Point-to-point uncertainty on sqrt(s) with dimuons and momentum scale stability

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FCC-ee Physics Performance Meeting
14 Dec 2020

Motivation

- EW observables at the Tera-Z at FCC-ee will be measured with statistical precision down to several orders of magnitude
  - **Z total decay width** can be measured in an energy scan ($\sqrt{s}$ = 87.9, 91.2, 93.8 GeV) with **4 keV statistical precision**

- Need to bring down the systematic uncertainties as close as possible to the statistical precision
  - From LEP: a limiting systematic factor is the **uncorrelated point-to-point uncertainty** on $\sqrt{s}$ of the 3 energy scan points
  - At FCC-ee: this factor can be possibly **controlled in-situ with invariant mass distribution of dimuon samples**
    - Preliminary studies with a parameterization of the CLD detector show that a precision of **40 keV** can be reached, splitting the dataset in independent samples and looking at the dimuon peak position in these subsamples https://arxiv.org/pdf/1909.12245v1.pdf
      - **First goal of this study: estimate this precision with fast simulation and reconstruction**
  - Important ingredient for this precision to hold is the **stability of the mass scale**, e.g. from one fill to the next (especially the magnetic field) *
    - "a control of $\sqrt{s}$ to 40 keV precision with the dimuon peak demands a control of the scale at the level of 40 keV / 91 GeV = **sub 10^{-6}**. Monitoring the detector field at this level may be challenging with NMR probes.
    - **Second goal of this study: estimate the level of stability in-situ with low-mass resonances, i.e. J/ψ and D0**

* Another important ingredient is the very good control of ISR required, as it shifts the peak position depending on $\sqrt{s}$.
[To be calculated, but out of today's talk topic]

Dimuon samples

Analysis steps

- Analysis chain performed with custom-made FCCSW samples and using FCCAnalysis framework for analysis and plotting

- Pythia samples at $\sqrt{s}$ = 87.9, 91.2, 93.8 GeV, **with 0.132% BES**, and ISR+FSR on
- Delphes cards: IDEAtrkCov and CLDtrkCov (= IDEAtrkCov, except for the tracking from CLD)
- Produced 1e6 events at each energy point and for each detector card (statistics validated below)

- Muons selected with p_T > 10 GeV, isolation > 0.4, polar angle > 20°
  - modified `selectParticlePtIso` to include the cut in angle
- Used `ResonanceBuilder` to create dimuon combinations and select them based on the closest mass to the Z mass

$Z \to \mu\mu$ sample normalization

91.2 GeV: 100ab-1

- from Pythia: σ(ff) = 46 nb => x L_int x BR($Z \to \mu\mu$) = 1.38e11 events
  - but: possibly some QED-correction already included
- from Tab. 21 [1]: σ($\mu\mu$) = 1.5 nb => x L_int = 1.5e11 events
  - 1e6 events produced => **scaling factor** = 1.5e11/1e6 **= 1.5e5**

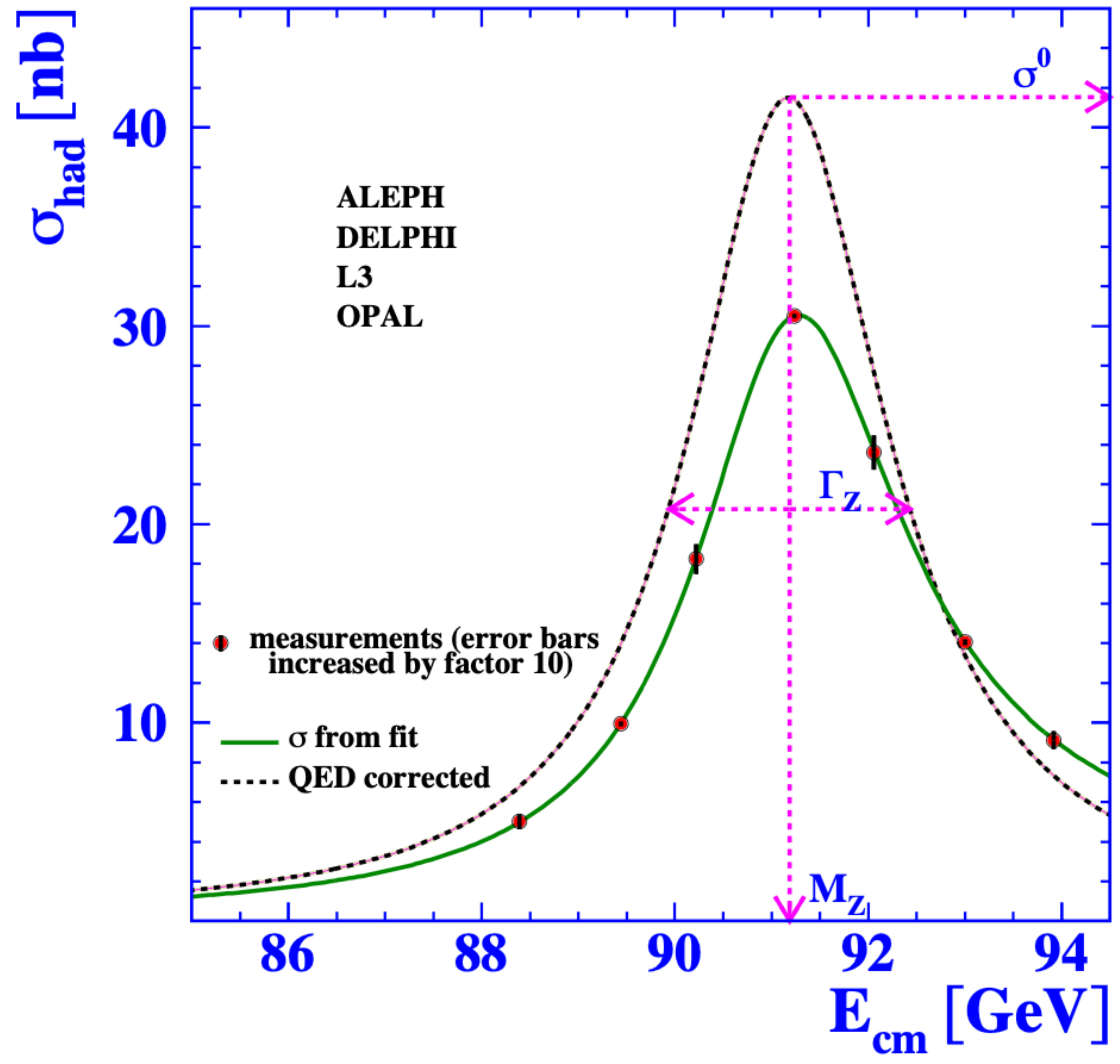
87.9 GeV: 25ab-1

- from Pythia: σ(ff) = 9.6 nb => x L_int x BR($Z \to \mu\mu$) = 7.2e9 events
- from Tab. 21[1] _at 88.2_: σ($\mu\mu$) = 0.24 nb => x L_int = 6e9 events
  - 1e6 events produced => **scaling factor** = 6e9/1e6 **= 6e3**

93.8 GeV: 25ab-1

- from Pythia: σ(ff) = 15 nb => x L_int x BR($Z \to \mu\mu$) = 1.1e10 events
- from Tab. 21 [1] _at 93.7_: σ($\mu\mu$) = 0.5 nb => x L_int = 1.25e10 events
  - 1e6 events produced => **scaling factor** = 1.25e10/1e6 **= 1.25e4**

https://arxiv.org/pdf/hep-ex/0509008.pdf

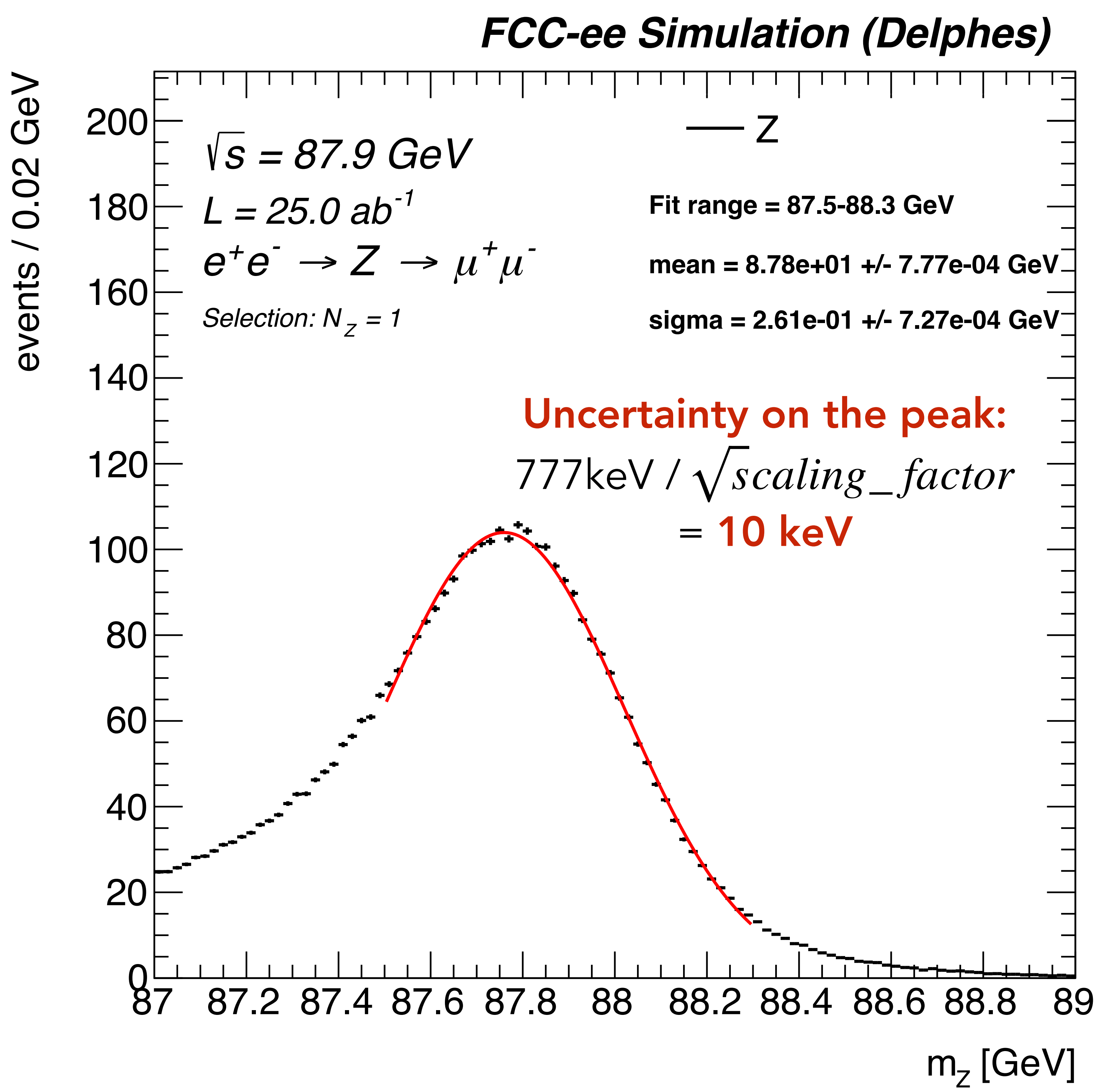


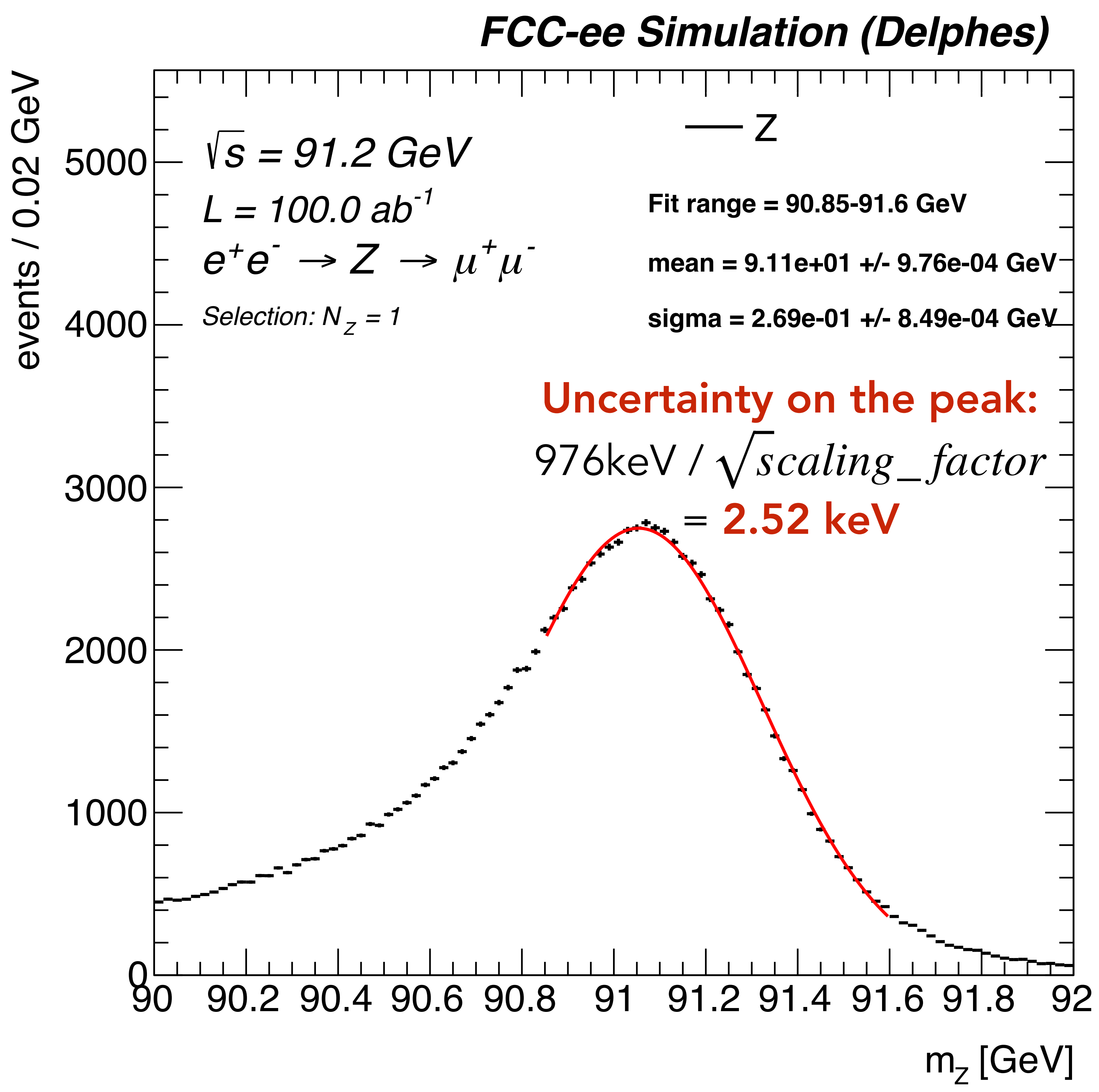
[1] Eur Phys J C 14 (2000) 1

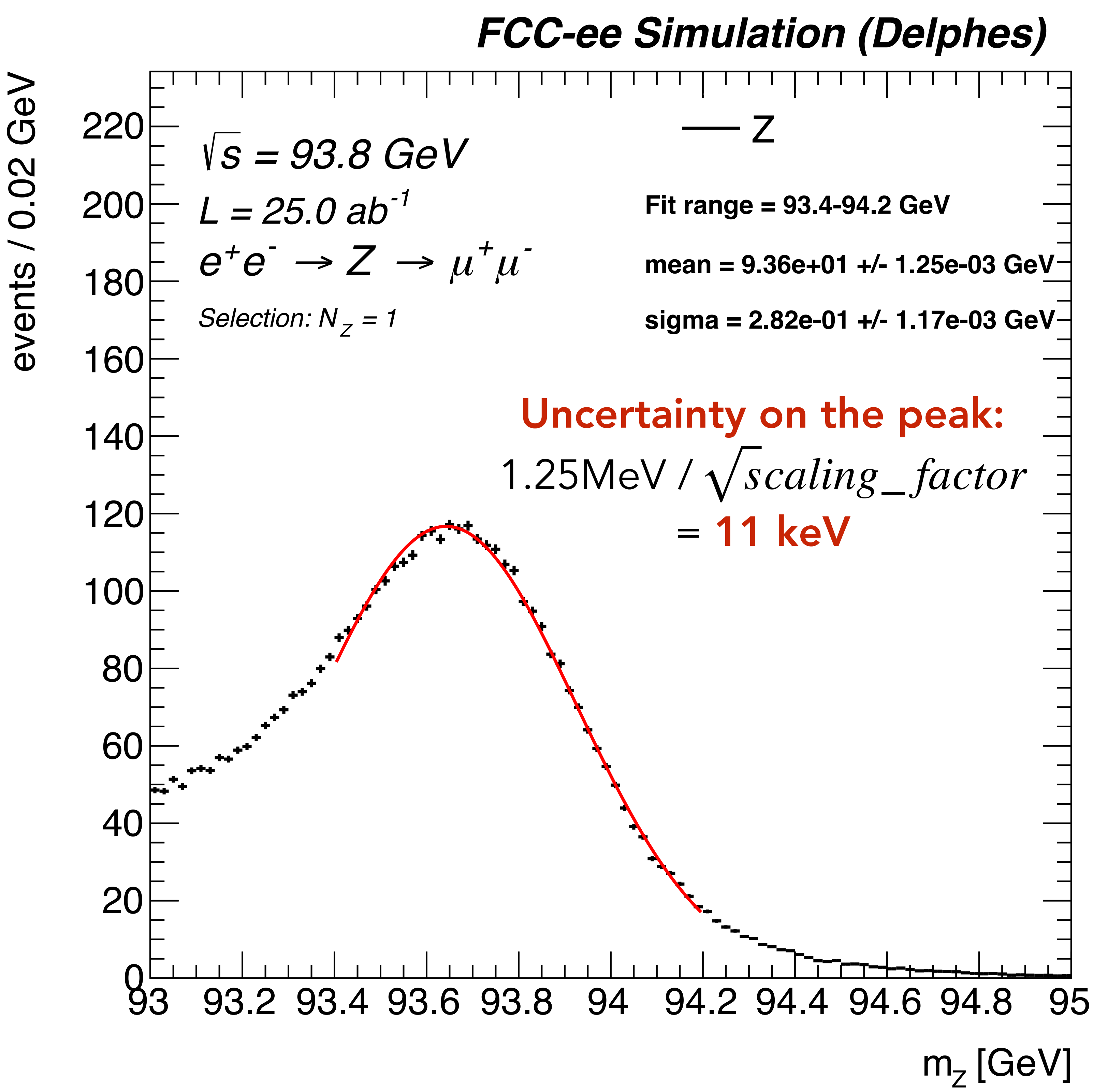
Fit of the dimuon invariant mass around peak at $\sqrt{s}_-$, $\sqrt{s}$, $\sqrt{s}_+$

CLD

✦ Gaussian fit values correspond to the luminosity of the Monte Carlo samples. Distributions are normalized as from slide #5.







