The first CERN Philippine School

Physics Analyses

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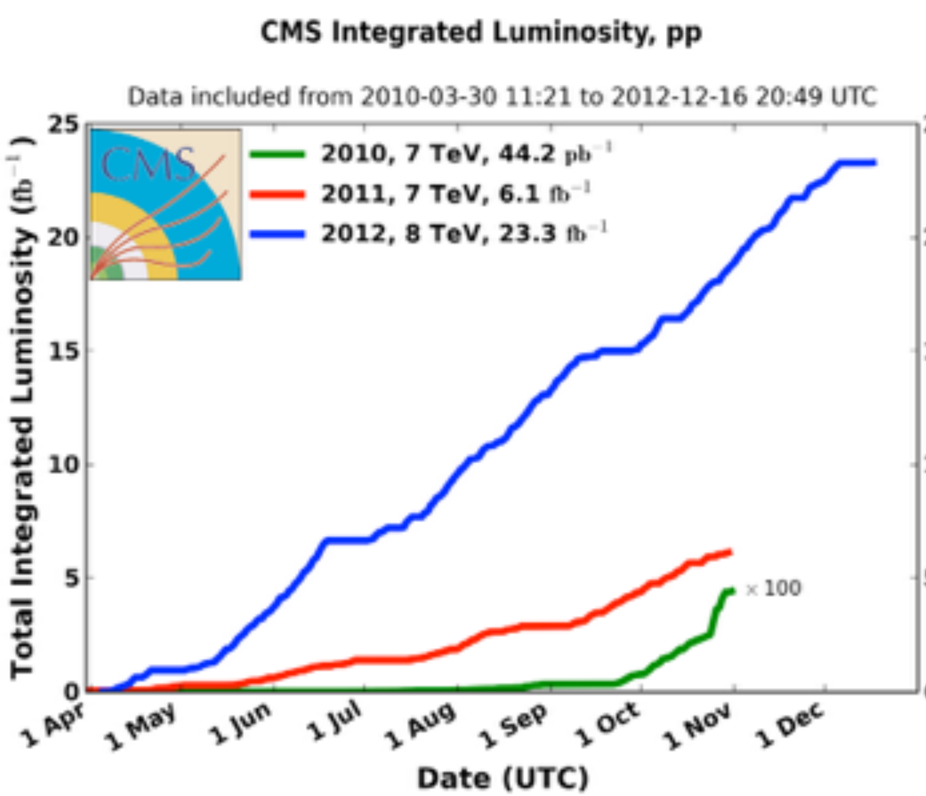
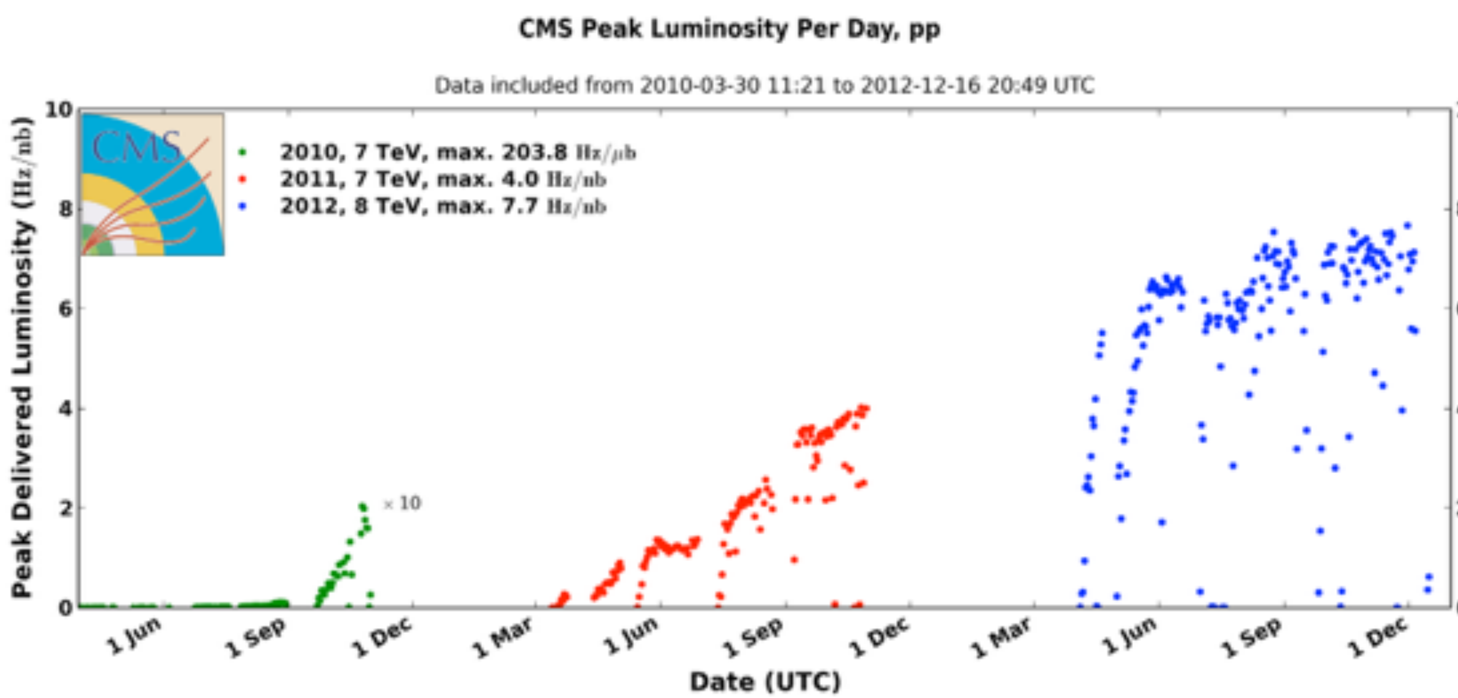
Lecture 3 : Physics Analyses

- Single W and Z analysis
- W charged asymmetry
- Diboson Wγ and Zγ production
- Triboson WVγ production
- H→Zγ

Luminosity from 2010 to 2012

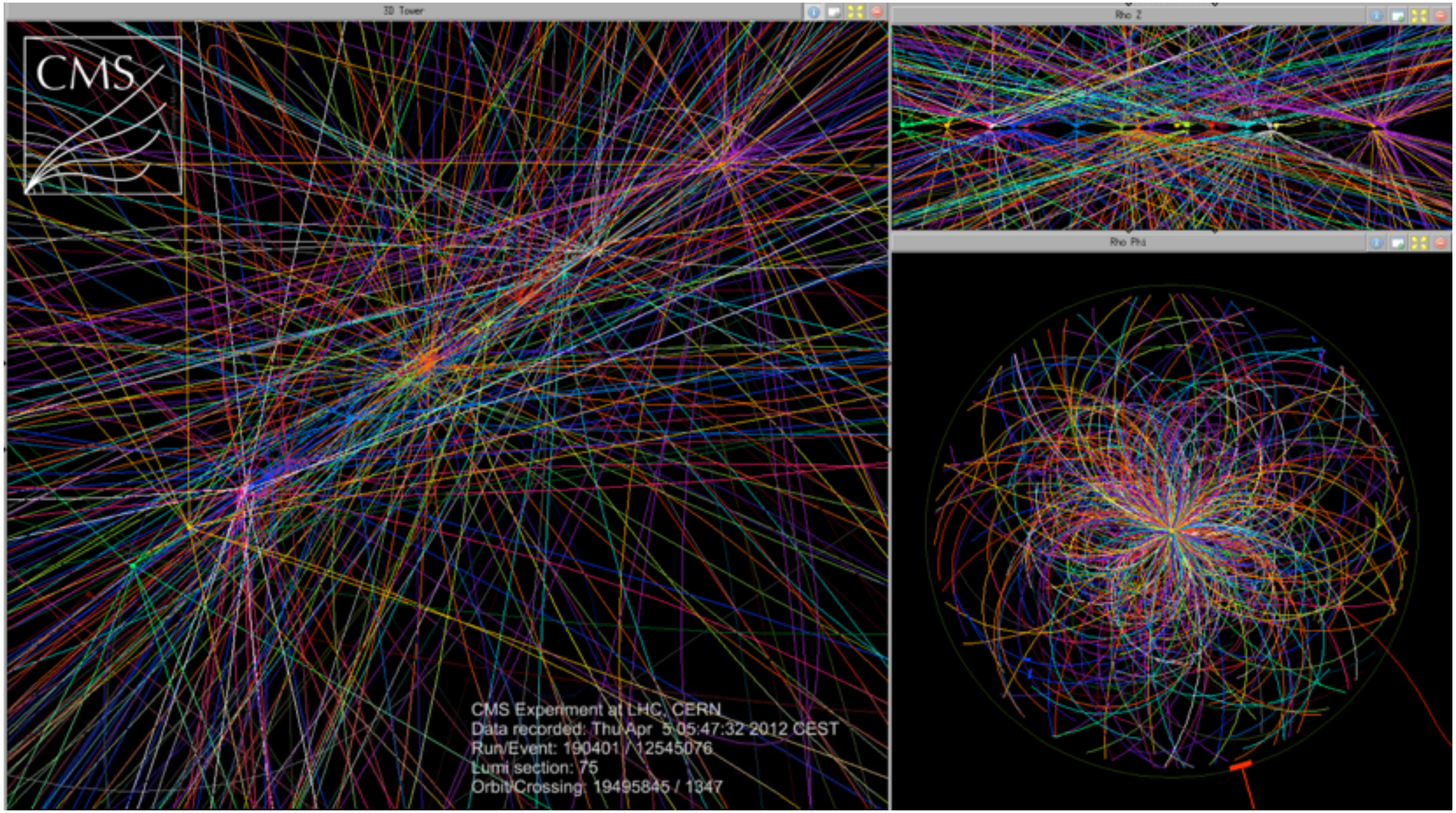
- CMS performance
  - Overall data taking efficiency ~91%
  - Average fraction of operation channel per subsystem > 98.5%



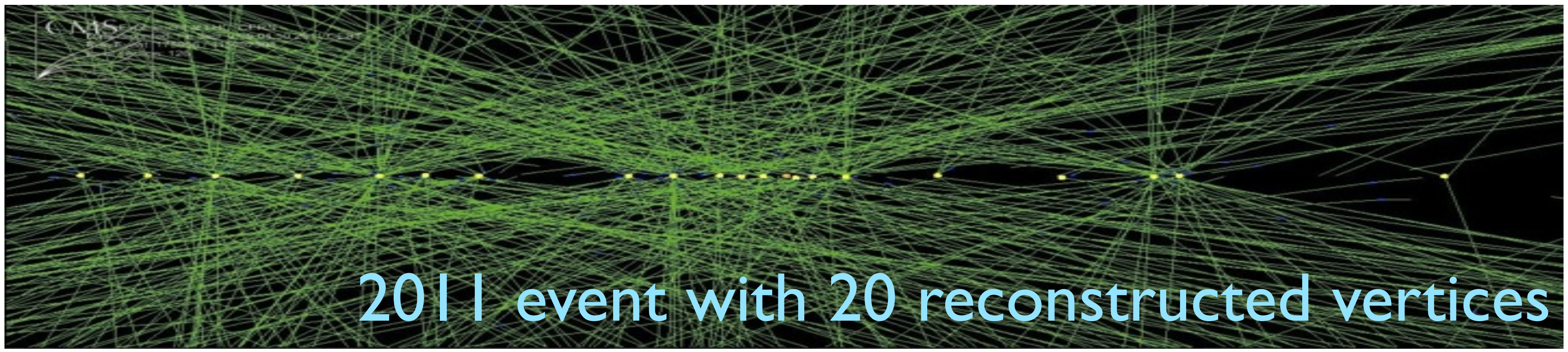


The challenge : Pile-Up

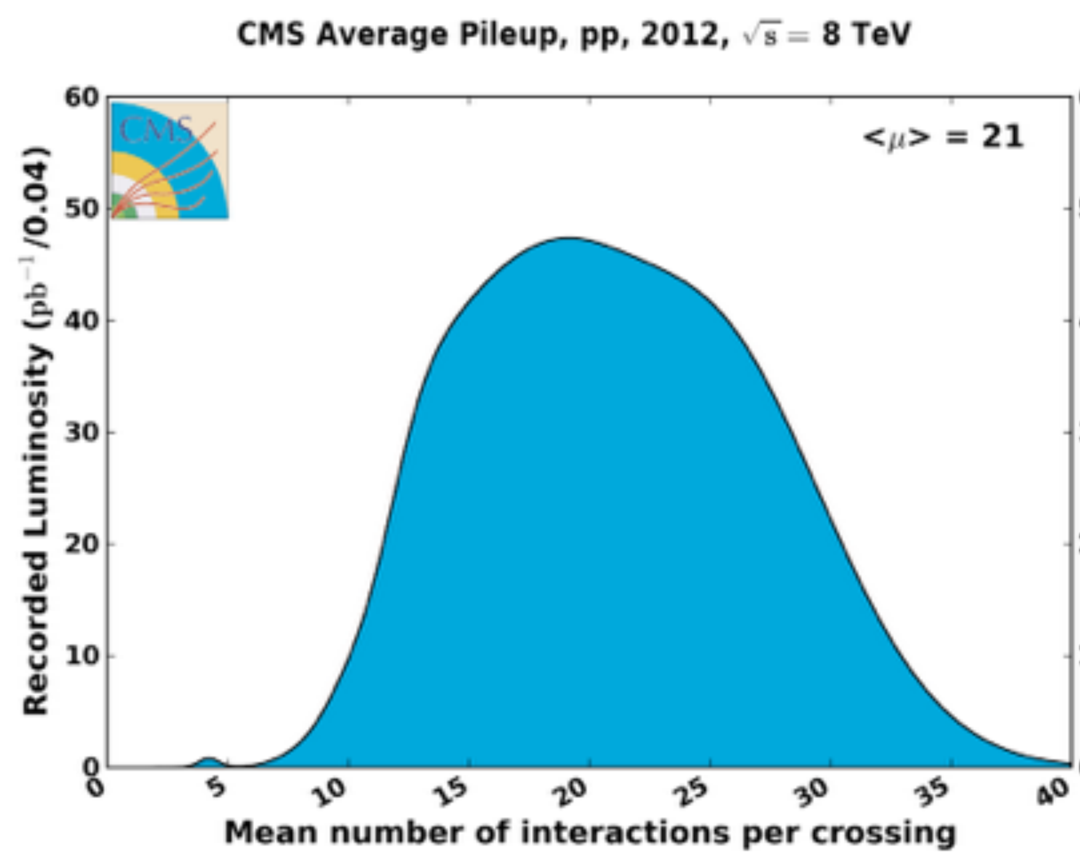
An event with 29 vertices within a single crossing of the LHC beam (not the worst !)



The challenge : Pile-Up



- A ZZ event can be a fake one due to pile-up
- Spoil the "isolation" and MET resolution
- Additional challenge for H→γγ channel, where the hard-scattering vertex is often not known well
    - picking a wrong vertex would make the mass resolution worse



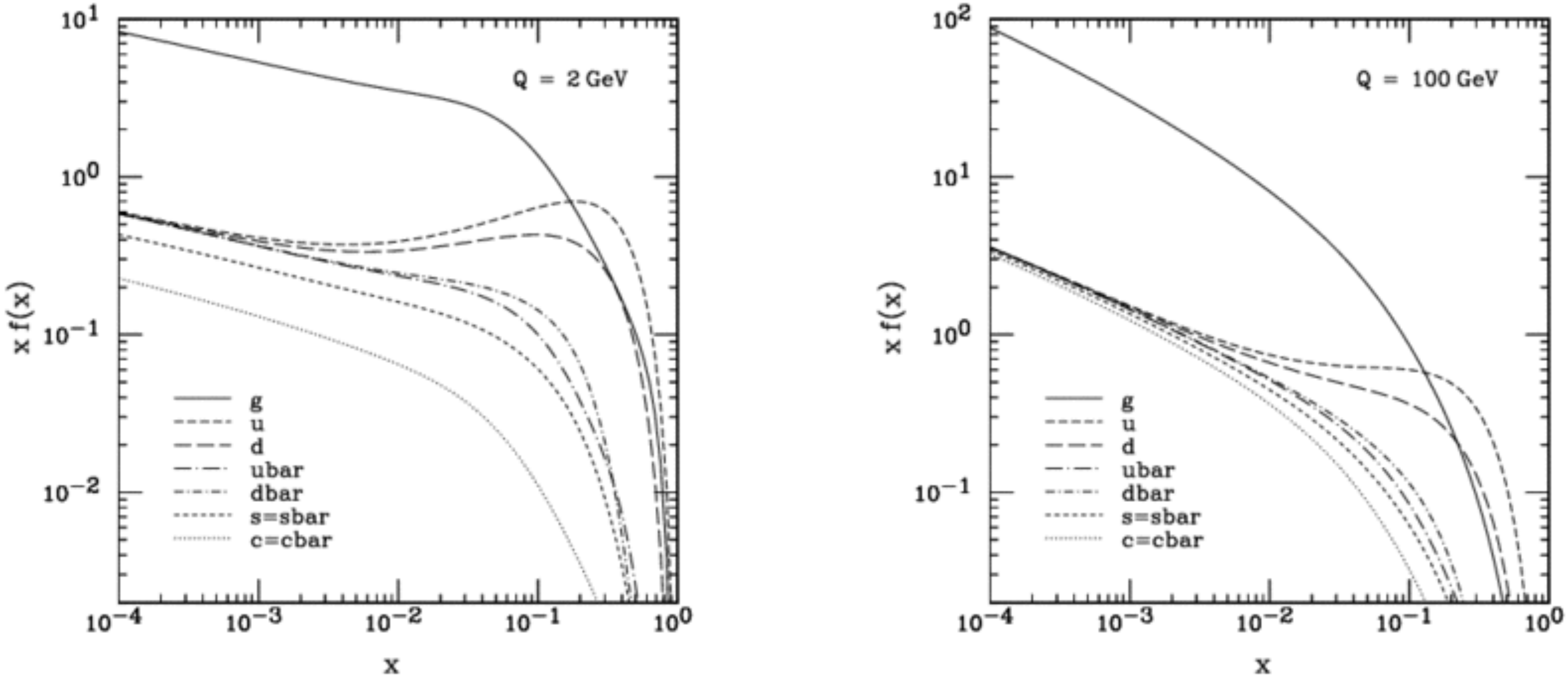
Motivation of W and Z production measurement

- One of the most prominent examples of hard scattering processes at hadron colliders
- Theoretical predictions are available at next-to-next-leading order (NNLO) in perturbative quantum chromodynamics (QCD)
- Precise measurements of inclusive cross sections provide tests of perturbative QCD and validate the theoretical predictions of higher-order corrections
- Additionally, accurate measurements can be used to constrain parton distribution functions (PDFs)

PDF

- A precise knowledge of the PDFs of the proton is important in order to make predictions for the SM and beyond the SM processes at hadron collider
- The PDF $f_i(x, Q^2)$ gives the probability of finding in the proton a parton of flavor i (quarks or gluon) carrying a fraction x of the proton momentum with Q being the energy scale of the hard interaction
- QCD does not predict the parton content of the proton. Thus, the distributions of the PDFs are determined by a fit to data from experimental observables in various processes

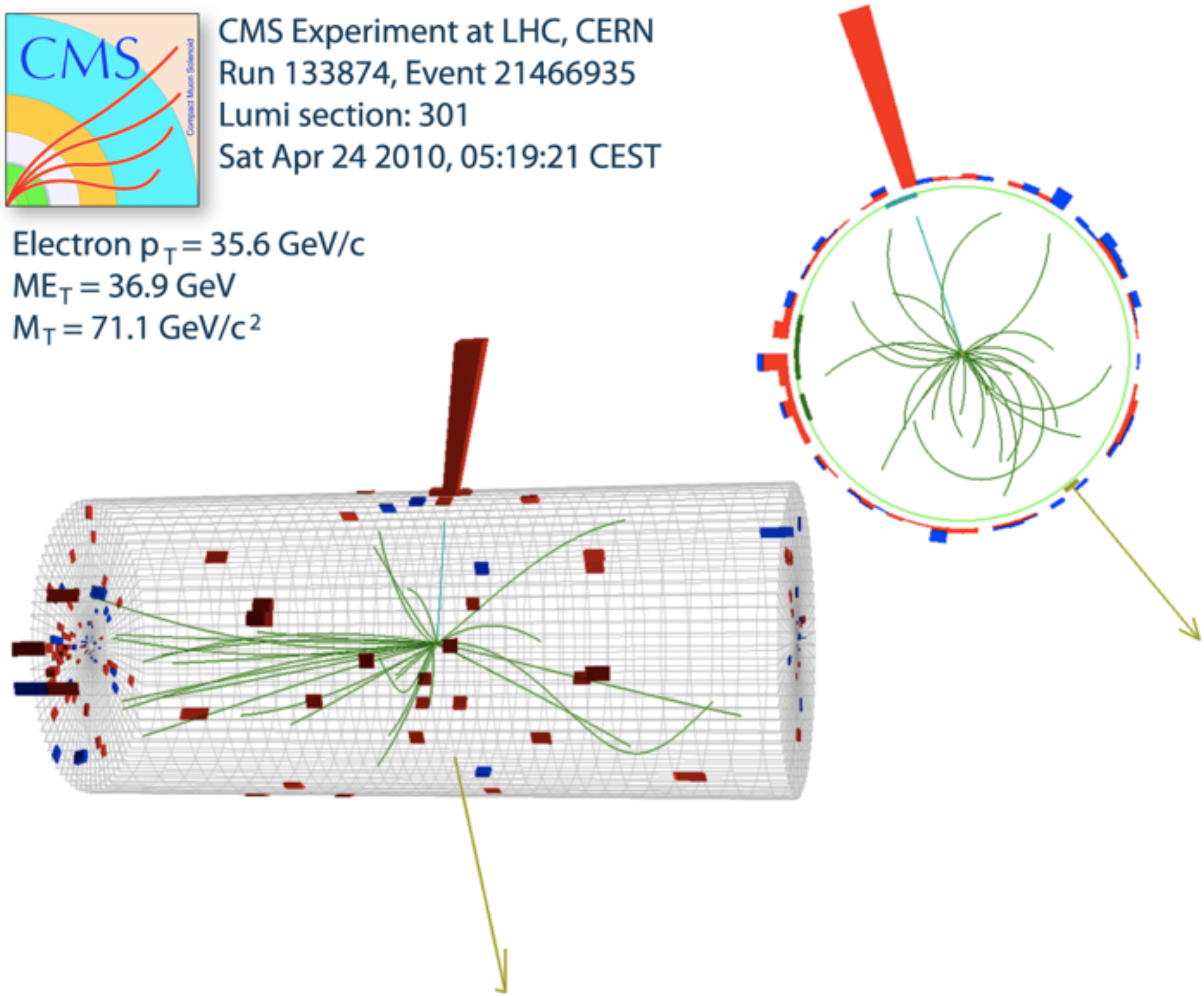
PDF



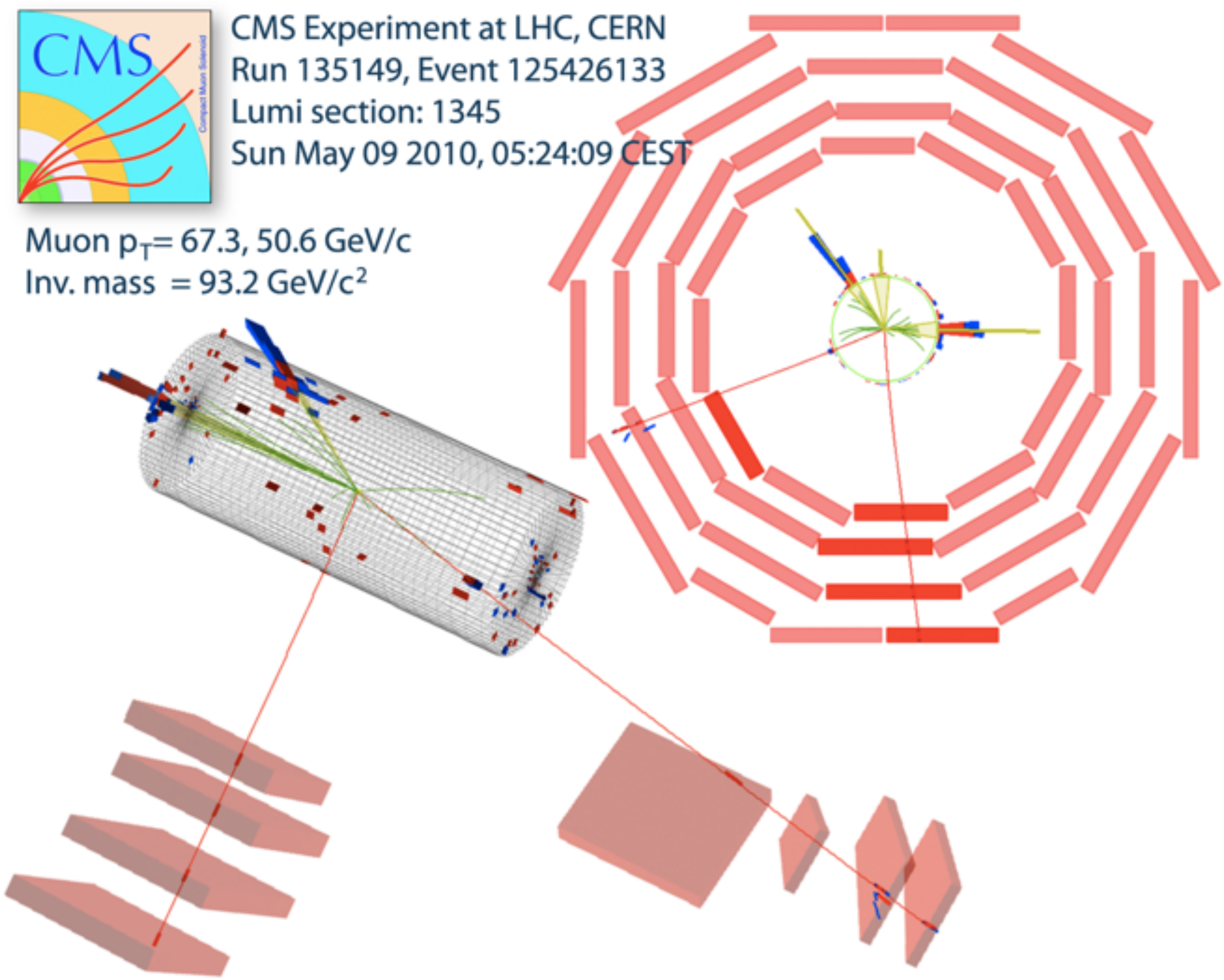
The general plan for an analysis

- The good event signature to look for
- Trigger
- Physics object selection
- Efficiency measurements
- Background estimations
- Systematic uncertainties
- Theoretical predictions

