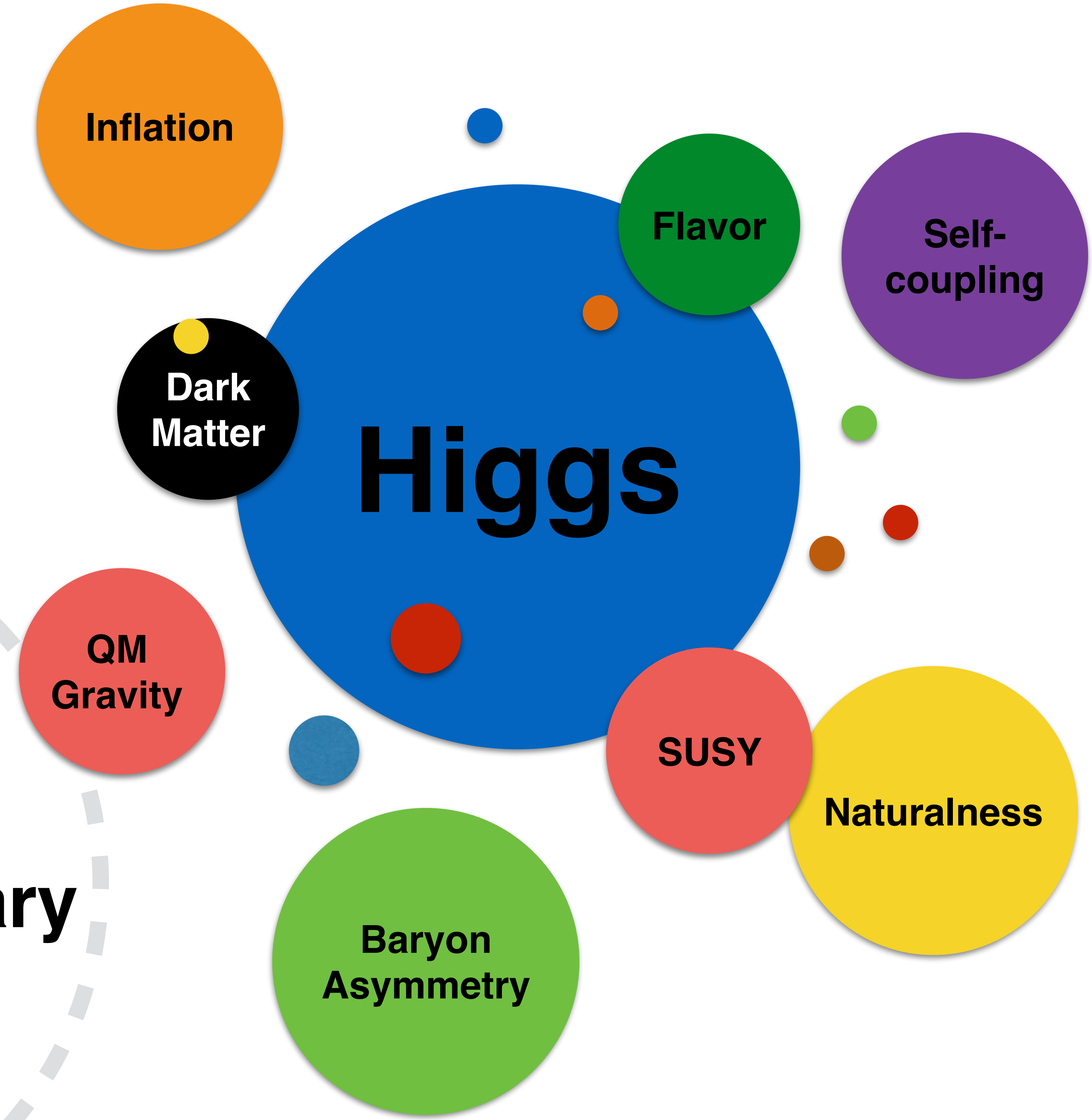


Workshop Summary and Discussion

Markus Klute
September 25th, 2015
First FCC-ee Workshop on Higgs Physics

Many Thanks

- **… to all speaker for excellent presentations**
- **… to all participants for lively discussion**

Schedule

Talk	Speaker	Location	Time
Welcome and Introduction	*Krisztian PETERS*	*Salle Anderson, CERN*	09:00 - 09:20
Summary of FCC-ee Higgs results	*Markus KLUTE*	*Salle Anderson, CERN*	09:20 - 09:55
Higgs Physics at the HL-LHC and complementarity to FCC-ee	*Lorenzo BIANCHINI*	*Salle Anderson, CERN*	09:55 - 10:30
Higgs Physics at the FCC-hh and complementarity to FCC-ee	*Heather GRAY*	*Salle Anderson, CERN*	10:50 - 11:25
Higgs Physics at the ILC	*Tim BARKLOW*	*Salle Anderson, CERN*	11:25 - 12:00
Muon Collider as a Higgs Factory	*Mark PALMER*	*Salle Anderson, CERN*	12:00 - 12:25
Comparing the Higgs Physics program at FCC-ee and Muon Collider	*Patrick JANOT*	*Salle Anderson, CERN*	12:25 - 12:50

Talk	Speaker	Location	Time
Theory input for FCC-ee Higgs precision measurements	*Ayres FREITAS*	*Salle Anderson, CERN*	14:00 - 14:45
EW and Higgs physics interplay		*Salle Anderson, CERN*	14:45 - 15:20
BSM models relevant for Higgs precision measurements	*Francesco RIVA*	*Salle Anderson, CERN*	15:20 - 16:05
Rare and exotic Higgs decays	*Julia SHELTON*	*Salle Anderson, CERN*	16:30 - 17:00
Prospects on MC tools for FCC-ee	*Olivier Pierre C MATTELAER*	*Salle Anderson, CERN*	17:00 - 17:30
Status of Analysis Software for FCC-ee studies	*Colin BERNET*	*Salle Anderson, CERN*	17:30 - 18:00

