Physics perspectives with future hadrons colliders

Michele Selvaggi

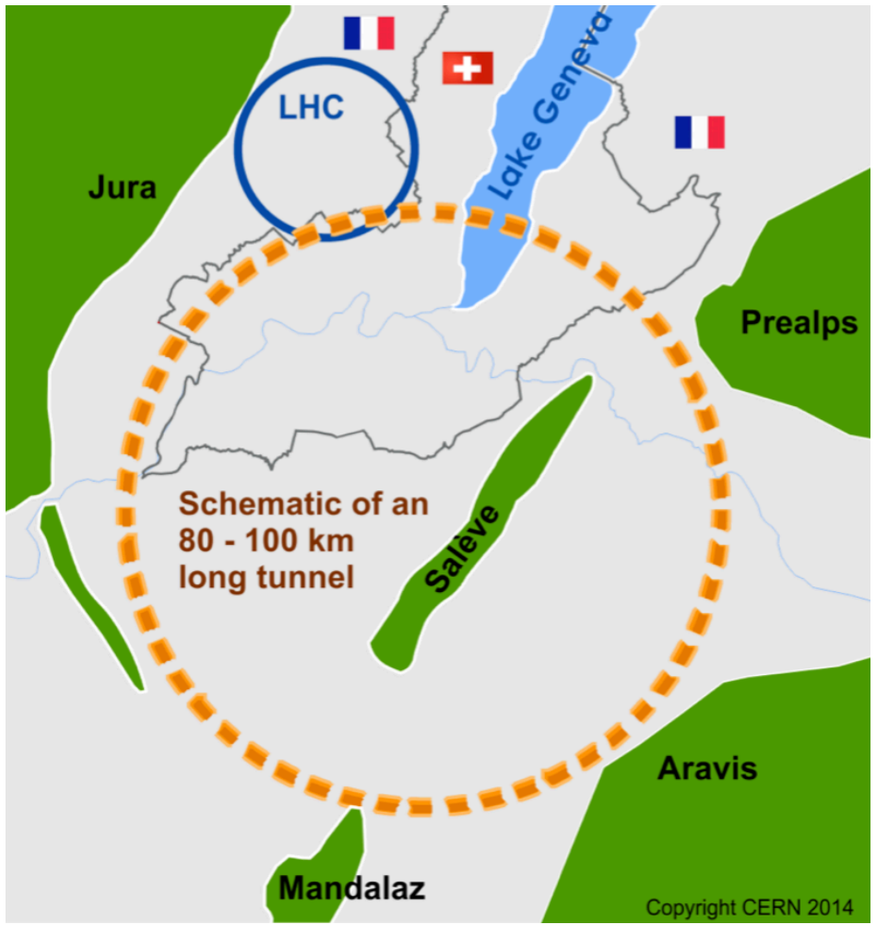
CERN

LHCP ’20 - Online

Motivations for pp colliders beyond the LHC

- Future projects in HEP have two objectives:
  - explore the energy frontier, since solutions to known and un-explained phenomena beyond the standard model **<u>might</u>** be within reach at the next high energy collider:
    - Dark Matter
    - Neutrino mass
    - Matter-antimatter asymmetry
  - measure to high precision the physics of the electroweak symmetry breaking:
    - the shape of the Higgs potential
    - Higgs couplings, in particular to first two generations and gauge bosons → guaranteed deliverable!

The FCC project



see Daniel Schulte's presentation

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

- pp-collider (FCC-hh)
  - defines infrastructure requirements
  - 16 T → 100 TeV in 100 km tunnel
- ee-collider (FCC-ee):
  - as a (potential) first step
- 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/

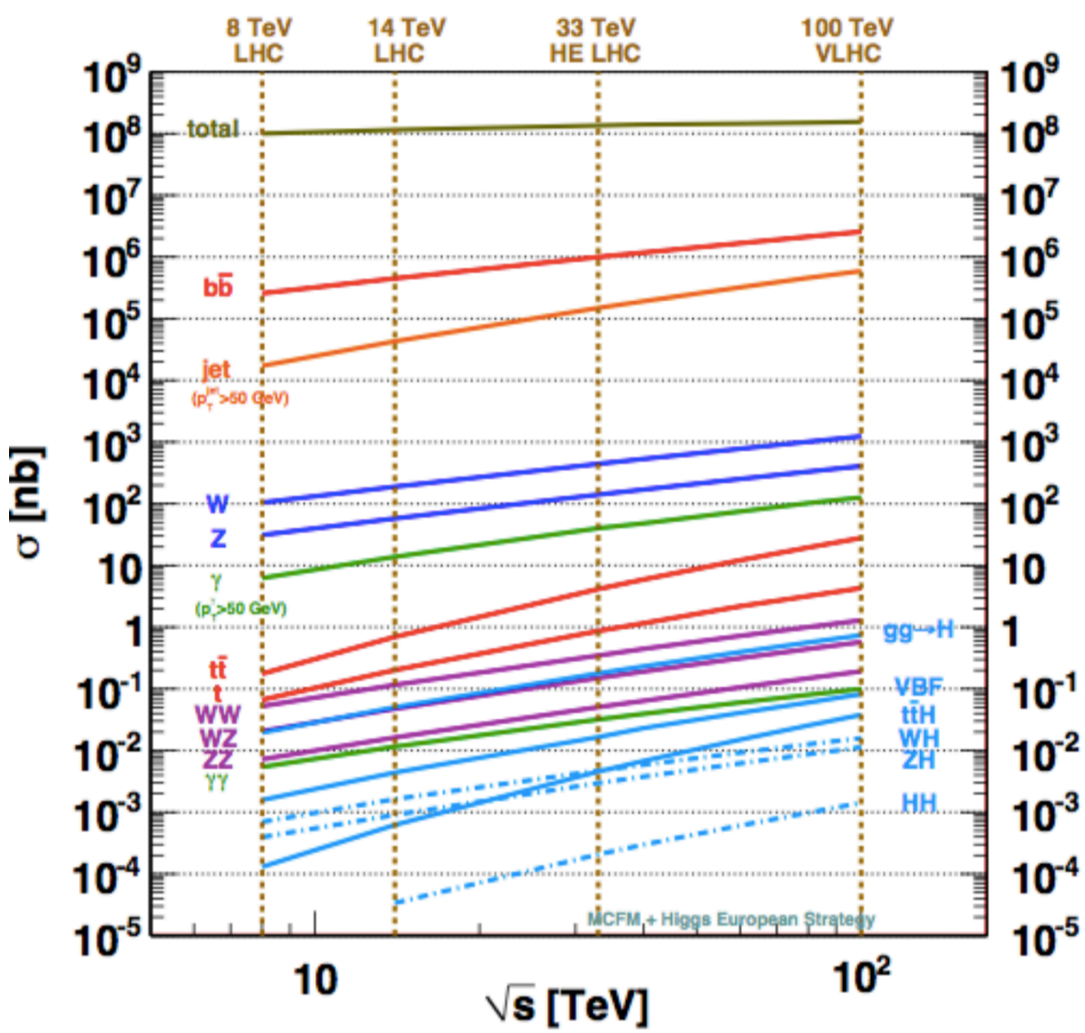
Physics goals for a 100 TeV collider

- Precision machine
  - probe Higgs **self-coupling** to few % level, and %-level precision for top yukawa and 2nd generation.
  - measure **SM parameters** with high precision
  - exploit **complementarity with e^+e^-** by accessing rare decays/ **high dim.operators** (EFT) in **extreme kinematic** regimes (boosted)

- Discovery machine
  - **directly** probe new physics up to **unprecendented** scale
  - discover/exclude:
    - heavy resonances "strong" m(q*) ≈ 50 TeV,
      "weak" m(Z') ≈ 40TeV,
    - SUSY m(gluino) ≈ 15 TeV,
      m(stop). ≈ 10 TeV

Physics program spans over very wide range of characters energy scales !

Inclusive SM cross sections



- 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.

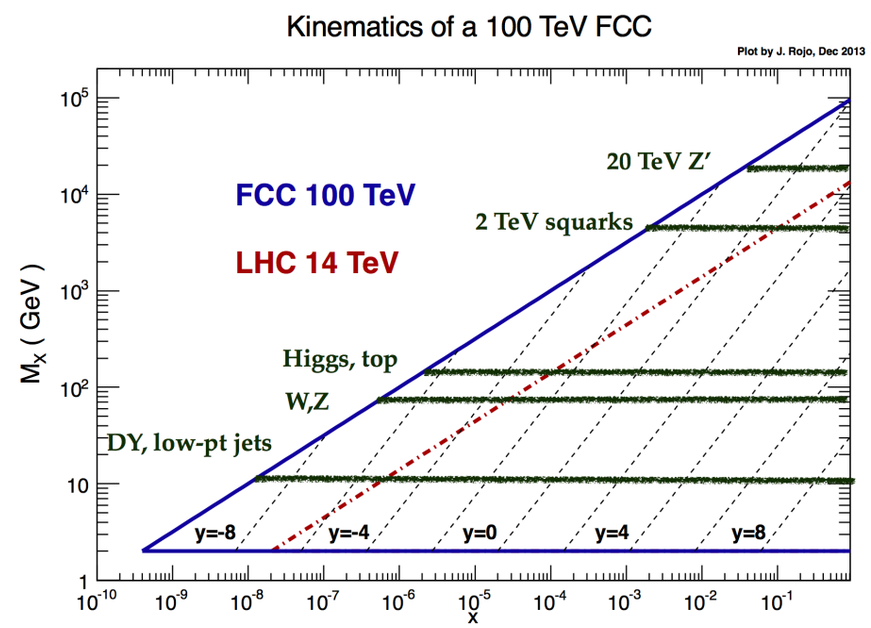
- *Inclusive cross-section* for relevant processes (single and HH) show a significant increase.
  - x 20-50 increase

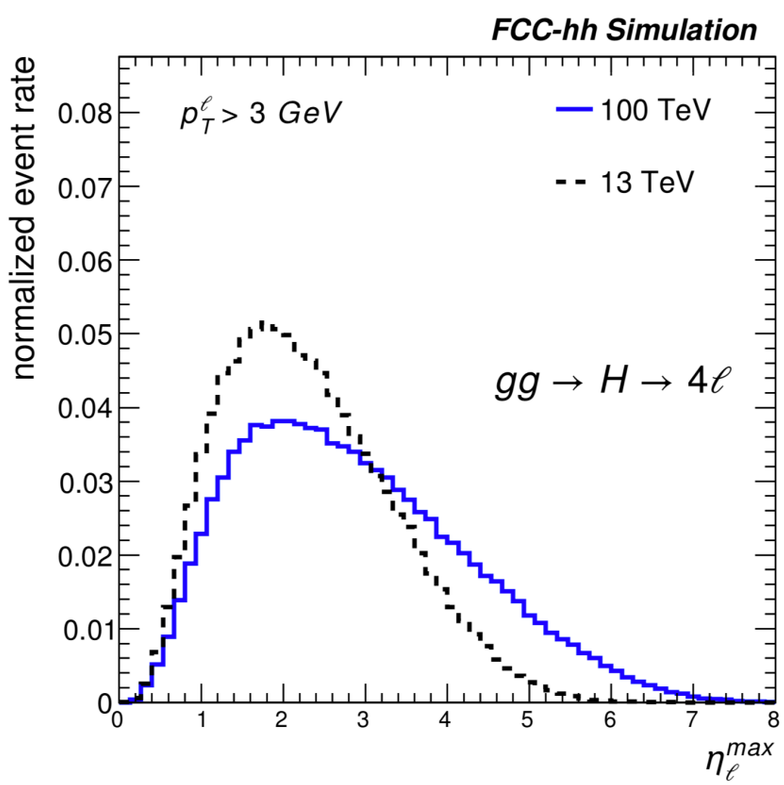
→ interesting physics sticks out more !

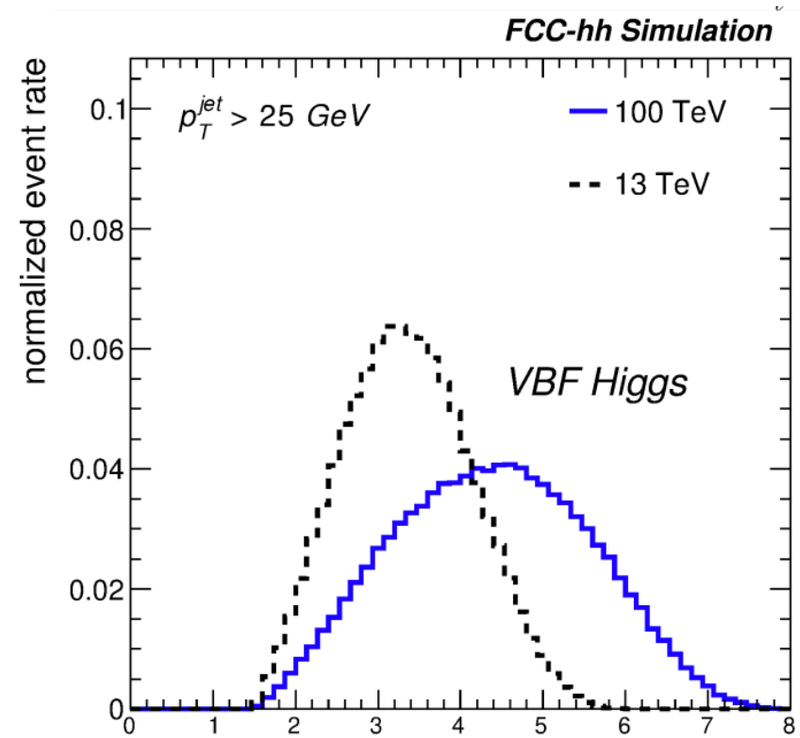
Detector constraints from "threshold" physics

SM Physics produced at threshold is more forward @100TeV
→ in order to maintain sensitivity need **large rapidity** (with tracking) and **low p_T** coverage

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







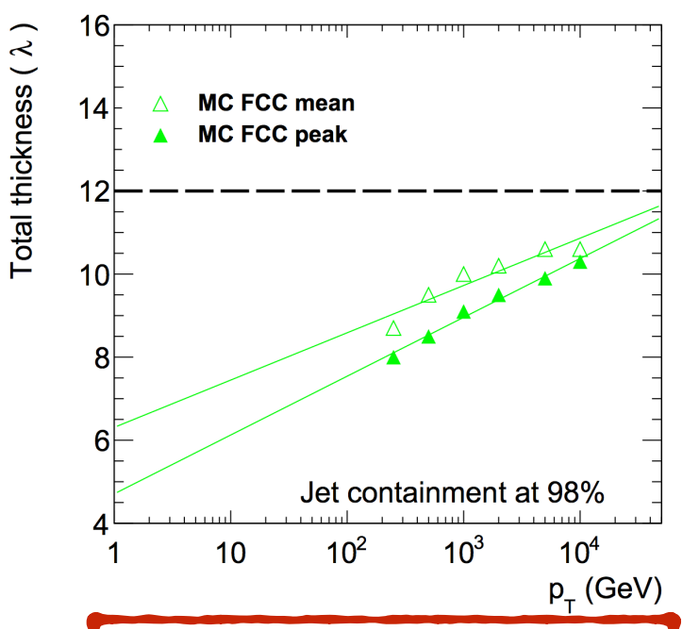
Detector constraints from "boosted" physics

- The boosted regime:
  → measure leptons, jets, photons, muons originating multi-TeV resonances