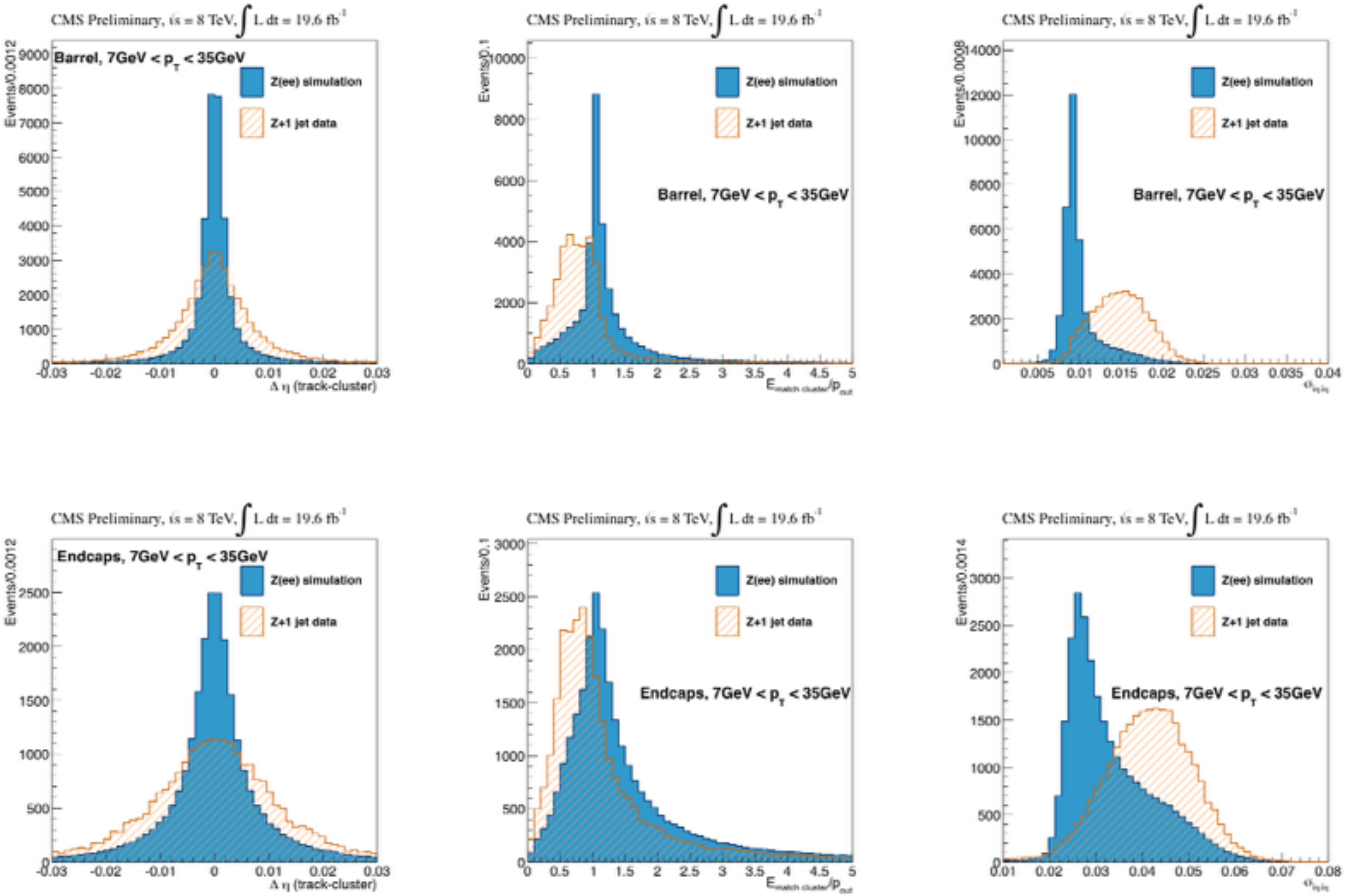
A W→eν candidate



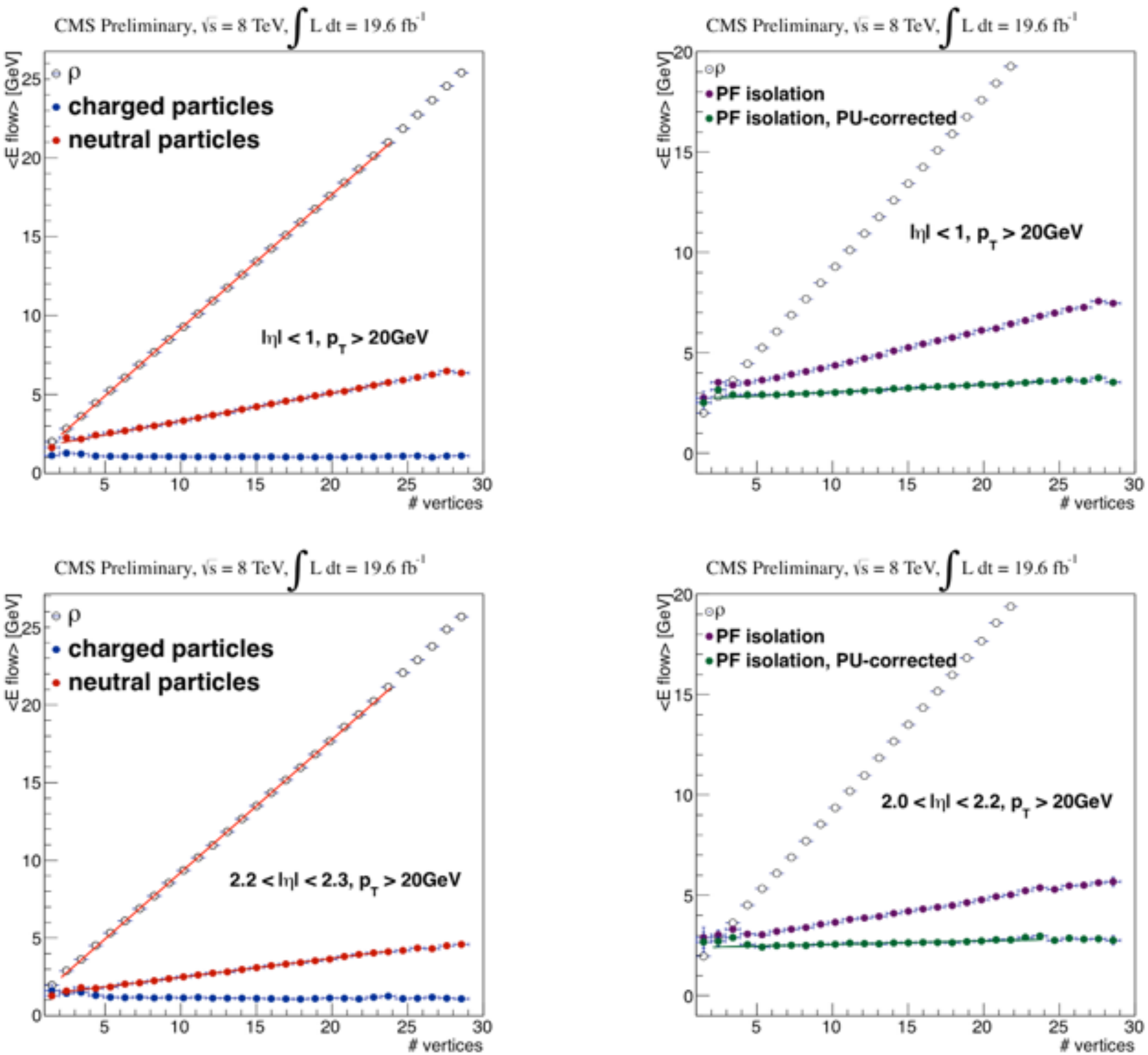
A $Z \to \mu\mu$ candidate



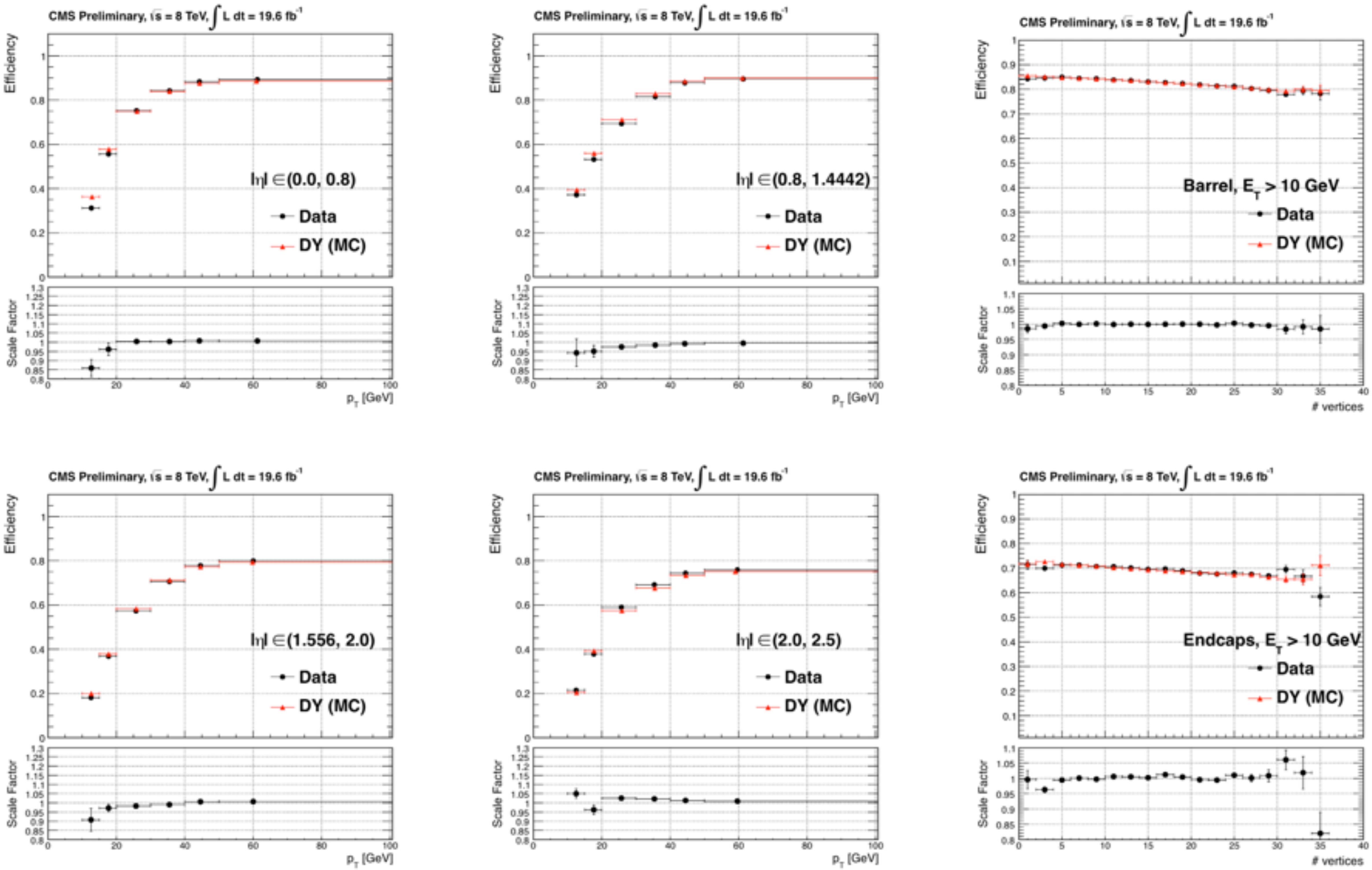
Electron ID variables



Electron isolations

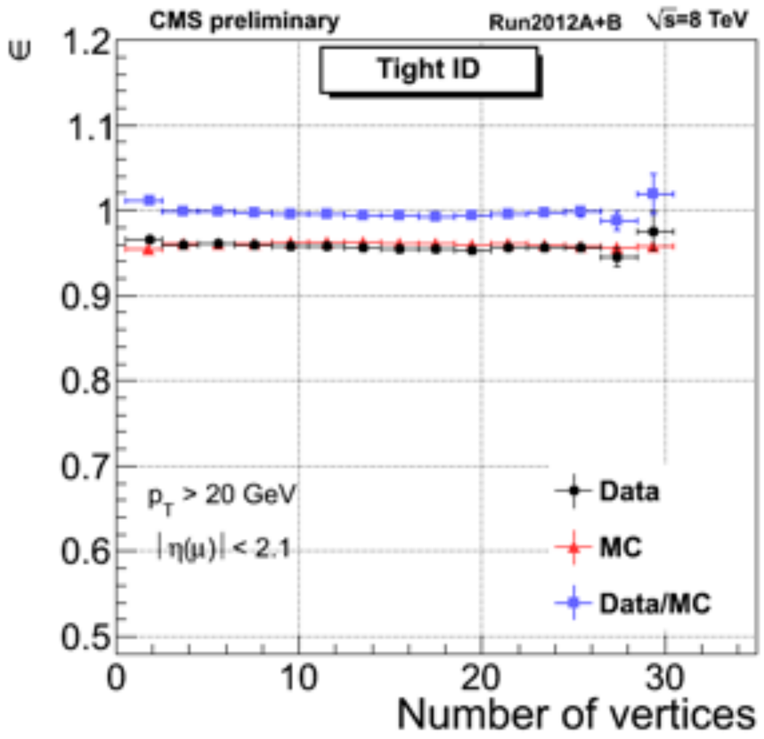


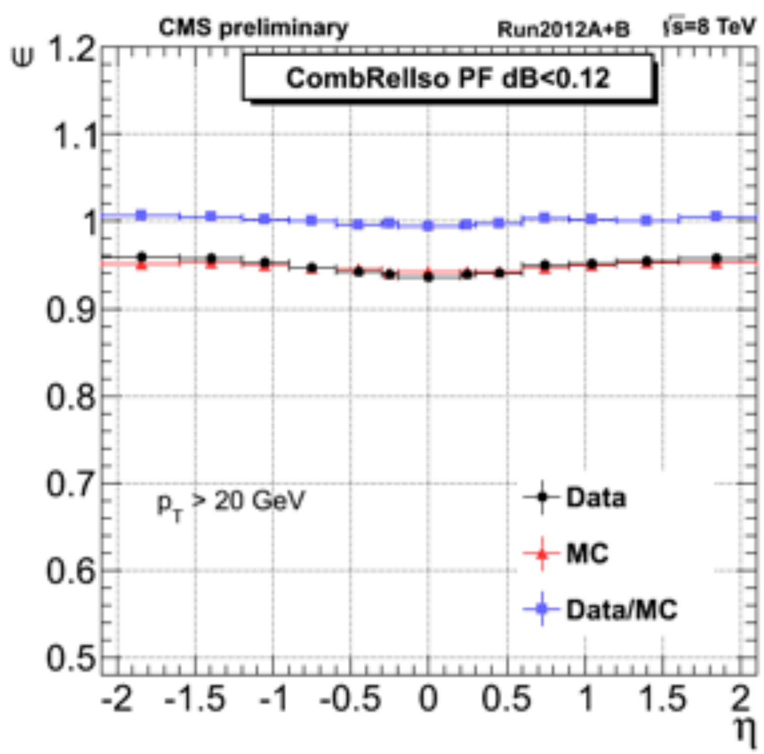
Electron ID efficiency



Muon ID

- ID variables
  - global muon
  - PF muon
  - globalTrack.normalizedChi2 < 10
  - globalTrack.numberOfValidMuonHits > 0
  - number of matched stations > 1
  - |dxy| < 0.2 cm, |dz| < 0.5 cm
  - number of valid pixel hits > 0
  - tracker layers with measurement > 5
- Isolation

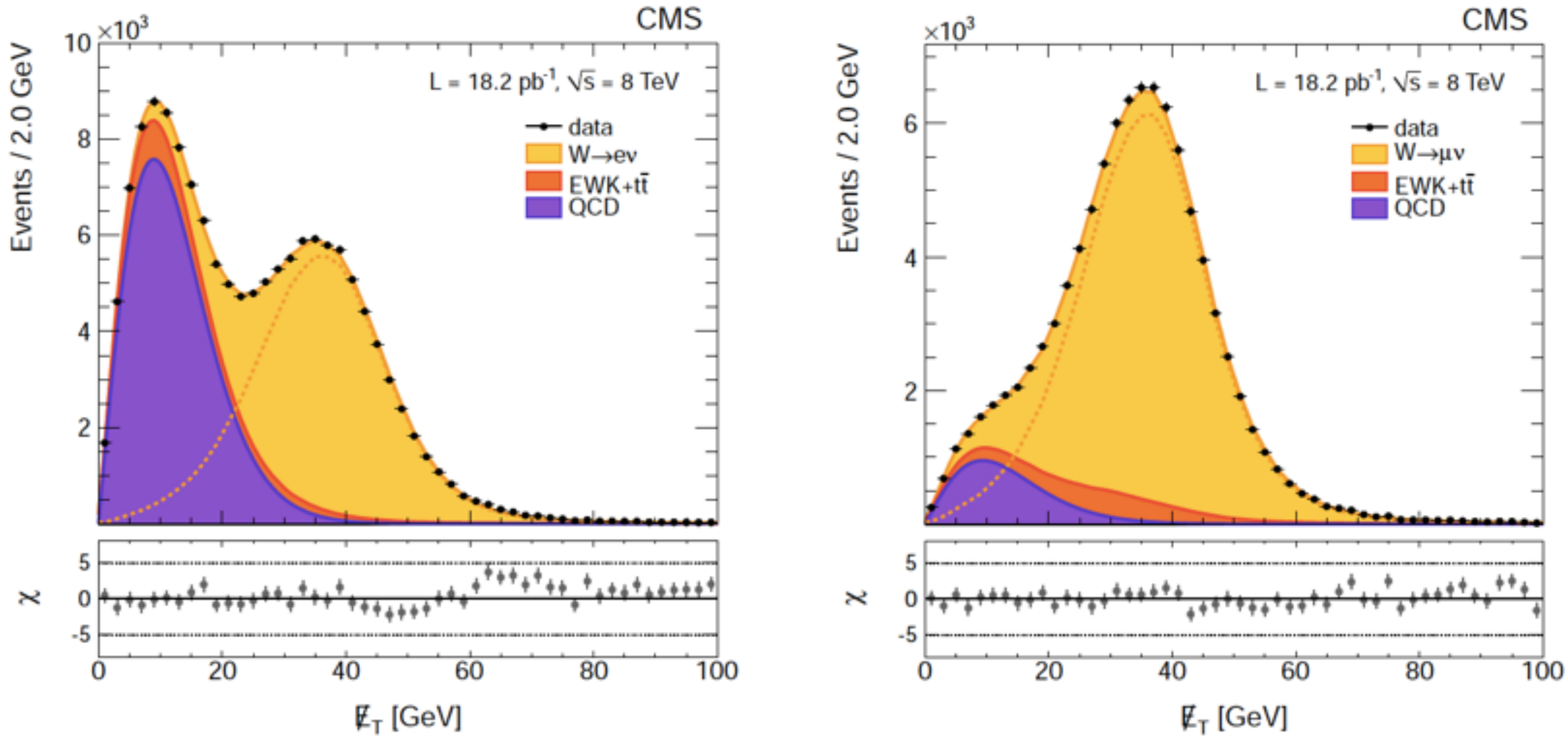




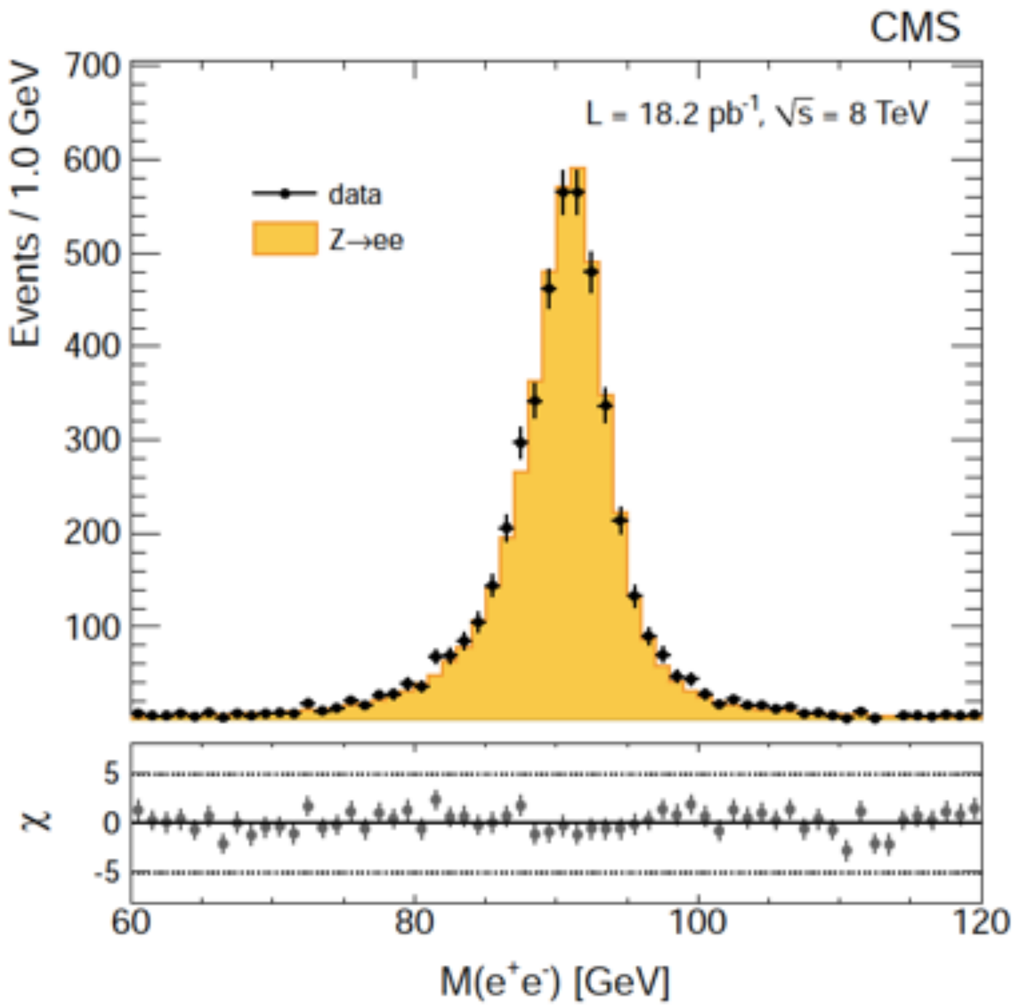
Inclusive W and Z production cross sections

