# Exclusive production of WW with AFP

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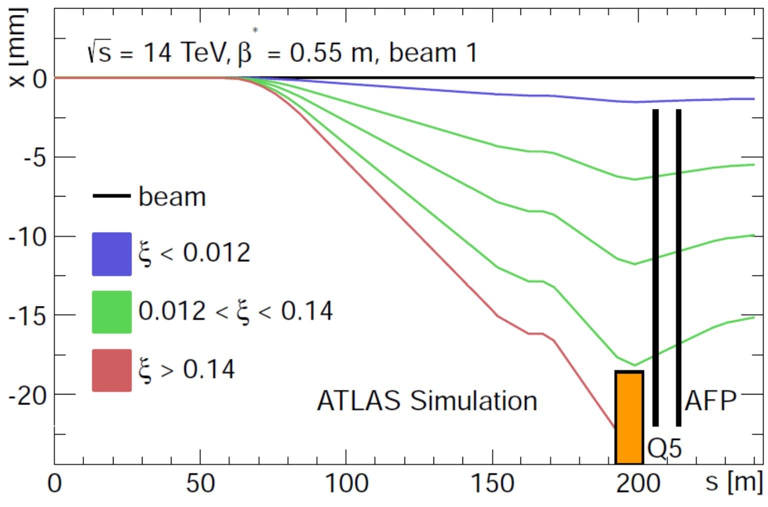
# Outline

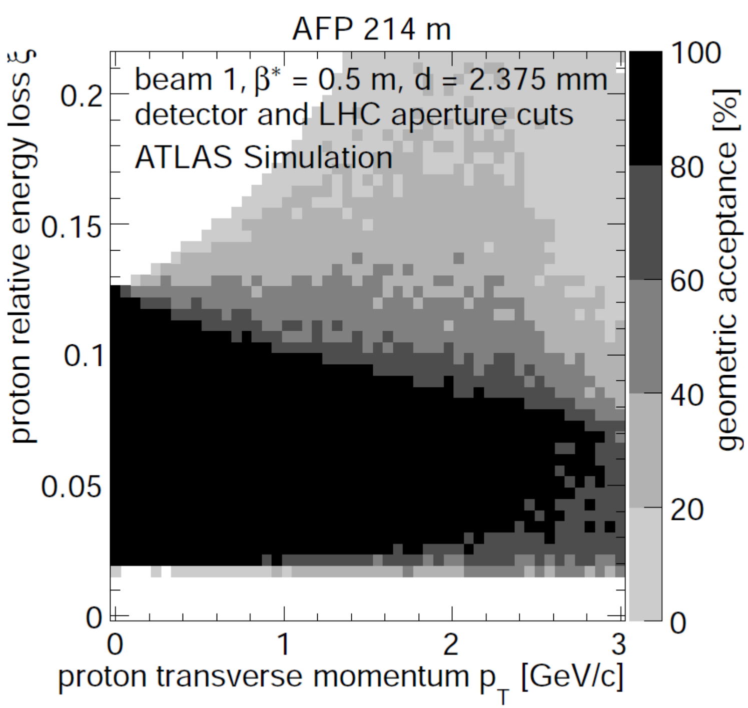
- Summary of proton detection capabilities at 210 m from IP
- Sensitivity to anomalous quartic gauge boson couplings
  - Analysis with no pile-up 210 + 420m
  - Analysis using full simulation of ATLAS with pile-up for 210 case
- Pile-up forward proton rates using MC

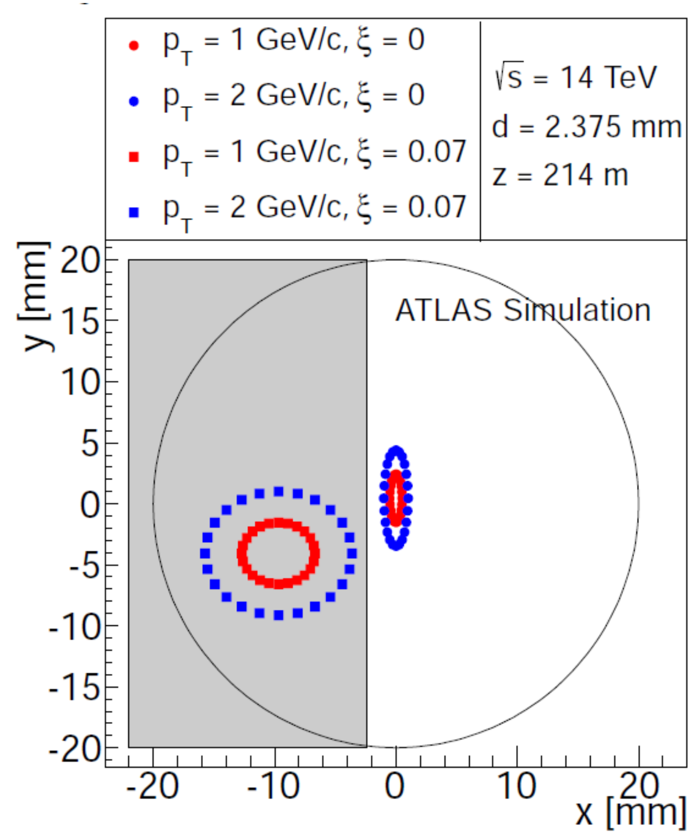
- Summary

# Forward protons




- For increasing relative proton momentum loss $\xi \simeq (1-E/E_0)$ protons scatter outside the ring
- Acceptance large for $0.012 < \xi < 0.14$
- $d$ at $15\sigma$: 2.3mm = 0.13x15 + 0.3 mm