Talk	Speaker	Location	Time
Benchmarks for FCC-ee detectors	*Krisztian PETERS*	*Salle Anderson, CERN*	09:00 - 09:20
FCC-ee (125 GeV): s-channel Higgs production	*David D'ENTERRIA*	*Salle Anderson, CERN*	09:20 - 09:40
Light quark couplings	*Rick Sandeepan GUPTA*	*Salle Anderson, CERN*	09:40 - 10:00
CP measurements	*Aram APYAN*	*Salle Anderson, CERN*	10:00 - 10:20
Effective field theory approach	*Tevong YOU*	*Salle Anderson, CERN*	10:20 - 10:40
Higgs and dark photon searches	*Matti HEIKINHEIMO*	*Salle Anderson, CERN*	11:00 - 11:20
Higgs production through sterile neutrinos	*Oliver FISCHER*	*Salle Anderson, CERN*	11:20 - 11:40
Workshop summary and discussion	*Markus KLUTE*	*Salle Anderson, CERN*	11:40 - 12:10

HL-LHC

- Entering phase of precision measurements with Run II
- HL-LHC will set a high bar
- Significant improvement wrt to projections possible by improvement on systematic uncertainties

Optimistic scenario: for one experiment

	$\delta\kappa/\kappa$	
κ_V, κ_γ	**3%**	**Gauge bosons**
κ_b	**4%**	**Bottom Yukawa**
κ_t	**5%**	**Top Yukawa**
κ_τ	**3%**	**Leptons**
κ_μ	**5%**	**2nd family**

Channel	Sensitivity	$\delta\mu$ ($\approx 1.3\,\delta\lambda$)
$bb\gamma\gamma$	1.3σ	~80%
$bb\tau\tau$	0.9σ	~100%
$bbWW$	-	> 200%
$bb\gamma\gamma + bb\tau\tau$	**1.9σ**	**54%**

$\delta\lambda$ ~50%
(per experiment)
possible @ HL-LHC

FCC-hh

- Focus on HH, ttH and rare decays ($\mu,\gamma,Z\gamma$)
- Qualifying detector design
- Clear and more subtle complementarity between FCC-ee and FCC-hh Higgs program

Observable	FCC-hh	FCC-ee
Heavy Higgs States		
Rare Higgs Decays		
EW Precision Observables		
Higgs Couplings		
ZH cross-section		
Higgs self-coupling		

ILC

- Comparing and combining ILC and FCC-ee results
- Combination and conclusion based on ILC-upgrade performance

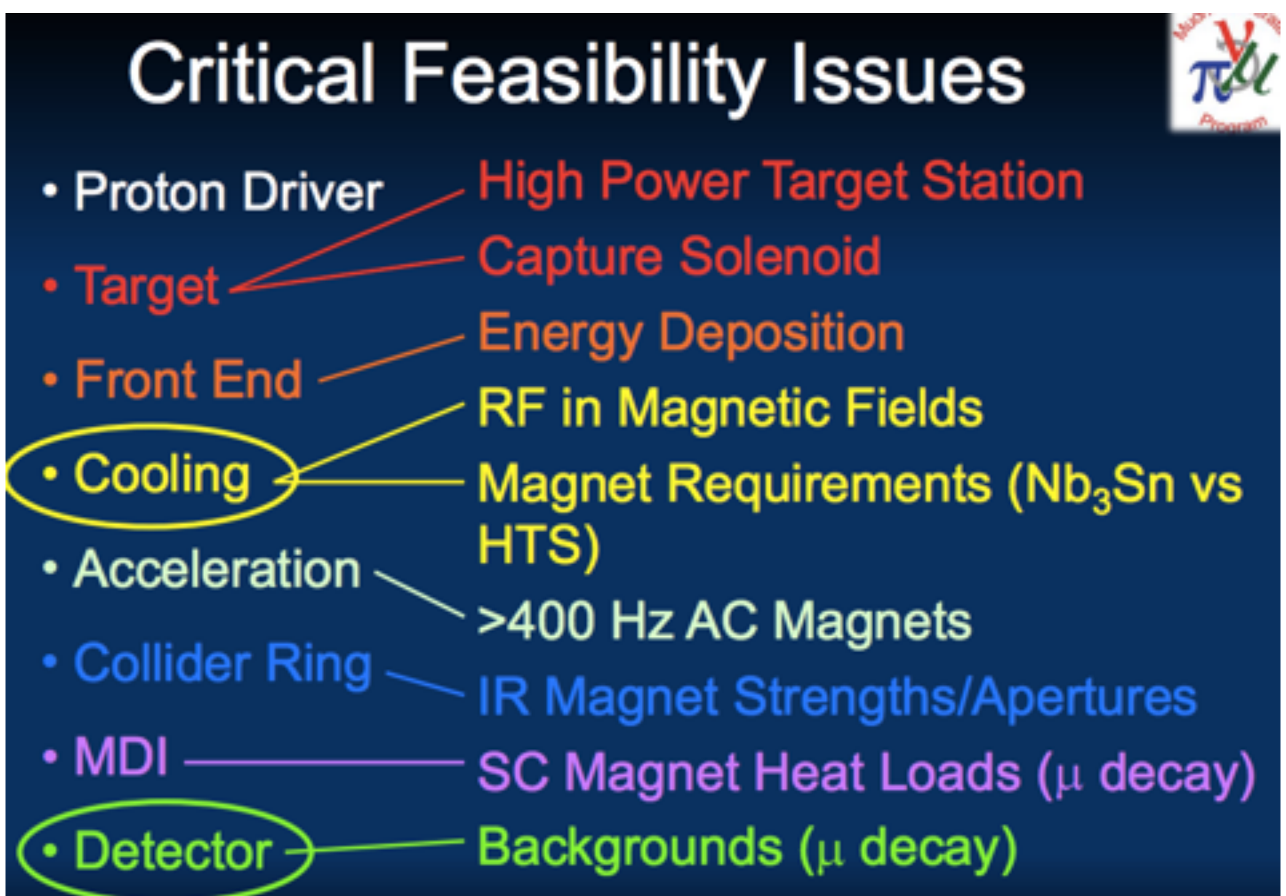
- ILC helps FCC-ee:
  - The 0.25% measurement of $\sigma(\nu\nu h)XBR(H\rightarrow bb)$ reduces errors on all Higgs couplings
  - The 2.4% Top Yukawa coupling measurement from ttH production improves upon the 13% measurement from the tt threshold scan.
  - ILC $\sigma(ZHH)$ measurement provides a 27% tree-level determination of the Higgs self-coupling, and could help clarify a Higgs self-coupling interpretation of the precision FCC-ee $\sigma(ZH)$ measurement.

