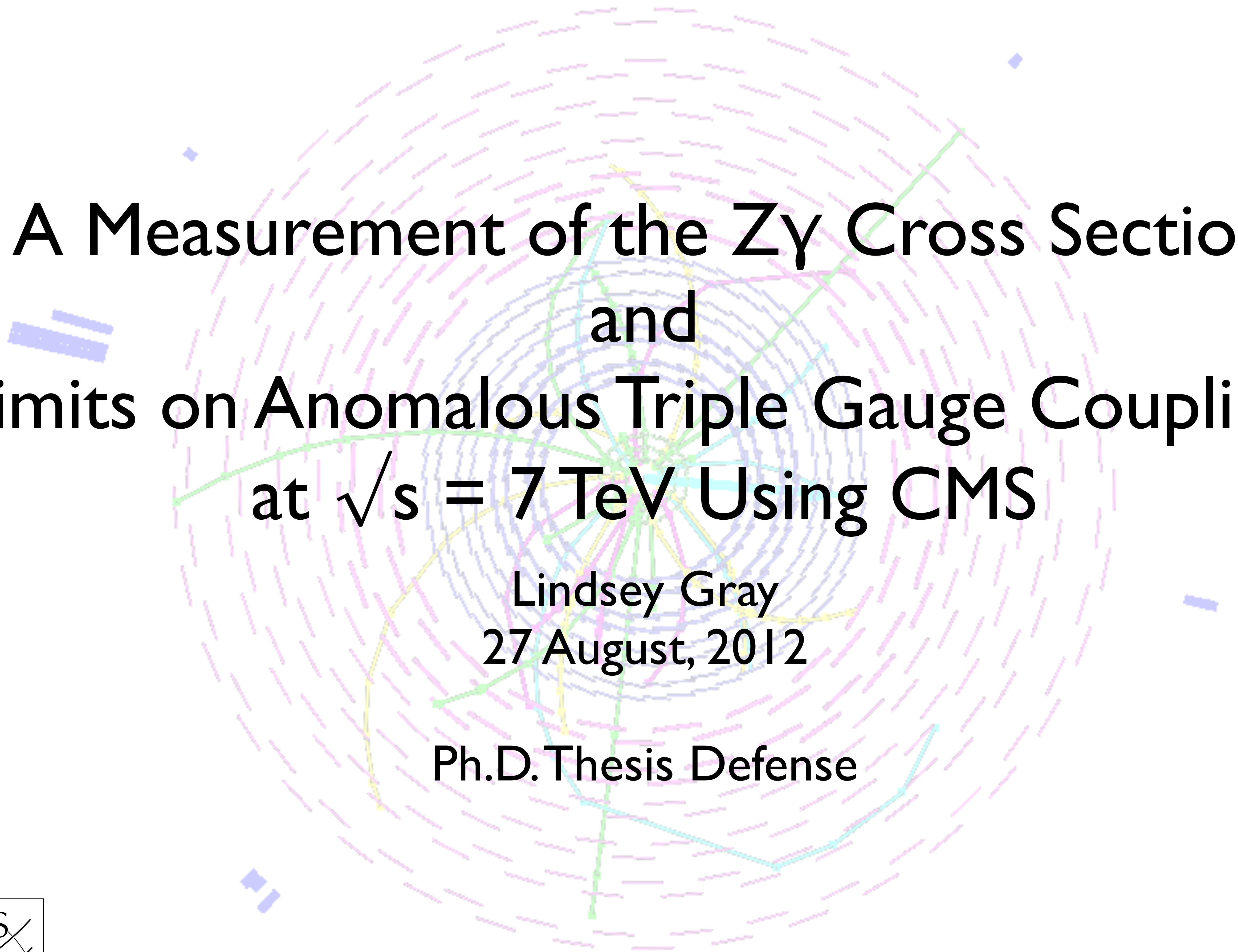
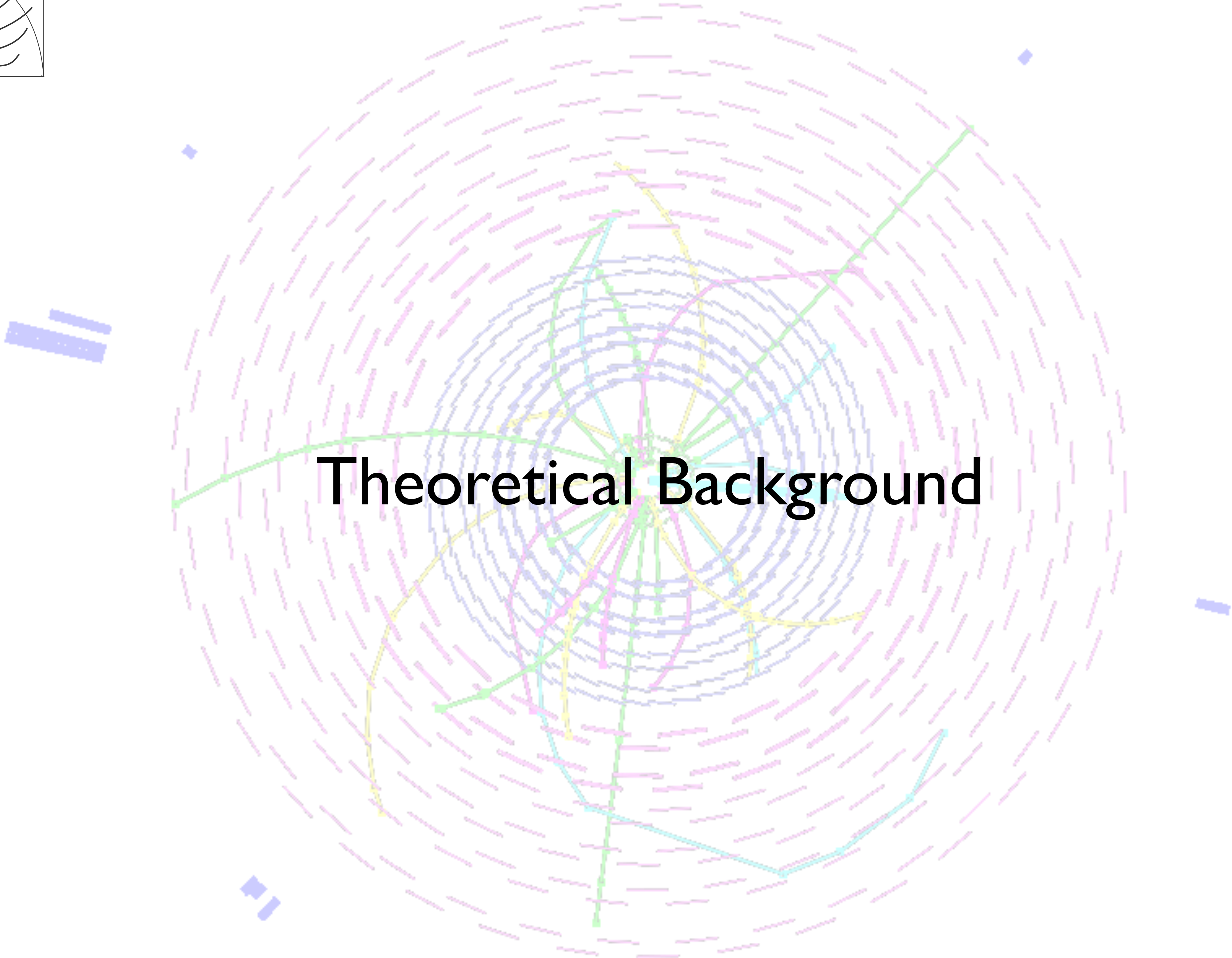


A Measurement of the Zγ Cross Section
and
Limits on Anomalous Triple Gauge Couplings at $\sqrt{s}$ = 7 TeV Using CMS

Lindsey Gray
27 August, 2012

Ph.D. Thesis Defense



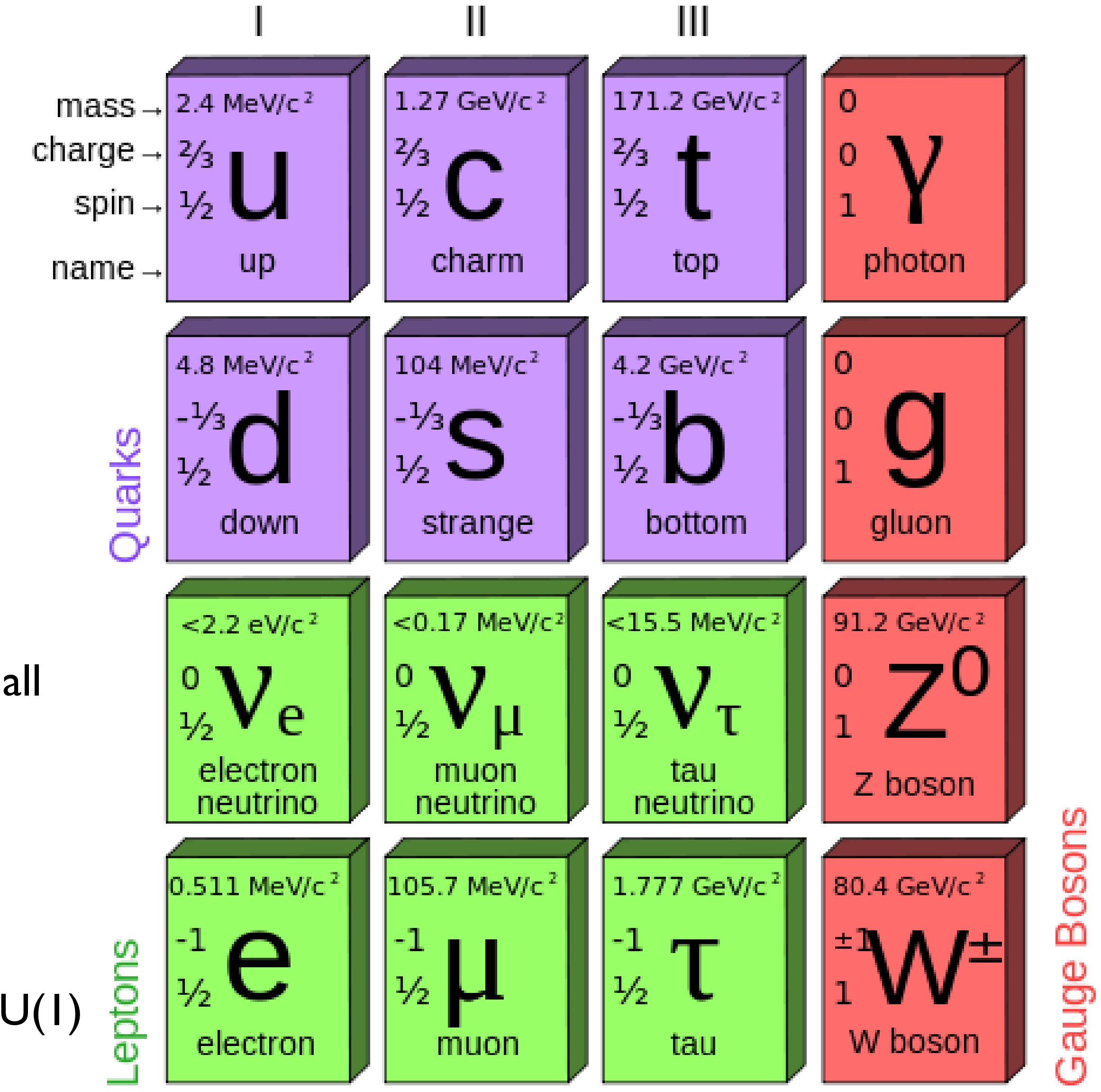
Theoretical Background

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 Δm^2 between generations!
- Force Carriers
  - Massless Photon (γ): EM Force
  - Massive $W^\pm$, Z: Weak Force
  - 8 massless gluons: Strong Force

} unified under SU(2)$_L$xU(1)

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



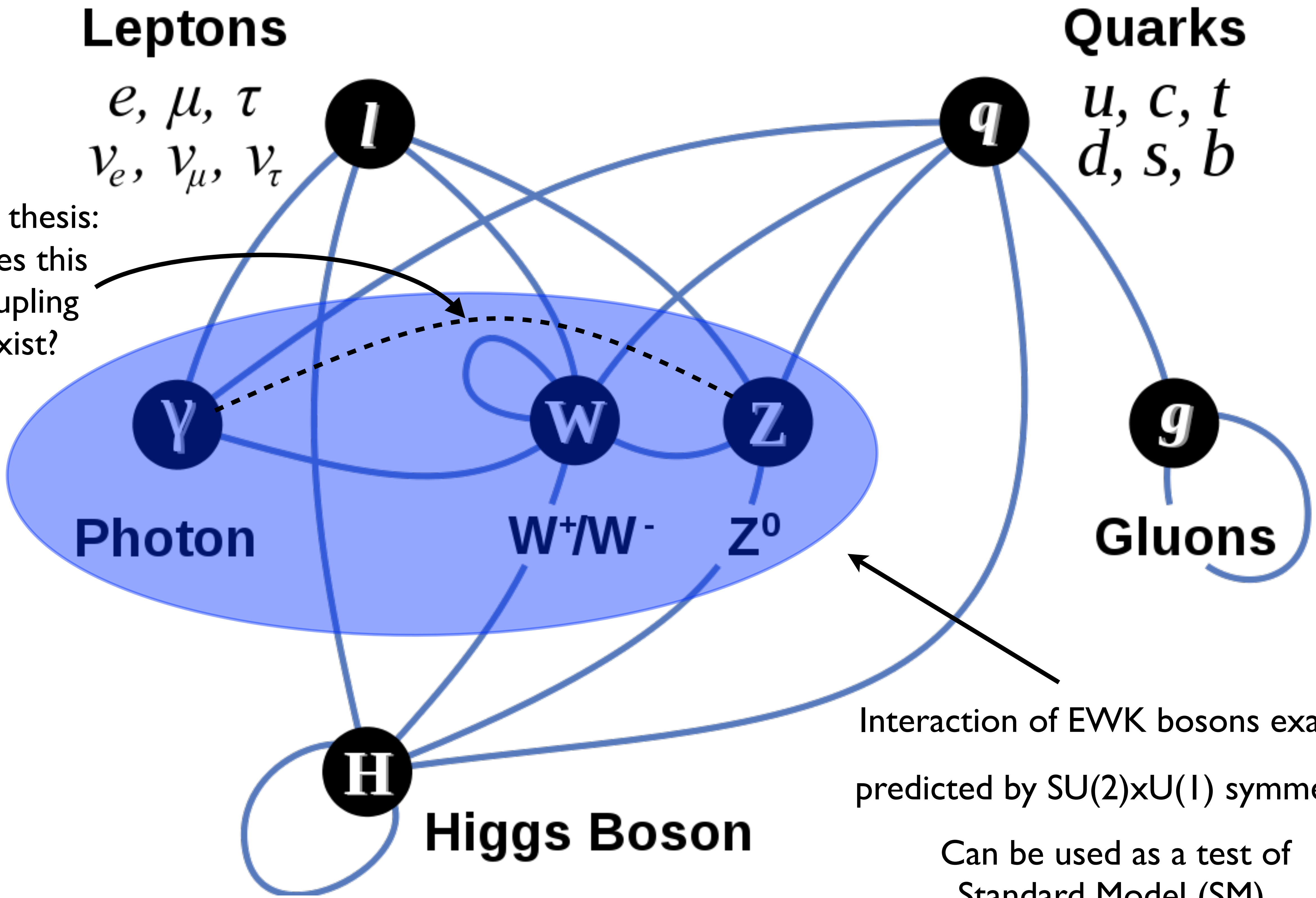
	I	II	III	
mass → charge → spin → name →	2.4 MeV/c^2 ⅔ ½ u up	1.27 GeV/c^2 ⅔ ½ c charm	171.2 GeV/c^2 ⅔ ½ t top	0 0 1 γ photon
Quarks	4.8 MeV/c^2 -⅓ ½ d down	104 MeV/c^2 -⅓ ½ s strange	4.2 GeV/c^2 -⅓ ½ b bottom	0 0 1 g gluon
	<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<15.5 MeV/c^2 0 ½ ν_τ tau neutrino	91.2 GeV/c^2 0 1 Z^0 Z boson
Leptons	0.511 MeV/c^2 -1 ½ e electron	105.7 MeV/c^2 -1 ½ μ muon	1.777 GeV/c^2 -1 ½ τ tau	80.4 GeV/c^2 ±1 1 $W^\pm$ W boson

Higgs Boson

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

Uses SU(3)xSU(2)$_L$xU(1) symmetry to describe forces

Interactions in the Standard Model

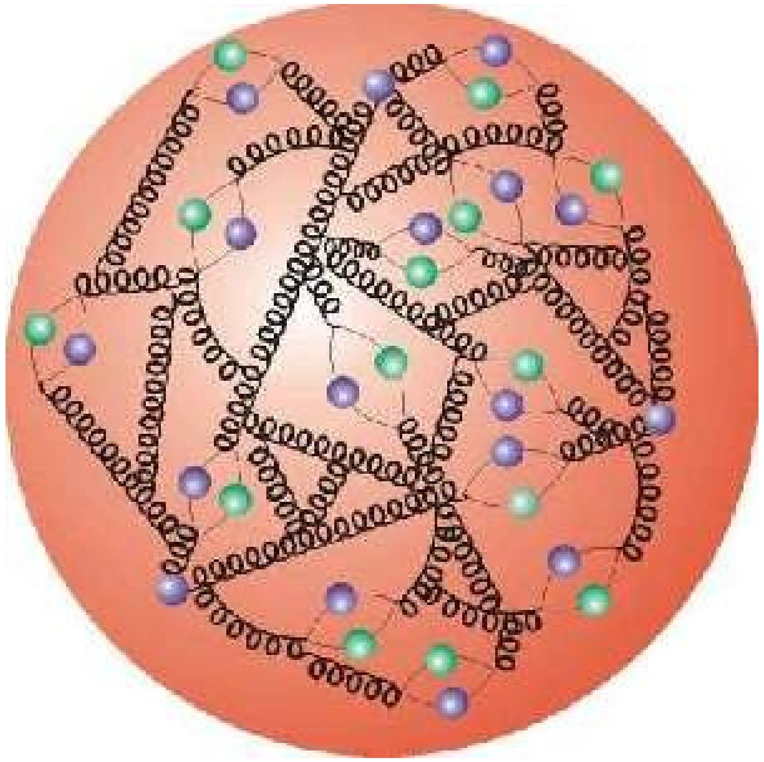


This thesis:
Does this
coupling
exist?

Interaction of EWK bosons exactly predicted by SU(2)xU(1) symmetry.

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

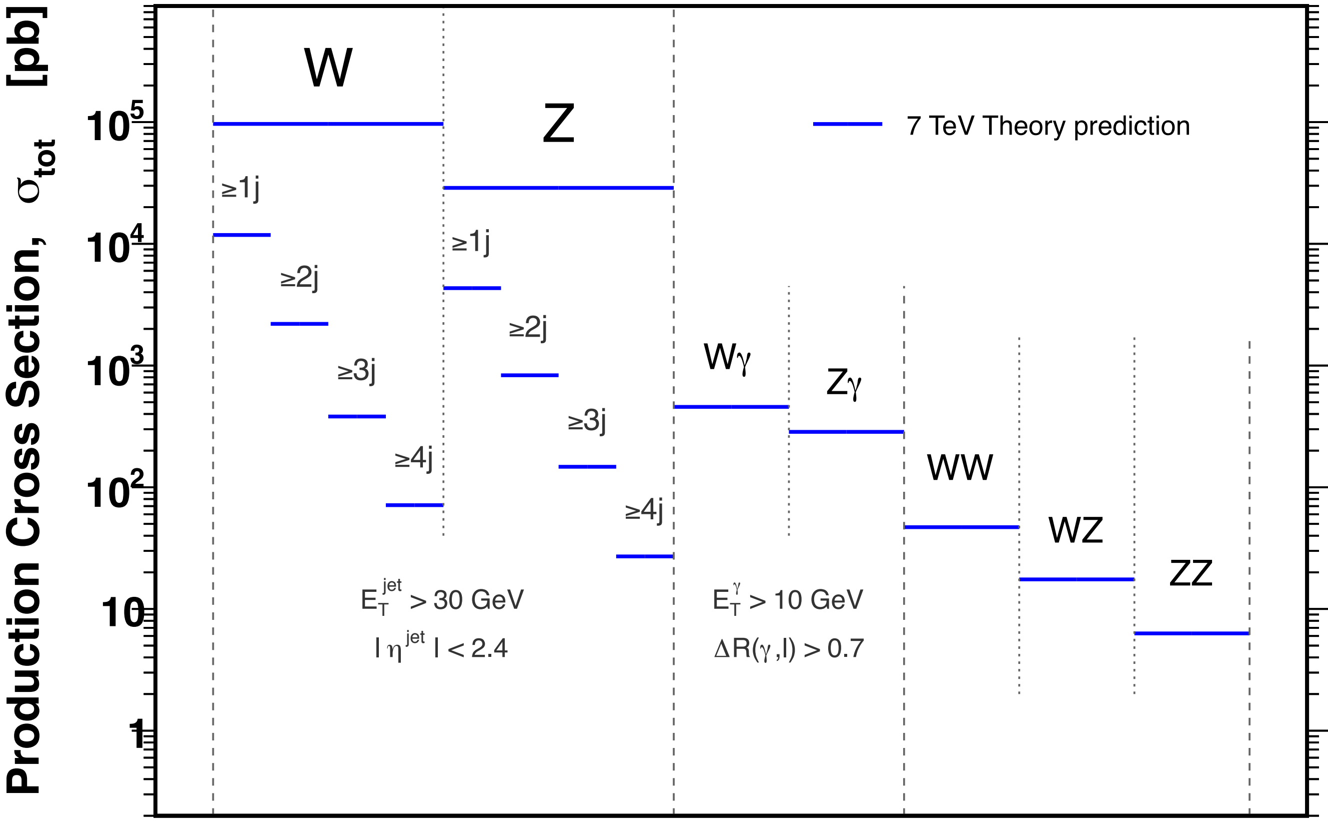
The Structure of the Proton



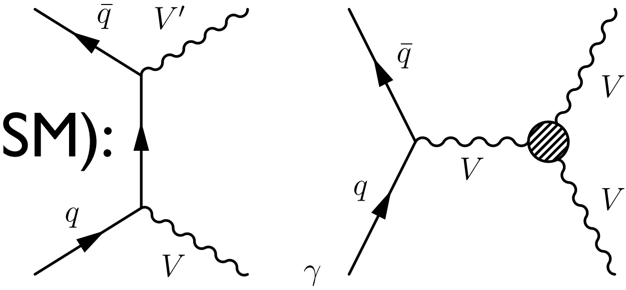
- The proton has substructure
  - In collisions this substructure is probed
  - One 'parton' from each colliding proton
- Proton is a bound state of quarks
  - Valence quarks (uud) are exchanging virtual gluons
    - may split into u,d,s,c,b quarks creating 'sea' of partons
      - ➡ Effect present at 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

Production of Dibosons

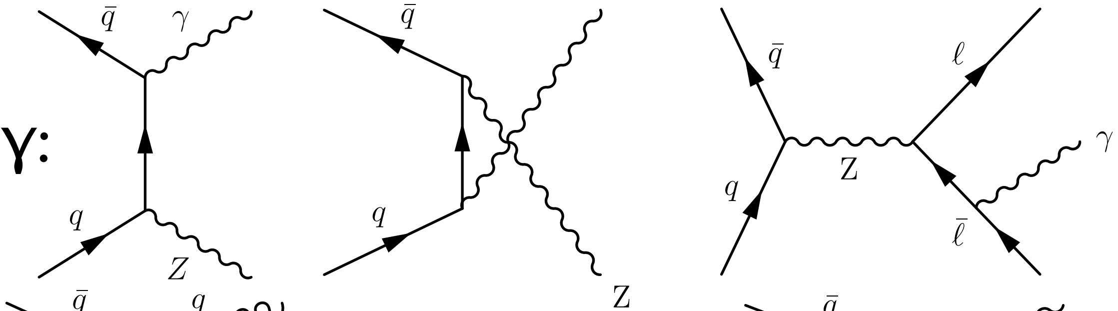
- Produced by boson radiation or annihilation off quarks, triple gauge couplings where allowed
  - Triple gauge couplings (TGC) are between three vector bosons
  - Wγ, WZ, and WW final states have Triple Gauge Couplings
  - Zγ and ZZ TGCs forbidden in SM
- This thesis aims to study the Zγ final state
  - Measure cross section and test for anomalous gauge couplings (aTGC)
  - Energetic QCD ever present at LHC
    - NLO calculations necessary to model data



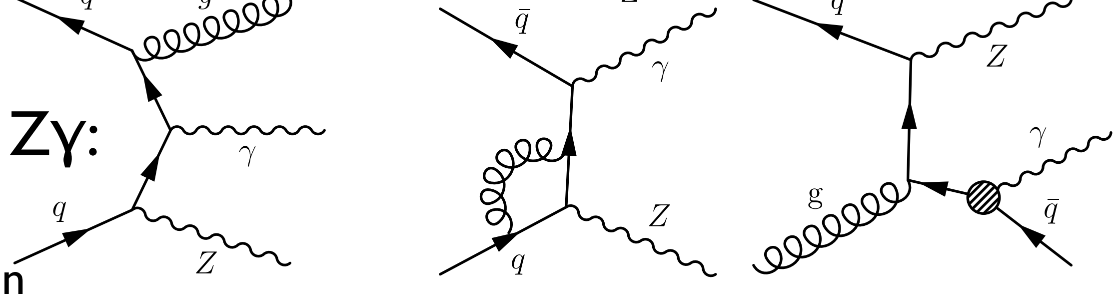
General Dibosons (SM):



LO Zγ:

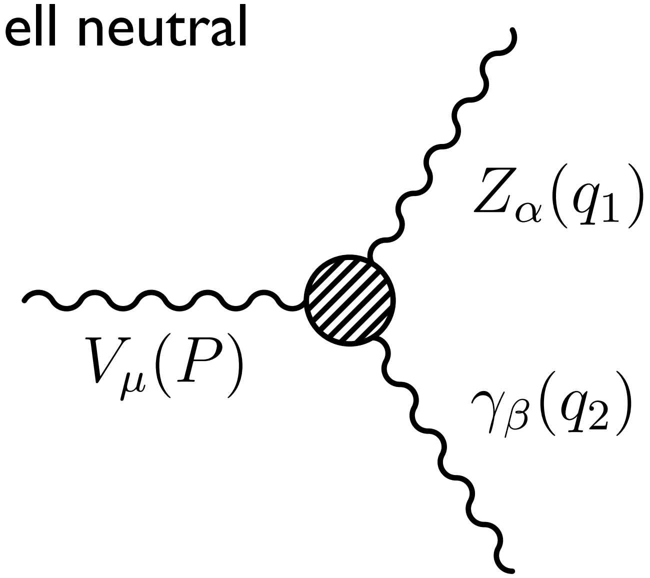


NLO Zγ:



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
    - Produce different final state boson transverse moment (p_T) distributions
    - Search for deviation from SM distributions to test for aTGC
    - Zγ advantage: direct access to boson (γ)
  - Form factor sometimes used to enforce unitarity
    - Unitarity only need be enforced where there are data
    - No form factor used in this thesis



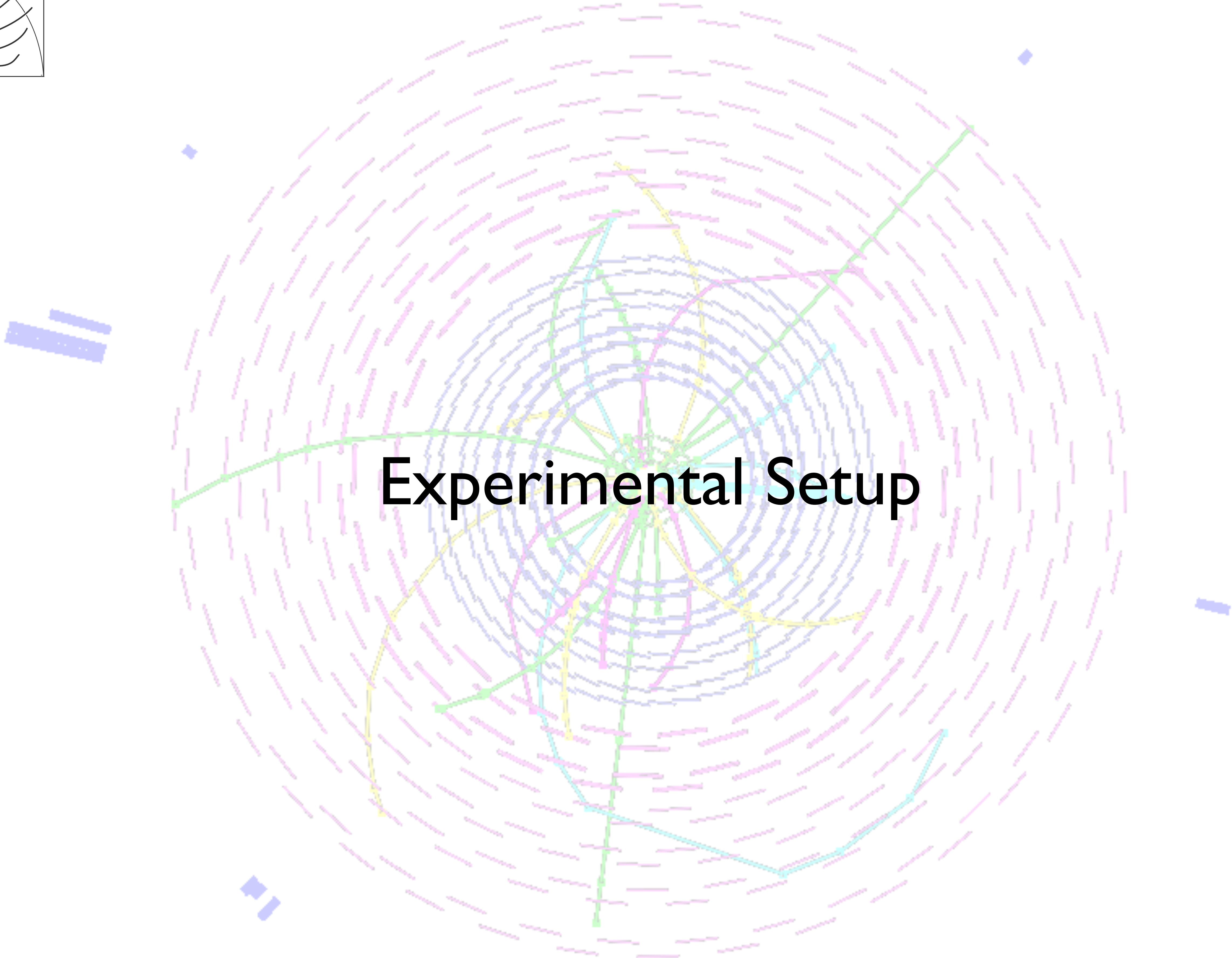
$$= ie\Gamma^{\alpha\beta\mu}(P,q_1,q_2)$$

$$\Gamma^{\alpha\beta\mu}_{Z\gamma Z}(q_1,q_2,P) = \frac{P^2-q_1^2}{m_Z^2}\left[h_1^Z(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}) + \frac{h_2^Z}{m_Z^2}P^\alpha\left[(P\cdot q_2)g^{\mu\beta} - q_2^\mu P^\beta\right] + h_3^Z\epsilon^{\mu\alpha\beta\rho}q_{2\rho} + \frac{h_4^Z}{m_Z^2}P^\alpha\epsilon^{\mu\beta\rho\sigma}P_\rho q_{2\sigma}\right]$$

8 couplings allowed at tree level in Lorentz structure

$$\frac{P^2-q_1^2}{m_Z^2} \rightarrow \frac{P^2}{m_Z^2} \quad \text{and} \quad h^Z_{1-4} \rightarrow h^\gamma_{1-4}$$