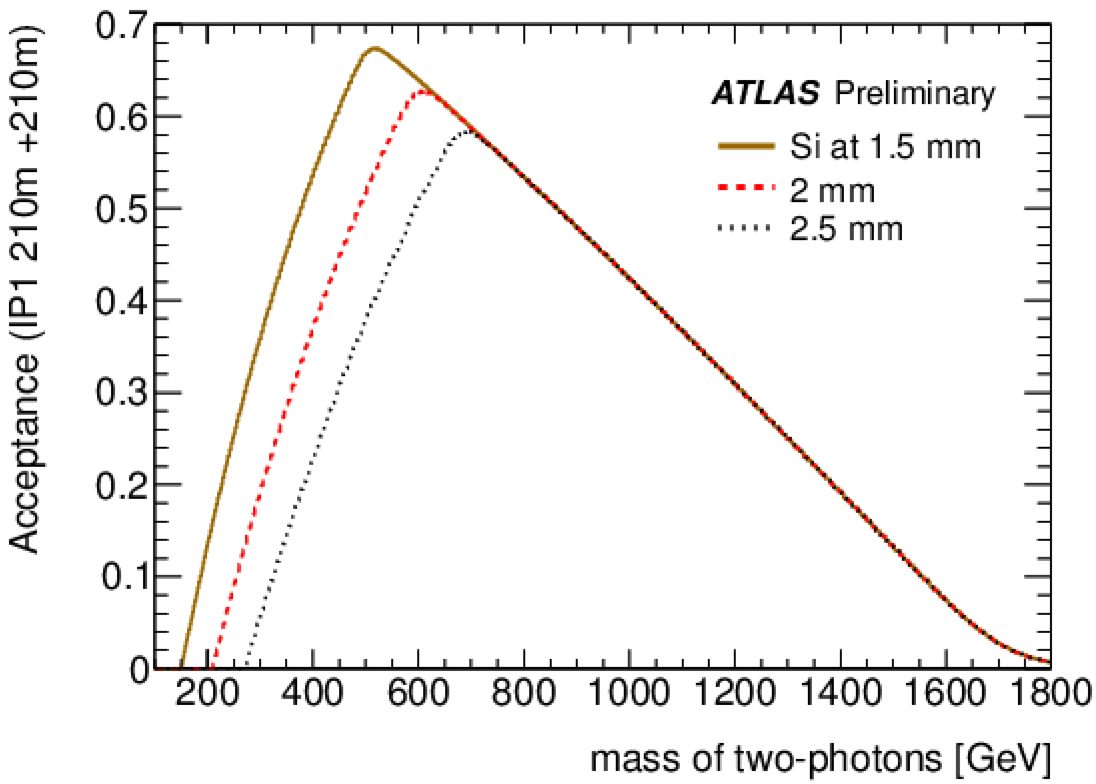


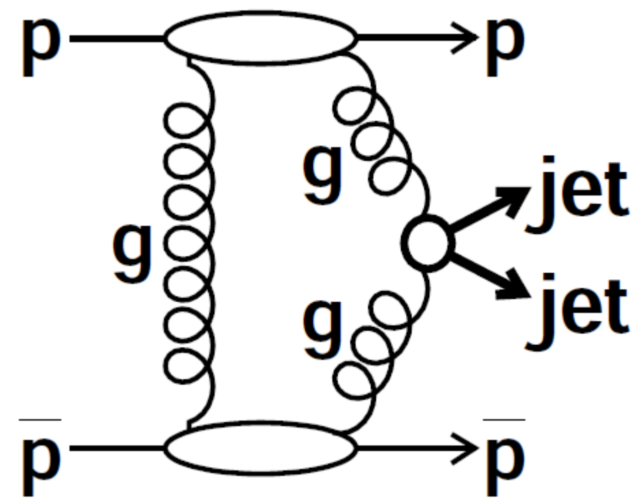



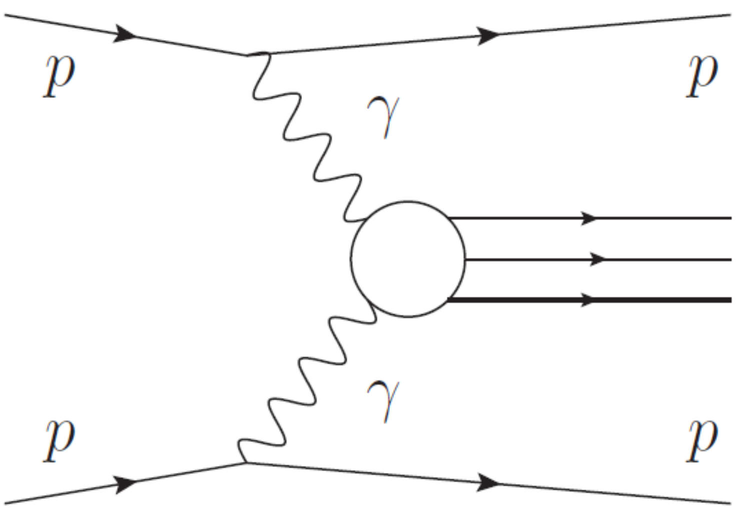
# Acceptance

- Acceptance up to ~1TeV scale
- Very small acceptance below 350 GeV

$$W = \sqrt{s\xi_1\xi_2}$$



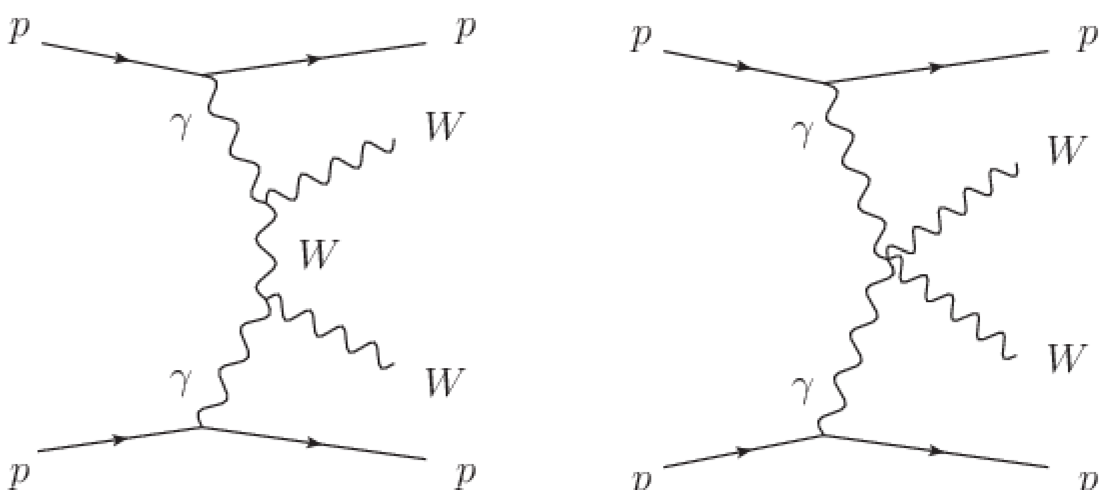



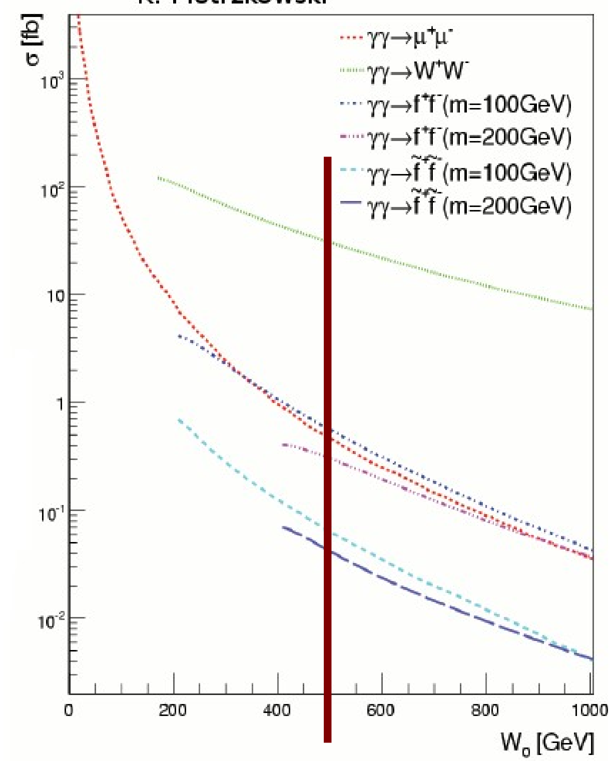
# Exclusive QED production

# VBS in exclusive mode

- AFP turn LHC pp machine into an effective photon-photon collider
  - But also gamma-pomeron
- Photon induced vector boson scattering process
  - No particle produced from underlying event involving MPI
  - No color flow – possible jet gap as in VBF




K. Piotrzkowski arXiv:0908.2020




Cross sections for $\gamma\gamma$ processes as a function of the minimal $\gamma\gamma$ cms energy $W_0$

- Improving anomalous TGC/QGC constraints showed on ha
  - Exciting mainly for anomalous aQGC, sensitivity to aTGC compa limits

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# Anomalous Quartic Gauge Coupling

- Stringent test of the electroweak symmetry breaking by proton tagging

  SM: γγWW    BSM: γγZZ, (γγγγ)

- aQGC γγ → WW can be measured very precisely looking in deviations in m(γγ), or $p_T$(lep) spectrum → ~$10^{-6}$
- 4 orders of magnitude improvement wrt. LEP
  - Hadron level analysis considering diffractive background with primary int.