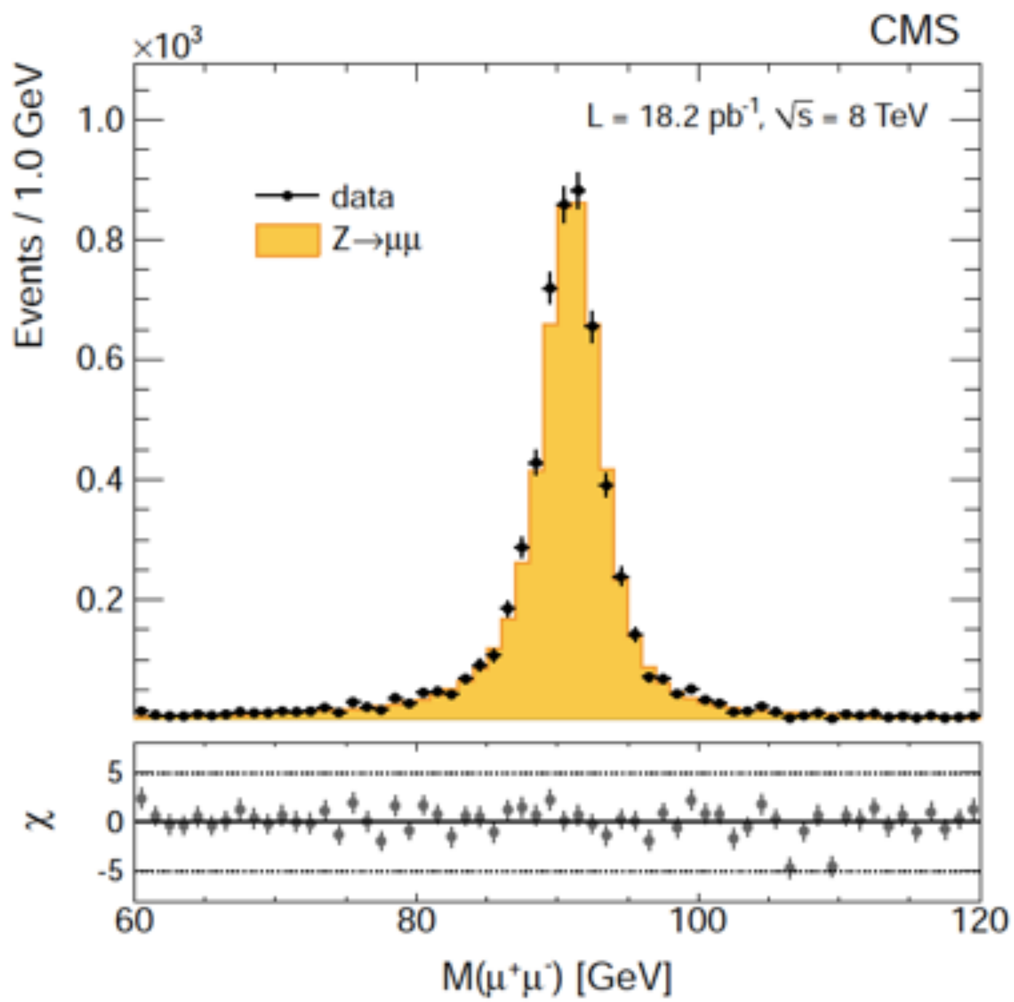
- Data sample : 8 TeV, 18.2/pb
- Low PU : an average of 4 interactions per bunch crossing
- Trigger : single electron, single muon
- CMS-PAS-SMP-12-011

W MET distributions



Z mass distributions





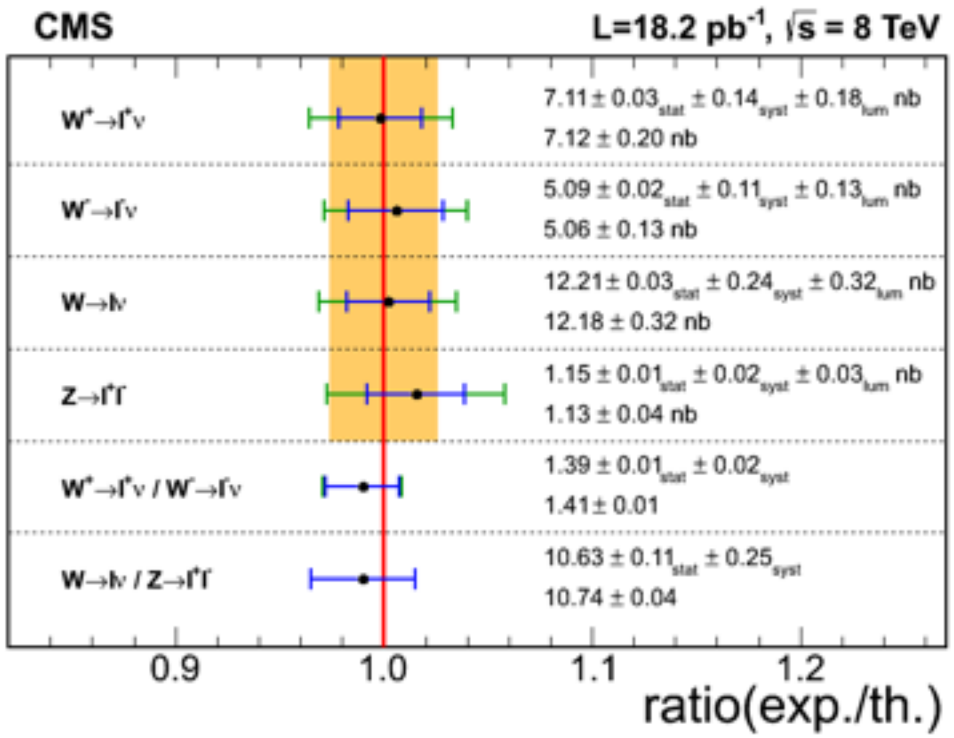
Cross section measurements

$$\sigma = \frac{N^{Data} - N^{Bkg}}{(A \times \epsilon)_{MC} \times \frac{\epsilon^{reco}_{Data}}{\epsilon^{reco}_{MC}} \times \frac{\epsilon^{sel}_{Data}}{\epsilon^{sel}_{MC}} \times \frac{\epsilon^{trg}_{Data}}{\epsilon^{trg}_{MC}} \times L}$$

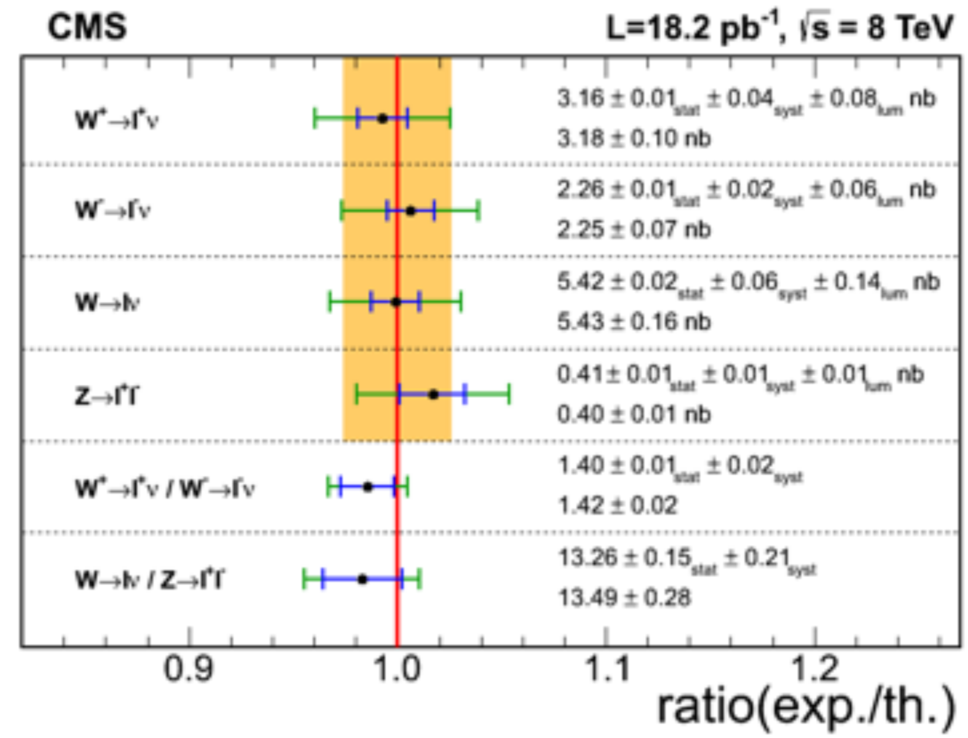
Systematic uncertainties

Sources	W$^+$ e	W$^+$ μ	W$^-$ e	W$^-$ μ	W e	W μ	W$^+$/W$^-$ e	W$^+$/W$^-$ μ	Z e	Z μ	W/Z e	W/Z μ
Lepton reconstruction & identification	2.8	1.0	2.5	0.9	2.5	1.0	3.8	1.2	2.8	1.1	3.8	1.5
Momentum scale & resolution	0.4	0.3	0.7	0.3	0.5	0.3	0.3	0.1	—	—	0.5	0.3
E_T^{miss} scale & resolution	0.8	0.5	0.7	0.5	0.8	0.5	0.3	0.1	—	—	0.8	0.5
Background subtraction / modeling	0.2	0.2	0.3	0.1	0.3	0.1	0.1	0.2	0.4	0.4	0.5	0.4
Total experimental	3.0	1.2	2.7	1.1	2.7	1.2	3.8	1.2	2.8	1.2	3.9	1.7
Theoretical uncertainty	2.1	2.0	2.6	2.5	2.7	2.2	1.5	1.4	2.6	1.9	2.0	2.5
Luminosity	2.6	2.6	2.6	2.6	2.6	2.6	—	—	2.6	2.6	—	—
Total	4.5	3.5	4.6	3.8	4.6	3.6	4.1	1.8	4.6	3.4	4.4	3.0

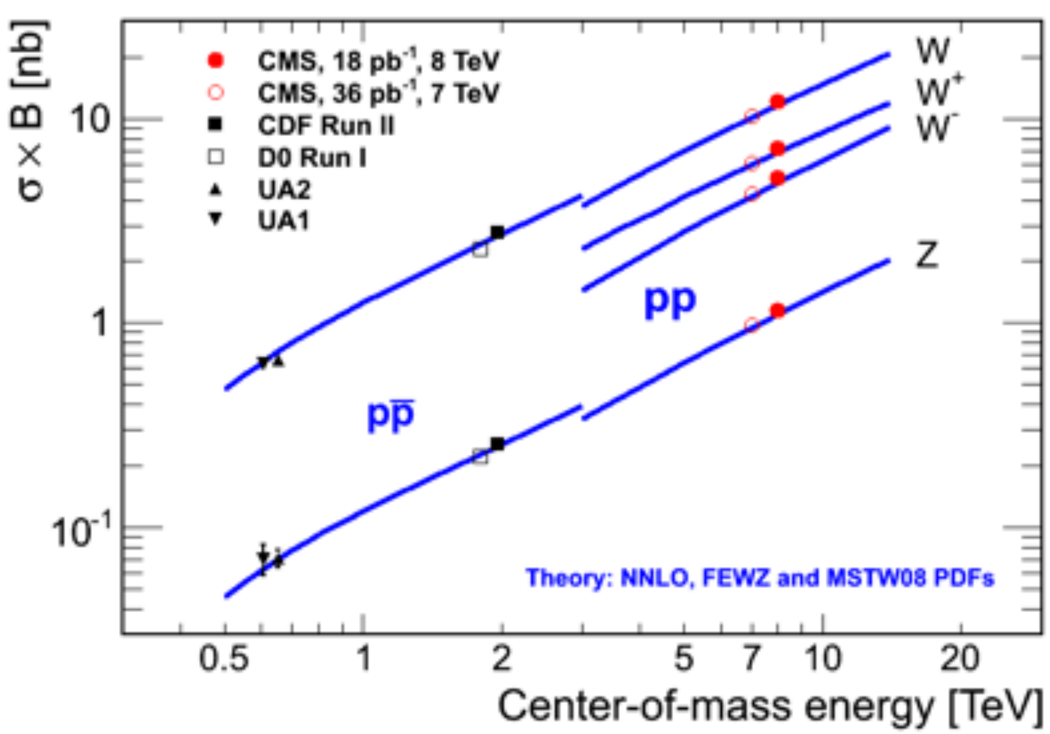
W/Z Results



CMS
L=18.2 pb^{-1}, $\sqrt{s}$ = 8 TeV
$W^+ \to l^+\nu$
$7.11 \pm 0.03_{stat} \pm 0.14_{syst} \pm 0.18_{lum}$ nb
7.12 ± 0.20 nb
$W^- \to l^-\nu$
$5.09 \pm 0.02_{stat} \pm 0.11_{syst} \pm 0.13_{lum}$ nb
5.06 ± 0.13 nb
$W \to l\nu$
$12.21 \pm 0.03_{stat} \pm 0.24_{syst} \pm 0.32_{lum}$ nb
12.18 ± 0.32 nb
$Z \to l^+l^-$
$1.15 \pm 0.01_{stat} \pm 0.02_{syst} \pm 0.03_{lum}$ nb
1.13 ± 0.04 nb
$W^+ \to l^+\nu$ / $W^- \to l^-\nu$
$1.39 \pm 0.01_{stat} \pm 0.02_{syst}$
1.41 ± 0.01
$W \to l\nu$ / $Z \to l^+l^-$
$10.63 \pm 0.11_{stat} \pm 0.25_{syst}$
10.74 ± 0.04
0.9
1.0
1.1
1.2
ratio(exp./th.)



CMS
L=18.2 pb^{-1}, $\sqrt{s}$ = 8 TeV
$W^+ \to l^+\nu$
$3.16 \pm 0.01_{stat} \pm 0.04_{syst} \pm 0.08_{lum}$ nb
3.18 ± 0.10 nb
$W^- \to l^-\nu$
$2.26 \pm 0.01_{stat} \pm 0.02_{syst} \pm 0.06_{lum}$ nb
2.25 ± 0.07 nb
$W \to l\nu$
$5.42 \pm 0.02_{stat} \pm 0.06_{syst} \pm 0.14_{lum}$ nb
5.43 ± 0.16 nb
$Z \to l^+l^-$
$0.41 \pm 0.01_{stat} \pm 0.01_{syst} \pm 0.01_{lum}$ nb
0.40 ± 0.01 nb
$W^+ \to l^+\nu$ / $W^- \to l^-\nu$
$1.40 \pm 0.01_{stat} \pm 0.02_{syst}$
1.42 ± 0.02
$W \to l\nu$ / $Z \to l^+l^-$
$13.26 \pm 0.15_{stat} \pm 0.21_{syst}$
13.49 ± 0.28
0.9
1.0
1.1
1.2
ratio(exp./th.)



$\sigma \times B$ [nb]
CMS, 18 pb^{-1}, 8 TeV
CMS, 36 pb^{-1}, 7 TeV
CDF Run II
D0 Run I
UA2
UA1
W
W$^+$
W$^-$
Z
pp
p$\bar{p}$
Theory: NNLO, FEWZ and MSTW08 PDFs
10
1
10^{-1}
0.5
1
2
5
7
10
20
Center-of-mass energy [TeV]

W charged asymmetry

Rapidity and momentum fraction.

NO: 1
DATE: 5 / 17 / 2013

The rapidity, y, is a quantity that is Lorentz invariant under transformations along the z-axis. It's defined as

$$y = \frac{1}{2}\ln\frac{E+P_z}{E-P_z}$$

Now let's consider the system $q\bar{q} \rightarrow X$

$$E_x = E_q + E_{\bar{q}} \quad \text{(energy conservation)}$$

the particles are highly relativistic $E_q = P_q$

$$E_x = P_q + P_{\bar{q}}$$

In addition, $\vec{P}_x = \vec{P}_q + \vec{P}_{\bar{q}}$ (momentum conservation)

In our collisions, all momenta are along the z-axis so the above equation can be reduced to the scalar equation

$$P_x = P_q - P_{\bar{q}}$$

If we insert E_x and P_x into rapidity definition, we get

$$y = \frac{1}{2}\ln\frac{P_q}{P_{\bar{q}}}$$

(note that y is the rapidity of W here)

→ Equation (1)

the above equation can be rewritten in terms of $x_i = \frac{P_i}{P}$, $P \sim P_{beam}$

$$y = \frac{1}{2}\ln\frac{x_q}{x_{\bar{q}}} \quad \text{or} \quad e^{2y} = \frac{x_q}{x_{\bar{q}}}$$

The above equations show that the rapidity of the W boson is a measure of the relative momenta of the partons

Additionally, $E_x^2 = P_x^2 + M_x^2$ can be rewritten as $x_q x_{\bar{q}} = \frac{M_x^2}{s}$

where $\sqrt{s} = 2E_{beam}$ (note that $E_{beam} = P$, which is mentioned above), $P \sim P_{beam}$

$$x_q x_{\bar{q}} = \frac{m_x^2}{s}$$

NO: 2
DATE: 5 / 17 / 2013

If we combine e^{2y} and $x_q x_{\bar{q}}$ formula, we can obtain

$$x_q = \frac{M_x e^{y}}{\sqrt{s}} \qquad x_{\bar{q}} = \frac{M_x e^{-y}}{\sqrt{s}}$$

Since the valence quarks typically carry more momentum than the sea quarks $x_u > x_{\bar{d}}$, W^+ bosons are produced preferentially in the direction of the u quark, and similarly W^- bosons in the d quark direction. From equation (1), the W^+ bosons tend to be produced at larger y_W compared to W^-. Moreover, the difference in production rates for W^+ and W^- increases with y_W, and is directly related to the difference in the u and d PDF curves.

The W rapidity asymmetry, defined as

$$A = \frac{d\sigma^{W^+}/dy - d\sigma^{W^-}/dy}{d\sigma^{W^+}/dy + d\sigma^{W^-}/dy}$$

at small x: $x_{\bar{u}} \approx x_{\bar{d}}$

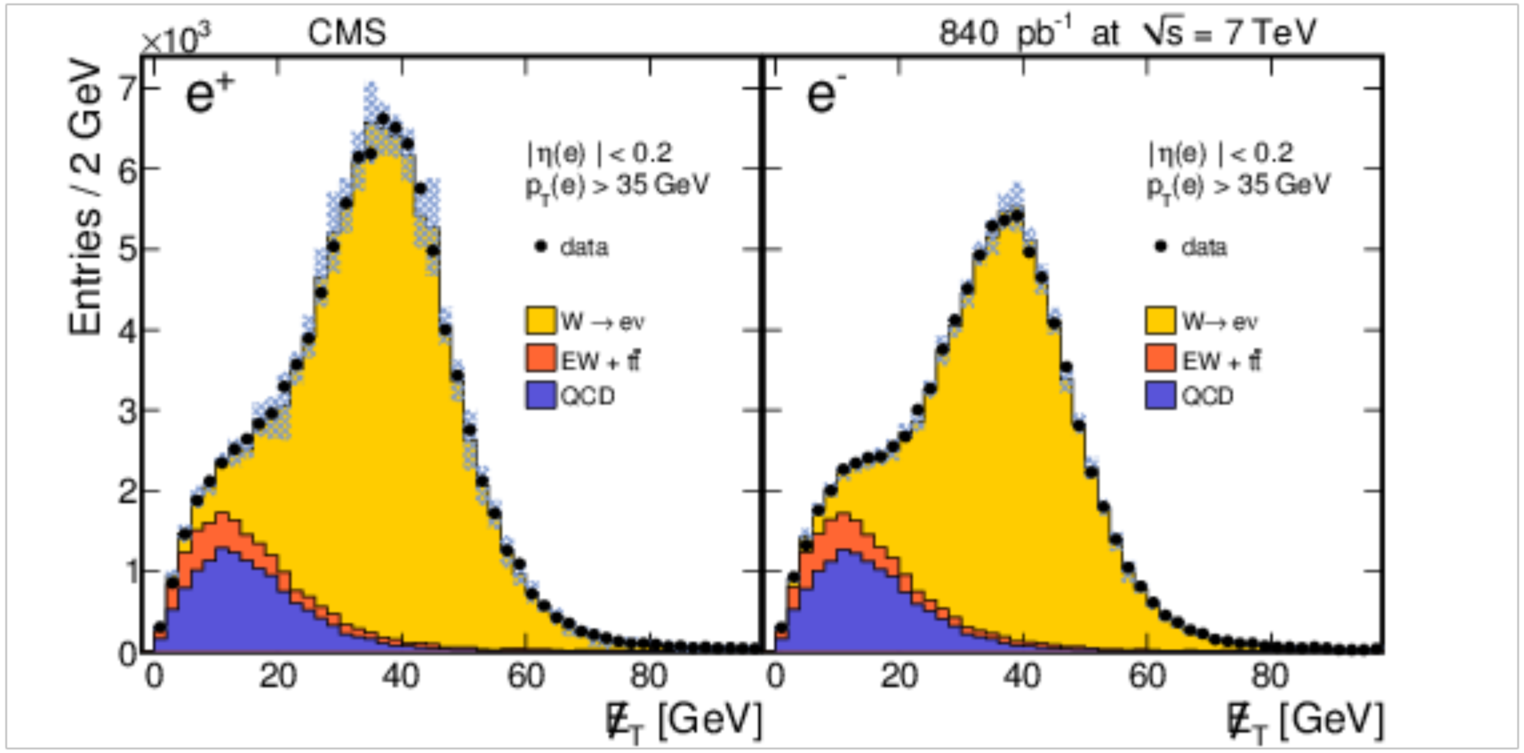
$$\approx \frac{x_u x_{\bar{d}} - x_d x_{\bar{u}}}{x_u x_{\bar{d}} + x_d x_{\bar{u}}}$$

