Experimental Physics at Lepton Colliders

CERN Summer Student Lecture, 2019

Lecture 2

Mogens Dam

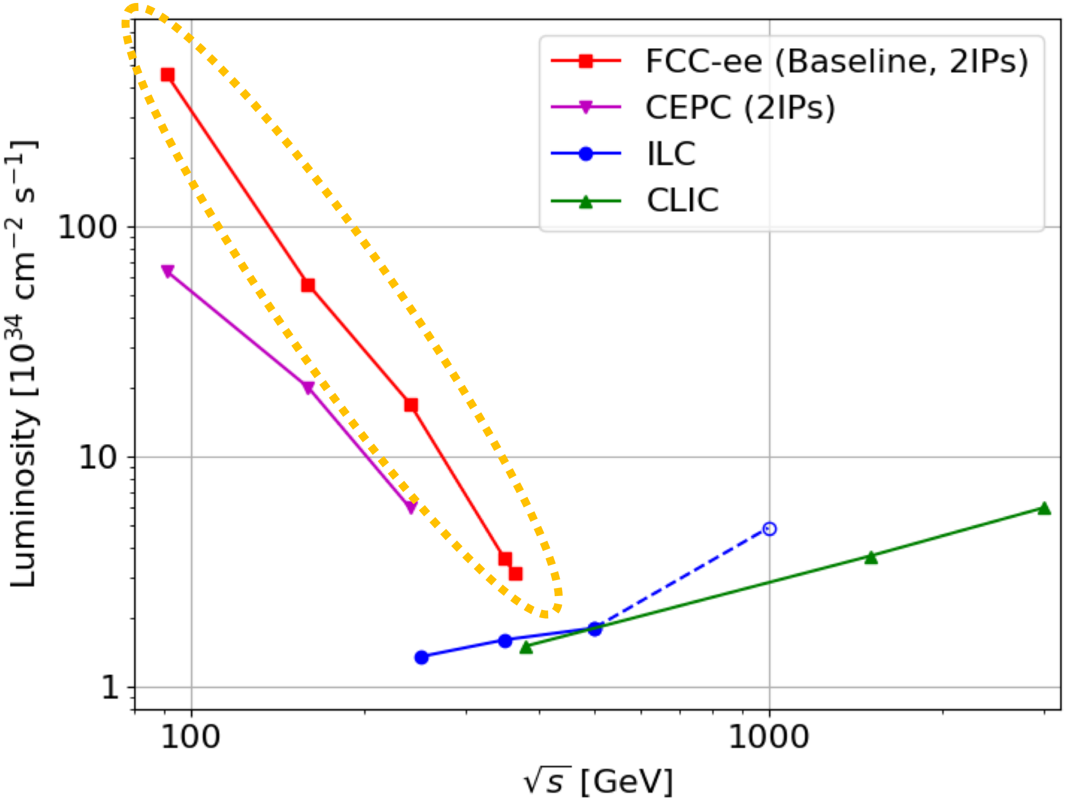
Niels Bohr Institute, Copenhagen

Physics at Lepton Colliders

- Lecture 1 (Wednesday 31 July, 9:15)
  - ☐ Introduction: Why Lepton Colliders ?
  - ☐ Where we stand: Status of the Standard Model
  - ☐ An experimental strategy for the future: e^+e^- colliders
  - ☐ Precision Higgs Physics

- Lecture 2 (Thursday 1 August, 10:25)
  - ☐ Electroweak Precision Physics: FCC-ee
  - ☐ GigaZ physics: Flavour Physics and Direct Discoveries
  - ☐ High Energy e^+e^- Physics: CLIC
  - ☐ Instrumentation: Detectors for e^+e^- physics
  - ☐ Thinking out of the box: Muon colliders
  - ☐ Rounding off: Summary and Conclusions

Electroweak Precision Physics
FCC-ee



FCC-ee Goals in Numbers

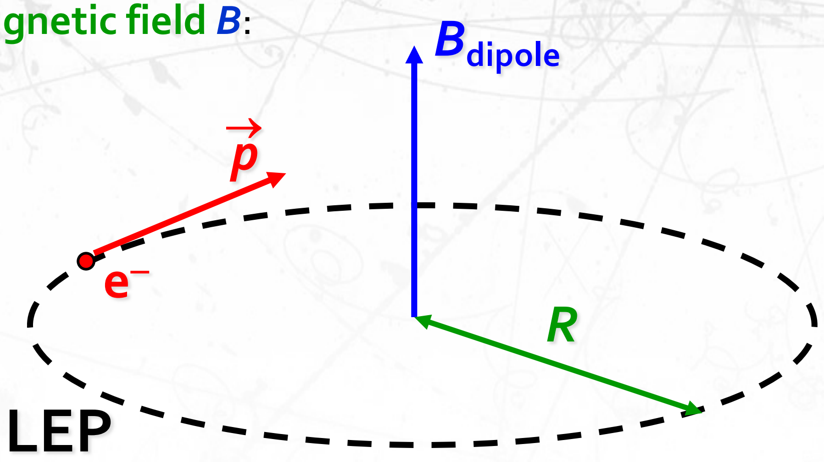
Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$ threshold…	… and above
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340 – 350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	100	200	25	7	0.8	1.4
Lumi/year (2 IP)	24 ab^{-1}	48 ab^{-1}	6 ab^{-1}	1.7 ab^{-1}	0.2 ab^{-1}	0.34 ab^{-1}
Physics goal	150 ab^{-1}		10 ab^{-1}	5 ab^{-1}	0.2 ab^{-1}	1.5 ab^{-1}
# events	5×10^{12} Z		10^{8} WW	10^{6} HZ	10^{6} $t\bar{t}$	45000 WW→H
Run time (years)	2	2	2	3	1	4

- FCC-ee is the ultimate Z, W, Higgs and top factory
  - 10^5 times more Zs and 10^3 times more Ws than LEP1 and LEP2
    - Potential statistical accuracies are mind-boggling !
- Predicting accuracies with 200 times smaller statistical precision than at LEP is hard
  - Conservatively, use LEP experience for systematics
- Example: The uncertainty on E_{BEAM} (2 MeV) was the dominant uncertainty on m_Z, Γ_Z
  - Can we do significantly better at FCC-ee ?

FCC-ee Precsion Physics: Beam Energy (1)

- **Measurement of the beam energy at LEP**
  - Ultra-precise measurement crucial for m_Z, Γ_Z, ...
  - Unique to circular colliders

Electron with momentum *p* in a uniform vertical magnetic field *B*:



L = 2πR = 27km

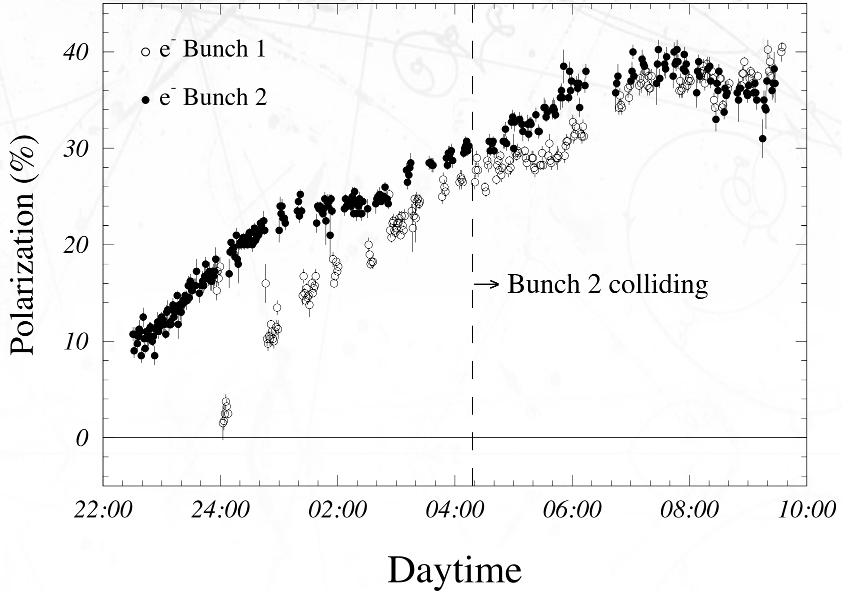
$$E \sim p = e\,B\,R = (e/2\pi)\,B\,L$$

In real life, *B* non-uniform, LEP ring not circular

$$\boxed{E = \frac{e}{2\pi} \oint_{\mathrm{LEP}} B\,\mathrm{d}l}$$

To be measured

The electrons get transversally polarized (i.e., their spin tends to align with *B*)



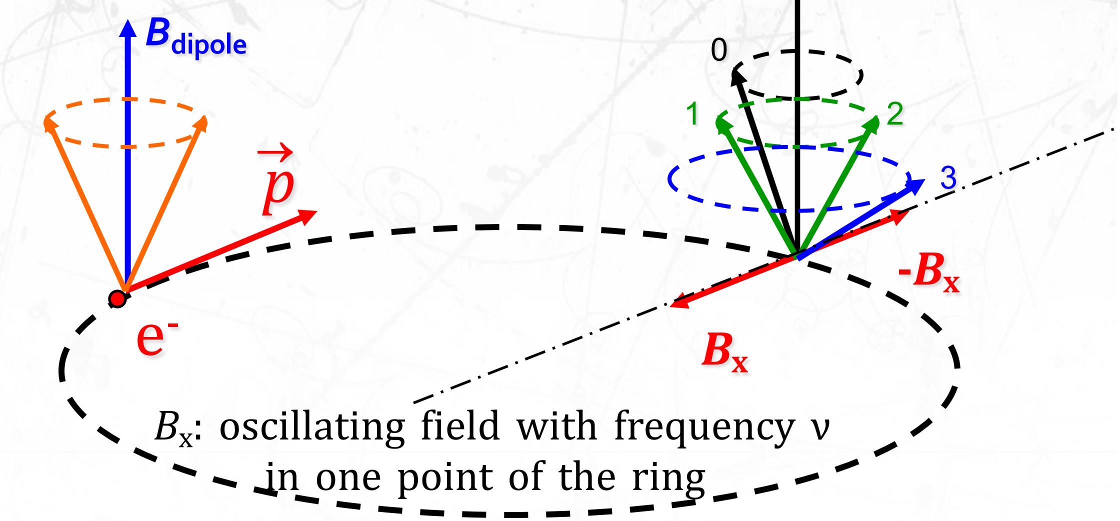
Slow process (~ 1 hour to get 10% polarization)

NB. Polarization can be kept in collision (was attempted only once at LEP).

FCC-ee Precision Physics: Beam Energy (2)

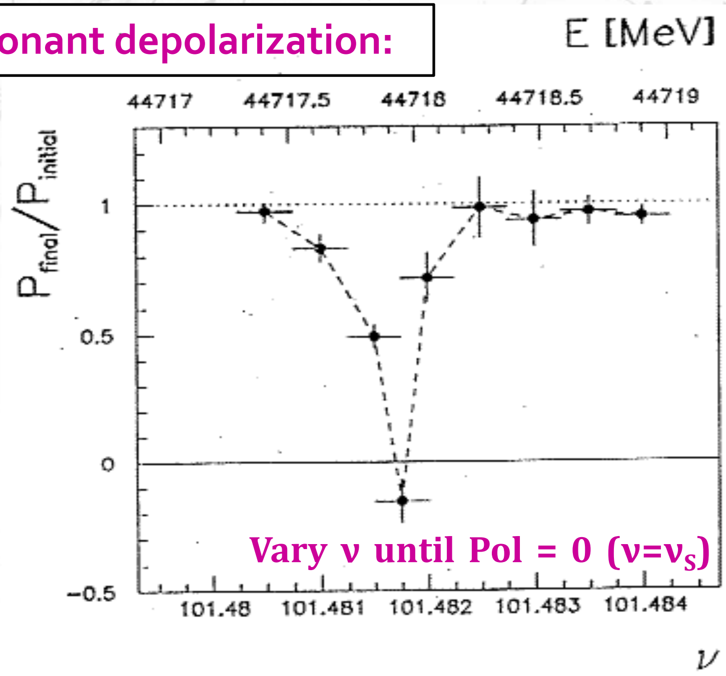
- **Measurement of the beam energy at LEP (cont'd)**
  - The spin precesses around *B* with a frequency proportional to *B* (Larmor precession)
    - Hence, the precession frequency ν_S for each LEP turn is proportional to $\int B dl$

$$\nu_s = \frac{g_e - 2}{2m_e} \times E_{\text{beam}}$$



B_x: oscillating field with frequency ν in one point of the ring

Resonant depolarization:

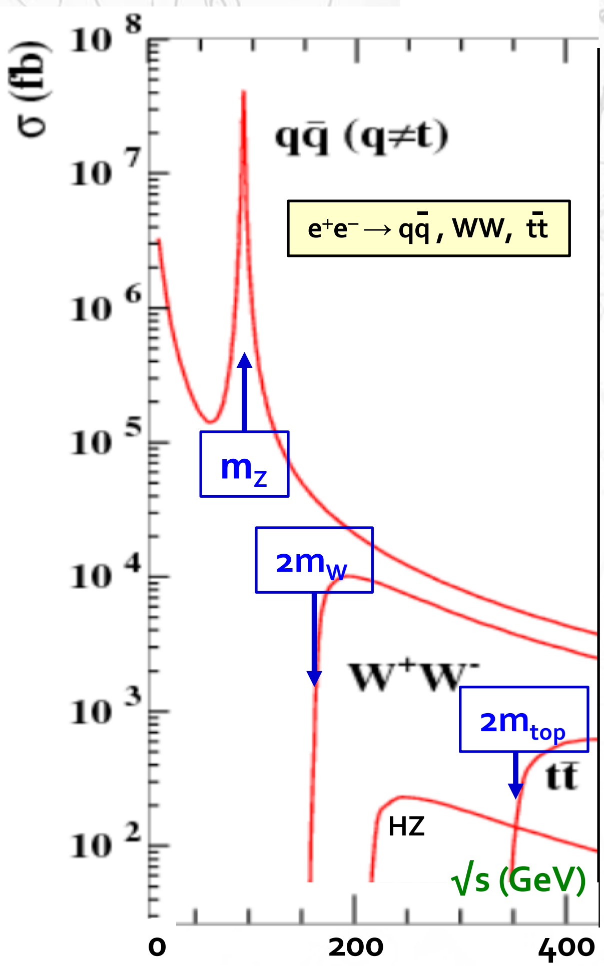


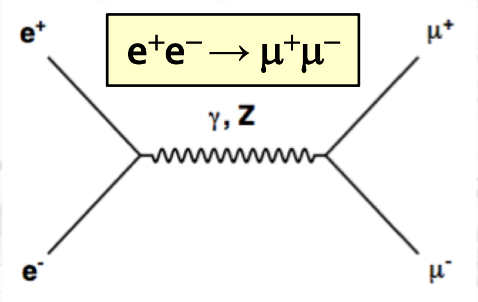
Vary ν until Pol = 0 ($\nu = \nu_S$)

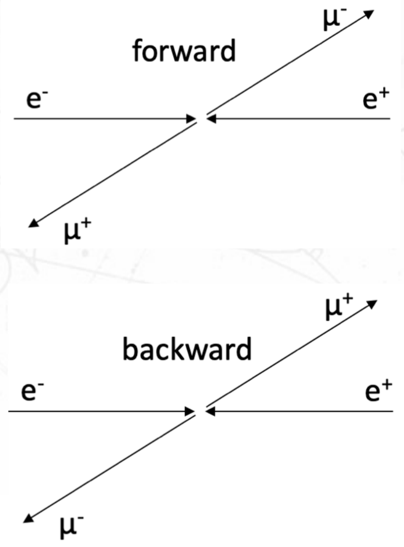
- LEP was colliding 4 bunches of e^+ and e^-; FCC-ee will have 1,000's of bunches
  - Use ~10 "single" bunches to measure E_{BEAM} with resonant depolarization
    - Each measurement gives 100 keV precision, with no extrapolation uncertainty

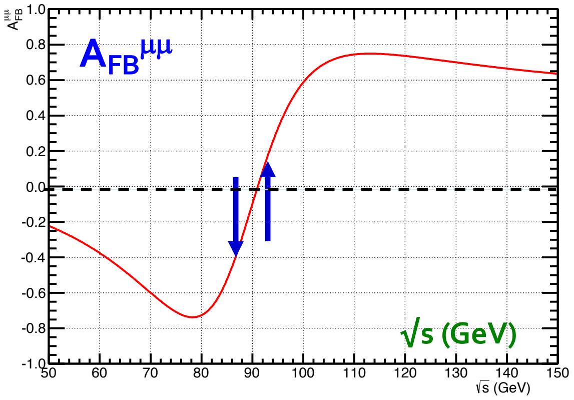
FCC-ee Precision EW Physics Measurements (1)

- Boils down to measuring cross sections and asymmetries









$$A_{FB}^{\mu\mu} = \frac{N_F^{\mu+} - N_B^{\mu+}}{N_F^{\mu+} + N_B^{\mu+}} \approx f(\sin^2\vartheta_W^{eff}) + \alpha_{QED}(s)\frac{s - m_Z^2}{2s} g(\sin^2\vartheta_W^{eff})$$

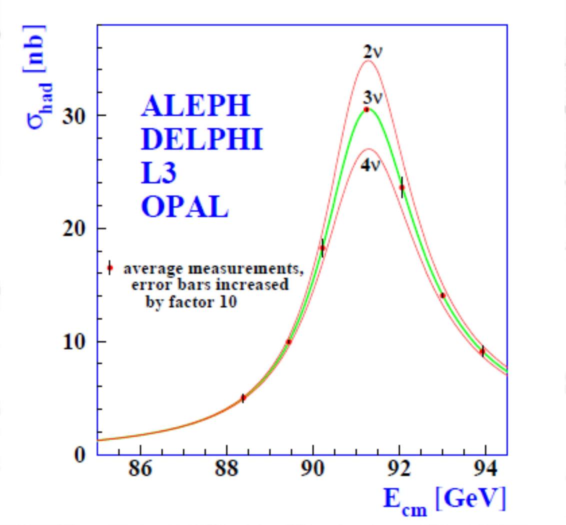
- Measure $\sin^2\theta_W$ with A_{FB} at $\sqrt{s} = m_Z$
- Measure $\alpha_{QED}(m_Z)$ with A_{FB} at $\sqrt{s}$ = 87.9 and 94.3 GeV

- ☐ The dominant experimental uncertainties (still!) come from the beam energy knowledge

FCC-ee Precision EW Physics Measurements (2)

- EW precision measurements at FCC-ee (see arXiv:1308.6176 and CDR)

