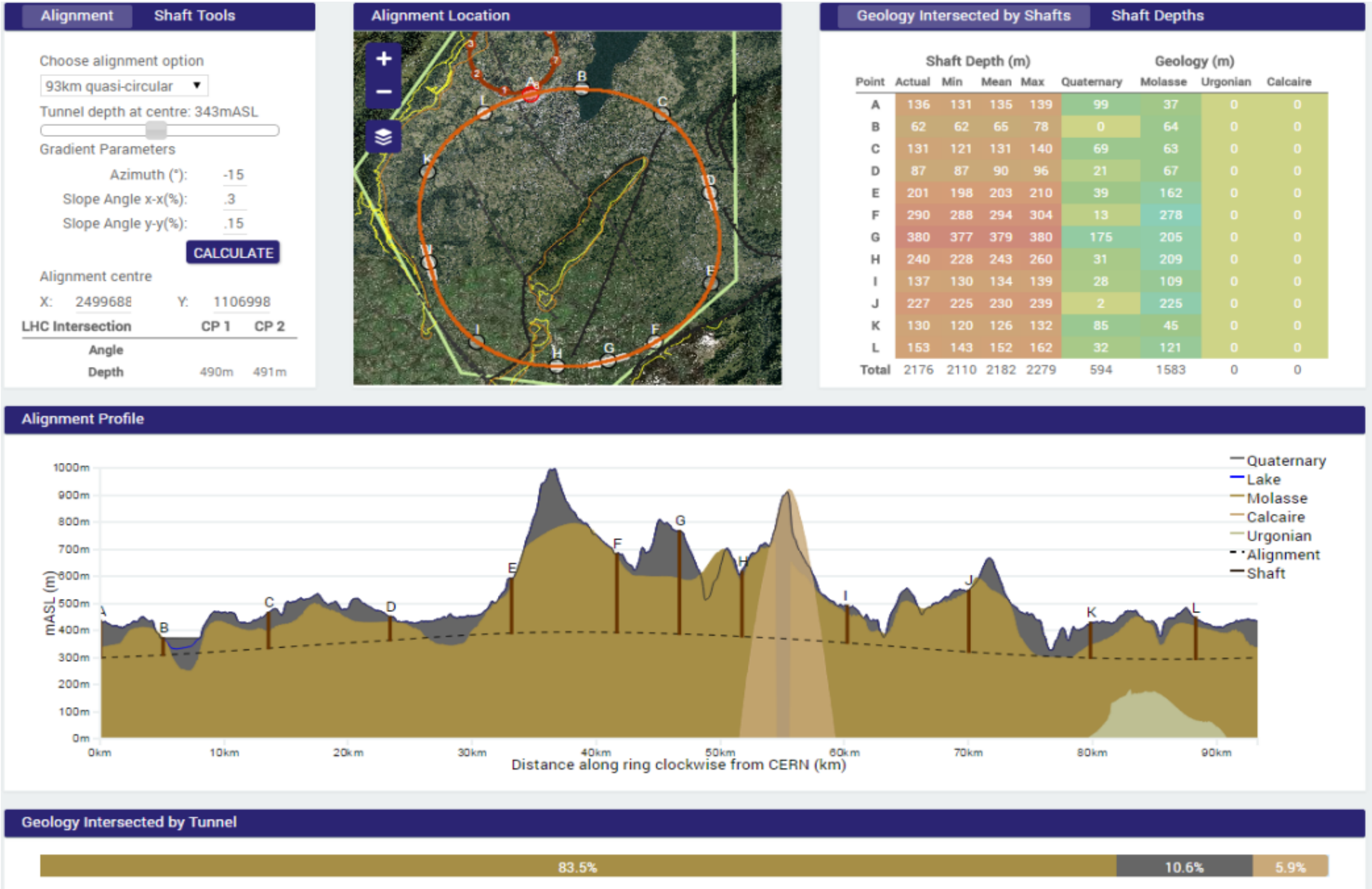
FCC_hh: the physics program



	Shaft Depth (m)				Geology (m)			
Point	Actual	Min	Mean	Max	Quaternary	Molasse	Urgonian	Calcaire
A	136	131	135	139	99	37	0	0
B	62	62	65	78	0	64	0	0
C	131	121	131	140	69	63	0	0
D	87	87	90	96	21	67	0	0
E	201	198	203	210	39	162	0	0
F	290	288	294	304	13	278	0	0
G	380	377	379	380	175	205	0	0
H	240	228	243	260	31	209	0	0
I	137	130	134	139	28	109	0	0
J	227	225	230	239	2	225	0	0
K	130	120	126	132	85	45	0	0
L	153	143	152	162	32	121	0	0
Total	2176	2110	2182	2279	594	1583	0	0

Main ingredients/questions

1. Could we understand the dynamics of the Electroweak Symmetry Breaking?

2. Search for physics beyond the Standard Model using precision measurements of the Standard Model particles.

3. Could we interpret the bariogenesis as a sub-product of the cosmological Electrowek phase transition?

4. Search for physics beyond the Standard Model looking for new massive particles or new interactions.
   A "natural solution" for the hierarchy problem?

5. Is TeV scale dynamics (i.e. WIMPS) at the origin of Dark Matter?

Assumption: The “dream” scenario.

1. FCC-hh starts 5y after FCC-ee yielded fantastic precision measurements on Higgs couplings, top and W mass +…..
2. FCC-ee and FCC-hh run in parallel.
3. Integrated luminosity for FCC-hh: 3-10ab^{-1}.

Disclaimer

No mention of HI, fixed target experiments and many other opportunities (including physics with the injectors) to perform marvelous physics measurements at FCC-hh.

The Standard Model
or
"The Theory"?

With the inclusion in the Standard Model of a 125GeV Higgs boson, for the first time in history, we have a description of nature that could be consistent up to very high energy.