✦ Distributions agree with the reference paper (width ~ 280 MeV) https://arxiv.org/pdf/1909.12245v1.pdf

✦ Fit range was varied to assess fit stability

87.9 GeV	Fit range	mean err
	87.4-88.3	7.6E-04
	87.5-88.3	7.8E-04
	87.6-88.3	1.2E-03

91.2 GeV	Fit range	mean err
	90.8-91.6	8.2E-04
	90.85-91.6	9.8E-04
	90.9-91.6	1.3E-03

93.8 GeV	Fit range	mean err
	93.3-94.2	9E-04
	93.4-94.2	1.3E-03
	93.5-94.2	2E-03

✦ Fit with Crystal Ball for $\sqrt{s}$ = 91.2 GeV in backup

Fit of the dimuon invariant mass around peak at $\sqrt{s}_-$, $\sqrt{s}$, $\sqrt{s}_+$

IDEA

- ✦ Gaussian fit values correspond to the luminosity of the Monte Carlo samples. Distributions are normalized as from slide #5.

- ✦ At the Z peak, the width of the distribution ~ x2 smaller than for CLD
- ✦ Fit range was varied to assess fit stability

87.9 GeV	Fit range	mean err	91.2 GeV	Fit range	mean err	93.8 GeV	Fit range	mean err
	87.6-88.1	3.3E-04		90.8-91.5	3E-04		93.5-94	5E-04
	87.7-88.1	5.4E-04		90.9-91.5	3.6E-04		93.6-94	9.2E-04
	87.8-88.1	1.8E-03		91-91.5	6E-04		93.7-94	3E-03

Summary (1/2)

- We have studied how to control the point-to-point uncertainty on $\sqrt{s}$ on the 3 energy scan points at the FCC-ee Tera-Z **in-situ with invariant mass distribution of dimuon samples**
- These studies reproduce the distributions shown in the reference paper https://arxiv.org/pdf/1909.12245v1.pdf
- The fit results differ from the reference paper, where a **~40 keV** precision was obtained with 100 subsamples
  - at $\sqrt{s}$ = 87.9, 91.2, 93.8 GeV we observe the following uncertainties on the peak positions:
    - 10, 2.5, 11 keV with CLD
    - 7, 0.9, 8 keV with IDEA
  - by splitting the full statistics in 100 subsamples (e.g. in time, one per fill), we get:
    - **~ 100 keV with CLD**
    - **~ 70 keV with IDEA**
- After discussion with Patrick, we foresee to refine our fitting strategy, e.g. by using the constrained kinematics to reconstruct the energy of the ISR photons, and thus correct the raw dimuon mass with the result of a much more Gaussian distribution

Momentum scale stability

Two low-mass resonances exploited:

✦ **J/ψ**: at FCC-ee #($Z \to J/\psi + X, J/\psi \to \mu\mu$) / #($Z \to \mu\mu$) = 1 / 150, but $J/\psi \to \mu\mu$ peak reconstructed with very good resolution

=> set strong constraints on scale stability

✦ **D0**: BR($Z \to D0\bar{D}0 + X$) = 20%, BR($D0 \to K\pi$) = 4%

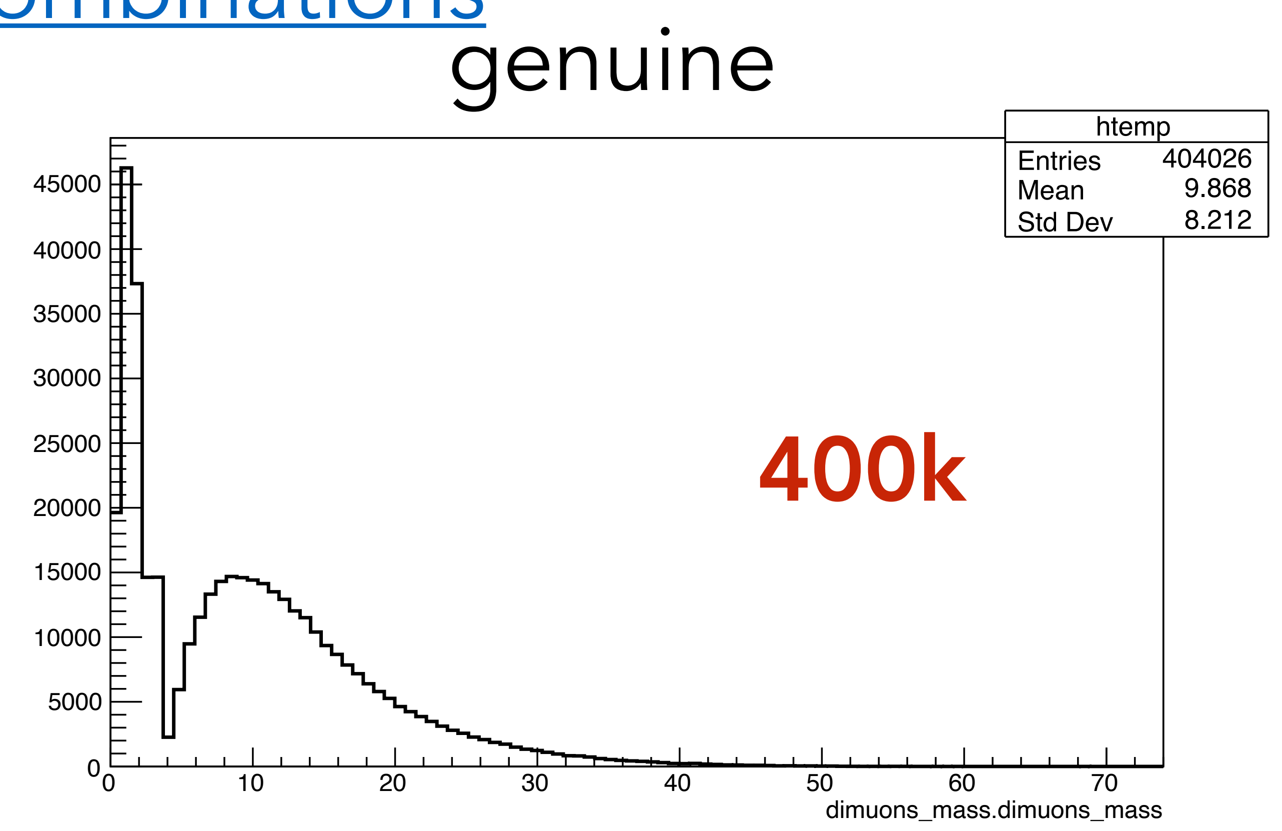
=> O(40x) more Kπ pairs from D0/D0bar than dimuon pairs from J/ψ

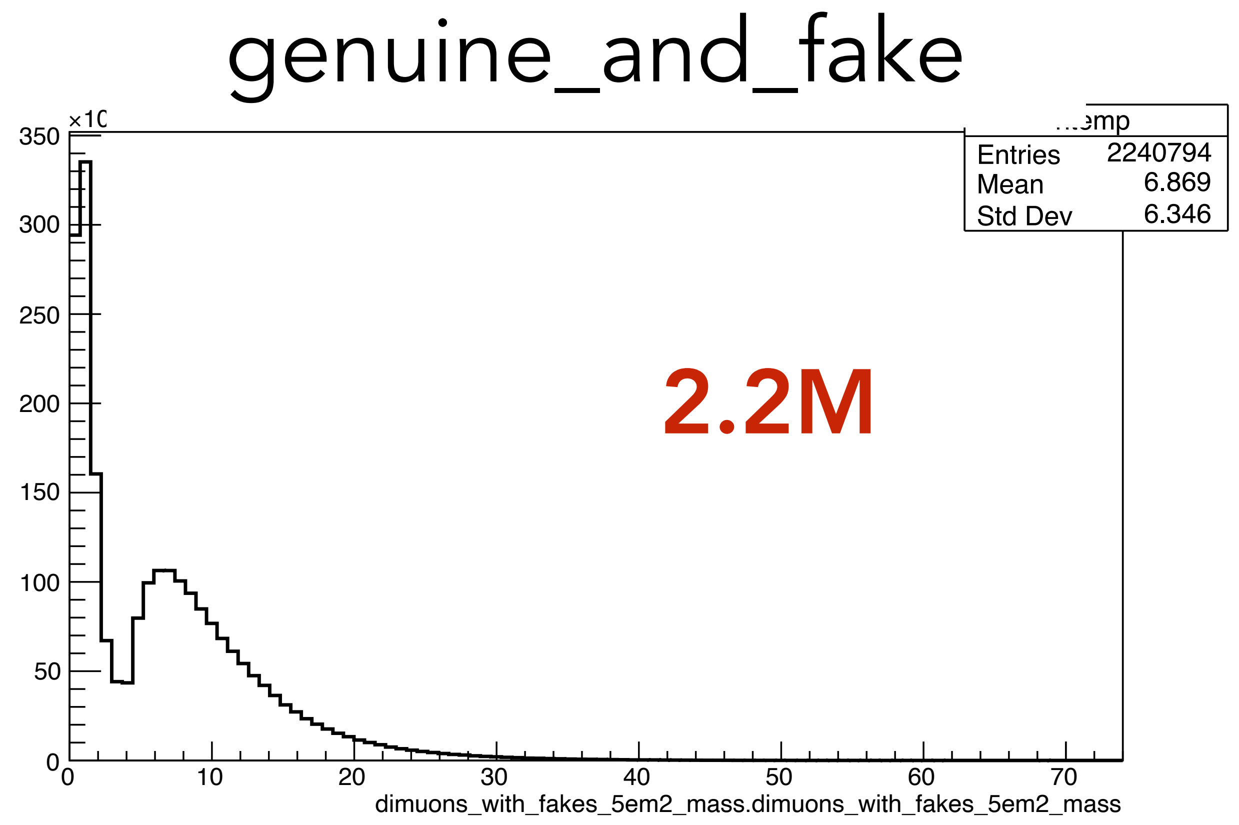
J/ψ : Analysis steps

- Centrally-produced EDM4hep samples in /eos
- FCCAnalysis framework for analysis
  - some simple custom functions developed within FCCAnalysis, some could be included in the common code
- Pythia samples of $Z \to bb, \to cc, \to uds$ at $\sqrt{s}$ = 91.2, no BES, and ISR+FSR on
- Delphes cards: IDEAtrkCov
- Processed O(1e7) events for each decay

- NB: ‘Muons’ objects from EDM4hep not used, as they only contain isolated muons
- ‘Genuine’ muons selected from the RecoParticles associated with a MonteCarlo muon with E > 2 GeV
- Genuine+Fake: reconstructed tracks not associated to a MonteCarlo muon or electron, assigned to muons with random probability (5%), added to genuine sample

- Saved all dimuon combinations





- 1e7 $Z \to bb$ events, $b \to \mu$ O(20%) => 0.4 genuine muons per event
- In $Z \to bb$ O(13) tracks x 5% fake rate = 0.6 additional fake muons
- x 2.5 more muons
- => 2.5**2 more combinations

$Z \to hadrons$ normalization

Z->bb

- Cross section from pythia: 6645.46 pb
- Number of events processed: 1.01e7
- Luminosity: 1519 pb-1

Z->cc

- Cross section from pythia: 5215.46 pb
- Number of events processed: 1.01e7
- Luminosity: 3662 pb-1

=> to scale to Z->bb luminosity, reweigh by 1519/3662 = 0.42

Z->uds

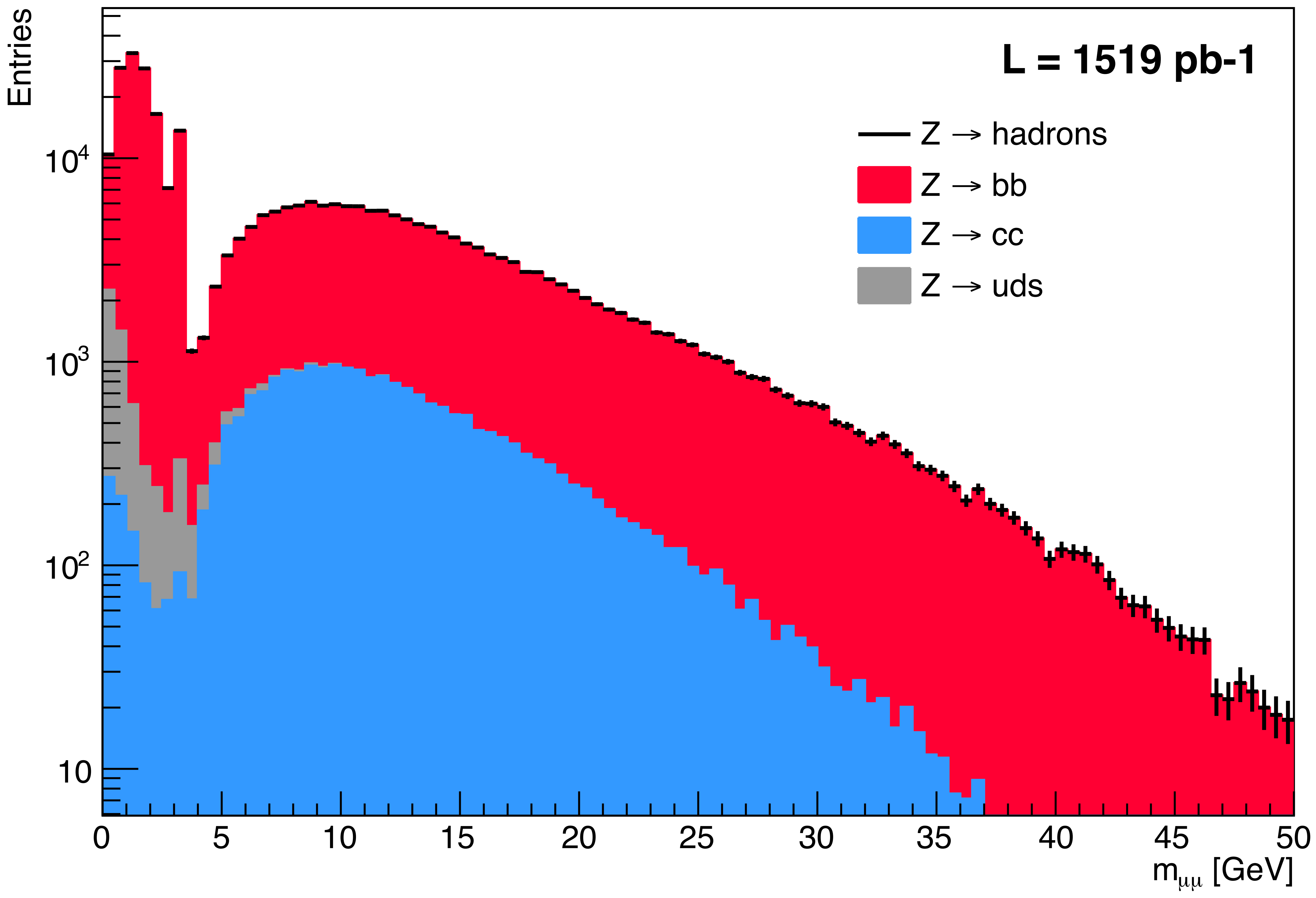
- Cross section from pythia: 18616.5 pb
- Number of events processed: 1.03e7
- Luminosity: 553 pb-1

