Measurement of the W mass and width at FCC-ee

LoI: #166

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Measurement of the W mass and width at FCC-ee

Contribution to Snowmass 2021

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https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF4_EF5_Paolo_Azzurri-166.pdf

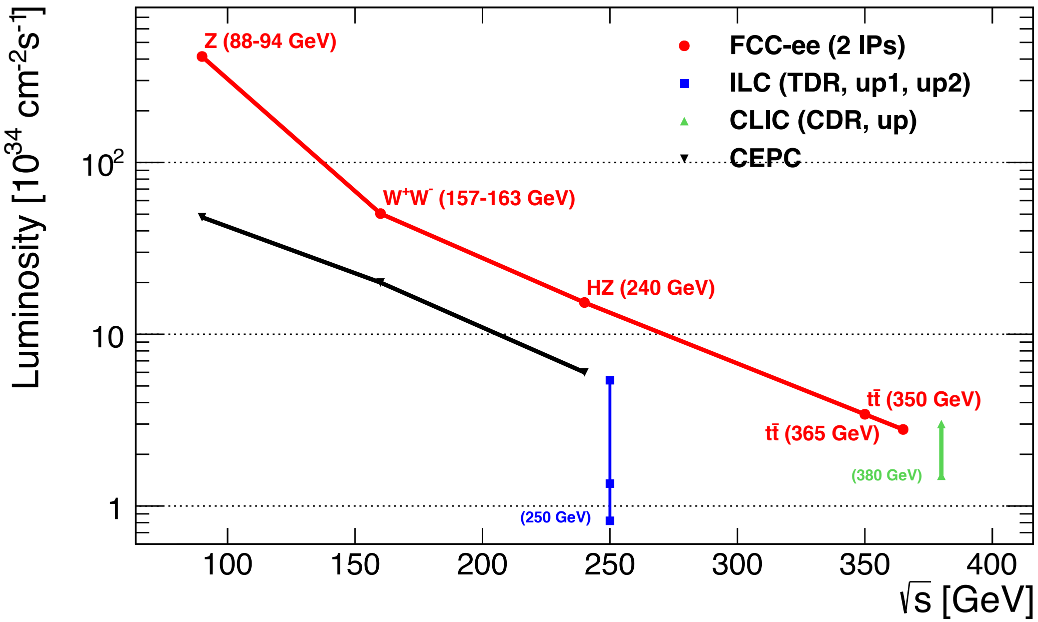
Two independent W mass and width measurements @FCCee :

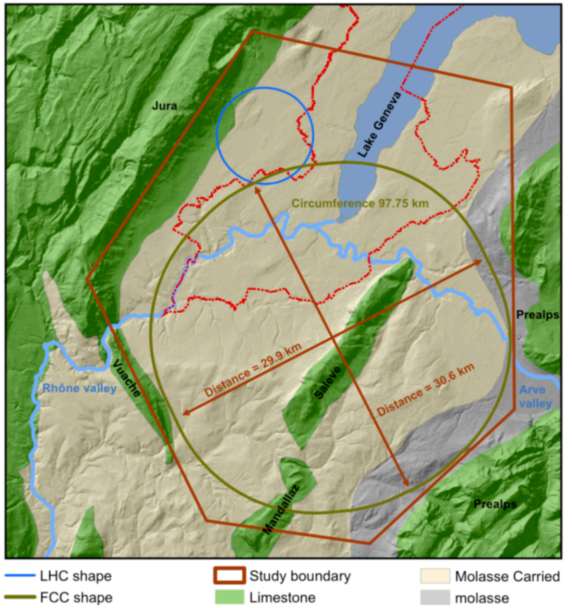
1. **The** m_W and Γ_W determinations from the WW threshold cross section lineshape, with 12/ab at $E_{CM} \simeq$ 157.5-162.5 GeV

2. Measurements of m_W and Γ_W from the decay products kinematics, with qqlv and 4q decays at $E_{CM} \simeq$ 162.5-240-365 GeV

P. A., The W mass and width measurement challenge at FCC-ee in A future Higgs and Electroweak factory (FCC): EPJ+ special issue, arXiv:2107.04444

The FCC-ee program





√s=162 GeV : L~3 10^{35} collect 12/ab
45-60 10^6 WW decays

$3 \cdot 10^5$ (LEP 161)

√s=240 GeV : L~0.7 10^{35} collect 5/ab
80 10^6 WW decays

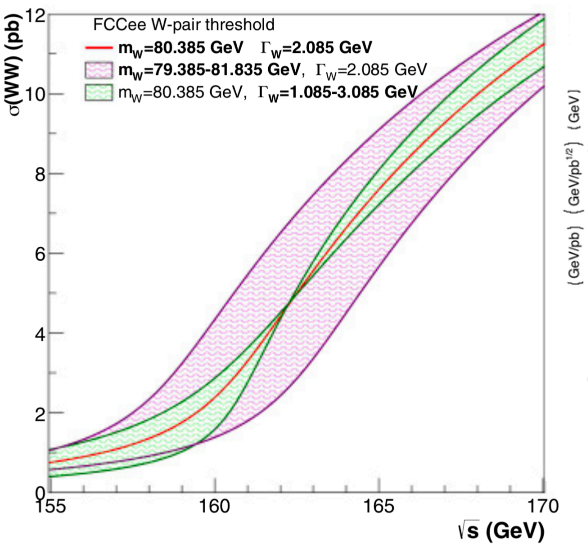
$2 \cdot 10^3$ (LEP 200)

