Hot Topics in MBI

MBI 2015, Hamburg

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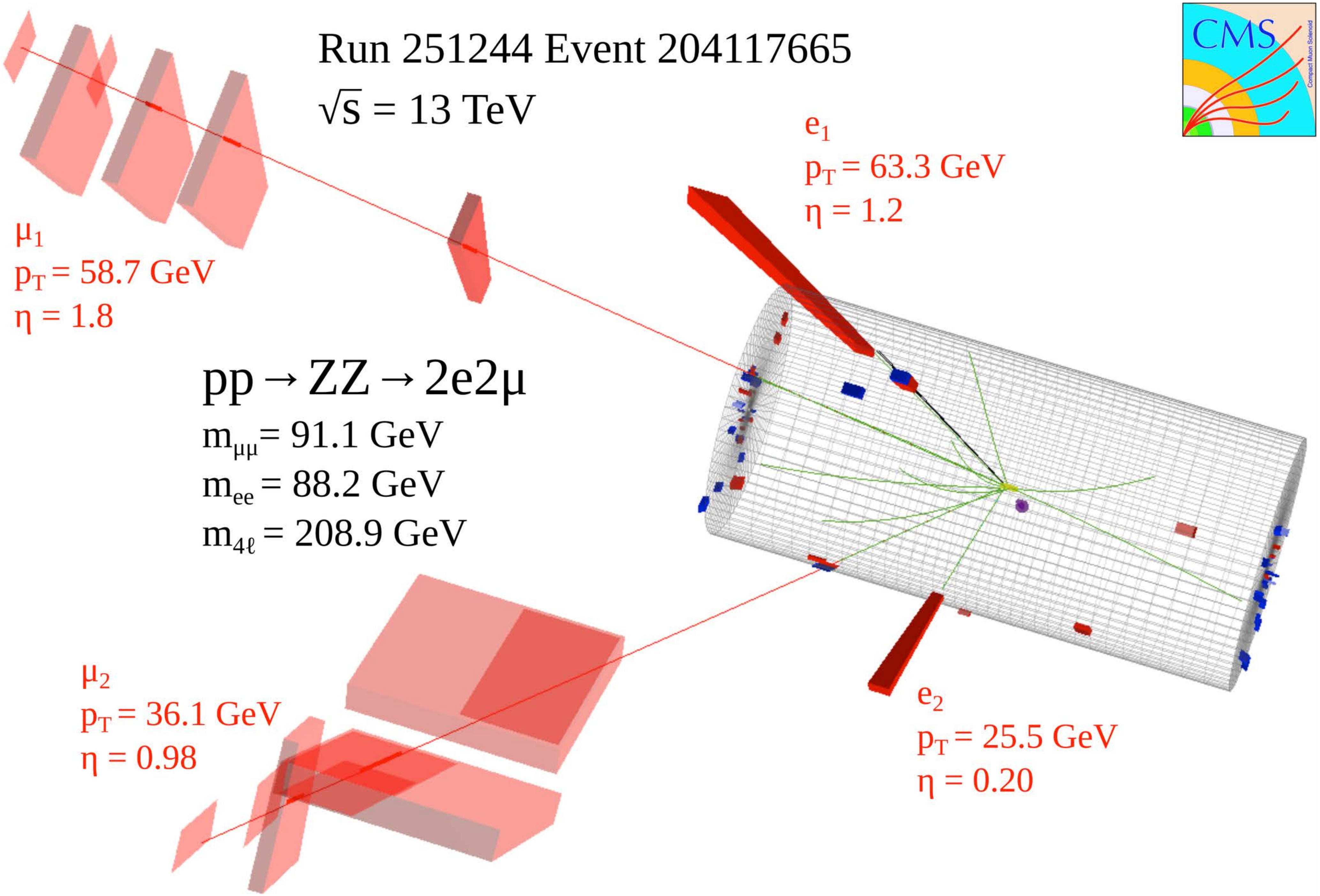
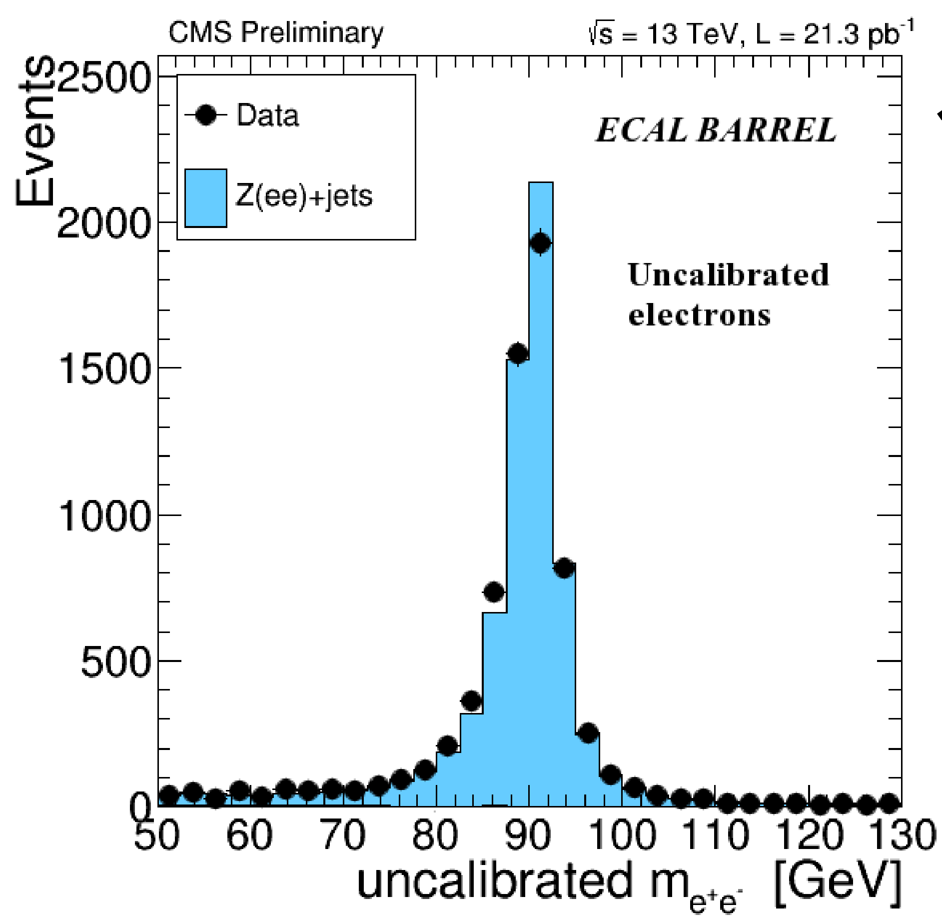
Run II Di-Boson Results

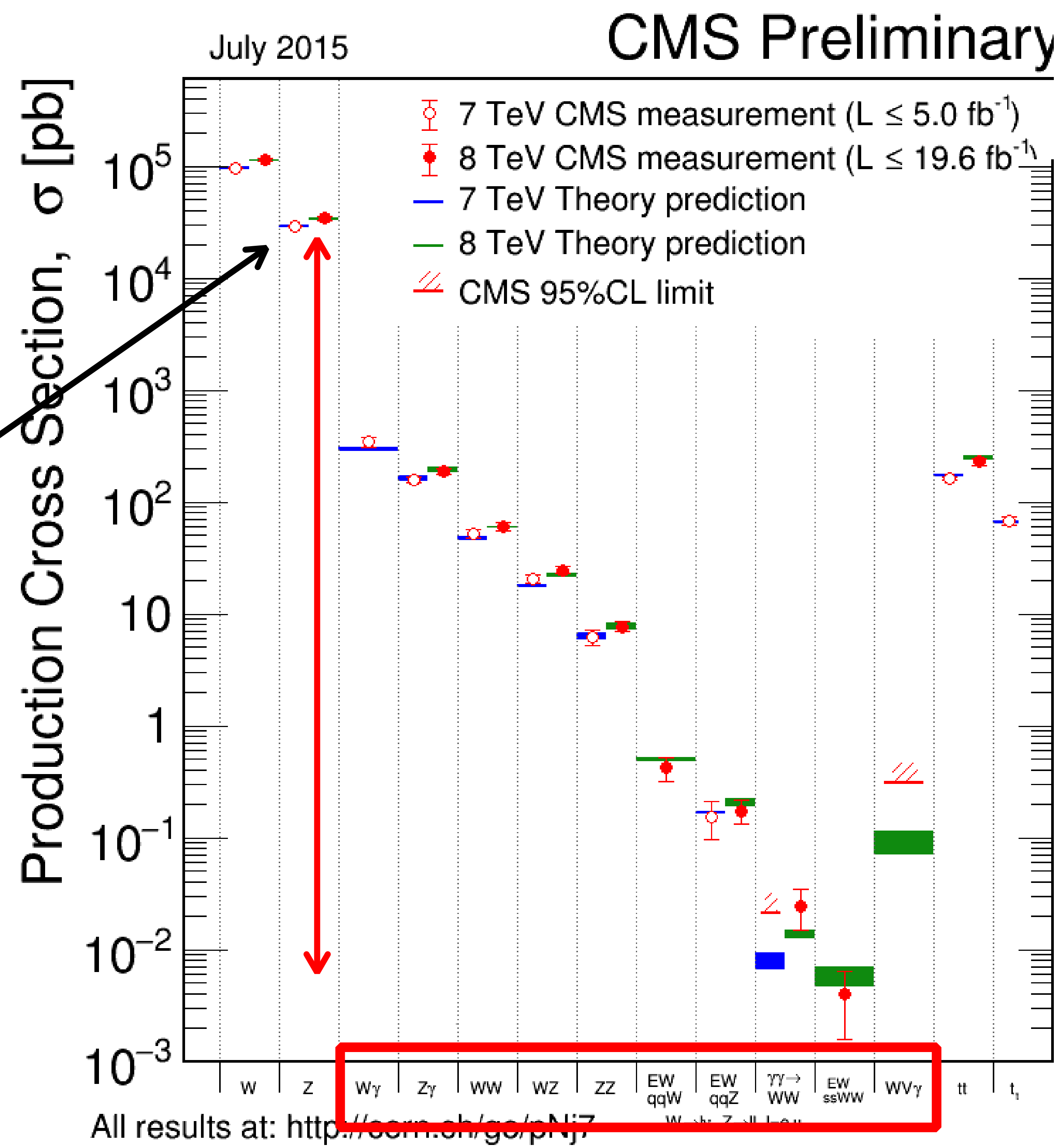
- ~~1fb^{-1}~~ 40pb^{-1}: ~~lots~~ little lumi to do di-boson physics with



Current Developments

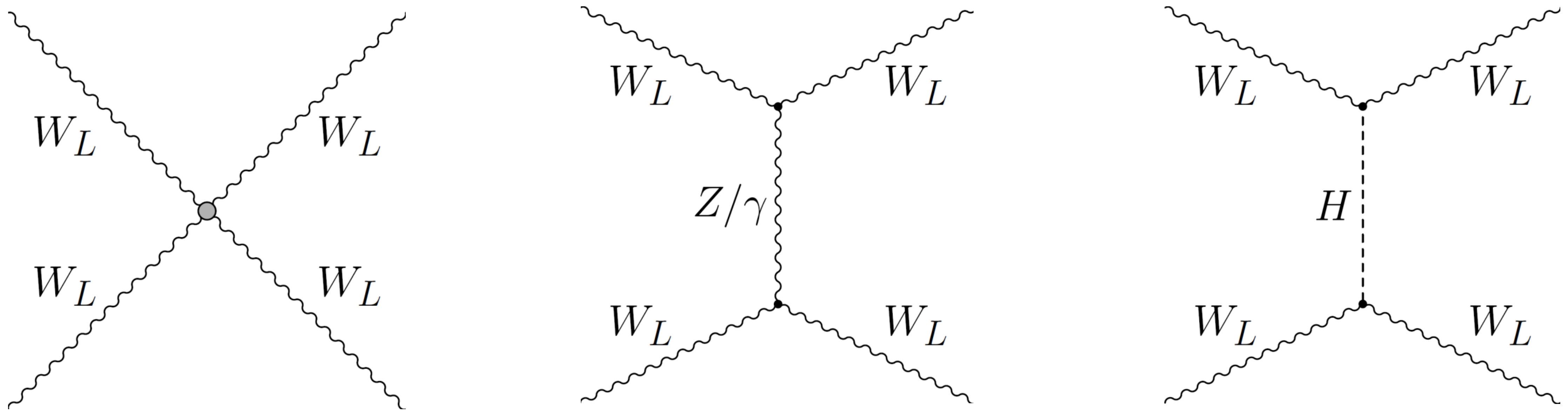
- No serious Run II results yet
- But 8TeV results still being finished
  => some highlights