=> to scale to Z->bb luminosity, reweigh by 1519/553 = 2.75

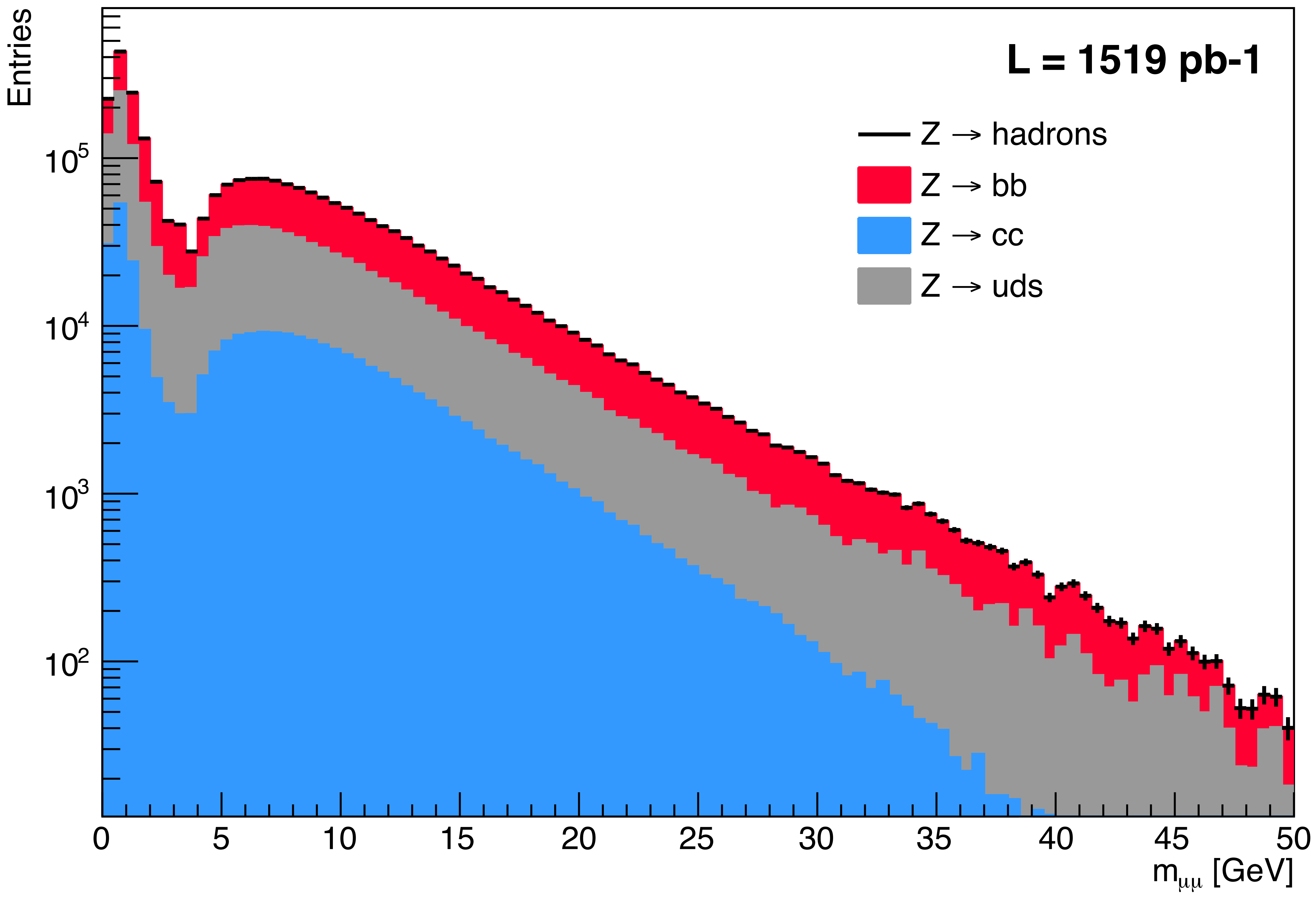
Dimuon invariant mass in hadronic Z decays

✦ Selected muons of opposite charge.

no fakes



+ 5% fakes



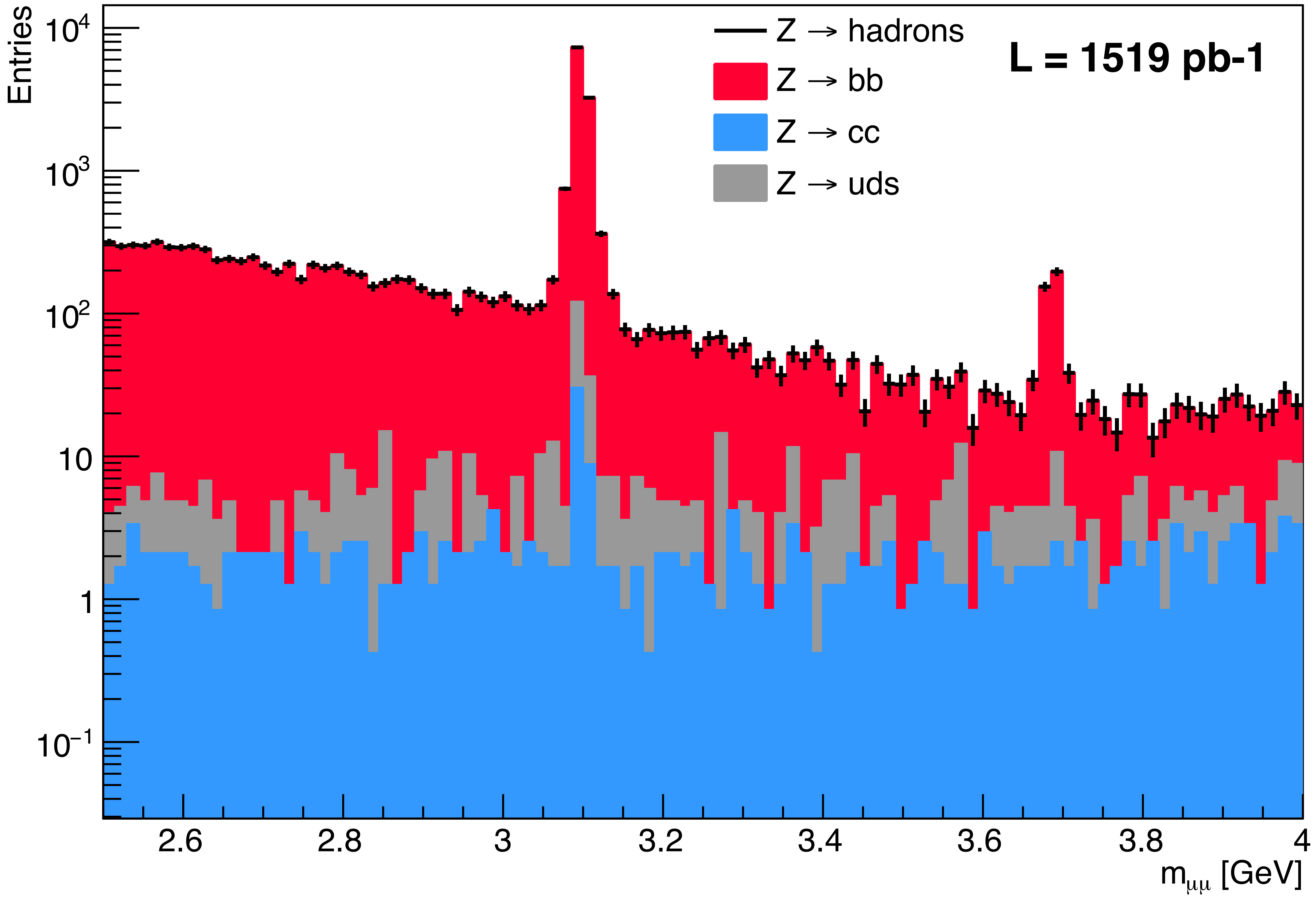
✦ With no fakes, dimuon events are largely dominated by $Z \to bb$

✦ With fakes, not negligible contributions from other samples

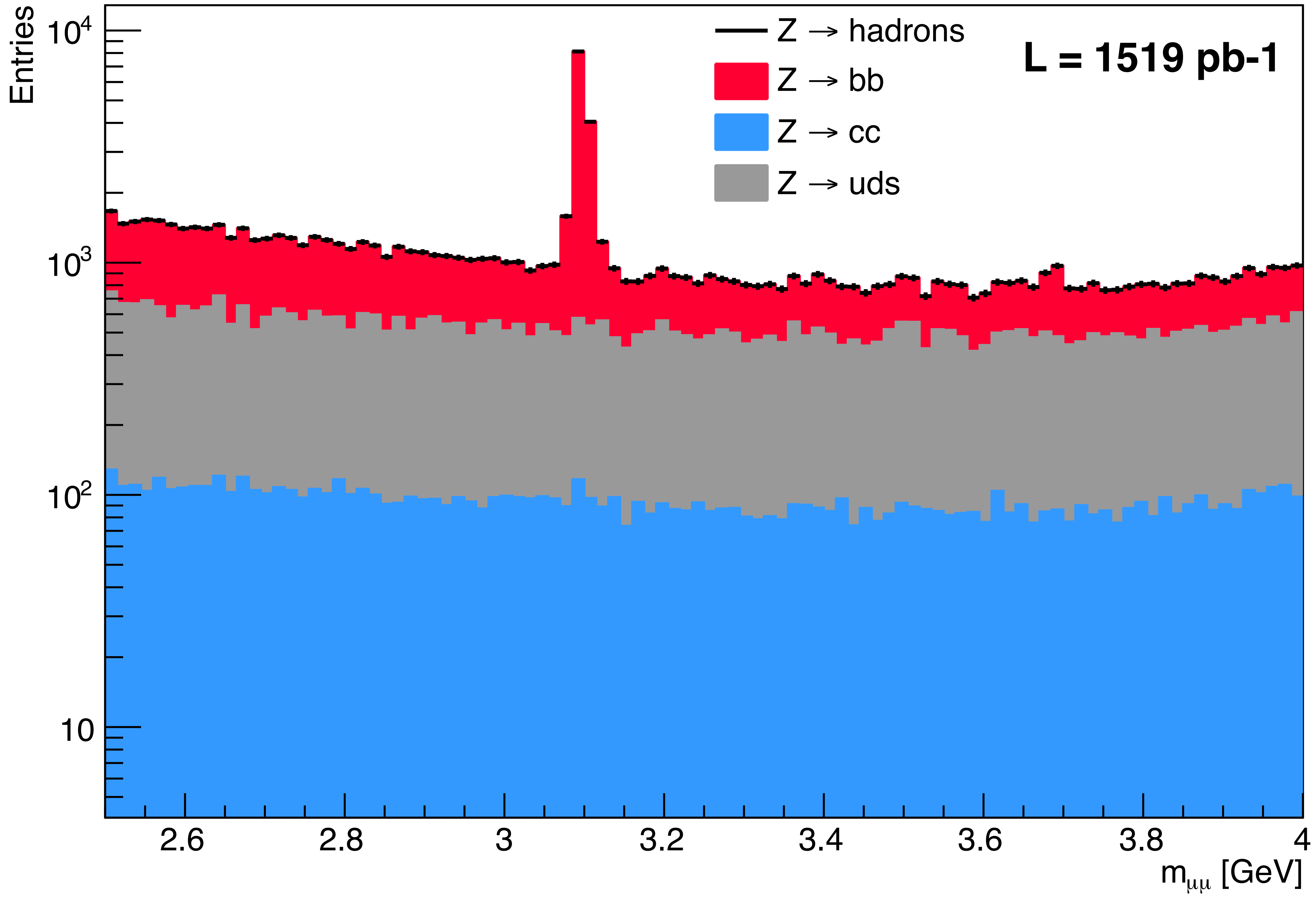
Dimuon invariant mass in hadronic Z decays around J/ψ

- Selected muons of opposite charge.
  - in 100k $Z \to bb$ events, expected O(2400) J/ψ, hence 150 $J/\psi \to \mu\mu$