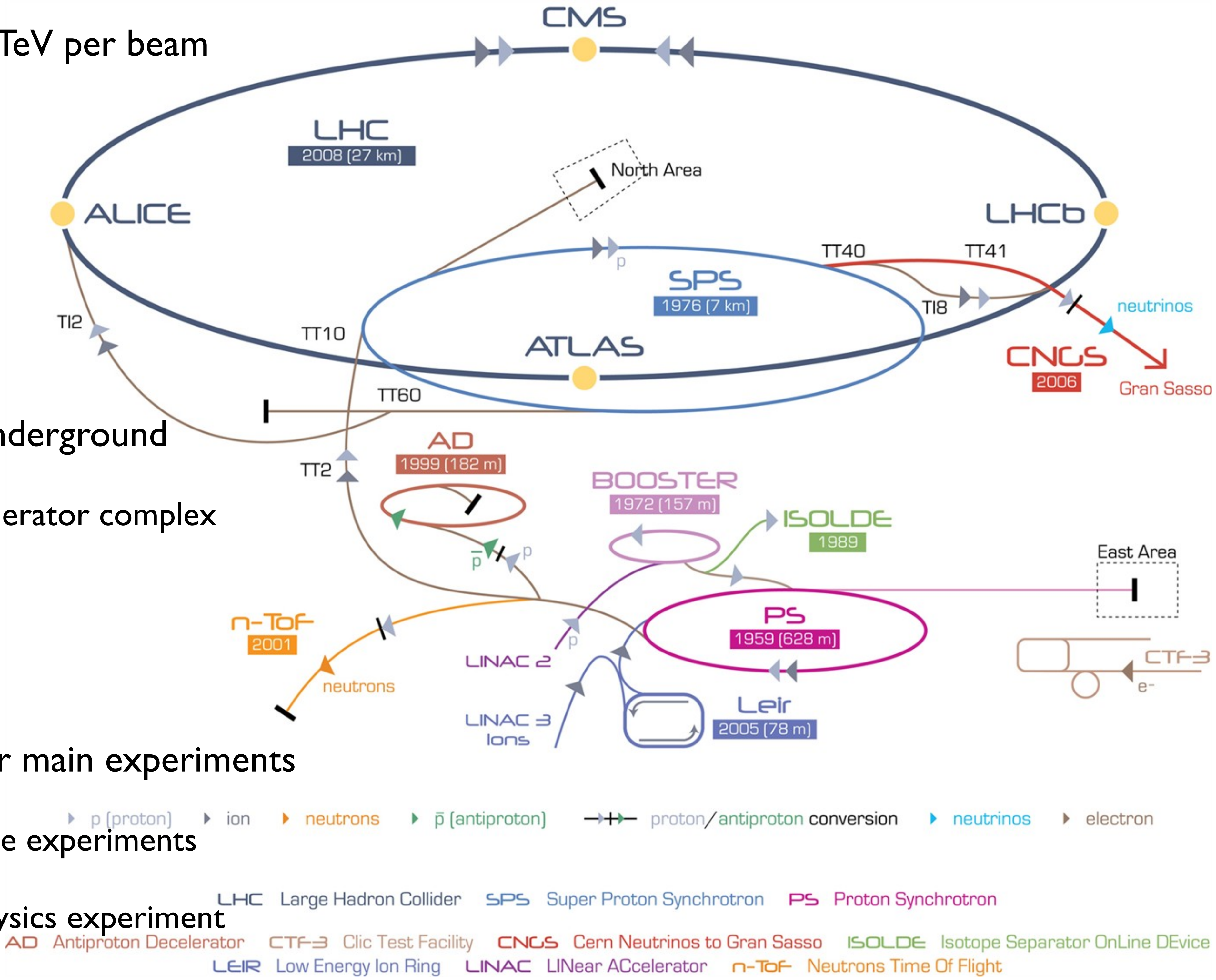
Form Factor = $f(\hat{s}) = \dfrac{1}{(1+\hat{s}/\Lambda^2)^n}$



Experimental Setup

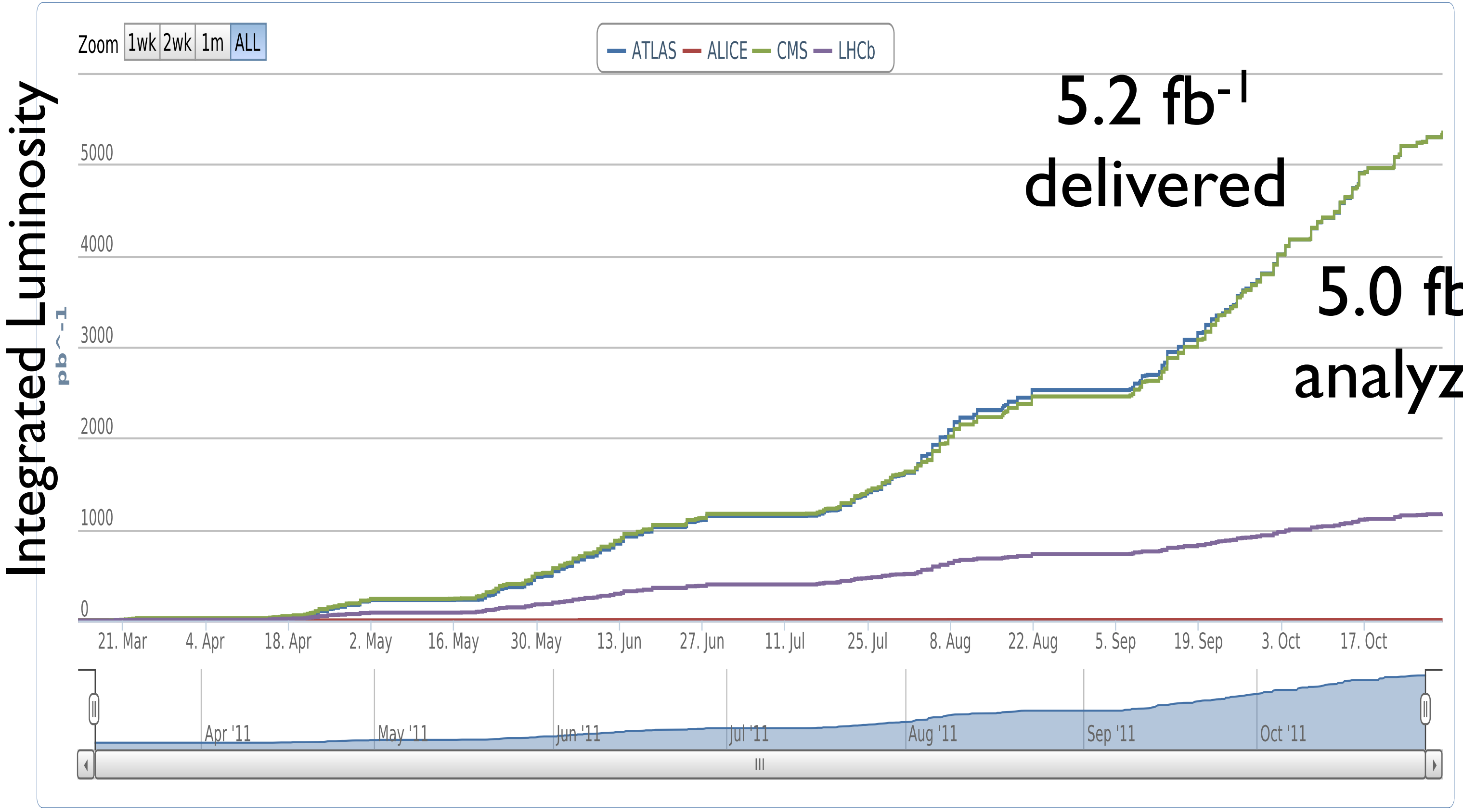
The Large Hadron Collider

- 3.5 (2011), 4 (2012), 7(design) TeV per beam
  - 7, 8, 14 TeV center of mass
  - proton-proton or heavy ion
- 27 km circumference, 100m underground
  - Beams provided by cern accelerator complex
- LHC provides collisions to four main experiments
  - ATLAS & CMS: General purpose experiments
  - ALICE: Dedicated heavy ion physics experiment
  - LHCb: Dedicated b-physics experiment



LHC Operation in 2011

	Design	2011
Beam Energy	7 TeV	3.5 TeV
Bunches per Beam	2835	max of 1380
Bunch Spacing	25 ns	50 ns
Peak Luminosity	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	$3.6\text{x}10^{33}\text{cm}^{-2}\text{s}^{-1}$
Mean Interactions per Crossing	5	5.1-8.0



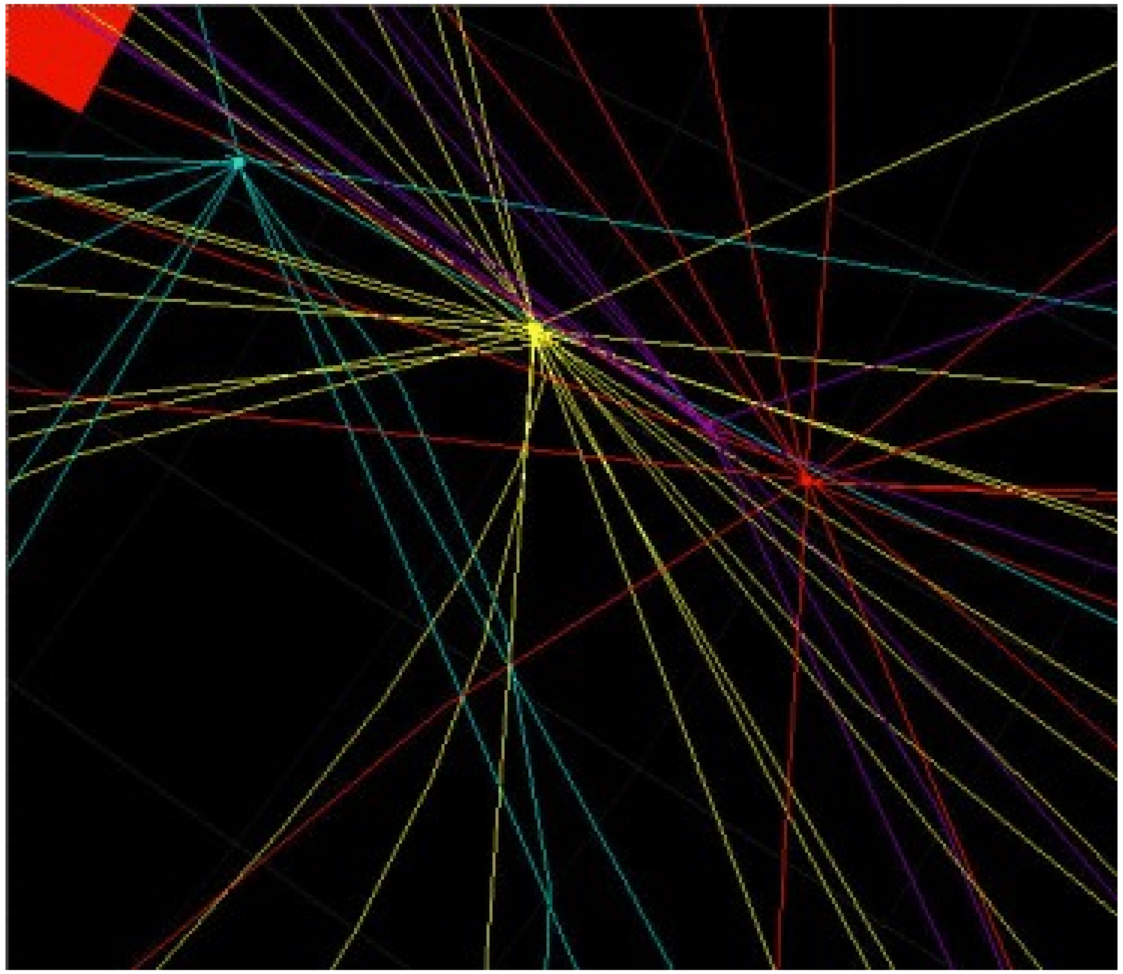
$5.2\ \text{fb}^{-1}$ delivered

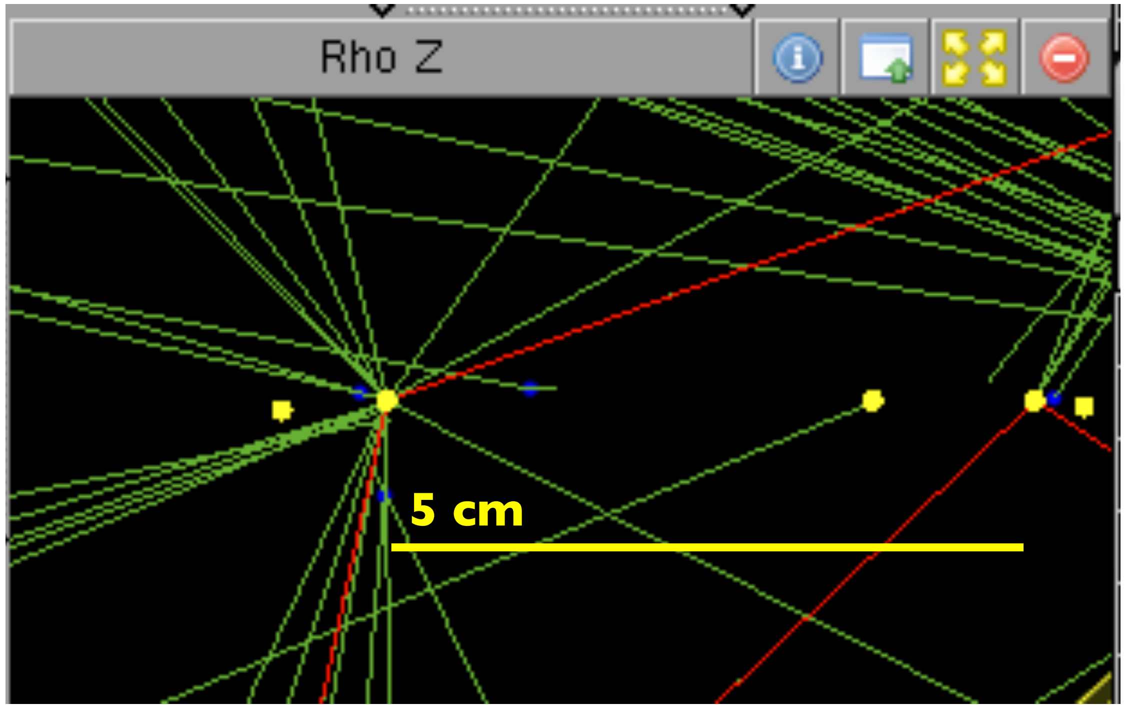
$5.0\ \text{fb}^{-1}$ analyzed

- Number of events for a given process is: $$N = \sigma \int \mathcal{L}_{inst} \mathrm{d}t$$
  - σ is the cross section of the process
  - L_{inst} is the instantaneous luminosity ('integrated luminosity' = amount of data taken)
    - Flux per unit time
- 2011 run aimed to maximize luminosity given 50ns bunch spacing
  - Improved beam sizes, higher bunch population

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

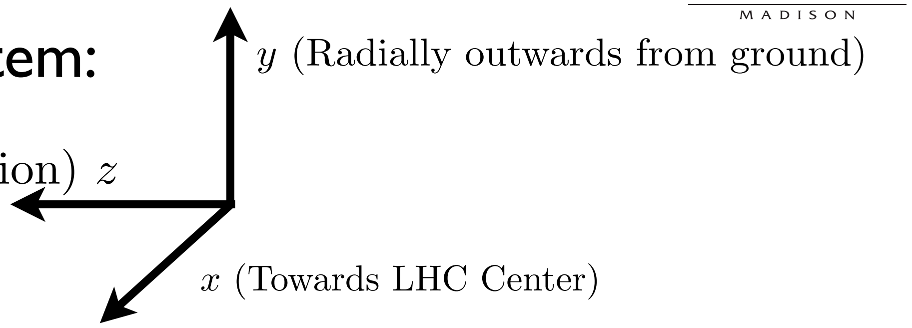




The Compact Muon Solenoid

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

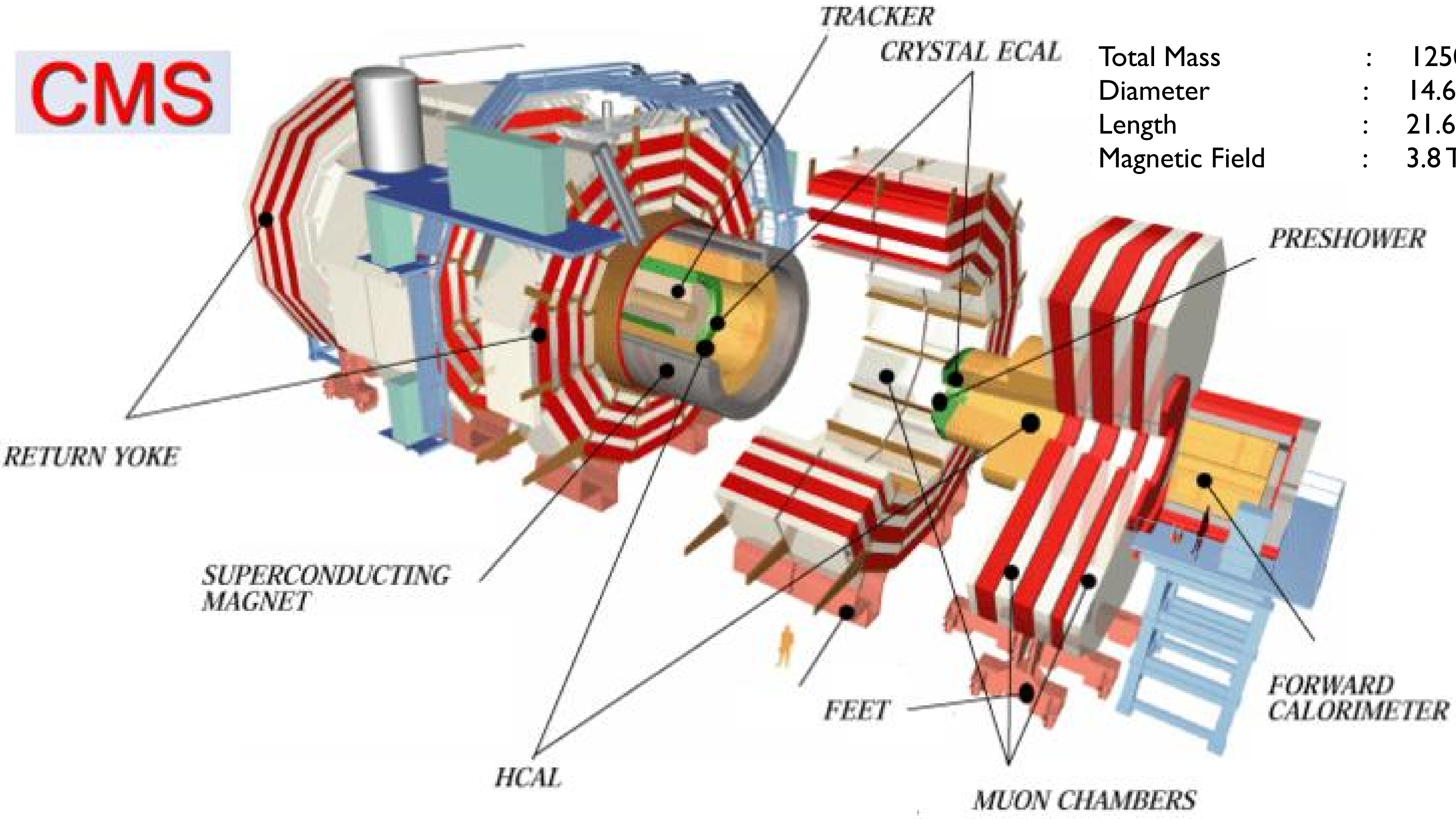
Right handed coordinate system:



y (Radially outwards from ground)

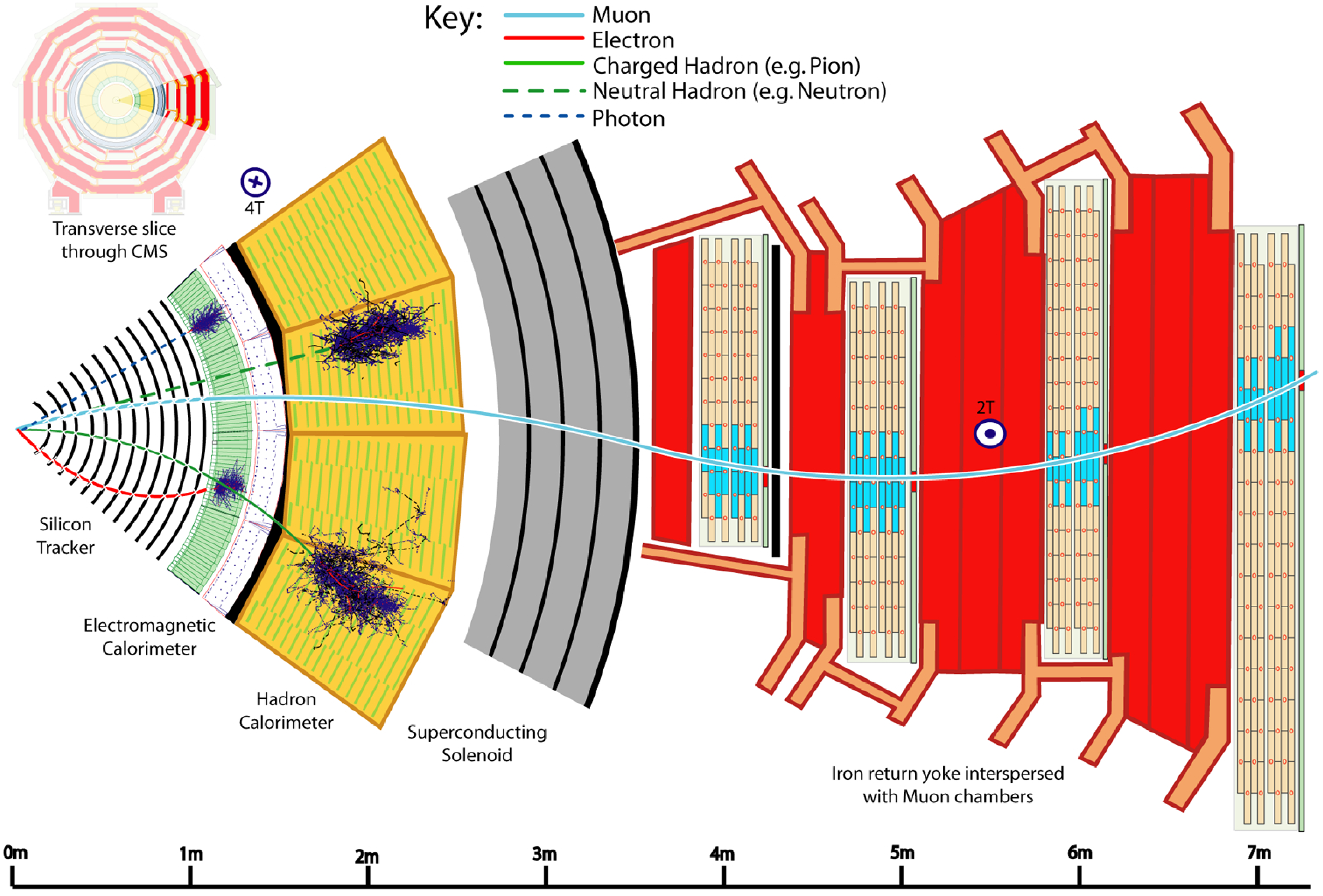
(Anti-Clockwise beam direction) z

x (Towards LHC Center)



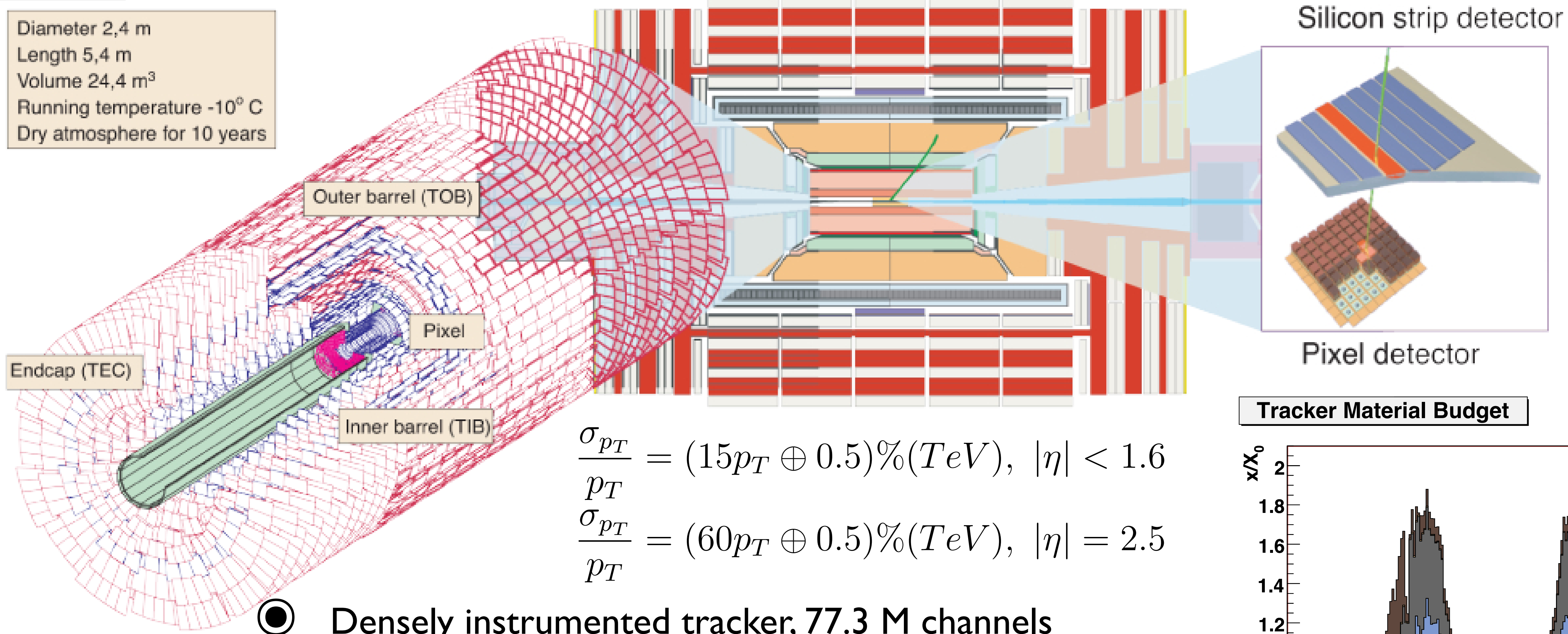
Total Mass	:	12500 T
Diameter	:	14.6 m
Length	:	21.6 m
Magnetic Field	:	3.8 Tesla

Particle Detection in CMS



CMS: Silicon Tracker

Diameter 2,4 m
Length 5,4 m
Volume 24,4 m^3
Running temperature -10° C
Dry atmosphere for 10 years

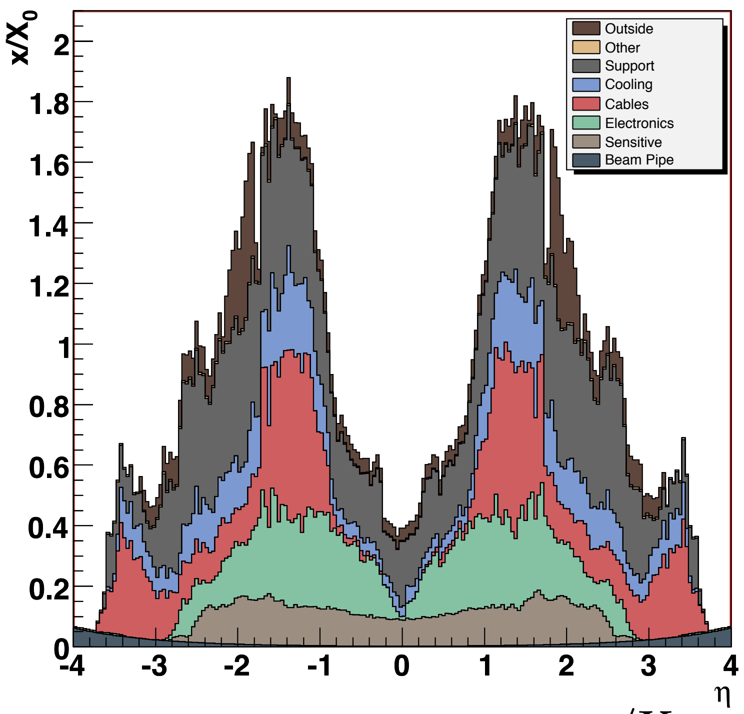


$$\frac{\sigma_{p_T}}{p_T} = (15p_T \oplus 0.5)\%(TeV), \ |\eta| < 1.6$$

$$\frac{\sigma_{p_T}}{p_T} = (60p_T \oplus 0.5)\%(TeV), \ |\eta| = 2.5$$

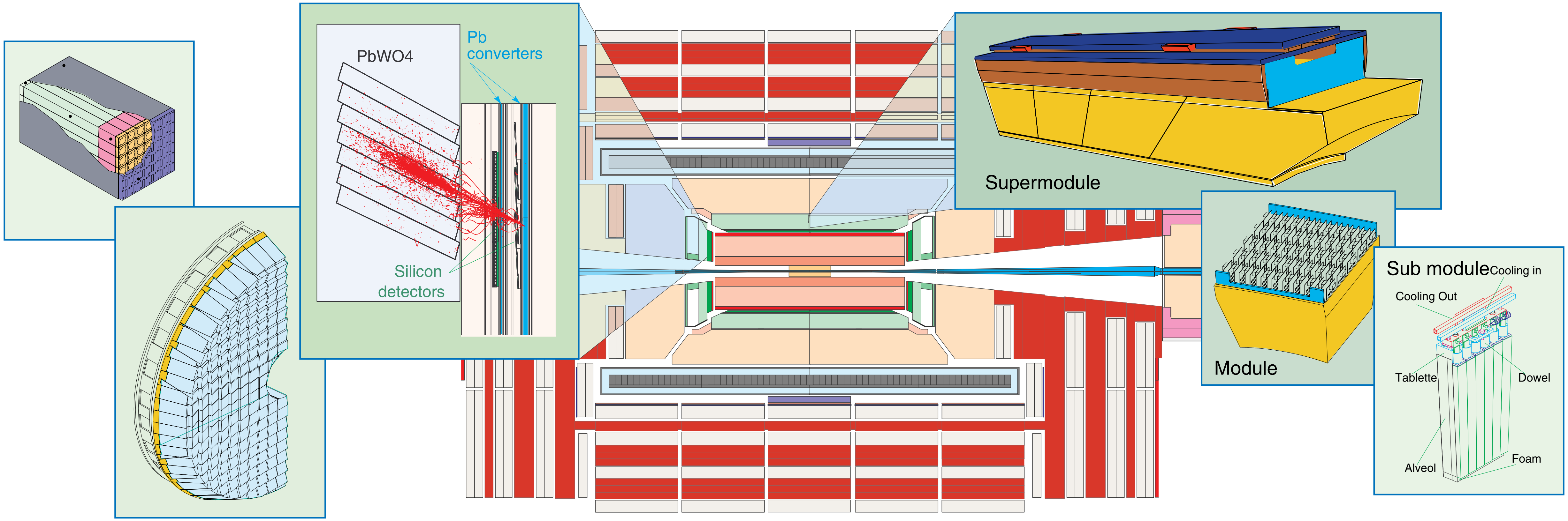
- Densely instrumented tracker, 77.3 M channels
- High granularity, aided by strong 3.8 T magnetic field
  - pile up not a problem
- High resolution
  - 0.6% for track with 40 GeV p_T in barrel
- Large number of channels creates high material budget
  - Services to tracker modules bulk of material
  - Converted photons, average of 55% of photons convert in tracker, depending on η

