Higgs Measurements at a Future Circular Collider

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The Case for Future Colliders

What we found at the LHC...

- A Higgs boson.
  $m_h = 125$ GeV,
  $\Gamma_h = 4.1$ MeV

... and what is still missing.

- Dark matter/energy?
- Origin of neutrino masses?
- ...

- On-going and diverse LHC physics programme...
  - Run 2+3: 300 fb^{-1} by 2023
  - HL-LHC: 3000 fb^{-1} by 2035
- ... but need to plan for post-LHC era now!

Is it the SM Higgs?

- Couplings to lightest fermions (e, u, d, s)
- Higgs potential: trilinear+quartic couplings

Is it a key to BSM physics?

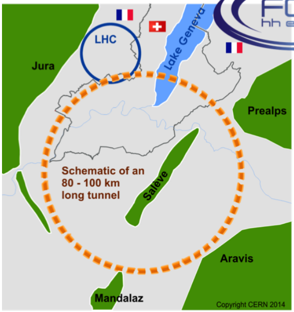
- Precision on b, τ, ... couplings
  Sub-percent precision for $\Lambda \approx \mathcal{O}(1-10)$ TeV!
- Invisible decays to DM?

- Many promising options with complementary physics programmes

ilc CLIC CEPC FCC hh ee he

A Future Circular Collider (FCC)

- FCC international collaboration
- Studying options for circular collider(s) in a new ∼100 km tunnel at CERN
- Kick-off meeting in 2014; latest news: [FCC Week Berlin]
- **Goal:** CDR and cost review in 2018



- **FCC-ee** [TLEP]: e^+e^- collider at 90-350 GeV
  - Could start in 2038 (after HL-LHC)
- **FCC-hh**: pp collider at 100 TeV
  - In the same tunnel
- **FCC-eh**: ep collider
  - See next talk

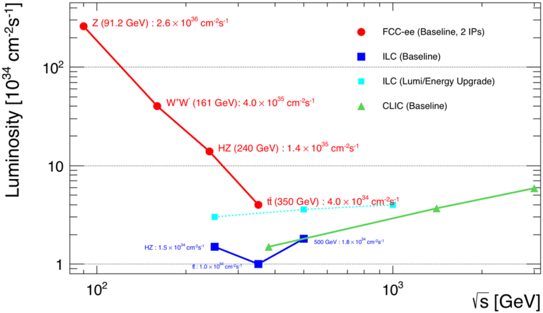
- Similar studies in China: CepC, followed by SppC

FCC Projected Luminosity

Tomorrow:
EW@FCC-ee
Elisabeth Locci

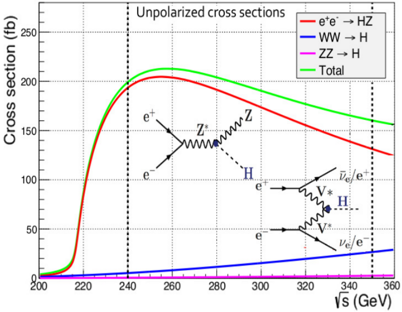
	FCC-ee Z	FCC-ee WW	FCC-ee H	FCC-ee TOP	FCC-hh
√s [GeV]	90	160	240	350	100,000
Inst. Lumi [10^{34}cm^{-2}s^{-1}/IP]	65, then 130	20	7	2.0	5-30
Physics goal [ab^{-1}]	150	8-10	5	1.5	17.5
Runtime [yrs]	6	2	3	3	20

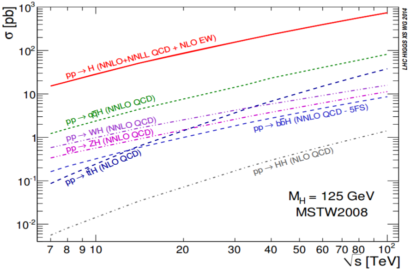
Assuming baseline optics with 2IPs. Runtime estimate tentative.



- Steepling falling luminosity due to bremsstrahlung losses $\propto E^4/R$

FCC - Higgs Factories





FCC-ee

- $\sigma(e^+e^- \to h + X) \approx 200$ fb
- $2 \cdot 10^6$ Higgs events
- Low backgrounds, no pile-up

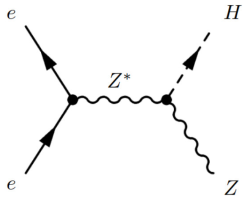
FCC-hh

- $\sigma(pp \to h + X) \approx 900$ pb
  $\Rightarrow$ 18 $\times$ LHC cross-section at 13 TeV
- $2 \cdot 10^{10}$ Higgs event

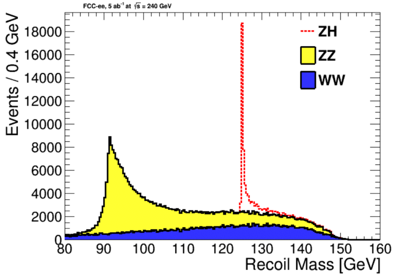
- Optimal conditions for Higgs precision measurements and BSM searches!