no fakes



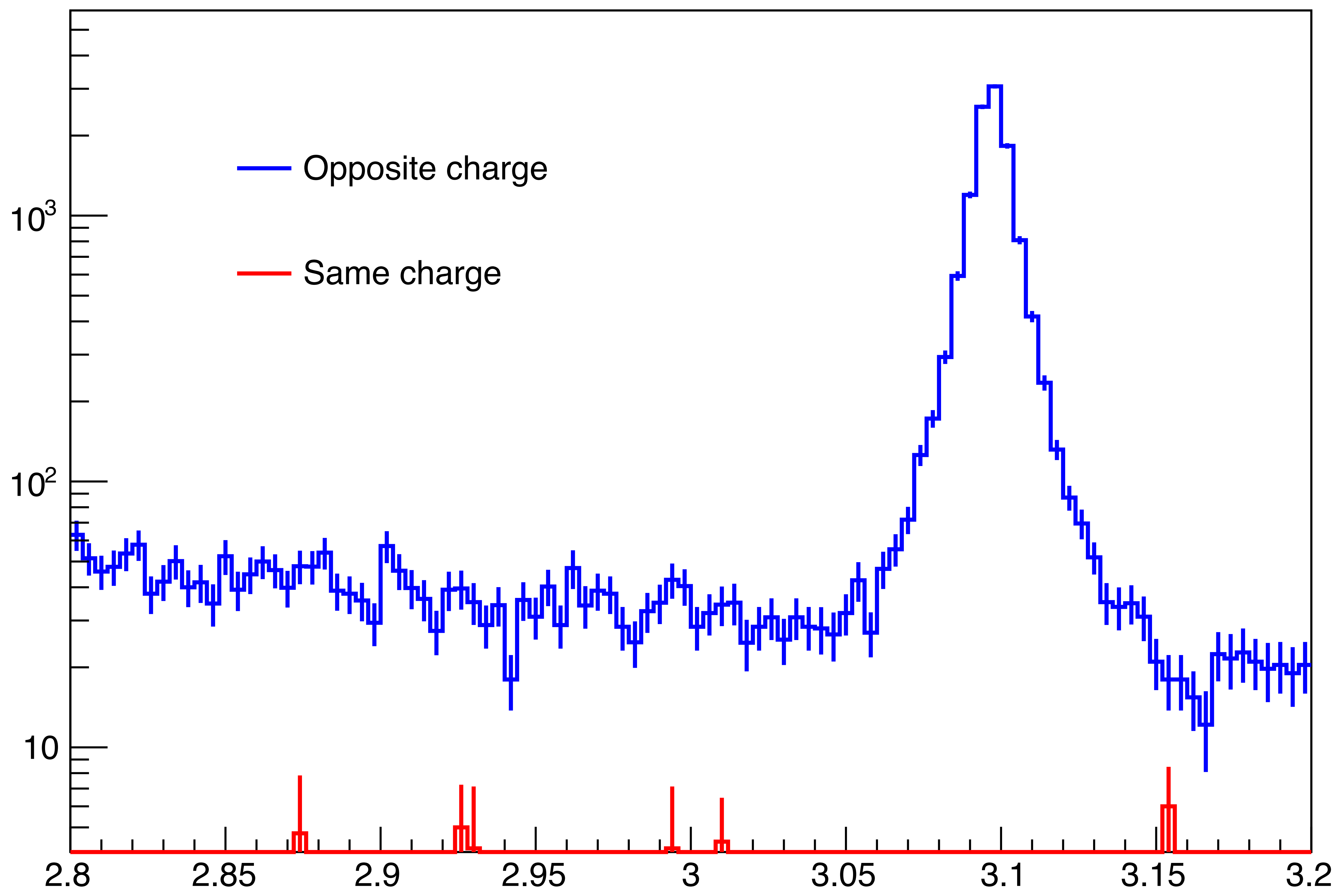
+ 5% fakes



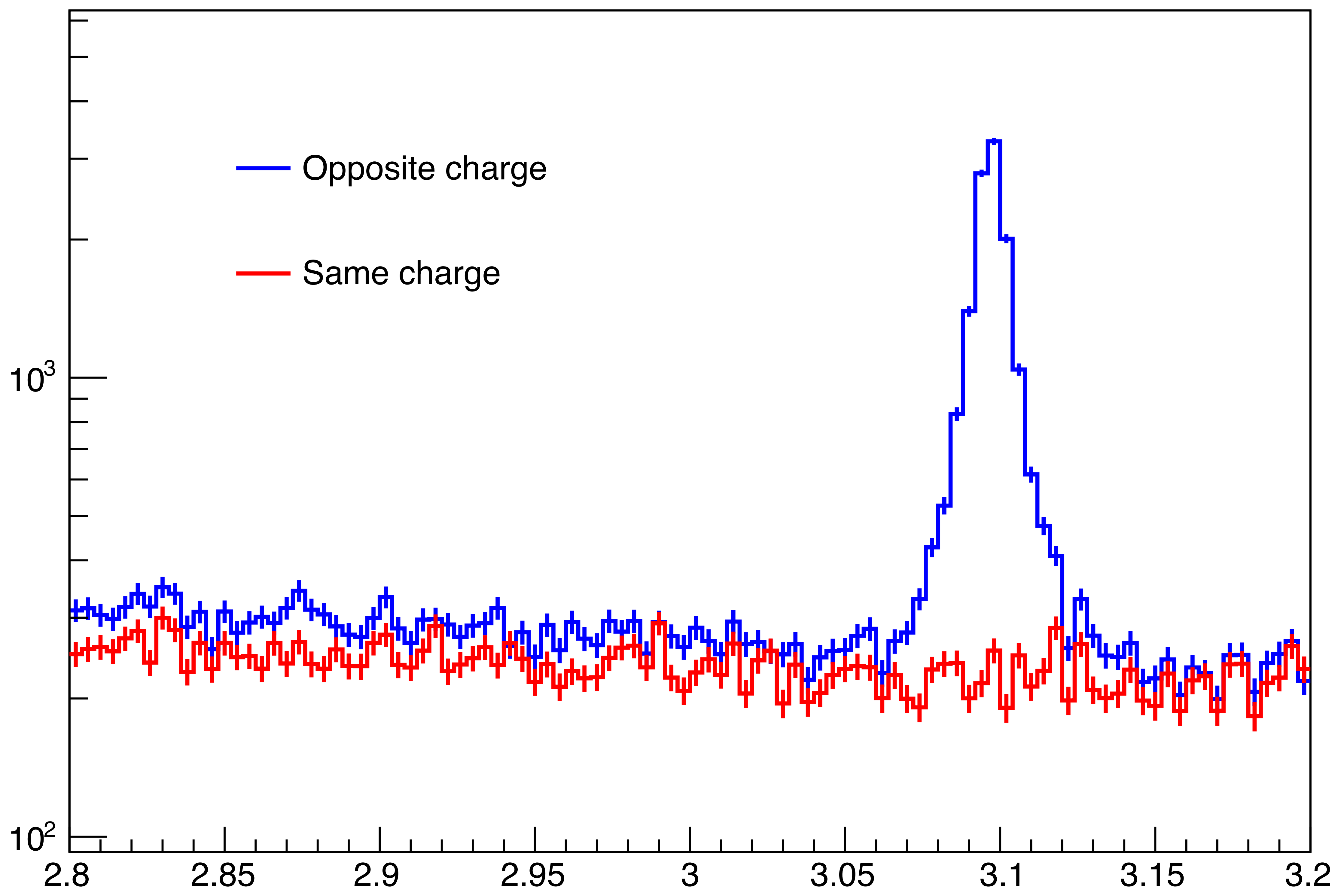
- With no fakes, J/ψ and ψ2S visible
- With fakes, ψ2S peak disappears, but J/ψ still visible

Dimuon invariant mass in hadronic Z decays around J/ψ

no fakes



+ 5% fakes

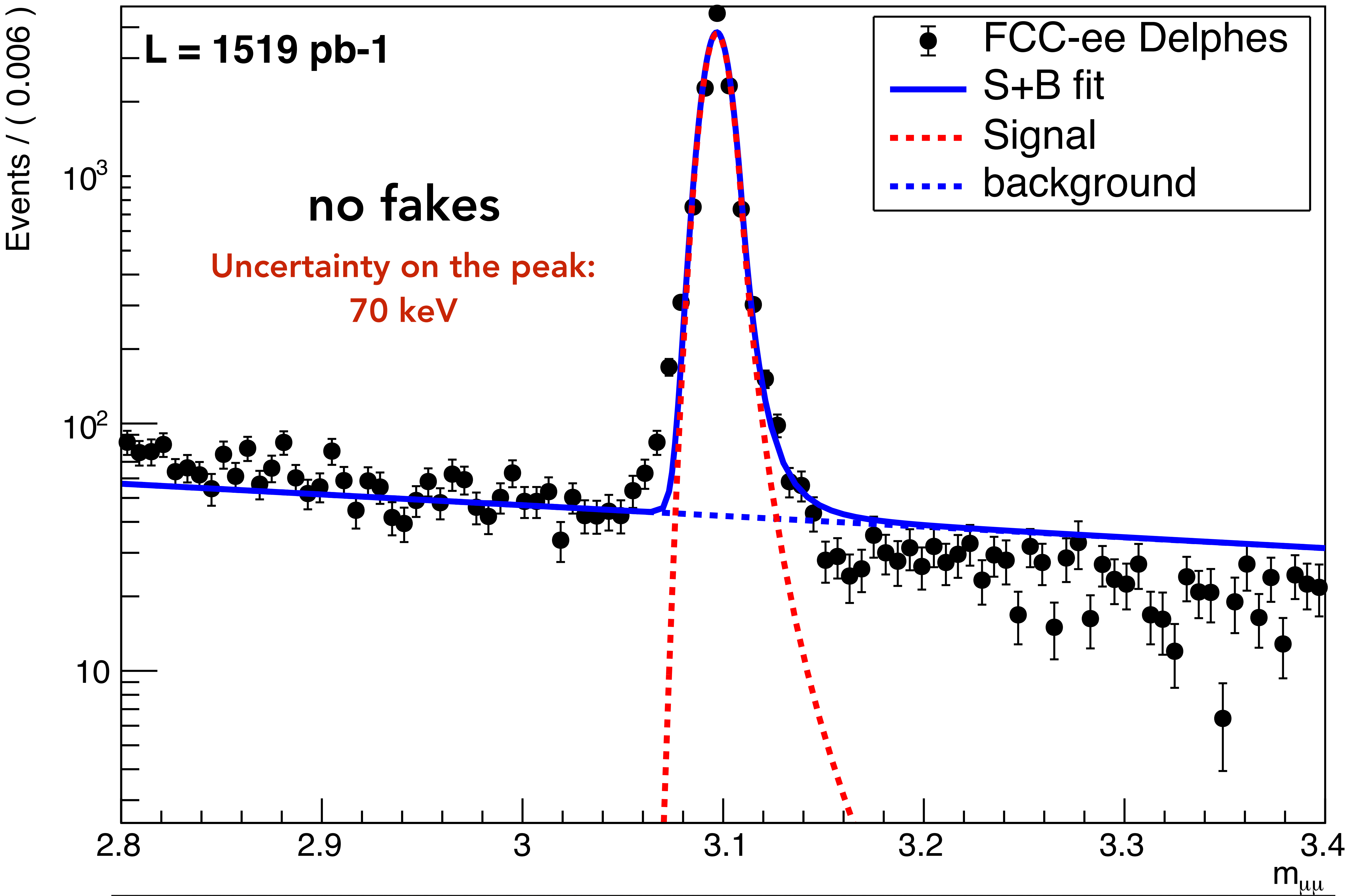


Combinations of opposite-charge muons and of same-charge muons shown separately

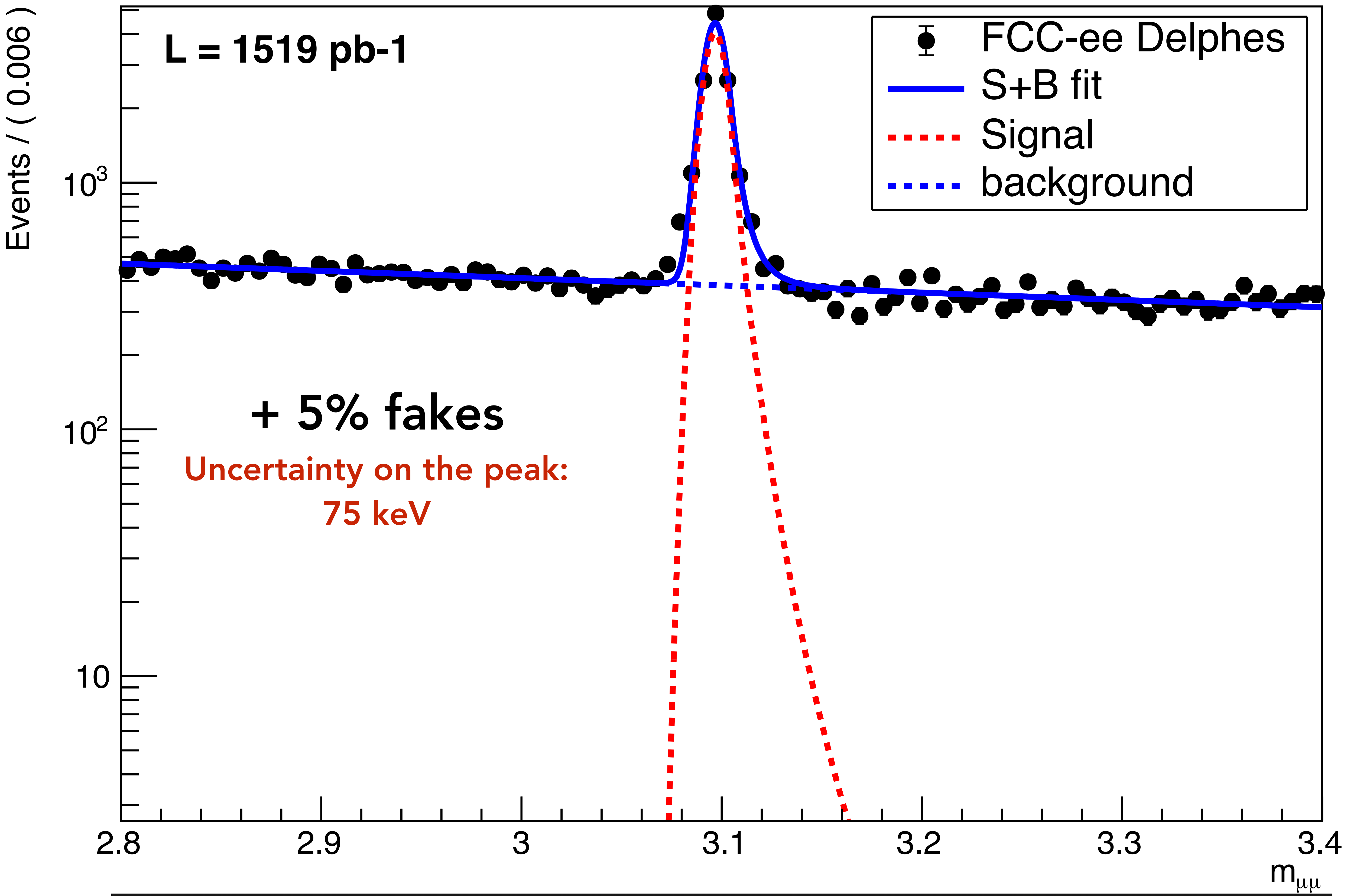
- ✦ Very few same-charge combinations from genuine muons only
- ✦ When fakes are added, the same-charge combinations are not good enough to predict the background under the peak, but they could be used to predict the background shape

Fit of dimuon invariant mass in hadronic Z decays around J/ψ

- Fit with a Crystal Ball on top of an exponential background



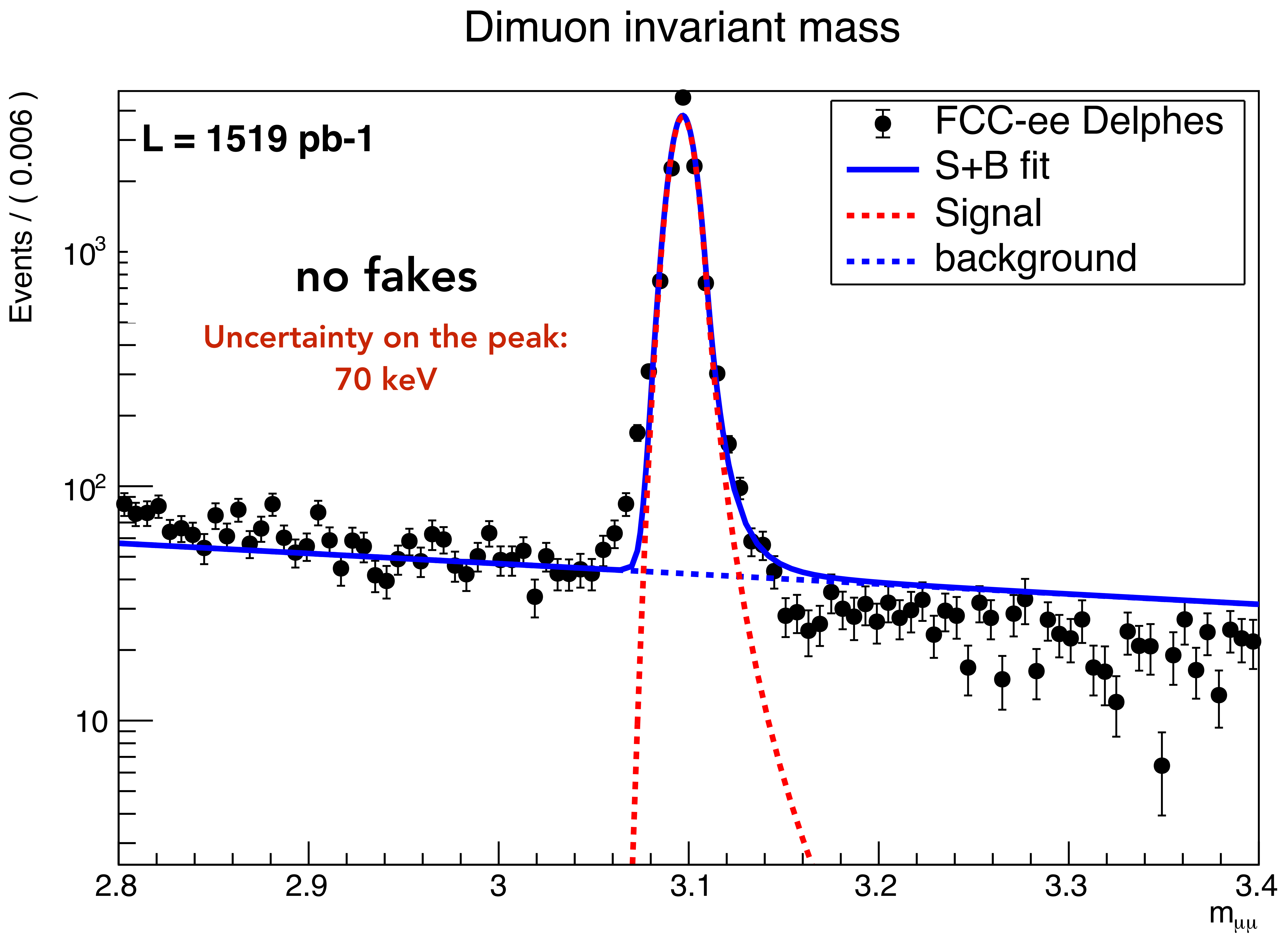

```
alpha      = -1.80698     +/-   0.0447431 (limited)
cbmean     = 3.09686      +/-   7.13595e-05         (limited)
cbsigma    = 0.0069056    +/-   6.2759e-05          (limited)
```




```
alpha      = -1.33186     +/-   0.0405004 (limited)
cbmean     = 3.09674      +/-   7.53424e-05         (limited)
cbsigma    = 0.00606396   +/-   7.72734e-05         (limited)
```

- Error on the fitted peak position varies only slightly with the addition of fakes
- Different fits were tried, with similar results on the peak uncertainty (see backup)

Calculation of the scale stability



At 91.2 GeV

- sample luminosity = 1519 pb-1
- 70 keV / $\sqrt{(100ab^{-1}/1519pb^{-1})}$ = 0.27 keV
- 0.27 keV / $m_{J/\psi}$ = 9e-8
- dividing in 100 subsamples: 9e-8 x sqrt(100) = 9e-7
  - e.g. one subsample = one fill, to check potential time variation of the scale at this granularity

Off peak

- 4x less luminosity
- 30x less statistics: 9e-7 x sqrt(30) = 5e-6

=> **J/ψ allows to monitor in-situ the stability of the scale at the level of 5e-6**

