

**A Measurement of the $Z\gamma$ Cross Section
and
Limits on Anomalous Triple Gauge Couplings
at $\sqrt{s} = 7\text{ TeV}$ Using CMS**

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9 October, 2012

Interactions in the Standard Model

Leptons

e, μ, τ
 ν_e, ν_μ, ν_τ

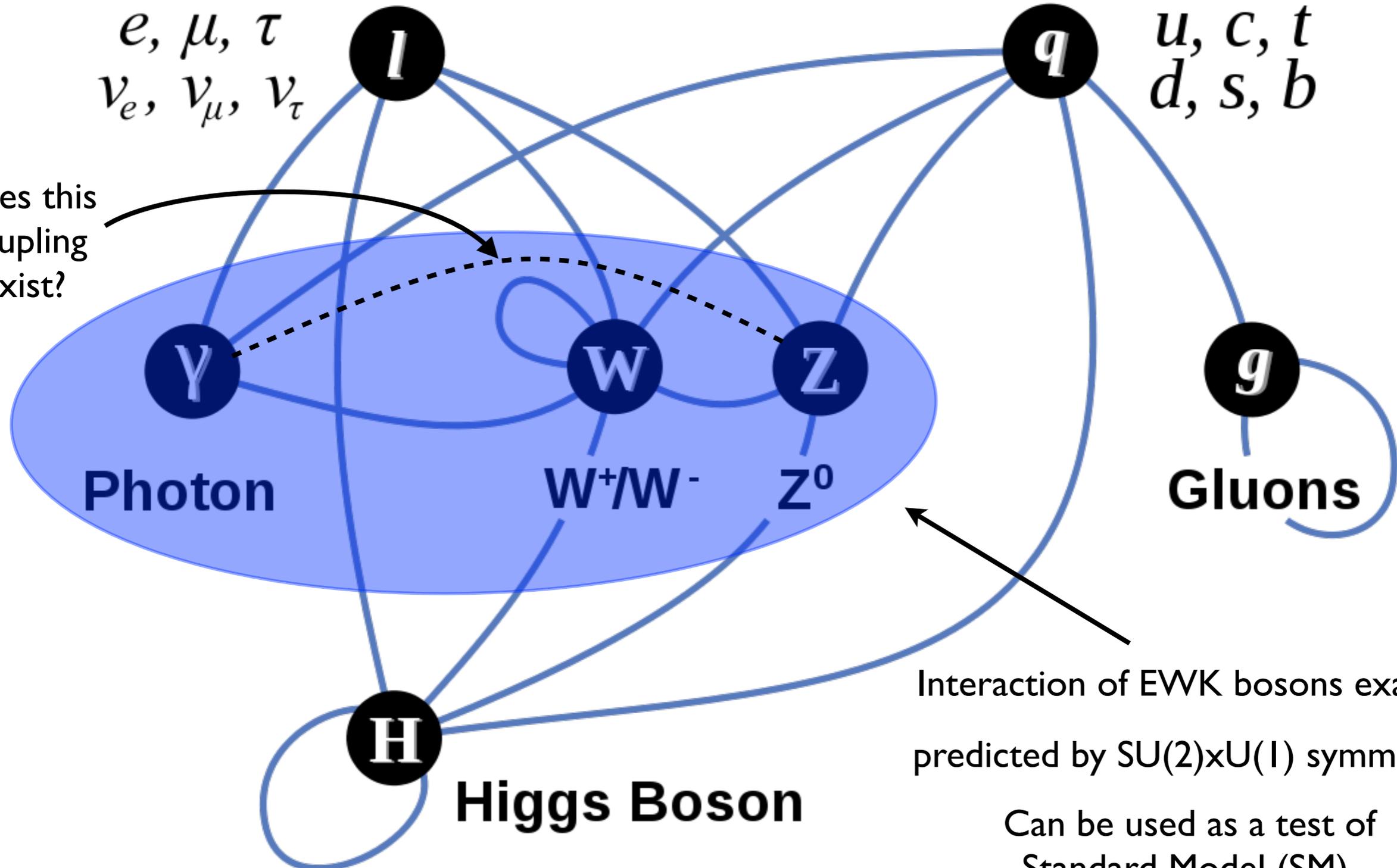
l

Quarks

u, c, t
 d, s, b

q

Does this coupling exist?

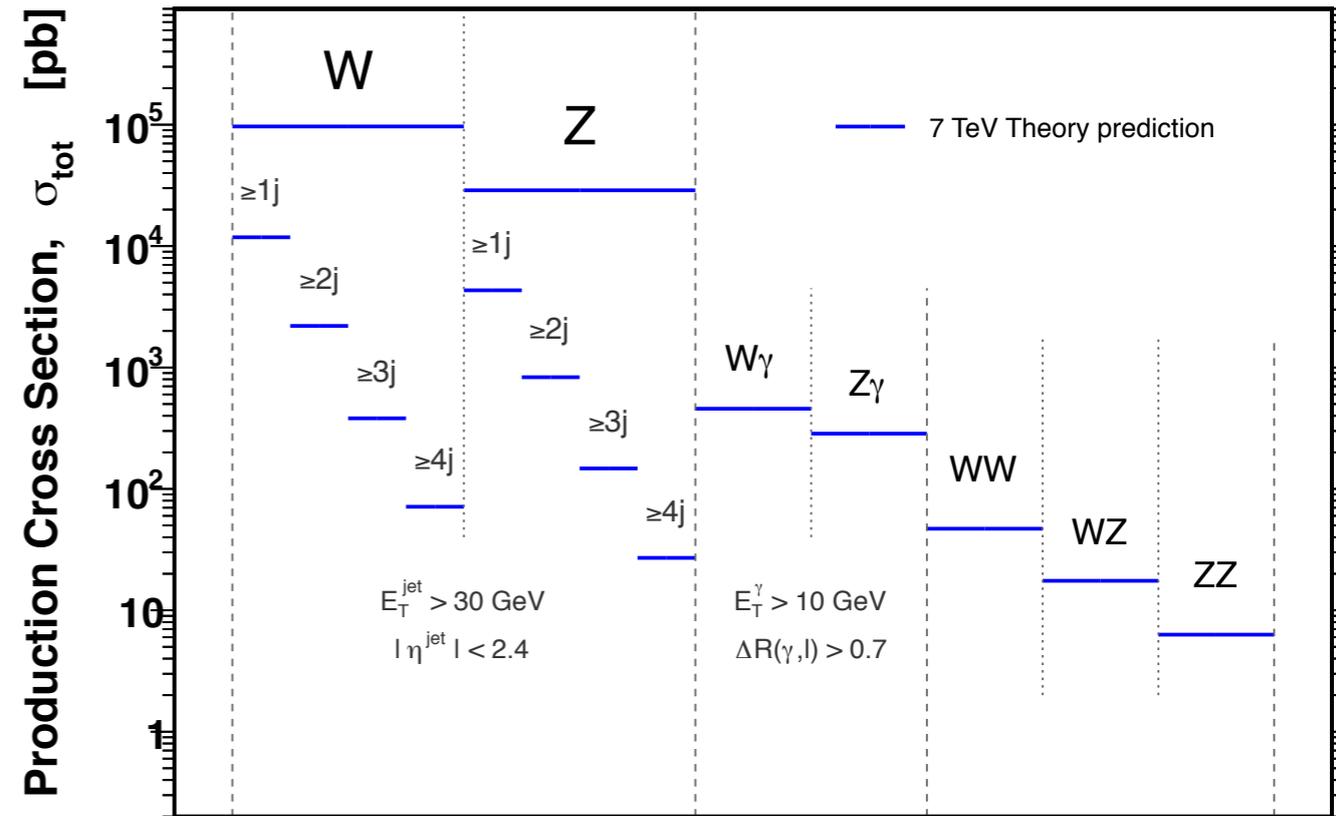


Interaction of EWK bosons exactly predicted by $SU(2) \times U(1)$ symmetry.

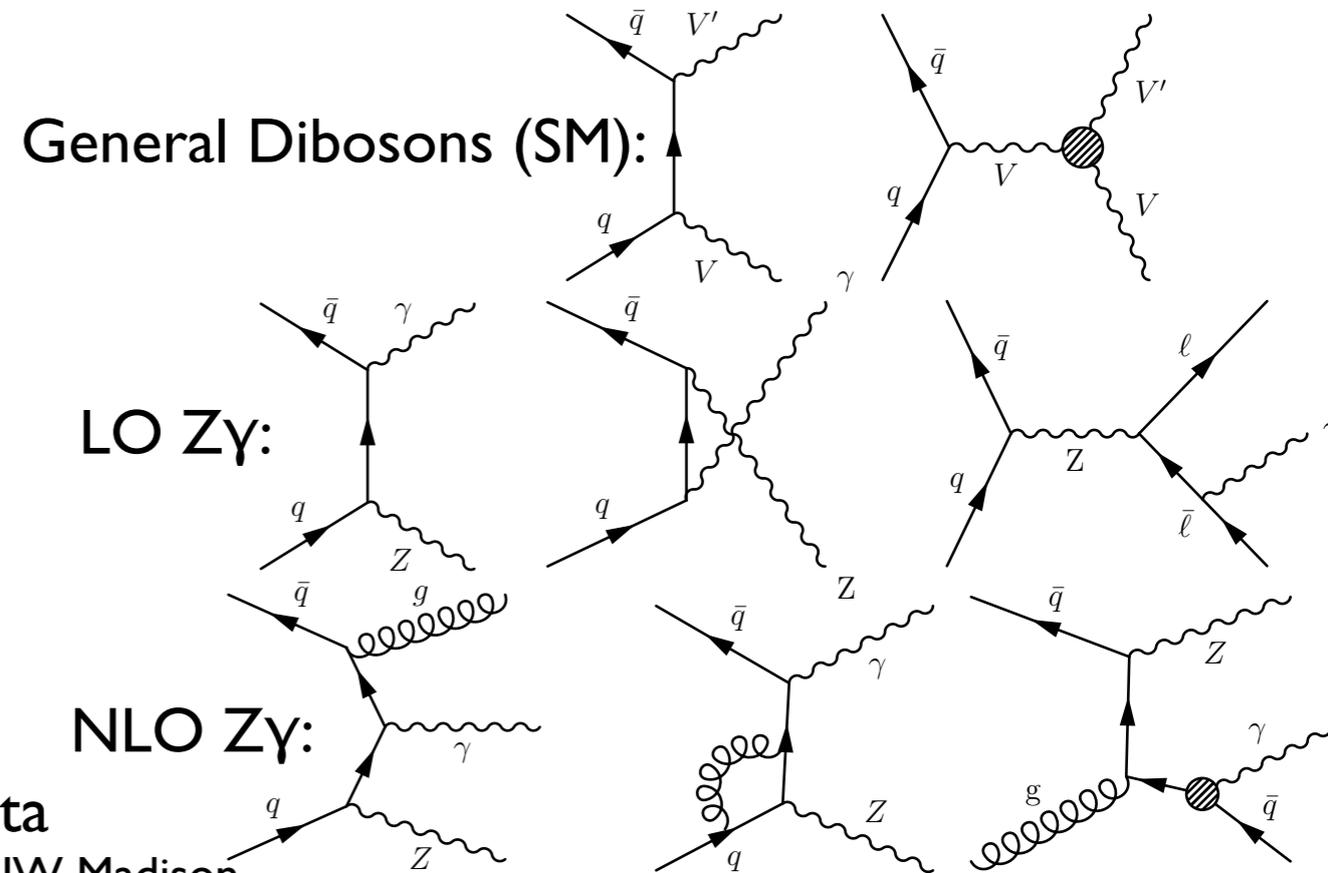
Can be used as a test of Standard Model (SM).

Production of Dibosons

- Produced by boson radiation or annihilation off quarks, triple gauge couplings where allowed
- Triple gauge couplings (TGC) are between three vector bosons
- $W\gamma$, WZ , and WW final states have Triple Gauge Couplings
- $Z\gamma$ and ZZ TGCs forbidden in SM



- Goal: Study the $Z\gamma$ final state
- Measure cross section and test for anomalous gauge couplings (aTGC)
- Energetic QCD ever present at LHC
 - NLO calculations necessary to model data



Neutral Anomalous Triple Gauge Couplings

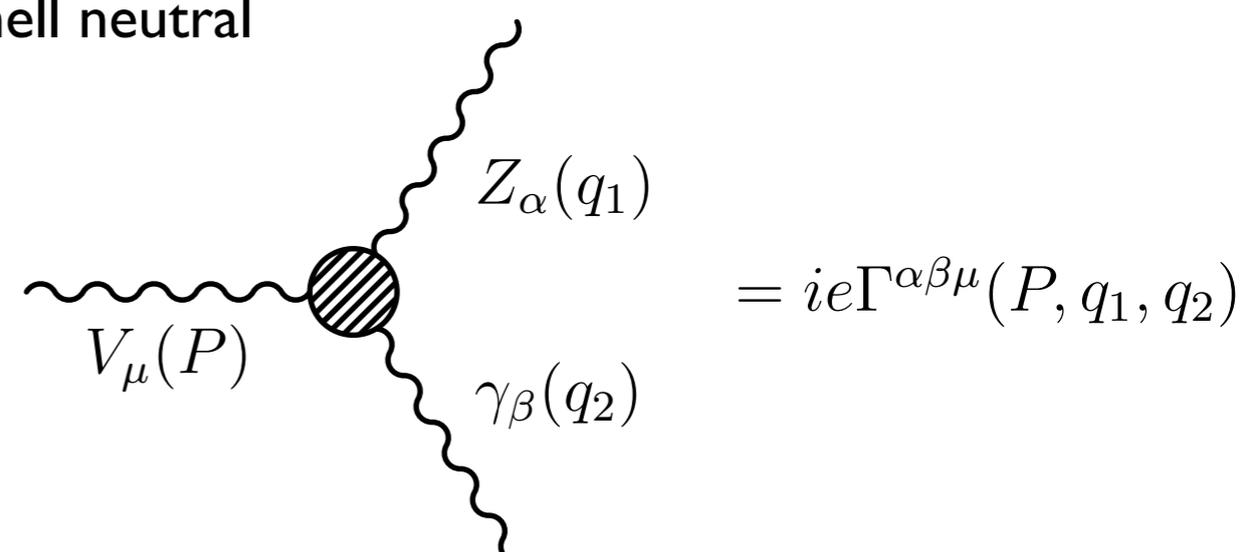
● An on-shell neutral vector cannot decay into two on-shell neutral vectors

- Yang's Theorem

● Furthermore, Z is not charged

- SM γ does not couple

● EWK symmetries not fundamental and Lorentz invariance allows more couplings



- Neutral aTGCs allowed in this case and their structure is well defined

- All dimension 6 or 8 operators

8 couplings allowed at tree level in Lorentz structure

- Produce different final state boson transverse moment (p_T) distributions
- Search for deviation from SM distributions to test for aTGC
- Zy advantage: direct access to boson (γ)

$$\frac{P^2 - q_1^2}{m_Z^2} \rightarrow \frac{P^2}{m_Z^2} \quad \text{and} \quad h_{1-4}^Z \rightarrow h_{1-4}^\gamma$$

- Form factor sometimes used to enforce unitarity

- Unitarity only need be enforced where there are data
- No form factor used in this thesis

$$\text{Form Factor} = f(\hat{s}) = \frac{1}{(1 + \hat{s}/\Lambda^2)^n}$$

● Matrix Element (ME) calculations and event generators

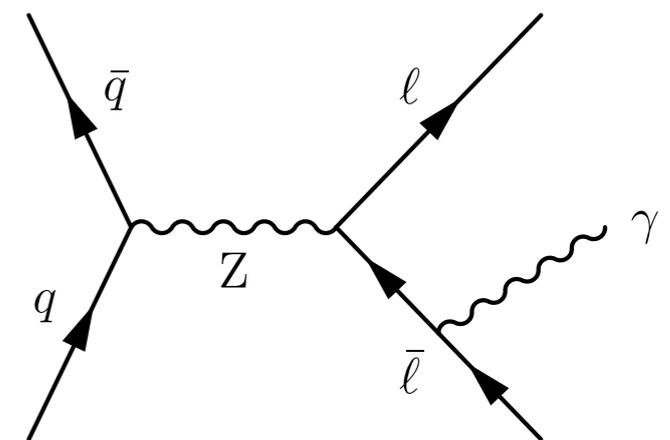
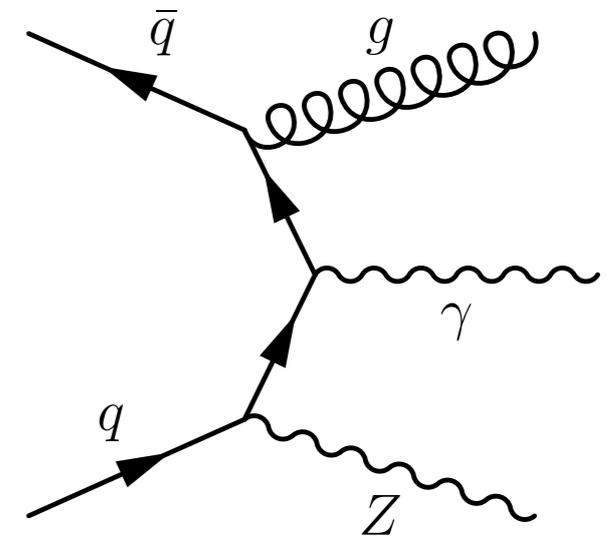
- Use monte carlo methods to integrate phase space
- Describe hard scatter, where perturbative methods accurate

● Event generators unweight events from calculation

- Generates final state distributed as shape of ME
- First stage of simulation input

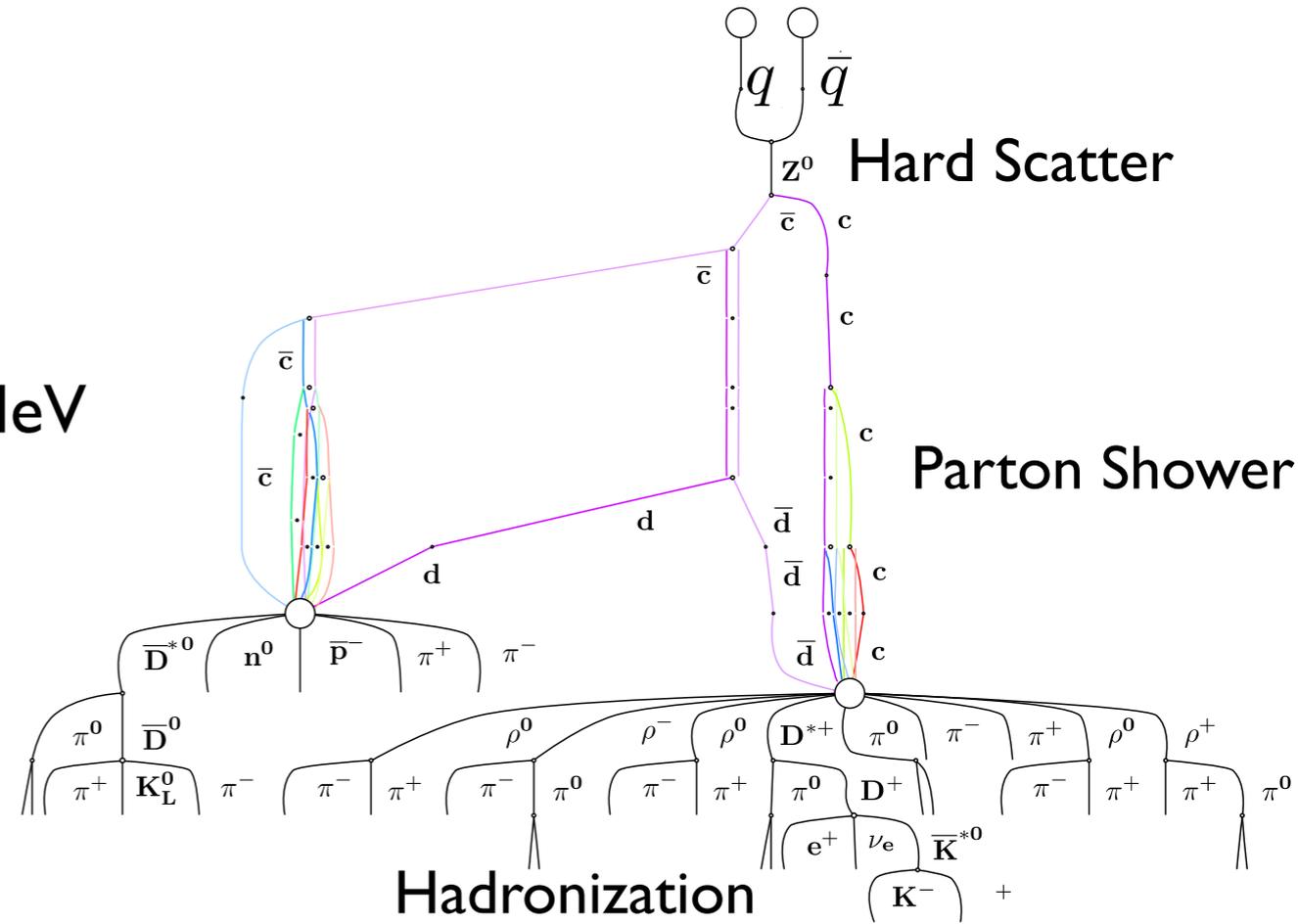
● Implementations Used

- MCFM (MonteCarlo for Femtobarn Measurement)
 - Cross section calculator, accurate at NLO α_s for $Z\gamma$
- MadGraph 5
 - Multipurpose event generator, accurate at fixed orders in α_s
 - Contains important bugfix relevant to signal generation
- Sherpa
 - Multipurpose fixed order generator, accurate at fixed orders in α_s
 - Includes aTGC signal and is used to generate aTGC samples for limit setting



● Parton Showers

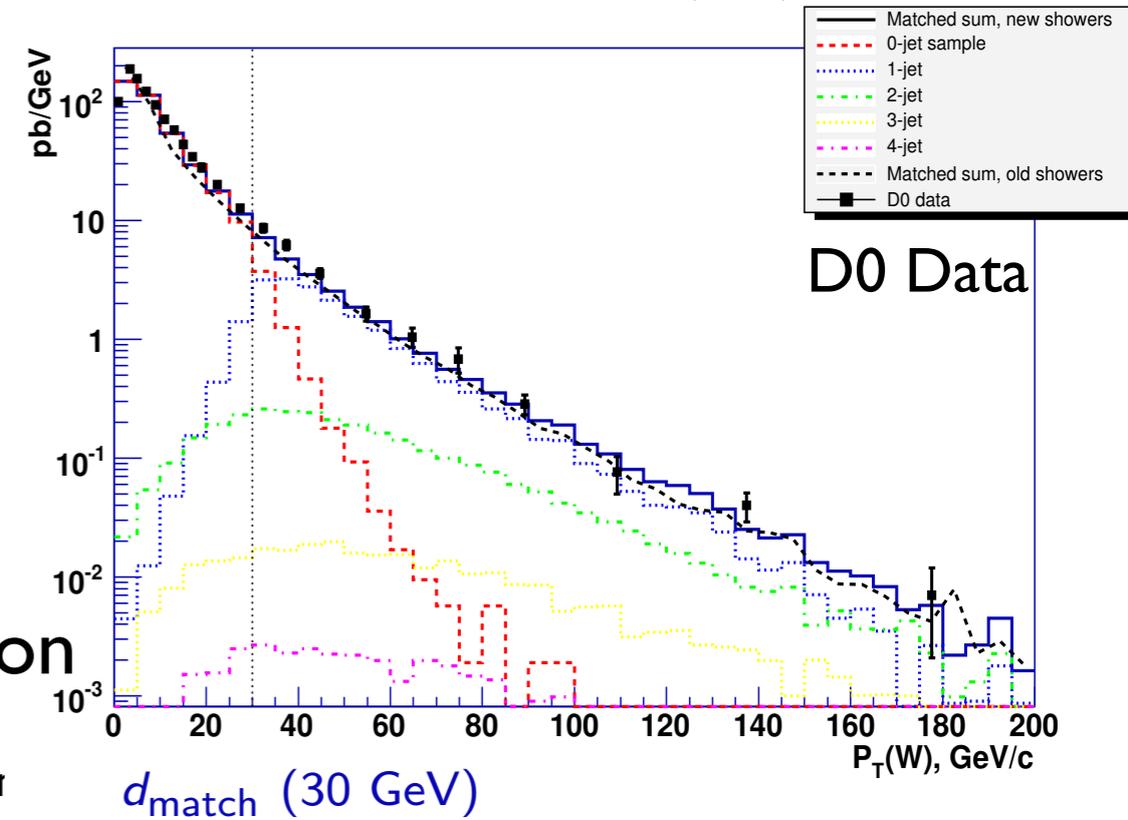
- Describe splitting of partons into jets
- Evolve partons down to $\Lambda_{\text{QCD}}=217\pm 24$ MeV
 - Creates 'showers' of partons
- Limit phase space of produced jets
 - Poor description of multijet systems
 - Solve with inclusive matching

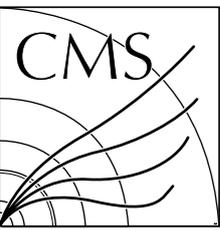


● Hadronization

- Phenomenologically driven models
 - Create color singlet hadrons from shower
- Reproduction of EM-rich showers known issue

● Use Pythia for parton shower and hadronization



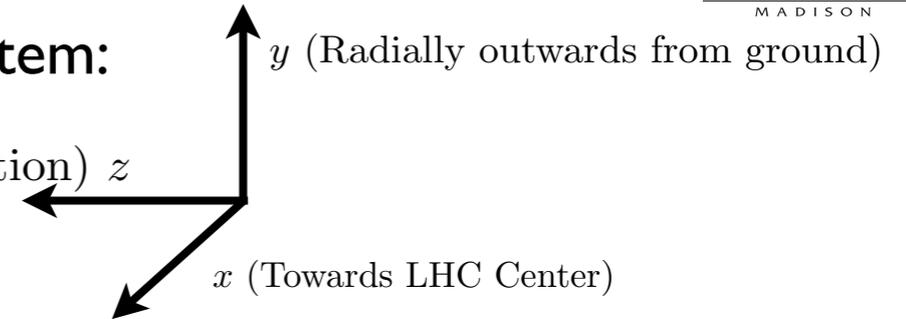


The Compact Muon Solenoid

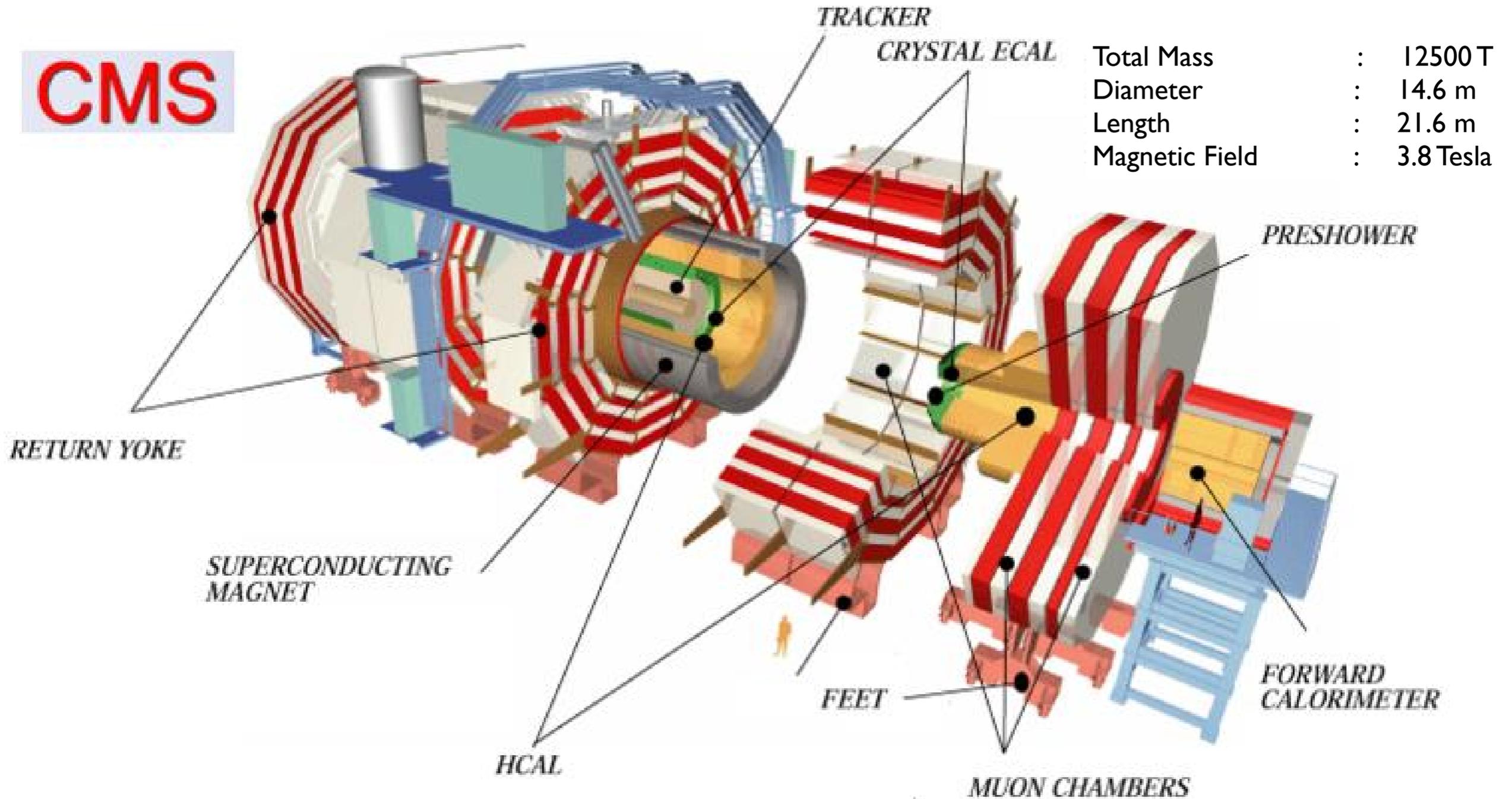
$$\eta = -\ln \tan \frac{\vartheta}{2}$$

