KU PALOOZA

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The Role of Beam Energy Calibration

By:

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Contents

Introduction to proposed colliders:

- ILC, the linear e+e- collider
- FCC-ee , the circular e+e- collider and possible LHC successor

Intro to Beam Energy

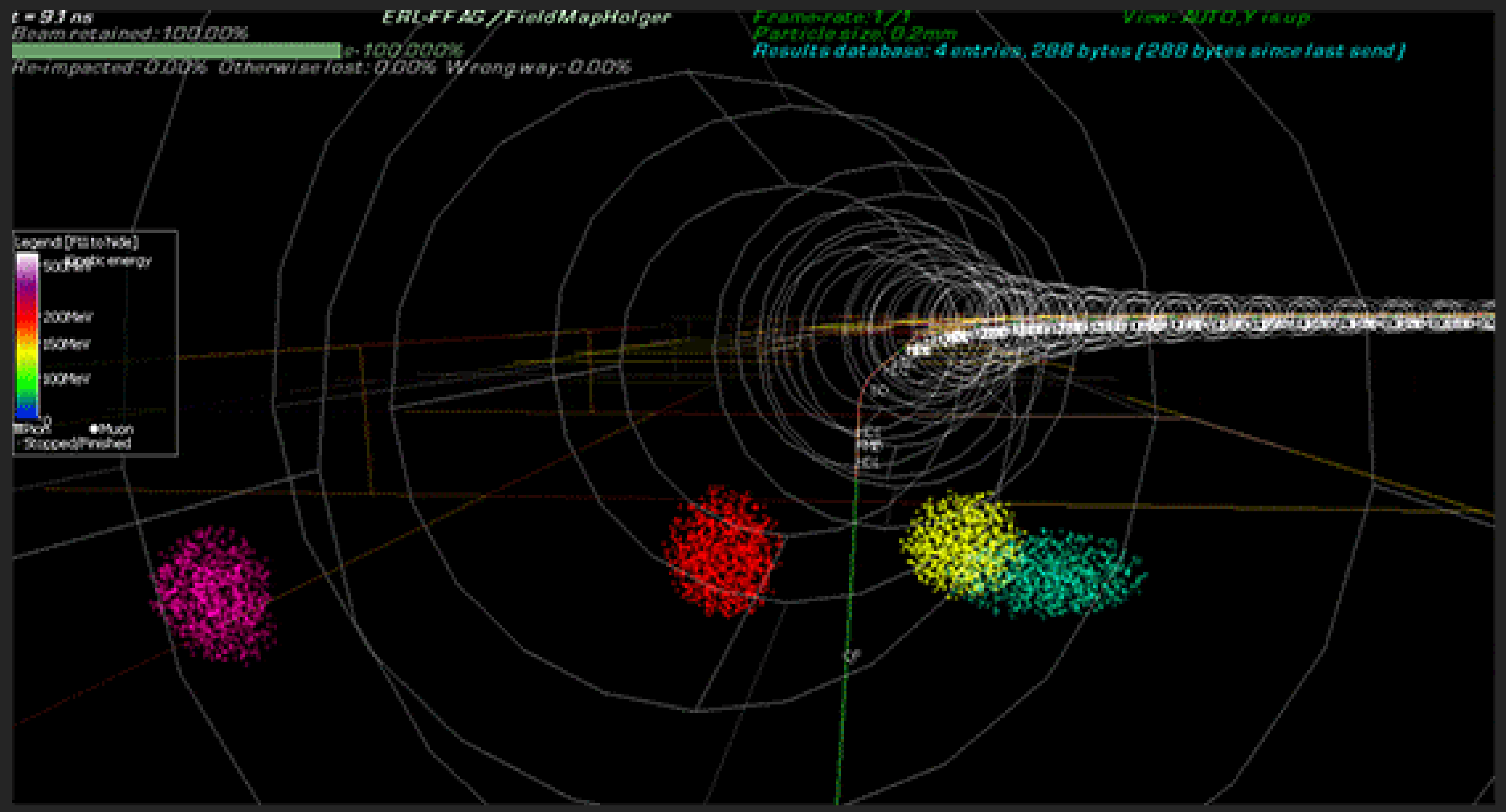
- Examples, Motivation
- How to simulate?
- What contributes?

Energy Calibration Methods

- RDP at LHC, FCC-ee
- ILC's Radiative Return , $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$

Abstract:

The precision of beam energies at LEP, LHC, ILC, FCC-ee will be discussed and compared. A general introduction to the proposed ILC, FCC-ee experiments will also be given. Energy calibration methods of resonant depolarization (RDP) and some "standard candle" energy calibration events will be presented. Emphasis will be given on ILC's Z->mu+mu- method. The experiments are then compared in a mockup, only considering beam calibration, of their ability to measure invariant mass and transverse energy.



Credit: Stephen Brooks

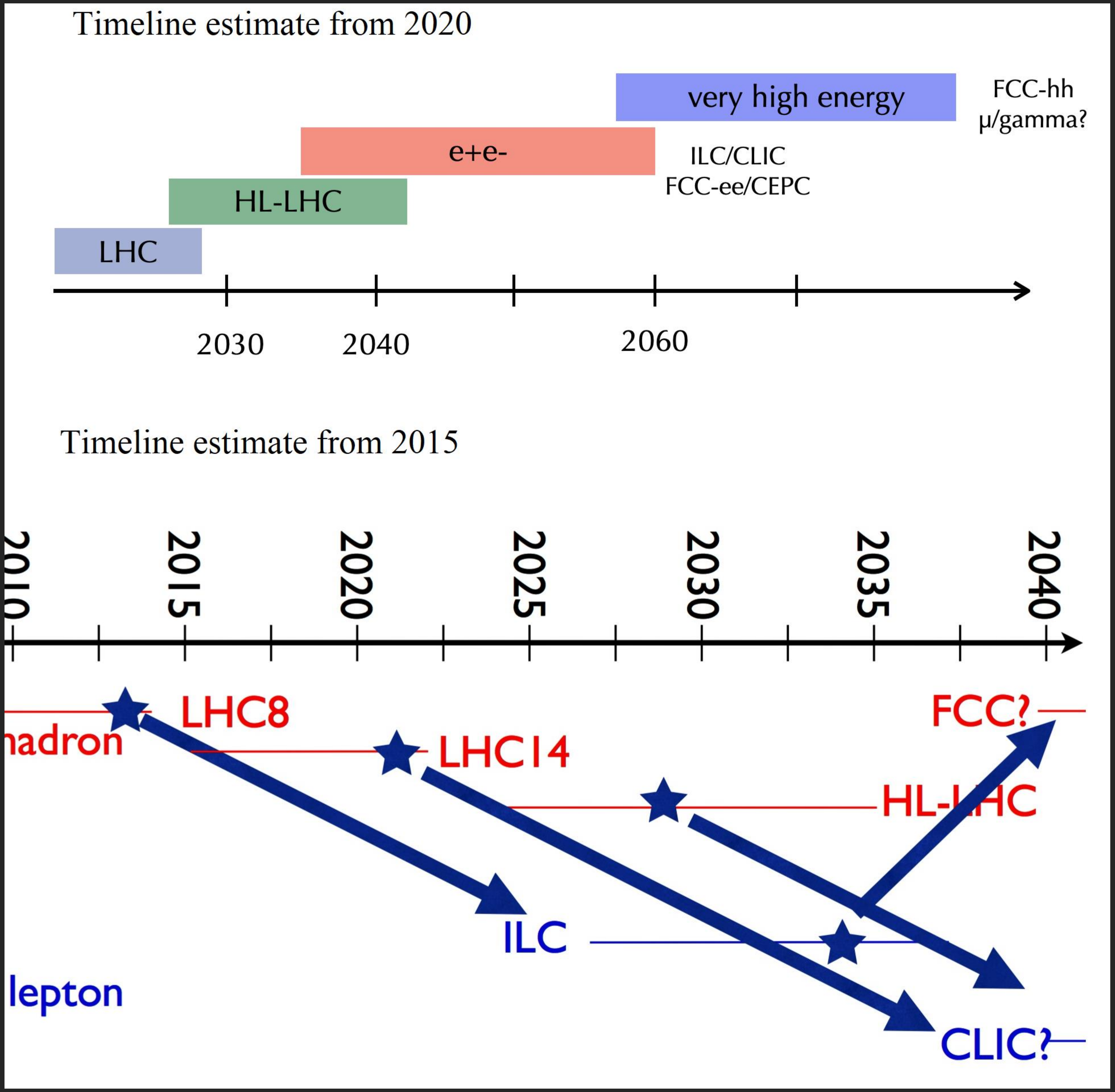
The setting

What we have:

- LHC , HL-LHC

Where we are (hopefully) going:

- International Linear Collider (ILC)
- Future Circular Collider (FCC)
    - FCC-ee for electron
    - FCC-hh for proton



Intro to Proposed Experiments:

Main difference between Linear and Circular :

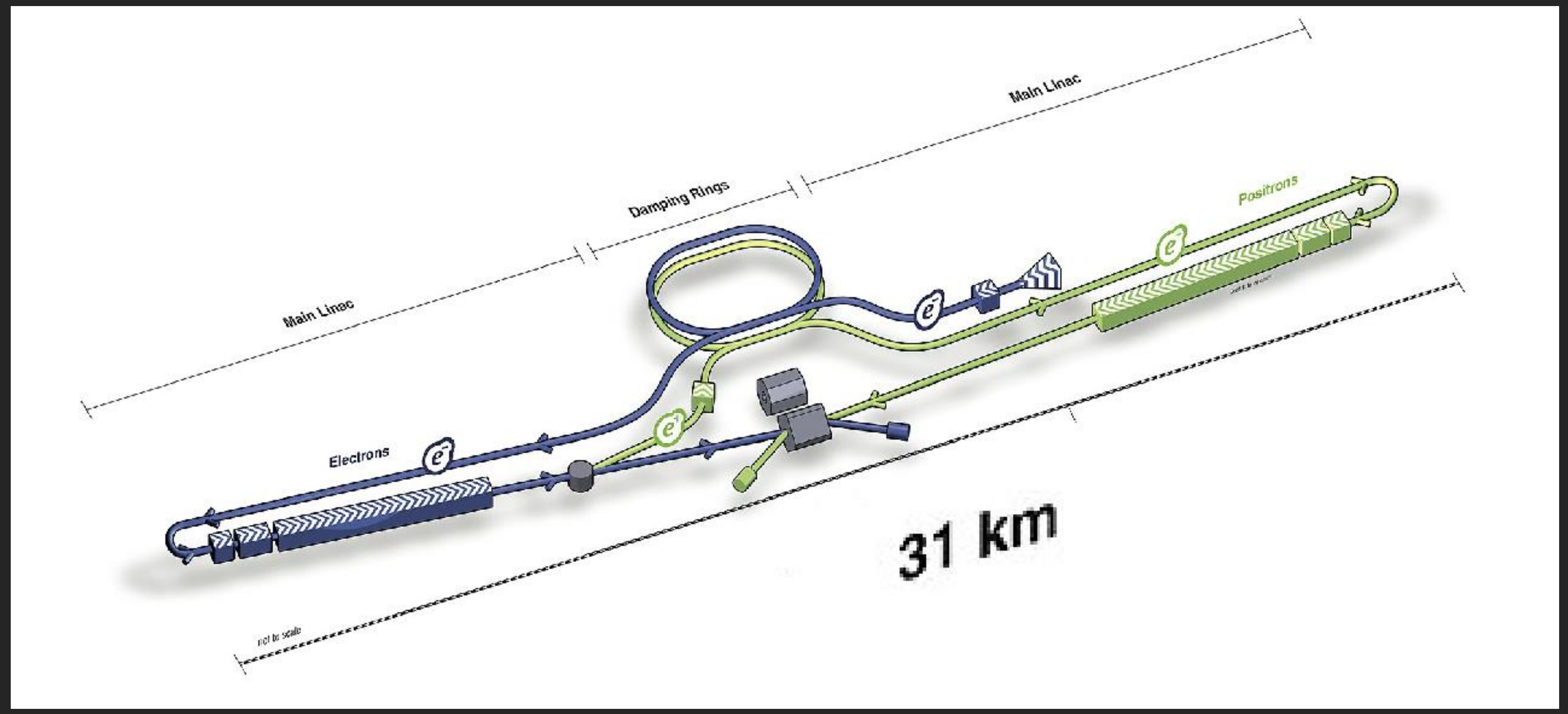
Linear Colliders , International Linear Collider (ILC):

- No resonant depolarization (RDP)
- “RF Gun” acceleration to minimize RF distortion and increase energy
  - https://cds.cern.ch/record/438632
- Easier to upgrade energy (increase length, RF energy)
- Overall smaller, costs less
- ILC is older than FCC-ee
- Energy increase goes as ~= Length

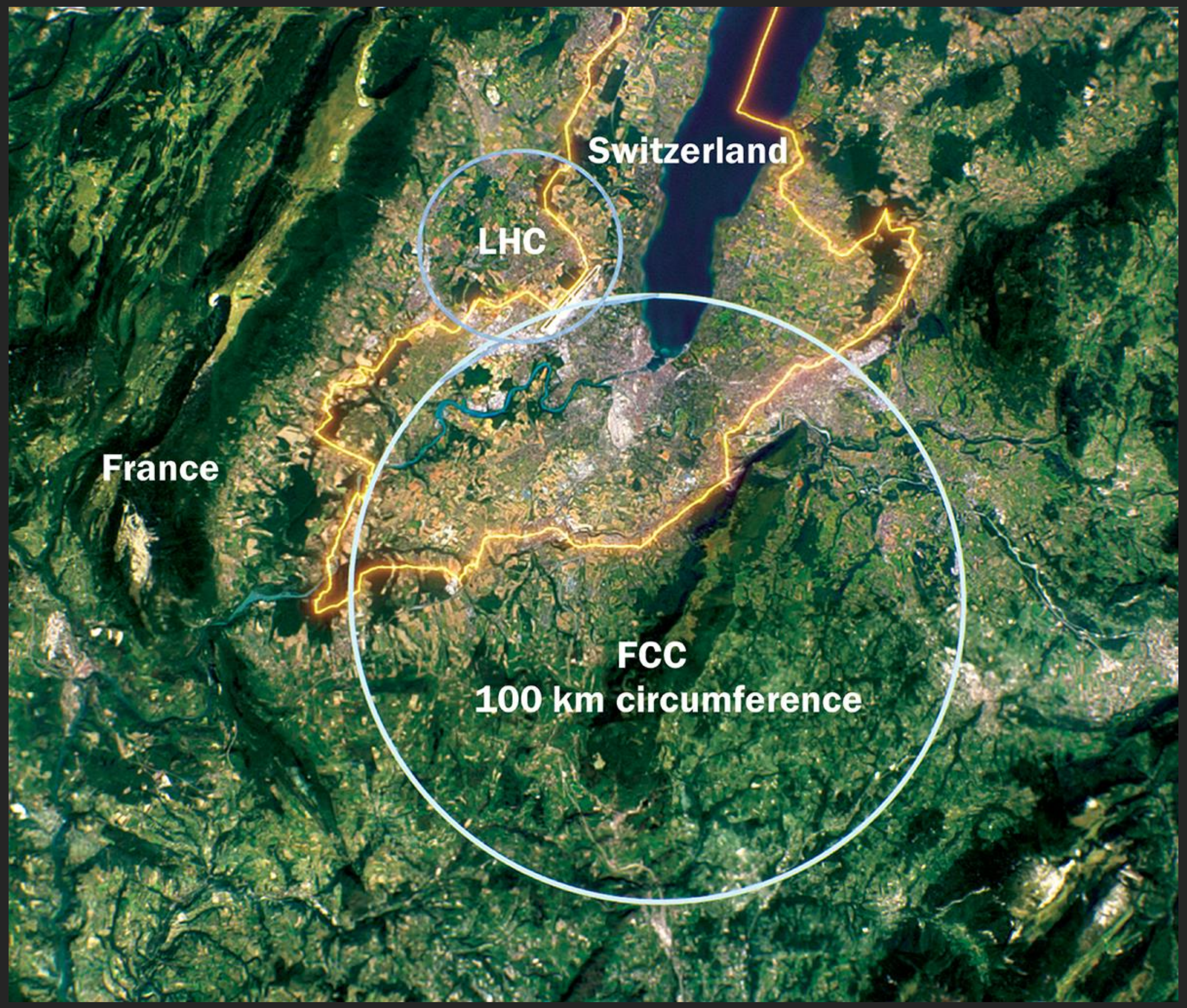
Circular Colliders , Future Circular Collider, (FCC-ee):

