Standard Model Physics in CMS

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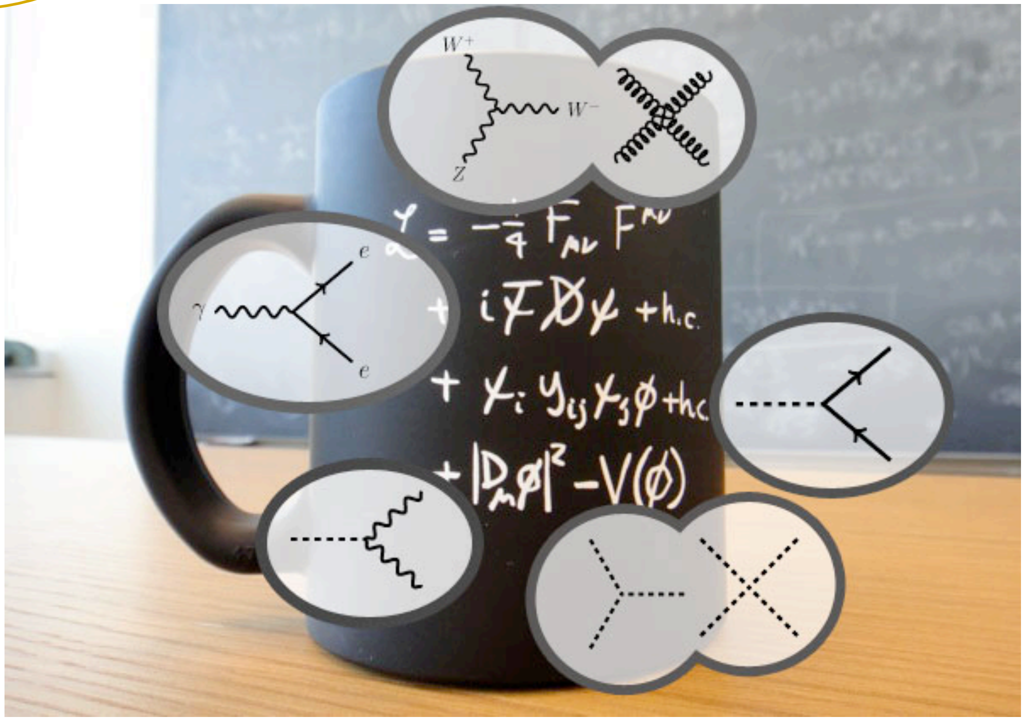
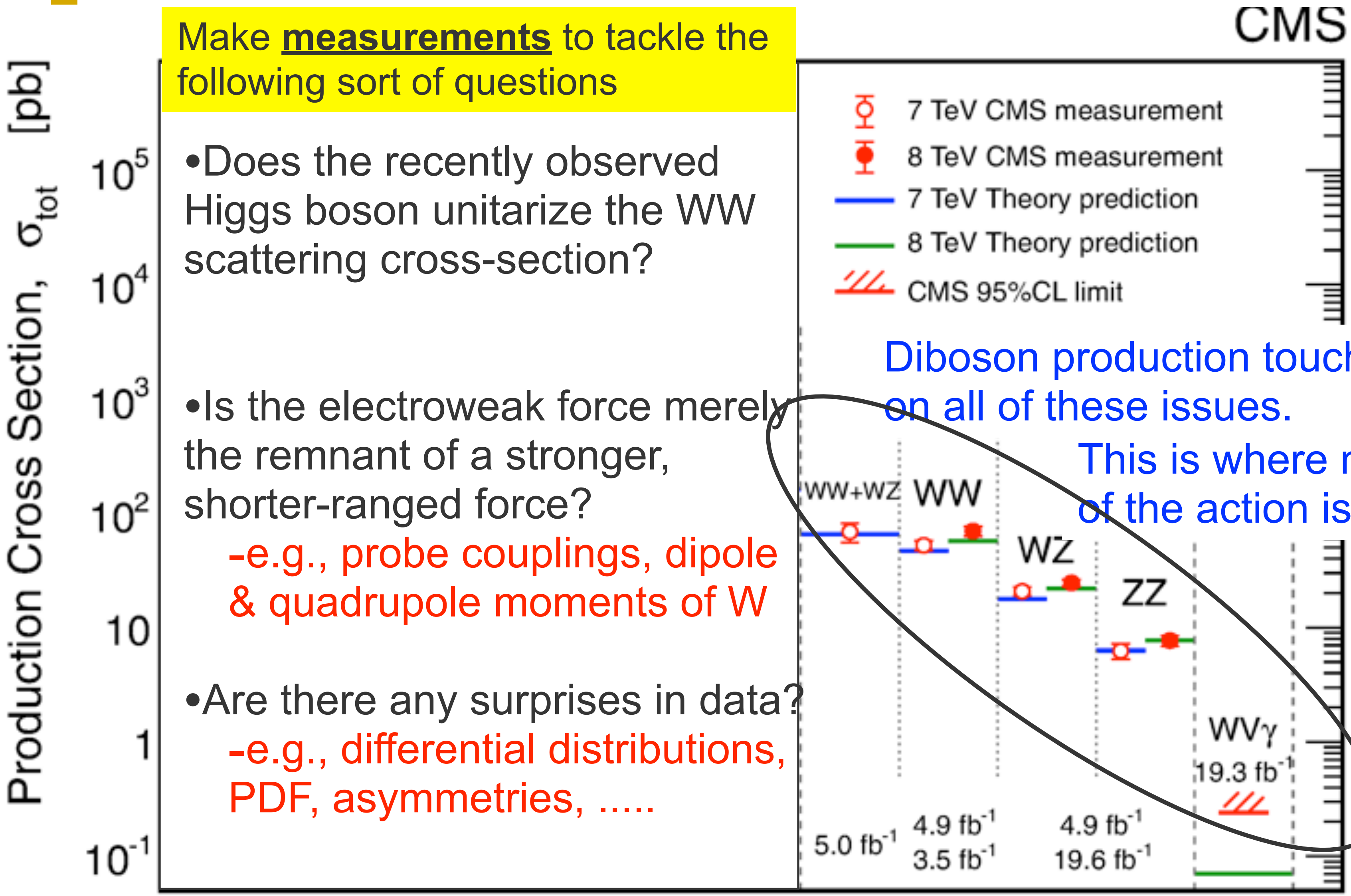


CMS Week Taipei
Opening Plenary
Sept 9, 2013

Standard Model physics in the post-Higgs era

Make **measurements** to tackle the following sort of questions

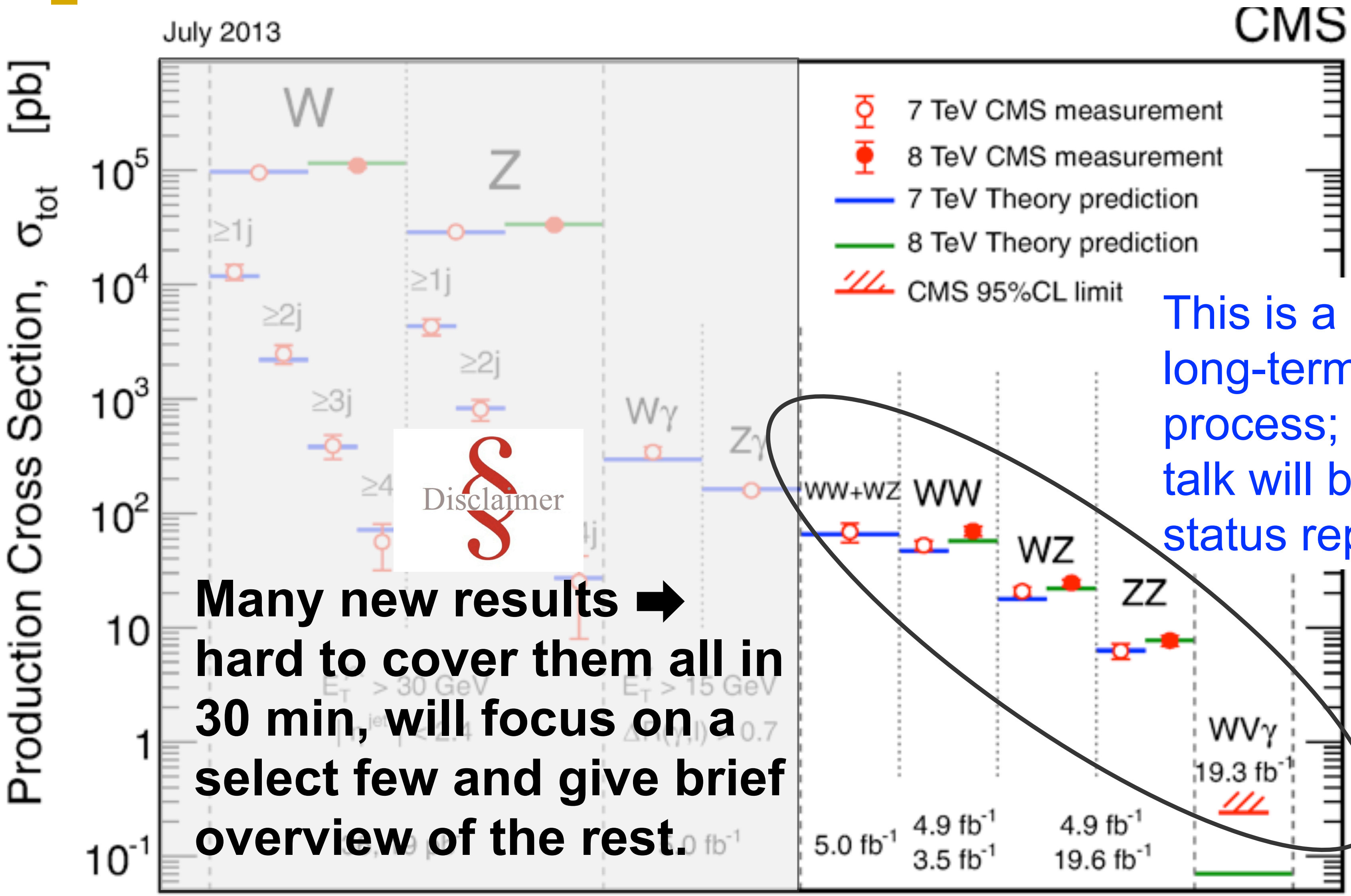
- Does the recently observed Higgs boson unitarize the WW scattering cross-section?
- Is the electroweak force merely the remnant of a stronger, shorter-ranged force?
  - e.g., probe couplings, dipole & quadrupole moments of W
- Are there any surprises in data?
  - e.g., differential distributions, PDF, asymmetries, ...



Diboson production touches on all of these issues.

This is where most of the action is !

Outline

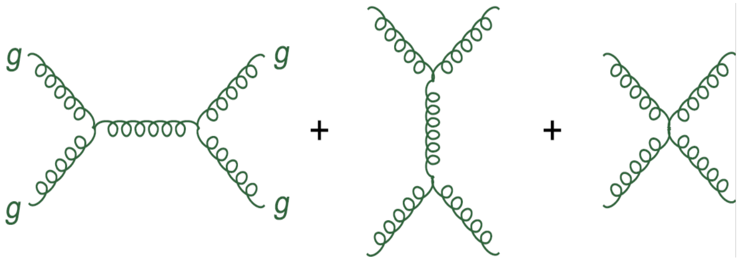


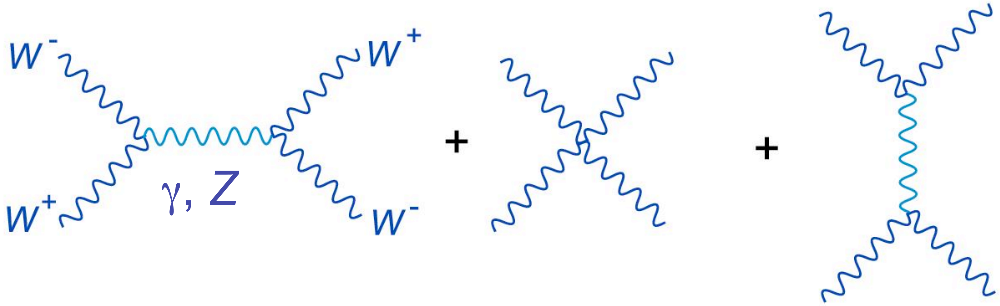
Many new results ➡ hard to cover them all in 30 min, will focus on a select few and give brief overview of the rest.

This is a long-term process; this talk will be a status report.

Probe of gauge boson couplings

A non-Abelian gauge theory will exhibit gauge boson self-interactions. For example



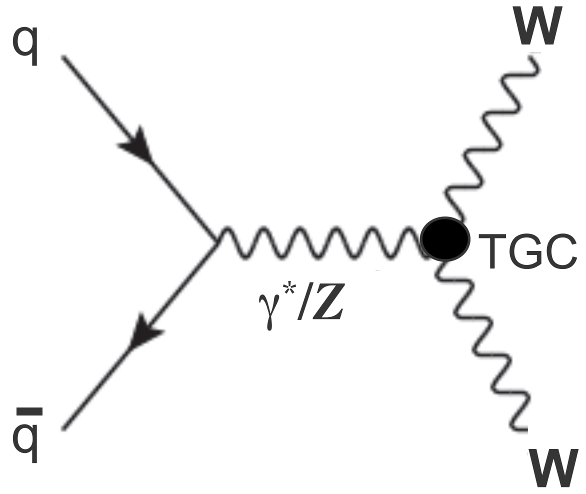


In the case of electroweak theory the self interaction could be

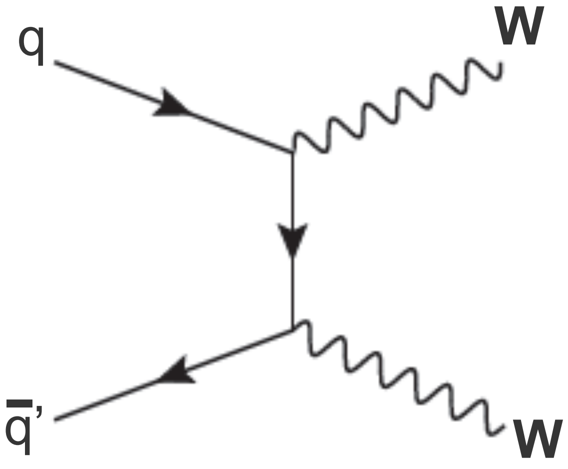
- trilinear (WWγ, WWZ) or
- quartic (WWγγ, WWZγ, WWZZ, WWWW)

At the LHC we have the opportunity to test these couplings with unprecedented precision. Observations of anomalous couplings would be an indication of new physics.

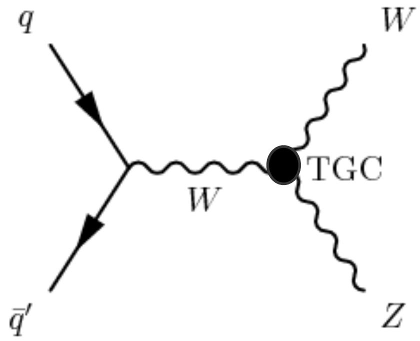
Heavy diboson production: the most potent probe of TGC

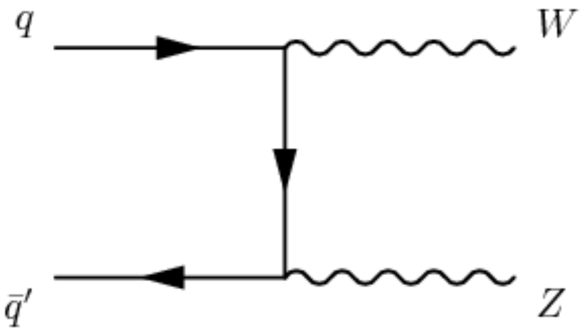


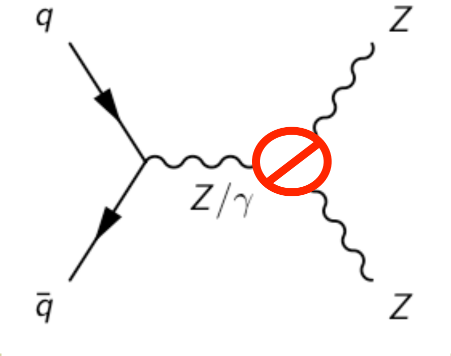
s-channel



t-channel





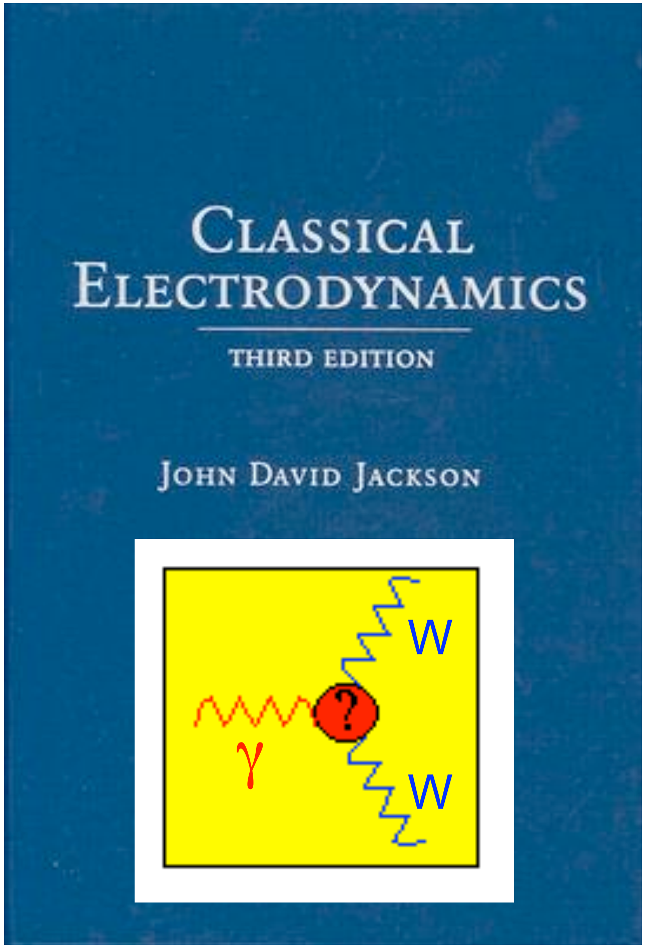


- Rate is a mix of TGC processes and ISR/FSR
- There are no all-neutral couplings in the SM

§ Disclaimer

I will focus on WZ and ZZ results which are new for this summer.