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

*O. K. et al, Phys. Rev. D 81, 074003 (2010)*

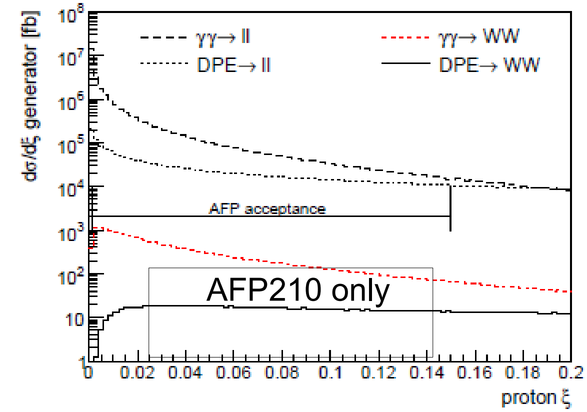
*T. Pierzchala et al, Nucl. Phys. Proc. Suppl. 179-180 (2008) 257*

- Effecti
  - Conserve *C*, *P*, *T*, and custodial symmetries

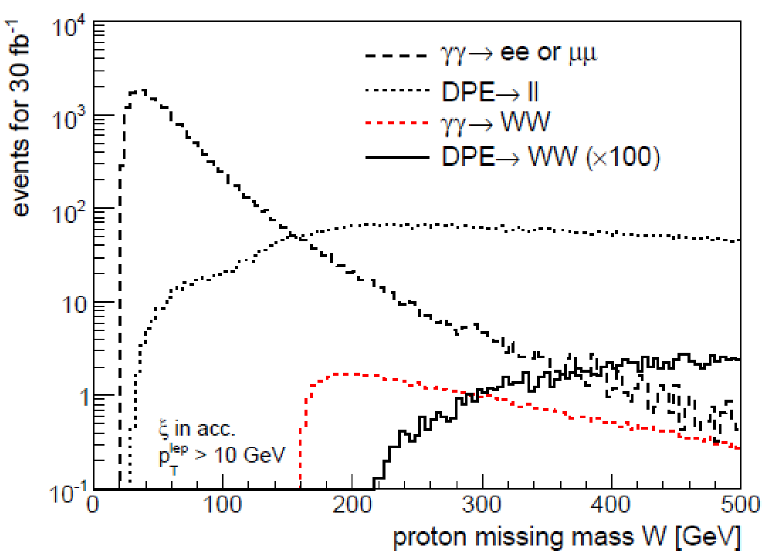
$$\mathcal{L}_{\mathrm{eff}}^{\mathrm{BSM}} = -\frac{e^2}{8}\frac{a_0^W}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W_\alpha^- - \frac{e^2}{16}\frac{a_C^W}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W_\beta^- + W^{-\alpha}W_\beta^+) - \frac{e^2}{16\cos^2\theta_W}\frac{a_0^Z}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}Z^\alpha Z_\alpha - \frac{e^2}{16\cos^2\theta_W}\frac{a_C^Z}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}Z^\alpha Z_\beta$$

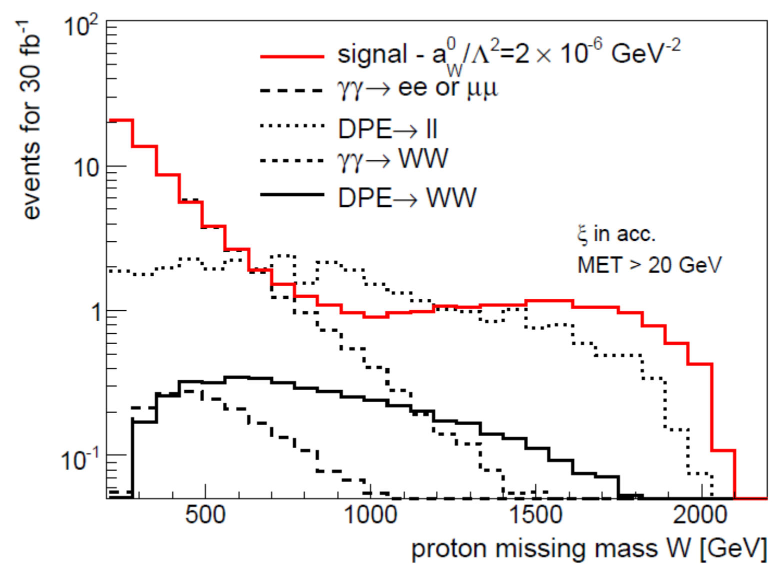
# Details of the analysis

- Use both 210m and 420m detectors
- Consider: γγ and double pomeron exchanges
- Neglect pile-up




- Not a realistic scenario anymore
- Large rates of SM process at low mass




- Since anomalous shows up at high mass, 420m actually not needed …

# Implementation of the aQGC

New couplings violate unitarity, couplings need to be accompanied by Form factors regularizing the effect of cross section at high mass

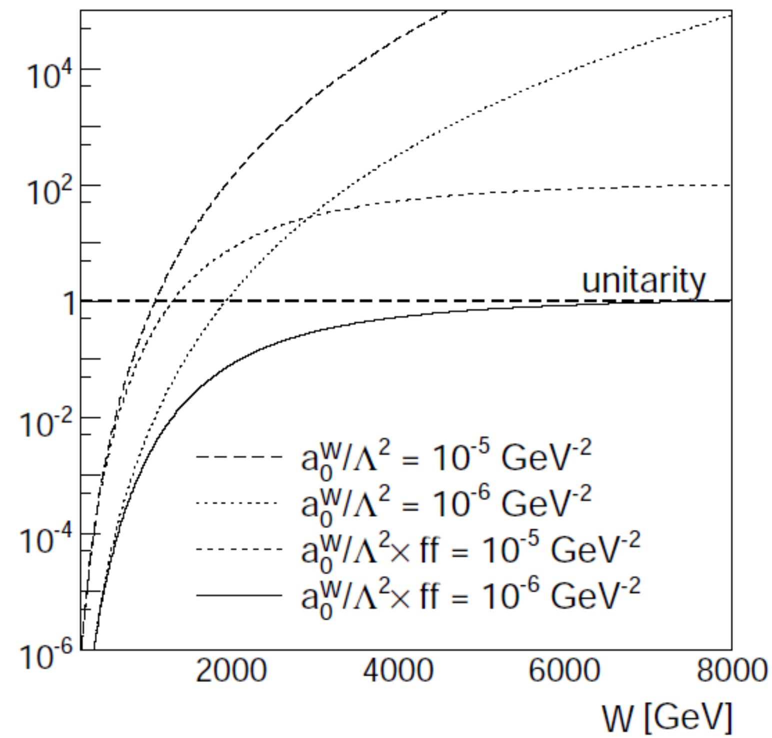
$$a \rightarrow \frac{a}{[1+(W_{\gamma\gamma}/2\,\mathrm{TeV})^2]^2}$$

- Unitarity condition for anomalous coupling (J. P. Eboli) as a function of the invariant mass measured in AFP

$$\frac{1}{N}\left(\frac{\alpha a s}{16}\right)^2\left(1-\frac{4M_W^2}{s}\right)^{1/2}\left(3-\frac{s}{M_W^2}+\frac{s^2}{4M_W^4}\right) \le 1 \text{ for } V = W$$

$$\frac{1}{N}\left(\frac{\alpha a s}{16\cos^2\theta_W}\right)^2\left(1-\frac{4M_Z^2}{s}\right)^{1/2}\left(3-\frac{s}{M_Z^2}+\frac{s^2}{4M_Z^4}\right) \le 1 \text{ for } V = Z$$

- Moreover: Acceptance of AFP serves as a natural cutof
- Limits do NOT differ by more then factor of 2 with or wit



# Improvments of the analysis

- Consider multiple proton – proton colissions
- Aim at higher luminosities, and up to 46 interactions per bunch crossings
- Try to avoid missing energy
- I this possible? Yes, the crucial points are:
  - Timing detectors
  - Counting tracks in the inner detector

# Suppression of pile-up

- Require difference between proton arrival times compatible with primary vertex

$$z_0 = \frac{c}{2}(t_1 - t_2) \qquad \Delta t_{1,2} = 10\,\text{ps} \rightarrow \Delta z_0 = 2.1\,\text{mm}$$

- Smearing both in time and position - rejection at 1σ level (2.1mm)

Summary:

- Acceptance

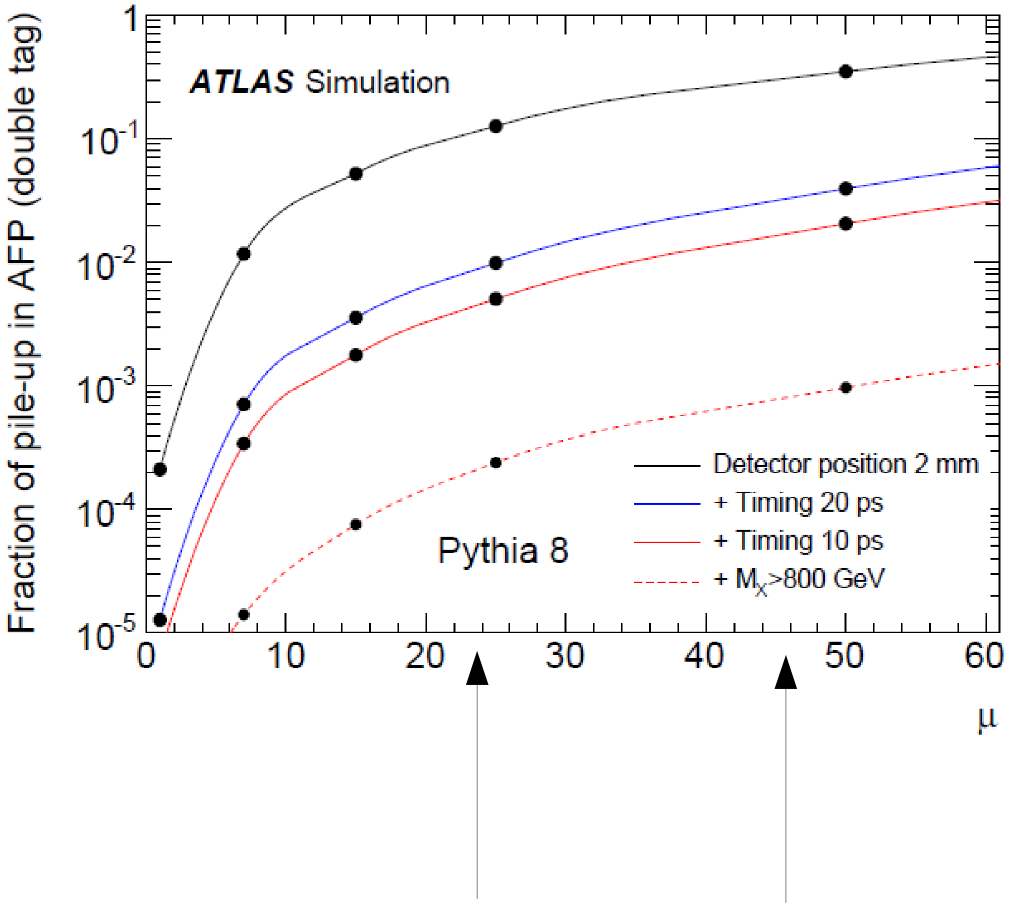
  μ = 23: $10^{-1}$ μ = 46: $3 \times 10^{-1}$