- Generally, can have a higher luminosity , data rate
- Recycle beam particles
- Upgrade to hadron collider
- Resonant depolarization (RDP) to monitor beam
- Energy increase goes as < Length

Footprint of ILC; Kitakami, Japan



Proposed footprint of FCC-ee



Intro to Proposed Experiments:

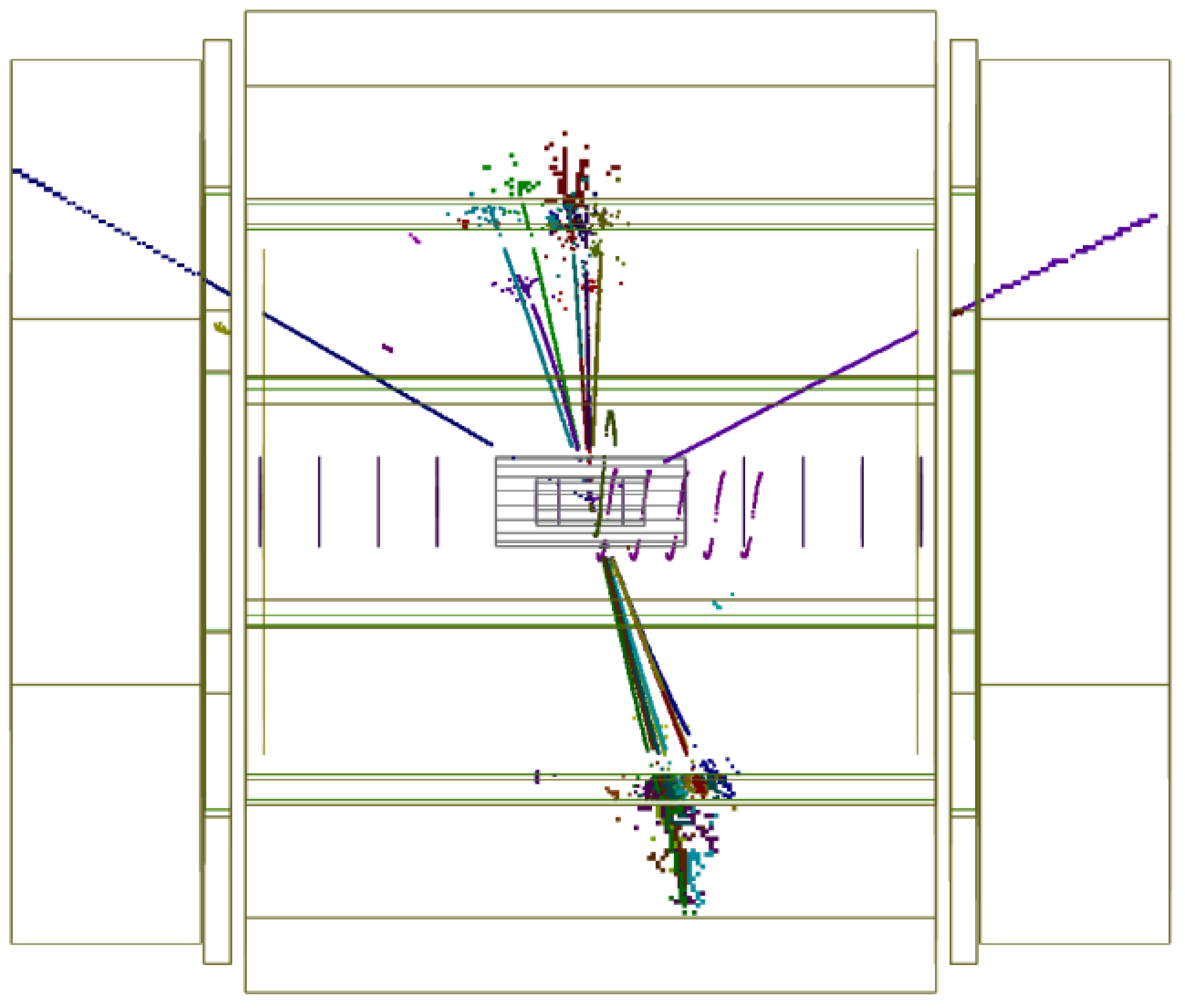
International Linear Collider (ILC) Info:

ILC:

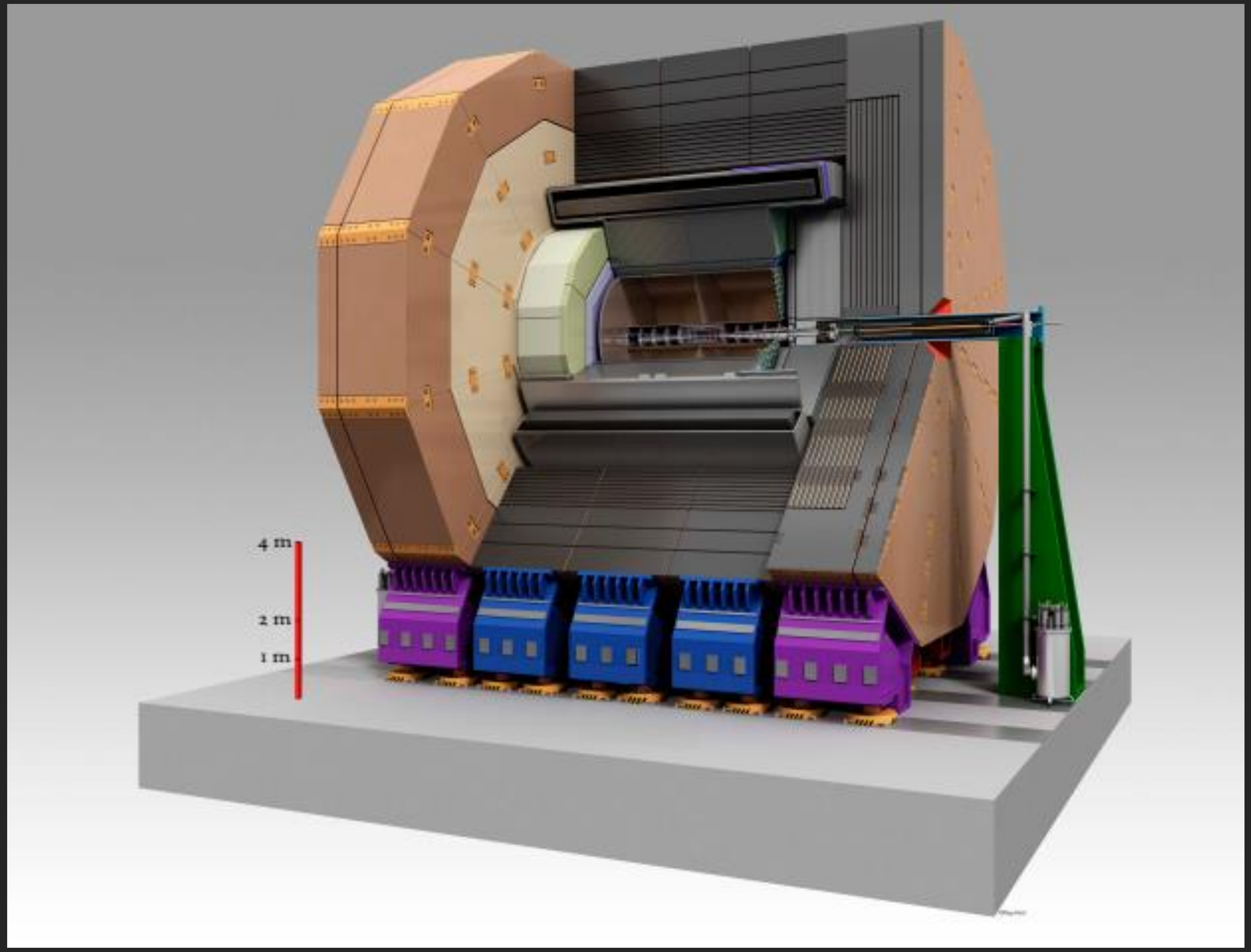
- Location: Kitakami , Japan
- Size: ~31 km
- Cost: 7.92 ± 1.98 Billion USD for ILC and ILD
- Beam (GeV): e+e- from 250 to at least 500
- Polarizations: LL , RL , LR, RR
- Energy Precision: <= 3 ppm
- Luminosity: $1.35 * 10^{34}$
- Beamstrahlung Υ = 0.06 , classical
- Detector: International Large Detector (ILD)
  - TPC, pixels, silicon tracker
  - Vertex Reconstruction: 4 µm , 3 µs
  - https://arxiv.org/pdf/2003.01116.pdf

Figure 2.1
An event of reaction $e^+e^- \to Zh$, with $Z \to \mu^+\mu^-$, $h \to b\bar{b}$, as it would be observed in the ILD detector at the ILC.

ZH Event



ILD for scale



Intro to Proposed Experiments:

International Linear Collider (ILC) Info:

ILD Benchmarks:

Table 2.1. Table of benchmark reactions which are used by ILD to optimize the detector performance. The analyses are mostly conducted at 500 GeV centre-of-mass energy, to optimally study the detector sensitivty. The channel, the physics motivation, and the main detector performance parameters are given.

Measurement	Main physics question	main issue addressed
Higgs mass in $H \to b\bar{b}$	Precision Higgs mass determination	Flavour tag, jet energy resolution, lepton momentum resolution
Branching ratio $H \to \mu^+\mu^-$	Rare decay, Higgs Yukawa coupling to muons	High-momentum p_t resolution, μ identification
Limit on $H \to$ invisible	Hidden sector / Higgs portal	Jet energy resolution, Z or recoil mass resolution, hermeticity
Coupling between Z and left-handed τ	Contact interactions, new physics related to 3rd generation	Highly boosted topologies, τ reconstruction, π^0 reconstruction
Cross section of $e^+e^- \to \nu\nu qqqq$	Vector Bosons Scattering, test validity of SM at high energies	W/Z separation, jet energy resolution, hermeticity
Left-Right asymmetry in $e^+e^- \to \gamma Z$	Full dim-6 EFT interpretation of Higgs measurements	Jet energy scale calibration, lepton and photon reconstruction
Hadronic branching ratios for $H \to b\bar{b}$ and $c\bar{c}$	New physics modifying the Higgs couplings	Flavour tag, jet energy resolution
A_{FB}, A_{LR} from $e^+e^- \to b\bar{b}$ and $t\bar{t} \to b\bar{b}qqqq/b\bar{b}ql\nu$	Form factors, electroweak coupling	Flavour tag, PID, (multi-)jet final states with jet and vertex charge
Discovery range for low ΔM Higgsinos	Testing SUSY in an area inaccessible for the LHC	Tracks with very low p_t, ISR photon identification, finding multiple vertices
Discovery range for WIMP's in mono-photon channel	Invisible particles, Dark sector	Photon detection at all angles, tagging power in the very forward calorimeters
Discovery range for extra Higgs bosons in $e^+e^- \to Zh$	Additional scalars with reduced couplings to the Z	Isolated muon finding, ISR photon identification.

Intro to Proposed Experiments:

Future Circular Collider, Lepton Collider (FCC-ee) Info as of 2018:

FCC-ee:

- Location: Switzerland and France. Around Geneva.
- Size: 97.75 km circumference
- Cost: 11.6 Billion CHF (~12.5 Billion USD) , No detectors ?
- Beam (GeV): e+e- , five energies between 90 and 365
- Polarizations: **NO?**
- Energy Precision: 3 ppm
- Luminosity: $\mathbf{8.5} * \mathbf{10^{34}}$ e+e- / second
- Beamstrahlung Υ < 1 , Classical
- Detector: CLD , IDEA ?

FCC Civil Engineering

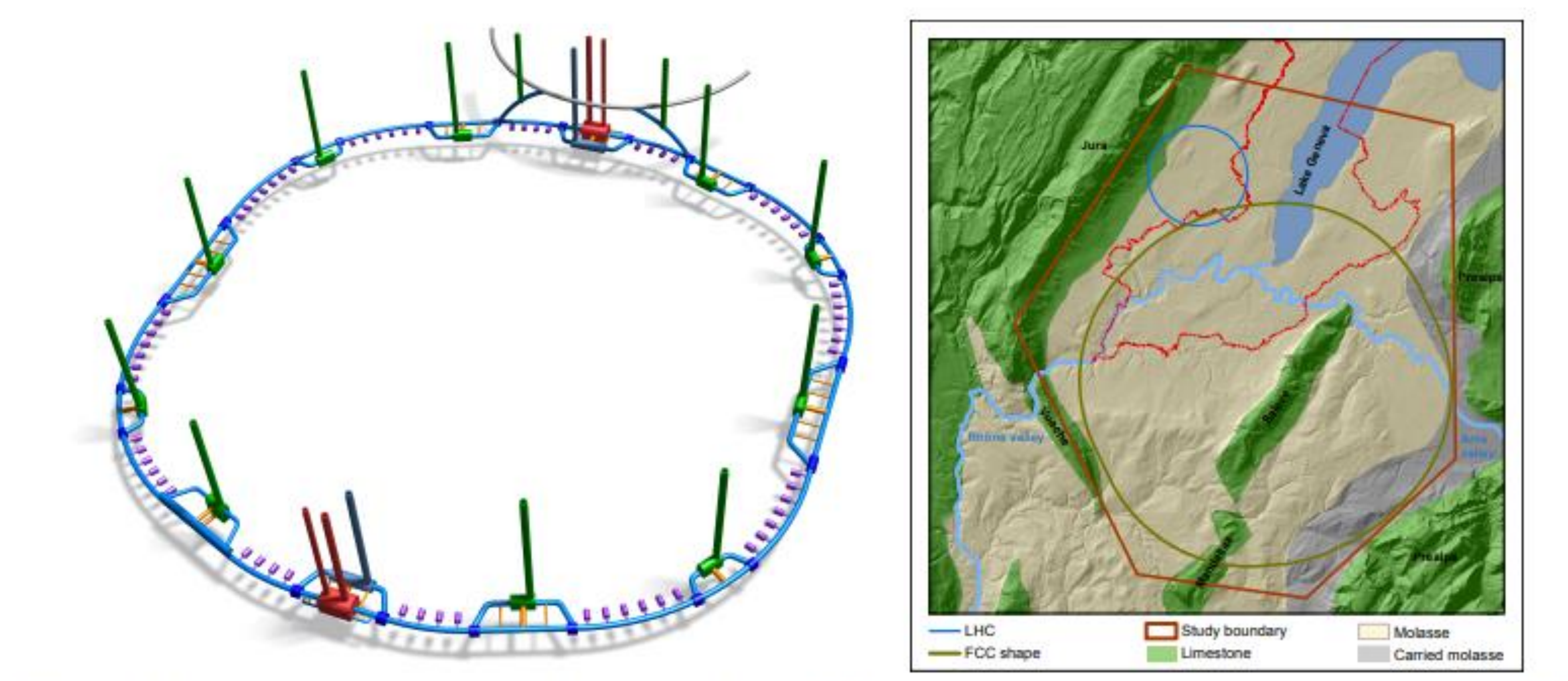


Figure S.5: Left: 3D, not-to-scale schematic of the underground structures. Right: study boundary (red polygon), showing the main topographical and geological structures, LHC (blue line) and FCC tunnel trace (brown line).