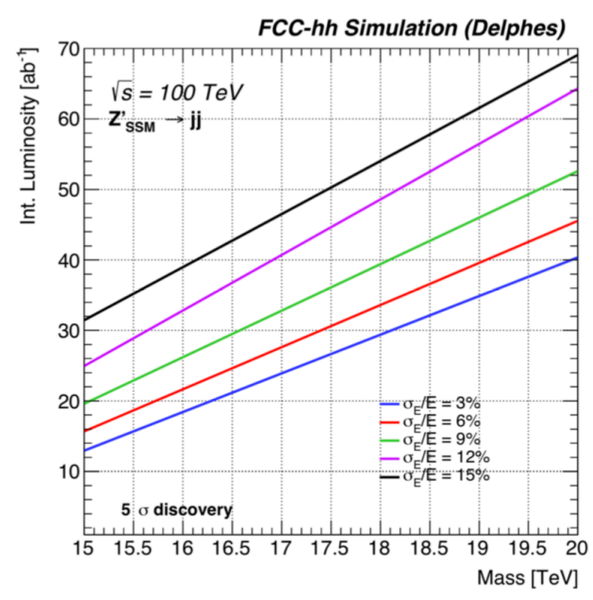
Tracking: $\frac{\sigma(p)}{p} \approx \frac{p\sigma_x}{BL^2}$

Calorimeters: $\frac{\sigma(E)}{E} \approx \frac{A}{\sqrt{E}} \bigoplus B$

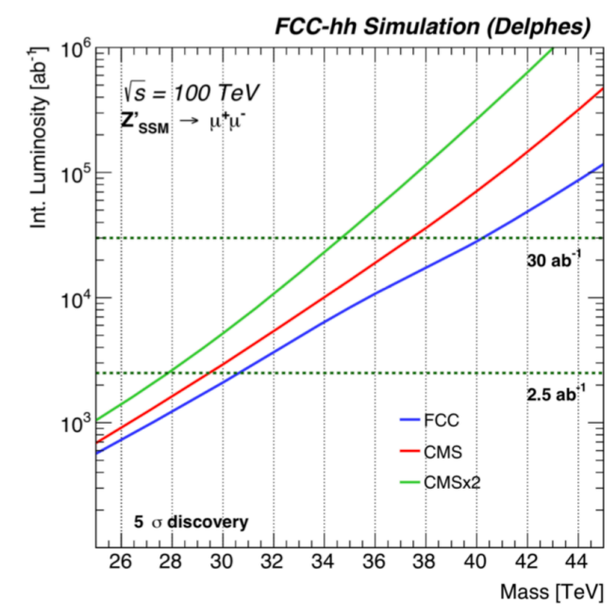
- Tracking target : **σ / p = 20% @10 TeV**
- Muons target: **σ / p = 10% @20 TeV**
- Calorimeters target: containment of p_T = 20 TeV jets



≳11 λ_I for EM + Had



high p_T jets



high p_T muons

Detector constraints from "boosted" physics

- The boosted regime:

→ measure b-jets, taus from multi-TeV resonances

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

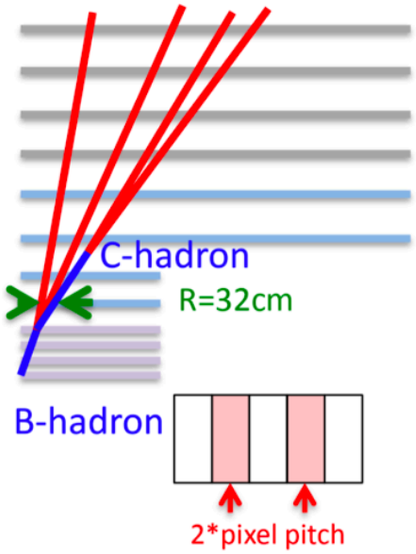
ex: 5 TeV **b-Hadron** travels **50 cm** before decaying
5 TeV **tau lepton** travels **10 cm** before decaying

→ extend pixel detector further?

- useful also for exotic topologies (disappearing tracks and generic BSM Long-lived charged particles)

→ re-think reconstruction algorithms:

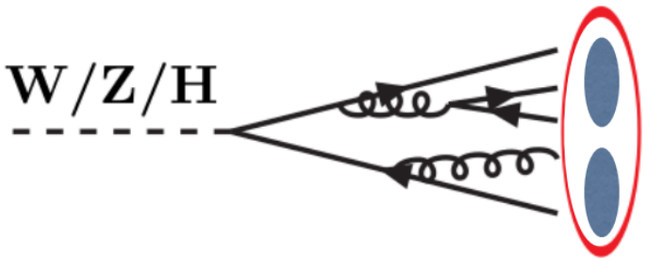
- hard to reconstruct displaced vertices
- **exploit hit multiplicity discontinuity**



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

- displaced vertices

- highly granular sub-detectors:
  - Tracker - pixel: 10 μm @ 2cm → $\sigma_{\eta\times\varphi} \approx$ 5 mrad
  - Calorimeters: 2 cm @ 2m → $\sigma_{\eta\times\varphi} \approx$ 10 mrad



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

Why Higgs at future hadron colliders?

- Large Higgs production rates (x20-60 cross-section wrt to LHC):
  - 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?)

Why measuring Higgs @future hadron colliders

- 100 TeV provides **unique and complementary measurements** to ee colliders:
  - **Higgs self-coupling**
  - **top Yukawa**
  - **Higgs → invisible**
  - **rare decays** (BR(μμ), BR(Zɣ), 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

- Assuming, we know production xsec and luminosity, at pp colliders we **measure BR(i) = Γ_i / Γ_H**

- By performing measurements of ratios of couplings, (or BRs), FCC-ee allows to "convert" **relative measurements into absolute** via **HZZ**

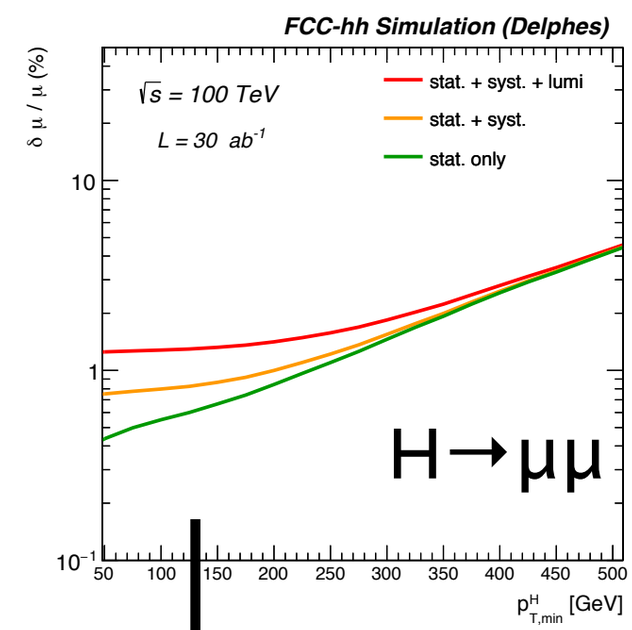
$$BR(H \to XX) / BR(H \to ZZ) \approx g_X^{\,2} / g_Z^{\,2}$$

FCC-ee

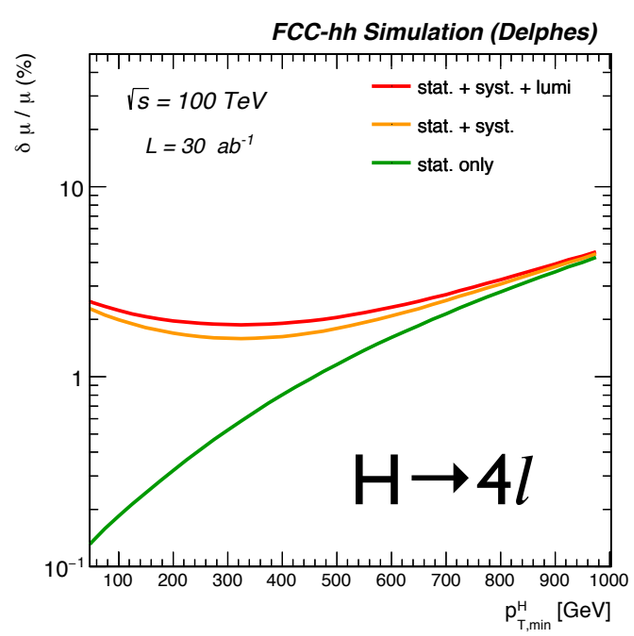
Higgs decays

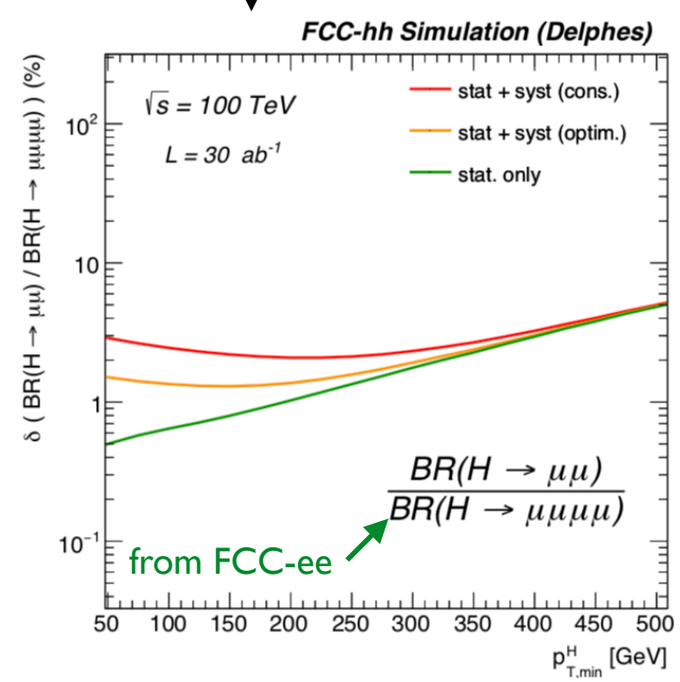
- study sensitivity as a function of **minimum $p_T(H)$** requirement in the **γγ, ZZ(4l), μμ and Z(ll)γ** channels
- **low** $p_T(H)$: **large statistics** and **high syst.** unc.
- **large** $p_T(H)$: **small statistics** and **small syst.** unc.
- **O(1-2%) precision on BR** achievable up to very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

- 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 $p_T \to \infty$



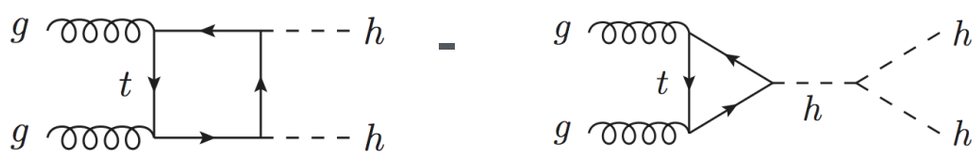
- measure **ratios of BRs** to cancel correlated sources of systematics:
  - luminosity
  - object efficiencies
  - production cross-section (theory)



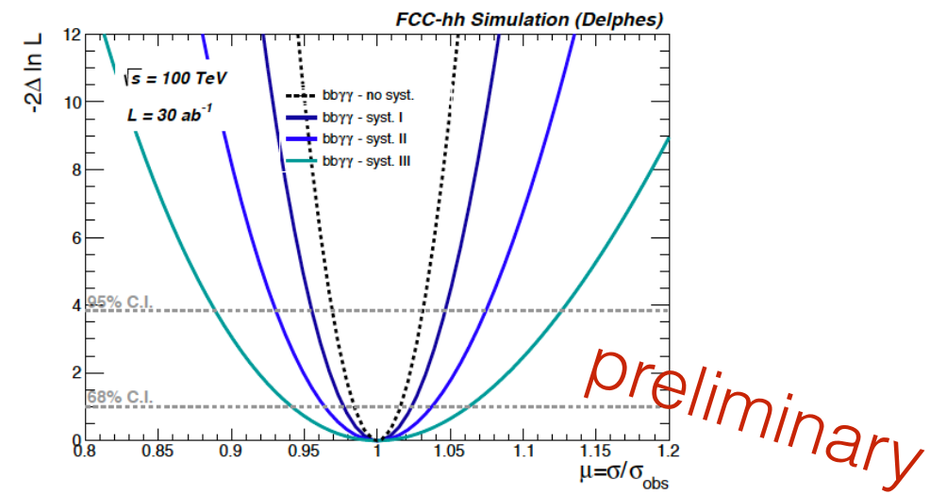


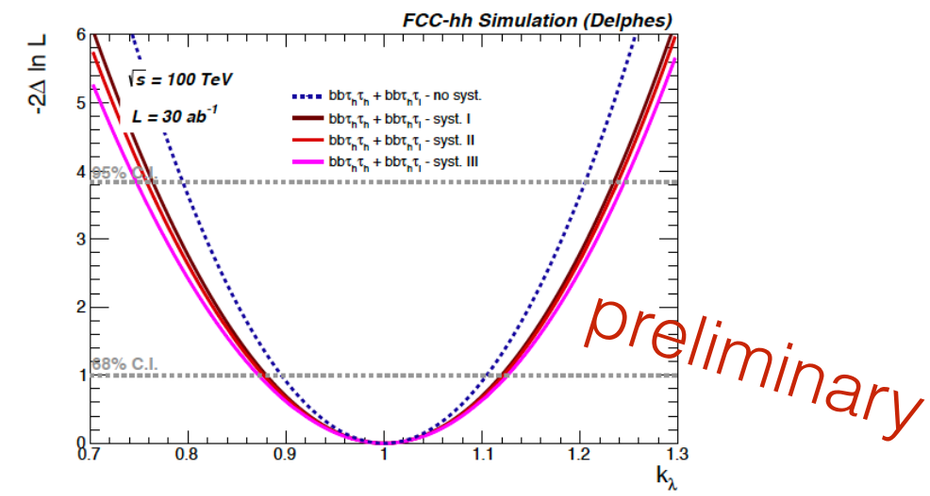
G. Ortona, MS, MLM
[2004.03505]

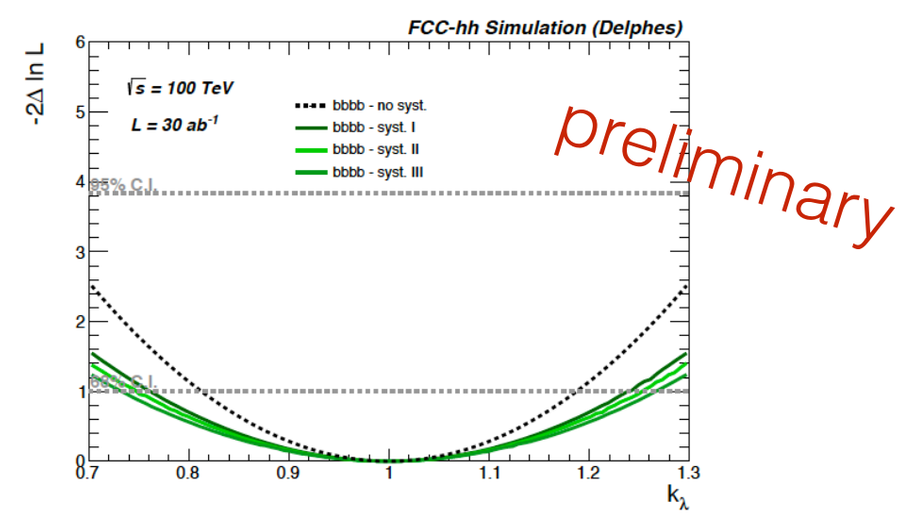
Higgs self-coupling



- 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:
  - $\sigma(100\,\text{TeV})/\sigma(14\,\text{TeV}) \approx 40$ (and Lx10)
  - x400 in event yields and x20 in precision
- main channels studied (using MVA):
  - bbγγ ($\delta k_\lambda / k_\lambda$ ~3-8%)
  - bbττ ($\delta k_\lambda / k_\lambda$ ~12%)
  - bbZZ(4l) ($\delta k_\lambda / k_\lambda$ ~15%)
  - bbbb ($\delta k_\lambda / k_\lambda$ ~22%)





