Z→$\mu\mu$ Cross Section @ CMS

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Physics at LHC startup

- Physics at LHC startup: $Z \rightarrow \mu\mu(ee)$.
- Useful for tracker and muon system alignment and calorimeter calibration.
- Z events are setting the lepton momentum and lepton energy scales.
- Result should be cross section or luminosity.

Strategy for $pp \to Z/\gamma^* \to \mu^+\mu^-$

- "Master" formula to estimate cross section or luminosity:

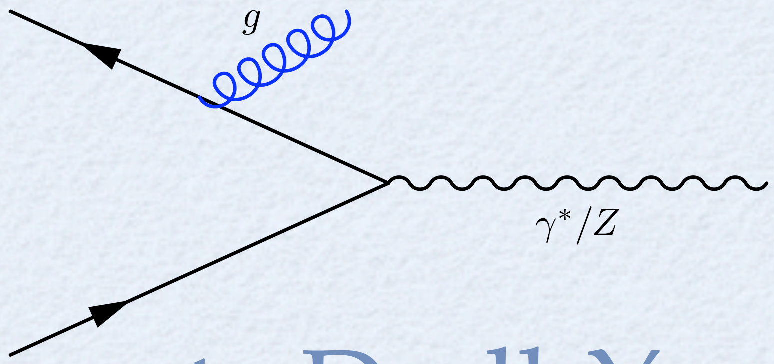
$$\sigma(pp \to Z/\gamma^* \to \mu^+\mu^-) = \frac{N_{\mathrm{cand}}\,(1-f_{b\bar{b}})\,(1-f_{t\bar{t}})\,(1-f_{\mathrm{cosmics}})\,(1-f_{\tau\tau})\,(1-f_{pp\to\mu X})\,(1-f_{W\to\mu\nu})}{\epsilon_{total}\int L\mathrm{d}t}$$

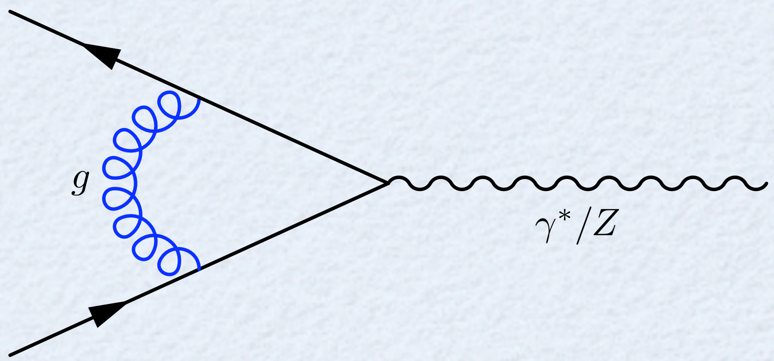
- f_i : Fraction of candidate events attributed to $b\bar{b}$ ($t\bar{t}$), cosmic μ, $Z \to \tau\tau$, $pp \to \mu X$ and $W \to \mu\nu$.

- $\varepsilon_{\mathrm{total}}$: Efficiency of selection cuts and detector acceptance.

MC@NLO

- Reminder: crucial for precision measurements.
- Using MC@NLO: $\mathcal{O}(\alpha_s)$ (Frixione, Webber; hep-ph/0204244, hep-ph/0305252)
- NLO provides a more accurate answer for the integrated cross section.
- MC@NLO computes all QCD NLO diagrams before starting the shower.

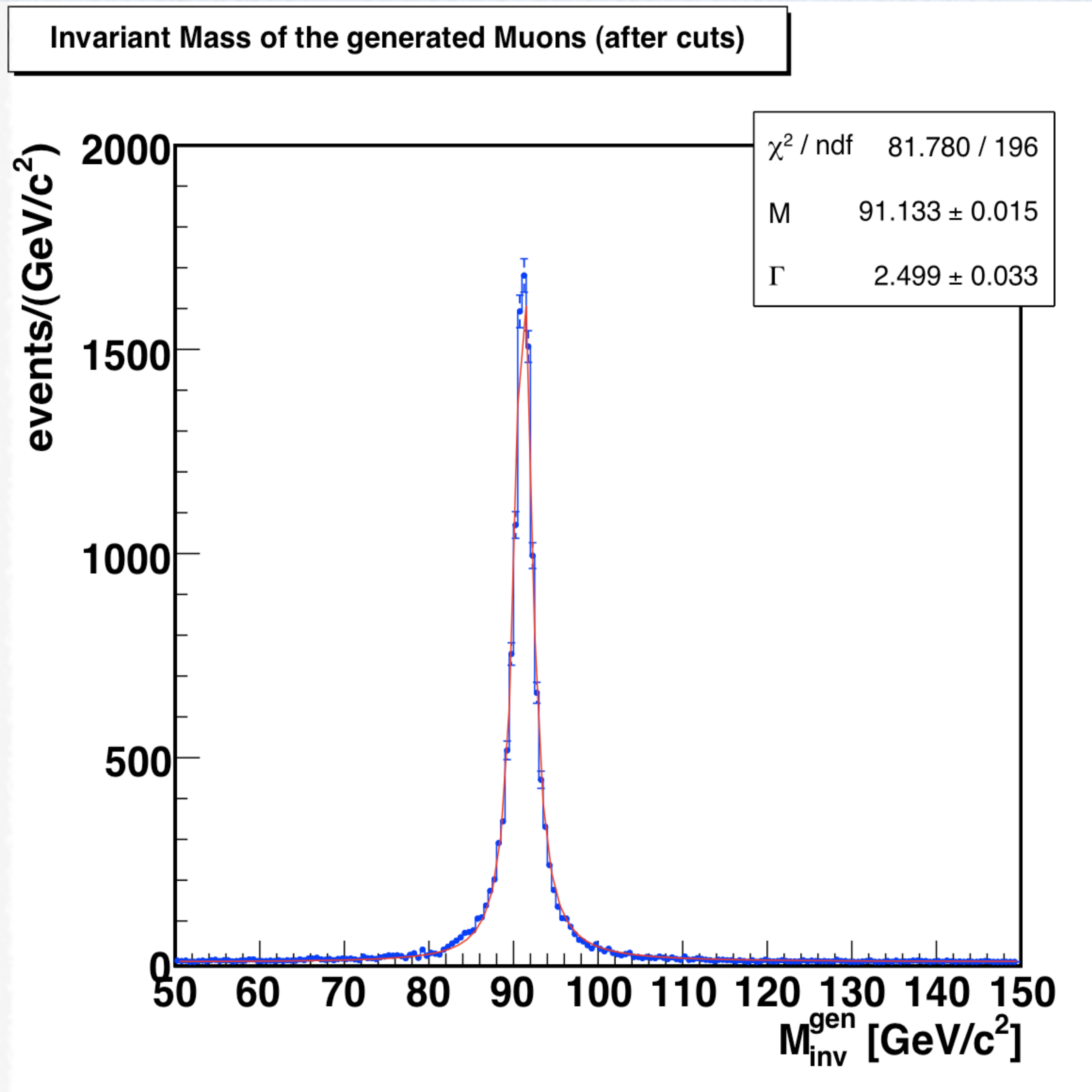




- generate Drell-Yan processes ... $Z \to \mu\mu$
  ... use Herwig for showering ...
  ... do full CMS detector simulation ...