The Key to Higgs Precision at FCC-ee

- **Production cross-section** $\sigma_{hZ} \propto g_{hZ}^2$
  - Sensitive to BSM physics that renormalises Higgs couplings by universal factor
  - Determination of absolute couplings and total width $\Gamma_{\text{tot}} \propto \frac{\sigma_{hZ}{}^2}{\sigma_{hZ} \times \text{BR}(h \to ZZ)}$
- **Recoil method**: tag events independent of Higgs boson decay
  - Unique to lepton colliders
  - Model-independent measurement!



Recoil mass: $m_{\text{R}}^2 = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p_{\ell\ell}}|^2$
Only $Z \to e^+e^-$ or $\mu^+\mu^-$



Results for 5 ab^{-1} at 240 GeV

- $\delta\sigma_{hZ}/\sigma_{hZ} \approx 0.4\% \Rightarrow \delta g_{hZ}/g_{hZ} \approx 0.2\%$
- Probe $\Lambda \approx 3$ TeV

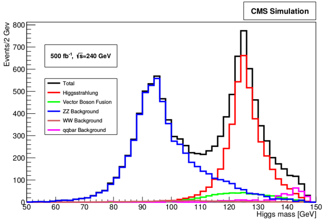
Higgs Couplings

- Measure $\sigma(e^+e^- \to Zh) \cdot \mathrm{BR}(h \to X)$ by tagging X
- Couplings from global, model-independent fit to measured values in all final states
- Combining measurements at 240 and 350 GeV

in %	HL-LHC	FCC-ee
g_{HZ}	2-4	0.21
g_{HW}	2-5	0.43
g_{Hb}	5-7	0.64
g_{Hc}	-	1.04
g_{Hg}	3-5	1.18
$g_{H\tau}$	5-8	0.81
$g_{H\mu}$	5	8.79
$g_{H\gamma}$	2-5	2.12
Γ_H	5-8%	1.55

arXiv:1307.7135 arXiv:1308.6176

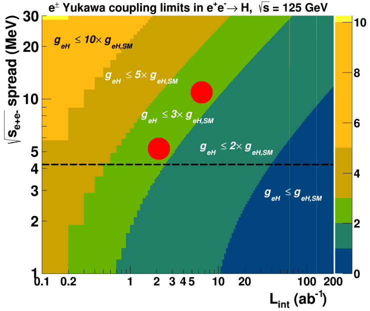
$e^+e^- \to Zh \to (\nu\bar{\nu})(b\bar{b})$



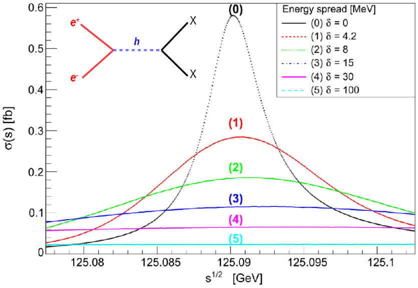
- Factor 10 improvement in most cases!
- FCC-ee numbers obtained for CMS-like detector
- Studies with alternative detector configurations (e.g. ILD) under way

Electron Yukawa Coupling

- Resonant s-channel production: $\sigma(e^+e^- \to h) = 1.64$ fb
- Reduced by factor x due to
  - Initial-state photon radiation
  - Beam energy spread δs
- Total reduction x=0.17 at $\delta s = \Gamma_h$
  - Via monochromatisation



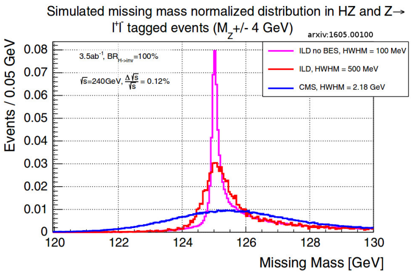
S. Jadach, R.A. Kycia / Physics Letters B 755 (2016) 58-63



- Preliminary study based on "cut-and-count" in 10 different decay channels
- Baseline: $\delta s = 6$ MeV, L=2 ab^{-1}
- Optimised: $\delta s = 10$ MeV, L=7 ab^{-1}
- 95% CL upper bound on y_e: $3.5\times$ SM expectation

