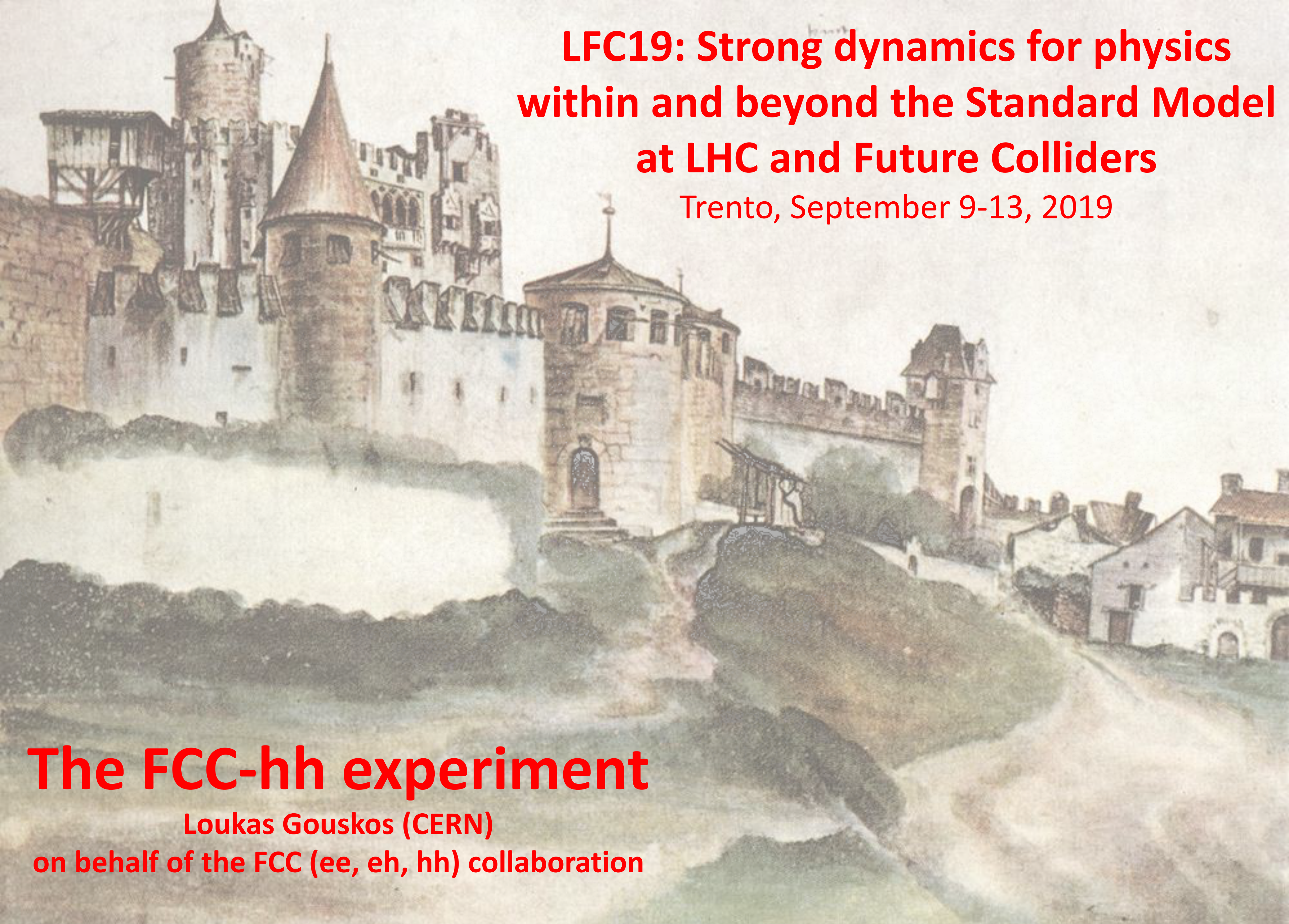
LFC19: Strong dynamics for physics within and beyond the Standard Model at LHC and Future Colliders

Trento, September 9-13, 2019

The FCC-hh experiment

Loukas Gouskos (CERN)
on behalf of the FCC (ee, eh, hh) collaboration



The Castle at Trento, painted by A. Dürer on his way back from Venice (1495, watercolor 19.8 x 27.7). British Museum, London

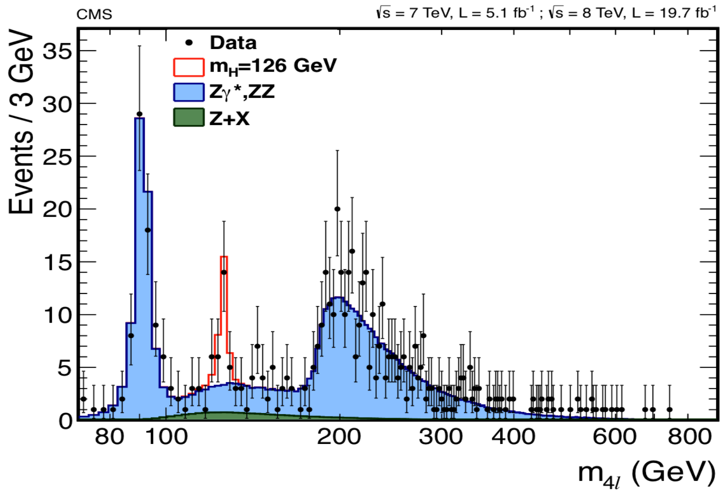
Disclaimer:

→ Impossible to give justice to all physics opportunities with the FCC-hh; a personal/biased selection of results

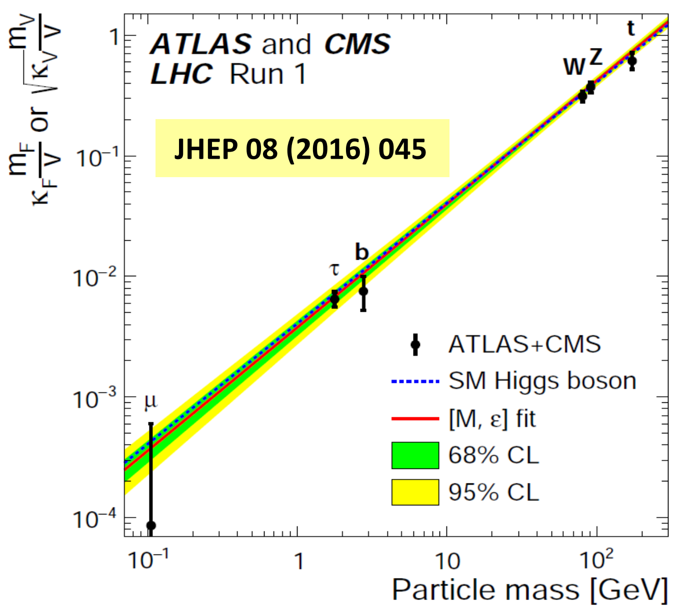
→ Any mistakes, misunderstandings, misconceptions are solely my responsibility

Physics landscape [after 10 yrs of LHC]

- Discovery of a Higgs boson with m_H = 125.09 ± 0.24 GeV (~0.2%)



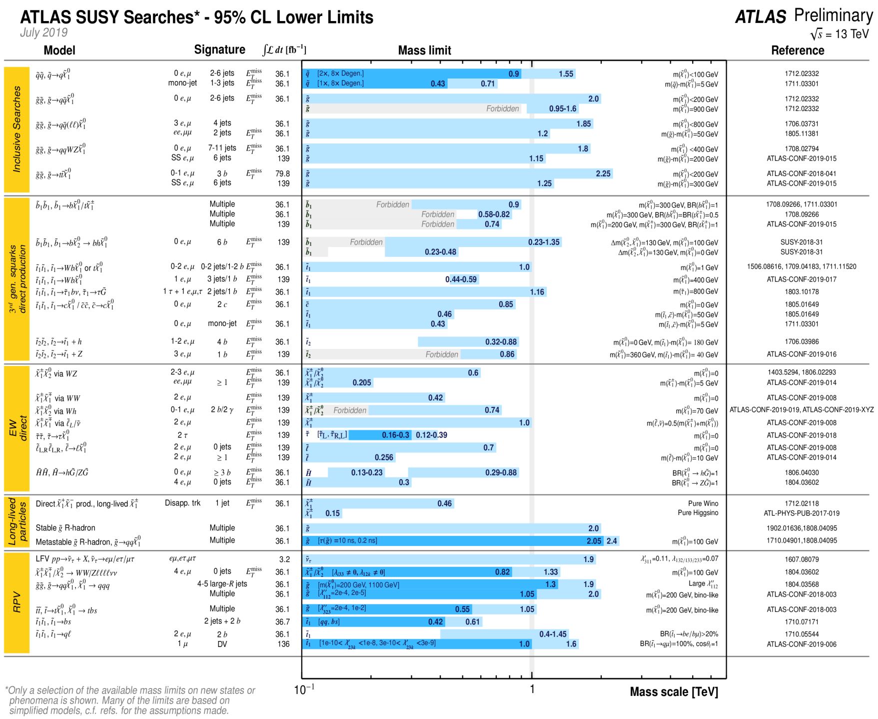
- **A whole new chapter of exploration opened:** i.e. detailed measurement of the Higgs particle properties & interactions
  - Inclusive production rates & interactions with vector bosons (W,Z, γ) & 3rd-gen particles already established
  - Next: 2nd-gen particles
  - Self-couplings, etc …



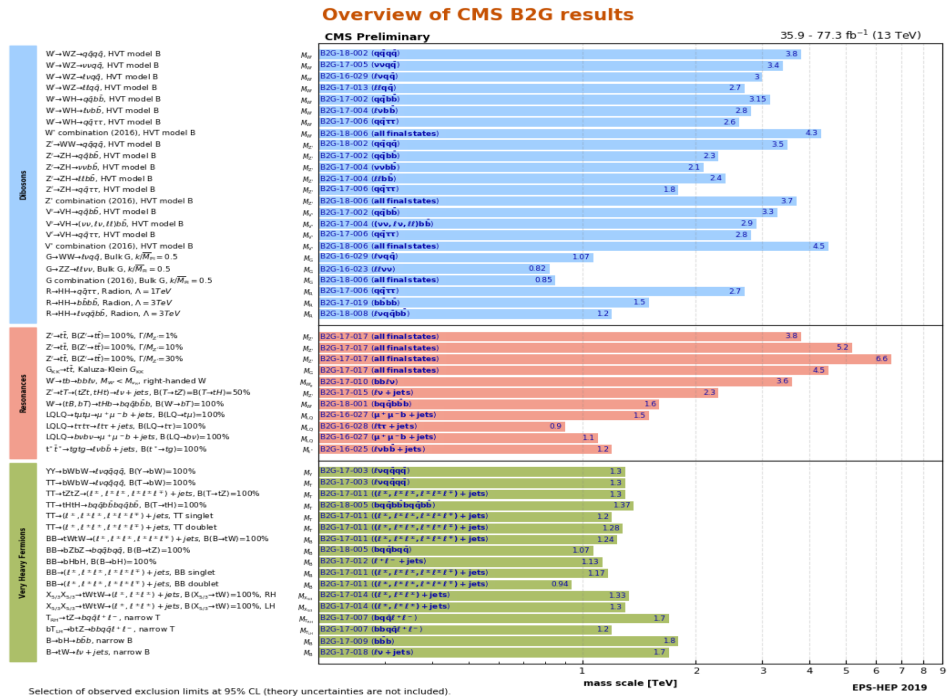
Physics landscape [after 10 yrs of LHC] (II)

- A plethora of searches for BSM signals exploring the energy frontier
  - Mass limits:

e.g. SUSY



e.g. Heavy resonances



  - .. and many many more channels/topologies/signatures
- No signs of BSM physics
  - New particles with masses up to ~few TeV already excluded.

The big open questions .. that beg for BSM

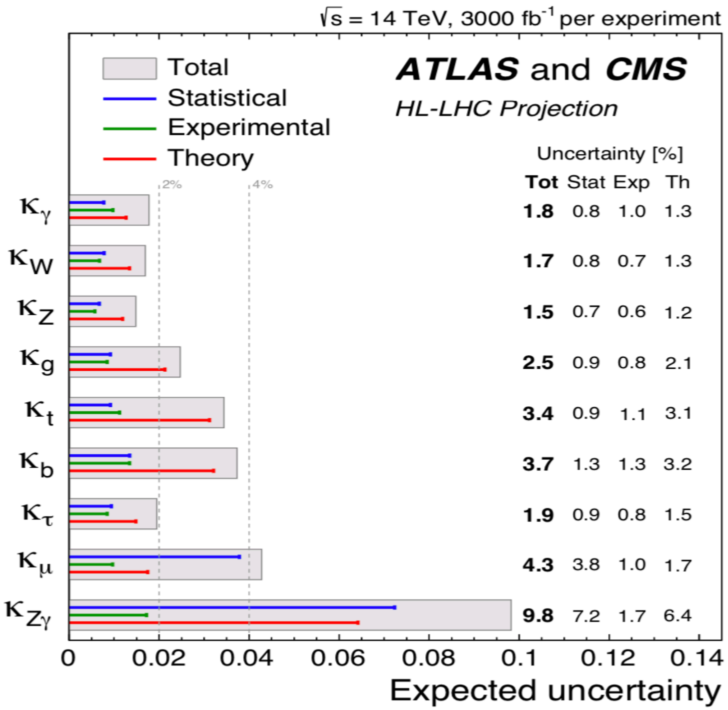
- From Michelangelo Mangano's talk [Higgs Hunting 2019]:

- **Data driven:**
  - DM
  - Neutrino masses
  - Matter vs antimatter asymmetry
  - Dark energy
  - …
- **Theory driven:**
  - The hierarchy problem and naturalness
  - The flavour problem (origin of fermion families, mass/mixing pattern)
  - Quantum gravity
  - Origin of inflation
  - …

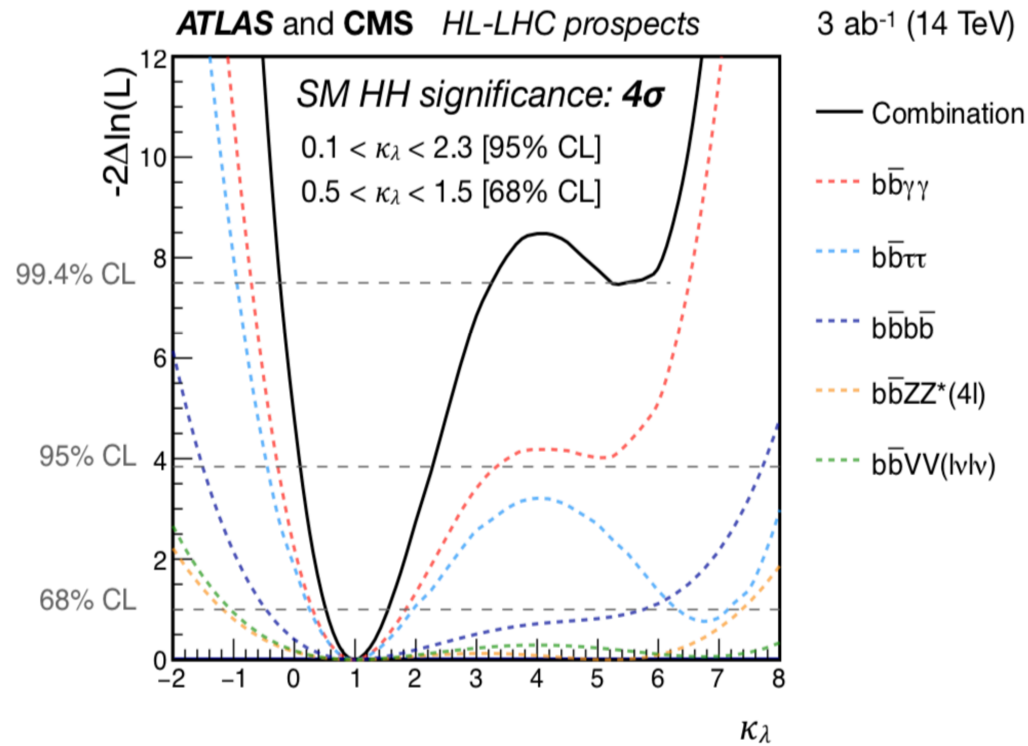
- Procedure to address [at least a part of] the above questions:
  - Measure exhaustively the Higgs boson properties/interactions
  - Direct BSM searches [e.g. SUSY, heavy exotic particles, ..]
  - Precise determination of the EKW/top observables
    - Which level of precision is necessary?
  - Flavour physics, ….

The landscape at the end of HL-LHC

Higgs couplings



Higgs self-coupling



+ Probe new resonances (particles) up to ~8 (~4) TeV

- Current (LHC) results: do not concretely point to any BSM scenario/mass scale
  - Not the case before the start of LHC
- **HL-LHC:** Cannot guarantee definite answers to any of the <u>big open questions</u>

Possible future colliders

- Where is New Physics:
  - **within LHC reach** but "hidden" in difficult corners of the parameter space and/or very small cross section
  - **Beyond the LHC reach** $\rightarrow$ very massive new particles
- Both cases: **new colliders** are **necessary** to continue exploring the TeV-regime

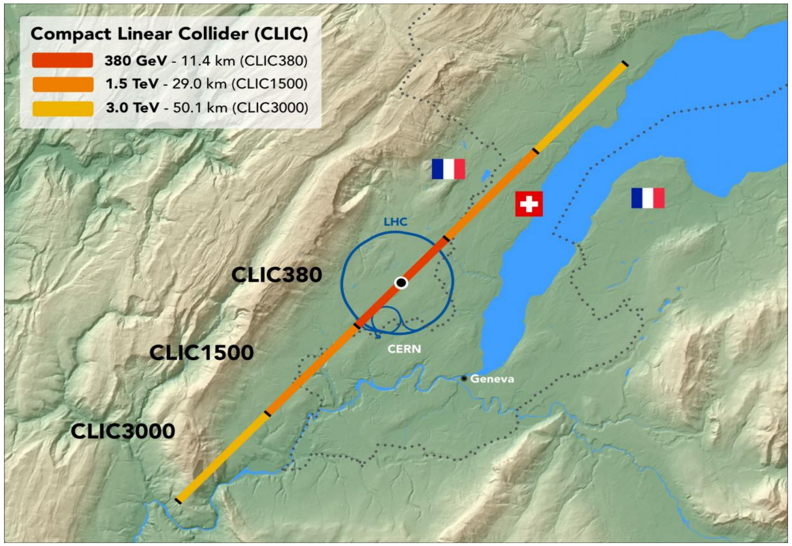
- Guiding principles for future experiments:
  - Sensitive tests of standard models (SM) parameters
    - "precision" not necessarily the same as "sensitivity"
  - Explore an as broad as possible set of scenarios
    - All directions is impossible
  - Provide definite answers to concrete scenarios

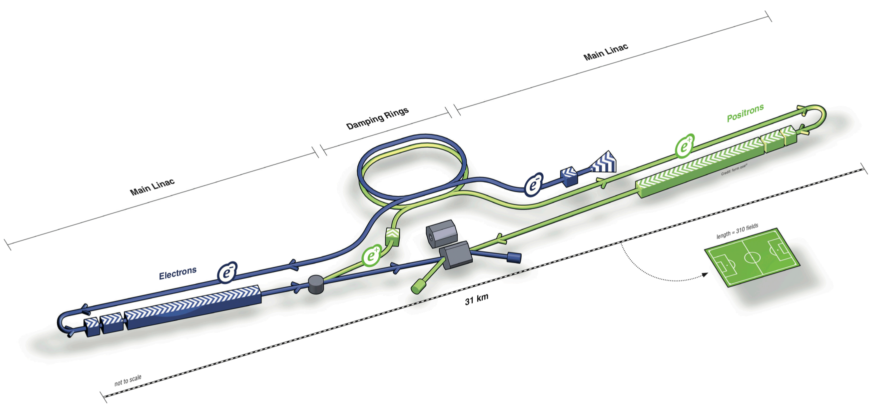
There are no **"guaranteed discoveries"**, rather than **"guaranteed deliverables"**

- Typically two approaches [not necessary mutually exclusive]:
  - **High precision:** lepton colliders (e^+e^-)
  - **Larger rates/ mass reach:** hadron colliders (pp, ep, HI)