Understanding W interaction in semi-classical theory



✦Interaction between W and e.m. field completely determined by three numbers:

- -W's electric charge
  - •Effect on the E-field goes like $1/r^2$
- -W's magnetic dipole moment
  - •Effect on the H-field goes like **$1/r^3$**
- -W's electric quadrupole moment
  - •Effect on the E-field goes like **$1/r^4$**

✦Measuring Triple Gauge Couplings (WWγ) ≡ measuring the 2nd and 3rd numbers

- -Because of the higher powers of $1/r$, these effects are largest at small distances
- -Small distance = high energy ($\hat{s}$)

Sensitivity to new physics is at short distances/ high $\hat{s}$

Couplings in more detail

$$L = \boxed{g}\left(W^{\dagger}_{\mu\nu} W^{\mu} A^{\nu} - W^{\dagger}_{\mu} A_{\nu} W^{\mu\nu}\right) + \boxed{(1+\Delta\kappa_{\gamma})}\left(W^{\dagger}_{\mu} W_{\nu} F^{\mu\nu}\right) + \frac{\boxed{\lambda_{\gamma}}}{M_W^2}\left(W^{\dagger}_{\rho\mu} W^{\mu}_{\nu} F^{\nu\rho}\right)$$

(with)

$$W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu - g W_\mu \times W_\nu$$

\+ three similar terms for the Z

\+ nine other terms that do evil things (violate CP and/or EM gauge invariance)

Think of these parameters as ≡ muon "g-2"

- The convention is that every parameter you'll see (e.g. Δg_1^Z, $\Delta\kappa_\gamma$, λ_γ) is zero in the SM.
- Dimension 4 operators alter Δg_1^Z, $\Delta\kappa_\gamma$ and $\Delta\kappa_Z$: effects grow as $\hat{s}^{1/2}$
- Dimension 6 operators alter λ_γ and λ_Z :effects grow as $\hat{s}$. ⬅ Much more constrained at LHC than at previous colliders

$$\mu_W = e\frac{2+\Delta\kappa_\gamma+\lambda_\gamma}{2M_W}$$

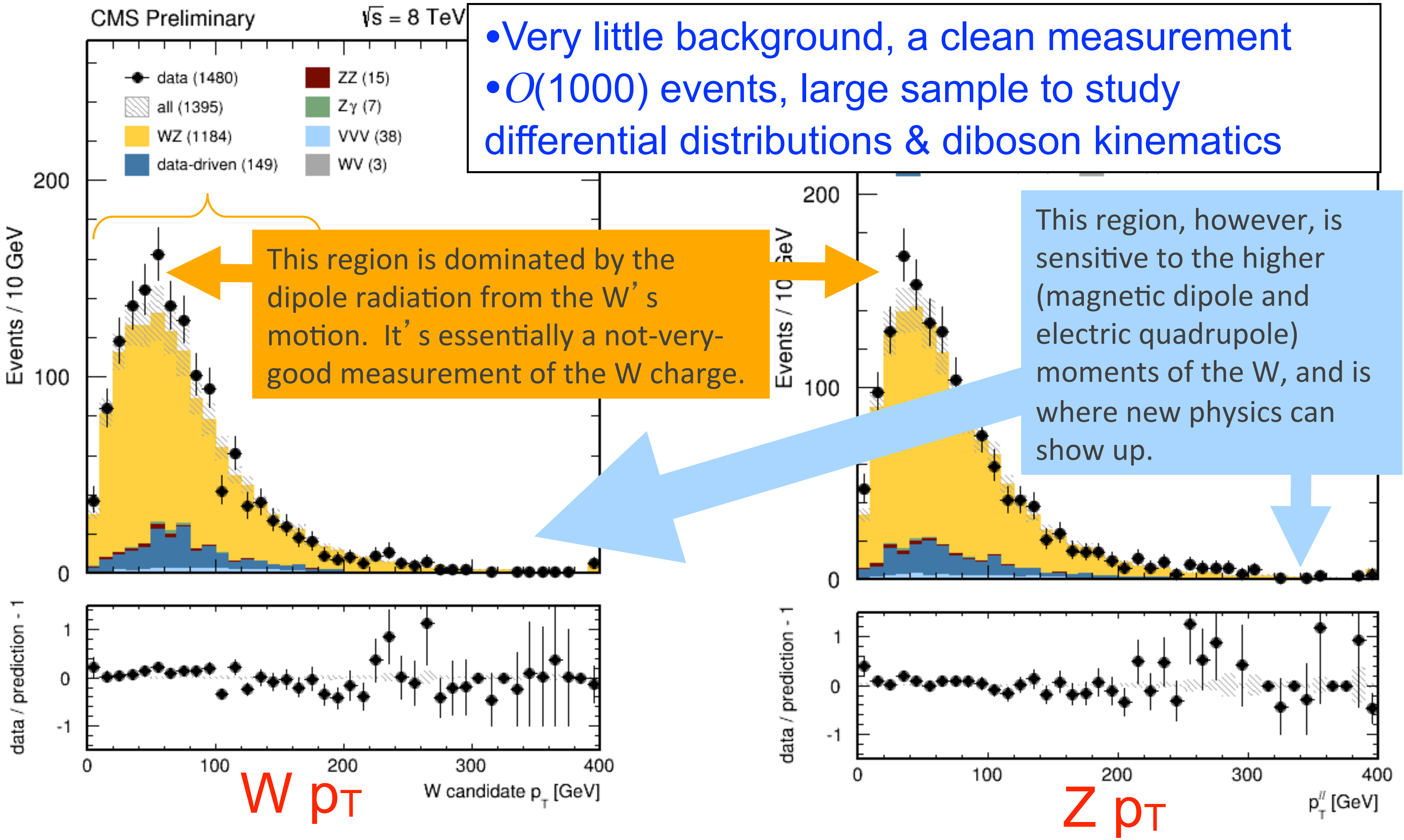
Jackson Eq. 5.59, 3rd ed.

$$Q_W = -e\frac{1+\Delta\kappa_\gamma-\lambda_\gamma}{M_W^2}$$

Jackson Eq. 4.9, 3rd ed.

What we measure: WZ to leptons

CMS PAS SMP-12-006



- Very little background, a clean measurement
- $\mathcal{O}$(1000) events, large sample to study differential distributions & diboson kinematics

This region is dominated by the dipole radiation from the W’s motion. It’s essentially a not-very-good measurement of the W charge.

This region, however, is sensitive to the higher (magnetic dipole and electric quadrupole) moments of the W, and is where new physics can show up.

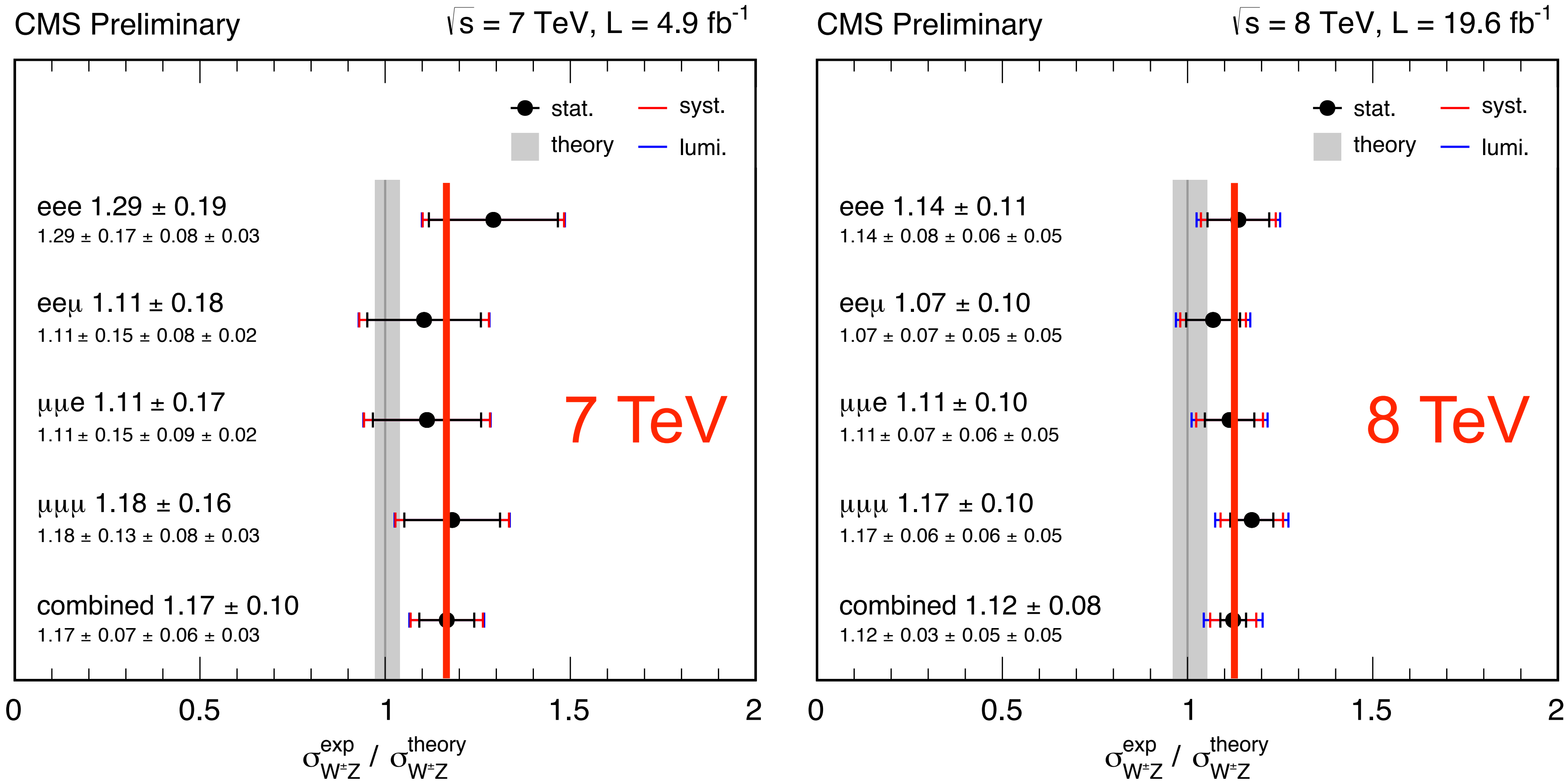
W p_T

Z p_T

WZ total cross section

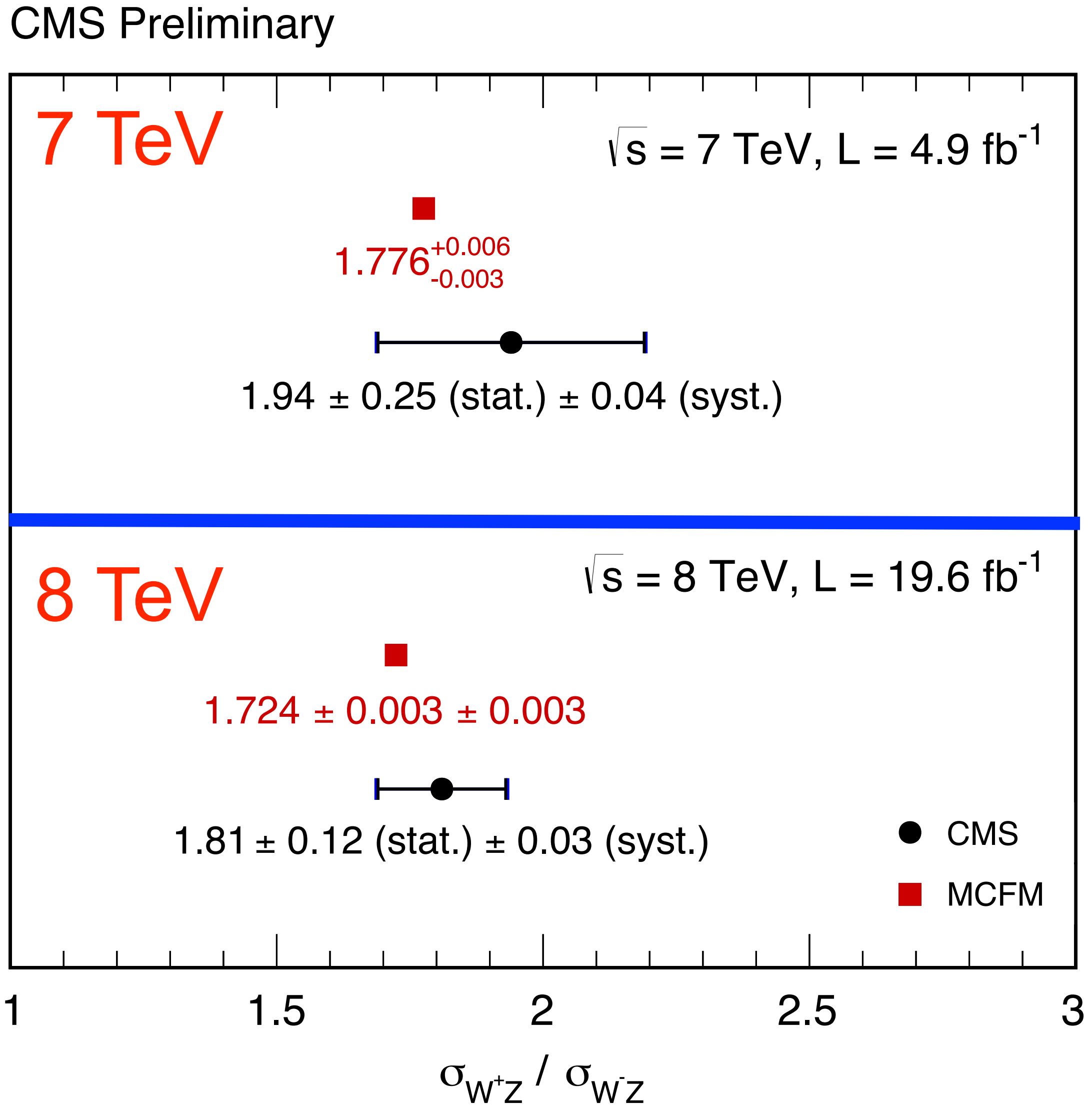
CMS PAS SMP-12-006

Consistent with NLO prediction, although both 7 TeV & 8 TeV values are a bit higher. Similar situation as in WW and WV (semi-leptonic) measurements.



W^+Z / W^-Z ratio

CMS PAS SMP-12-006



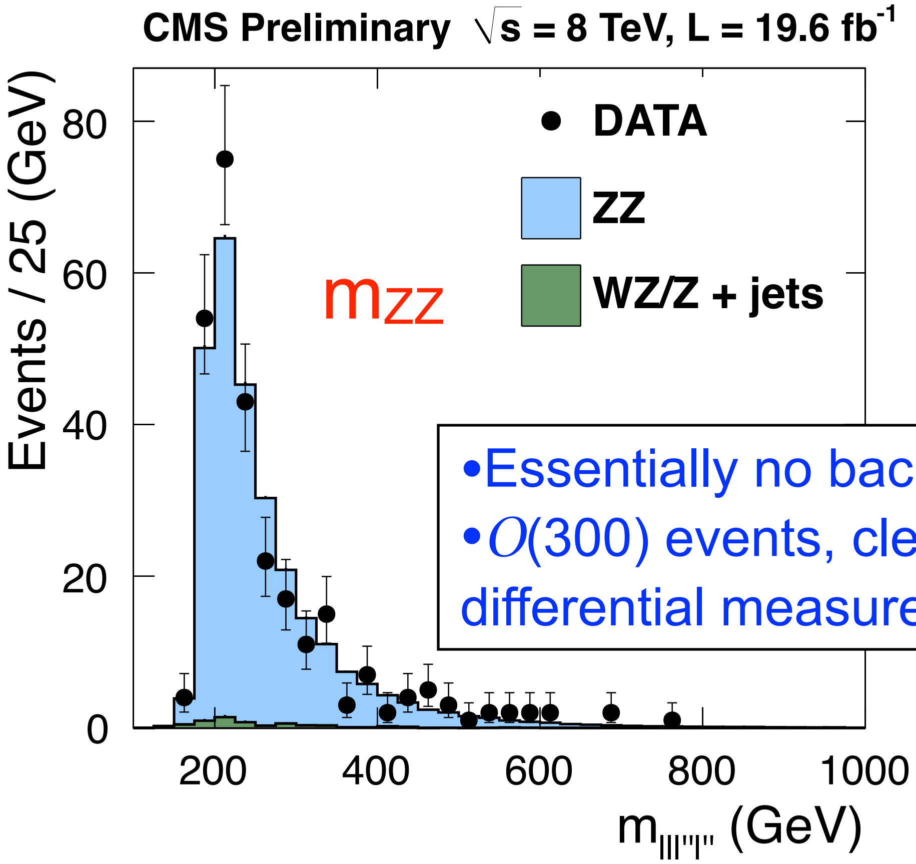
- So, we are seeing higher production rate for W^+Z than NLO prediction, while W^-Z is close to prediction
- Perhaps NNLO correction important for W^+Z, 13 TeV data will shed some light
- All differential distributions are consistent with the SM predictions

ZZ to leptons

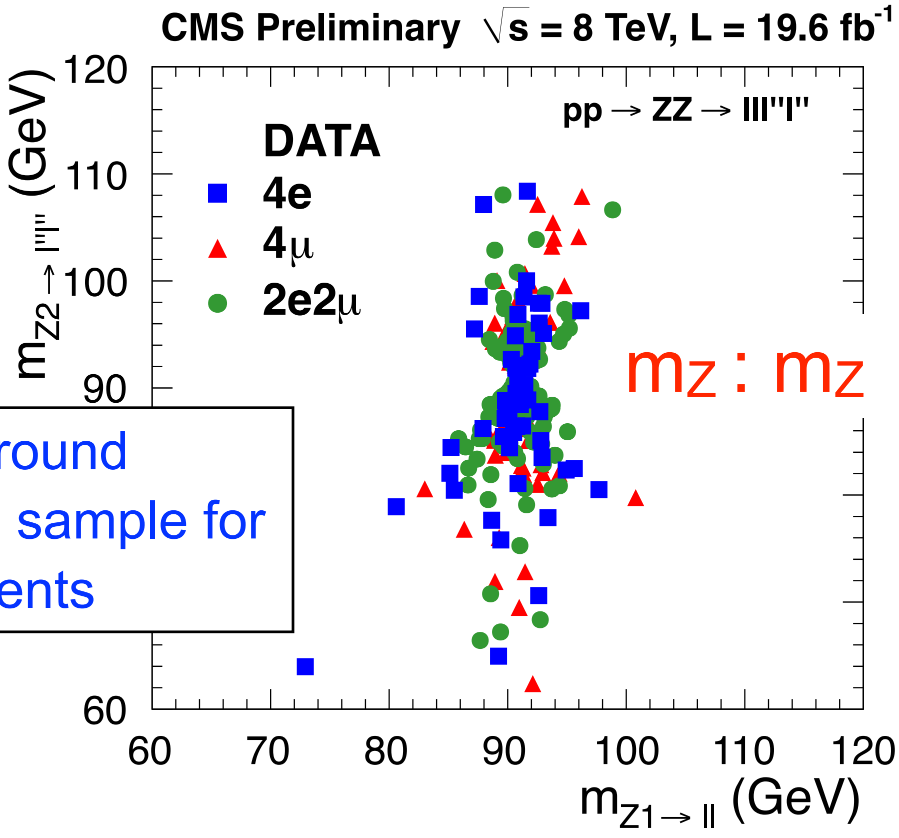
CMS PAS SMP-13-005

$$\sigma(pp \to ZZ) = 7.7 \pm 0.5(stat)^{+0.5}_{-0.4}(syst) \pm 0.4(theo) \pm 0.3(lumi)$$

