Physics opportunities at the Future Circular Collider(s)

Michele Selvaggi

CERN

The big questions

- What is the origin of Dark Matter / Energy ?
- What is the origin of matter/anti-matter asymmetry ?
- What is the origin on neutrino masses — the flavour puzzle ?
- What is the origin of the Electro-weak symmetry breaking ?
- What is the solution to hierarchy problem ?

The Standard Model does not provide answers to these questions

There is new physics out there (beyond the Standard Model)

Collider or not collider?

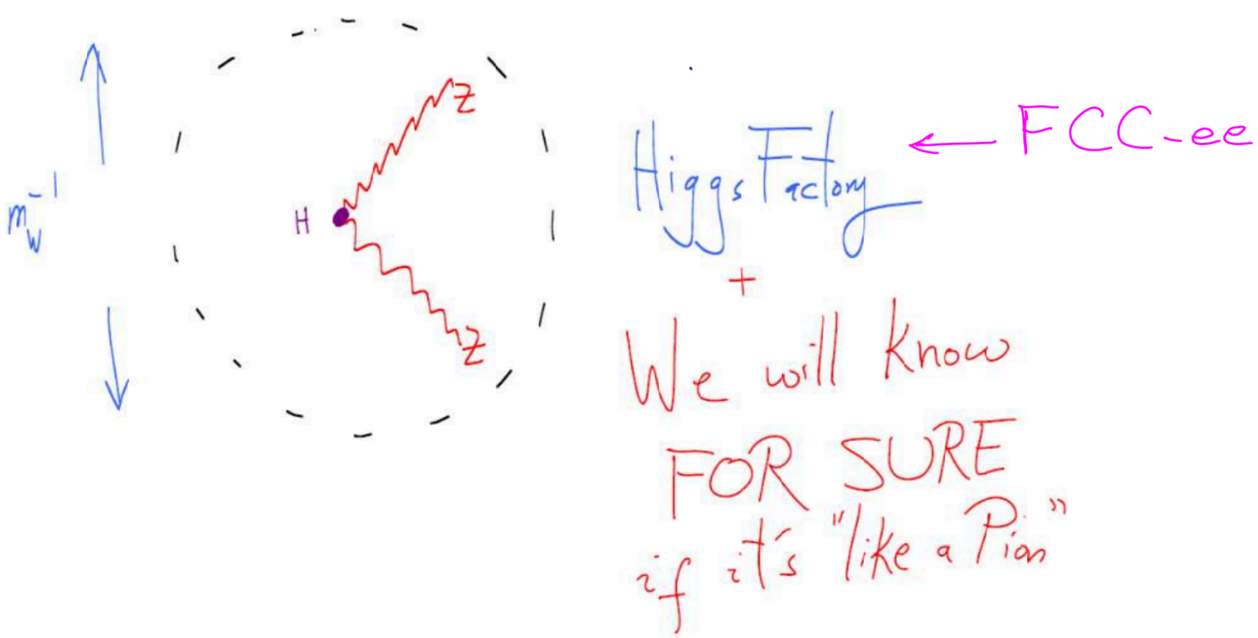
- No single experiment can:
  - explore all directions at once
  - guarantee discovery

- Design projects that can deliver:
  - precision
  - (inclusive) sensitivity to new as many as possible scenarios of new physics
  - clear yes/no answers to concrete scenarios

The Higgs particle

is new physics …

from Arkani Hamed
FCC week



elementary scalar ?

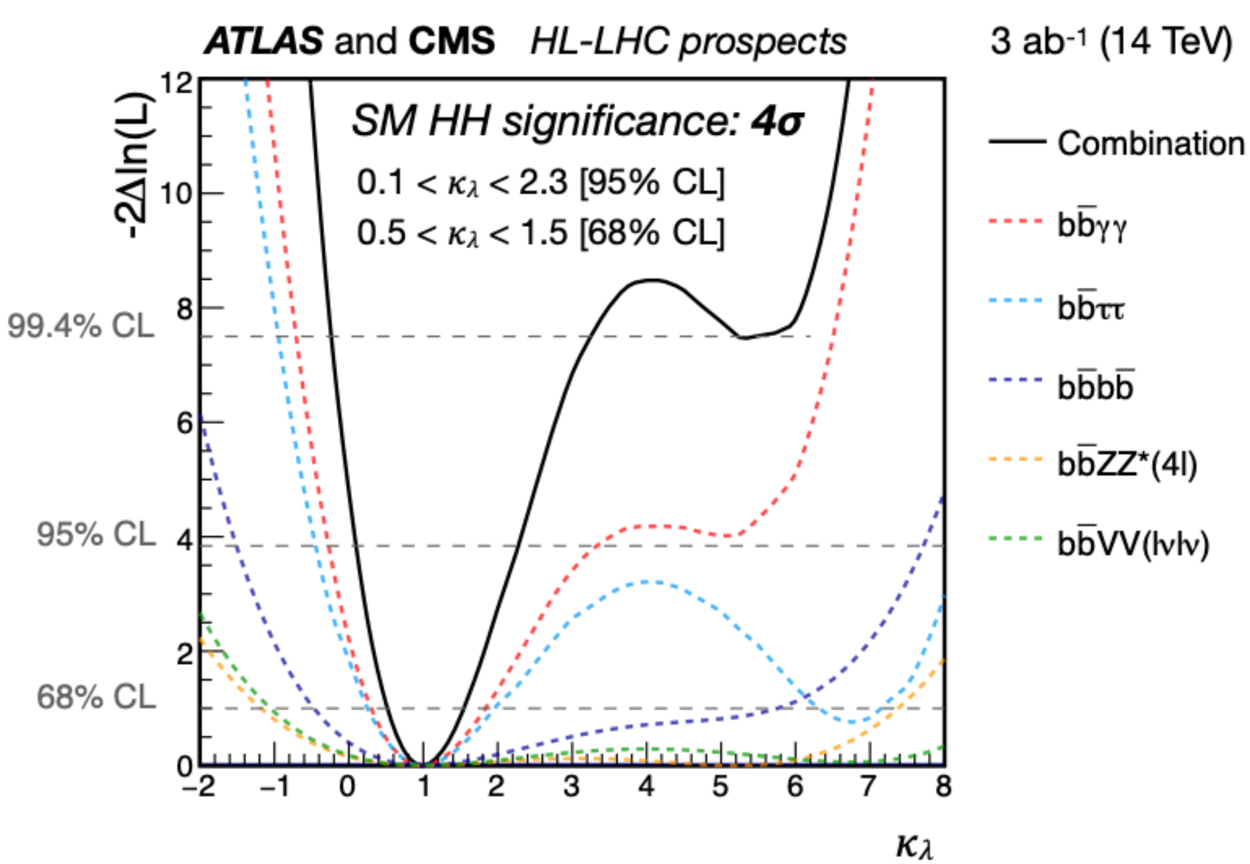
self-interacting?

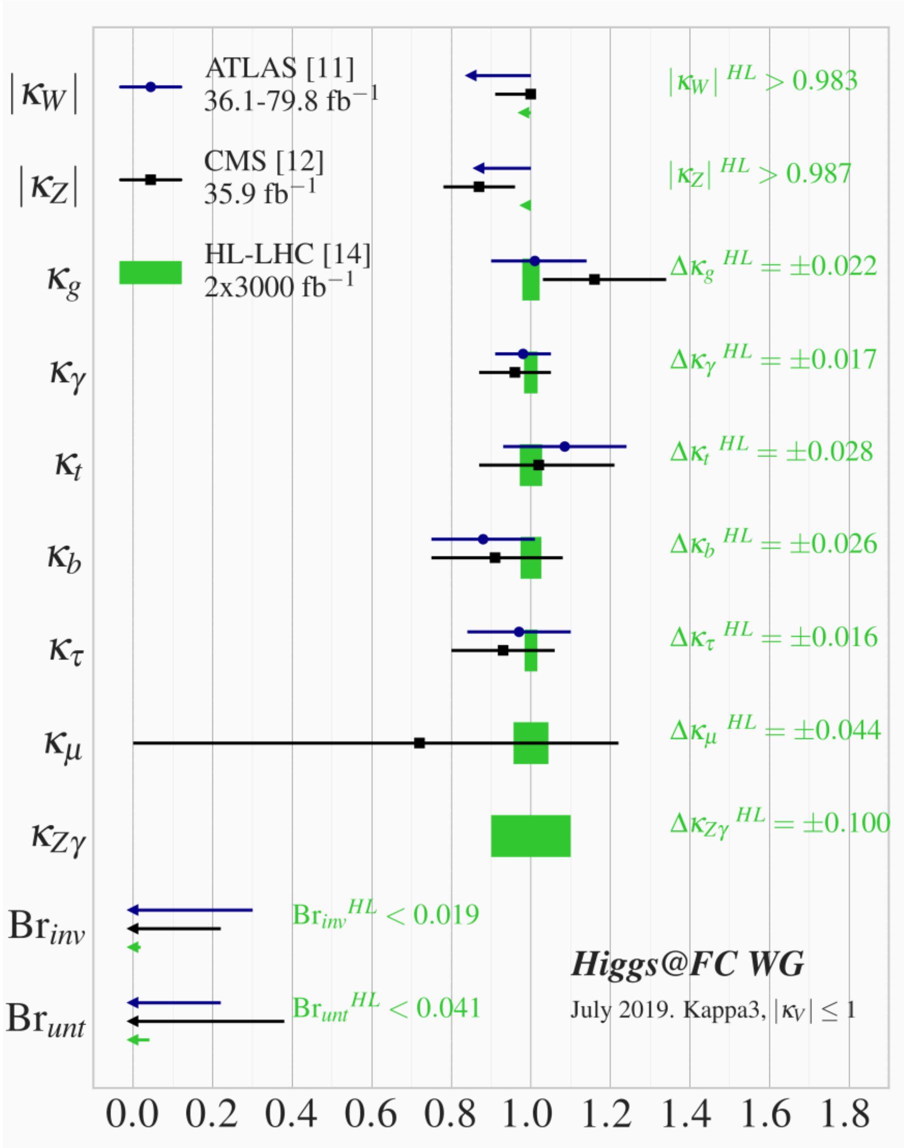
"let's put it under a microscope"

Why studying the Higgs properties

After Higgs discovery, still many open questions:

- Is the Higgs composite or fundamental?
  - Is there more than 1 Higgs
- Does it generate light fermion masses? What about neutrino masses?
- does it couple to dark matter?
- nature of the Higgs potential
  - and its relation to the EWPT





Need to go beyond the LHC precision measurements

Long term strategy

Case made by the European Strategy, updated by CERN Council in 2020

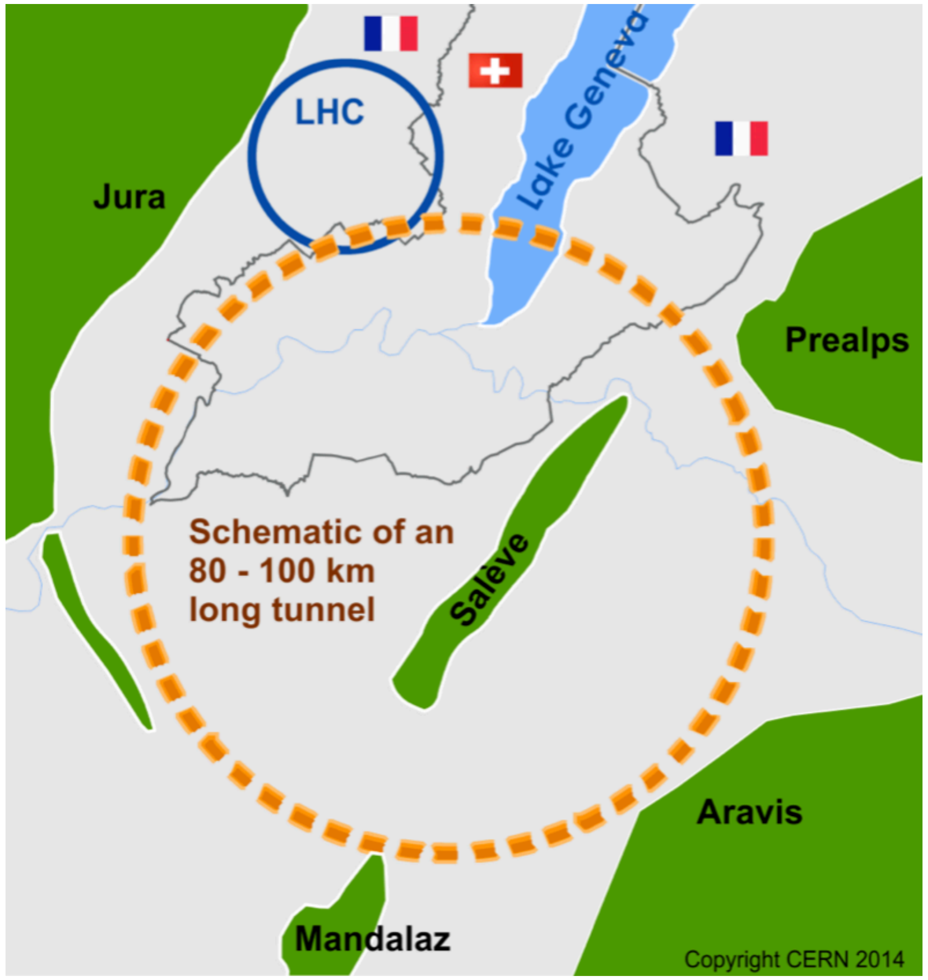
"An electron-positron Higgs factory is the highest priority collider"

"For the longer term, the European Particle Physics community has the ambition to operate a proton-proton collider at the highest achievable energies."

- HL-LHC will collect data until ~ 2040,
  - big physics projects take ~20 yrs time to plan and build

NOW is the right time top start defining the future of HEP.

The FCC



Within the FCC collaboration (CERN as host lab), 5 main accelerator facilities have been studied:

- ee-collider (FCC-ee):
  - as a first step
- pp-collider (FCC-hh)
  - defines infrastructure requirements
  - 16 T → 100 TeV in 100 km tunne
- ep collider (FCC-eh)
- HE-LHC :
  - 27 TeV (16T magnets in LHC tunnel)
- Low E FCC-hh
  - 100 km - 6T - 37 TeV

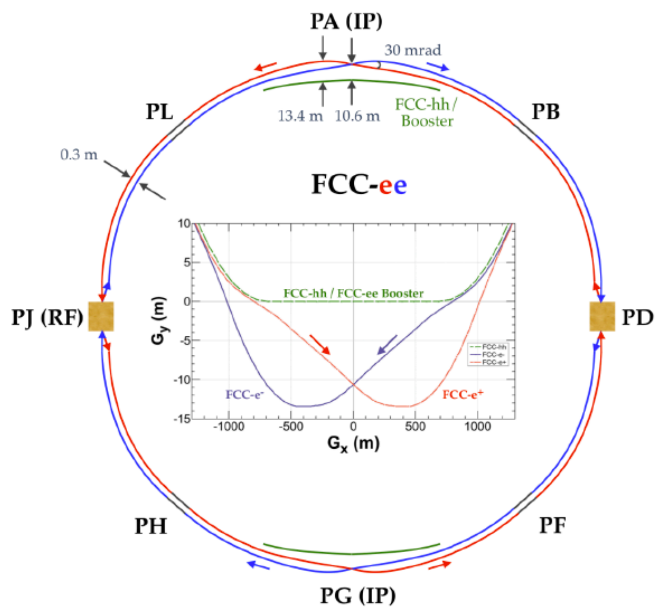
CERN-FCC-PHYS-2019-0001

CDRs and European Strategy documents have been made public in Jan. 2019

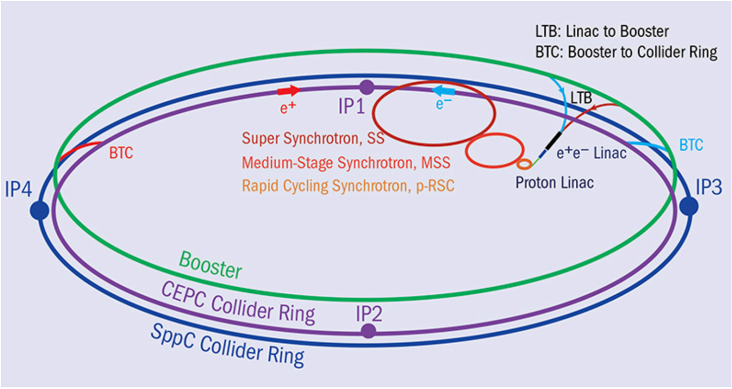
https://fcc-cdr.web.cern.ch/

Future e+e- machines

FCC-ee



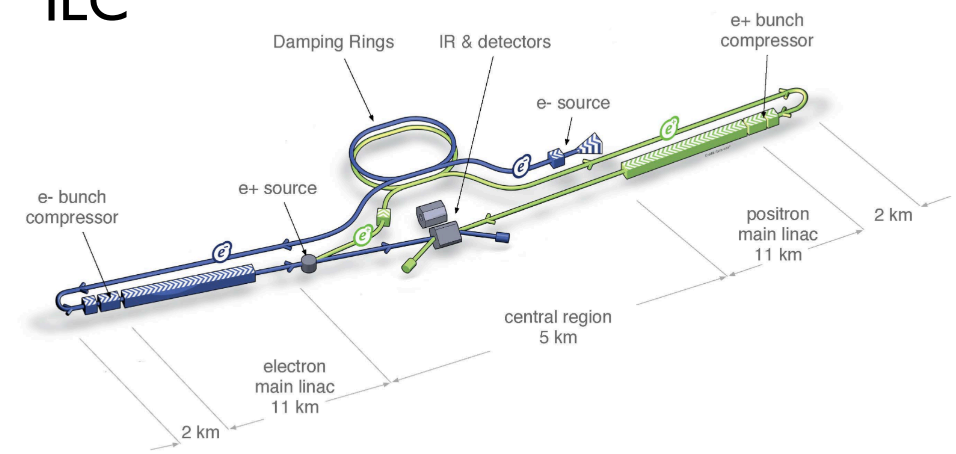
CEPC



- Maximum E_{CM} ~ 350 GeV (limited by synchrotron radiation)
- Very high luminosity at low energy (Z > W > H > t)
- Allows multiple experiments

Parameter	Z	W	H	t
Cm E [GeV]	91.2	160	240	350
FCC-ee				
L [10^{34} $cm^{-2}s^{-1}$]	200	28	8.5	1.8
Years op.	4	2	3	5
Int. L / 2 IP [ab^{-1}]	150	10	5	1.5
CEPC				
L [10^{34} $cm^{-2}s^{-1}$]	32	10	3	
Years op.	2	1	7	
Int. L / 2 IP [ab^{-1}]	16	2.6	5.6	

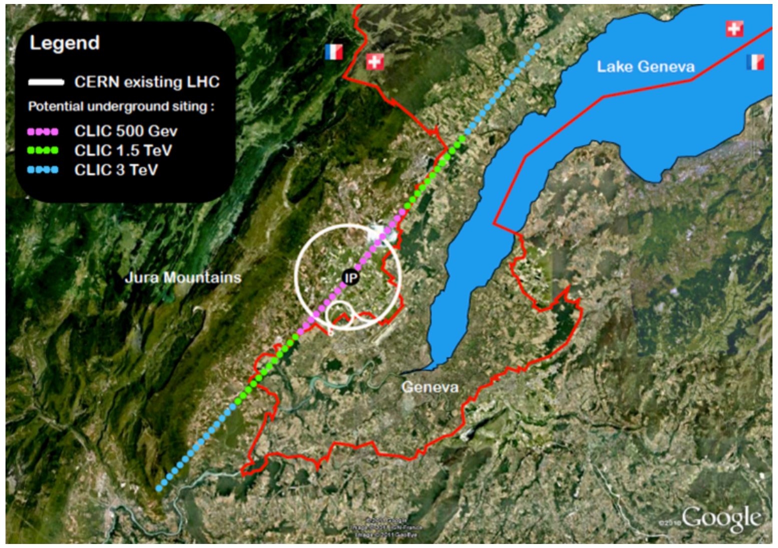
ILC



sqrt(s)	500 GeV	1 TeV
Lumi	4 ab^{-1}	8 ab^{-1}

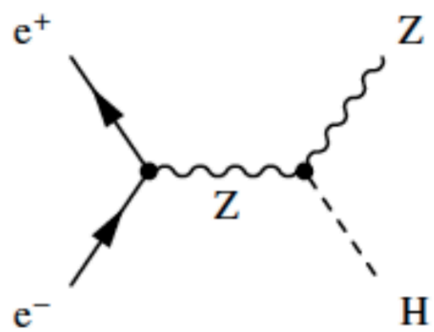
- Can reach high energies
- High lumi at high energies (ttH, HH, H …)

CLIC



sqrt(s)	1.5 TeV	3 TeV
Lumi	2.5 ab^{-1}	5 ab^{-1}

e+e- vs p p

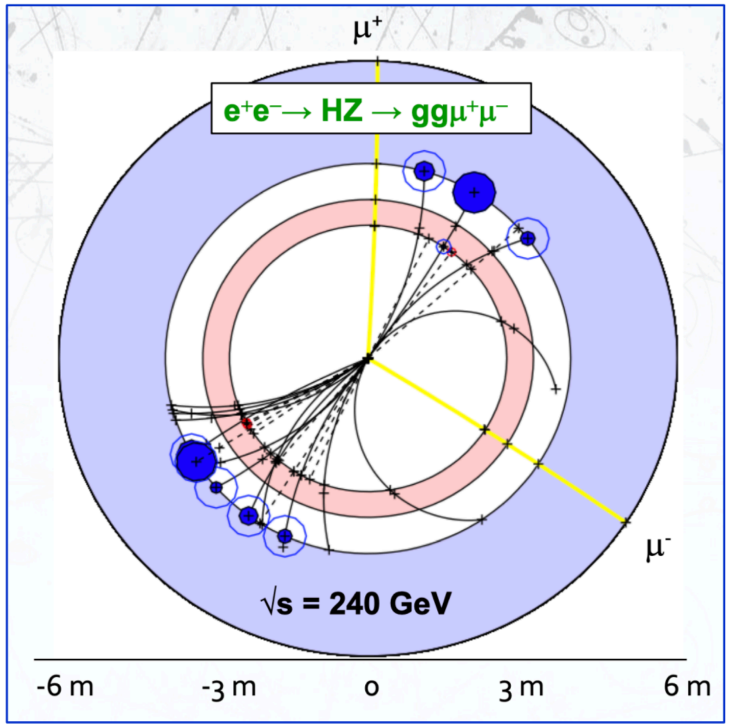


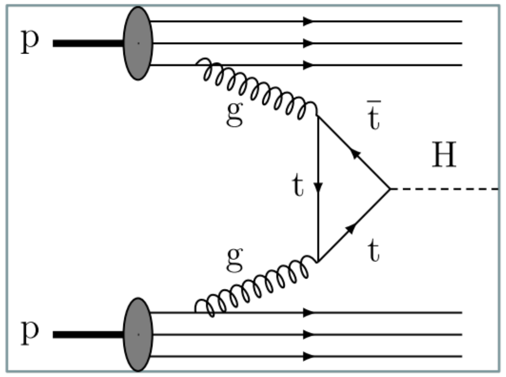
e^+e^- collisions

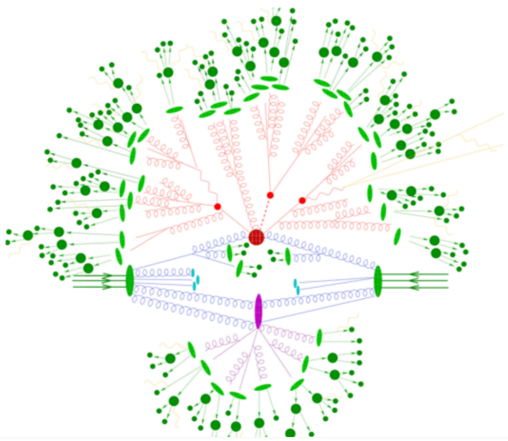
e^+/e^- are point-like
→ Initial state well defined (*E*, ***p***), polarisation
→ High-precision measurements

Clean experimental environment
→ (Almost) Trigger-less readout
→ Low radiation levels
Superior sensitivity for **electro-weak states**

- **Circular** e^+e^- colliders can deliver **very large luminosities**
- **Linear** collider can reach higher energies (>1TeV)





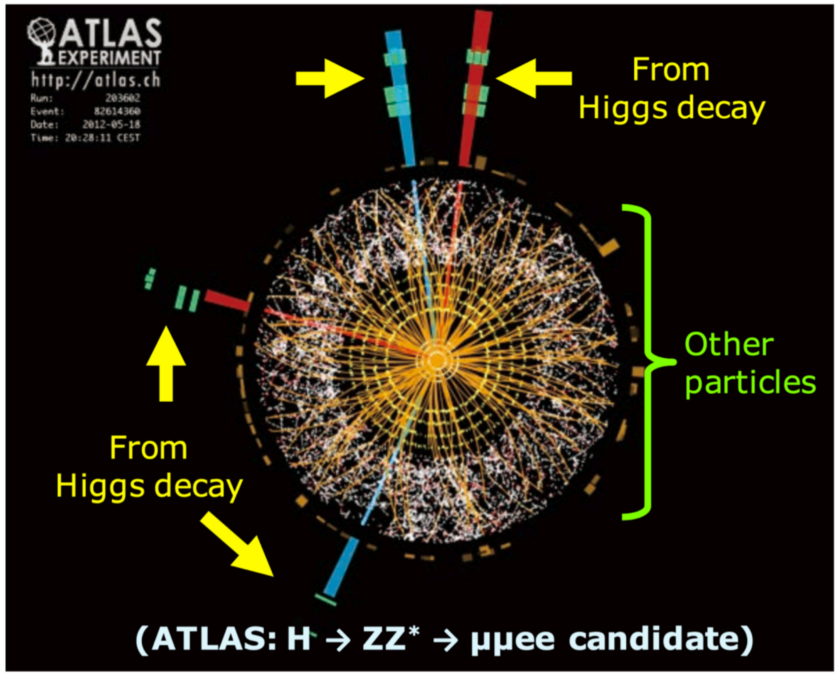


pp collisions

Proton is compound object
→ Initial state not known event-by-event
→ Limits achievable precision

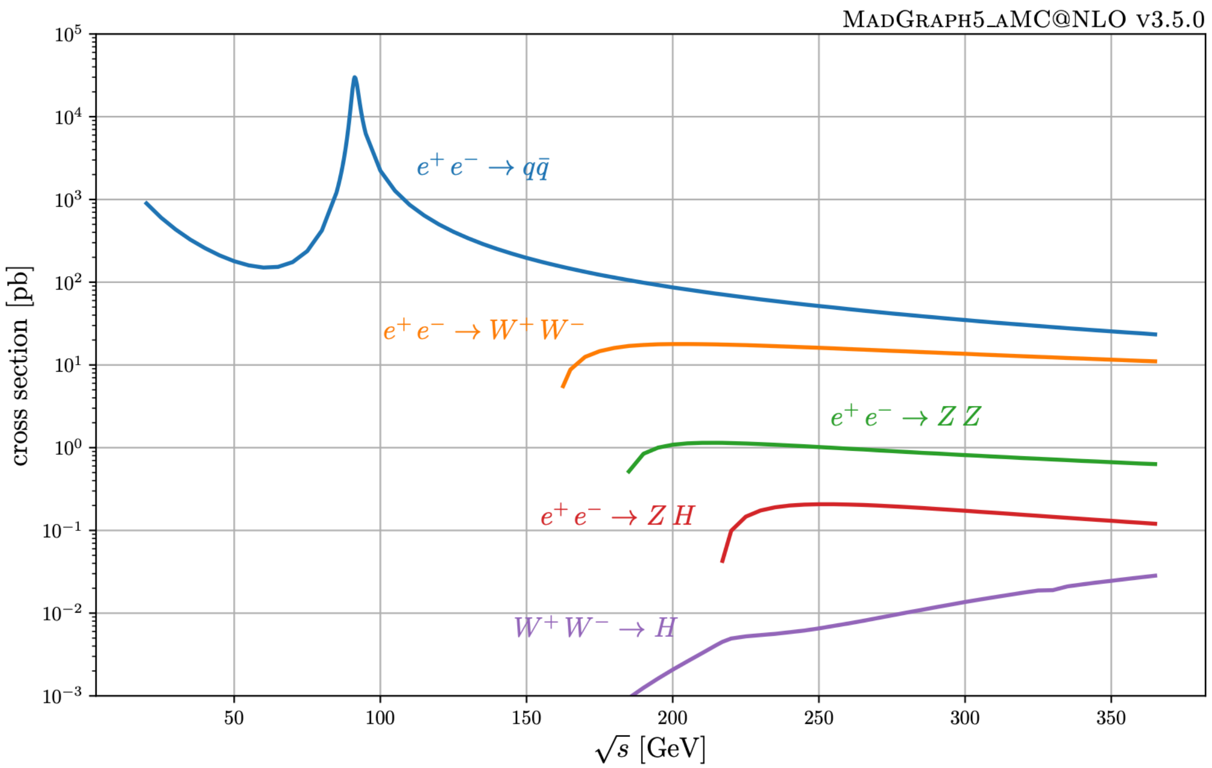
High rates of QCD backgrounds
→ Complex triggering schemes
→ High levels of radiation
High cross-sections for **colored-states**

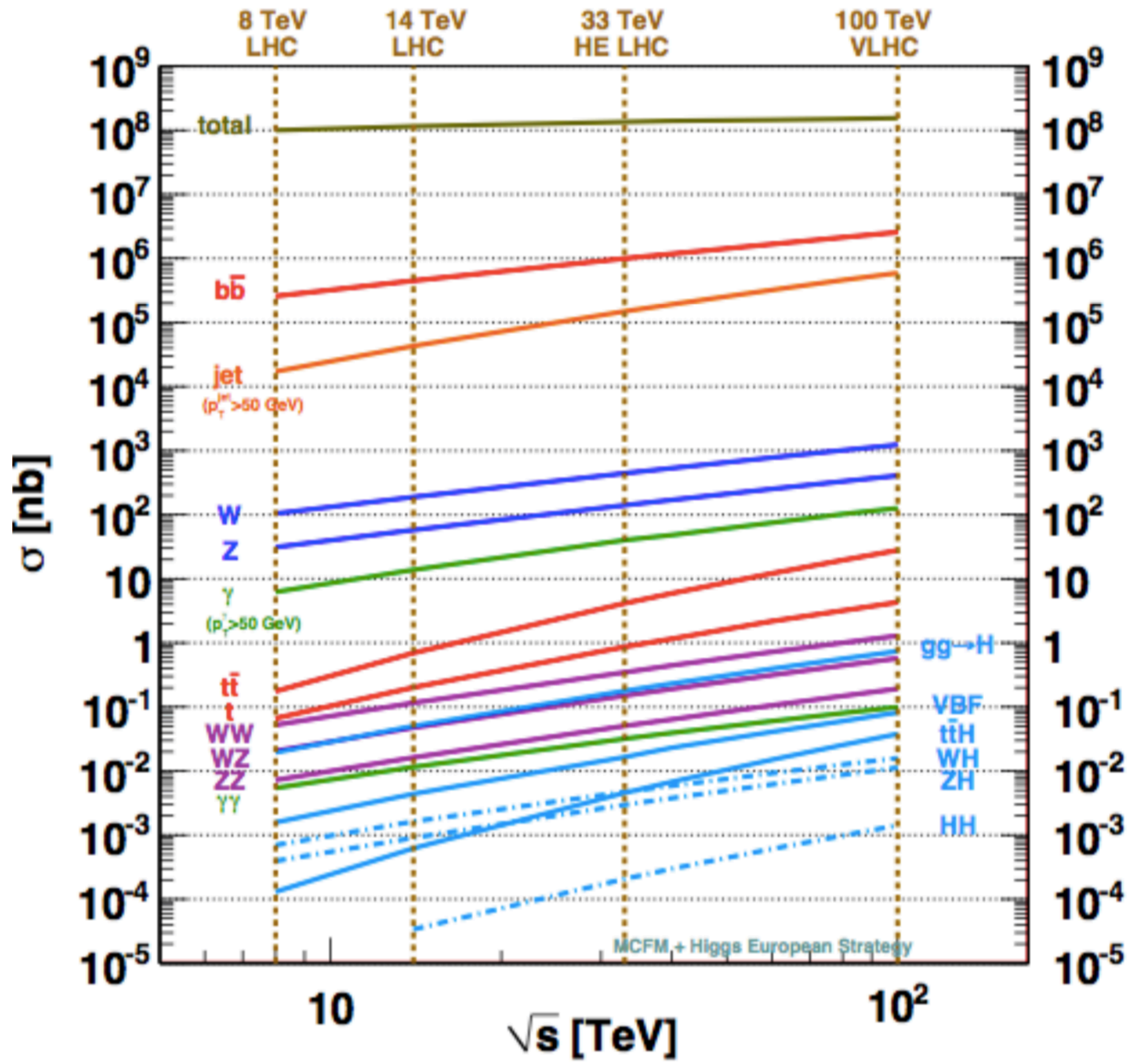
High-energy **circular** pp colliders feasible.
R&D on high field magnets needed.



Future e+e- machines cross sections

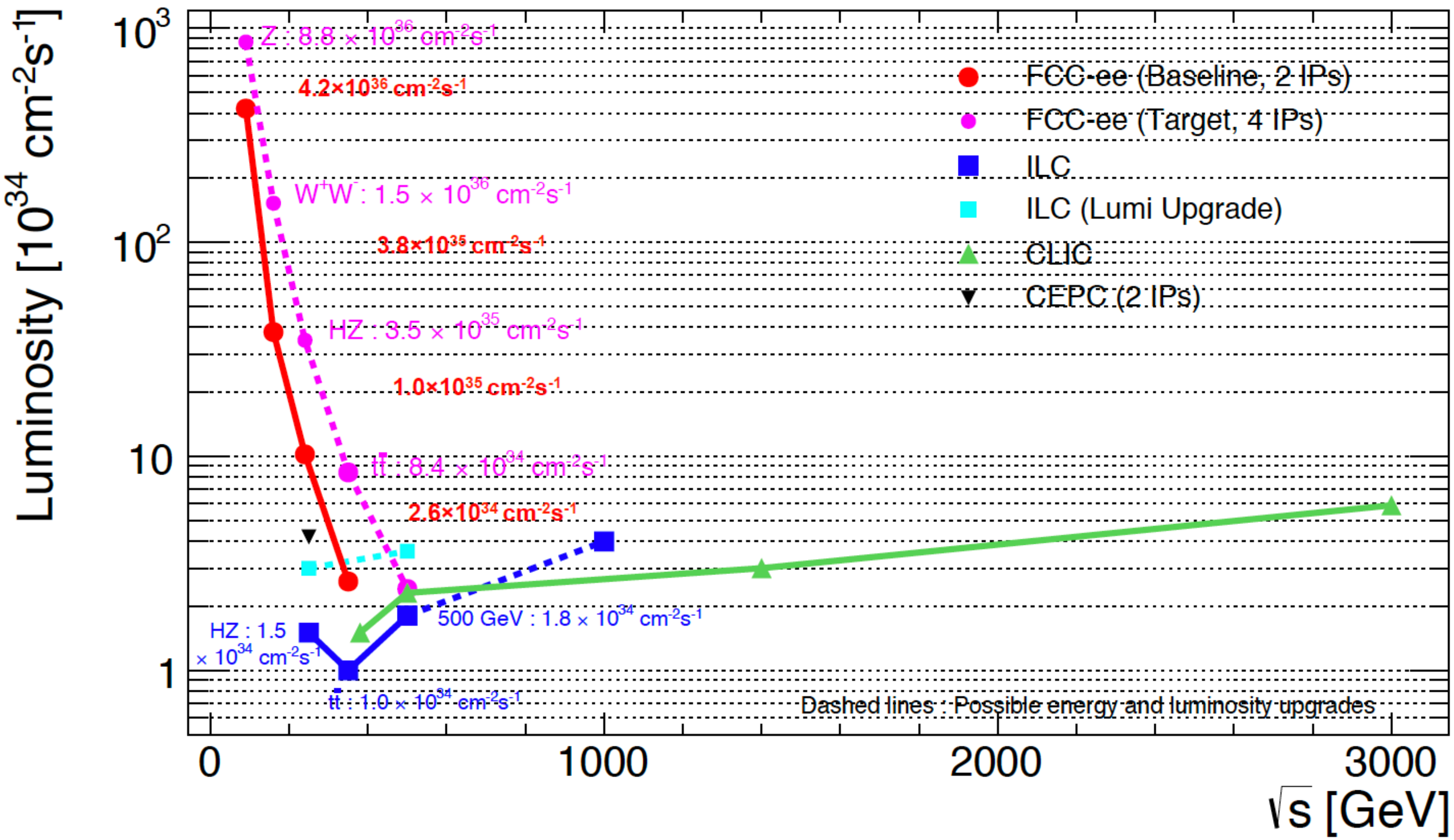
- Physics background are "small" in e^+e^-
  - s-channel ~ 1/s
  - t-channel ~ log s





S/B 10^{-2} at e^+e^- 10^{-10} at hadron colliders

Linear or circular ?



luminosity ultimate **precision** with **circular**

high **mass reach** with **linear**

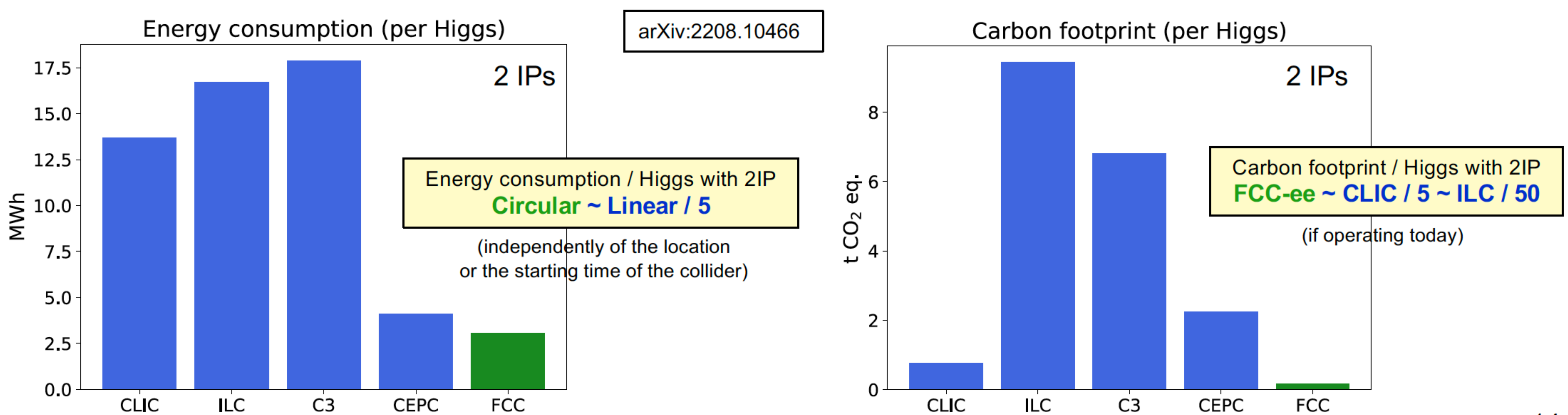
Carbon footprint/energy consumption

Circular colliders have a:

- much larger instantaneous luminosity
- operate several detectors

Circular is at CERN:

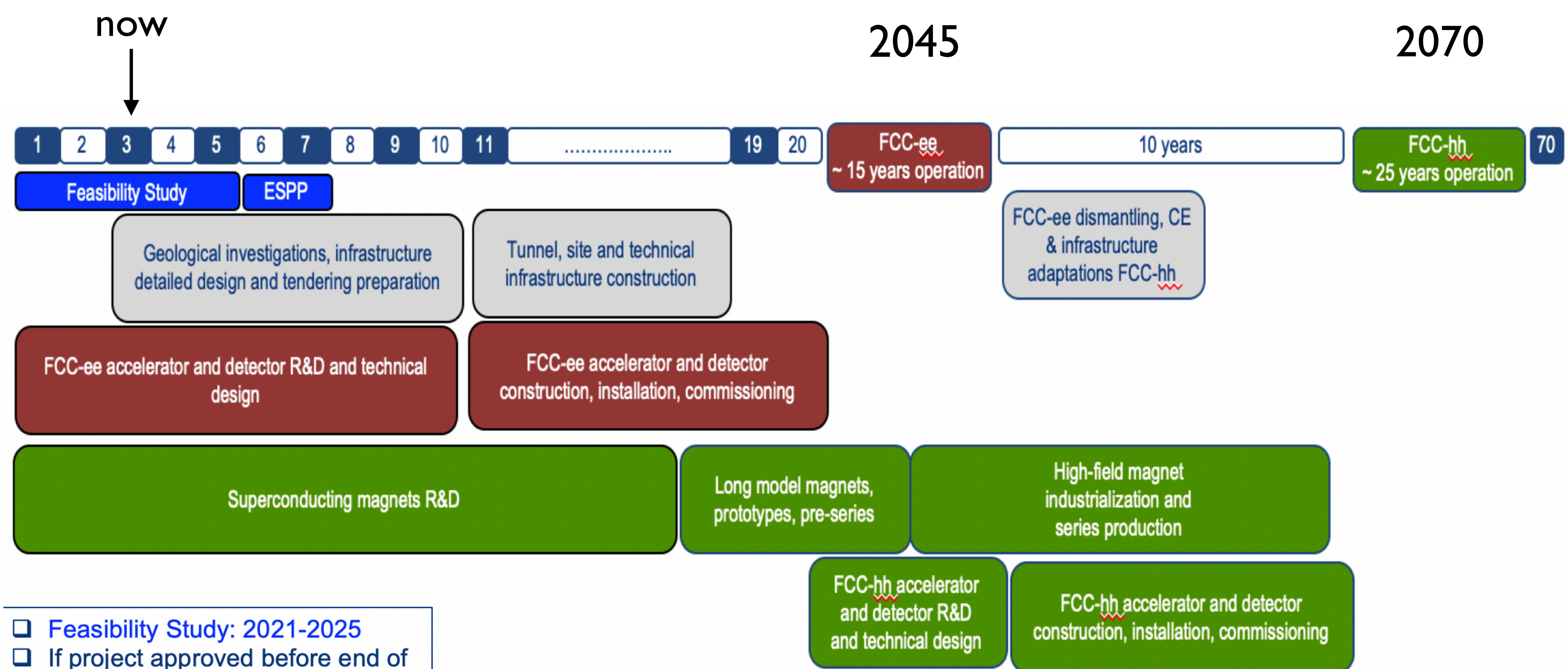
where electricity is already almost carbon-free (and will be even more so in 2048)



Energy consumption / Higgs with 4IP
Circular ~ Linear / 10

Carbon footprint / Higgs with 4IP
FCC-ee ~ CLIC / 10 ~ ILC / 100

Timeline of the integrated FCC project



- Feasibility Study: 2021-2025
- If project approved before end of decade → construction can start beginning 2030s
- FCC-ee operation ~2045-2060
- FCC-hh operation 2070-2090++

F. Gianotti

Now is perfect time to join the effort and contribute to the feasibility study

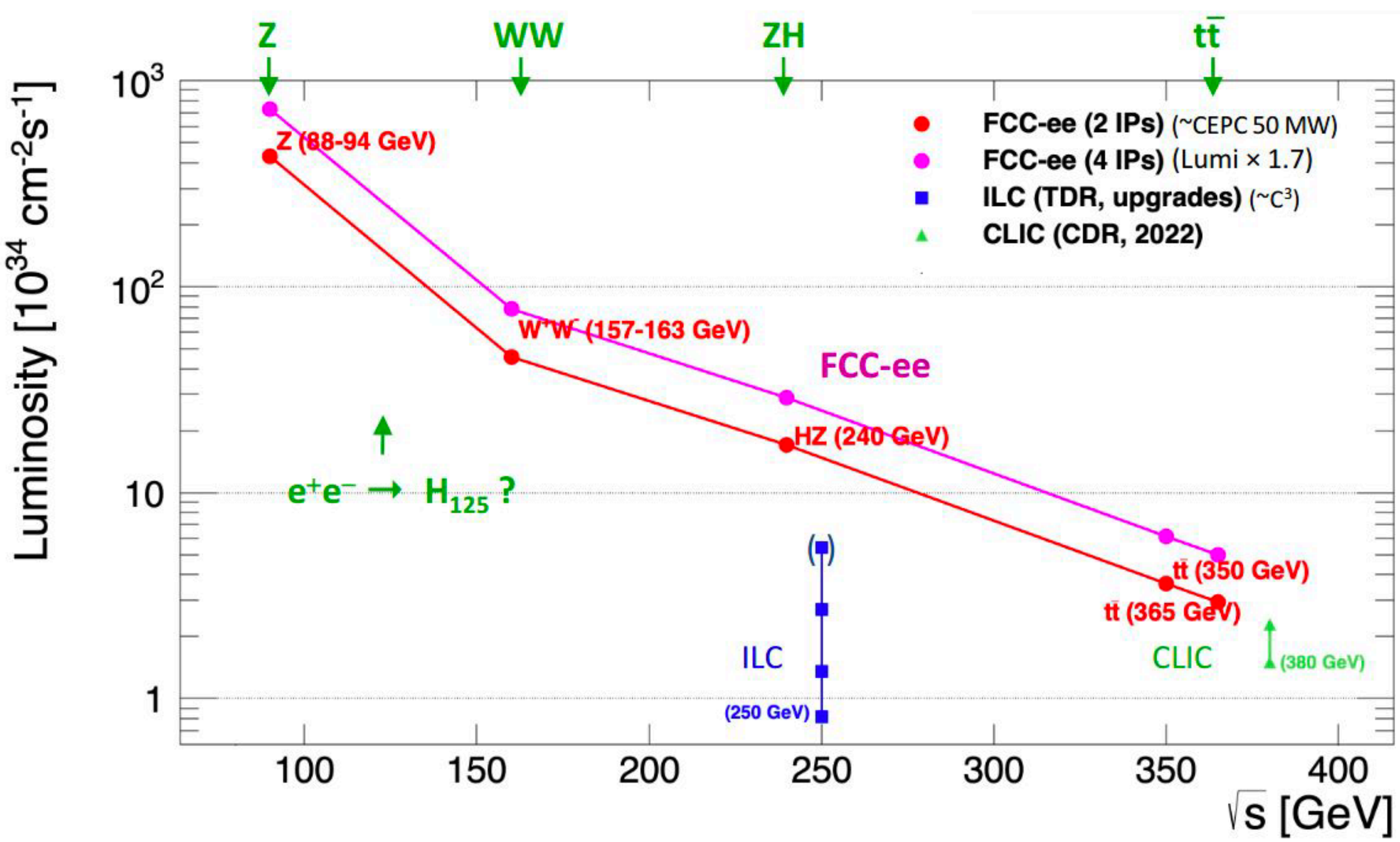
FCC-ee

15 (20?) years of operations

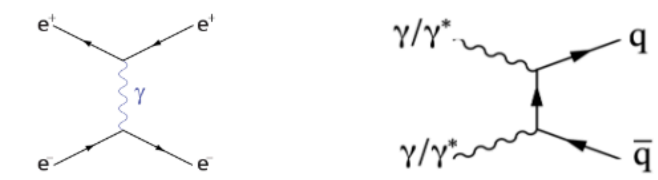
	Z pole	? H pole ?	WW	ZH	ttbar
√s [GeV]	88 - 91 - 94	125	157 - 161	240	350 - 365
Lumi / IP [10^{34} cm^2 s^{-1}]	182	80	19.4	7.3	1.33
Int. lumi / 4IP [ab^{-1} / yr]	87	38	9.3	3.5	0.65
N_{years}	**4**	**5**	**2**	**3**	**5**
N_{events}	8 Tera	8 K	300 M	2 M	2 M

