WG4 – Status and Goals

- **WG4 = (EPOL) Measurements in particle-physics experiments**
  - Status of
    - Centre-of-mass energy absolute determination
    - Centre-of-mass energy relative determination (a.k.a. point-to-point)
    - Crossing angle and centre-of-mass energy
    - Centre-of-mass energy
    - Absolute angle determination
    - QED predictions

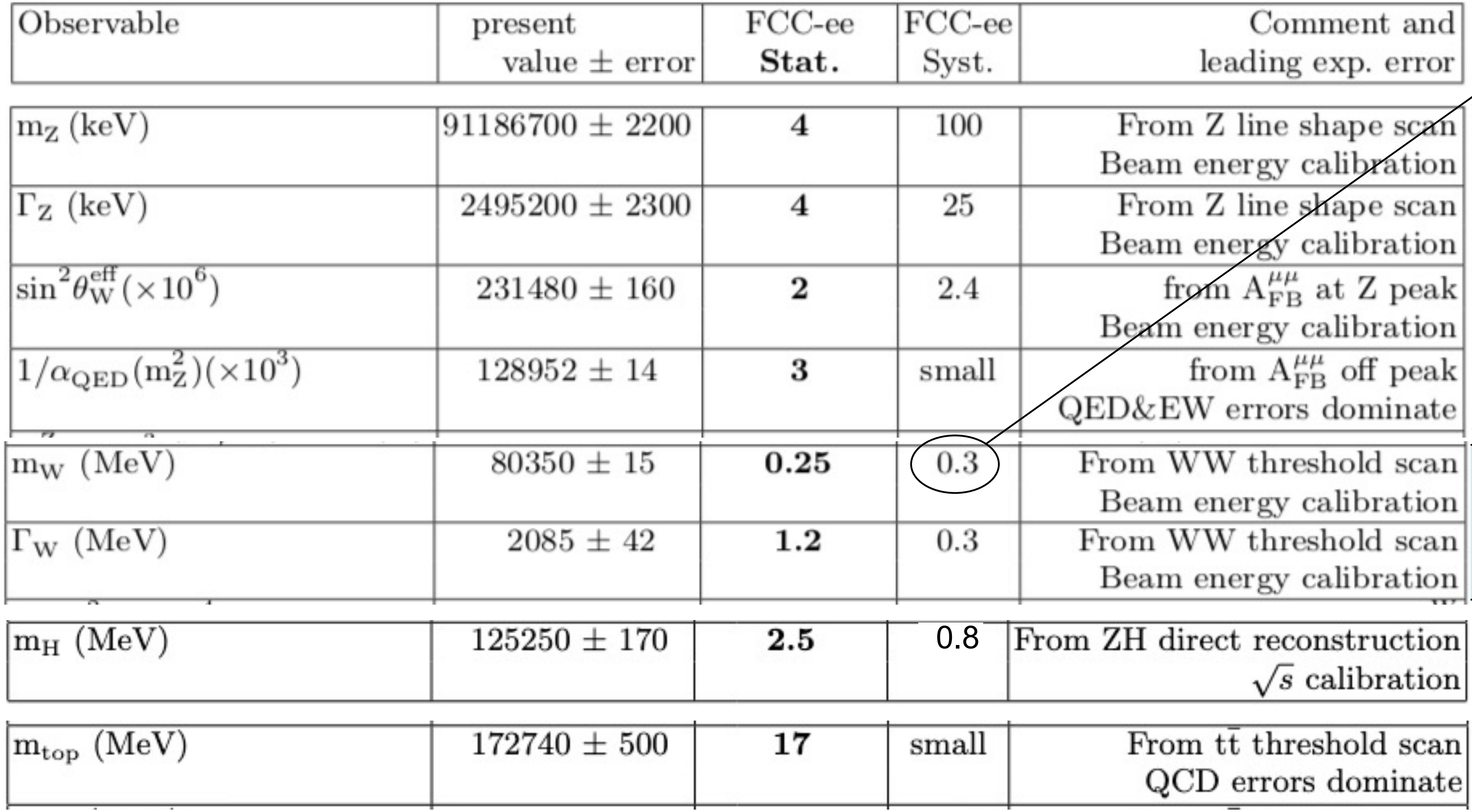
Status mostly unchanged since arXiv:1909.12245

  - Main goal of the workshop : Get new and young physicists interested in these studies
    - Restart, reproduce, improve, and complete existing studies
    - Develop new studies to improve the precision
  - Main goals of these studies
    - Precision EW / Higgs / top measurements

