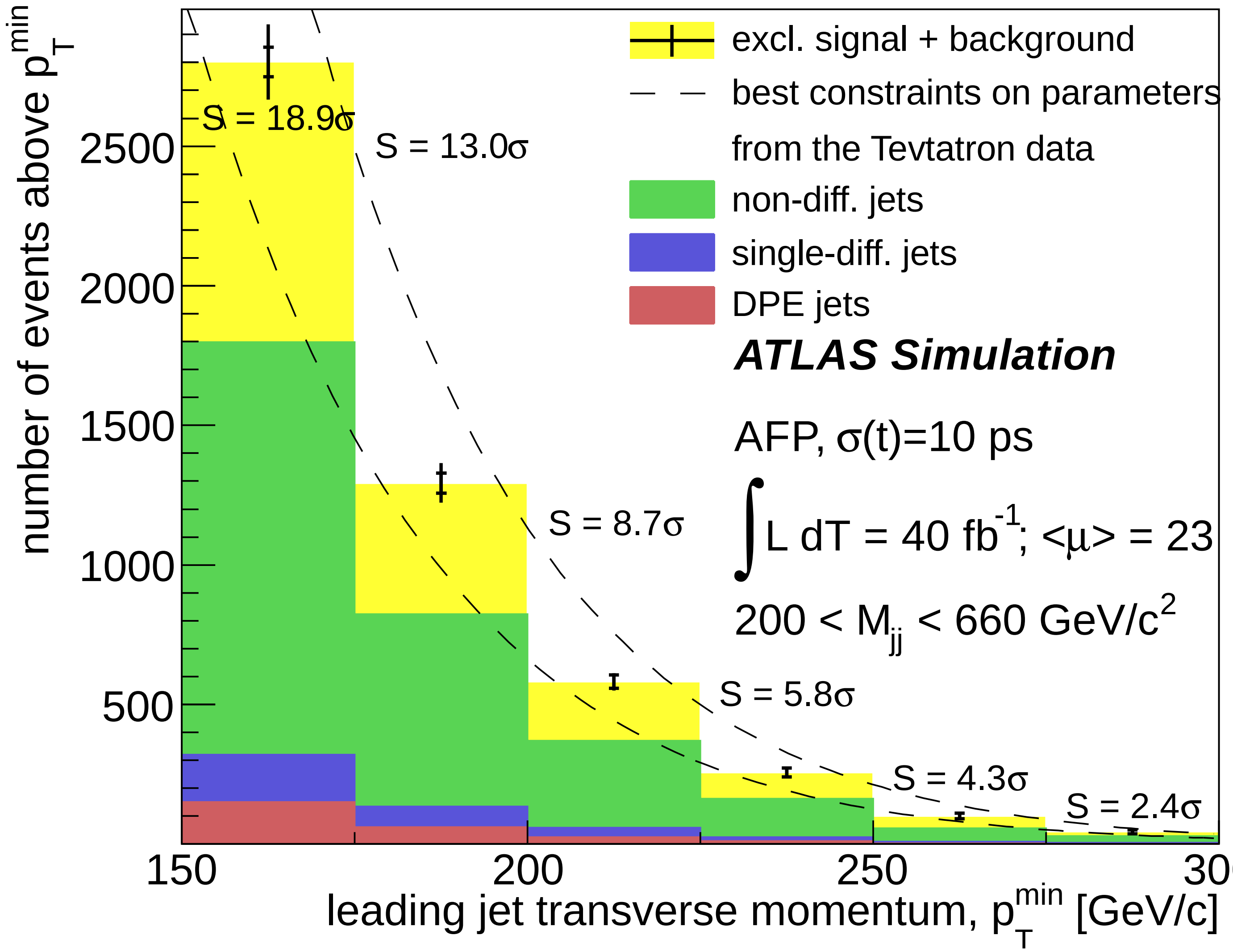
Inclusive Diffractive (2)

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
- See papers by Khoze, Martin, Ryskin, Szczurek, Peschanski, Royon...

