Geometric acceptance requirements for di-lepton and di-photons cross-sections at Z pole energies

A. Blondel, M. Dam, (also discussions with P. Janot, C. Paus, E. Perez etc)

Work in progress for discussions

1. Motivation
2. What is involved
3. (not included in this talk: ECM, theoretical calculations)
4. Final state selections, leading to detector requirements

A Blondel, M. Dam. FCC note: FCC-ee Detector requirements: geometric acceptance requirements for dilepton and diphoton events at Z pole energies (Aug 2023). https://doi.org/10.17181/v47k3-arh69

in 15 minutes + 5 minutes for questions

Overview

1. In the process towards feasibility study, an high priority output is:
   the publication of a set of detector requirements for the FCC-ee detector systems
   -- part of the contents of the mid-term review report
2. Essential also towards the (ECFA) EU-wide detector R&D plans and process, and the associated funding requests, which will orient soon the detector R&D efforts of the community.
   Emphasize that the FCC-ee has very specific aspects, in particular at the Z pole.
3. Essential to guide the development of detector concepts.

The precision measurements at the Z pole and WW threshold are particularly important tools of search for new physics via loops or mixing in a context where

1. the SM is complete (except perhaps RH neutrinos, which are sterile)
2. its predictions well defined (up to parametric and calculation uncertainties)
3. We know that new physics exists but we do not know what/mass scale/couplings to SM particles

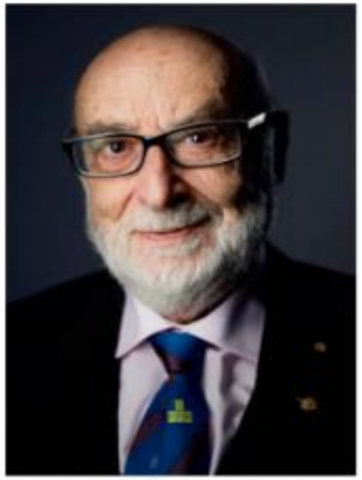
Improve precision → improve discovery potential

Jan Eysermans (also AB@Krakow23) described the measurement of the e+e- → $q\bar{q}$ (hadrons) rate which requires that the angle of detection be as low as possible. This governed the requirement that the low angle limit of the machine elements be contained in a cone of 100mrad around the detector axis. → Two-photon processes, Fragmentation..& tricks

Today we discuss further the low angle region which governs the processes

e+e- → lepton pairs and e+e- → $\gamma\gamma$

The Nobel Prize in Physics 2013



© Nobel Media AB. Photo: A. Mahmoud

François Englert

Prize share: 1/2

© Nobel Media AB. Photo: A. Mahmoud

Peter W. Higgs

Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

Share this: 951

The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Particle physics after the discovery that neutrinos have mass

« Beyond the Standard Model » because SM is defined as having massless neutrinos

Neutrinos oscillate

3x3 oscillation → possibility of CP violation
➔ T2K, HyperK, DUNE

‘near future’ (2030-2040..) and after that?

Of *great* interest to FCC: New degrees of freedom

Fermion number is no longer a conserved quantity (at particle level)
Neutrino coupling with Higgs boson (?)
➔ right handed neutrinos
minimal see-saw ➔ Heavy Majorana Neutral Leptons

Sakharov condition for generation of the
Baryon Asymmetry of the Universe:
-- Fermion number violation
-- CP or T violation and
-- out-of-equilibrium universe (Big Bang)

➔ Baryogenesis or Leptogenesis + sphalerons

Massive neutrinos are a very natural candidate to explain the dominance of matter over antimatter in the universe.

Manifestations of right handed neutrinos

one family see-saw :
$\theta \approx (m_D/M)$
$m_\nu \approx \frac{m_D^2}{M}$
$m_N \approx M$
$|U|^2 \propto \theta^2 \approx m_\nu / m_N$

$$\nu \;=\; \nu_L \;\cos\theta \;-\; N^c_R \;\sin\theta$$

$$N = N_R \;\cos\theta + \;\nu_L{}^c \;\sin\theta$$

what is produced in W, Z decays is:

$$\nu_L = \;\nu \cos\theta \;+ N \;\;\sin\theta$$

ν = light mass eigenstate
N = heavy mass eigenstate HNL
$\neq \nu_L$, active neutrino
which couples to weak inter.
and $\neq N_R$, which does'nt.

-- mixing with active neutrinos leads to various observable consequences

-- if very light (eV) , possible effect on neutrino oscillations ('eV sterile neutrino' (LSND/miniBooNE/reactor anomalies etc... but ruled out since PLANCK mission MINOS/ICECUBE/DAYABAY/microBooNE. Search still ongoing in broader region)

-- if in 5-100 keV region (dark matter), monochromatic photons from galaxies with $E=m_N/2$, KATRIN

-- possibly measurable effects at High Energy

➔ If N is heavy it will decay in the detector → spectacular

➔ Higgs, Z, W visible exotic decays H→ $\nu_i \; \bar{N}_i$ and Z→ $\nu_i \; \bar{N}_i$, W-> $l_i \; \bar{N}_i$ **N_ν**

➔ also in K, charm and b decays via W*-> $l_i^{\pm} \; \bar{N}$, N → $l_j^{\pm}$
with any of six sign and lepton flavour combination

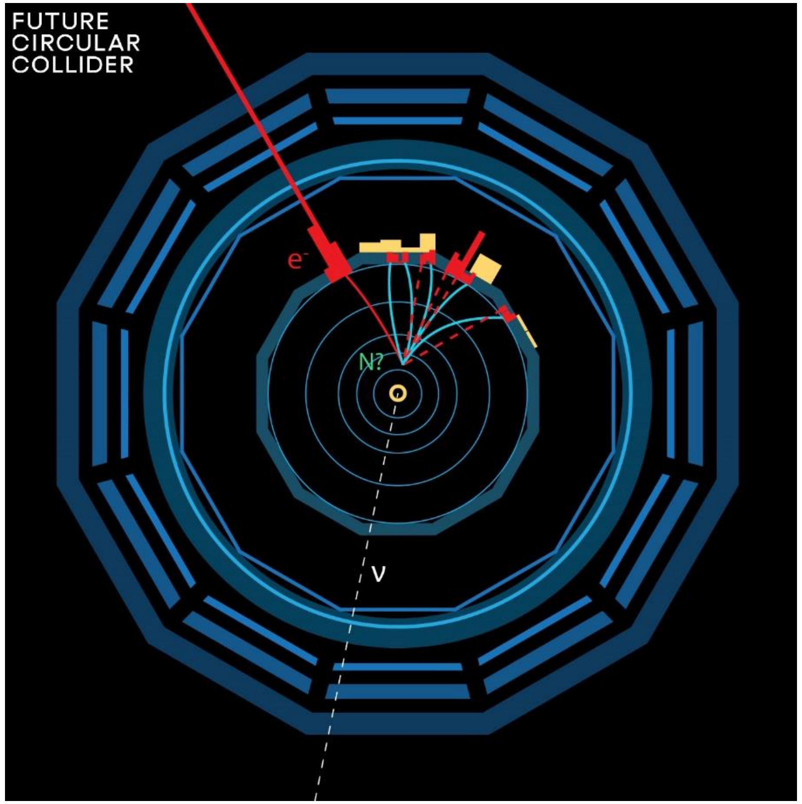
➔ violation of unitarity and lepton universality in Z, W or τ decays

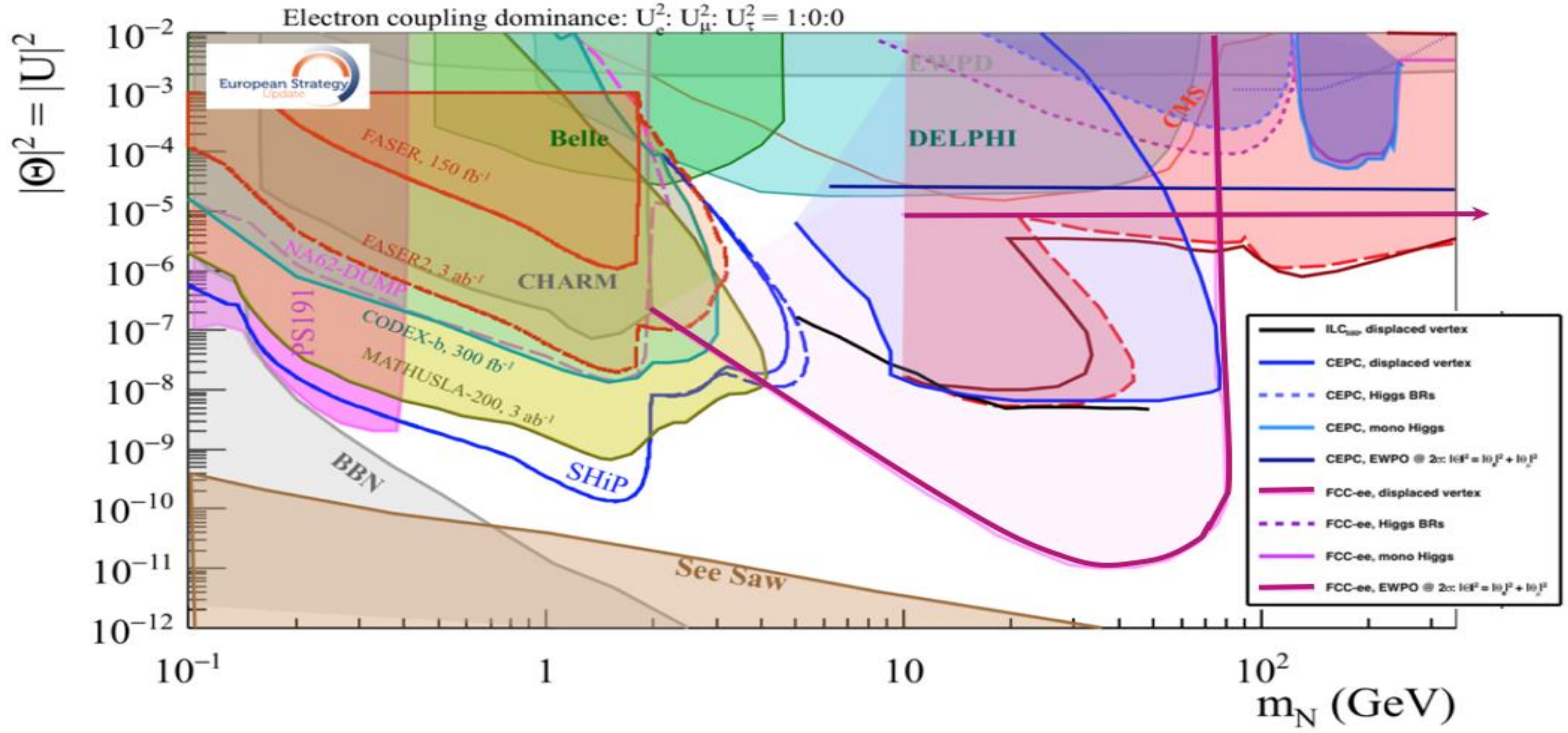
➔ PMNS matrix unitarity violation and deficit in Z «invisible» width

-- etc... etc...