FCC-ee precision measurements

- **Strong √s dependence at all centre-of-mass energies!**

Table from arXiv:2106.13885

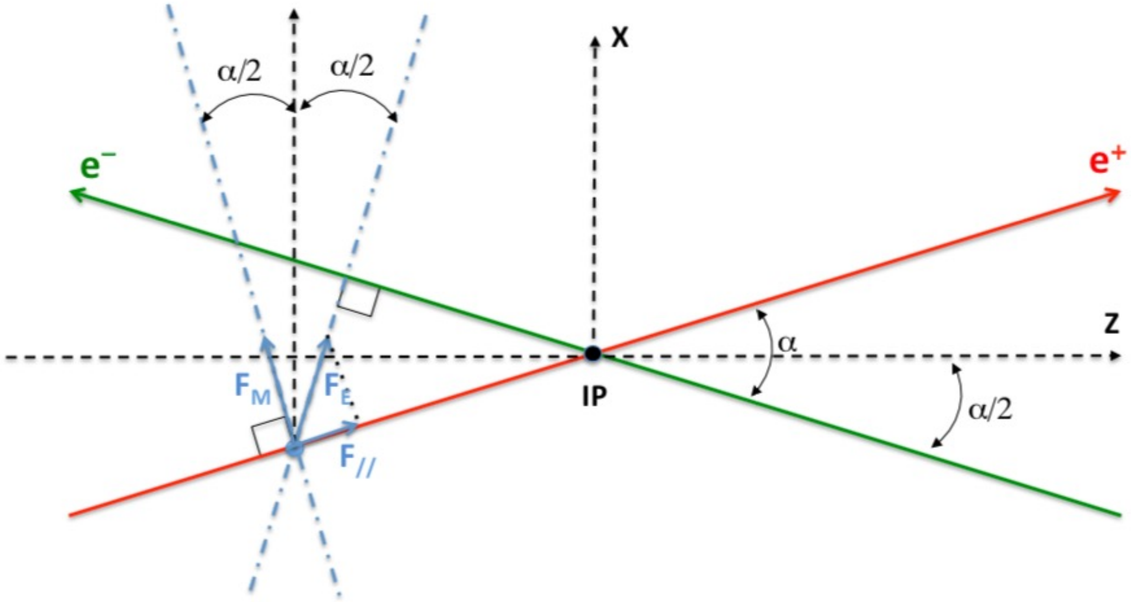


	Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error	
√s	m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration	$\sqrt{s} \sim m_Z$
Spread	Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration	
√s	$\sin^2\theta_W^{\text{eff}} (\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration	
Spread	$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate	
√s	m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration	$\sqrt{s} \sim 2m_W$
Spread	Γ_W (MeV)	2085 ± 42	**1.2**	0.3	From WW threshold scan Beam energy calibration	
√s	m_H (MeV)	125250 ± 170	**2.5**	0.8	From ZH direct reconstruction $\sqrt{s}$ calibration	$\sqrt{s} \sim 240$ GeV
√s	m_{top} (MeV)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate	$\sqrt{s} \sim 2\, m_{top}$

Or is it 0.15 MeV?

Centre-of-mass energy $\sqrt{s}$

- Beams cross at an angle α in the horizontal plane



$$\sqrt{s} = 2\sqrt{E_e^+ E_e^- \cos\frac{\alpha}{2}}$$

$$e^+\left(E_e^+ \sin\frac{\alpha}{2}, 0, \quad E_e^+ \cos\frac{\alpha}{2}, E_e^+\right)$$

$$e^-\left(E_e^- \sin\frac{\alpha}{2}, 0, -E_e^- \cos\frac{\alpha}{2}, E_e^-\right)$$

- Measure E_e^+ and E_e^- with Resonant Depolarization at $\sqrt{s} \sim m_Z$ and $2m_W$
  - Requires the measurement of the crossing angle α (either in situ, or "directly)
    - ➔ WATCH OUT: α and $E_e^\pm$ change when approaching the IP due to beam-beam "attraction"

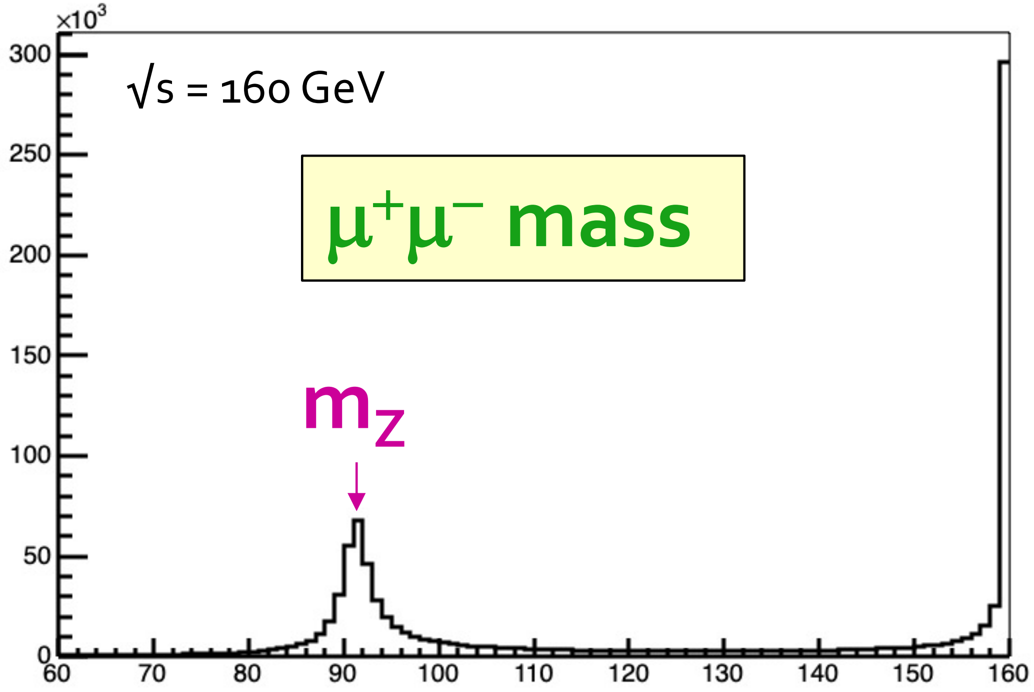
See Emmanuel Perez' talk
on Wednesday 21/09

- AND/OR Measure $\sqrt{s}$ in situ with particle physics events

In situ √s measurements

See Graham Wilson's talk on Wednesday 21/09
Also arXiv:2209.03281

- **Above the Z pole (including at the WW threshold)**
  - First possibility : use radiative returns to the Z pole, e.g., $e^+e^- \to \mu^+\mu^- (\gamma)$ ← Initial state radiation



Four energy-momentum conservation equations

$$\begin{aligned}
E^+\sin\theta^+\cos\varphi^+ + E^-\sin\theta^-\cos\varphi^- + |p_z^\gamma|\tan\alpha/2 &= \sqrt{s}\tan\alpha/2,\\
E^+\sin\theta^+\sin\varphi^+ + E^-\sin\theta^-\sin\varphi^- &= 0,\\
E^+\cos\theta^+ + E^-\cos\theta^- + p_z^\gamma &= \sqrt{s}\,\varepsilon,\\
E^+ + E^- + |p_z^\gamma|/\cos\alpha/2 &= \sqrt{s}/\cos\alpha/2,
\end{aligned}$$

$(with\ \varepsilon = \dfrac{E_e^+ - E_e^-}{E_e^+ + E_e^-}$, and with terms in ε^2 neglected: $s \to s(1-\varepsilon^2)$)

One mass constraint (m_Z)

Five unknowns (p_z^γ, ε, E^+, E^-, $\sqrt{s}$)

- In principle, can easily obtain √s just from the muon angle measurements
  - Exercise : Establish the above equations, and solve them, e.g., for √s !

