INFN Padova & Universita' 27 Febbraio 2015

The physics of the FCC program

P. Azzi - INFN Padova

Outline

- Introduction
- Expected performances at High Luminosity (FCC-ee) & High Energy (FCC-hh)
  - Higgs
  - EWK
  - Top
  - New physics searches
- Conclusions

FCCs: European Strategy implementation

Y. Sirois

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

LHC and HL-LHC

c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme. *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

pp and ee HE frontier

d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. *CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

Precision e+e-

e) There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. *Europe looks forward to a proposal from Japan to discuss a possible participation.*

the FCC Project

- Build a 100 km tunnel in the Geneva region
- Ultimate goal: highest energy reach in pp collisions: 100 TeV
  - need time to develop the technology to get there
- Intermediate step: extreme precision circular e+e- collider
  - variable beam energy from 90-175 GeV
- Two complementary machines covering the largest phase space in the high energy frontier
  - a complete physics program for the next 50 years

Future Circular Collider Study

FCC ▾ Physics ▾ Accelerators ▾ Society ▾ Opportunities ▾

Search this site

Our Goal

CERN is undertaking an integral design study for post-LHC particle accelerator options in a global context. The Future Circular Collider (FCC) study has an emphasis on proton-proton and electron-positron (lepton) high-energy frontier machines. It is exploring the potential of hadron and lepton circular colliders, performing an in-depth analysis of infrastructure and operation concepts and considering the technology research and development programs that would be required to build a future circular collider. A conceptual design report will be delivered before the end of 2018, in time for the next update of the European Strategy for Particle Physics.

NOTE!!!

News and Events

Press Releases

CERN prepares its long-term future

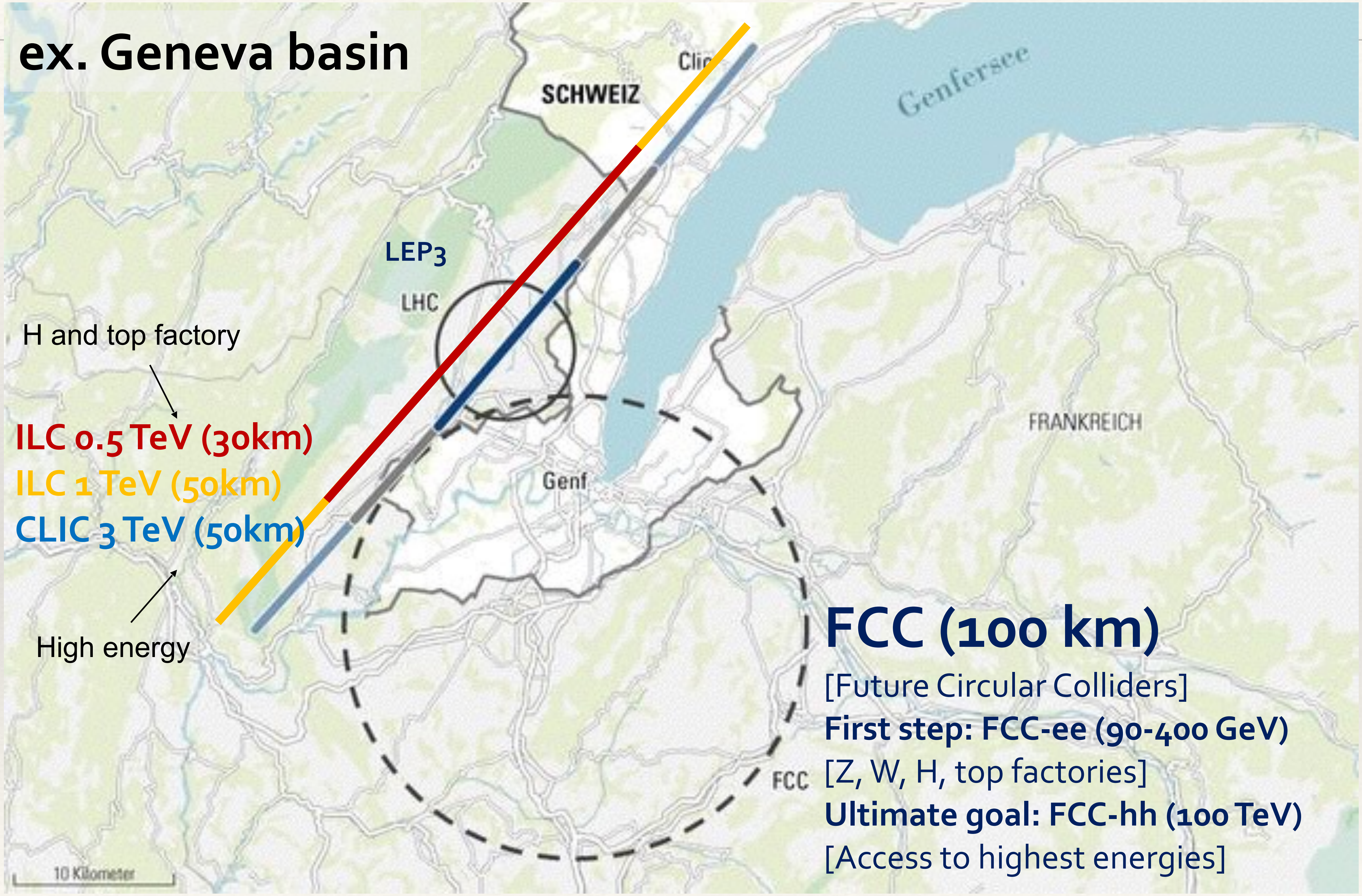
ARUP develops BIM tool for design of future particle accelerator

FCC Study Coordination Group

Study Coordination	M. Benedikt, F. Zimmermann
Hadron Collider Physics and Experiments	F. Gianotti, A. Ball, M. Mangano
Lepton Collider Physics and Experiments	A. Blondel, J. Ellis, P. Janot
e-p Physics, Experiments, IP Integration	M. Klein, O. Bruning
Hadron Injectors	B. Goddard
Hadron Collider	D. Schulte, M. Syphers, J.M. Jimenez
Lepton Injectors	Y. Papaphilippou (tbc)
Lepton Collider	J. Wenninger, U. Wienands, J.M. Jimenez
Accelerator R & D Technologies	M. Benedikt, F. Zimmermann
Infrastructures and Operation	P. Lebrun, P. Collier
Costing Planning	F. Sonnemann, P. Lebrun

M. Benedikt

The Future Colliders on the map



LHC Run2 comes first

- 300 fb-1 at 14 TeV, first results in 2016

FIND A NEW HEAVY PARTICLE(S)

➡HL-LHC can study it

➡if m<1TeV and produced in e+e- collision CLIC is a good option

➡larger energies and luminosities needed to fully study the spectrum (FCC-hh)

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)

FIND NO NEW PARTICLE, STANDARD HIGGS PROPERTIES

➡push precision measurements to their limits (FCC-ee)

➡push energy frontier to its limits hoping the NP scale is reachable (FCC-hh)

the Bottom line

- Physics opportunities at FCC-hh are unique
  - Discovery reach for massive particles superior to multi-TeV e^+e^- machines (CLIC)
  - Better precision than e^+e^- machines for processes requiring large $\sqrt{s_{ee}}$
    - e.g., ttH, HHH, WW scattering
  - Fantastic potential for rare decays
  - FCC-hh is the ultimate energy-frontier machine – and the study is only beginning !
- It will take time before FCC-hh be realized (> 2050 ?)
  - Loads of R&D ahead for high-field dipoles magnets
  - Power consumption is a challenge
  - Beyond-the-state-of-the-art detectors must be conceived
  - Huge construction costs must be reduced to make it affordable
  - CERN budget is what it is… (so far)
- The next machine after the LHC will probably be an e^+e^- collider
  - Be it only to measure precisely the properties of the newly-discovered Higgs boson
    - “We would be crazy not to study the ee option in the FCC ring” (Rolf Heuer)

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^{12} W bosons from top decays
  - =>10^{12} b hadrons from top decays
  - =>10^{11} t->W->taus
  - few 10^{11} t->W charm hadrons

➡precision measurements
➡rare decays
➡FCNC probes: H->eμ

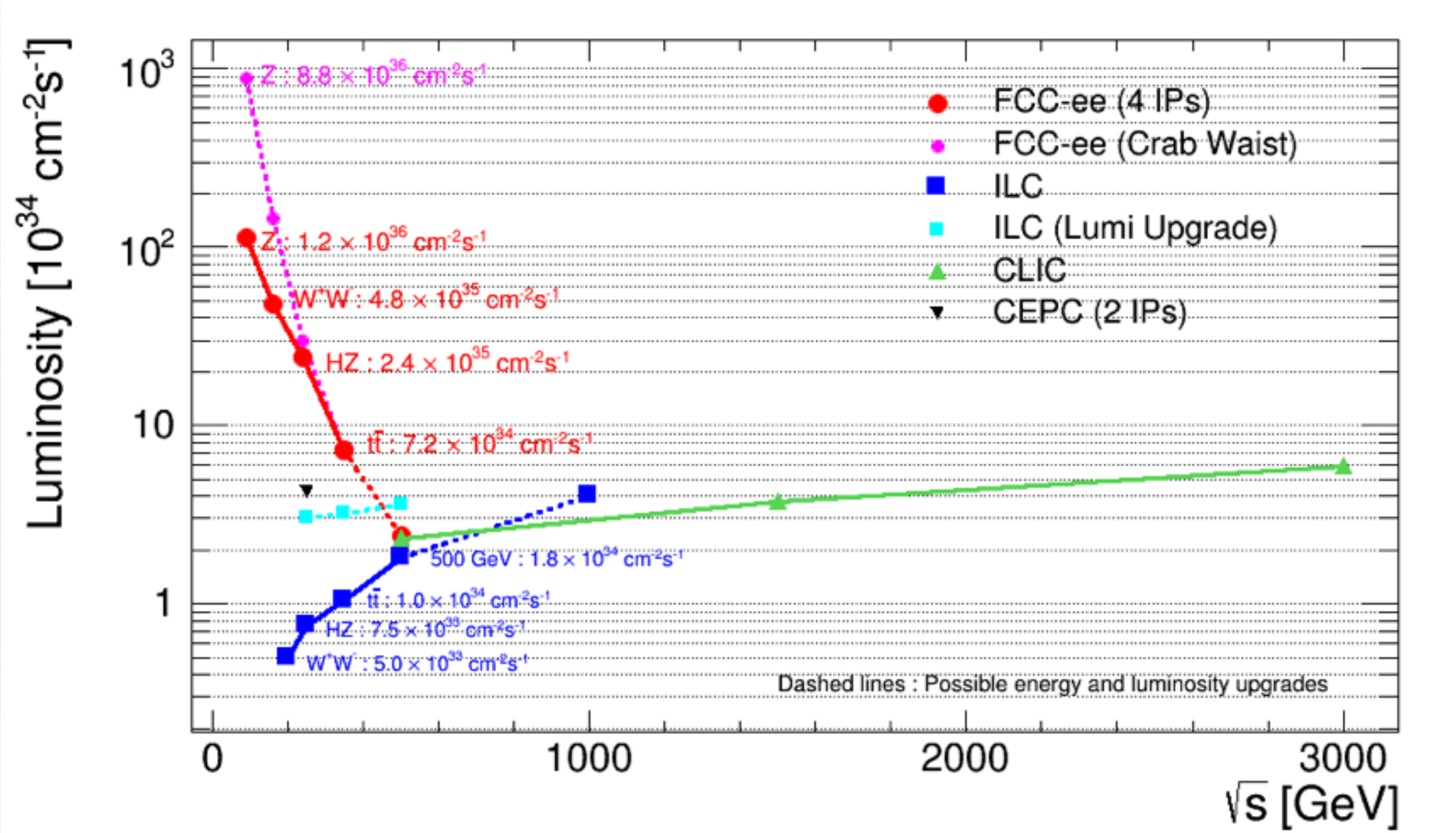
➡precision measurements
➡rare decays
➡FCNC probes: t->cV (V=Z,g,γ), t->cH
➡CP violation
➡BSM decays ???

➡rare decays τ->3μ, μγ, CPV

➡rare decays D->$\mu^+\mu^-$,… CPV

Amazing potential, extreme detector and reconstruction challenges

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



Unprecedented precision: a challenge also to theory expectations

First let's study the Higgs!

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%

- 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.
- The large statistics 3ab^{-1} allows sensitivity to H->μμ
  - measurement of the coupling to 10%
- is this precision *good enough* for a discovery?
  - **Need 1% precision on coupling for a 5σ discovery if Λ =1TeV**

Typically, expect deviations:

$\Delta\kappa/\kappa < \sim 5\,\% / \Lambda^2$

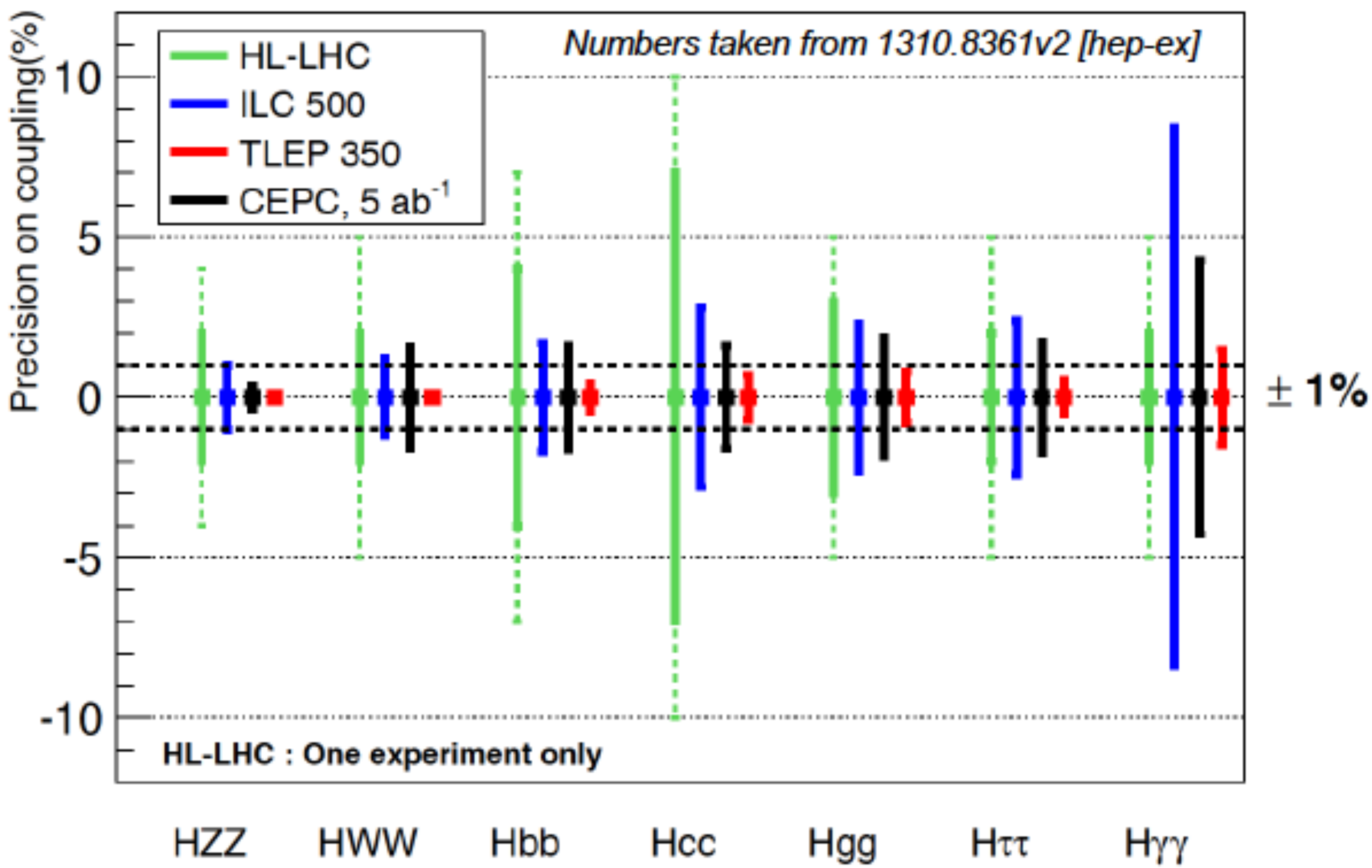
(with Λ in TeV)

