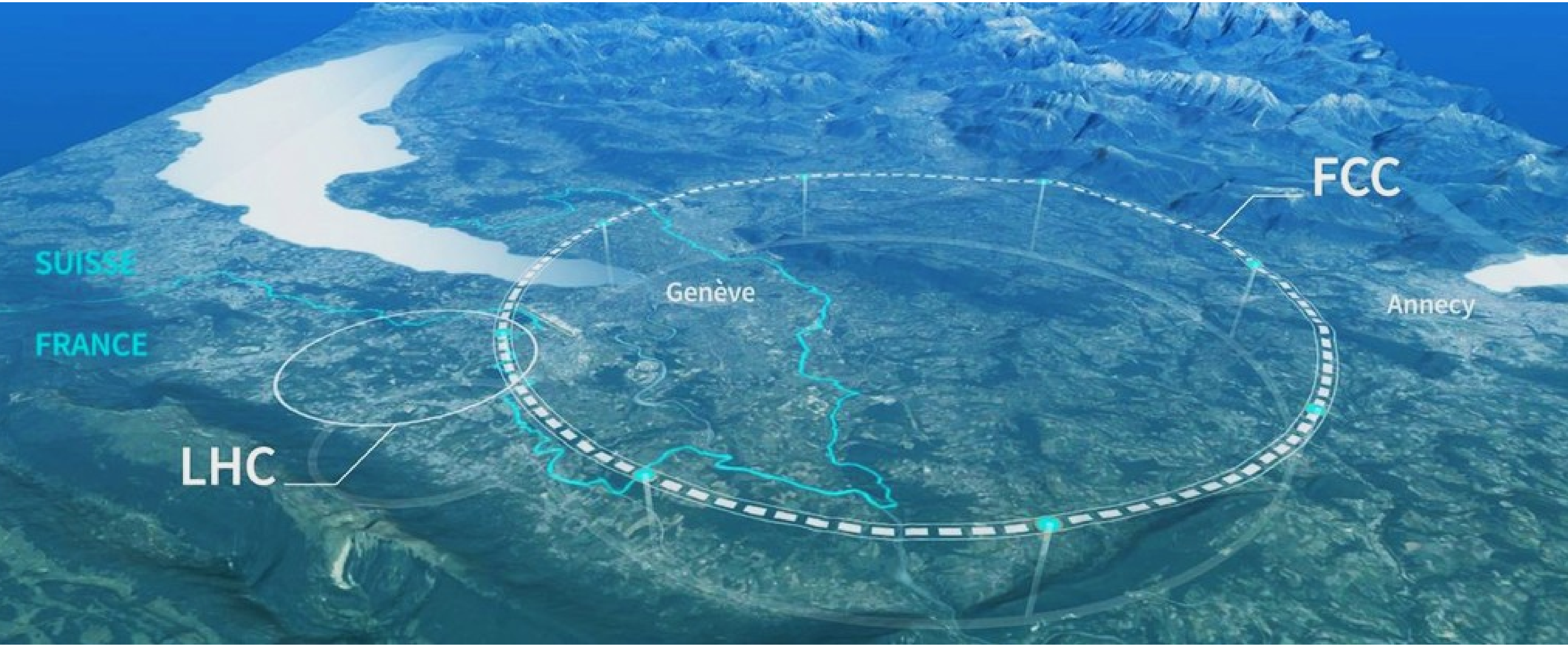
8.FCC - January Research Projects on
the Future Circular Collider (FCC-ee)

Basic Measurements
[January 8, 2025]



Dream of a Particle Physicist

Break the Standard Model

It is not complete, but does explain all the particle physics measurements made so far

We learn little essentially new if we ‘confirm’ the standard model

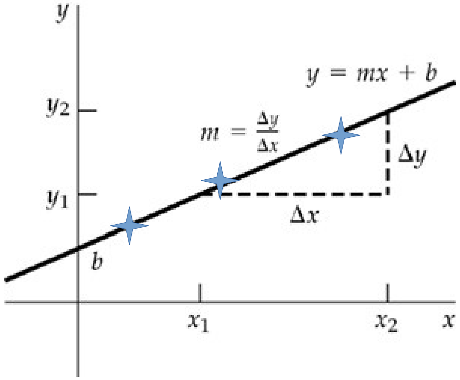
How can we do it?