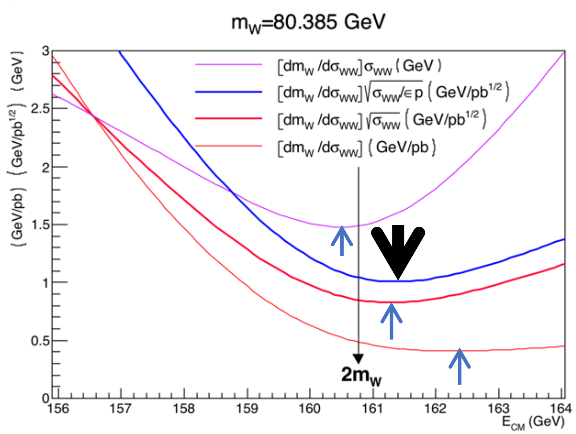
√s=365 GeV : L~ 10^{34} collect 1.65/ab
20 10^6 WW decays

In total ➔ **300 10^6 W decays**

WW threshold lineshape

arXiv:1703.01626
arXiv:1909.12245
CDR(V2) Eur. Phys. J. ST 228 (2019) 261
Eur.Phys.J.C 80 (2020) 1 (with CEPC)

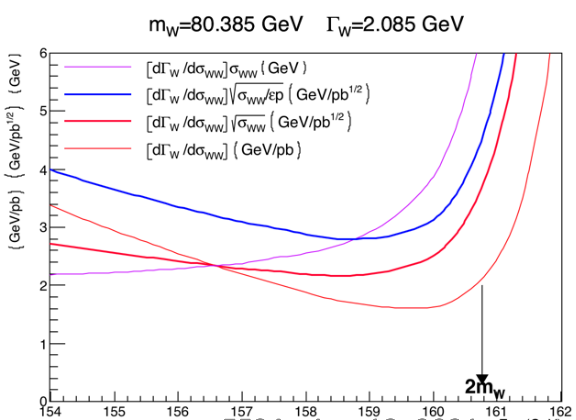




5/ab@**157.3** GeV
+7/ab@**162.6** GeV

Δm_W=0.5 MeV **$\Delta\Gamma_W$=1.2 MeV**

$(dm_W/d\sigma_{WW})_{min}$=0.5MeV/fb



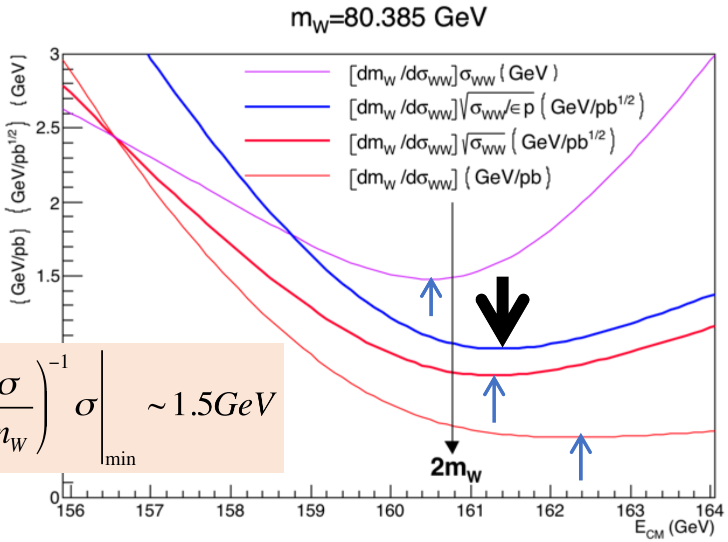
need syst control on :

- ΔE(beam)<0.5 MeV (**6x10^{-6}**)
- $\Delta\varepsilon/\varepsilon$, $\Delta L/L$ < **2 10^{-4}**
- $\Delta\sigma_B$<1 fb (2 **10^{-3}**)

Need to improve TH uncertainty to <1fb (2 **10^{-4}**)

WW threshold lineshape

$$\Delta m_W = \left(\frac{d\sigma}{dm_W}\right)^{-1} \Delta\sigma$$



$$\Delta m_W(stat) = \left(\frac{d\sigma}{dm_W}\right)^{-1} \frac{\sqrt{\sigma}}{\sqrt{L}} \frac{1}{\sqrt{\varepsilon p}}$$

$\sqrt{\varepsilon p}$ with fixed : $\varepsilon=0.75$ and $\sigma_B=0.3$pb

$$\left(\frac{d\sigma}{dm_W}\right)^{-1} \sigma \Big|_{min} \sim 1.5 GeV$$

$$\Delta\sigma_{WW} = \frac{\Delta\sigma_B}{\varepsilon}$$

$$\Delta m_W(B) = \left(\frac{d\sigma}{dm_W}\right)^{-1} \frac{\Delta\sigma_B}{\varepsilon}$$

$$\left(\frac{d\sigma}{dm_W}\right)^{-1} \Big|_{min} \sim 0.41 \frac{GeV}{pb}$$

$$\Delta\sigma_{WW} = \sigma\left(\frac{\Delta\varepsilon}{\varepsilon} \oplus \frac{\Delta L}{L}\right)$$

$$\Delta m_W(\varepsilon) = \sigma\left(\frac{d\sigma}{dm_W}\right)^{-1}\left(\frac{\Delta\varepsilon}{\varepsilon} + \frac{\Delta L}{L}\right)$$

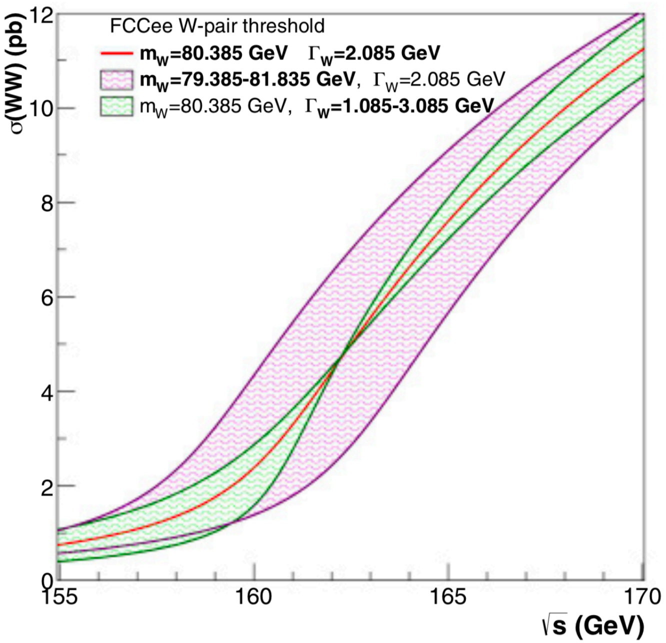
$$\left[\left(\frac{d\sigma}{dm_W}\right)^{-1} \frac{\sqrt{\sigma}}{\sqrt{\varepsilon p}}\right]_{min} \approx 1.01 \frac{GeV}{pb^{1/2}}$$

