Z vertex form factor with $Z \to \ell^+\ell^-\gamma$ process (update)

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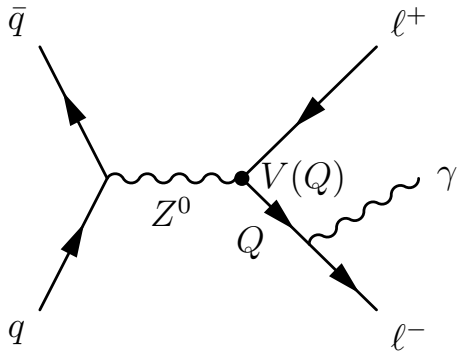
Overview

$Z \to \ell^+\ell^-$ vertex function V(Q) is expressed by formula:

$$\langle f\bar{f}|\, J_Z^\mu\, |0\rangle = V_f(q^2)\bar{u}_f\gamma_\mu\left[\frac{I_{3f}(1-\gamma_5)}{2} - \hat{k}_f(q^2)\hat{s}^2 Q_f\right] v_f$$

[A. Sirlin, A. Ferroglia. Rev.Mod.Phys., V85 (2013): eq. (59) p273.]



- Z decays to real lepton and virtual one,
- $Z \to \ell^+\ell^-$ vertex depends on lepton virtuality Q,
- This vertex function is called "form factor"
- $V(Q)$ can be sensible to effects of a "new physics"

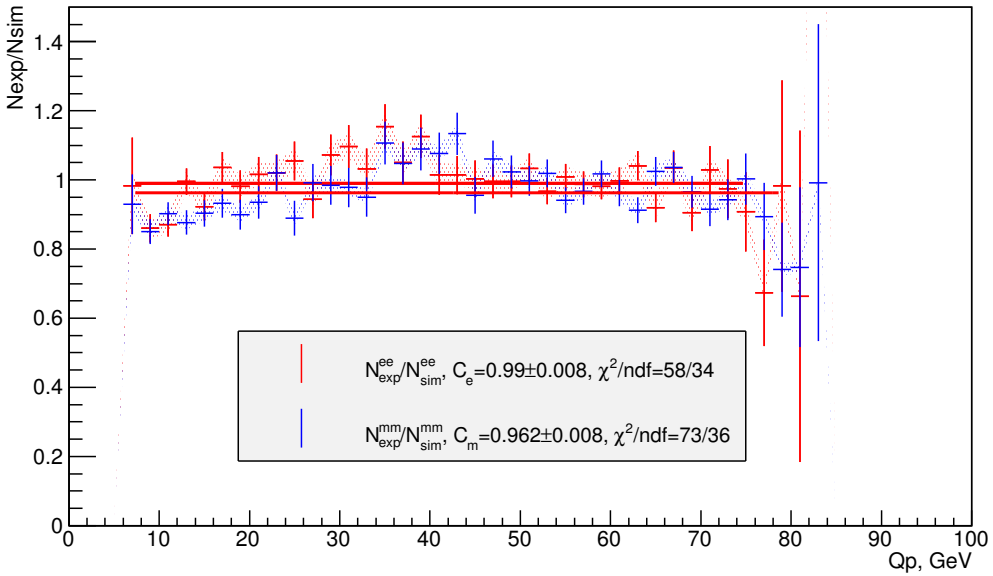
From PDG for non SM decays:

- $\mathcal{B}(Z \to e^+e^-\gamma) < 5.2 \times 10^{-4}$
- $\mathcal{B}(Z \to \mu^+\mu^-\gamma) < 5.6 \times 10^{-4}$
- $\mathcal{B}(Z \to \tau^+\tau^-\gamma) < 7.3 \times 10^{-4}$

[P. D. Acton *et al.* OPAL Collaboration, Phys. Lett. B **273**, 338 (1991).]

Form factor

Qp is the invariant mass of $\ell^+\gamma$. Also the invariant mass for $\ell^-\gamma$ is Qm.



$$F(Q) = \frac{\left(\frac{\partial\sigma}{\partial Q}\right)_{\text{Data}}}{\left(\frac{\partial\sigma}{\partial Q}\right)_{\text{MC}}}$$

We divide the differential Qp, Qm distribution to the MC prediction. If only the vertex function $V(Q)$ is modified by the "New Physics", then such fraction will give $V^2(Q)$.

MC was normalized to experimental $\mathcal{L}$, with NNLO k-factor

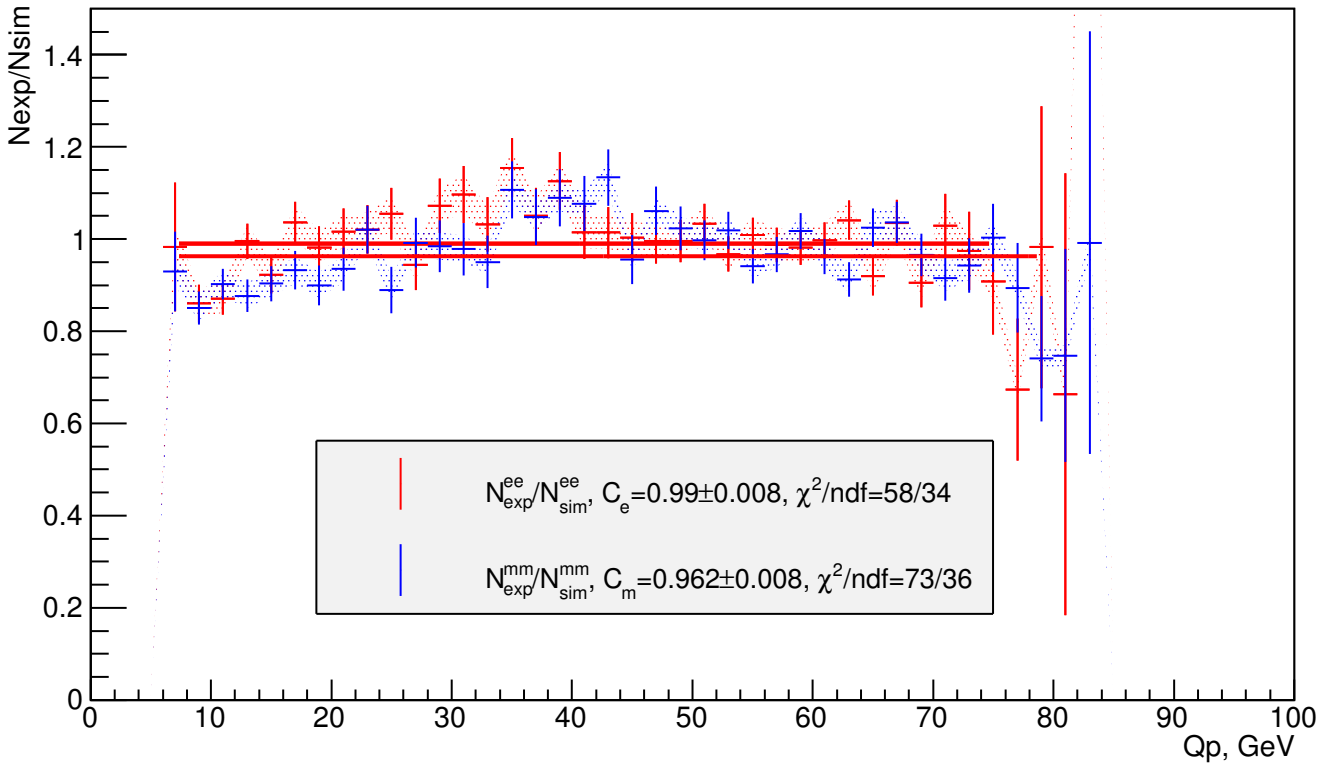
Used 8 TeV data, $\mathcal{L} = 20.3\,\text{fb}^{-1}$