Invisible Higgs Decays

- SM: BR$(h \to ZZ^* \to 2\nu 2\bar{\nu}) = 0.1\%$
- Significantly enhanced in various BSM models, e.g. Higgs portal models
- Current LHC upper limit: $\text{BR}_{95\%}(h \to \text{inv}) < 25\%$ [Signatures: VBF, $Z(\ell\ell)h$, $V(jj)h$]



- Missing mass from recoil method
- Sensitivity depends on
  - Tracking resolution (CMS vs ILD)
  - Beam energy spread

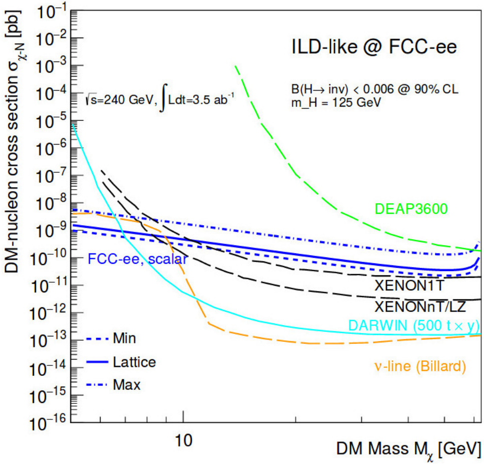
	$BR_{95\% limit}$	$BR_{5\sigma}$
CMS-like	$0.92 \pm 0.32\%$	$2.5 \pm 0.2\%$
ILD-like	$0.63 \pm 0.22\%$	$1.7 \pm 0.1\%$

- Results for $Z \to \ell\ell$ and L=3.5 ab^{-1}
- $Z \to q\bar{q}$ and update to L=5.0 ab^{-1} under study

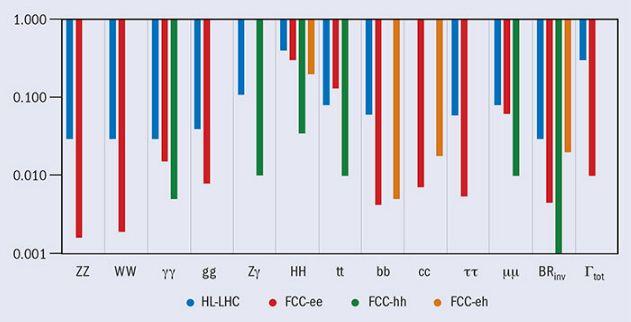
Invisible Higgs Decays and DM

- Re-interpretation in terms of DM-nucleon cross-section
- FCC-ee competitive with future direct-detection experiments for $m_{\mathrm{DM}} < 10$ GeV

Higgs portal model; comparison from [arxiv:1605.00100]

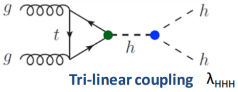


Complementarities



- Studies on-going to optimise FCC-ee detector design(s)
- Synergies with non-Higgs measurements (EW, diboson, top) not considered

- FCC-ee drives sensitivity for many properties
- Notable exceptions: due to luminosity constraints above the hh and $t\bar{t}$ thresholds
  - Higgs self coupling
  - Top Yukawa coupling (e.g. via $t\bar{t}h/t\bar{t}Z$ ratio)



- Crucial inputs to FCC-hh from FCC-ee (e.g. Γ_{tot}, $t\bar{t}Z$ coupling)

Summary and Outlook

- FCC programme provides exciting opportunities for Higgs and BSM physics
  - Precision measurements of couplings to gauge bosons and fermions
  - Measurements of trilinear and quartic couplings
  - Searches for invisible and rare Higgs decays
  - ...
- Complementarity between FCC-ee and FCC-hh
- Success of Higgs programme depends on developments in other fields
  - Advancements in beam optics
  - Optimisation of detector design(s)
  - Reduction of uncertainty on theoretical predictions

    Goal: $\Delta_{\mathrm{th.}} \ll \Delta_{\mathrm{exp.}}$, currently: $\Delta_{\mathrm{th.}} \approx \mathcal{O}(1\%)$

- CDR and cost estimate in 2018
- **Stay tuned for new results!**

THANK YOU!

References

- FCC-hh Higgs Physics (2016): Contino et al. [arxiv:1606.09408]
- FCC-ep Baseline: EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017
- LEP3 Note: CMS NOTE 2012/003 [arxiv:1208.1662]
- TLEP Paper: JHEP 01 (2014) 164 [arxiv:1308.6176]

Many thanks to Markus Klluthe, Alain Blondel, and Christophe Grojean for their input!