- FCC-ee helps ILC:
  - Precision measurement of g_{HZZ} and various σXBR at 240 GeV help turn the ILC 0.25% measurement of $\sigma(\nu\nu h)XBR(H\rightarrow bb)$ into $\Delta g_{WW} = 0.22\%$
  - Much better meas. of Higgs invisible width, BSM decays, rare decays such as $\gamma\gamma$ and $\mu\mu$ Note: $\sum BR_i = 1$ can be used to improve all coupling errors if $\Delta BR(H \rightarrow BSM) < 1\%$
  - Unique access to Higgs coupling to 1st generation fermions.

- FCC-ee+ILC combination helps the particle physics community:
  - Higgs Z coupling error $\Delta g_{HZ} = 0.16\%$
  - Higgs W coupling error $\Delta g_{WW} = 0.22\%$
  - Higgs b coupling error $\Delta g_{bb} = 0.38\%$
  - Higgs self coupling error $\Delta g_{HHH} = 20\%$

Muon Collider

- Significant progress on muon cooling
- Missing detailed analysis with detector performance and beam background



A muon collider at $\sqrt{s}$ = 125 GeV is a pretty Higgs factory
- But not necessarily the one we need
  - Only a few Higgs couplings are accessible (b, μ, W, τ) with a 2-5% precision
    - The Higgs total decay width can be measured with a 5% precision
  - If H is a single particle, we will know more from e^+e^- collisions at the FCC-ee
    - All Higgs couplings can be measured with 0.1 – 1% precision
    - Sensitive to the Higgs invisible branching fraction down to 0.1%
  - Important : e^+e^- colliders can measure the Higgs width very well
    - Precision of 0.9% at the FCC-ee (4% at the ILC)

Muon colliders may have a case if H(125) is formed by nearby peaks
- Separated by less than few 100 MeV and by more than a few MeV
  - Can be observed via $e^+e^- \to hA$ at FCC-ee
  - A similar situation occurs for heavy H and A: requires $m_{H,A}$ to be known beforehand
  - Open the possibility of nice (and unique) CP studies

Muon colliders may be the best way to reach $\sqrt{s}$ > 3 TeV with leptons
- Much R&D remain to be done in cooling and acceleration

Theory Input

EWPOs:

- FCC-ee will reduce exp. error by factor $\gtrsim 10$ compared to LEP/SLC
  $\longrightarrow$ Current SM theory calculations not sufficient
  $\longrightarrow$ 3-loop and partial 4-loop (5-loop?) corrections needed!

- Good control over input parameters m_{t}, M_{W}, α_{s} and $\Delta\alpha_{\mathrm{rad}}$ is crucial
  $\longrightarrow$ Can possibly be all determined at FCC-ee itself (cross-checks?)
  $\longrightarrow$ Probably limited by theory uncertainties!

Higgs observables:

- Theory predictions for Higgs decays under good control
  $\longrightarrow$ Improvements for $h \to WW^*$, ZZ^* needed but probably manageable
  $\longrightarrow$ Improvements for $h \to gg$ challenging (5-loop QCD)

- Significant work needed for Higgs production in e^+e^- (2-loop electroweak!)

- Good control over input parameters m_b and α_{s} crucial
  $\longrightarrow$ Improvements of lattice techniques for m_b?

EW Precision

- Time needed to achieve this ambitious programme
  - Number of events expected for each year of running at the FCC-ee