Generator Check #1

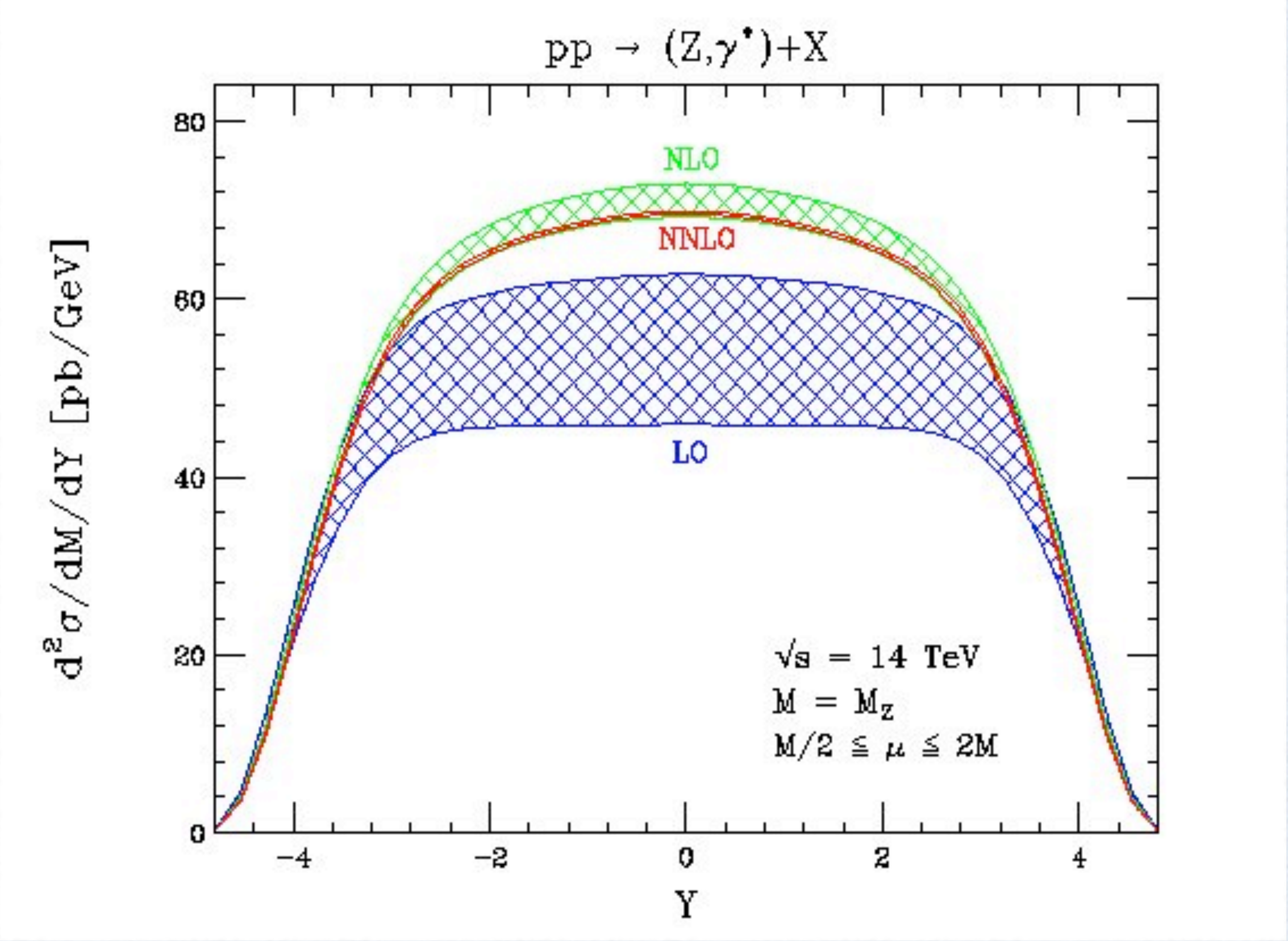
- MC@NLO: Z mass from generator



mass, width and Breit-Wigner fit okay...

GENERATOR CHECK #2

Check MC@NLO with independent calculations:



(From Anastasiou et al, hep-ph/0312266)

- Integration yields the total cross section times branching ratio. Assume narrow width approximation in M and integrate over η numerically ($Y = \eta$).

Generator Check #2

- Results after integrating the plot:

LO, lower edge	$\sigma = 1.389$ nb	very unsafe
NLO	$\sigma = 2.011$ nb	rather safe

- For comparison with our simulation: MC@NLO, NLO: $\sigma = 1.910\text{-}2.053$ nb depending on PDF.

- Agreement nice!

- Strategy: Using MC@NLO as the generator and NNLO calculations for the cross section.

Z production: $\mathcal{O}(\alpha_s^2)$

- QCD NNLO[a]: Spin correlations and γ-Z interference included.
- FEWZ is not a generator!
- Is able to calculate Xsec in LO, NLO and NNLO:

$$\sigma_{\gamma^*/Z\to\mu\mu} = (2.031 \pm 0.002)\ \text{nb} \quad \textit{NLO}$$

$$\sigma_{\gamma^*/Z\to\mu\mu} = (1.988 \pm 0.014)\ \text{nb} \quad \textit{MC@NLO}$$

… using the same PDFs and $66\ \text{GeV} \leq m_{\mu\mu} \leq 166\ \text{GeV}$

- γ contribution added for MC@NLO.
- Renormalization and factorization scales equal.
- Agreement within $\Delta \approx 2\ \%$.

[a] K.Melnikov, F.Petriello, hep-ph/0609070; source code available at http://www.phys.hawaii.edu/~kirill/FEHiP.htm

Cross section for NNLO

- Varying the renormalization μ_r and factorization μ_f scales.

$\mu_r = \mu_f = m_Z$

$$\sigma_{\gamma^*/Z\to\mu\mu} = (1.964 \pm 0.020)\ \mathrm{nb}$$

$\mu_r = \mu_f = \frac{1}{2}\, m_Z$

$$\sigma_{\gamma^*/Z\to\mu\mu} = (1.971 \pm 0.018)\ \mathrm{nb}$$

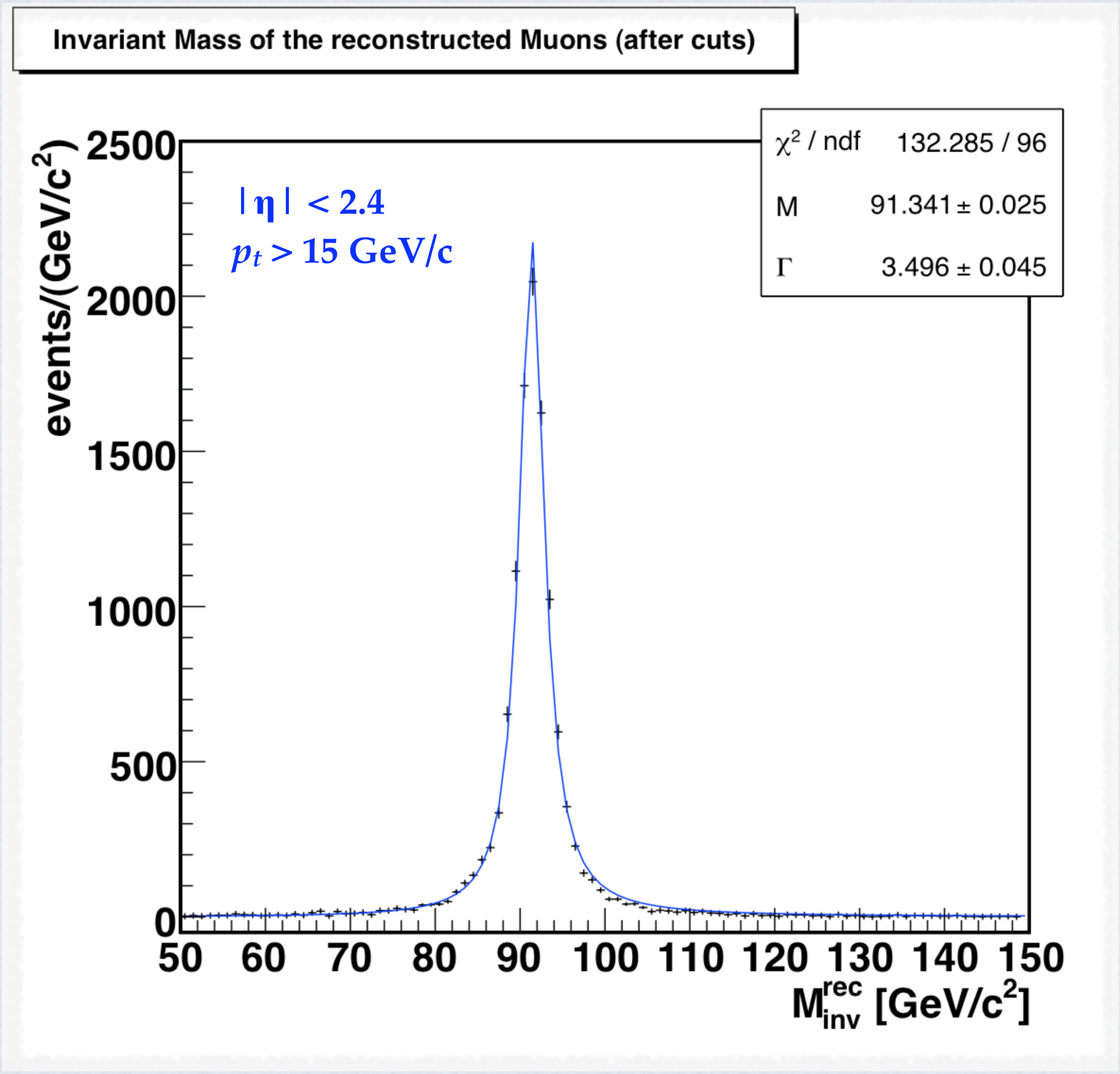
$\mu_r = \mu_f = 2\, m_Z$

$$\sigma_{\gamma^*/Z\to\mu\mu} = (1.994 \pm 0.020)\ \mathrm{nb}$$

- Independent on scales!
- Slightly smaller than NLO from this calculation.
- Same check performed for MC@NLO with similar result!