Z reconance: TeraZ



Lineshape

- Exquisite E_{beam} (unique!)
- m_Z, Γ_Z to < 100 keV (2.2 MeV)

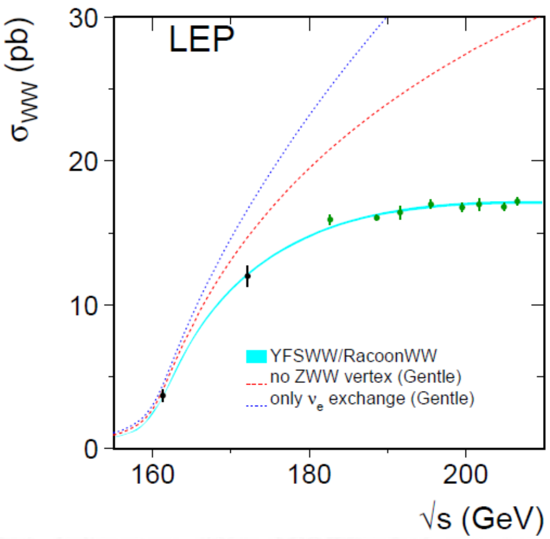
Asymmetries

- $\sin^2\theta_W$ to 6×10^{-6} (1.6×10^{-4})
- $\alpha_{QED}(m_Z)$ to 3×10^{-5} (1.5×10^{-4})

Branching ratios R_l, R_b

- $\alpha_S(m_Z)$ to 0.0002 (0.002)

WW threshold scan: OkuW



Threshold scan

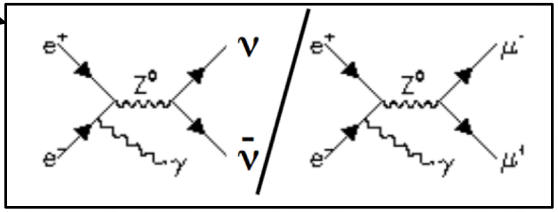
- m_W to 0.6 MeV (12 MeV)

Branching ratios R_l, R_b

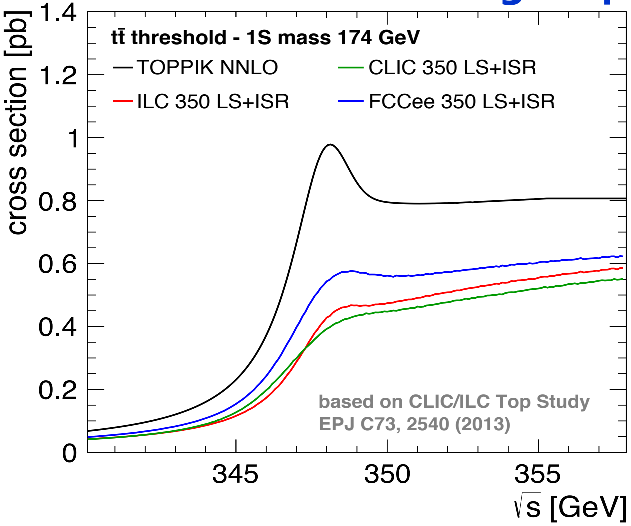
- $\alpha_S(m_W)$ to 0.0002

Radiative return $e^+e^- \rightarrow Z\gamma$

- N_ν to 0.001 (0.008)



$t\bar{t}$ threshold scan: MegaTop

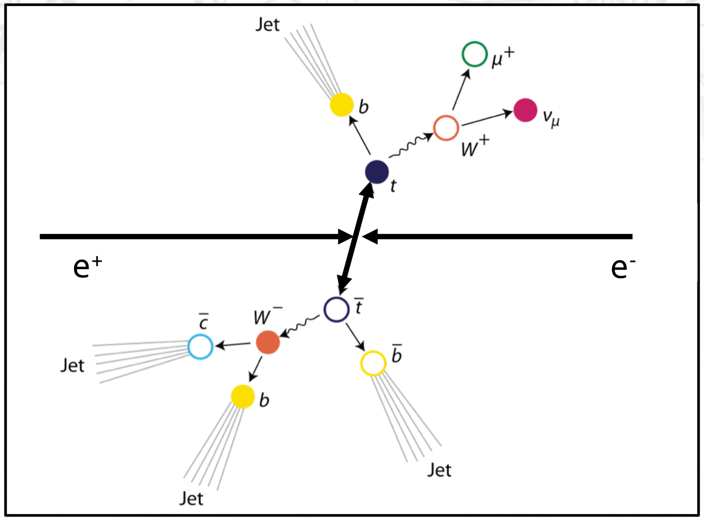


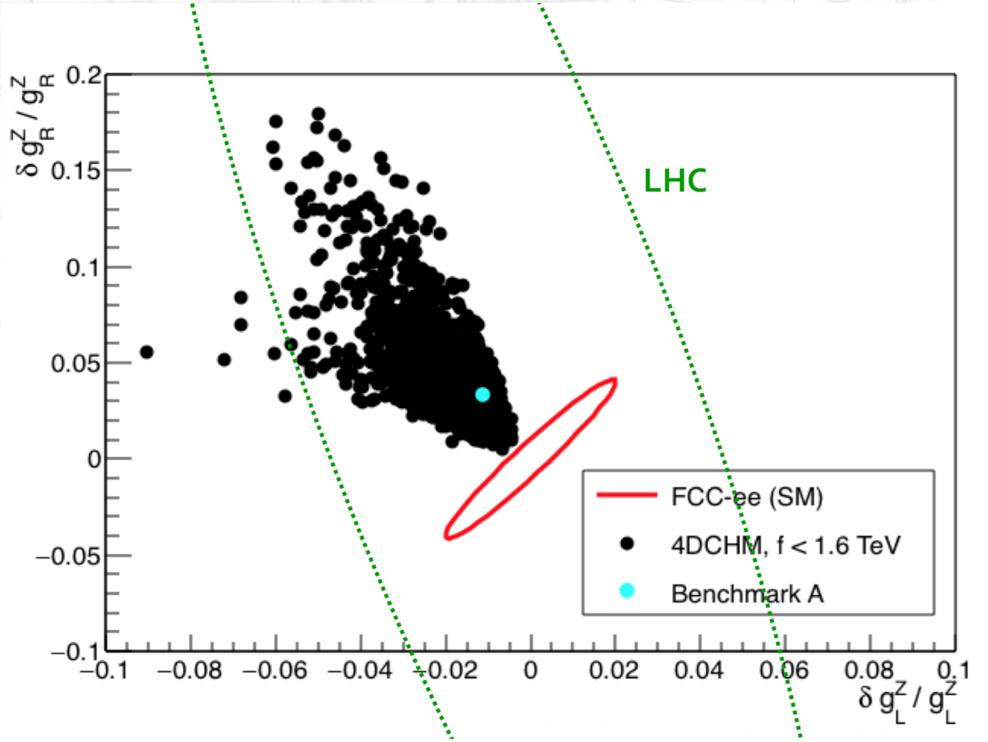
Threshold scan

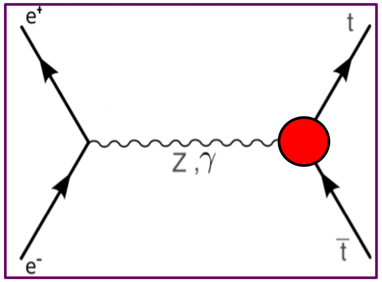
- m_{top} to 20 MeV (500 MeV)
- λ_{top} to 10%
- EW couplings to 2%

FCC-ee Precision EW Physics Measurements (3)

- Measurements of t_Lt_LZ and t_Rt_RZ couplings, g_L and g_R
  - At FCC-ee@365 GeV, couplings extracted from “top polarization measurement”: Leptons and b-jet distributions
  - Couplings sensitive to, e.g., composite Higgs models





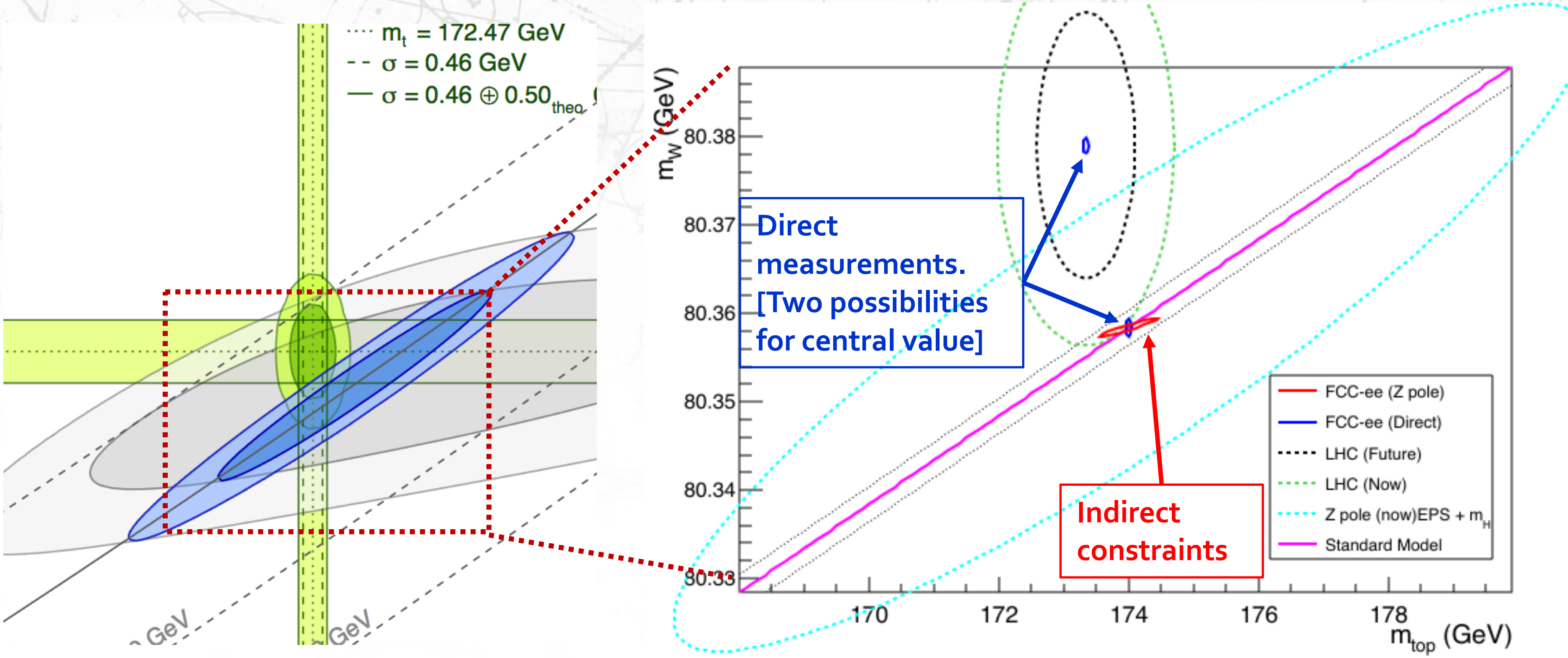


FCC-ee EW Measurements: Summary of Precisions

Observable	Measurement	Current precision	FCC-ee **stat.**	**FCC-ee syst.**	Challenge	
m_Z (keV)	Z lineshape	91186700 ± **2200**	**5**	**100**	Beam energy calib	Z
Γ_Z (keV)	Z lineshape	2495200 ± **2300**	**8**	**100**	Beam energy calib	
R_l (×10³)	Ratio of hadrons to leptons	20767 ± **25**	**0.01**	**0.2−1**	Acceptance for leptons	
$\alpha_s(m_Z)$ (×10⁴)	From R_ℓ	1196 ± **30**	**0.1**	**0.4−1.6**	ditto	
R_b (×10⁶)	Ratio of bb to hadrons	216290 ± **660**	**0.3**	**< 60**	g → bb	
N_ν (×10³)	Peak hadronic cross section	2991 ± **7**	**0.005**	**< 1**	Lumi meast	
$\sin^2\theta_W^{eff}$ (×10⁶)	From $A_{FB}^{\mu\mu}$ at Z peak	231480 ± **160**	**3**	**2−5**	Beam energy calib	
$1/\alpha_{QED}(m_Z)$ (×10³)	From $A_{FB}^{\mu\mu}$ off-peak	128952 ± **14**	**4**	**small**	QED corr.	
$A_{FB}^{pol,\tau}$ (10⁴)	τ polarization charge assym	1498 ± **49**	**0.15**	**< 2**	τ decay physics	
m_W (MeV)	WW threshold scan	80385000 ± **15000**	**600**	**300**	Beam energy calib	WW
N_ν	$e^+e^-\to\gamma Z, Z\to\nu\nu, \ell\ell$	2.92 ± **0.05**	**0.001**	**< 0.001**	?	
$\alpha_s(m_W)$ (×10⁴)	From R_ℓ^W	1170 ± **420**	**3**	**small**	Lepton acceptance	
m_{top} (MeV)	tt threshold scan	172740 ± **500**	**20**	**small**	QCD corr	$t\bar{t}$
Γ_{top} (MeV)	tt threshold scan	1410± **190**	**40**	**small**	QCD corr	
$\lambda_{top} / \lambda_{top}^{SM}$	tt threshold scan	1.2 ± **0.3**	**0.08**	**small**	QCD corr	

Extremely Precise EW Consistency Checks

- Combination of all precision electroweak measurements
  - FCC-ee precision allows m_{top}, m_W, $\sin^2\theta_W$ to be predicted within the SM
    - … and to be compared to the direct measurements



Direct measurements. [Two possibilities for central value]

Indirect constraints

- New Physics ?
  - Direct meast (blue ellipse) and indirect constraints (red ellipse) may or may not overlap

SMEFT Fit to FCC-ee EW Measurements

- Higher-dimensional operators as a parametrization of new physics
  - Possible corrections to the Standard Model
    - Standard Model Effective Theories (SMEFT)

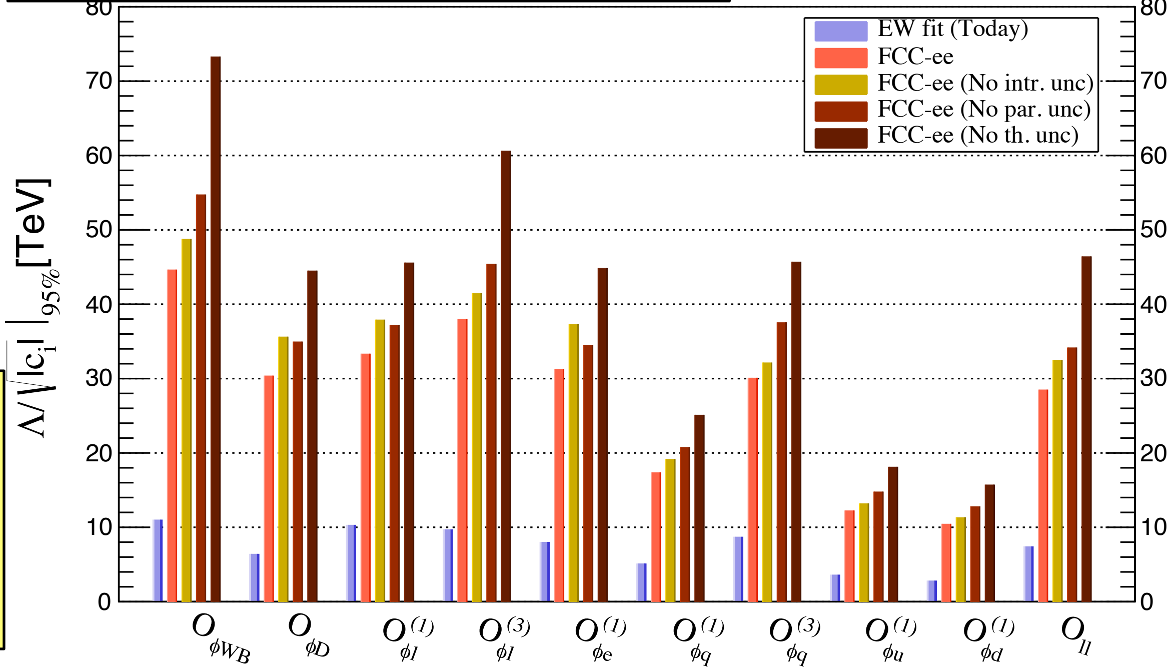
Standard Model

Dimension-6 operators

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

~scale of new decoupled physics

Electroweak precison measurements



Limits on new physics scale, **Λ**:

Today:
Λ > 4-10TeV

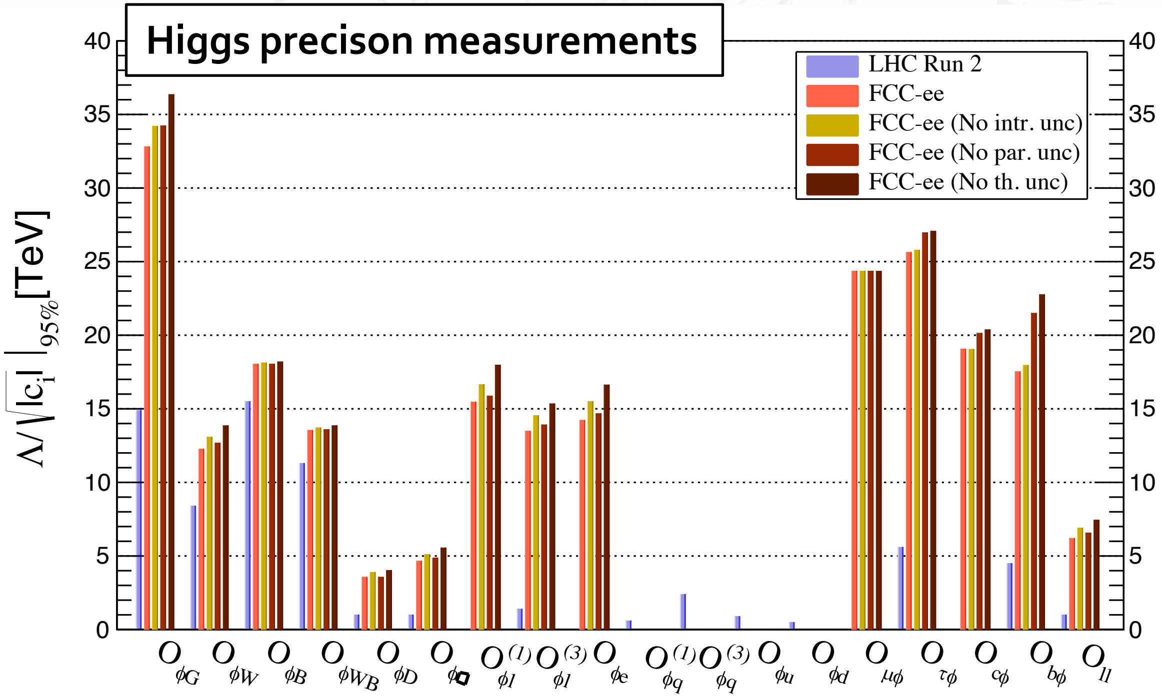
Sensitivity to new physics scale, **Λ**:

After FCC-ee:
Λ > 20-70 TeV

SMEFT Fit to FCC-ee Higgs Measurements

- **Interpret also precisely measured <u>Higgs couplings</u> (Lecture 1) in terms of higher-dimension operators**

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



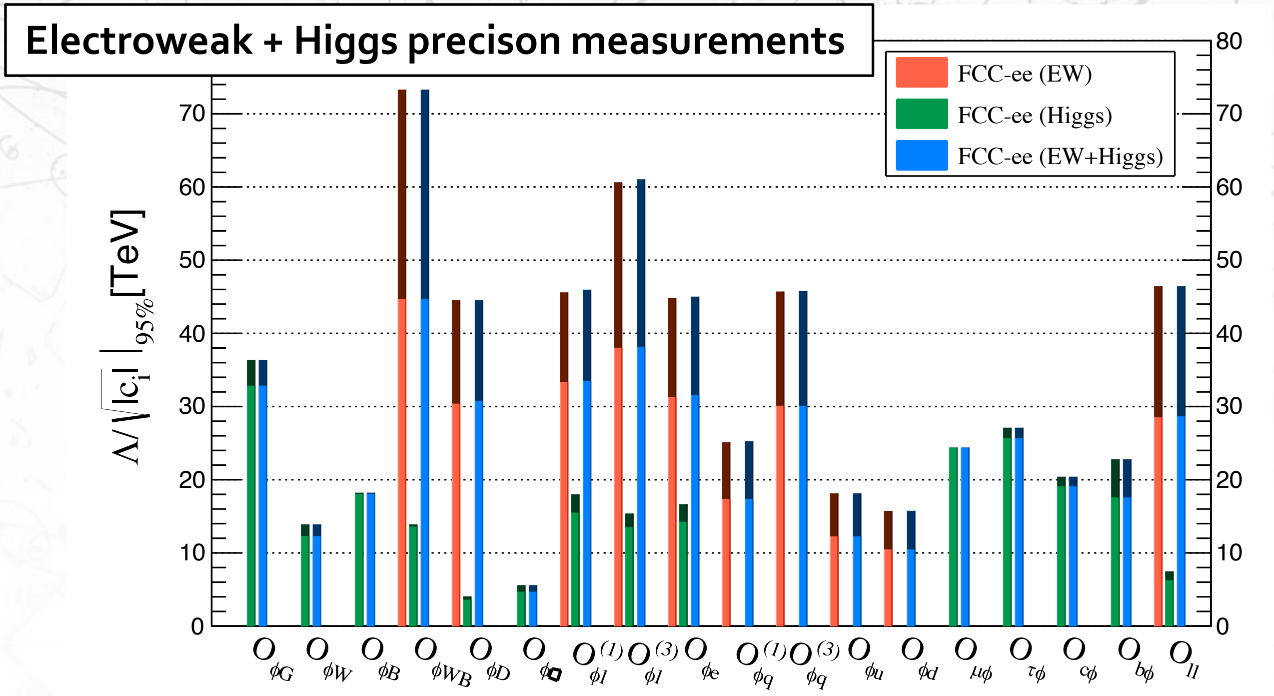
Limits on new physics scale, Λ:

Today:
Λ > 1-15 TeV

Sensitivity to new physics scale, Λ:
After FCC-ee:
Λ > 1-35 TeV

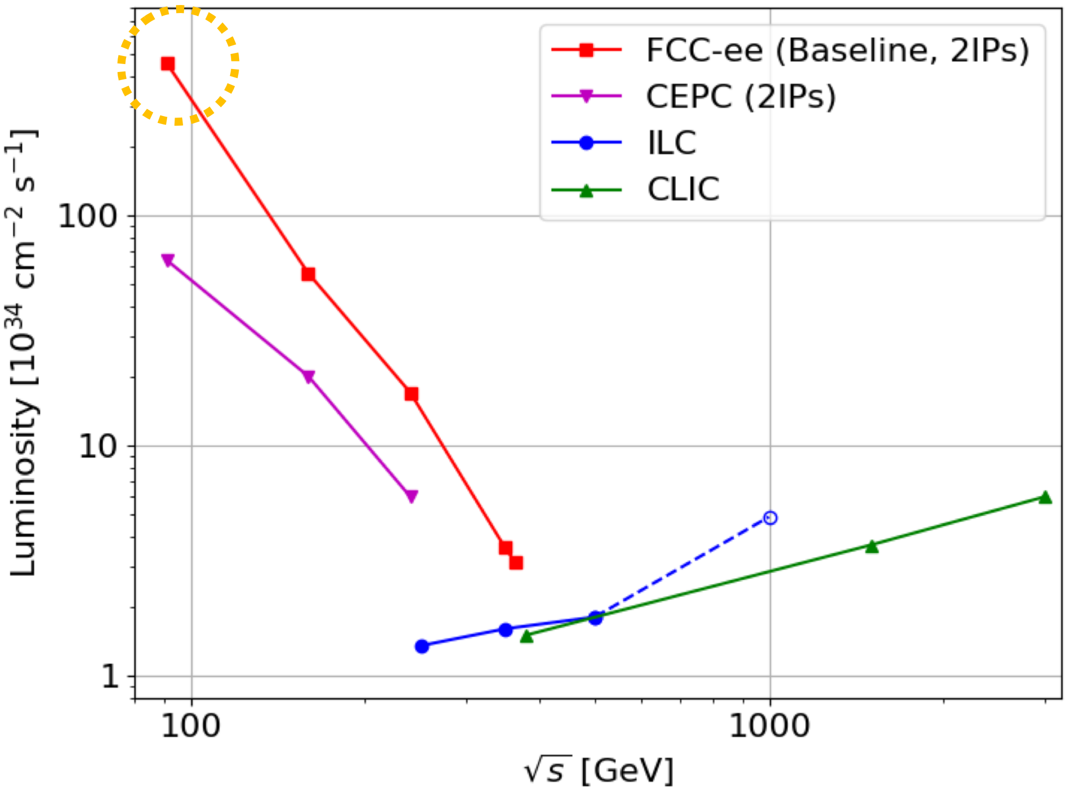
Combined FCC-ee SMEFT Fit

- Combine EW precision observables with precise Higgs coupling measurements via higher-dimensional operators



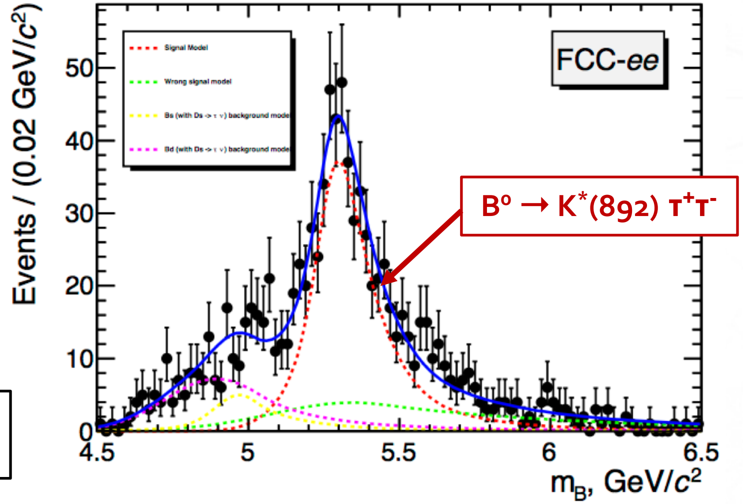
- The EW and Higgs measurements are highly complementary
  - Together they provide precise constraints on a large number of operators
  - Different New Physics models give different pattern of deviations from SM
    - Pattern provides fingerprint to differentiate among models

GigaZ Physics:
Flavour Physics and Direct Discoveries



Flavour Physics at FCC-ee

- 5×10^{12} Z decays: 10^{12} $b\bar{b}$ events, 1.7×10^{11} $\tau^+\tau^-$ events
  - FCC-ee is also the ultimate factory for the study of (heavy) flavours
    - lifetime, branching fractions, rare decays, test of Universality
- Example from b-physics:
  - Current tensions (several 2–3 σ deviations) of LHCb data with SM predictions
    - In particular, lepton flavour universality is challenged in $b \to s\,\ell^+\ell^-$ transitions
      - For example, the rates of B^0 $(B^+) \to K^{*0}$ (K^+) $\ell^+\ell^-$ are different for $\ell = e$ and $\ell = \mu$
      - Differences are also observed in the lepton angular distributions
    - This effect, if real, could be enhanced for $\ell = \tau$, in $B \to K^{(*)}\,\tau^+\tau^-$
      - With 10^{12} $Z \to bb$, FCC-ee is beyond any foreseeable competition
      - Decay can be fully reconstructed
      - Full angular analysis possible



J.F. Kamenik et al.
arXiv:1705.11106

τ physics

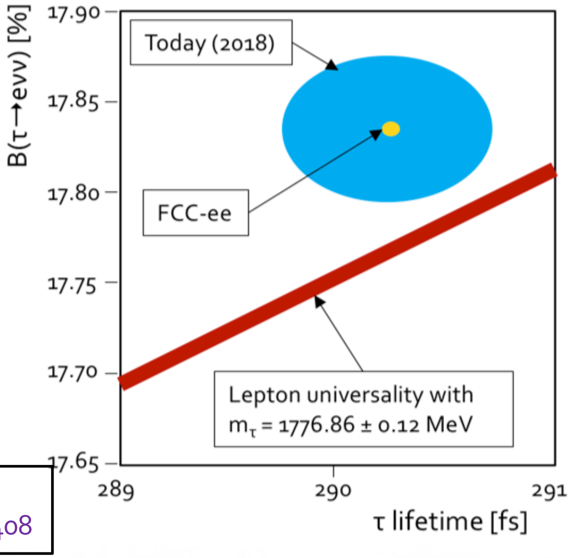
τ Properties and Universality

- τ branching fractions and lifetime provide strong test of Universality of the α–ν_α CC coupling, α = e, μ, τ
  - Sensitive to light-heavy neutrino mixing
  - Need also (more) precise mass measurement

Visible Z decays	3×10^{12}
$Z \to \tau^+\tau^-$	1.3×10^{11}
1 vs. 3 prongs	3.2×10^{10}
3 vs. 3 prong	2.8×10^{9}
1 vs. 5 prong	2.1×10^{8}
1 vs. 7 prong	< 67,000
1 vs 9 prong	?

Observable	Current precision	FCC-ee **stat.**	Possible syst.
m_τ [MeV]	1776.86 **± 0.12**	**0.004**	**0.1**
τ_τ [fs]	290.3 **± 0.5 fs**	**0.001**	**0.04**
B($\tau \to e\nu\nu$) [%]	17.82 **± 0.05**	**0.0001**	**0.003**
B($\tau \to \mu\nu\nu$) [%]	17.39 **± 0.05**		

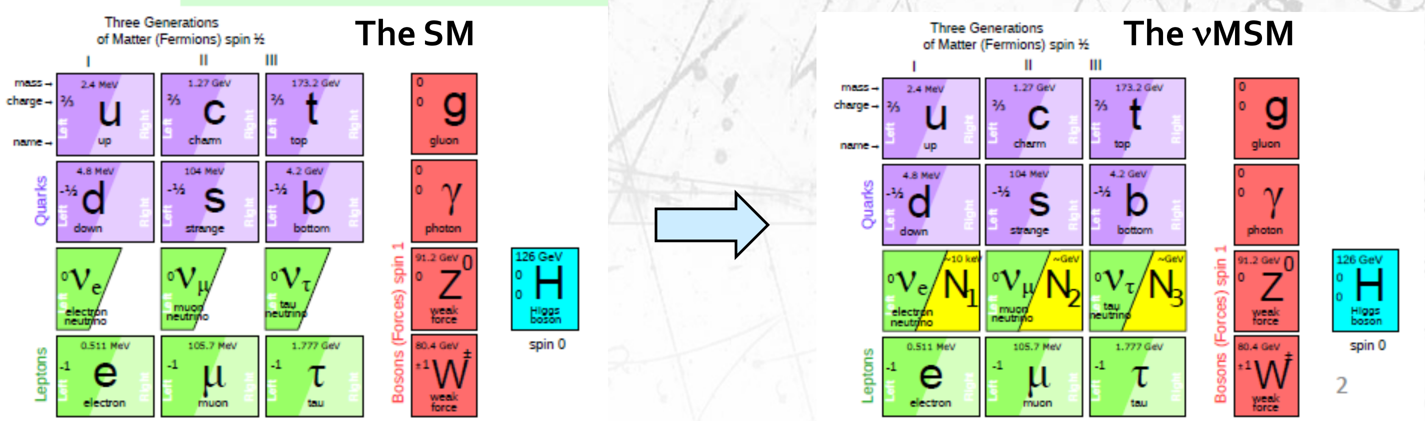
Quantity	Measurement	Current precision	FCC-ee precision
$\lvert g_\mu/g_e \rvert$	$\Gamma_{\tau\to\mu} / \Gamma_{\tau\to e}$	1.0018 **± 0.0014**	**Improvement by a factor 10 or more**
$\lvert g_\tau/g_\mu \rvert$	$\Gamma_{\tau\to e} / \Gamma_{\mu\to e}$	1.0030 **± 0.0015**	



M.Dam
arXiv:1811.09408

Direct discoveries from Z decays

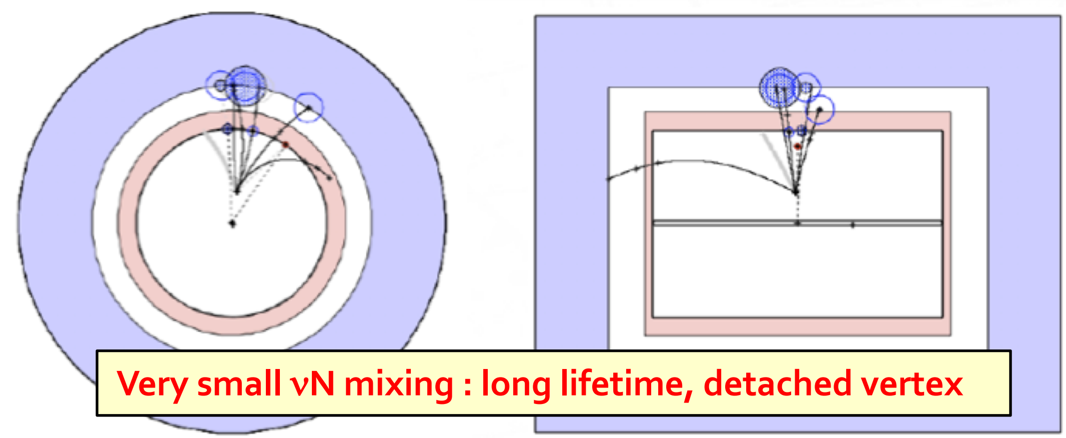
- **Discover right-handed neutrinos**
  - νMSM : Complete particle spectrum with the missing three right-handed neutrinos



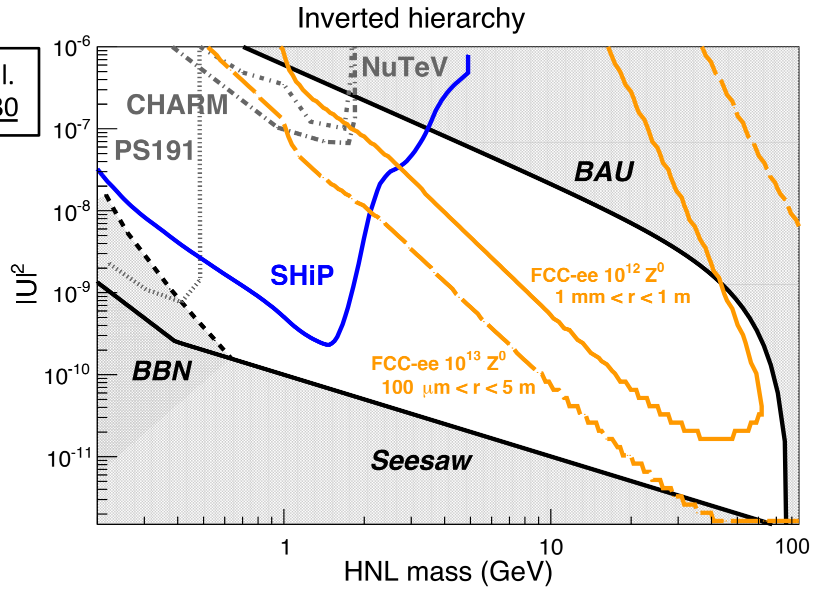
- Could explain everything: Dark matter (N_1), Baryon asymmetry, Neutrino masses

- Searched for in very rare Z → $\nu N_{2,3}$ decays
  - Followed by $N_{2,3}$ → $W^*\ell$ or $Z^*\nu$

