Future Hadron Colliders

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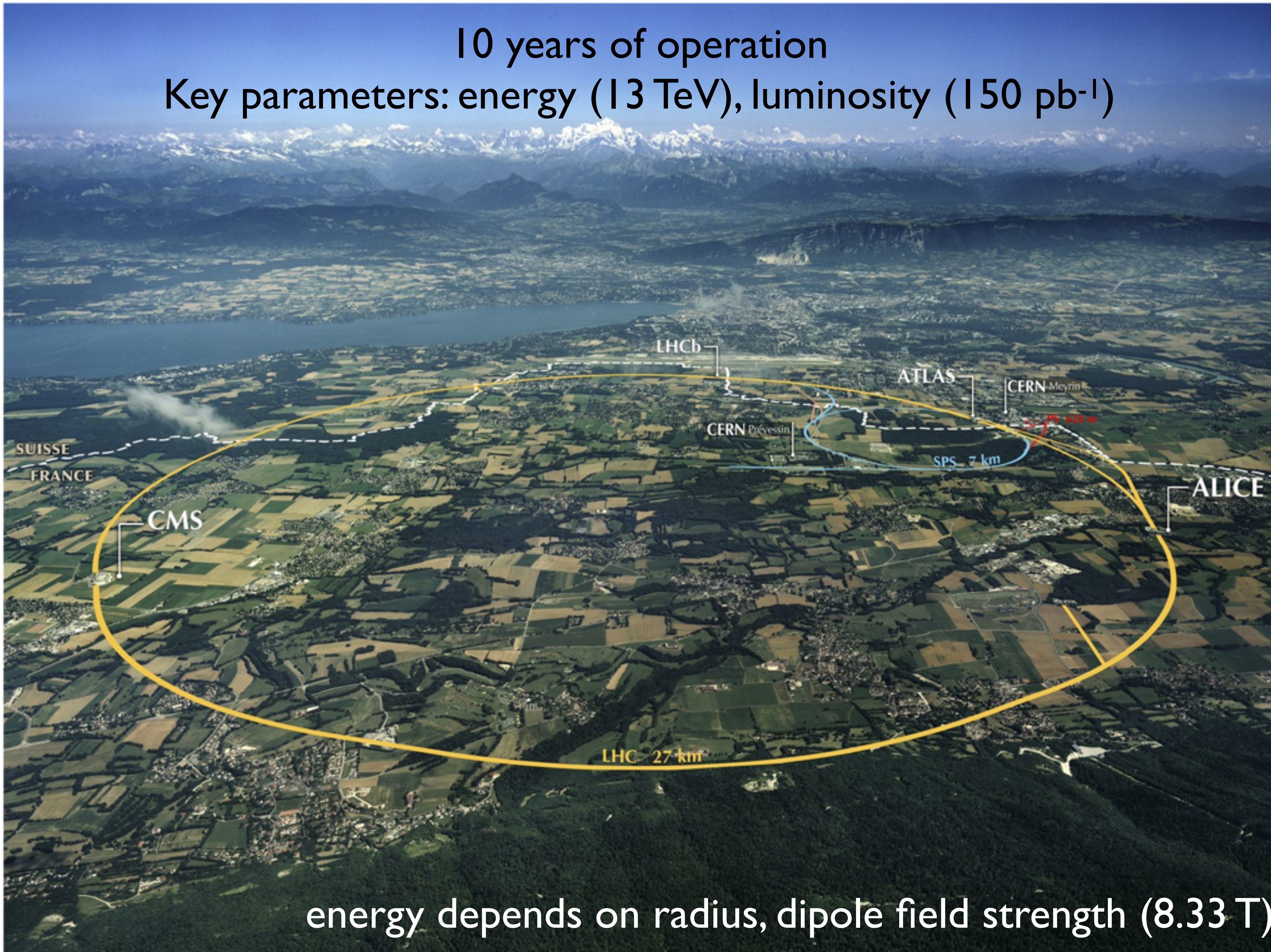
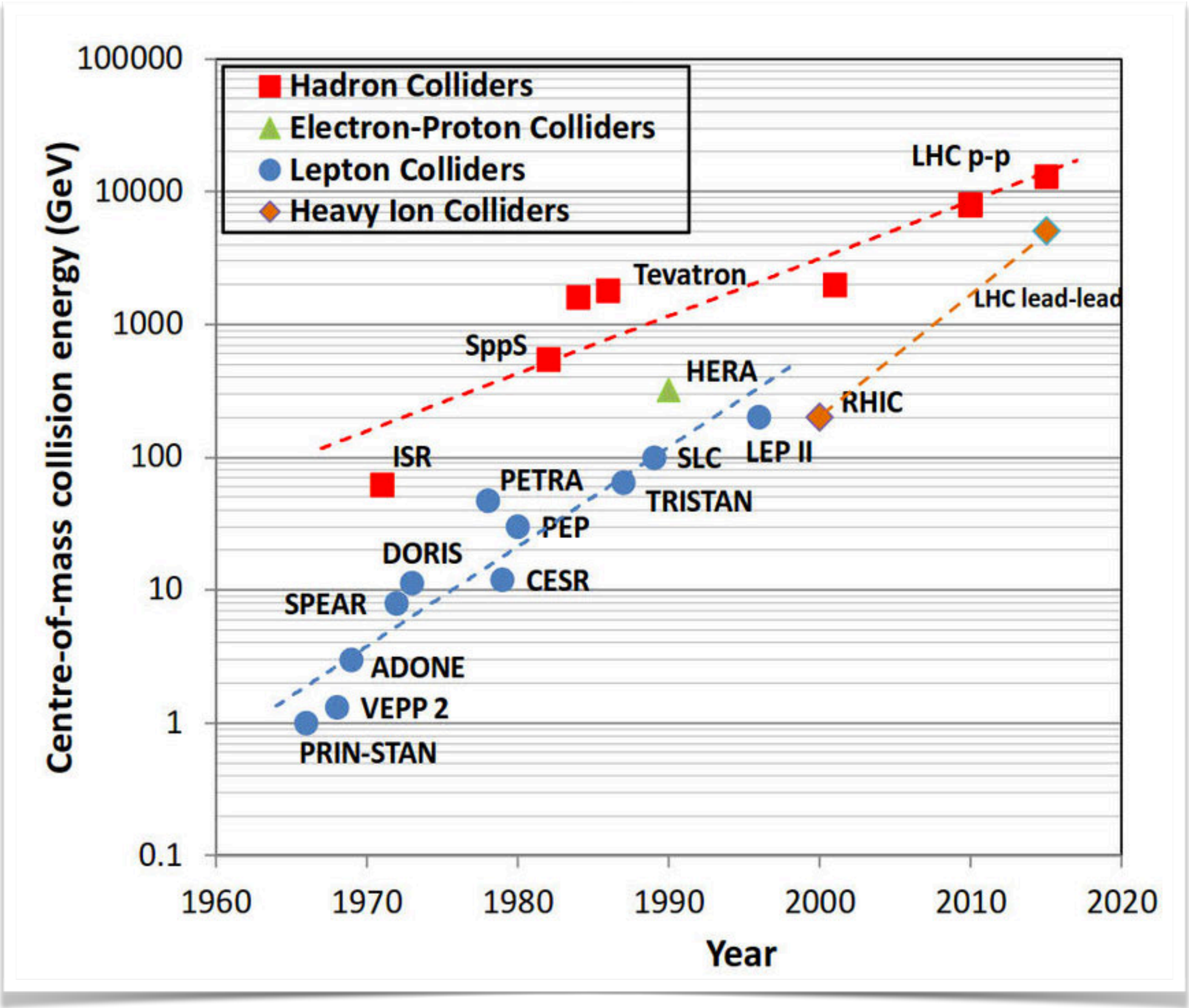
Almost all results shown today are from those shown at the European Strategy Meeting in Granada last months
Please see the individual talks and the inputs for more details

The Large Hadron Collider



Particle Colliders in History

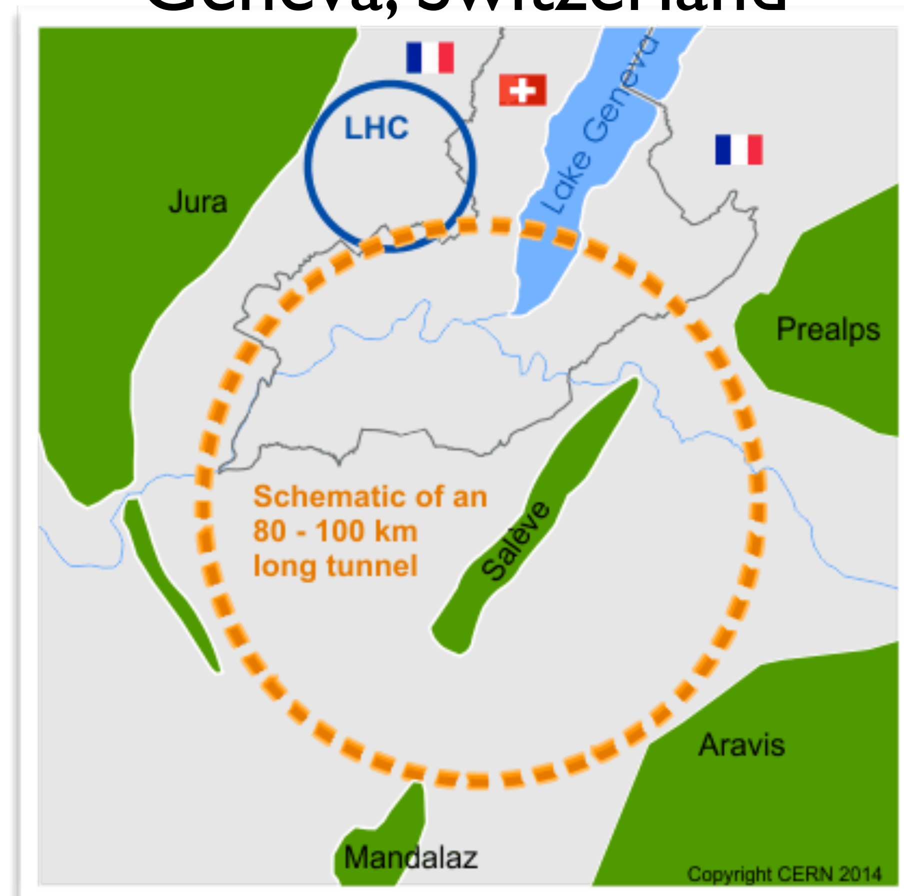


Future Hadron Colliders

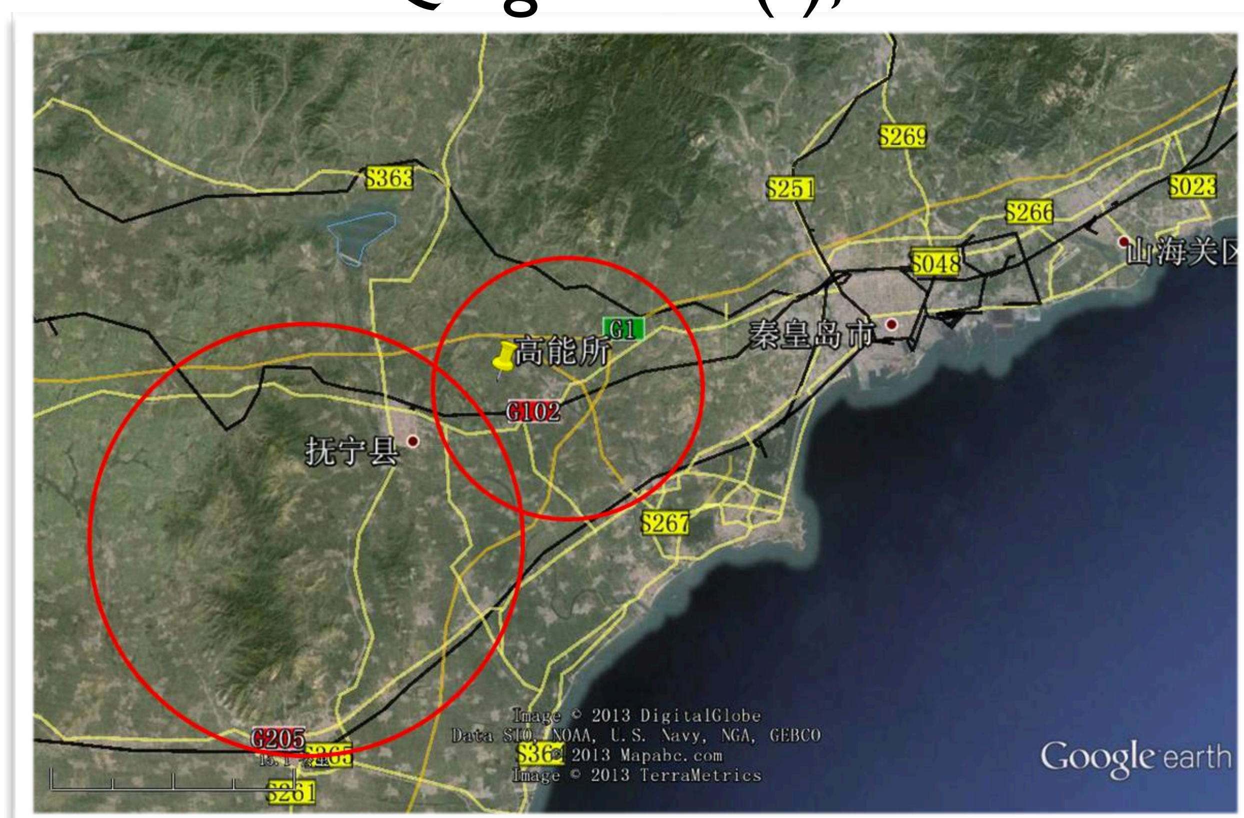
- Currently four future hadron collider options are being discussed
  - High-luminosity LHC (**HL-LHC**)
  - High-energy LHC (**HE-LHC**)
  - Future Circular Collider (**FCC-hh**)
  - Super Proton-Proton Collider (**SppC**)

- Not covered in this talk
  - Lepton colliders (previous talk from Alain Blondel)
  - LHeC/FCC-eh
  - FCC-HI, heavy-ion physics
  - Flavour physics