In situ √s measurements

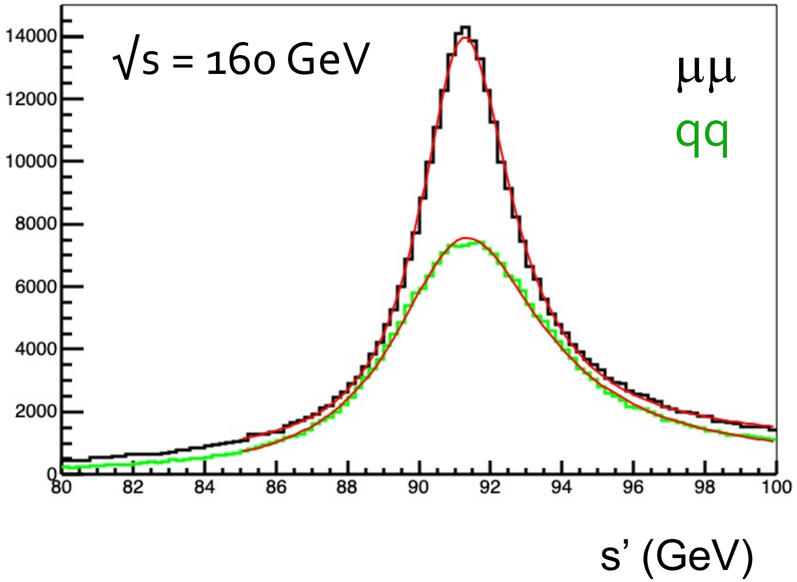
- **First estimates with radiative returns: muons, electrons, taus, and jets can be used.**
  - Muons: momenta above 10 GeV, polar angle above 10 degrees from the z axis
    - Use MC truth and smear muon angles by 0.1 mrad, s' between 80 and 100 GeV
  - Jets: Energies above 20 GeV, polar angle above 25 degrees from the z axis
    - Use MC truth and smear quark angles by 15 mrad, s' between 80 and 100 GeV

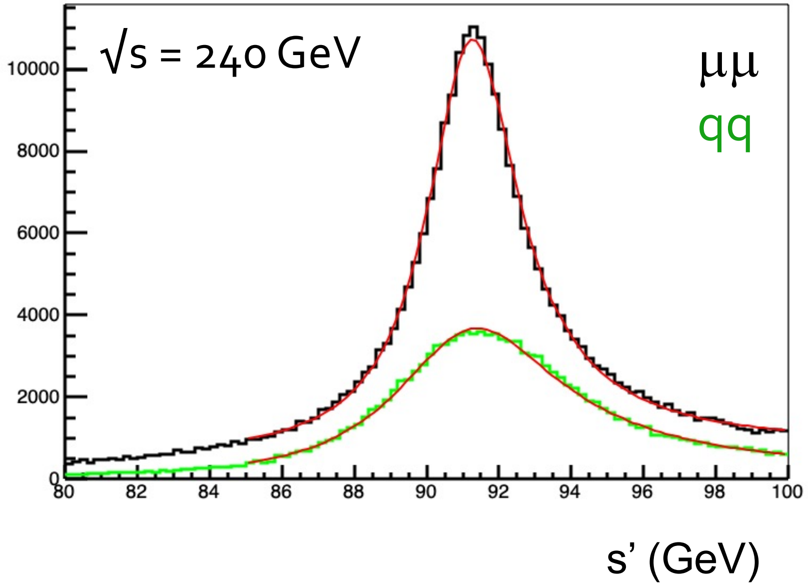
	$\sqrt{s}$	E_γ (GeV)	$N_{\mu\mu}$ ($\times 10^6$)	N_{qq} ($\times 10^6$)	$\sigma_{\sqrt{s}}$ ($\mu\mu$)	$\sigma_{\sqrt{s}}$ (qq)	$\sigma_{\sqrt{s}}$ (EPOL)
12 ab^{-1}	$2m_W$	54	47	667	**900 keV**	**340 keV**	**300 keV**
5 ab^{-1}	240 GeV	102	5.6	53	**4.2 MeV**	**2.4 MeV**	–
0.2 ab^{-1}	$2m_{top}$	163	0.1	0.3	**51 MeV**	**60 MeV**	–

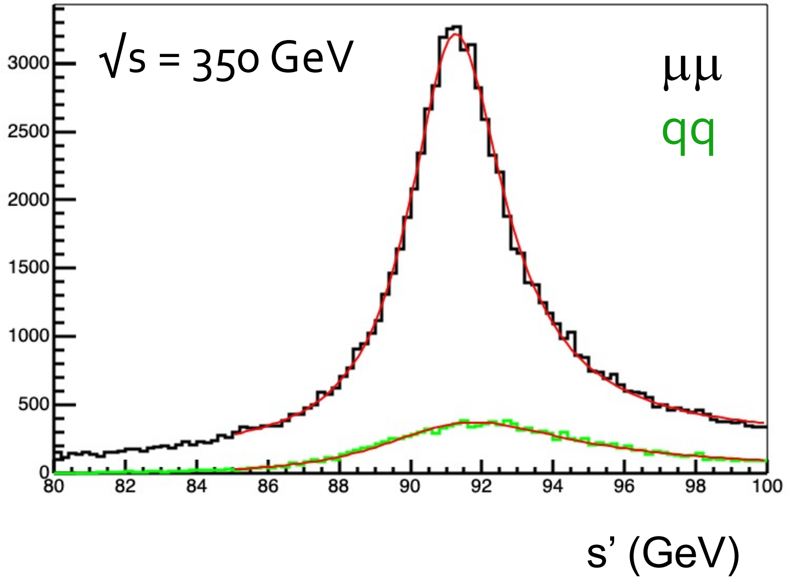
  - Bonus: RDP available at the WW threshold, with similar precision (300 keV vs 280 keV)
    - RDP can be used to calibrate / validate the radiative return method
      - ➔ And then use it at 240/350 GeV with confidence (1.7 / 25 MeV combined precision)

In situ √s measurements

- ❑ Examples of dimuon and dijet mass distributions (all done with 10^6 events)







s' = effective e^+e^- centre-of-mass energy after ISR

- ◆ Same fitting formula for all distributions (BW * 2nd order polynomial)
  - Systematic understanding at √s = 160 GeV may translate well to √s = 240 GeV
    - ➔ Understanding of initial state radiation is crucial here: is its theoretical description already sufficient ?