For SM used MC12 8 TeV simulation

145161 Sherpa CT10 eegammaPt10 (32.3 pb, 8844673 events)

145162 Sherpa CT10 mumugammaPt10 (32.3 pb, 9188579 events)

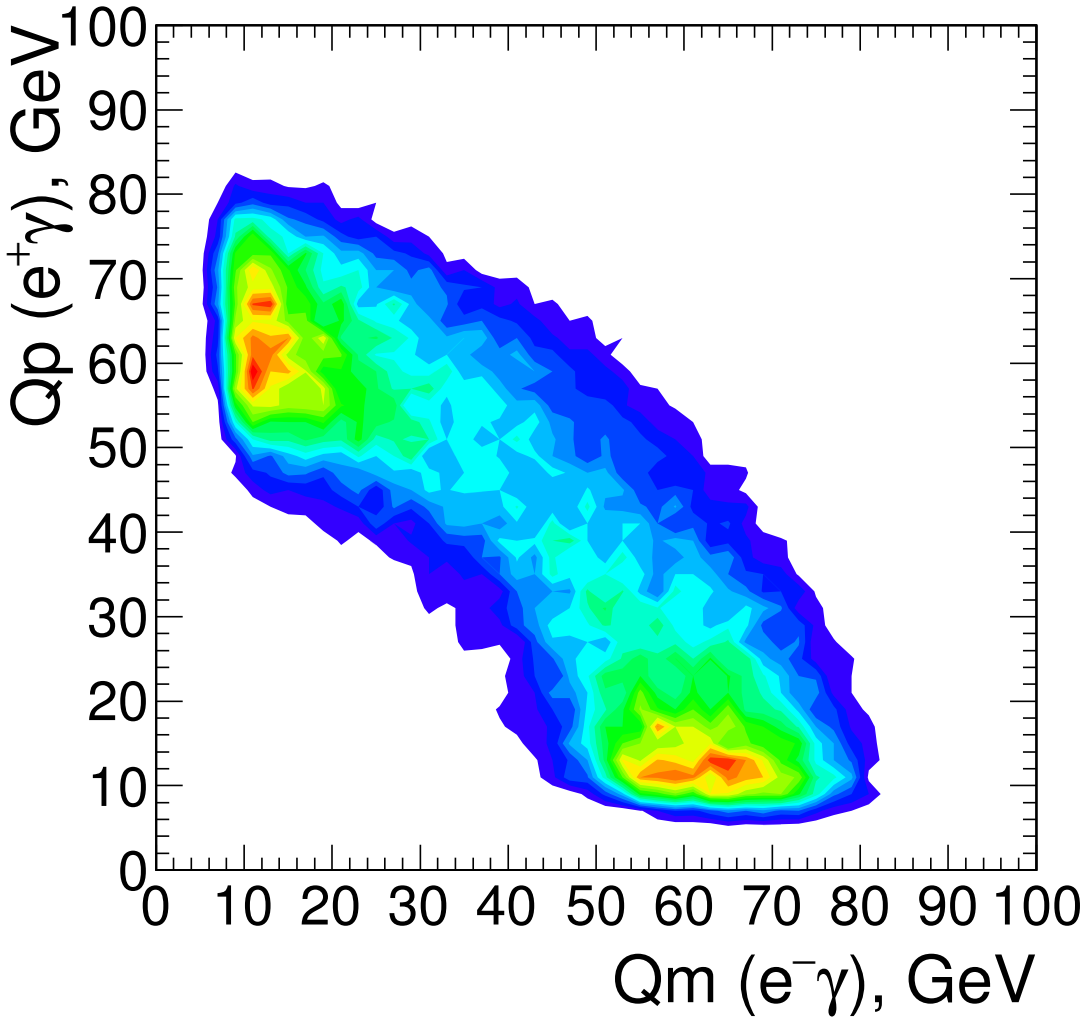
Form Factor (Qp)



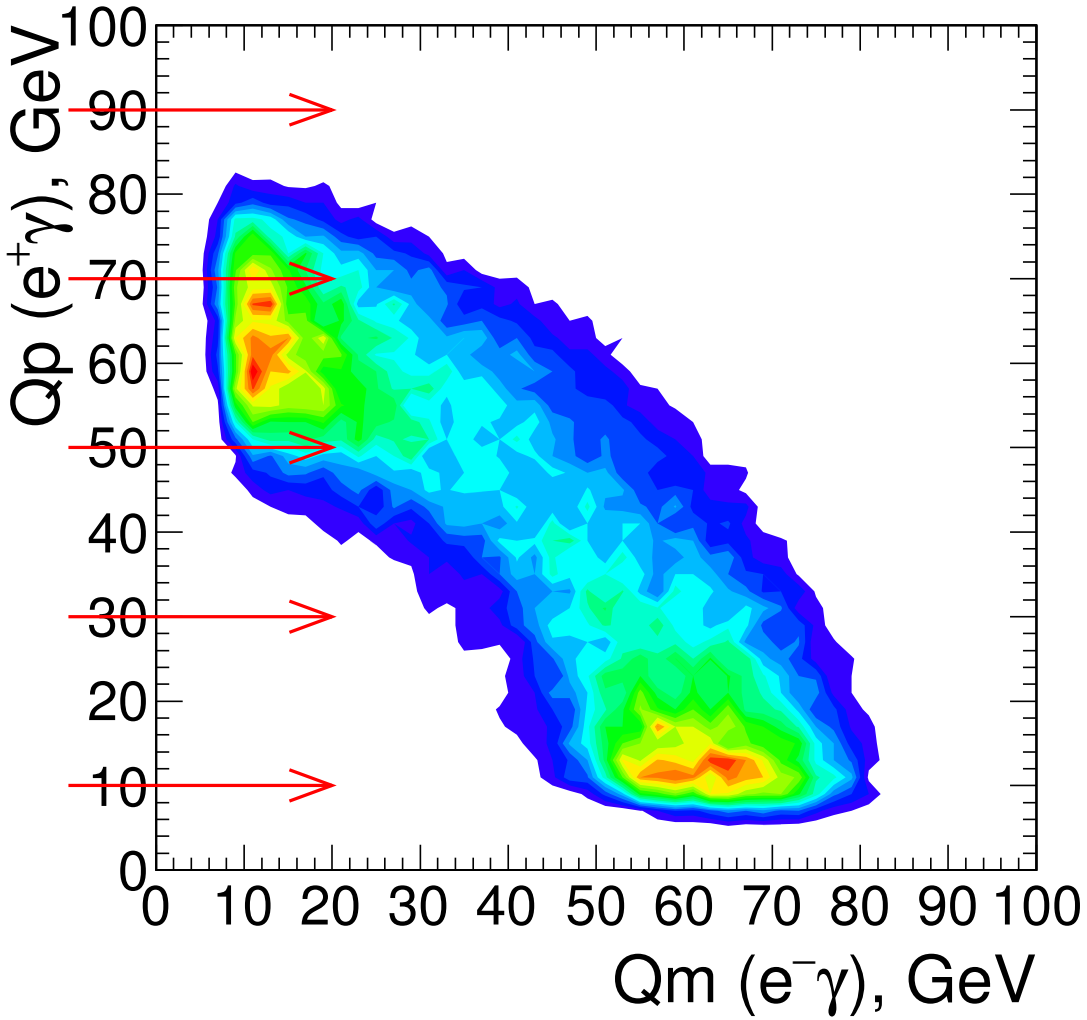
MC was normalized to experimental $\mathcal{L}$, with NNLO k-factor

