Beam Energy Spread Measurement @ FCC-ee

- **Thank you !**
  - Mogens
  - Patrizia
  - Mike
  - Jorg
    - For challenging me and asking me questions about the beam energy spread measurement in the past months / years
  - There would have been no talk possible today without this pre-existing thinking and coding
    - I realize that I was expected to present something only two days ago, while browsing the agenda !
- **Piece of advice:**
  - To all workshop organizers
    - Invite speakers one by one (as opposed to bulk mailing)
      - ➨ With a personal e-mail indicating the desired content of the presentation
      - ➨ Well ahead of time (several months), to allow for original and substantial work
      - ➨ Several times until you get a personal reply

Initial requirements w/o energy spread

- Targets set in the TLEP paper
  - Precision on the Z width : 100 keV
  - Precision on the Z mass : 100 keV
  - Precision on the peak cross section : 10^{-4}

- We will run at least with three beam energies around the Z pole
  - E_{beam} = 45.6 GeV , i.e., the Z pole
    - σ_{peak} ~ 30 nb , L_{peak} ~ 100 ab^{-1}, N_{peak} ~ 3×10^{12} events
  - E_{beam} = 43.95 GeV and 47.15 GeV, for the $\alpha_{QED}(m_Z)$ measurement
    - $\sigma_{peak\pm3}$ ~ 6 nb; $L_{peak\pm3}$ ~ 25 ab^{-1}, $N_{peak\pm3}$ ~1.5×10^{11} events
  - Statistics large enough to be limited by systematic uncertainties for m_Z, Γ_Z and σ_o

- To reach the aforementioned targets w/o energy spread, we need
  - A measurement of the beam energy (e^+ and e^-) with a precision of 50 keV
  - A point-to-point relative integrated luminosity measurement precision of 5×10^{-5}
  - An absolute integrated luminosity measurement precision of 10^{-4}
    - Result of a 3-parameter fit: $\sigma(m_Z)$ = 96 keV, $\sigma(\Gamma_Z)$ = 104 keV, $\sigma(\sigma_o)/\sigma_o$= 10^{-4}

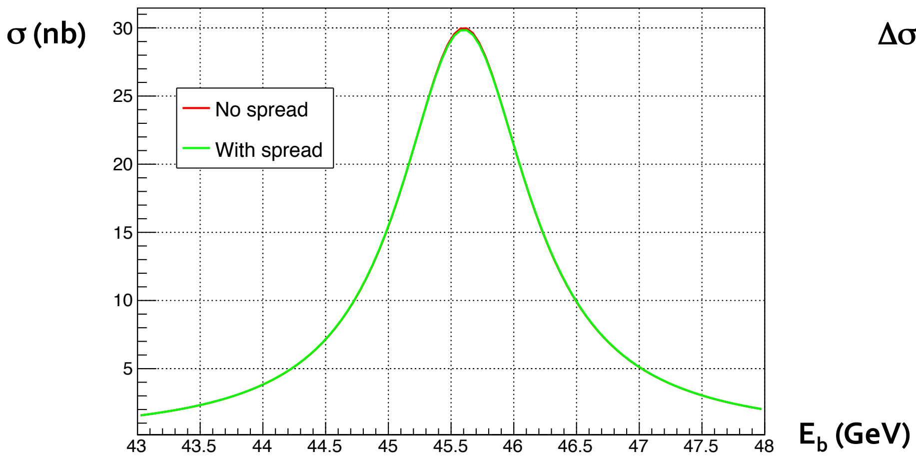
Side remark : what beam energies ?

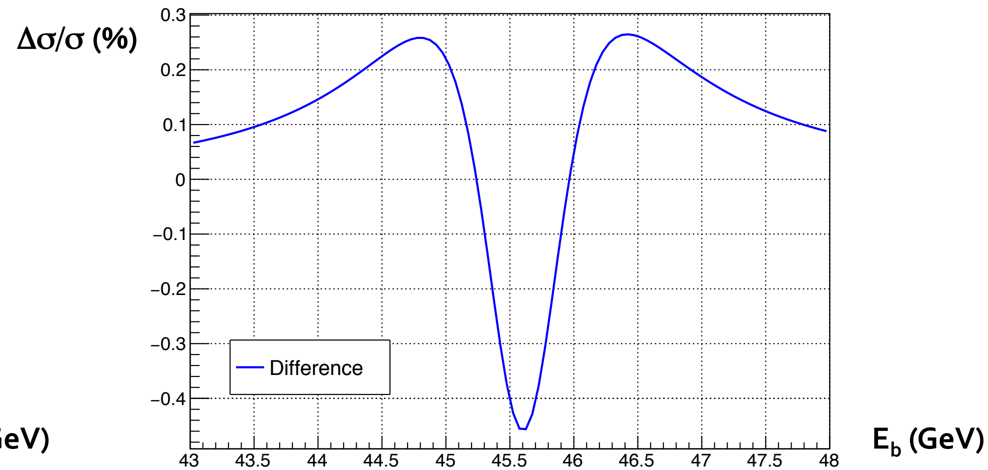
- With the same precision on the beam energy and luminosity, no spread
  - Result of the fit with Peak±2 instead of Peak±3
    - $\sigma(m_Z)$ = 86 keV, $\sigma(\Gamma_Z)$ = 140 keV, $\sigma(\sigma_0)/\sigma_0 = 10^{-4}$
  - Result of the fit with Peak±1 instead of Peak±3
    - $\sigma(m_Z)$ = 84 keV, $\sigma(\Gamma_Z)$ = 263 keV, $\sigma(\sigma_0)/\sigma_0 = 10^{-4}$
  - Target not reached for the Z width
    - Almost no difference for the mass and the peak cross section

➨ Let's stick to Peak±3 for the time being

What happens with energy spread ?

- **Let's take the current beam energy spread with beamstrahlung**
  - E_{spread} = 0.132% E_{beam} (~60 MeV) for each beam – Spread assumed to be Gaussian (??)
    - Cross section differs by -0.4% to +0.3% , i.e., much larger than uncertainties



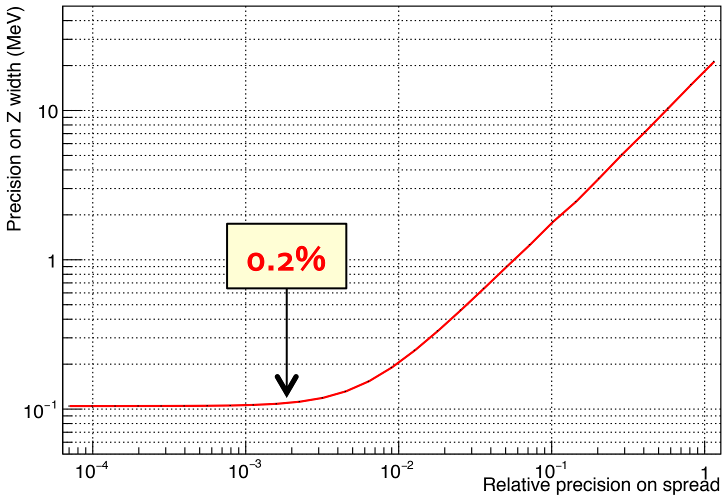


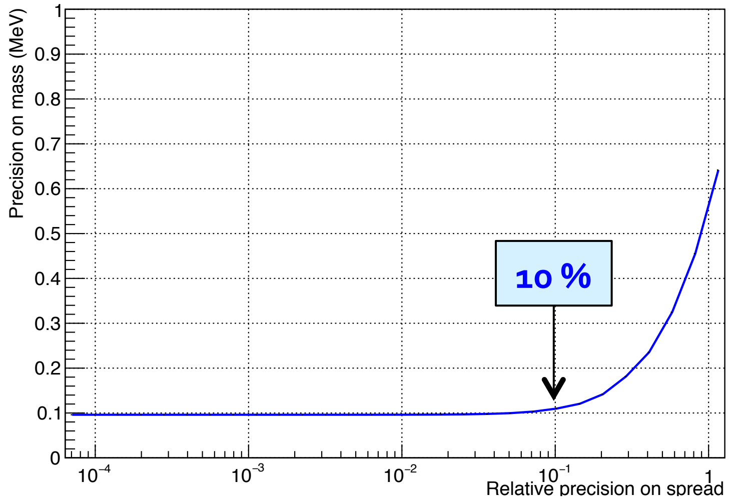
  - Dominant effect on the width measurement: reduction of the peak cross section
    - With a three parameter fit and three energies: $\Gamma_Z \rightarrow [\Gamma_Z^2 + 8E_{spread}^2]^{1/2}$
      - ➨ $\Delta\Gamma_Z > 8\Gamma_Z(E_{spread}/\Gamma_Z)^2 \times \Delta E_{spread}/E_{spread}$ (= 12 MeV × $\Delta E_{spread}/E_{spread}$ for E_{spread} = 60 MeV)