      Multi-photon emission, photon energy spectrum, photon angular distribution

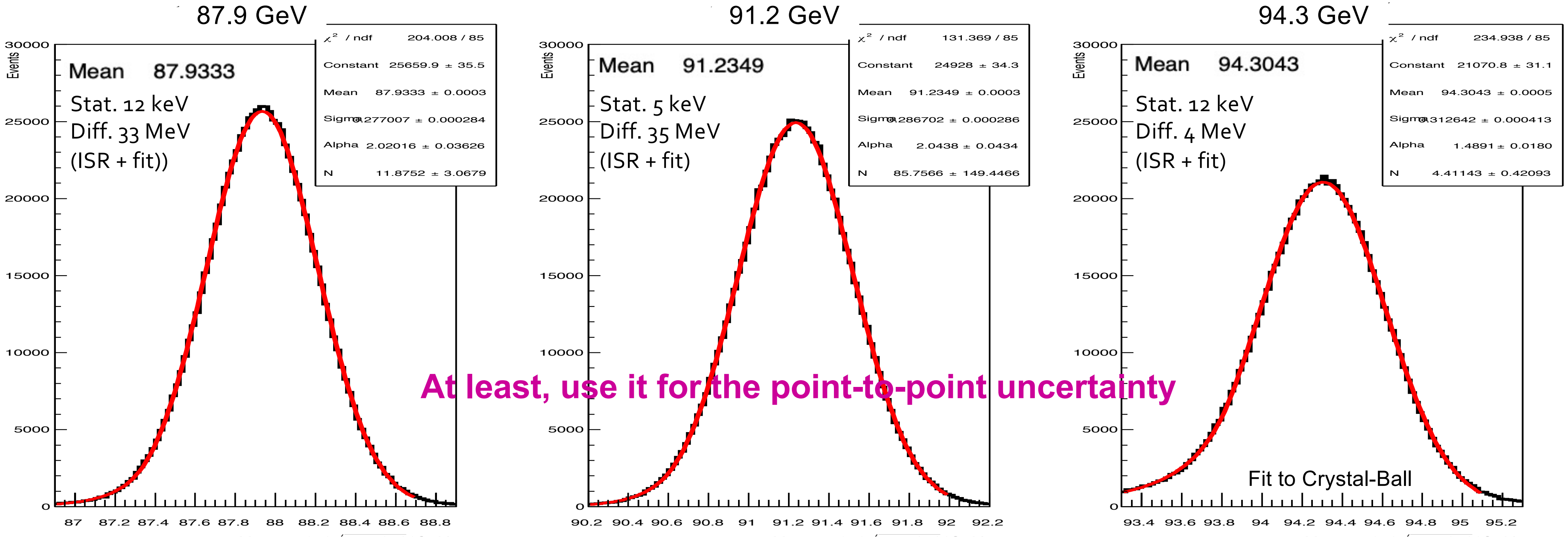
In situ √s measurements

- At the top-pair threshold, use the 2 million WW events (+E,p conservation)
  - With known √s, can be used to measure the W mass with a statistical precision of 2.2 MeV
    - And even 1.1 MeV with the fully hadronic final state
      - ➔ See Marina Béguin's thesis : https://tel.archives-ouvertes.fr/tel-02490574
  - Alternatively, with a known m_W (from the threshold measurement)
    - Can be used to measure √s with a precision of 10 MeV (5 MeV)
      - ➔ Which translates to a top mass systematic uncertainty of 5 MeV (2.5 MeV)
  - According to Marina's thesis, the W mass is best measured at the WW threshold
    - With the cross-section lineshape (all final states used)
    - With direct reconstruction (from the lepton momentum with the semi-leptonic final state)
      - ➔ Study performed with DELPHES, and its CLD parameterization
  - The colour reconnection effects in the fully hadronic final state should be controllable (?)
    - To better than 1 MeV with 100 million WW events collected at √s = 240 GeV
      - ➔ Maybe also use ZZ events in the fully hadronic final state + knowledge of the Z mass?

In situ √s measurements

- At the Z pole, complement the RDP measurement with $e^+e^- \to \mu^+\mu^- (\gamma)$
  - No radiative return to the Z (!), and therefore no Z mass constraint
    - The Z pole data are used to measure the Z mass, anyway ☺
  - Need to inject the muon momenta in the four energy-momentum conservation equations
    - With MC truth and smeared momenta according to $\Delta(1/p_T) / (1/p_T) = 4.10^{-3}$ (typical of CLD)

RMS dominated by muon momentum resolution



Mean 87.9333
Stat. 12 keV
Diff. 33 MeV
(ISR + fit))

Mean 91.2349
Stat. 5 keV
Diff. 35 MeV
(ISR + fit)

Mean 94.3043
Stat. 12 keV
Diff. 4 MeV
(ISR + fit)

Fit to Crystal-Ball

At least, use it for the point-to-point uncertainty

$\sqrt{s} = M_{\mu\mu}/\sqrt{(1-2x_\gamma)}$ $\sqrt{s} = M_{\mu\mu}/\sqrt{(1-2x_\gamma)}$ $\sqrt{s} = M_{\mu\mu}/\sqrt{(1-2x_\gamma)}$

In situ √s measurements: Possible projects

- **At the Z pole**
  - Understand how well ISR should be known to master the ~30 MeV excursion
  - Use better description of the detector concepts (CLD, IDEA)
    - With DELPHES **(E. Leogrande started in 2019)** and with full simulation
  - Propose and implement methods to calibrate the muon momenta (J/ψ, K^0_S ?)
    - Assumed to be perfectly calibrated in the previous plots

See Graham Wilson's talk
on Wednesday 21/09

- **Above the Z pole**
  - Implement a credible analysis for the Zγ final state (a.k.a. radiative returns)
    - With all Z decays, with fast and full simulation, at all centre-of-mass energies
    - Systematic studies (ISR, etc.) and calibration feasibility at the WW threshold
    - Improve it at 240 and 350 GeV for a better statistical precision
  - Repeat, cross check and improve Marina's W mass with direct reconstruction method
    - At the WW threshold, at 240 GeV, at the top-pair threshold
    - Possibly with full simulation as well, with complete systematic studies (col. reconnection, etc.)