A. Blondel et al.
arXiv:1411.5230

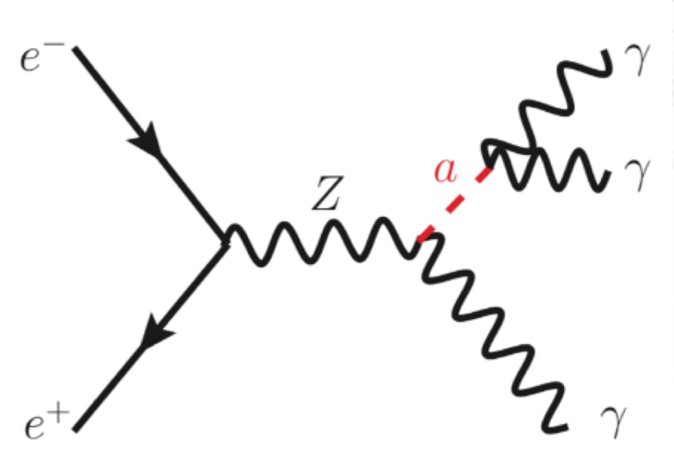


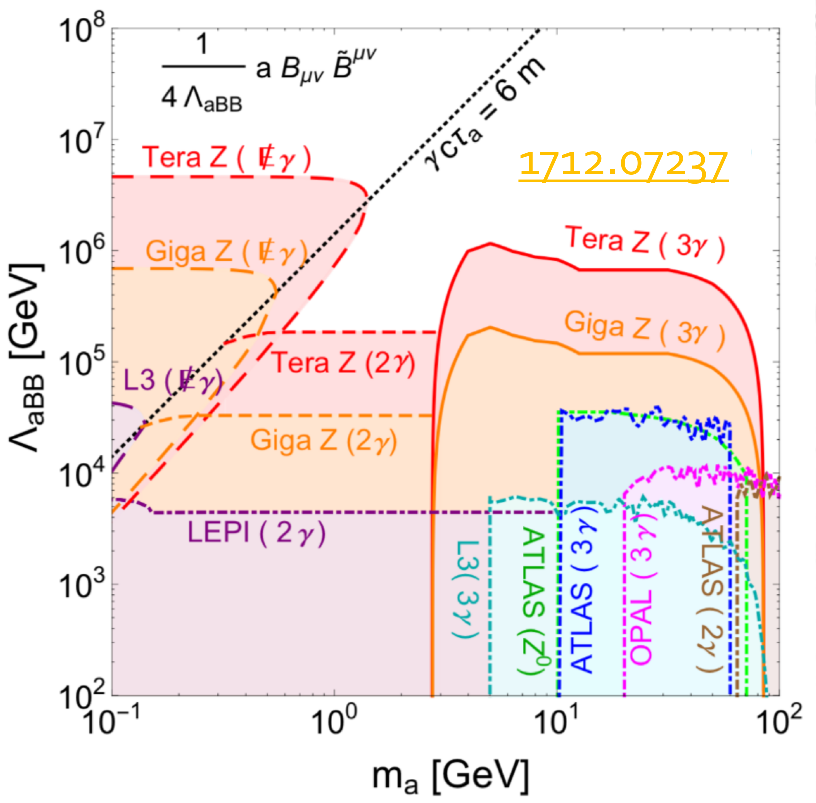
Very small νN mixing : long lifetime, detached vertex



Direct discoveries (cont'd)

- Discover the dark sector
  - A very-weakly-coupled window to the dark sector is through light "Axion-Like Particles" (ALPs)





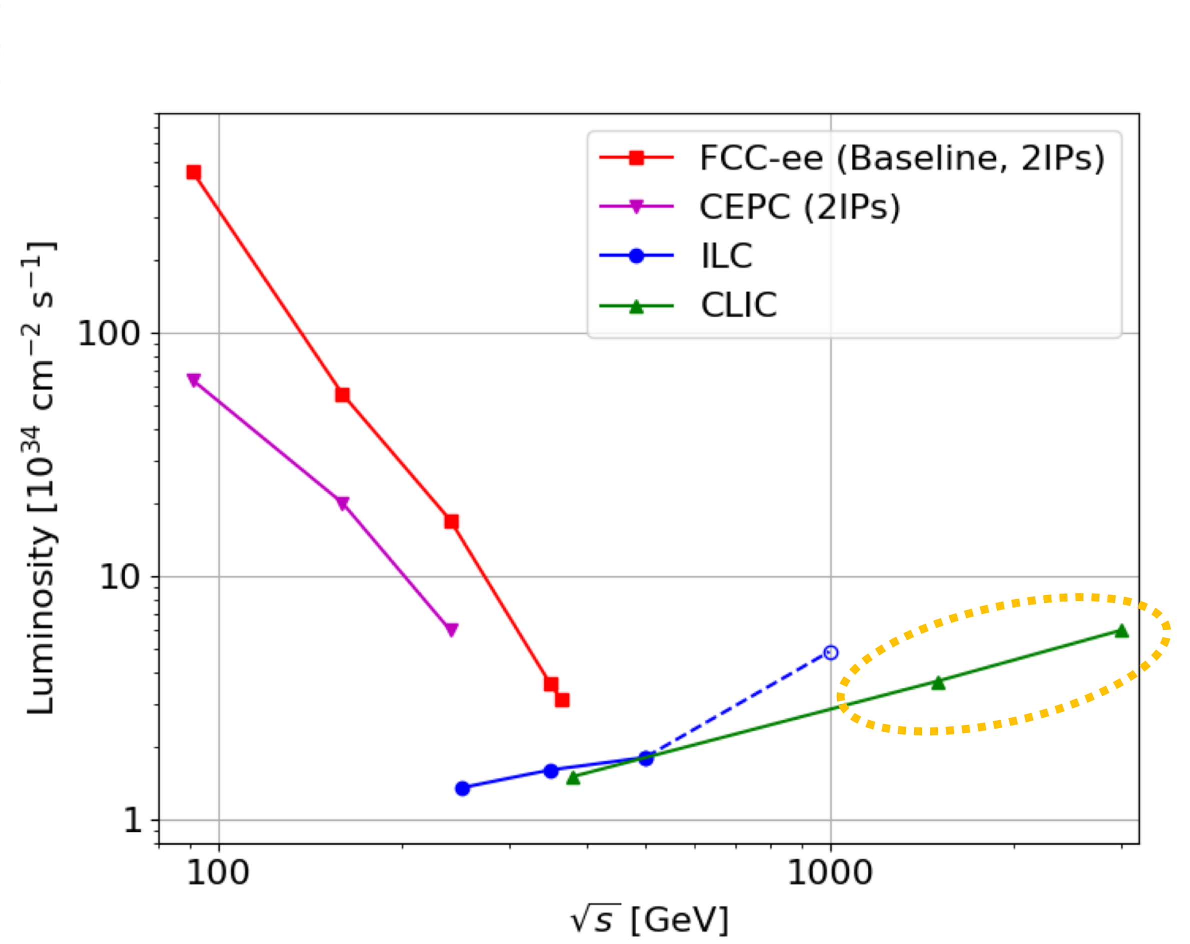
1712.07237

- $\gamma + E_{MISS}$ for very light a
- $\gamma\gamma$ for light a
- $\gamma\gamma\gamma$ for heavier a

- Orders of magnitude of parameter space accessible at FCC-ee

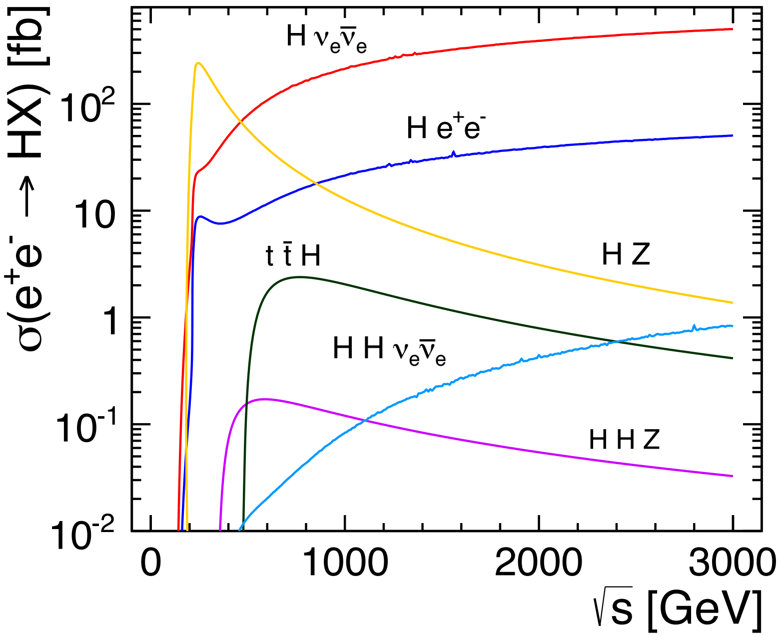
Lecture 2

High Energy e^+e^- Physics
CLIC



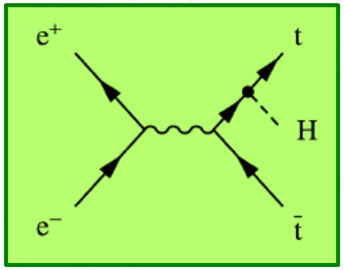
Precision: Higgs properties at high energy (1)

- Why do precision Higgs physics at high $\sqrt{s}$?
  - Precision achieved with e^+e^- colliders at $\sqrt{s}$=240-500 GeV : 0.1% - 1%
    - Superior to what can be done at higher energy
      - σ_{HZ} decreases, kinematics less favourable, backgrounds increase, …
- However …
  - Some production processes are not directly accessible at low-energy e^+e^- colliders
    - Hence more couplings might become measurable at larger energy
      - Htt, HHH, HHHH, …



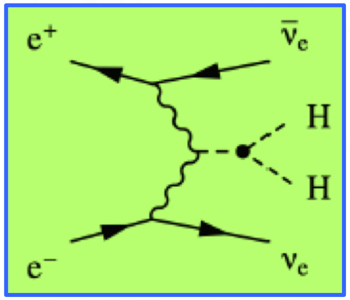
Htt

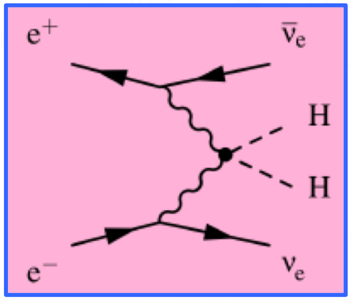
$\sqrt{s}$ > 500 GeV



HHH

$\sqrt{s}$ > 1 TeV





Background

Precision: Higgs properties at high energy (2)

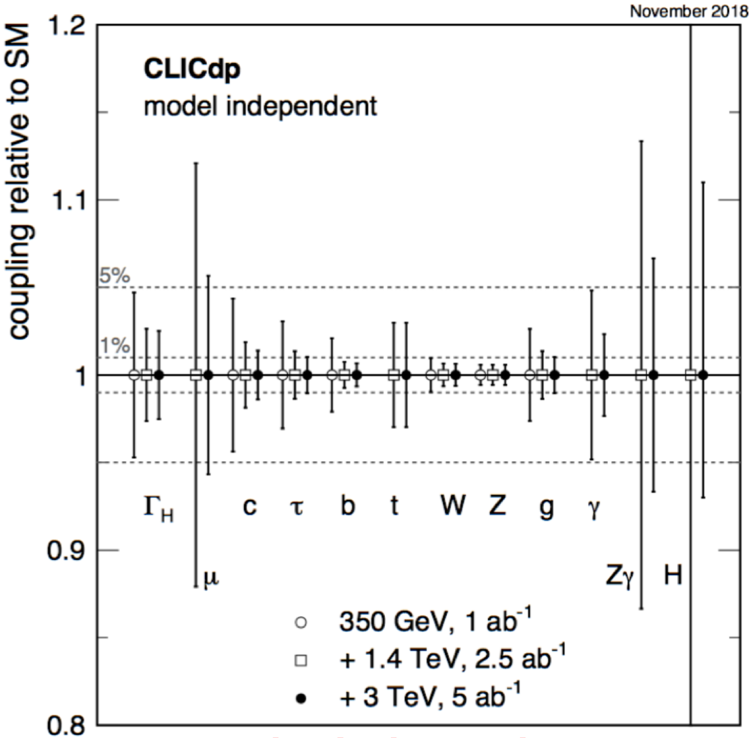
- Achievable precisions

Collider	HL-LHC	CLIC$_{3000}$	FCC-ee	FCC-ee+hh
$\Delta g_{Htt}/g_{Htt}$	3%	2.6%	10% (*)	1%
$\Delta g_{HHH}/g_{HHH}$	50%	$^{+11}_{-7}$ %	19%	5%

(*) indirect

- Combined CLIC Higgs results
  - ❑ 380 GeV; 1.5 TeV, 3.0 TeV

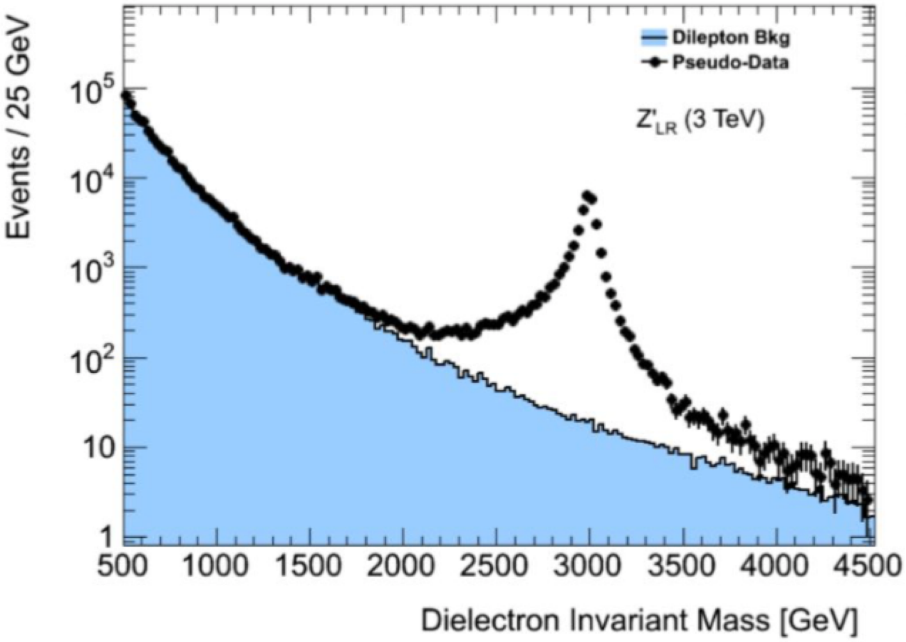
Full CLIC program, ~27 yrs of running in total
- Precision of $\mathcal{O}$(1%) for most couplings
- Accuracy on Higgs width: ±1.6%



Model-independent

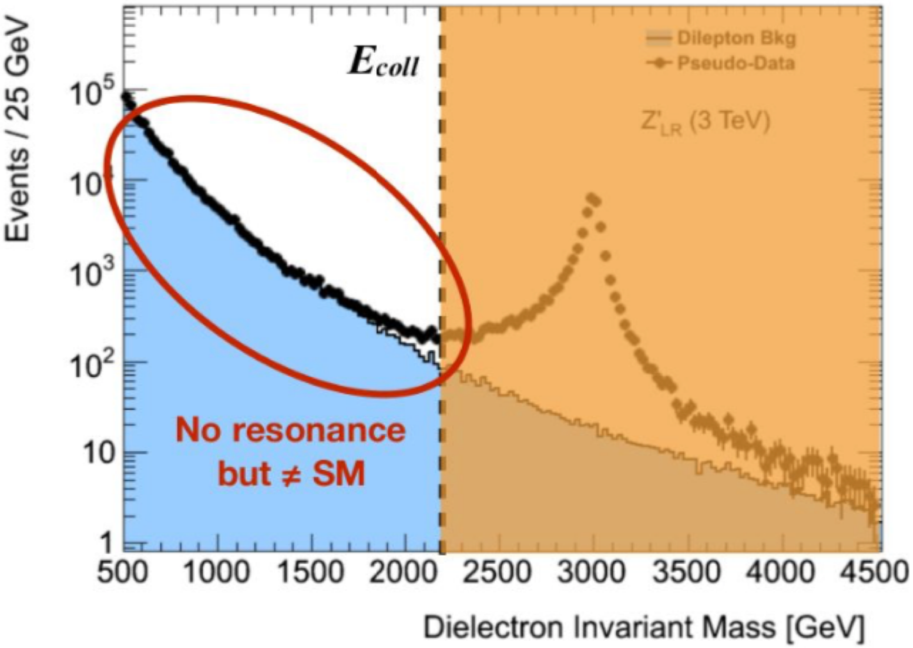
High-mass searches: peak vs. mass tails

Example: Z′ at 3 TeV



- Seeing the "peak". Mass reach:
  - mass < √s for lepton colliders
  - mass ≲ 0.3–0.5 √s at hadron for couplings ~ weak couplings

accelerator only goes to √s = 2.2 TeV



No resonance but ≠ SM

- Deviations in high-mass tails:
  - Very well suited for lepton colliders; sentitive to [mass/couplings] ≫ √s

Direct BSM sensitivity – Example SUSY

- Unique opportunity to directly probe new particles with masses up to 1.5 TeV

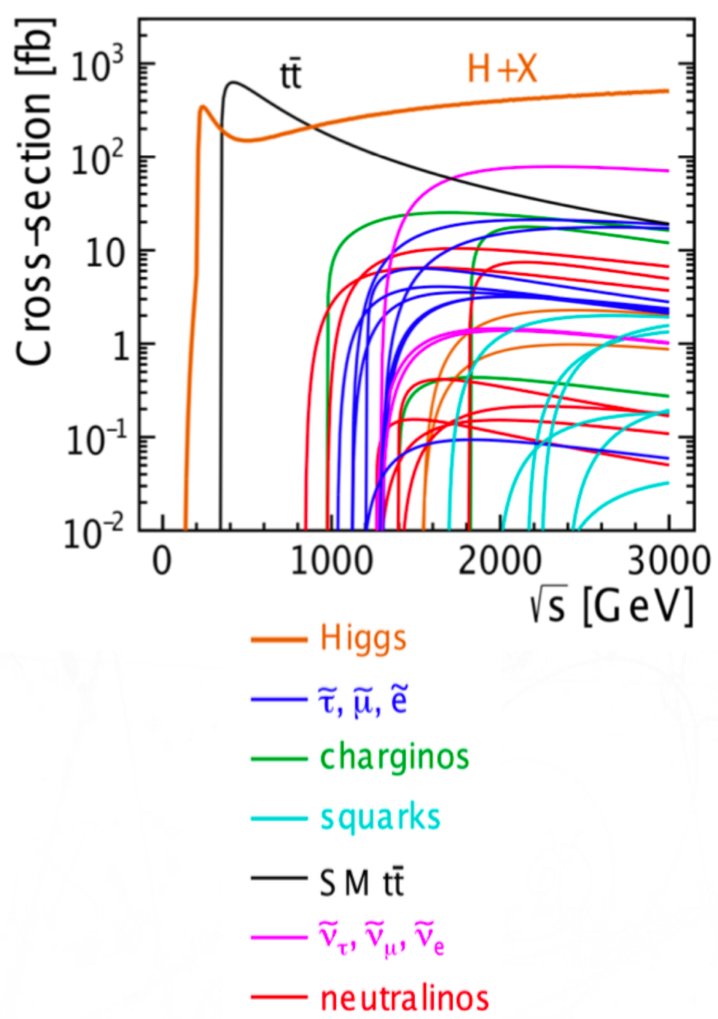
- Direct observation of particles coupling to γ^*/Z/W
  - precision measurement, $\mathcal{O}(1\%)$, of new particle masses and couplings

