Physics at Future Circular Colliders (FCC)

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Where is everybody? (Nima)

- There *must* be something beyond the Standard Theory (or totally different!)
- Experimental proofs such as:
  - Cosmological Dark Matter
  - Baryon Asymmetry of the Universe
  - non-zero (but very small) neutrino masses
- Plus, the small Higgs boson mass hints to crucial questions specific to the TeV scale that demand an answer and require exploration:
  - Hierarchy problem/Naturalness
  - EW dynamics above the symmetry breaking scale
- Which way to go?
  - Indirect search for effects of new physics on W,Z,H,top —> Colliders with unprecedented accuracy
  - Direct searches for new heavy particles —> Colliders with larger energies
  - Or maybe both?

The (evolving) HEP landscape

FIND NO NEW PARTICLE, BUT HINTS FOR NON STANDARD HIGGS BEHAVIOR OR OTHER EXCESSES

➡**HL-LHC can somewhat improve precision**

➡**Higgs and Z factories very interesting machines (FCC-ee)**

➡**push energy frontier to its limits (FCC-hh)**

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machines (FCC-ee)

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FIND A NEW HEAVY PARTICLE(S)

➡HL-LHC can study it some of its properties

➡spectrum may include partners out of reach

➡larger energies and luminosities needed to fully study the new physics scenario (FCC-hh)

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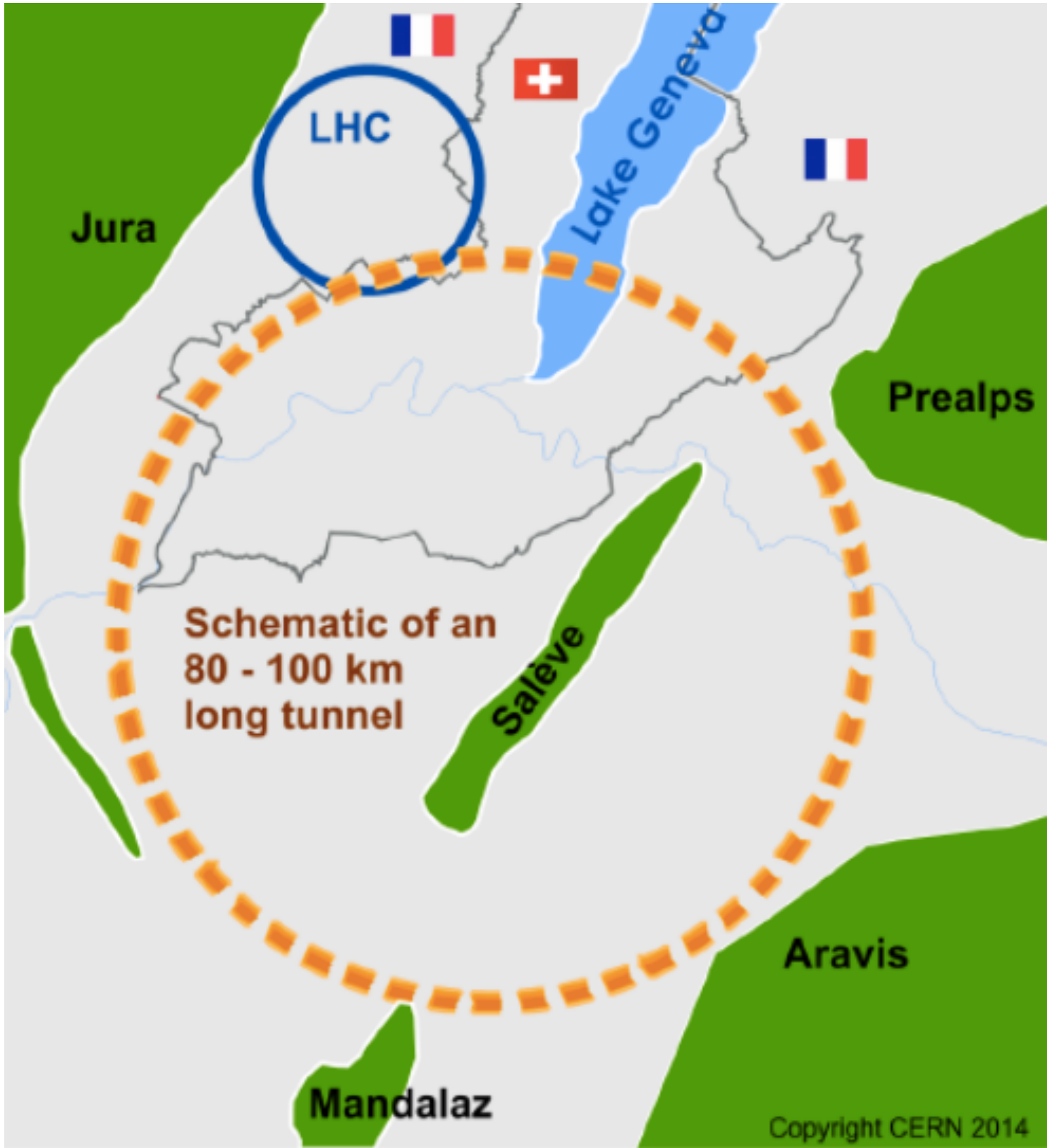
The FCC project

- Build a 100 km tunnel in the Geneva region with the ultimate goal of pp collisions at 100TeV
- Intermediate step: precision circular e+e- collider (same tunnel) variable beam energy: 90-350 GeV
- possibility of ep collisions



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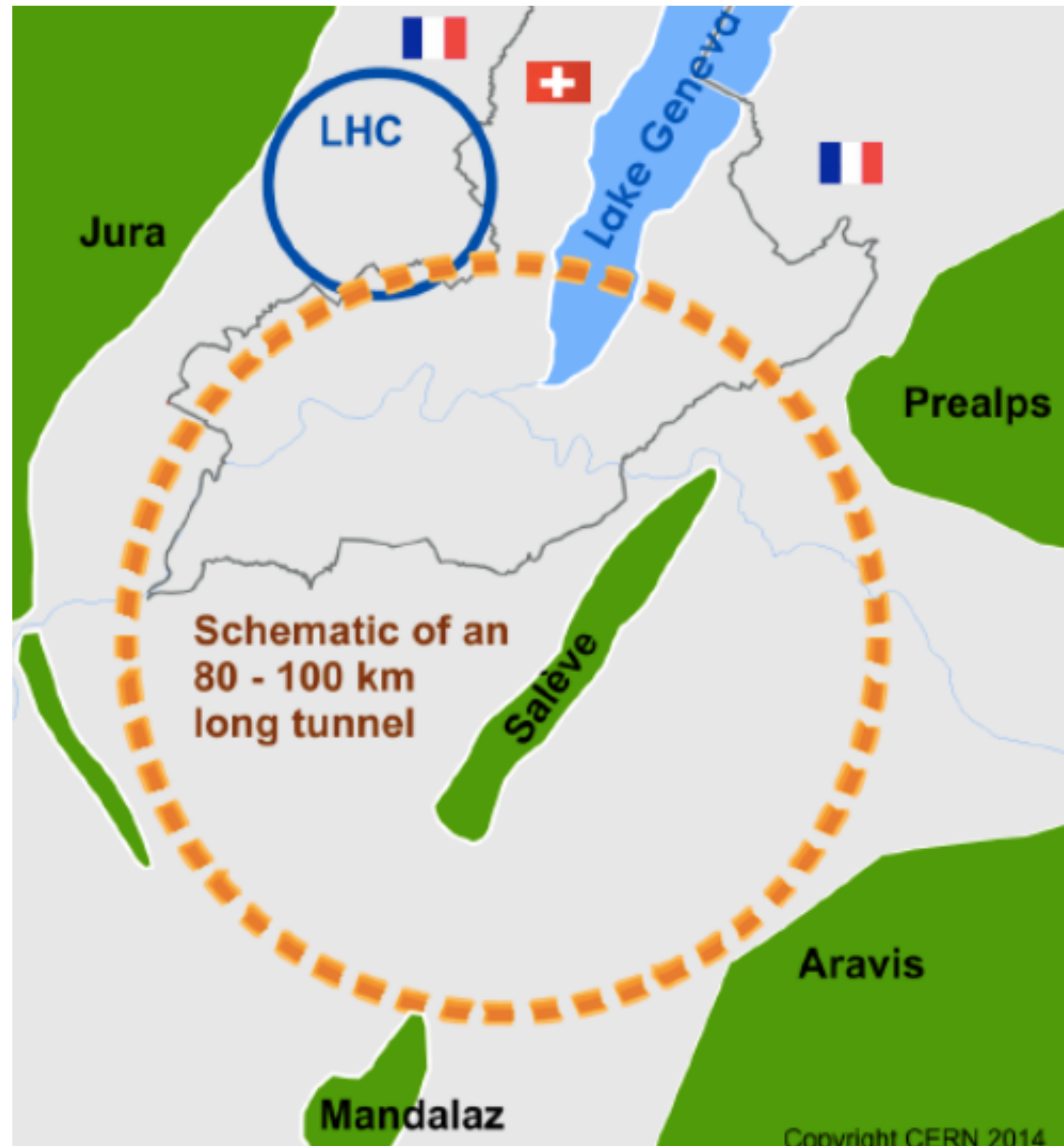
FCC Collaboration Status

FCC hh ee he

72 collaboration members & CERN as host institute, 1 Feb. 2016

ALBA/CELLS, Spain
Ankara U., Turkey
U Belgrade, Serbia
U Bern, Switzerland
BINP, Russia
CASE (SUNY/BNL), USA
CBPF, Brazil
CEA Grenoble, France
CEA Saclay, France
CIEMAT, Spain
Cinvestav, Mexico
CNRS, France
CNR-SPIN, Italy
Cockcroft Institute, UK
U Colima, Mexico
UCPH Copenhagen, Denmark
CSIC/IFIC, Spain
TU Darmstadt, Germany
TU Delft, Netherlands
DESY, Germany
DOE, Washington, USA
TU Dresden, Germany
Duke U, USA
EPFL, Switzerland
UT Enschede, Netherlands
U Geneva, Switzerland
Goethe U Frankfurt, Germany
GSI, Germany
GWNU, Korea
U. Guanajuato, Mexico
Hellenic Open U, Greece
HEPHY, Austria
U Houston, USA
IIT Kanpur, India
IFJ PAN Krakow, Poland
INFN, Italy
INP Minsk, Belarus
U Iowa, USA
IPM, Iran
UC Irvine, USA
Istanbul Aydin U., Turkey
JAI, UK
JINR Dubna, Russia
FZ Jülich, Germany
KAIST, Korea
KEK, Japan
KIAS, Korea
King's College London, UK
KIT Karlsruhe, Germany
KU, Seoul, Korea
Korea U Sejong, Korea
U. Liverpool, UK
MAX IV, Lund, Sweden
MEPhI, Russia
UNIMI, Milan, Italy
MIT, USA
Northern Illinois U, USA
NC PHEP Minsk, Belarus
U Oxford, UK
PSI, Switzerland
U. Rostock, Germany
RTU, Riga, Latvia
UC Santa Barbara, USA
Sapienza/Roma, Italy
U Siegen, Germany
U Silesia, Poland
TU Tampere, Finland
TOBB, Turkey
U Twente, Netherlands
TU Vienna, Austria
Wigner RCP, Budapest, Hungary
Wroclaw UT, Poland

- A complete physics program for the next 50 years



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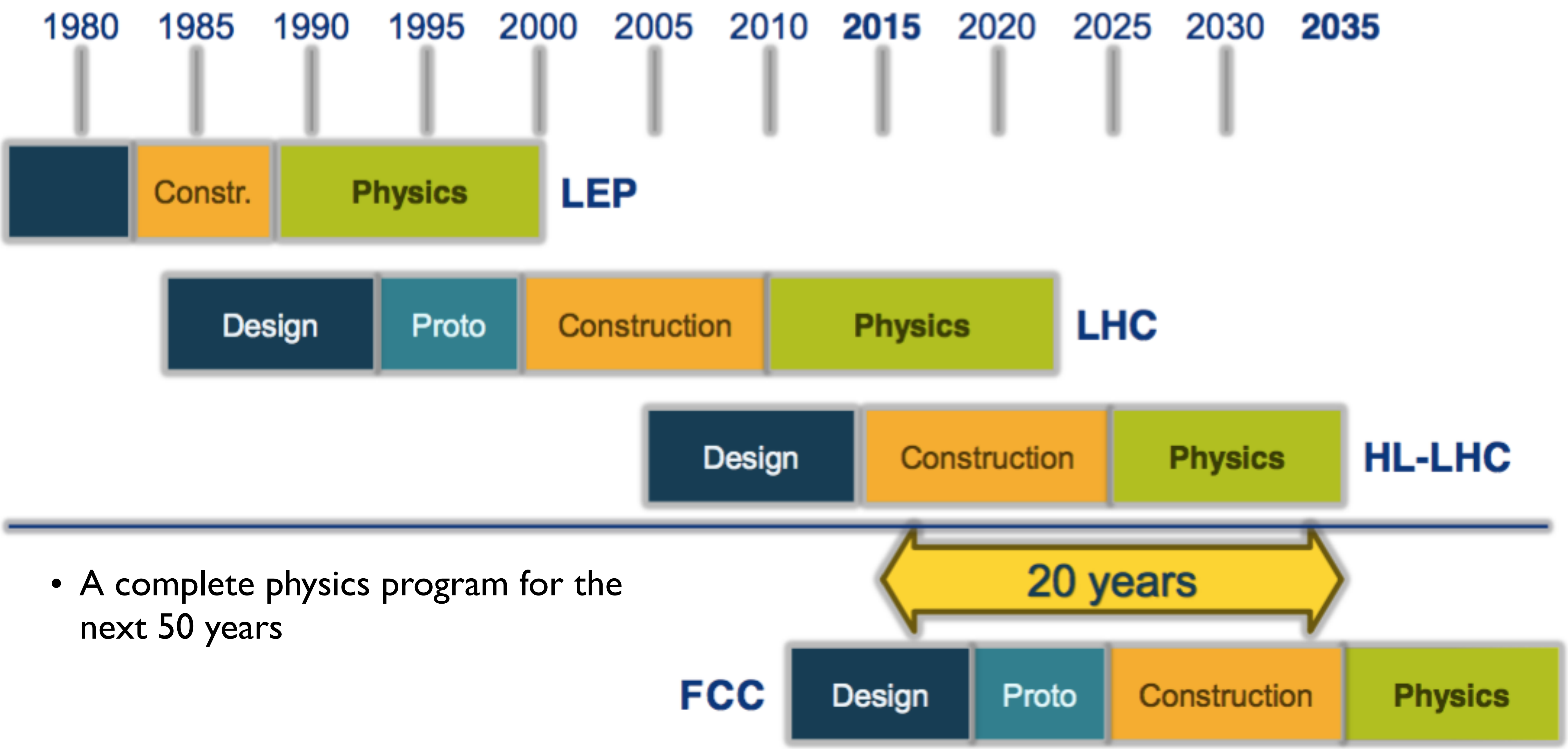

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The FCC project

The FCC-ee
variable energy collider

parameter	FCC-ee			CEPC	LEP2
energy/beam [GeV]	**45**	**120**	**175**	**120**	105
bunches/beam	90000	770	78	50	4
beam current [mA]	1450	30	6.6	16.6	3
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**70**	**5**	**1.3**	**2.0**	0.0012
energy loss/turn [GeV]	0.03	1.67	7.55	3.1	3.34
synchrotron power [MW]	**100**			**103**	22
RF voltage [GV]	0.08	3.0	10	6.9	3.5

*CEPC/SPPC e' il progetto analogo cinese

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The FCC-hh
100 TeV pp collider

Parameter	FCC-hh		SPPC	LHC	HL LHC
collision energy cms [TeV]	100		71.2	14	
dipole field [T]	16		20	8.3	
# IP	2 main & 2		2	2 main & 2	
bunch intensity [10^{11}]	1	1 (0.2)	2	1.1	2.2
bunch spacing [ns]	25	25 (5)	25	25	25
luminosity/Ip [10^{34} $cm^{-2}s^{-1}$]	5	~25	12	1	5
events/bunch crossing	170	~850 (170)	400	27	135
stored energy/beam [GJ]	8.4		6.6	0.36	0.7
synchrotron radiation [W/m/aperture]	30		58	0.2	0.35

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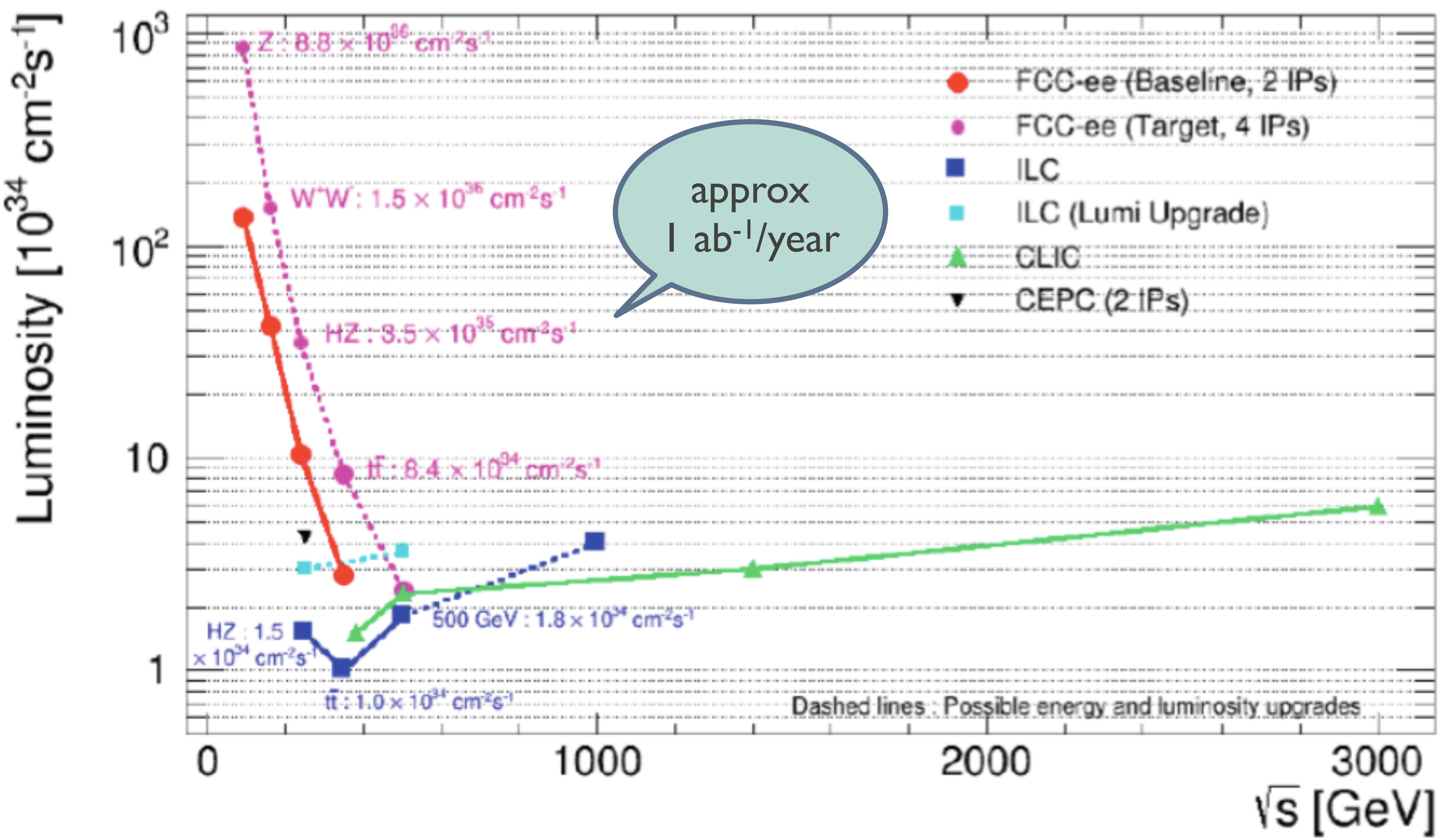
FCC-ee: high luminosity from sqrt(s)=90-350GeV



Different runs at 90(Z)-160(WW)-240(ZH)-350(tt)GeV to probe different physics
Possibility of having a 125(H) run to probe s-channel Higgs production

Higgs couplings and NP(1)

- The projections for the Higgs coupling at the HL-LHC bring a factor 1.5 to 2 on top of the Run2 (300 fb^{-1}). Limited by systematic uncertainties.
  - measurement of the coupling to ~5-10%
- is this precision *good enough* for a discovery?
  - **Need ~1% precision on coupling for a 5σ discovery if Λ =1TeV**