Example of beam precision:

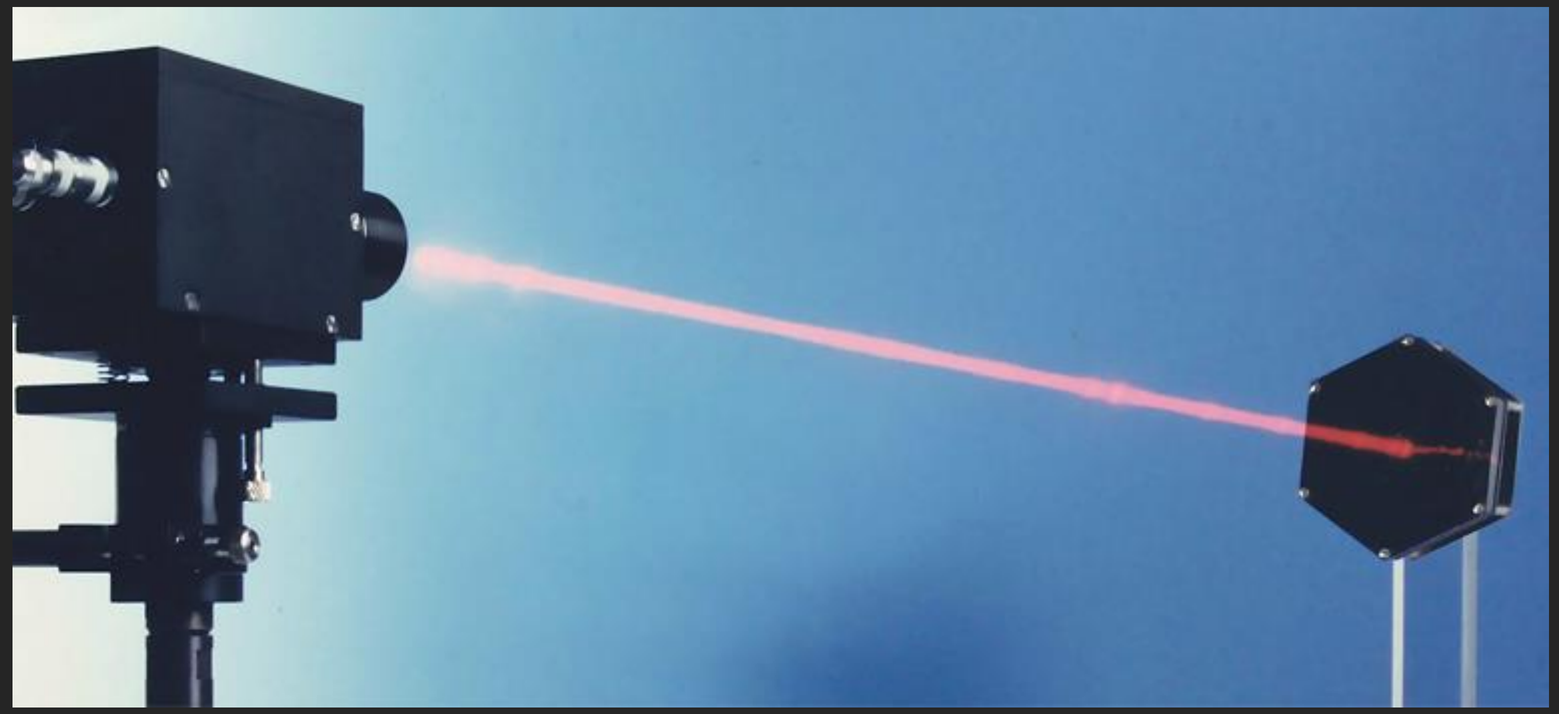
Approximation for understanding energy precision

Consider the following homework problem:

You conduct an experiment where you use a laser beam, with an instantaneous energy of E_i = 10 +- 0.1 MJ, with a solar panel, of efficiency of ε = 10% +- 0.01%, to charge a battery.

Assume the conversion is 1:1 an that there is no correlation in their uncertainties.

How much energy is stored (E_f) in this idealized scenario?



Its 1:1 so:

$E_f = E_i * \varepsilon$ = 1 MJ

What is the uncertainty?

Propagation of uncertainty!

$$\sigma_f^2 = \varepsilon^2\sigma_i^2 + E_i^2\sigma_\varepsilon^2 = (100 + 1) * 10^{-6}(MJ)^2$$

Which term is dominant? The left hand term. Its at 100 ppm while the right term is at 1 ppm.

Here, the beam is dominant source of uncertainty

Motivating new experiments:

Why should we care about precision?

Precision measurements of the most massive particle accessible to LEP, the Z boson, gave us:

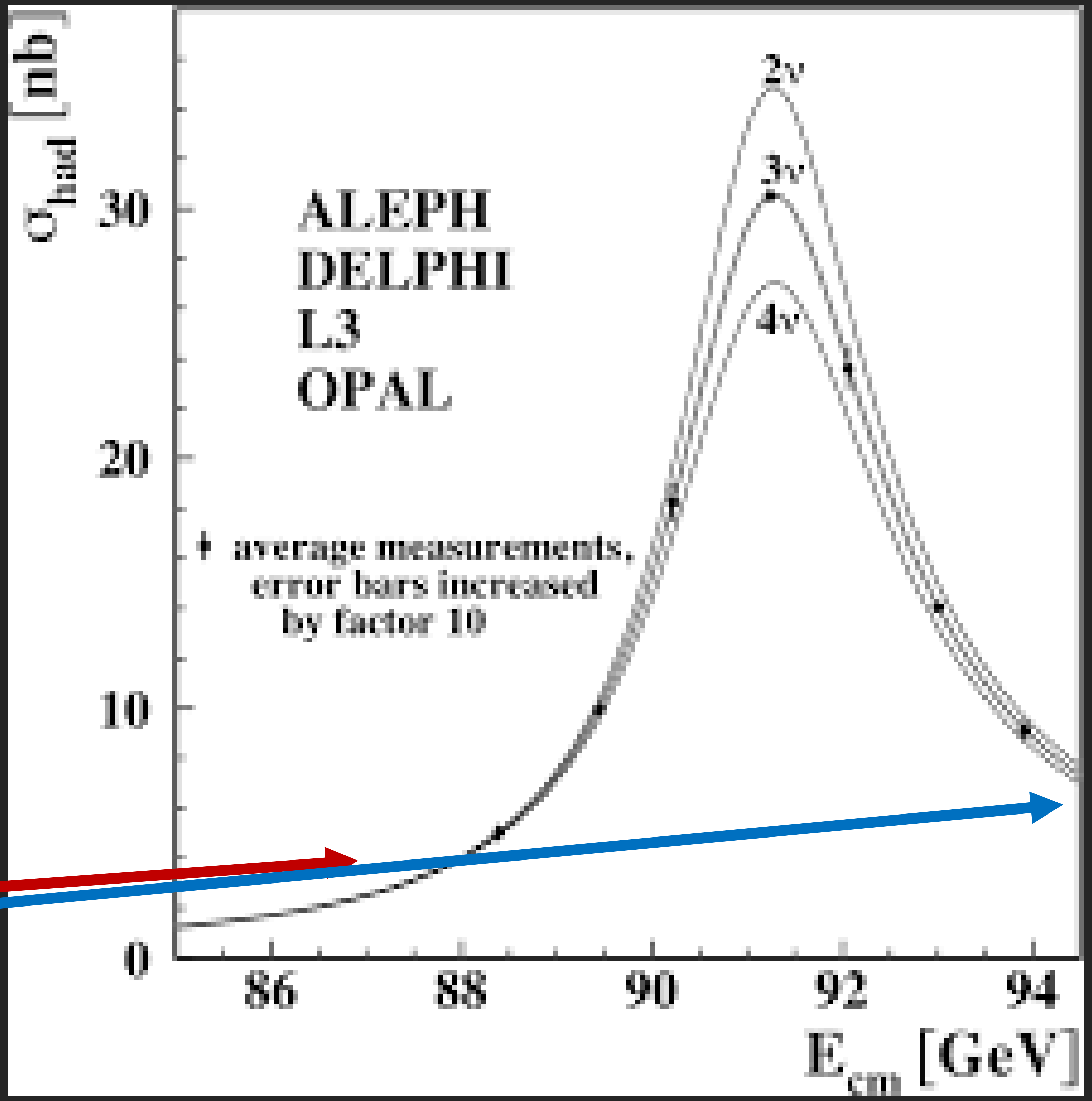
- Constraint on number of low mass neutrinos , 2.984 ± 0.013
- Anomaly in strong force at 162^{+29}_{-16} GeV
- Anomaly in electroweak force at 390^{+750}_{-280} GeV
- Source from 2000 https://arxiv.org/abs/hep-ex/0012018

Z boson distribution is fundamentally described by Breit-Wigner

Likely won't see in experiment due to precision.

Rising side is usually larger due to radiative effects.

ISR, FSR, beamstrahlung

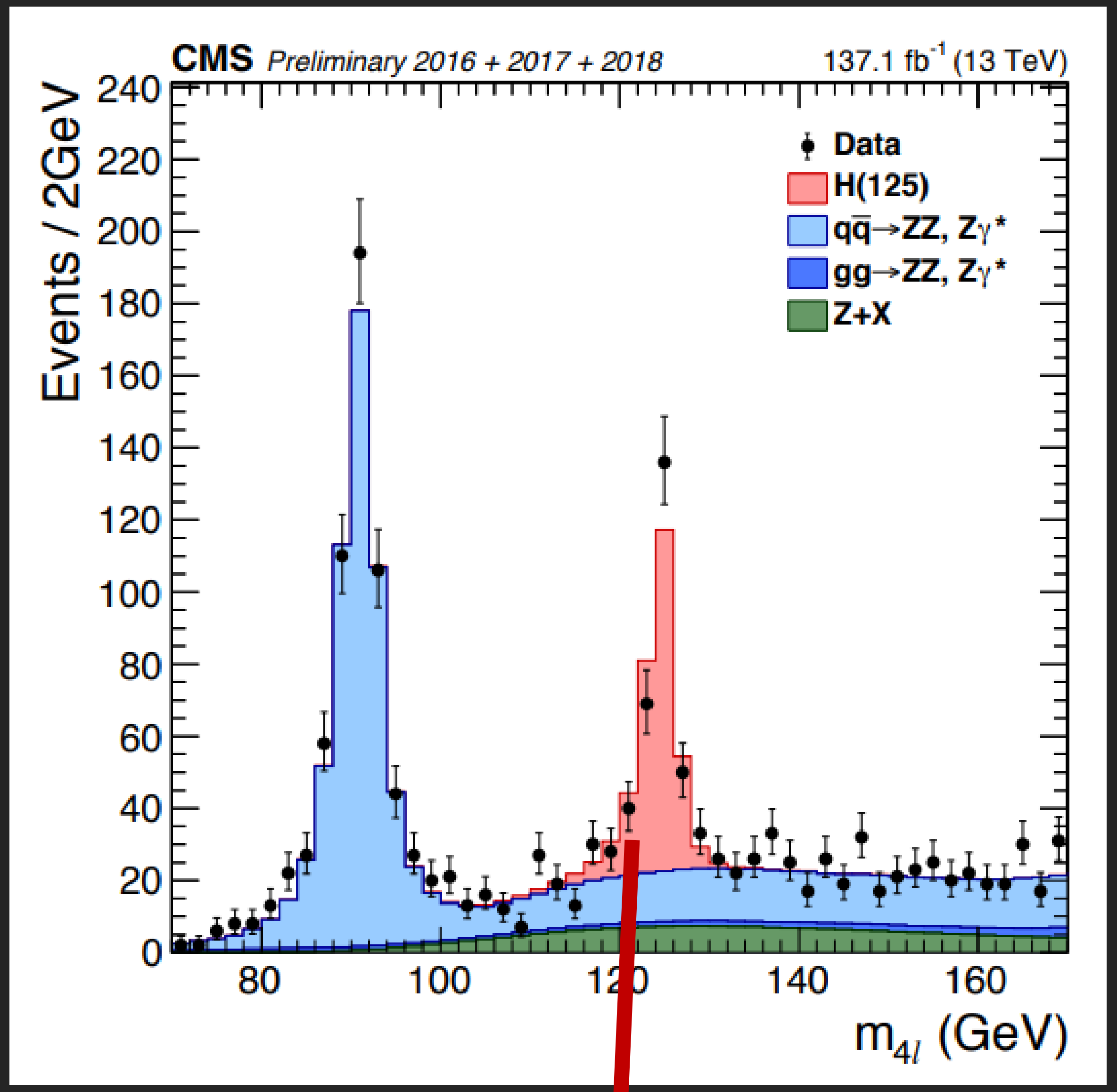


Motivating new experiments:

Why should we work towards new particle colliders?

We want scanning of the fundamental mass distribution of:

- Z Boson (Width ~2.5 GeV)
- Higgs Boson (Width ~4 MeV)
- Top quark (Width ~1.35 GeV , https://pdg.lbl.gov/2019/reviews/rpp2019-rev-top-quark.pdf)

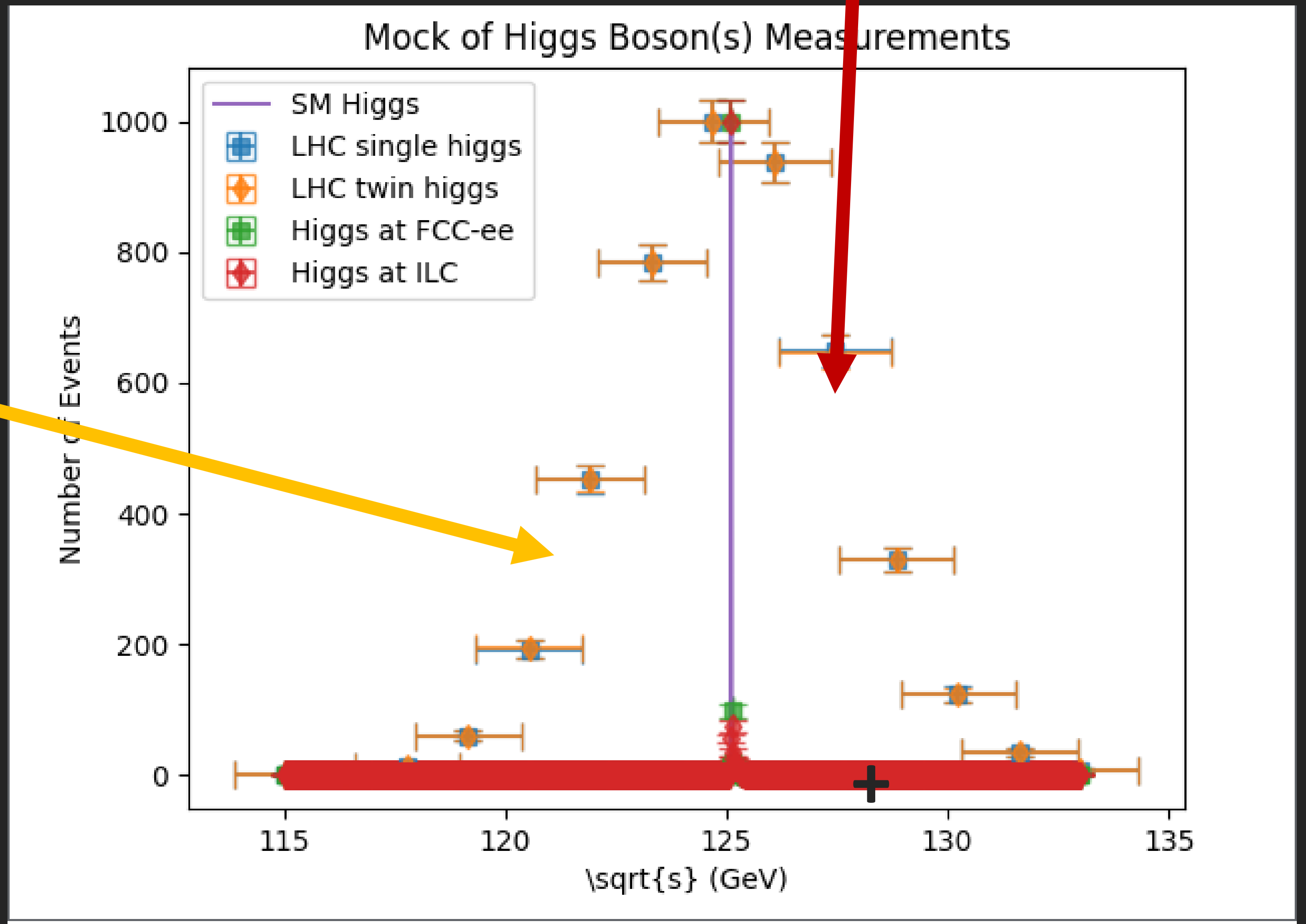


Can’t resolve Higgs width at LHC

Invariant mass alone is not sufficient to prove Higgs as SM Higgs

Can’t resolve if the Higgs peak is single Higgs or twin Higgs

What about ILC, FCC-ee ?