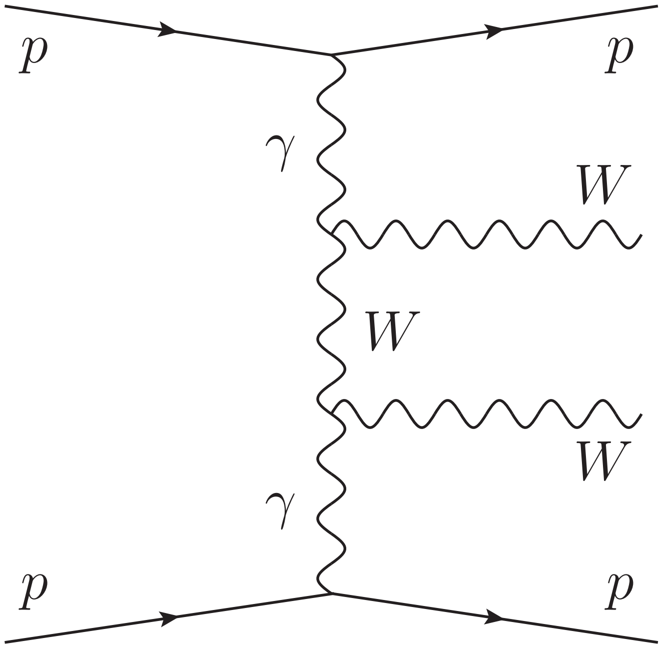
Exclusive jet production at the LHC

- 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

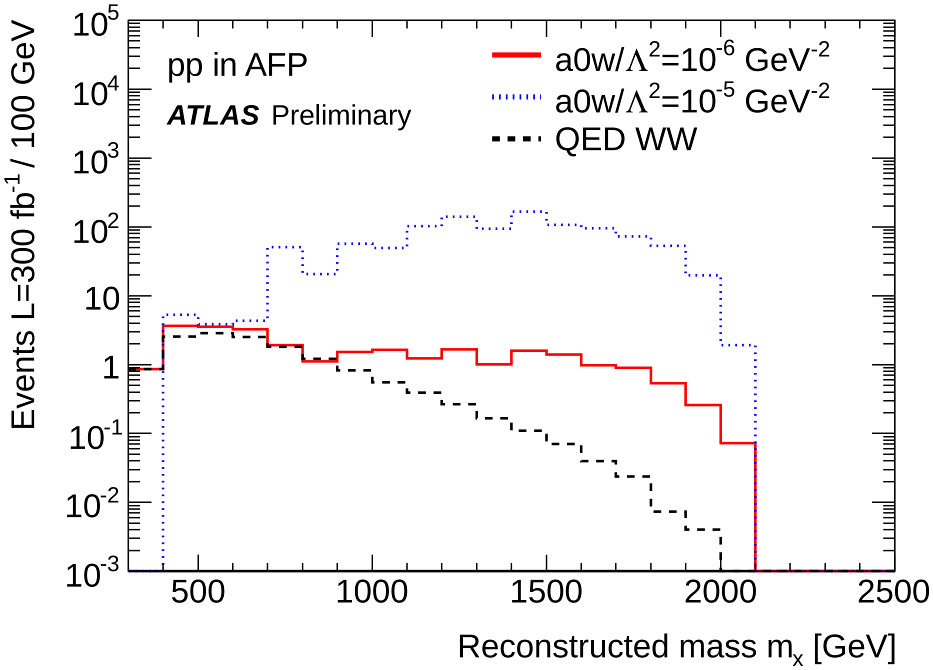
Search for $\gamma\gamma WW$ quartic anomalous coupling

