Electroweak precision at e^+e^- colliders

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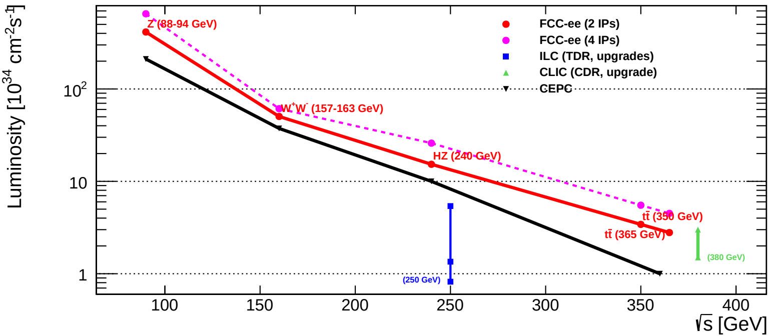
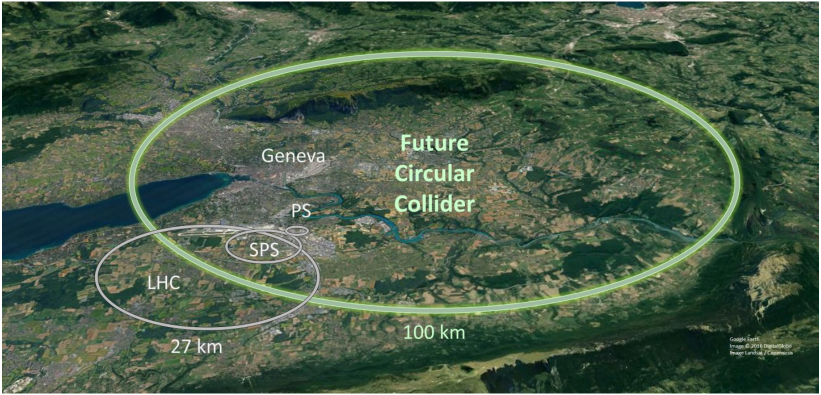
THE ROYAL SOCIETY

FCC Snowmass Report '22

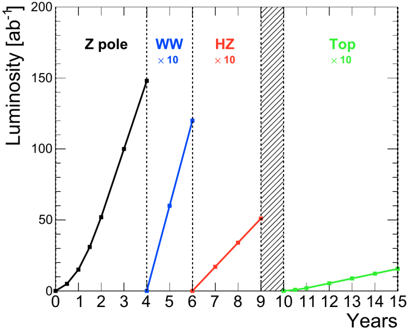


This talk will mainly focus on the electroweak physics of FCC-ee.



FCC-ee precision machine, discovery through precision observables
FCC-eh necessary complement to FCC-hh, proton substructure
FCC-hh discovery through high energy reach and luminosity

Overview



Z pole

EW precision observables
$(m_Z,\ \Gamma_Z,\ \sin^2\theta_W^{\text{eff}},\ \ldots)$
running couplings
$(\alpha(m_Z),\ \alpha_s(m_Z),\ \ldots)$

WW threshold

W spectroscopy
$(m_W,\ \Gamma_W,\ \text{couplings})$

$t\bar{t}$ threshold

top spectroscopy
$(m_t,\ \Gamma_t,\ \text{couplings})$

Zh threshold

Higgs spectroscopy
$(m_h,\ \Gamma_h,\ \text{couplings})$

Highest precision measurements need highest precision theory predictions to make full use of the data.

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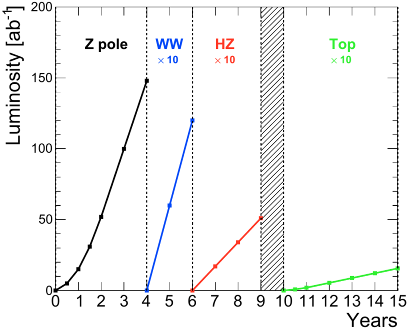

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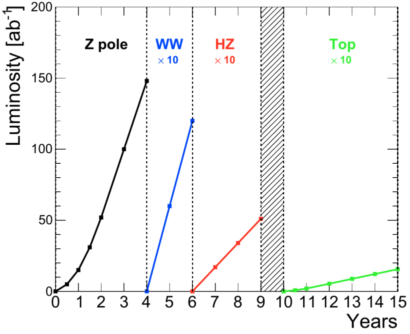