Twin Higgs e.g. H1 = 125.11 , H2 = 125.09

LHC Single Higgs, Twin Higgs Permutation pvalue : 99.906%

LHC Single Higgs, SM Higgs Permutation pvalue : ~0.0000%

Reject that this is enough evidence to prove LHC Higgs as SM Higgs

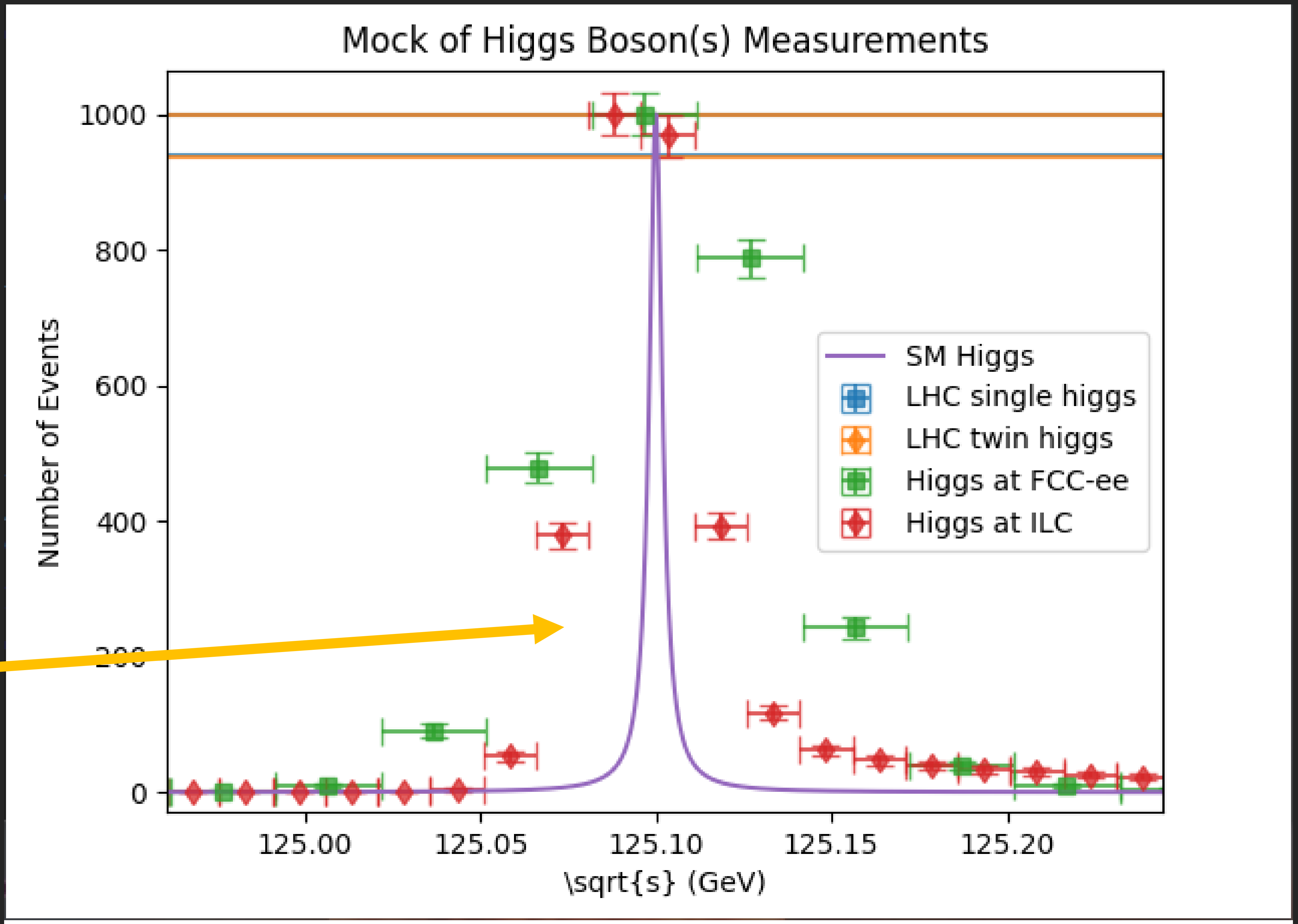
Motivating new experiments:

Hopeful for ILC , FCC-ee?

Focus on scanning of the fundamental mass distribution of:

- Higgs Boson (Width ~4 MeV)

Even with these very optimistic scans still can't resolve Higgs



Still not able to resolve SM Higgs width!

How much more events would these need?

ILC : ~4.6x LHC FCC-ee : ~3.7x LHC

FCC-ee = less data + higher luminosity = less time

Is there another way?

Yes, measure it indirectly using partial widths!

Notice, FCC-ee has advantage due to luminosity

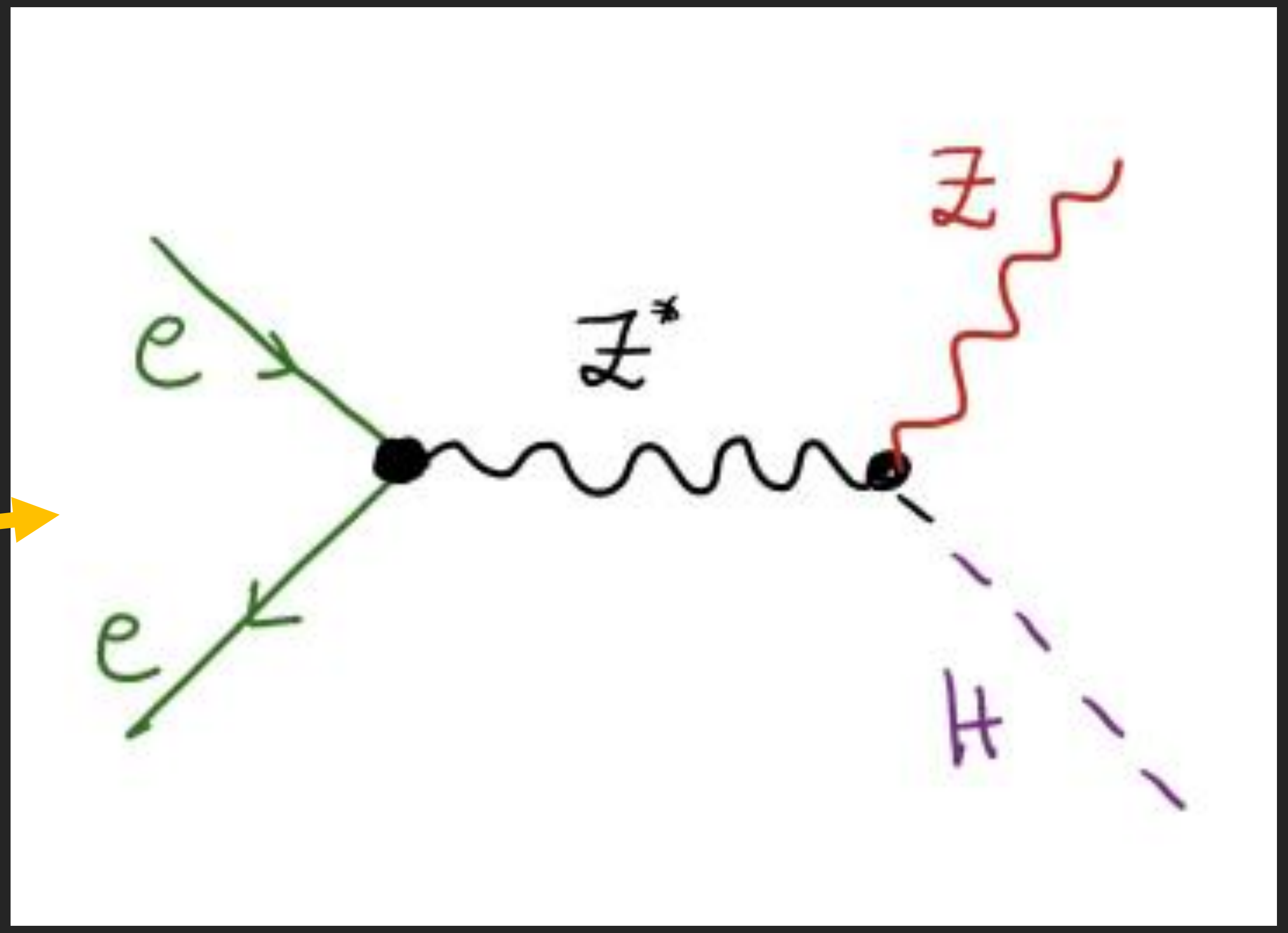
Motivating new experiments:

Measure width indirectly?

How? Measure the widths of certain Higgs processes.

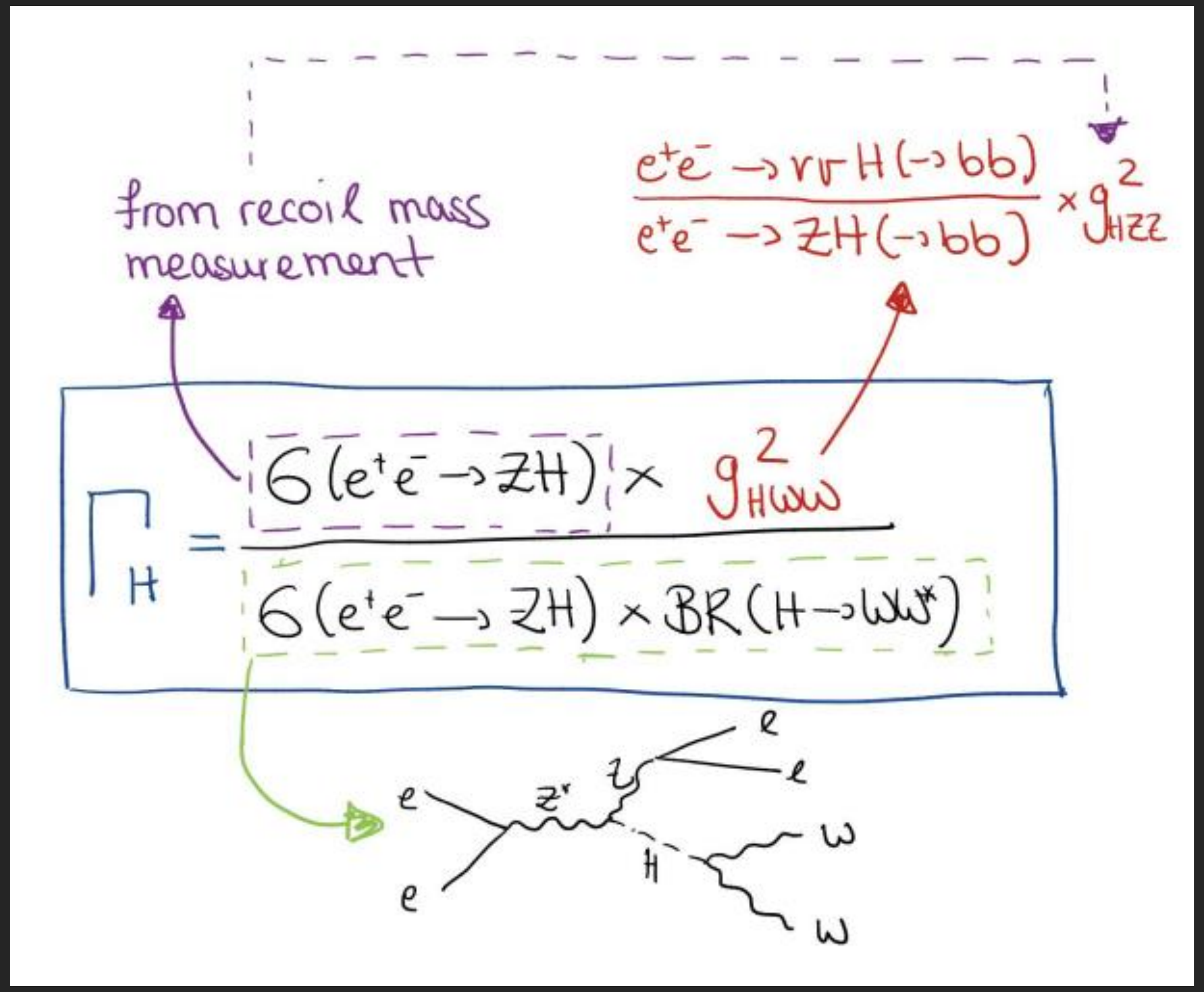
Take Higgstrahlung (why? Recoil mass shows up even if Higgs is invisible)

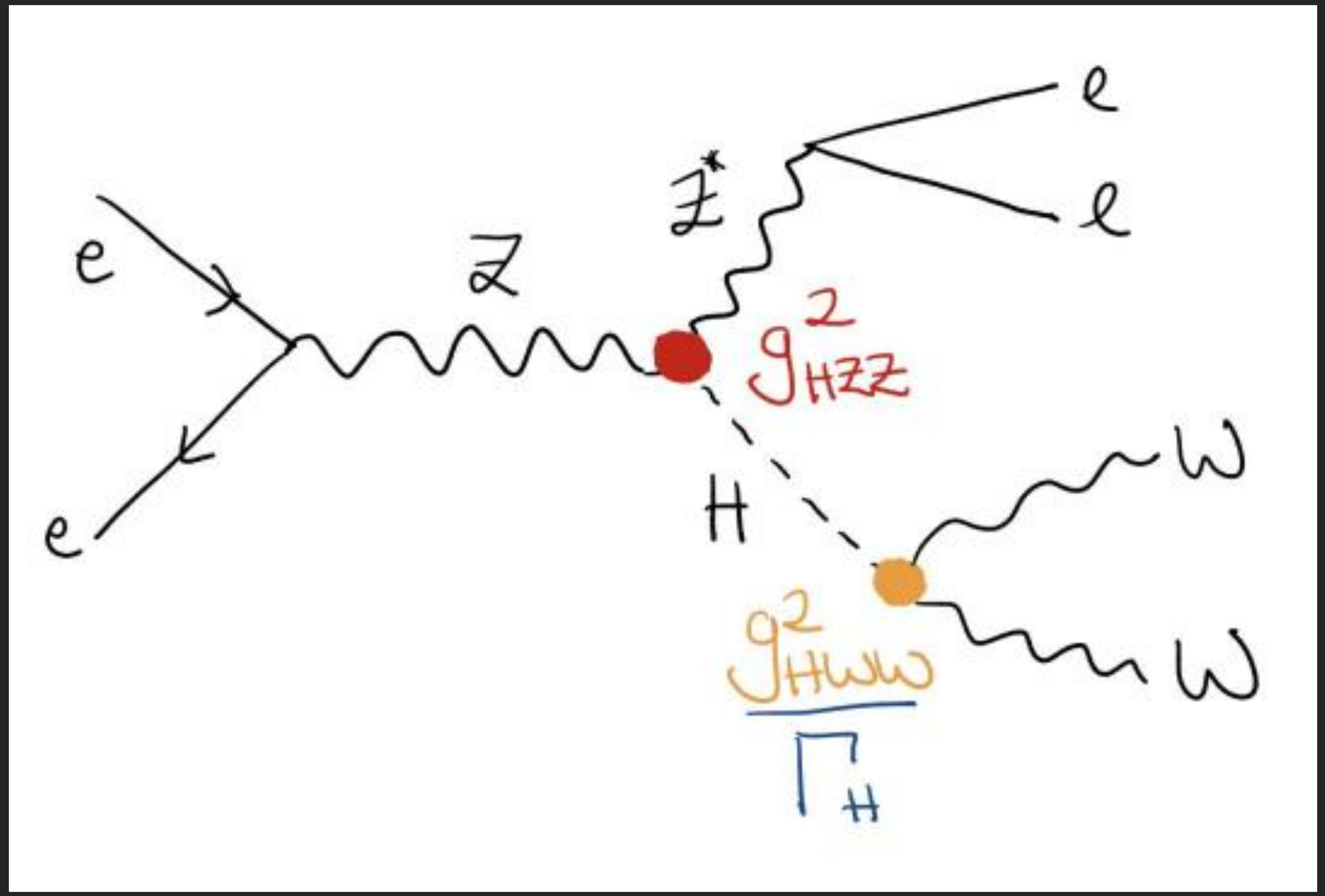
- Source: https://indico.nikhef.nl/event/2143/#9-project-d-ilc-higgs-width-me
- We want to compare this branching fraction to one of the specific Higgs branching fractions. Use $H \rightarrow W^-W^+$ since its large.
- Use $Z \rightarrow l^-l^+$ since its visible, precise



ILC simulated result:

- Expect ~2% precision on width
- $\boldsymbol{\Gamma_H = 4 \pm 0.08\ MeV}$

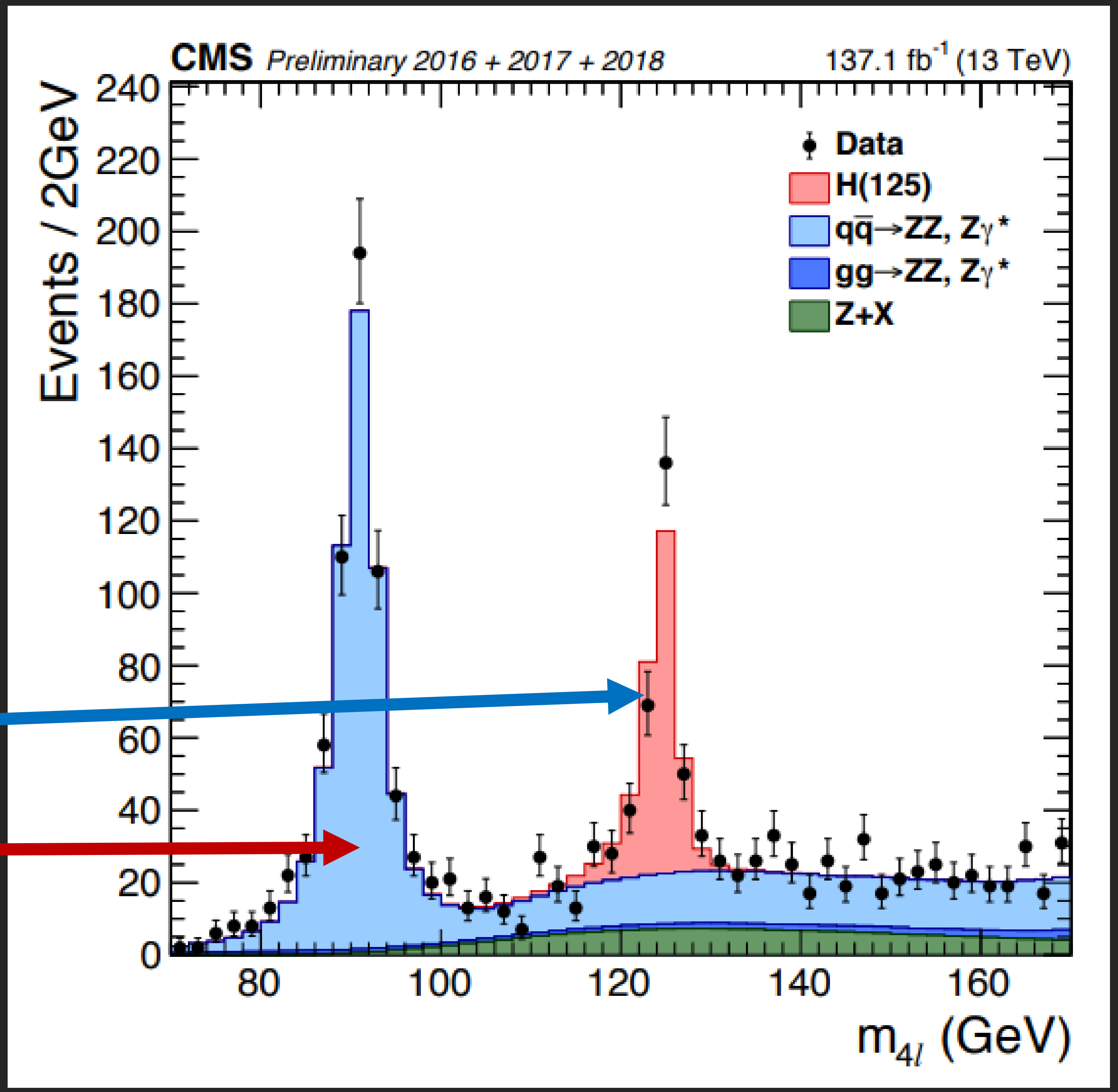




Intro to Beam Energy:

Quick comment and transition!

This CMS plot is deceptive. Higgs width about **4 MeV** (35 ppm), same as **2.5 GeV** of the Z?



Why? Energy precision effects…

Need to better understand , model energy precision

Focus on beam energy for today -> How do we simulate this?

Intro to Beam Energy:

How to simulate? What do we need?

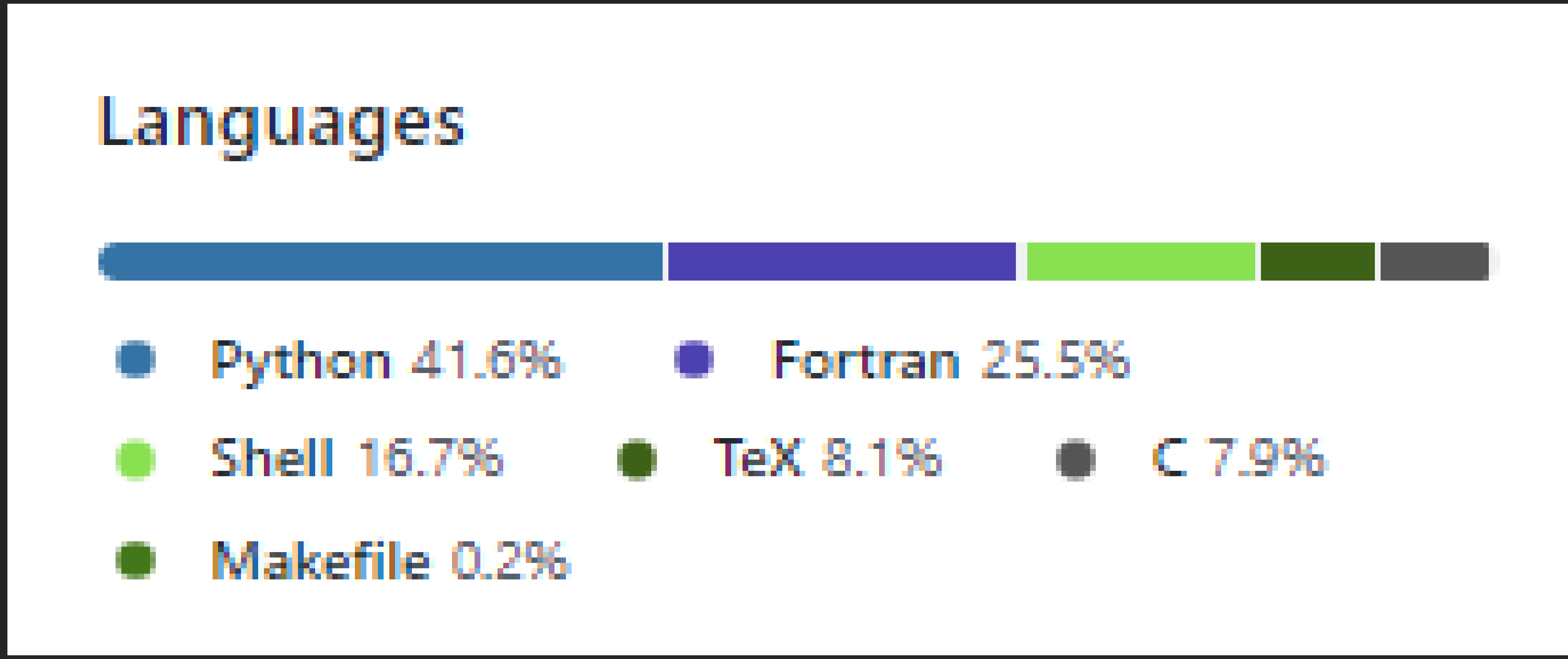
A bunch of things. My programming setup for simulating on KU's HPC is at

https://github.com/BrendonMadison/GPUP (in case you wanted to do this for some reason...)

GPUP = Guinea Pig Updated Peripherals

Need GuineaPig++ installed (https://gitlab.cern.ch/clic-software/guinea-pig)

Check out the diversity of my programming languages:



Intro to Beam Energy Calibration:

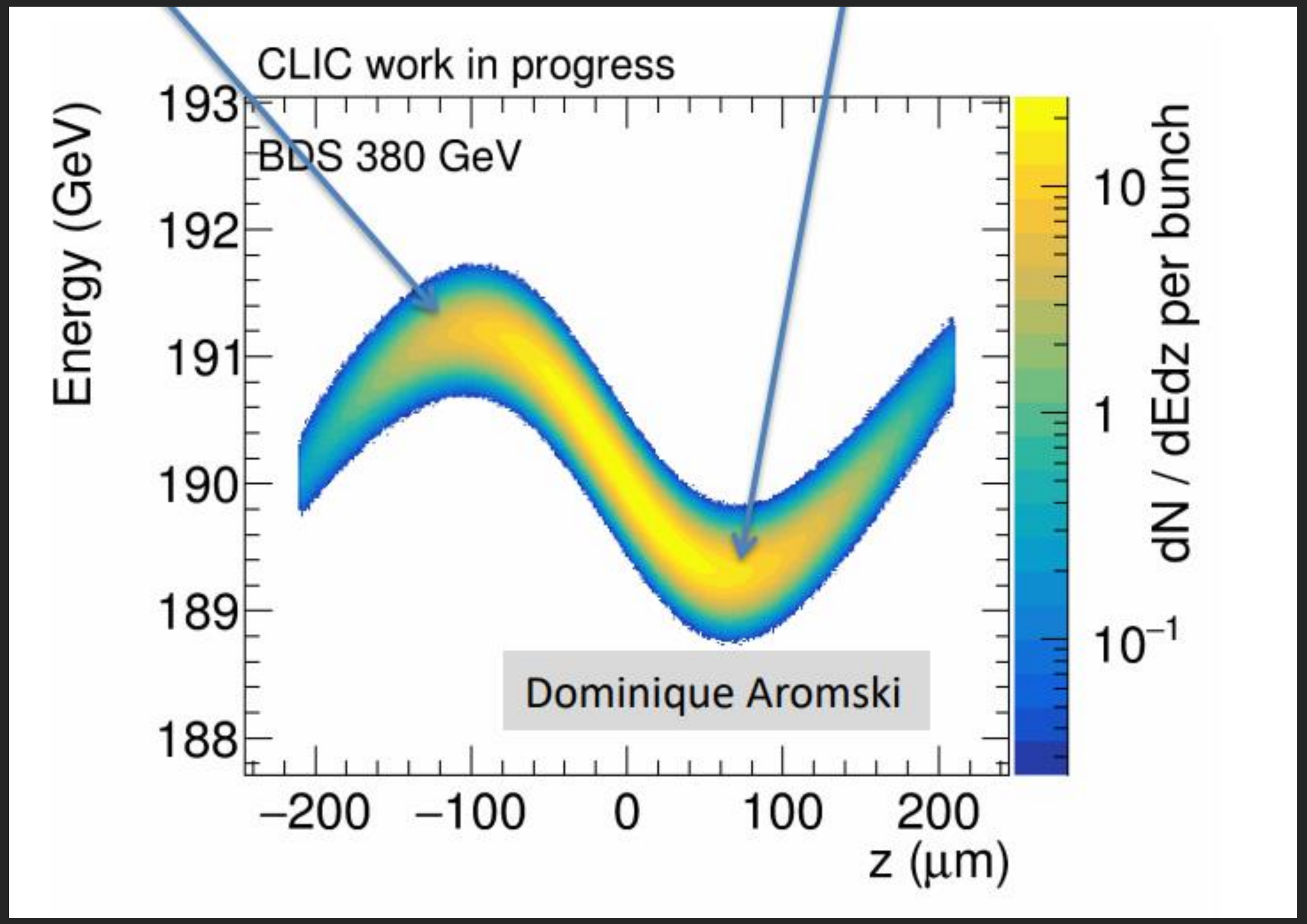
How to simulate? What do we need?

Input correlation, particle geometry ->

See **MultivariateGaussian.C** in GPUP Github

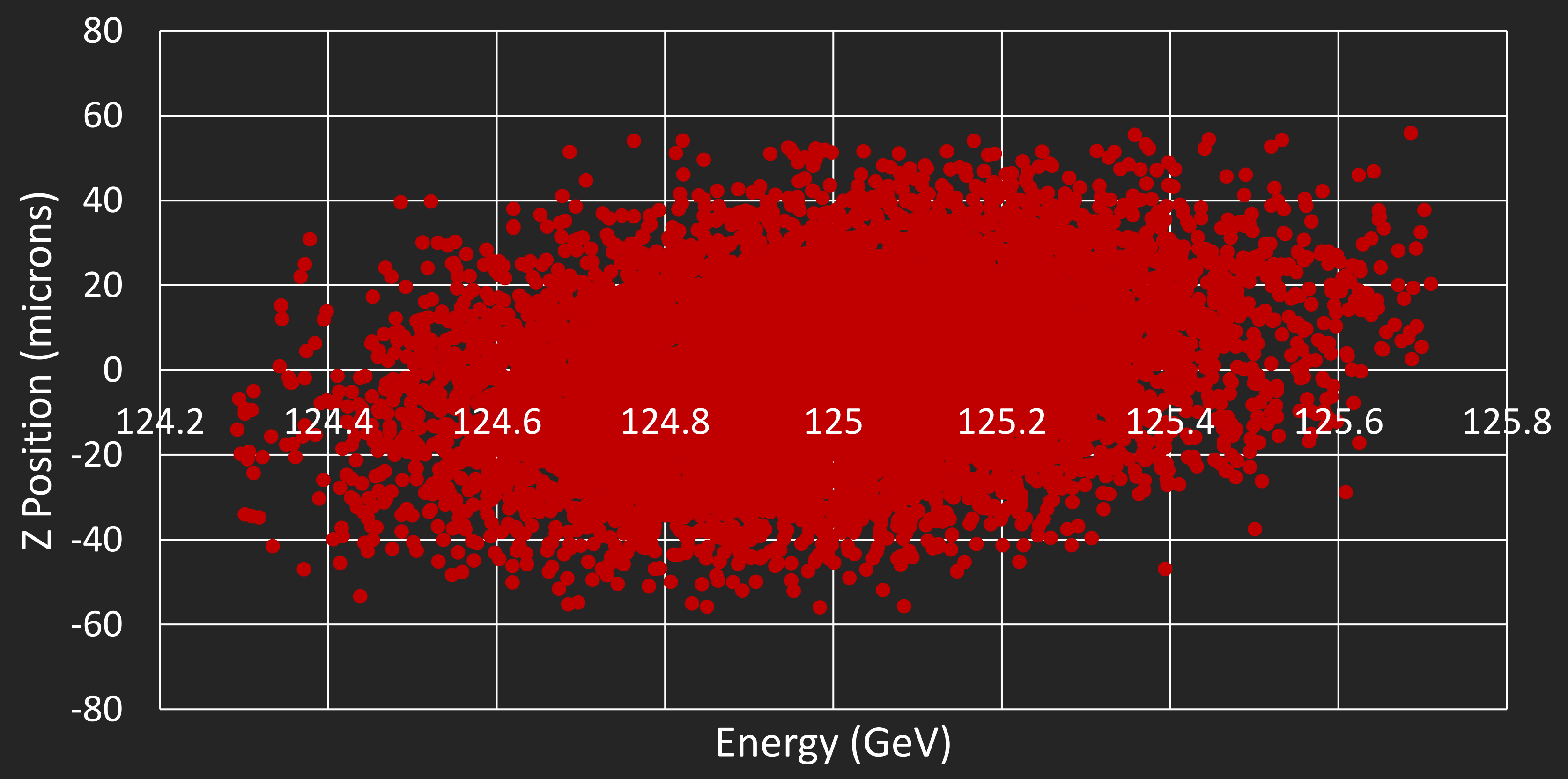
We need to know:

- Any initial correlations between:
  - Momenta
  - Energy
  - Position
- Particles in the beam:
  - Charge
  - Mass
  - Polarizations (LH , RH, spin)
- Beam:
  - Number of beam particles
  - x,y,z emittance (essentially angle)
  - x,y,z velocity (β)
  - Energy
  - Intrinsic Energy spread
  - Disruption (analogous to optical magnification)



CLIC Beam Energy , z correlation
significant electron wakefield

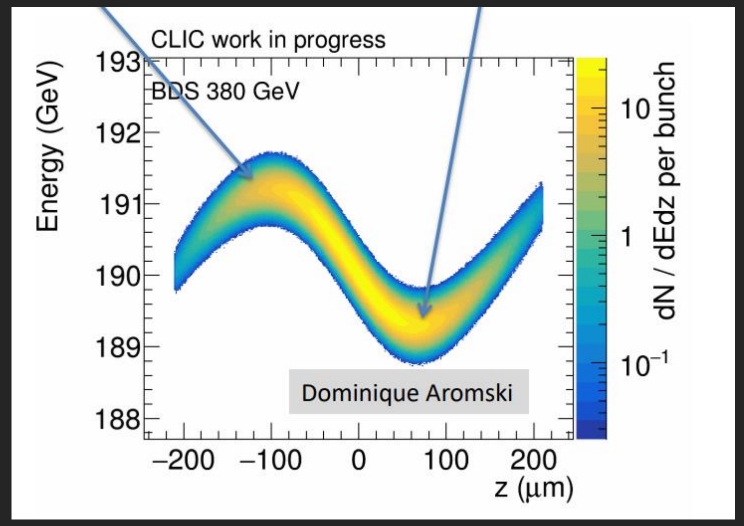
ILC 250 GeV Correlated Electron Beam



Intro to Beam Energy Calibration:

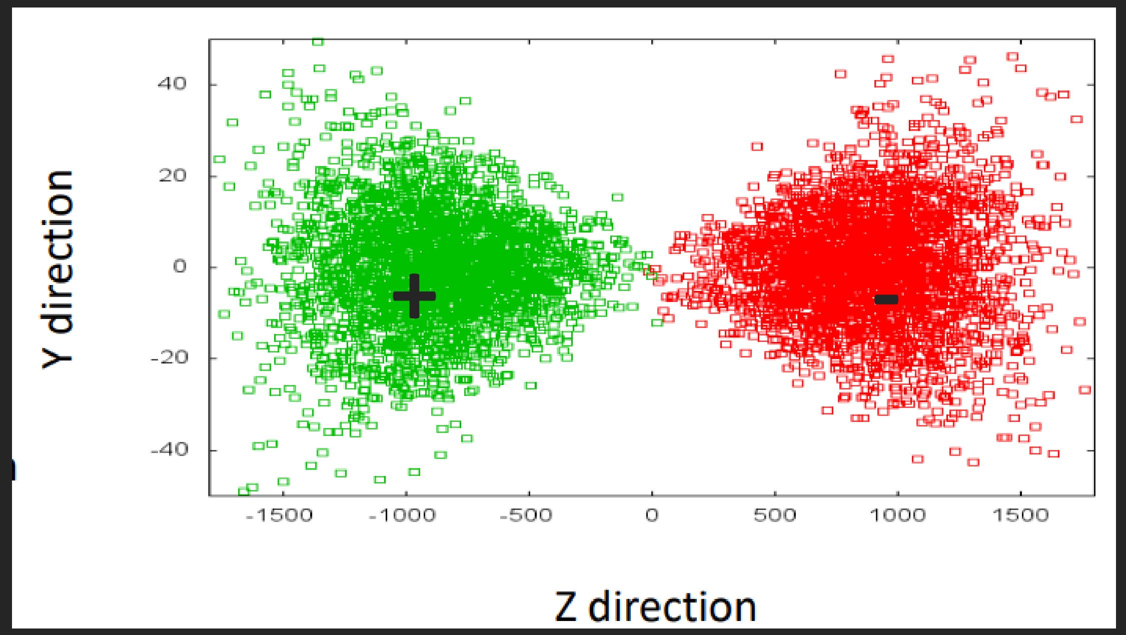
Electrodynamic effects :

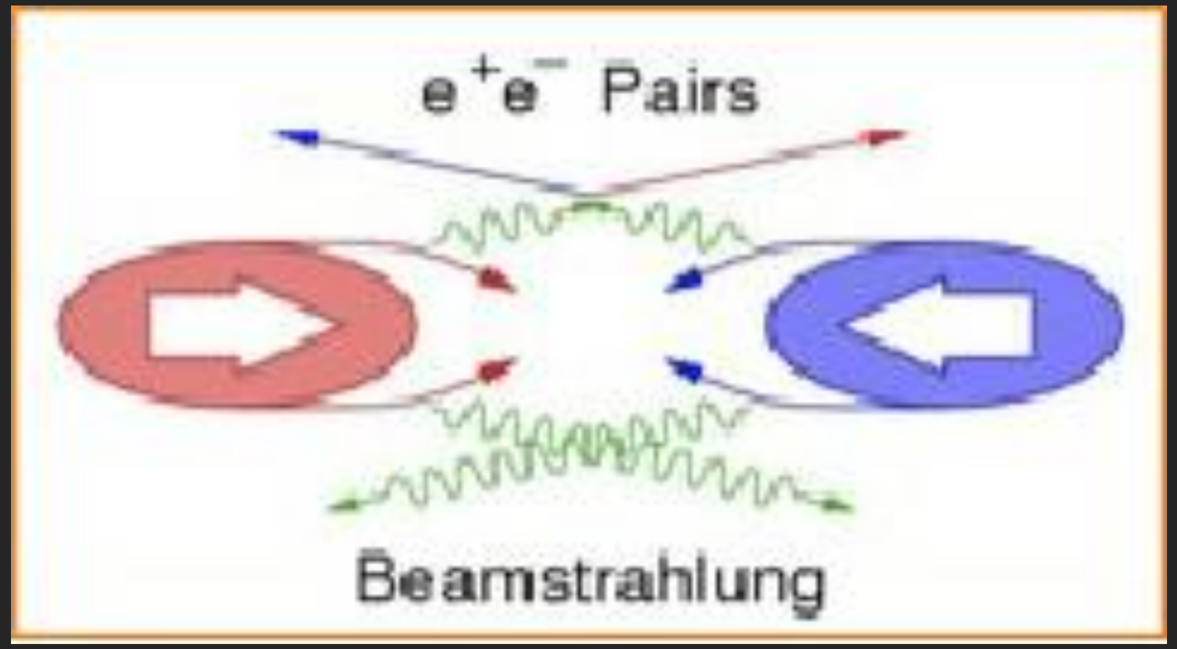
- Synchrotron radiation
  - Everyone knows this one…relativistic charges in a circle…
  - Energy limitation for circular colliders
- Pinch Effect
  - As bunches get close, they increase magnification/disruption
  - Creates E, z correlation
- Beamstrahlung
  - As bunches get close, pass each other they interfere and “brake”
  - Biggest effect for energy precision in linear colliders
- Wakefield Effect
  - Changes bunch shape, creates correlations
- Resonant Depolarization
  - Causes energy and polarization change
  - Only relevant for circular colliders



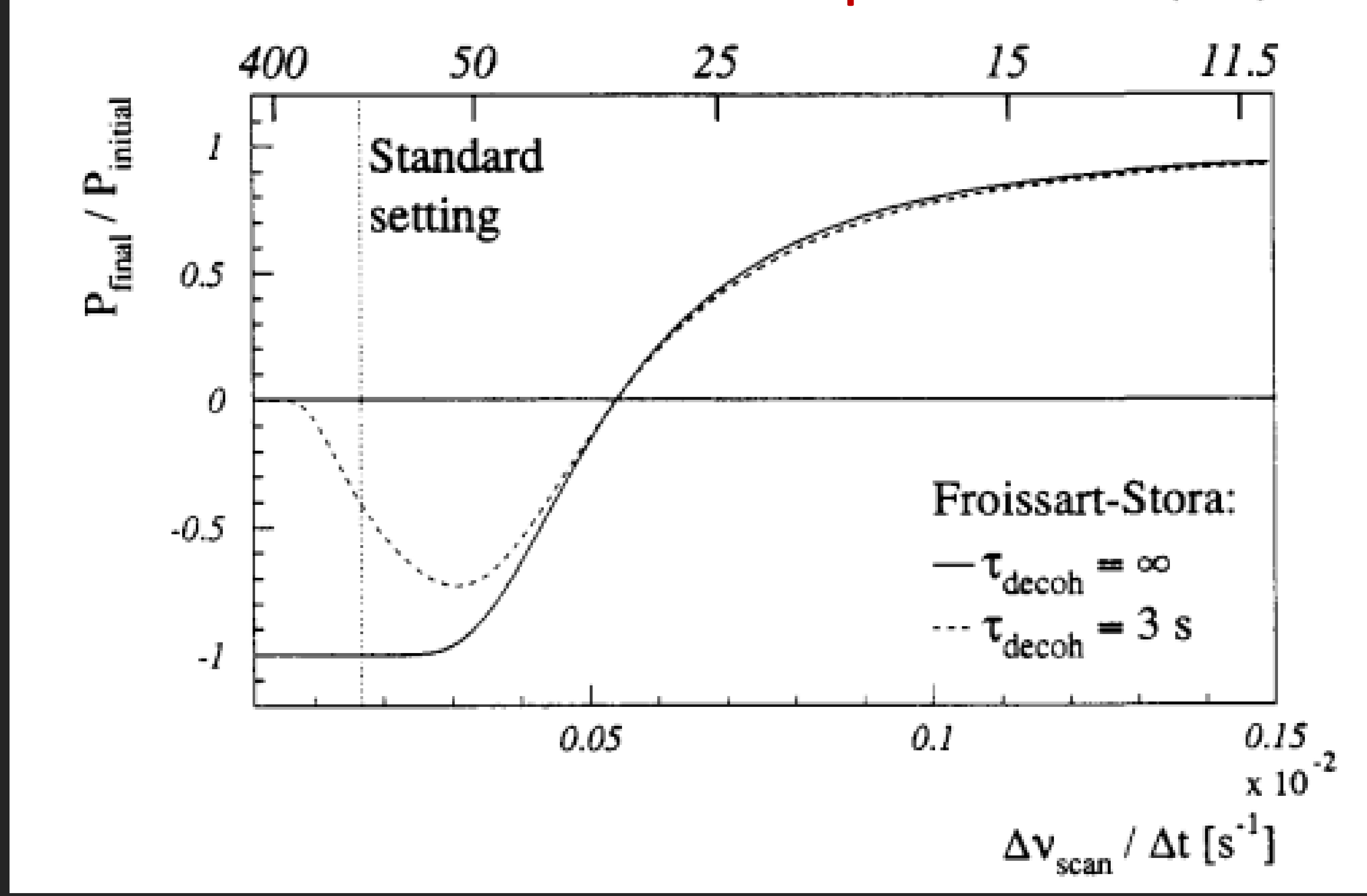
Wakefield

“Pinch Effect”





Resonant Depolarization

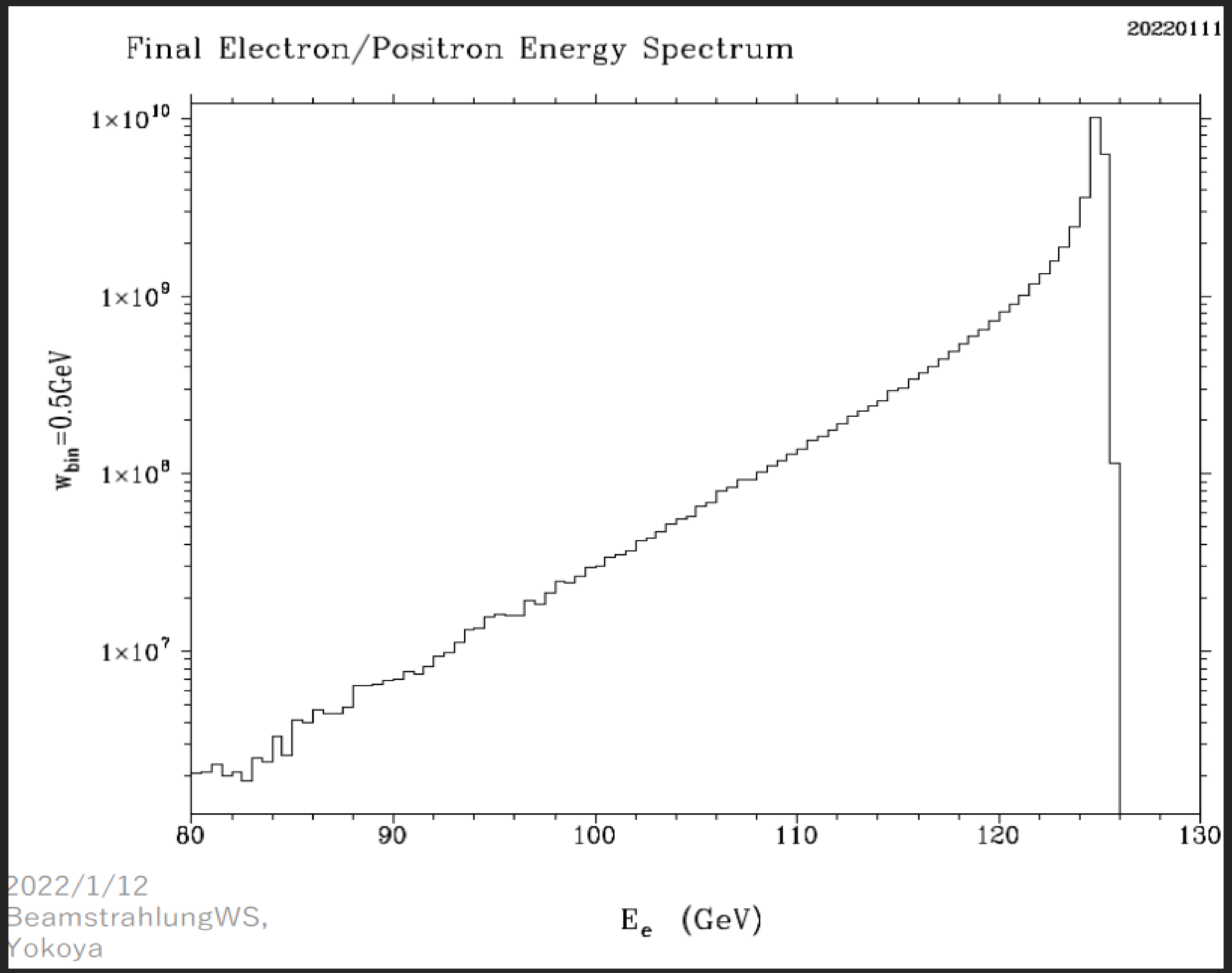


Intro to Beam Energy Calibration:

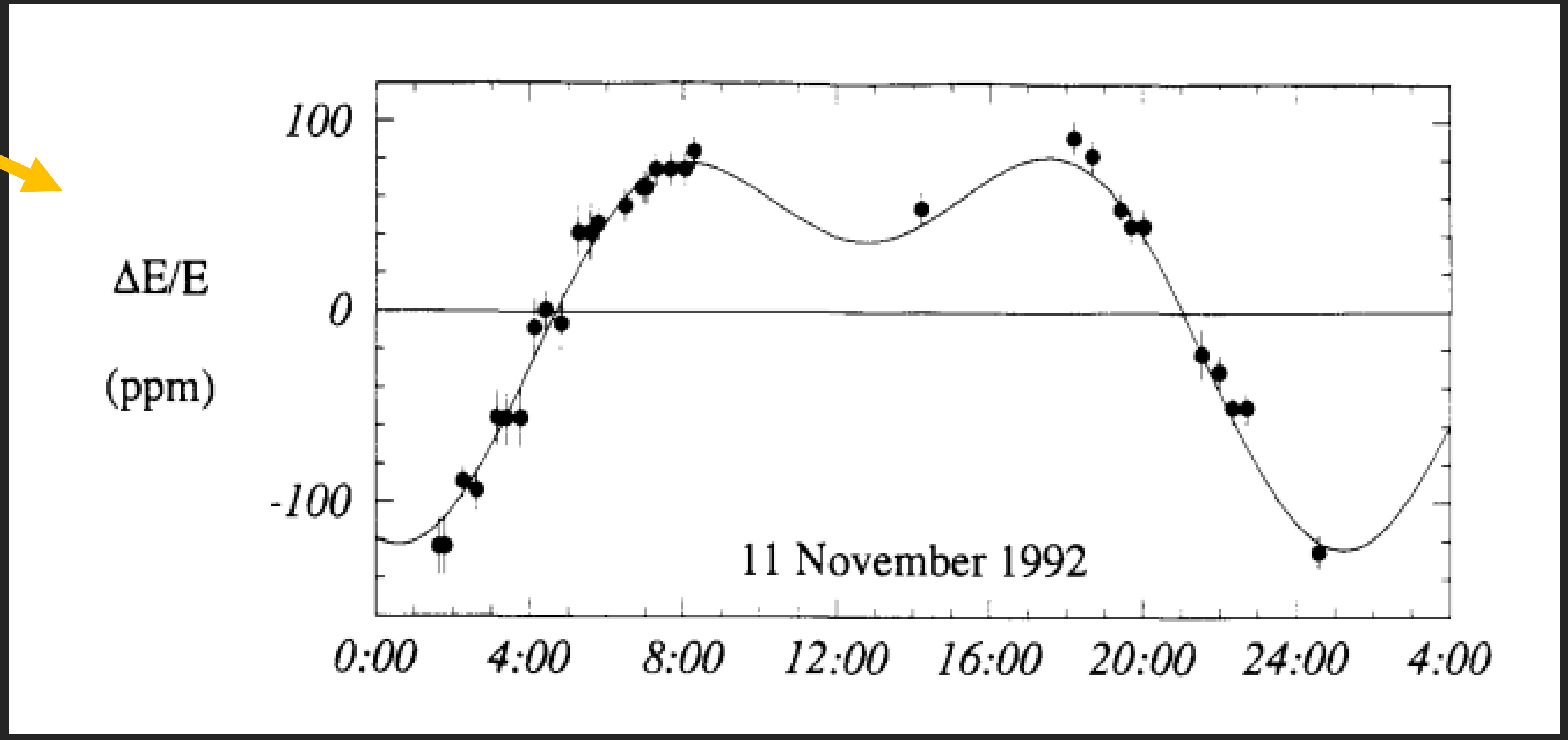
Beam difference between Linear and Circular :