- Wider capability than only SUSY: reconstructed particles can be interpreted as “states of given mass, spin and quantum numbers”

- Very rare processes accessible due to low backgrounds
  - CLIC especially suited fro electroweak states

- Polarised electron beam and threshold scans may be useful to constrain the underlying theory

“model III”
- smuons, selectrons, staus, gauginos



BSM example: Z′ sensitivity

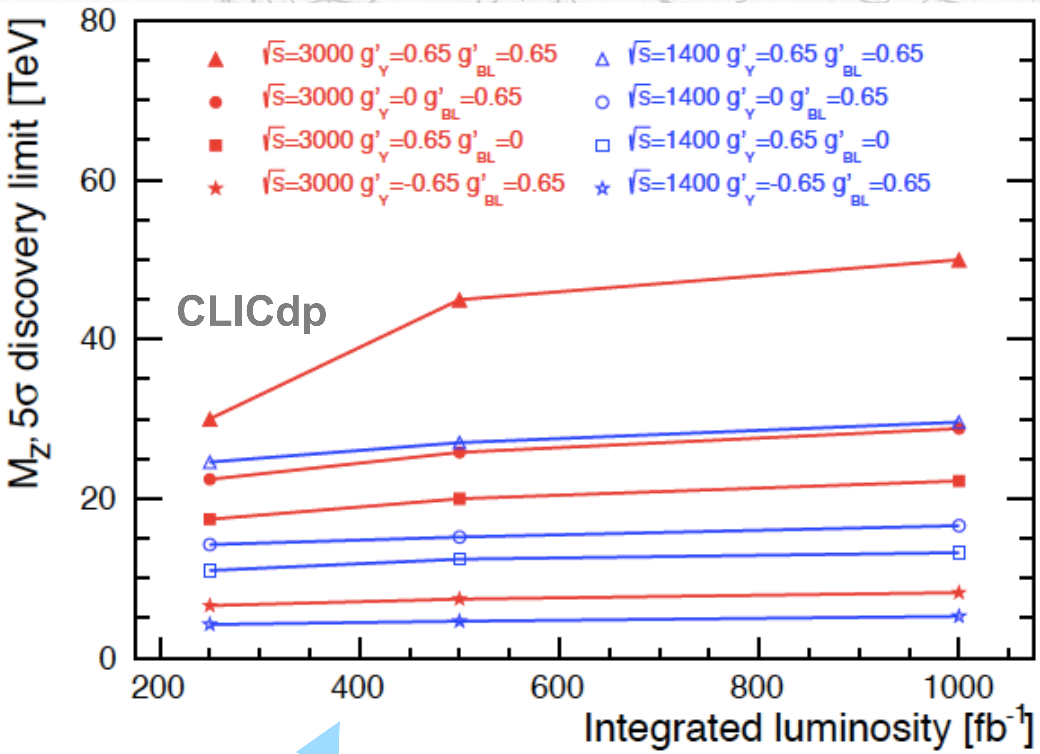
Minimal anomaly-free Z′ model

$$Q_f = g_Y'(Y_f) + g'_{BL}(B\text{-}L)_f$$

Observables:

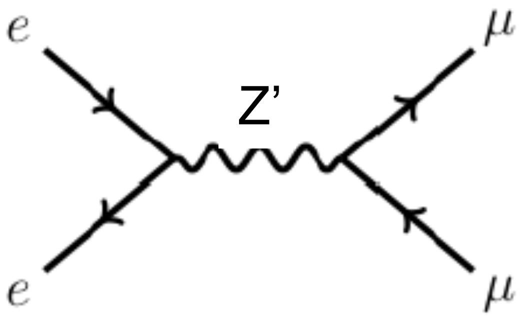
- Total $e^+e^- \rightarrow \mu^+\mu^-$ cross section
- Forward-backward asymmetry
- Left-right asymmetry

(with ±80% e^- polarisation)



- ◆ If LHC discovers Z′ (e.g. for $M_{Z'}$ = 5 TeV)
  - ❑ CLIC precision measurement of effective couplings
- ◆ Otherwise:
  - ❑ CLIC discovery reach up to tens of TeV

    (depending on the couplings)



CLIC Global Sensitivity to BSM Effects

Standard Model

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

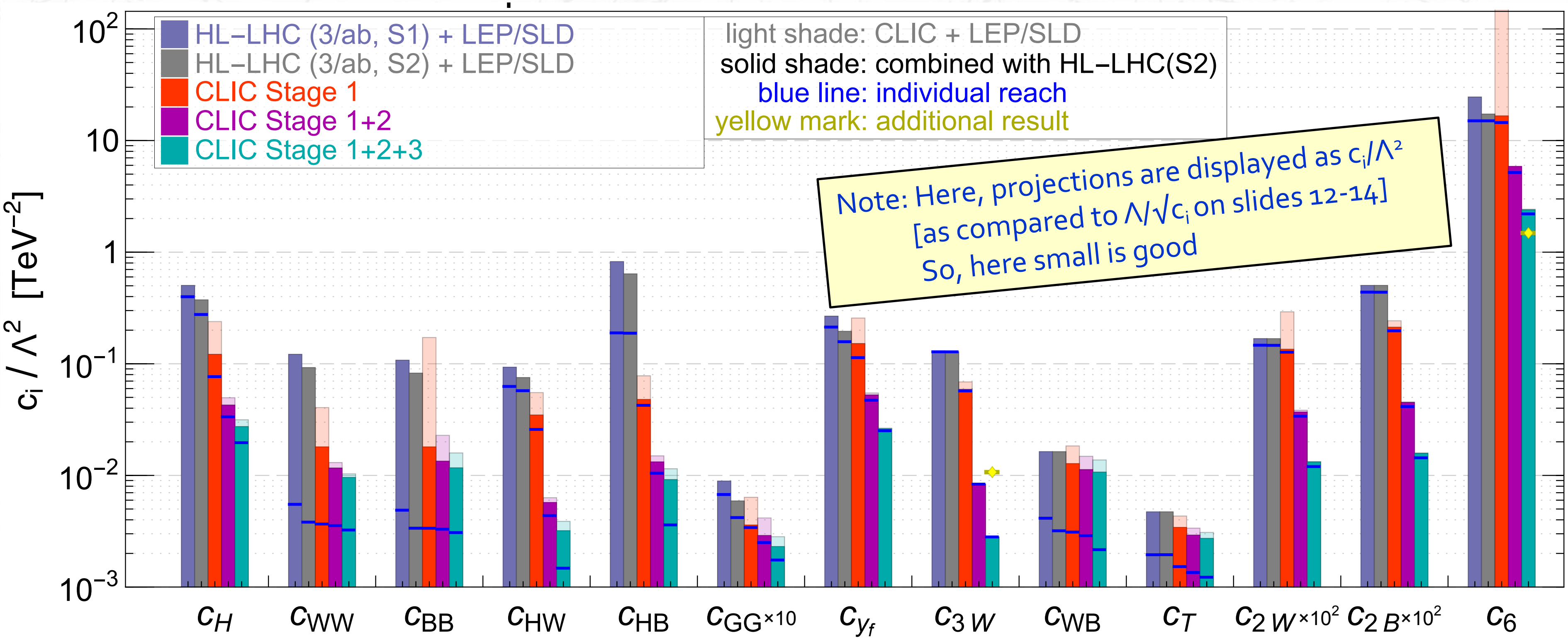
Scale of new decoupled physics

Dimension-6 operators

Universal EFT fit

Includes CLIC measurements of:
- Higgs
- Top
- WW
- $e^+e^- \rightarrow f\bar{f}$

Strong benefits from high-energy running



Note: Here, projections are displayed as c_i/Λ^2 [as compared to $\Lambda/\sqrt{c_i}$ on slides 12-14]
So, here small is good

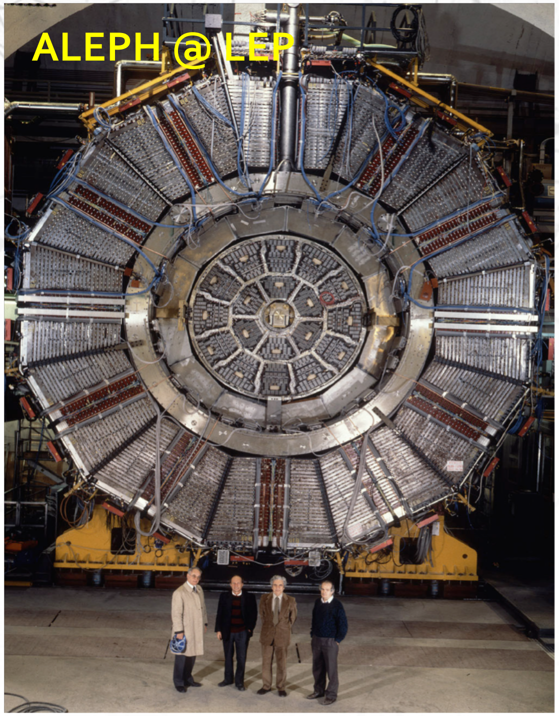
Lecture 2

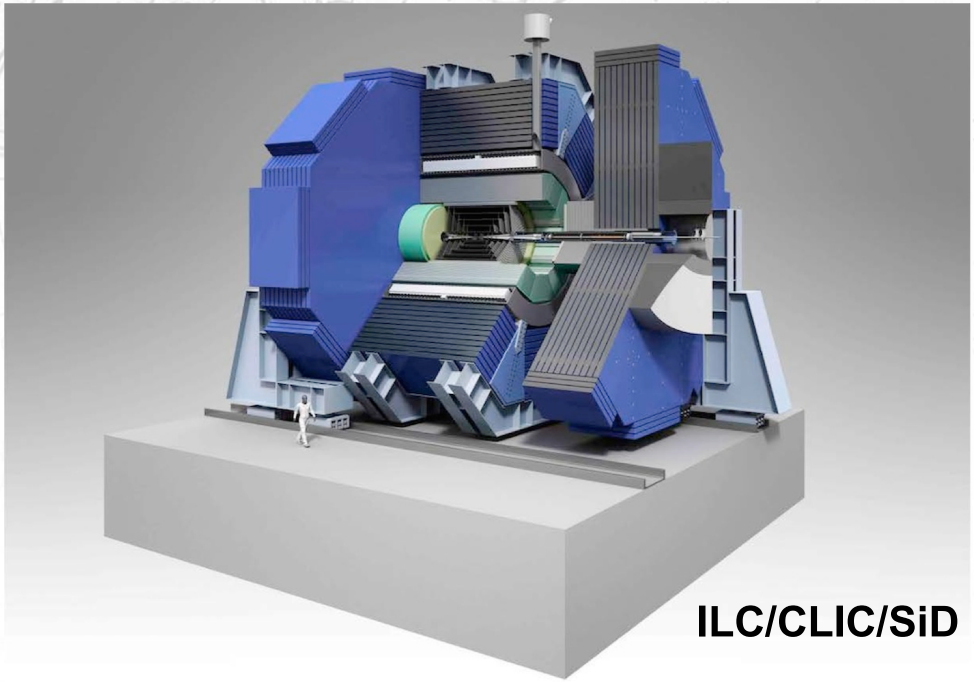
Instrumentation

Detectors for e^+e^- physics

Detectors e^+e^- colliders

- We know today how to build a detector for e^+e^- precision physics
  - ❑ Experience with LEP detectors and 20-years R&D with ILC/CLIC detectors





  - ❑ Compared to LHC, less challenging w.r.t. radiation damage, pile-up, etc.
  - ❑ However, need ultimate systematic precision to match the formidable statistical precision
    - ❖ Rememeber, up to 6 x 10^{12} Z decays

Typical Modern e^+e^- Detector

B-field: **2-5 Tesla**

- Limited to 2 Tesla at FCC-ee due to the 30 mrad crossing angle

Calorimetry:

- Jet energy (1/3 x LEP)

$$\boxed{\frac{\sigma_E}{E} \approx 3-4\,\%}$$

Momentum: (1/10 x LEP)

$$\boxed{\sigma_{1/p} < 5\times10^{-5}\,\mathrm{GeV}^{-1}}$$

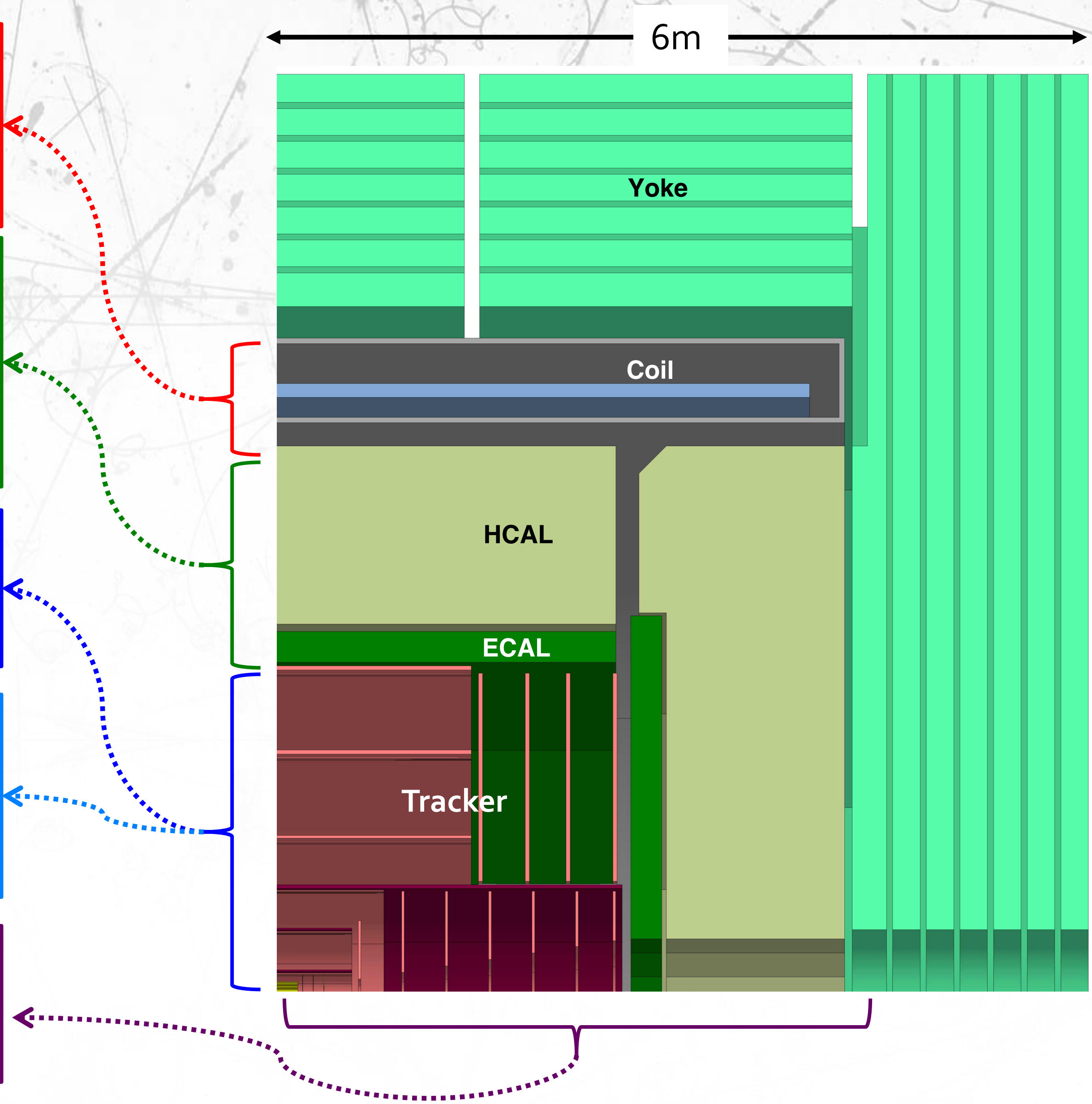
Impact parameter: (1/3 x SLD)

- e.g. b/c-tagging

$$\boxed{\sigma_{r\phi} = 5 \oplus 10/(p\sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}}$$

Hermetic: down to θ ≃ 5 mrad

- Not possible with 30 mrad crossing angle, however



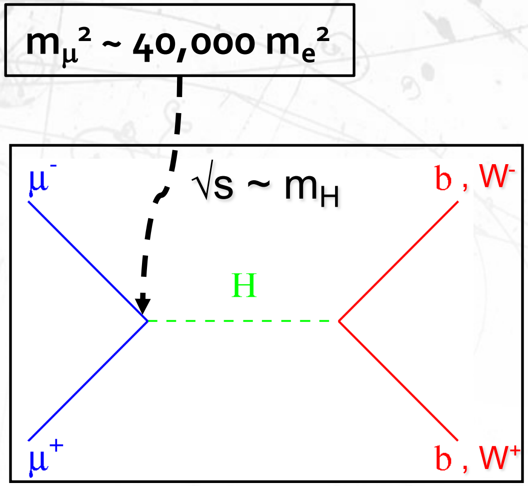
Lecture 3 (2nd part)

Thinking out of the box

Muon Colliders

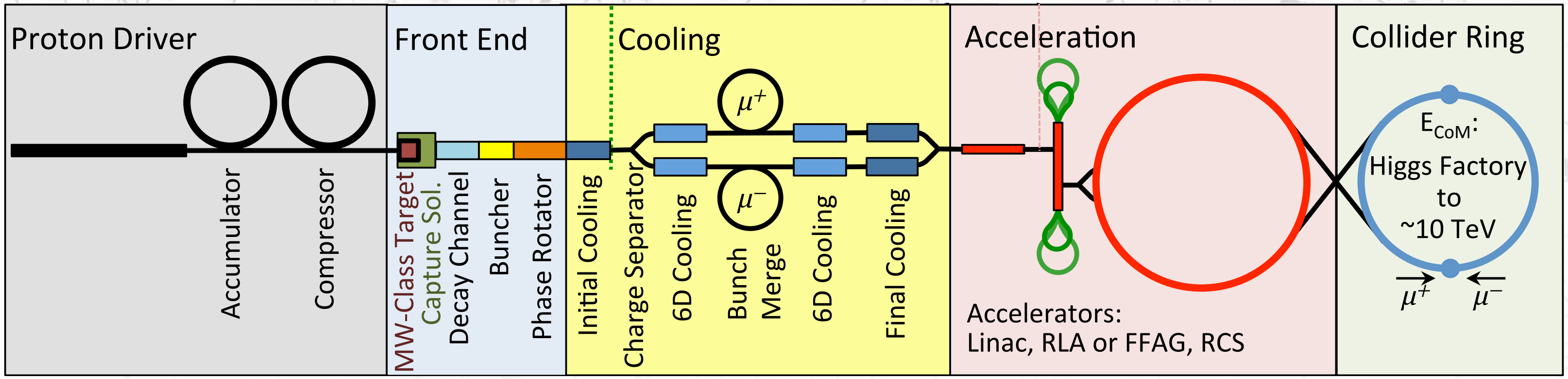
Why muon colliders ?