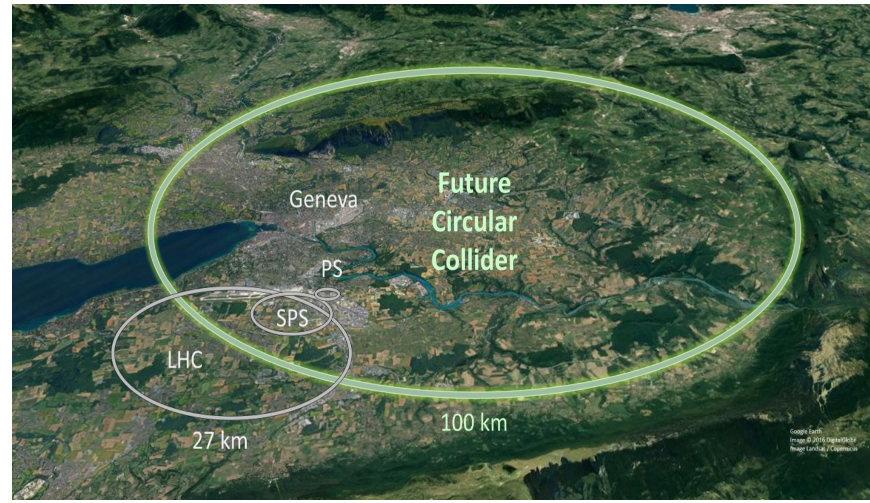
Possible future colliders

Linear (e^+e^-) colliders



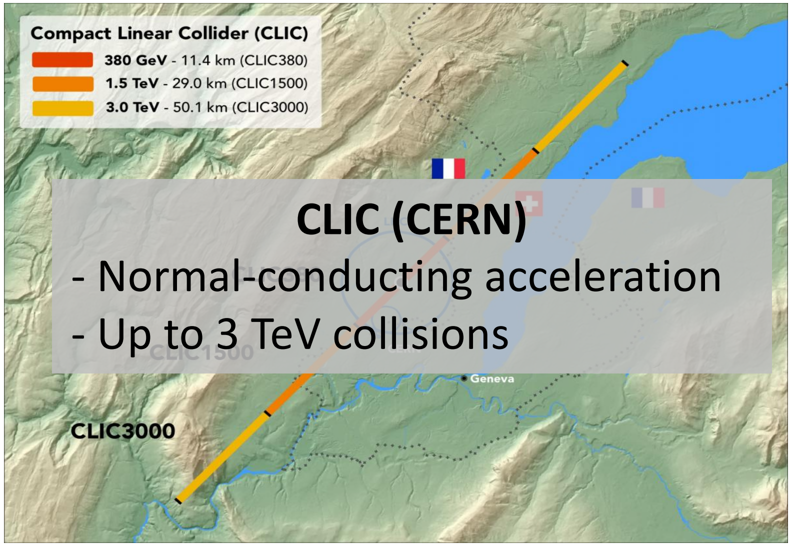


Circular (e^+e^-/hh) colliders

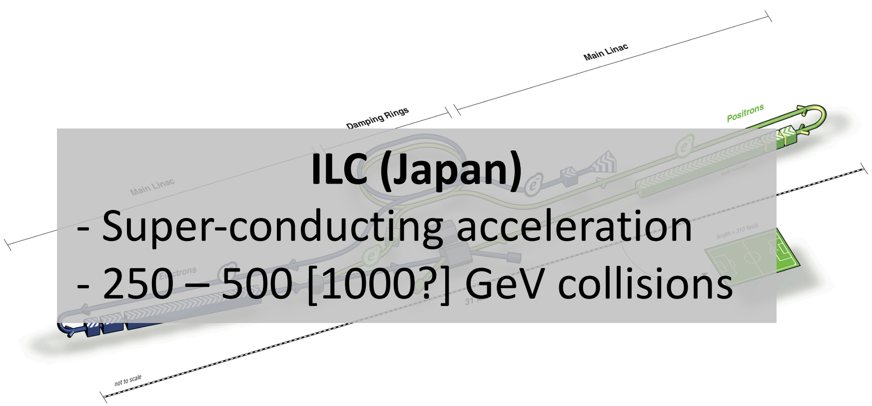


Possible future colliders

Linear (e^+e^-) colliders

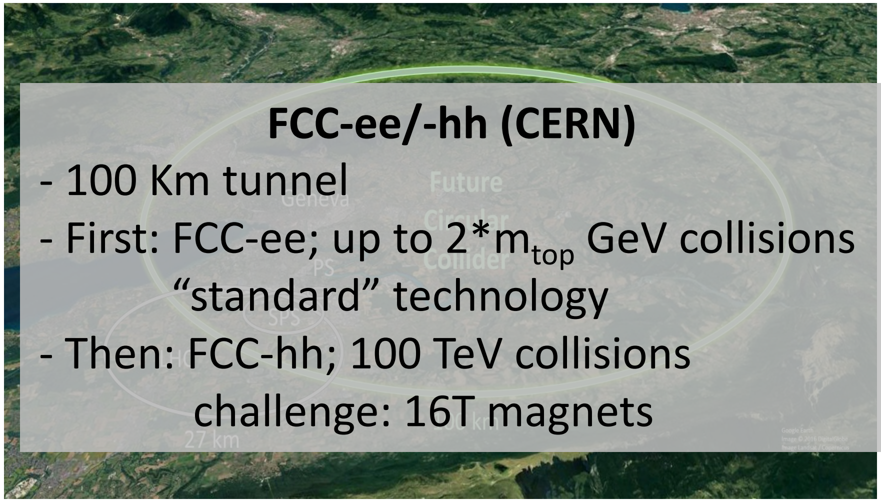


CLIC (CERN)
- Normal-conducting acceleration
- Up to 3 TeV collisions



ILC (Japan)
- Super-conducting acceleration
- 250 – 500 [1000?] GeV collisions

Circular (e^+e^-/hh) colliders



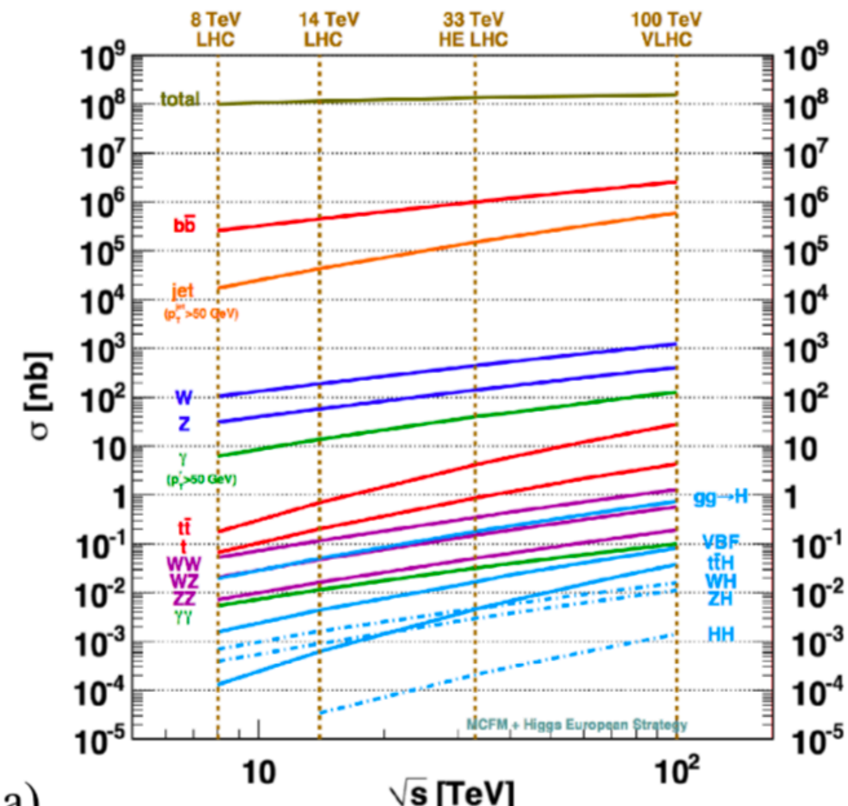
FCC-ee/-hh (CERN)
- 100 Km tunnel
- First: FCC-ee; up to $2*m_{top}$ GeV collisions
  "standard" technology
- Then: FCC-hh; 100 TeV collisions
  challenge: 16T magnets

CEPC/SppC (China)
- 100 Km tunnel
- Essentially an FCC-ee/ FCC-hh
- More conservative luminosity scenarios

The FCC(-hh) experiment

Motivation for FCC-hh: i.e. pp @ 100 TeV

- **~100 TeV pp collider** is necessary and sufficient to:
  - Achieve crucial measurements & give definite answers to many of the "big open questions" after HL-LHC
  - Explore scenarios that could emerge from a future e^+e^- collider



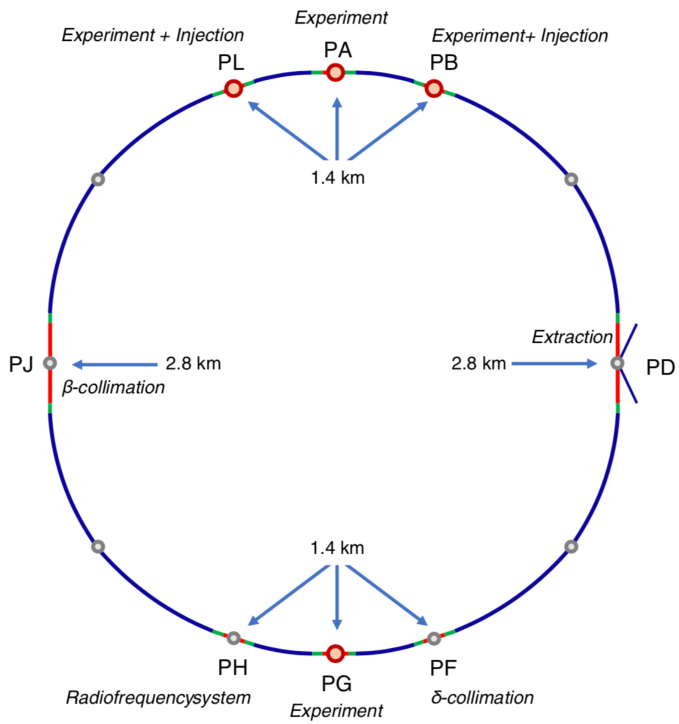
a)

Big gain [> O(10)] in production cross-section of many physics processes
[e.g. $\sigma_{HH}(100)/\sigma_{HH}(14)$=~39, $\sigma_{VBF}(100)/\sigma_{VBF}(14)$~17]

→ **Measure SM** to unprecedented precision (~% or less)

→ **Explore the energy frontier** (probe particles with masses up to ~50 GeV

The FCC-hh layout



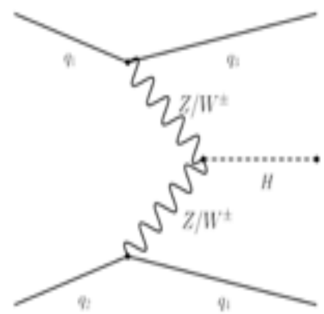
	LHC	HL-LHC	FCC-hh
√s [TeV]	13/14	14	100
Circumference [km]	~27	~27	~100
Dipole field [T]	8	8	<16
Number of IPs	2+2	2+2	2+2
$\mathcal{L}_{inst}$ [10^{34} $cm^{-2}s^{-1}$]	1	5	<30
$\mathcal{L}_{int}$ [ab^{-1}]	0.3	3	30
Peak pp col. rate [GHz]	0.8	4	31
Avg PU / bunch crossing	~50	~150	~1000
Rate of charged tracks [GHz]	~60	~300	~4000

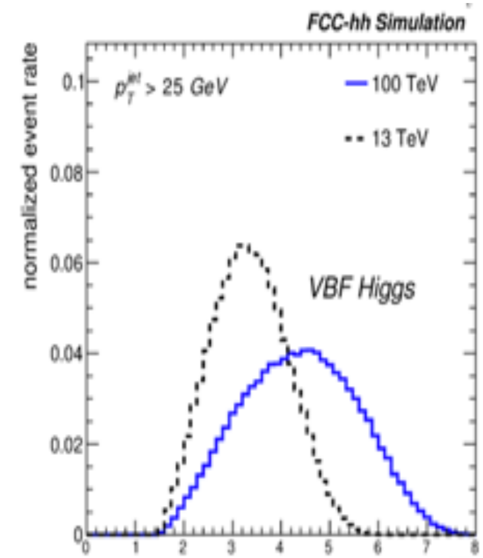
- Challenges [on the accelerator front]:
  - 16T magnets: R&D started based on existing technology [also alternative options]
  - Pile-Up: ~1000 inelastic events/collisions; begs for timing detector
  - ~4 THz of charged tracks: Needs: very granular tracking system; operate at extreme rates
- Luminosity goal: measure rare Higgs couplings (self-coupling) ~1% (5%) level

Kinematics @ 100 TeV

Table 7.1: Key numbers relating the detector challenges at the different accelerators.

Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
$b\bar{b}$ cross-section	mb	0.5	0.5	1	2.5
$b\bar{b}$ rate	MHz	5	25	250	750
$b\bar{b}$ $p_T^b > 30$ GeV/c cross-section	μb	1.6	1.6	4.3	28
$b\bar{b}$ $p_T^b > 30$ GeV/c rate	MHz	0.02	0.08	1	8
Jets $p_T^{jet} > 50$ GeV/c cross-section [331]	μb	21	21	56	300
Jets $p_T^{jet} > 50$ GeV/c rate	MHz	0.2	1.1	14	90
$W^+ + W^-$ cross-section [333]	μb	0.2	0.2	0.4	1.3
$W^+ + W^-$ rate	kHz	2	10	100	390
$W^+ \to l + \nu$ cross-section [333]	nb	12	12	23	77
$W^+ \to l + \nu$ rate	kHz	0.12	0.6	5.8	23
$W^- \to l + \nu$ cross-section [333]	nb	9	9	18	63
$W^- \to l + \nu$ rate	kHz	0.1	0.5	4.5	19
Z cross-section [333]	nb	60	60	100	400
Z rate	kHz	0.6	3	25	120
$Z \to ll$ cross-section [333]	nb	2	2	4	14
$Z \to ll$ rate	kHz	0.02	0.1	1	4.2
$t\bar{t}$ cross-section [333]	nb	1	1	4	35
$t\bar{t}$ rate	kHz	0.01	0.05	1	11





- **High-p_T particles** (quarks, leptons, photons) from the increased E_{CM}
- **Physics more forward** wrt (HL-)LHC
  - Hence: must preserve sensitivity to the "moderate p_T" regime

Detector considerations

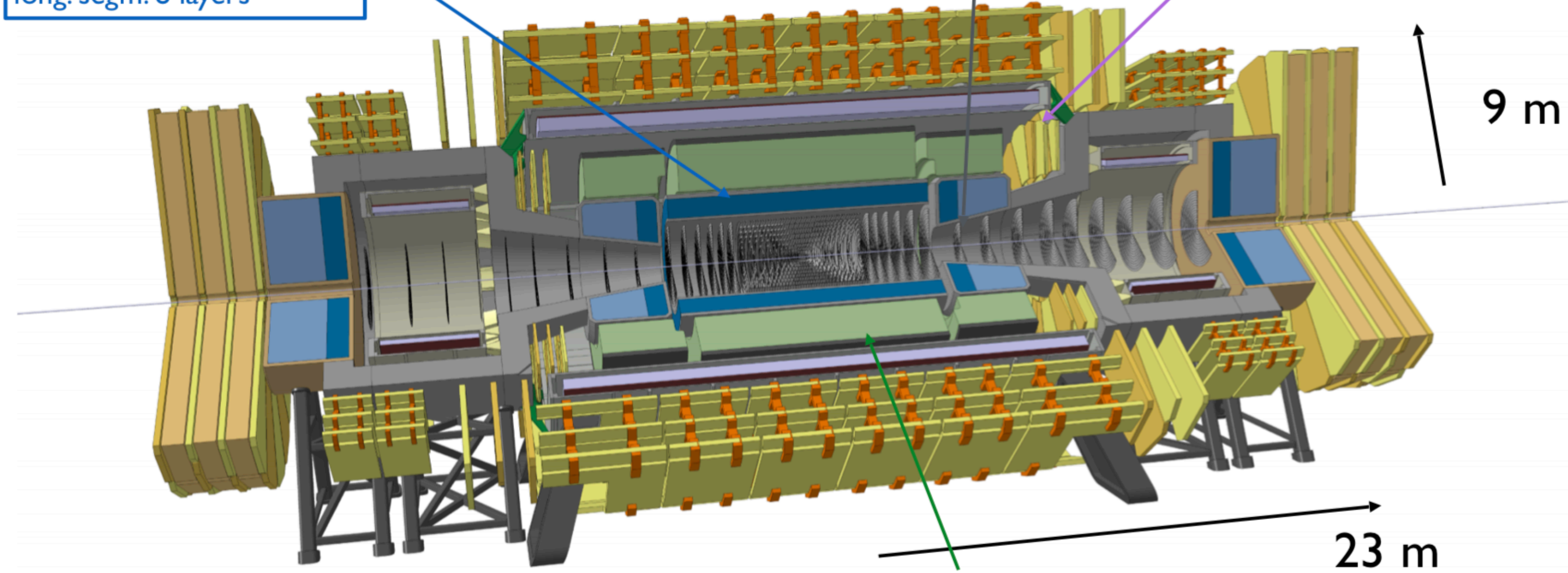
→ Measure multi-TeV objects (jets, leptons, photons)
→ Extend coverage to forward region
→ Sufficient detector granularity:
(a) to cope with large occupancy
(b) for jet substructure [i.e. Heavy object tagging]

The FCC-hh detector

Barrel ECAL: LAr/Pb
$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.7\ \%$
30 X_0
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 8 layers

Tracker: $\sigma_{pT}/p_T \sim 20\%$ at 10 TeV (1.5m radius)

Central Magnet + Fwd solenoids 4T



Fwd ECAL: LAr/Cu
$\sigma_E/E \sim 30\%/\sqrt{E} \oplus 1\ \%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 6 layers

Fwd HCAL: LAr/Cu
$\sigma_E/E \sim 100\%/\sqrt{E} \oplus 10\ \%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.05$
long. segm: 6 layers

Barrel HCAL: Sci/Pb/Fe
$\sigma_E/E \sim 50\text{-}60\%/\sqrt{E} \oplus 3\ \%$
11 λ (ECAL+HCAL)
lat. segm: $\Delta\eta\Delta\phi \approx 0.025$
long. segm: 10 layers

+ Timing detector with resolution ~5ps

The FCC-hh detector (II)

- Serves as a "reference detector"
  - i.e. not a technical design for implementation
  - used for subsystem / physics studies & identify areas that require further R&D

- Detector design based on current (HL-)LHC technology/design
  - CMS-like detector [e.g. large silicon tracker, calorimeters inside solenoid]
  - ATLAS-like dimensions

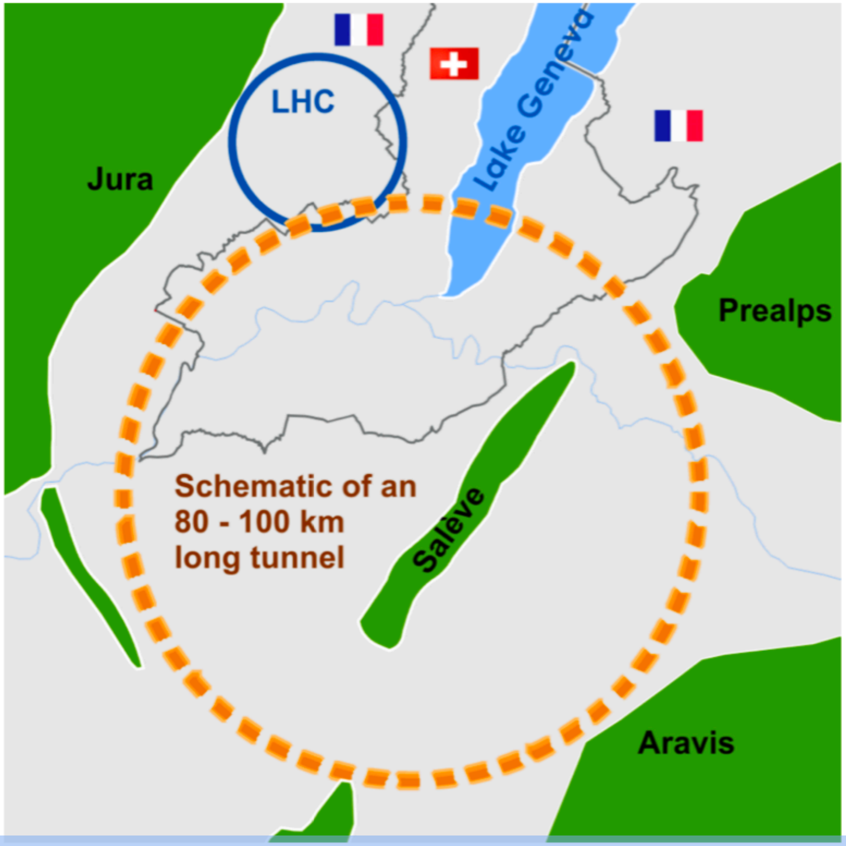
- [Main] Challenges:
  - Trigger/DAQ:
    - 40 MHz Tracker readout $\rightarrow$ ~1000 TByte/sec
    - Can L1Calo+Muon triggers provide enough selectivity to ~O(1) MHz TRK readout?
  - Tracker:
    - Operate at extreme rates
    - Radiation hardness $\rightarrow$ requires R&D for the inner-most part of Tracker
      - With current technology operational for ~days

The FCC experiment in a nutshell

- A new 100 km tunnel fitting in Genevois
  - First: **FCC-ee experiment**
    - Probably the fastest and cheapest way to 100 TeV

√s	$\mathcal{L}_{int}$ [ab^{-1}]
m_Z	~150
$2*m_W$	~12
240 GeV	~5
$2*m_{top}$	~0.2-1.5

    - **Tentative plan:** Start after the end of HL-LHC
  - Ultimate goal: **FCC-hh [@100 TeV]**
    - Lumi: 30 ab^{-1}
    - HI and e-h options
    - Challenge: The 16T magnets



Early 2019: Release of CDR covering:
→ physics opportunities
→ detector configurations & technical challenges
→ costs and schedule

Combination of FCC-ee and FCC-hh produces most of physics
A successful model: LEP (1989-200) → **(HL-)LHC** (2010-2039) → **FCC** [?]