NLO (MCFM): 7.7 ± 0.6 pb, includes gg→ZZ

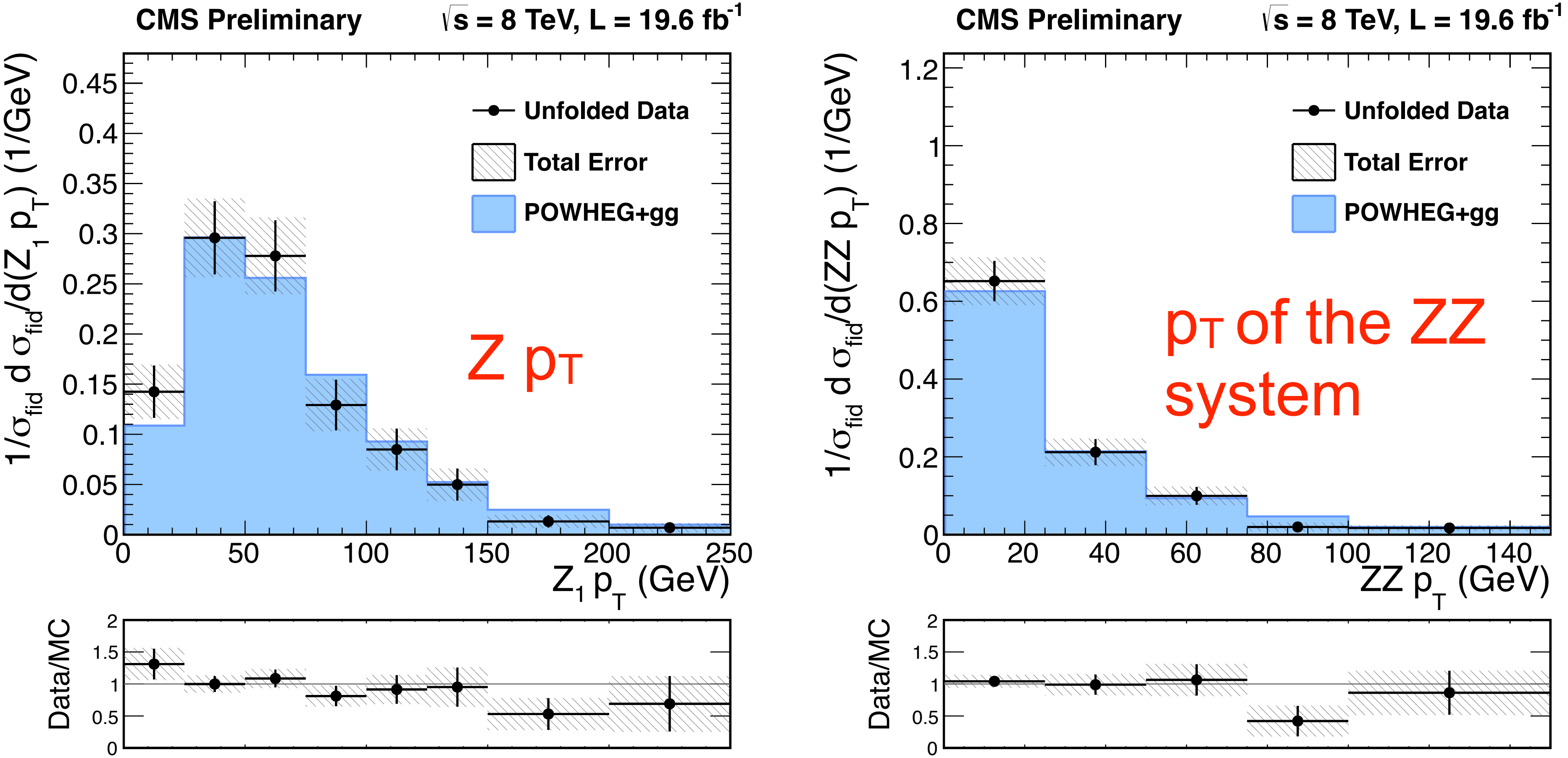


- Essentially no background
- $\mathcal{O}$(300) events, clean sample for differential measurements



ZZ unfolded distributions

CMS PAS SMP-13-005



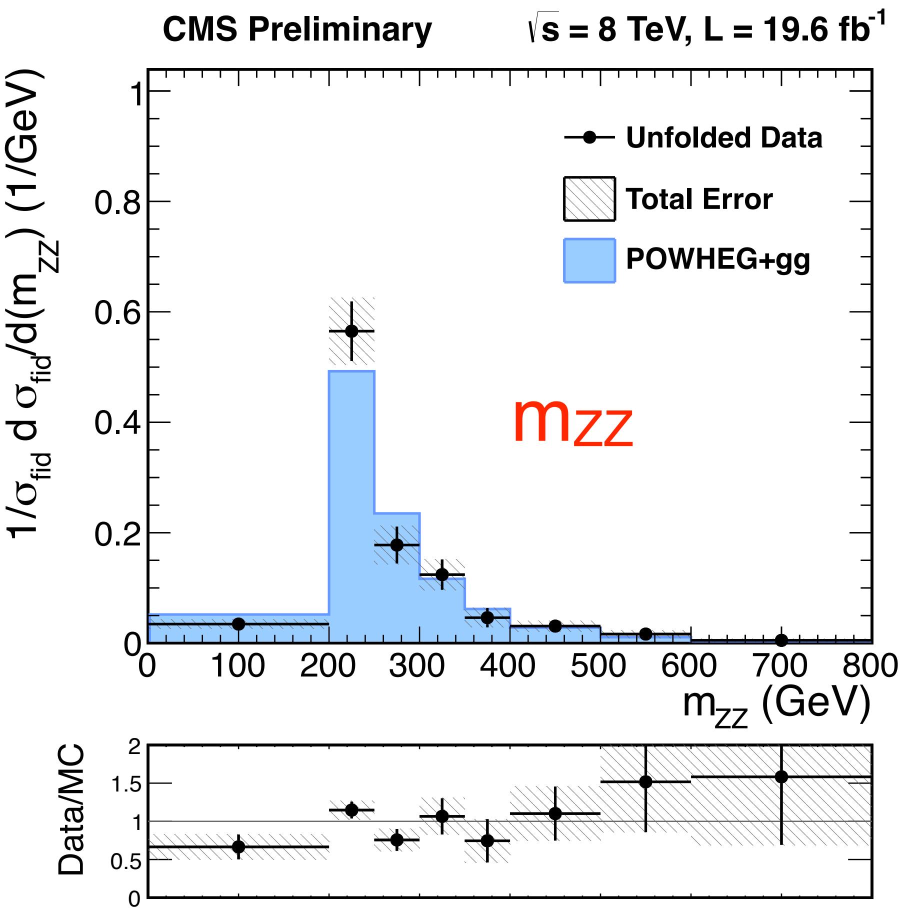
Z p_T

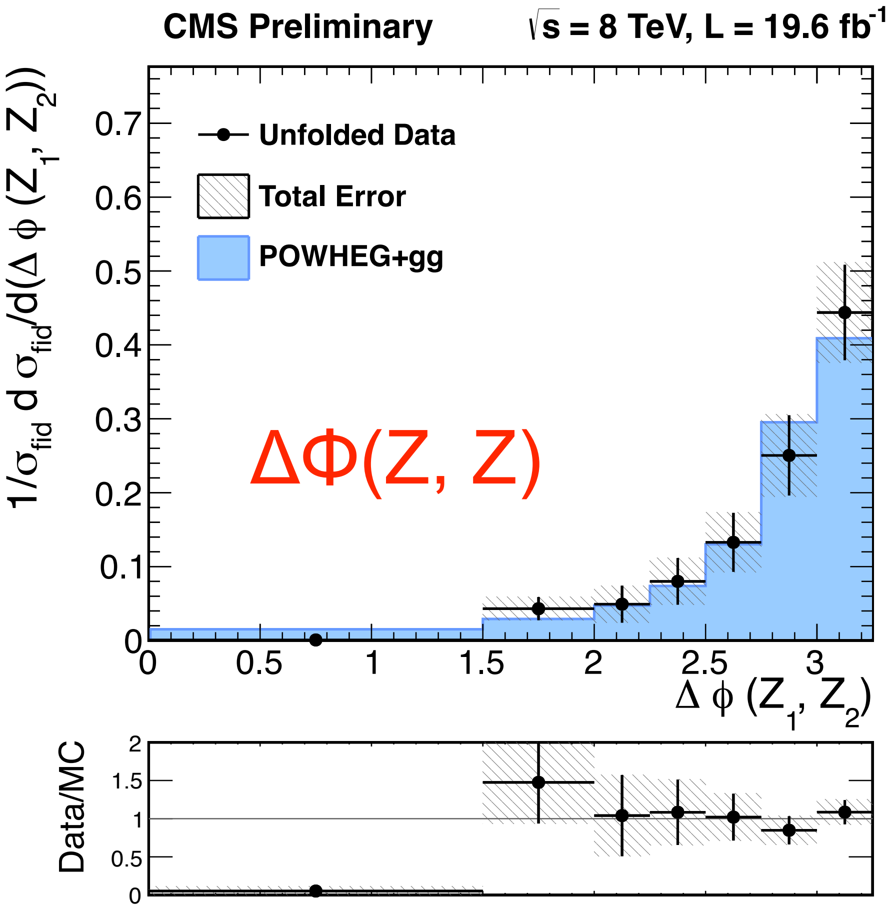
p_T of the ZZ system

Later plots in the talk will show other variables, but all are measurements of or proxies for the diboson system invariant mass, ŝ.

ZZ unfolded distributions

CMS PAS SMP-13-005

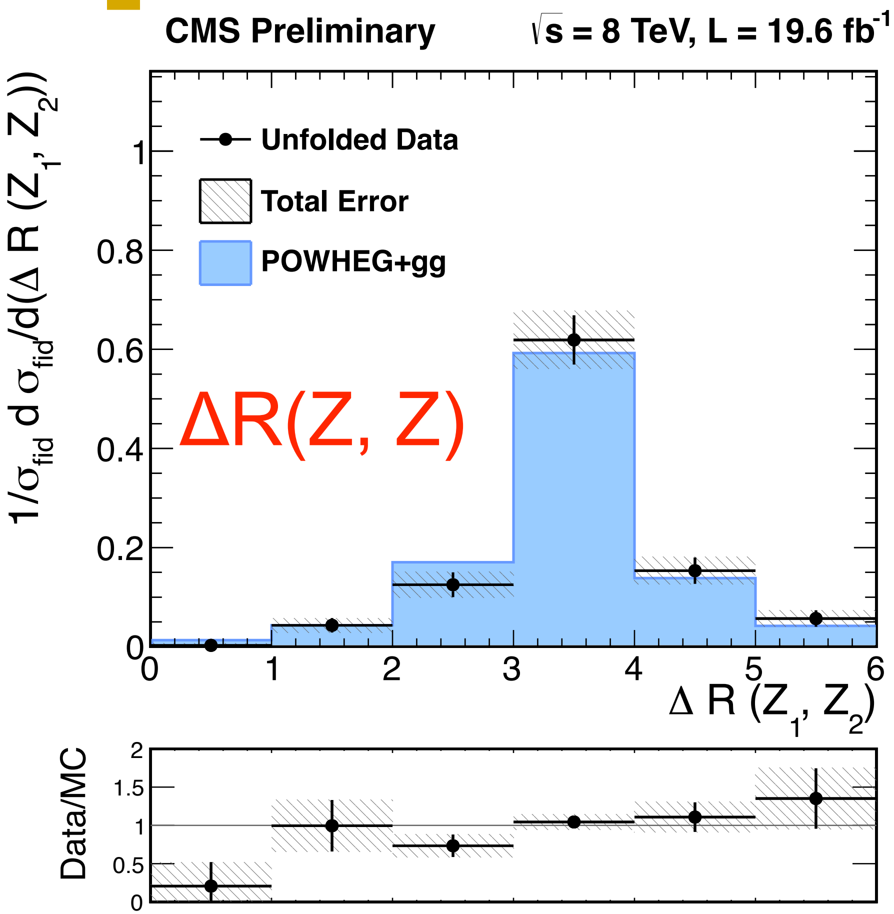




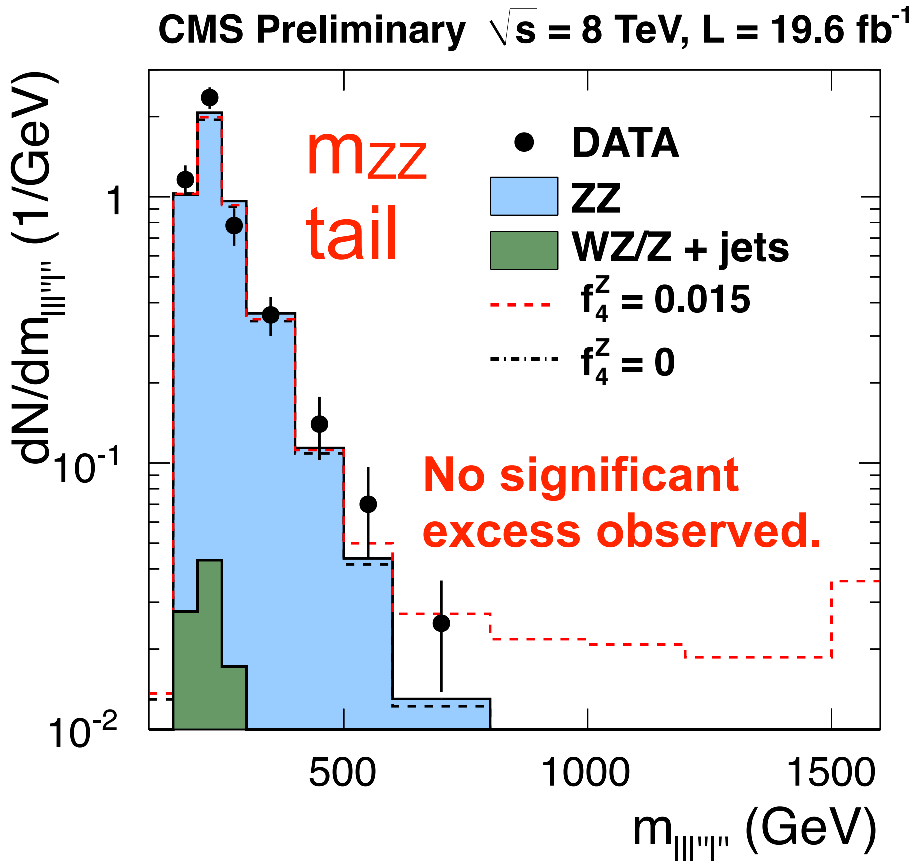
Need to keep an eye on these distributions in the next Run.

Probe of neutral TGC

CMS PAS SMP-13-005



ΔR(Z, Z)



m_{ZZ} tail

No significant excess observed.

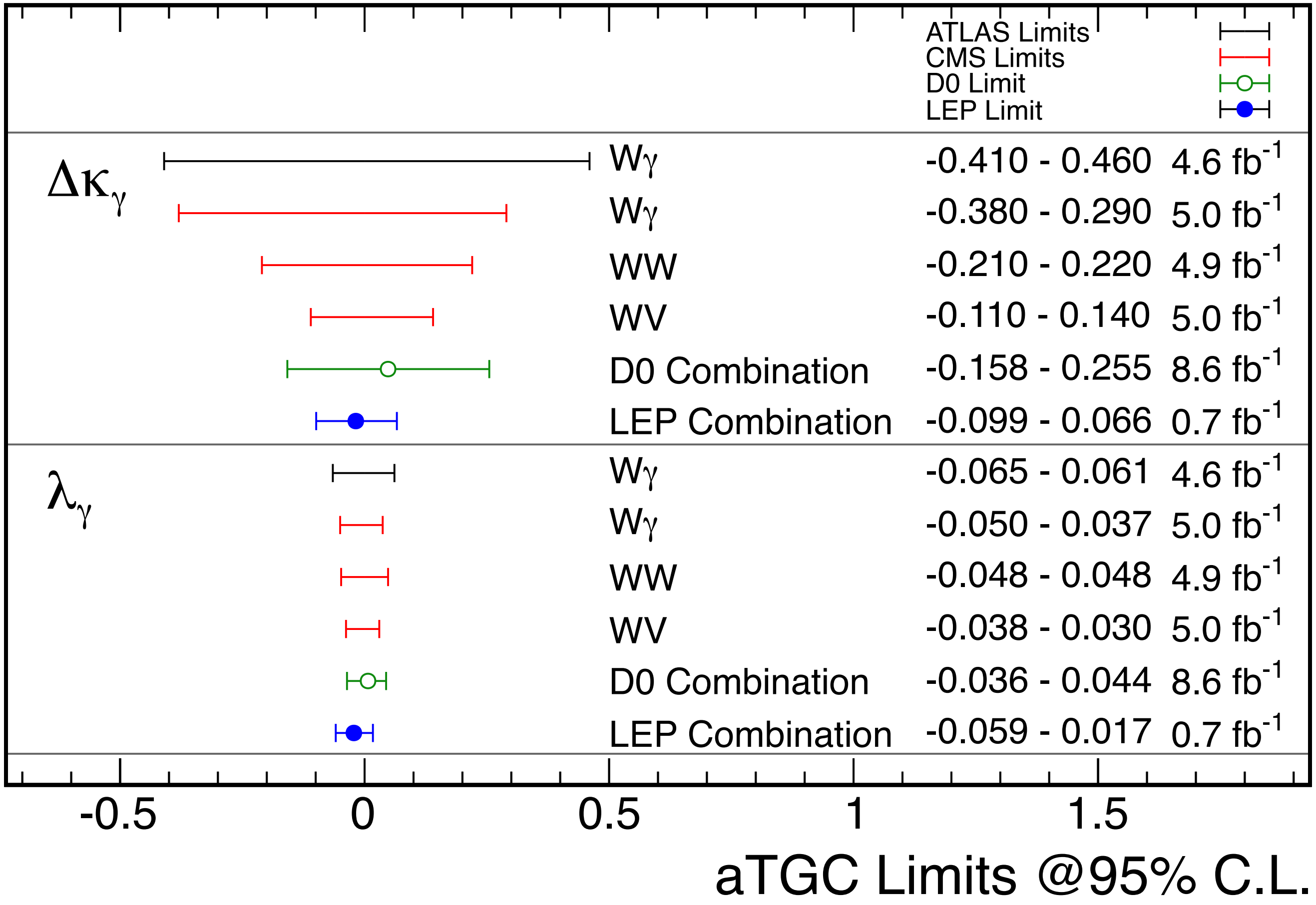
Very constraining for neutral TGC. LHC makes more ZZ events than LEP & TeV, and it makes many more at high m_{ZZ} where the sensitivity is.

Putting it all together: WWγ couplings

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

This table only includes 7 TeV published results. The most sensitive channel is **WV semi-leptonic**. The 8 TeV results are in preparation.

