Theory opportunities at the FCC-ee

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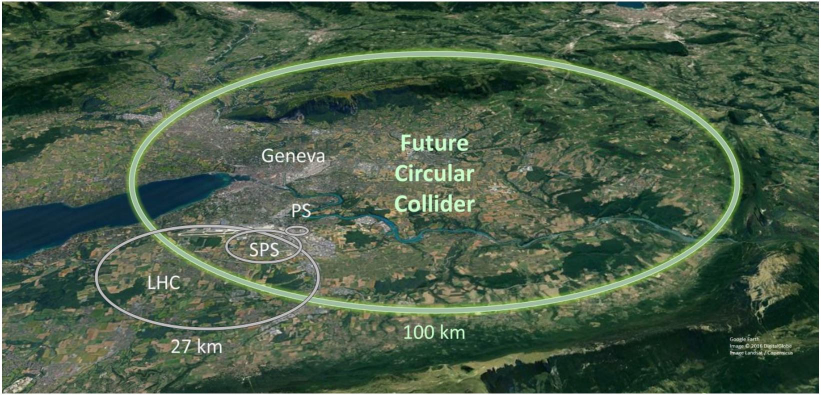
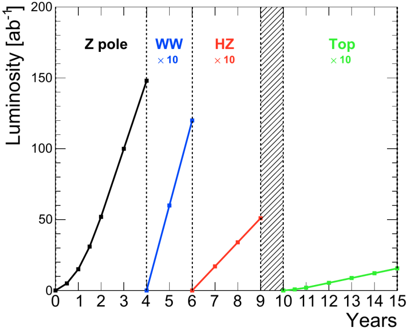


FCC-ee precision machine, discovery through precision observables
FCC-eh necessary complement to FCC-hh, proton substructure
FCC-hh discovery through high energy reach and luminosity

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
(mass, width, couplings)

$t\bar{t}$ threshold

top spectroscopy
(mass, width, couplings)

Zh threshold

Higgs spectroscopy
(mass, width, couplings)

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

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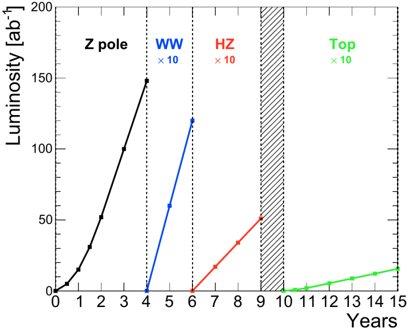

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- running couplings $(\alpha(m_Z), \alpha_s(m_Z), \ldots)$

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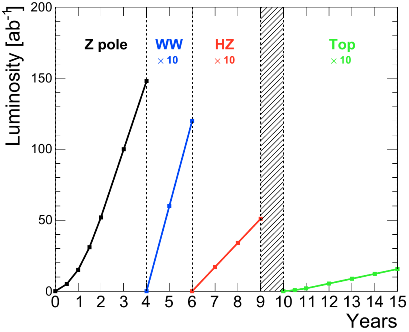

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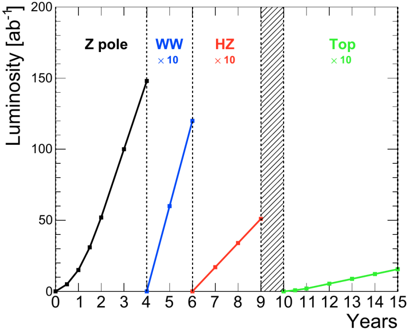

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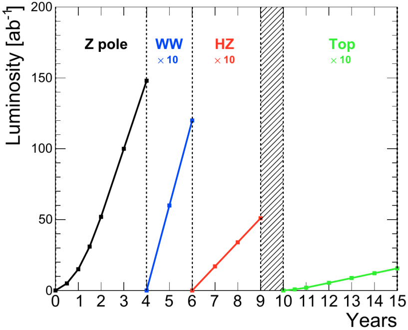

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FCC-ee physics opportunities

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.