Precision on Higgs couplings

- **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.**

Facility		ILC		ILC(LumiUp)	FCC-ee (4 IP)			CLIC	
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	< 0.9%	< 0.9%	0.4%	0.19%	< 0.19%			

Precision on Higgs couplings



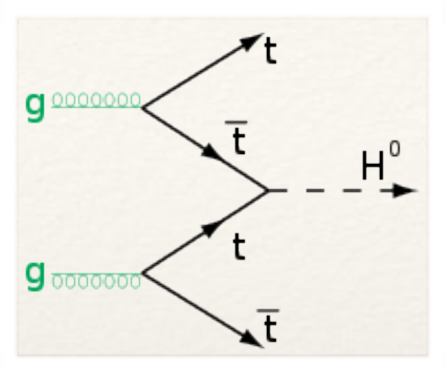
HL-LHC(3 ab^{-1}, 1 detector) with **assumption** ~ g(HVV) ≤ g(HVV)$|_{SM}$, g(Hcc) ~ g(Huu)

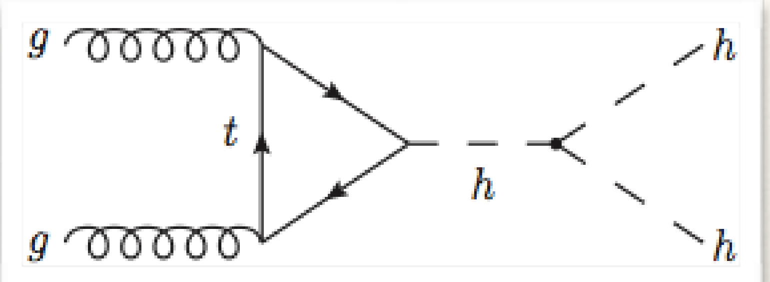
ILC 500: 250 fb^{-1} @ 250 GeV, 500 fb^{-1} @ 500 GeV
TLEP 350: 10 ab^{-1} @ 240 GeV, 2.6 ab^{-1} @ 350 GeV
CEPC, 5 ab^{-1} @ 250 GeV

FCC-hh

Higgs physics @ 100 TeV

- **ttH & HHH coupling**



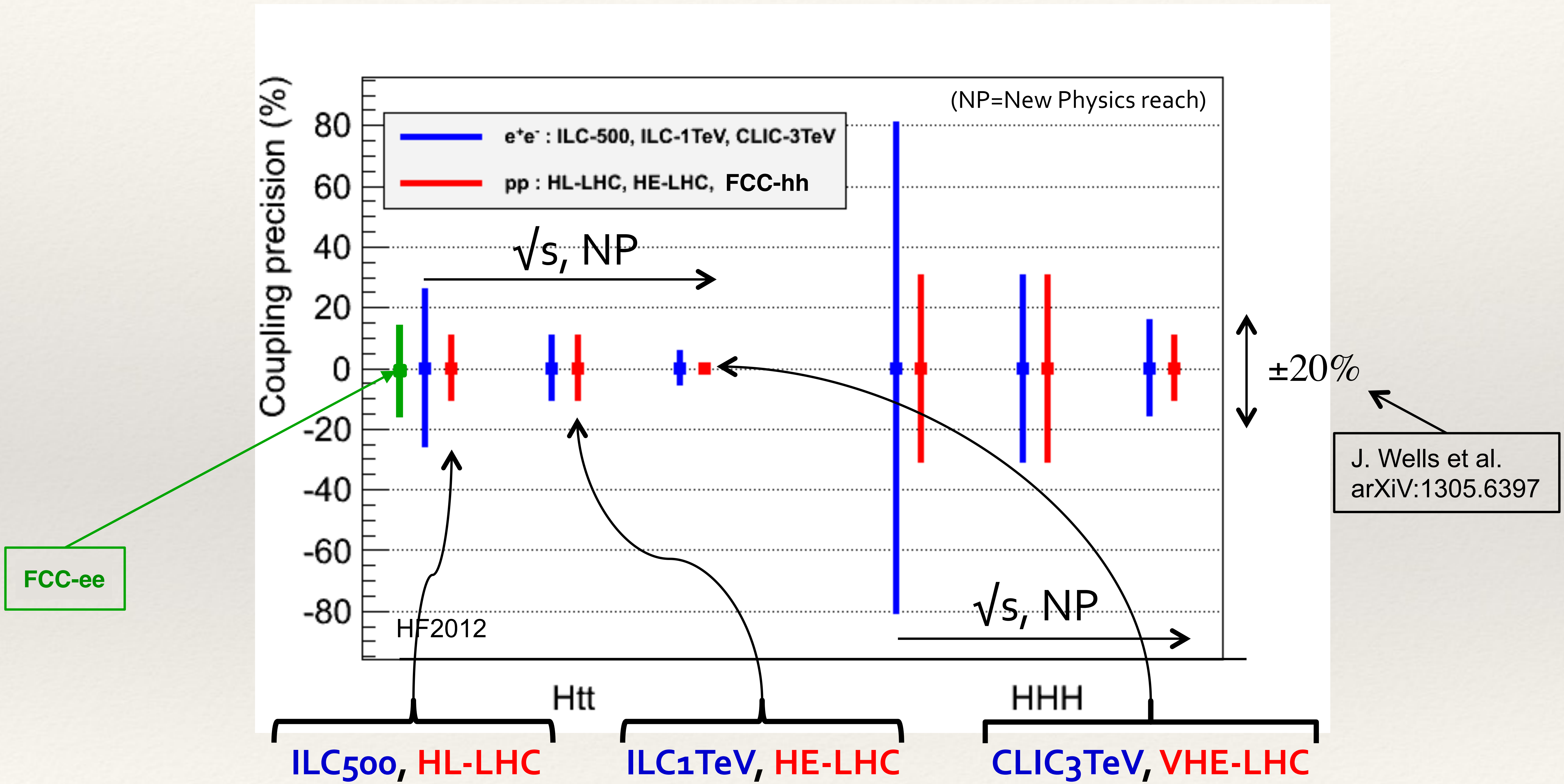


Process	14 TeV	33 TeV	100 TeV
gg → ttH	0.62 pb	4.5 pb × 7.3	37.8 pb × 61
gg → HH	33.8 fb	206 fb × 6.1	1.41 pb × 42

advantage even bigger
R(100)=250 for
σ(ttH, Pt(t) >500GeV)

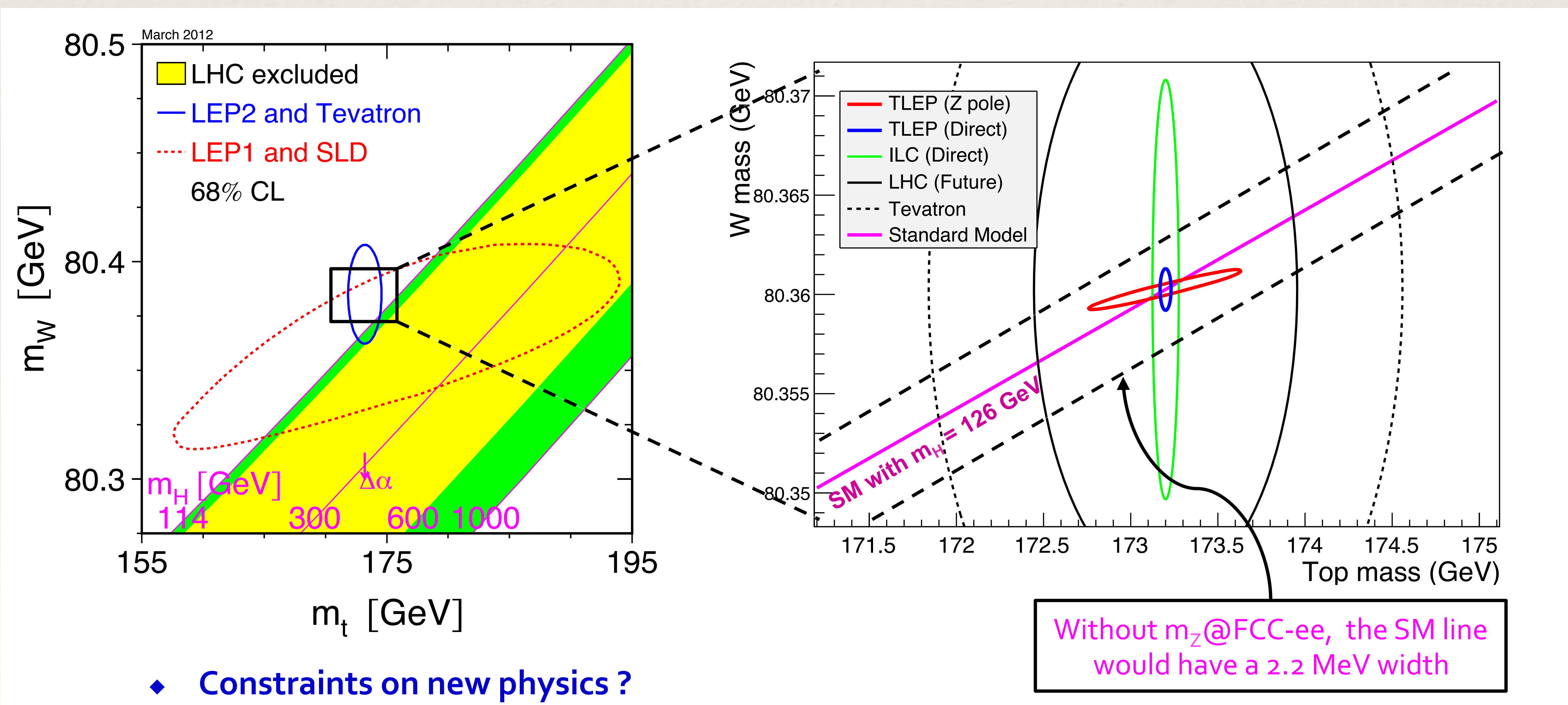
	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000	500	1600‡	500/1000	1600/2500‡	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%
λ_t	4%	14%		4%	2%	4%	<4%	3%	1%

Higgs Physics @100TeV



SM after FCC-ee

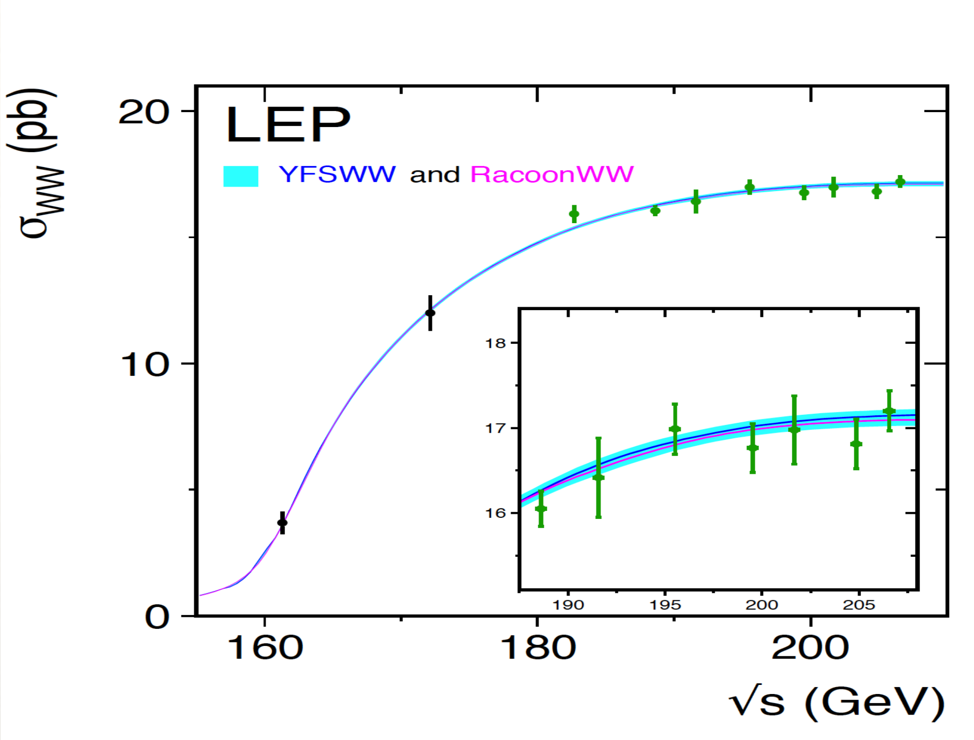
- **EWK fits** have shown their predicting power in the case of the Higgs mass: they could show the presence of new physics effects
    - theory needs to advance as well as the experiments to match the precision expected at the Fcc-ee
    - precision goals to be confirmed by complete studies
- In absence of New Physics the m_{top} vs m_W plot would look like this:

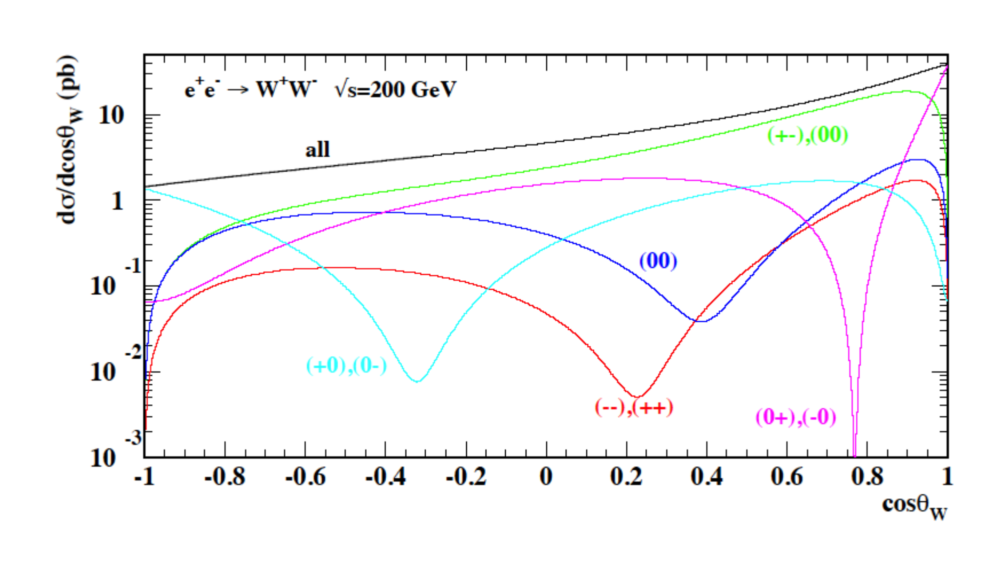


FCC-ee

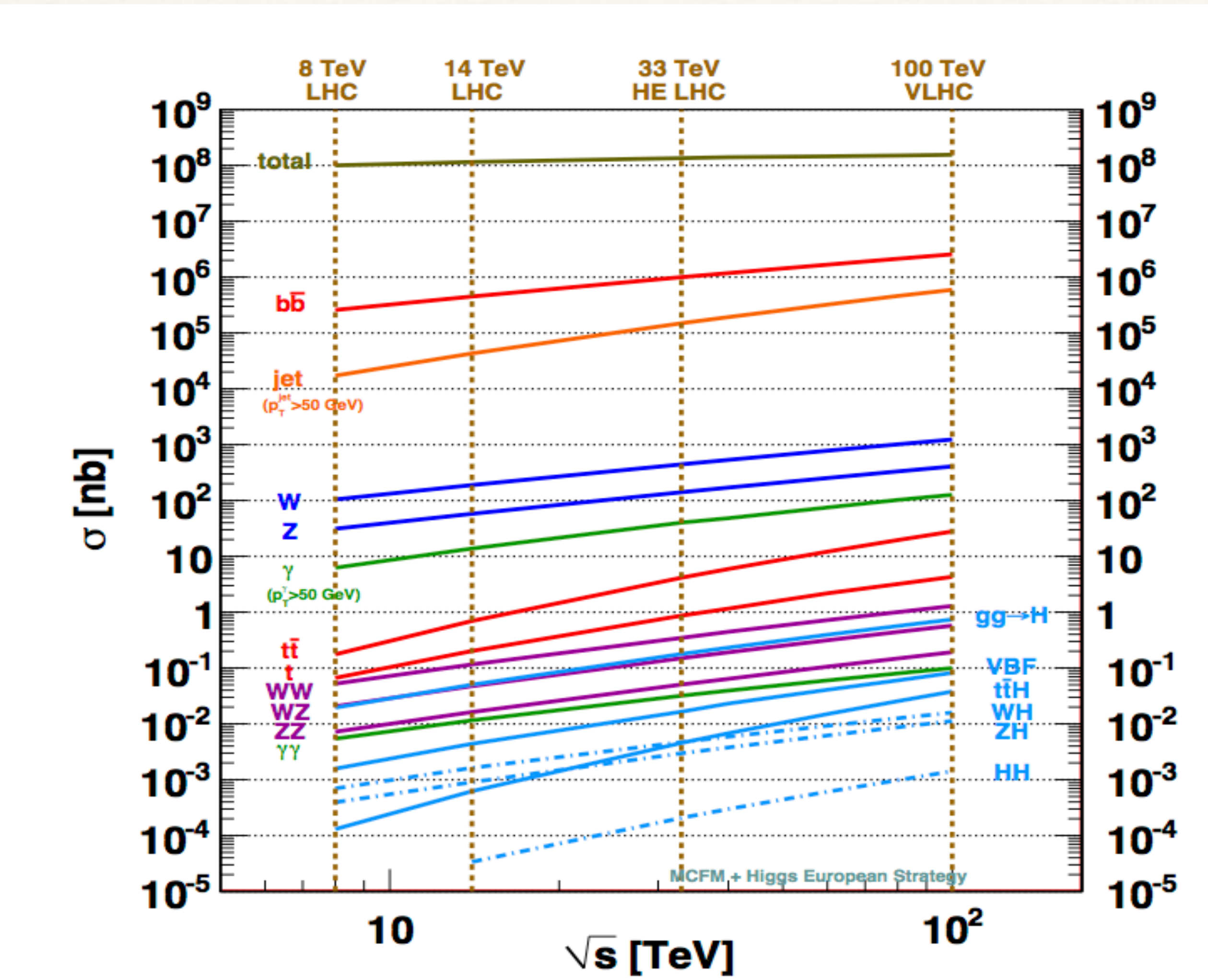
Tera-Z and Oku-W

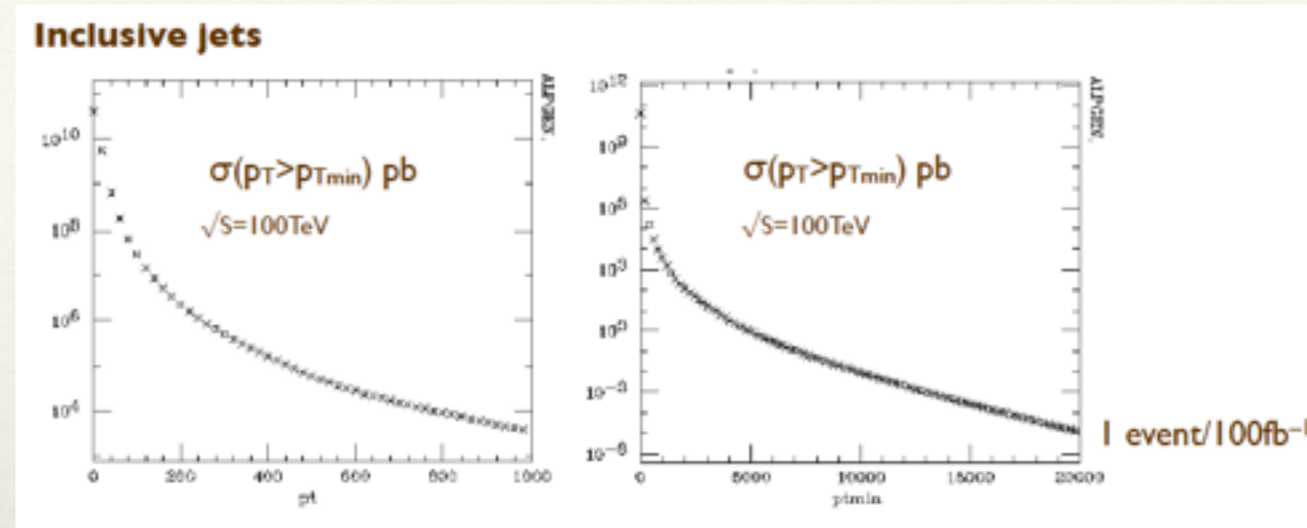
- **Hadronic Z event rate** ~15kHz in the detector.
  - *LEP1 physics program in 15 minutes!*
- **Measure the Z line shape** accumulating 10^{12} Z bosons in a energy scan. **Could reach 100 keV on M_Z and Γ_Z**
  - improvement on method to measure the c.o.m. energy (profit on the large number of bunches)
- **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 ~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



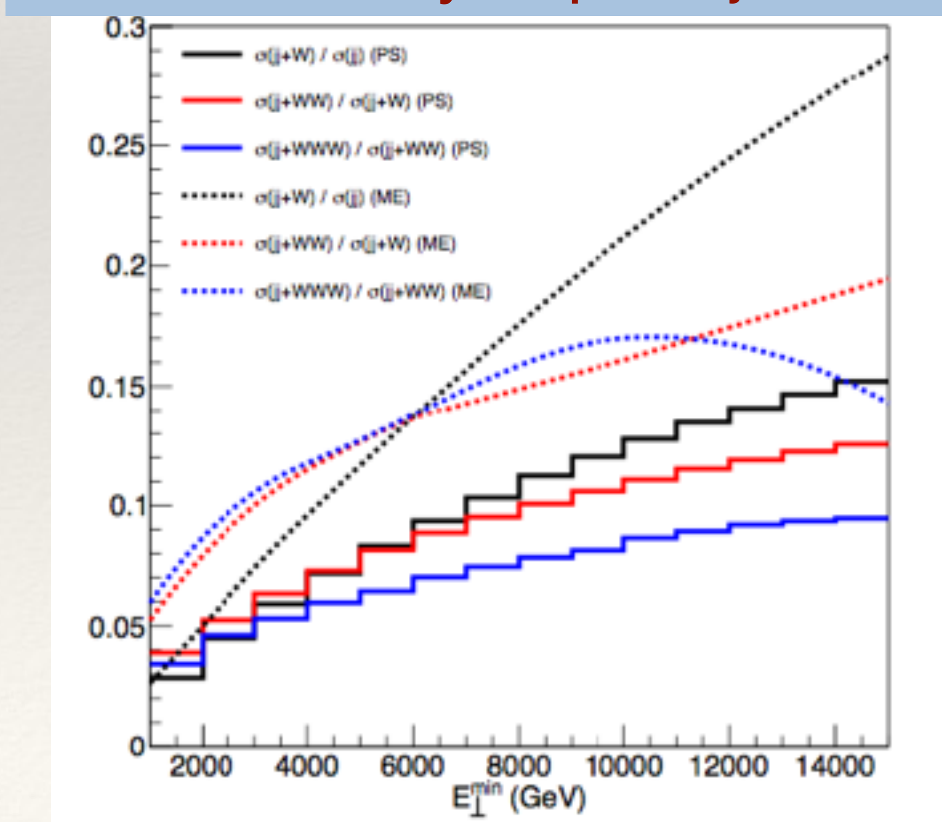


what changes at 100 TeV: SM





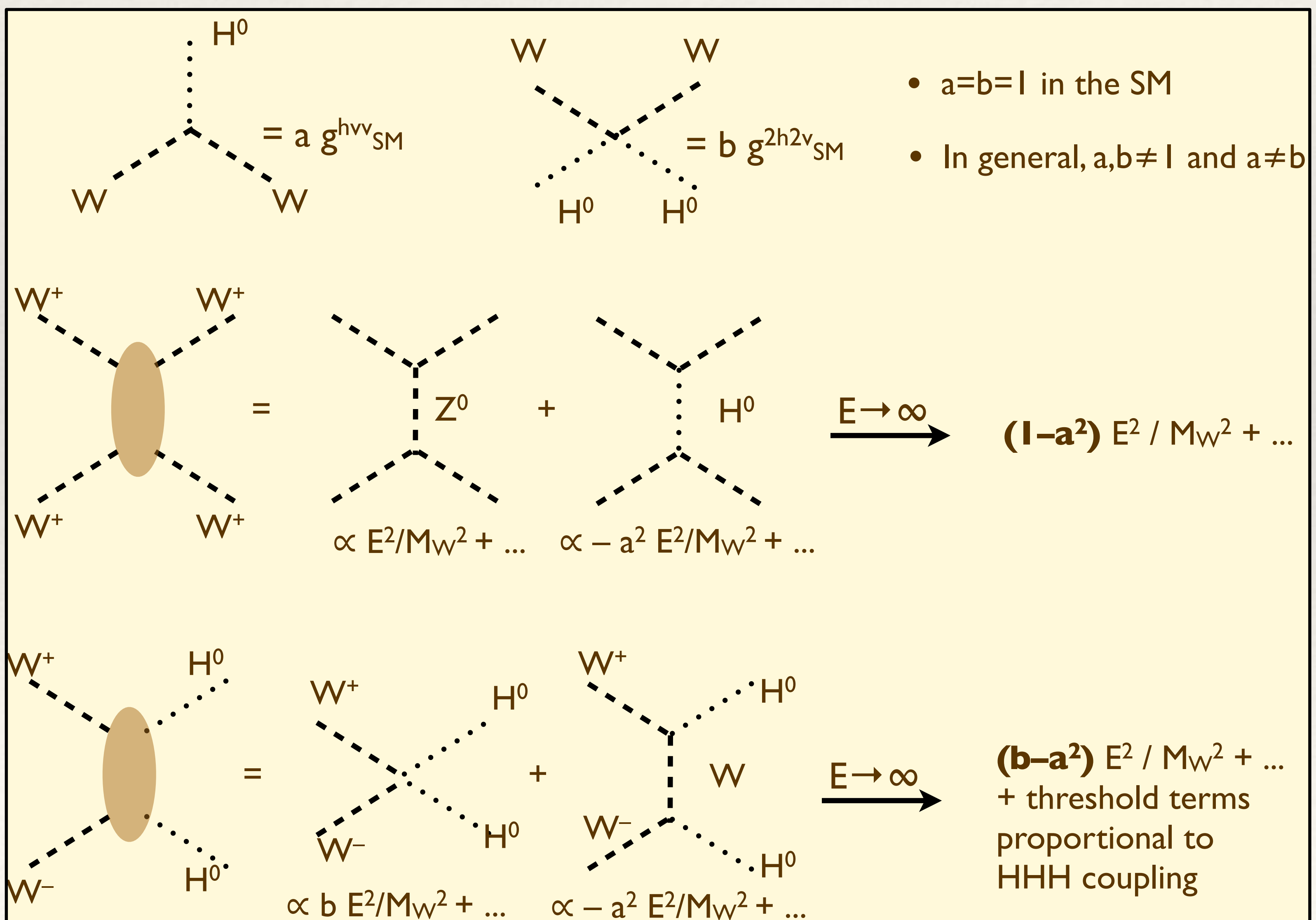
10% probability for a W emission by a quark jet!

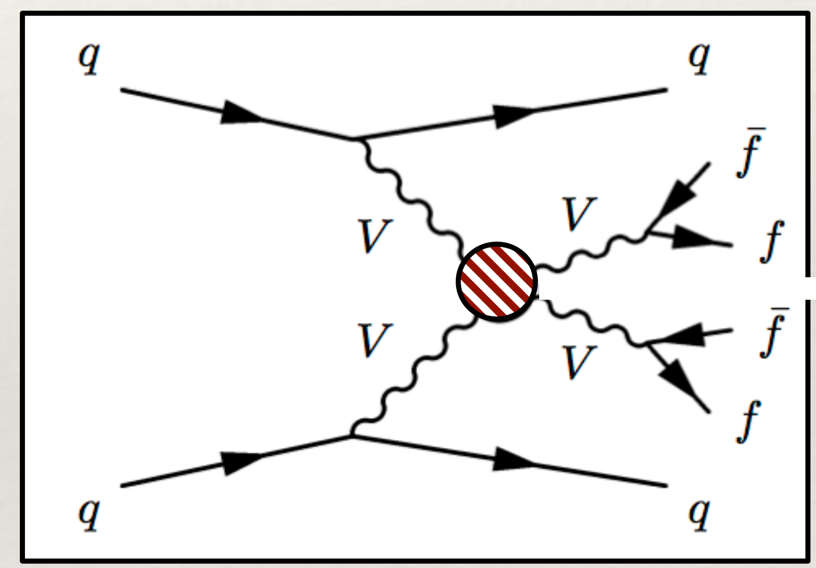


- Higher rate for sub-TeV phenomena: also populating the high boost tails
- Access to rare decays and multi-boson production

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 $\mathbf{m^4_{WW,HH}}$

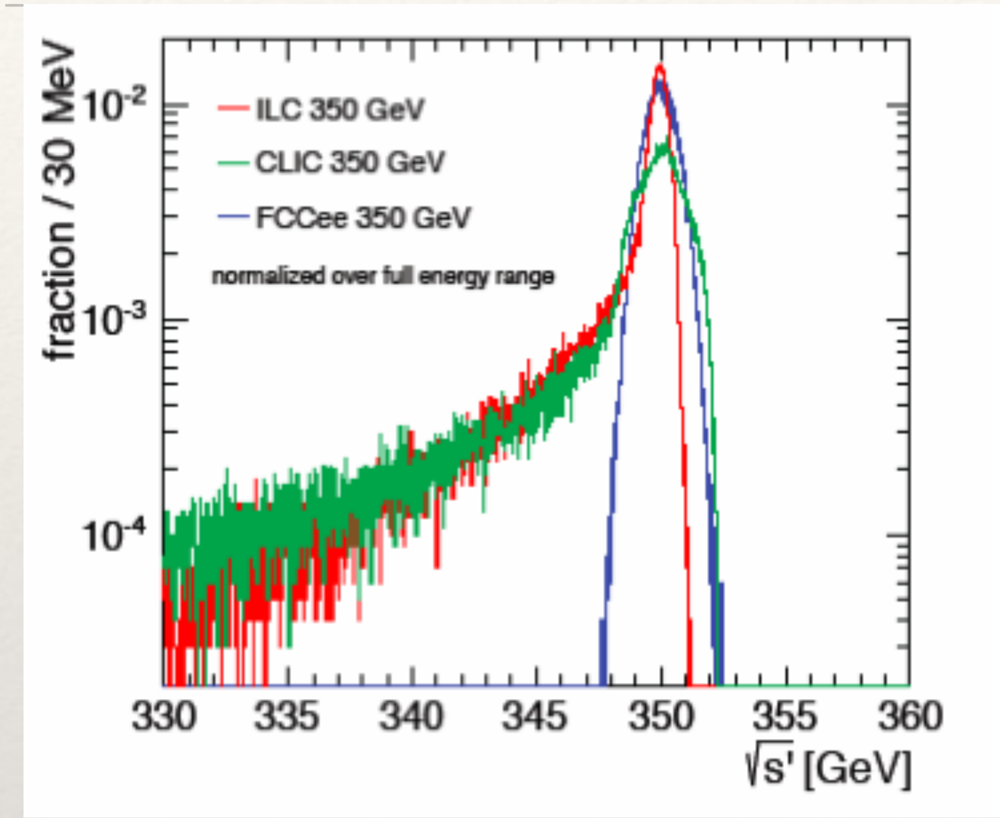


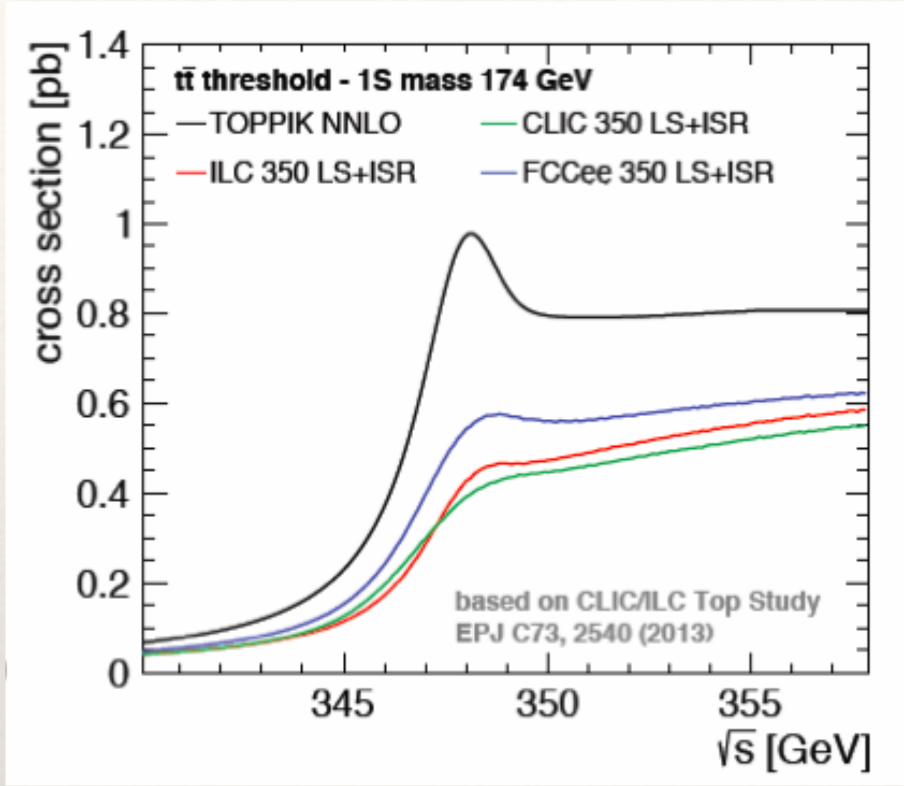


Precision on **a** and **b**:
~30% at HL-LHC 14 TeV
~1% with FCC-hh 100 TeV

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

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}	$\Delta\Gamma_{top}$	$\Delta\lambda_{top}/\lambda_{top}$
TLEP	4 × 650 fb^{-1}	1,000,000	10 MeV	12 MeV	13%

