Study of $V\gamma$ production at CMS

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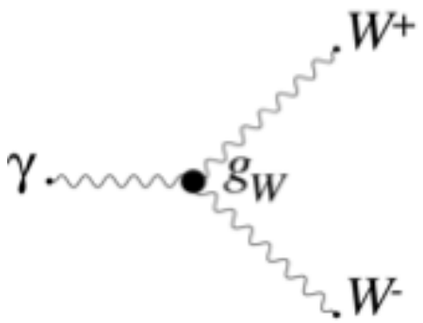
Diboson physics

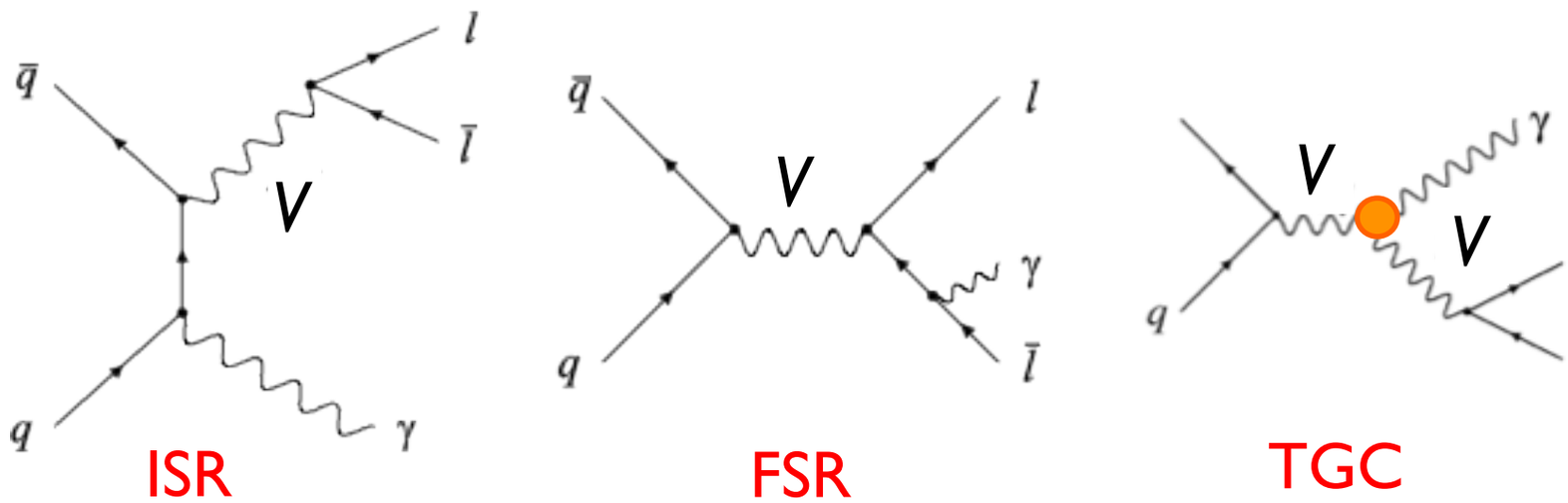
- Production of two bosons: $\gamma\gamma$, $W\gamma$, $Z\gamma$, WW, WZ, ZZ
  - Test of trilinear gauge couplings



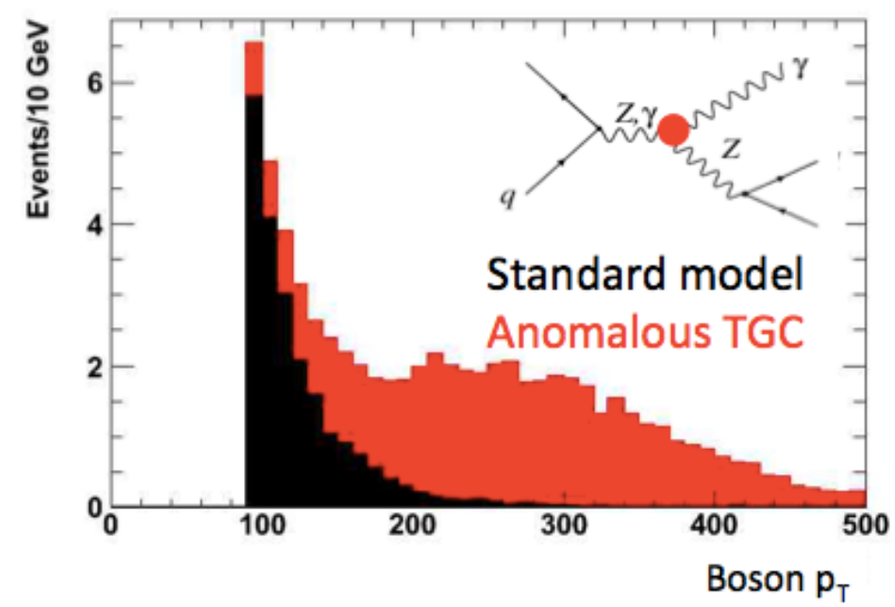
    - Fully fixed in the Standard Model (SM)
  - A number of new physics phenomena that predict production of multiple bosons:
    - Technicolor, SUSY, extra-dimensions, new heavy gauge bosons, some heavy neutrino scenarios, extra-dimension based Higgs-less models, …
  - Major background to Higgs production

Wγ and Zγ production

- Three distinct production mechanisms at LO
  - Initial state radiation (ISR), final state radiation (FSR), and via trilinear gauge vertex



  - Anomalous values of TGC would result in excess of the measured cross section
    - Excess of energetic bosons



Modeling of aTGC

- To model generic new physics signal we work with the effective Lagrangian

  - Example: WVγ vertex (V = Z, γ)

$$\frac{\mathcal{L}_{eff}^{WWV}}{g_{WWV}} = ig_1^V(W^*_{\mu\nu}W^\mu V^\nu - W^*_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^*_\mu W_\nu V^{\mu\nu} + i\frac{\lambda_V}{M_W^2}W^*_{\lambda,\mu}W^\mu_\nu V^{\nu\lambda} - g_4^V W^*_\mu W_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu)$$
$$+ g_5^V\epsilon^{\mu\nu\lambda\rho}(W^*_\mu\partial_\lambda W_\nu - \partial_\lambda W^*_\mu W_\nu)V_\rho + i\tilde{\kappa}_V W^*_\mu W_\nu \tilde{V}^{\mu\nu} + i\frac{\tilde{\lambda}_V}{M_W^2}W^*_{\lambda\mu}W^\mu_\nu\tilde{V}^{\nu\lambda},$$

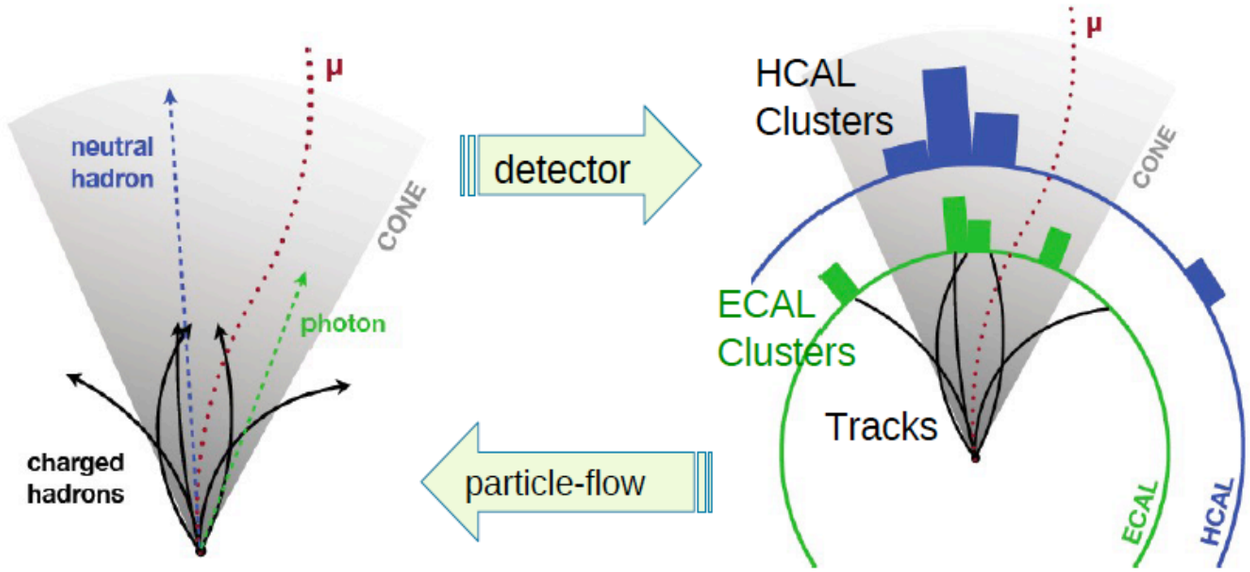
  - The number of free parameters can be reduced if one takes some assumptions (*e.g.* photon does not have an electric charge, *etc.*)