$$\Delta m_W(E) = \left(\frac{d\sigma}{dm_W}\right)^{-1}\left(\frac{d\sigma}{dE}\right)\Delta E \leq \frac{1}{2}\Delta E$$

Max stat sensitivity at
$\sqrt{s}=2m_W+600$ MeV = 161.4 GeV

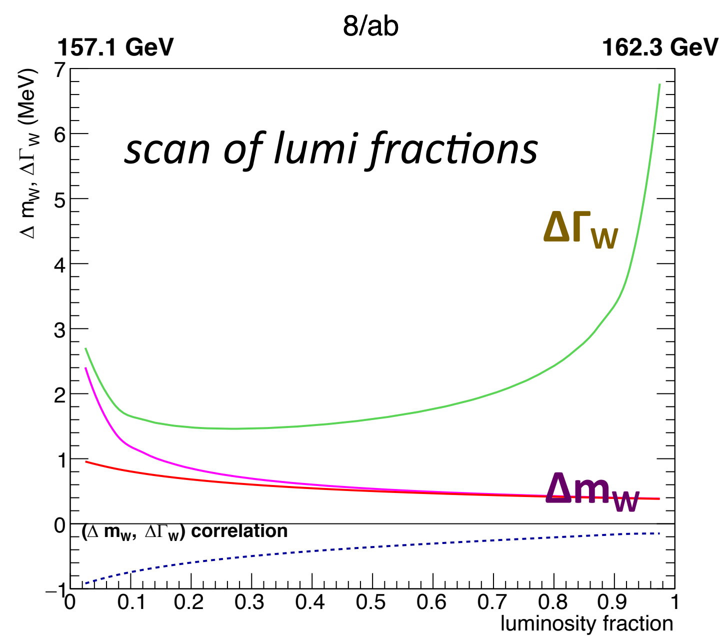
$$\Delta m_W(E_b) =\leq \Delta E_b$$

WW threshold lineshape



Measure σ_{WW} at two energy points E_1, E_2 with a fraction f of lumi in E_1
➔ measure both m_W & Γ_W