In situ √s measurements: Possible projects

- **At all centre-of-mass energies**
  - Propose ways to measure the crossing angle "directly" with the required precision
    - Far from the IP (but after the last magnetic element)

  - Propose ways to measure the change of crossing angle at the IP "in situ"

$$\boxed{\alpha = 2\arcsin\left[\frac{\sin\left(\varphi^- - \varphi^+\right)\sin\theta^+\sin\theta^-}{\sin\varphi^-\sin\theta^- - \sin\varphi^+\sin\theta^+}\right]}$$

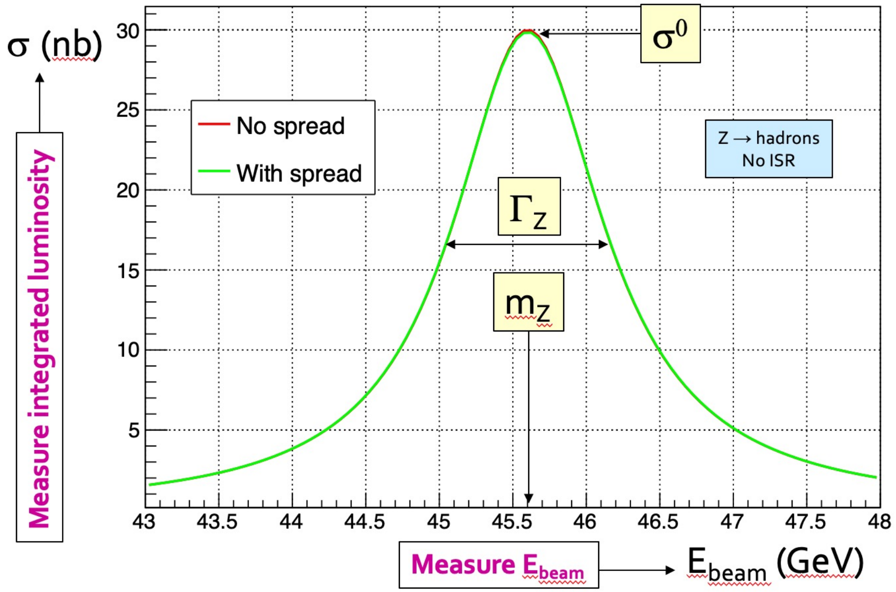
- Method 1: use the beam intensity variation between two injections
- Method 2: use the machine filling period
  - ➔ Are these methods realistic ?
  - ➔ Do we need to have a "per-bunch" estimate of the crossing angle ?
- Method 3: other proposals ?

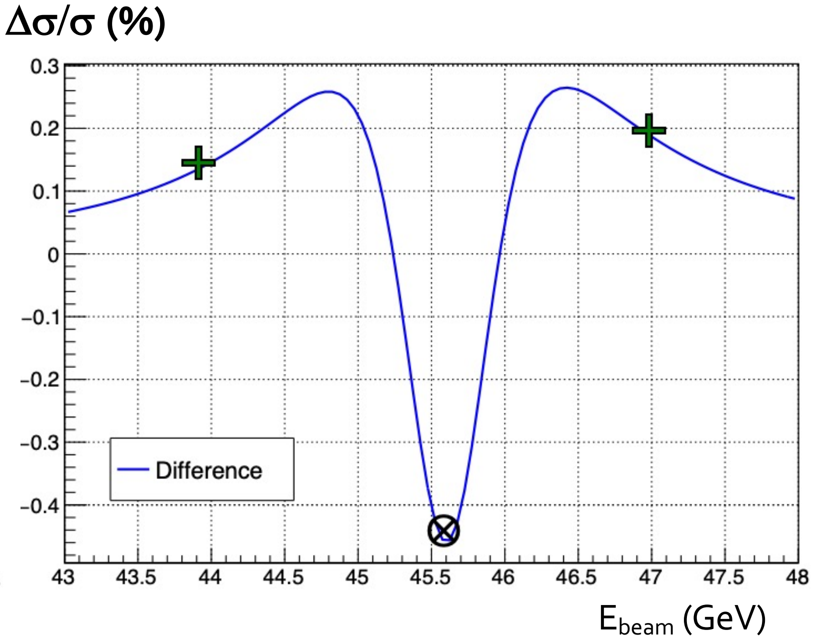
arXiv:1909.12245

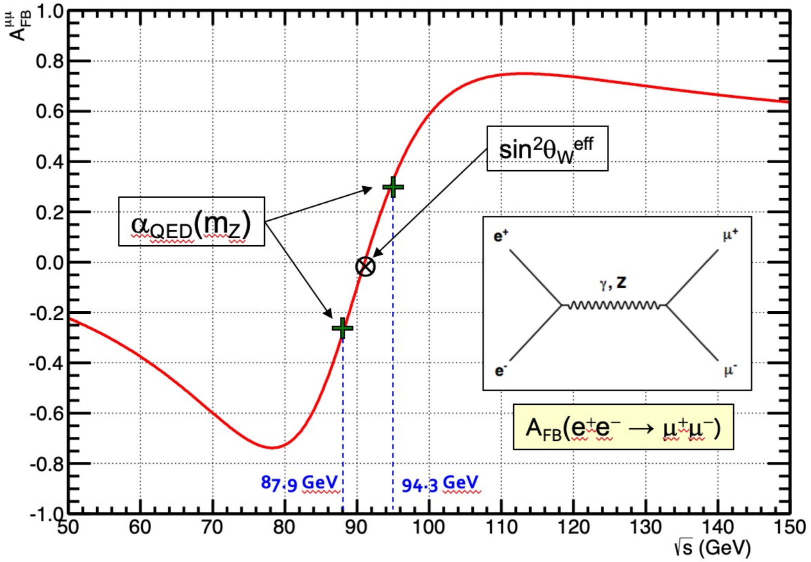
See Emmanuel Perez' talk
on Wednesday 21/09

√s spread (a.k.a. luminosity spectrum)