Feb 2013

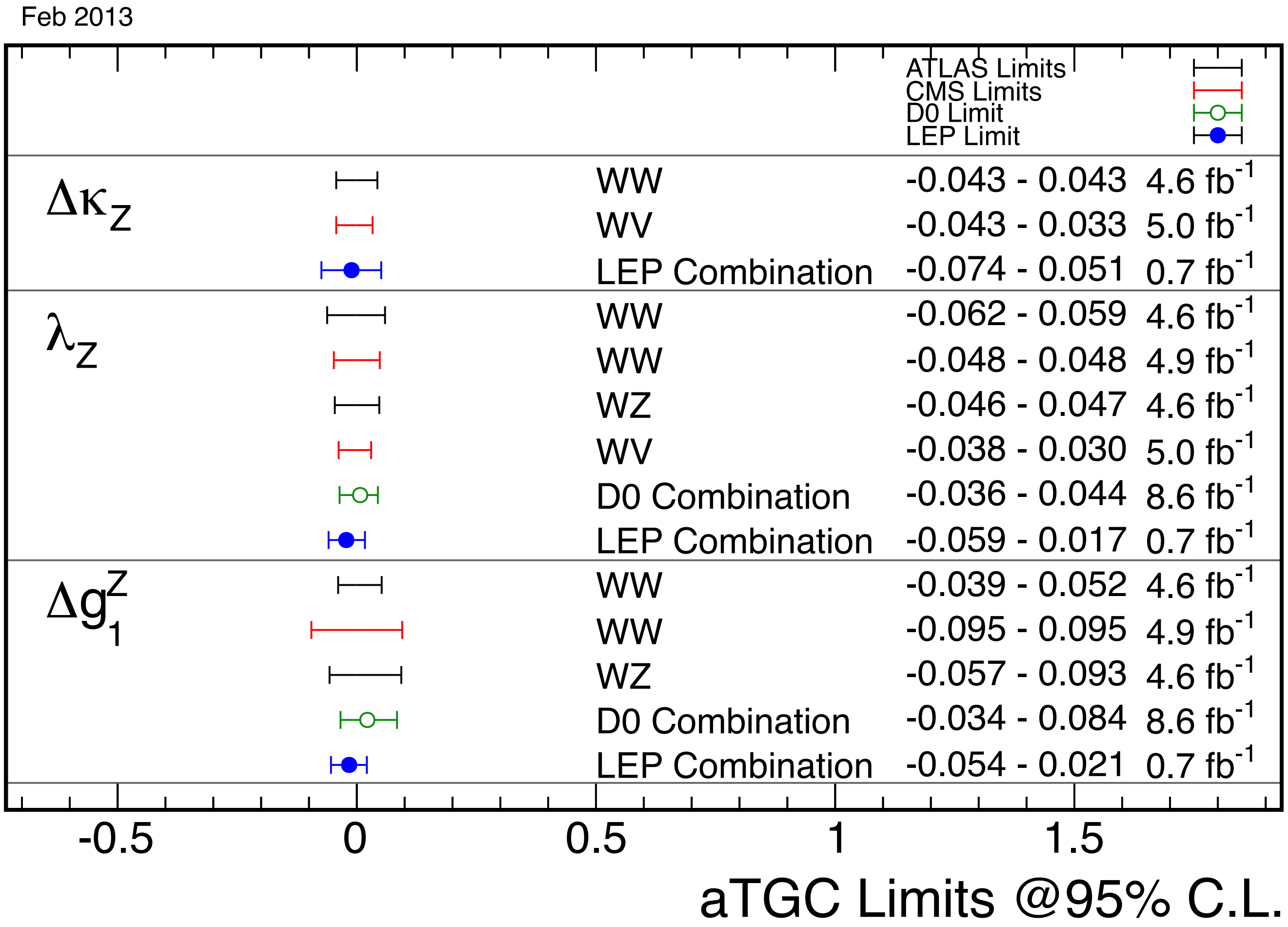


Dipole moment of W constrained at $\mathcal{O}(10^{-2})$, quadrupole moment at $\mathcal{O}(10^{-4})$. Compare this to muon “g−2” which differs by 0.1% from the SM value !!!

Constraints on WWZ couplings

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Only includes 7 TeV published results.



Obtained assuming equal coupling parametrization

$$\lambda_Z = \lambda_\gamma = \lambda$$

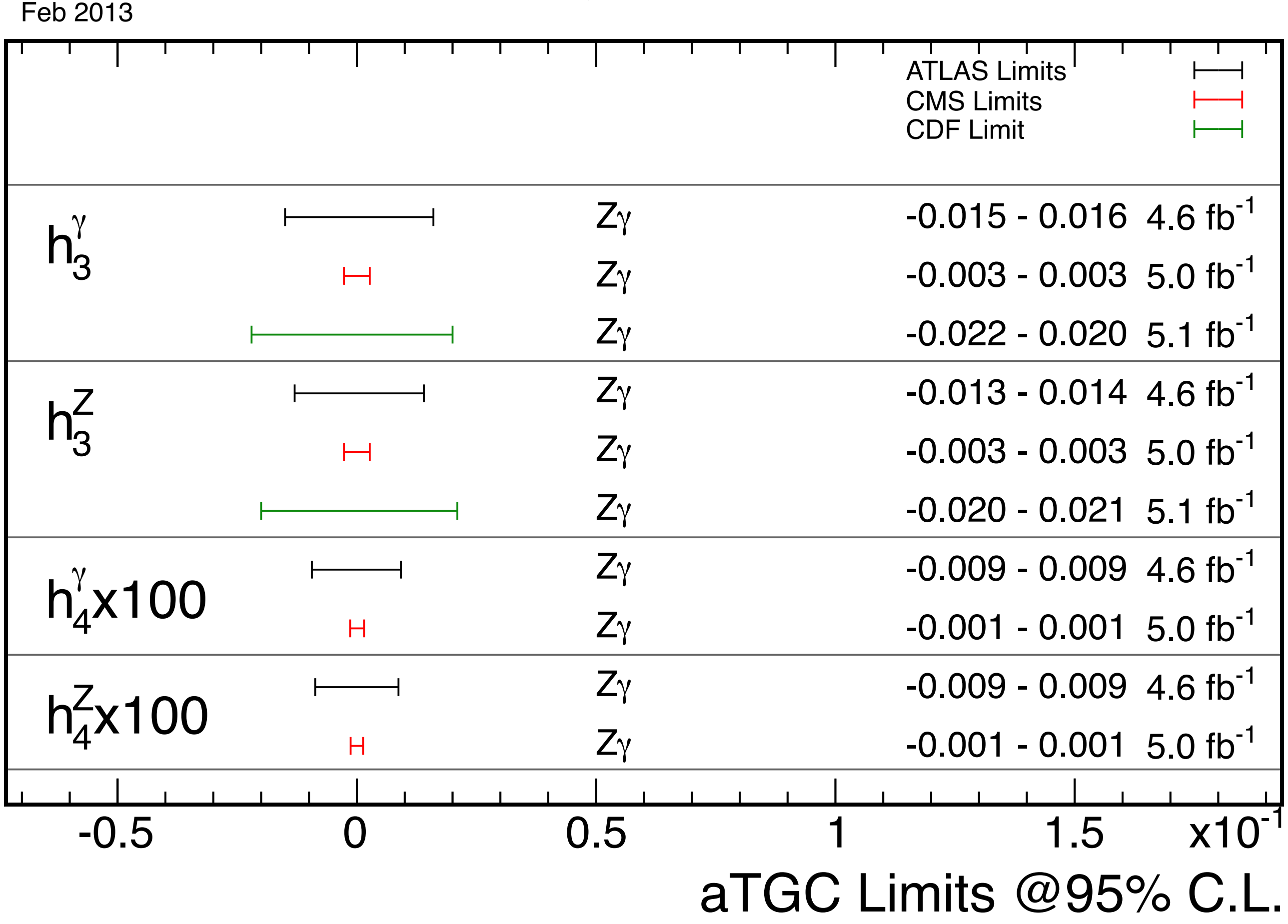
$$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \cdot \tan^2\theta_W$$

The CMS limits shown here and on the previous slide are the most stringent in the world, to date.

Constraints on neutral TGC: Zγγ and ZZγ

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

This table only includes 7 TeV published results. The most sensitive channel is **Z(νν)γ**. The 8 TeV results are in preparation.



Not allowed in SM since they give rise to diagrams like Z→γγ and Z→Zγ !

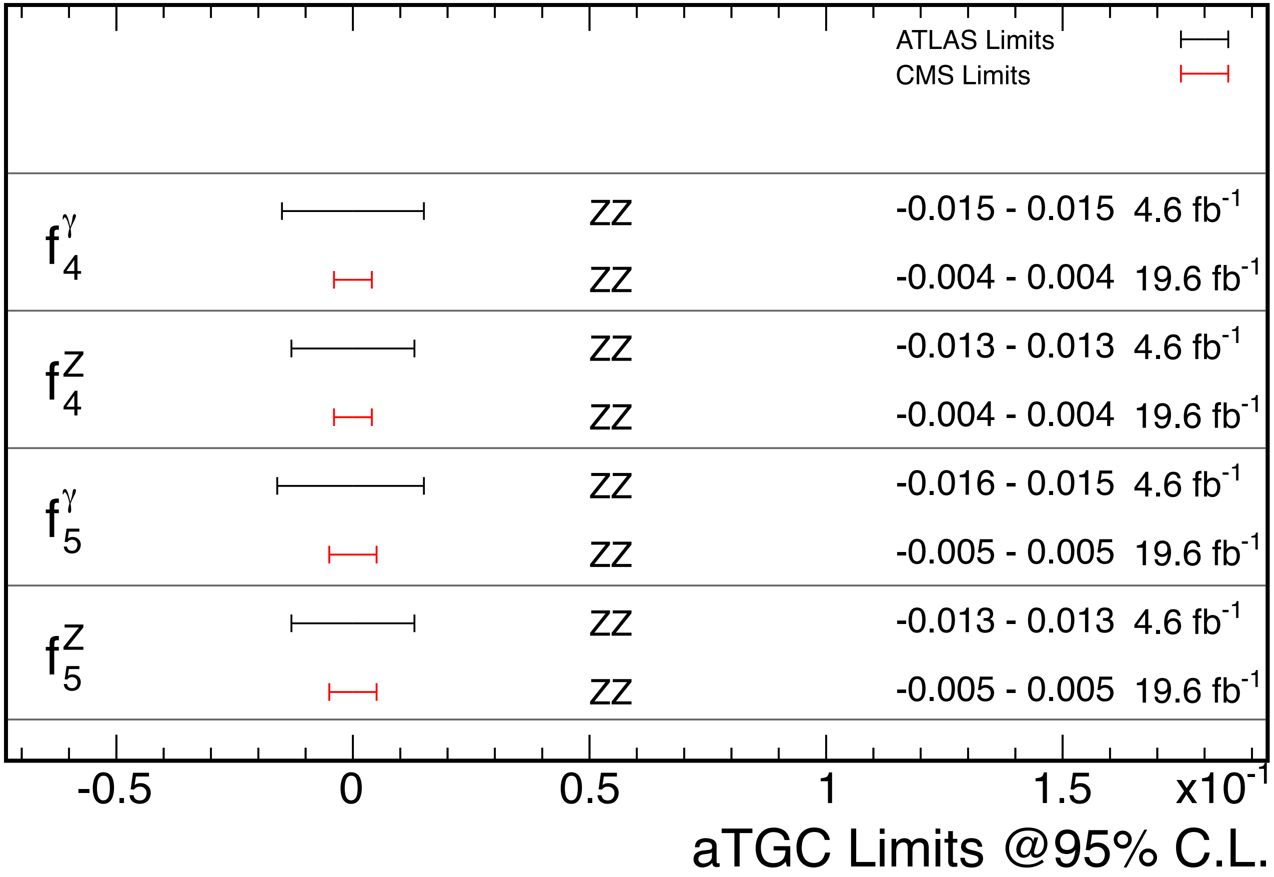
Our limits are highly constraining and the most stringent to date.

Constraints on neutral TGC: ZZγ and ZZZ

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Includes 8 TeV results. The only contributing channel is **ZZ (4ℓ)**.

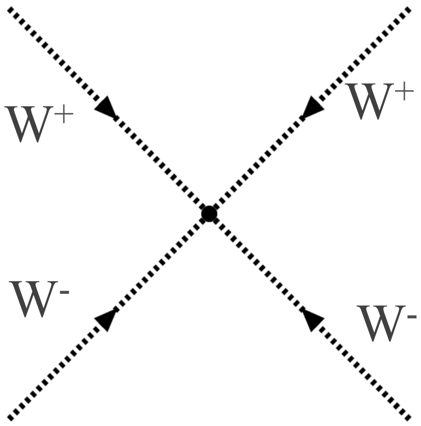
July 2013



For the all-neutral couplings (dim 6 and 8), we are setting limits at $\mathcal{O}(10^{-2})$. These are highly constraining (equivalent in dipole units of $\mathcal{O}(10^{-4}-10^{-5})$) !!!

Quartic gauge couplings involving W boson

This is a high priority – we need to understand QGCs to tell if the Higgs unitarizes the process WW→WW



- In the SM, the allowed couplings are:
  WWγγ, WWZγ, WWWW, WWZZ
- Observable in two topologies at the LHC
  - Triple gauge boson production (e.g., Wγγ, WWγ, WWW, WWZ: very rare processes)
  - Scattering process (γγ → WW, WW → WW)
- Anomalous couplings introduced via effective Lagrangian
  - Should use the linear realization with light Higgs
  - aQGCs for SM allowed processes introduced at dimension 6
  - However they are the same operators as aTGC (very constrained now)
- Lowest independent aQGC interactions are dimension 8

Anomalous quartic couplings in dimension 8

All D8 aQGC operators in Eboli's notation

hep-ph/0606118
Eboli et. al.

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

$$\mathcal{L}_{S,1} = \left[(D_\mu \Phi)^\dagger D^\mu \Phi \right] \times \left[(D_\nu \Phi)^\dagger D^\nu \Phi \right]$$

L_M have D6 equivalents (a_0, a_c),
<u>L_T are novel to D8</u>

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

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

$$\begin{aligned}
\mathcal{L}_{T,8} &= B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta} \\
\mathcal{L}_{T,9} &= B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}
\end{aligned}$$

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$, $\mathcal{L}_{M,6}$, $\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}$, $\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$, $\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O	O
$\mathcal{L}_{T,0}$, $\mathcal{L}_{T,1}$, $\mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}$, $\mathcal{L}_{T,6}$, $\mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,9}$, $\mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X	X

QGC: dimension-6 vs dimension-8

- In the two realizations
  - Linear: all lowest order independent aQGCs are dimension 8
  - Nonlinear: a number of dimensions, QGCs involving γ are dim 6
- Consider $WW\gamma\gamma$, the largest contributing nonlinear terms are
  - Dimension 6: limits set on a/Λ^2

$$L_6^0 = -\frac{e^2}{16\Lambda^2} a_0 F^{\mu\nu} F_{\mu\nu} \vec{W}^\alpha \cdot \vec{W}_\alpha$$

$$L_6^c = -\frac{e^2}{16\Lambda^2} a_c F^{\mu\alpha} F_{\mu\beta} \vec{W}^\beta \cdot \vec{W}_\alpha$$

  - Equivalent dimension 8 terms (L_{M2}, L_{M3}), limits set on q/Λ

$$\frac{q_i}{\Lambda^4} = \frac{8a_i}{\Lambda^2 M_W^2}$$

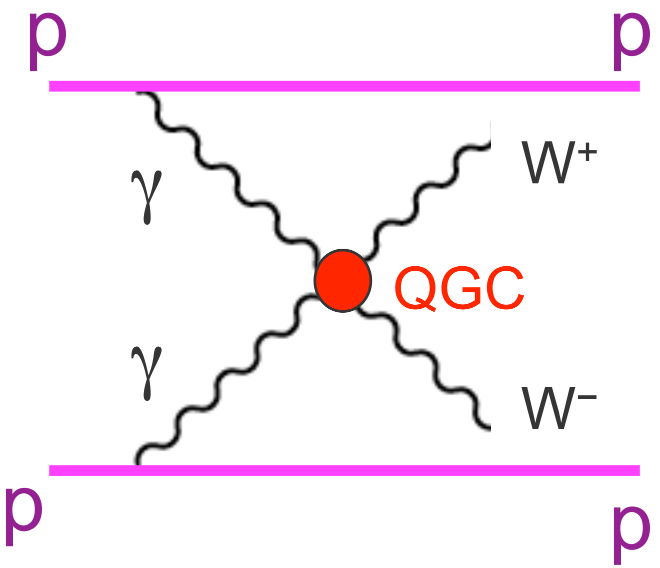
Straightforward conversions

Burden of legacy

- Adopt dim 8 (linear) approach for setting aQGC limits
- However, in order to easily compare with the existing results
  - use D6 equivalents for operators that exist in both D6 and D8

Quartic couplings in γγ→WW process

CMS-FSQ-12-010



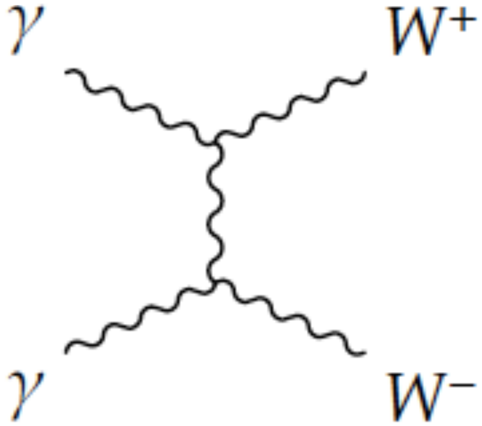
arXiv:1305.5596

Limits on aQGC without form-factors:

$$-2.80 \times 10^{-6} < a_0^W/\Lambda^2 < 2.80 \times 10^{-6}\ \mathrm{GeV}^{-2}$$

$$-1.02 \times 10^{-5} < a_C^W/\Lambda^2 < 1.02 \times 10^{-5}\ \mathrm{GeV}^{-2}$$

$\mathcal{O}(10^2)$ times more constraining than the LEP combined limit



These are the most stringent limits on anomalous QGC to date. Will return to it a bit later in this talk.