-- Couplings are very small ($|U|^2 = m_\nu / m_N$) for one family. For three families they can be somewhat larger **but most interesting region is near the one-family see-saw limit**

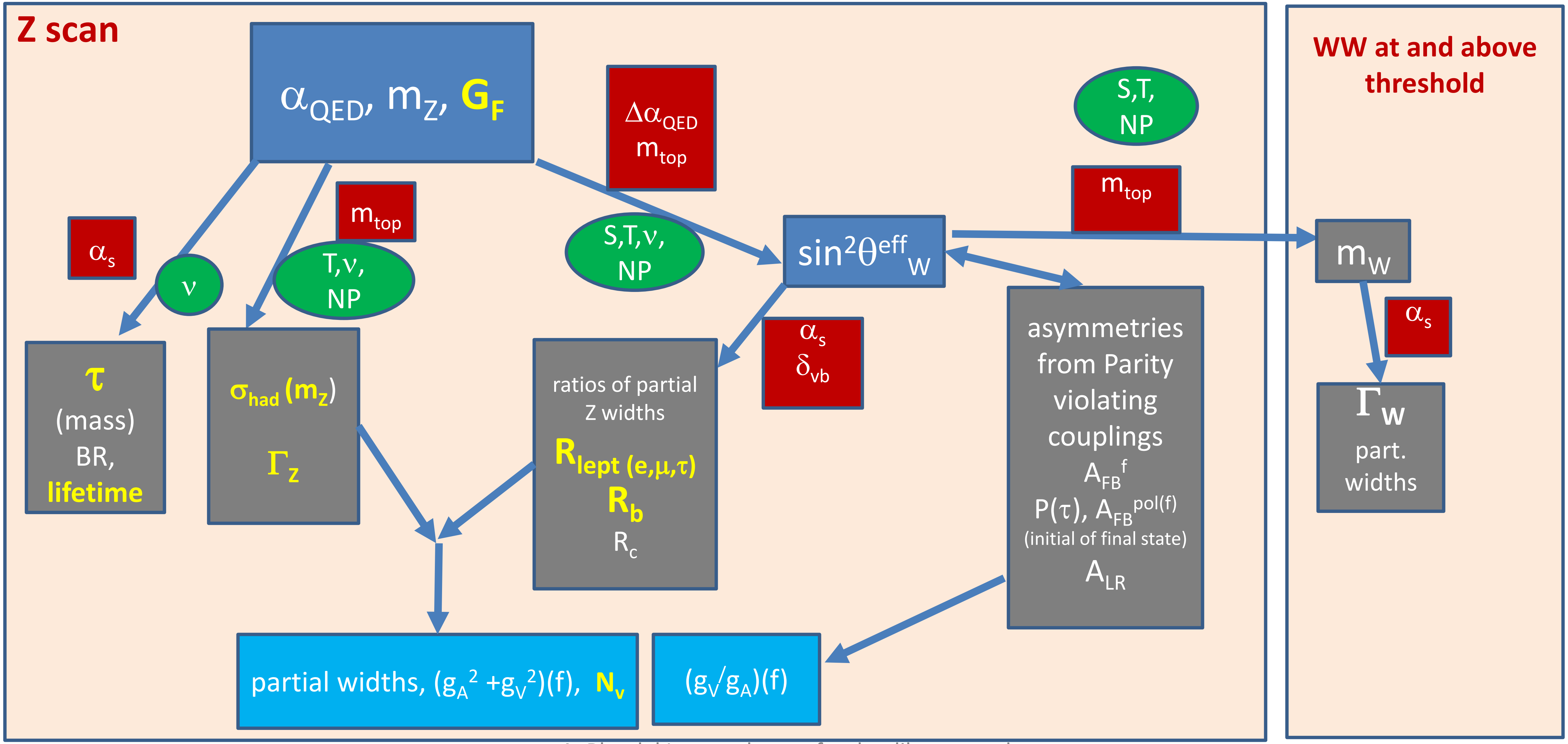
This picture from the briefing book is relevant to Neutrino, Dark sectors and High Energy Frontiers.
FCC-ee (Z) compared to the other machines for right-handed (sterile) neutrinos
How close can we get to the 'see-saw limit'?





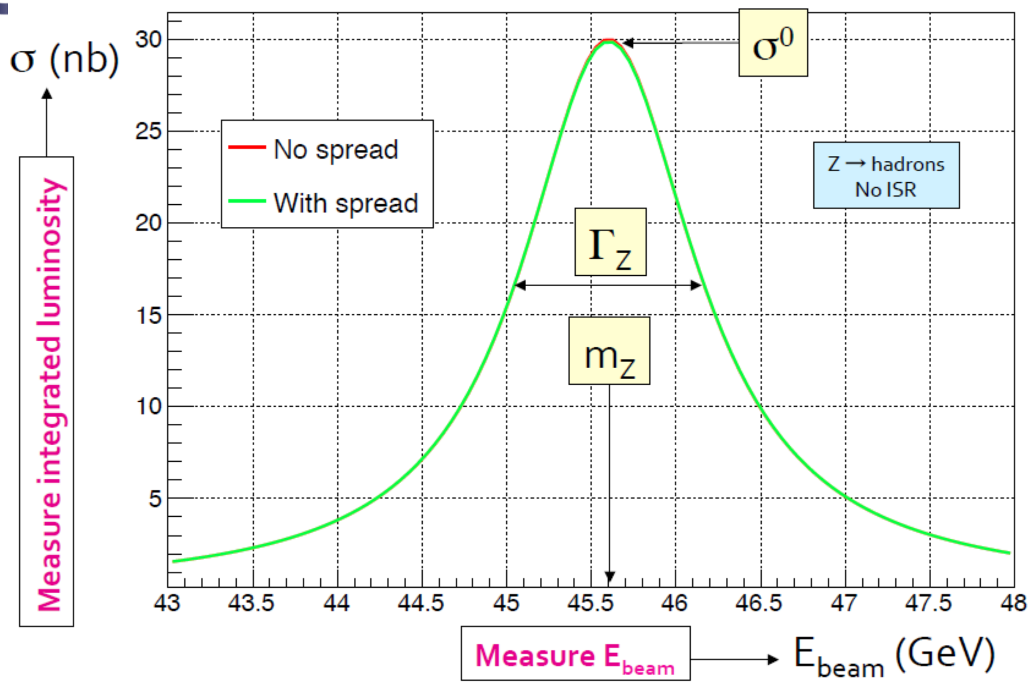
-- the purple line shows the 95% CL limit if no HNL is observed. (here for 10^{12} Z),
-- the horizontal line represents the sensitivity to **mixing of neutrinos** to the dark sector, using EWPOs (G_F vs $\sin^2\theta_W^{eff}$ and m_Z, m_W, N_ν, tau decays) which extends sensitivity to 10^{-5} mixing all the way to very high energies (500-1000 TeV at least). arxiv:2011.04725

Overview of loop correction relationships and examples of new physics effects



bottom line: FCCee provides both the SM inputs and the SM measurements → unprecedented exploration of BSM!

FCC scan points for m_Z and m_W



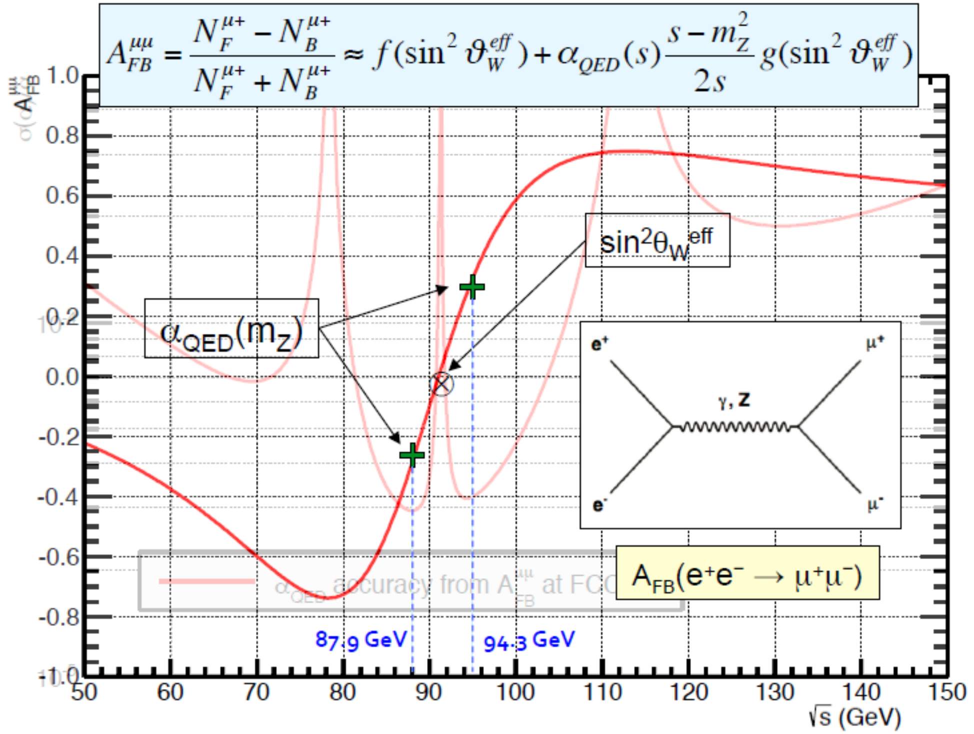
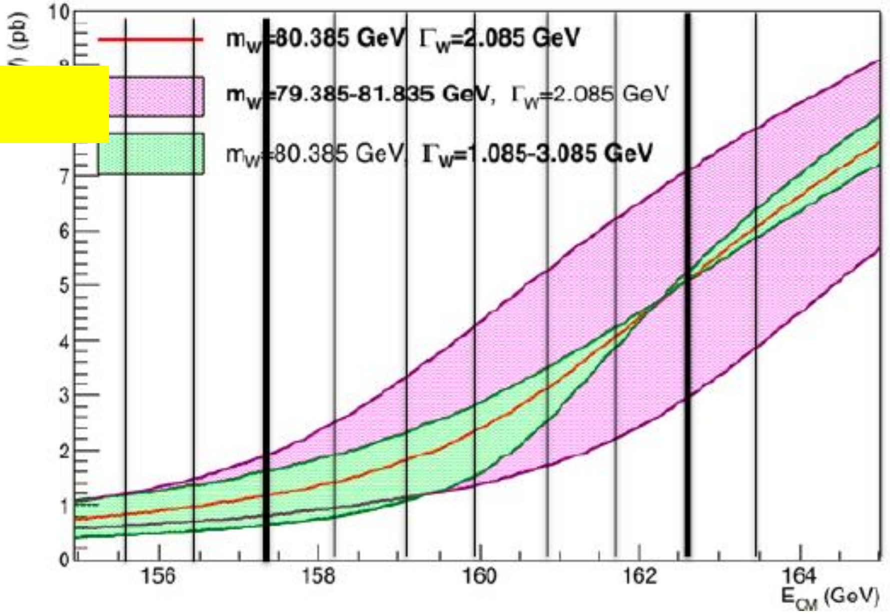


Table 3: Center-of-mass energies for the proposed Z scan. The points noted A and B are half integer spin tune points with energies closest to the requested energies.

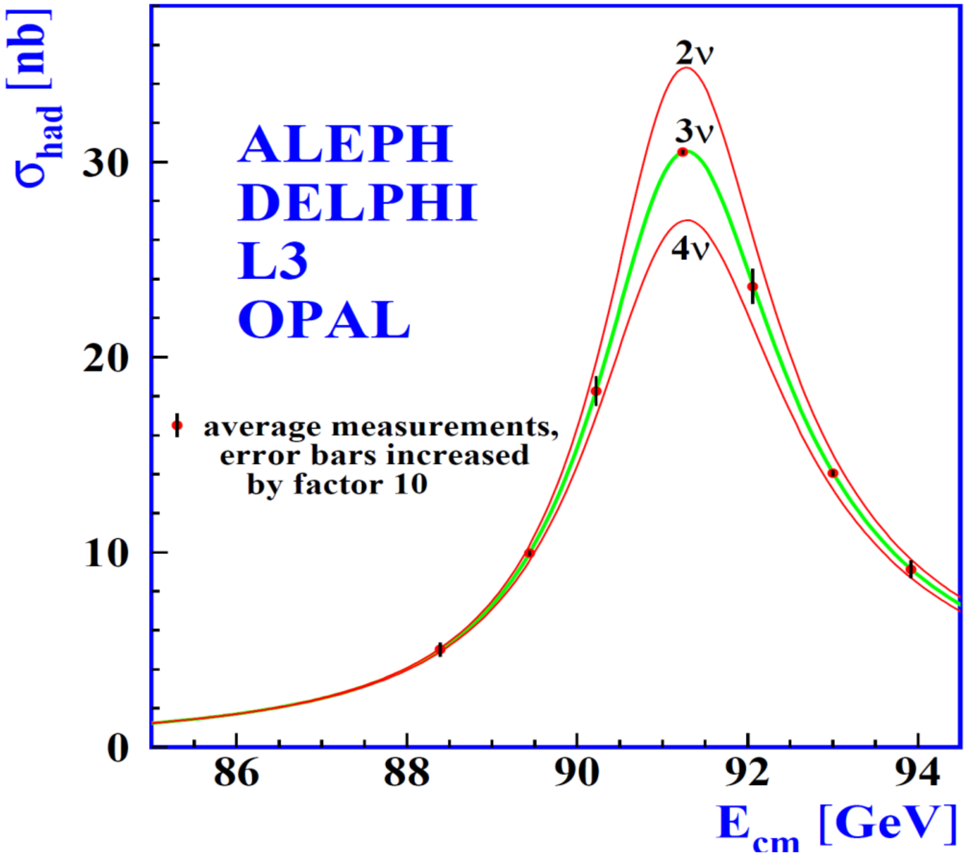
from arXiv:1909.12245 – 2 exp

Scan point	Centre-of-mass Energy	Beam Energy	Spin tune	
E^-_{CM} A	87.69	43.85	99.5	
E^-_{CM} Request	87.9	43.95	99.7	30 ab-1
E^-_{CM} B	88.57	44.28	100.5	
E^0_{CM}	91.21	45.61	103.5	90 ab-1
E^+_{CM} A	93.86	46.93	106.5	
E^+_{CM} Request	94.3	47.15	107.0	30 ab-1
E^+_{CM} B	94.74	47.37	107.5	



$$N_\nu = \frac{\Gamma_\ell}{\Gamma_\nu} \cdot \left(\sqrt{\frac{12\pi R_\ell}{M_Z^2 \sigma_{had}^{peak,0}}} - R_\ell - 3 \right).$$

$$R_\ell \equiv \Gamma_{had}/\Gamma_\ell$$



1 family on neutrinos ←→ -13% on peak cross section. Present precision: +- 0.007 of 3 neutrino families.
Dominant uncertainty is the absolute determination of luminosity at the Z pole.