Unprecedented luminosity

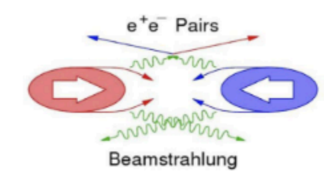
- 100K Z bosons / second
  - LEP dataset in 1 minutes
- 10k W boson / hour
- 2k Higgs bosons / day
- 3k tops / day



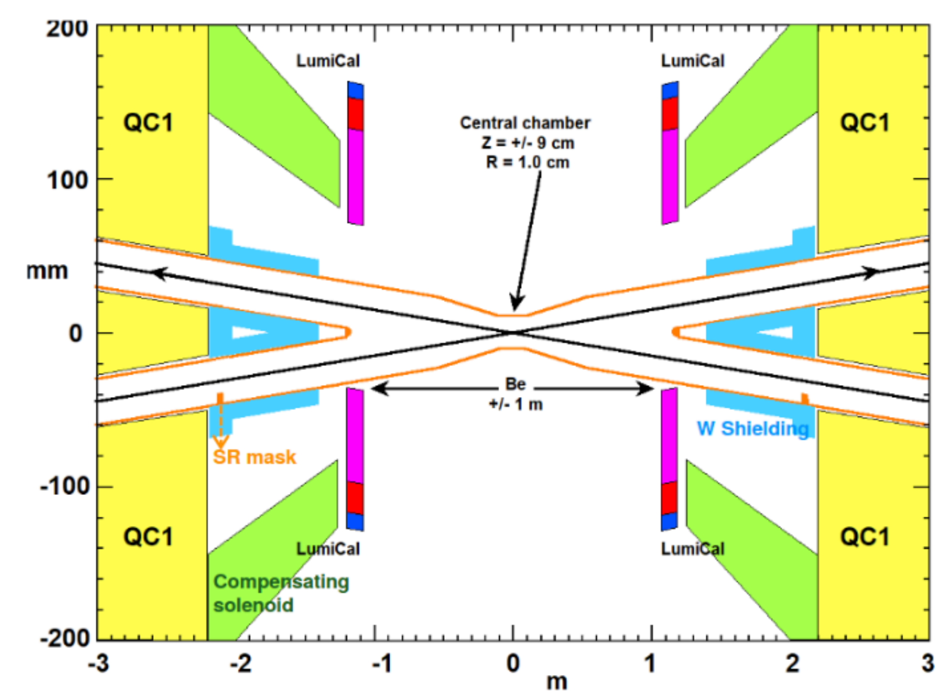
Detector requirements - machine



- Requirements for Higgs and above have been studied to some extent by LC:
  - have to be revised by FCC-ee
  - we want a detector that is able to withstand a large dynamic range:
    - in energy ($\sqrt{s}$ = 90 - 365 GeV)
    - in luminosity (L = 10^{34} - 10^{36} cm^2/s)



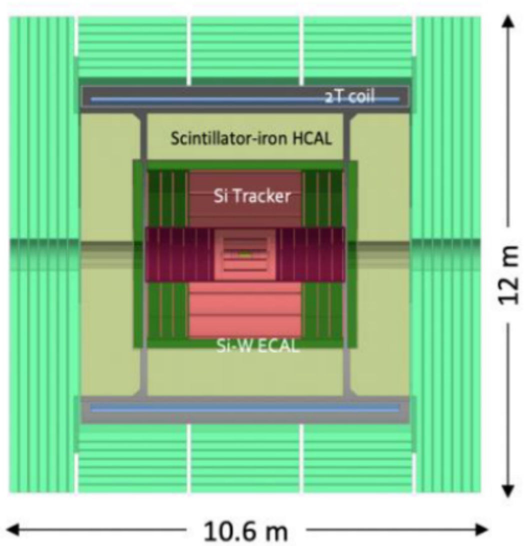
- most of the machine induced limitations are imposed by the Z pole run:
  - large collision rates ~ 33 MHz and continuous beams
    - no power pulsing possible
  - large event rates ~ 100 kHz
    - fast detector response / triggerless design challenging (but rewarding)
    - high occupancy in the inner layers/forward region (Bhabha scattering/γγ hadrons)
  - beamstrahlung



- complex MDI: last focusing quadrupole is ~ 2.2m from the IP
  - magnetic field limited to B = 2T at the Z peak (to avoid disrupting vertical emittance/inst. Lumi via SR)
    - limits the achievable track momentum resolution
  - “anti”-solenoid
    - limits the acceptance to ~ 100 mrad

Detector concepts

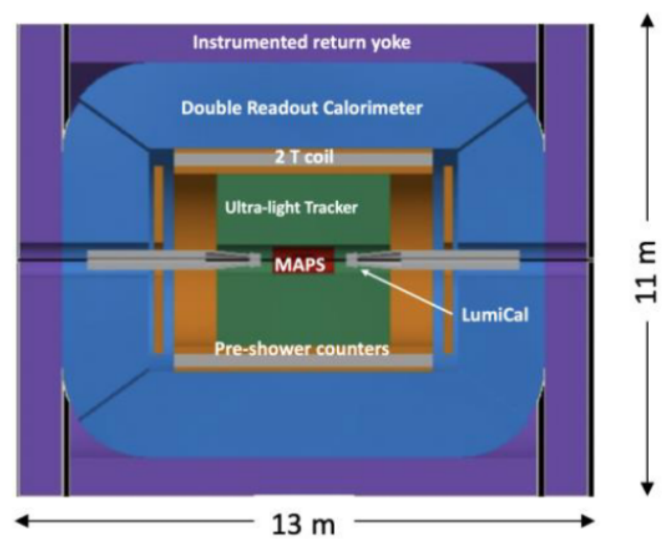
CLD



- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - …

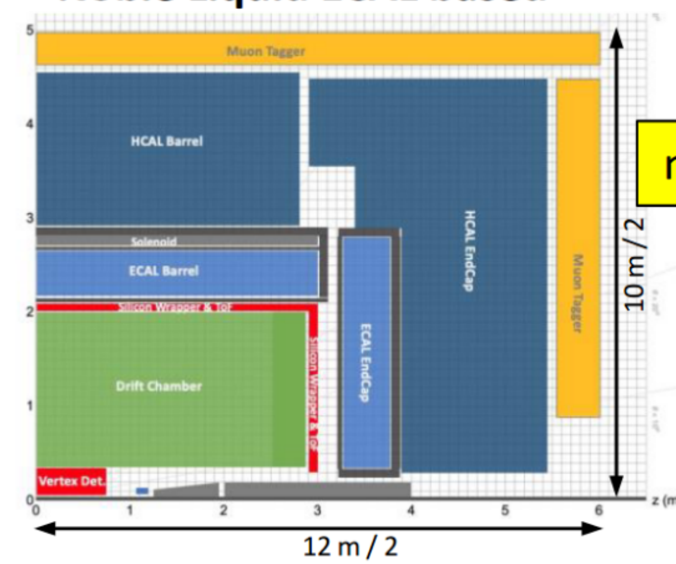
CDR

IDEA



- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber w powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, …

Noble Liquid ECAL based



new

- A design in its infancy
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

FCC-ee CDR: https://link.springer.com/article/10.1140/epjst/e2019-900045-4

Measurement landscape

Higgs
factory

m_H, σ, Γ_H
self-coupling
H→ bb, cc, ss, gg
H→inv
ee→H
H→bs, ..

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
"boosted" B/D/τ factory:

CKM matrix
CPV measurements
Charged LFV
Lepton Universality
τ properties (lifetime, BRs..)

$B_c \to \tau \nu$
$B_s \to D_s K/\pi$
$B_s \to K^* \tau \tau$
$B \to K^* \nu \nu$
$B_s \to \varphi \nu \nu$ …

QCD - EWK
most precise SM test

m_Z , Γ_Z , Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ , R_b, R_c

$A_{FB}^{b,c}$, τ pol.

α_S ,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons (HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

Detector requirements - physics

Higgs
factory

track momentum resolution (low X_0)

IP/vertex resolution for flavor tagging

PID capabilities for flavor tagging

jet energy/angular resolution (stochastic and noise) and PF

Flavor
"boosted" B/D/τ factory:

track momentum resolution (low X_0)

IP/vertex resolution

PID capabilities

Photon resolution, pi0 reconstruction

QCD - EWK
most precise SM test

acceptance/alignment knowledge to 10 μm

luminosity

BSM
feebly interacting particles

Large decay volume

High radial segmentation
- tracker
- calorimetry
- muon

impact parameter resolution for large displacement

timing

triggerless

Tera Z - Electroweak precision observables

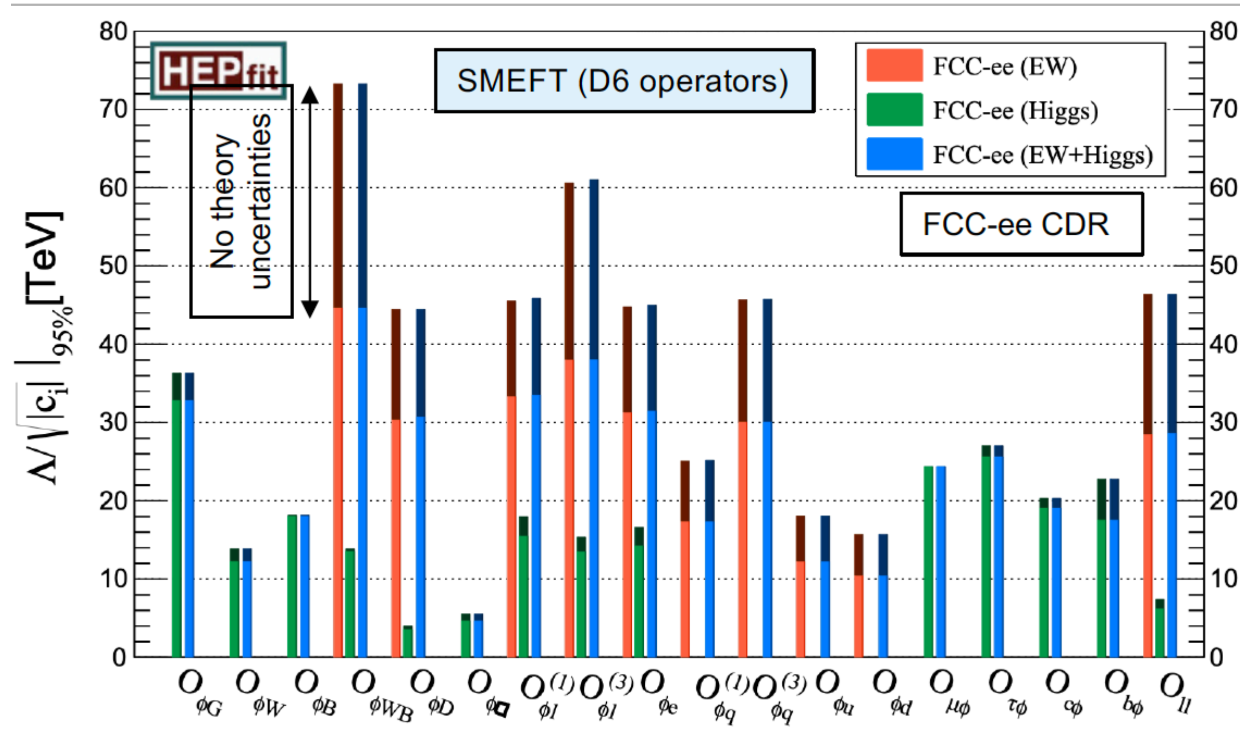
Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	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 polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	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
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365$ GeV run

10^5 x LEP events → 100x reduction in stat

→ 10x increase in NP scale reach

name of the game:

→ bring down systematics down to stat. level



1/Λ new physics (SMEFT) → 30 – 70 TeV

Tera Z flavour

With 5×10^{12} Z, FCC-ee is of special relevance for b, c and tau physics

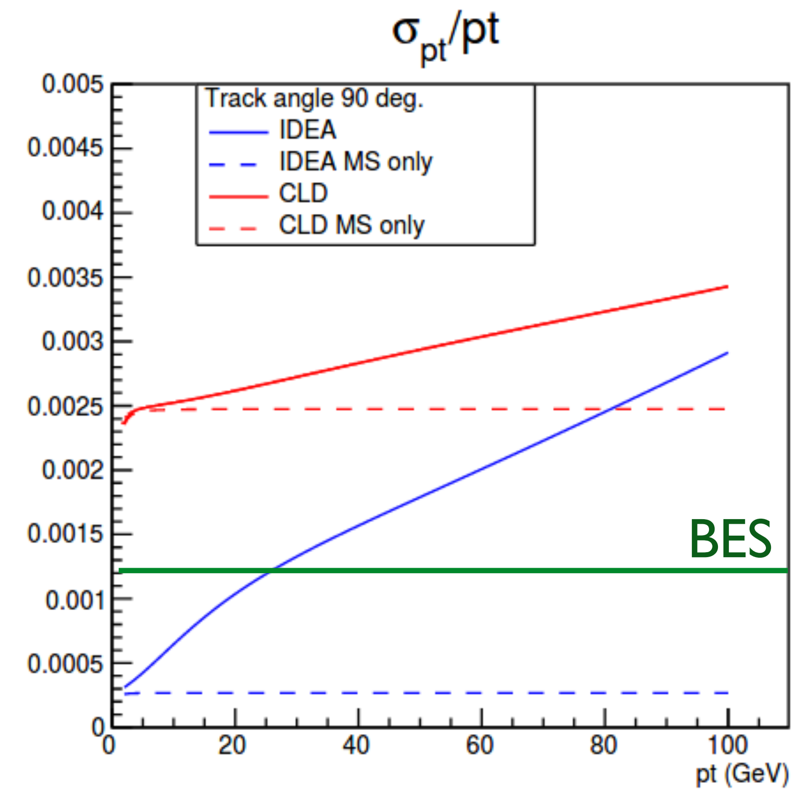
Production rate @Z pole an 10x more than the anticipated Belle II statistics

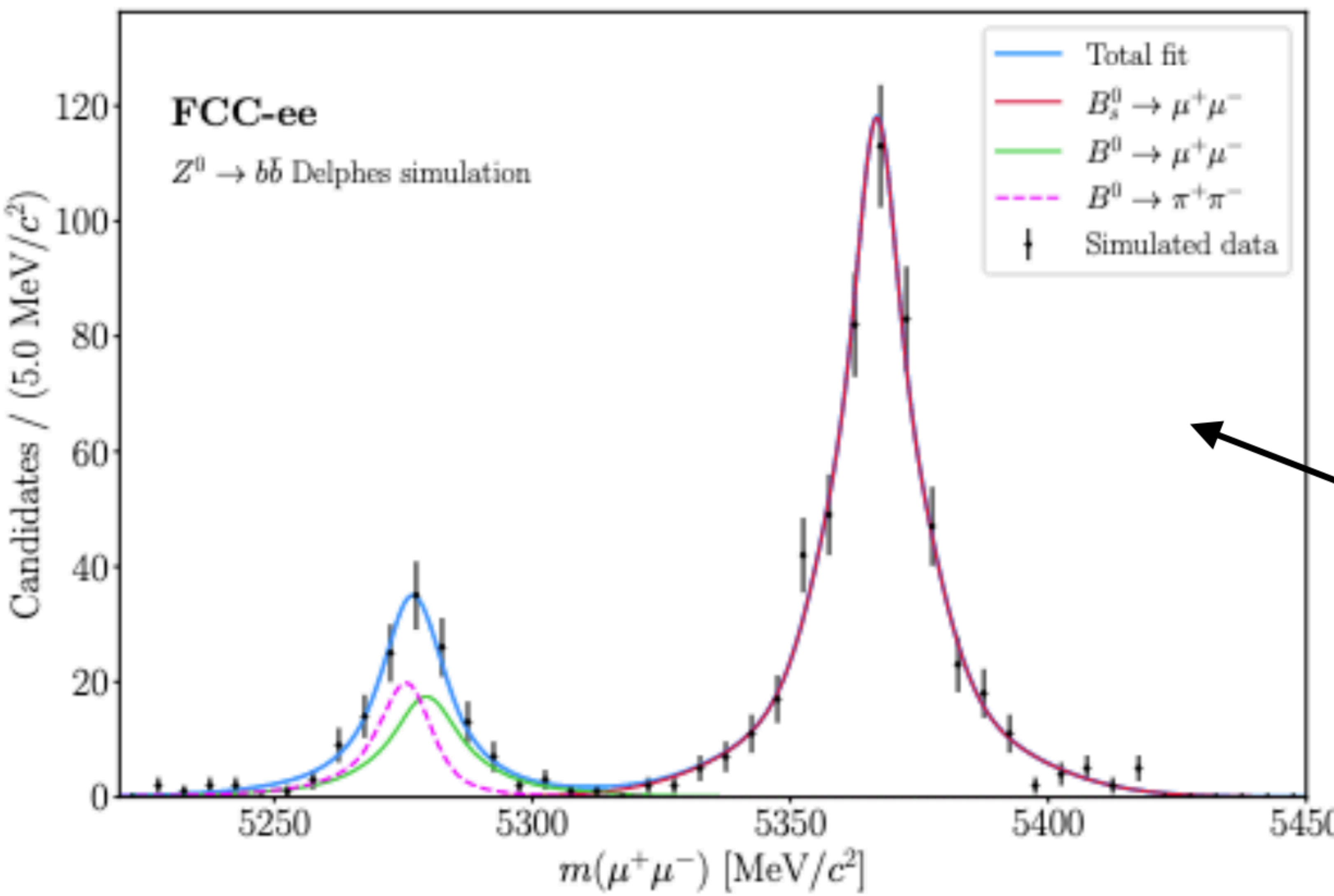
Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\bar{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150

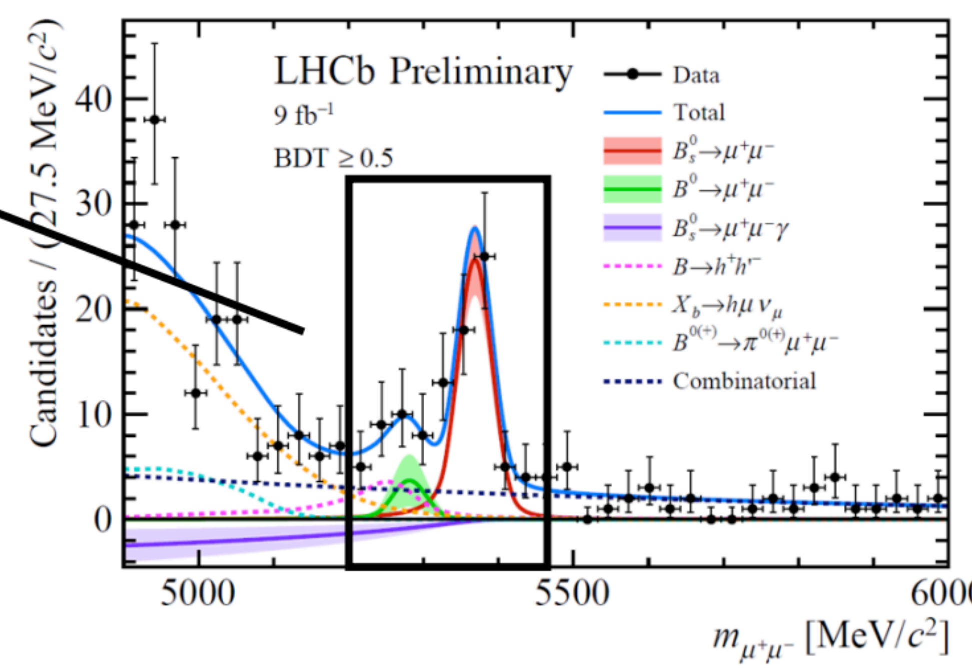
Attribute	$\Upsilon(4S)$ (Belle2)	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

- Sensitivity to low momentum particles
- Excellent momentum resolution
- Excellent Impact parameter resolution

Tera Z flavour: Bs→μμ







Bs→μμ mass resolution driven by the tracking
Low mass tracker essential

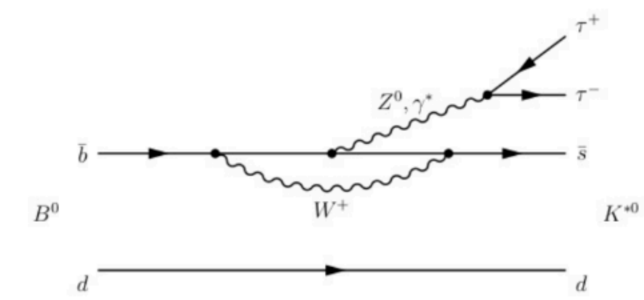
Tera Z flavour

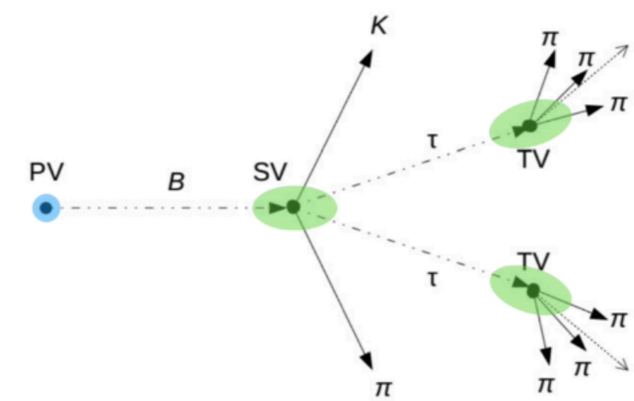
- $B_s \to K^*\tau\tau$ important channel to study **LFU** in **b→s transitions**
  - focusing on 3-prong τ decays

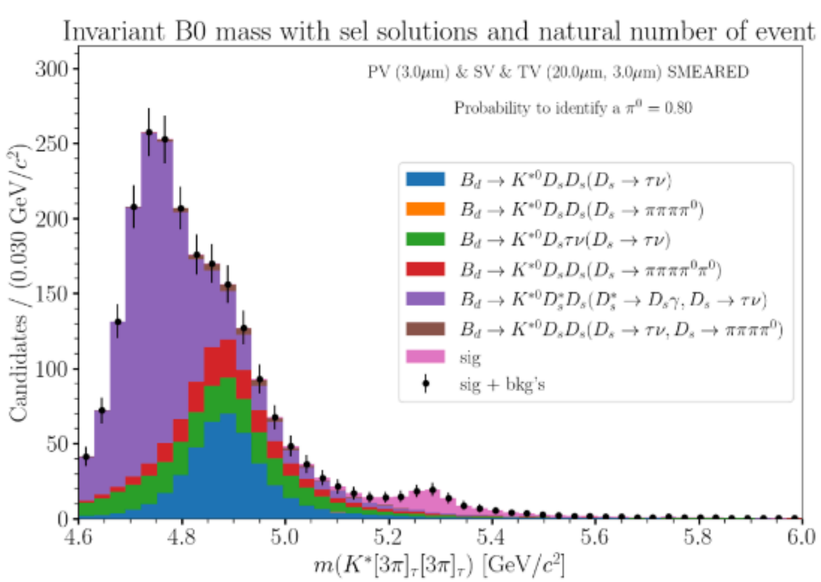
- very rich signature with :
  - 8 visible particles (1K, 7π)
  - 1 secondary vertex and tertiary vertices

- very complex analysis: many **backgrounds** and **combinatorics**

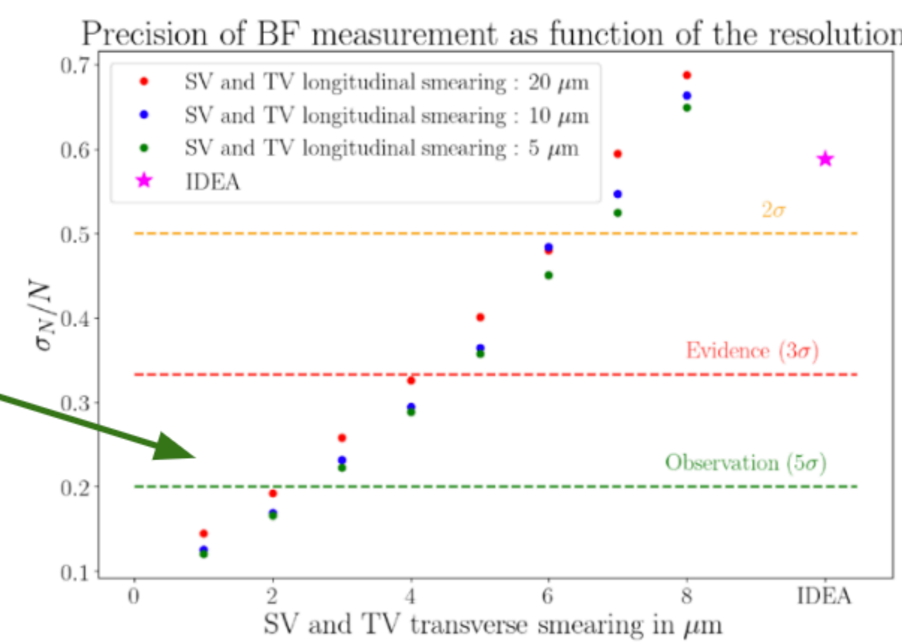
- $B_s \to K^*\tau\tau$ sensitivity driven by **vertex resolution** to make maximal use of kinematic constraints





