Determination of the Z width at FCC-ee

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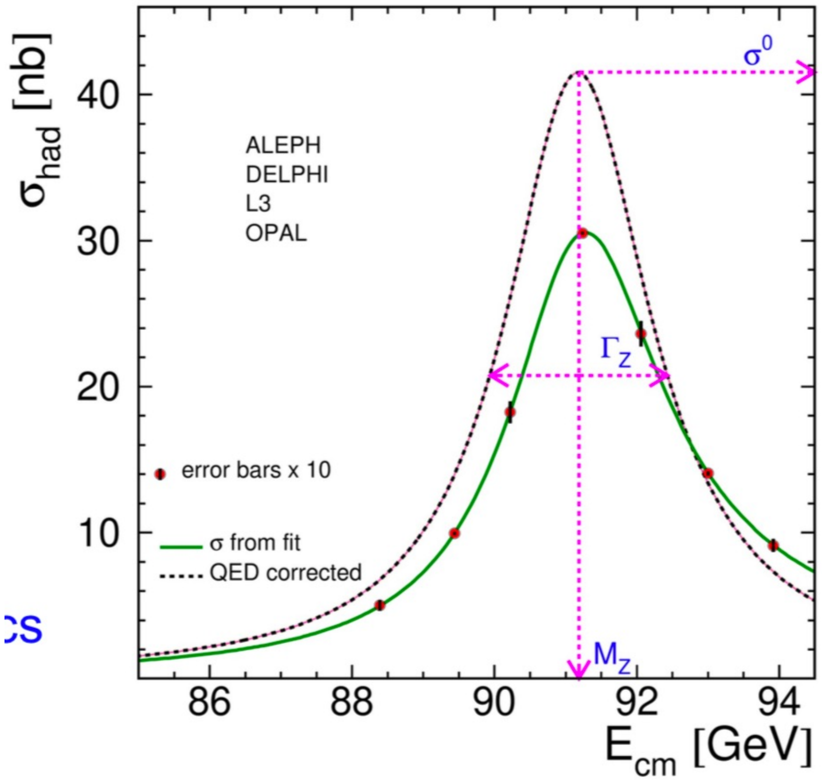
Work in progress…

Determination of the Z width from the line-shape

Expected statistical uncertainty: 5 keV   (cf e.g. mid-term report)

- Absolute calibration of √s: key for the determination of the Z mass
- But for the Z width: what matters if the relative, point-to-point uncertainty on √s, between the off-peak points used in the line-shape scan
  - Other important systematic: BES
  - With BES known to 0.5 per-mill: uncertainty on Γ_Z is 10 keV



With δ(√s)$_{ptp}$ ~ 10 keV, syst. uncertainty on Γ_Z would be 5 keV, at the level of the stat. !

NB: δ(√s)$_{ptp}$ also important systematic for sin2thetaW from AFB(μμ). Need a few 10's of keV to reach the stat. uncertainty of 2e-6

Point-to-point uncertainty on √s from dimuon events

Use e.g. the ”peak position” of the Mμμ distribution in dimuon events, at √s = MZ and at the off-peak points

arXiv:1909.12245

Key = exquisite momentum resolution

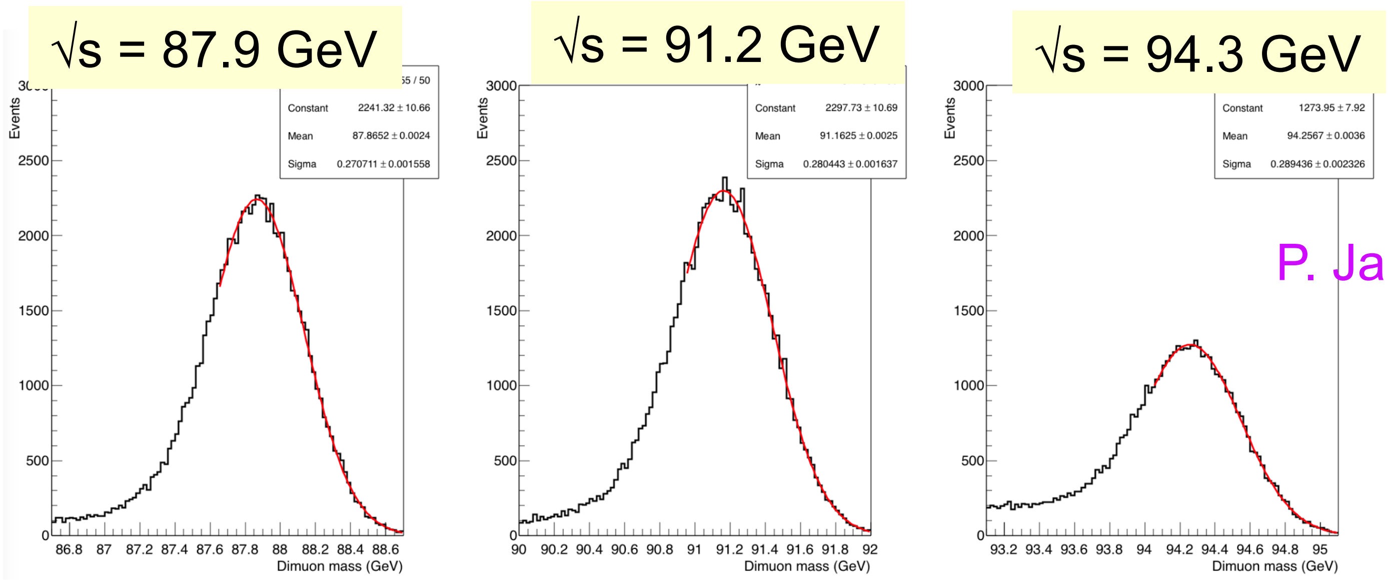


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Figure 58. Invariant mass distribution of 10^5 muon pairs in the CLD detector, at centre-of-mass energies of (left-to-right) 87.9, 91.2 and 94.3 GeV respectively; the width of the distribution is dominated by the muon momentum measurement uncertainty. The data correspond to 521 pb^{-1}, 69 pb^{-1}, and 257 pb^{-1}, which can be acquired in 4 minutes, 35 seconds and 2 minutes respectively

May not be good enough for an absolute calibration of √s, but could provide $\delta(\sqrt{s})_{ptp}$ to better than √2 x RDP uncertainty.

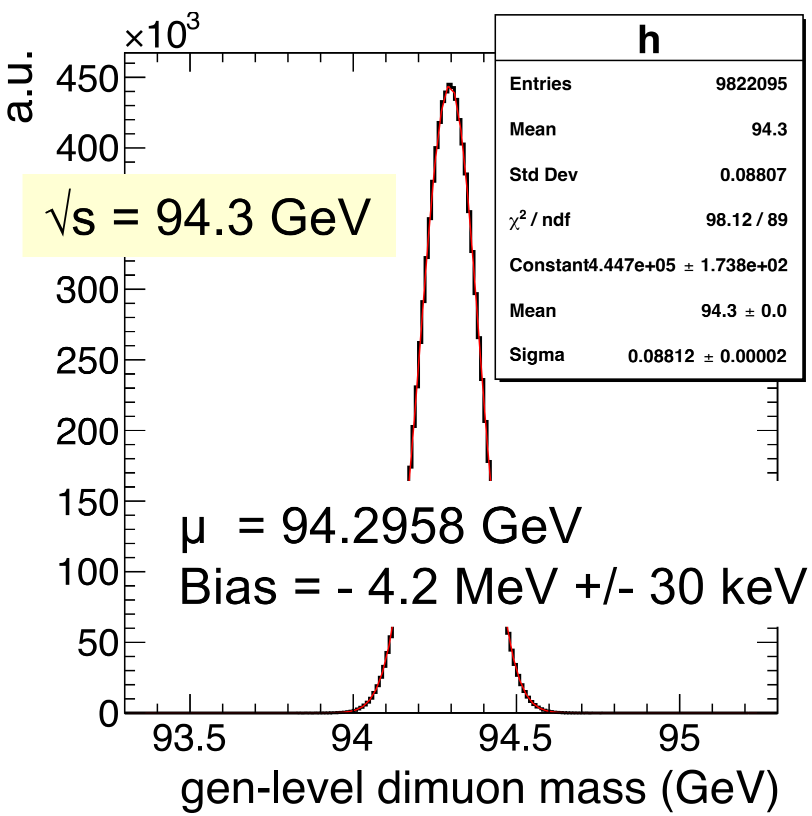
First follow-up: E. Leogrande, E.P, Dec. 2020…