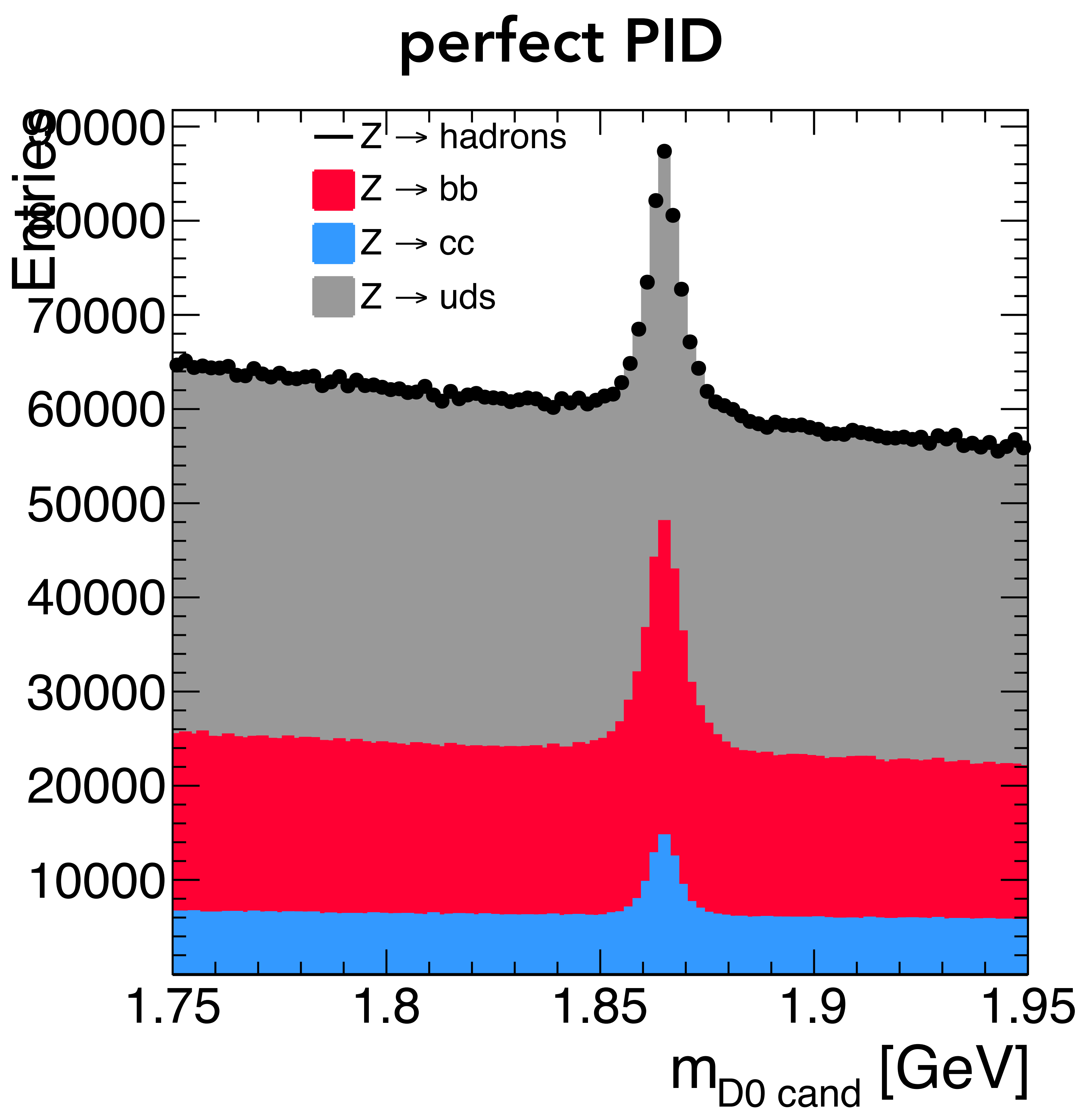
D0: Analysis steps

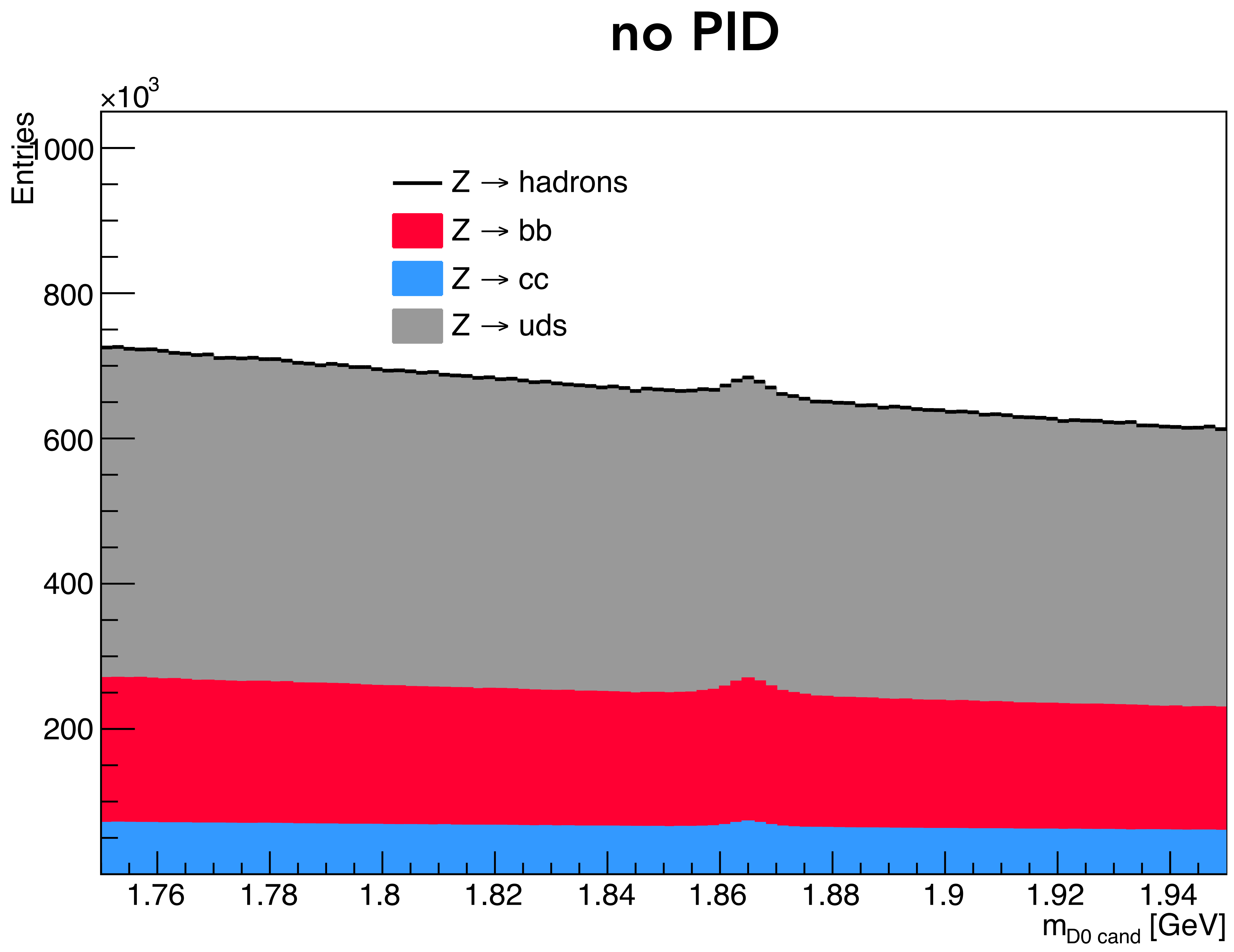
- Centrally-produced EDM4hep samples in /eos
- FCCAnalysis framework for analysis

- Pythia samples of $Z \rightarrow bb, \rightarrow cc, \rightarrow uds$ at $\sqrt{s}$ = 91.2, no BES, and ISR+FSR on
- Delphes cards: IDEAtrkCov
- Processed O(2e6) events for each decay

- D0 candidates built under extreme hypotheses:
  - with perfect PID, i.e. each track associated to a MonteCarlo kaon (pion) is flagged as a kaon (pion)
  - with no PID, i.e. use all track to make combinations, with each track entering the kaon and the pion hypothesis in turn

Dimuon invariant mass in hadronic Z decays around D0

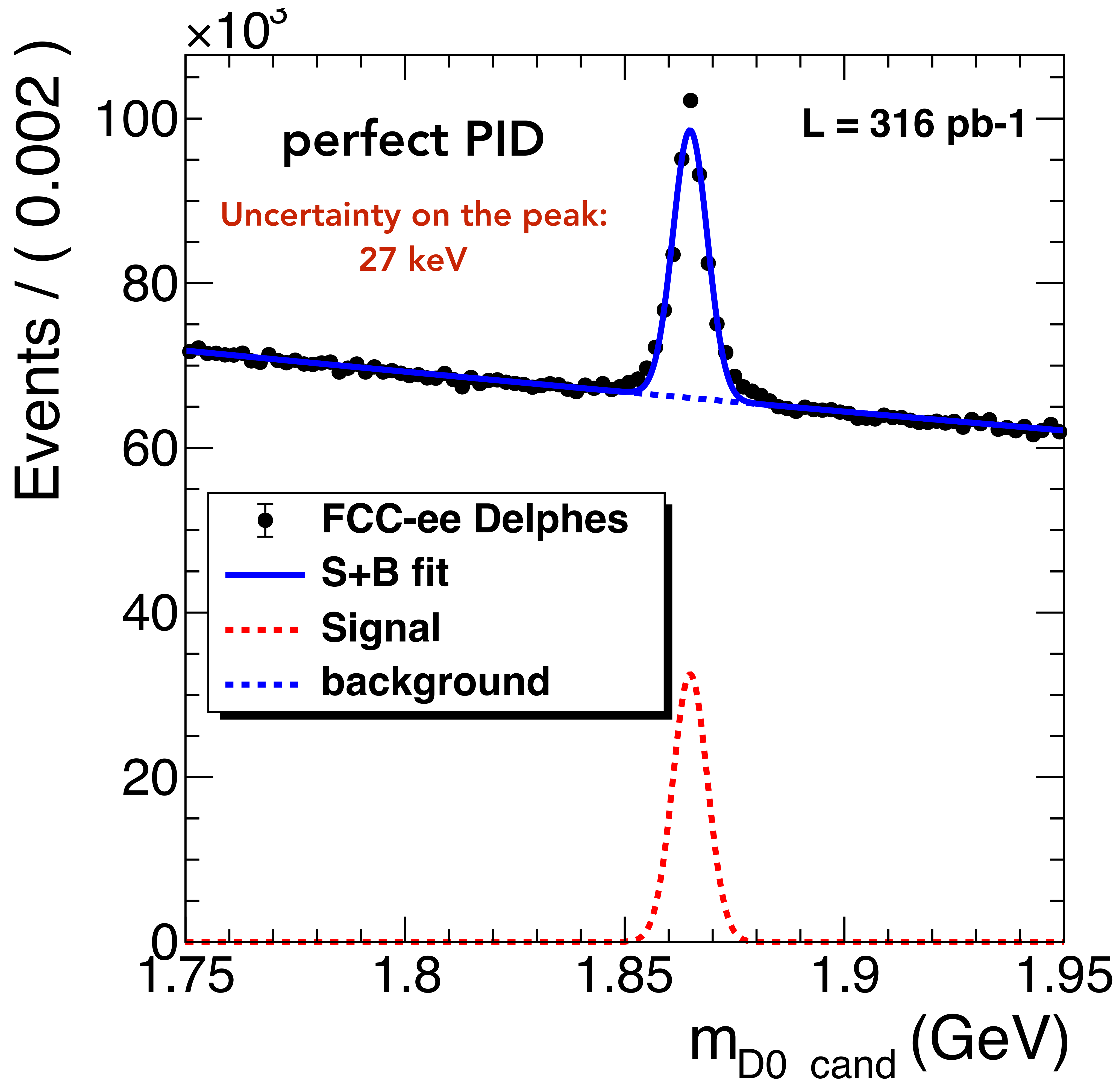


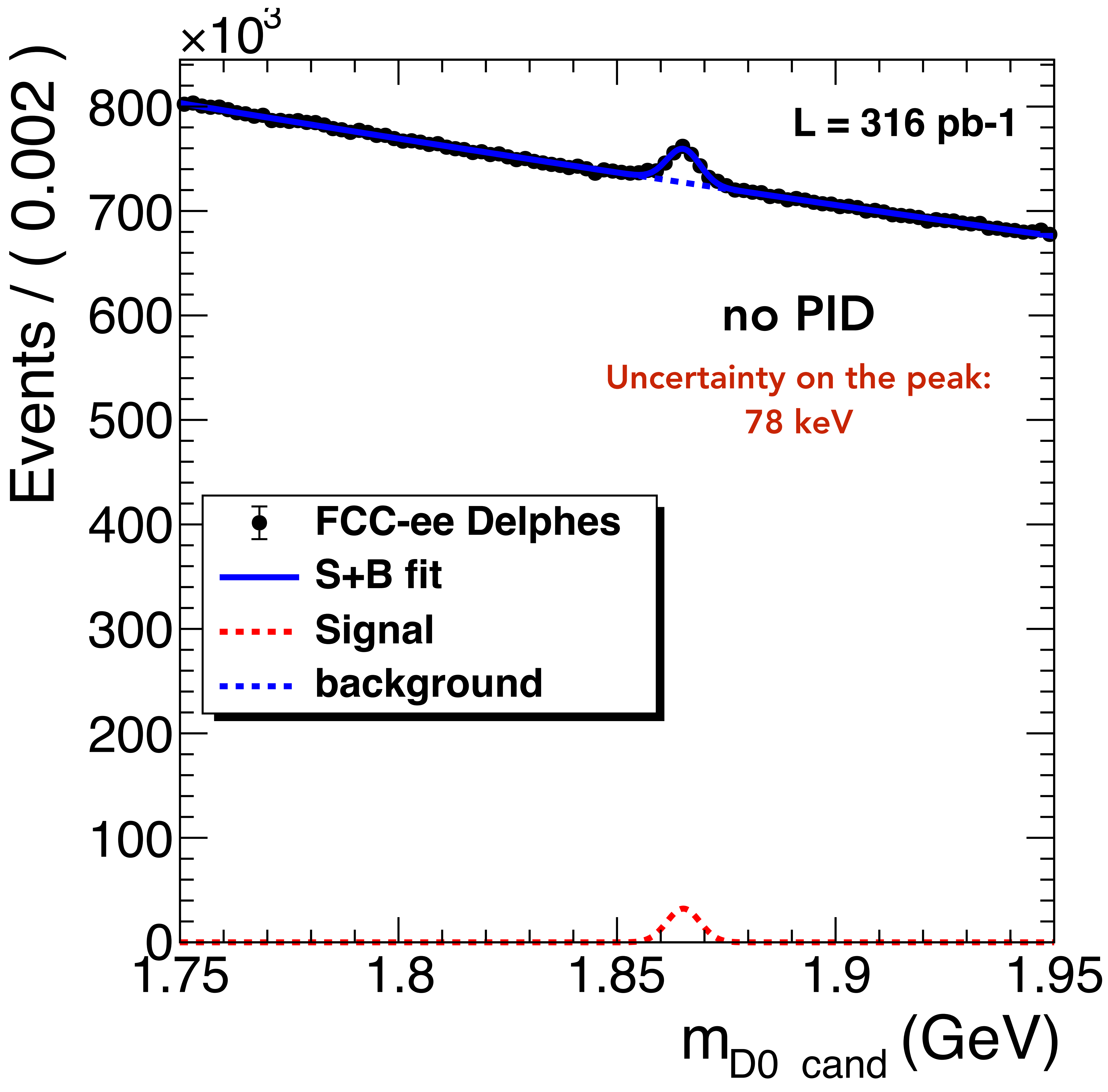


- Off-peak combinations dominated by uds sample as expected
- D0 come mostly from bb, then cc, and a negligible combination from uds
  - in 100k $Z \rightarrow bb$ events: O(130k D0+D0bar mesons)
  - in 100k $Z \rightarrow cc$ events: O(115k D0+D0bar mesons)
  - in 100k $Z \rightarrow uds$ events: O(4k D0+D0bar mesons)
- With no PID at all: background 10x larger than with perfect PID