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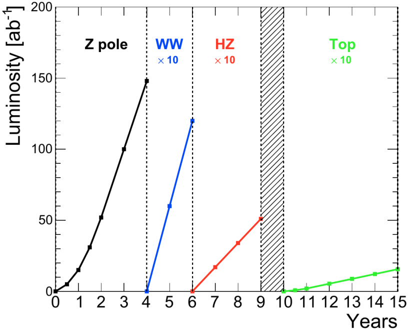

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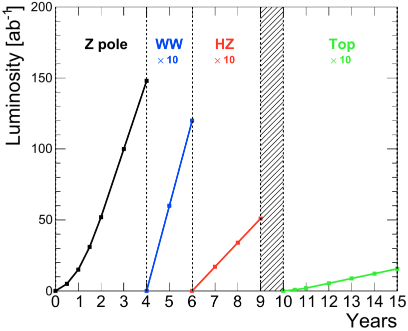

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FCC-ee physics opportunities

Generally, lepton colliders allow for fewer processes/signatures to be studied compared to hadron colliders, but with much higher precision.

FCC-ee statistics much larger than any other e^+e^- machine, allows for study of very interesting but rare processes

- $\gamma\gamma$ physics
- γ structure function (pert. and non-pert.)
- BFKL effects

Need precise electron structure functions which are also differential in the photon (and other partons at $\mathcal{O}(\alpha^2)$).

Needs precise calculation of Bhabha scattering (at least N^{3}LO) for luminosity determination.

The role of the electron structure function

Although the electron is a point-like object, it has a substructure (QED).

YFS soft-photon resummation
Yennie, Frautschi, Suura '61

- resums soft-photon logs
- photon radiation explicit
- most appropriate when $\sqrt{s}$ near resonance

Collinear structure function
Kuraev, Fadin '85

- resums collinear logs
- photon radiation integrated out
- most appropriate when $\sqrt{s}$ well above resonance

⇒ **in practice yield similar results**

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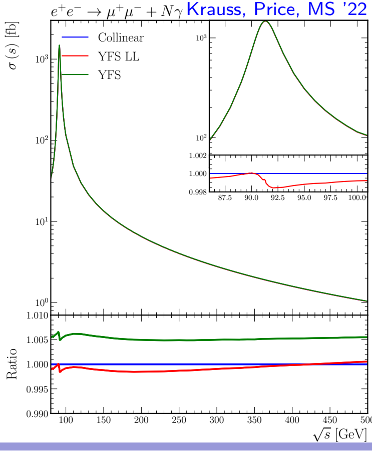
Krauss, Price, MS '22



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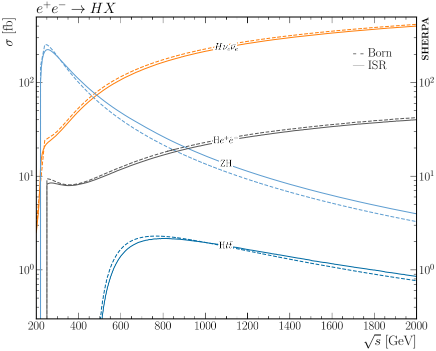


The role of the electron structure function

Bertone et.al. '19

Electron PDF

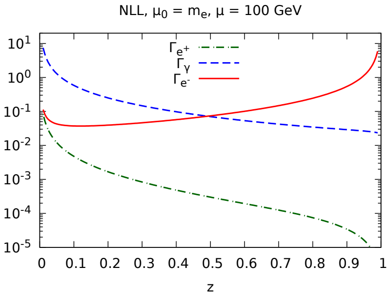
- access to complete partonic content of SM through QED+EW+QCD evolution

$\mathcal{O}(\alpha)$ γ, $W^\pm$, Z, (h)

$\mathcal{O}(\alpha^2)$ $e^\pm$, $\mu^\pm$, $\tau^\pm$, ν

u, d, s, c, b, t

$\mathcal{O}(\alpha^2\alpha_s)$ g



High luminosities allow to study rare process.
Photon luminosity of particular interest.