Physics opportunities with FCC-hh

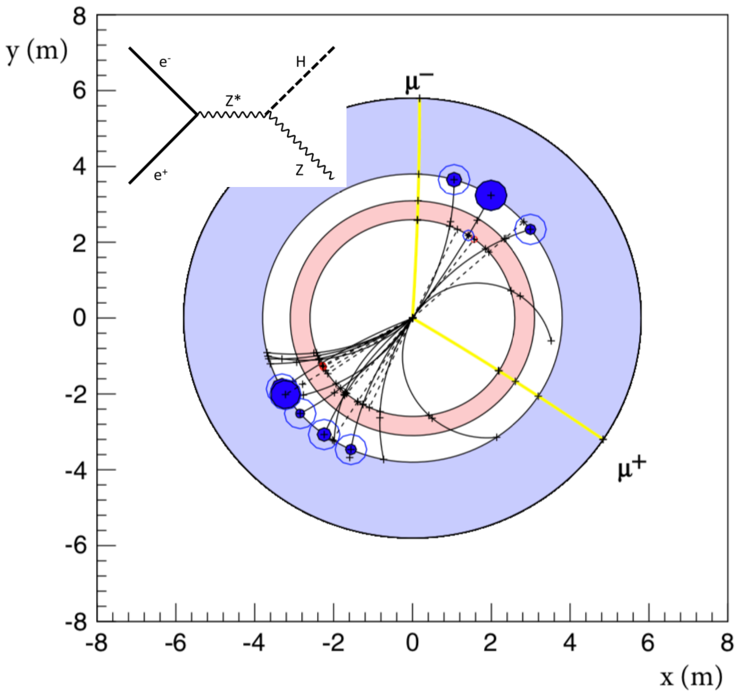
just a subset of the results documented in:

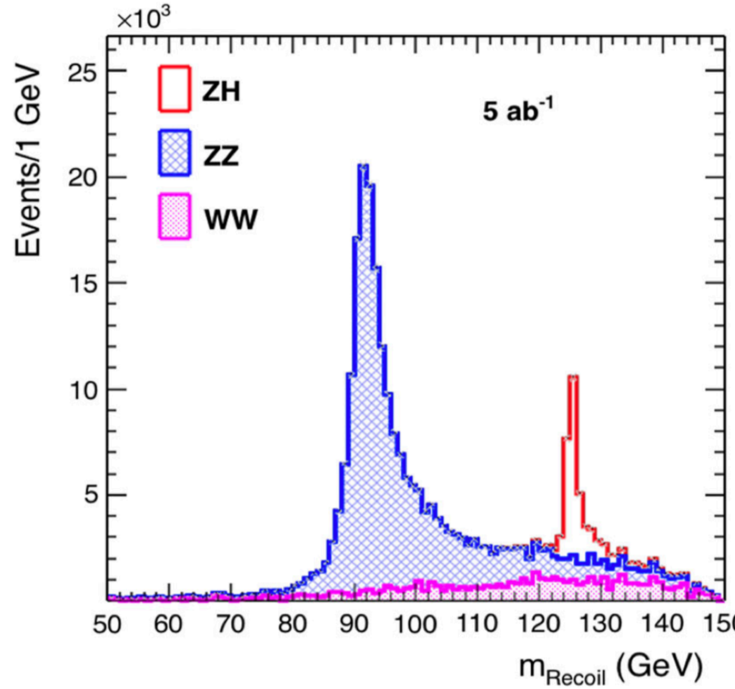
$\rightarrow$ FCC CDR Vol. 1 & 3

$\rightarrow$ Additional results from other sources [shown at the FCC Week in Brussels]

A highlight from FCC-ee

- Measure Higgs couplings & width at % or better in a **model independent** way





- Measure m_H from Z recoil:

$$m^2_{\mathrm{Recoil}} = s + m^2_Z - 2\sqrt{s}(E_{\ell+} + E_{\ell-})$$

Many more details about the physics opportunities in e^+e^- by Franco

→ ~1M Higgs @ FCC-ee (5 ab^{-1})
First: Measure H production inclusively and its coupling to Z
rate ~ $g_{HZZ}^2 \rightarrow \delta g_{HZZ}/g_{HZZ}$ ~ 0.1%

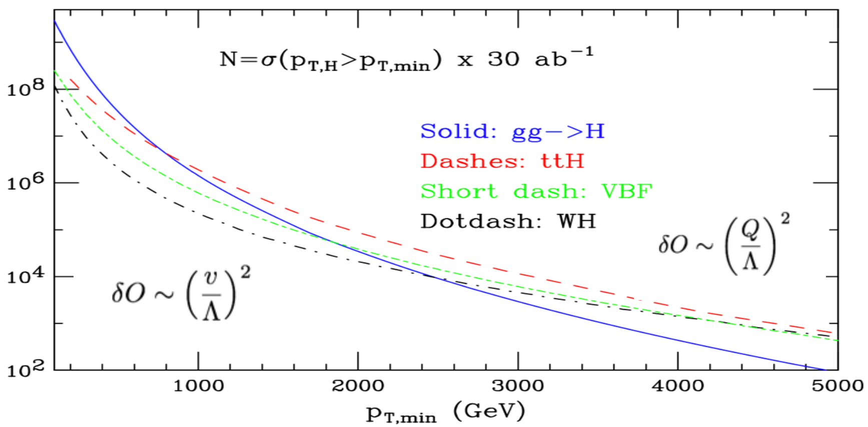
→ **Then:** measure ZH(→ZZ)
rate ~ $g_{HZZ}^4/\Gamma_H \rightarrow \delta\Gamma_H/\Gamma_H$ ~ 1%

→ **Last:** measure ZH(→XX)
rate ~ $g_{HZZ}^2\, g_{HXX}^2 \rightarrow \delta g_{HXX}/g_{HXX}$ ~ 1%

Higgs physics

- Higgs production at FCC-hh
  - **large statistics:** (a) enable precise measurements of branching ratios of rare decay channels (e.g. μμ, Zγ)
    (b) sensitivity to forbidden channels e.g. τμ
  - **Large kinematic range / probe the multi-TeV regime:**
    (a) often better signal purity
    (b) more sensitive to BSM physics

Higgs production rates: 100 TeV, 30 ab^{-1}



More than 1M Higgs with p_T>1 TeV

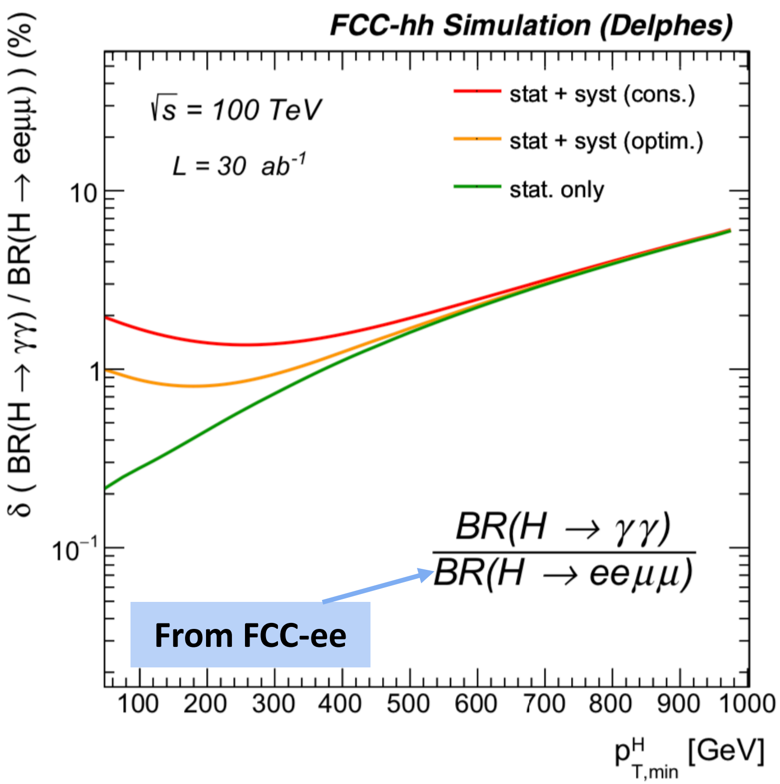
→ ttH (VBF) surpasses ggH for p_T>800 (2000) GeV distinct signature -> better BKG suppression

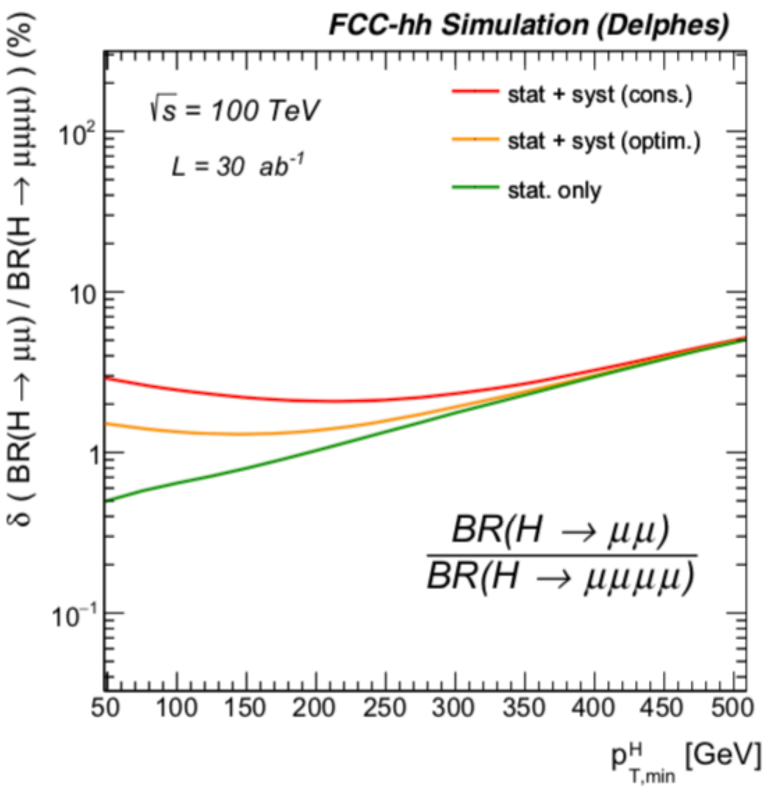
→ High p_T(H) regime: indirect probe of BSM Heavy new particles running in the loop

- **General strategy:**
  - Given the HZZ coupling from FCC-ee (~0.1% level)
  - Calculate ratios of branching ratios (BR), e.g. BR(H->X)/BR(H->ZZ->4L)
    - Cancelation of many systematic uncertainties
    - Also: sensitive to BSM effects that affect BRs in different ways
  - Then: Extract absolute couplings at the order of ~%

Synergy and **complementarity** between the FCC-ee and FCC-hh physics programs

Higgs physics: rates, couplings





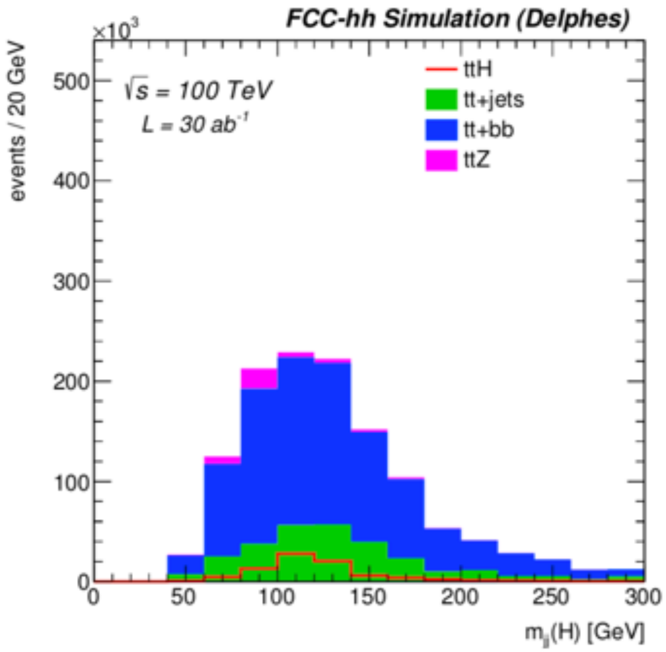
- Two systematic scenarios:
  - for uncertainties related to object ID
- Signal & BKG uncertainty: 1%
- Luminosity: 1%

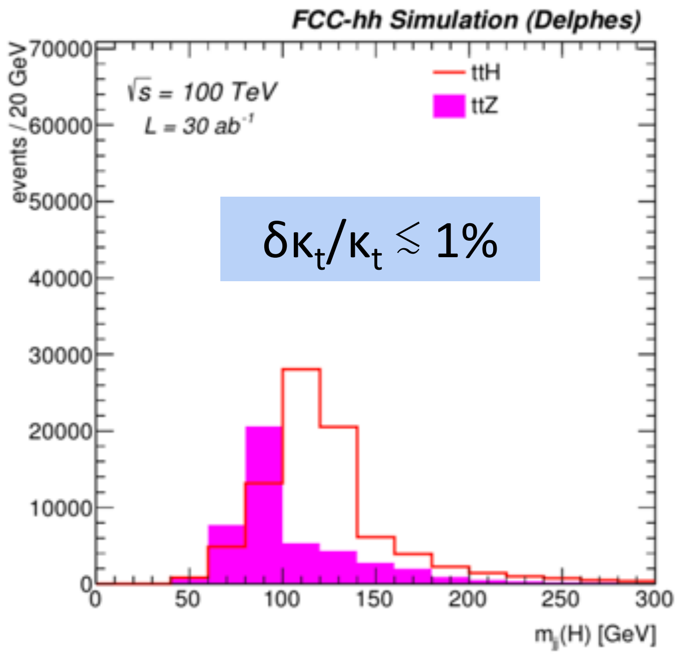
→ Achieve precision better than 2% (10%) in the low- (high-) $p_T(H)$ regime

→ Use FCC-ee HZZ coupling and translate ratios to <u>absolute</u> measurements

Higgs physics: top-H Yukawa coupling

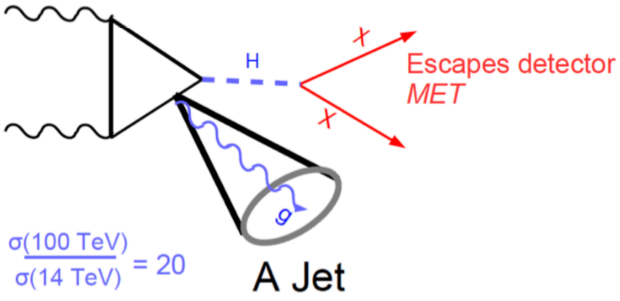
- Access top-H Yukawa coupling from $\sigma_{ttH}/\sigma_{ttZ}$
  - Large cancelation of systematic uncertainties
- Measure ratio in the H/Z$\rightarrow$bb decay mode in the boosted-regime semileptonic channel
  - Large BR ; exploit jet substructure techniques
- Inputs from FCC-ee: g_{ttZ} and BR(H$\rightarrow$bb) ~1% level

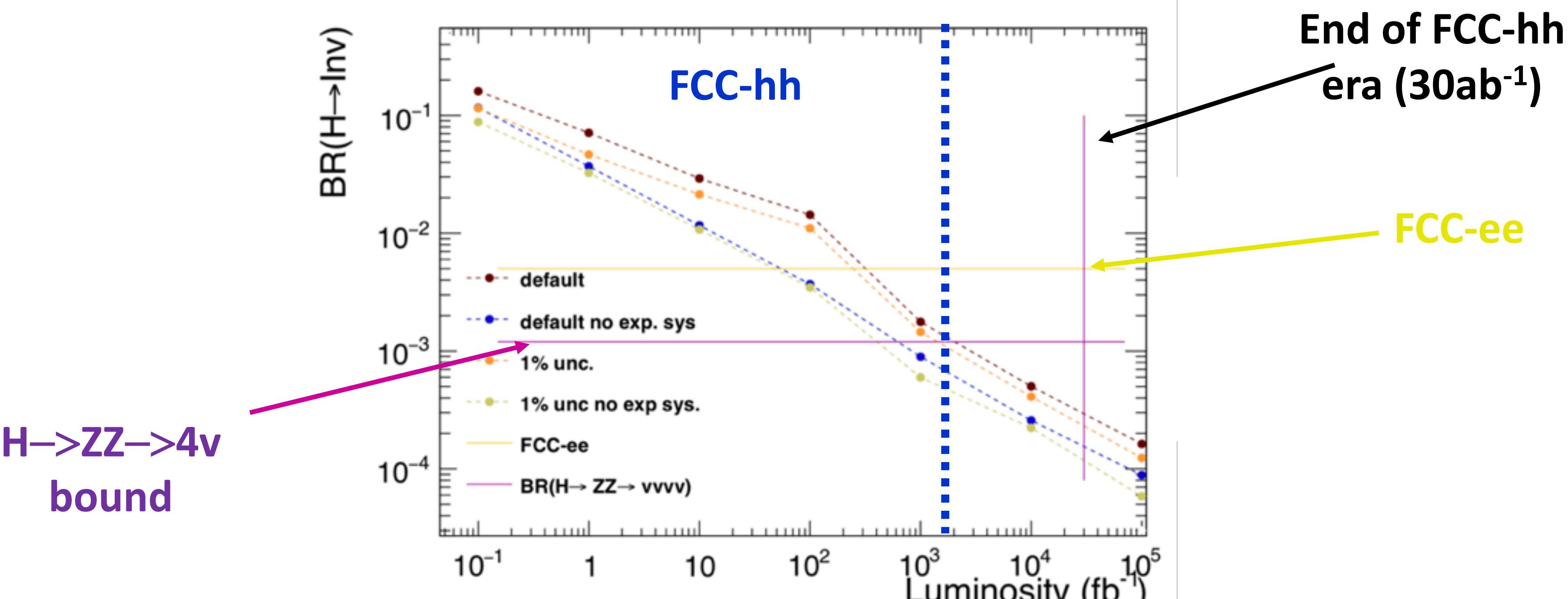




Higgs physics: H→inv

- Higgs recoiling against a jet: jets+ME_T final state
  - Signal extraction by fitting ME_T distribution
  - Main BKGs constrained from data control samples
    - Z→νν estimation down to ~% level using Z->μμ,ee and γ+jets control samples and state-of-the-art theory calculations





→ Reach/exceed the SM neutrino bound already with ~2 ab^{-1} with FCC-hh
→ Significant improvement wrt HL/LHC and FCC-ee

Di-Higgs: Nature of Higgs potential

- Higgs potential:

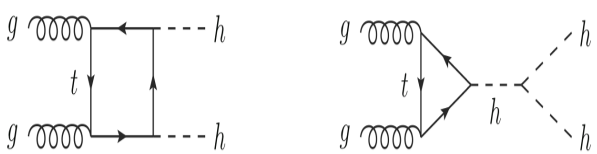
$$V(h) = \frac{1}{2} M_H^2 H^2 + \frac{1}{3!}\sqrt{3\lambda_H} M_H H^3$$

Higgs boson mass
Already measured
with <0.1% accuracy

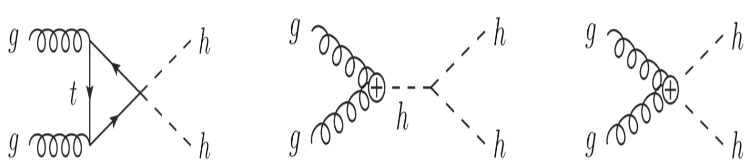
Higgs self-coupling (λ_3)
shape of Higgs potential
λ_3 @HL-LHC (FCC-ee): 50 (35)% unc.
Goal for FCC-hh: ~5% uncertainty on λ_3

- Measure Higgs self-coupling is of fundamental importance.
  - Challenging: very small x-section
    - Destructive interference in SM
    - Can be significantly modified in BSM
    - 14→100 TeV: 40x increase in x-sec
  - Main channels:
    - bbγγ, bbZZ, VBF HH

SM:

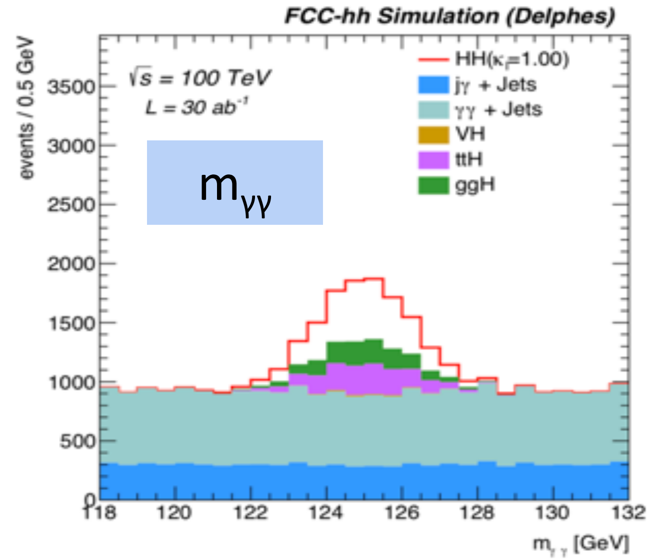


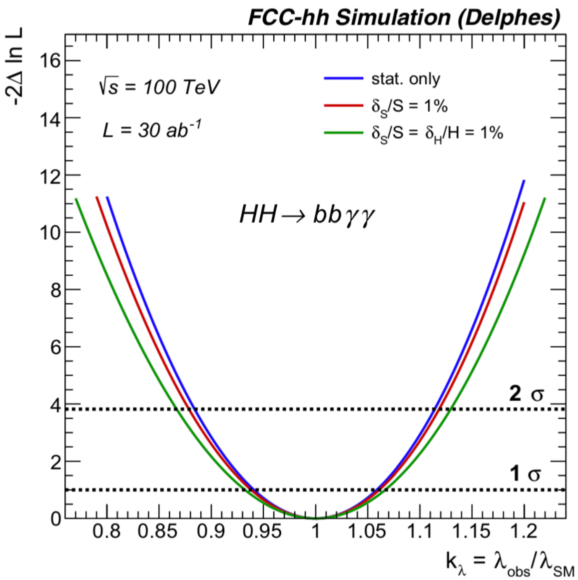
+ BSM:

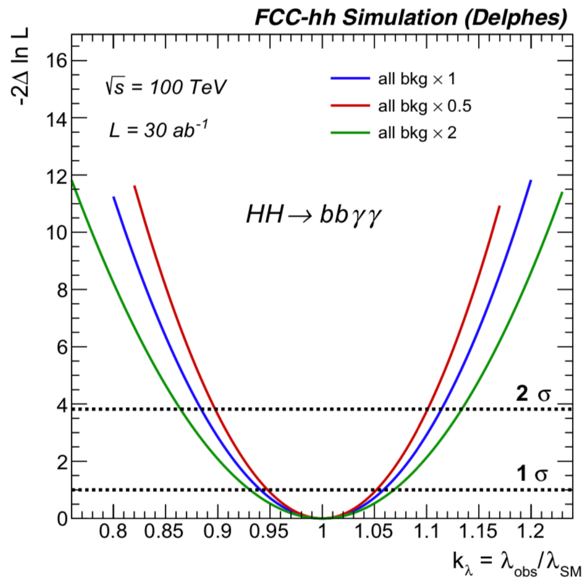


Di-Higgs: HH→bbγγ

- Dominant BKG: QCD and ttH/ggH
- Search strategy:
  - Exploit correlation of $m_{\gamma\gamma}$ and m_{bb} in signal
    - Fit them simultaneously
    - BKG modeling using a parametric fit
  - Studied effect of different systematic sources:
    - $m_{\gamma\gamma}$ resolution, γ-reco efficiency, γ mis-ID
    - Impact on results < ~1-2% [absolute]







→ $\delta\kappa_\lambda/\kappa_\lambda$ ~ 5 (7) % stat (stat+syst)

→ Expect $\delta\kappa_\lambda/\kappa_\lambda$ ~ 5% with stat+syst after combination of all channels:

Channel	$\delta\kappa_\lambda/\kappa_\lambda$ [%]
bbZZ(→4L)	14
bbWW(→2jLv)	40
4b+ISR	30

Interpretation of results

- ***kappa*(κ)-framework:**
  - Simplest parametrization which can probe deviations from the SM by BSM physics

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

    - Does not require any BSM computations
    - Fits for 10 κ-parameters: κ_W, κ_Z, κ_c, κ_b, κ_t, κ_τ, κ_μ, κ_γ, κ_g, $\kappa_{Z\gamma}$
  - but:
    - Higgs couplings preserve same helicity structure
    - also blind to polarization/ angular-dependent observables

- **Effective Field Theory [EFT] description:**
  - Extension of the κ-framework: probe helicity structure and polarization
  - Sensitive to higher-order effects [via operators]

$$\mathcal{L}_{\mathrm{Eff}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \cdots, \qquad \mathcal{L}_d = \sum_i c_i^{(d)} \mathcal{O}_i^{(d)}$$

Grand summary: Single-H couplings

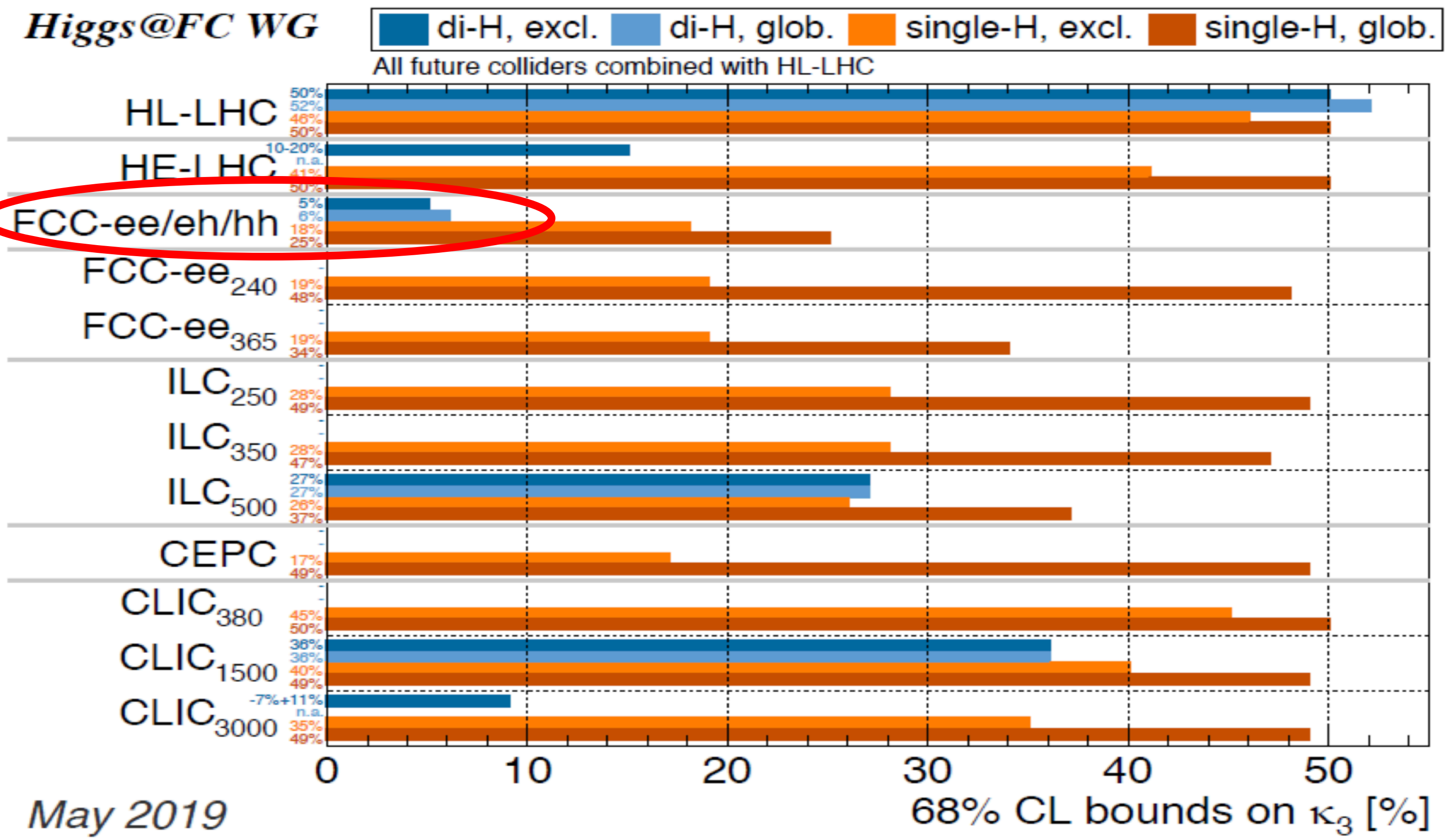
Ref: 1905.03764

kappa-3 scenario	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	HL-LHC+ $CLIC_{3000}$	CEPC	FCC-ee_{240}	FCC-ee_{365}	FCC-ee/eh/hh
κ_W (%)	1.1	0.29	0.75	0.4	0.38	0.95	0.95	0.41	0.2
κ_Z(%)	0.29	0.23	0.44	0.39	0.39	0.18	0.19	0.17	0.17
κ_g(%)	1.4	0.84	1.5	1.1	0.86	1.1	1.2	0.89	0.53
κ_γ (%)	1.3	1.2	1.5∗	1.3	1.1	1.2	1.3	1.2	0.36
$\kappa_{Z\gamma}$ (%)	11.∗	11.∗	11.∗	8.4	5.7	6.3	11.∗	10.	0.7
κ_c (%)	2.	1.2	4.1	1.9	1.4	2.	1.6	1.3	0.97
κ_t (%)	2.7	2.4	2.7	1.9	1.9	2.6	2.6	2.6	0.95
κ_b (%)	1.2	0.57	1.2	0.61	0.53	0.92	1.	0.64	0.48
κ_μ (%)	4.2	3.9	4.4∗	4.1	3.5	3.9	4.	3.9	0.44
κ_τ (%)	1.1	0.64	1.4	0.99	0.82	0.96	0.98	0.66	0.49
BR_{inv} (<%, 95% CL)	0.26	0.22	0.63	0.62	0.61	0.27	0.22	0.19	0.024
BR_{unt} (<%, 95% CL)	1.8	1.4	2.7	2.4	2.4	1.1	1.2	1.	1.

- Full FCC program:
  - An order of magnitude improvement in precision with respect to HL-LHC for all couplings
  - All couplings better than 1% level
    - Couplings to W/Z and Inv. down to 10^{-3}
  - Allows to probe small modifications to Higgs couplings from BSM

Grand summary: HH coupling

Ref: 1905.03764



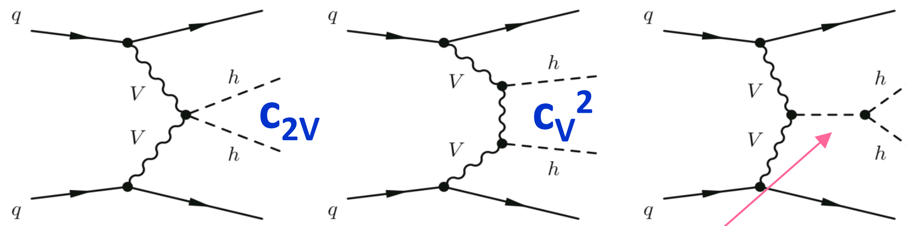
- HH coupling down to 5% for the full FCC program
  - Improvement of a factor ~10 wrt HL-LHC;
    Almost a factor of ~2 improvement wrt CLIC

Higgs measurements as a probe of BSM physics [a couple of examples]

VBF di-Higgs: Measure VVHH coupling

- Measure VVHH coupling:

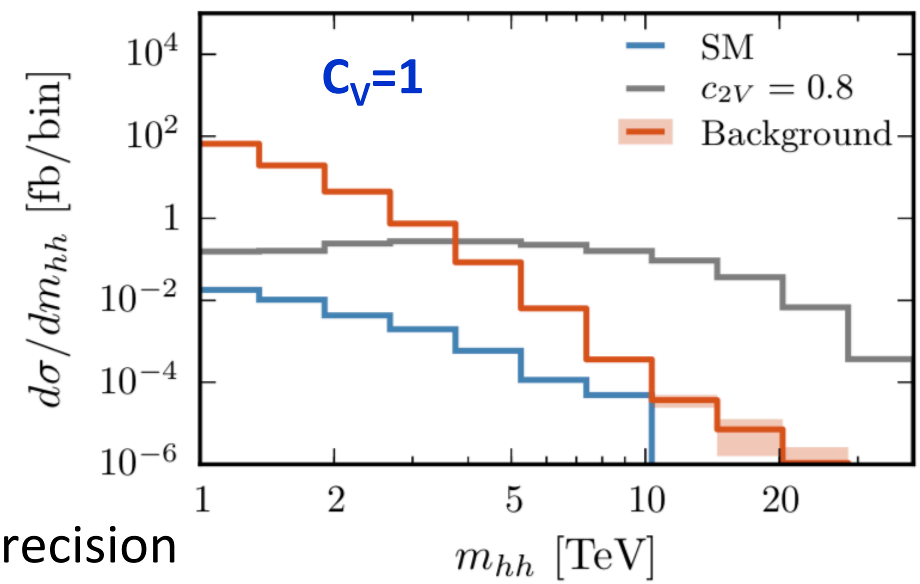
$$A(V_L\, V_L \to HH) \sim \frac{\hat{s}}{v^2}(c_{2V} - c_V^2) + \mathcal{O}(m_W^2/\hat{s}),$$



SM: vanishes
BSM: can be significantly modified
grows with E

SM: negligible at large m_{HH}
highly off-shell

- Strategy: HH→4b (large BR)
  - Large p_T(H); suppress many BKGs
  - Further suppress BKG using jet-substructure
  - Fit m_{HH} spectrum

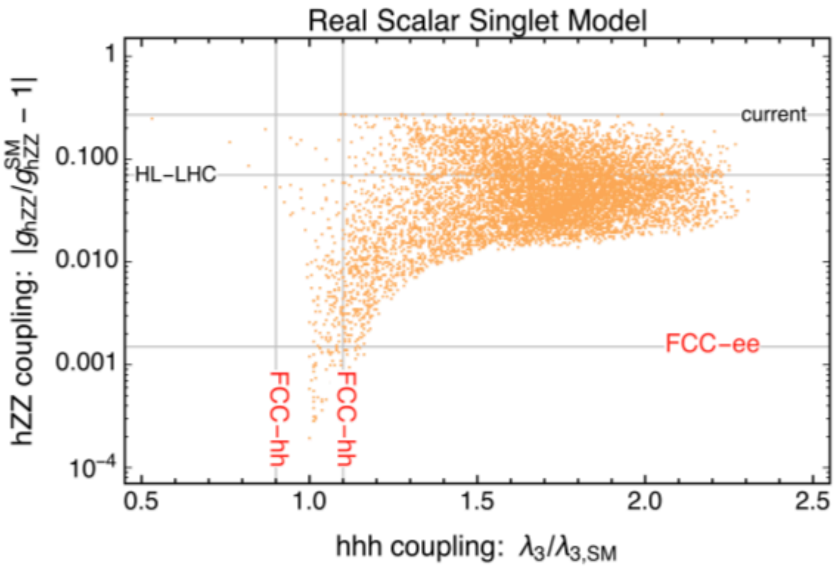


- Input from FCC-ee: C_V (κ_V)~O(0.1%) precision
  - $\delta(C_{2V})$ better than 1% at FCC-hh

Matter-antimatter asymmetry

- Possible explanation: new elementary particles produced through EWSB
  - "violent" transition to the broken symmetry: 1^{st} order phase transition
    - New particles typically ~TeV scale
  - Existence of CP-violation sources
    - New particles/interactions up to O(100) TeV
  - Small cross-sections (~fb)

None of these conditions satisfied in the SM

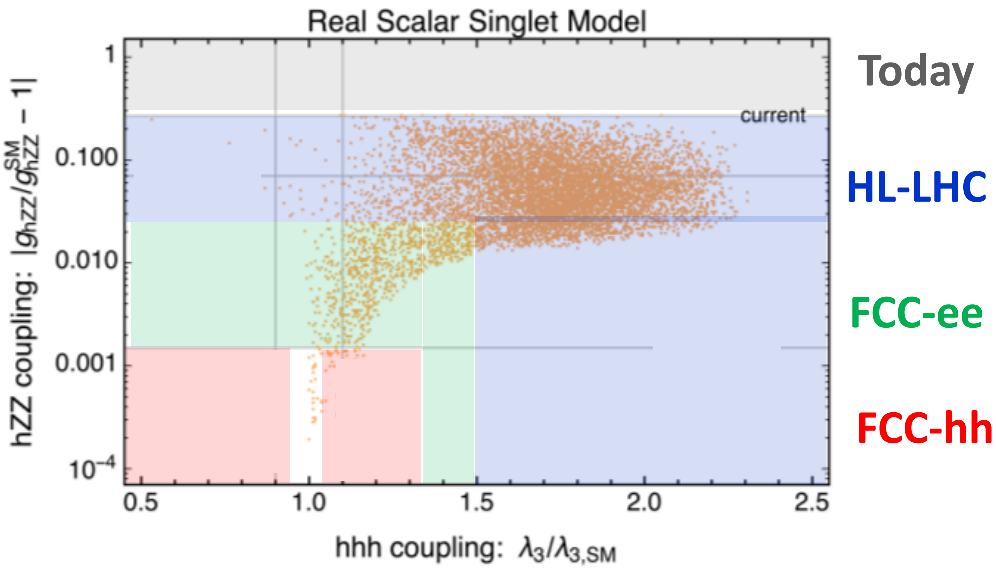


- Simplest extension to SM: additional singlet scalar
  - Two Higgs-like scalars: h1 (m=125 GeV) and h2
    - Modification of Higgs self-coupling (~few %) and in the Zh1 associated production
    - Direct production of scalar pairs -> Resonant Di-Higgs production

Measurement of Higgs properties at % level or better, essential

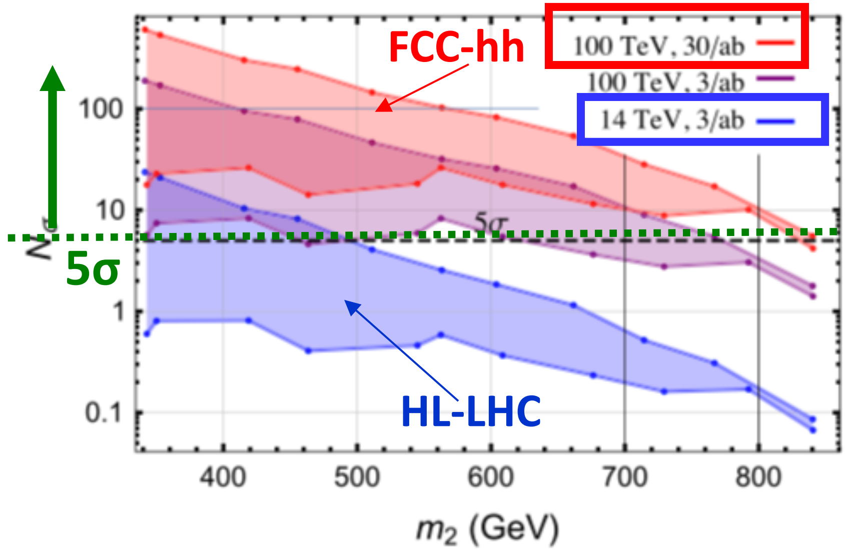
Matter-antimatter asymmetry (II)

Deviation from SM Higgs couplings



- → **Modification on Higgs self-coupling**
  Direct probe with FCC-hh
  Indirect at FCC-ee from a global fit on single Higgs data
- → **Modification n Higgs-Z coupling**
  both FCC-ee, FCC-hh sensitive
- → **FCC-ee + FCC-hh:** sensitivity to almost the entire parameter space
  Very little sensitivity at the LHC

Discovery potential in resonant Di-Higgs searches



- → **FCC-hh discovery potential** over the entire viable parameter space
- → Very limited discovery potential at HL-LHC
- → Non-resonant production of other combination of scalars also possible
  FCC-hh provides sensitivity to these models as well

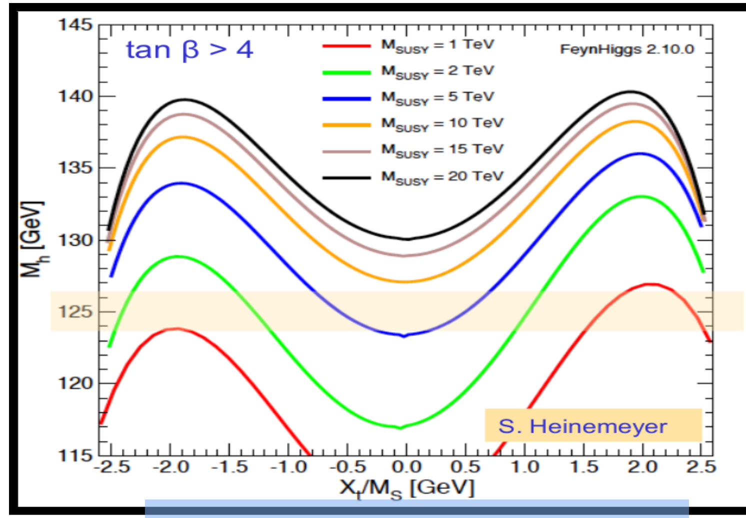
Direct BSM searches

The origin of m_H: Extended scalar sector

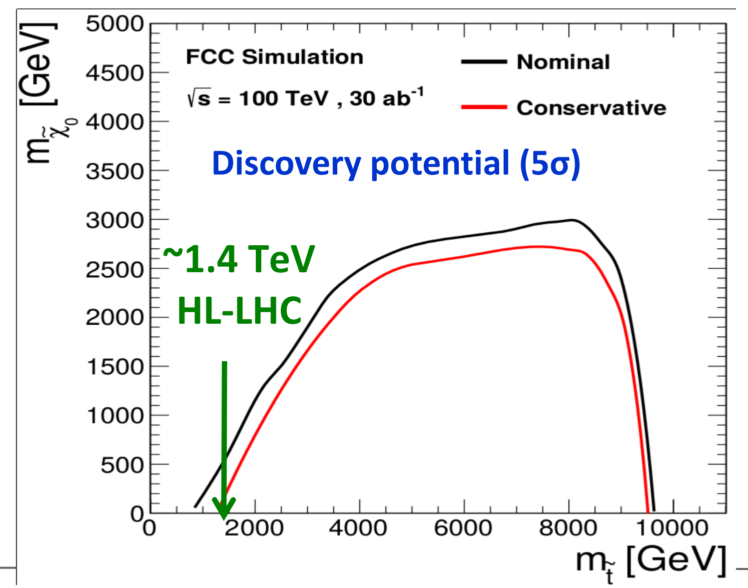
- The origin of m_H and the associated hierarchy problem is still a fundamental question
  - **Option A:** Higgs is an elementary particle
    - A possible solution: **SU**per**SY**mmetry
- No signs of SUSY at the LHC
  - Either: too heavy – beyond (HL-)LHC reach
    - With significant level of fine tuning

$$\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{126\ \mathrm{GeV}}{m_H}\right)^2 \left(\frac{\Lambda_{\mathrm{UV}}}{500\ \mathrm{GeV}}\right)^2$$