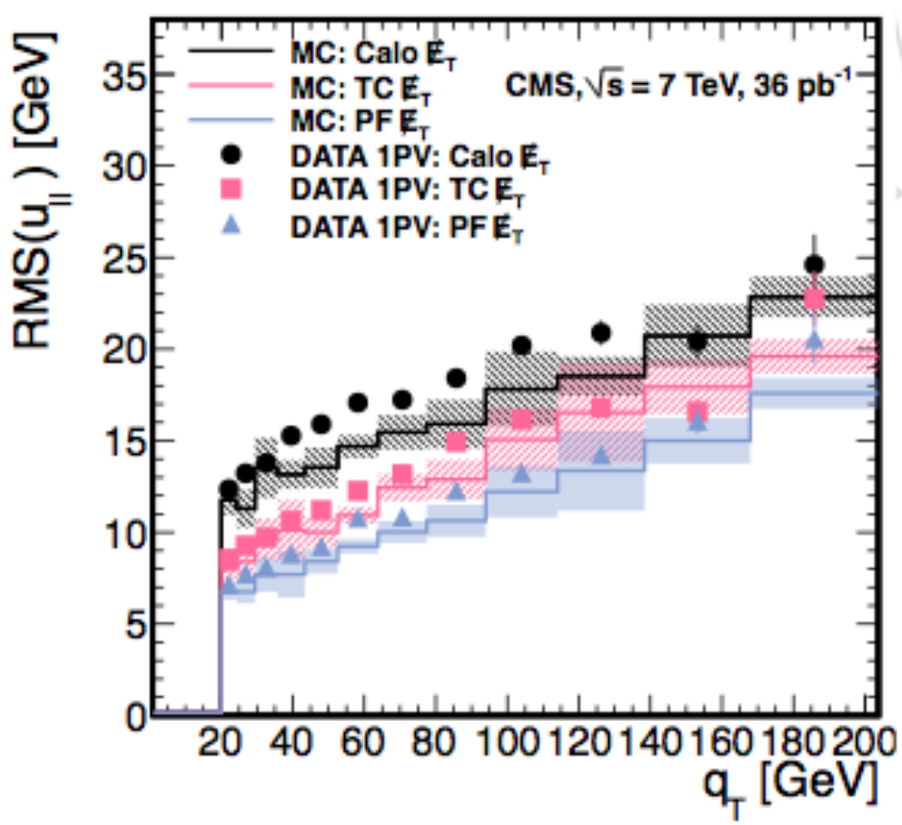
- Several generators exist on the market

  - MCFM and VBFNLO are first true NLO generators that include both ISR and FSR processes: use for normalization

  - MadGraph (v5!) & Sherpa give Vγ+njets at LO: Acc x eff

Particle flow (GED)





- Build particle candidates from tracks and energy deposits
- Exploits the good separation of charged particles due to the large tracker volume and high magnetic field and the good ECAL granularity
- Significant improvement in energy resolution using GED methods: much better measured imbalance of transverse energy (MET)

Event selection

- This talk: $W\gamma$ and $Z\gamma$ with charged lepton decay mode based on 36 /pb and first look at $\nu\nu\gamma$ production with 5 /fb

$W\gamma \rightarrow \ell\nu\gamma$

Lepton selection

- p_T > 20 GeV
- no second lepton

MET > 25 GeV

Photon selection

- E_T > 10 GeV
- $\Delta R(\ell, \gamma)$ > 0.7

$Z\gamma \rightarrow \ell\ell\gamma$

Lepton selection

- p_T > 20 GeV

Dilepton mass > 50 GeV

Photon selection

- E_T > 10 GeV
- $\Delta R(\ell, \gamma)$ > 0.7

γ+MET ($Z\gamma \rightarrow \nu\nu\gamma$)

Photon selection

- p_T > 145 GeV

MET > 130 GeV

No other significant activity in the event: jets, leptons, *etc.*

- Standard event selection criteria for leptons and photons (currently centrally supported in CMS)

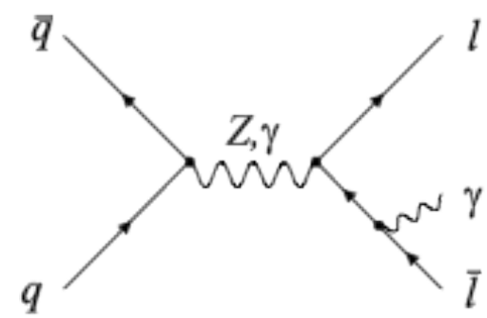
Data-Model comparison

stolen from D. Lincoln's slides

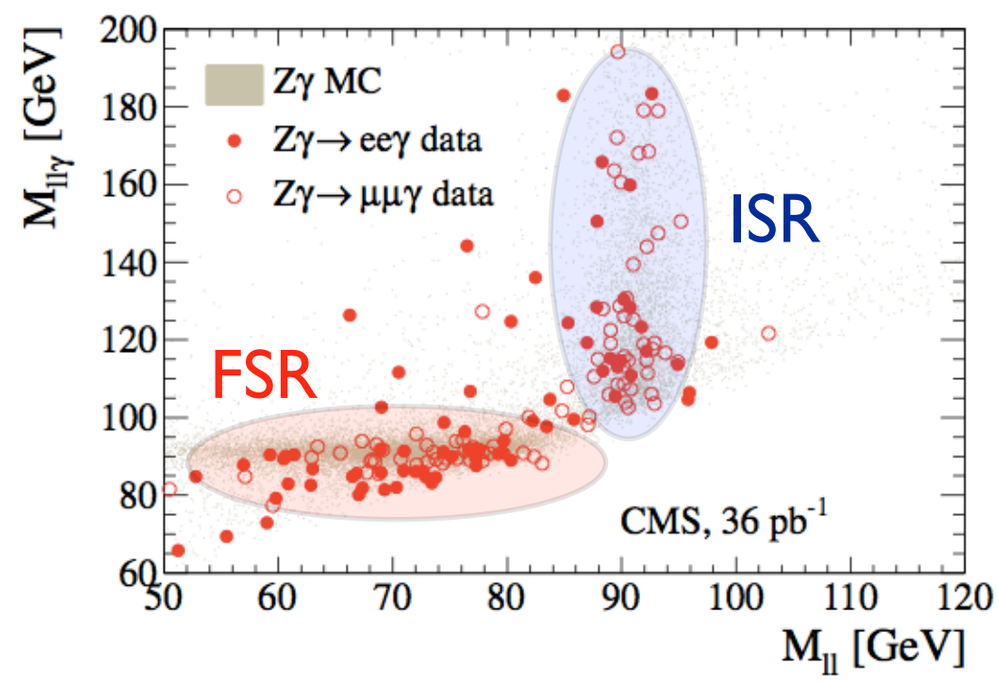
- Extract efficiencies from data using leptonic Z boson production
  - Lepton and photon identification via "Tag and Probe" method; MET resolutions studies; *etc*.

In situ γ calibration

- The Vγ cross section strongly depends on the threshold of $E_T(\gamma)$



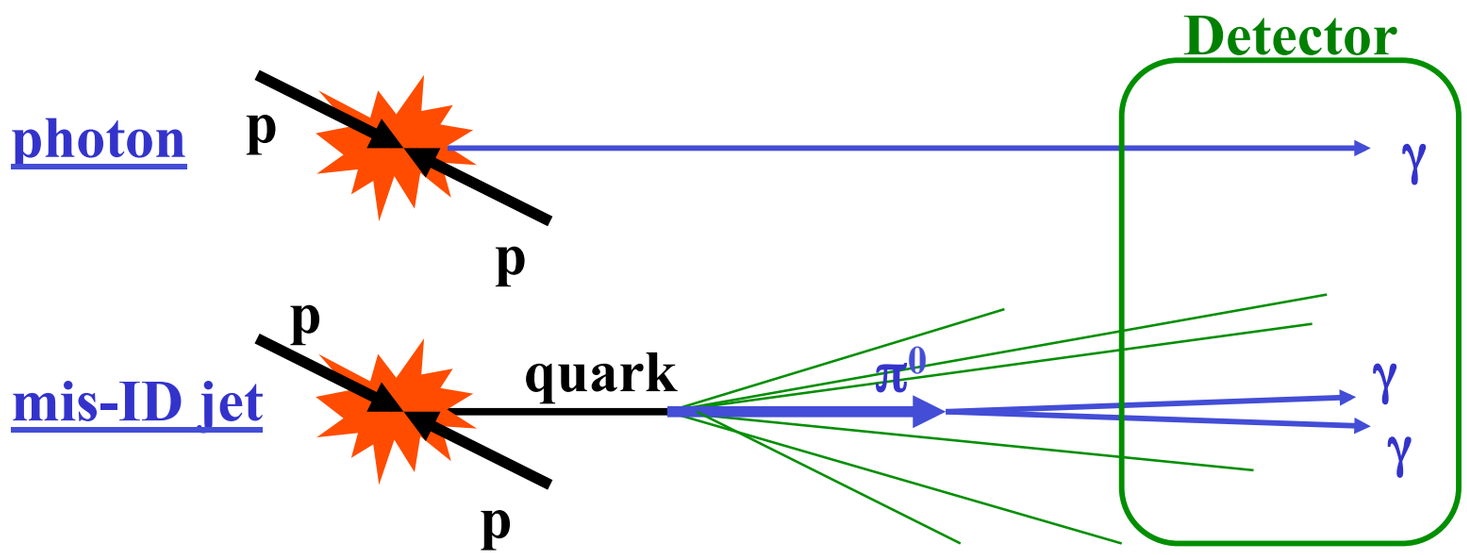
  - Use FSR $Z \rightarrow \mu\mu\gamma$ final state as the almost pure source of low-E_T photons
  - Obtain a relative calibration of photons (with respect to $Z \rightarrow \mu\mu$ invariant mass)