Invariant Mass

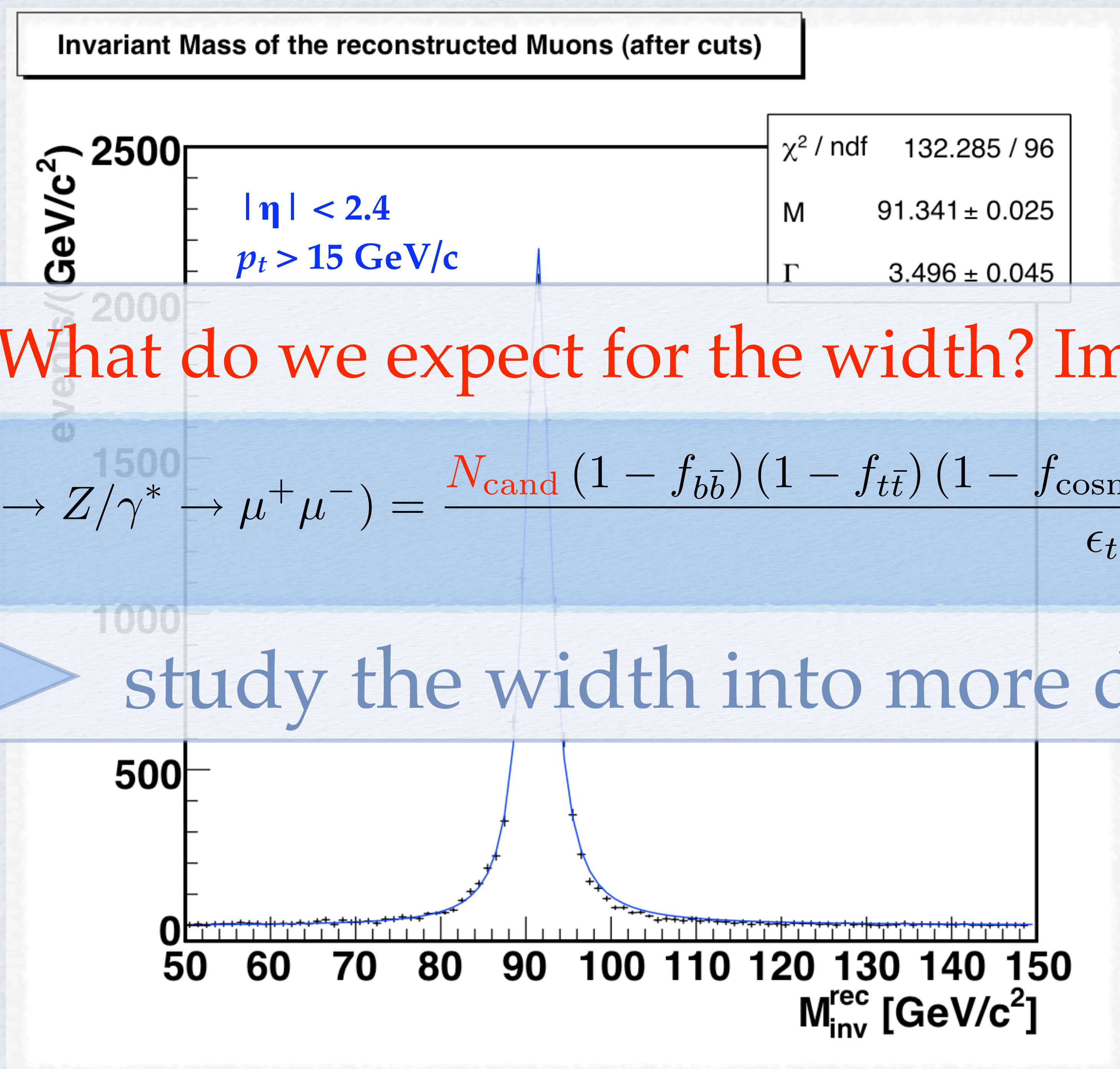
Mass Z after reconstructing 2 μ's



- Fit is good with Breit-Wigner alone. This is in principle wrong and just by chance.

Invariant Mass

Mass Z after reconstructing 2 μ's



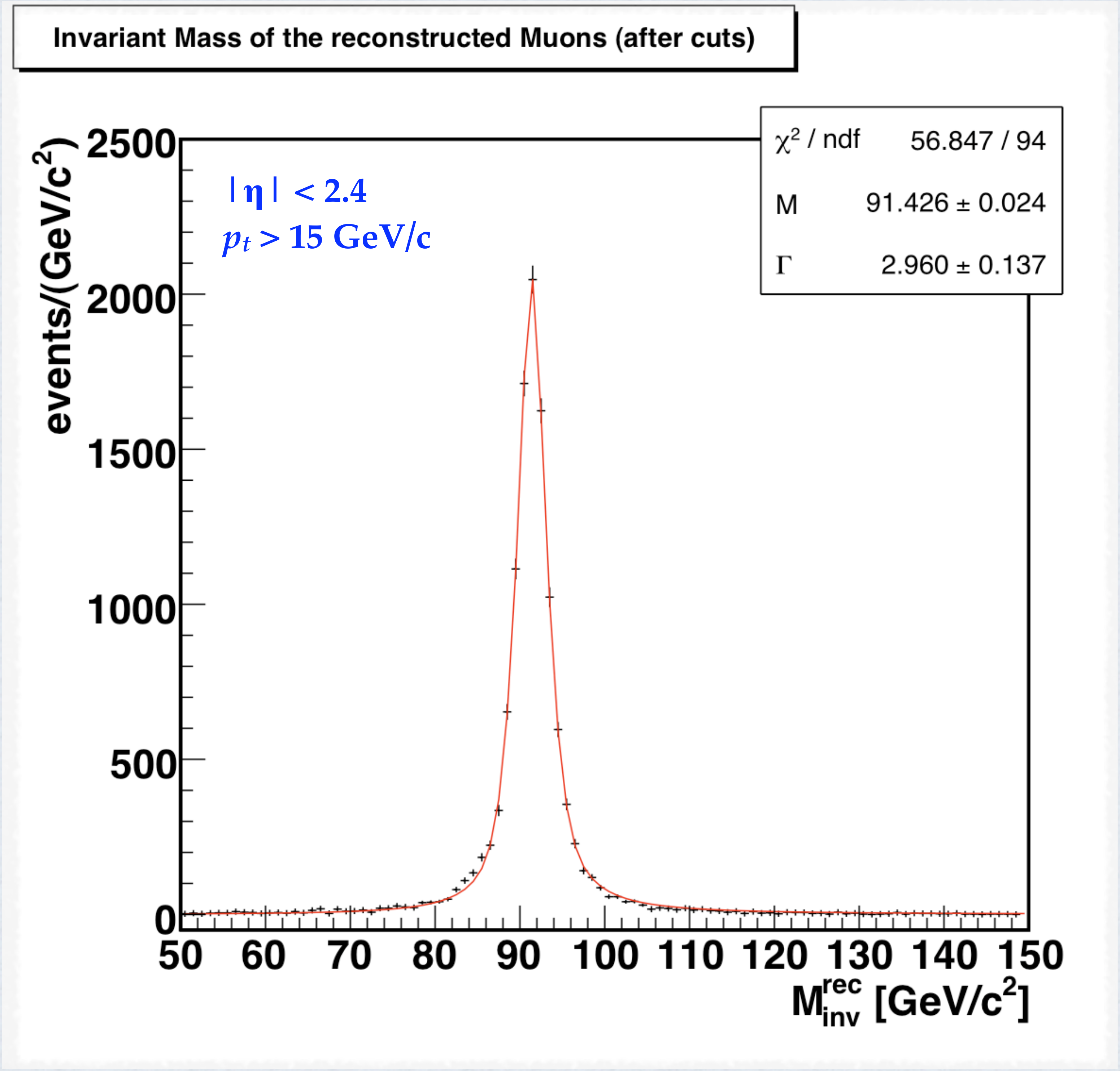
- What do we expect for the width? Important to get N_{cand} right.

$$\sigma(pp \to Z/\gamma^* \to \mu^+\mu^-) = \frac{N_{\text{cand}}\,(1-f_{b\bar{b}})\,(1-f_{t\bar{t}})\,(1-f_{\text{cosmics}})\,(1-f_{\tau\tau})\,(1-f_{pp\to\mu X})\,(1-f_{W\to\mu\nu})}{\epsilon_{total}\int L dt}$$