  - Or: in difficult corners of the SUSY parameter space
- Top squark reach with FCC-hh
  - All hadronic; large ME_T
  - Dedicated top-tagging algorithm



Mostly outside HL-LHC reach

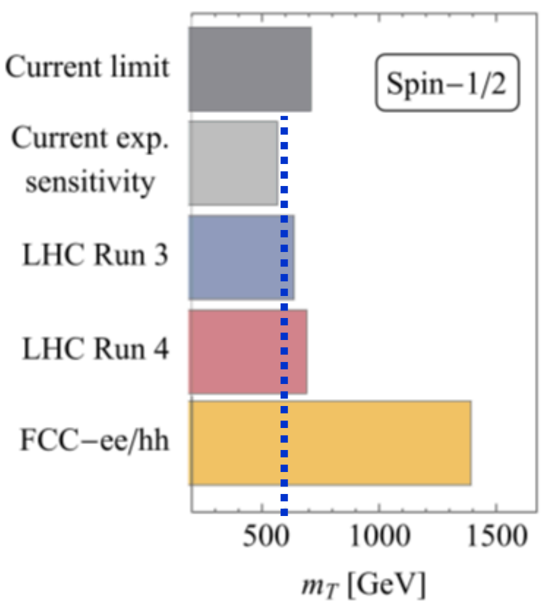


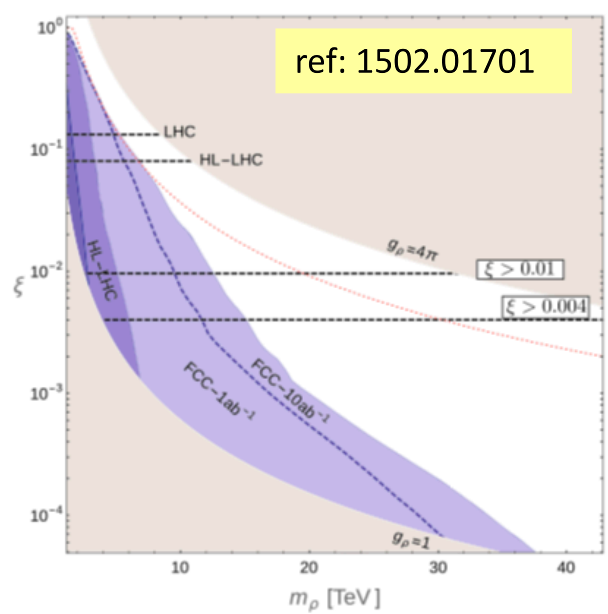
Reach the m_{stop}~10 TeV milestone with FCC-hh @ 30 ab^{-1}

The origin of m_H: Composite Higgs

- The origin of m_H and the associated hierarchy problem is still a fundamental question
  - **Option α:** Composite Higgs [*ala* QCD]
    - Predict new gauge interactions and new fermions

- Search based on:
  - Direct searches ("bump hunt") for new heavy resonances
  - Global fits on Higgs data looking for deviation from SM predictions





$$\xi = \frac{g_\rho^2}{m_\rho^2} v^2$$

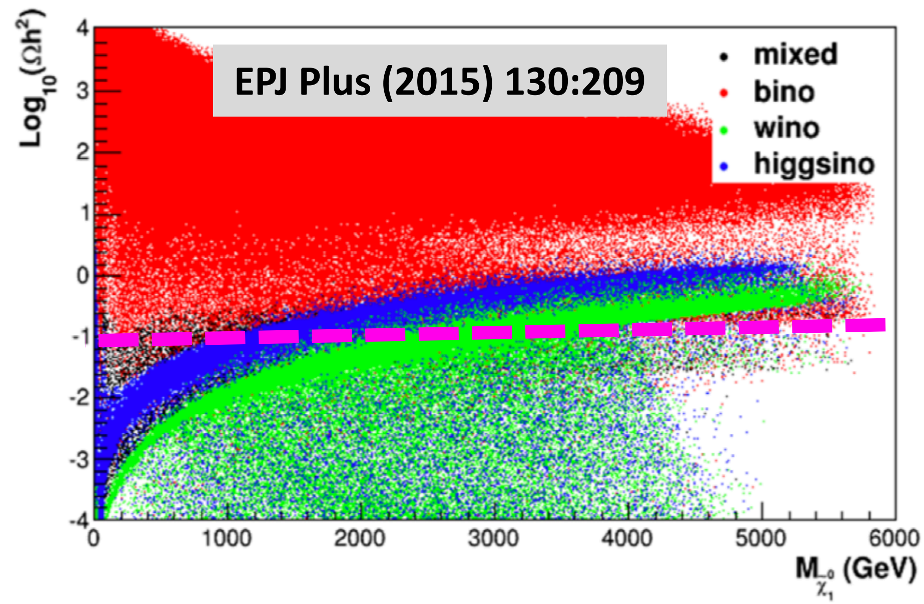
couplings to SM (→ g_ρ^2)

EW scale (→ v^2)

Significant reach by FCC

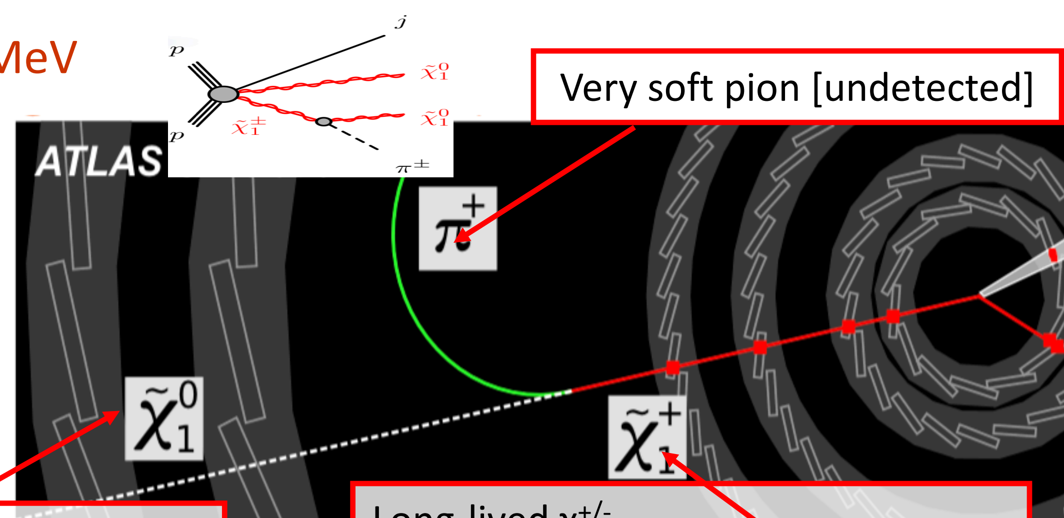
Thermal Dark Matter (DM)

- Neutralino: excellent DM candidate
  - Mass bounds from the observed dark matter relic density
    - Purely Wino: ~< 3 TeV
    - Purely Higgsino: ~< 1 TeV



- For purely wino/higgsino LSP, the LSP and the lightest $\chi^{+/-}$ are degenerated
  - Wino: Δm(LSP, $\chi^{+/-}$) ~160 MeV
  - Higgsino: Δm(LSP, $\chi^{+/-}$) ~350 MeV

- Very soft decay products
  - Requires dedicated analysis techniques and detector configuration



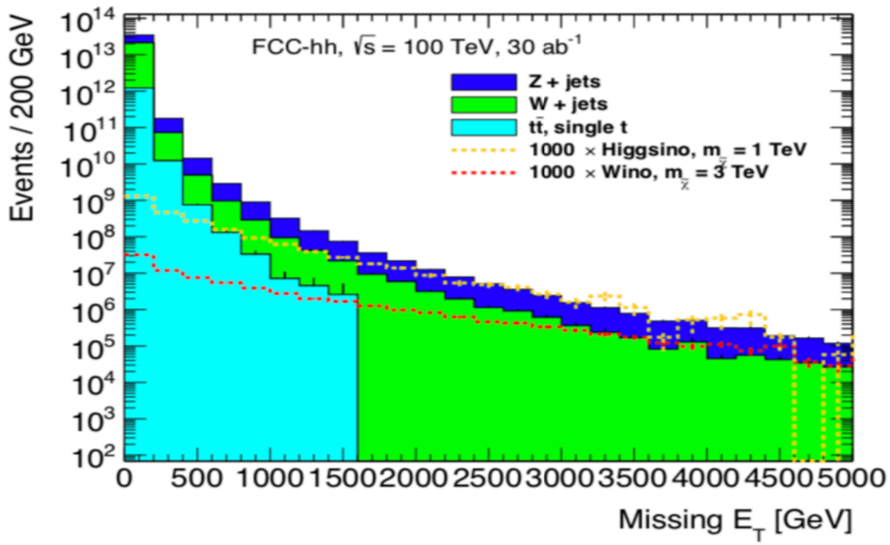
Very soft pion [undetected]

ME_T from the undetected LSP

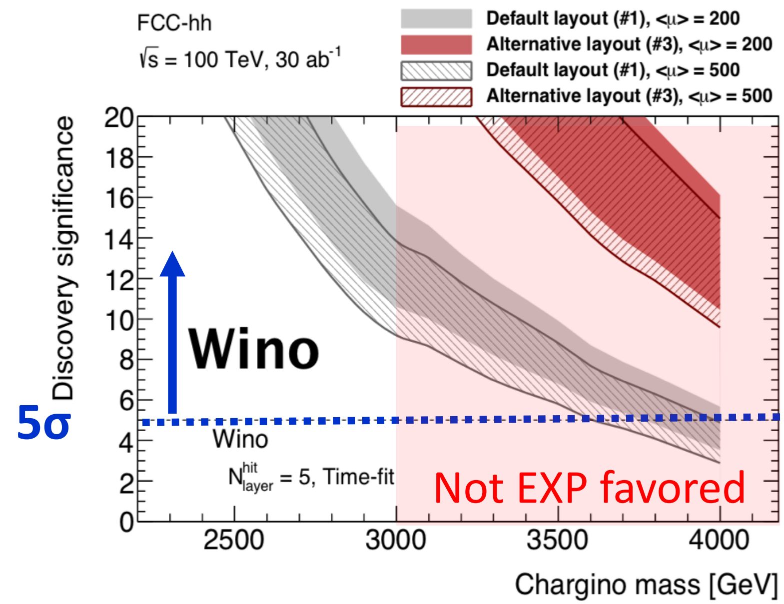
Long-lived $\chi^{+/-}$
ctau ~6 cm (Wino), ~7mm (Higgsino)
Hits in the pixel/tracker

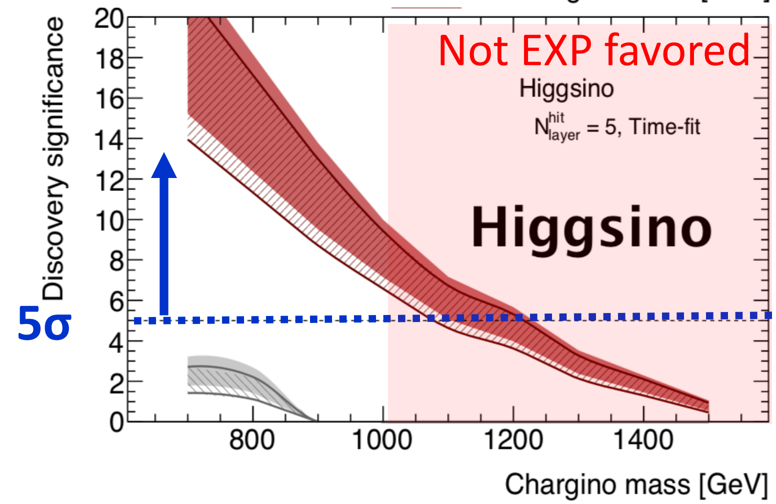
Dark Matter (DM) (II)

- High-p_T ISR jet and large ME_T signature
  - Veto leptons



  - Disappearing track finder
    - No associated tracks after a layer
    - At least 4 or 5 hits in each track (|η|<1)





→ All theory motivated scenarios for thermal DM can be **discovered** with FCC-hh

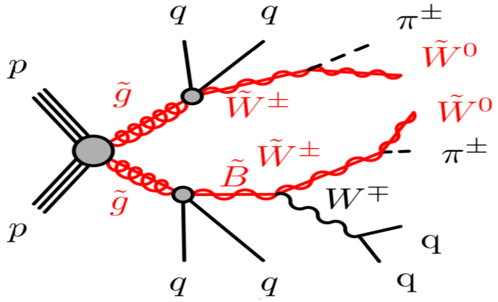
→ Yet, after modifications on the "reference FCC detector" i.e. **introduce** a <u>5-layer pixel detector</u>

→ And, the use of a **timing detector**

Dark matter: Mass determination

Ref: 1901.10389

- One step further: Characterize possible excess consistent with DM
  - Determine the gaugino masses [e.g. Wino case]



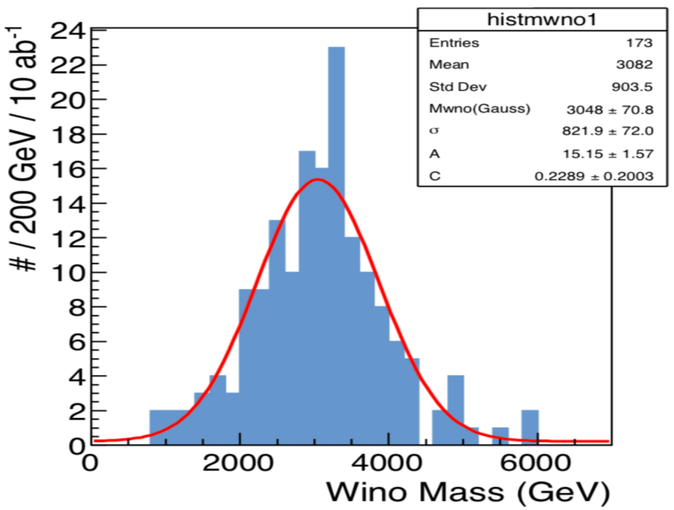
Event Selection:
→ 2 disappearing tracks with displacement >10 (5) cm for 1st (2nd)
→ ME_T > 1 TeV

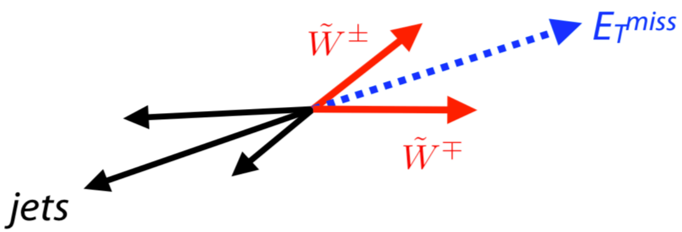
- Wino reconstruction:

$$m_{\tilde{W}}^{(\rm rec)} = \frac{\sqrt{1-\beta_I^2}}{\beta_I} |\vec{P}_{\tilde{W}_I}|$$

β: from timing info
[~6% resolution for r>10cm & β<0.8]

p: by splitting ME_T into Wino directions
[determined from disappearing tracks]





Similar strategy for the determination of Bino and gluino masses

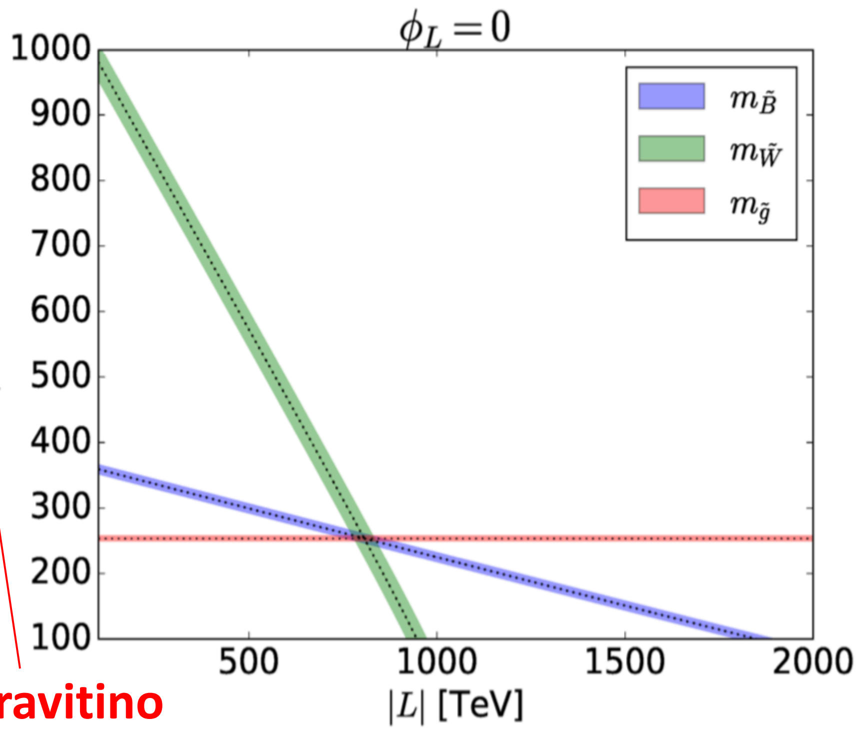
Implications in SUSY models

ref: 1901.10389

- e.g. Pure Gravity Mediation (PGM) model:
  - gaugino masses depend on $m_{3/2}$, $|L|$ & ϕ_L=arg(L)

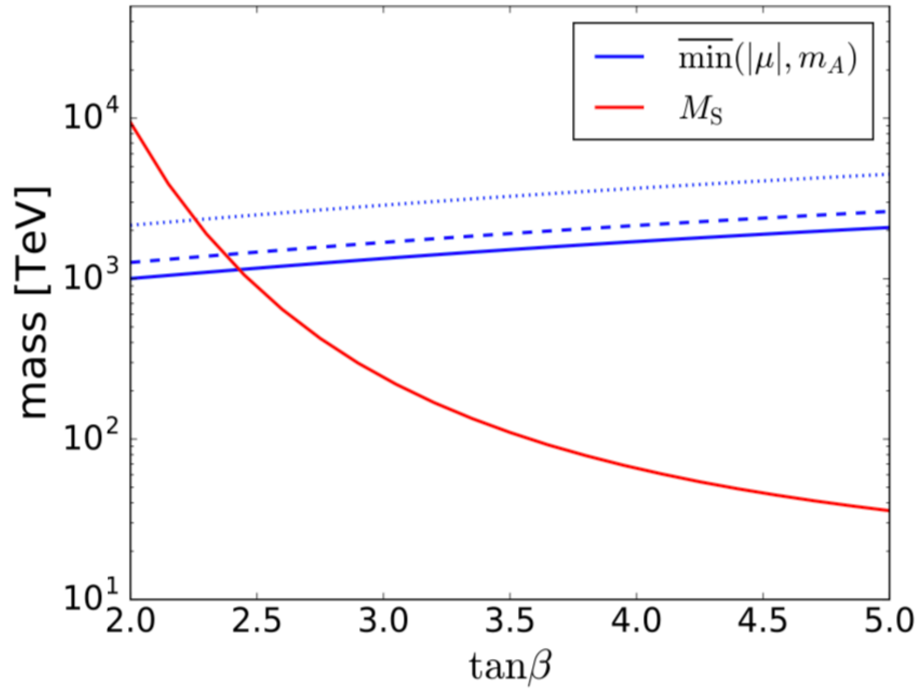
$$L \equiv \mu_H \sin 2\beta \frac{m_A^2}{|\mu_H|^2 - m_A^2} \ln \frac{|\mu_H|^2}{m_A^2}.$$

	Point 1
$m_{3/2}$ [TeV]	250
L [TeV]	800
$m_{\tilde{B}}$ [GeV]	3660
$m_{\tilde{W}}$ [GeV]	2900
$m_{\tilde{g}}$ [GeV]	6000
$\sigma(pp \to \tilde{g}\tilde{g})$ [fb]	7.9



gravitino mass

Info about mass scale of Higgsinos & heavy Higgses



Upper bound on **Heavy Higgs and Higgsino** (**sfermion**) mass scales

Heavy resonance searches

- Exotic resonances/particles/forces
  - Multi-TeV objects: “stress-test” for detector design/performance and object reconstruction techniques
- **FCC-ee [indirect]:** no bump but search for deviations from SM in the tails
- **FCC-hh [direct]:** “classical” bump-hunt search