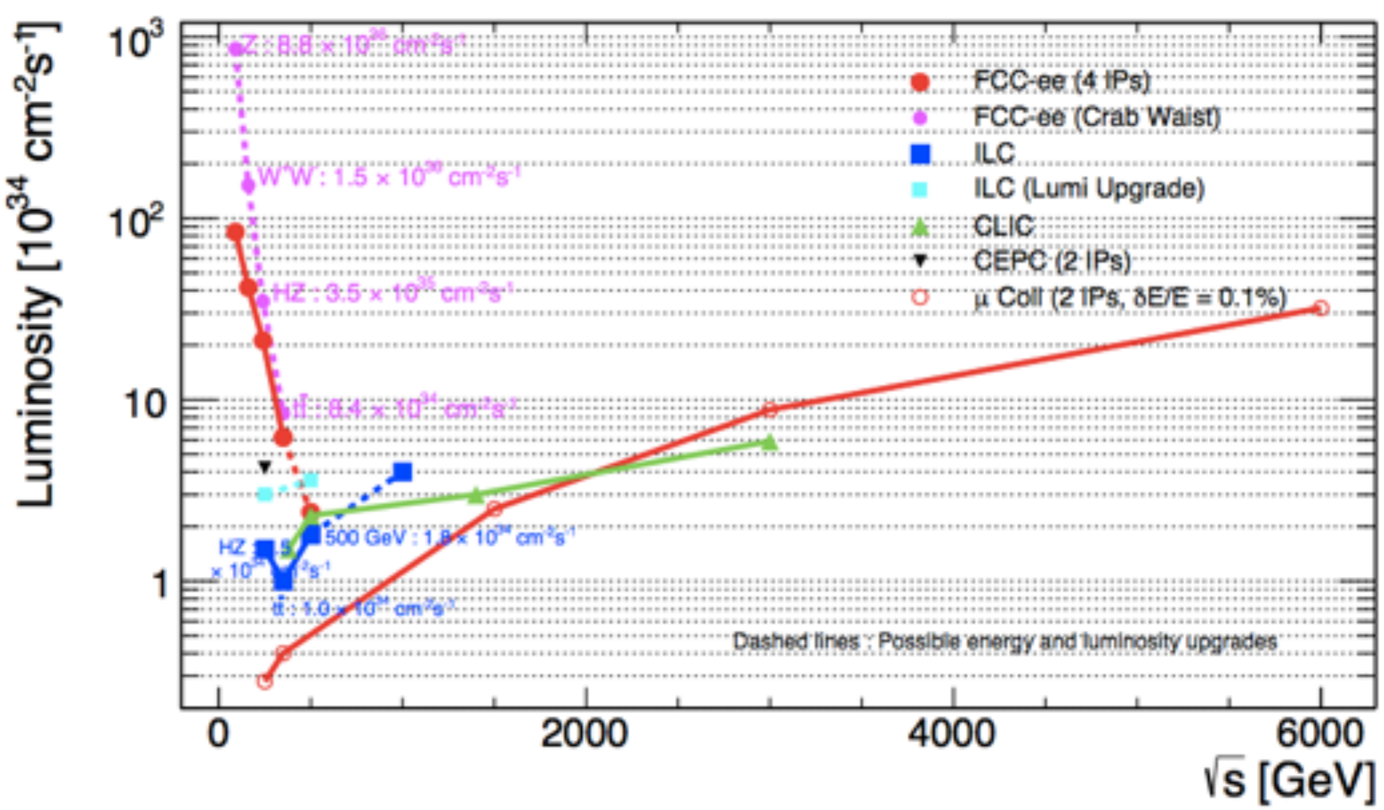
Top couplings

√s (GeV)	90 (Z)	160 (WW)	240 (HZ)	350 (tt)	350+ (WW→H)
Lumi (ab^{-1}/yr)	86.0	15.2	3.5	1.0	1.0
Events/year	3.7×10^{12}	6.1×10^{7}	7.0×10^{5}	4.2×10^{5}	2.5×10^{4}

- Number of years needed to complete the core programme $N_Z=10^{(12)13}$ 1 year = 10^7 s

# years	(0.3) 2.5	1	3	0.5	3

With 4 IP can execute Z,W,H,t program in 10 years of full luminosity operation (10^7 s/year)
Commissioning etc, to be added -- but as usual, hard to guess



In view of the accelerator design:
-- energy calibration is essential
-- Jury is still open on longitudinal polarization
-- no obvious need except perhaps at the Z peak
-- nobody complains about too much luminosity (pile-up < 0.001)
-- for the EW fits, we need to cover Z,W, and top.

In view of the design study report:
-- unprecedented precisions can be achieved on all fronts
-- All parametric errors can be considerably reduced to below the exprimental uncertainties and reveal the
absolute need to improve the theoretical accuracies
==> a plan for this has to be included in the design report.

more observables to investigate (A_{FB}^b, R_b, etc...)

-- the resulting precision in terms of reach for new physics can be quantified in various ways -- we need to work on this.

BSM and Exotics

The power of Indirect Searches

- In weakly coupled UV theories? Coefficients of order 1

$E \to m_h$ for most effects

$$\sigma \simeq \sigma_{SM} \left(1 + \frac{E^2}{\Lambda^2}\right)$$

Can this give access to scales untouched by LHC?

