

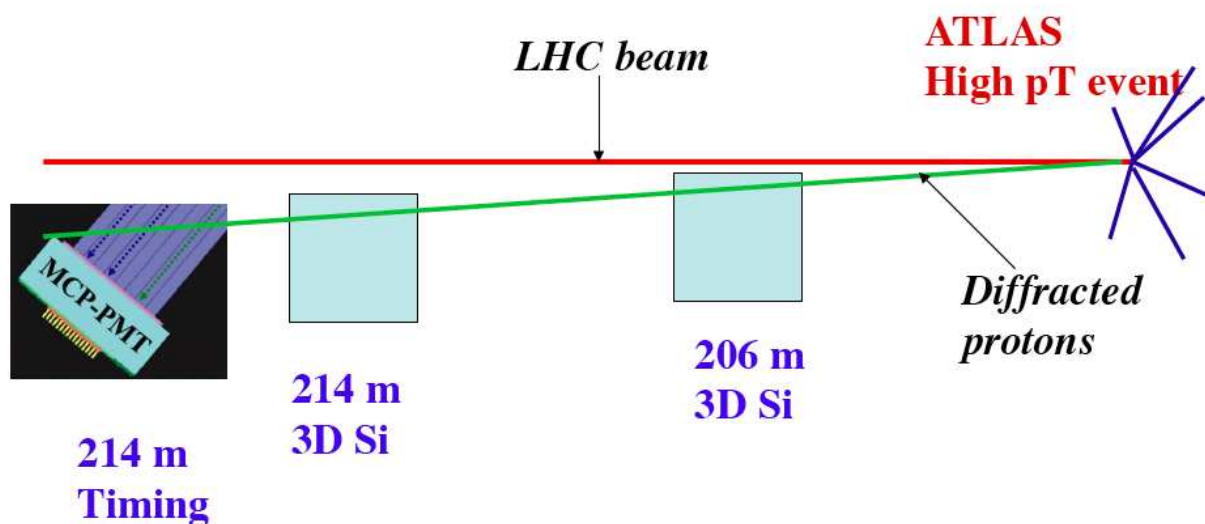
Forward Physics using proton tagging at the LHC

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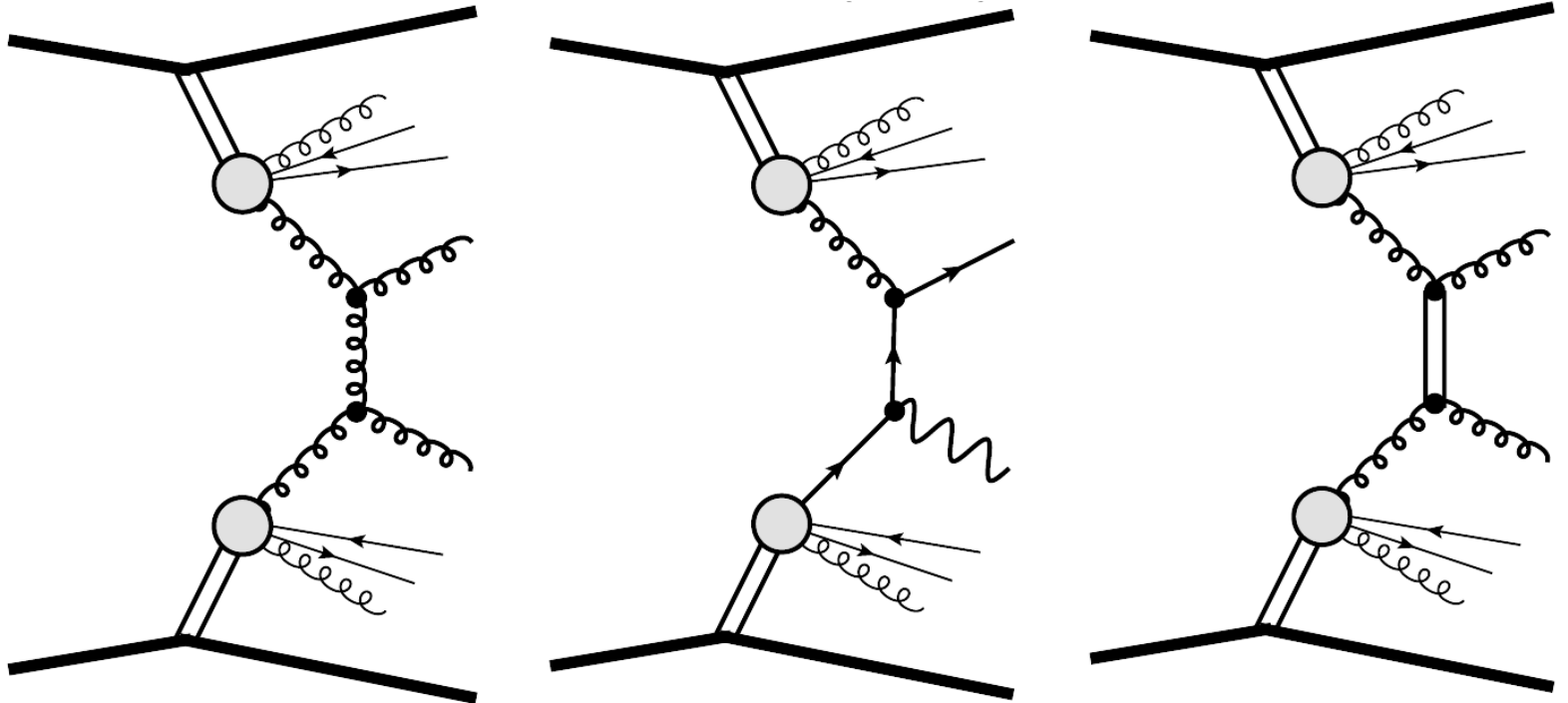
Contents:

- Pomeron structure: DPE dijets and γ +jet
- Soft colour interaction models
- BFKL tests: Jet gap jets
- 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