Tracker Material Budget

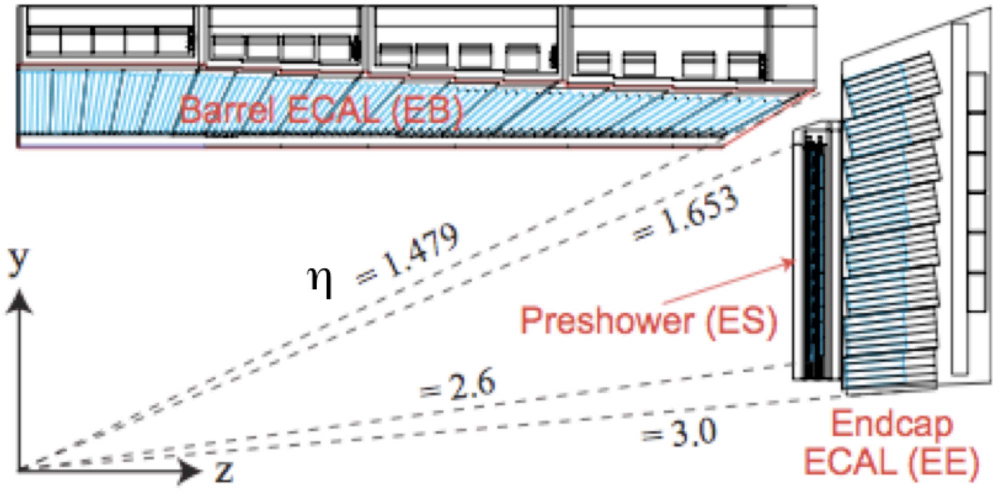


$$E(\mathrm{x})/E_0 = e^{-\mathrm{x}/\mathrm{X}_0}$$

CMS: Electromagnetic Calorimeter

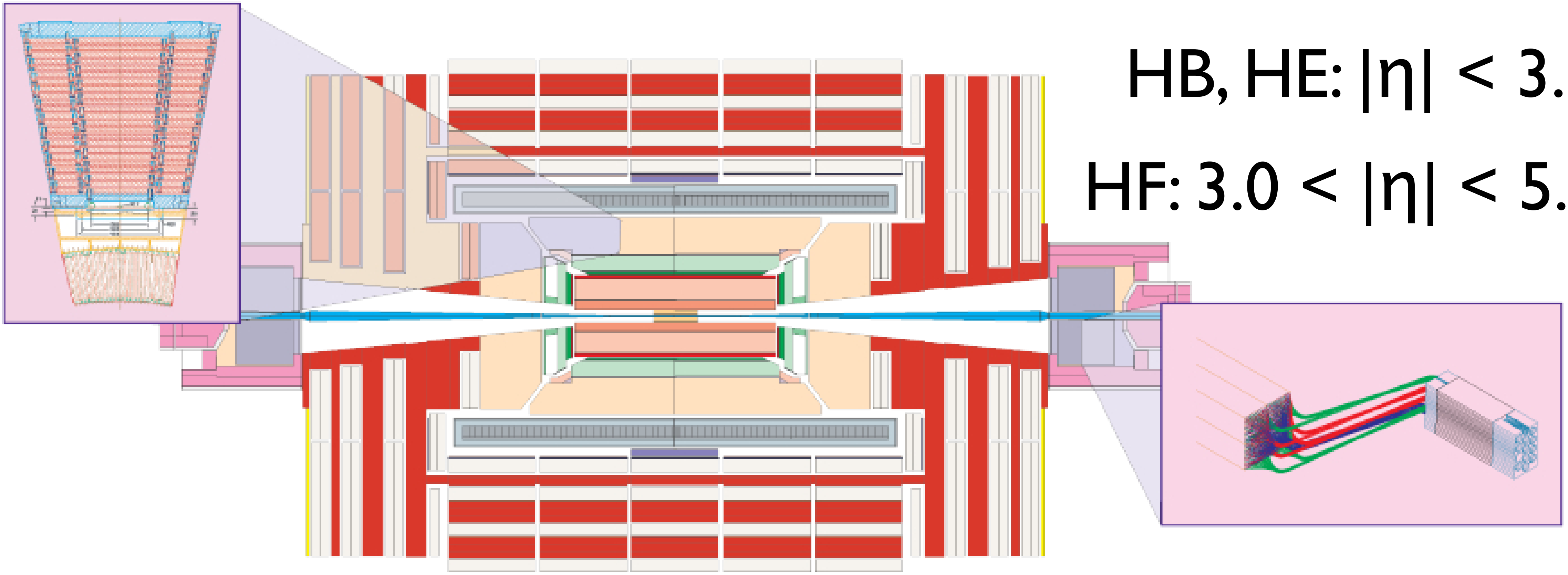


- 76832 lead tungstate crystals used as radiator and light collector
  - X_0 = 8.9mm, Moliere Radius (R_M) = 22 mm
- EB - projective crystals in ‘super modules’
  - 1 crystal = 22mm x 22mm x 230 mm
- EE - projective ‘super-crystals’
  - trapezoidal crystals, 30mmx30mm at rear
- ES - lead radiator with silicon strips used to identify π^0s
- Good energy resolution, 5% at 45 GeV



$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right) + (0.30\%)^2$$

CMS: Hadronic Calorimeter



HB, HE: $|\eta| < 3.0$

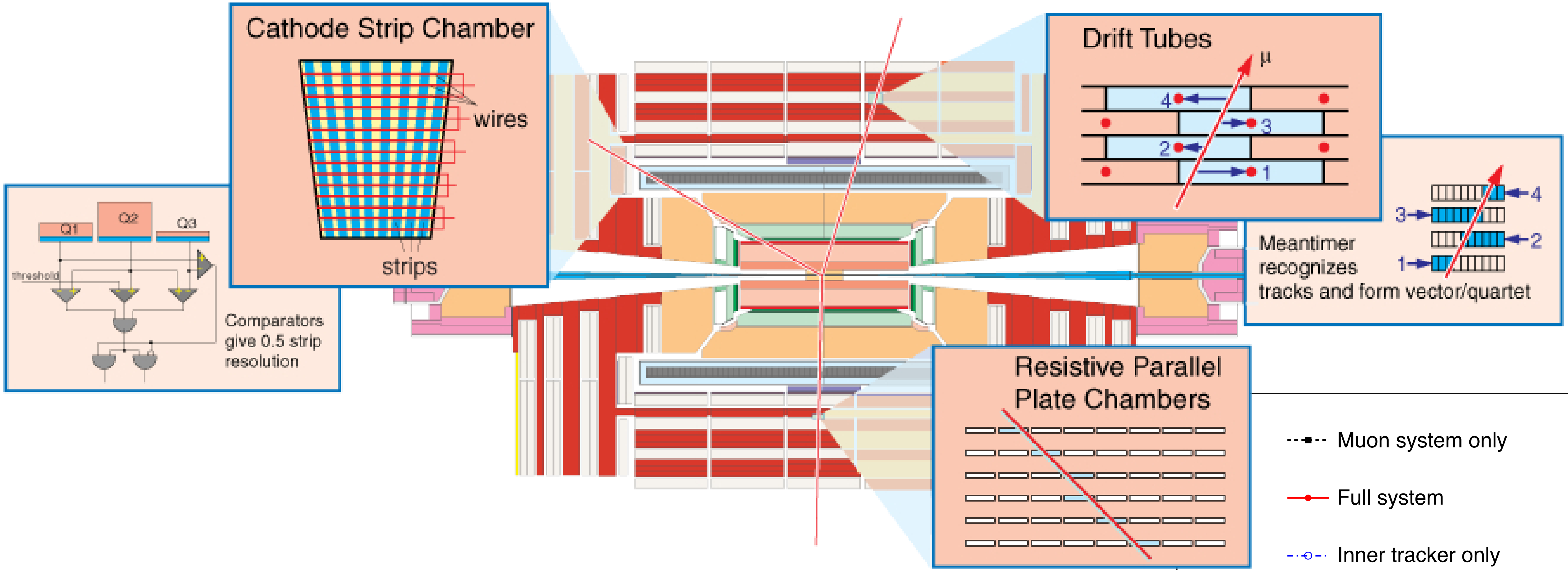
HF: $3.0 < |\eta| < 5.0$

- HB / HE - Brass radiator with interleaved scintillating plates
- HF - steel with embedded quartz wavelength shifting fibers
  - Gives hermetic coverage to calorimetry
- Designed to measure energetic jets
- Used to isolate leptons and photons in this analysis

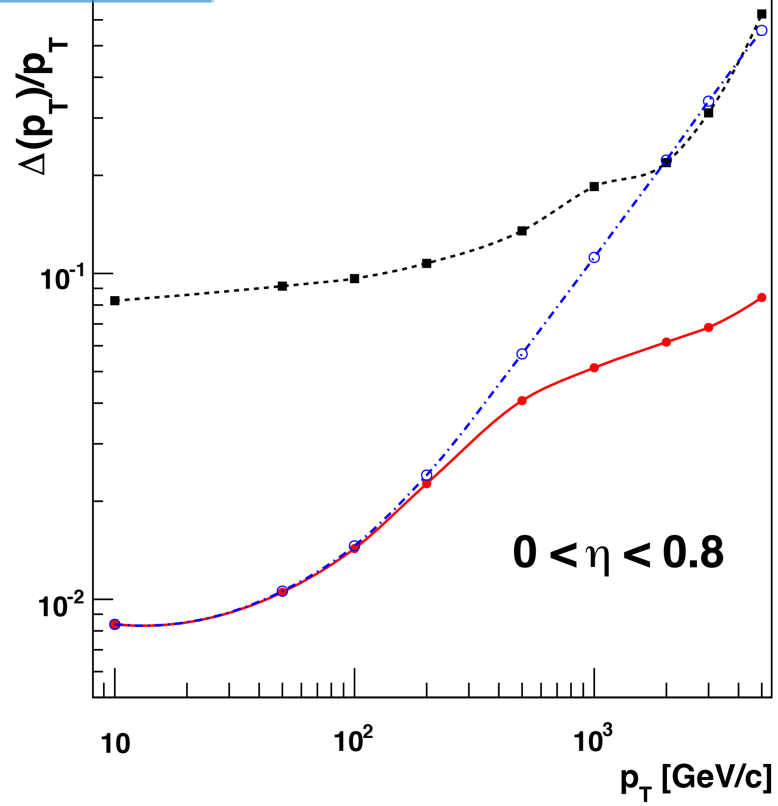
$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{90\%}{\sqrt{E}}\right)^2 + (4.5\%)^2 \quad \text{HB and HE}$$

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{172\%}{\sqrt{E}}\right)^2 + (9.0\%)^2 \quad \text{HF}$$

CMS: Muon Systems

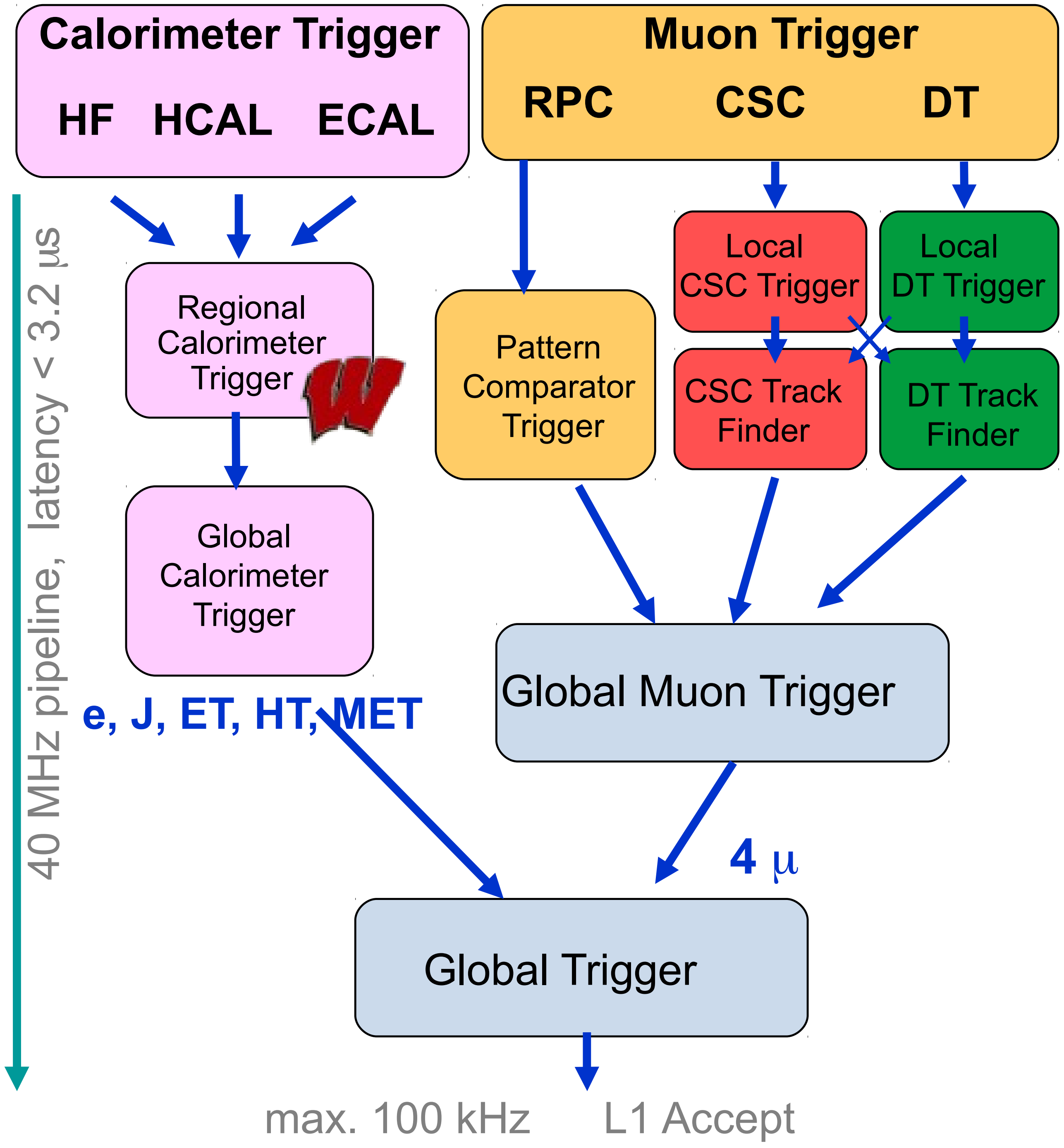


- DT - measure drift time of ions from gas ionization by muons
  - 3.8 ns for three consecutive, staggered drift cells
- CSC - measure in 2D using induced charge and drift time
  - 7 ns for an entire chamber
- RPC - Measure position from charge avalanche on strips
  - 1 ns timing resolution, fast triggering
- Yields improved tracking resolution at high muon momentum



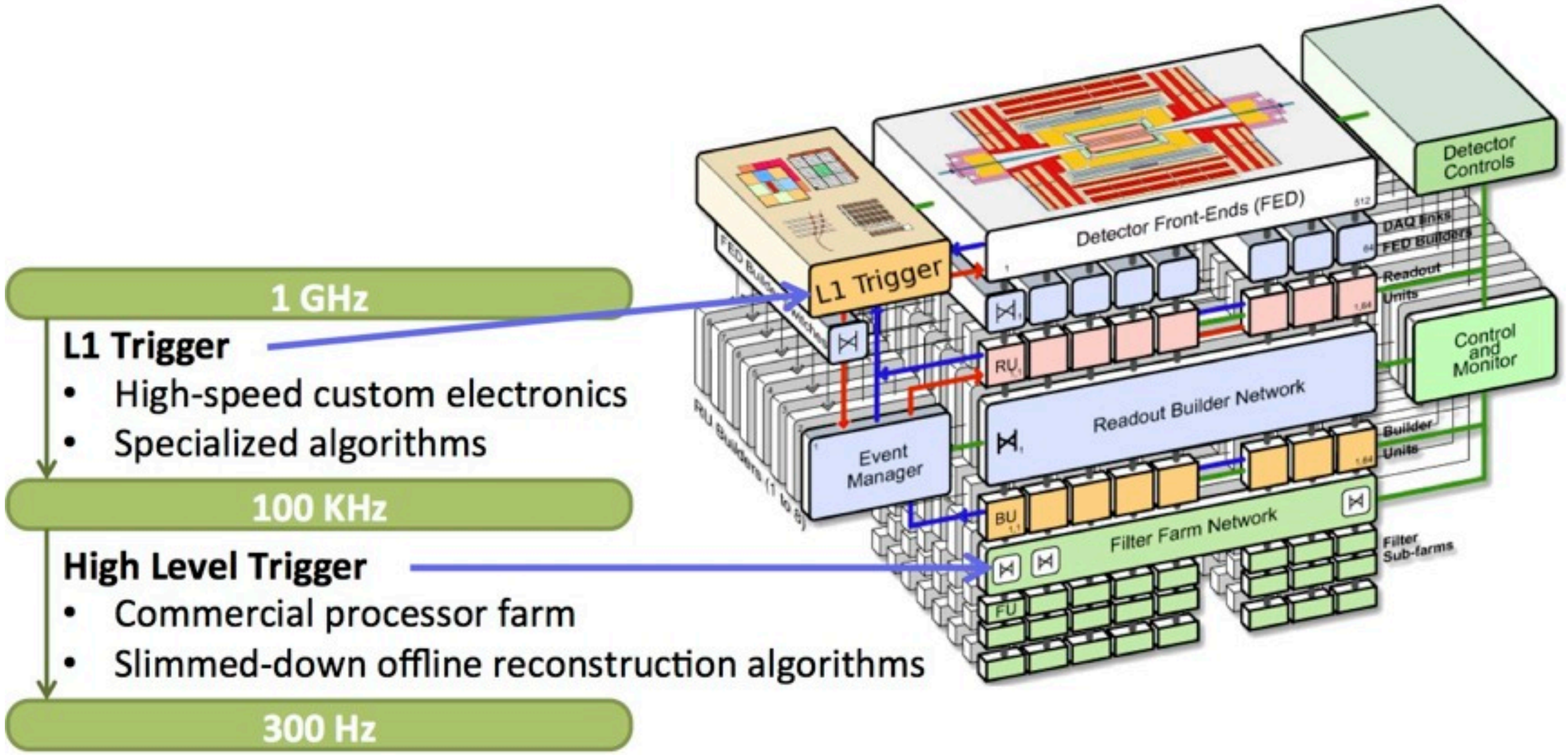
CMS: L1 Trigger

- ◉ 40 MHz pipelined physics processor
    - latched to LHC clock
    - no tracking information
    - output rate of 50-90 kHz in 2011
        - 100 kHz @ design
- ◉ Chooses best of:
    - <u>4 muon candidates</u>
    - <u>4 isolated EM candidate</u>
    - <u>4 non-isolated EM candidates</u>
    - 4 jets
    - 4 tau candidates
    - Scalar and vector energy sums



CMS: High Level Trigger

- Events selected at L1 are processed further using hierarchy of optimized or simplified versions of offline reconstruction algorithms
- Highly configurable, some analyses have tailored triggers
- Zγ uses inclusive di-muon and di-electron triggers
- Saves raw detector data for offline reconstruction



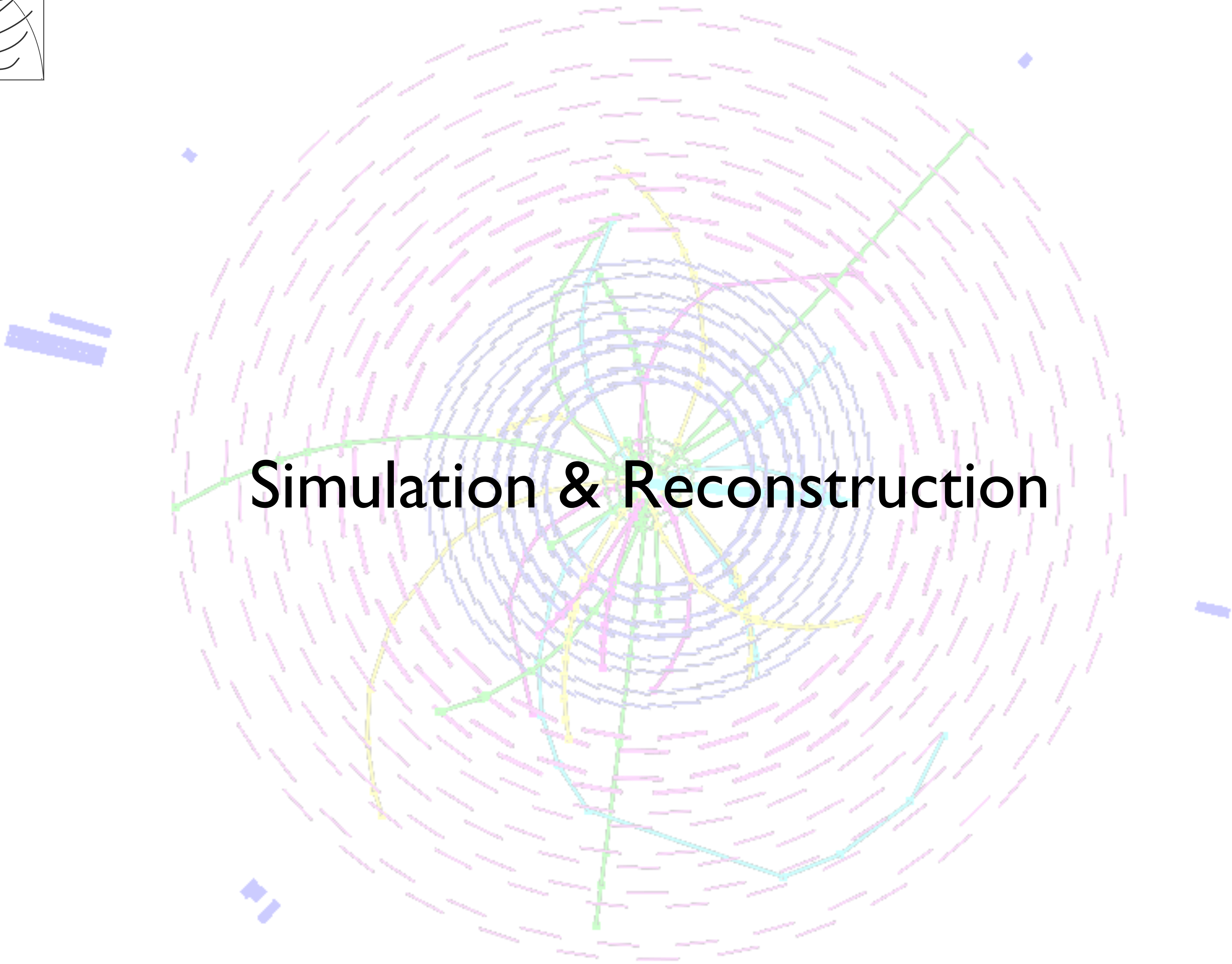
1 GHz

L1 Trigger
- High-speed custom electronics
- Specialized algorithms

100 KHz

High Level Trigger
- Commercial processor farm
- Slimmed-down offline reconstruction algorithms

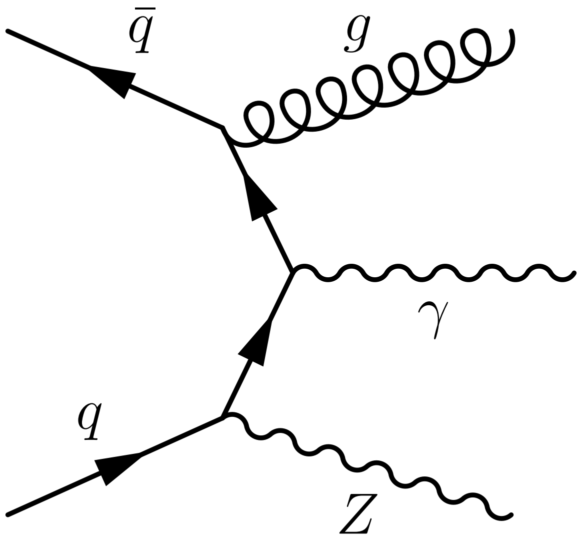
300 Hz

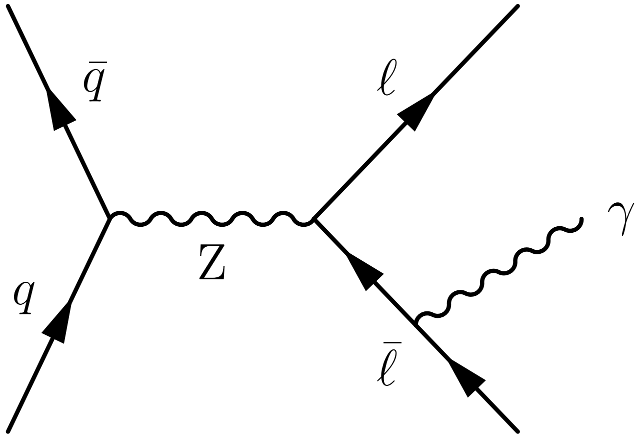


Simulation & Reconstruction

Monte Carlo Generators: Matrix Element

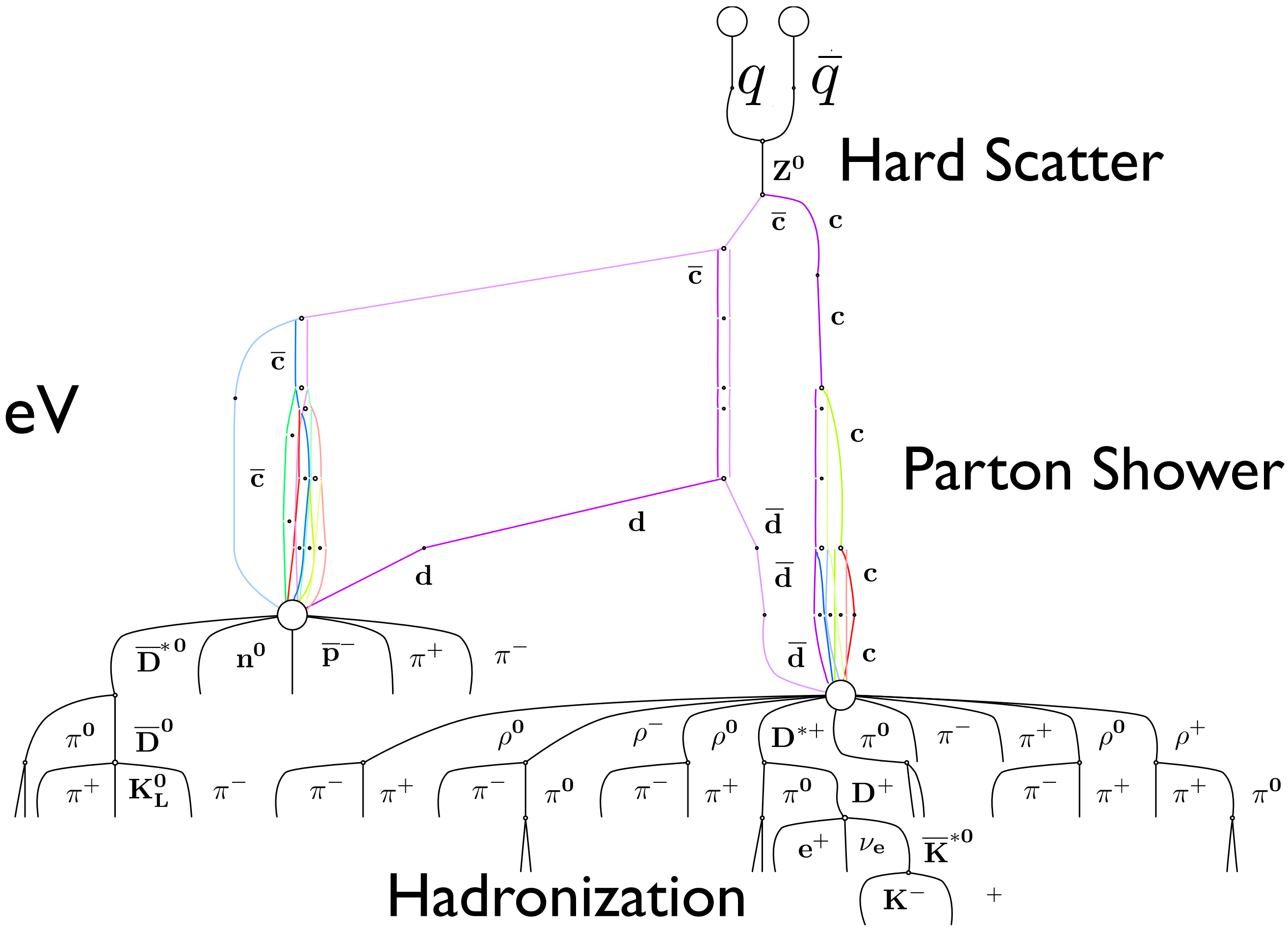
- Matrix Element (ME) calculations and event generators
  - Use monte carlo methods to integrate phase space
  - Describe hard scatter, where perturbative methods accurate
- Event generators unweight events from calculation
  - Generates final state distributed as shape of ME
  - First stage of simulation input
- Implementations Used
  - MCFM (MonteCarlo for Femtobarn Measurement)
    - Cross section calculator, accurate at NLO α_s for Zγ
  - MadGraph 5
    - Multipurpose event generator, accurate at fixed orders in α_s
    - Used to generate signal and primary background samples
  - 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

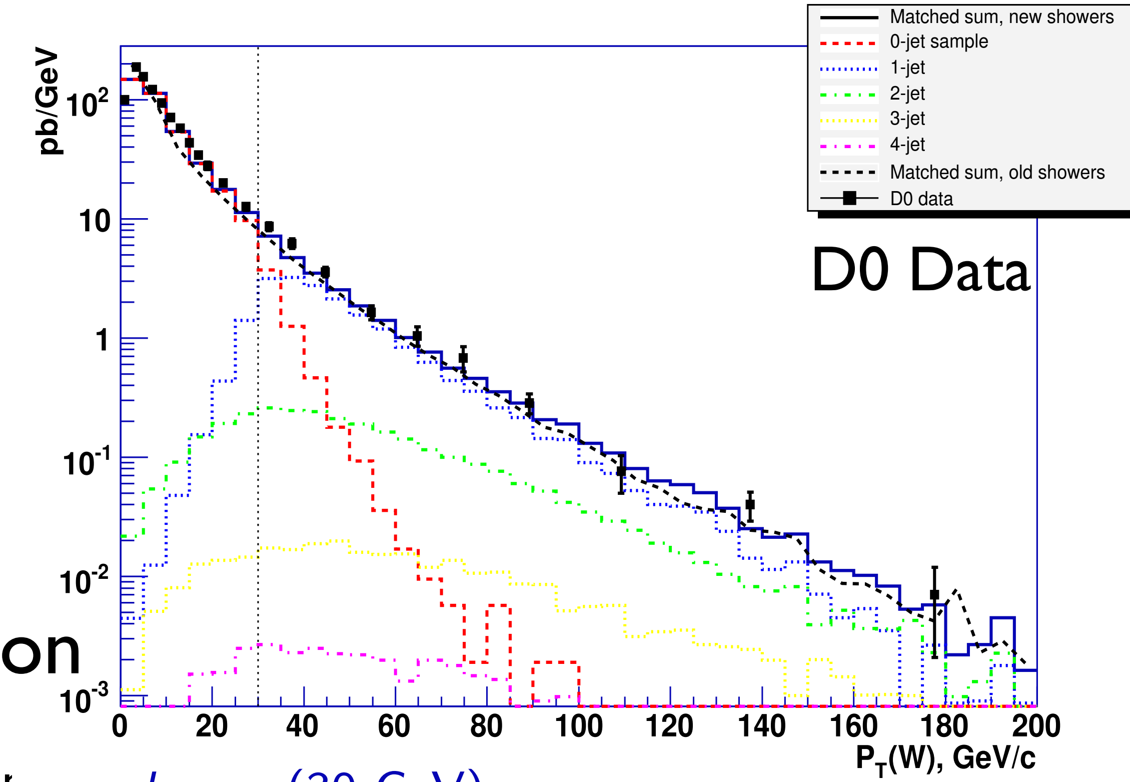




Monte Carlo Generators: Parton Shower

- Parton Showers
  - Describe splitting of partons into jets
  - Evolve partons down to Λ_{QCD}=217±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

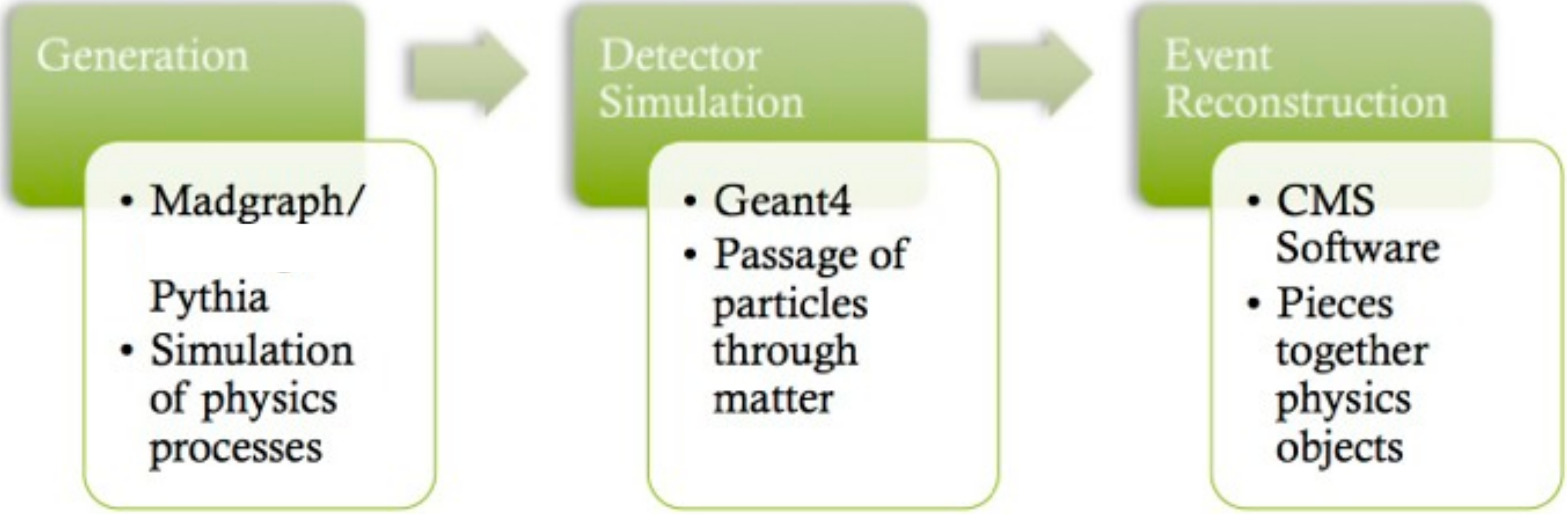




d_{match} (30 GeV)

Event Simulation

- GEANT4 package for interaction of particles with material
- Custom simulation of detector electronics
  - Including trigger
- Simulated output data format as in real detector