Hot Topics at 8TeV

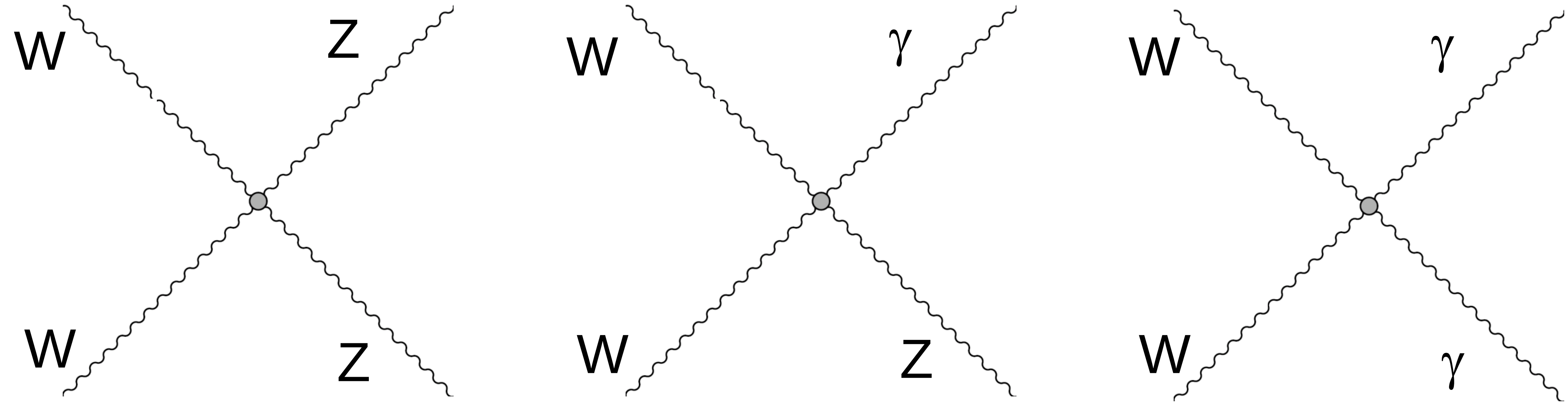
- SM Quartic Gauge Vertex
- Not easily studied at LEP
- Central to EWK Symmetry breaking



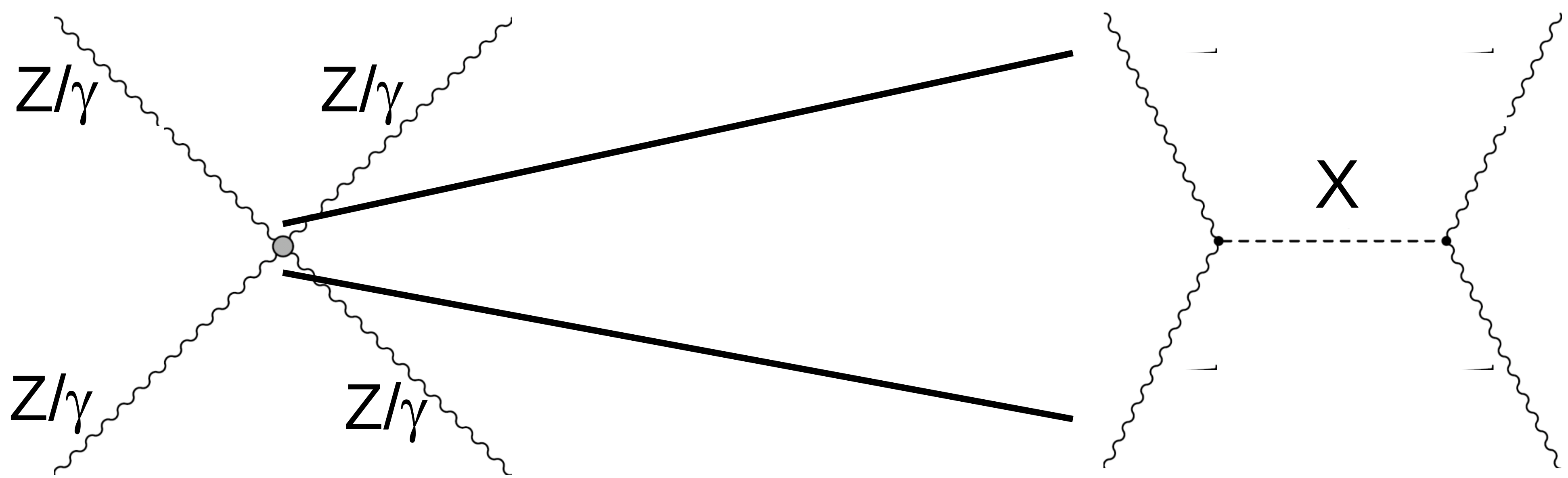
- First results in $W^{\pm}W^{\pm}$ final states from the LHC
  => will be hot again with more Run II data

Other Quartic Vertices

- WW scattering not the only SM quartic vertex



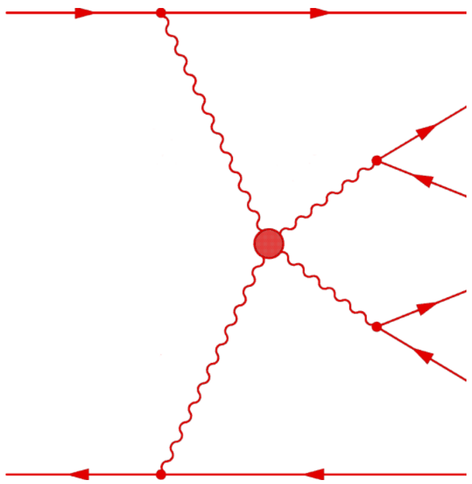
- All Neutral vertices forbidden in SM
  => but maybe new high scale physics?

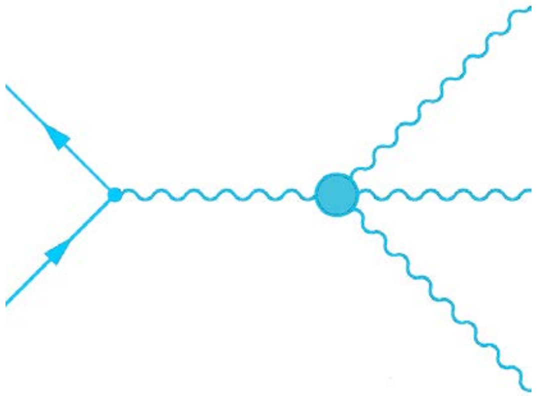


Places to Look

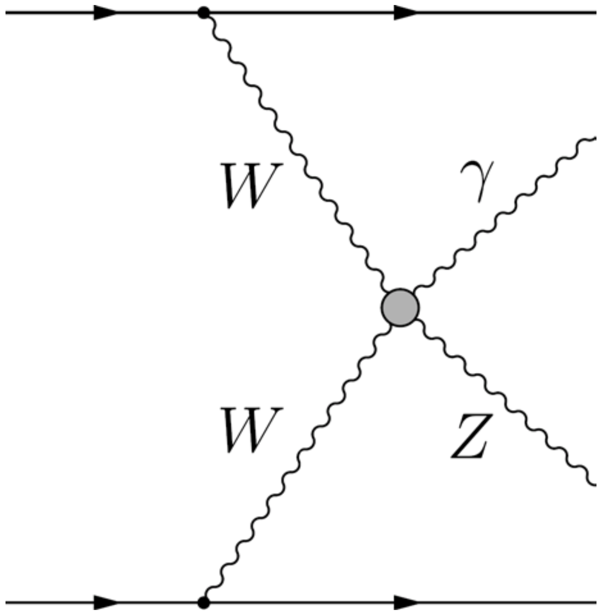
- WVγ — Phys. Rev. D 90, 032008 (2014)
- Zγ + 2jets (a.k.a. ewk Zγ) — SMP-14-018 NEW
- exclusive WW (a.k.a $\gamma\gamma \rightarrow$ WW) — FSQ-13-008 NEW, JHEP 07 (2013) 116
- W^+W^+ + jets (a.k.a. ewk ss WW) — PRL 114 (2015) 051801

=> covering the whole SM Lagrangian



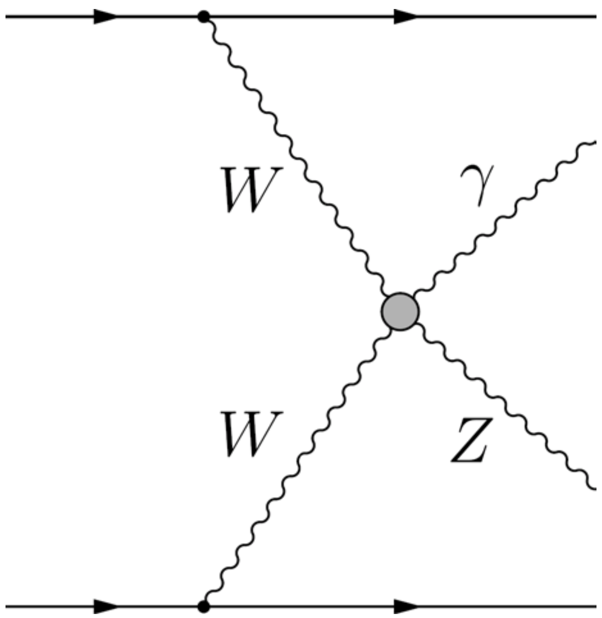


EWK Z+γ



QGC

EWK Z+γ



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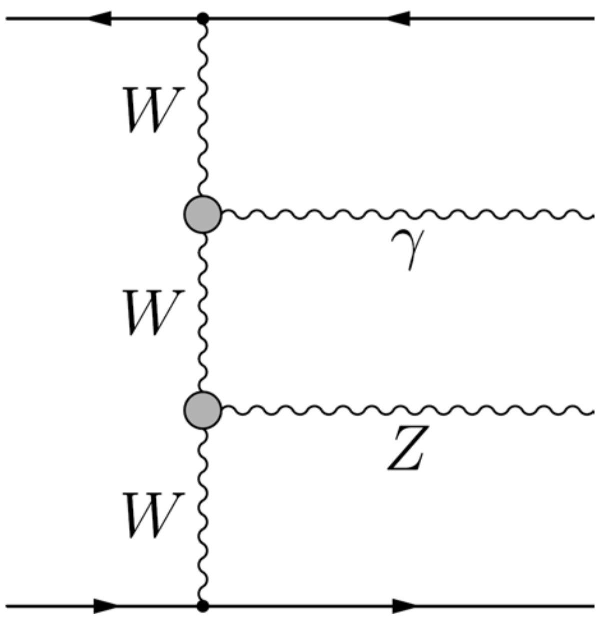
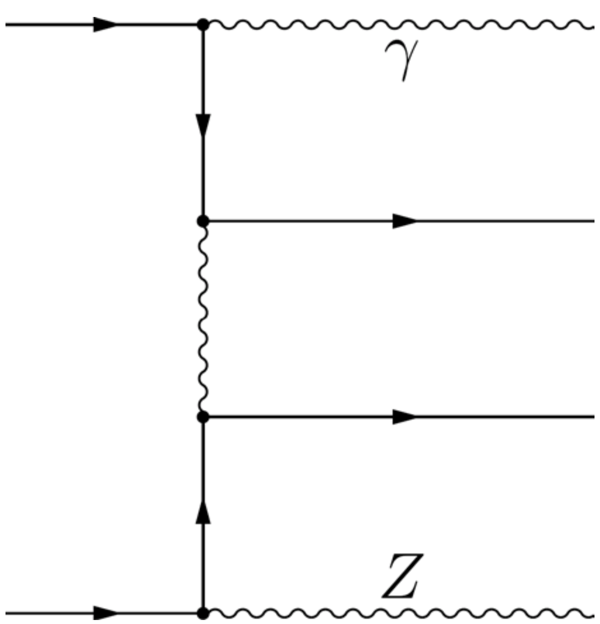