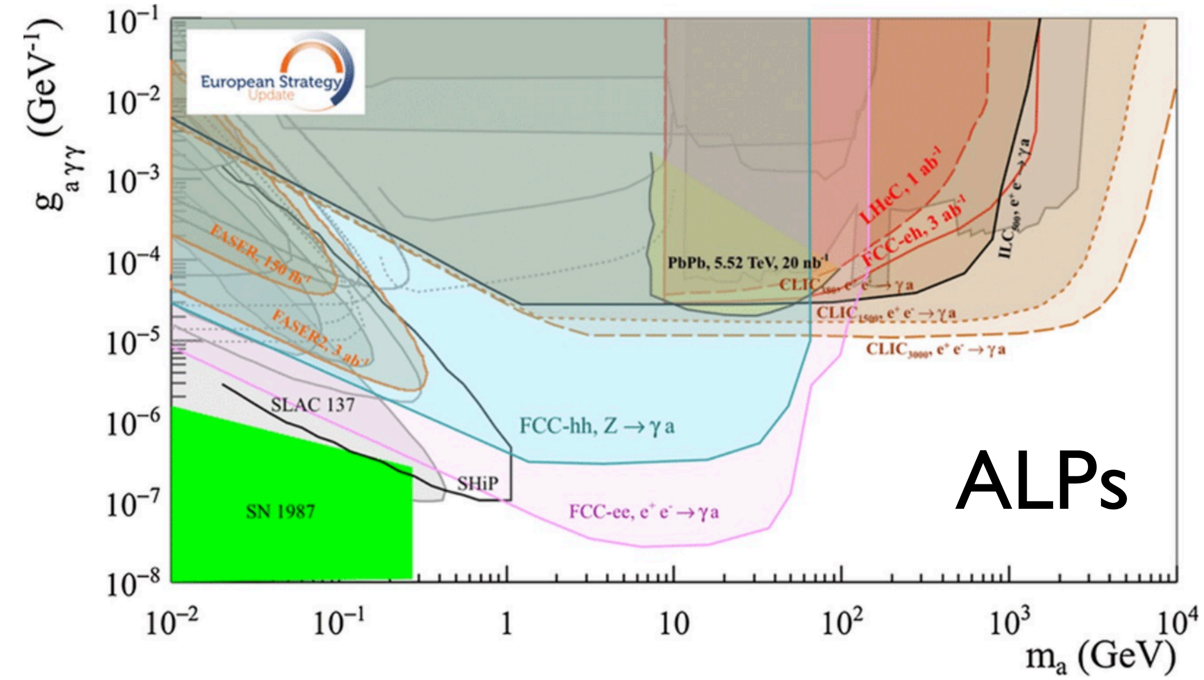


5σ observation with **2 μm** vertex resolution

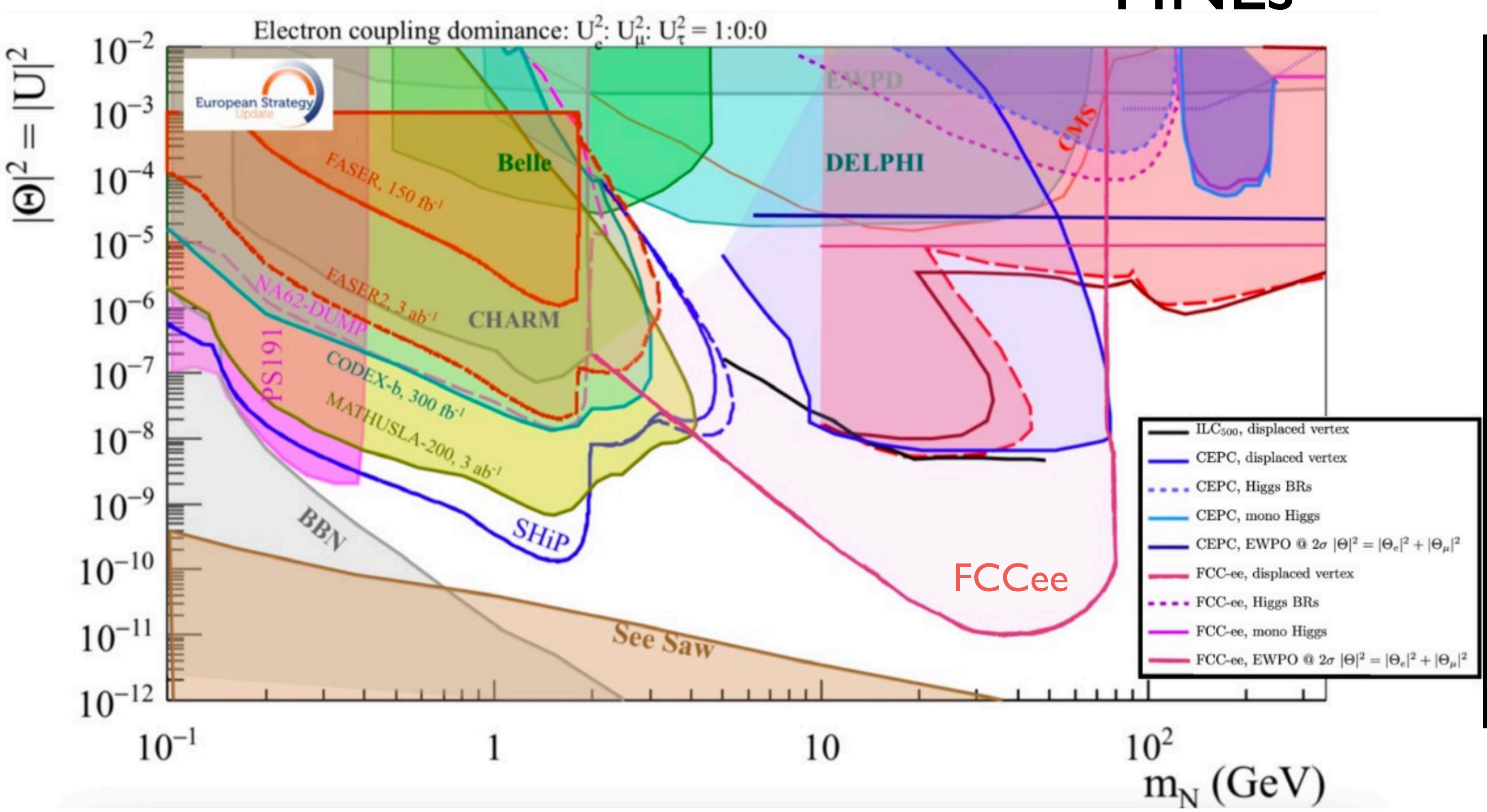


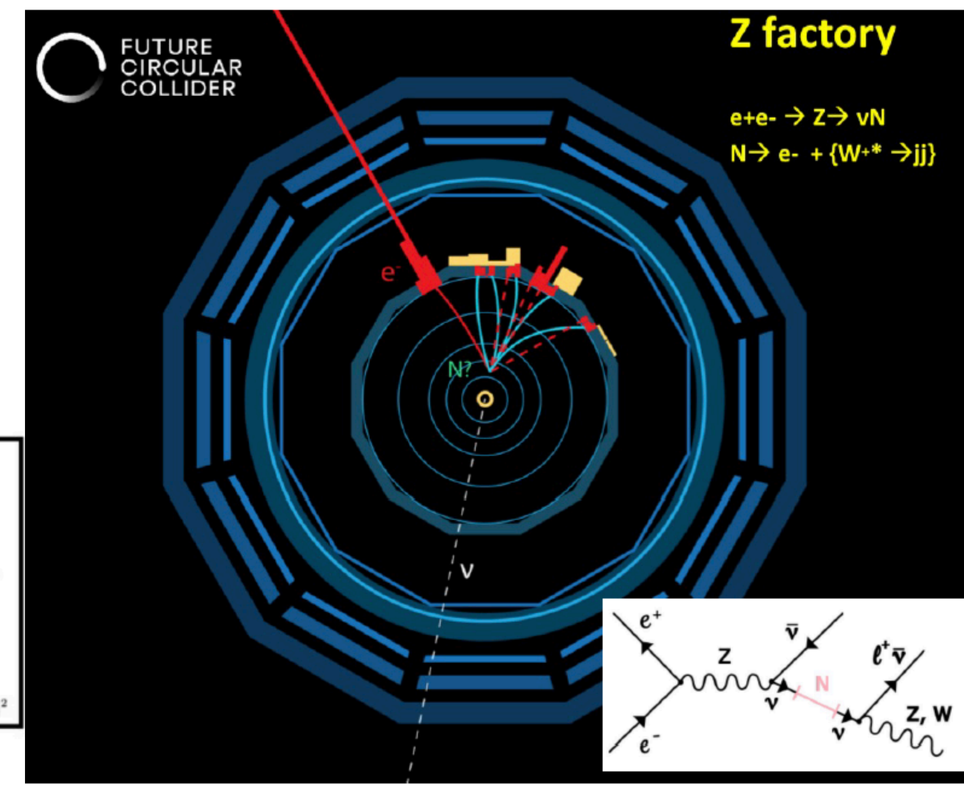
Tera Z - new physics

- No trigger requirements
- Displaced vertex reco for low LLP lifetime



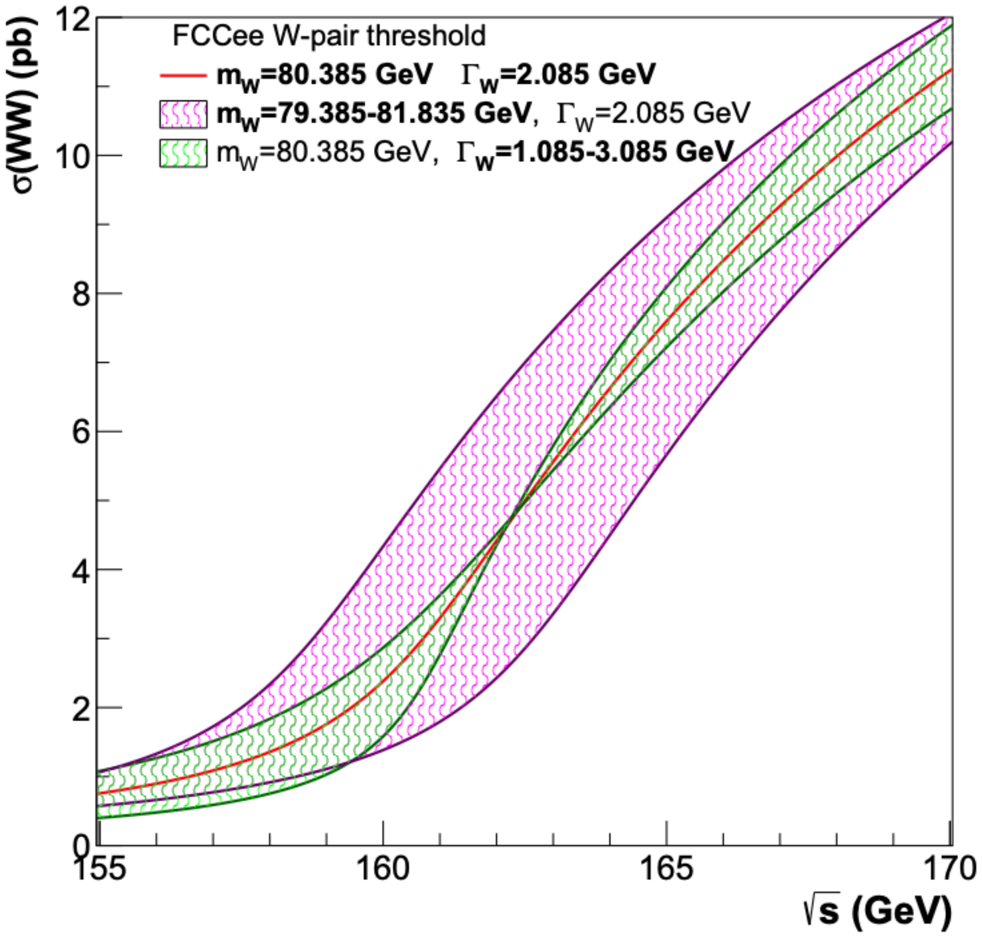
HNLs





WW threshold

W mass and width

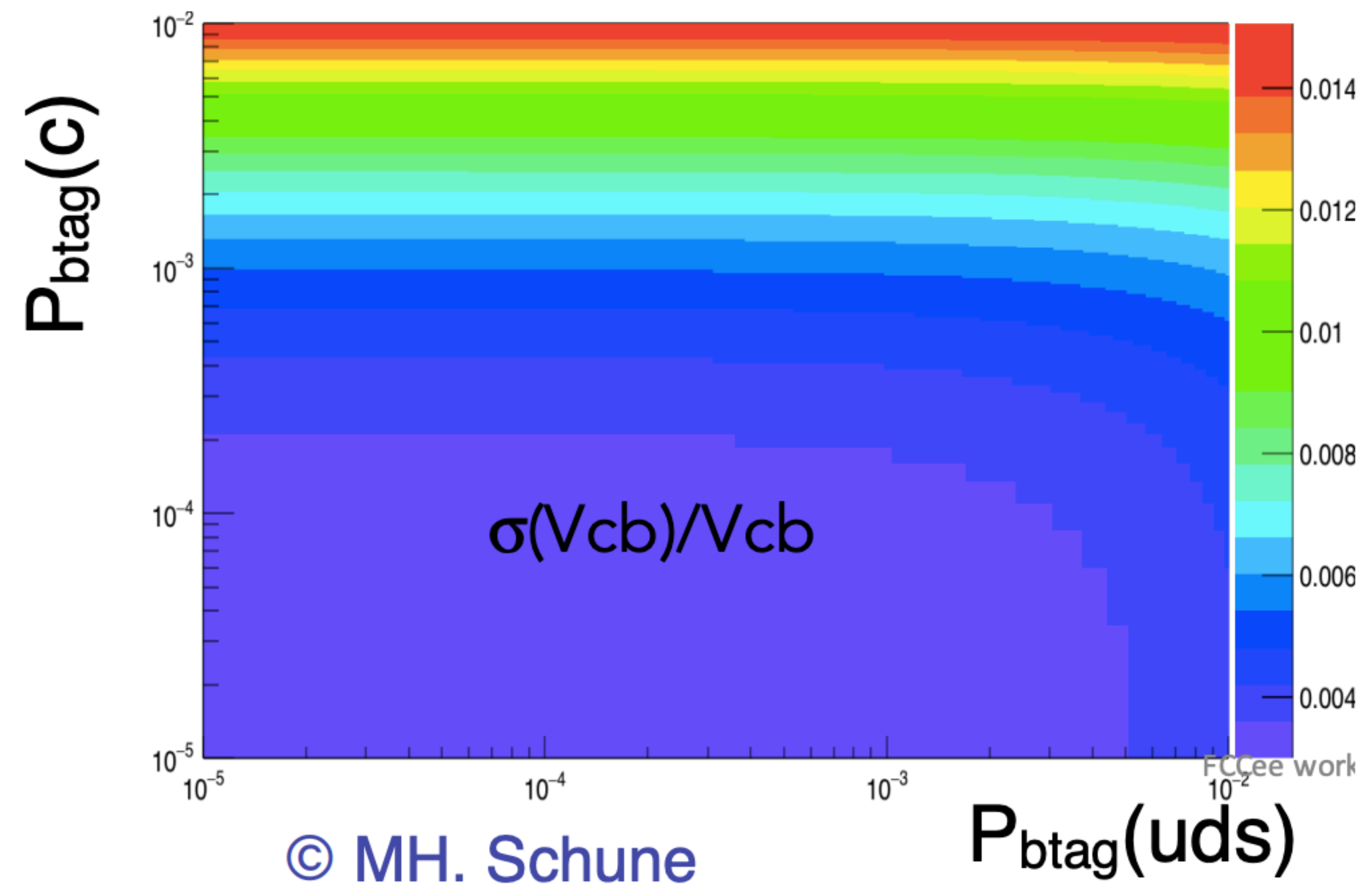


30x improvement
w.r.t LHC

precision reach:
$\delta(m_W) \sim 0.5$ MeV
$\delta(\Gamma_W) \sim 1$ MeV

syst. uncertainties on hadronic W decay modeling

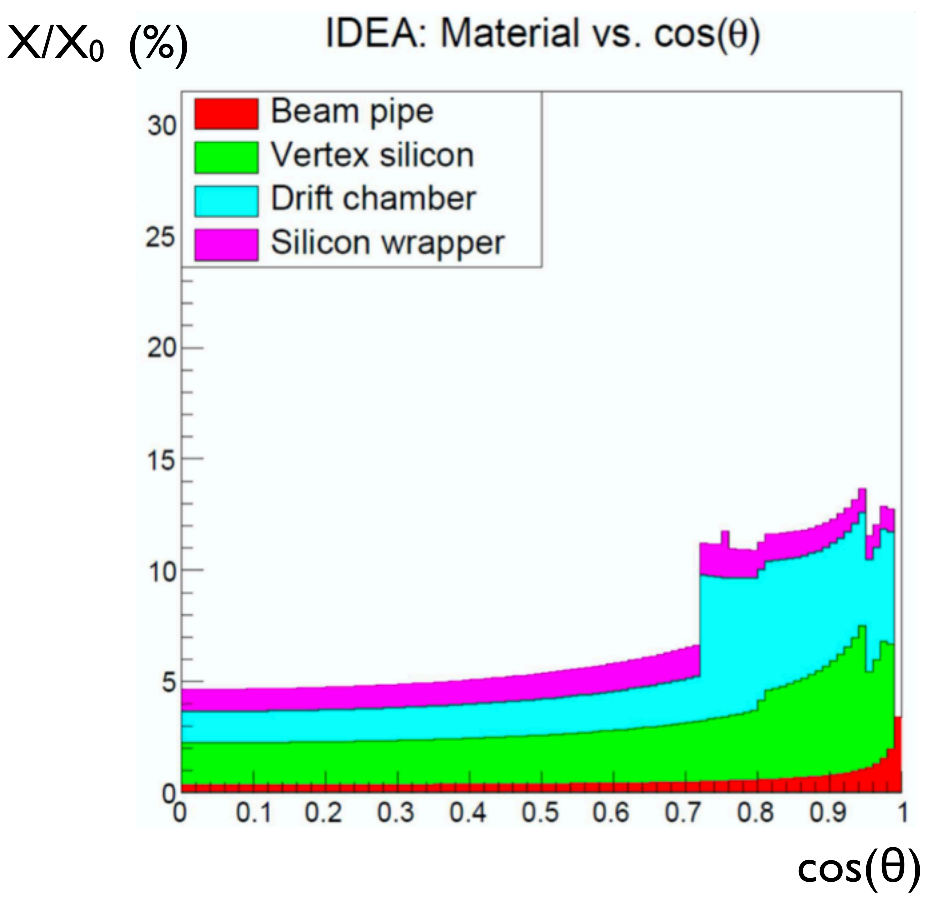
Vcb

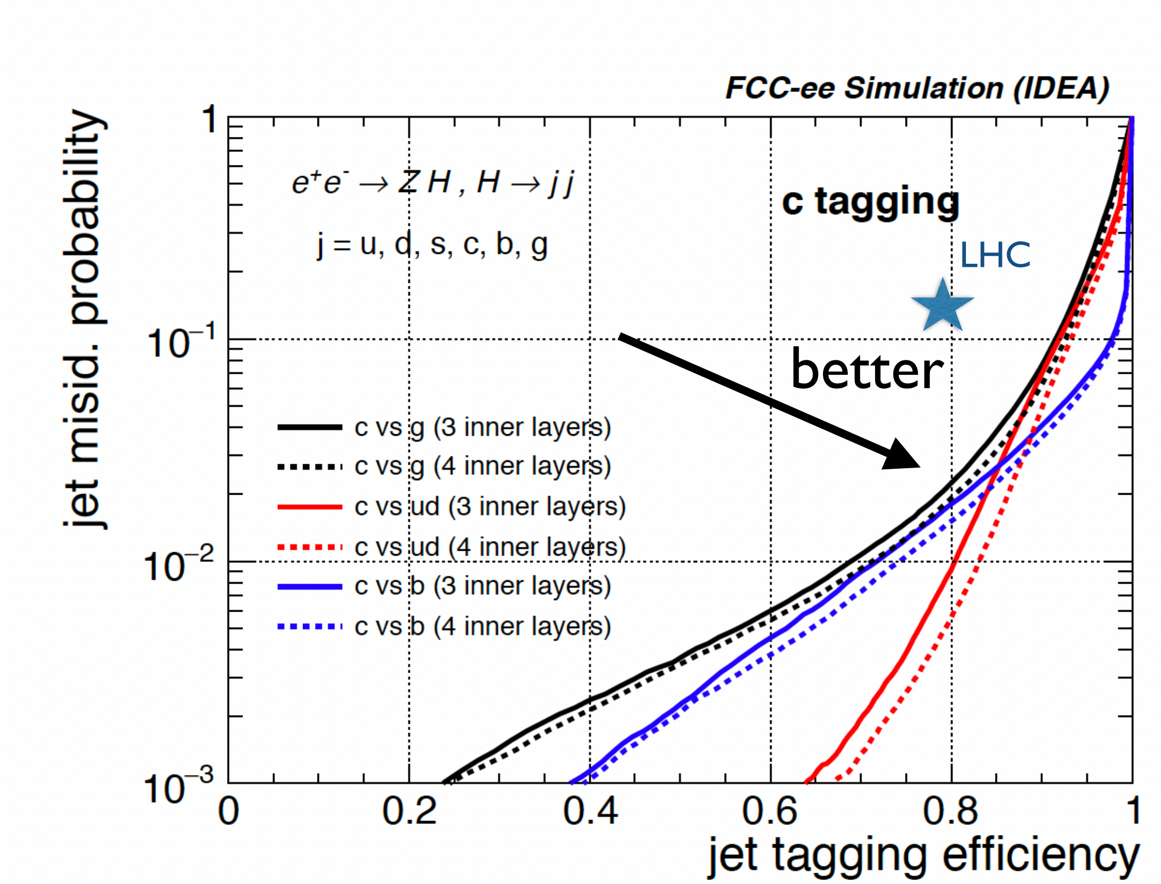


precision reach:
$\delta(V_{cb}) \sim 1.4\% \rightarrow 0.12\%$

requires excellent flavour tagging

Flavor tagging

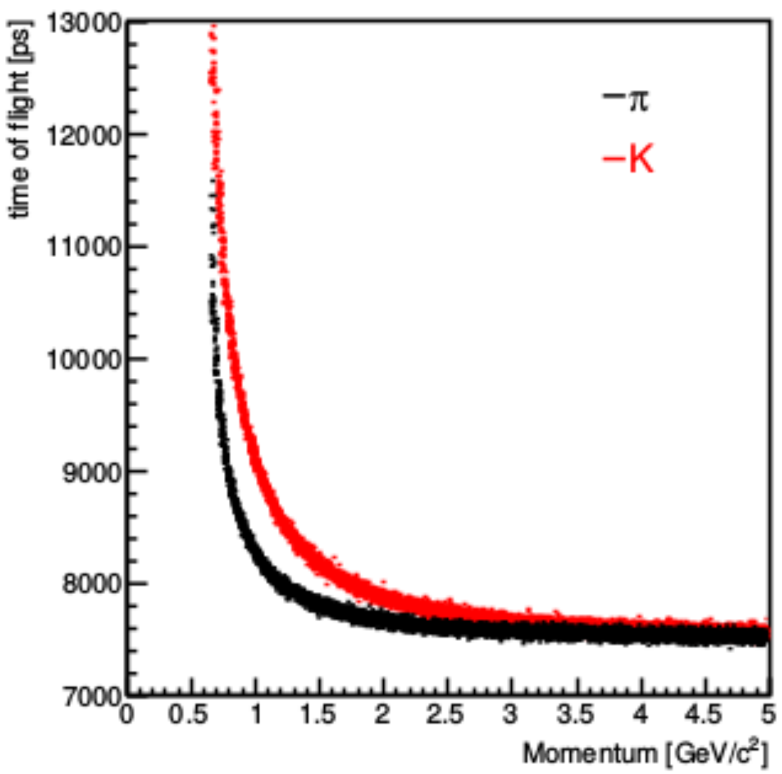


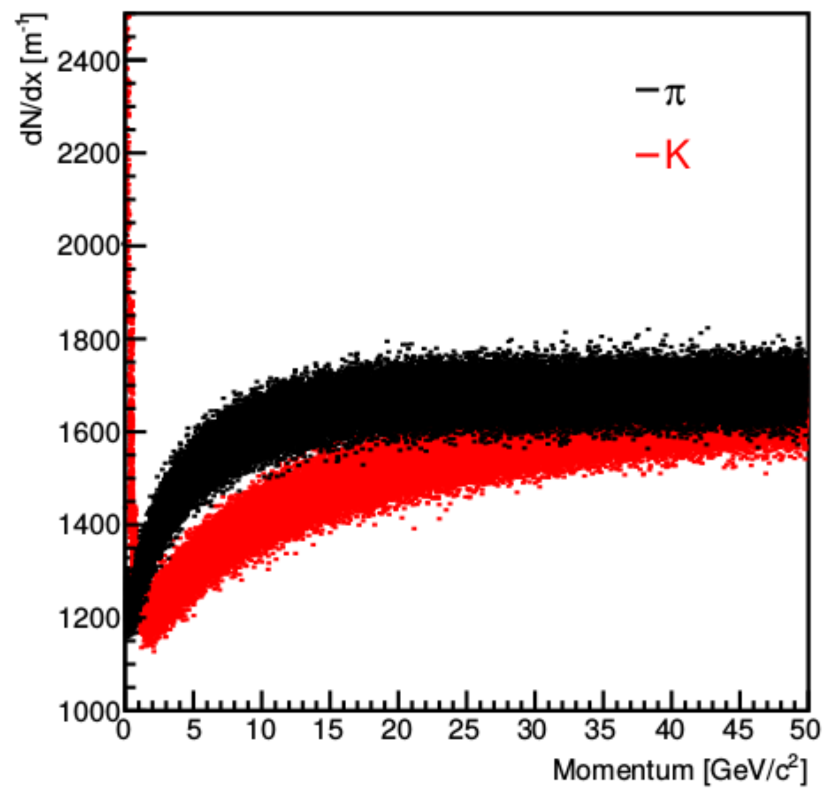


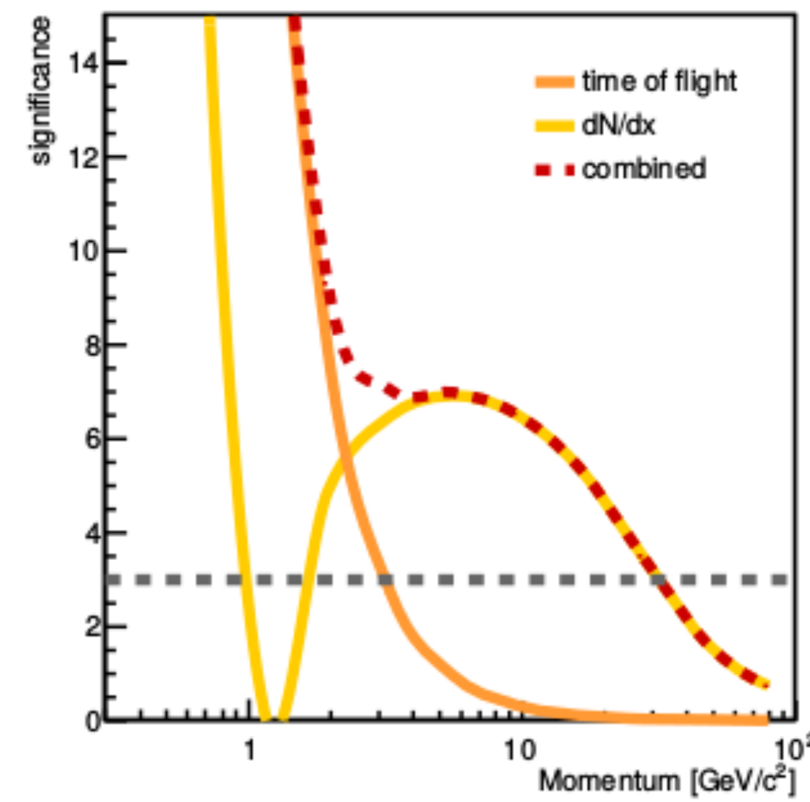
Light tracker, first measurement layer close to IP:

- excellent b/c-tagging performance
  - crucial to measure and to isolate clean H→bb/cc/gg samples

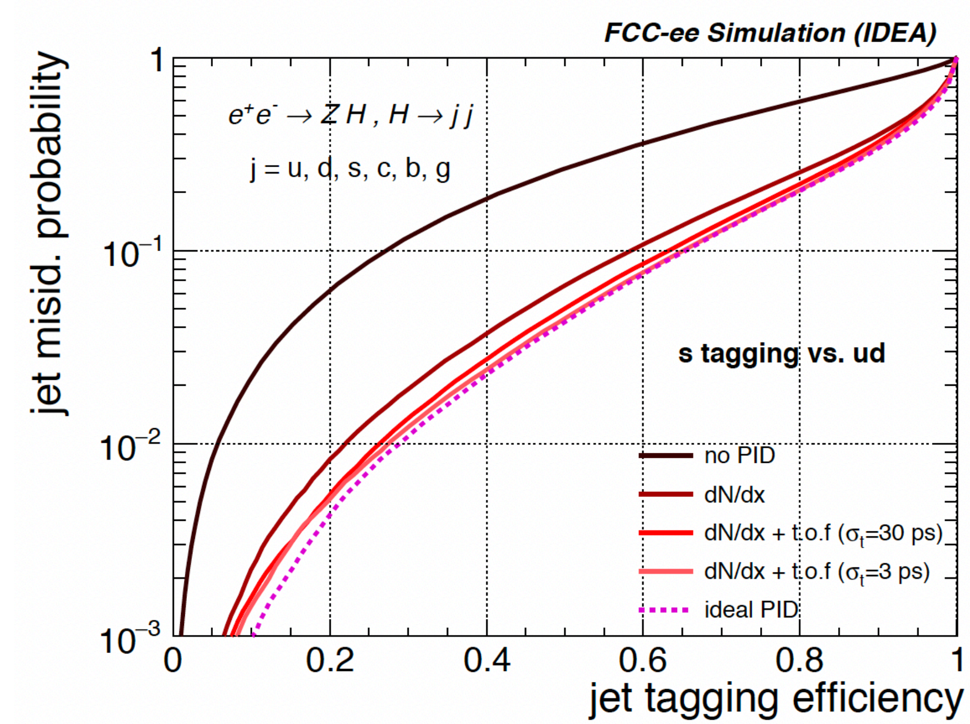
Particle ID







- Particle Id for **strange** jet identification:
  - ToF at low momenta
  - dN/dX at high momenta
- Possible to measure strange Yukawa at FCC-ee ?

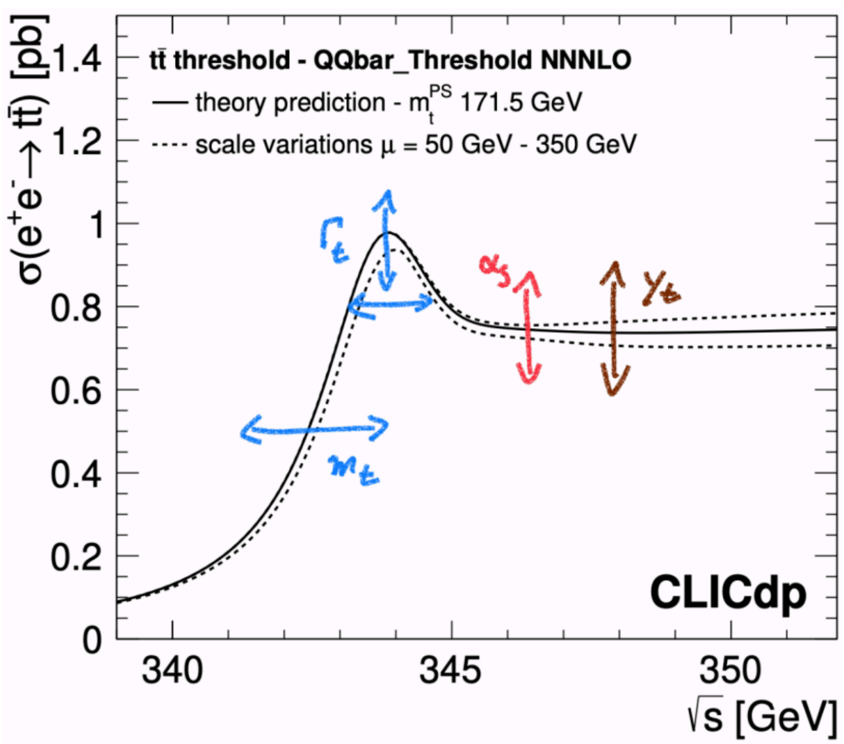


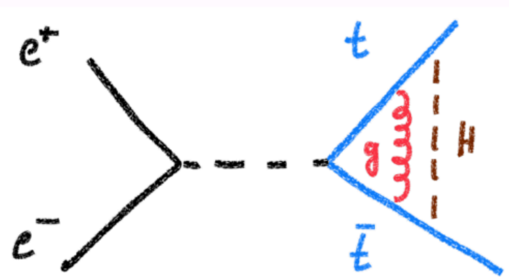
Top

CP conserving ... CPV

$$\Gamma_\mu^{ttV}(k^2,\, q,\, \bar{q}) = -ie\left\{\gamma_\mu \left(F_{1V}^V(k^2) + \gamma_5 F_{1A}^V(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}\,(q+\bar{q})^\nu \left(iF_{2V}^V(k^2) + \gamma_5 F_{2A}^V(k^2)\right)\right\}$$

Top mass and width

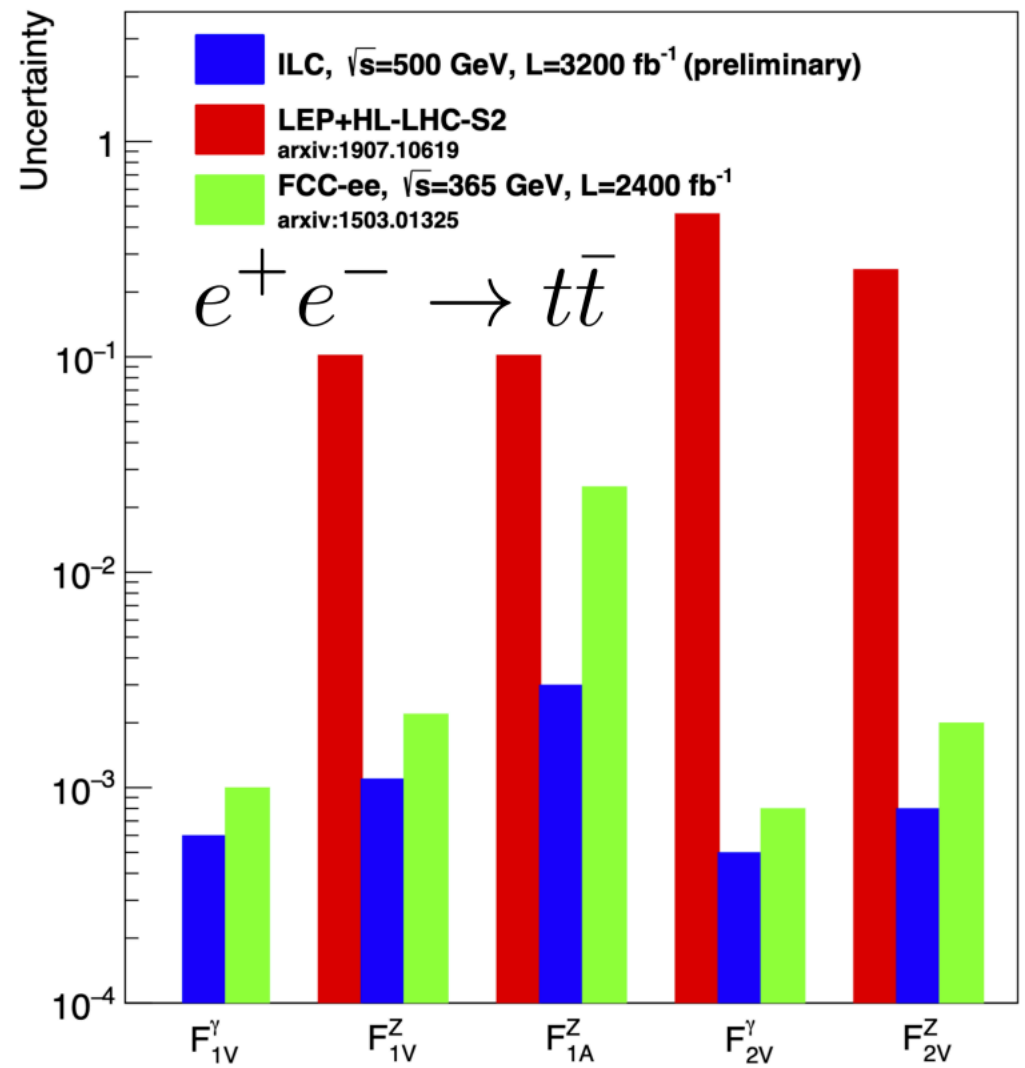




$\delta(m_t) \sim$ 10-20 MeV

20x improvement
w.r.t LHC

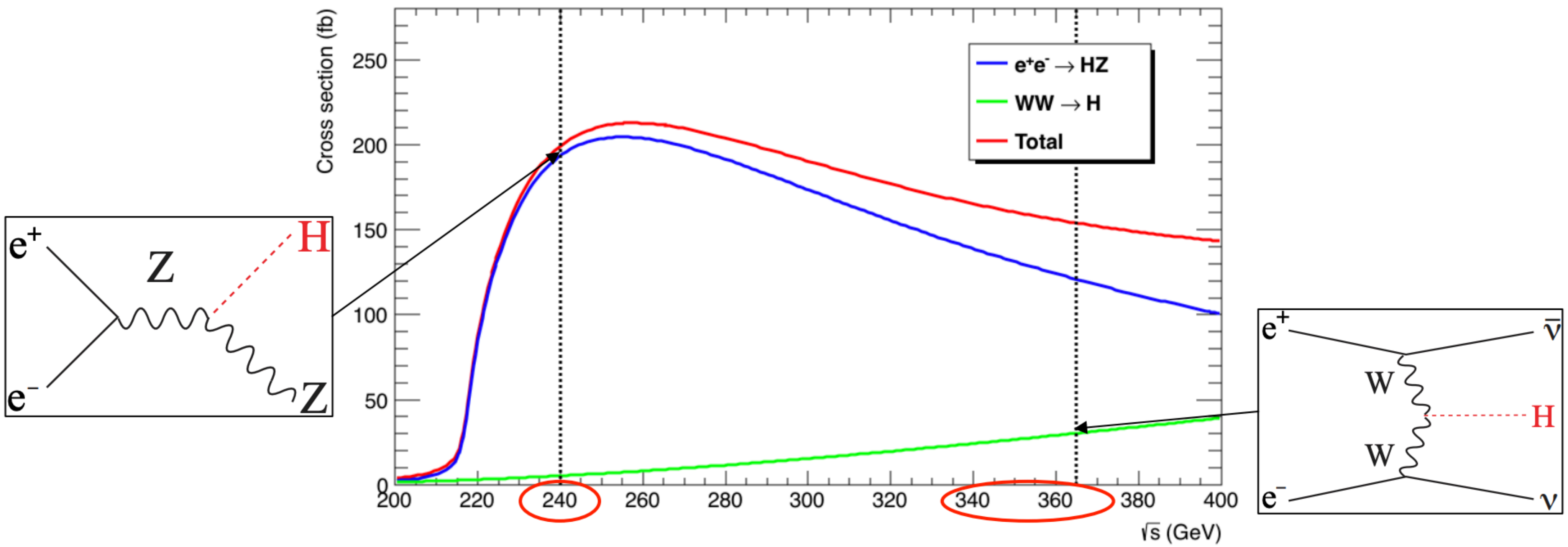
Top EWK couplings (ttZ)



ttZ coupling required for
ttH/ttZ interpretation at the FCC-hh
requires excellent flavour tagging

The FCC-ee as a Higgs factory

e+e- → ZH largest event rate at √s = 240 GeV



- (2) 10^6 e^+ e^- events with 5(10) ab^{-1}
  - target: per mille stat. limited precision
  - plus few 100k events at √s=350-365 GeV
    - of which 30% in WW fusion channel (needed for Γ_H)

Higgs @FCC-ee vs. HL-LHC?

production cross section uncertainties are typically much smaller that @pp colliders (no PDFs, no luminosity uncertainty)

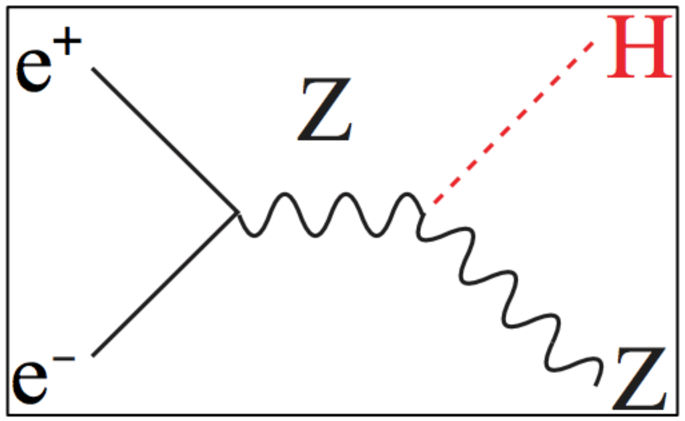
	HL-LHC (*)	FCC-ee
$\delta\Gamma_H / \Gamma_H$ (%)	SM (**)	**1.3**
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	**4.3**	9.0
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	**1.8**	3.9
$\delta g_{Htt} / g_{Htt}$ (%)	**3.4**	–
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	**9.8**	–
$\delta g_{HHH} / g_{HHH}$ (%)	**50**	~40 (indirect)
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**

Need to improve (applies to the $H\mu\mu$ through HHH rows)

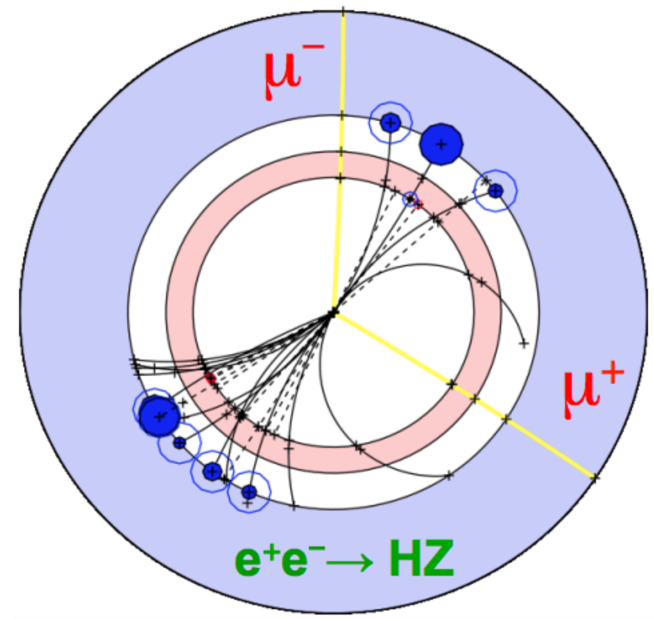
Caveat: cannot measure rare Higgs decays or production modes to high precision (because lack of statistics)

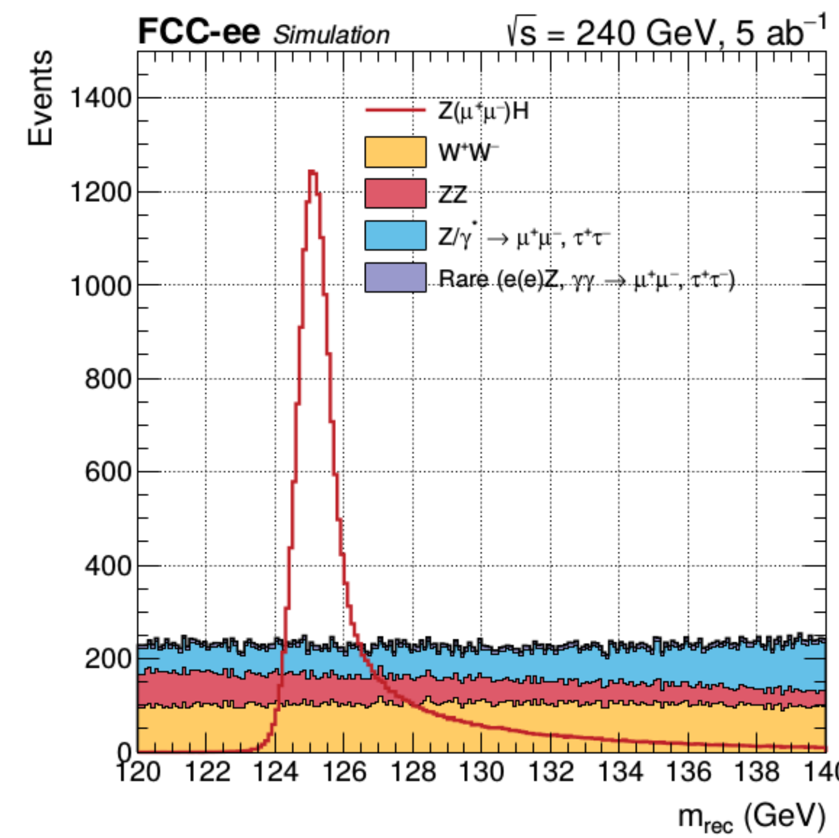
Higgs @ FCC-ee, √s = 240 GeV

- **Higgs tagged by a Z, Higgs mass from Z recoil**



$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$





Higgs recoil mass measurement → production cross section:

- 10^6 Higgs produced @ FCC-ee
- rate ~ $g_Z^{\,2}$ → $\delta g_Z/g_Z$ ~ 0.1 %

provides absolute g_Z coupling in e+e-

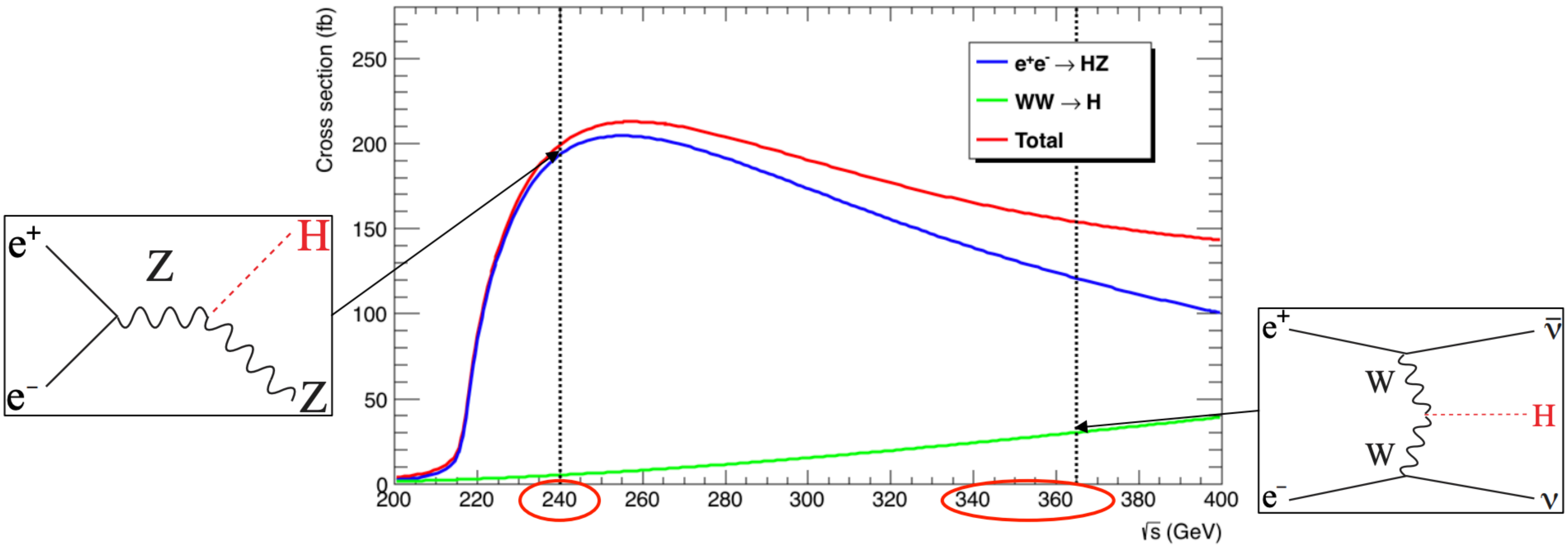
- Then measure ZH → ZZZ
- rate ~ $g_Z^{\,4} / \Gamma_H$ → $\delta\Gamma_H / \Gamma_H$ ~ 1 %

BUT limited statistics:

- for rare decay modes
- HH production

- Then measure ZH → ZXX
- rate ~ $g_Z^{\,2} g_X^{\,2} / \Gamma_H$ → $\delta g_X/g_X$ ~ 1 %

What can √s = 365 GeV bring ?



WW fusion added value

- $\nu\nu H \rightarrow \nu\nu bb \sim g_W^2\, g_b^2 / \Gamma_H$
  - $\nu\nu bb$ / (ZH(bb) ZH(WW) ~ $g_Z^4 / \Gamma_H = R$
    - Γ_H precision at 1%
- Then do $\nu\nu H \rightarrow \nu\nu WW \sim g_W^4 / \Gamma_H$
  - $R / \nu\nu WW \sim g_W^4 / g_Z^4$
    - g_W precision to few permil

$$\Gamma_H \propto \frac{\sigma\left(e^+e^- \rightarrow \nu\bar{\nu}H, H \rightarrow bb\right)\sigma\left(e^+e^- \rightarrow ZH\right)^2}{\sigma\left(e^+e^- \rightarrow ZH, H \rightarrow bb\right)\sigma\left(e^+e^- \rightarrow ZH, H \rightarrow WW\right)}$$

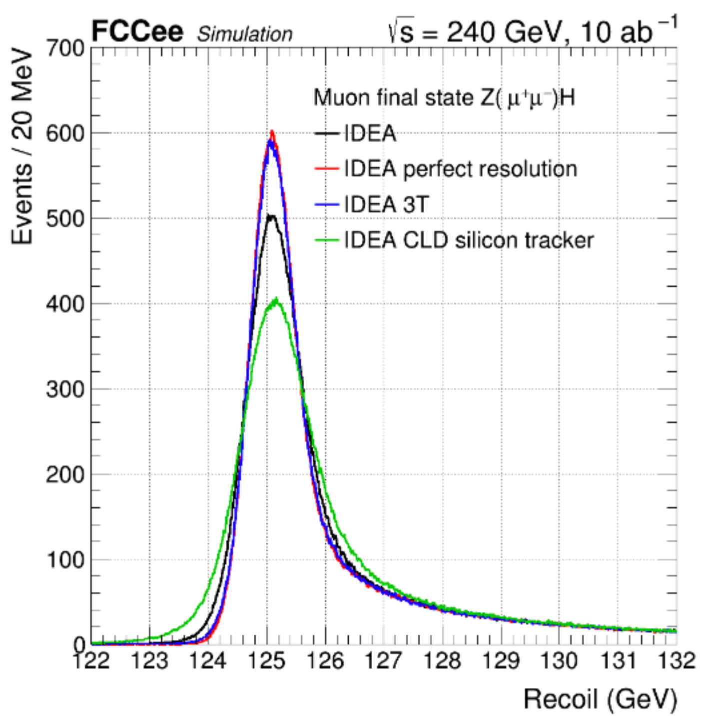
Running at the top does not simply add statistics
it exploits complementary production mode to improve constraints

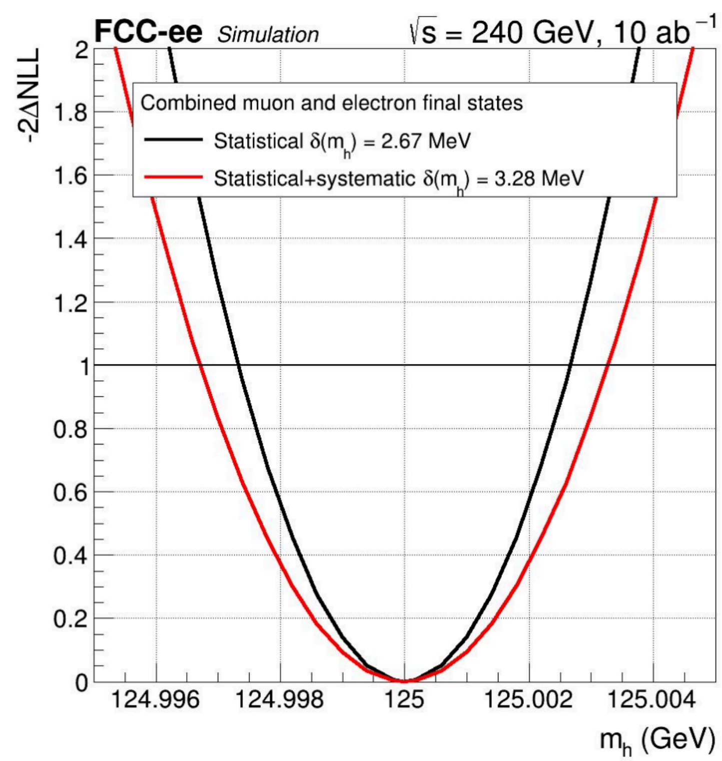
Mass

$$\sin^2\theta_W = \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{A^2}{1-\Delta r}$$

$\Delta r \sim \ln(m_H)$
$\Delta r \sim m_t^2$
$\Delta r \sim$ new physics?

- Why measure Higgs mass:
  - O(10 MeV) need for permil precision of g_Z and g_W
  - O(Γ_H = 4 MeV) can constrain electron Yukawa
- Defines stringent detector constraints





using μμ channel

tracking system	Δm_H (MeV) stat.only	Δm_H (MeV) stat + syst
IDEA 2T	**3.49**	**4.27**
Perfect	**2.67**	**3.44**
IDEA 3T	**2.89**	**3.97**
CLD 2T	**4.56**	**5.32**

~150 MeV
in ATLAS/CMS

- sensitivity dominated by the Z(μμ) final state
  - superior momentum resolution, driven by **tracking**
- track momentum resolution limits sensitivity if > beam energy spread (BES = 0.182% at 240 GeV, i.e 222 MeV)
  - multiple-scattering limit < BES
    - for CLD ~ 30% above
      - **transparent** tracker is key

ZH inclusive cross-section

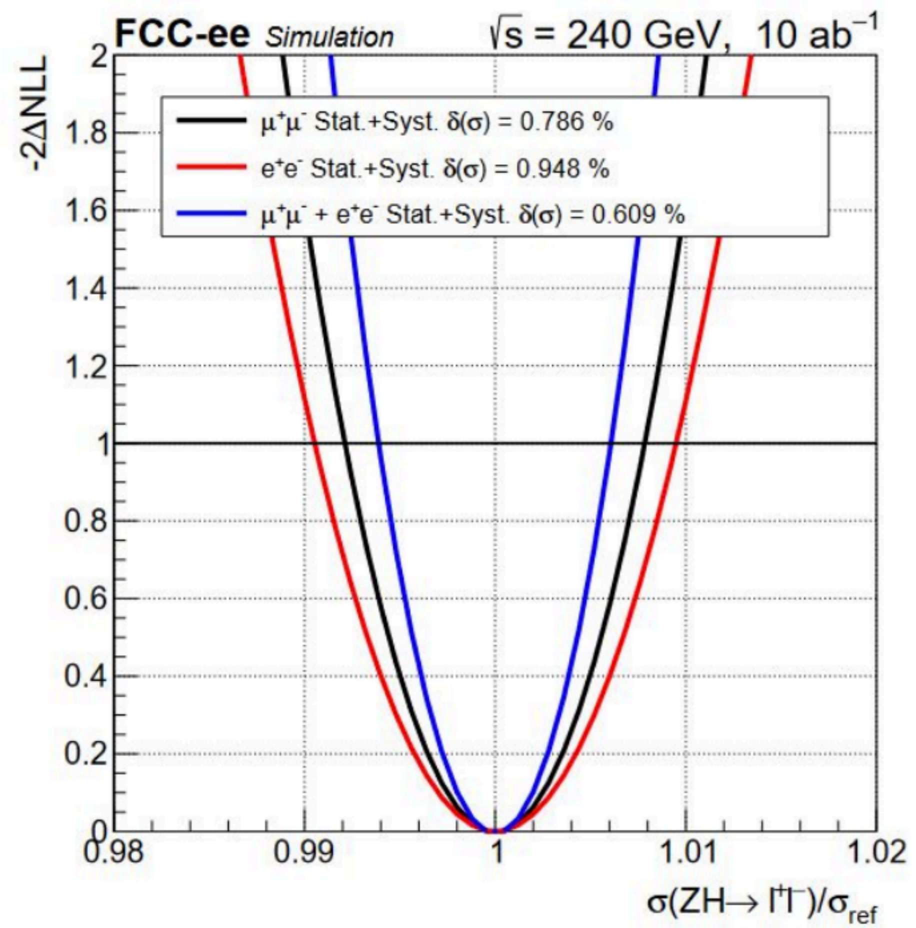
- Crucial is to measure HZZ coupling strength in a model-independent way
- Unique to e+ e - colliders because of known initial state, not possible at hadron colliders

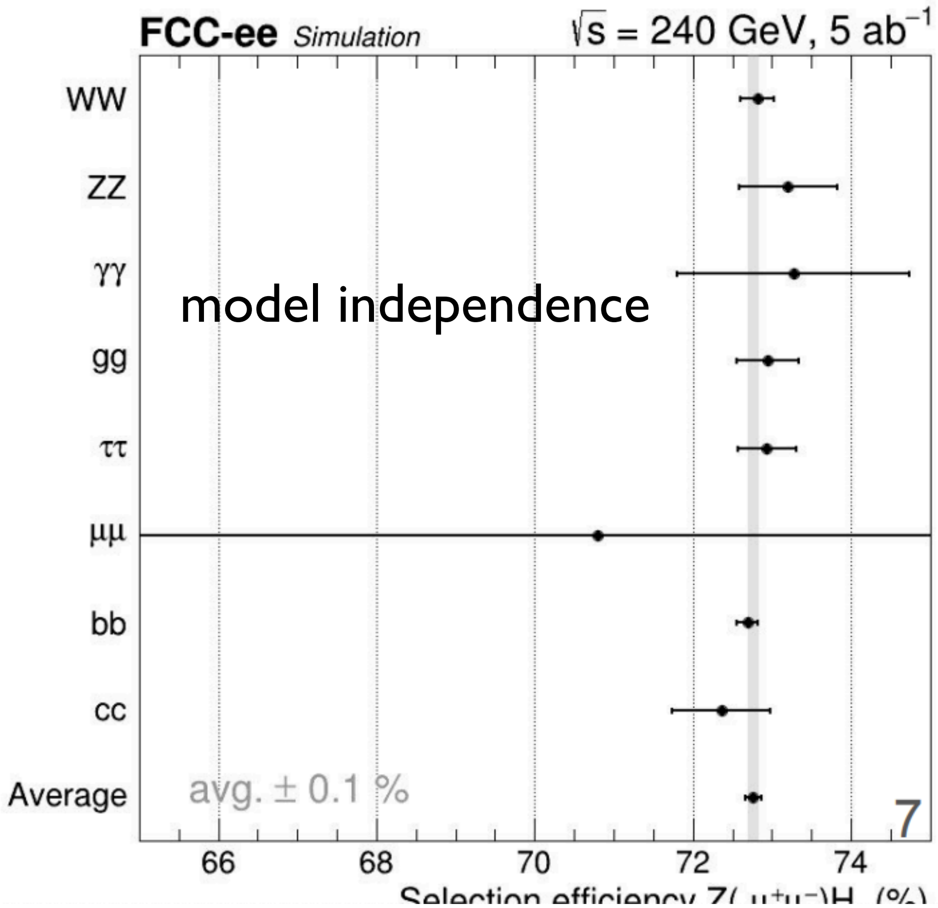
$$\Gamma_H \propto \frac{\sigma\left(e^+e^- \to ZH, H \to ZZ\right)^2}{\sigma\left(e^+e^- \to ZH\right)}$$

- Challenge to ensure model-independence ("easy for Z(ll)") — no preference to given final state
- FCC-ee sensitivity prediction to ~ 0.15%

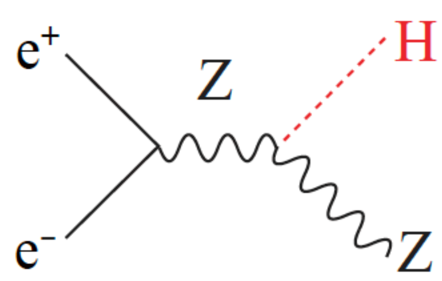
Example analysis in Z(ll)H(XX) final state:

Reach **0.6% (stat. only)**, combined muon and electron channels

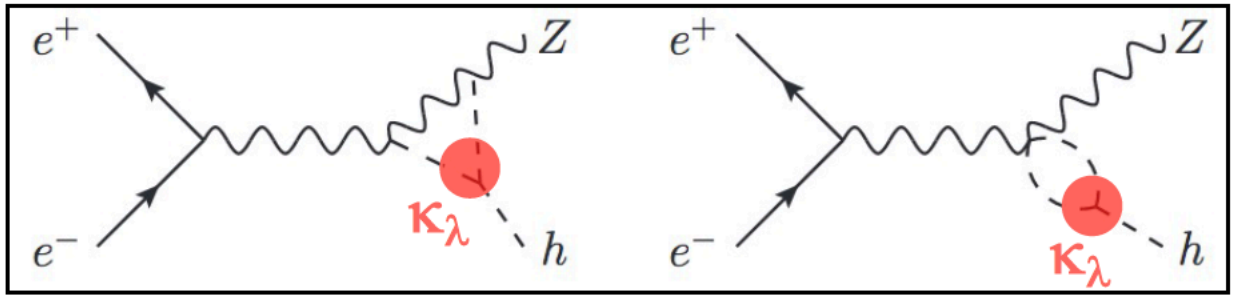




Higgs self-coupling at the FCC-ee

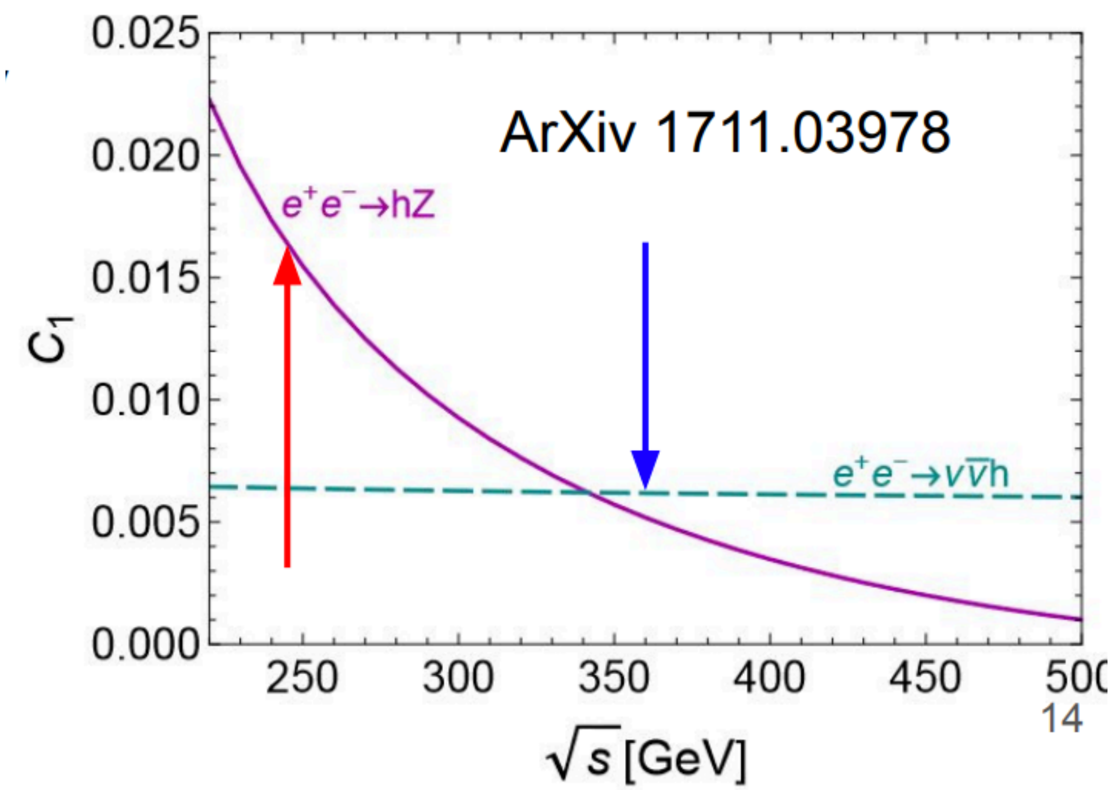


+



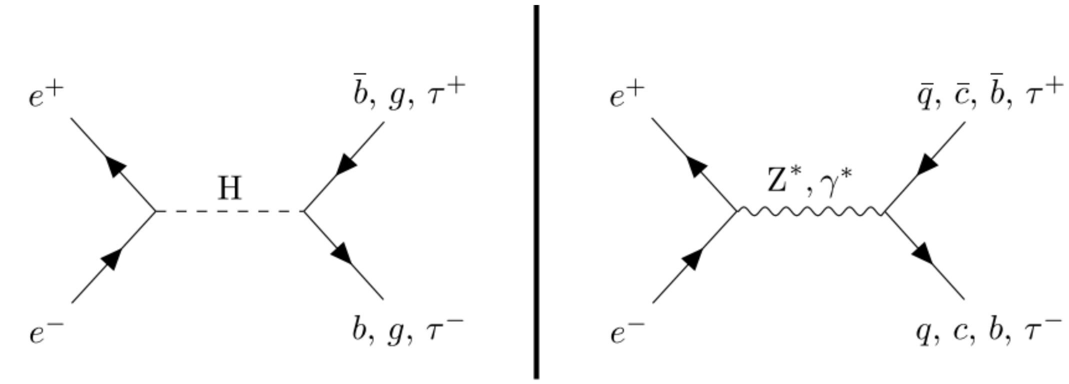
Infer self-coupling sensitivity from inclusive recoil mass cross-section measurment

