CMS Monte-Carlo Analysis of $Z/\gamma^* \rightarrow \mu^- \mu^+ + X$ at $\sqrt{s} = 10\,TeV$

Outline:

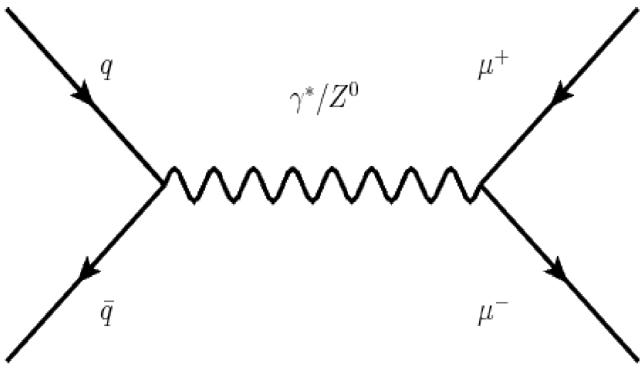
- NLO corrections of $Z/\gamma^* \rightarrow \mu^- \mu^+$
- Detector effects (after reconstruction)
- Measuring of $Z/\gamma^* \rightarrow \mu^- \mu^+$ cross-section
- Detection of radiative corrections

$Z \rightarrow \mu^- \mu^+$ NLO-Corrections I

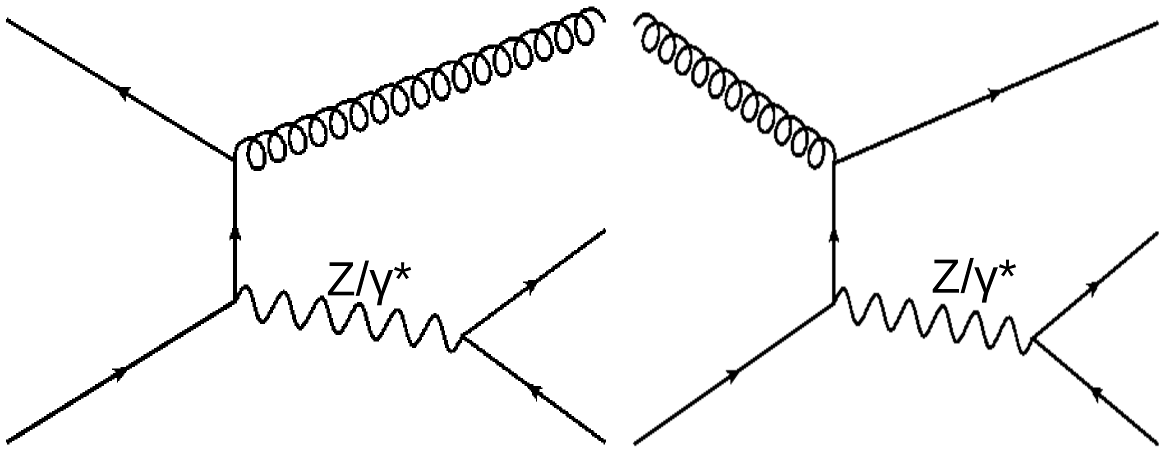
For a detailed analysis it is neccessary to consider NLO-corrections.

These corrections can be analysed with the help of NLO-Monte-Carlo Generators:

LO of the hard process is calculated by Herwig6 internally.
→ Herwig6 is used the for the Parton-Shower and Hadronization



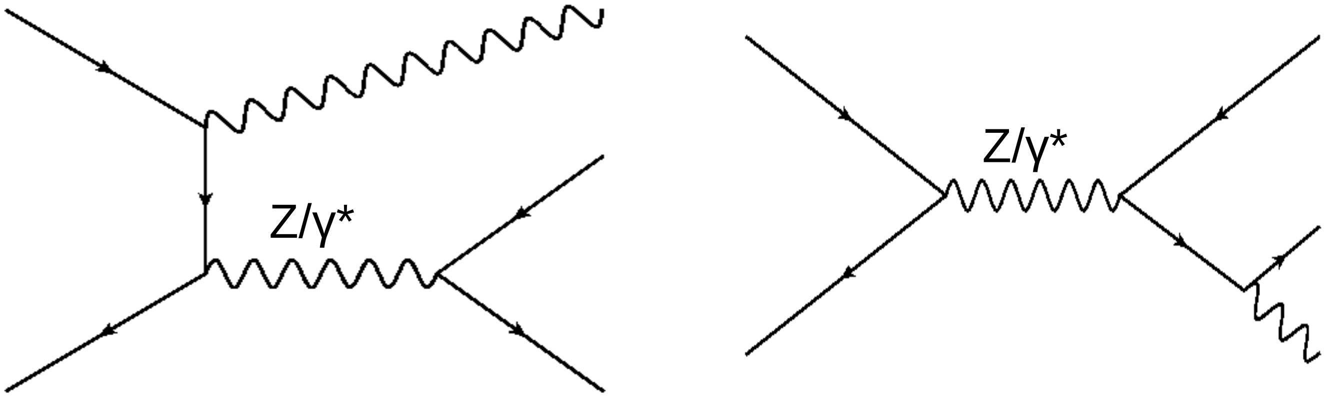
NLO-QCD is done by MC@NLO. It calculates $O(\alpha_s)$ corrections with matrixelements like:



These are matched with Herwig6's approximation of the parton shower.

$Z \rightarrow \mu^- \mu^+$ NLO-Corrections II

NLO-EW corrections to the hard process are done with Horace by calculating complete O(α) corrections with matrixelements like:



Horace results are interfaced to Herwig6 to calculate the Parton-Shower.

For this analysis we need **both corrections** but there is no MC-generator available to do this. To combine EW-, and QCD-corrections we use:

$$\frac{d\sigma}{dO} = \left(\frac{d\sigma}{dO}\right)_{MC@NLO} + \left\{\left(\frac{d\sigma}{dO}\right)_{Horace} - \left(\frac{d\sigma}{dO}\right)_{LO}\right\}_{PS(Hewig)}$$

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Where O is any observable.

$Z \to \mu^- \mu^+$ Monte-Carlo Samples

These samples were used for the analysis:

Generator	Gen. Events	$A\sigma_{Z\gamma^*}$ [pb]	Luminosity [pb^{-1}]
Herwig (LO)	101500	615	165
MC@NLO (QCD-NLO)	82900	743	112
Horace (EW-NLO)	211800	599	354
EW-QCD	-	726	

Best approximation

With acceptance cut A= 51%:
70 GeV < $M_{\mu\mu}$ < 110 GeV, |η| < 2.5, $P_{t\mu}$ > 10 GeV