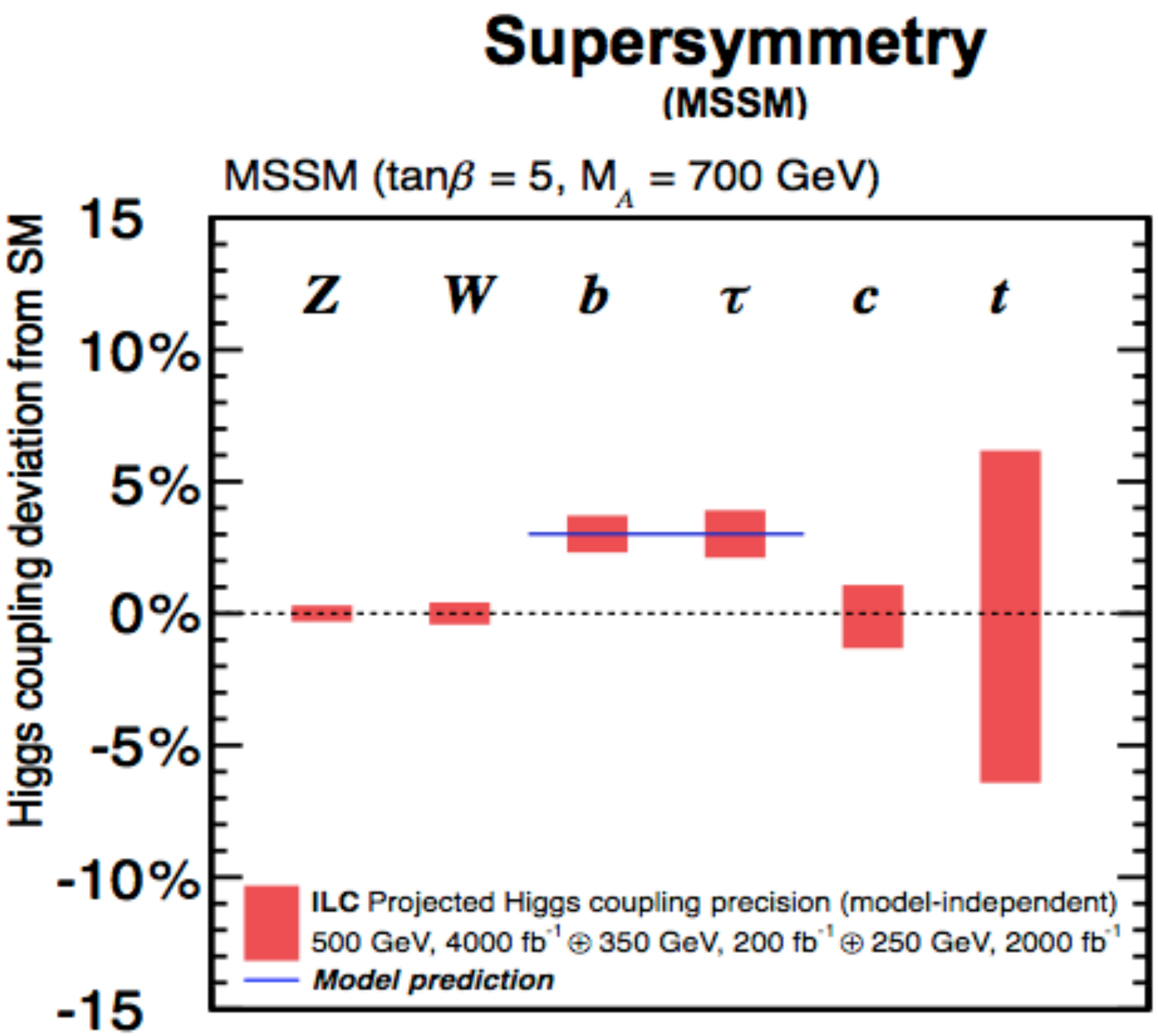
Coupling	LHC Run1	LHC (300 fb^{-1})	LHC (1 ab^{-1})	HL-LHC
κ_W	15%	4-6%	3-5%	2-5%
κ_Z	20%	4-6%	3-5%	2-4%
κ_t	50%	14-15%	10-12%	7-10%
κ_b	40%	10-13%	6-10%	4-7%
κ_τ	25%	6-8%	4-6%	2-5%

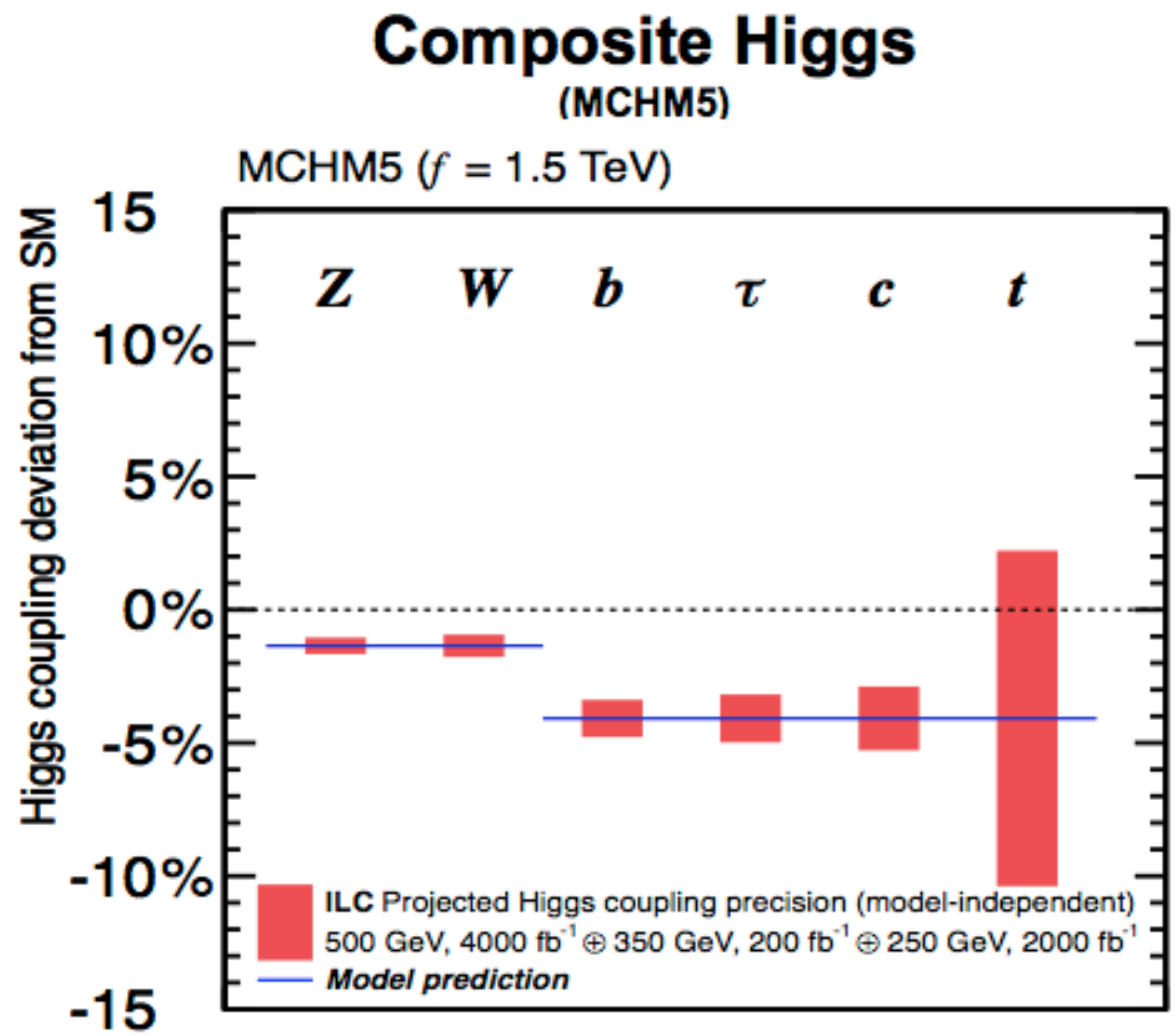
- **Lepton colliders easy choice when looking for extreme precision:**
  - No pile-up. No backgrounds. Triggering is easy
  - No underlying event. Known energy and momentum of the final state: can use conservation laws!
  - **FCC-ee might achieve a precision <1% on the Higgs couplings. Sensitive to multi-TeV NP effects.**

Higgs couplings and NP(2)

FCC-ee

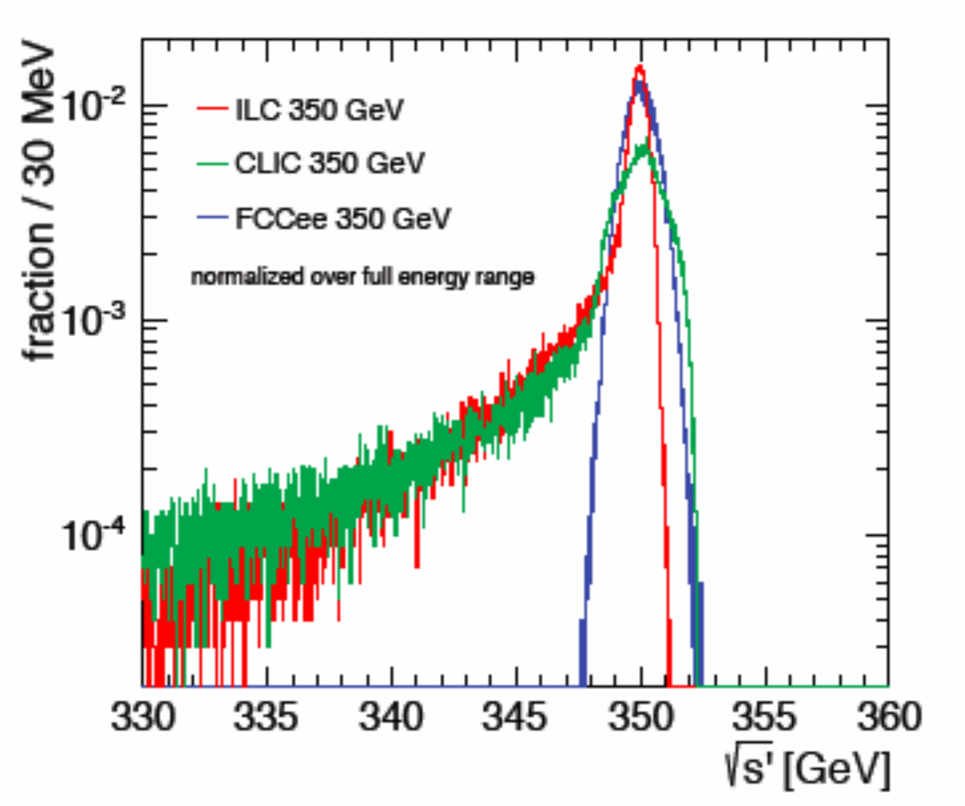
The pattern of Higgs coupling deviations is a signature of the underlying dynamics.

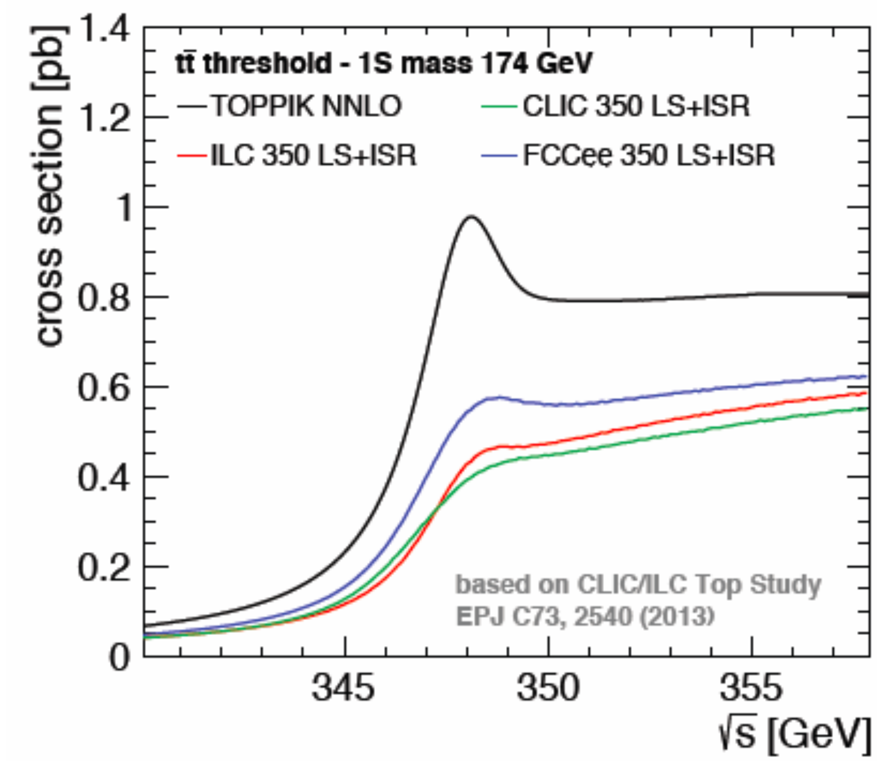




PS better precision on top Yukawa achievable at HL-LHC/FCC-hh through ttH/ttZ

Precision top physics: mass





λ_{top} ~13% with indirect extraction from threshold scan.

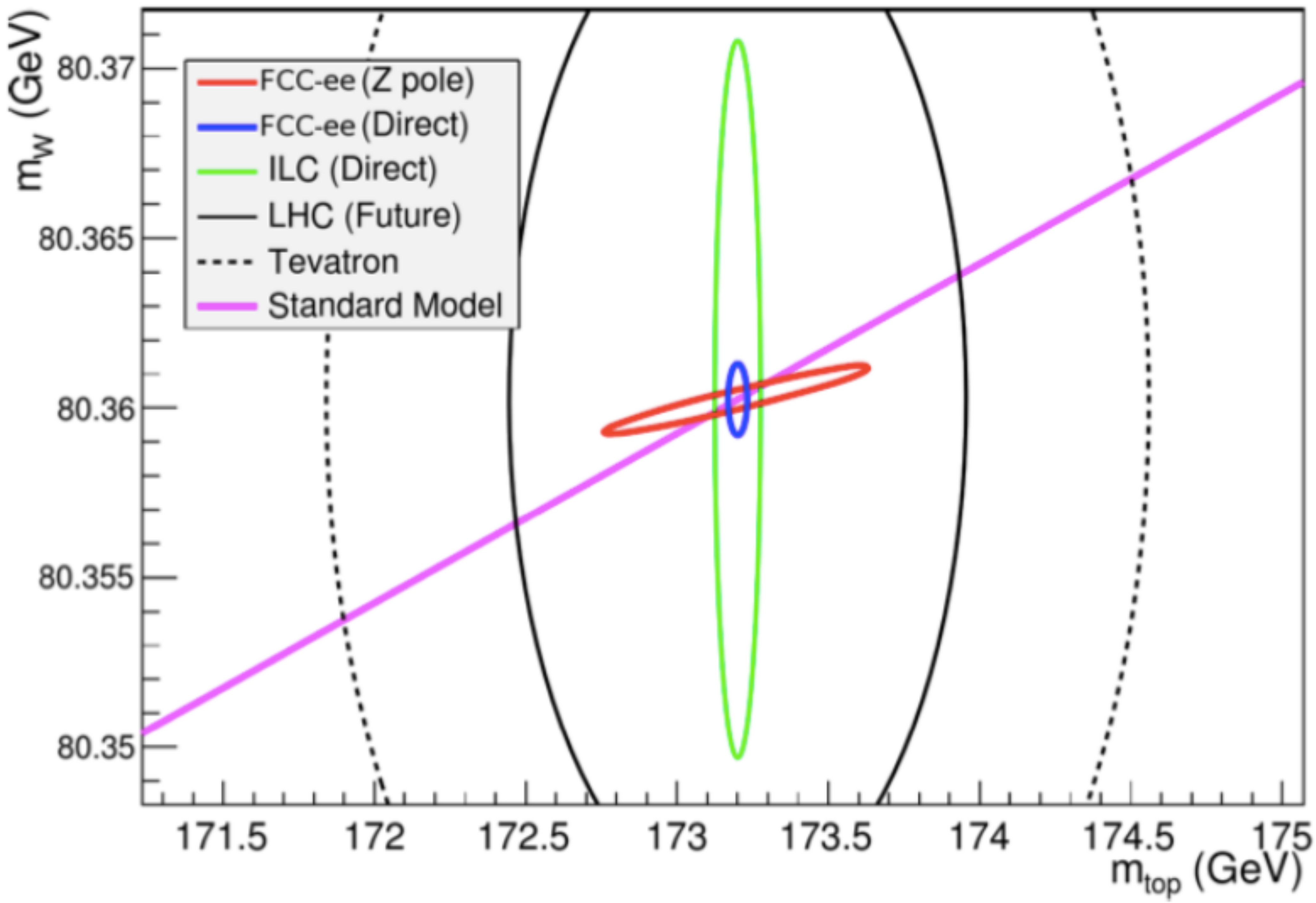
To improve need higher energy or FCC-hh.

- Different luminosity spectra in different machines: no beamstrahlung tail for FCC-ee. Keeps a sharper main peak, which means better statistics & sensitivity
- For 100 fb^{-1}, with 1D mass fit 16 MeV achievable (from a study performed with ILC software). Possible improvements down to 10 MeV using α_s information from Tera-Z
- Expected 1M top pairs produced: classic event reconstruction strategy can be used as well (different systematics)

	Lumi / 5 years	# top pairs	Δm_{top}	$\Delta\Gamma_{top}$	$\Delta\lambda_{top}/\lambda_{top}$
FCC	4 × 650 fb^{-1}	1,000,000	10 MeV	12 MeV	13%

FCC-ee

SM after FCC-ee



Pinning down the Standard Model

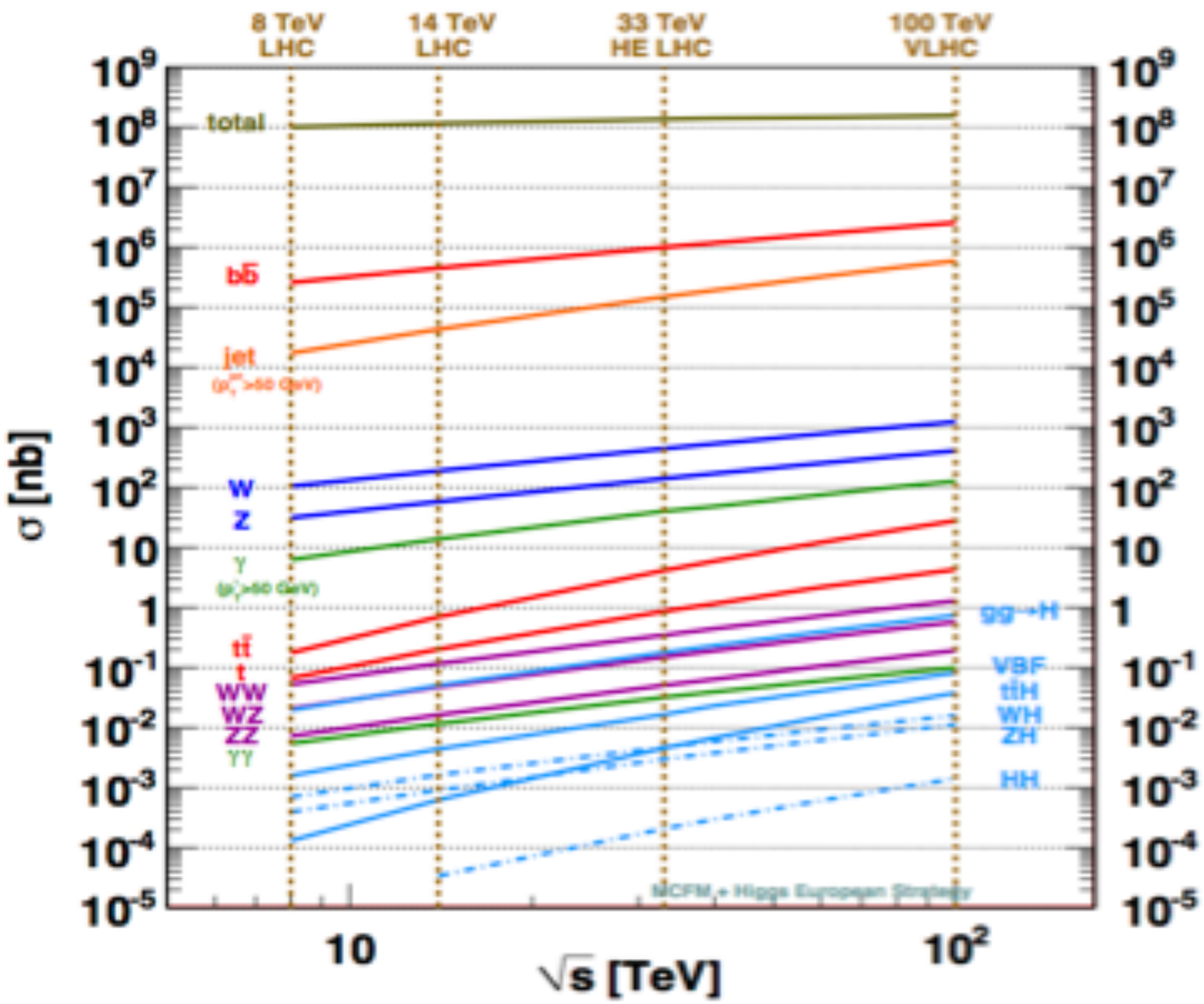
- **EWK fits** have shown their predicting power in the case of the Higgs mass: they could show the presence of new physics effects
  - theory needs to advance as well as the experiments to match the precision expected at the Fcc-ee
  - precision goals to be confirmed by complete studies

Quantity	Physics	Present precision	Measured from	Statistical uncertainty	Systematic uncertainty	Key	Challenge
m_Z (keV)	Input	91187500 ± 2100	Z Line shape scan	5 (6) keV	< 100 keV	E_{beam} calibration	QED corrections
Γ_Z (keV)	$\Delta\rho$ (not $\Delta\alpha_{had}$)	2495200 ± 2300	Z Line shape scan	8 (10) keV	< 100 keV	E_{beam} calibration	QED corrections
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	0.00010 (12)	< 0.001	Statistics	QED corrections
N_ν	PMNS Unitarity, ...	2.984 ± 0.008	Z Peak	0.00008 (10)	< 0.004		Bhabha scat.
N_ν	... and sterile ν's	2.92 ± 0.05	$Z\gamma$, 161 GeV	0.0010 (12)	< 0.001	Statistics	
R_b	δ_b	0.21629 ± 0.00066	Z Peak	0.000003 (4)	< 0.000060	Statistics, small IP	Hemisphere correlations
A_{LR}	$\Delta\rho, \epsilon_3, \Delta\alpha_{had}$	0.1514 ± 0.0022	Z peak, polarized	0.000015 (18)	< 0.000015	4 bunch scheme, 2exp	Design experiment
m_W (MeV)	$\Delta\rho$, $\epsilon_3, \epsilon_2, \Delta\alpha_{had}$	80385 ± 15	WW threshold scan	0.3 (0.4)MeV	< 0.5 MeV	E_{beam}, Statistics	QED corrections
m_{top} (MeV)	Input	173200 ± 900	$t\bar{t}$ threshold scan	10 (12) MeV	< 10 MeV	Statistics	Theory interpretation

From arXiv:1308.6176

FCC-hh: life at sqrt(s)=100TeV

- Numerology for 10ab^{-1} @100TeV
- **10^{10} Higgs bosons =>** 10^4x today
- **10^{12} top quarks =>** 5 10^4 x today
- 10^{7-9} **new physics particles of your choice =>** ∞ x today



Amazing potential, extreme detector and reconstruction challenges

FCC-hh

Higgs physics @ 100 TeV(2)