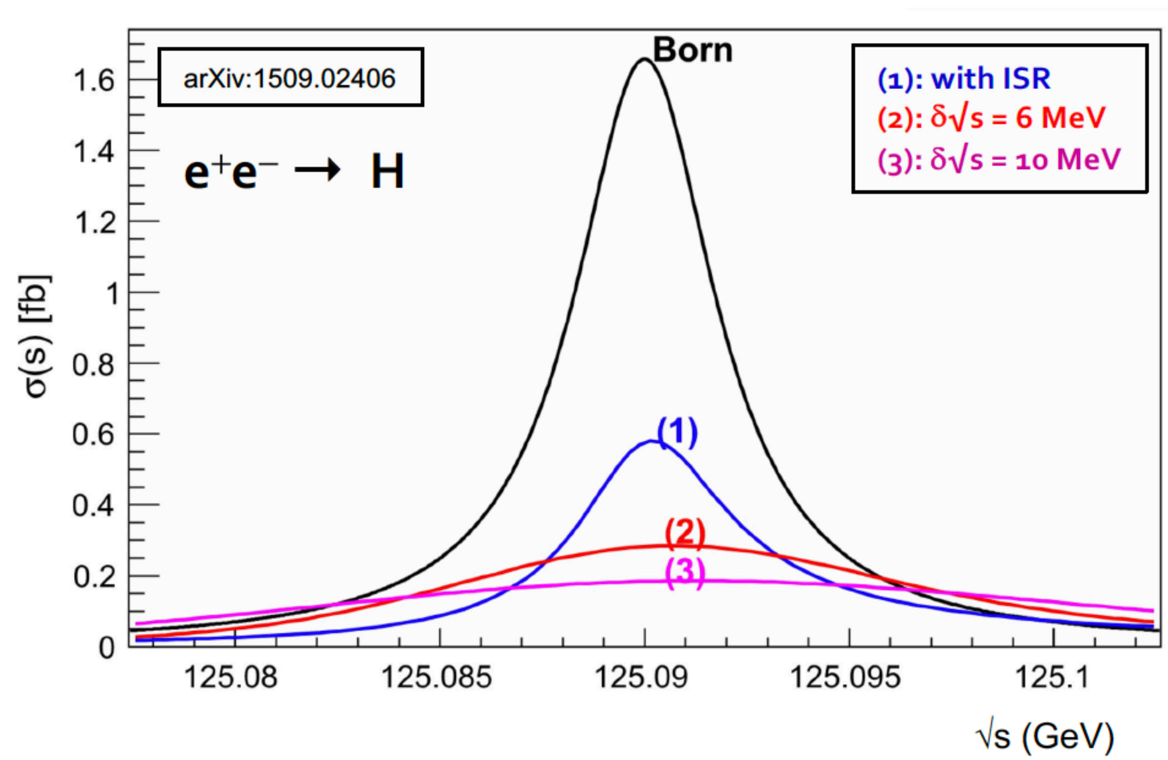
- Use $\sqrt{s}$ = 240 AND 365 GeV to resolve κ_λ , κ_{VV} degeneracy …
- $\delta\kappa_\lambda$ ~ 25% with 4IP from global fit

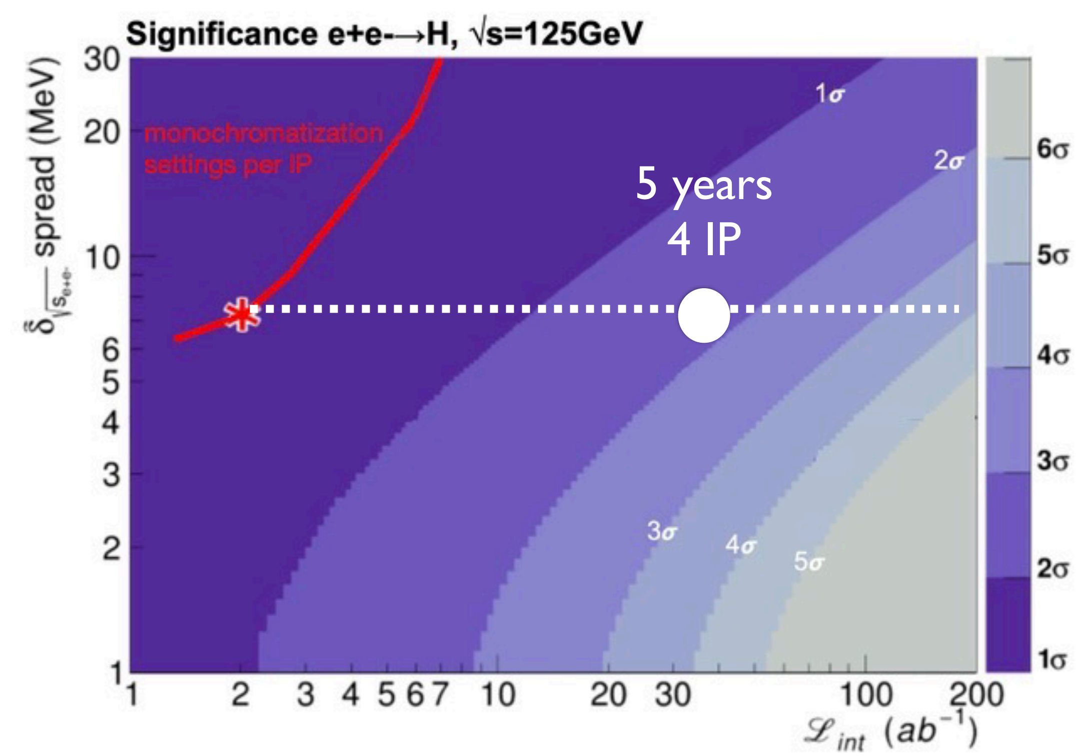


Electron Yukawa @ √s = 125 GeV

- take advantage of extreme luminosity at 125 GeV
- s-channel production with beam mono-chromatisation at √s = 125 GeV
  - Requires prior knowledge of m_H
  - ISR+FSR leads to 40% + with beam spread ~ Γ_H another 45%
    - plus potentially uncertainty on the Higgs mass





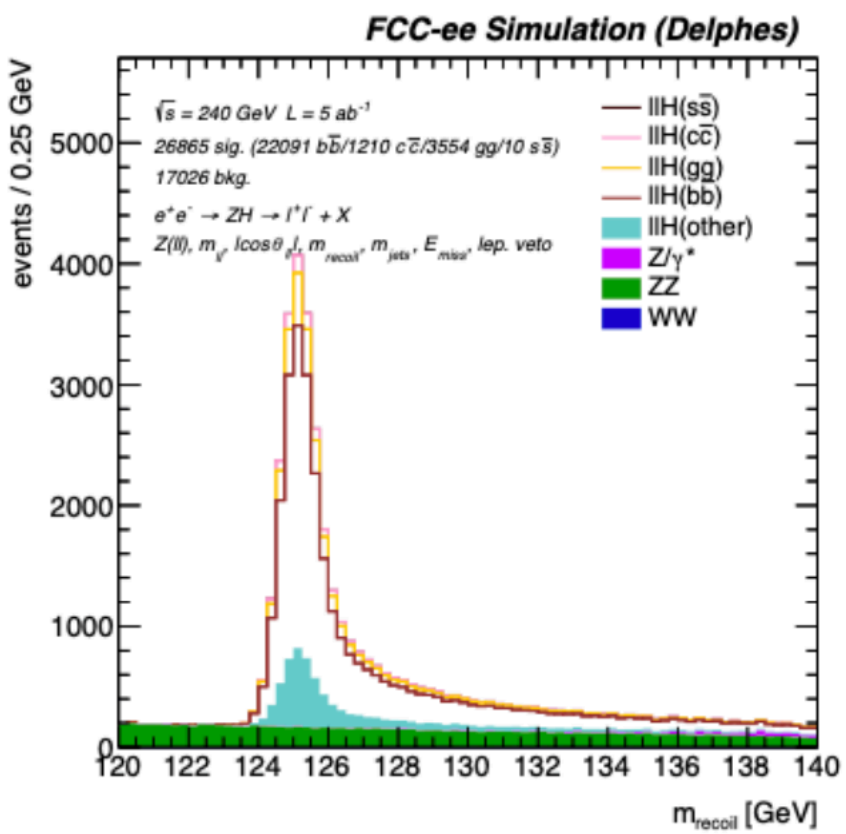


can hope for ~ 2σ with 5 years and 4 IPs

H→jj (di-lepton final state)

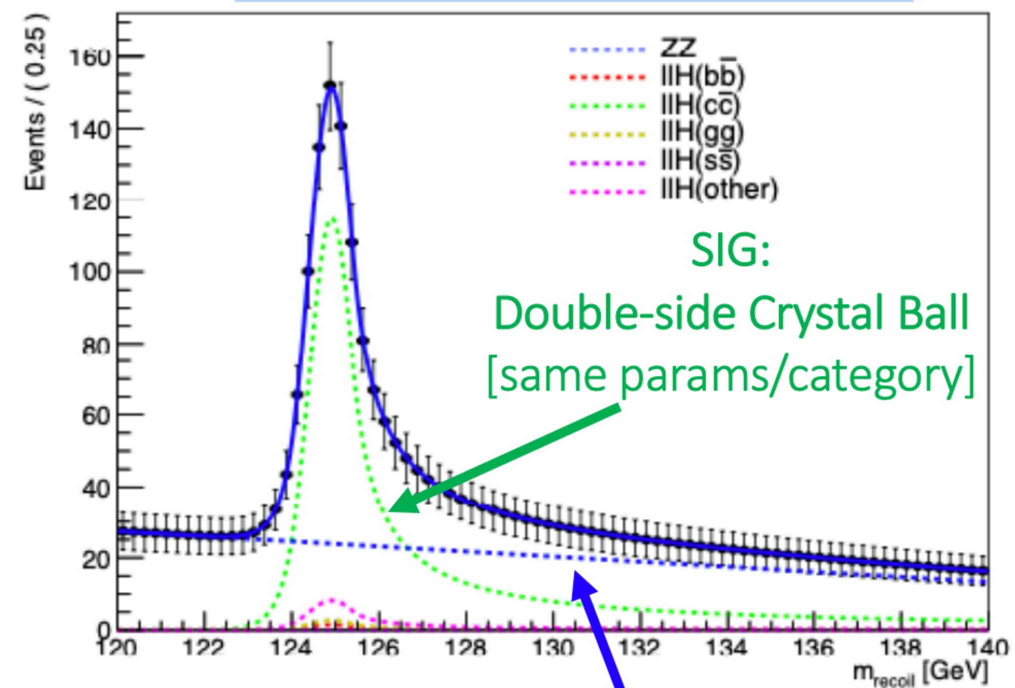
j=b,c,s,g

- Analysis channels
  - Z(→LL)H: clean but smaller signal acceptance
  - Z(→νν)H: good compromise b/ signal acceptance and purity
  - Z(→hadrons)H: Largest signal acceptance, but.. jets [work in progress]



Z(→LL)H channel

Z(→LL)H(→cc) category



SIG:
Double-side Crystal Ball
[same params/category]

BKG:
1st order polynomial

N=2 Durham k_T exclusive clustering

4 free-floating signal strength fit

Results @10 ab^{-1}

Z(→LL)H(→qq)	bb	cc	ss	gg
δμ/μ (%)	0.6	3.5	290	1.5

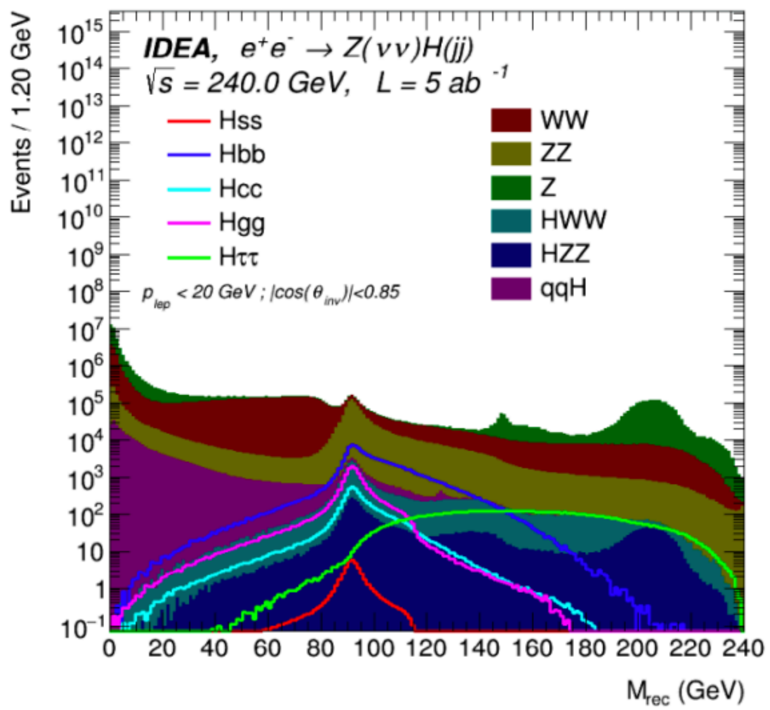
H→jj (missing energy final state)

j=b,c,s,g

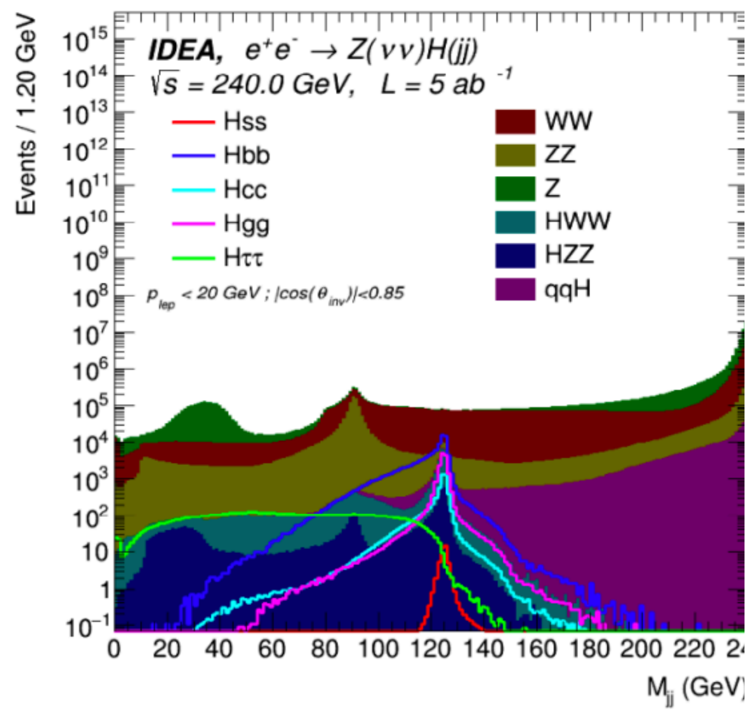
SIG-vs-BKG discrimination

- Different SIG and BKGs shapes in m_{rec} & m_{jj}
- Bump hunt in 2D
  - simultaneous fit in all categories

m_{rec}



m_{jj}



N=2 Durham k_T exclusive clustering

4 free-floating signal strength fit

Results @10 ab^{-1}

Systematics:
- 5 (0.1)% BKG (SIG)
  - uncorrelated b/w processes
    BKG: constrained to O(1)%
- Limited MC statistics

Z(→νν)H(→qq)	bb	cc	ss	gg
δμ/μ (%)	0.3	2.1	100	0.8

* $|BR_{H\to ss}|<1.3$

room to contribute

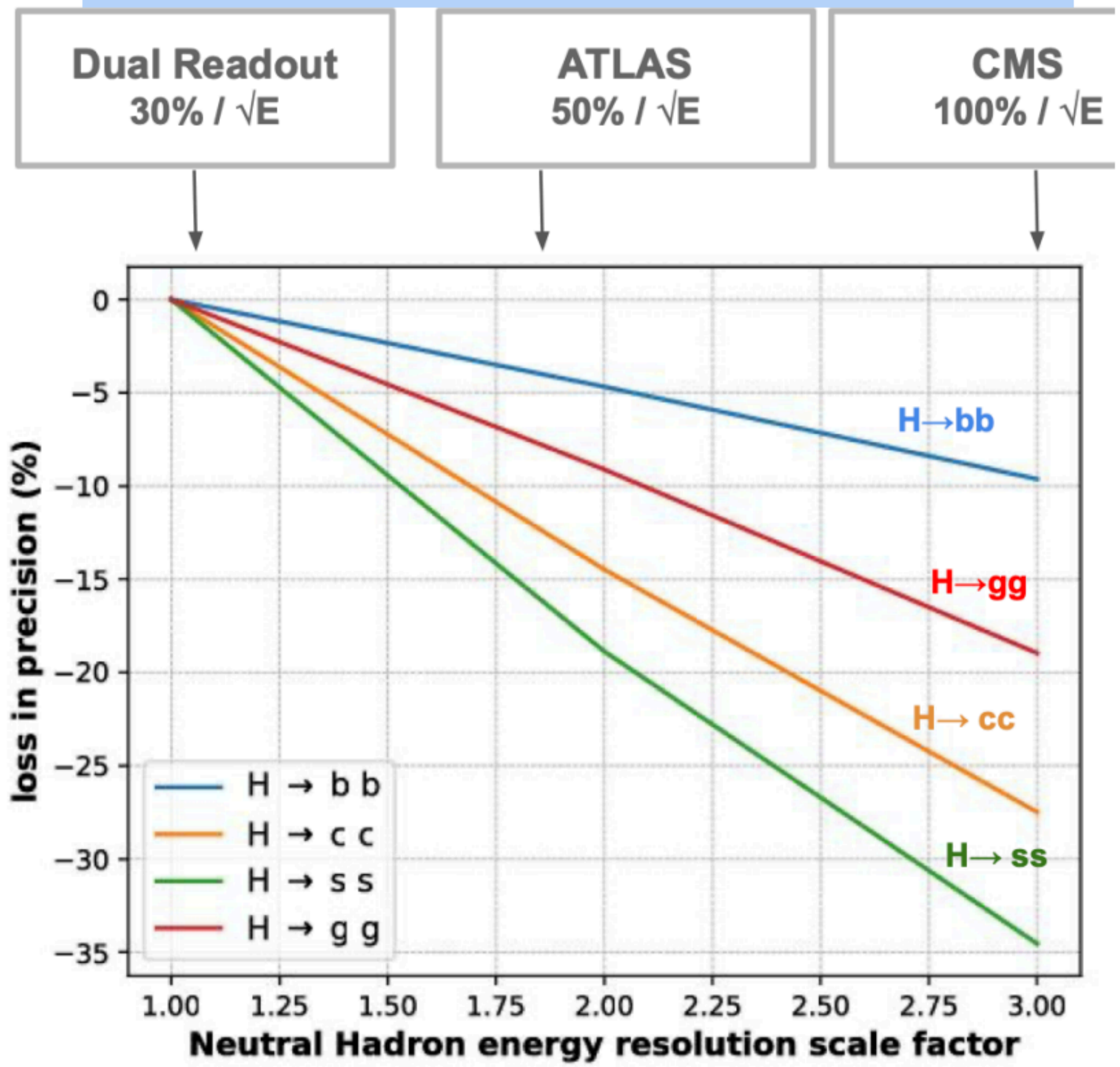
strange Yukawa $\delta(\kappa_S)$ ~ 50% !!!

most likely 3σ within reach using the fully hadronic channel still …

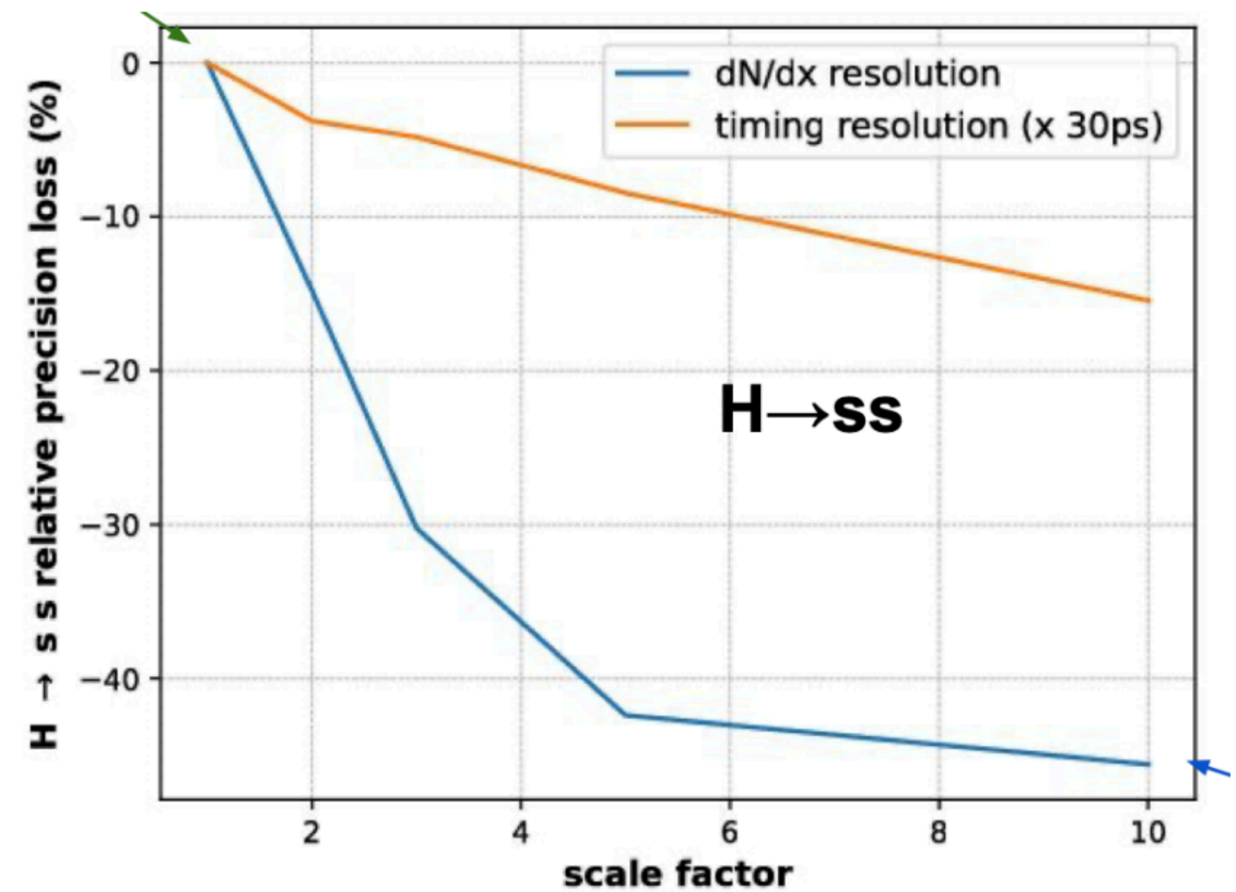
H→jj (detector requirements)

j=b,c,s,g

Neutral Hadron resolution



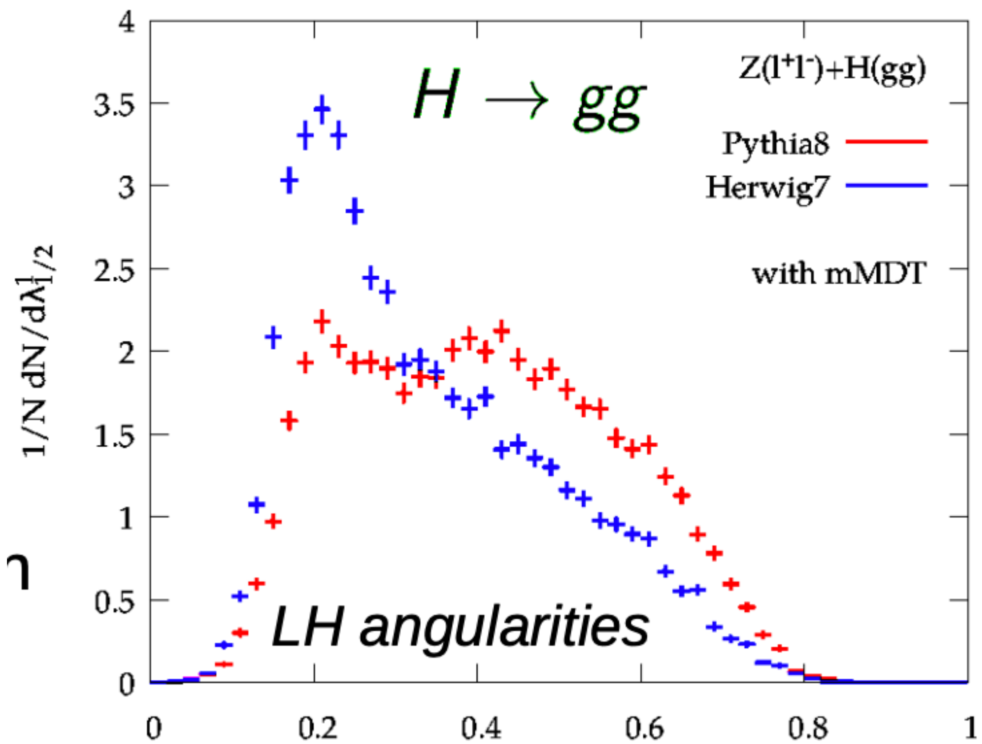
PID

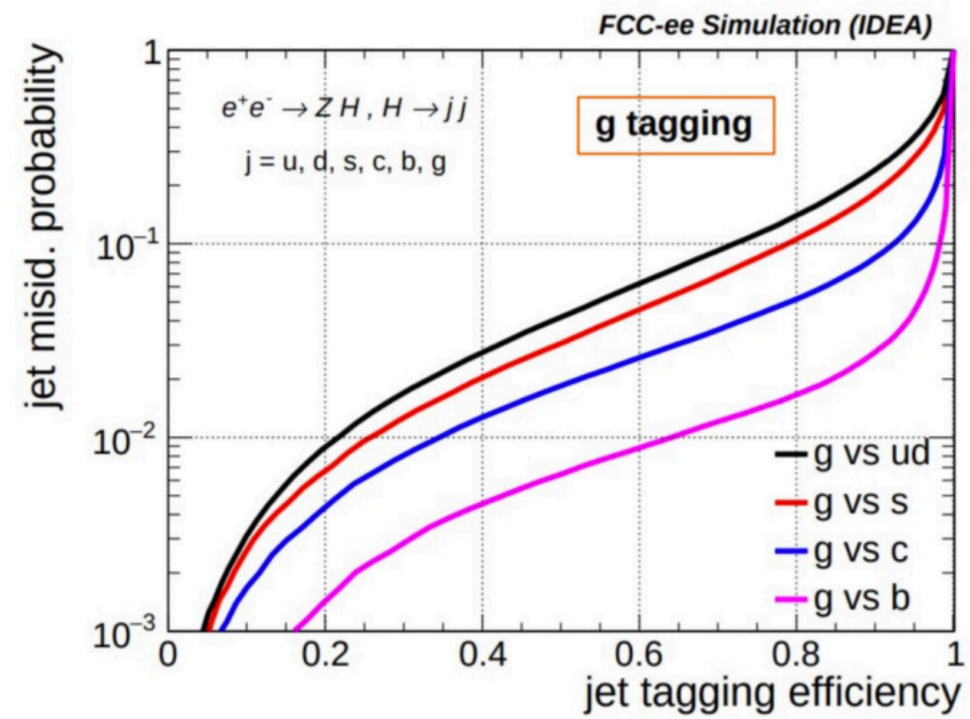


Hadronic resolution critical for all H→jj

Powerful **PID** essential for **strange Yukawa**

H→gluons





40% H → gg for 0.1% H → cc

0.01% H → bb

- with powerful gluon taggers:
  - measure Higgs to gluon coupling
  - exploit it as a gluon factory
    - 100k extra clean gluon events
    - study gluon radiation and jet properties

Higgs at FCC-ee: to be studied …

Higgs experimental programme widely covered, but still some key analyses missing/not started

Higgs width - Preliminary studies started, more person power needed
- all ZH(ZZ) final states to be studied 2,4,6 jets
- multi jet environment – 6 jets final state ZH(ZZ*), ZH(WW*) – challenging

Possibility to also exploit 365 GeV (ee → $\nu\nu$H)

Taus - Reconstruction/identification/tagging
- Coupling strength, angular, CP

Rare ($\gamma\gamma$, $\mu\mu$, Zγ, qq)

Exotic (FCNCs H→bs, …)

Angular analysis, differential measurements

and corresponding detector requirements

NOW IS A PERFECT TIME TO JOIN AND MAKE AN IMPACT

~ 2 more years to complete the feasibility study

Coupling measurements at ee vs hh

At pp colliders we can only measure:

$$\sigma_{prod}\, BR(i) = \sigma_{prod}\, \Gamma_i \,/\, \Gamma_H$$

→ we do not know the total width

In order to perform global fits, we have to make **model-dependent assumptions**

Instead, by performing measurements of ratios of BRs at hadron colliders:

$$BR(H\to XX) \,/\, BR(H\to ZZ) \approx g_X{}^2 \,/\, g_Z{}^2$$

from e^+e^-

We can "convert" **relative measurements into absolute** via g_Z thanks to e^+e^- measurement

→ synergy between lepton and hadron colliders

Why measuring Higgs @100TeV?

- 100 TeV provides **unique and complementary measurements** to ee colliders:
  - Higgs **self-coupling**
  - **top Yukawa**
  - **Higgs → invisible**
  - **rare decays** (BR(μμ), BR(Zγ), ratios, ..) measurements will be **statistically limited** at FCC-ee

	HL-LHC	FCC-ee
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	**4.3**	9.0
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	**1.8**	3.9
$\delta g_{Htt} / g_{Htt}$ (%)	**3.4**	–
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	**9.8**	–
$\delta g_{HHH} / g_{HHH}$ (%)	**50**	40
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**

Need to improve ($\delta g_{H\mu\mu}$ to δg_{HHH})

Large rates for rare modes and HH production at FCC-hh

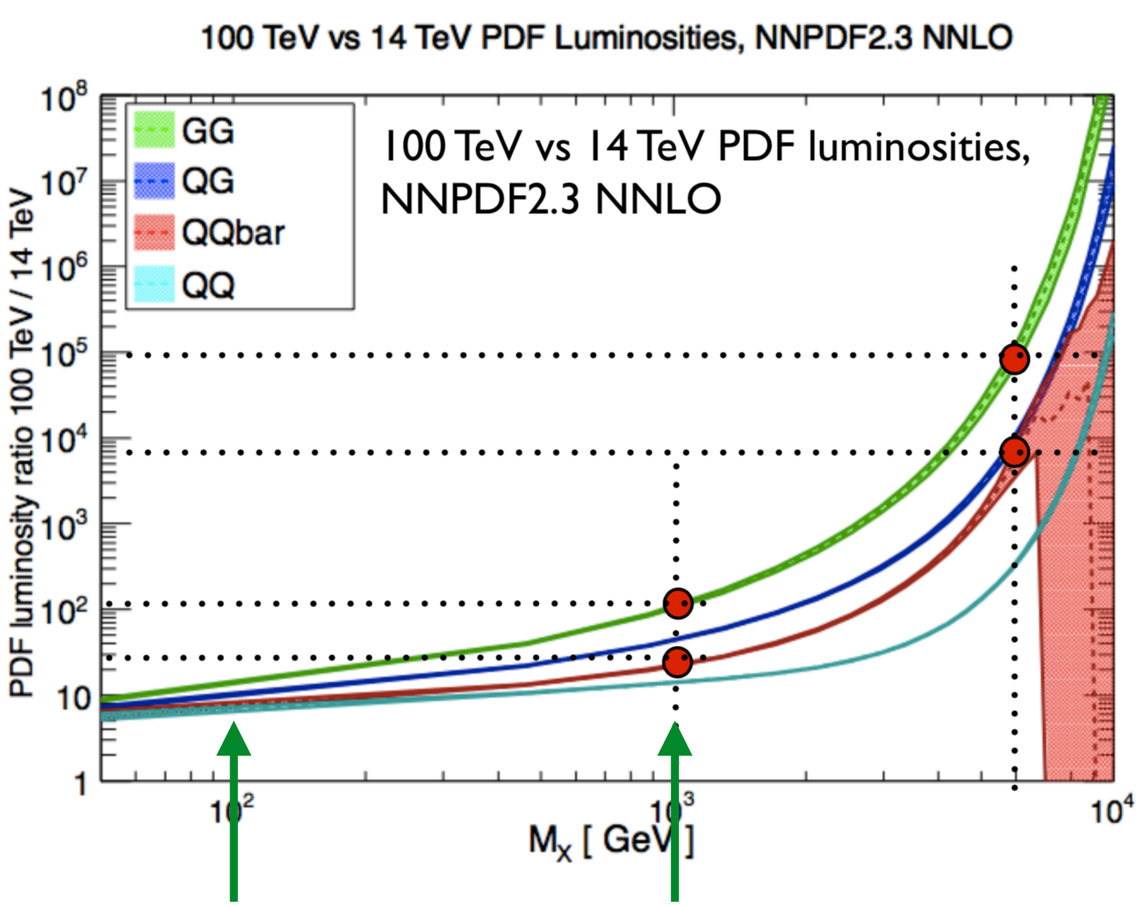
→ complementary to e^+e^-

Reach at high energies (III)

For more details see L. Wang lectures at IAS '17

How does the rate of a **given process** (e.g. single Higgs production) scale from 14 TeV to 100 TeV

$$\frac{\text{cross-section } (\sqrt{s} = 100 \text{ TeV})}{\text{cross-section } (\sqrt{s} = 14 \text{ TeV})} \approx L_1 / L_2 \approx (s_2 / s_1)^a \approx (100/14)^{2a}$$



	σ(100)/σ(14)
ggH	15
HH	40
ttH	55
H (p_T > 1 TeV)	400

Very large rate increase by increasing center of mass energy

NB: this improvement only comes from the cross-section (neglects integrated luminosity)

Summary of Higgs direct measurements

Observable	Parameter	Precision (stat.)	Precision (stat.+syst.+lumi.)
$\mu = \sigma(H) \times B(H \to \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.45%
$\mu = \sigma(H) \times B(H \to \mu\mu)$	$\delta\mu/\mu$	0.28%	1.22%
$\mu = \sigma(H) \times B(H \to 4\mu)$	$\delta\mu/\mu$	0.18%	1.85%
$\mu = \sigma(H) \times B(H \to \gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.61%
$\mu = \sigma(HH) \times B(H \to \gamma\gamma)\, B(H \to b\bar{b})$	$\delta\lambda/\lambda$	5%	7.0%
$R = B(H \to \mu\mu)/B(H \to 4\mu)$	$\delta R/R$	0.33%	1.3%
$R = B(H \to \gamma\gamma)/B(H \to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = B(H \to \gamma\gamma)/B(H \to 2\mu)$	$\delta R/R$	0.29%	1.38%
$R = B(H \to \mu\mu\gamma)/B(H \to 4\mu)$	$\delta R/R$	0.58%	1.82%
$R = \sigma(t\bar{t}H) \times B(H \to b\bar{b})/\sigma(t\bar{t}Z) \times B(Z \to b\bar{b})$	$\delta R/R$	1.05%	1.9%
$B(H \to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

$\delta R/R$	HE-LHC	LE-FCC	FCC-hh
$R = B(H\to\gamma\gamma)/B(H\to 2e2\mu)$	1.7%	1.5%	0.8%
$R = B(H\to\mu\mu)/B(H\to4\mu)$	3.6%	2.9%	1.3%
$R = B(H\to\mu\mu\gamma)/B(H\to\mu\mu)$	8.4%	6%	1.8%
$R = B(H\to\gamma\gamma)/B(H\to 2\mu)$	3.5 %	2.8%	1.4%

- **Percent level precision on σ x BR** in most rare decay channels achievable only at 100 TeV
- **Percent level precision on couplings** if HZZ coupling known from FCC-ee (to 0.2%)

Summary direct Higgs couplings at the FCC

	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	**0.65** (*)
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	**0.4** (*)
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	–	**0.95** (**)
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	**0.91** (*)
$\delta g_{HHH} / g_{HHH}$ (%)	50	~30 (indirect)	**5**
BR_{exo} (95%CL)	BR_{inv} < 2.5%	**< 1%**	**BR_{inv} < 0.025%**

* From BR ratios wrt B(H→4l) @ FCC-ee

** From pp→ttH / pp→ttZ, using B(H→bb) and ttZ EW coupling @ FCC-ee

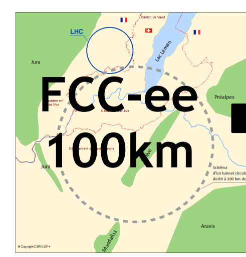
Future of HEP

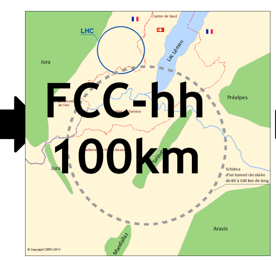
Tevatron 2TeV → x 7 → LHC 14TeV → x 7 → FCC-hh 100TeV

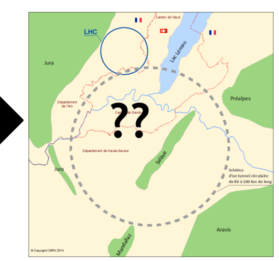
M. Aleksa pECFA

27km tunnel

The next step: 100km tunnel







The FCC design study is establishing the feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology

Both FCC-ee and FCC-hh have outstanding physics cases

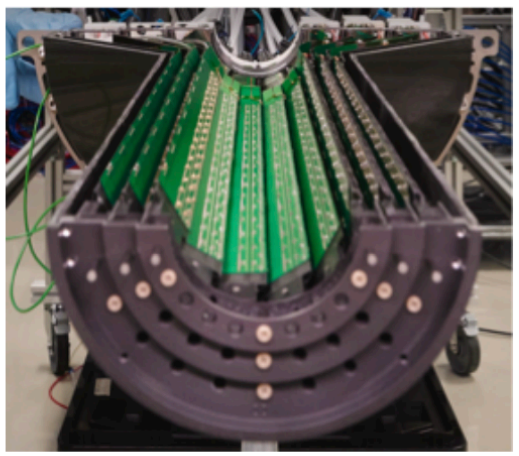
Backup

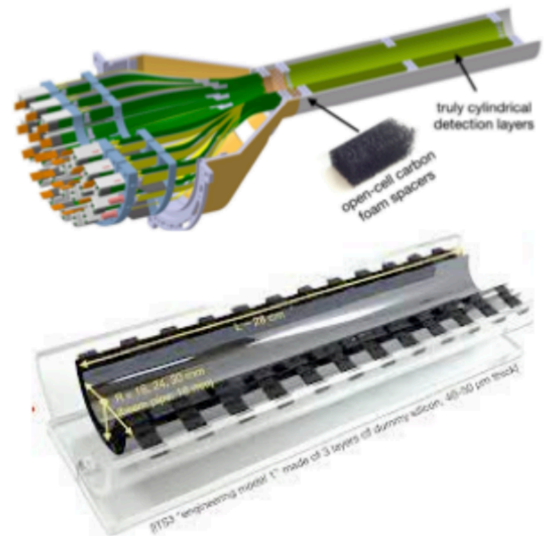
Vertex detectors

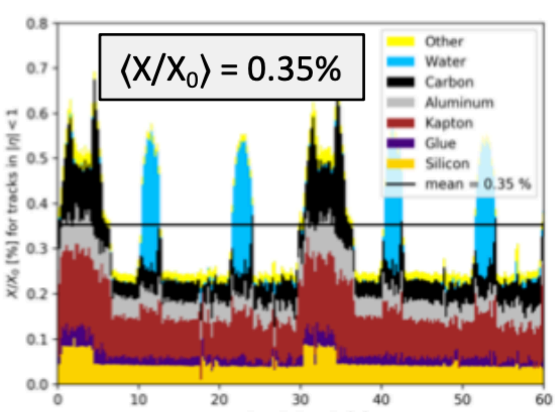
ALICE Vertex detector development

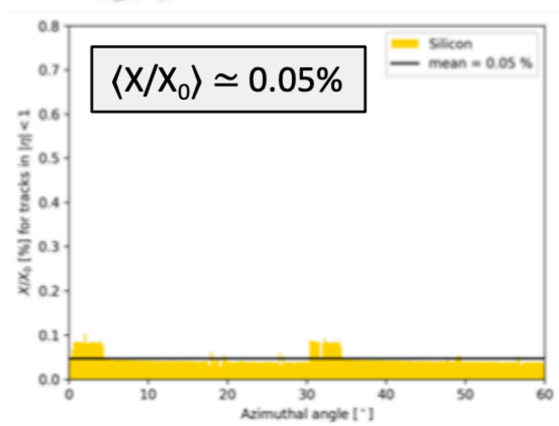
ITS2: installed in 2021

ITS3: installation 2027/2028



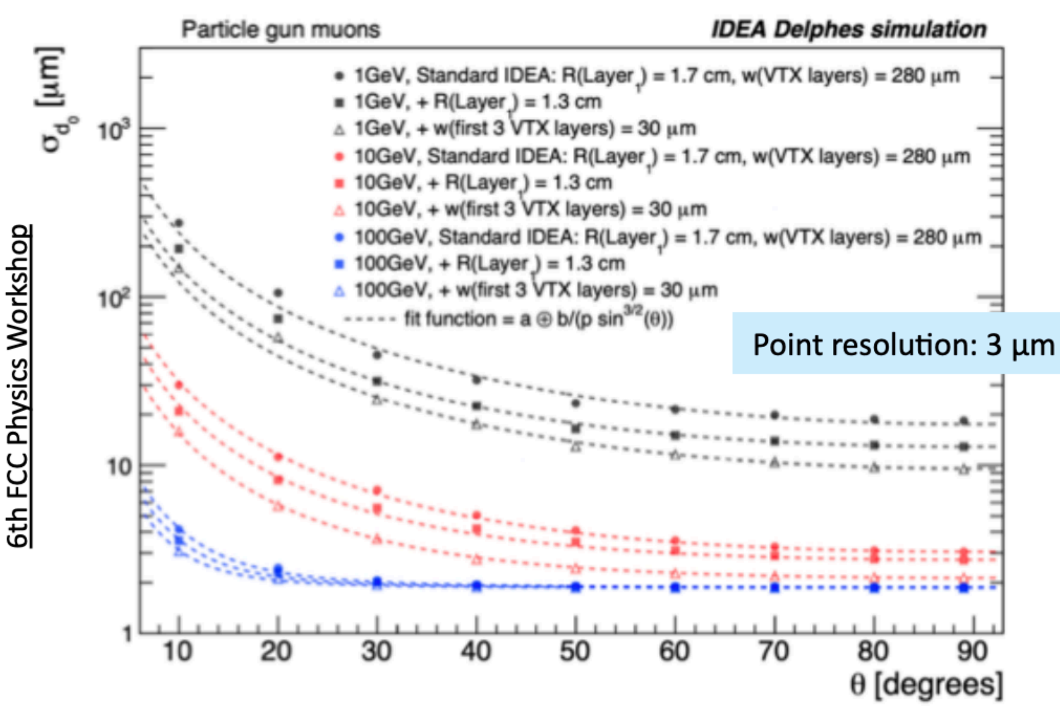






Keywords: thinning (40-50 µm) , bending (r ≳ 10 mm), stitching (one crystal per half barrel)

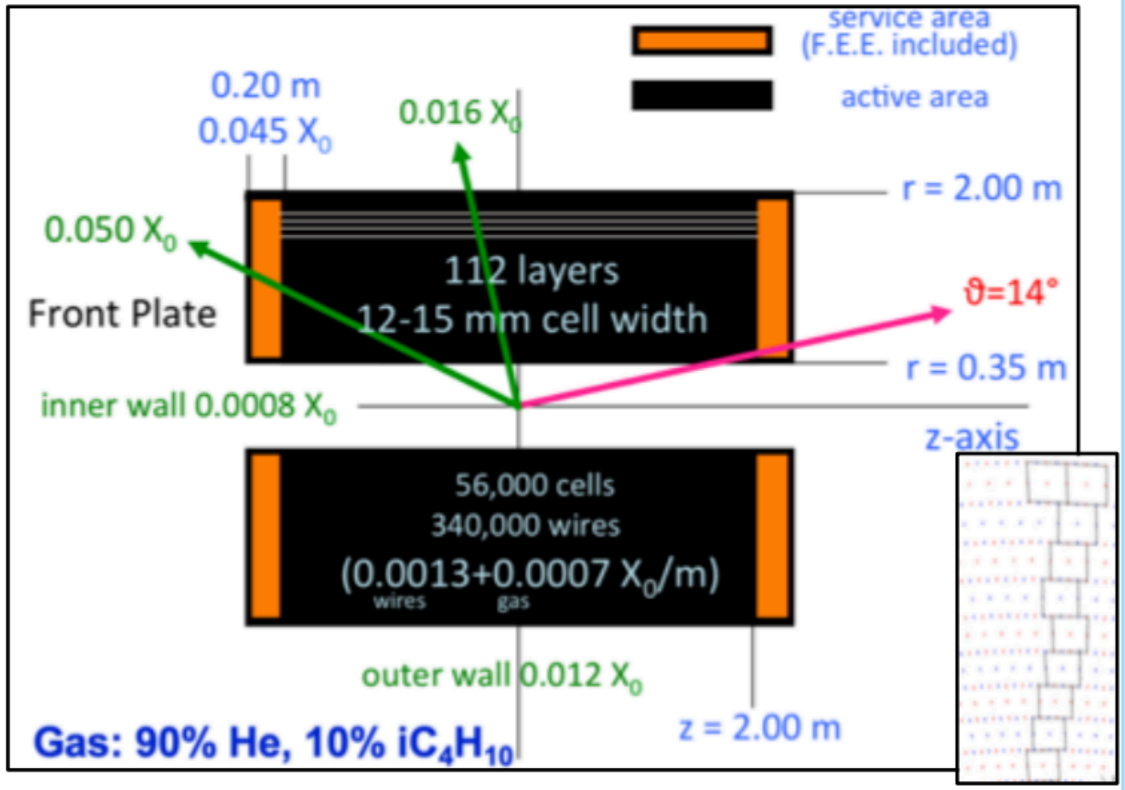
- Many conditions/requirements common between ALICE and e^+e^- colliders
  - Moderate radiation environments
  - No need for picosecond timing
  - High resolution and low multiple scattering is key
- FCC-ee detector simulation
  - Closer (■), lighter (△): Substantial improvement on impact parameter resolution in particular at low momenta