Precision top physics: FCNC & Rare-decays

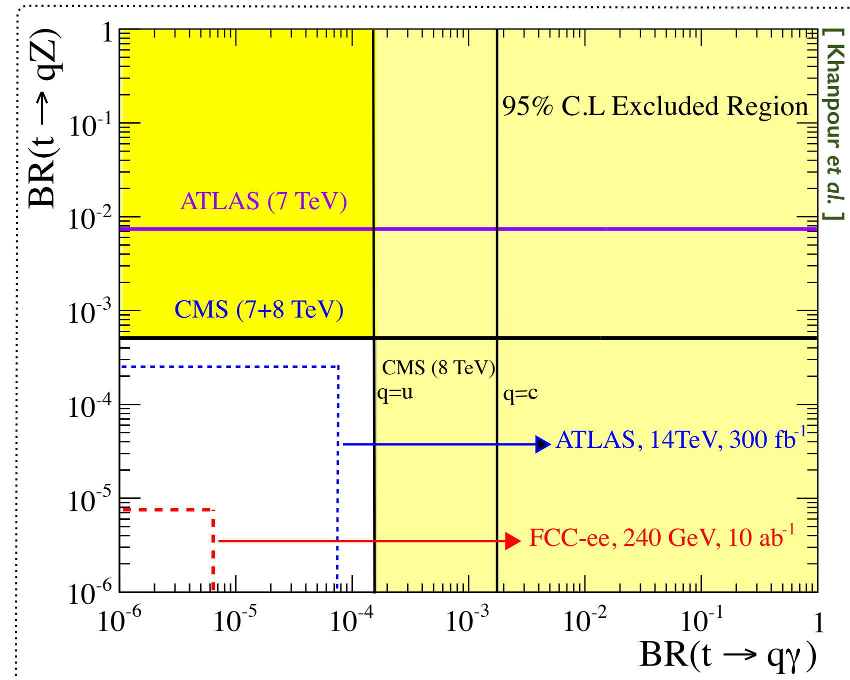
- The large statistics allows to improve significantly the measurement of the various **top couplings: g_{tWZ}, ttZ/ttγ**
- But **rare decays and FCNC** are the real gold mine (i.e. t->Zq, γq, Zc). The improvements come from:
  - large statistic at 350GeV in pair production
  - can profit of single top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

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}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

✦ FCNC production of a top and a light quark

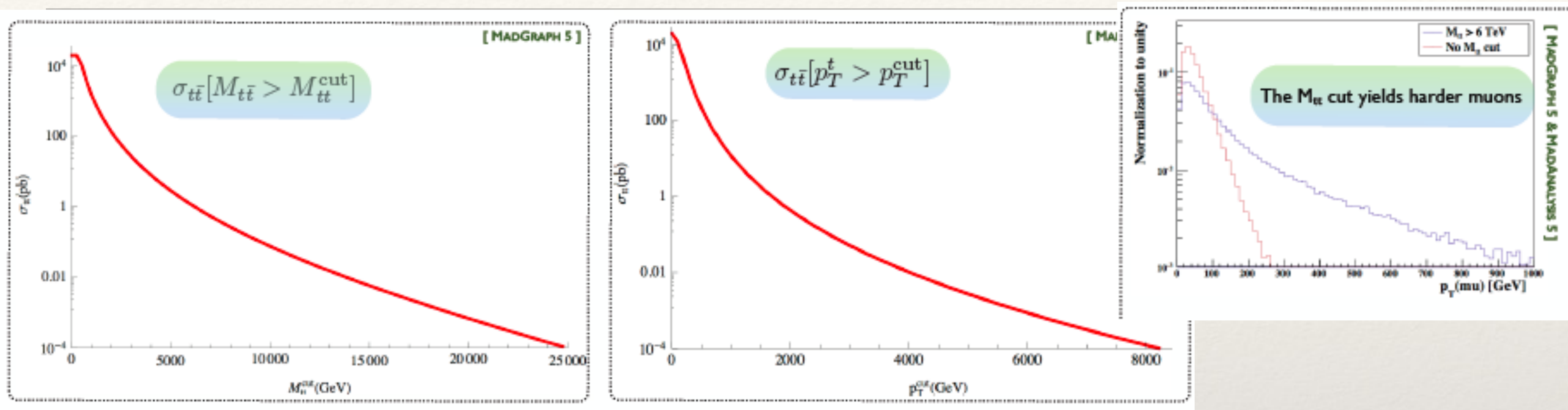
✤ At a center-of-mass energy of 240 GeV



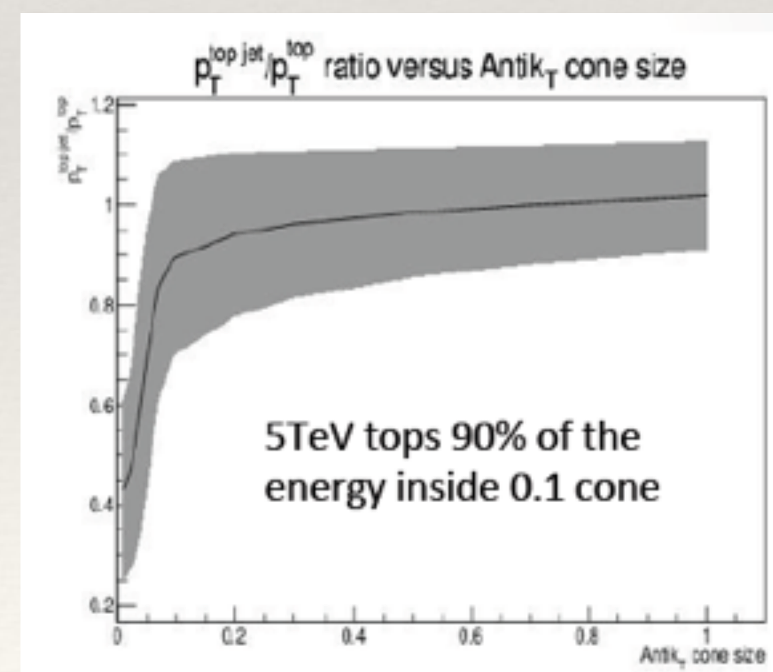
✤ Gain of 1.5 order of magnitude w.r.t. LHC

Easy way to find new physics signatures!

top physics @100 TeV

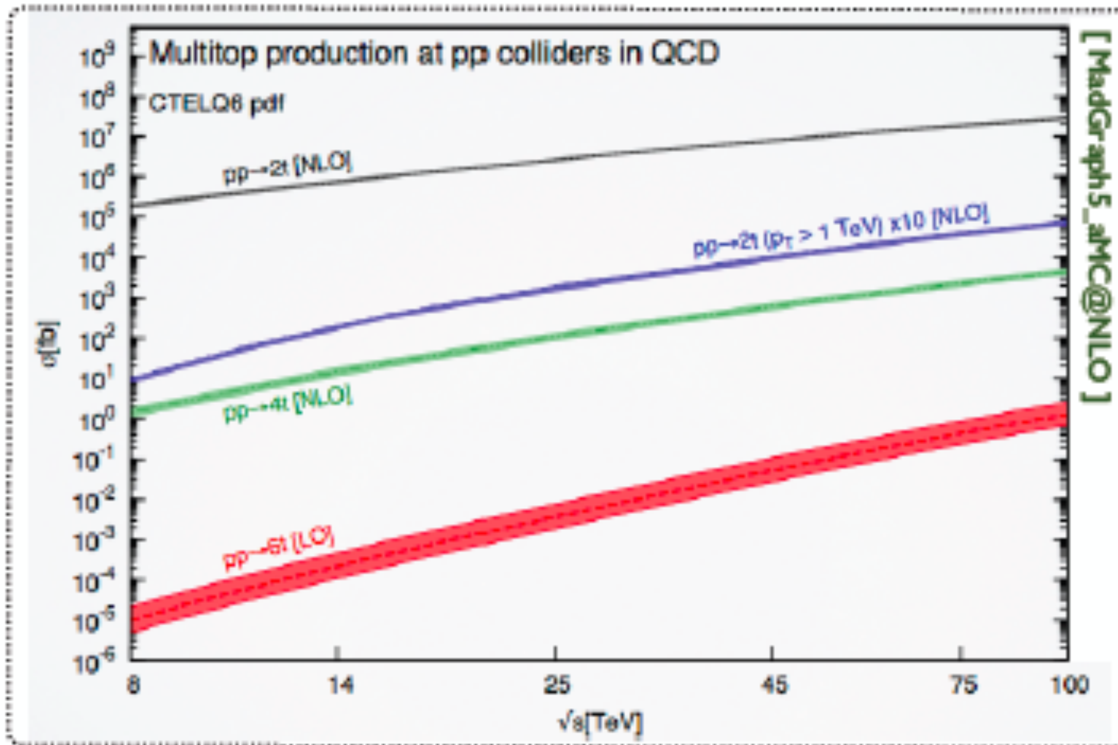


- Many produced top-antitop systems have a very large invariant mass
- Produced top(anti)quarks have a very large transverse momentum tails
  - Explore tagging of multi-TeV top!
- study mass resolution for resonance searches, define search potential (σBSM vs MBSM)



Opening the multi-top window

✦ Multitop hadroproduction

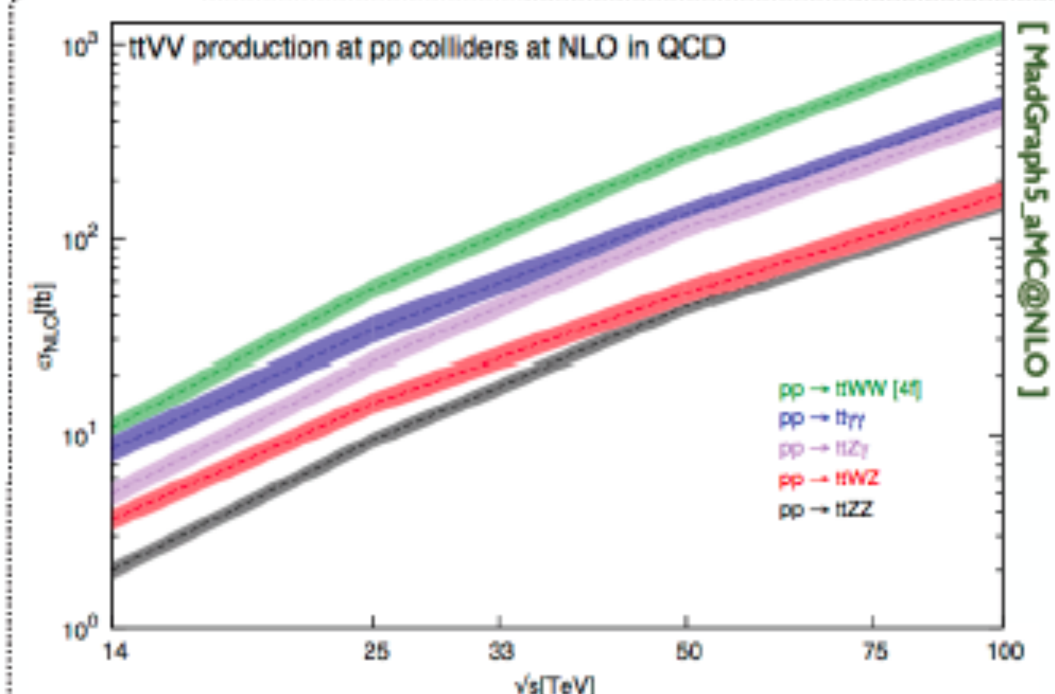


✤ 100 fb^{-1}: thousands of tttt events (≈5 with 300 fb^{-1} LHC collisions at 14 TeV)

✤ 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

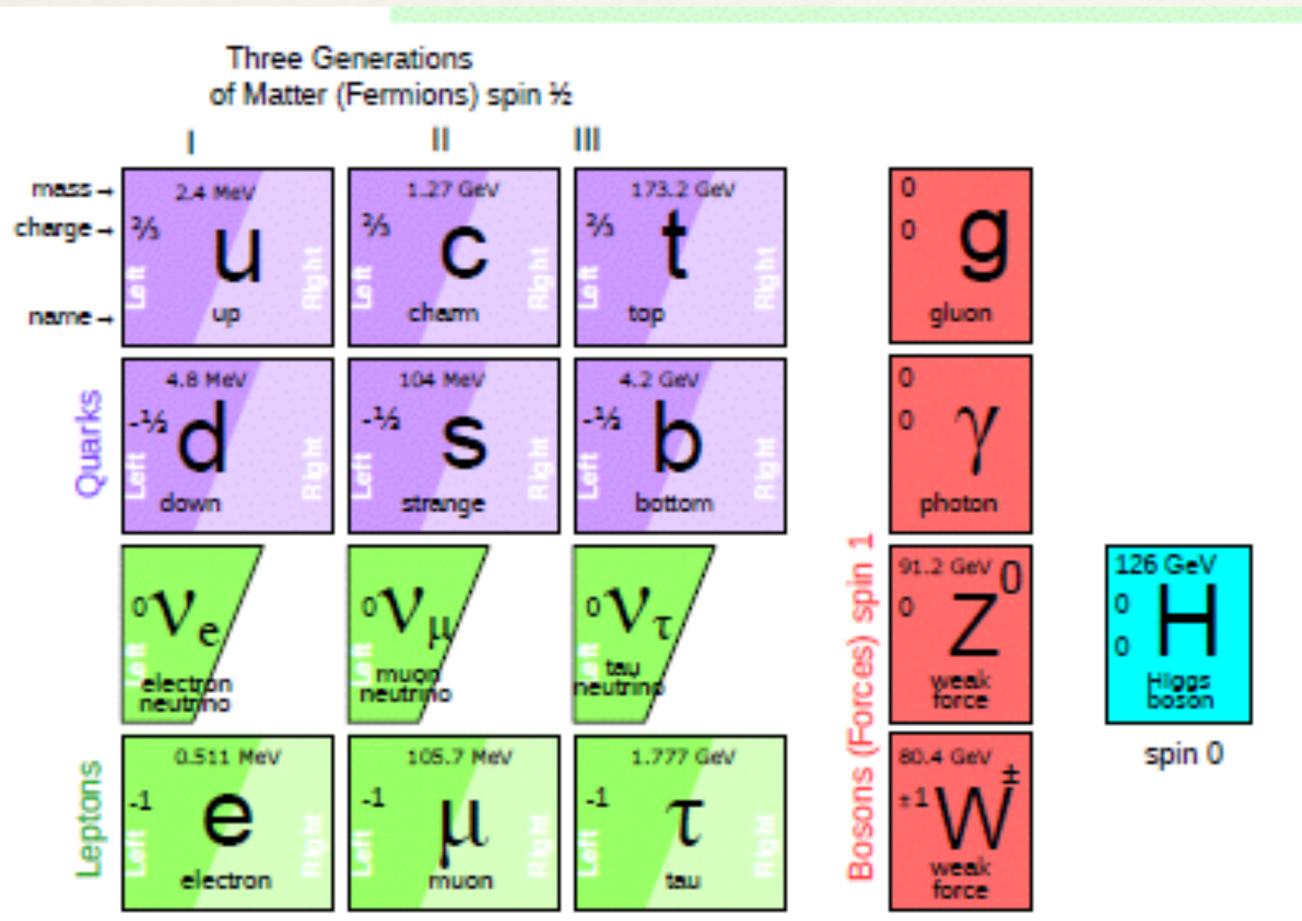
✤ Largest enhancement: ttWW production (≈10000 expected events for 100 fb^{-1})