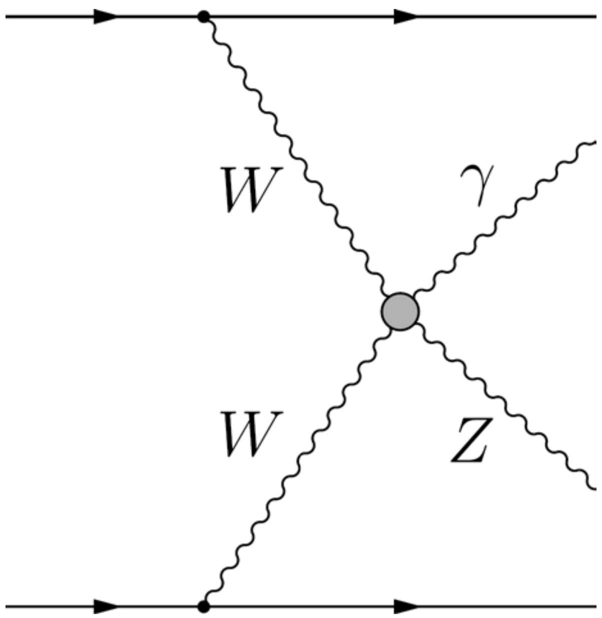
TGC



Double Brem

+ … (other α^5)

EWK Z+γ



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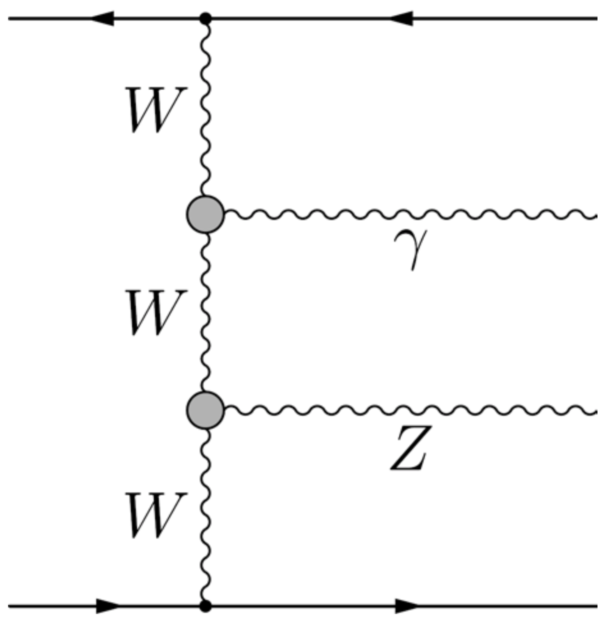

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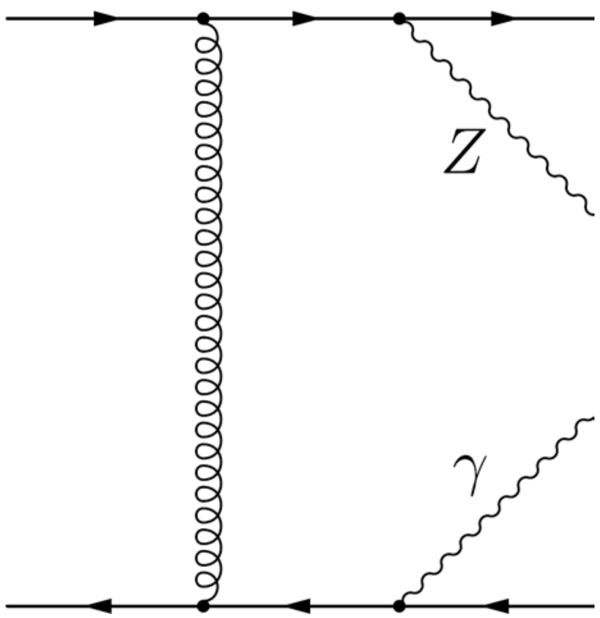
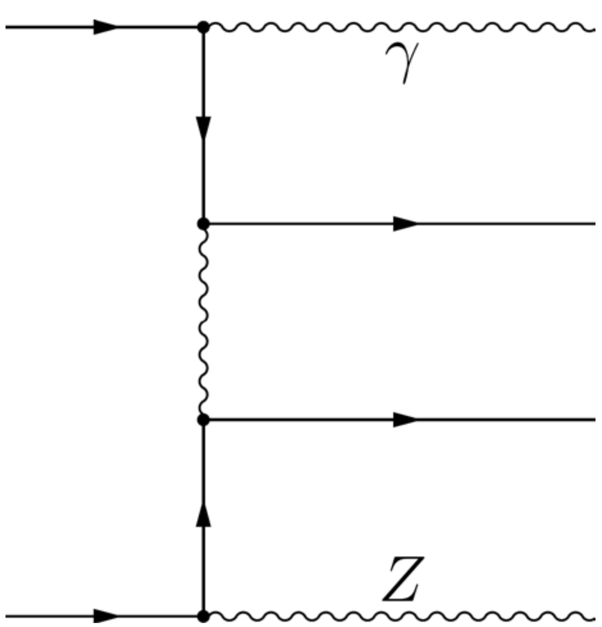
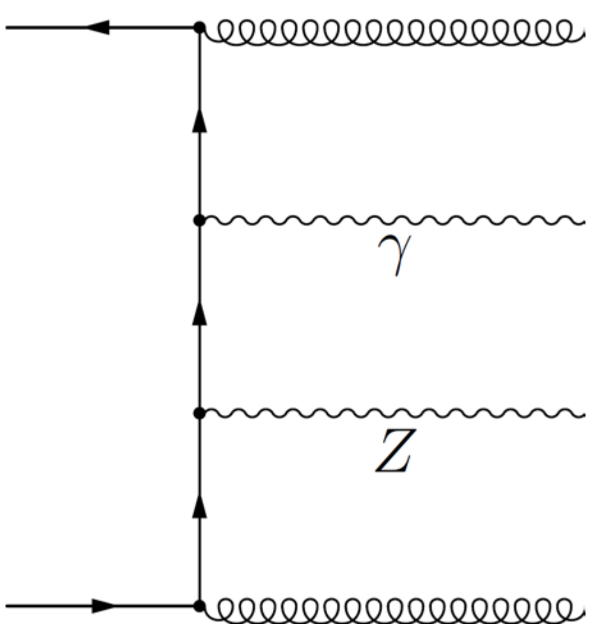




Double Brem

+ … (other α^5)



+ … (other $\alpha^3\alpha_s^2$)

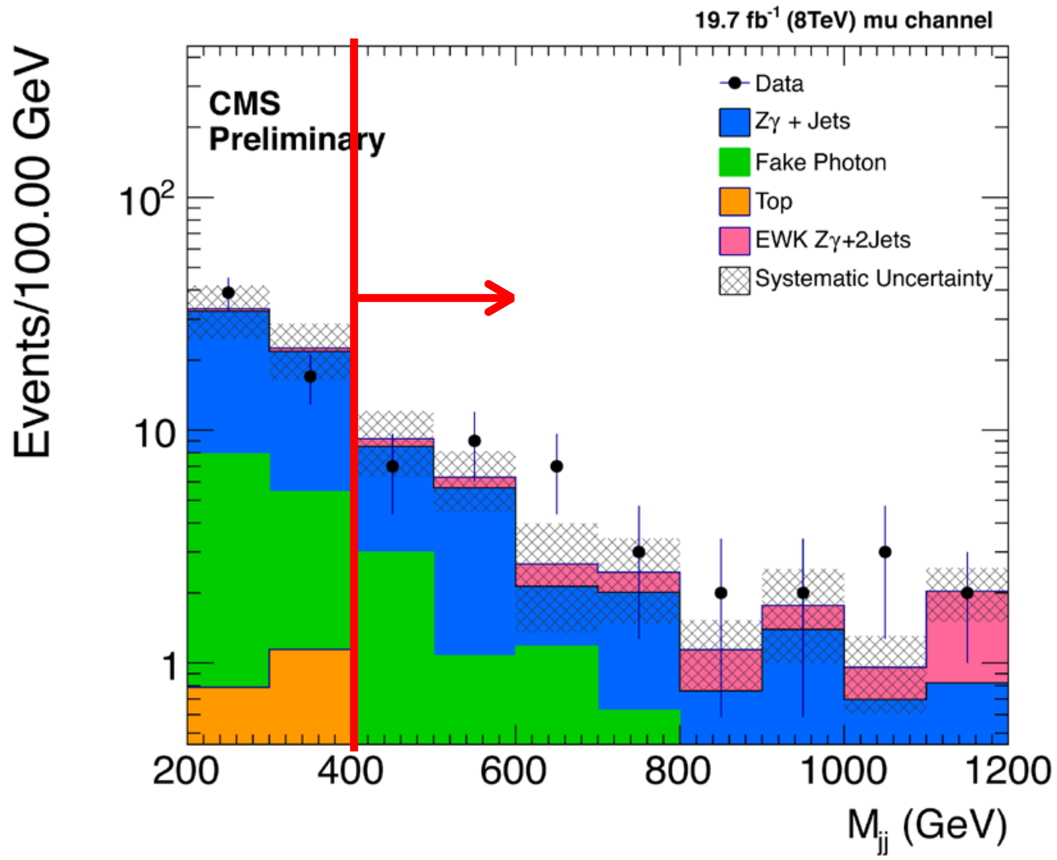
VBS Selection

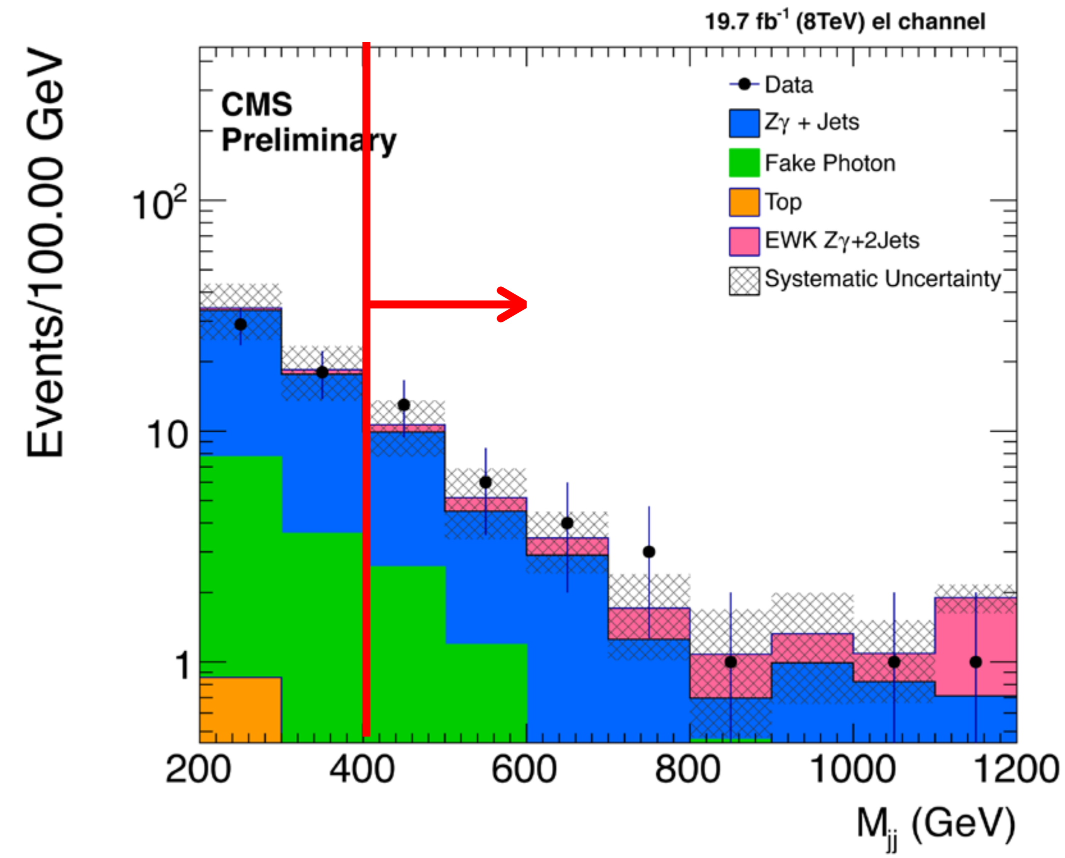
- enrich ewk component with VBS cuts:

	EWK	EWK+QCD
$\Delta\eta_{jj}$	> 1.6	> 1.6
M_{jj}	> 400 GeV	> 800 GeV
$\Delta\phi_{Z\gamma,jj}$	> 2.0	-
$\lvert y_{Z\gamma} - y_{jj}^{avg}\rvert$	<1.2	-

- trading purity for statistics
- Define an additional phase space region which has
  => lower non $Z\gamma$ background
  => higher significance for EWK+QCD $Z\gamma$
  => more QCD contribution + interference