Geneva, Switzerland

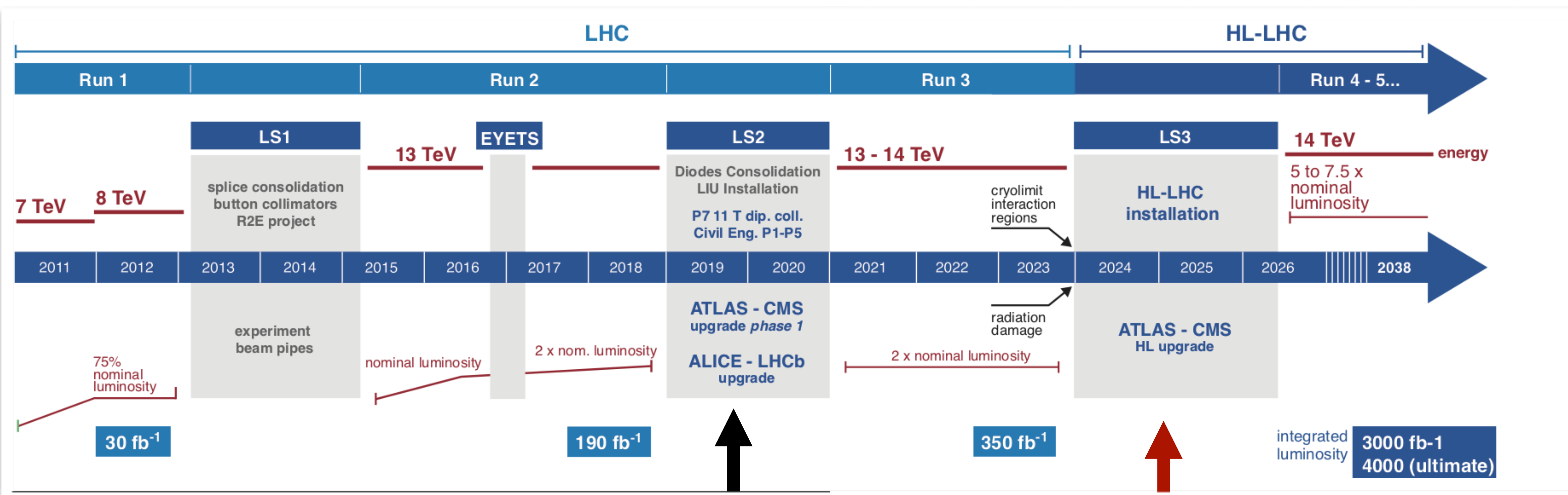


Qinghuada (?), China



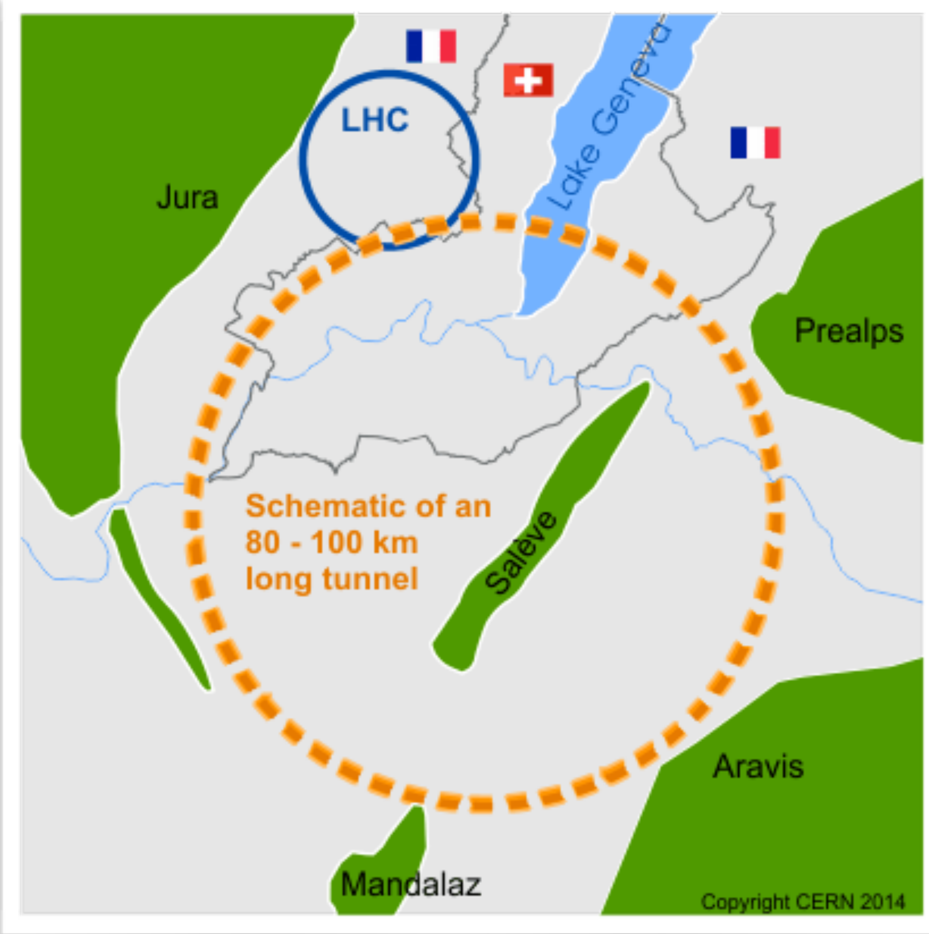
HL-LHC

- Reuse the LHC tunnel
- Increase energy from 13 to 14 TeV
- Increase in luminosity by factor of 5-7
- Major upgrade to the accelerator
  - Injector replaced now during LS2
  - Upgrade magnets
- Major upgrades to ATLAS and CMS: mitigate pile up of 200 events/crossing



FCC-hh

- New tunnel ~100 km tunnel located at CERN
- New 16 T magnets (20 T for 80 km)
  - Very challenging target
- Energy: 100 TeV
- One stage of overall FCC project
  - Full spectrum from e^+e^- to heavy ions

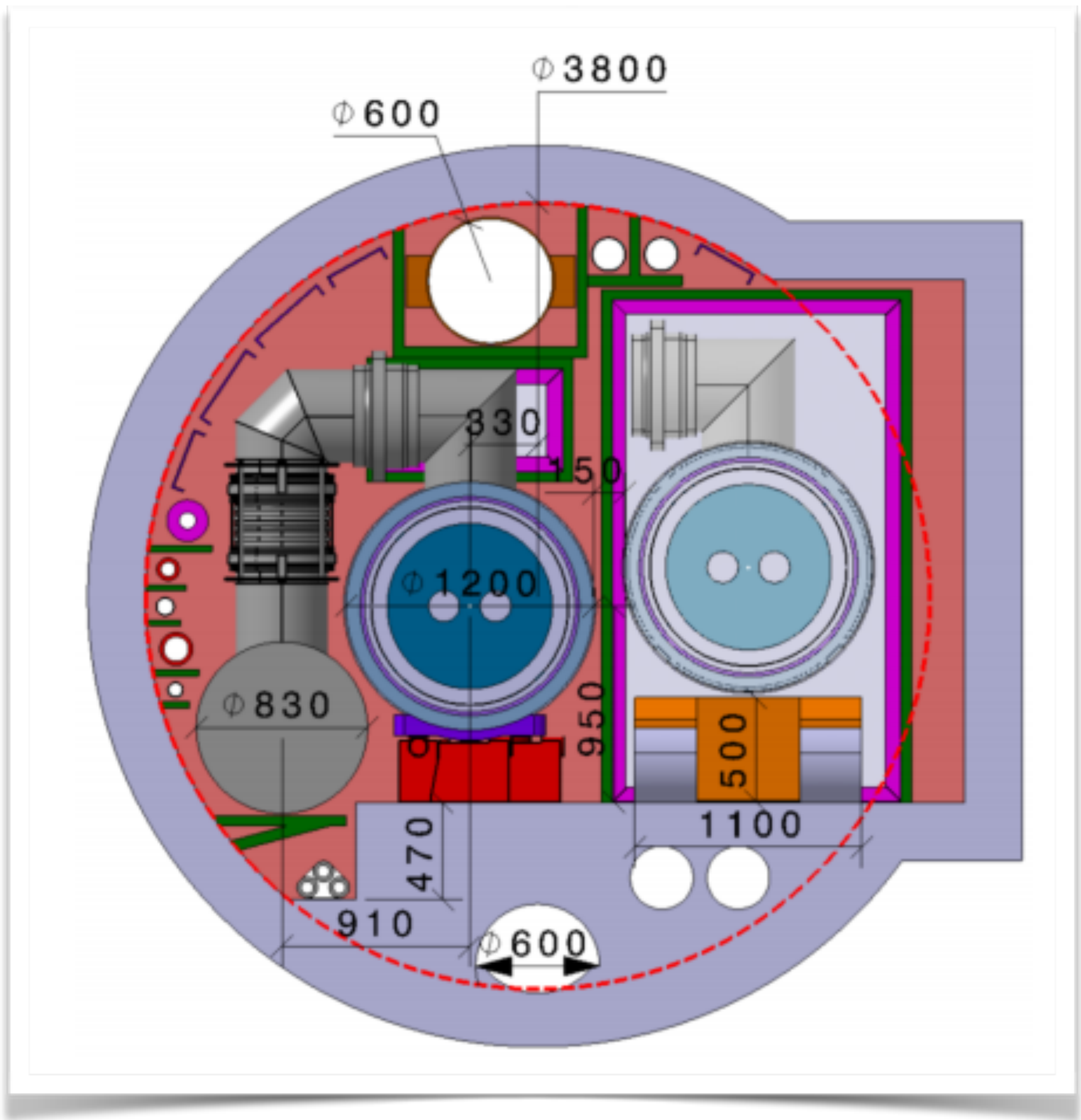


	√s		L /IP ($cm^{-2} s^{-1}$)	Int. L /IP(ab^{-1})	Comments
e^+e^- FCC-ee	~90 GeV 160 240 ~365	Z WW H top	230 $\times 10^{34}$ 28 8.5 1.5	75 ab^{-1} 5 2.5 0.8	2 experiments Total ~ 15 years of operation
pp FCC-hh	100 TeV		5 x 10^{34} 30	2.5 ab^{-1} 15	2+2 experiments Total ~ 25 years of operation
PbPb FCC-hh	$\sqrt{s_{NN}}$ = 39 TeV		3 x 10^{29}	65 nb^{-1}/run	1 run = 1 month operation
ep Fcc-eh	3.5 TeV		1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb Fcc-eh	$\sqrt{s_{eN}}$ = 2.2 TeV		0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

FCC-hh Submission

HE-LHC

- Reuse the existing LHC tunnel
- Increase the magnetic field by installing the 16 T magnets from the FCC-hh
    - ➡Energy increases from 14 to 27 TeV
- Factor of 3 increase in luminosity over HL-LHC: 10 ab^{-1}

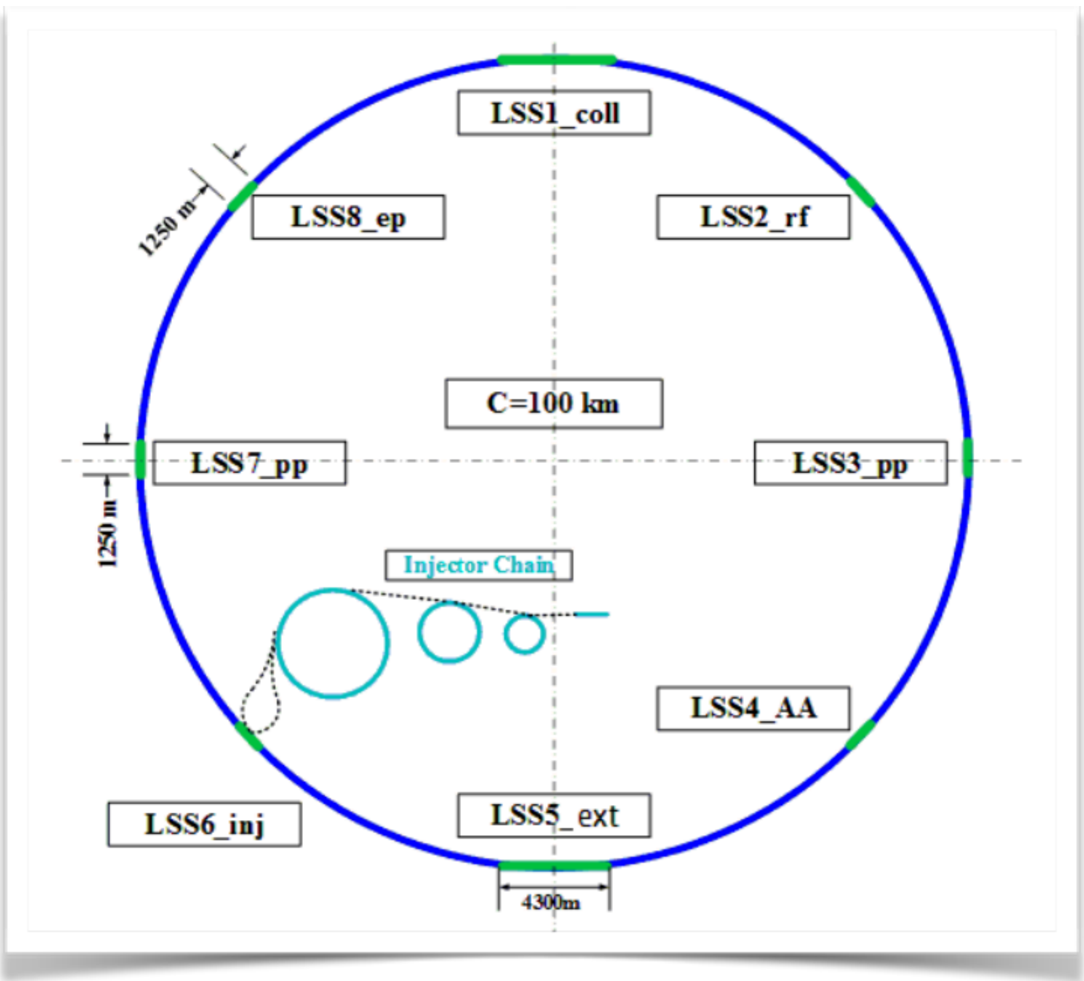


HE-LHC Submission

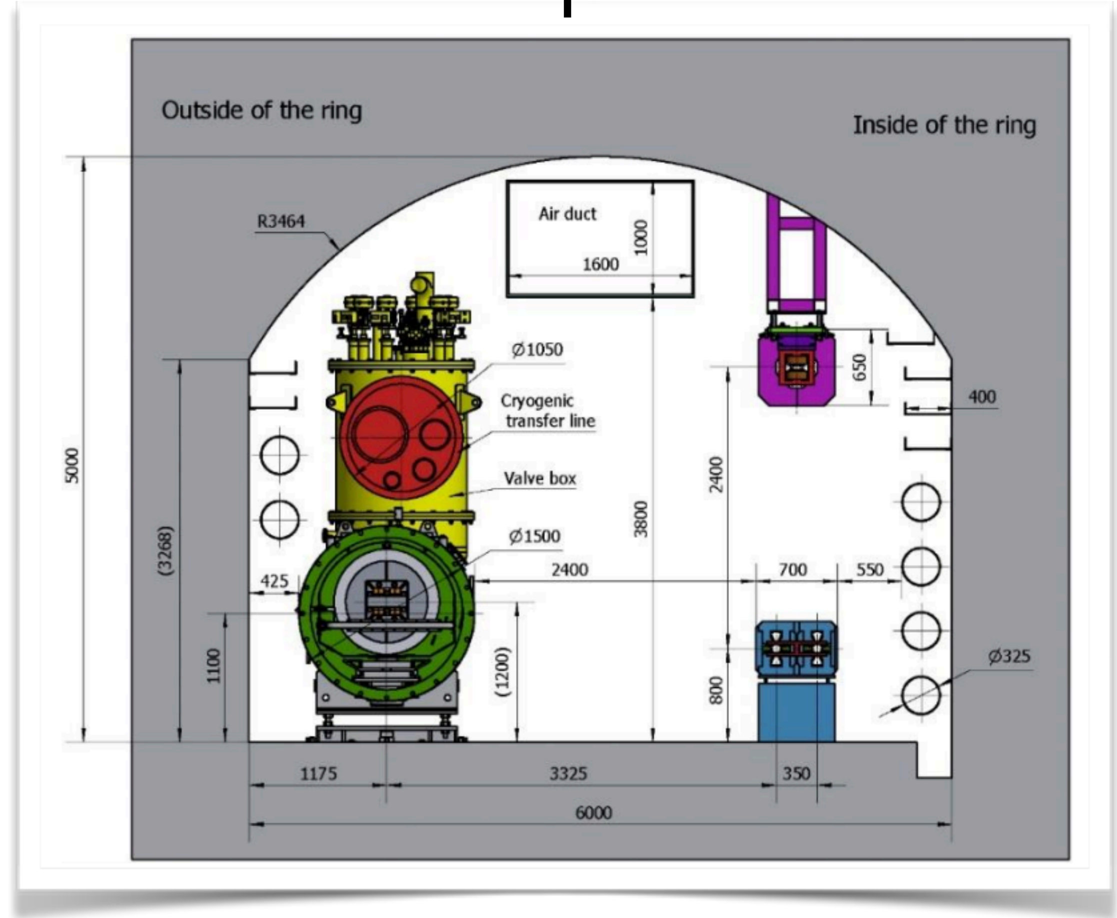
SppC

- New 100 km tunnel in China
- Magnets: initially 12 T; later 20 T
- Energy: 75 - 150 TeV
- Luminosity: 30 ab^{-1}