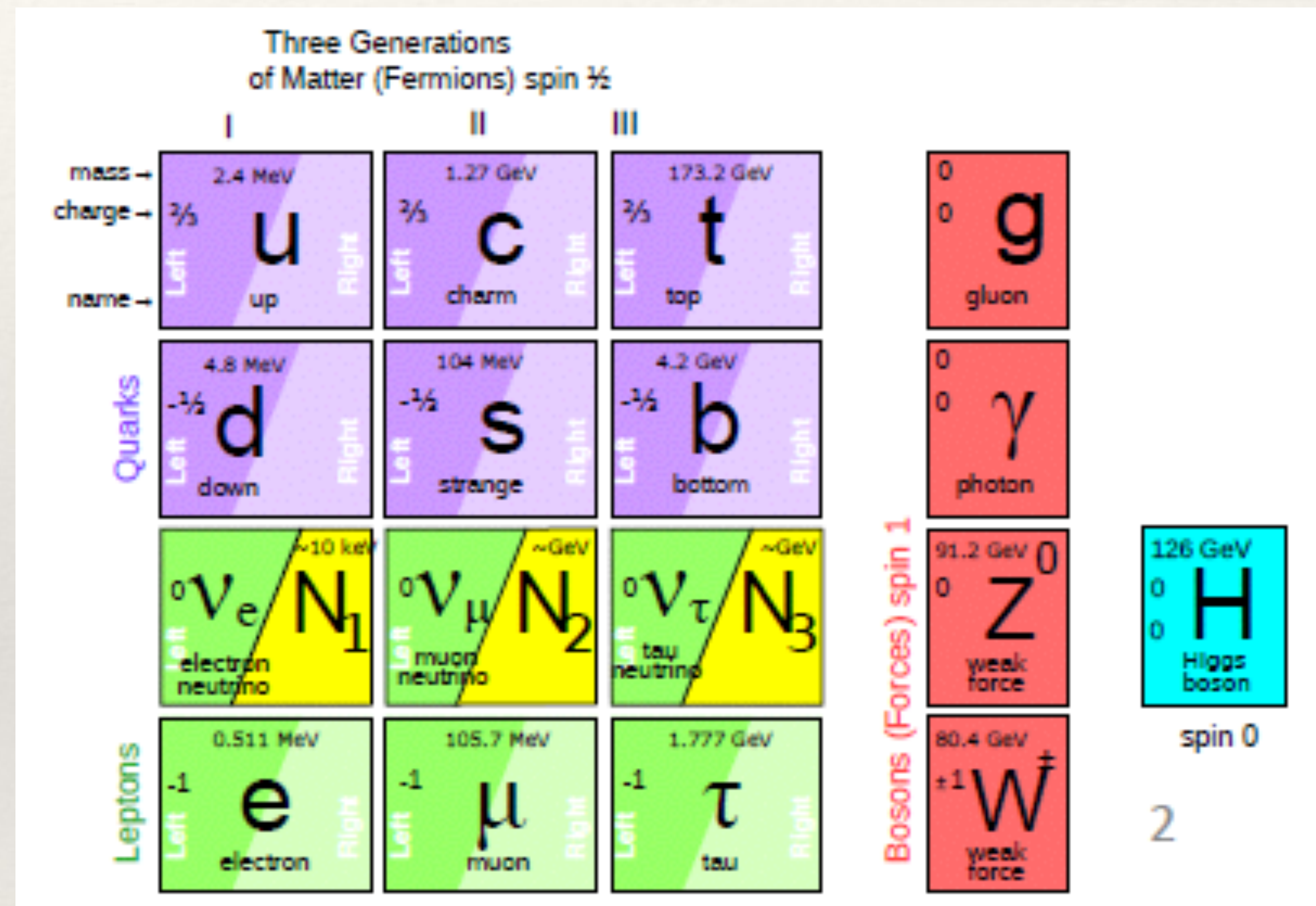
[Torrielli]

Discovery potential: The neutrino connection (1)

- New physics might not be heavy – only couplings may be very small
  - Example : three sterile right-handed neutrinos to complete SM (νMSM)

M. Shaposhnikov





- **Nearly impossible to find, but could perhaps explain it all !**

S. Lavignac

  - **Small m_ν (see-saw), DM (light N_1), and B.A.U. ($\nu N_{2,3}$ osc.)**
  - **Small deficit in Z invisible width (νN mixing), reactor anti-neutrino anomaly, …**

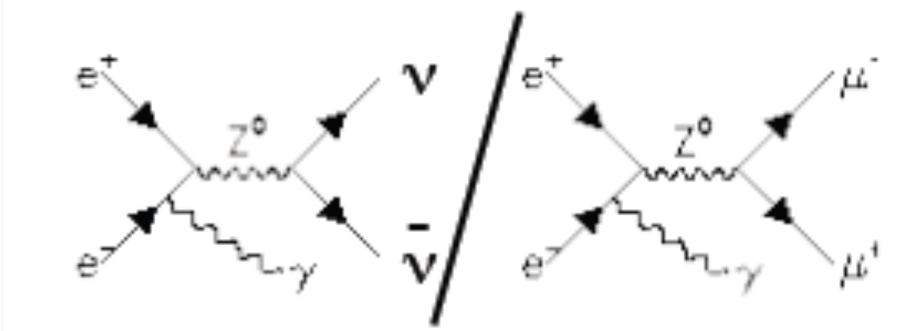
BSM Physics: Sterile Neutrinos ?

- **Number of neutrino families from LEP Nv=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:**

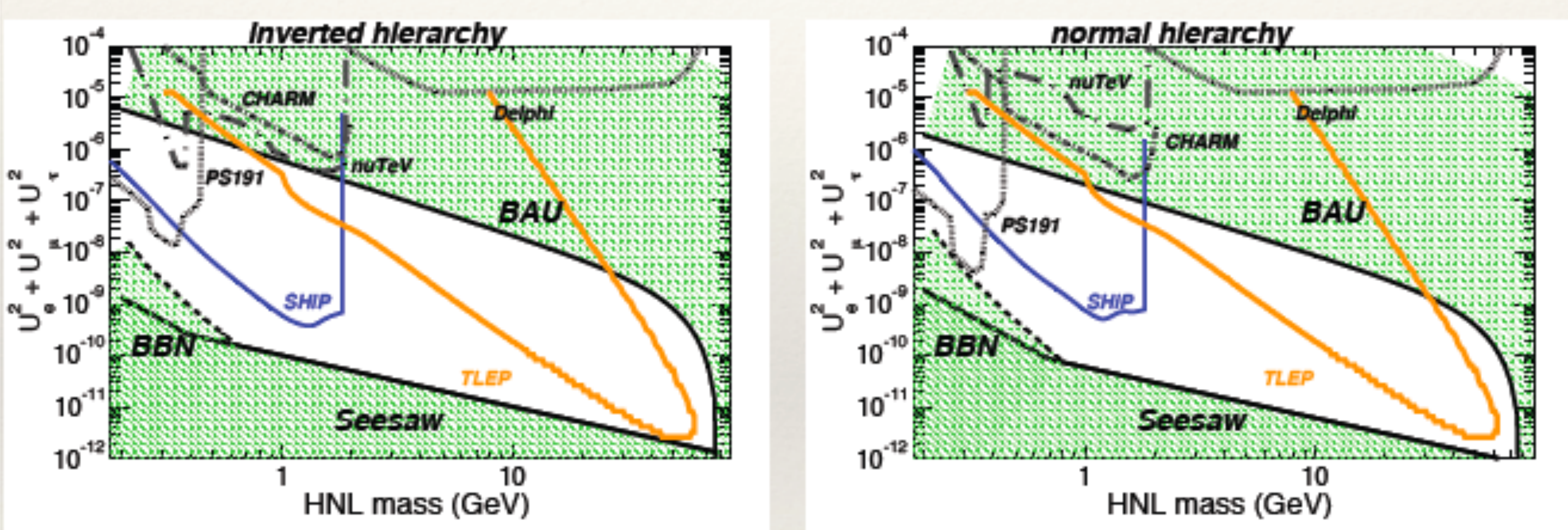
$$\boxed{Z \rightarrow N\nu_i,\ \text{with } N \rightarrow W^{*}l \text{ or } Z^{*}\nu_j}$$

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

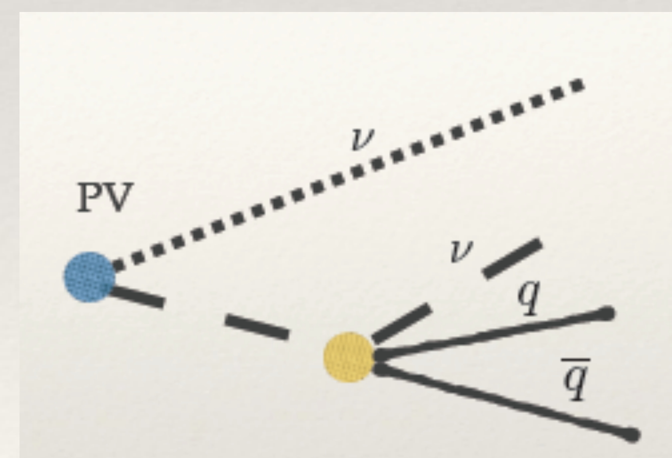
$$N_\nu \sim \sigma(e^+e^- \rightarrow \nu\bar{\nu}\gamma) \,/\, 2\sigma(e^+e^- \rightarrow \mu^+\mu^-\gamma)$$



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



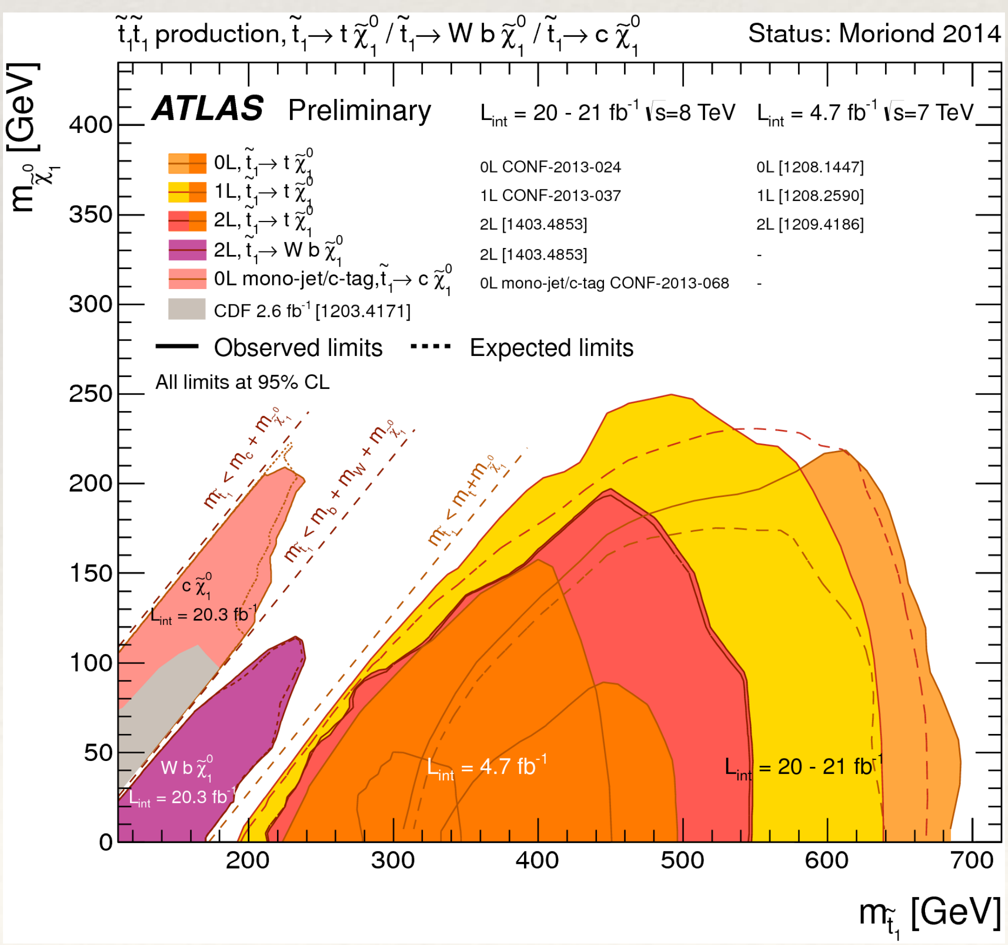
N. Serra 7th FCC-ee workshop

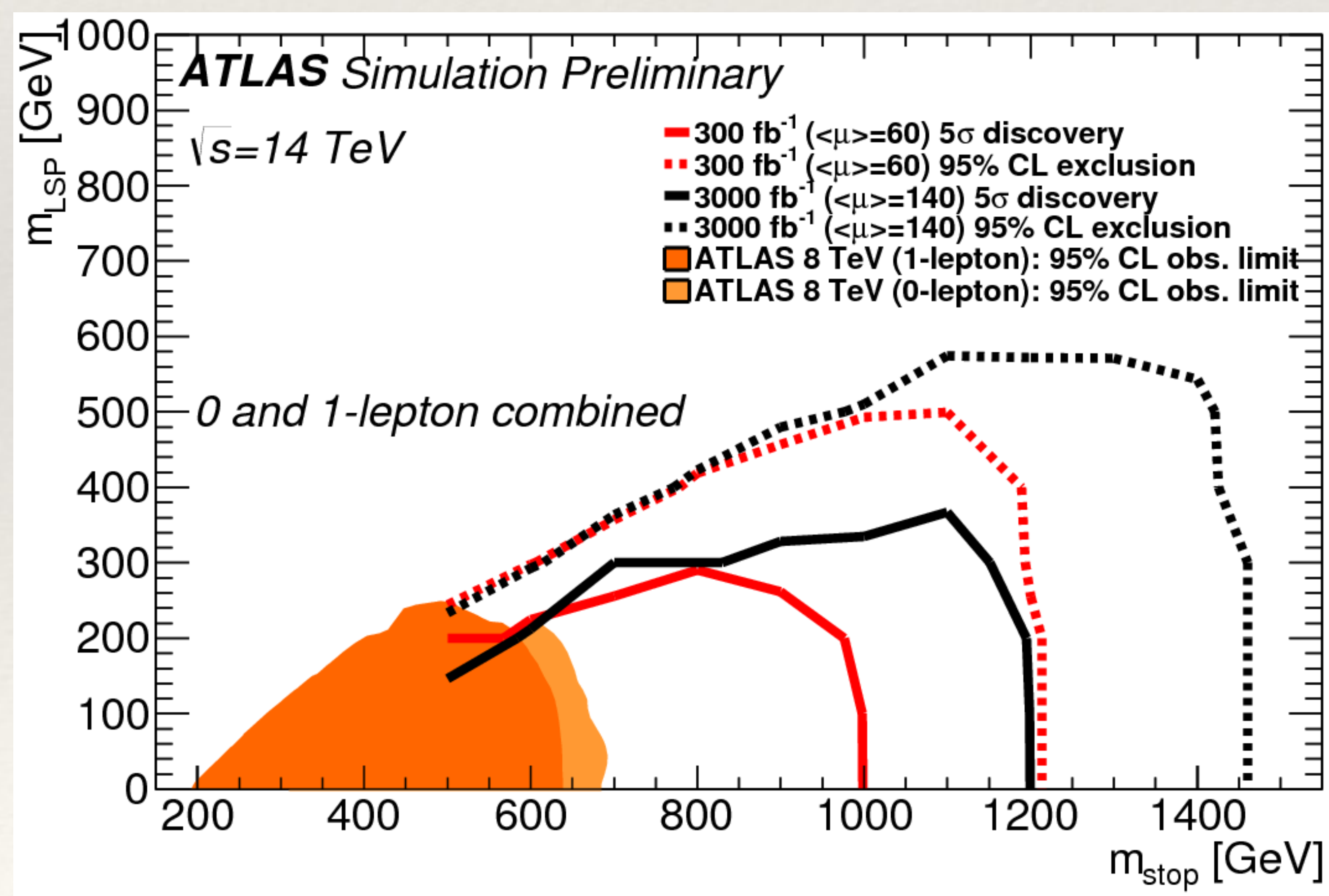


(Very) Displaced SV, detector challenge!