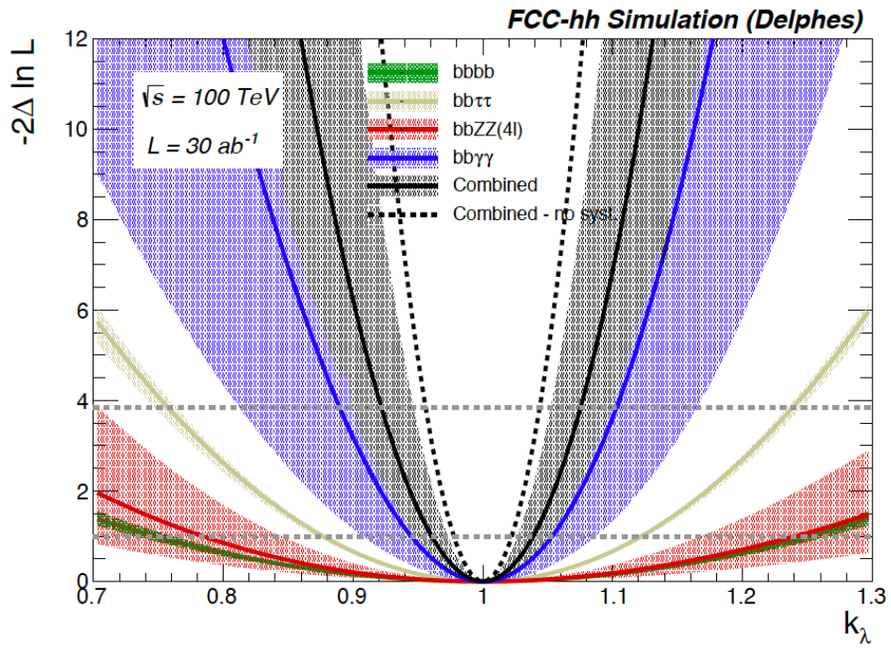


Higgs self-coupling (combination)

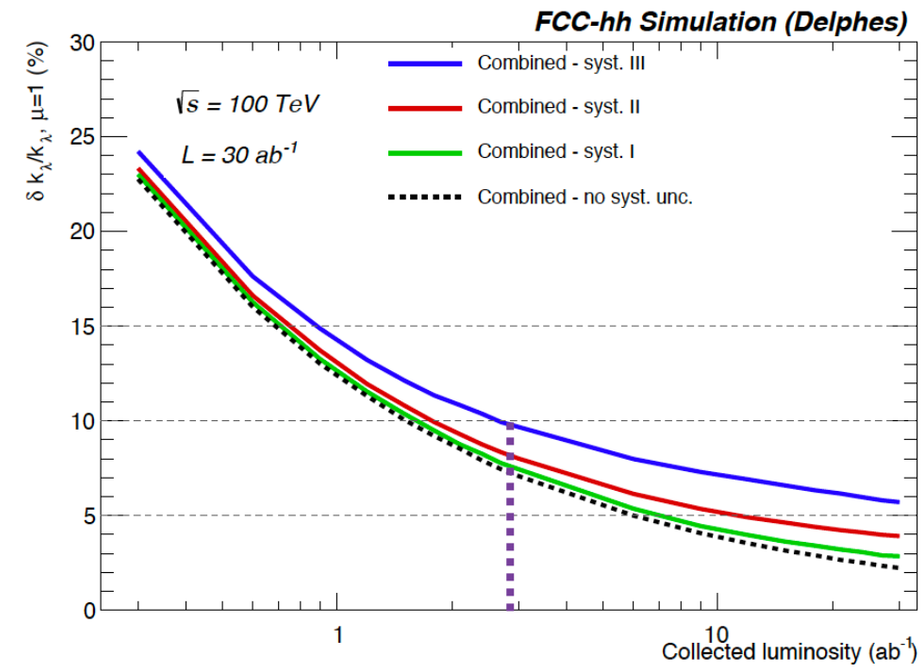
preliminary

G. Ortona, MS, MLM

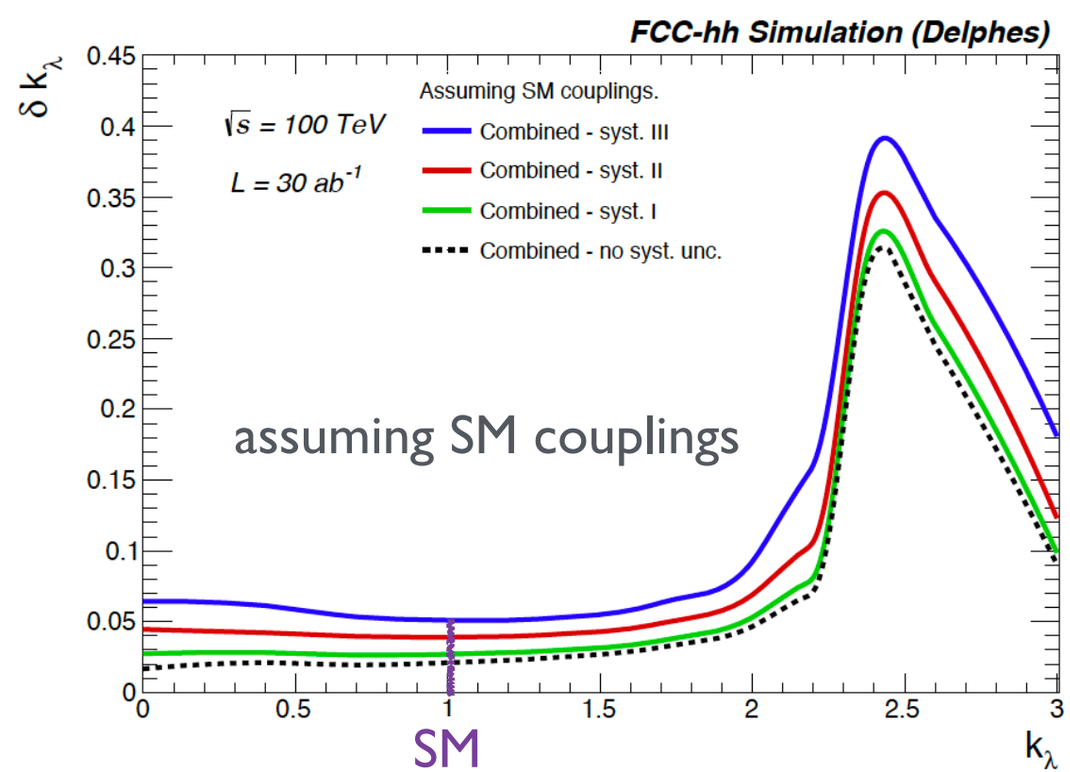
[2004.03505]



$\delta k_\lambda / k_\lambda$ ~3.0-5.5% assuming SM couplings



only 3 ab^{-1} , few years of running @100 TeV to reach 10% precision



Summary Higgs measurements

	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%**	**$BR_{inv} < 0.025\%$**

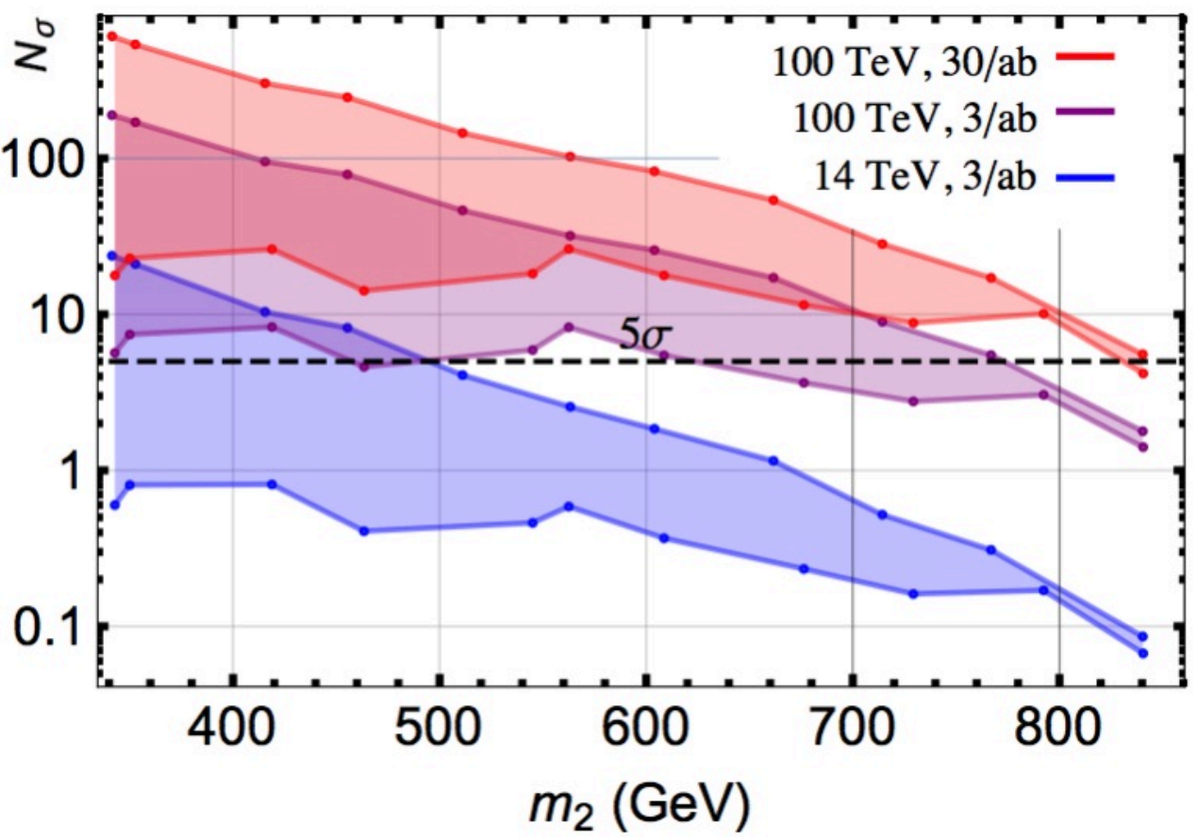
* From BR ratios wrt B(H→4l) @ FCC-ee

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

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

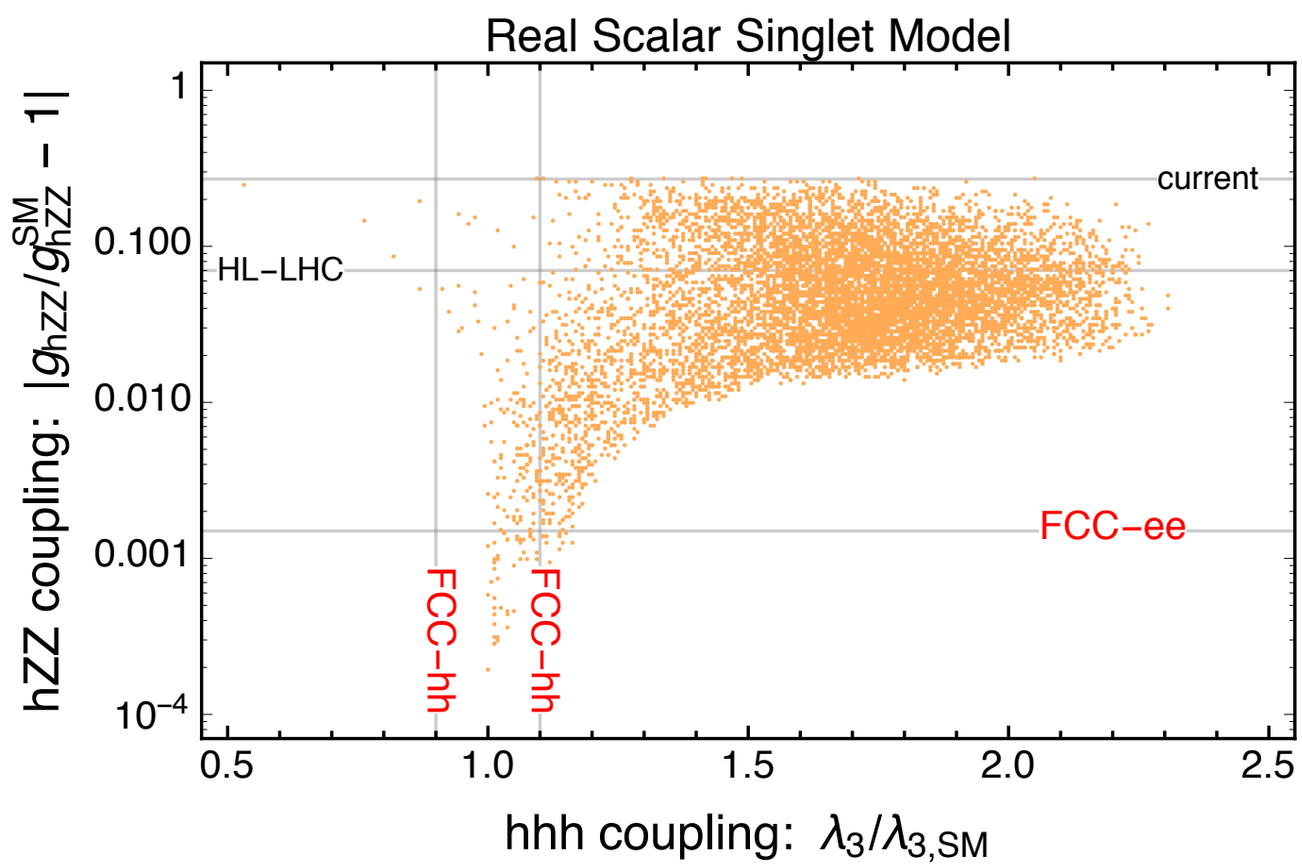
- **Strong 1st order EWPT** (and CP violation) needed to explain large observed **baryon asymmetry** in our universe
- Can be achieved with extension of SM + singlet

Direct detection of extra Higgs states



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

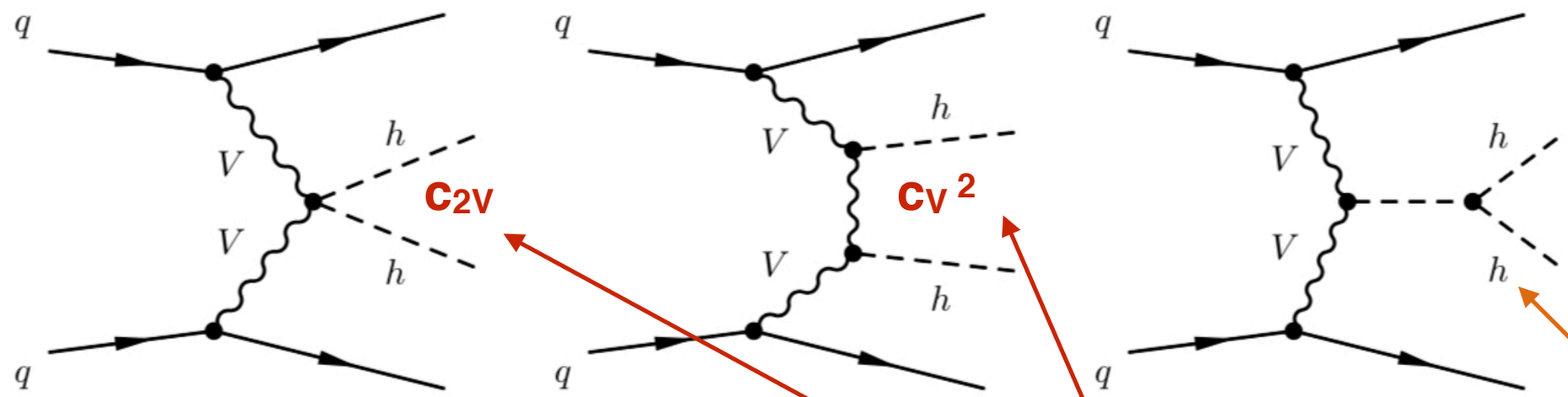
Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh



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

$W_L W_L \to HH$

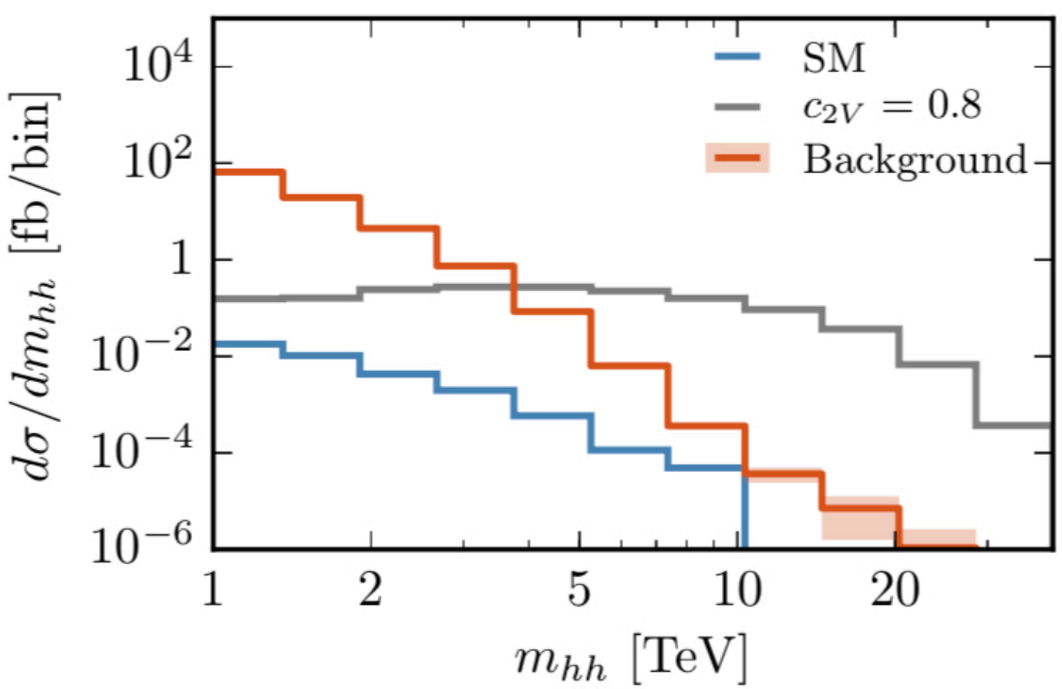
F. Bishara, R. Contino, J. Rojo

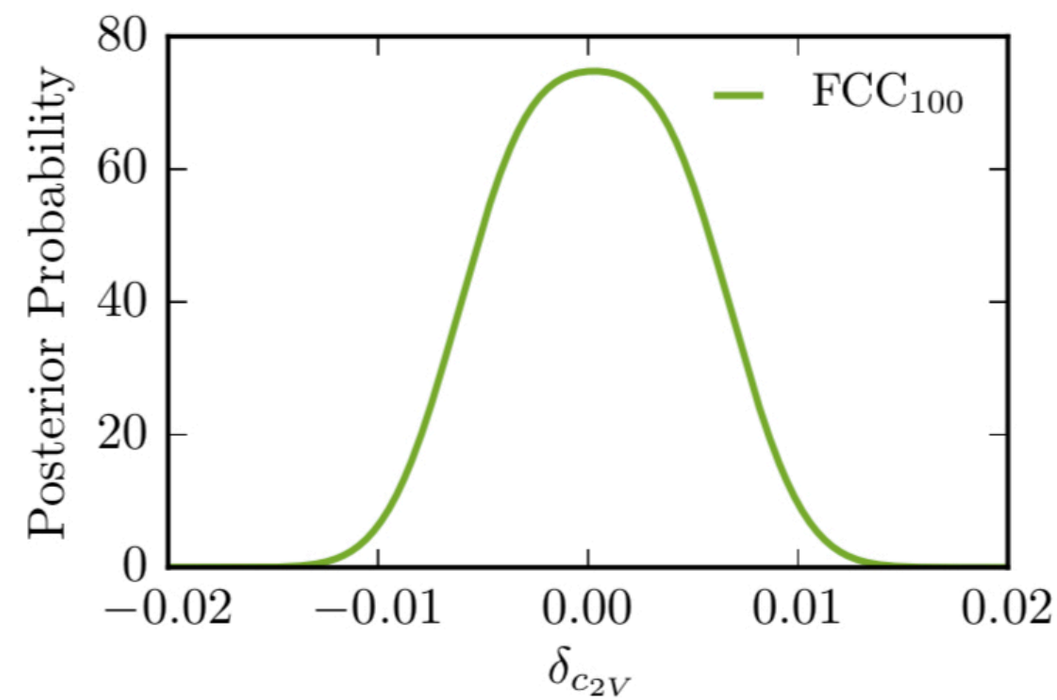


negligible at large m_{HH}

$$A(\mathrm{V_L V_L} \to \mathrm{HH}) \sim \frac{\hat{s}}{v^2}\underbrace{(c_{2V} - c_V^2)}_{0 \text{ in the SM}} + \mathcal{O}(m_W^2/\hat{s}),$$

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

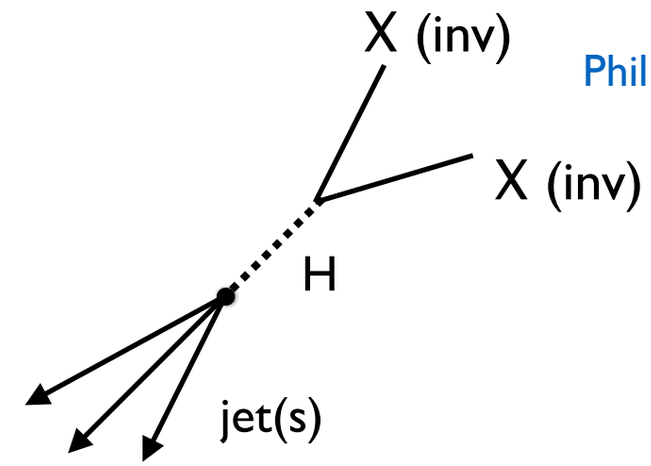




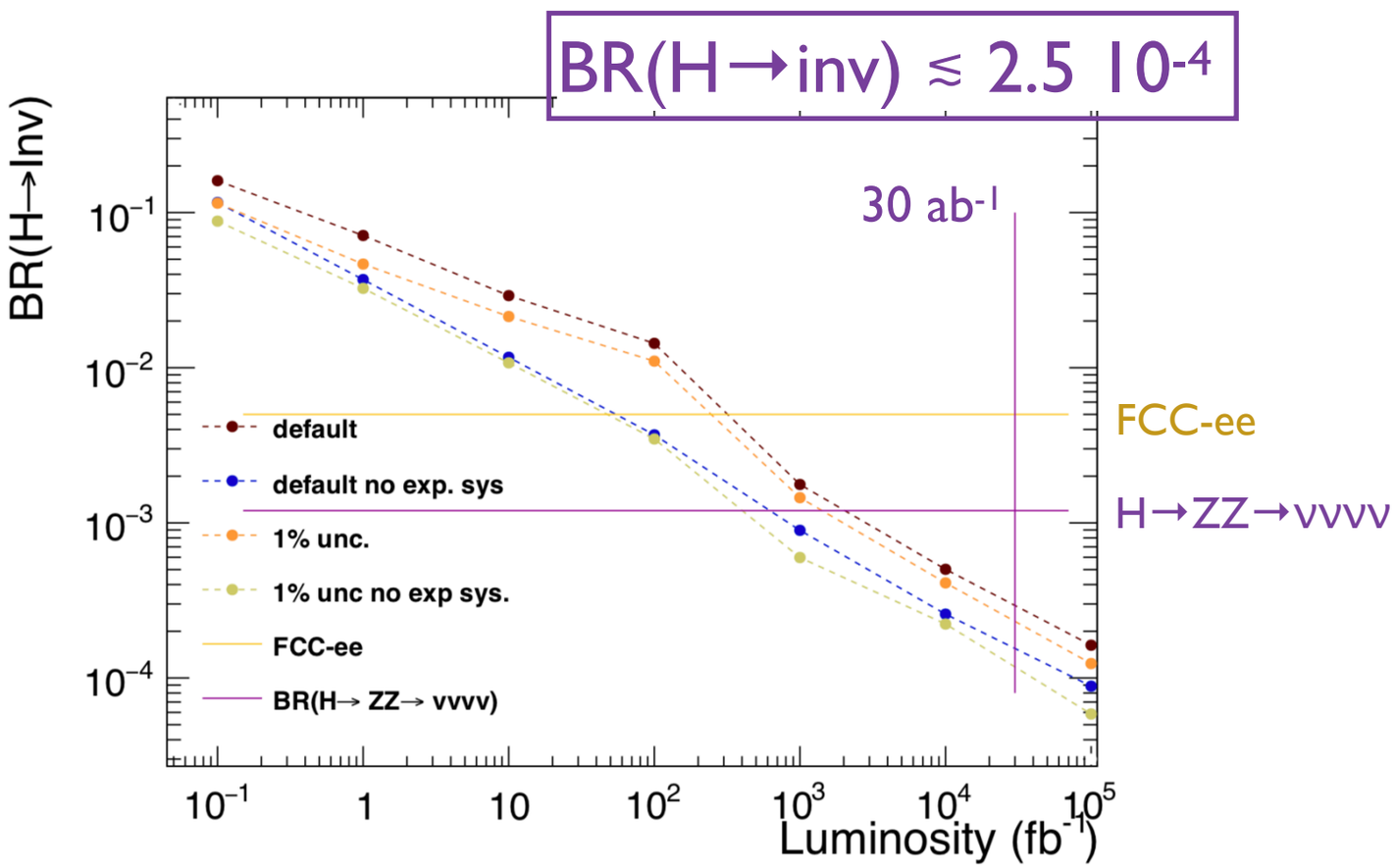
With c_V from FCC-ee, $\delta c_{2V} < 1\%$

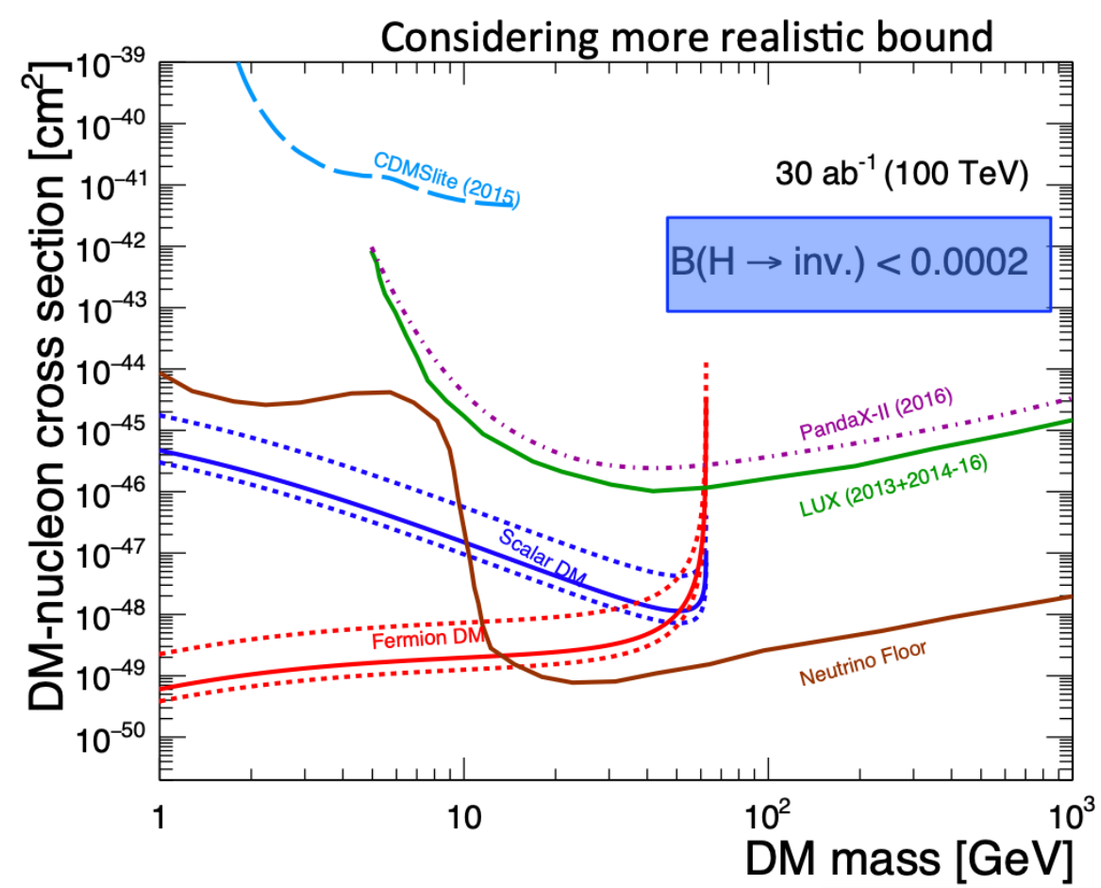
H→invisible

Phil Harris



- 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 from Z→ee/μμ control regions (high stat).

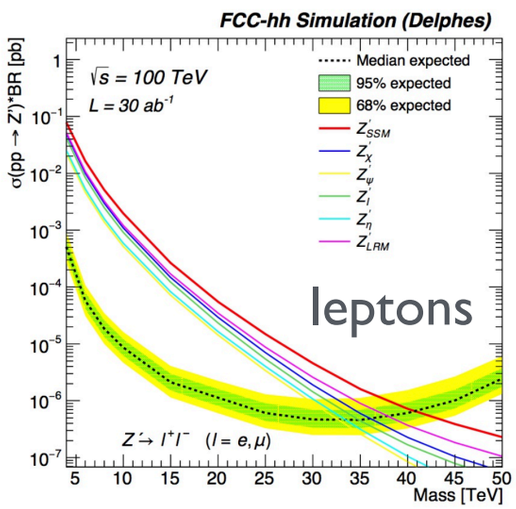


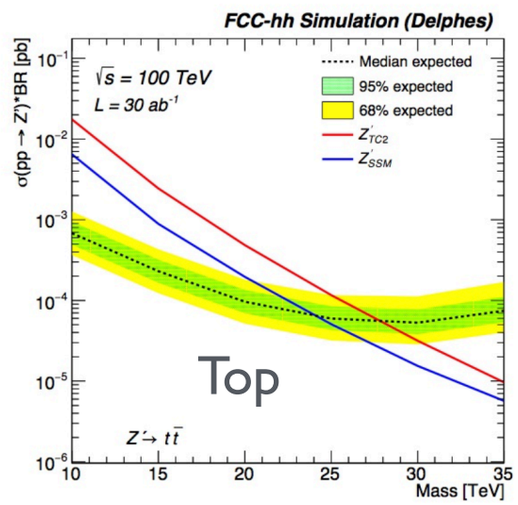


Direct searches: Heavy Resonances

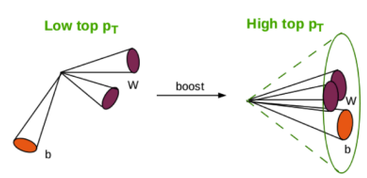
[1902.11217]

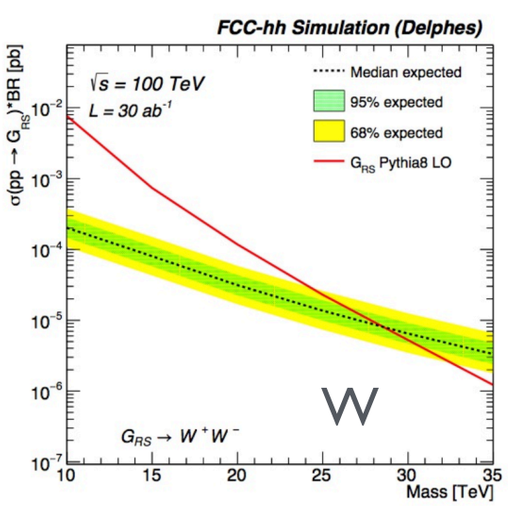
- Mass reach should increases by a factor ~7 from LHC to FCC-hh
- Direct "simple" sensitivity allow to assess collider potential, and help designing detector …

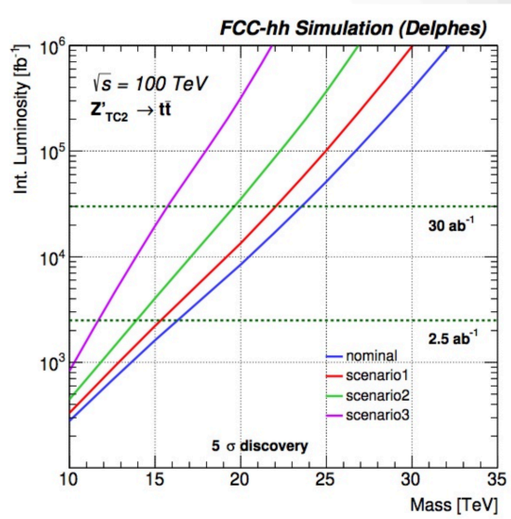




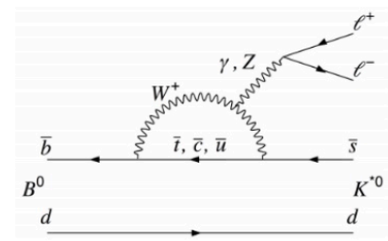
Reach up to 40TeV this very simple case!