- Beamstrahlung
  - As bunches get close, pass each other they interfere and “brake”
  - Present in both collider types
  - Changes beam energy but in continuous and consistent way
- Resonant Depolarization
  - Causes energy and polarization change
  - Changes beam energy in discrete way; your beam is discrete too
  - Depends on environmental factors (Tide, trains etc.)
  - Tidal effects can be calibrated out
  - https://cds.cern.ch/record/267514

ILC250 Beam simulation from CAIN, Yokoya:



Resonant Depolarization over time:



Intro to Beam Energy Calibration:

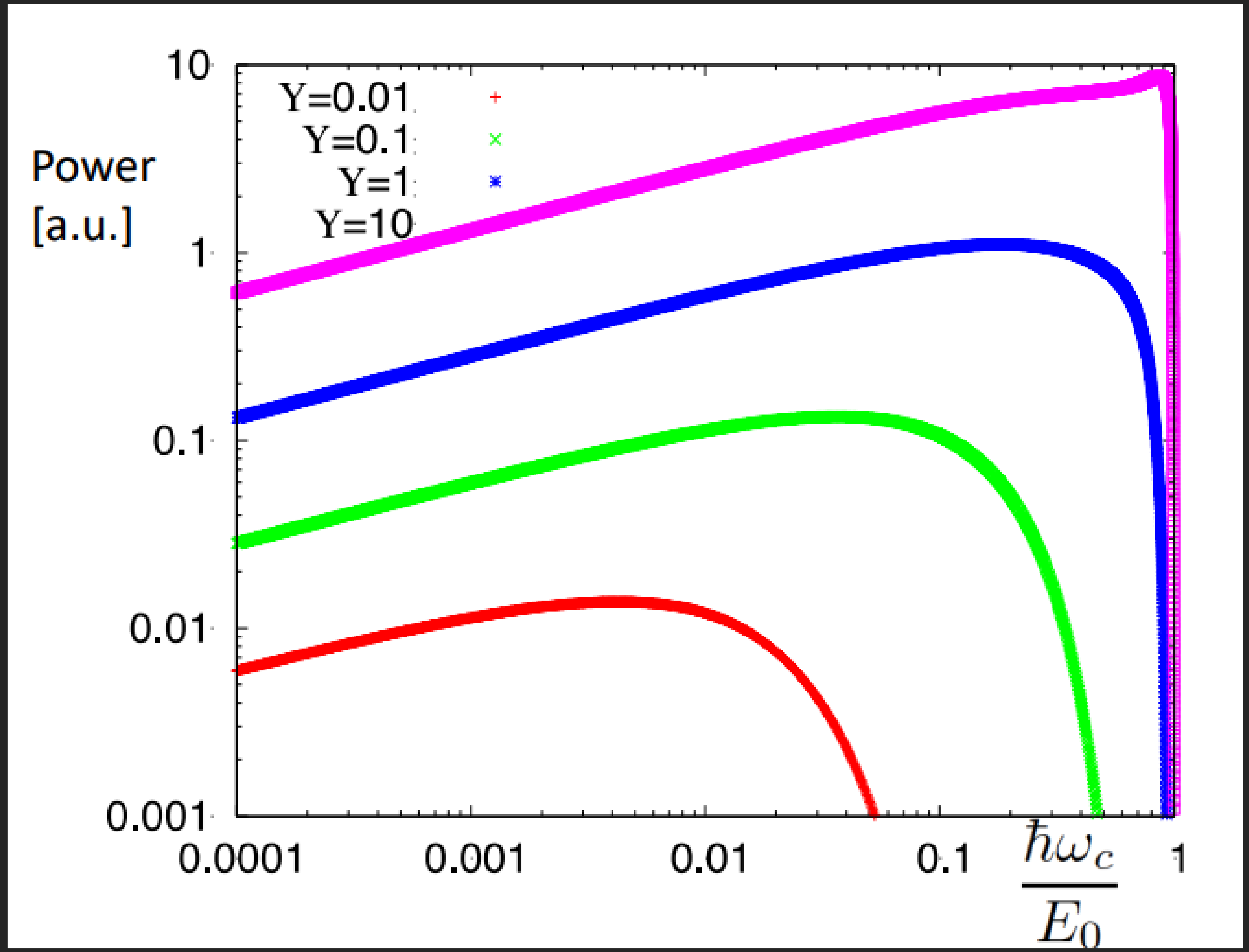
More on Beamstrahlung :

- Beamstrahlung
  - As bunches get close, pass each other they interfere and "brake"
  - Present in both collider types
  - Changes beam energy but in continuous and consistent way

- Beamstrahlung also has the "beamstrahlung parameter":
  - $\Upsilon = \frac{\hbar\gamma^3 c}{\rho E_0}$ ~= 0.06 for ILC at 250 GeV
- At Υ << 1 Beamstrahlung is in classical regime
- At Υ >> 1 Beamstrahlung is in quantum regime
- Quantum : pair creation, hadronization, ISR, FSR
  - More energy loss , energy loss is less precise
- Spectrum described by Sokolov-Ternov:

$$\frac{d\dot{w}}{d\omega} = \frac{\alpha}{\sqrt{3}\pi\gamma^2}\left[\int_x^\infty K_{\frac{5}{3}}(x')dx' + \frac{\hbar\omega}{E}\frac{\hbar\omega}{E-\hbar\omega}K_{\frac{2}{3}}(x)\right]$$

Beamstrahlung spectrum:



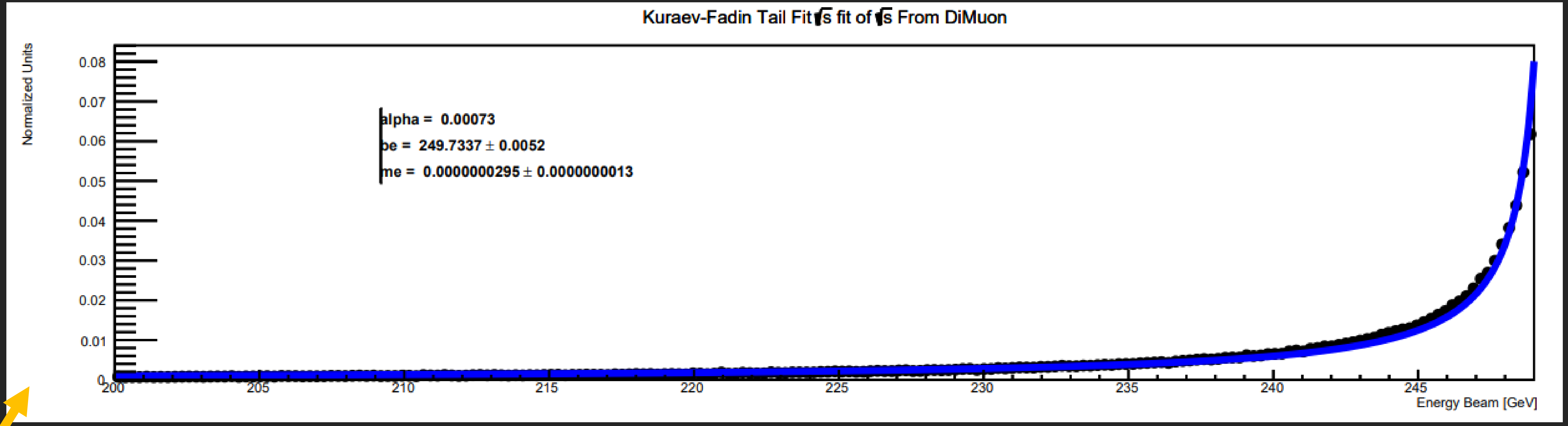
Credit: Daniel Schulte

Intro to Beam Energy Calibration:

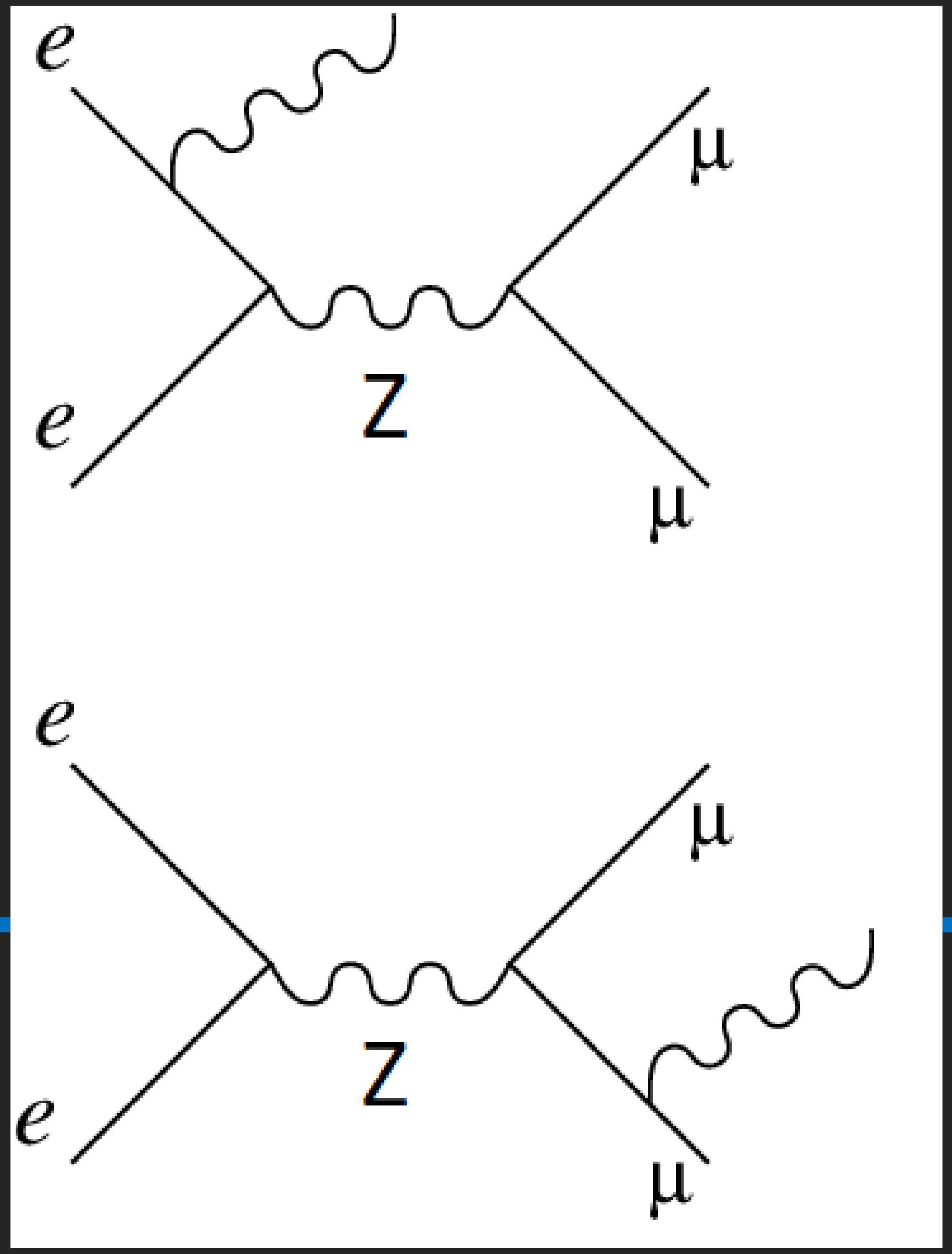
What are ISR, FSR ?

Initial State Radiation (ISR)

- Lower energy of initial state by emission of boson
- Can use Kuraev-Fadin equation to get power spectrum



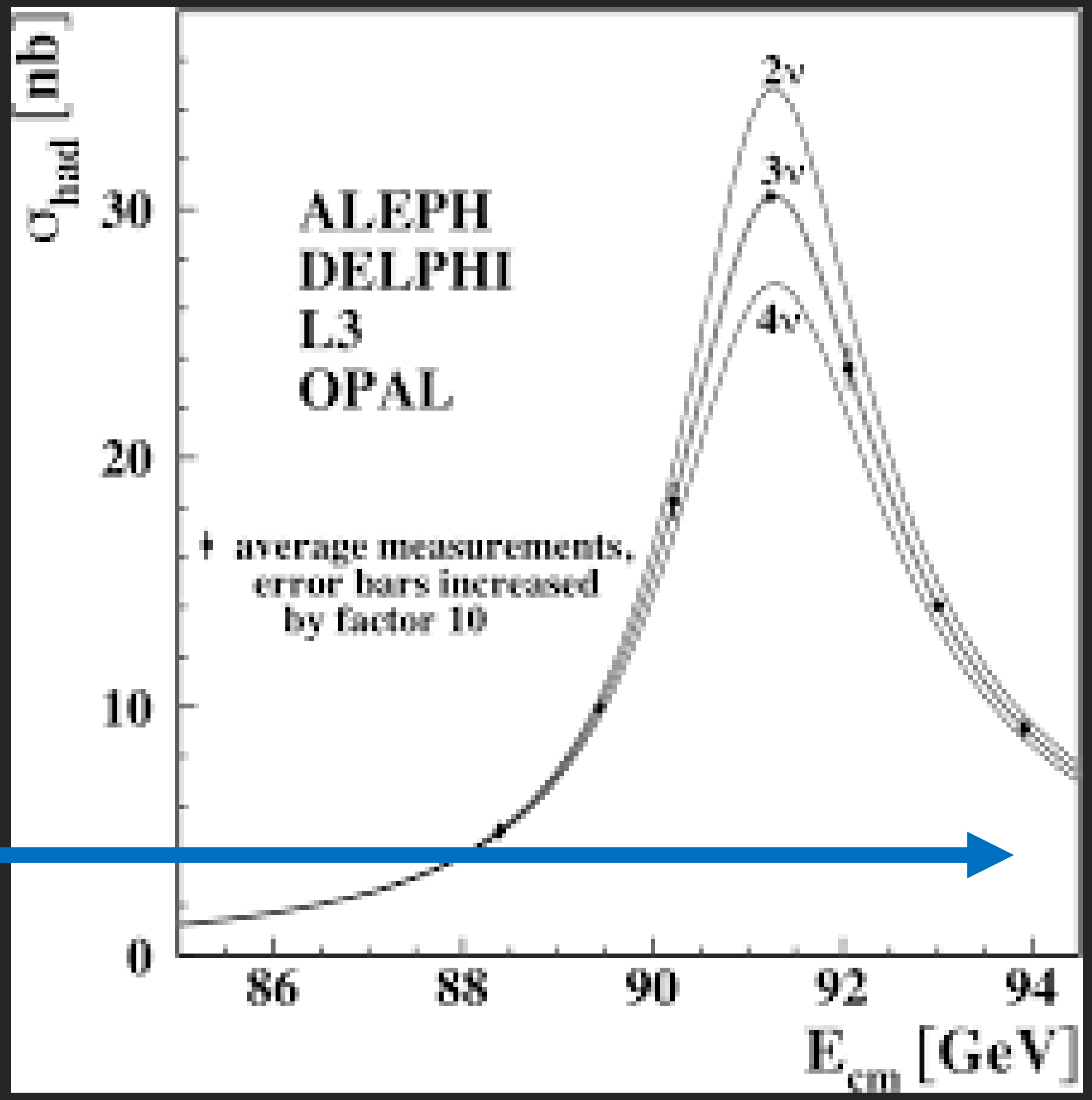
ISR, FSR in Z->mu+mu-



Final State Radiation (FSR)

- Lower energy of final state by emission of boson

More likely when beam is similar in energy to a resonance since particles tunnel



Energy Calibration Methods:

Resonant Depolarization?