Right handed coordinate system:

(Anti-Clockwise beam direction) z

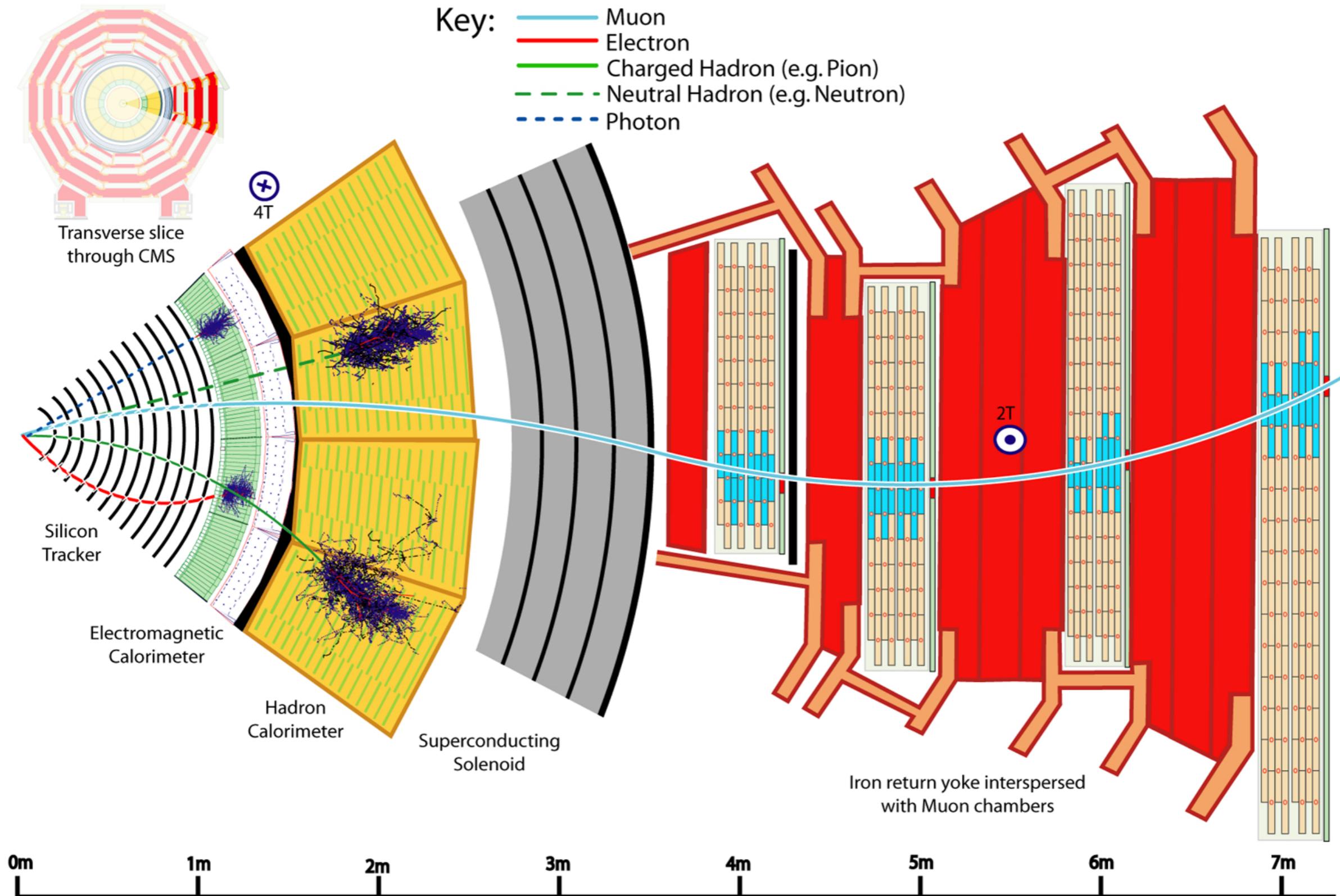


CMS



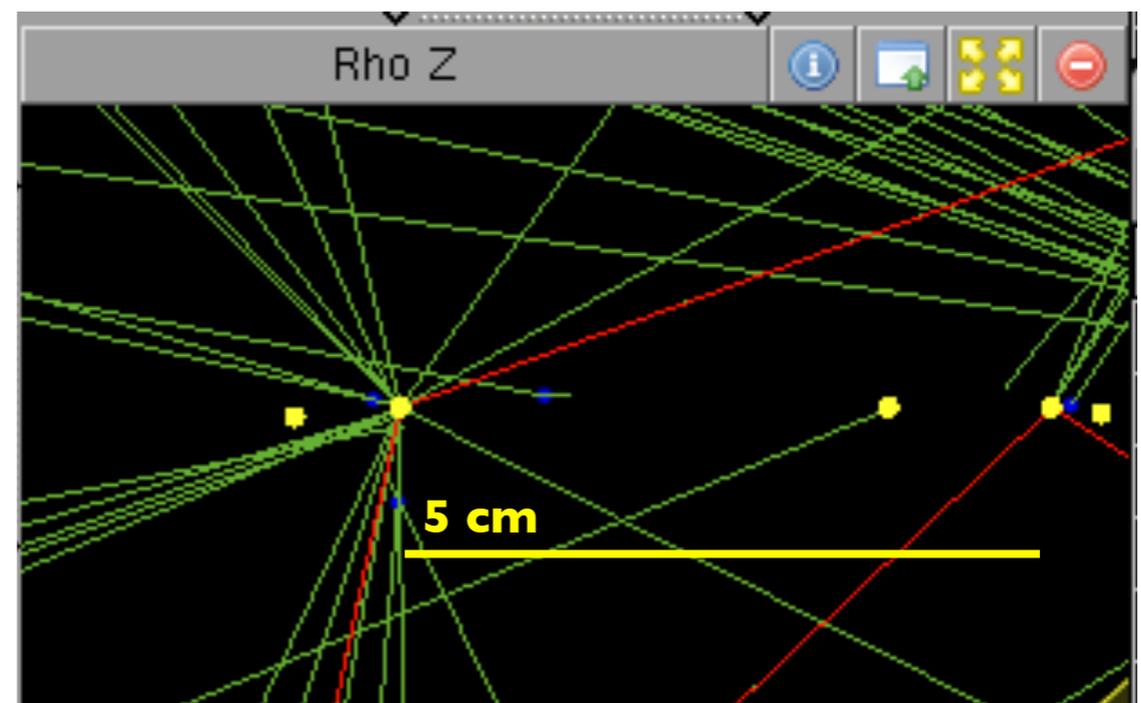
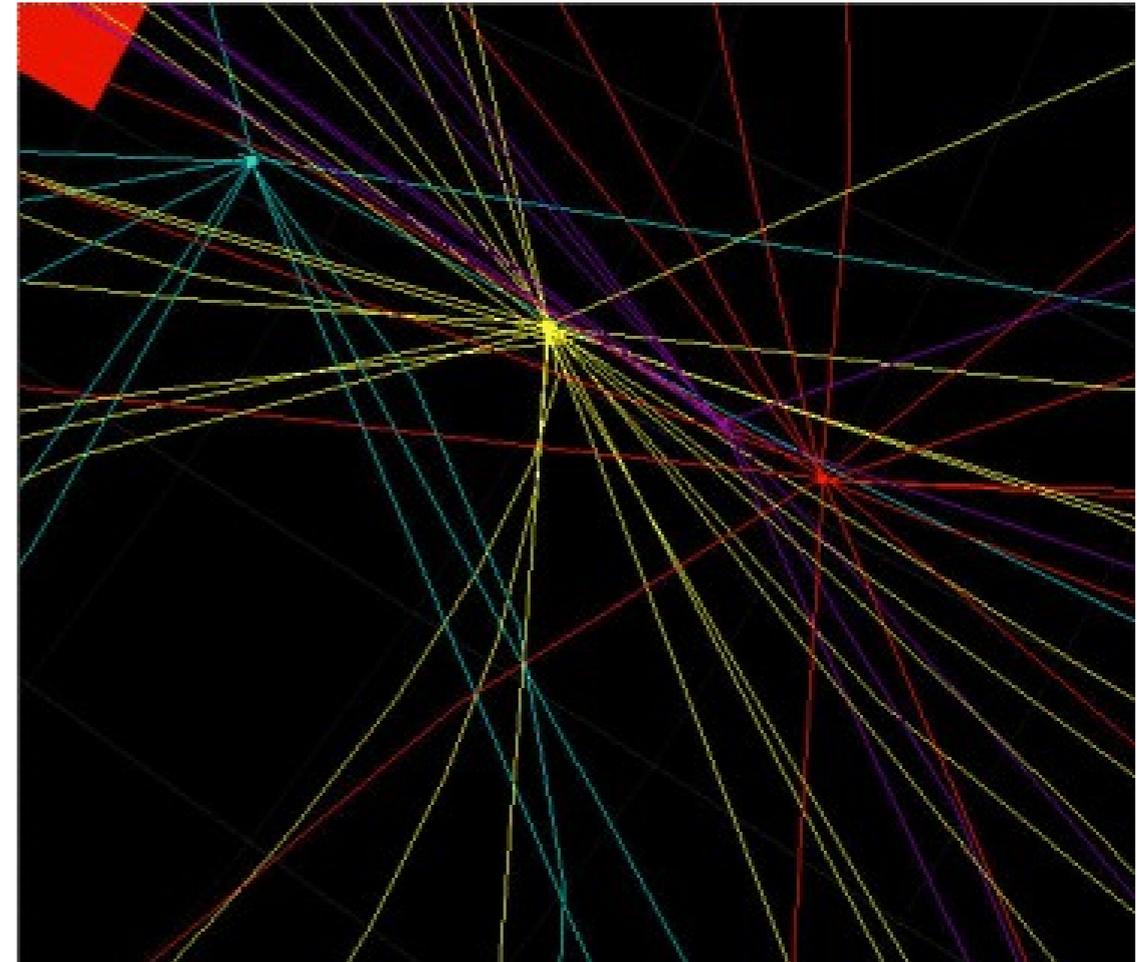
Total Mass	:	12500 T
Diameter	:	14.6 m
Length	:	21.6 m
Magnetic Field	:	3.8 Tesla

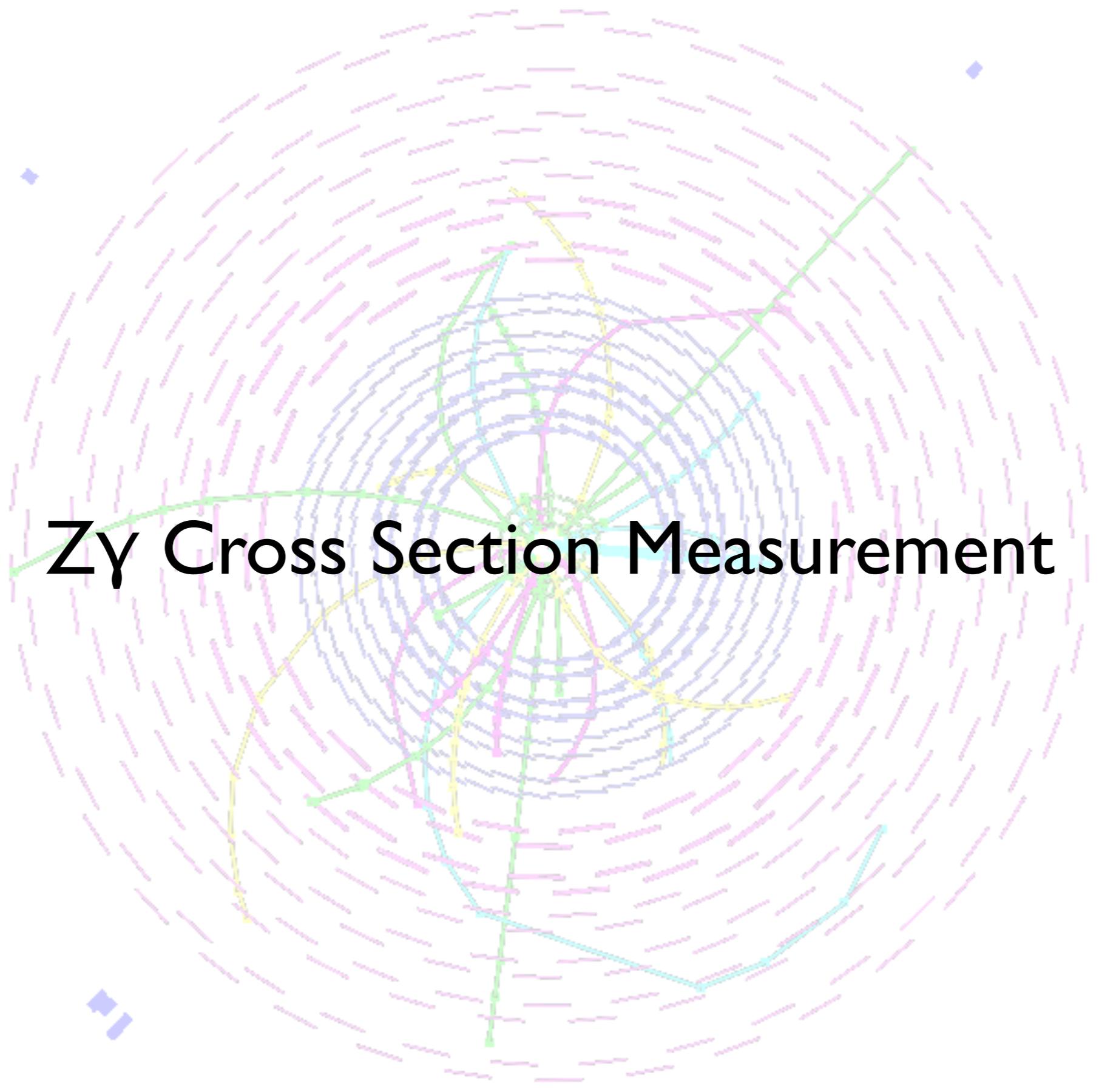
Particle Detection in CMS



The Problem of Pileup

- ⦿ Luminosity improvement = pileup
 - Smaller bunch size
 - Higher bunch population
- ⦿ Hard scatters overlaid with random events
 - Random events mainly soft QCD
 - ▬ Increase in calorimeter activity
 - Particle ID must account for pileup effects to maintain performance
- ⦿ Even other hard scatter events
 - bottom display is 2 Zs

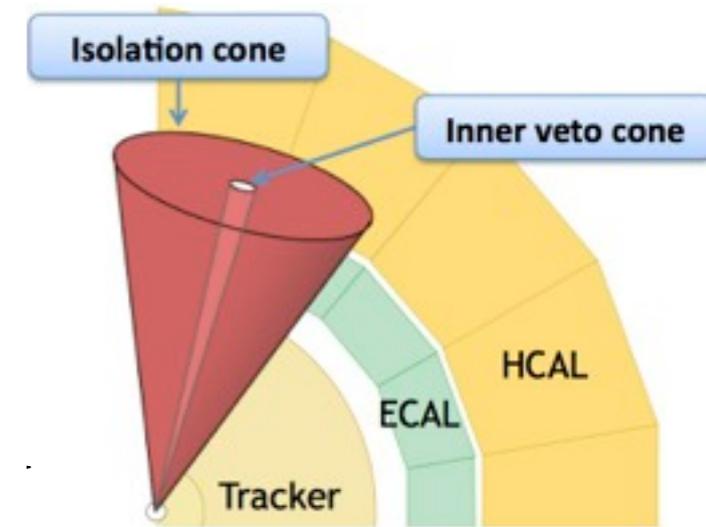




Zy Cross Section Measurement

Muon Identification

- Require muons in detector and consistent with EWK boson
- High track quality by number of hits
 - Pixels, strip and muons
- Good track fit
- Consistent with most energetic vertex in event
- Relative combined isolation $\Delta R=0.3$ rejects jets
 - Rel. Comb. Iso. = $\left(\text{Iso.}^{\text{ECAL}} + \text{Iso.}^{\text{HCAL}} + \text{Iso.}^{\text{Trk}} - \pi \Delta R^2 \rho \right) / p_T$
 - Subtract pileup using average energy density ρ
 - Veto cone about muon, $\Delta R = 0.1$



Cut Summary:

Description	criterion
Kinematics	$p_T > 20 \text{ GeV}$ and $ \eta < 2.4$
Number of pixel hits	> 0
Number of tracker hits	> 10
$\chi^2/\text{n.d.f}$ of the global muon fit	< 10
Number of muon hits	> 0
Number of chambers with matched segments	> 1
Vertex d_0	$< 0.1 \text{ cm}$
Vertex d_z	$< 0.02 \text{ cm}$
Relative Combined Isolation	< 0.1

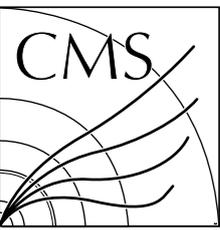
Electron Identification

- Require $p_T > 20$ GeV and $|\eta| < 1.4442$ or $1.560 < |\eta| < 2.5$
- Require ECAL deposit and track consistent
 - Rejects combinatorial background
- Reject conversions using distance and angle to conversion track candidate
 - $\cot \Delta\theta, |\text{dist}|$
- Use shower η width, $\sigma_{i\eta i\eta}$ and isolation to reject jets
 - $\sigma_{i\eta i\eta}^2 = \frac{\sum (\eta_i - \bar{\eta})^2 w_i}{\sum w_i}$, $\bar{\eta} = \frac{\sum \eta_i w_i}{\sum w_i}$, $w_i = \max(0, 4.7 + \log(E_i/E_{5 \times 5}))$
- Selection criteria organized as 85% and 80% efficiency ‘working points’

	WP85		WP80	
	Barrel	Endcap	Barrel	Endcap
$\Delta\varphi_{\text{vtx}}$	0.039	0.028	0.027	0.021
$\Delta\eta_{\text{vtx}}$	0.005	0.007	0.005	0.006
$ \cot \Delta\vartheta $	0.02	0.02	0.02	0.02
$ \text{dist} $	0.02	0.02	0.02	0.02
$\sigma_{i\eta i\eta}$	0.01	0.031	0.01	0.031
Combined relative isolation	0.053	0.042	0.04	0.033

85% Working Point (WP85)
main analysis selection

80% Working Point (WP80)
used to compare EM shower behavior



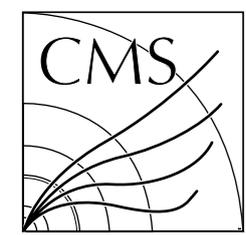
Photon Identification

- Photon $p_T > 15 \text{ GeV}$, $|\eta| < 1.4442$ and $1.560 < |\eta| < 2.5$
- Require little HCAL activity behind SuperCluster (H/E)
- Use $\sigma_{i\eta i\eta}$ to reject/estimate jet-fakes
- Electron rejection (pixel seed veto)
- Isolation pileup corrected with effective areas
 - Complex veto regions around photon SC,
 - Remove conversion tracks, remove extended conversion deposit
 - Different for each subdetector

Description	criterion
Kinematics	$E_T > 15 \text{ GeV}$ $1.4442 < \eta < 1.566$ and $ \eta < 2.5$
Ratio of HCAL to ECAL energy (H/E)	< 0.05
Shower width, $\sigma_{i\eta i\eta}$	< 0.011 in EB and < 0.030 in EE
Photon has pixel seed	False for both EB and EE photons
Tracker Isolation	$I_{\text{trk}} - 0.001 \cdot E_T - \rho \cdot A_{\text{eff}}^{\text{trk}} < 2.0$
ECAL Isolation	$I_{\text{ECAL}} - 0.006 \cdot E_T - \rho \cdot A_{\text{eff}}^{\text{ECAL}} < 4.2$
HCAL Isolation	$I_{\text{HCAL}} - 0.0025 \cdot E_T - \rho \cdot A_{\text{eff}}^{\text{HCAL}} < 2.2$

Effective Areas:

Isolation	barrel	endcap
Tracker	0.0167	0.032
ECAL	0.183	0.090
HCAL	0.062	0.180



Event Selection: Trigger & Clean Crossing



● Double Object Triggers: (use DoubleMu/E)

- Isolated electrons 17 GeV leading, 8 GeV trailing thresholds
- Non-isolated muons 13 GeV leading, 8 GeV trailing
- 5.0 fb⁻¹ recorded

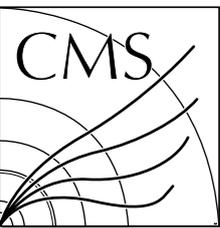
● Require a well measured vertex to be present

- $|d_0| < 2 \text{ cm}$, $|dz| < 24 \text{ cm}$, $ndof > 4$

● Remove events with beam scraping

- 25% of all tracks present point towards interaction region

Z γ Event Selection Summary



Before Cuts: 58582068 evts.

● Z(ee) γ (two good electrons)

- Apply run-dependent energy scale correction
- $p_T > 20$ GeV
- In ECAL fiducial region
- Use WP85 selection criteria
- Require HLT match to both legs of trigger

After Z Selection: 84045 evts.

● Dilepton Mass > 50 GeV

● Select the highest p_T photon passing selection

- Apply run dependent energy scale correction
- $p_T > 15$ GeV, ECAL fiducial cuts
- Passes photon isolation and ID criteria
- $\Delta R(l, \gamma) > 0.7$

After Full Z γ Selection: 4108 evts.

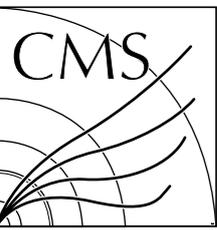
Before Cuts: 56945443 evts.

● Z($\mu\mu$) γ (two good muons)

- $p_T > 20$ GeV, $|\eta| < 2.4$
- Well-reconstructed track
- PU corrected rel. comb. iso $< .1$
- Require HLT match to both legs of trigger

After Z Selection: 130961 evts.

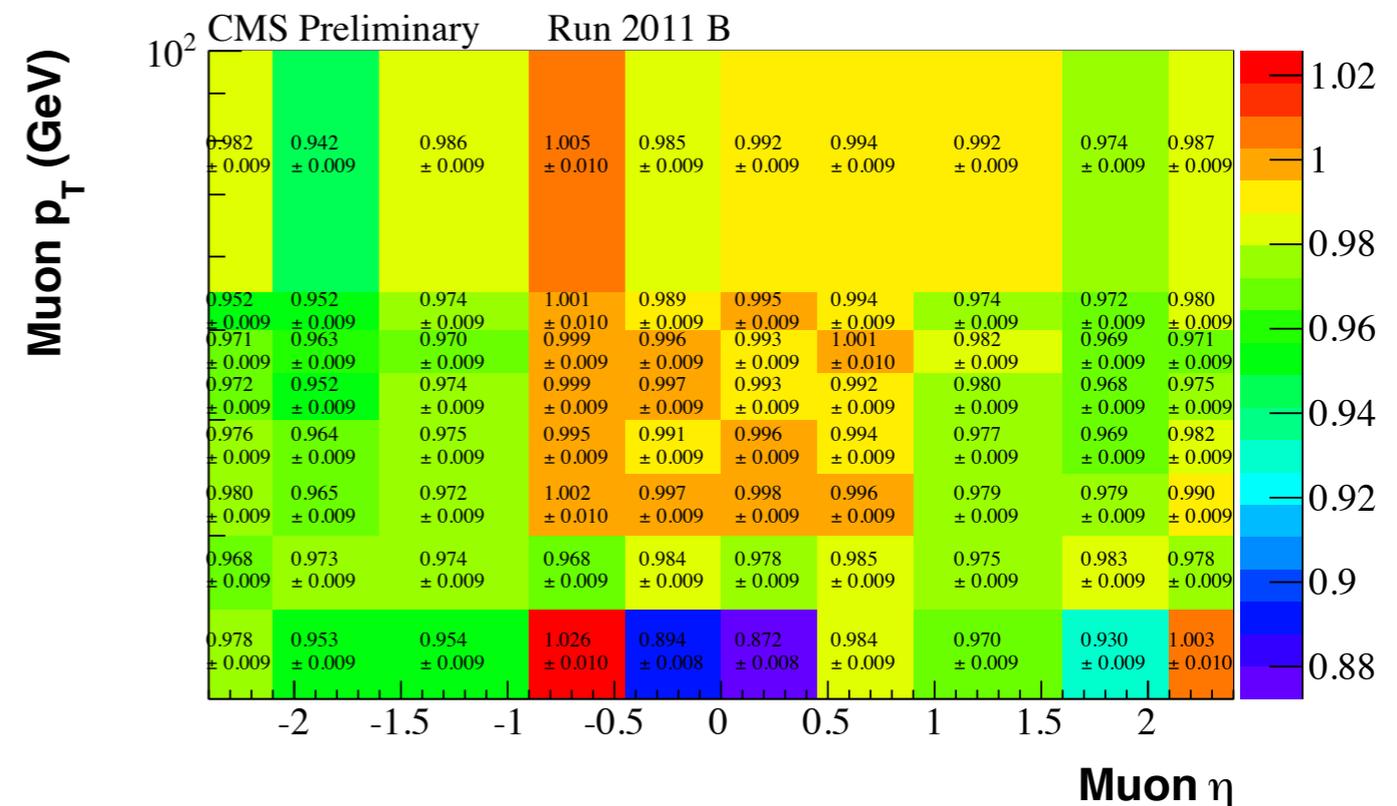
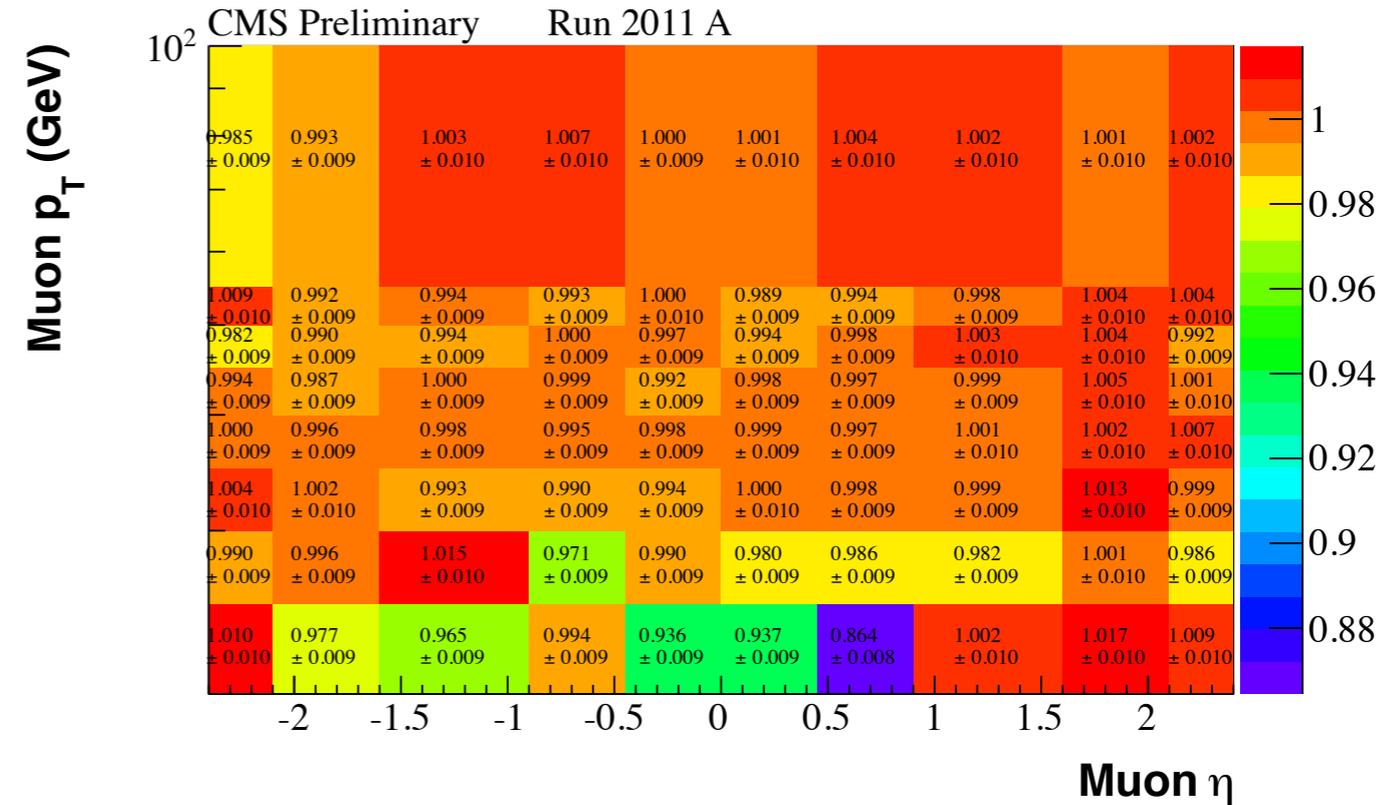
After Full Z γ Selection: 6463 evts.