- Muons are leptons (like electrons)
  - Collisions at the full energy, small physics background, (E,p) conservation
    - Muons can *a priori* do all what electrons can do
- Muons are heavy (like protons)
  - Negligible synchrotron radiation, no beamstrahlung
    - Small circular colliders, up to large $\sqrt{s}$
    - Excellent energy definition (up to a few 10^{-5})
  - Large direct coupling to the Higgs boson
    - Unique *s*-channel Higgs factory at $\sqrt{s} = 125.093$ GeV
- Muons are naturally longitudinally polarized (100%)
  - Because arising from $\pi^{\pm}$ decays to $\mu^{\pm}\nu_{\mu}$
    - Ultra-precise beam energy and beam energy spread measurement
- Muons eventually decay (in 2.2 μs) to $e\nu_{\mu}\bar{\nu}_{e}$
  - Outstanding neutrino physics programme
    - Muon colliders could be the natural successors of neutrino factories ?


$m_{\mu}^2 \sim 40{,}000\ m_e^2$

Muon colliders challenges

- **Muons decay: Produce, Collect, Cool, Accelerate and Collide them *fast* !**



- ❑ Intense proton driver to get the adequate number of muons
  - ❖ At least 4 MW for the desired muon luminosities
- ❑ Robust target to not evaporate at the first proton bunch
  - ❖ Re-circulating liquid metal
- ❑ Efficient muon collector from pion decays
  - ❖ Magnetic fields of 20T
- ❑ Unique 6D muon cooling
  - ❖ To reduce beam sizes and beam energy spread
- ❑ Fast acceleration and injection into circular ring(s)

All these aspects are at the level of intense R&D. Will require decades to demonstrate feasibility

Muon collider challenges since 2014 ?

- Clever alternative muon source

- Intense e^+ beam with $E \simeq 45$ GeV
  - 100 kW for the desired muon intensity
- Non-destructive target for $e^+e^- \to \mu^+\mu^-$
  - Keep the e^+ beam in a ring
    - Possible synergy with FCC-ee
    - Energy Recovery Linac is also a possibility
- Production at $\mu^+\mu^-$ threshold ($\sqrt{s} \simeq 2\, m_\mu$)
  - Quasi-monocromatic muons, much less need for cooling
    - Except for a Higgs factory
  - Not obvious it is possible to cool at 23 GeV anyway ??
- Fast acceleration and injection into circular ring(s) remain as in the proton-driver option

If feasible, this design would probably be faster, cheaper, and easier than the proton-driver option

Muon collider optimal circumference(s)

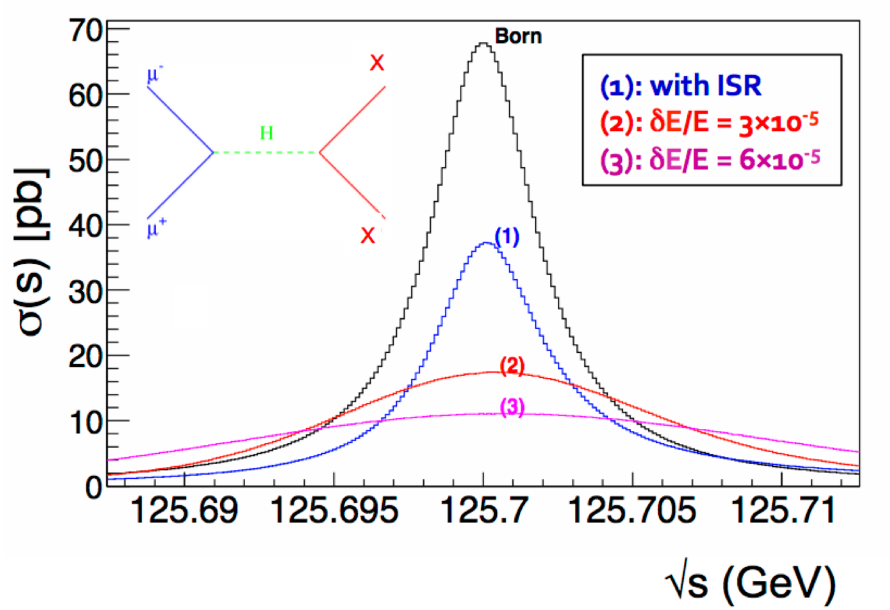
- Muon decay: Minimize the ring circumference
  - To allow the produced muons to collide as many times as possible before they decay
    - Optimal ring size is proportional to E_{μ}. With 14 T state-of-the-art dipoles:

√s	91 GeV	125 GeV	161 GeV	350 GeV	6 TeV	24 TeV
$t = \gamma\tau_m$	0.94 ms	1.30 ms	1.67 ms	3.64 ms	62.3 ms	249 ms
$L = \gamma\beta c\tau_m$	283 km	389 km	501 km	1090 km	18700 km	74000 km
Ring	100 m	140 m	180 m	390 m	6.6 km	27 km
N_{turns}	~2800 turns					

  - One ring per centre-of-mass energy
    - Two very small rings for precision studies
      - One for Z and H factories (140 m circumference)
      - One for W and top pair thresholds (390 m circumference)
    - Larger ring(s) for the energy frontier
      - √s = 6 TeV can fit, for example, in the Tevatron tunnel (6.6 km circumference)
      - √s = 24 TeV can fit in the LHC tunnel
    - Plus a number of rings for first stages of fast acceleration

Muon collider as a Higgs factory (1)

- Challenges for the Higgs factory
  - Γ_H is small (4.2 MeV in the SM)
    - Similar or smaller beam energy spread is required (3×10^{-5})
      - Fast longitudinal cooling to reduce energy spread
    - Beam energy reproducibility must be at the same level or better



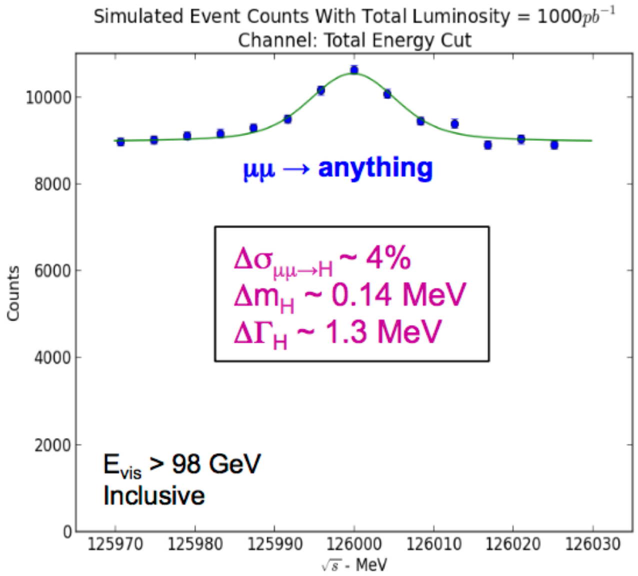
  - $\sigma(\mu^+\mu^- \to H)$ is about 20 pb
    - Luminosity must be at the level of 1.6×10^{32} cm^{-2}s^{-1} for the same number of Higgs bosons as ILC …
    - and at the level of 1.6×10^{33} cm^{-2}s^{-1} for the same number of Higgs bosons as FCC-ee
      - Fast transverse cooling to reduce beam spot dimensions

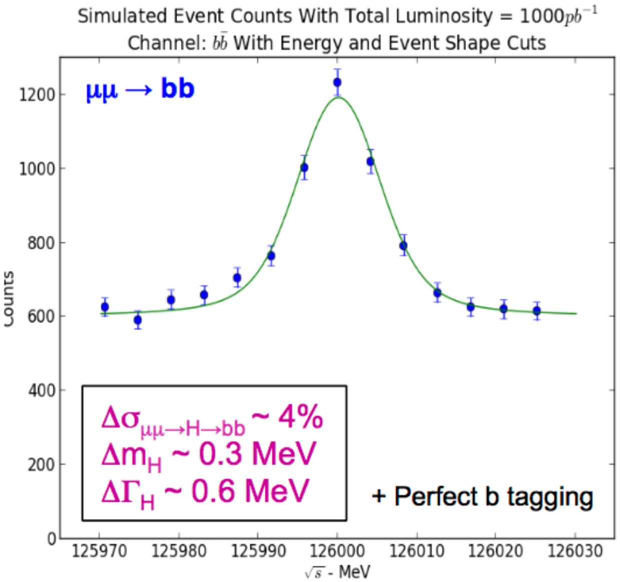
And the Higgs bosons produced are not tagged with a Z anyway …

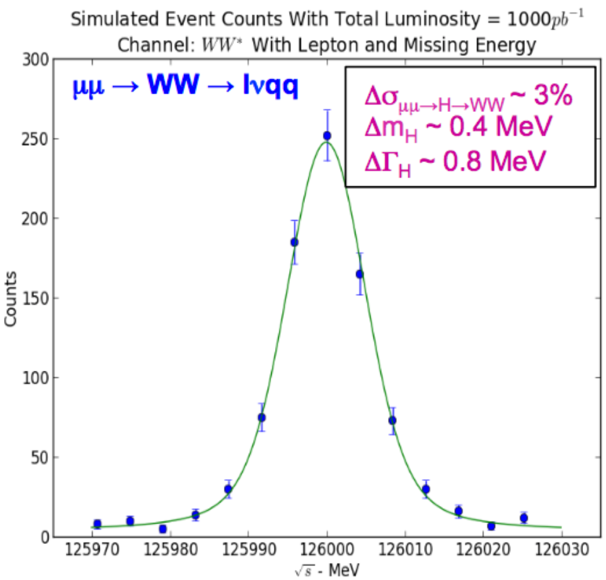
  - Problem
    - Longitudinal and transverse cooling are antagonistic
      - Luminosity is limited (as of today's knowledge) to a few 10^{31} cm^{-2}s^{-1}

Muon collider as a Higgs factory (2)

- Physics performance of a Higgs factory
  - Scan of Higgs resonance in the inclusive $b\bar{b}$ and WW final states
    - Ten years of data taking at 10^{31} cm^{-2}s^{-1}, just count events







- Measure Γ_H to 5% in 10 years (cf. 4% at ILC, <1% at FCC-ee)
  - Only way to see a structure in the resonance (several Higgs bosons?)
- Measure σ_{peak} ~ $BR_{\mu\mu}$ to 2-3% in 10 years
- Other expected measurement on the figures

Muon collider as a Higgs factory (3)

- Summary of precision measuremetns (after ~10 years of running)

Error on	μμ collider	ILC$_{250}$	FCC-ee
m_H (MeV)	0.06	14	8
Γ_H (MeV)	0.17	0.11	0.06
g_{Hbb}	2.3%	1.8%	0.61%
g_{HWW}	2.2%	1.7%	0.43%
$g_{H\tau\tau}$	5%	1.9%	0.80%
$g_{H\gamma\gamma}$	10%	6.4%	3.8%
$g_{H\mu\mu}$	2.1%	13%	8.6%
g_{HZZ}	-	0.35%	0.17%
g_{Hcc}	-	2.3%	1.2%
g_{Hgg}	-	2.2%	1.0%
BR_{invis}	-	<0.5%	<0.1%

Not obvious what is the practical use of such high precision on m_H

The Higgs width is best measured at ee colliders

These Higgs couplings are best measured at ee colliders

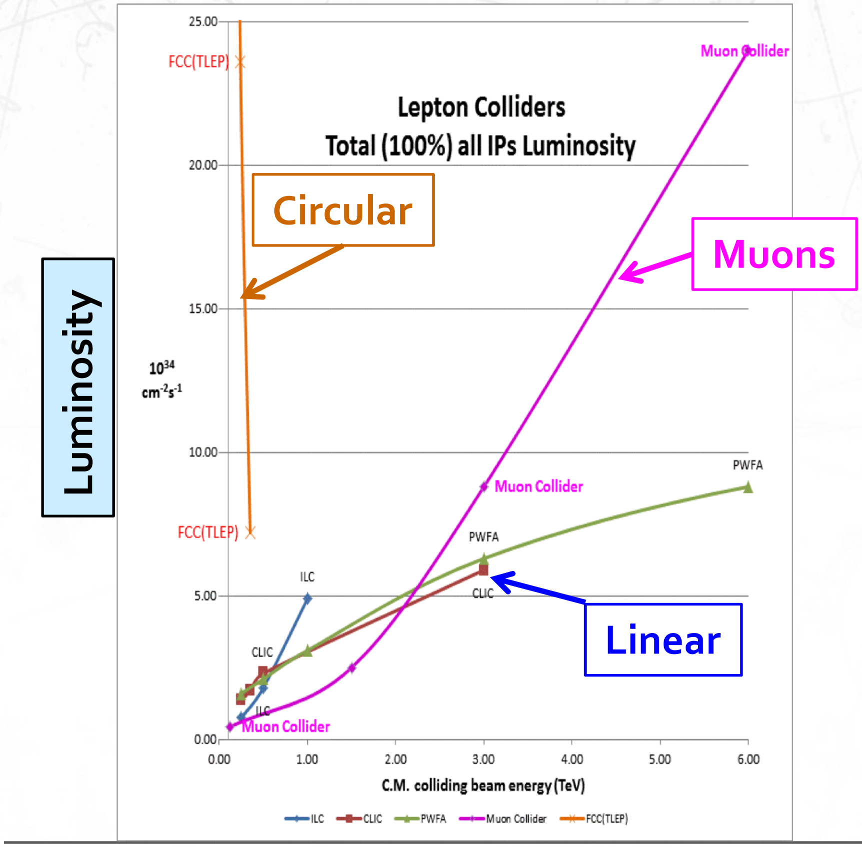
The Higgs coupling to muons is *the* added value of a μμ collider

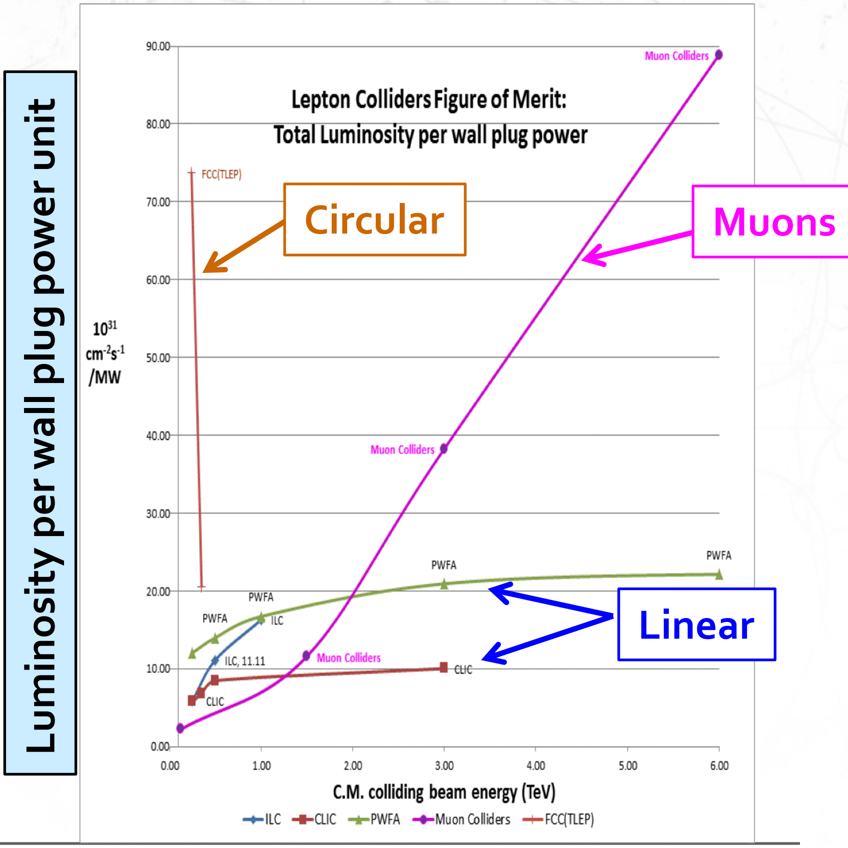
These Higgs couplings are *only* measured at ee colliders *)

- **Note: BR(H→μμ) can be also measured with % precision af FCC-hh (Will be already 5% after HL-LHC)**

Muon colliders at the energy frontier

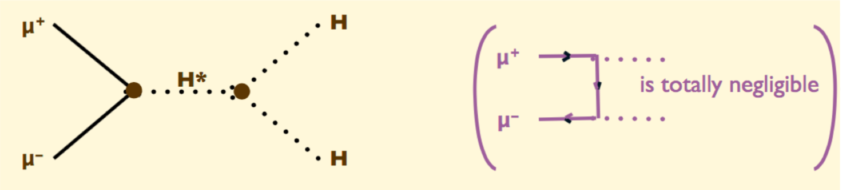
- Muon colliders might be a solution for high energy in the (far?) future
  - ❑ Many challenges to solve with sustained R&D and innovative thinking, as to
    - ❖ Increase luminosity for precision studies
    - ❖ Solve the radiation hazard at high energy (decay neutrino interactions in Earth)
  - ❑ Target luminosity competitive with CLIC above 2-3 TeV
    - ❖ With the possibility of several IPs





Muon colliders: Summary

- A muon collider may be the best way to get lepton collisons at √s ≥ 3 TeV
  - Much R&D remain in, e.g., muon cooling/acceleration
- A muon collider at √s = 125 GeV is a very pretty Higgs factory ($\mu^+\mu^- \rightarrow H$)
  - But not necessarily the one we need
    - If H(125) is a single particle, the process $e^+e^- \rightarrow HZ$ @ 240 GeV is better suited
      - In particular, the Higgs width can be measured very well in e^+e^- collisions
    - A muon collider can also do that, but much higher luminosity would be necessary
      - At least two orders of magnitude – limited by the proton/positron source
- Several quasi-degenerate Higgs bosons is a strong case for μμ Higgs factory
  - If Δm is between 4 MeV (Γ_H) and ~100 MeV (LHC resolution)
    - Such a situation may occur with two Higgs doublets, and quasi-degenerate H & A
      - Isolate the two peaks and perform nice CP studies !
- A muon collider at √s > 2 m_H provides the only way to *cleanly* probe HHH coupling



- A muon collider is the natural second step of neutrino factories
- Conclusion: don’t write them off completely, but don’t oversell them !