For the first time we hope to use e+e- → γγ events to reduce systematic to 2 10-5 (e.g. ΔNν ~ ±0.00015)
The ratio of hadrons to leptons provide test of quark and lepton vs lepton universality, α_s (mZ)
aim at tests of universality below 10^{-5} in neutral currents couplings.

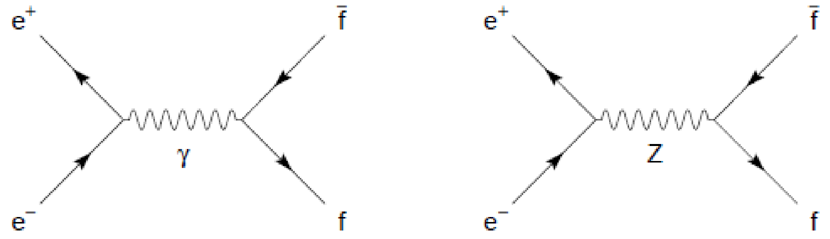


Figure 1.1: The lowest-order s-channel Feynman diagrams for $e^+e^- \to f\bar{f}$. For e^+e^- final states, the photon and the Z boson can also be exchanged via the t-channel. The contribution of Higgs boson exchange diagrams is negligible.

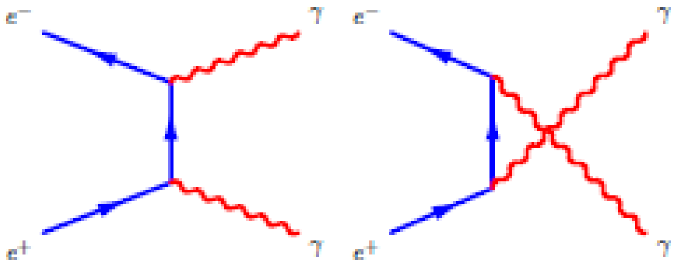
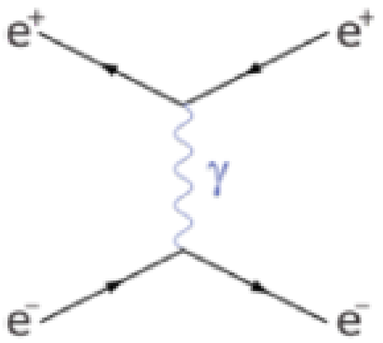


Figure 1. Feynman diagrams for two-gamma-quantum annihilation.

s-channel: Z→ ee = Z→μμ = Z→ ττ

ee → γγ

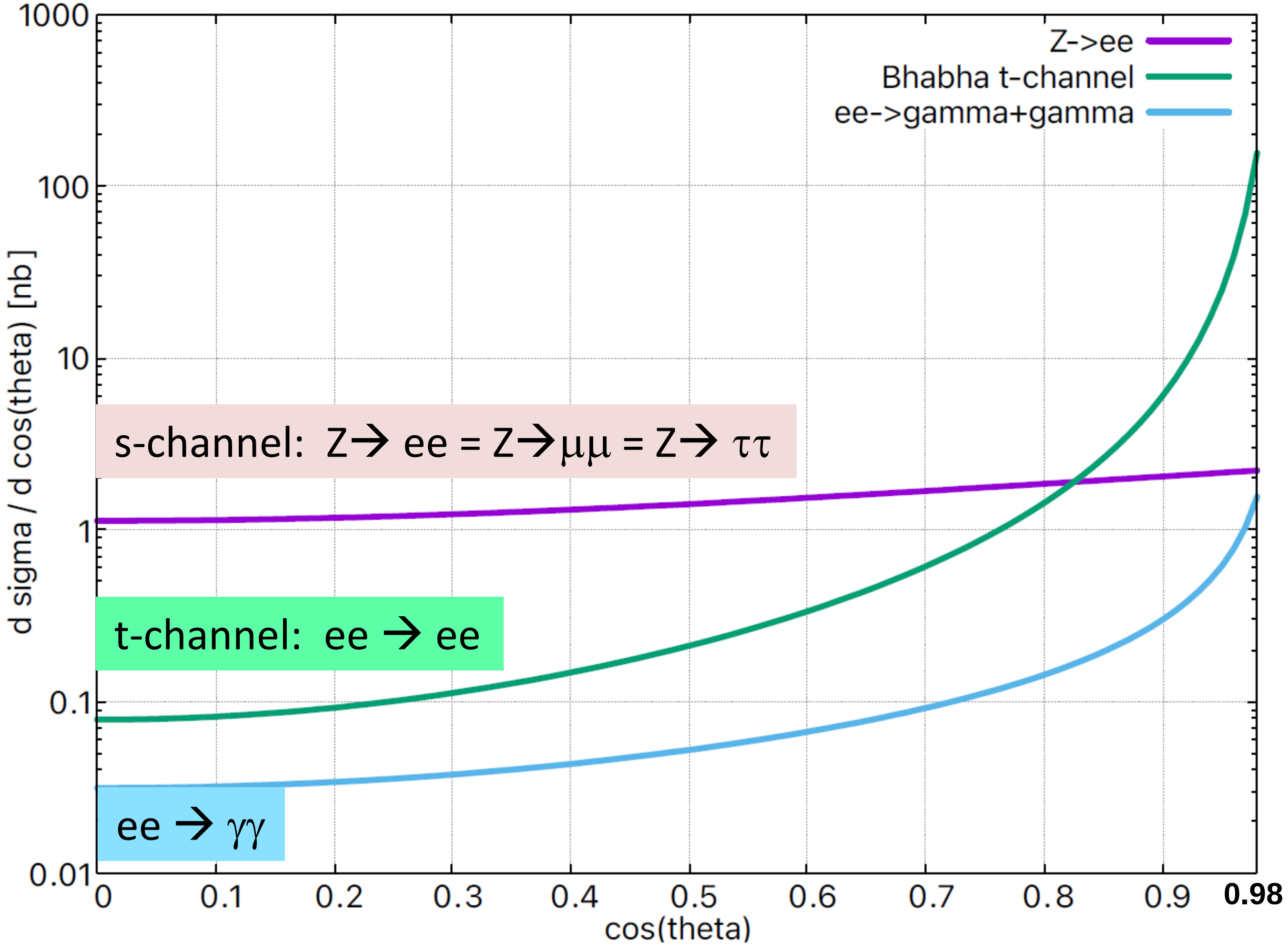
$R_{lept\,(e,\mu,\tau)} \equiv \Gamma_{had}/\Gamma_{lept\,(e,\mu,\tau)}$



Luminosity measurement
NEW and UNIQUE to FCC-ee and CEPC absolute. Also useful off-peak and at the higher energy points

t-channel: ee → ee

Luminosity measurement → fast, point to point measurement



NB **at the Z pole** s(imaginary) and t(real) channels do not interfere

Systematic precision target ≤ statistical error

45 ab-1 in one experiment at the Z pole

Z→ lepton pairs = 3x1.5nb x 45 ab-1= 2 10^{11} evts

relative statistical precision: **2.3 10^{-6}**

Z → hadrons = 31.4 nb x 45 ab-1 = 1.4 10^{12} evts

rel. statistical precision 8.5 10^{-7}

e+e- → γγ (20pb for 20 deg. cut) =0.9 10^{9} events

rel stat. precision 3.3 10^{-5} for a 20 degrees cut (0.94)

Physics interest

hadronic cross-section → N_ν (L-R neutrino mixing)

ratio of hadrons to leptons R_l → α_s (m_Z)+ l-q univ.

Z width → rho/T parameter

Z mass (and W mass) and their ratios

Bhabha ee → ee and ee → γγ are precious to determine the absolute and relative luminosity.
ee → γγ offers good hope to improve the absolute luminosity uncertainty wrt Bhabha. FCC-ee specific

Leptonic event selection

for each experiment
-- statistics 6.8 10^{10} events in each channel ➔ 1.9 10^{11} leptonic events provide $1/\sqrt{N} = 2.3\ 10^{-6}$

Paradoxically leptonic event selection is much more prone to systematics than the hadronic selection
The main reason is that it is much easier to lose one track than a whole jet.

For instance if two tracks are required the loss of efficiency is twice the track reconstruction inefficiency $\varepsilon(\theta)$

➔ selection might start with single track selection, second track to be used to ensure both
-- high efficiency
-- measurement of efficiency (2 tracks vs 1 track)

Also low angle definition is essential, as it is not compensated by the wider 'jet' structure

Similarly to luminosity measurement, it is useful to select one track with tight cut and the other with looser cut and switching the "tight side" from one side to the other event by event.
→ this eliminates effectively the issues of misalignment of the beam axis wrt detector axis (old trick by G. Barbielini)
→ the main question is the **solid angle** under which the limit of the tight cut is seen from the vertex.
→ **That solid angle refers to the angle wrt the nominal direction of the exiting beams (not the detector axis!)**

Typical dilepton selection

-- define a inclusive dilepton selection (goal to measure number of leptons pairs with highest precision)

-- within this sample evaluate ee/ mumu/ tautau fractions

-- e/mu/tau separation requires **dedicated tau analysis**

-- ee channel comprises both Z decays, t-channel (Bhabha scattering, non resonant) and their interference required **dedicated treatment of e+e- channel**

must impose a low angle limit of selection (necessary because of low angle bhabha scattering)

sensitivity to low angle cut

-- a cut such as $|\cos\theta|<0.95$ has a typical efficiency of 0.9 for a process with angular distribution $(1 + \cos^2\theta)$

-- what is the precision required on this angle to ensure a overall precision matched with the statistical precision?

-- this cut is correlated between channels and must be considered globally.

-- as for luminosity measurement one could consider a tight-lose method (switch on event by event basis) requirement applies to tight cut.

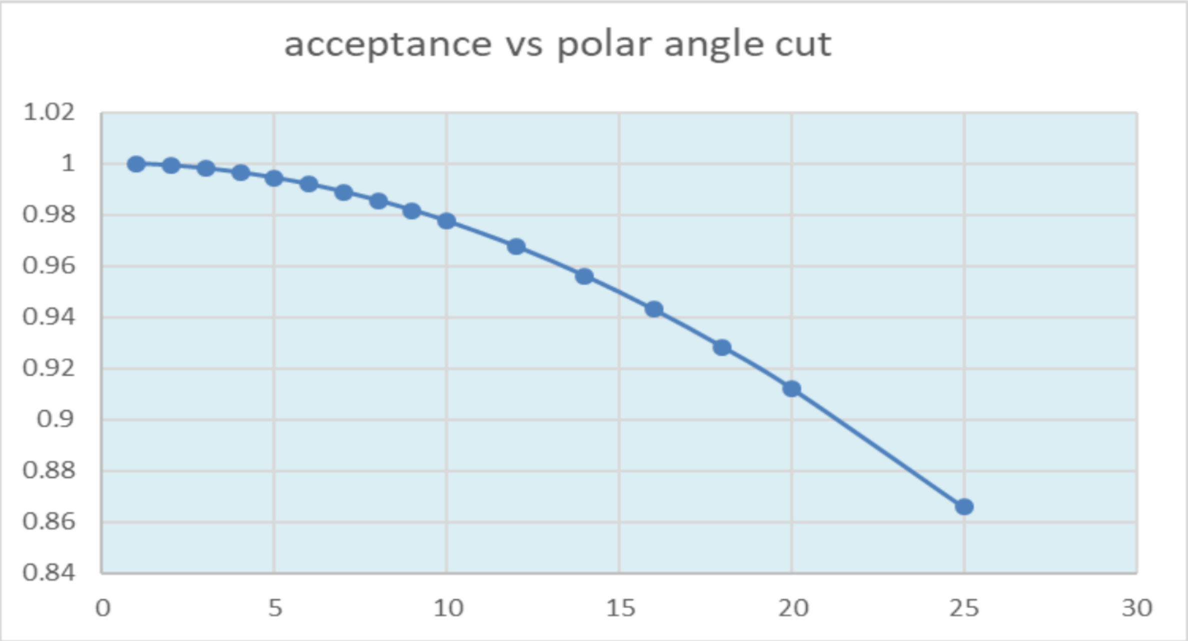
Answer: at an angle of 20 degrees, a 2mrad change of polar angle → 10^{-3} change of acceptance.