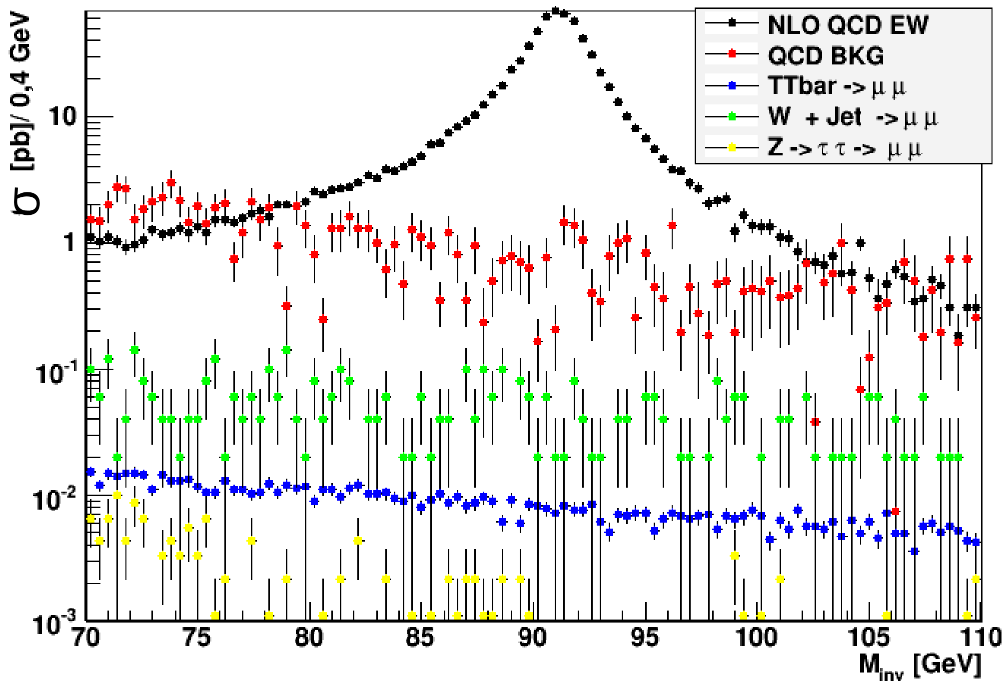
→ QCD-corrections increase the LO-cross-section by 20.7%.
→ EW-corrections decrease by 2.6%.
→ Total Cross-section **1423 pb**

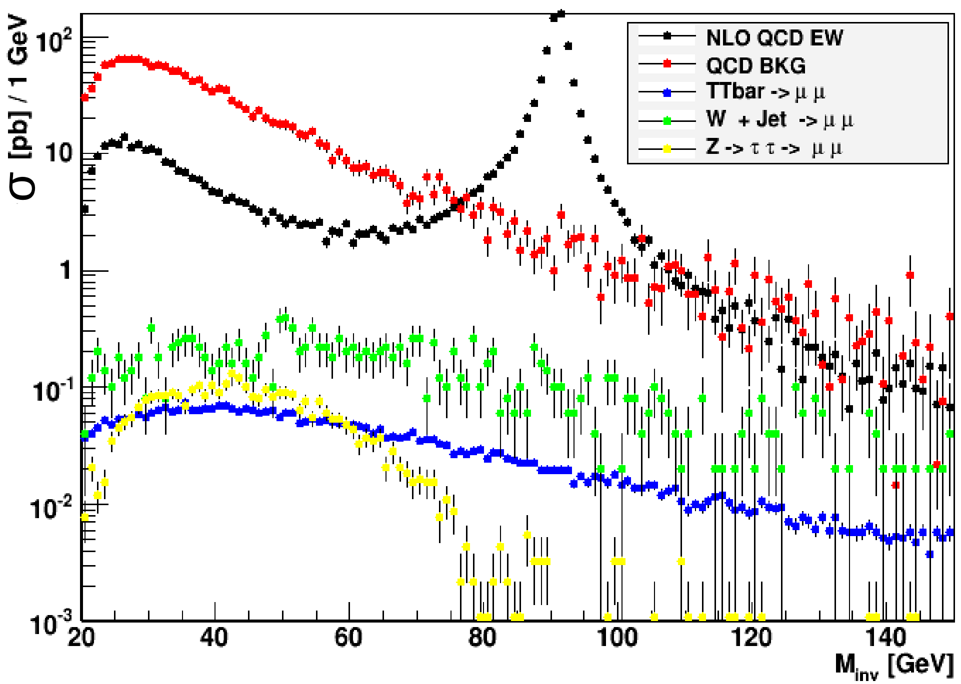
Background on Generator Level

Important background processes:

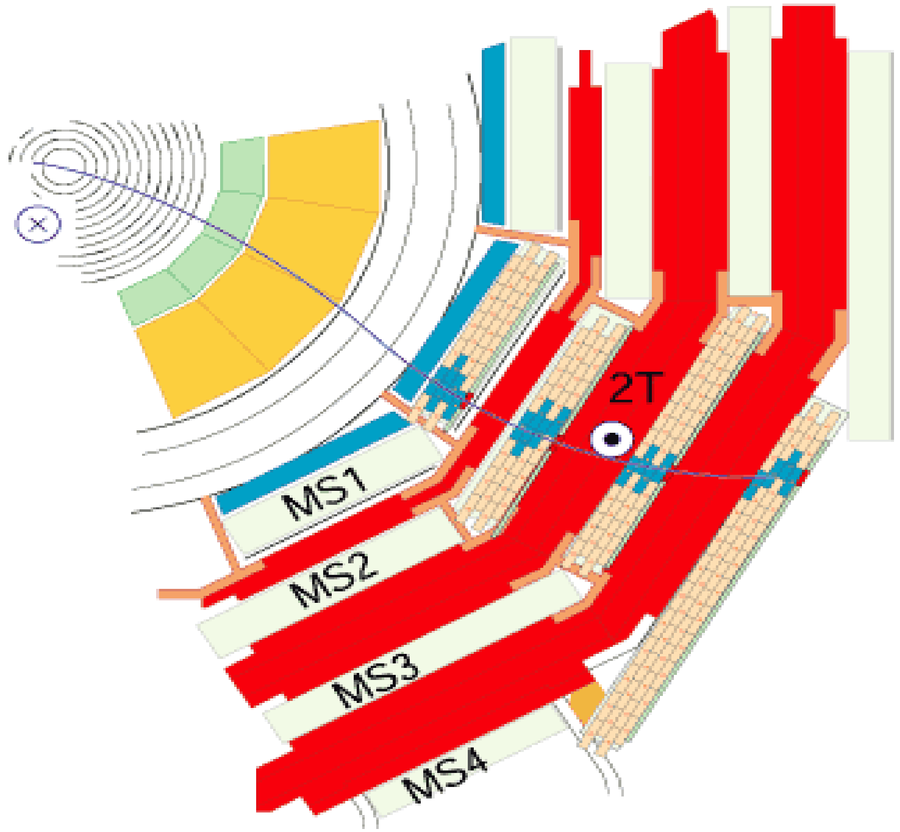
Process	$A\sigma_{bkg}$ [pb]
$Z^0 \to \tau^-\tau^+ \to \mu^-\mu^+$	0.12
$W^+/W^- + Jet \to \mu^+\mu^-$	4.24
$t\bar{t} \to \mu^+\mu^-$	0.94
$b\bar{b}, c\bar{c} \to \mu^+\mu^-$	93.0
Total	98.3

We will see how to reduce this later on reconstruction level





CMS Muon Reconstruction



Muons are detected three times with the CMS-Detector

- The Inner-Tracking-System (silicon pixel and stripe detectors)
- A small energy deposition in the calorimeters
- Muon-System (Barrel: Drift Tube Chambers, Endcap: Cathode Strip Chambers)

This provides a clear signature of muons.