A. Ilg, L. Freitag, 6th FCC Physics Workshop

Tracking detectors

IDEA Drift Chamber



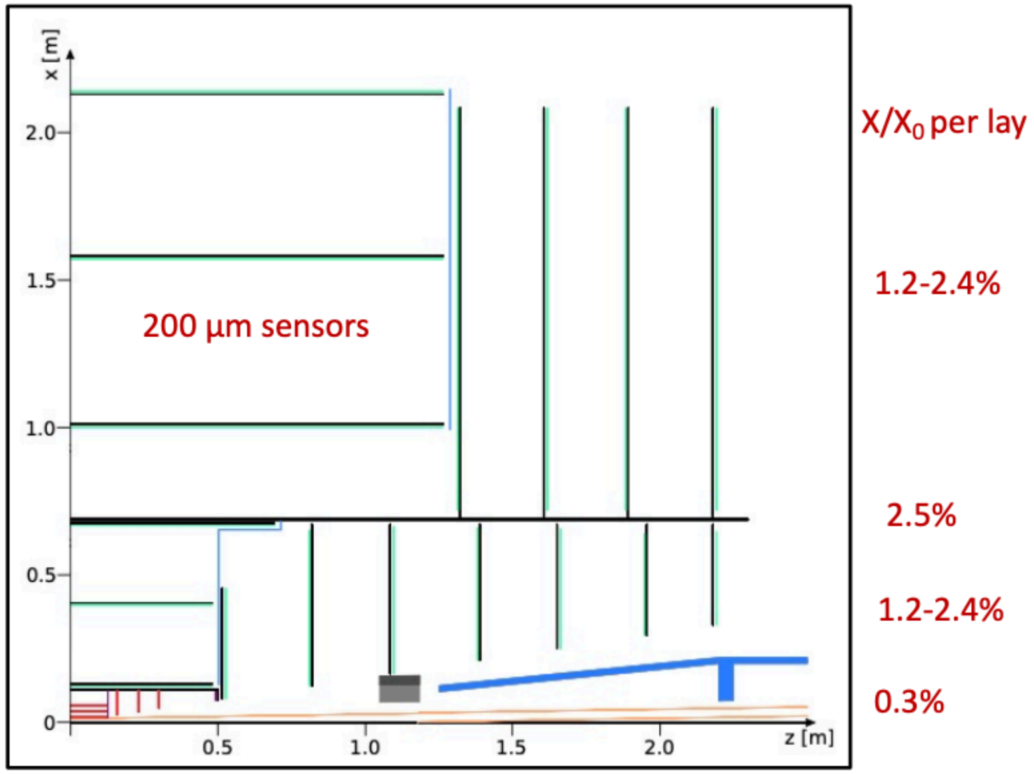
Pros:

- Very low material budget
- Proven technologi: KLOE at Daϕne
- Continous tracking; advantage for secondary vertex finding
- Particle ID via dE/dx (dN/dx) measurement

Challenges:

- Need to prove operation at ~100 kHz FCC-ee physics rate and realistic backgrounds via full simulation studies

CLD - Full Silicon tracker



Pros:

- Very precise space points
- Proven technologi, e.g. LHC detectors
- No gas system

Challenges:

- No precise Particle Identification
  - Possibly TOF
- Optimisation of sensor thickness for lower material budget
- Design of (light) cooling system for operation at continous collisions

Detector concepts

Optimised for PFA:

- Very fine resolution "Imaging Calorimeters"
  - Linear Colliders: ILD, SiD, CLICdp
  - Circular Colliders: CLD, CEPC Baseline

Example, CLD

HCAL

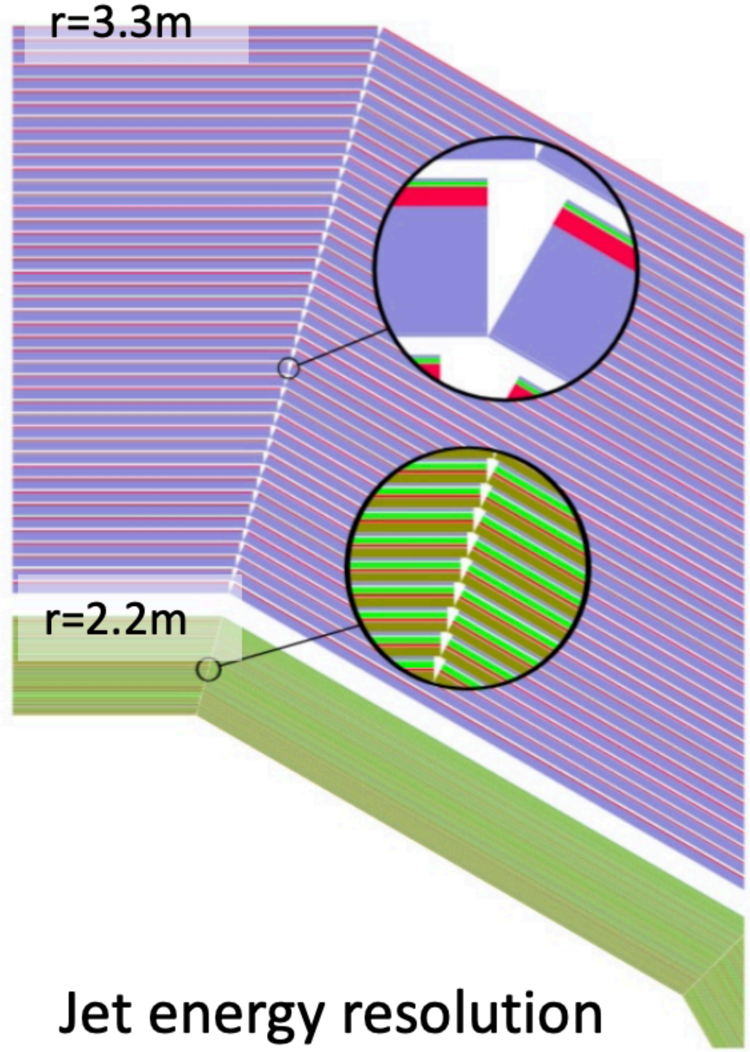
- 44 layers, 19 mm steel absorber, 5.5 (+1) λ
- 3 mm thick scintillator tiles with 3 × 3 cm^2 granularity

ECAL

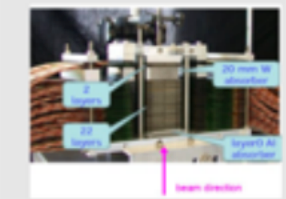
- 40 layers, 1.9 mm tungsten absorbers, 22 X_0
- 0.5 mm thick silicon sensors with 5 × 5 mm^2 granularity

$$\frac{\sigma}{E} \approx \frac{16\,\%}{\sqrt{E}}$$

- Optimisation studies ongoing



Jet energy resolution ~4% at 50 GeV

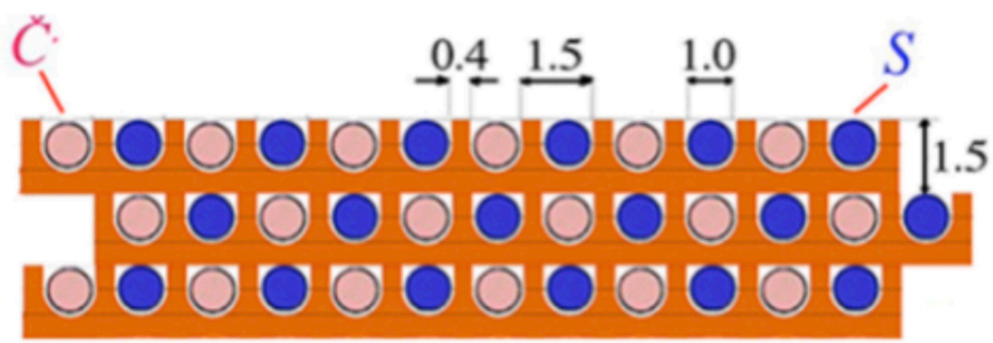
Si-W ECAL	(ALICE FoCAL)
	
0,5×0,5 cm² ×15 (→30) Si layers + W	0,003×0,003 cm² × 24 MIMOSA layers + W

[Scint-W ECAL]	AHCAL
	
0,5×4,5 cm² ×30 Scint+SiPM lay. + SS	3×3 cm² × 38 Scint+SiPM lay. + SS

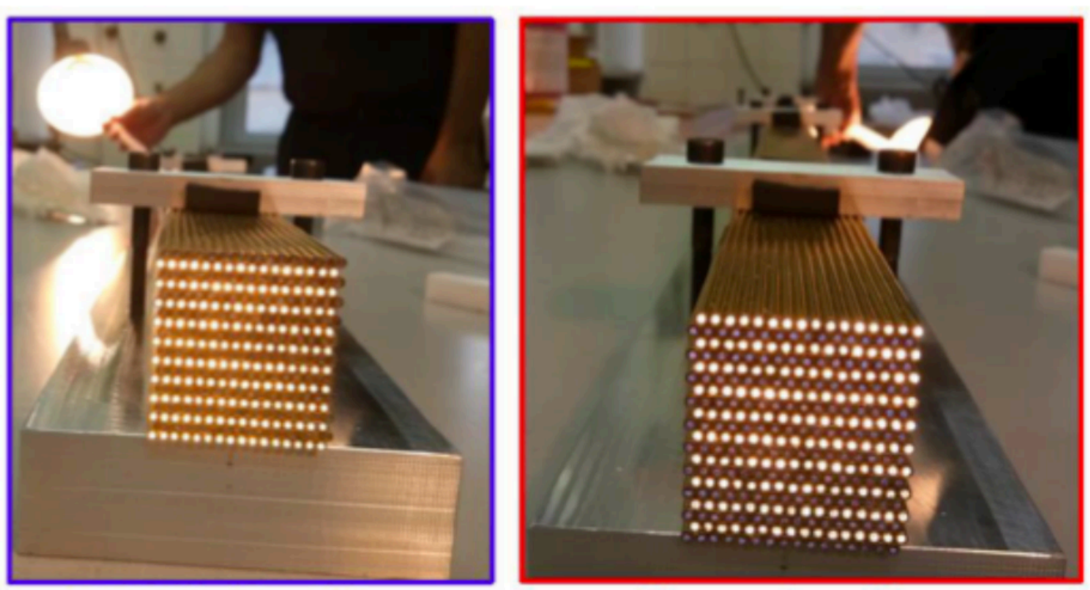
SDHCAL

1×1 cm² × 48 layers GRPC + SS

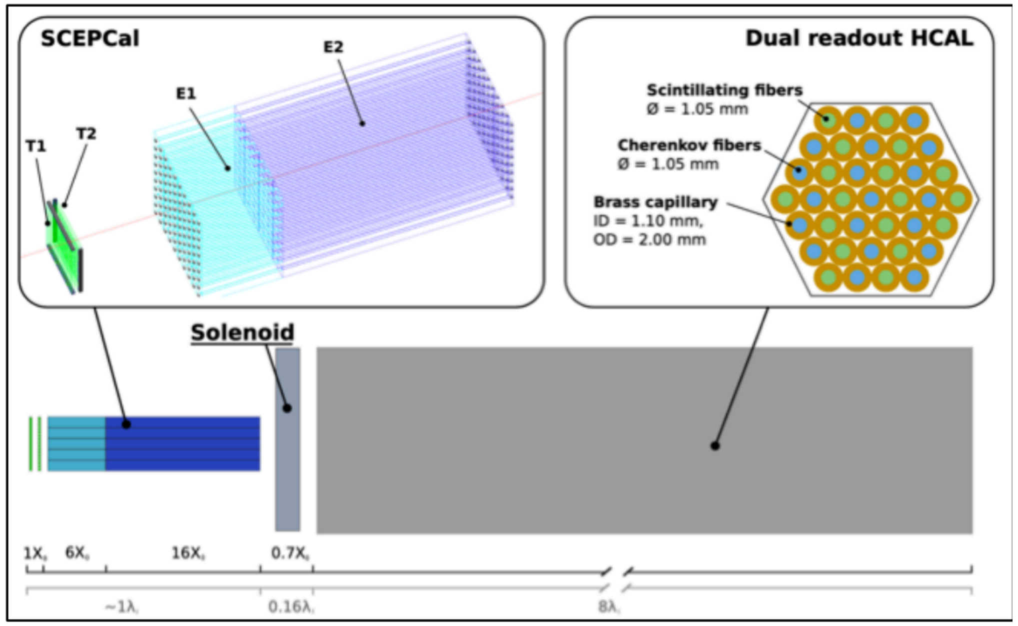
Detector concepts (Dual Readout calorimeters)



- Measure simultaneously:
  - Scintillation signal (*S*)
  - Cherenkov signal (*C*) (mainly from $e^{+/-}$)
- Calibrate both signals with e^-
- Unfold event-by-event using *C* and *S* signals to obtain energy corrected for non-compensation ($h/e < 1$)



Scintillation fibers Cherenkov fibers



crystal option

Full GEANT4 simulation:

Single hadron

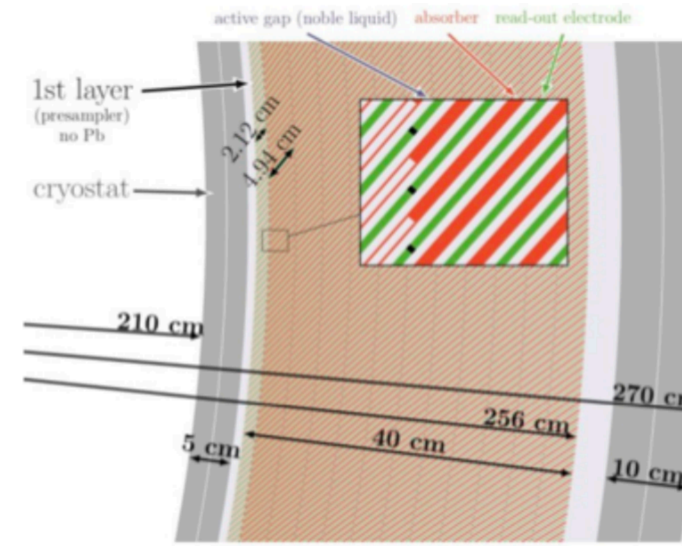
$$\frac{\sigma}{E} = \frac{31\%}{\sqrt{E}} + 0.4\%$$

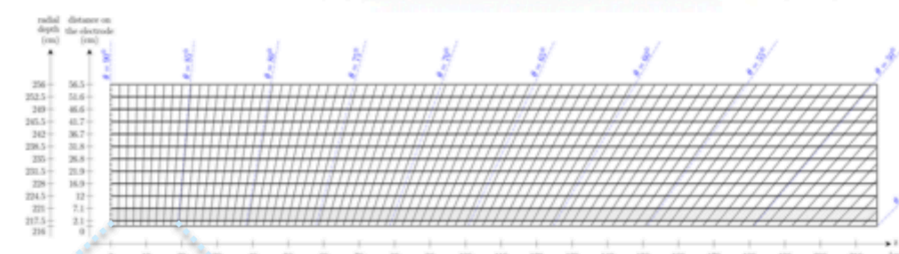
Electromagnetic

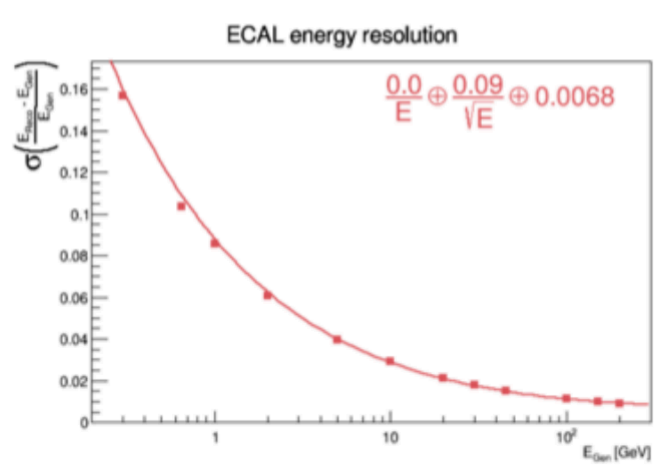
$$\frac{\sigma}{E} = \frac{13.0\%}{\sqrt{E}} + 0.2\%$$

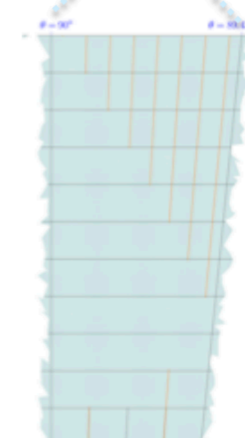
Detector concepts (LAr calorimetry)

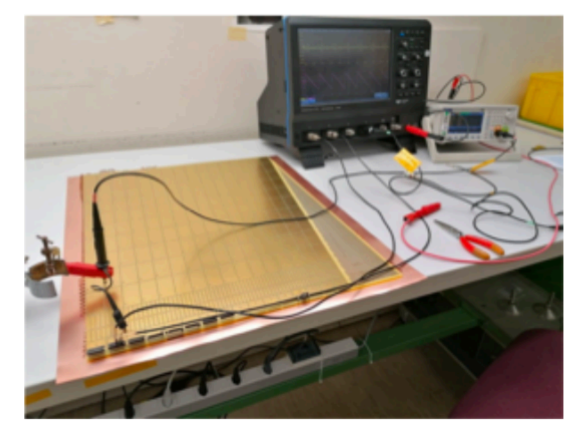
- Good experience with noble liquid ECALs in a number of experiments, e.g. DØ, H1, NA48/62, ATLAS
  - Good energy resolution, $\sigma_{EM} \sim 10\%/\sqrt{E}$
  - Linearity, uniformity, stability of response
    - Low systematics
- Baseline design for FCC-ee detector
  - 1536 straight inclined (50.4°) 1.8mm Pb absorber plates, 22 X_0
  - Multi-layer PCBs as readout electrodes. Segmentation:
    - 11 longitudinal compartments
    - $\Delta\theta$ = 10 (2.5) mrad for regular (1st comp. strip) cells,
    - $\Delta\phi$ = 8 mrad
  - Implemented in FCC-SW Fullsim
    - $\sigma_{EM} \sim 9\%/\sqrt{E}$
  - Definition of end-cap geometry ongoing
  - ECAL shares cryostat with coil (as in ATLAS)
    - Coil outside ECAL
  - Possible options, R&D ongoing
    - LKr or Lar actives; W or Pb absorber
    - Al or carbon fibre cryostat
    - Warm or cold electronics





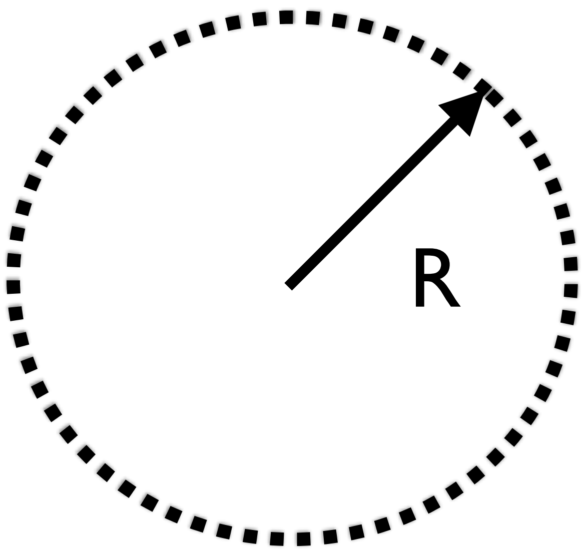






Possible future colliders: pp

$$p[\,\text{TeV}/c\,] = 0.3\, B[\,\text{T}\,]\, R[\,\text{km}\,]$$



Pros:

- high center of mass, not limited by synchrotron radiation ~ $(m_e/m_p)^4$
- high luminosity → high rates
- large cross-sections for strong production

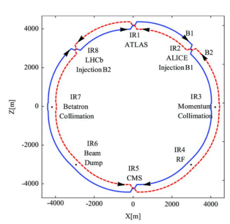
Cons:

- large backgrounds QCD ($\alpha_S \sim 10\ \alpha_{EM}$)
- collide partons (not all ECM available)
- pile-up (due to high lumi)

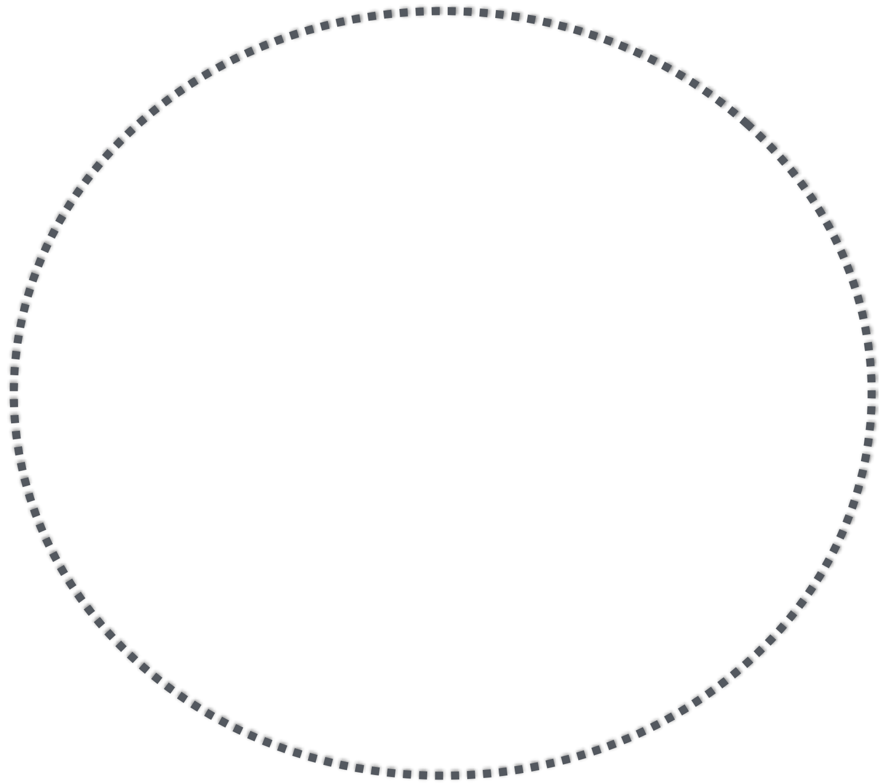
For fixed size, limited only by field strength B

- Discovery machines for heavy new states
- Thanks to high rates, well suited for precision

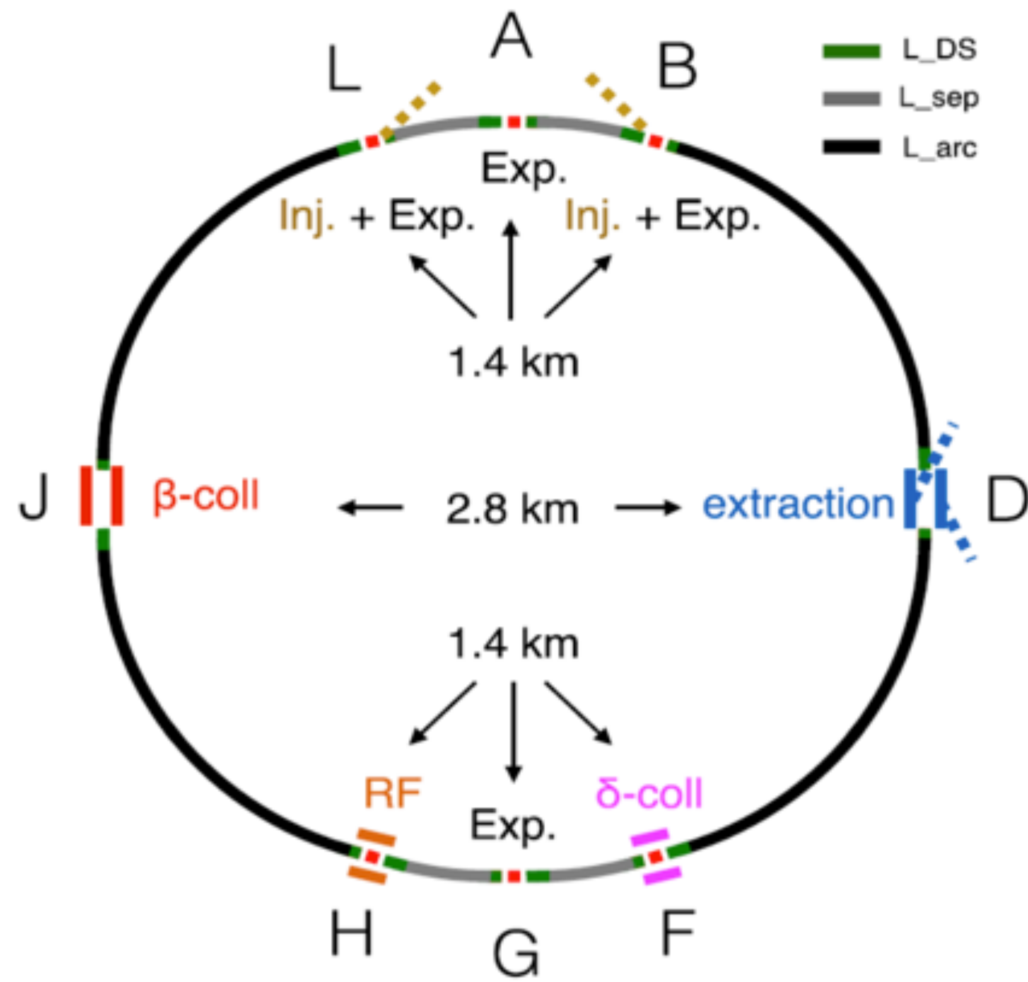
High energy hadron machines



HE-LHC



LE-FCC



FCC-hh

sqrt(s)	27 TeV
Lumi	15 ab^{-1}
B	16 T
circ.	27 km

sqrt(s)	37 TeV
Lumi	15 ab^{-1}
B	6 T
circ.	100 km

sqrt(s)	100 TeV
Lumi	30 ab^{-1}
B	16 T
circ.	100 km

A 100 TeV proton-proton collider

Explore the energy frontier:

- Can directly produce heavy resonances up to 50 TeV
- Can completely exclude a class of WIMP dark matter candidates that are not accessible at the LHC (EWK doublets-triplets)

Measure SM to unprecedented precision:

- **Gives direct and indirect handles on the Higgs potential and the electro-weak phase transition EWPT**
- Produces 10^{10} Higgs bosons, giving access to percent level precision on most couplings (including rare decay channels)
- Probe the SM in a completely new dynamical regime (where EW symmetry is restored)

Precision vs. sensitivity

- We often talk about "**precise**" SM measurements. What we actually aim at is "**sensitive**" tests of the Standard Model, where *sensitive* refers to the ability to reveal BSM behaviours.

- **Sensitivity** may not require extreme precision. Going after "sensitivity", rather than *just* precision, opens itself new opportunities .

- For example, in the context of dim. 6 operators in EFT, some operators grow with energy:

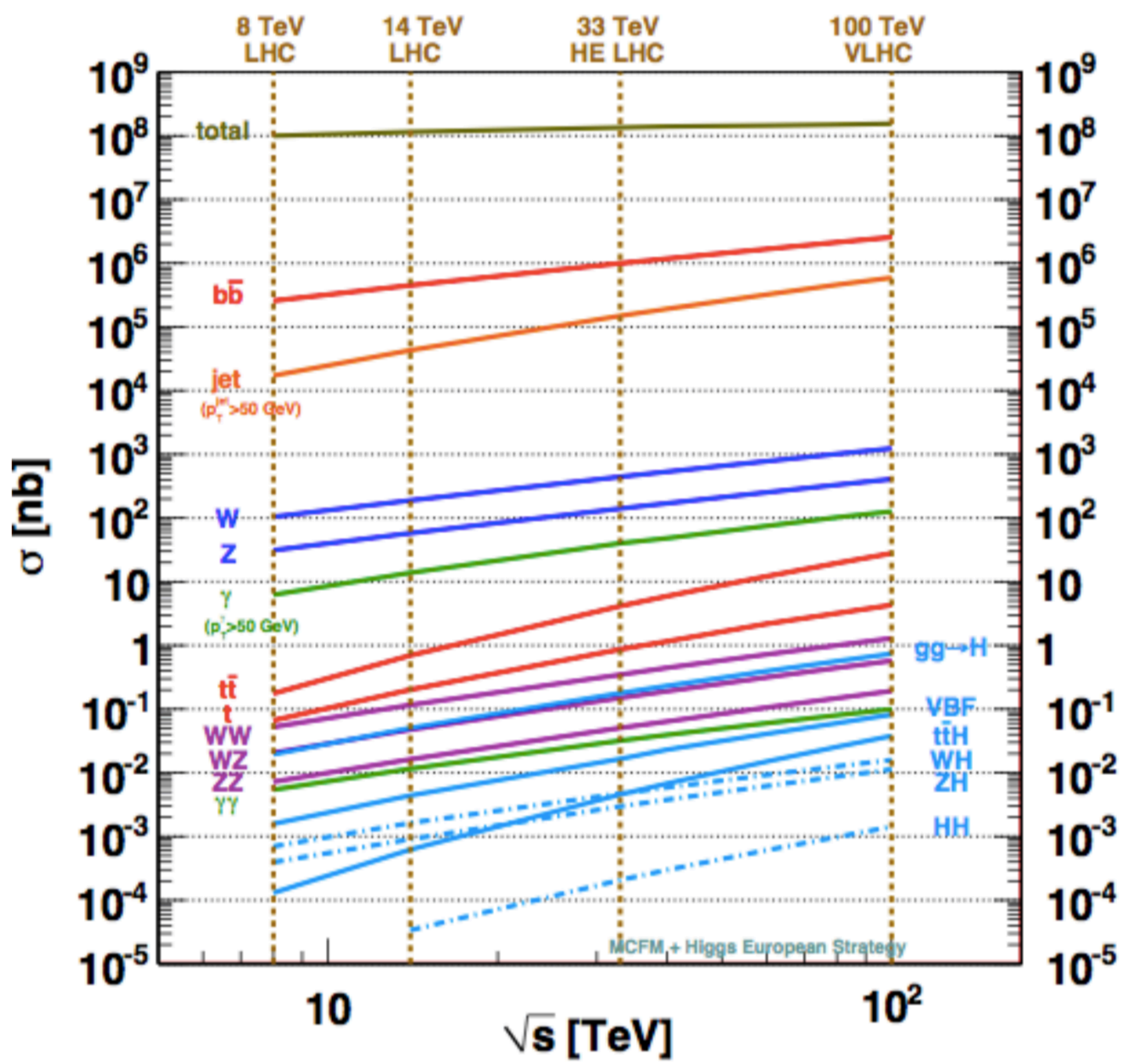
BR measurement: $\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2$ ⇒ **precision** probes large Λ

e.g. δO=1% ⇒ Λ ~ 2.5 TeV

$\sigma(p_T > X)$: $\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$ ⇒ **kinematic reach** probes large Λ

e.g. δO=15% at Q=1 TeV ⇒ Λ~2.5 TeV

(SM) Physics processes @high energy



- Total pp cross-section and Minimum bias multiplicity show a modest increase from 14 TeV to 100 TeV

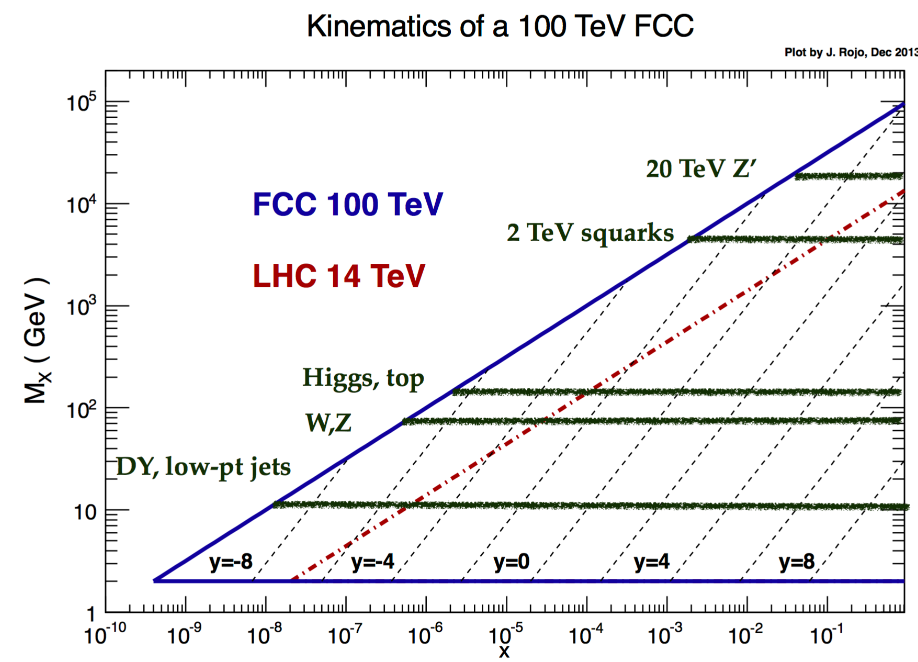
→ Levels of pile-up will scale basically as the instantaneous luminosity.

- *Inclusive cross-section* for relevant processes (single and HH) show a significant increase.
  - x 20-50 increase

→ interesting physics sticks out more !

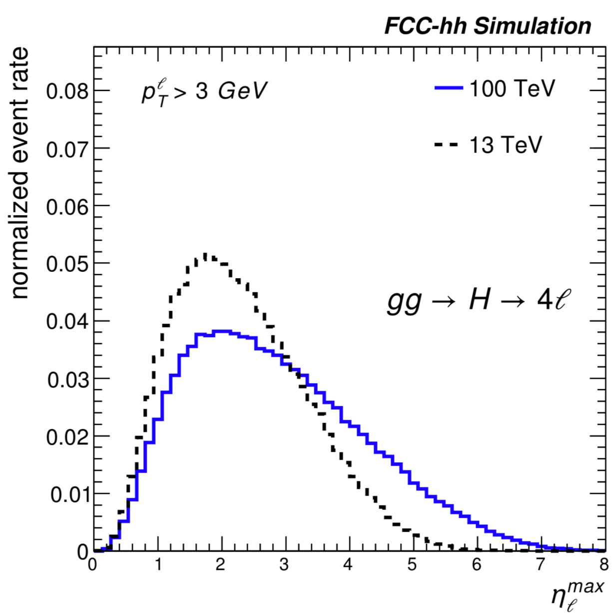
Higgs @threshold

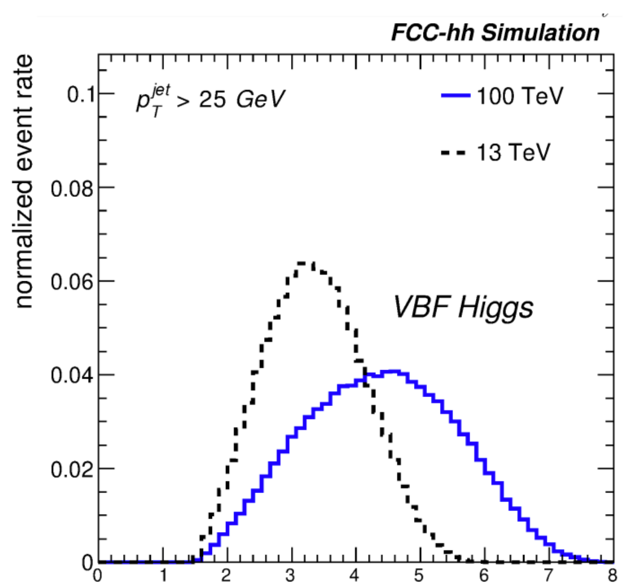
$x_{min} \sim M^2 / s$

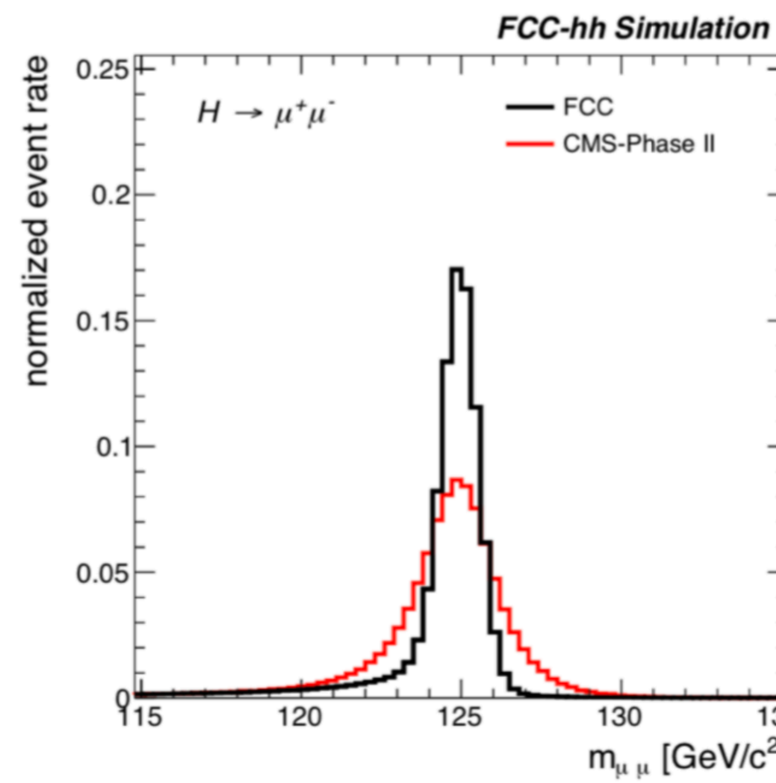


SM Physics produced at threshold is more forward @100TeV

→ in order to maintain sensitivity need **large rapidity** (with tracking) and **low p_T** coverage



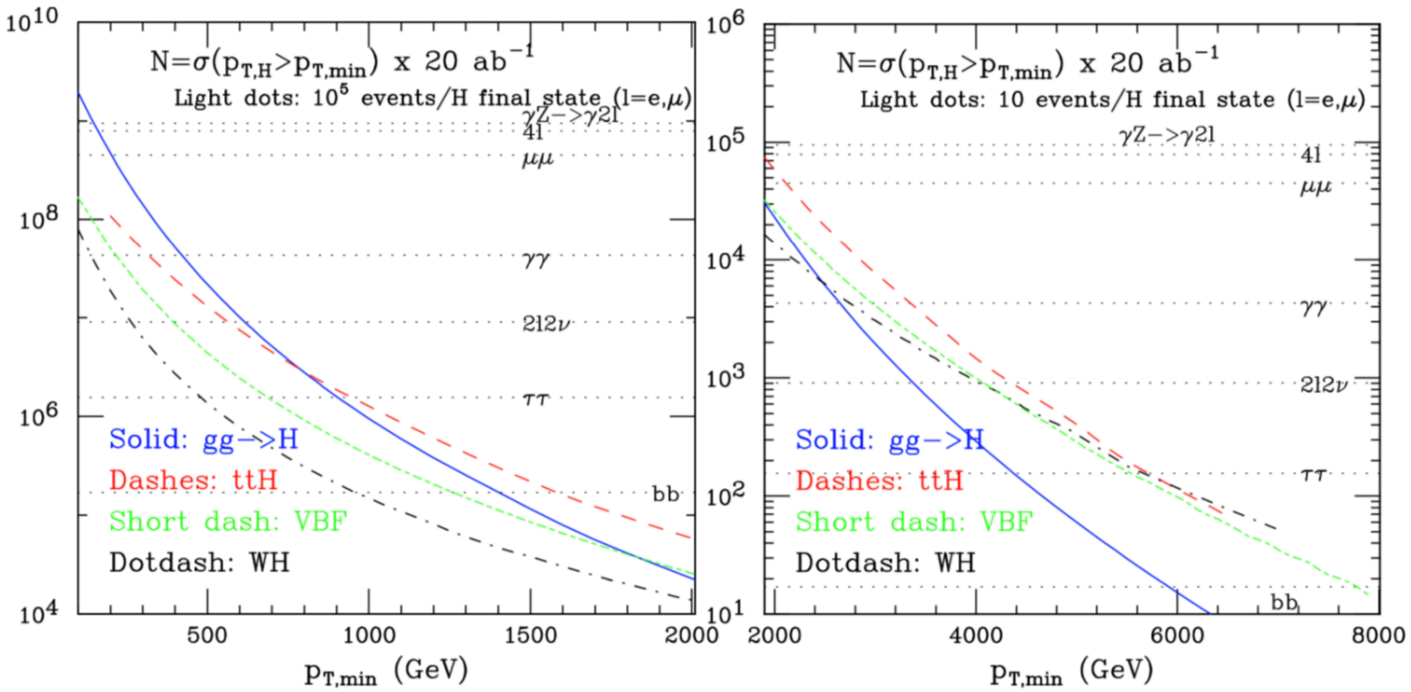




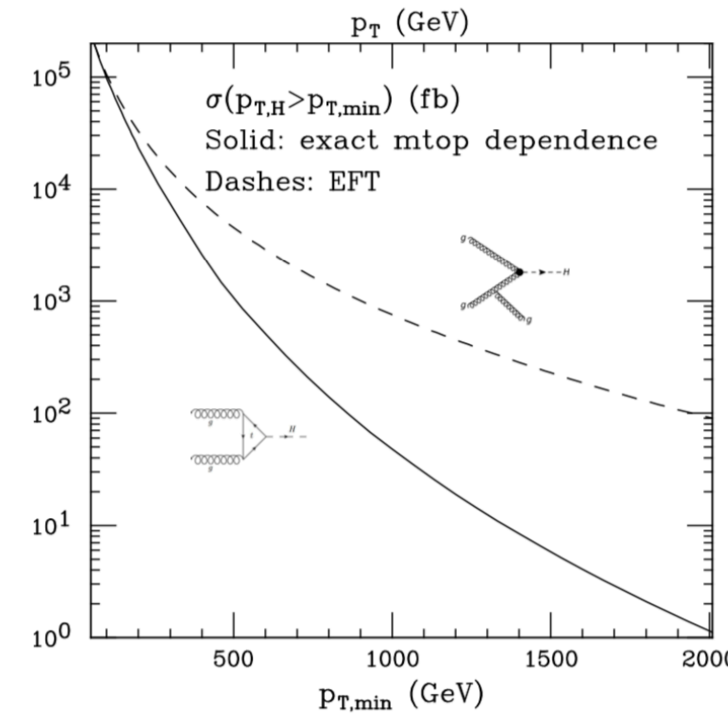
low p_T muons → resolution dominated by MS

- Goals:
  - **Precision spectroscopy** and calorimetry up to **|η| < 4**
  - Tracking and calorimetry up to |η| < 6

Higgs at large p_T



$N(p_T > p_{T,min})$

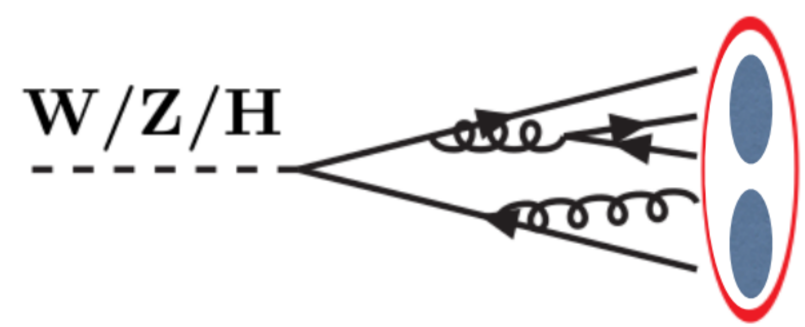


Huge rates at large p_T :

- **> 10^6 Higgs** produced with p_T > 1 TeV
- Higher probability to produce large p_T Higgs from ttH/VBF/VH at large
- Even rare decay modes can be accessed at large p_T

Opportunity to measure the Higgs **in a new dynamical regime**

- Higgs p_T spectrum highly sensitive to new physics.



$\Delta R = 0.1$

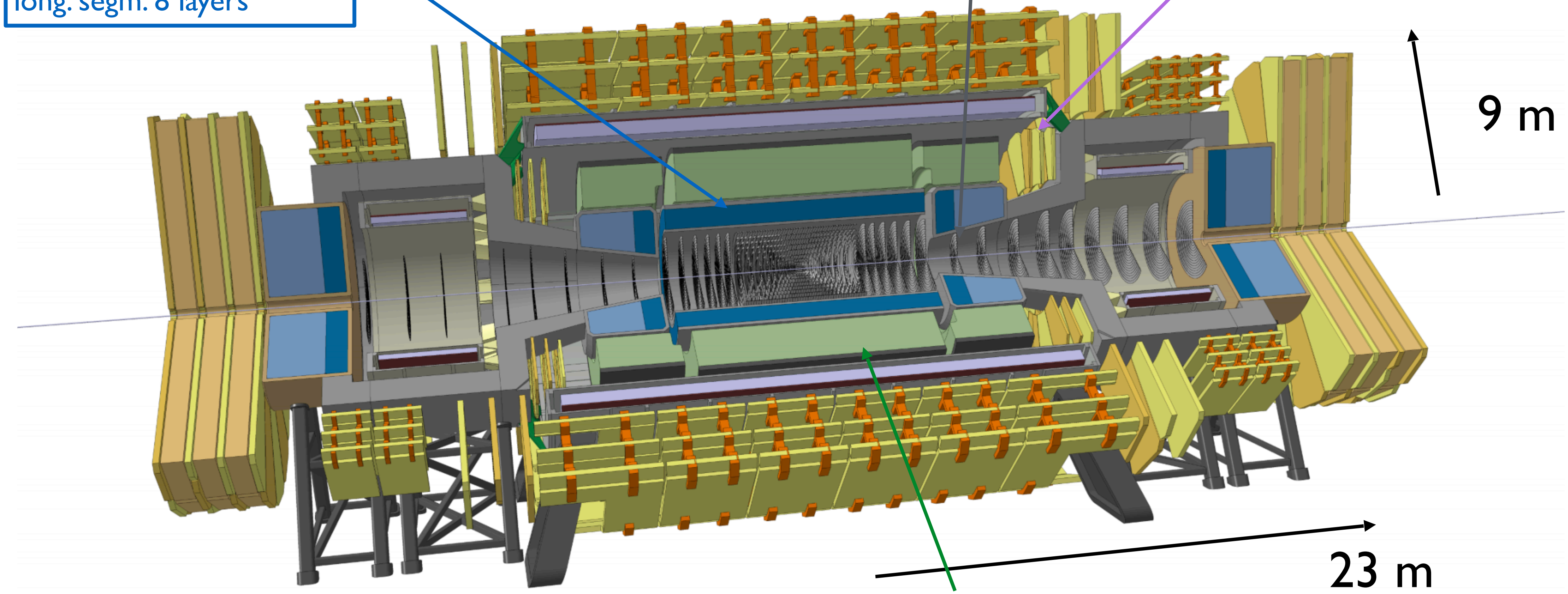
- highly granular sub-detectors:
  - Tracker - pixel:10 μm @ 2cm → $\sigma_{\eta x \phi} \approx$ 5 mrad
  - Calorimeters: 2 cm @ 2m → $\sigma_{\eta x \phi} \approx$ 10 mrad
- good energy/p_T resolution at large p_T:
  - σ_p / p = 2% @ 1 TeV

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

Central Magnet +
Fwd solenoids



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

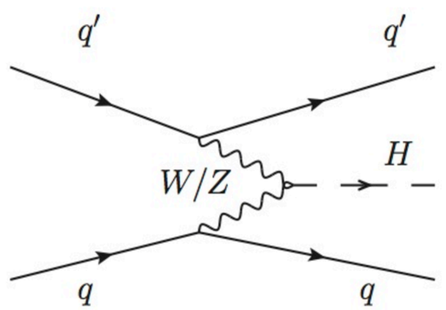
Fwd HCAL: LAr/Cu
$\sigma_E/E \sim 100\%/\sqrt{E} \oplus 10\ \%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.05$
long. segm: 6 layers

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

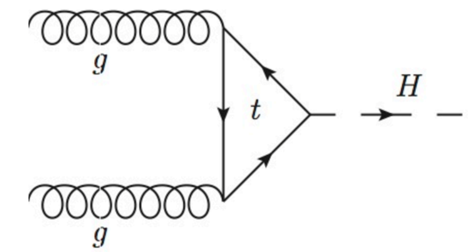
Higgs physics at future hadron colliders

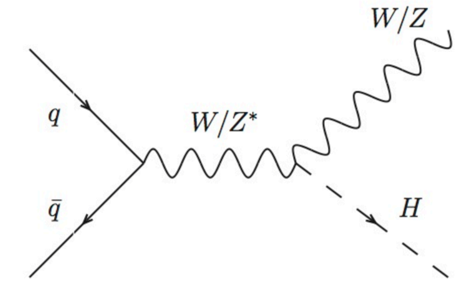
- Large Higgs production rates:
  - access (very) rare decay modes (eg. 2nd gen,), complementary to ee colliders
  - push to %-level Higgs self-coupling measurement
- Large dynamic range for H production (in p_T^H, m(H+X) , …):
  - new opportunities for reduction of syst. uncertainties (TH and EXP)
  - develop indirect sensitivity to BSM effects at large Q^2 , complementary to that emerging from precision studies (*e.g. decay BRs*) at $Q \sim m_H$
- High energy reach:
  - direct probes of BSM extensions of Higgs sector (e.g. SUSY)
  - Higgs decays of heavy resonances
  - Higgs probes of the nature of EW phase transition (strong 1st order? crossover?)