Fit of dimuon invariant mass in hadronic Z decays around D0

- Fit with a Gaussian on top of an exponential background

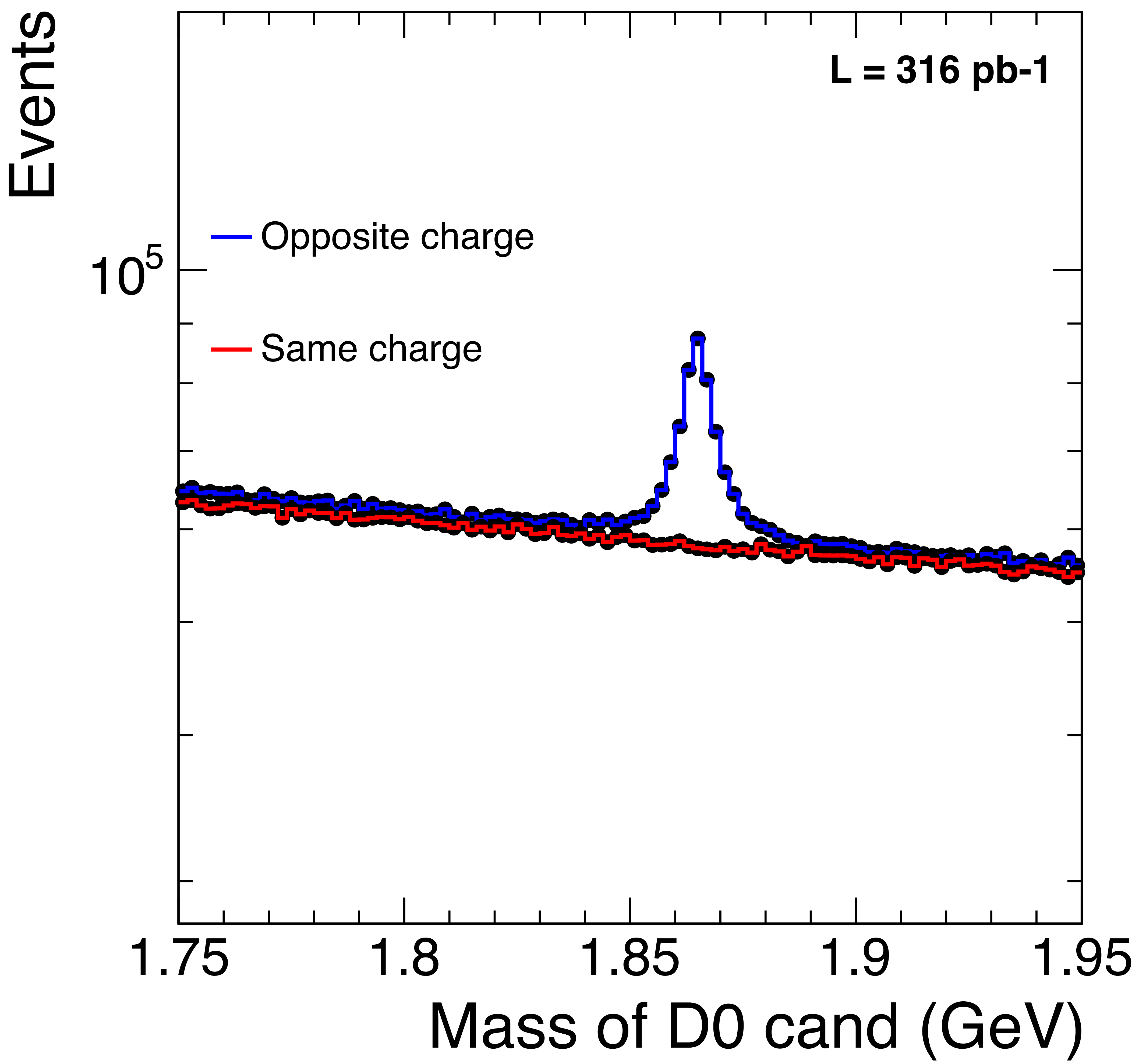


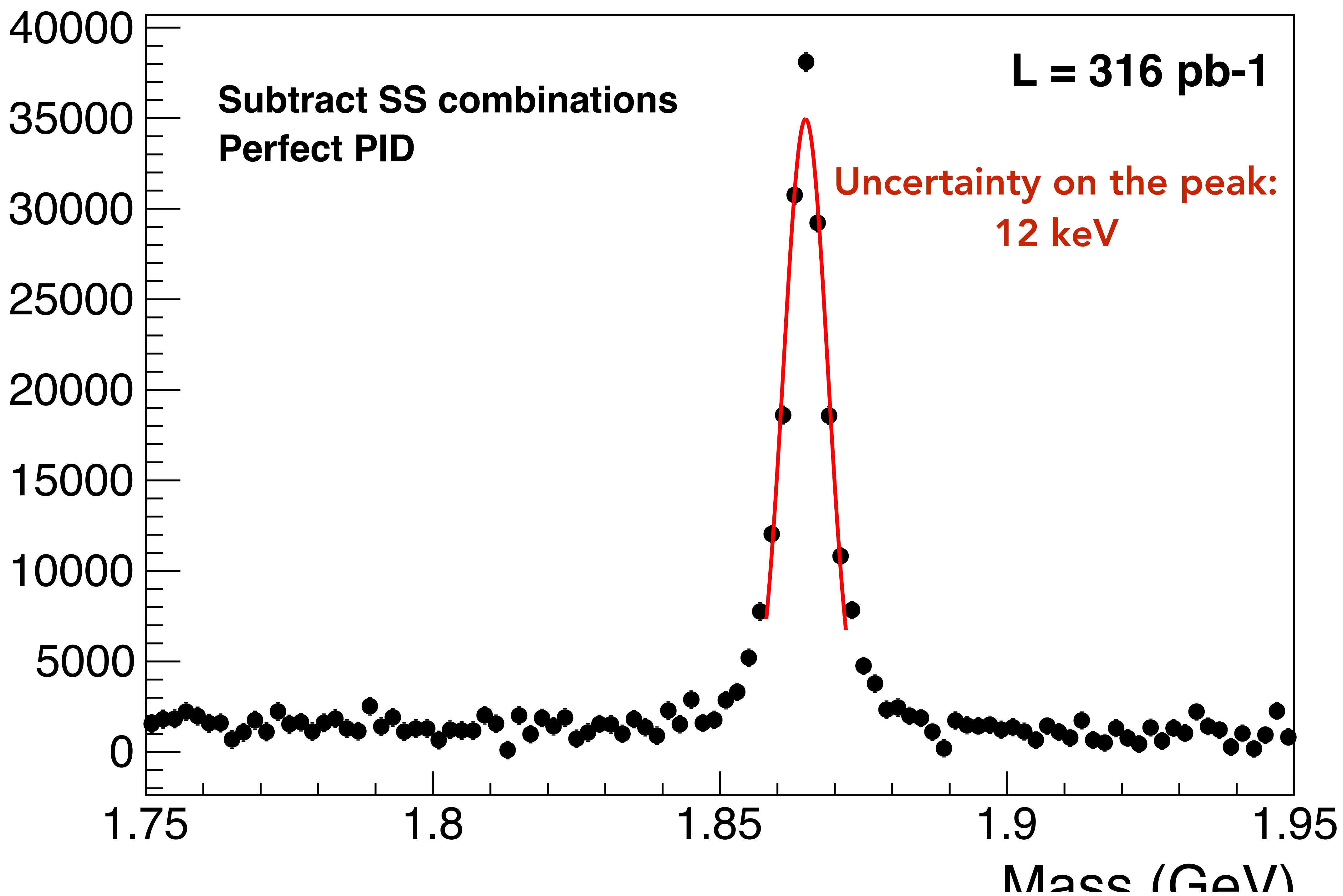


- With a scaling similar to slide #16: **stability monitored to 1.4e-6 (perfect PID) and 4e-6 (no PID)**

Fit of dimuon invariant mass in hadronic Z decays around D0

✦ Subtraction of opposite and same charge with perfect PID





✦ Same-charge combination predict the background not too badly

✦ Subtracting the same- from the opposite-charge combinations, the signal peak sits on top of a flat residual background

✦ a Gaussian fit of this peak leads to O(2x) better determination of the peak position

Summary (2/2)

- We have estimated the **scale stability in-situ with the J/ψ and D0**
  - with the J/ψ: relative scale monitoring of **5x10-6**
  - with the D0: relative scale monitoring of
    - **1.4e-6 (perfect PID)**
    - **4e-6 (no PID)**
    - **6e-7 (subtracting same-charge)**
    - next: we will consider $K \to \pi^+\pi^-$

Extra

$Z \to \mu\mu$ sample normalization

[1] Eur Phys J C 14 (2000) 1

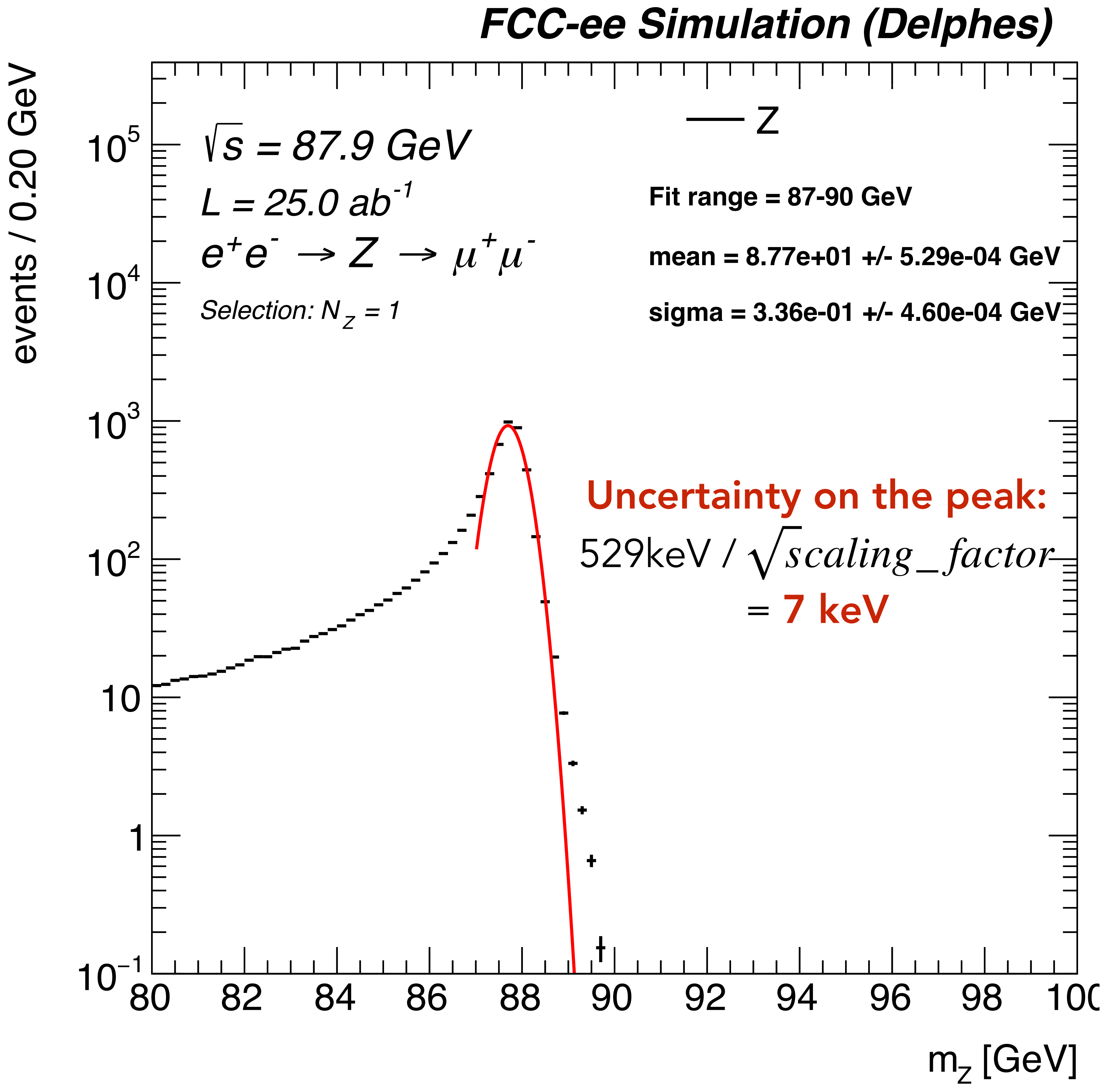
Year	$\sqrt{s}$ (GeV)	$\mathcal{L}(\text{nb}^{-1})$	σ_{had} (nb)	$\sigma_{e^+e^-}$ (nb)	$\sigma_{\mu^+\mu^-}$ (nb)
1990	88.223	482	$4.63 \pm 0.11 \pm 0.01$	$0.241 \pm 0.038 \pm 0.002$	$0.244 \pm 0.025 \pm 0.001$
	89.217	520	$8.44 \pm 0.15 \pm 0.01$	$0.330 \pm 0.041 \pm 0.003$	$0.498 \pm 0.034 \pm 0.001$
	90.217	447	$18.43 \pm 0.26 \pm 0.02$	$0.914 \pm 0.063 \pm 0.003$	$0.903 \pm 0.050 \pm 0.002$
	91.215	3624	$30.43 \pm 0.14 \pm 0.03$	$1.473 \pm 0.026 \pm 0.004$	$1.428 \pm 0.022 \pm 0.003$
	92.207	555	$21.84 \pm 0.25 \pm 0.03$	$1.083 \pm 0.054 \pm 0.004$	$1.009 \pm 0.047 \pm 0.003$
	93.209	597	$12.44 \pm 0.17 \pm 0.02$	$0.627 \pm 0.040 \pm 0.002$	$0.637 \pm 0.036 \pm 0.002$
	94.202	642	$8.00 \pm 0.12 \pm 0.01$	$0.402 \pm 0.031 \pm 0.002$	$0.430 \pm 0.029 \pm 0.001$
1991	91.238	4609	$30.64 \pm 0.12 \pm 0.03$	$1.451 \pm 0.023 \pm 0.003$	$1.476 \pm 0.020 \pm 0.002$
	88.464	668	$5.50 \pm 0.10 \pm 0.01$	$0.266 \pm 0.034 \pm 0.002$	$0.260 \pm 0.022 \pm 0.001$
	89.455	797	$10.06 \pm 0.13 \pm 0.01$	$0.533 \pm 0.038 \pm 0.002$	$0.541 \pm 0.029 \pm 0.001$
	90.212	753	$18.14 \pm 0.20 \pm 0.02$	$0.879 \pm 0.047 \pm 0.003$	$0.917 \pm 0.039 \pm 0.002$
	91.207	2937	$30.65 \pm 0.15 \pm 0.03$	$1.534 \pm 0.029 \pm 0.003$	$1.543 \pm 0.025 \pm 0.002$
	91.952	693	$25.39 \pm 0.27 \pm 0.03$	$1.207 \pm 0.051 \pm 0.004$	$1.196 \pm 0.046 \pm 0.003$
	92.952	677	$14.67 \pm 0.17 \pm 0.02$	$0.687 \pm 0.039 \pm 0.002$	$0.655 \pm 0.034 \pm 0.002$
	93.701	797	$10.15 \pm 0.13 \pm 0.01$	$0.506 \pm 0.031 \pm 0.002$	$0.503 \pm 0.028 \pm 0.001$
1992	91.276	12298	$30.734 \pm 0.071 \pm 0.022$	$1.493 \pm 0.014 \pm 0.003$	$1.488 \pm 0.012 \pm 0.001$
	91.270	8749	$30.632 \pm 0.070 \pm 0.022$	$1.509 \pm 0.017 \pm 0.003$	$1.490 \pm 0.014 \pm 0.001$
1993	91.303	5314	$30.645 \pm 0.089 \pm 0.022$	$1.496 \pm 0.021 \pm 0.003$	$1.470 \pm 0.018 \pm 0.002$
	89.432	8070	$9.891 \pm 0.037 \pm 0.011$	$0.489 \pm 0.012 \pm 0.002$	$0.4810 \pm 0.0085 \pm 0.0010$
	91.187	9135	$30.468 \pm 0.068 \pm 0.021$	$1.459 \pm 0.016 \pm 0.003$	$1.484 \pm 0.014 \pm 0.002$
	93.015	8690	$14.032 \pm 0.043 \pm 0.013$	$0.699 \pm 0.011 \pm 0.002$	$0.6724 \pm 0.0097 \pm 0.0015$
1994	(†) 91.219	12440	$30.454 \pm 0.071 \pm 0.022$	$1.488 \pm 0.014 \pm 0.002$	$1.473 \pm 0.012 \pm 0.001$
	91.197	42695	$30.390 \pm 0.031 \pm 0.022$	$1.4938 \pm 0.0075 \pm 0.0024$	$1.4808 \pm 0.0065 \pm 0.0013$
1995	(†) 91.293	12396	$30.669 \pm 0.071 \pm 0.022$	$1.479 \pm 0.014 \pm 0.003$	$1.500 \pm 0.012 \pm 0.002$
	89.440	8121	$9.978 \pm 0.041 \pm 0.012$	$0.495 \pm 0.012 \pm 0.002$	$0.4927 \pm 0.0086 \pm 0.0011$
	91.282	4873	$30.53 \pm 0.12 \pm 0.02$	$1.497 \pm 0.022 \pm 0.003$	$1.464 \pm 0.019 \pm 0.002$
	92.968	9373	$14.297 \pm 0.049 \pm 0.013$	$0.697 \pm 0.011 \pm 0.002$	$0.7114 \pm 0.0097 \pm 0.0016$