A light boson, could in principle rule its self-interactions and the Yukawa interactions with fermions in such a way that the theory could remain weakly coupled up to the Planck scale without any dynamics appearing beyond the EWK scale.

If we could be able to prove it, this would be in itself an outstanding discovery: for the first time we could describe nature with a theory that remains valid over 15 orders of magnitude in energy.

In this scenario we should definitely change the name and use instead "The Theory"

Too early tough!

The Higgs boson: a source of a new set of questions

- What's the real origin of the Higgs potential, which breaks EW symmetry?
  - underlying strong dynamics? composite Higgs?
  - RG evolution from GUT scales?
  - Are there partners of the Higgs (e.g. $H^{\pm}$, A^0, $H^{\pm\pm}$, ... , EW-singlets, ...)

- The hierarchy problem: what protects the smallness of m_H / $m_{Plank,GUT,...}$?

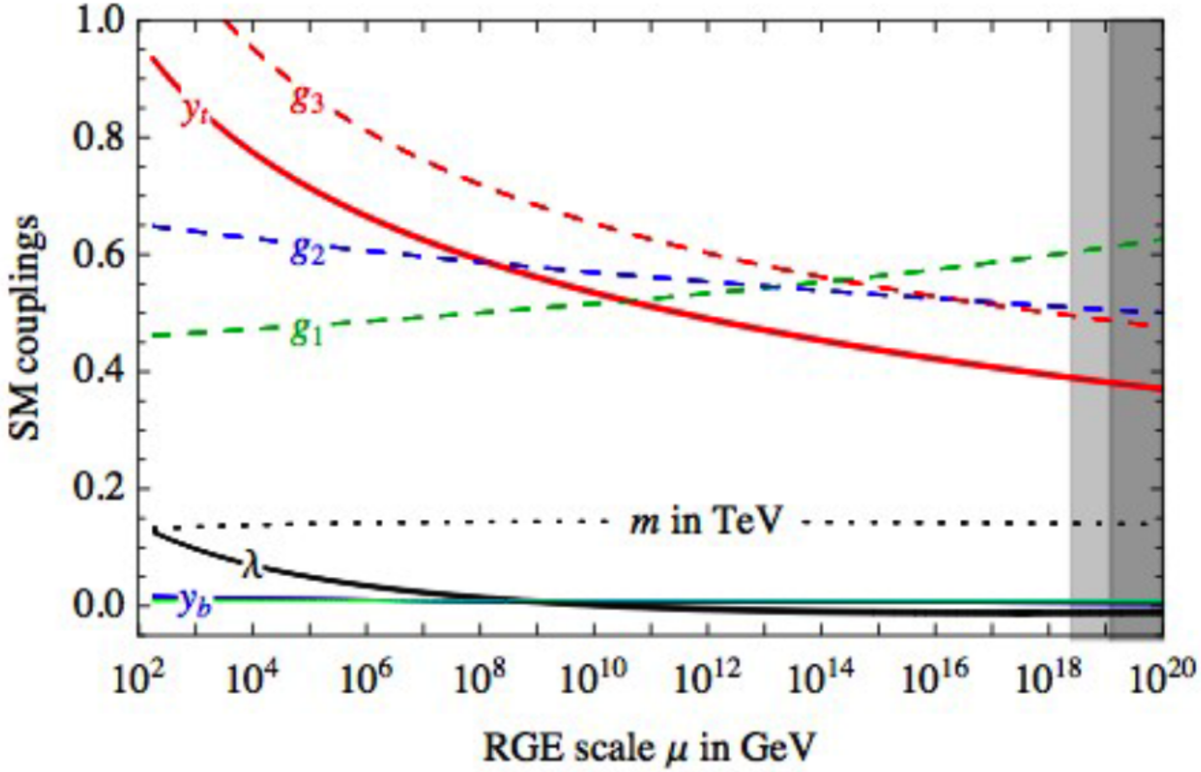
- Is there a relation between Higgs, EWSB and Dark Matter?

- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?
  - does the PT wash out possible pre-existing baryon asymmetry?
  - is there a relation between baryogenesis and DM?

MLM FCC Kick-off Meeting

Can we live without new physics?

Buttazzo et al '13



Can the SM (without new physics)
be valid up to M_{Pl} and remain weakly coupled?

Christophe Grojean Precision Frontier @ High Energies 6 Geneva, Feb. 12, 2014

Why 100TeV?

Fully understand the dynamics of the EWSB

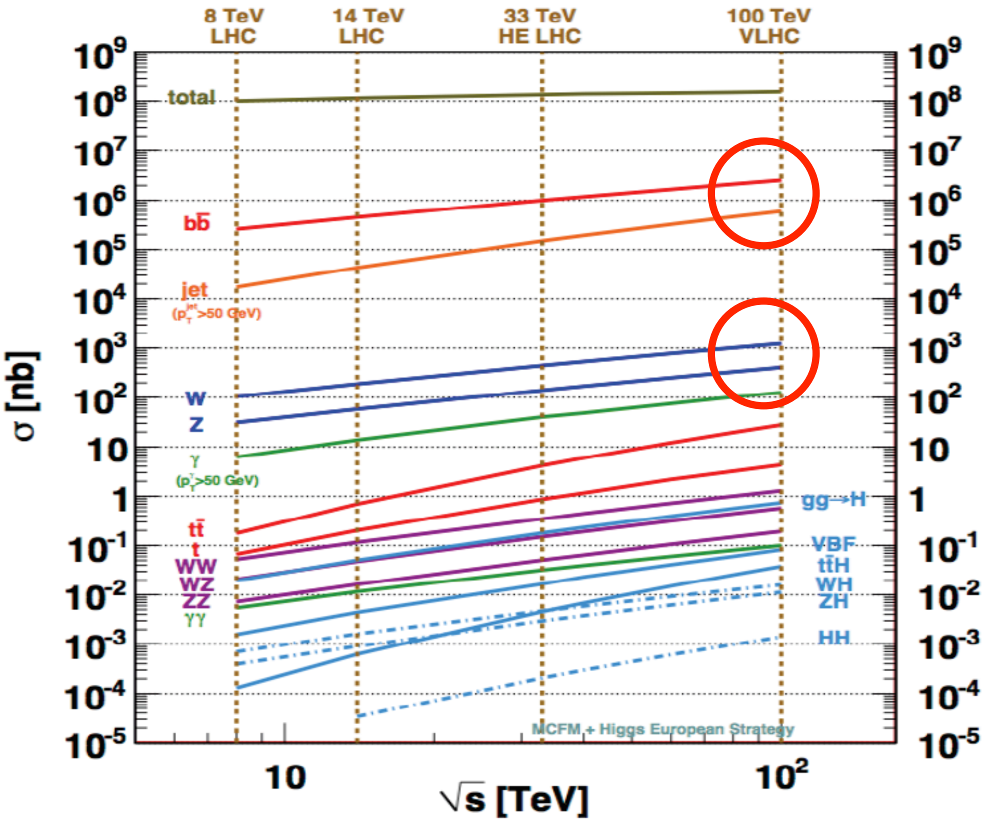
Direct access to the EW theory in the unbroken regime $\sqrt{s} \gg v = 246$GeV.