- Golden path: **Search for and find new particles / phenomena**
- Next best: Measure predicted observables very precisely and show that they do not agree with the predicted values

Standard Model (SM)

Parameters

Constants that determine how the Model looks like in detail.
Think of a straight line: y = m x + b → m and b are parameters that determine how the line looks like.



Standard Model parameters (19):

- Masses: fermions (9) and bosons (3)
- Coupling strength (3)
- Mixing parameters (quarks and neutrinos, 4)

But how can we measure the parameters?

- For the line: measure distinct points on the line and determine m and b
- For SM: Measure ‘observables’ that depend on these parameters and extract the parameters

Signal and Background

Signal

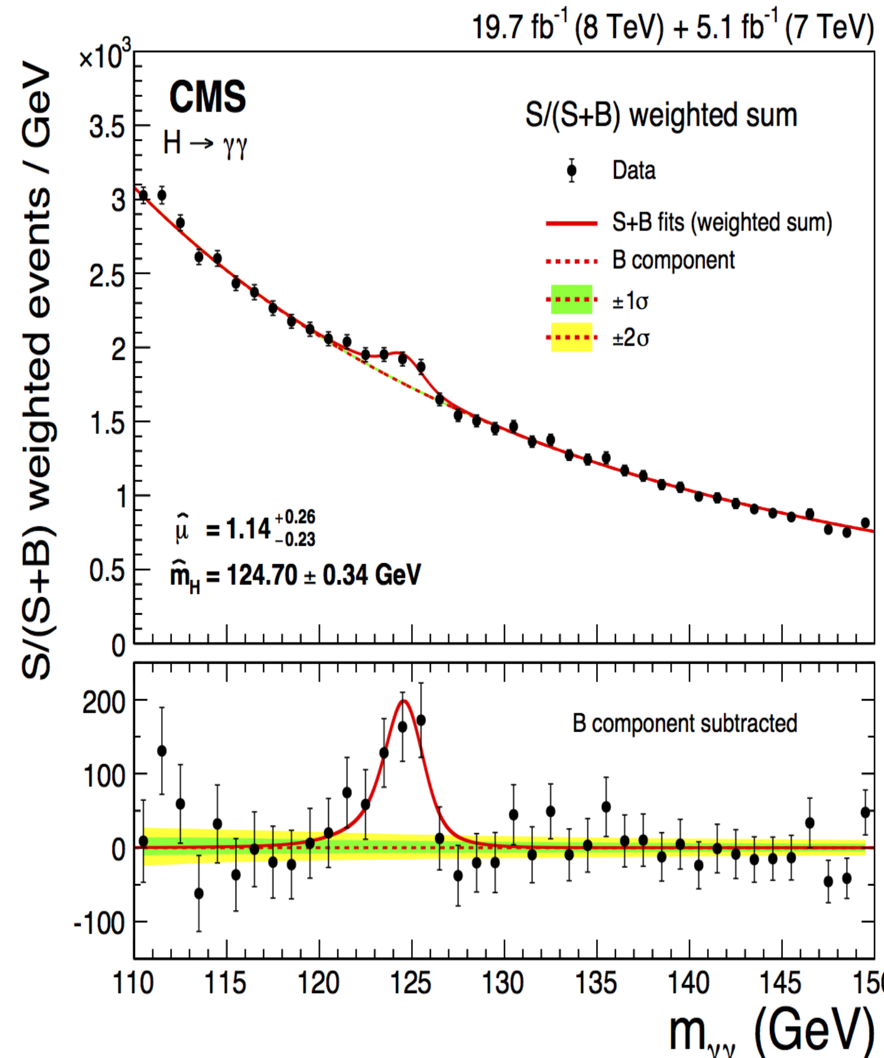
A process you like to study: *ex.* **$e^+e^- \rightarrow \mu^+\mu^-$**