Generation

- Madgraph/ Pythia
- Simulation of physics processes

Detector Simulation

- Geant4
- Passage of particles through matter

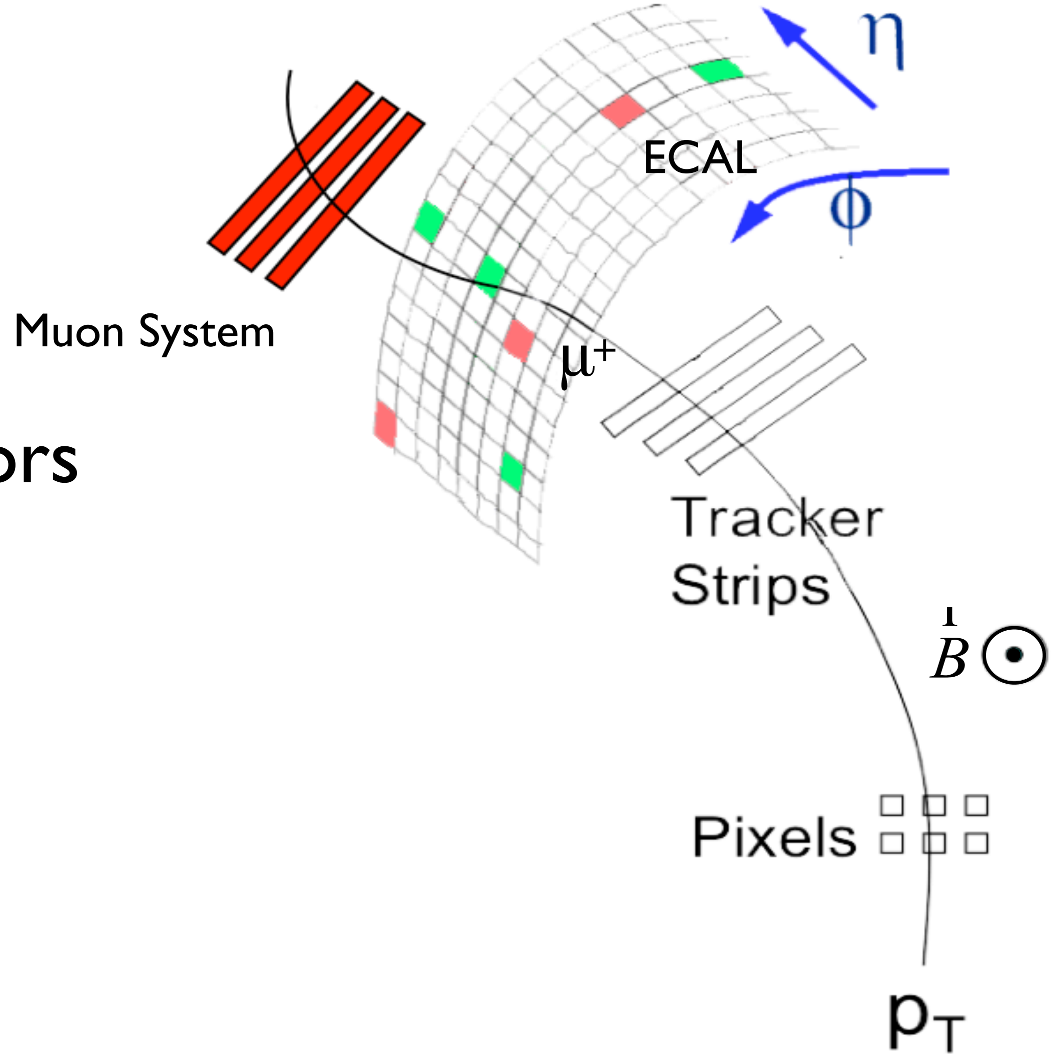
Event Reconstruction

- CMS Software
- Pieces together physics objects

Muon Reconstruction

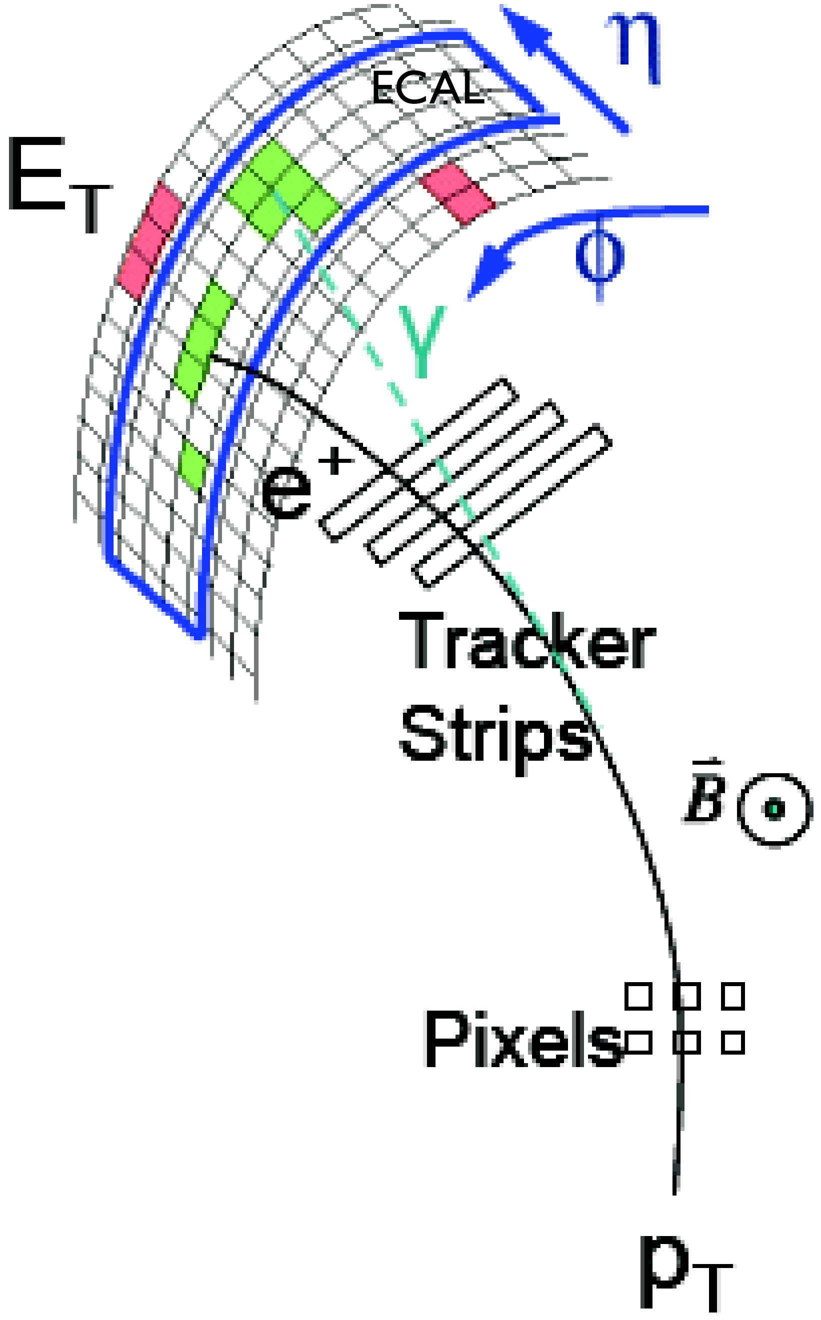
2 Reconstruction Algorithms

- ‘Global’ Muons
  - Reconstruct track in muon system
  - Search for matching Si track within errors
- ‘Tracker’ Muons
  - Propagate track from silicon
  - Search for hits within propagated error
  - muon kept if at least one segment matched



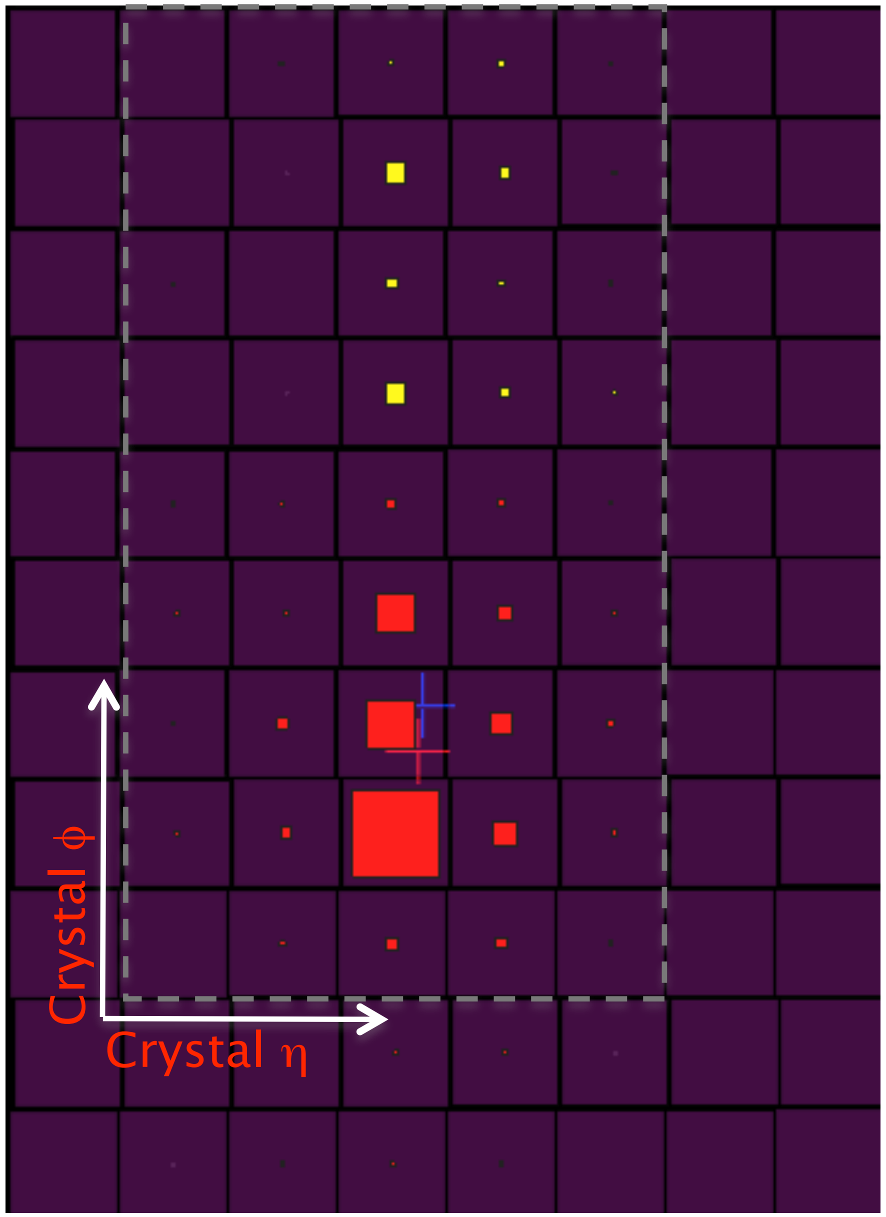
Electron Reconstruction

- ‘Supercluster’ (SC) of energy reconstructed from ECAL deposits
  - Extended deposit in phi to capture bremsstralung
  - Nearby track or searched for
- Track re-reconstructed with Gaussian Sum Filter algorithm
  - Algorithm able to account for stochastic losses, i.e. bremsstralung
- Track-Cluster matching
  - Discriminate against jets using ratio of track momentum to ECAL energy

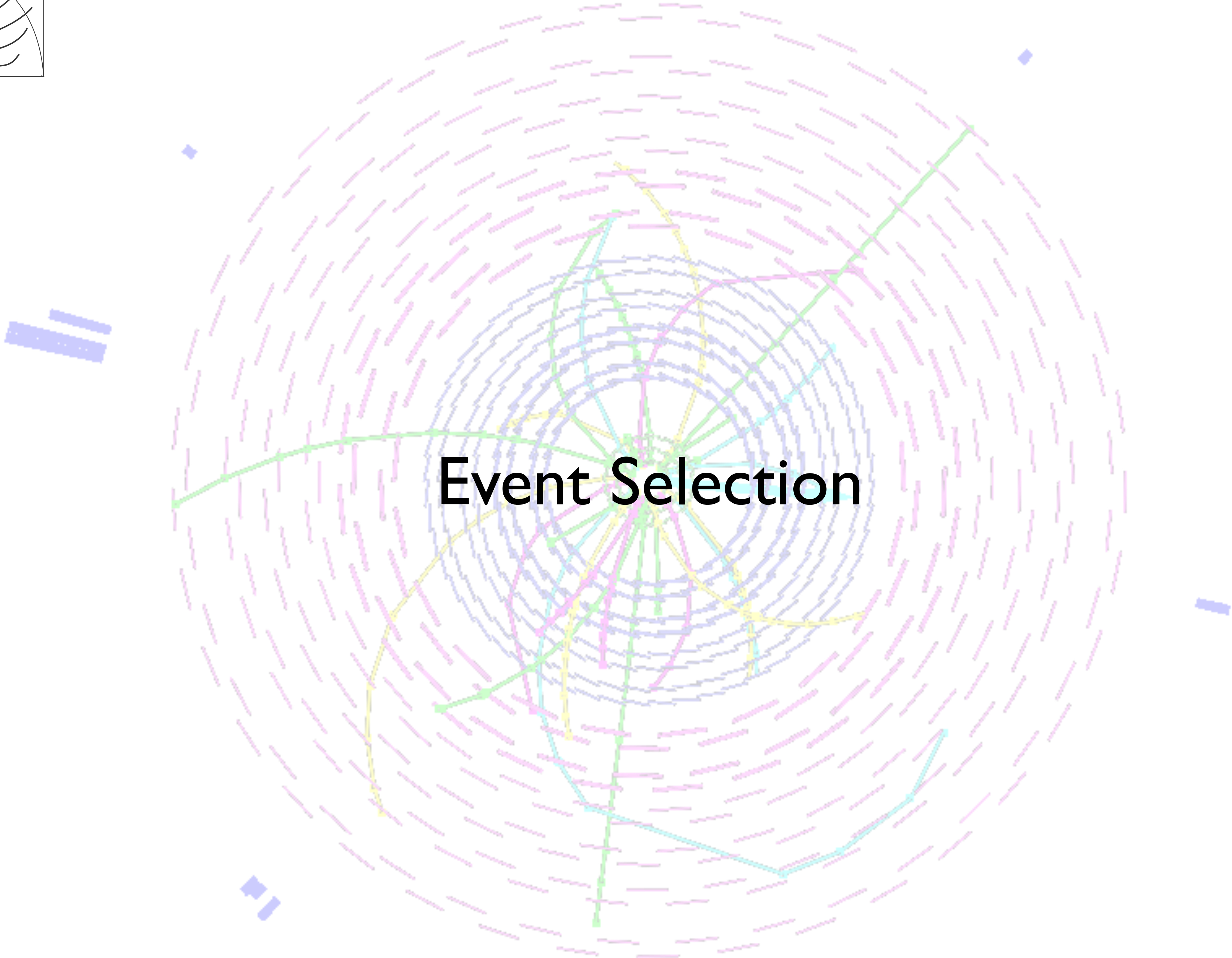


Photon Reconstruction

- Same super clusters as electron
  - Conversions extended in phi
  - Start with 5x5 square of crystals about high energy ‘seed’
- Large EM rich jet background
  - π^0 production in jets



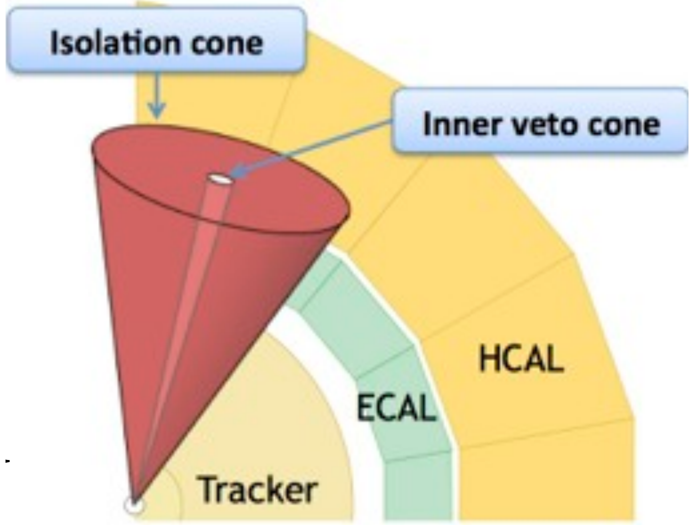
🟥 Crystals in Seed Cluster
🟨 Other crystals within Supercluster
--- Supercluster boundary



Event Selection

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 ΔR=0.3 rejects jets
  - $\mathrm{Rel.\ Comb.\ Iso.} = \left(\mathrm{Iso.}^{\mathrm{ECAL}} + \mathrm{Iso.}^{\mathrm{HCAL}} + \mathrm{Iso.}^{\mathrm{Trk}} - \pi \Delta R^2 \rho\right) / p_{\mathrm{T}}$
  - Subtract pileup using average energy density ρ
  - Veto cone about muon, ΔR = 0.1



Cut Summary:

Description	criterion
Kinematics	$p_T > 20$ GeV and $\lvert\eta\rvert < 2.4$
Number of pixel hits	> 0
Number of tracker hits	> 10
χ^2/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 cm
Vertex d_z	< 0.02 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 $\Delta\theta$, |dist|
- Use shower η width, $\sigma_{i\eta i\eta}$ and isolation to reject jets
  - $\sigma^2_{i\eta i\eta} = \frac{\sum (\eta_i - \bar{\eta})^2 w_i}{\sum w_i}, \; \bar{\eta} = \frac{\sum \eta_i w_i}{\sum w_i}, \; w_i = \max(0, 4.7 + \log(E_i / E_{5\times5}))$
- Selection criteria organized as 85% and 80% efficiency ‘working points’

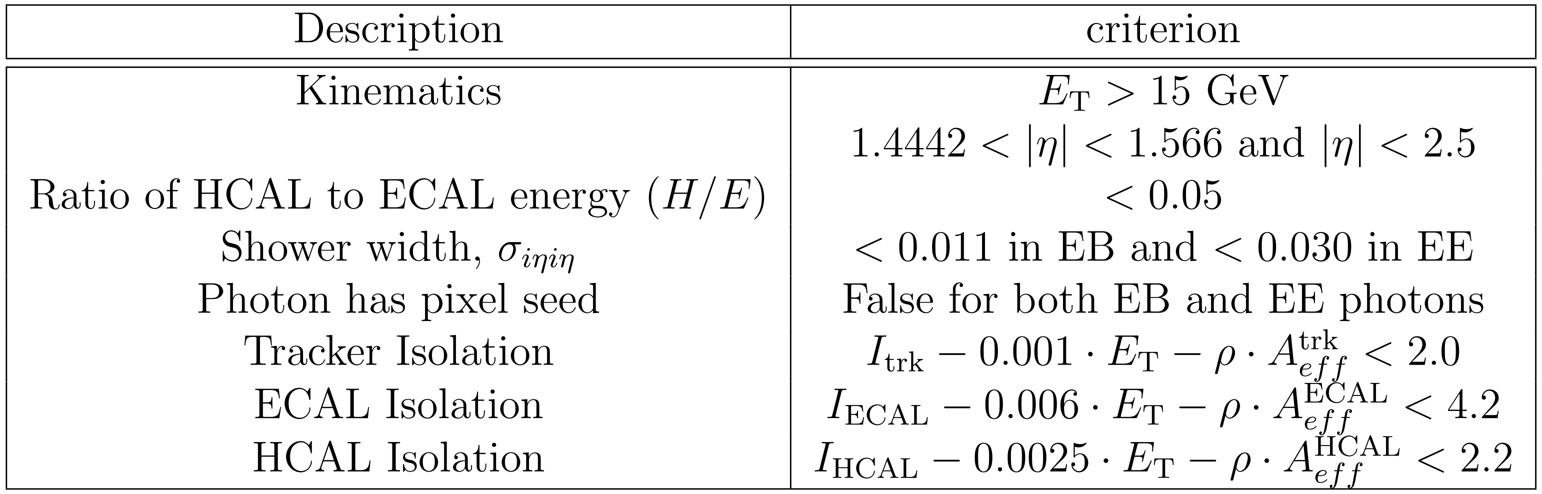
	WP85		WP80	
	Barrel	Endcap	Barrel	Endcap
$\Delta\varphi_{vtx}$	0.039	0.028	0.027	0.021
$\Delta\eta_{vtx}$	0.005	0.007	0.005	0.006
$\lvert\cot\Delta\vartheta\rvert$	0.02	0.02	0.02	0.02
$\lvert$dist$\rvert$	0.02	0.02	0.02	0.02
$\sigma_{i\eta i\eta}$	0.01	0.031	0.01	0.031
Combined relative isolation	0.053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

85% Working Point (WP85)
main analysis selection

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

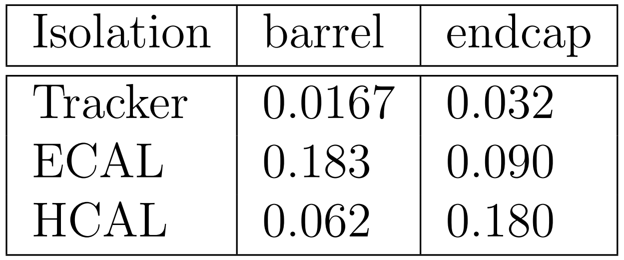
Event Selection: Photon Identification

- Photon $p_T > 15$ 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	$E_{\mathrm{T}} > 15$ GeV $1.4442 < \lvert\eta\rvert < 1.566$ and $\lvert\eta\rvert < 2.5$
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	$I_{\mathrm{trk}} - 0.001 \cdot E_{\mathrm{T}} - \rho \cdot A_{eff}^{\mathrm{trk}} < 2.0$
ECAL Isolation	$I_{\mathrm{ECAL}} - 0.006 \cdot E_{\mathrm{T}} - \rho \cdot A_{eff}^{\mathrm{ECAL}} < 4.2$
HCAL Isolation	$I_{\mathrm{HCAL}} - 0.0025 \cdot E_{\mathrm{T}} - \rho \cdot A_{eff}^{\mathrm{HCAL}} < 2.2$

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
  - $|d_0| < 2$ cm , $|d_Z| < 24$ cm , ndof > 4
- Remove events with beam scraping
  - 25% of all tracks present point towards interaction region

Zγ 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.

Before Cuts: 56945443 evts.

- Z(μμ)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.

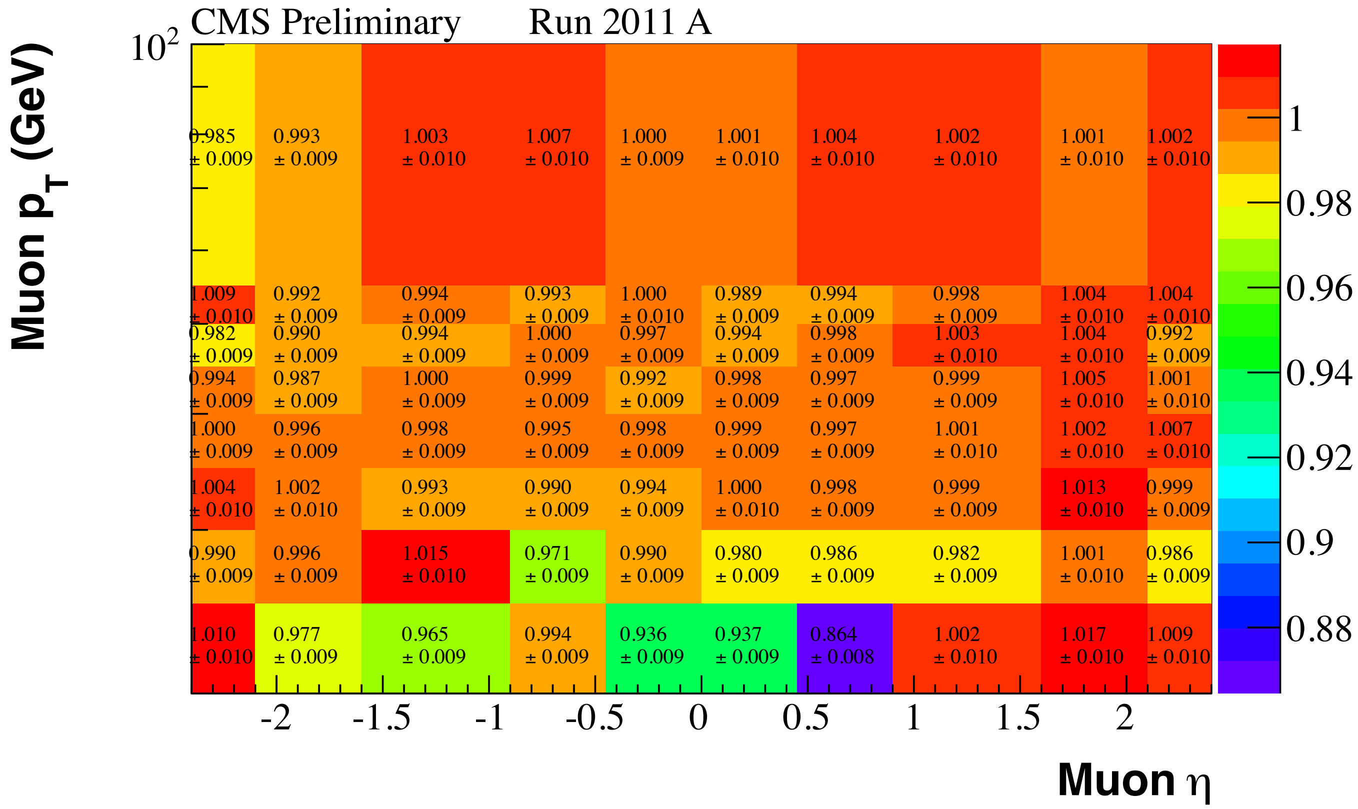
- Dilepton Mass > 50 GeV
- Select the highest p_T photon passing selection
  - Apply run dependent energy scale correction
  - $p_T > 15$ GeV, ECAL fiducial cuts
  - Passes photon isolation and ID criteria
  - $\Delta R(l,\gamma) > 0.7$

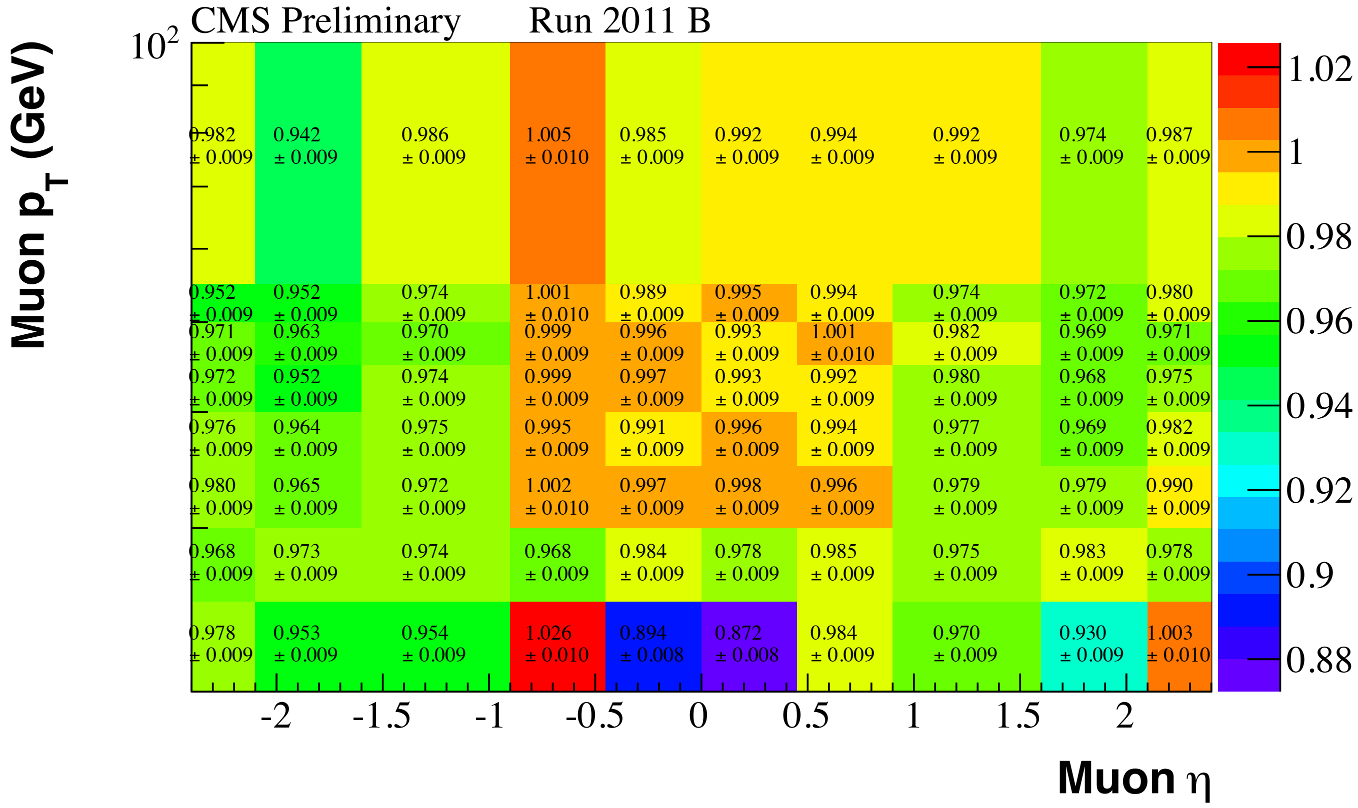
After Full Zγ Selection: 4108 evts.

After Full Zγ Selection: 6463 evts.