Probably

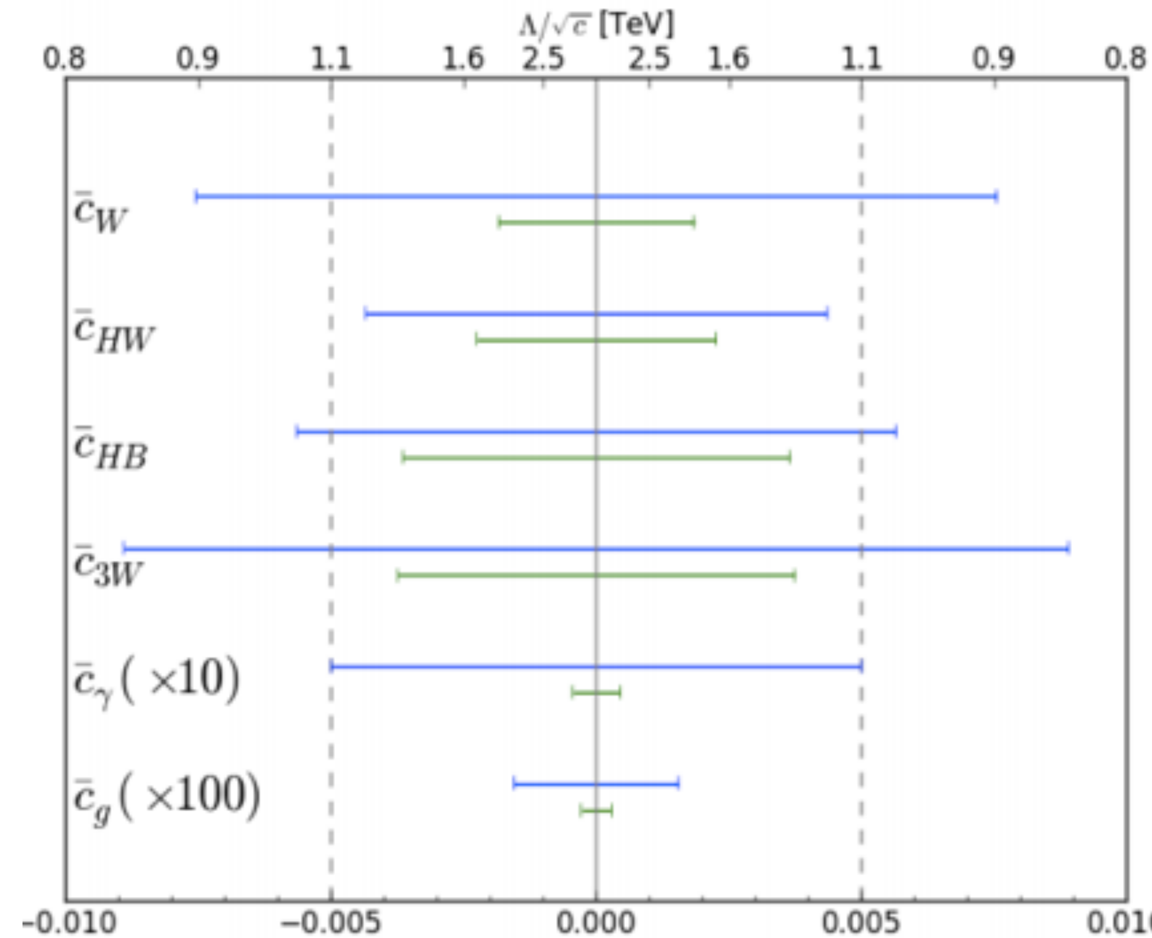
- In Strongly coupled theories? Coefficients enhanced by $g^* \approx 4\pi$

$$\sigma \simeq \sigma_{SM} \left(1 + \frac{g_*^2}{g^2}\frac{E^2}{\Lambda^2}\right)$$

Access to scales 10x higher than weakly coupled theories Surely!

Higgs Physics Only	EW and Higgs physics
$\mathcal{O}_r = \lvert H\rvert^2 (D_\mu H)^\dagger (D^\mu H)$	$\mathcal{O}_{WB} = \frac{gg'}{4}(H^\dagger \sigma^a H) W^a_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$	$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$
$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R$	$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$
$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \tilde{H} u_R$	$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$
$\mathcal{O}_{GG} = \frac{g_s^2}{4}\lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}_{BB} = \frac{g'^2}{4}\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$
$\mathcal{O}_{WW} = \frac{g^2}{4}\lvert H\rvert^2 W^a_{\mu\nu} W^{a\mu\nu}$	$\mathcal{O}_L^{(3)q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$
$\mathcal{O}_6 = \lambda \lvert H\rvert^6$	$\mathcal{O}_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$
	$\mathcal{O}_L^{(3)} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \sigma^a \gamma^\mu L_L)$

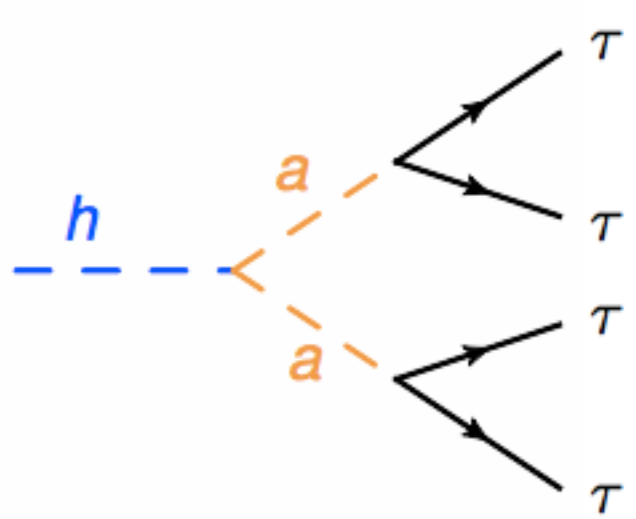
EFT approach window to heavy new physics