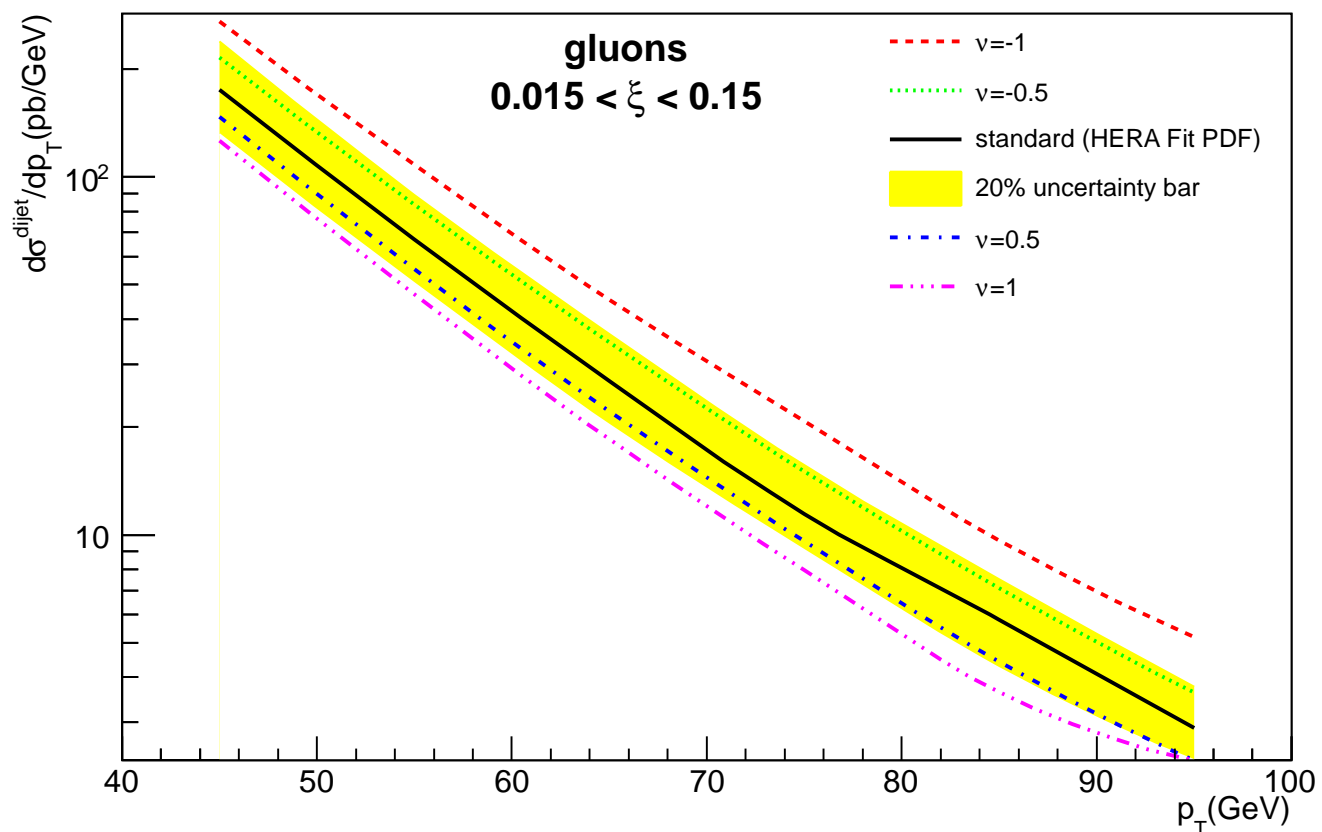


Forward Physics Monte Carlo (FPMC)

- 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 and also to the full simulation including pile up

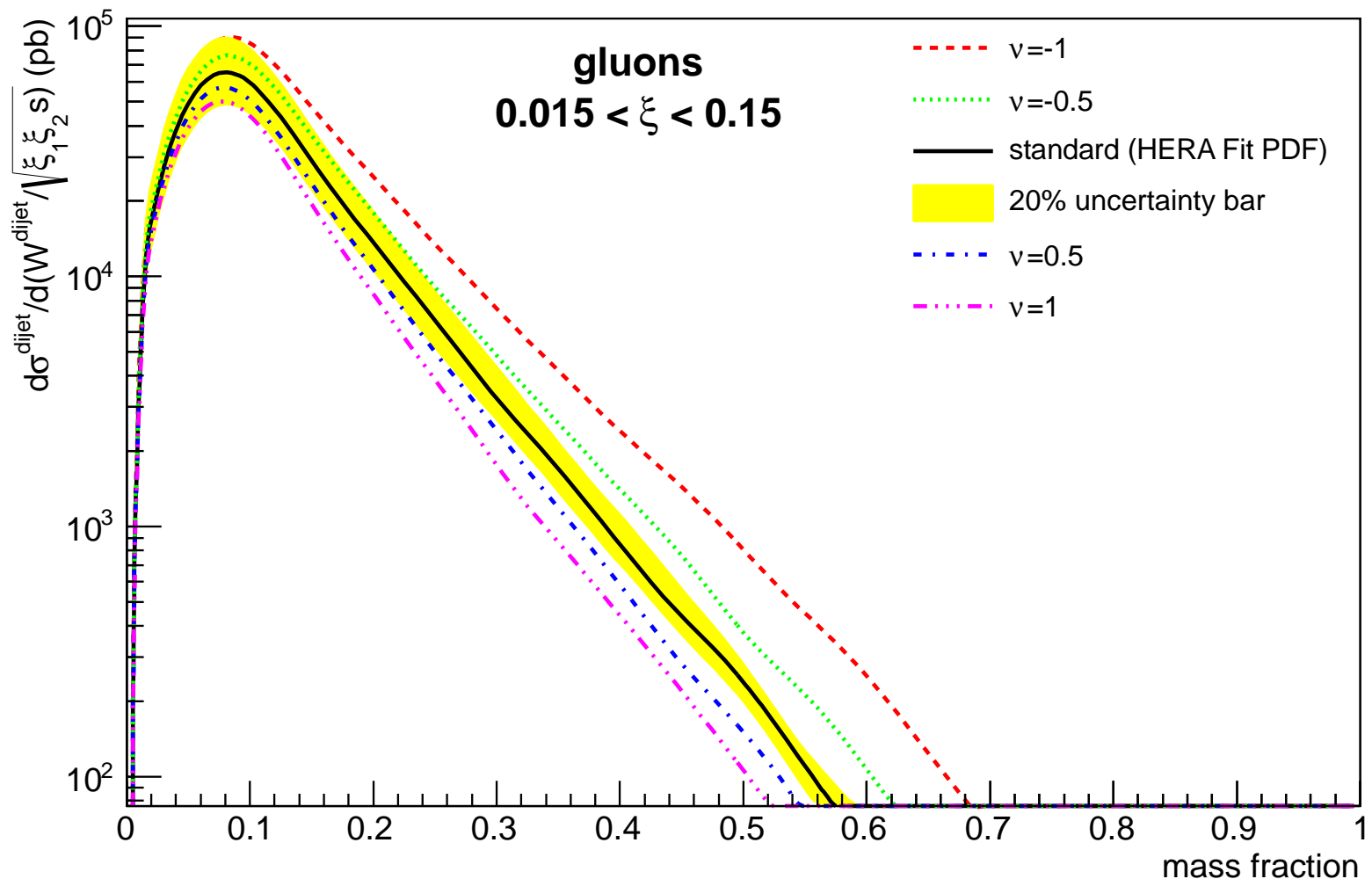
Inclusive diffraction at the LHC: sensitivity to gluon density

- 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 $\nu = -1, \dots, 1$
- Measurement possible with 10 pb^{-1} , allows to test if gluon density is similar between HERA and LHC (universality of Pomeron model)
- If a difference is observed, it will be difficult to know if it is related to the survival probability or different gluon density



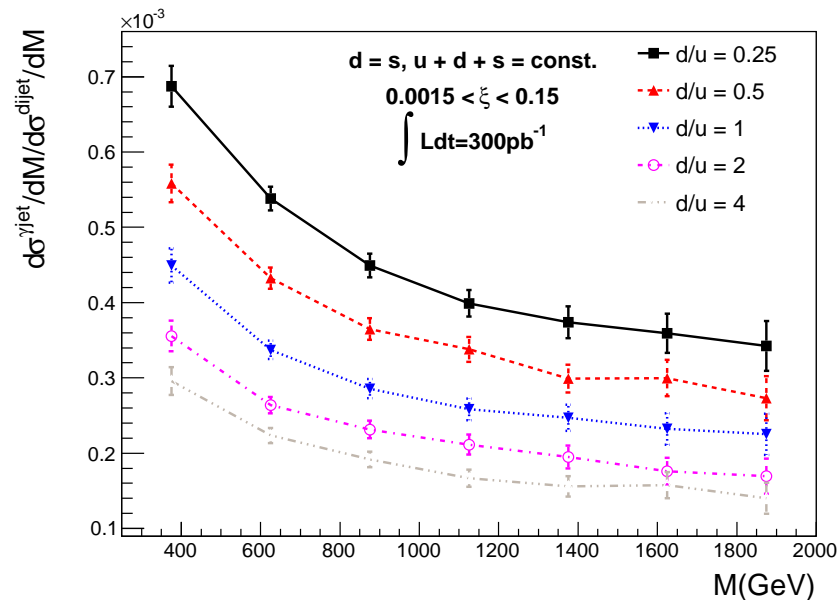
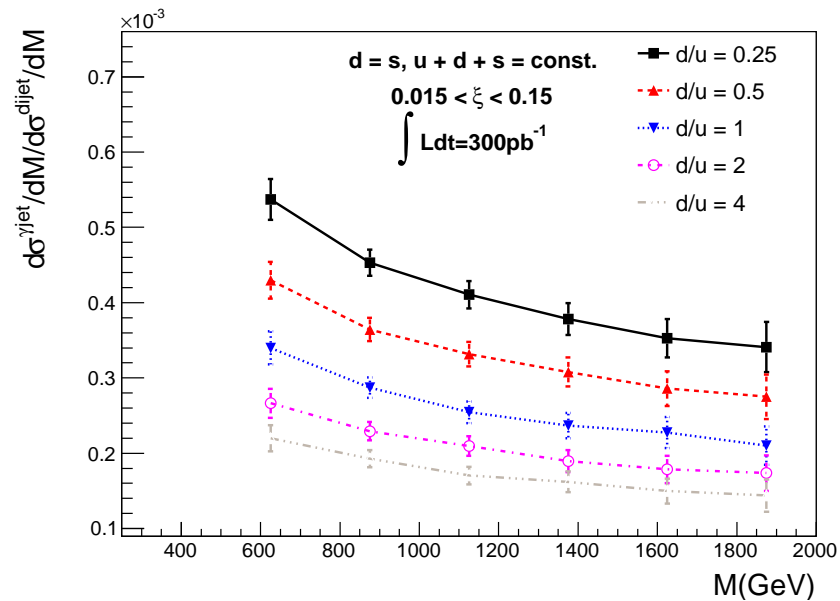
Dijet mass fraction: sensitivity to gluon density