- **Probing the unitarization of WW scattering at m(WW)>>TeV**
  What is the underlying dynamics? Weakly or strongly interacting?

- **Explore the dynamics well above EWSB**
  Other interactions? Other particles beyond the SM Higgs?

"Fatti non foste a viver come bruti ma per seguire virtute e canoscenza"
Dante Alighieri
Inferno CantoXXVI

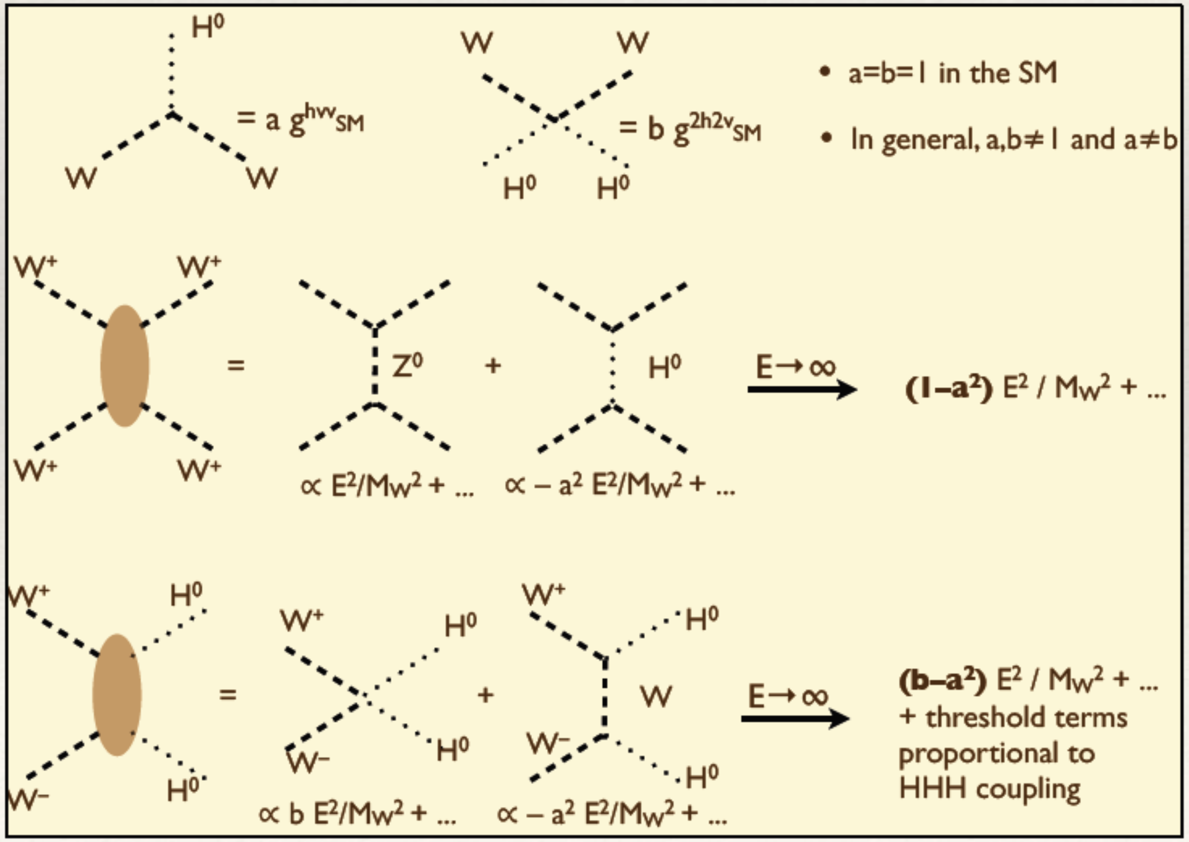
“Bread&butter”@100TeV

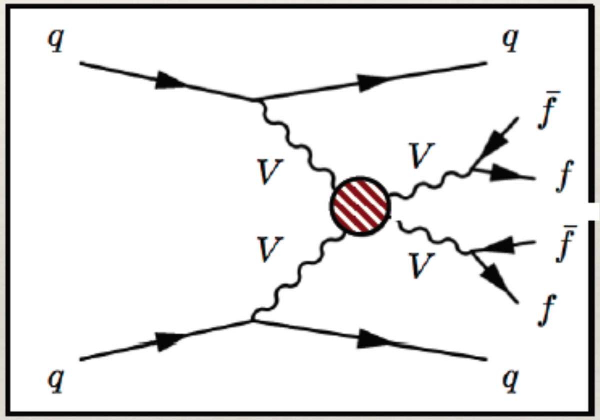


- QCD jets up to 25-30TeV: running of α_s
- Explore quark compositeness up to 140TeV!
- Off-shell W and Z production above 10TeV DY mass→ measurement of the running of the EW couplings (sensitive to new weakly-interacting particles).