Event Selection: Muon Efficiency

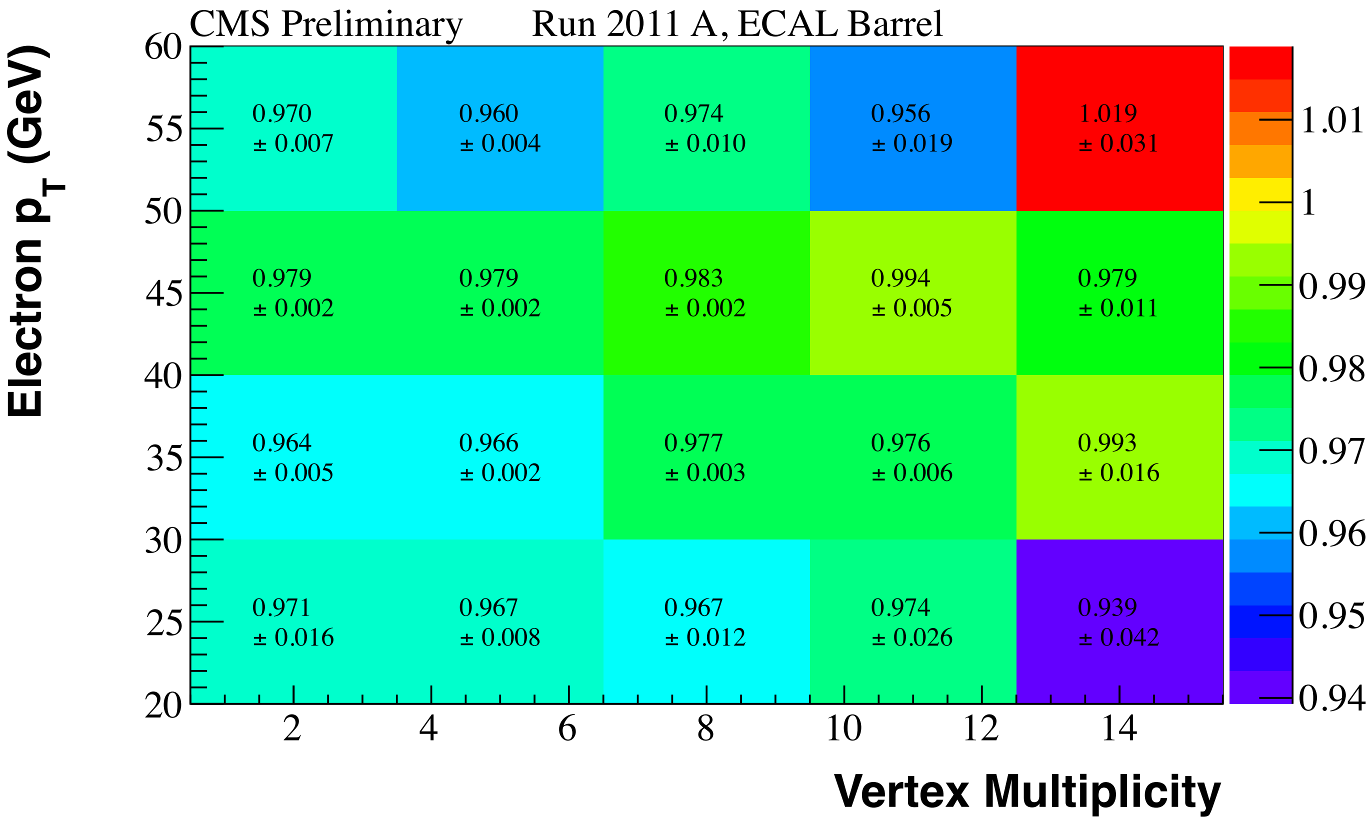
- Tag and Probe to measure efficiencies
    - Exploit Z(μμ) resonance
    - Tag fully identified muon
    - Probe passes or fails selection criteria
    - Fit Z peak to extract efficiency
- In this analysis use efficiency ratios to scale MC to data efficiencies
    - Maps of 'scale factors' adjust efficiencies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

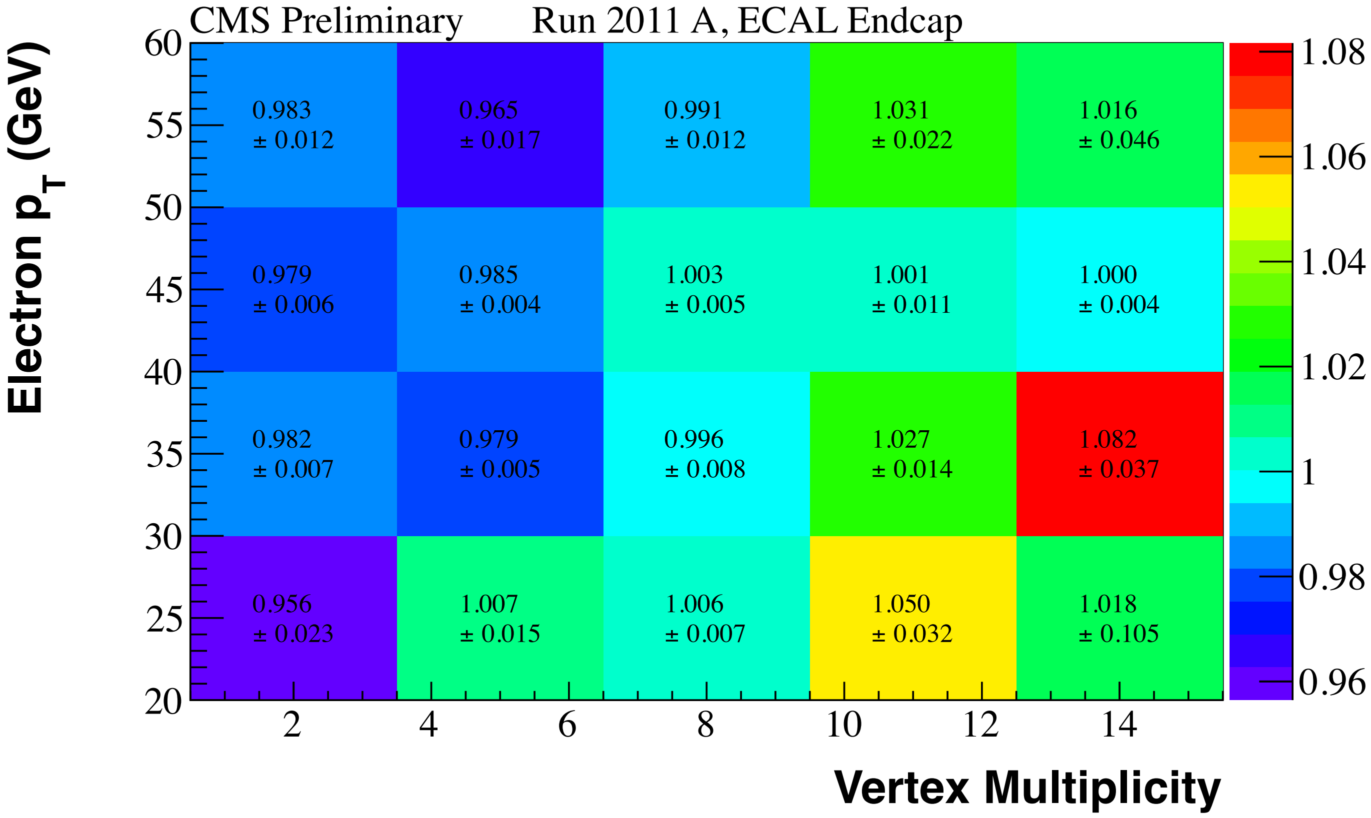




Event Selection: Electron Efficiency

- ◉ 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



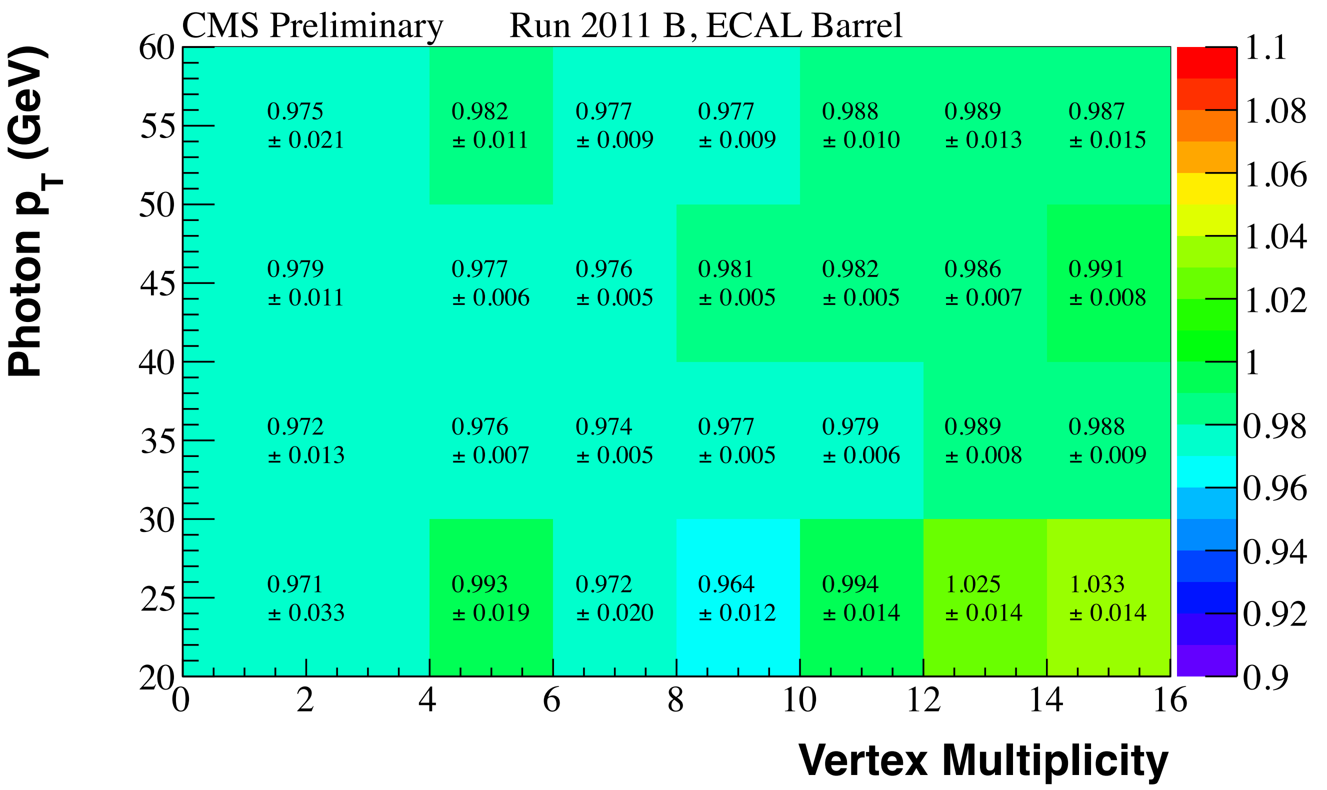


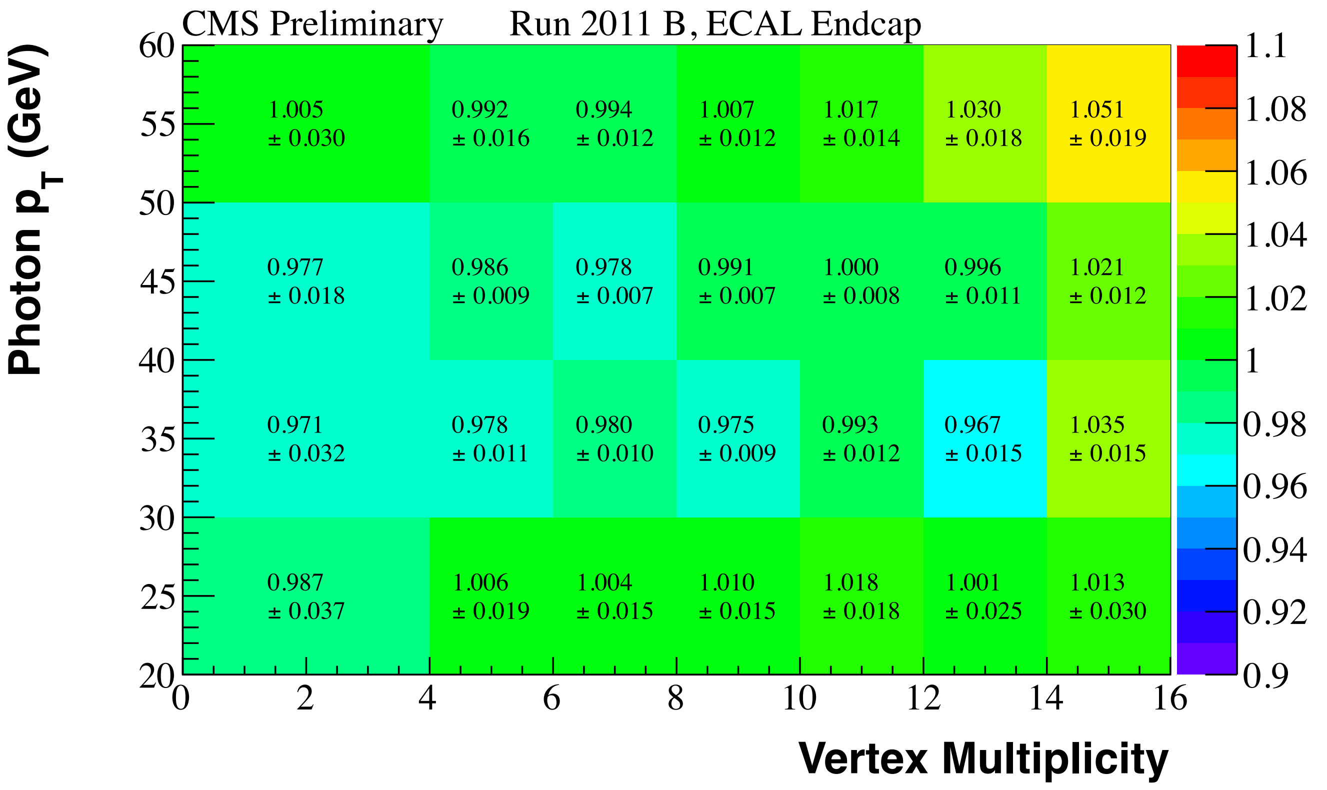
Event Selection: Photon Efficiency

- 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(μμγ) events
  - Tag and probe using offshell Z as tag and photon as probe

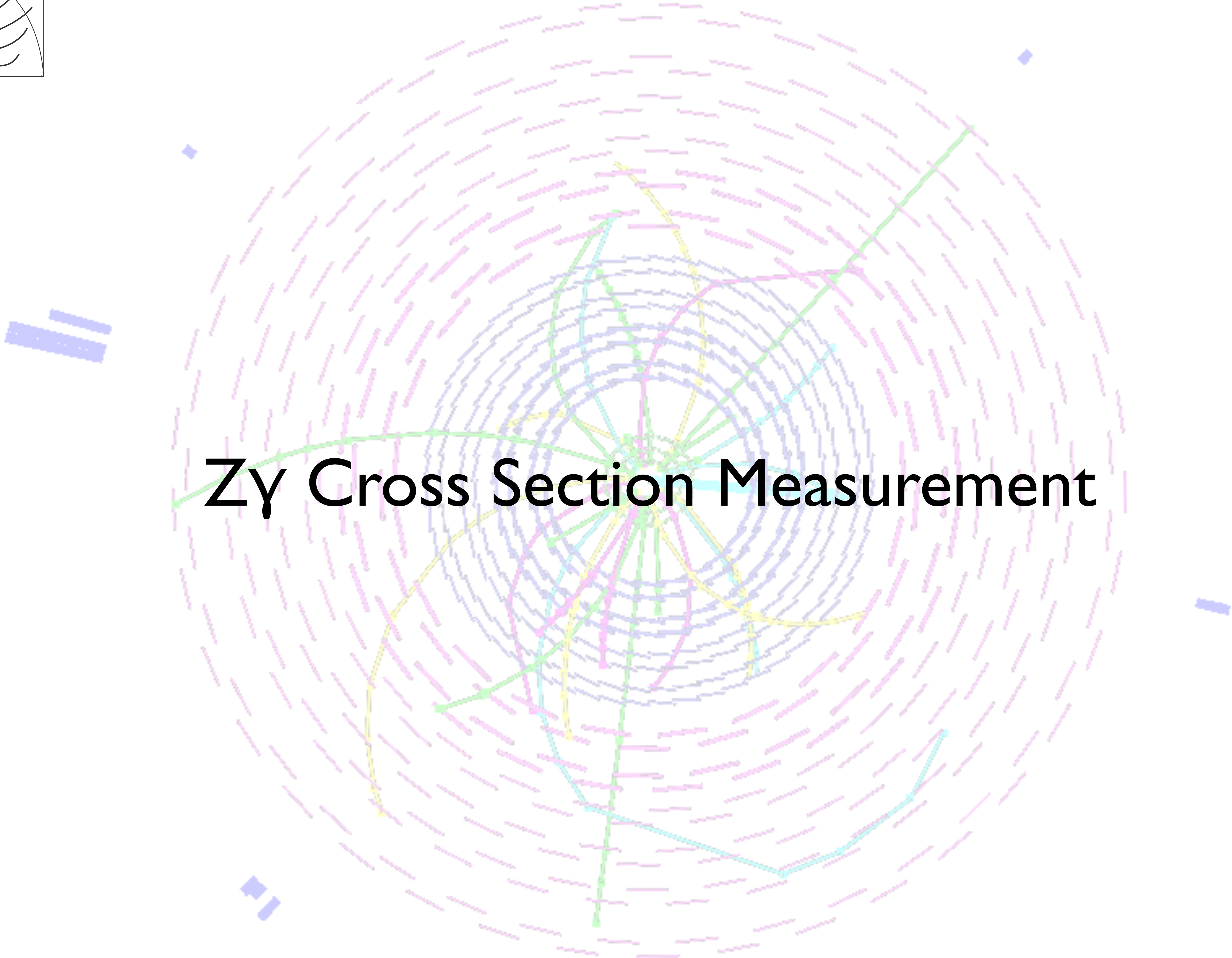
Pixel Seed Veto Efficiencies:

	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





Zγ Cross Section Measurement



Zγ Cross Section: Backgrounds

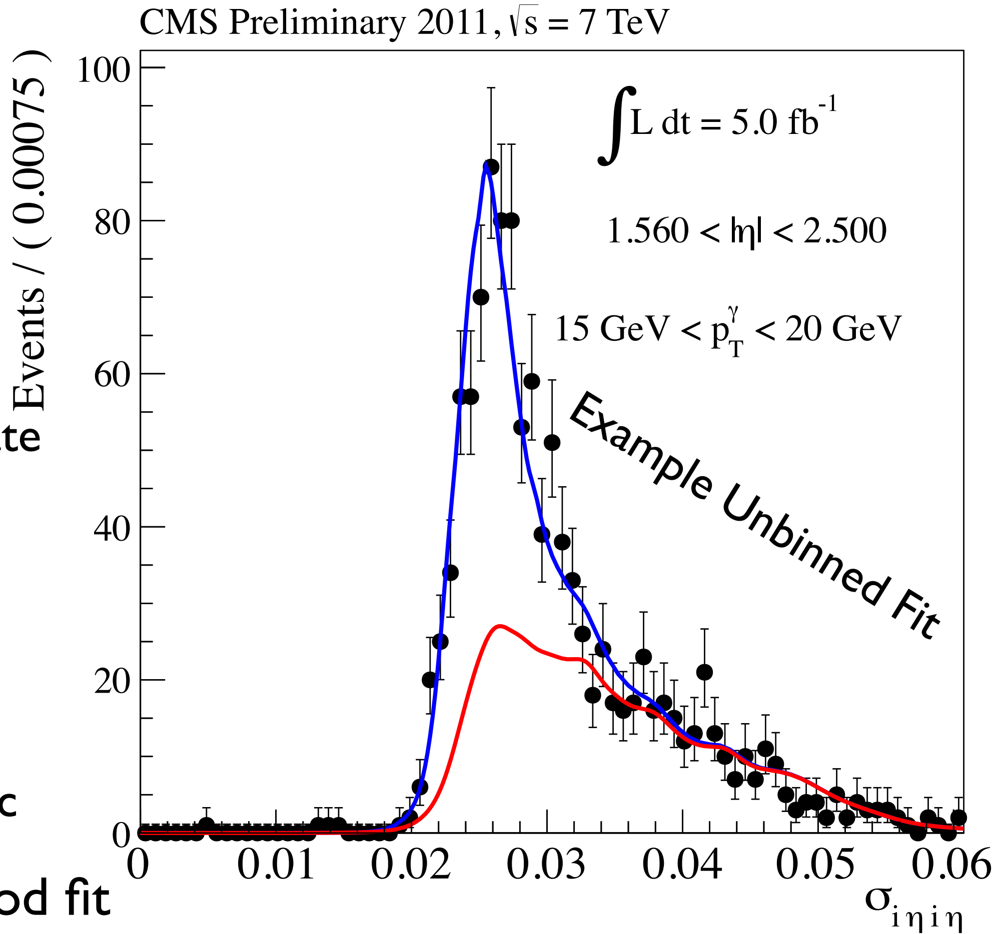
- There are three main sources of background for Zγ
  - Photons from jet-fakes
    - Determine amount using Template Method (next slide)
  - TTbar: Real leptons + fake photon (Taken from MC)
  - Z(ττ)γ: τ decays to e/μ + ν (Taken from MC)

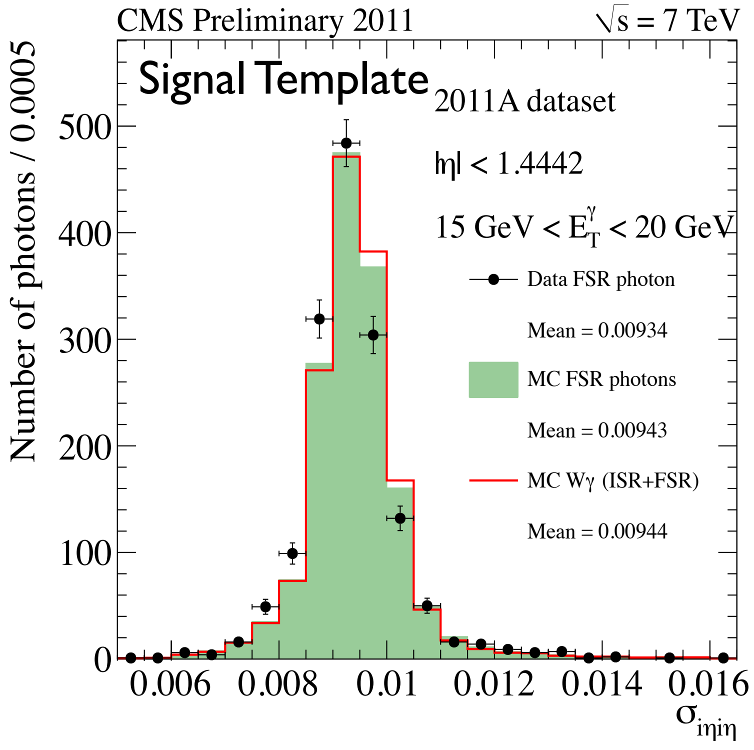
Fake γ Bkg: Template Method

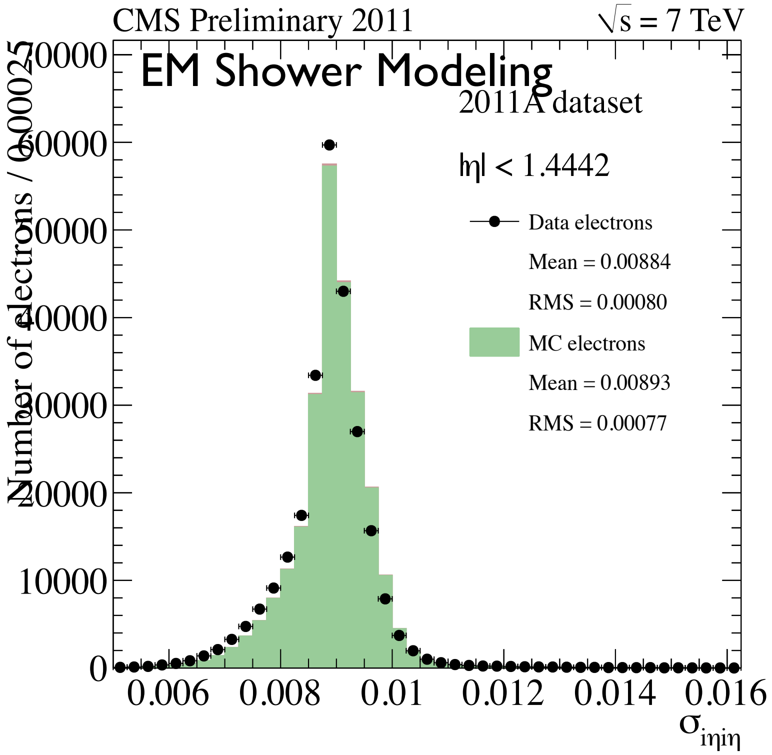
- Use two component fit:

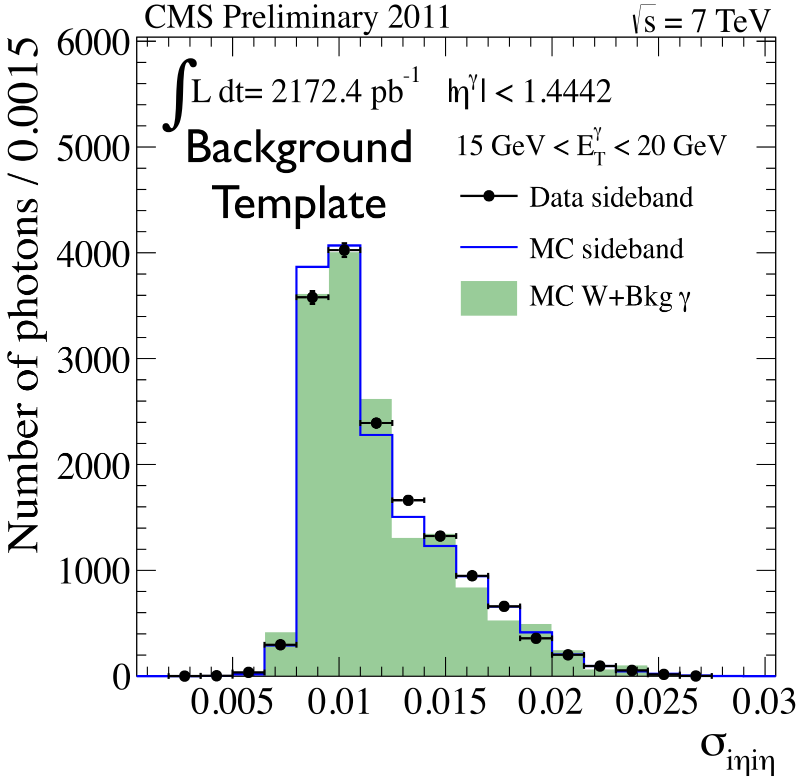
$$f(\sigma_{i\eta i\eta}) = \mathrm{N_S} \cdot S(\sigma_{i\eta i\eta}) + \mathrm{N_B} \cdot B(\sigma_{i\eta i\eta})$$

- Signal templates are obtained from Madgraph W/Zγ samples
  - Use Zee candidates to determine Data/MC shift
  - Templates from FSR Zγ used as a cross check to validate MC signal template
- Background templates are <u>data-driven</u>
  - Taken from inverted track isolation sideband in Jet dataset
    - $2\ \mathrm{GeV} < Iso_{TRK} - 0.001E_T^{\gamma} - 0.0167\rho < 5\ \mathrm{GeV\ for\ EB}$
      $2\ \mathrm{GeV} < Iso_{TRK} - 0.001E_T^{\gamma} - 0.0320\rho < 3\ \mathrm{GeV\ for\ EE}$
  - Shape difference between MC and data-driven templates used as systematic
- The fit is performed using an unbinned extended maximum log likelihood fit



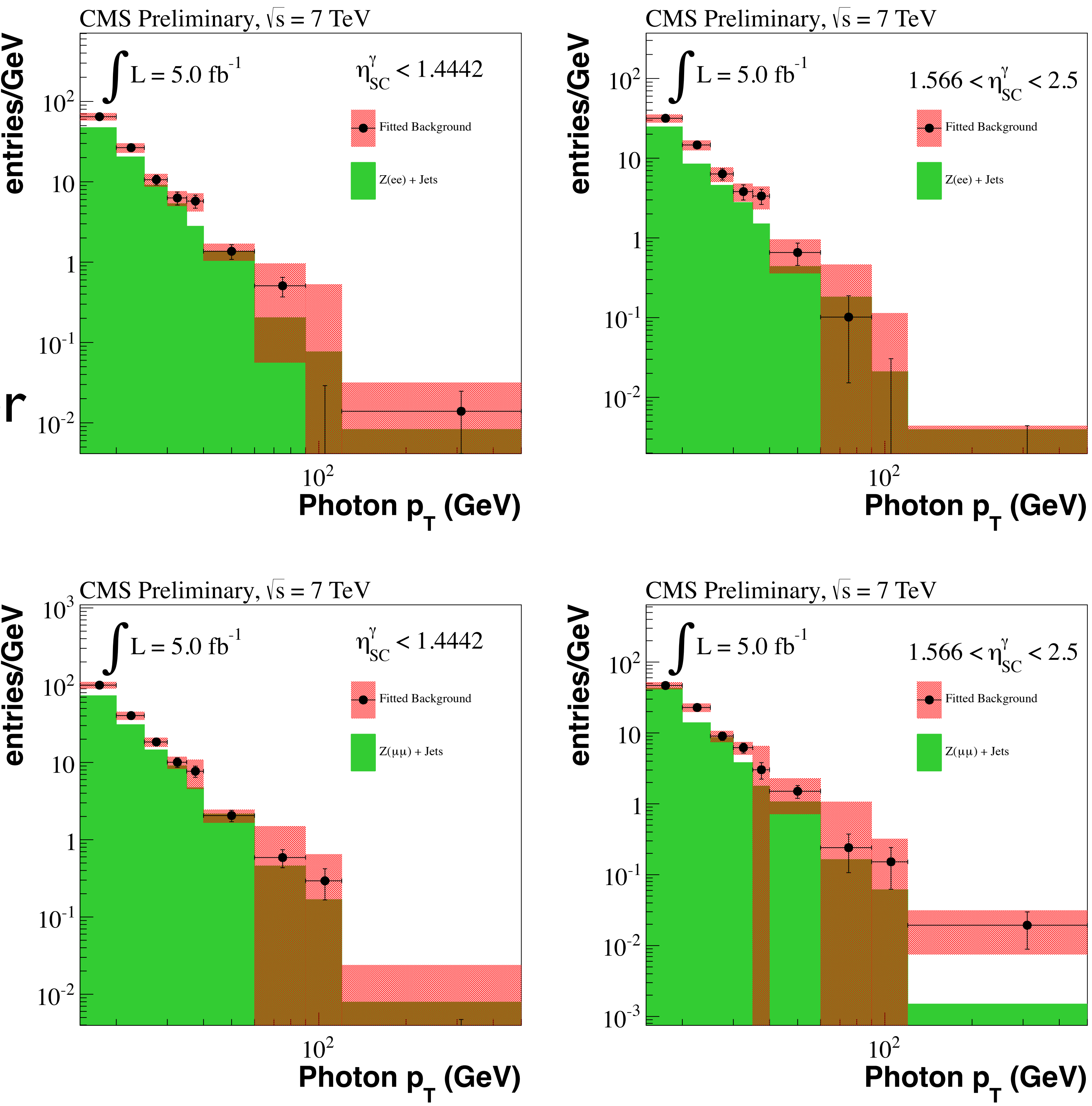






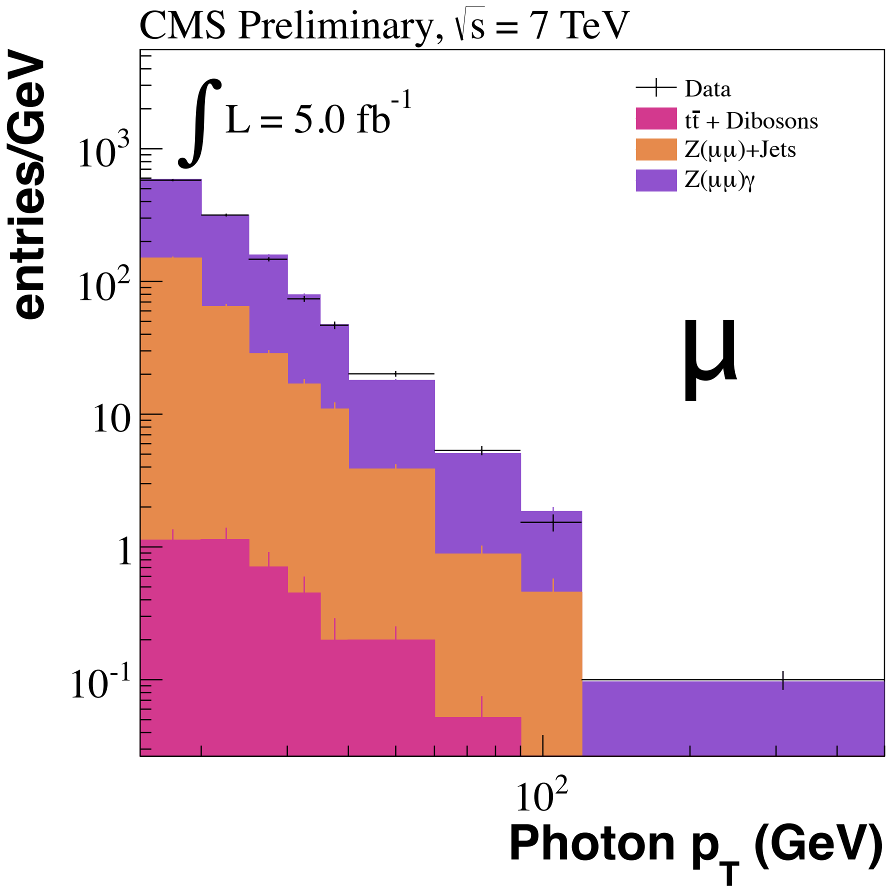
Zγ Template Method Yields

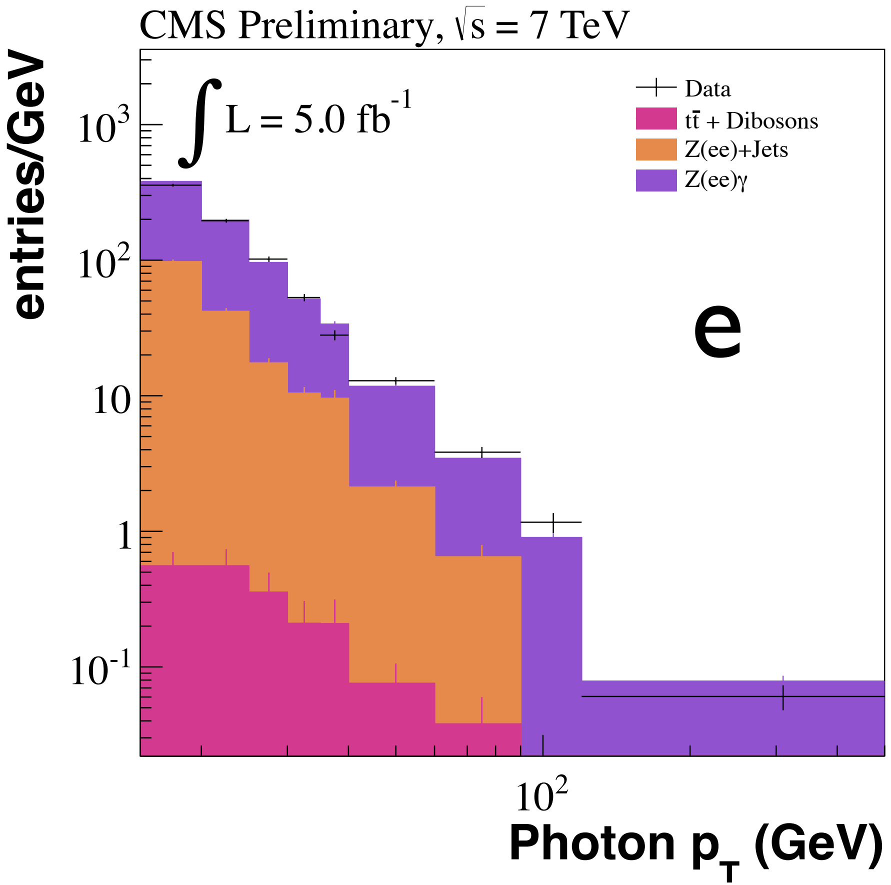
- Underestimation Z +Jets background a known effect
  - Data-driven method described jet-fakes better by construction
  - Reweigh MC Z+Jets
    - $w_i = \dfrac{\text{Template Yield}_i}{\text{MC Yield}_i}$
  - Reweighed in photon p_T
    - Projected into other quantities