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



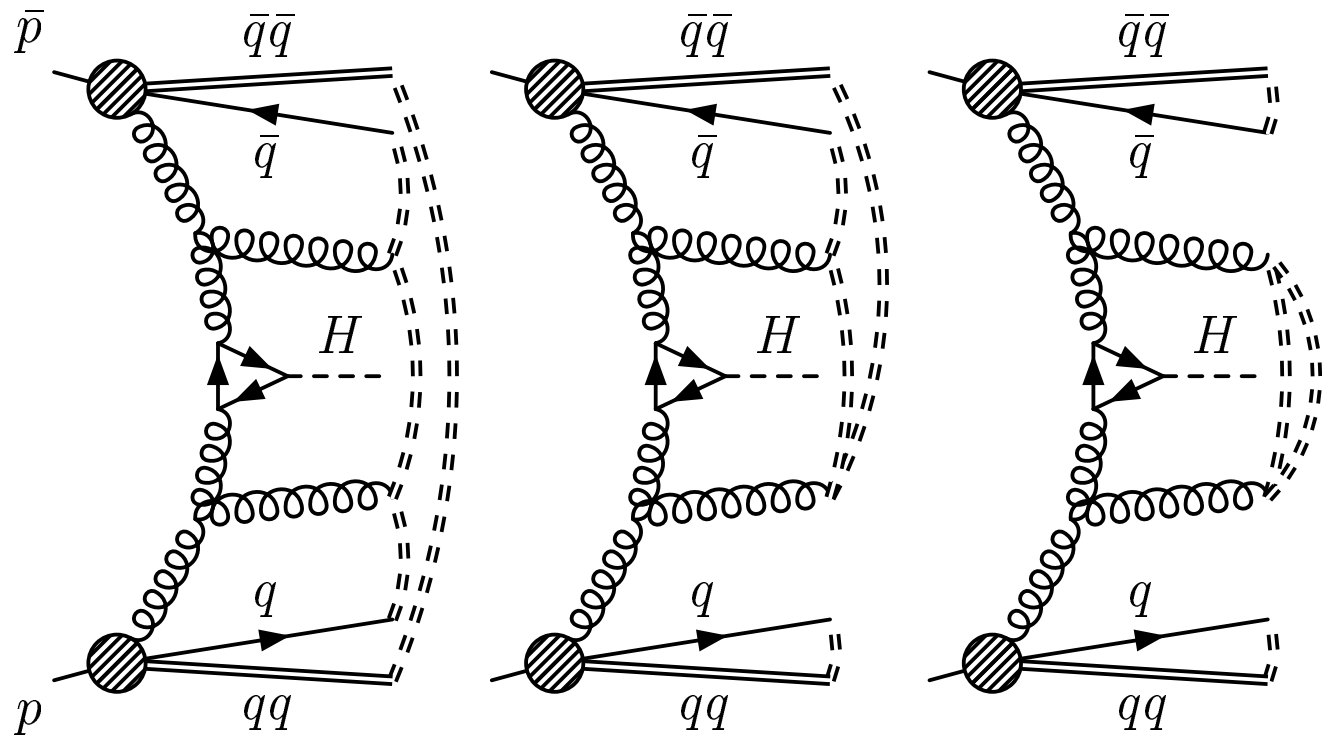
Inclusive diffraction at the LHC: sensitivity to quark densities

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



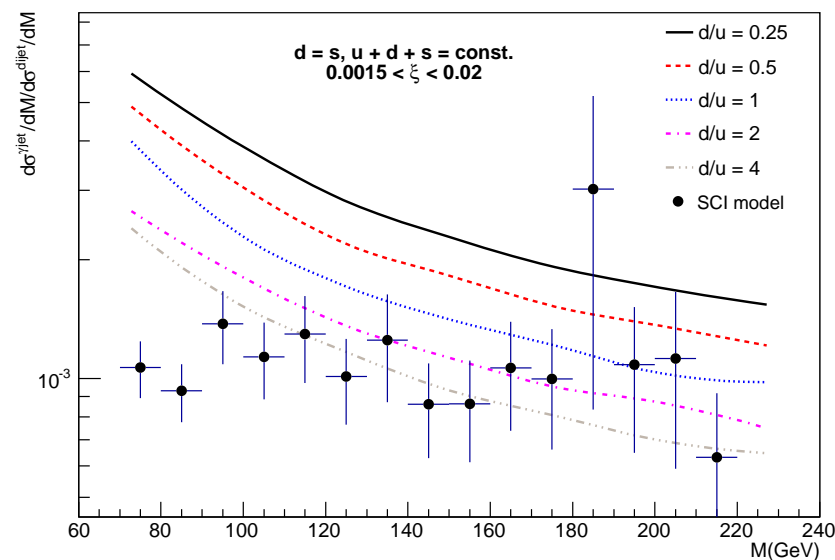
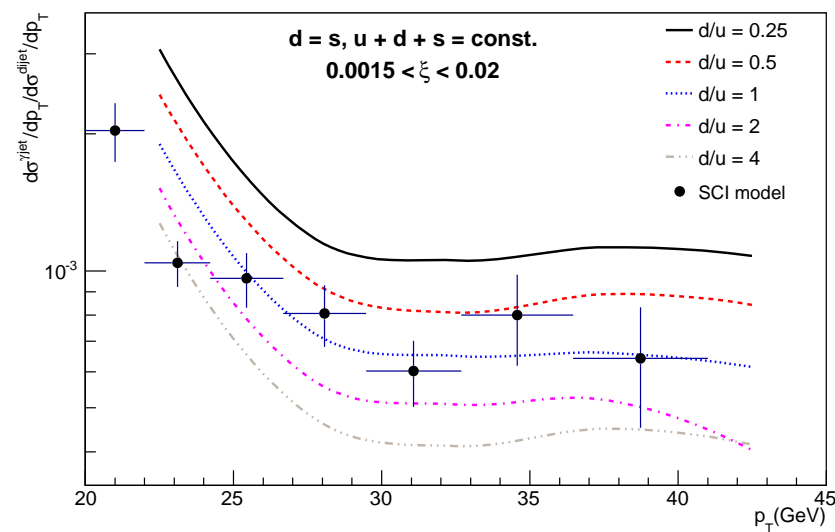
Soft Colour Interaction models