EWK Z+γ

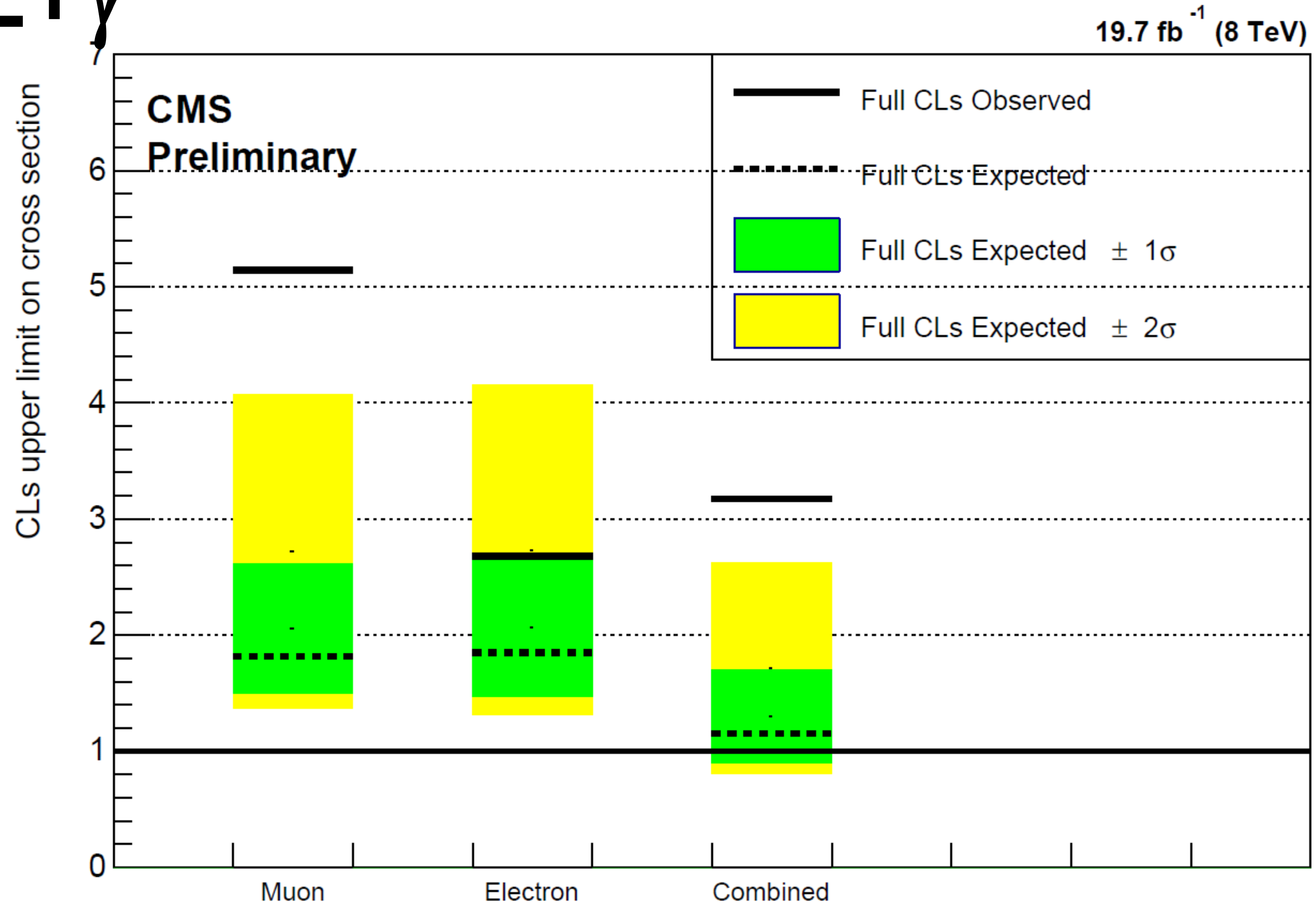




[SMP-14-018]

- Study cross section with template fits
  => two bins M < 800 GeV   M > 800 GeV
- Low cross sections => make limits as well as measurements

EWK Z+γ



[SMP-14-018]

- fid. xsec from template fit: $1.86^{+0.89}_{-0.75}(stat.)^{+0.41}_{-0.27}(sys.) \pm 0.05(lumi.)$ fb
- significance: 3.0 σ (2.1 σ expected)
- fid. xsec from theory (Madgraph): $1.26 \pm 0.11(scale) \pm 0.05(PDF)$

Effective Field Theory

- Use Dim8 Basis of Eboli et.al.:Phys.Rev.D74:073005,2006
  => 20 additional operators

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
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$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

Zγ: Relevant operators

- Use Dim8 Basis of Eboli et.al.:Phys.Rev.D74:073005,2006
  => 9 relevant for Zγ

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
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Zγ: Relevant operators

- Use Dim8 Basis of Eboli et.al.:Phys.Rev.D74:073005,2006
  => 2 previously unconstrained

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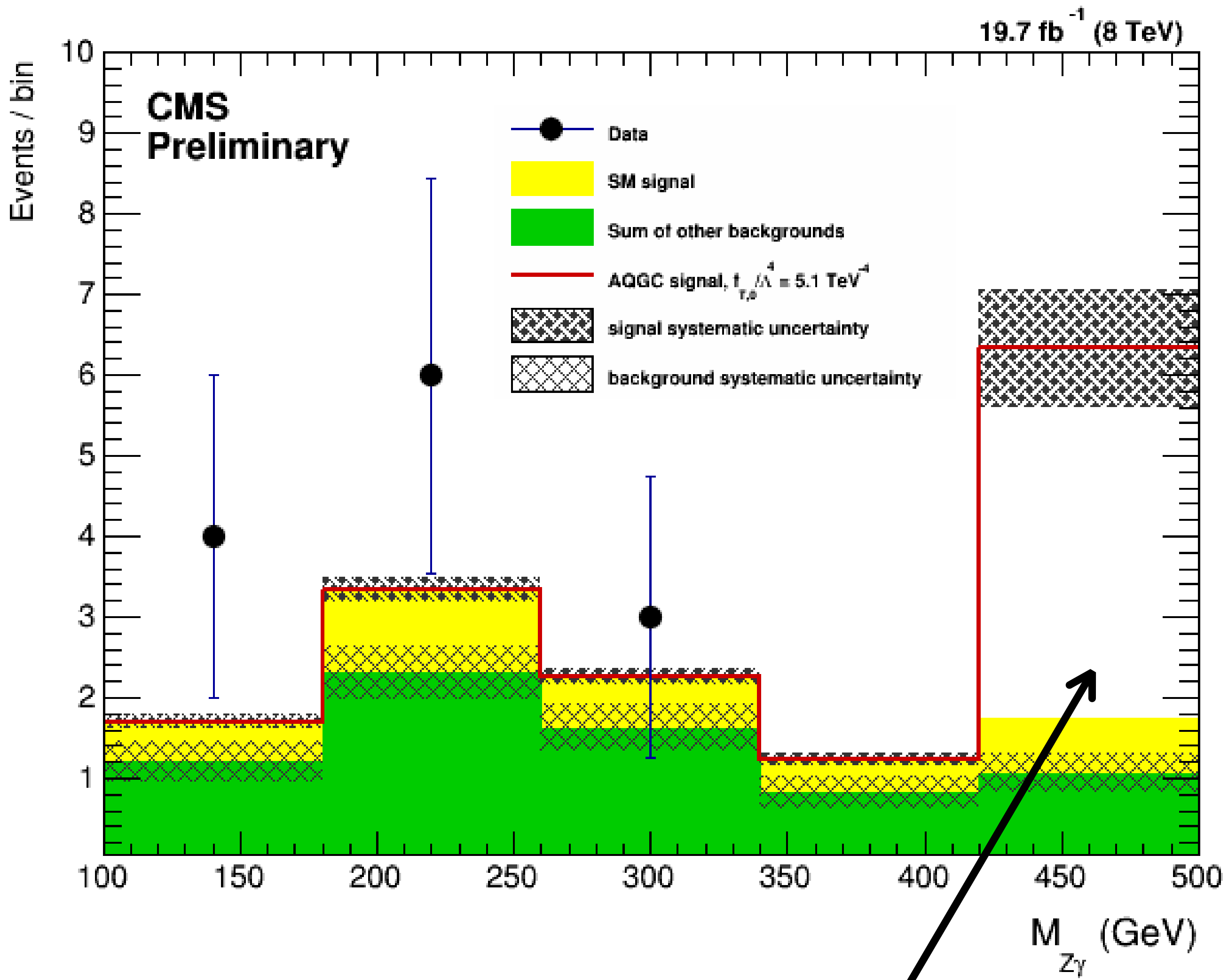
aQGC Limits

- Similar technique as Wγ
- Fully reconstructed final state
  => use $M_{Z\gamma}$
- Signal region:
  => no $\Delta\phi$, Zeppenfeld cuts
  => $\Delta\eta_{jj} > 2.6$
  => $p_{T,\gamma} > 60$ GeV
- All aQGCs studied in isolation
- No form factors
- Limit from likelihood ratios of template fits
- Very low statistics

[SMP-14-018]



Data excess has little influence on limit

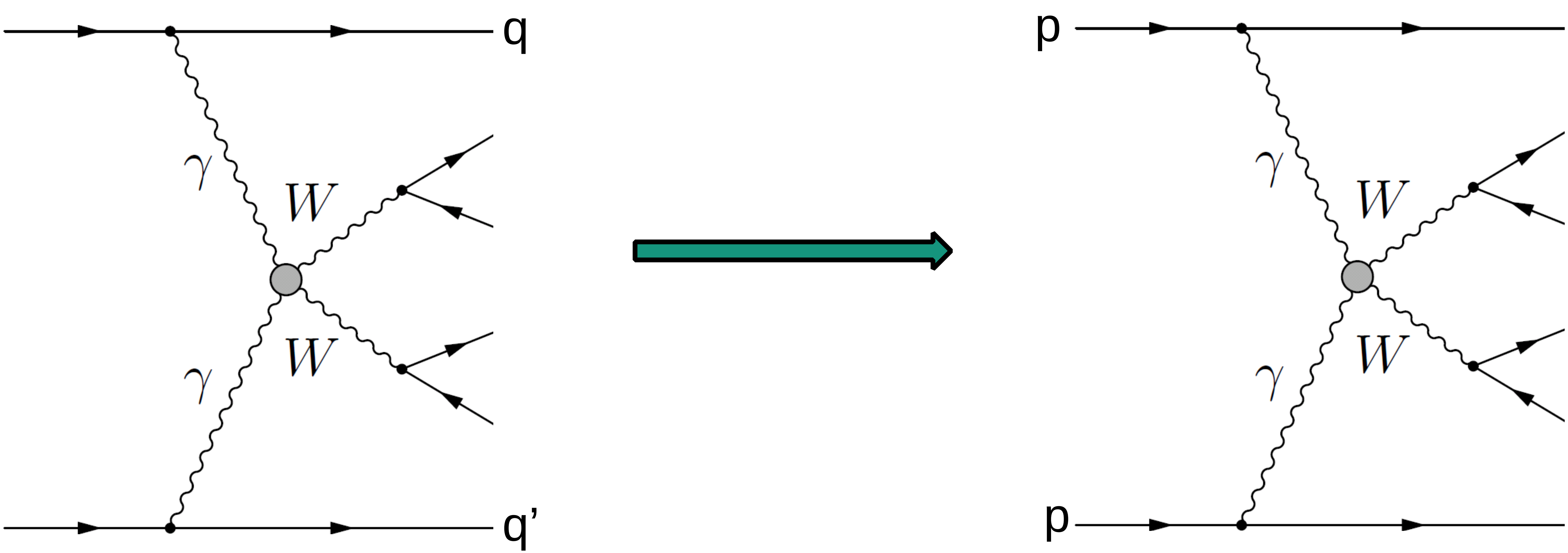
aQGC Limits

Observed Limits	Expected Limits
-71 (TeV^{-4}) $< f_{M0}/\Lambda^4 <$ 75 (TeV^{-4})	-109 (TeV^{-4}) $< f_{M0}/\Lambda^4 <$ 111 (TeV^{-4})
-190 (TeV^{-4}) $< f_{M1}/\Lambda^4 <$ 182 (TeV^{-4})	-281 (TeV^{-4}) $< f_{M1}/\Lambda^4 <$ 280 (TeV^{-4})
-32 (TeV^{-4}) $< f_{M2}/\Lambda^4 <$ 31 (TeV^{-4})	-47 (TeV^{-4}) $< f_{M2}/\Lambda^4 <$ 47 (TeV^{-4})
-58 (TeV^{-4}) $< f_{M3}/\Lambda^4 <$ 59 (TeV^{-4})	-87 (TeV^{-4}) $< f_{M3}/\Lambda^4 <$ 87 (TeV^{-4})
-3.8 (TeV^{-4}) $< f_{T0}/\Lambda^4 <$ 3.4 (TeV^{-4})	-5.1 (TeV^{-4}) $< f_{T0}/\Lambda^4 <$ 5.1 (TeV^{-4})
-4.4 (TeV^{-4}) $< f_{T1}/\Lambda^4 <$ 4.4 (TeV^{-4})	-6.5 (TeV^{-4}) $< f_{T1}/\Lambda^4 <$ 6.5 (TeV^{-4})
-9.9 (TeV^{-4}) $< f_{T2}/\Lambda^4 <$ 9.0 (TeV^{-4})	-14.0 (TeV^{-4}) $< f_{T2}/\Lambda^4 <$ 14.5 (TeV^{-4})
-1.8 (TeV^{-4}) $< f_{T8}/\Lambda^4 <$ 1.8 (TeV^{-4})	-2.7 (TeV^{-4}) $< f_{T8}/\Lambda^4 <$ 2.7 (TeV^{-4})
-4.0 (TeV^{-4}) $< f_{T9}/\Lambda^4 <$ 4.0 (TeV^{-4})	-6.0 (TeV^{-4}) $< f_{T9}/\Lambda^4 <$ 6.0 (TeV^{-4})

