Prospects for searches of new physics at future facilities beyond HL-LHC

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Context (only 20mins to cover an ocean of possibilities)

European Strategy Recommendations released June 2020

Europe, together with its international partners, should investigate
the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with
an electron positron Higgs and EW factory as a possible first stage.

Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

Context (only 20mins to cover an ocean of possibilities)

1. Only one future hadron collider possible in the world, thus only one circular tunnel

2. If the infrastructure exist for 1. why not using it for a cheap e^+e^- machine first? (FCC-ee/FCC-hh, CepC/SppC)

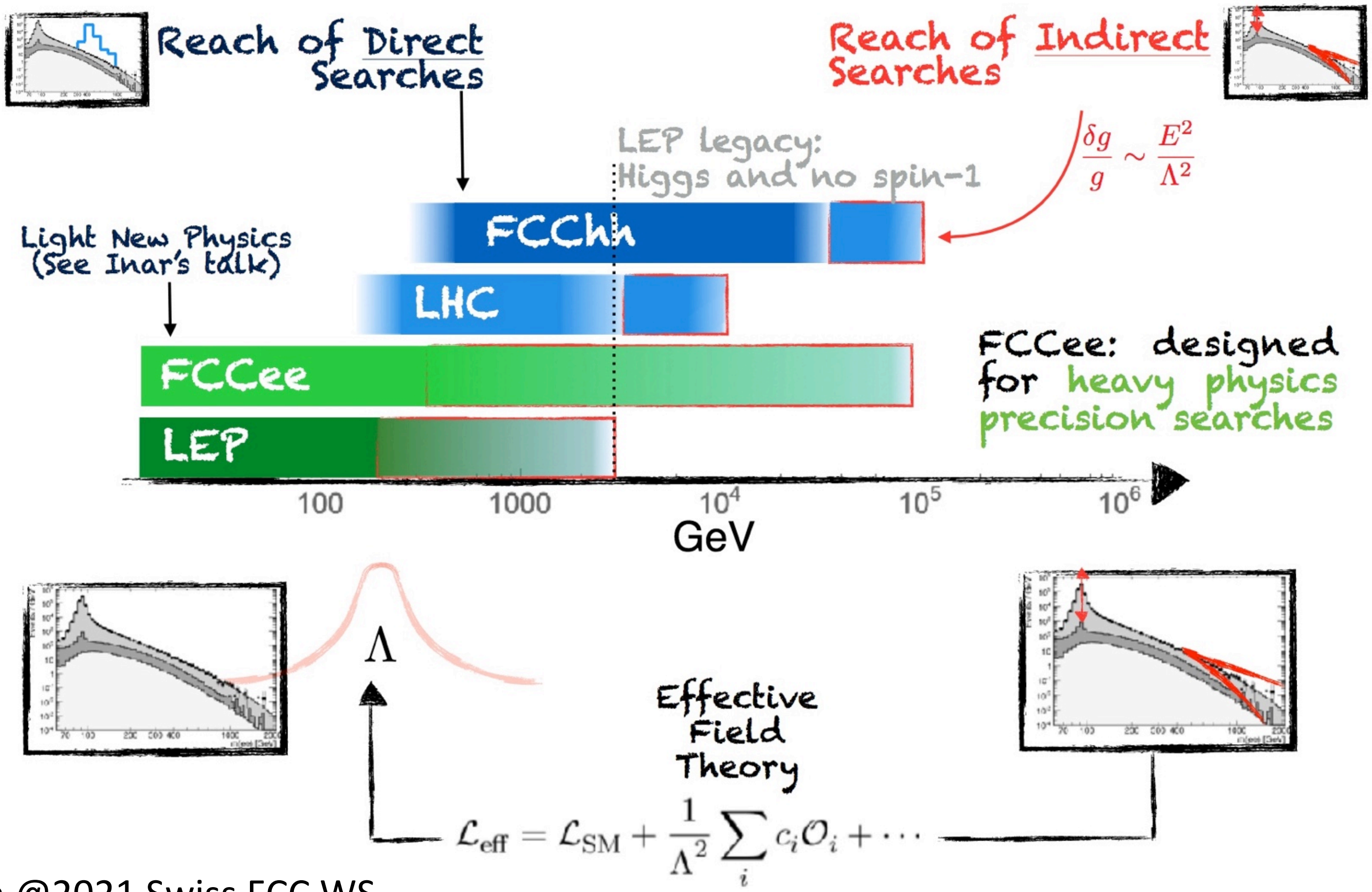
3. If a circular tunnel at CERN, no linear tunnel for CLIC

4. If a circular tunnel at CERN, only ILC could survive (or C^3)

5. If a circular tunnel in China, could CLIC/ILC/C^3 survive?

6. Belle II is a lepton collider beyond HL-LHC

Circular Colliders



F. Riva @2021 Swiss FCC WS

Lepton colliders

Expectation from lepton future colliders

Explore

- 10-100 TeV energy scale (and beyond) with Precision Measurement
- ~20-50 (stat 400...) fold improved precision on many EW quantities
  (eq. x 5-7 in mass m_Z, m_W, m_{top} , $\sin^2\theta_W^{eff}$, R_b , α_{QED} (m_z), α_s (m_Z m_W m_τ), top quark couplings
- Model-independent Higgs width and couplings measurements at percent-permil level
- Discovery of effect of Higgs self-coupling
- Possible investigation of Hee coupling at $\sqrt{s} = m_H$

Discover

- A violation of flavour conservation or universality and unitarity of PMNS @10^{-5}
  ex FCNC (Z -> $\mu\tau$, $e\tau$) in 5×10^{12} Z decays and τ BR in 2×10^{11} Z->τ τ
  \+ flavour physics (10^{12} bb events) (B->s τ τ etc..)
- Dark matter as «invisible decay» of H or Z (or in LHC loopholes)

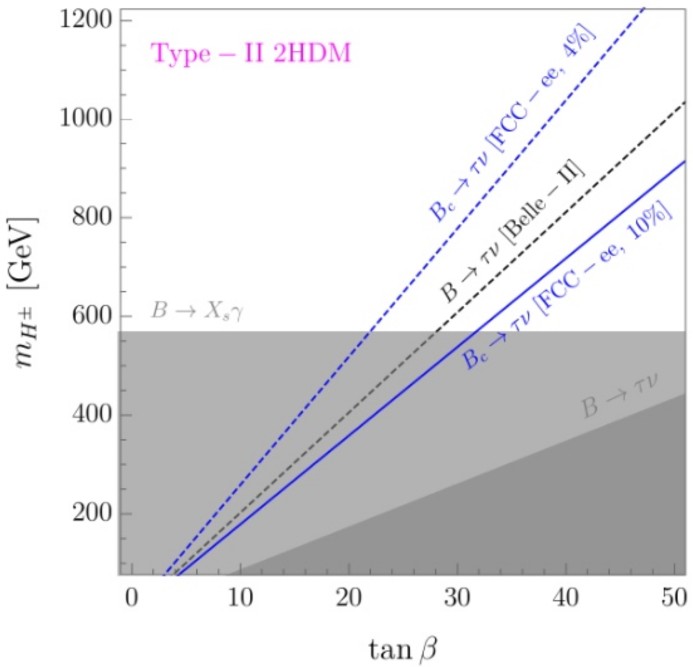
Direct discovery

- Of very weakly coupled particle such as: Right-Handed neutrinos, Dark Photons, FIP etc...

$B^+/B_c^+ \to \tau^+\nu_\tau$

arxiv:2105.13330

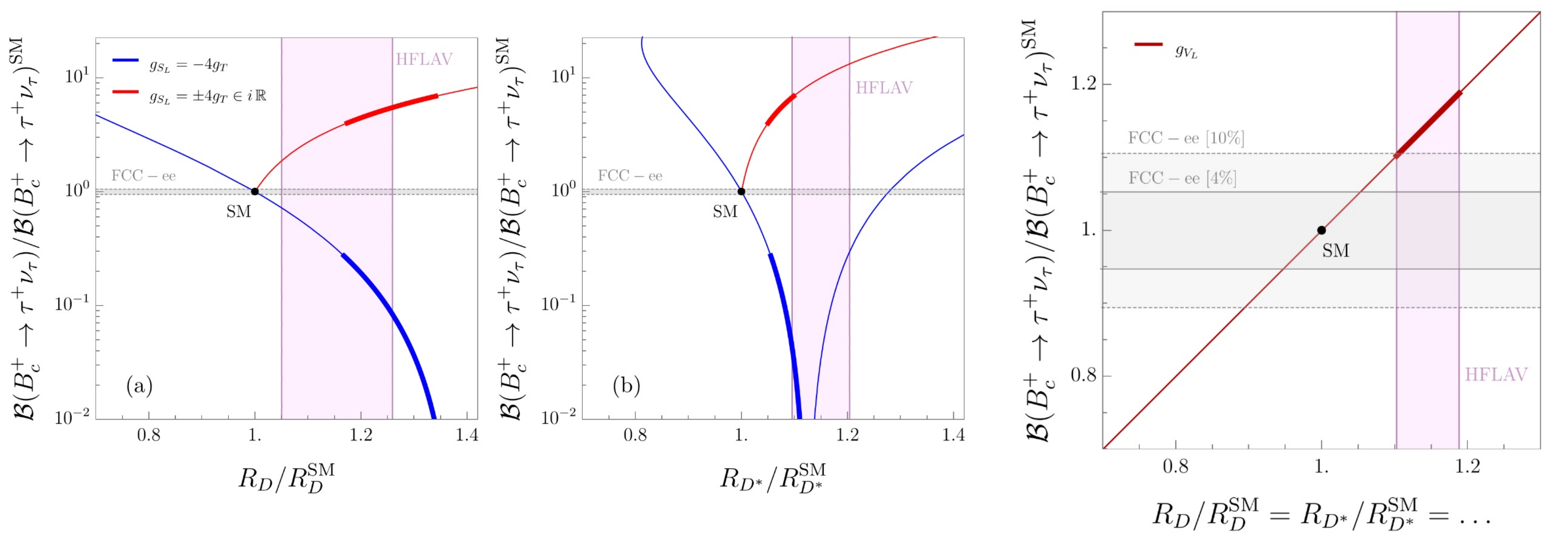
- R_c measurement at FCC-ee can strongly constraint 2HDM parameter space in a complementary manner to B^+ at Belle II