- 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



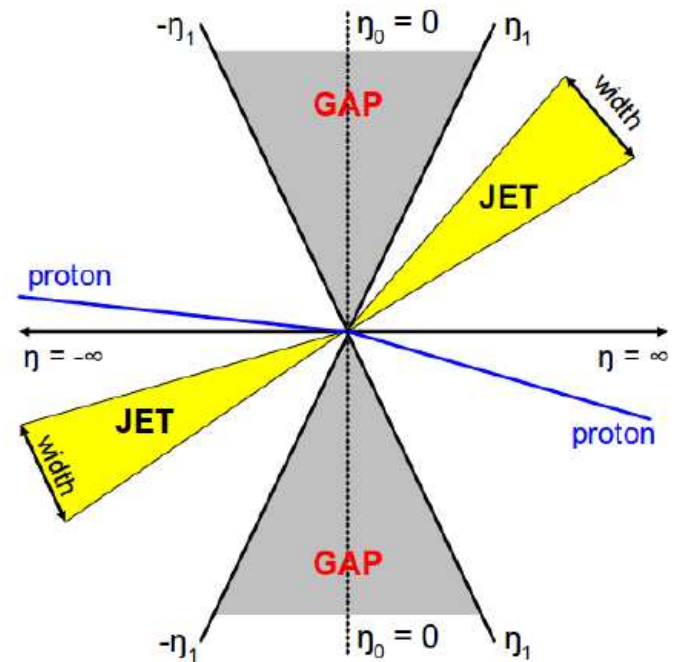
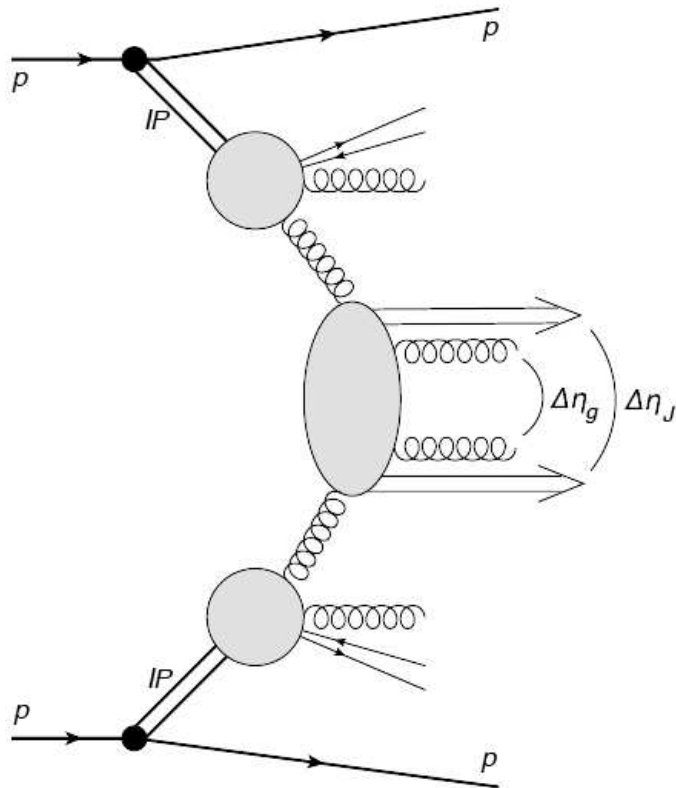
Inclusive diffraction at the LHC: sensitivity to soft colour interaction