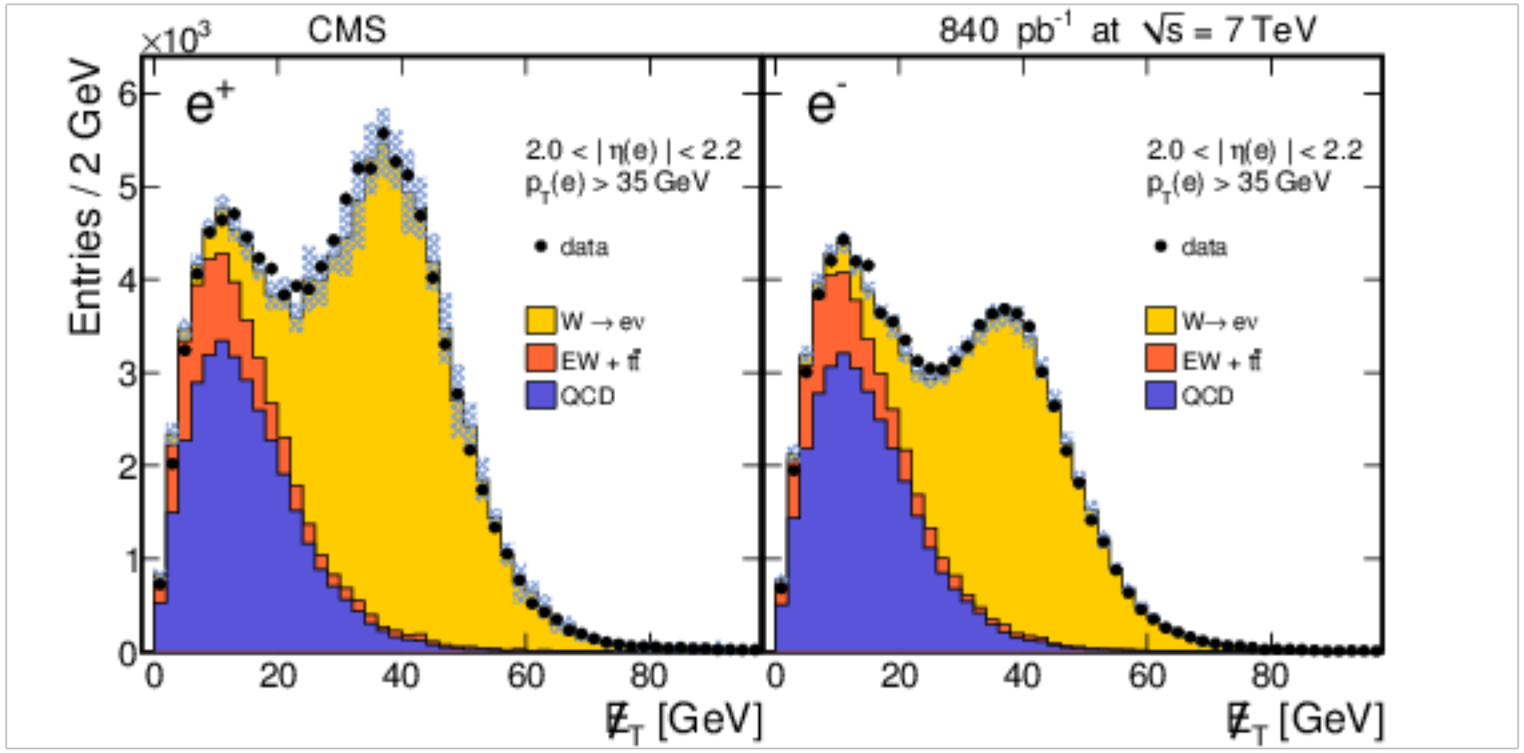
In case of small values of x, where $\bar{u} \sim \bar{d} \sim \bar{q}$, the dependence can be simplified as

$$A \sim \frac{u-d}{u+d}$$

This indicates that the asymmetry at low x is sensitive to the valence quark PDFs.

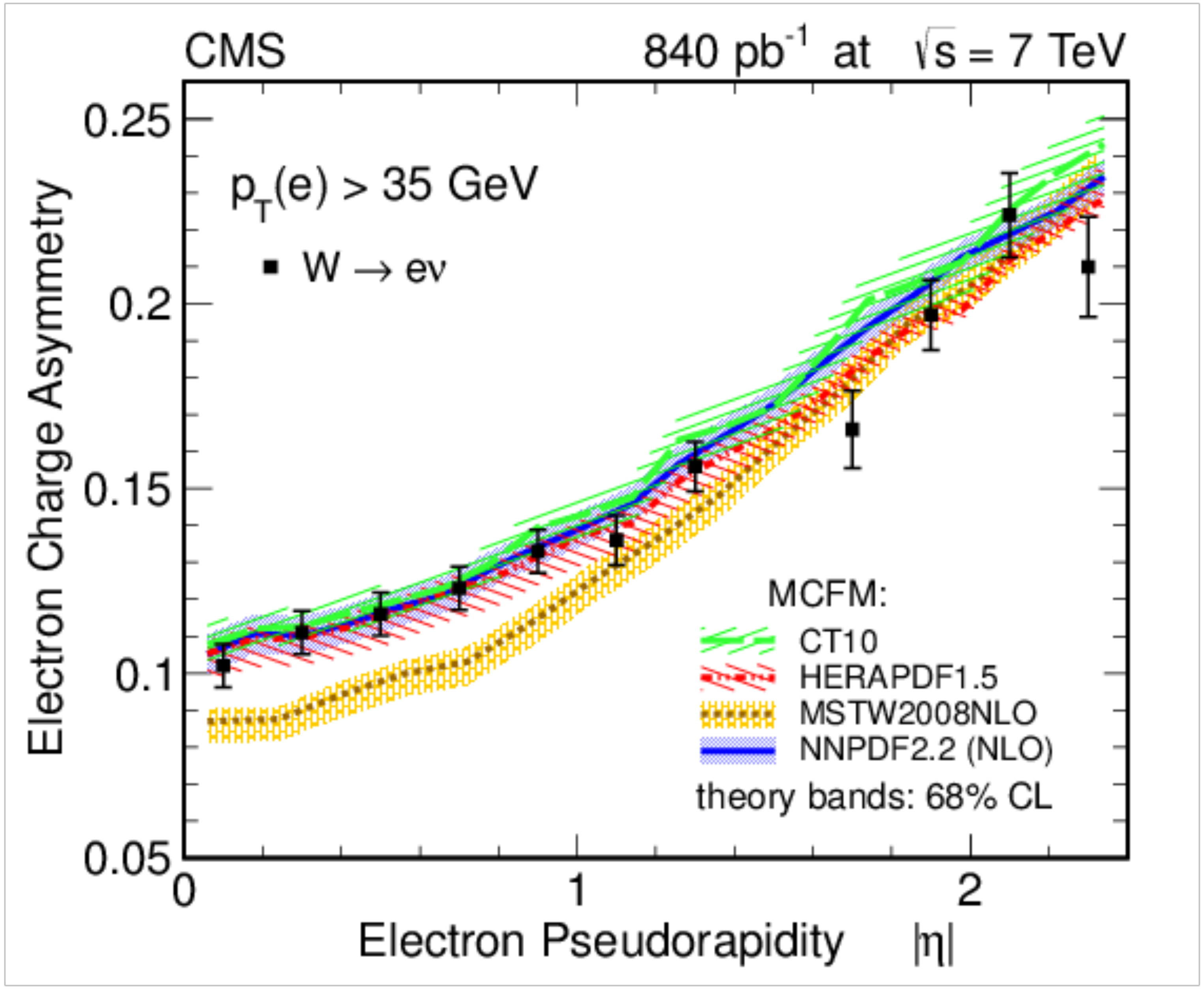
W charged asymmetry





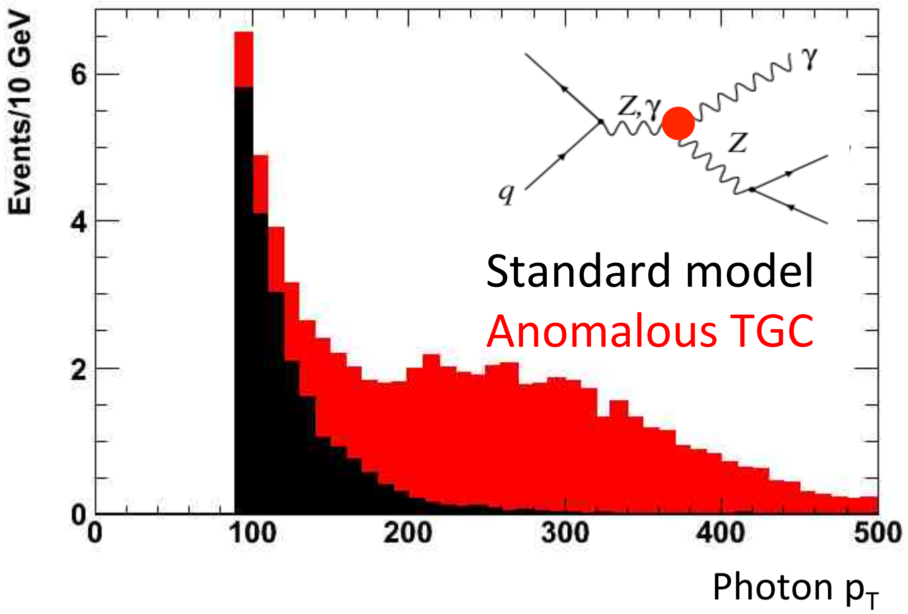
W charged asymmetry

$$\mathcal{A}(\eta) = \frac{d\sigma/d\eta(W^+ \to e^+\nu) - d\sigma/d\eta(W^- \to e^-\bar{\nu})}{d\sigma/d\eta(W^+ \to e^+\nu) + d\sigma/d\eta(W^- \to e^-\bar{\nu})}$$



Motivation of multiboson physics

- The measurements of diboson ($W\gamma$, $Z\gamma$, WW, WZ, ZZ) and triboson ($WW\gamma$, $WZ\gamma$, WWW and so on) are an important test of the Standard Model (SM)
- Multiboson processes present the primary backgrounds to Higgs and new physics search
- The self-interactions of electroweak gauge bosons are fundamental prediction of SM resulting from non-Abelian nature of SU(2)xU(1) gauge theory
  - values of triple and quartic gauge boson couplings (TGCs, QGCs) are fully fixed in the SM
  - new phenomena can induce changes in TGCs/QGCs so that cross sections and kinematics deviate from SM prediction
    - provides an indirect search for new physics



Triple Gauge-boson Couplings

- Most general description of the TGC vertex by an Lorentz invariant effective Lagrangian

$$
\begin{aligned}
L_{WWV}/g_{WWV} = & \; i g_1^V (W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} \\
& + i \frac{\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda} - g_4^V W^\dagger_\mu W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \\
& + g_5^V \epsilon^{\mu\nu\lambda\rho} (W^\dagger_\mu \partial_\lambda W_\nu - \partial_\lambda W^\dagger_\mu W_\nu) V_\rho \\
& + i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} + i \frac{\tilde{\lambda}_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu \tilde{V}^{\nu\lambda}
\end{aligned}
$$

V=Z,γ

Signatures of anomalous couplings

- enhancement of cross section
- large scattering angle → small rapidity region
- enhancement at high P_T

	g_1^V	κ_V	λ_V	g_4^V	g_5^V	$\tilde{\kappa}_V$	$\tilde{\lambda}_V$
C	even	even	even	odd	odd	even	even
P	even	even	even	even	odd	odd	odd
CP	even	even	even	odd	even	odd	odd
SM	1	1	0	0	0	0	0

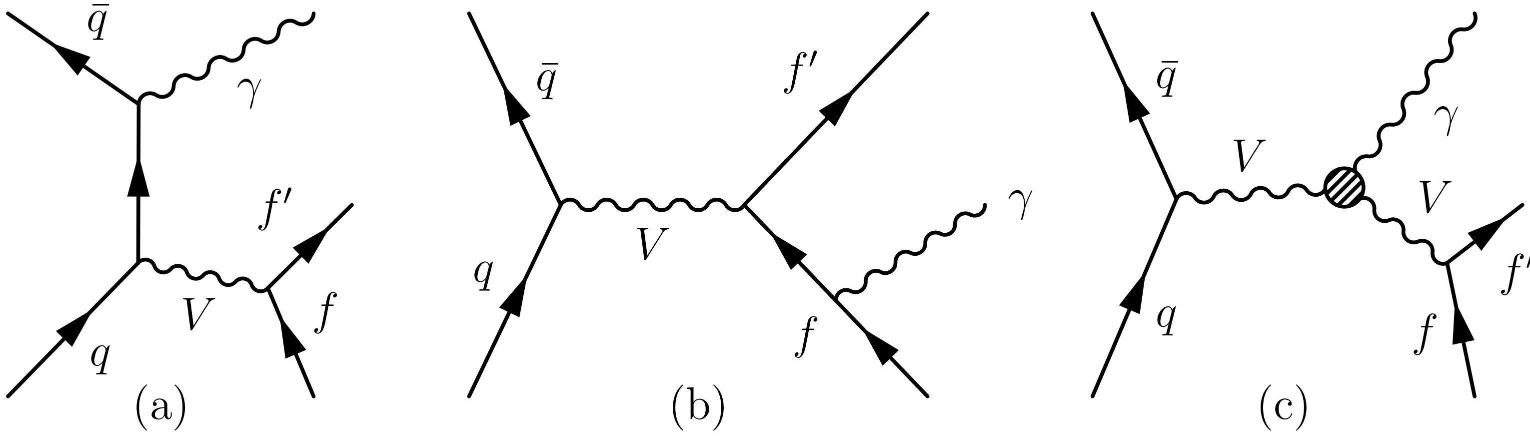
$\Delta\kappa = \kappa - 1 \quad \Delta g_1^Z = g_1^Z - 1$

WWZ : $\Delta g_1^Z \; \Delta\kappa_Z \; \lambda_Z$

WWγ : $\Delta\kappa_\gamma \; \lambda_\gamma$

($g_1^\gamma = 1$: EM gauge invariance)

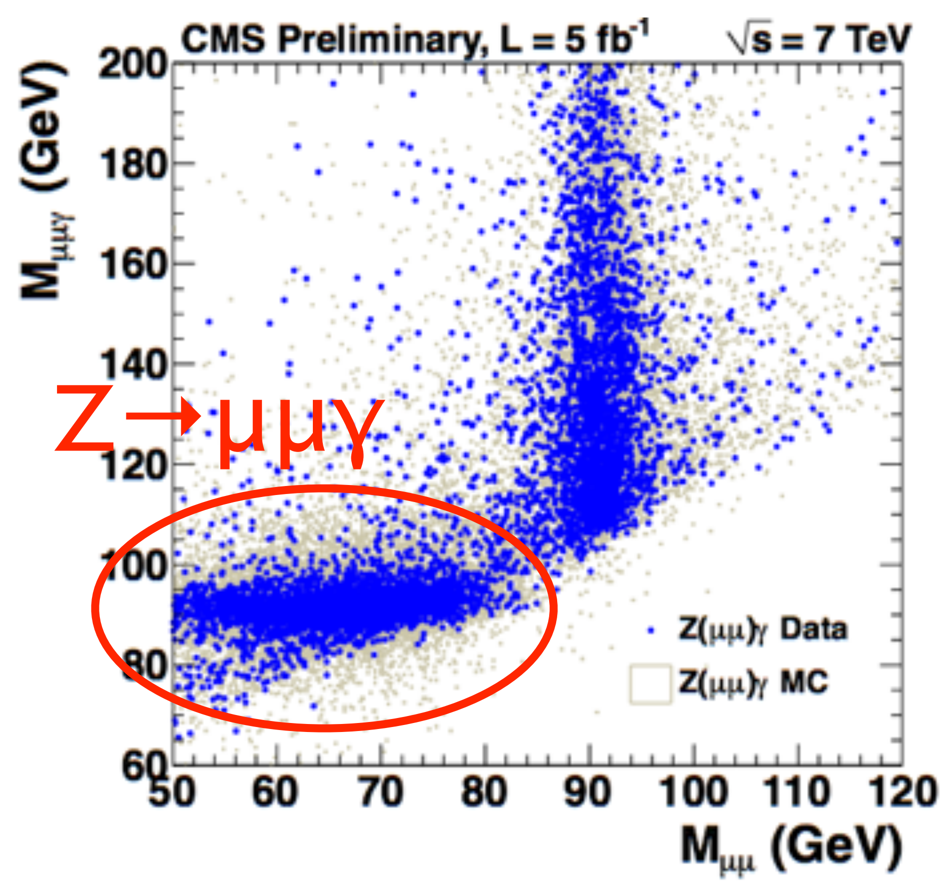
Wγ and Zγ signature



ISR FSR TGC

WWγ vertex is allowed in SM
ZZγ, Zγγ vertex are not allowed

- Measurements based on leptonic W and Z boson decays: eνγ, μνγ, eeγ, μμγ, ννγ
  - for ννγ, only ISR diagram exists in SM
  - using 5/fb of 7 TeV data
  - CMS PAS EWK-11-009 (PRD) and SMP-12-020 (JHEP)
- FSR Z→llγ process provides pure photon control sample
  - photon energy scale and resolution from data
  - check photon selection efficiency

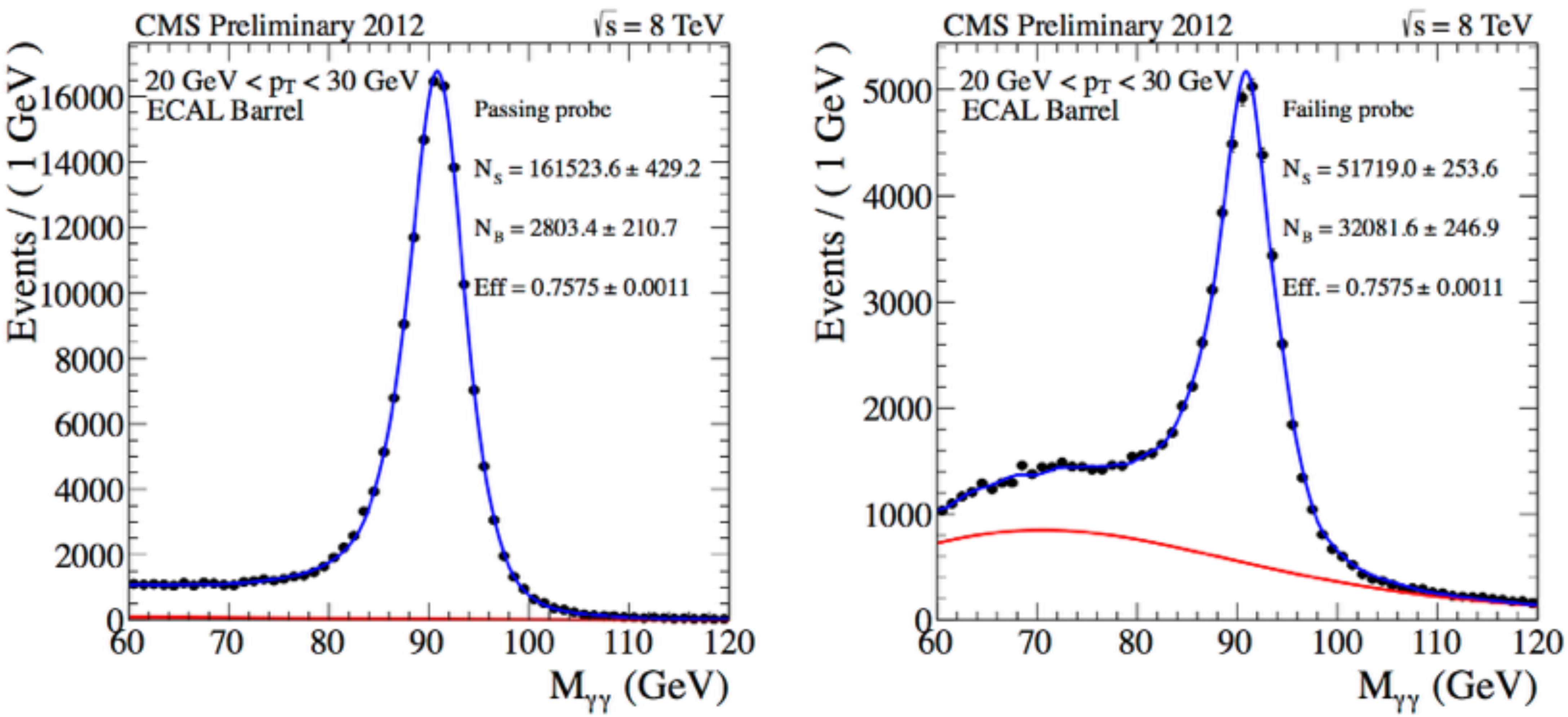


$W\gamma/Z\gamma$ *event selection*

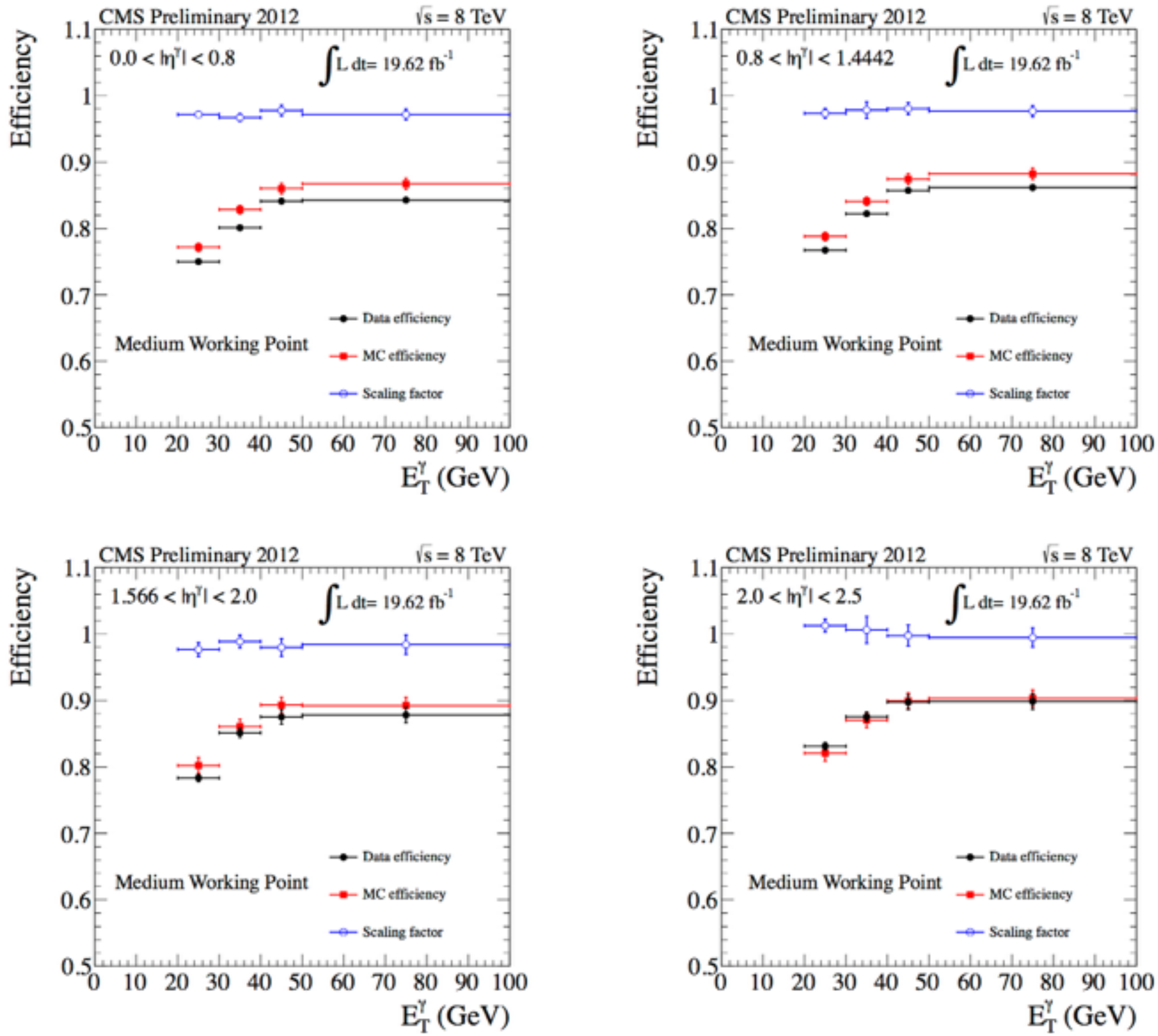
	$W\gamma \to l\nu\gamma$ (l = e, μ)	$Z\gamma \to ll\gamma$ (l = e, μ)	$Z\gamma \to \nu\nu\gamma$ (γ+MET)
Trigger	Single lepton	Dilepton	Single photon
Lepton Selection	p	p	
Photon Selection	P_T $\Delta R(l, \gamma) > 0.7$ $\|\eta^{\gamma}$	P_T $\Delta R(l, \gamma) > 0.7$ $\|\eta^{\gamma}$	P_T $\|\eta$
Presence of ν	M		MET > 130 GeV
additional requirements	no second lepton	M	- no other significant activity in the event: jets, leptons. etc. - ECAL timing/shape requirement on photons to remove non-collision backgrounds