SppC Layout



Second step after CEPC



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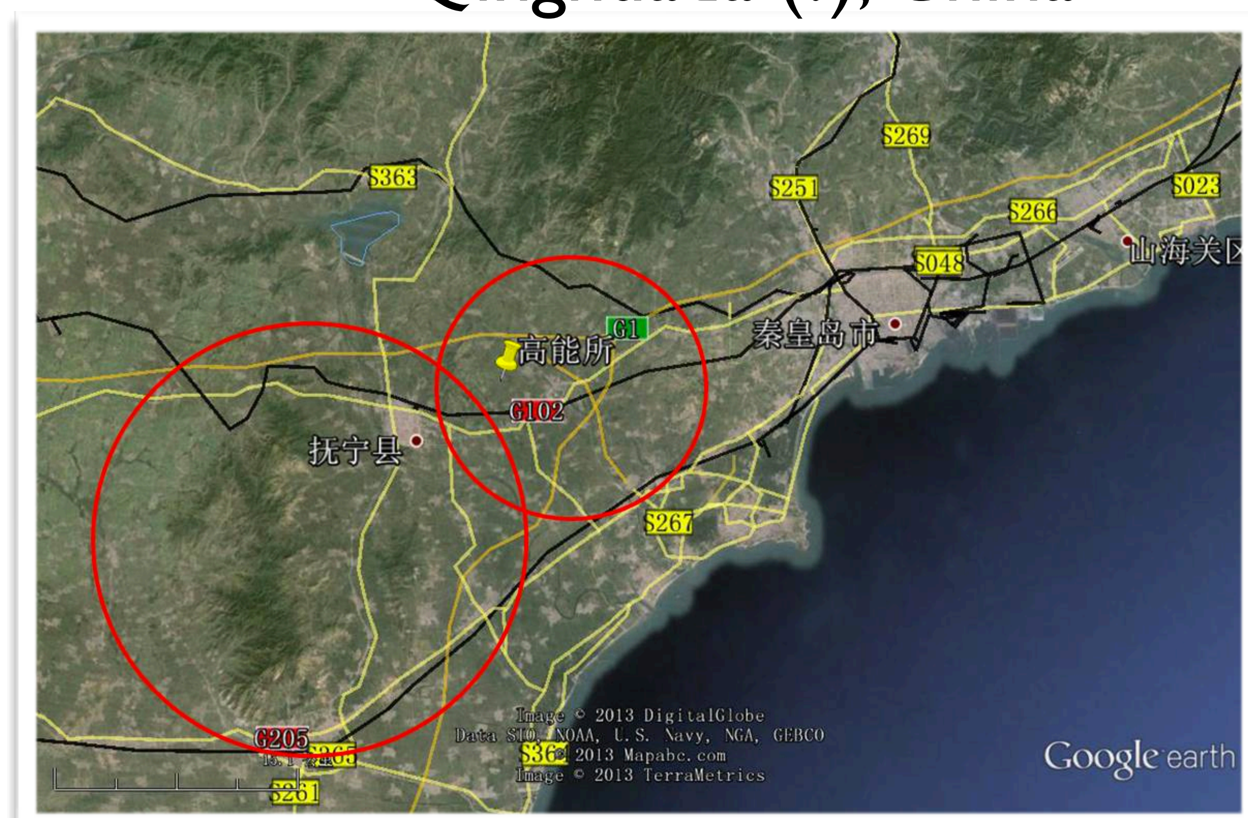
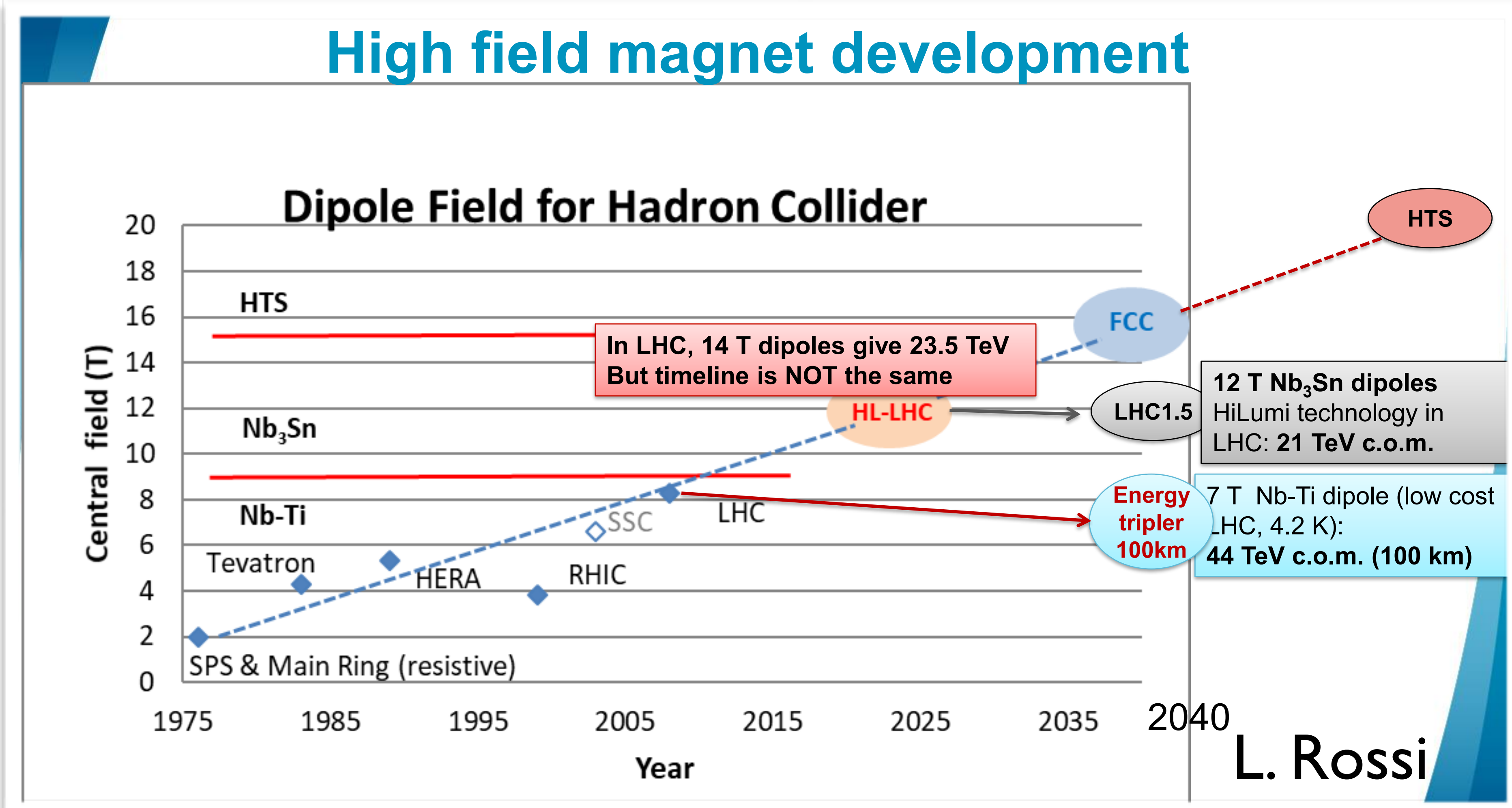


SppC Submission

Hadron Collider Challenge: High field magnets



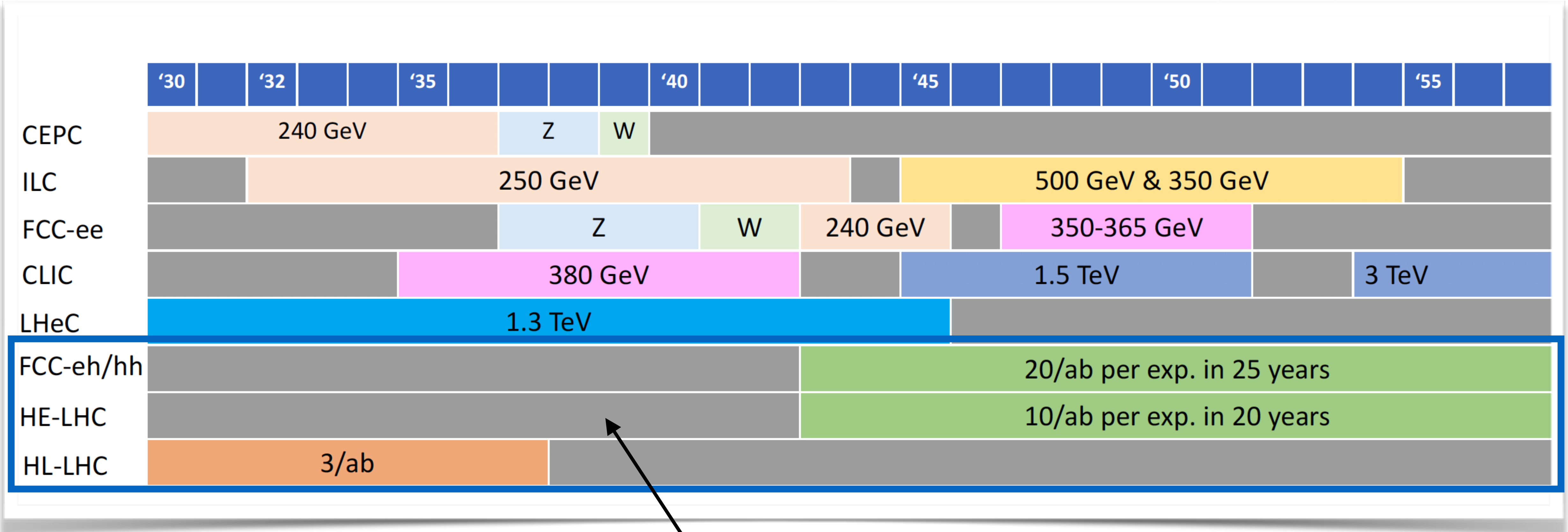
Personal (A. Yamamoto) View on Relative Timelines

Timeline	~ 5	~ 10	~ 15	~ 20	~ 25	~ 30	~ 35
Hadron Collider (CC)							
8~(11)T NbTi /(Nb3Sn)	Proto/pre-series	Construction		Operation			Upgrade
12~14T Nb_3Sn	Short-model R&D	Proto/Pre-series		Construction		Operation	
14~16T Nb_3Sn	Short-model R&D		Prototype/Pre-series			Construction	

Note: LHC experience: NbTi (10 T) R&D started in 1980's --> (8.3 T) Production started in late 1990's, in ~ 15 years

hadron collider schedule depends on magnet R&D

Timescale and cost for Hadron Colliders



start date driven by magnet R&D

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

tunnel cost

D. Schulte

Physics Potential of Future Hadron Colliders

"Big Questions" for European Strategy

- Higgs/Electroweak
  - How well can the Higgs boson **couplings** to fermions, gauge bosons and to itself be probed at current and future colliders?
  - How do **precision electroweak observables** inform us about the Higgs boson properties and/or BSM physics?
  - What progress is needed in **theoretical developments** in QCD and EWK to fully capitalize on the experimental data?
  - What is the best path towards measuring the **Higgs potential**?
- Beyond the Standard Model
  - To what extent can we tell whether the Higgs is **fundamental** or **composite**?
  - Are there **new interactions** or **new particles** around or above the electroweak scale?
  - What cases of **thermal relic WIMPs** are still unprobed and can be fully covered by future collider searches?
  - To what extent can current or future accelerators probe **feebly interacting sectors**?

Big Questions for ES

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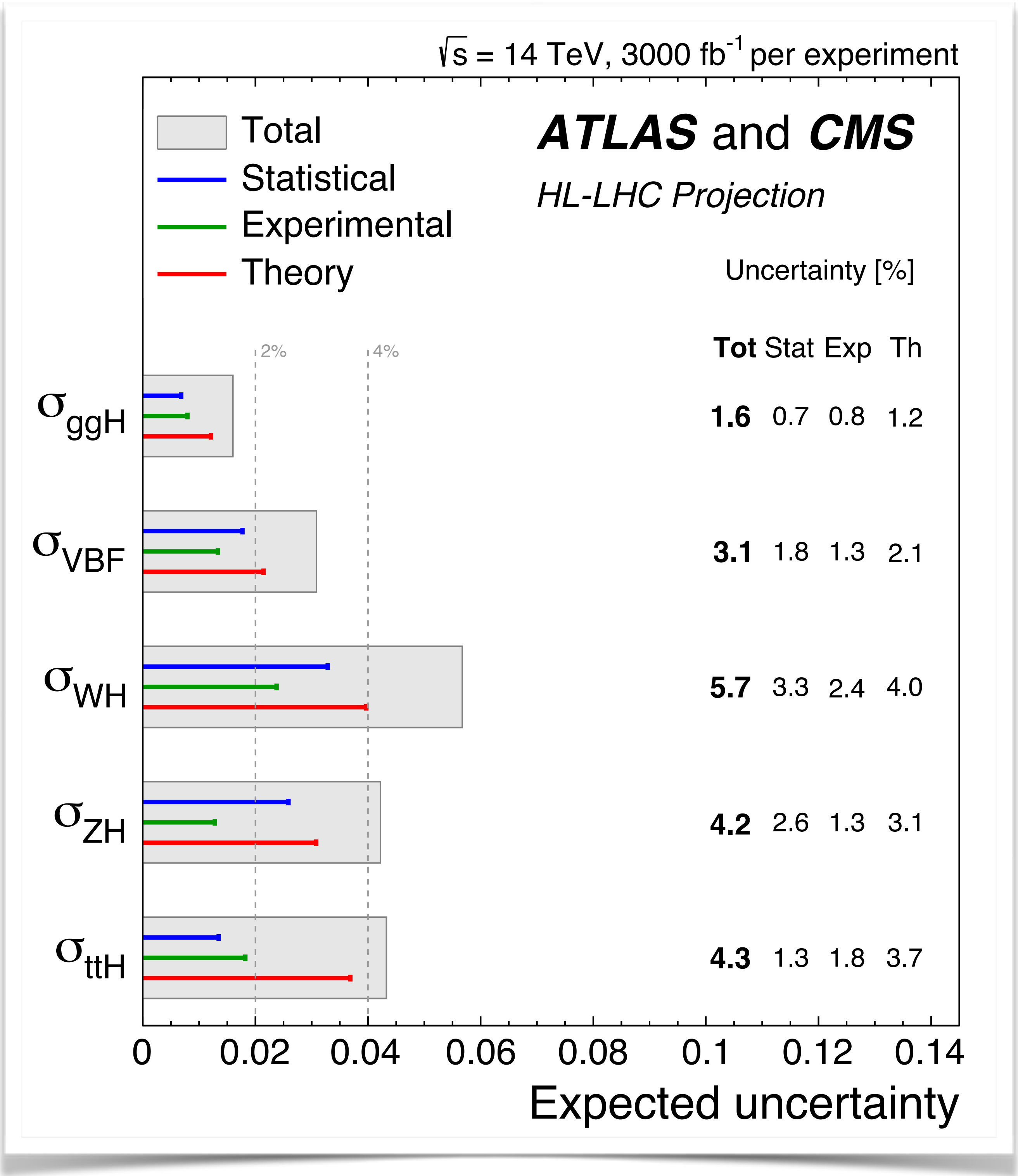
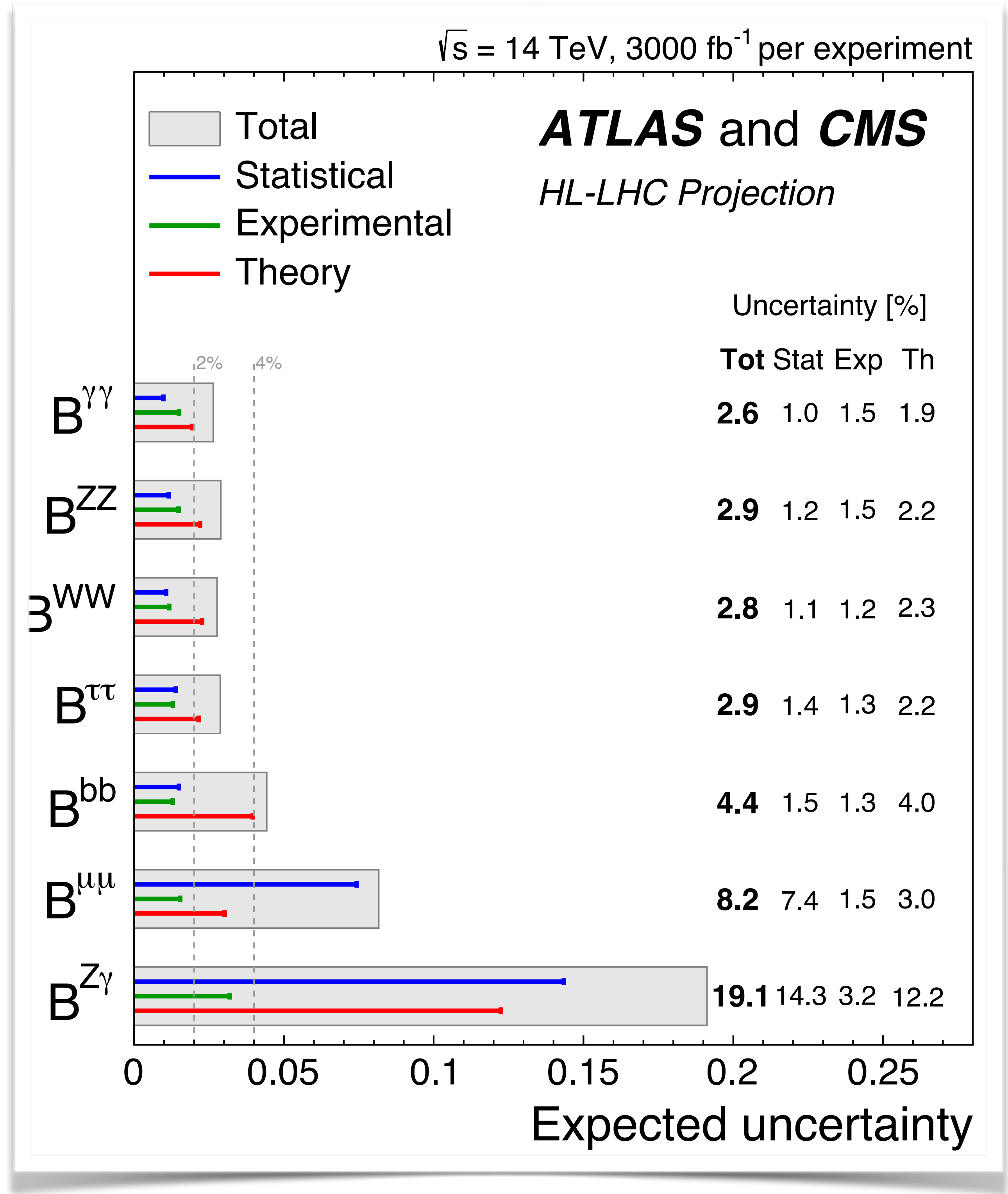
Higgs Boson couplings at the HL-LHC