Event Selection: Muon Efficiency



- Tag and Probe to measure efficiencies
 - Exploit $Z(\mu\mu)$ resonance
 - Tag fully identified muon
 - Probe passes or fails selection criteria
 - Fit Z peak to extract efficiency
- In this analysis use efficiency ratios to scale MC to data efficiencies
 - Maps of 'scale factors' adjust efficiencies differentially
 - Realistic modification of MC muon distributions

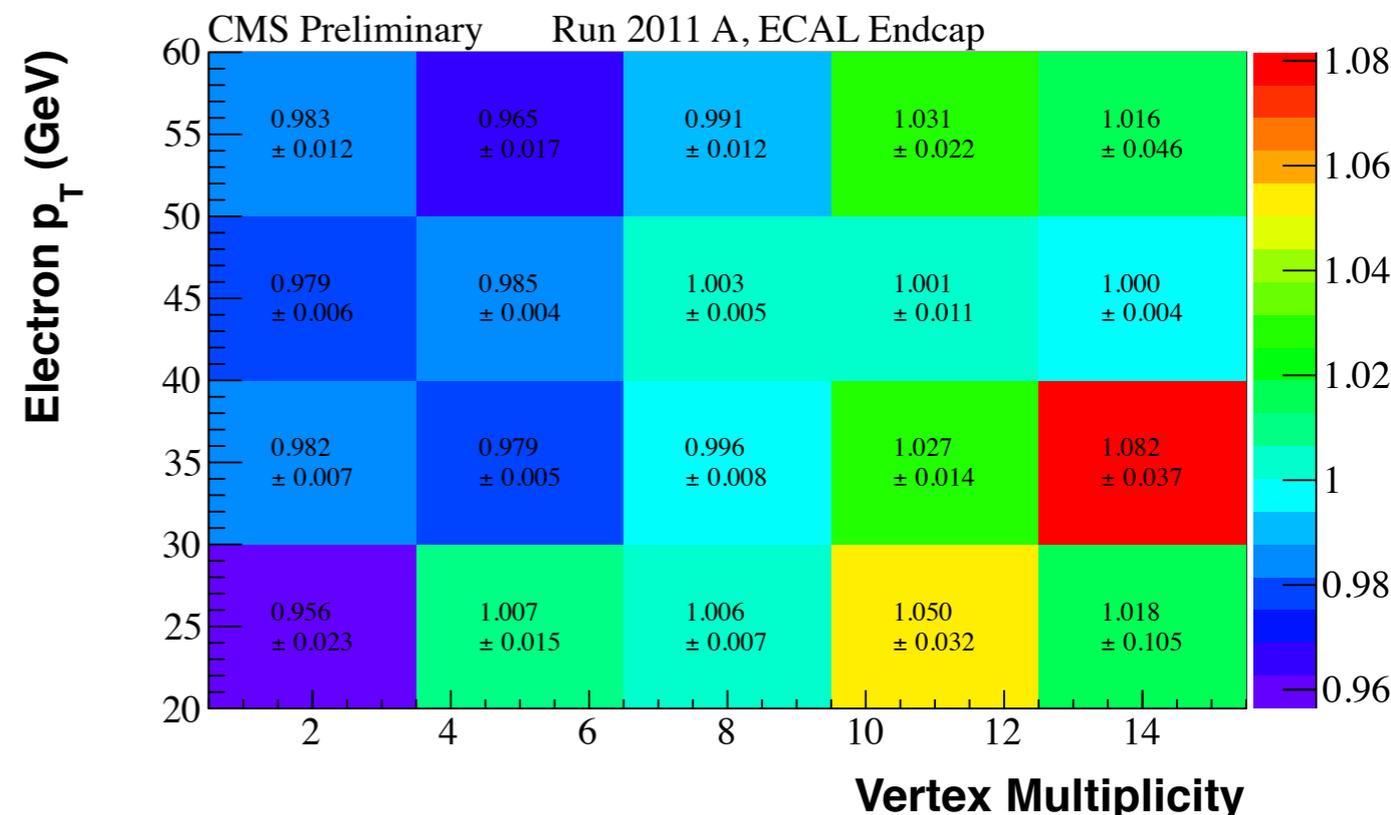
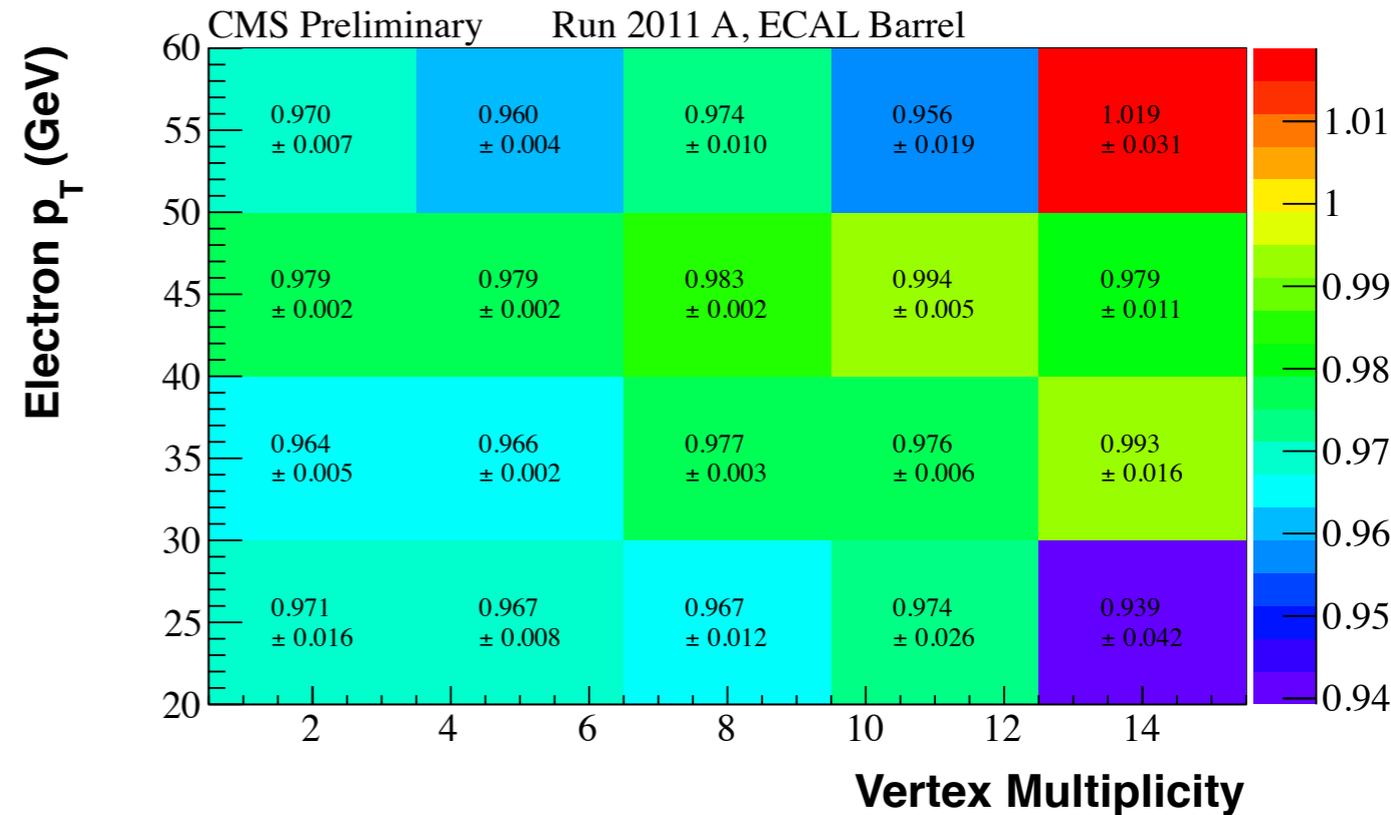


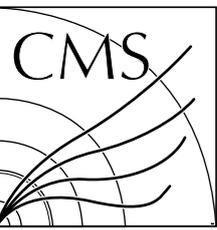
Two Tag & Probe Steps

- Measure ID eff. using Triggered Electron + HLT SuperCluster
- Measure trigger eff. using Triggered Electron + non-isolated trigger electron

Apply to MC statistically

- Scale factors evolve with time
 - changing beam conditions
- Ensure MC approximates composition of data





Event Selection: Photon Efficiency



● Photons not triggered

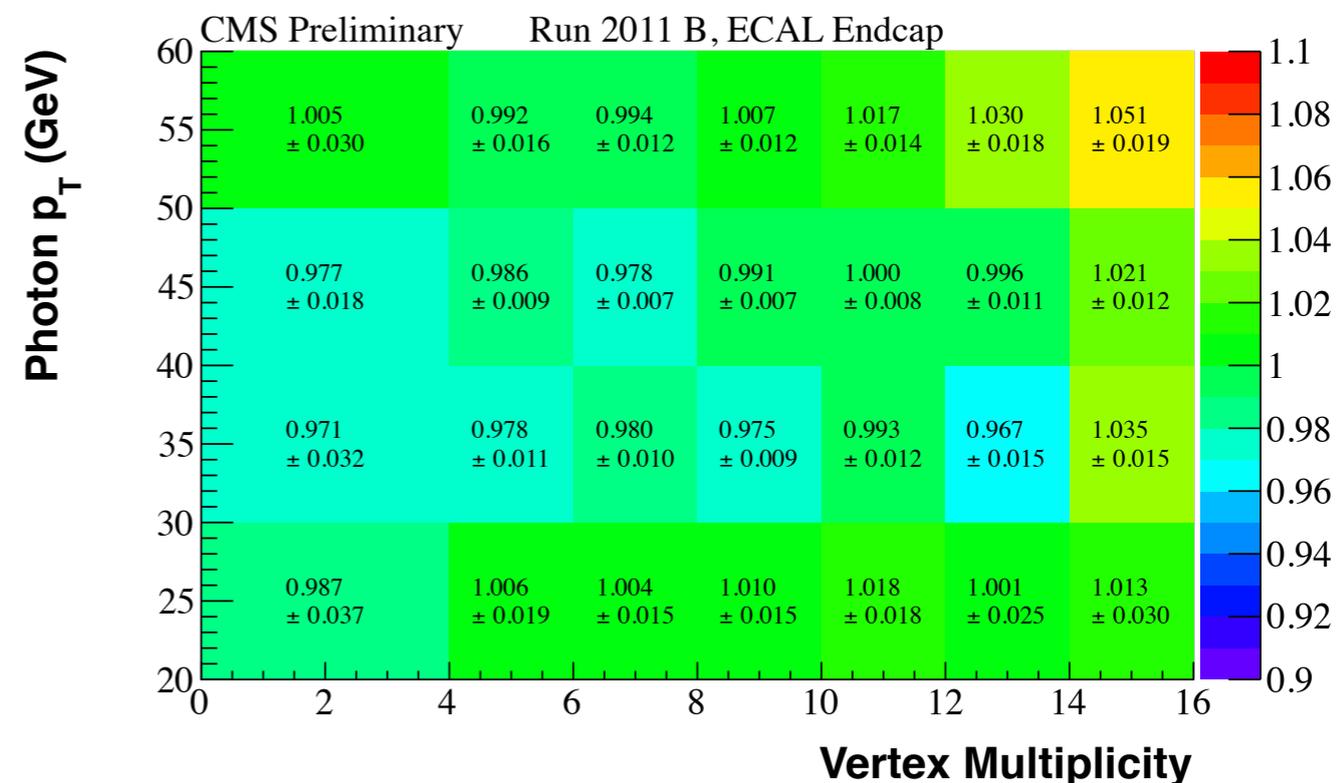
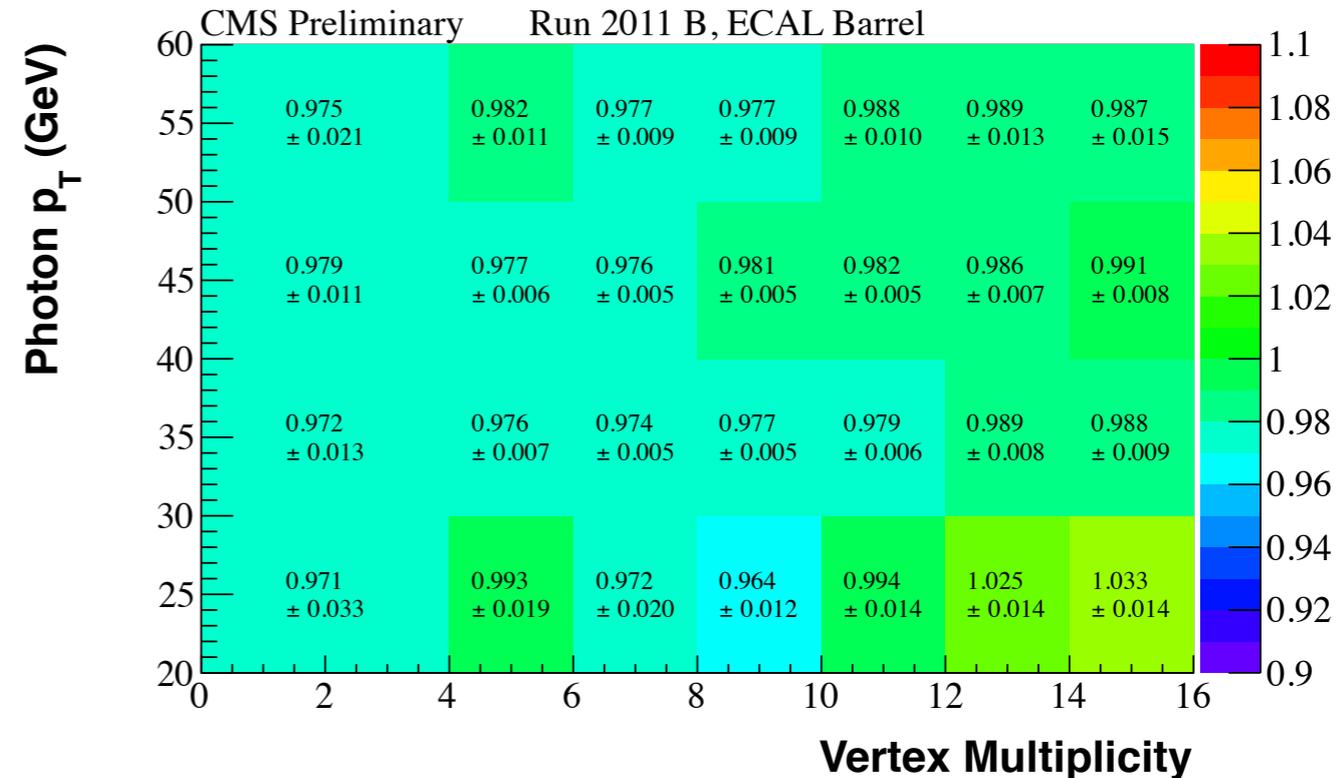
- but hard to find pure source of photons
- Use Z electrons to measure efficiency except pixel seed veto

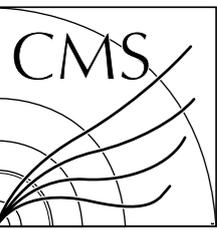
● Measure pixel seed veto efficiency with high-purity FSR Z($\mu\mu\gamma$) events

- Tag and probe using offshell Z as tag and photon as probe

Pixel Seed Veto Efficiencies:

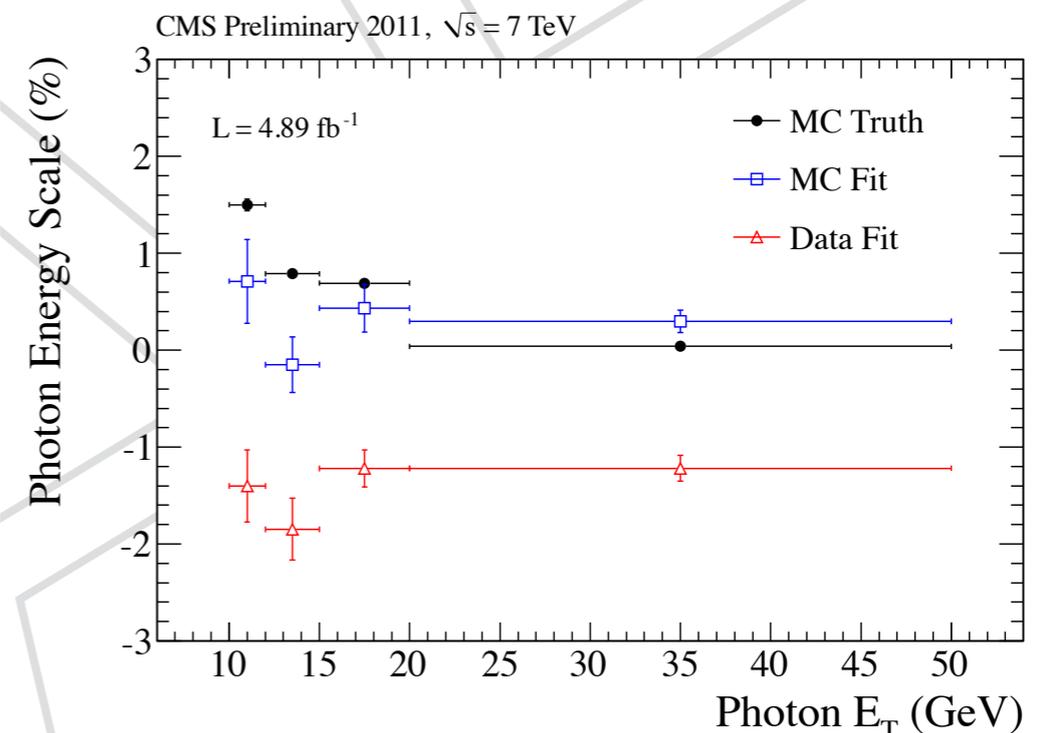
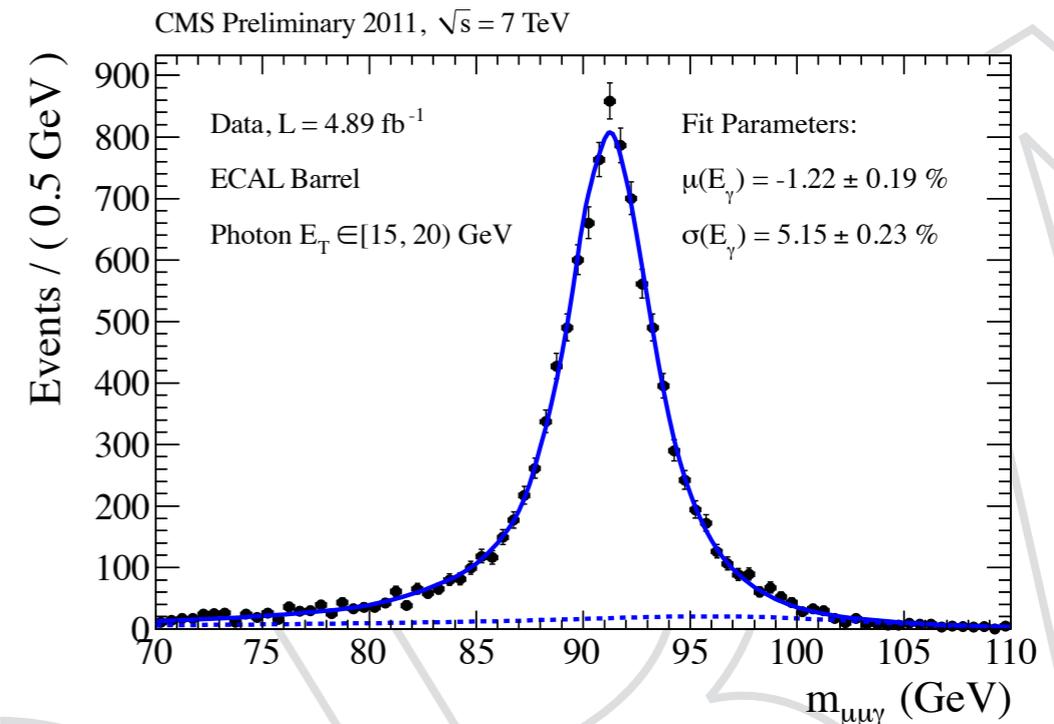
	Data (%)	MC (%)	Data/MC (%)
Run 2011 A			
EB	97.2 ± 0.3	97.8 ± 0.2	99.4 ± 0.3
EE	90.0 ± 0.9	91.0 ± 0.5	98.9 ± 0.9
Run 2011 B			
EB	96.1 ± 0.4	97.1 ± 0.2	99.0 ± 0.4
EE	87.3 ± 1.3	89.3 ± 0.5	97.8 ± 1.6

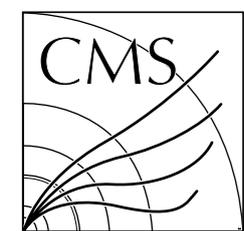




Photon Energy Corrections From PHOSPHOR

- Data-driven fit of PHOton Scale and Resolution
- Uses FSR $\mu\mu\gamma$ invariant mass
 - Energy Scale from Z peak position
 - Energy Resolution from Z width
- Pileup dependence of energy scale is averaged over by run period
- Scale in data is different from MC due to
 - Material budget mis-modeling
 - GEANT4 shower mis-modeling
 - ECAL calibration





$Z\gamma$ Cross Section: Backgrounds



- There are three main sources of background for $Z\gamma$
 - Photons from jet-fakes
 - Determine amount using Template Method (next slide)
 - $T\bar{T}$: Real leptons + fake photon (Taken from MC)
 - $Z(\tau\tau)\gamma$: τ decays to $e/\mu + \nu$ (Taken from MC)

Fake γ Bkg: Template Method

● Use two component fit:

$$f(\sigma_{i\eta i\eta}) = N_S \cdot S(\sigma_{i\eta i\eta}) + N_B \cdot B(\sigma_{i\eta i\eta})$$