Due to the different direction of the magnetic field the inner Track is bent the other way round.

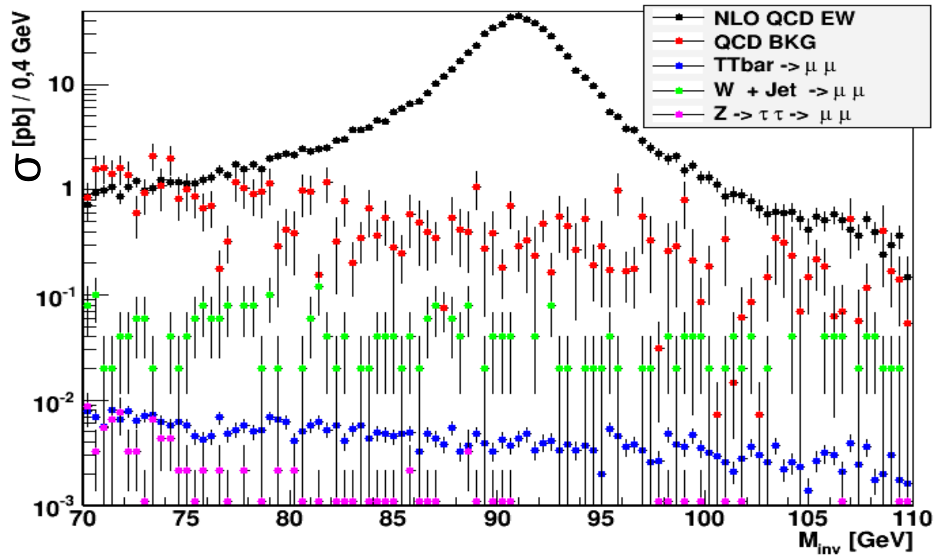
Up to 100 GeV momentum resolution is reached by the Inner-Tracking-System, above a combination of Inner-Tracking and Muon-System provides best momentum resolution.

For this analysis **Global Muons** are demanded, detected in Inner-Tracking and Muon-System.

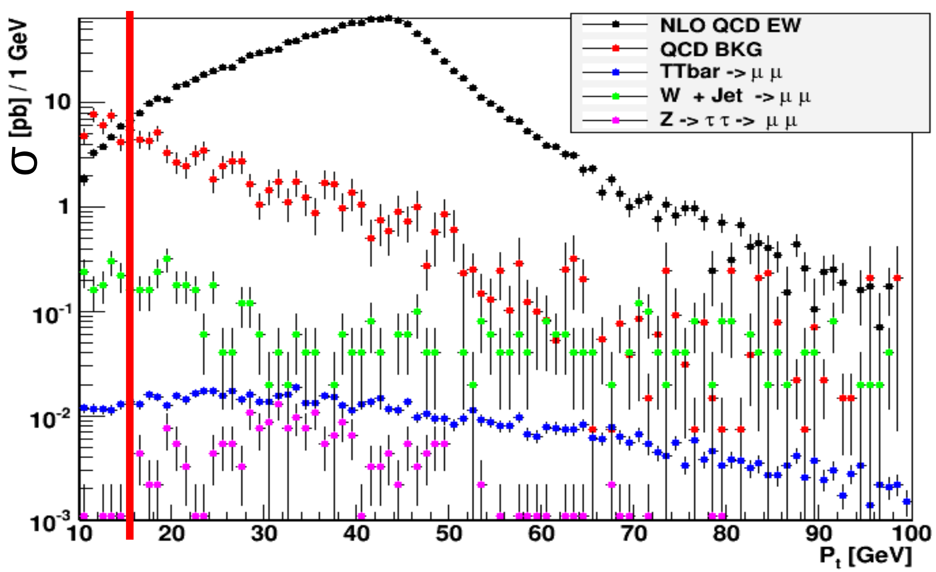
For simulation the ideal detector geometry is used (no misalignment).

Reduction of Background I

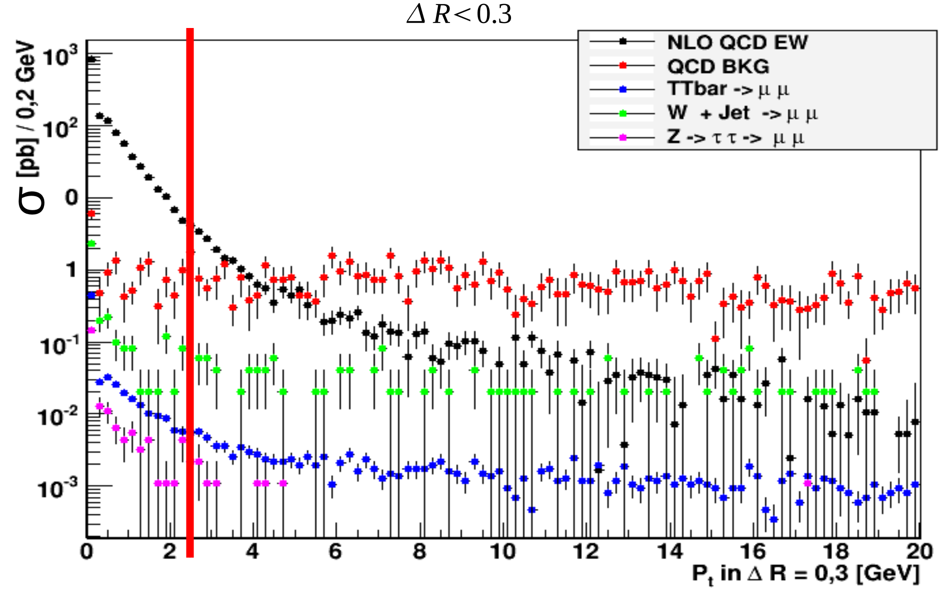
Selection: Two opposite charged Global Muons.