WW scattering @ very high energy

In the SM the Z and H exchange diagrams diverge but cancel exactly each other.
Any anomaly in the couplings (parametrized as **a** and **b**) would have dramatic effects
The total WW scattering/Higgs pair cross section would diverge with the fourth power m^4(WW,HH).





Precision on **a** and **b**:

~30% at HL-LHC 14 TeV

~1% with FCC-hh 100 TeV

Precision on **a**:

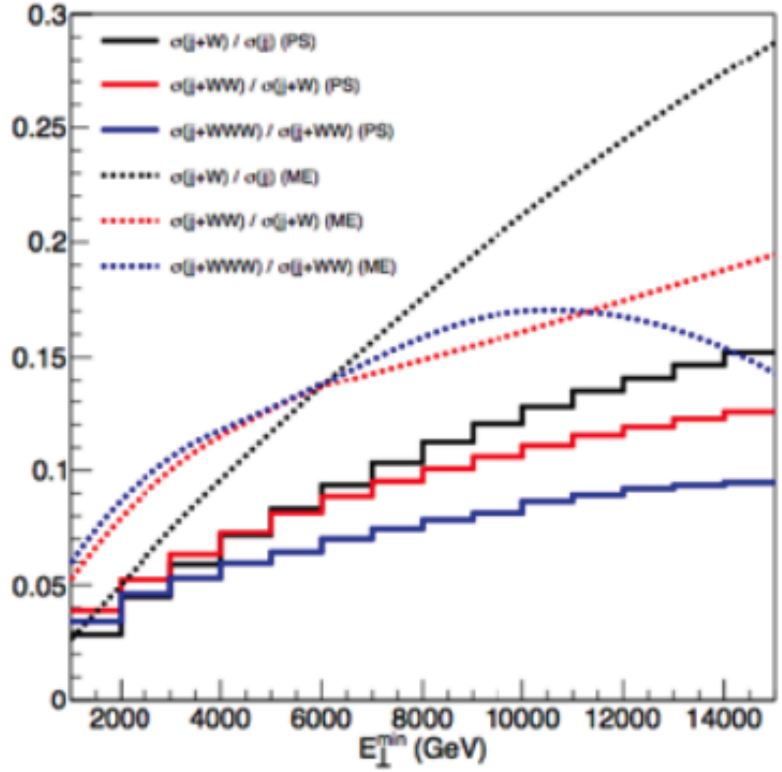
~1% with ILC

~ 0.1% with FCC-ee

Electroweak interactions at high energy

Large statistics of multiboson events.
Significant signals also in the high mass tails.

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



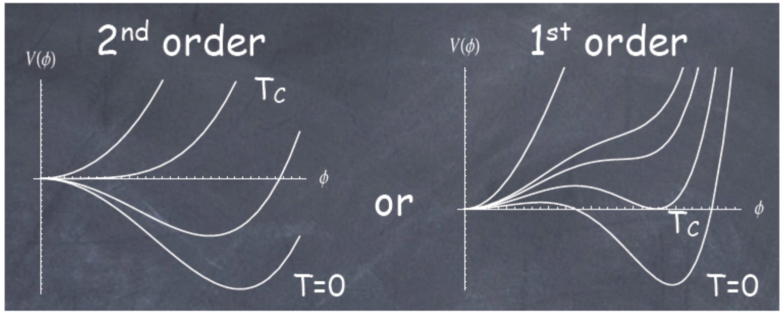
Extensive probing of the EW interaction in the High Energy regime.

Precision study of the EW Phase Transition

Dynamics of EW phase transition and Cosmology

The asymmetry between matter-antimatter can be created dynamically
it requires an out-of-equilibrium phase in the cosmological history of the Universe

An appealing idea is EW baryogenesis associated to a first order EW phase transition



the dynamics of the phase transition is determined by Higgs effective potential at finite T
which we have no direct access at in colliders (LHC≠Big Bang machine)