Limits slightly better than expected

Not reaching unitarity limits

WW Exclusive Production



- Low photon virtuality
  => protons don't dissociate
- mostly EWK processes
- Can be very pure for strict dissociation vetos

Analysis Strategy

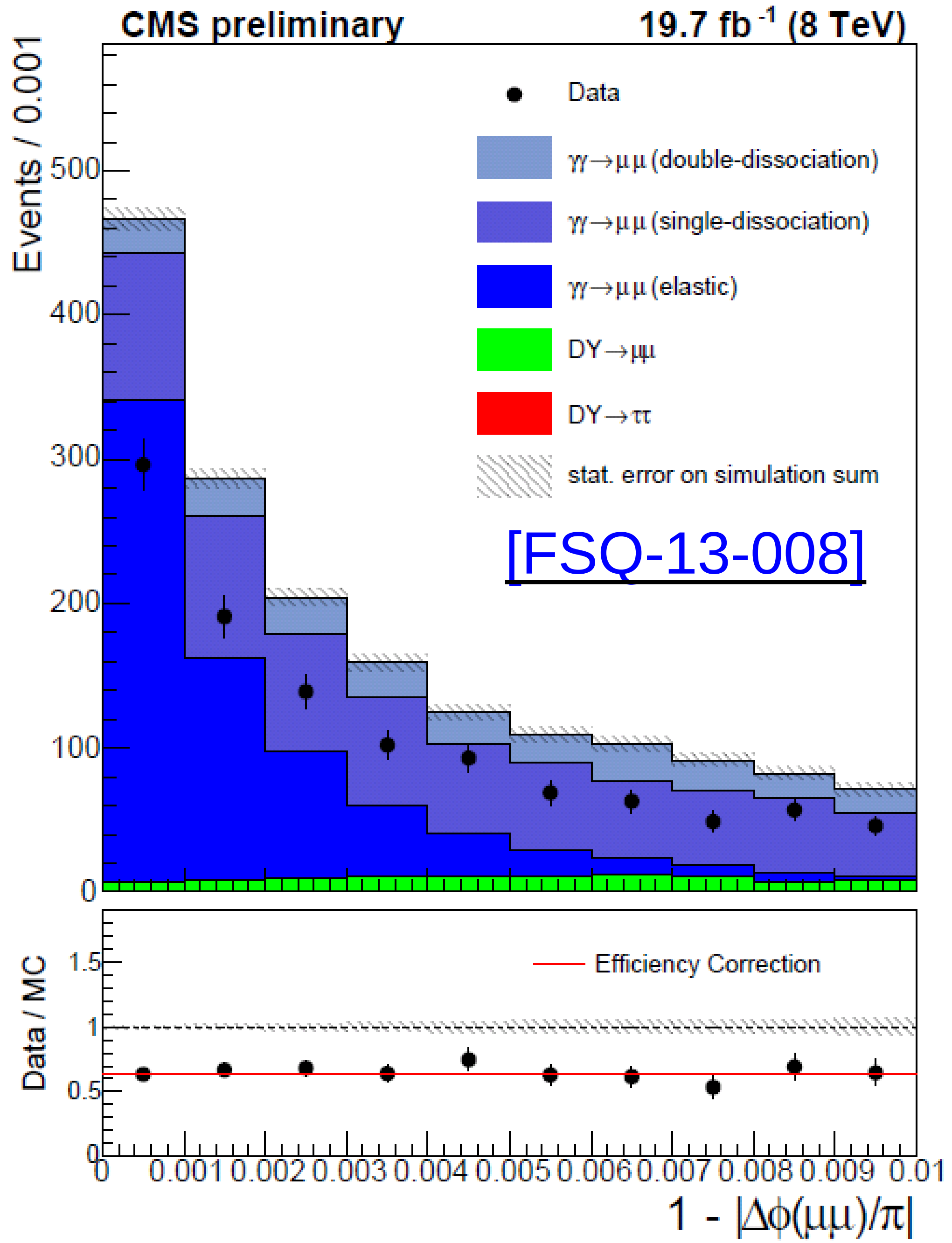
- Select e + μ (opposite charge)
  => suppress DY
  => suppress $\gamma\gamma \to ll$
- $p_T(e\mu) > 30$ GeV
  => suppress $\gamma\gamma \to \tau\tau$
- Veto **all** tracks other than e,μ tracks from PV
  => suppress dissociative processes
- Worry about modeling the tiny corner of phase space left

Tricks of the Trade

- Excellent understanding of tracking efficiency, fakes
- PU estimates, vertexing
- Arcane hadronic physics effects:
  => Pomerons
  => rescattering / gap-survival propability
- Specialized MC generators
  => POMPYT (diffractive WW)
  => Madgraph with Effective Photon Approximation
  => LPAIR for EWK ll
- Many uncommon features
  => can’t just trust background simulation
  => extensive studies of control regions

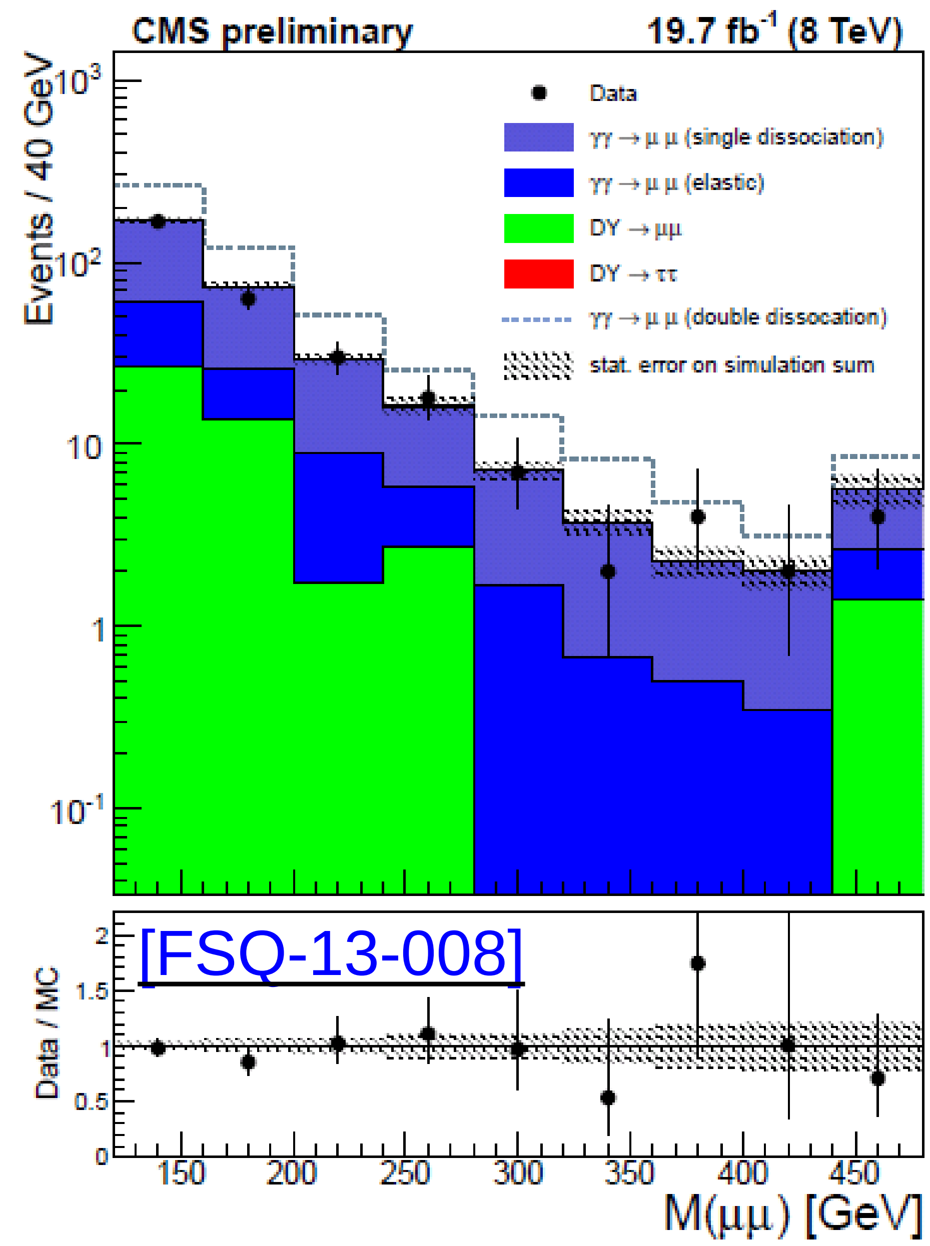
Track Mis-Association

- Mistaken association of PU tracks
- check $\gamma\gamma \rightarrow ll$ events
- track veto enriches ewk process
- look at very low acoplanarity:
  => enriches elastic contribution
- Data yield lower than MC
  => low p_T forward tracks common
  => high chance of mis-association
- Corrected with flat scale factor
  => causes significant uncertainty