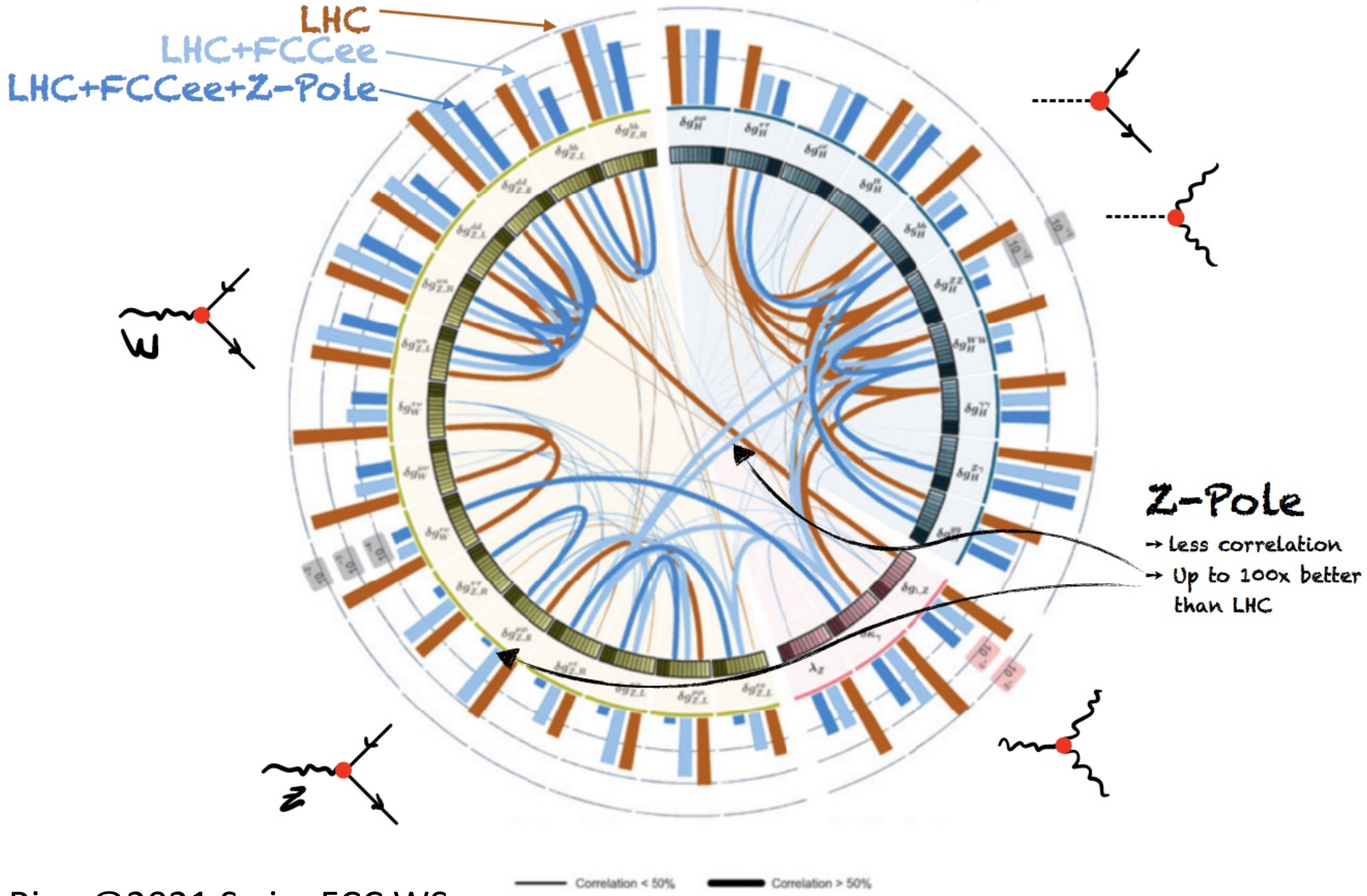
$B_c^+ \to \tau^+\nu_\tau$

arxiv:2105.13330

- R_c measurement at FCC-ee can strongly constraint both 2HDM and leptoquark parameter space in a complementary manner to other key observables
  - Leptoquark couplings can introduce O(10-100) variations



Reach on modified Couplings



F. Riva @2021 Swiss FCC WS

From deBlas'21 and deBlas,Durieux,Grojean,Gu,Paul'19

Feebly-interacting particles: the four portals

I. Timiryasov @2021 Swiss FCC WS

New particles (DM candidates, mediators, heavy neutrinos) must be SM singlets. Therefore possible couplings are limited by the gauge invariance.

The lowest dimension portals:

Portal	Coupling
Dark Photon, A'_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$
Sterile Neutrino, N	$y_N L H N$

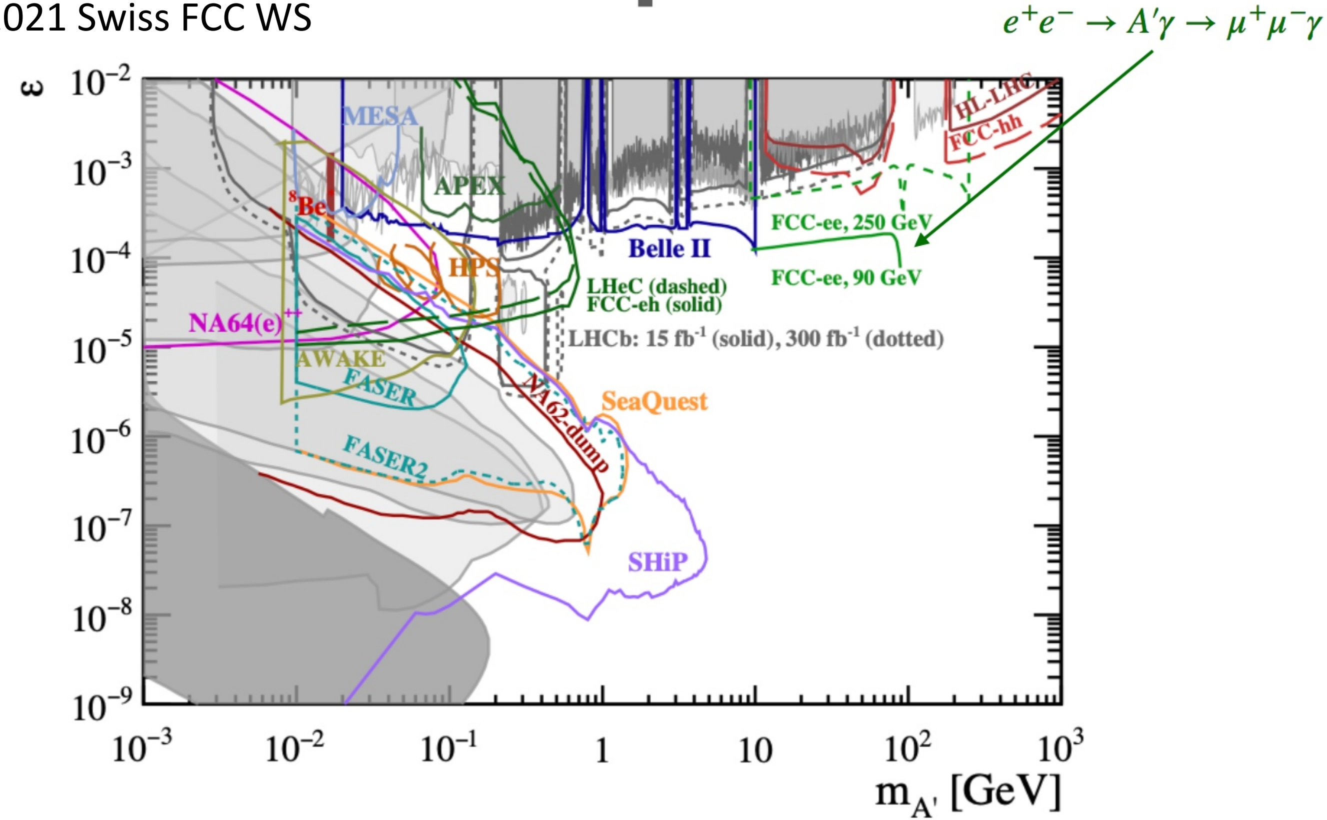
Specific benchmark models:

PBC report https://arxiv.org/abs/1901.09966

* FIPs 2020 Workshop Report mentions the fifth portal — millicharged particles

Vector portal

I. Timiryasov @2021 Swiss FCC WS

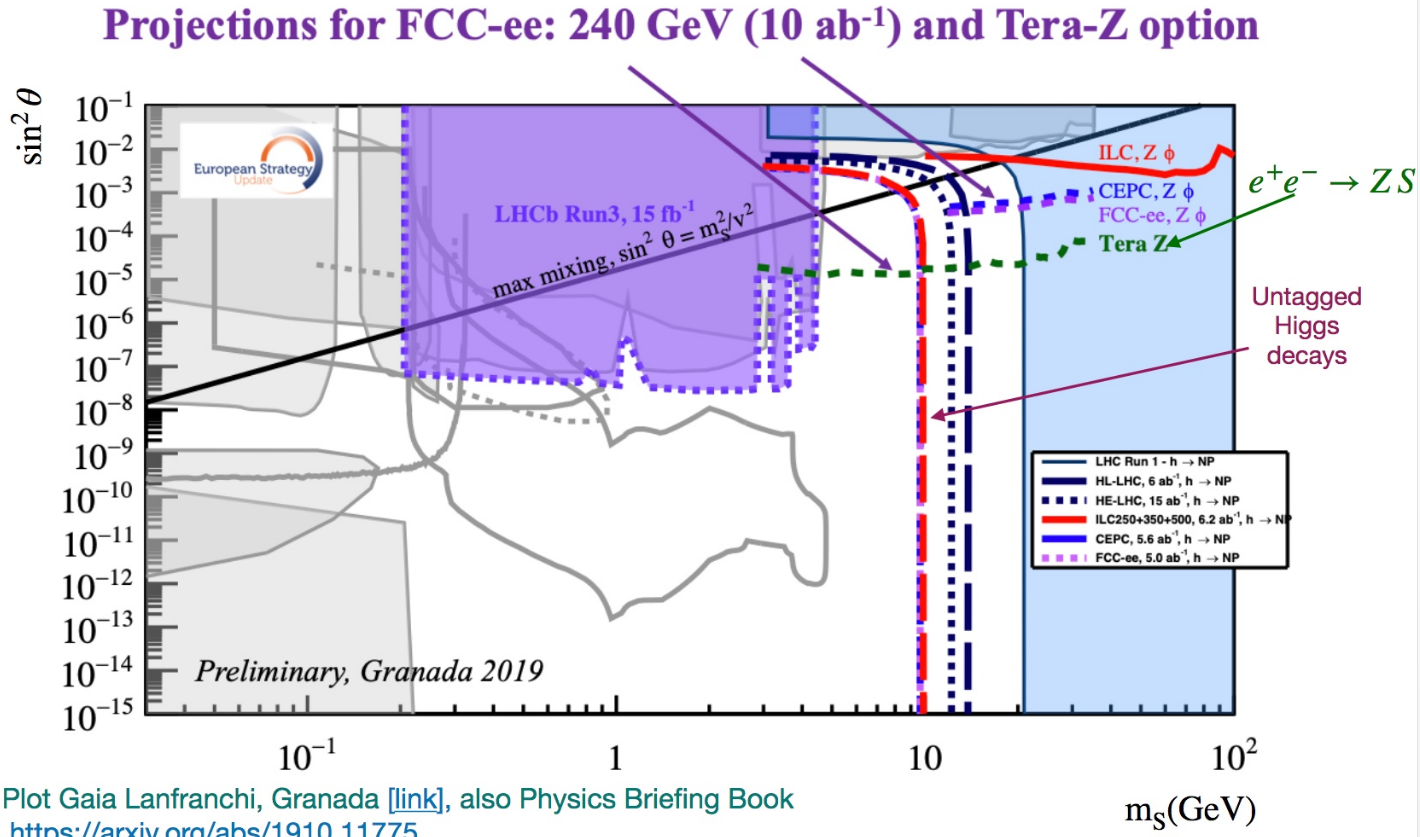


Source: Fabbrichesi, Gabrielli, and Lanfranchi https://arxiv.org/abs/2005.01515

FCC-ee limits: Karliner, Low, Rosner, and Wang http://arxiv.org/abs/1503.07209

Scalar portal

I. Timiryasov @2021 Swiss FCC WS



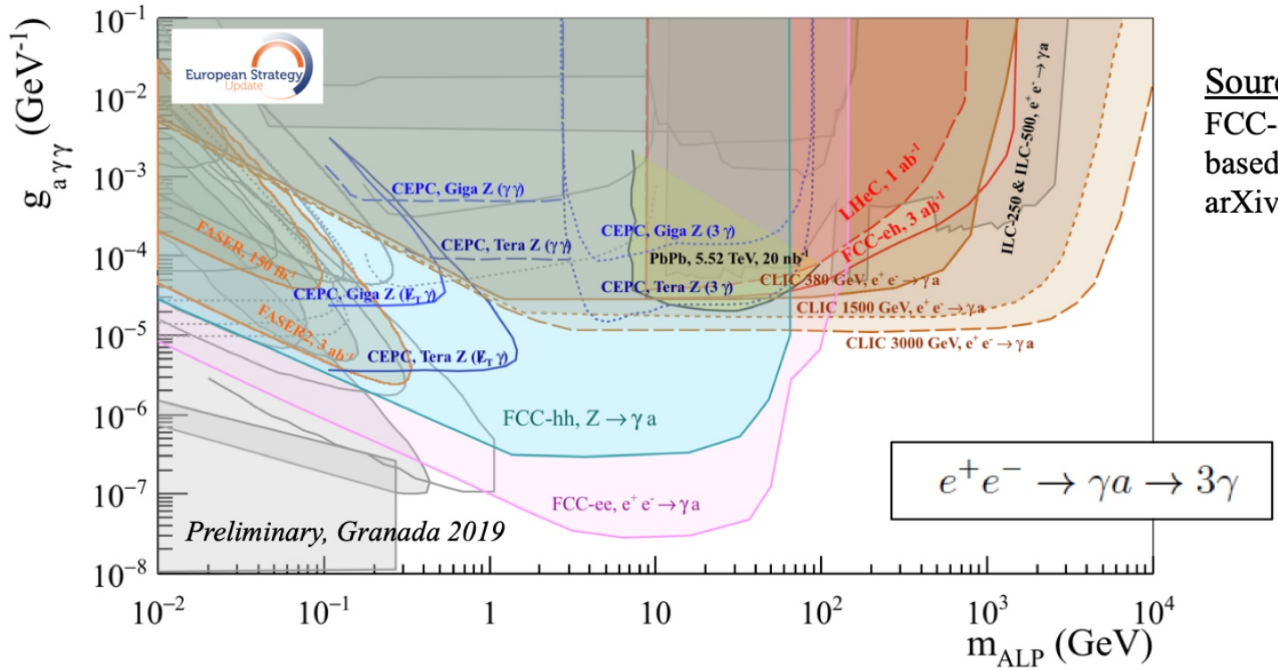
Plot Gaia Lanfranchi, Granada [link], also Physics Briefing Book https://arxiv.org/abs/1910.11775

Data: Frugiuele, Fuchs, Perez, and Schlaffer arXiv:1807.10842

Pseudo-scalar portal

I. Timiryasov @2021 Swiss FCC WS

Prospects for FCC-ee : combination of data at the Z-pole, 2 m_W and 240 GeV.



Source:
FCC-ee physics groups based on Bauer et al., arXiv:1808.10323

$$e^+e^- \to \gamma a \to 3\gamma$$

From Gaia Lanfranchi, Granada [link]

Hadron collider

Expectation from hadron future collider

Guaranteed deliverables

- Study Higgs and top-quark properties and exploration of EWSB phenomena with unmatchable precision and sensitivity

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 firm answers to questions like