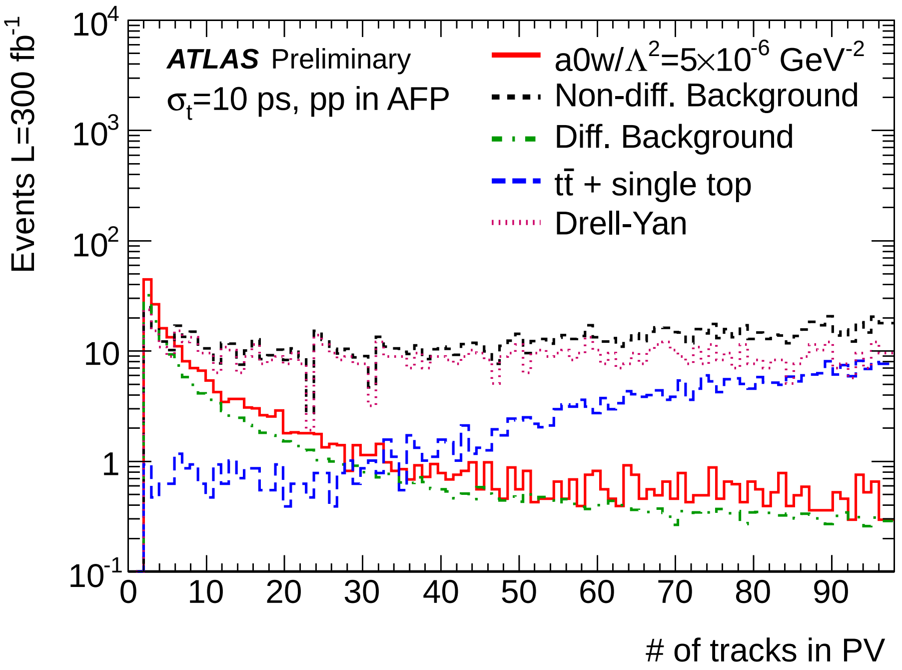


- Study of the process: $pp \rightarrow ppWW$
- Standard Model: $\sigma_{WW} = 95.6$ fb, $\sigma_{WW}(W = M_X > 1TeV) = 5.9$ fb
- Process sensitive to anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$; motivated by studying in detail the mechanism of electroweak symmetry breaking, predicted by extradim. models
- Many additional anomalous couplings to be studied involving Higgs bosons (dimension 8 operators); $\gamma\gamma$ specially interesting (C. Grojean, S. Fichet, G. von Gersdorff)
- Rich $\gamma\gamma$ physics at LHC: see E. Chapon, O. Kepka, C. Royon, Phys. Rev. D78 (2008) 073005; Phys. Rev. D81 (2010) 074003; S.Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert, ArXiv 1312.5153

Anomalous couplings studies in WW events

- Reach on anomalous couplings studied using a full simulation of the ATLAS detector, including all pile up effects; only leptonic decays of Ws are considered
- Signal appears at high lepton p_T and dilepton mass (central ATLAS) and high diffractive mass (reconstructed using forward detectors)
- Cut on the number of tracks fitted to the primary vertex: very efficient to remove remaining pile up after requesting a high mass object to be produced (for signal, we have two leptons coming from the W decays and nothing else)





Results from full simulation

- 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
$\mathcal{L} = 40\ fb^{-1}, \mu = 23$ $\mathcal{L} = 300\ fb^{-1}, \mu = 46$	5.5 10^{-6} 3.2 10^{-6}	2.4 10^{-6} 1.3 10^{-6}	0.02

