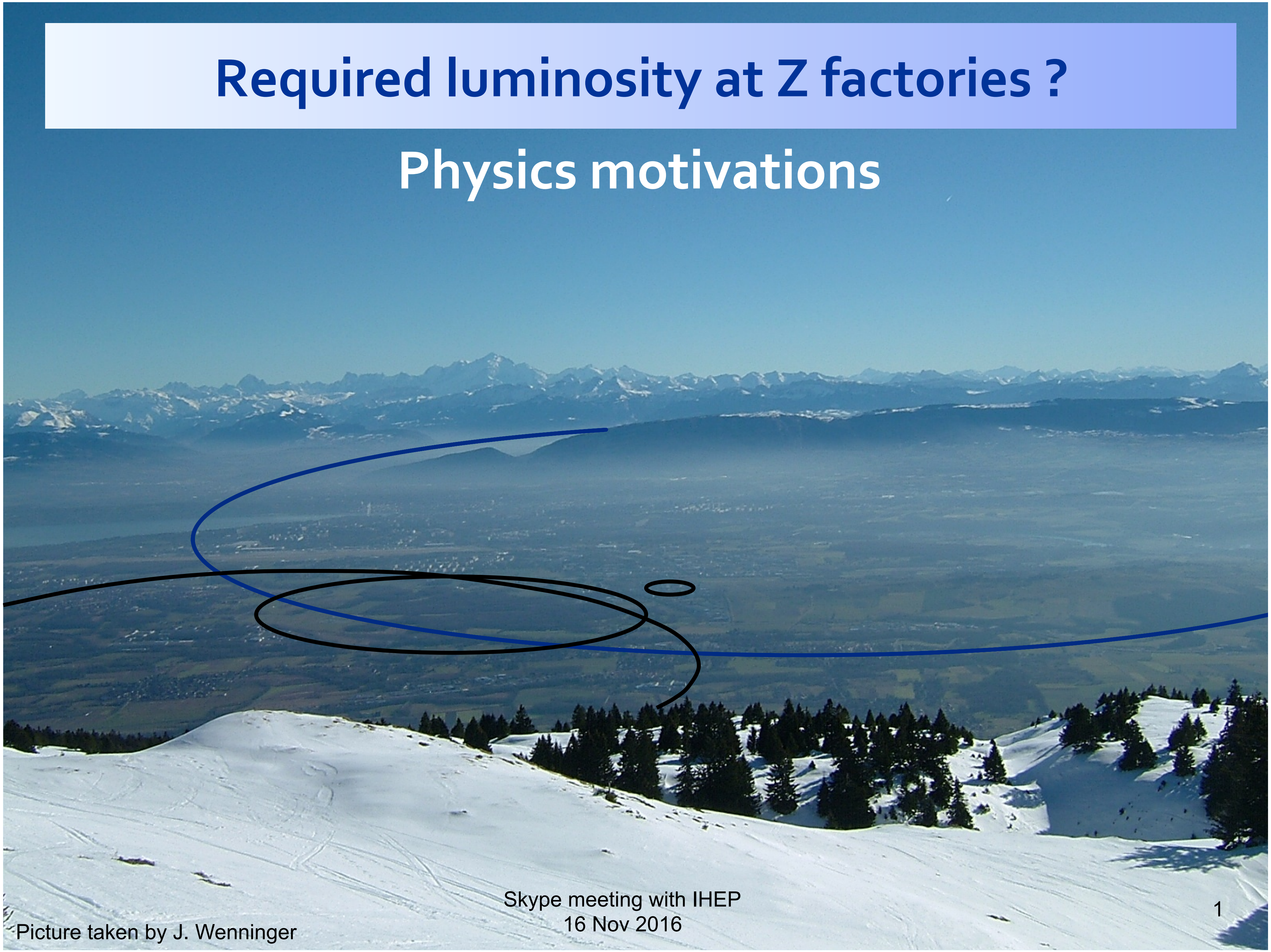
Required luminosity at Z factories ?