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

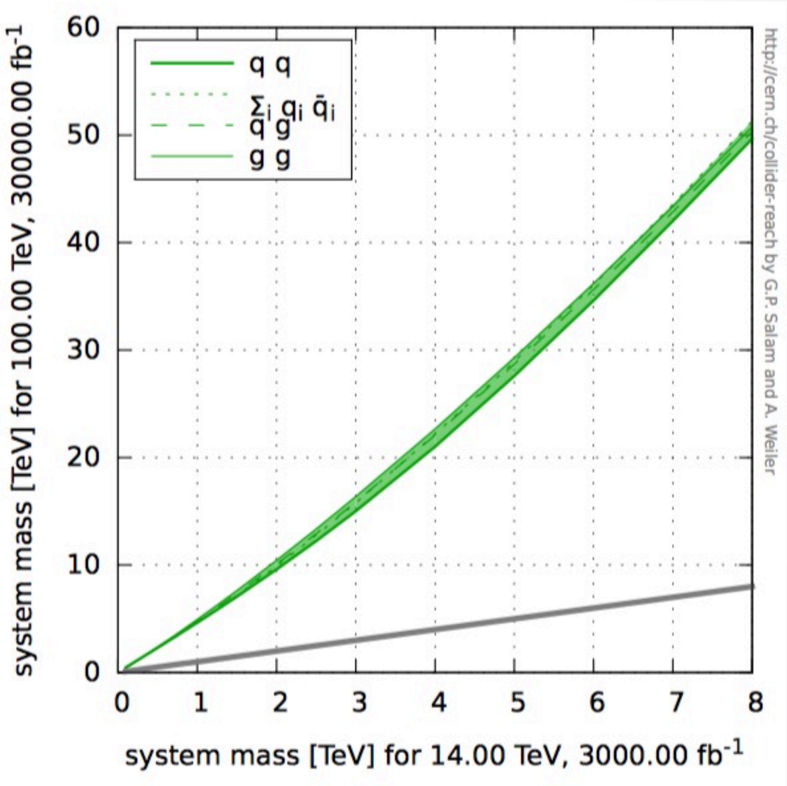
Environment and detector requirements

@100TeV FCC-hh

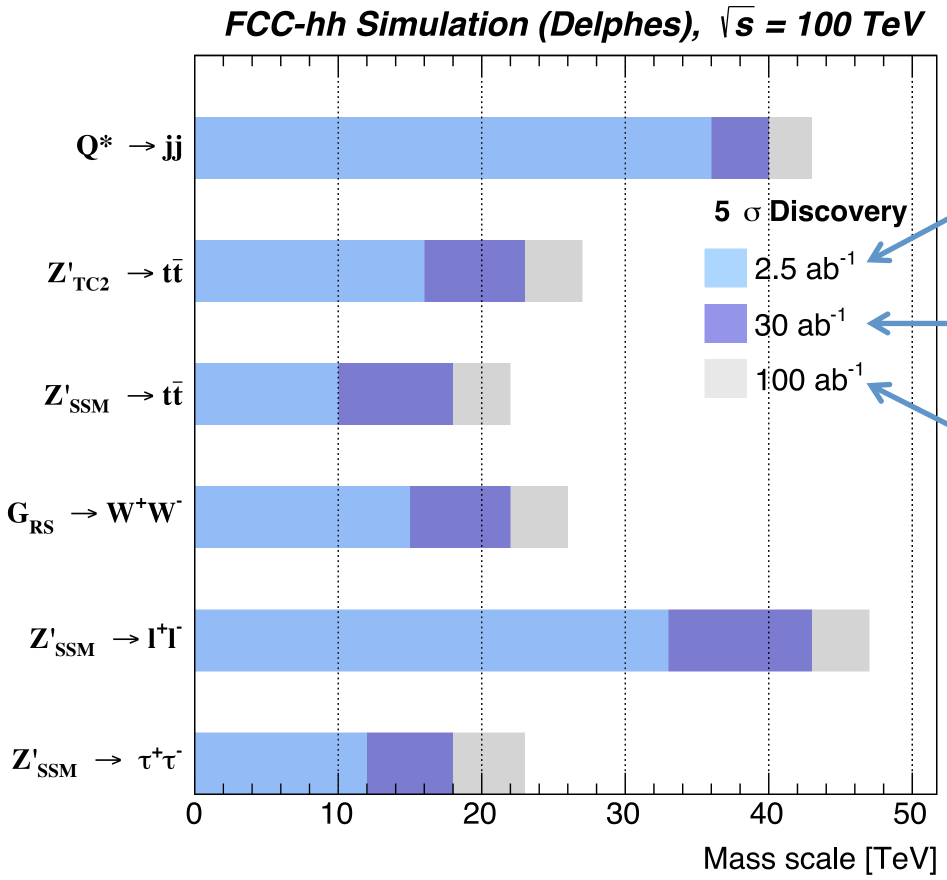
- pp cross-section from 14 to 100 TeV only grows by a factor 2
- 10 times more fluence compared with HL-LHC (x100 wrt to LHC)
  - Need radiation hard detectors
- Radiation level increase mostly driven by the jump in instantaneous luminosity
- More forward physics -> larger acceptance
  - Precision momentum spectroscopy and energy measurements up to $|\eta|<4$
  - Tracking and calorimetry up to $|\eta|<6$ (at 10 cm of beam line at 18 m of IP)
- More energetic particles
  - Colored hadronic resonances up to 40 TeV -> Full containment of jets up to 20 TeV
  - Resonances decaying to boosted objects (top, bosons) -> need very high granularity to resolve such sub-structure

Direct discovery reach at 100TeV

- To first approximation
  - The discovery reach at the highest masses is driven by the energy increase wrt to LHC
  - For √s=100TeV we expect the reach to be extended by factors 5-7 wrt LHC for the same BSM parameters