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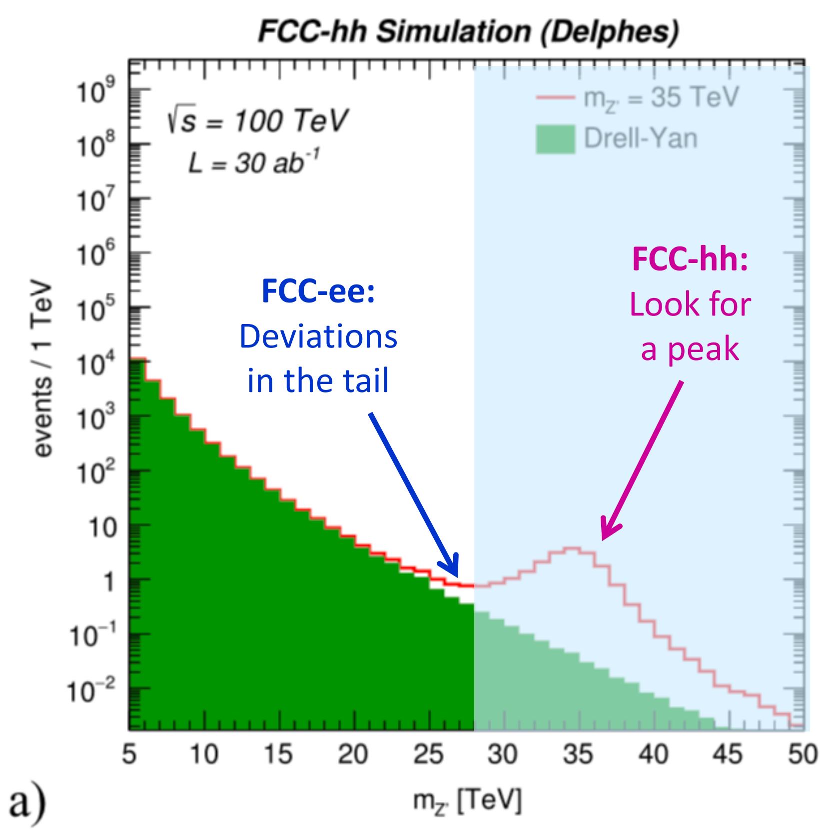
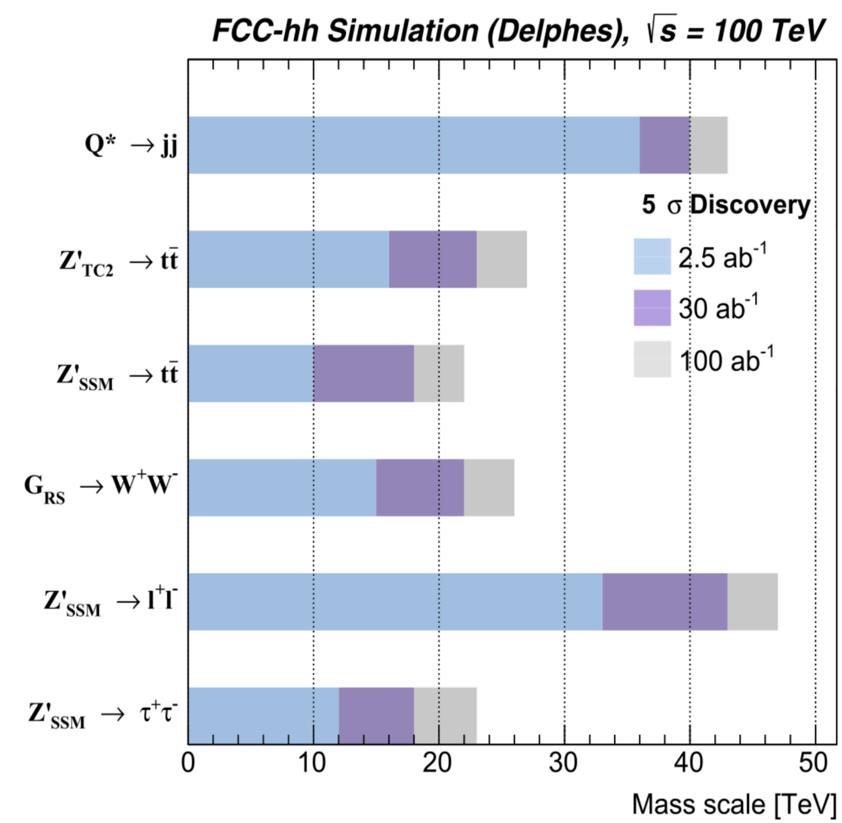




Summary

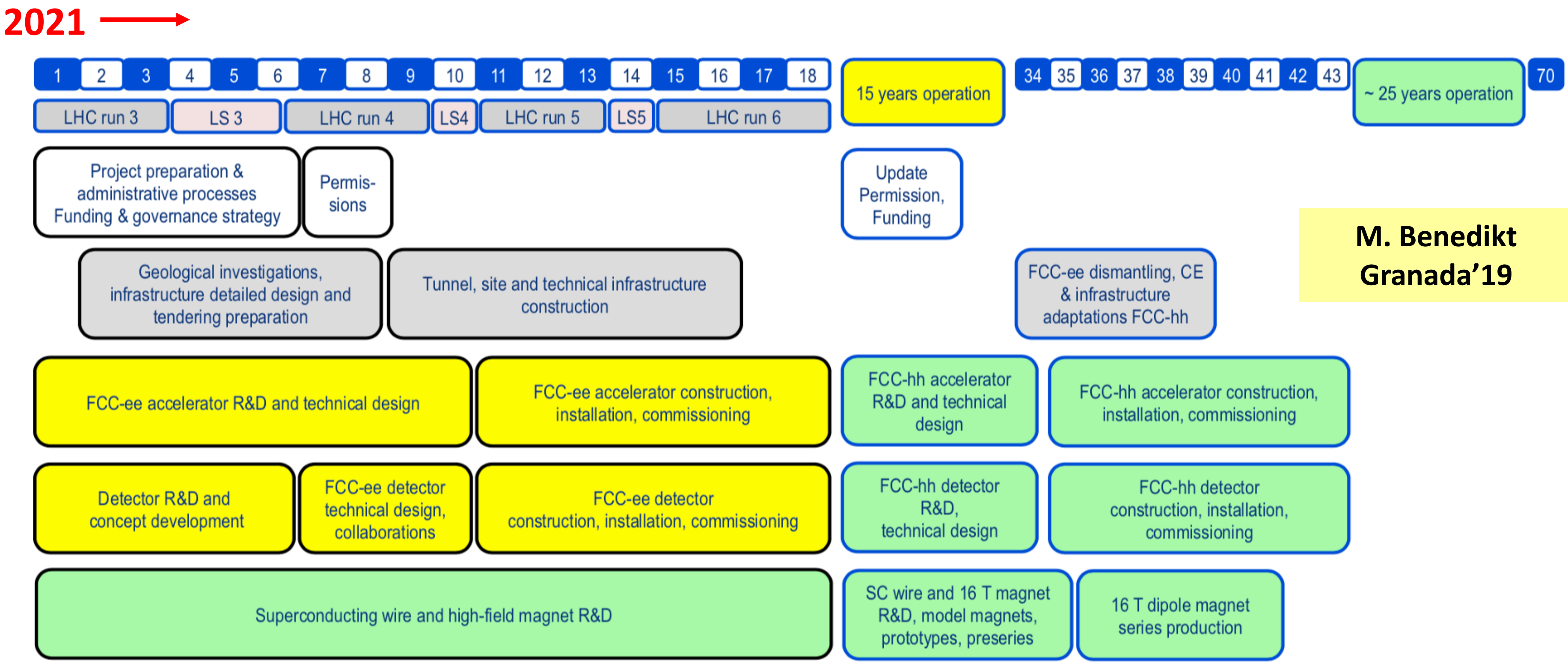
- The FCC-hh has a very clear physics case:
  - is able to provide <u>definite answers</u> to many of the "big questions"
    → **guaranteed deliverables**
  - It is the only planned or proposed project that probes such large mass scales
  - Measure SM to unprecedented precision

- Maximal physics outcome is achieved by taking advantage of the **<u>complementarity</u>** and **<u>synergy</u>** between the three colliders (ee, eh, hh)
  - Only way to explore the full FCC physics potential

- Many more physics results discussed in the Conceptual Design Report (CDR)

https://fcc-cdr.web.cern.ch/

Timeline for the Full FCC project



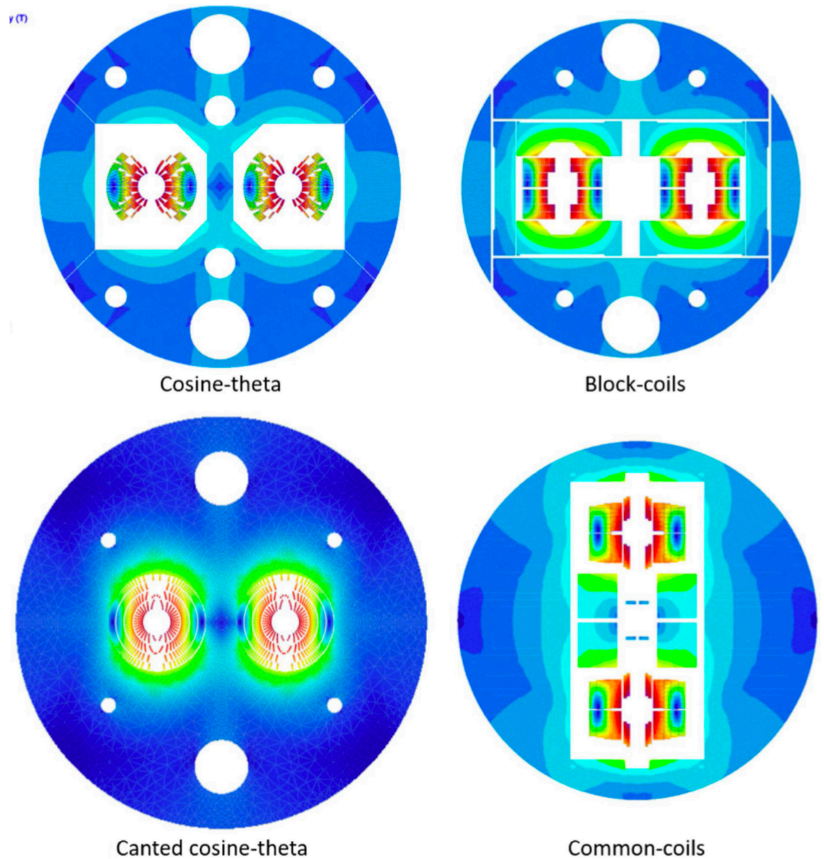
→ FCC project fully integrated with (HL-)LHC physics program

→ There is a long way ahead: We should start defining the future of HEP **now**

Backup

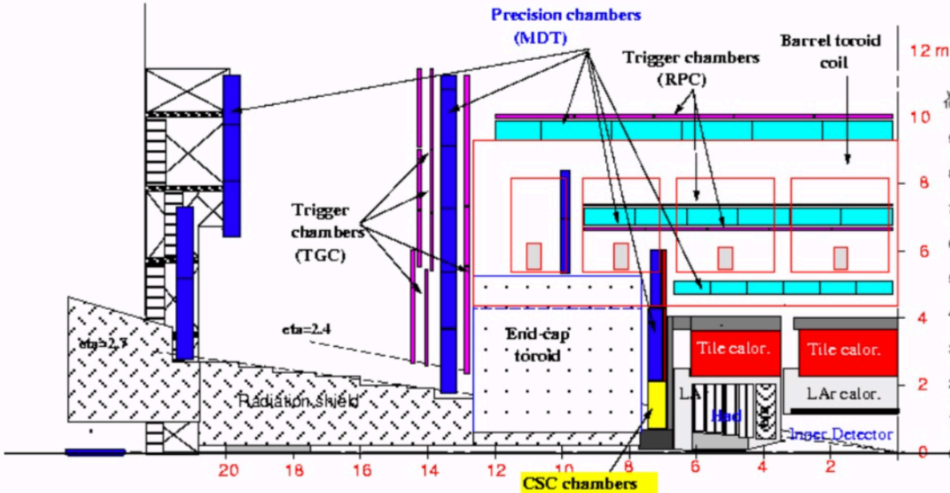
Dipole magnets at 16 T

- Based on HL-LHC Technology:
  - 4x more magnets
  - 2x increase in field amplitude
    - HL-LHC: max field ~11-12T
- Large cost: Dipoles use Nb_3Sn conductors at 2K
  - R&D: Increase max current density in conductor to 1500 A/mm^2 at ~4K
    - currently 1200 A/mm^2
- Alternative options are explored
  - particularly if FCC-hh follows FCC-ee 15-20 years of R&D

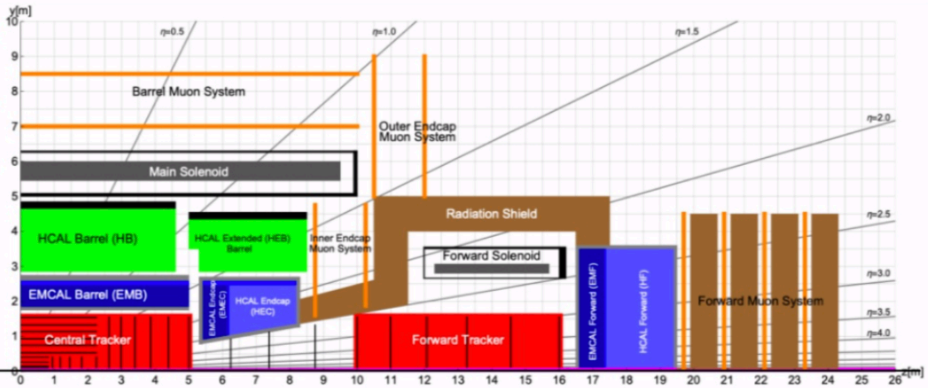


The FCC-hh detector

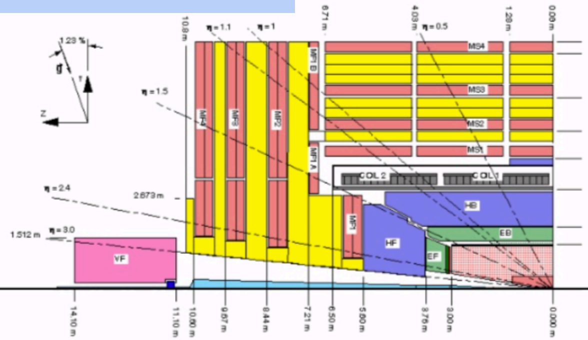
ATLAS

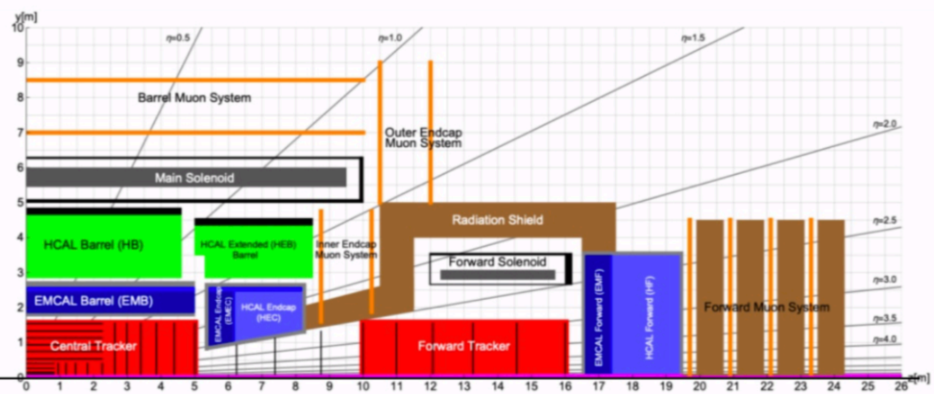


FCC-hh

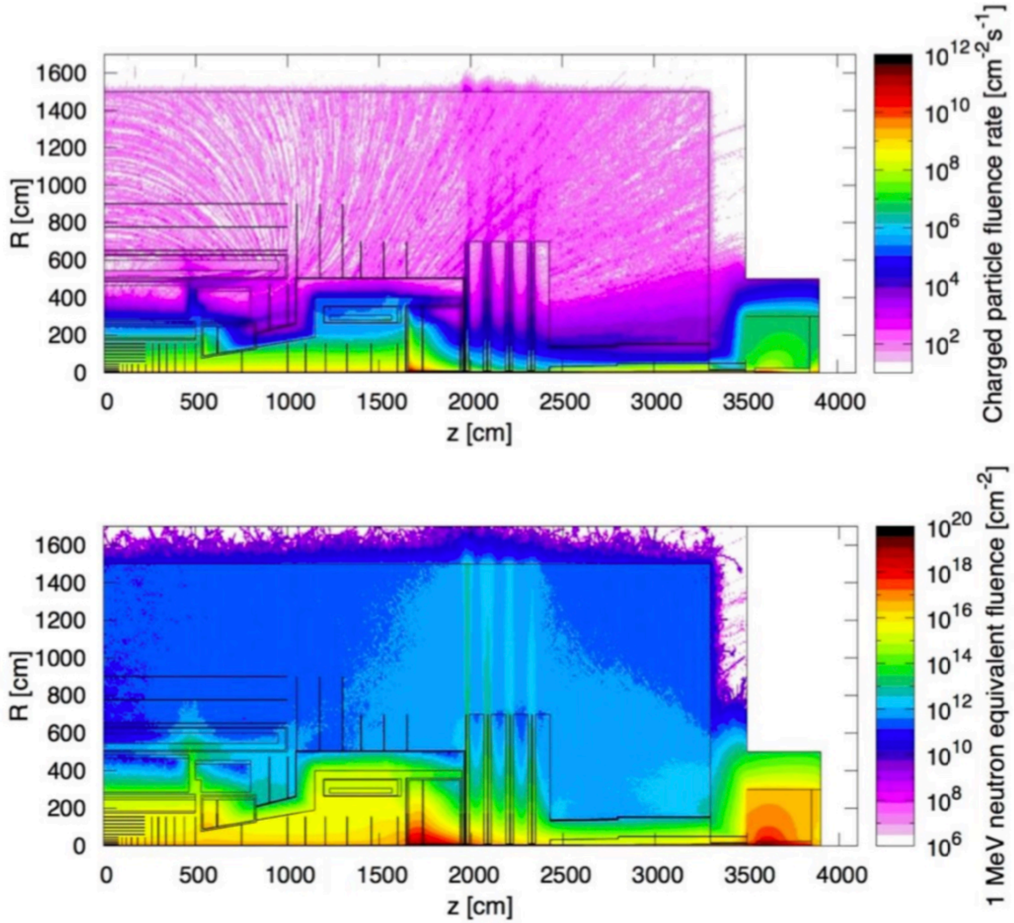


CMS



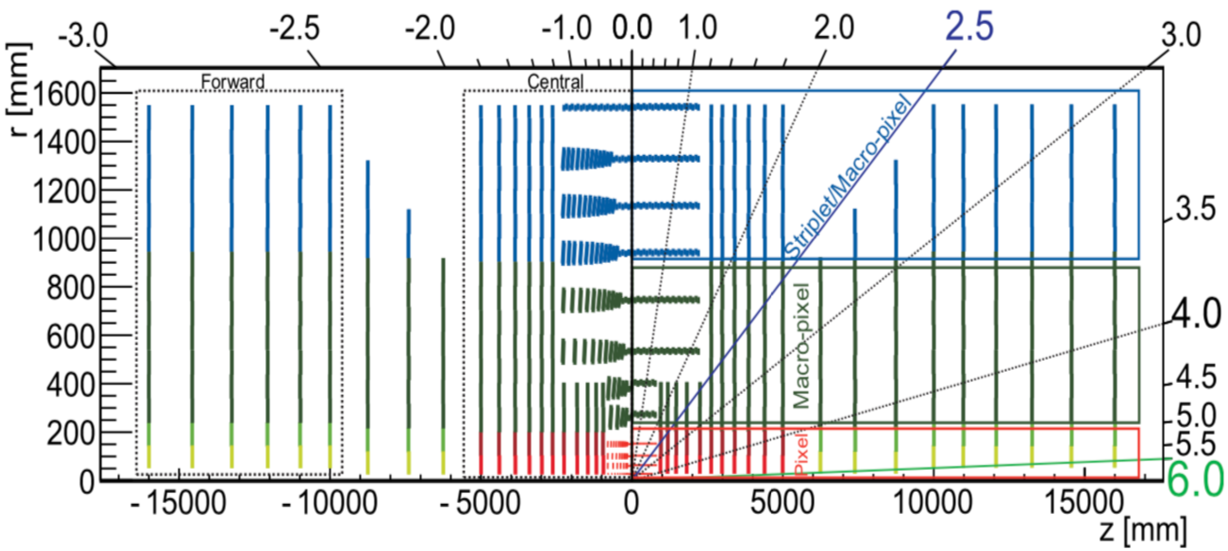


Radiation studies

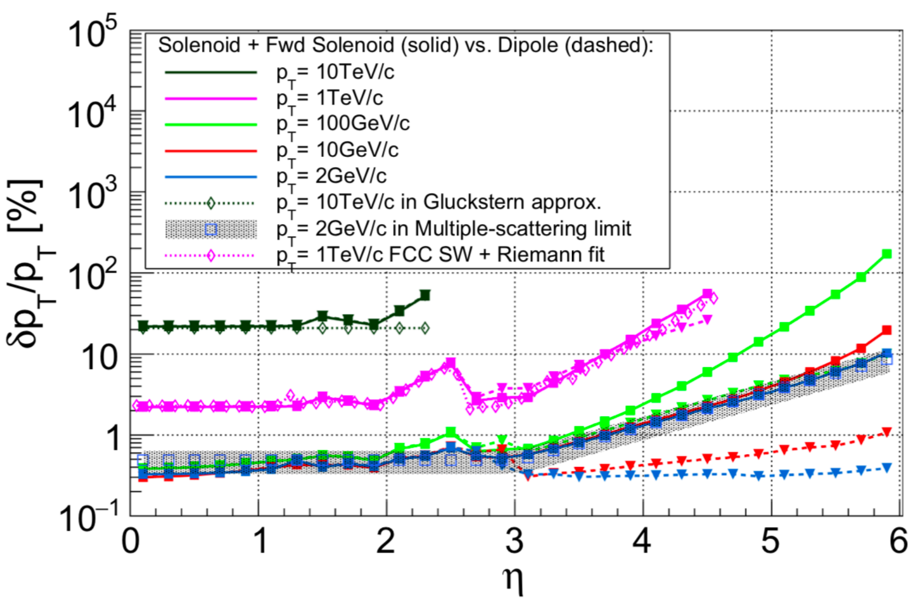


The FCC-hh detector: TRK

Titled geometry | **Flat geometry**



- → **Titled geometry:** ~50% less material, better performance 390 m² Silicon/ 250 m² CMS
- → Material budget less than CMS/ATLAS
- → **16x10⁹ readout chan.** 3 (8)x more than CMS (ATLAS)