Probing quartic couplings via WVγ production

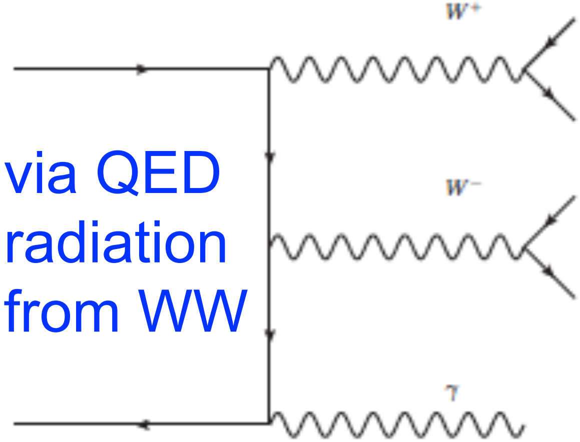
Leading order diagrams

References:

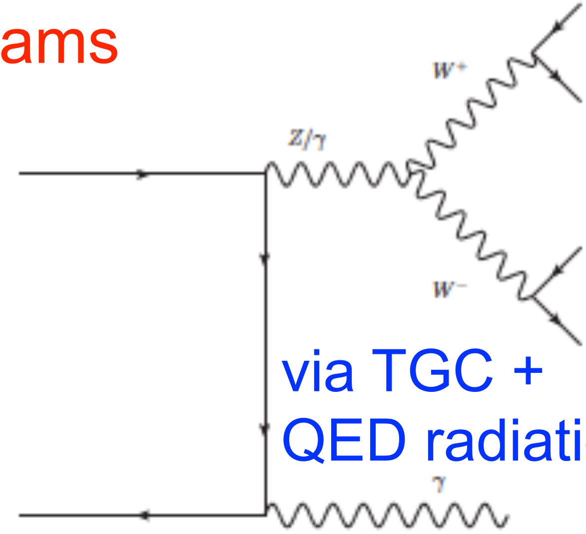
1.) Yang et al, arXiv: 1211.1641

2.) LEP combination, hep-ex/0612034

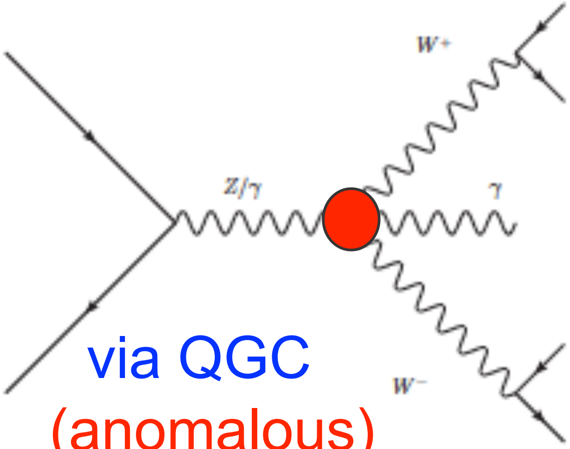
3.) Bozzi et al, arXiv: 0911.0438



via QED radiation from WW



via TGC + QED radiation



via QGC (anomalous)

- SM production highly suppressed
  - By a factor of 10^3 compared to WW
- aQGC at WWγγ and WWγZ vertices can enhance production for high photon p_T events by several factors

Some representative diagrams from aMC@NLO

Born

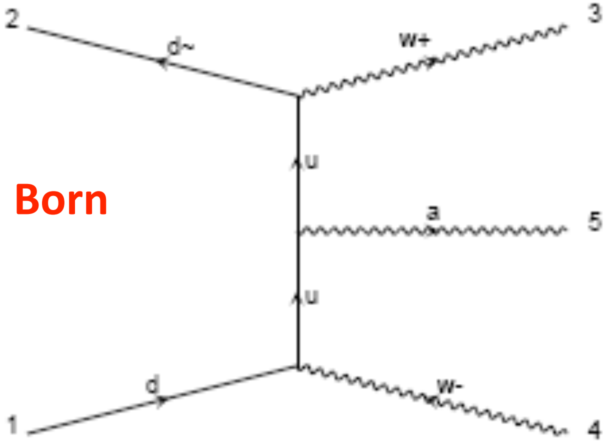
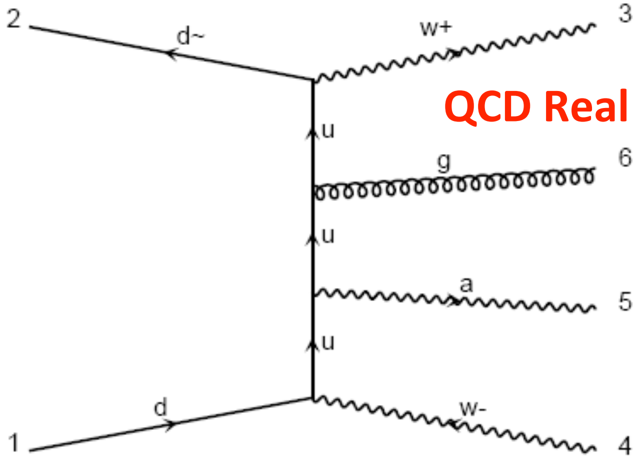


diagram 7 QCD=0, QED=3

QCD Real emission



real diagram 1 QCD=1, QED=3

One-loop QCD

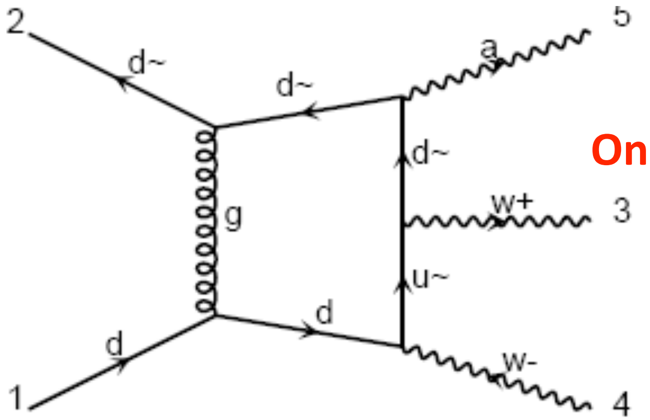


diagram 38 QCD=2, QED=3

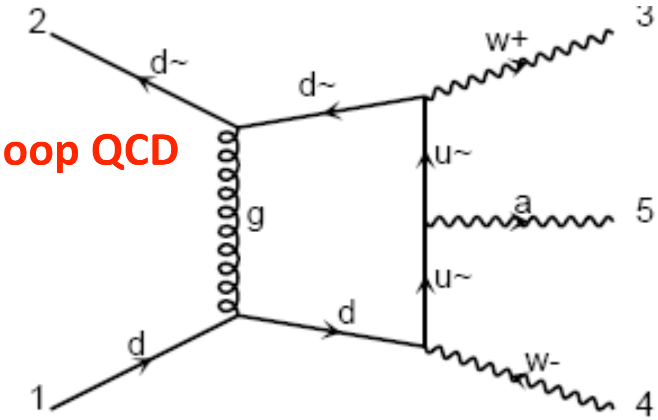
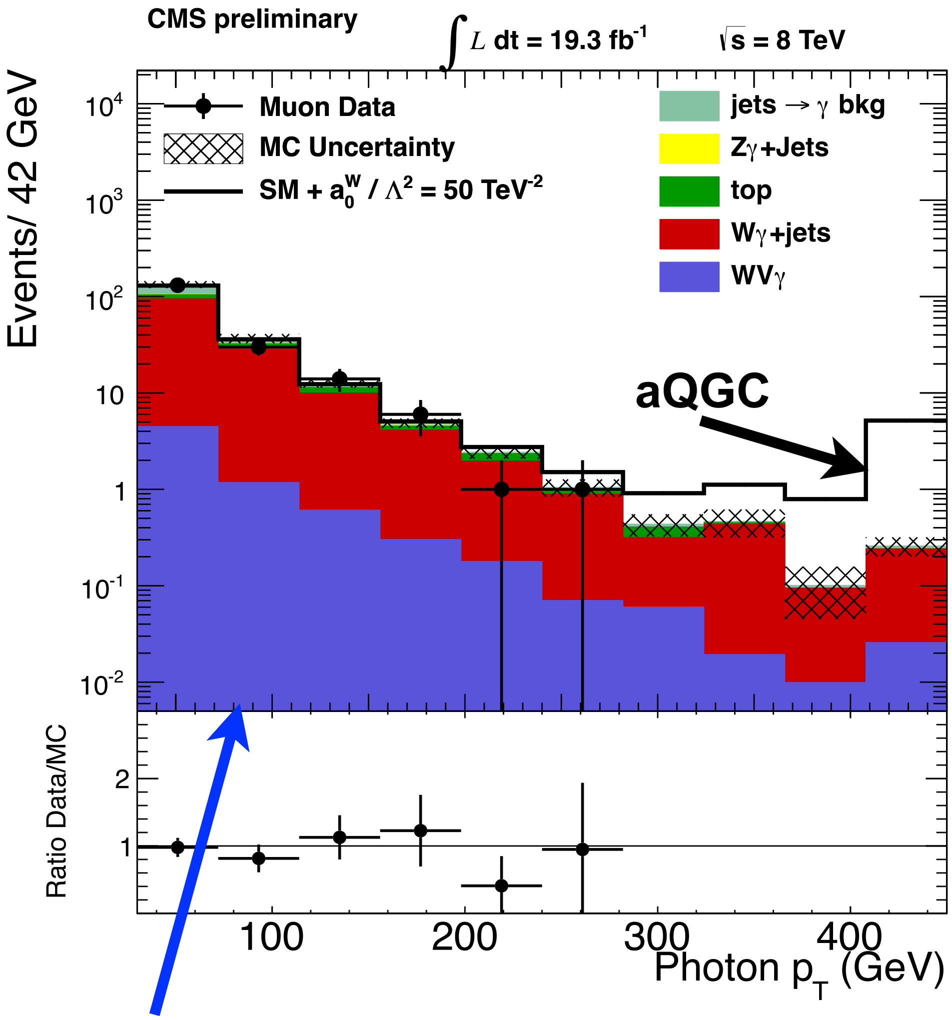


diagram 39 QCD=2, QED=3

Cross section for WVγ

CMS PAS SMP-13-007

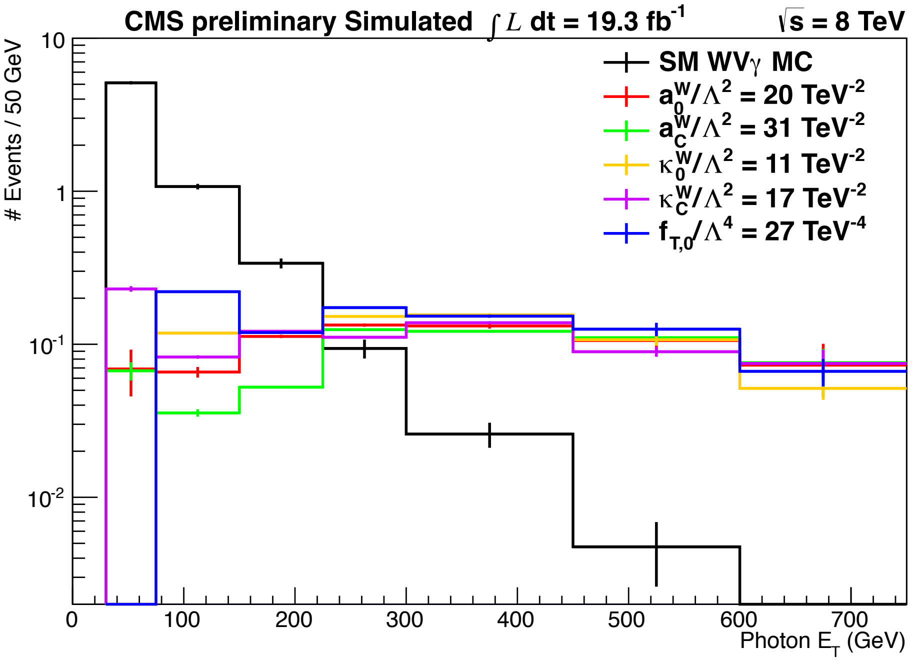


aQGC

SM WVγ

$\sigma(WV\gamma) < 241$ fb, 3.4x σ_{SM}

Not sensitive yet to SM rate. Set limits on anomalous quartic couplings.



Limits on WW$\gamma\gamma$ and WWZγ couplings

SMP-13-007

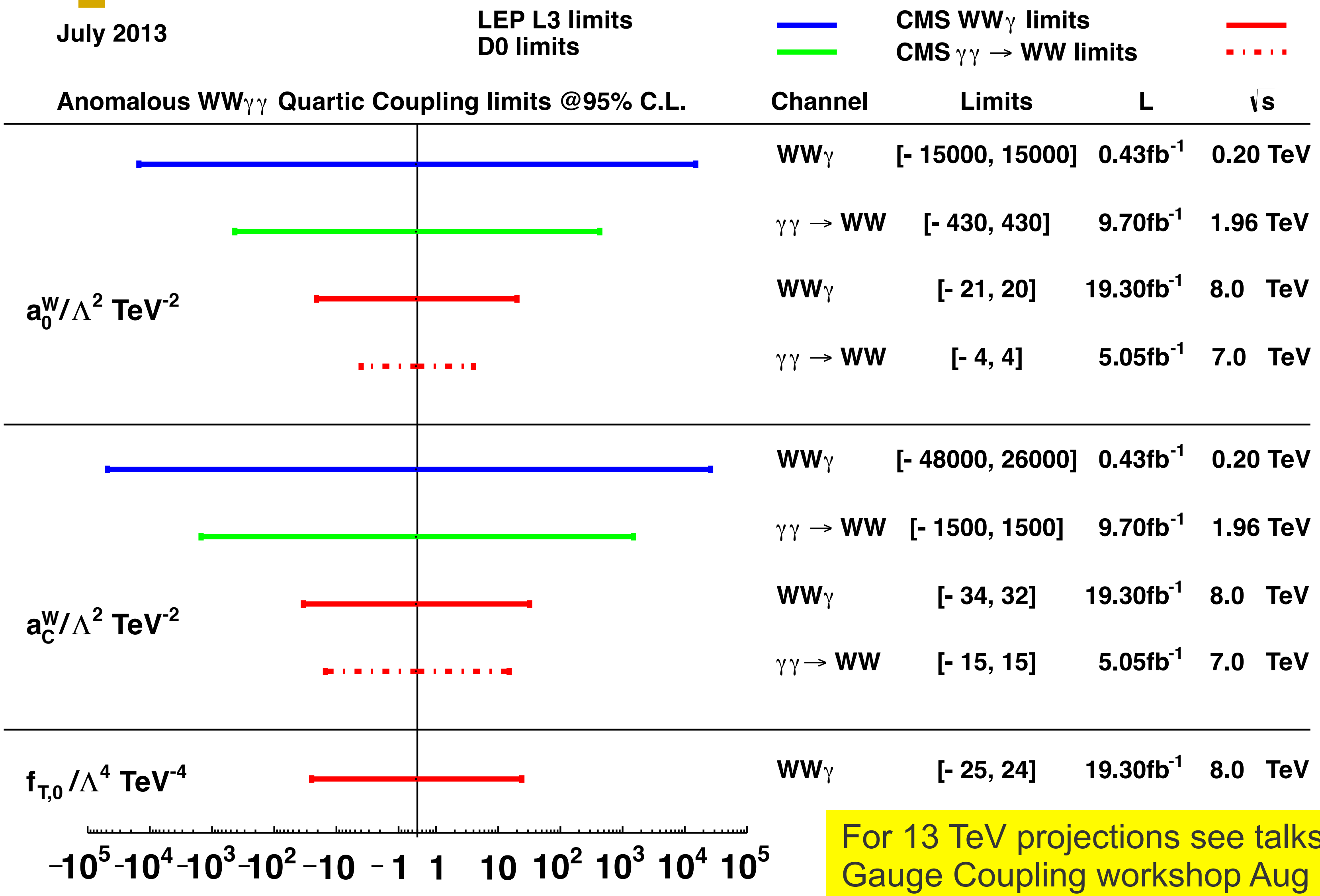
Observed Limits	Expected Limits
$-21\ (\mathrm{TeV}^{-2}) < a_0^W/\Lambda^2 < 20\ (\mathrm{TeV}^{-2})$	$-24\ (\mathrm{TeV}^{-2}) < a_0^W/\Lambda^2 < 23\ (\mathrm{TeV}^{-2})$
$-34\ (\mathrm{TeV}^{-2}) < a_C^W/\Lambda^2 < 32\ (\mathrm{TeV}^{-2})$	$-37\ (\mathrm{TeV}^{-2}) < a_C^W/\Lambda^2 < 34\ (\mathrm{TeV}^{-2})$
$-25\ (\mathrm{TeV}^{-4}) < f_{T,0}/\Lambda^4 < 24\ (\mathrm{TeV}^{-4})$	$-27\ (\mathrm{TeV}^{-4}) < f_{T,0}/\Lambda^4 < 27\ (\mathrm{TeV}^{-4})$
$-12\ (\mathrm{TeV}^{-2}) < \kappa_0^W/\Lambda^2 < 10\ (\mathrm{TeV}^{-2})$	$-12\ (\mathrm{TeV}^{-2}) < \kappa_0^W/\Lambda^2 < 12\ (\mathrm{TeV}^{-2})$
$-18\ (\mathrm{TeV}^{-2}) < \kappa^W/\Lambda^2 < 17\ (\mathrm{TeV}^{-2})$	$-19\ (\mathrm{TeV}^{-2}) < \kappa^W/\Lambda^2 < 18\ (\mathrm{TeV}^{-2})$

Order of magnitude improvement over LEP, but less stringent than $\gamma\gamma \rightarrow$WW. In the dipole units, these limits are probing QGC *O*(100 %) !!

Observed Limits	Expected Limits
$-77\ (\mathrm{TeV}^{-4}) < f_{M,0}/\Lambda^4 < 81\ (\mathrm{TeV}^{-4})$	$-89\ (\mathrm{TeV}^{-4}) < f_{M,0}/\Lambda^4 < 93\ (\mathrm{TeV}^{-4})$
$-131\ (\mathrm{TeV}^{-4}) < f_{M,1}/\Lambda^4 < 123\ (\mathrm{TeV}^{-4})$	$-143\ (\mathrm{TeV}^{-4}) < f_{M,1}/\Lambda^4 < 131\ (\mathrm{TeV}^{-4})$
$-39\ (\mathrm{TeV}^{-4}) < f_{M,2}/\Lambda^4 < 40\ (\mathrm{TeV}^{-4})$	$-44\ (\mathrm{TeV}^{-4}) < f_{M,2}/\Lambda^4 < 46\ (\mathrm{TeV}^{-4})$
$-66\ (\mathrm{TeV}^{-4}) < f_{M,3}/\Lambda^4 < 62\ (\mathrm{TeV}^{-4})$	$-71\ (\mathrm{TeV}^{-4}) < f_{M,3}/\Lambda^4 < 66\ (\mathrm{TeV}^{-4})$

The first ever limit on WWZγ couplings κ_0^W and κ_C^W. The first limit on dim 8 parameters f_M.

Many studies of QGC done: now some complete analysis!



July 2013

LEP L3 limits 🟦
D0 limits 🟩
CMS WWγ limits 🟥
CMS γγ → WW limits ▪ · ▪ ·

Anomalous WWγγ Quartic Coupling limits @95% C.L.