⇨ study the width into more detail…

Invariant Mass

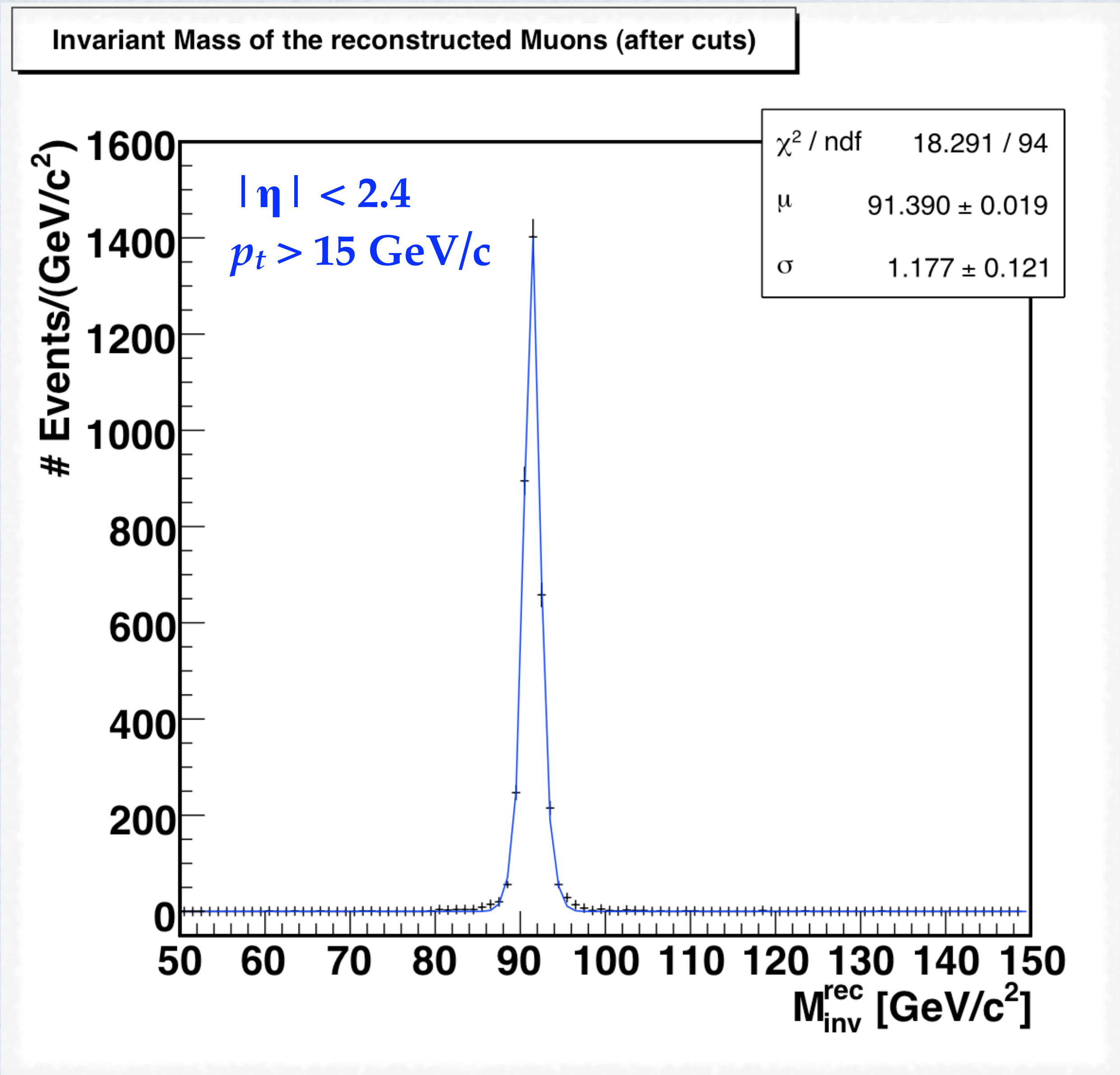
Mass Z after reconstructing 2 μ's… another fit



- Fit in peak region okay with Breit-Wigner + one Gaussian (in principle one should fit more Gaussians…)
- We expect from Z width and detector resolution a width of 2.8 GeV / c^2.

Invariant Mass

Mass Z after reconstructing 2 μ's from narrow width Z



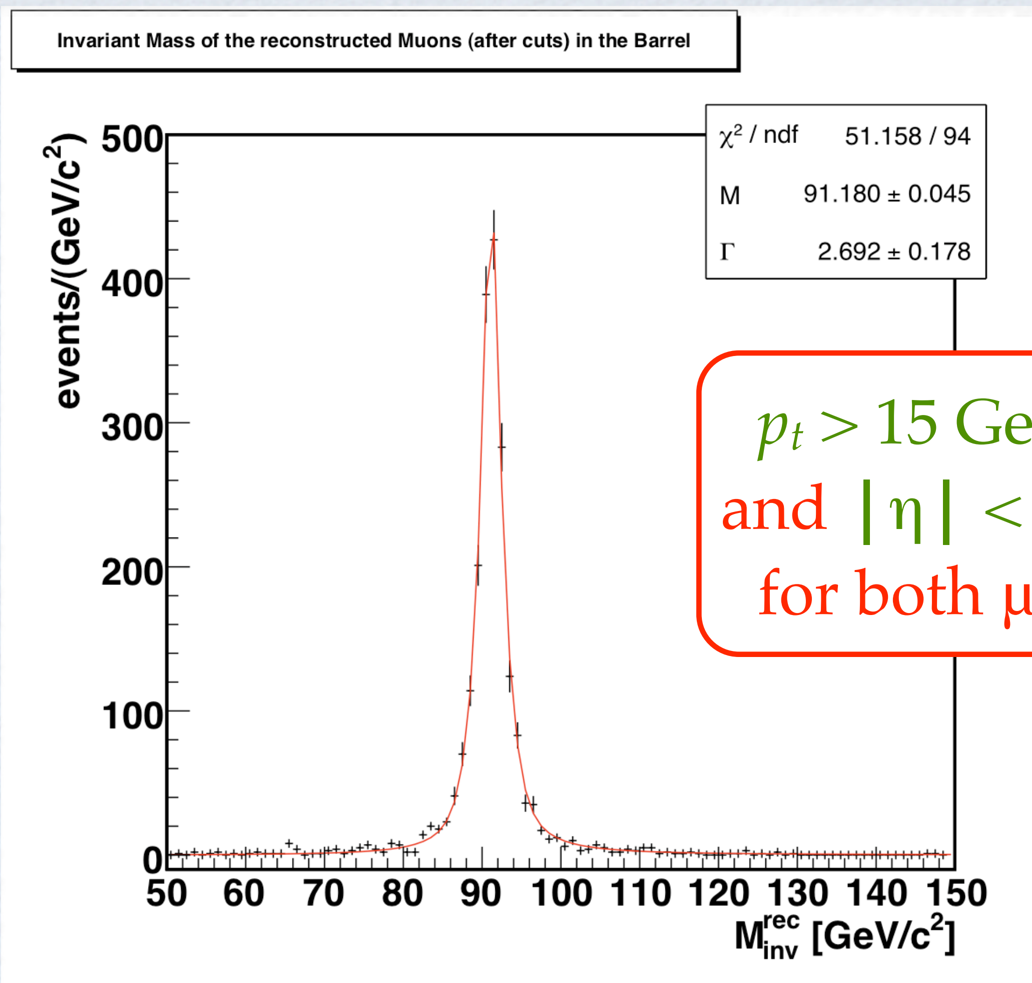
Pure resolution effect visible!

Width = 1.18 GeV / c^2

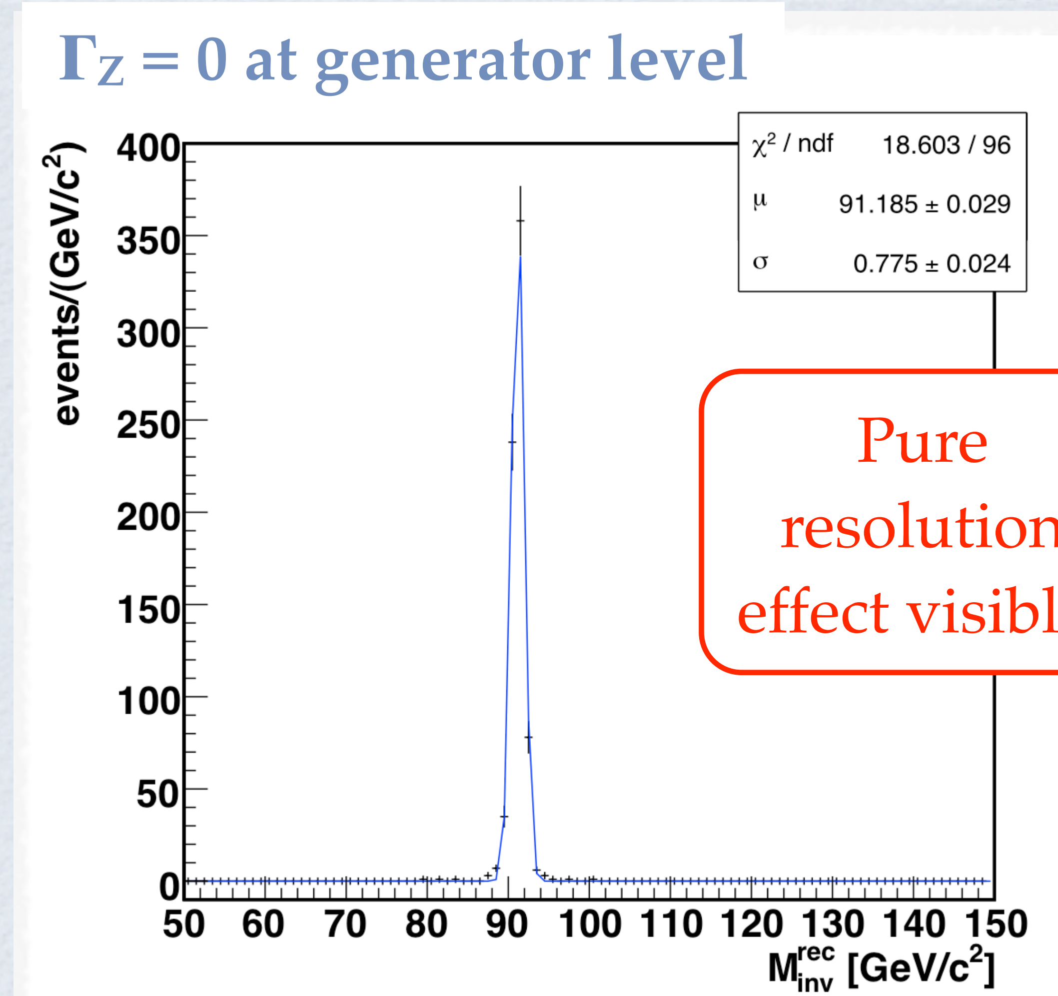
- Fit with 2 Gaussians, detector resolution only!
- We find what we roughly expect from naive calculations.