Zγ Distributions: Photon E_T

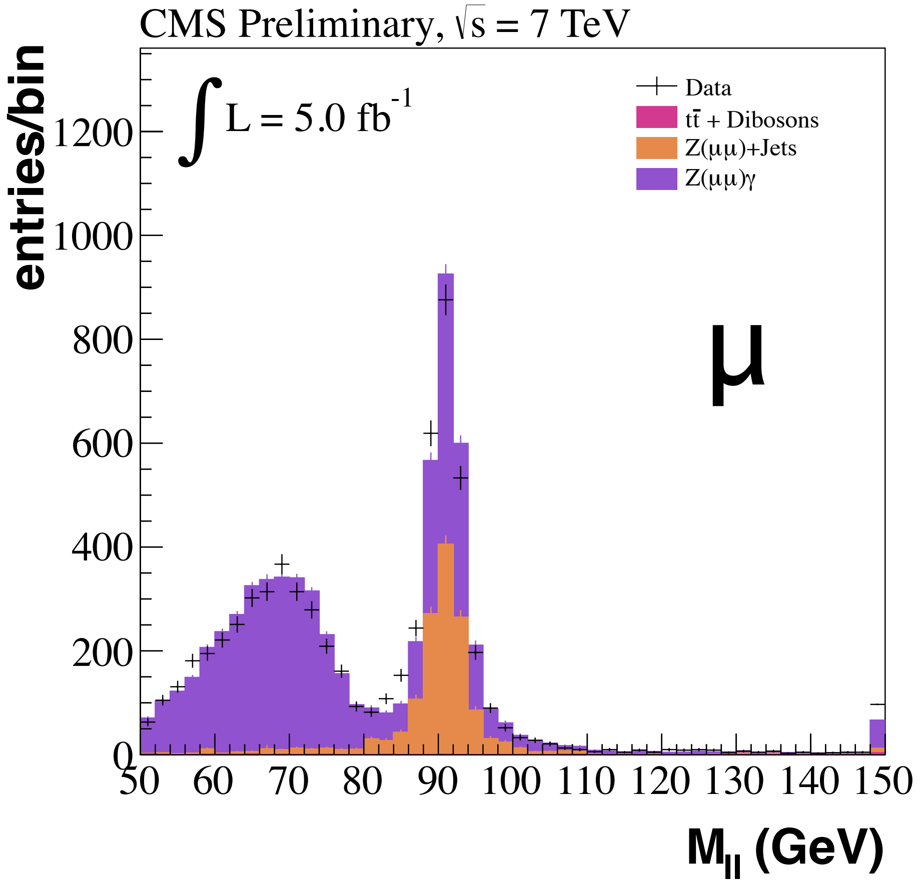
- Photon E_T distribution agrees with MadGraph5
  - Normalized to MCFM
  - Agreement over nearly two orders of magnitude
- Z+Jets Background distribution normalized to template method yield and shape

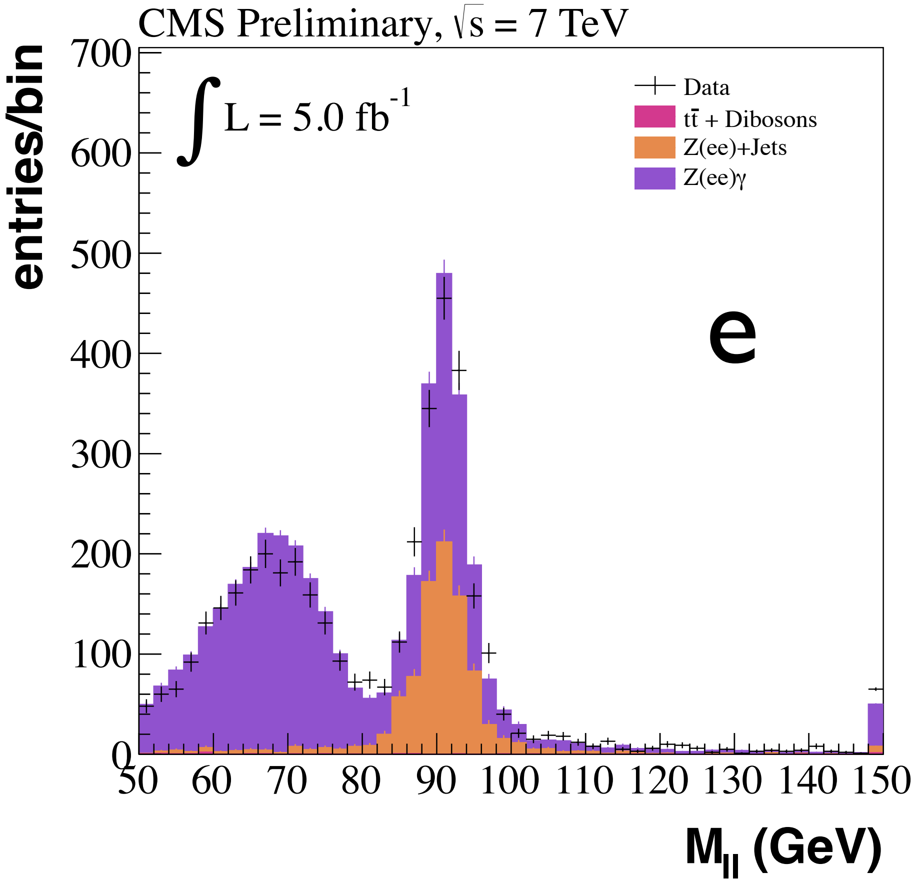




Zγ Distributions: M_Z

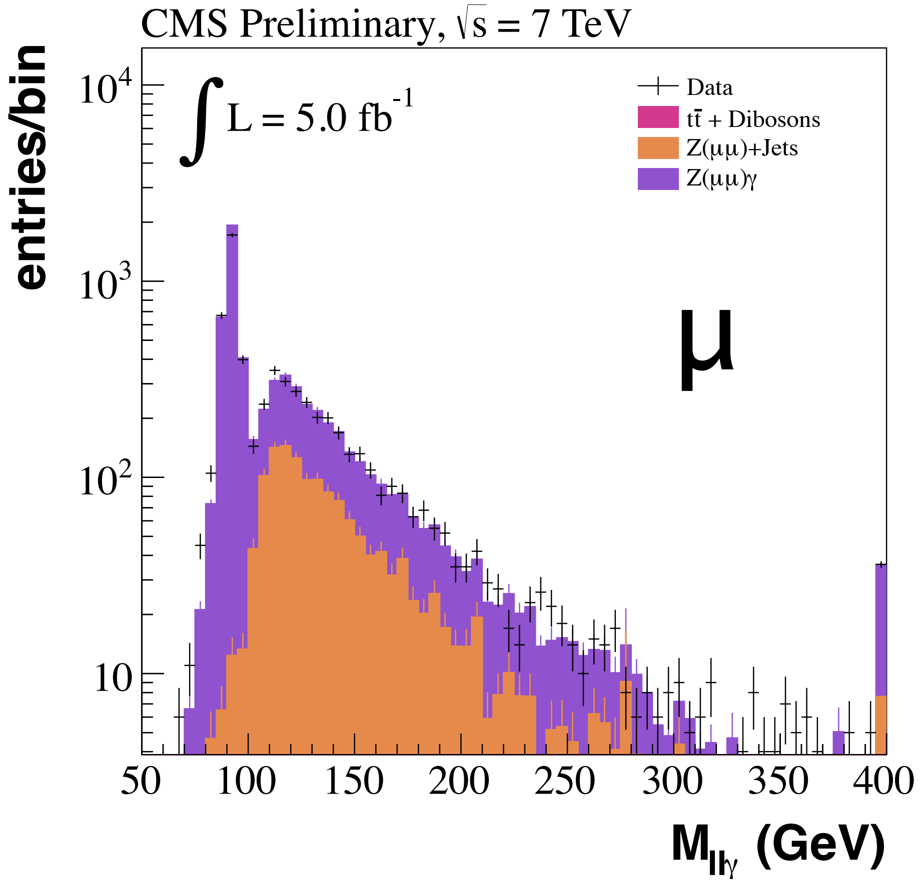
- EM I/FSR turned off in MG5 samples
  - Causes poor modeling of Z peak FSR tail
  - Initially to avoid double counting
  - Effect < 1% on acceptance

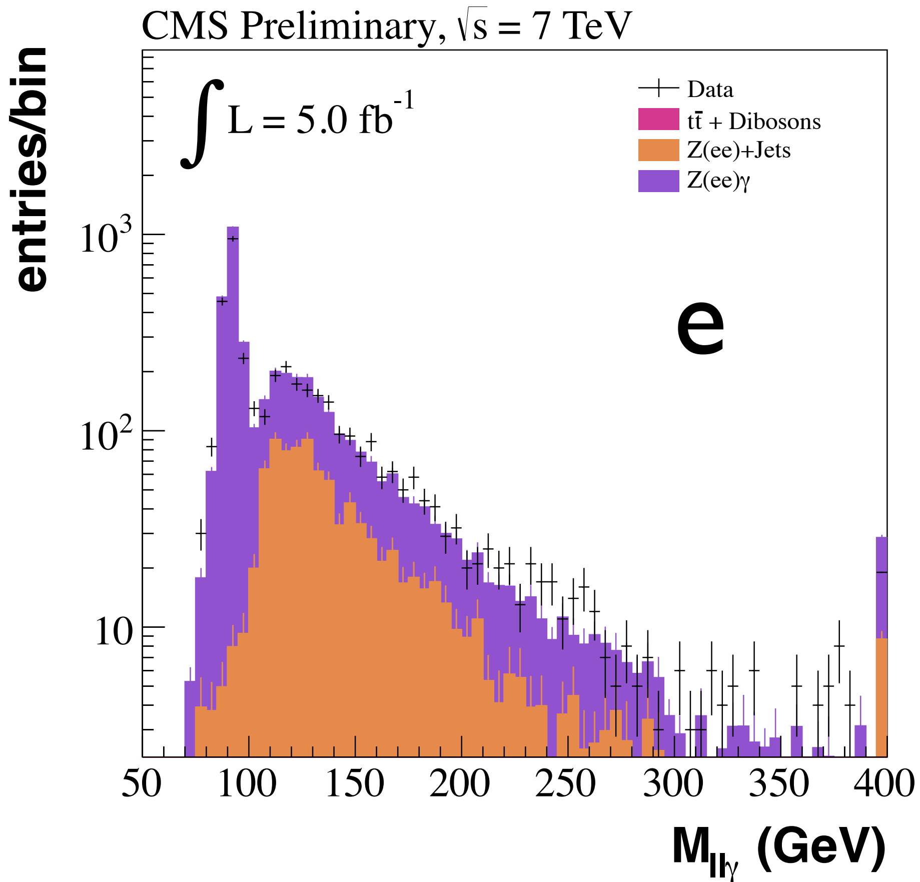




Zγ Distributions: $M_{Z\gamma}$

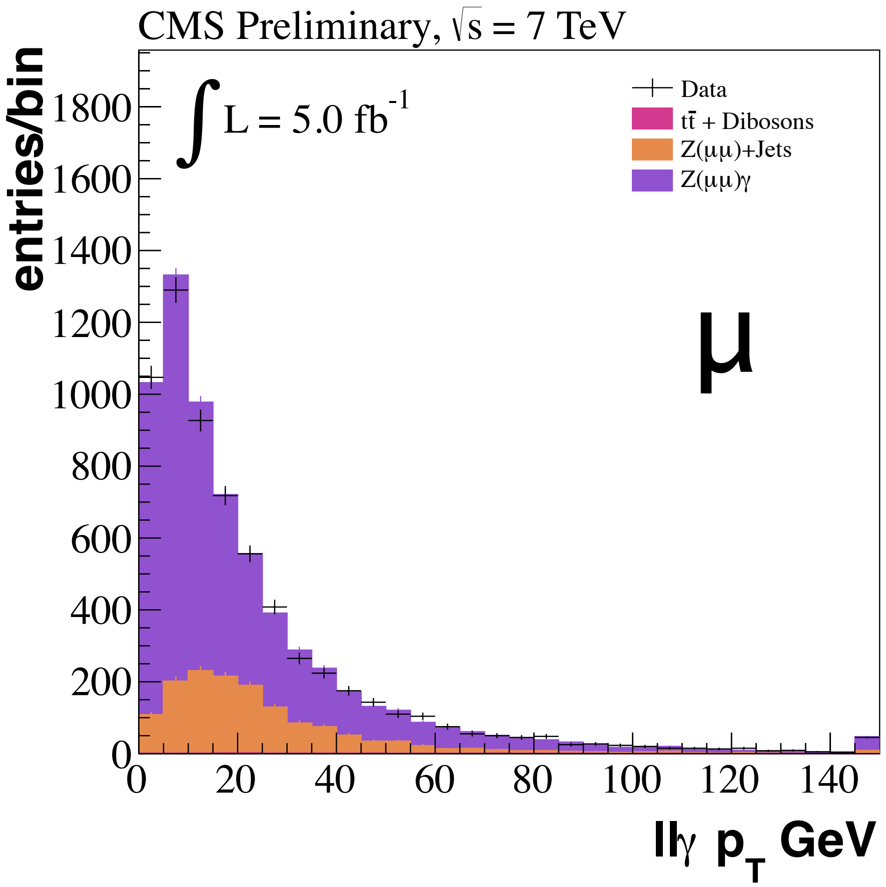
- ISR spectrum is well modeled by MC
- Good agreement to high invariant mass

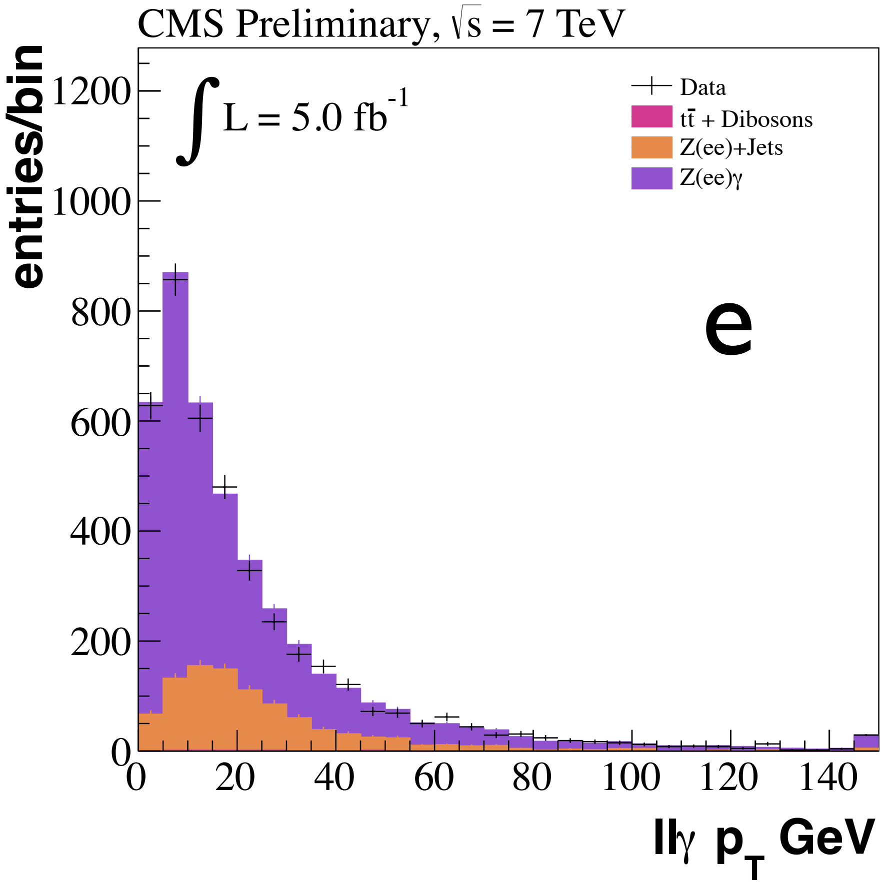




Zγ Distributions: Zγ p_T Distributions

- Distributions in both channels agree
  - Inclusively matched Zγ sample describes data





Zγ 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 eeγ 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

Zγ 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 $\sigma_{i\eta i\eta}$
    - 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

Zγ 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	eeγ
	4.9% (EB), 5.8% (EE)	n/a	5.5%	μμγ
Total uncertainty on background		5.1 %	5.5%	
Source	Systematic uncertainty	Effect on luminosity		
Luminosity	2.2%	2.2%	2.2%	

Zγ Cross Section: Measurement

- Theoretical Cross Section: 5.45 +/- 0.27 pb (scale + PDF)
- Cross Section from data:

$$\sigma(\mathbf{pp} \rightarrow \mathbf{Z}\gamma \rightarrow \mathbf{ee}\gamma) = \mathbf{5.20} \pm \mathbf{0.13}\ (\text{stat.}) \pm \mathbf{0.30}\ (\text{syst.}) \pm \mathbf{0.11}\ (\text{lumi.})$$
$$\sigma(\mathbf{pp} \rightarrow \mathbf{Z}\gamma \rightarrow \mu\mu\gamma) = \mathbf{5.43} \pm \mathbf{0.10}\ (\text{stat.}) \pm \mathbf{0.29}\ (\text{syst.}) \pm \mathbf{0.12}\ (\text{lumi.})$$

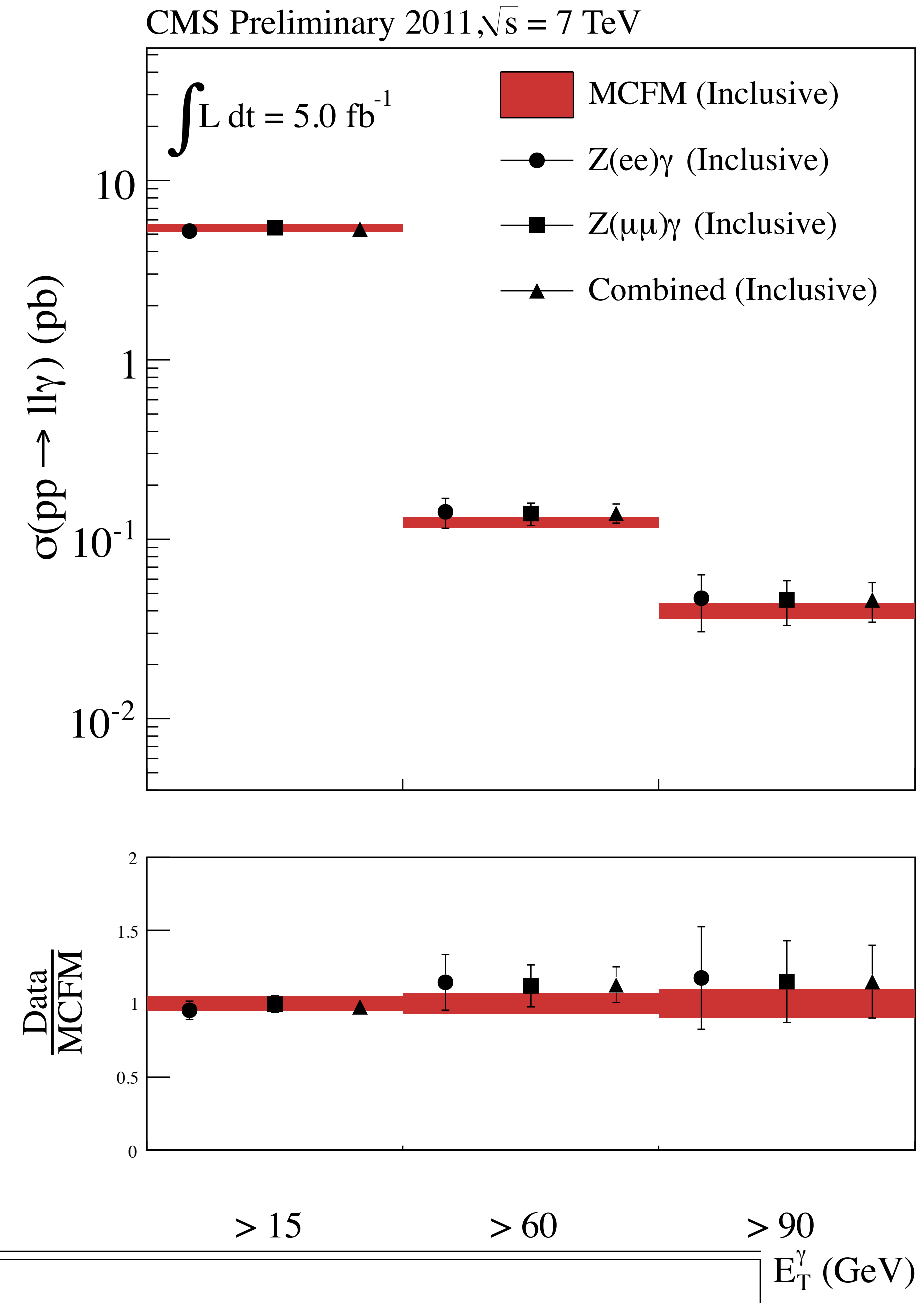
$$\sigma(pp \rightarrow Z\gamma \rightarrow \ell\ell\gamma) = 5.33 \pm 0.08\ (\text{stat.}) \pm 0.25\ (\text{syst.}) \pm 0.12\ (\text{lumi.})\ \text{pb.}$$

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

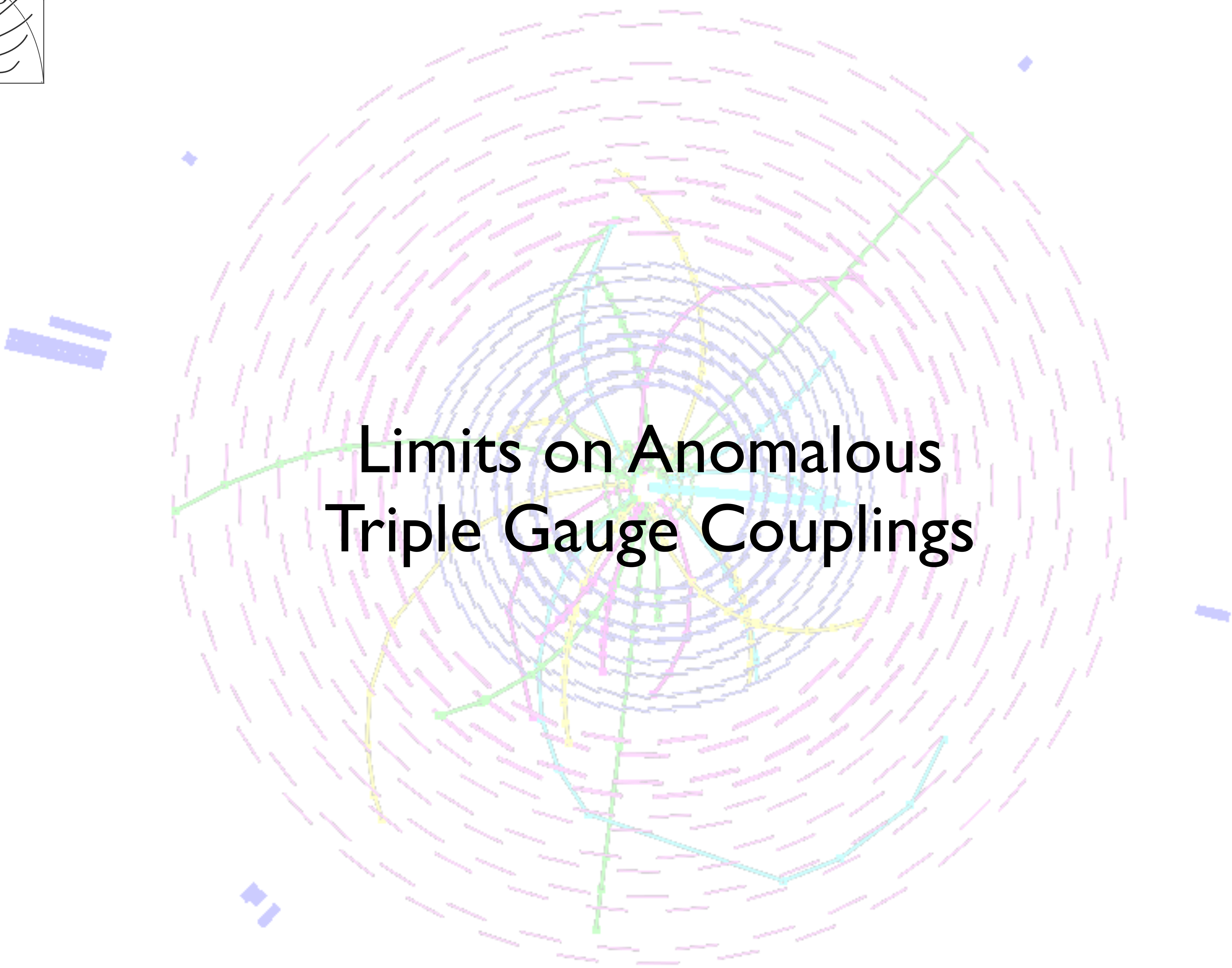
Parameters	$Z\gamma \rightarrow ee\gamma$	$Z\gamma \rightarrow \mu\mu\gamma$
$N_{observed}$	4108 ± 64.1 (stat.)	6463 ± 80.4 (stat.)
$N^{DataDriven}_{background}$	905.9 ± 49.8 (stat.) ± 31.5 (syst.)	1404.3 ± 56.4 (stat.) ± 77.0 (syst.)
$N^{other}_{background}$	21.2 ± 1.8 (stat.)	23.7 ± 2.2 (stat.)
N_{Sig}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

Zγ Cross Section: Theory Comparison

- Zγ cross section consistent with MCFM at higher p_T
  - Error is half systematic at > 60, 90 GeV



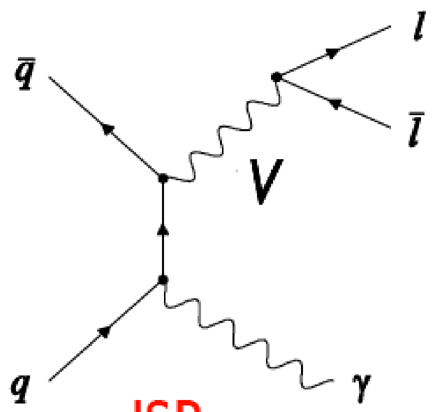
	Zγ	
	$ee\gamma$	$\mu\mu\gamma$
$E_T^\gamma > 60$ GeV	0.142 ± 0.019(stat.) ± 0.019(syst.) ± 0.003(lumi.)	0.139 ± 0.013(stat.) ± 0.015(syst.) ± 0.003(lumi.)
Combination	0.140 ± 0.011(stat.) ± 0.013(syst.) ± 0.003(lumi.) pb	
NLO Prediction	0.124 ± 0.009 pb	
$E_T^\gamma > 90$ GeV	0.047 ± 0.013(stat.) ± 0.010(syst.)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



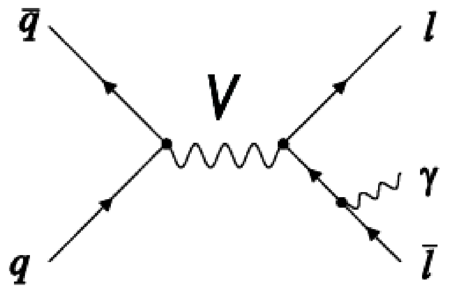
Limits on Anomalous Triple Gauge Couplings

aTGC Limits

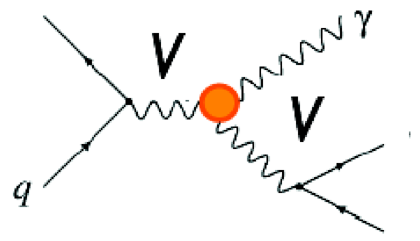
- Non-Abelian $SU(2)_L \times U(1)$ symmetry of SM exactly predicts couplings of gauge bosons
  - Least well-measured portion of the SM
  - Anomalous gauge couplings are a clear sign of BSM physics
- Zγ has no natural triple gauge couplings in the SM
  - CMS sets limits on $h_3^{Z,\gamma}$ and $h_4^{Z,\gamma}$



ISR



FSR



TGC

(ZZγ and Zγγ are not allowed in SM!)