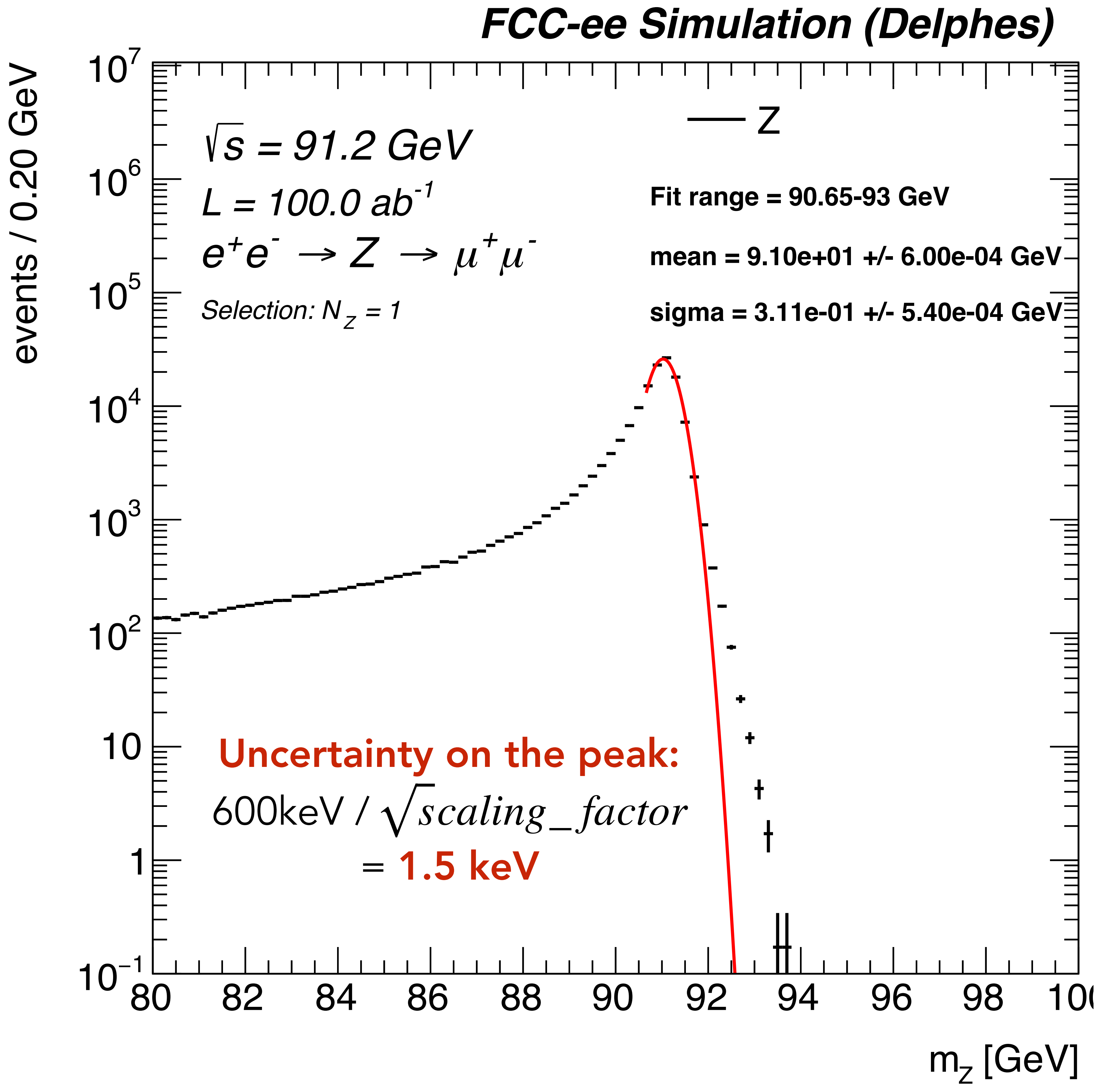
Preliminary study with parametrized CLD

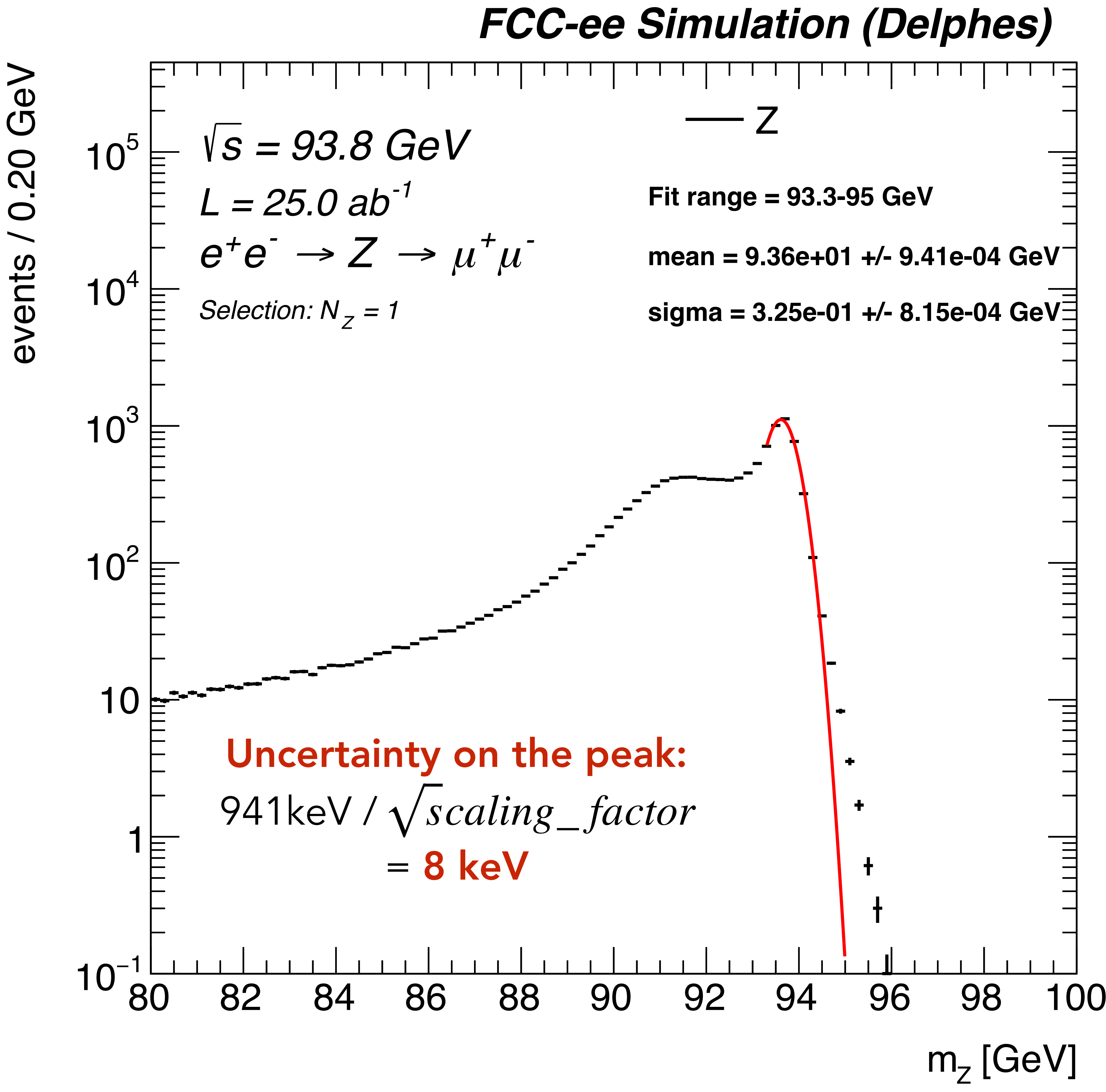
Fit of the dimuon invariant mass at $\sqrt{s_-}, \sqrt{s}, \sqrt{s_+}$

CLD

✦ Gaussian fit values correspond to the luminosity of the Monte Carlo samples. Distributions are normalized as from slide #5.







✦Fit range was varied to assess fit stability

Fit range	mean err
86.5-90	7E-04
87-90	5.29E-04
87.5-90	7E-04

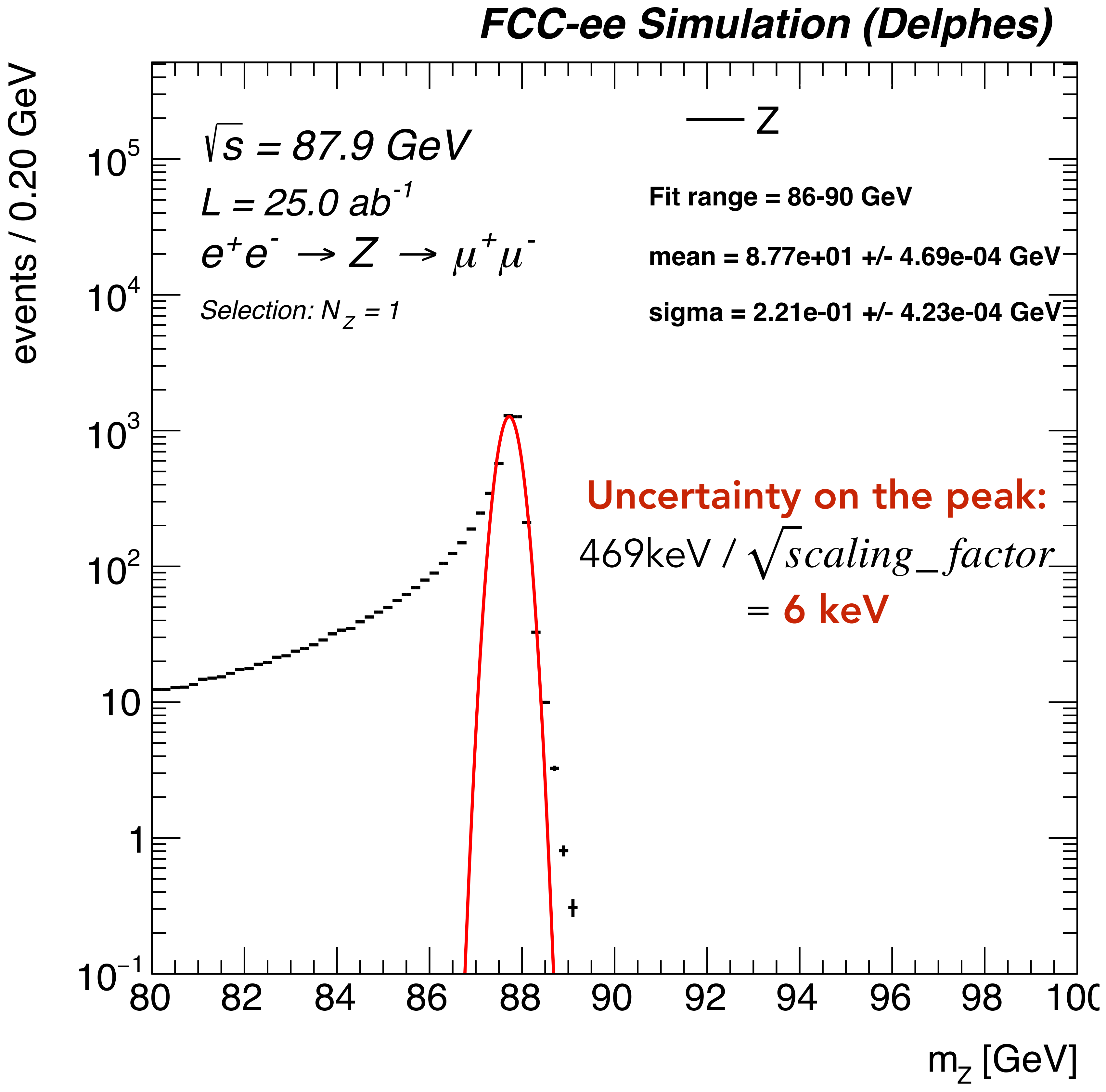
Fit range	mean err
90.55-93	6E-04
90.65-93	6E-04
90.75-93	1.2E-03

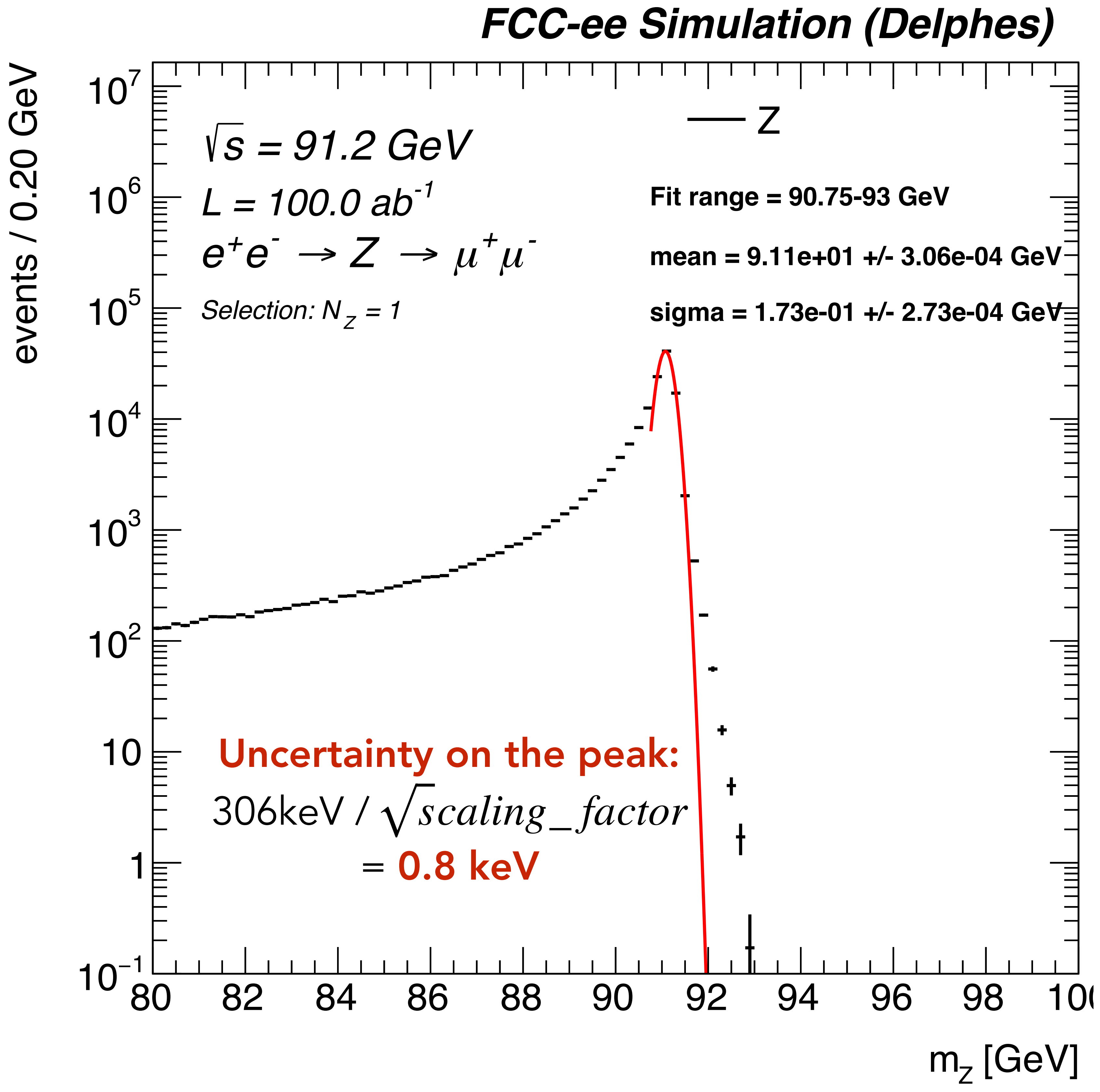
Fit range	mean err
93.25-95	9.4E-04
93.3-95	9.4E-04
93.4-95	1.8E-03