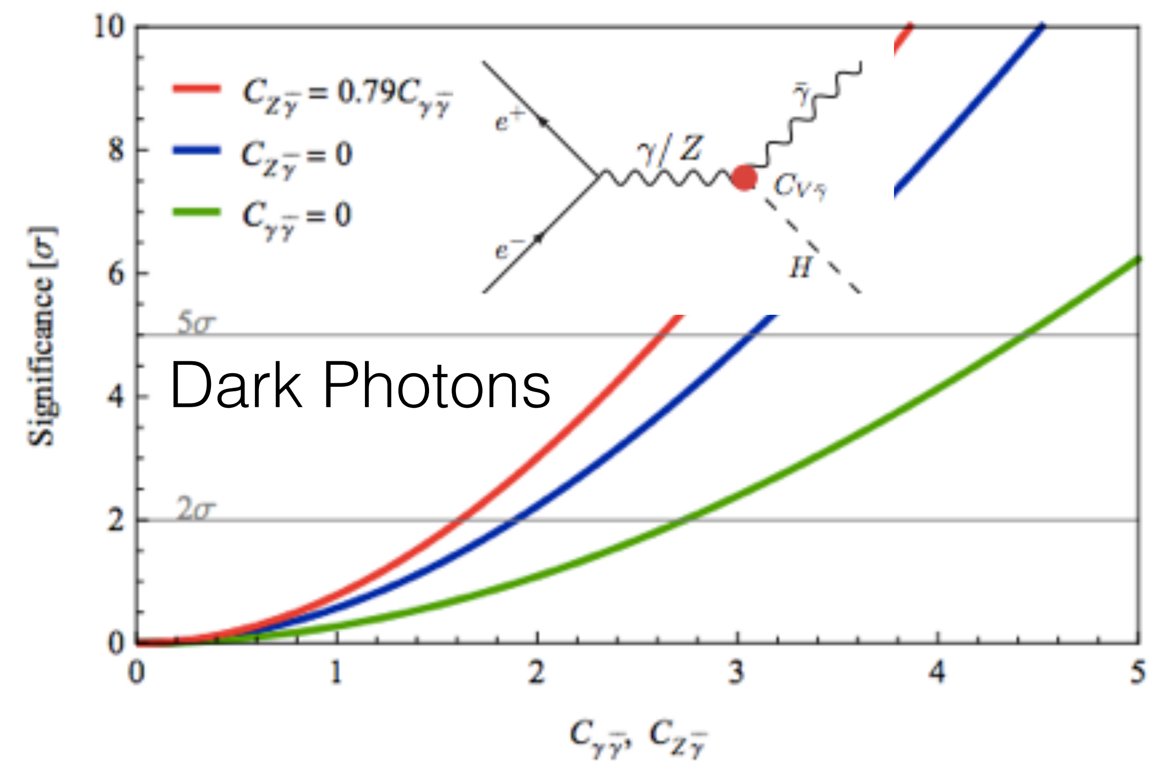
-Blue: ILC250 with TGC at $\mathcal{O}(10^{-4})$
-Green: FCC-ee with TGC at $\mathcal{O}(10^{-4})$

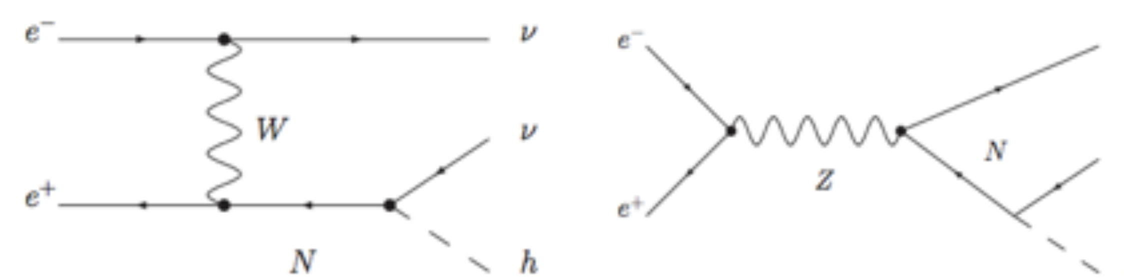
BSM and Exotic Higgs

- Exotics: largely unexplored territory!



- A Higgs factory will give an excellent opportunity to search for new physics in Higgs decays
- Many well-motivated BSM theories predict weak-scale particles that couple to the SM dominantly through the Higgs boson
- Major advantages of FCC-ee for exotic Higgs decays:
  - inclusive width measurement
  - direct searches for "messy" decay modes, where hadron machines cannot exploit their statistical advantage





Sterile neutrinos are well motivated extensions of the SM.

Symmetry protected scenarios allow for large Yukawa couplings and masses in the interesting range.

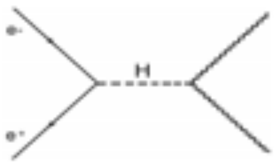
$\sqrt{s} =$ 350 GeV is almost as sensitive as 240 GeV.

Higher center-of-mass energies lead to increased production cross sections.

1st and 2nd generation coupling

Electrons

- Resonant s-channel Higgs production at FCC-ee ($\sqrt{s}$ = 125 GeV):



$\sigma(e^+e^- \to H)_{B\text{-}W} \sim 1.64$ fb

$\sigma(e^+e^- \to H)_{visible} \sim 290$ ab (ISR + $\sqrt{s}_{spread} \sim \Gamma_H = 4.2$ MeV)

- Signal + backgrounds study for 7 decay channels:
  WW*(2j,lν) (σ = 28 ab), WW*(2l2ν) (σ = 6.7 ab), WW*(4j) (σ = 29.5 ab)
  ZZ*(2j2ν) (σ = 2.3 ab), ZZ*(2l2j) (σ = 1.14 ab),
  bb (2j) (σ = 156 ab), gg (2j) (σ = 24 ab)
- Preliminary analysis ($L_{int} = 10$ ab^{-1}):
  S=0.65: BR(Hee) < $3\times BR_{SM}$ (95% CL), $g_{eH} < 1.75\times g_{eH,SM}$ (95% CL)
  Evidence (observation?) will require further improvements in large-BR (huge background) jet channels: H→ bb, H → WW → 4j
- Challenging performances: Mono-chromatization to achieve $\sqrt{s}_{spread} \sim \Gamma_H$
- Fundamental & unique physics accessible if measurement feasible:
  → Electron Yukawa coupling
  → Higgs width measurable (“natural” threshold scan)

Light quarks

Whether observed Higgs responsible for light quark masses, and whether it couples to light quarks is an open question.

In very reasonable, motivated, models Higgs coupling to light quarks can differ drastically from SM.