  - Precision of photon energy is 2-3% depending on pseudorapidity and energy

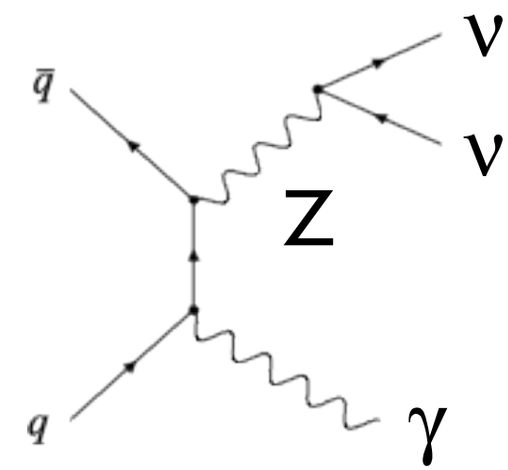
Backgrounds: Vγ

- Major backgrounds are from processes with jets misidentified as photons



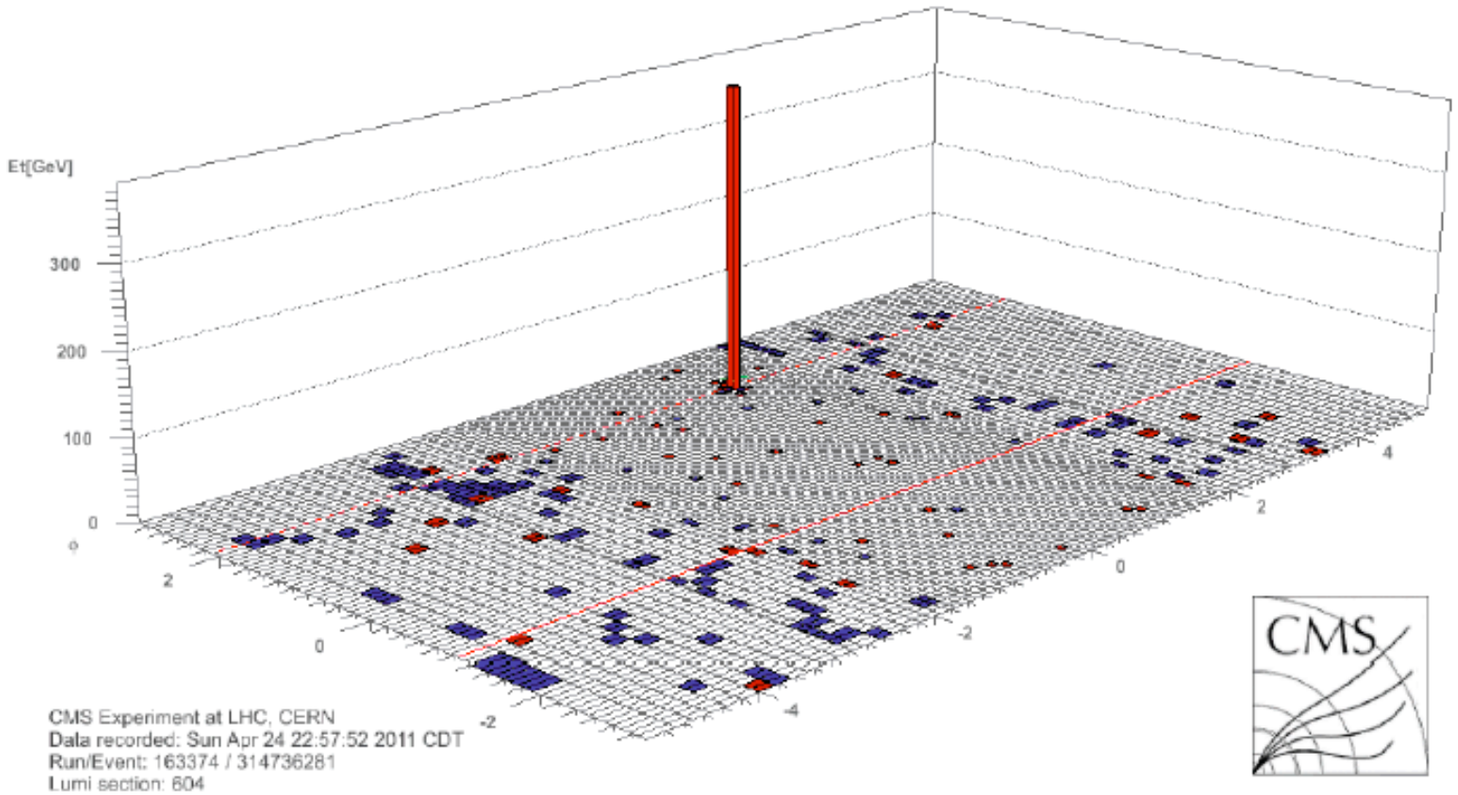
- Several ways to extract backgrounds using data
  - Example: ratio method $N_{V+\text{jets}} = \left(\frac{N_{\text{isolated }\gamma}}{N_{\text{non-isolated }\gamma}}\right)_{QCD} \times N_{V+\text{non-isolated }\gamma}$
- Systematic uncertainties:
  - gluon vs. quark composition in control QCD sample and signal, artificial MET dependence that cause bias, ...

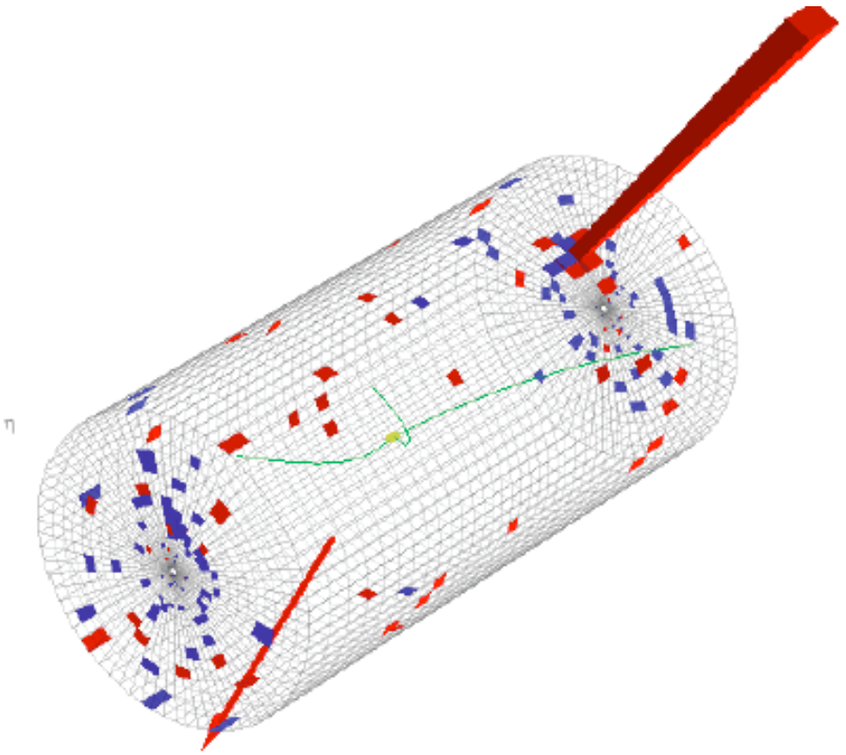
Backgrounds for $\nu\nu\gamma$

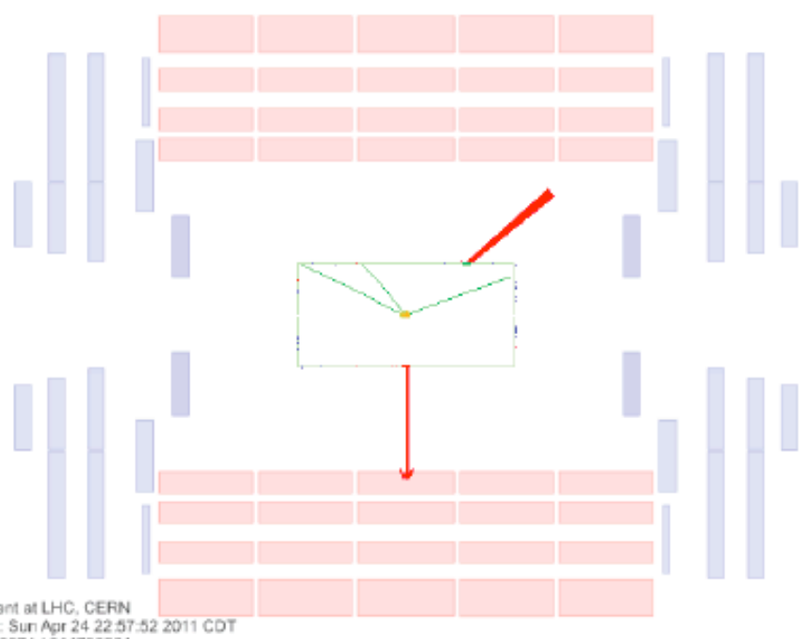


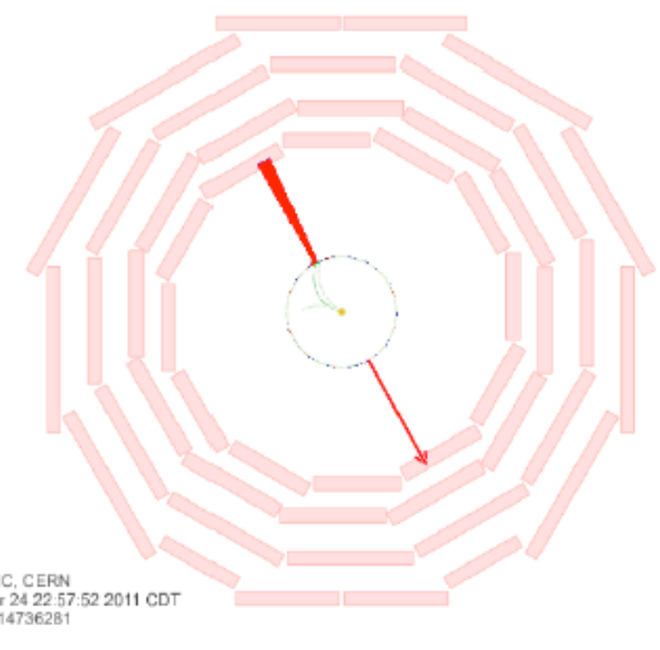
- Final state: two neutrinos (MET) and a photon
  - Only ISR component exists in SM
- Prompt backgrounds
  - $pp \to W \to e\nu$ with electron mis-ID as γ (from data)
  - $pp \to jets \to$ "γ" + MET (from data)
  - $pp \to \gamma + jet$ (small, from MC)
  - $pp \to W\gamma \to \ell\nu\gamma$ (small, from MC)
- Backgrounds unrelated to pp collissions:
  - Cosmics, beam halo, neutron-induced signals