Production

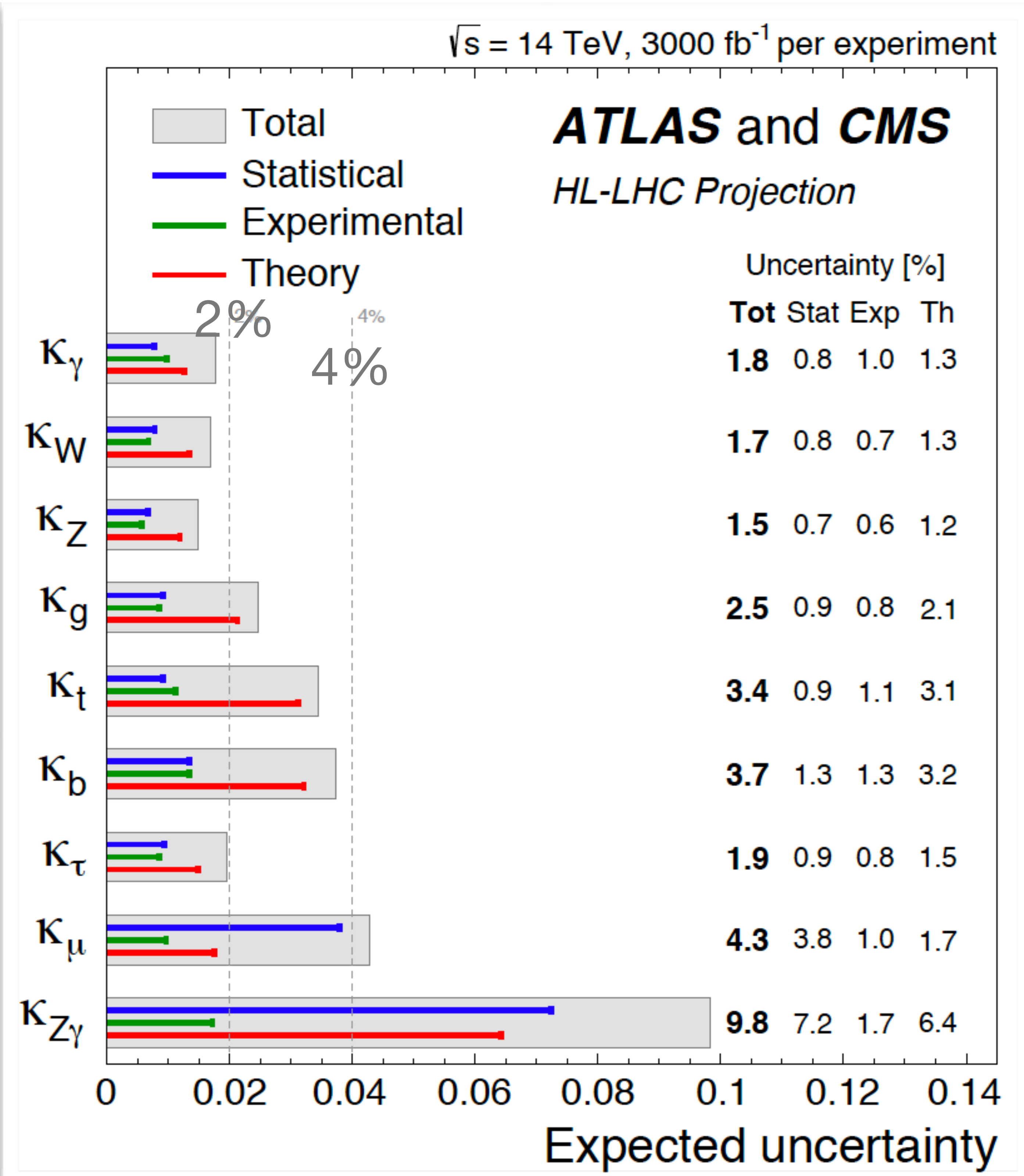


Decays

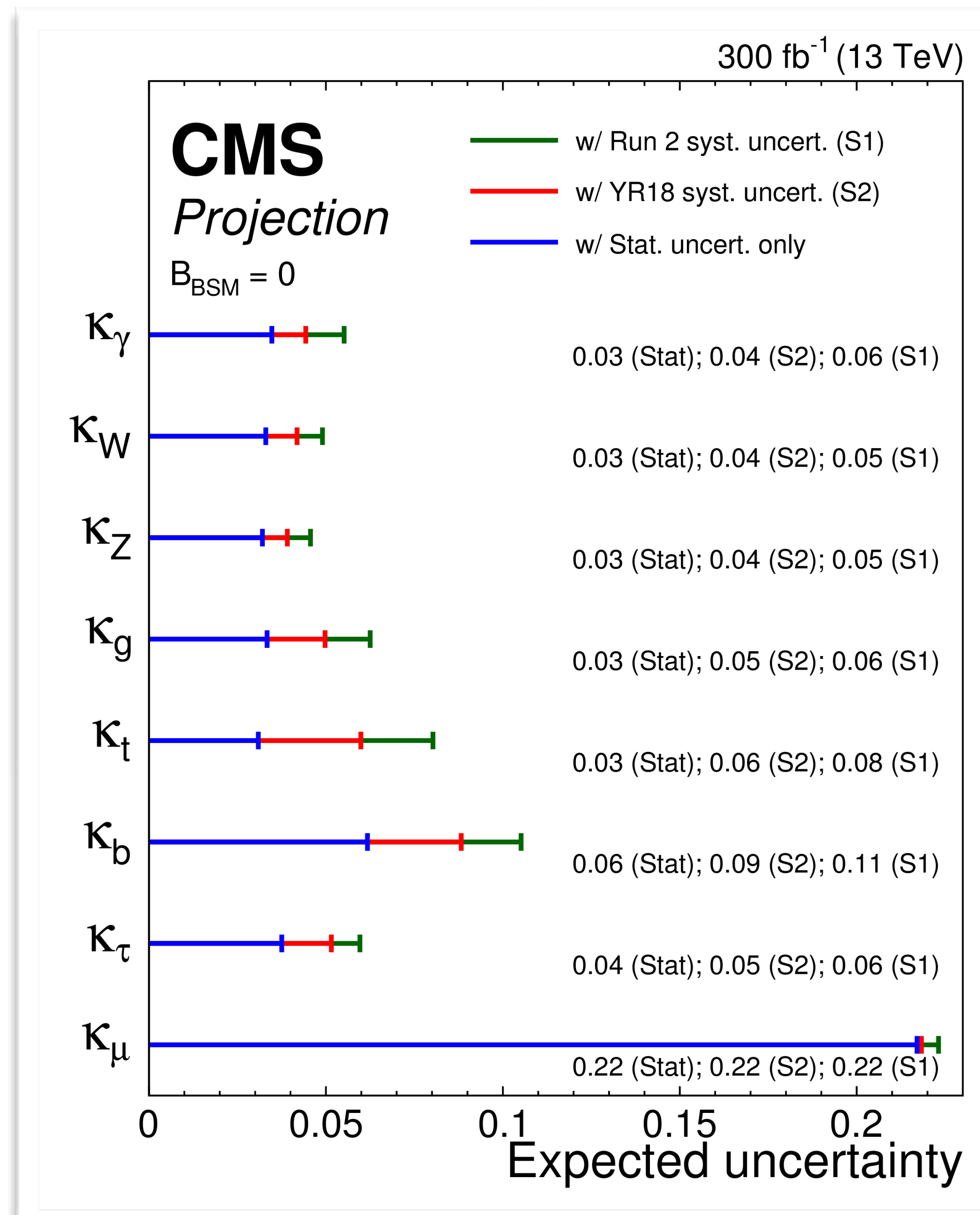


Higgs at Future Colliders report: arXiv:1905.03764, P. Azzi

HL-LHC: Interpretation in κ framework



Many couplings reach ~2% precision
Limited by theory uncertainties



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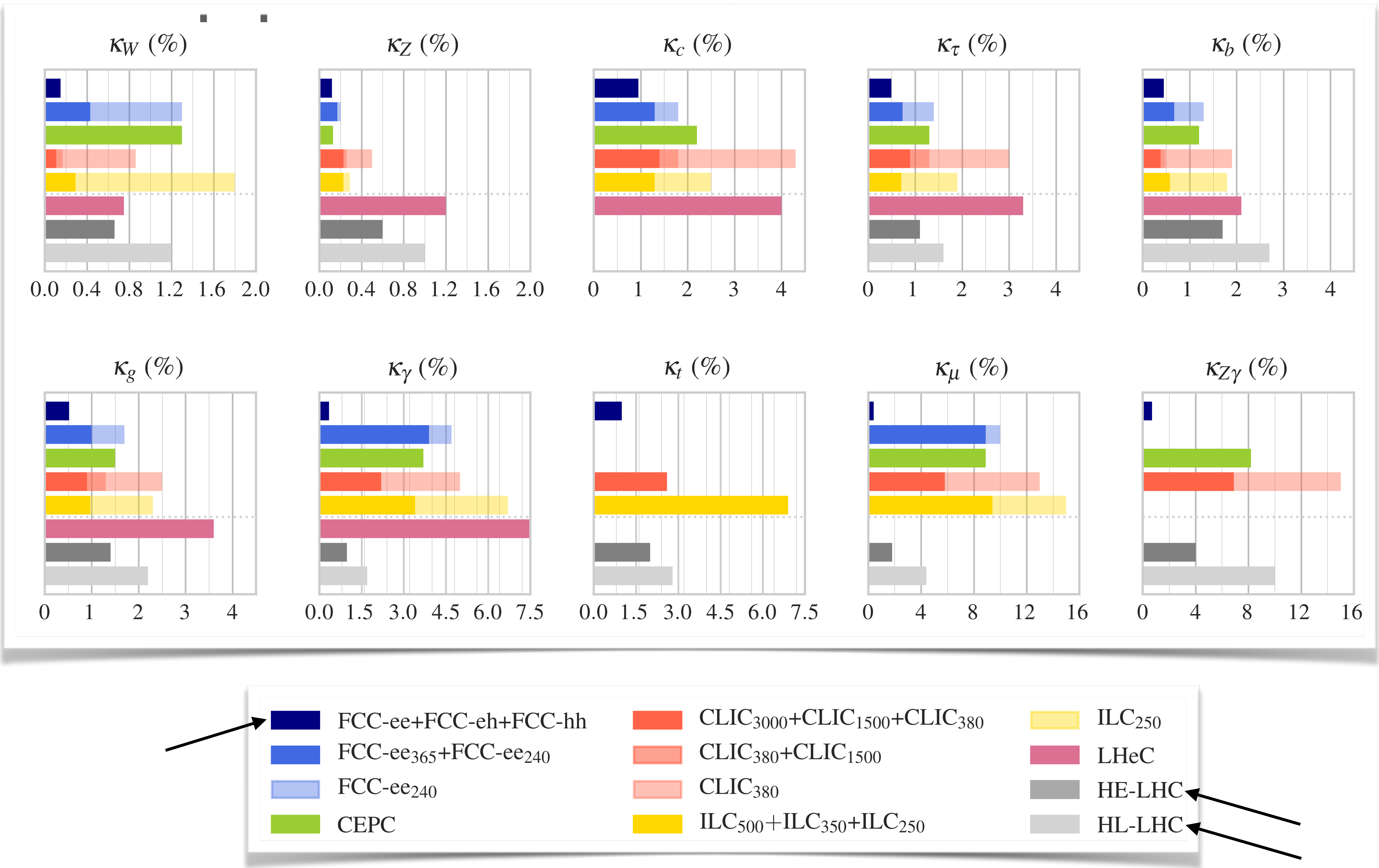
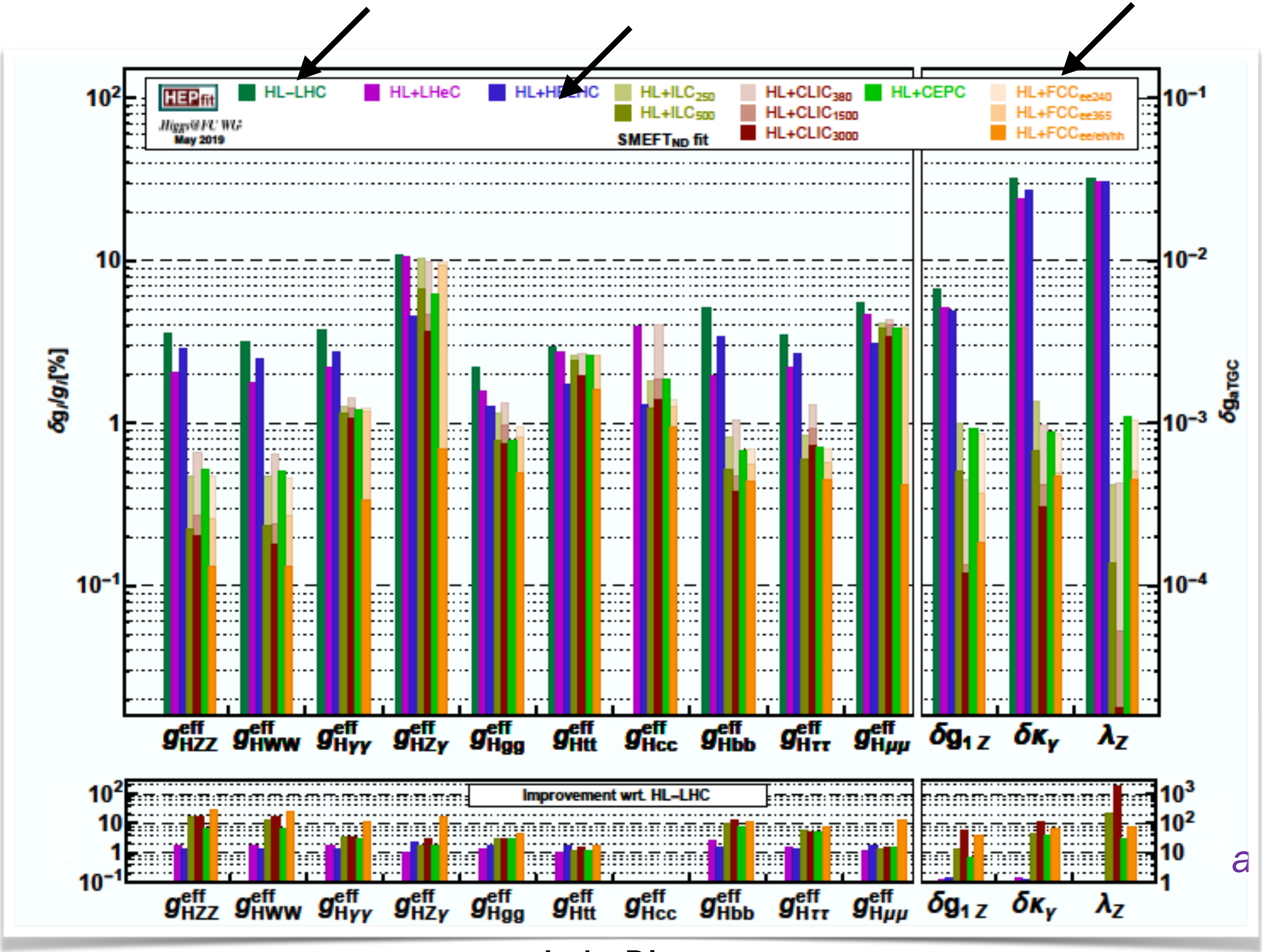
Higgs Precision at HE-LHC and FCC