- Resonant Depolarization (RDP)
  - Causes energy and polarization change but:
    - Proportional to beam energy!
  - Follows from Thomas-BMT equation. Spin Frequency:

The motion of the spin vector $\vec{S}$ of a relativistic electron in electromagnetic fields $\vec{E}$ and $\vec{B}$ is described by the Thomas-BMT equation [14] :

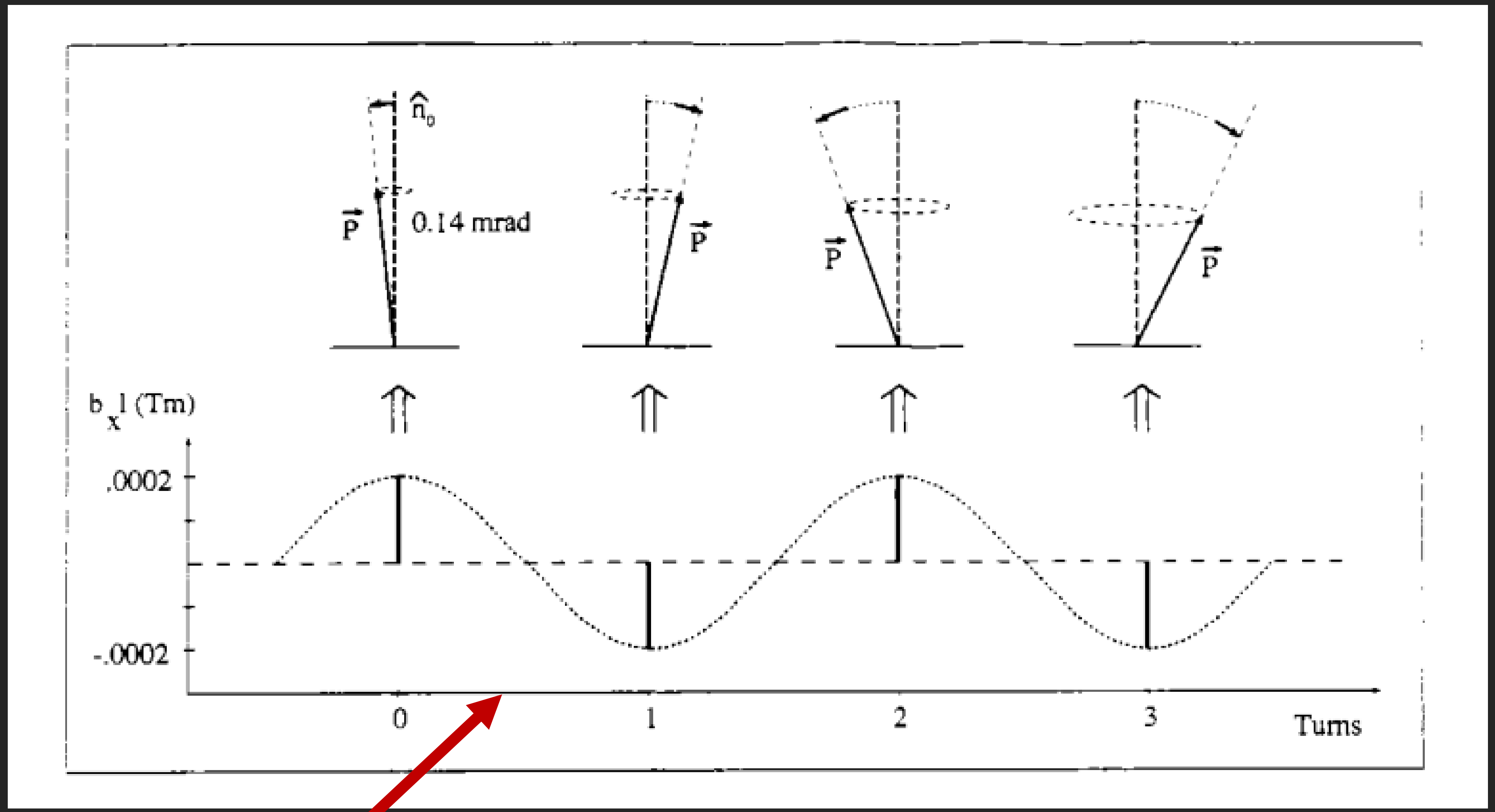
(1) $$\frac{d\vec{S}}{dt} = \vec{\Omega}_{\mathrm{BMT}} \times \vec{S}$$

(2) $$\vec{\Omega}_{\mathrm{BMT}} = -\frac{e}{\gamma m}\left[(1+a\gamma)\vec{B}_{\perp} + (1+a)\vec{B}_{\parallel} - \left(a\gamma + \frac{\gamma}{1+\gamma}\right)\vec{\beta} \times \frac{\vec{E}}{c}\right]$$

  - The average number of precessions:

$$\nu = a\gamma = \frac{aE}{mc^2}$$

  - Which is clearly dependent on the average beam energy!
  - NOTE: This calibrates the beam



Experimentally measure bunch polarization and how many times it changes sign

Energy Calibration Methods:

Resonant Depolarization?

- Resonant Depolarization (RDP)
  - Has limitations of precision due to distortion:

$$\frac{\Delta E}{E} = -\frac{1}{\alpha}\frac{\Delta f_{\mathrm{RF}}}{f_{\mathrm{RF}}}$$

  - This is the distortion factor
  - Also, becomes less viable at higher energies
- Frequencies, circumferences, minimum energy precision from RDP:
  - LEP: 1.1 MHz, 21 km, 2 ppm
  - LHC: 400 MHz, 21 km, >100 ppm ?
  - FCC-ee: 400&800 MHz, 97 km, 3 ppm ?

Larger circumference
= improve energy precision

$$\frac{\Delta E}{E_0} == -\frac{1}{\chi}\frac{C - C_c}{C_c}$$

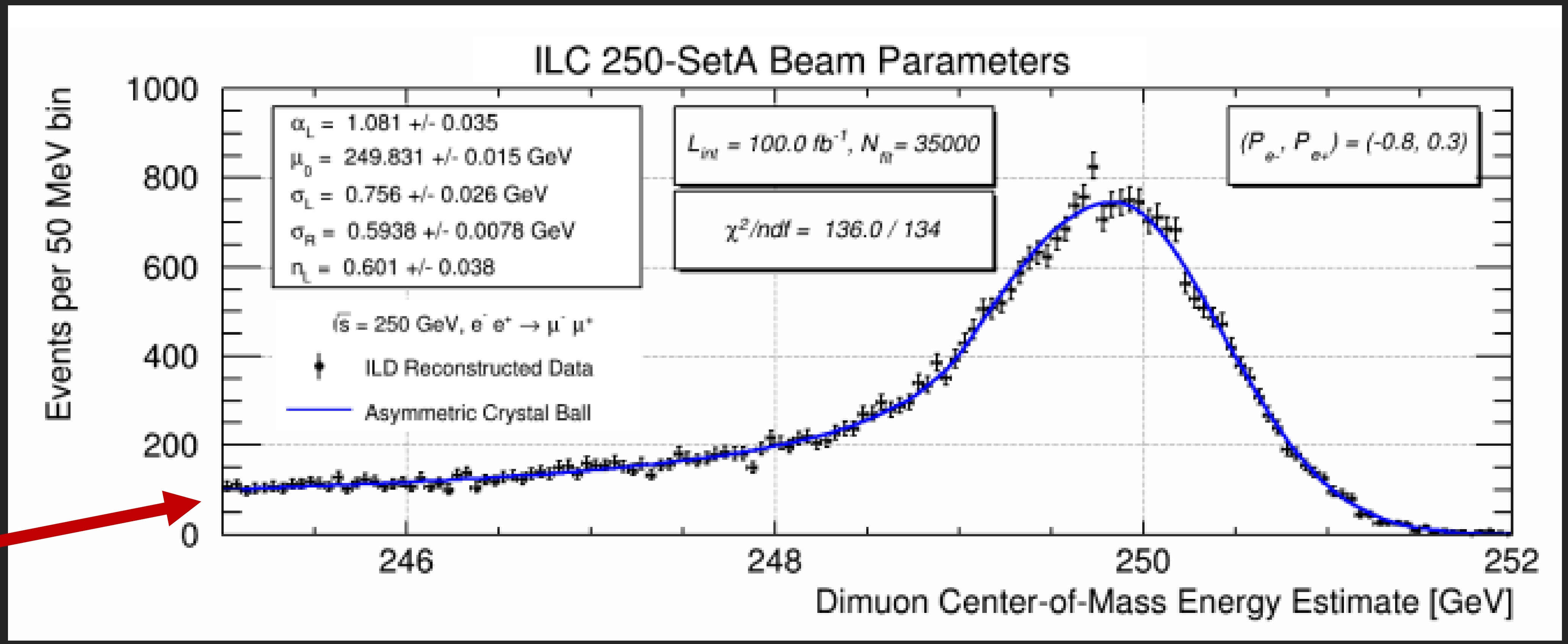
Energy Calibration Methods:

Radiative Return Events

- Radiative Return :
  - Focus on at ILC's $e^+e^- \rightarrow \mu^+\mu^-$ (Dimuon)
    - Clean events , get $\sqrt{s}$ of final state for beam+detector
  - Problem –
    - Common for emission of photon$e^+e^- \rightarrow \mu^+\mu^-\gamma$
    - Need to factor in crossing angle α
  - Solution –
    - Solve for $\sqrt{s}$ using average energy E_{ave} and energy difference ΔE instead
    - Assume missing energy is given by the photon
- Four vector changes to:
- $p_{\mu,final} = (E_1 + E_2 + E_\gamma\,, \vec{p_1} + \vec{p_2} + \vec{p_\gamma})$
- $\sqrt{s}$ can be written as:

$$\sqrt{s} = 2\sqrt{E_{\text{ave}}^2 - (\overline{\Delta E_{\text{b}}})^2}\cos(\alpha/2)$$

Where we are going:



Energy Calibration Methods:

Radiative Return Events

- Radiative Return :
- $\sqrt{s}$ can be written as:

$$\sqrt{s} = 2\sqrt{E_{\text{ave}}^2 - (\overline{\Delta E_{\text{b}}})^2 \cos(\alpha/2)}$$

- **Need** E_{ave} and ΔE :
- Can constrain E_{ave} from both energy and momentum:

$$E_1 + E_2 + E_3 = 2\,E_{\text{ave}}$$

$$\vec{p}_1 + \vec{p}_2 + \vec{p}_3 = (2\,E_{\text{ave}} \sin(\alpha/2), 0, 2\,\overline{\Delta E_{\text{b}}} \cos(\alpha/2))$$

- Rewrite as a quadratic:
  - In the case of no beam energy difference recover original $\sqrt{s}$
- Solving for "x" gives E_{ave}
- Solving for coefficients can get ΔE

$$(2E_{\text{ave}} - E_1 - E_2)^2 = p_{\text{initial}}^2 + (p_{12})^2 - 4(p_{12}^x)E_{\text{ave}} \sin(\alpha/2) - 4(p_{12}^z)\overline{\Delta E_{\text{b}}} \cos(\alpha/2)$$

Now substituting for p_{initial} we find,

$$(2E_{\text{ave}} - E_1 - E_2)^2 = 4E_{\text{ave}}^2 \sin^2(\alpha/2) + 4\overline{\Delta E_{\text{b}}}^2 \cos^2(\alpha/2) + (p_{12})^2 - 4(p_{12}^x)E_{\text{ave}} \sin(\alpha/2) - 4(p_{12}^z)\overline{\Delta E_{\text{b}}} \cos(\alpha/2)$$

This is a quadratic, $(AE_{\text{ave}}^2 + BE_{\text{ave}} + C = 0)$, in E_{ave} with coefficients (after simplification) of

$$A = \cos^2(\alpha/2)$$

$$B = -E_{12} + p_{12}^x \sin(\alpha/2)$$

$$C = (M_{12}^2)/4 + p_{12}^z \overline{\Delta E_{\text{b}}} \cos(\alpha/2) - \overline{\Delta E_{\text{b}}}^2 \cos^2(\alpha/2)$$

Energy Calibration Methods:

Radiative Return Events

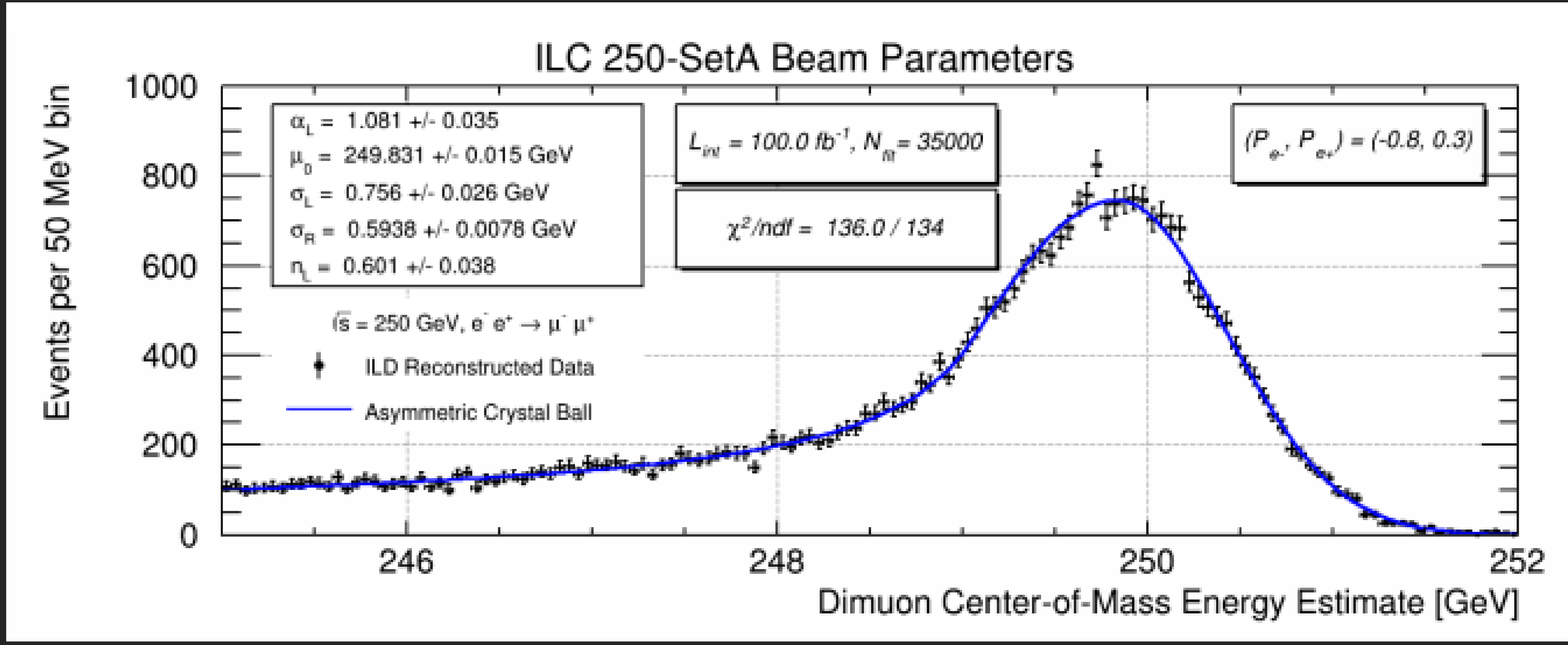
- Radiative Return :
- Use this with ILCSOFT (ILC simulation) dimuon events
- Empirical Fit for asymmetric crystal ball function from RooFit:
- Measure:
- $\sqrt{s} \cong 249.831 \pm 0.015$ -> ~ 60 ppm precision
- Can be improved by only varying the mean…

$$f(m; m_0, \sigma, \alpha_L, n_L, \alpha_R, n_R) = \begin{cases} A_L \cdot (B_L - \frac{m-m_0}{\sigma_L})^{-n_L}, & \text{for } \frac{m-m_0}{\sigma_L} < -\alpha_L \\ \exp\left(-\frac{1}{2} \cdot \left[\frac{m-m_0}{\sigma_L}\right]^2\right), & \text{for } \frac{m-m_0}{\sigma_L} \leq 0 \\ \exp\left(-\frac{1}{2} \cdot \left[\frac{m-m_0}{\sigma_R}\right]^2\right), & \text{for } \frac{m-m_0}{\sigma_R} \leq \alpha_R \\ A_R \cdot (B_R + \frac{m-m_0}{\sigma_R})^{-n_R}, & \text{otherwise,} \end{cases}$$

times some normalization factor, where

$$A_i = \left(\frac{n_i}{|\alpha_i|}\right)^{n_i} \cdot \exp\left(-\frac{|\alpha_i|^2}{2}\right)$$

$$B_i = \frac{n_i}{|\alpha_i|} - |\alpha_i|$$



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