Determine f, E_1, E_2 such to mimimise ($\Delta\Gamma_W$, Δm_W) with some target

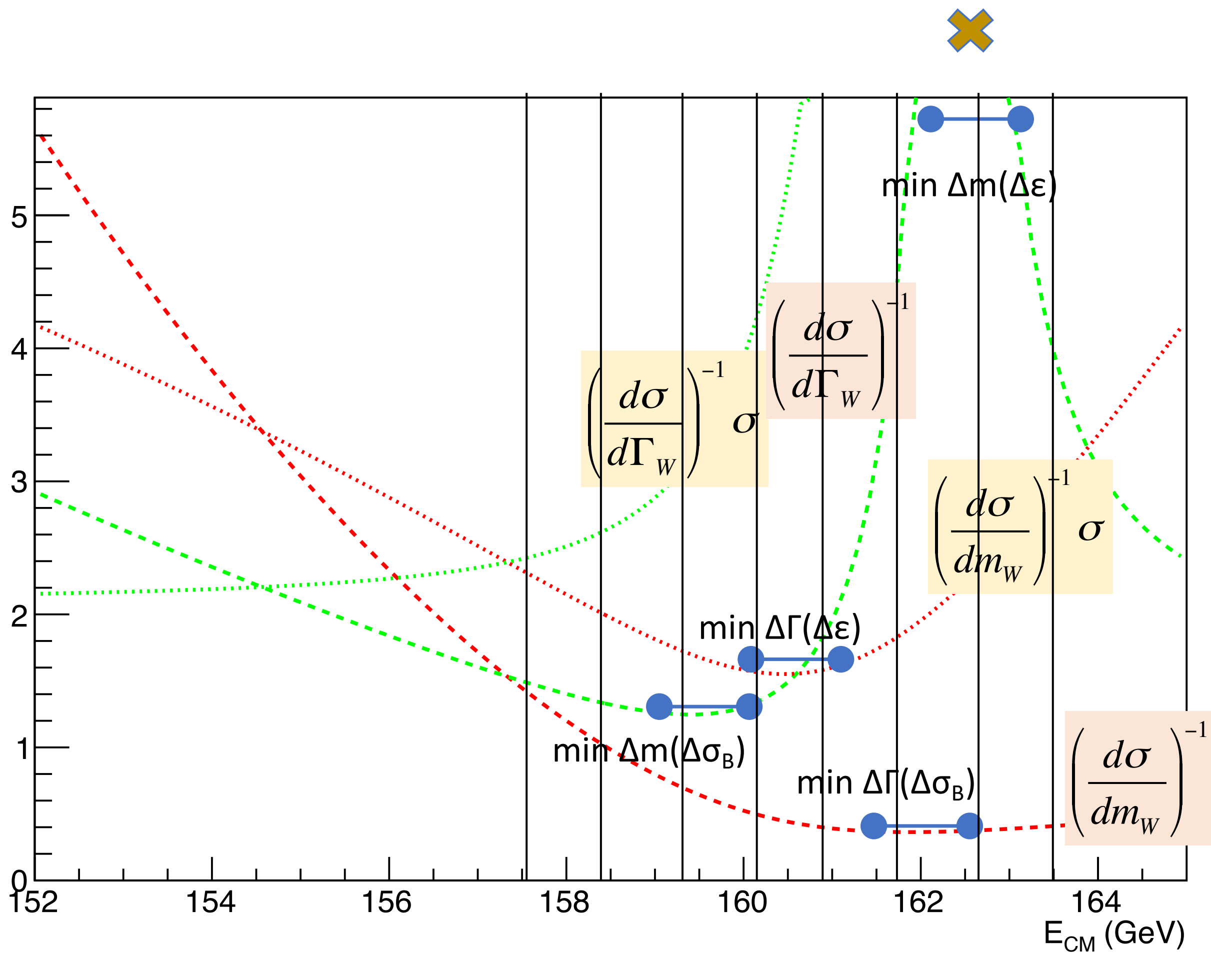


Δm_W , $\Delta\Gamma_W$: error on W mass and width from fitting both

Δm_W : error on W mass from fitting only m_W

m_W & Γ_W from σ_{WW}

optimal E points with limiting **correlated** systs



impact of **correlated** systs can cancel out taking data at more E_{CM} points where

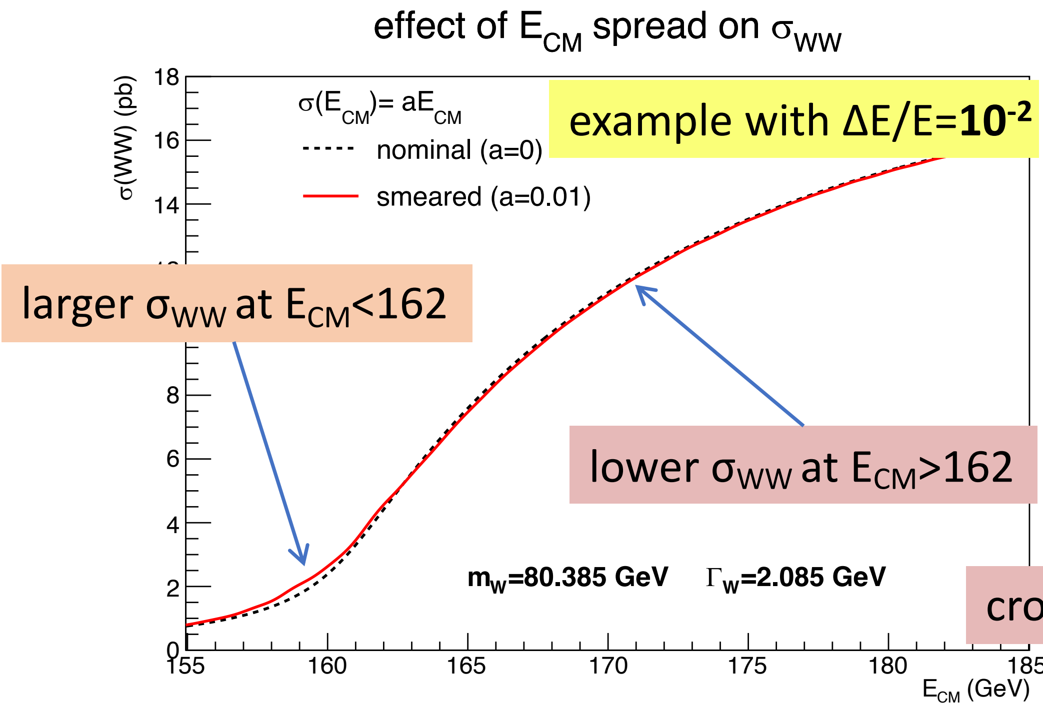
$$\left(\frac{d\sigma}{d\Gamma_W}\right)^{-1} \qquad \left(\frac{d\sigma}{dm_W}\right)^{-1}$$

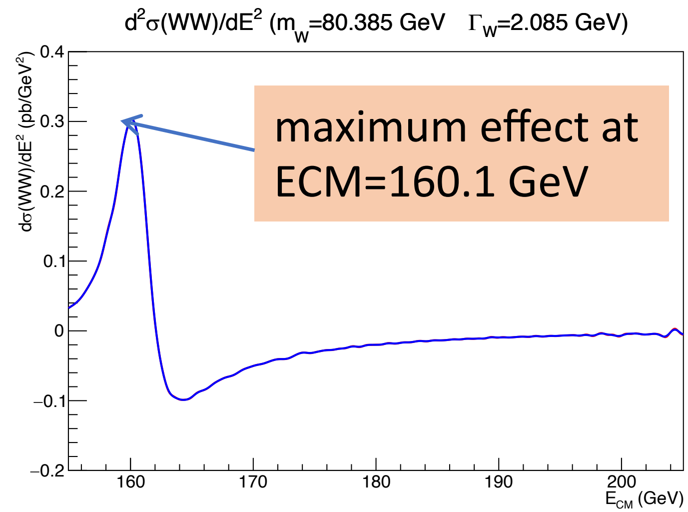
$$\left(\frac{d\sigma}{dm_W}\right)^{-1}\sigma \qquad \left(\frac{d\sigma}{d\Gamma_W}\right)^{-1}\sigma$$

differential factors are equal

optimal to take data at different E_{CM} points in the 159-163 range where the derivative factors are equal (around their minima)