M. Cepeda

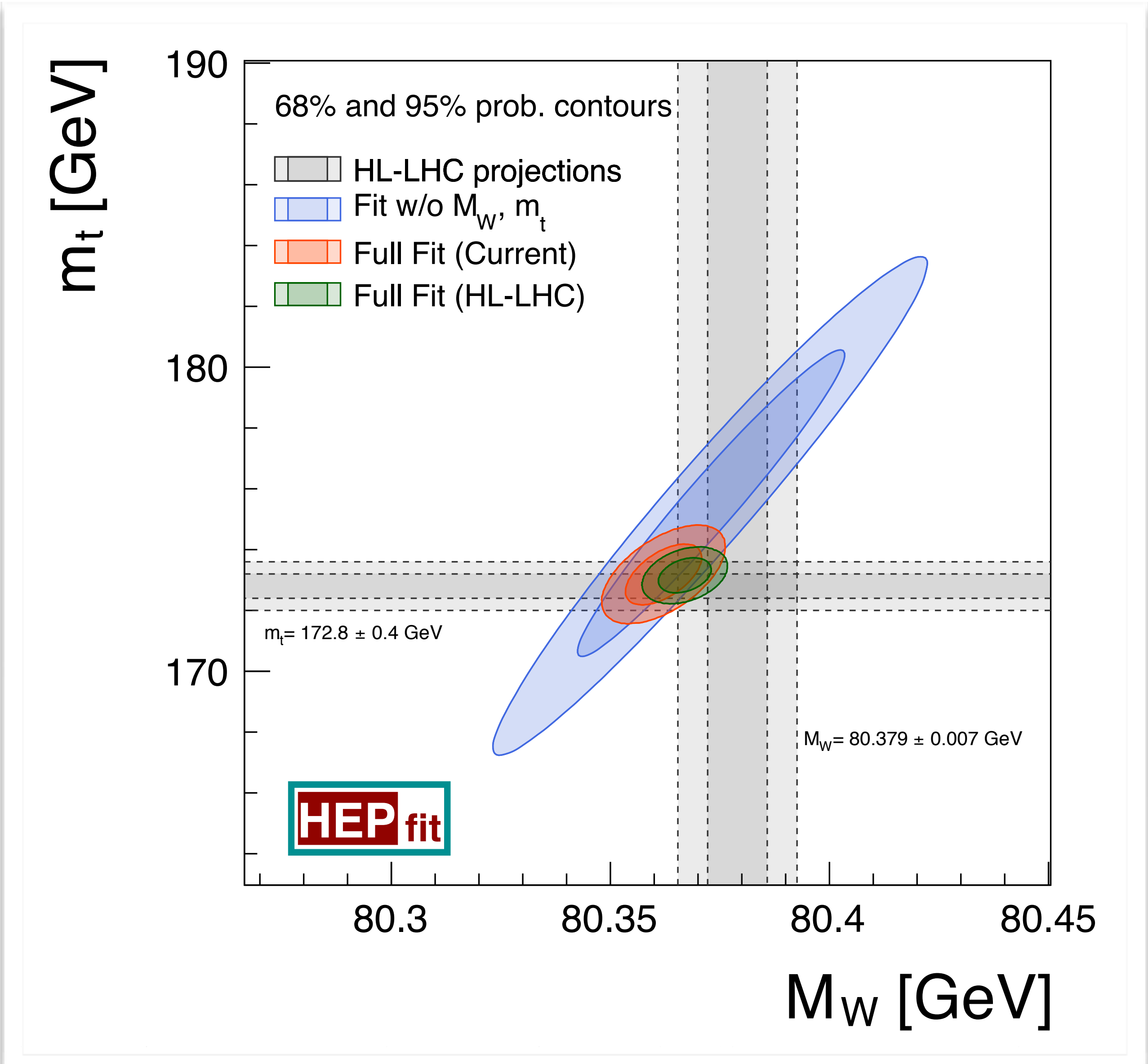
Interpretation within EFT Framework



J. de Blas

Other SM measurements

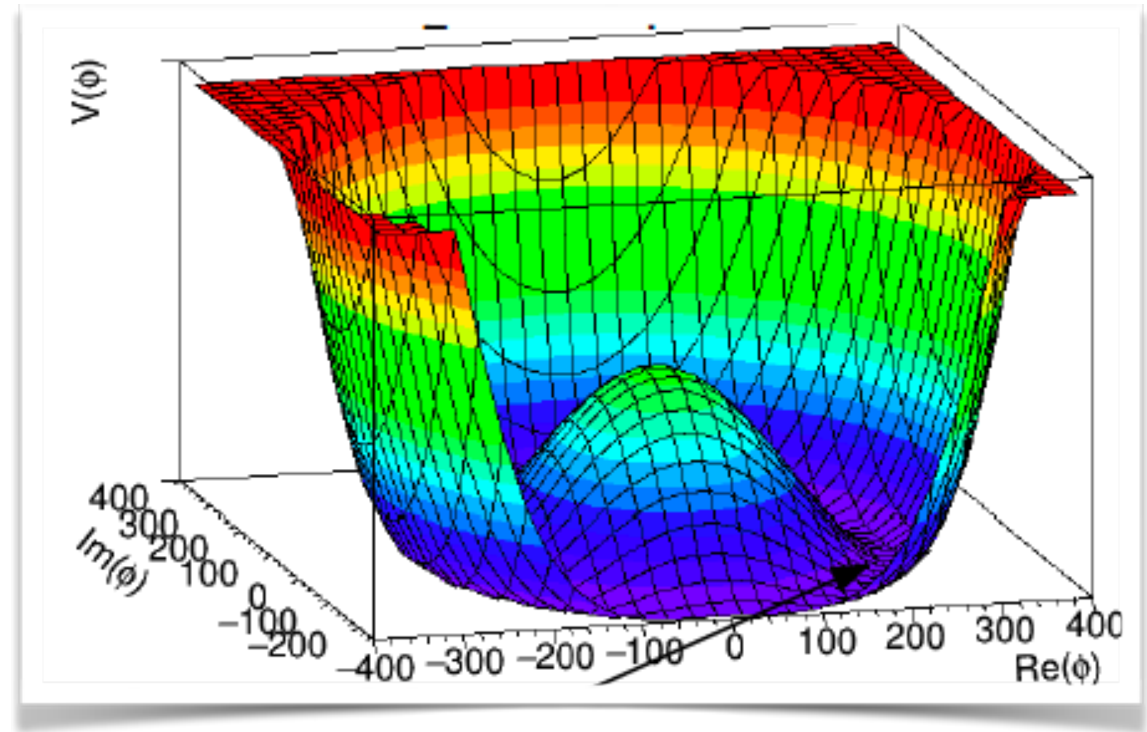
- HL-LHC: Higgs mass to ~20 MeV
- HL-LHC low pile up run (200 pb^{-1} at 14 TeV; 5-10 weeks of running)
  - W mass 6 MeV (requires precise PDF)
  - Top mass 0.2-1.2 GeV (relation to pole mass)

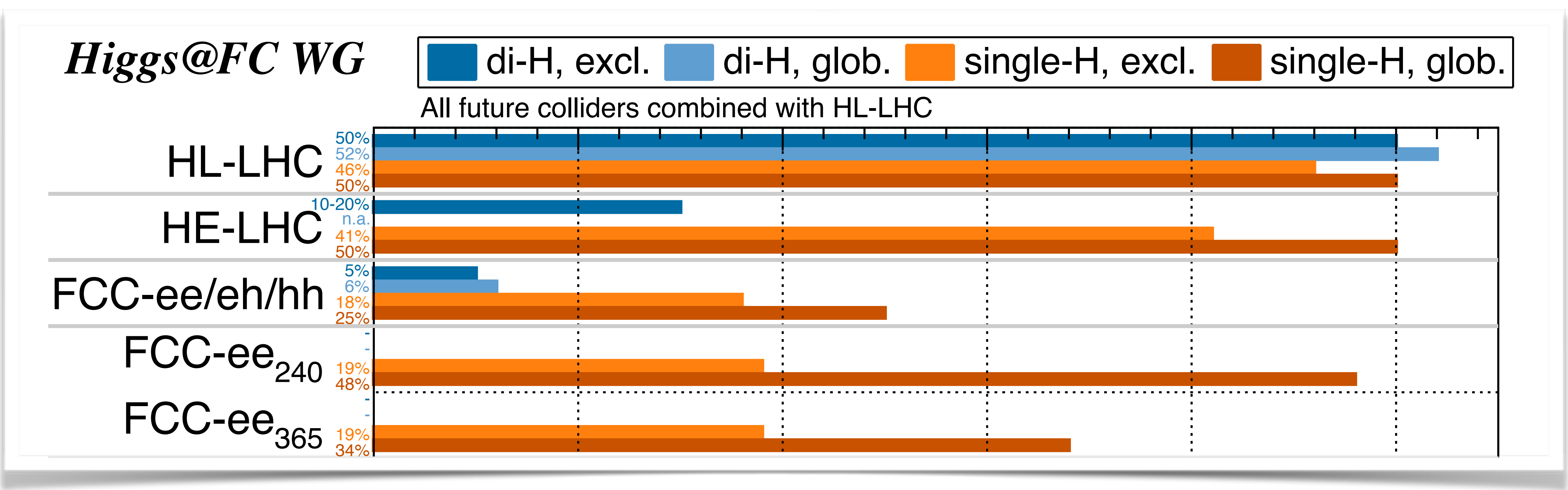


P. Azzi

Higgs Self-coupling

- Higgs potential
  - $V(\Phi) = \frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4$
- Approximate expansion around the vev
  - $V(\Phi) \approx \lambda v^2 h + \lambda v h^3 + \frac{1}{4} h^4$
- Methods to search for diHiggs production
  - Direct searches
  - Indirect constraints from single Higgs production through loop effects