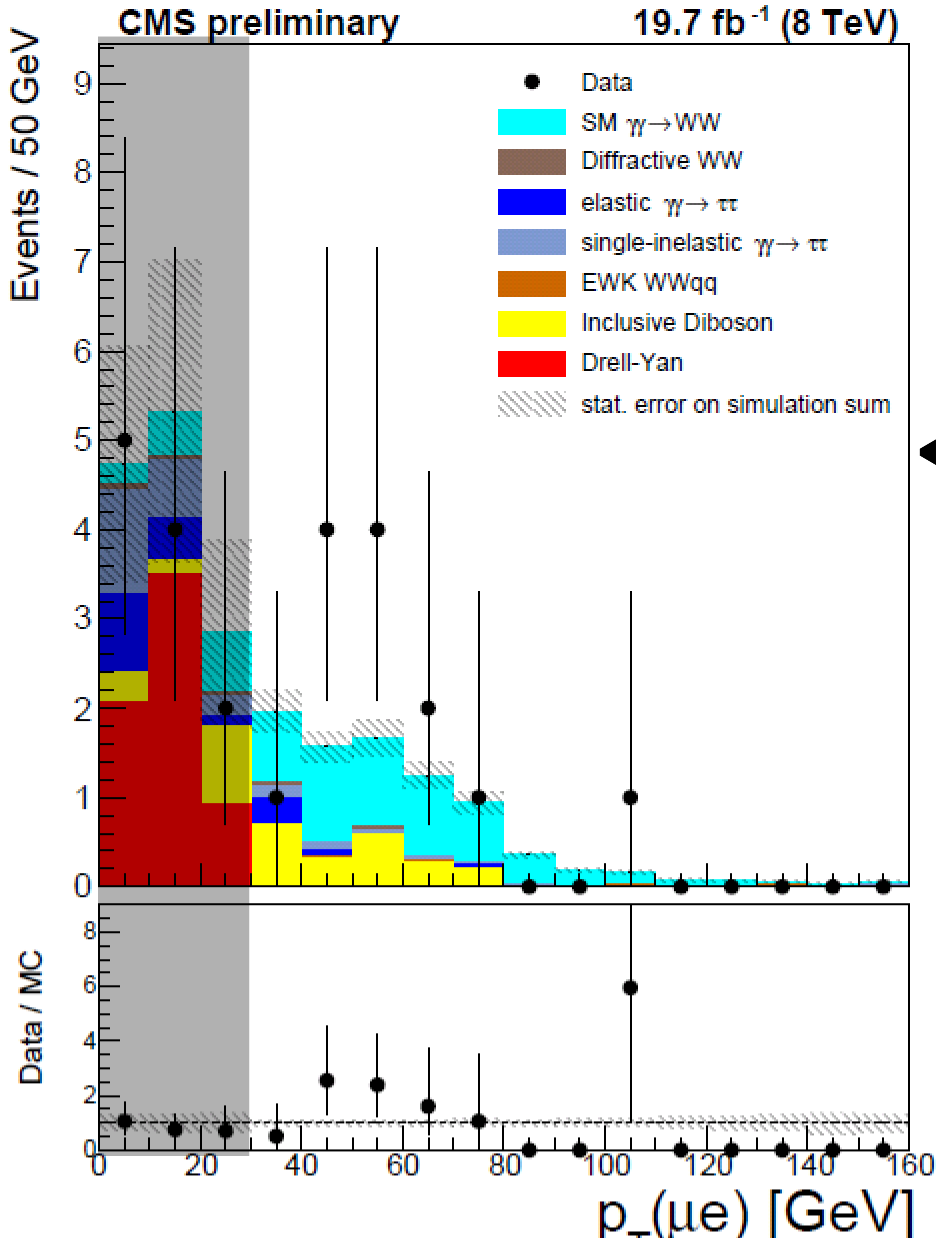
Rescattering

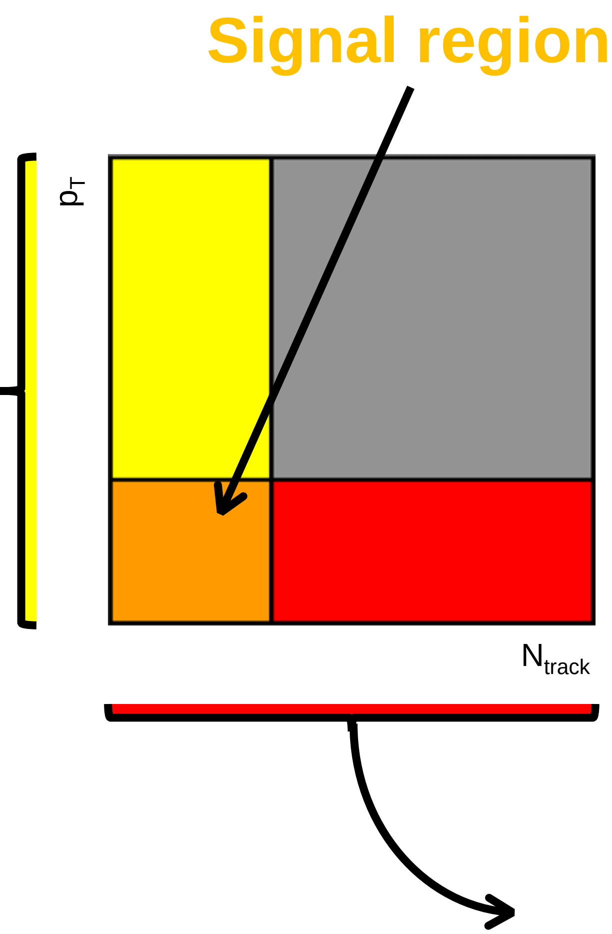
- Rescattering probability in elastic and quasi-elastic pp collisions not well understood
- Long standing issue in comparisons of Tevatron and HERA diffraction
- Significantly different for
  elastic => little rescattering
  single diss. => ???
  double diss. => high rescattering
- Use $\gamma\gamma \rightarrow ll$ to estimate survival eff.
  => constrain to $M_{ll} > 2M_W$
- Single largest systematic uncertainty (~10%)

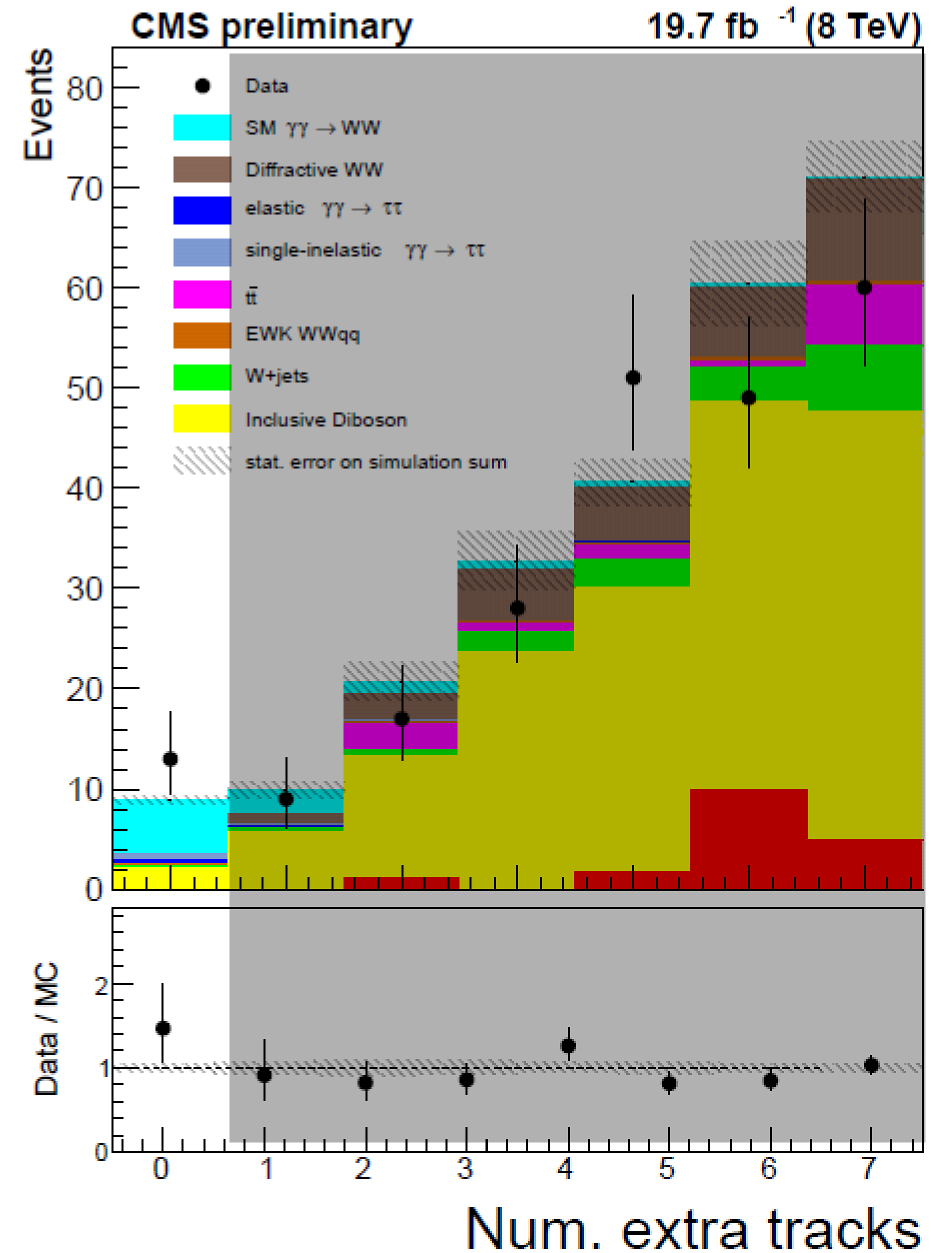


[FSQ-13-008]

Results







- 13 events observed (8.8 expectes)
  => 3.6σ (2.4σ expected)

[FSQ-13-008]

$$\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}) = 12.3^{+5.5}_{-4.4}\text{fb}.$$

Anomalous couplings

- Use Dim8 Basis of Eboli et.al.:Phys.Rev.D74:073005,2006

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu}$$
$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu}$$
$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$$
$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$
$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$
$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$
$$\mathcal{L}_{T,3} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\hat{W}^{\nu\alpha}\right] \times B_{\beta\nu}$$
$$\mathcal{L}_{T,4} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\alpha\mu}\hat{W}^{\beta\nu}\right] \times B_{\beta\nu}$$
$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$
$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$
$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

- Additionally provide limits on operators of Belanger & Boudjema Phys.Lett. **B288** (1992) 201–209

Observed Limits

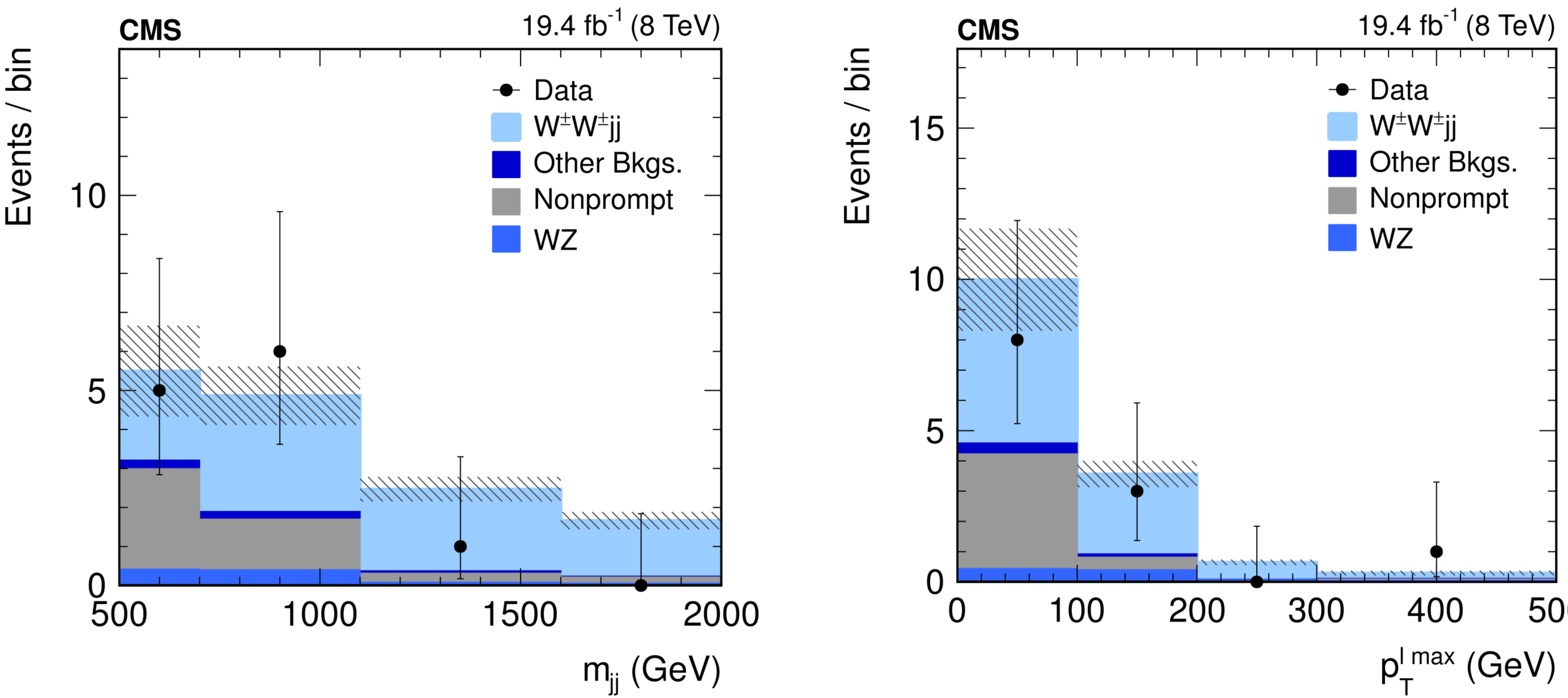
- Use $p_T(e\mu)$ spectrum for "shape analysis"
  => two bins, one SM-rich, one aQGC-rich

$$-4.2 \times 10^{-10} < f_{M,0}/\Lambda^4 < 3.8 \times 10^{-10}\,\mathrm{GeV}^{-4} \quad (\Lambda_{\mathrm{cutoff}} = 500\,\mathrm{GeV}),$$
$$-16 \times 10^{-10} < f_{M,1}/\Lambda^4 < 13 \times 10^{-10}\,\mathrm{GeV}^{-4} \quad (\Lambda_{\mathrm{cutoff}} = 500\,\mathrm{GeV}),$$
$$-2.1 \times 10^{-10} < f_{M,2}/\Lambda^4 < 1.9 \times 10^{-10}\,\mathrm{GeV}^{-4} \quad (\Lambda_{\mathrm{cutoff}} = 500\,\mathrm{GeV}),$$
$$-8.0 \times 10^{-10} < f_{M,3}/\Lambda^4 < 6.4 \times 10^{-10}\,\mathrm{GeV}^{-4} \quad (\Lambda_{\mathrm{cutoff}} = 500\,\mathrm{GeV}).$$
$$-4.6 \times 10^{-12} < f_{M,0}/\Lambda^4 < 4.6 \times 10^{-12}\,\mathrm{GeV}^{-4} \quad (\text{no form factor}),$$
$$-17 \times 10^{-12} < f_{M,1}/\Lambda^4 < 17 \times 10^{-12}\,\mathrm{GeV}^{-4} \quad (\text{no form factor}),$$
$$-2.3 \times 10^{-12} < f_{M,2}/\Lambda^4 < 2.3 \times 10^{-12}\,\mathrm{GeV}^{-4} \quad (\text{no form factor}),$$
$$-8.3 \times 10^{-12} < f_{M,3}/\Lambda^4 < 8.3 \times 10^{-12}\,\mathrm{GeV}^{-4} \quad (\text{no form factor}).$$