Lecture 2

Rounding off

Summary and Conclusions

Summary & Conclusions (1)

- Since LEP, there has been a dramatic development in e^+e^- accelerator technology
  - Linear colliders: Energy reach up to $\sqrt{s} = 3$ TeV
  - Circular colliders: Increase of instantaneous luminosity by 4-5 orders of magnitude
    - For $\sqrt{s} < 400$ GeV, circular colliders provide very high luminosities
      - Repeat of LEP1 programme every ~5 min !
- With the discovery of the light Higgs boson and the non-discovery (so far) of new heavier states, e^+e^- communities are now zooming in on the $\sqrt{s} < 400$ GeV region
  - ILC: Higgs factory at $\sqrt{s} = 250$ GeV as first stage (12 years)
    - Possibly later upgraded to $\sqrt{s} = 500$ GeV (and $\sqrt{s} = 1$ TeV ?)
  - CLIC: "Affordable" Higgs/top factory at $\sqrt{s} = 380$ GeV as first stage
    - Later upgraded to $\sqrt{s} = 1.5$ TeV and possibly $\sqrt{s} = 3$ TeV
- An e^+e^- Higgs factory with $\mathcal{O}(10^6)$ Higgs decays provides sub-% level measurement of (most) Higgs couplings
  - Strong New Physics reach !
- Electroweak precison measurements provide a strong test of SM
  - A e^+e^- collider with $90 < \sqrt{s} < 400$ GeV could improve precision of all electroweak parameters by 1 – 2 orders of magnitude
    - Ultimate precision for Z, W, Higgs, and top (and flavour: b and τ)
  - Strong New Physics reach !

Summary & Conclusions (2)

- CLIC programme at $\sqrt{s}$ = 1.5 and 3 TeV, has access to complementary measurements
  - Higgs self-coupling to sub-10% level
  - Precise top quark studies
  - Direct (indirect) access to new physics if m < 1.5 TeV (m>1.5 TeV)
- In the long-term future, muon colliders may be the way to go for energy frontier lepton colliders

Personal views

- Muon colliders provide a potential interesting option for *long-term* future high energy lepton colliders
  - Without major technological breakthroughs they unfortunately do not provide sufficient luminosity to be interesting as a Higgs factory
- Very clear physics case for an e^+e^- collider with $90 < \sqrt{s} < 370\text{-}500$ GeV
  - Precision Higgs and electroweak physics
    - Strong complementary programmes
- Slightly harder to make physics case for e^+e^- colliders with $\sqrt{s} > 370-500$ GeV
  - At least without clear evidence for accessible new particles
    - Produced copiously in e^+e^- or $\gamma\gamma$ collisions
- Exploration of energy frontier seems best done with a hadron collider
  - e.g., the 100 TeV FCC-hh proton-proton collider

The FCC integrated programme

Base the next generation of colliders on a proven model

- 27 km tunnel

LEP (e^+e^-)
1989 - 2000

LHC (pp)
2009 – 2035?

- The next step: 100 km tunnel

FCC-ee
100km

FCC-hh
100km

1 2 3 4 ~ 17 18 15 years operation 33 34 35 36 37 38 39 40 41 42 43 ~ 25 years operation 70

End of the second lecture

Questions…

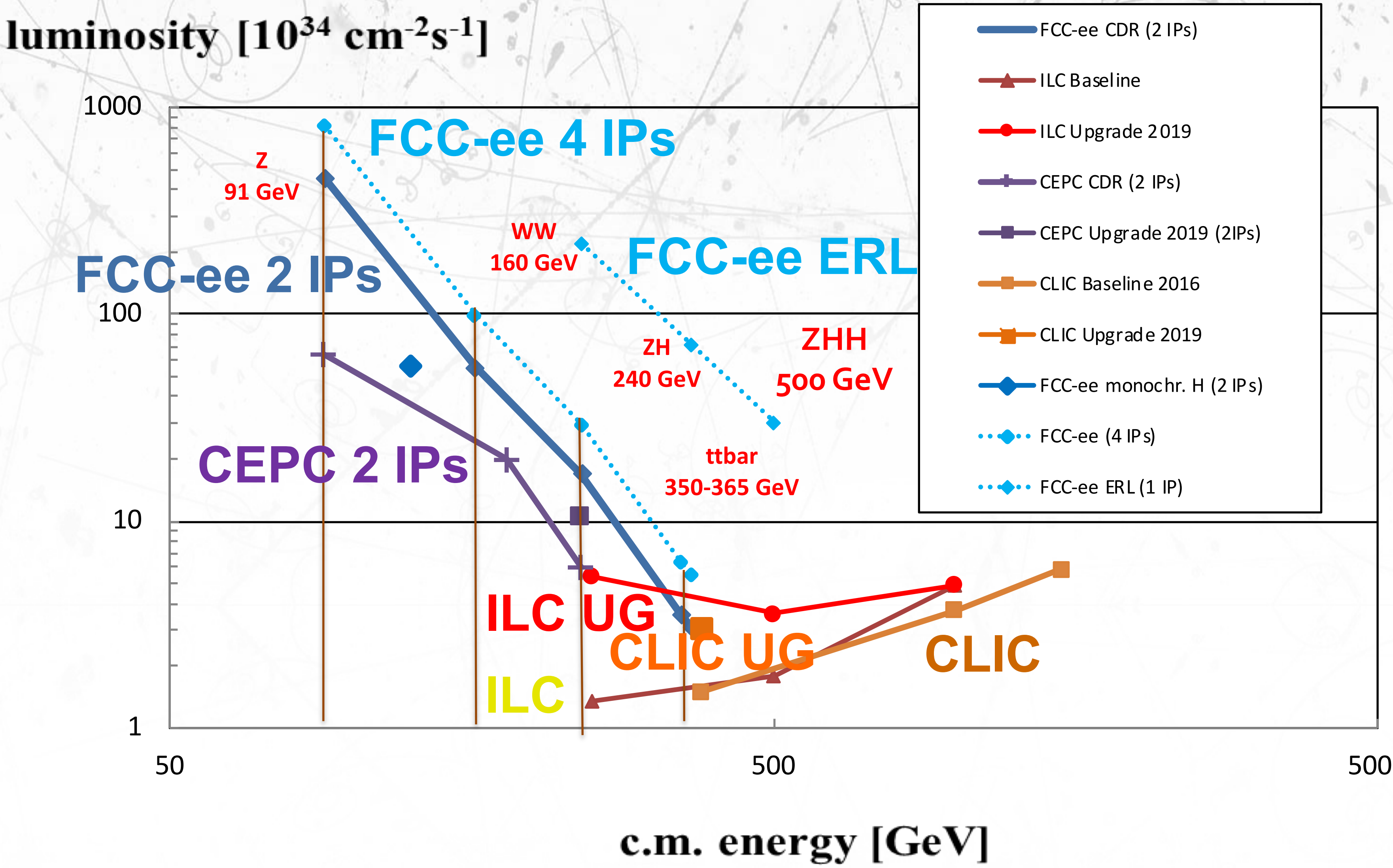
"*No doubt that future high energy colliders are extremely challenging projects.*

However, the correct approach, as scientists, is not to abandon our exploratory spirit, nor give in to financial and technical challenges. The correct approach is to use our creativity to develop the technologies needed to make future projects financially and technically affordable."

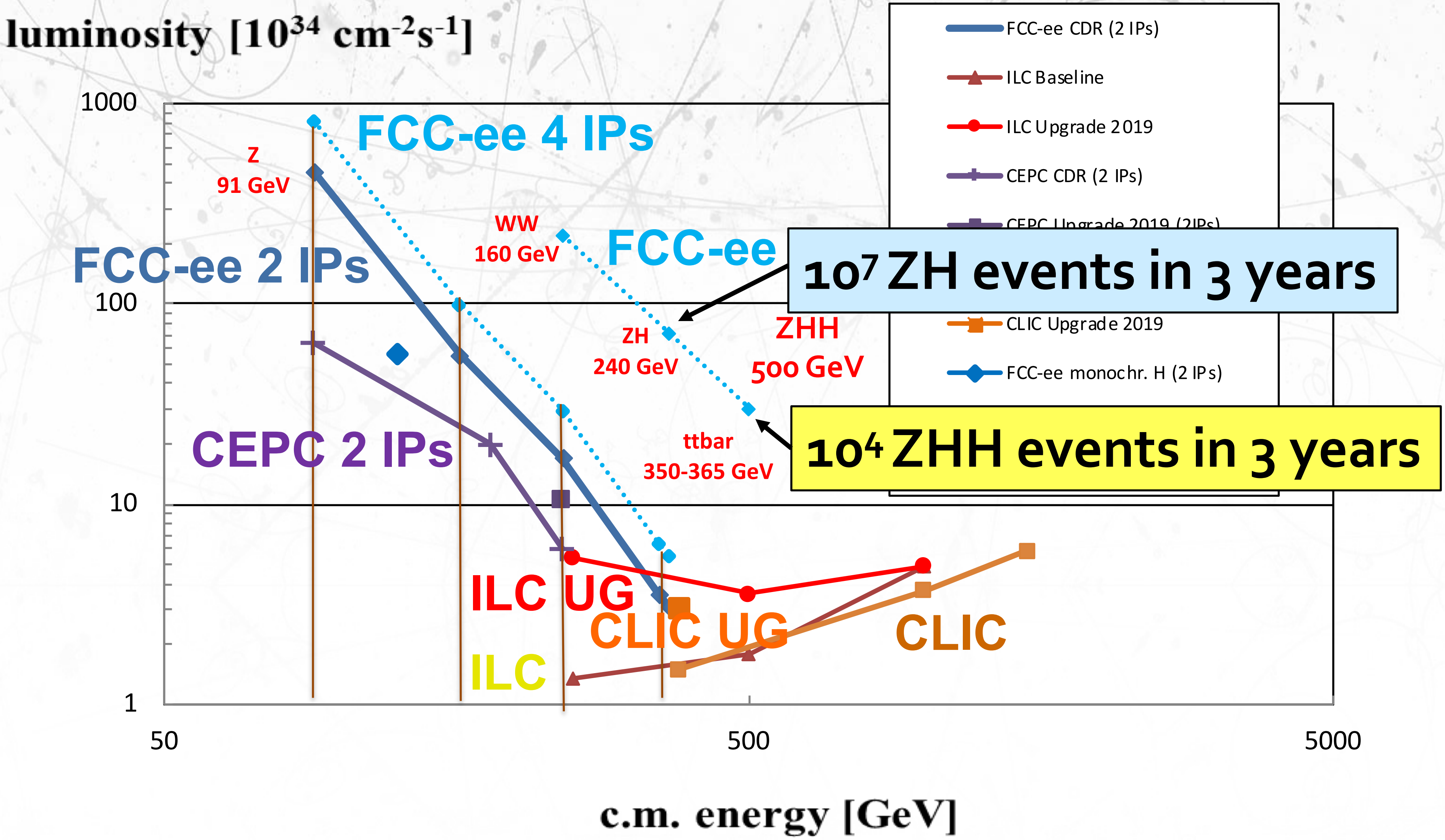
Fabiola Gianotti, DG CERN

Extra Material

e^+e^- colliders – a field in very rapid development



e^+e^- colliders – a field in very rapid development

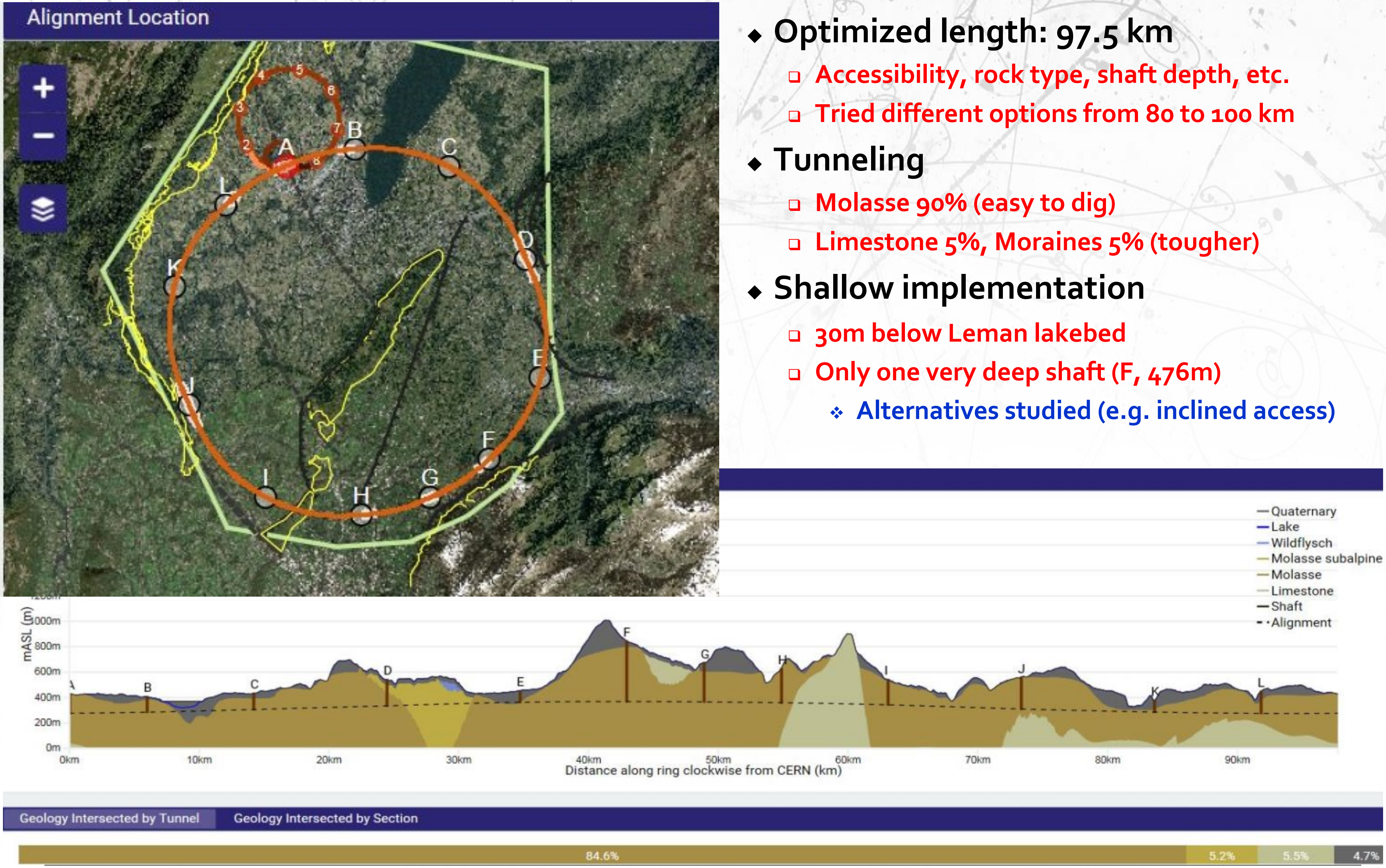


10^7 ZH events in 3 years

10^4 ZHH events in 3 years

The FCC Home

- Optimized length: 97.5 km
  - Accessibility, rock type, shaft depth, etc.
  - Tried different options from 80 to 100 km
- Tunneling
  - Molasse 90% (easy to dig)
  - Limestone 5%, Moraines 5% (tougher)
- Shallow implementation
  - 30m below Leman lakebed
  - Only one very deep shaft (F, 476m)
    - Alternatives studied (e.g. inclined access)



FCC-ee basic design choices

double ring e^+e^- collider ~100 km

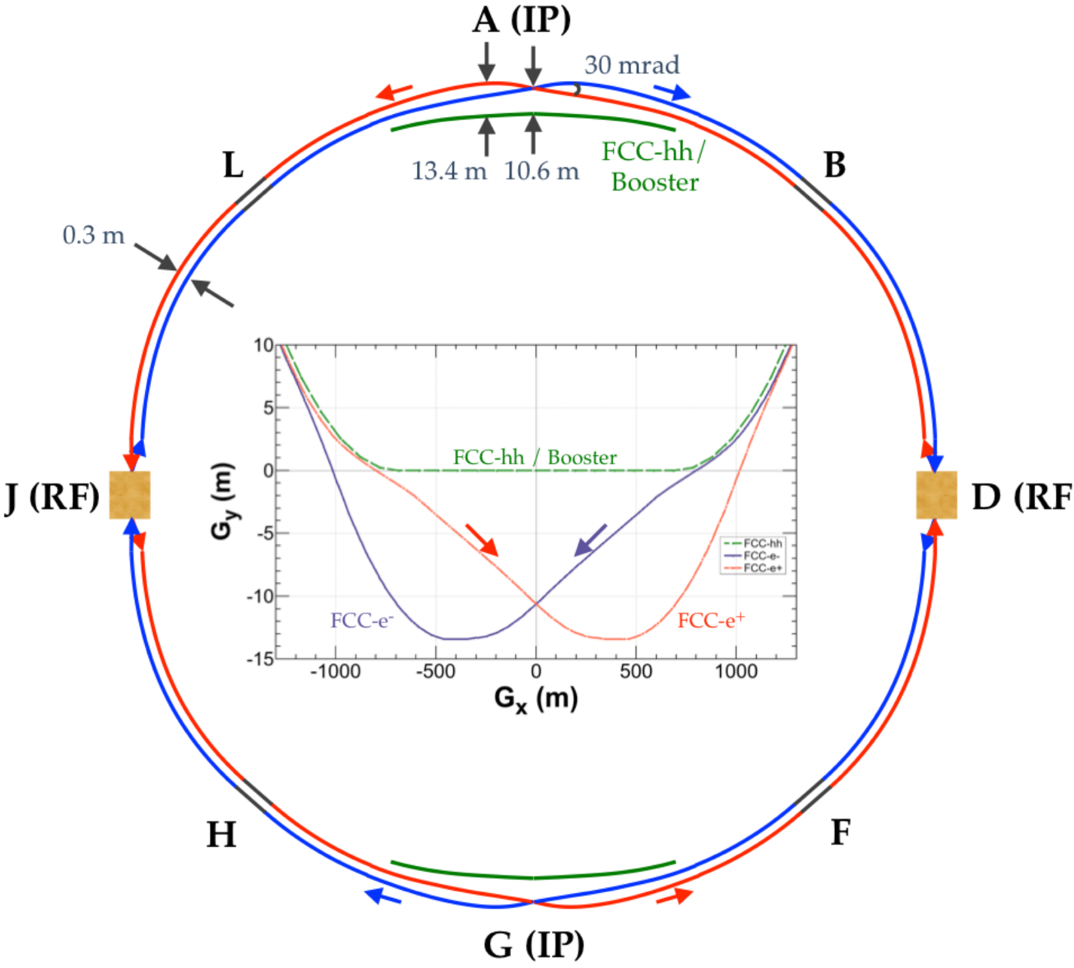
follows footprint of FCC-hh, except around IPs