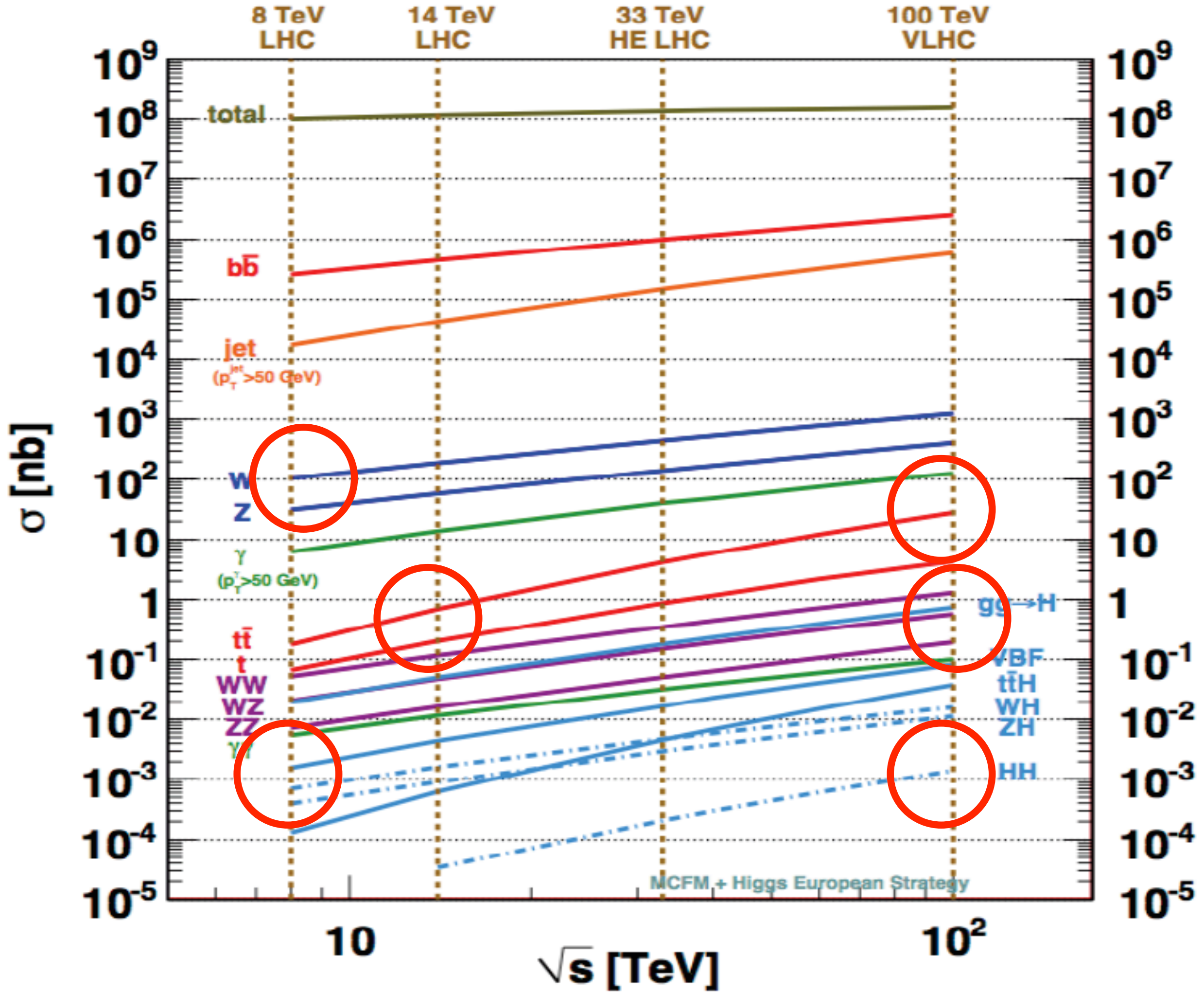
finite T Higgs potential ⟺ Higgs couplings at T=0

SM: first order phase transition iff mH < 47 GeV
BSM: first order phase transition needs some sizeable deviations in Higgs couplings

Christophe Grojean — Precision Frontier @ High Energies — 17 — Geneva, Feb. 12, 2014

1. **O(1%) precision in measuring the Higgs couplings could be as important as direct searches for new physics.**
2. **Study of triple Higgs coupling (… and quadruple).**
3. **Search for new sources of CP violation connected to Higgs interactions.**

Higgs/top cross sections @100TeV



Higgs and top physics with $10ab^{-1}$@100TeV

10^{10} Higgs bosons
10^4 today's statistics

Precision measurements, rare decays, probe FCNC decay modes (i.e. H→eμ)

10^{12} top quarks
$5x10^4$ today's statistics

Precision measurements, rare decays, probe FCNC decay modes (i.e. t→cH, t→cZ, or cg, cγ); CP violation; BSM decays

Clean, high intensity particles "beams" from the top decays

- **10^{12} W bosons**
- **10^{12} b jets**
- **10^{11} t→W→τν**
- **a few 10^{11} t→W→charmed hadrons**
- **….**

Rare decays of the τ (τ→3μ, τ→μγ, CPV..) and of the charm (D→μμ, CPV..)

Room for new ideas on detectors optimized for special final states

Higgs Physics @100TeV

NLO rates $\mathbf{R(E)} = \sigma(E\ \text{TeV})/\sigma(14\ \text{TeV})$

	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

The two most difficult processes, ttH and HH, will be key players in the new machine.
If you require high invariant mass in the final states the gain can be much higher.
i.e. ttH with p_T^{top}>500GeV→ gain of ~250

Higgs Physics @100TeV

There is a "natural" complementarity between FCC-ee and FCC-hh for what concerns the Higgs couplings.

Coupling like HWW and HZZ are already strongly constrained by EWPT and deviations from the SM values (if any) are supposed to be small.
FCC-ee could do here a great job:

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%	$-/5.5/<5.5\%$	1.45%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%	1.3%	0.72%	$3.5/1.4/<1.3\%$	0.51%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

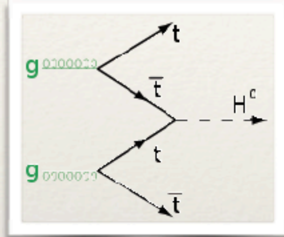
Coupling involved in rare decays $H\rightarrow\mu\mu$ $H\rightarrow Z\gamma$ and HHH will be much less constrained even by FCC-ee.

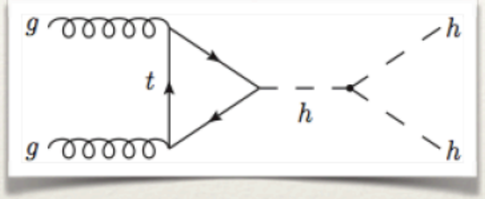
FCC-hh is the big player for λ, λ_t, k_μ $k_{Z\gamma}$

.

ttH and HHH coupling

ttH & HHH coupling





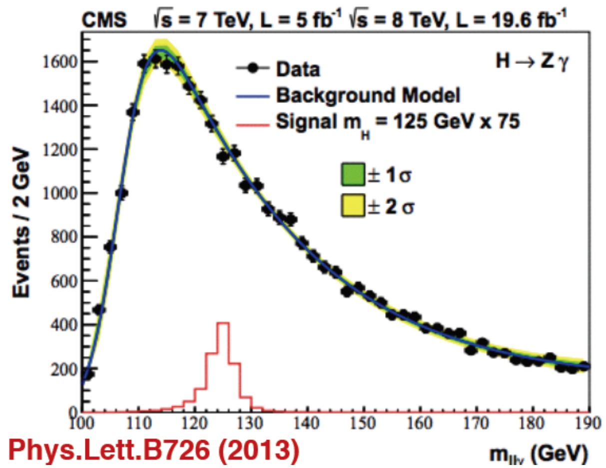
Process	14 TeV	33 TeV	100 TeV
gg → ttH	0.62 pb	4.5 pb × 7.3	37.8 pb × 61
gg → HH	33.8 fb	206 fb × 6.1	1.41 pb × 42