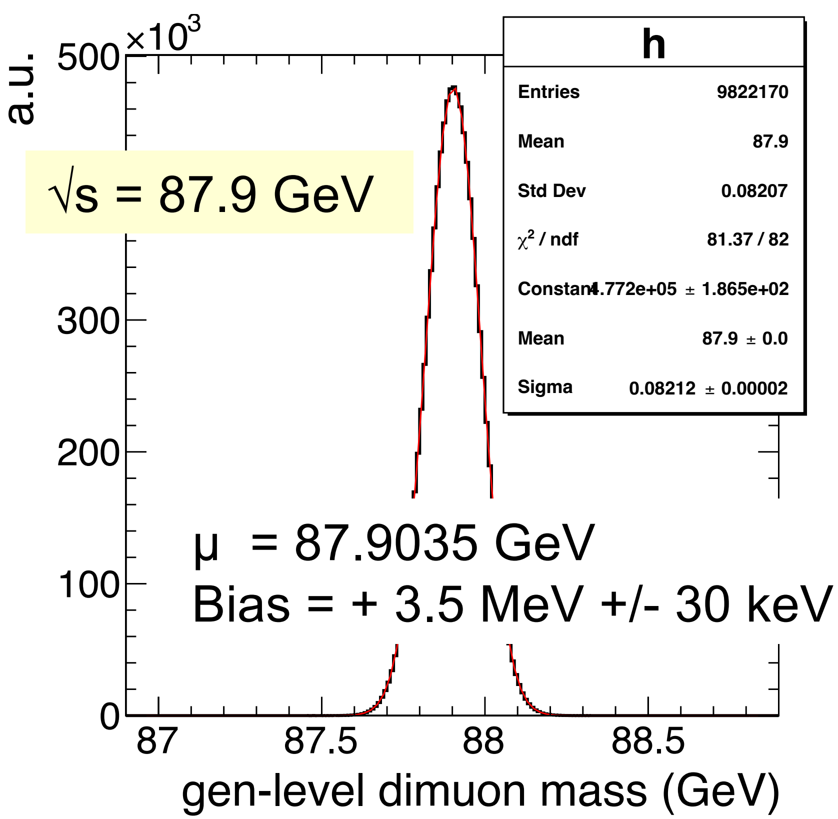
Bias of the estimator of √s

- Any proxy to √s (e.g. the “peak position” of the Mμμ distribution, or some parameter extracted from a fit) will show a bias
  - in particular due to ISR/FSR

- And this bias depends on √s !

Example: no ISR, no FSR, gen-level dimuon mass. Simple gaussian fit:





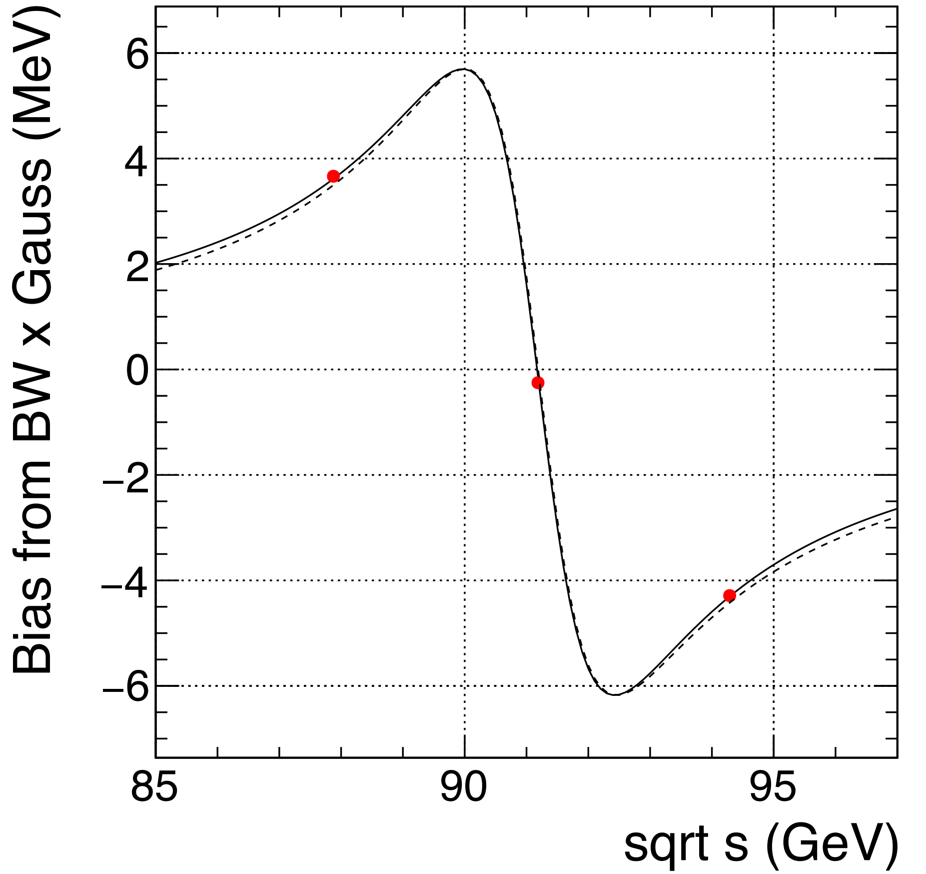
Bias of the estimator of sqrts: simplest case

The bias in the previous plots comes from the product of the Breit-Wigner with the Gaussian that represents the beam-energy spread (BES).

- Below MZ : the BW pulls the distribution towards MZ, positive bias
- Above MZ : negative bias

The value of the bias can be determined analytically by maximizing BW x Gauss(BES).

The bias varies quadratically with the BES.



Samples, fit procedure

Delphes samples of ee -> mumu from Whizard and KKMC
- BES, ISR and FSR

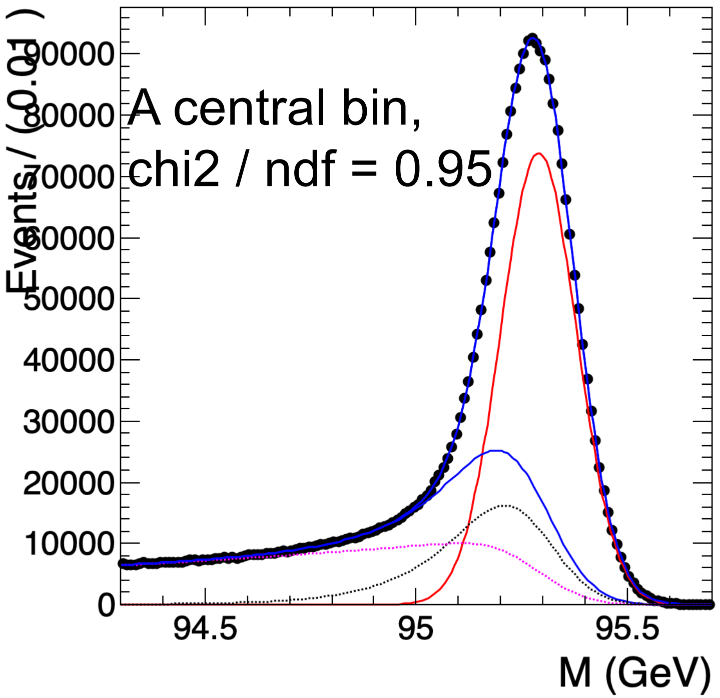
Energies: 91.188 GeV, 87.9 GeV and 94.3 GeV ; +/- 300 keV around these values; and a few other off-peak points for checks