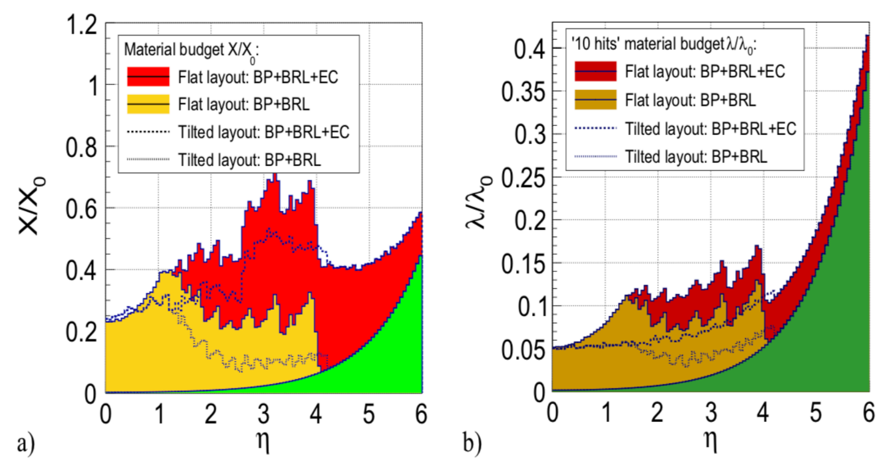
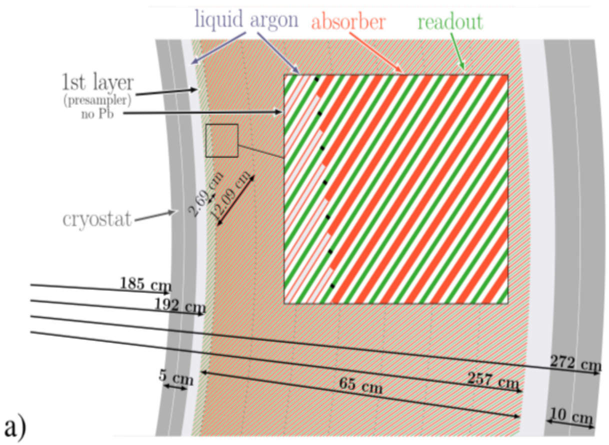
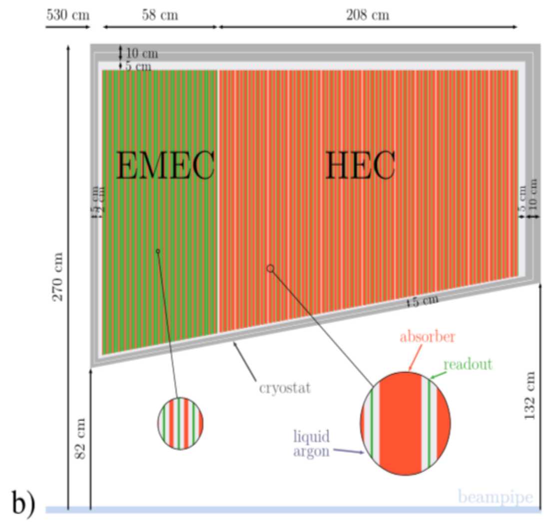


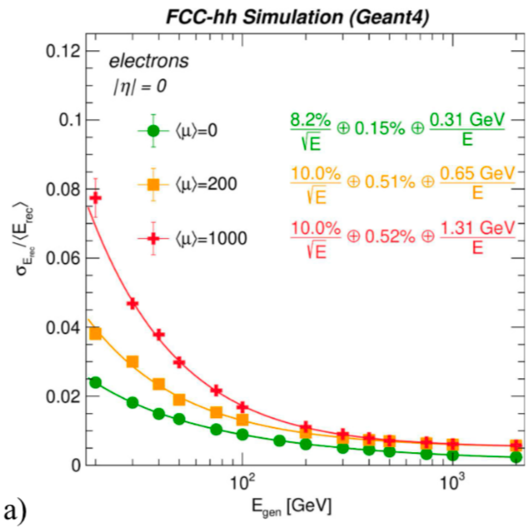
Fig. 7.14. (a) Material budget in units of radiation length for the flat and tilted tracker geometries. (b) Material budget in units of nuclear interaction length for the flat and tilted tracker geometries, assuming a limit of 10 hits on the track.

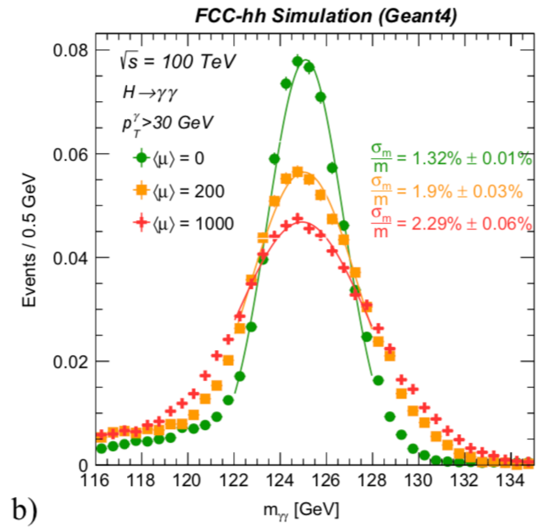
The FCC-hh detector: ECAL





- → **LAr/Pb (Lar/Cu):** Barrel (Fwd) rad hard & stability alternative ala CMS-HGCal [Si/Pb(W)]
- → **ΔηxΔϕ~0.01x0.01:** ~4x more granular than ATLAS/CMS
- → **Long. segmentation:** 8 layers

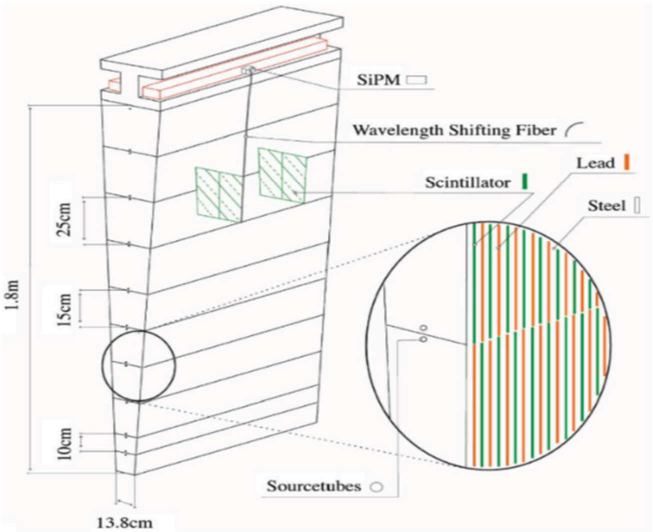




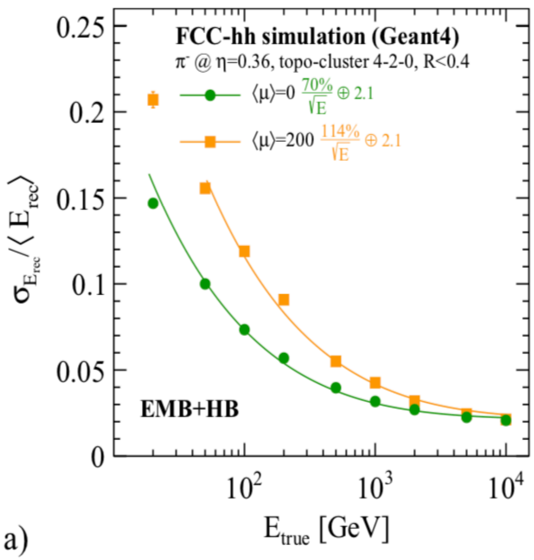
- → comparable mass resolution with CMS in the case of low PU
- → ~2x degradation in $m_{\gamma\gamma}$ resolution for PU=1000

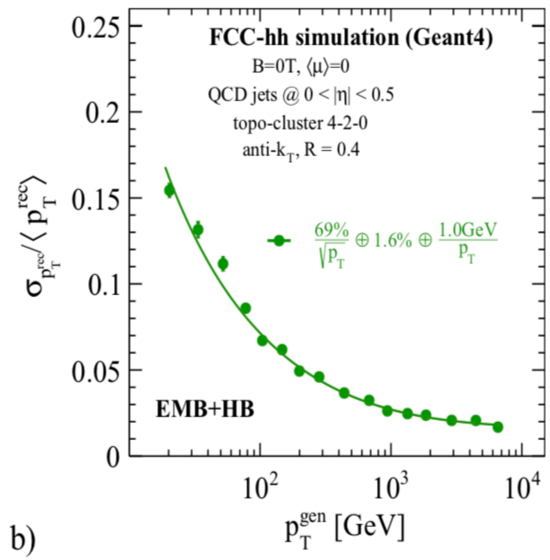
  However: no TRK info exploited

The FCC-hh detector: HCAL



- → **Organic scintillating tiles & steel with wavelength shifting fibers (WLS)**: Similar technology to ATLAS
- → **ΔηxΔϕ~0.025x0.025:** ~4x more granular than ATLAS/CMS
- → **Long. segmentation:** 8 or 10 layers





- → comparable mass resolution with CMS in the case of low PU
- → Effect of PU significant: Needs more sophisticated algorithms and TRK information

The FCC-hh detector: Calo summary

Table 7.3. Calorimeter system for the reference detector.

	η_{min}	η_{max}	a	c	$\Delta\eta$	$\Delta\phi$	Fluence	Dose	Material	Mix	Seg.
Unit			$\%\sqrt{\text{GeV}}$	%			cm^{-2}	MGy			
EMB	0	1.5	10	0.7	0.01	0.009	5×10^{15}	0.2	LAr/Pb/PCB	1/0.47/0.28	8
EMEC	1.5	2.5	10	0.7	0.01	0.009	3×10^{16}	4	LAr/Pb/PCB	1/0.75/0.6	6
EMF	2.5	4	10	0.7	0.025	0.025			LAr/Cu/PCB	1/50/6	6
	4	6	30	1	0.025	0.025	5×10^{18}	5000	LAr/Cu/PCB	1/50/6	6
HB	0	1.26	50	3	0.025	0.025	3×10^{14}	0.006	Sci/Pb/Fe	1/1.3/3.3	10
HEB	0.94	1.81	50	3	0.025	0.025	3×10^{14}	0.008	Sci/Pb/Fe	1/1.3/3.3	8
HEC	1.5	2.5	60	3	0.025	0.025	2×10^{16}	1	LAr/Cu/PCB	1/5/0.3	6
HF	2.5	4	60	3	0.05	0.05	5×10^{18}	1000	LAr/Cu/PCB	1/200/6	6
	4	6	100	10	0.05	0.05	5×10^{18}	1000	LAr/Cu/PCB	1/200/6	6

Notes. Acceptance, performance goals (single electron for ECAL and single pion for ECAL+HCAL), granularity, radiation levels for $\mathcal{L}_{\text{int}} = 30\,\text{ab}^{-1}$ and technologies chosen.

The FCC-hh detector: Muons

- MDTs technologies ala ATLAS

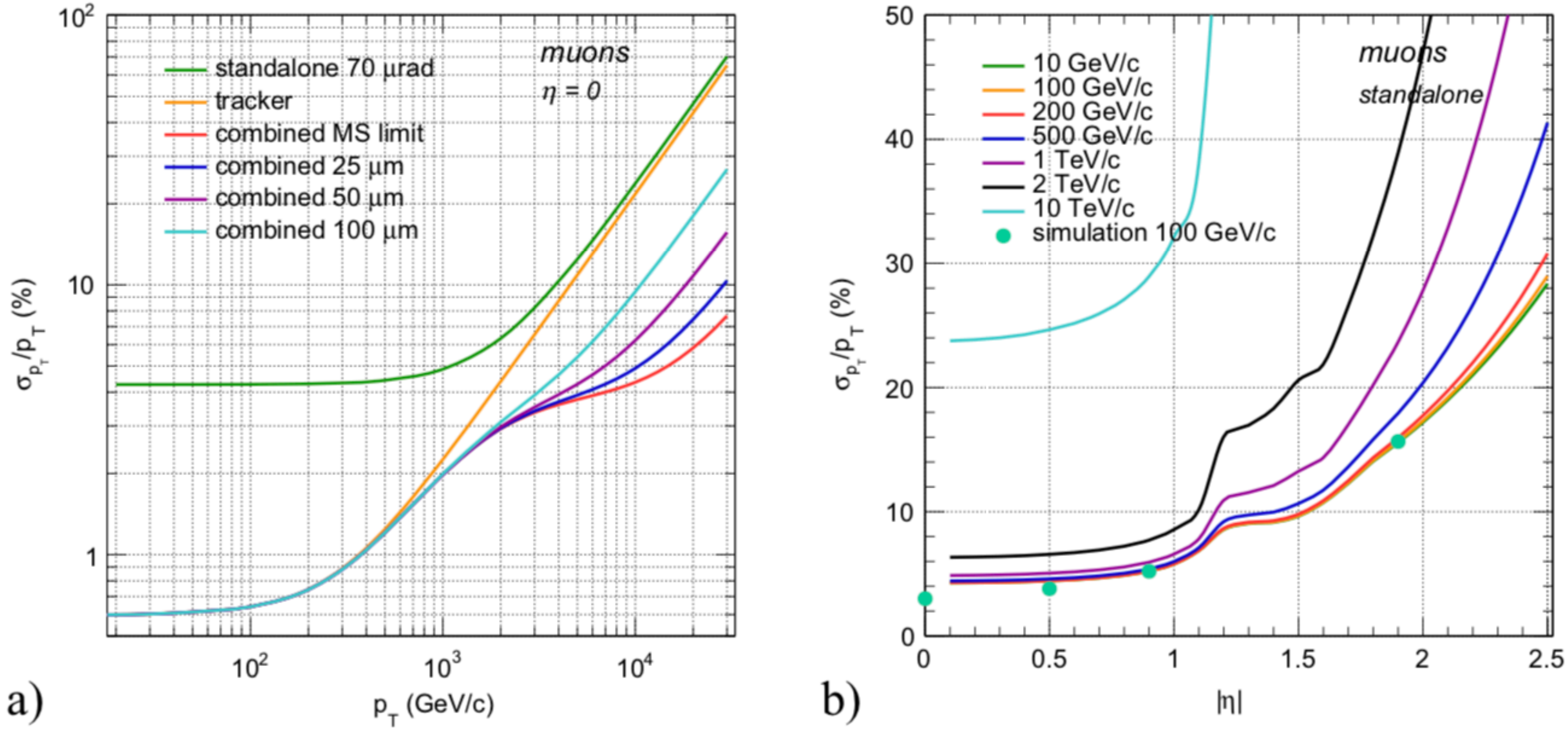
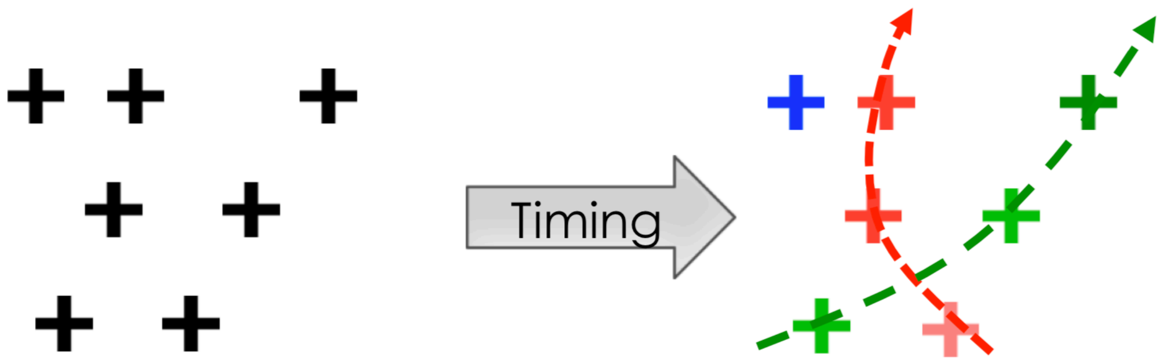


Fig. 7.21. (a) Muon momentum resolution at $\eta = 0$. (b) Muon stand-alone momentum resolution as a function η for different muon momenta.