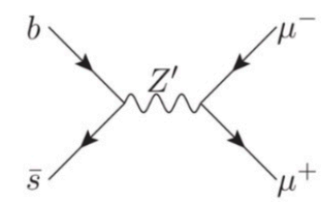




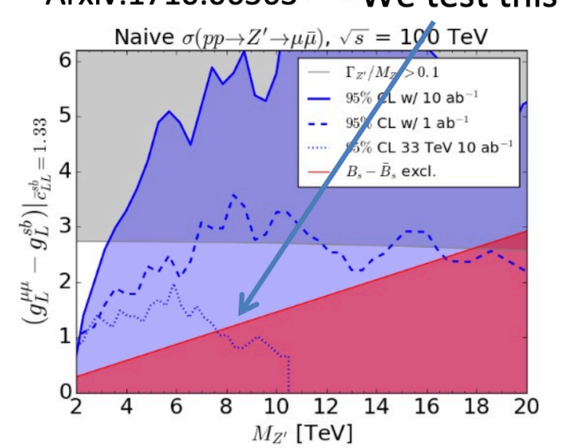


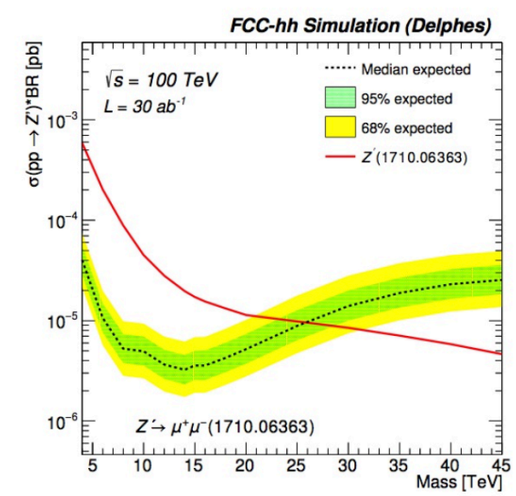
"Flavour anomalies" inspired model





Arxiv:1710.06363 We test this line

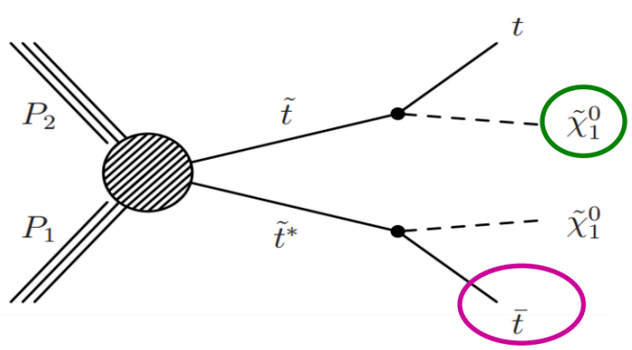


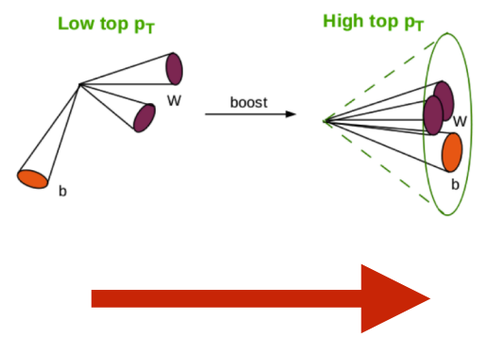


The FCC-hh can exclude all the allowed parameter space

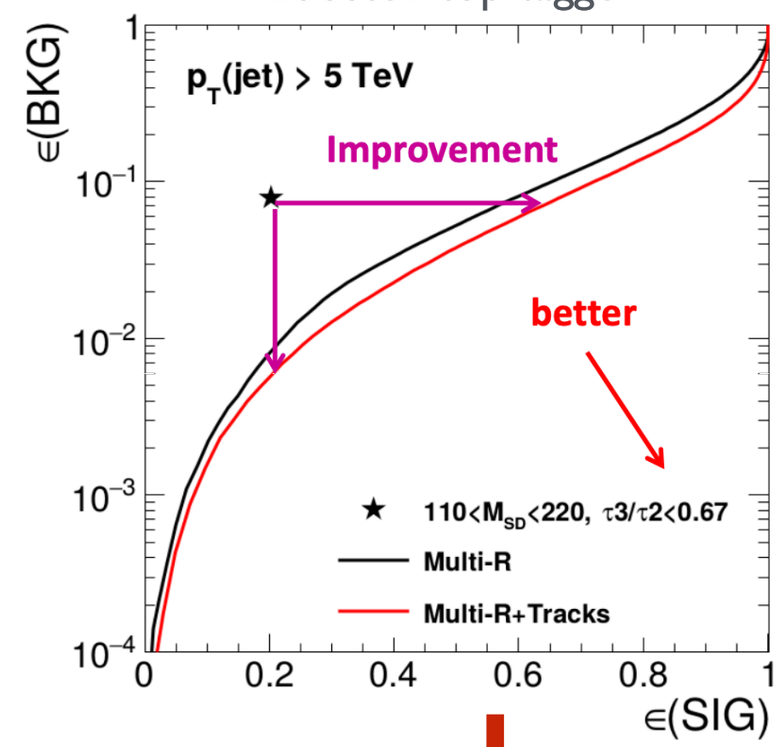
Direct searches: SUSY

Hadronic stop search

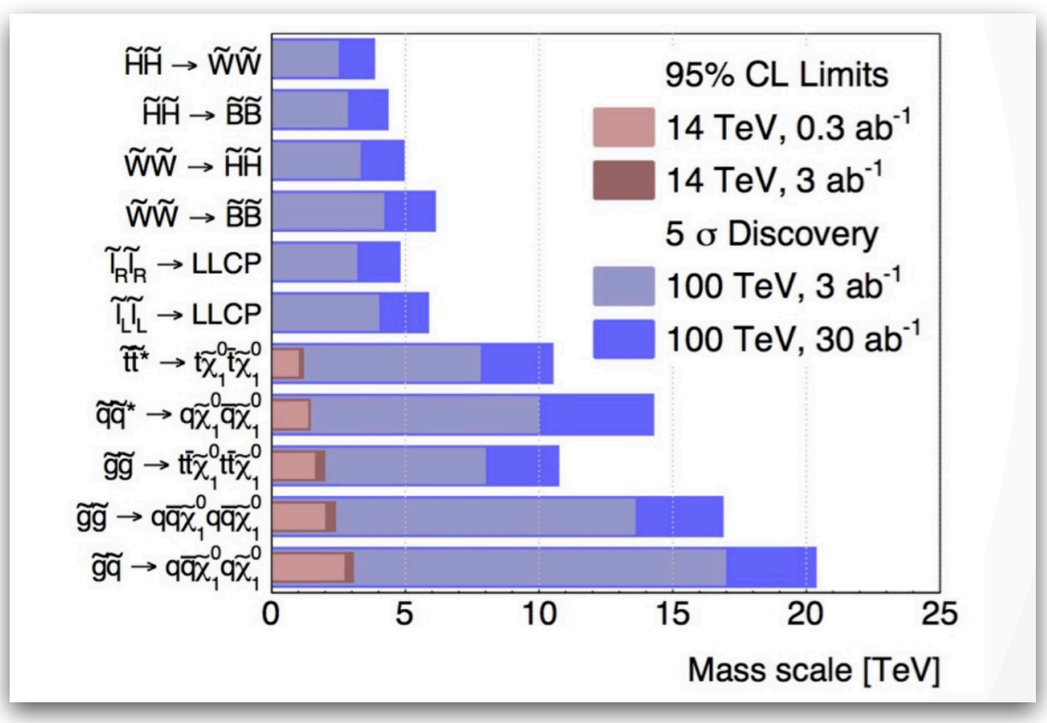


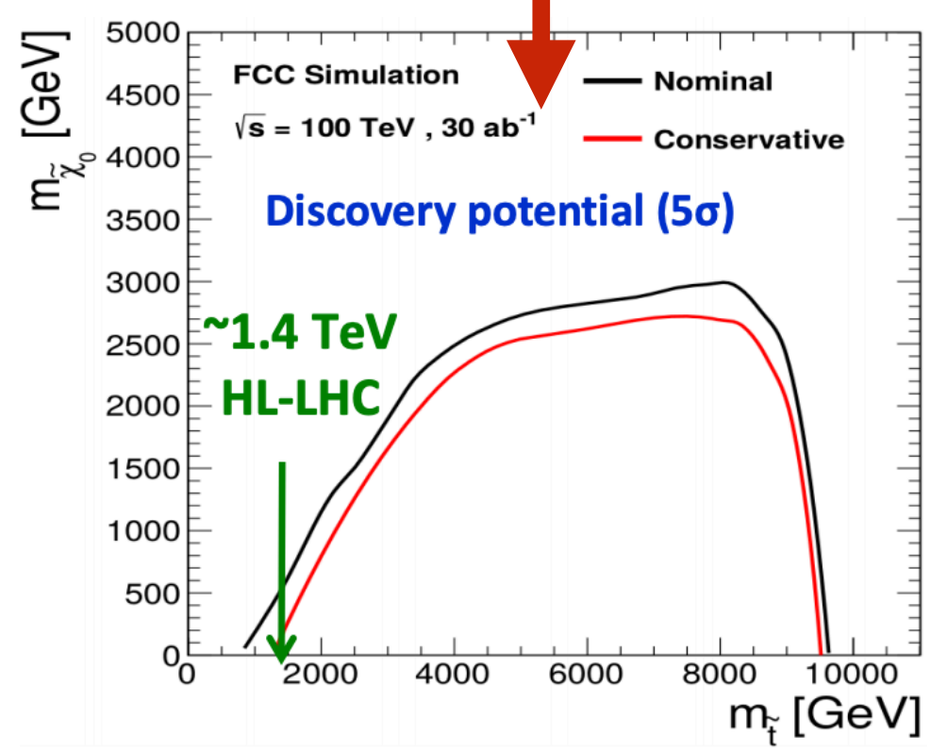


Boosted top tagger



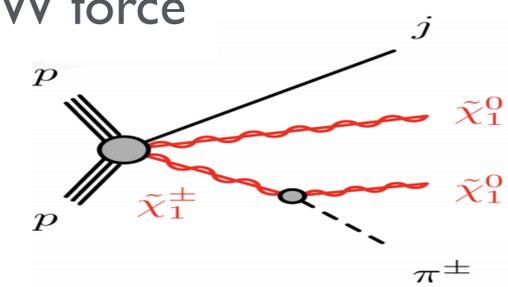
- stop m = 10 TeV
- gluino m = 15 TeV



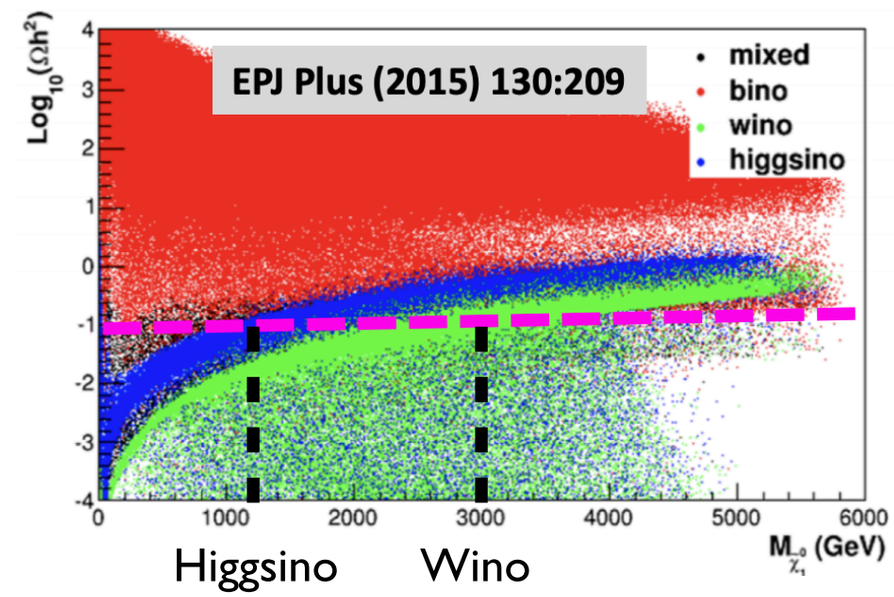


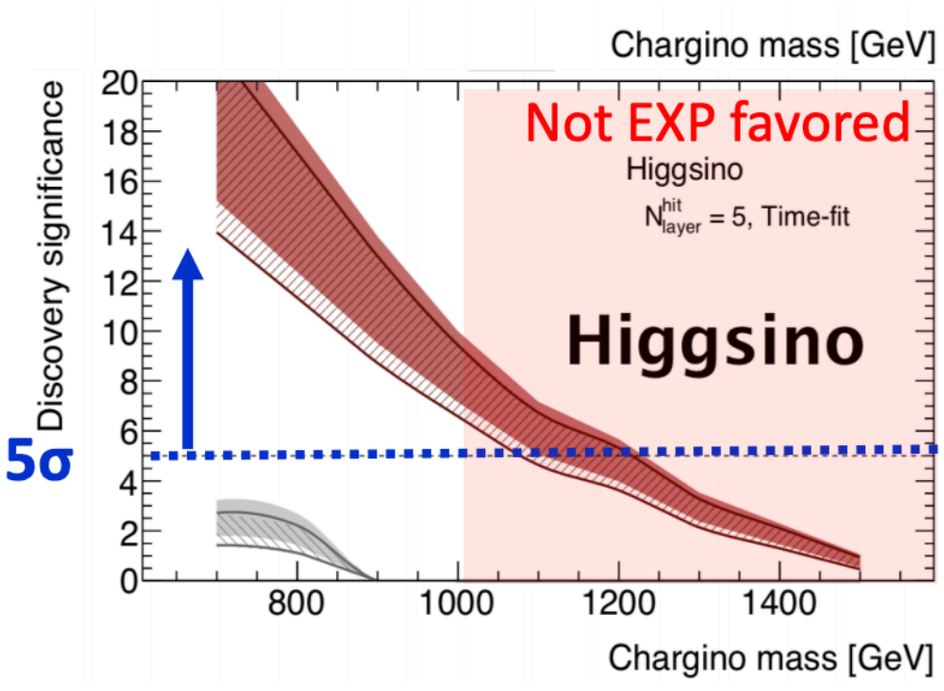
Disappearing tracks

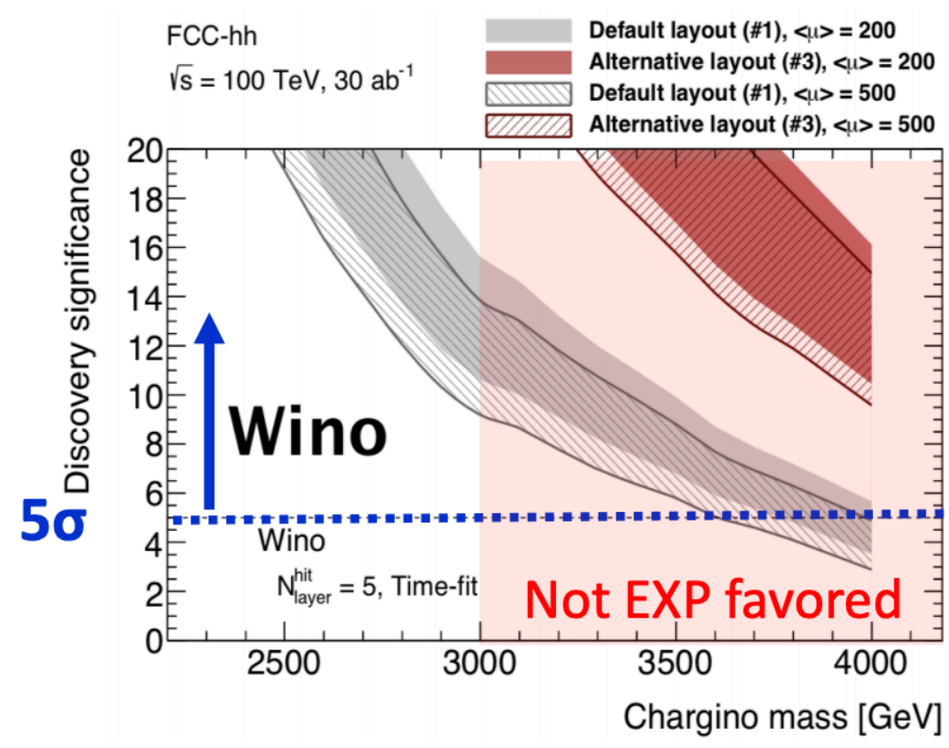
- Simplest WIMP DM that annihilate with EW force
- Higgsino (1 TeV), Wino (3 TeV) DM
- $\Delta m(\chi^{\pm}, \mathrm{LSP}) \sim 160$ MeV/350 MeV
  - hardly detectable soft pion
  - leads to characteristic "disappearing track" signature"



observed relic abundance







FCC-hh can discover Higgsino and Wino dark matter

Conclusions & outlook

- **Large statistics** (**10^{10} Higgs bosons**) 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)
- Can directly and indirectly exclude compelling classes of models compatible with 1st order electro-weak phase transition
- Unprecedented reach for direct searches , heavy resonances, SUSY, Dark Matter searches