Design your analysis to retain all events that are signal

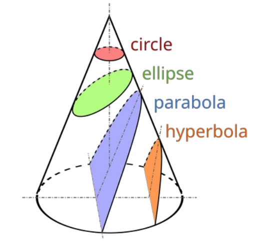
Background

Anything that is not the signal: *ex.* $e^+e^- \rightarrow e^+e^-$, $e^+e^- \rightarrow \tau^+\tau^-$, …

Design your analysis to remove all events that are background



Total Cross Section

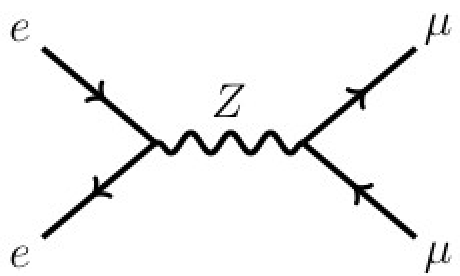


Definition

In physics, the total cross section is a measure of the probability that a specific process will take place in a collision of two particles.

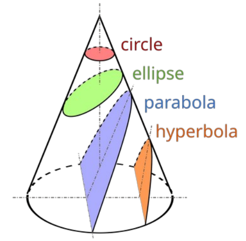
To measure the probability we ask

- Did the process (*ex.* $e^+e^-\rightarrow\mu^+\mu^-$) take place? → numerator
- How many times did we try? → denominator



https://en.wikipedia.org/wiki/Cross_section_(physics)

Total Cross Section



Units

Probabilities have no units … but the cross section has: it is in ‘barns’ which is a unit of an area.

How to best explain this?

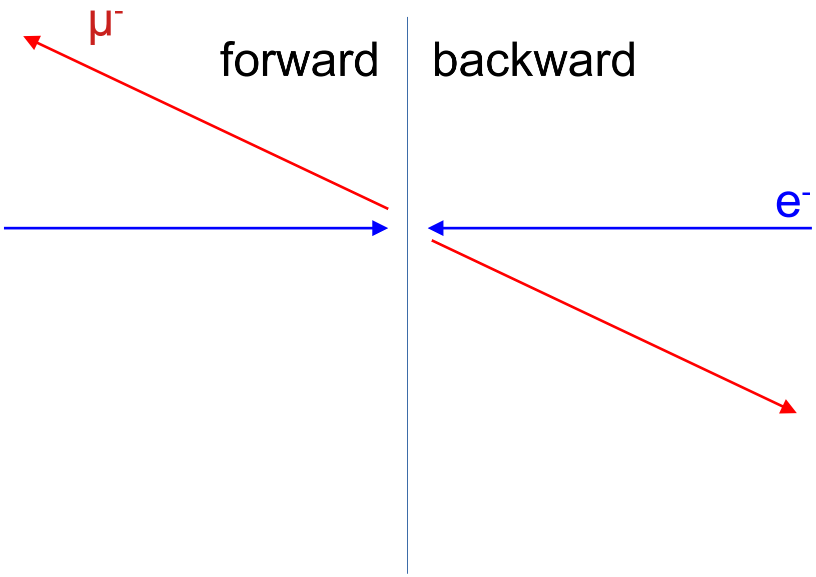
… it can be thought of as the size of the object that the incoming particle must hit in order for the process to occur, but more exactly, *it is a parameter of a stochastic process*.

https://en.wikipedia.org/wiki/Cross_section_(physics)

Forward-Backward Asymmetry

Definition

$$A_{FB} = \frac{n_F - n_B}{n_F + n_B}$$



What makes this interesting?