$$\left\{\sum \left(y_i^{ee} - y_i^{\mu\mu}\right)^2 / \left((\delta y_i^{ee})^2 + (\delta y_i^{\mu\mu})^2\right)\right\} / n_{\text{points}} = 31/34$$

Qp vs Qm

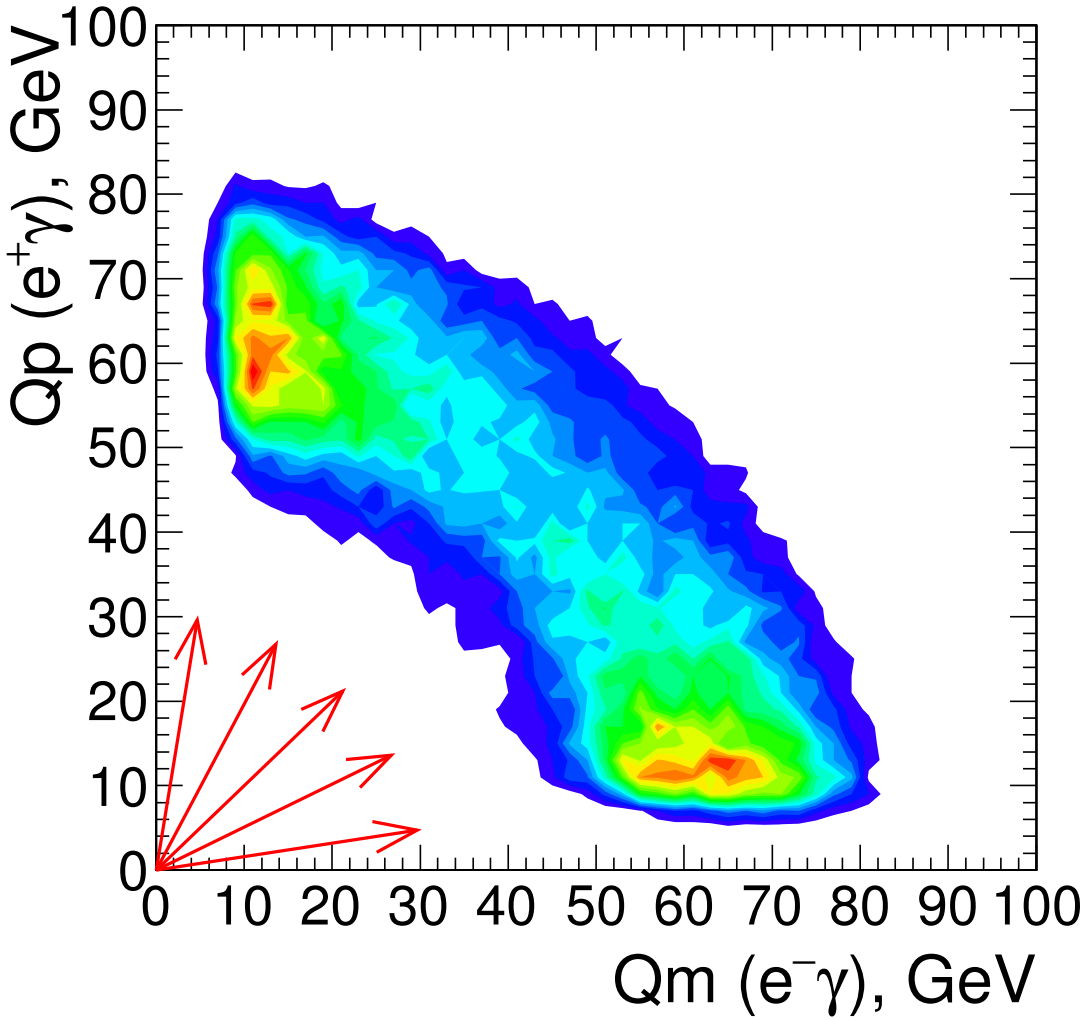