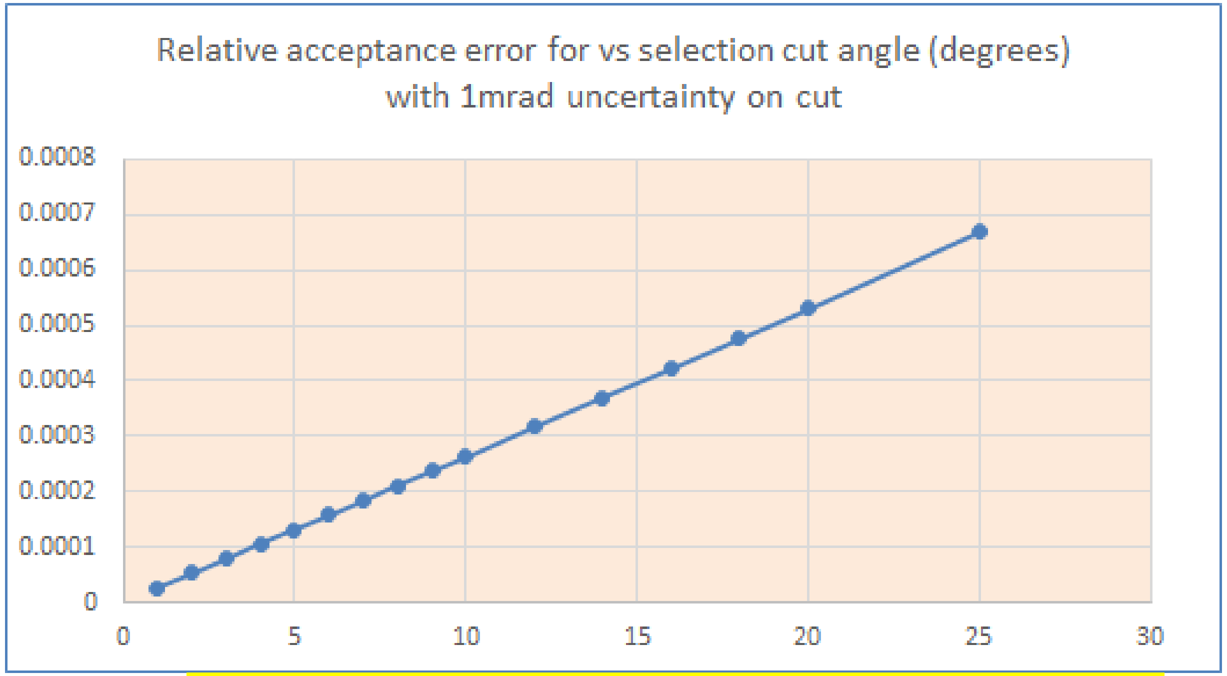
a precision of 1.4 10^{-6} will require a (hardware or alignment) with precision of 3 μrad (i.e. 6 microns at 2m)

For an angle of 10 degrees the precision required is relaxed by 2 – 6 μrad or 12 microns at 2m

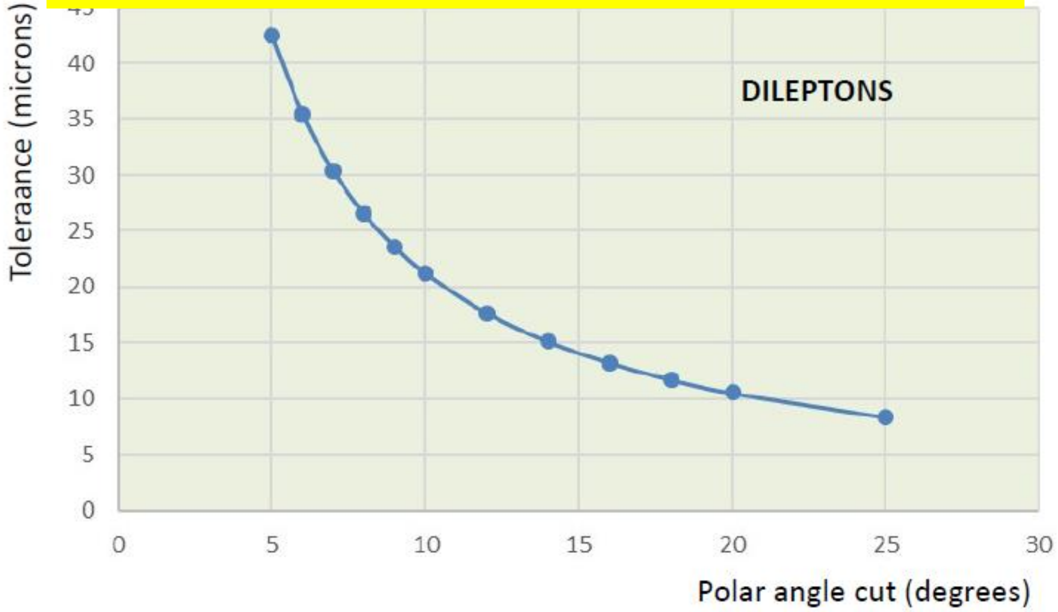
This question is synergetic with the luminosity measurement from e+e- → $\gamma\gamma$ events

s-channel: Z→ ee = Z→μμ = Z→ ττ

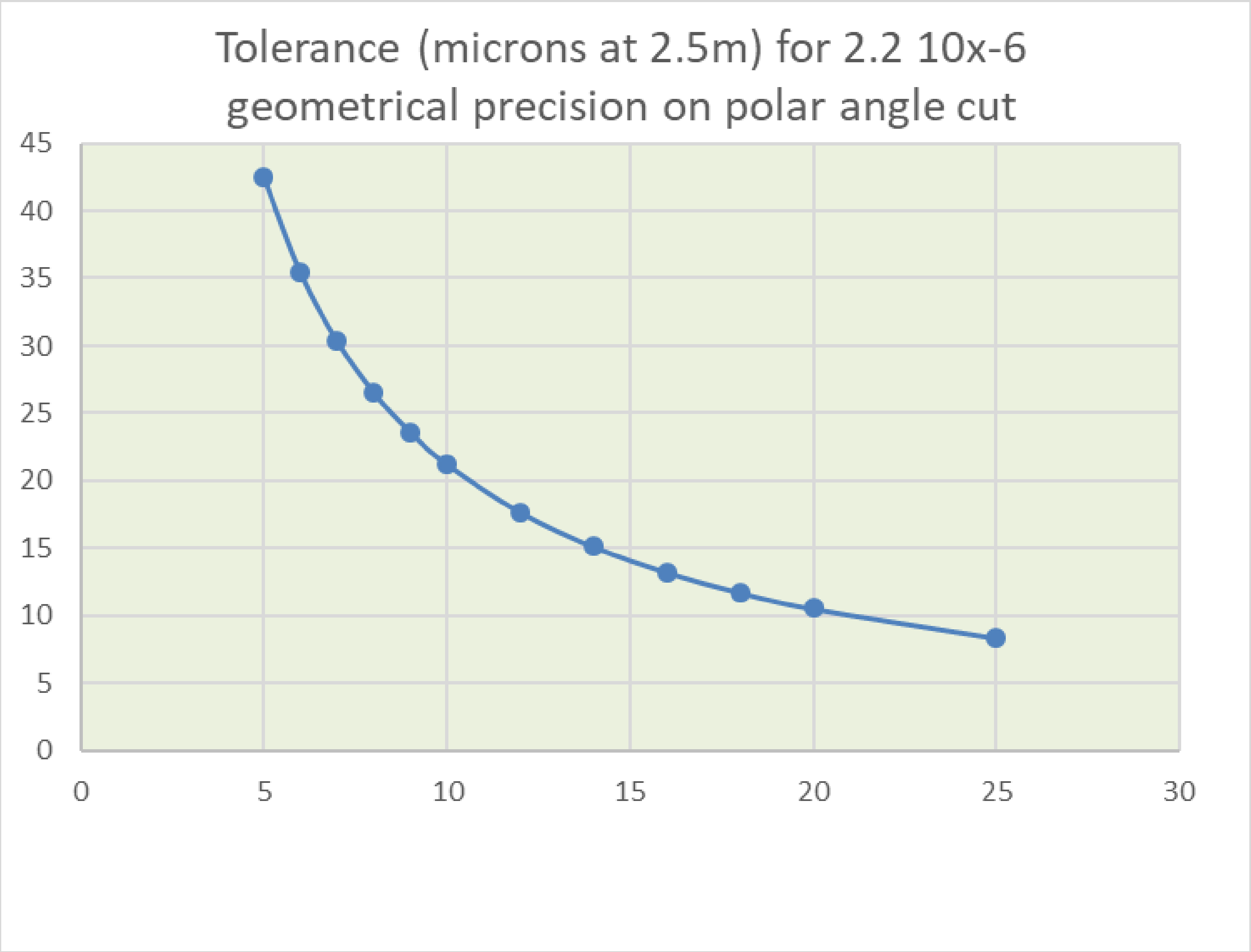




tolerance such that systematic error= stat. error



Larger cut angle
→ tighter tolerance
→ 10 degrees gives tolerance of 22 microns at 2.5 m
→ 20 degrees gives 11 microns



Larger cut angle
- **→ tighter tolerance**
- **→ 10 degrees gives tolerance of 22μm at 2.5 m**
- **→ 20 degrees gives 11μm**

Fig. 3 Tolerance on the accuracy of the cut angle on dilepton events that would ensure a systematic precision of 2.2×10−6, expressed as a position measurement accuracy for a detector situated at 2.5m from the IP, as a function of the polar angle cut in degree

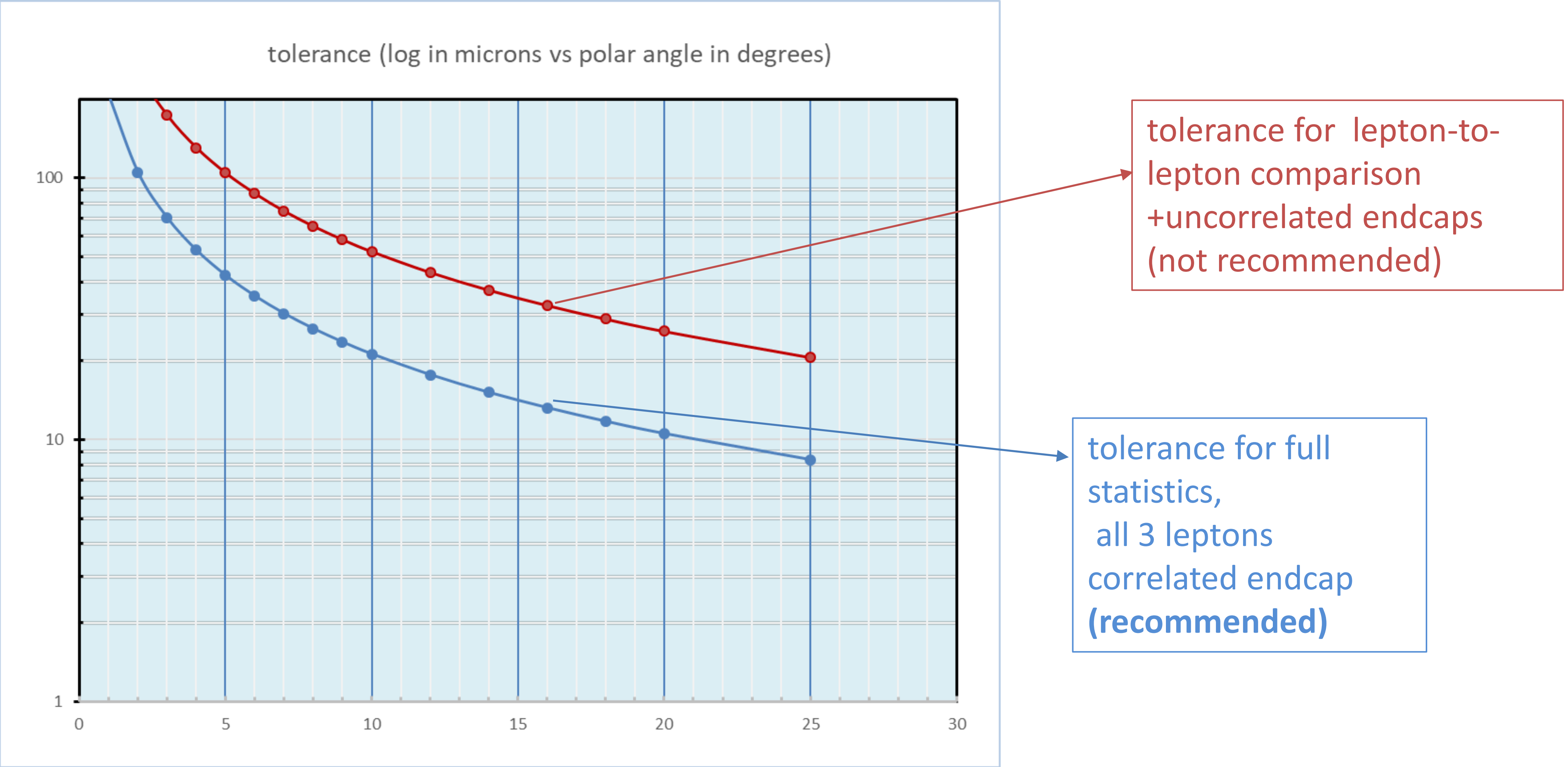
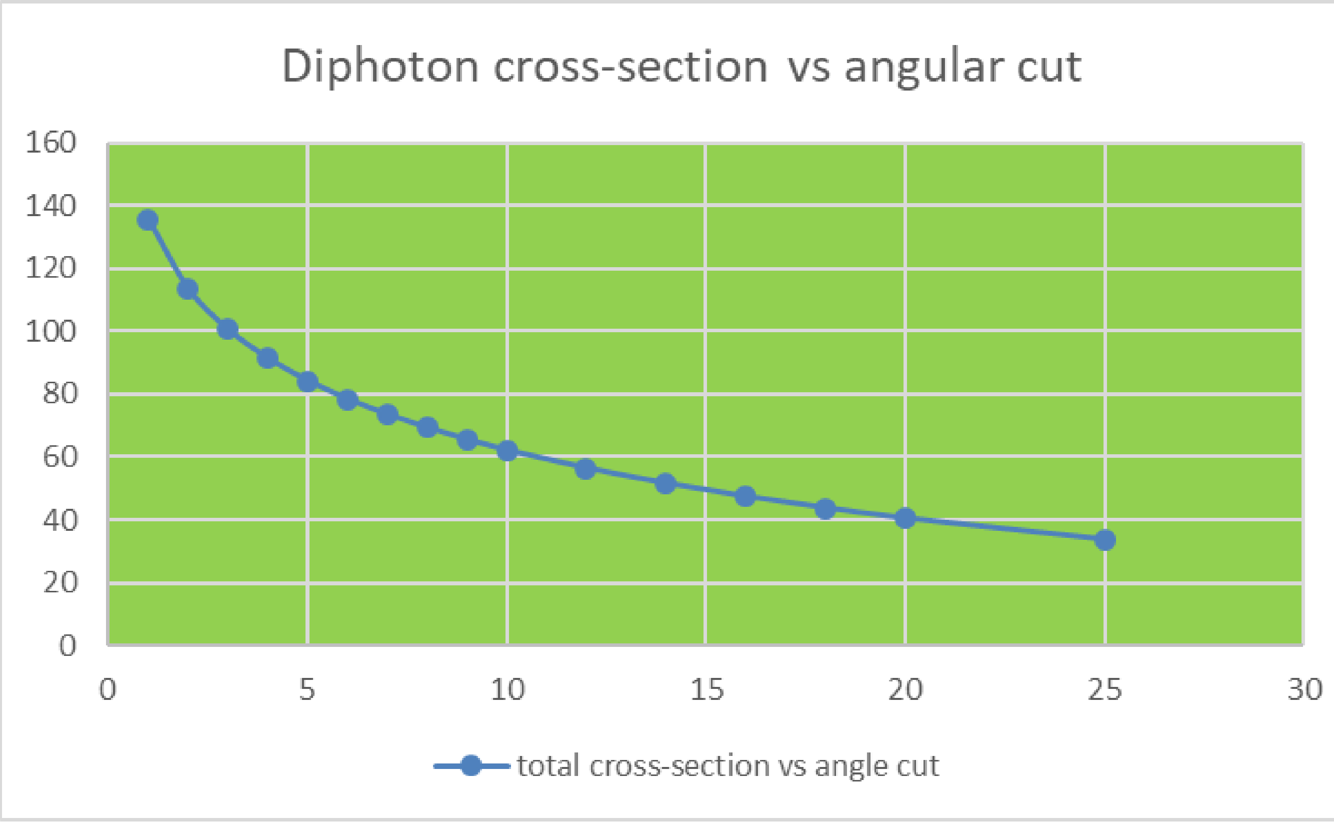