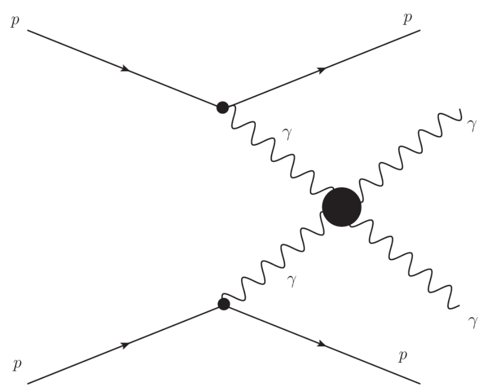
Reach at LHC

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

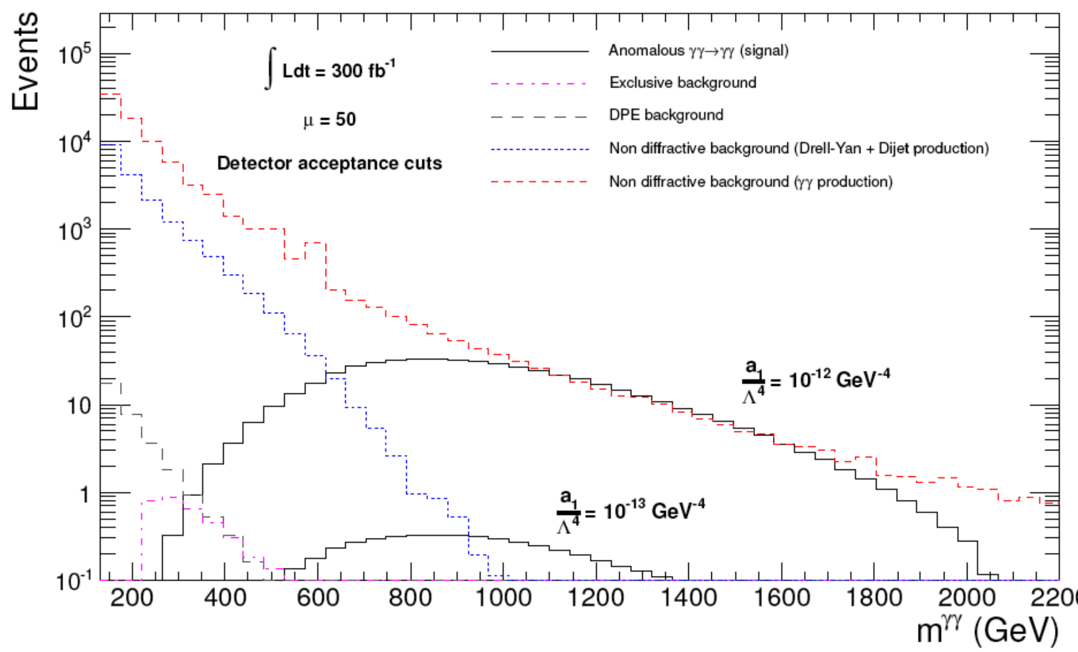
Couplings	OPAL limits [GeV^{-2}]	Sensitivity @ $\mathcal{L} = 30$ (200) fb^{-1} 5σ	95% CL
a_0^W/Λ^2	[-0.020, 0.020]	5.4 10^{-6} (2.7 10^{-6})	2.6 10^{-6} (1.4 10^{-6})
a_C^W/Λ^2	[-0.052, 0.037]	2.0 10^{-5} (9.6 10^{-6})	9.4 10^{-6} (5.2 10^{-6})
a_0^Z/Λ^2	[-0.007, 0.023]	1.4 10^{-5} (5.5 10^{-6})	6.4 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, and of D0/CMS results by $\sim$two orders of magnitude
- 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

Search for quartic $\gamma\gamma$ anomalous couplings

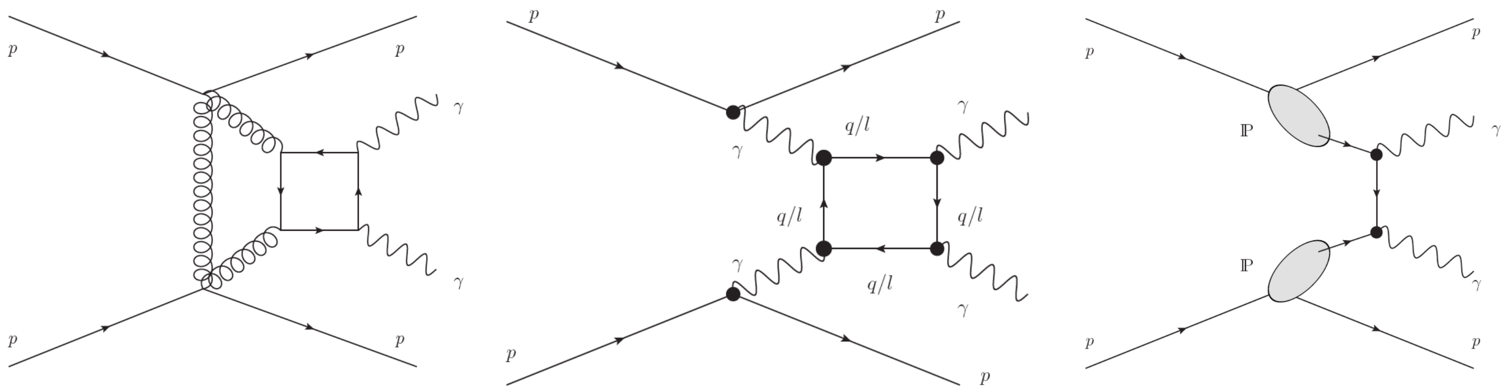


- Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- Diphoton events appear at high mass
- S.Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert, ArXiv 1312.5153