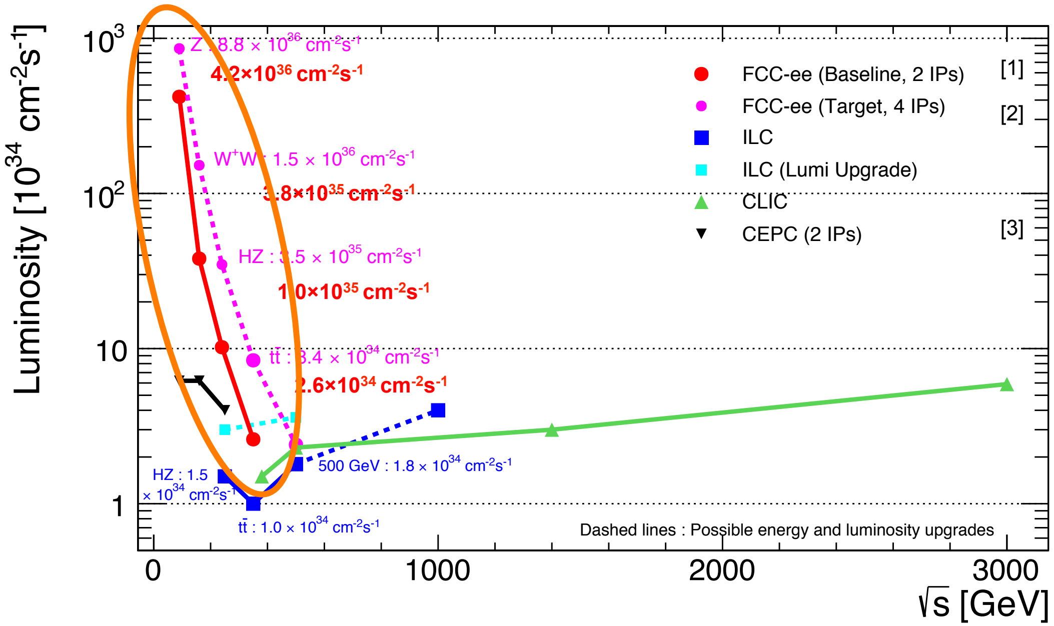
Physics motivations



Picture taken by J. Wenninger

FCC-ee luminosity and running scenario

- **Expected luminosities**



2 x 10^{36} cm^{-2}s^{-1} / IP at the Z pole

[1] Conservative baseline, FCC week in Rome (2016)
[2] Ultimate target, FCC week in Washington (2015)
[3] Proceedings of IPAC 2016

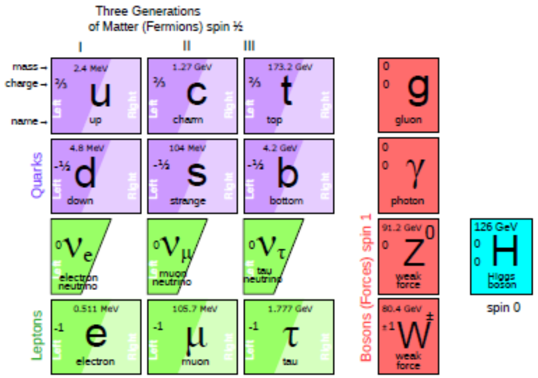
- **Running plan: 160 days of physics / year, availability 65%, 2 or 4 experiments**

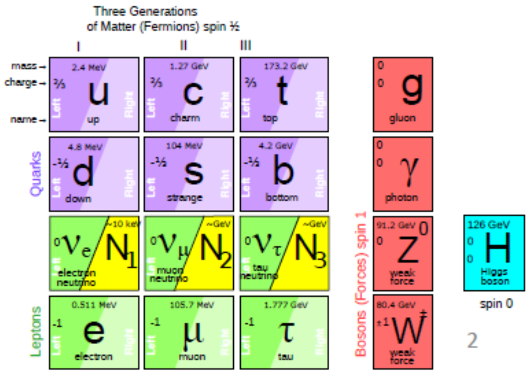
Mode	Lumi / year	# years	# events	Lumi / IP
Z (88-94)	40-80 ab^{-1}	3-5	Up to 10^{13} Z	2 × 10^{36} cm^{-2}s^{-1}
WW (161)	4-15 ab^{-1}	1-2	Up to 10^8 WW	2-4 × 10^{35} cm^{-2}s^{-1}
HZ (240)	1-3.5 ab^{-1}	3-5	1-2 × 10^6 HZ	5-10 × 10^{34} cm^{-2}s^{-1}
$t\bar{t}$ (350-370)	0.25-1 ab^{-1}	3-5	1-2 × 10^6 $t\bar{t}$	1-2 × 10^{34} cm^{-2}s^{-1}

Why so high luminosity ?