- +10ps timing

  μ = 23: $4 \times 10^{-3}$ μ = 46: $2 \times 10^{-2}$

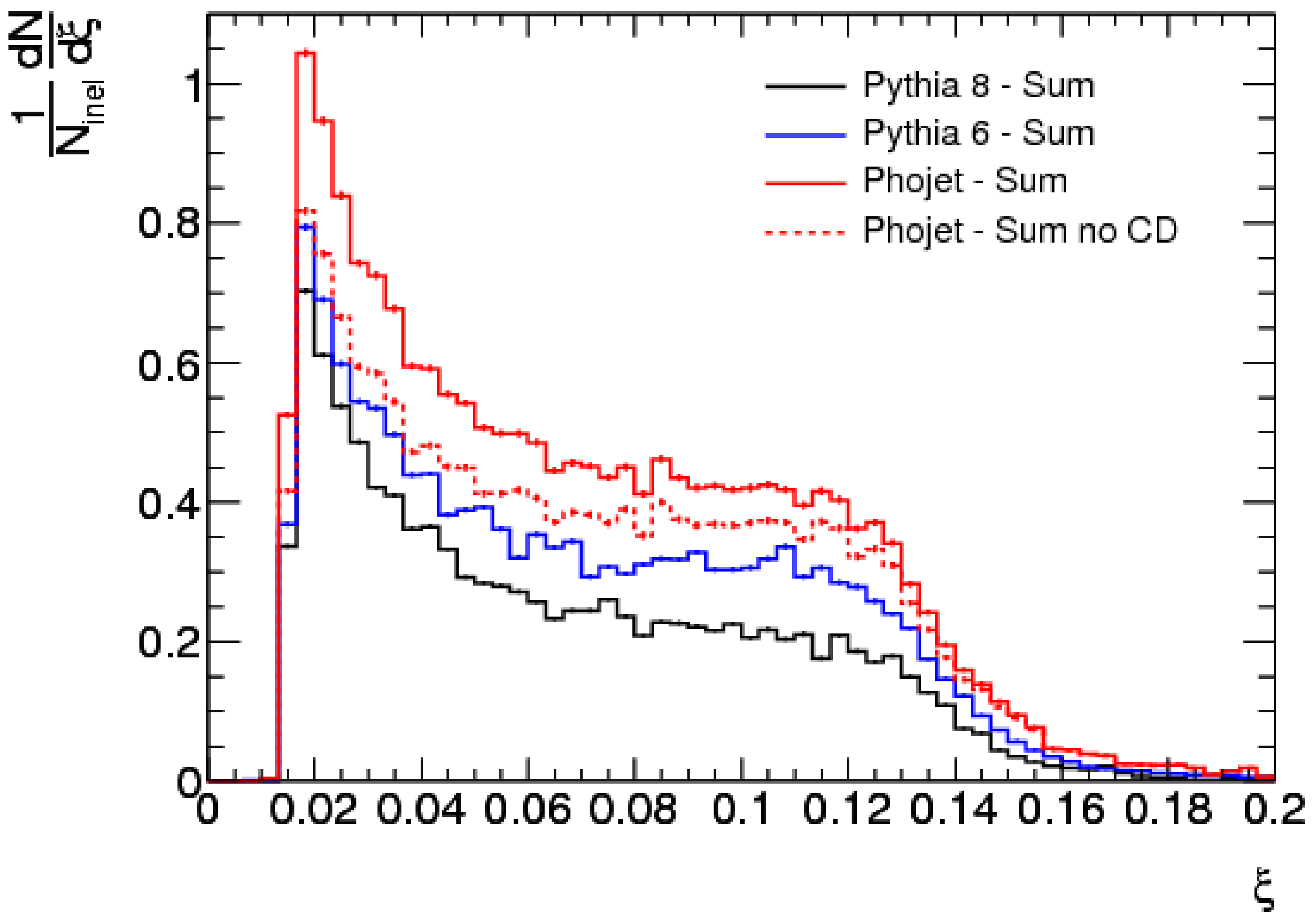
- +High mass W>800GeV

  μ = 23: $2 \times 10^{-4}$ μ = 46: $10^{-3}$



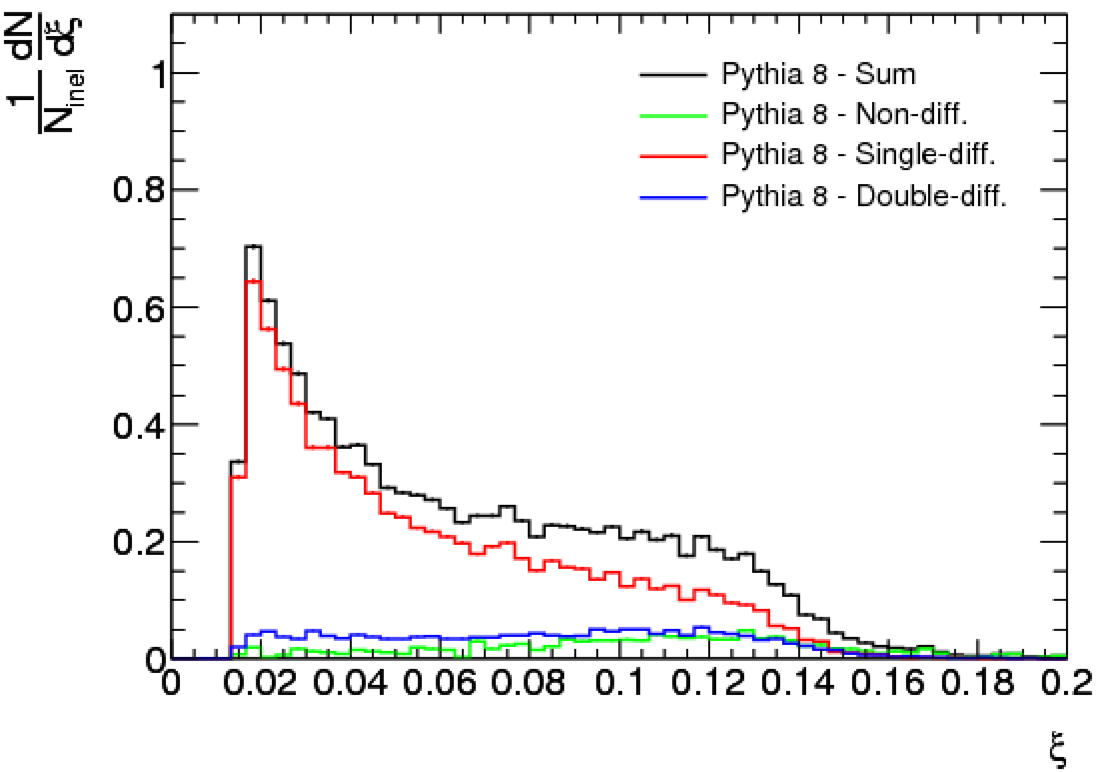
# Modeling of pile-up

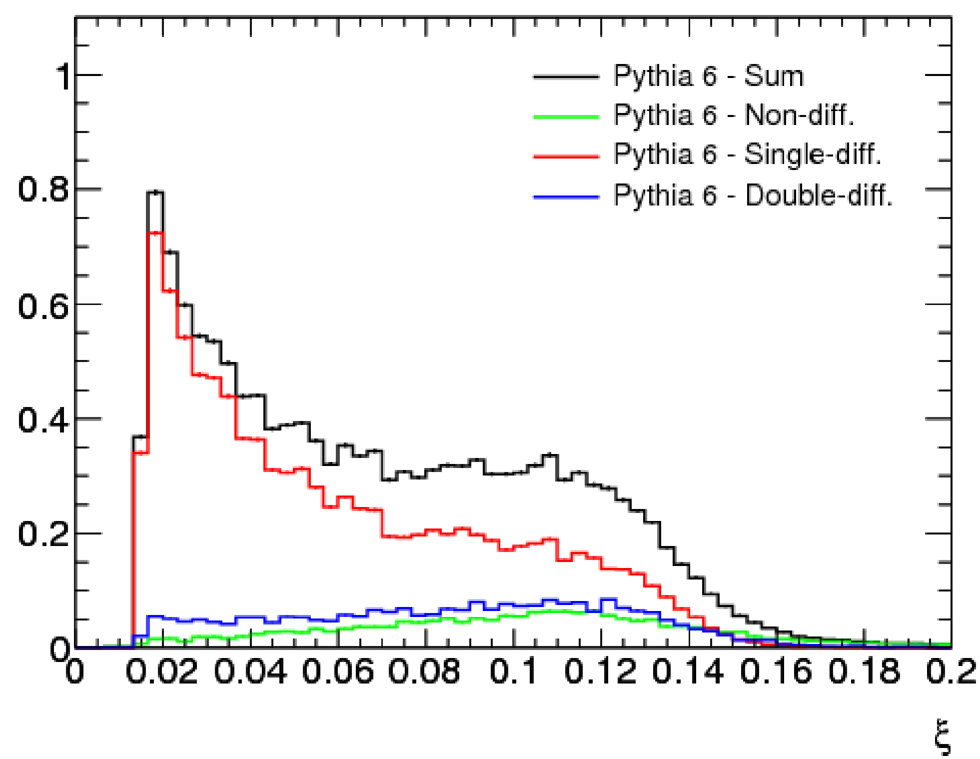
- Differences between models yield uncertainty in the modeling of pile-up rates in AFP
- Largest deviation for Phojet by factor of 2



# Pythia 6 / 8

- Differences in the modelling of large xi region – uncertainty ~ 50%
- Significant contribution of the non-diffractive and double diffractive events
- Forward physics community should aim at constraining the prediction (ALFA/TOTEM)



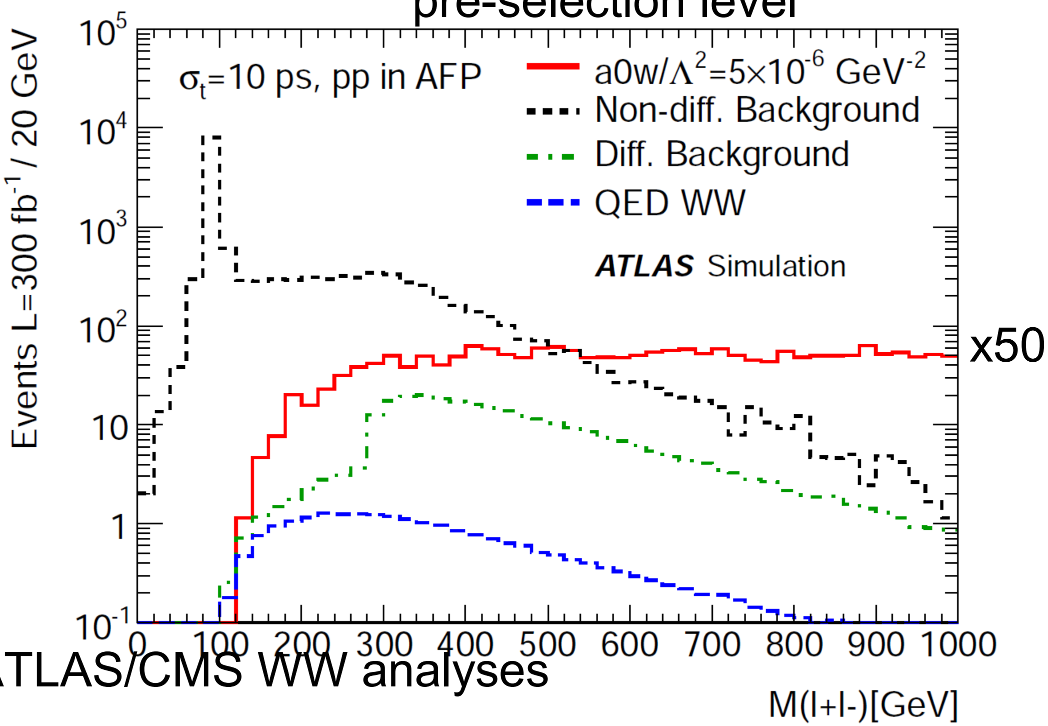



# Event selection

- Protons tracked through magnetic field of LHC, detector position at 206, 214m @ 1.5 mm from the beam (FPTracker), AFP approximate acceptance $0.02 < \xi < 0.14$

- Analysis for medium pile-up $\mu=23$
  - $p_T$(lead lep) > 150 GeV   $p_T$(sub-lead lep) > 20GeV
  - m(ll)>300 GeV
  - $N_{tracks}$ <=3
  - $\Delta\varphi$(ll) < 3.1rad
  - $m_X$ > 800 GeV
- Analysis for high pile-up $\mu=46$
  - increase lepton threshold
  - $p_T$(lead lep) > 300 GeV