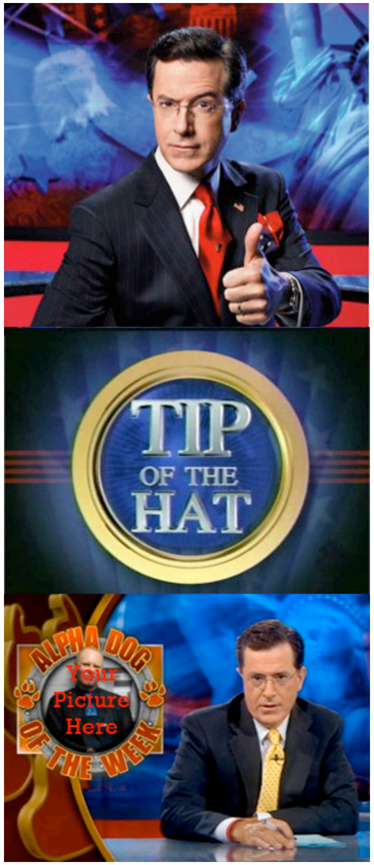
	Channel	Limits	L	√s
a_0^W/Λ^2 TeV^{-2}	WWγ	[- 15000, 15000]	0.43fb^{-1}	0.20 TeV
	γγ → WW	[- 430, 430]	9.70fb^{-1}	1.96 TeV
	WWγ	[- 21, 20]	19.30fb^{-1}	8.0 TeV
	γγ → WW	[- 4, 4]	5.05fb^{-1}	7.0 TeV
a_C^W/Λ^2 TeV^{-2}	WWγ	[- 48000, 26000]	0.43fb^{-1}	0.20 TeV
	γγ → WW	[- 1500, 1500]	9.70fb^{-1}	1.96 TeV
	WWγ	[- 34, 32]	19.30fb^{-1}	8.0 TeV
	γγ → WW	[- 15, 15]	5.05fb^{-1}	7.0 TeV
$f_{T,0}/\Lambda^4$ TeV^{-4}	WWγ	[- 25, 24]	19.30fb^{-1}	8.0 TeV

For 13 TeV projections see talks in LPC Gauge Coupling workshop Aug 19-20

https://indico.cern.ch/conferenceDisplay.py?confId=252071

Changing gear: Other recent measurements

IMO, these are some of the most beautiful measurements by CMS!



☑ Each of these required <u>beyond the baseline</u> understanding of physics objects
- this is why they took so long

☑ Some notable examples of such analyses are

W charge asymmetry: has exquisitely tuned muon p_T and MET

Inclusive jet cross section: exposed some shortcomings in the standard JEC

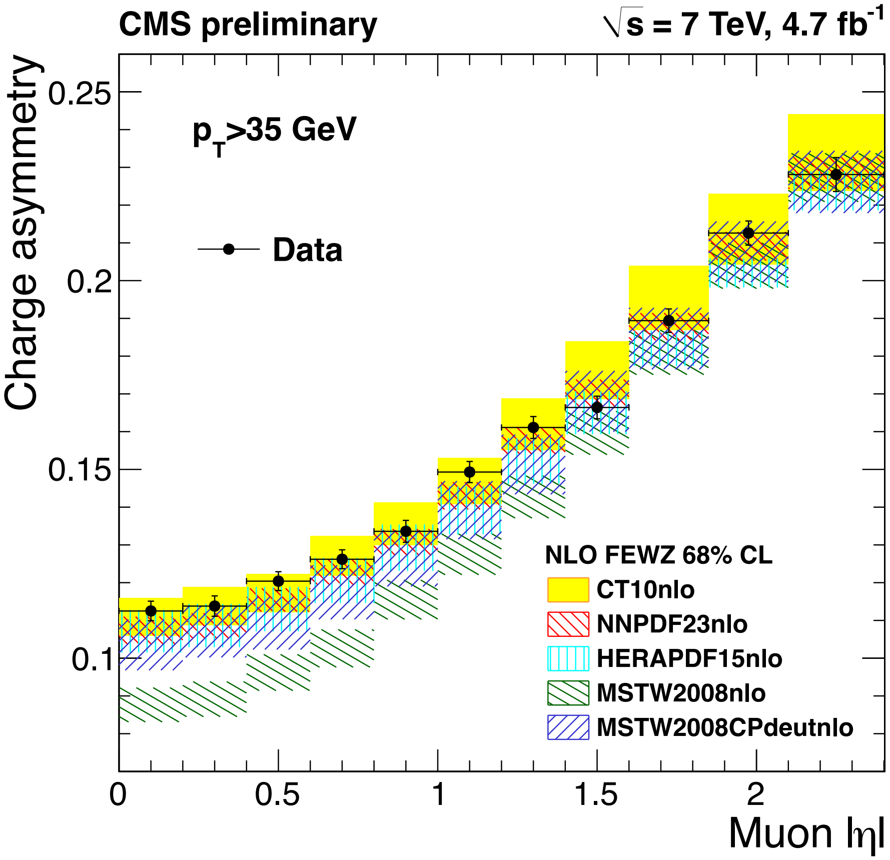
Diphoton rate: is a tour de force of ECAL isolation modeling, effectively back-ported many features of CMS SW 7 to SW 4.4

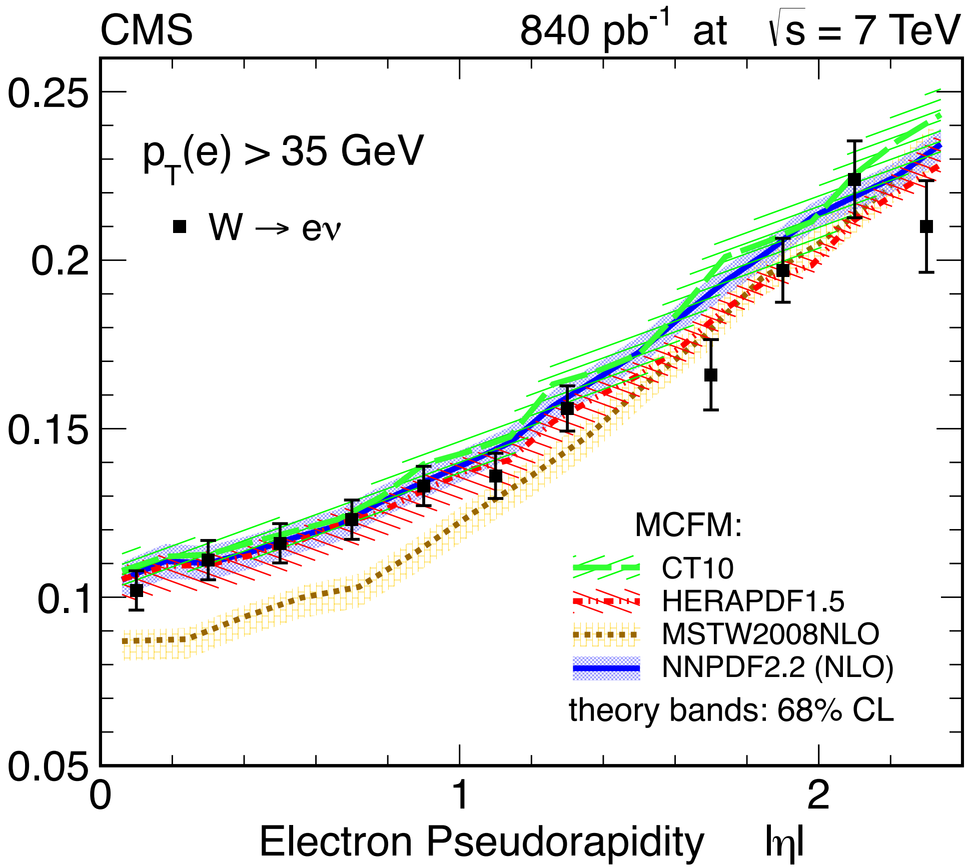
Each of them stimulated improvements in detector performance & understanding.

W charge asymmetry

CMS-SMP-12-021

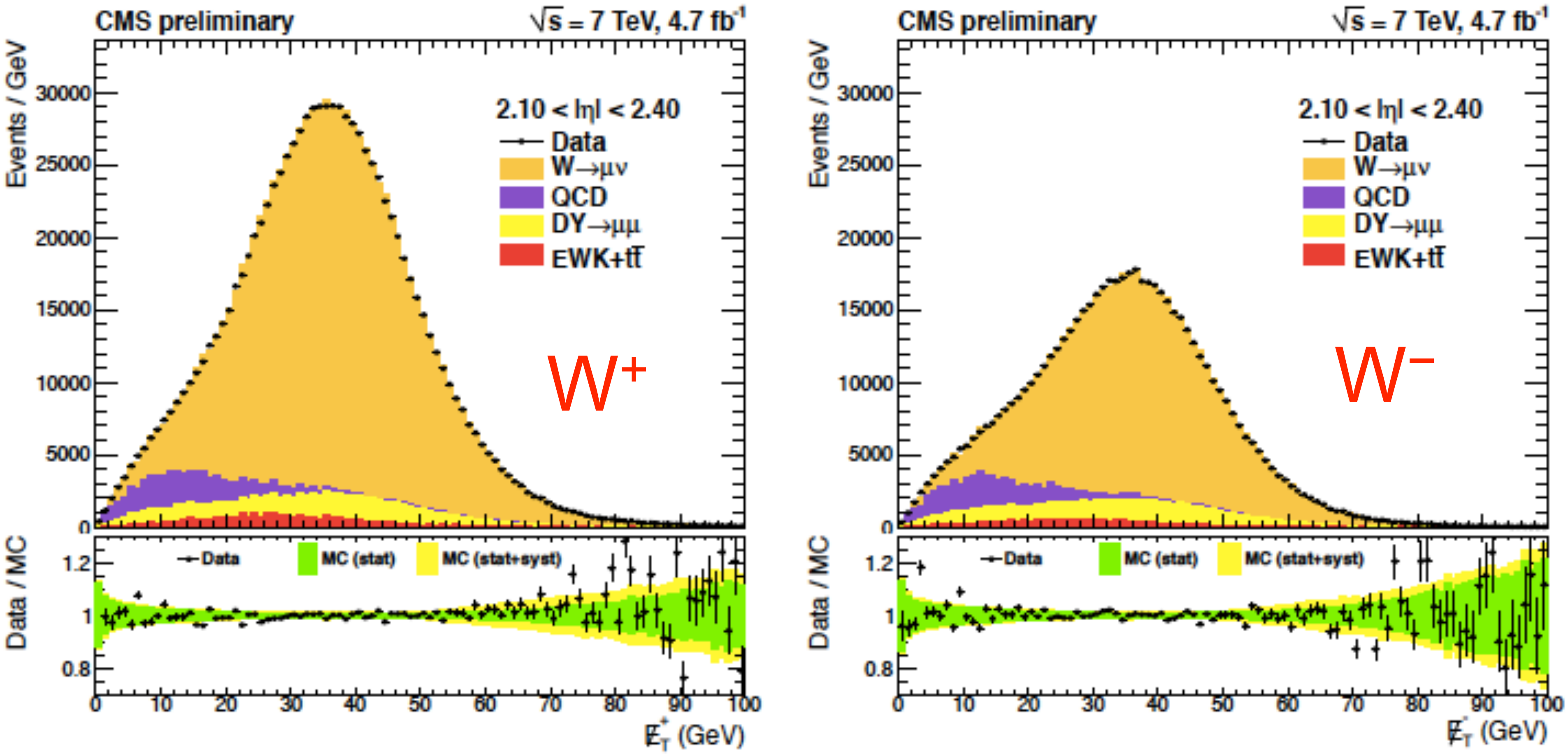
CMS-PAS-EWK-11-005





Can help constrain PDF significantly. Clearly see that MSTW2008 and HERAPDF need tuning.

An example of W signal extraction from MET fit



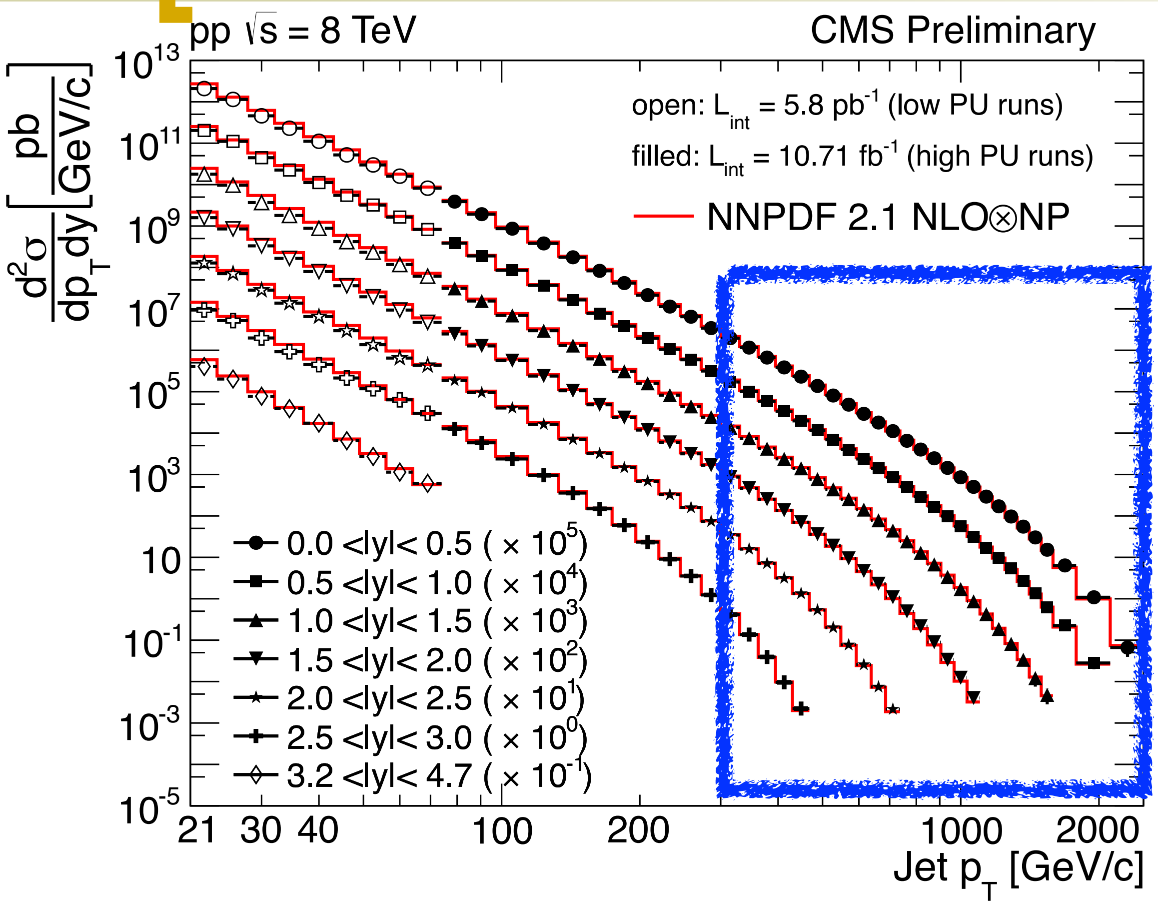
Notice that the MET distribution starts at 0 !!!
(more such beautiful plots in the backup)

Inclusive jet differential cross section at 8 TeV

CMS-PAS-SMP-12-012

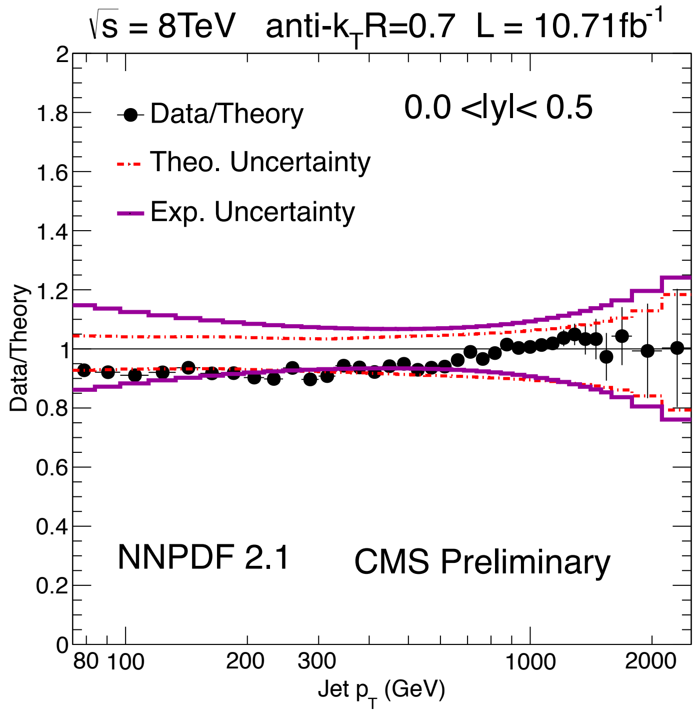
CMS-PAS-FSQ-12-031

Lots of events at large $\hat{s}$, experimental & theory uncertainties are ~ equal.

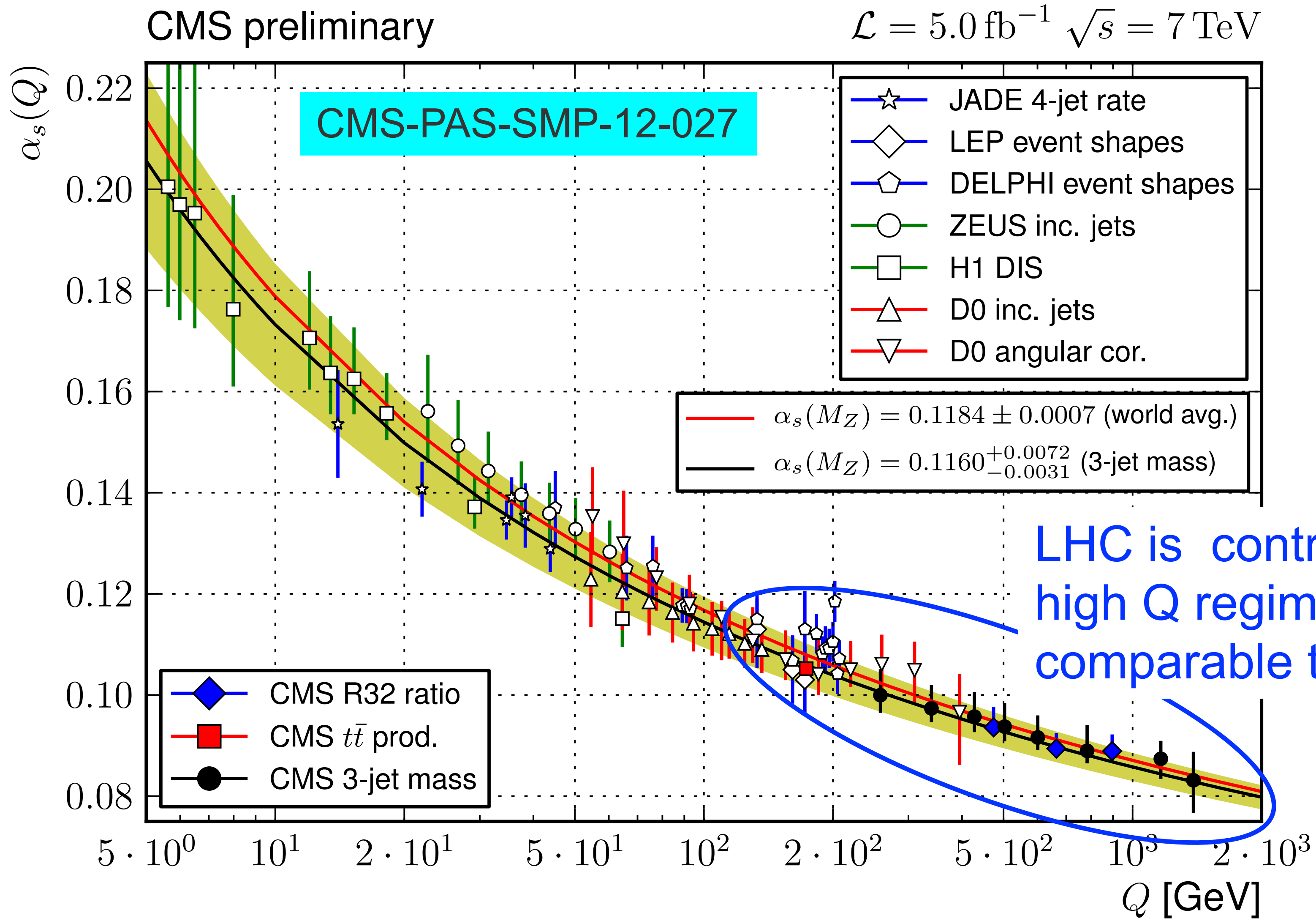


A region actively searched for BSM signals

Probe QCD rate over 15 orders of magnitude !!! No surprises up to 2 TeV.