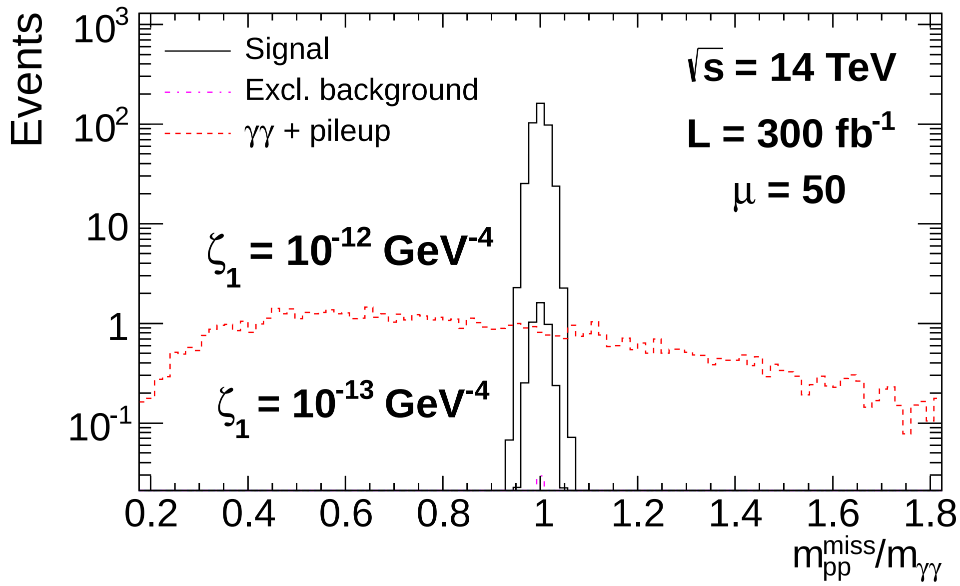


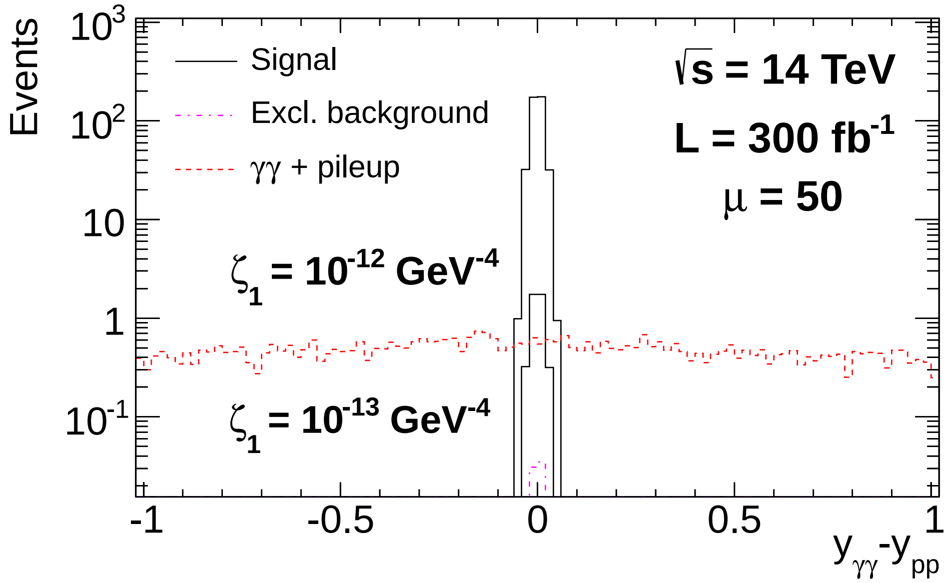
Considered background

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



Search for quartic $\gamma\gamma$ anomalous couplings





- Exclusivity cuts: diphoton mass compared from missing mass computed using protons, rapidity difference between diphoton and proton systems: suppresses all pile up background
- For 300 fb^{-1} and a pile up of 50: 0 background event for 15.1 (3.8) signal events for an anomalous coupling of 2 10^{-13} (10^{-13})