        1% uncertainty of E_{spread} leads to > 120 keV uncertainty on Γ_Z !
  - Need to find a way to determine the energy spread to a few per mil
    - And fit the cross section to the convolution of a Breit Wigner with a Gaussian
      - ➨ That's a four parameter fit (m_Z, Γ_Z, σ_0, E_{spread})

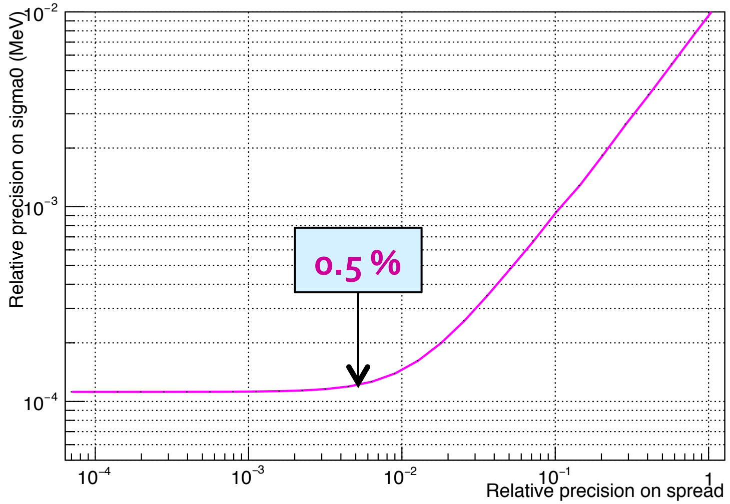
Four-parameter fit with three energies

- **We need an external measurement of the beam energy spread**
  - The precisions on m_Z, Γ_Z, and σ_0 depend on the precision of this measurement





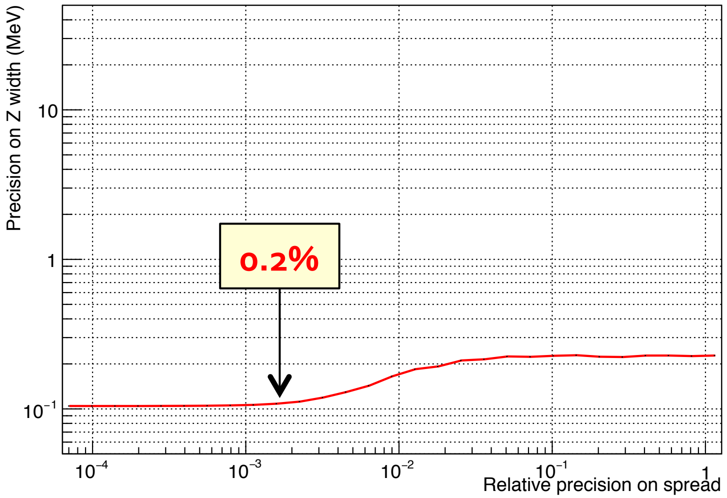
- Relative precision of 0.2% required !
  - ➨ Challenging beam instrumentation
  - ➨ See next talk ?

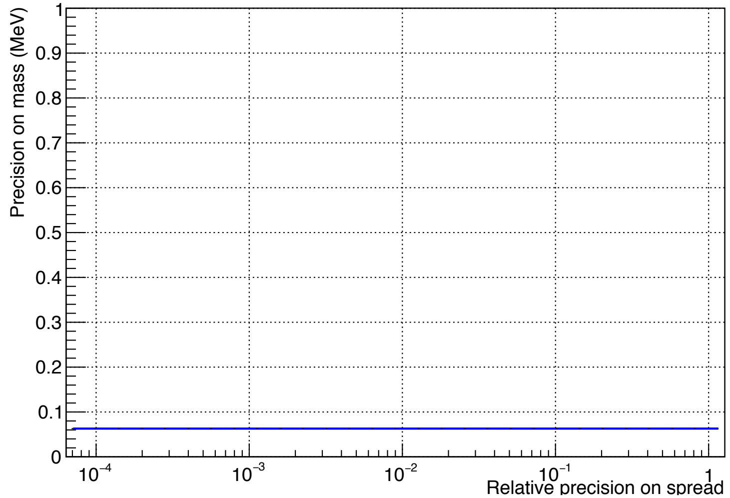


- Can we help with collision data ?

Add two energy points ?

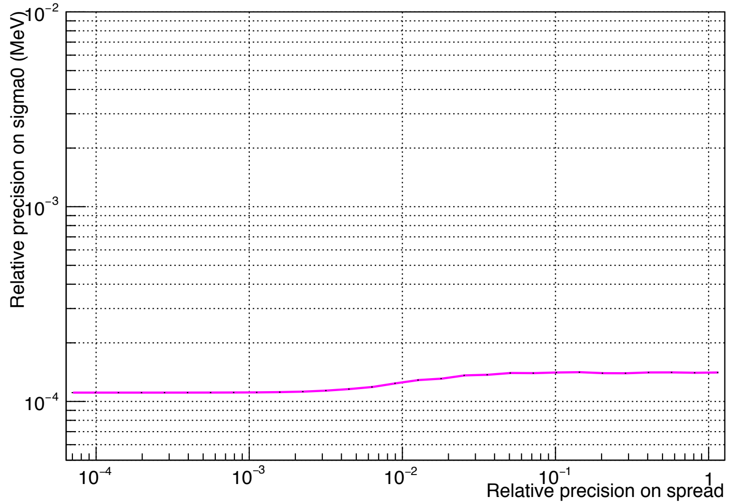
- The optimal choice is to add Peak±1
  - Energy spread determined with ~1% relative precision … not quite enough