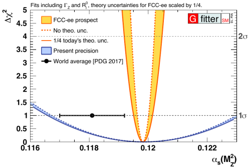
Z pole

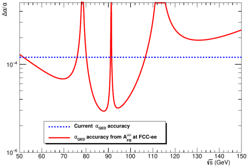
EW precision observables:

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** (N^{3}LO 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.





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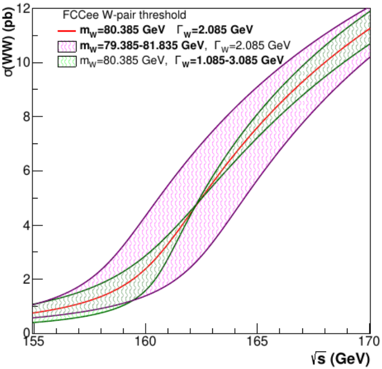
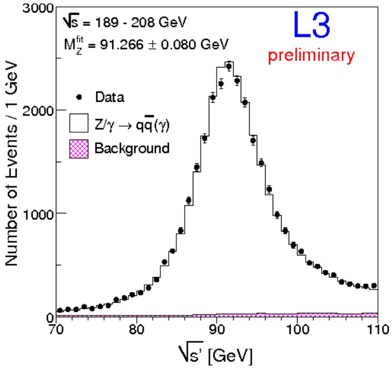


W mass and width determination

- 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)
- $\Delta m_W \approx 0.7\,\text{MeV}$, $\Delta\Gamma_W \approx 1.5\,\text{MeV}$

Radiative return



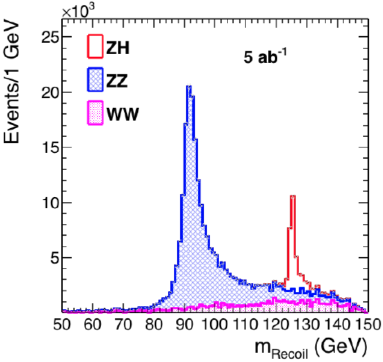
Mainly relevant to determine the invisible Z decay width through $R_\mu^{\text{inv.}} = (\text{inv.} + \gamma)/(\mu^+\mu^- + \gamma)$.

$R_\mu^{\text{inv.}}(s) \neq R_\mu^{\text{inv.}}(3\nu, \text{SM})$ 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

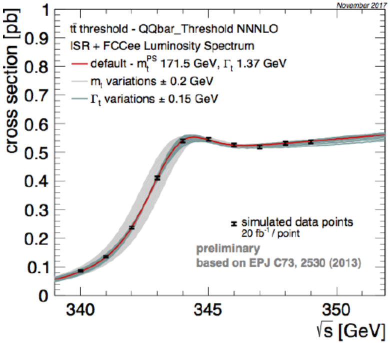


Higgs spectroscopy

- 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.

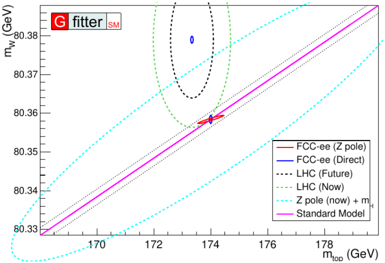
$t\bar{t}$ threshold



top mass and width determination

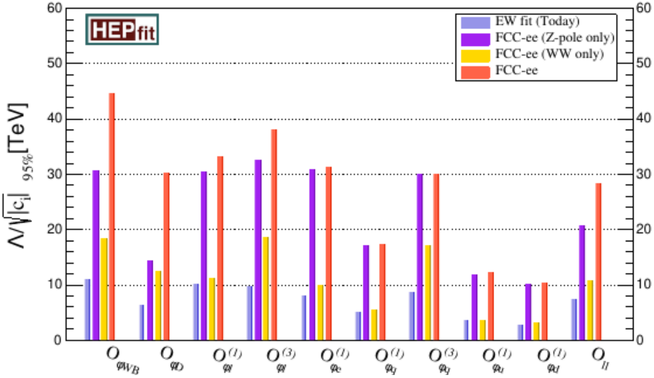
- needs precision calculation (NNLO QCD, QCD-EW) and QED+QCD threshold resummation
- implemented in Monte-Carlo event generators to account for finite fiducial region, top decay kinematics, colour reconnection, hadronisation, etc.
- $\Delta m_{\text{top}} \approx 20\,\text{MeV}$, $\Delta\Gamma_{\text{top}} \approx 40\,\text{MeV}$

EW precision fit



Vast improvement 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
- need precision calculation in SM+EFT

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.