Transverse momentum: $P_t > 15$ GeV

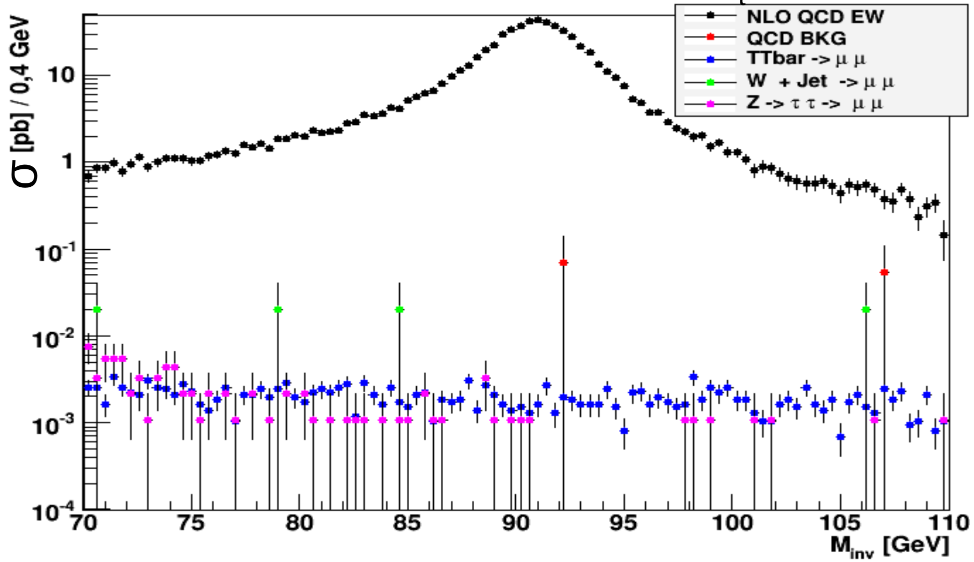


Isolation: $I = \sum_{\Delta R < 0.3} P_t\ of\ tracks < 2.5\, GeV$



Reduction of Background II

Additional cuts: $I < 2.5$ GeV, $P_t > 15$ GeV



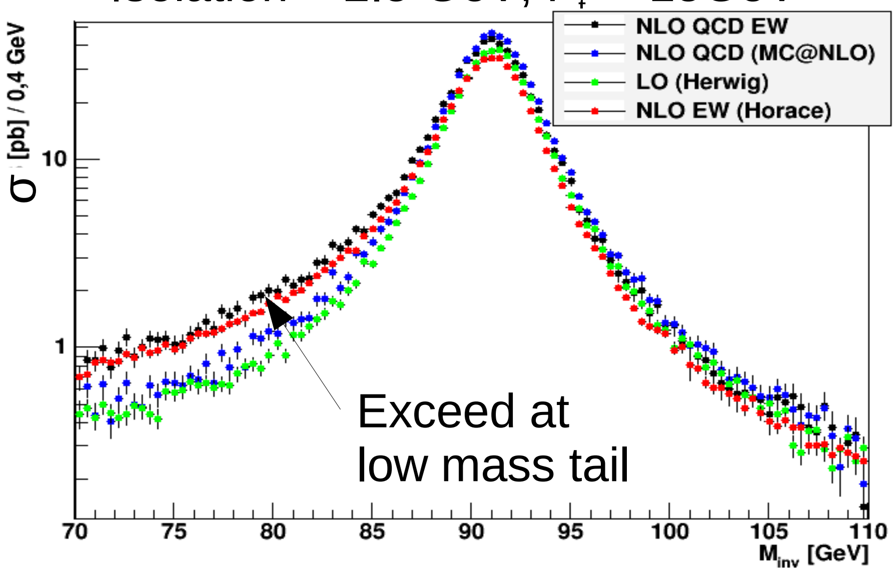
After these cuts the background is less than one per mille (0.07%).

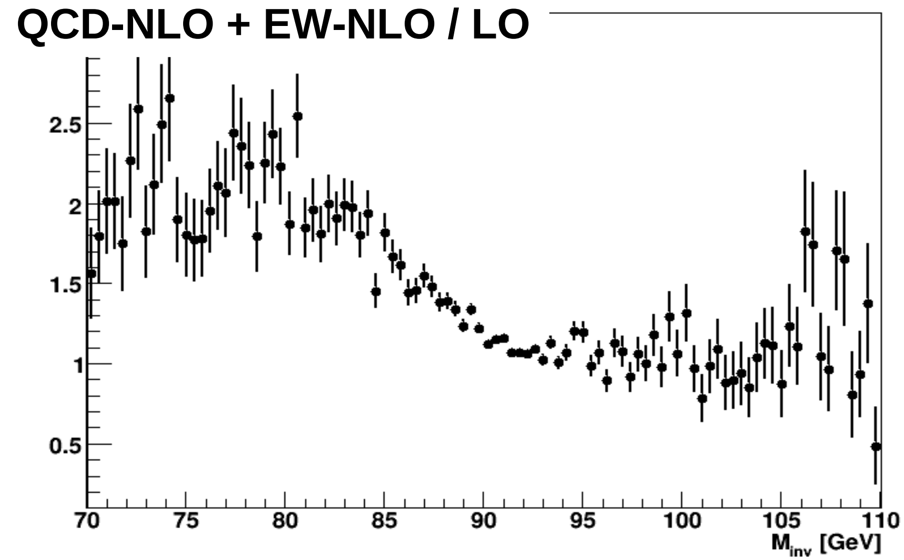
Two different HL-Triggers are discussed here:
-Mu9: At least one muon with $P_t > 9$ GeV
-DoubleMu3: At least two muons with $P_t > 3$ GeV

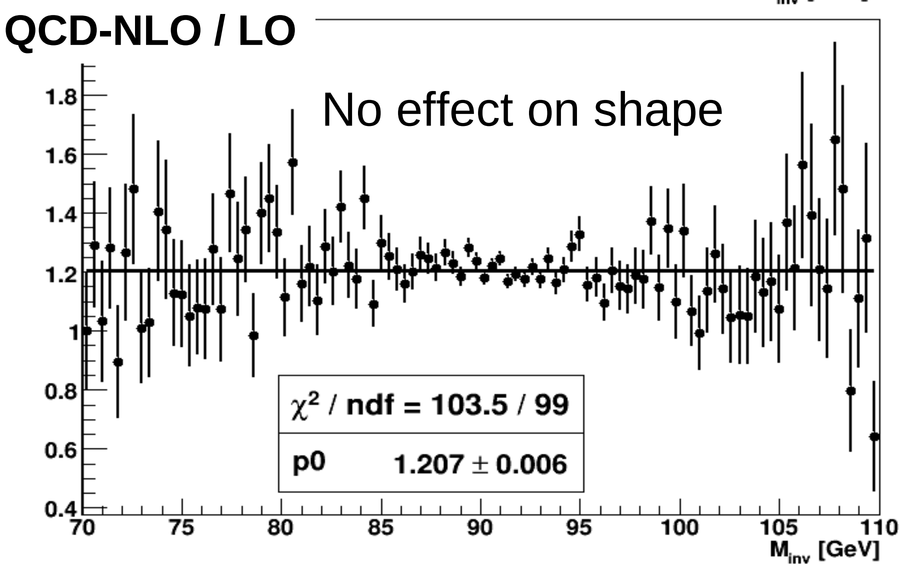
	Rec	x Cut	x Mu9 (DoubleMu3)	x Acceptance
Z	93.5%	88.1%	86.0% (78.5%)	43.8%
BKG	56.7%	0.5%	0.5% (0.47%)	