Example of γ+MET event

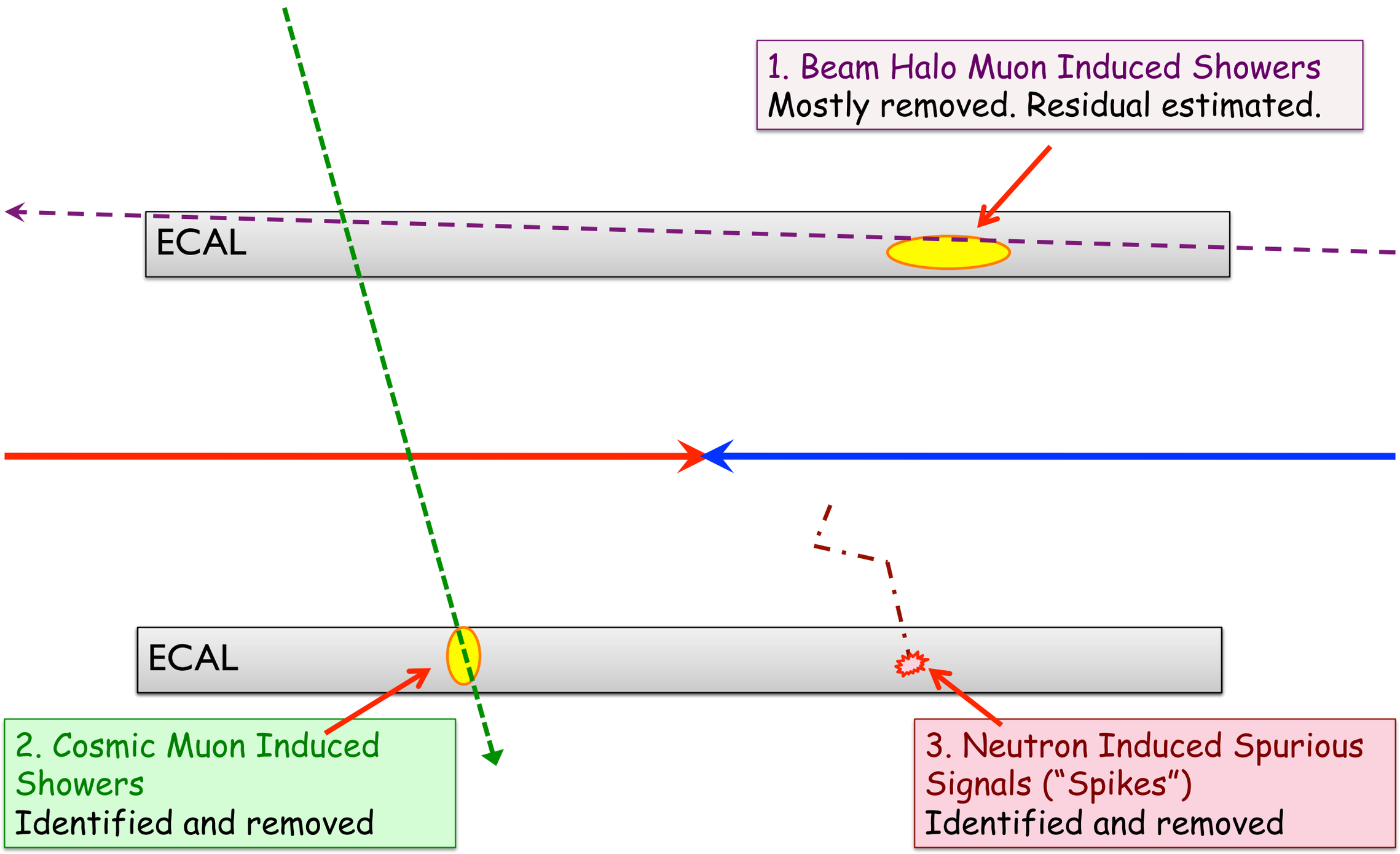






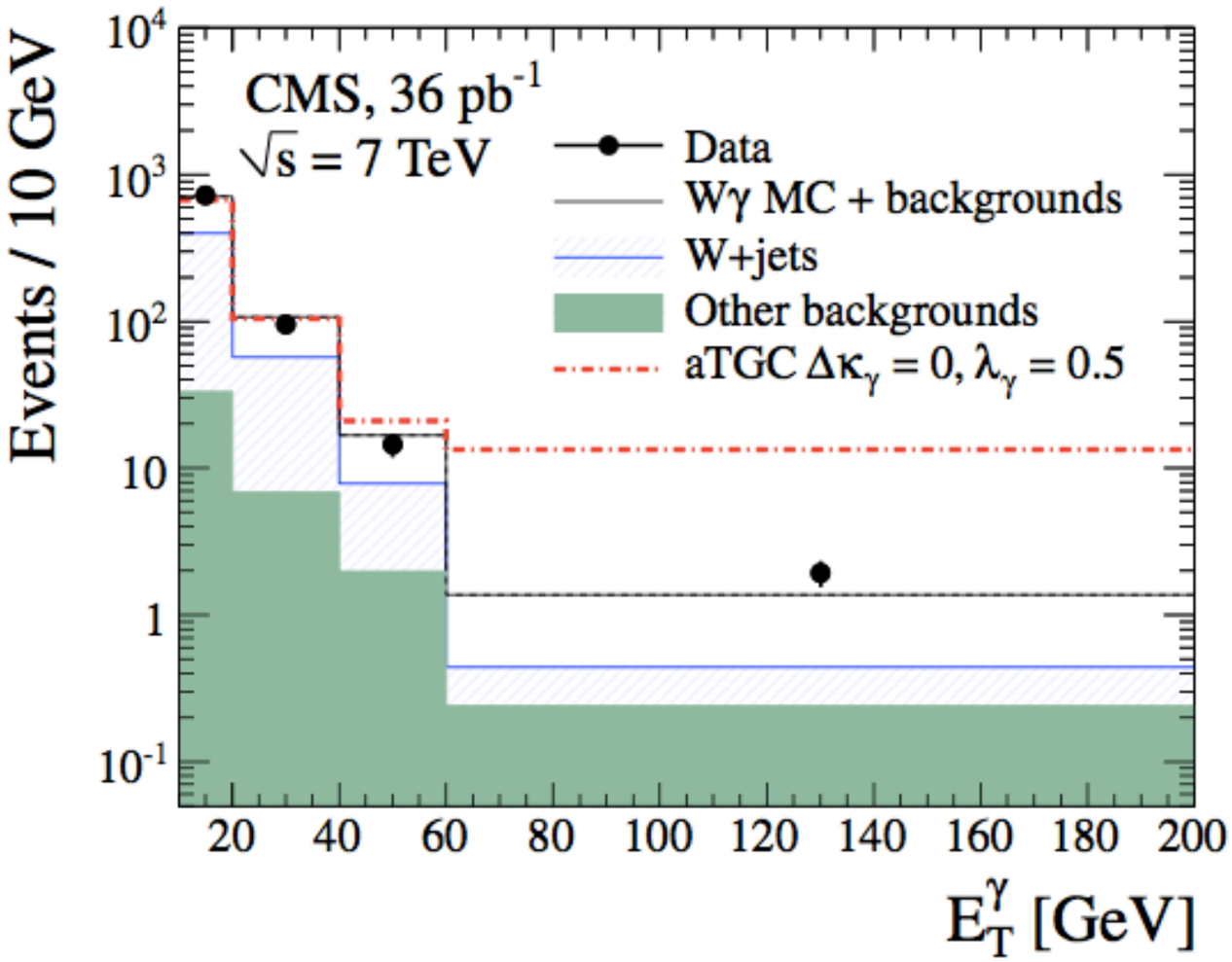


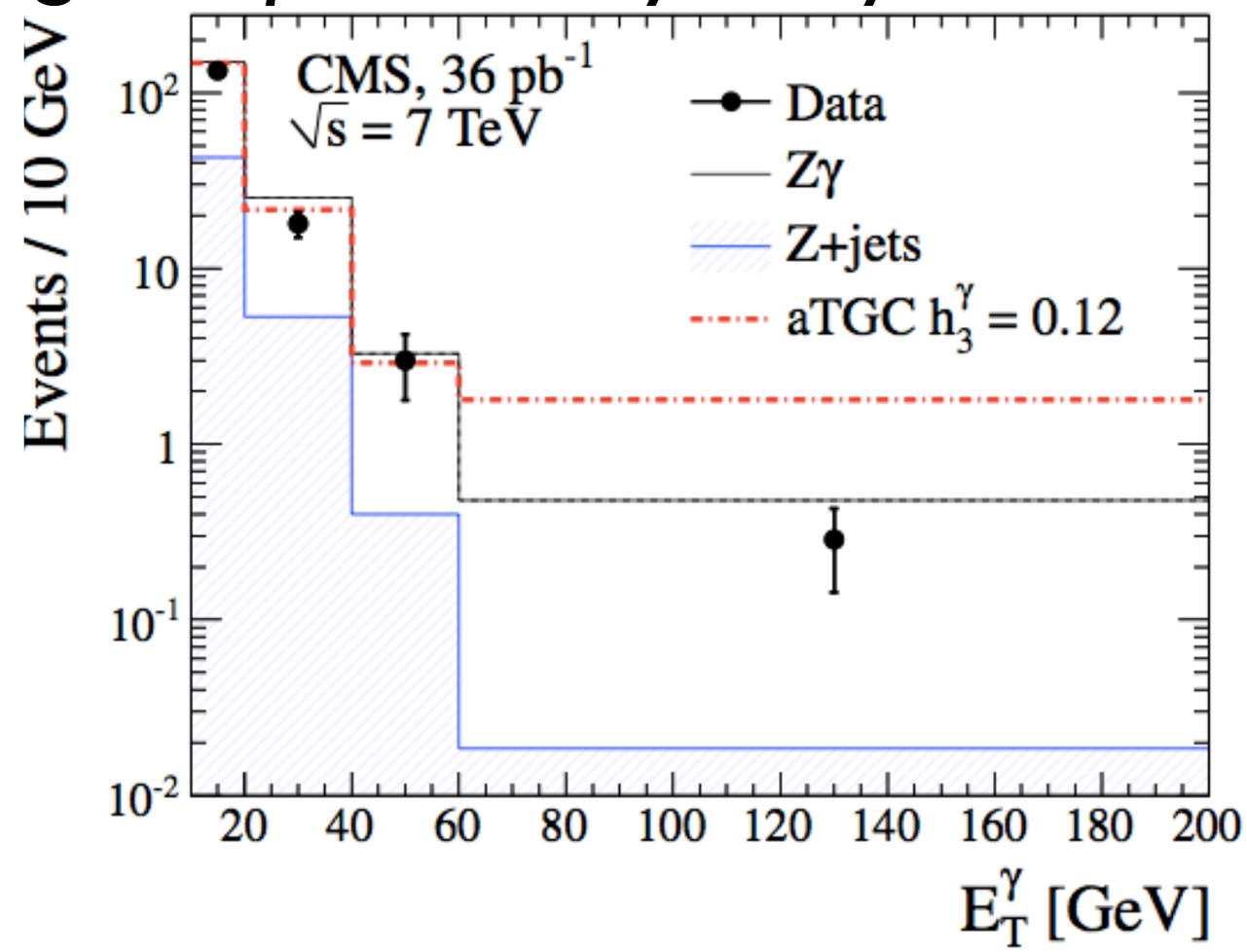
Non-collision backgrounds in γ+MET



Results: Wγ and Zγ

charged lepton decays only





- An excellent agreement with NLO prediction
  - Wγ: σ x Br = 56.4 ± 5.0 (stat) ± 5.0 (syst) ± 2.3 (lumi) pb — 49.4 ± 3.8 pb (NLO)
  - Zγ: σ x Br = 9.4 ± 1.0 (stat) ± 0.6 (syst) ± 0.4 (lumi) pb — 9.6 ± 0.4 pb (NLO)

aTGC modeling

- All aTGC violate unitarity at sufficiently high energy
  - All Tevatron results assume form-factor normalization of the couplings to recover unitarity

$$\alpha \to \alpha(s) \equiv \frac{\alpha_0}{(1+\hat{s}/\Lambda_{\rm NP})^n}$$

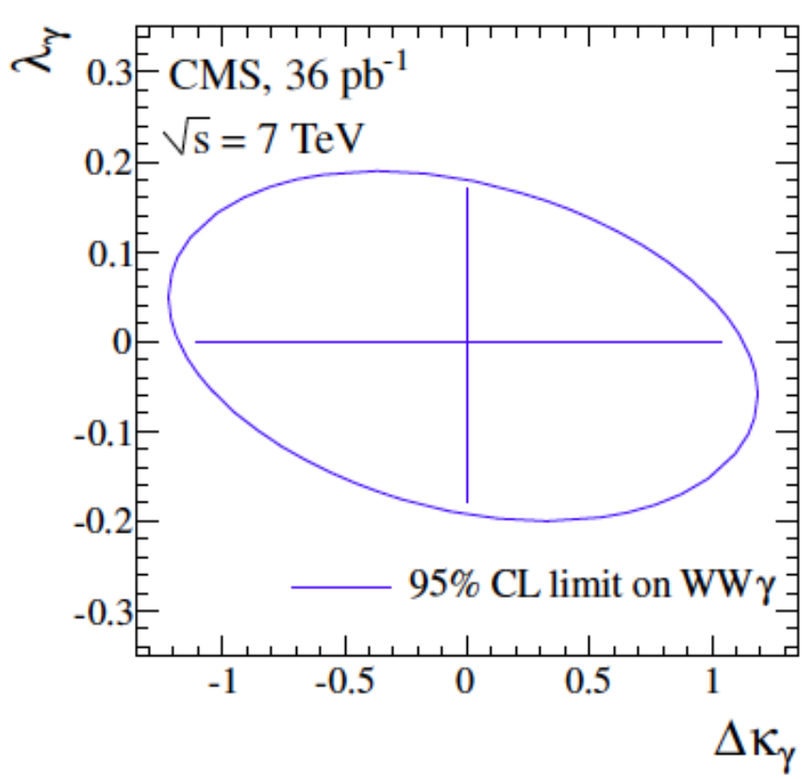