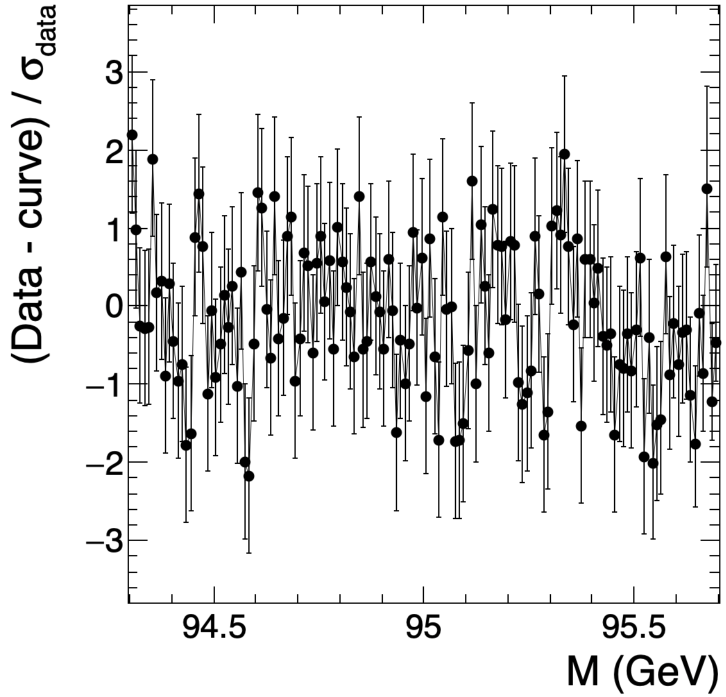
About 100 M events for each sample

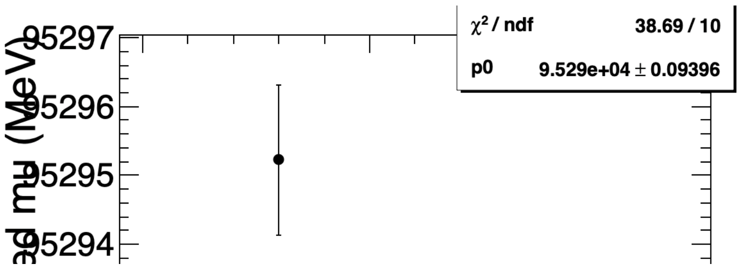
- Fit the dimuon mass distribution
  - so far, only the "raw" dimuon mass (no "correction" for colinear ISR photon, no Sp yet)
- Fit model: Gauss $\otimes$ (delta + two exponentials)
  - cf 2022 paper from G. Wilson & B. Madison, arXiv:2209.03281
  - Provides good fits – for this MC statistics
- Fits done in theta bins (angular dependence of the momentum resolution)
- To have 1D bins only: demand that the mu+ and the mu- be in the "same" theta bin (accop cut : | theta+ + theta- - Pi | < 0.1 rad)
- Keep only good fits
  - Equivalent : chi2 < Ndf + 3 x sqrt(2 * Ndf)
- Proxy for $\sqrt{s}$: weighted average of the means of the Gaussian in the various theta bins

Example fits

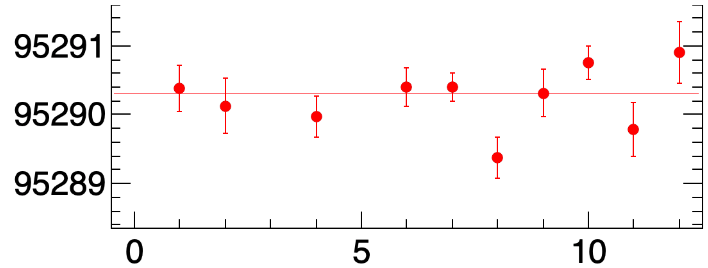
Gen-level mass
√s = 95.3 GeV



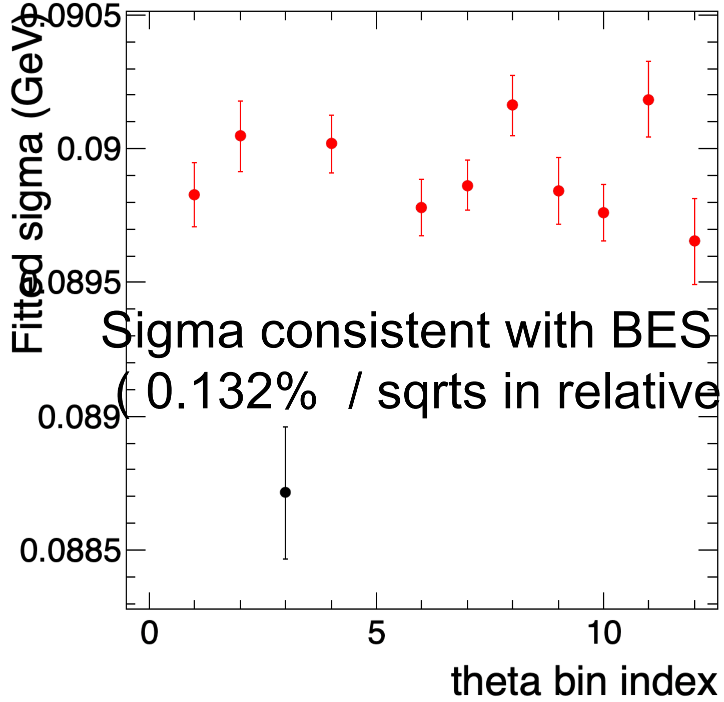




Fitted mu is the same in all bins
(outliars are removed)



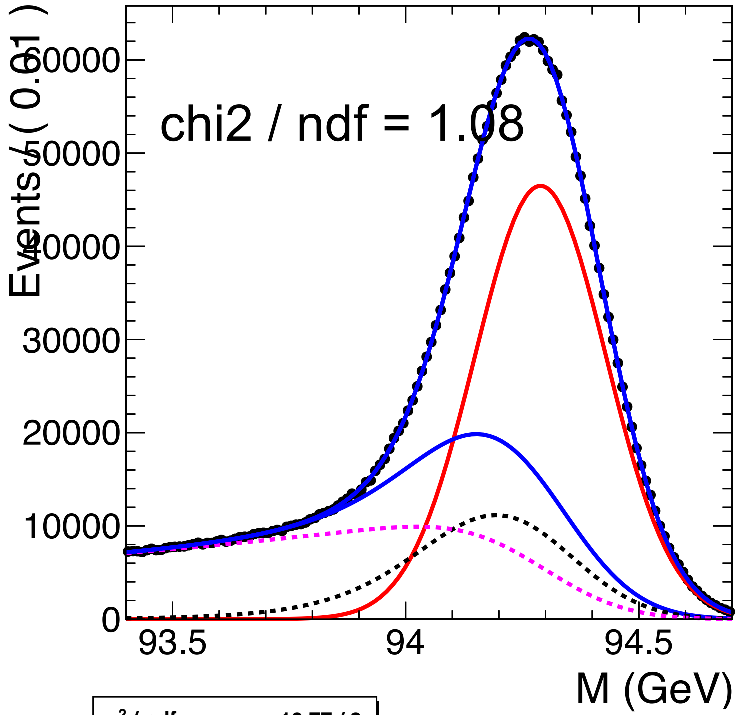
[central]
[fwd/bwd]