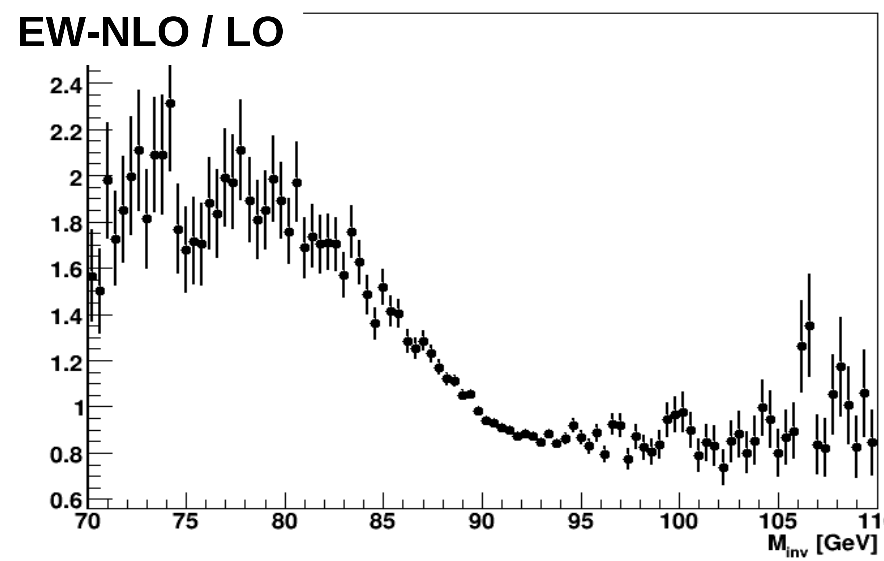
The Z-Peak after Reconstruction

Isolation < 2.5 GeV, P_t > 15GeV



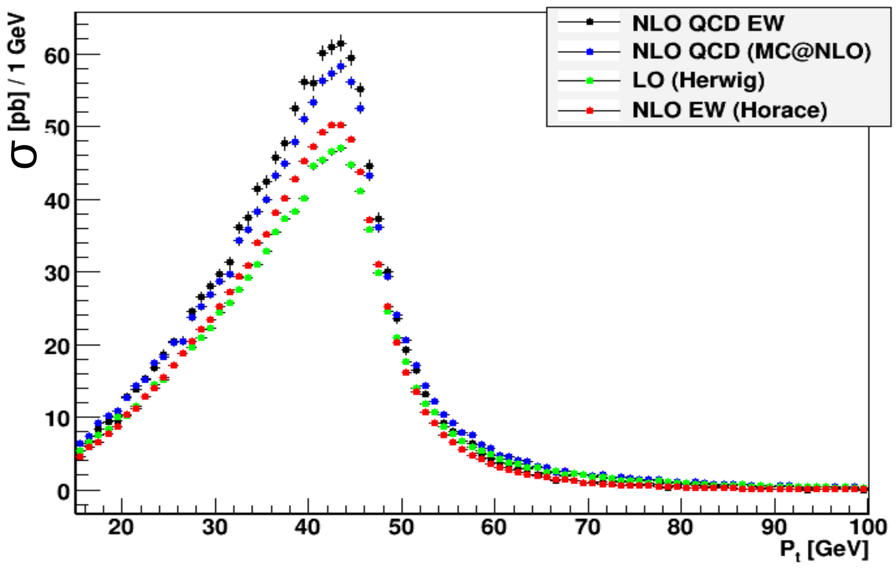


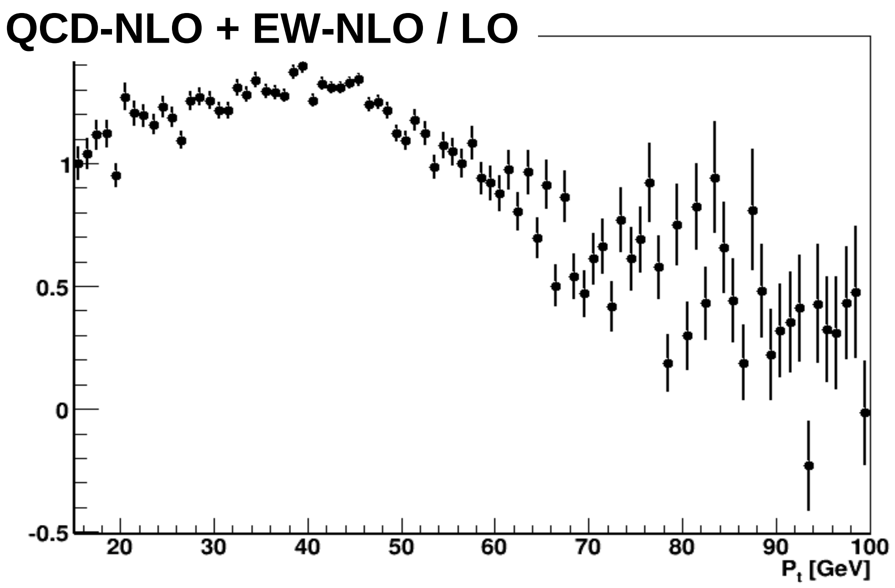


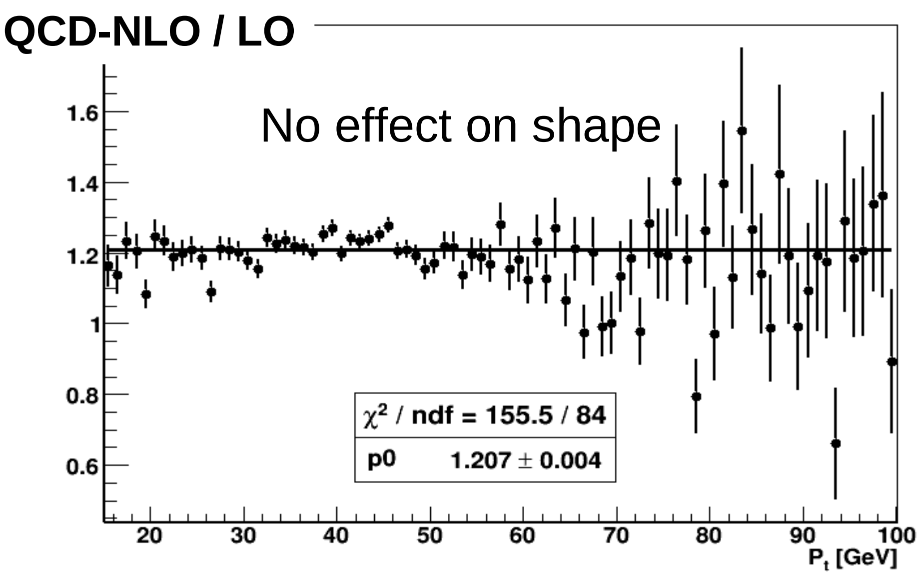


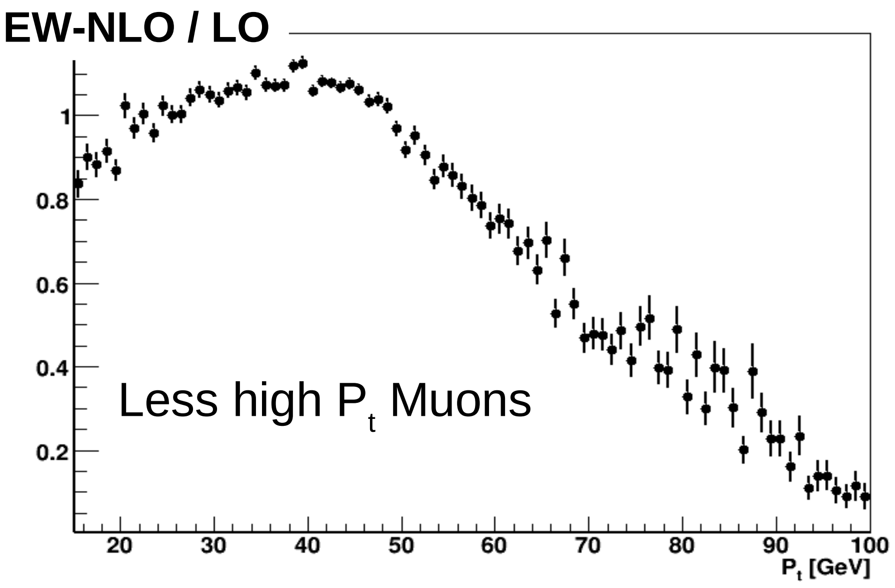
After reconstruction NLO-effects are still important and the same as on gen. level