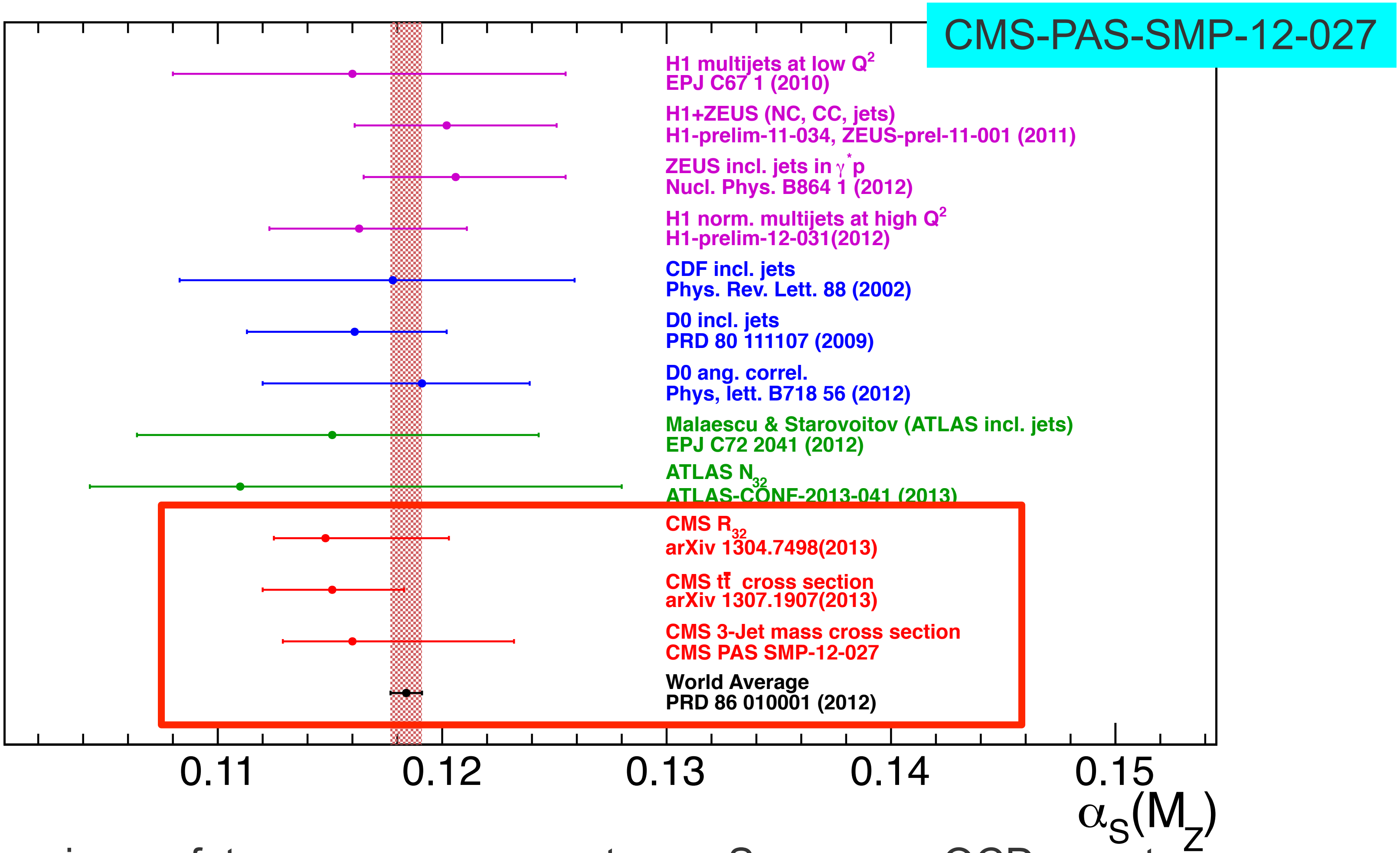


Measurement of α_S from 3-jet events



LHC is contributing in high Q regime. Precision comparable to HERA.

α_S world average and CMS measurements

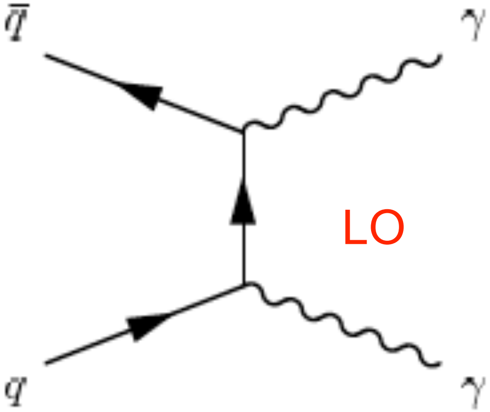


CMS-PAS-SMP-12-027

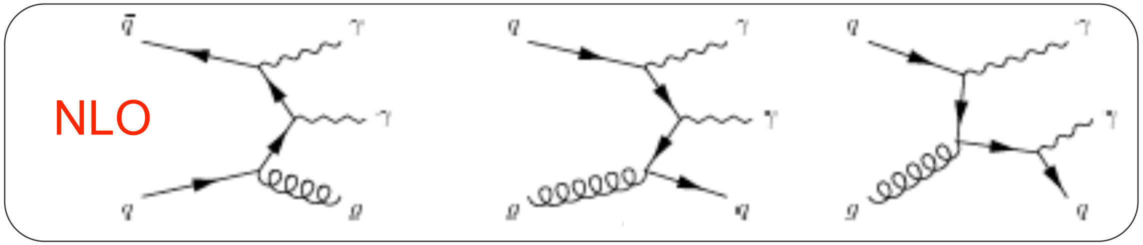
For discussion on future α_S measurements see Snowmass QCD report
http://www.snowmass2013.org/tiki-index.php?page=Quantum+Chromodynamics+and+the+Strong+Force

Diphoton production

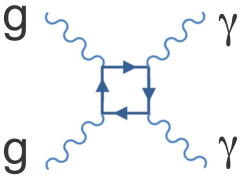
CMS PAS SMP-13-001



LO



NLO



NNLO: Box diagram

Sensitive to ISR soft gluon emissions and the non-perturbative quark-gluon fragmentation to photons in the final state.

$$\sigma_{data} = 16.8 \pm 0.2\ \text{(stat.)} \pm 1.8\ \text{(syst.)} \pm 0.4\ \text{(lumi) pb}$$

$$\sigma_{\text{NNLO}}(2\gamma\text{NNLO}) = 16.2^{+1.5}_{-1.3}(\text{scale})\ \text{pb}$$

$$\sigma_{\text{NLO}}(\text{DIPHOX+GAMMA2MC}) = 12.8^{+1.6}_{-1.5}(\text{scale})^{+0.6}_{-0.8}(\text{pdf}+\alpha_s)\ \text{pb}$$

$$\sigma_{\text{NLO}}(\text{RESBOS}) = 14.9^{+2.2}_{-1.7}(\text{scale}) \pm 0.6(\text{pdf}+\alpha_s)\ \text{pb}$$

$$\sigma_{\text{LO}}(\text{SHERPA}) = 15.2^{+3.2}_{-1.9}(\text{scale})\ \text{pb}$$

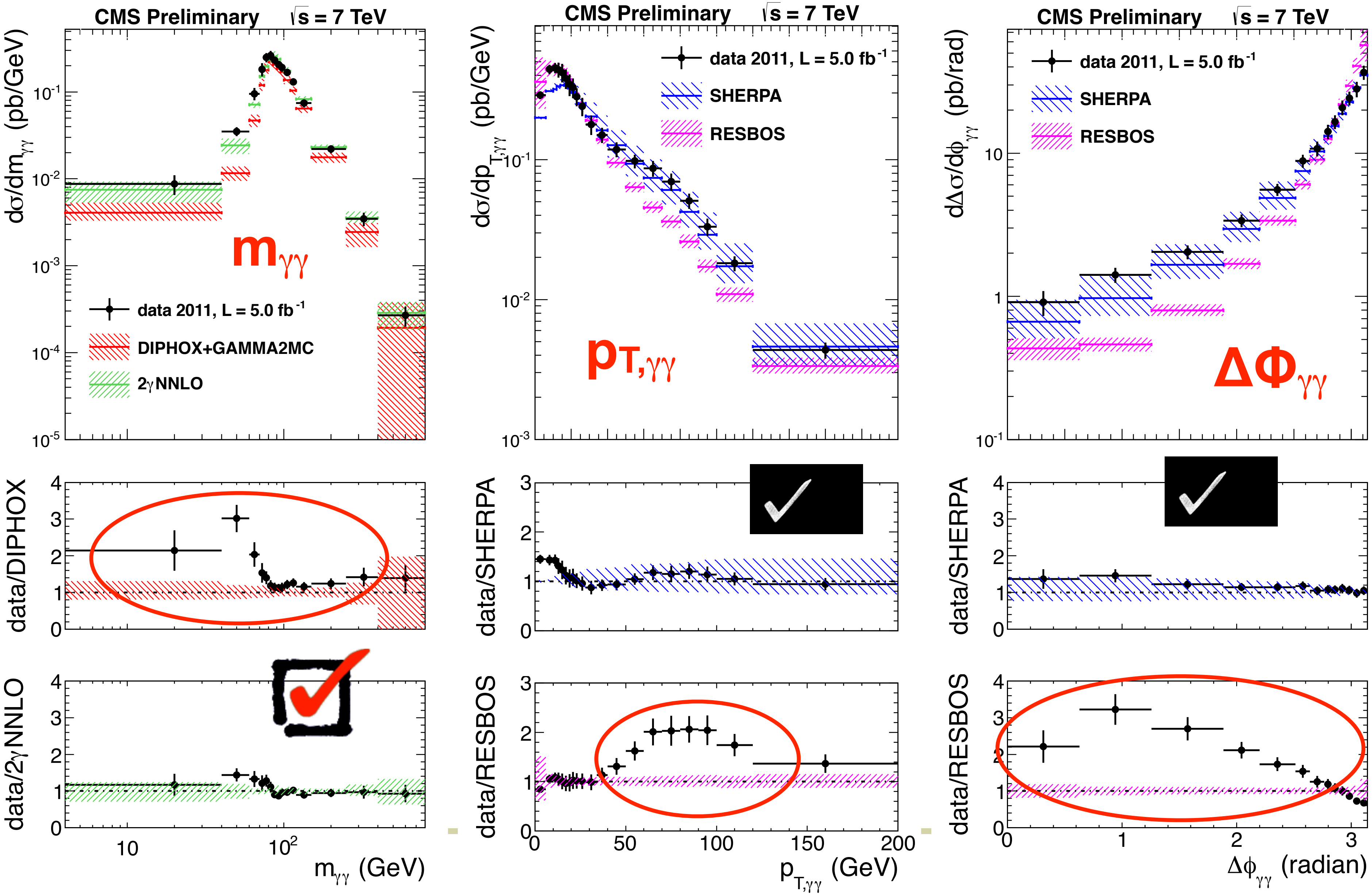
Experimental precision ≈Theory uncertainty

In the fiducial volume at √s = 7 TeV

$$p_{T,\gamma 1} > 40\ \text{GeV},$$
$$p_{T,\gamma 2} > 25\ \text{GeV},$$
$$|\eta_\gamma| < 2.5,$$
$$\Delta R(\gamma_1, \gamma_2) > 0.45.$$

γγ differential cross section

CMS PAS SMP-13-001



Making sense of diphoton measurement

It is fun to beat up on RESBOS and DIPHOX, their limitations have been well known for a while. Sherpa LO (which includes up to 3 extra jets) has turned out to be doing a pretty good job.

But the real story is the unreasonably good agreement with 2γNNLO.

Just like it took BlackHat/NLO to get V+jets to look good, it took NNLO to get photons to look good. In both cases there are still regions of phase space: low $\Delta\Phi$, high p_T, where even higher orders might be necessary.

Remember, due to FSR and fragmentation, you always want a bit higher order for photons than other processes.

Some concluding remarks

☑ Standard Model stubbornly refuses to be falsified by experiment

- Rare processes like multi-bosons & VV scattering no exception
- However, unlike for the muon, our understanding of "g-2" for W is still at the percent level ➜ 14 TeV run will take us to 0.1% level

☑ New ideas are starting to realize their potential

- W/Z/top being reconstructed in boosted/merged jets
- Higher dimension gauge operators are being probed for anomalous gauge and Higgs couplings at large ŝ

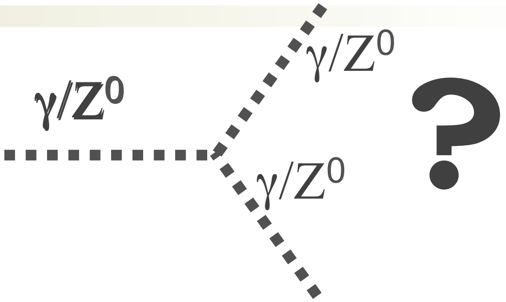
Which is why 14 TeV running is so important to the program

Thank you for your attention.

BACKUP SLIDES

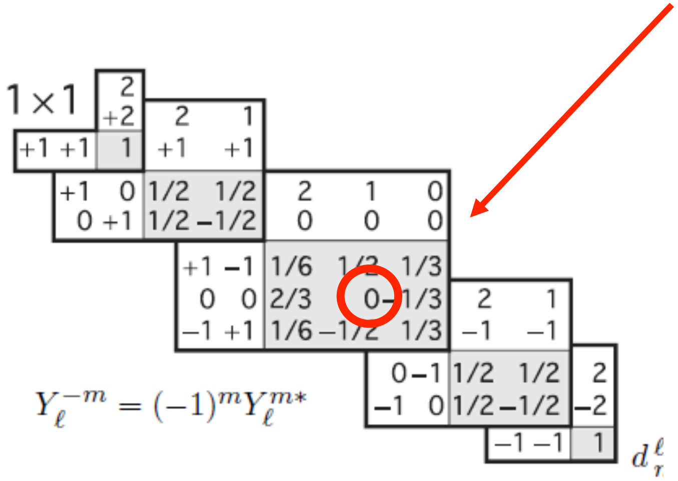
Why no all-neutral couplings in the SM?

Here's where thinking about the unbroken SU(2) X U(1) symmetry helps.



- Trilinear Coupings
  - B-B-B: zero because U(1)'s are Abelian
  - B-B-w_3
  - B-w_3-w_3
  - w_3-w_3-w_3
    - The Clebsch-Gordon coefficient for (1,0)+(1,0)=(1,0) is **zero**.
    - This is the SU(2) symmetry in action

The w's don't carry hypercharge, and the B doesn't carry isospin. So the "mixed couplings" are zero