Ewk W^+W^+

- WW final state directly sensitive to W_LW_L coupling
- same charge requirement suppresses many backgrounds:
  => DY (with fake MET)
  => tt
  => QCD WW (no gluon induced diagram)
- Can reach very high purity
- Some tricky issues:
  => needs good understanding of charge reconstruction
  => lepton fake rate
  => b-tags (to further reduce top-backgrounds)

Ewk W^+W^+



[PRL 114 (2015) 051801]

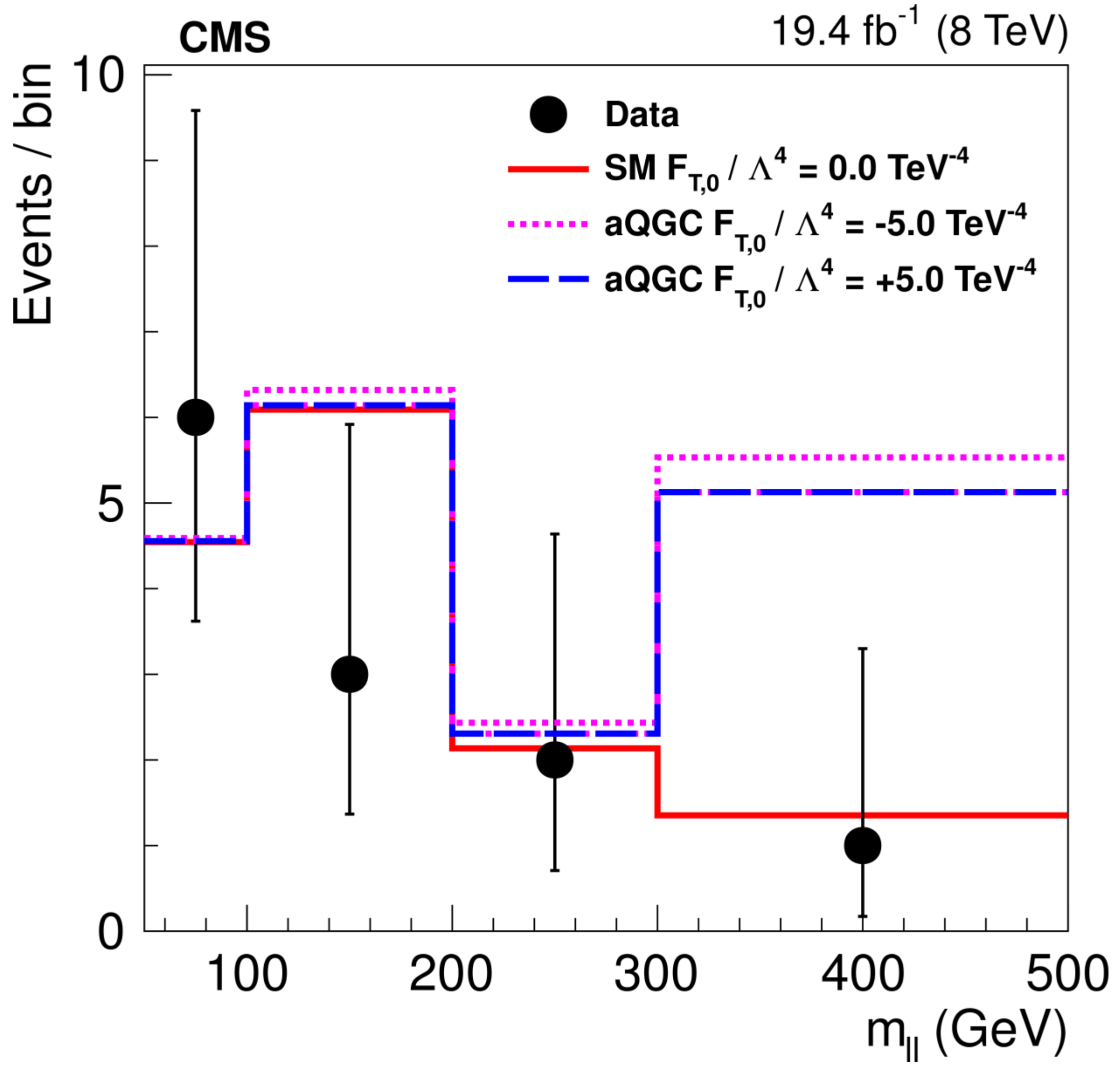
- Very pure, but low statistics => marginal cross section measurement

$$\sigma_{\text{fid}}(W^{\pm}W^{\pm}jj) = 4.0^{+2.4}_{-2.0}\,(\text{stat})^{+1.1}_{-1.0}\,(\text{syst})\,\text{fb}$$

- Theory: 5.8 ± 1.2 (Madgraph + VBFNLO)
- significance: 2.0 σ (expected: 3.1 σ)

Ewk W^+W^+

- Limits extracted from M_{ll} spectrum
- Profits from high purity
- Also looking for $H^{\pm\pm}$

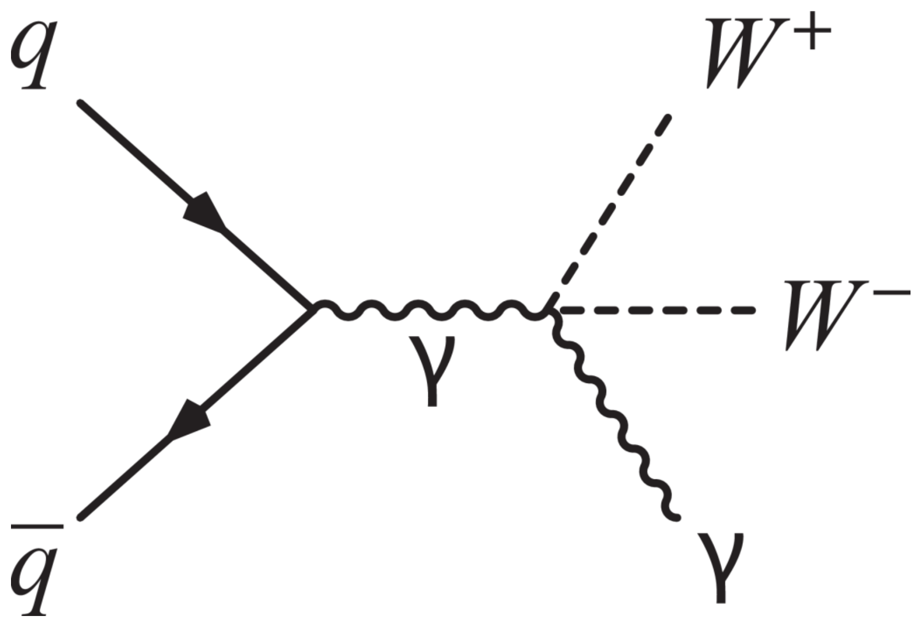


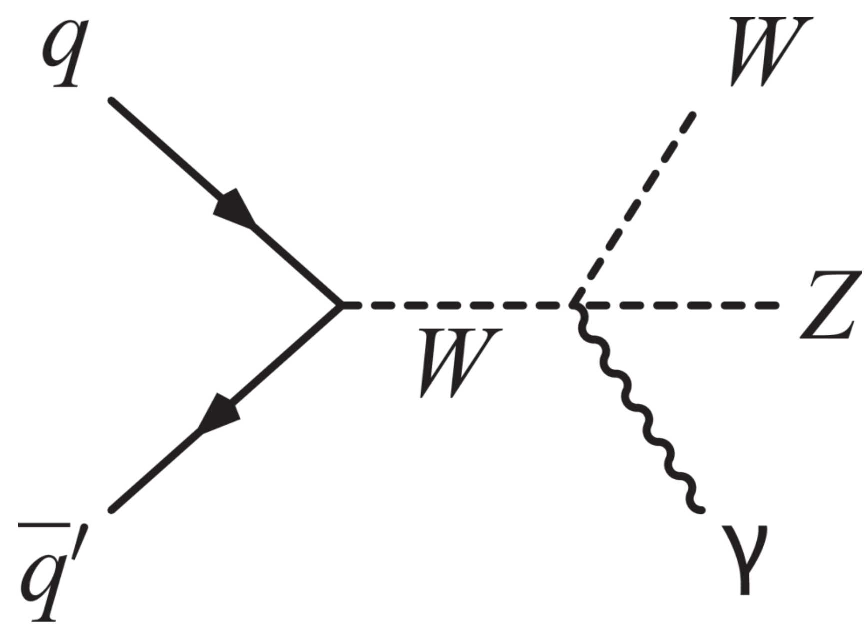
[PRL 114 (2015) 051801]

Operator coefficient	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity limit
$F_{S,0}/\Lambda^4$	−42	43	−38	40	0.016
$F_{S,1}/\Lambda^4$	−129	131	−118	120	0.050
$F_{M,0}/\Lambda^4$	−35	35	−33	32	80
$F_{M,1}/\Lambda^4$	−49	51	−44	47	205
$F_{M,6}/\Lambda^4$	−70	69	−65	63	160
$F_{M,7}/\Lambda^4$	−76	73	−70	66	105
$F_{T,0}/\Lambda^4$	−4.6	4.9	−4.2	4.6	0.027
$F_{T,1}/\Lambda^4$	−2.1	2.4	−1.9	2.2	0.022
$F_{T,2}/\Lambda^4$	−5.9	7.0	−5.2	6.4	0.08