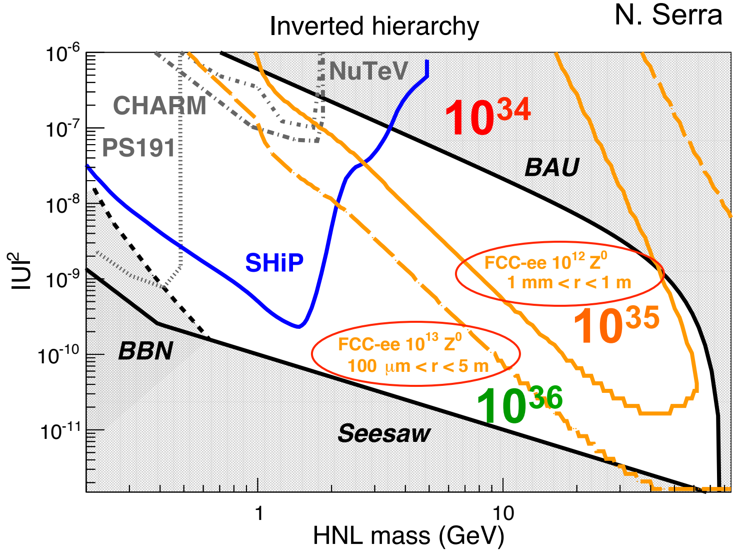
- **Because it is possible**
  - No physicist will ever complain that the luminosity is too high
    - Pile-up is not a concern: less than one γγ collision every 300 bunch crossings

- **Sensitivity to very rare processes increases with statistics**
  - Example: Very weakly coupled right-handed neutrinos
    - Good dark matter candidate





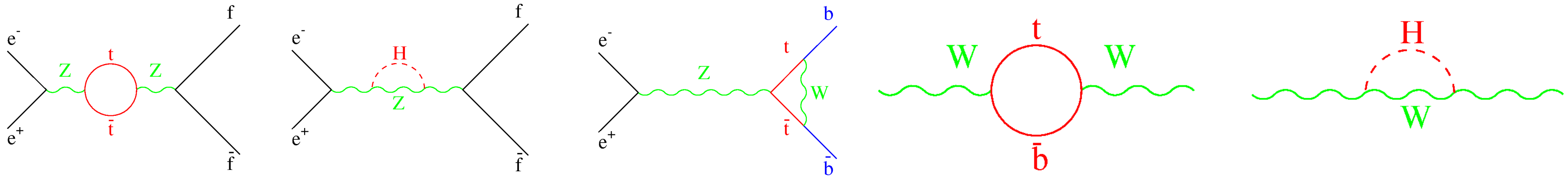
The νMSM, M. Shaposhnickov



  - ➨ Almost blind with 10^{34}
  - ➨ Most of the relevant parameter space covered with 10^{36}
- Many other examples can be cited (LFV, FCNC, Flavours, …)

Why so high luminosity ? (cont'd)

- Electroweak observables sensitive to heavy particles in "loops"
  - The more precise their measurement, the heavier particles tested
    - Statistics is one of the keys for that purpose
- For example, in the standard model



- Without a top quark and a Higgs boson

$$\Gamma_{ll} = \frac{G_F}{\sqrt{2}} \frac{m_Z^3}{24\pi} \left(1 + \left[\frac{1}{4} - \sin^2 \theta_W^{eff} \right]^2 \right)$$

$$m_W^2 = \frac{\pi \alpha_{QED} \left(m_Z^2 \right)}{\sqrt{2} G_F \sin^2 \theta_W^{eff}}$$