beam energy spread





crossing point near the $d\sigma_{WW}/\Gamma_W=0$ point

$\sigma(E_{CM})=$**(0.47-1.10) 10^{-3}** E_{CM}

Optimal m_W & Γ_W points @E_{CM}=**157.3 & 162.6** GeV

➔ $\Delta\sigma_{WW}$ = +(0.24-1.3) fb & = -(0.18-1.0) fb

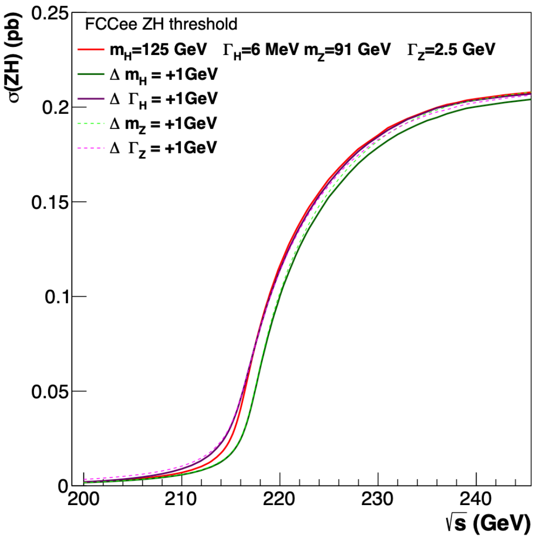
➔ **Δm_W = -(0.09-0.48) MeV**

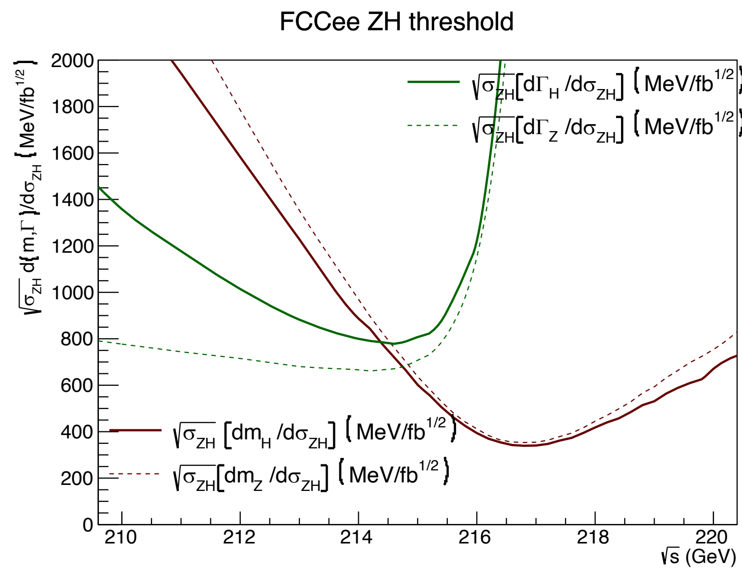
➔ **$\Delta\Gamma_W$ = +(0.6-3.3) MeV**

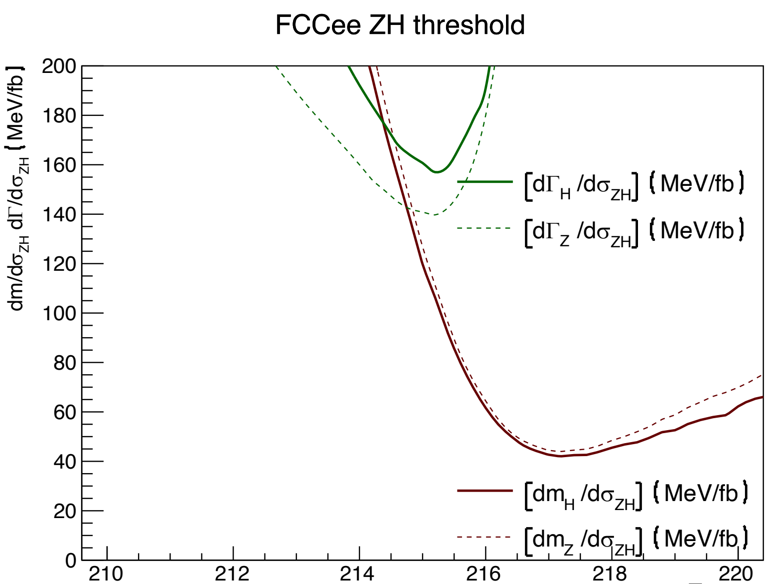
Maximum effects are at the level of Δm_W(stat) and 2x $\Delta\Gamma_W$ (stat) so that control on the beam energy RMS <50% is required to avoid additional syst contributions from this source

interlude : the ZH threshold

On the way to the electron-Yukawa







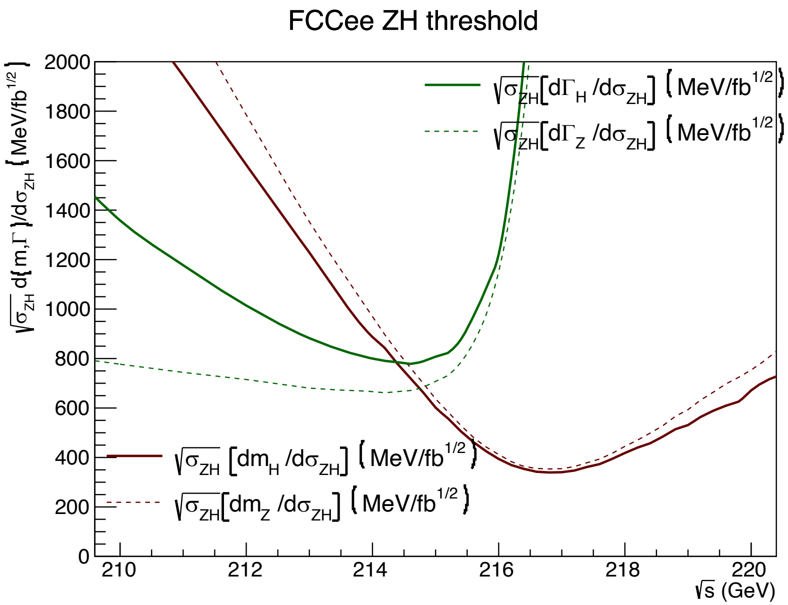
Optimal data-taking point for min **Δ**m_H(stat)
Is $E_{CM} \simeq m_Z + m_H + 0.6 \sim$ **217 GeV**