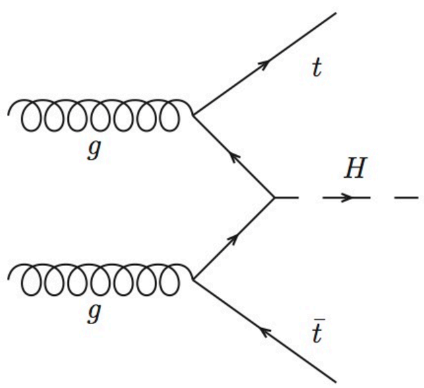
Single Higgs production @FCC-hh



	σ(13 TeV)	σ(100 TeV)	σ(100)/σ(13)
ggH (N^3LO)	49 pb	803 pb	16
VBF (N^2LO)	3.8 pb	69 pb	16
VH (N^2LO)	2.3 pb	27 pb	11
ttH (N^2LO)	0.5 pb	34 pb	55







	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

$N_{100} = \sigma_{100\,\text{TeV}} \times 20\ \text{ab}^{-1}$

$N_8 = \sigma_{8\,\text{TeV}} \times 20\ \text{fb}^{-1}$

$N_{14} = \sigma_{14\,\text{TeV}} \times 3\ \text{ab}^{-1}$

Factor: 1/100 1/10

reduction in stat. unc.

Large statistics in various Higgs decay modes allow:

- for **% - level precision in statistically limited** rare channels (μμ, Zɣ)
- in **systematics limited** channels, to isolate **cleaner samples** in regions (e.g. @large Higgs p_T) with :
  - higher S/B
  - smaller (relative) impact of systematic uncertainties

MLM, D. Jamin, C. Helsens, G. Ortona, MS

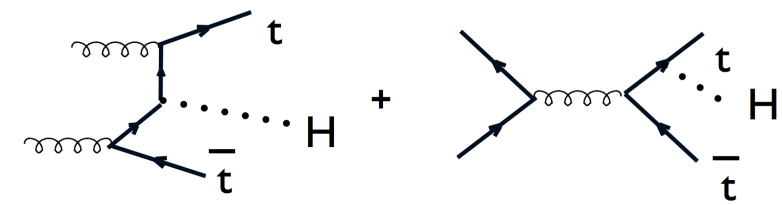
Top Yukawa (production)

- production ratio **σ(ttH)/σ(ttZ)** ≈ $y_t^2\ y_b^2 /\ g_{ttZ}{}^2$
- measure **σ(ttH)/σ(ttZ)** in **H/Z→bb** mode in the boosted regime, in the **semi-leptonic** channel
- perform **simultaneous fit of double Z and H peak**
- (lumi, scales, pdfs, efficiency) **uncertainties cancel out** in ratio

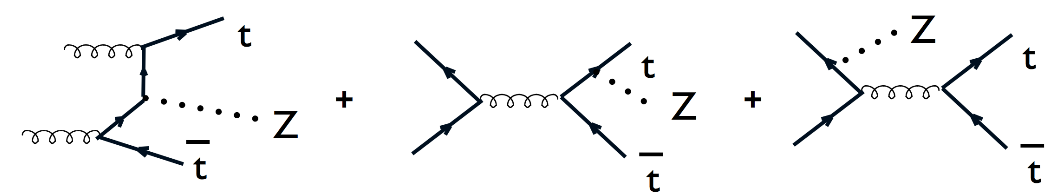
- assuming g_{ttZ} and κ_b known to 1% (from FCC-ee),

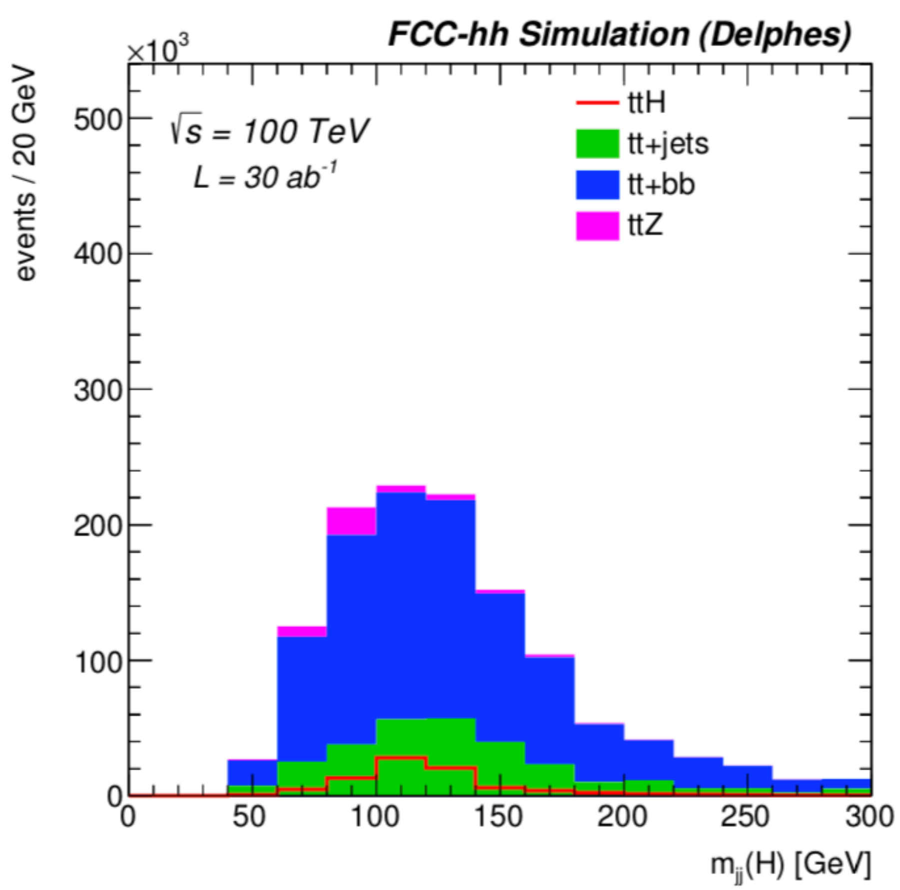
  → measure y_t to 1%

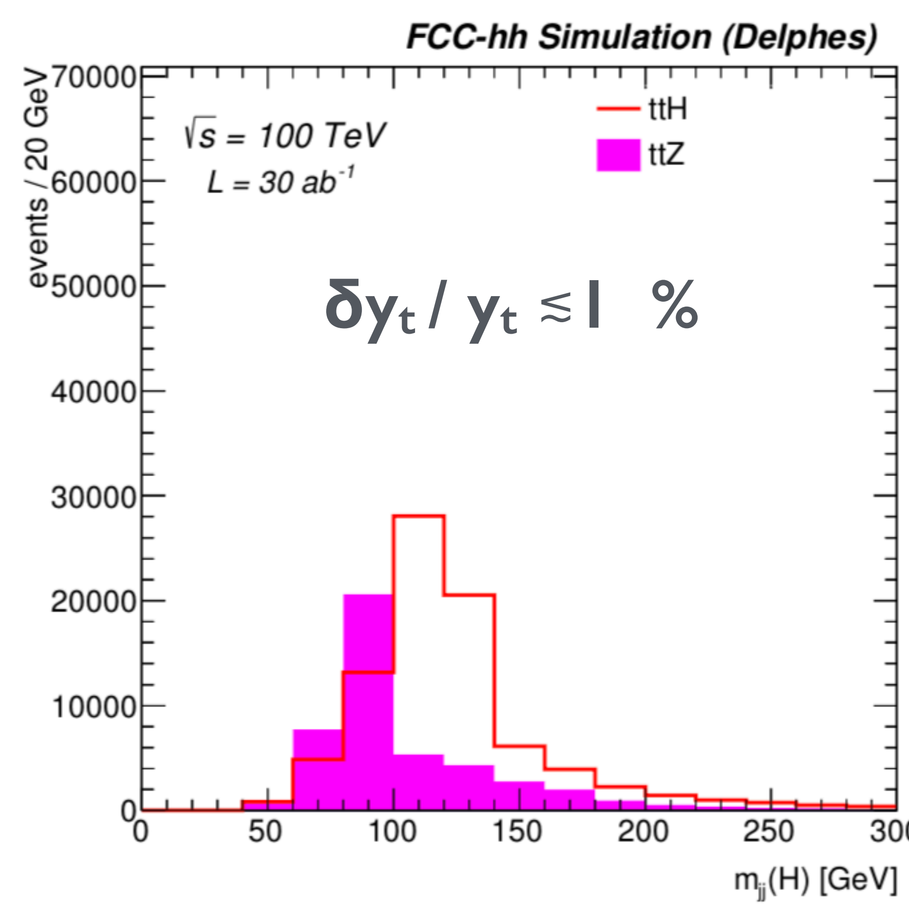
ttH



ttZ







Higgs decays: γγ - ZZ - Zγ - μμ

- **1% systematics on (production x luminosity)**, meant as a reference target. Assumes good theoretical progress over the next years, and **reduction of PDF+α_S uncertainties with HL-LHC + FCC-ee**.

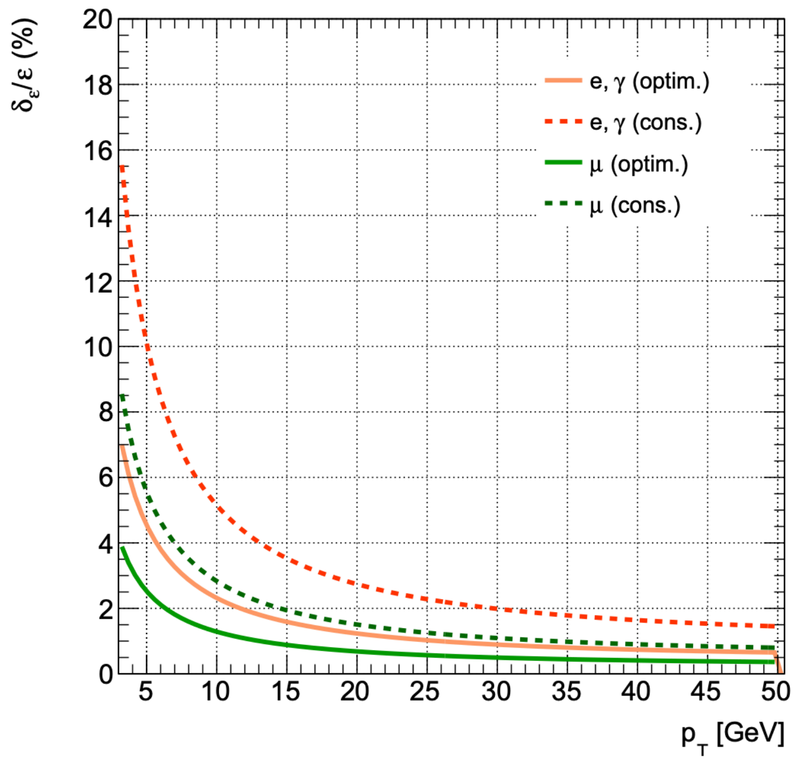
- **e/μ/γ efficiency systematics** (shown on the right). In situ calibration, with the immense available statistics in possibly new clean channels ($Z \rightarrow \mu\mu\gamma$), will most likely reduce the uncertainties.

- All final states considered here rely on **reconstruction of m_H** to within few GeV.
  - **backgrounds** (physics and instrumental) to be **determined with great precision from sidebands** (~ infinite statistics)

  - **Impact of pile-up**: hard to estimate with today's analyses.
    → **Focus on high-p_T objects** will help to decrease relative impact of pile-up

  - Following **scenarios** are considered:

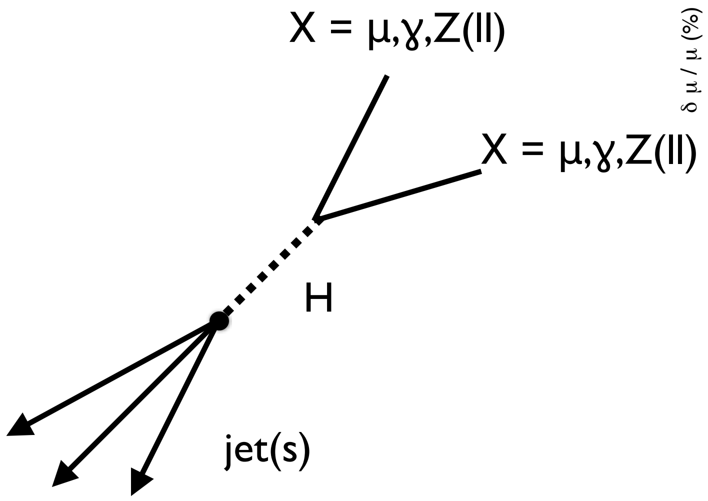
    - δ_{stat} → stat. only (I) (signal + bkg)
    - δ_{stat} , δ_{eff} → stat. + syst. (II)
    - δ_{stat} , δ_{eff} , δ_{prod} = 1% → stat. + syst. + prod (III)

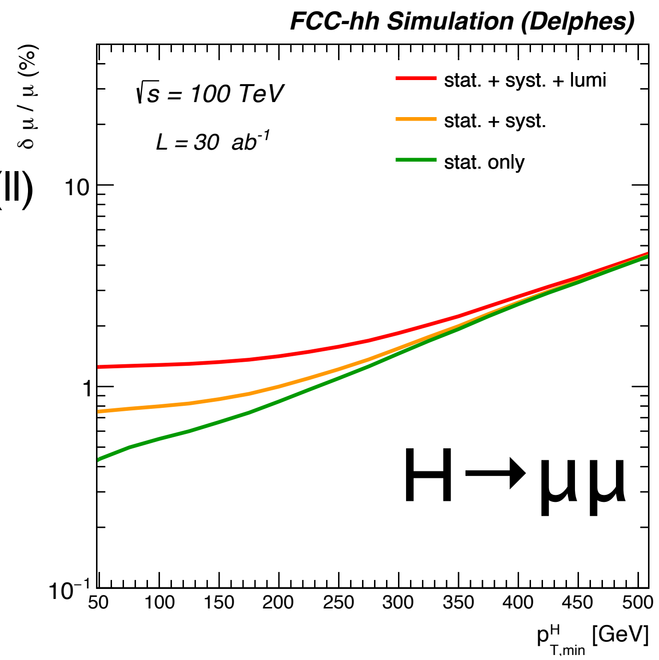


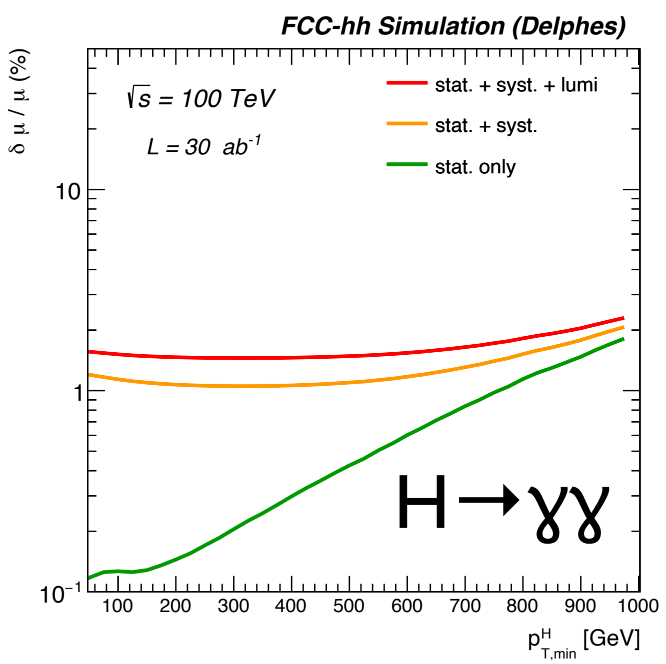
Higgs decays (signal strenth)

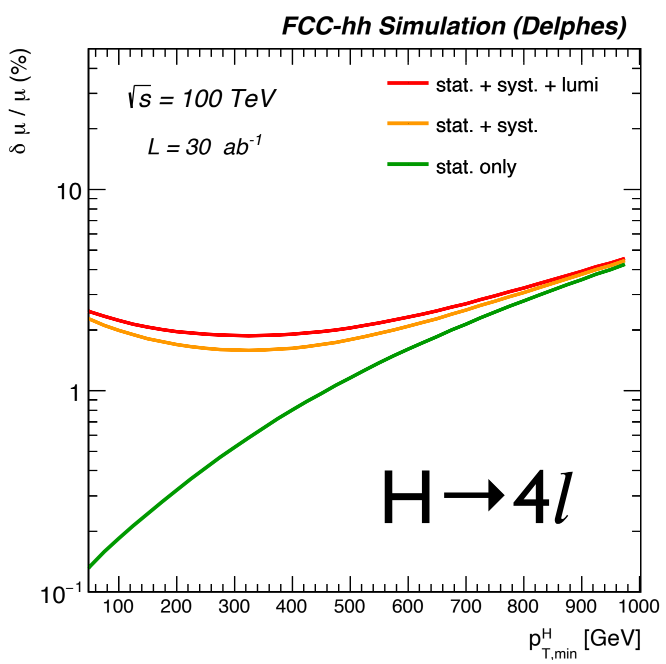
- 1% lumi + theory uncertainty
- p_T dependent object efficiency:
  - $\delta\varepsilon(e/\gamma)$ = 0.5 (1)% at $p_T \to \infty$
  - $\delta\varepsilon(\mu)$ = 0.25 (0.5)% at $p_T \to \infty$

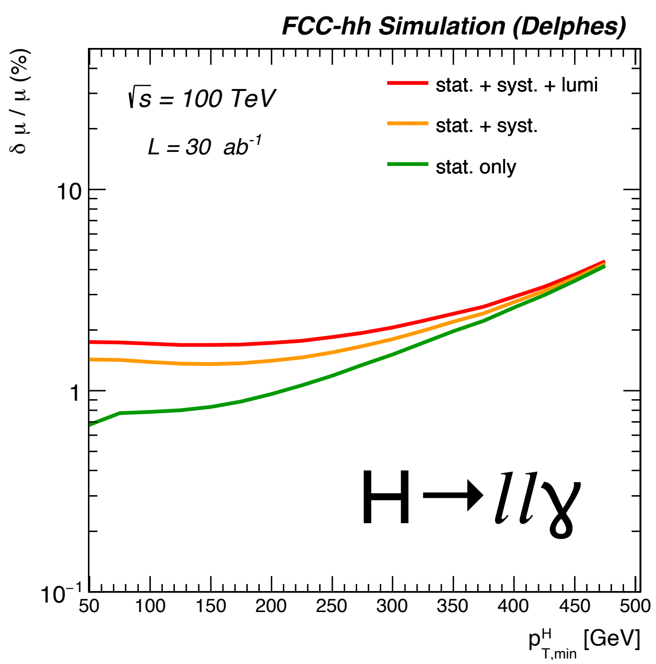
- study sensitivity as a function of **minimum p_T(H)** requirement in the **γγ, ZZ(4l), μμ and Z(ll)γ** channels
- **low** p_T(H): **large statistics** and **high syst**. unc.
- **large** p_T(H): **small statistics** and **small syst**. unc.
- **O(1-2%) precision on BR** achievable up to very high p_T (means 0.5-1% on the couplings)







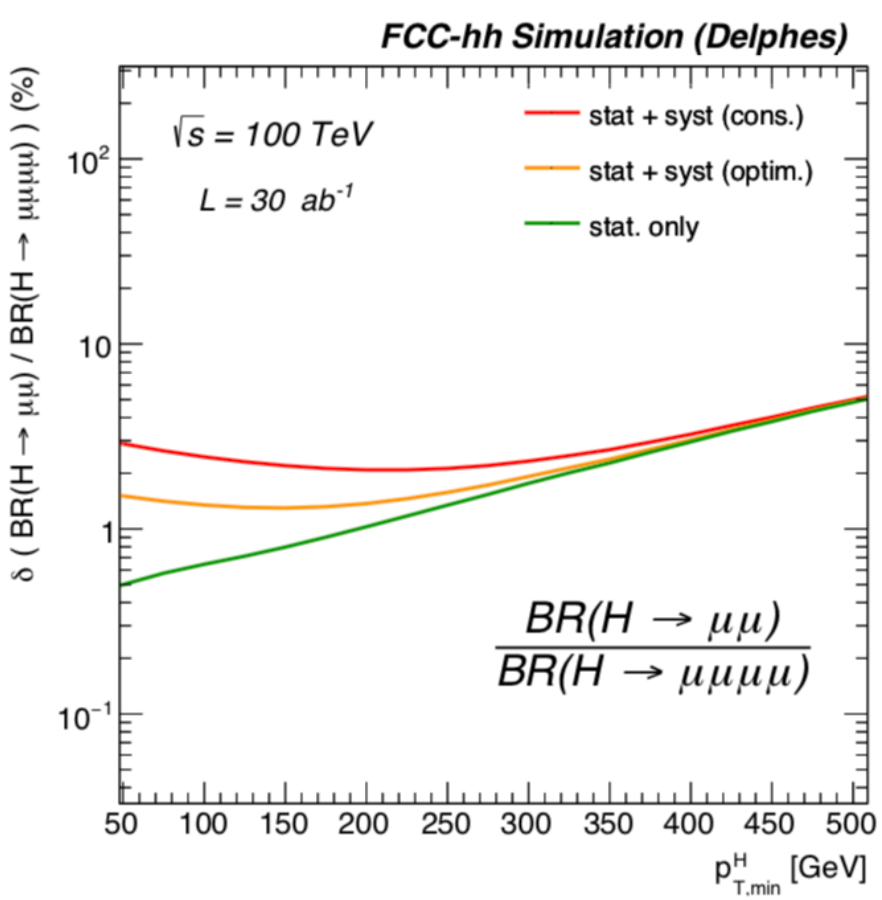


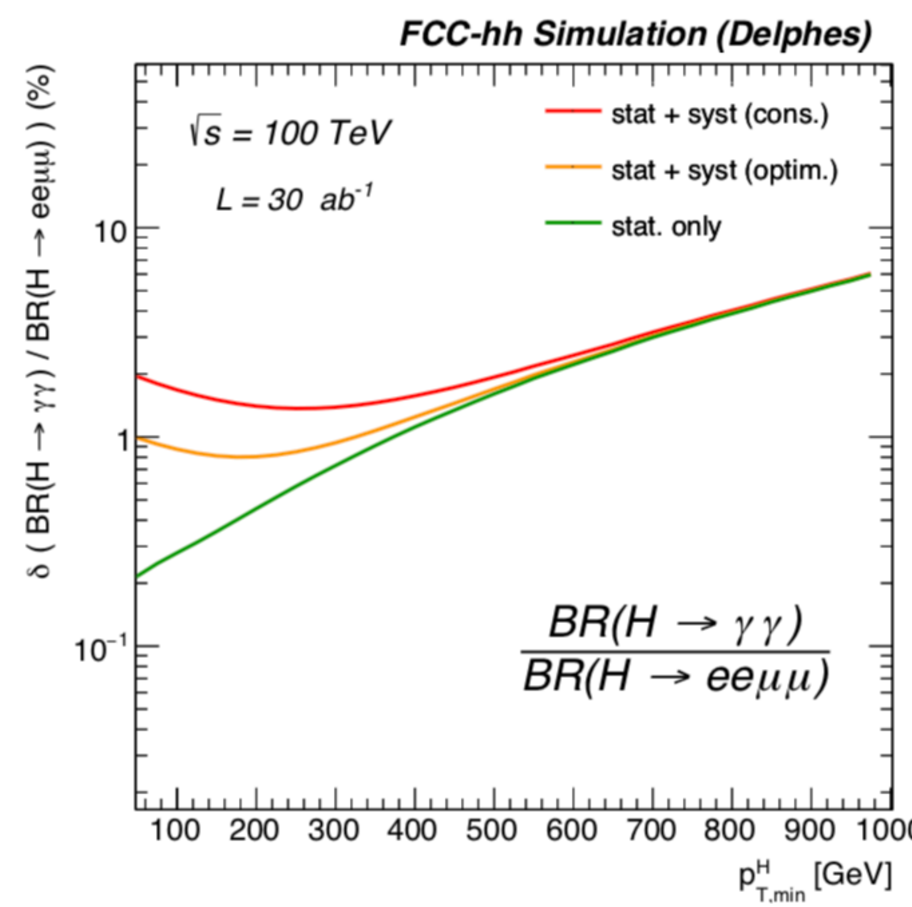


Ratios of BR(H→XX) / BR(H→ZZ)

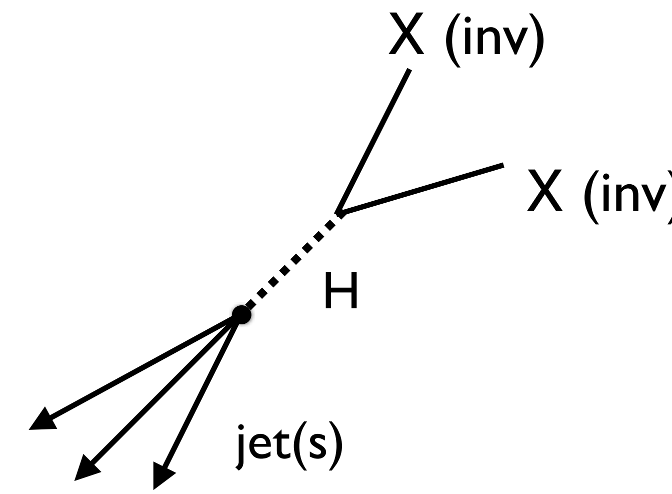
MLM, MS

- measure **ratios of BRs** to cancel correlated sources of systematics:
  - luminosity
  - object efficiencies
  - production cross-section (theory)
- Becomes **absolute precision** measurement in particular if combined with **H→ZZ** measurement from e^+e^- (at 0.2%)

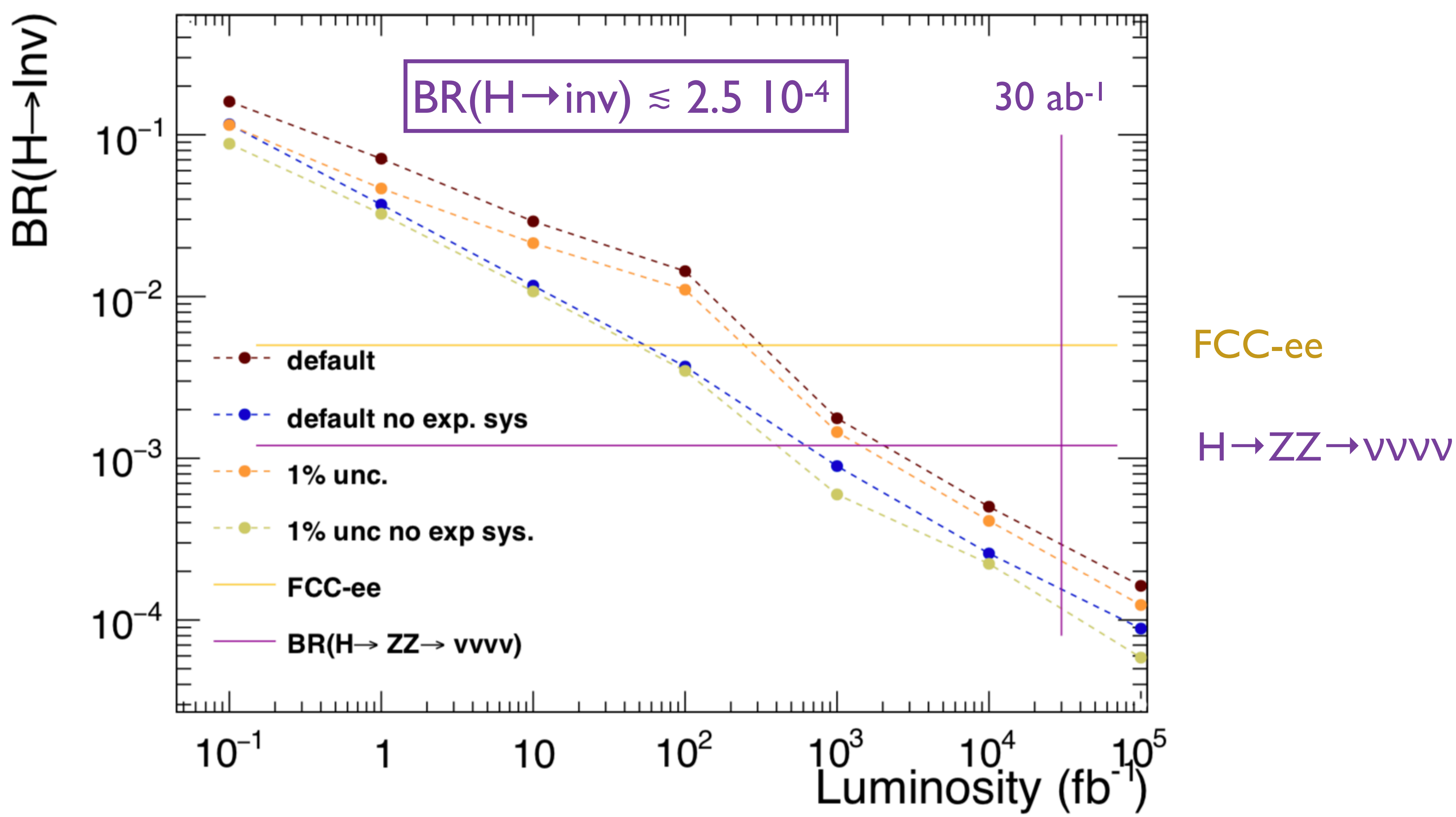




H→invisible

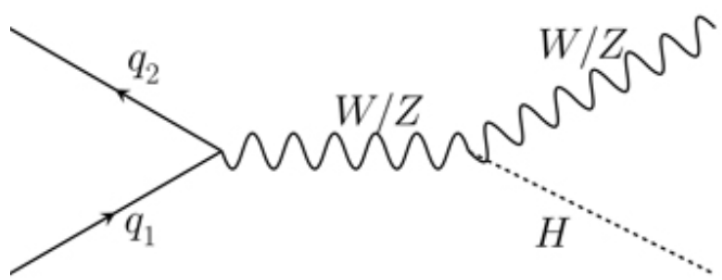


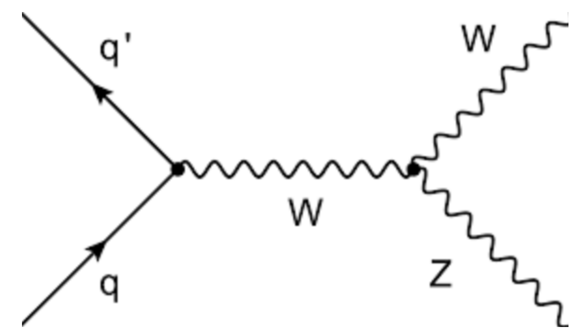
- Measure it from H + X at **large p_T(H)**
- Fit the $\mathbf{E_T^{miss}}$ spectrum
- Constrain background p_T spectrum from **Z→νν** to the % level using NNLO QCD/EW to relate to measured Z,W and γ spectra (low stat)
- Estimate Z→νν (W→lν) from Z→ee/μμ (W→lν) control regions (high stat).



Standalone 100 TeV Higgs measurements

- Following the principle of **reducing** as much as possible **the impact of systematics** assumptions on future measurements, additional **ratio measurements**:





$\sigma(WH[\to\gamma\gamma]) / \sigma(WZ[\to e^+e^-])$ → $G_W = g^2_{HWW} \times BR(H \to \gamma\gamma)$

$\sigma(WH[\to\tau\tau]) / \sigma(WZ[\to\tau\tau])$ → $G_\tau = g^2_{HWW} \times BR(H \to \tau\tau)$

$\sigma(WH[\to bb]) / \sigma(WZ[\to bb])$ → $G_b = g^2_{HWW} \times BR(H \to bb)$

parton level study

p_T^{min} (GeV)	W[e]Z[e] (pb)	W[e]H (pb)	W[ℓ]Z[e] $\times$ L	W[ℓ]H[$\gamma\gamma$] $\times$ L	$\delta R/R$
100	2.1E-2	1.0E-1	1.3E6	1.4E4	8.5E−3
150	1.0E-2	6.3E-2	6.0E5	8.7E3	1.1E−2
200	5.6E-3	3.8E-2	3.4E5	5.2E3	1.4E−2
300	2.1E-3	1.6E-2	1.3E5	2.2E3	2.1E−2

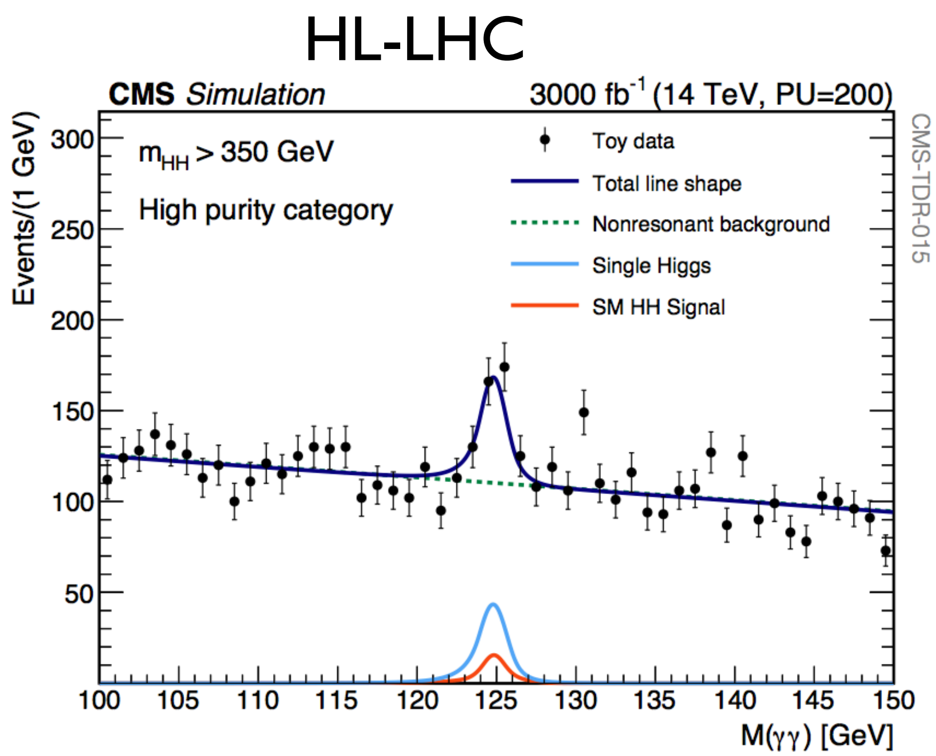
p_T^{min} (GeV)	W[e]Z[τ] (pb)	W[e]H (pb)	W[ℓ]Z[τ] $\times\varepsilon_\tau$ L	W[ℓ]H[$\tau\tau$] $\times\varepsilon_\tau$ L	$\delta R/R$
100	2.1E-2	1.0E-1	1.3E5	3.8E4	5.9E−3
150	1.0E-2	6.3E-2	6.0E4	2.4E4	7.7E−3
200	5.6E-3	3.8E-2	3.4E4	1.4E4	1.0E−2
300	2.1E-3	1.6E-2			
400	9.8E-4	7.9E-3			

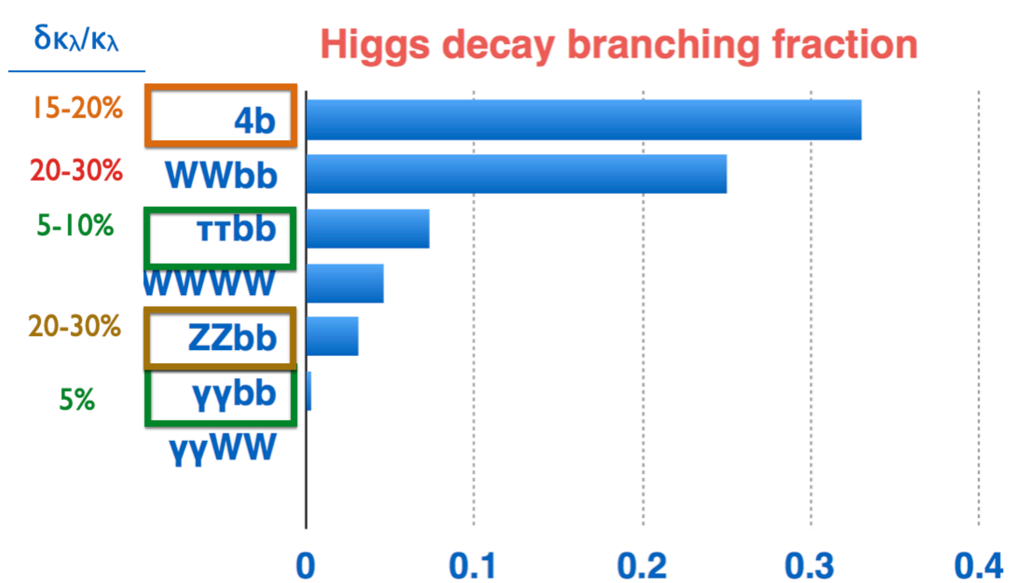
δG/G < 1%

p_T^{min} (GeV)	W[e]+bb (pb) $m[bb] \in m_Z$	W[e]Z[bb] (pb)	W[e]+bb (pb) $m[bb] \in m_H$	W[e]H (pb)	W[ℓ] bb $\times\varepsilon_b$ L $m[bb] \in m_Z$	W[ℓ]Z[bb] $\times\varepsilon_b$ L	W[ℓ] bb $\times\varepsilon_b$ L $m[bb] \in m_H$	W[ℓ]H[bb] $\times\varepsilon_b$ L	$\delta R/R$
200	3.3E−2	2.5E−2	2.3E−2	3.8E−2	9.9E5	7.5E4	6.9E5	6.6E5	2.5E−3
300	1.2E−2	9.2E−3	8.8E−3	1.6E−2	3.6E5	5.5E4	2.6E5	2.8E5	3.2E−3
400	5.5E−3	4.3E−3	4.1E−3	7.9E−3	1.7E5	2.6E5	1.2E5	1.4E5	4.5E−3
600	1.7E−3	1.4E−3	1.3E−3	2.6E−3	5.1E4	8.4E4	3.9E4	4.5E4	7.8E−3
800	6.8E−4	6.2E−4	5.0E−4	1.2E−3	2.0E4	3.7E4	1.5E4	2.1E4	1.1E−2

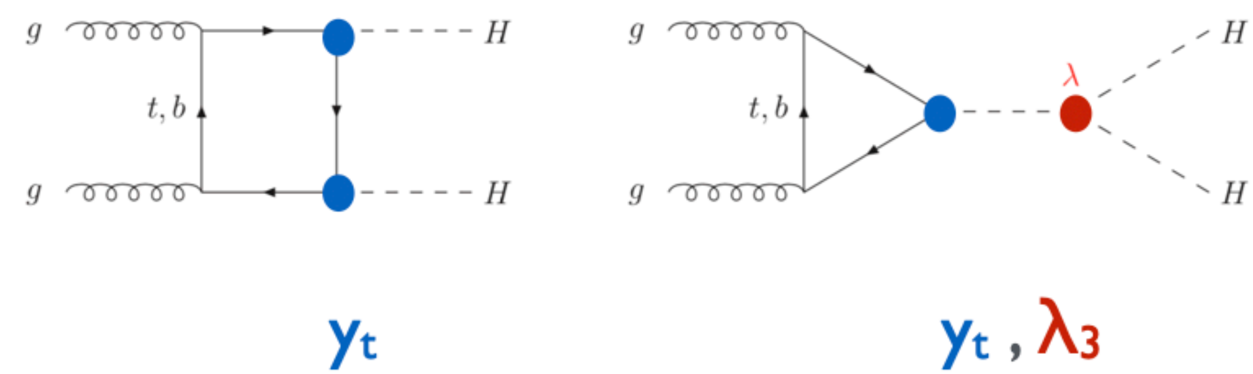
also: $\sigma(Z[\nu\nu]H[\to\gamma\gamma]) / \sigma(Z[\nu\nu]Z[\to e^+e^-])$

Higgs self-coupling



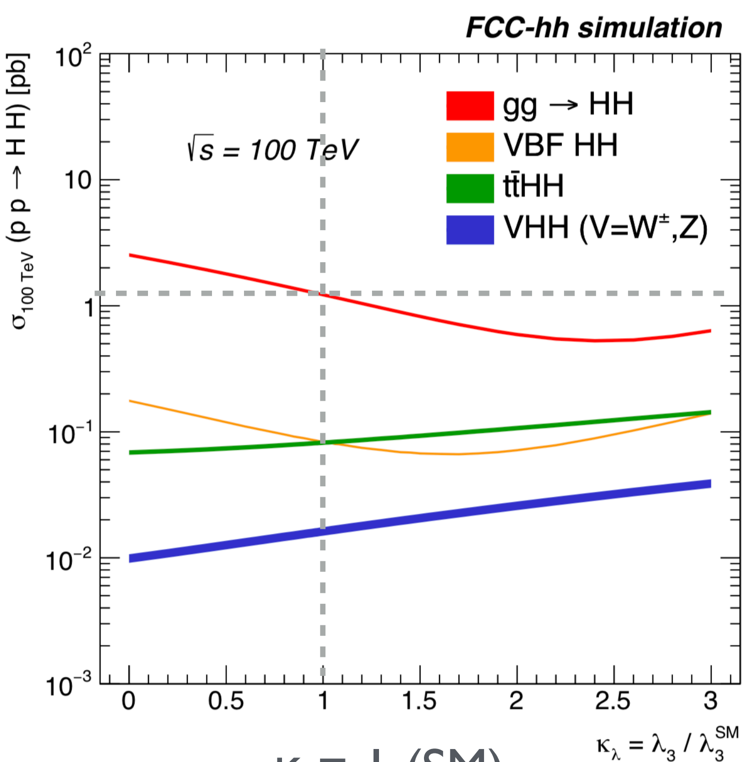


gluon fusion



- Very small cross-section due to negative interference with box diagram
- HL-LHC projections : $\delta k_\lambda / k_\lambda \approx 50\%$
- Expect large improvement at FCC-hh:
  - σ(100 TeV)/σ(14 TeV) ≈ 40 (and Lx10)
  - x400 in event yields and x20 in precision
- main channels studied:
  - bbγγ (most sensitive - discussed here)
  - bbττ
  - bbZZ(4l)
  - bbbb

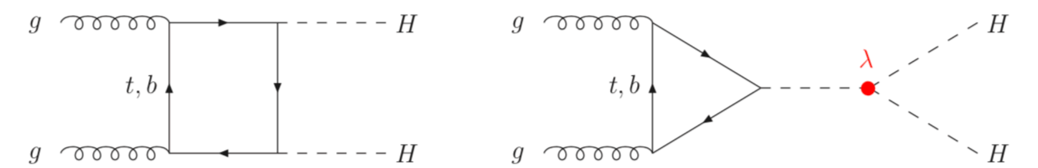
Higgs pair production at the FCC-hh



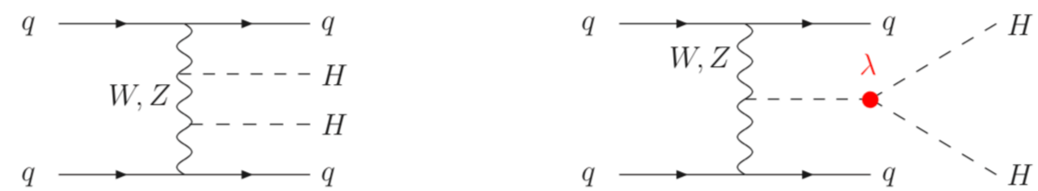
κ = 1 (SM)

σ ≈ 1 pb

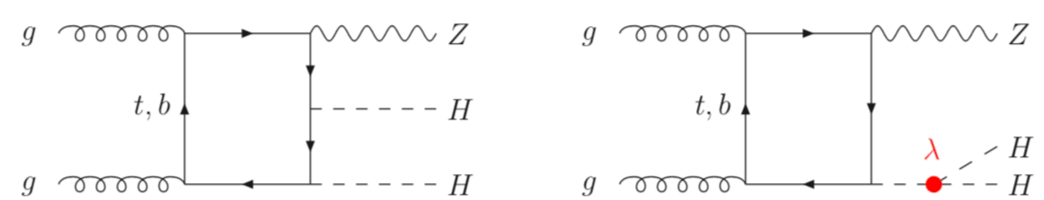
gluon fusi



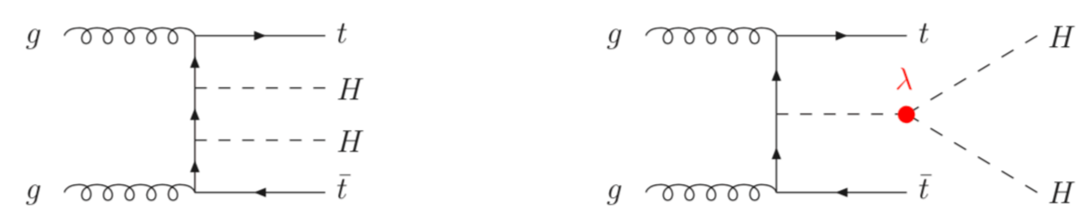
vbf HH:



VHH:



ttHH:



Expected precision:

$$\delta_{\kappa_\lambda} = \frac{\delta_\mu}{\left.\frac{d\mu}{d\kappa_\lambda}\right|_{SM}}$$