- 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



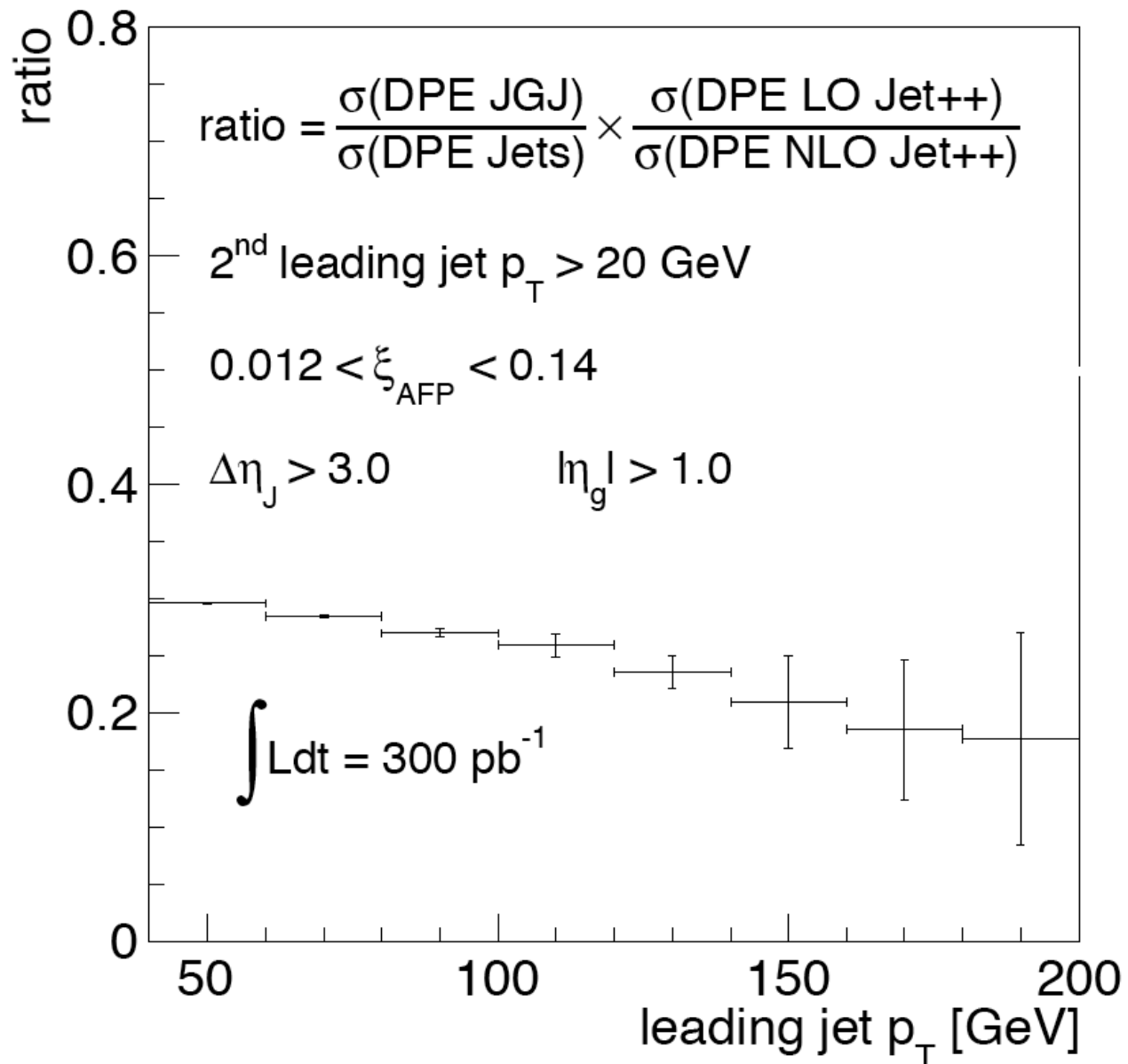
Jet gap jet events in diffraction

- 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

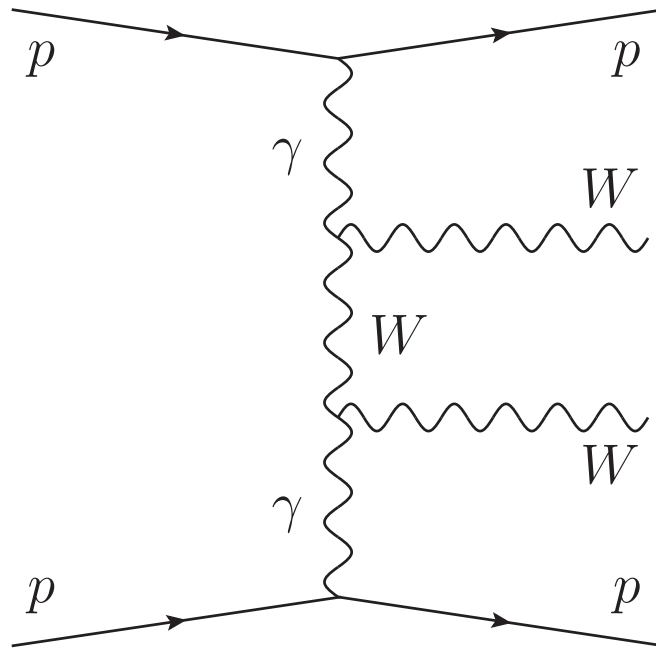


Jet gap jet events in diffraction

- 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



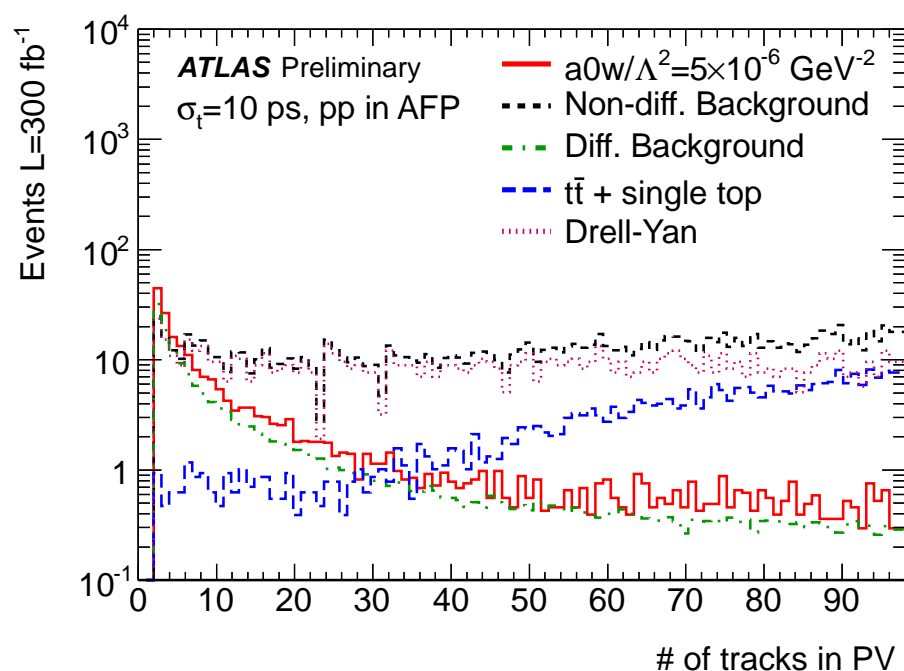
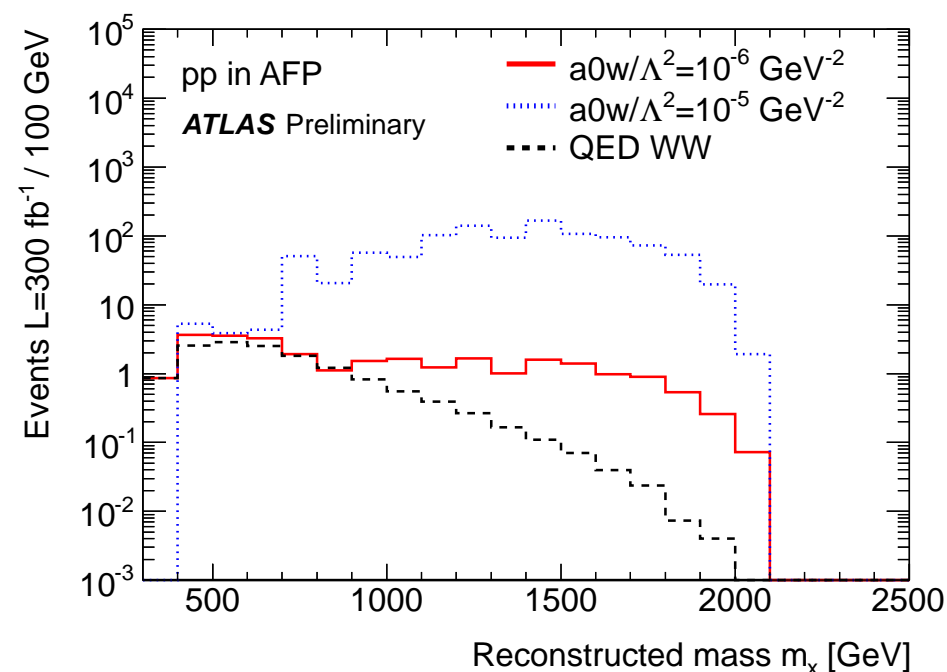
Search for $\gamma\gamma WW$ quartic anomalous coupling



- Study of the process: $pp \rightarrow ppWW$
- Standard Model: $\sigma_{WW} = 95.6 \text{ fb}$, $\sigma_{WW}(W = M_X > 1\text{TeV}) = 5.9 \text{ fb}$
- 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 W s 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	Diff.	$a_0^W/\Lambda^2 = 5 \cdot 10^{-6} \text{ GeV}^{-2}$
timing < 10 ps $p_T^{lep1} > 150 \text{ GeV}$ $p_T^{lep2} > 20 \text{ GeV}$	5198	601	20093	1820	190	282
$M(l\bar{l}) > 300 \text{ GeV}$	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
$m_X > 800 \text{ GeV}$	0.6	0.4	7.3	0	1.1	50
$p_T^{lep1} > 300 \text{ GeV}$	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 $40/300 \text{ fb}^{-1}$ at LHC (CMS mentions that their exclusive analysis will not improve very much at high lumi because of pile-up)