Photon selection efficiency measurements

- ID + ISO efficiency is measured with Z→ee using tag-and-probe method
- Electron veto efficiency is measured using Z→μμγ using counting method

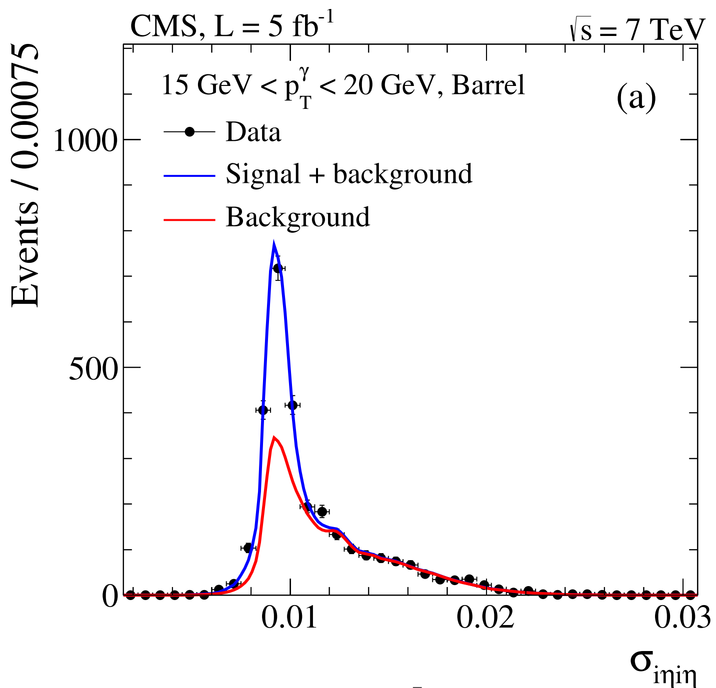


Photon selection efficiency



Backgrounds for Wγ and Zγ→llγ

- Major background arises from events in which jets, originating mostly from W+jets and Z+jets events, are misidentified as photons
  - Use η-width of the photon candidate as a discriminant and then perform two-component fit using the signal and background templates



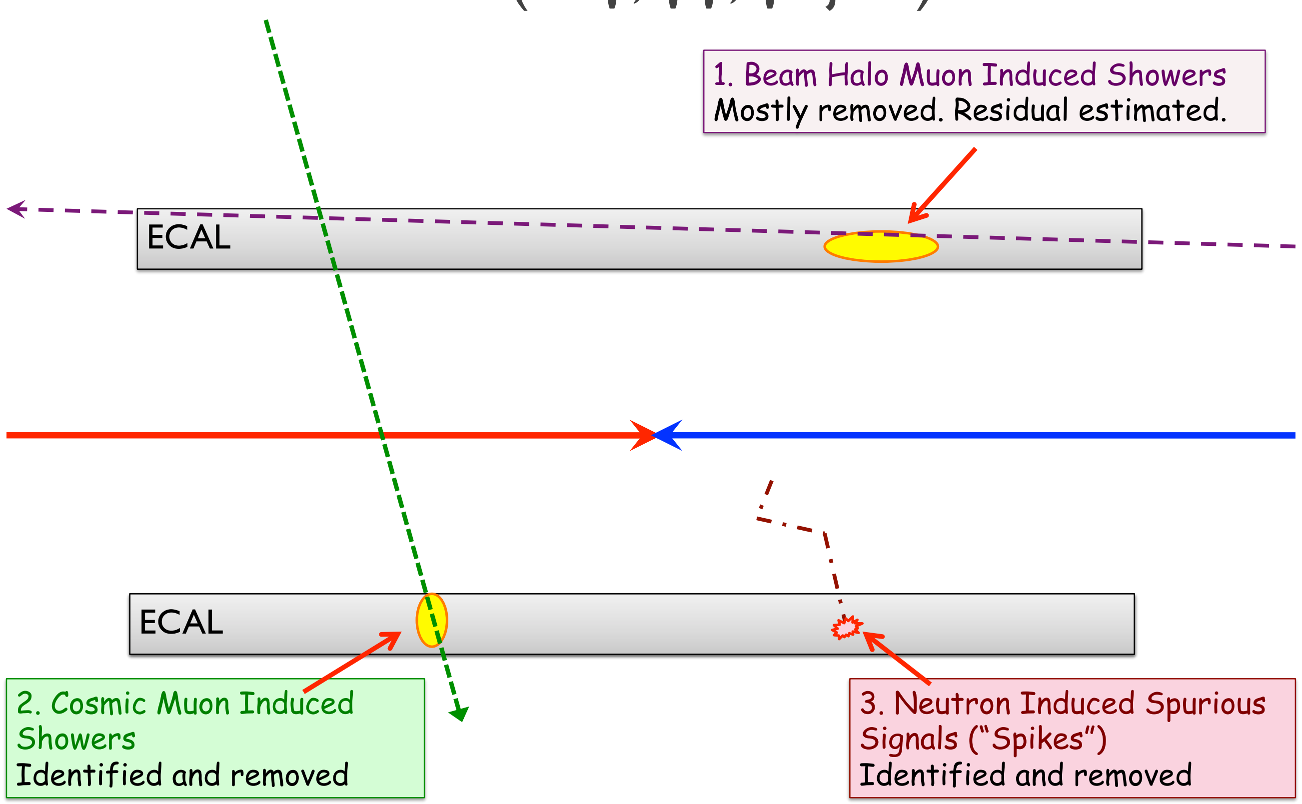
- Second major background to Wγ is the processes where an electron is misidentified as a photon such as Z+jets, WZ, etc.
  - Measured in data using Z→ee process
- Other sources are small and estimated from simulation

Backgrounds for Zγ→ννγ

- jet→γ misidentification estimated from data using "ratio method" : use QCD enriched sample to determined the ratio of isolated fake photon to non-isolated fake photon

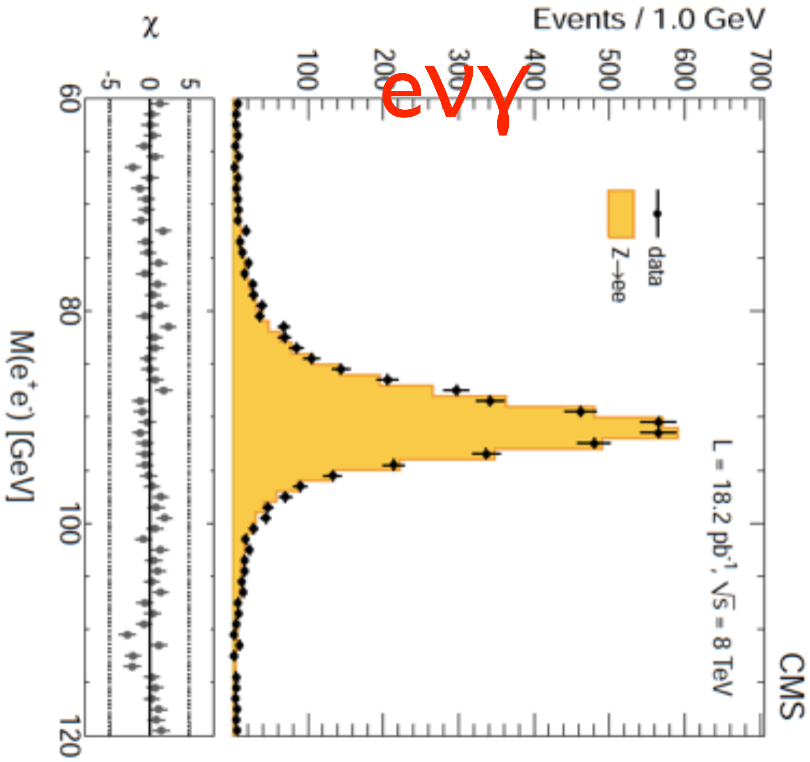
$$N_{V+jets} = \frac{N_{\text{isolated } \gamma \text{ in QCD}}}{N_{\text{non-isolated } \gamma \text{ in QCD}}} \times N_{V+\text{non-isolated } \gamma}$$

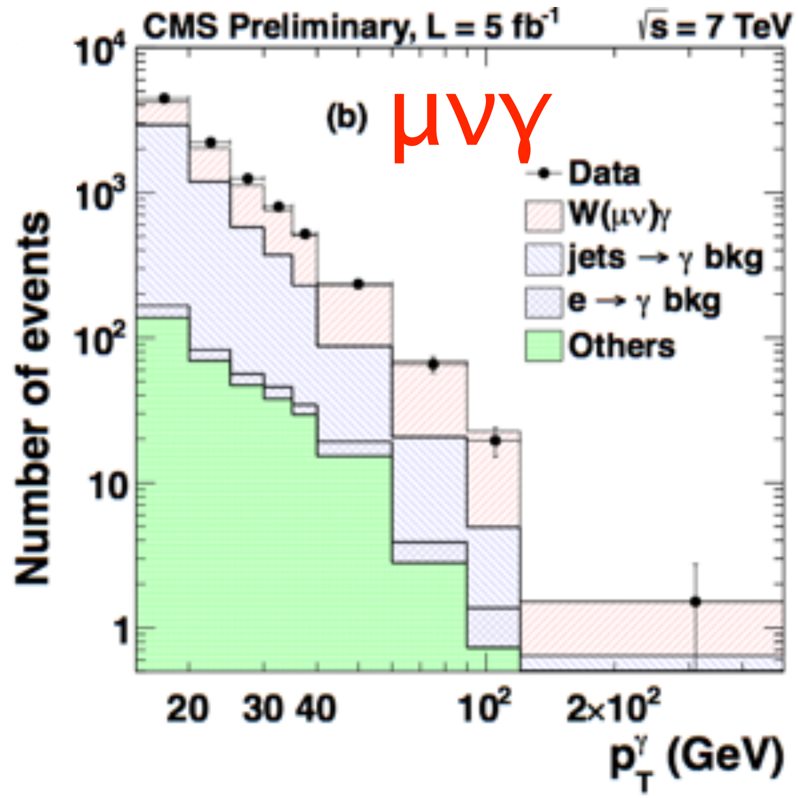
- The residual non-collision background (mainly beam-halo) is estimated from data
- e→γ misidentification estimated from data
- Other sources (Wγ, γγ, γ+jets) are estimated from simulation

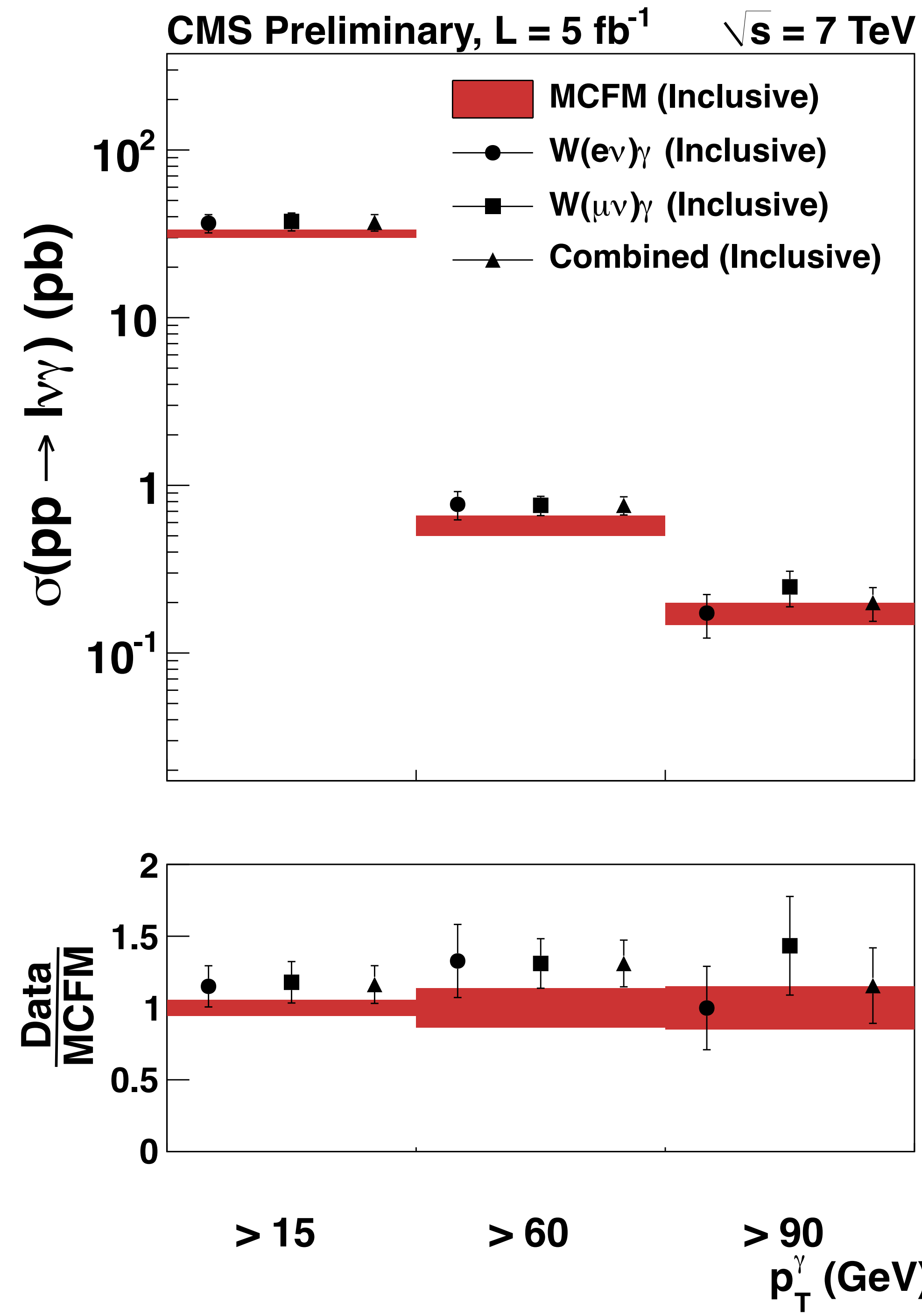


Source	Estimate
Misidentified jets	11.2 ± 2.8
Beam-gas processes	11.1 ± 5.6
Misidentified electrons	3.5 ± 1.5
$W\gamma$	3.3 ± 1.0
$\gamma\gamma$	0.6 ± 0.3
γ+jet	0.5 ± 0.2
Total	30.2 ± 6.5
$Z\gamma \rightarrow \nu\nu\gamma$ (NLO)	45.3 ± 6.9
data	73

Wγ results



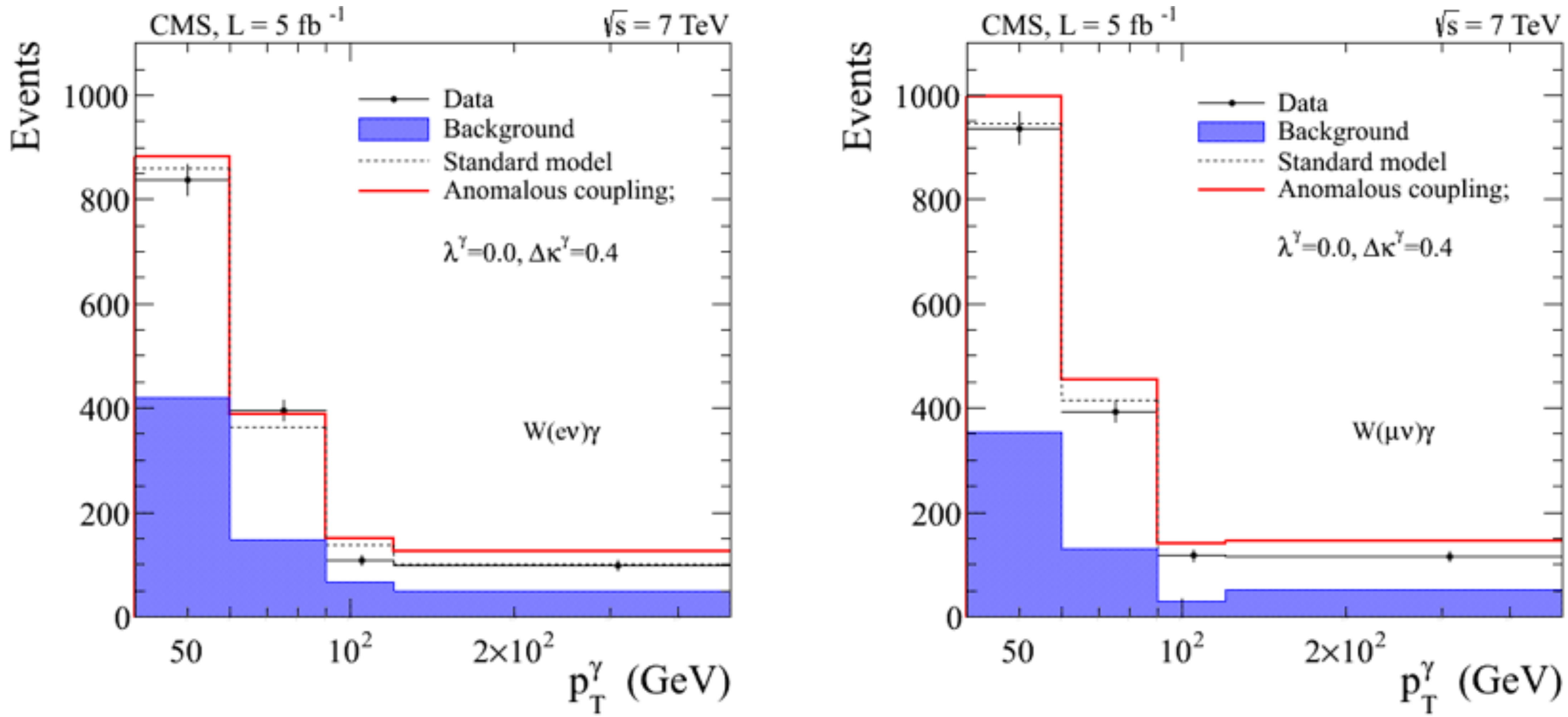




CMS measurement (P	MCFM prediction
37.0 ± 0.8 (stat) ± 4.0 (syst) ± 0.8 (lumi) pb	31.8 ±1.8 pb

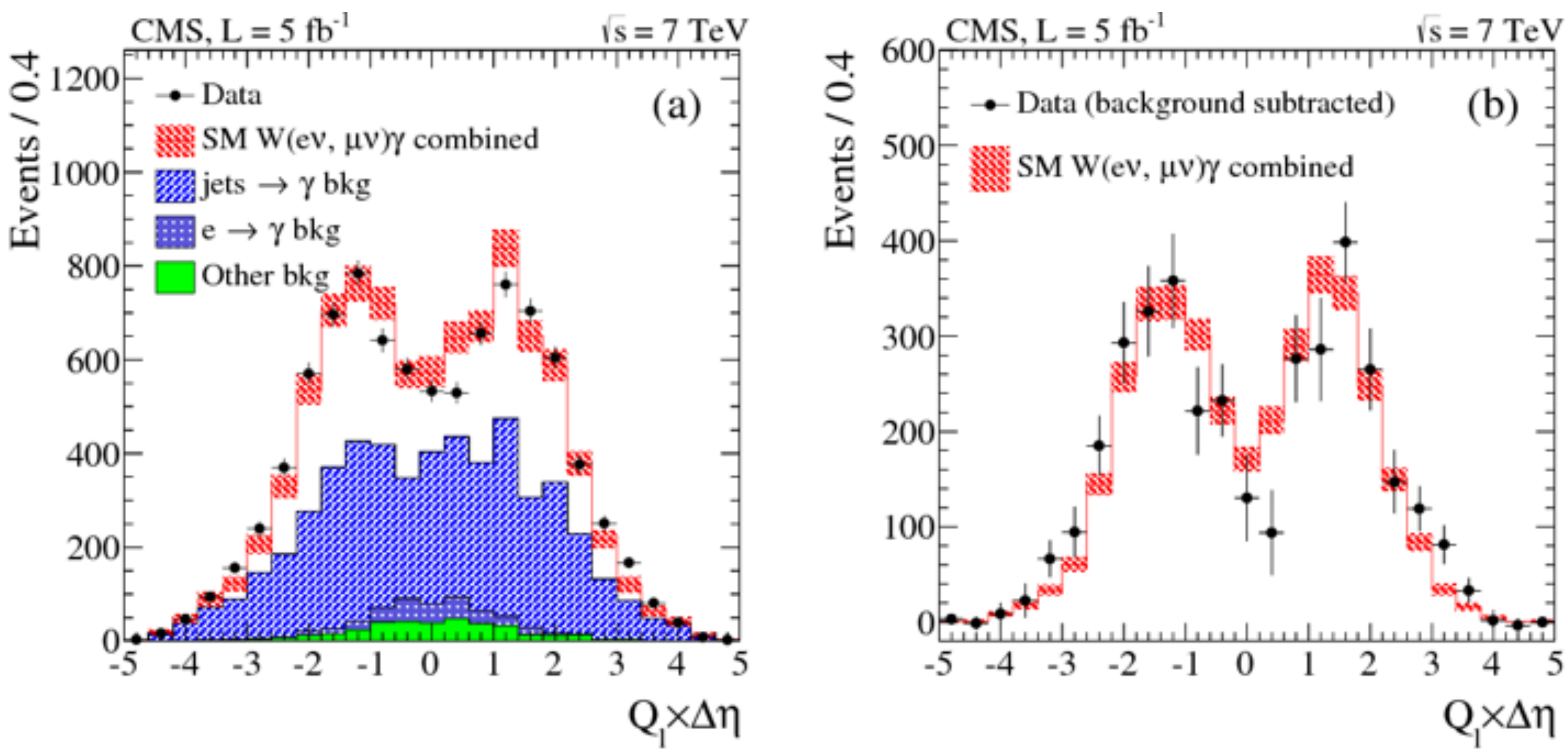
- Measured cross sections are in agreement with SM NLO predictions from MCFM