INVARIANT MASS

Mass Z after reconstructing 2 μ's in barrel region



$p_t > 15$ GeV and $|\eta| < 0.8$ for both μ's

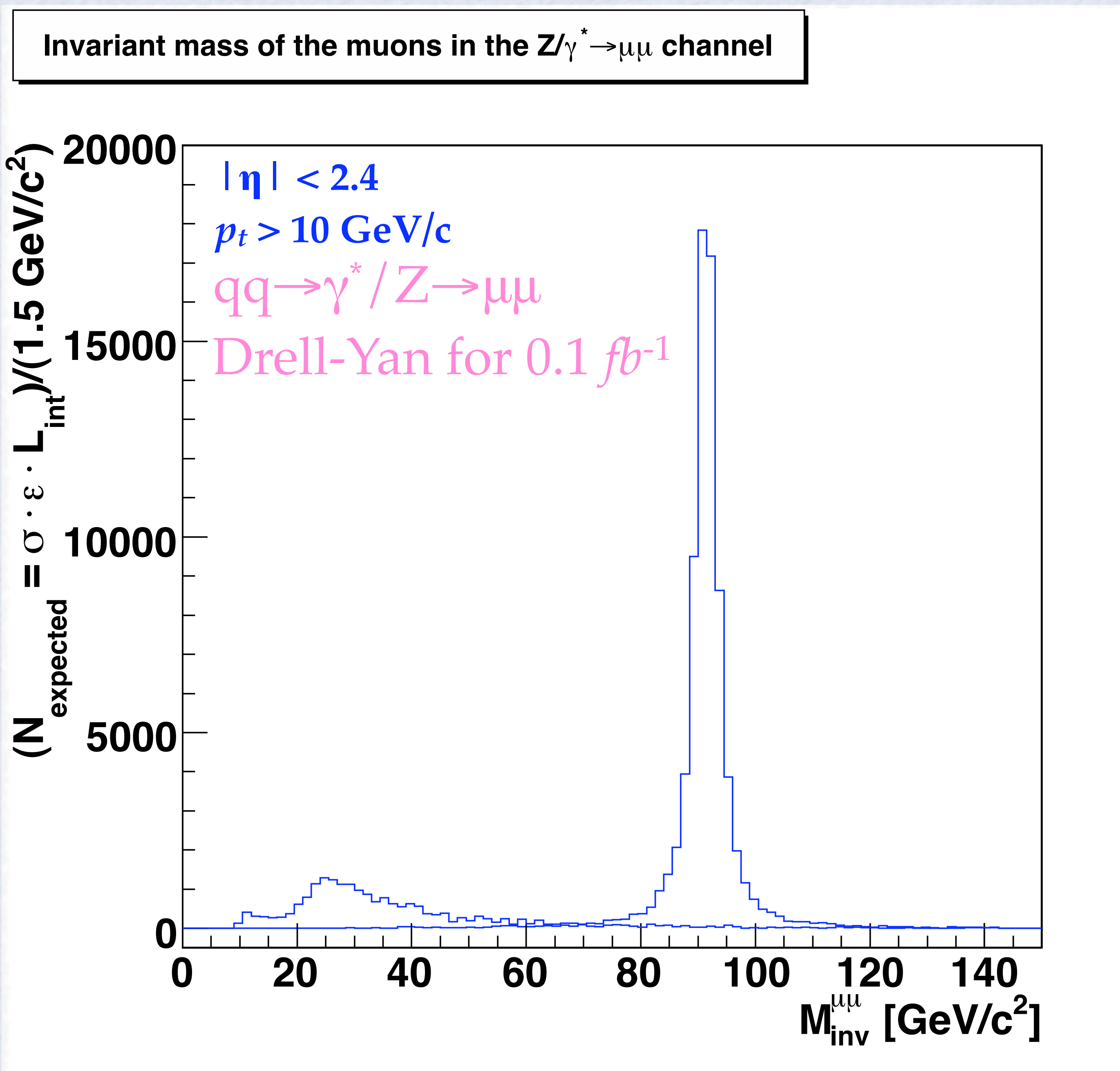


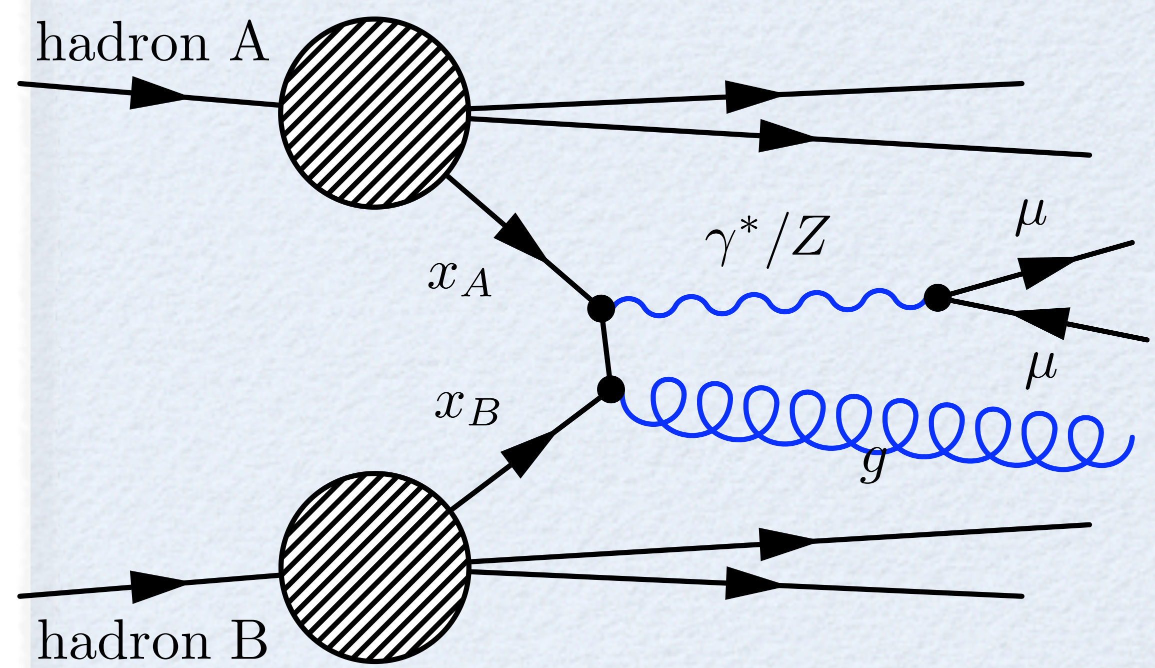
Pure resolution effect visible!

- Breit-Wigner and Gaussian fitted.
- Width 2.63 GeV / c² expected in this region.
- 2 Gaussians fitted: $\sigma = 0.78$ GeV / c².
- From the fit we obtain (2.69 ± 0.18) GeV / c²!

$pp \rightarrow \gamma^*/Z \rightarrow \mu^+\mu^- + X$

Expected number of μμ events for 0.1 fb^{-1} for the LHC with the CMS detector:





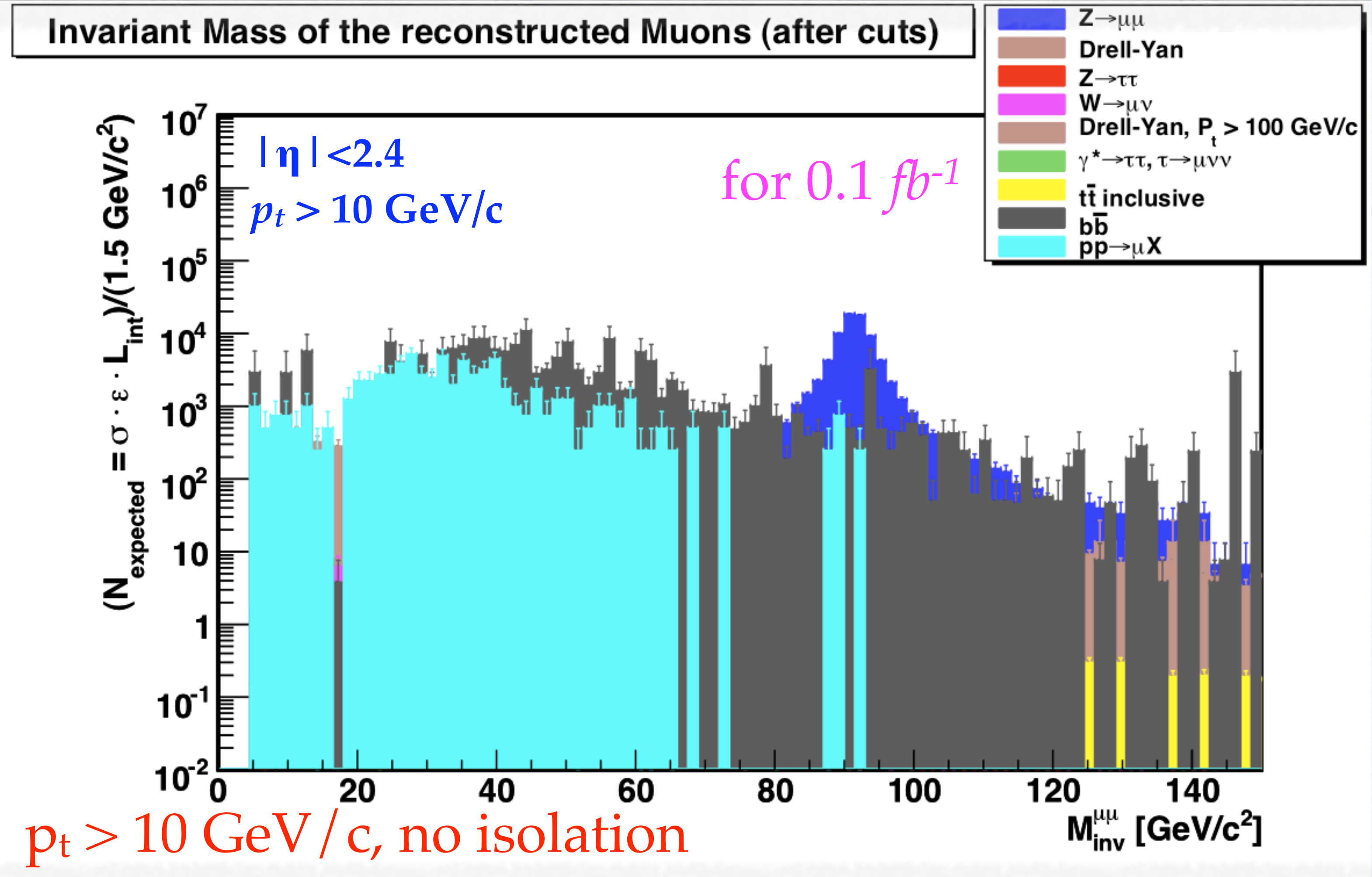
BACKGROUND

- $f_{b\bar{b}}$ ($f_{t\bar{t}}$) from data (e.g. isolation criteria).
- $f_{\tau\tau}$ irreducible (e.g. from MC)!!
- $f_{W\to\mu\nu}$ from data (e.g. # candidate events ≥ 2μ).
- $f_{pp\to\mu X}$: events stemming from qq→qq, gg→gg, gq→gq and gg→qq processes.
- $f_{cosmics}$ from data (e.g. time info!?).

$$\sigma(pp \to Z/\gamma^* \to \mu^+\mu^-) = \frac{N_{\text{cand}}\,(1-f_{b\bar{b}})\,(1-f_{t\bar{t}})\,(1-f_{\text{cosmics}})\,(1-f_{\tau\tau})\,(1-f_{pp\to\mu X})\,(1-f_{W\to\mu\nu})}{\epsilon_{total}\int L dt}$$

Signal & Background

- Main contribution from $b\bar{b}$ events.



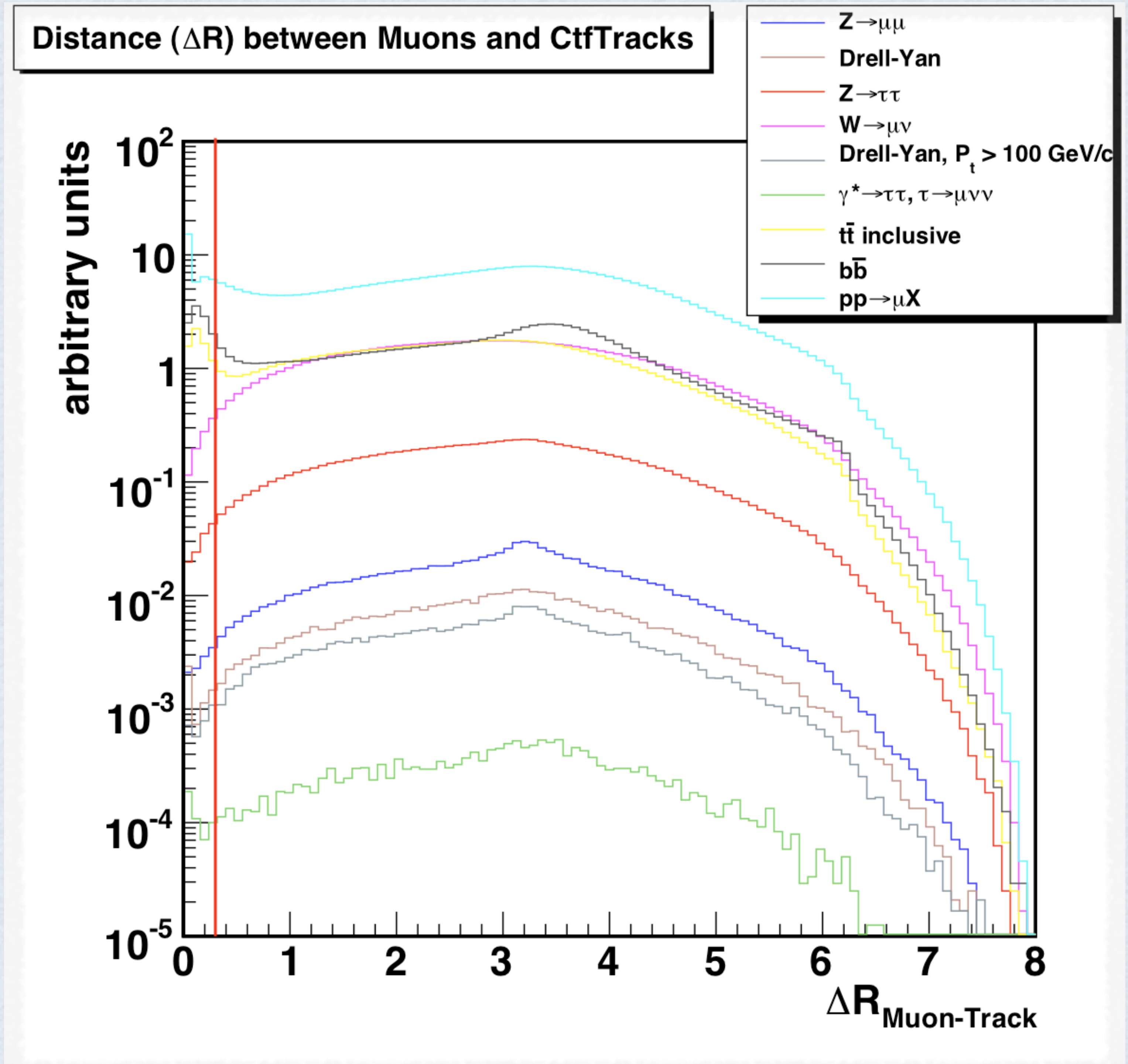
Background	$p_t > 10$ GeV/c	$p_t > 15$ GeV/c	$p_t > 20$ GeV/c	$p_t > 25$ GeV/c
$pp \to \mu + X$	$1.81 \cdot 10^{-2}$	$7.43 \cdot 10^{-3}$	$8.16 \cdot 10^{-3}$	$< 8 \cdot 10^{-3}$
$b\bar{b}$	$7.89 \cdot 10^{-2}$	$7.23 \cdot 10^{-2}$	$2.31 \cdot 10^{-2}$	$1.32 \cdot 10^{-2}$
$W \to \mu\nu$	$4.85 \cdot 10^{-4}$	$3.23 \cdot 10^{-4}$	$2.81 \cdot 10^{-4}$	$1.67 \cdot 10^{-4}$
$t\bar{t}$	$7.17 \cdot 10^{-5}$	$6.56 \cdot 10^{-5}$	$5.79 \cdot 10^{-5}$	$4.72 \cdot 10^{-5}$
$pp \to \gamma^*/Z \to \tau\tau$	$5.78 \cdot 10^{-6}$	$5.93 \cdot 10^{-6}$	$5.49 \cdot 10^{-6}$	$5.22 \cdot 10^{-6}$

Background/signal ratios f_i in $85.6\ \text{GeV}/c^2 \leq M \leq 97.2\ \text{GeV}/c^2$.