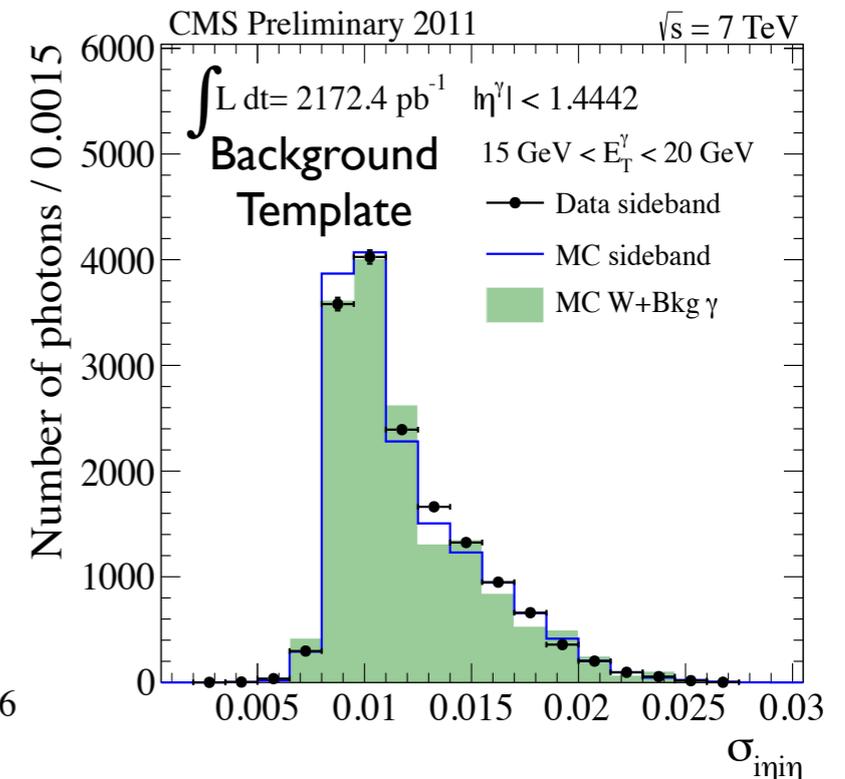
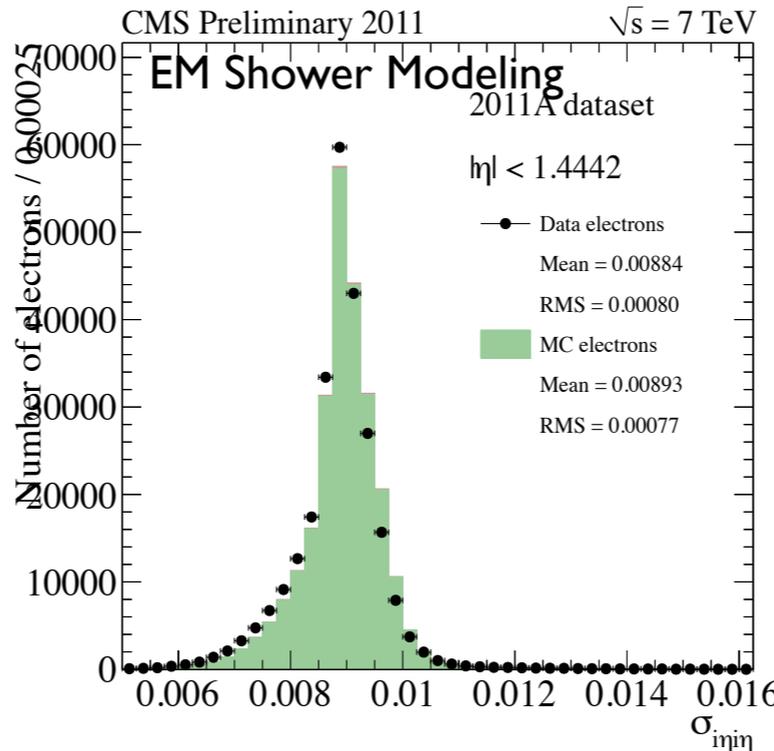
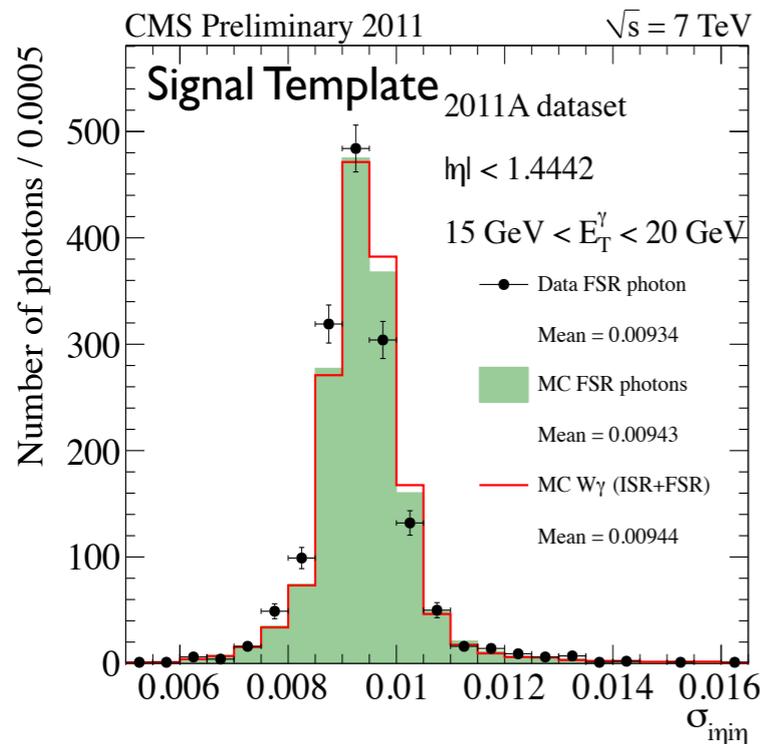
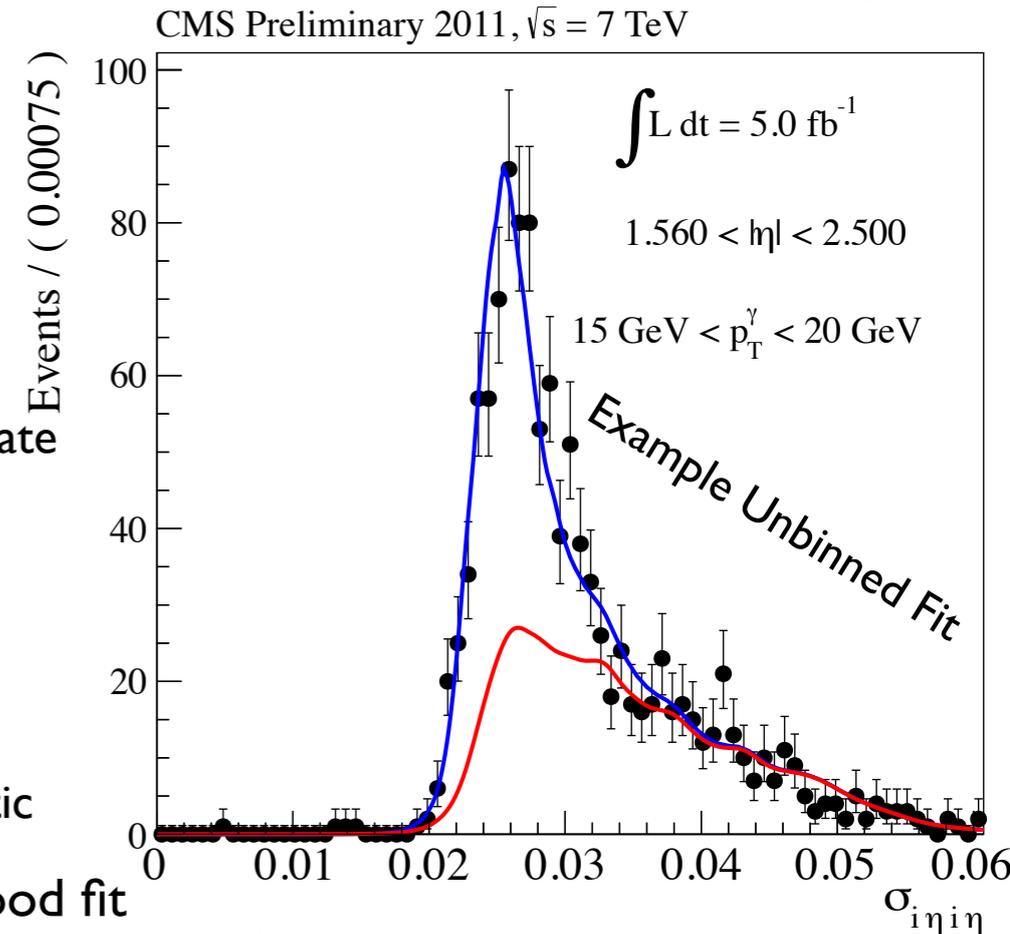
● Signal templates are obtained from Madgraph W/Z γ samples

- Use Zee candidates to determine Data/MC shift
- Templates from FSR Z γ used as a cross check to validate MC signal template

● Background templates are data-driven

- Taken from inverted track isolation sideband in Jet dataset
 - $2 \text{ GeV} < ISO_{TRK} - 0.001 E_T^\gamma - 0.0167 \rho < 5 \text{ GeV}$ for EB
 - $2 \text{ GeV} < ISO_{TRK} - 0.001 E_T^\gamma - 0.0320 \rho < 3 \text{ GeV}$ for EE
- Shape difference between MC and data-driven templates used as systematic

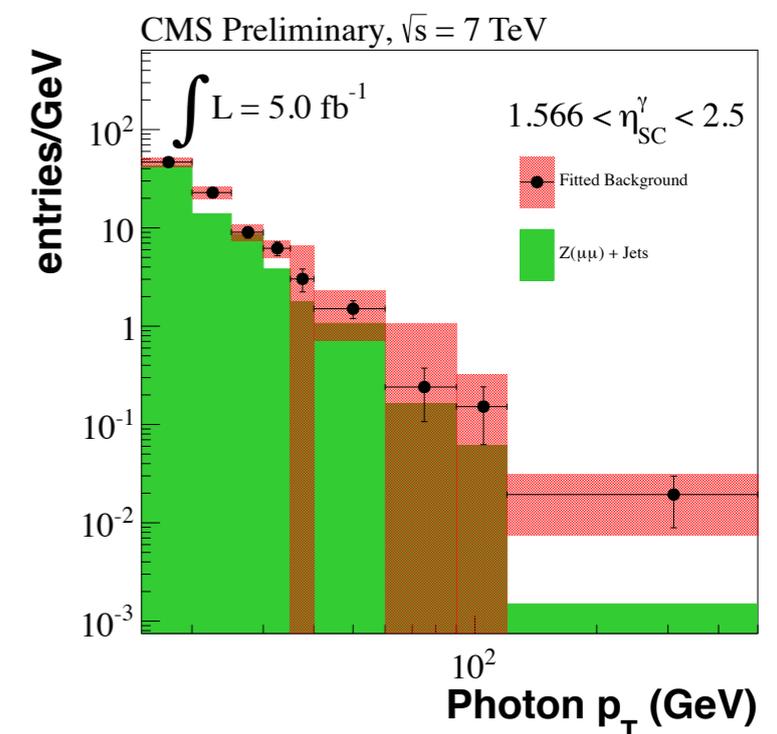
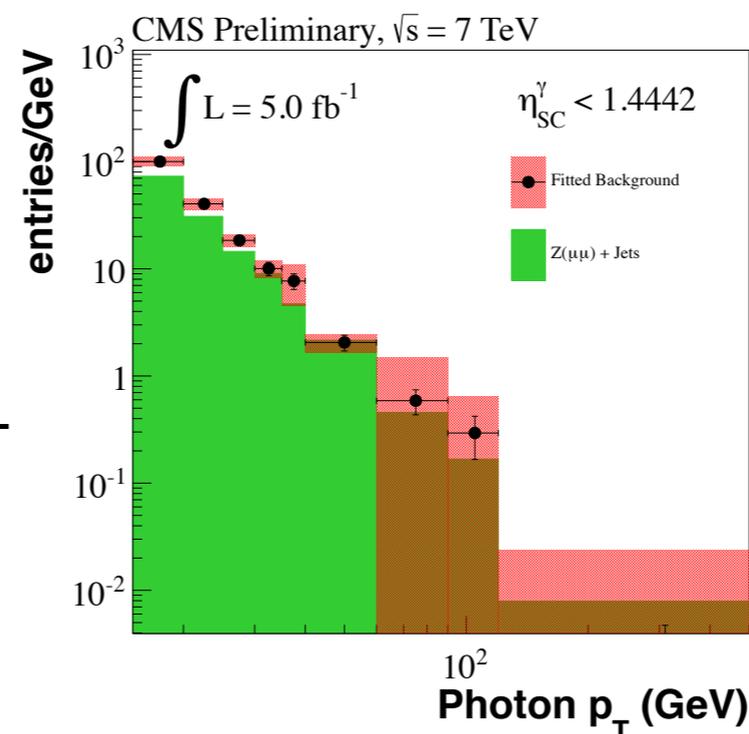
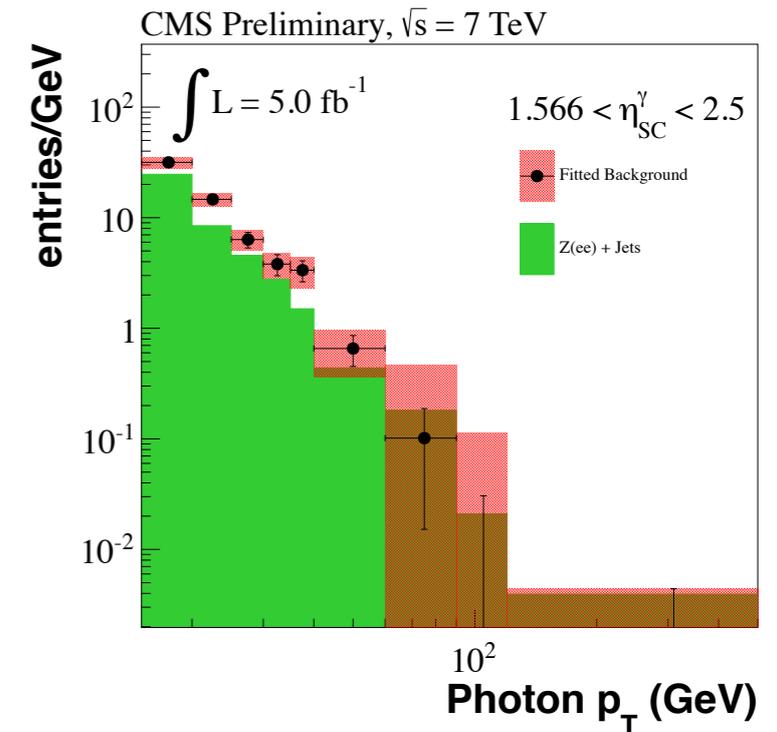
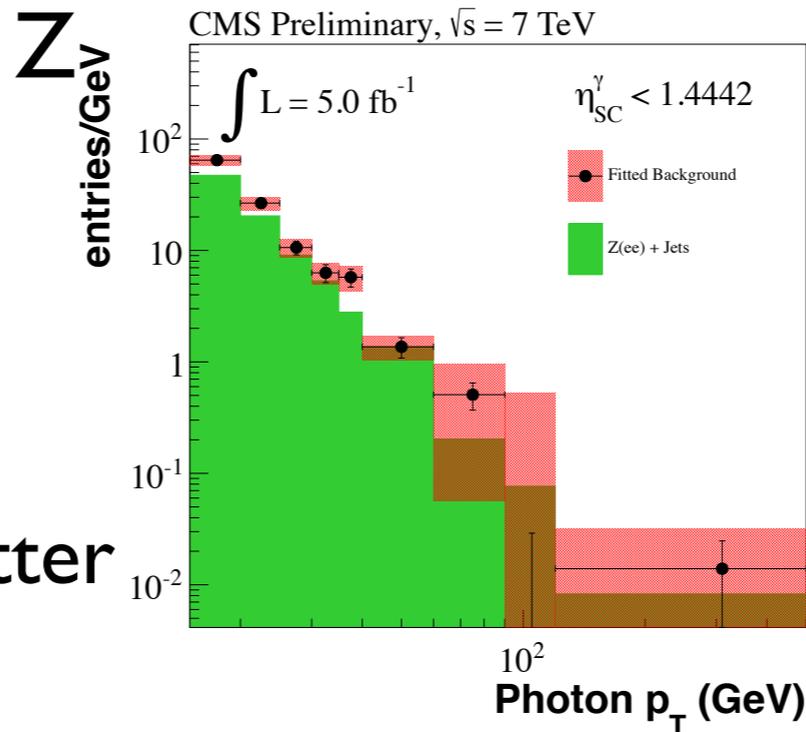
● The fit is performed using an unbinned extended maximum log likelihood fit



Z γ Template Method Yields

Underestimation +Jets background a known effect

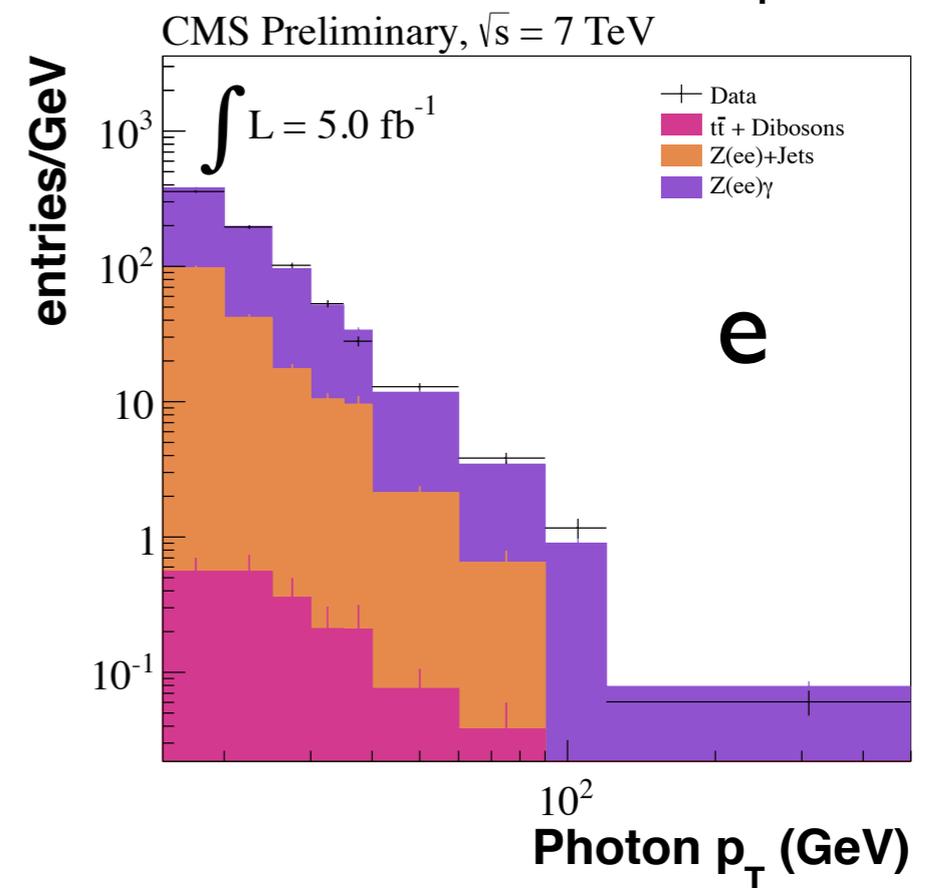
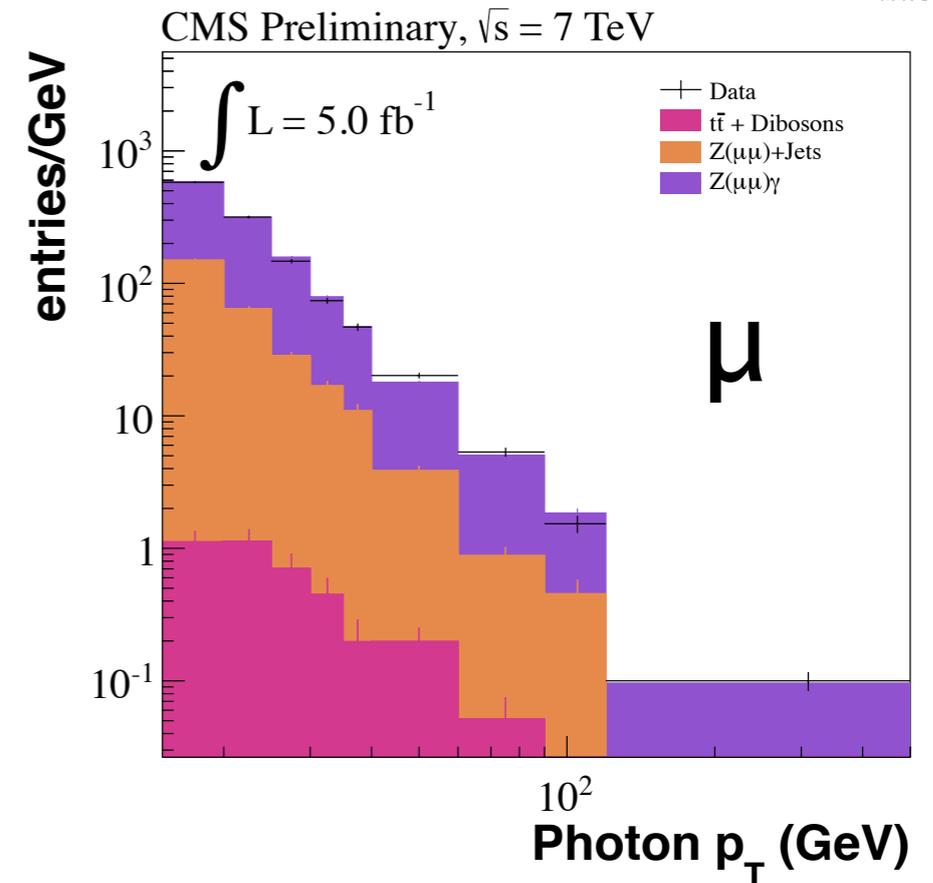
- Data-driven method described jet-fakes better by construction
- Reweigh MC Z+Jets
 - $w_i = \frac{\text{Template Yield}_i}{\text{MC Yield}_i}$
- Reweighed in photon p_T
 - Projected into other quantities



Z γ Distributions: Photon E_T

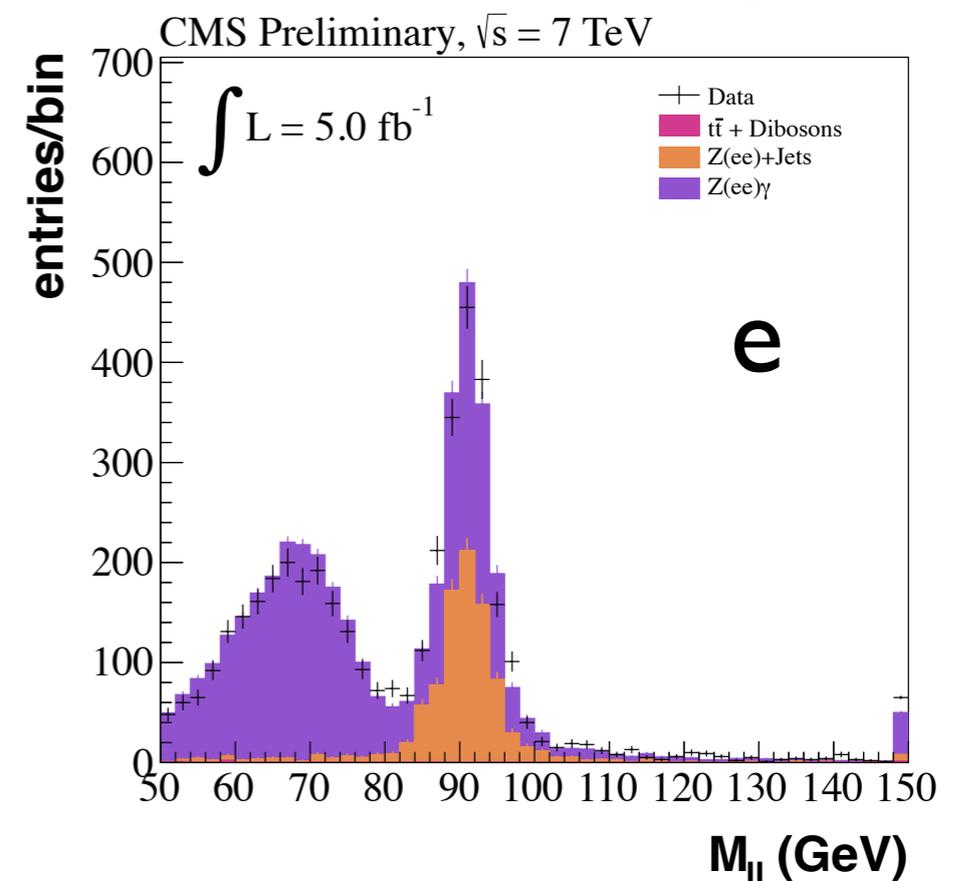
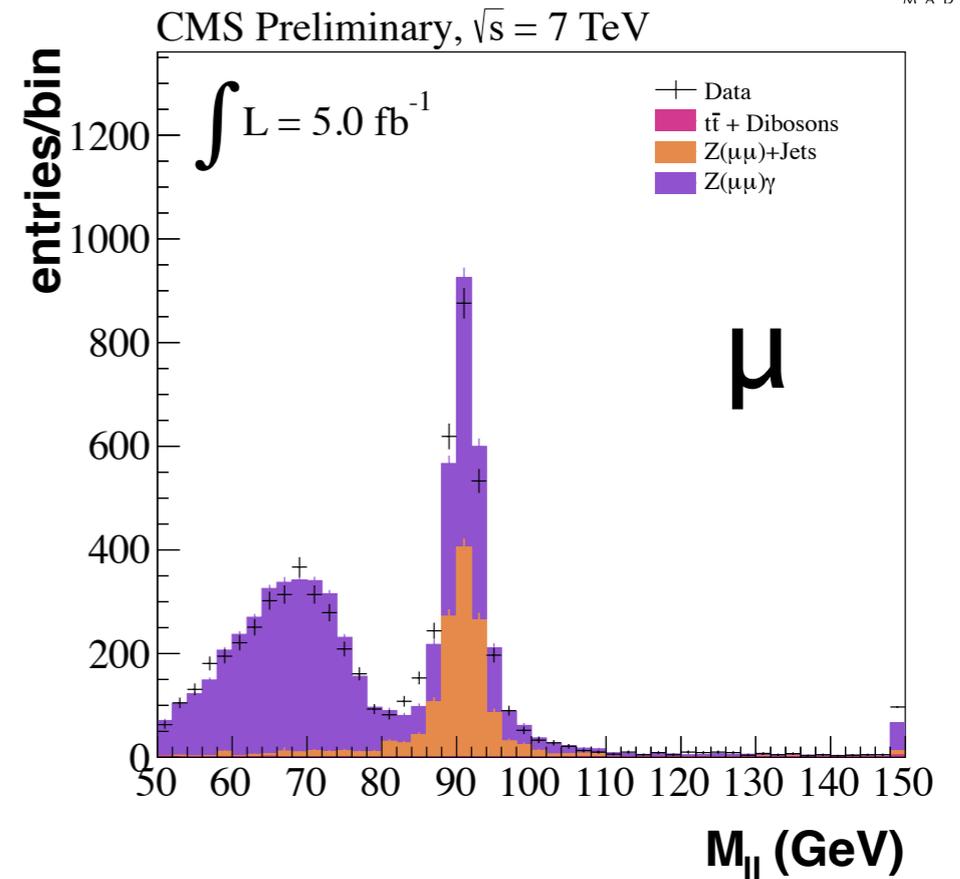
- Photon E_T distribution agrees with MadGraph5
 - Normalized to MCFM
 - Agreement over nearly two orders of magnitude

- Z+Jets Background distribution normalized to template method yield and shape



Z γ Distributions: M_Z

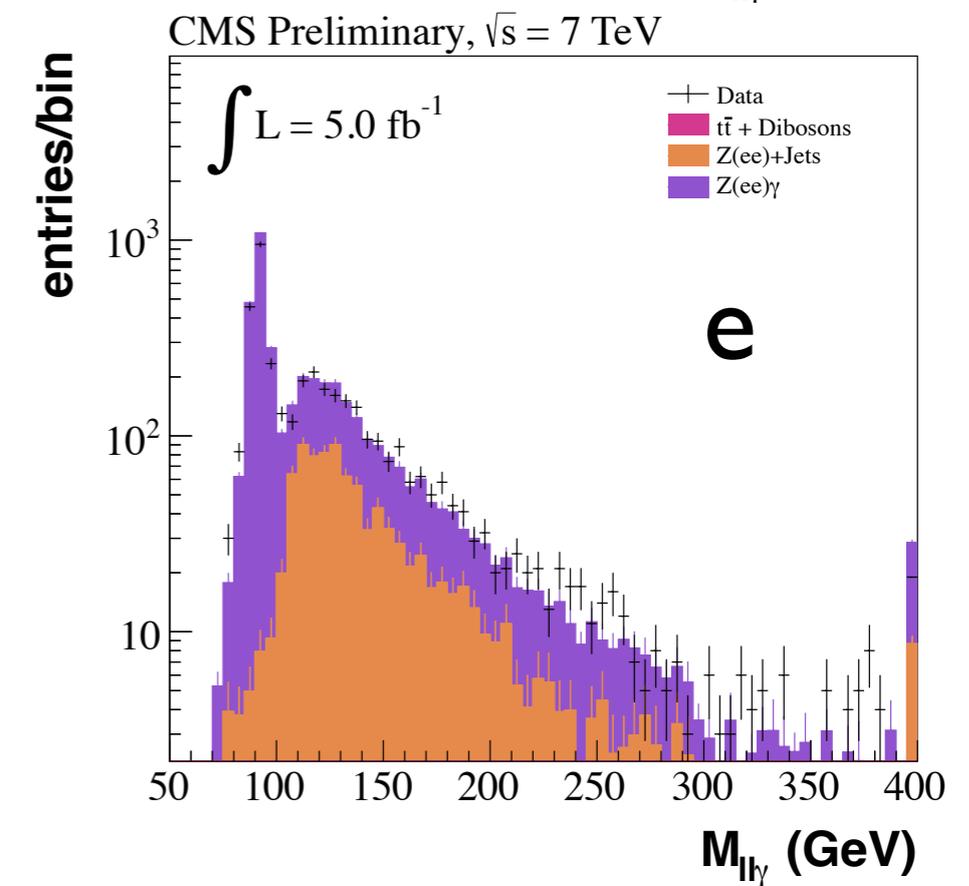
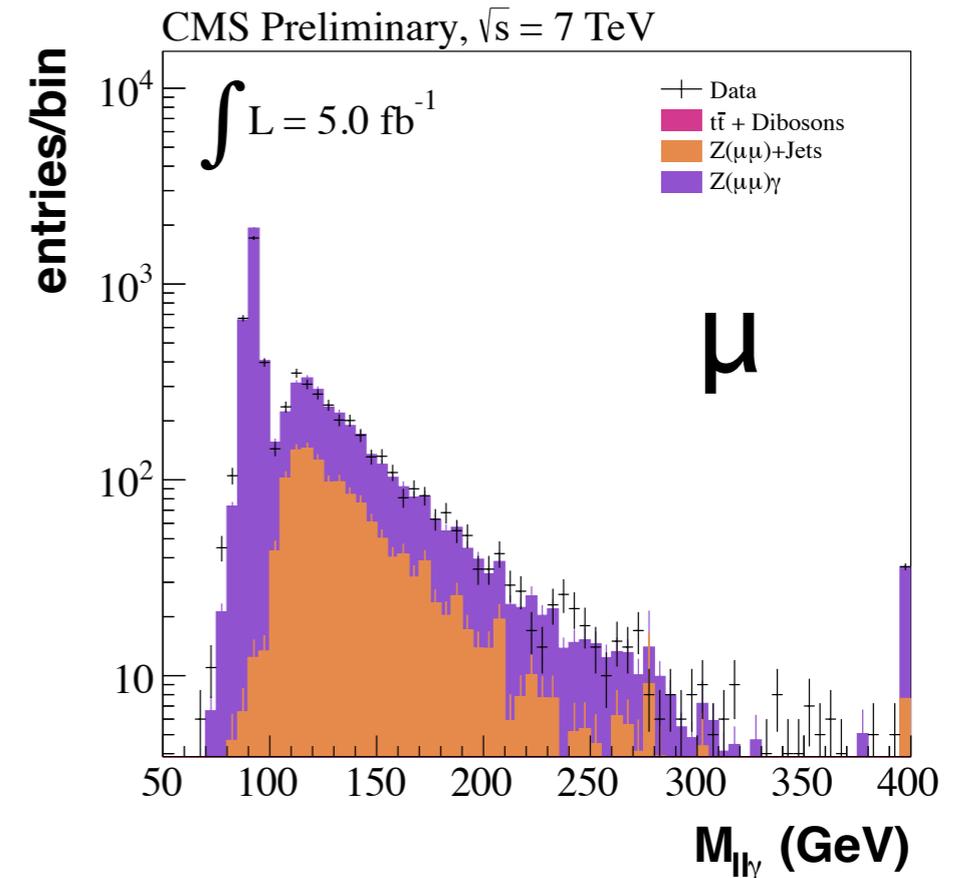
- EM I/FSR turned off in MG5 samples
- Causes poor modeling of Z peak FSR tail
- Initially to avoid double counting
- Effect < 1% on acceptance