  - LHC experiments switch to form-factorless normalization: no energy-dependent assumption is made (no need to guess n and Λ)
- Use $E_T(\gamma)$ as a sensitive observable and Sherpa/MadGraph/MCFM combo to simulate aTGC in a few points, then extrapolate to continuum aTGC space assuming quadratic aTGC dependence of the cross section

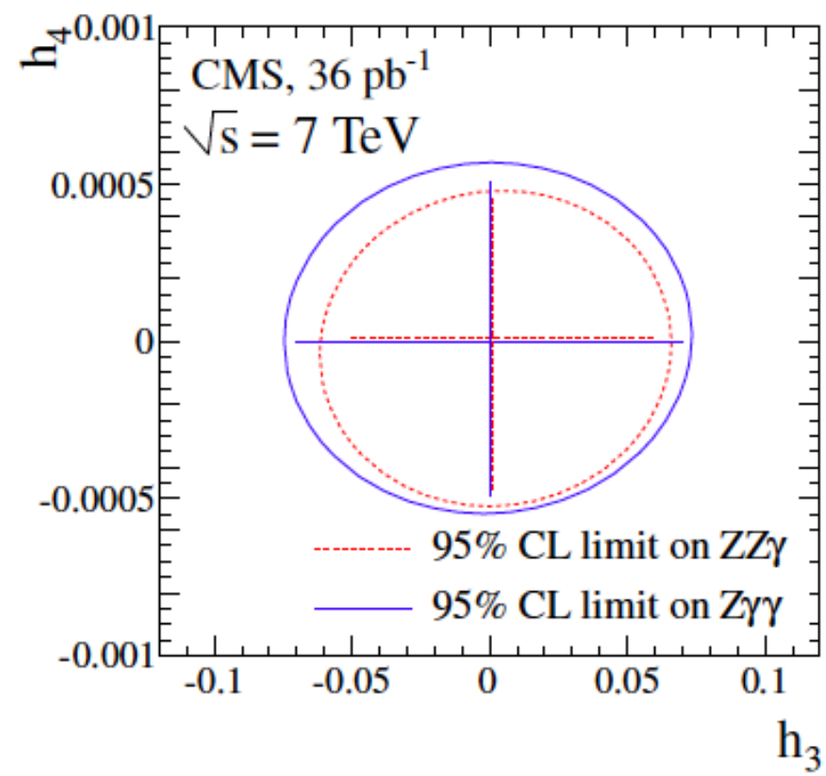
Extracting limits on aTGC

charged lepton decays only

- Current results indicate no evidence for aTGC
  - Results are complementary with those obtained by Tevatron (different energy and form-factor choice makes the comparison difficult)

$WW\gamma$	$ZZ\gamma$	$Z\gamma\gamma$
$-1.11 < \Delta\kappa_\gamma < 1.04$	$-0.05 < h_3 < 0.06$	$-0.07 < h_3 < 0.07$
$-0.18 < \lambda_\gamma < 0.17$	$-0.0005 < h_4 < 0.0005$	$-0.0005 < h_4 < 0.0006$