Heavy resonances reach at 100TeV



arxiv:1902.11217

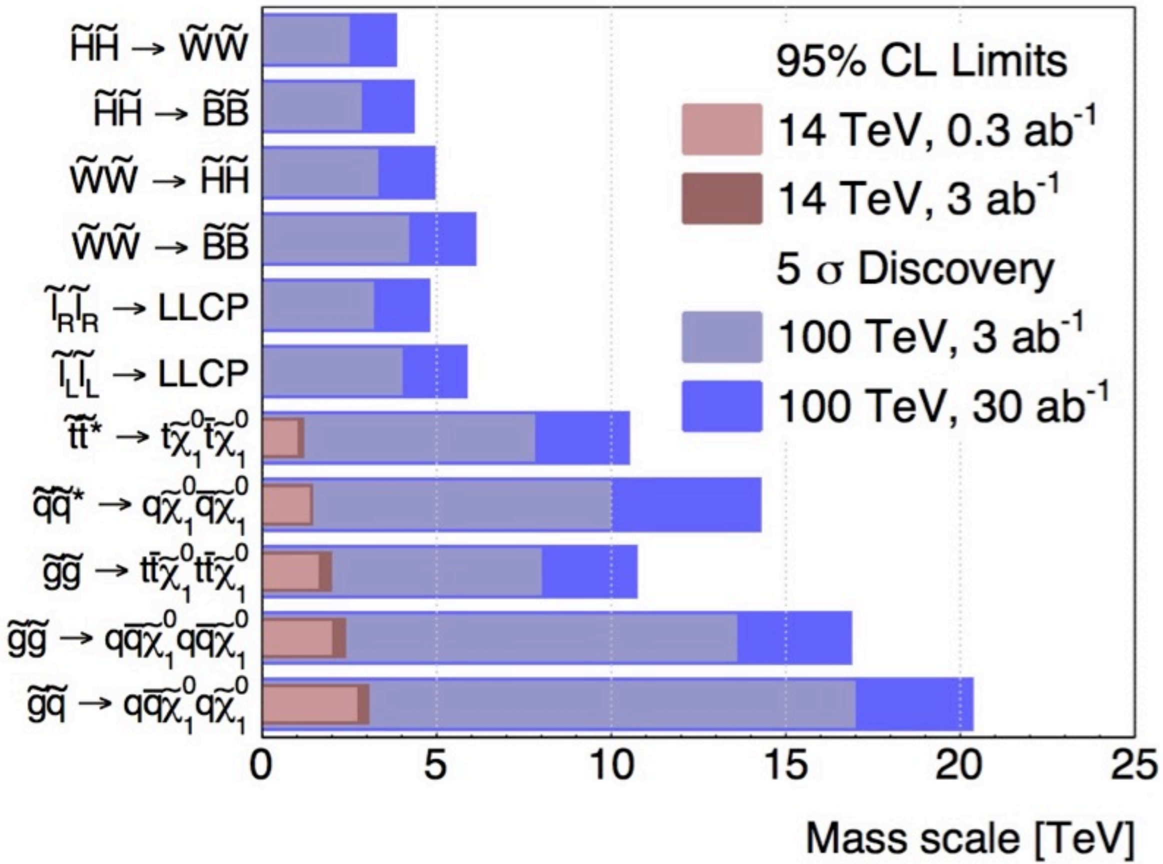
10 years at baseline

Full lifetime

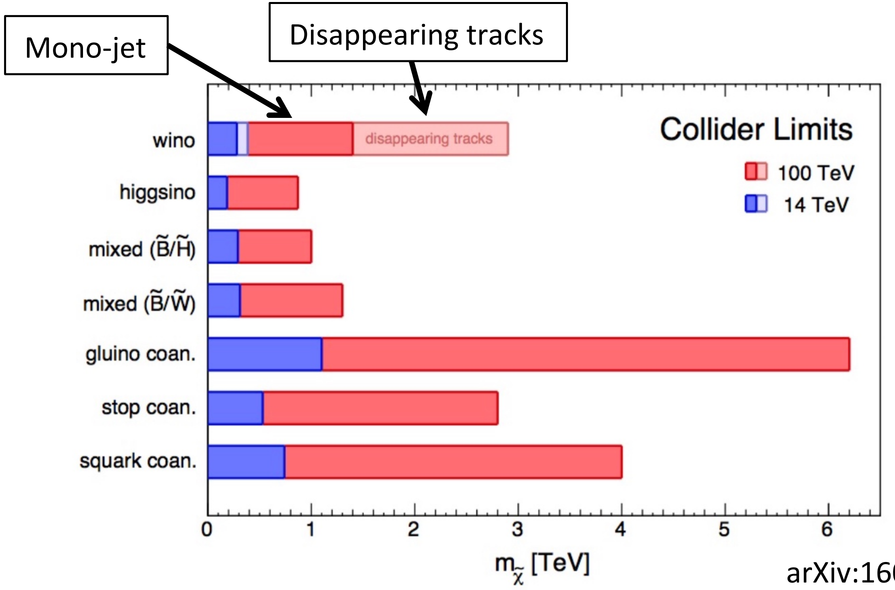
To show much higher number

Susy reach at 100TeV

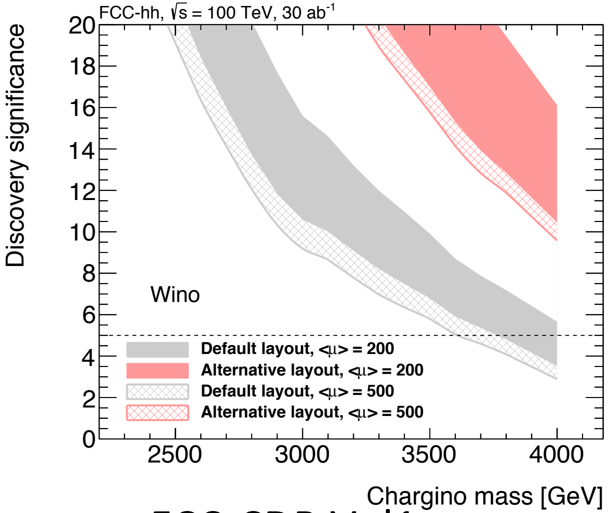
FCC-CDR Vol3



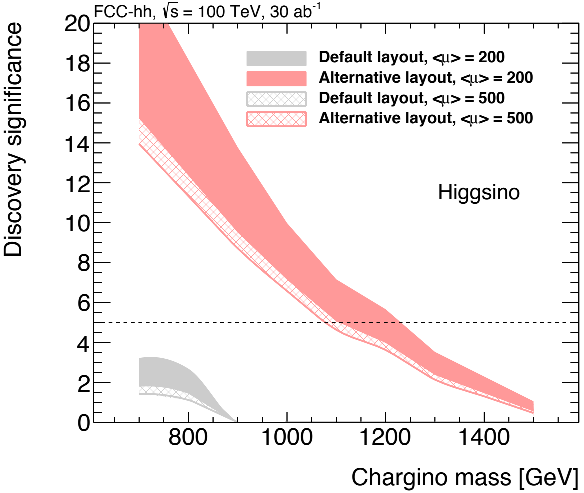
Dark matter reach at 100TeV



arXiv:1606:00947

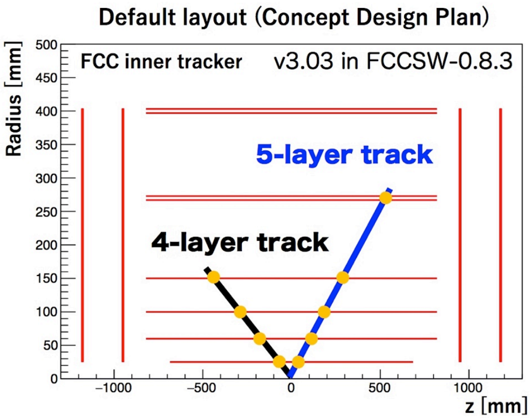


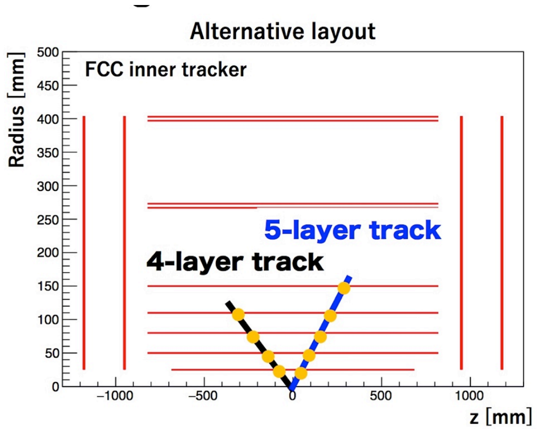
FCC-CDR Vol1

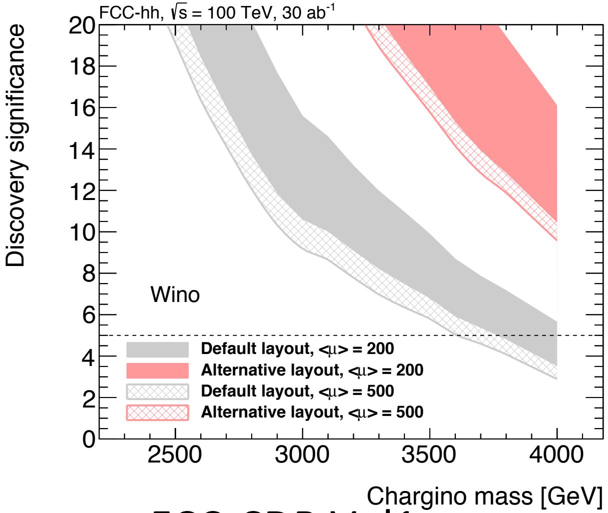


- Observed relic density of Dark Matter Higgsino-like: 1TeV, Wino-like: 3TeV
- Mass degeneracy: wino 170MeV, Higgsino 350MeV
- Wino/Higgsino LSP meta-stable chargino, cτ= 6cm(wino) 7mm(higgsino)
- Disappearing tracks analysis shows discovery reach beyond upper limits of M_{DM}
- In a similar way FCC-hh can explore conclusively EW charged WIMP models

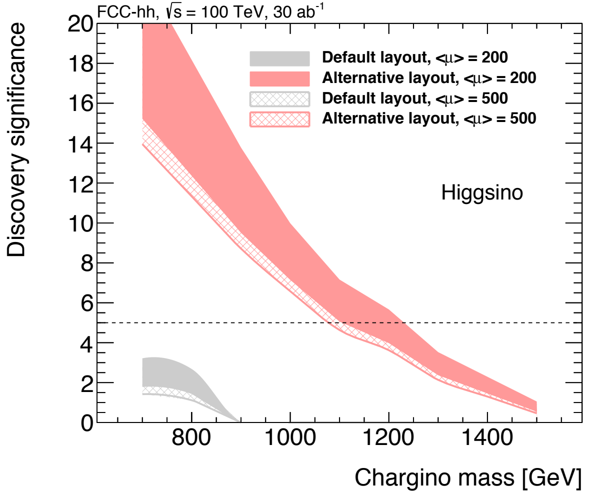
Dark matter reach at 100TeV







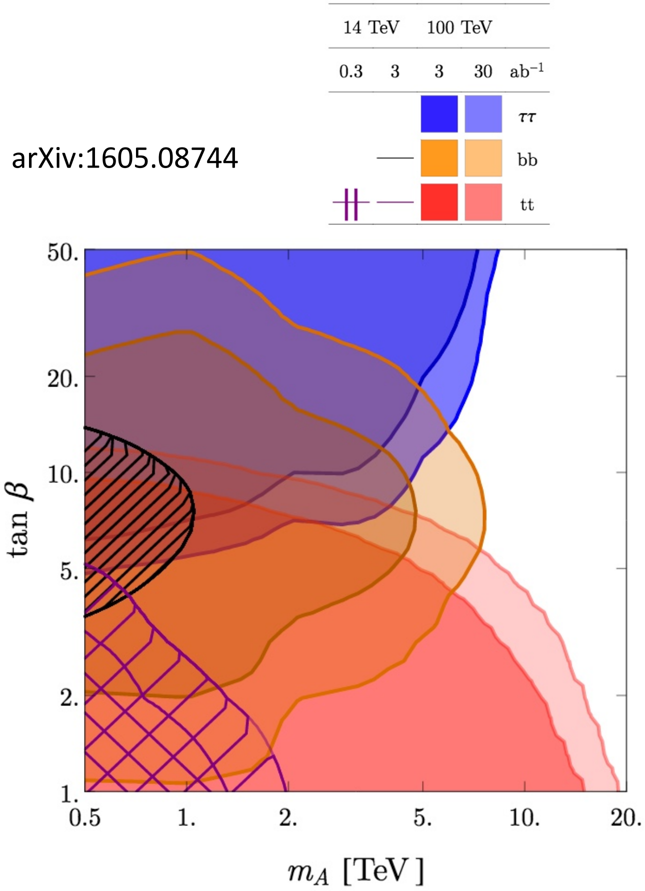
FCC-CDR Vol1

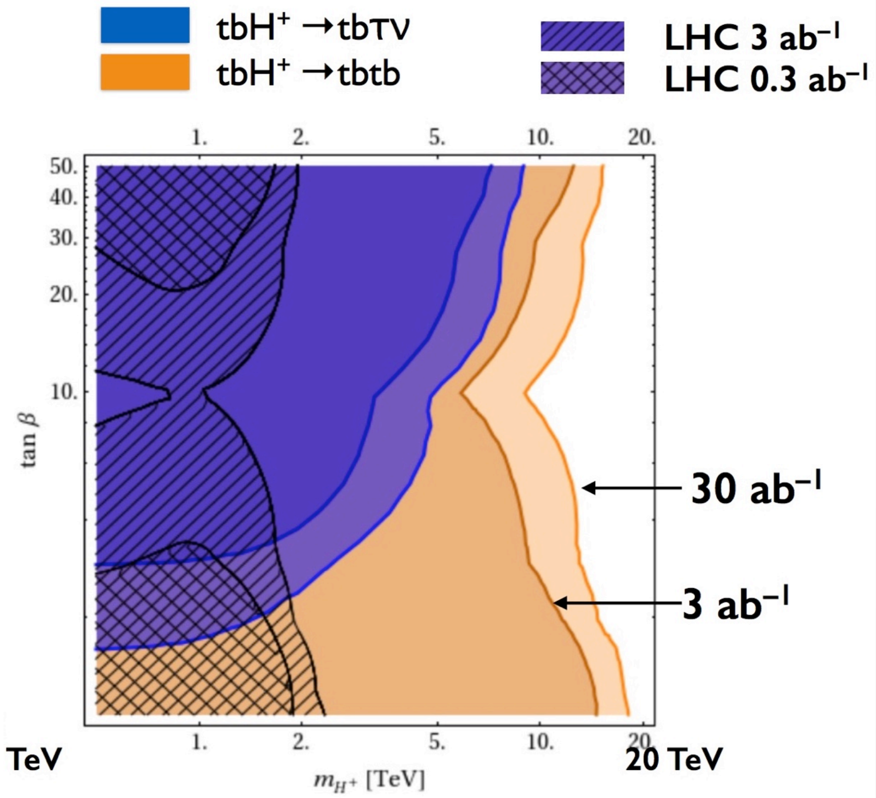


- Five space points are needed to reduce the fake-track rate
- For the signal acceptance, a smaller radius of the fifth layer is better
- Tilted silicon layout decrease BG significantly the high |η| region
- Lower <μ> is better due to the rapid rise of the fake-track BG rate