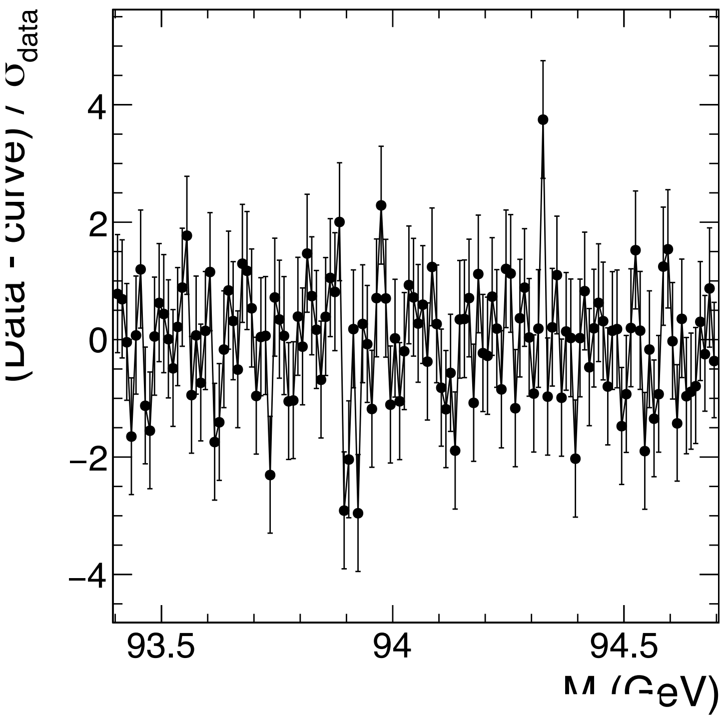


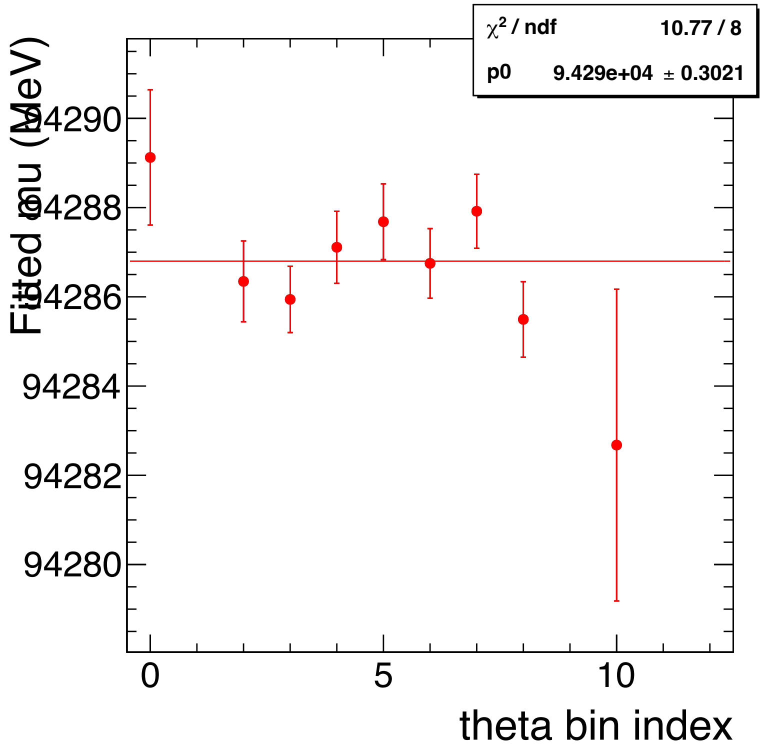
Sigma consistent with BES
(0.132% / sqrts in relative)

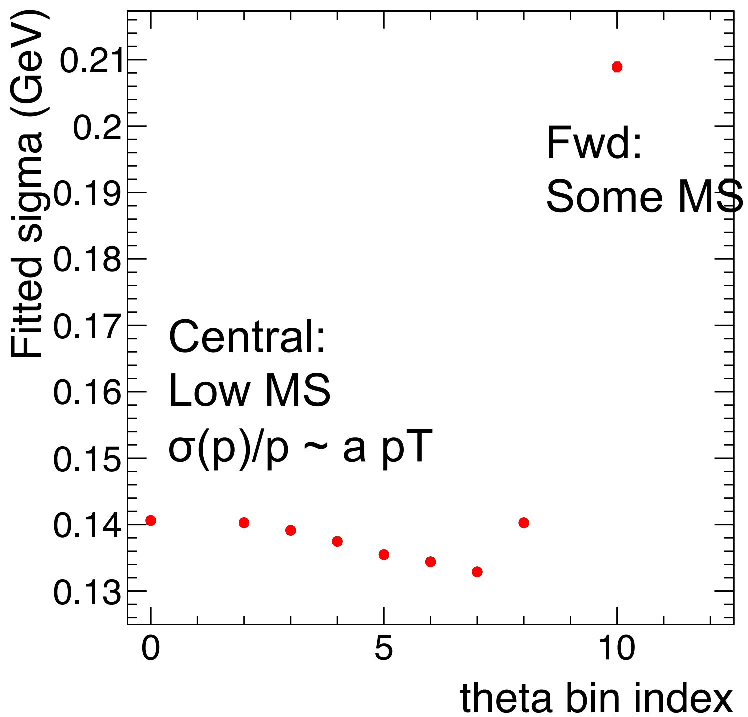
Example fits (2)