pre-selection level




- Considering complete background set as in ATLAS/CMS WW analyses

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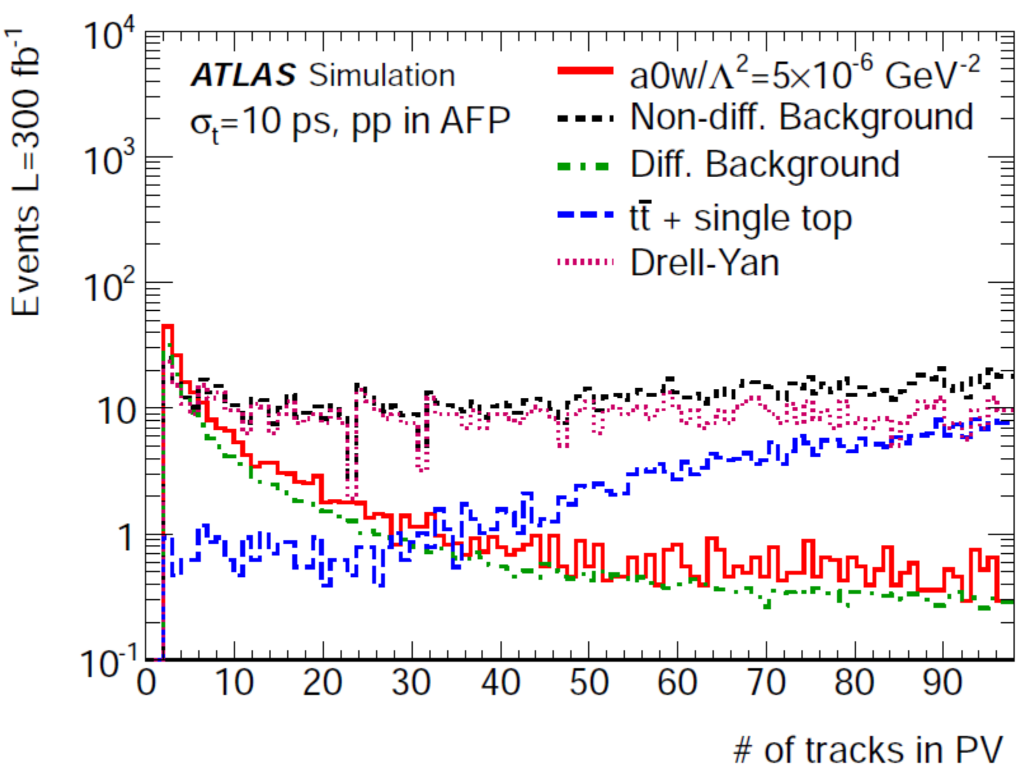
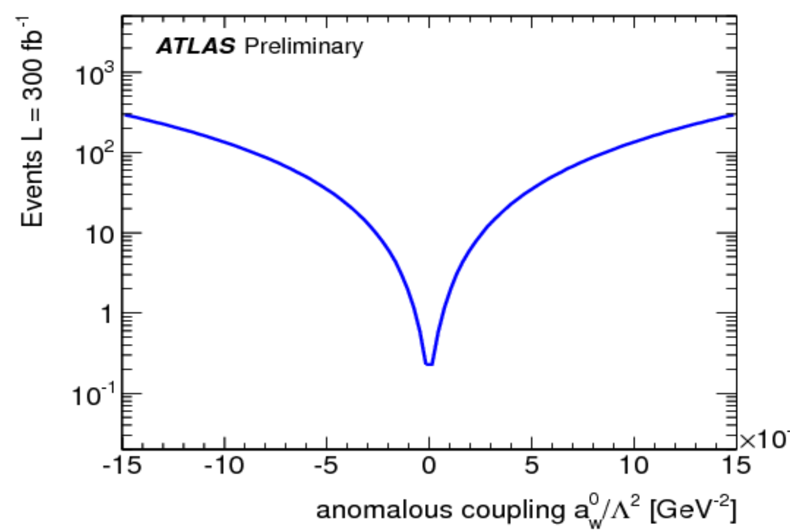
# Event selection

- Exclusivity cut – number of tracks >= 3 ($p_T$> 500MeV)
  - Main improvement wrt. hadron level studies, which couldn't use tracks without a realistic simulation of tracker and pile-up
- Non-diffractive productions has larger tails
  - Tracker and vertexing performs extremely well in pile-up
- Fully simulated samples for 4 couplings, dependence fitted with a formula including polynomial and exponential distribution



# Final limits

- Fully simulated samples for 4 couplings, dependence fitted with a formula including polynomial and exponential distribution
- Background of the order of ~0.5 events in both μ=23 and 46 scenarios

| Cuts | Top | Dibosons | Drell-Yan | W/Z+jet | Diffr. | $a_0^W/\Lambda^2 = 5 \cdot 10^{-6}$ GeV$^{-2}$ |
|---|---|---|---|---|---|---|
| timing < 10 ps<br>$p_T^{lep1} > 150$ GeV<br>$p_T^{lep2} > 20$ GeV | 5198 | 601 | 20093 | 1820 | 190 | 282 |
| M(ll)>300 GeV | 1650 | 176 | 2512 | 7.7 | 176 | 248 |
| nTracks $\leq 3$ | 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 |

- Final obtained limit

| | $a_0^W/\Lambda^2$ Sensitivity | |
|---|---|---|
| | $5\sigma$ | 95% C.L. |
| $\mathscr{L} = 40\ fb^{-1}, \mu = 23$ | $5.5\ 10^{-6}$ | $2.4\ 10^{-6}$ |
| $\mathscr{L} = 300\ fb^{-1}, \mu = 46$ | $3.2\ 10^{-6}$ | $1.3\ 10^{-6}$ |

- Precision of ~$10^{-6}$ GeV$^{-2}$ where the BSM effect could show-up maintained
- Mainly due to exclusivity requirement

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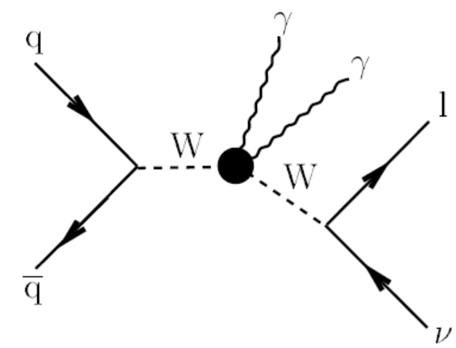
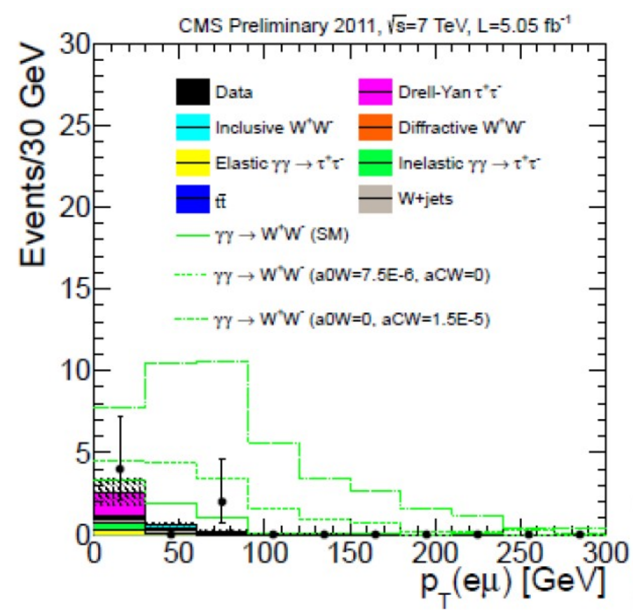
# Comparison with existing methods

- Wγγ – binned maximum likelihod fit of Mγγ distribution
  - Unitary safe limits improve lep results by two orders of magnitude
  - AFP adds 1-2 orders better sensitivity




- New CMS preliminary result
  - Exclusive production without tagging, results very promissing, sensitivity to be determined ..
  - Same models should be compared between AFP a (are these unitary safe limits?)