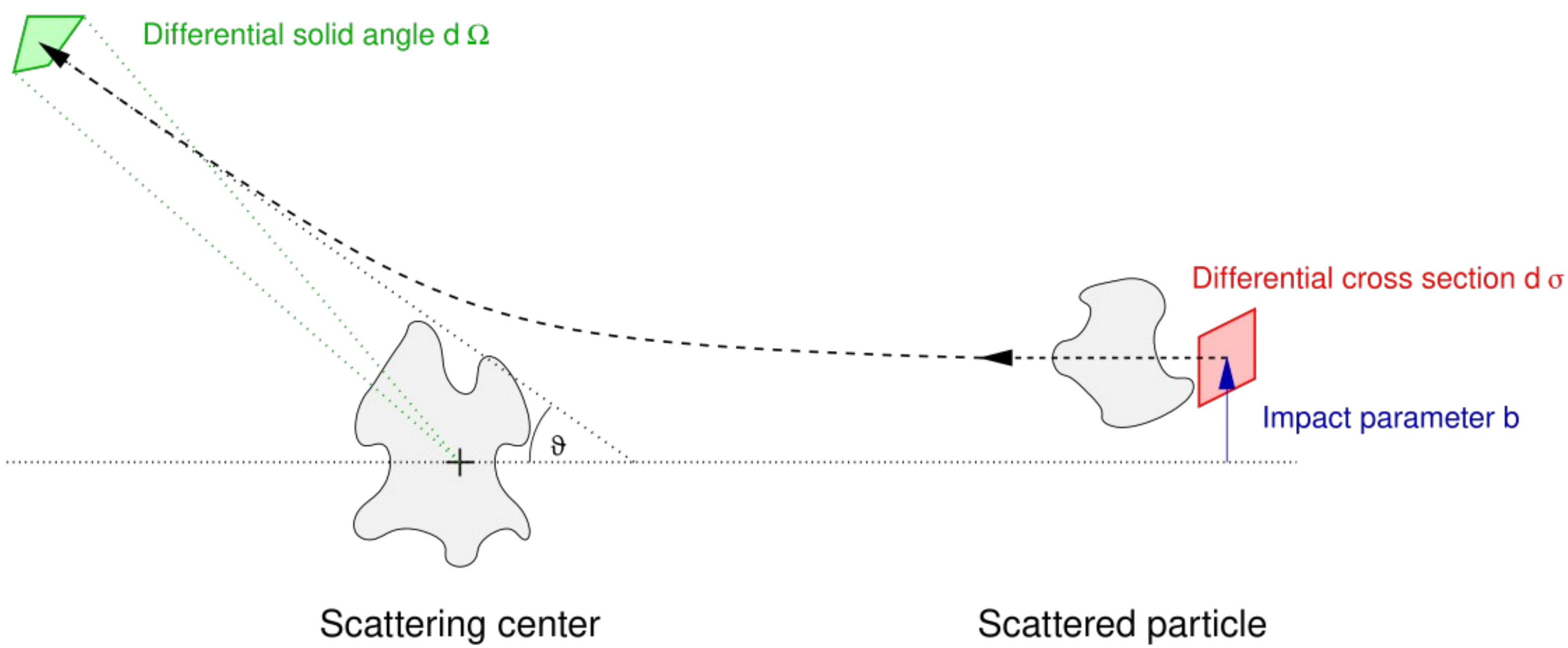
Z boson is not symmetric and a ratio removes a lot of effects that cause systematic uncertainties

Very sensitive to ‘higher order’ corrections

Differential Cross Section

Differential cross section

- Measure the cross section *in a specifically defined area*
- Most obvious: use the scattering angle with respect to the target
- … but the phase space can be subdivided as you like
- Differential cross are more difficult to calculate and measure
- … but they make the data usually much more sensitive to various parameters



https://en.wikipedia.org/wiki/Cross_section_(physics)

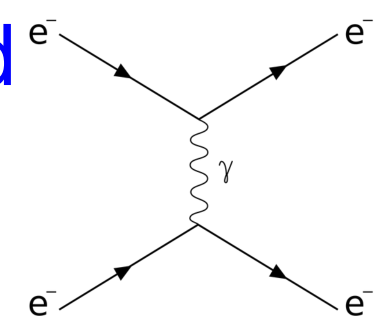
Luminosity (in scattering)

Definition

… luminosity (L) is the ratio of the number of events detected (dN) in a certain period of time (dt) to the cross-section (σ).