Qp vs Qm



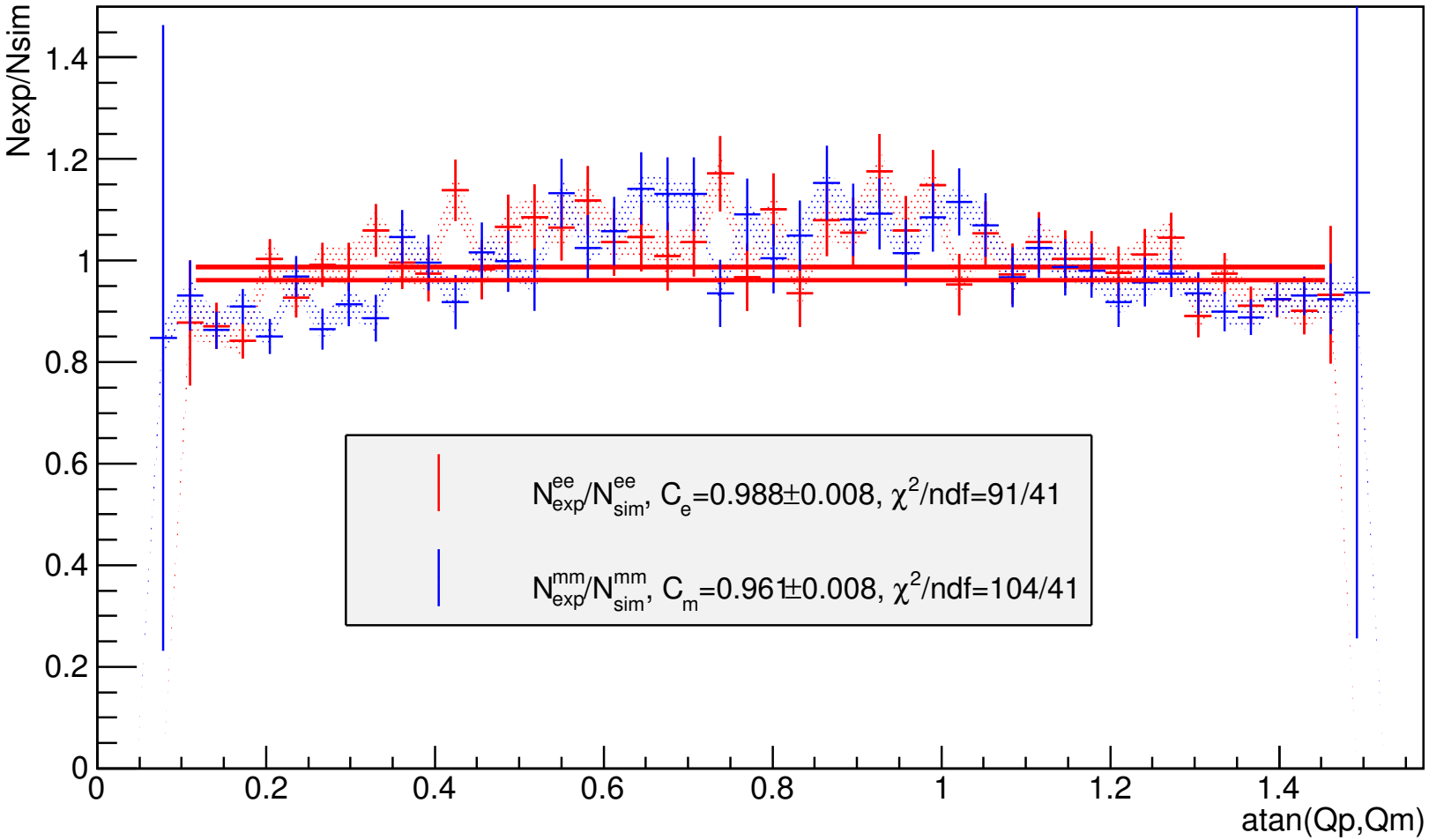
Look at on Qp distribution

Qp vs Qm



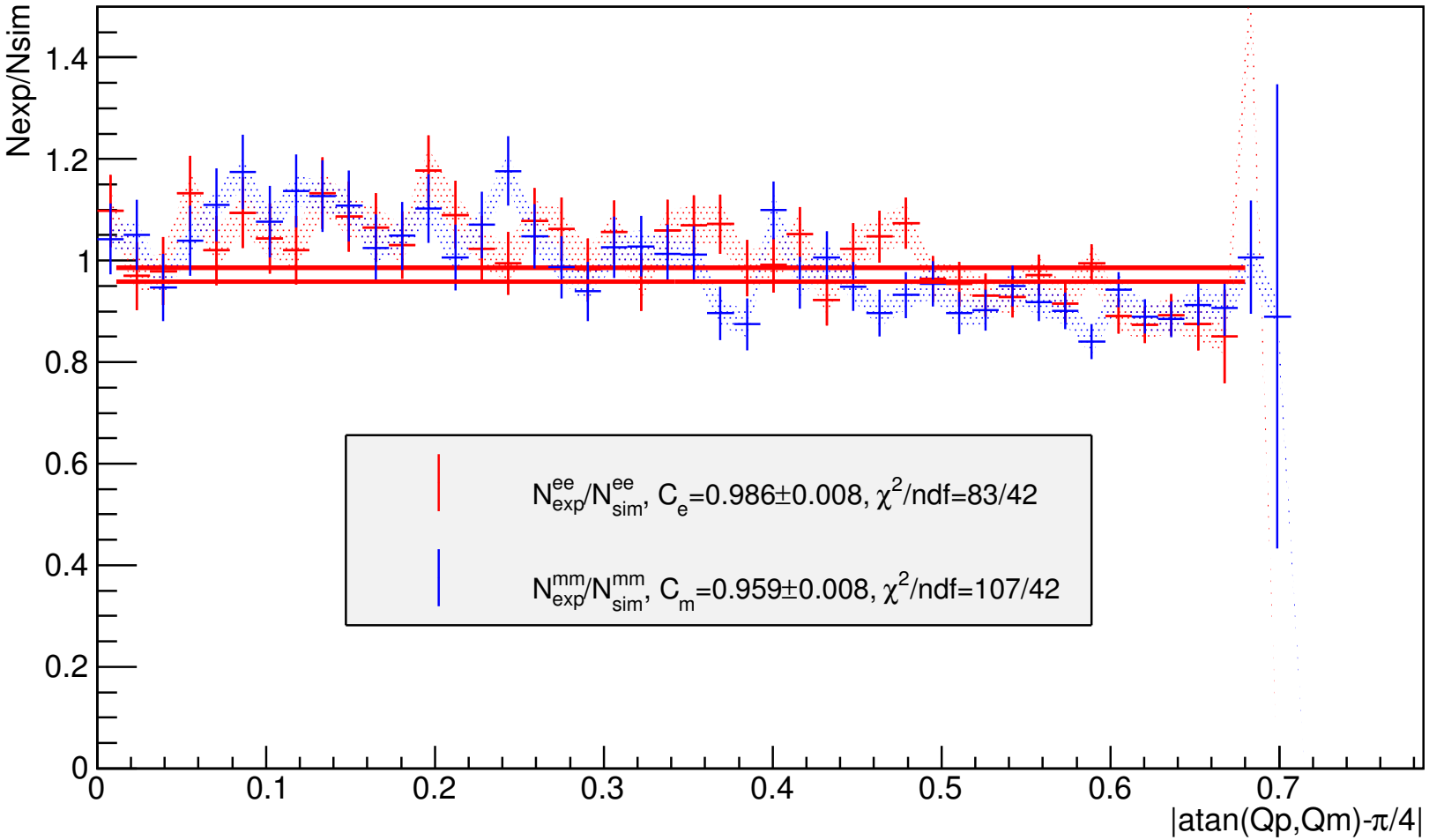
Look at on atan(Qp,Qm) distribution

atan(Qp,Qm)