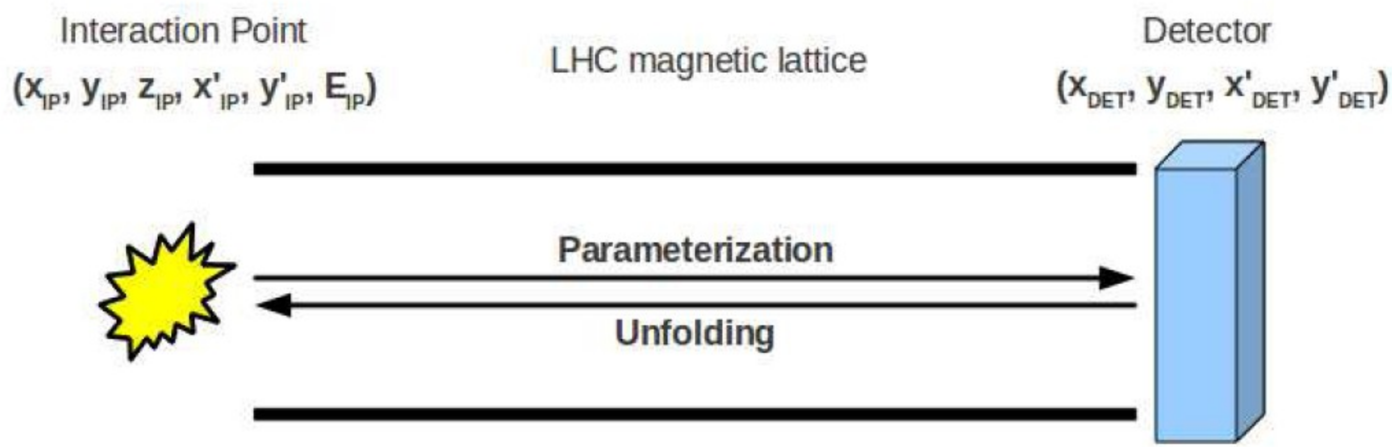


# Summary

- Feasibility study of search for high mass object decaying into leptons in exclusive events using detector stations at 210m from IP
- By 1-2 orders of magnitude better sensitivity than the conventional method
  - Analysis of W expects sensitivity ~$10^{-4}$ only
  - Competition sensitivity on exclusive WW with 8TeV data to be seen
- Anomalous γγZZ not mentioned, but experimentally simpler then WW – employ correlation of Mx in forward detectors and 4 leptons
- With 420m one could measure DPE/γγ packgrounds directly
  - However, for sensitivity to aQGC not crucial
- More studies to be done:
  - Exclusive production of di-photons as a probe of anomalous coupling
  - Investigation of semi-leptonic decays of WW to improve limits

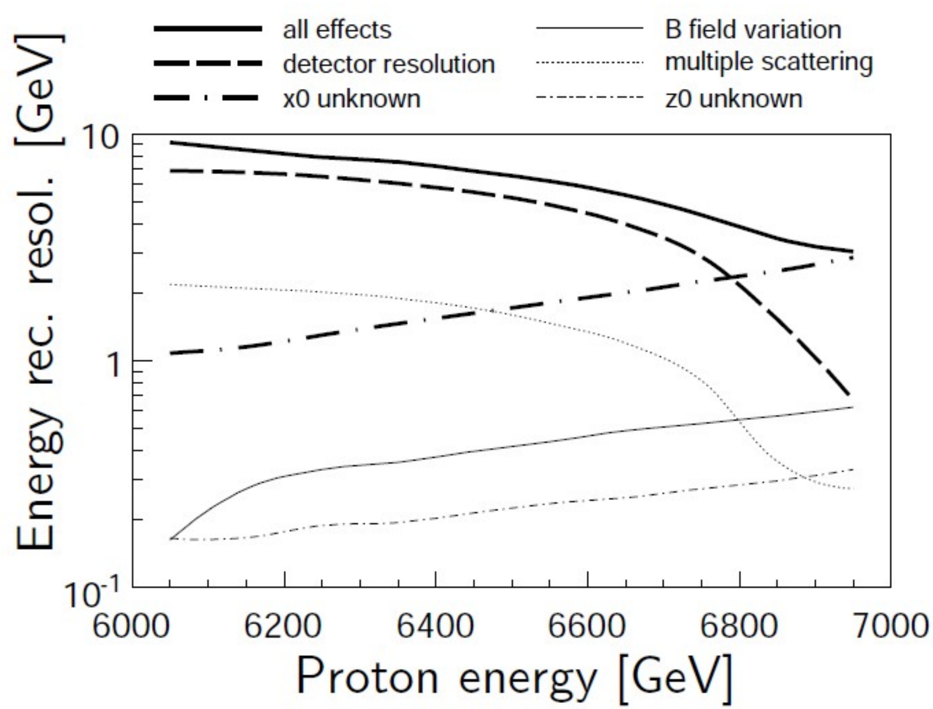
# Backup

# Proton kinematic reconstruction




Knowing proton position at both AFP stations one can reconstruct energy and momentum at the Interaction Point.

The energy reconstruction resolution is **better than 10 GeV**!

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# Momentum fraction loss profiles

- Intact protons in non-diffractive and double-diffractive sample make about 50% of intact protons hitting AFP
- Right: single diffractive  events
  - Comparing side with forward proton and the side with dissociated system
  - Rejection power could be increased by cutting on particular XxY patterens
- Needs to be measured!
  - Starting ALFA diffractive program can provide important constraints to pile-up in AFP

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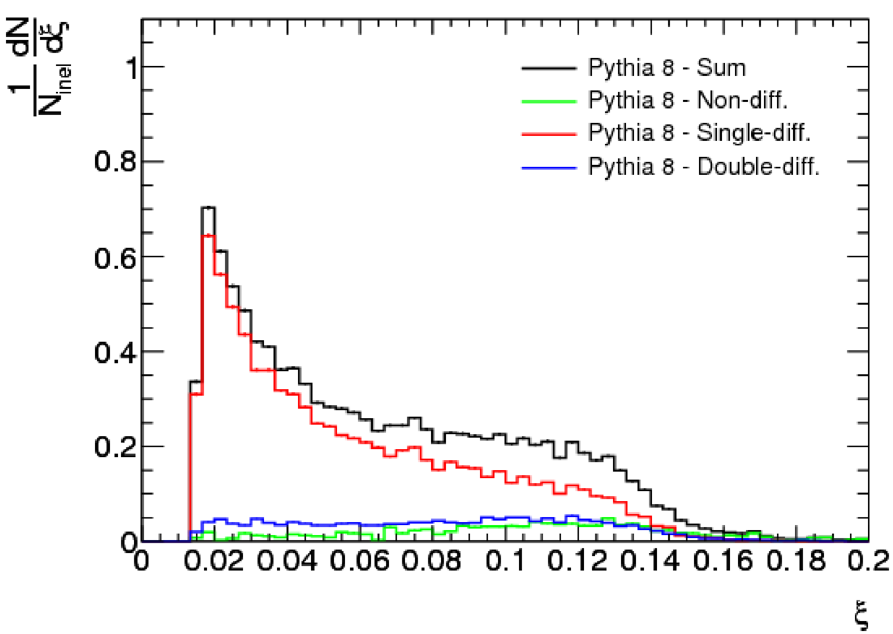