BSM Physics: Supersymmetry?

- one (my favorite) example: 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



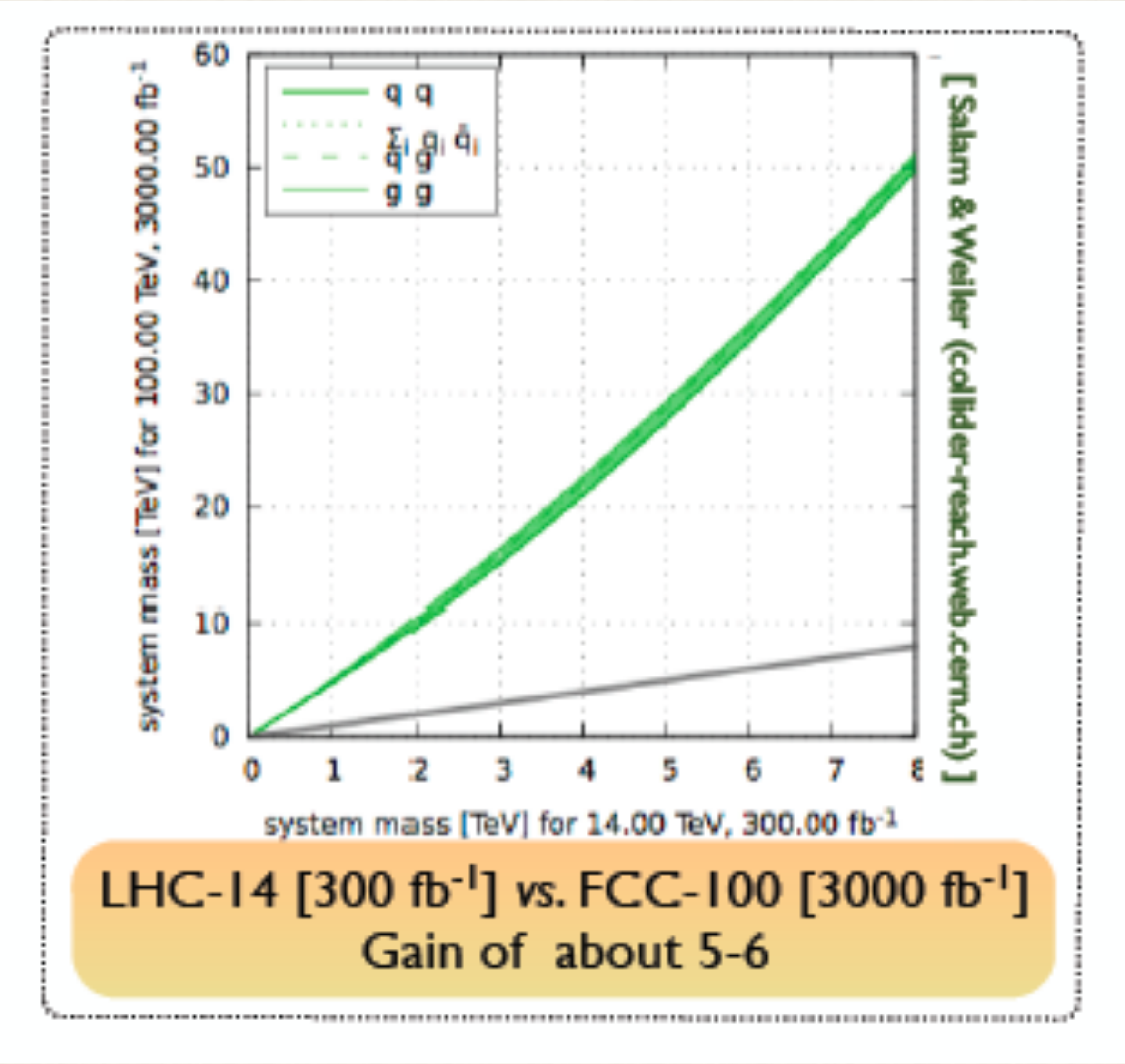


FCC-hh : Discovery opportunities

- Potential for new particle discovery : Rules of thumb
  - A factor ~5 in mass reach from LHC (14 TeV, 300 fb^{-1}) to FCC-hh (100 TeV,3 ab^{-1})
    - Then add ~1 to this factor for each increase of luminosity by a factor 10.

Based on parton luminosities

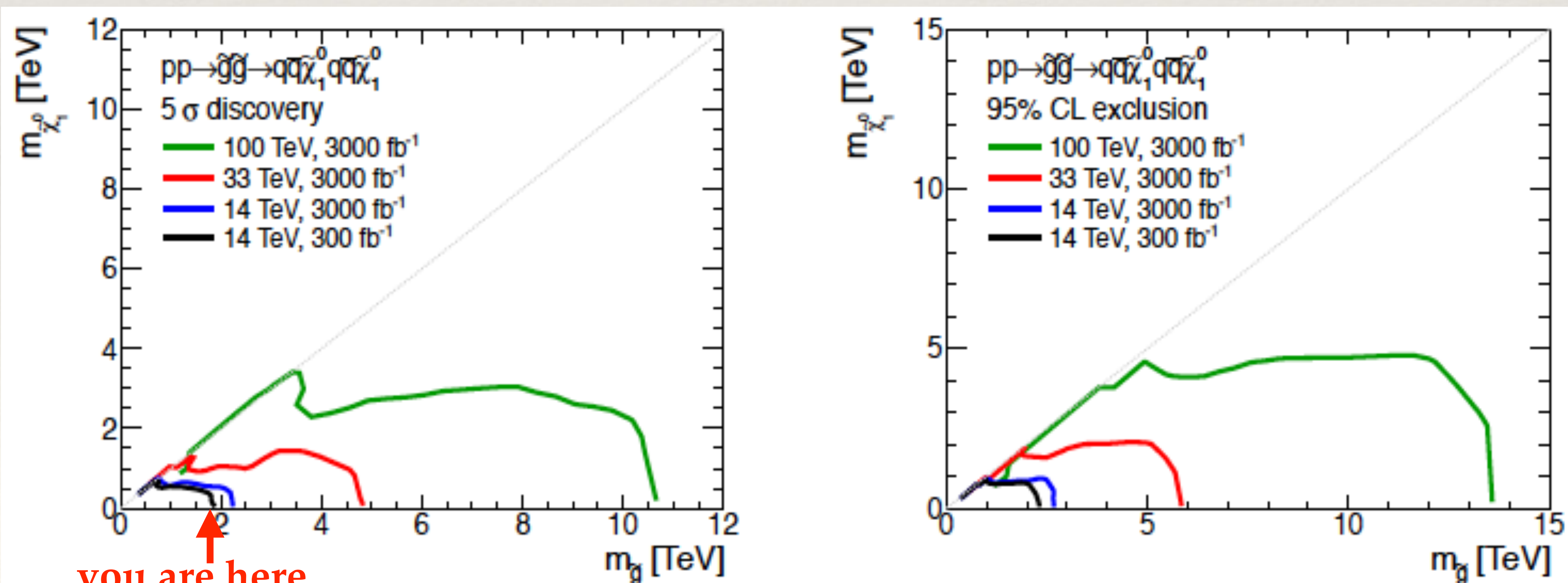
Particle	LHC, 300 fb^{-1}	FCC-hh, 3 ab^{-1}
Gluino	*2 TeV*	*11 TeV*
Stop	*1.2 TeV*	*6 TeV*
Z′, W′	*5 – 6 TeV*	*30 – 35 TeV*



- Comparison with CLIC-3TeV (Z’)
  - Direct: ~1.5 TeV
  - Indirect: ~15 TeV

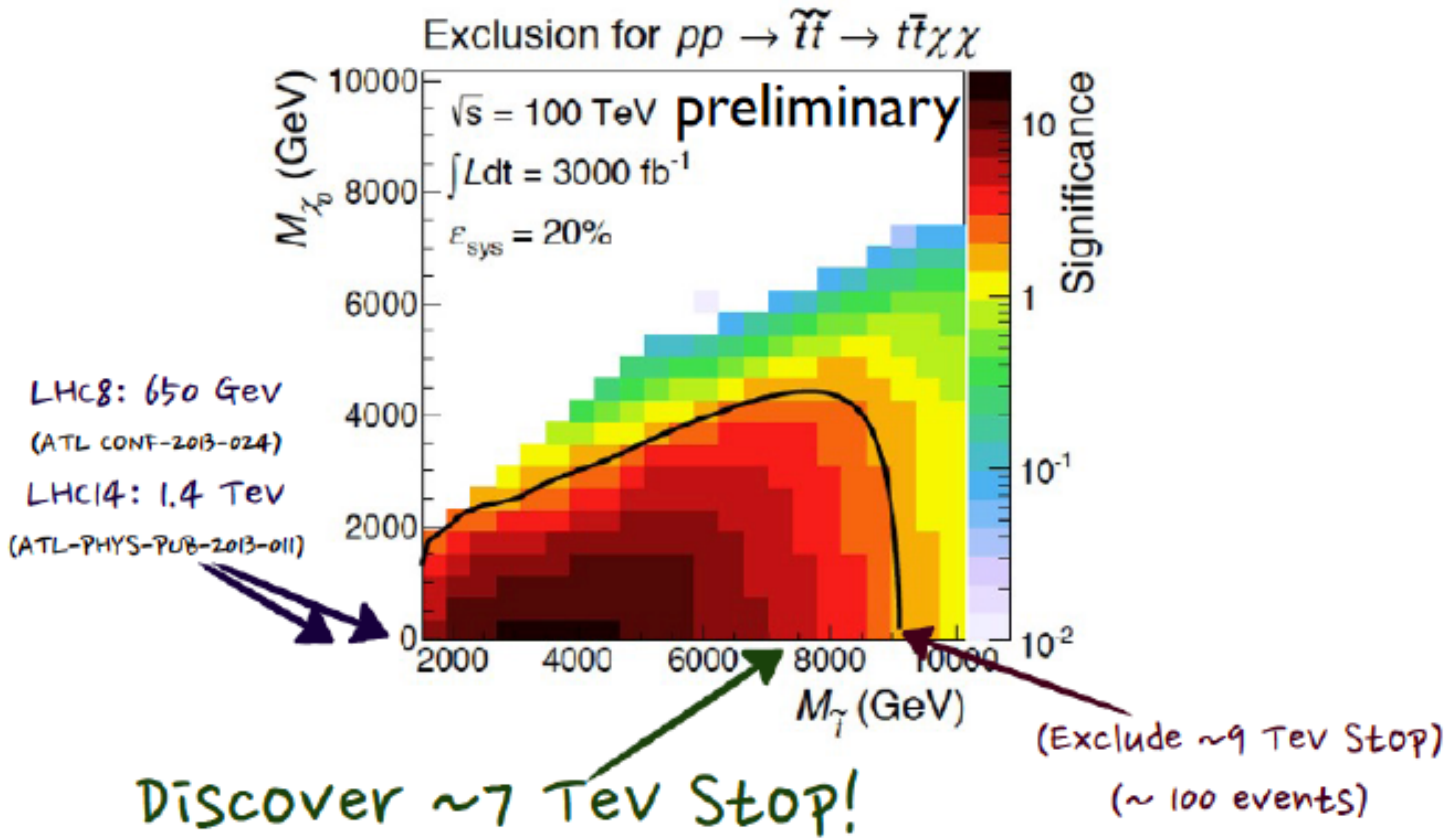
Supersymmetry @100TeV

- 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

Stops at 100 TeV



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 for precision on rare and (hopefully) new processes at higher energy with FCC-hh
  - If no new physics is found in Run2 of the LHC this program would allow to push further the boundaries of our knowledge.
- 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.