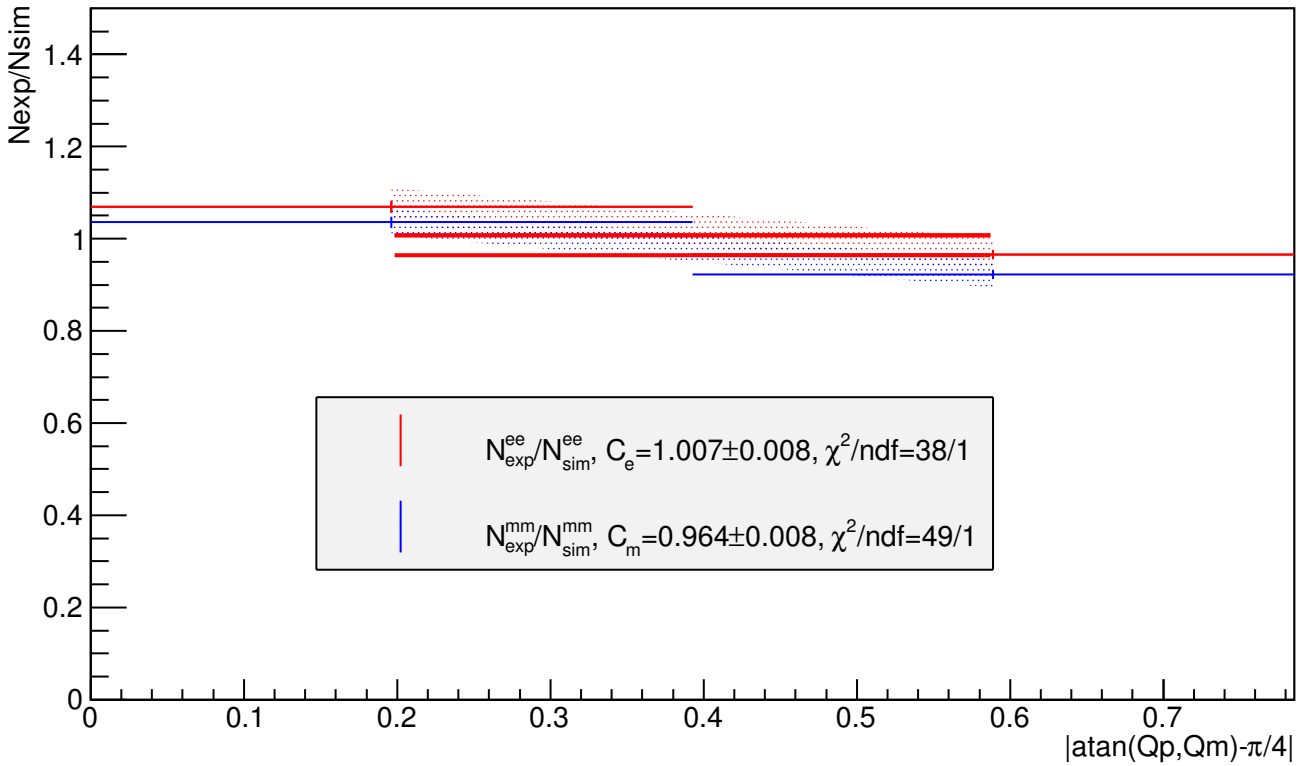
MC was normalized to experimental $\mathcal{L}$, with NNLO k-factor

|atan(Qp,Qm)−π/4|



MC was normalized to experimental $\mathcal{L}$, with NNLO k-factor

|atan(Qp,Qm)−π/4|



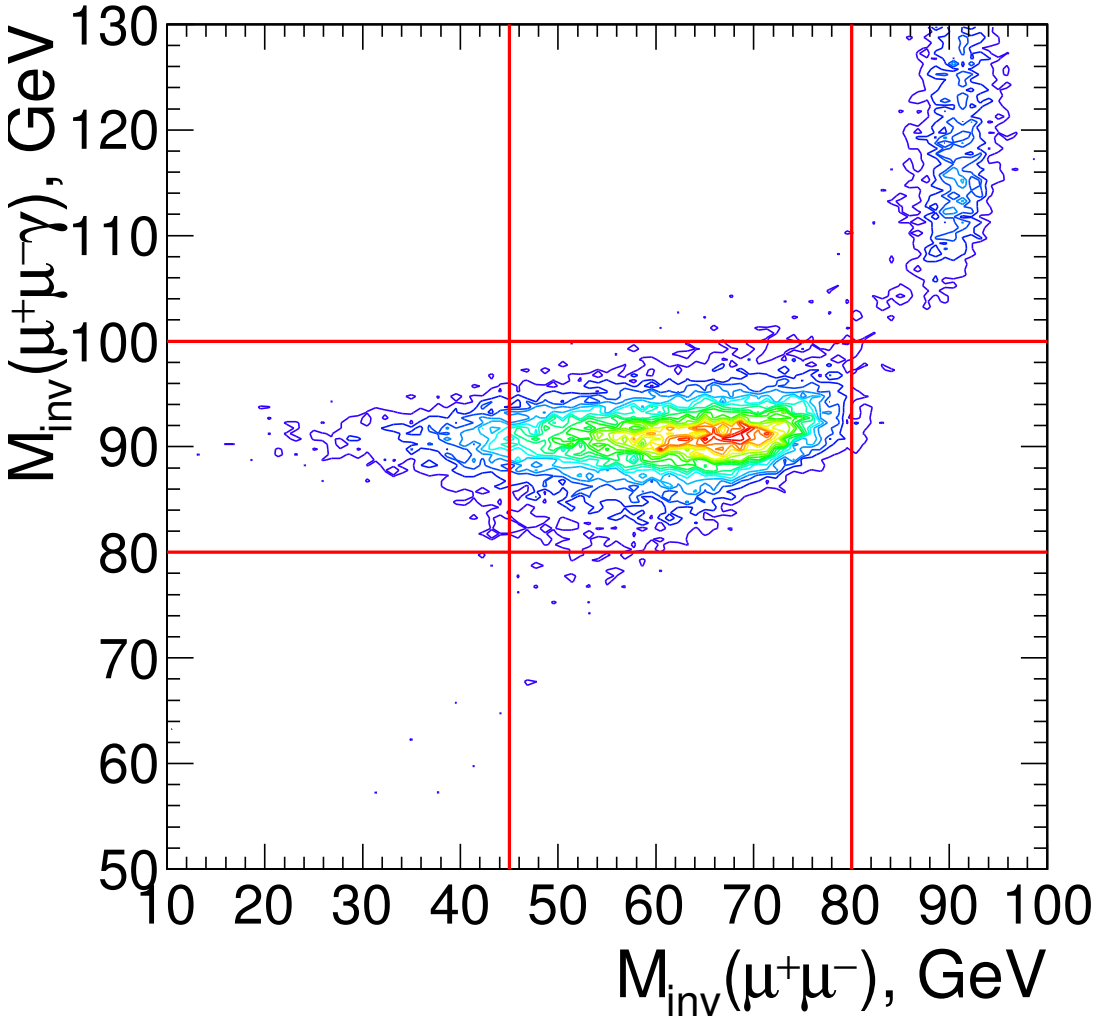
$$\mathcal{K}^{ee} = \frac{y_1^{ee} - y_2^{ee}}{(y_1^{ee} + y_2^{ee})/2} = (9.7 \pm 1.7)\%$$

$$\mathcal{K}^{\mu\mu} = \frac{y_1^{\mu\mu} - y_2^{\mu\mu}}{(y_1^{\mu\mu} + y_2^{\mu\mu})/2} = (11.5 \pm 1.6)\%$$

Object selection (1)

- e $p_t > 10$ GeV, topoEtcone40$/p_t < 0.3$, $|\eta| < 2.47$
- μ $p_t > 10$ GeV, topoEtcone40$/p_t < 0.2$, $|\eta| < 2.47$
- γ Photon with highest p_t, $p_t > 15$ GeV, $|\eta| < 2.37$ and $|\eta| \notin (1.37, 1.52)$, topoEtcone40 < 4 GeV, $\Delta R(\gamma\ell) > 0.4$, pass tight ID requirement
- $\ell\ell$ 45 GeV $<$ Invariant Mass $\ell^+\ell^- < 80$ GeV
- $\ell\ell\gamma$ 80 GeV $<$ Invariant Mass $\ell^+\ell^-\gamma < 100$ GeV, the closest to Z-mass $\ell^+\ell^-\gamma$ combination from selected above