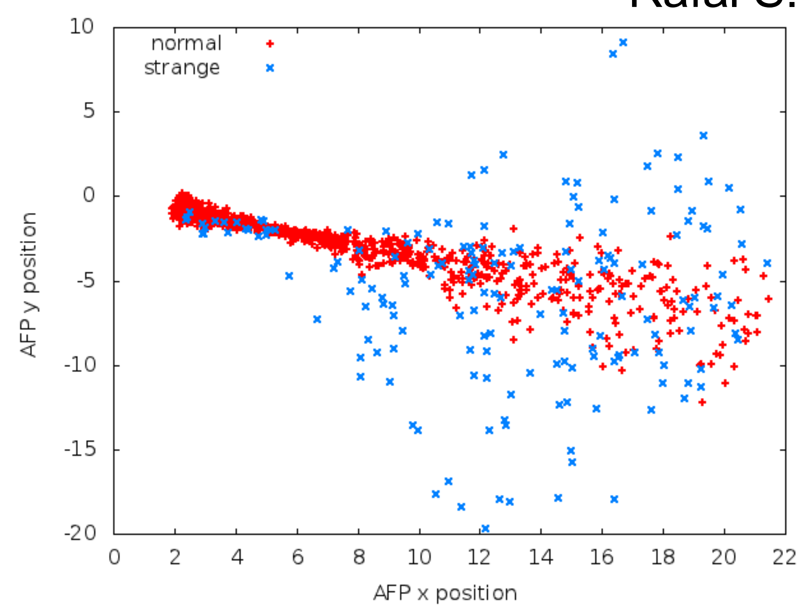


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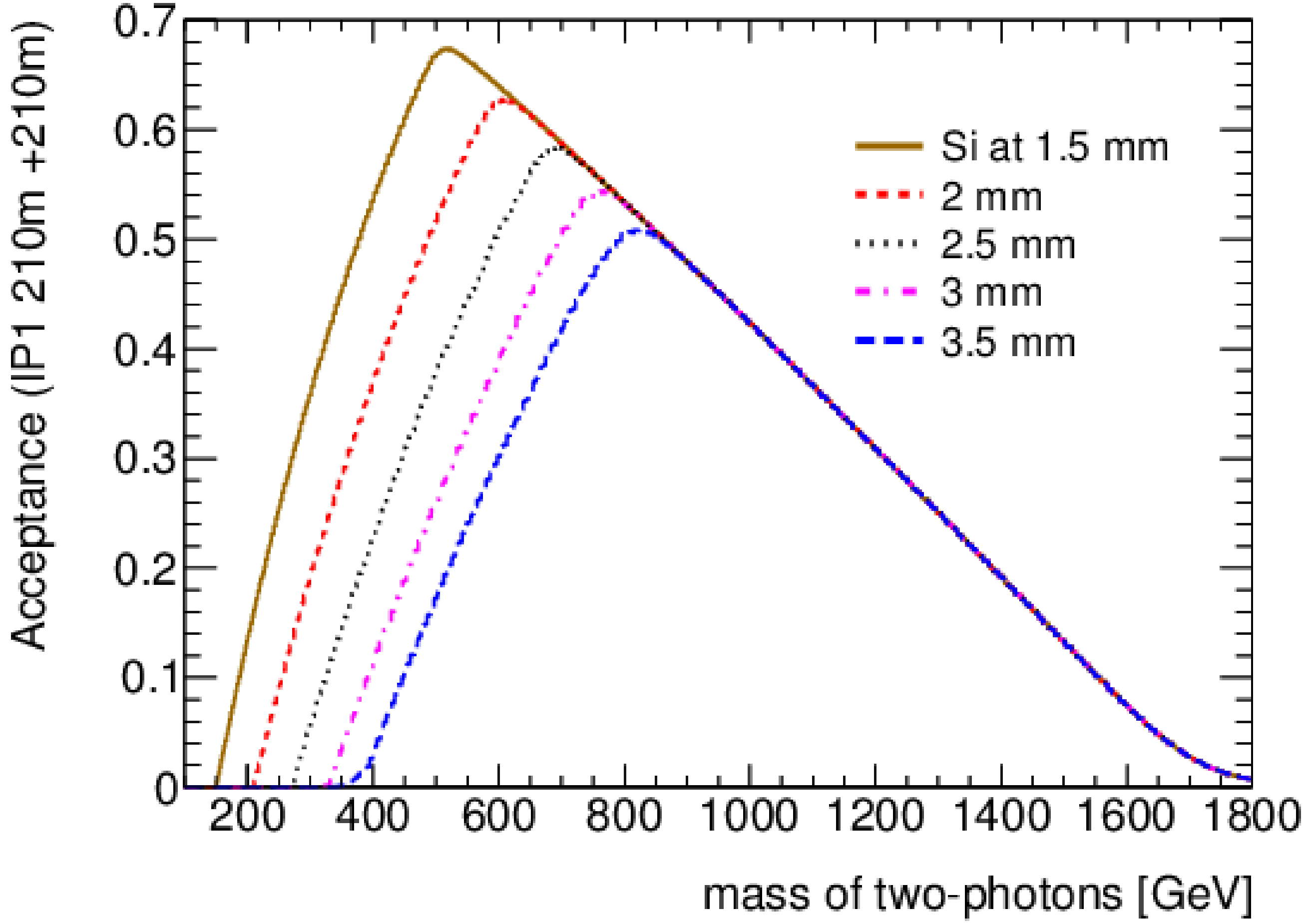
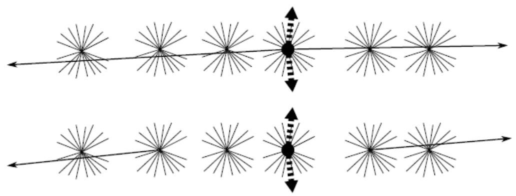
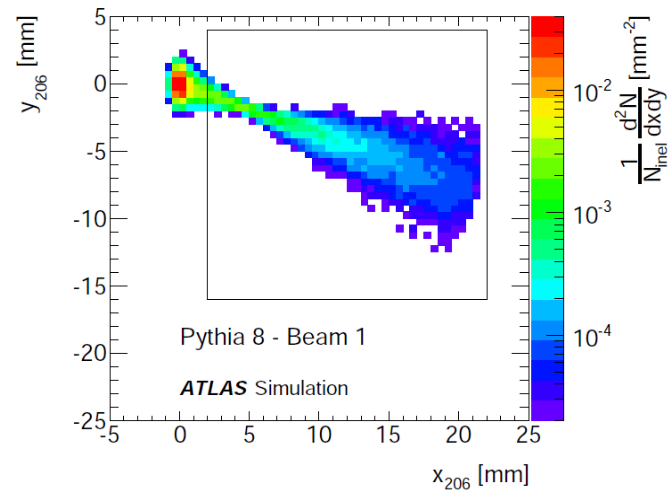

Acceptance (IP1 210m +210m)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
200
400
600
800
1000
1200
1400
1600
1800
mass of two-photons [GeV]
Si at 1.5 mm
2 mm
2.5 mm
3 mm
3.5 mm

# Multiple p-p collisions (Pile-up)



- Non-diffractive event in coincidence with two SD protons from MB events fake signal

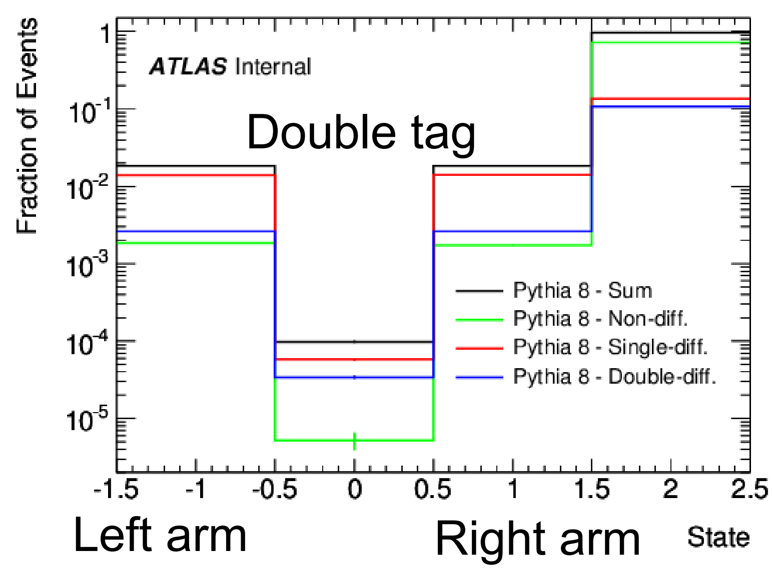



- MB interaction hits one detector in 2% cases
- Fake double tag in 0.01% cases

- ND/DD events (and SD on the side of broken proton) also show intact protons especially at high ξ

- Pythia 6 predicts by about factor 10 higher rates than Pythia8

- Starting ALFA diffractive program can provide important constraints to pile-up in AFP



# Study with Full Simulation

Signal:

- QED WW SM, with QGC, semi-leptonic decays

Backgrounds

- non-diffractive (+pile-up)
  - WW, WZ, ZZ, Drell-Yan, W/Z+jet, ttbar, single top
- diffractive
  - QED ll, SD WW, DPE WW, DPE ll

- Neglecting: Photon+Pomeron exchanges

- Generators: FPMC, Herwig++, Pythia8

- Fully simulated samples in Athena rel. 16
  - μ=23, 46 – corresponding to 40 and 300 $fb^{-1}$