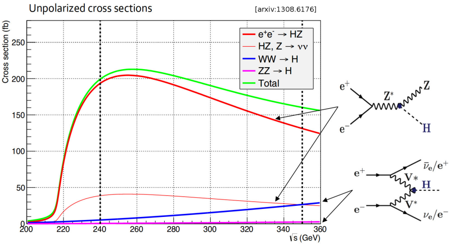
Additional Material

Higgs Total Width

Key observation

$\Gamma(h \to ZZ) \propto \sigma_{hZ}$

- Select Higgsstrahlungs events with $h \to ZZ$
- $\Gamma_{\text{tot}} = \frac{\Gamma(h \to ZZ)}{\text{BR}(h \to ZZ)} \propto \frac{\sigma_{hZ}^2}{\sigma_{hZ} \times \text{BR}(h \to ZZ)}$



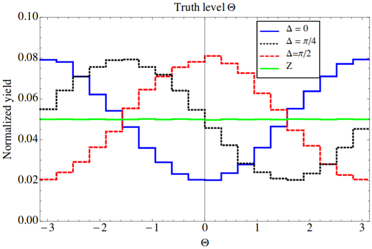
- Same argument for VBF production with $h \to WW$
- Combine measurements at 240 GeV and 350 GeV for optimal precision

CP Structure of Higgs-Fermion Couplings

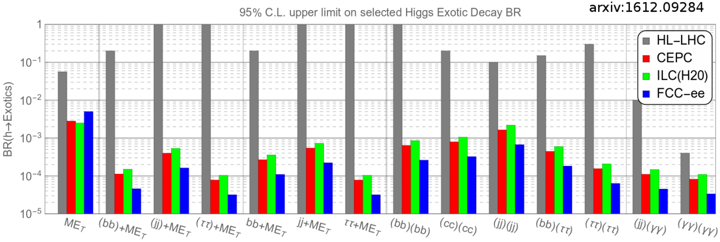
- BSM physics may lead to CP violation in Higgs-fermion couplings

$$\mathcal{L}_{hff} \propto h\bar{f}(\cos\Delta + i\gamma_5 \sin\Delta)f \quad (1)$$

- CP phase Δ from spin of $f\bar{f}$ final state
- $h \to \tau\tau$ provides complex, yet clean enough final state
- Focus on $\tau \to \rho^{\pm}\nu_\tau \to \pi^{\pm}\pi^0\nu_\tau$ decay (25% BR)



Exotic Higgs Decays



Why Higgs Precision Measurements?

- BSM states at scale $\Lambda \Rightarrow$ Higgs couplings g_{hXX} deviate from SM expectation
  - Model-independent description via SM Effective Field Theory (EFT)
  - Coupling of BSM states g^* where usually $g^* = 1$ is assumed

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i \text{ with dim-6 operators } \mathcal{O}_i$$

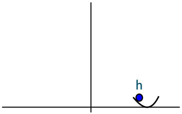
Relative change of Higgs couplings

$$\frac{\delta g_{hXX}}{g_{hXX}^{\text{SM}}} \leq 5\% \cdot \left(\frac{g^*}{1}\right) \cdot \left(\frac{1\text{TeV}}{\Lambda}\right)^2$$

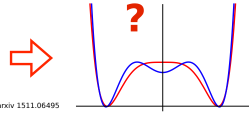
- **Need sub-percent precision to probe $\Lambda \approx \mathcal{O}(1-10)$ TeV!**

Higgs Trilinear Coupling

Current measurements

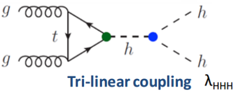


arxiv 1511.06495

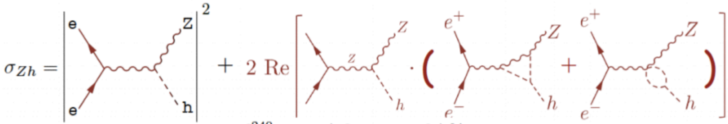


$$V_{\rm h} = \frac{m_h^2}{2} h^2 + (1+\kappa_3)\lambda_{hhh}^{\rm SM} v h^3 + \frac{1}{4}(1+\kappa_4)\lambda_{hhhh}^{\rm SM} h^4$$

- FCC-hh
- - Direct measurements from Higgs pair production
  - Need sufficient statistics above *hh* threshold



- FCC-ee
  - Indirect measurement via NLO loop corrections to σ_{hZ} (model-dependent)
  - Benefit from high precision on σ_{hZ}



$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

Crab Waist Scheme

- Large crossing angle θ and narrow beam (small σ_z/σ_x)
- Rotate β-function waist to be parallel to direction of other beam
- M. Zobov et al. [arxiv:1608.06150]