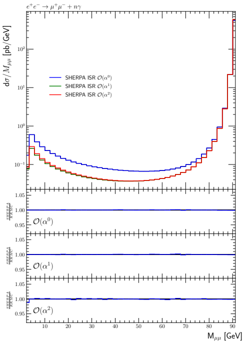
This typically involves dedicated efforts of large groups over 10+ years.
Simpler problems for comparison: $pp \to jj$ @ NNLO QCD,
$pp \to h$ @ N^{3}LO QCD.
The EW sector is much more complex than QCD,
and grows further with the inclusion of EFT operators.

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.

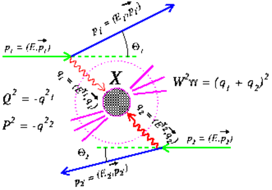
- Dedicated e^+e^- generators developed with ILC in mind, but accuracy demands very different.
- Current multi-purpose generators (HERWIG/PYTHIA/SHERPA) geared towards LHC needs, but capable of *ee*, *ep*. But not nearly at the precision needed.
- Highest precision MCs still from LEP (KKMC, YFSWW, RACOONWW, ...).



from A. Price's PhD thesis

Dedicated effort of 1 PhD student (4 years) to recover LEP-time accuracy (here only KKMC) in modern MC event generator.

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

In this field the UK has leading theory expertise.

Challenges and opportunities for the UK

− relatively few theorists with EW expertise
→ **need to attract more experts**

− precision calcs need large groups and long-term dedicated effort, large continuous individual funding
at odds with current funding structure

\+ world-leading expertise in precision QCD multi-loop calculations and resummation

\+ world-leading expertise in precision Monte-Carlo event generators, still needs long-term concerted effort to reach required precision

\+ world-leading expertise in New Physics/EFT interpretation, EFT higher-order computations

FCC-eh and FCC-hh

FCC-hh mostly commences along similar lines as (HL-)LHC.
Broad spectrum of signatures/process with moderate precision reqs.
Hence, the **UK** is **in good shape to drive theory developments**.

However, some aspects will manifest themselves only at FCC-hh energies:

Consider DY or ggh @ 100 TeV:
$Q^2 \approx 10^4\,\text{GeV}^2$, $x \approx 10^{-3} \ldots 10^{-5}$.
Needs input from FCC-eh or similar for precision PDFs.

In addition, small-x dynamics, BFKL effects, γ-PDFs, etc.

Leading expertise in the UK.

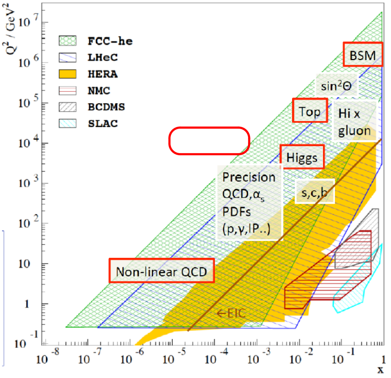


figure from M. Klein's slides

Conclusions

- UK theory generally well positioned to play a leading role at FCC
- FCC-ee has most room for improvement
  - demands high-precision calculation of few signatures
  - needs large groups and long-term effort
    $\rightarrow$ long-term concerted funding support to play leading role
  - although few EW experts, world-leading expertise in precision calculations that can be "repurposed"
- leading role in Monte-Carlo event generator development
  - needs concerted effort to increase accuracy for e^+e^-
- leading role in New Physics/EFT interpretation of precision data

Thank you!

Backup