Reco'ed mass,
IDEA
√s = 94.3 GeV



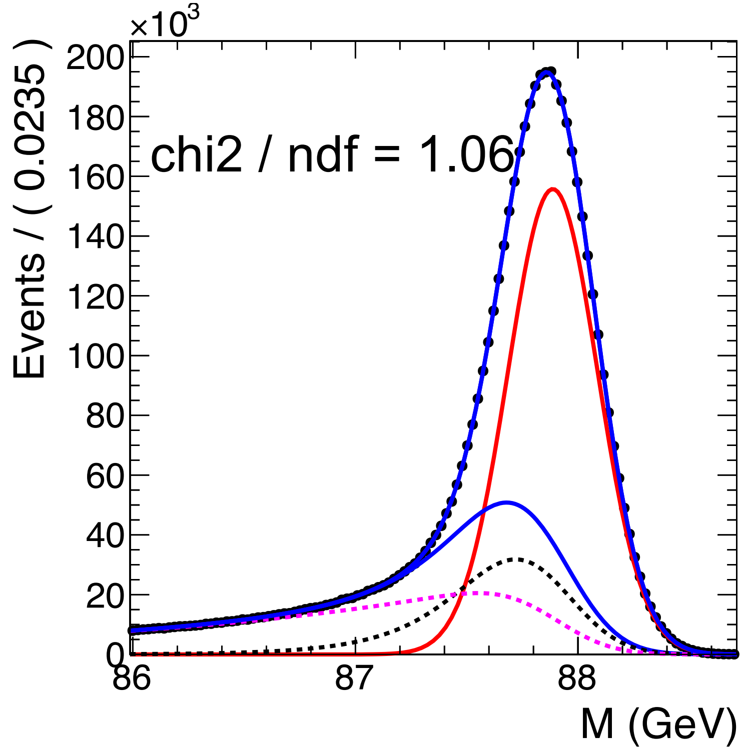


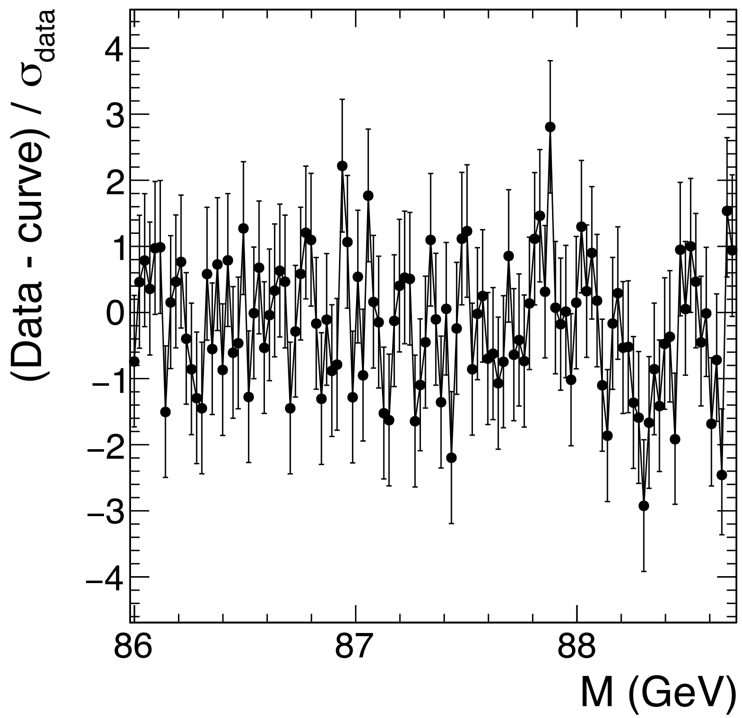


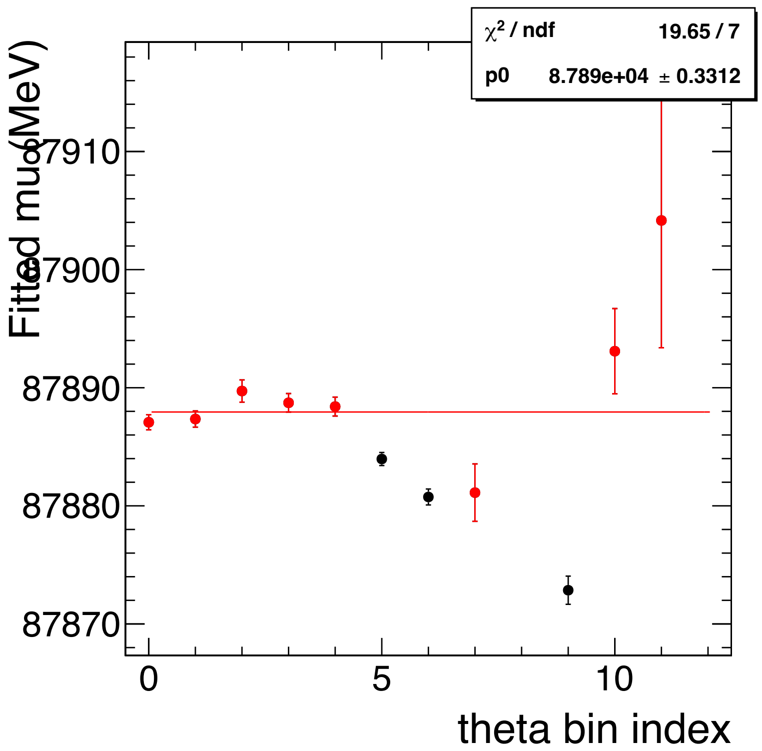


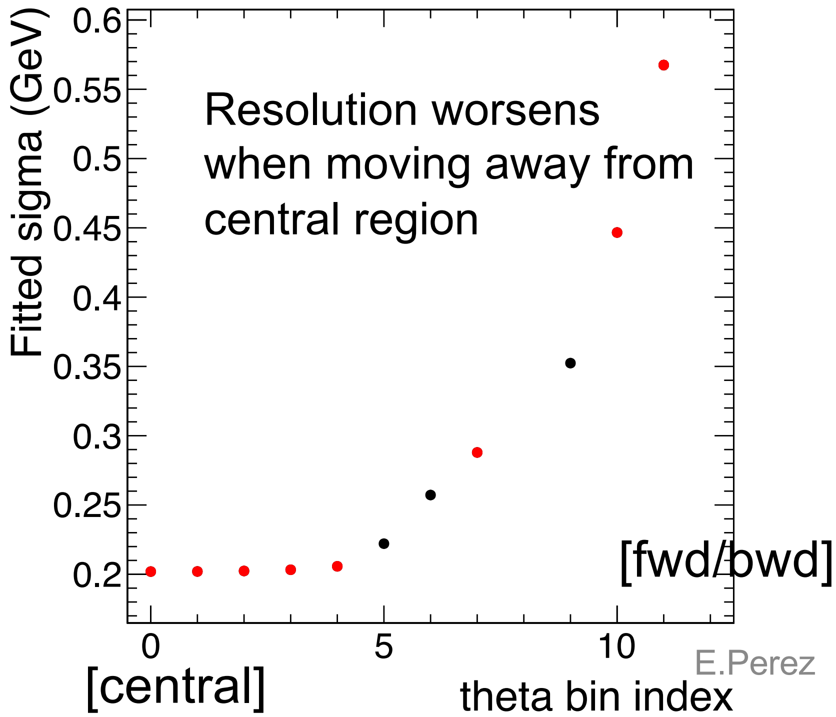
Example fits (3)