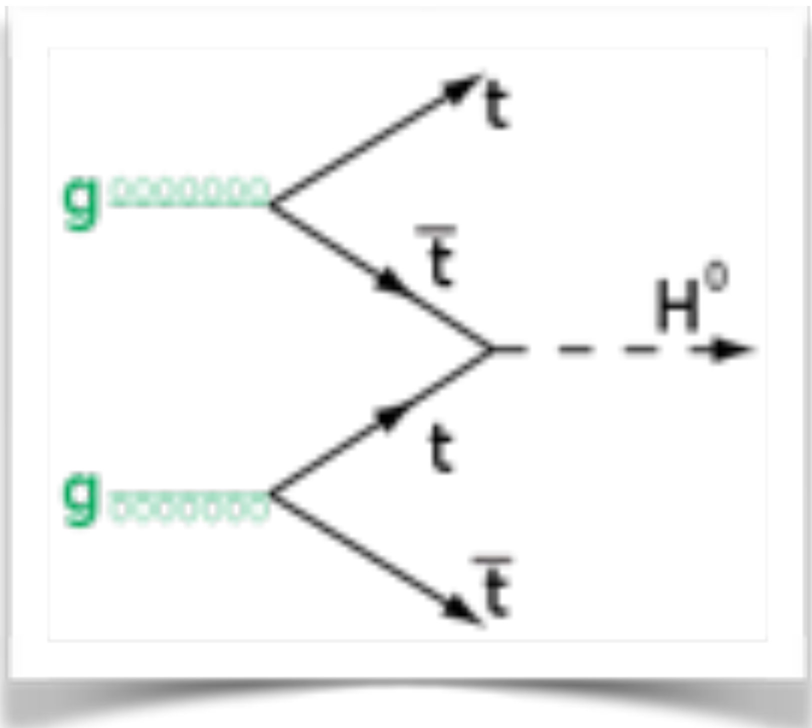
NLO rates **R(E)** = σ(E TeV)/σ(14 TeV)

	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

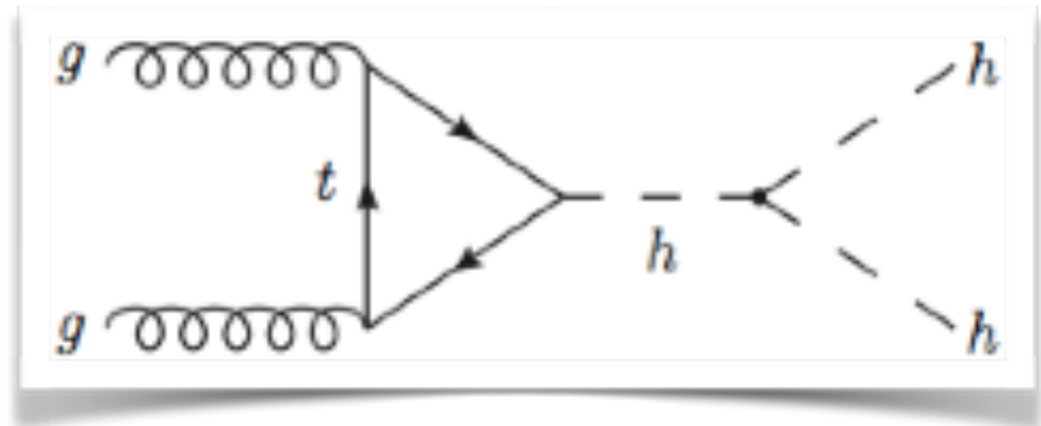
In several cases, the gains in terms of "useful" rate are much bigger.
E.g. when we are interested in the large-invariant mass behaviour of the final states:
$\sigma(ttH, p_T^{top} > 500\ \mathrm{GeV}) \Rightarrow R(100) = 250$

Higgs physics @ 100 TeV(2)

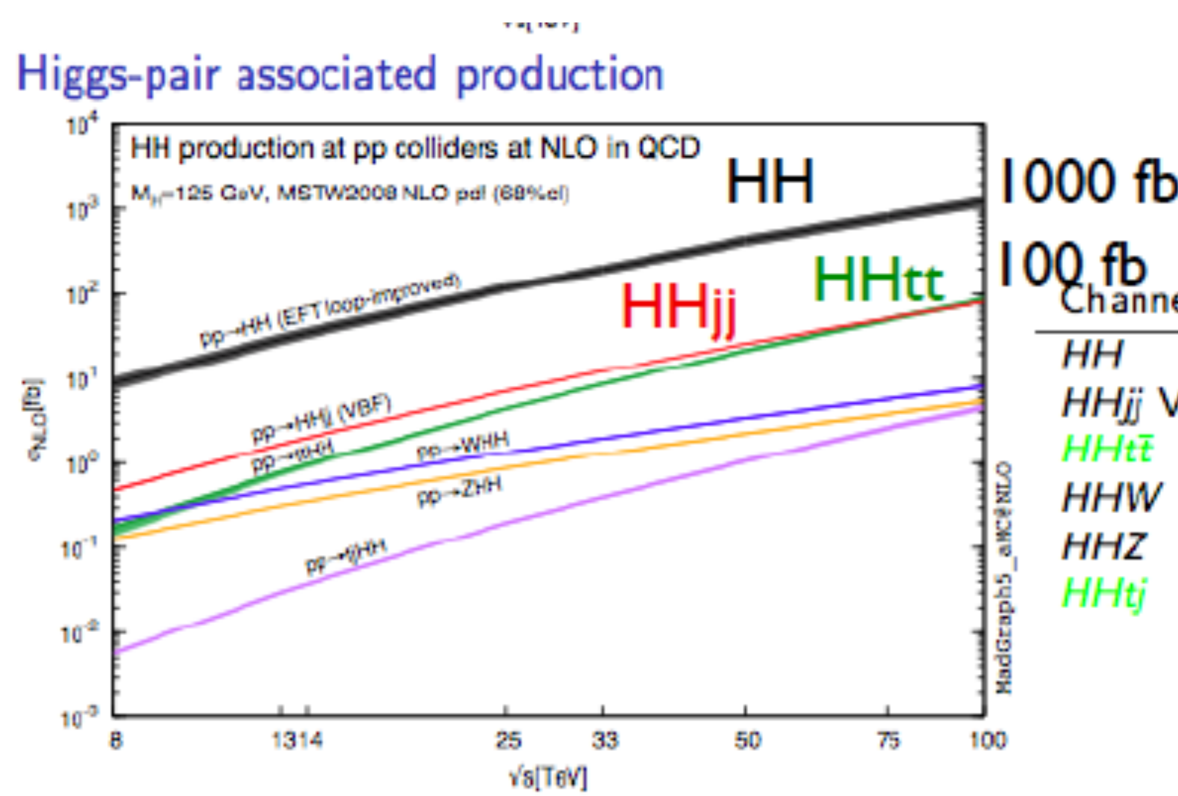
ttH



HH



- Interesting probe of new mass generation mechanism.
- Input to Higgs self-interaction

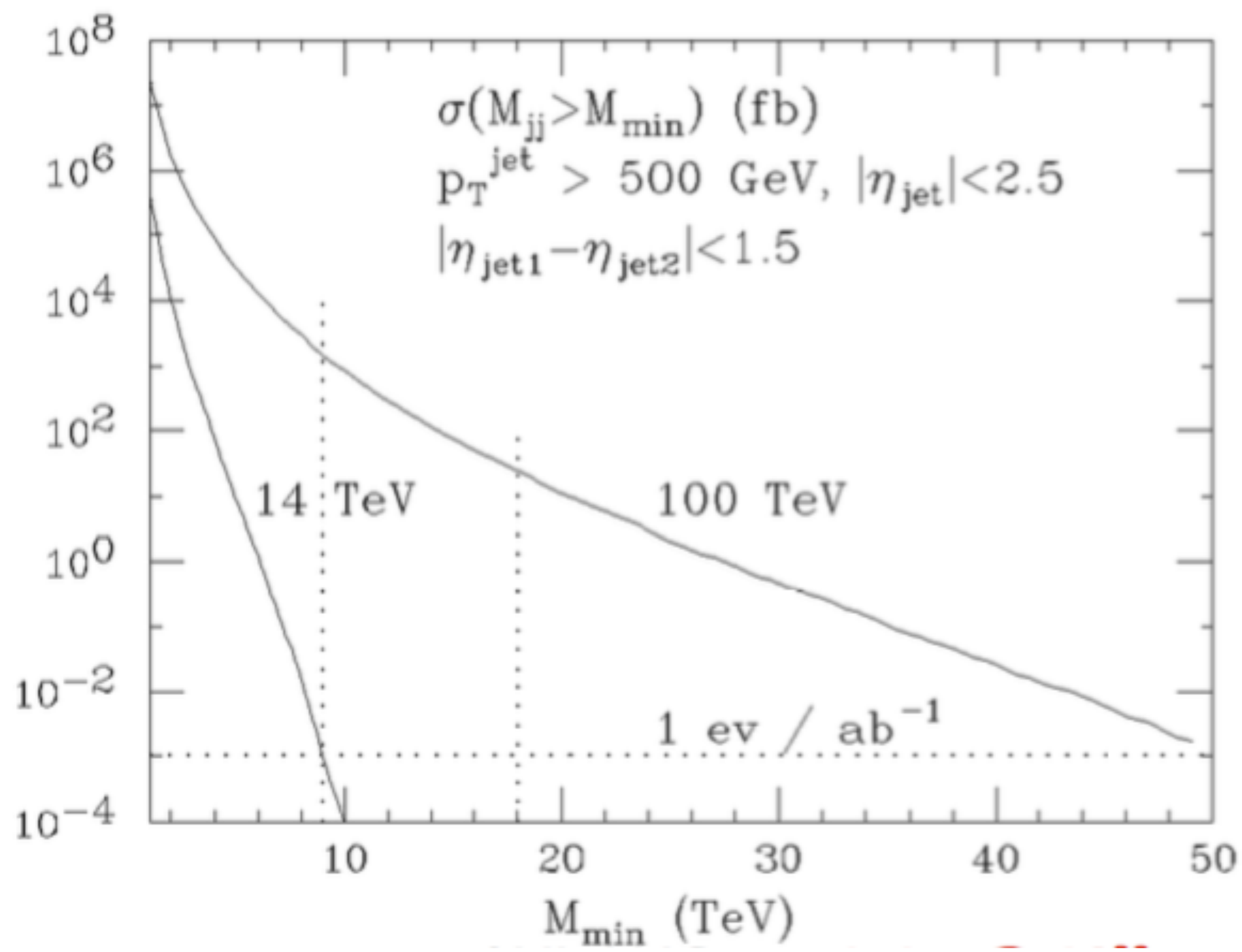


Channel	$\frac{\sigma_{100}}{\sigma_{14}}$	$\frac{\sigma_{100}}{\sigma_{8}}$
HH	35	150
$HHjj$ VBF	45	180
$HHt\bar{t}$	100	600
HHW	15	40
HHZ	15	40
$HHtj$	130	800

FCC-hh

The SM at 100 TeV

Dijet rates comparison



At large sqrt(s)

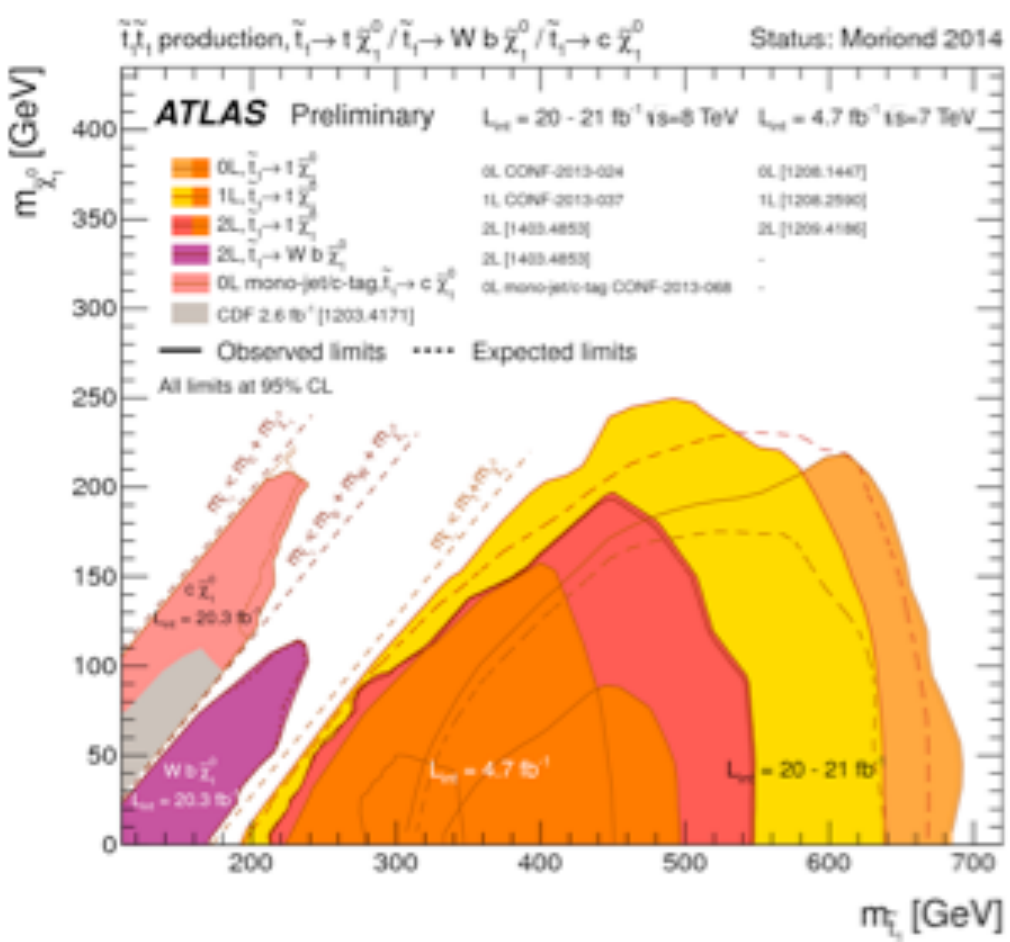
1 pb^{-1} to recover sensitivity of HL-LHC ⇒< 1 day @ 10^{32}

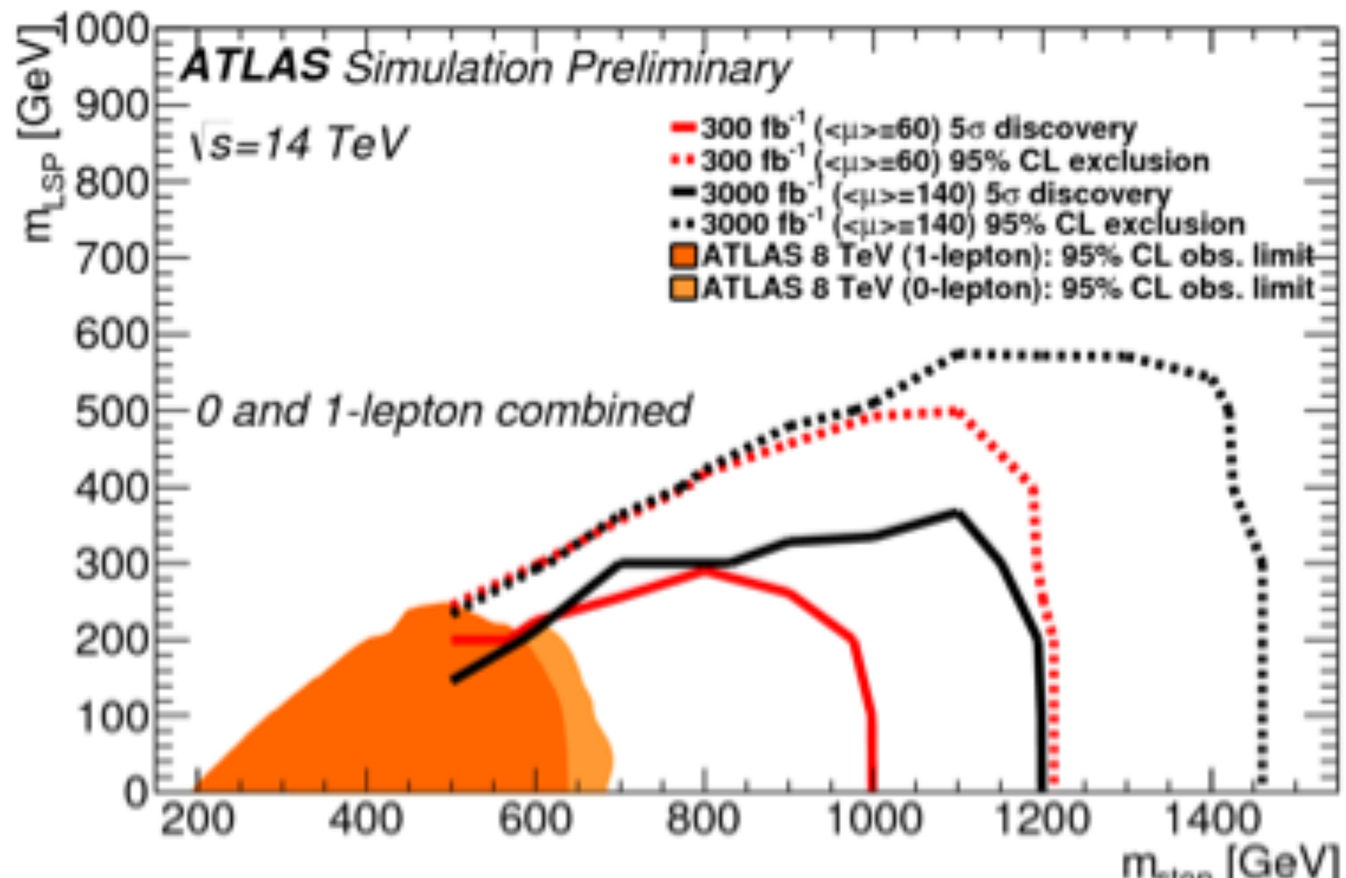
50pb^{-1} to 2x the sensitivity of HL-LHC ⇒< 1 month @ 10^{32}

1fb^{-1} to 3x the sensitivity of HL-LHC ⇒< 1 year @ 2x10^{32}

BSM Physics: Supersymmetry?

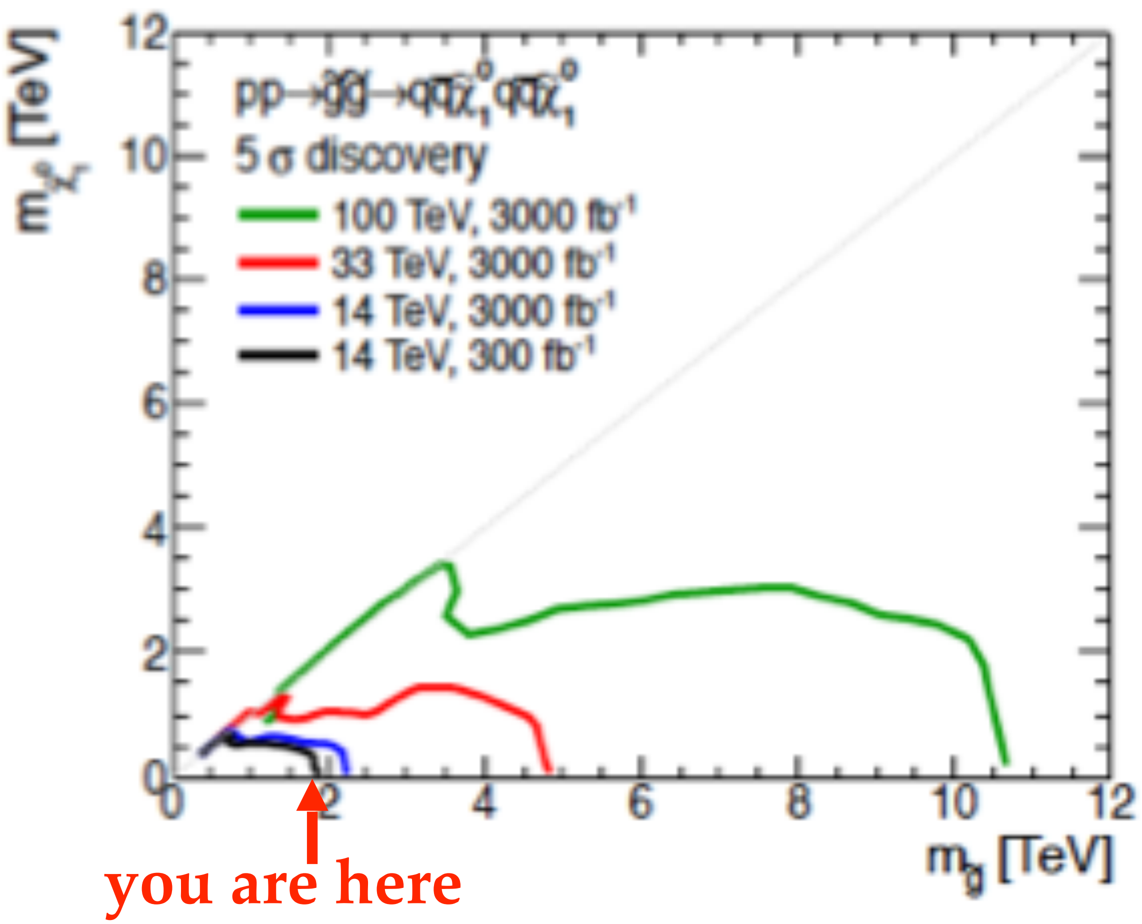
- search for third generation squarks
  - Mass reach extended by a factor 2 with LHC 14TeV(Run2) : covers the 1TeV (favorite) region
    - HL-LHC extends the reach by 20%
  - However if NO excess in 300fb^{-1} the HL-LHC potential vanishes entirely