Invariant mass cuts



Experiment 8 TeV data

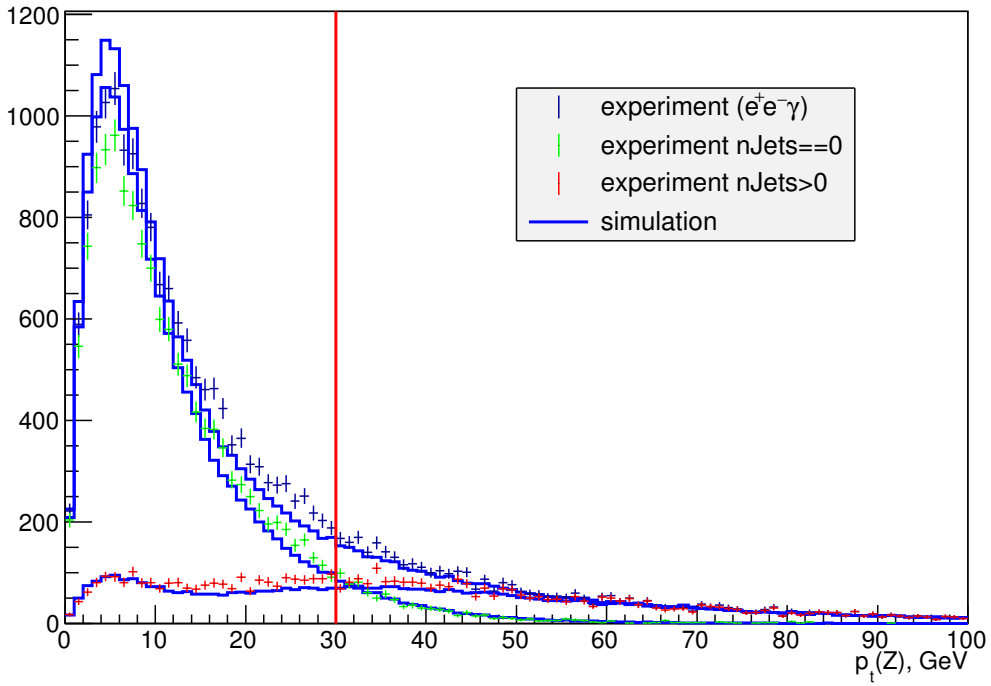
$\mathcal{L} = 20.3\,\text{fb}^{-1}$

Selected events:

$N_{e^+e^-\gamma} = 15723$

$N_{\mu^+\mu^-\gamma} = 16511$

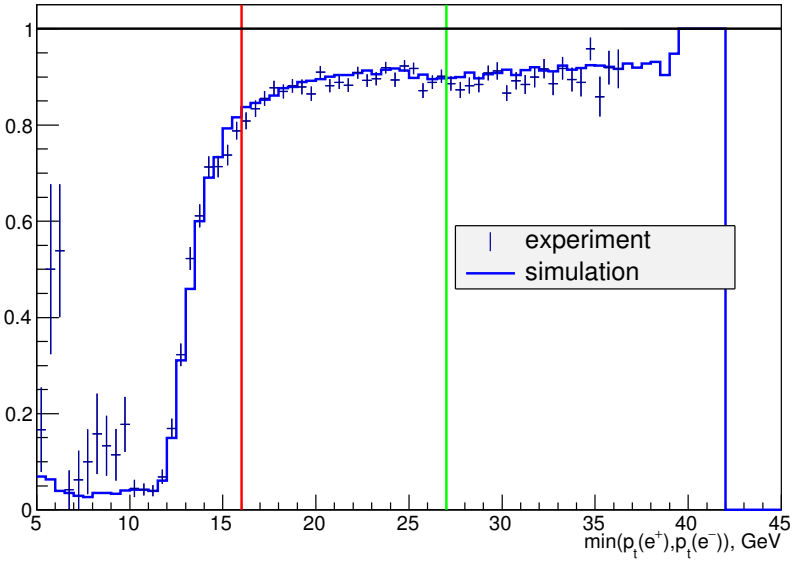
$p_t(Z)$ distribution and Object selection (2)

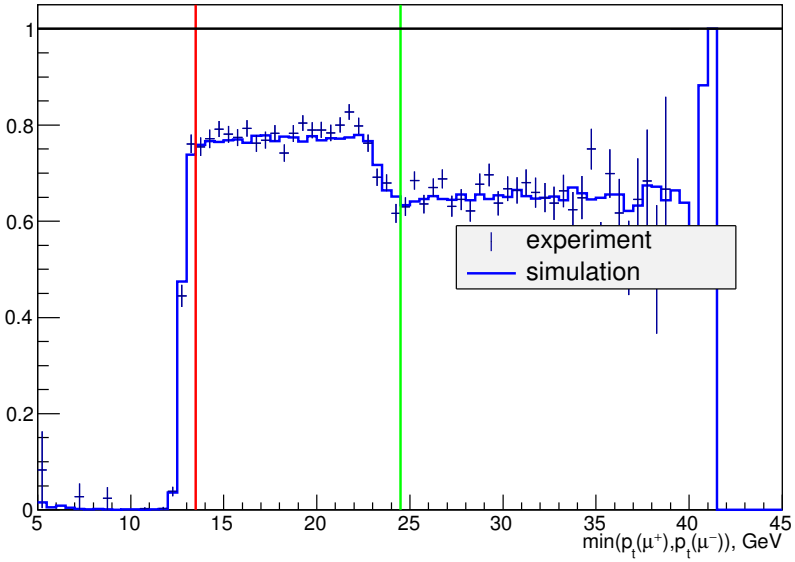


Z $p_t < 30\,\text{GeV}$ + reweighting over $p_t(Z)$

	$e^+e^-\gamma$		$\mu^+\mu^+\gamma$	
	$\mathcal{K} \pm \Delta\mathcal{K}$ (%)	diff (%)	$\mathcal{K} \pm \Delta\mathcal{K}$ (%)	diff (%)
no $p_t(Z)$ rew.	10.8 ± 1.8	$+1.1$	12.7 ± 1.6	$+1.2$
+ no $p_t(Z)$ cut	9.5 ± 1.5	-0.2	11.6 ± 1.4	$+0.1$

p_t^{min} efficiency 2ℓ trigger over 1ℓ trigger and Obj. sel. (3)