Fig. 4 Same as Fig. 3, but in logarithmic scale. The harder requirement (in blue) corresponds to the statistical uncertainty for a measurement of the total leptonic partial width, for which all leptons are considered, when also the acceptance systematic uncertainty for the two endcaps are considered to be fully correlated. Also indicated, in red, is the most relaxed target, corresponding to the case of the comparison between two lepton species, and with the acceptances for the two sides of the event assumed to be uncorrelated.

ee → $\gamma\gamma$



Lower angle cut gives higher cross-section, but angle cut tolerance becomes tighter.
The precision is never as good as the statistical error of the large angle lepton samples but for a 10 degrees cut the required tolerance is not as tight.
The angular tolerance is accompanied with a z position requirement which is typically 5-10 times looser.

Larger cut angle
→ less statistics and less precision
→ looser tolerance
→ 10 degrees gives tolerance of 25 microns at 2.5 m
→ 20 degrees gives 38 microns

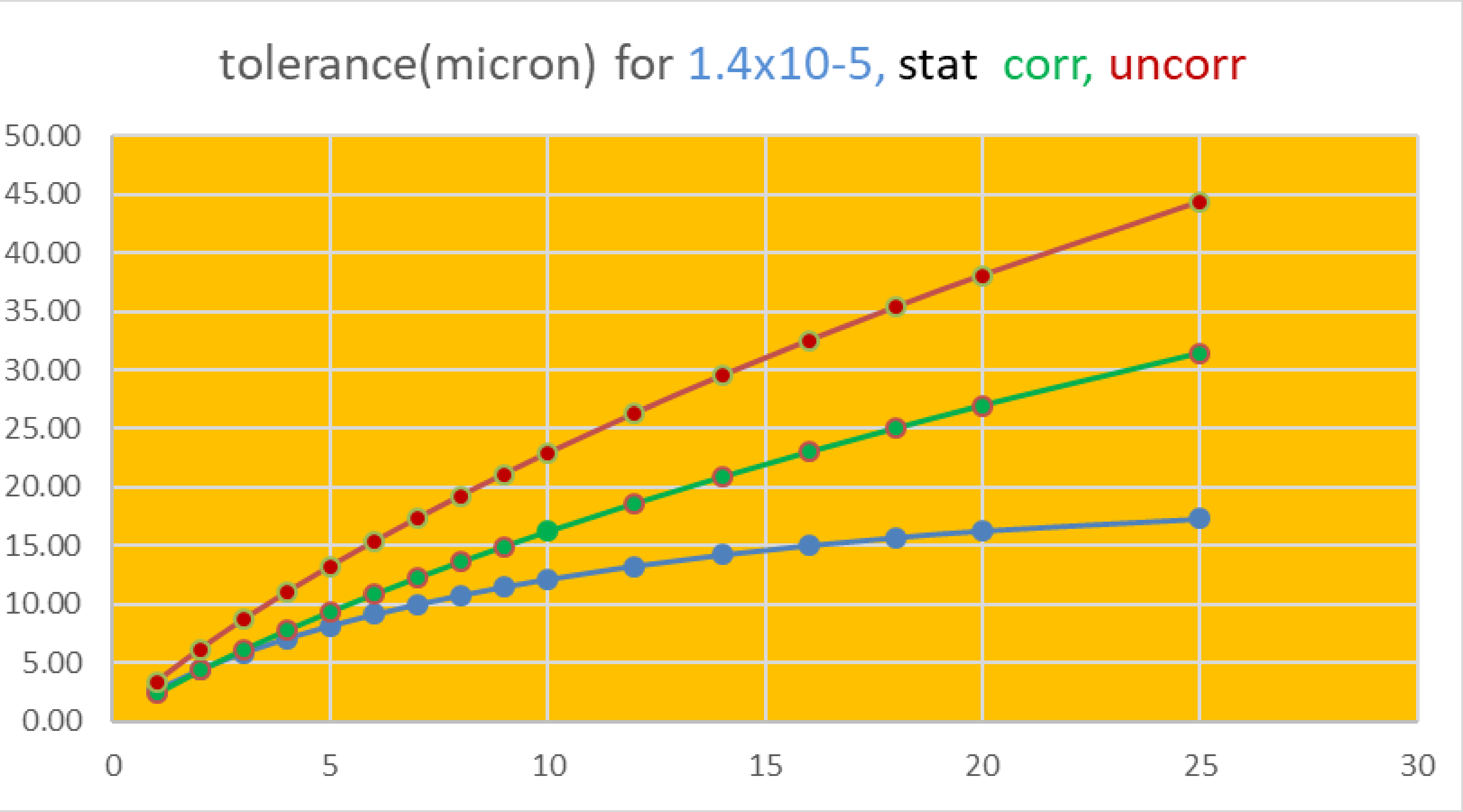
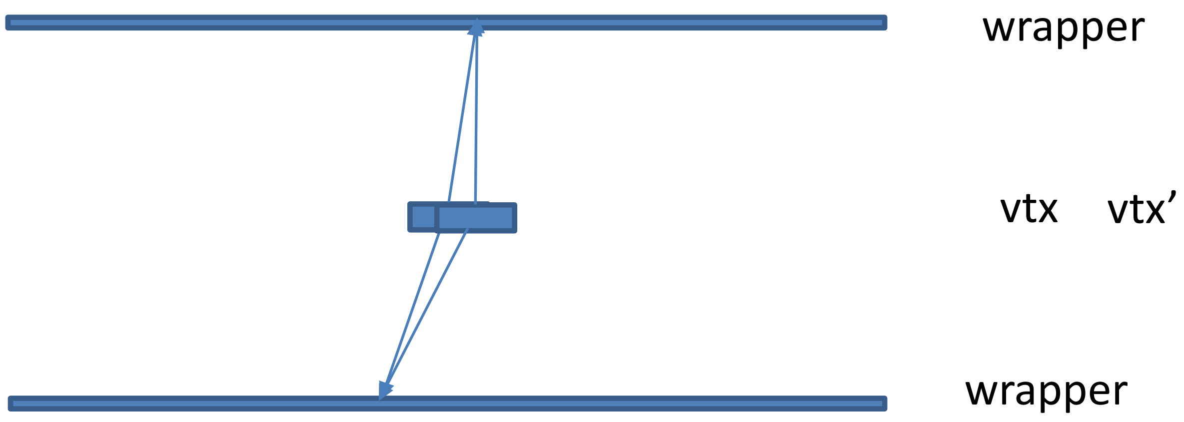


Fig. 6 Tolerance, for diphotons, on the accuracy of the cut angle that would ensure a systematic precision of 1.5 × 10−5 (in blue). Also indicated the requirement such that the uncertainty equals the statistical precision expressed as a position measurement accuracy for a detector situated at 2.5m from the IP, as a function of the polar angle cut in degree – in green assuming fully correlated systematics between the two endcaps, in red assuming uncorrelated systematics.

Possibility of in-situ alignment using dimuons

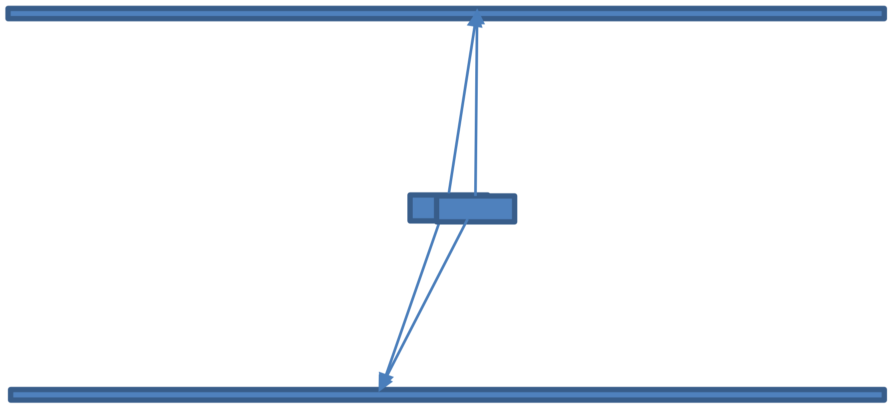
refer to Patrick's presentation in London, based on measurement of the acollinearity in Z→ $\mu\,\mu$ events
This is a beutiful and potentially very powerful method. The statistical precision will be quickly sufficient.
A fundamental difficulty is that many sources of misalignment exist that affect the measurement of track angles.

Example of a difficulty:
the internal alignment of the detector leads to systematic uncertainties in the track angle measurements -- we are not measuring the angle directly, but basically from the position of a set of space points. A relative shift of the vertex detector assembly wrt the outer part (wrapper) of the tracker by only 30 microns ➔ acollinearity shift by 30microrad. This is very similar to a longitudinal shift in CM boost. The slight difference can be observed by analysis of the dilepton sample, but can also be mimicked by a small deformation of the outside detector, in which one encap has a slightly larger diameter than the other.



In other words, the 'global' in-situ alignment require a 'global' fit to a great many sources of misalignment simultaneously, and it is not guaranteed that there will not remain blind directions.