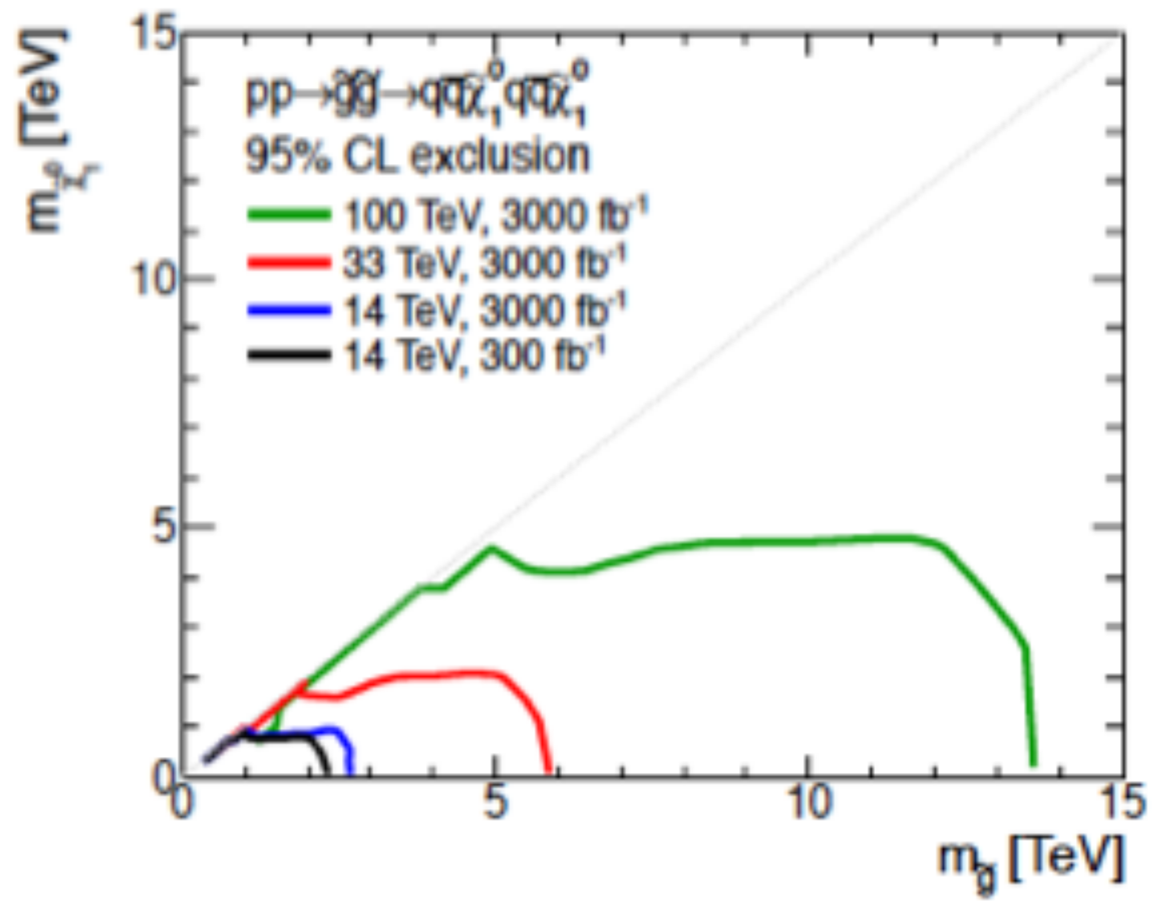




Supersymmetry @100TeV

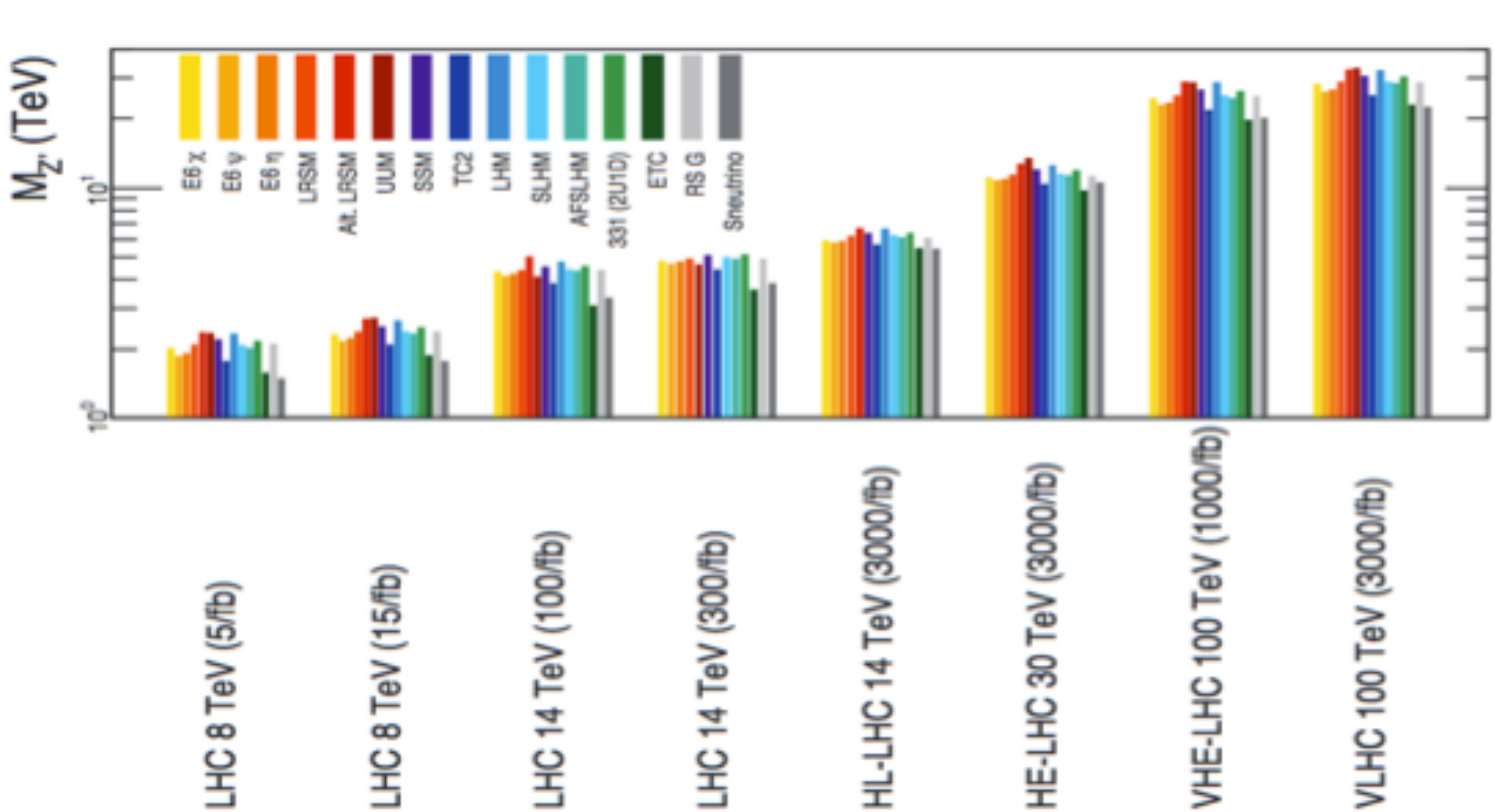
- Production in pp collisions:
  - if the spectrum is heavier only higher energy can extends the discovery reach
  - if no hints at Run2, the HL-LHC has no chance of discovery
- **Discovery reach for gluino: up to 5 TeV at HL-LHC —> 11 TeV with FCC-hh**
- **Discovery reach for stop: up to 3TeV with HL-LHC —> up to 6 TeV with FCC-hh**





FCC-hh

Heavy Resonances



Rule of thumb: about a factor 5 in mass reach comparing LHC(14 TeV, 300 fb^{-1}) to FCC-hh(100TeV, 3000fb^{-1})

FCC-hh sensitive to $m_{Z'}$ in dileptons(!) up to 30-35 TeV

FCC Week 2016

Rome, 11-15 April 2016

http://cern.ch/fccw2016

IEEE CSC
Council on Superconductivity

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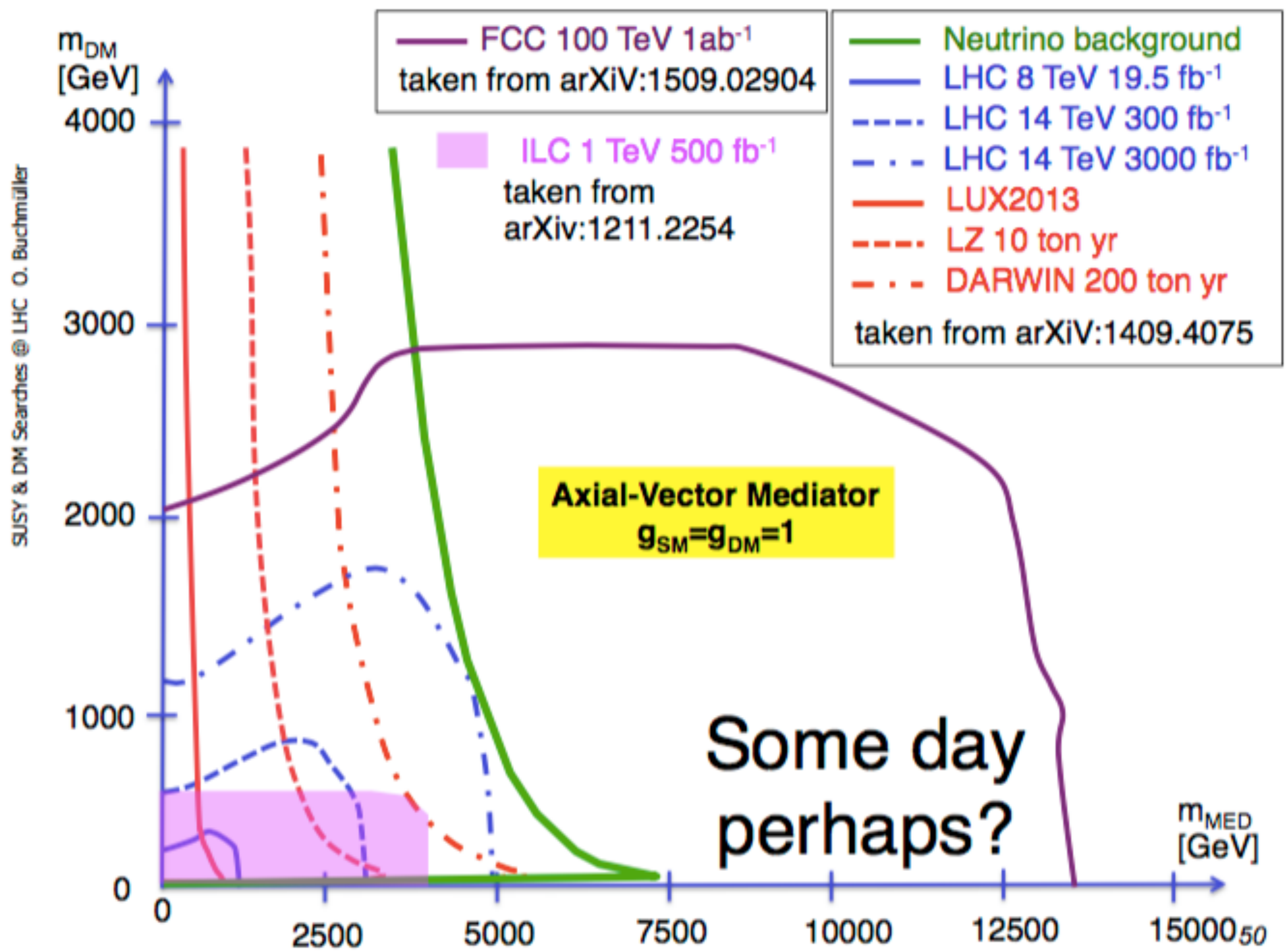
Conclusions

- The physics potential of the FCC project, in its complete form, allows:
  - ***unprecedented precision measurements*** at very large integrated luminosity and a clean environment with FCC-ee
  - ***unprecedented reach*** on rare - or entirely new - processes at higher energy with FCC-hh
- To achieve this immense physics program there are extreme accelerator, detector, reconstruction and theory challenges to be studied and overcome in the next 30 years.
  - Lots of room for contributions!

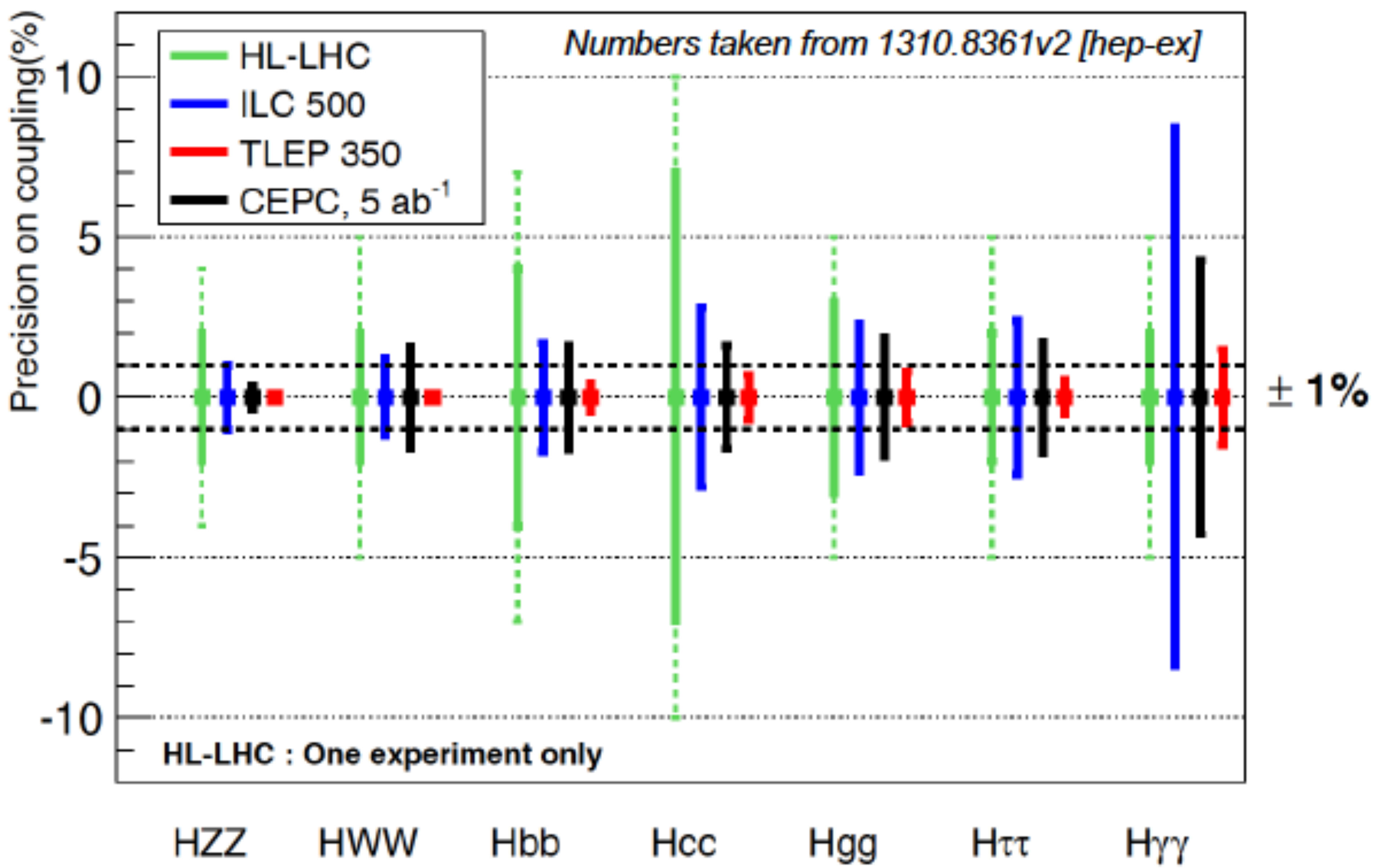
BACKUP INFORMATION

Dark matter 100 TeV



FCC-ee

Precision on Higgs couplings

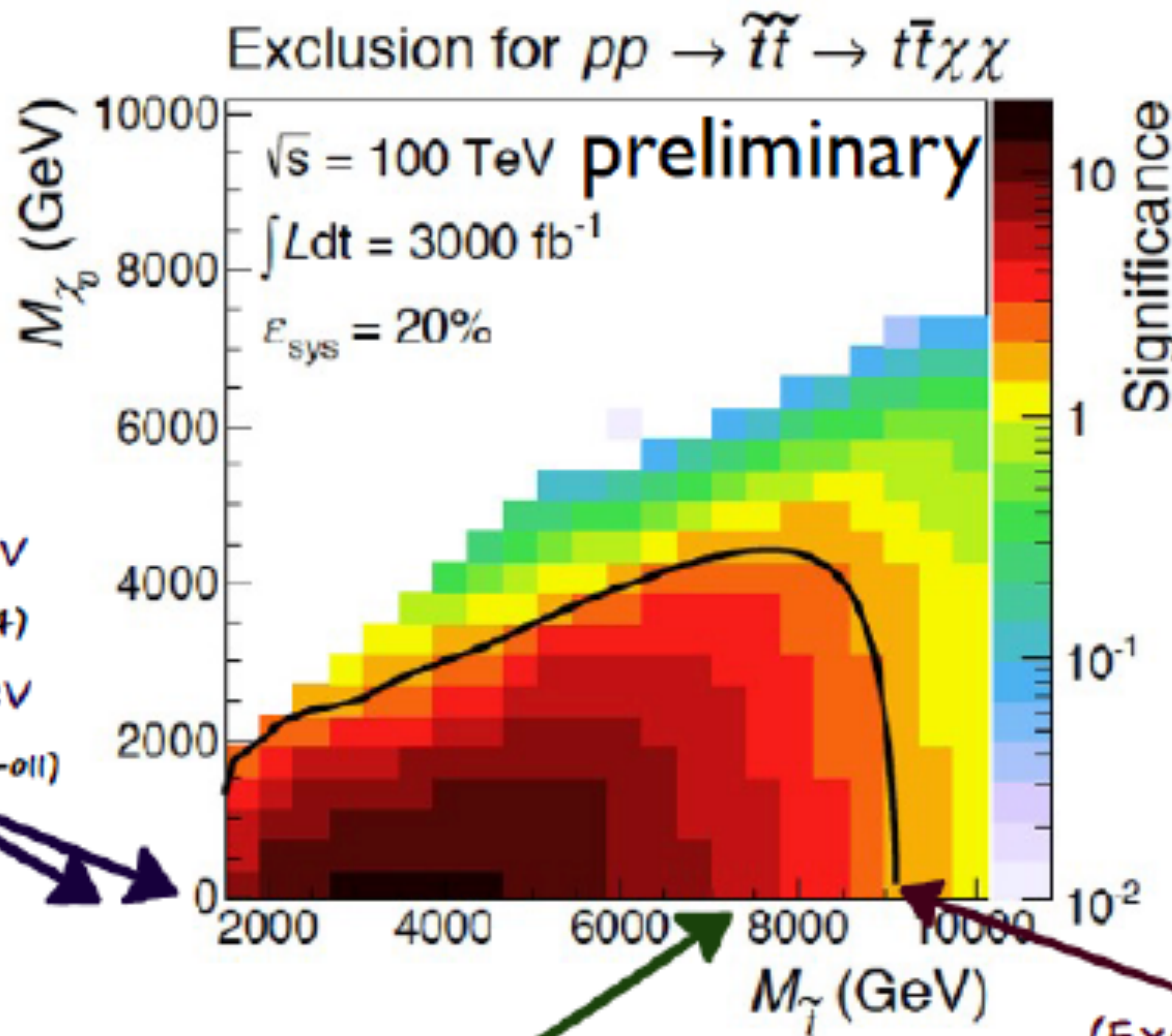


HL-LHC(3 ab^{-1}, 1 detector) with **assumption** ~ g(HVV) ≤ g(HVV)|$_{SM}$, g(Hcc) ~ g(Huu)

ILC 500: 250 fb^{-1} @ 250 GeV, 500 fb^{-1} @ 500 GeV
TLEP 350: 10 ab^{-1} @ 240 GeV, 2.6 ab^{-1} @ 350 GeV
CEPC, 5 ab^{-1} @ 250 GeV

Stops at 100 TeV

LHC8: 650 Gev
(ATL CONF-2013-024)
LHC14: 1.4 Tev
(ATL-PHYS-PUB-2013-011)

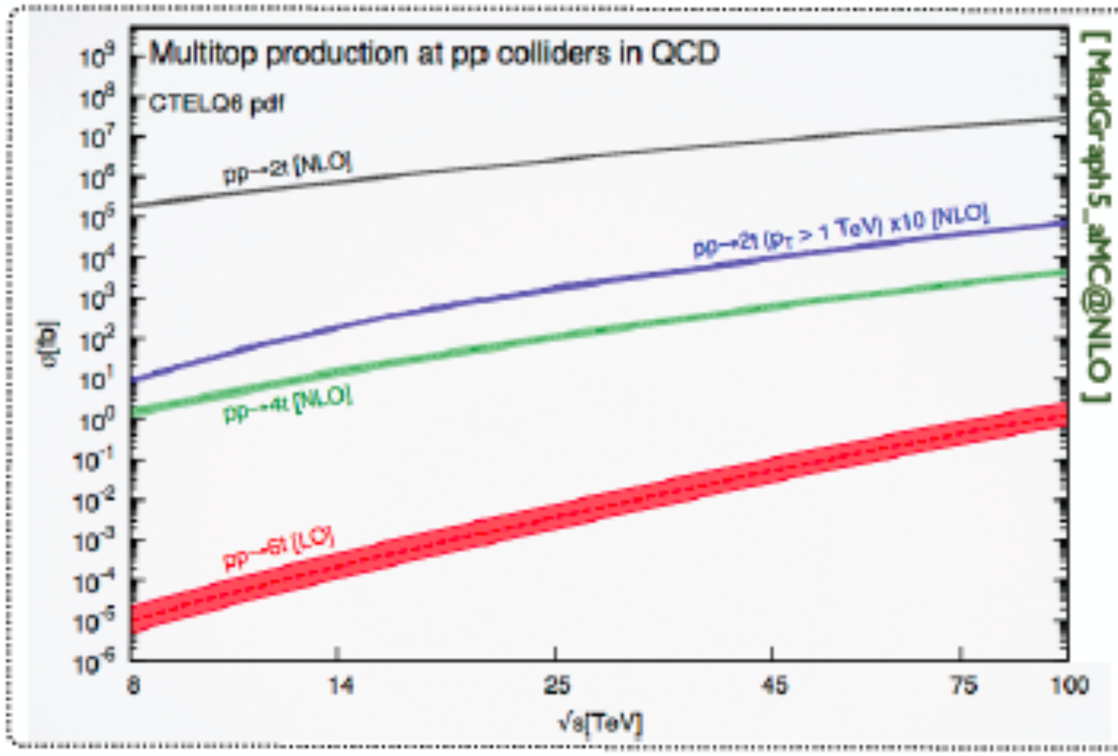


(Exclude ~9 Tev Stop)
(~ 100 events)

Discover ~7 Tev Stop!