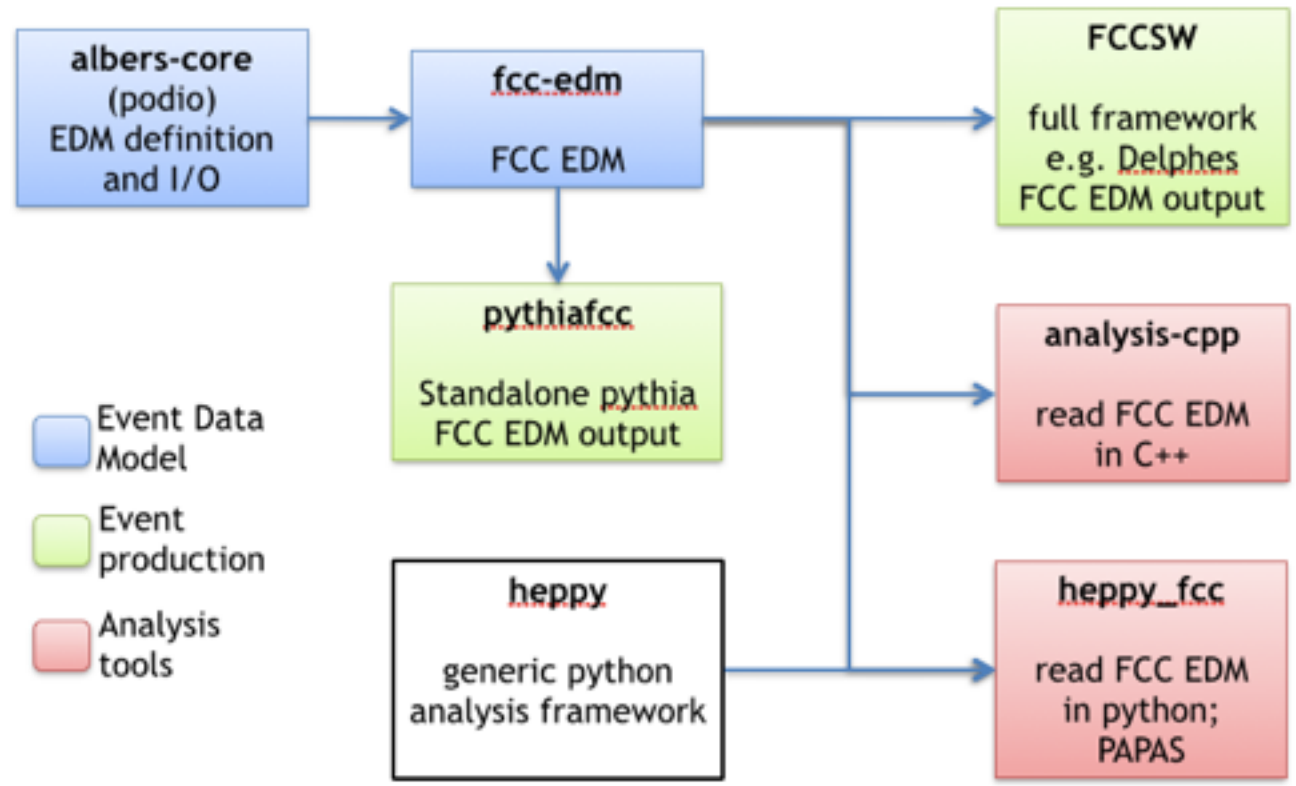
Reduced Higgs couplings can be best probed by FCC-ee.

We discuss a viable model where observed Higgs couples to 3rd generation and the first two generations get masses from new EWSB source, eg. technicolor.

MC Tools and Software

	Tree (SM)	Tree (BSM)	NLO (QCD) (SM)	NLO (QCD) (BSM)	NLO (EW) (SM)	NLO (EW) (BSM)	Loop Induced (SM)	Loop Induced (BSM)
LHC								
Fix Order	✓	✓	✓	✓	✓ (orange)	✗	✓	✓
+Parton Shower	✓	✓	✓	✓	✗	✗	✓	✓
Merged Sample	✓	✓	✓	?	✗	✗	✓	✓
EE								
Fix Order	✓	✓	✓	✓	✓ (orange)	✗	✓	✓
ISR	✓ (orange)	✓ (orange)	✓ (orange)	✓ (orange)	?	?	✓ (orange)	✓ (orange)