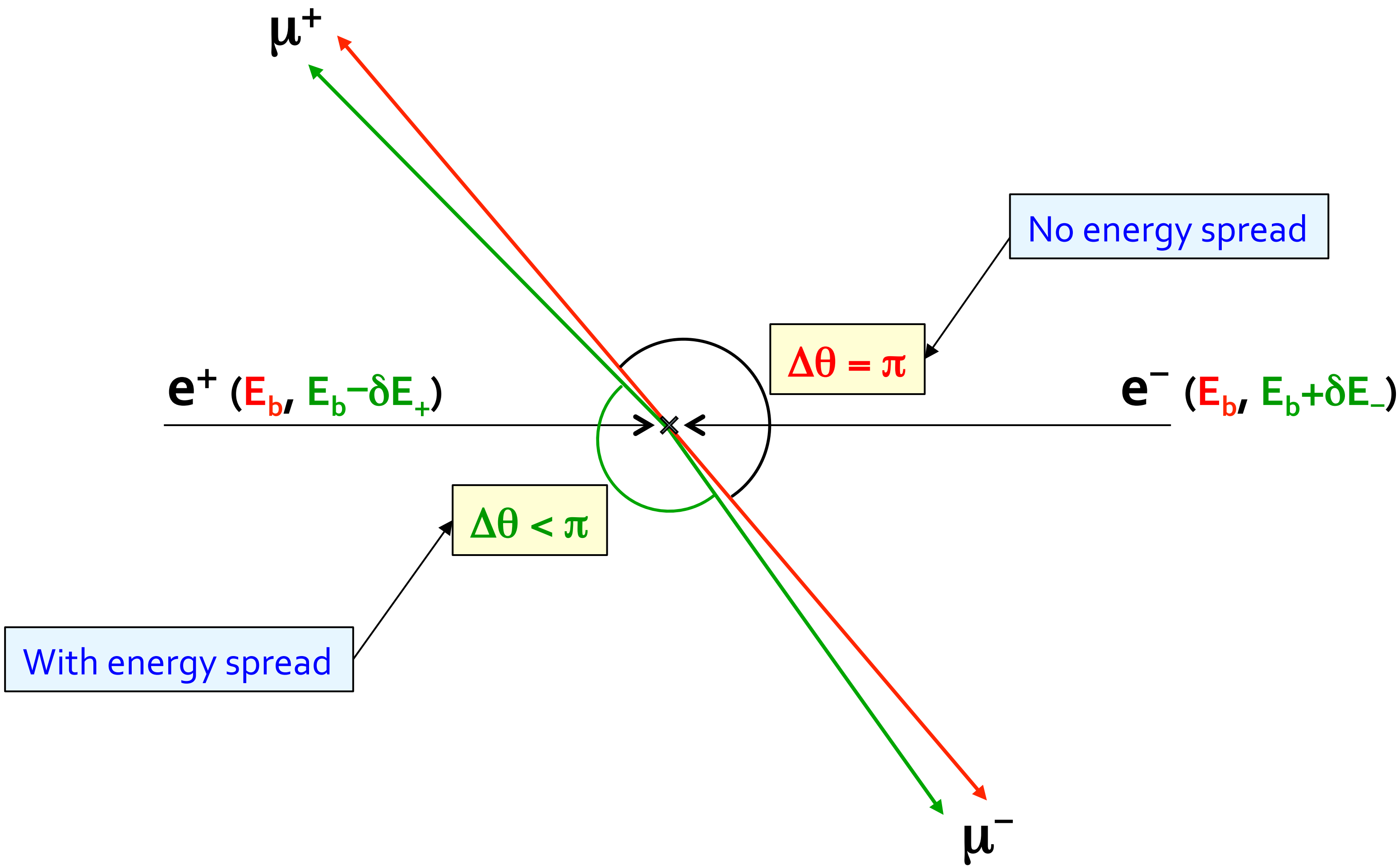
- Still need external measurement for Γ_Z
  - ➨ Precision 200 keV otherwise

    (160 MeV with 1% external)
- Good to have, but…
  - Reduction in total Z statistics
  - Assumes a <u>constant</u> Gaussian spread
    - ➨ Other (better) ideas required



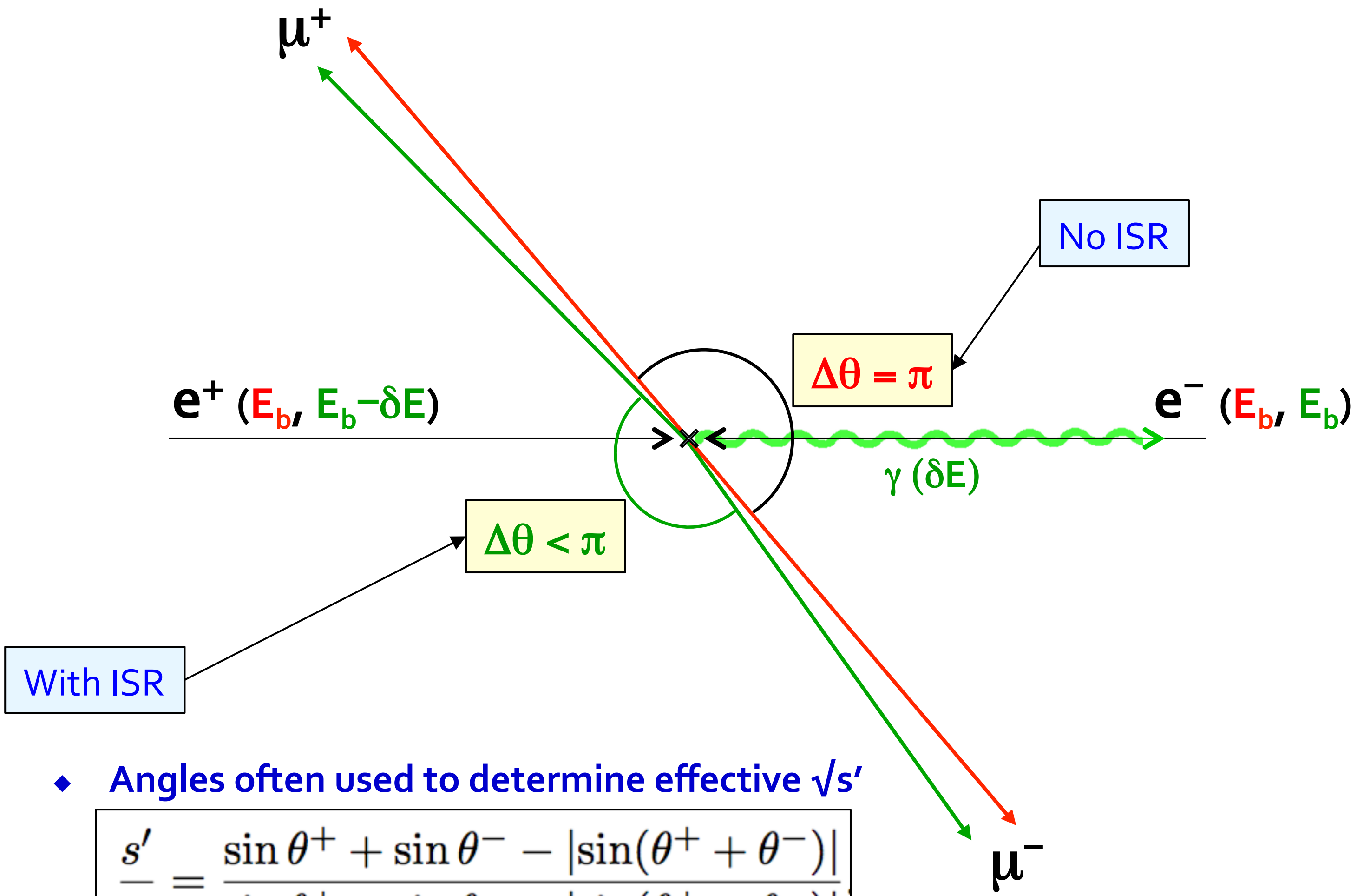
Make use of $e^+e^- \rightarrow \mu^+\mu^-$ events

- How are the events modified with energy spread ?