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

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

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

- No background after cuts for 300 fb^{-1}
- Sensitivities for anomalous quartic couplings
- all sensitivites for 300 fb^{-1}, pile up of 50, for > 1 converted or non converted γ, except for the last column: 6000 fb^{-1}, 200 pile up

Luminosity	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	6000 fb^{-1}
pile-up (μ)	50	50	50	200
coupling (GeV^{-4})	≥ 1 conv. γ 5 σ	≥ 1 conv. γ 95% CL	all γ 95% CL	all γ 95% CL
ζ_1 f.f.	$1 \cdot 10^{-13}$	$7 \cdot 10^{-14}$	$4 \cdot 10^{-14}$	$2 \cdot 10^{-14}$
ζ_1 no f.f.	$3 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$1 \cdot 10^{-14}$	$6 \cdot 10^{-15}$
ζ_2 f.f.	$3 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$8 \cdot 10^{-14}$	$4 \cdot 10^{-14}$
ζ_2 no f.f.	$7 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$1 \cdot 10^{-14}$

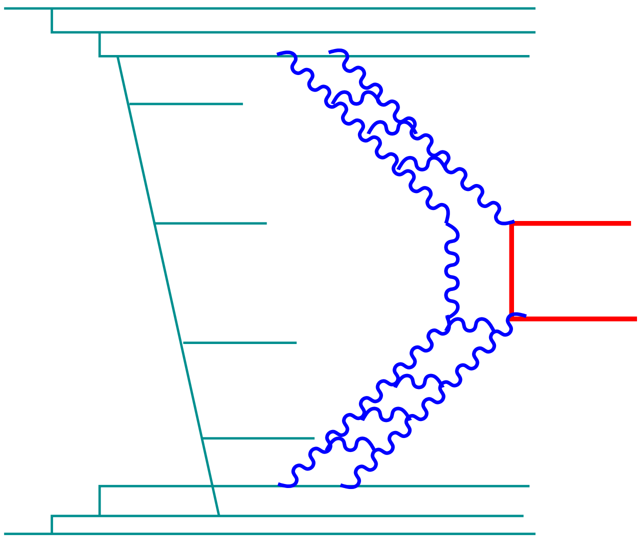
Conclusion

- Pomeron structure at hadronic colliders and compare with results obtained at HERA/Tevatron:
  - Hard diffractive events might be due to Pomeron and also to soft exchanges (combination of the two)
  - Dijet data and especially dijet mass fraction sensitive to the gluon density in Pomeron; Ratio γ+jet to dijet cross sections sensitive to quark structure in the Pomeron, especially as a function of diffractive mass computed using forward detectors (smallest systematics)
  - Possibility to distinguish between SCI and Pomeron like models
- Jet gap jet events in DPE exchanges: clean test of BFKL evolution
- Clean test of electroweak symmetry breaking mechanism and search for extra dimensions: search for anamalous $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$ couplings; unprecedented precision at colliders, reaching the values predicted by extradim models
- Bibliography

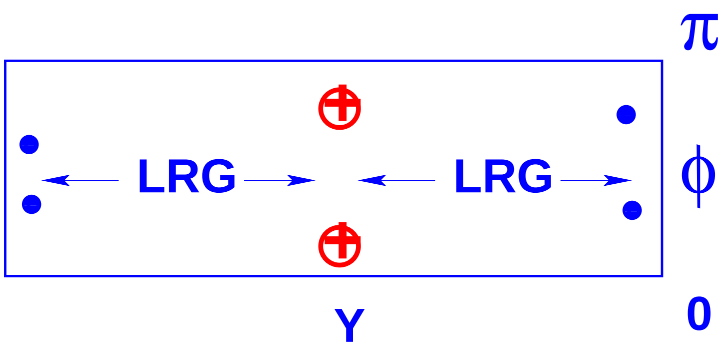
  - C. Marquet, C. Royon, M. Saimpert, D. Werder, Phys. Rev D 88 (2013) 074029
  - C. Marquet, C. Royon, M. Trzebinski, R. Zlebcik, Phys. Rev. D 87 (2013) 034010; O. Kepka, C. Marquet, C. Royon, Phys. Rev D 83 (2011) 034036
  - E. Chapon, C. Royon, O. Kepka, Phys. Rev. D 81 (2010) 074003; O. Kepka, C. Royon, Phys. Rev. D 78 (2008) 073005; S. Fichet, G. von Gersdorff, O. Kepka, C. Royon, M. Saimpert, ArXiv 1312.5153

Factorisation at Tevatron/LHC?