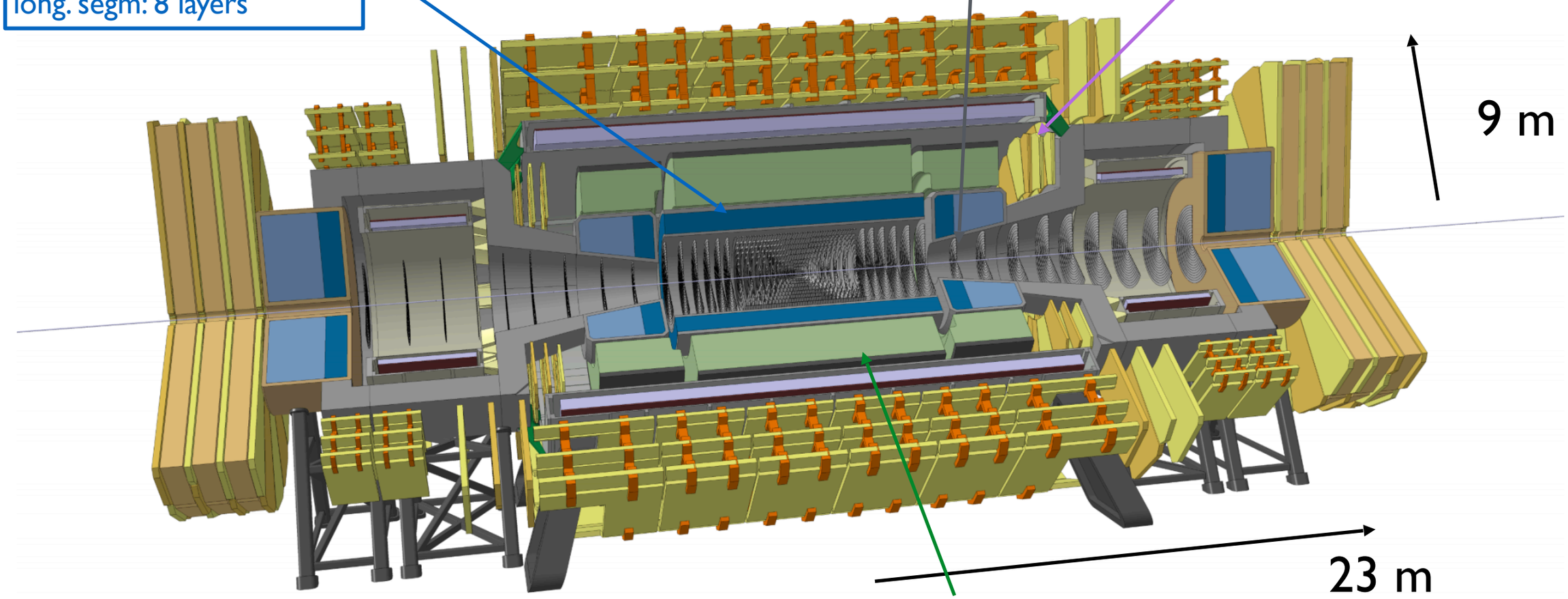
Backup

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



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

Machine and detector requirements

lumi & pile-up

parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
circumference	km	26.7	26.7	26.7	97.8
peak $\mathcal{L} \times 10^{34}$	$cm^{-2}s^{-1}$	1	5	25	30
bunch spacing	ns	25	25	25	25
number of bunches		2808	2808	2808	10600
goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel}	mbarn	85	85	91	108
σ_{tot}	mbarn	111	111	126	153
BC rate	MHz	31.6	31.6	31.6	32.5
peak pp collision rate	GHz	0.85	4.25	22.8	32.4
peak av. PU events/BC		27	135	721	997
rms luminous region σ_z	mm	45	57	57	49
line PU density	mm^{-1}	0.2	0.9	5	8.1
time PU density	ps^{-1}	0.1	0.28	1.51	2.43
$dN_{ch}/d\eta\|_{\eta=0}$		7	7	8	9.6
charged tracks per collision N_{ch}		95	95	108	130
Rate of charged tracks	GHz	76	380	2500	4160
$<p_T>$	GeV/c	0.6	0.6	0.7	0.76
Number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm est.(FLUKA)	GHz cm^{-2}	0.1	0.7	2.7	8.4 (12)
1 MeV-neq fluence at 2.5 cm est.(FLUKA)	10^{16} cm^{-2}	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm est.(FLUKA)	MGy	1.3	13	54	270 (400)
$dE/d\eta\|_{\eta=5}$	GeV	316	316	427	765
$dP/d\eta\|_{\eta=5}$	kW	0.04	0.2	1.0	4.0

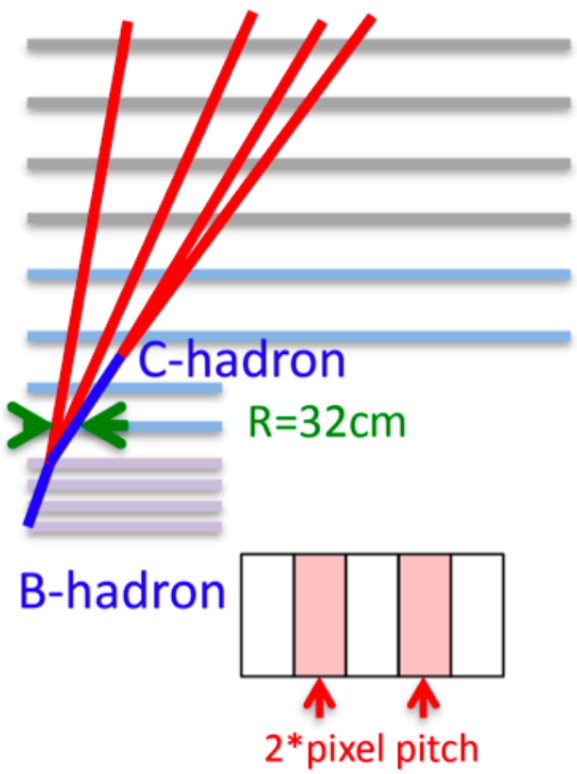
→ x6 HL-LHC

LHC: 30 PU events/bc
HL-LHC: 140 PU events/bc
FCC-hh: 1000 PU events/bc

High granularity and precision timing needed to reduce occupancy levels and for pile-up rejection

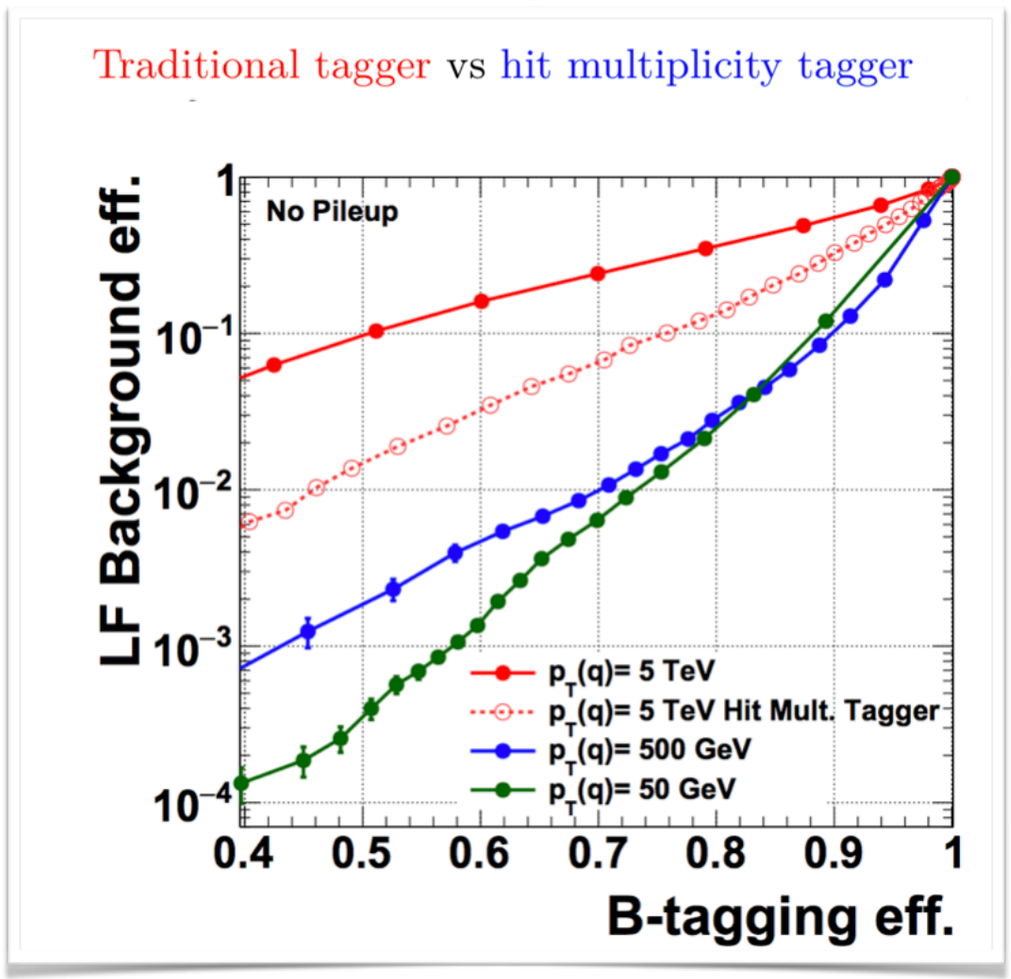
Detector requirements from high p_T searches

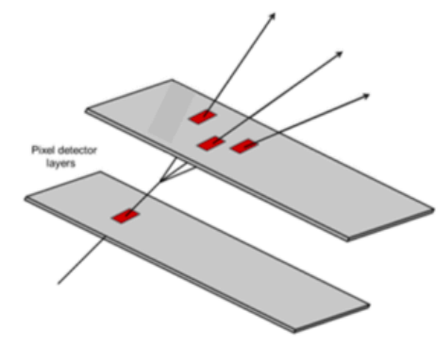
- Change in paradigm: heavy flavour tagging
- multi-TeV b-Hadrons decay outside the pixel volume
- Need to adapt identification algorithms for maintaining sensitivity in in high mass searches .



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

- displaced vertices





arXiv:1701:06832

To be verified in high pile-up environment.

Precision vs. sensitivity

- **Higher statistics shifts the balance between systematic and statistical uncertainties**. It can be exploited to define different signal regions, **with better S/B**, better systematics, **lower impact of pile-up**, pushing the potential for better measurements beyond the "systematics wall" of low-stat measurements.

- We often talk about "**precise**" Higgs measurements. What we actually aim at is "**sensitive**" tests of the Higgs properties, 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:

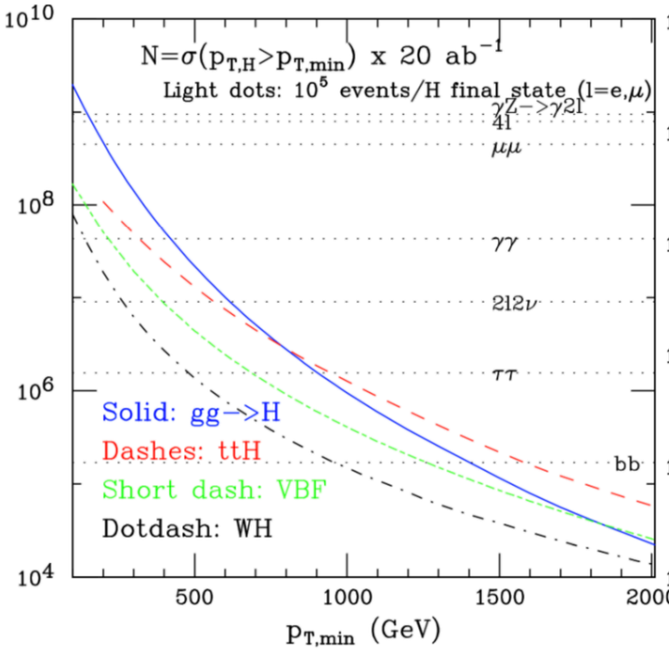
BR measurement: $\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\mathrm{TeV}}{\Lambda}\right)^2$ ⇒ **precision** probes large Λ