Make use of $e^+e^- \rightarrow \mu^+\mu^-$ events

- Competes with initial state radiation (that you cannot get rid of)



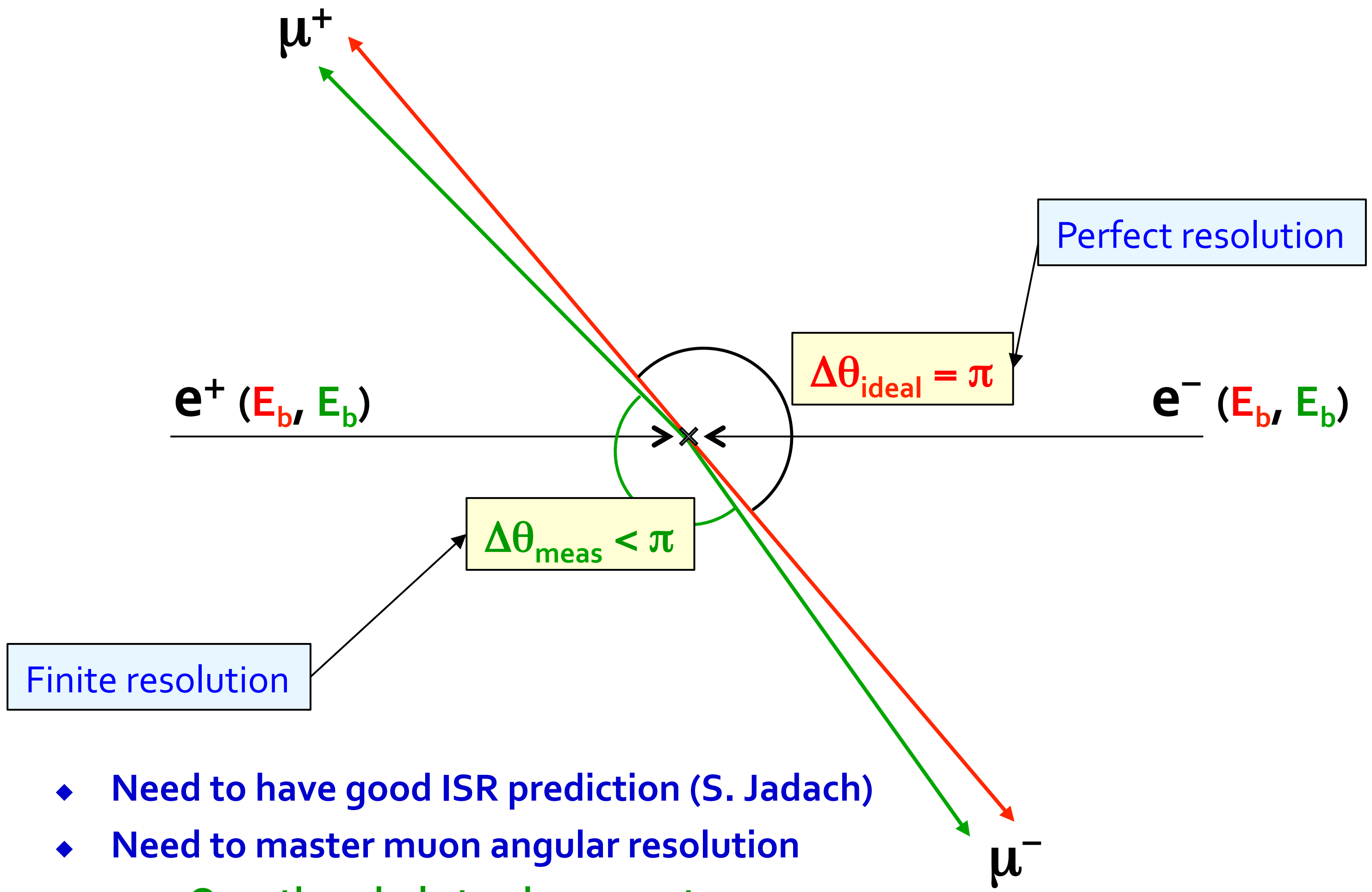
- Angles often used to determine effective √s'

$$\frac{s'}{s} = \frac{\sin\theta^+ + \sin\theta^- - |\sin(\theta^+ + \theta^-)|}{\sin\theta^+ + \sin\theta^- + |\sin(\theta^+ + \theta^-)|}$$

Plots that follow show √s' distributions

Make use of $e^+e^- \rightarrow \mu^+\mu^-$ events

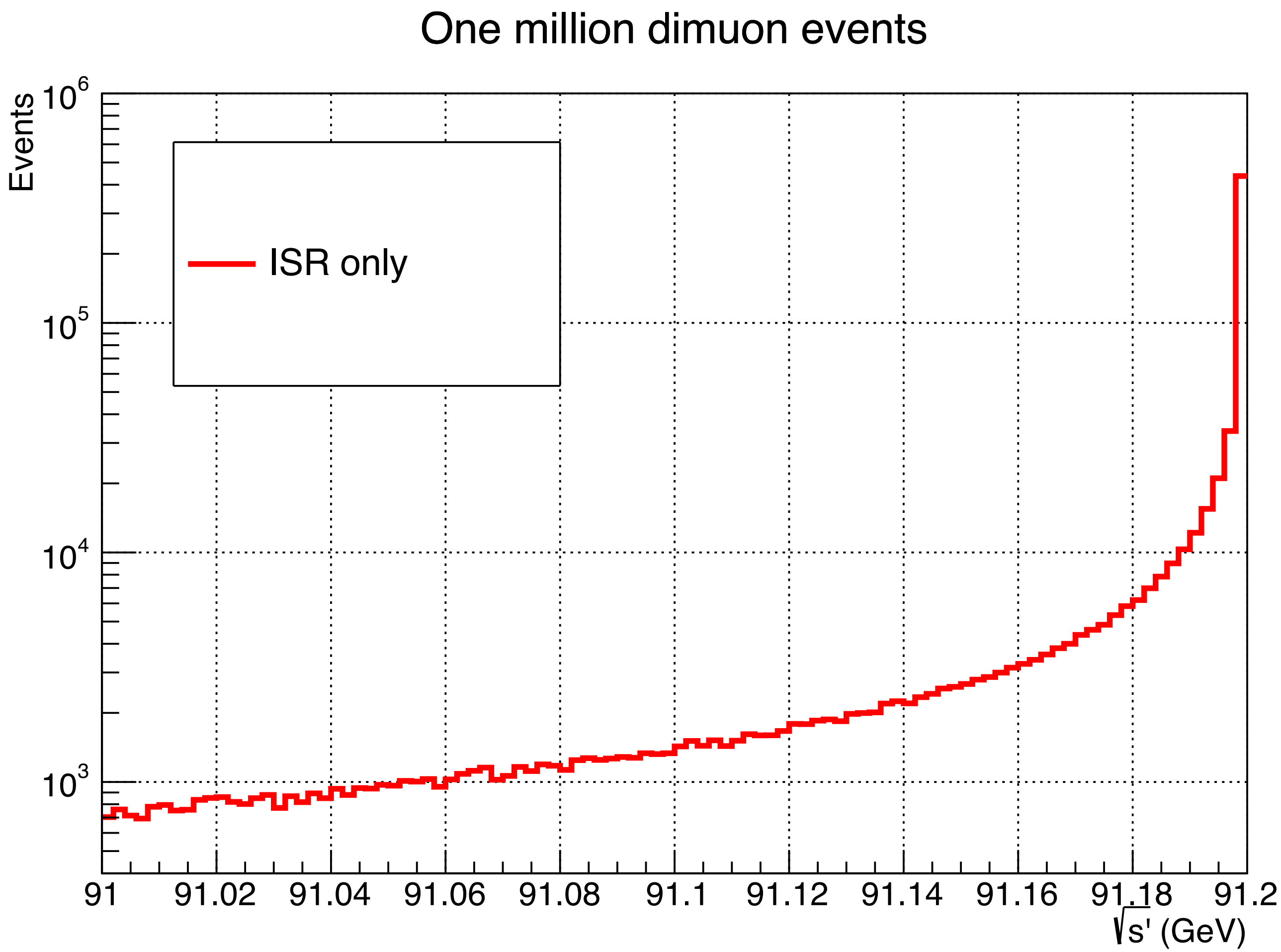
- **Also competes with muon angular resolution …**



- **Need to have good ISR prediction (S. Jadach)**
- **Need to master muon angular resolution**
  - **Over the whole tracker accpetance**