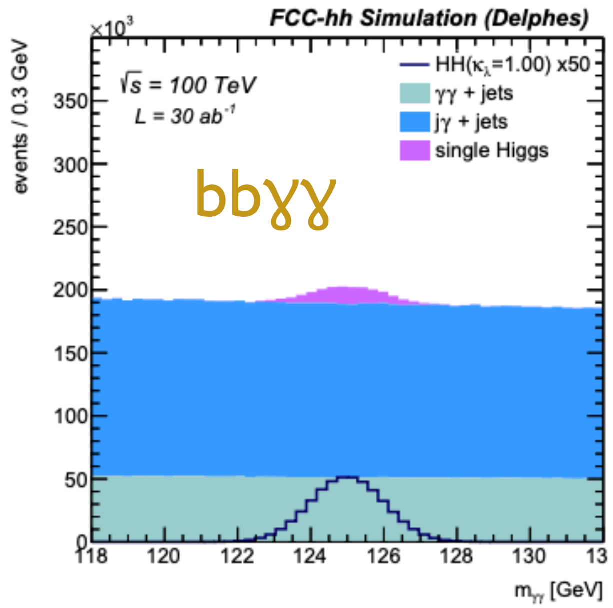
→ ~1

where: $\kappa_\lambda = \lambda_3/\lambda_3^{SM}$

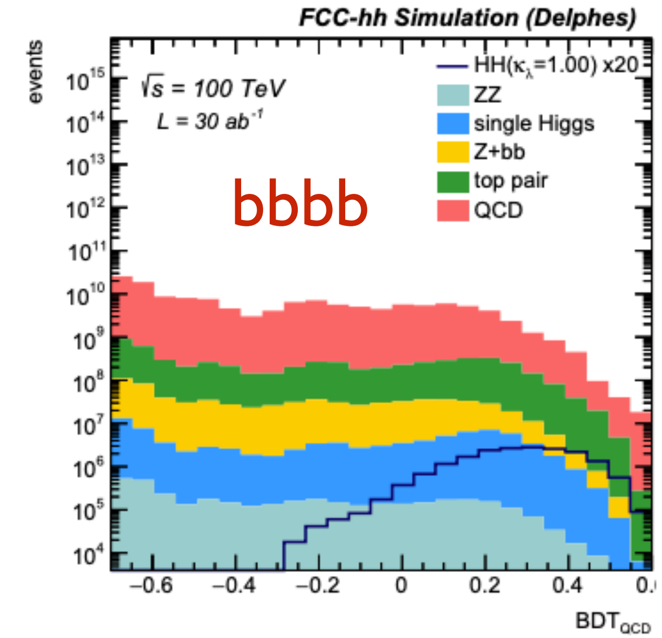
$\mu = \sigma/\sigma_{SM}$

Self-coupling at the FCC-hh

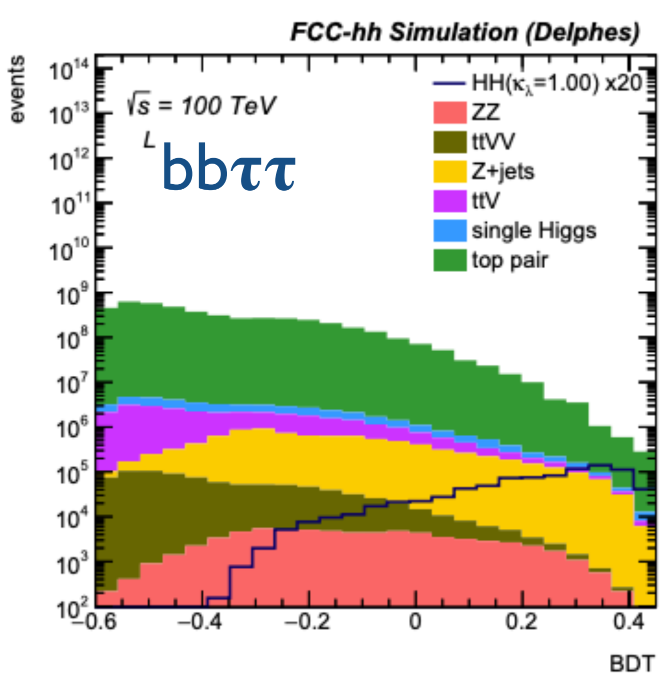
2004.03505 [hep-ph]



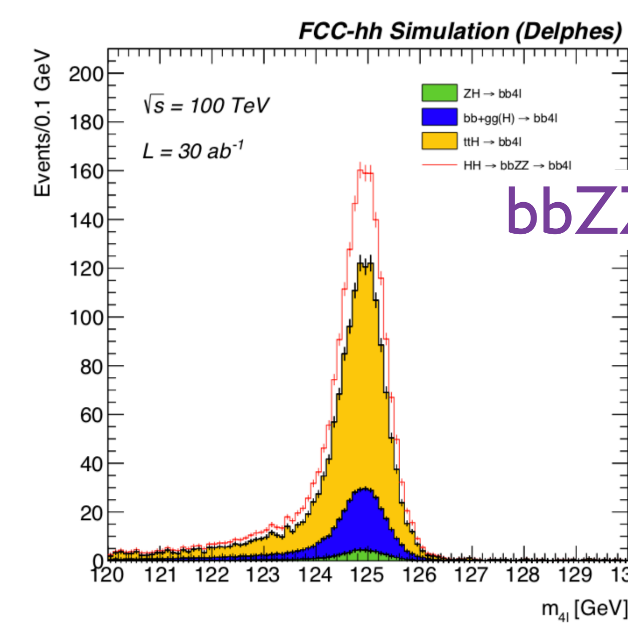
- Channels:
  - bbγγ (golden channel)
  - bbττ
  - bbbb
  - bbZZ(4l)



- Defined 3 scenarios with various detector assumptions and systematics:

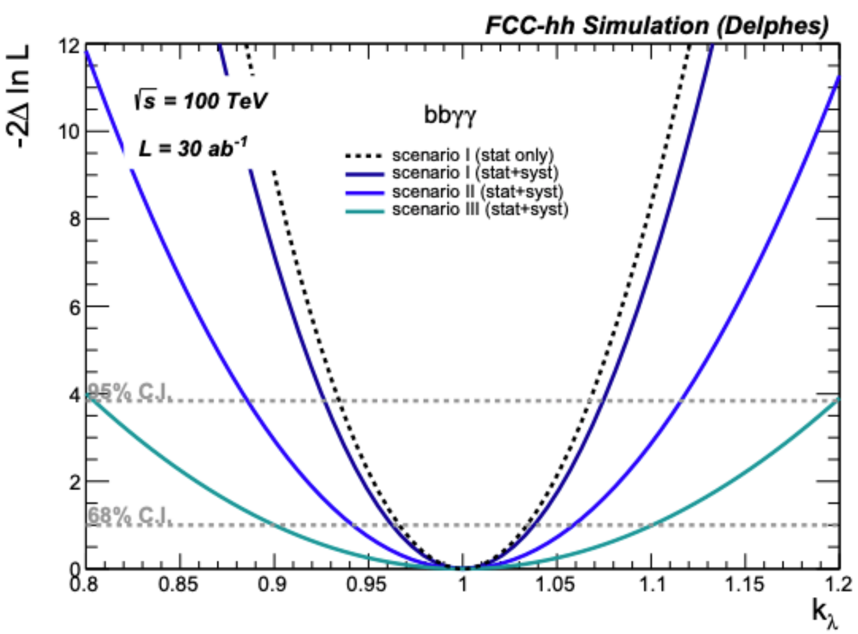


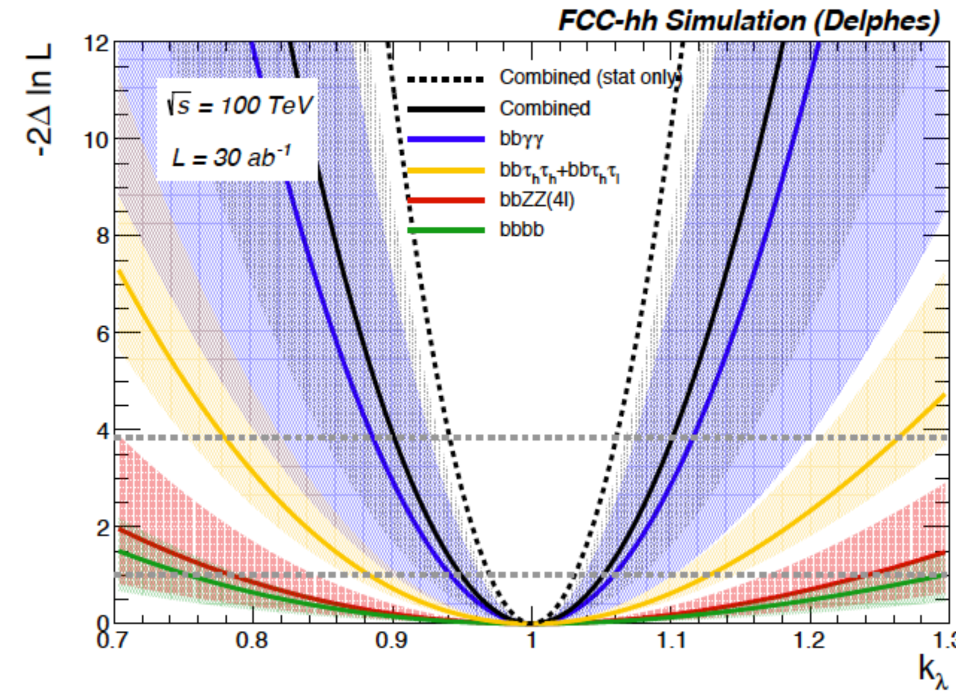
parameterisation	scenario I	scenario II	scenario III
b-jet ID eff.	82-65%	80-63%	78-60%
b-jet c mistag	15-3%	15-3%	15-3%
b-jet l mistag	1-0.1%	1-0.1%	1-0.1%
τ-jet ID eff	80-70%	78-67%	75-65%
τ-jet mistag (jet)	2-1%	2-1%	2-1%
τ-jet mistag (ele)	0.1-0.04%	0.1-0.04%	0.1-0.04%
γ ID eff.	90	90	90
jet $\to \gamma$ eff.	0.1	0.2	0.4
$m_{\gamma\gamma}$ resolution [GeV]	1.2	1.8	2.9
m_{bb} resolution [GeV]	10	15	20



Self-coupling at the FCC-hh

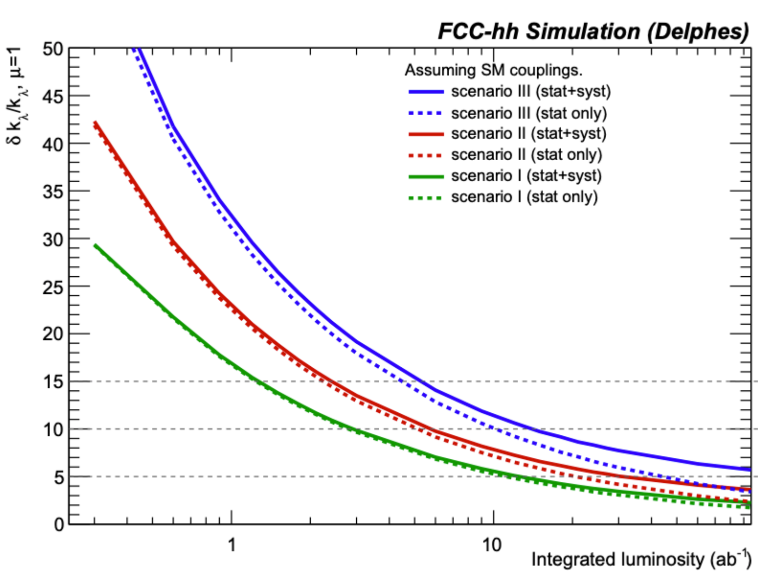
2004.03505 [hep-ph]



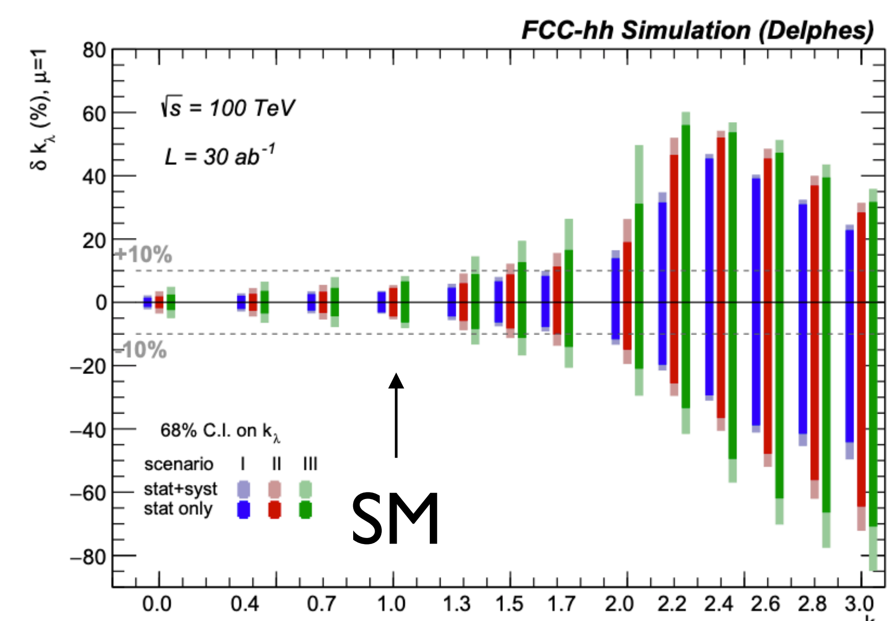


- Expected precision:

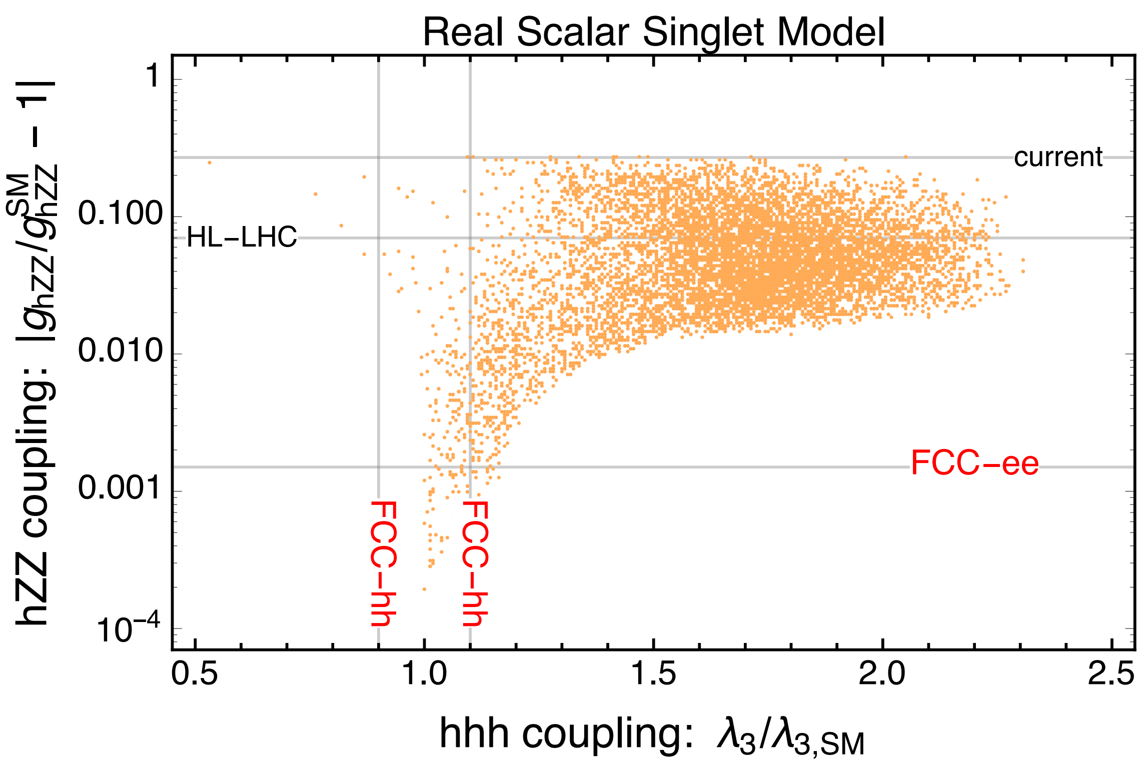
@68% CL	scenario I	scenario II	scenario III
bbγγ	3.8	5.9	10.0
bbττ	9.8	12.2	13.8
bbbb	22.3	27.1	32.0
comb.	3.4	5.1	7.8



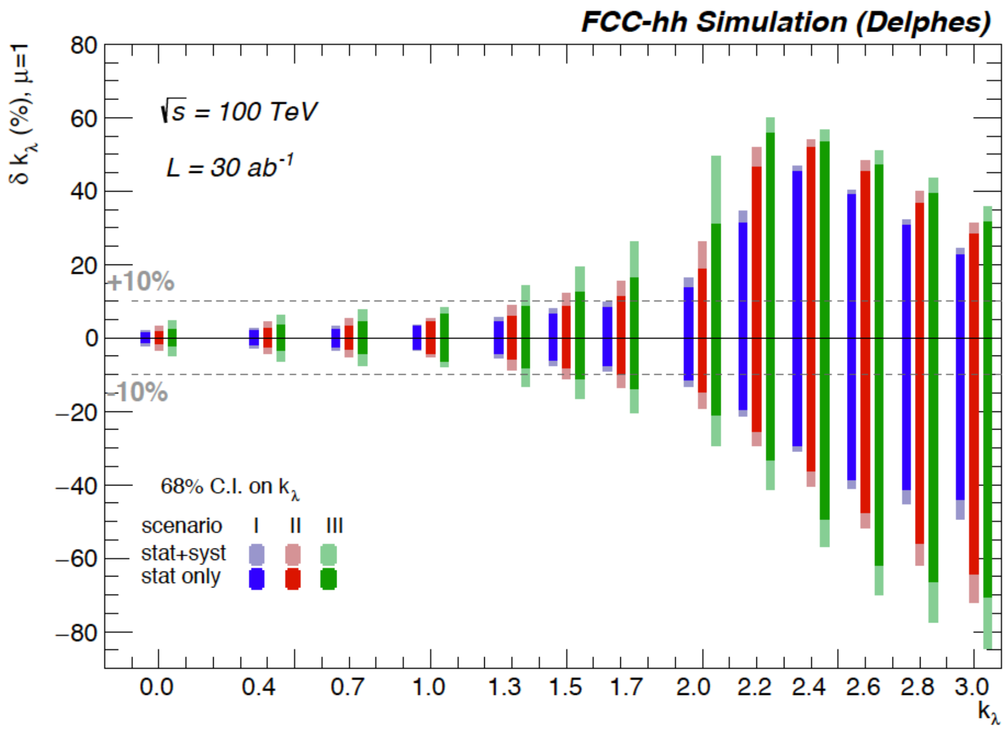
- Combined precision:
  - 3.5-8% for SM (3% stat. only)
  - 10-20% for $\lambda_3 = 1.5^* \lambda_3^{SM}$



BSM sensitivity



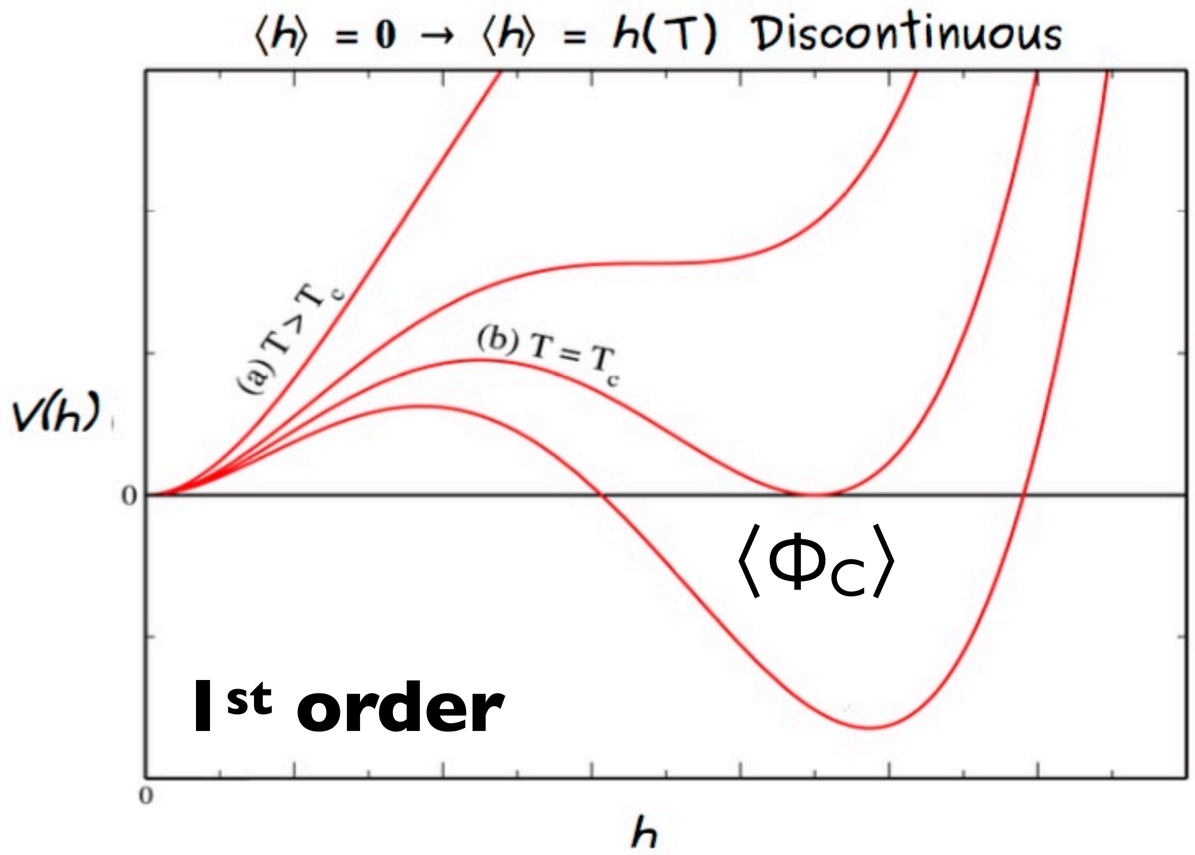
Parameter space scan for a **singlet model extension** of the Standard Model. The points indicate **a first order phase transition.**

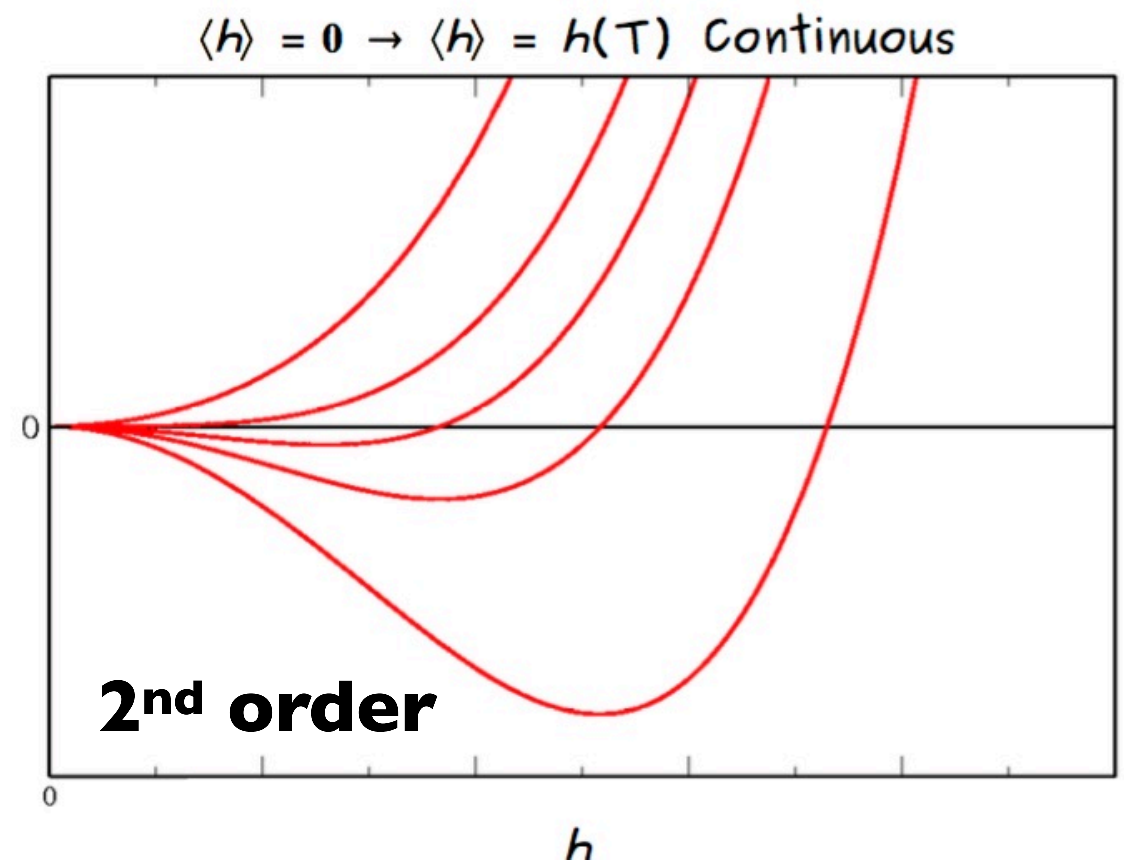


- $\delta\kappa_\lambda^{stat+syst}$ (κ_λ = 1.5) ≈ 10 %
- $\delta\kappa_\lambda^{stat+syst}$ (κ_λ = 1.7) ≈ 15 %
- $\delta\kappa_\lambda^{stat+syst}$ (κ_λ = 2.0) ≈ 20 %

CAVEAT: assumes all SM-like couplings except for trilinear

The nature of the EW phase transition





Strong 1st order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

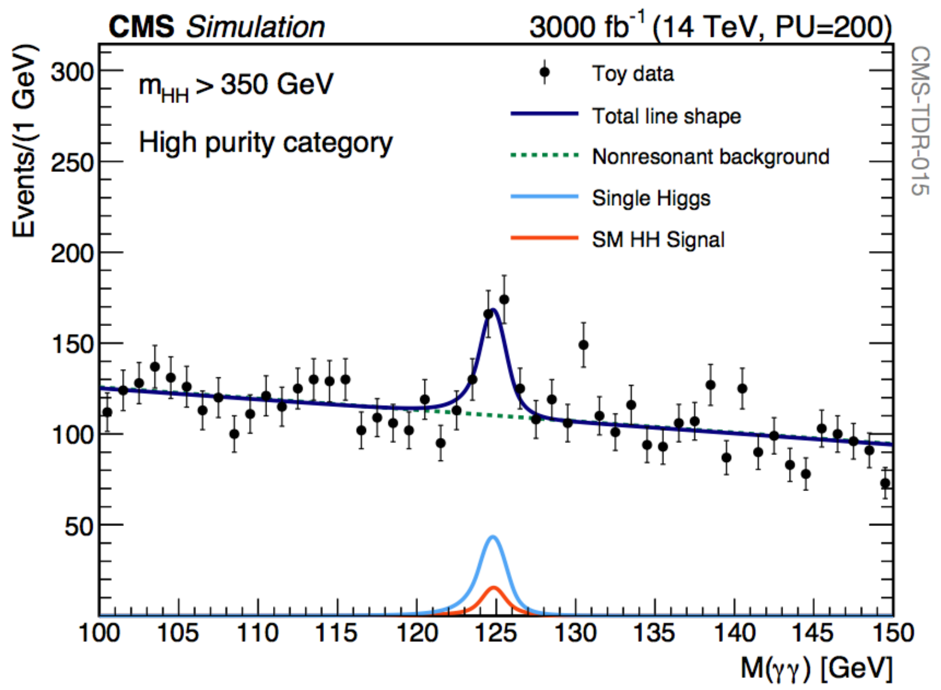
Strong 1st order phase transition ⇒ $\langle \Phi_C \rangle > T_C$

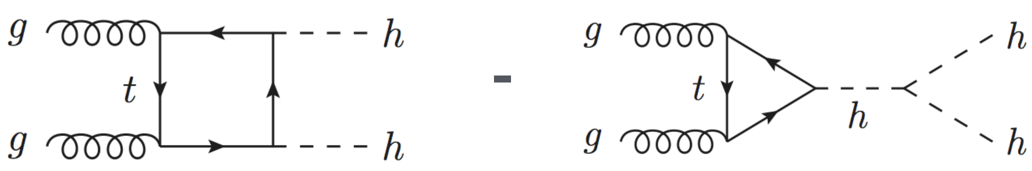
This requires O(1) deviations in the 3rd derivative of the Higgs potential w.r.t to value predicted in the SM

- Probe higher-order terms of the Higgs potential (selfcouplings)
- Probe the existence of other particles coupled to the Higgs

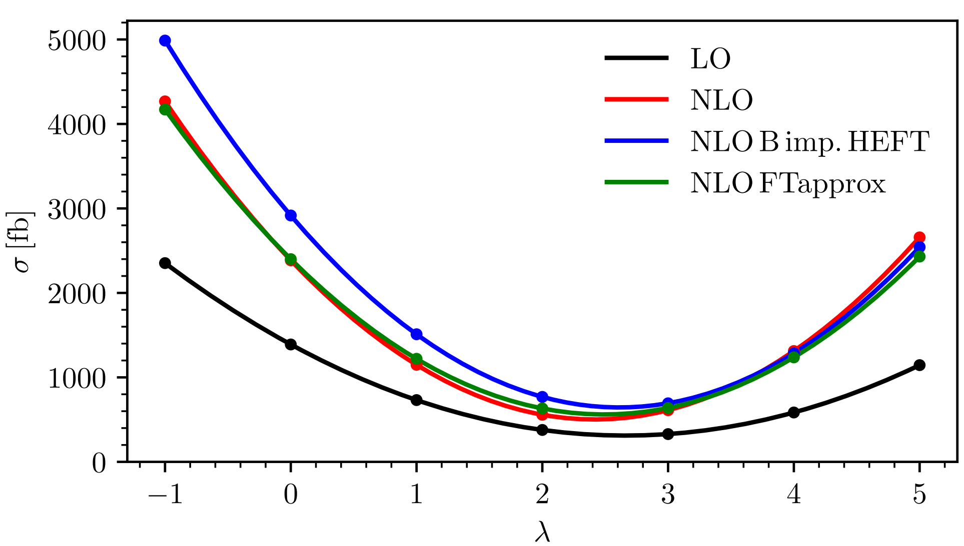
Higgs self-coupling at FCC-hh

HL-LHC



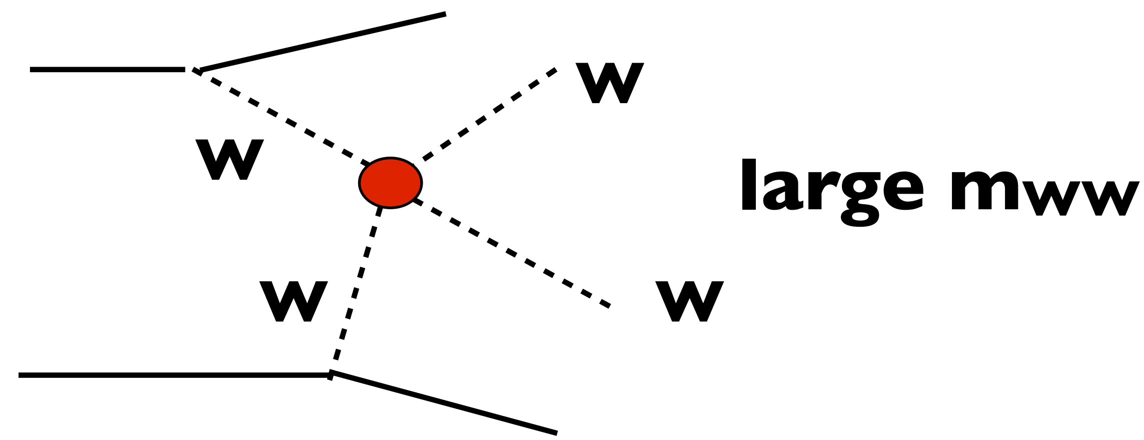


G. Heinrich et.al [1608.04798]

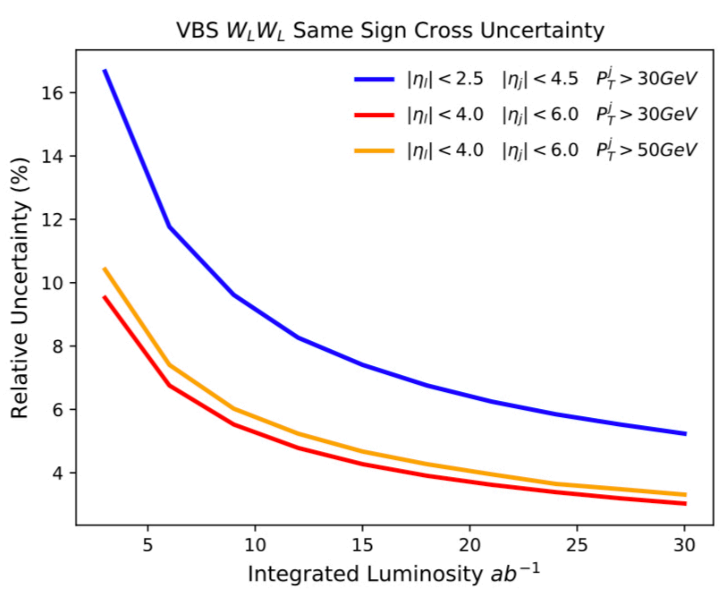


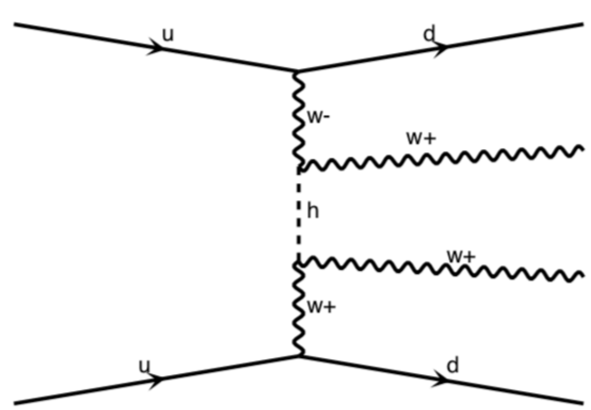
- Very small cross-section due to negative interference with box diagram
- HL-LHC projections : $\delta k_\lambda / k_\lambda \approx 50\%$
- Expect large improvement at FCC-hh:
  - σ(100 TeV)/σ(14 TeV) ≈ 40 (and Lx10)
  - x400 in event yields and x20 in precision
- main channels studied:
  - bbγγ (most sensitive - discussed here)
  - bbZZ(4l) (in backup)
  - bbbbj (boosted) (in backup)
- Two very sensitive channels not considered yet:
  - bbττ ($\delta k_\lambda / k_\lambda \approx 8\%$ from [1802.01607])
  - 4b

Vector Boson Scattering



- Sets constraints on **detector acceptance** (fwd jets at **η≈4**)
- Study **$W^{+/-}$-$W^{+/-}$ (same-sign)** channel
- **Large WZ** background at FCC-hh
- **3-4% precision on W_LW_L scattering** xsec. achievable with full dataset (only 3σ HL-LHC)
- Indirect measurement of HWW coupling possible, **$\delta\kappa_W/\kappa_W \approx 2\%$**





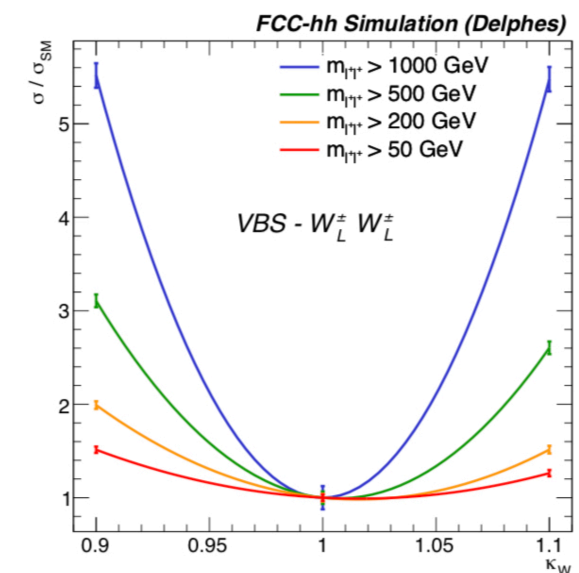
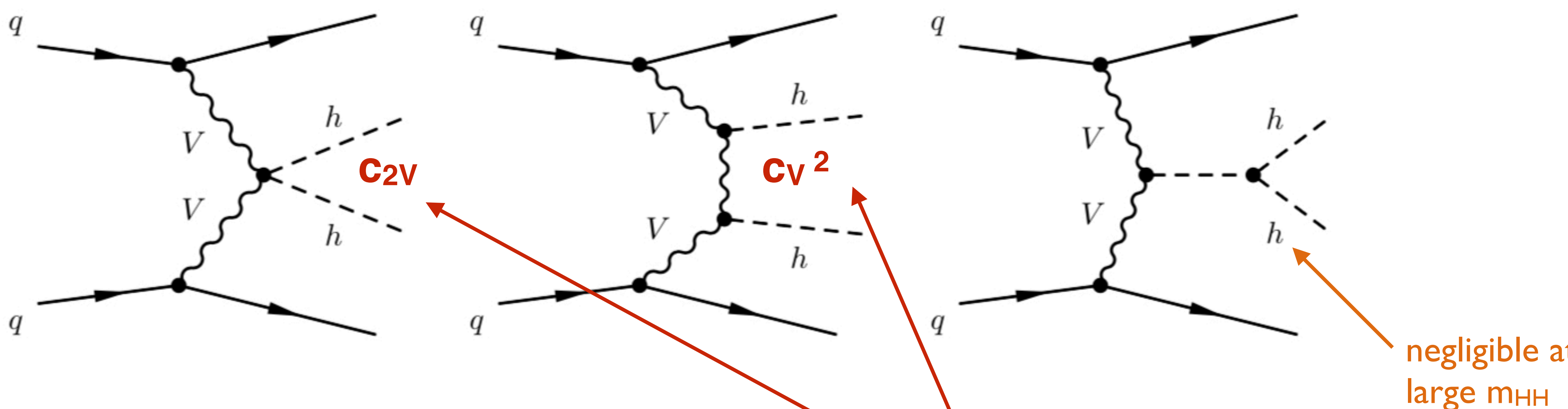


Table 4.5: Constraints on the HWW coupling modifier κ_W at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the $W_LW_L \to HH$ process.

$m_{l^+l^+}$ cut	> 50 GeV	> 200 GeV	> 500 GeV	> 1000 GeV
$\kappa_W \in$	[0.98,1.05]	[0.99,1.04]	[0.99,1.03]	[0.98,1.02]

$W_L W_L \to HH$

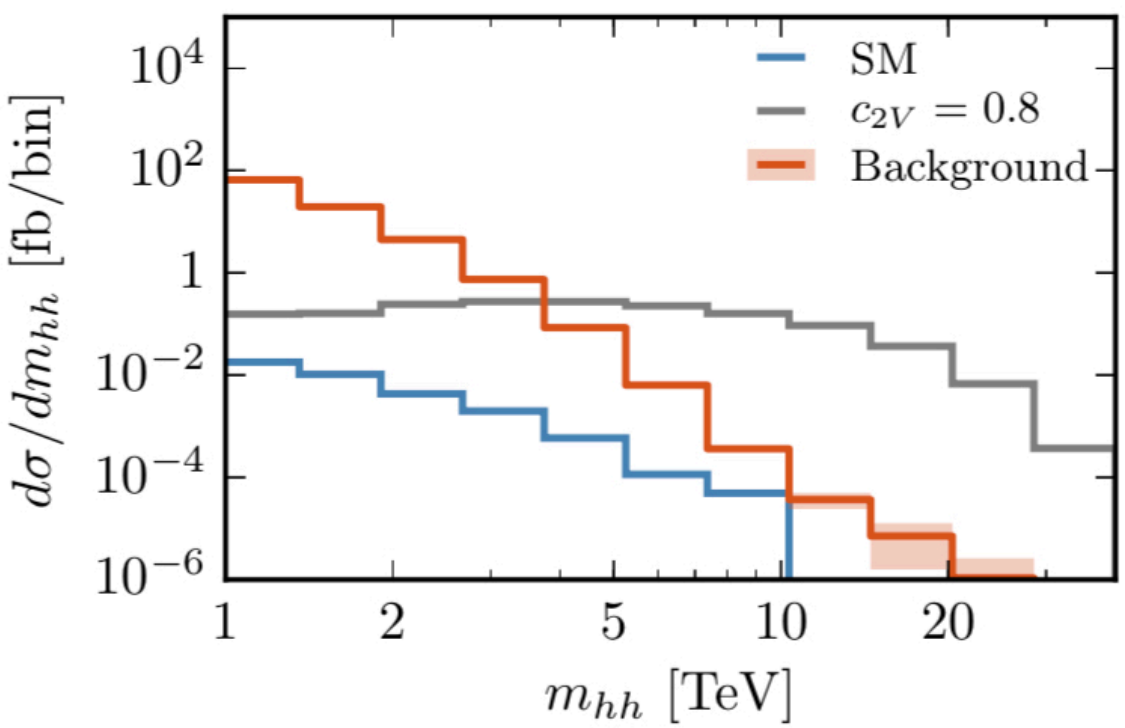
F. Bishara, R. Contino, J. Rojo

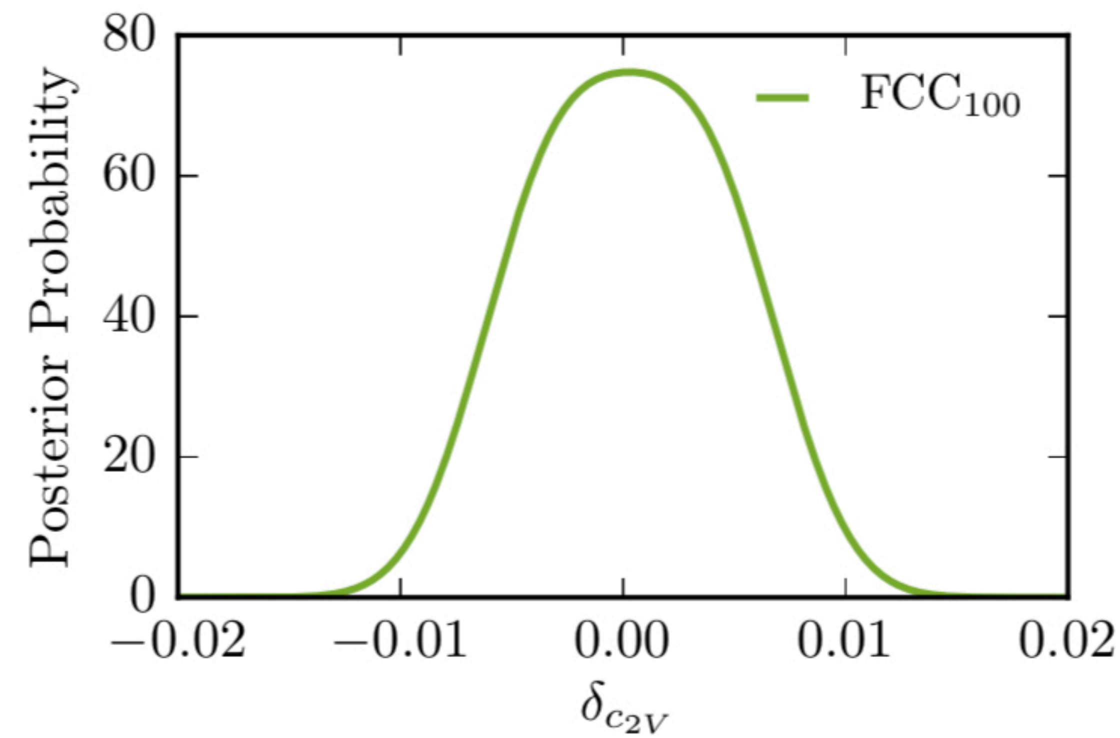


$$A(\mathrm{V_L V_L \to HH}) \sim \frac{\hat{s}}{v^2}(c_{2V} - c_V^2) + \mathcal{O}(m_W^2/\hat{s}),$$

0 in the SM

high energy behaviour driven by C_{2V} and C_V, if $\delta C_{2V} \neq 0$, grows with E



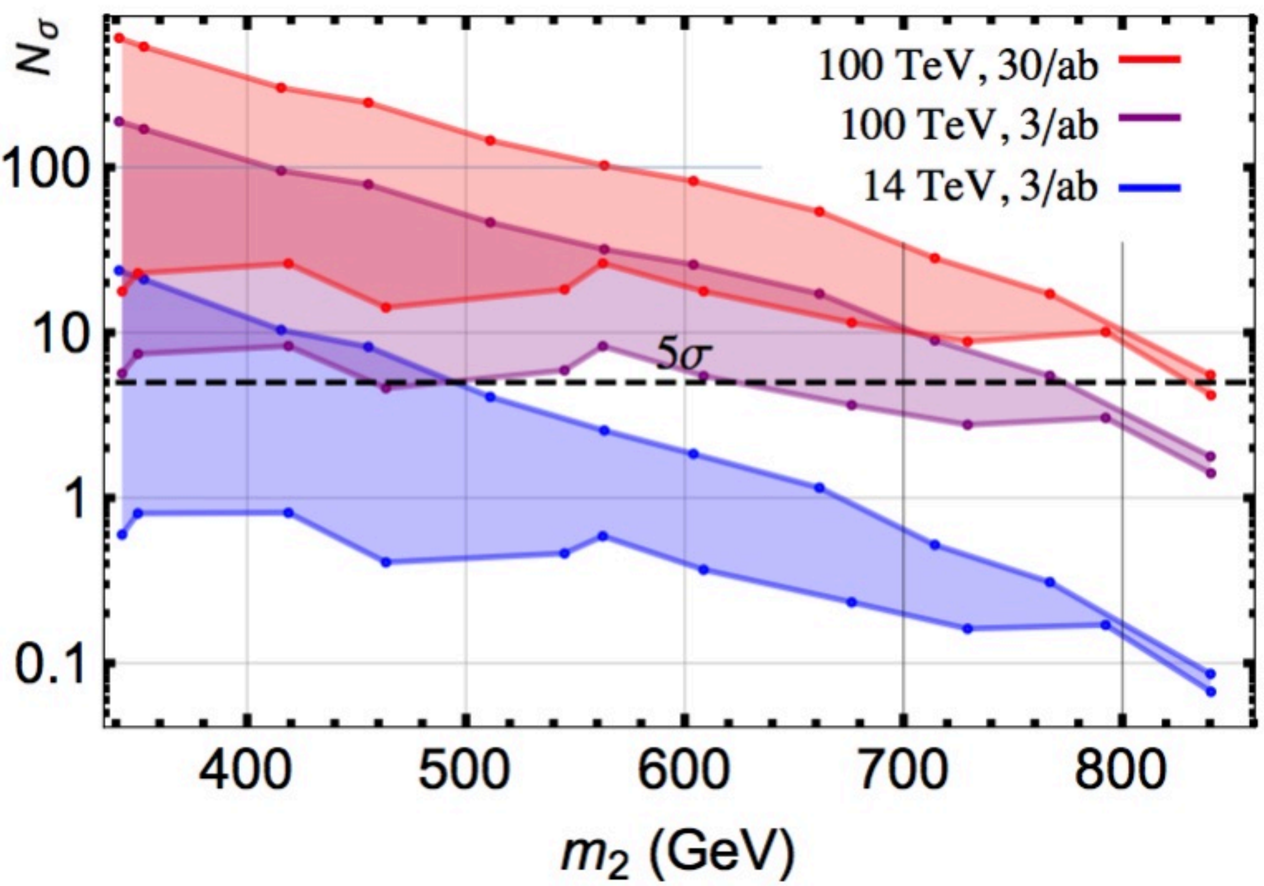


With c_V from FCC-ee, $\delta c_{2V} < 1\%$

Higgs Self-coupling and constraints on models with 1st order EWPT

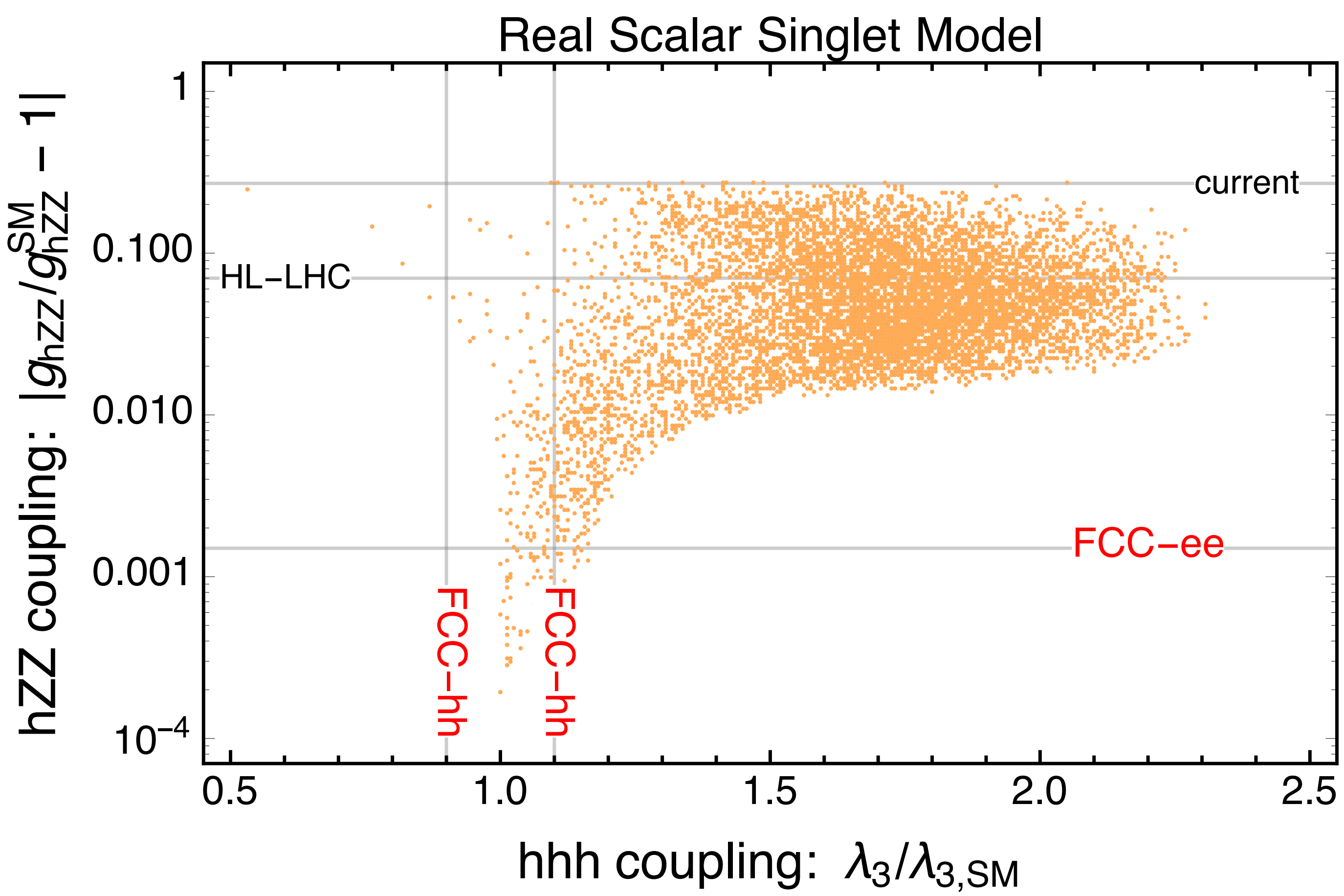
- **Strong 1st order electroweak phase transition** (and CP violation) needed to explain large observed **baryon asymmetry** in our universe
- Can be achieved with extension of SM + singlet

Direct detection of extra Higgs states



$h_2 \to h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$

Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh



Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

Summary of Higgs & SM

- The FCC-hh machine will produce > **10^{10} Higgs bosons**

- Such **large statistics** open up a whole new range of possibilities, allowing for precision in new kinematic regimes, and rare decay channels → **complementary to FCC-ee**

- Measuring **ratios of couplings** (or equivalently BRs), allows to cancel systematics (1% precision on "rare" couplings within reach after absolute HZZ measurement in e+e-)

- Higgs-self coupling can be measured with **$\delta\kappa_\lambda$(stat) ≈ 5%** precision at FCC-hh (best achievable precision among all future facilites)

- **VBS** longitudinal polarisations **$V_L V_L$** can be measured at **3-4%** precision($W_L W_L$ same sign), provides percent level precision HWW coupling measurement.