E. Petit

Big Questions for ES

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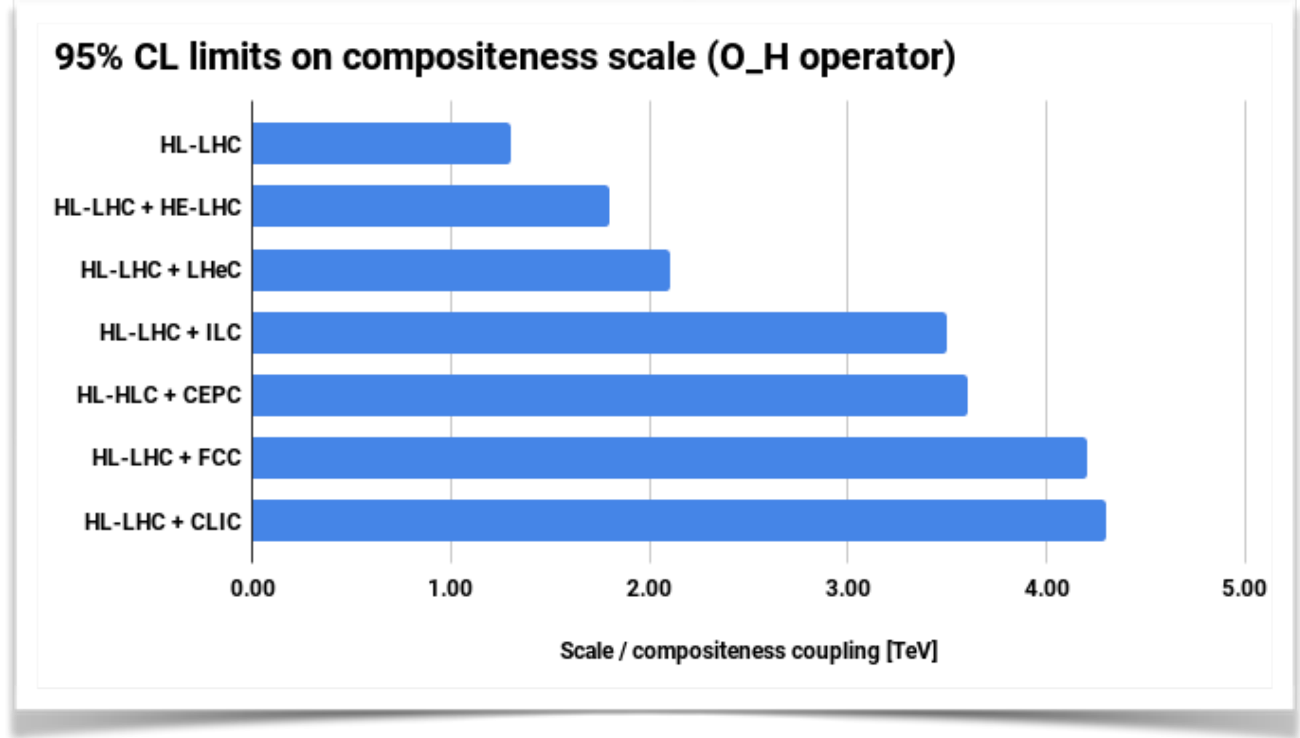
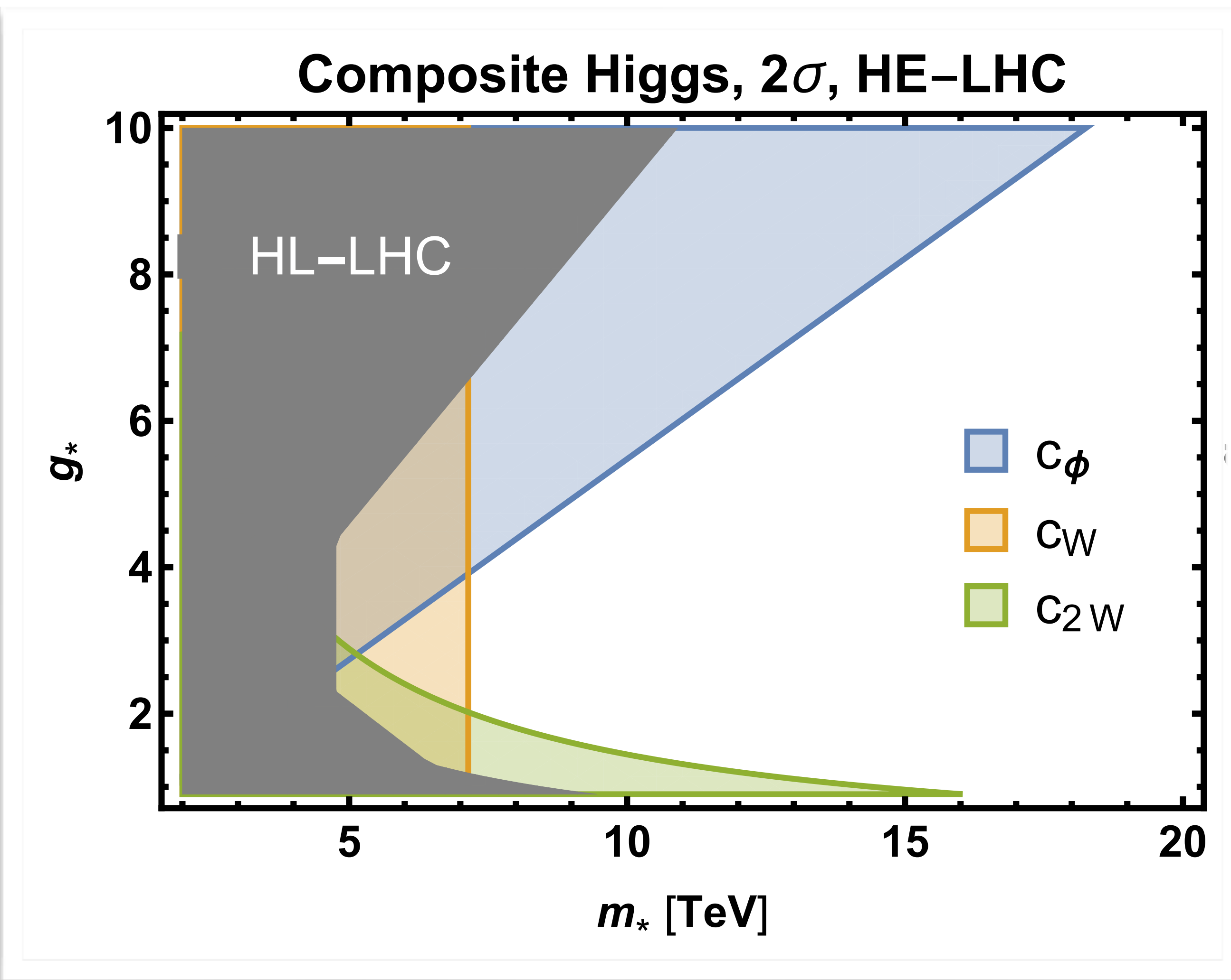
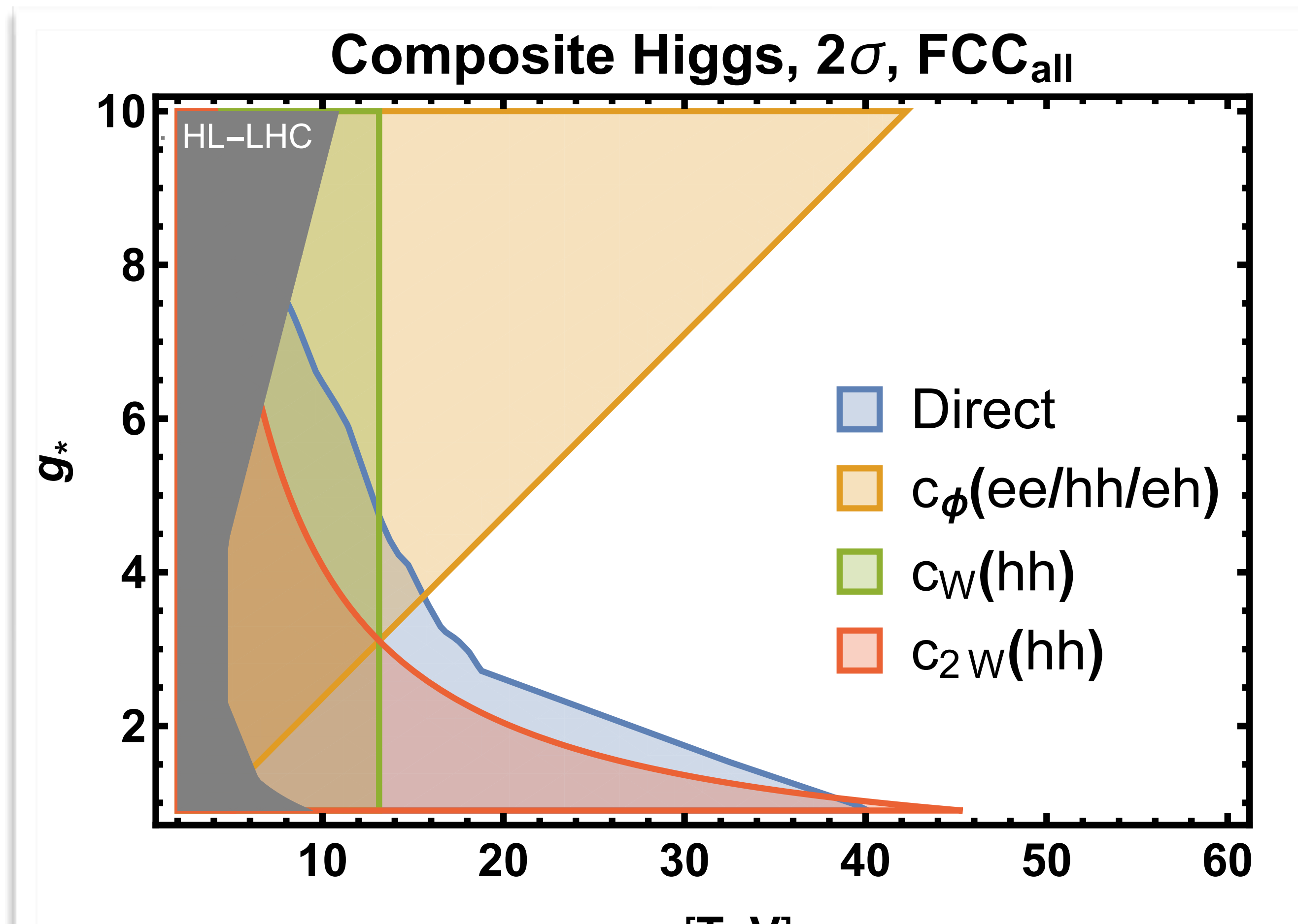
Higgs Compositeness

- Set limits on compositeness via fit to Higgs couplings
- Obtain limits on compositeness scale from ~1-4 TeV



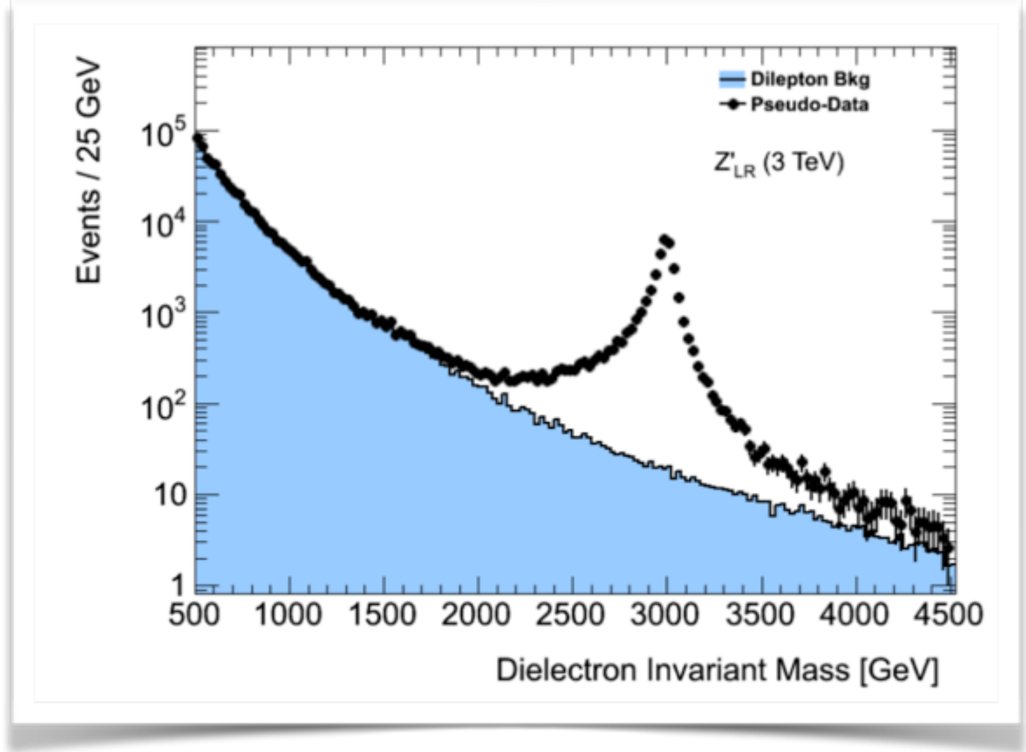


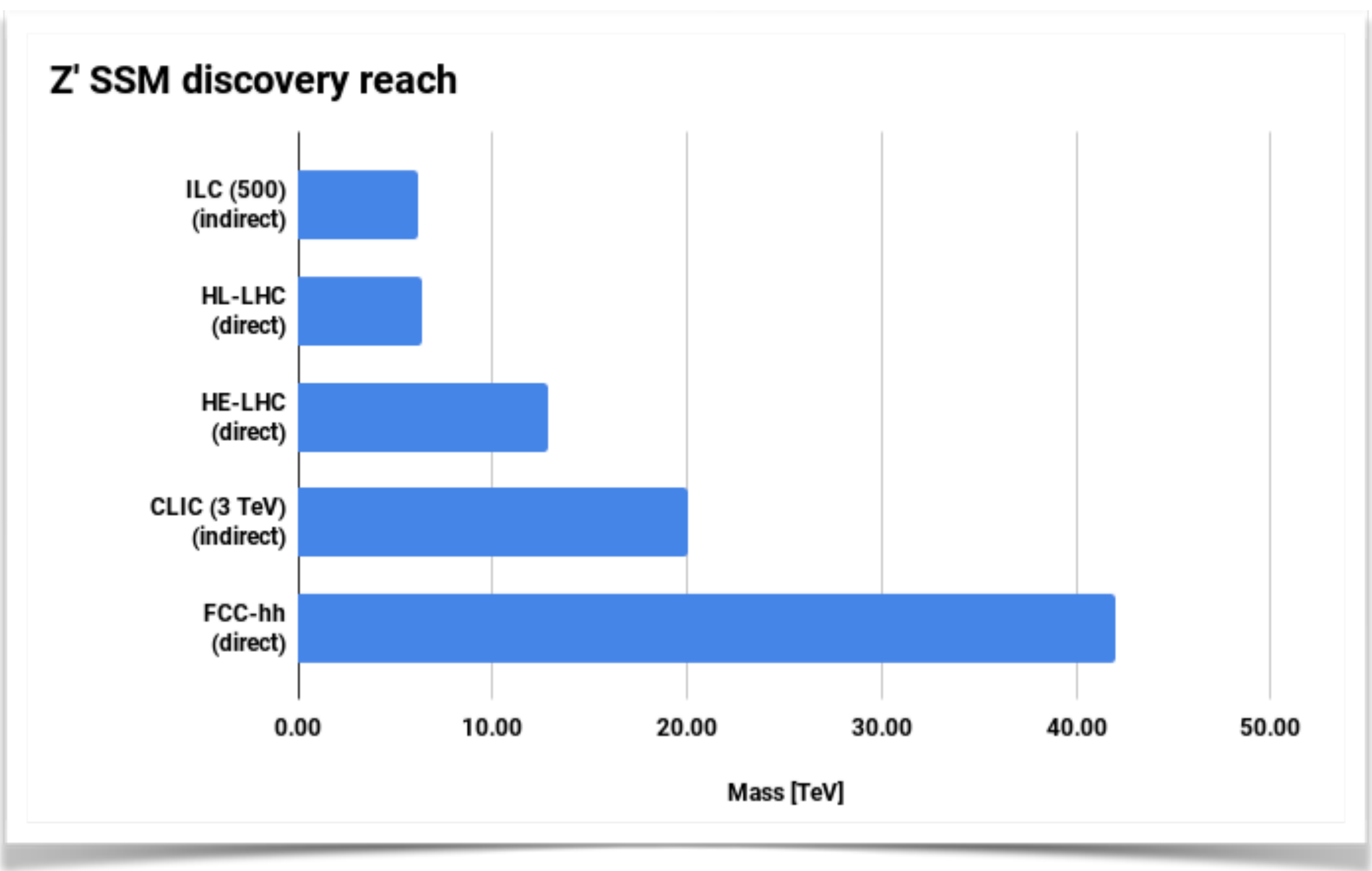


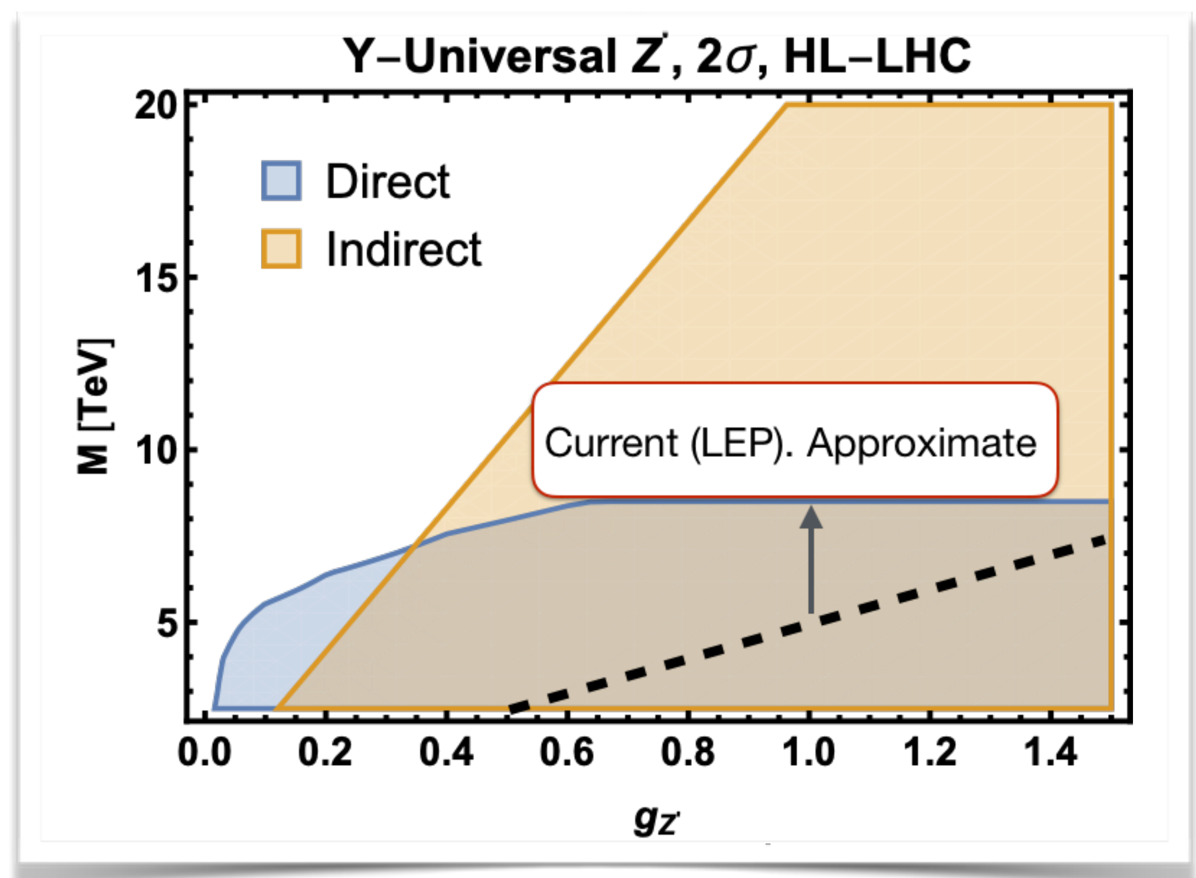
J. Alcaraz

New Interactions or Particles

- Direct (peak) or indirect (couplings)
- Direct observation
  - M ≲ 0.3-0.5$\sqrt{s}$ for hadron collides
- Interpretation within simple sequential Z' model