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

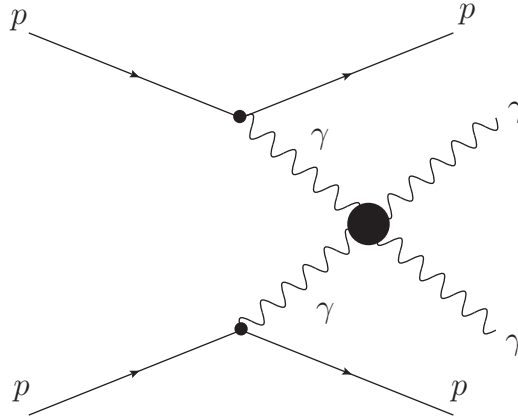
Reach at LHC

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

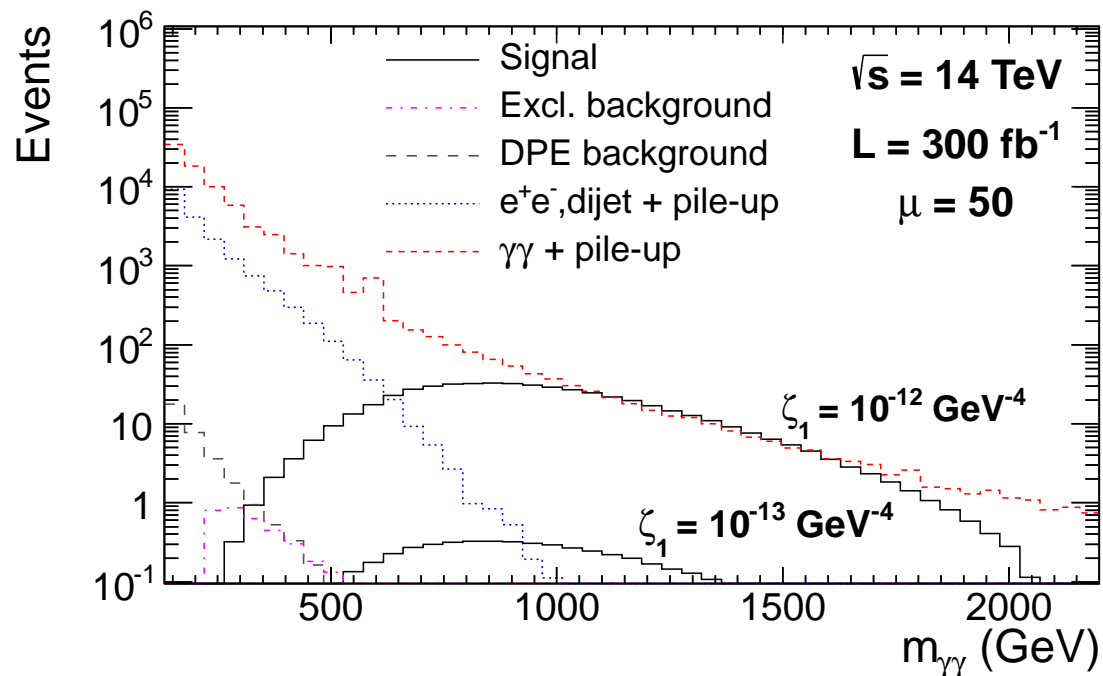
Couplings	OPAL limits [GeV ⁻²]	Sensitivity @ $\mathcal{L} = 30$ (200) fb ⁻¹	
		5 σ	95% CL
a_0^W/Λ^2	[-0.020, 0.020]	5.4 10 ⁻⁶ (2.7 10 ⁻⁶)	2.6 10 ⁻⁶ (1.4 10 ⁻⁶)
a_C^W/Λ^2	[-0.052, 0.037]	2.0 10 ⁻⁵ (9.6 10 ⁻⁶)	9.4 10 ⁻⁶ (5.2 10 ⁻⁶)
a_0^Z/Λ^2	[-0.007, 0.023]	1.4 10 ⁻⁵ (5.5 10 ⁻⁶)	6.4 10 ⁻⁶ (2.5 10 ⁻⁶)
a_C^Z/Λ^2	[-0.029, 0.029]	5.2 10 ⁻⁵ (2.0 10 ⁻⁵)	2.4 10 ⁻⁵ (9.2 10 ⁻⁶)

- Improvement of LEP sensitivity by more than 4 orders of magnitude with 30/200 fb⁻¹ at LHC, and of D0/CMS results by \sim two orders of magnitude (only $\gamma\gamma WW$ couplings)
- Reaches the values predicted by extra-dimension models

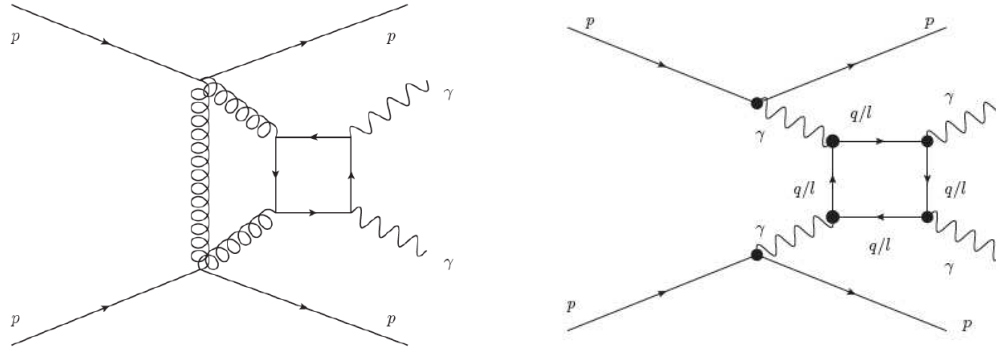
Search for quartic $\gamma\gamma$ anomalous couplings



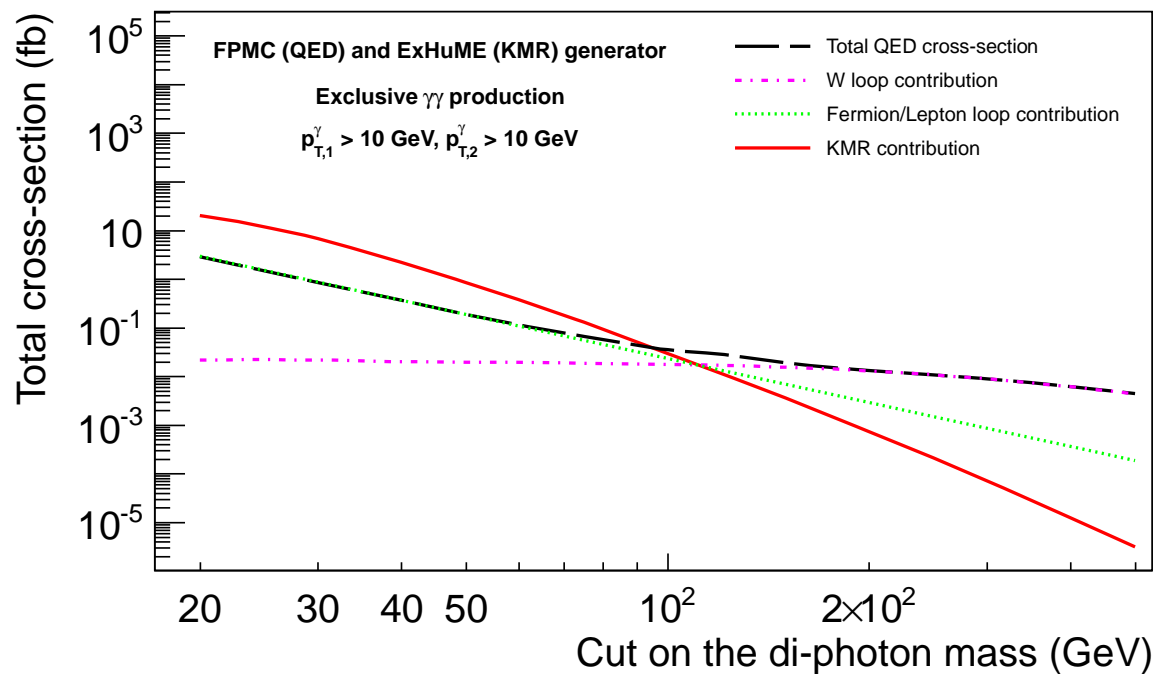
- Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- Analysis performed at hadron level including detector efficiencies, resolution effects, pile-up...



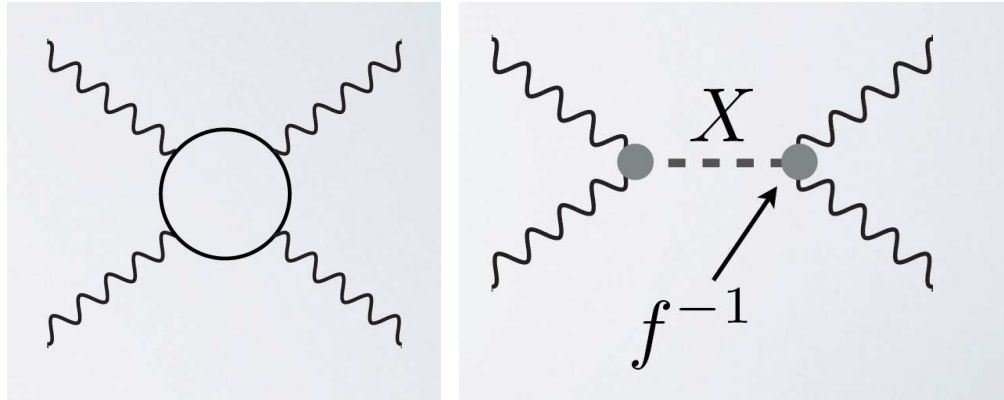
SM QED exclusive $\gamma\gamma$ production