	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%

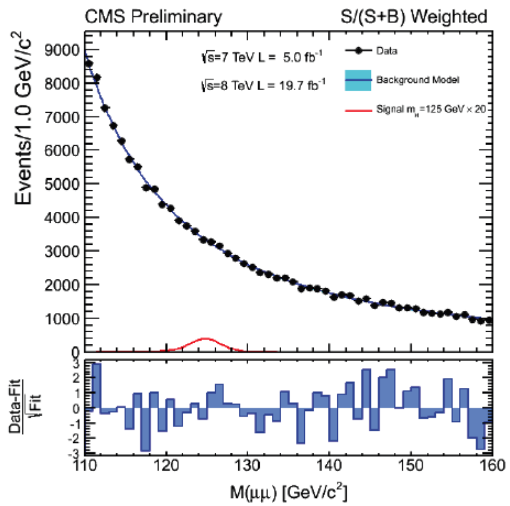
NB the triple Higgs boson coupling here is measured considering only the bbγγ final state.

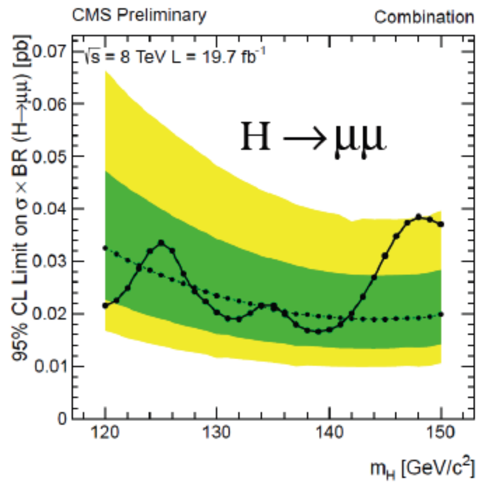
Higgs rare decays

H→Zγ



H→μμ





$k_{Z\gamma}$ measured at 40% with 300fb^{-1} and 10% with 3000fb^{-1} at LHC13; difficult to go much below for FCC-ee.

k_{μ} direct coupling to fermions of the second generation measured at 20% with 300fb^{-1} and 7% with 3000fb^{-1} at LHC13; difficult to go much below for FCC-ee.

FCC-hh could target the 1% precision for these couplings.

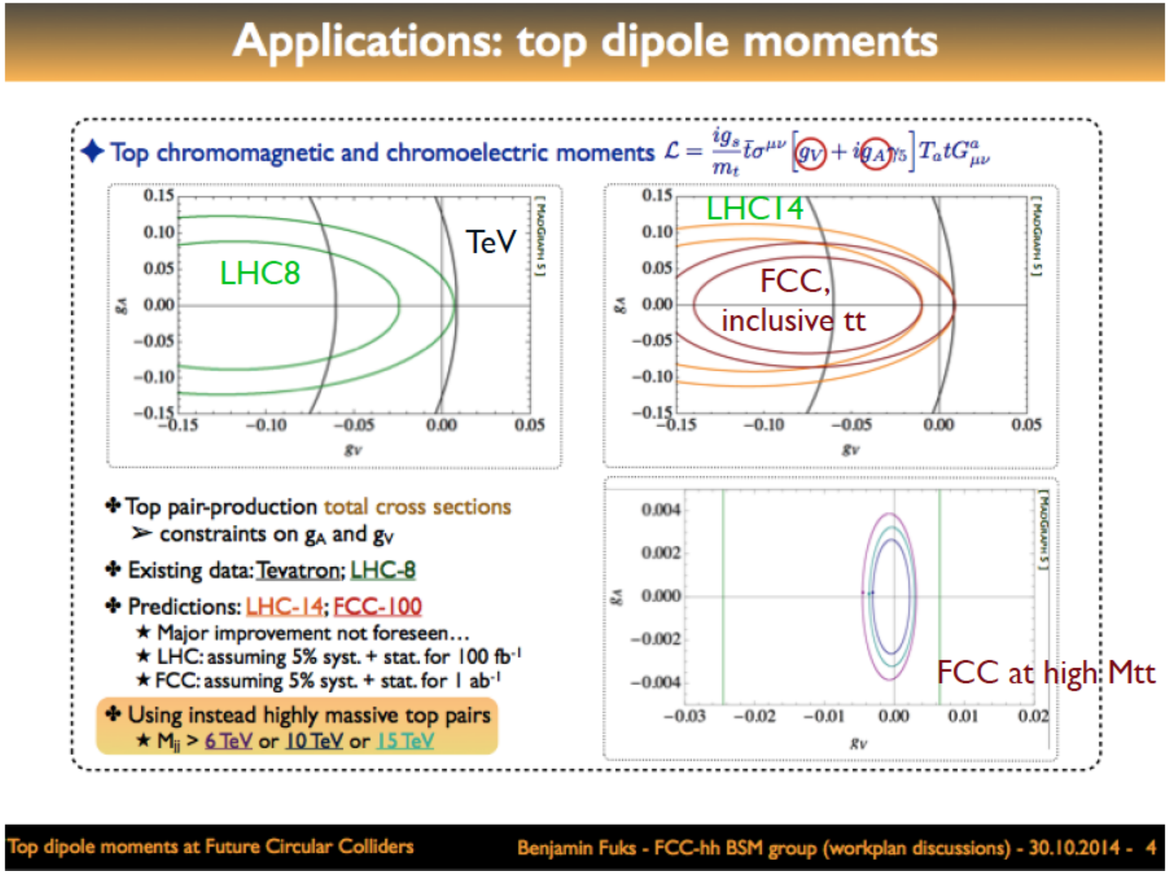
In many cases we could use the ratio of the Branching Ratios to export the sub % precision of the FCC-ee to channels accessible to FCC-hh