BACKUP INFORMATION

FCC-hh

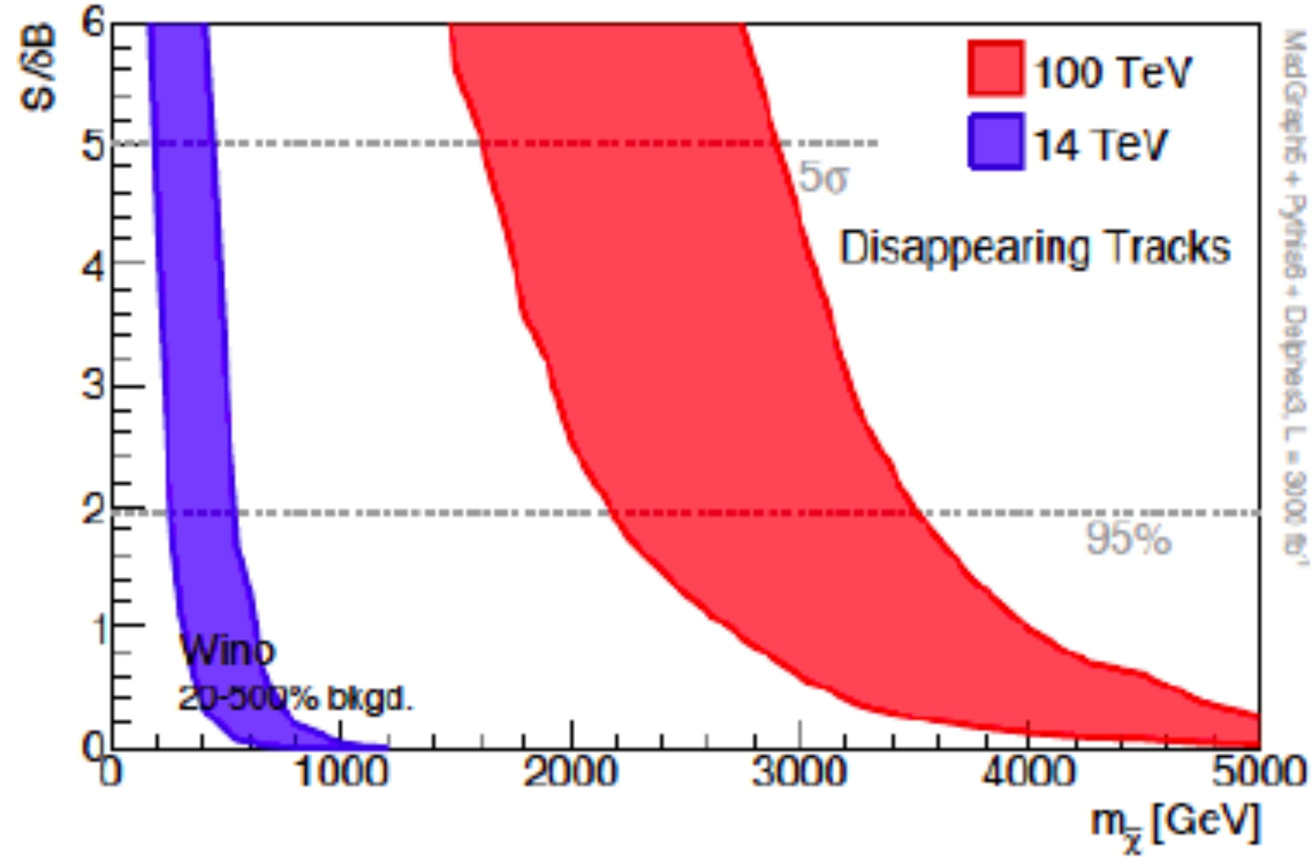
Dark Matter

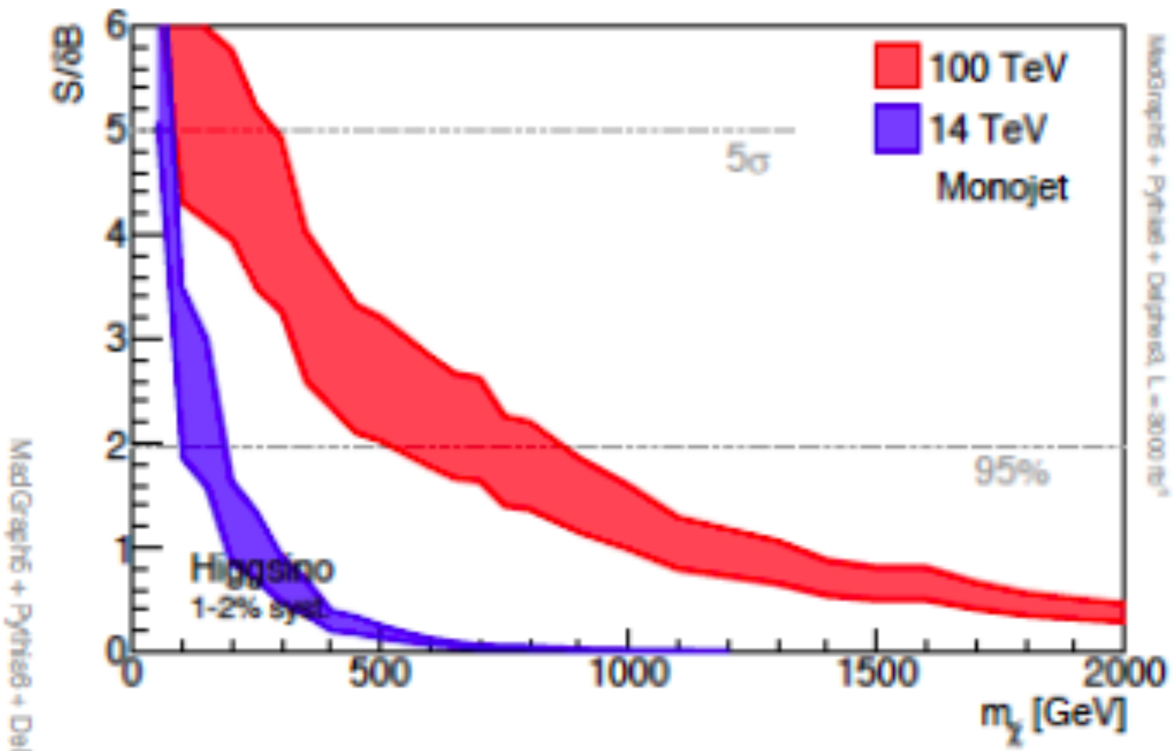
<u>DM overclosure upper limits:</u>

$M_{WIMP} < 1.8$ TeV $(g^2/0.3)$ $\Rightarrow$

wino: m≲3 TeV

higgsino: m≲1.1 TeV





Higgsino LSP

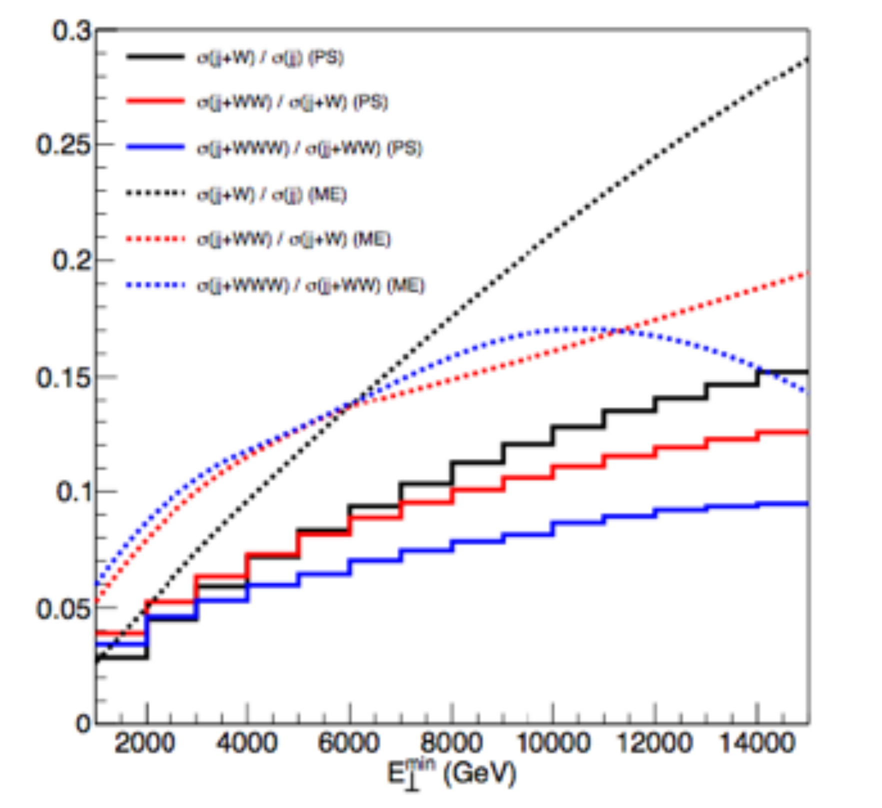
→ Wino case pretty much covered!

Wino LSP

L-T. Wang, FCC Kickoff preparatory workshop

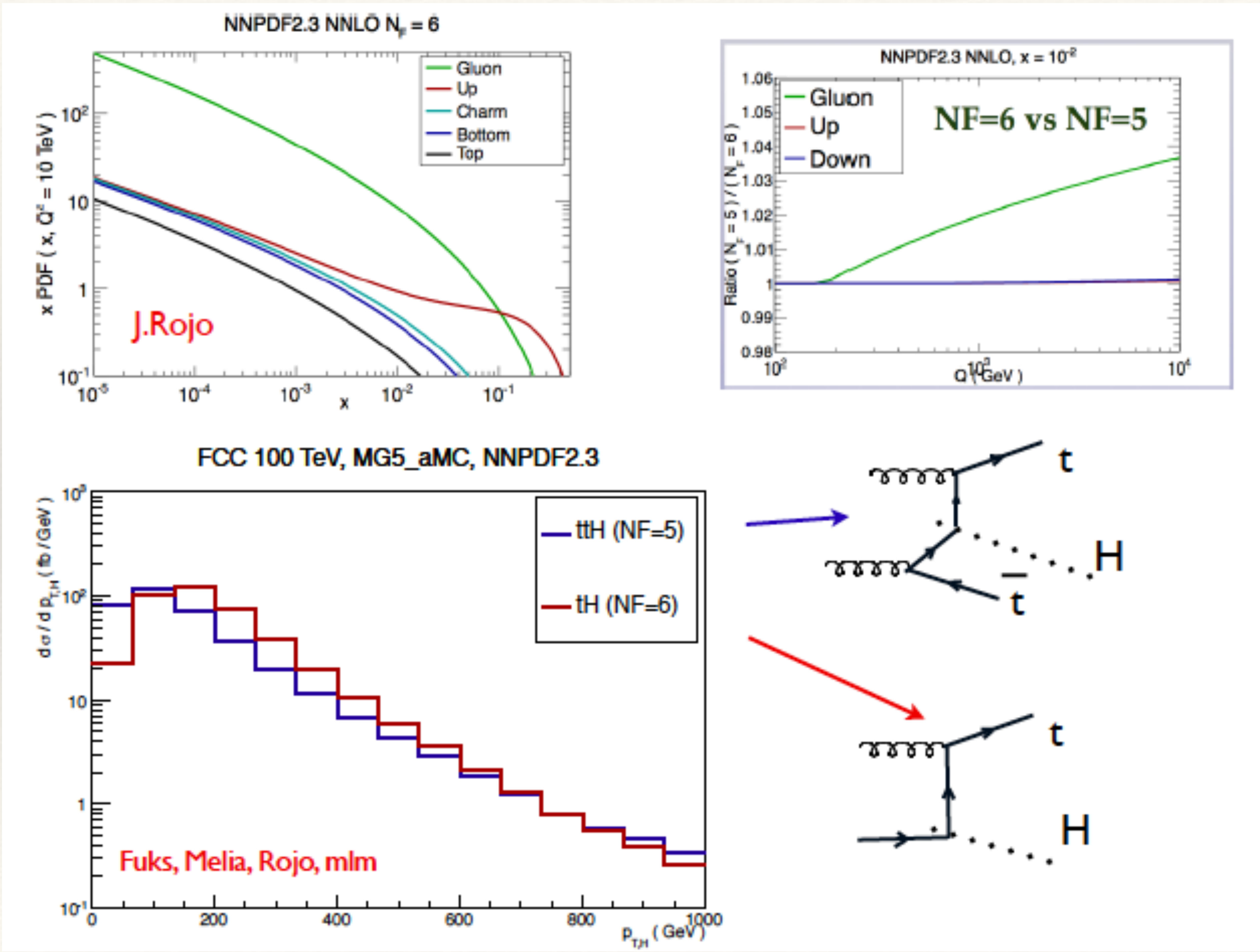
EW interactions at high energy

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!

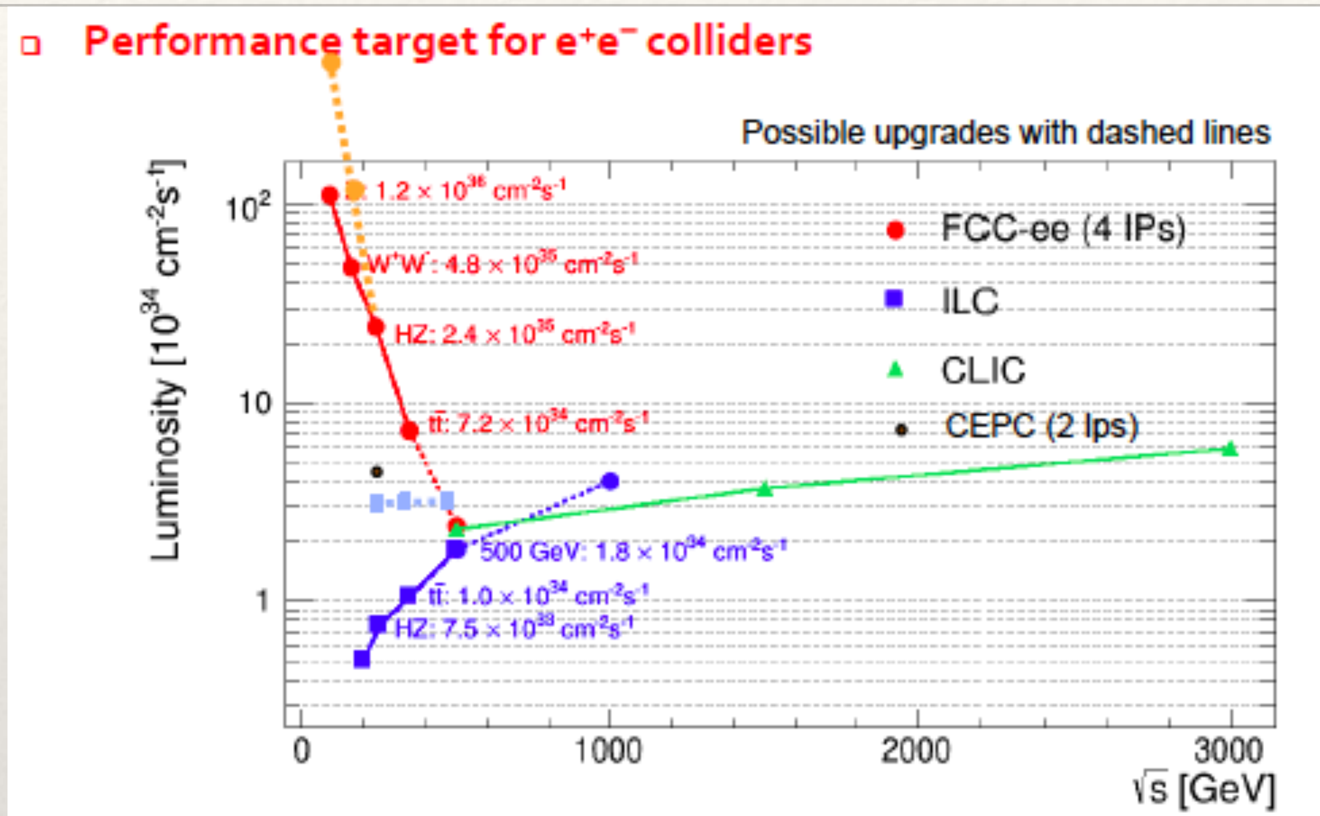
Access the top PDFs

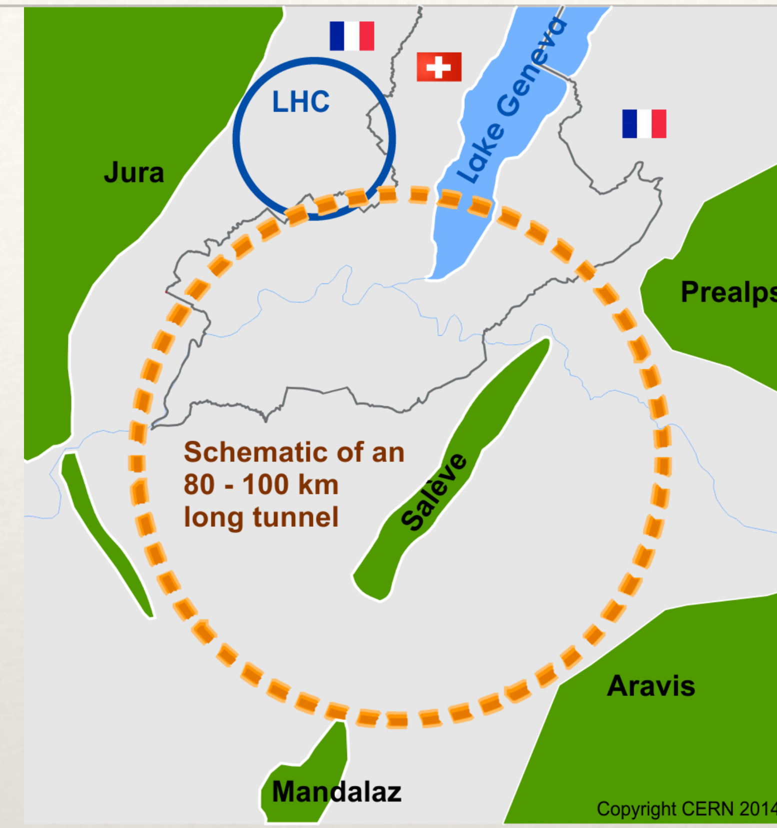


An historical perspective

- 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

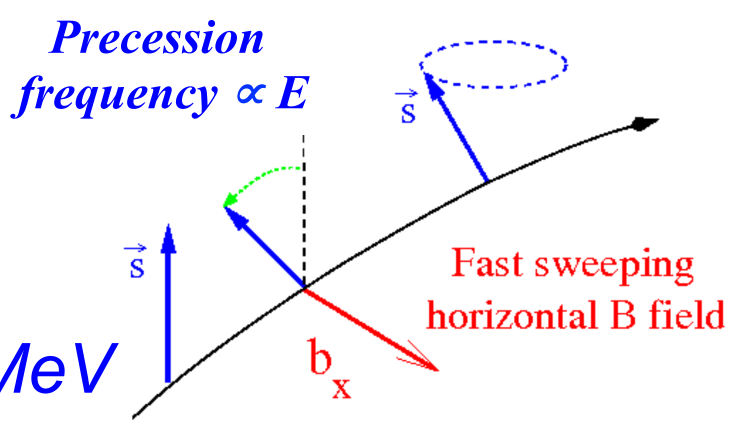
- if new physics scale at 1TeV

	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 $\mathbf{M_Z}$, $\mathbf{\Gamma_Z}$, $\mathbf{M_W}$
  - *Nice feature of circular machines, δM_Z, $\delta \Gamma_Z$ ~ 0.1 MeV*