$\sqrt{\sigma_{ZH}}(dm_H/d\sigma_{ZH})_{min}$=350 MeV/√fb

With **5/ab ⇒ Δm_H(stat) = 5 MeV**
Not including $Q=\sqrt{\sum \varepsilon_i p_i}$ (over all channels)

$(dm_H/d\sigma_{ZH})$=40 MeV/fb

interlude : the ZH threshold

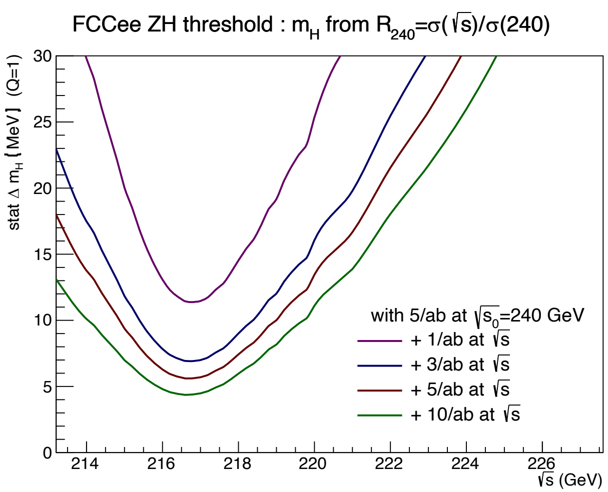


need syst control on :

- ΔE(beam)<5 MeV (**5×10^{-5}**)
- $\Delta\varepsilon/\varepsilon$, $\Delta L/L <$ **10^{-3}**
- $\Delta\sigma_B$<0.1 fb (~**10^{-3}**)

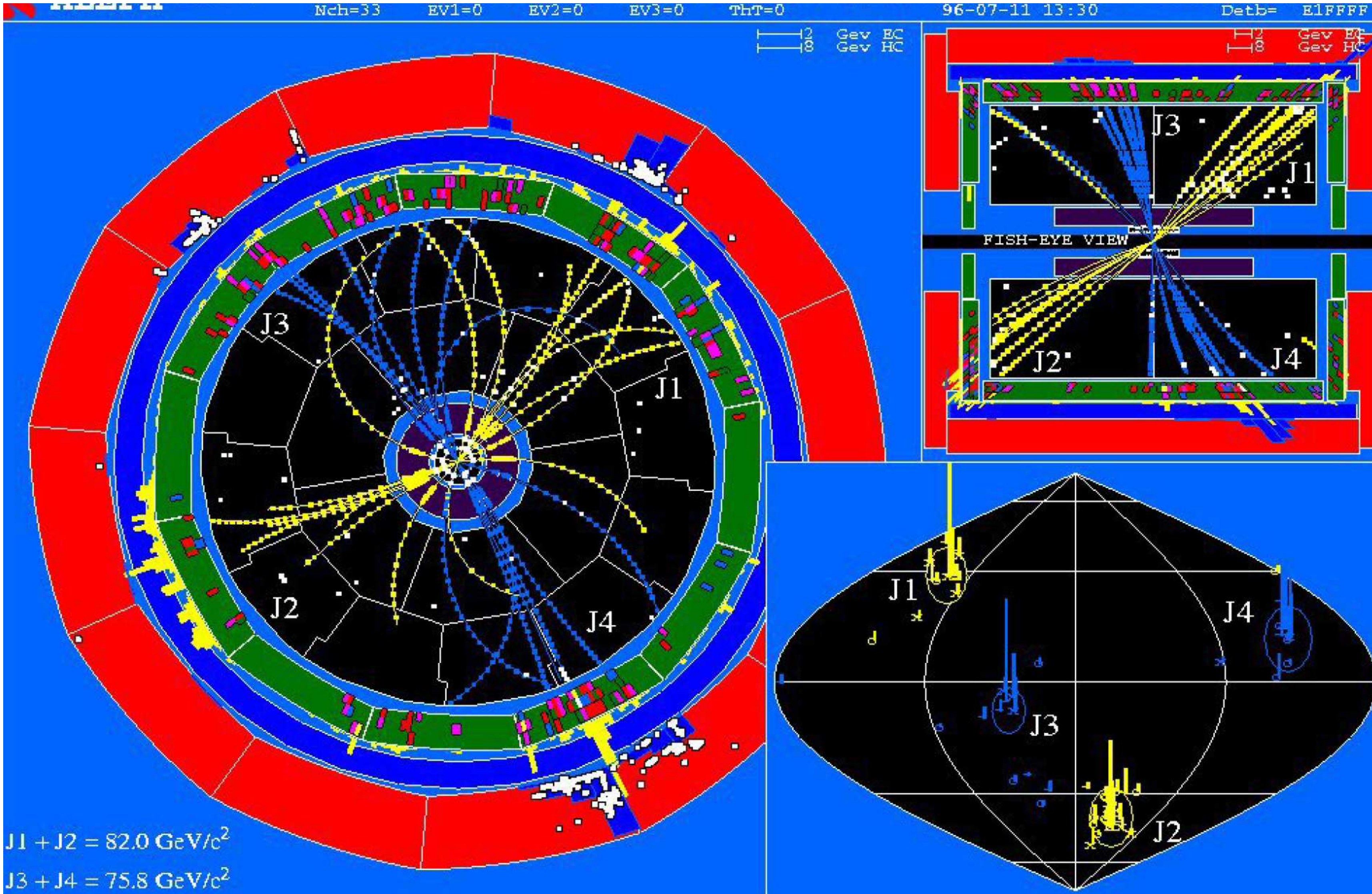
Taking some /ab at $E_{CM}\simeq$214-215GeV (off shell) should be sensitive to $\boldsymbol{\Delta\Gamma}_H\simeq$40 MeV