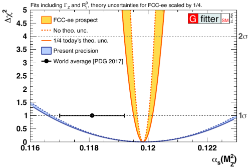
Z pole

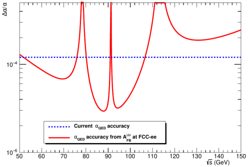
EW precision observables:

use on- and off-peak data to measure Z lineshape, $A_{\mathrm{FB}}(s)$, R_ℓ, . . . ,
and determine m_Z, Γ_Z, $\sin^2\theta_W^{\mathrm{eff}}$, $\alpha(m_Z)$, $\alpha_s(m_Z)$, . . .

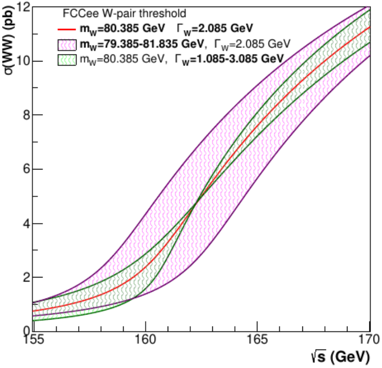
To exploit full data precision theory predictions must keep pace,
otherwise parameter extractions are severely theory limited.

- **NNLO EW needed throughout** ($\mathrm{N^3LO}$ in some places) including ISR, FSR resummation and initial-final interference (IFI)
- need **highest precision Monte-Carlo event generators** to account for finite fiducial region, bremsstrahlung effects, hadronisation corrections, etc.





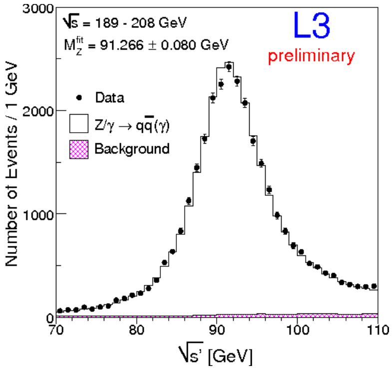
WW threshold



W mass and width determination

- needs precision calculation (NNLO QCD, QCD-EW, EW) and QED threshold resummation
- including implementation in Monte-Carlo event generators to account for finite fiducial region, colour reconnection, hadronisation, etc.
- highest precision calculations still from LEP (YfsWW and RacoonWW)
- $\Delta m_W \approx 0.7$ MeV, $\Delta\Gamma_W \approx 1.5$ MeV

Radiative return



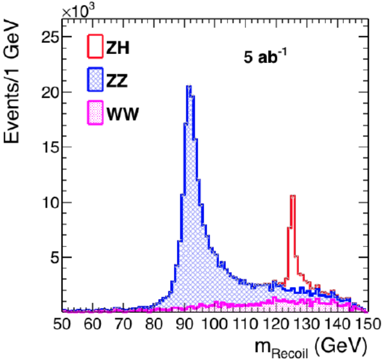
Mainly relevant to determine the invisible Z decay width through $R_\mu^{\text{inv.}} = (\text{inv.} + \gamma)/(\mu^+\mu^- + \gamma)$.

$R_\mu^{\text{inv.}}(s) \neq R_\mu^{\text{inv.}}(3\nu, \text{SM})$ can hint at DM candidates.

QED/EW corrections strongly dependent on precise experimental selection.

Needs **highest precision** fully exclusive **Monte-Carlo event generator** containing multi-loop higher-order QED and EW effects.

Zh threshold

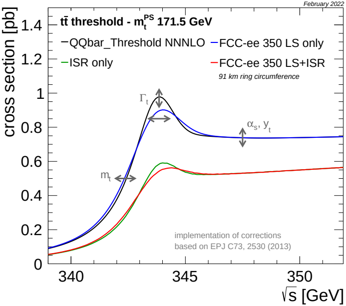


Higgs spectroscopy

- precise mass determination
- direct access to all Higgs decay channels incl. $h \to gg$ and $h \to$ inv.
- **precision fit of EFT parameters**

Monte-Carlo event generators with highest precision for both production mechanisms and Higgs decays necessary.