Different interpretation

- Normalization of the couplings in the Lagrangian is really arbitrary

$$\frac{\mathcal{L}_{eff}^{WWV}}{g_{WWV}} = ig_1^V(W^*_{\mu\nu}W^\mu V^\nu - W^*_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^*_\mu W_\nu V^{\mu\nu} + i\frac{\lambda_V}{M_W^2}W^*_{\lambda,\mu}W^\mu_\nu V^{\nu\lambda} - g_4^V W^*_\mu W_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu)$$
$$+ g_5^V\epsilon^{\mu\nu\lambda\rho}(W^*_\mu\partial_\lambda W_\nu - \partial_\lambda W^*_\mu W_\nu)V_\rho + i\tilde{\kappa}_V W^*_\mu W_\nu\tilde{V}^{\mu\nu} + i\frac{\tilde{\lambda}_V}{M_W^2}W^*_{\lambda\mu}W^\mu_\nu\tilde{V}^{\nu\lambda},$$

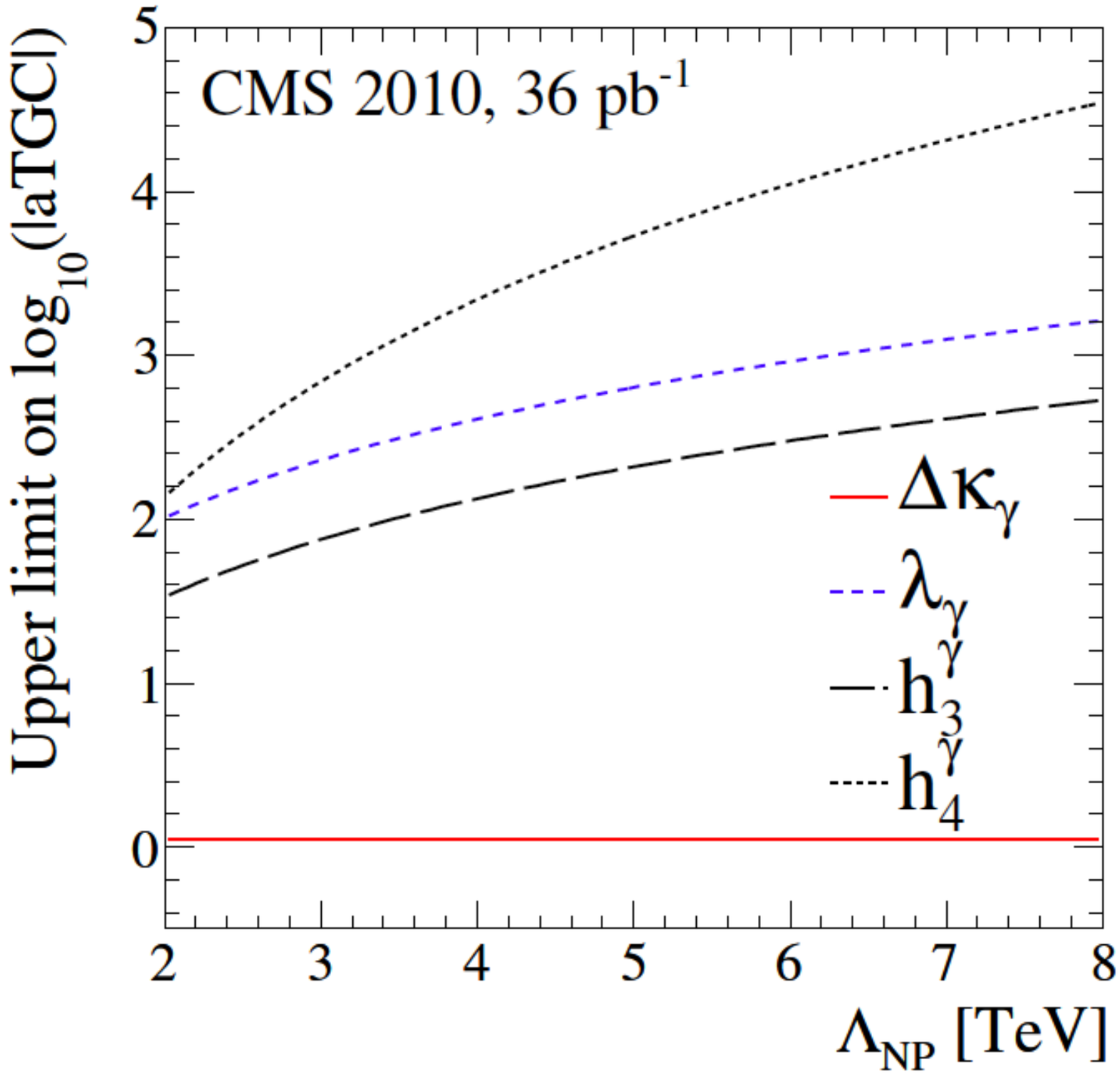
  - Instead of MV one should have taken Λ_{NP}: a characteristic scale of new physics

- Redefine couplings: $\frac{\alpha}{M_V^n} \rightarrow \frac{\alpha'}{\Lambda_{NP}^n}$

  - Assume that Λ_{NP} is large, i.e., beyond our reach, then extract limits on aTGC as a function of Λ_{NP}

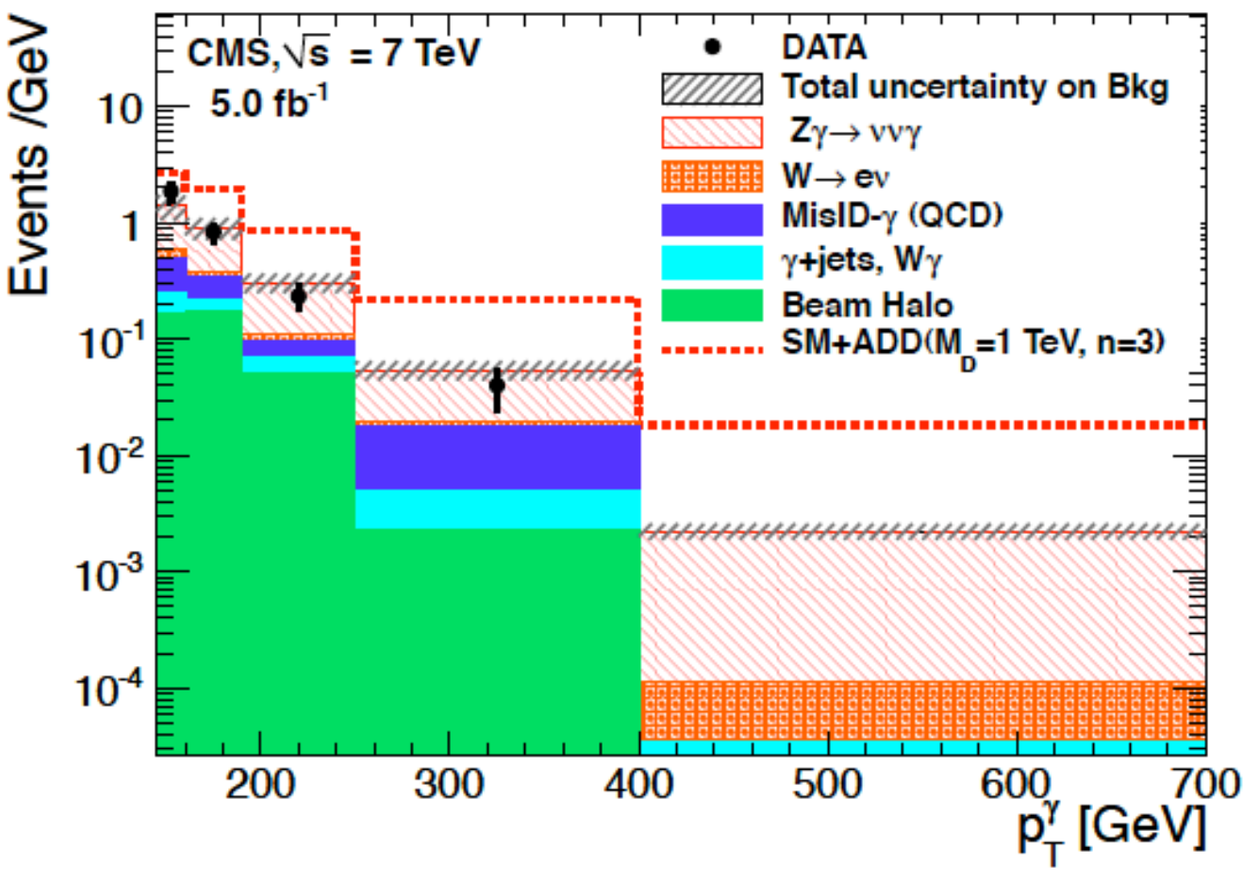
aTGC *vs* Λ_{NP}

charged lepton decays only



$Z\gamma \rightarrow \nu\nu\gamma$ results

- Observed data agrees well with SM production



Source	Estimate
jet → γ	11.2 ± 2.8
Beam halo	11.1 ± 5.6
e → γ	3.5 ± 1.5
Wγ	2.8 ± 0.9
γ + jet	0.5 ± 0.3
Z(νν)γ	42.4 ± 6.3
Total	**71.9 ± 9.1**
Data	**73**