Wγ aTGC : photon p_T distributions

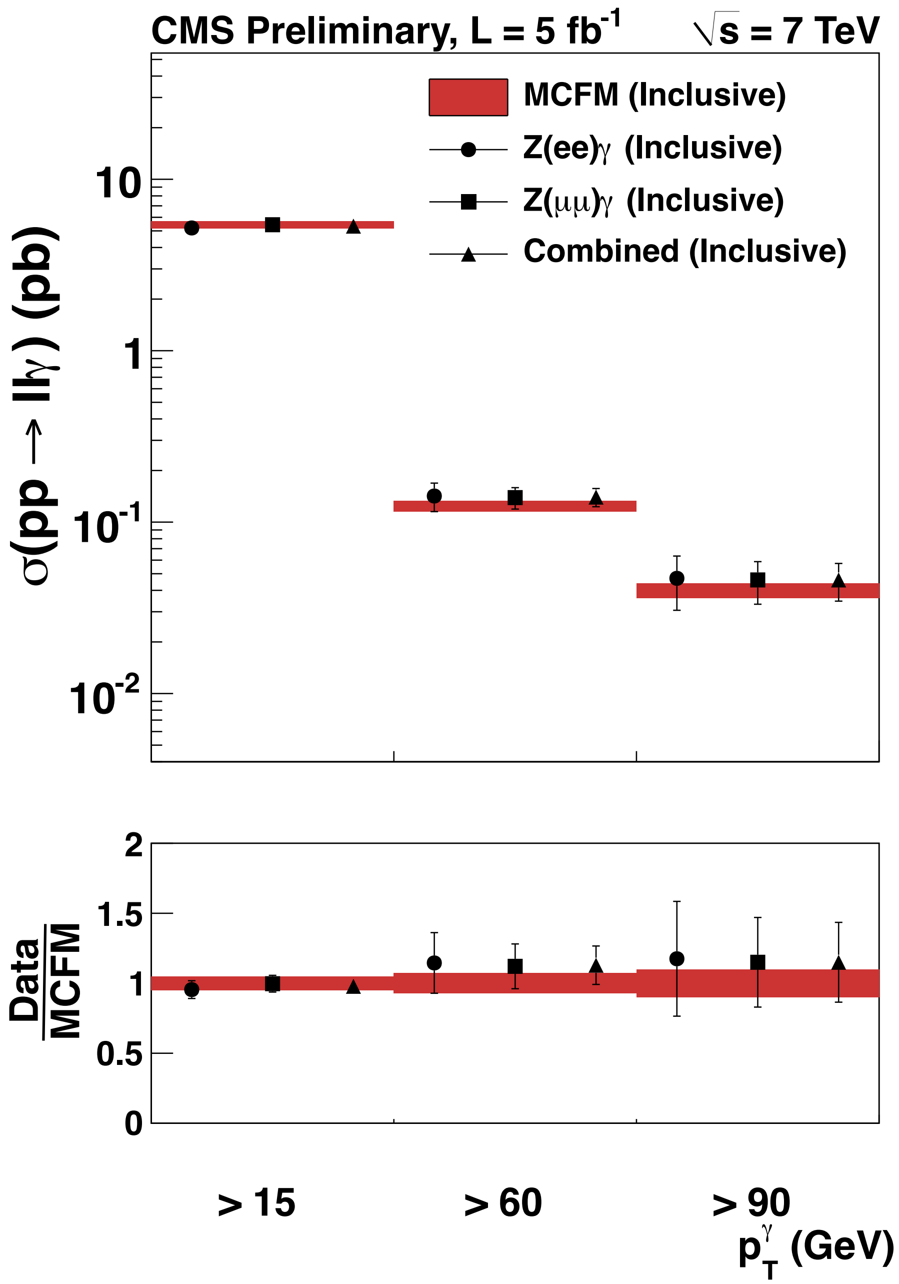


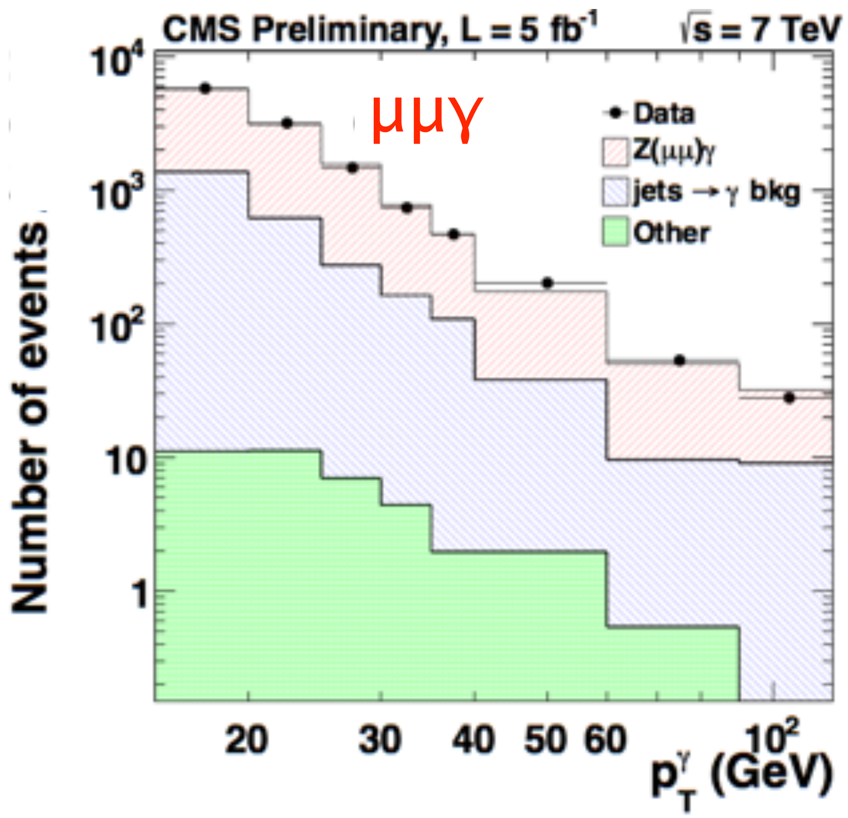
W±γ Radiation Amplitude Zero

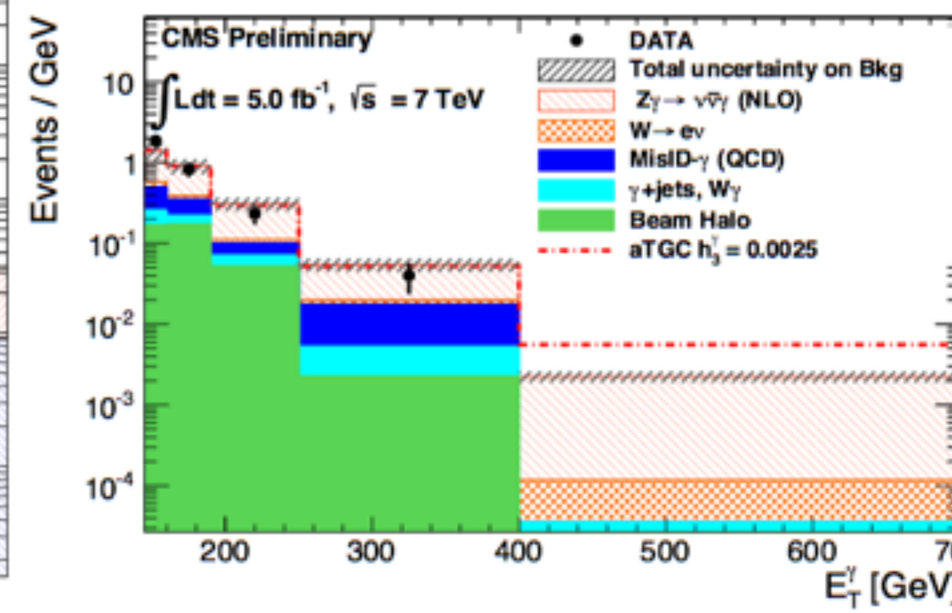
- three tree-level processes (s-channel WWγ vertex, u-, t-channel W +ISR γ) interfere with each other, resulting in a radiation-amplitude zero (RAZ) in the angular distribution of the photon
  - NLO corrections, FSR, aTGC and backgrounds obscure the dips



Zγ results







	$ll\gamma$	$\nu\nu\gamma$
CMS measurement	5.33 ± 0.08 (stat) ± 0.25 (syst) ± 0.12 (lumi) pb	0.021 ± 0.004 (stat) ± 0.004 (syst) ± 0.001 (lumi) pb
NLO prediction	5.45 ± 0.27 pb	0.022 ± 0.001 pb

- Measured cross sections are in agreement with SM NLO predictions

Systematic uncertainties

Wγ

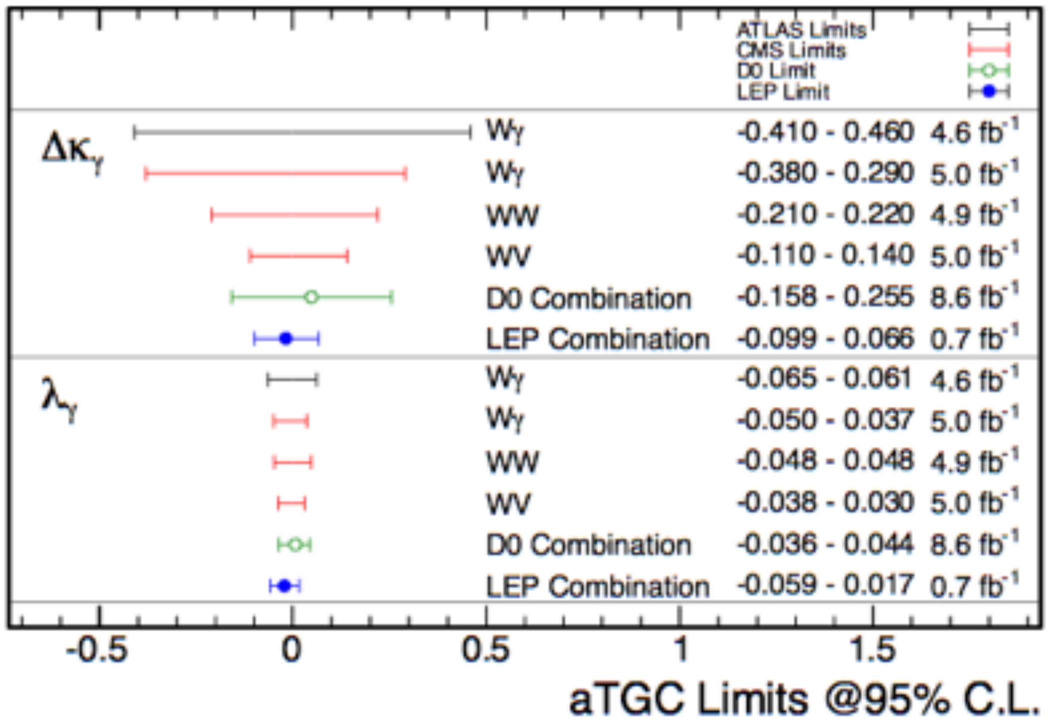
		$e\nu\gamma$	$\mu\nu\gamma$
Source (Group 1)	Uncertainties	Effect from N_{sig}	
e/γ energy scale	(e: 0.5%; γ: 1% (EB), 3% (EE))	2.9%	n/a
γ energy scale	(1% (EB), 3% (EE))	n/a	2.9%
μ p_T scale	(0.2%)	n/a	0.6%
Total uncertainty in N_{sig}		2.9%	3.0%
Source (Group 2)	Uncertainties	Effect from $\mathcal{F}_S = A_S \cdot \epsilon_S$	
e/γ energy resolution	(1% (EB), 3% (EE))	0.3%	n/a
γ energy resolution	(1% (EB), 3% (EE))	n/a	0.1%
μ p_T resolution	(0.6%)	n/a	0.1%
Pileup	(Shift pileup distribution by $\pm$ 5%)	2.4%	0.8%
PDF		0.9%	0.9%
Modeling of signal		5.0%	5.0%
Total uncertainty in $\mathcal{F}_S = A_S \cdot \epsilon_S$		5.6%	5.1%
Source (Group 3)	Uncertainties	Effect from ρ_{eff}	
Lepton reconstruction		0.4%	1.5%
Lepton trigger		0.1%	0.9%
Lepton ID and isolation		2.5%	0.9%
$\not{E}_T$ selection		1.4%	1.5%
γ identification and isolation	(0.5% (EB), 1.0% (EE))	0.5%	0.5%
Total uncertainty in ρ_{eff}		2.9%	2.5%
Source (Group 4)		Effect from background yield	
Template method		9.3%	10.2%
Electron misidentification		1.5%	0.1%
MC prediction		0.8%	0.5%
Total uncertainty due to background		9.5%	10.2%
Source (Group 5)			
Luminosity		2.2%	2.2%

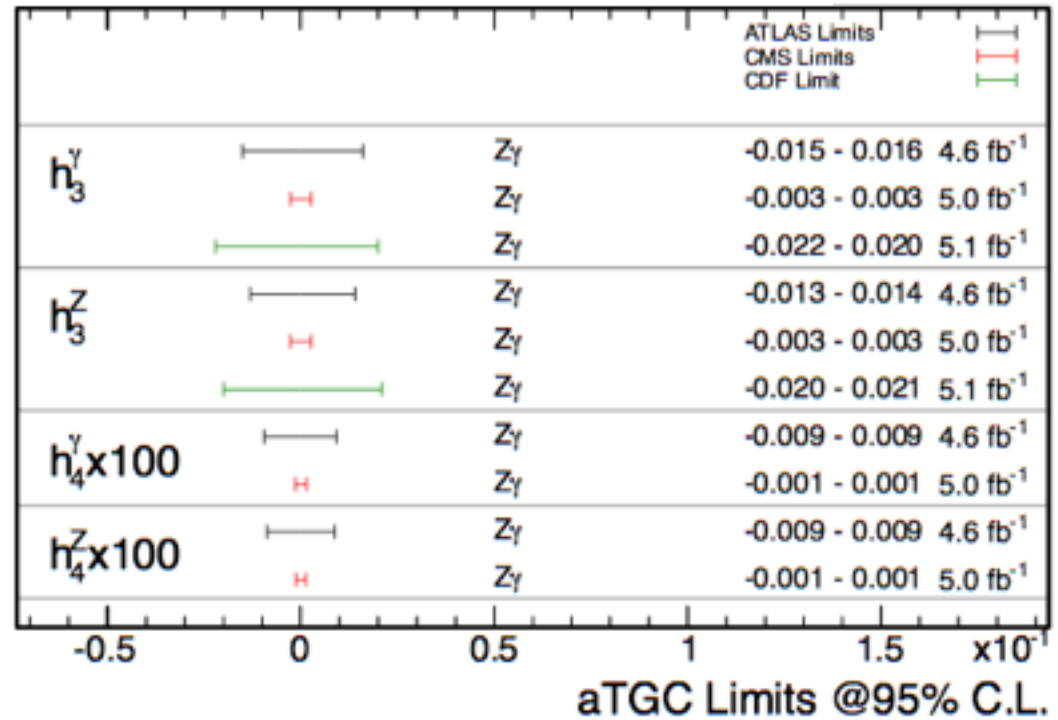
Zγ

		$ee\gamma$	$\mu\mu\gamma$
Source (Group 1)	Uncertainties	Effect from N_{sig}	
e energy scale	(0.5%)	3.0%	n/a
μ p_T scale	(0.2%)	n/a	0.6%
γ energy scale	(1% (EB), 3% (EE))	n/a	4.2%
Total uncertainty in N_{sig}		3.0%	4.2%
Source (Group 2)	Uncertainties	Effect from $\mathcal{F}_S = A_S \cdot \epsilon_S$	
e/γ energy resolution	(1% (EB), 3% (EE))	0.2%	n/a
γ energy resolution	(1% (EB), 3% (EE))	n/a	0.1%
μ p_T resolution	(0.6%)	n/a	0.2%
Pileup	Shift pileup distribution by $\pm$ 5%	0.6%	0.4%
PDF		1.1%	1.1%
Modeling of signal		0.6%	0.5%
Total uncertainty in $\mathcal{F}_S = A_S \cdot \epsilon_S$		1.4%	1.3%
Source (Group 3)	Uncertainties	Effect from ρ_{eff}	
Lepton reconstruction		0.8%	1.0%
Lepton trigger		0.1%	1.0%
Lepton ID and isolation		5.0%	1.8%
Photon ID and isolation	(0.5% (EB), 1.0% (EE))	0.5%	1.0%
Total uncertainty in ρ_{eff}		5.1%	2.5%
Source (Group 4)		Effect from background yield	
Template method		1.2%	1.5%
Total uncertainty due to background		1.2%	1.5%
Source (Group 5)			
Luminosity		2.2%	2.2%

anomalous TGC results

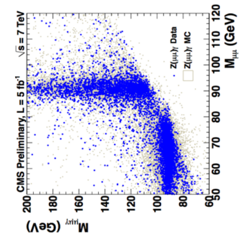
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC



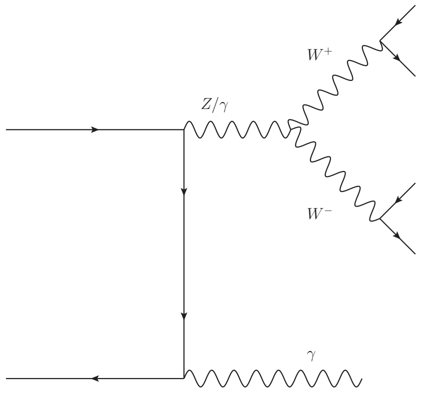


- To model generic new physics signal, we work with the effective Lagrangian
  - Example : WWV vertex (V = Z, γ)
  - The number of coupling parameters can be reduced if one takes some assumptions (e.g. C and P conservation)
- Use P_T^{γ} shape to extract limits on aTGC
- λ_{γ} results competitive with most sensitive measurements
- Results of neutral TGC are world's most sensitive
- No evidence observed for physics beyond the SM

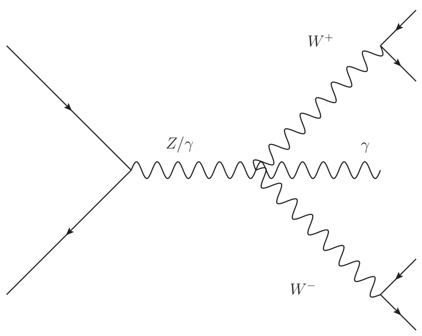
WWγ and WZγ signature and event selections



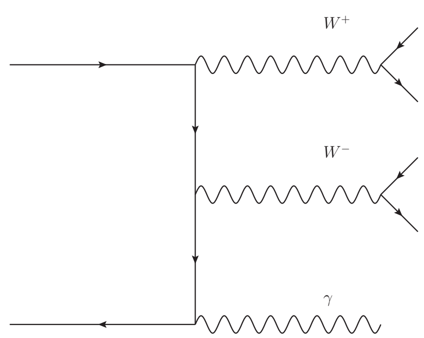
- Measurements based on final state of WVγ→lν+dijet+γ (l = e,μ)
  - using 19.3/fb of 8 TeV data
  - CMS PAS SMP-13-009
- single lepton trigger
- p_T^e > 30 GeV, p_T^μ > 25 GeV
- Minimum of 2 jets with p_T > 30 GeV and $|\eta|$ < 2.4
- MET > 35 GeV, ΔΦ(MET, leading jet) > 0.4, M_T^W > 30 GeV
- p_T^γ > 30 GeV, ECAL barrel only, and well separated from jets and lepton
- Exactly one lepton, anti-b tag for jets
- $|\Delta\eta_{jj}|$ < 1.4, 70 < M_{jj} < 100 GeV, and $|M_{\gamma e} - M_Z|$ > 10 GeV



TGC



QGC

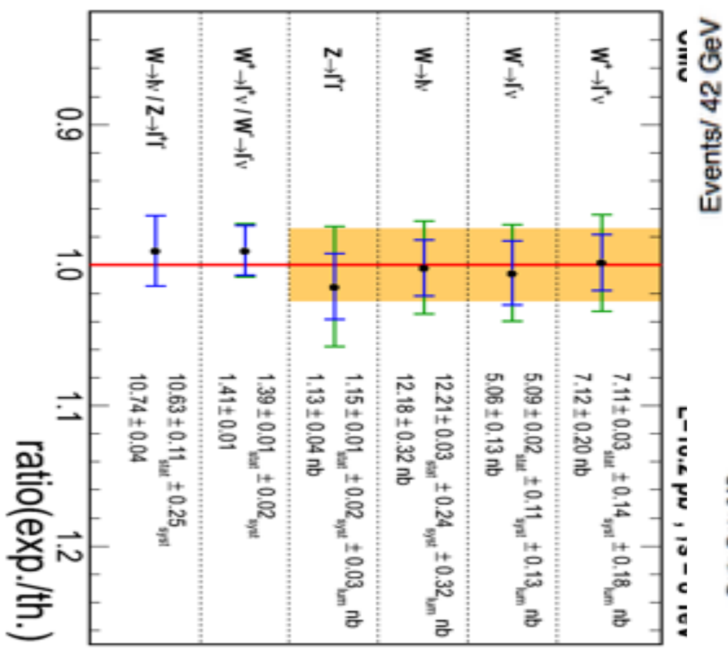


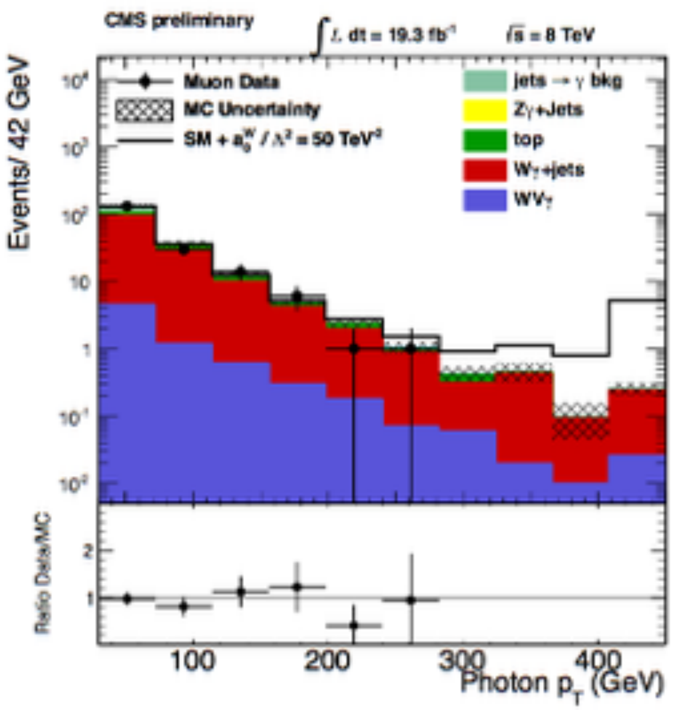
QED radiation

Backgrounds for WVγ

- Major background : Wγ + jets
  - Data and MC dijet mass sidebands (0-70 and 100-190 GeV) used to estimate the data-driven Wγ+jets normalization
- jet→γ : WV+jets
  - estimated from data using "ratio method"
- Others (tt+γ, t, Zγ+jets, QCD) are estimated from simulation