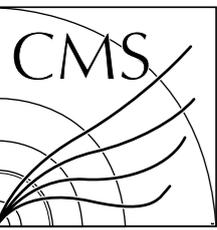


Z γ Distributions: M_{Z γ}

● ISR spectrum is well modeled by MC

● Good agreement to high invariant mass



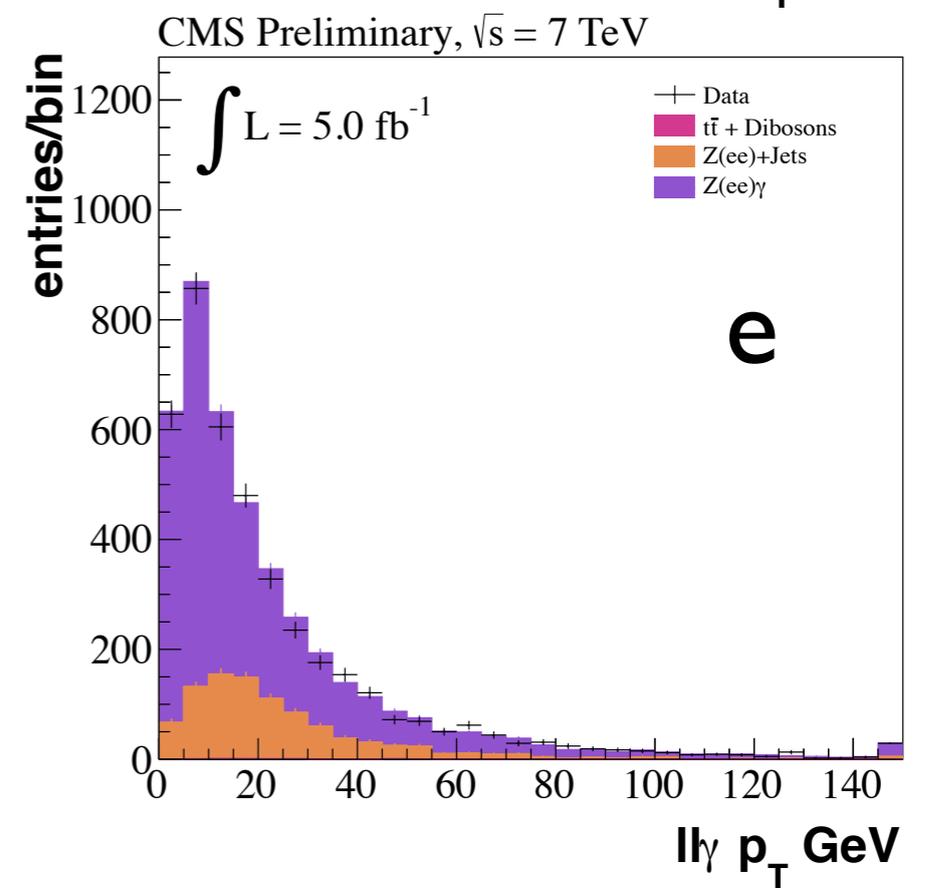
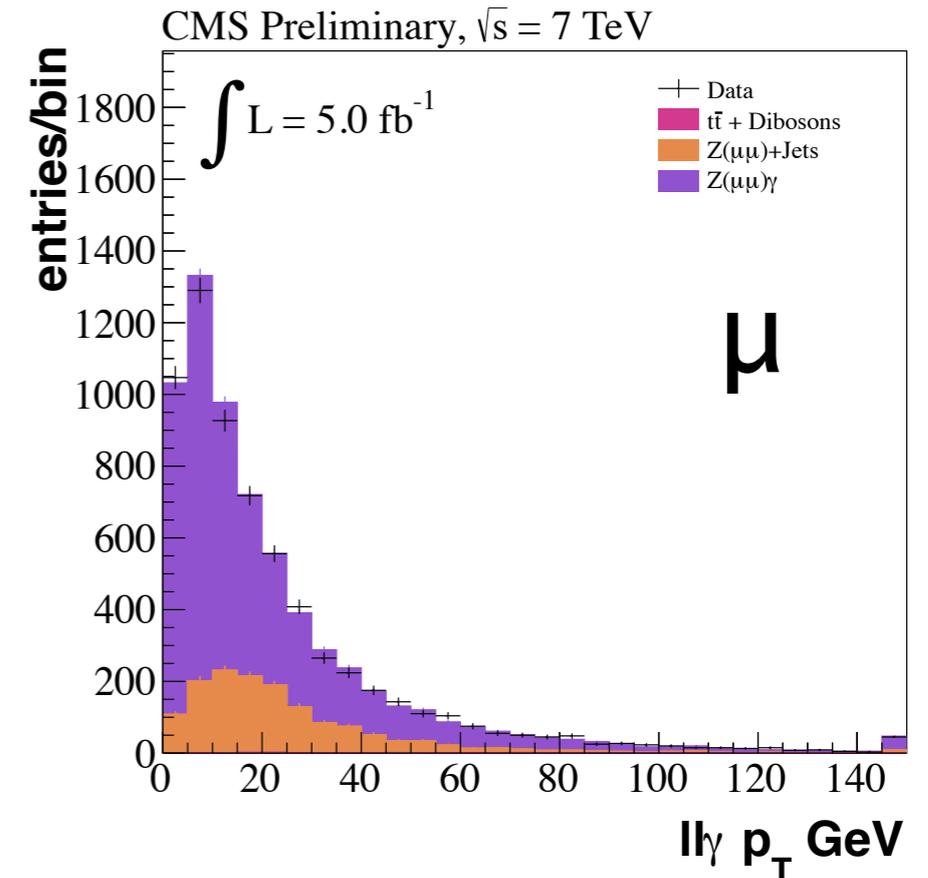


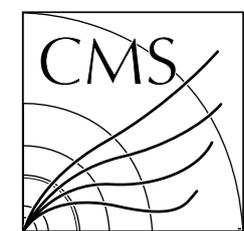
Z γ Distributions: Z γ p_T Distributions



● Distributions in both channels agree

- Inclusively matched Z γ sample describes data





Z γ Cross Section: Systematics



● Luminosity uncertainty

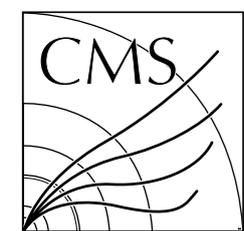
- Luminosity measured by pixel cluster counting
- Driven by uncertainty in luminous region, activation

● Photon/Electron energy scale uncertainty

- Absolute photon energy scale measured from data
- Uncertainties on scale drive bin migrations
- Photon & Electron scales correlated and varied simultaneously in ee γ channel

● Photon/Electron energy resolution

- Resolution of electrons and photons in MC not same as data
- Smear MC to match data resolution
- Change in selected events used to estimate error



Z γ Cross Section: Systematics



● Pileup estimation

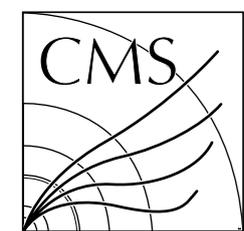
- MC pileup distribution is reweighed to match data
- Measured proton-proton cross section used
 - 68.3 ± 3.4 mb
- Vary to determine effect on MC acceptance

● PDF uncertainties

- PDFs experimentally measured
- Vary associated error eigenvectors to created weights
 - Measure reweighting effect on acceptance

● Data / MC scale factor uncertainties

- Data/MC scale factors have statistical uncertainties
- Also uncertainty on bkg model choice
- Vary individual scale factors, assess change in data-averaged scale factor



Template Method Systematics

● Shift of the MC signal template

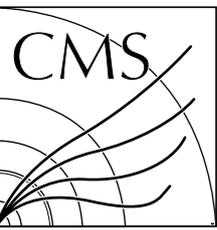
- Known GEANT4 'feature': EM showers are not properly simulated, resulting in larger showers
- Extract background with and without shift, assign difference as systematic

● Sideband Bias & Signal Contamination

- Tracking Isolation sideband is chosen to be minimally correlated with σ_{in}
 - Some bias remains
- Tracking isolation sideband is not completely free of real photons, makes template more 'signal-like'
- Estimate both using MC by vetoing or enhancing the real photon contribution

● Statistical Sampling of the Underlying Distribution

- Statistical sampling of background template is finite and for low statistics can under-sample tails, causing a bias.
- Estimate bias using a bootstrapping procedure, estimating variance with 'toy templates' that have the statistics of the data-driven templates

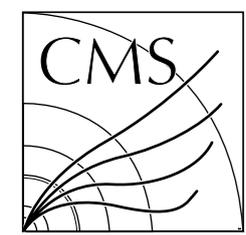


Z γ Cross Section: Systematics Summary



		$ee\gamma$	$\mu\mu\gamma$
Source	Systematic uncertainty	Effect on N_{sig}	
Electron and photon energy scale	ele: 0.5%; pho: 1% (EB) 3% (EE)	3.0 %	n/a
Photon energy scale	1% (EB) 3% (EE)	n/a	4.19%
Muon p_T scale	0.2%	n/a	0.60%
Total uncertainty on N_{sig}		3.0 %	4.23%
Source	Systematic uncertainty	Effect on $\mathcal{F} = A \cdot \epsilon_{MC}$	
Electron and photon energy resolution	1% (EB), 3% (EE)	0.2 %	n/a
Photon energy resolution	1% (EB), 3% (EE)	n/a	0.06%
Muon p_T resolution	0.6%	n/a	0.08%
Pileup	Vary estimated PU using 68.3 ± 3.4 mb	0.6 %	0.44%
PDF	CTEQ6L reweighting	1.1%	1.10%
Signal Modeling		0.6 %	1.10%
Total uncertainty on $\mathcal{F} = A \cdot \epsilon_{MC}$		1.4 %	1.22%
Source	Systematic uncertainty	Effect on ρ_{eff}	
Electron reconstruction	0.4%	0.8 %	n/a
Electron trigger	0.1%	0.1 %	n/a
Electron ID and isolation	2.5%	5.0 %	n/a
Muon trigger	1.5%	n/a	1.0 %
Muon reconstruction	0.9%	n/a	1.0 %
Muon ID and isolation	0.9%	n/a	2.30%
Photon ID and isolation	0.5% (EB), 1.0% (EE)	0.5 %	1.00%
Total uncertainty on ρ_{eff}		5.1 %	2.51%
Source	Systematic uncertainty	Effect on background yield	
Template method	4.4% (EB), 5.6% (EE)	5.1 %	n/a
	4.9% (EB), 5.8% (EE)	n/a	5.5%
Total uncertainty on background		5.1 %	5.5%
Source	Systematic uncertainty	Effect on luminosity	
Luminosity	2.2%	2.2%	2.2%

$ee\gamma$
 $\mu\mu\gamma$



Z γ Cross Section: Measurement



● Theoretical Cross Section: 5.45 ± 0.27 pb (scale + PDF)

● Cross Section from data:

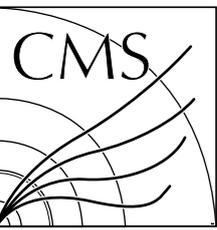
$$\sigma(\text{pp} \rightarrow \text{Z}\gamma \rightarrow \text{ee}\gamma) = 5.20 \pm 0.13 \text{ (stat.)} \pm 0.30 \text{ (syst.)} \pm 0.11 \text{ (lumi.)}$$

$$\sigma(\text{pp} \rightarrow \text{Z}\gamma \rightarrow \mu\mu\gamma) = 5.43 \pm 0.10 \text{ (stat.)} \pm 0.29 \text{ (syst.)} \pm 0.12 \text{ (lumi.)}$$

$$\sigma(\text{pp} \rightarrow \text{Z}\gamma \rightarrow \ell\ell\gamma) = 5.33 \pm 0.08 \text{ (stat.)} \pm 0.25 \text{ (syst.)} \pm 0.12 \text{ (lumi.) pb.}$$

Input parameters for: $\sigma = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\mathcal{F} \cdot \rho_{\text{eff}} \cdot \mathcal{L}}$

Parameters	Z γ \rightarrow ee γ	Z γ \rightarrow $\mu\mu\gamma$
N_{observed}	4108 \pm 64.1 (stat.)	6463 \pm 80.4 (stat.)
$N_{\text{DataDriven background}}$	905.9 \pm 49.8 (stat.) \pm 31.5 (syst.)	1404.3 \pm 56.4 (stat.) \pm 77.0 (syst.)
$N_{\text{Other background}}$	21.2 \pm 1.8 (stat.)	23.7 \pm 2.2 (stat.)
N_{Sig}	3154.2 \pm 81.0 (stat.) \pm 95.1 (syst.)	5034.9 \pm 98.2 (stat.) \pm 213.2 (syst.)
$A \cdot \epsilon_{MC}$	0.132 \pm 0.0018 (syst.)	0.196 \pm 0.001 (stat.)
ρ_{eff}	0.929 \pm 0.0466 (syst.)	0.945 \pm 0.016 (syst.)
$\int L dt$	4961.1 \pm 109.1 (syst.)	4998.9 \pm 110.0 (syst.)

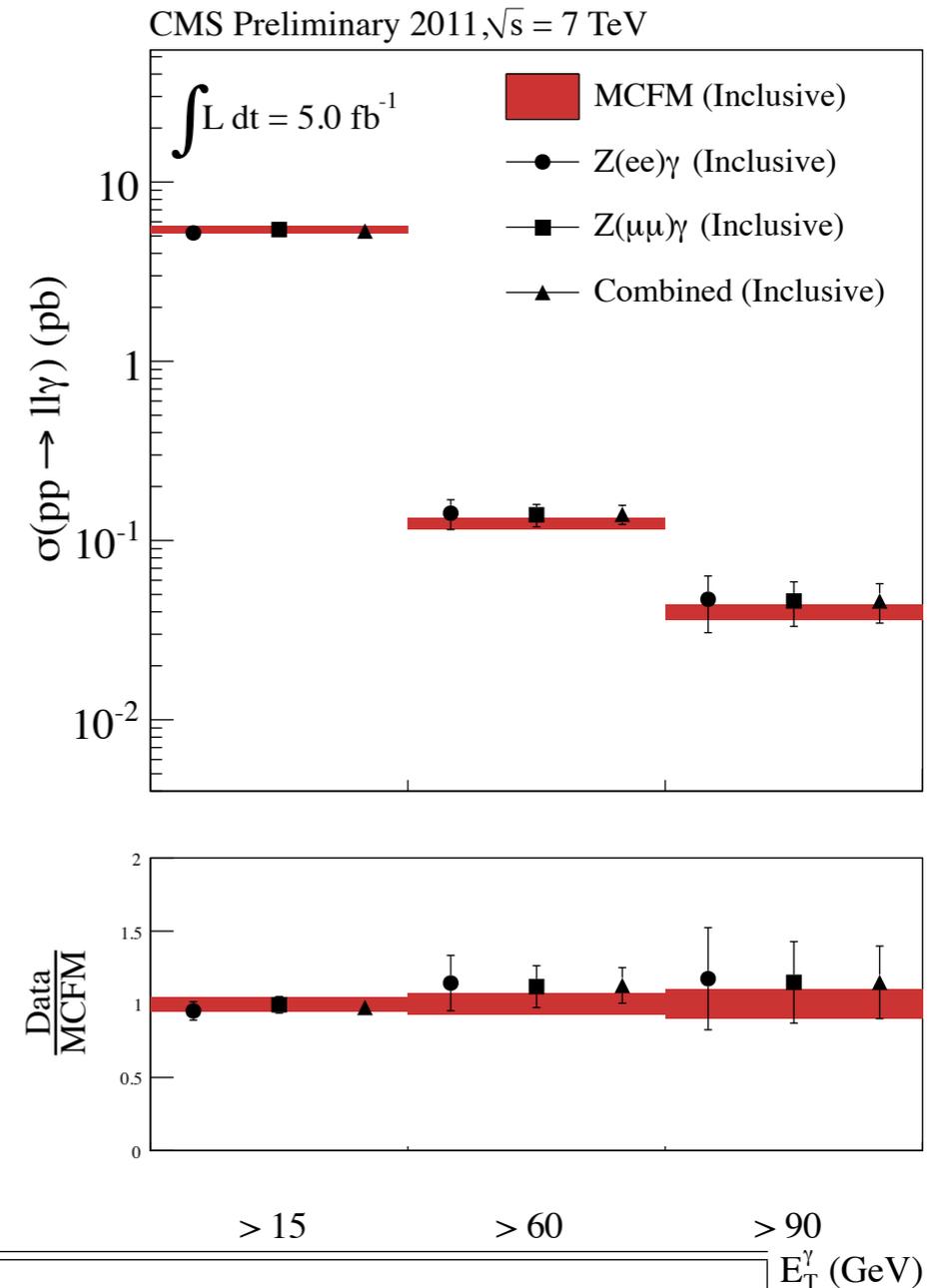


Z γ Cross Section: Theory Comparison



● Z γ cross section consistent with MCFM at higher p $_T$

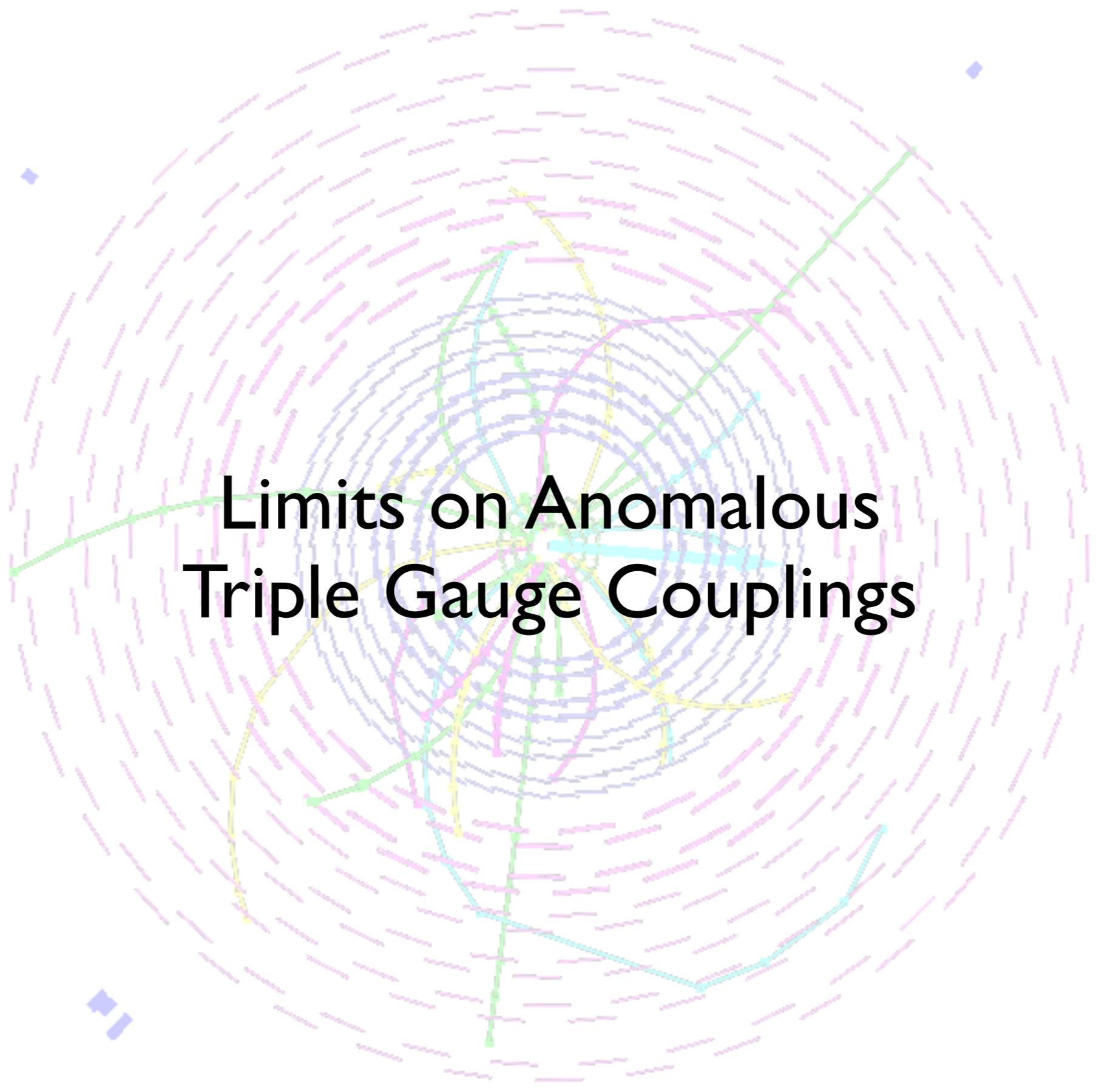
- Error is half systematic at > 60, 90 GeV



		Z γ	
		$ee\gamma$	$\mu\mu\gamma$
$E_T^\gamma > 60$ GeV		$0.142 \pm 0.019(\text{stat.}) \pm 0.019(\text{syst.}) \pm 0.003(\text{lumi.})$	$0.139 \pm 0.013(\text{stat.}) \pm 0.015(\text{syst.}) \pm 0.003(\text{lumi.})$
Combination		$0.140 \pm 0.011(\text{stat.}) \pm 0.013(\text{syst.}) \pm 0.003(\text{lumi.})$ pb	
NLO Prediction		0.124 ± 0.009 pb	
$E_T^\gamma > 90$ GeV		$0.047 \pm 0.013(\text{stat.}) \pm 0.010(\text{syst.}) \pm 0.001(\text{lumi.})$	$0.046 \pm 0.008(\text{stat.}) \pm 0.010(\text{syst.}) \pm 0.001(\text{lumi.})$
Combination		$0.046 \pm 0.007(\text{stat.}) \pm 0.009(\text{syst.}) \pm 0.001(\text{lumi.})$ pb	
NLO Prediction		0.040 ± 0.004 pb	

E_T^γ (GeV)

Limits on Anomalous Triple Gauge Couplings



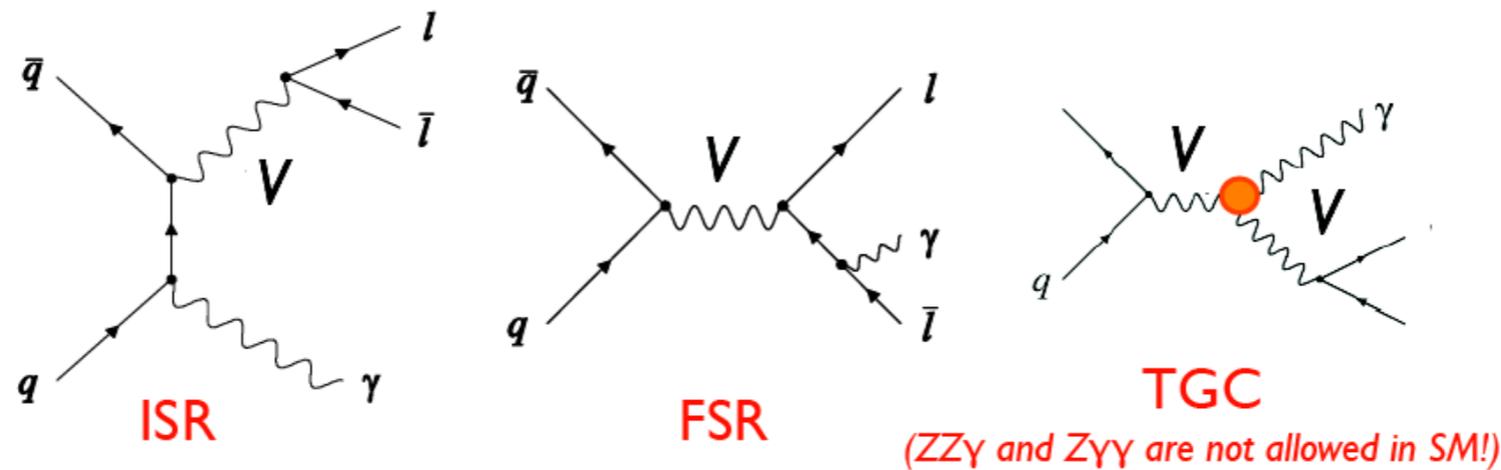
aTGC Limits

● Non-Abelian $SU(2)_L \times U(1)$ symmetry of SM exactly predicts couplings of gauge bosons

- Least well-measured portion of the SM
- Anomalous gauge couplings are a clear sign of BSM physics

● $Z\gamma$ has no natural triple gauge couplings in the SM

- CMS sets limits on $h_3^{Z,\gamma}$ and $h_4^{Z,\gamma}$



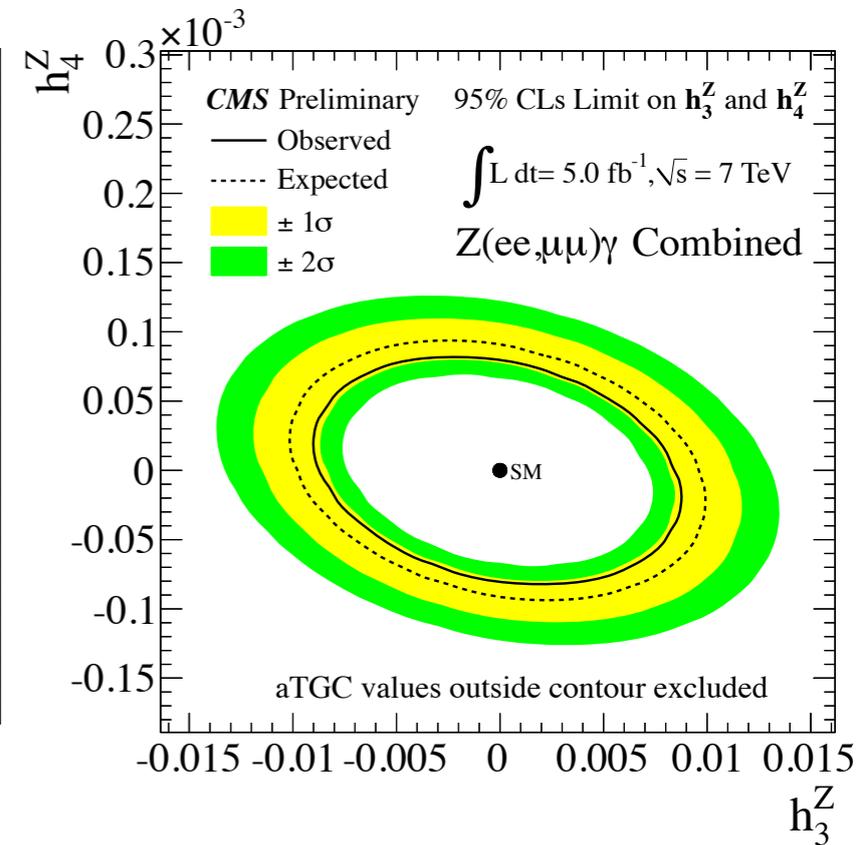
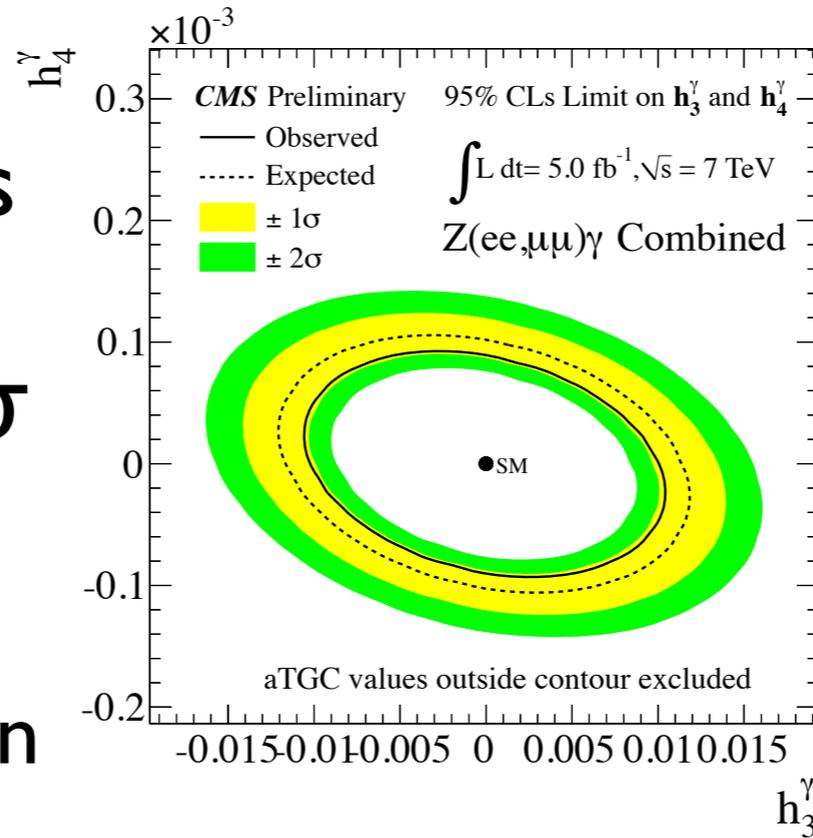
● Form factor **not** applied