1×1

	2 +2
+1 +1	1

	2 +1	1 +1
+1 0	1/2	1/2
0 +1	1/2	−1/2

	2 0	1 0	0 0
+1 −1	1/6	1/2	1/3
0 0	2/3	0	−1/3
−1 +1	1/6	−1/2	1/3

	2 −1	1 −1
0 −1	1/2	1/2
−1 0	1/2	−1/2

	2 −2
−1 −1	1

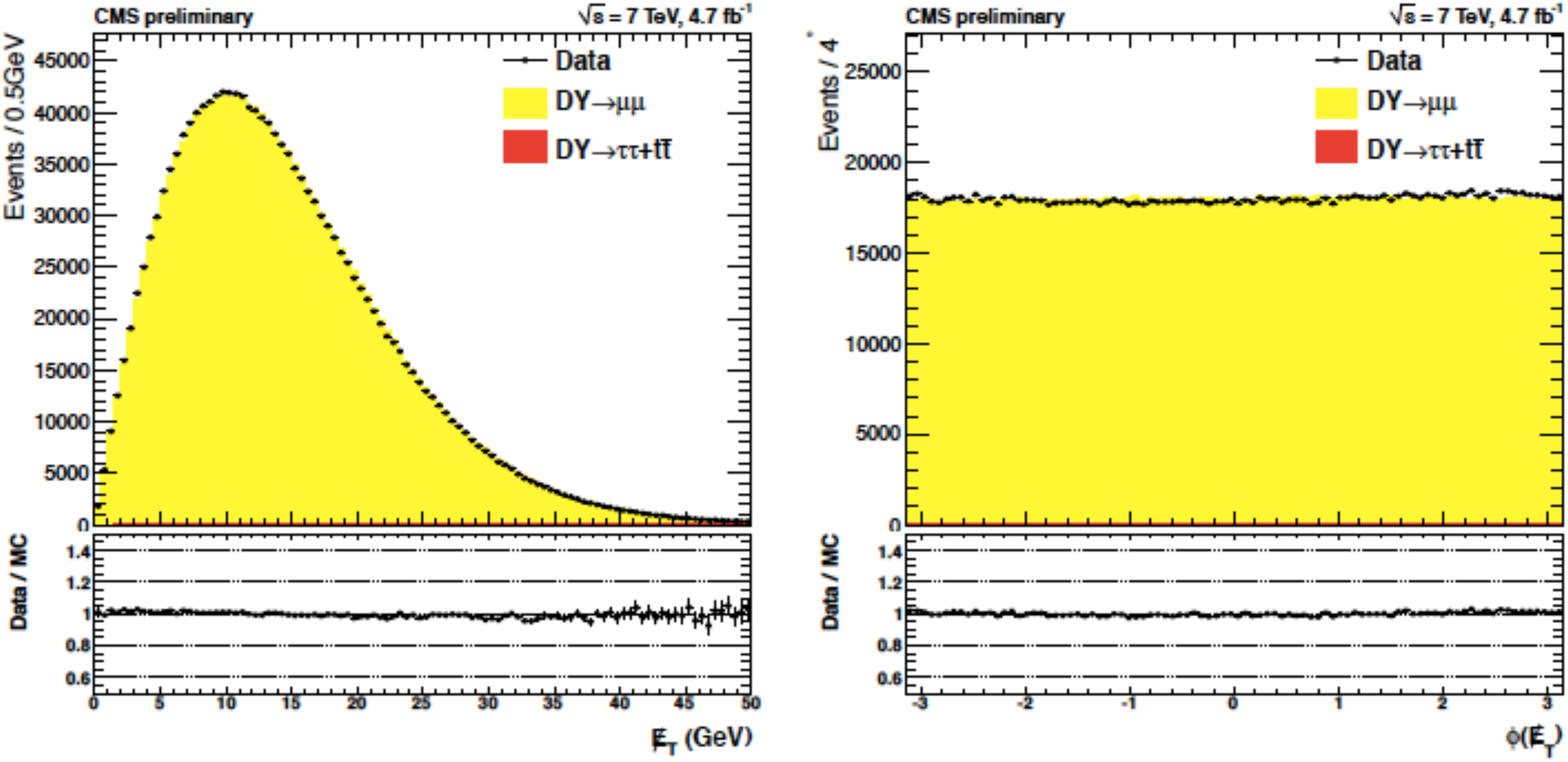
$Y_\ell^{-m} = (-1)^m Y_\ell^{m*}$

d^ℓ_r

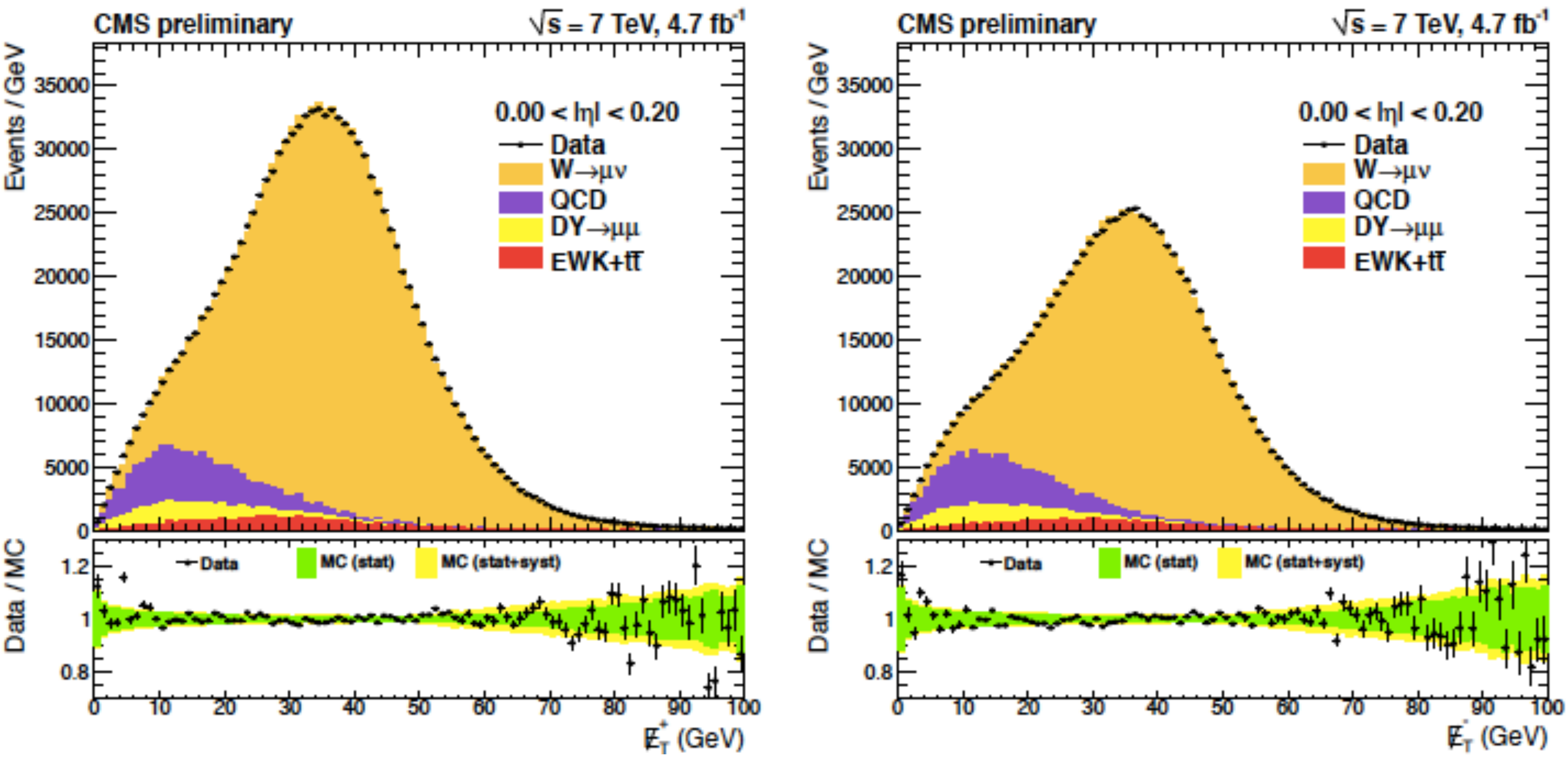
These are all zero. Any linear combination (like the γ and Z) of zeros is still zero.

A similar argument holds for the quartic couplings.

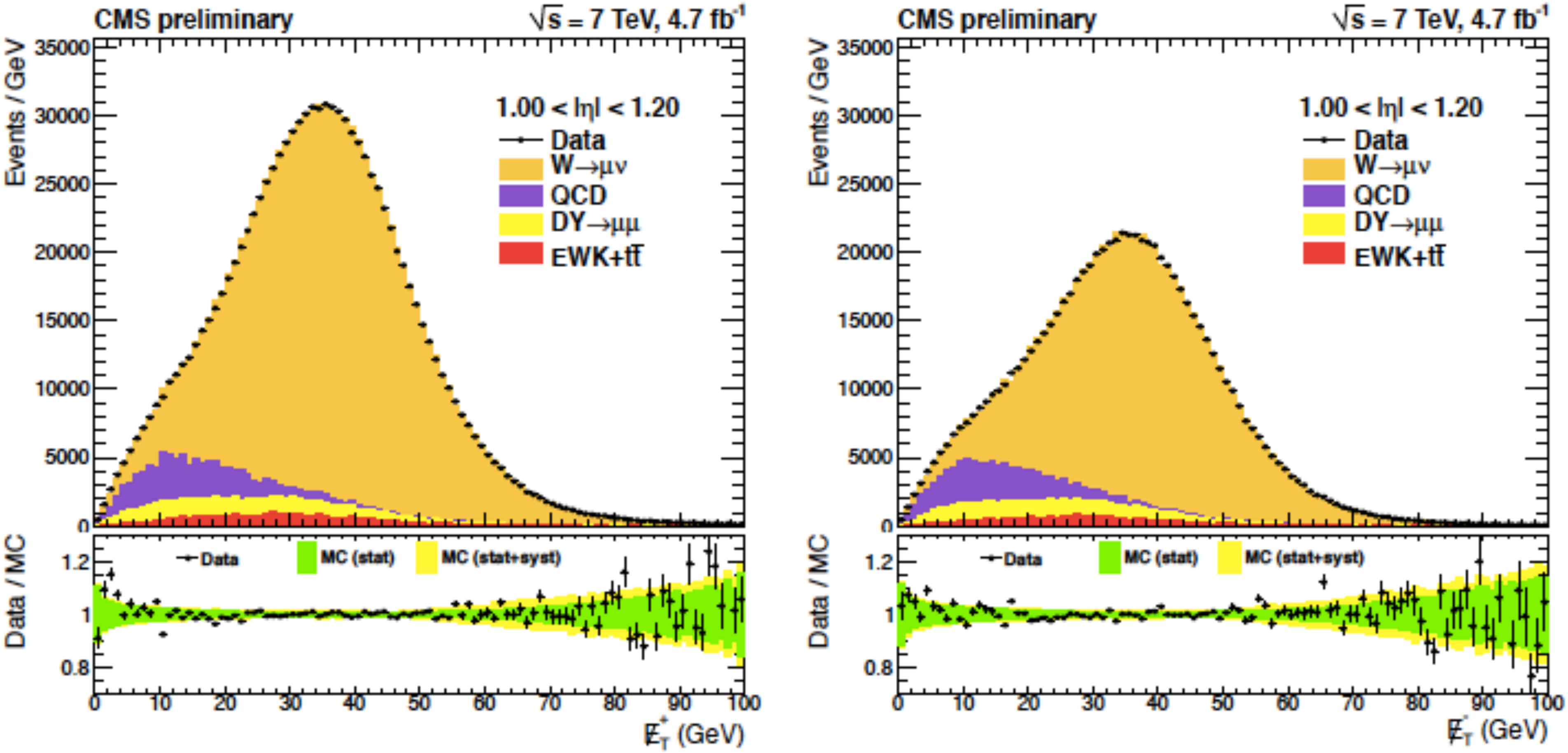
W charge asymmetry: MET in DY calibration sample



W charge asymmetry: W signal extraction



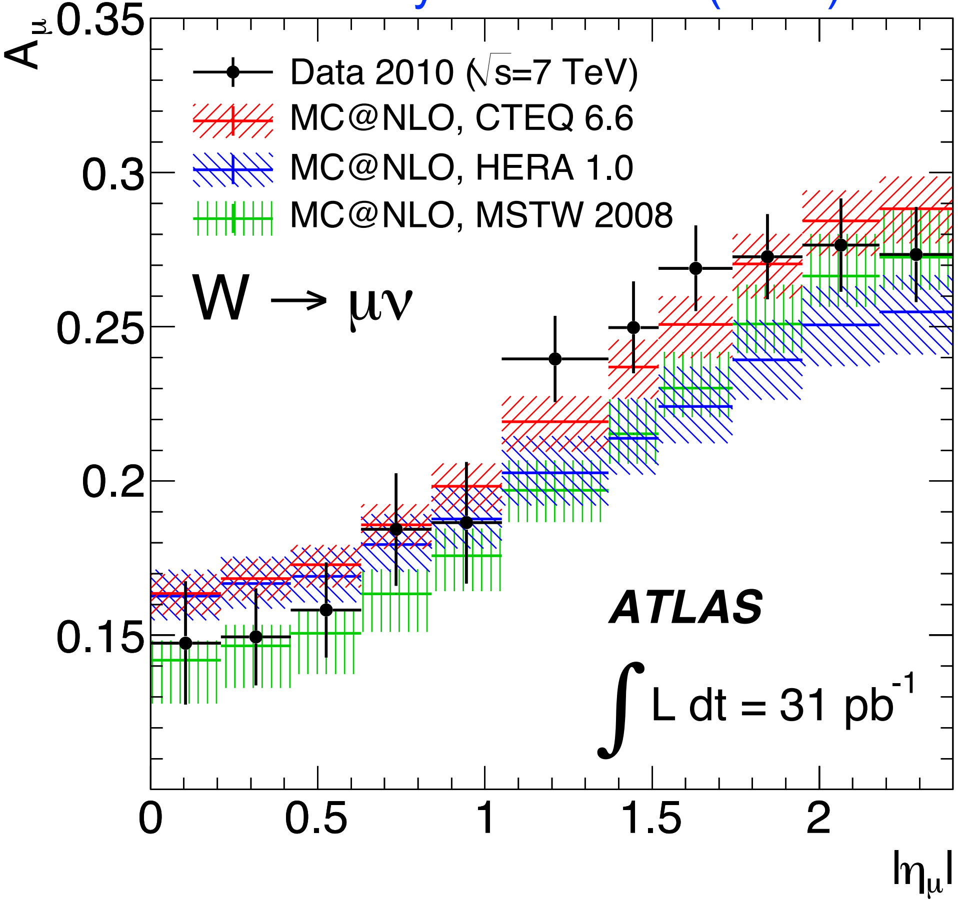
W charge asymmetry: W signal extraction



W charge asymmetry: blowback from PDF folks .....

ATLAS result is more muddled.

Phys.Lett. B701 (2011) 31



γγ : prompt photon isolation in data & MC

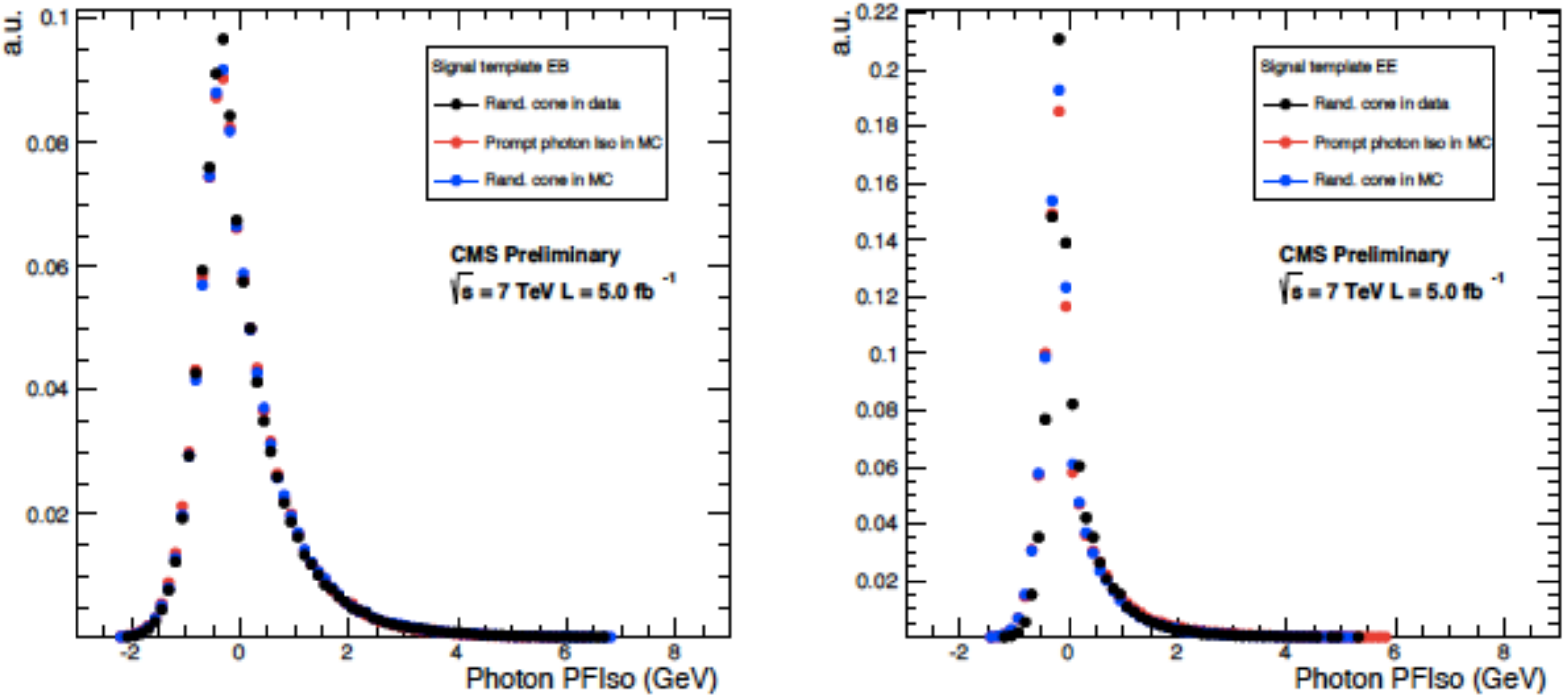


Figure 1: Signal templates comparison: MC-truth prompt-photons (red), prompt-photon templates extracted with the random-cone technique from MC (blue) and data (black). (left) candidates in the ECAL barrel, (right) candidates in the ECAL endcaps.

γγ : fake photon isolation template

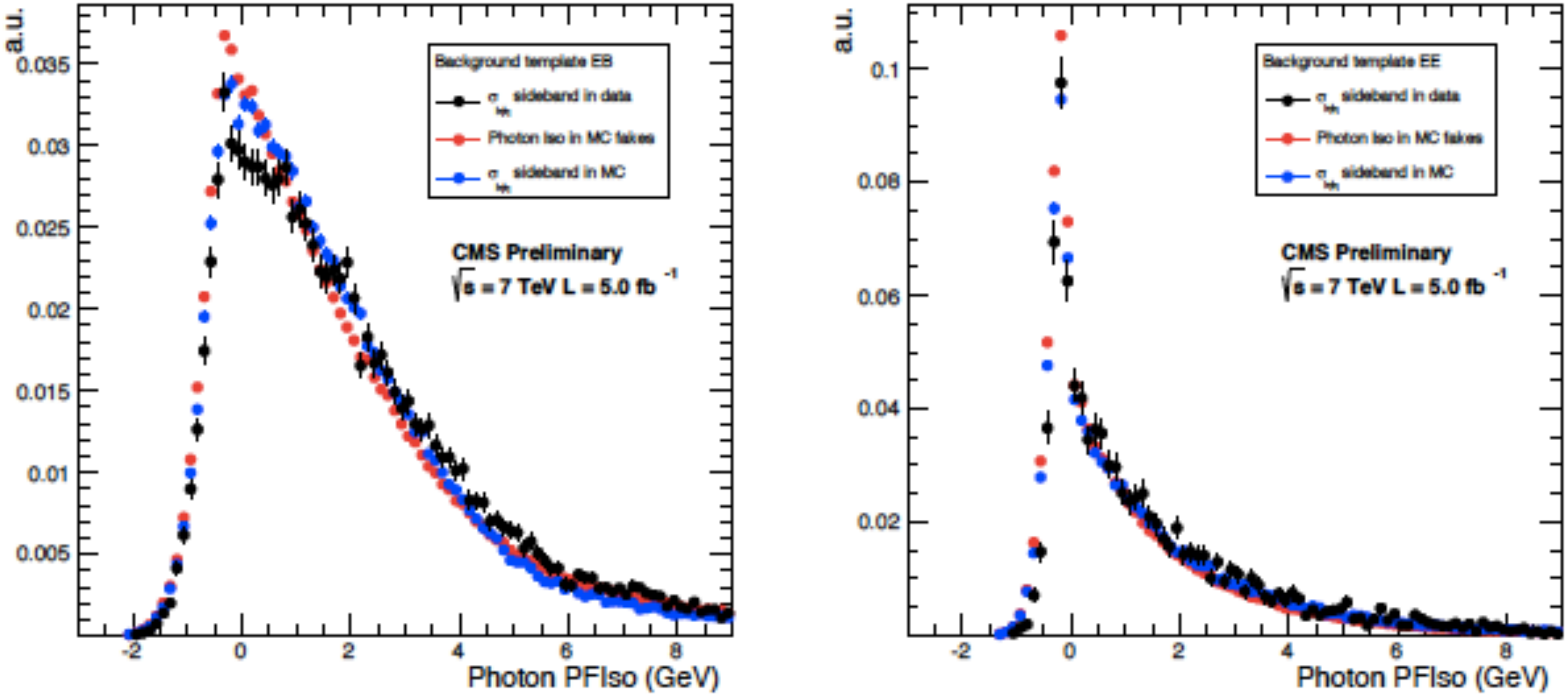


Figure 2: Background templates comparison: MC-truth fake-photons (red), fake-photon templates extracted with the sideband technique from MC (blue) and data (black). (left) candidates in the ECAL barrel, (right) candidates in the ECAL endcaps.

γγ : examples of template fit