- QCD exclusive contribution dominant at low masses (KMR)
- Different loop contributions: fermions (quarks, leptons), vectors (W bosons)
- W loop contributions and massive fermions added in the calculation: W loop dominates at high mass



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



- Two effective operators at low energies

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

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

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

where the coupling depends only on $Q^4 m^{-4}$ (charge and mass of the charged particle) and on spin, $c_{1,s}$ depends on the spin of the particle

This leads to ζ_1 of the order of 10^{-14} - 10^{-13}

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

Warped extra-dimensions (Gero von Gersdorff)

✗ Warped Extra Dimensions **solve hierarchy problem** of SM

✗ 5th dimension bounded by two branes

✗ SM on the visible (or TeV) brane

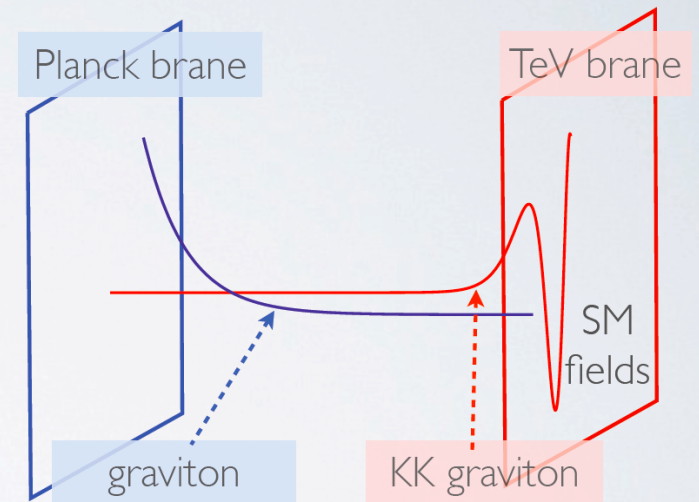
✗ The **Kaluza Klein** modes of the graviton couple with **TeV** strength

$$\mathcal{L}^{\gamma\gamma h} = f^{-2} h_{\mu\nu}^{\text{KK}} \left(\frac{1}{4} \eta_{\mu\nu} F_{\rho\lambda}^2 - F_{\mu\rho} F_{\rho\nu} \right)$$

$$f \sim \text{TeV} \quad m_{\text{KK}} \sim \text{few TeV}$$

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

✗ The **radion** can produce similar effective couplings



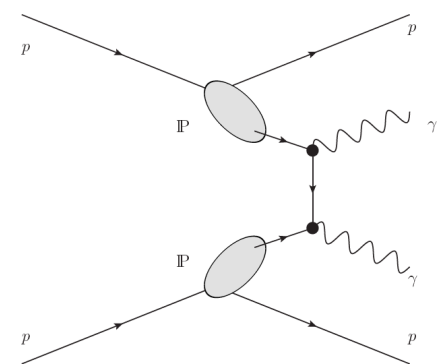
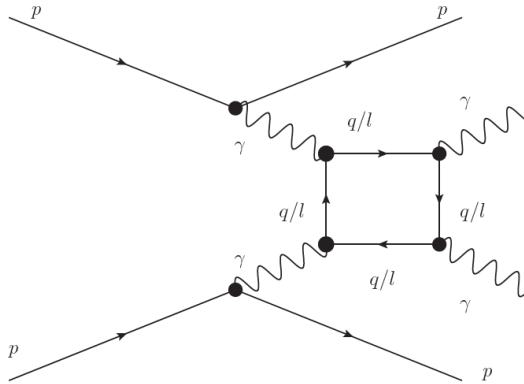
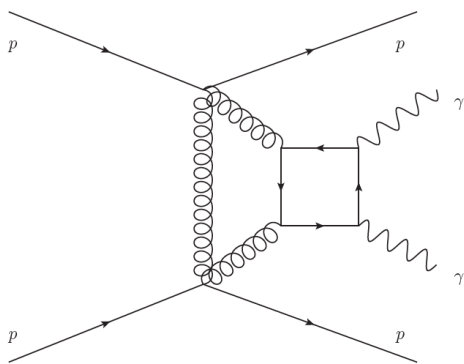
- Which models/theories are we sensitive to using AFP/PPS
- Beyond standard models predict anomalous couplings of $\sim 10^{-14} - 10^{-13}$
- Work in collaboration with Sylvain Fichet, Gero von Gersdorff

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

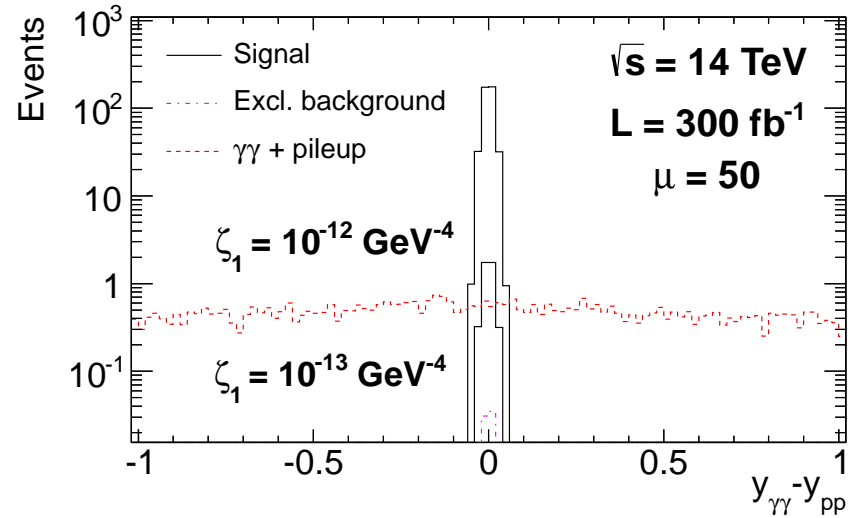
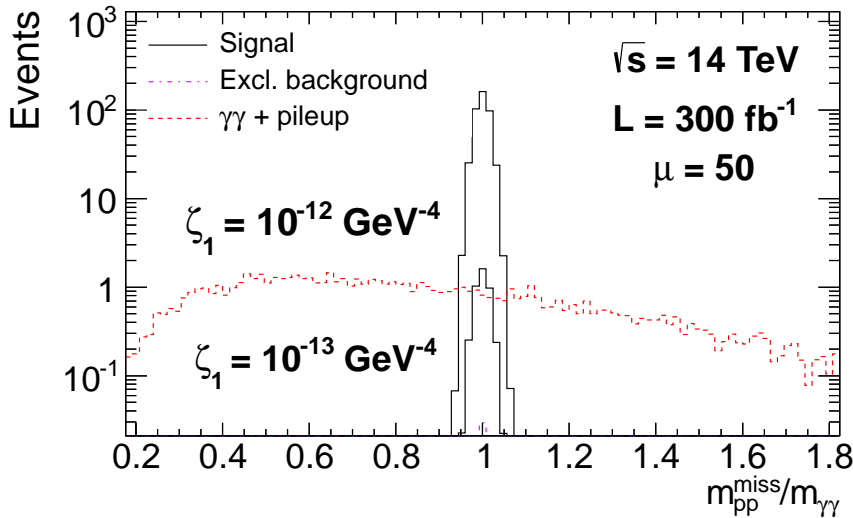
- Studies performed at hadron level but taking into account the main detector/pile-up effects
- By default, $> 1\gamma$ converted is requested (1 mm resolution), but all γ are also considered, and can handle pile-up thanks to the “pointing” ATLAS calorimeter (contrary to CMS...)
- pile-up simulated in AFP: 50, 100, 200 pile-up events per bunch crossing are considered
- Exclusive diffractive /DPE/ND backgrounds are considered and the largest one is pile-up
- Main detector effects are included (from ATLAS ECFA studies ATL-PHYS-PUB-2013-009), for instance:
 - Photon conversion probability: 15% in barrel, 30% in the end-caps; γ rapidity, Φ , and p_T resolutions taken into account as well as the reconstruction efficiency
 - Misidentification of electron as a γ : 1%
 - Misidentification of jet as a γ : 1/4000,
 - See: S.Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert, Phys. Rev. D89 (2014) 114004
 - Interesting to look also in the heavy ion mode: study in progress