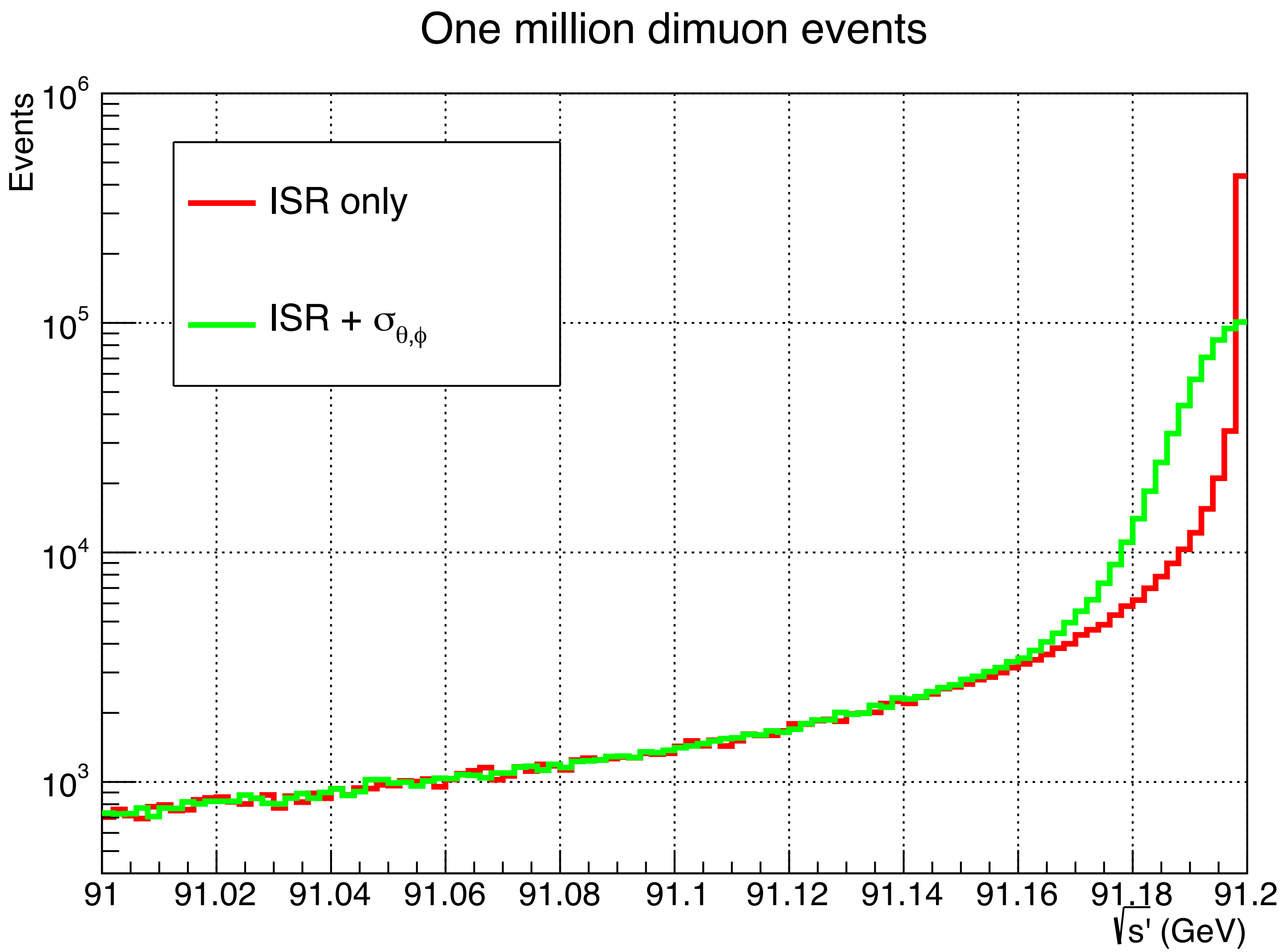
The competition

- Distributions of $\sqrt{s'}$ with 10^6 $e^+e^- \to \mu^+\mu^-$ events at $\sqrt{s}$ = 91.2 GeV
  - With ISR only



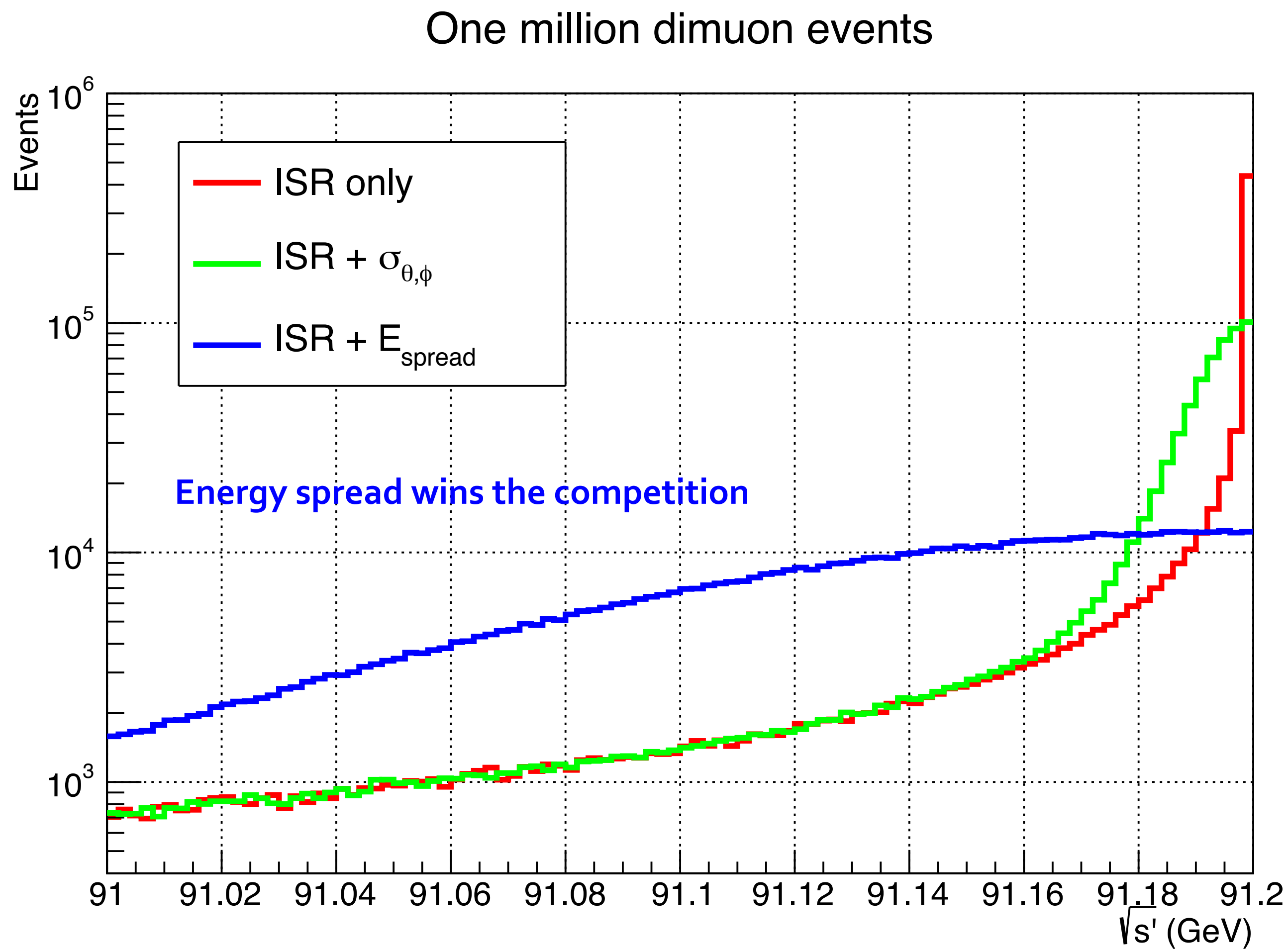
The competition

- Distributions of $\sqrt{s'}$ with 10^6 $e^+e^- \to \mu^+\mu^-$ events at $\sqrt{s}$ = 91.2 GeV
  - With ISR and 0.1 mrad angular resolution (typical of CLIC and IDEA)