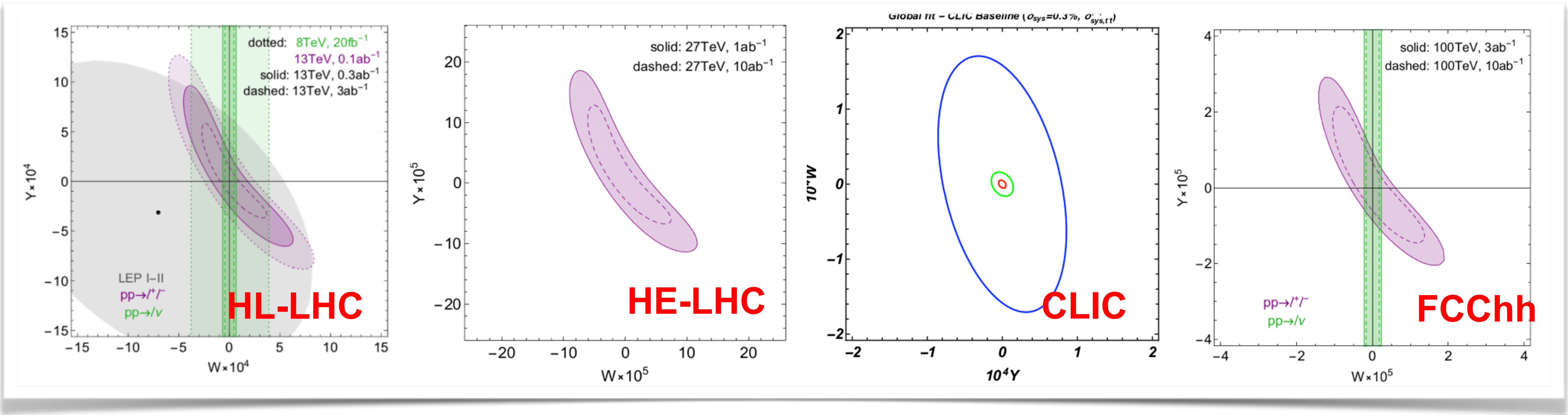


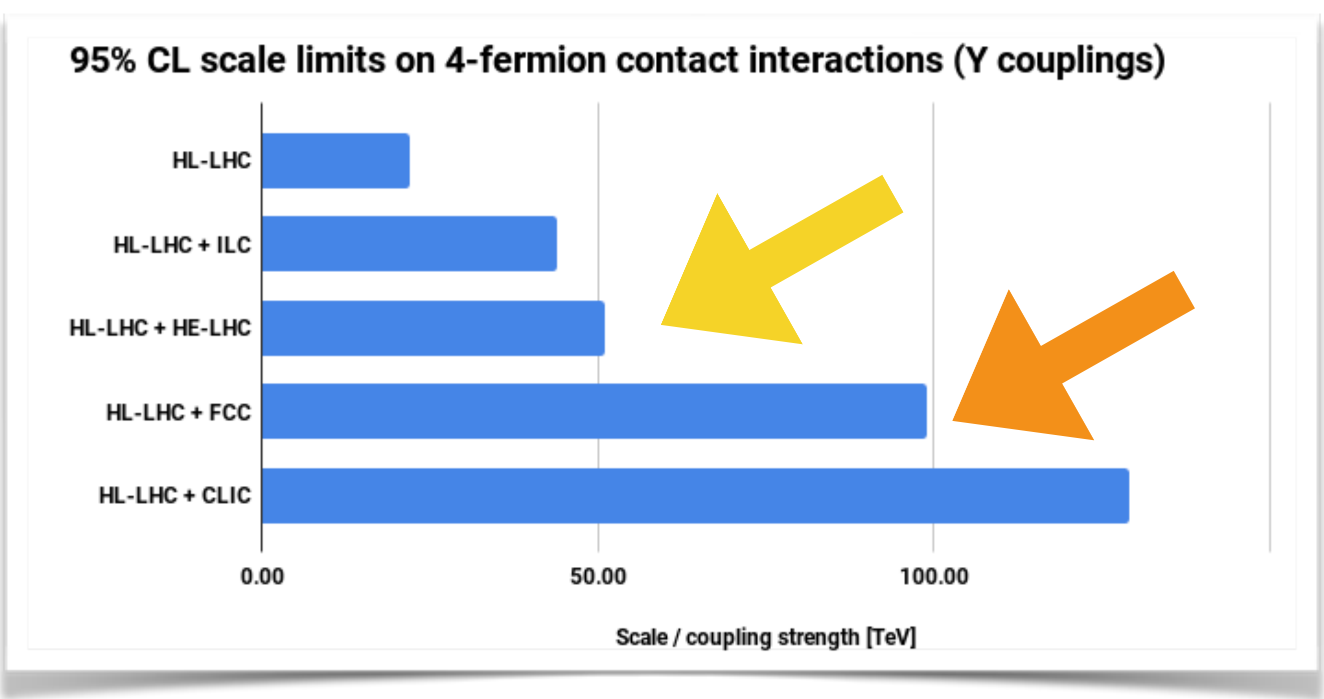


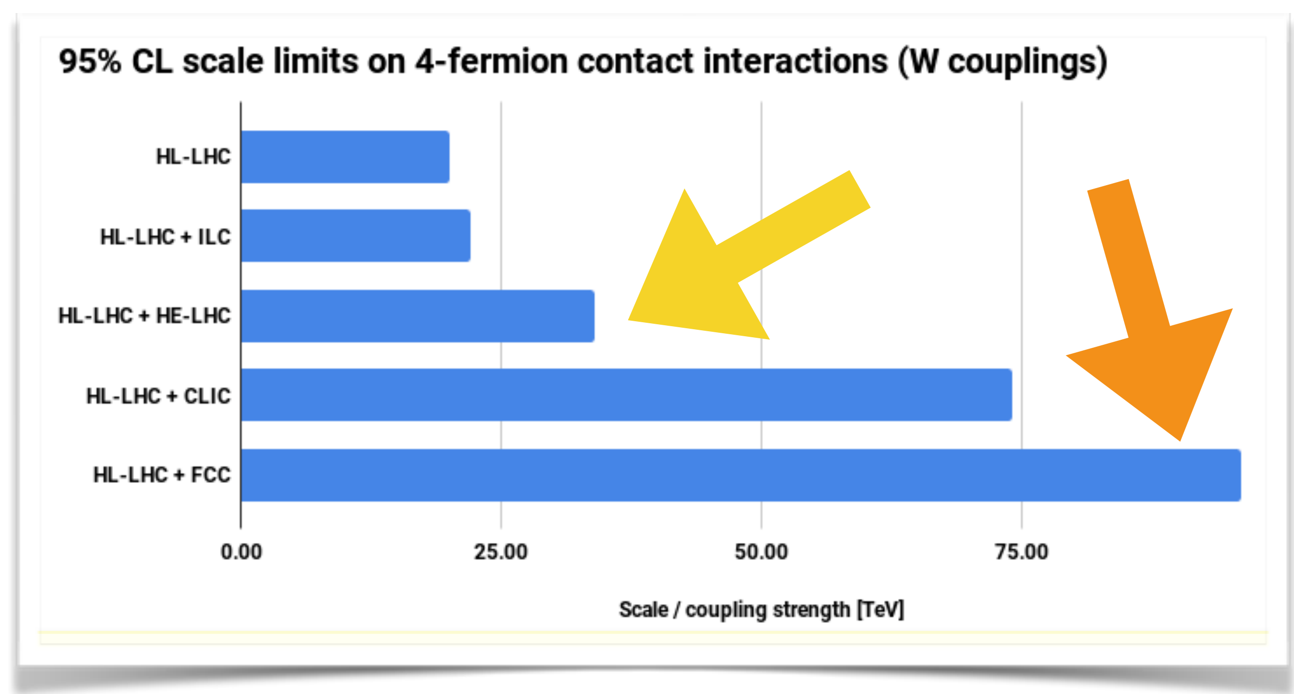


J. Alcaraz, A. Wulzer

Contact Interactions

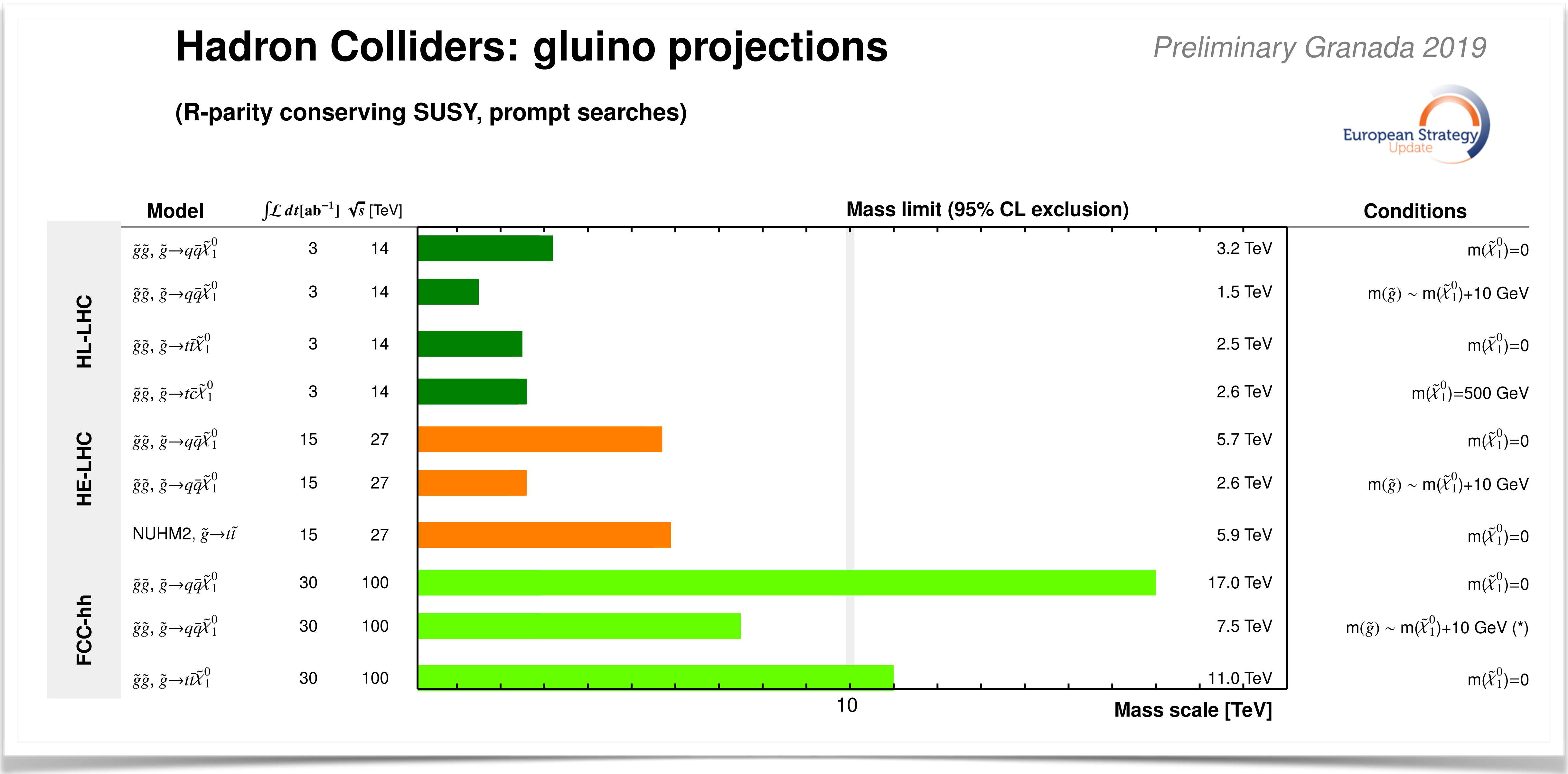






J. Alcaraz

Strong SUSY: gluinos

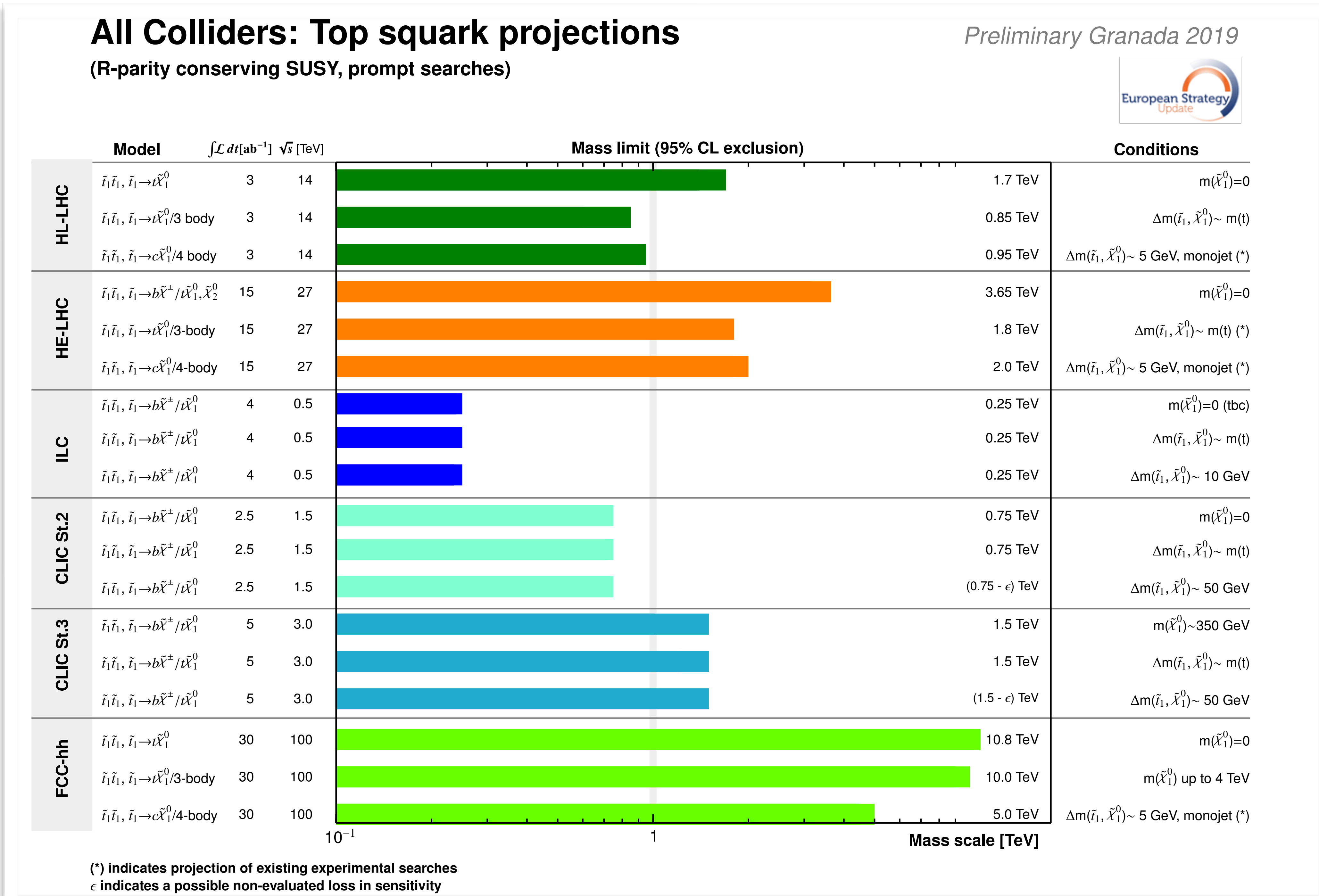


HE-LHC extends HL-LHC mass reach by a factor of ~2

FCC-hh extends HL-LHC mass reach by a factor of ~5

M. D’Onofrio

Strong SUSY: squarks

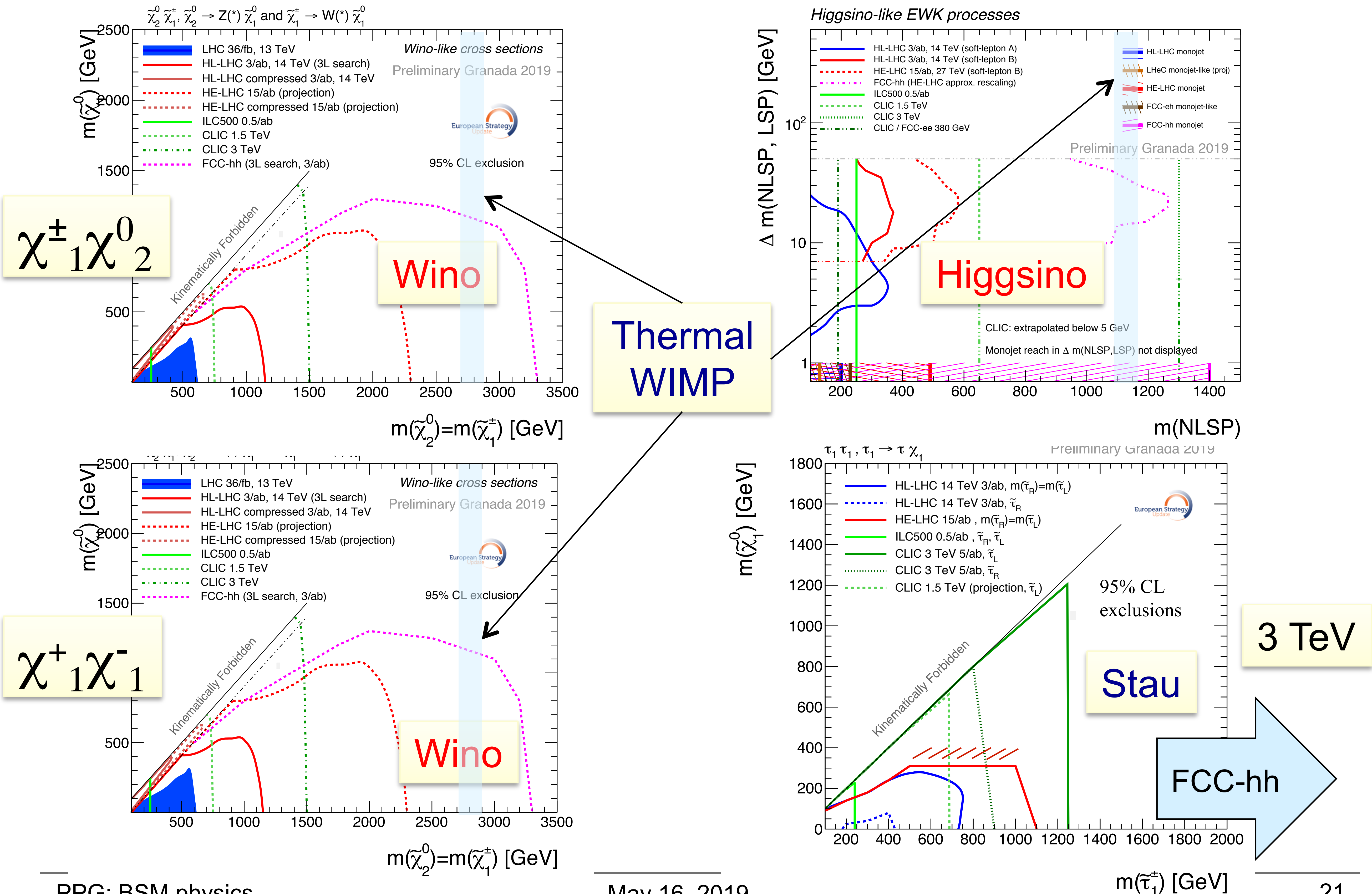


HE-LHC extends HL-LHC mass reach by a factor of ~2

FCC-hh extends HL-LHC mass reach by a factor of ~6

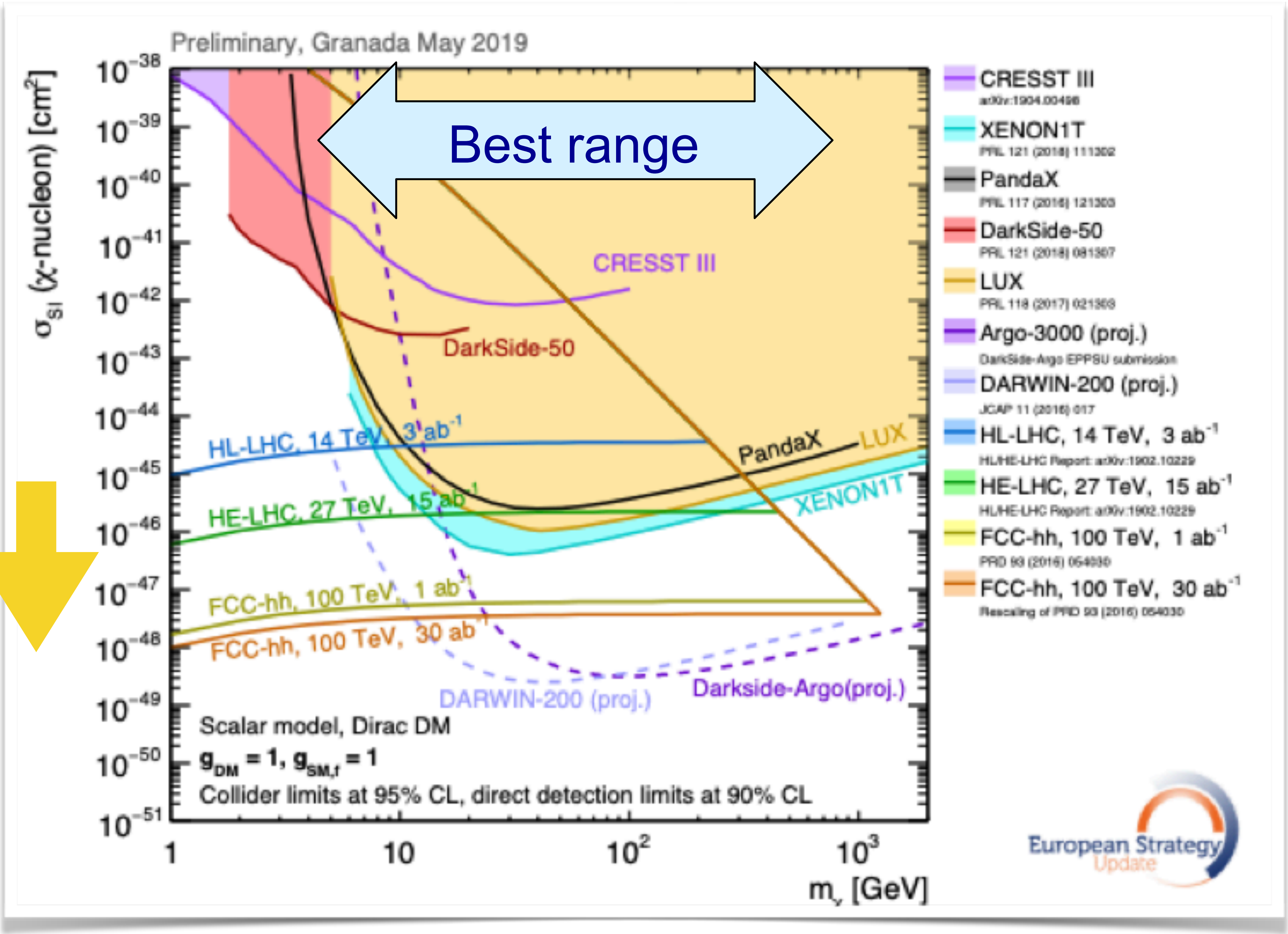
M. D'Onofrio

Electroweak SUSY



P. Sphicas, M. D'Onofrio

Dark Matter



Model-dependent limits probe the low mass range

C. Doglioni