$t\bar{t}$ threshold – mass and width



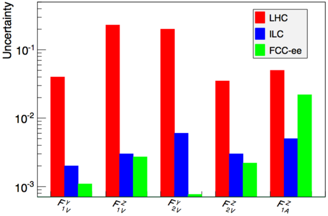
Determination of m_t and Γ_t

- measurement through kinematic reconstruction suffer large systematic uncertainties and ambiguous interpretation
- use shape of production cross section near threshold
  $\rightarrow \Delta m_{\text{top}} \approx 17$ MeV,
  $\Delta\Gamma_{\text{top}} \approx 45$ MeV

$t\bar{t}$ threshold – electroweak couplings

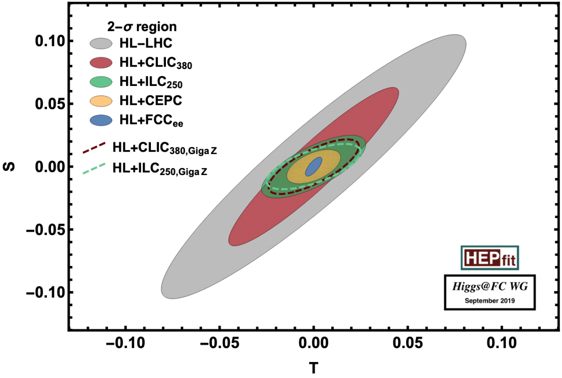
Determination of top quark electroweak couplings, $g_{tt\gamma}$, $g_{t_L t_L Z}$, $g_{t_R t_R Z}$, etc.

- typically using kinematical information above threshold (spin-correlations of final state leptons)
- needs precision Monte-Carlo event generators (NNLO QCD, QCD-EW) to account for finite fiducial region, top decay kinematics, colour reconnection, hadronisation, etc.
  $\rightarrow \delta g_{t_L t_L Z}$, $\delta g_{t_R t_R Z} \approx 2\%$



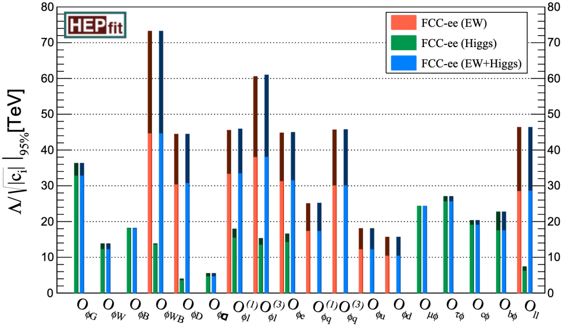
Barducci et.al. '15

EW precision fit



- vast improvements in uncertainties on EW precision data and theory may point towards inconsistencies in the Standard Model

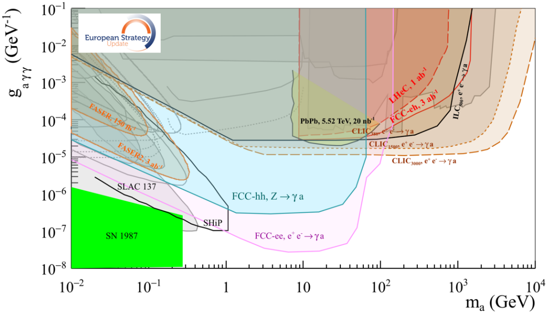
New Physics – EFT interpretation



- extraction from precision data through quantum corrections

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

New Physics – ALPs



- axion-like particles' (ALPs) masses and widths can be constrained mainly through $ee \to \gamma a$
- large parts of the parameter space (medium mass, small coupling) can be excluded thanks to high statistics of FCC-ee
- complementary exclusion of high-mass ALPs for CLIC_{3000}

Common themes (1) – precision

Need for multi-loop (2/3-loop) calculations in the EW sector with its broken symmetry and multiple different mass scales.

This typically involves dedicated efforts of large groups over 10+ years.
Simpler problems for comparison: $pp \to jj$ @ NNLO QCD,
$pp \to h$ @ N^{3}LO QCD.
The EW sector is much more complex than QCD, and grows further with the inclusion of EFT operators.

Examples: Bhabha scattering at $\mathcal{O}(\alpha^5)$ (3-loop QED/EW),
$e^+e^- \to \mu^+\mu^-$ @ $\mathcal{O}(\alpha^5), \mathcal{O}(\alpha^4\alpha_s)$ (3-loop QED/2-loop EW + QED res.)
$e^+e^- \to q\bar{q}$ @ $\mathcal{O}(\alpha^4), \mathcal{O}(\alpha^3, \alpha_s)$ (2-loop QCD+EW + QCD+QED res.)
$\mathcal{O}(\alpha^2\alpha_s^3)$ (3-loop QCD + QCD res.)