Opening the multi-top window

✦ Multitop hadroproduction

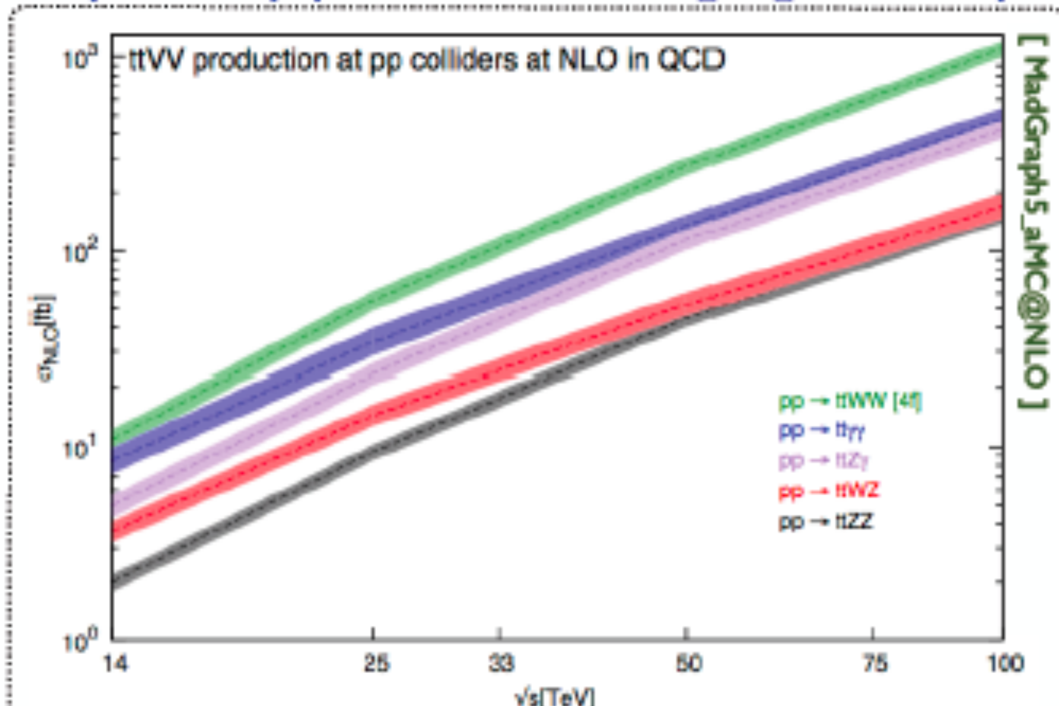


✤ 100 fb^{-1}: thousands of tttt events (≈5 with 300 fb^{-1} LHC collisions at 14 TeV)

✤ Large number of very hard tt pairs

[Deandrea & Deutschmann (JHEP '14)]

✦ Top-antitop production with gauge boson pairs



Process	σ(100 TeV) / σ (14 TeV)
ttWW	≈100
ttγγ	≈60
ttγZ	≈80
ttWZ	≈50
ttZZ	≈70

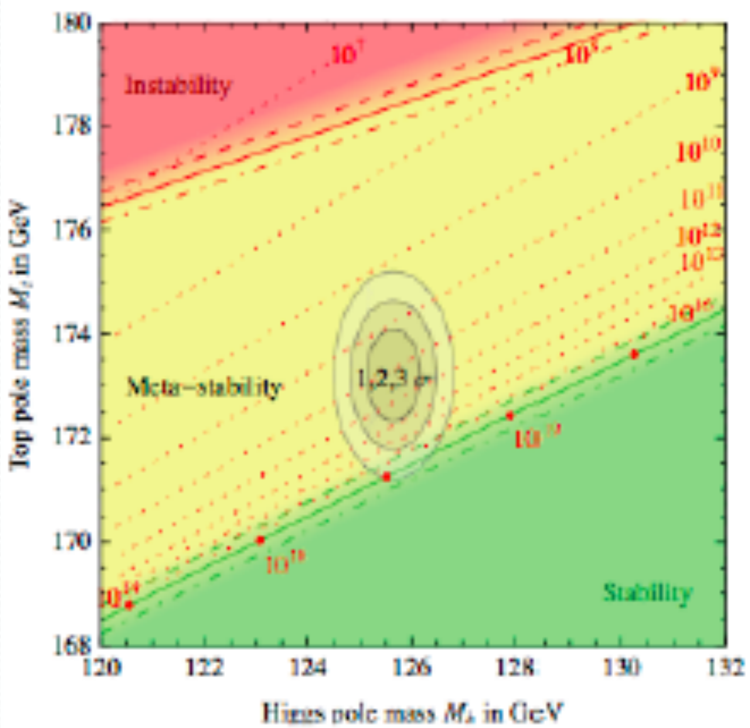
✤ Largest enhancement: ttWW production (≈10000 expected events for 100 fb^{-1})

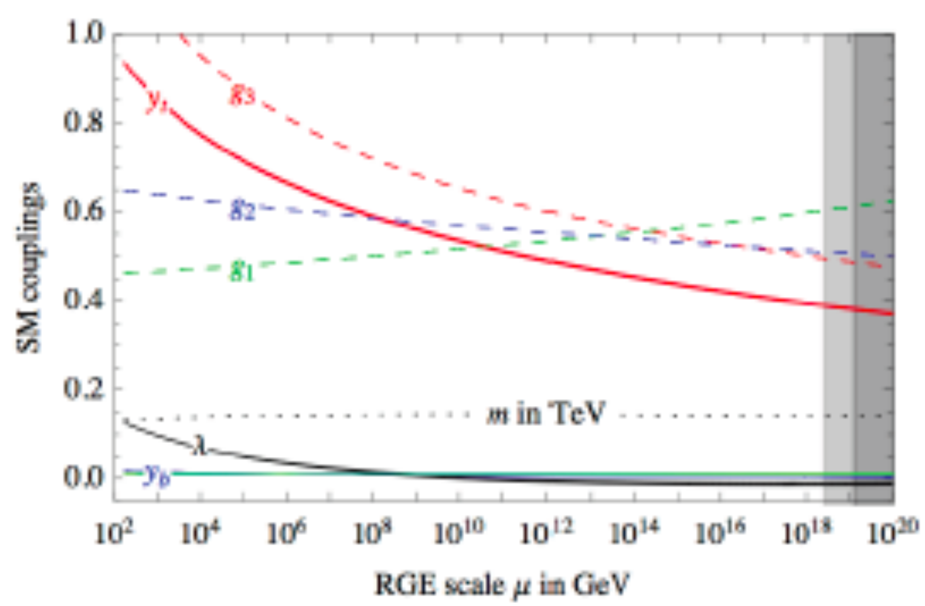
[Torrielli]

Physics Motivation

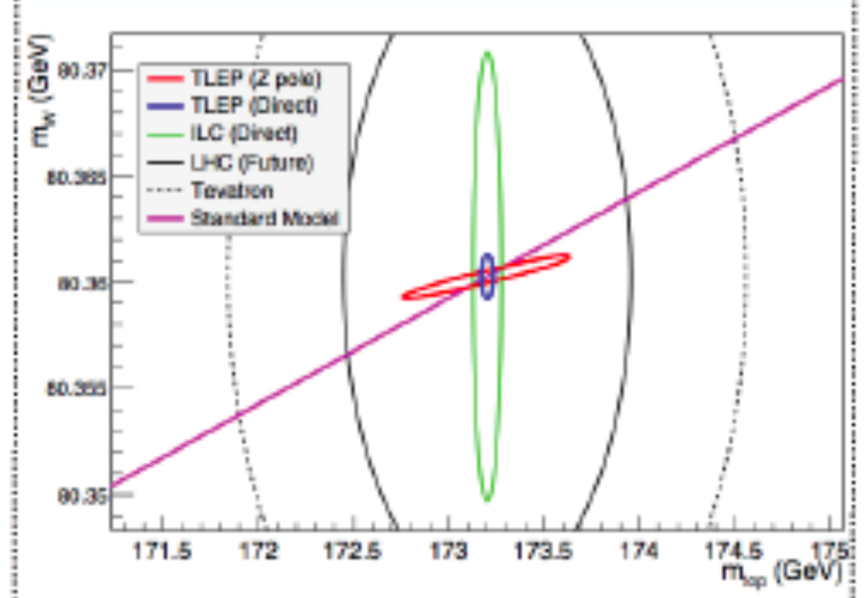
- (For the first time) The Standard Model is a consistent theory up to very high energies
  - all couplings remain perturbative
  - the standard model vacuum is however in a near-critical condition
  - the Higgs quartic coupling crosses zero below the Planck scale (suggest new physics or at least the study of λ)

[Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia (JHEP'13)]





[TLEP Design Working Group (JHEP'14)]



More precision improves the picture

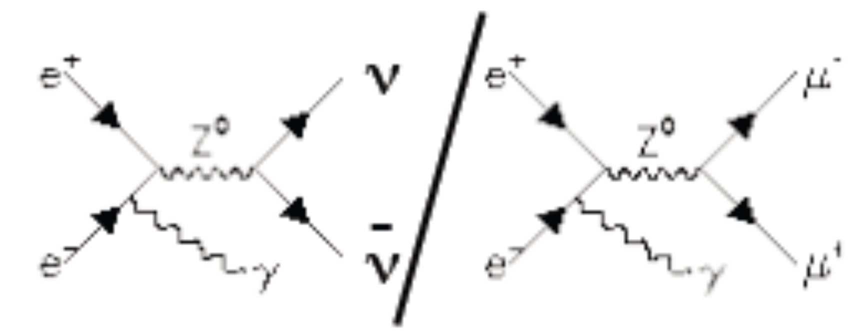
BSM Physics: Sterile Neutrinos ?

- **Number of neutrino families from LEP Nν=2.984±0.008**
  - potential to improve to ±0.001 using e+e—>Zγ (not enough statistics at LEP)
- **Search for sterile neutrinos in Z decays:**

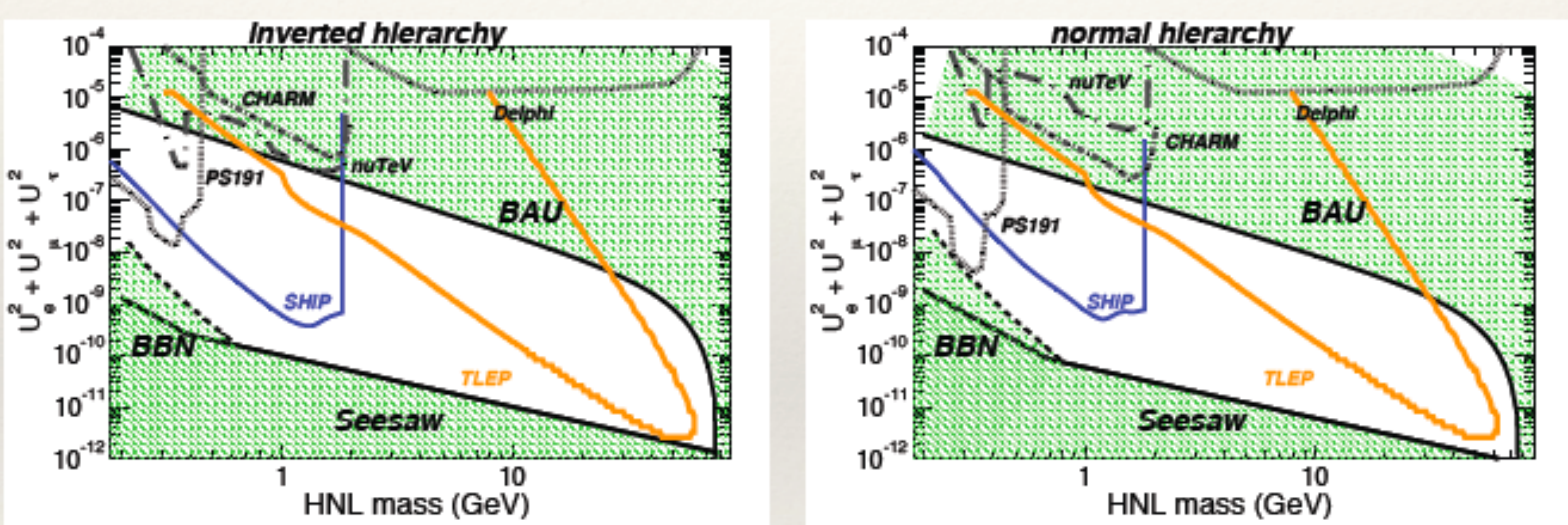
$$Z \rightarrow N\nu_i,\ \text{with}\ N \rightarrow W^{*}l\ \text{or}\ Z^{*}\nu_j$$

  - Number of events depends on mixing between N and ν, and m_N

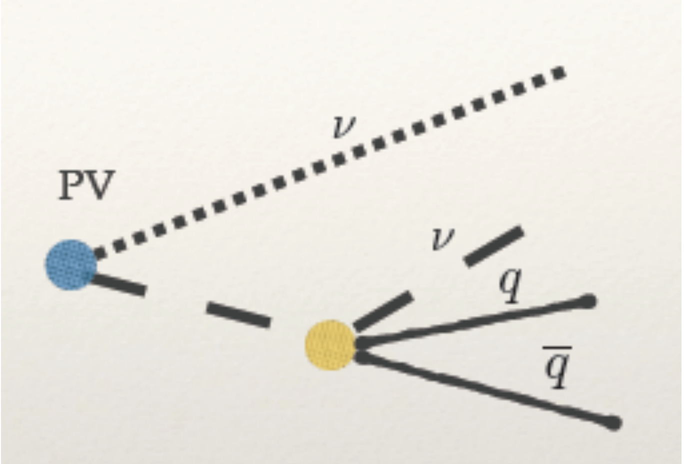
$N_\nu \sim \sigma(e^+e^- \rightarrow \nu\bar{\nu}\gamma)\,/\,2\sigma(e^+e^- \rightarrow \mu^+\mu^-\gamma)$



Assuming zero background in the region 10cm and 5m with 10^{13} Z^0



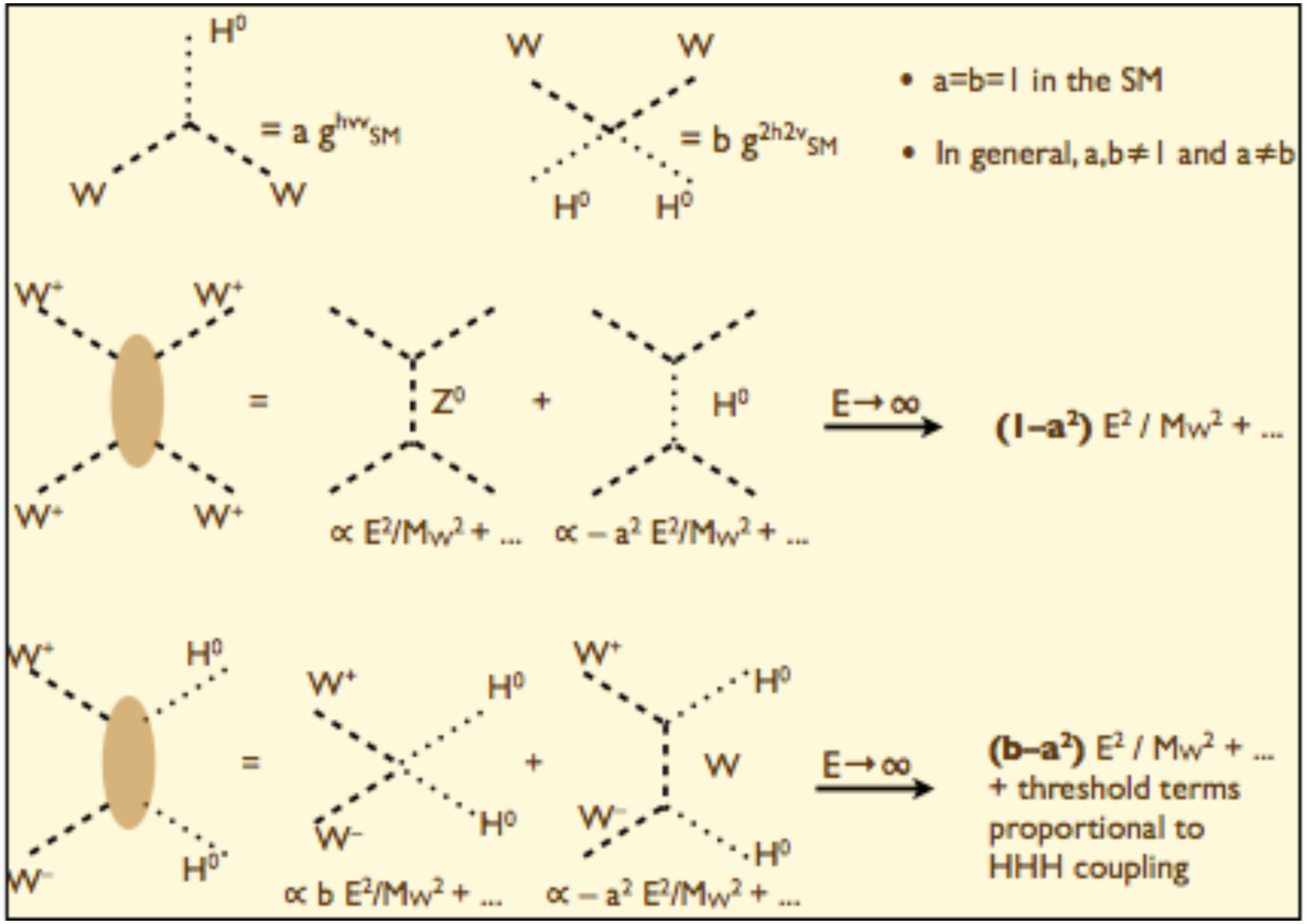
N. Serra 7th FCC-ee workshop

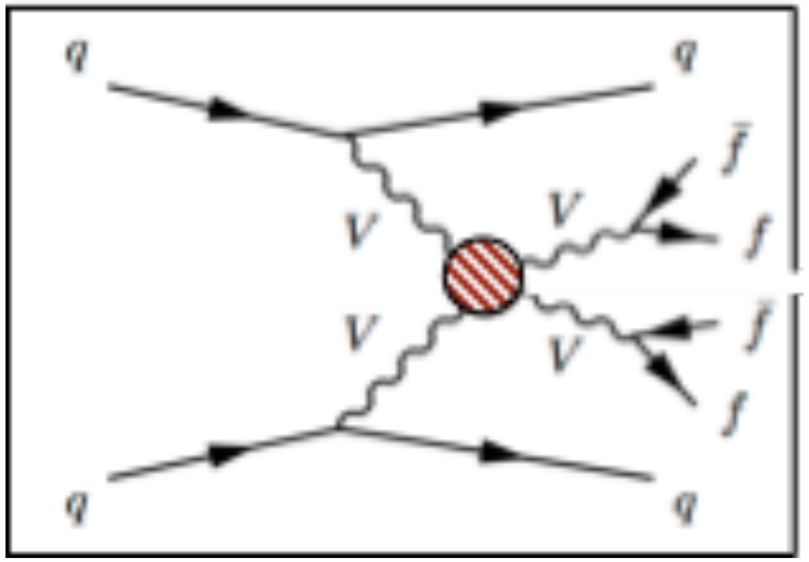


(Very) Displaced SV, detector challenge!

WW scattering at high energy

- In the SM the Z and H exchange diagrams diverge but *exactly* cancel each other
  - anomalous couplings, as hints from New Physics, would have dramatic effects
  - the total WW scattering/Higgs pair cross section diverge with $\mathbf{m^4_{WW,HH}}$



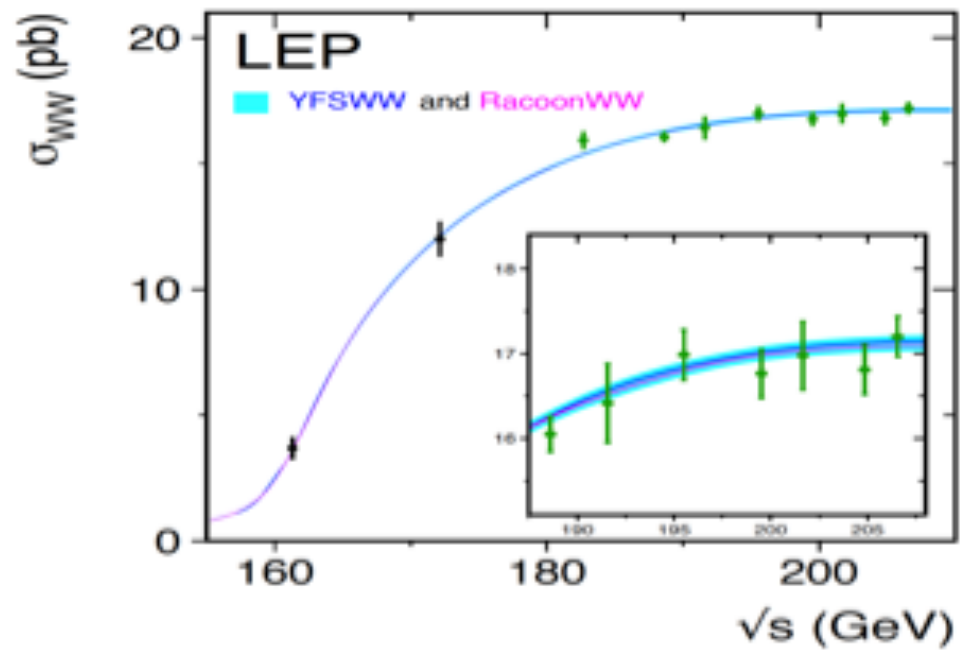


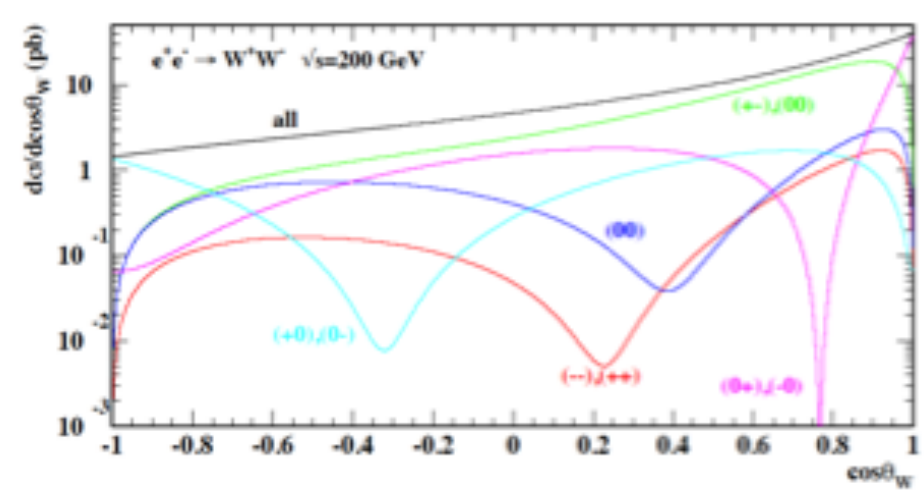
Precision on **a** and **b**:
~30% at HL-LHC 14 TeV
~1% with FCC-hh 100 TeV