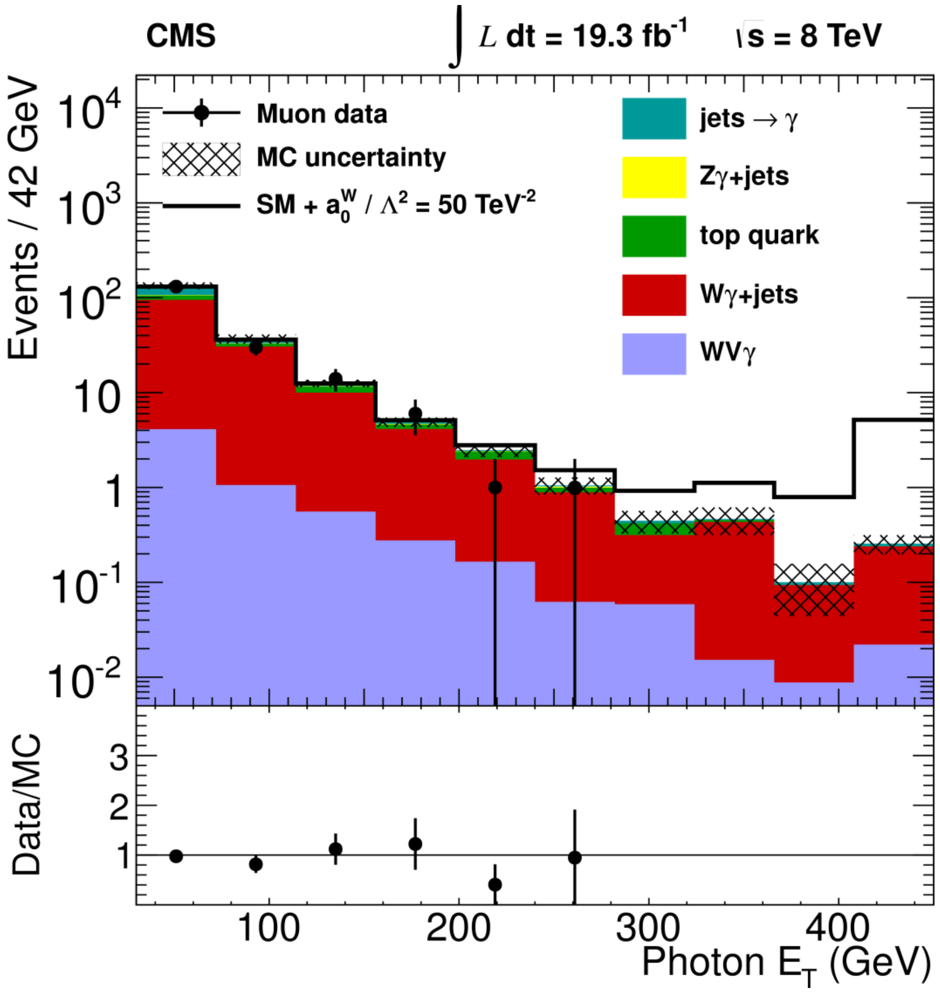
WVγ

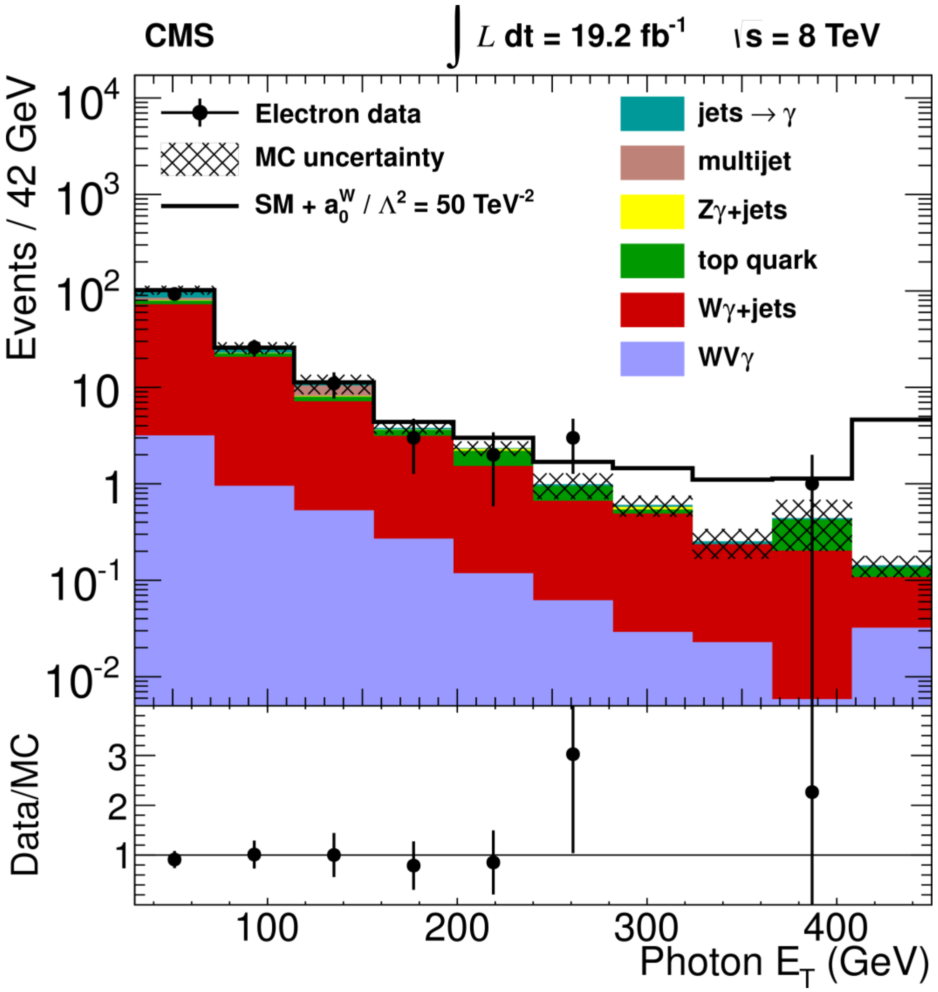
- Only triple-boson analysis in CMS so far
- Use one leptonic W decay for trigger
- Second heavy boson decays hadronically
  => gain high branching ratio
  => gain huge Wγ + jets background
  => W/Z not distinguished
- Uses only jet-pairs to reconstruct W/Z
  => future analysis could profit from boosted V techniques





WVγ



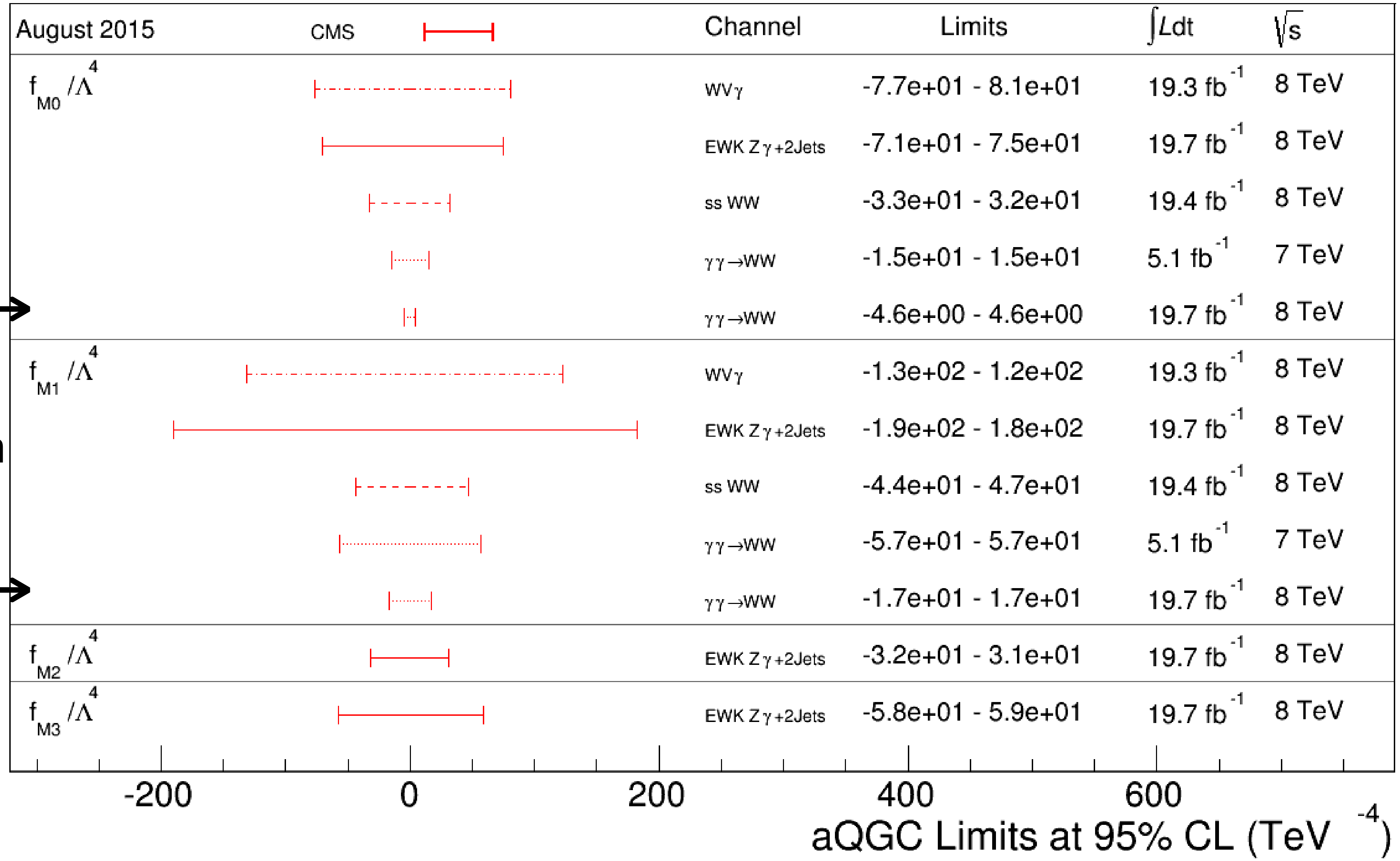


[Phys. Rev. D 90, 032008 (2014)]

- W+jets background larger than SM WVγ => limits only
  $\sigma < 311$fb (95% CL)   Theory: 92 ± 22fb
- Extract aQGC limits from photon p_T spectrum

Comparisons

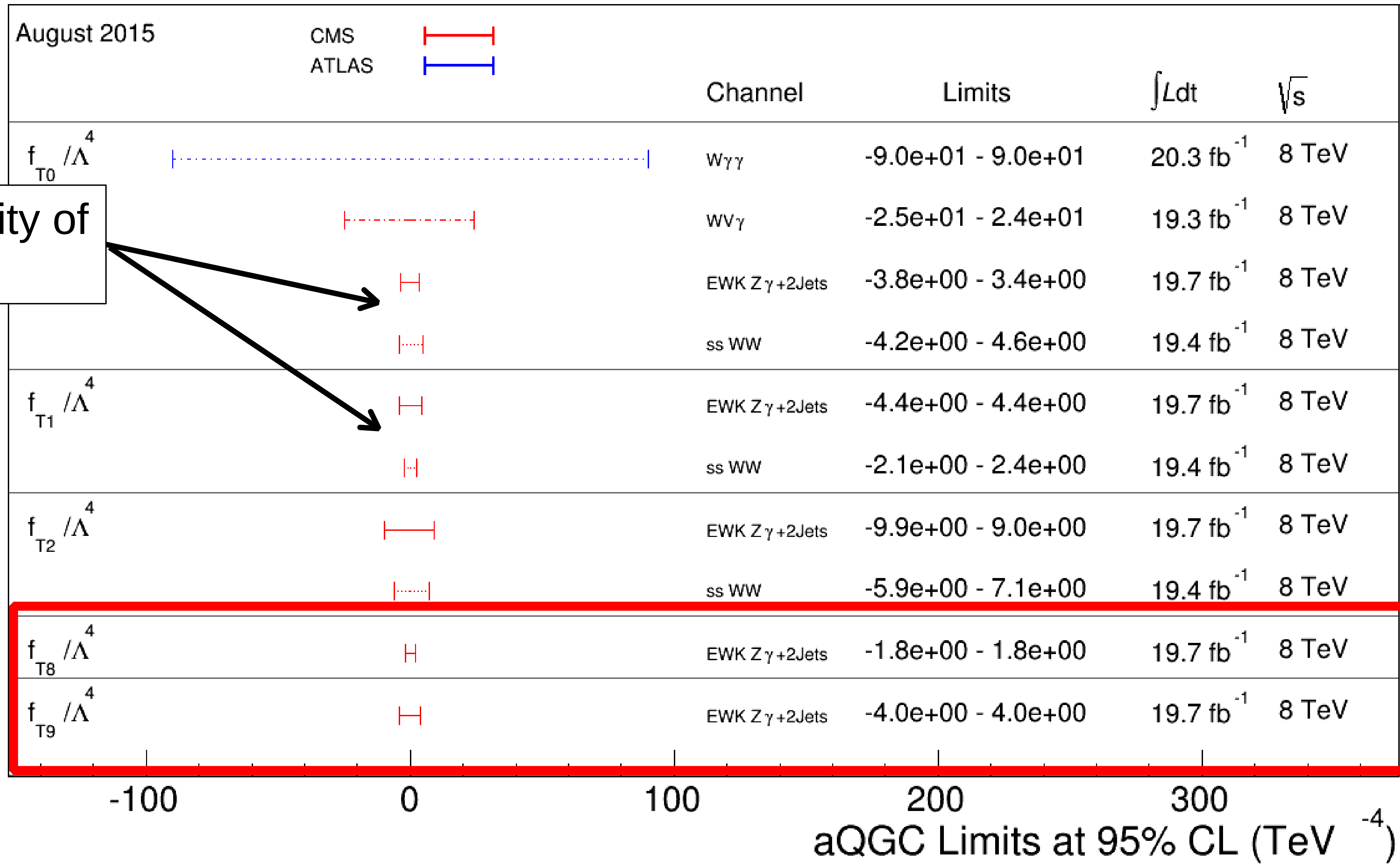
Karlsruher Institut für Technologie



Exclusive production extremely powerful

Comparisons

Similar Sensitivity of ssWW and Zγ



Summary

- Run II promising, but no results yet
- Finishing Run I analyses: still many exciting analysis left
- Mapping out the quartic vertex
  => more comprehensive set of studies than ever
  => limits on aQGCs not studied before
- Sensitivity to Dim8 operators still mostly lower than unitarity bound
  => not straightfoward to interpret
- Stay tuned for EWK Wγ

Backup

$Z\gamma$ fiducial region

- $p_T^{j1,j2} > 30$ GeV, $|\eta^{j1,j2}| < 4.7$,
- $M_{jj} > 400$ GeV, $\Delta\eta_{jj} > 2.5$,
- $p_T^{l1,l2} > 20$ GeV, $|\eta^{l1,l2}| < 2.4$,
- 70 GeV $< M_{ll} <$ 110 GeV,
- $p_T^{\gamma} > 20$ GeV, $|\eta^{\gamma}| < 1.4442$,
- $\Delta R_{jj}, \Delta R_{j\gamma}, \Delta R_{l\gamma}, \Delta R_{jl} > 0.4$,