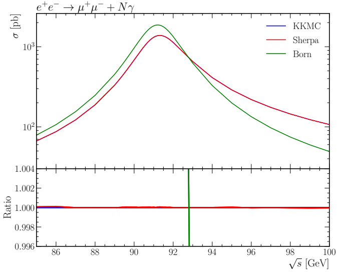
Common themes (2) – event generators

Need for new directions in Monte-Carlo event generator development.

Dedicated e^+e^- generators developed with ILC in mind, but accuracy demands very different.

Current multi-purpose generators (HERWIG/PYTHIA/SHERPA) geared towards LHC needs, but capable of *ee*, *ep*. But not nearly at the precision needed.

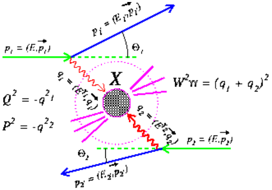
Highest precision MCs still from LEP (KKMC, YFSWW, RACOONWW, ...).



Krauss, Price, MS '22

Dedicated efforts to recover LEP-time accuracy in modern Monte-Carlo event generators has just begun, but sustained dedicated effort needed.

Photon collider

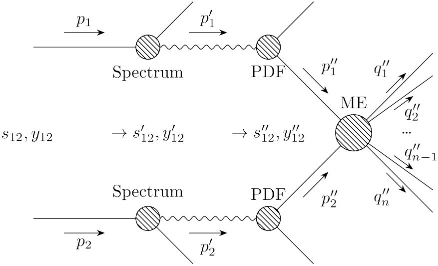


Due to the high luminosity also rare events can be studied, e.g. $e\gamma$ and $\gamma\gamma$ collisions.

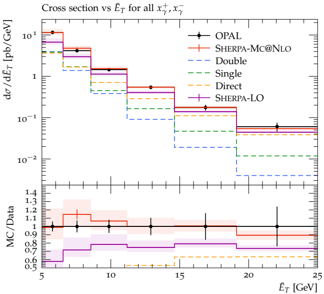
Different types of photonic events:

1) photons produced elastically
   bremsstrahlung photons, produced quasi-classically by interaction of EM field of both incident electrons (equiv. photon approx., EPA)
2) photons produced inelastically
   $e \to \gamma + X$ DGLAP splitting
3) colliding photon has substructure
   $\to$ inner structure of photons is resolved, $\gamma^* \to x$ PDF

Photon collider



Höche, Krauss, Meinzinger '23



Resolved photon collisions

- $e^\pm$ radiate low-virt. photons $\to$ Weizsäcker-Williams/EPA
- substructure of photons resolved using photon PDFs
  - γ mixes with ρ, ω, ϕ, J/ψ

QCD aspects at e^+e^- colliders

Inclusive QCD production, *ee* $\rightarrow$ jets

- integrated over individual hadron properties
- event shapes are an excellent testbed for precision QCD calculations (higher orders, analytic resummation, parton showers) $\rightarrow$ extract α_s

Need a **fully differential higher-order parton shower resummation**, beyond simple *K*-factor modifications of LO showers.

$\Rightarrow$ **see talk by F. Krauss**

QCD aspects at e^+e^- colliders

Identified hadron production

- identified hadron spectra
- perturbative parton evolution
- large non-perturbative component, still poorly understood from first principles, but well modelled by hadronisation models
  $\rightarrow$ precise data will help to kickstart this field

Need a much better understanding of **non-perturbative QCD dynamics**.

Conclusions

e^+e^- colliders, and FCC-ee in particular, offer great physics opportunities, however

- demands high-precision calculation of a number of signatures
  - needs large groups and long-term effort
    $\rightarrow$ long-term concerted funding support to play leading role
  - although few EW experts in the UK, world-leading expertise in precision calculations that can be "repurposed"
- Monte-Carlo event generator development indispensable
  - needs concerted effort to increase accuracy for e^+e^-
  - requires EW Monte-Carlo experts

UK theory generally well positioned to play a leading role at e^+e^- colliders, but needs to be supported accordingly.

Thank you!

Backup