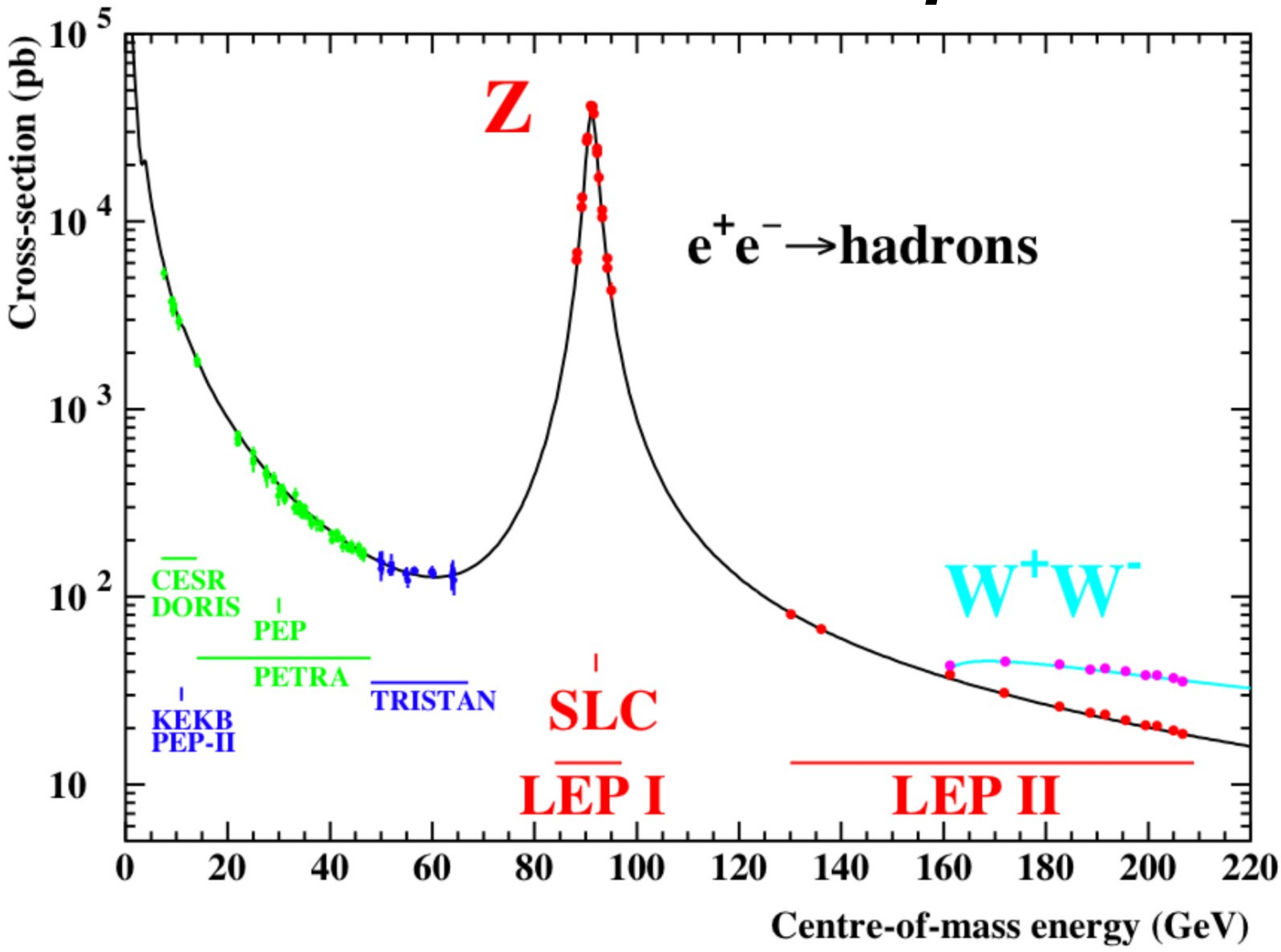
Luminosity is usually *instantaneous*: per time interval
→ usefull when characterizing the intensity of the collosions