- √s spread strongly affects √s-dependent observables
  - Must therefore be measured with adequate precision
    - So that related uncertainty be smaller than the expected statistical precision







- If not attended, the centre-of-mass energy spread:
  - Increases Γ_Z, reduces σ^0, increases A_{FB}(87.9 GeV), decreases A_{FB}(94.3 GeV)

√s spread (a.k.a. luminosity spectrum)

- **Solve (E,p) conservation for $x_\gamma = p_z^\gamma / \sqrt{s}$ with $\mu^+\mu^-(\gamma)$ events**

$$\begin{aligned}
E^+\sin\theta^+\cos\varphi^+ + E^-\sin\theta^-\cos\varphi^- + |p_z^\gamma|\tan\alpha/2 &= \sqrt{s}\tan\alpha/2,\\
E^+\sin\theta^+\sin\varphi^+ + E^-\sin\theta^-\sin\varphi^- &= 0,\\
E^+\cos\theta^+ \qquad + E^-\cos\theta^- \qquad + \; p_z^\gamma &= \sqrt{s}\,\varepsilon,\\
E^+ \qquad\qquad + E^- \qquad\qquad + \; |p_z^\gamma|/\cos\alpha/2 &= \sqrt{s}/\cos\alpha/2,
\end{aligned}$$

◆ In arXiv:1909.12245, the solution is proposed with no longitudinal boost ($\varepsilon = 0$)

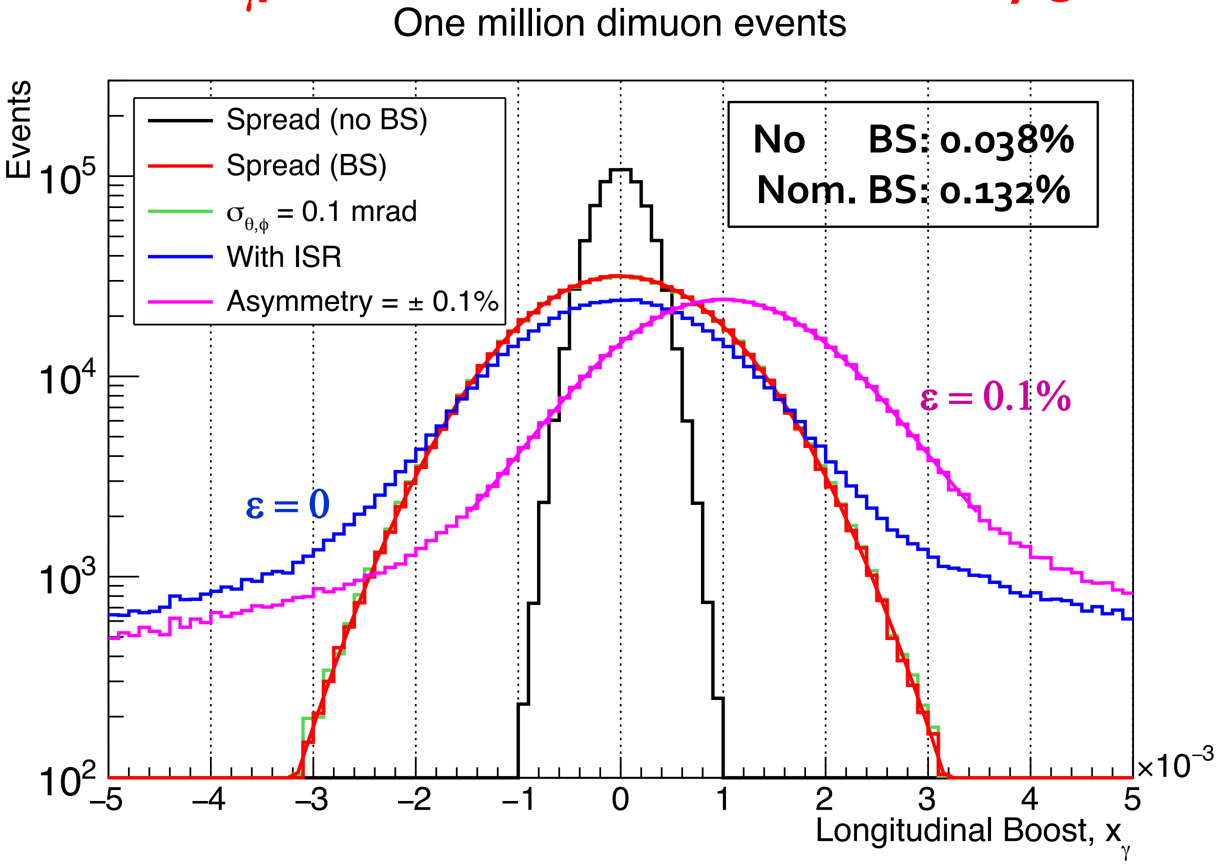
$$\boxed{x_\gamma = -\frac{x_+\cos\theta^+ + x_-\cos\theta^-}{\cos(\alpha/2) + |x_+\cos\theta^+ + x_-\cos\theta^-|}}$$

With $x_\pm = \dfrac{\mp\sin\theta^\mp\sin\varphi^\mp}{\sin\theta^+\sin\varphi^+ - \sin\theta^-\sin\varphi^-}$

See PJ's talk
on Wednesday 21/09

√s spread (a.k.a. luminosity spectrum)