Reco'ed mass,
CLD
$\sqrt{s}$ = 87.9 GeV



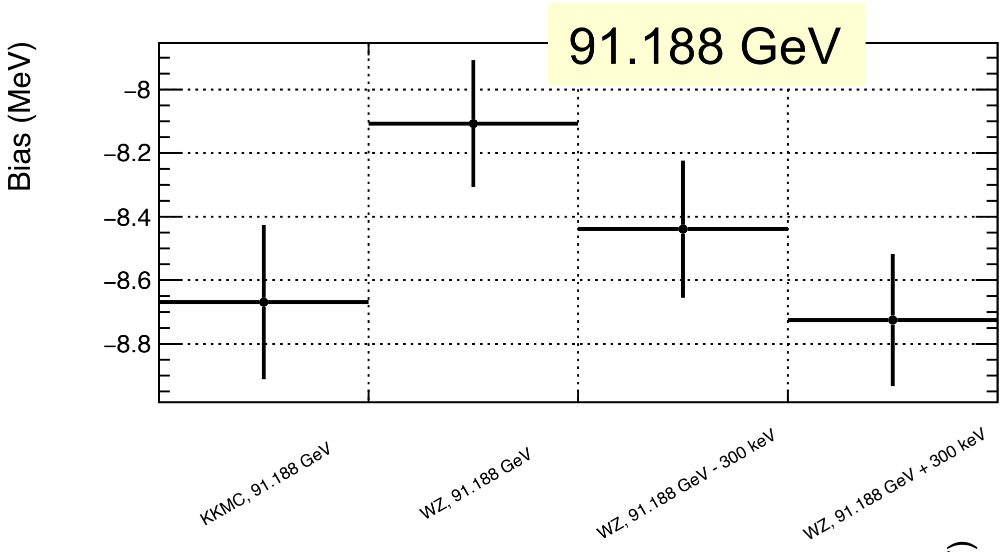






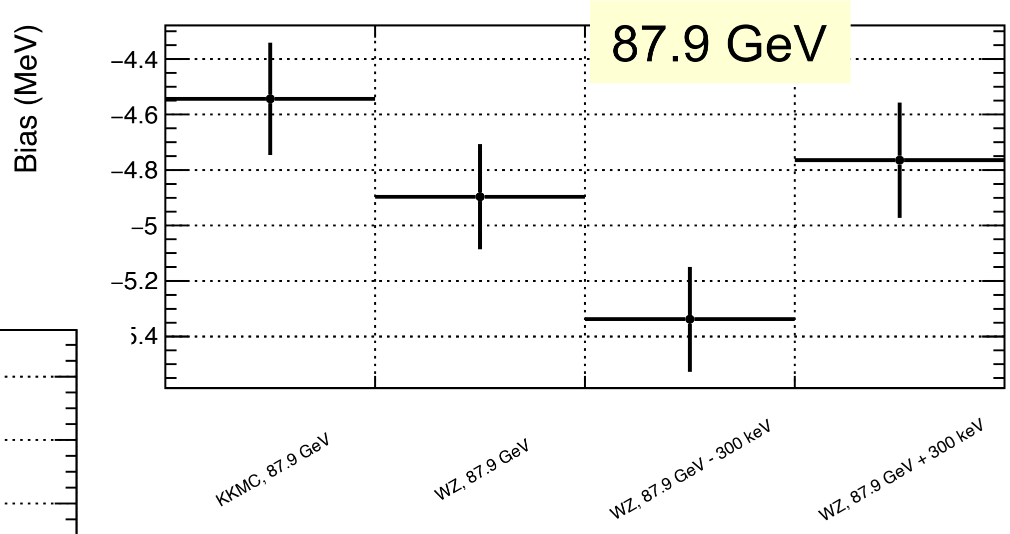
Bias, numerical values (IDEA)

Reco'ed mass, IDEA

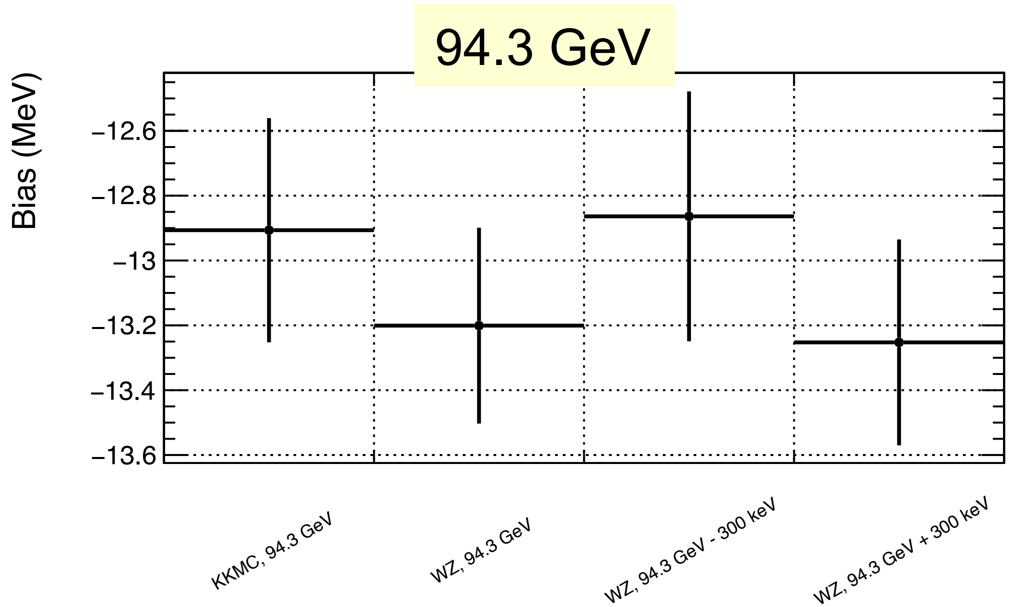


Within uncertainties (~ 200 keV with current MC statistics) :

- KKMC ~ Whizard
- Bias is "locally constant" when $\sqrt{s}$ varies by +/- 300 keV ($\sqrt{s}$ will be known from RDP to within 100 keV or better)



Bias = proxy (average mu) - $\sqrt{s}$



Statistical uncertainties on the $\sqrt{s}$ proxy

- With 1e8 events, uncertainties of 200 – 300 keV
- Rescaling to the number of events expected with 40 / 125 / 40 ab-1 at 87.9 / 91.2 / 94.3 GeV :
  < μ > would be known to ~ 4 keV at 91.2 GeV, ~ 20 keV off-peak

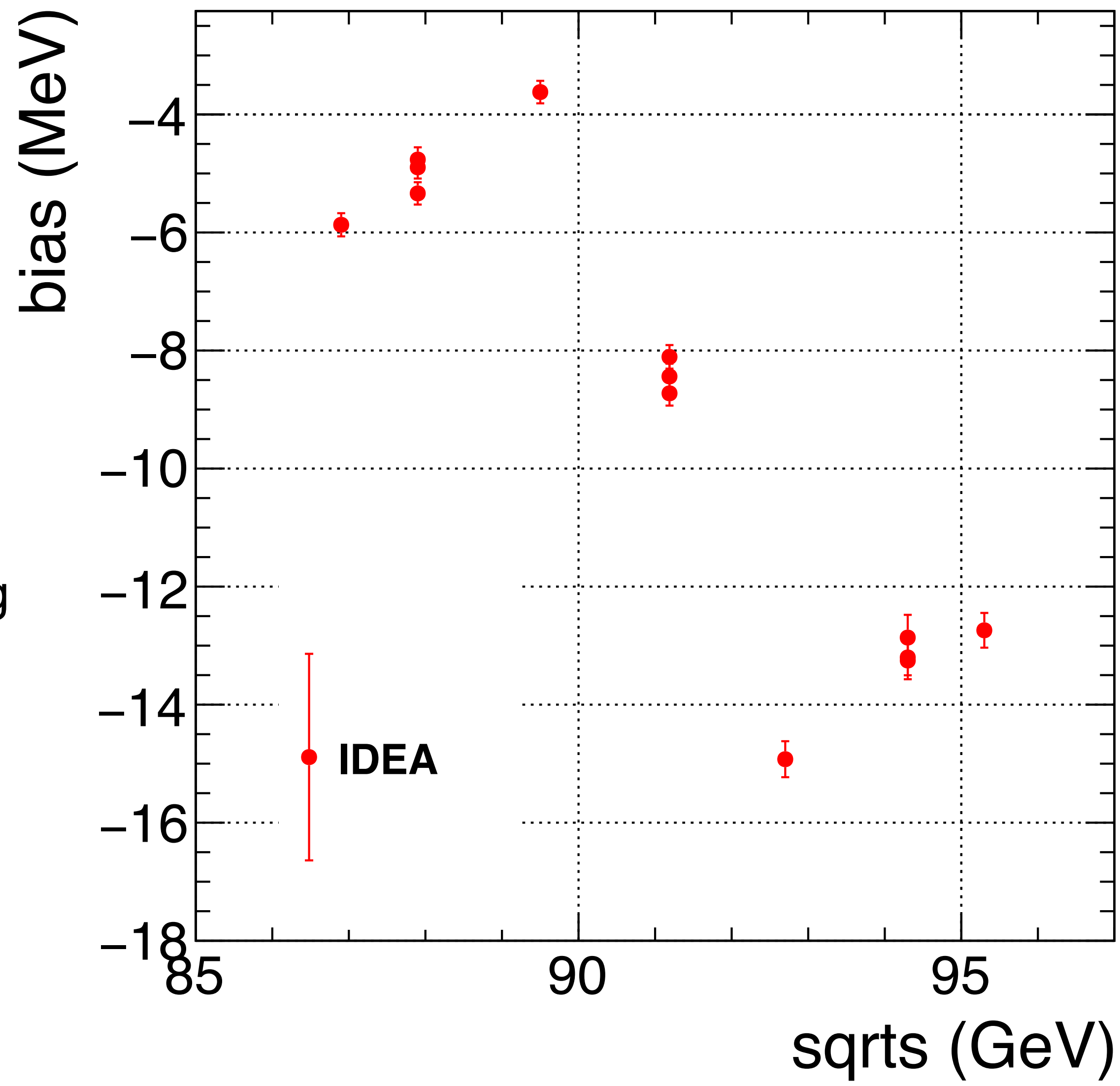
If the bias is known (e.g. from MC-based calibration) to better than that, one would know $\sqrt{s+} - \sqrt{s-}$ to ~ 28 keV from the difference < μ (s+) > - < μ (s-) >

The bias determination relies on MC modeling, esp. ISR. Need a good theoretical control, see later.