Muon Track Distance

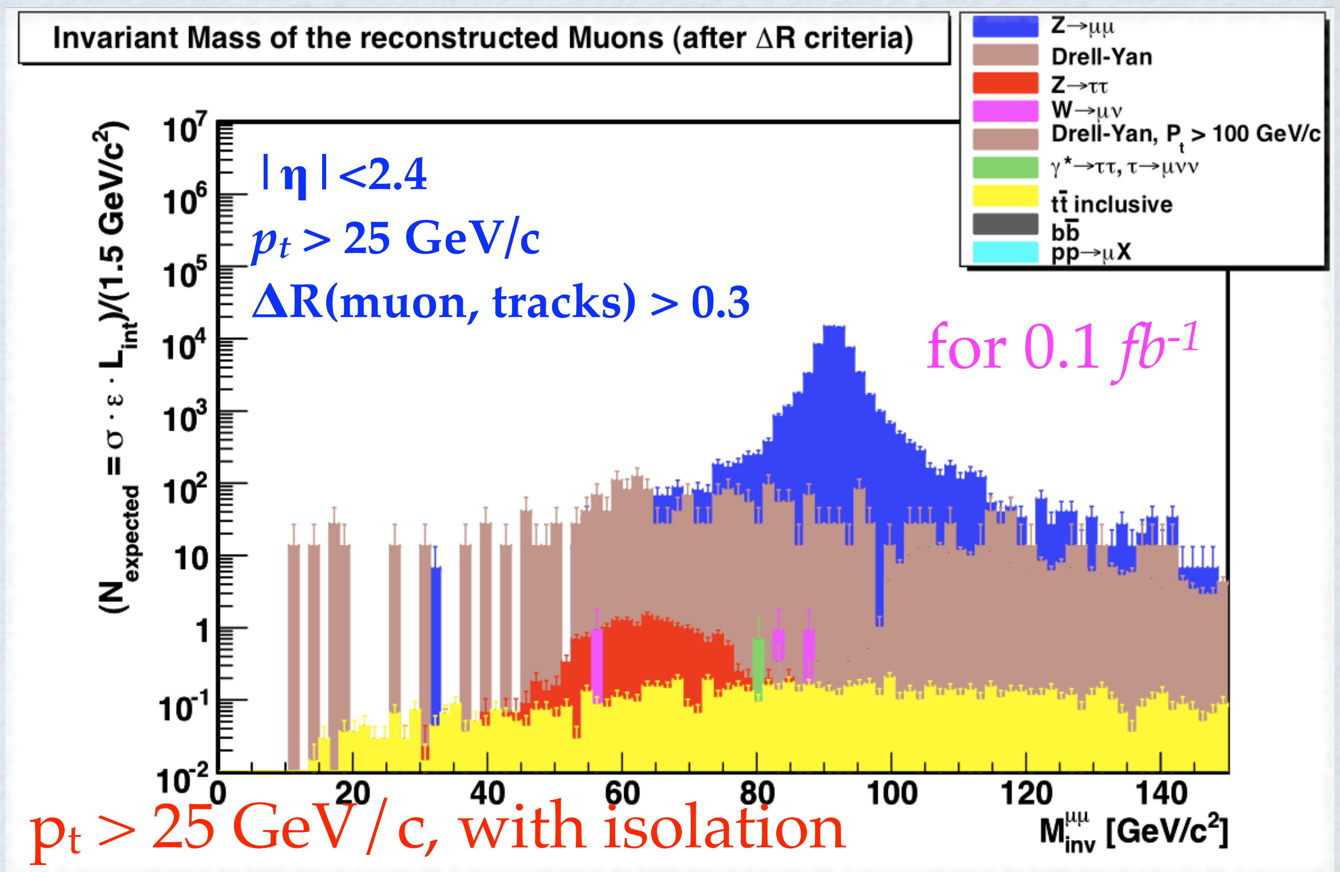
- Background can be reduced by requiring isolated muons.

- Consider a muon isolated if no tracks are present in a cone $\Delta R < 0.3$ around the muon.

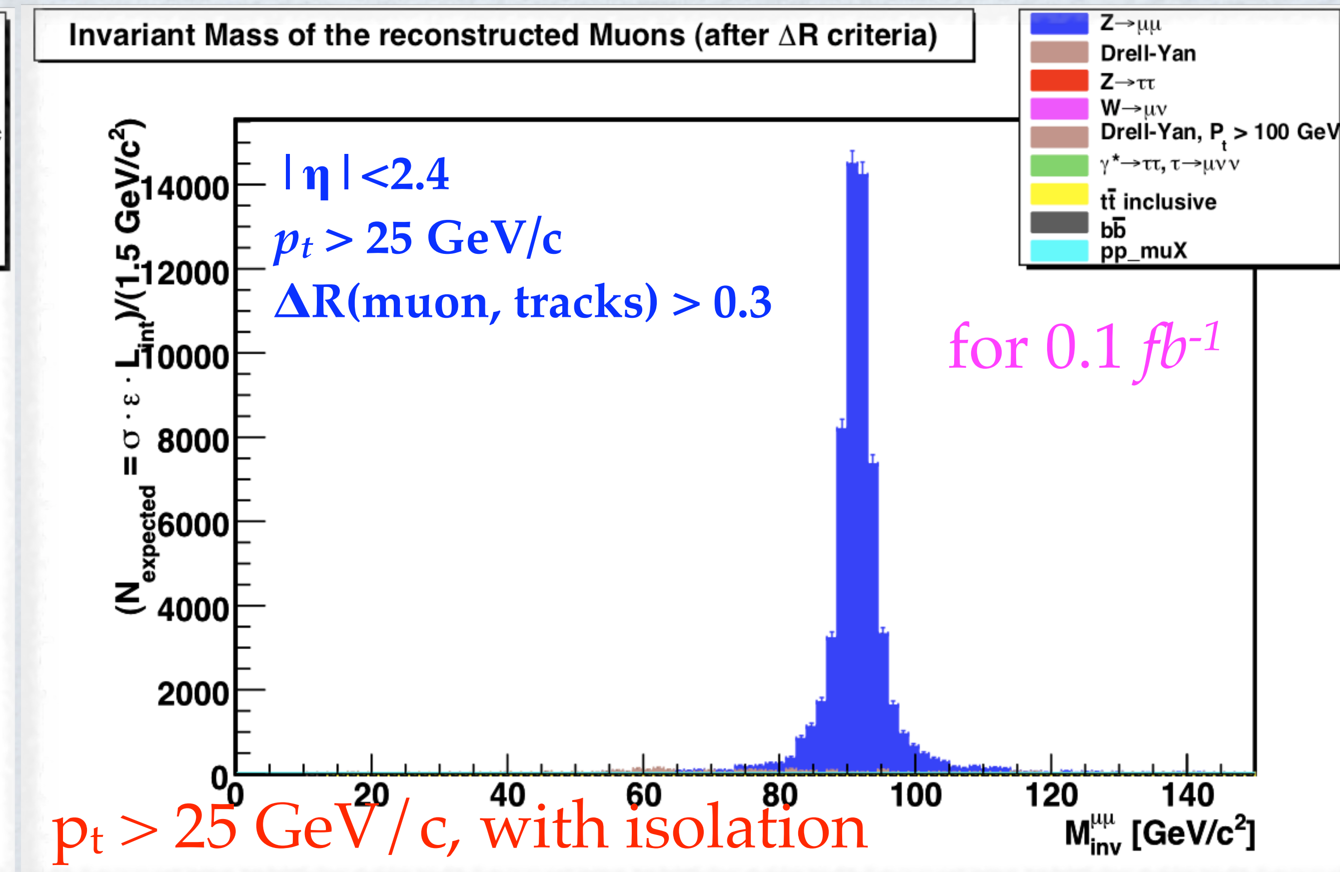


$$\Delta R\,(\text{muon},\text{track}) = \sqrt{(\eta_{\text{muon}} - \eta_{\text{track}})^2 + (\varphi_{\text{muon}} - \varphi_{\text{track}})^2}$$