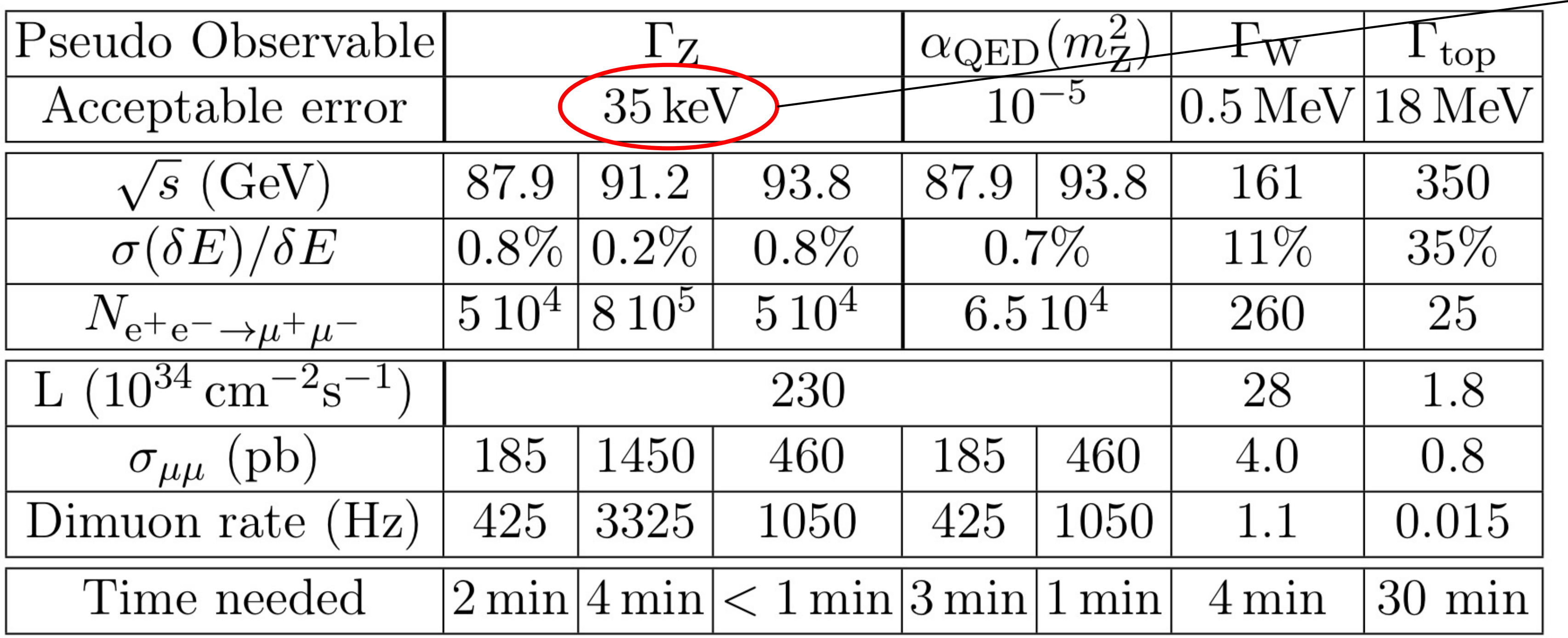
- **Resulting distributions of x_γ, for 10^6 dimuon events (every 5 minutes at the Z pole)**



- **The distribution of x_γ contains ISR + √s spread + muon angular resolution**
  - **Exercise: solve the equations with $\varepsilon \neq 0$**

√s spread (a.k.a. luminosity spectrum)

- **Extract from the conclusions of arXiv:1909.12245**



Pseudo Observable	Γ_Z			$\alpha_{QED}(m_Z^2)$		Γ_W	Γ_{top}
Acceptable error	35 keV			10^{-5}		0.5 MeV	18 MeV
$\sqrt{s}$ (GeV)	87.9	91.2	93.8	87.9	93.8	161	350
$\sigma(\delta E)/\delta E$	0.8%	0.2%	0.8%	0.7%		11%	35%
$N_{e^+e^- \to \mu^+\mu^-}$	$5\,10^4$	$8\,10^5$	$5\,10^4$	$6.5\,10^4$		260	25
L (10^{34} cm^{-2}s^{-1})	230					28	1.8
$\sigma_{\mu\mu}$ (pb)	185	1450	460	185	460	4.0	0.8
Dimuon rate (Hz)	425	3325	1050	425	1050	1.1	0.015
Time needed	2 min	4 min	< 1 min	3 min	1 min	4 min	30 min

To be revised

- **See also presentation from André Sailer on Wednesday**
  - **Another method with Bhabha events proposed in the linear collider context**

√s spread: Possible projects

- All reported numbers obtained with
  - A home-made event generator, including home-made ISR generation (no FSR)
  - Gaussian smearing of muon momenta and angles
  - Standalone analysis code

- Reproduce/check all conclusions, at all centre-of-mass energies, with
  - A professional generator (e.g., KKMC) which contains ISR, FSR, IFI
  - Fast and full simulation, and FCCAnalysis code
  - All lepton species
    - At least e and μ, τ might be more difficult due to degraded angular resolution (to be checked)

- The proposed method does not disentangle ISR, √s spread, angular resolution
  - Question: Is it needed?
  - If it is, what is the required precision on ISR prediction?
  - Implement ways to measure muon angular resolution from the data

√s spread: Possible projects

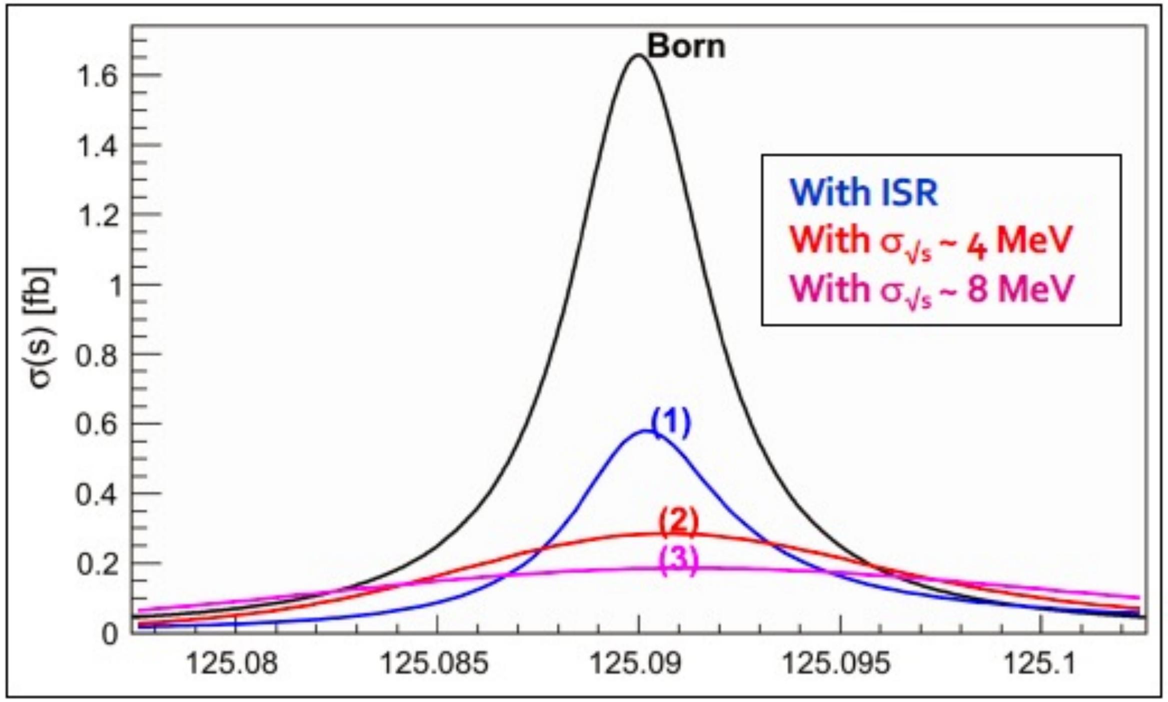
- Implement Andre's method, and apply it to FCC-ee