Muon P_t after Reconstruction

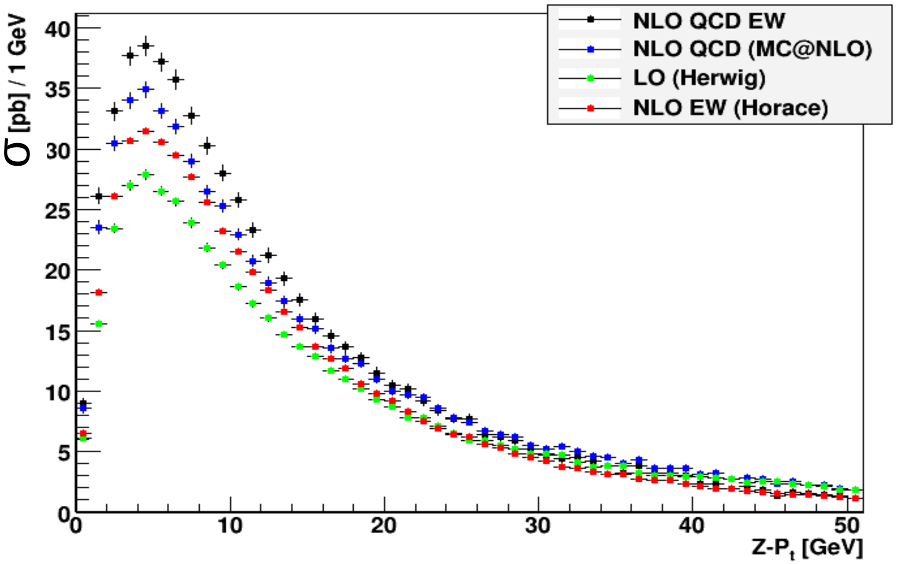


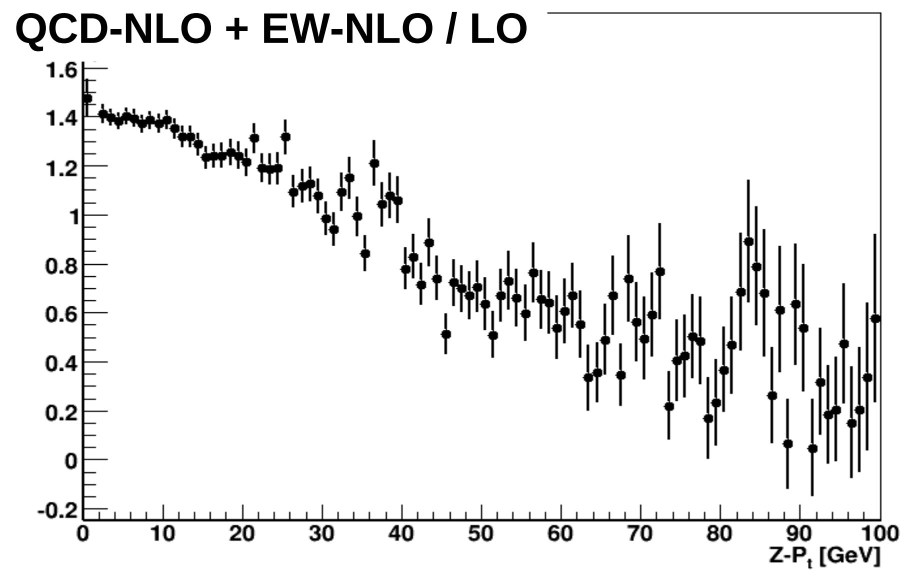


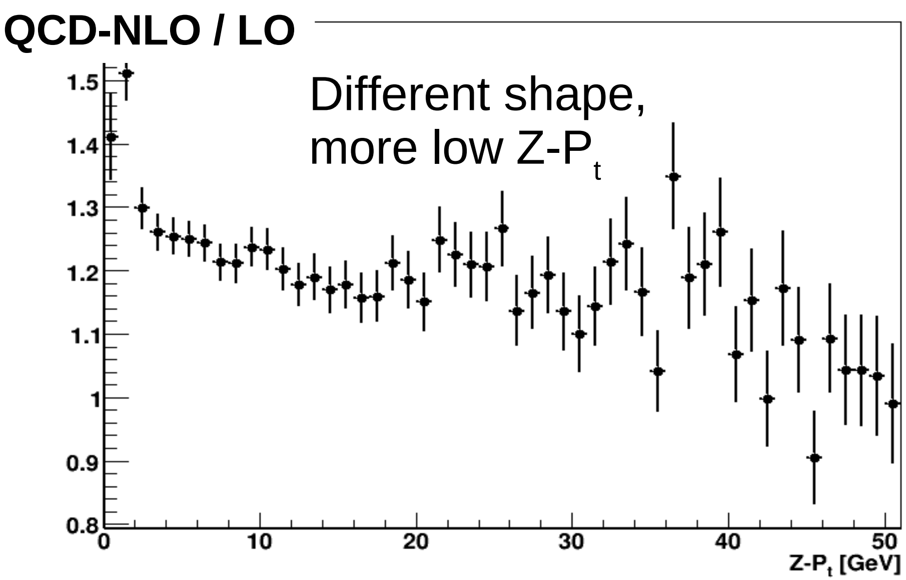




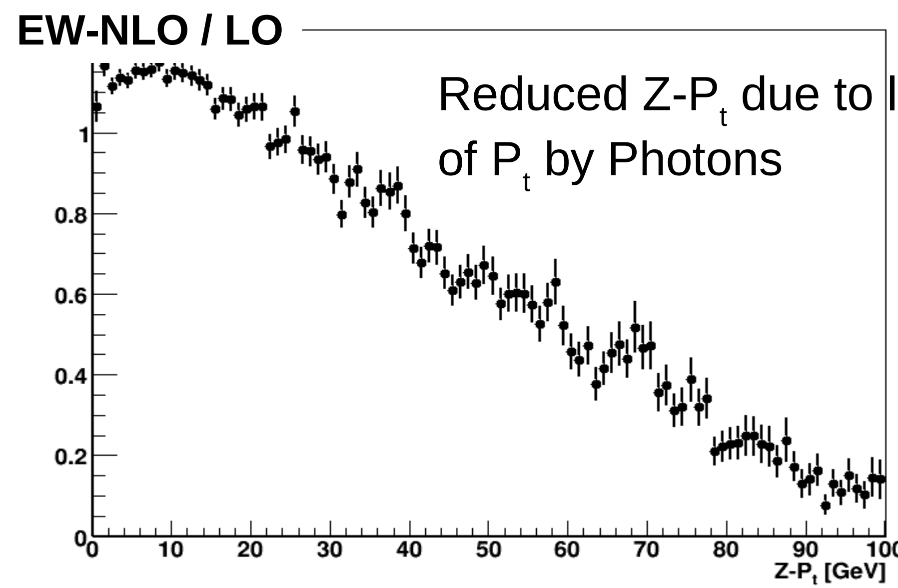
Z-P_t after Reconstruction







Different shape, more low Z-P_t



Reduced Z-P_t due to loss of P_t by Photons

The Cross-Section for 100 pb^{-1}

We expect to measure 62300±250 Events with 100 pb^{-1}.

$$\sigma_Z = 1423 \pm (\sigma_{sys} = 90) \pm (\sigma_{stat} = 5.7)\, pb$$

→ Luminosity measurement will be the most important source of uncertainties.
→ Misalignment, Trigger, and B-Field have been and will be improved.
→ PDF uncertainty is not negligible.