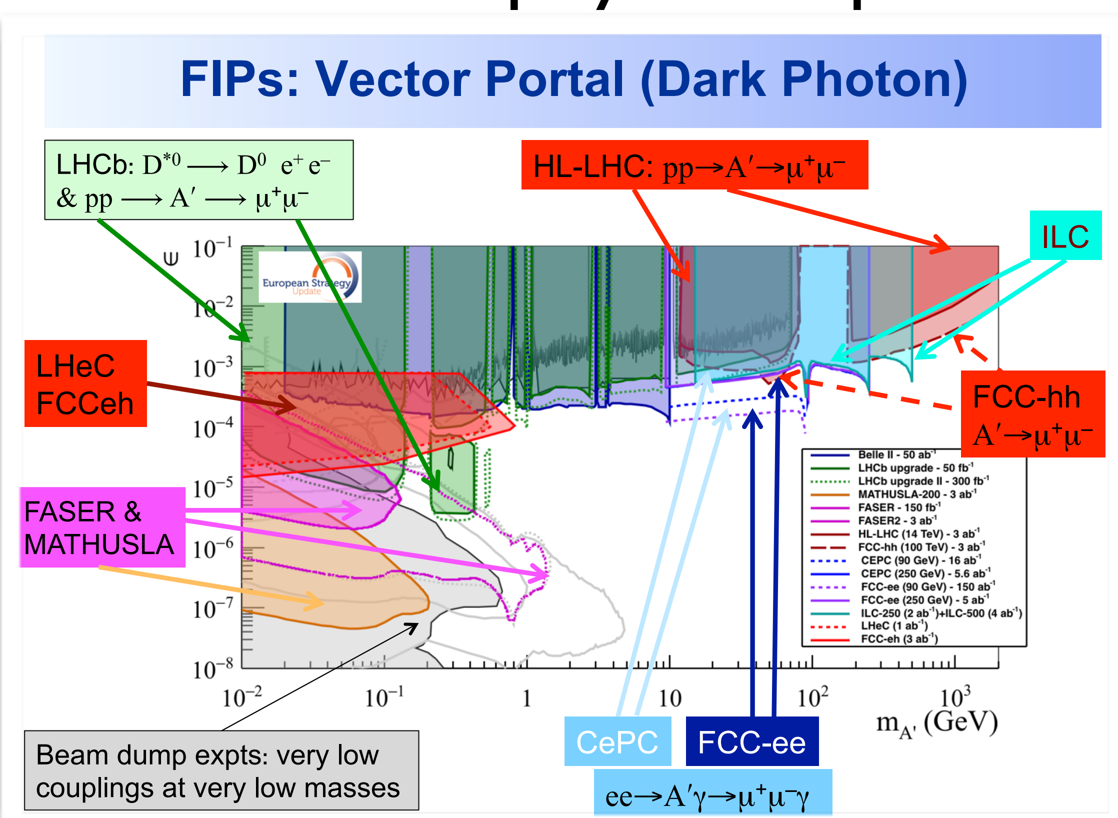
Feebly Interacting Particles (FIPs)

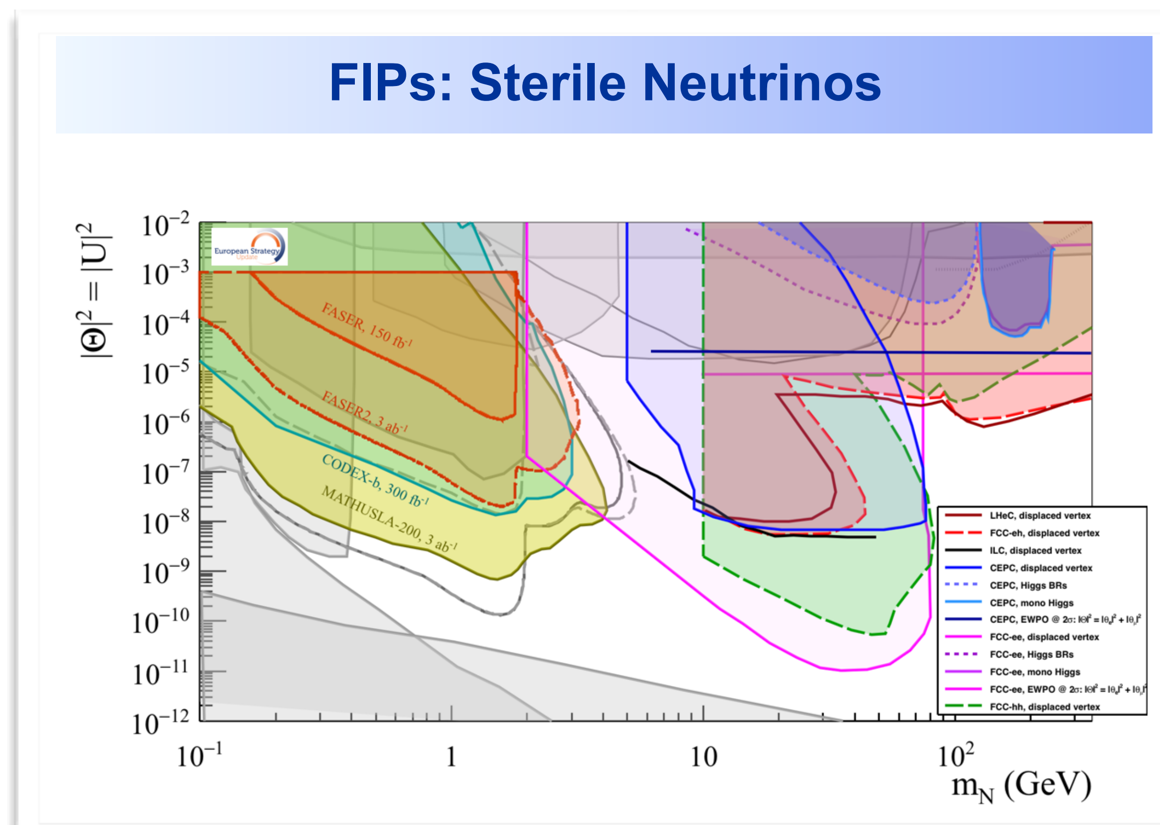
- Wide range of possibilities and models

PBC report, arXiv:1901.09966

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

- Hadron colliders play a complementary role to targeted experiments





P. Sphicas, G. Lanfranchi

Conclusion

- Critical turning point for our field as we evaluate options and try to converge on what machine(s) we want to build next
- Short review of the hadron colliders which were proposed and discussed in Granada as part of the European Strategy Process
  - HL-LHC, HE-LHC, FCC-hh and SppC
- Key physics capabilities include precision Higgs couplings, the Higgs self-coupling and a wide range of BSM searches