- The precision of the method depend on the precise, absolute, angle determination
  - Here, "absolute" means relative to the beams
    - As opposed to relative to the tracker axis or the magnetic field direction
  - A method has been proposed in arXiv:1909.12245
    - It will be presented on Wednesday (PJ)
  - Would need to implement the method with realistic simulation/reconstruction
    - And maybe find other methods
  - Can the method be applied to determined the detector acceptance with precision?

- Projects common to all measurements
  - Extract requirements on the detector performance to reach the required precision
    - Absolute alignment, absolute momentum calibration
    - Momentum resolution, angular resolution

√s monochromatization

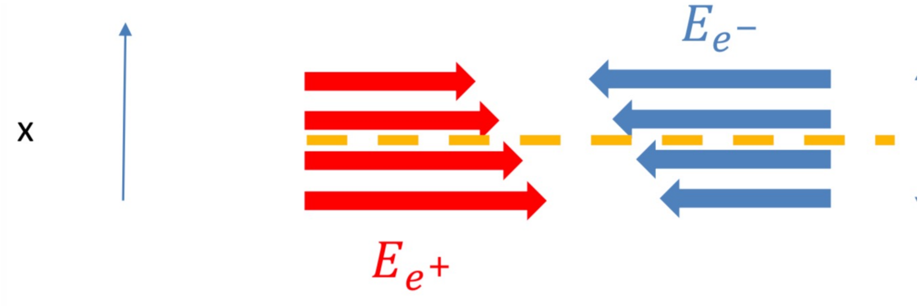
- Monochromatization essential for s-channel Higgs direct production ($\Gamma_H \sim 4$ MeV)

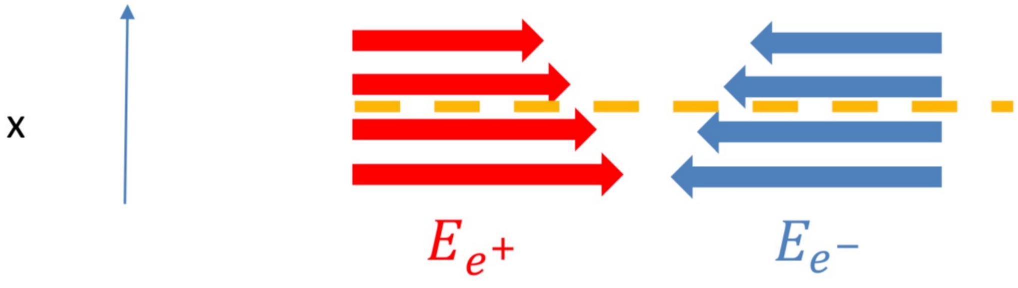


- Run at √s = mH – within what tolerance ?
- Measure continuously √s with a great precision – what precision is needed ?
- Measure the √s spread with a great precision – what precision is needed ?

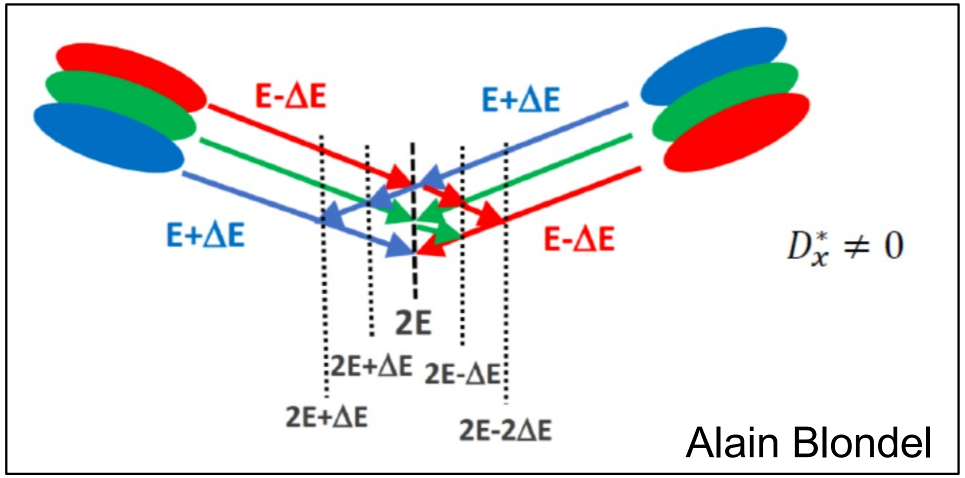
√s monochromatization

- **Monochromatization** **Chromatization**





- Apply previous techniques to monochromatization monitoring
  - With crossing angle
    - Boost remains constant with x position
    - Monitor the correlations
      - ➔ Between the boost and the IP position & time
  - Everything is to be done here
    - Including the understanding of this drawing ☺



Alain Blondel

A lot of work ahead !

- But also a lot of fun (speaking from experience)
  - And a possibility for many single-author publications

- IMPORTANT ! A tutorial is foreseen on Thursday afternoon (Marcin)
  - Learn how to generate, simulate, analyse dimuon events and more in FCCSW
    - Come with your computer !
  - And apply what you have learnt to determine $\sqrt{s}$, spread, boost, angles, axes, etc.