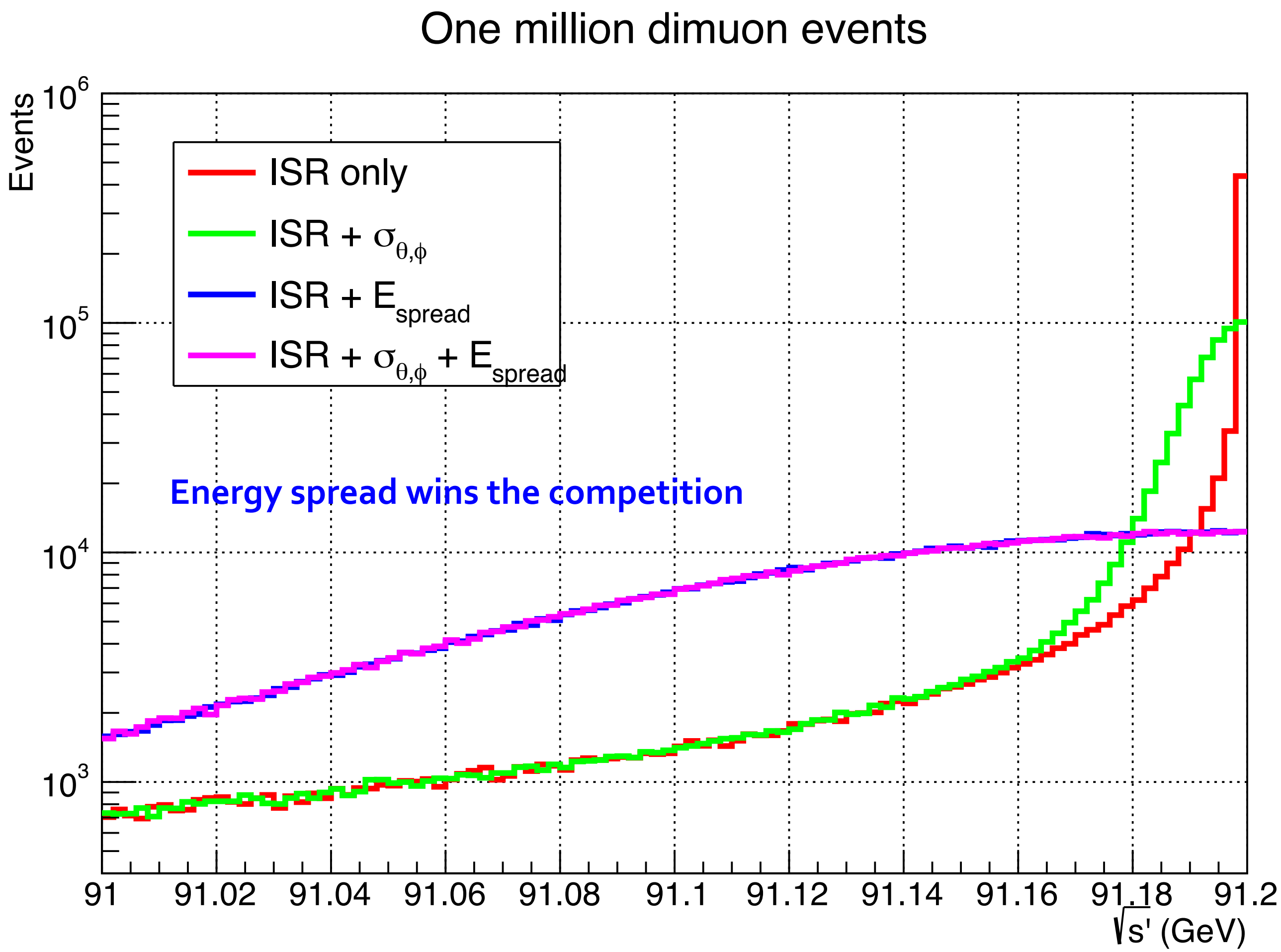
The competition

- Distributions of $\sqrt{s'}$ with 10^6 $e^+e^- \to \mu^+\mu^-$ events at $\sqrt{s}$ = 91.2 GeV
  - With ISR and 0.132% of beam energy spread



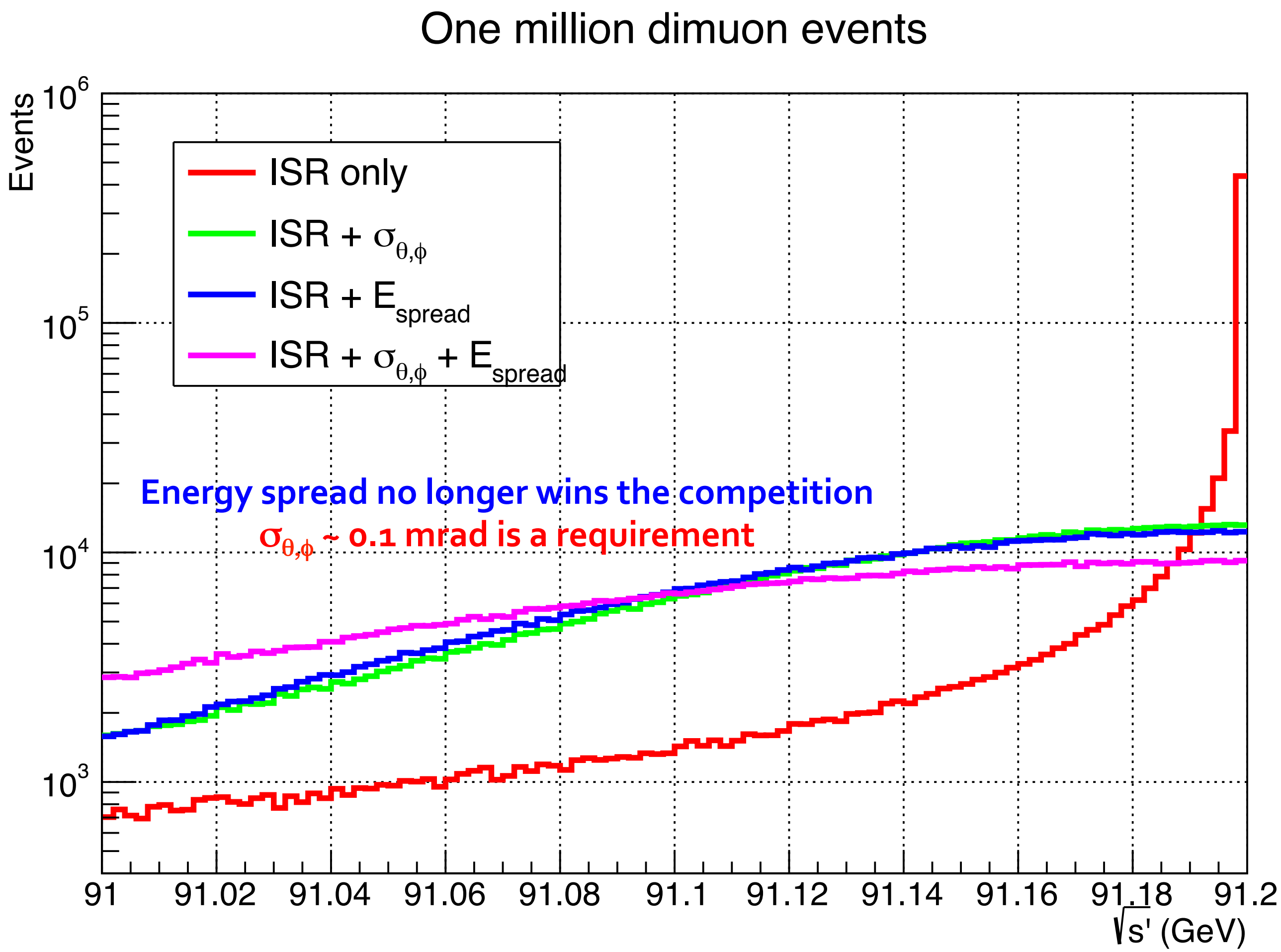
The competition

- Distributions of $\sqrt{s'}$ with 10^6 $e^+e^- \to \mu^+\mu^-$ events at $\sqrt{s}$ = 91.2 GeV
  - With ISR + beam energy spread + angular resolution