Additional Higgs

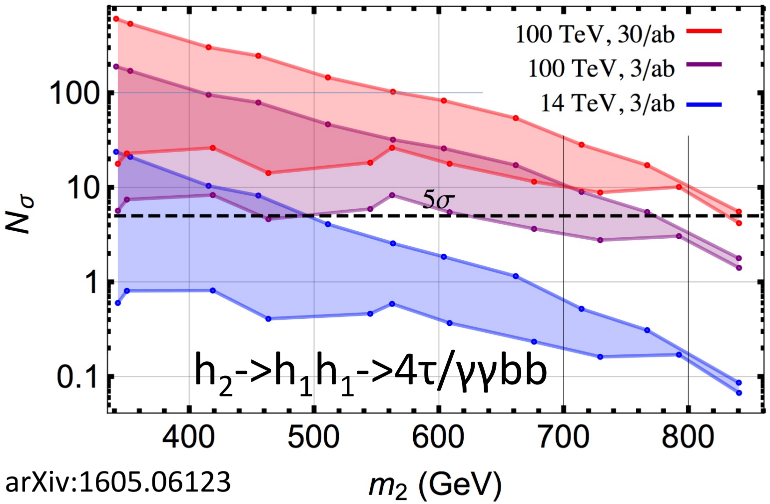
arXiv:1605.08744



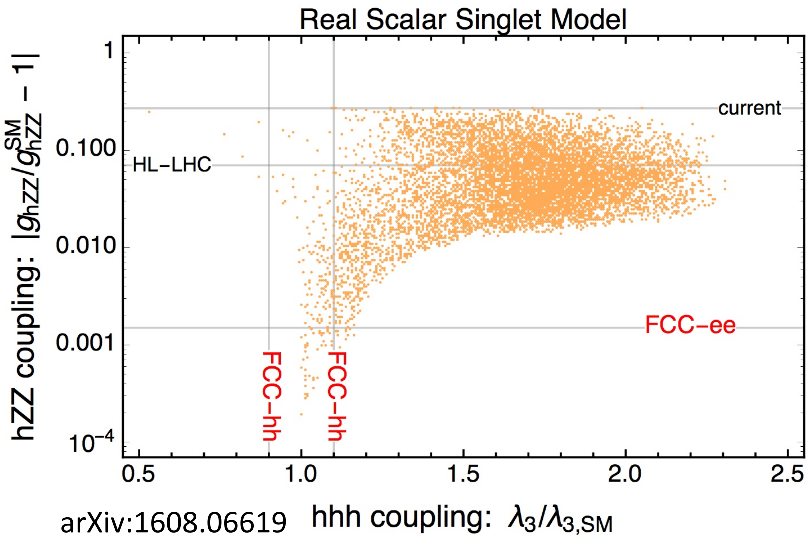


Higgs and EW phase transition

- Strong 1st order EWPT required to induce matter-antimatter asymmetry at EW scale
- Simple model: extension of the SM scalar sector with a single real singlet scalar
  - Contains 2 higgs scalar, h_1 and h_2
  - Interaction of scalar potential can lead to 1st EWPT when SM-like state h_1 has a mass of 125GeV
  - Modifications in Higgs self coupling, shift in Zh_1, direct production of scalar pairs
- Parameter space scan for this simple model extension of the SM



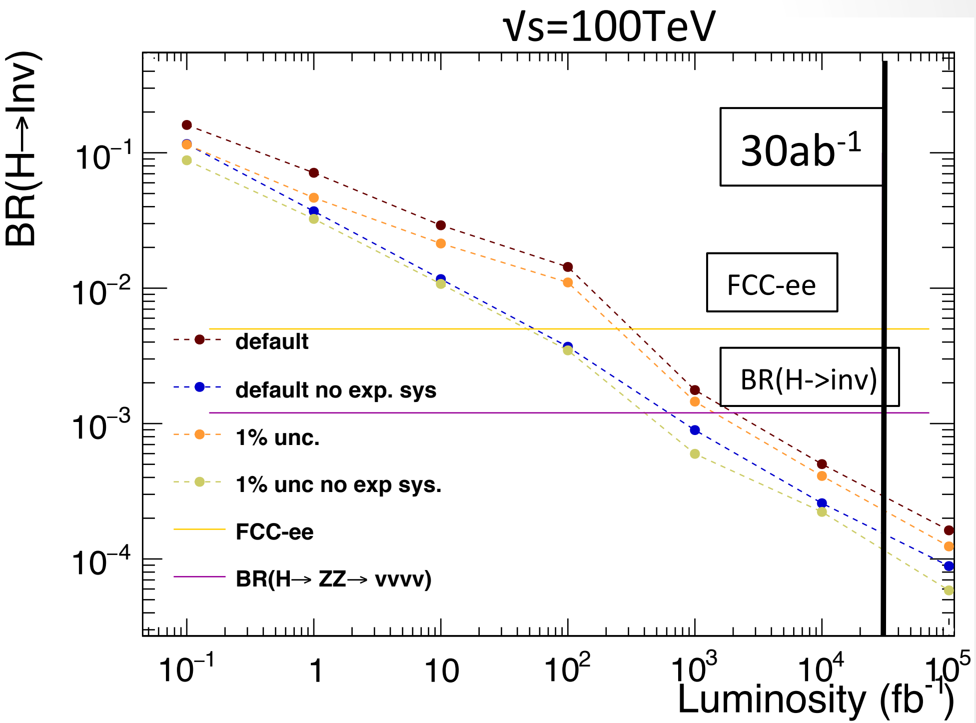
arXiv:1605.06123



arXiv:1608.06619

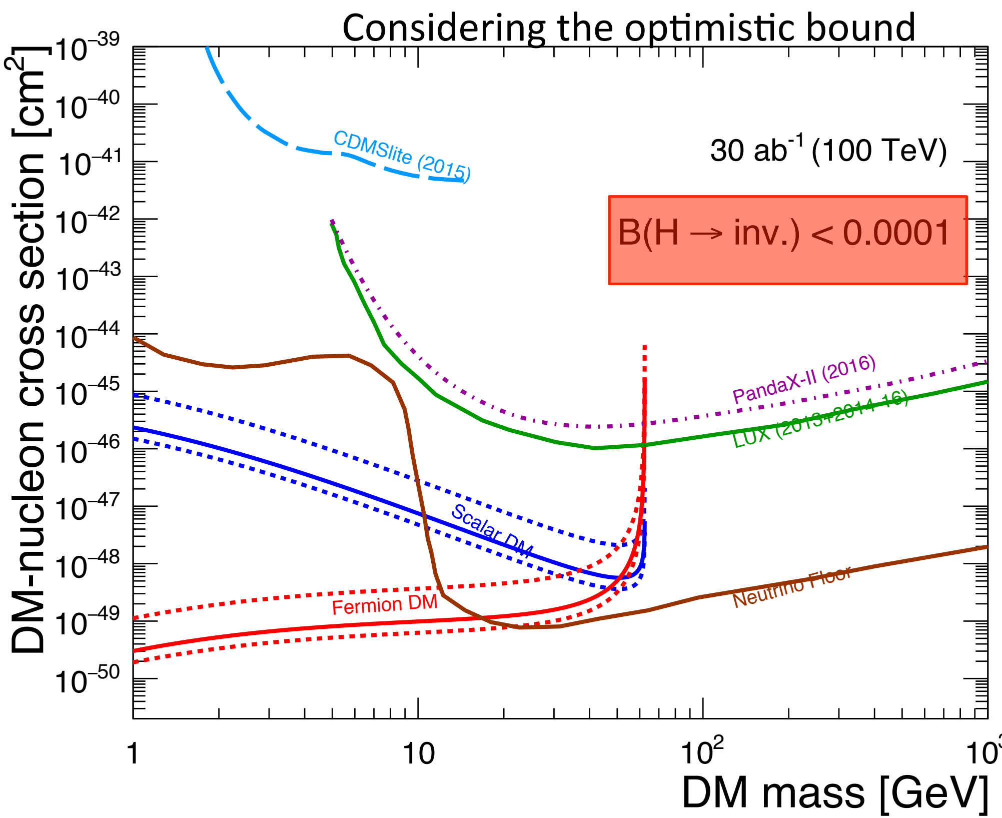
BR(H->inv) in H+X production at large p_T

- Uses missing transverse energy as a probe to higgs p_T
  - S/B increases with MET
- Signal extracted using a simultaneous fit to all control regions (Z+jets, W+jets, γ+jets)
- Z->νν background constrained to the percent level using NNLO QCD/EW to relate to measured Z->ee, W and gamma spectra



Impact on Dark Matter bounds

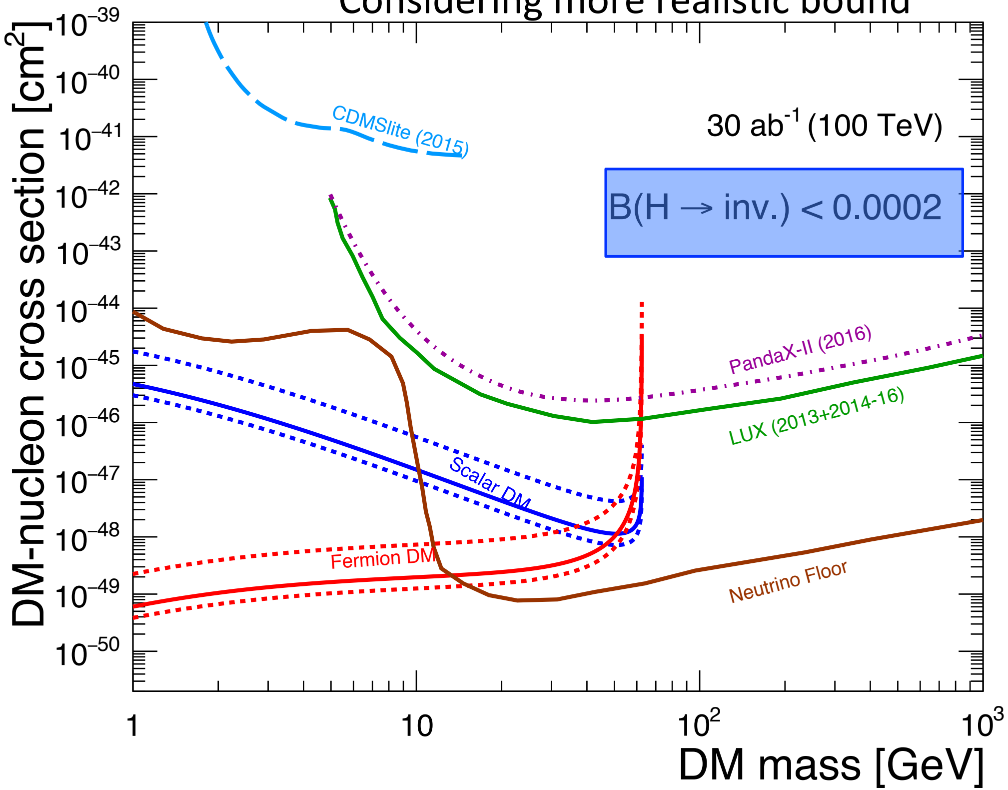
- Competitive with the best direct detection experiments down to the neutrino floor (neutral current neutrino interactions)