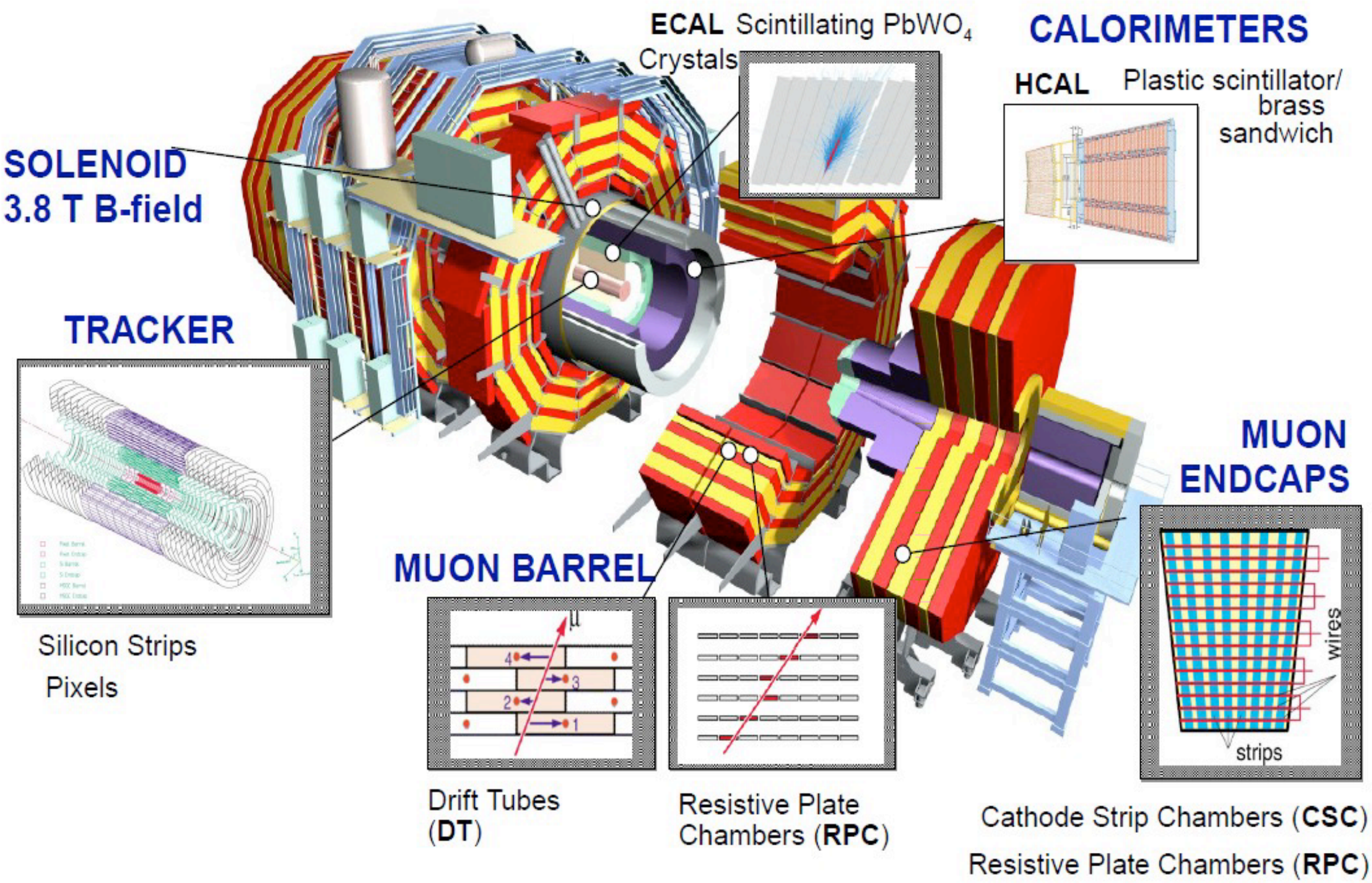
- No excess is observed: an ongoing work to interpret this result in terms of $\nu\nu\gamma$ cross section and aTGC (expect much higher sensitivity in neutral couplings than in charged lepton decay mode)

Summary

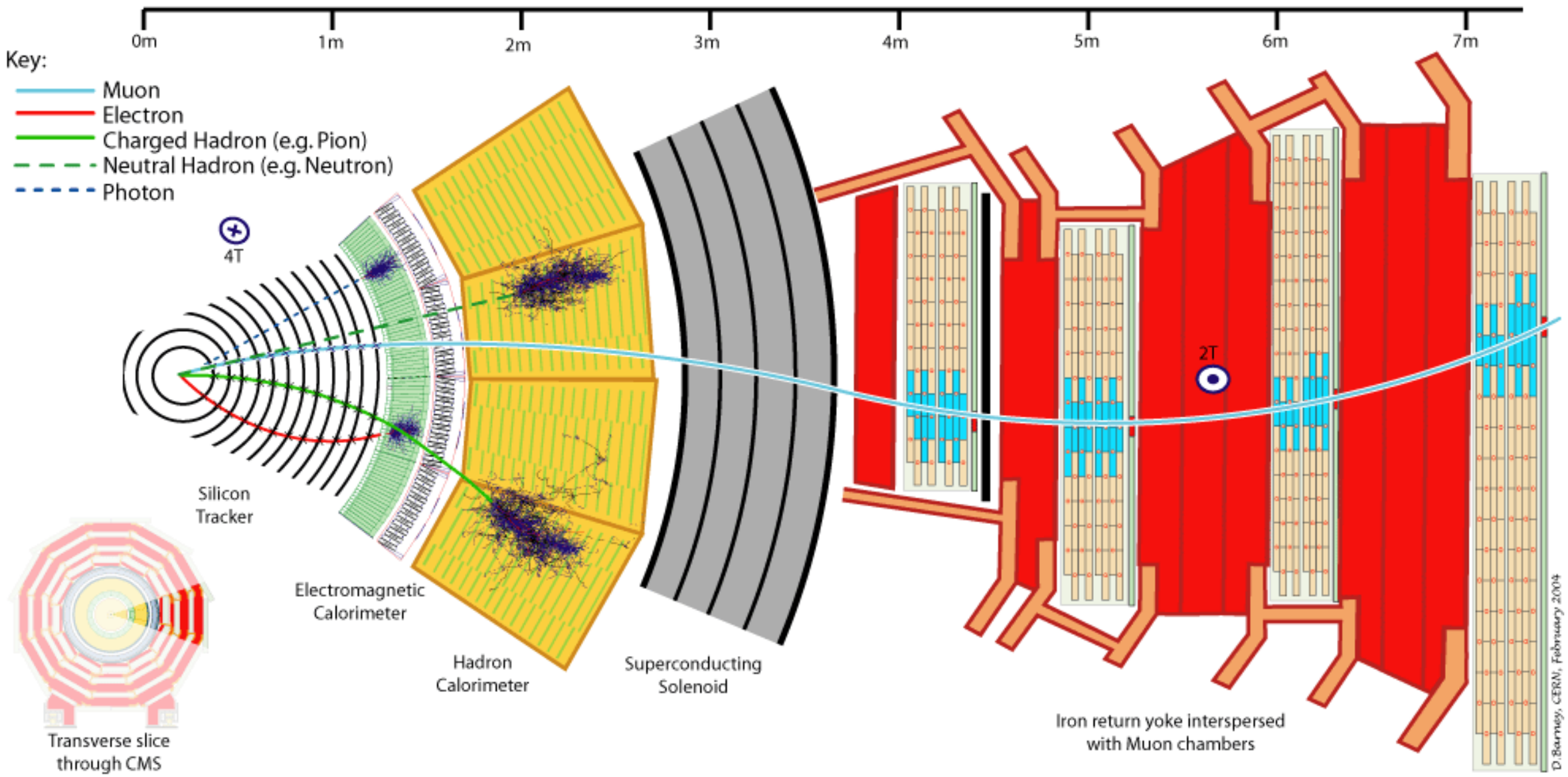
- Studies of $V\gamma$ final states allow one performing stringent test of the EWK sector of the standard model and search for new physics
  - Very challenging, mostly due to photon in the final state
  - New interpretation of the results is being proposed by the LHC EWWG: no form factors, new normalization definition (M_W & $M_Z \rightarrow \Lambda_{NP}$)
- First results with 5 /fb in MET + γ are being re-interpreted in terms of $\nu\nu\gamma$ cross section and TGC measurement
- Finalizing 5 /fb $V\gamma$ results + combination: expect updates this summer!