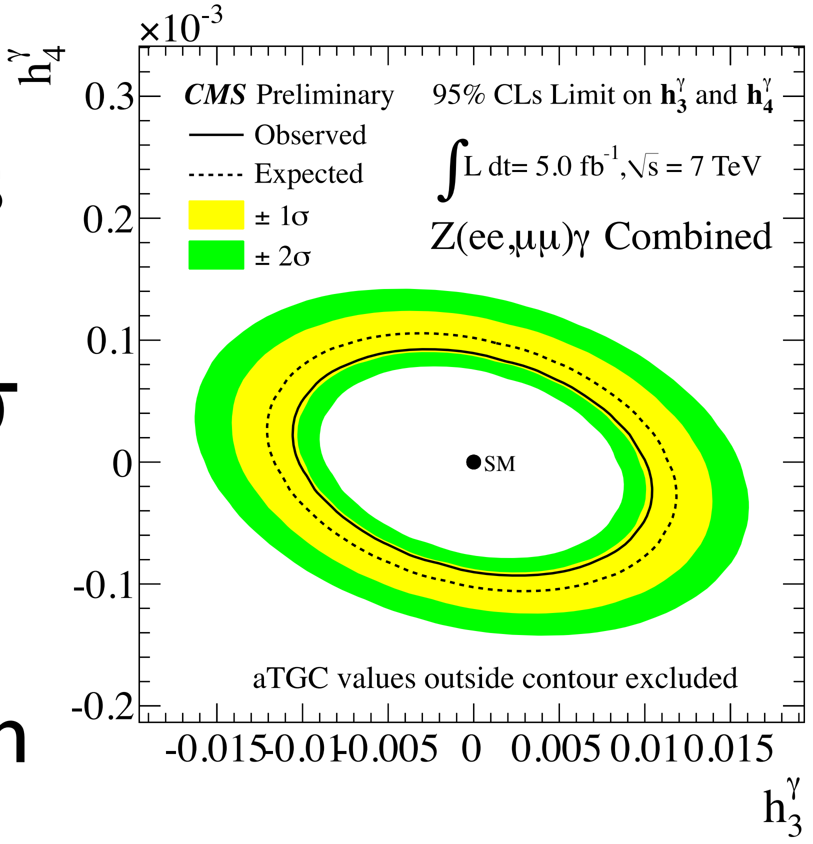
- Form factor **not** applied
  - 'Raw' coupling limits presented

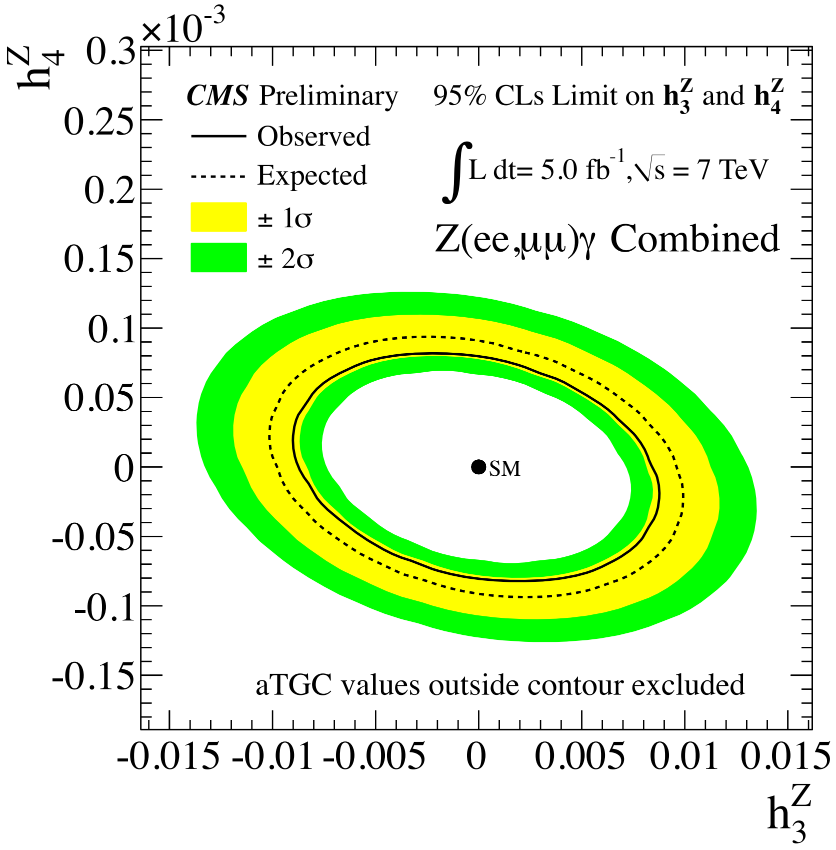
$$\cancel{f(\hat{s}) = \frac{1}{(1+\hat{s}/\Lambda^2)^n}}$$

- Limits set using modified frequentist CLs methodology,

aTGC Limits: Zγ, ee + μμ

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

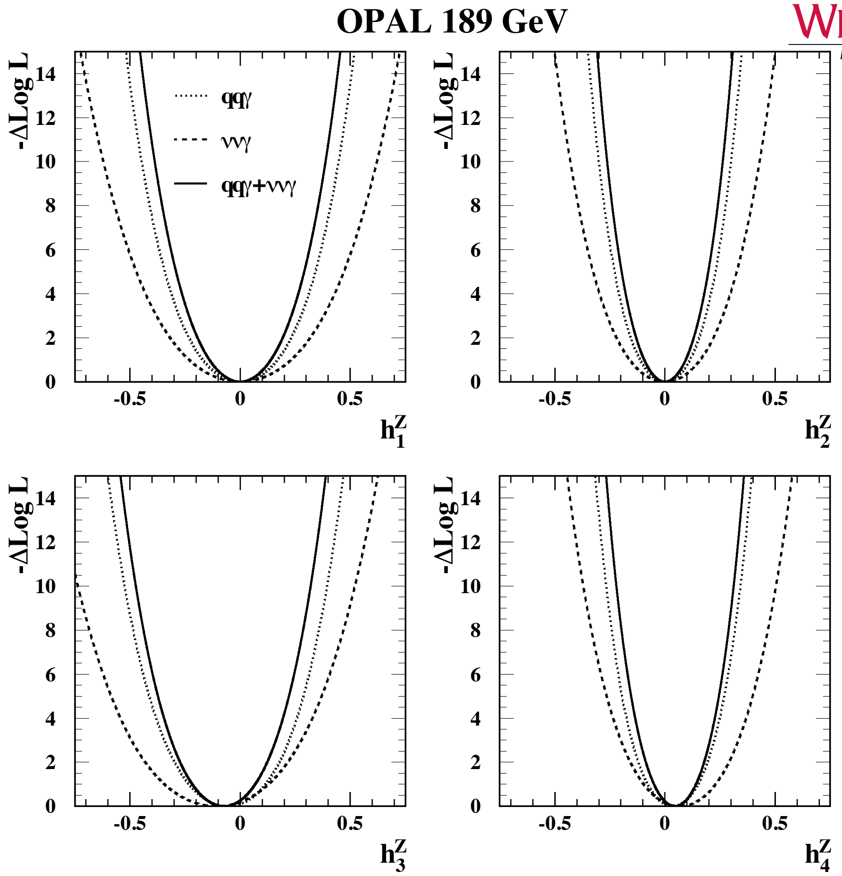


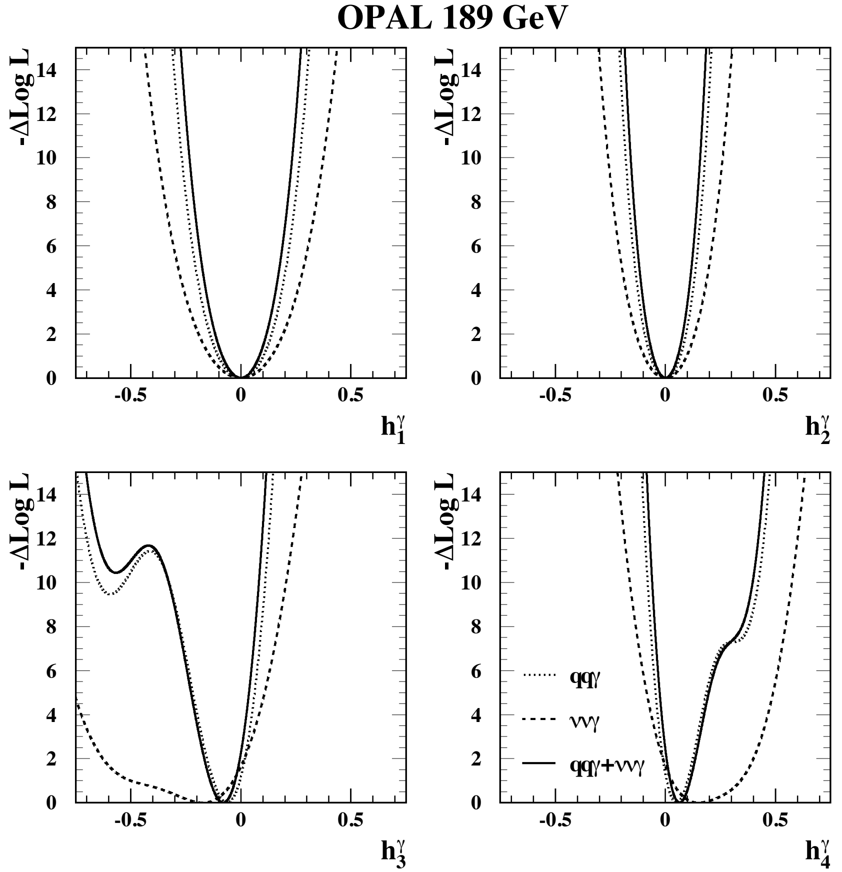


	h_3^γ	h_4^γ	h_3^Z	h_4^Z
$Z\gamma \to ee\gamma$	[-0.013, 0.013]	[-1.1e-4, 1.1e-4]	[-0.011, 0.011]	[-9.9e-5, 9.5e-5]
$Z\gamma \to \mu\mu\gamma$	[-0.013, 0.013]	[-1.1e-4, 1.2e-4]	[-0.011, 0.011]	[-1.0e-4, 1.1e-4]
$Z\gamma \to \ell\ell\gamma$	[-0.010, 0.010]	[-8.8e-5, 8.8e-5]	[-8.6e-3, 8.4e-3]	[-8.0e-5,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

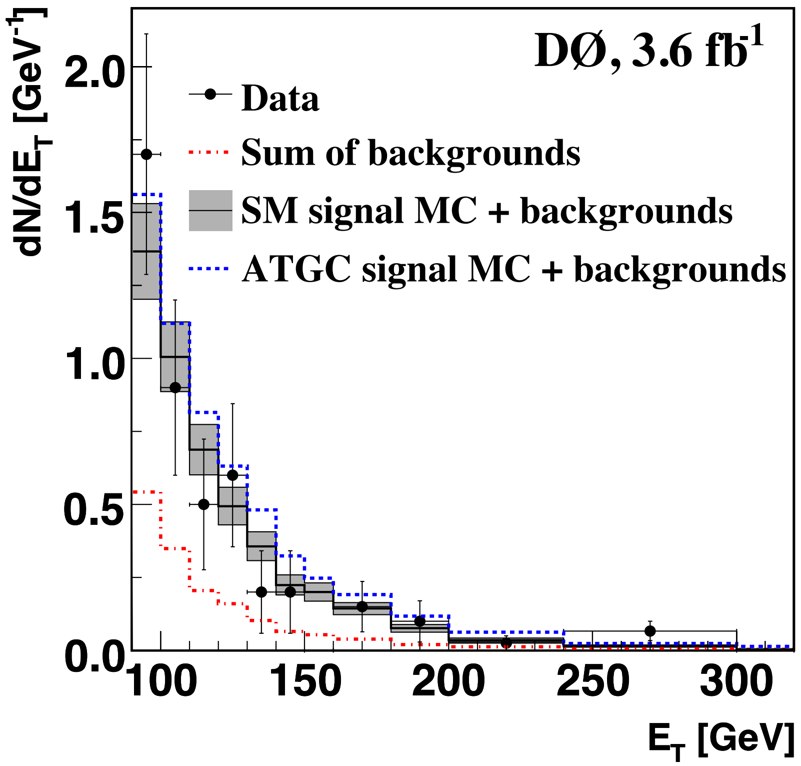


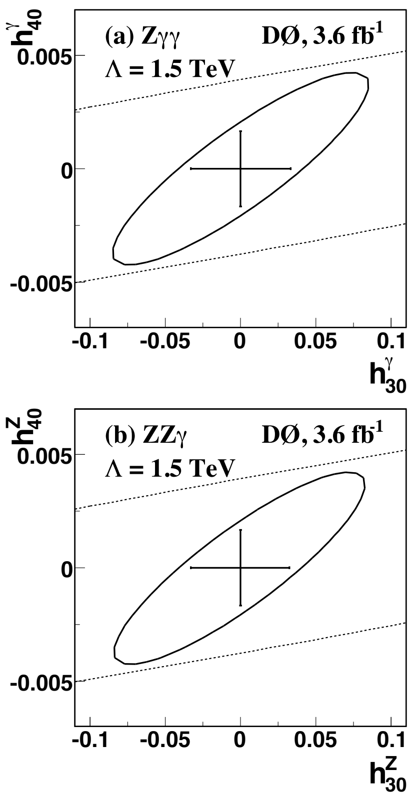


95% CL @ $-\Delta \log L = 1.96$

CMS aTGC Limits Comparison: Tevatron

- All Tevatron limits set using form factor and p_T distribution
  - Λ < energies at LHC
  - LHC would resolve particles responsible for low energy aTGCs in this case
    - Not physically relevant scenario
    - Arbitrarily limits LHC sensitivity
  - Cannot directly compare





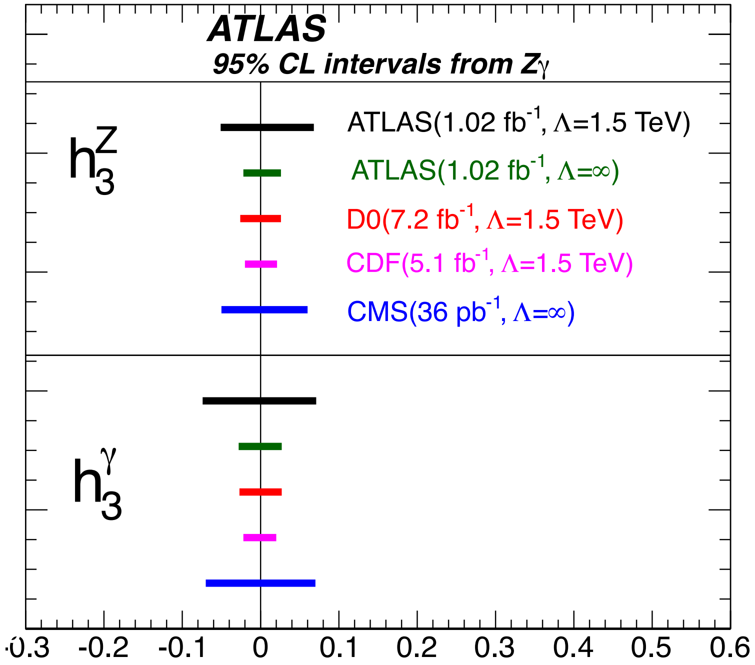
CDF:

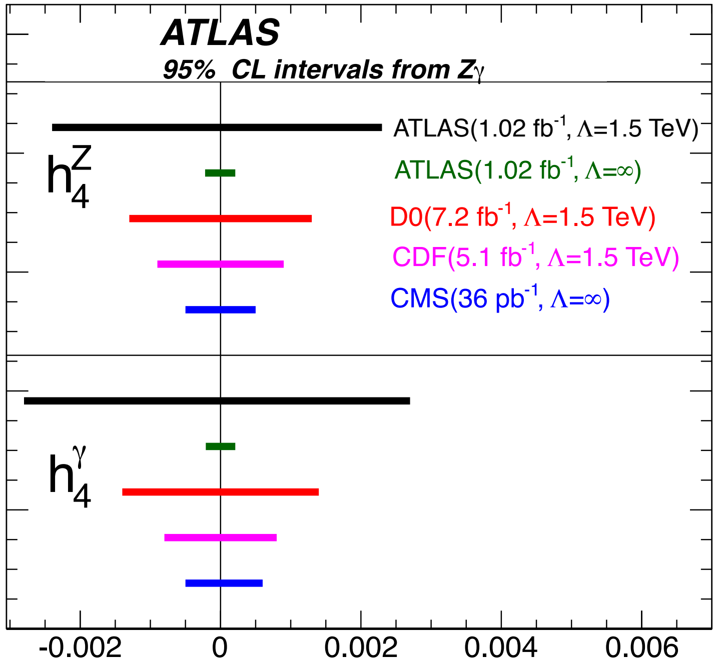
Parameter	$(\Lambda = 1.2$ TeV$)$	$(\Lambda = 1.5$ TeV$)$
h_3^Z	[-0.024,0.027]	[-0.020,0.021]
h_4^Z	[-0.0013,0.0013]	[-0.0009,0.0009]
h_3^γ	[-0.026,0.026]	[-0.022,0.020]
h_4^γ	[-0.0012,0.0013]	[-0.0008,0.0008]

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

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 $1/\sqrt{5}$





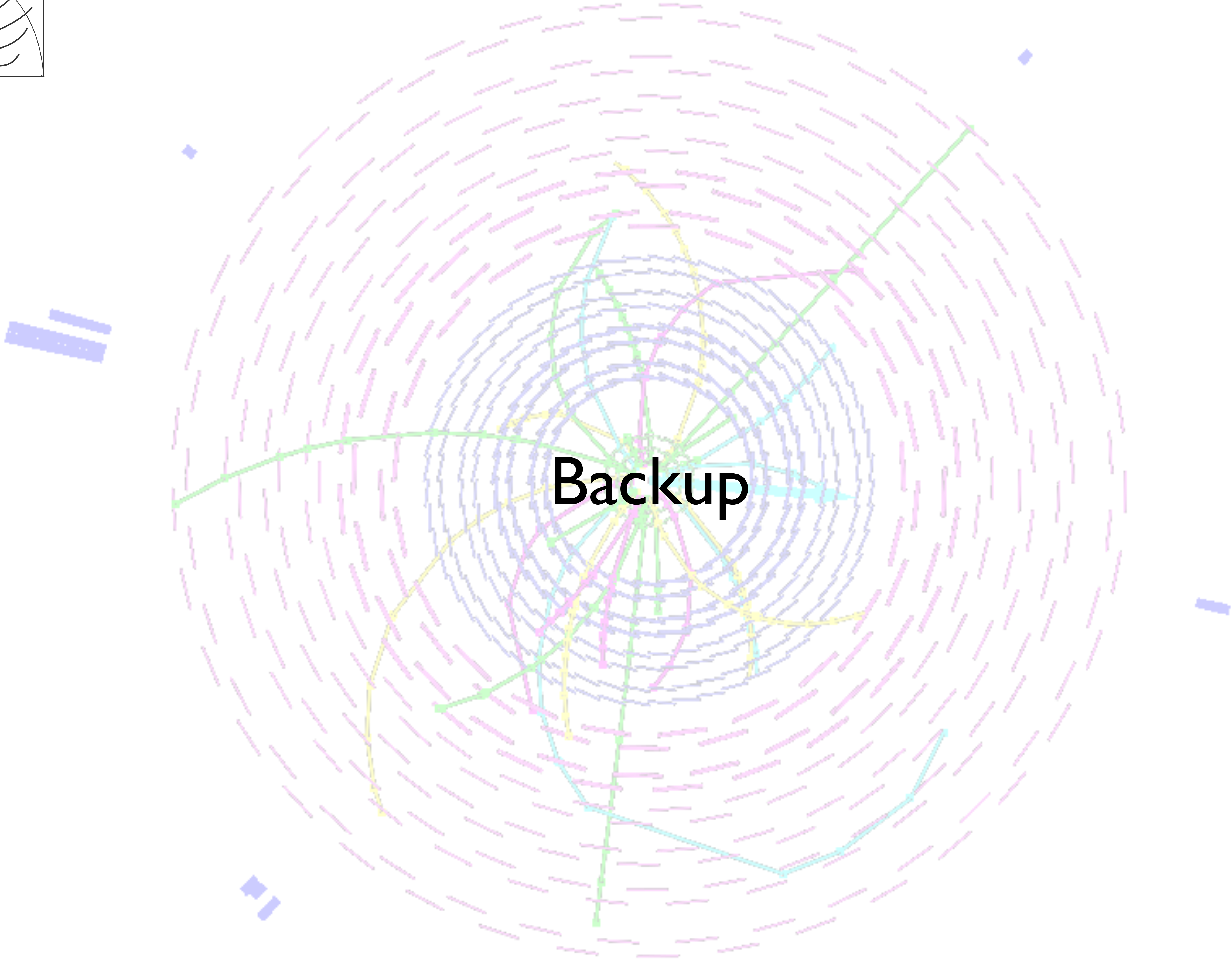
	Measured	Measured	Expected
Λ	1.5 TeV	∞	∞
h_3^γ	(-0.074,0.071)	(-0.028,0.027)	(-0.027,0.027)
h_3^Z	(-0.051,0.068)	(-0.022,0.026)	(-0.022,0.025)
h_4^γ	(-0.0028,0.0027)	(-0.00021,0.00021)	(-0.00021,0.00021)
h_4^Z	(-0.0024,0.0023)	(-0.00022,0.00021)	(-0.00022,0.00021)

CMS:

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

Conclusions

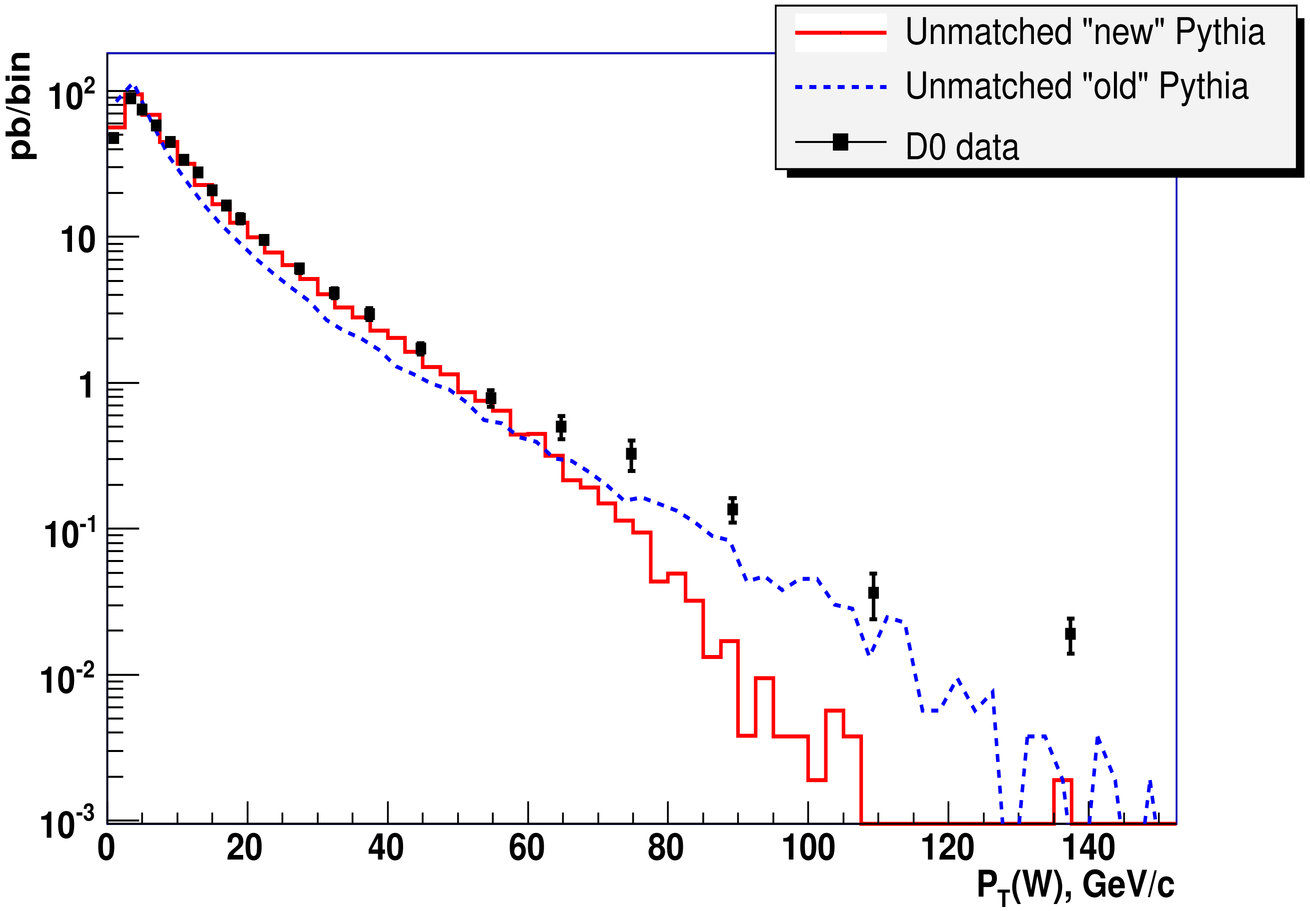
- Presented a complete analysis of the Zγ final state
    - Cross Section measurements:
        - photon p_T > 15, 60, 90 GeV
    - Anomalous triple gauge coupling limits
        - Better than most recent ATLAS by statistics in charged lepton channels
- Outlook
    - 2012 LHC data at 8 TeV improves kinematic reach
        - Zγ 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



Backup

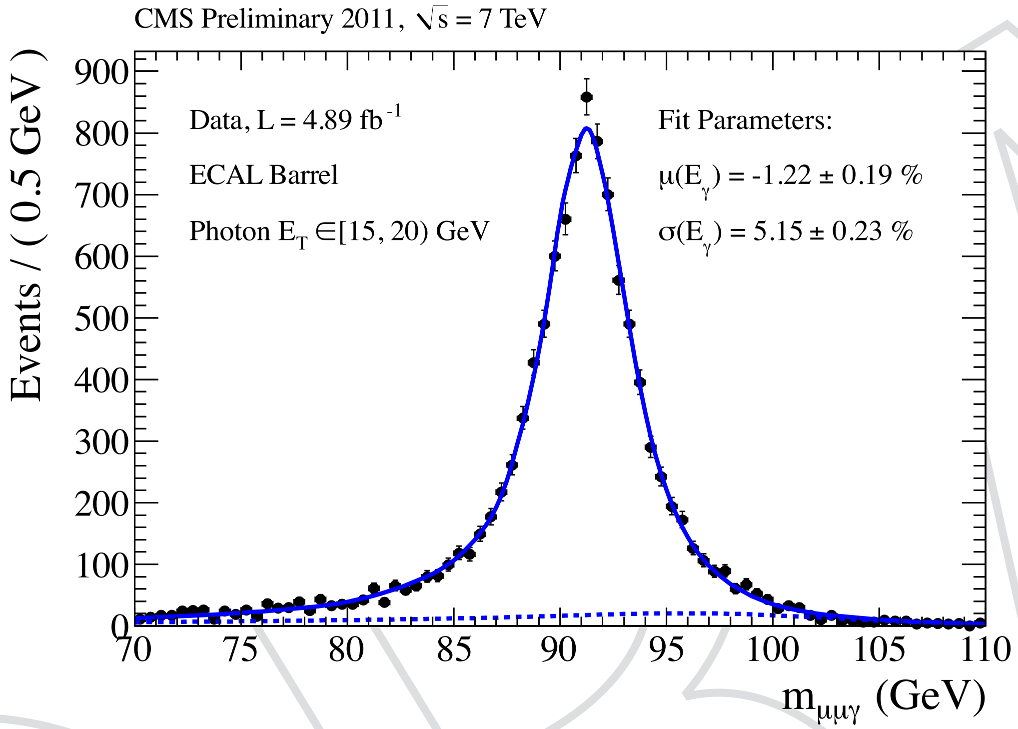
Limited Phase Space in Shower MC

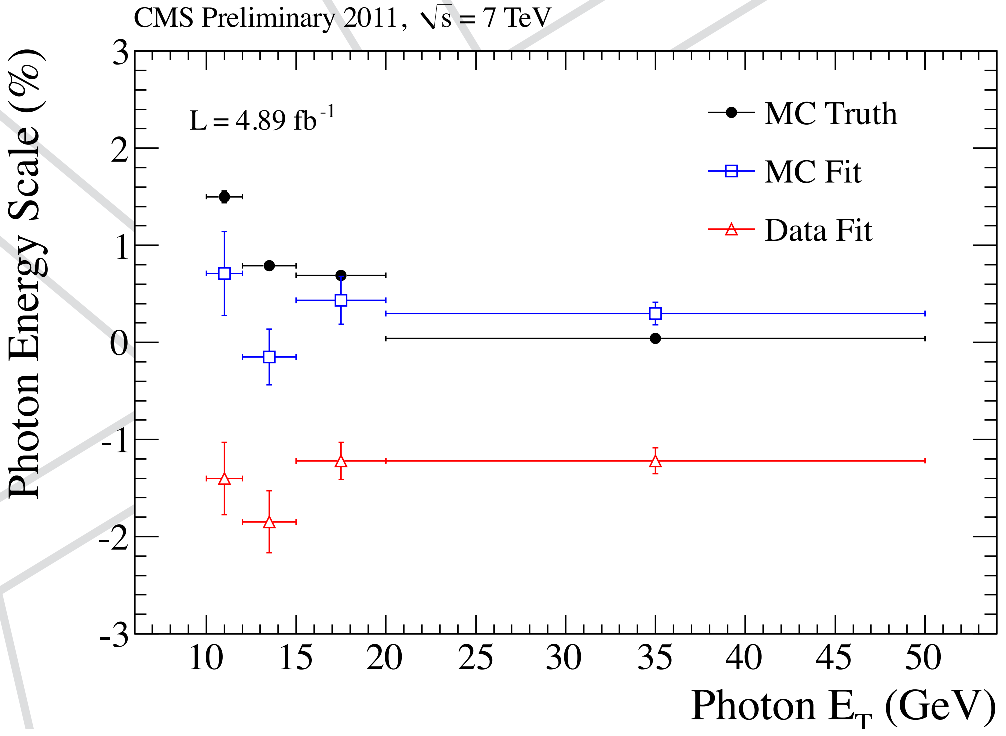
- Each SMC hard parton considered alone
  - Limits phase space
  - Results in poor modeling at high p_T of the matrix element part of the event



Photon Energy Corrections From PHOSPHOR

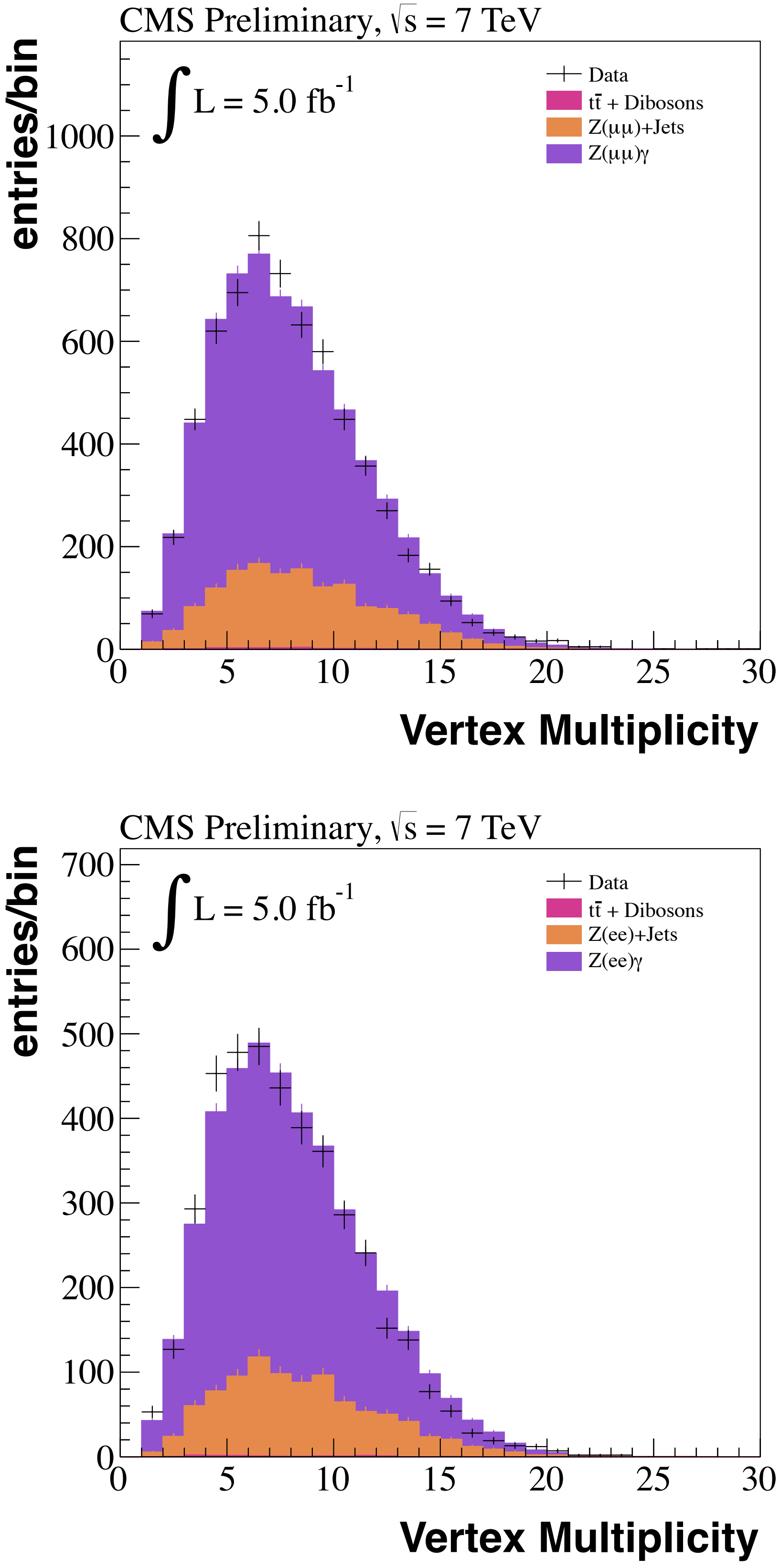
- Data-driven fit of PHOton Scale and Resolution
- Uses FSR μμγ invariant mass
  - Energy Scale from Z peak position
  - Energy Resolution from Z width
- Pileup dependence of energy scale is averaged over by run period
- Scale in data is different from MC due to
  - Material budget mis-modeling
  - GEANT4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





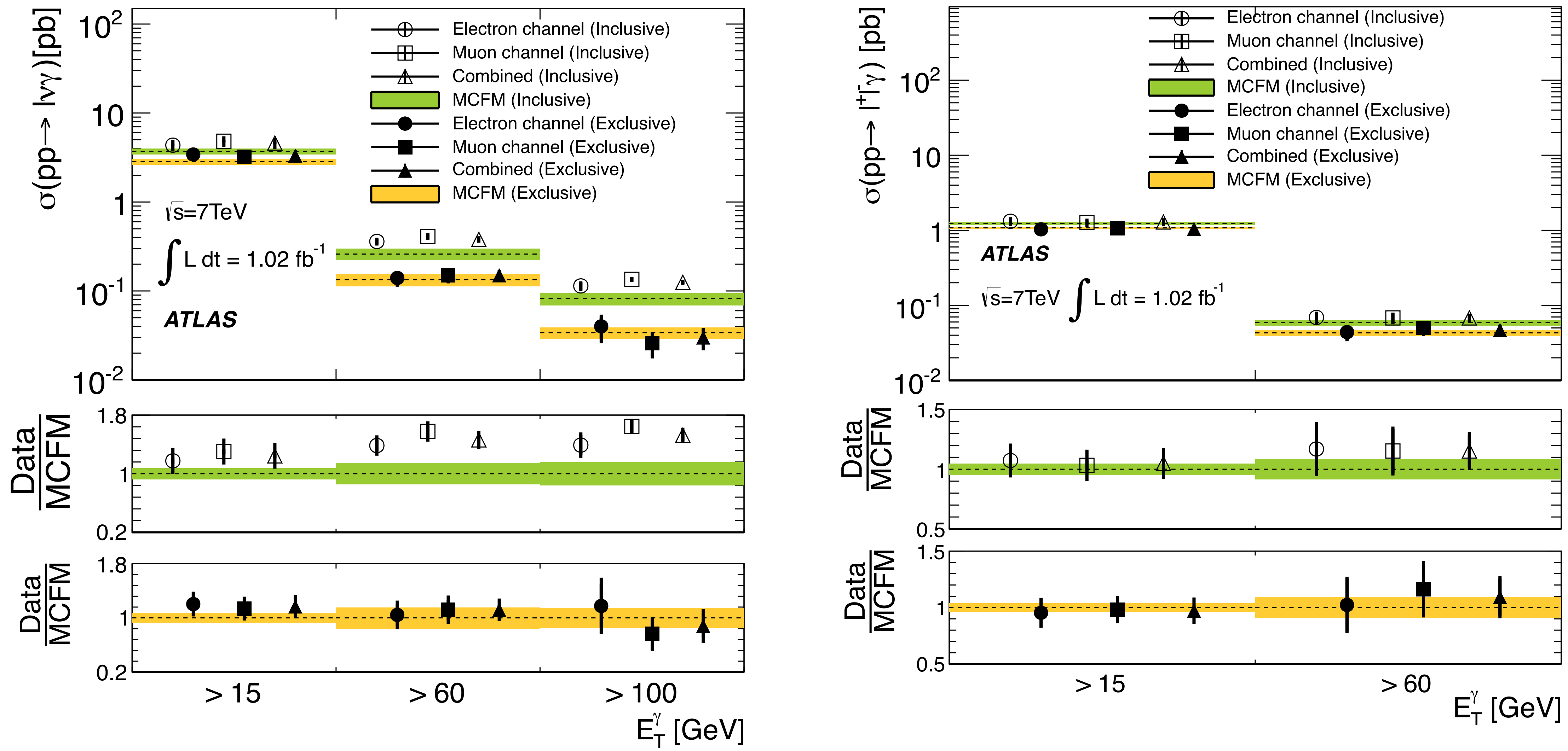
Zγ Distributions: Vertex Multiplicity

- Pileup Reweighing checks out fine



ATLAS Results: Cross Section

http://arxiv.org/abs/1205.2531



(a)

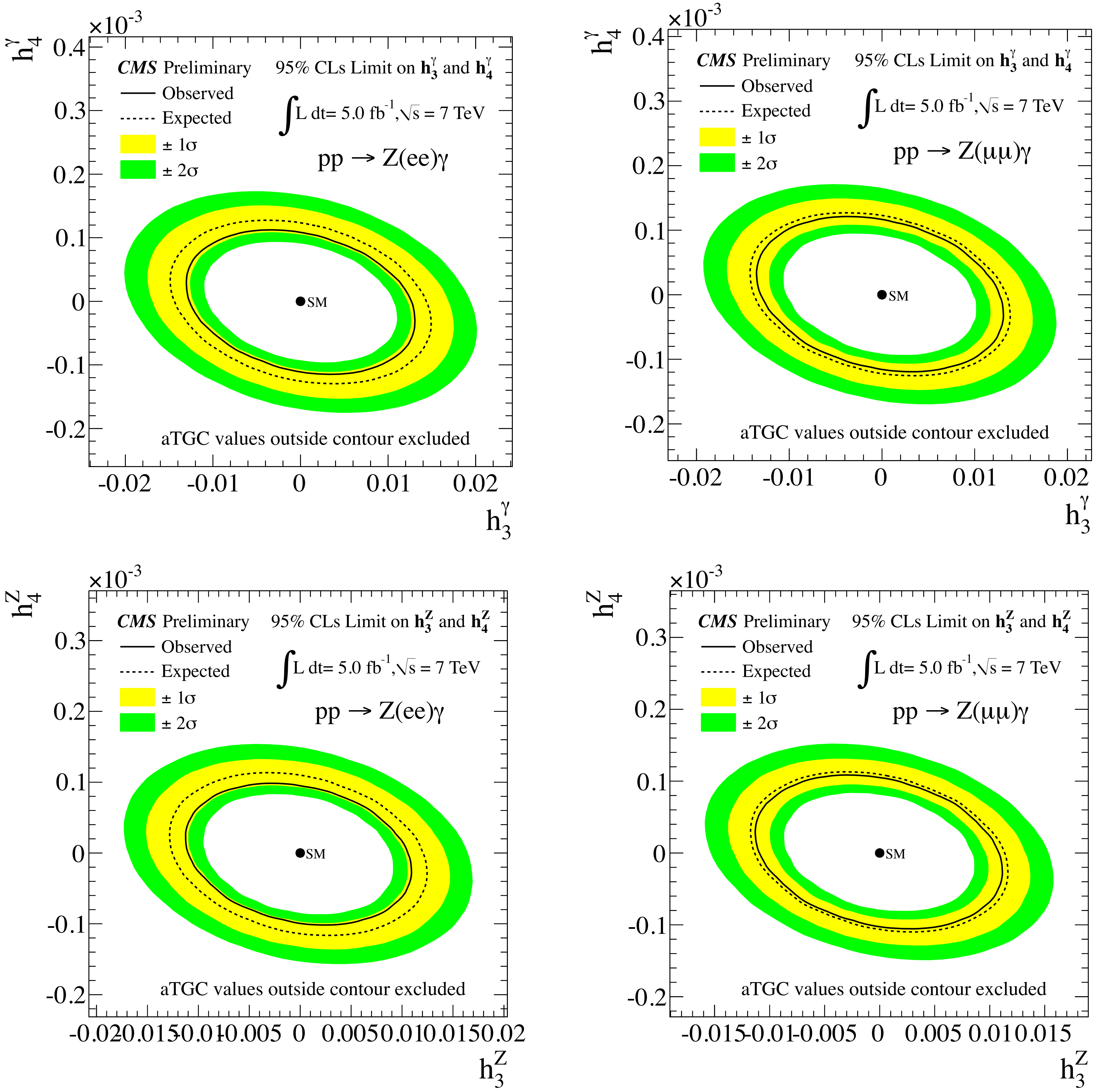
(b)

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.