Precision on **a**:
~1% with ILC
~ 0.1% with FCC-ee

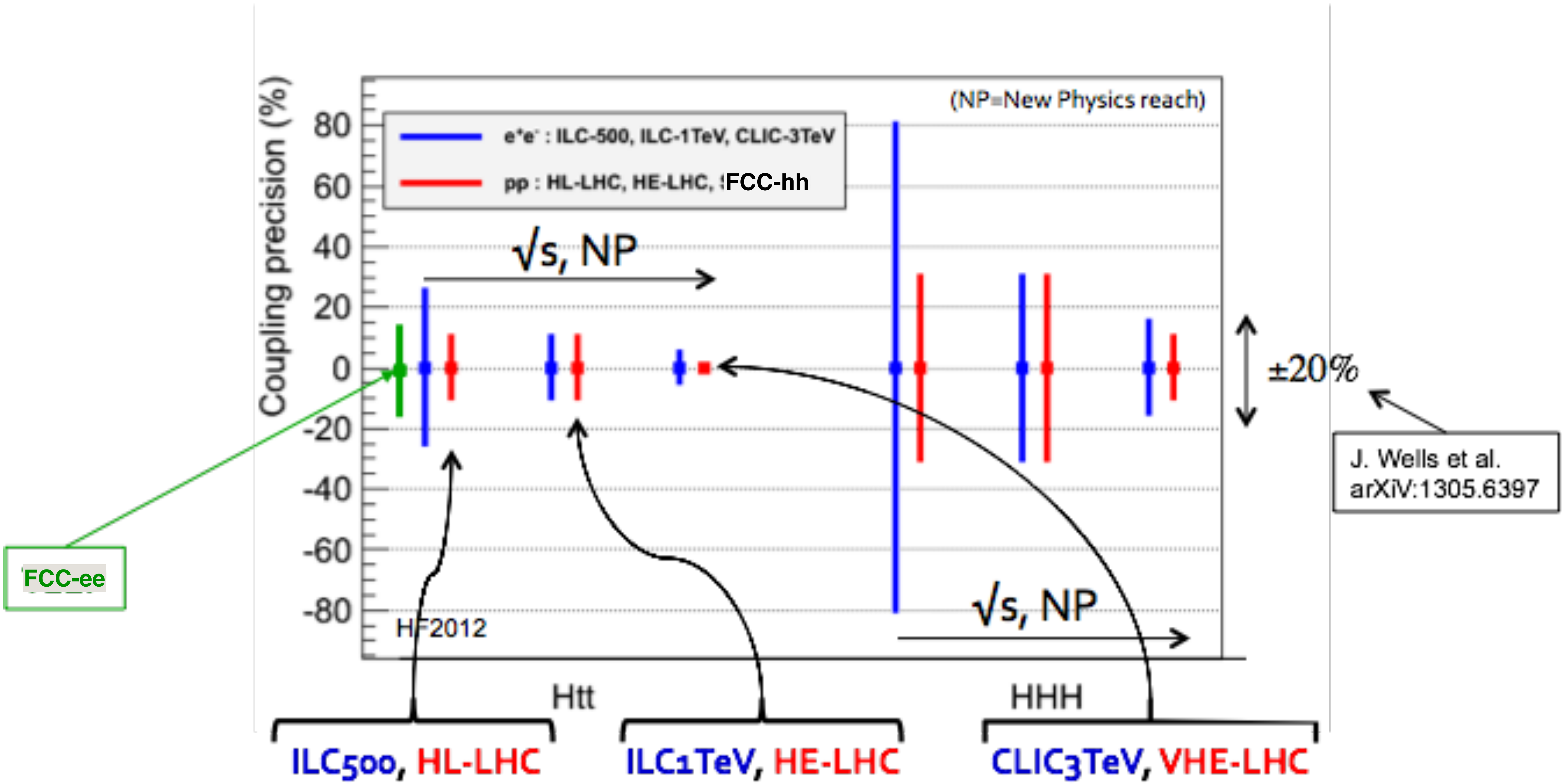
Tera-Z and Oku-W

- **Hadronic Z event rate** ~15kHz in the detector.
  - LEP1 physics program in 15 minutes
- **Measure the Z line shape** accumulating 10_{12} Z bosons in a energy scan. **Could reach 100 keV on M_Z and Γ_Z**
  - improvement on method to measure the c.o.m. energy (profit on the large number of bunches)
- **Huge statistics allows improvement on many other observables like R_l and $\alpha_s(M_Z)$ determination**
- **Measurement of A_{LR}** with longitudinal polarization: could reach $\sim 2.10_{-6}$ on sin2theta
  - challenging, dedicated run with lower luminosity?
- **M_W mass** measurement from WW production threshold scan, could reach ~0.5 MeV
- **Multi-gauge bosons production:** VV, but also WWγ, WWZ, γγγ, WWH. Using differential distribution to separate for example, the different polarization components





Higgs Physics @100TeV



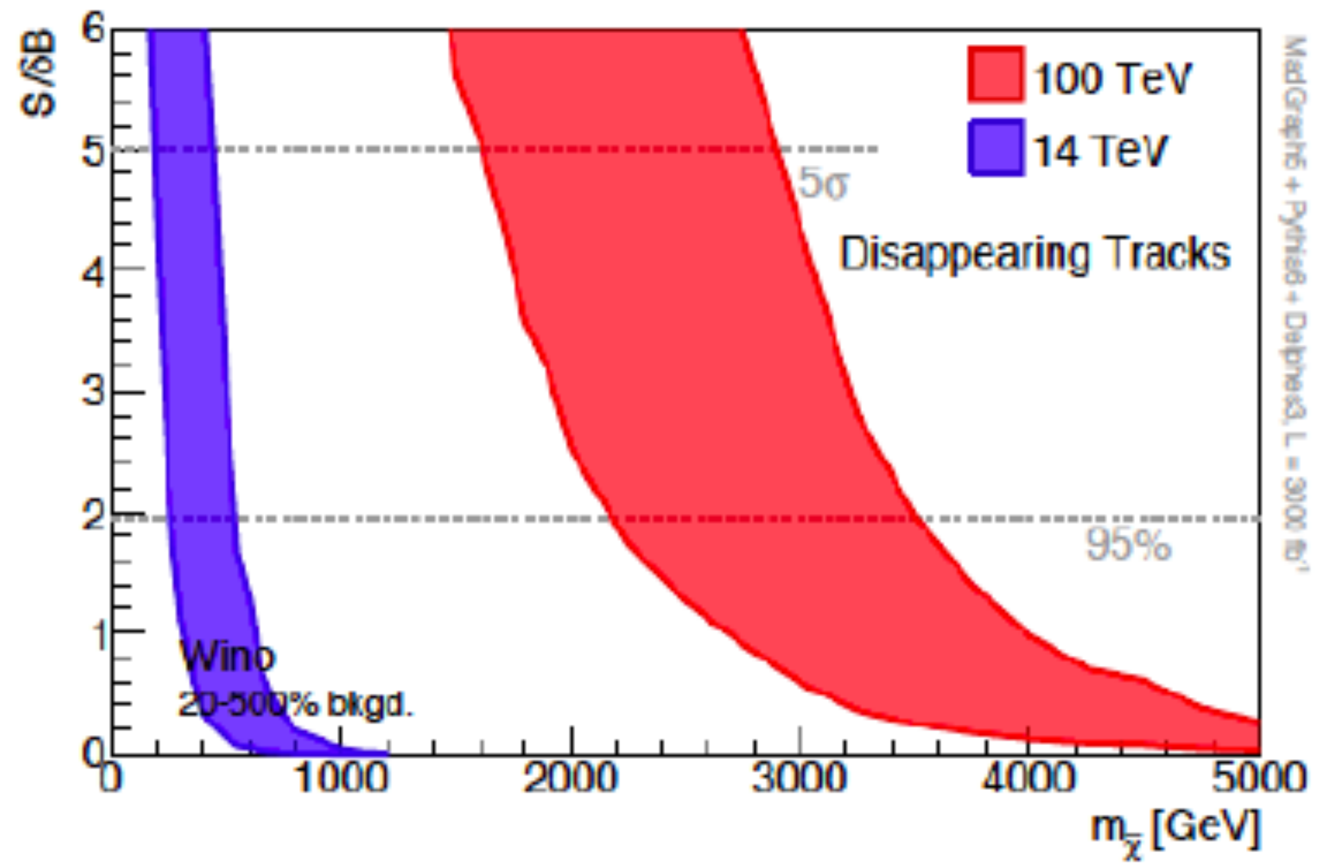
Dark Matter

DM overclosure upper limits:

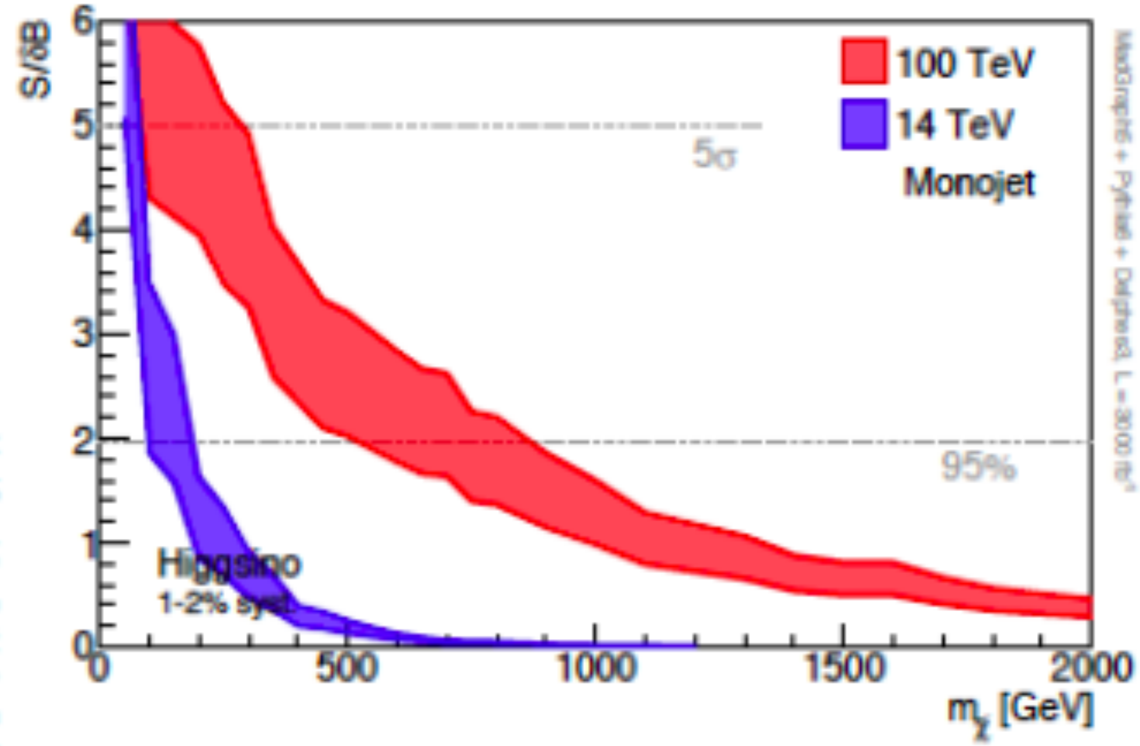
$M_{WIMP} < 1.8$ TeV $(g^2/0.3)$ ⇒

wino: m≲3 TeV

higgsino: m≲1.1 TeV



Wino LSP



Higgsino LSP

→ Wino case pretty much covered!

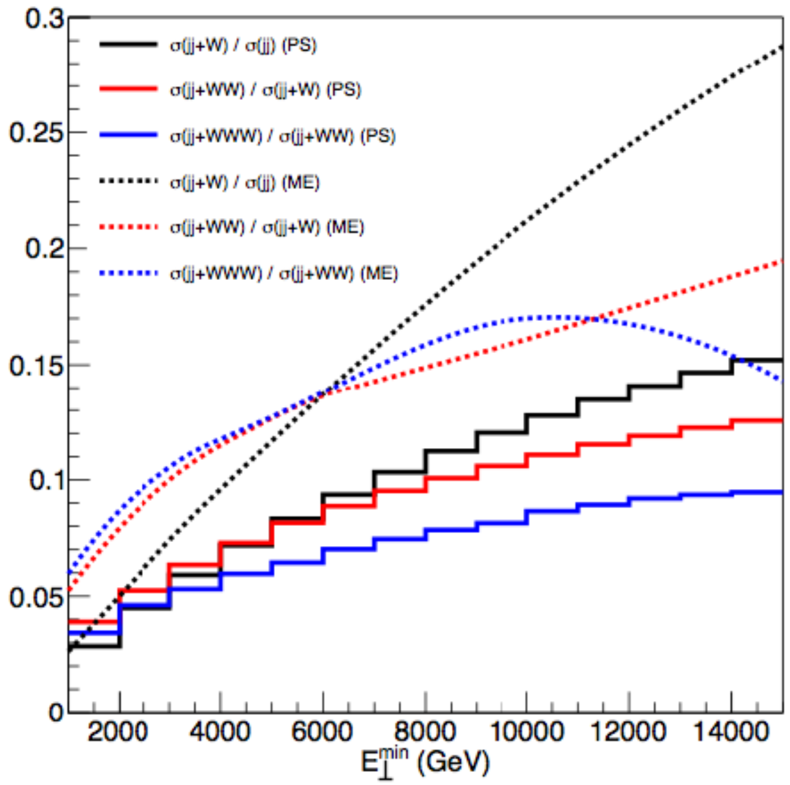
L-T. Wang, FCC Kickoff preparatory workshop

FCC-hh

EW interactions at high energy

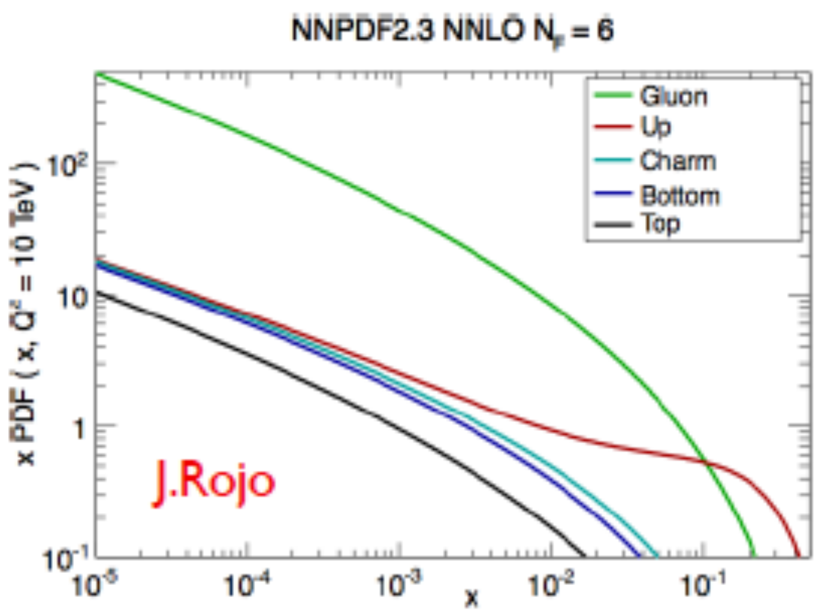
WW	σ=770 pb
WWW	σ=2 pb
WWZ	σ=1.6 pb
WWWW	σ=15 fb
WWWZ	σ=20 fb

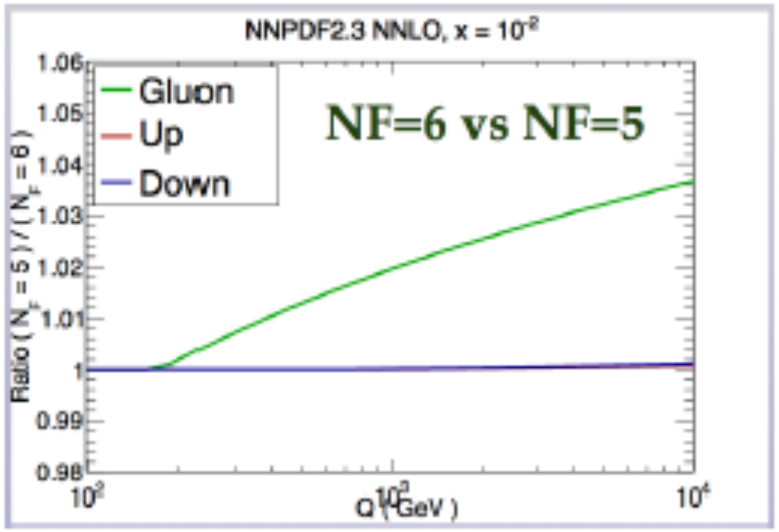
....

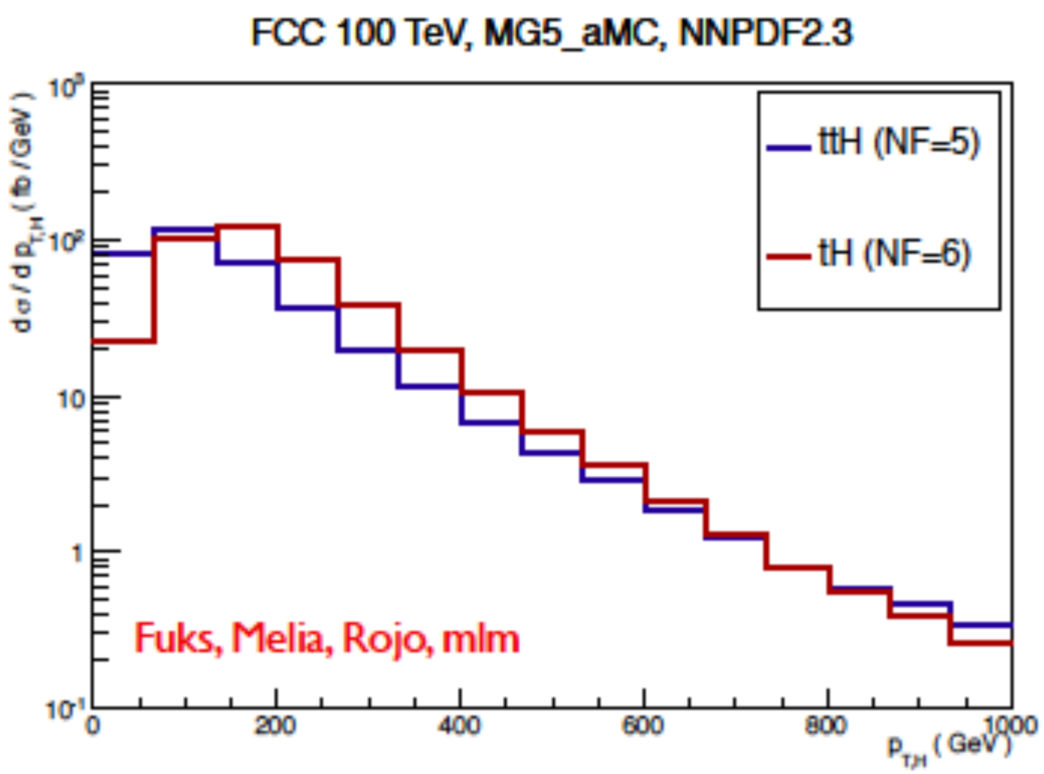


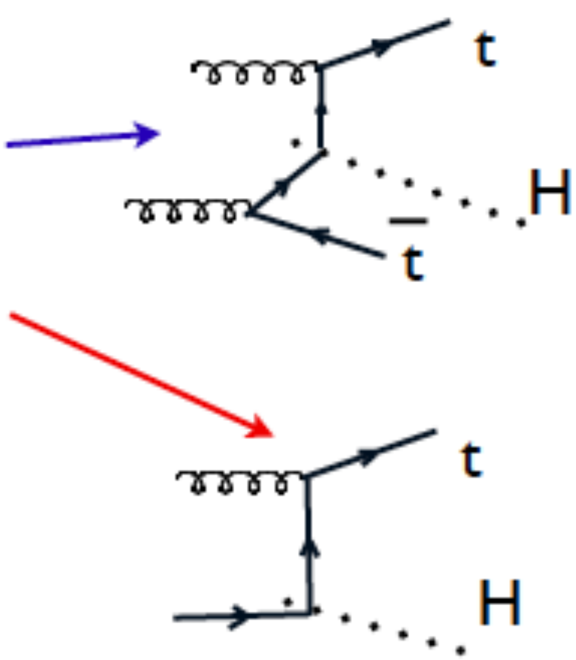
- At 100TeV large statistic of multi-boson production events
- Need to see how high can we go in multiplicity?
  - Experimental issues important: acceptances/ efficiencies.
  - Can we use (boosted) hadronic decays?
- what can we learn? How?
  - 100fb with M(WW)>~3 TeV
  - 1fb with M(HH)>~1 TeV
- For instance there is a 10% probability of a W emission from a quark jet!