The benefit from cosmic muons

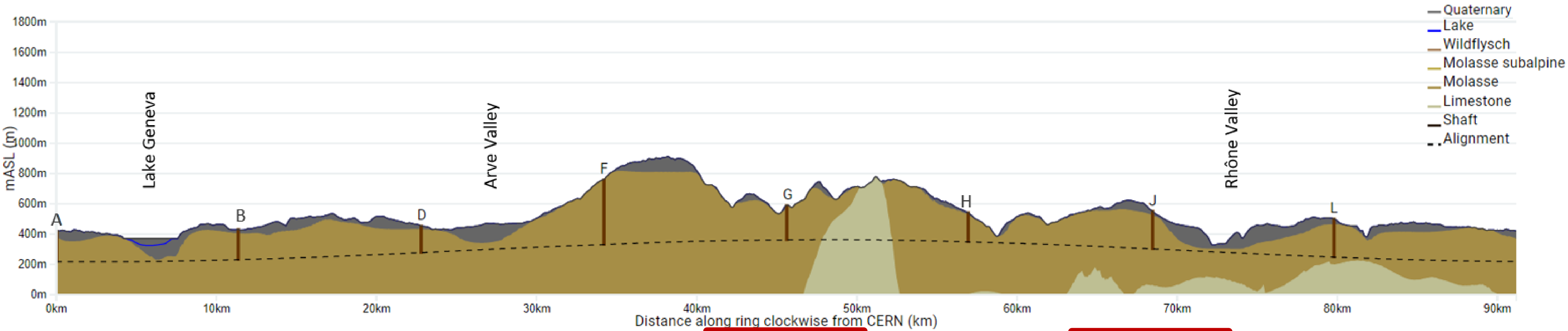


This type of misalignment cannot be eliminated using tracks originating from the vertex, Traditionally this is constrained by using cosmic tracks that are going through all the detectors of concern.
The FCC caverns are far deeper (over 200m) than CMS (~70m), ATLAS (~57m) or even ALEPH (125m) (see next slide)

Difficulty here is the smallness of the vertex detector and the depth of the caverns that both reduce the number of useful cosmic muons. Energy of the muons has to be >~5 GeV at entrance into detector. Each muon will provide an alignment constraint equivalent to ~3-5 microns on the relative longitudinal position of the vtx detector.

A few 100 cosmics will be sufficient to efficiently constrain the longitudinal boost around micron level.
In order to obtain a precision of 10keV on the longitudinal boost as desirable for the Z mass measurement around O(100’000) useful muons might be necessary. Is this possible? **TO BE FOLLOWED!**
The availability of both, direct mechanical contraint and in-situ alignment, is precious redundancy and should be pursued

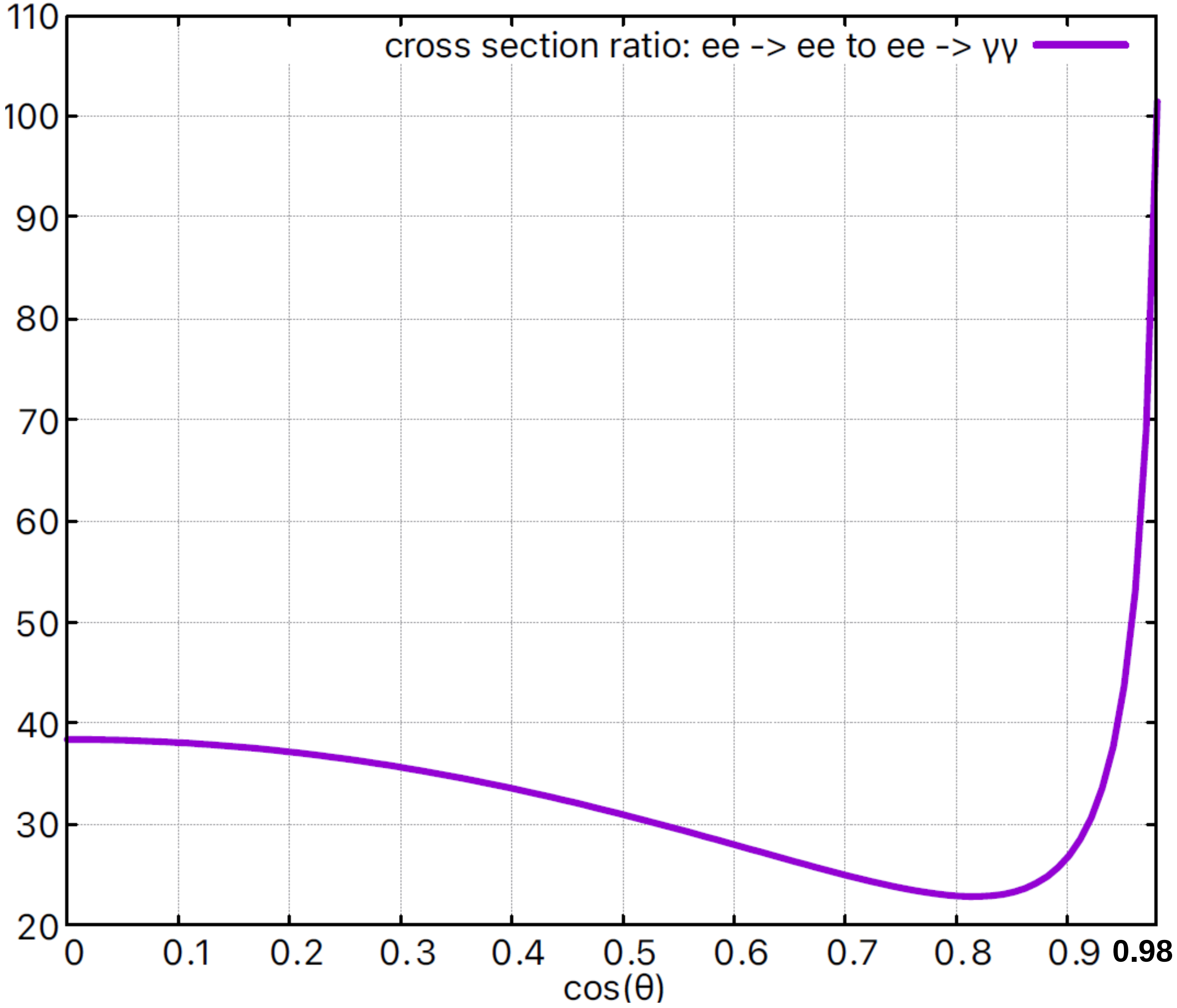
From T. Watson’s talk



PA	PB	PD	PF	PG	PH	PJ	PL
201 m	201m	181 m	400 m	226m	235m	253 m	250m

Detector considerations

The main background for the diphoton channel is the t-channel Bhabha scattering.



1. It is essential to place a tracker in front of the calorimeter in order to separate electron from photon.

2. The least material between the IP and the first sensitive element the better.

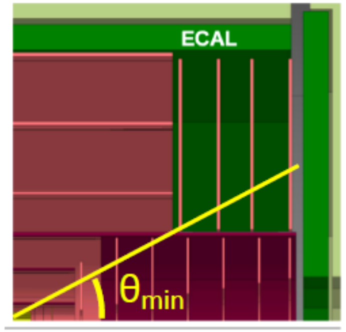
3. the critical number if 'how many 45 GeV electrons give no track' (catastrophic bremsstrahlung)

4. presence of two sides per event will be of great help.

whenever possible tracking elements should be perpendicular to the beam axis

- All other contributions have to be kept very low
  - No holes, no cracks ...

see G. Wilson talk



status and outlook

for Z leptonic decays, and two gamma channel, a dominant and straightforward systematic uncertainty arises from the definition of the low angle cut, which defines a solid angle in space.

Examples and curves have been produced. Independence between sides remain to be understood.
The requirements for the 2 channels vary in opposite directions as a function of the angle of the fiducial cut – for a 15 degrees cut, a accuracy 15 microns at 2.5 m (6 microradians) will equate this source of systematic error with the statistical precision for both channels.
An ambitious collaboration might want to reduce this by a factor 3. d

The availability of both, direct mechanical contraint and in-situ alignment, is precious redundancy and should be pursued

➔Detector design for the low angle region of the endcaps is truly critical.

Particle physics after the discovery of the Higgs boson

Two facets:

The Higgs boson is very special

It generates (couples to) mass. Alone?

-- W,Z masses ⇔ Higgs coupling to WW, ZZ? FCC-ee

-- (all) fermion masses ⇔ Higgs couplings? FCC-ee

FCC-hh(+ee) decays ($\gamma\gamma$, gg, Zγ) ⇔ SM particle content?

-- are all elementary particles given mass this way?

FCC-ee(?) even electrons? and even the neutrinos?

Yukawa (→ ν_R , sterile → Majorana HNL) FCC-ee

Higgs couples to itself!

-- Spontaneous Symmetry Breaking

-- What is the value of the self-coupling?

-- impact on σ_{HZ} near threshold FCC-ee

-- HH production

FCC-hh, high energy lepton colliders

FCC-hh

The SM is « complete »

-- Higgs and top masses predicted from EWPOs

assuming no new SM coupled particles exist

-- SM extrapolates to the Plank scale

assuming no new SM coupled particles exist

-- SM works wonderfully... **So why continue?**

-- SM does not explain everything

Baryon Asymmetry of the Universe

Dark Matter

Neutrino masses

and more.... ➔ require new particles!

nature and **mass scale is unknown**

FCC-ee: EWPO Flavour

Are there any further SM-coupled particles?

FCC-hh

-- no guarantee or exp. indication that any exist

-- but many BSM solutions include them...

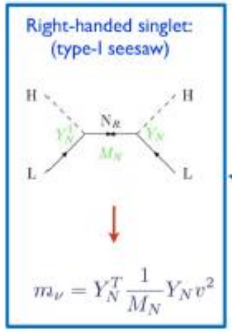
-- DARK SECTOR → possibly light, sterile particles

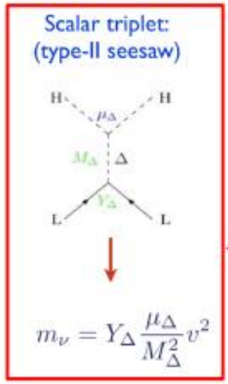
FCC-ee: LLP EWPO Flavour

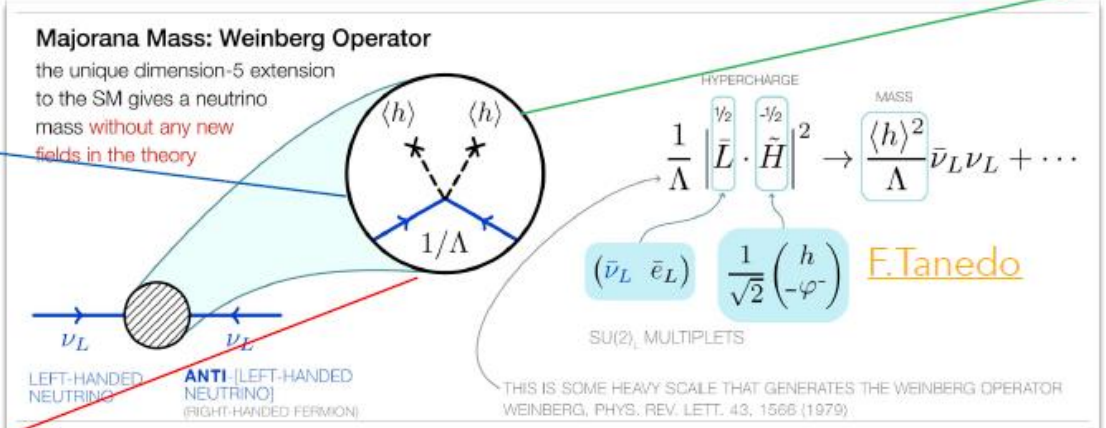
Seesaw Model

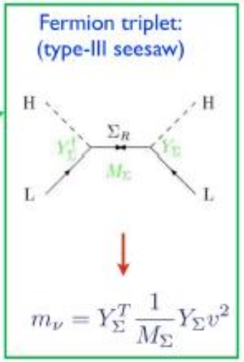
The minimal neutrino Standard Model
is type I see-saw (just complete with RH ν's)

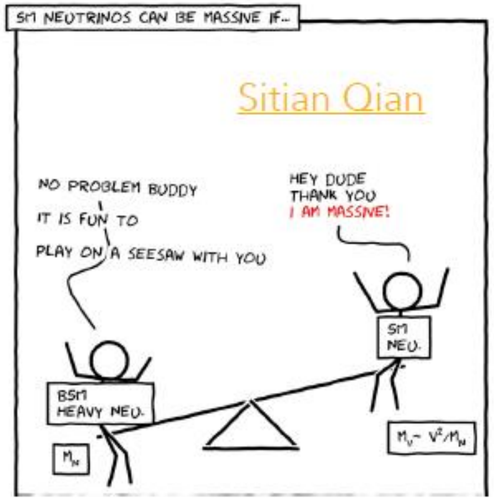
- Opening the black box of Weinberg Operator requires a "**seesaw**"
  - Only three different kinds of realization at Born-level are allowed











- Heavier BSM particles lead to lighter SM neutrinos

« The Standard Model is complete »

This statement is correct in the following sense, which allows to separate ‘SM’ from ‘BSM’

we should distinguish
A. ‘Standard Theory of particle physics’
based on Quantum Field Theory, relativity, quantum mechanics, principles of Gauge invariance etc... using in particular the SU(3)_color ⊗ SU(2)_L ⊗ U(1) gauge groups or extensions thereof.
In itself it is not necessarily predictive, but provides a wide toolset to include further discoveries.
** definitely not complete**, but completeness is not the
and
B. « the Standard Model » which is one possible model witihin the above, with a specific set of constituants (fermions and gauge bosons), their couplings, chiralities and their masses, which are all extracted from experiment
It was created (and named in ~1976) after the discovery of the Neutral Currents (1973), Charm (74/76) and the tau and ν_τ (75-77)
With the discovery of the Higgs boson, the Standard Model is complete and forms a predictive and quantitative tool.
-- assumes neutrinos are massless
-- comprises 3 families of quarks and leptons and a single, elementary Higgs boson, and as such
contains no free parameter (only parametric uncertainties) ANY DEVIATION from SM is BSM DISCOVERY

-- does not explain in a unique way the neutrino masses or the Baryon Asymetry of the Universe, does not comprise a candidate DM particle, etc... for which we know for sure that BSM is needed

A hard look at the situation...