Impact on Dark Matter bounds

- Competitive with the best direct detection experiments down to the neutrino floor (neutral current neutrino interactions)

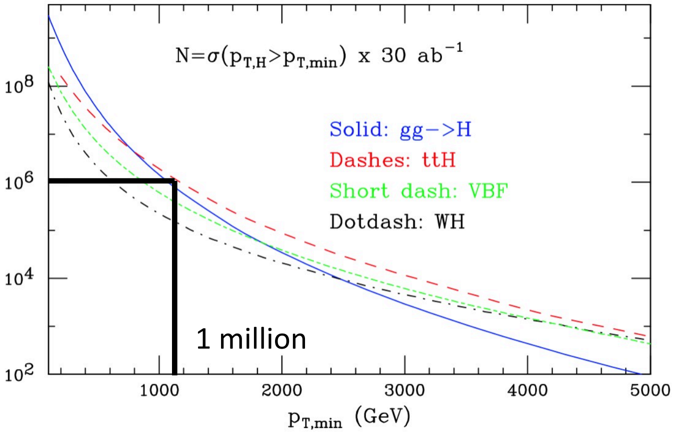
Considering more realistic bound



Higgs as a probe for BSM: precision/reach

$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots$$

$$O = |\langle f|L|i\rangle|^2 = O_{SM}\left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$



- For H decays, or inclusive production, μ~O(v,m_H)

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

- Precision probes large Λ e.g. δ*O*=1% ⇒ Λ ~ 2.5 TeV

- For H production off-shell or with large momentum transfer Q, μ~O(Q)

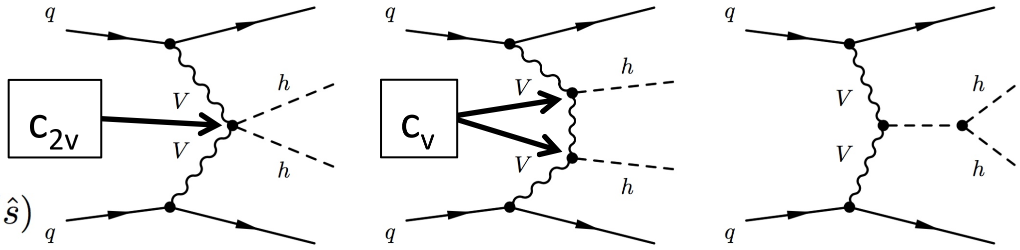
$$\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$$

- kinematic reach probes large Λ even if precision is "low" e.g. δ*O*=10% at Q=1.5 TeV ⇒ Λ~5 TeV

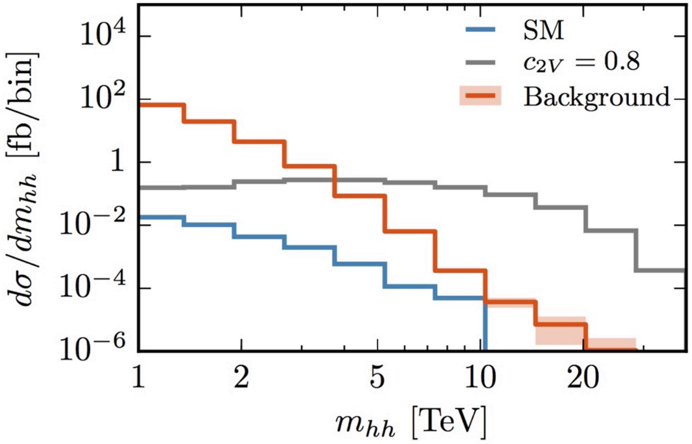
Complementarity between super-precise measurements at ee collider and large-Q studies at 100 TeV

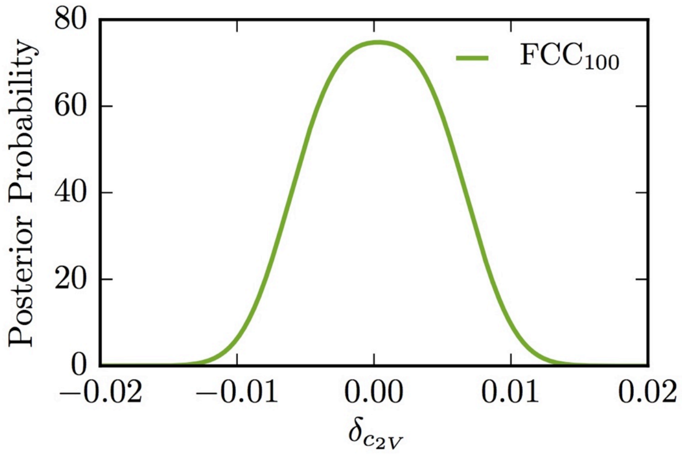
Di-higgs in VBF

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



In the SM, $c_{2v}=c_v^2$





arXiv:1611.03860

- Considering the 4b boosted final state
- c_v measured at per mille a FCC-ee

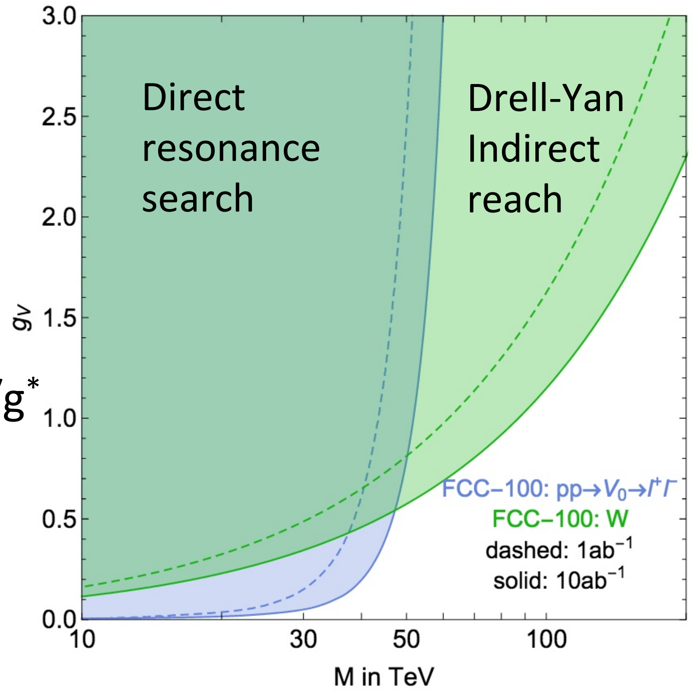
Indirect sensitivity to high scales: EW

arXiv:1609.08157

$$\mathrm{W} = \frac{g_V^2}{g^2}\frac{m_W^2}{M^2} + O(\mathrm{W}^2)$$

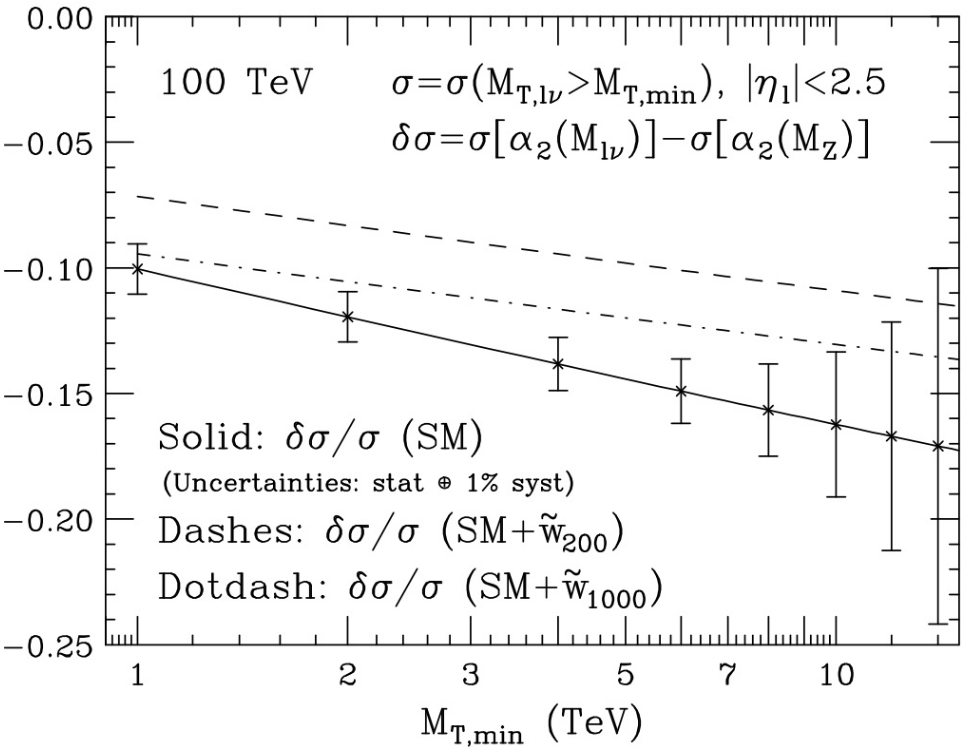
- Large cross-section and interference at LO with SM
- Drell-Yan ideal process to test new physics
- Simple BSM effects: oblique parameters
- Sensitivity up to the 200TeV range
- Improve constraints on by two orders of magnitude