Access the top PDFs





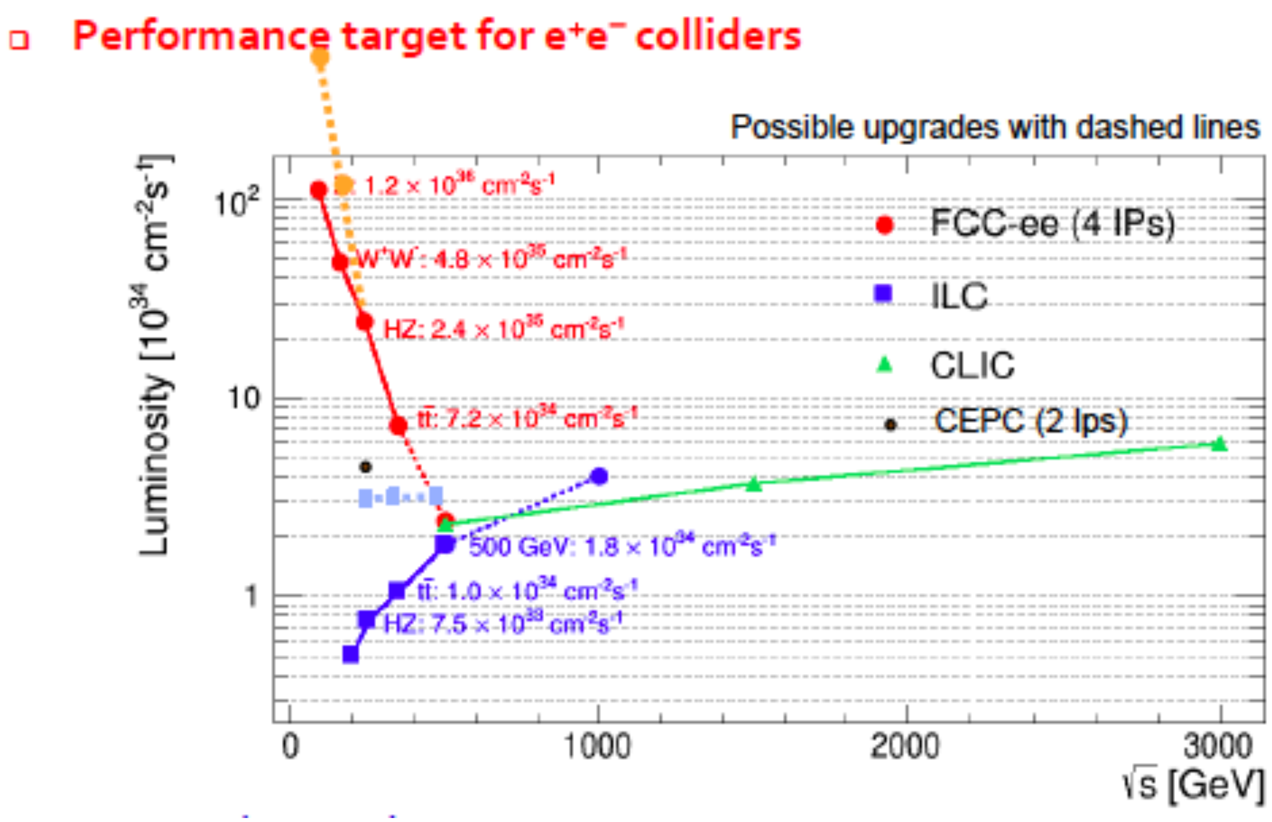


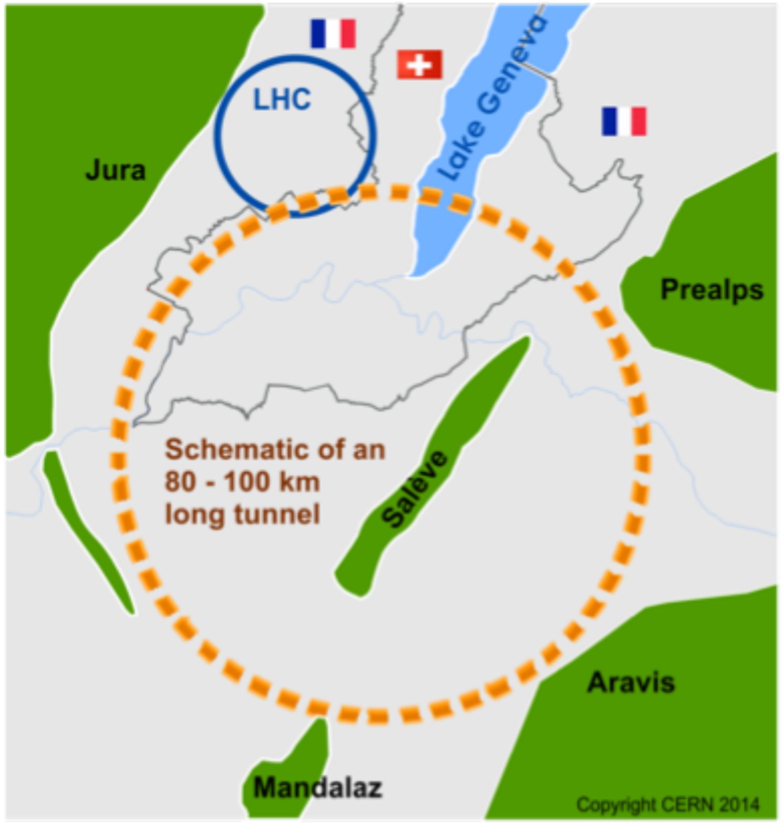


An historical perspective

- 1970-1990
  - **Precision measurements** of neutral currents: **predicted** m_W and m_Z
  - The CERN SppS(UA1, UA2) **discovered** the W and the Z
  - The CERN LEP(and SLC) **nailed** the Gauge sector
- 1990-2000
  - **Precision measurements** of the gauge sector at LEP/SLC: predicted top
  - The FNAL Tevatron(CDF,D0) **discovered** the top
  - A collider to **nail** the top sector? Does the LHC suffice?
- 1995-2015
  - **Precision measurements** of m_W and m_{top}(LEP, TeVatron): predicted m_H
  - The CERN LHC(CMS,ATLAS) **discovered** the SM Higgs boson
  - A collider to **nail** the scalar sector? Does the LHC suffice?

FCC-ee in one page (reminder)





- Intermediate step in the FCC global project
- Very high luminosity + up to 4 Interaction Points
- Beam energy from 45 to 175(250) GeV
- Main physics Program vs beam energies:

Z(45.5 GeV): Z pole, 'TeraZ', high precision M_Z, Γ_Z

W(80 GeV): W pair production threshold (Oku-W)

H(120GeV): ZH production threshold

t(175 GeV): tt threshold (Mega-top)

Expected deviations from benchmark models

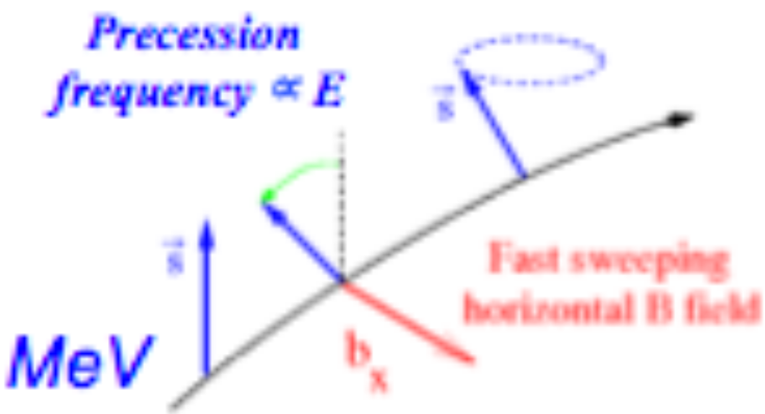
- if new physics scale at 1TeV

	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

Polarization

Two main interests for polarization:

- Accurate energy calibration using resonant depolarization ⇒ measurement of $\mathbf{M_Z}$, Γ_Z, $\mathbf{M_W}$
  - *Nice feature of circular machines, δM_Z, $\delta\Gamma_Z$ ~ 0.1 MeV*



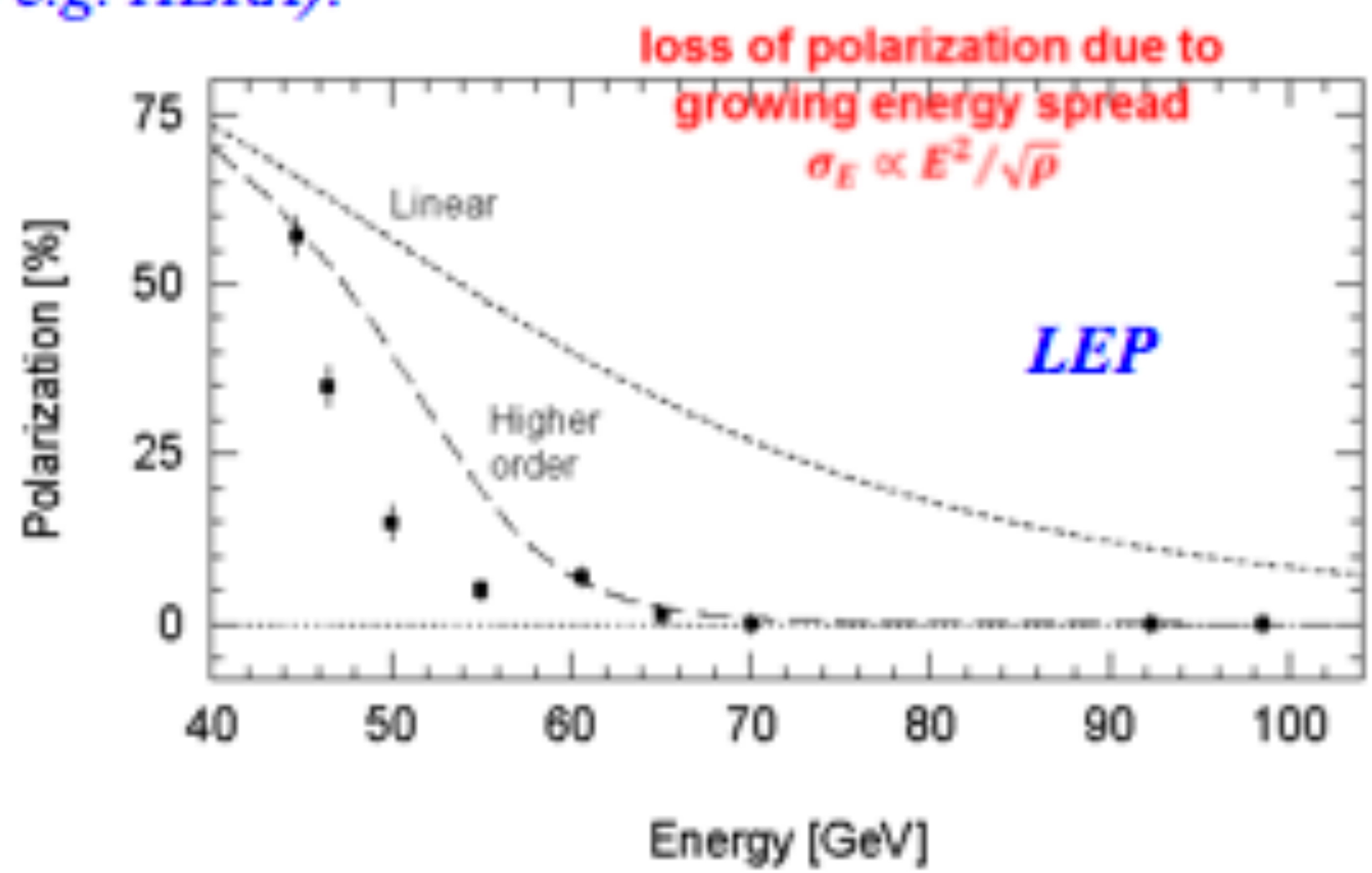
- Physics with longitudinally polarized beams.
  - *Transverse polarization must be rotated in the longitudinal plane using spin rotators (see e.g. HERA).*

Scaling the LEP observations :

polarization expected up to the WW threshold !

Integer spin resonances are spaced by 440 MeV:

energy spread should remain below ~ 60 MeV



More SM fundamental measurements

* Off-shell W/Z production above 10 TeV DY mass. E.g.

- measure the running of EW couplings, sensitive to new weakly-interacting particles, possibly hidden from direct discovery (⇒ Rudermann at BSM@100 TeV wshop, Galloway at SLAC)

- 10^4 pp → W^* → top+ bottom with M(tb) > 7 TeV

* QCD jets up to 25-30 TeV ⇒ running of α_S , ...

* SM violation of B+L via EW anomaly (not viable below 30 TeV) (⇒ Khoze and Ringwald at BSM@100 TeV wshop)

* Growth of heavy flavour densities inside proton (c, b and ultimately top) ⇒new opportunities for studies within and beyond the SM (⇒ Perez at BSM@100 TeV wshop)

* ....

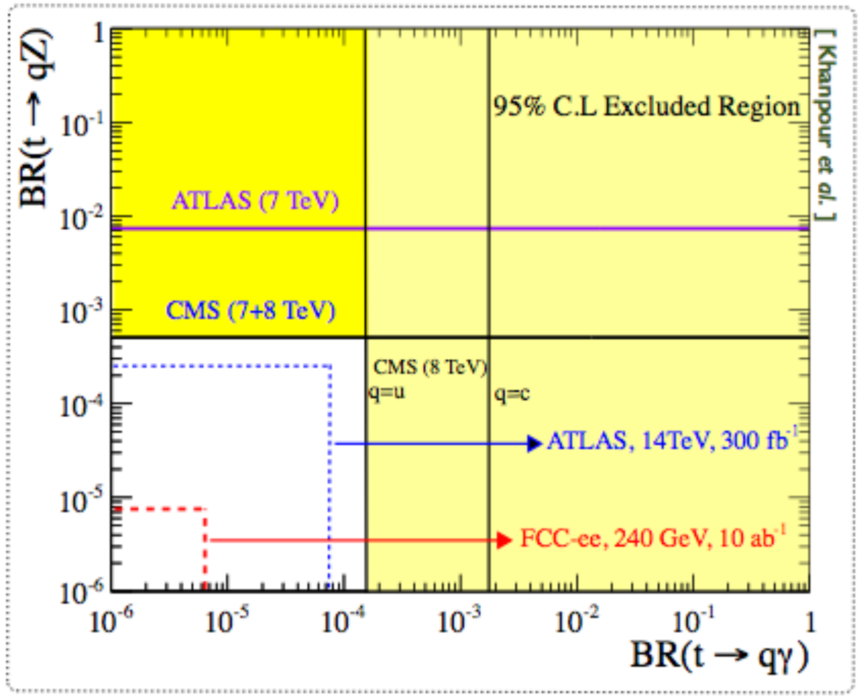
Plenty of room for new ideas

Precision top physics: FCNC & Rare-decays

- The large statistics allows to improve significantly the measurement of the various **top couplings: g_{tWZ}, ttZ/ttγ**
- But **rare decays and FCNC** are the real gold mine (i.e. t->Zq, γq, Zc). The improvements come from:
  - large statistic at 350GeV in pair production
  - can profit of single top production at 240 GeV
  - clean final states

✦ FCNC production of a top and a light quark

✤ At a center-of-mass energy of 240 GeV



✤ Gain of 1.5 order of magnitude w.r.t. LHC

expectations from theory

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

Easy way to find new physics signatures!

W decays

- o W mass ??
- o SM rare decays -- Examples:

$W^{\pm} \rightarrow \pi^{\pm} \gamma$ $BR_{SM} \sim 10^{-9}$, CDF $\leq 6.4 \times 10^{-5}$

$W^{\pm} \rightarrow D_s^{\pm} \gamma$ $BR_{SM} \sim 10^{-9}$, CDF $\leq 1.2 \times 10^{-2}$

What is the theoretical interest in measuring these rates? What else ?

- o SM inclusive decays -- Examples:

$R = BR_{had} / BR_{lept}$: what do we learn ? Achievable precision for CKM, α_S , ... ?

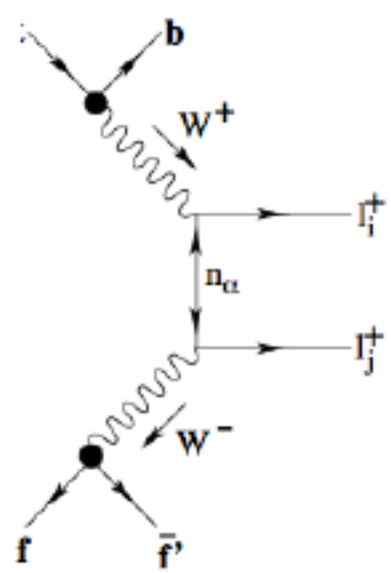
- o BSM decays -- Are there interesting channels to consider?

-- Example

BNL-HET-06/9
OITS-784

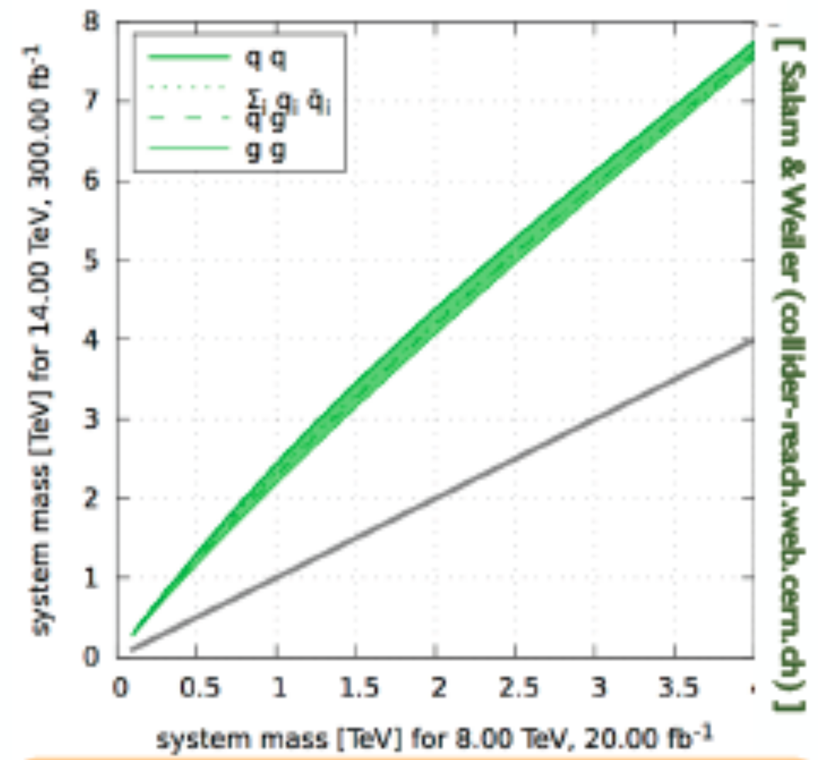
Majorana neutrinos and lepton-number-violating signals in top-quark and W-boson rare decays

Shaouly Bar-Shalom[a,*] Nilendra G. Deshpande[b,†] Gad Eilam[a,‡] Jing Jiang[b,§] and Amarjit Soni[c,¶]

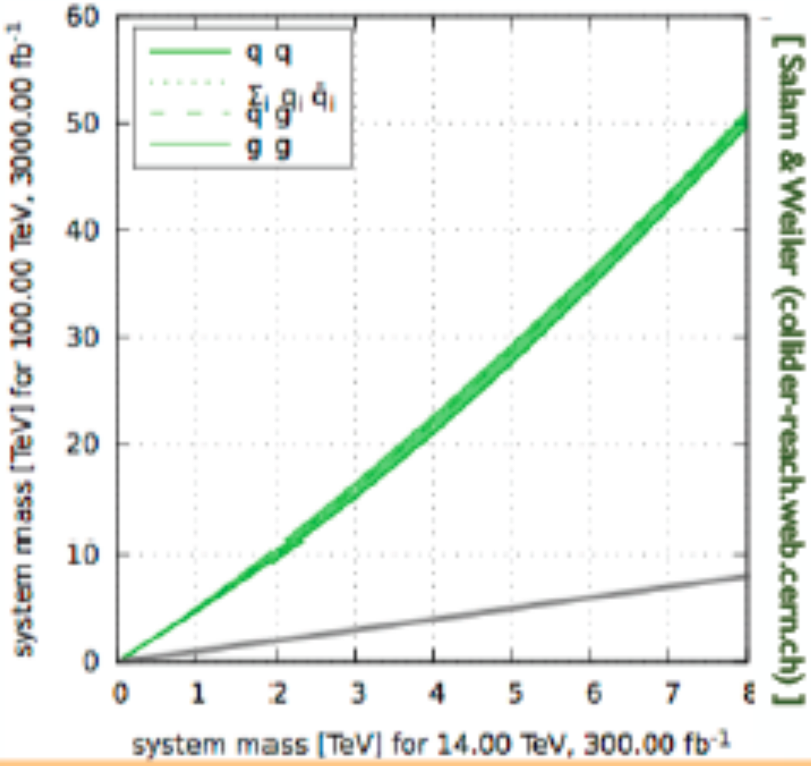


BSM: what changes at 100 TeV

- Access to new particles in the few-30TeV mass range, way beyond LHC reach
- Higher rates for sub-TeV phenomena
- Access to very rare processes. Allow search for stealth phenomena, invisible at the LHC
- *Ignoring at this point all the detector and reconstruction challenges!!!*



LHC-8 [20 fb^{-1}] vs. LHC-14 [300 fb^{-1}]
Gain of 1-2



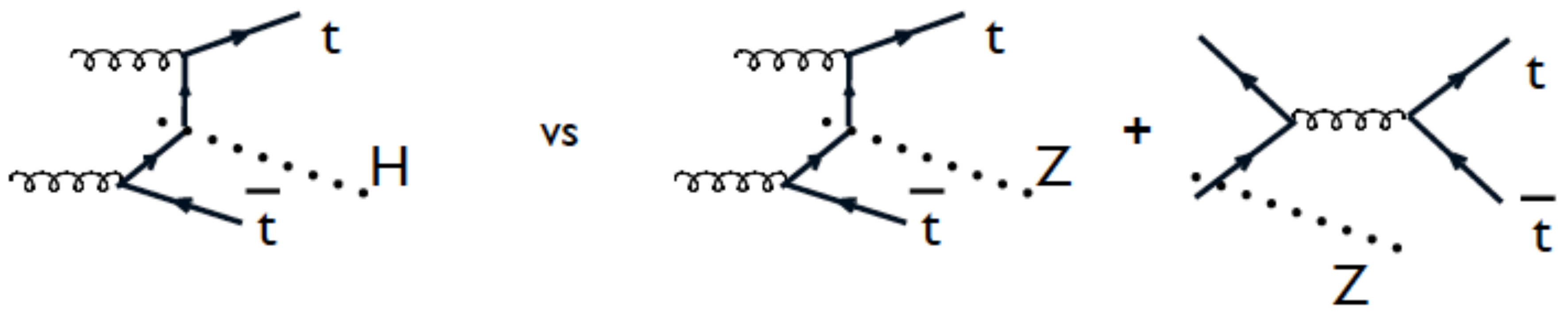
LHC-14 [300 fb^{-1}] vs. FCC-100 [3000 fb^{-1}]
Gain of about 5-6

ttH <1%

Example: Top Yukawa to sub-% precision ?

pp→tt H vs pp→tt Z

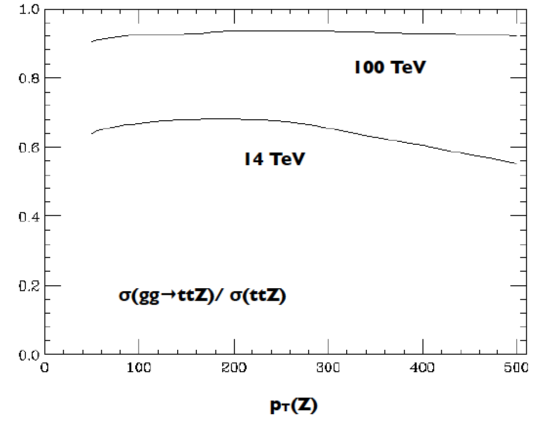
MLM, J.Rojo
in preparation



To the extent that one can neglect the qqbar → tt Z contribution:

- **Identical production dynamics:**
  - o **correlated QCD corrections, correlated scale dependence**
  - o **correlated α_S systematics**
- **$m_Z \sim m_H \Rightarrow$ almost identical kinematic boundaries:**
  - o **correlated PDF systematics**
  - o **no m_{top} systematics**

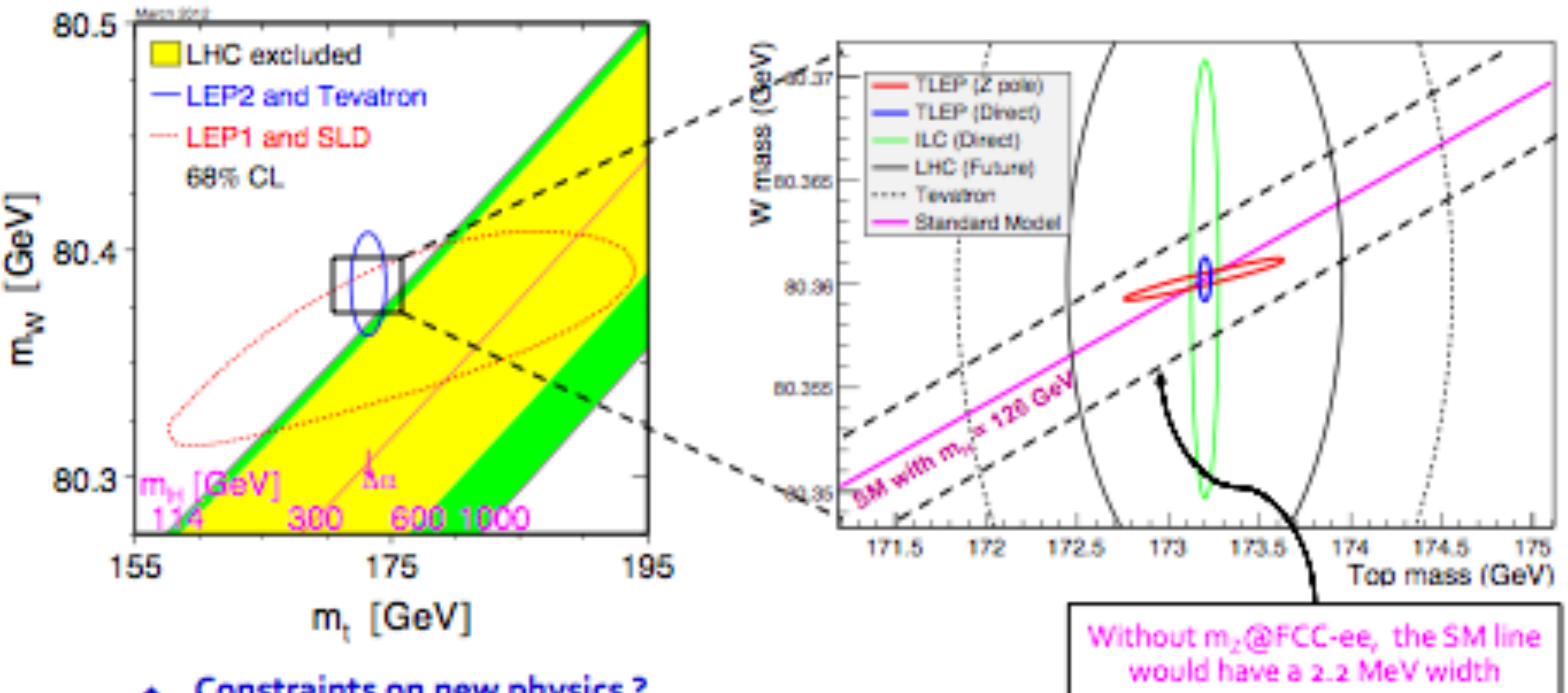
At 100 TeV, gg→ttZ is indeed dominant ....



For a given y_{top}, $\sigma(ttH)/\sigma(ttZ)$ can be predicted theoretically with a sub-% precision

Precision electroweak physics at FCC-ee (10)

- **Comparison with potential precision measurements at linear colliders**
  - Beam energy measurement (compton back-scattering, spectrometer) to ~10^{-4}
    - m_Z and m_W not measured to better than 5-10 MeV at ILC
      - ➡ In absence of new physics, the (m_{top}, m_W) plot would look like this

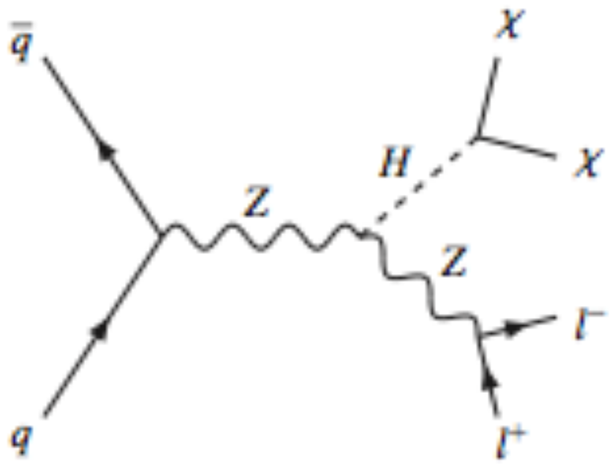


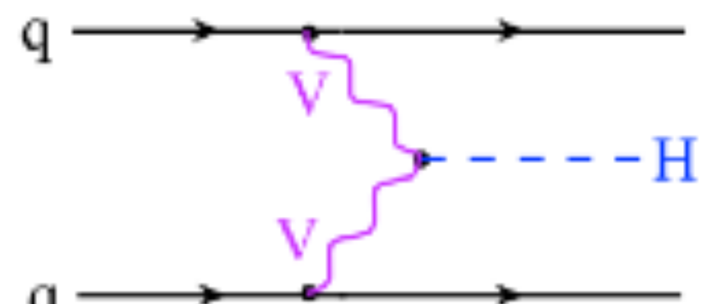
- Constraints on new physics ?

FCC-ee

FCC-hh

High precision: Higgs physics

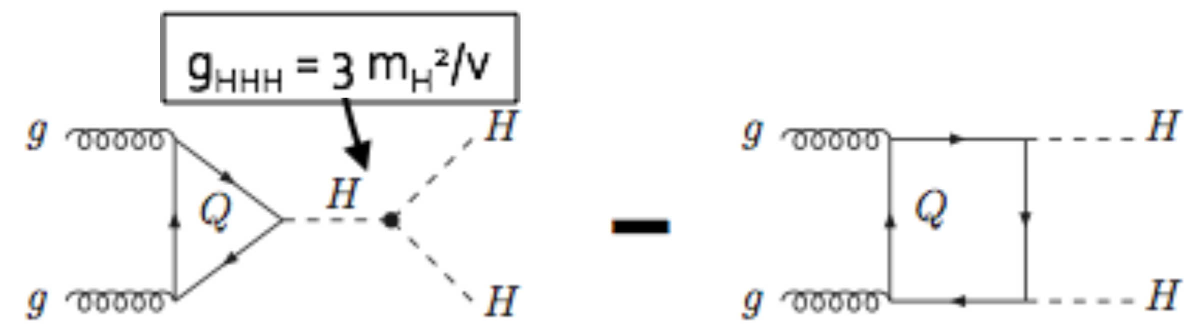




Expected 95% upper limits

	BR_{inv} (95% CL)
LHC Run1	40-50%
LHC 300 fb^{-1}	20-30%
HL-LHC	10-15%

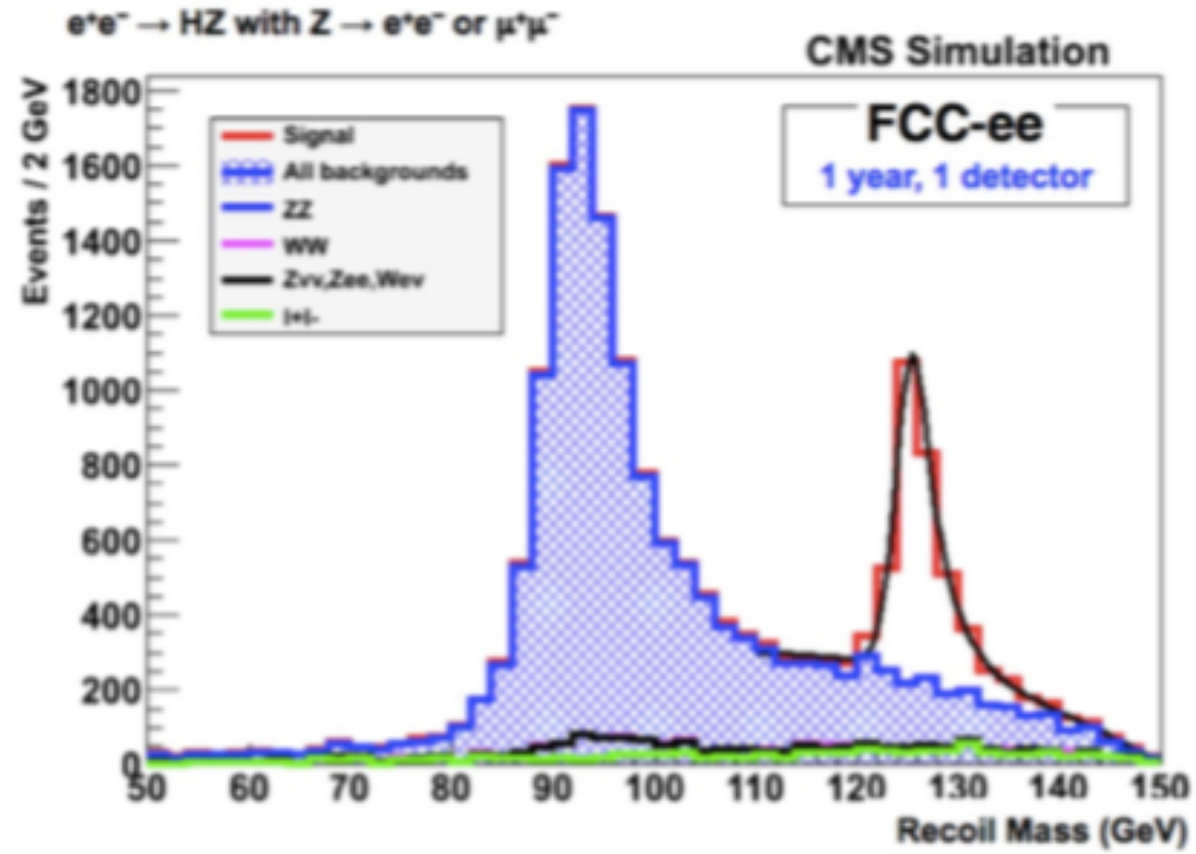
- Invisible Higgs decay: complementary to direct DM search
  - Improves the DM search at low masses
  - Could reach <0.2%(model independent)
- Higgs self coupling
  - difficult, but measurable via double Higgs production
  - Expected precisions still being worked out, possibly a 30% reachable with the full @HL-LHC statistics (using bbγγ)
  - new physics models do not predict deviation larger than 20%==> FCC-hh



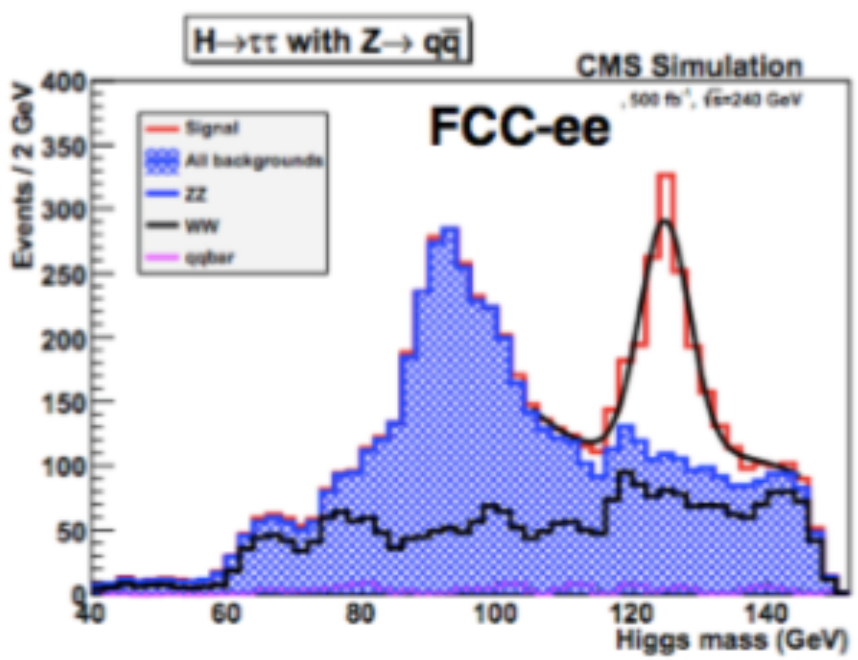
Higgs detection at FCC-ee

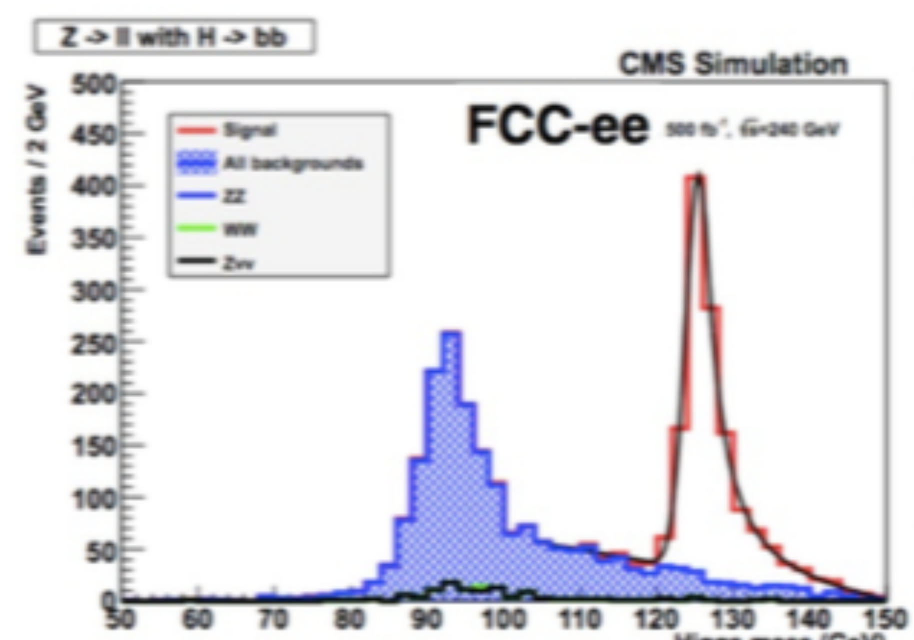
$$m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$

- Reconstructed peak at $m_{recoil} = m_H$ independent of H decay mode!
- Direct measurement of $\sigma(e^+e^- \rightarrow ZH)$
- Model independent determination of g_{ZZH}



Tagging of events under the peak allows determination of individual decay BR's

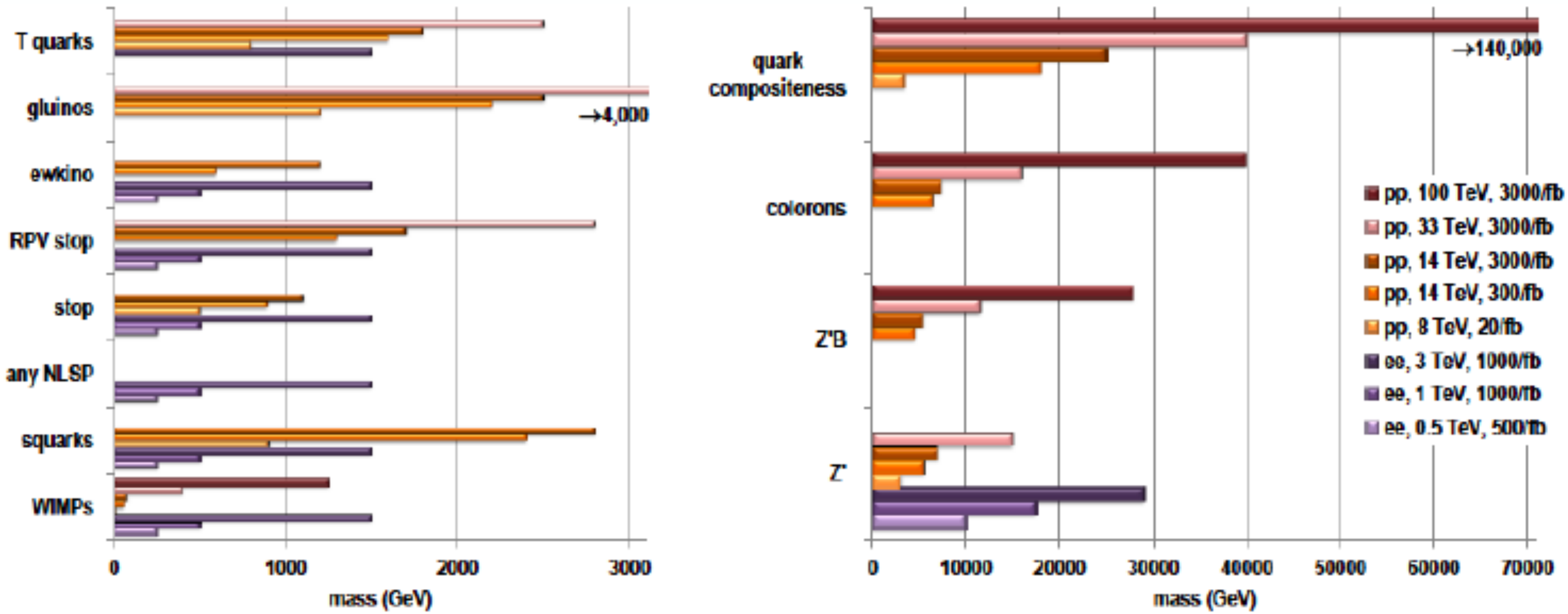




FCC-hh

Other exotica

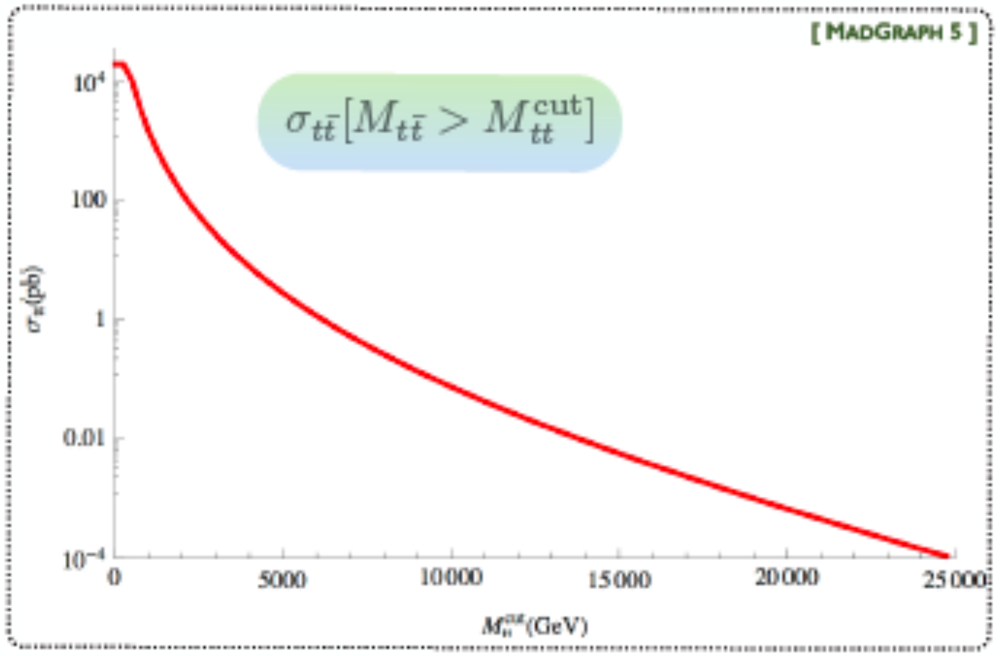
Future colliders comparison

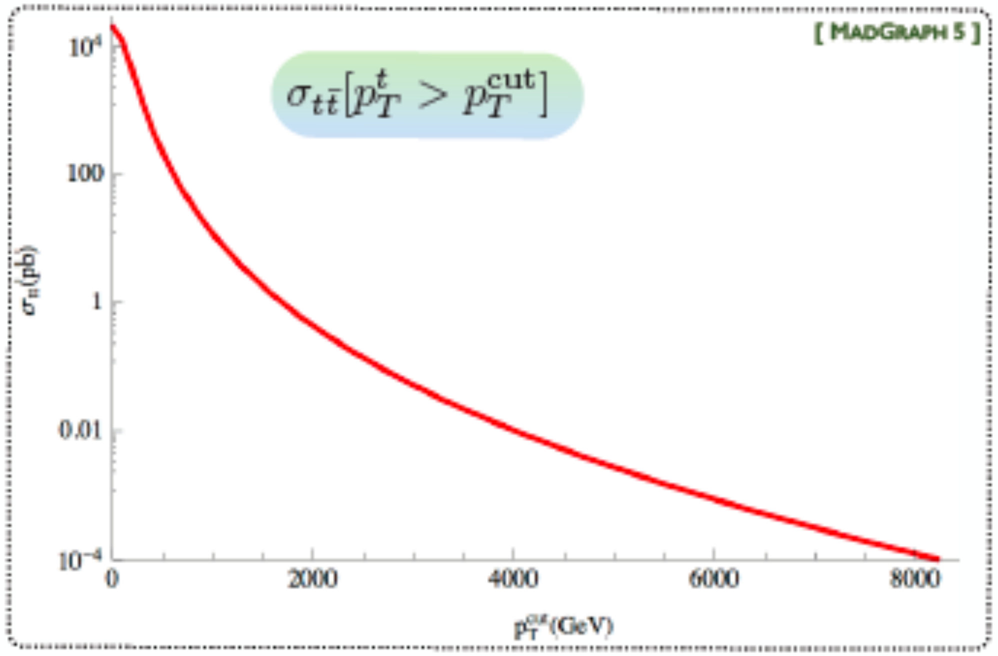


Energy Frontier Snowmass study (1311.0299)

FCC-hh

top physics @100 TeV





- Many produced top-antitop systems have a very large invariant mass
- Produced top(anti)quarks have a very large transverse momentum tails
    - Explore tagging of multi-TeV top!
- study mass resolution for resonance searches, define search potential (σBSM vs MBSM)