Since the NC discovery we have been relying on increasing collider energies for the next SM particle to show up...
... or else a drama would happen (t-less models, no-lose theorem, etc...).

This is no longer the case
The SM-coupled particles predicted by the SM have all been found, yet unexplained phenomena are observed. (DM. BAU)
While it is quite possible that no more SM-coupled particle exist!
The question **'are there any more particles with SM couplings?'** must be tested by all possible means!
➔ **Any solid set of SM deviations would be a big discovery**
➔ EW+Flavours at colliders and high precision facilities with several orders of magnitude increase of precision.

The new physics there is : Higgs boson and massive neutrinos.
What is predicted are sterile particles with couplings many many orders of magnitude smaller than SM and whose mass can vary between few keV and 10^{10} GeV...

➔ **High precision, huge intensities and more energy are required.**

A NEW ERA OF EXPLORATION

FCC

Fermion number conservation

Is *not* in itself a law or a symmetry of the Standard Model

For charged fermions (e/mu/tau and the quarks) it is not possible to transform a fermion into an antifermion **because of charge conservation**

For neutrinos, which are neutral, the SM assumes they are massless.
neutrino is left-handed (identical if massless to negative helicity)
and the antineutrino has positive helicity
neutrino <-> antineutrino transition is forbidden by **angular momentum conservation**

This results in practice in <u>apparent, accidental, conservation of fermion number</u>

The existence of massive neutrinos allows for spin flip and thus in principle a neutrino-antineutrino transition
since a left-handed field (EW eigenstate) has a component of the opposite helicity (EW state $\neq$ physical state)
$\nu_L \approx \nu_- + \nu_+ \, m/E$ (mass is what allows to flip the helicity)

for the allowed masses of light neutrinos this is very, very small: for m_ν =50 meV and P^*_π =30 MeV ➔ $(m/E)^2 = 10^{-18}$

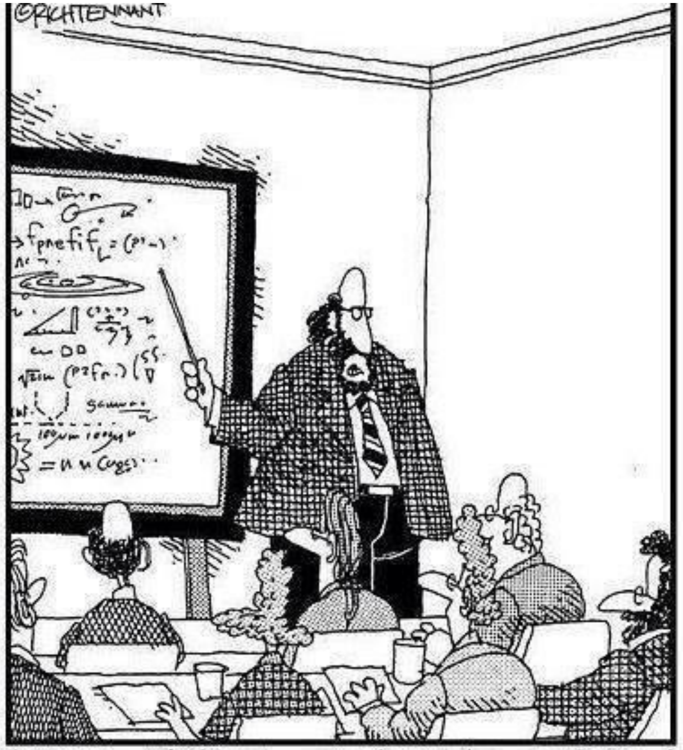
This can be observed in neutrino less double beta decay or by searching directly for the right-handed neutrinos

my SM training in 1976

NEUTRINO MASSES

Electroweak eigenstates

I = 1/2	I = 0	
$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R \ (\mu)_R \ (\tau)_R$	Q= -1
	$(\nu_e)_R \ (\nu_\mu)_R \ (\nu_\tau)_R$	Q= 0



"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

Right handed neutrinos
are singlets
no weak interaction
no EM interaction
no strong interaction

can't produce them
can't detect them
-- so why bother? –
Also called 'sterile'

NB unlike for ν_L, nothing distinguishes the particle and antiparticle of ν_R which is a singlet (no 'charge') → naturally a Majorana particle

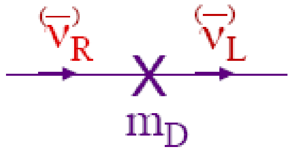
FCC

Neutrino masses occur via processes which are intimately related to the Higgs boson what are the couplings of the H(125) to neutrinos?

Let us follow the steps of the Standard Model to construct a minimal neutrino mass model

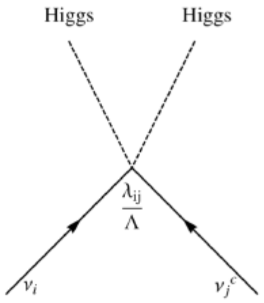
Adding neutrino masses to the Standard model 'simply' by adding a Dirac mass ➔ right-handed neutrino

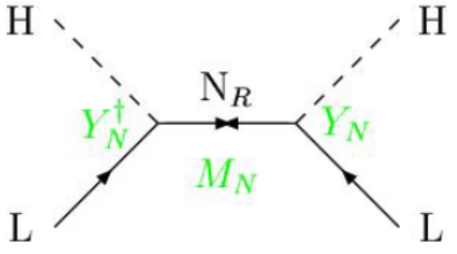
$m_D \overline{\nu_L} \nu_R$



m_D is the Higgs **Yukawa coupling** (like everybody else). Then the right handed neutrinos are sterile, (**except** that they couple to both the Higgs boson and gravitation).
Things become more interesting: **a Majorana mass term** arises (So-called **Weinberg Operator**) using the Higgs boson and the neutrino Yukawa coupling:

Origin of neutrino mass:





Pilar Hernandez, Granada 2019-05

Majorana mass term is extremely interesting as this is the **particle-to-antiparticle transition** that we want in order to explain **the Baryon asymmetry of the Universe** (+ CP violation in e.g. neutrinos)

$M_R \overline{\nu_R{}^c} \nu_R$

B. Kayser 1989)

Having two mass terms per family , neutrinos undergo level splitting ➔ Mass eigenstates

See-saw type I :

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L, \bar{N}^c_R)\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}\begin{pmatrix} \nu^c_L \\ N_R \end{pmatrix}$$

$M_R \neq 0$
$m_D \neq 0$
Dirac + Majorana mass terms

$$\tan 2\theta = \frac{2\, m_D}{M_R - 0} \qquad \ll 1$$

$$m_\nu = \tfrac{1}{2}\left[(0 + M_R) - \sqrt{(0 - M_R)^2 + 4\, m_D^2}\right] \qquad \simeq -m_D^2/M_R$$

$$M = \tfrac{1}{2}\left[(0 + M_R) + \sqrt{(0 - M_R)^2 + 4\, m_D^2}\right] \qquad \simeq M_R$$

general formula — if $m_D \ll M_R$

$M_R = 0$
$m_D \neq 0$
Dirac only, (like e- vs e+):

m ↑

	ν_L	ν_R	$\bar{\nu}_L$	$\bar{\nu}_R$
I_{weak}=	½	0	½	0

4 states of equal masses

Some have I=1/2 (active)
Some have I=0 (sterile)

$M_R \neq 0$
$m_D = 0$
Majorana only

m ↑

	ν_L	$\bar{\nu}_R$
I_{weak}=	½	½

2 states of equal masses

All have I=1/2 (active)

$M_R > m_D \neq 0$ — see-saw

Dirac + Majorana

m ↑

dominantly:

	ν	N	$\bar{\nu}$	N
I_{weak}=	½	0	½	0

4 states , 2 mass levels

m_1 have ~I=1/2 (~active)
m_2 have ~I=0 (~sterile)

The fundamental reference

CERN-PH-EP/2005-041
SLAC-R-774
hep-ex/0509008
7 September 2005

Precision Electroweak Measurements on the Z Resonance

The ALEPH, DELPHI, L3, OPAL, SLD Collaborations,[1]
the LEP Electroweak Working Group,[2]
the SLD Electroweak and Heavy Flavour Groups

Accepted for publication in *Physics Reports*

Basic papers of the 4 LEP experiments

[41] ALEPH Collaboration, D. Decamp *et al.*, Z. Phys. **C48** (1990) 365–392;
ALEPH Collaboration, D. Decamp *et al.*, Z. Phys. **C53** (1992) 1–20;
ALEPH Collaboration, D. Buskulic *et al.*, Z. Phys. **C60** (1993) 71–82;
ALEPH Collaboration, D. Buskulic *et al.*, Z. Phys. **C62** (1994) 539–550;
ALEPH Collaboration, R. Barate *et al.*, Eur. Phys. J. **C14** (2000) 1–50.

[42] DELPHI Collaboration, P. Abreu *et al.*, Nucl. Phys. **B367** (1991) 511–574;
DELPHI Collaboration, P. Abreu *et al.*, Nucl. Phys. **B417** (1994) 3–57;
DELPHI Collaboration, P. Abreu *et al.*, Nucl. Phys. **B418** (1994) 403–427;
DELPHI Collaboration, P. Abreu *et al.*, Eur. Phys. J. **C16** (2000) 371–405.

[43] L3 Collaboration, B. Adeva *et al.*, Z. Phys. **C51** (1991) 179–204;
L3 Collaboration, O. Adriani *et al.*, Phys. Rept. **236** (1993) 1–146;
L3 Collaboration, M. Acciarri *et al.*, Z. Phys. **C62** (1994) 551–576;
L3 Collaboration, M. Acciarri *et al.*, Eur. Phys. J. **C16** (2000) 1–40.

[44] OPAL Collaboration, G. Alexander *et al.*, Z. Phys. **C52** (1991) 175–208;
OPAL Collaboration, P. D. Acton *et al.*, Z. Phys. **C58** (1993) 219–238;
OPAL Collaboration, R. Akers *et al.*, Z. Phys. **C61** (1994) 19–34;
OPAL Collaboration, G. Abbiendi *et al.*, Eur. Phys. J. **C19** (2001) 587–651.

Reference: https://inspirehep.net/literature/691576
Phys.Rept. 427 (2006) 257-454

FCC

A very useful reference

High Energy Physics - Phenomenology

[Submitted on 18 Jun 2019 (v1), last revised 26 Jun 2019 (this version, v2)]

Electroweak corrections to $e^+e^- \to \gamma\gamma$ as a luminosity process at FCC-ee

Carlo M. Carloni Calame, Mauro Chiesa, Guido Montagna, Oreste Nicrosini, Fulvio Piccinini

We consider large-angle two photon production in e^+e^- annihilation as a possible process to monitor the luminosity of a future e^+e^- circular collider (FCC-ee). We review and assess the status of the theoretical accuracy by performing a detailed phenomenological study of next-to-leading order electroweak corrections and leading logarithmic QED contributions due to multiple photon radiation. We also estimate the impact of photonic and fermion-loop corrections at next-to-next-to-leading order and the uncertainty induced by the hadronic contribution to the vacuum polarization. Possible perspectives to address the target theoretical accuracy are briefly discussed.

Comments: 13 pages, 3 figures, 3 tables. Extended version, with theoretical details and further numerical results, of the contribution to the workshop proceedings arXiv:1905.05078 by the same authors. v2: minor text modification, one reference added

Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - Experiment (hep-ex)

Cite as: arXiv:1906.08056 **[hep-ph]**
(or arXiv:1906.08056v2 **[hep-ph]** for this version)
https://doi.org/10.48550/arXiv.1906.08056

Related DOI: https://doi.org/10.1016/j.physletb.2019.134976

A great reference!