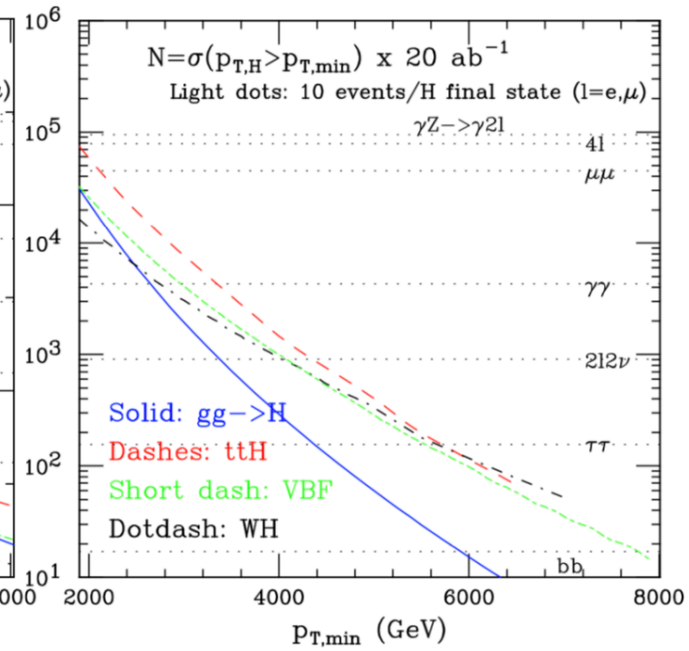
e.g. δO=1% ⇒ Λ ~ 2.5 TeV

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

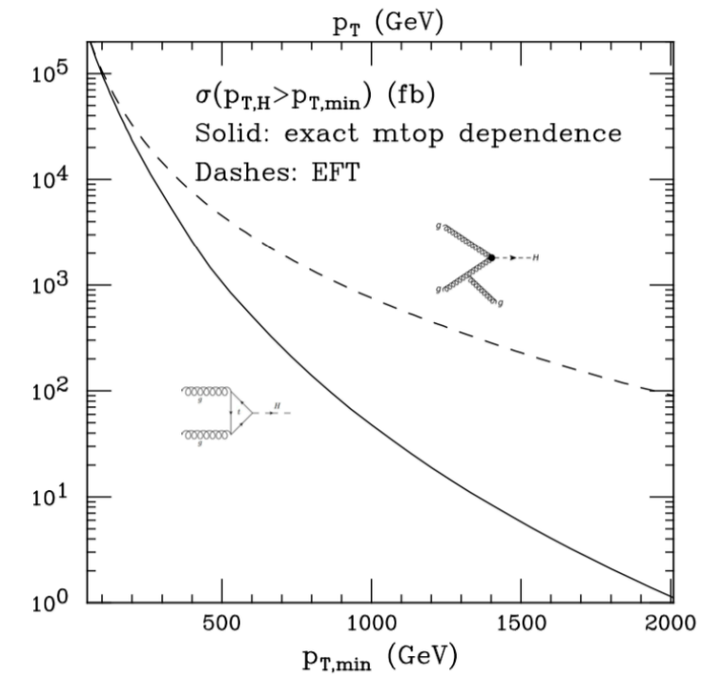
e.g. δO=15% at Q=1 TeV ⇒ Λ~2.5 TeV

Higgs at large p_T



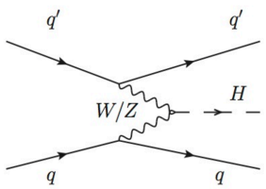


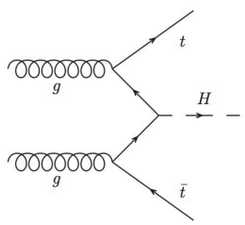
$N(p_T > p_{T,min})$



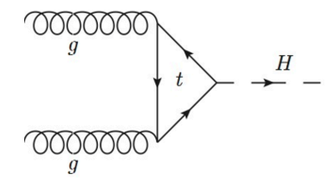
- Huge rates at large p_T :
  - **> 10^6 Higgs** produced with p_T > 1 TeV
  - Higher probability to produce large p_T Higgs from ttH/VBF/VH at large
  - Even rare decay modes can be accessed at large p_T
- Opportunity to measure the Higgs **in a new dynamical regime**
  - Higgs p_T spectrum highly sensitive to new physics.

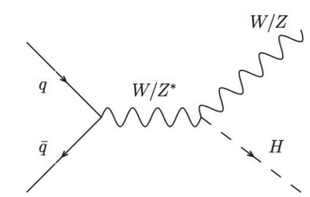
Single Higgs production @FCC-hh





	σ(13 TeV)	σ(100 TeV)	σ(100)/σ(13)
ggH (N³LO)	49 pb	803 pb	16
VBF (N²LO)	3.8 pb	69 pb	16
VH (N²LO)	2.3 pb	27 pb	11
ttH (N²LO)	0.5 pb	34 pb	55





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

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

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

	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

Factor: 1/100 1/10

reduction in stat. unc.

<u>Large statistics in various Higgs decay modes allow:</u>

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

Higgs decays: γγ - ZZ - Zγ - μμ

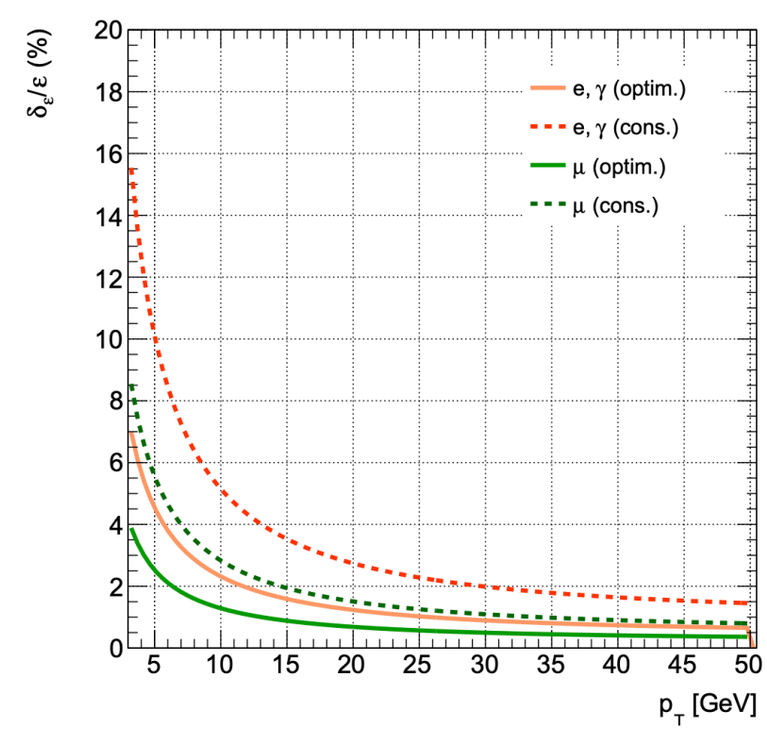
- **1% systematics on (production x luminosity)**, meant as a reference target. Assumes good theoretical progress over the next years, and **reduction of PDF+α_S uncertainties with HL-LHC + FCC-ee**.

- **e/μ/γ efficiency systematics** (shown on the right). In situ calibration, with the immense available statistics in possibly new clean channels (Z→μμγ), 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)



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

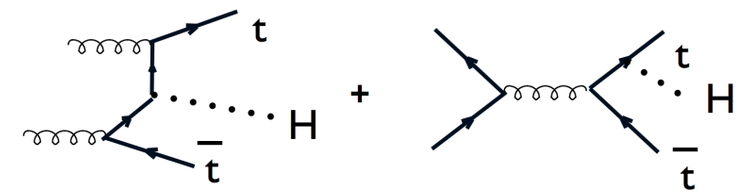
Top Yukawa (production)

- production ratio **$\sigma(ttH)/\sigma(ttZ) \approx y_t^2\, y_b^2 / g_{ttZ}^{\,2}$**
- measure **$\sigma(ttH)/\sigma(ttZ)$** in **$H/Z \to bb$** 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

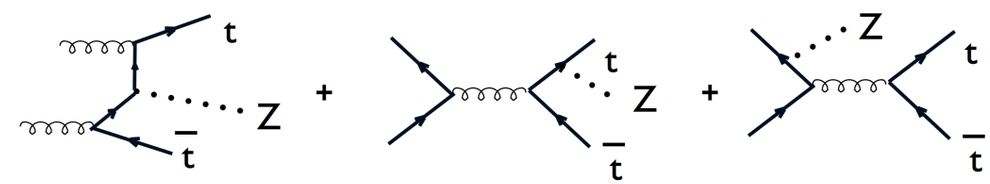
- assuming g_{ttZ} and κ_b known to 1% (from FCC-ee),

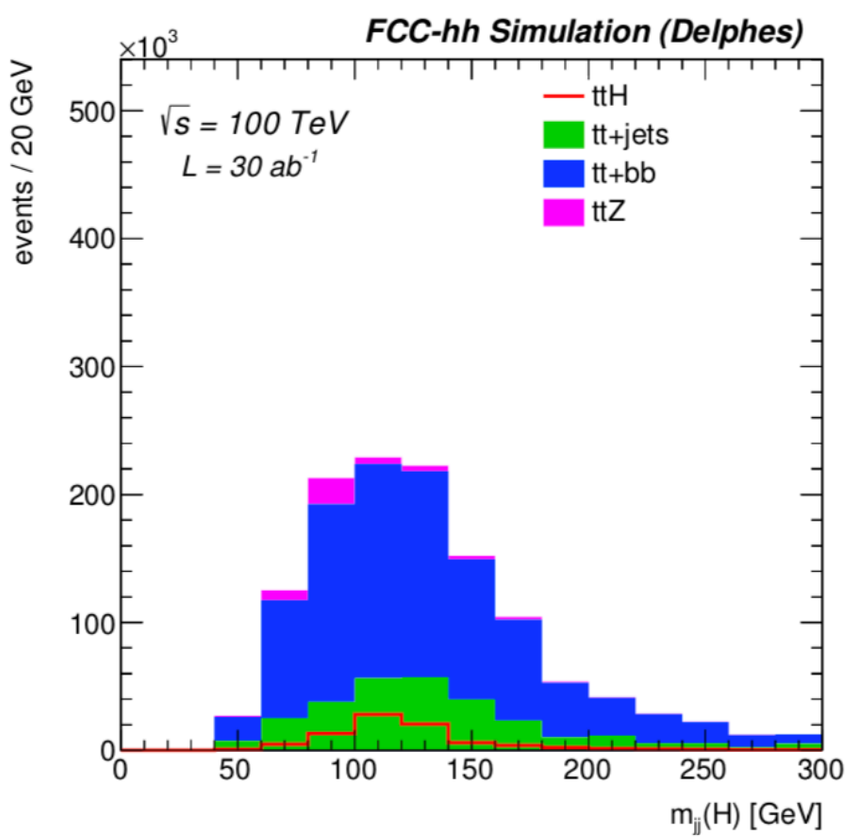
  → measure y_t to 1%

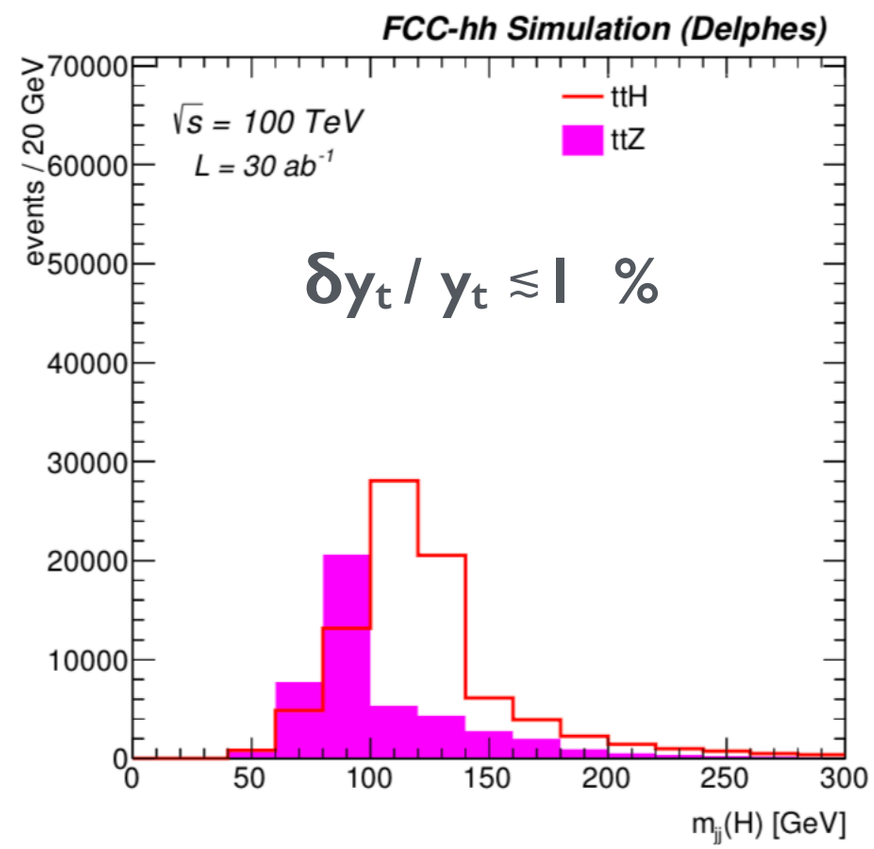
ttH



ttZ

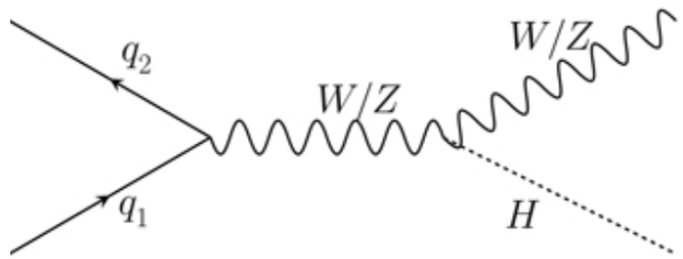


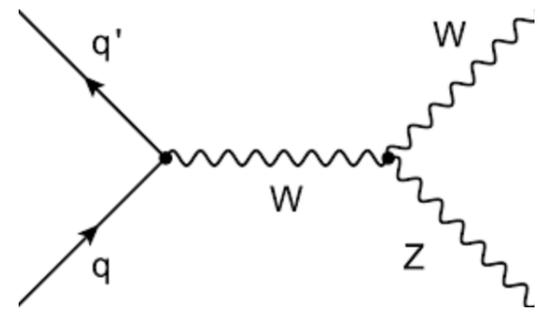




Standalone 100 TeV Higgs measurements

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





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

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

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

parton level study

$\delta G/G < 1\%$

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

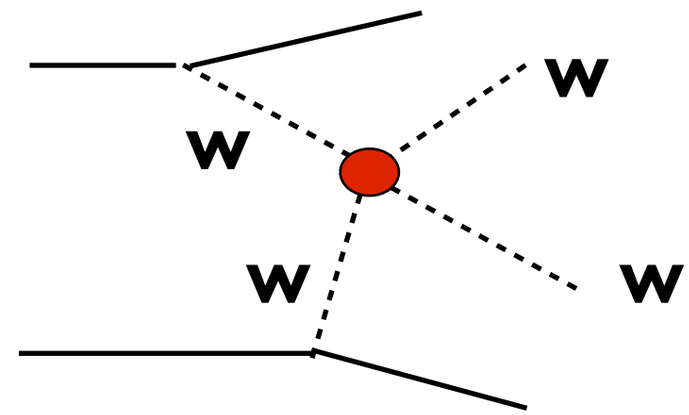
p_T^{min} (GeV)	W[e]Z[τ] (pb)	W[e]H (pb)	W[ℓ]Z[τ] $\times\varepsilon_\tau$ L	W[ℓ]H[$\tau\tau$] $\times\varepsilon_\tau$ L	$\delta R/R$
100	2.1E-2	1.0E-1	1.3E5	3.8E4	5.9E−3
150	1.0E-2	6.3E-2	6.0E4	2.4E4	7.7E−3
200	5.6E-3	3.8E-2	3.4E4	1.4E4	1.0E−2
300	2.1E-3	1.6E-2			
400	9.8E-4	7.9E-3			

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: $\sigma(\mathrm{Z}[\nu\nu]\mathrm{H}[\to\gamma\gamma])\,/\,\sigma(\mathrm{Z}[\nu\nu]\mathrm{Z}[\to e^+e^-])$