$g_V = g^2/g^*$



		LEP	ATLAS 8	CMS 8	LHC 13		100 TeV	ILC	TLEP	CEPC	ILC 500 GeV
luminosity		$2\times10^7\,Z$	$19.7\,\mathrm{fb}^{-1}$	$20.3\,\mathrm{fb}^{-1}$	$0.3\,\mathrm{ab}^{-1}$	$3\,\mathrm{ab}^{-1}$	$10\,\mathrm{ab}^{-1}$	$10^9\,Z$	$10^{12}\,Z$	$10^{10}\,Z$	$3\,\mathrm{ab}^{-1}$
NC	$\mathrm{W}\times10^4$	$[-19,3]$	$[-3,15]$	$[-5,22]$	±1.5	±0.8	±0.04	±4.2	±1.2	±3.6	±0.3
	$\mathrm{Y}\times10^4$	$[-17,4]$	$[-4,24]$	$[-7,41]$	±2.3	±1.2	±0.06	±1.8	±1.5	±3.1	±0.2

Drell-Yan at high mass



- wino: SU(2) triplet of Majorana fermions (eg SUSY partners of W/Z)

My personal view as a summary

HEP Landscape

- Particle accelerators are built to answer some of the most fundamental questions
- Physics priorities are likely to shift swiftly, as we advance in our exploration
  - both experimentally and theoretically
- There are many unknowns ahead of us that may reshuffle the cards
  - e.g. any discoveries during HL-LHC operation

→ We need a broad and bold program capable of adapting to the swift changes in the physics landscape that are likely to happen

→ Precision e^+e^- collider + energy frontier (~100 TeV) hadron collider – In times of uncertainty, bold exploration is the way to go

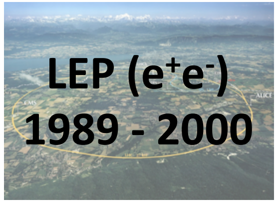
This is the FCC integrated program

A 100km circular collider as next the step

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

27km tunnel

The next step: 100km tunnel



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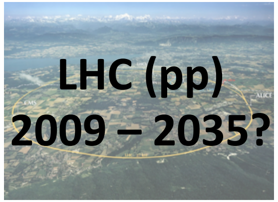

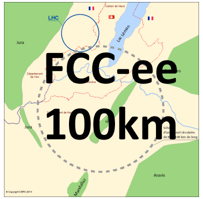

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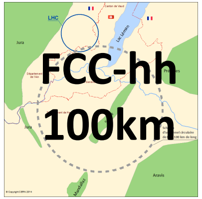

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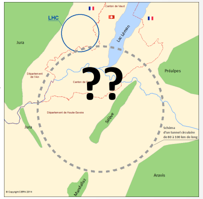


The FCC design study is establishing the feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology

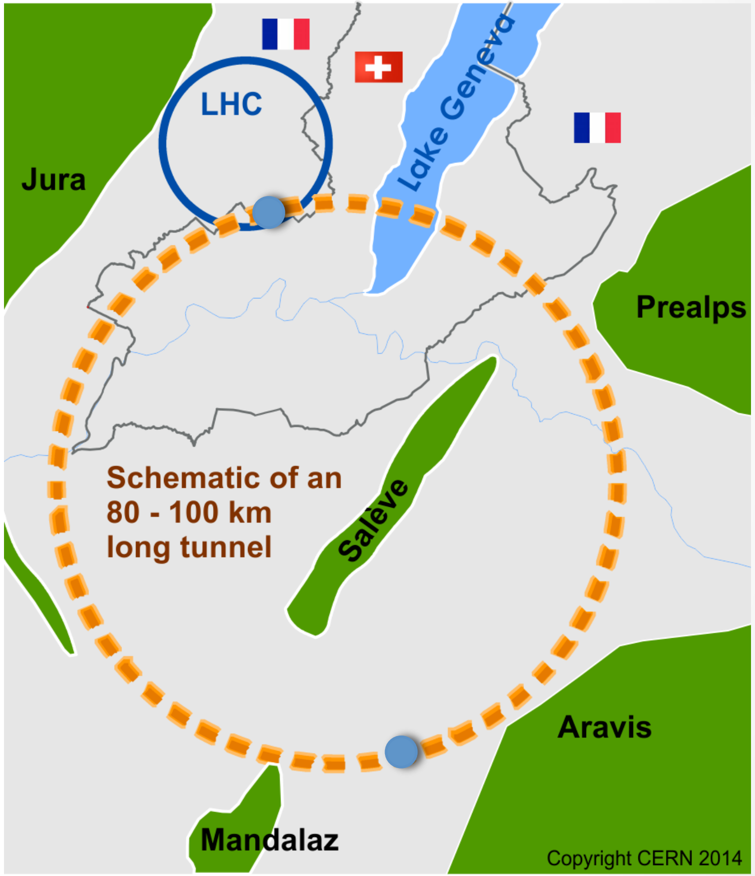
Both FCC-ee and FCC-hh have outstanding physics cases

Extra material

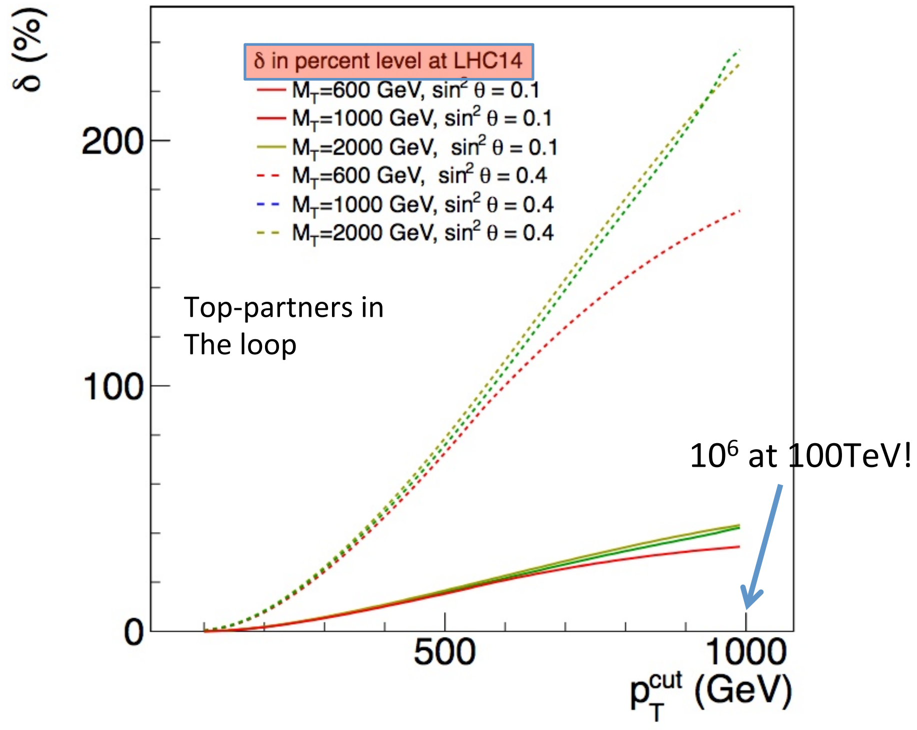
Circular hadron projects @CERN

FCC-hh

- Need a new 100km tunnel
- Need 16 Telsa magnet to reach 100TeV in 100km
- Baseline Luminosity (10y)
  - 5 10^{34} cm^{-2} s^{-1} (HL-LHC) <μ>200
- Ultimate luminosity (15y)
  - 30 10^{34} cm^{-2} s^{-1} <μ>1000
- 2.4MW sync rad/ring x300 HL-LHC
- Considering $30ab^{-1}$ for the study

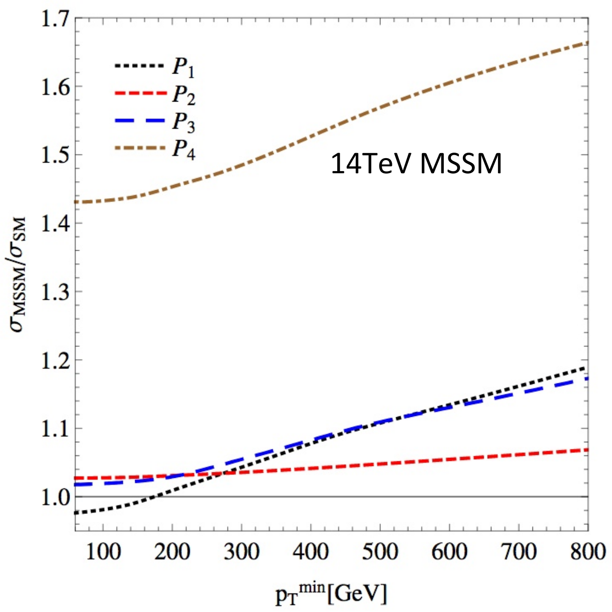


Deviations in the Higgs p_T spectrum



arXiv:1308.4771

Point	$m_{\tilde{t}_1}$ [GeV]	$m_{\tilde{t}_2}$ [GeV]	A_t [GeV]	Δ_t
P_1	171	440	490	0.0026
P_2	192	1224	1220	0.013
P_3	226	484	532	0.015
P_4	226	484	0	0.18



arXiv:1312.3317

VH production at large m(VH)

arXiv:1512.02572

- Considering anomalous couplings to gauge boson
- Treated here in the context of an effective field theory (EFT)