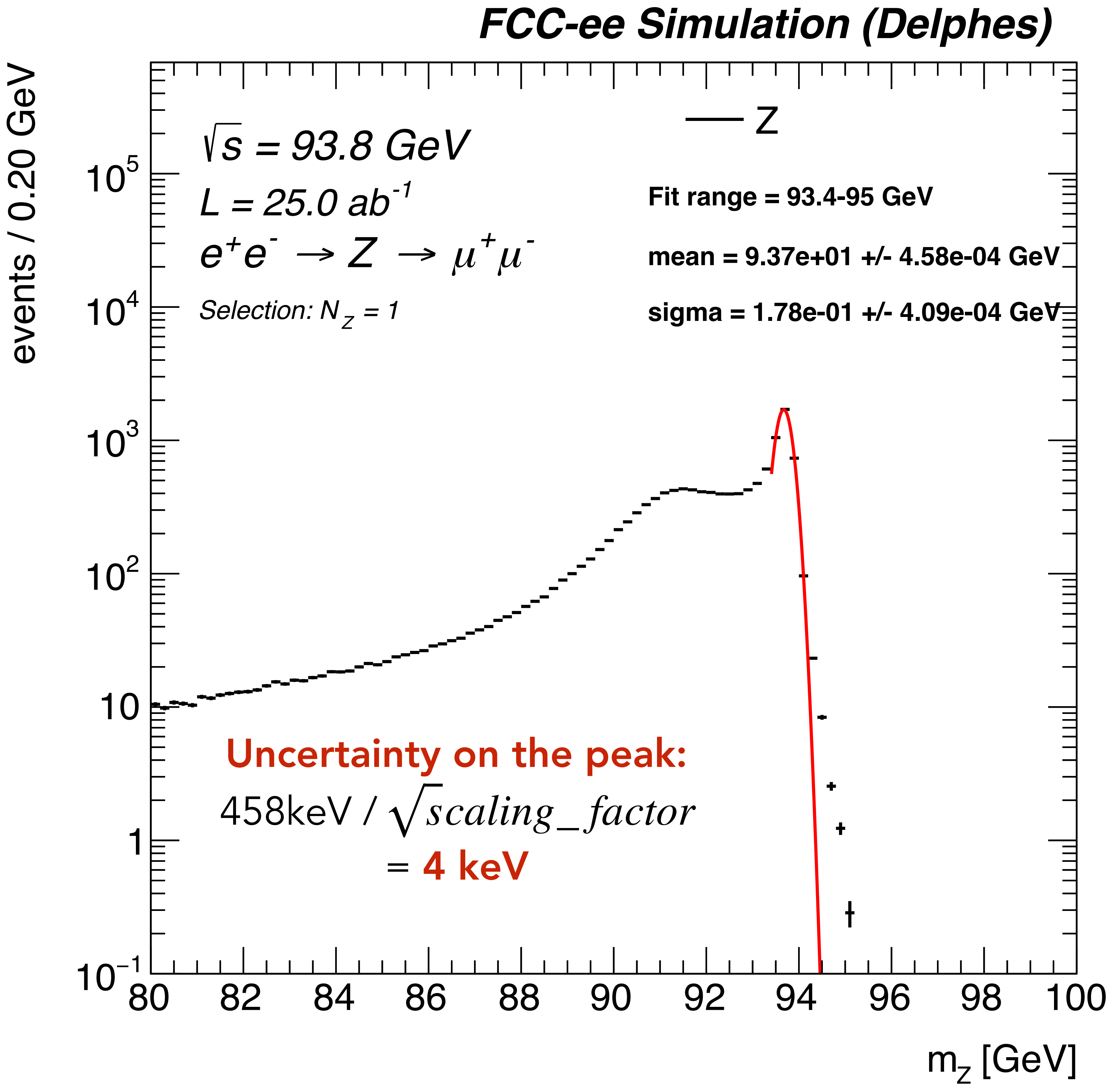
Fit of the dimuon invariant mass at $\sqrt{s}_-$, $\sqrt{s}$, $\sqrt{s}_+$

IDEA

✦ Gaussian fit values correspond to the luminosity of the Monte Carlo samples. Distributions are normalized as from slide #5.







✦Fit range was varied to assess fit stability

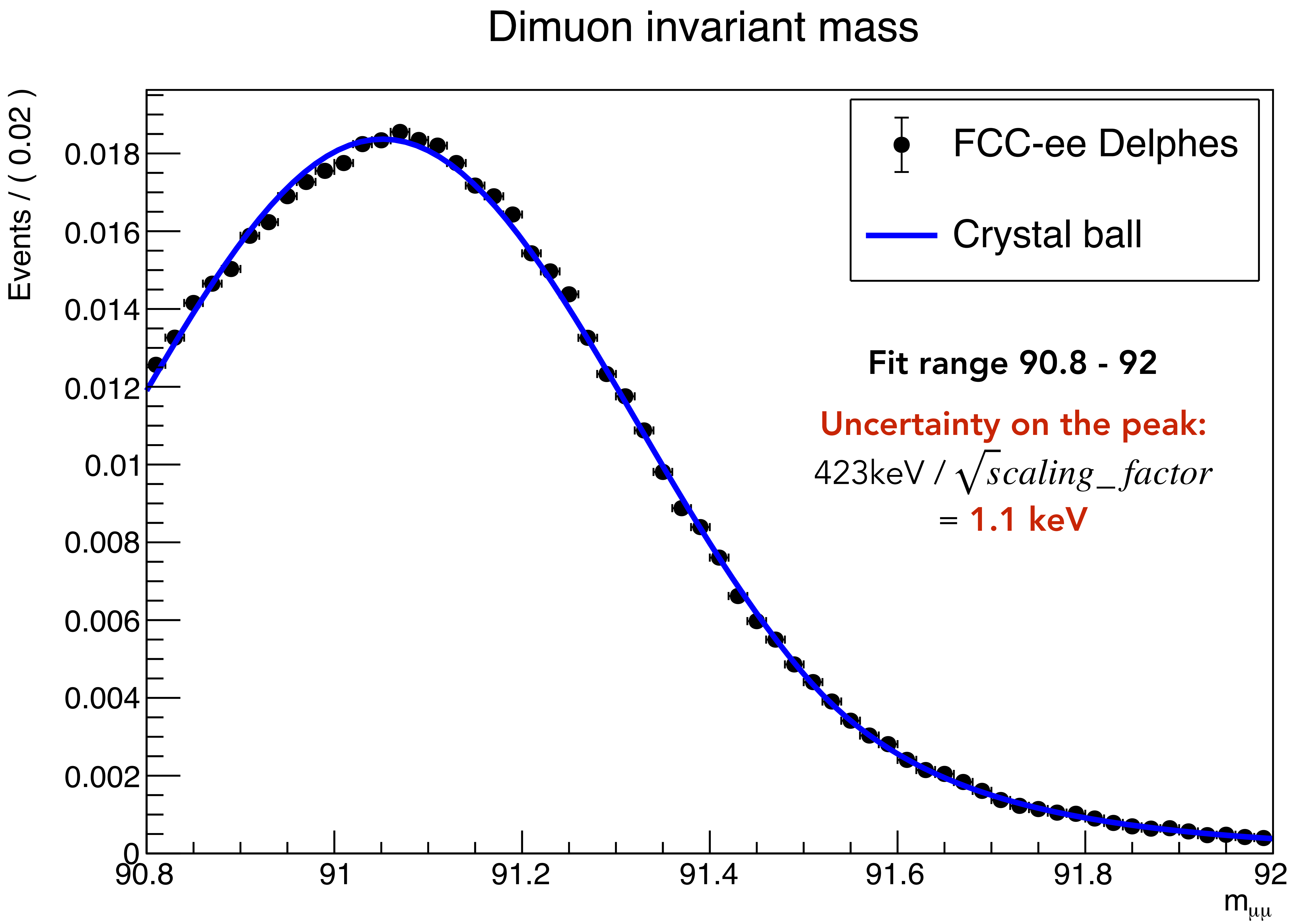
Fit range	mean err
85-90	4.73E-04
86-90	4.69E-04
87-90	4.41E-04

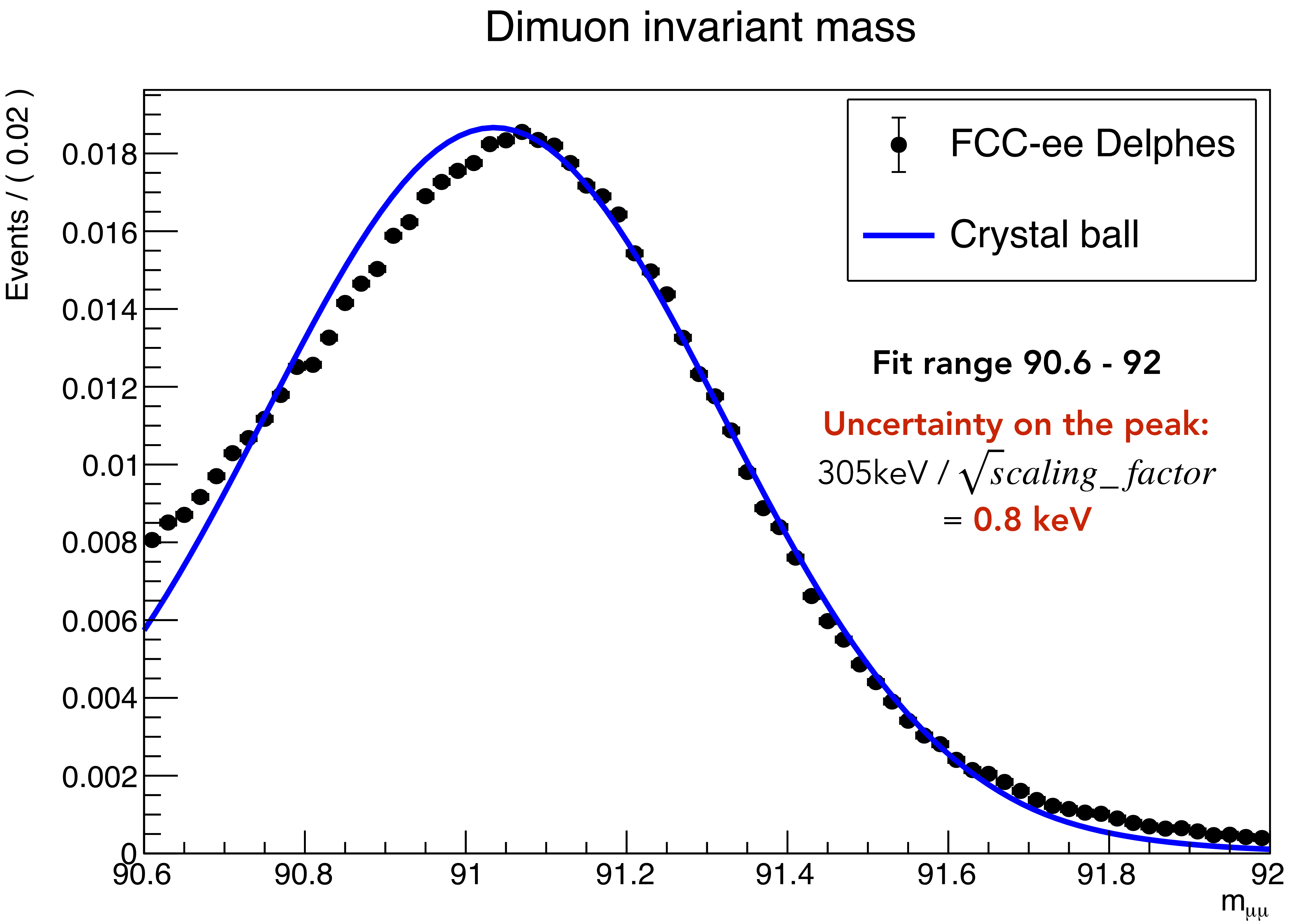
Fit range	mean err
90.65-93	3.34E-04
90.75-93	3.06E-04
90.85-93	3.06E-04

Fit range	mean err
93.3-95	5.02E-04
93.4-95	4.58E-04
93.5-95	4.58E-04

Fit of the dimuon invariant mass at $\sqrt{s}$ = 91.2 GeV

CLD

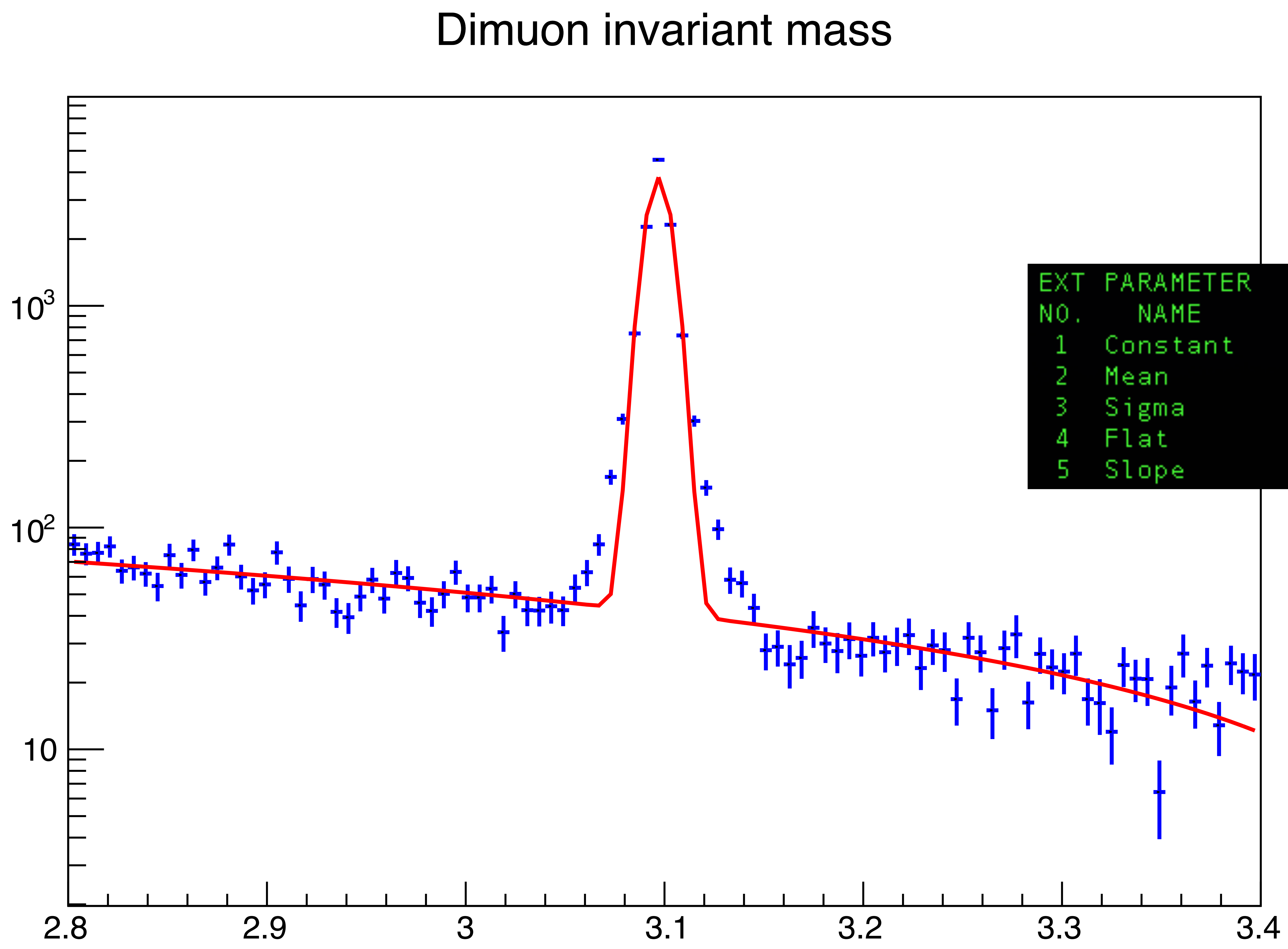





```
alpha      = -1.66737   +/-  4.11728   (limited)
cbmean     = 91.0514    +/-  0.423227  (limited)
cbsigma    = 0.269859   +/-  0.300631  (limited)
n          = 6.01242    +/-  87.8489   (limited)
nsig       = 0.521481   +/-  0.505541  (limited)
```

```
alpha      = -2.31337   +/-  3.6506    (limited)
cbmean     = 91.0351    +/-  0.305708  (limited)
cbsigma    = 0.283271   +/-  0.258363  (limited)
n          = 64.6105    +/-  67.4503   (limited)
nsig       = 0.616486   +/-  0.78328   (limited)
```

Fit of dimuon invariant mass in hadronic Z decays around J/ψ



- Gauss + pol1

EXT NO.	PARAMETER NAME	VALUE	ERROR	STEP SIZE	FIRST DERIVATIVE
1	Constant	6.34180e+01	6.29898e-01	8.30770e-03	-2.79553e-05
2	Mean	3.09702e+00	6.76504e-05	1.47677e-06	2.64118e-01
3	Sigma	6.72731e-03	7.45430e-05	9.81699e-07	-3.24253e-01
4	Flat	3.43330e+02	1.13278e+01	7.97800e-03	6.71729e-06
5	Slope	-9.74911e+01	3.55105e+00	2.50128e-03	2.00793e-06

Energy distributions of pions and kaons from D0 decays