We often talk about luminosity as integrated
→ instantaneous integrated over a period
→ tells us the size of the data samples



https://cds.cern.ch/record/261063/files/p117.pdf

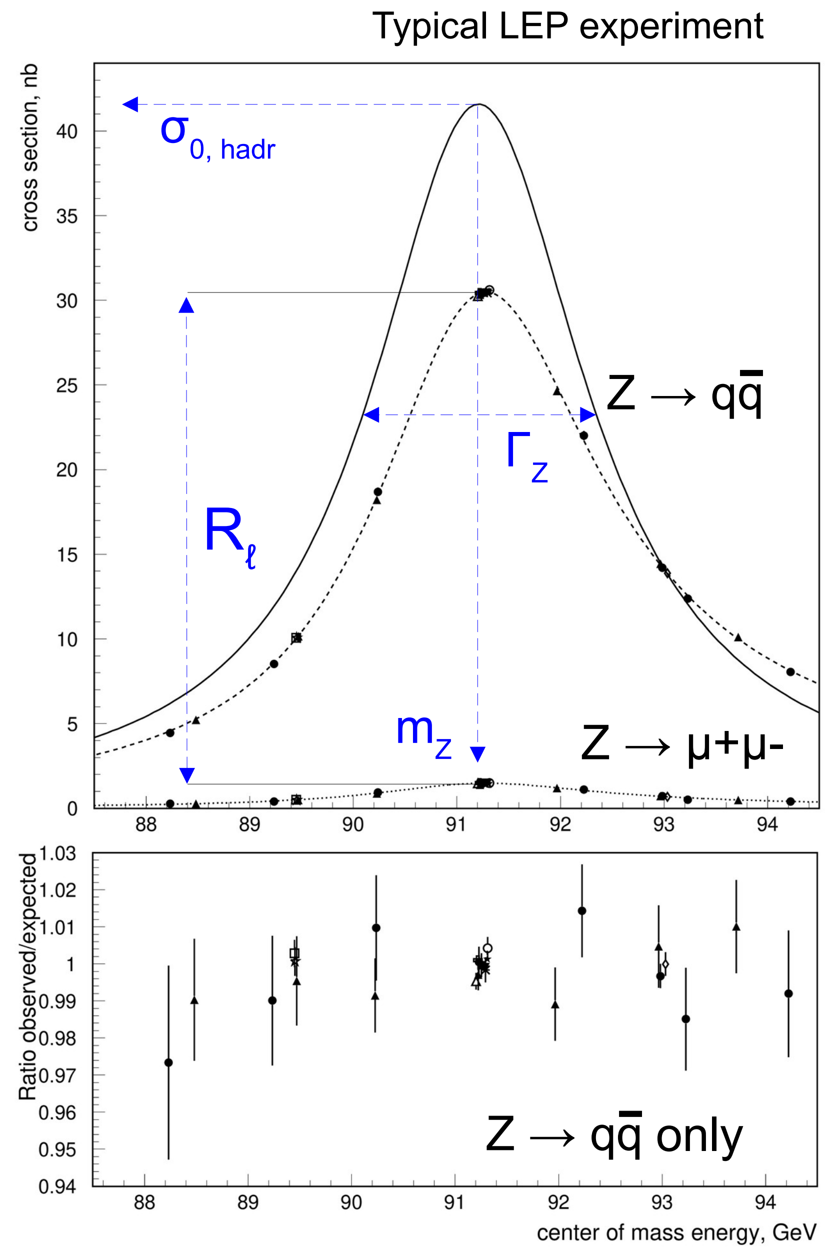
The Lineshape



The Lineshape

Cross section

$$\sigma(\sqrt{s}) = \frac{N_{\text{signal}}}{\mathcal{L}} = \frac{N_{\text{selected}} - N_{\text{background}}}{\varepsilon A \mathcal{L}}$$



What can we extract?