The competition

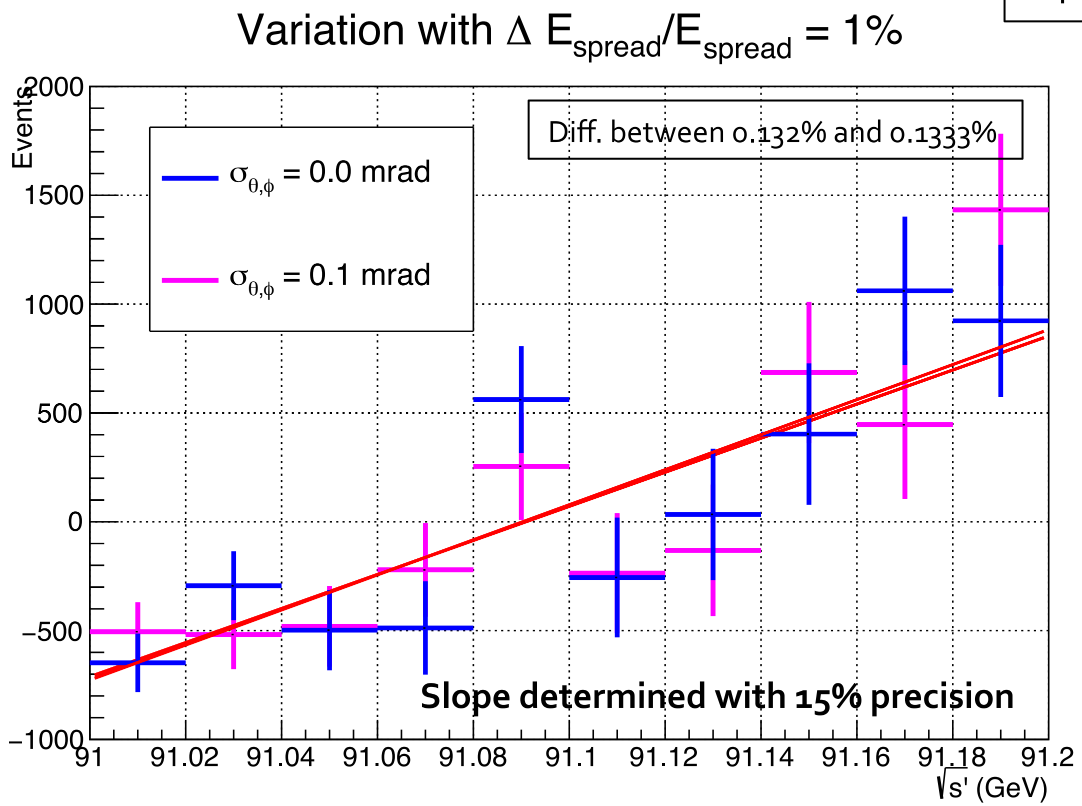
- Distributions of $\sqrt{s'}$ with 10^6 $e^+e^- \rightarrow \mu^+\mu^-$ events at $\sqrt{s}$ = 91.2 GeV
  - Same as before but with an angular resolution of 1 mrad



Energy spread determination: Sensitivity

- **With precise prediction of ISR and knowledge of angular resolution**
  - **The √s′ distribution is sensitive to the energy spread**

Needed anyway for all other FCC-ee measurements

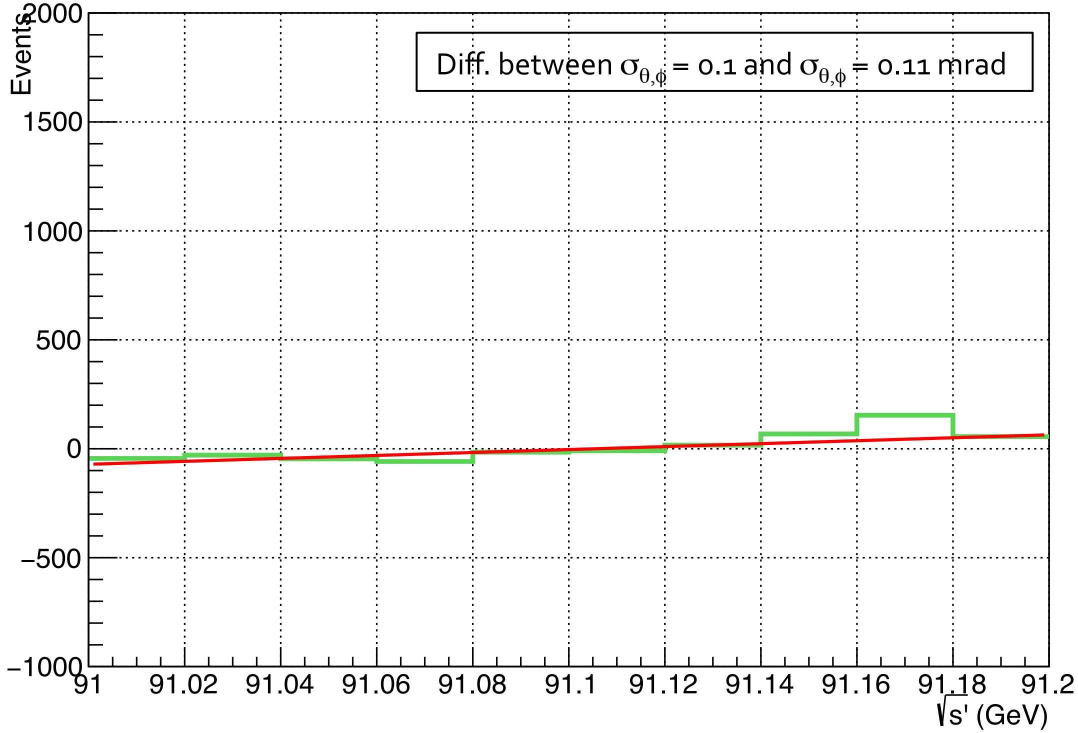


- **Sensitivity to $\Delta E_{spread}/E_{spread}$ ~ 0.15%, every 10^6 $e^+e^- \rightarrow \mu^+\mu^-$ events !**
  - **Independently of the actual angular resolution (0.0 or 0.1 mrad shown)**

Energy spread determination: Sensitivity

- Still the angular resolution must be known with a certain accuracy
  - The $\sqrt{s'}$ distribution is sensitive to $\sigma_{\theta,\phi}$ (although the dependence with E_{spread} is not)

Variation with $\Delta\sigma_{\theta,\phi}/\sigma_{\theta,\phi}$ = 20%



- Effect of a 20% knowledge of $\sigma_{\theta,\phi}$ equivalent to $\Delta E_{spread}/E_{spread}$ ~ 0.1%
  - ➨ Need to determine $\sigma_{\theta,\phi}$ to ± 0.01 mrad or better (as a function of θ and ϕ)

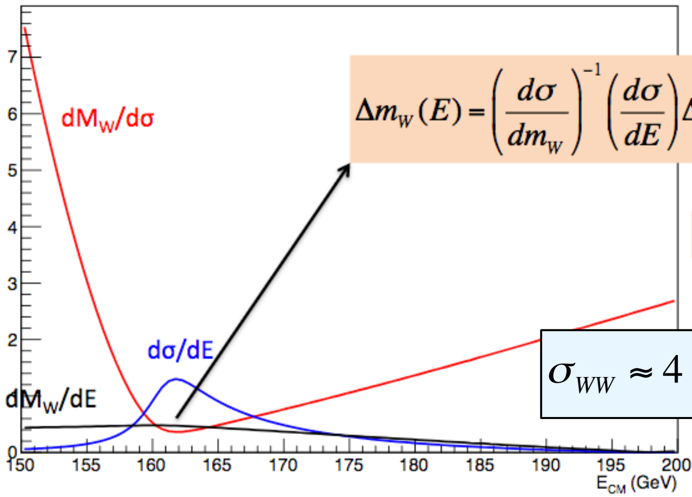
A permanent monitoring

- At the Z pole, $\sigma(e^+e^- \rightarrow \mu^+\mu^-) \sim 1.5$ nb
  - With $2.3 \cdot 10^{36}$ cm^{-2} s^{-1} collect 3.5 kHz of $e^+e^- \rightarrow \mu^+\mu^-$ events / detector
    - Enjoy one million events every 5 minutes
    - Monitor the beam energy spread to 0.2% precision every 3 minutes.
- At Peak ± 3 GeV, the cross section is reduced to 0.3 nb
  - Monitor the beam energy spread to 0.2% every 15 minutes
    - Probably can afford a worse precision at these points
      - ➨ Due to smaller sensitivity of the cross section to E_{spread} than at the peak
- Bonus: we have to such independent monitorings (two detectors)