Signal & Background



$p_t > 25$ GeV/c, with isolation



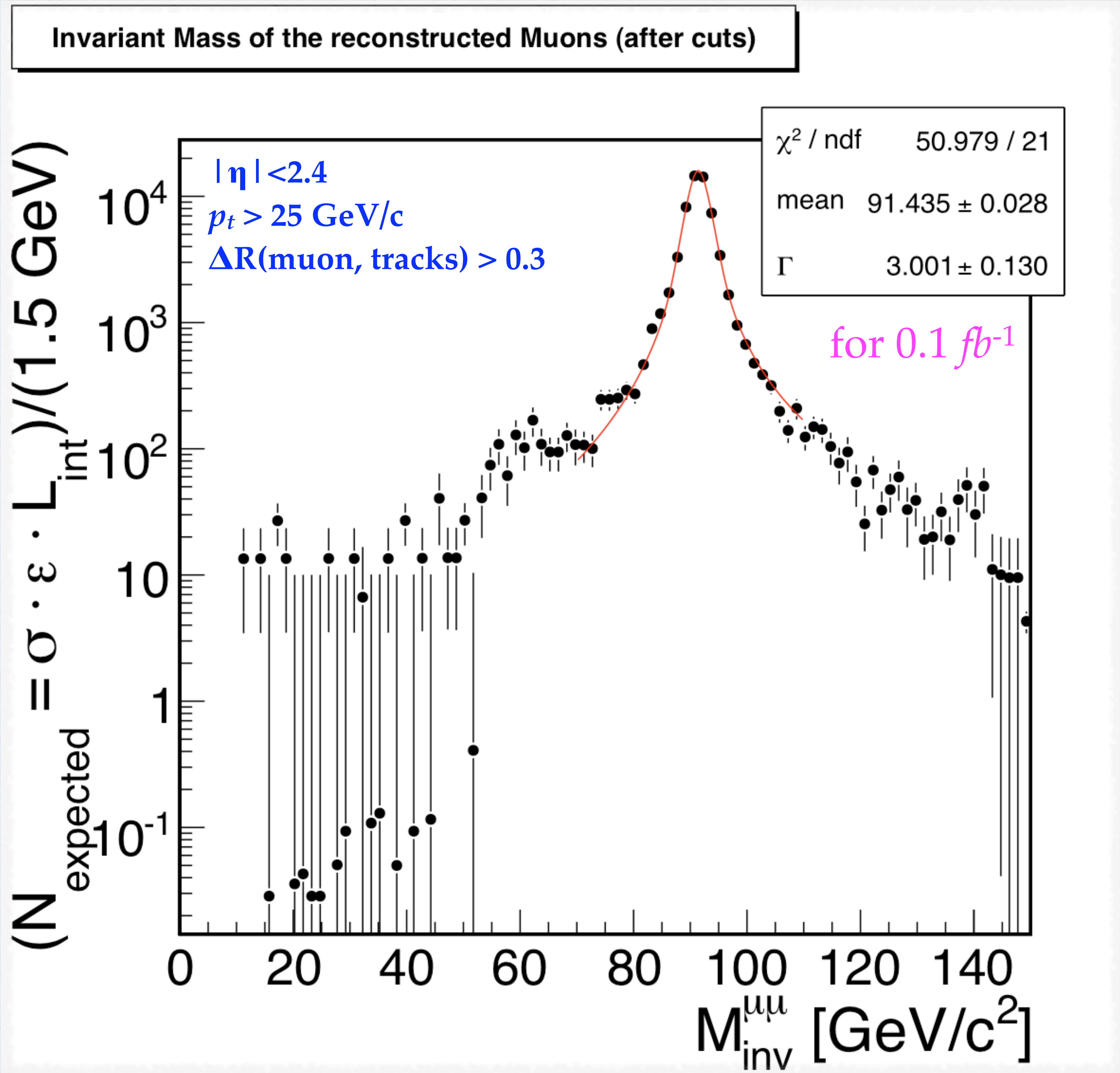
$p_t > 25$ GeV/c, with isolation

Background / signal ratios f_i in
85.6 GeV / c² ≤ M ≤ 97.2 GeV / c²:

Background	$p_t > 10$ GeV/c	$p_t > 15$ GeV/c	$p_t > 20$ GeV/c	$p_t > 25$ GeV/c
pp→μ+X	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$
$b\bar{b}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$
W→μν	$4.29 \cdot 10^{-5}$	$2.93 \cdot 10^{-5}$	$1.54 \cdot 10^{-5}$	$1.65 \cdot 10^{-5}$
$t\bar{t}$	$2.58 \cdot 10^{-5}$	$2.54 \cdot 10^{-5}$	$2.32 \cdot 10^{-5}$	$2.11 \cdot 10^{-5}$
pp→ γ^* / Z→ττ	$4.56 \cdot 10^{-6}$	$4.67 \cdot 10^{-6}$	$3.76 \cdot 10^{-6}$	$4.05 \cdot 10^{-6}$

Summary: the number of **μμ** pairs from other sources than **Z** or γ^* is rather small!!

Inclusive di μ mass



Systematics

Systematic uncertainties due to:

- PDFs
- Muon and Tracker alignment
- Trigger
- Magnetic field
- ...

Systematic error

- Contributions to the total systematic uncertainty from:
  - Alignment: $\sigma^{alignment} = 2.9\ \%$
  - PDF: $\sigma^{PDF} = 3.8\ \%$ (cross section), 1.9% (acceptance)
  - Trigger: $\sigma^{HLT} = 0.8\ \%$
  - B field: $\sigma^{B\ field} = 0.5\ \%$ (CMS AN-2007/031)
- Total systematic uncertainty:

$$\sigma^{sys} = \sigma^{alignment} \oplus \sigma^{PDF} \oplus \sigma^{HLT} \oplus \sigma^{B\ field} \approx 5\ \%\ (4\ \%)$$

- Finally we obtain a systematic uncertainty $\sigma^{sys} \approx 5\ \%$ for luminosity and $\sigma^{sys} \approx 4\ \%$ for cross section measurement.

Final Results

- **Final results**: production cross section **or** luminosity:

  - Cross section (with $\varepsilon = (31.19 \pm 0.56)\%$ and assuming $L = (0.10 \pm 0.01)\ fb^{-1}$):

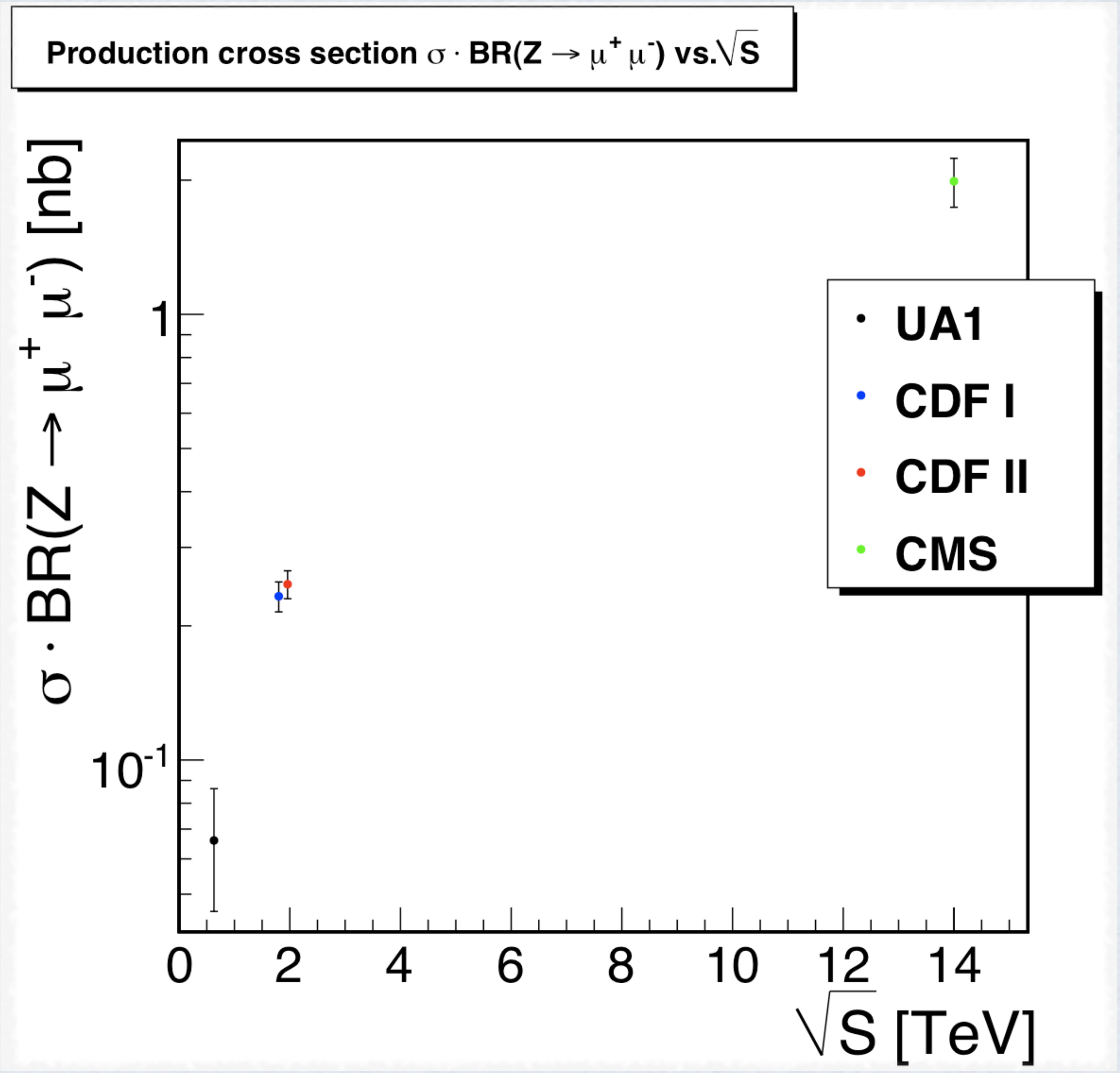
    $\sigma_{pp \to \gamma^*/Z0 \to \mu\mu} = (1.989 \pm 0.114^{stat} \pm 0.071^{sys} \pm 0.199^{lumi})$ nb.

  - Luminosity (with $\sigma_{NNLO} = (1.964 \pm 0.020)\ nb$):

    $L = (0.100 \pm 0.006^{stat} \pm 0.005^{sys})\ fb^{-1}$.

Final Results

- Compare cross section measurement with other *pp* and *p$\bar{p}$* experiments:



UA1: Albajar et al, Phys. Lett. B198 (1987)
CDF I: Abe et al, Phys. Rev. D 59(5) (Jan 1999)
CDF II: Acosta et al, Phys. Rev. Lett. 94 (2005)

$$\sigma_{pp\to\gamma^*/Z0\to\mu\mu} = (1.989 \pm 0.114^{stat} \pm 0.071^{sys} \pm 0.199^{lumi})\text{ nb.}$$

Summary

- Z production in high energy pp collisions has a clean signature through e.g. $Z \to \mu\mu$.
- The background is very low.
- Potential luminosity monitor: the most important ingredient is the accuracy to which the cross section for Z production can be theoretically calculated. We find in this analysis that the accuracy of the luminosity measurement $\approx 7\%$.
- Cross section: if we determine the cross section the main uncertainty stems from the error of the luminosity, at least at the beginning of data taking.