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 probabilities in ATLAS)
- Pile up background: Non diffractive production and pile up (50, 100, 200), Drell-Yan, dijet, diphoton
- Assume at least 1 photon to be converted, high p_T photons (above 200 GeV)
- Further reduction using timing detectors: Reject background by a factor 40 for a pile up of 50 (10 ps resolution assumed)



Search for quartic $\gamma\gamma$ anomalous couplings



- **Trigger:** 2 high p_T central photons, $P_{T_1} > 200$ GeV, no special AFP trigger needed
- **Protons are detected in AFP at high $\xi > \sim 0.04$:** massive objects are produced, we do not need to be very close to the beam
- **Exclusivity cuts:** diphoton mass compared from missing mass computed using protons, rapidity difference between diphoton and proton systems: suppresses all pile-up backgrounds
- **For 300 fb^{-1} and a pile-up of 50:** 0 background event for 15.1 (3.8) signal events for an anomalous coupling of $2 \cdot 10^{-13}$ (10^{-13})
- **Exclusivity cuts are fundamental to suppress all background and increase the sensitivity**
- **NB:** theoretical uncertainties are larger in the case of non-exclusive production (usual study in ATLAS) since it is sensitive to the poorly known photon structure function at high energy

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

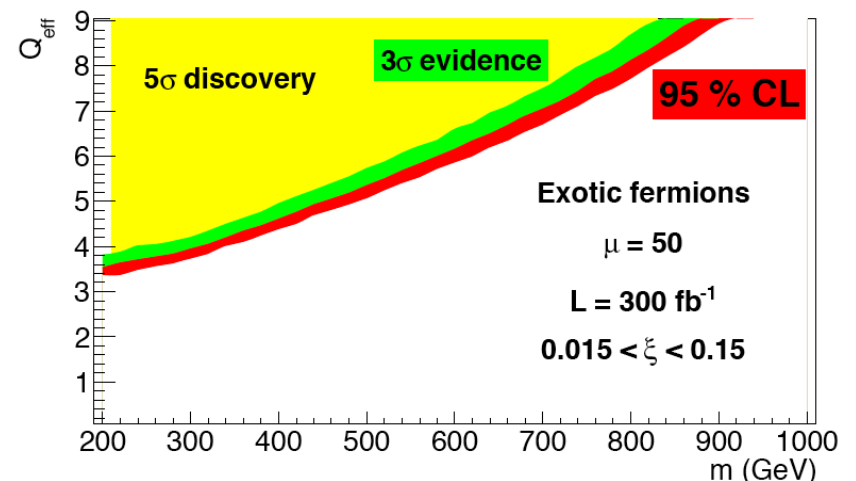
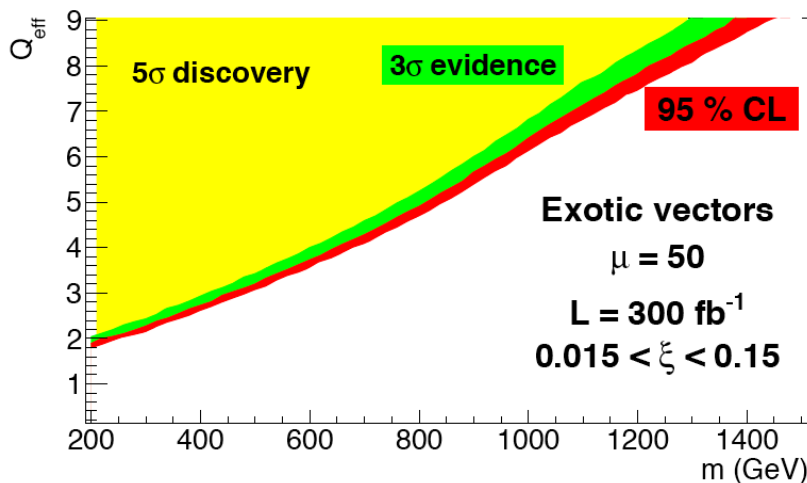
Cut / Process	Signal	Excl.	DPE	e^+e^- , dijet + pile-up	$\gamma\gamma$ + pile-up
$0.015 < \xi < 0.15, p_{T1,2} > 50 \text{ GeV}$	20.8	3.7	48.2	$2.8 \cdot 10^4$	$1.0 \cdot 10^5$
$p_{T1} > 200 \text{ GeV}, p_{T2} > 100 \text{ GeV}$	17.6	0.2	0.2	1.6	2968
$m_{\gamma\gamma} > 600 \text{ GeV}$	16.6	0.1	0.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

- No background after cuts for 300 fb^{-1} **without needing time detector information**
- Exclusivity cuts needed to suppress backgrounds:
 - Without exclusivity cuts using AFP: background of 80.2 for 300 fb^{-1} for a signal of 16.2 events ($\zeta_1 = 2 \cdot 10^{-13}$)
 - With exclusivity cuts: 0 background for 15,1 signal
- String theory/grand unification models predict couplings via radions/heavy charged particles/dilatons for instance up to 10^{-14} - 10^{-13}

Luminosity	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
pile-up (μ)	50	50	50	200
coupling (GeV^{-4})	$\geq 1 \text{ conv. } \gamma$ 5σ	$\geq 1 \text{ conv. } \gamma$ 95% CL	all γ 95% CL	all γ 95% CL
$\zeta_1 \text{ f.f.}$	$1 \cdot 10^{-13}$	$9 \cdot 10^{-14}$	$5 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$
$\zeta_1 \text{ no f.f.}$	$3.5 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$	$7 \cdot 10^{-15}$
$\zeta_2 \text{ f.f.}$	$2.5 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$1 \cdot 10^{-13}$	$4.5 \cdot 10^{-14}$
$\zeta_2 \text{ no f.f.}$	$7.5 \cdot 10^{-14}$	$5.5 \cdot 10^{-14}$	$3 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$

Full amplitude calculation

- Full amplitude calculation for generic heavy charged fermion/vector contribution
- Existence of new heavy charged particles enhances the $\gamma\gamma\gamma\gamma$ couplings in a model independent way
- Enhancement parametrised with particle mass and effective charge $Q_{eff} = QN^{1/4}$ where N is the multiplicity
- Publication in preparation with G. von Gersdorff, S. Fichet, M. Saimpert, O. Kepka, B. Lenzi, C. Royon
- Unprecedented sensitivities at hadronic colliders reaching the values predicted by extra-dim models



Conclusion

- **QCD: structure of Pomeron:** constrain the gluon density in Pomeron in a new kinematical domain using especially the dijet mass fraction
- **QCD: structure of Pomeron:** constrain for the first time the quark densities in Pomeron using γ +jet events
- **Test alternative models of diffraction:** soft colour interaction models leading to a flat dependence of the γ +jet to dijet cross section ratios as a function of diffractive mass
- **Probe BFKL resummation effects:** using jet gap jet in diffraction
- **Exploratory physics I:** look for $\gamma\gamma WW$ and $\gamma\gamma ZZ$ anomalous couplings
- **Exploratory physics II:** Anomalous $\gamma\gamma\gamma\gamma$ couplings, test extra-dimension models with unprecedented precision, reaching the values predicted by some generic models
- **Outlook:** Implement loops of charged particles in $\gamma\gamma\gamma\gamma$ anomalous couplings, less model dependence, sensitivities to any new particle produced