In the Standard Model

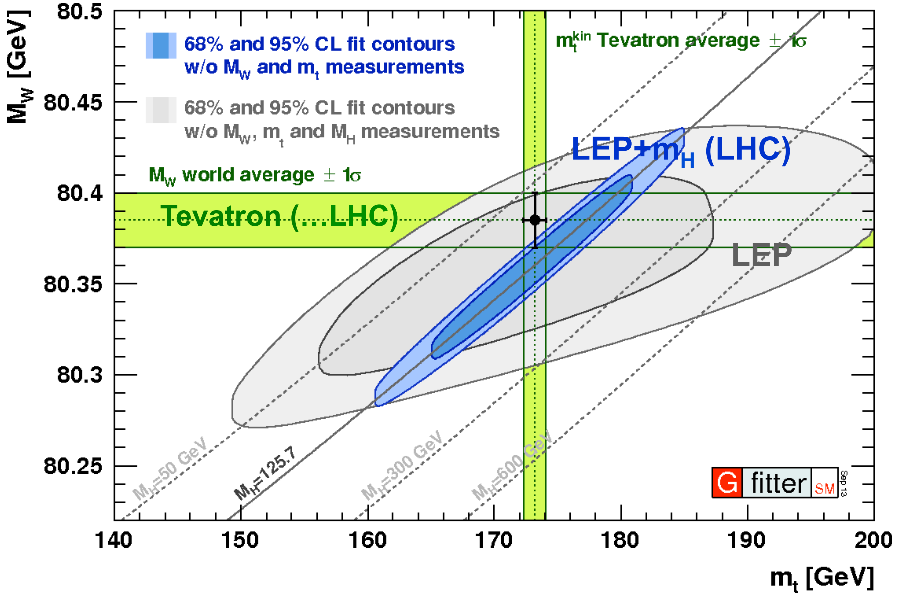
$$\times (1 + \Delta\rho), \text{ with } \Delta\rho = \frac{\alpha}{\pi} \frac{m_t^2}{m_Z^2} - \frac{\alpha}{4\pi} \mathrm{Log} \frac{m_H^2}{m_Z^2} + \cdots \approx 1\%$$

$$\times \frac{1}{1 - \Delta r}, \text{ with } \Delta r = -\frac{\cos^2 \vartheta_W}{\sin^2 \vartheta_W} \Delta\rho + \frac{\alpha}{3\pi} \left[\frac{1}{2} - \frac{1}{3} \frac{\sin^2 \vartheta_W}{1 - \tan^2 \vartheta_W} \right] \mathrm{Log} \frac{m_H^2}{m_Z^2} + \cdots \approx 1\%$$

- With m_{top} & m_W directly measured with precision
  - And accurate measurements of m_Z, m_H, $\alpha_{QED}(m_Z^2)$ and $\sin^2\theta_W^{eff}$ to predict m_{top} & m_W
    - The standard model has nowhere to go
      - ➨ Precision measurements become sensitive to other particles in the loops

Example: the W mass

- **Current status**



Direct measurement

$$M_W = 80.385 \pm 0.015 \text{ GeV}$$

Prediction from precision measurements

$$\begin{aligned} M_W &= (80.3593 \pm 0.0056_{m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\rm had}} \\ &\qquad \pm 0.0017_{\alpha_S} \pm 0.0002_{M_H} \pm 0.0040_{\rm theo})\ \text{GeV}, \\ &= (80.359 \pm 0.011_{\rm tot})\ \text{GeV}, \end{aligned}$$

Baak, Kogler, arXiv:1306:0571

Prediction more precise than direct measurement

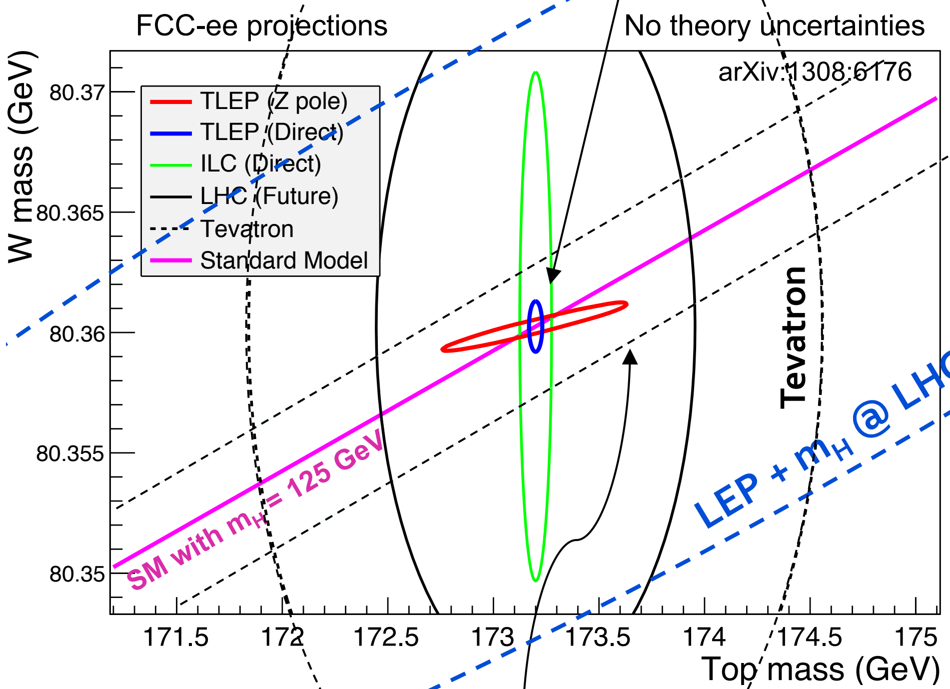
Requires polarization at the WW threshold (i.e., a large ring)