- Z mass (m_Z), Z width (Γ_Z)
- Hadronic peak cross section ($\sigma_{0,\ hadr}$)
- Ratio of leptons (R_ℓ)
- (Number of light neutrinos)

Hadrons "win" (quarks have color)

- mass, width and σ_0

Theory needed

- Deconvolute QED and the EW/QCD corrections…. tricky

Ingredients

Cross section

$$\sigma(\sqrt{s}) = \frac{N_{\mathrm{selected}} - N_{\mathrm{background}}}{\varepsilon A \mathcal{L}}$$

CM energy: $\sqrt{s}$

- Resonant depolarization and many more ‘tricks’

Luminosity: $\mathcal{L}$

- How tightly packed is the beam?
- Basic idea: find accurately calculable process and count, it should not depend on the Z boson (too much).

Event counts: N_{selected}, $N_{\mathrm{background}}$

- Selected events contain signal and the remaining background

Acceptance, A, and efficiency, ε

- Acceptance loss: particle outside detector fiducial volume
- Efficiency loss: particle inside detector volume, but not identified

Energy Calibration $\sqrt{s}$

Resonant depolarization is key

- It will be run in situ using pilot bunches during data taking

Other important feature

- Absolute calibration will be transported precisely from point-to-point
- Calibration repetition rate needs to be considered
- Beam energy spread and its uncertainty will affect Z width and $\alpha_{QED}(m_Z)$
- Can dimuons/dielectrons to measure beamspread or even center-of-mass energy and help beam calibrations? Needs calibrated muons/electrons using well known resonances… see W mass from LHC/CDF

Compared to LEP

- Main calibration idea is the same
- ... but much more precise with huge data rate and in situ calibration schemes substantially expanding the scope
- A lot more detail but not for this talk

From: arxiv:1909.12245

Energy Calibration $\sqrt{s}$

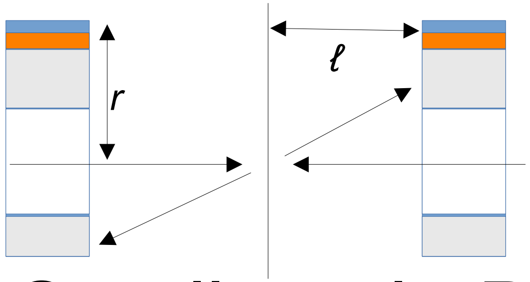
FCC calibration is still in rapid development

- Latest studies showed a much improved point-to-point uncertainty and more is to come
- The latest study is summarized below
- *Overall uncertainty still needs to be shrunk...*

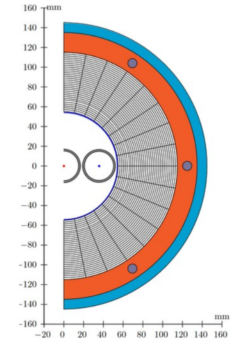
Table 15. Calculated uncertainties on the quantities most affected by the centre-of-mass energy uncertainties, under the final systematic assumptions.

Observable	statistics	$\Delta\sqrt{s}_{abs}$ 100 keV	$\Delta\sqrt{s}_{syst-ptp}$ **40 keV**	calib. stats. 200 keV $/\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ 85 ± **0.05** MeV
m_Z (keV)	4	100	**28**	1	–
Γ_Z (keV)	4	2.5	**22**	1	**10**
$\sin^2\theta_W^{eff} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{QED}(m_Z^2)}{\alpha_{QED}(m_Z^2)} \times 10^5$	3	0.1	**0.9**	–	**0.1**

From: arxiv:1909.12245



Luminosity



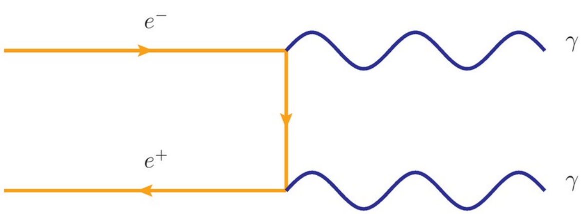
Small angle Bhabha scattering from LEP?