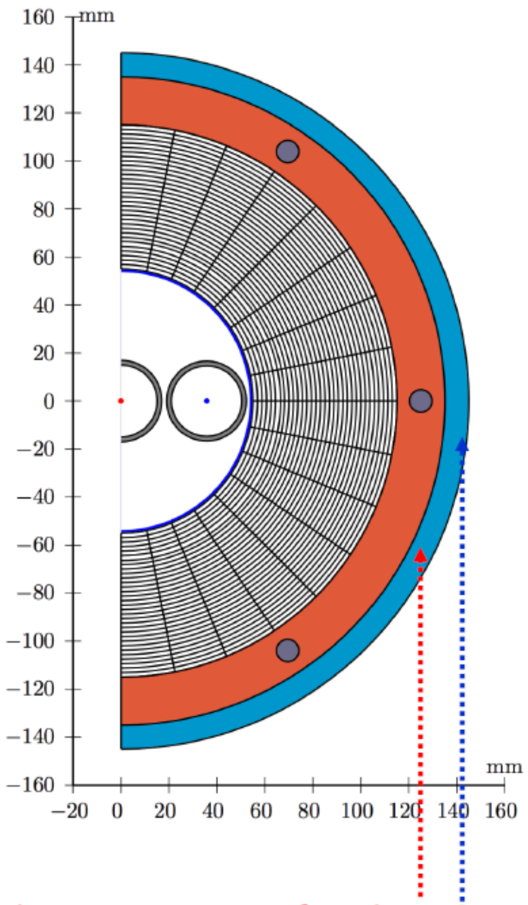
A detector for precise cross-section measurements

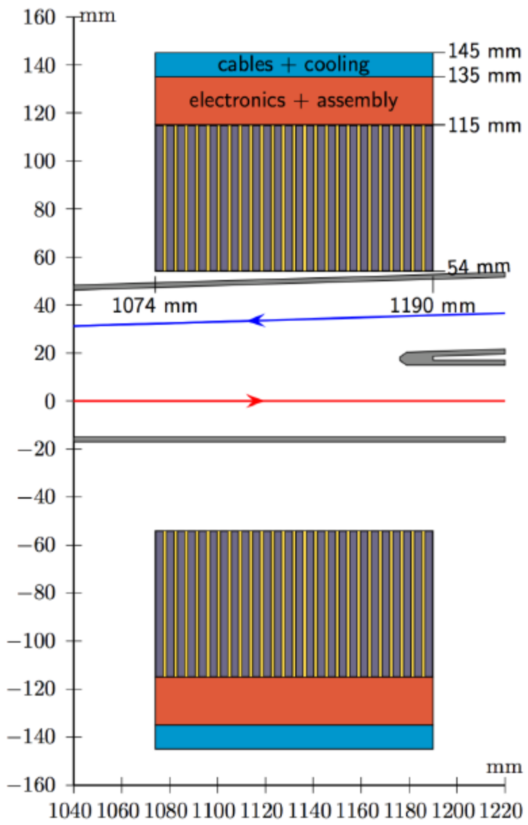
Mogens Dam
Niels Bohr Institute

4th FCC Physics and Experiments Workshop
CERN/zoom, 9-13 November, 2020

LumiCal CDR Design

- W+Si sandwich: 3.5 mm W + Si sensors in 1 mm gaps
  - Effective Molière radius: ~15 mm
- 25 layers total: 25 X_0
- Cylindrical detector dimensions:
  - Radius: 54 < r < 145 mm
  - Along outgoing beam line: 1074 < z < 1190 mm
- Sensitive region:
  - 55 < r < 115 mm;
- Detectors centered on (and perpendicular to) outgoing beam line
- Angular coverage (>1 Molière radius from edge):
  - Wide acceptance: 62-88 mrad
  - Narrow acceptance: 64-86 mrad
  - Bhabha cross section @ 91.2 GeV: 14 nb
- Region 115 < r < 145 mm reserved for services:
  - Red: Mechanical assembly, **read-out electronics**, cooling, equipment for alignment
  - Blue: Cabling of signals from front-end electronics to digitizers (behind LumiCals?)





Precision goal: 1 x 10^{-4}

A hard look at the situation...

Since the NC discovery we have been relying on increasing collider energies for the next SM particle to show up...
... or else a drama would happen (t-less models, no-lose theorem, etc...).

This is no longer the case
The SM-coupled particles predicted by the SM have all been found, yet unexplained phenomena are observed. (DM. BAU)
While it is quite possible that no more SM-coupled particle exist!
The question **'are there any more particles with SM couplings?'** must be tested by all possible means!
➔ **Any solid set of SM deviations would be a big discovery**
➔ EW+Flavours at colliders and high precision facilities with several orders of magnitude increase of precision.

The new physics there is : Higgs boson and massive neutrinos.
What is predicted are sterile particles with couplings many many orders of magnitude smaller than SM and whose mass can vary between few keV and 10^{10} GeV...

➔ **High precision, huge intensities and more energy are required.**

A NEW ERA OF EXPLORATION

Fermion number conservation

Is *not* in itself a law or a symmetry of the Standard Model

For charged fermions (e/mu/tau and the quarks) it is not possible to transform a fermion into an antifermion **because of charge conservation**

For neutrinos, which are neutral, the SM assumes they are massless.
neutrino is left-handed (identical if massless to negative helicity)
and the antineutrino has positive helicity
neutrino <-> antineutrino transition is forbidden by **angular momentum conservation**

This results in practice in <u>apparent, accidental, conservation of fermion number</u>

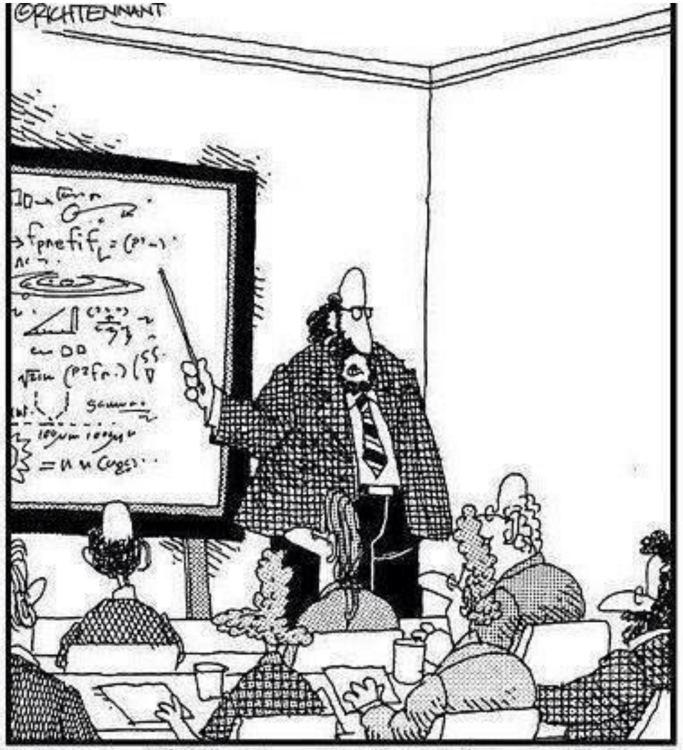
The existence of massive neutrinos allows for spin flip and thus in principle a neutrino-antineutrino transition
since a left-handed field (EW eigenstate) has a component of the opposite helicity (EW state $\neq$ physical state)
$\nu_L \approx \nu_- + \nu_+ \, m/E$ (mass is what allows to flip the helicity)

for the allowed masses of light neutrinos this is very, very small: for m_ν =50 meV and P^*_π =30 MeV ➔ $(m/E)^2 = 10^{-18}$

This can be observed in neutrino less double beta decay or by searching directly for the right-handed neutrinos

NEUTRINO MASSES

Electroweak eigenstates	I = 1/2	I = 0	
	$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$ $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$ $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R$ $(\mu)_R$ $(\tau)_R$	Q= -1
		$(\nu_e)_R$ $(\nu_\mu)_R$ $(\nu_\tau)_R$	Q= 0



"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

Right handed neutrinos are singlets
no weak interaction
no EM interaction
no strong interaction

can't produce them
can't detect them
-- so why bother? –
Also called 'sterile'

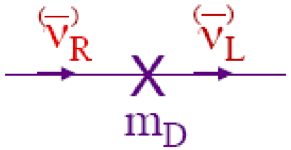
NB unlike for ν_L, nothing distinguishes the particle and antiparticle of ν_R which is a singlet (no 'charge')
→ naturally a Majorana particle

Neutrino masses occur via processes which are intimately related to the Higgs boson what are the couplings of the H(125) to neutrinos?

Let us follow the steps of the Standard Model to construct a minimal neutrino mass model

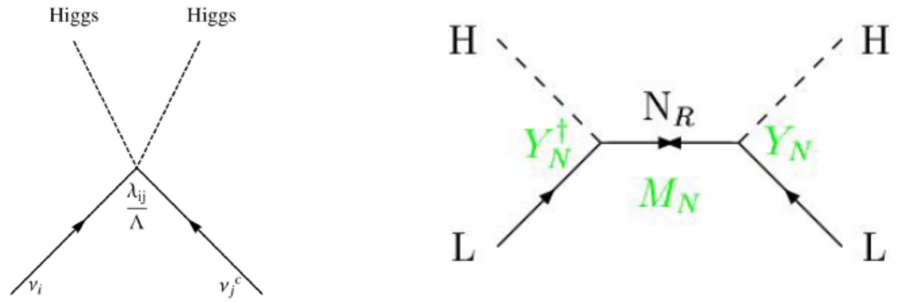
Adding neutrino masses to the Standard model 'simply' by adding a Dirac mass ➔ right-handed neutrino

$m_D \overline{\nu_L} \nu_R$



m_D is the Higgs **Yukawa coupling** (like everybody else). Then the right handed neutrinos are sterile, (**except** that they couple to both the Higgs boson and gravitation).
Things become more interesting: **a Majorana mass term** arises (So-called **Weinberg Operator**) using the Higgs boson and the neutrino Yukawa coupling:

Origin of neutrino mass:



Pilar Hernandez, Granada 2019-05

Majorana mass term is extremely interesting as this is the **particle-to-antiparticle transition** that we want in order to explain **the Baryon asymmetry of the Universe** (+ CP violation in e.g. neutrinos)

$M_R \overline{\nu_R{}^c} \nu_R$

B. Kayser 1989)

Having two mass terms per family , neutrinos undergo level splitting ➔ Mass eigenstates

See-saw type I :

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L, \bar{N}^c_R) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

$M_R \neq 0$
$m_D \neq 0$
Dirac + Majorana mass terms

$$\tan 2\theta = \frac{2\, m_D}{M_R - 0} \qquad \ll 1$$

$$m_\nu = \tfrac{1}{2}\left[(0 + M_R) - \sqrt{(0 - M_R)^2 + 4\, m_D^2}\right] \qquad \simeq -m_D^2/M_R$$

$$M = \tfrac{1}{2}\left[(0 + M_R) + \sqrt{(0 - M_R)^2 + 4\, m_D^2}\right] \qquad \simeq M_R$$

general formula — if $m_D \ll M_R$

$M_R = 0$
$m_D \neq 0$
Dirac only, (like e- vs e+):

m ↑

	ν_L	ν_R	$\bar{\nu}_L$	$\bar{\nu}_R$
I_{weak}=	½	0	½	0

4 states of equal masses

Some have I=1/2 (active)
Some have I=0 (sterile)

$M_R \neq 0$
$m_D = 0$
Majorana only

m ↑

	ν_L	$\bar{\nu}_R$
I_{weak}=	½	½

2 states of equal masses

All have I=1/2 (active)

$M_R > m_D \neq 0$ see-saw

Dirac + Majorana

m ↑

dominantly:

	ν	N	$\bar{\nu}$	N
I_{weak}=	½	0	½	0

4 states , 2 mass levels

m_1 have ~I=1/2 (~active)
m_2 have ~I=0 (~sterile)

Motivation for the precision measurements *and* precision calculations

1. Given that **the minimal SM is complete** with the Higgs discovery, how do we find out:
-- if the Higgs boson is exactly what is foreseen by the standard model? (→ Higgs Factory)
-- where/what are the new physics phenomena that must be present to explain:
baryon asymmetry
dark matter,
neutrino masses (and other mysteries we don't understand) (→ EW/top factory)

2. A powerful and broadly efficient method is to perform **precision EW measurements**
-- many **observables** contain sensitivity to new phenomena, either by loops, direct long distance propagator effects, or mixing with SM coupled particles.

«T»

➔ are there any more weakly coupled particles?
The top quark effect at LEP was 10σ! (➔ there is *not* another t-b quark system)
any custodial SU(2)-violating effect appears **regardless of mass scale**

$\Delta\rho = \Delta T/\alpha = \alpha/\pi$. $(\mathbf{m^2_{top}-m^2_b)/m^2_W}$

«ν»

-- is there mixing ? in particular active-sterile neutrino mixing

«S»

-- high mass SM-coupled and custodial SU(2)-respecting → (ex: Z' or degenerate SuSy)
(see

not to forget:
QCD
Lepton-quark
lepton and quark family
Universality

Emphasis on different observables depending on the question asked.