Top physics with $10ab^{-1}$@100TeV

10^{12} top quarks 5x10^4 today's statistics

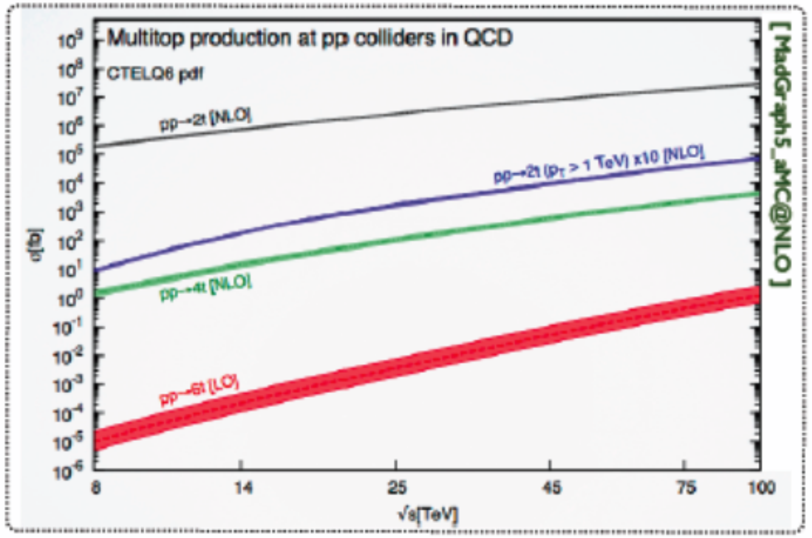
σ_{LO} [pb]	No M_{tt} cut	M_{tt} > 1 TeV	M_{tt} > 2 TeV	M_{tt} > 3TeV	M_{tt} > 5 TeV
LHC-14	560 pb	14.5 pb	0.31 pb	0.017 pb	9.93 10^{-5} pb
FCC-100	19700 pb (x35)	1510 pb (x100)	135.9 pb (x440)	27.2 pb (x1600)	2.86 pb (x30000)

Huge statistics of tt-bar systems at very high invariant mass→large indirect sensitivity to new physics (virtual effects producing anomalies in well predicted variables)



Entering the multi-top world

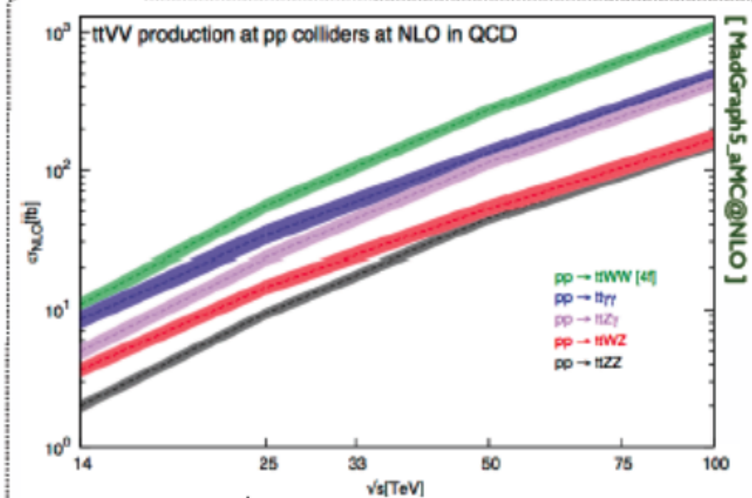
✦ Multitop hadroproduction



- 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

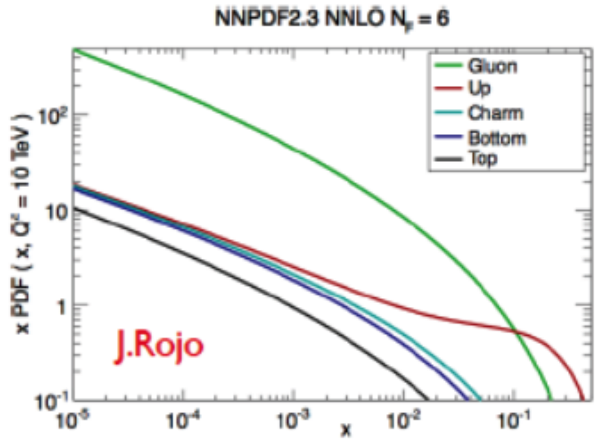


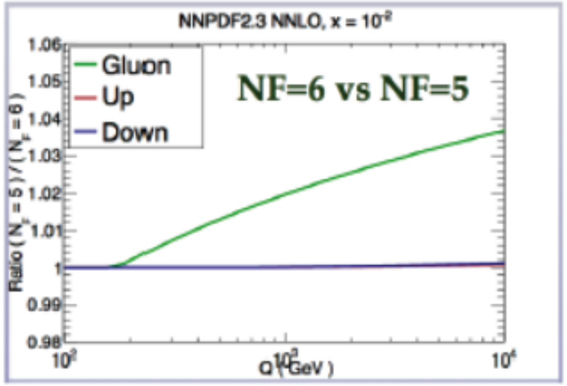
Process	σ(100 TeV) / σ (14 TeV)
ttWW	≈100
ttγγ	≈60
ttγZ	≈80
ttWZ	≈50
ttZZ	≈70