$\Longrightarrow$ *not very interesting*



[arXiv:2106.15438](https://arxiv.org/abs/2106.15438)
submitted to EPJ+

W kinematic reconstruction

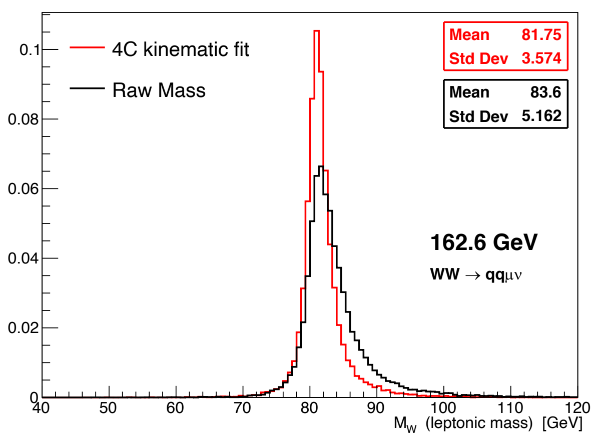


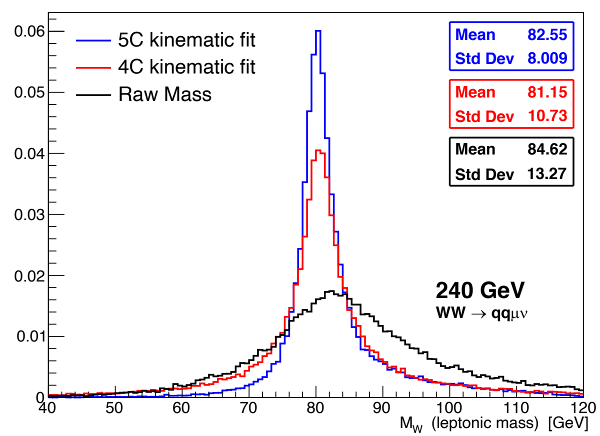
W kinematic reconstruction

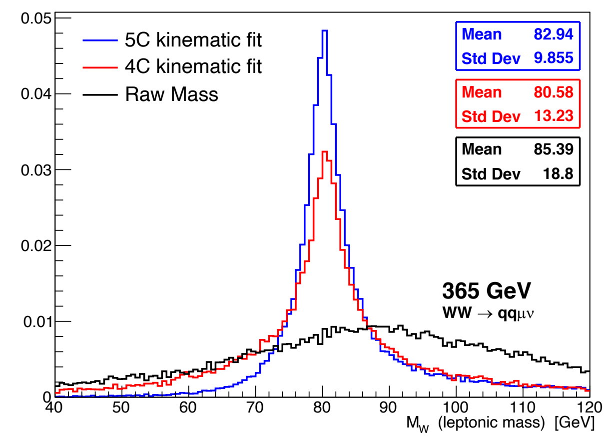
12/ab @157-162 GeV : **50 10^6 WW**
5/ab @240 GeV : **80 10^6 WW**
1.65/ab@365 GeV: **20 10^6 WW**
Total ~150M WW

$$M_Z^2 = s\frac{\beta_1 \sin\theta_1 + \beta_2 \sin\theta_2 - \beta_1\beta_2|\sin(\theta_1+\theta_2)|}{\beta_1 \sin\theta_1 + \beta_2 \sin\theta_2 + \beta_1\beta_2|\sin(\theta_1+\theta_2)|}$$

θ, β: jet polar angles and velocities





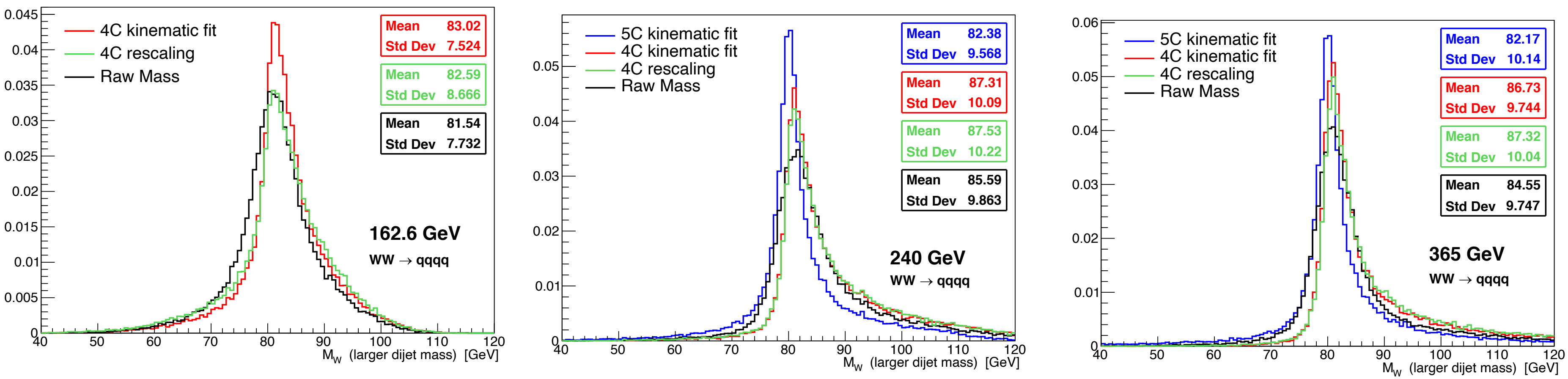


M. Béguin, PhD thesis https://cds.cern.ch/record/2710098
PA, M. Béguin, E.Locci *PoS* EPS-HEP2019 (2020) 653
https://doi.org/10.22323/1.364.0653

➔ Δm_W (stat) ~ 0.5 MeV
➔ $\Delta\Gamma_W$ (stat) ~ 1 MeV

W kinematic reconstruction

fully hadronic channel



Preliminary studies of FSI effects and how to reduce their impact
Jet reconstructions with cone / momentum cuts degrade stat precision by 4%-10%-15% at 162 – 240 – 365 GeV, reducing sensitivity on FSI effects by factors 2-3.