Dependence of the bias vs √s

Most of the dependence seems to come from the interplay of the Breit-Wigner with the Gaussian describing the BES (see slide 5).

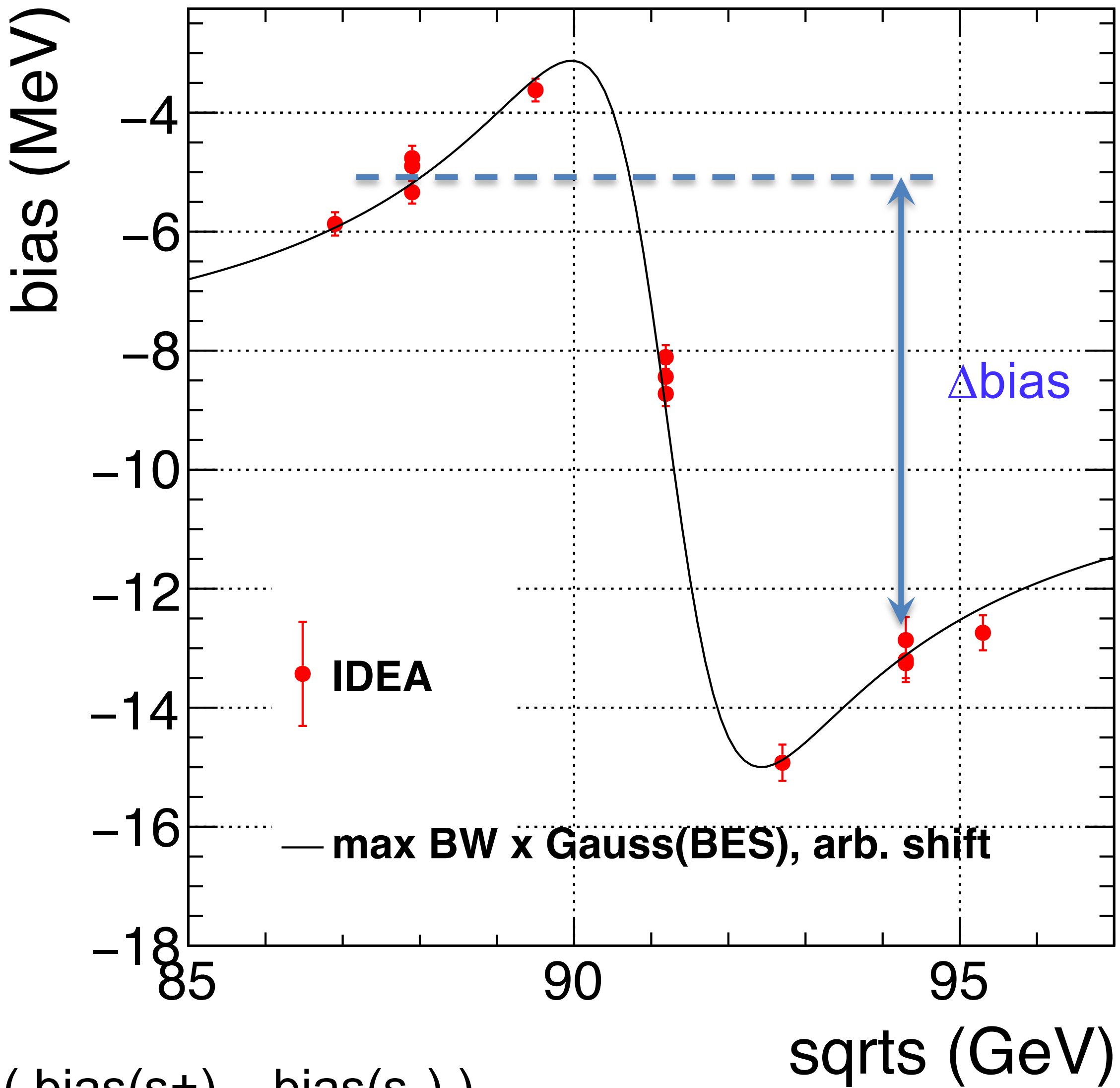
Same shape, modulo a constant shift.



Dependence of the bias vs √s (IDEA)

The derivative of this dependence can be used to assess the fact that the bias is locally constant (to much better than the ~ 200 keV that we get from the current MC statistics)

Constant to better than 1 keV when √s varies by +/- 100 keV.
Negligible w.r.t. stat. uncertainty on the proxy (~ 20 keV)

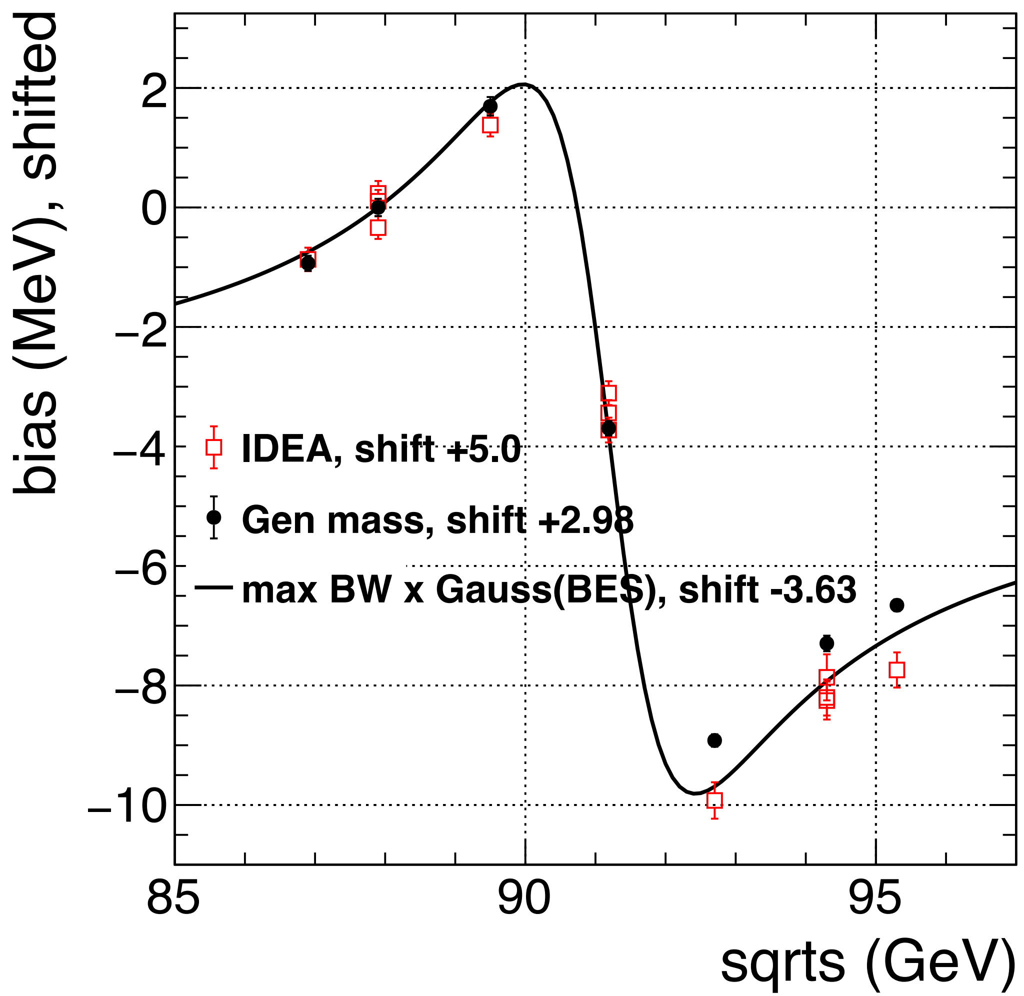


√s+ - √s- = μ (s+) – μ (s-) – (bias(s+) – bias(s-))
So what matters is Δbias between the two off-peak points.