- ‘Raw’ coupling limits presented

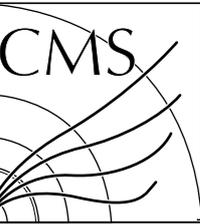
~~$$f(\hat{s}) = \frac{1}{(1 + \hat{s}/\Lambda^2)^n}$$~~

● Limits set using modified frequentist CLs methodology,

- No observed excess
- Observed limit is 1σ under-fluctuated
 - Comes from electron channel
- Most stringent limits on aTGCs thus far



	h_3^γ	h_4^γ	h_3^Z	h_4^Z
$Z\gamma \rightarrow ee\gamma$	[-0.013, 0.013]	[-1.1e-4, 1.1e-4]	[-0.011, 0.011]	[-9.9e-5, 9.5e-5]
$Z\gamma \rightarrow \mu\mu\gamma$	[-0.013, 0.013]	[-1.1e-4, 1.2e-4]	[-0.011, 0.011]	[-1.0e-4, 1.1e-4]
$Z\gamma \rightarrow \ell\ell\gamma$	[-0.010, 0.010]	[-8.8e-5, 8.8e-5]	[-8.6e-3, 8.4e-3]	[-8.0e-5, 7.9e-5]



CMS aTGC Limits Comparison: LEP



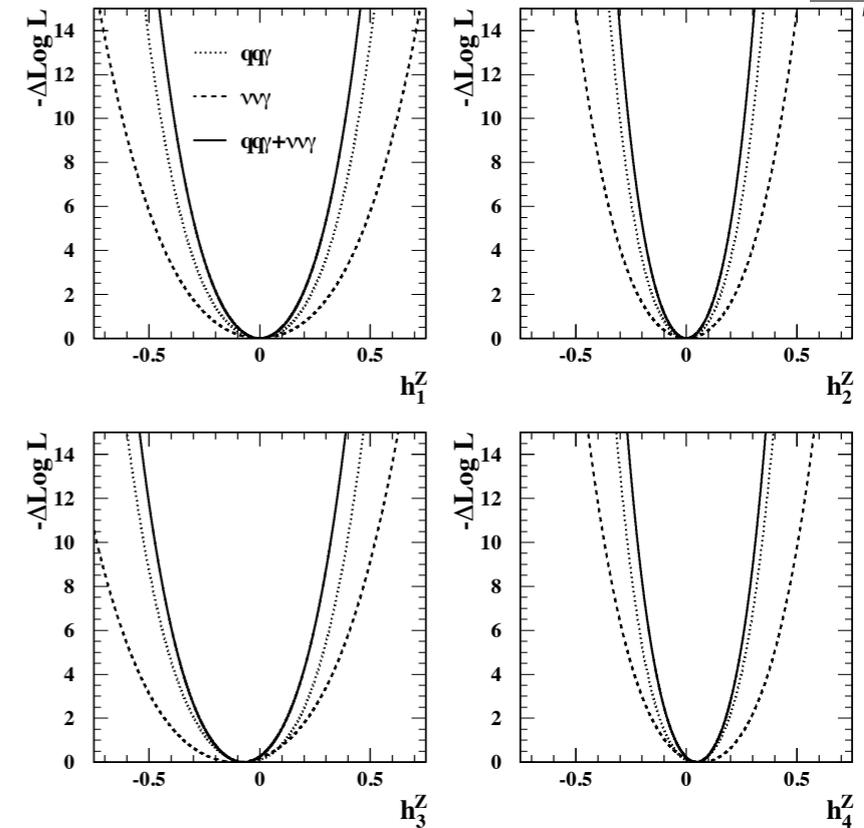
● LEP limits set with no form factor using p_T and decay angles

- Used neutrino and quark decays of Z
- Can differentiate $h^{1,2}$ from $h^{3,4}$
- Access to sign of $h^{3,4}$

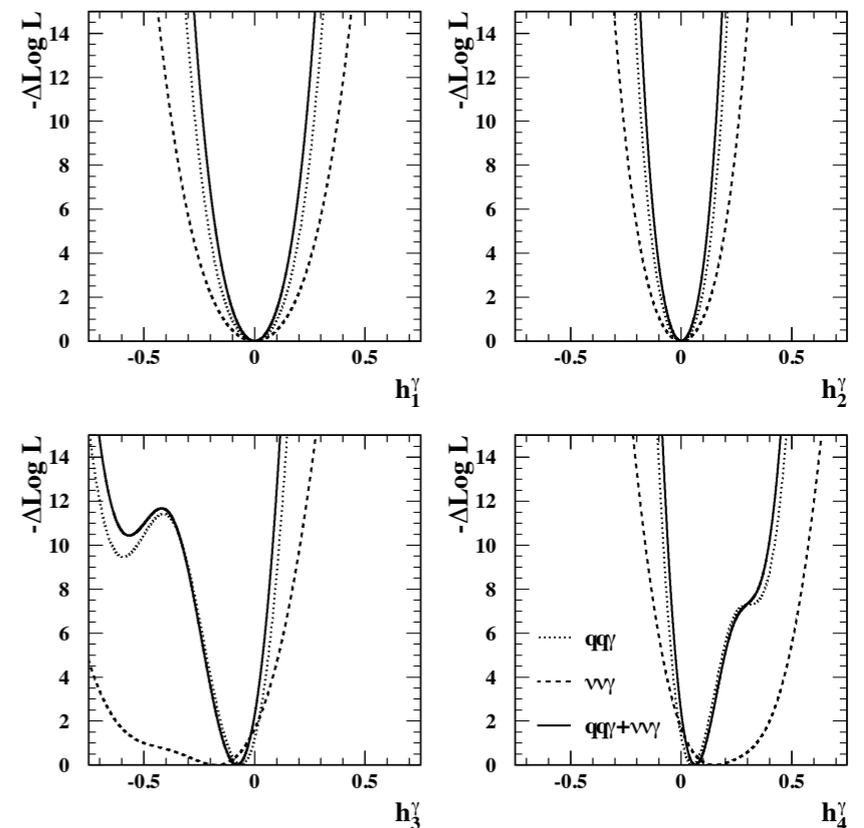
● All limits from LEP beat by CMS

- More than 2 orders of magnitude
- Due to extended kinematic reach and statistics

OPAL 189 GeV



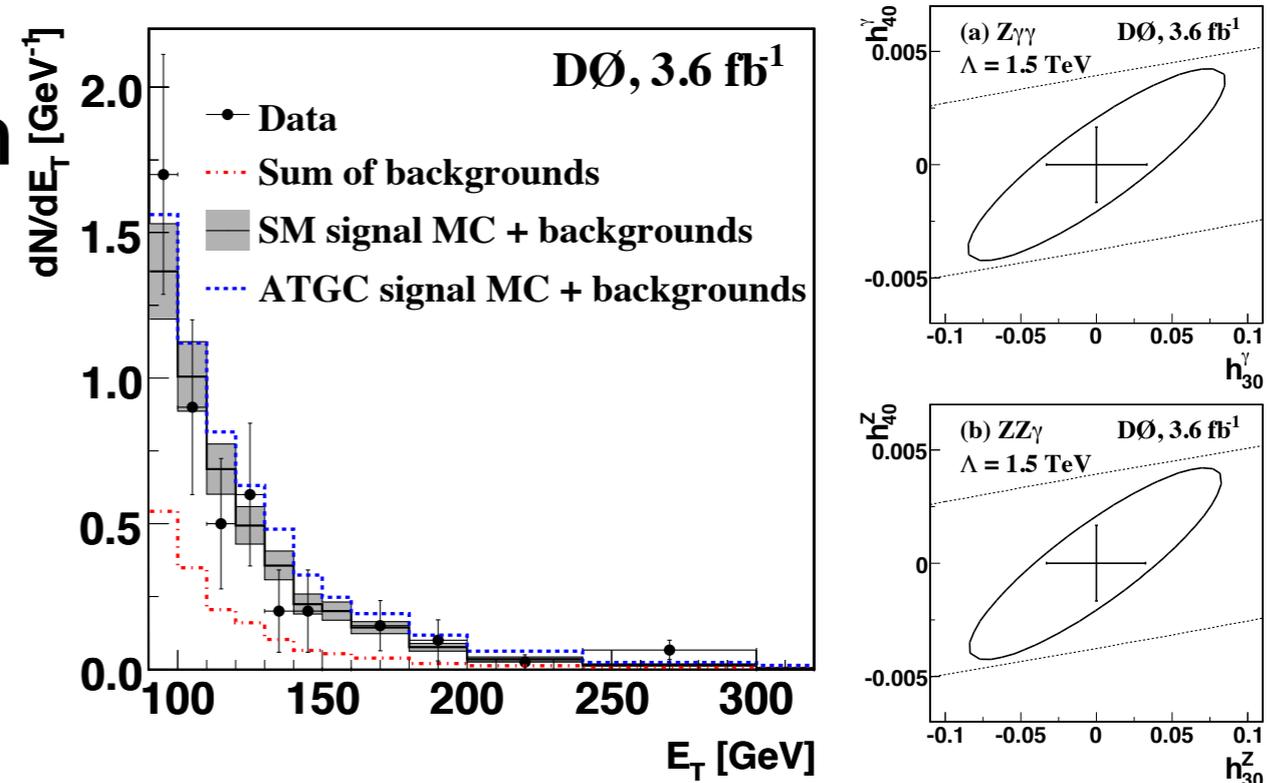
OPAL 189 GeV



95% CL @ $-\Delta \log L = 1.96$

● All Tevatron limits set using form factor and p_T distribution

- $\Lambda <$ energies at LHC
- LHC would resolve particles responsible for low energy aTGCs in this case

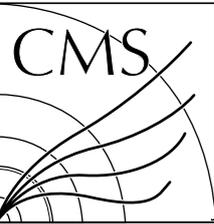


CDF:

Parameter	($\Lambda = 1.2$ TeV)	($\Lambda = 1.5$ TeV)
h_3^Z	[-0.024, 0.027]	[-0.020, 0.021]
h_4^Z	[-0.0013, 0.0013]	[-0.0009, 0.0009]
h_3^γ	[-0.026, 0.026]	[-0.022, 0.020]
h_4^γ	[-0.0012, 0.0013]	[-0.0008, 0.0008]

- Cannot directly compare

$$f(\hat{s}) = \frac{1}{(1 + \hat{s}/\Lambda^2)^n}$$



CMS aTGC Limits Comparison: ATLAS



● ATLAS limits set using fifth of 2011 dataset

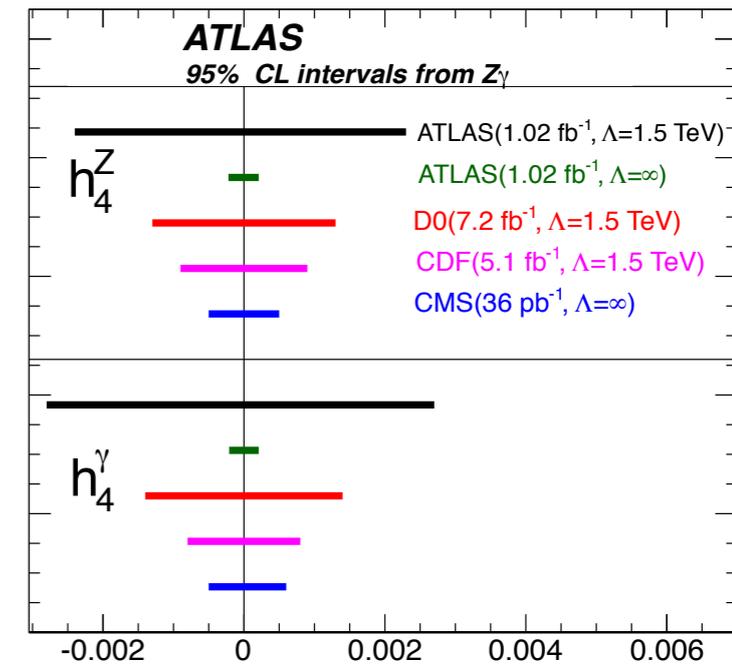
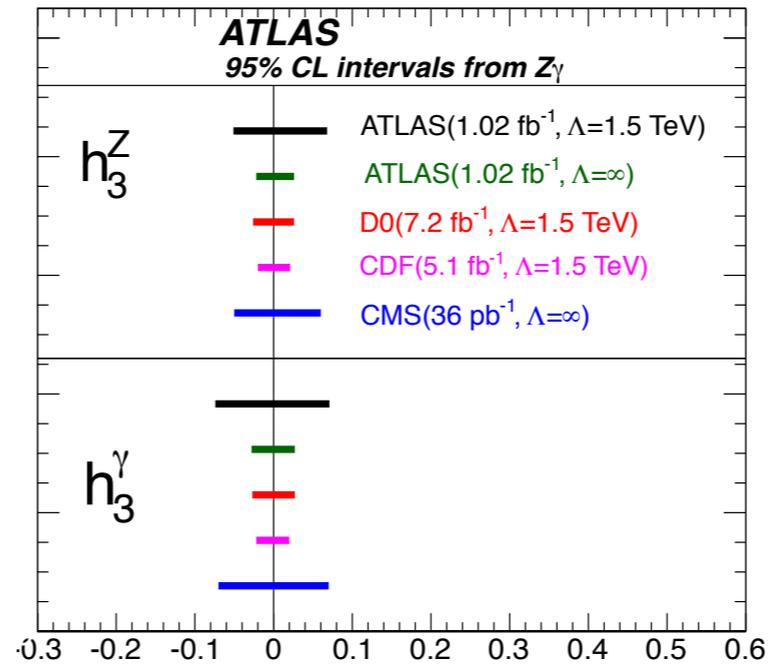
● Compared to CDF, D0, and CMS

- Used unphysical form factor for comparison

- Some comparison of statistical power between LHC, Tevatron

- No-form factor limits too

- CMS combined limits better by statistical factor of $1/\sqrt{5}$



	Measured	Measured	Expected
Λ	1.5 TeV	∞	∞
h_3^γ	(-0.074, 0.071)	(-0.028, 0.027)	(-0.027, 0.027)
h_3^Z	(-0.051, 0.068)	(-0.022, 0.026)	(-0.022, 0.025)
h_4^γ	(-0.0028, 0.0027)	(-0.00021, 0.00021)	(-0.00021, 0.00021)
h_4^Z	(-0.0024, 0.0023)	(-0.00022, 0.00021)	(-0.00022, 0.00021)

CMS:

	h_3^γ	h_4^γ	h_3^Z	h_4^Z
$Z\gamma \rightarrow ee\gamma$	[-0.013, 0.013]	[-1.1e-4, 1.1e-4]	[-0.011, 0.011]	[-9.9e-5, 9.5e-5]
$Z\gamma \rightarrow \mu\mu\gamma$	[-0.013, 0.013]	[-1.1e-4, 1.2e-4]	[-0.011, 0.011]	[-1.0e-4, 1.1e-4]
$Z\gamma \rightarrow ll\gamma$	[-0.010, 0.010]	[-8.8e-5, 8.8e-5]	[-8.6e-3, 8.4e-3]	[-8.0e-5, 7.9e-5]

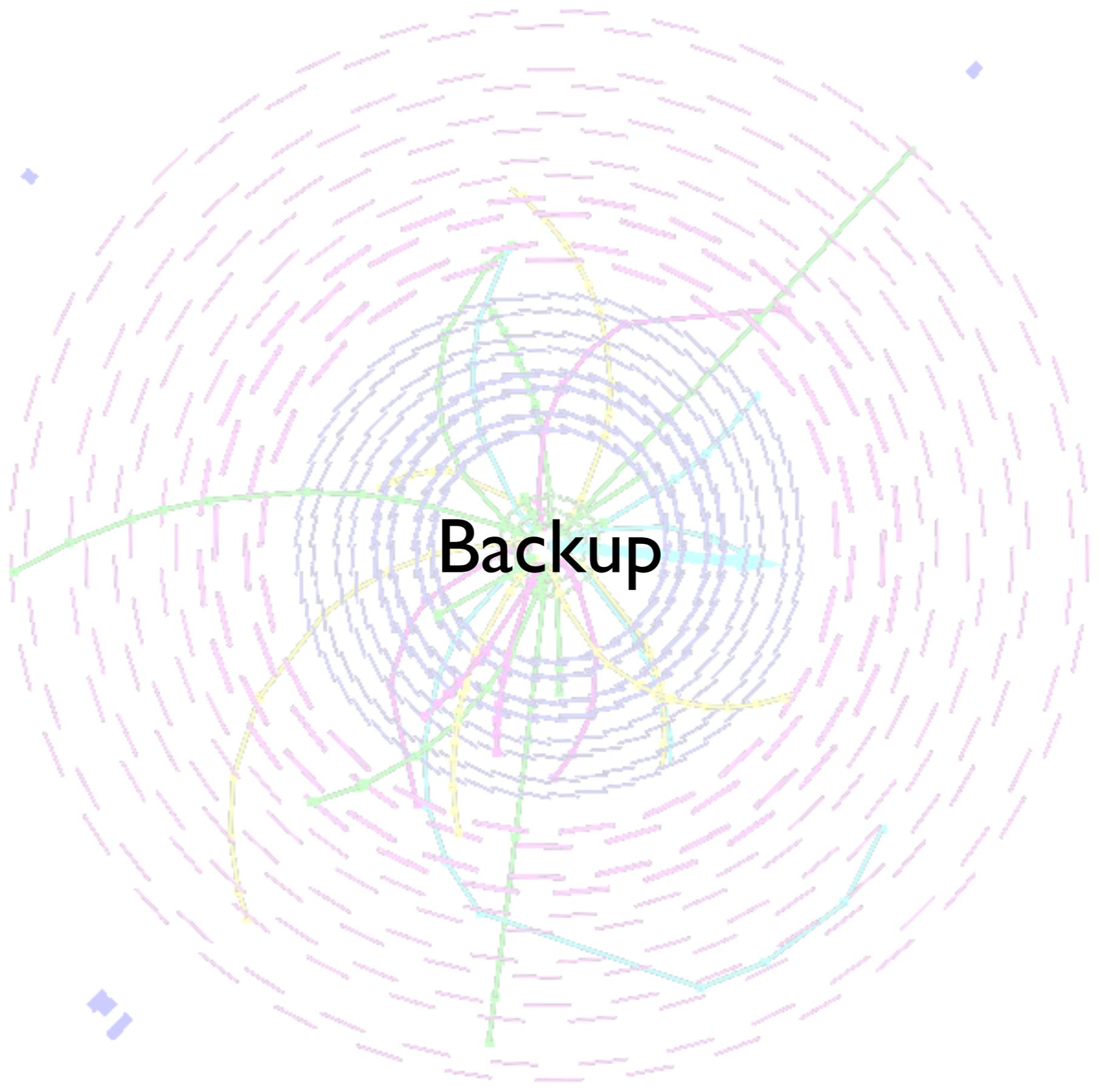
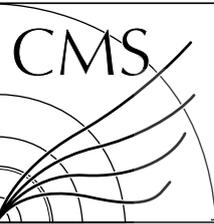
Conclusions

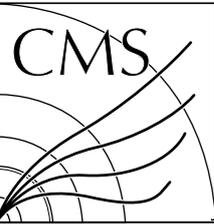
● Presented an analysis of the $Z\gamma$ final state

- Cross Section measurements:
 - photon $p_T > 15, 60, 90$ GeV
- Anomalous triple gauge coupling limits
 - Better than most recent ATLAS by statistics in charged lepton channels

● Outlook

- 2012 LHC data at 8 TeV improves kinematic reach
 - $Z\gamma$ cross section larger
- At least 4x more integrated lumi. than 2012
 - Improve limits by at least 2x (not including kinematic factor!)
- New treatment of aTGCs from T. Stelzer et al. promising
 - More theoretically consistent treatment of anomalous couplings





The Standard Model



☉ Thee Generations of Matter

- 6 quarks
 - 3 'up' type, 3 'down' type
- 6 leptons
 - 3 charged (e, μ, τ)
 - 3 neutral (ν_e, ν_μ, ν_τ), 'neutrinos'
 - ➔ Massless in SM, but recent experiments demonstrate small Δm² between generations!

☉ Force Carriers

- Massless Photon (γ): EM Force
 - Massive W[±], Z: Weak Force
 - 8 massless gluons: Strong Force
- } unified under SU(2)_LxU(1)

☉ Higgs Boson

- In SM Provides mass to W, Z through spontaneous symmetry breaking
- 125 GeV Higgs-like excess in 2011+2012 LHC data

	I	II	III	
mass →	2.4 MeV/c ²	1.27 GeV/c ²	171.2 GeV/c ²	0
charge →	2/3	2/3	2/3	0
spin →	1/2	1/2	1/2	1
name →	u up	c charm	t top	γ photon
	4.8 MeV/c ²	104 MeV/c ²	4.2 GeV/c ²	0
	-1/3	-1/3	-1/3	0
	1/2	1/2	1/2	1
	d down	s strange	b bottom	g gluon
Quarks				
	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²	91.2 GeV/c ²
	0	0	0	0
	1/2	1/2	1/2	1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z⁰ Z boson
	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	80.4 GeV/c ²
	-1	-1	-1	±1
	1/2	1/2	1/2	1
	e electron	μ muon	τ tau	W[±] W boson
Leptons				

Gauge Bosons

Higgs Boson

Responsible for EWK
Symmetry breaking
Predicted J^{PC} = 0⁺⁺

Uses SU(3)xSU(2)_LxU(1)
symmetry to describe forces

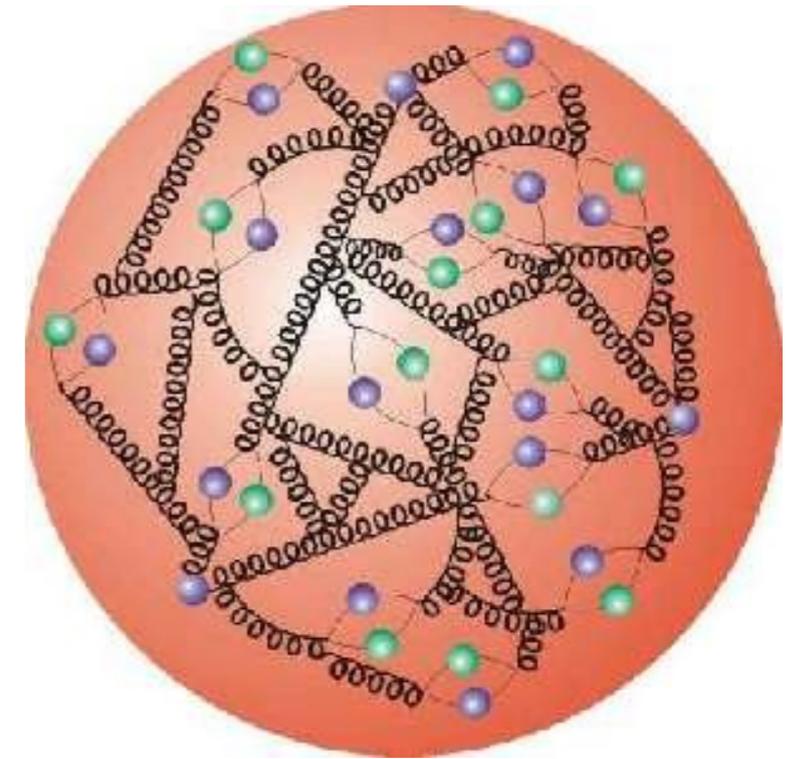
The Structure of the Proton

● The proton has substructure

- In collisions this substructure is probed
- One 'parton' from each colliding proton

● Proton is a bound state of quarks

- Valence quarks (uud) are exchanging virtual gluons
 - may split into u,d,s,c,b quarks creating 'sea' of partons
 - ➔ Effect present at all times, 'intrinsic sea'
 - splitting to gluons allowed as well
- Valence quarks carry roughly half of proton total momentum

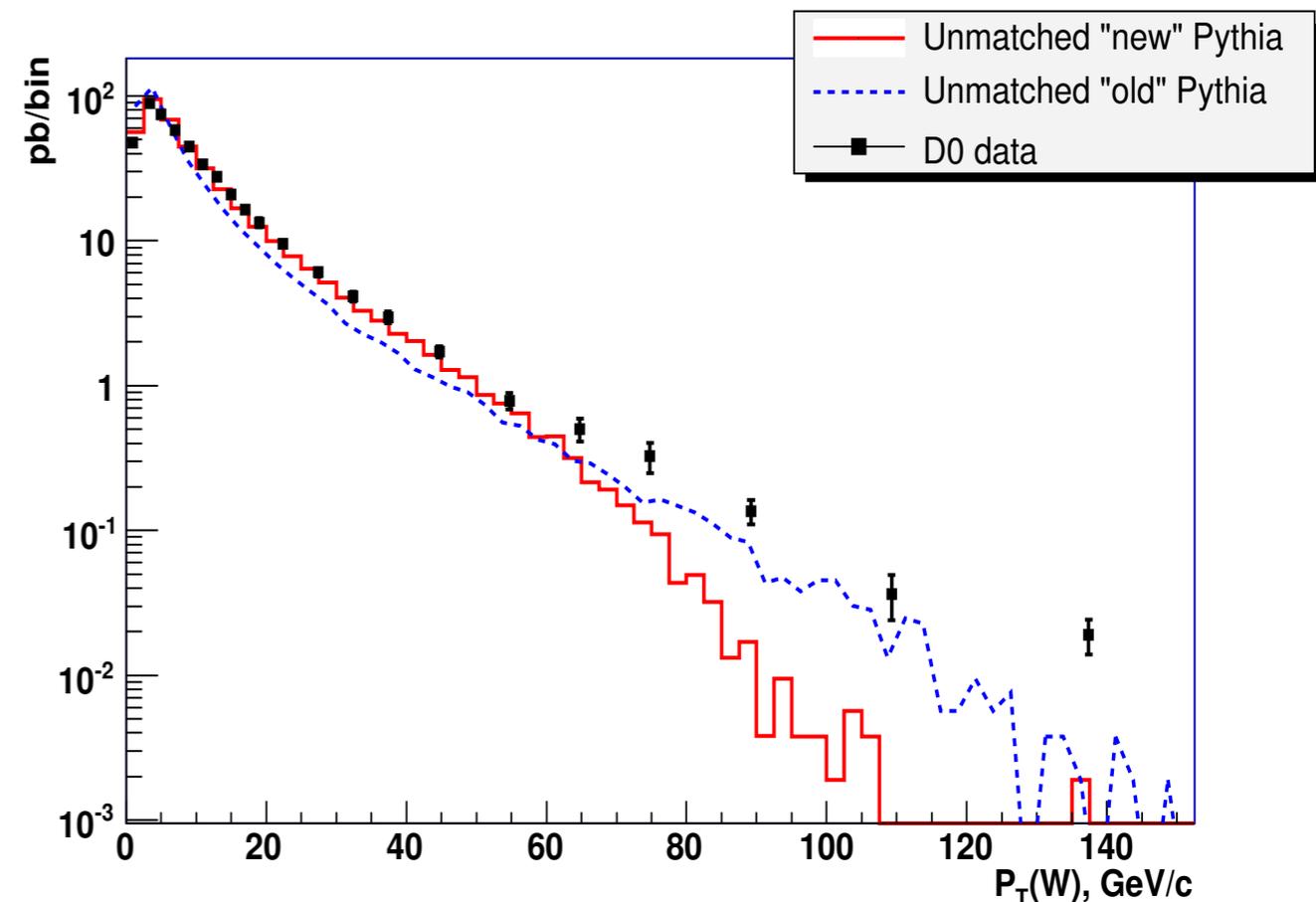


● Parton Distribution Functions describe structure

- Describe probability $f_i(x, Q^2)$ to find parton type 'i', with momentum fraction 'x' at momentum transfer Q^2
- Measured from experiment and evolved to various Q^2
- This means hadron colliders sample a wide range of energies
 - $\hat{s} = xyS$ for momentum fractions x, y in two partons and beam energy S