WVγ results

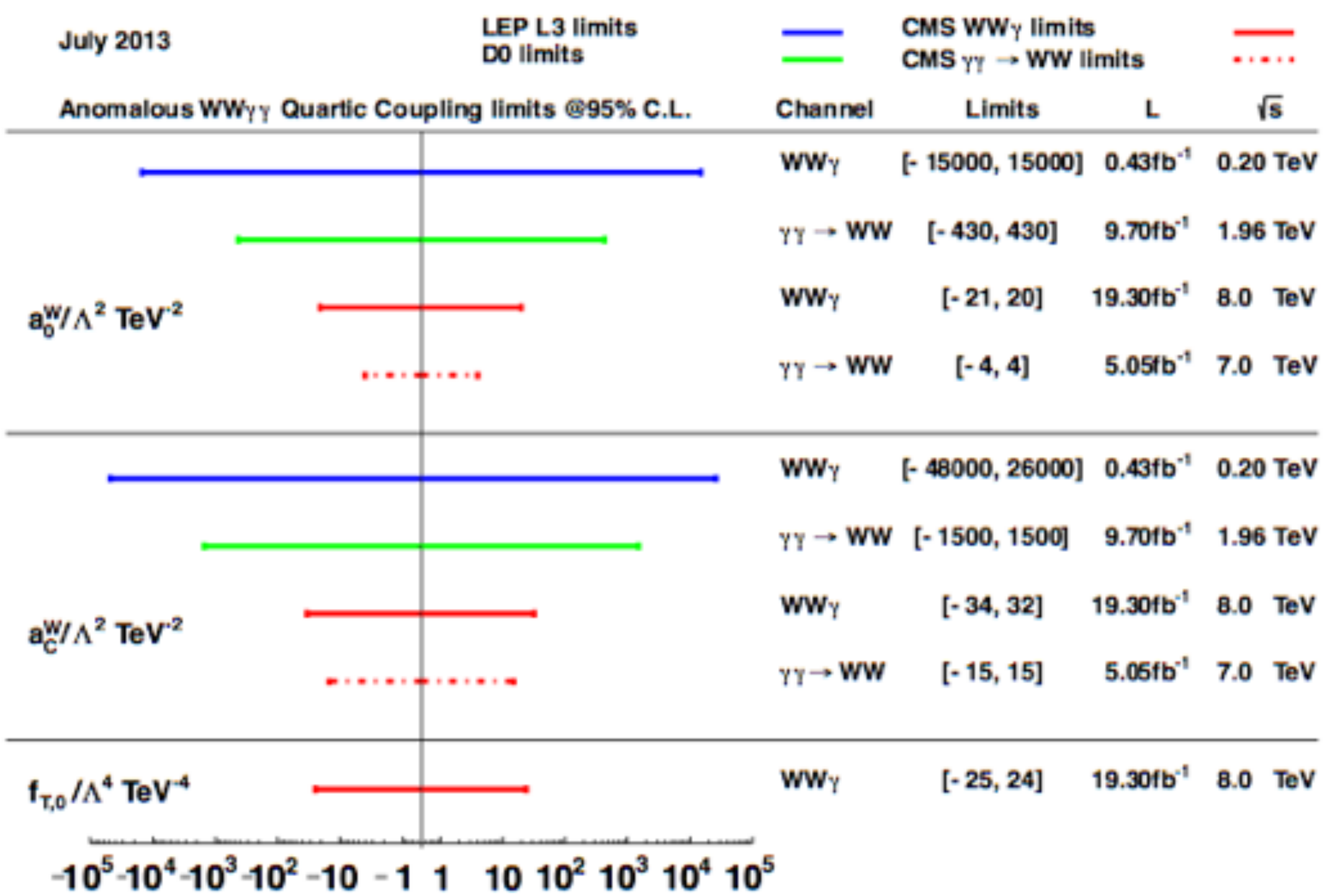


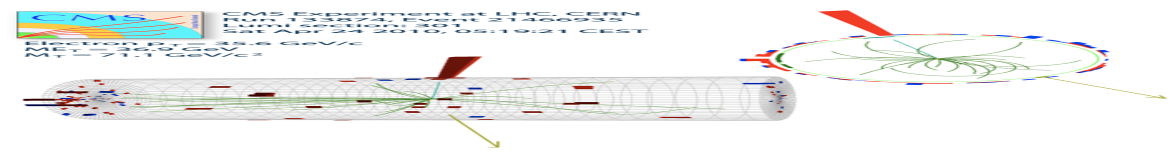


Process	muon channel number of events	electron channel number of events
$W\gamma$+jets	136.9 ± 3.5 ± 9.2 ± 0.0	101.6 ± 2.9 ± 8.0 ± 0.0
WV+jet, jet→ γ	33.1 ± 1.3 ± 4.6 ± 0.0	21.3 ± 1.0 ± 3.1 ± 0.0
MC $t\bar{t}\gamma$	12.5 ± 0.8 ± 2.9 ± 0.5	9.1 ± 0.7 ± 2.1 ± 0.4
MC single top	2.8 ± 0.8 ± 0.2 ± 0.1	1.7 ± 0.6 ± 0.1 ± 0.1
MC $Z\gamma$+jets	1.7 ± 0.1 ± 0.1 ± 0.1	1.5 ± 0.1 ± 0.1 ± 0.1
multijets	<0.2± 0.0 ± 0.1 ± 0.0	7.2 ± 3.6 ± 3.6 ± 0.0
SM $WW\gamma$	6.3 ± 0.1 ± 1.5 ± 0.3	4.7 ± 0.1 ± 1.1 ± 0.2
SM $WZ\gamma$	0.6 ± 0.0 ± 0.1 ± 0.0	0.5 ± 0.0 ± 0.1 ± 0.0
Total predicted	193.9 ± 3.9 ± 10.8 ± 1.0	147.6 ± 4.8 ± 9.6 ± 0.7
Data	183	139

- good agreement between measurements and predictions
- an upper limit for WWγ and WZγ cross section, 241 fb, is set at 95% C.L. for p_T^{γ} > 10 GeV
  - about 3.4 times larger than SM prediction, 70.3 fb, from aMC@NLO

anomalous QGC results

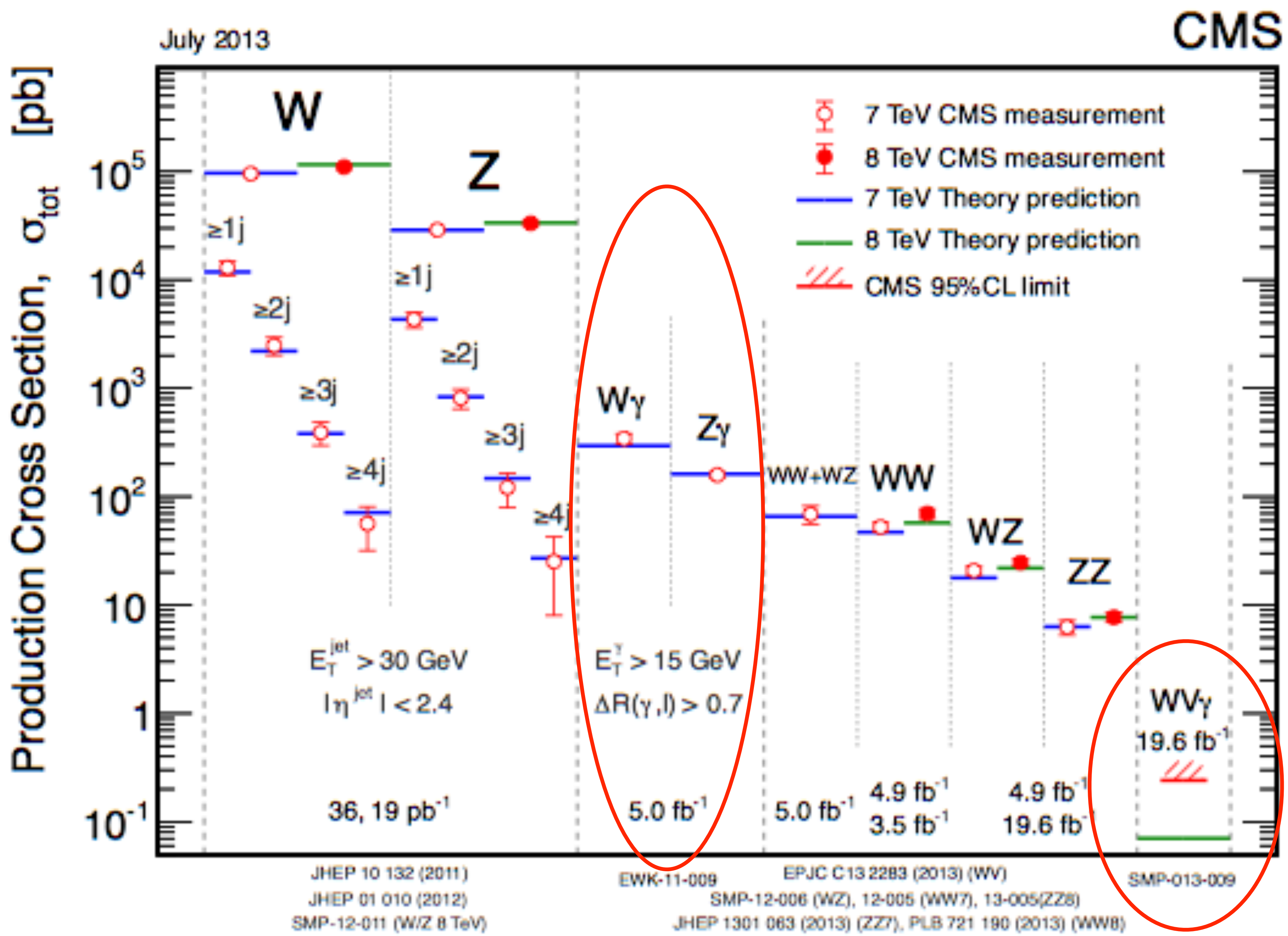




WWZγ vertex	
κ	[-12, 10] TeV
κ	[-18, 17] TeV

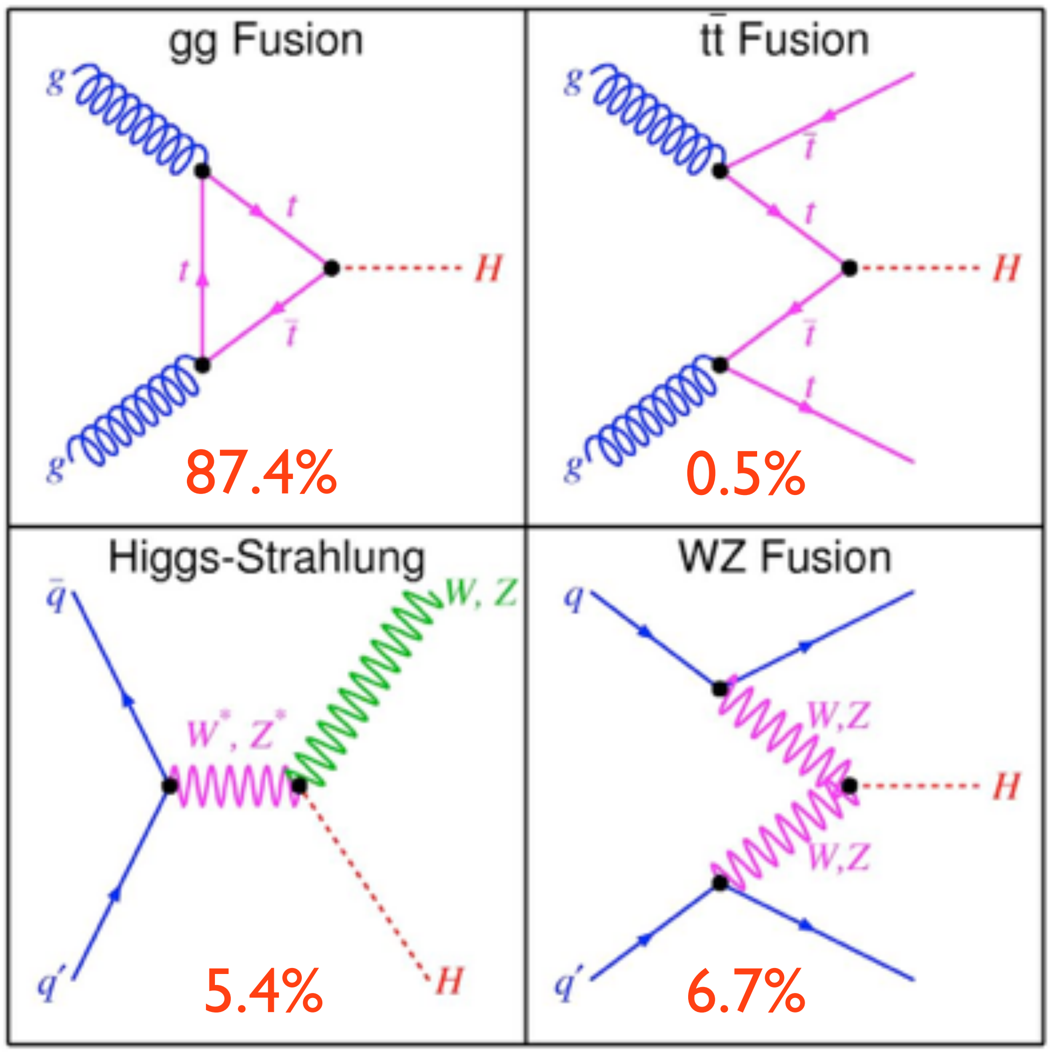
- Use P_T^{γ} shape to extract limits on anomalous quartic gauge couplings
- focus on anomalous vertices that may be associated to dimension 6 and 8 effective operators
- first constraint on the κ_0^W and k_C^W parameter of WWZγ vertex
- No evidence of anomalous QGC is found

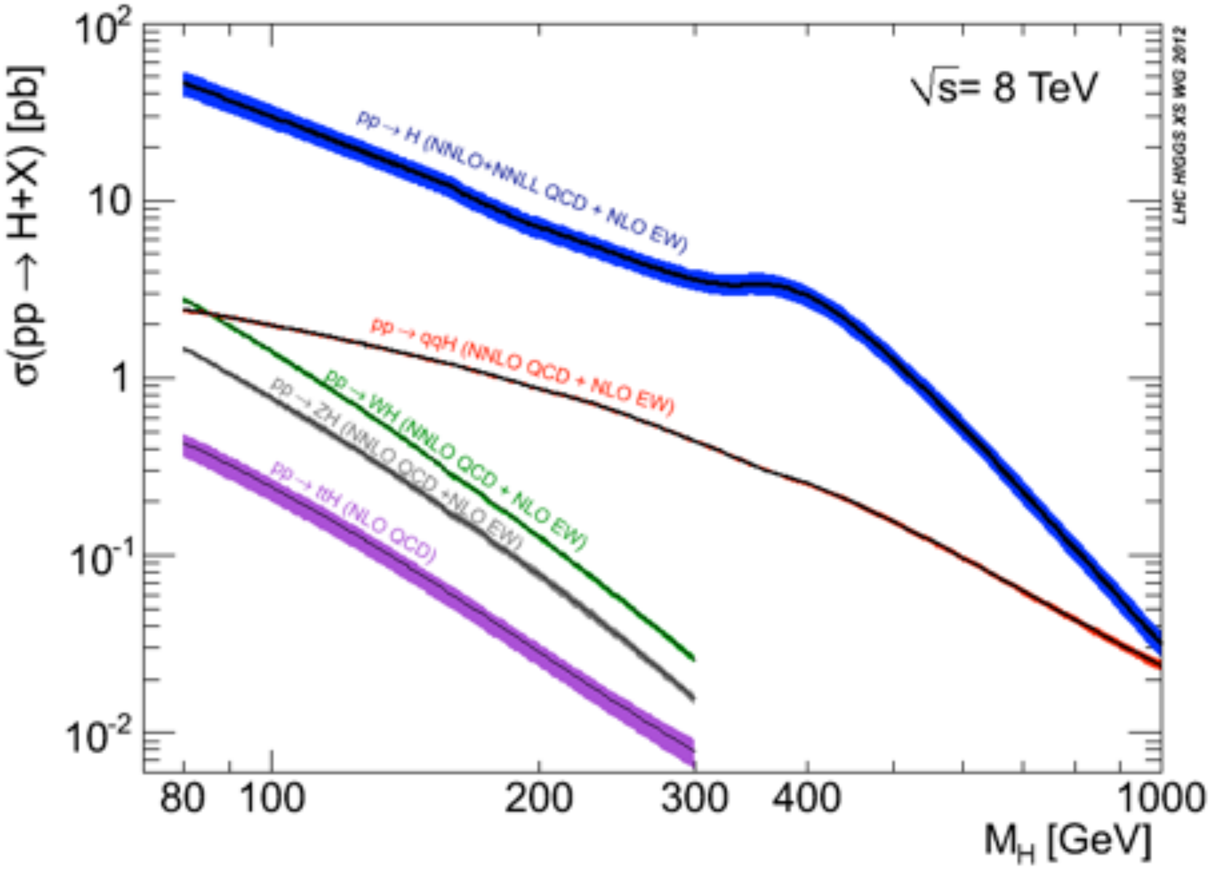
Current status of EWK production measurements in CMS



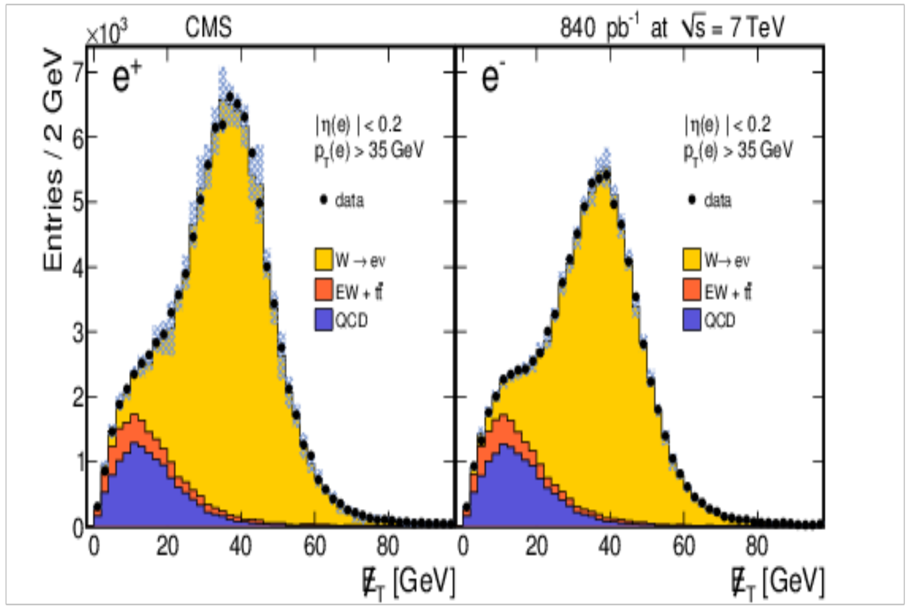
Higgs production

@ 120 GeV

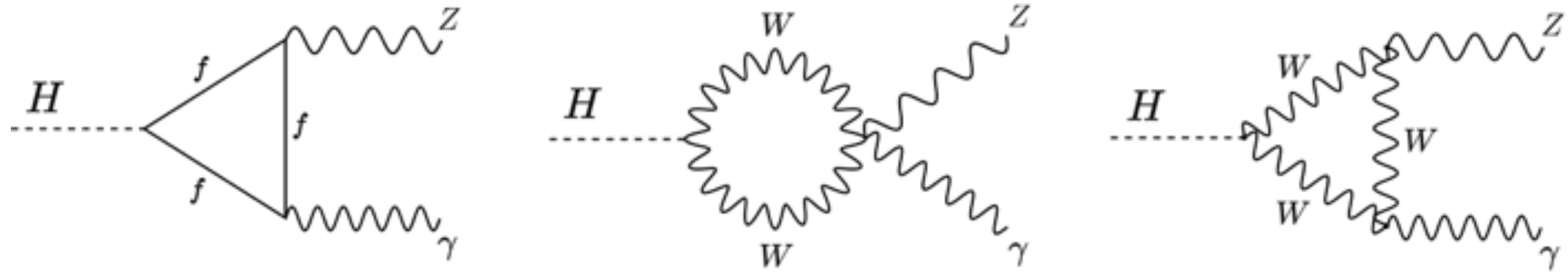




Higgs decay channels



$H \rightarrow Z\gamma$



- First $H \rightarrow Z\gamma$ measurement at LHC
- Within the SM, the partial width ($\Gamma_{Z\gamma}$) for the $H \rightarrow Z\gamma$ decay channel is rather small, resulting in a BR between 0.11% and 0.25% in 120-160 GeV
- The measurement of $\Gamma_{Z\gamma}$ provides important information on the underlying dynamics of the Higgs sector because it is induced by loops of heavy charged particles, just as $H \rightarrow \gamma\gamma$

$H \to Z\gamma$

- $\Gamma_{Z\gamma}$ is sensitive to physics beyond SM, and could be substantially modified by new charged particles without affecting the gluon-gluon fusion Higgs boson production cross section [1], such as derived from an extended Higgs sector [2], or by the presence of new scalars [3,4]

[1] M. Carena, I. Low, and C.E.M. Wagner, JHEP 8 (2012) 60
[2] C.-W. Chiang and K. Yagyu, PRD 87 (2013) 33003
[3] I. Low, J. Lykken, and G. Shaughnessay PRD 84 (2011) 35027
[4] C.-S. Chen, C.-Q. Geng, D. Huang, and L.-H. Tsai, PRD 87 (2013) 75019

H→Zγ search in CMS

- We look for H→Zγ with the Z boson decaying into an electron or a muon pair
- A clean final-state with good mass resolution (~1-3%)
- leading/trailing lepton p_T > 20/10 GeV, p_T^{γ} > 15 GeV
- $|\eta^{\gamma}| < 2.5$, but excluding the ECAL barrel-endcap transition region, $|\eta^{e}| < 2.5$ and $|\eta^{\mu}| < 2.4$
- $m_{ll} > 50$ GeV, $\Delta R(l, \gamma) > 0.4$
- $m_{ll\gamma}/p_T^{\gamma} > 15/110$ to suppress Z+jets
- $m_{ll} + m_{ll\gamma} > 185$ GeV
- $p_T^{jet} > 30$ GeV and $|\eta^{jet}| < 4.7$
- Zeppenfeld $\eta_{Z\gamma} - (\eta_{j1} + \eta_{j2})/2$
- $\Delta\eta jj > 3.5$, $\Delta\Phi(Z\gamma, jj) > 2.4$

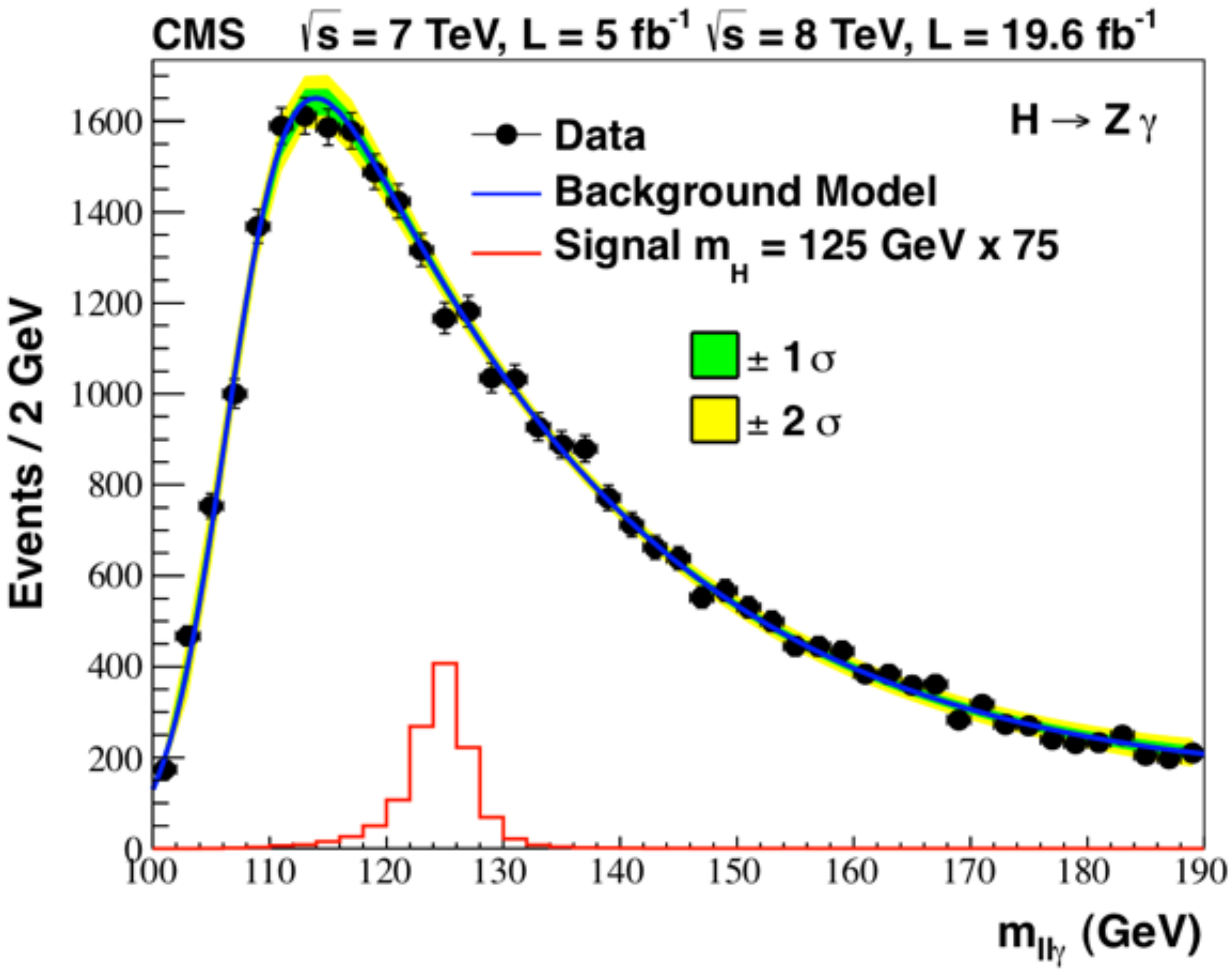
VBF dijet tag

Table 1: Observed and expected event yields for a 125 GeV SM Higgs boson.