- Technical details
  - The energy spread might not be Gaussian
    - Need to evaluate the sensitivity to the exact shape (e.g., rectangular w/ same RMS)
  - The angular resolution unfolding require full simulation, precisely tuned to the data
    - Need to measure this resolution with data in every direction
  - The extraction of the Z resonance parameters requires a multi-parameter fit
    - If E_{spread} varies rapidly, one parameter per period of 3 minutes …

Other energies

- **The W mass target precision is 500 keV**
  - It is measured at threshold (as opposed to "at the peak")
    - A place where the effect of the energy spread is much smaller
      - From Paolo Azzurri (yesterday):

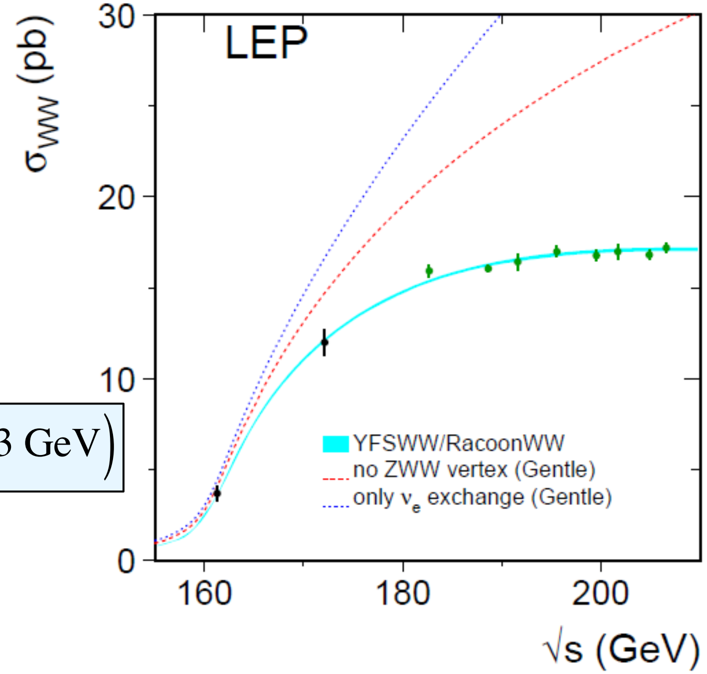


$$\Delta m_W(E) = \left(\frac{d\sigma}{dm_W}\right)^{-1}\left(\frac{d\sigma}{dE}\right)\Delta E \leq \frac{1}{2}\Delta E$$

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

Around 162.3 GeV

$$\sigma_{WW} \approx 4\ \text{pb} + 1.5\times\left(\sqrt{s} - 162.3\ \text{GeV}\right)$$



- Convolution of cross section with a Gaussian (E_{spread} = 0.153%):
  - No effect on σ_{WW} and m_W at 1st order, no effect at 2nd order, at $\sqrt{s}$ = 162.3 GeV

    (integral of an odd function at 1st order, and 2nd derivative is zero)

Other energies, cont'd

- The corresponding statistical precision on Γ_W (2.1 GeV) will be 1.5 MeV
  - With an additional run at 157.3 GeV (40% of the luminosity)
  - E_{spread} is 124 MeV, adds in quadrature to $\Gamma_W \rightarrow (\Gamma_W^2 + E_{spread}^2)^{1/2}$
    - $\Delta\Gamma_W = \Gamma_W (E_{spread}/\Gamma_W)^2 \times \Delta E_{spread}/E_{spread}$ (= 7 MeV × $\Delta E_{spread}/E_{spread}$)
      - ➨ A measurement of E_{spread} with a 5% precision is more than enough

        Increases uncertainty on the width to 1.55 MeV
      - ➨ About 900 $e^+e^- \rightarrow \mu^+\mu^-$ events suffice !

- At the WW threshold, $\sigma(e^+e^- \rightarrow \mu^+\mu^-) \sim 4$ pb
  - With $3.2 \cdot 10^{35}$ cm^{-2} s^{-1} collect 1.3 Hz of $e^+e^- \rightarrow \mu^+\mu^-$ events / detector
    - Enjoy 900 events and monitor E_{spread} to 5% precision every 12 minutes

- Note: This is only a back-of-the-envelope estimate
  - Gives the right ball park – but needs to be cross checked
    - By Paolo for the impact of energy spread on the W width precision
    - By me for the precision on E_{spread} with dimuon events at the WW threshold

Other energies, cont'd

- **The statistical precision on Γ_{top} (2 GeV) will be 25 MeV**
  - With a scan of the top threshold : 0.2 ab^{-1} around $\sqrt{s}$ = 346 GeV
  - E_{spread} is 346 MeV, adds in quadrature to $\Gamma_{top} \rightarrow (\Gamma_{top}^2 + E_{spread}^2)^{1/2}$
    - Corresponding uncertainty: $\Gamma_{top} (E_{spread}/\Gamma_{top})^2 \times \Delta E_{spread}/E_{spread}$ (= 60 MeV × $\Delta E_{spread}/E_{spread}$)
      - ➨ A measurement of E_{spread} with a 10% precision is more than enough

        Increases uncertainty on the width to 25.7 MeV
      - ➨ About 200 $e^+e^- \rightarrow \mu^+\mu^-$ events suffice !

- **At the top threshold, $\sigma(e^+e^- \rightarrow \mu^+\mu^-) \sim 1$ pb**
  - With $1.8 \cdot 10^{34}$ cm^{-2} s^{-1} collect 18 mHz of $e^+e^- \rightarrow \mu^+\mu^-$ events / detector
    - Enjoy 200 events and monitor E_{spread} to 10% precision every 3 hours

- **Note: This is only a back-of-the-envelope estimate**
  - Gives the right ball park – but needs to be cross checked
    - By Frank Simon for the impact of energy spread on the top width precision
    - By me for the precision on E_{spread} with dimuon events at the top threshold

- **I don't see why we would need a precise E_{spread} measurement at 240 or 365 GeV**
  - But we'll have it anyway !

Questions / remarks

- Is the beam energy profile expected to be Gaussian ?
  - In particular, is the beamstrahlung-induced spread expected to be Gaussian ?
  - Need to check with another shape (e.g., triangular, rectangular, same RMS)
- Is the beam energy profile at least expected to be symmetric ?
  - In particular, is the beamstrahlung-induced spread expected to be symmetric ?
  - If it is not symmetric, the effect on the masses will be larger
    - Need to check how much larger
      - ➨ And also predict the effect of such an asymmetry on the energy calibration
    - Need to check whether we can determine the actual shape with dimuon events
      - ➨ Require unfolding of ISR and angular resolution from $\sqrt{s'}$
    - Need some insights from beam instrumentation
- Is the beam energy profile expected to be the same at the two IPs ?
  - If not, can the difference be predicted from beam instrumentation ?
- Check if electrons (and maybe taus) can be used too
  - More difficult : electron bremstrahlung and tau decays affect the directions
- Investigate methods to map the θ and ϕ resolutions in the tracker
  - E.g., with other resonances decaying to $\mu^+\mu^-$ (ϕ, J/Ψ) or with $\mu^+\mu^-\gamma$ events ?