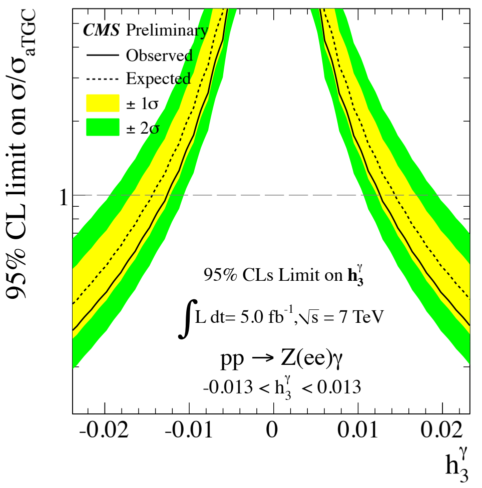
CMS Cross Section Theory Comparison

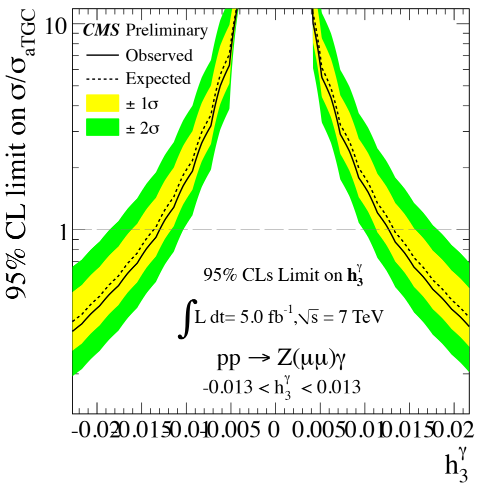
	Zγ	
	$ee\gamma$	$\mu\mu\gamma$
$E_{\mathrm{T}}^{\gamma} > 60$ GeV	$0.142 \pm 0.019(\text{stat.}) \pm 0.019(\text{syst.}) \pm 0.003(\text{lumi.})$	$0.139 \pm 0.013(\text{stat.}) \pm 0.015(\text{syst.}) \pm 0.003(\text{lumi.})$
Combination	$0.140 \pm 0.011(\text{stat.}) \pm 0.013(\text{syst.}) \pm 0.003(\text{lumi.})$ pb	
NLO Prediction	0.124 ± 0.009 pb	
$E_{\mathrm{T}}^{\gamma} > 90$ 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	

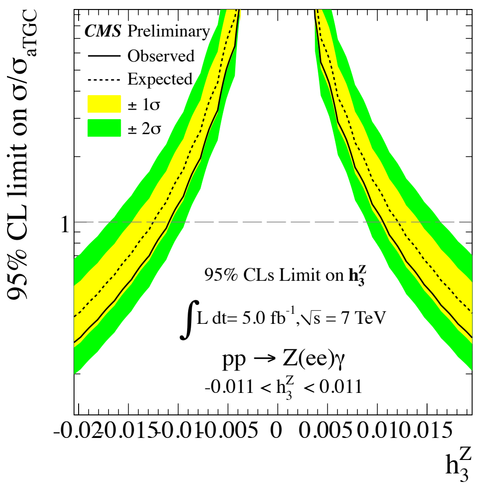
CMS aTGCs: Zγ Detail

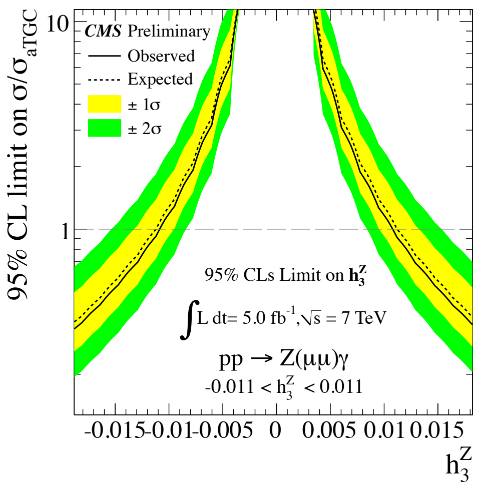


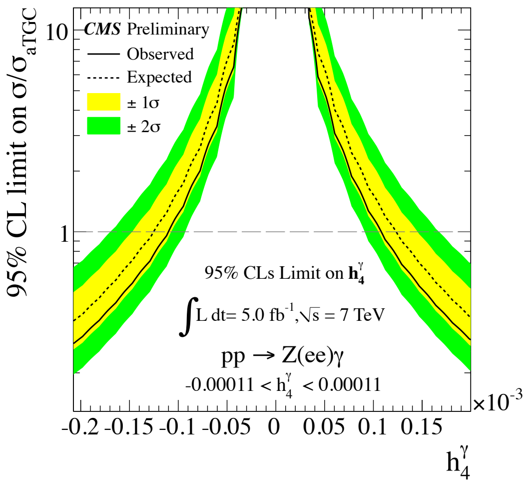
CMS aTGCs: Zγ Detail

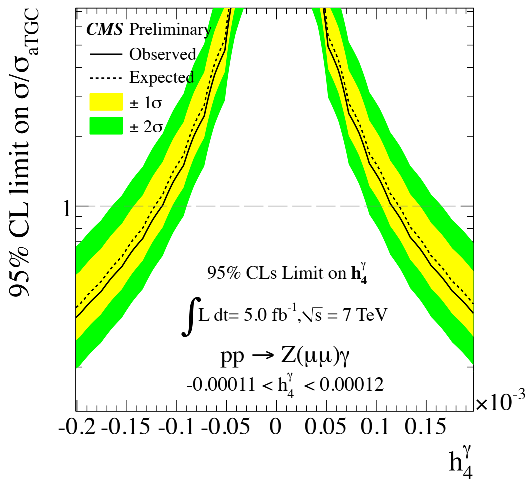


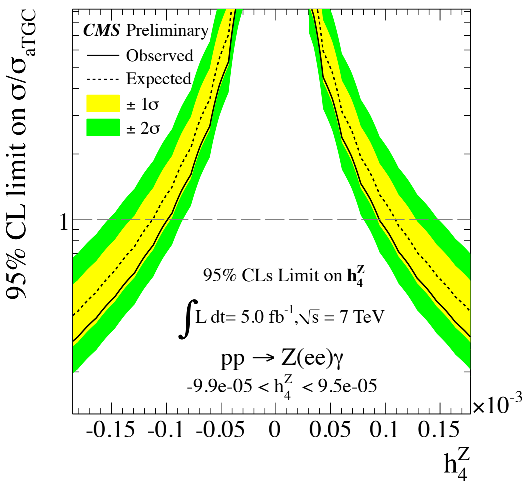


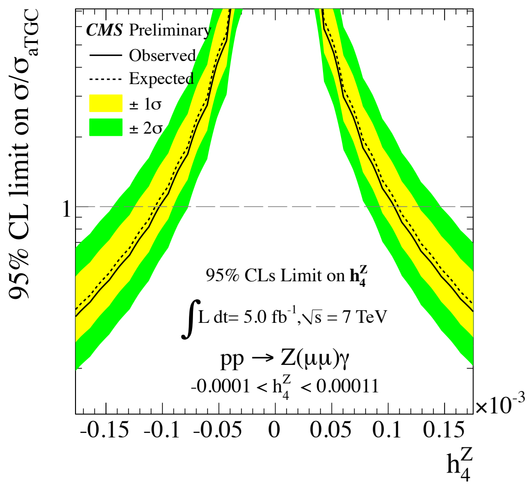






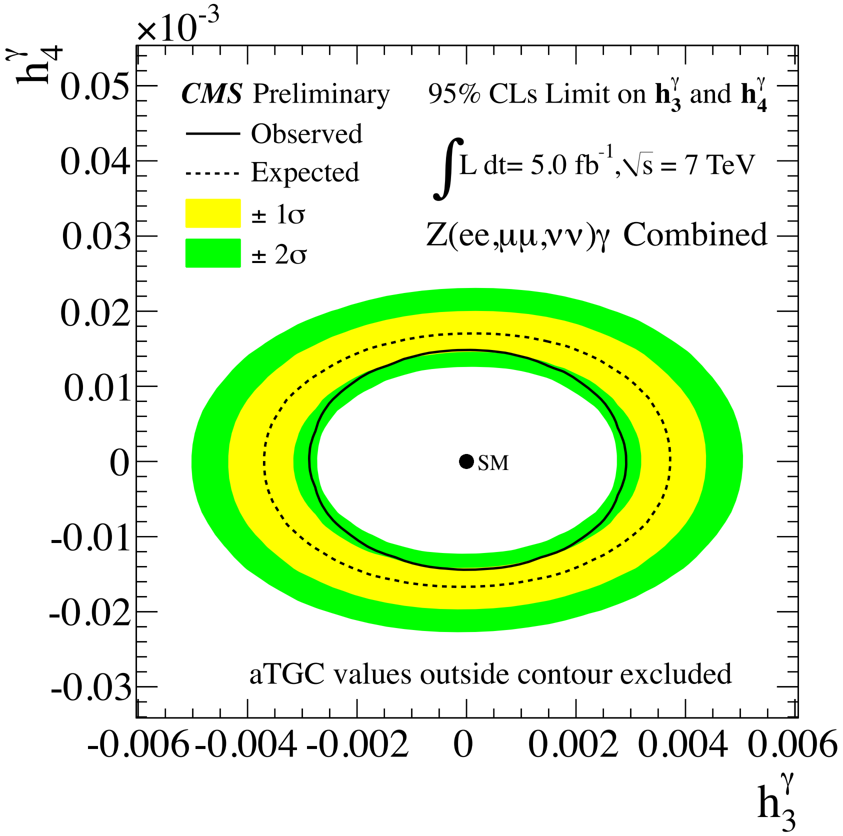


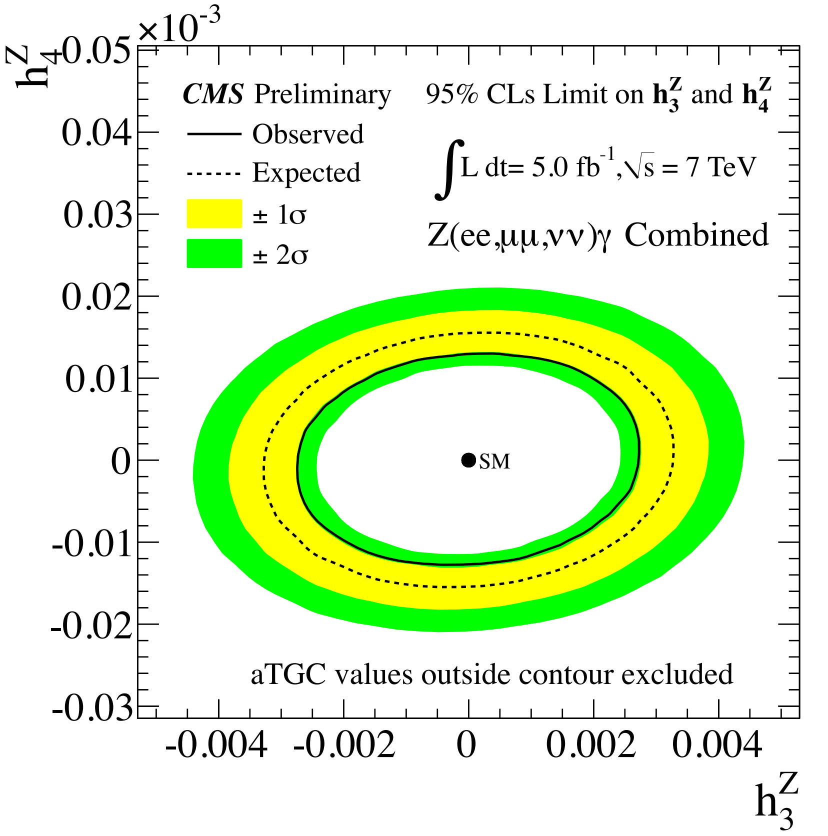




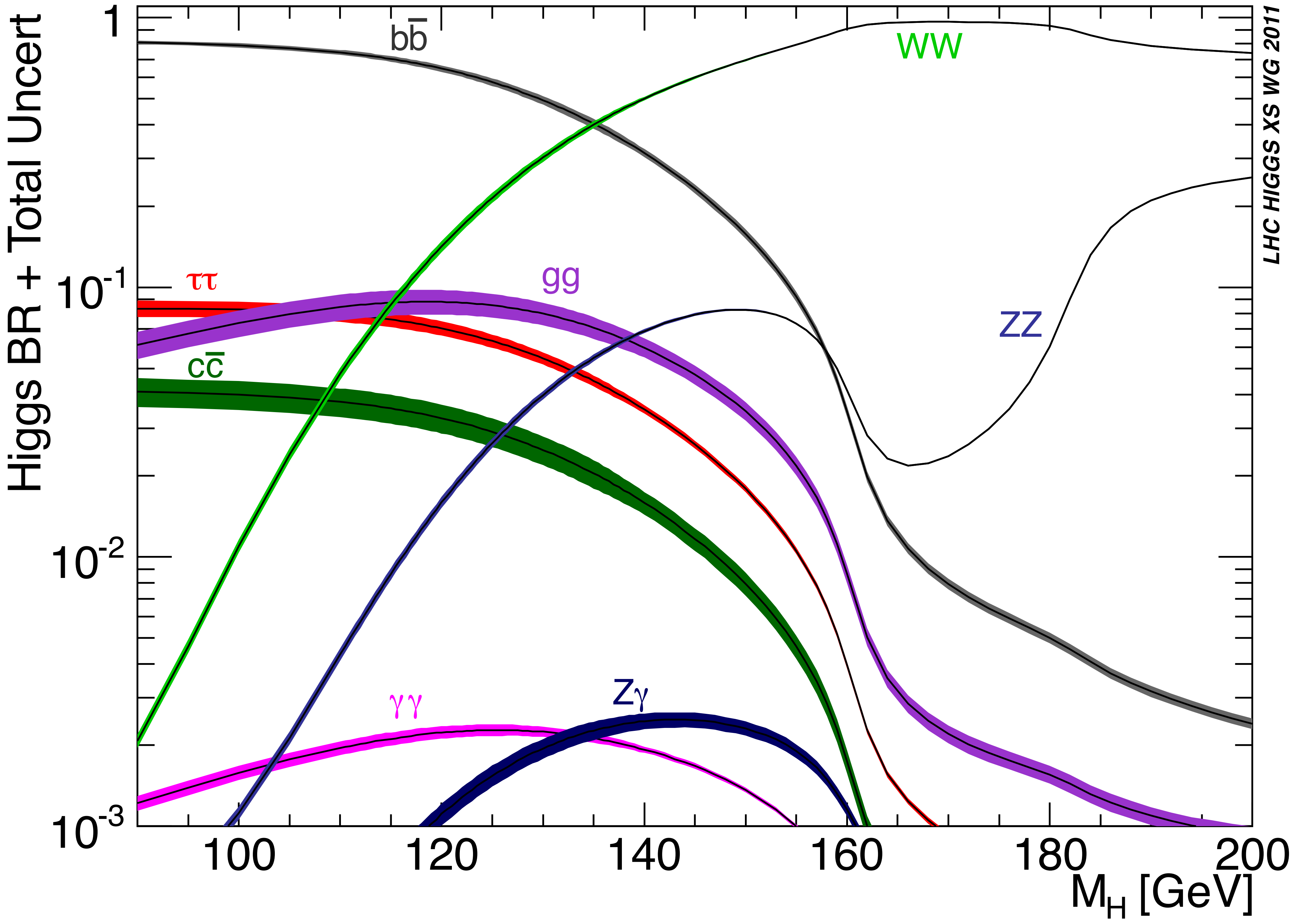
aTGC Limits: Zγ, ee + μμ + νν

- Z(νν)γ has significantly more statistical power at large photon p_T
  - Combine with charged lepton limit to achieve 6x improvement
- Limits 1-1.5σ under-fluctuated
  - Driven by under-fluctuations in ee and νν channels





Zγ and Higgs Production



Datasets Used in the Vγ Analyses

MC Signal:

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

*aTGC samples produced with SHERPA

Data:

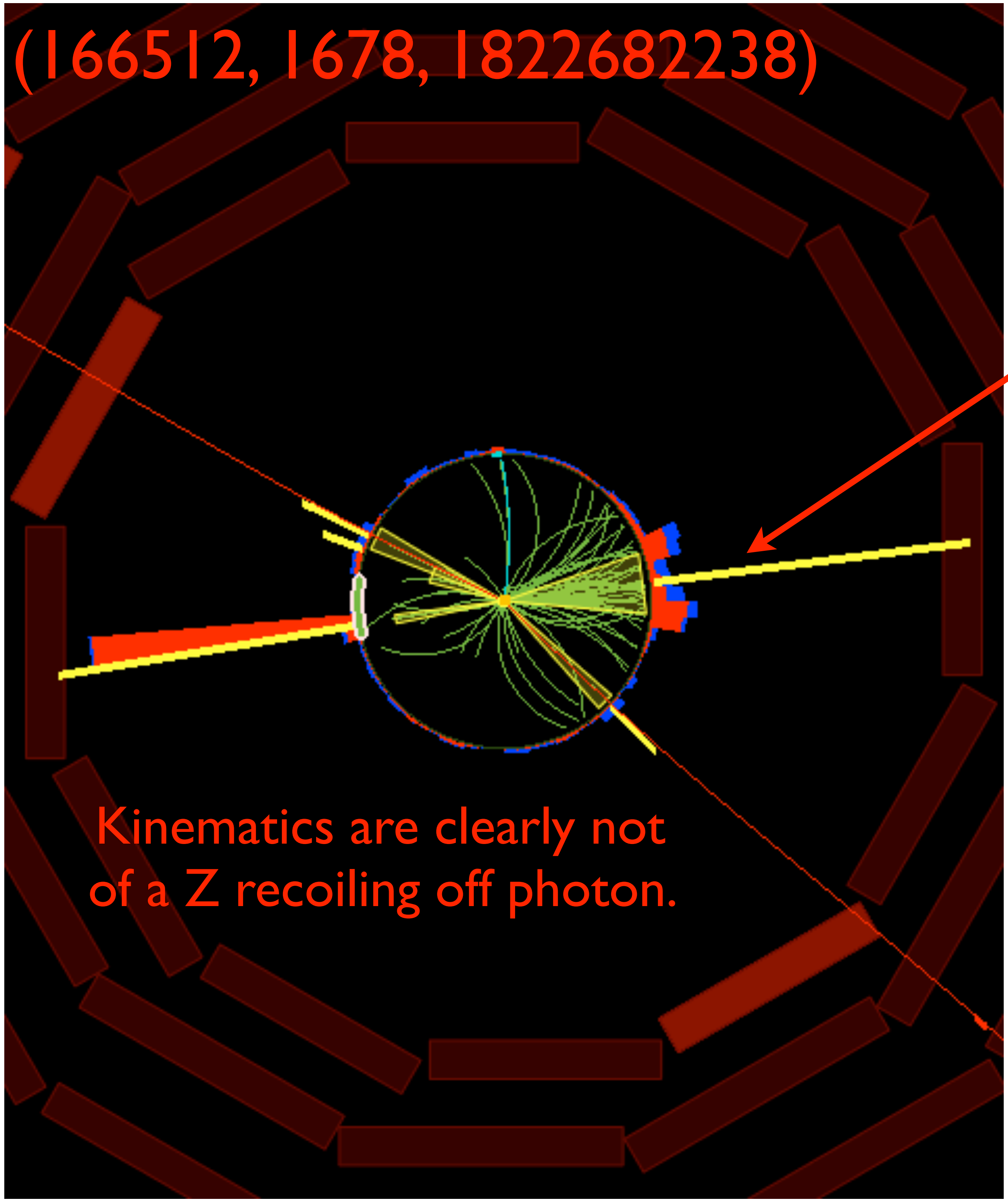
CMS Run Range	Dataset Name	Used by
160404 - 163869	/SingleElectron/Run2011A-May10ReReco-v1/AOD	$W\gamma \to e\nu + \gamma$
165071 - 167913	/SingleElectron/Run2011A-PromptReco-v4/AOD	$W\gamma \to e\nu + \gamma$
170249 - 172619	/SingleElectron/Run2011A-05Aug2011-v1/AOD	$W\gamma \to e\nu + \gamma$
172620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

Process (Fall11)	σ, pb	Dataset Name (AODSIM data tier)
$W\gamma \to e\nu\gamma$	137.3 (NLO)	`/WGToENuG_TuneZ2_7TeV-madgraph-tauola`
$W\gamma \to \mu\nu\gamma$	137.3 (NLO)	`/WGToMuNuG_TuneZ2_7TeV-madgraph-tauola`
$W\gamma \to \tau\nu\gamma$	137.3 (NLO)	`/WGToTauNuG_TuneZ2_7TeV-madgraph-tauola`
$Z\gamma \to ee\gamma$	45.2 (NLO)	`/ZGToEEG_TuneZ2_7TeV-madgraph-tauola`
$Z\gamma \to \mu\mu\gamma$	45.2 (NLO)	`/ZGToMuMuG_TuneZ2_7TeV-madgraph-tauola`
$Z\gamma \to \tau\tau\gamma$	45.2 (NLO)	`/ZGToTauTauG_TuneZ2_7TeV-madgraph-tauola`
$W \to l\nu + jets$	31314 (NNLO)	`/WJetsToLNu_TuneZ2_7TeV-madgraph-tauola`
$Z \to ll + jets$	3048 (NNLO)	`/DYJetsToLL_TuneZ2_M-50_7TeV-madgraph-tauola`
$t\bar{t} + jets$	165 (NNLO)	`/TTJets_TuneZ2_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)	`/GJet_Pt-20_doubleEMEnriched_TuneZ2_7TeV-pythia6`
$QCD(p_T - 30to40) DoubleEMEnriched$	9614 (LO)	`/QCD_Pt-30to40_doubleEMEnriched_TuneZ2_7TeV-pythia6`
$QCD(p_T - 40) DoubleEMEnriched$	40392 (LO)	`/QCD_Pt-40_doubleEMEnriched_TuneZ2_7TeV-pythia6`

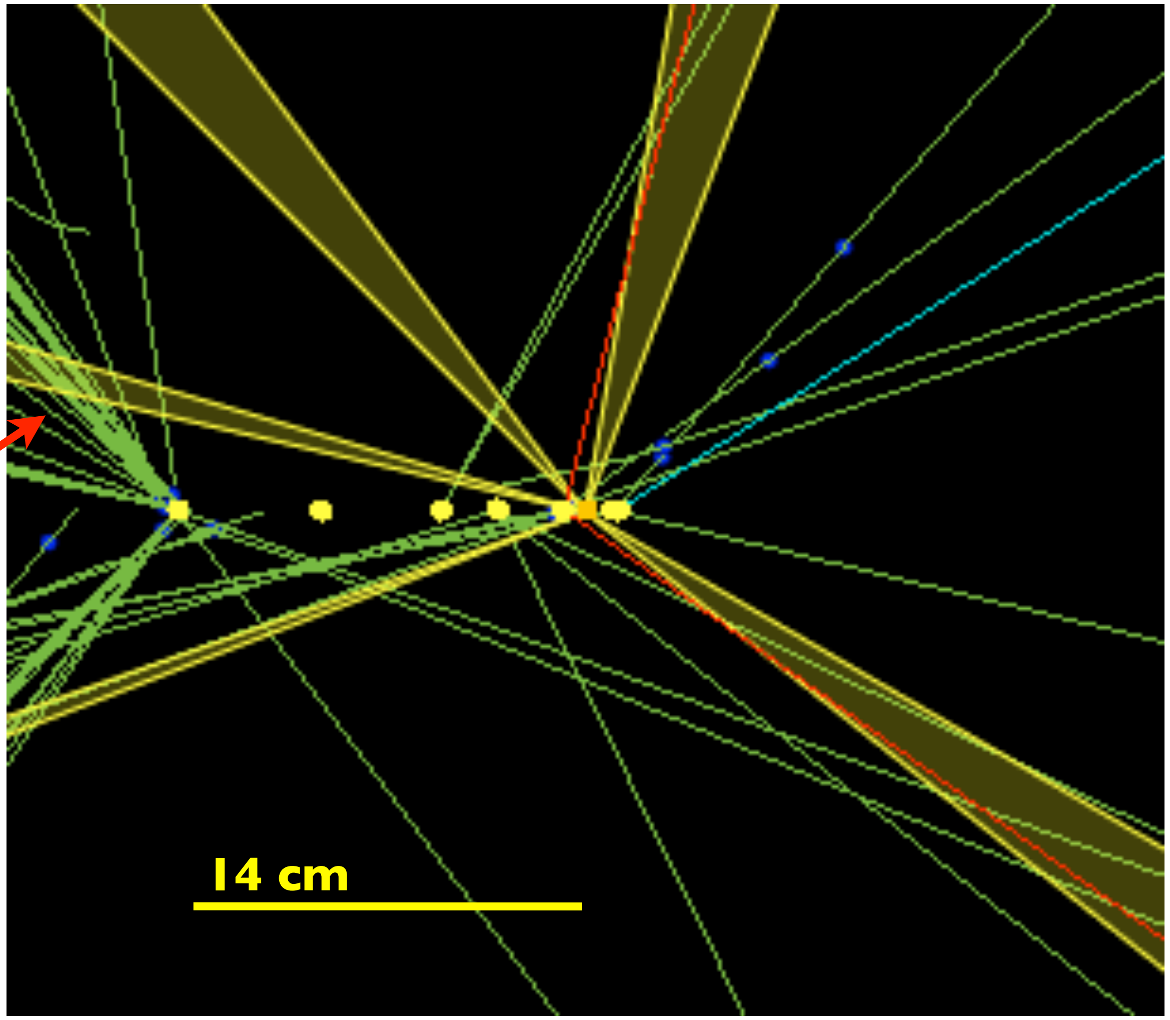
Process (Summer11)	σ, pb	Dataset Name (AODSIM data tier)
$\gamma + jets(\hat{p_T} : 0 - 15)$	8.420×10^7	`/G_Pt_0to15_TuneZ2_7TeV_pythia6`
$\gamma + jets(\hat{p_T} : 15 - 30)$	1.717×10^5	`/G_Pt_15to30_TuneZ2_7TeV_pythia6`
$\gamma + jets(\hat{p_T} : 30 - 50)$	1.669×10^4	`/G_Pt_30to50_TuneZ2_7TeV_pythia6`
$\gamma + jets(\hat{p_T} : 50 - 80)$	2.722×10^3	`/G_Pt_50to80_TuneZ2_7TeV_pythia6`
$\gamma + jets(\hat{p_T} : 80 - 120)$	4.472×10^2	`/G_Pt_80to120_TuneZ2_7TeV_pythia6`
$\gamma + jets(\hat{p_T} : 120 - 170)$	8.417×10^1	`/G_Pt_120to170_TuneZ2_7TeV_pythia6`
$\gamma + jets(\hat{p_T} : 170 - 300)$	2.264×10^1	`/G_Pt_170to300_TuneZ2_7TeV_pythia6`
$\gamma + jets(\hat{p_T} : 300 - 470)$	1.493	`/G_Pt_300to470_TuneZ2_7TeV_pythia6`
$QCD(\hat{p_T} : 5 - 15)$	3.675×10^{10}	`/QCD_Pt_5to15_TuneZ2_7TeV_pythia6`
$QCD(\hat{p_T} : 15 - 30)$	8.159×10^8	`/QCD_Pt_15to30_TuneZ2_7TeV_pythia6`
$QCD(\hat{p_T} : 30 - 50)$	5.312×10^7	`/QCD_Pt_30to50_TuneZ2_7TeV_pythia6`
$QCD(\hat{p_T} : 50 - 80)$	6.359×10^6	`/QCD_Pt_50to80_TuneZ2_7TeV_pythia6`
$QCD(\hat{p_T} : 80 - 120)$	7.843×10^5	`/QCD_Pt_80to120_TuneZ2_7TeV_pythia6`
$QCD(\hat{p_T} : 120 - 170)$	1.151×10^5	`/QCD_Pt_120to170_TuneZ2_7TeV_pythia6`
$QCD(\hat{p_T} : 170 - 300)$	2.426×10^4	`/QCD_Pt_170to300_TuneZ2_7TeV_pythia6`
$QCD(\hat{p_T} : 300 - 470)$	1.168×10^3	`/QCD_Pt_300to470_TuneZ2_7TeV_pythia6`
$QCD(\hat{p_T} : 470 - 600)$	7.022×10^1	`/QCD_Pt-470to600_TuneZ2_7TeV_pythia6`
$QCD(\hat{p_T} > 20)$	84679.3	`/QCD_Pt-20_MuEnrichedPt-15_TuneZ2_7TeV_pythia`

‘Zγ’ Pileup Combinatorial Event



(166512, 1678, 1822682238)

Kinematics are clearly not of a Z recoiling off photon.



This event removed from final selection.