1ℓ

- e: EF_e24vhi_medium1
- μ: EF_mu24i_tight

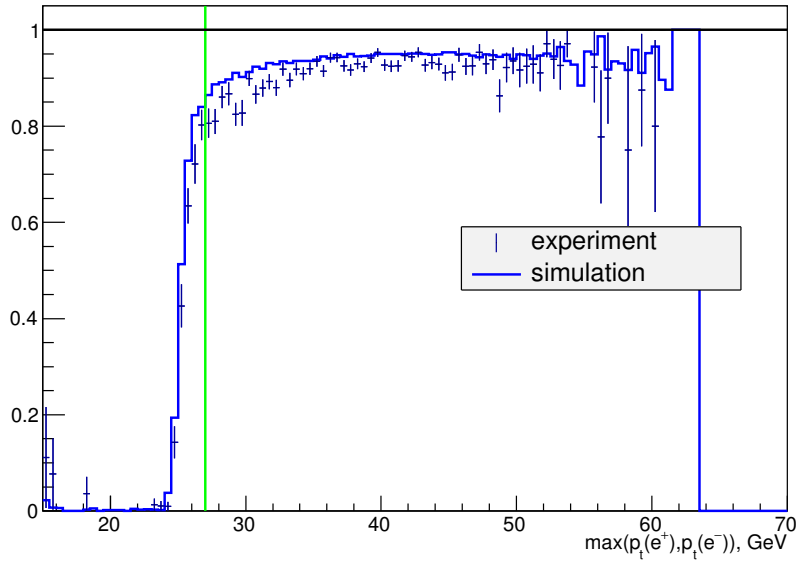
2ℓ

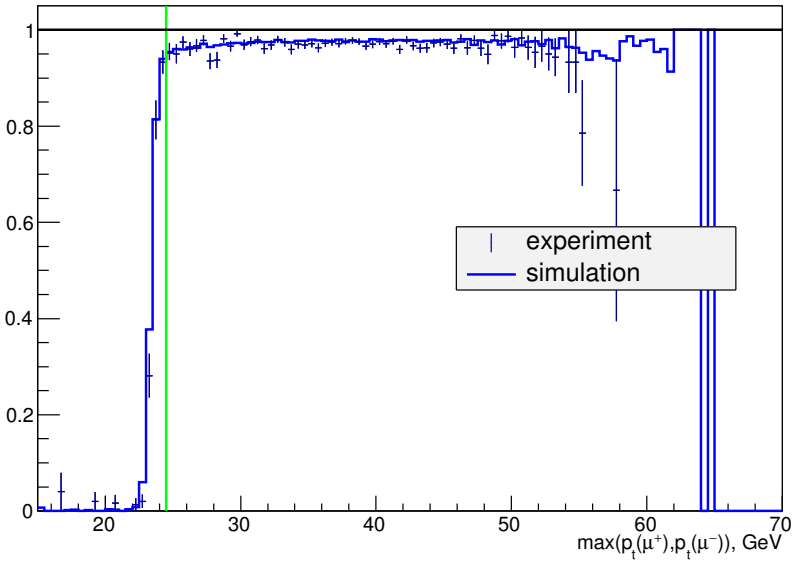
- ee: EF_2e12Tvh_loose1
- $\mu\mu$: EF_2mu13

p_t^{min} cut

- e: $p_t > 16$ GeV
- μ: $p_t > 13.5$ GeV

$p_t^{\max}$ efficiency 1ℓ trigger over 2ℓ trigger and Obj. sel. (4)





base trigger

- ee: EF_2e12Tvh_loose1
- $\mu\mu$: EF_2mu13

	$e^+e^-\gamma$		$\mu^+\mu^+\gamma$	
	$\mathcal{K} \pm \Delta\mathcal{K}$ (%)	diff (%)	$\mathcal{K} \pm \Delta\mathcal{K}$ (%)	diff (%)
$1\ell \,\|\|\, 2\ell$	10.6 ± 1.5	$+0.9$	13.1 ± 1.3	$+1.6$

Simulation comparison

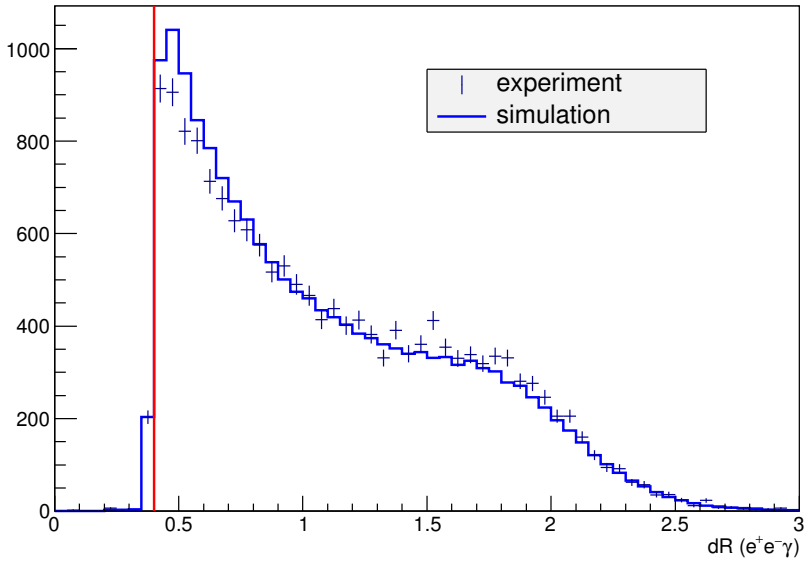
	$e^+e^-\gamma$		$\mu^+\mu^+\gamma$	
	$\mathcal{K} \pm \Delta\mathcal{K}$ (%)	diff (%)	$\mathcal{K} \pm \Delta\mathcal{K}$ (%)	diff (%)
Sherpa $Z \to \ell\ell\gamma$	9.7 ± 1.7	$+0.0$	11.5 ± 1.6	$+0.0$
PowhegPythia8	-6.5 ± 1.7	-16.2		
AlpgenJimmy	-9.5 ± 3.0	-19.2	-1.6 ± 3.1	-13.2
AlpgenPythia	-10.3 ± 3.1	-20.0	-8.0 ± 3.1	-19.5
$Z \to \ell\ell$+photos	9.1 ± 2.4	-0.6	12.3 ± 2.4	$+0.8$

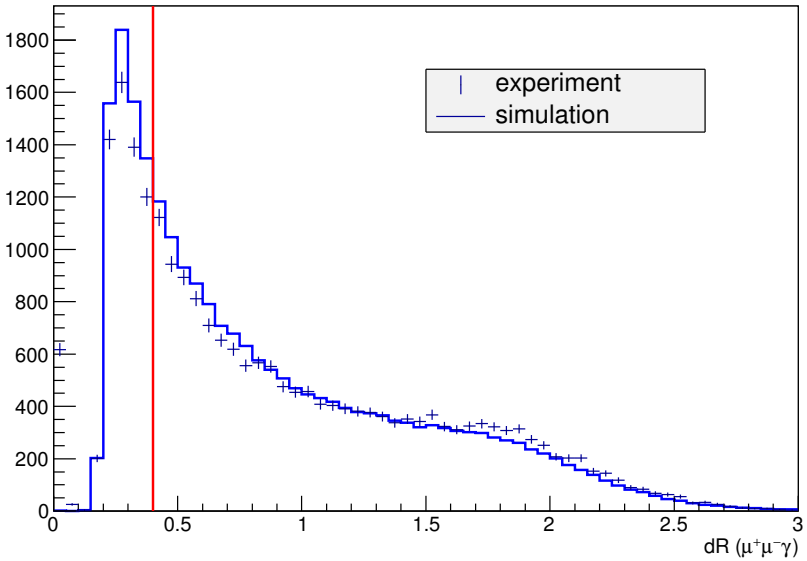
10% of uncertainty $\to$ 6 times lower $\mathcal{B}(Z \to \ell\ell\gamma$ non SM) PDG limits