- Can directly and indirectly exclude compelling classes of models compatible with 1st order electro-weak phase transition

- Extremely rich Higgs program at the FCC-hh, goes much beyond what has been presented here. Further studies are needed:

  - gauge boson pair production at large mass (to study anomalous couplings)
  - differential measurements: Higgs p_T in the multi-TeV, as a probe of BSM physics
  - VH production at large mass
  - missing HH decay channels (bb**ττ** (~8%), bbbb, etc …) and combination

What can the FCC-hh say about BSM physics

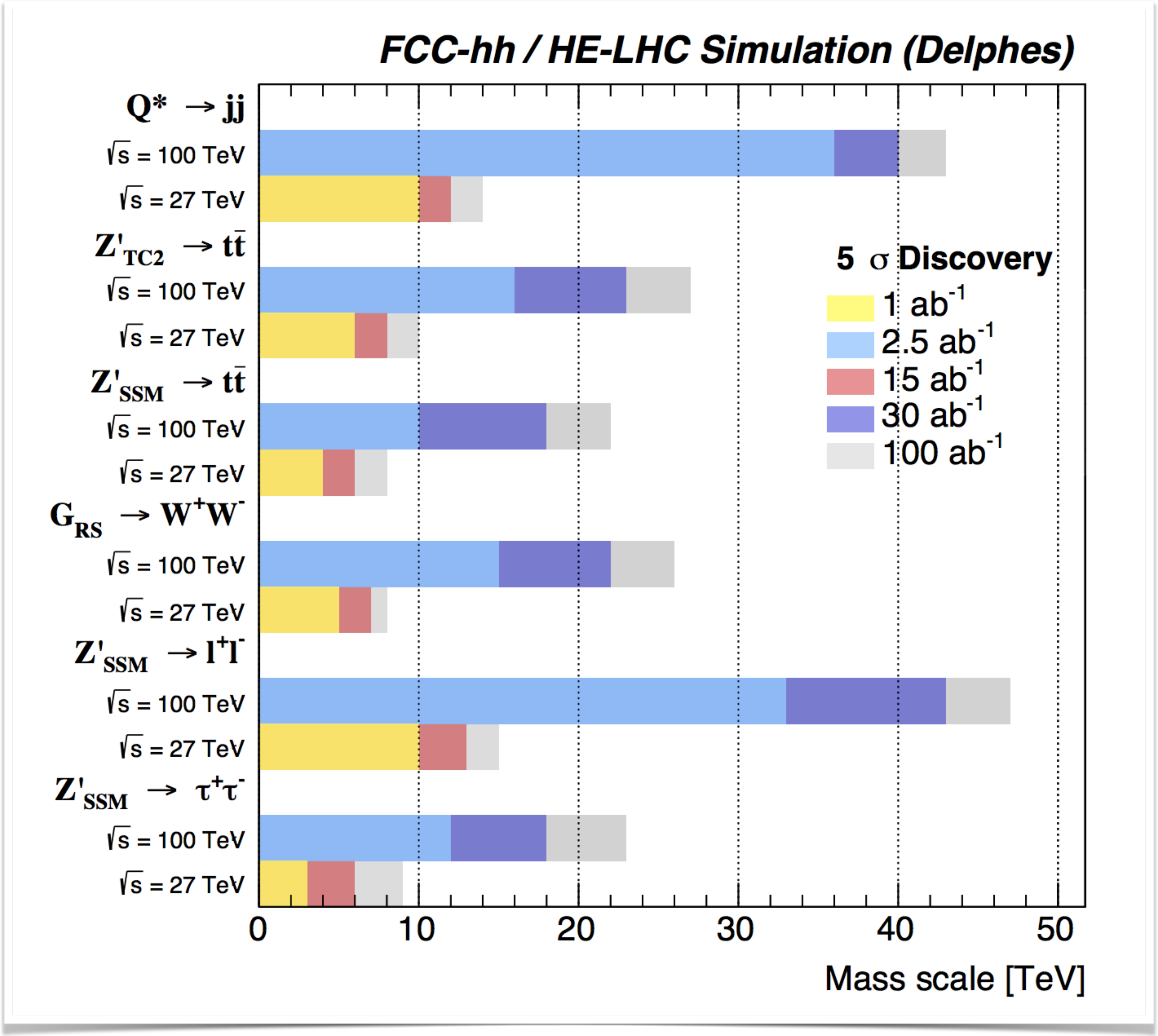
Exploration potential:

- New machines are build to make discoveries!
- Mass reach enhanced by factor $\sqrt{s}$/14TeV (5-7 at 100TeV)
- Statistics enhanced by several orders of magnitude for possible BSM seen at HL-LHC
- Benefit from both direct (large Q^2) and indirect precision probes

Could provide answers to questions such as:

- Is the SM dynamics all there at the TeV scale?
- Is there a TeV-Scale solution the hierarchy problem?
- Is Dark Matter a thermal WIMP?
- Was the cosmological EW phase transition 1st order? Cross-over?
- Could baryogenesis have taken place during EW phase transition?

Heavy resonances @ 100 TeV



Detector requirements from high p_T searches

Tracking: $$\frac{\sigma(p)}{p} \approx \frac{p\sigma_x}{BL^2}$$ calorimeters: $$\frac{\sigma(E)}{E} \approx \frac{A}{\sqrt{E}} \bigoplus B$$

- Tracking target : achieve **σ / p = 10-20% @10 TeV**
- Keep calorimeter **constant term** as small as possible.

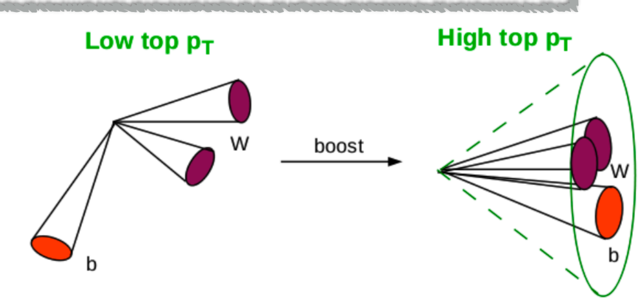
- Long-lived particles live **longer**:

ex: 5 TeV **b-Hadron** travels **50 cm** before decaying
5 TeV **tau lepton** travels **10 cm** before decaying

→ re-think reconstruction, include **dE/dx ?**

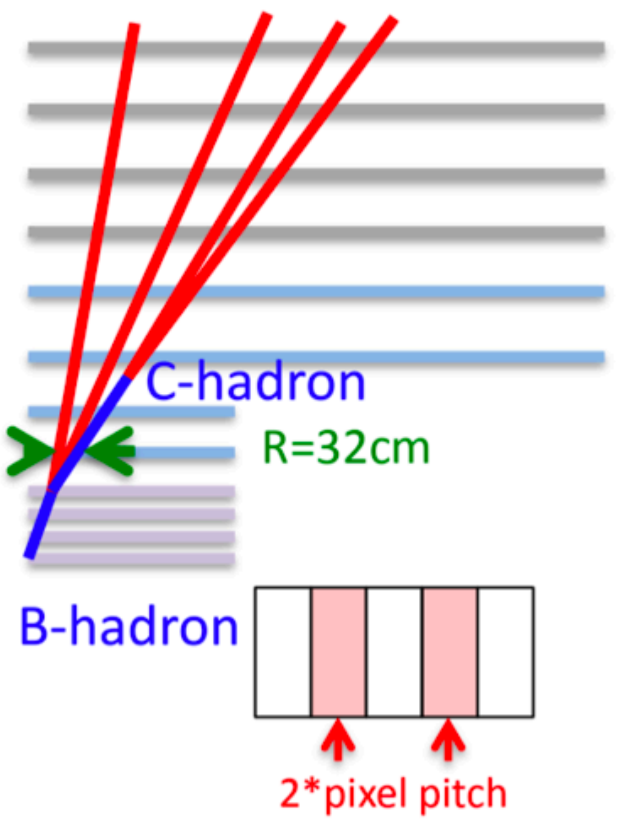
Require **high granularity** (both in tracker and calos):

ex: W(10 TeV) will have decay products separated by DR = 0.01



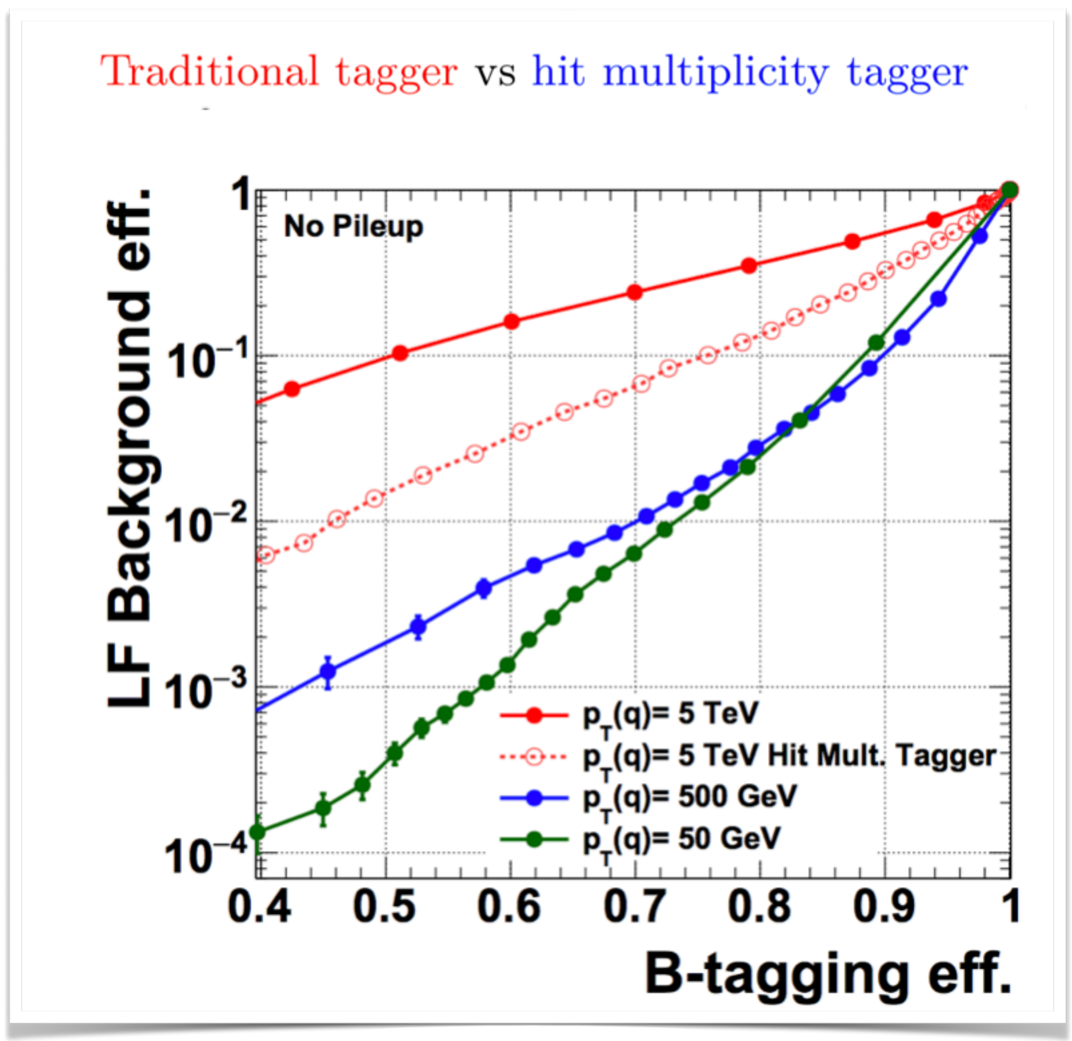
Detector requirements from high p_T searches

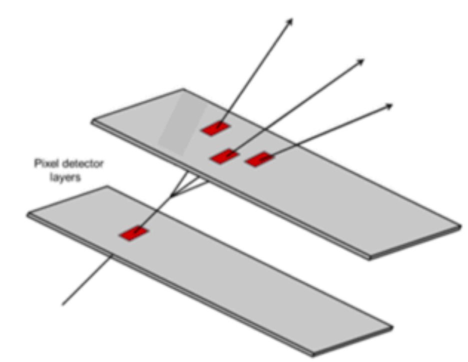
- Change in paradigm: heavy flavour tagging
- multi-TeV b-Hadrons decay outside the pixel volume
- Need to adapt identification algorithms for maintaining sensitivity in in high mass searches .



Only 71% 5 TeV b-hadrons decay < 5th layer.

- displaced vertices



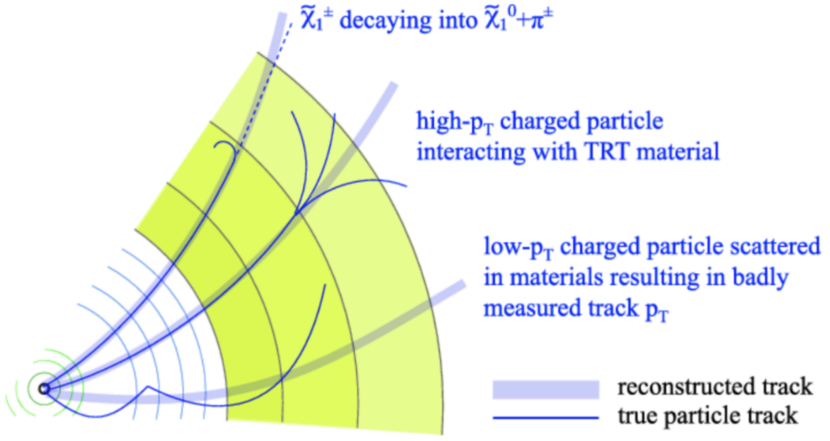


arXiv:1701:06832

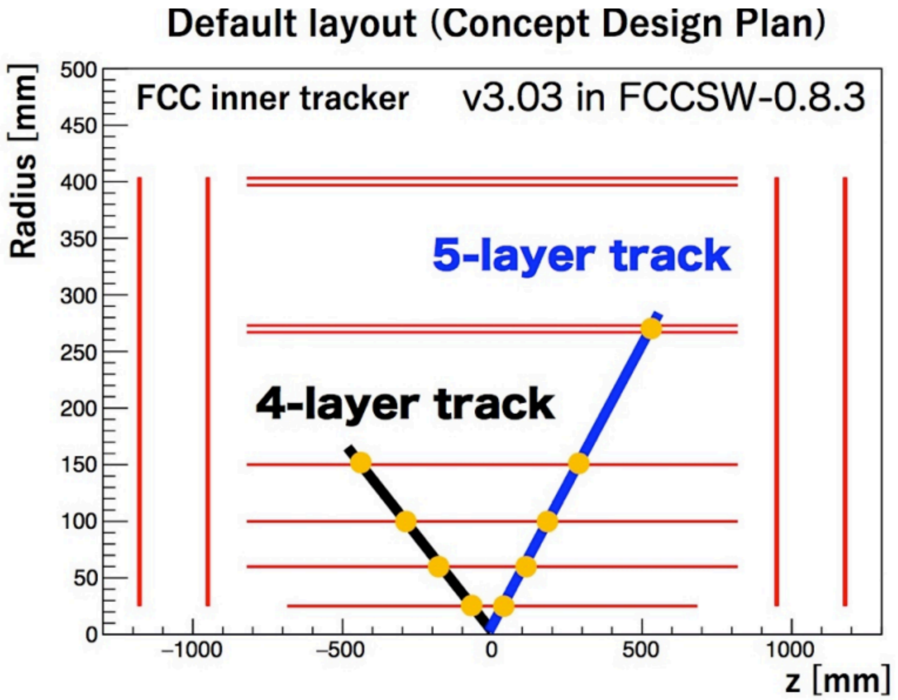
To be verified in high pile-up environment.

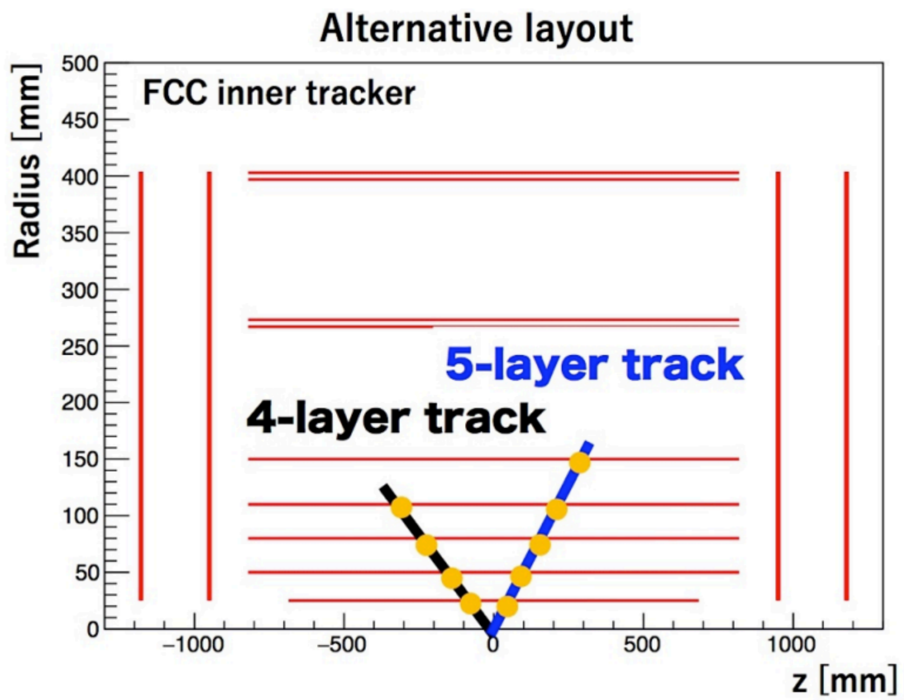
Disappearing Tracks

- Observed relic density of Dark Matter Higgsino-like: 1TeV, Wino-like: 3TeV
- Mass degeneracy: wino 170MeV, Higgsino 350MeV
- Wino/Higgsino LSP meta-stable chargino, cτ= 6cm(wino) 7mm(higgsino)



- Disappearing tracks analysis shows discovery reach beyond upper limits of MDM
- In a similar way FCC-hh can explore conclusively EW charged WIMP models, (low multiplets)





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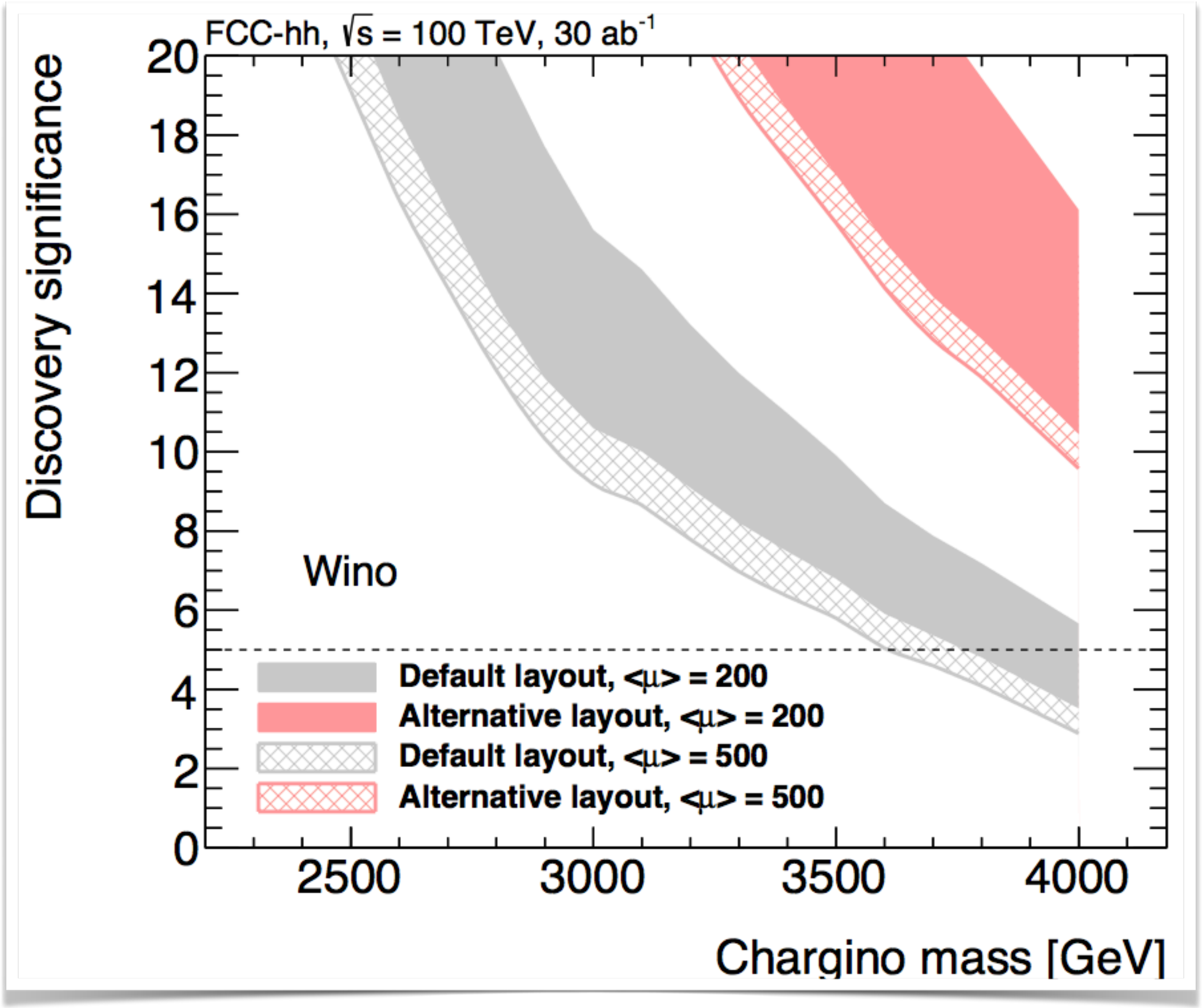

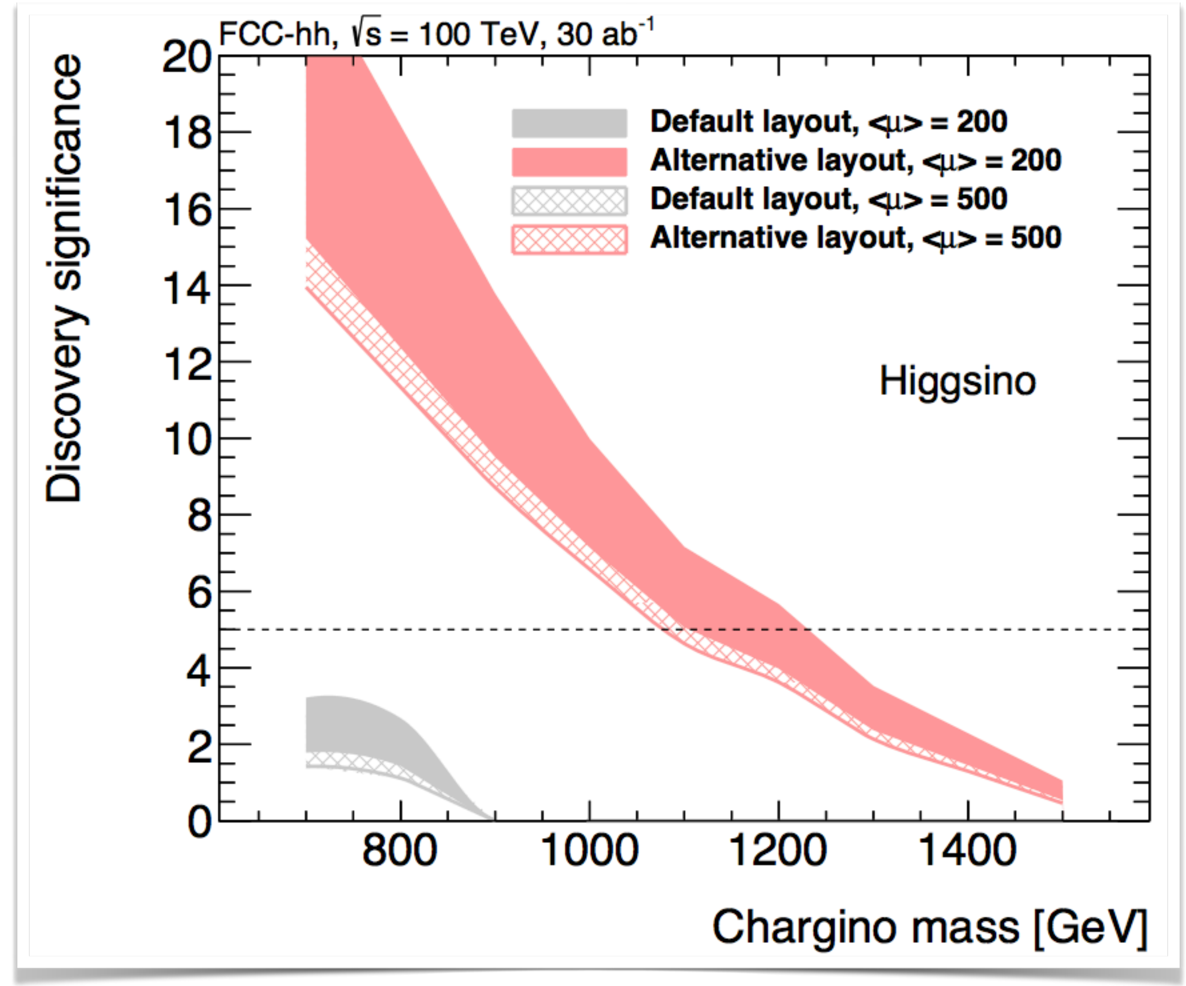

- M = 1 TeV Higgsino can be discovered
- M = 3 TeV Wino can be discovered

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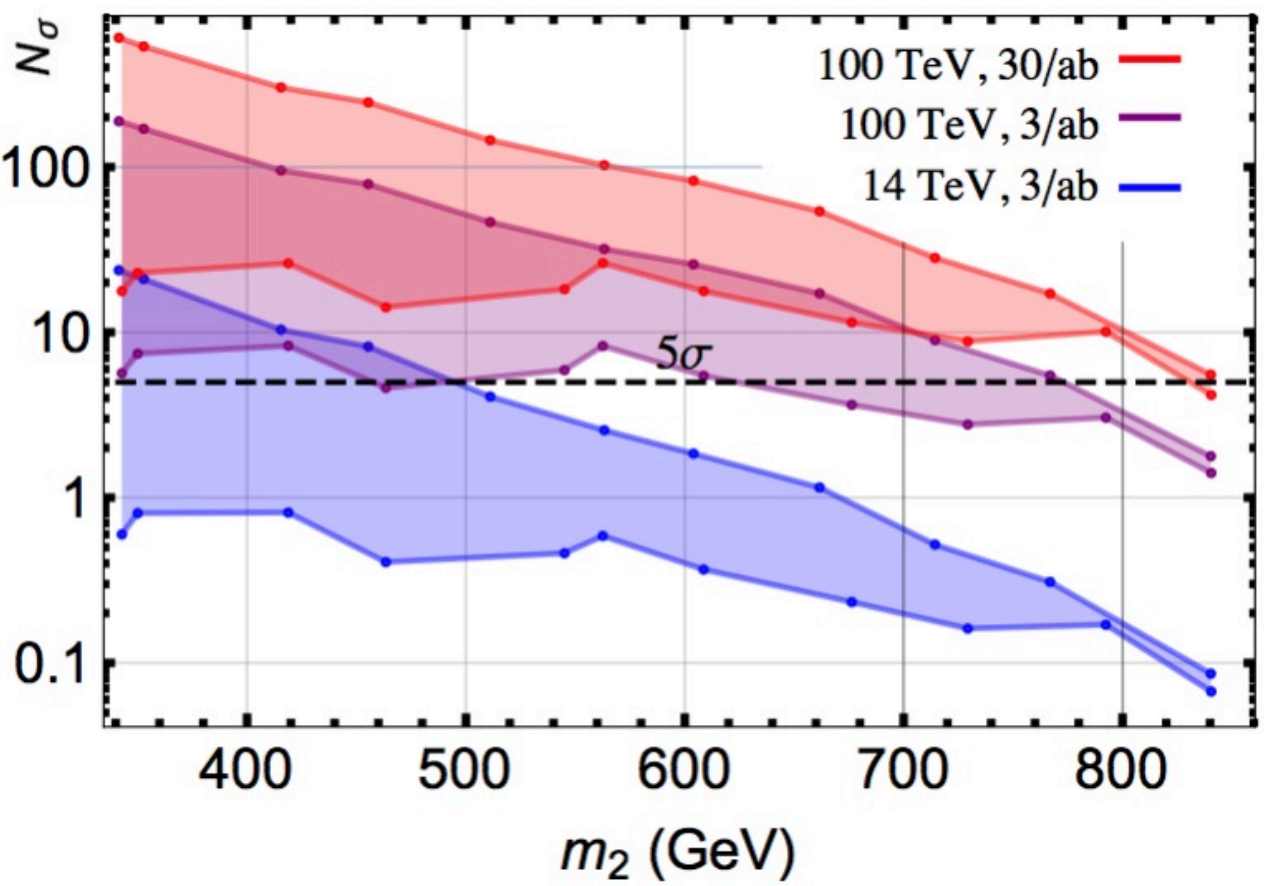

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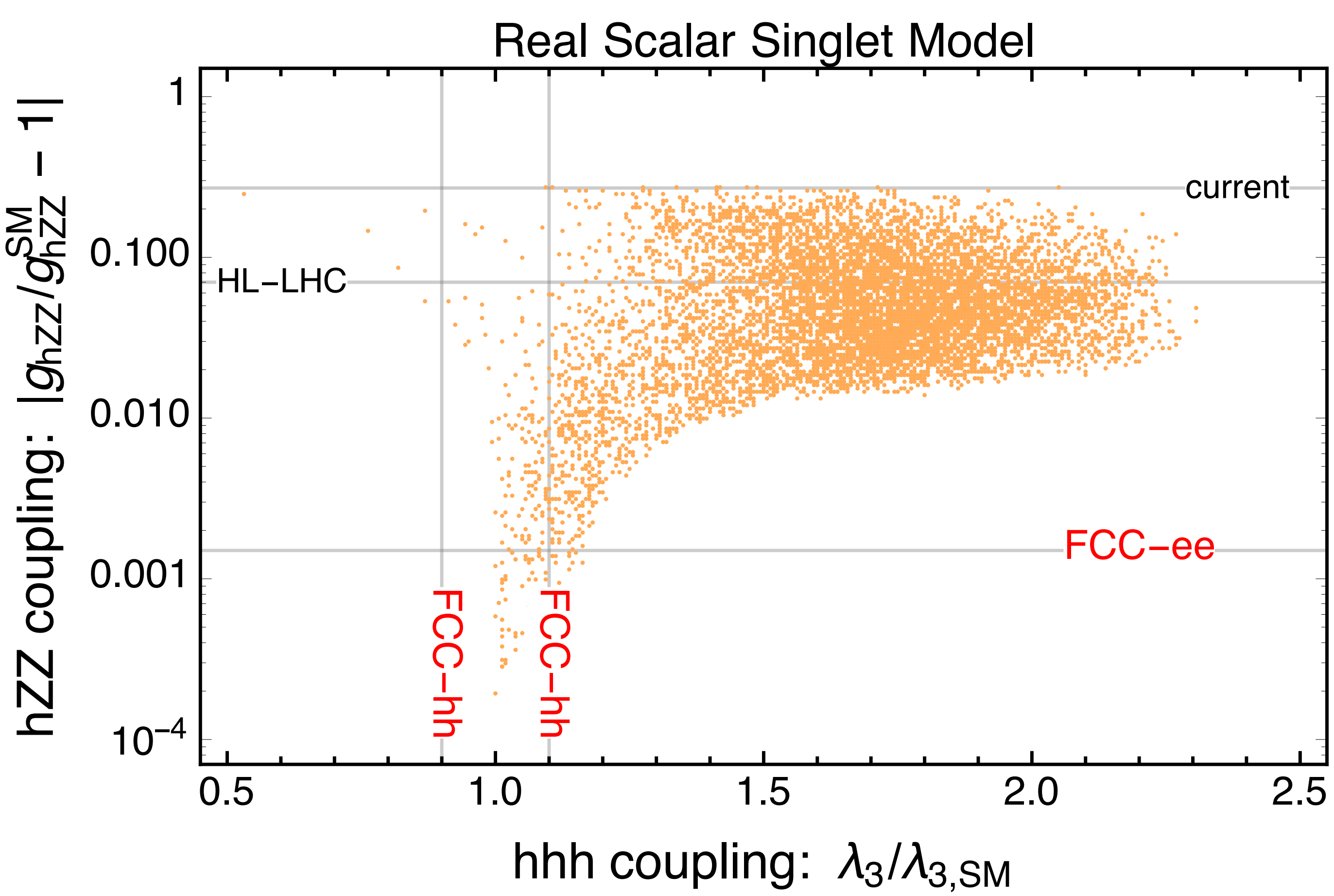

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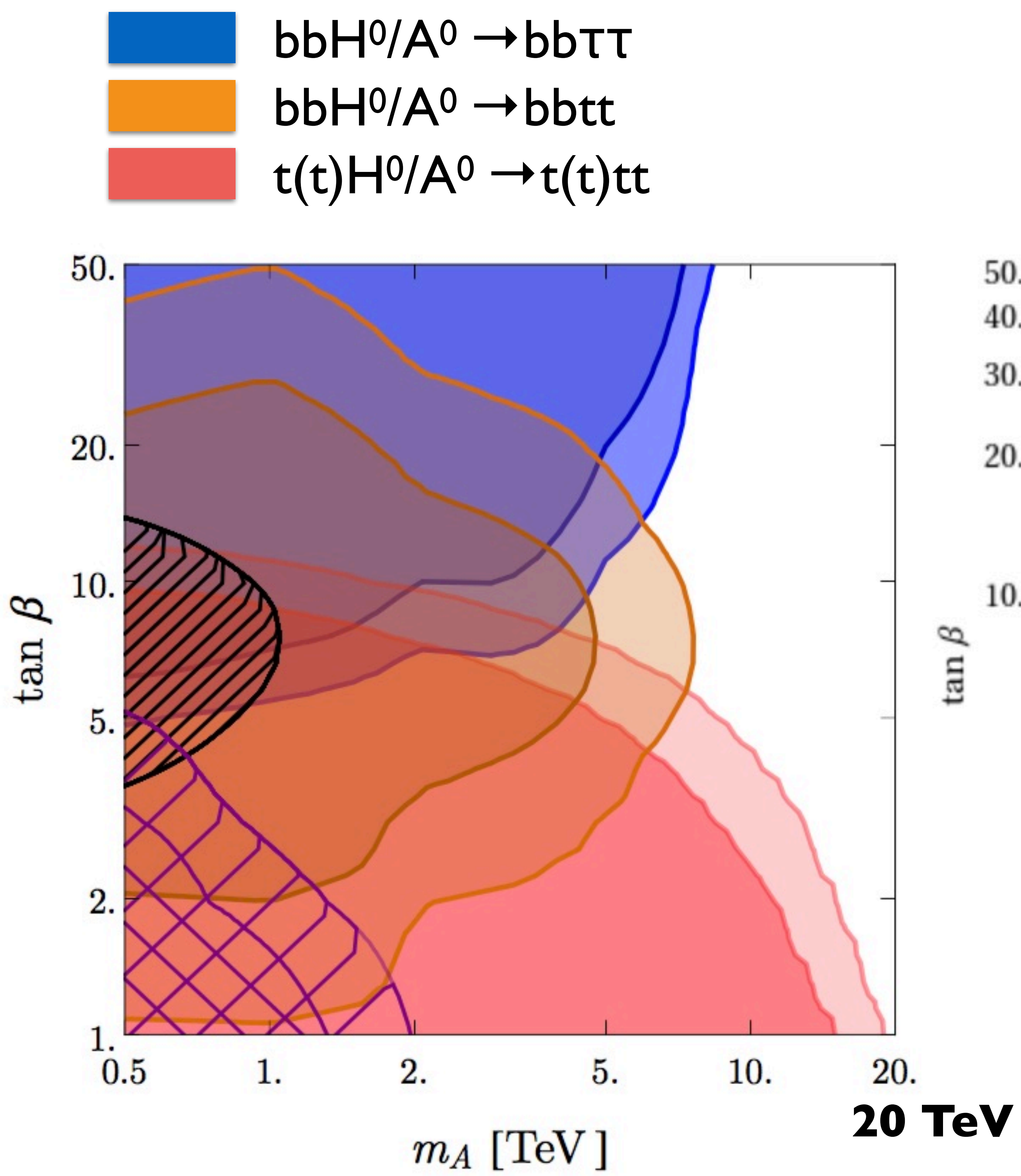
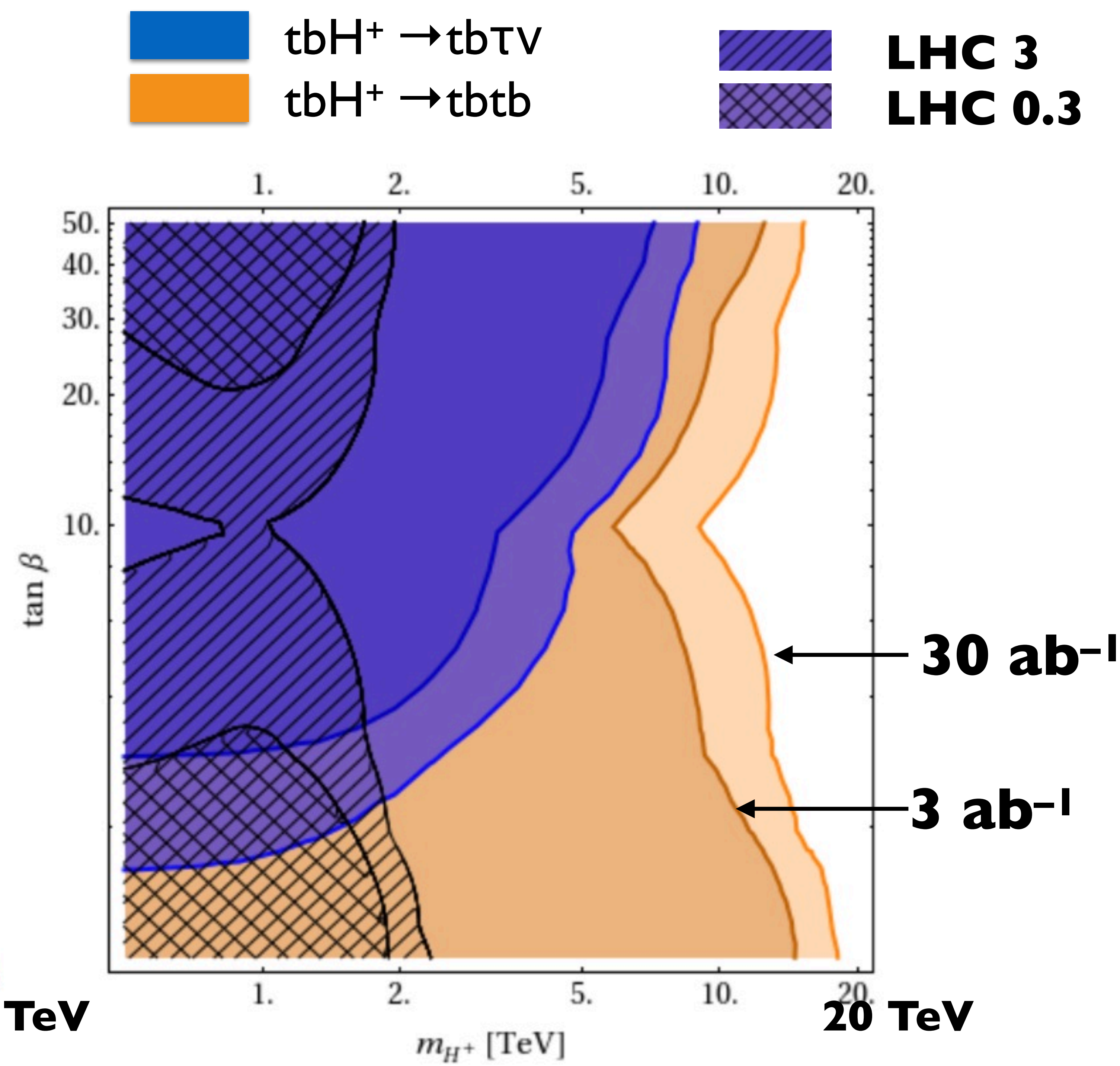
MSSM Higgs





N. Craig, J. Hajer, Y.-Y. Li, T. Liu, H. Zhang, arXiv:1605.08744

J. Hajer, Y.-Y. Li, T. Liu, and J. F. H. Shiu, arXiv:1504.07617