Sample	Integrated luminosity (fb^{-1})	Observed event yield for $100 < m_{\ell\ell\gamma} < 190$ GeV	Expected number of signal events for $m_H = 125$ GeV
2011 ee	5.0	2353	1.2
2011 $\mu\mu$	5.1	2848	1.4
2012 ee	19.6	12899	6.3
2012 $\mu\mu$	19.6	13860	7.0

- Signal yield is similar to H→ZZ→4l at 125 GeV
- Background processes :
  - SM Z+γ associated production
  - SM Z+jets where jet fakes photon

H→Zγ mass spectrum



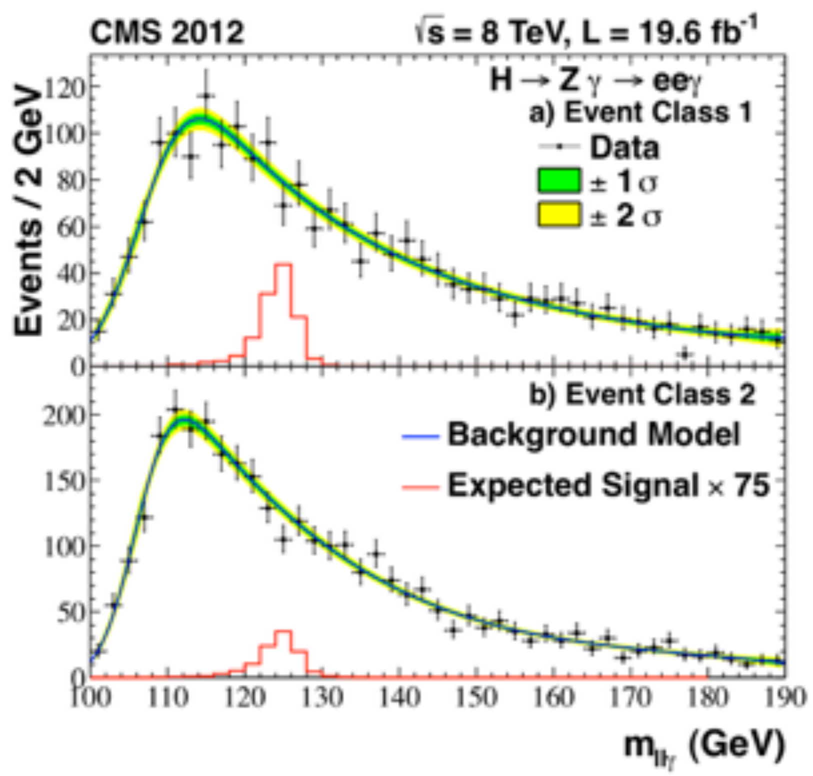
$H \to Z\gamma$ event classes

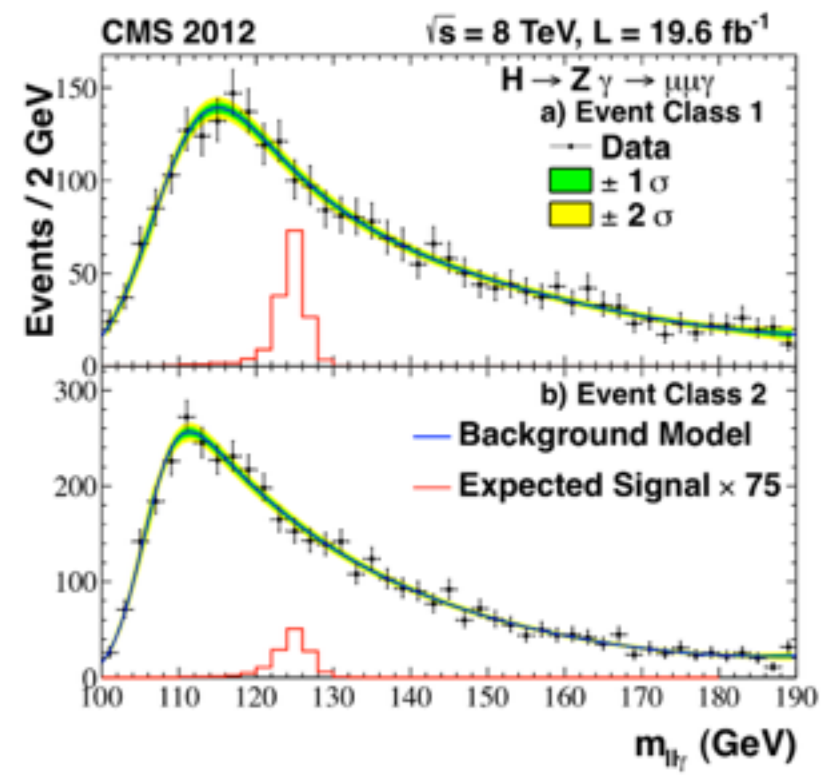
Table 2: Definition of the four untagged event classes and the dijet-tagged event class, the fraction of selected events for a signal with $m_{\mathrm{H}} = 125\,\mathrm{GeV}$ produced by gluon-gluon fusion at $\sqrt{s} = 8\,\mathrm{TeV}$, and data in a narrow bin centered at 125 GeV. The bin width is equal to two times the effective standard deviation (σ_{eff}). The expected full width at half maximum (FWHM) for the signal is also listed.

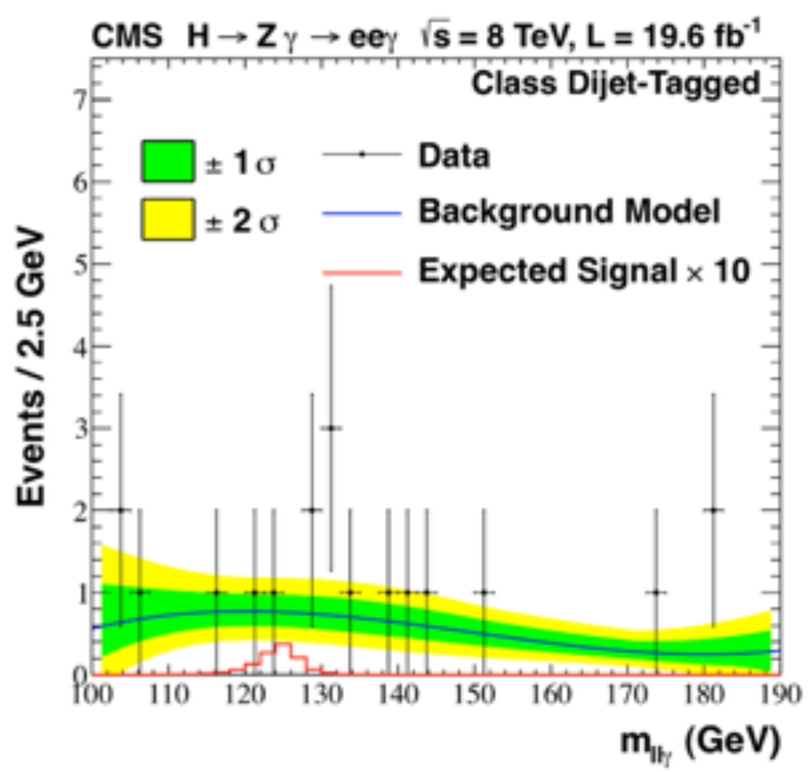
	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
	Event class 1	
	Photon $0 < \lvert\eta\rvert < 1.44$	Photon $0 < \lvert\eta\rvert < 1.44$
	Both leptons $0 < \lvert\eta\rvert < 1.44$	Both leptons $0 < \lvert\eta\rvert < 2.1$ and one lepton $0 < \lvert\eta\rvert < 0.9$
	$R_9 > 0.94$	$R_9 > 0.94$
Data	17%	20%
Signal	29%	33%
σ_{eff} (GeV)	1.9 GeV	1.6 GeV
FWHM (GeV)	4.5 GeV	3.7 GeV
	Event class 2	
	Photon $0 < \lvert\eta\rvert < 1.44$	Photon $0 < \lvert\eta\rvert < 1.44$
	Both leptons $0 < \lvert\eta\rvert < 1.44$	Both leptons $0 < \lvert\eta\rvert < 2.1$ and one lepton $0 < \lvert\eta\rvert < 0.9$
	$R_9 < 0.94$	$R_9 < 0.94$
Data	26%	31%
Signal	27%	30%
σ_{eff} (GeV)	2.1 GeV	1.9 GeV
FWHM (GeV)	5.0 GeV	4.6 GeV
	Event class 3	
	Photon $0 < \lvert\eta\rvert < 1.44$	Photon $0 < \lvert\eta\rvert < 1.44$
	At least one lepton $1.44 < \lvert\eta\rvert < 2.5$	Both leptons in $\lvert\eta\rvert > 0.9$ or one lepton in $2.1 < \lvert\eta\rvert < 2.4$
	No requirement on R_9	No requirement on R_9
Data	26%	20%
Signal	23%	18%
σ_{eff} (GeV)	3.1 GeV	2.1 GeV
FWHM (GeV)	7.3 GeV	5.0 GeV
	Event class 4	
	Photon $1.57 < \lvert\eta\rvert < 2.5$	Photon $1.57 < \lvert\eta\rvert < 2.5$
	Both leptons $0 < \lvert\eta\rvert < 2.5$	Both leptons $0 < \lvert\eta\rvert < 2.4$
	No requirement on R_9	No requirement on R_9
Data	31%	29%
Signal	19%	17%
σ_{eff} (GeV)	3.3 GeV	3.2 GeV
FWHM (GeV)	7.8 GeV	7.5 GeV
	VBF class	
	Photon $0 < \lvert\eta\rvert < 2.5$	Photon $0 < \lvert\eta\rvert < 2.5$
	Both leptons $0 < \lvert\eta\rvert < 2.5$	Both leptons $0 < \lvert\eta\rvert < 2.4$
	No requirement on R_9	No requirement on R_9
Data	0.1%	0.2%
Signal	1.8%	1.7%
σ_{eff} (GeV)	2.6 GeV	2.2 GeV
FWHM (GeV)	4.4 GeV	3.8 GeV

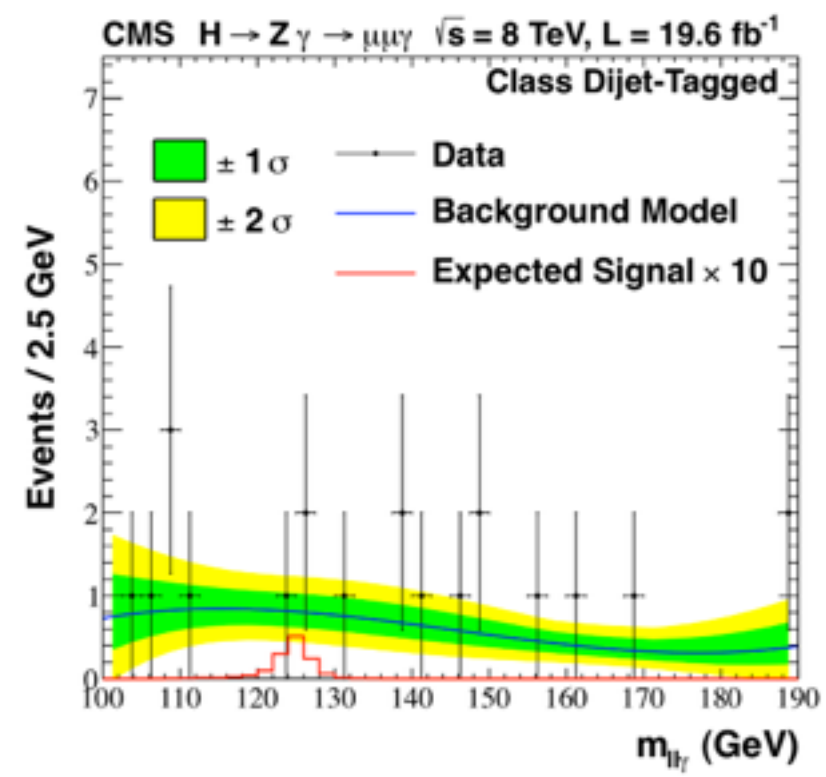
- Events are divided into 5 mutually exclusive classes
- 4 classes based on the expected mass resolution and signal-to-background ratio
- the 5th class is the VBF di-jet tag
- The search sensitivity is enhance by 20-40% by using the first 4 event classes
- A 10-15% increase in sensitivity is obtained by adding di-jet category

H→Zγ Background and signal modeling





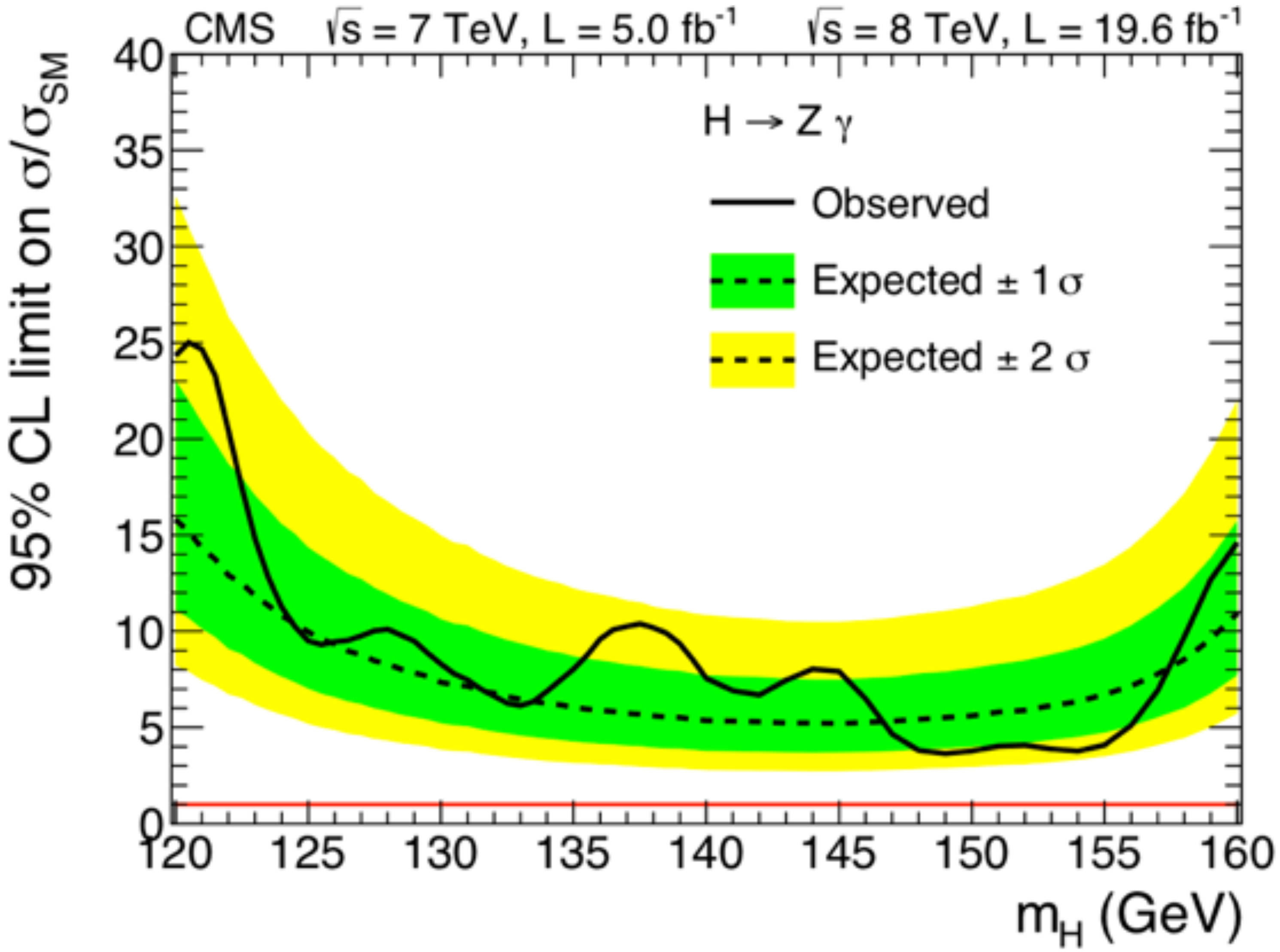




Systematic uncertainties

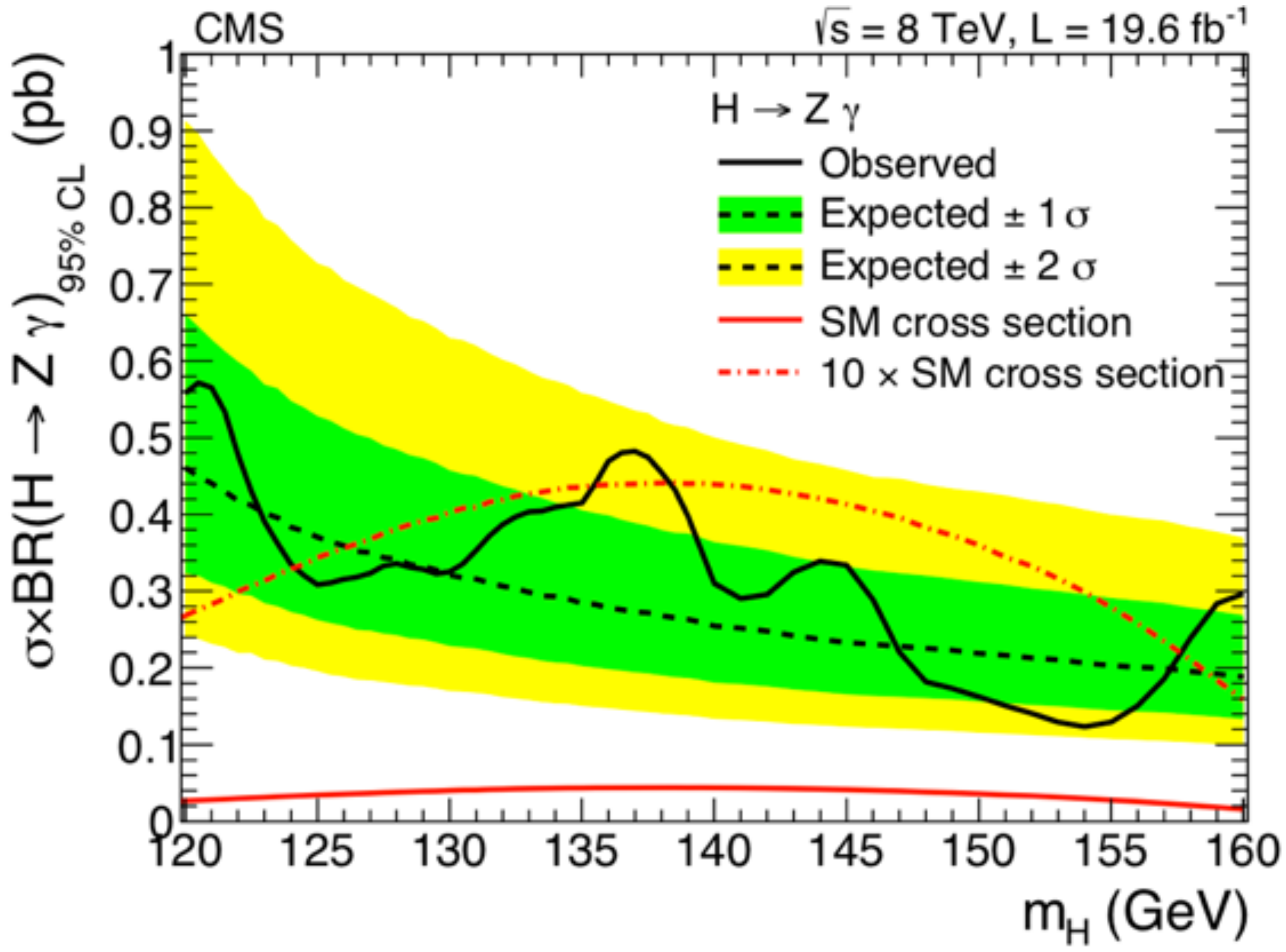
Source	Uncertainty
luminosity	2.2%, 4.4%
trigger efficiency	0.5-3.5%
PDF	0.3%-12.5%
Higgs branching ratio fraction prediction	6.7-9.4%
pile-up modeling	0.4-0.8%
lepton efficiency/energy scale/resolution	0.7-1.4%
photon efficiency/energy scale/resolution	0.5-1.0%
dijet selections (Jet ID, JEC, JER, UE)	8.8-28.5%
event migration between the first four classes	5.0%
event migration between dijet and rest classes	5.1-9.8%
signal modeling	1.0-5.0%

$H \rightarrow Z\gamma$ limits



- the observed and expected limits for $m_{ll\gamma}$ at 125 GeV are within one order of magnitude of the SM prediction

$H \to Z\gamma$ limits



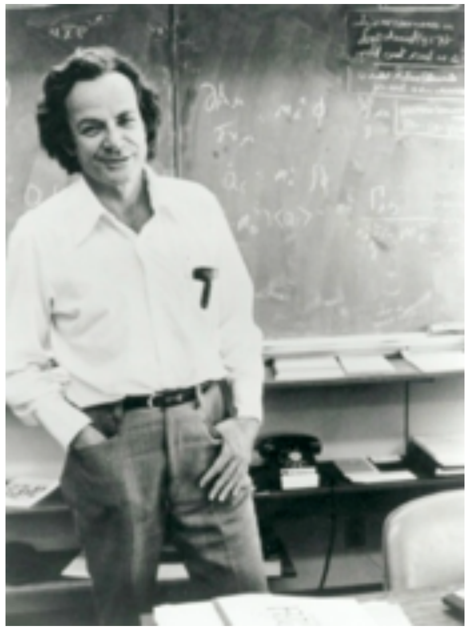
- Excludes models predicting σxBR to be larger than one order of magnitude of the SM prediction for 125-157 GeV mass range
- Models predicting significant enhancements for $\Gamma_{Z\gamma}$ with respect to the SM expectations due to a pseudoscalar admixture are now excluded

Summary

- The electroweak measurements and the search of rare Higgs decay are presented
- There are a lot of more physics analyses out there to be done

About discovery new laws

- "It does not make any difference how beautiful your guess is. It does not make any difference how smart you are, who made the guess, or what his name is ? If it disagrees with experiment it is wrong" R. P. Feynman



- Please come to join us !