Backup slides

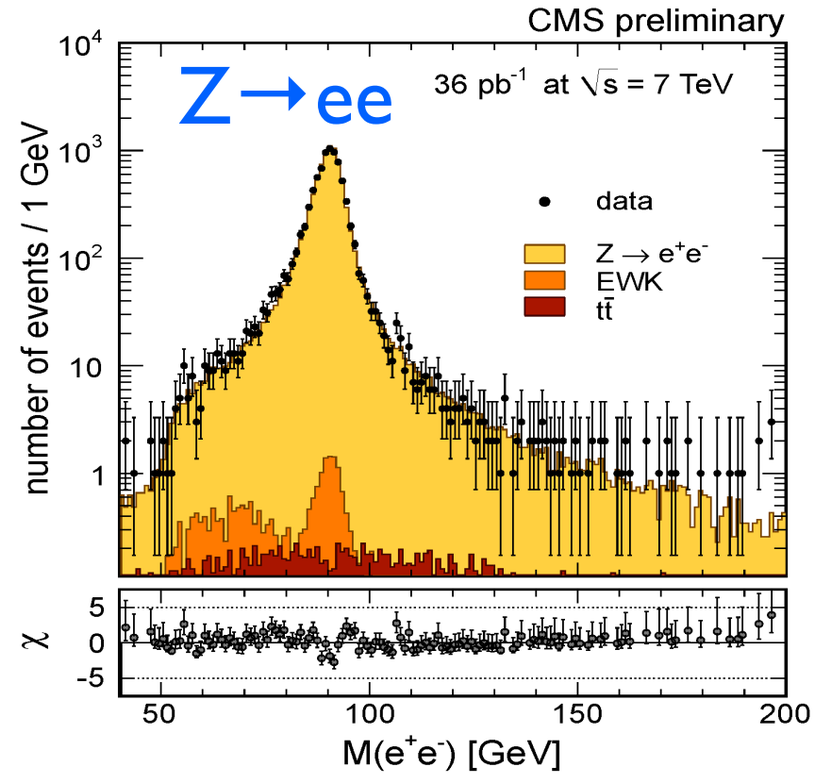
CMS Detector



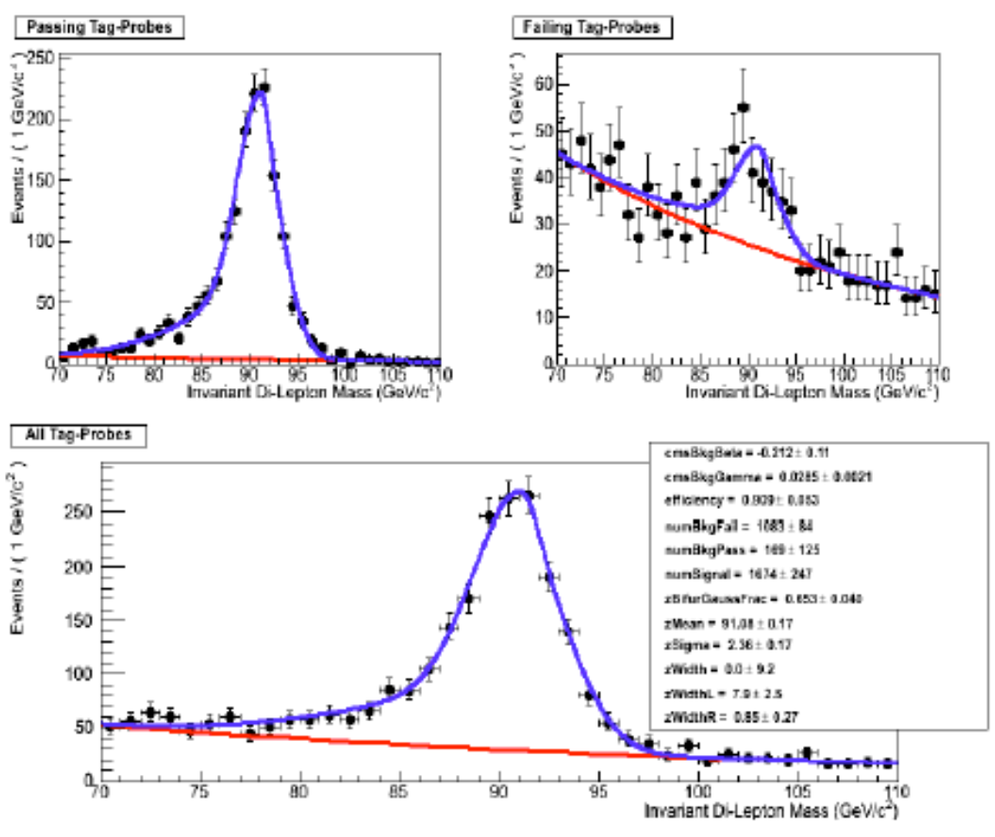
CMS Detector

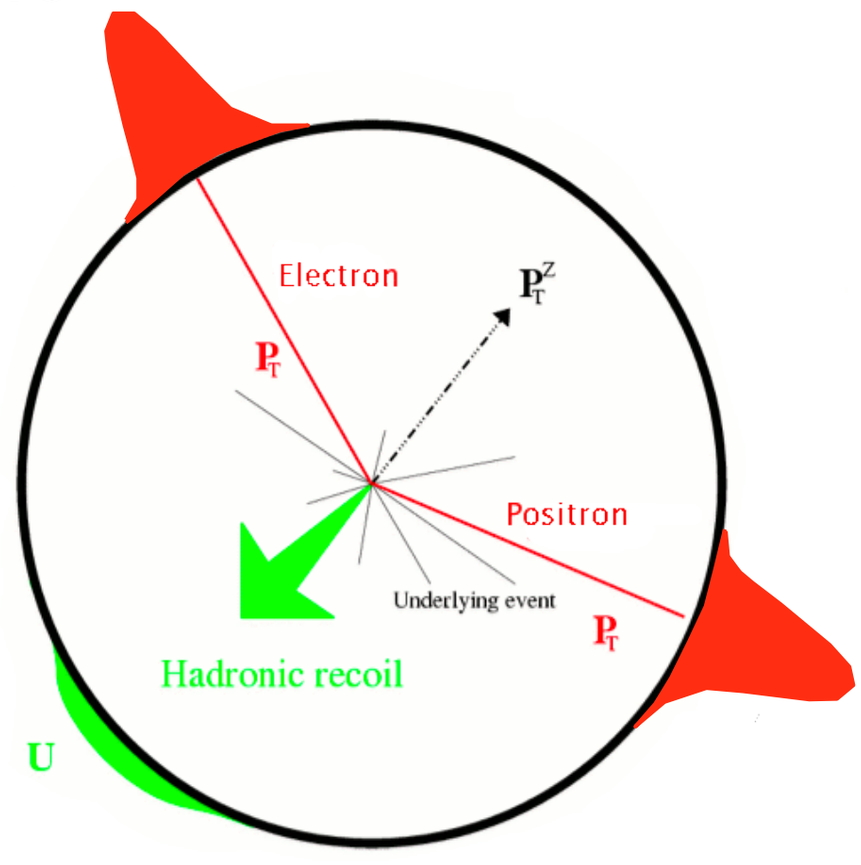


Tag and probe



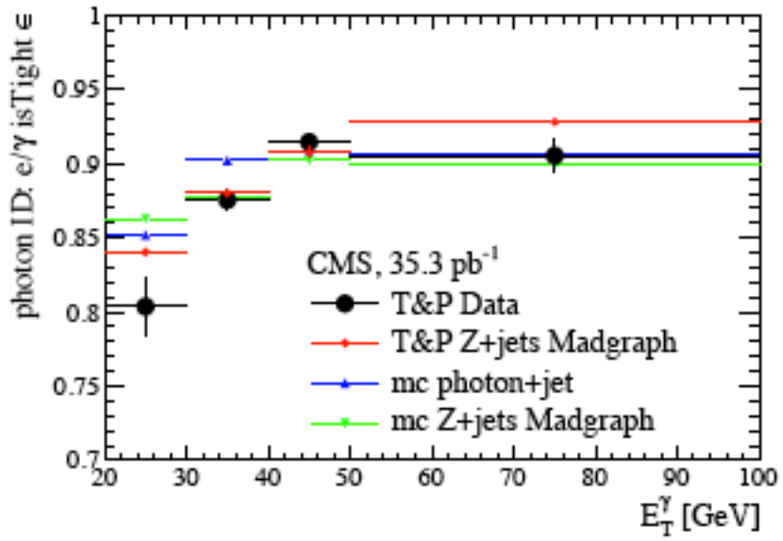
- $Z \to \ell\ell$ is a wonderful process
  - Very clean experimental signature
    - Two high-p_T leptons in the final state provide sufficient discrimination against backgrounds
  - Redundant number of leptons allows measuring efficiency as a function of various kinematic parameters

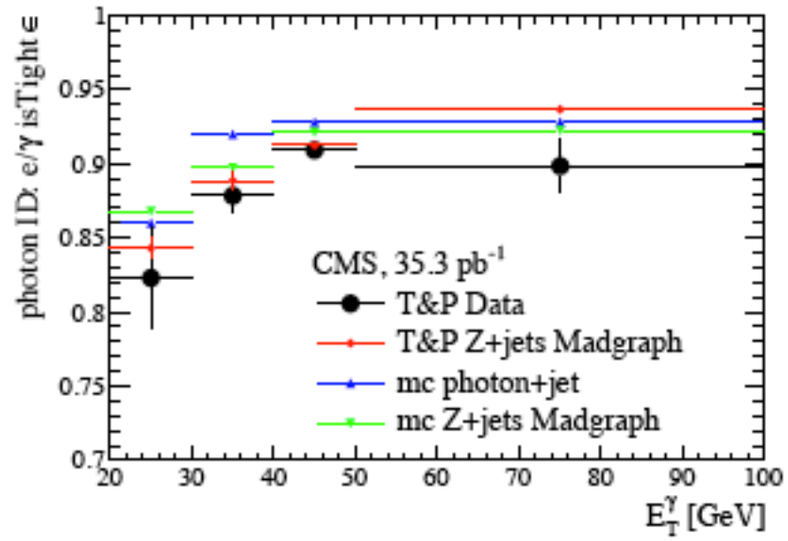




Photon modeling

- Use Z→ee data as a source of EM showers





- Assume MC models the difference between electrons and photons well: correct for photon ⟷ electron difference in MC

$$\gamma \text{ in data} = (e \text{ in } Z \to ee \text{ data}) \times \frac{\gamma \text{ MC}}{e \text{ MC}}$$

- Relatively good agreement for *isTight* photon ID except for pixel veto:

	"Tag and Probe"		Scale factor
ECAL	data	MC	data/MC
Barrel	$89.5\% \pm 0.4\%$	$89.1\% \pm 0.6\%$	1.004 ± 0.008
Endcap	$88.6\% \pm 2.9\%$	$89.5\% \pm 0.5\%$	0.990 ± 0.033