Simulation sample numbers

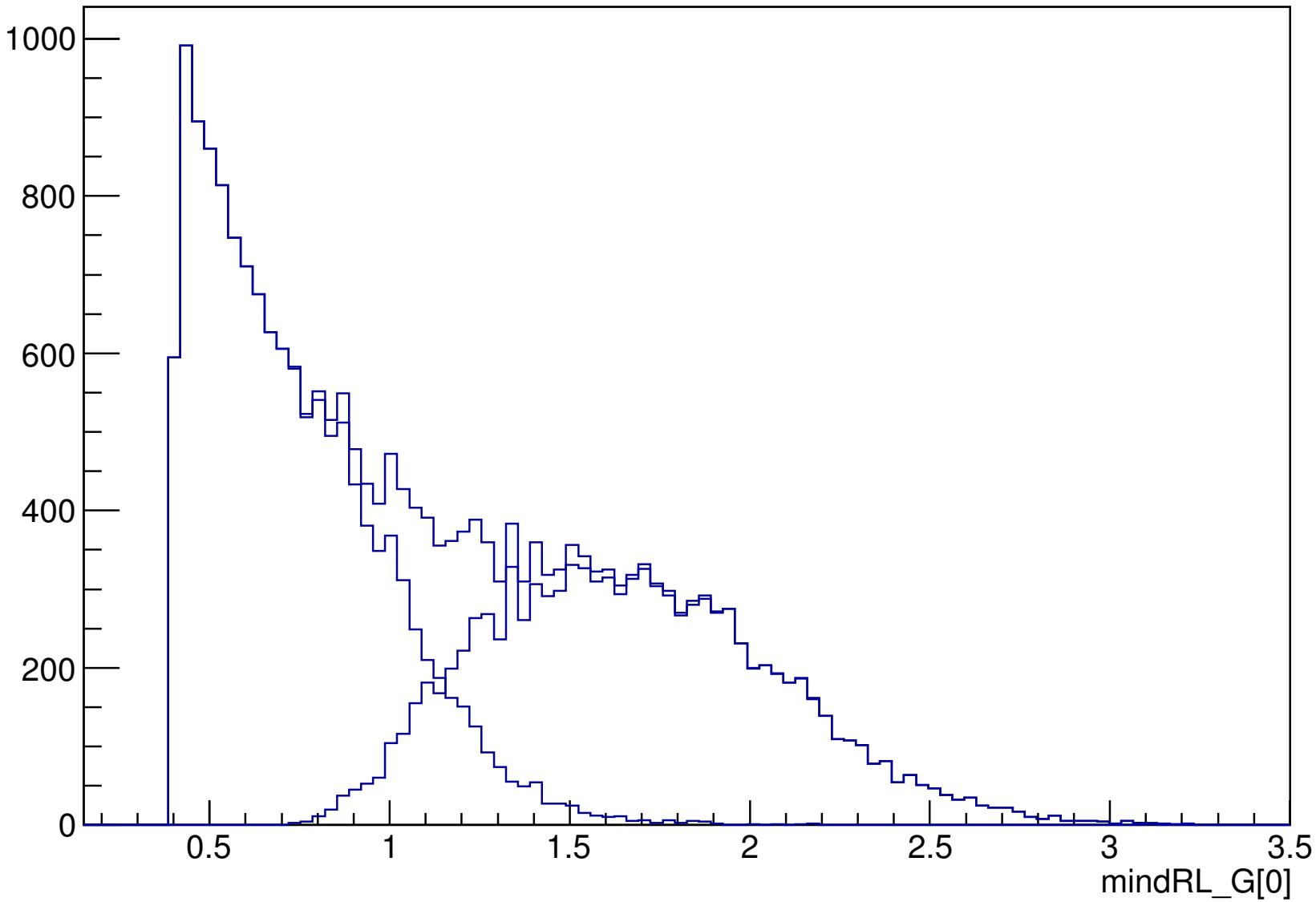
	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
Sherpa $Z \to \ell\ell\gamma$ PT10	145161	145162
PowhegPythia8	129250	
AlpgenJimmy	107650–107655	107660–107665
AlpgenPythia	117650–117655	117660–117665
$Z \to \ell\ell$+photos	147770	147771

ΔR

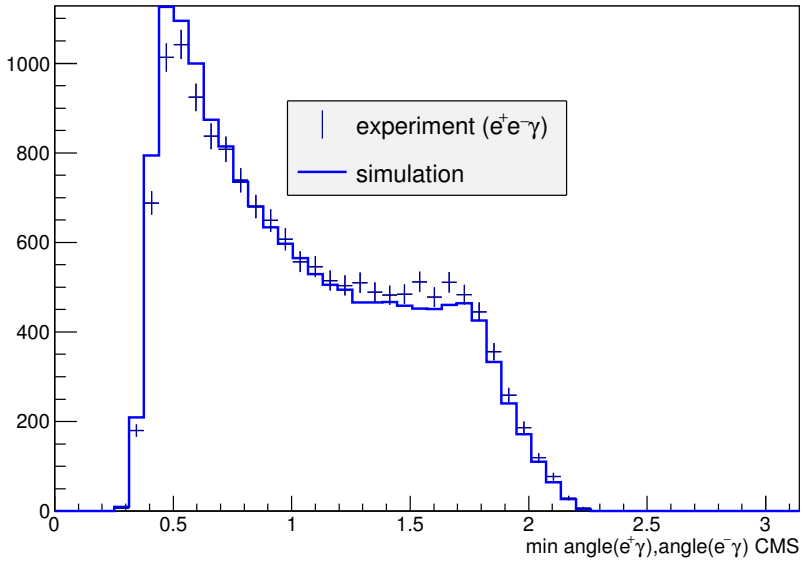

experiment
simulation
dR ($e^+e^-\gamma$)

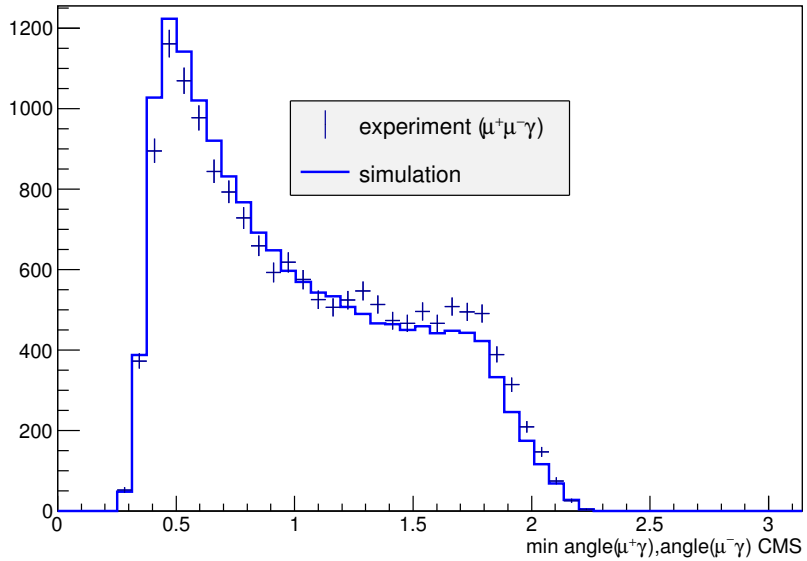

experiment
simulation
dR ($\mu^+\mu^-\gamma$)

dR fractions



minimum angle γ ℓ (CMS)





minimum angle γ ℓ fractions (CMS)