Timing layers

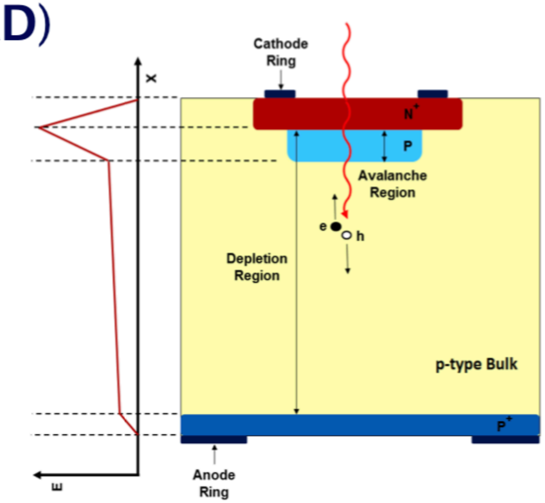


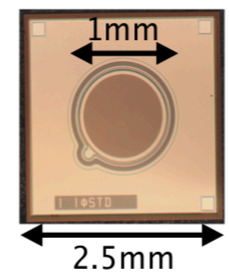
ref: 1901.10389

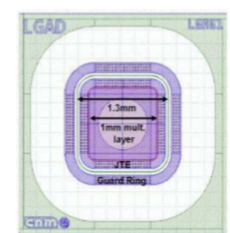
ATLAS HGTD

Low–Gain Avalanche Detector (LGAD)

- ≲ 30 ps time resolution feasible
- ongoing study for radiation hardness

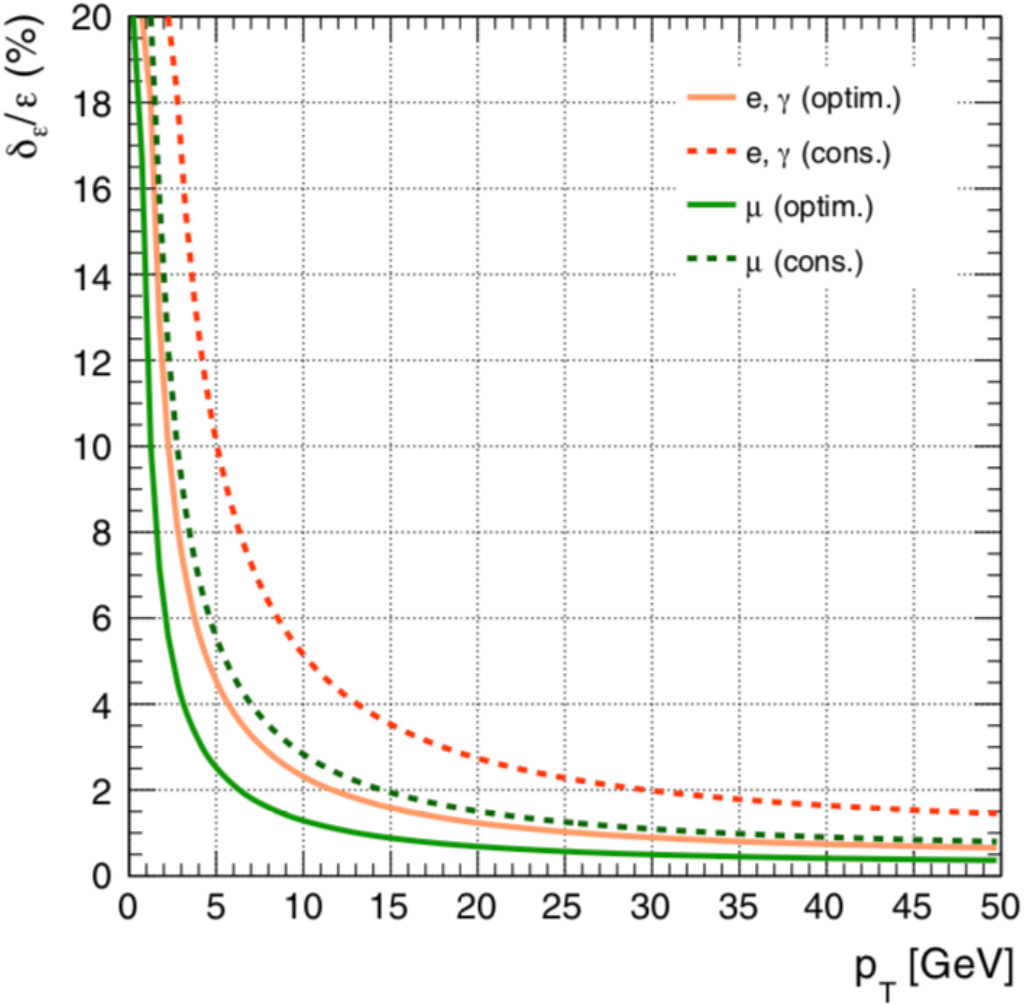






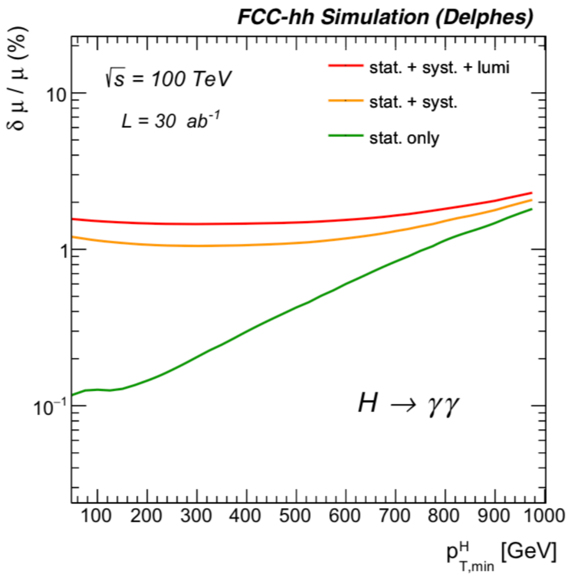
Assumed in this study that 30~50 ps time resolution can be achieved for the inner-pixel tracker at FCC

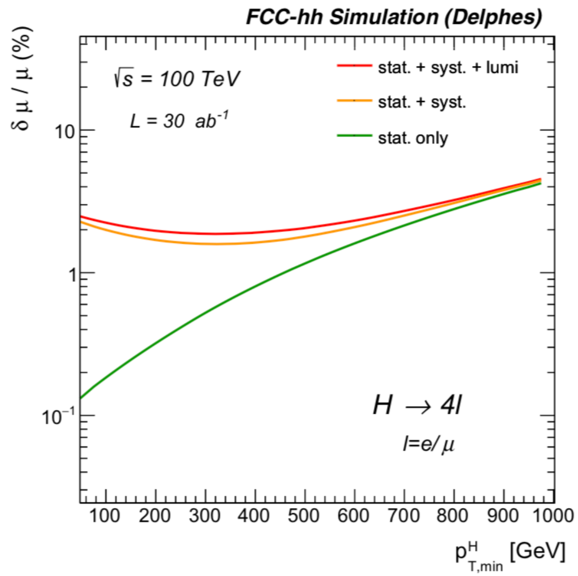
e/gamma/mu reco uncertainties

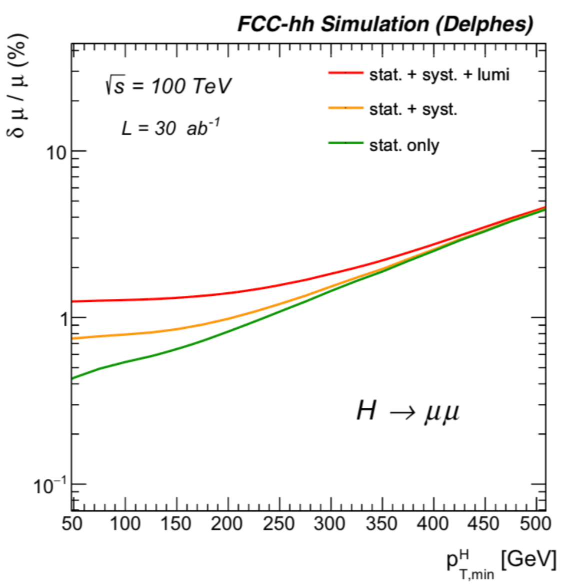


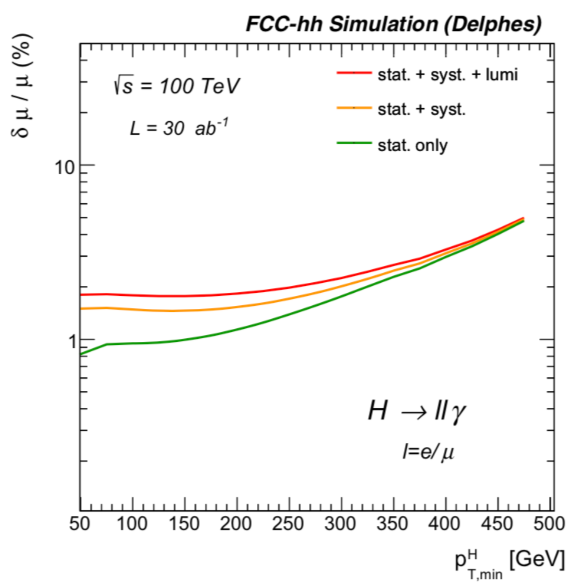
→ Expect to be significantly improved by using data-driven methods (e.g. Tag & Probe on Z)

Higgs: absolute uncertainties









syst: optimistic reco unc.

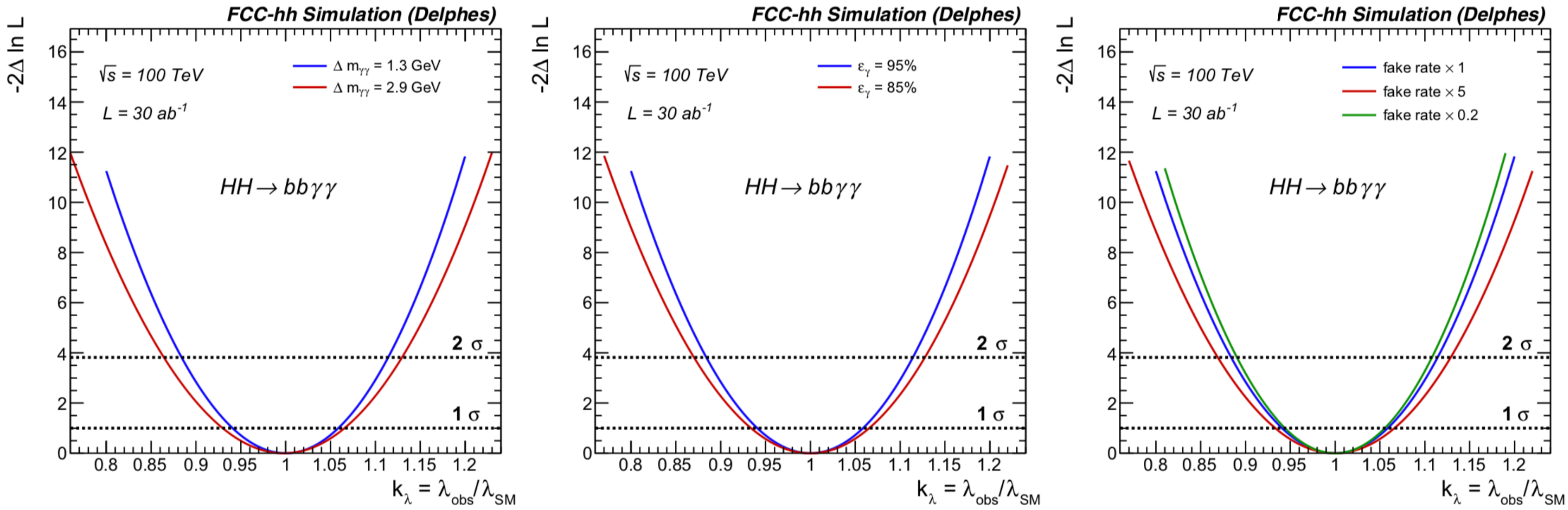
lumi: 1% for Lumi + production unc.

Lumi + Theory unc. can be both can be improved with better knowledge of PDF and FCC-eh results [~0.X%]

→ ~10% uncertainty in high p_T which is very sensitive to BSM physics

Double Higgs: HH->bbγγ

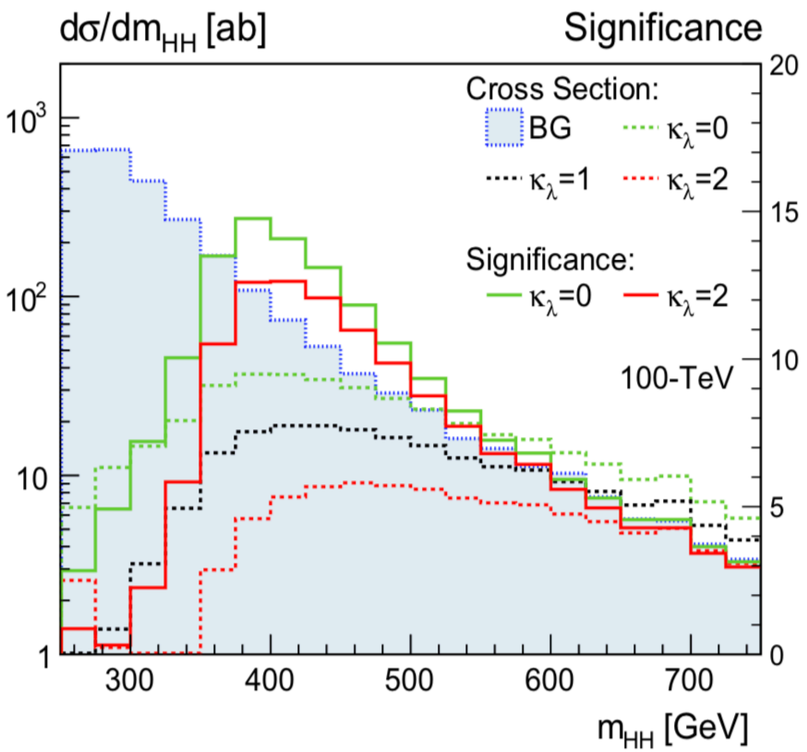
- More systematics scenarios:

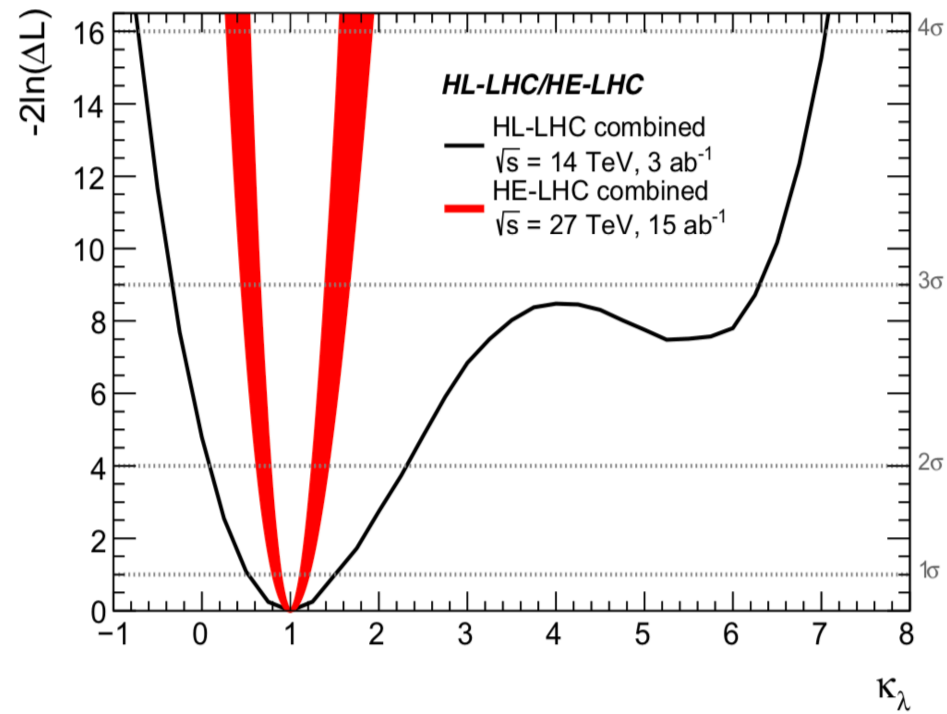


- Each scenario degrades precision by ~1-2%

Di-Higgs: Nature of Higgs potential (II)

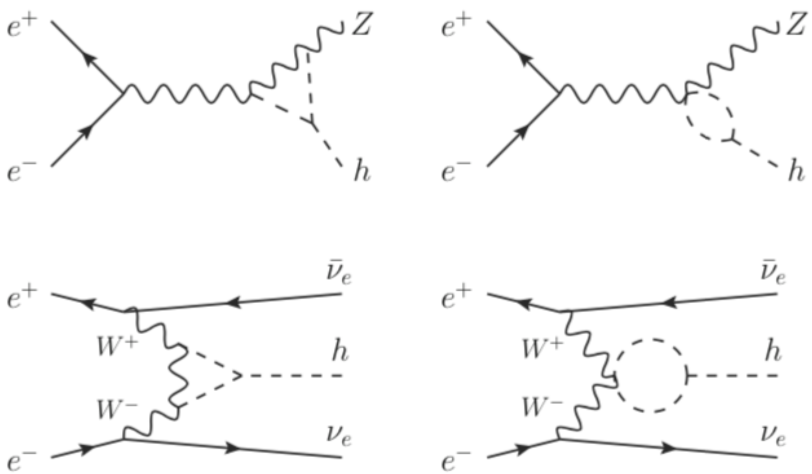
- m_{HH} very sensitive to BSM:
  - in SM amplitude vanishes at threshlod due to interference

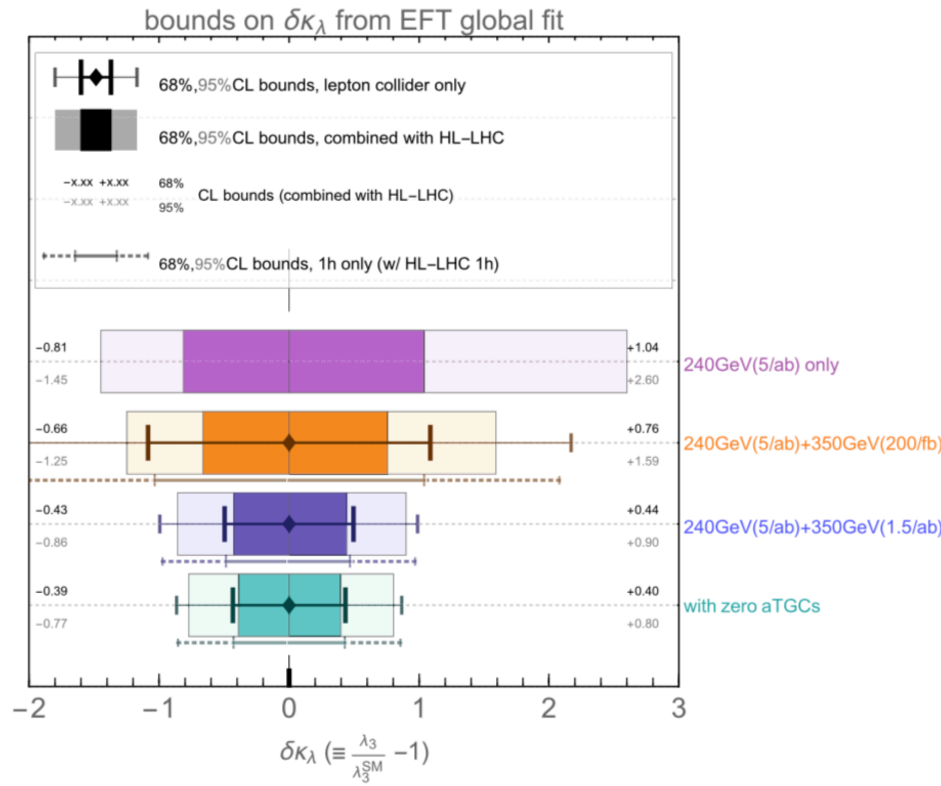




Higgs self coupling with single-H

- Measure Higgs self coupling indirectly in single-H processes through loops





Highlights from FCC-ee

- κ-framework:

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$LEP3_{240}$	$CEPC_{250}$	$FCC\text{-}ee_{240+365}$		
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	8	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	**0.61**	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	**1.01**	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	**0.74**	0.67
$\delta g_{Hmm}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	**9.0**	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	**3.9**	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–	3.1
BR_{EXO} (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 1.2	$< \mathbf{1.0}$	$< \mathbf{1.0}$

- scenarios:

Scenario	BR_{inv}	BR_{unt}	include HL-LHC
kappa-0	fixed at 0	fixed at 0	no
kappa-1	measured	fixed at 0	no
kappa-2	measured	measured	no
kappa-3	measured	measured	yes

Highlights from FCC-ee (II)

Table S.3 Measurement of selected electroweak quantities at the FCC-ee, compared with the present precision. The systematic uncertainties are present estimates and might improve with further examination. This set of measurements, together with those of the Higgs properties, achieves indirect sensitivity to new physics up to a scale Λ of 70 TeV in a description with dim 6 operators, and possibly much higher in some specific new physics models

Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.	Comment and dominant exp. error
m_Z (keV/c^2)	$91{,}186{,}700 \pm 2200$	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	$2{,}495{,}200 \pm 2300$	8	100	From Z line shape scan beam energy calibration
R_ℓ^Z ($\times 10^3$)	$20{,}767 \pm 25$	0.06	0.2–1	Ratio of hadrons to leptons acceptance for leptons
α_s (m_Z) ($\times 10^4$)	1196 ± 30	0.1	0.4–1.6	From R_ℓ^Z above
R_b ($\times 10^6$)	$216{,}290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
σ^0_{had} ($\times 10^3$) (nb)	$41{,}541 \pm 37$	0.1	4	Peak hadronic cross-section luminosity measurement
N_ν ($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	$231{,}480 \pm 160$	3	2–5	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}$ (m_Z) ($\times 10^3$)	$128{,}952 \pm 14$	4	Small	From $A_{FB}^{\mu\mu}$ off peak
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1–3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	0.15	< 2	τ Polarisation and charge asymmetry τ decay physics
m_W (MeV/c^2)	$80{,}350 \pm 15$	0.5	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan beam energy calibration
α_s (m_W) ($\times 10^4$)	1170 ± 420	3	Small	From R_ℓ^W
N_ν ($\times 10^3$)	2920 ± 50	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	$172{,}740 \pm 500$	17	Small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410 ± 190	45	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	$\pm 30\%$	0.5–1.5%	Small	From $E_{CM} = 365$ GeV run

EFT: Higgs pair production: scenarios

The sensitivity of the various future colliders to the Higgs cubic coupling can be obtained using five different methods:

1. an exclusive analysis of HH production, i.e., a fit of the double Higgs cross section considering only deformation of the Higgs cubic coupling;
2. a global analysis of HH production, i.e., a fit of of the double Higgs cross section considering also all possible deformations of the single Higgs couplings that are constrained by single Higgs processes;
   (a) the global fit does not consider the effects at higher order of the modified Higgs cubic coupling to single Higgs production and to Higgs decays;
   (b) these higher order effects are included;
3. an exclusive analysis of single Higgs processes at higher order, i.e., considering only deformation of the Higgs cubic coupling; technically, this will be a one dimensional EFT fit where only the linear combination of the two operators of Eq. (25) corresponding to the κ_3 deformation is turned on;
4. a global analysis of single Higgs processes at higher order, i.e., considering also all possible deformations of the single Higgs couplings. Technically, this will be a 30-parameter EFT fit done within the scenario $\mathrm{SMEFT_{ND}}$ scenario of Eq. (16). The contribution of κ_3 to EWPO at 2-loop could also be included but for the range of κ_3 values discussed here, the size of effects would be totally negligible.

Higgs production rates:

	$gg \rightarrow H$	VBF	WH	ZH	$t\bar{t}H$	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390
N_{27}	2.2×10^9	1.8×10^8	5.1×10^7	3.7×10^7	4.4×10^7	2.1×10^6
N_{27}/N_{14}	16	15	11	12	24	19