M. Béguin, PhD thesis https://cds.cern.ch/record/2710098
PA, M. Béguin, E.Locci *PoS* EPS-HEP2019 (2020) 653
https://doi.org/10.22323/1.364.0653

➔ Δm_W (stat) ~ 0.5 MeV
➔ $\Delta\Gamma_W$ (stat) ~ 1 MeV

W kinematic reconstruction

ΔE_{CM}=0.3 MeV at E_{CM}=162GeV with Resonant depolarization

$$M_Z^2 = s\frac{\beta_1 \sin\theta_1 + \beta_2 \sin\theta_2 - \beta_1\beta_2|\sin(\theta_1+\theta_2)|}{\beta_1 \sin\theta_1 + \beta_2 \sin\theta_2 + \beta_1\beta_2|\sin(\theta_1+\theta_2)|}$$

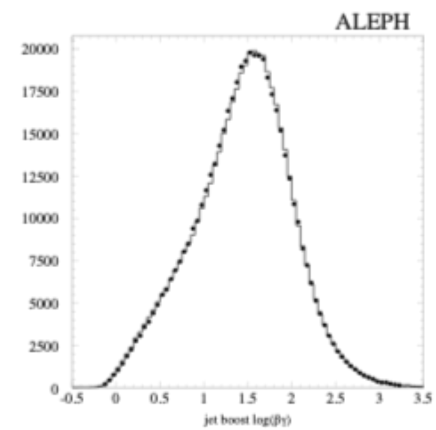
How to obtain ΔE_{beam}~1MeV at E_{CM}=240-365 GeV ?
Can make use of radiative Z-returns (Zγ) and ZZ events

What about other syst ?

Table 9: Summary of the systematic errors on m_W and Γ_W in the standard analysis averaged ove 183-209 GeV for all semileptonic channels. The column labelled $\ell\nu q\bar{q}$ lists the uncertainties in m_W use in combining the semileptonic channels.

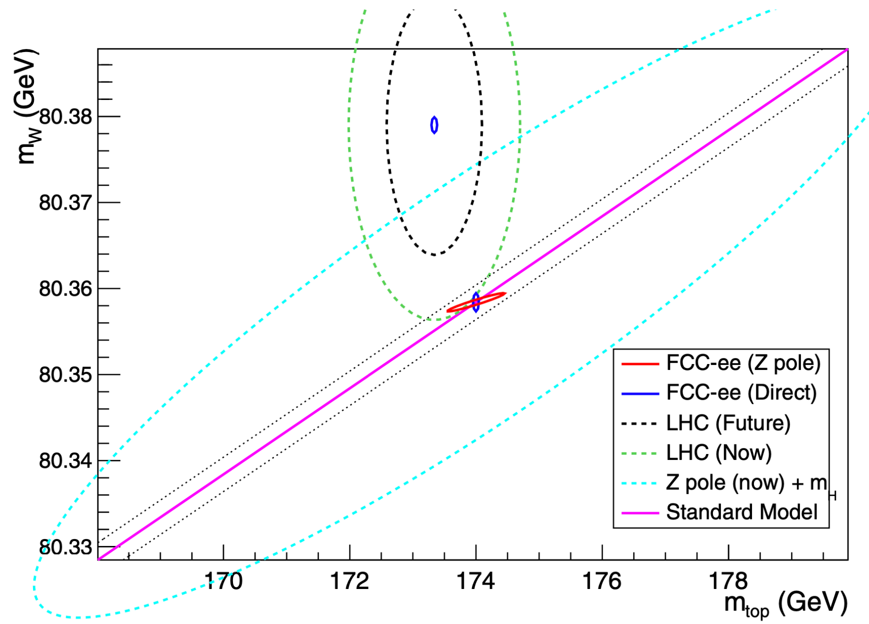
	Δm_W (MeV/c^2)				$\Delta\Gamma_W$ (MeV)			
Source	$e\nu q\bar{q}$	$\mu\nu q\bar{q}$	$\tau\nu q\bar{q}$	$\ell\nu q\bar{q}$	$e\nu q\bar{q}$	$\mu\nu q\bar{q}$	$\tau\nu q\bar{q}$	$\ell\nu q\bar{q}$
e+μ momentum	3	8	-	4	5	4	-	4
e+μ momentum resoln	7	4	-	4	65	55	-	50
Jet energy scale/linearity	5	5	9	6	4	4	16	6
Jet energy resoln	4	2	8	4	20	18	36	22
Jet angle	5	5	4	5	2	2	3	2
Jet angle resoln	3	2	3	3	6	7	8	7
Jet boost	17	17	20	17	3	3	3	3
Fragmentation	10	10	15	11	22	23	37	25
Radiative corrections	3	2	3	3	3	2	2	2
LEP energy	9	9	10	9	7	7	10	8
Calibration ($e\nu q\bar{q}$ only)	10	-	-	4	20	-	-	9
Ref MC Statistics	3	3	5	2	7	7	10	5
Bkgnd contamination	3	1	6	2	5	4	19	7

lepton and jet uncertainties from (Z) calibration data



FCCee EW physics summary

- Core repetition of the LEP physics program with large **precision improvements (x20-500) capabilities, and a large number of additional opportunities** given the huge luminosity and higher collision energies
  - Z mass and width, $\boldsymbol{\alpha}_{QED}(m_Z)$, $N_{\boldsymbol{\nu}}$
  - R_ℓ , $\boldsymbol{\alpha}_S(m_Z)$, R_b , R_c , ..
  - A_{FB}, $\sin^2\theta_{eff}$
  - W mass and width (threshold and kinematic)
  - Direct W universality and CKM elements
  - Gauge couplings
  - Multiboson productions and scattering
  - Z radiative returns (Direct invisible Z width)
  - ....



- Work still ongoing to evaluate with more care all possibilities, design the measurements, estimate (limiting) systematics, study ways to overcome them, and reflect on the detector design requirements