Dependence of the bias vs √s

Shift all curves such that the shifted bias is zero at √s- = 87.9 GeV.
To which precision do we know the point at √s+ = 94.3 GeV ?

- Black symbols vs curve: difference between radiations and no radiation at all
- Red vs black symbols: difference between detector-level and gen-level

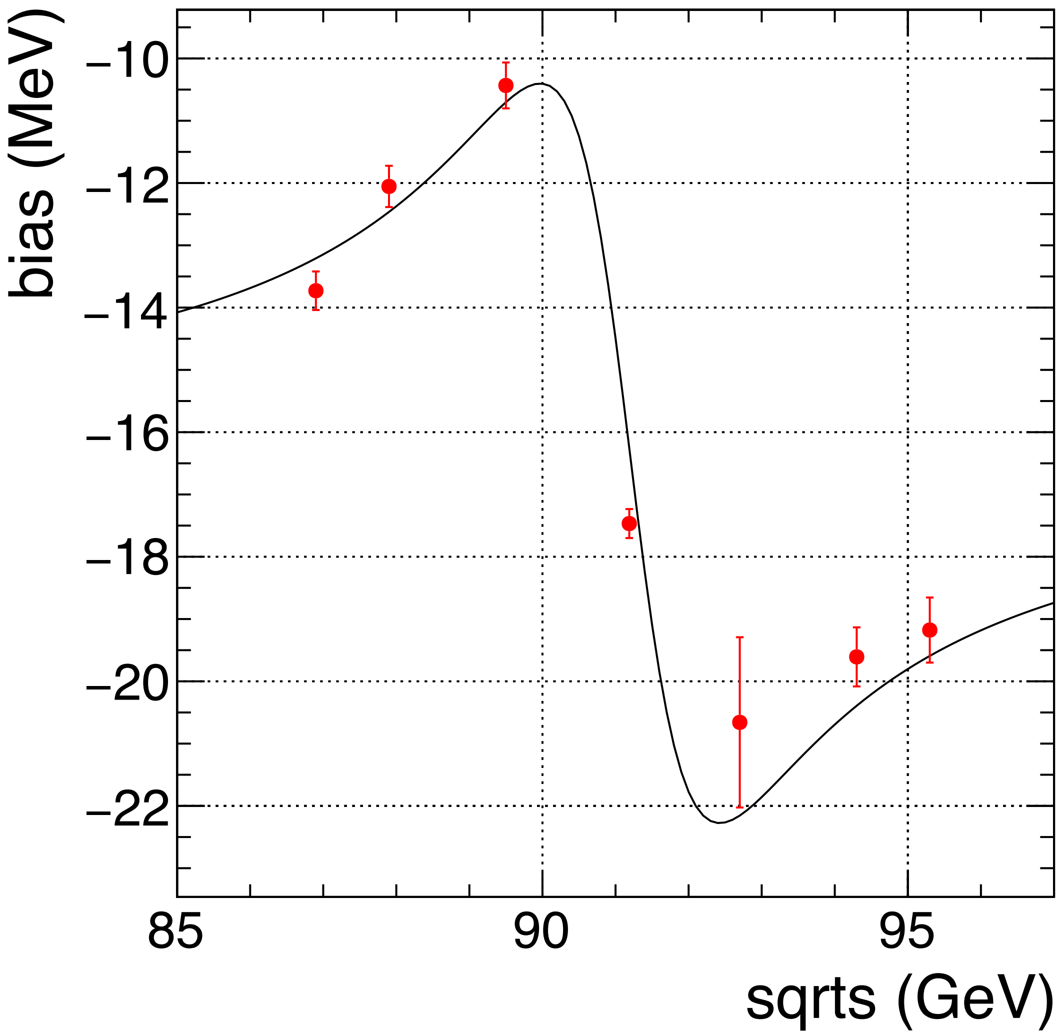


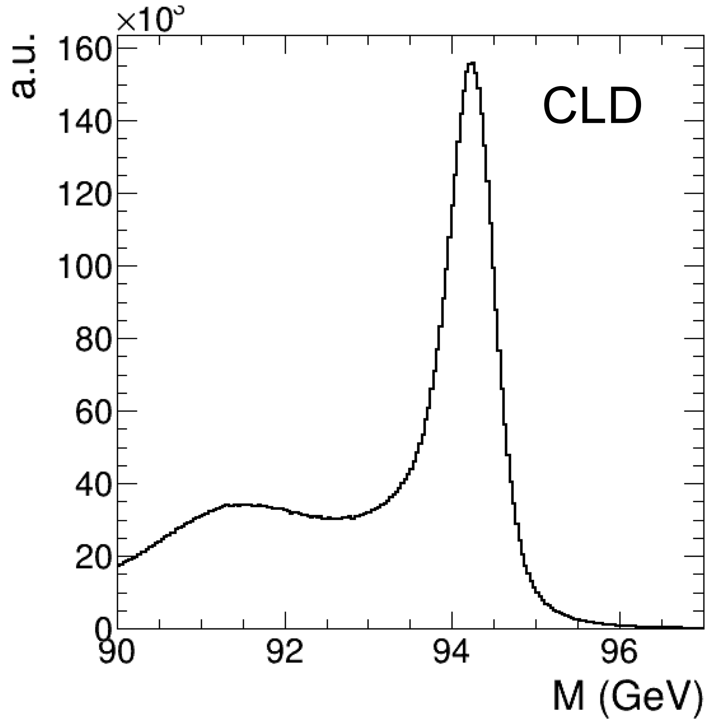
Full difference of ~ 500 keV.
Naively, would need to know the ISR/FSR effects and the detector response to 5% (1%) to ensure a systematic uncertainty on Δbias below 25 keV (5 keV).
Probably within reach.

CLD samples (Delphes)

Shifted by about -13 MeV compared to the fits to the IDEA samples.

NB: Difficult to fit at √s+ with this function with this exp. resolution. Limited lever-arm to fit the exp. tail w/o seeing the radiative return bump.





Conclusions and next steps

- Potential to control the point-to-point systematic uncertainty on sqrts to ~ 25 keV with the resolution of the IDEA tracker
  - Currently O(3x) worse with CLD samples (may be room for improvement from fit model)
  - Some sources of bias are not accounted for in Delphes (e.g muon energy loss in beam pipe). Should not be an issue for the relative bias anyway (t.b.c. e.g. with Bethe-Bloch formula)

- Requires that the momentum scale is stable to 25 keV / 100 GeV = a few 1e-7 !
  - NMR probes ? …
  - or in-situ, using low mass resonances
    - demands excellent momentum resolution for soft(er) tracks
    - may also put requirements on PID (e.g. for D0 -> K pi)
    - yet to be quantified