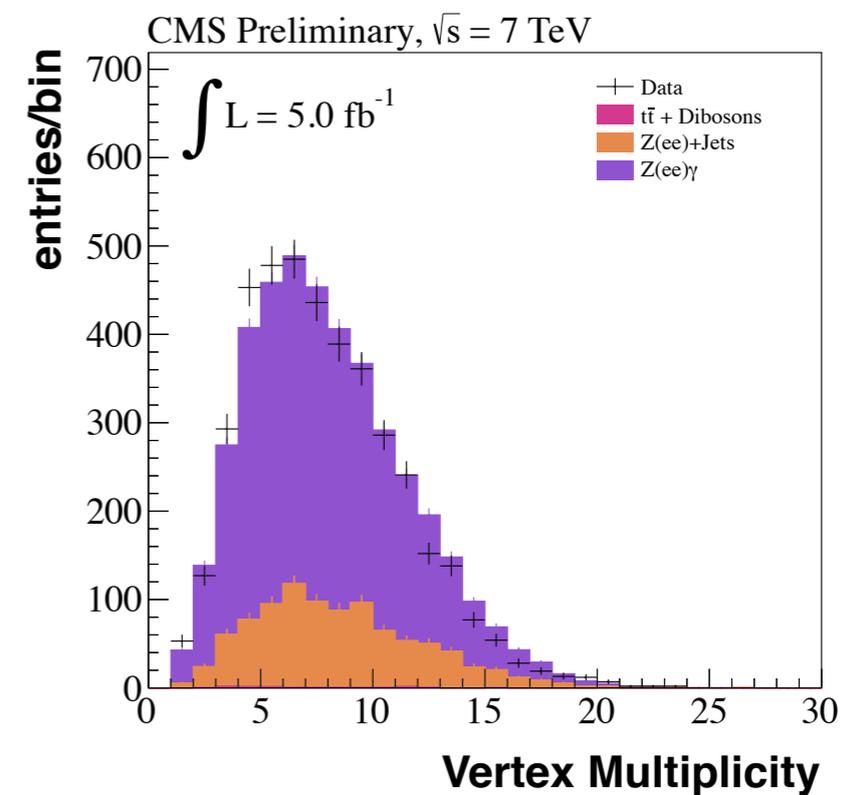
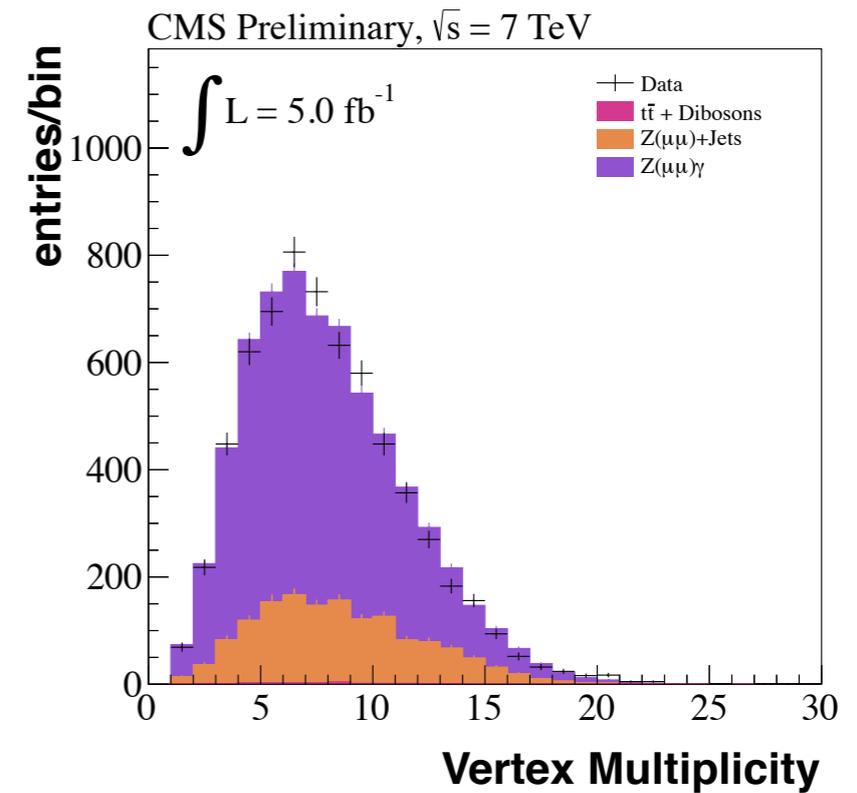
Limited Phase Space in Shower MC

- Each SMC hard parton considered alone
 - Limits phase space
 - Results in poor modeling at high p_T of the matrix element part of the event

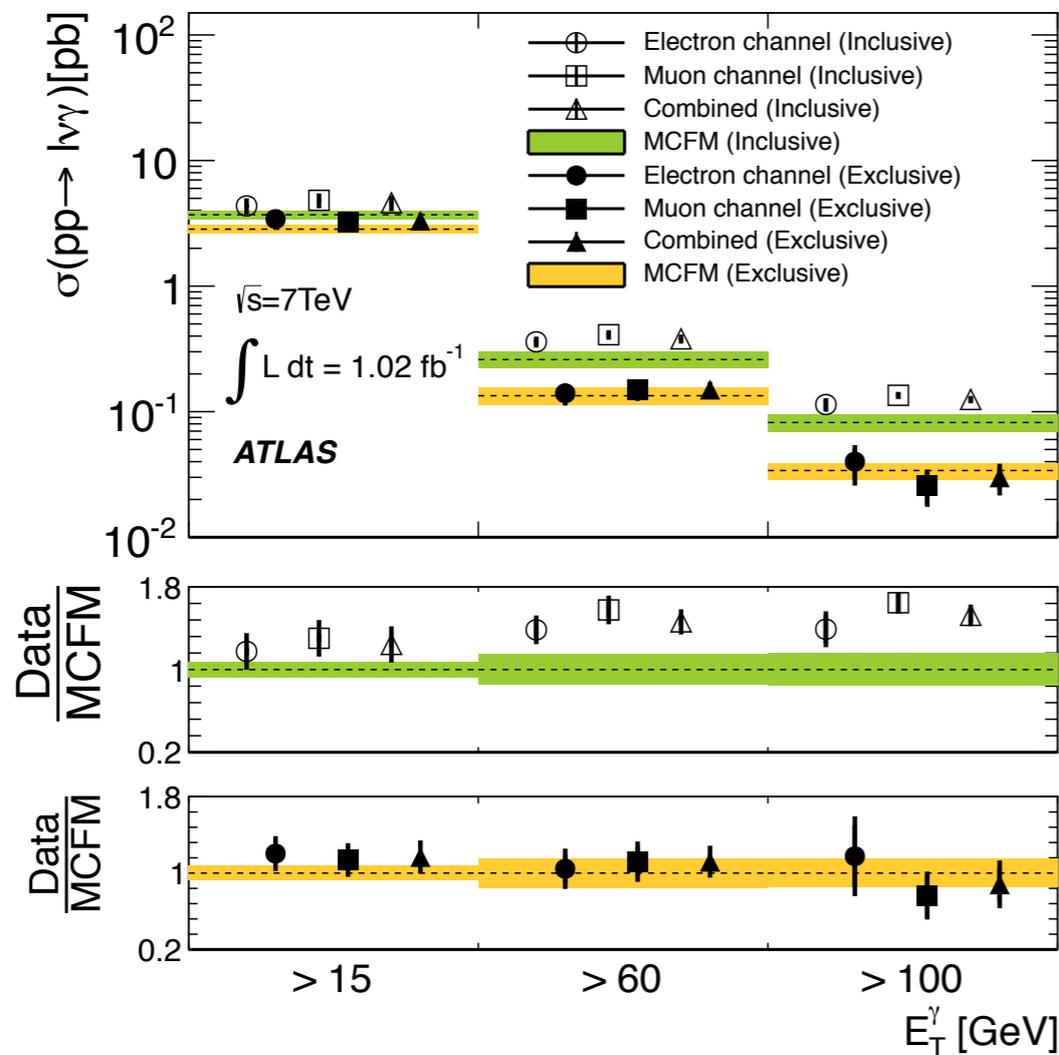


Z γ Distributions: Vertex Multiplicity

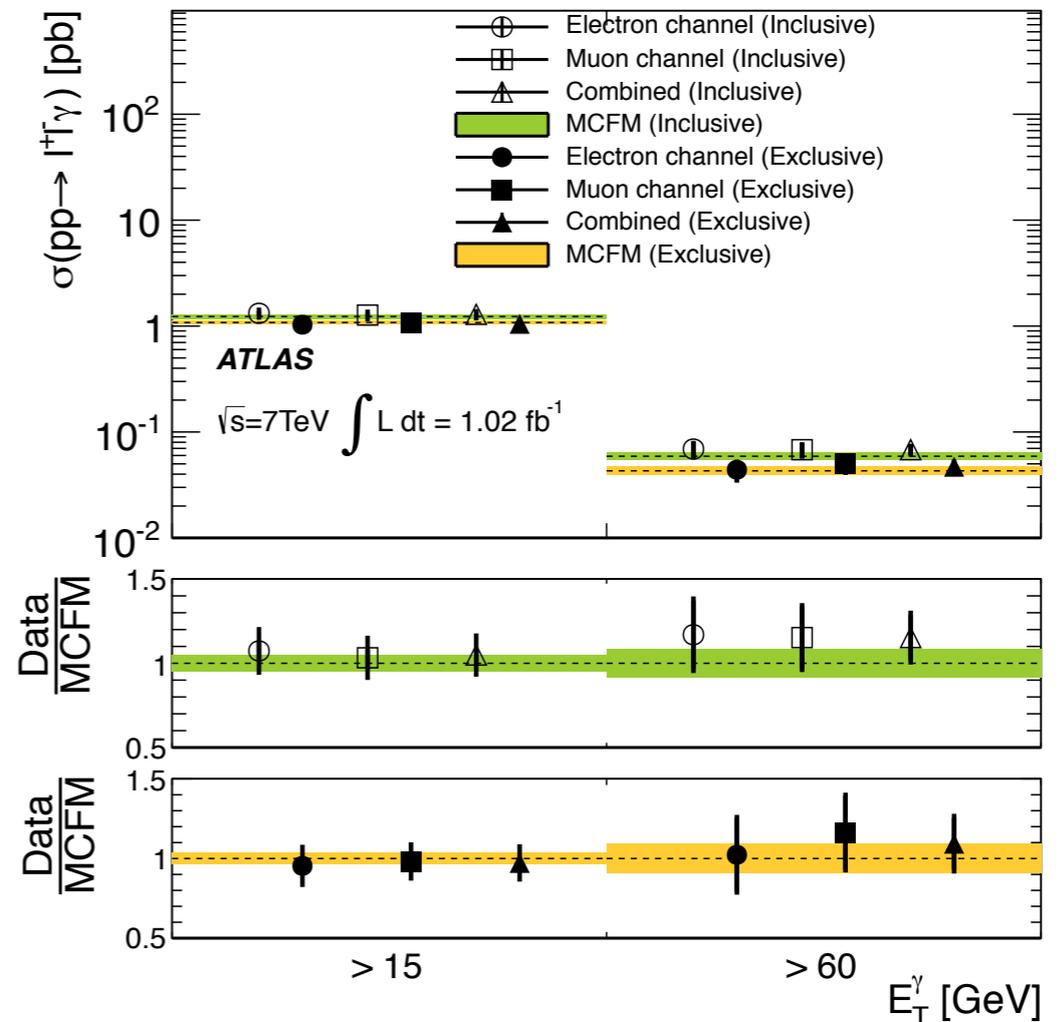
● Pileup Reweighting
checks out fine



<http://arxiv.org/abs/1205.2531>

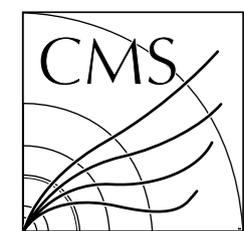


(a)



(b)

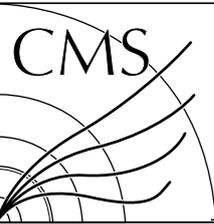
FIG. 3. The measured cross section for (a) $W\gamma$ production, (b) $Z\gamma$ production as a function of the photon transverse energy, in the extended fiducial region as defined in Table III, together with the SM model prediction. The lower plots show the ratio between the data and the prediction of the MCFM generator.



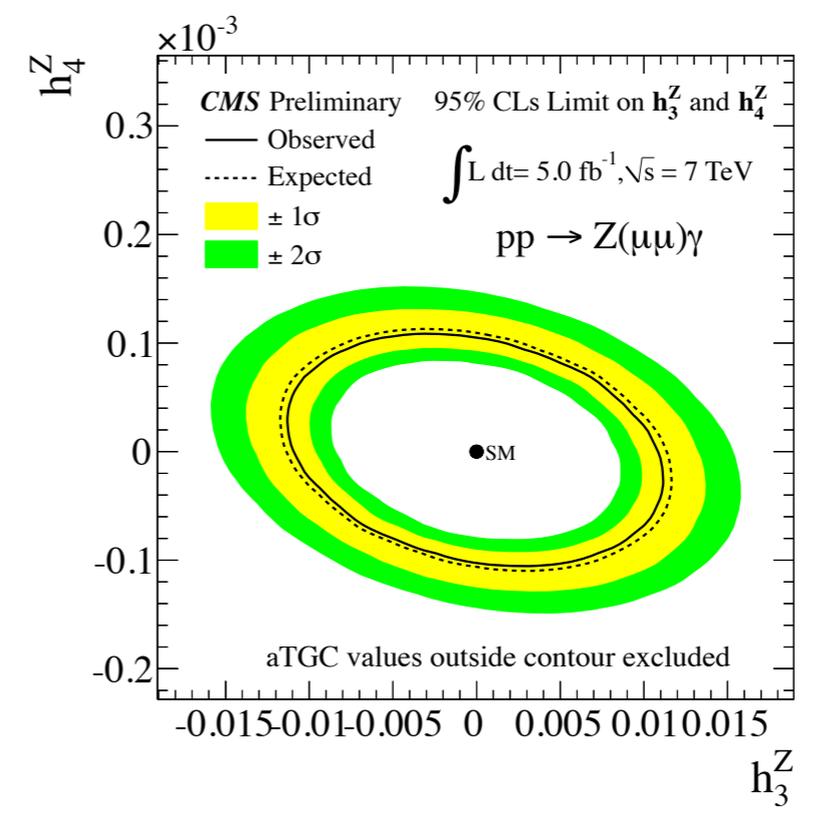
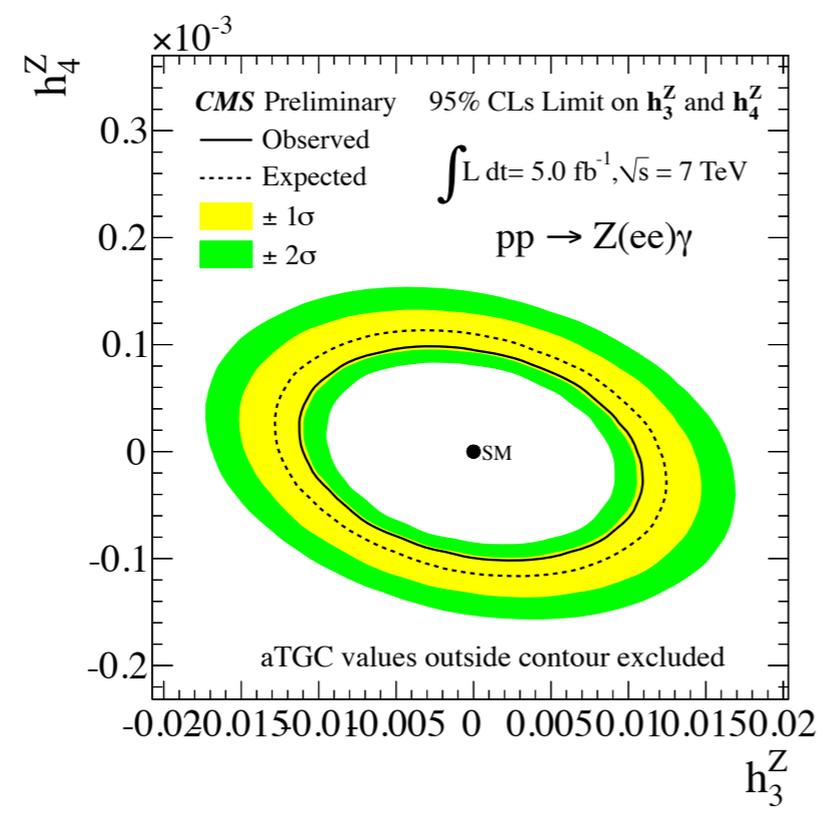
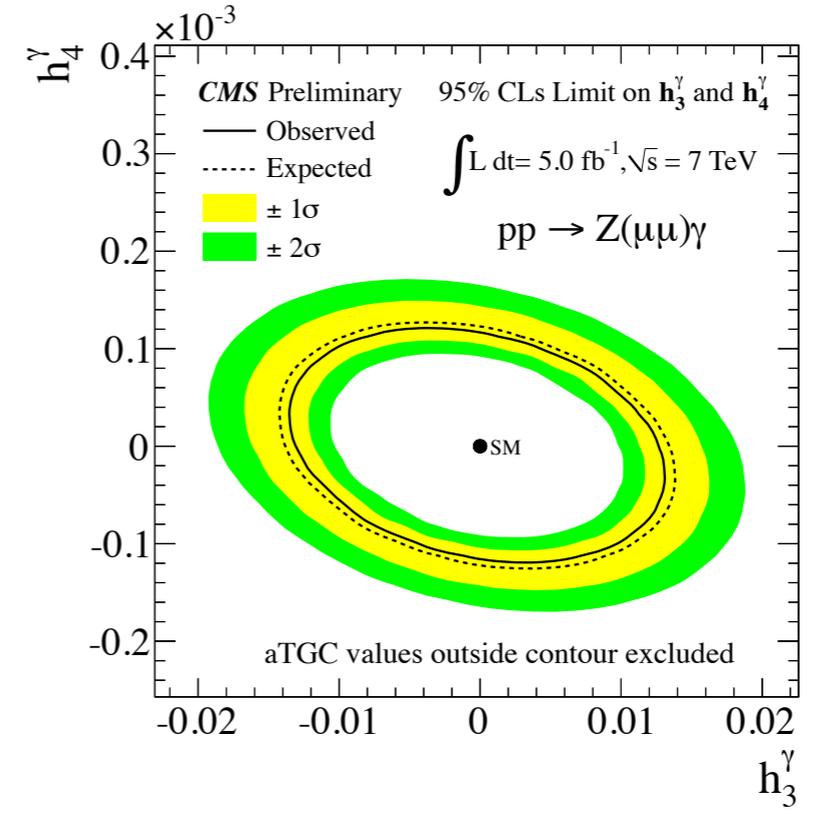
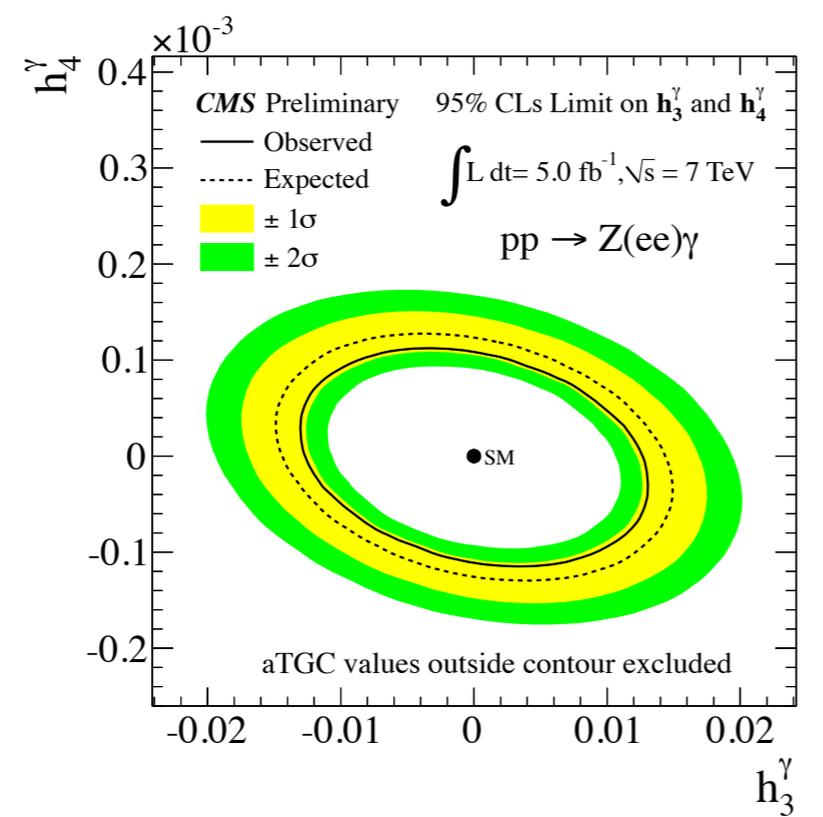
CMS Cross Section Theory Comparison

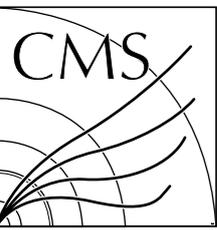


	$Z\gamma$	
	$ee\gamma$	$\mu\mu\gamma$
$E_T^\gamma > 60$ GeV	$0.142 \pm 0.019(\text{stat.}) \pm 0.019(\text{syst.}) \pm 0.003(\text{lumi.})$	$0.139 \pm 0.013(\text{stat.}) \pm 0.015(\text{syst.}) \pm 0.003(\text{lumi.})$
Combination	$0.140 \pm 0.011(\text{stat.}) \pm 0.013(\text{syst.}) \pm 0.003(\text{lumi.})$ pb	
NLO Prediction	0.124 ± 0.009 pb	
$E_T^\gamma > 90$ GeV	$0.047 \pm 0.013(\text{stat.}) \pm 0.010(\text{syst.}) \pm 0.001(\text{lumi.})$	$0.046 \pm 0.008(\text{stat.}) \pm 0.010(\text{syst.}) \pm 0.001(\text{lumi.})$
Combination	$0.046 \pm 0.007(\text{stat.}) \pm 0.009(\text{syst.}) \pm 0.001(\text{lumi.})$ pb	
NLO Prediction	0.040 ± 0.004 pb	

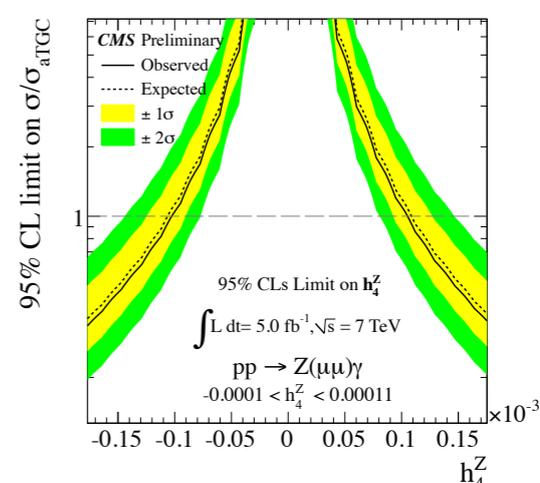
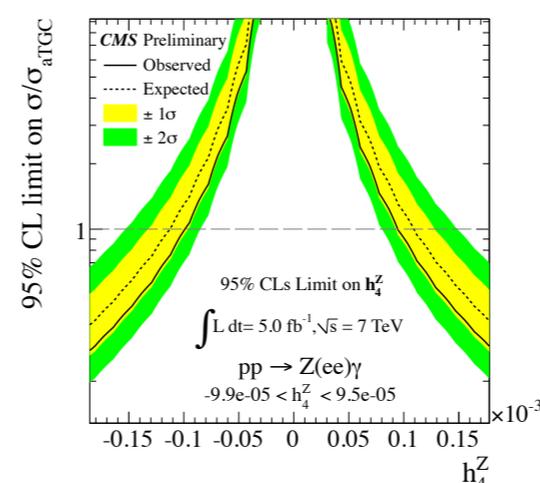
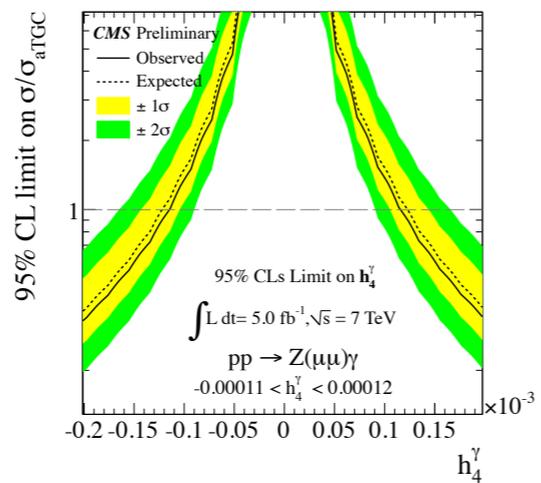
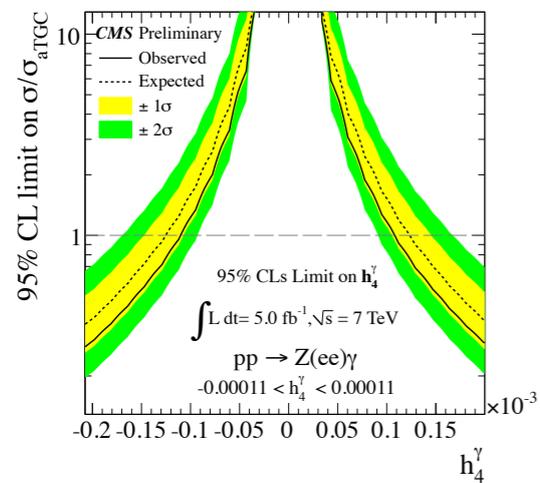
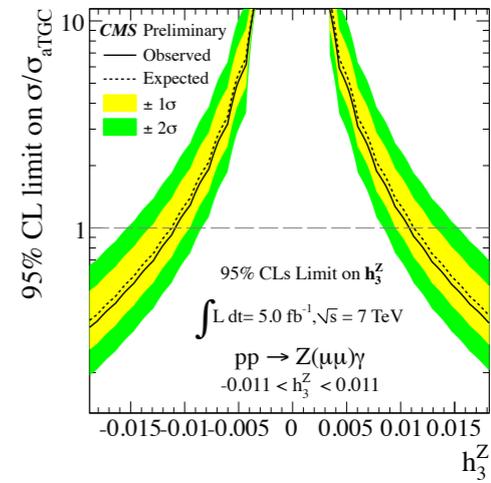
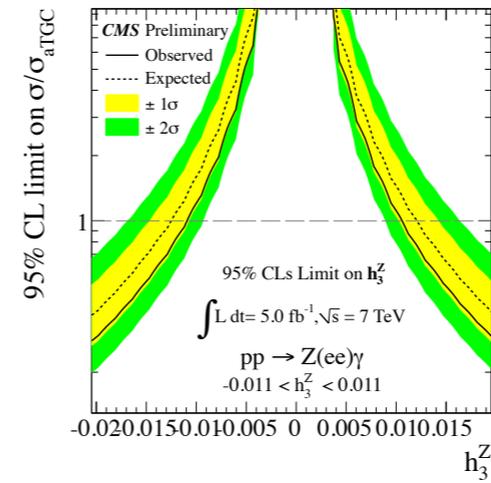
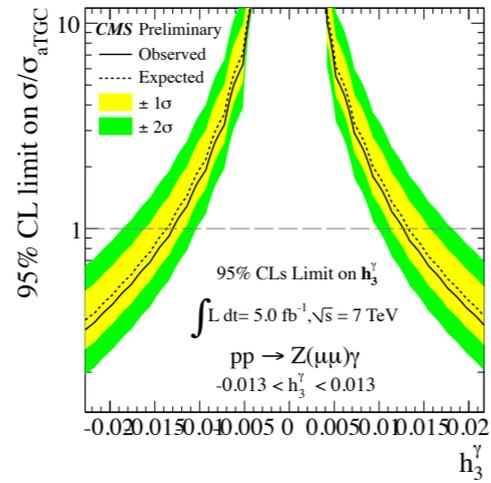
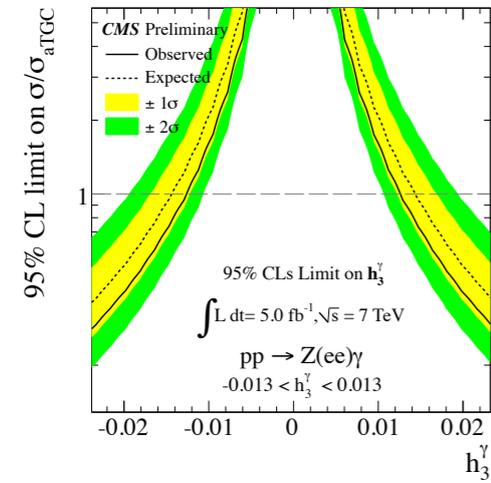