With CTEQ6.6 PDF-Sets there is an uncertainty of -1.6% and +2.3% of the NLO-QCD cross-section. We calculated the cross-section for each error PDF-Sets.

Uncertainty [pb]	Description
σ_{mc} = 10.8	Monte-Carlo statistic. Can be reduced.
σ_{stat} = 5.7	Statistical error.
σ_{lumi} = 14.2 $pb^2\,\sigma_L$	σ_L abs. uncertainty of the 100 pb^{-1} (5%)
σ_{pdf} = +22.6,-32.1	PDF uncertainty
σ_{align} =41.4	Values for 14 TeV analysis Start up scenario. PhD-Thesis RWTH, Maarten Thomas
σ_{HLT} =11.4	
σ_B=7.1	

EW-Corrections

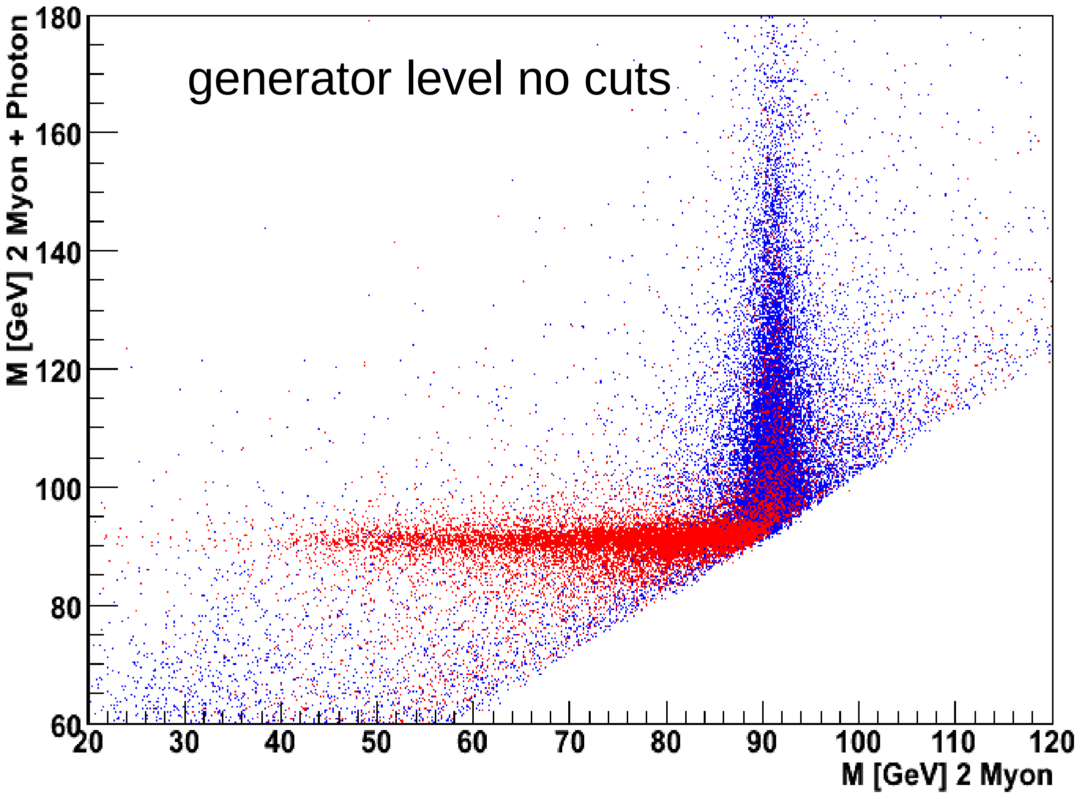
This means to detect additional Photons in $Z \rightarrow \mu^+ \mu^-$ events.
The cross-section of $Z \rightarrow \mu^+ \mu^- + \gamma$ can be calculated with Horace.

Cross-sections of $Z \rightarrow \mu^+ \mu^- + \gamma$

$P_t\ \mu^+\mu^-$ [GeV]	$\lvert\eta\rvert_{max}\ \mu\gamma$	$E_{min}\ \gamma$ [GeV]	
0	∞	0	$\sigma_\gamma = 810\,\mathrm{pb}$
10	2.5	8	$A\sigma_\gamma = 59\,\mathrm{pb}$

within detector acceptance

Select Events with:
2 Muons and 1 Photon.
→ Calculate M_{inv} *of the* 2 muons
→ Calculate M_{inv} of the 2 muons + photon



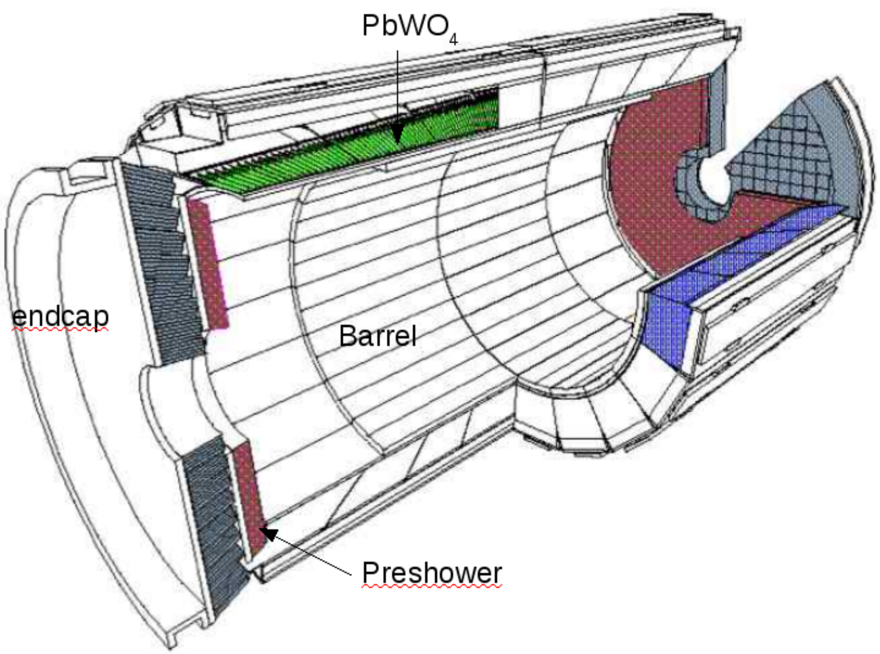
Red: γ was radiated by a Muon from Z.
Blue: γ from π^0 decay etc.