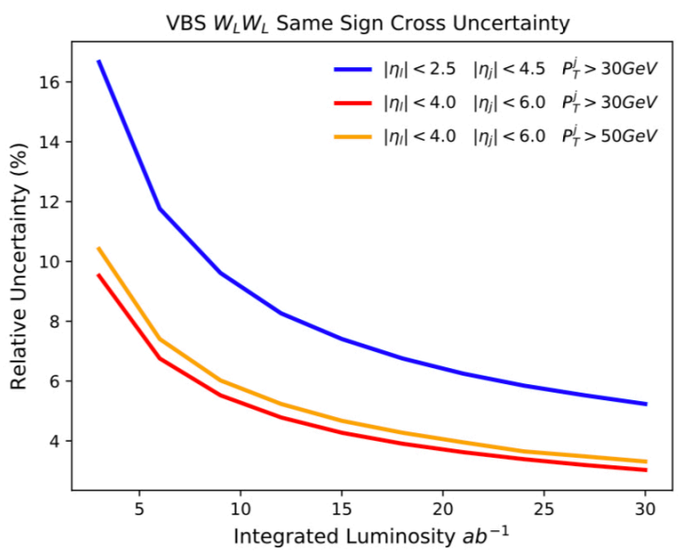
Vector Boson Scattering

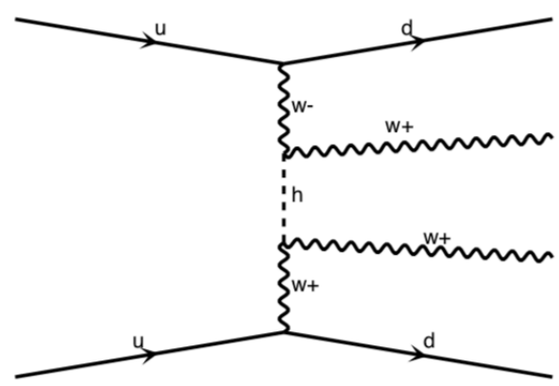
A. Sznajder, MS



large m_{WW}

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





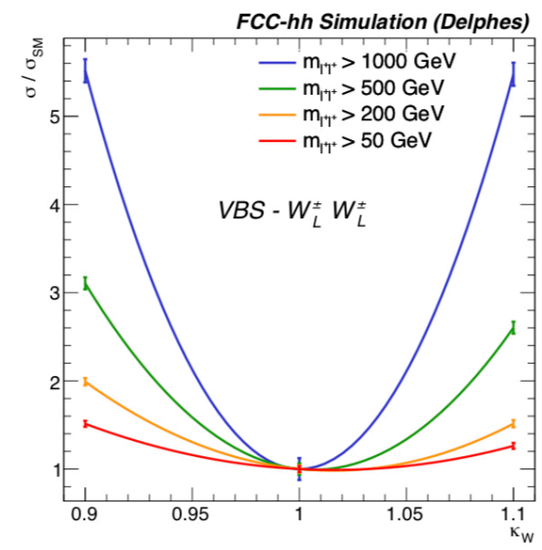
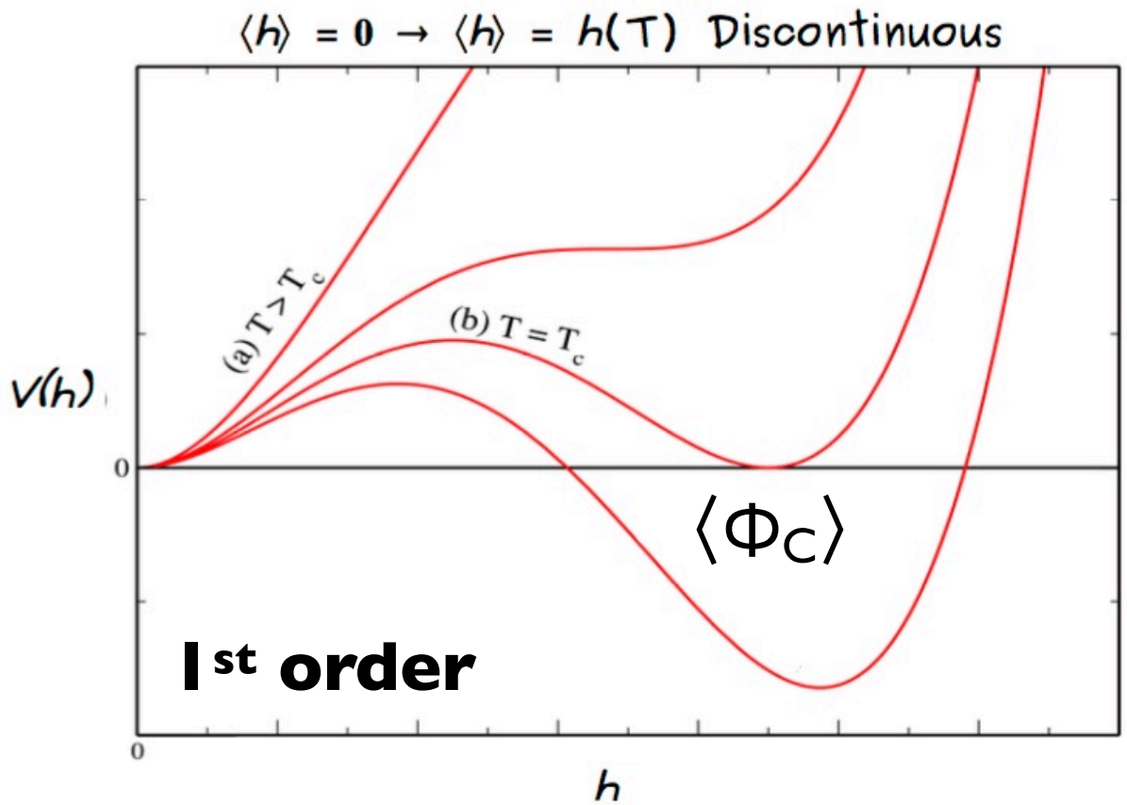
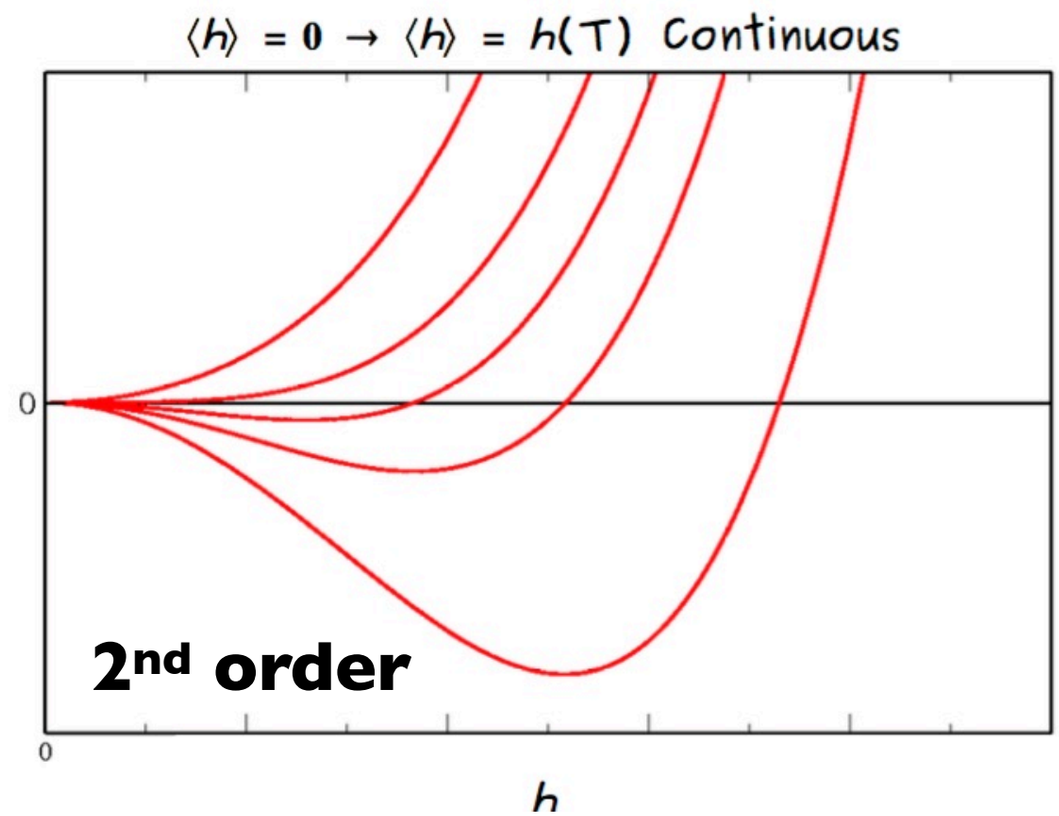


Table 4.5: Constraints on the HWW coupling modifier κ_W at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the $W_L W_L \to HH$ process.

$m_{l^+l^+}$ 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]

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

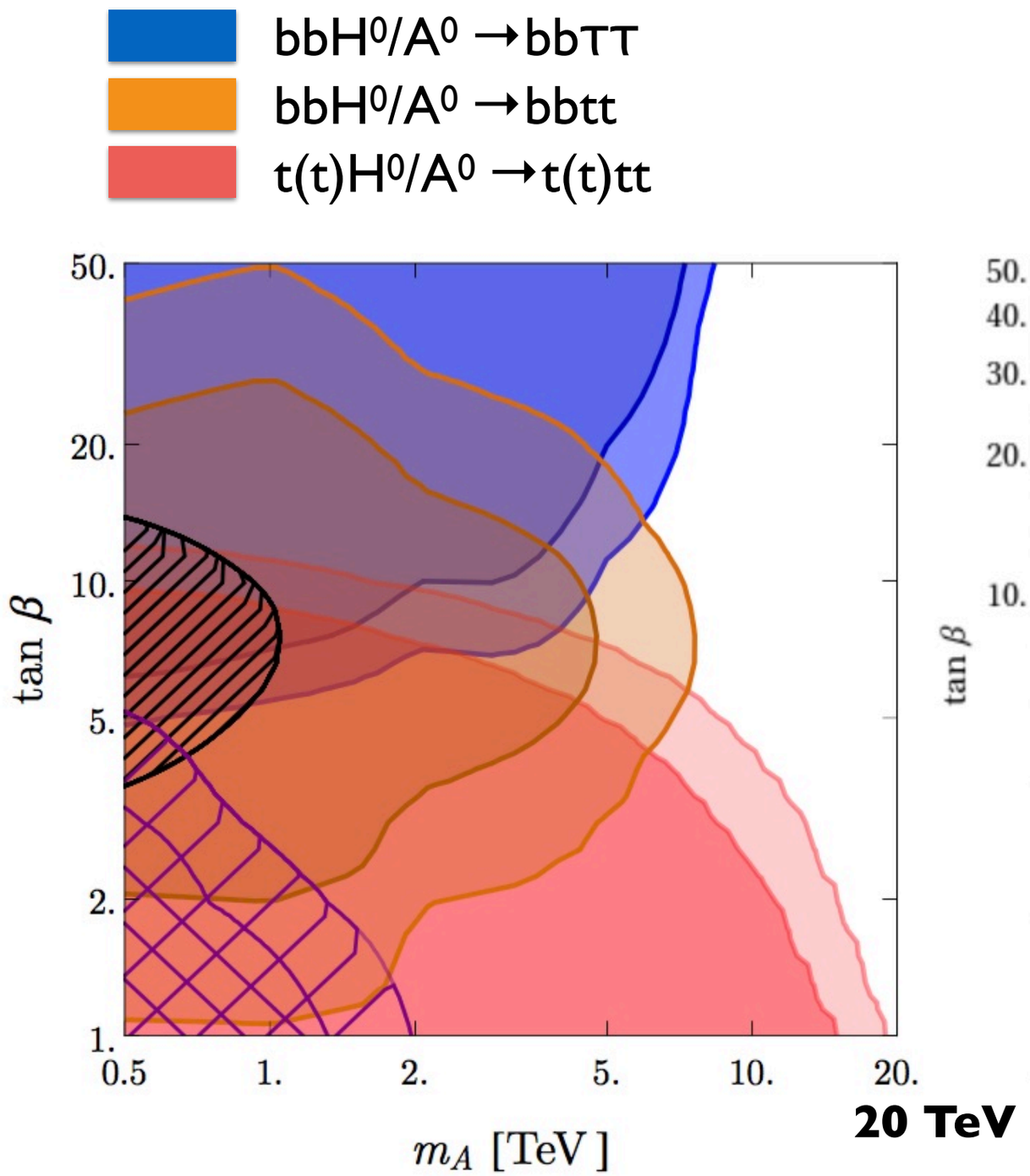
Strong 1st order phase transition $\Rightarrow$ $\langle \Phi_C \rangle > T_C$

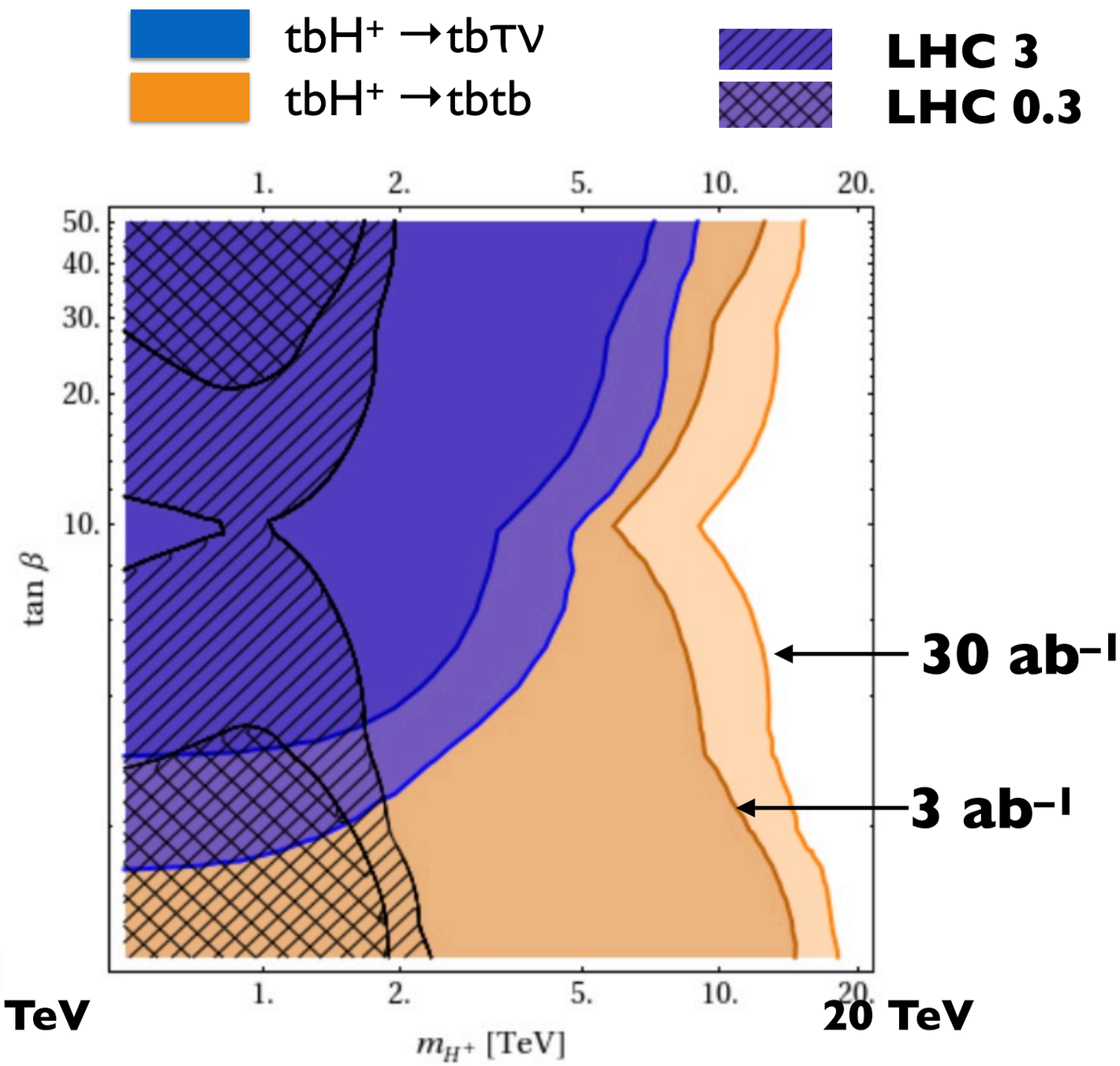
In the SM this requires $m_H \lesssim$ 80 GeV, else transition is a smooth crossover.

Since m_H = 125 GeV, **new physics**, coupling to the Higgs and effective at **scales O(TeV)**, must modify the Higgs potential to make this possible

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

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

Heavy resonances (summary)