- Cross section very large (78 nb): good statistical precision
- Need to have excellent control of the geometry: $O(10^{-5})$ precision
  - Precision on radial dimensions Δr ~1μm
  - Half distance between lumi monitors at $\Delta \ell$ ~50 μm
- Theory prediction improved from 0.061% at LEP to 0.037% recently, but still far from statistical precision of hadronic final states (~10^{-6})

https://arxiv.org/abs/1912.02067

Another clean and copious process?

- $e^+e^- \rightarrow \gamma\gamma$: precise prediction, no Z dependence and clean
- Only 1 in 1000 Z events – accuracy $O(10^{-4})$
- No perfect solution but pretty good



Best plan, so far

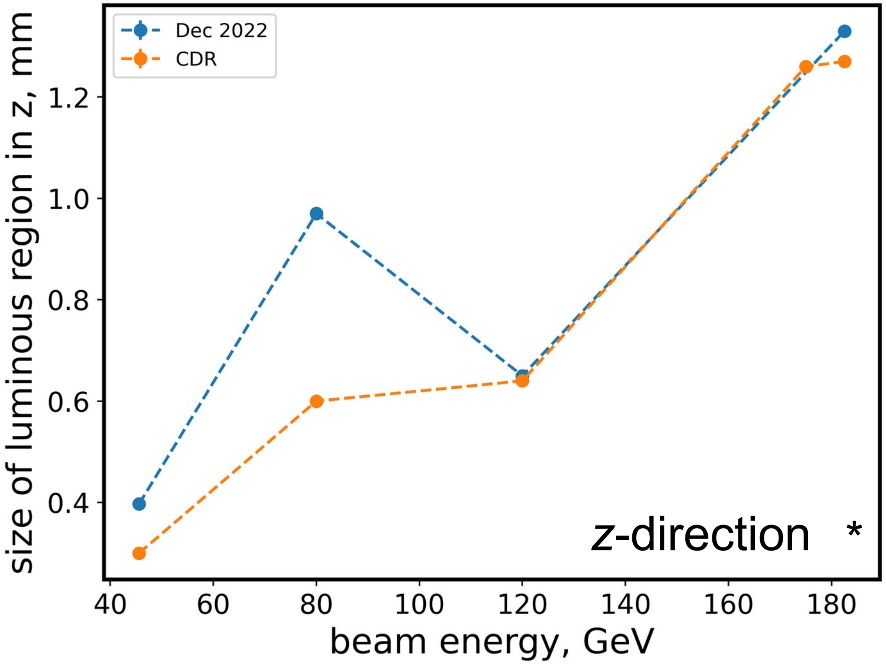
- Use $e^+e^- \rightarrow \gamma\gamma$ as overall normalization (global)
- Bhabha events to extrapolate across CM energies (σ_{theory}= 14 nb)
- Loose significant precision on $\sigma_{0,\ hadr}$ (# light neutrinos) and
- … some on m_Z, Γ_Z

From: Eur.Phys.J.Plus (2022) 137:81

Luminous region FCC

Size of the luminous region versus beam energy

- *y*-direction [nm], *x*-direction [µm]
- z- direction [mm] … at Z pole below mm level
- vertexing uncertainty at *µm level*



My conclusion on luminous region?

- Due to well focused beam and pristine vertex reconstruction neither significant beam crossing angle nor uncertainties on those should be an issues
- Event pileup at about 2 in a thousand events can be cleanly identified (µm vertex with 0.4 mm luminous region at Z pole)
- Needs to be careful implemented in MC and confirmed!

* *https://github.com/HEP-FCC/FCCeePhysicsPerformance/tree/master/General#vertex-distribution*

Quote of the Day

At a lepton collider
every event is a *signal event*,
while at a hadron collider
every event is a *background event*.

– Anonymous

This means that at lepton colliders we have basically no control regions and we have to heavily rely on Monte Carlo simulation to determine acceptance, efficiency and backgrounds.