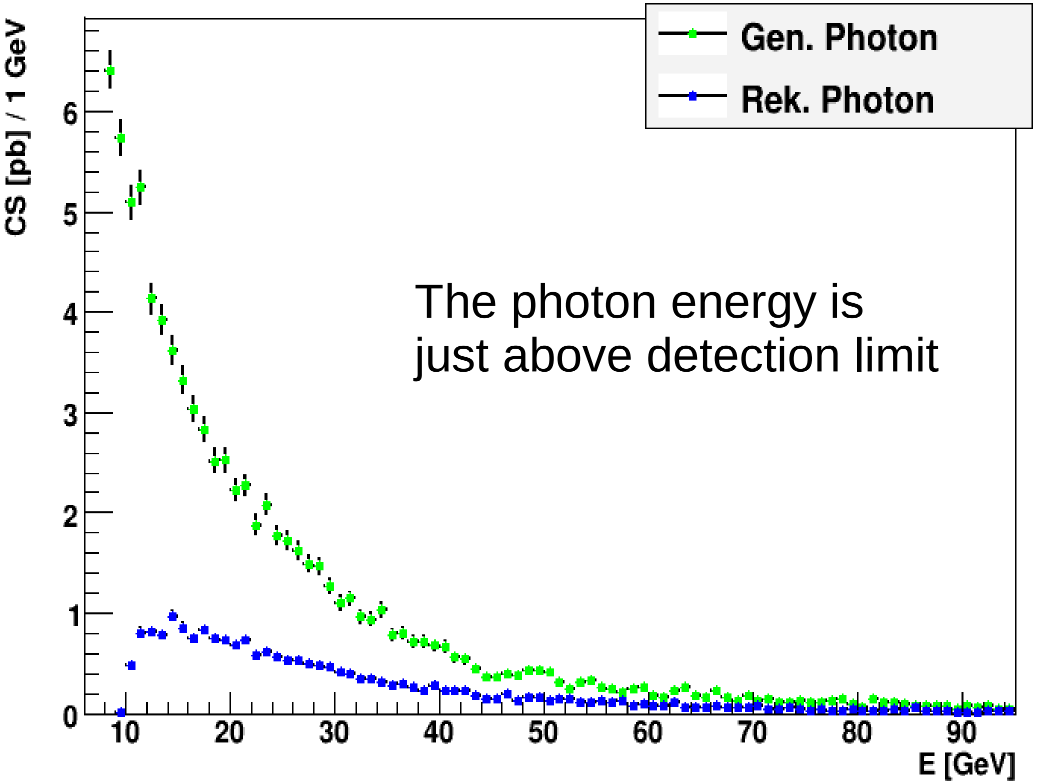
Photon Detection with CMS

Photons are detected in the CMS-ECAL.

→ Best energy resolution is reached for photons that depose nearly all its energy in small 3X3-cluster (crystal 2.2x2.2cm[2]) (σ = 1.5% 20GeV < E < 30GeV).

→ A large fraction of photons (56%) convert while passing the tracker into a e^+e^- -pair. Their energy is spread on a wide area and their energy resolution is worse (σ = 5.1% 20GeV < E < 30GeV).





The photon energy is just above detection limit

Event Selection

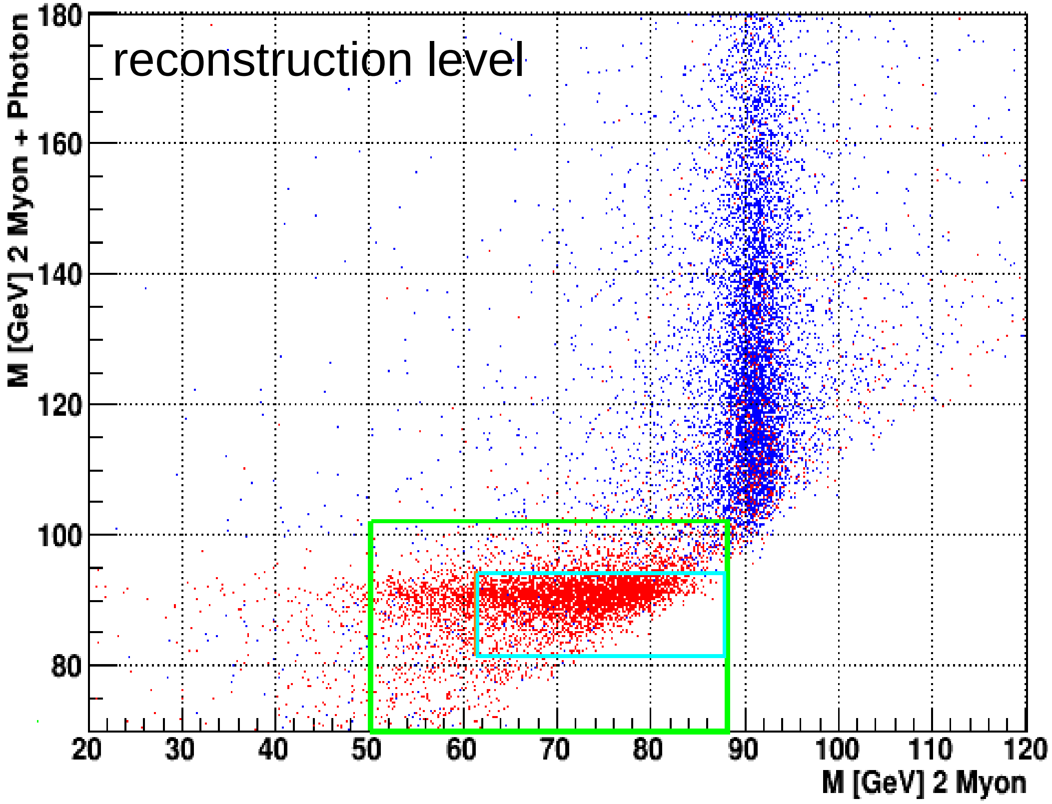
The same plot for **reconstructed** events:

Select the same events as for the $Z/\gamma^* \rightarrow \mu^- \mu^+$ analysis plus photon.

Events containing a photon radiated by a muon from Z-decay (red) can be separated cleanly.

→ Difference between the plots due to loss of low energy photons

→ For 100 pb^{-1} 1900 events are expected to be measured.



	$M_{\mu\mu}$ [GeV]	$M_{\mu\mu\gamma}$ [GeV]	$\epsilon_{tot}(\%)$	ϵ_{cut} (%)	γ_Z fraction (%)
Best purity:	50-88	70-102	30.1	86.8	93.3
Best ratio:	61-88	83-93	20.0	57.5	97.8

$$A\sigma_\gamma = 59 \pm (\sigma_{mc} = 0.86) \pm (\sigma_{stat} = 1.4) \pm (\sigma_{lumi} = 0.59\sigma_L); (\sigma_{pdf} = +0.94; -1.4)pb$$

Systematic errors like ECAL-calibration have to be studied.

Conclusion

→ NLO-effects are important for a detailed analysis
QCD increases cross-section (20%).
EW has influence of the shape of kinematic distributions.

→ $Z/\gamma^* \to \mu^- \mu^+$ cross-section measurement is limited by luminosity and alignment at the beginning but PDF uncertainties will be important, too. $\sigma_Z = 1423 \pm (\sigma_{sys} = 90) \pm (\sigma_{stat} = 5.7)\, pb$

→ Bremsphotons above 8 GeV can be detected and the NLO-EW-cross-section can be measured, but systematic uncertainties have to be studied.