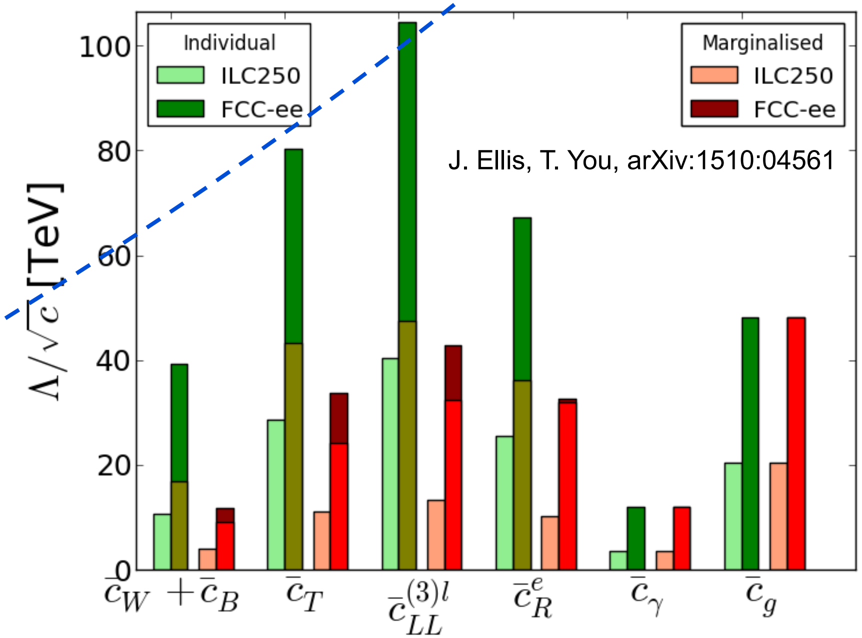
- **At the FCC-ee, direct measurement precision < 0.0005 GeV**
  - All precision measurements (esp. at the Z pole) need to be improved accordingly
    - Together with theoretical calculations (higher orders missing today)
      - Run at 350 GeV: improve m_{top} precision by a factor 25 → 0.0002 GeV — Large ring
      - Polarization at the Z pole: improve m_Z by a factor 25 → 0.0001 GeV — Many bunches
      - 4 years at 10^{36} cm^{-2}s^{-1}: improve α_{QED} by a factor 4 → 0.0004 GeV (P.J., arXiv:1512:05544) — 10^{36}
      - 2 years at 10^{36} cm^{-2}s^{-1}: improve α_s by a factor 10 → 0.0002 GeV (arXiv:1308:3176)

Sensitivity to new physics

- **Combining all measurements**
  - **In the context of the SM ... and beyond**

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$





After FCC-ee: Λ_{NP} > 100 TeV ?

Without m_Z (α_{QED})@FCC-ee, the SM line would have a 2.6 (1.7) MeV width
FCC-ee sensitivity severely drops without POLARIZATION + STATISTICS (and improved theory calculations) →

Need 10^{36} cm^{-2}s^{-1} and a large ring

In green: one operator at a time
In red: all operators together
ILC sensitivity vanishes w/o Z and WW runs

Summary

- **If the next e^+e^- collider is able to**
  - Measure the top mass to ~30 MeV
  - Measure the W mass to 0.5 MeV
    - Which both require a large ring
      - ➨ Transverse polarization at the WW threshold
      - ➨ Centre-of-mass energy up to 350 GeV

- **It must be complemented with**
  - A large statistics run at the Z (> 10^{36} $cm^{-2}s^{-1}$) (→ large ring)
  - Order-of-magnitude improvement in theory predictions
    - To be able to predict the W mass to 0.5 MeV (in particular) as well
      - ➨ And reap the benefits in sensitivity to new physics

- **This run also has unique capabilities for direct new physics discoveries**

- **This is what the FCC-ee design is aiming at, altogether**
  - If one ingredient is missing, the sensitivity to new physics drastically reduces