asymmetric IR layout & optics to limit synchrotron radiation towards the detector

presently 2 IPs (alternative layouts with 3 or 4 IPs under study), **large** horizontal crossing angle **30 mrad, crab-waist optics**

synchrotron radiation power 50 MW/beam at all beam energies; tapering of arc magnet strengths to match local energy

top-up injection scheme; requires **booster synchrotron in collider tunnel**



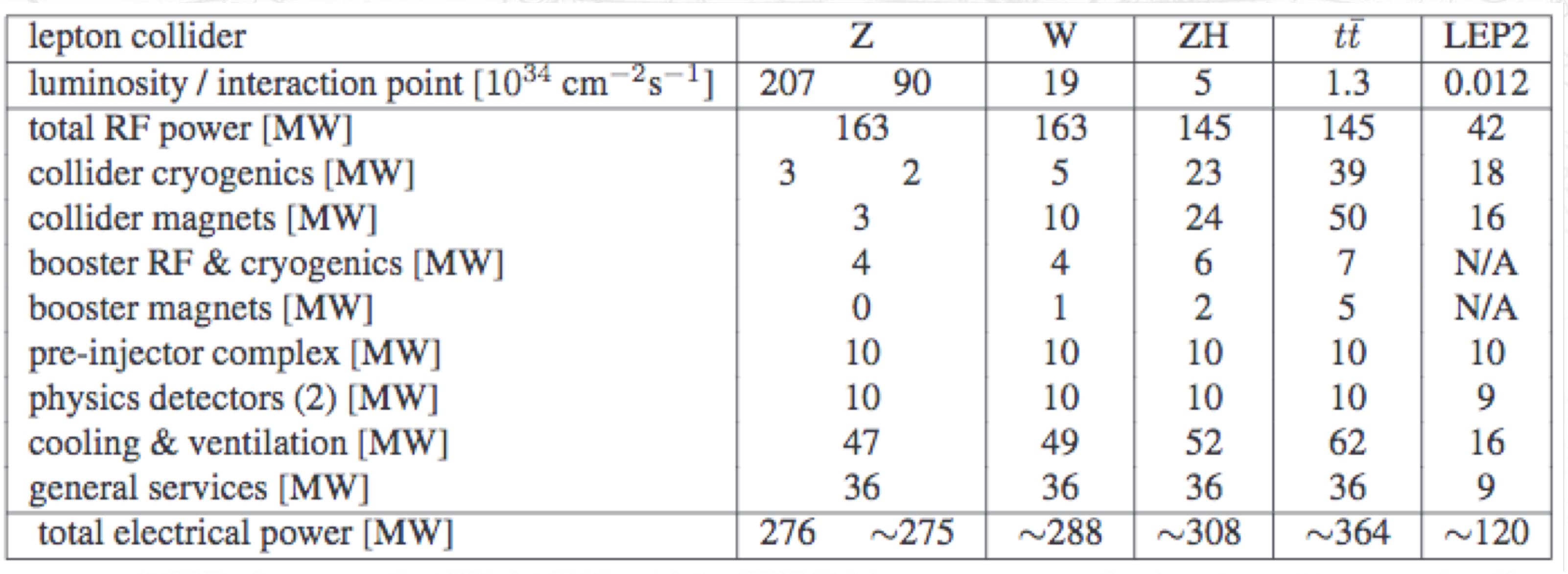
K. Oide et al.

FCC-ee Machine Parameters

FCC-ee parameters		**Z**	**W^+W^-**	**ZH**	**ttbar**	
Beam energy	**GeV**	**45.6**	**80**	**120**	**175**	**182.5**
Luminosity / IP	**10^{34} cm^{-2} s^{-1}**	**230**	**28**	**8.5**	**1.8**	**1.55**
Beam current	mA	1390	147	29	6.4	5.4
Bunches per beam	#	16640	2000	328	59	48
Average bunch spacing	ns	19.6	163	994	2763	3396
Bunch population	10^{11}	1.7	1.5	1.8	2.2	2.3
Horizontal emittance ε_x Vertical emittance ε_y	nm pm	0.27 1.0	0.84 1.7	0.63 1.3	1.34 2.7	1.46 2.9
β_x^* / β_y^*	**m / mm**	**0.15 / 0.8**	**0.2 / 1.0**	**0.3 / 1.0**	**1.0 / 1.6**	
beam size at IP: σ_x^* / σ_y^*	µm / nm	6.4 / 28	13 / 41	13.7 / 36	36.7 / 66	38.2/68
Energy spread: SR / total (w BS)	%	0.038 / 0.132	0.066 / 0.131	0.099 / 0.165	0.144 / 0.196	0.15 / 0.192
Bunch length: SR / total	mm	3.5 / 12.1	3 / 6.0	3.15 / 5.3	2.75 / 3.82	1.97 / 2.54
Energy loss per turn	**GeV**	**0.036**	**0.34**	**1.72**	**7.8**	**9.2**
RF Voltage /station	GV	0.1	0.75	2.0	4/5.4	4/6.9
Longitudinal damping time	turns	1273	236	70.3	23.1	20.4
Acceptance RF / energy (DA)	%	1.9 / ±1.3	2.3 / ±1.3	2.3 / ±1.7	3.5/ (-2.8; +2.4)	3.36 / (-2.8; +2.4)
Rad. Bhabha/ actual Beamstr. Lifetime	min	68 / > 200	59 / >200	38 / 18	37/ 24	40 / 18
Beam-beam parameter ξ_x/ ξ_y		0.004 / 0.133	0.01 / 0.141	0.016 / 0.118	0.088 / 0.148	0.099 / 0.126
Interaction region length	mm	0.42	0.85	0.9	1.8	1.8

FCC-ee Power consumption

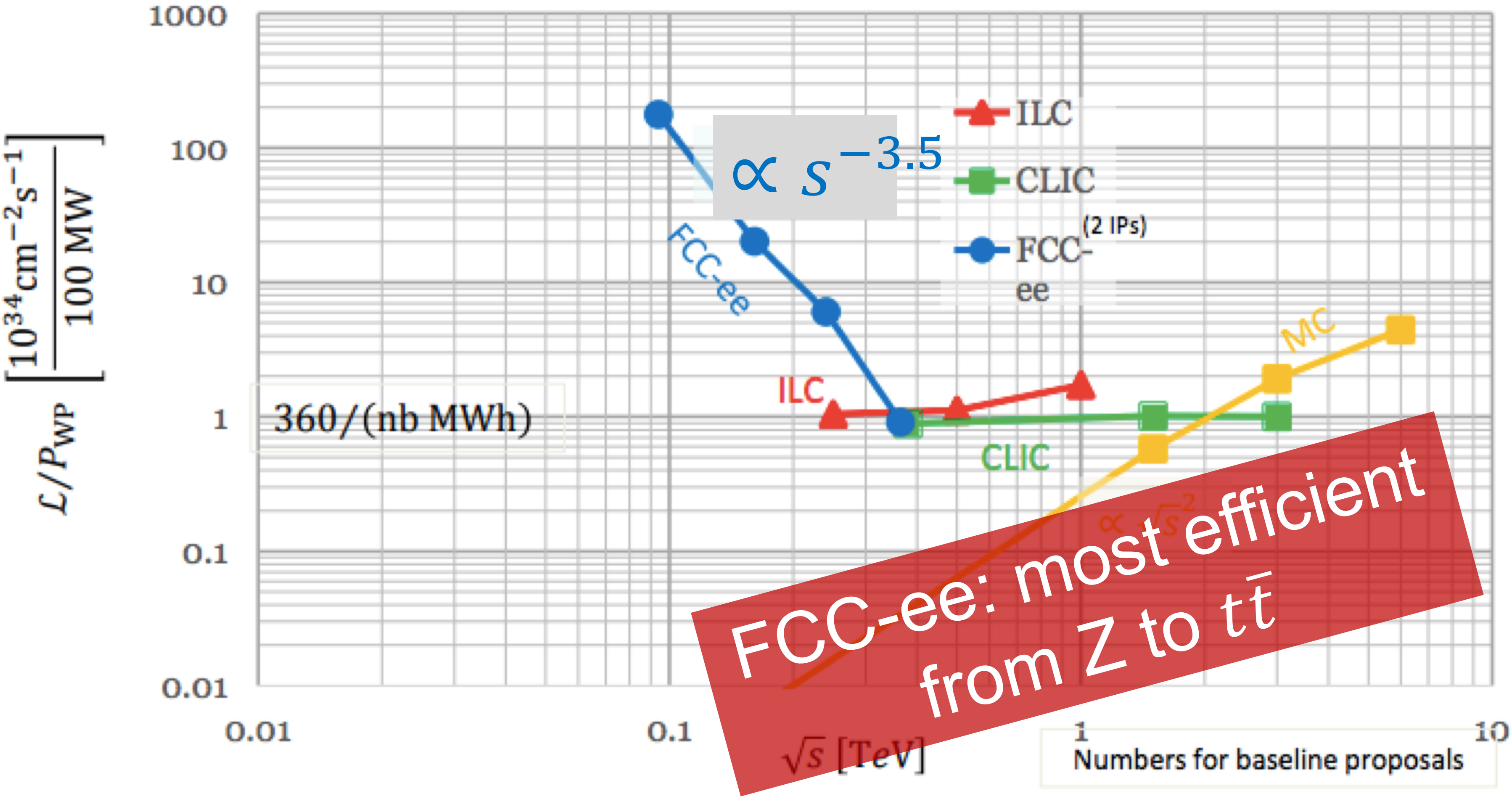
- The RF system needs to compensate for 100 MW SR losses
  - Corresponds to 200 MW electric power with 50% RF power sources (klystrons)
    - Klystron efficiency was ~55% at LEP2
  - Recent (2015) breakthroughs in klystron design promise 90% efficiency
    - Assume 85% will be achieved and take 10 – 20% margins



lepton collider	Z		W	ZH	$t\bar{t}$	LEP2
luminosity / interaction point [10^{34} cm^{-2}s^{-1}]	207	90	19	5	1.3	0.012
total RF power [MW]	163		163	145	145	42
collider cryogenics [MW]	3	2	5	23	39	18
collider magnets [MW]	3		10	24	50	16
booster RF & cryogenics [MW]	4		4	6	7	N/A
booster magnets [MW]	0		1	2	5	N/A
pre-injector complex [MW]	10		10	10	10	10
physics detectors (2) [MW]	10		10	10	10	9
cooling & ventilation [MW]	47		49	52	62	16
general services [MW]	36		36	36	36	9
total electrical power [MW]	276	~275	~288	~308	~364	~120

- For comparison
  - LHC Run1: 210 MW, HL-LHC: 260 MW, FCC-hh: ~500 MW
  - CLIC: 250 MW (at 380 GeV) to 580 MW (at 3 TeV)

figure of merit for lepton colliders



$\propto s^{-3.5}$

FCC-ee: most efficient from Z to $t\bar{t}$

E. Jensen, EPPSU symposium, Granada

Precision electroweak physics at FCC-ee (12)

- The predictions of m_{top}, m_W, m_H, $\sin^2\theta_W$ have theoretical uncertainties
  - Which may cancel the sensitivity to new physics
- For m_W and $\sin^2\theta_W$ today, these uncertainties are as follows

$$\begin{aligned} m_{\rm W} = \quad & 80.3584 \quad \pm 0.0055_{m_{\rm top}} \pm 0.0025_{m_{\rm Z}} \pm 0.0018_{\alpha_{\rm QED}} \\ & \qquad\qquad \pm 0.0020_{\alpha_{\rm S}} \pm 0.0001_{m_{\rm H}} \pm 0.0040_{\rm theory} \ {\rm GeV} \\ = \quad & 80.358 \quad \pm 0.008_{\rm total} \ {\rm GeV}, \end{aligned}$$

Exp: 0.012 GeV

$$\begin{aligned} \sin^2\theta_{\rm W}^{\rm eff} = \quad & 0.231488 \quad \pm 0.000029_{m_{\rm top}} \pm 0.000015_{m_{\rm Z}} \pm 0.000035_{\alpha_{\rm QED}} \\ & \qquad\qquad \pm 0.000010_{\alpha_{\rm S}} \pm 0.000001_{m_{\rm H}} \pm 0.000047_{\rm theory} \\ = \quad & 0.23149 \quad \pm 0.00007_{\rm total}, \end{aligned}$$

Exp: 0.00016

- Parametric uncertainties and missing higher orders in theoretical calculations:
  - Are of the same order
  - Smaller than experimental uncertainties

Precision electroweak physics at FCC-ee (13)

- Most of the parametric uncertainties will reduce at the FCC-ee
  - New generation of theoretical calculations is necessary to gain a factor 10 in precison
    - To match the precision of the direct FCC-ee measuremetns

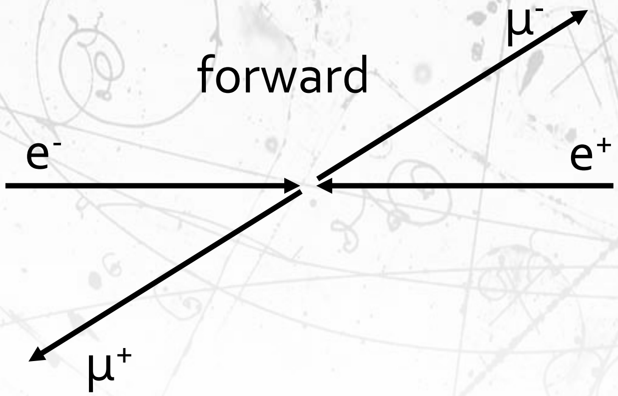
$$\begin{aligned} m_{\mathrm{W}} = \quad & 80.3584 \pm 0.0001_{m_{\mathrm{top}}} \pm 0.0001_{m_{\mathrm{Z}}} \pm 0.0003_{\alpha_{\mathrm{QED}}} \\ & \pm 0.0002_{\alpha_{\mathrm{S}}} \pm 0.0000_{m_{\mathrm{H}}} \pm 0.0040_{\mathrm{theory}}\ \mathrm{GeV} \\ = \quad & 80.358 \pm 0.005_{\mathrm{total}}\ \mathrm{GeV}, \end{aligned}$$

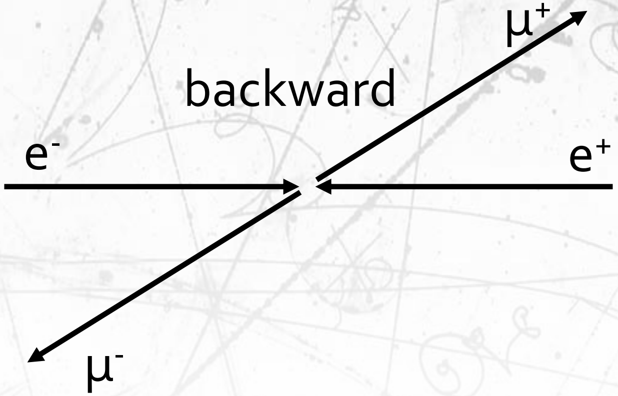
Exp: 0.0005

$$\begin{aligned} \sin^2\theta_{\mathrm{W}}^{\mathrm{eff}} = \quad & 0.231488 \pm 0.000001_{m_{\mathrm{top}}} \pm 0.000001_{m_{\mathrm{Z}}} \pm 0.000008_{\alpha_{\mathrm{QED}}} \\ & \pm 0.000001_{\alpha_{\mathrm{S}}} \pm 0.000000_{m_{\mathrm{H}}} \pm 0.000047_{\mathrm{theory}} \\ = \quad & 0.23149 \pm 0.00006_{\mathrm{total}}, \end{aligned}$$

Exp: 0.000006

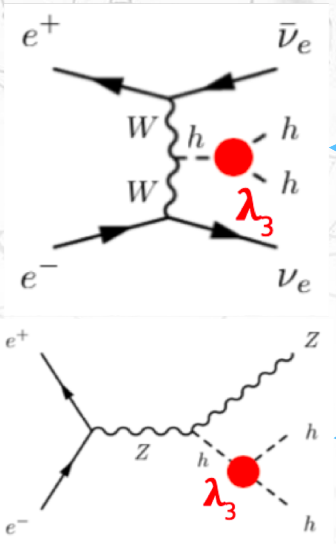
  - Will require calculations up to three or four loops to gain an order of magnitude
    - Might need a new paradigm in the actual computing methods
      - Lots of interesting work for future generations of theorists (you?)


μ^-
forward
e^-
e^+
μ^+

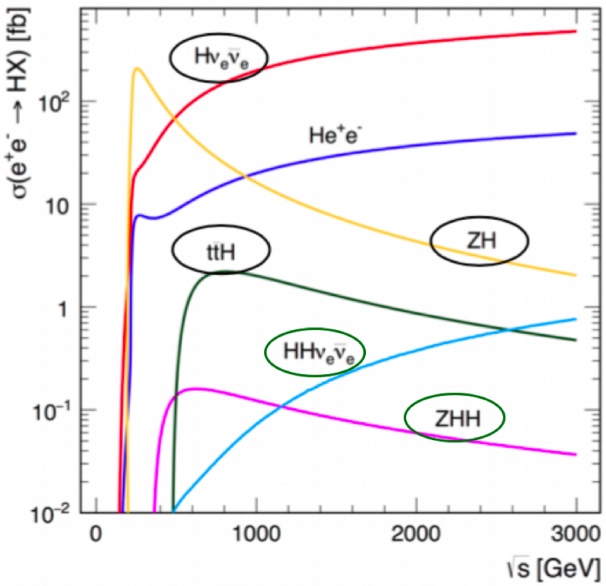

μ^+
backward
e^-
e^+
μ^-

Higgs Self-coupling

- **Higgs pair production requires high energy**



	1.4TeV	3TeV
σ($HH\nu_e\nu_e$)	>3σ EVIDENCE = 28%	>5σ OBSERVATION = 7.3%
σ(ZHH)	>5σ OBSERVATION	
g_{HHH}/g^{SM}_{HHH}	1.4TeV: –34%, +36% rate-only analysis	1.4 + 3TeV: **–7%, +11%** differential analysis



Among e^+e^- colliders, unrivalled sensitivity to Higgs self-coupling

$$\boxed{\Delta g_{HHH}/g_{HHH} = {}^{+11\%}_{-7\%}}$$