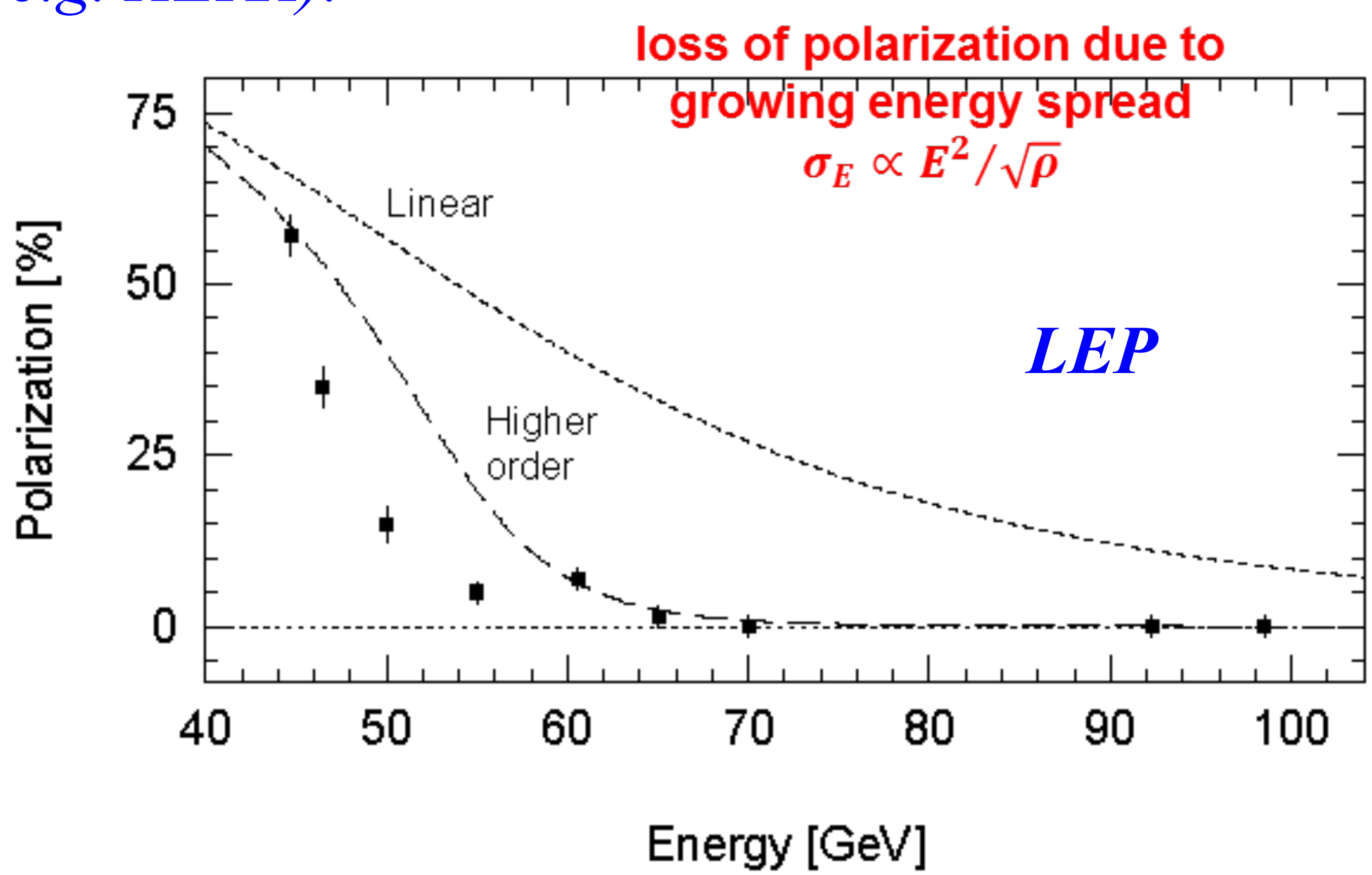
- Physics with longitudinally polarized beams.
  - *Transverse polarization must be rotated in the longitudinal plane using spin rotators (see e.g. HERA).*

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

W decays

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

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

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

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

- SM inclusive decays -- Examples:

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

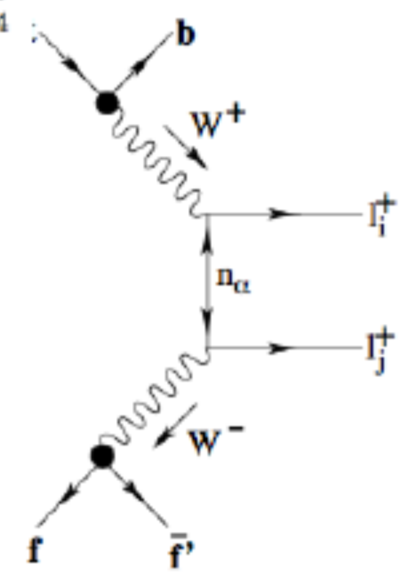
- BSM decays -- Are there interesting channels to consider?

-- 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,¶]

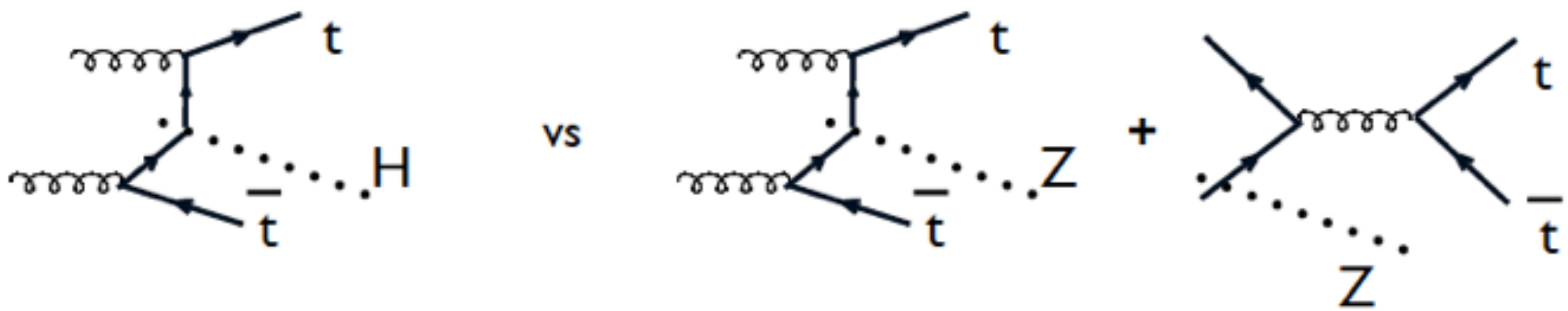


ttH <1%

Example: Top Yukawa to sub-% precision ?

MLM, J.Rojo
in preparation

pp→tt H vs pp→tt Z

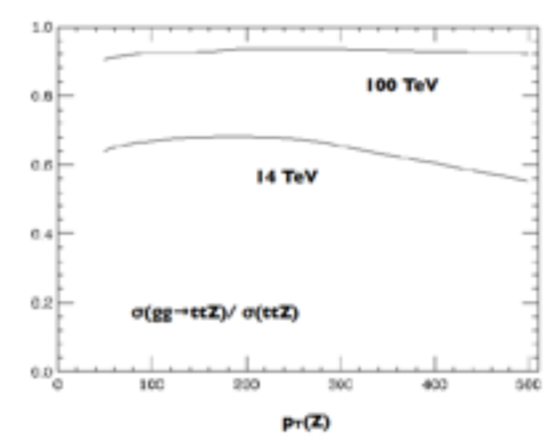


To the extent that one can neglect the qqbar → tt Z contribution:

- **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**

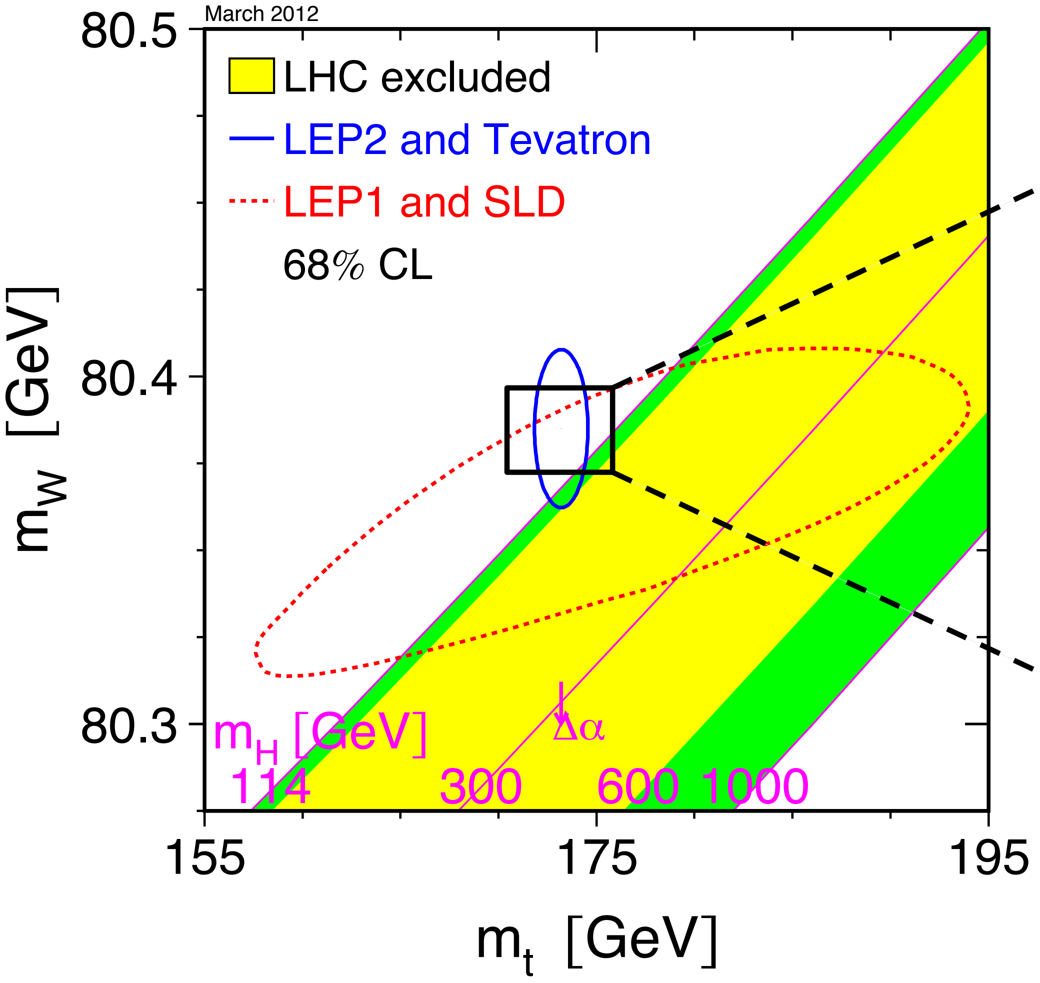
For a given y_{top}, σ(ttH)/σ(ttZ) can be predicted theoretically with a sub-% precision

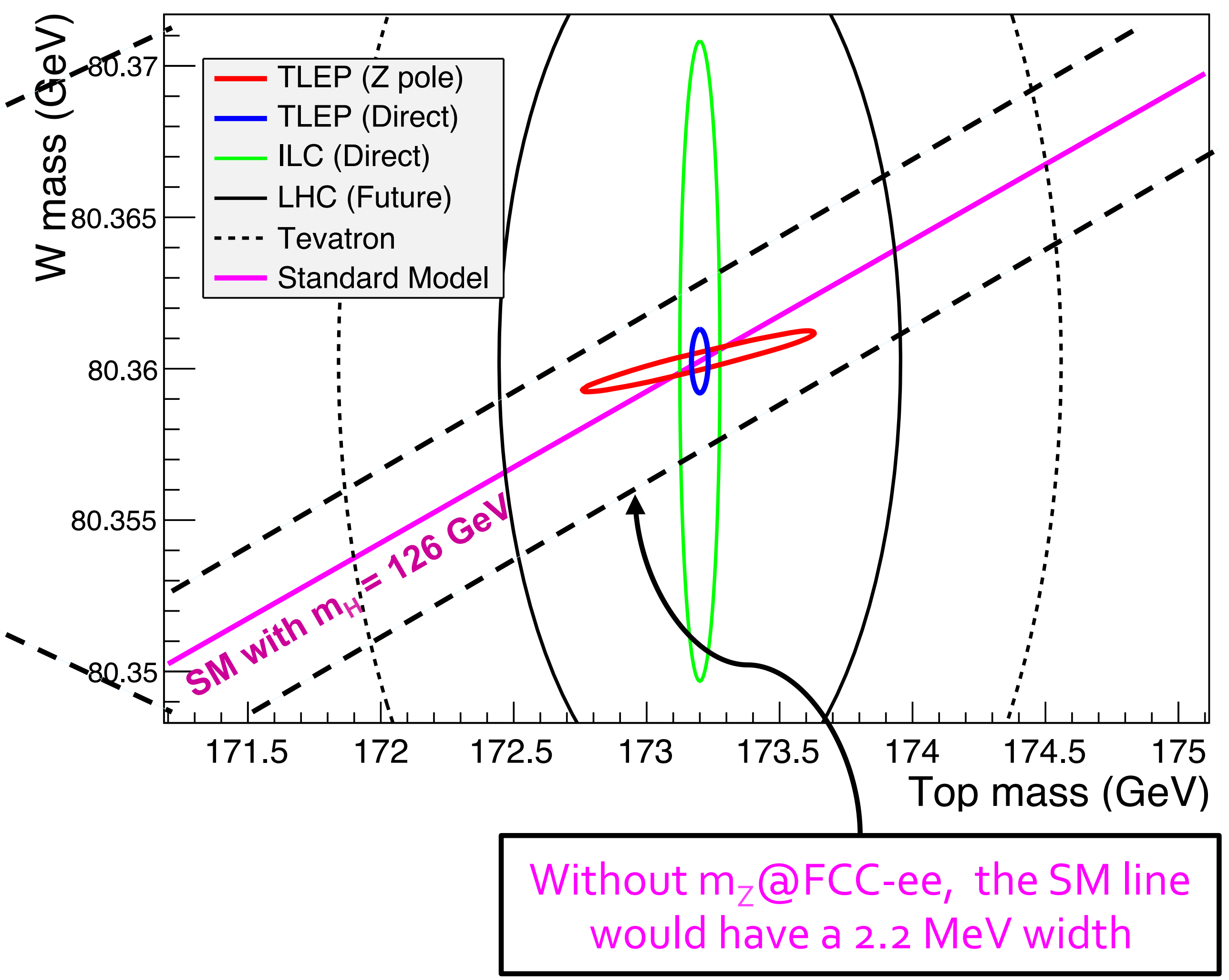
At 100 TeV, gg→ttZ is indeed dominant ....



Precision electroweak physics at FCC-ee (10)

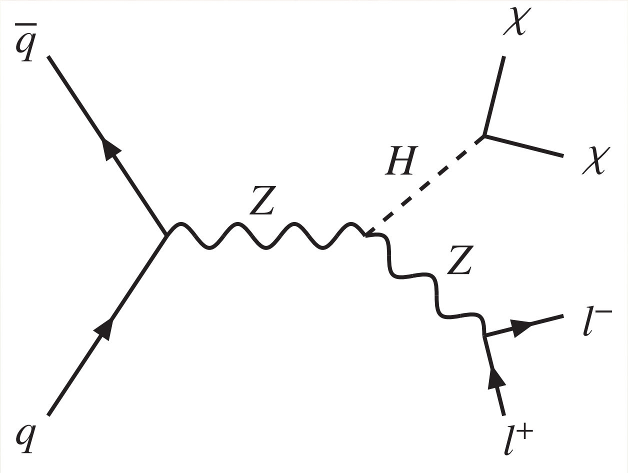
- **Comparison with potential precision measurements at linear colliders**
  - **Beam energy measurement (compton back-scattering, spectrometer) to ~10^{-4}**
    - **m_Z and m_W not measured to better than 5-10 MeV at ILC**
      - **➡ In absence of new physics, the (m_{top}, m_W) plot would look like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

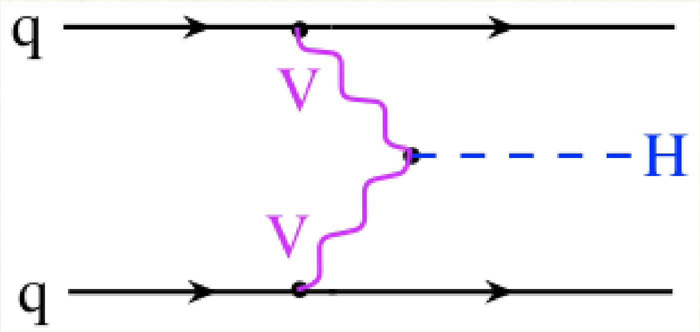




- **Constraints on new physics ?**

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

$g_{HHH} = 3\, m_H^2/v$