CMS aTGCs: $Z\gamma$ Detail





CMS aTGCs: $Z\gamma$ Detail



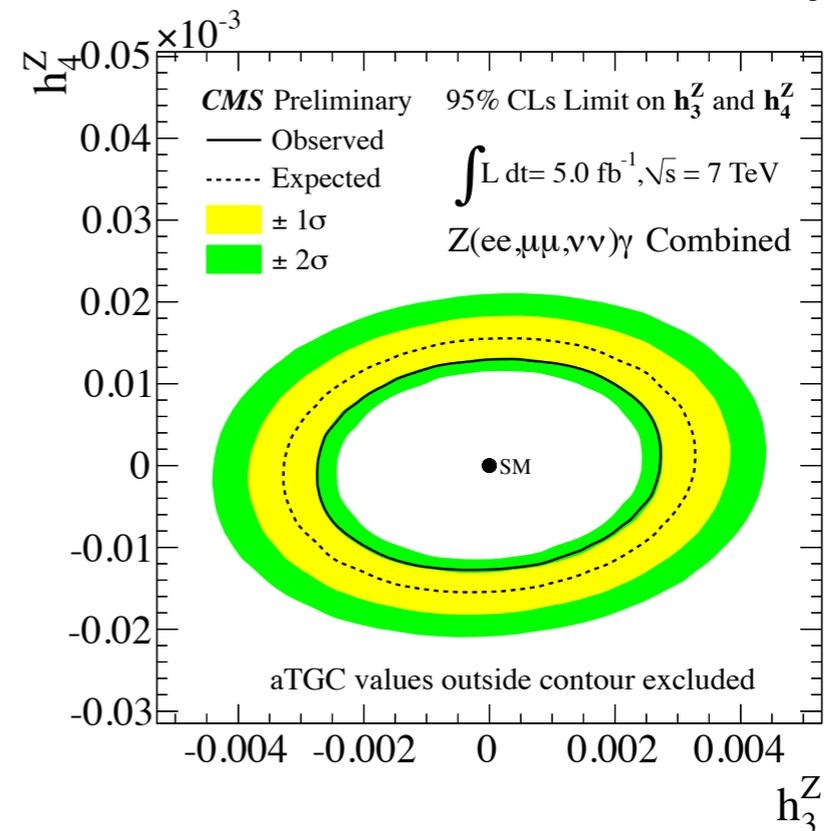
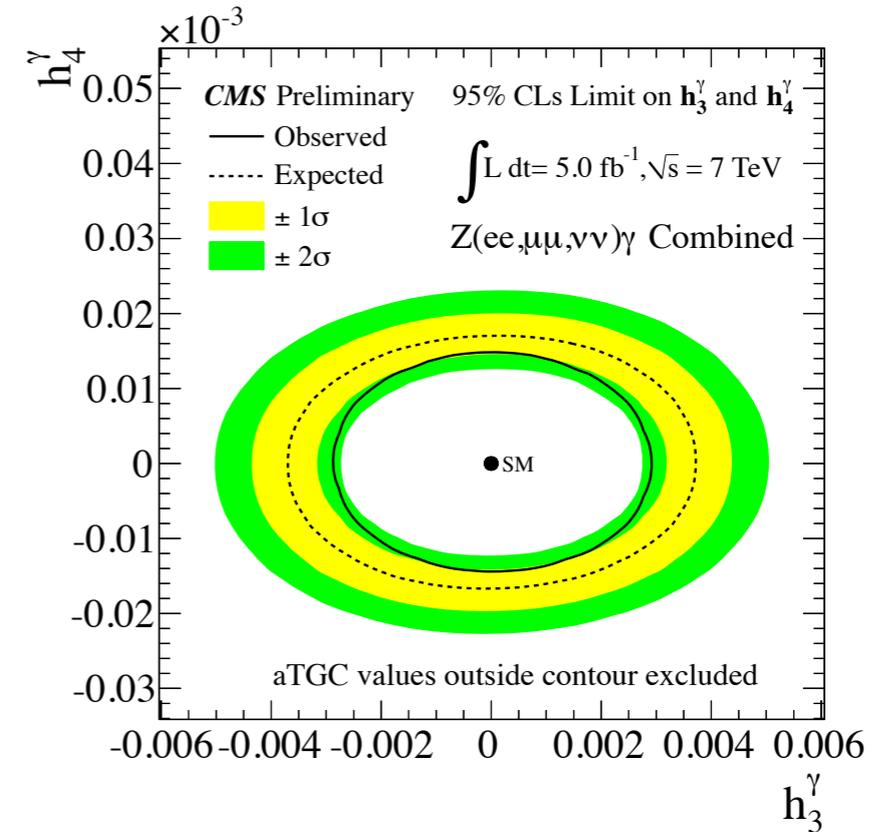
aTGC Limits: $Z\gamma, ee + \mu\mu + \nu\nu$

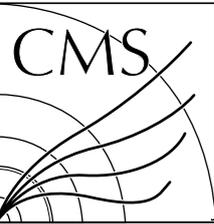
● $Z(\nu\nu)\gamma$ has significantly more statistical power at large photon p_T

- Combine with charged lepton limit to achieve 6x improvement

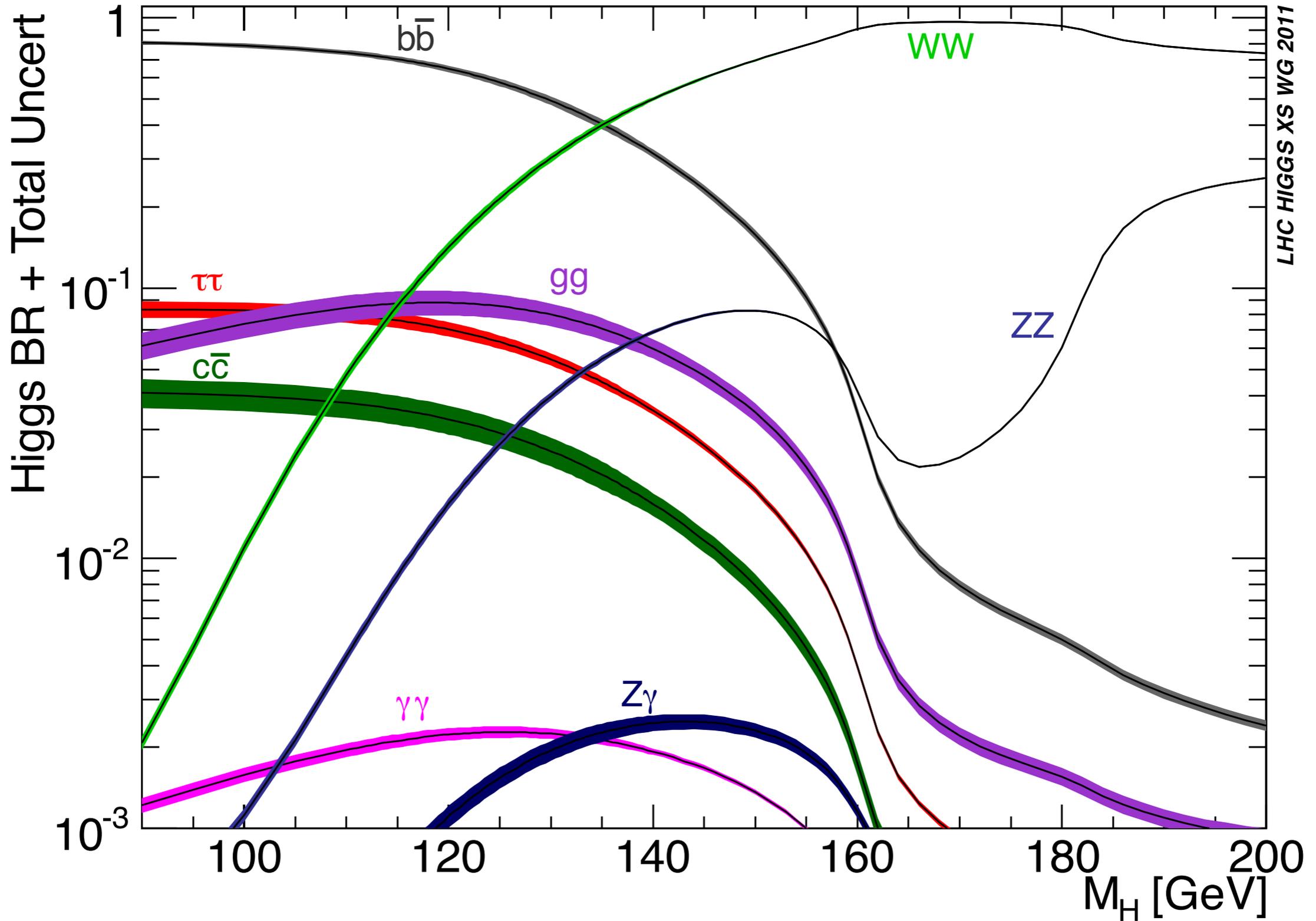
● Limits 1-1.5 σ under-fluctuated

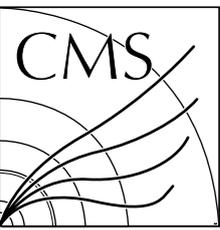
- Driven by under-fluctuations in ee and $\nu\nu$ channels





Z γ and Higgs Production





Datasets Used in the $V\gamma$ Analyses



Data:

CMS Run Range	Dataset Name	Used by
160404 - 163869	/SingleElectron/Run2011A-May10ReReco-v1/AOD	$W\gamma \rightarrow e\nu + \gamma$
165071 - 167913	/SingleElectron/Run2011A-PromptReco-v4/AOD	$W\gamma \rightarrow e\nu + \gamma$
170249 - 172619	/SingleElectron/Run2011A-05Aug2011-v1/AOD	$W\gamma \rightarrow e\nu + \gamma$
172620 - 173692	/SingleElectron/Run2011A-03Oct2011-v1/AOD	$W\gamma \rightarrow e\nu + \gamma$
175832 - 180252	/SingleElectron/Run2011B-PromptReco-v1/AOD	$W\gamma \rightarrow e\nu + \gamma$
160404 - 163869	/SingleMuon/Run2011A-May10ReReco-v1/AOD	$W\gamma \rightarrow \mu\nu + \gamma$
165071 - 167913	/SingleMuon/Run2011A-PromptReco-v4/AOD	$W\gamma \rightarrow \mu\nu + \gamma$
170249 - 172619	/SingleMuon/Run2011A-05Aug2011-v1/AOD	$W\gamma \rightarrow \mu\nu + \gamma$
172620 - 173692	/SingleMuon/Run2011A-03Oct2011-v1/AOD	$W\gamma \rightarrow \mu\nu + \gamma$
175832 - 180252	/SingleMuon/Run2011B-PromptReco-v1/AOD	$W\gamma \rightarrow \mu\nu + \gamma$
160404 - 163869	/DoubleElectron/Run2011A-May10ReReco-v1/AOD	$Z\gamma \rightarrow ee + \gamma$
165071 - 167913	/DoubleElectron/Run2011A-PromptReco-v4/AOD	$Z\gamma \rightarrow ee + \gamma$
170249 - 172619	/DoubleElectron/Run2011A-05Aug2011-v1/AOD	$Z\gamma \rightarrow ee + \gamma$
172620 - 173692	/DoubleElectron/Run2011A-03Oct2011-v1/AOD	$Z\gamma \rightarrow ee + \gamma$
175832 - 180252	/DoubleElectron/Run2011B-PromptReco-v1/AOD	$Z\gamma \rightarrow ee + \gamma$
160404 - 163869	/DoubleMuon/Run2011A-May10ReReco-v1/AOD	$Z\gamma \rightarrow \mu\mu + \gamma$
165088 - 167913	/DoubleMuon/Run2011A-PromptReco-v4/AOD	$Z\gamma \rightarrow \mu\mu + \gamma$
170249 - 172619	/DoubleMuon/Run2011A-05Aug2011-v1/AOD	$Z\gamma \rightarrow \mu\mu + \gamma$
172620 - 173692	/DoubleMuon/Run2011A-03Oct2011-v1/AOD	$Z\gamma \rightarrow \mu\mu + \gamma$
175832 - 180252	/DoubleMuon/Run2011B-PromptReco-v1/AOD	$Z\gamma \rightarrow \mu\mu + \gamma$
160404 - 163869	/Jet/Run2011A-May10ReReco-v1/AOD	Background estimation
165071 - 167913	/Jet/Run2011A-PromptReco-v4/AOD	Background estimation
170249 - 172619	/Jet/Run2011A-05Aug2011-v1/AOD	Background estimation
172620 - 173692	/Jet/Run2011A-03Oct2011-v1/AOD	Background estimation
175832 - 180252	/Jet/Run2011B-PromptReco-v1/AOD	Background estimation

MC Signal:

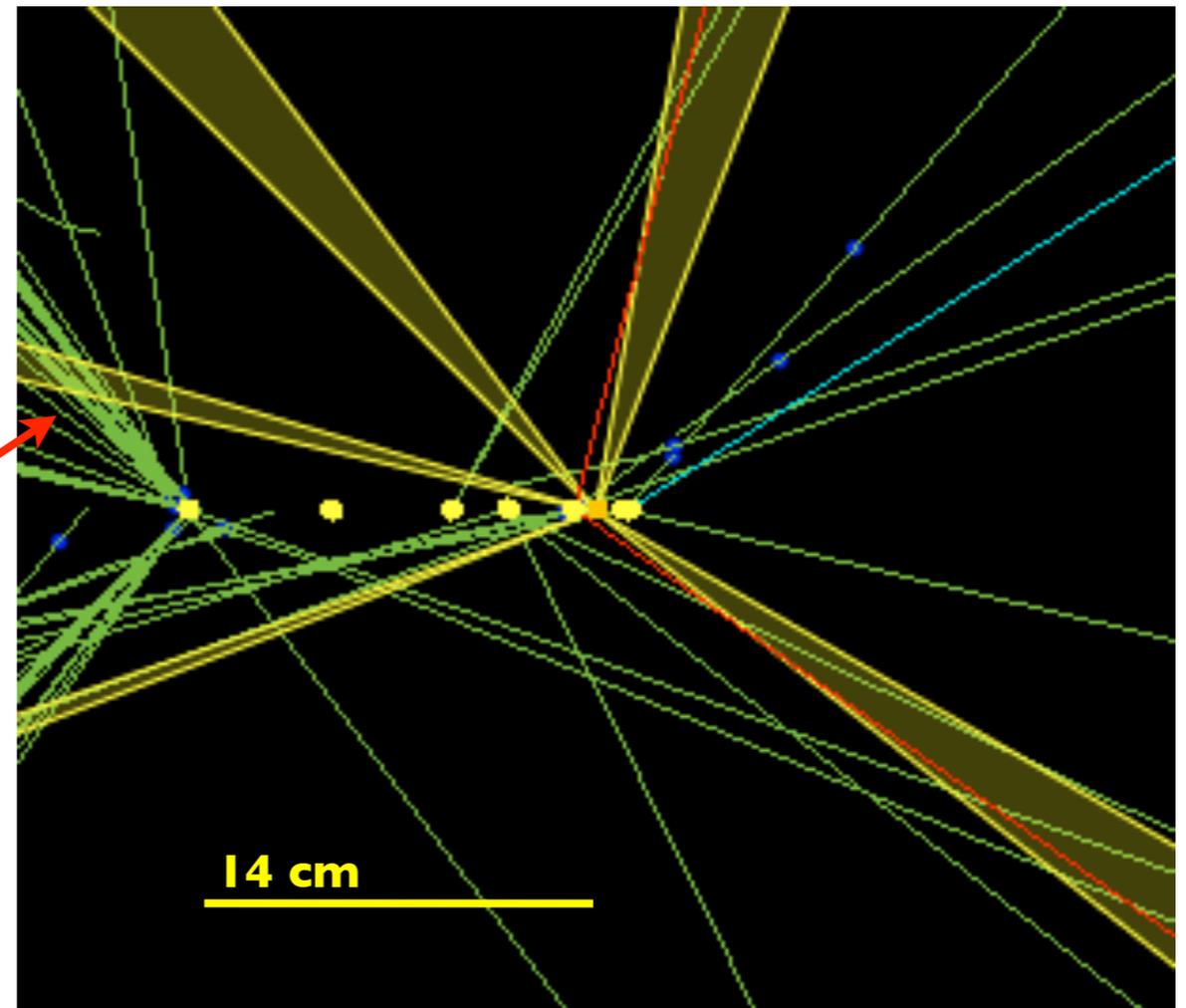
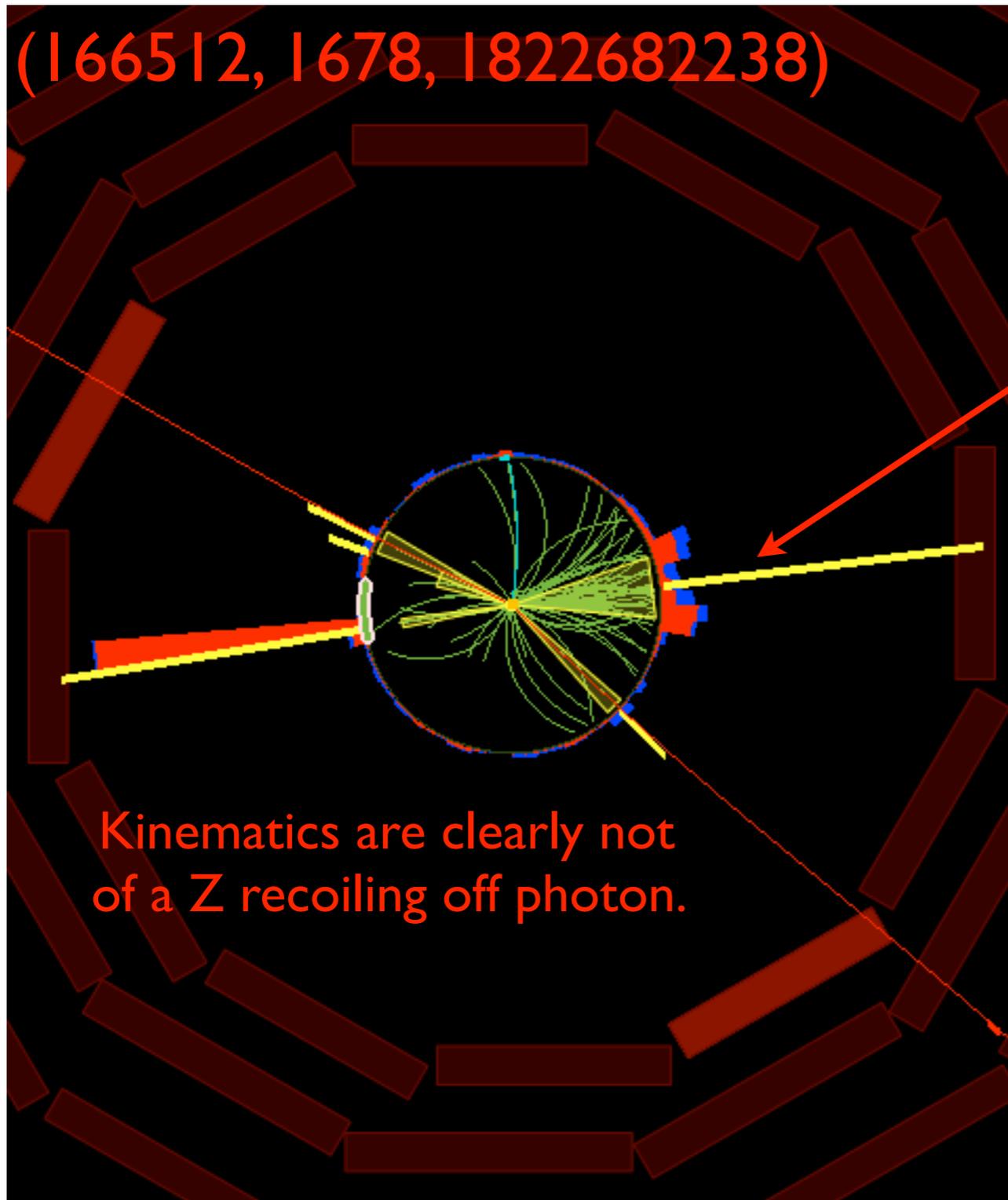
Process (private MG5)	$\sigma_{MadGraph}, \text{pb}$	σ_{NLO}, pb
$W \rightarrow e\nu + \gamma$	50.7	56.3
$W \rightarrow \mu\nu + \gamma$	50.7	56.3
$Z \rightarrow ee + \gamma$	10.6	12.3
$Z \rightarrow \mu\mu + \gamma$	10.6	12.3

*aTGC samples produced with SHERPA

MC Background:

Process (Fall11)	σ, pb	Dataset Name (AODSIM data tier)
$W\gamma \rightarrow e\nu\gamma$	137.3 (NLO)	/WGToENUG_TuneZ2_7TeV-madgraph-tauola
$W\gamma \rightarrow \mu\nu\gamma$	137.3 (NLO)	/WGTOMUNUG_TuneZ2_7TeV-madgraph-tauola
$W\gamma \rightarrow \tau\nu\gamma$	137.3 (NLO)	/WGTOAUNUG_TuneZ2_7TeV-madgraph-tauola
$Z\gamma \rightarrow ee\gamma$	45.2 (NLO)	/ZGTOEEG_TuneZ2_7TeV-madgraph-tauola
$Z\gamma \rightarrow \mu\mu\gamma$	45.2 (NLO)	/ZGTOUMUG_TuneZ2_7TeV-madgraph-tauola
$Z\gamma \rightarrow \tau\tau\gamma$	45.2 (NLO)	/ZGTOAUMUG_TuneZ2_7TeV-madgraph-tauola
$W \rightarrow l\nu + jets$	31314 (NNLO)	/WJETSLOLNU_TuneZ2_7TeV-madgraph-tauola
$Z \rightarrow ll + jets$	3048 (NNLO)	/DYJETSTOLL_TuneZ2_M-50_7TeV-madgraph-tauola
$t\bar{t} + jets$	165 (NNLO)	/TTJETSTuneZ2_7TeV-madgraph-tauola
$t\bar{t} + \gamma$	0.444 (LO)	privately produced
WW	5.7 (NLO)	/WWJETSTO2L2NU_TuneZ2_7TeV-madgraph-tauola
WZ	18.2 (NLO)	/WZ_TuneZ2_7TeV_pythia6_tauola
ZZ	5.9 (NLO)	/ZZ_TuneZ2_7TeV_pythia6_tauola
DiPhoton + jets	190.56 (NLO)	/DiPhotonJets_7TeV-madgraph
$\gamma + jets(p_T - 20)DoubleEMEnriched$	651.5 (NLO)	/GJetPt-20_doubleEMEnriched_TuneZ2_7TeV-pythia6
$QCD(p_T - 30to40)DoubleEMEnriched$	9614 (LO)	/QCDPt-30to40_doubleEMEnriched_TuneZ2_7TeV-pythia6
$QCD(p_T - 40)DoubleEMEnriched$	40392 (LO)	/QCDPt-40_doubleEMEnriched_TuneZ2_7TeV-pythia6
Process (Summer11)	σ, pb	Dataset Name (AODSIM data tier)
$\gamma + jets(p_T : 0 - 15)$	8.420×10^7	/G_Pt_0to15_TuneZ2_7TeV_pythia6
$\gamma + jets(p_T : 15 - 30)$	1.717×10^5	/G_Pt_15to30_TuneZ2_7TeV_pythia6
$\gamma + jets(p_T : 30 - 50)$	1.669×10^4	/G_Pt_30to50_TuneZ2_7TeV_pythia6
$\gamma + jets(p_T : 50 - 80)$	2.722×10^3	/G_Pt_50to80_TuneZ2_7TeV_pythia6
$\gamma + jets(p_T : 80 - 120)$	4.472×10^2	/G_Pt_80to120_TuneZ2_7TeV_pythia6
$\gamma + jets(p_T : 120 - 170)$	8.417×10^1	/G_Pt_120to170_TuneZ2_7TeV_pythia6
$\gamma + jets(p_T : 170 - 300)$	2.264×10^1	/G_Pt_170to300_TuneZ2_7TeV_pythia6
$\gamma + jets(p_T : 300 - 470)$	1.493	/G_Pt_300to470_TuneZ2_7TeV_pythia6
$QCD(p_T : 5 - 15)$	3.675×10^{10}	/QCDPt_5to15_TuneZ2_7TeV_pythia6
$QCD(p_T : 15 - 30)$	8.159×10^8	/QCDPt_15to30_TuneZ2_7TeV_pythia6
$QCD(p_T : 30 - 50)$	5.312×10^7	/QCDPt_30to50_TuneZ2_7TeV_pythia6
$QCD(p_T : 50 - 80)$	6.359×10^6	/QCDPt_50to80_TuneZ2_7TeV_pythia6
$QCD(p_T : 80 - 120)$	7.843×10^5	/QCDPt_80to120_TuneZ2_7TeV_pythia6
$QCD(p_T : 120 - 170)$	1.151×10^5	/QCDPt_120to170_TuneZ2_7TeV_pythia6
$QCD(p_T : 170 - 300)$	2.426×10^4	/QCDPt_170to300_TuneZ2_7TeV_pythia6
$QCD(p_T : 300 - 470)$	1.168×10^3	/QCDPt_300to470_TuneZ2_7TeV_pythia6
$QCD(p_T : 470 - 600)$	7.022×10^1	/QCDPt_470to600_TuneZ2_7TeV_pythia6
$QCD(p_T > 20)$	84679.3	/QCDPt-20_MuEnrichedPt-15_TuneZ2_7TeV_pythia

'Z γ ' Pileup Combinatorial Event



This event removed from final selection.