- Is factorisation valid at Tevatron/LHC? Can we use the parton densities measured at HERA to use them at the Tevatron/LHC?
- Factorisation is not expected to hold: soft gluon exchanges in initial/final states
- Survival probability: Probability that there is no soft additional interaction, that the diffractive event is kept
- Value of survival probability assumed in these studies: 0.1 at Tevatron (measured), 0.03 at LHC (extrapolated)



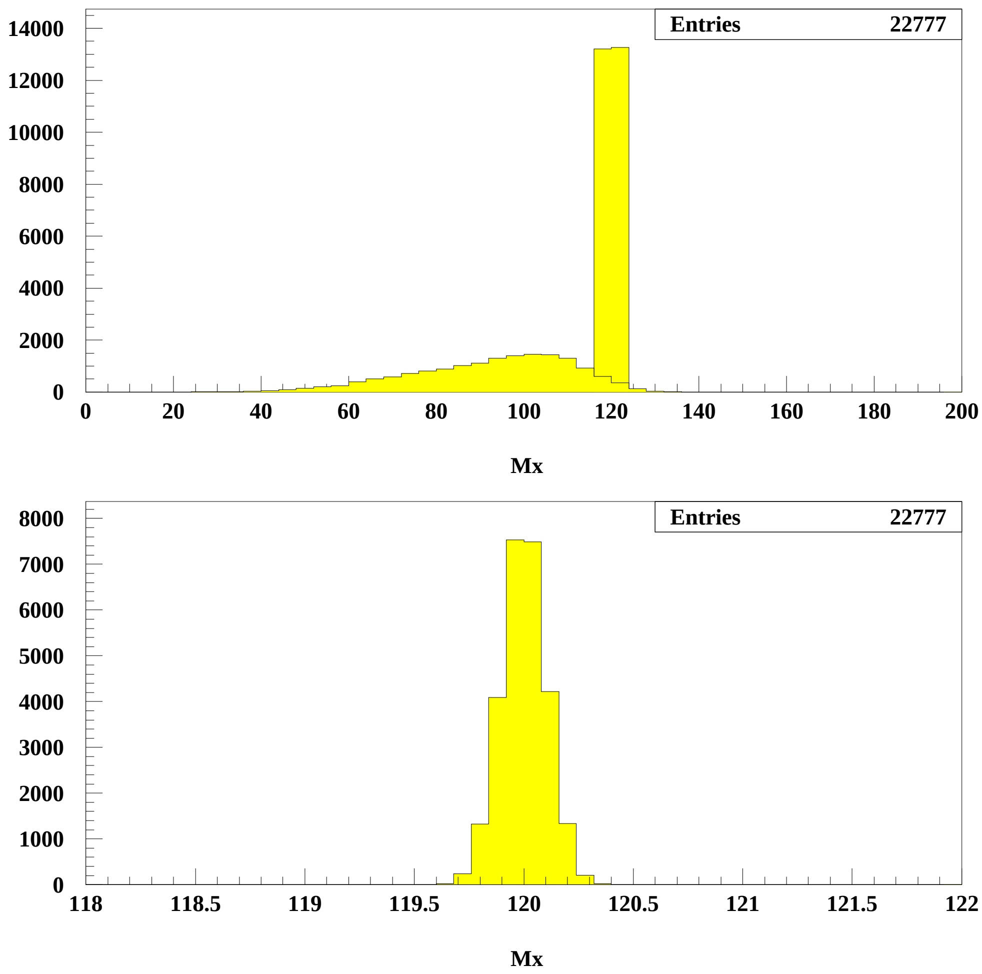
a)



b)

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



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