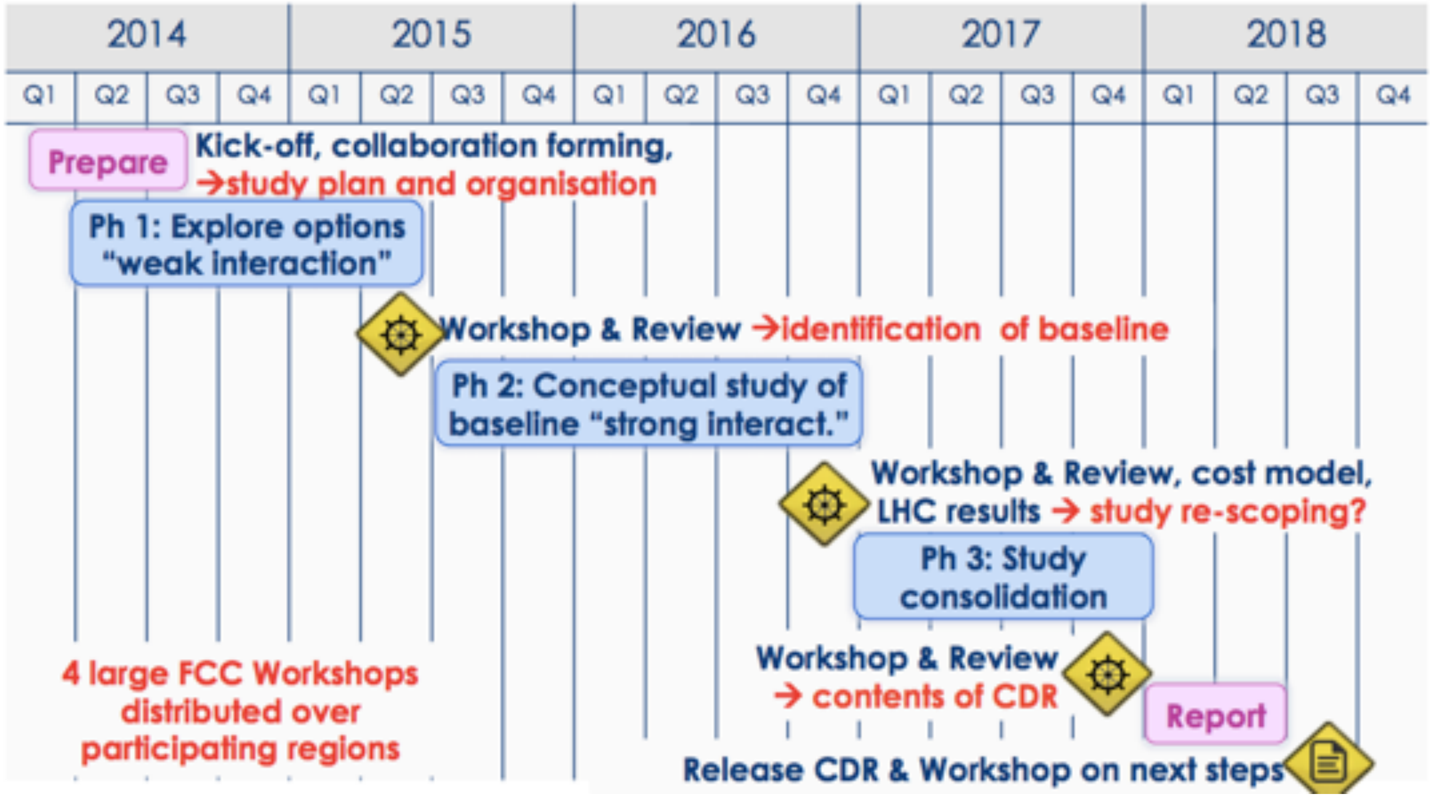
- Monte-carlo tools are available for ee collision
- Mainly similar to LHC workflows
- Still need improvement
  - ➡ ISR
  - ➡ NLO in electroweak



- The FCCSW is mostly ready for physics
  - PAPAS (python): almost done, detailed studies needed
  - Delphes (C++): almost done, FCC EDM output needed
  - heppy can be used to analyse any kind of events
- The situation is not great though
  - not sure we have any user so far ☺
    - user feedback is essential
  - sure we don't have enough contributors
    - still only 2 experienced developers at the moment
- you're all very welcome as users, we'll help as much as we can

Defining the baseline

1. Higgs-strahlung production (ee -> HZ)
   - Inclusive Z -> ll measurements
     - Measurement of the ZH cross section
   - Exclusive Z -> ll measurements
     - Hadronic Higgs decays (H -> bb, cc, gg, WW, ZZ)
     - Higgs to ZZ (Essential for the total width determination at $\sqrt{s}$ = 240 GeV)
     - Higgs to WW (with lepton decays)
     - Higgs to tau tau
   - Inclusive Z -> qq measurements
     - Measurement of the ZH cross section
   - Exclusive Z -> qq measurements
     - Four jet final state (H -> bb, cc, gg, WW, ZZ)
     - Six jet final state (H -> WW, ZZ, bb, cc, gg)
     - Jets plus leptons final states (H -> WW,ZZ,mumu)
     - Higgs to tau tau
   - Exclusive Z -> νν measurements
     - Higgs to bb
   - Invisible Higgs decays
   - Exotic Higgs decays (e.g. flavour changing decays)
2. Vector boson fusion production
3. Exclusive H-> γγ or H -> μμ (ee) production
4. Exclusive H -> Zγ production
5. ee -> Hγ production
6. ee -> H direct production
7. Other production processes
   - SM Higgs: bbH production, tau tau H production
   - 2HDM: hA production, bbH, tau tau production (enhanced with tan beta), and specific decays h -> AA, etc.



- Qualifying detector design
- Considering detector and systematic effects

Summary of FCC-ee Results

➡ **FCC-ee offers fantastic opportunities to gain understanding of the Higgs boson and EWSB**

- Sub-precent level Higgs coupling measurements
- Access to first and second generation Higgs couplings
- Precision mass measurement
- Higgs CP studies
- BSM and exotic Higgs

➡ **Substantial program of work ahead in FCC-ee Higgs study**

- Novel ideas appeared in recent workshops and are followed up on
- Many opportunities to contribute
- Program needs to be extended and work need to be repeated in the FCC-ee context
- **Qualify detector requirements**
- **Goal:** CDR and cost review by 2018

Next Steps

- ➡ **We would like to ask speaker to send us short write-ups (those who have not done this already).**
- ➡ **We will or you can post the documents on the agenda**
- ➡ **They will serve as inputs towards more comprehensive documentation**
- ➡ **More people/group need to engage in analysis activities**
- ➡ **Qualify detector and investigate systematic effects**
- ➡ **Follow up workshop in 2016/17 to consolidate studies**

- ➡ **Mini-workshop on α_s Oct 12-13th at CERN**
  - **https://indico.cern.ch/e/alphas2015**