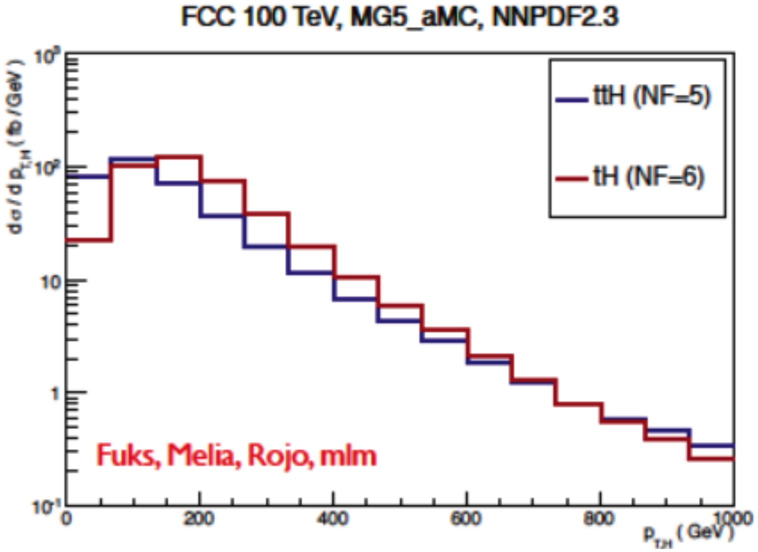
- Largest enhancement: ttWW production (≈10000 expected events for 100 fb^{-1})

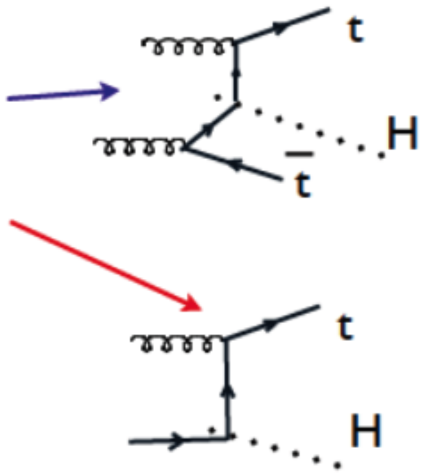
[Torrielli]

Access to the top PDF



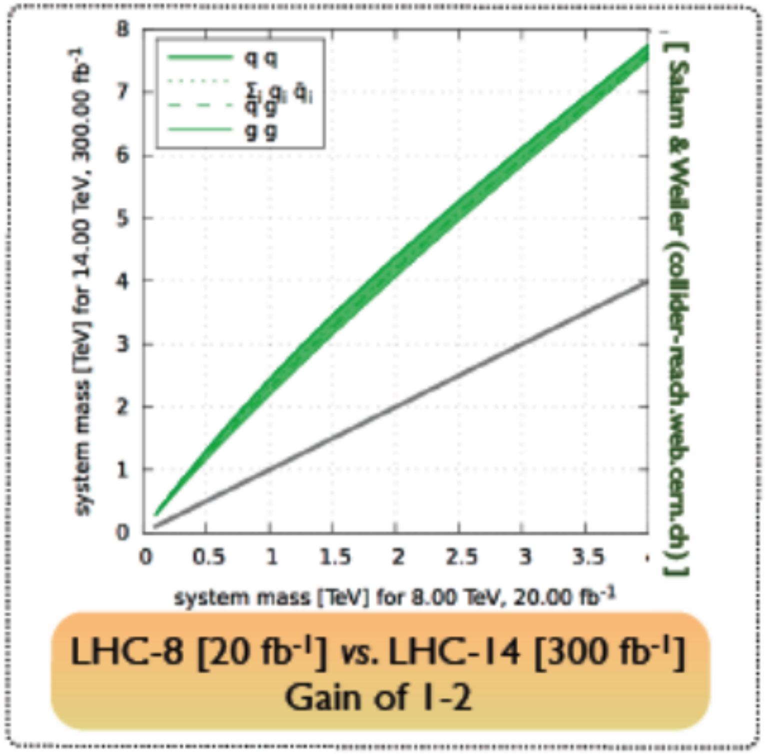


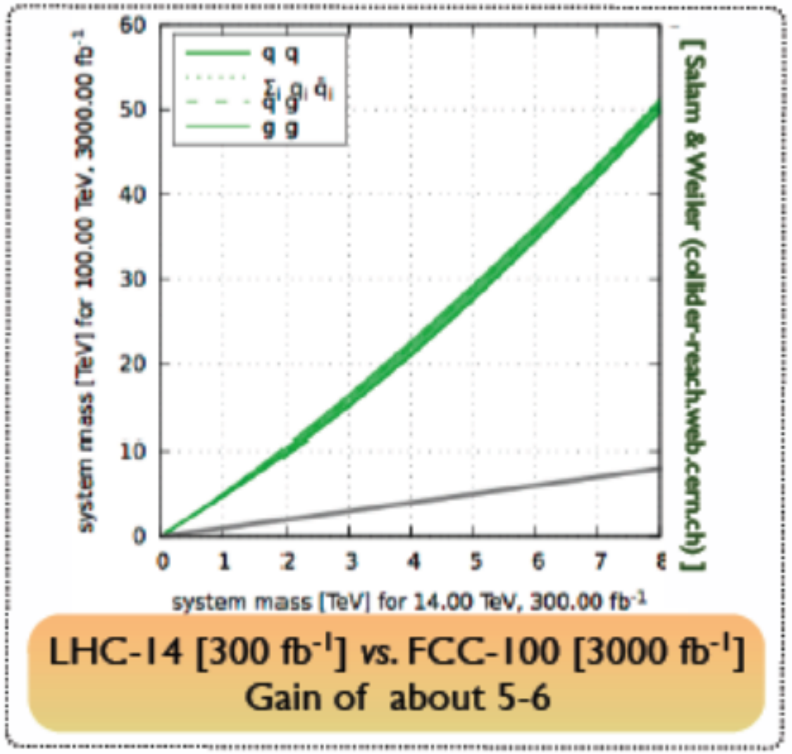




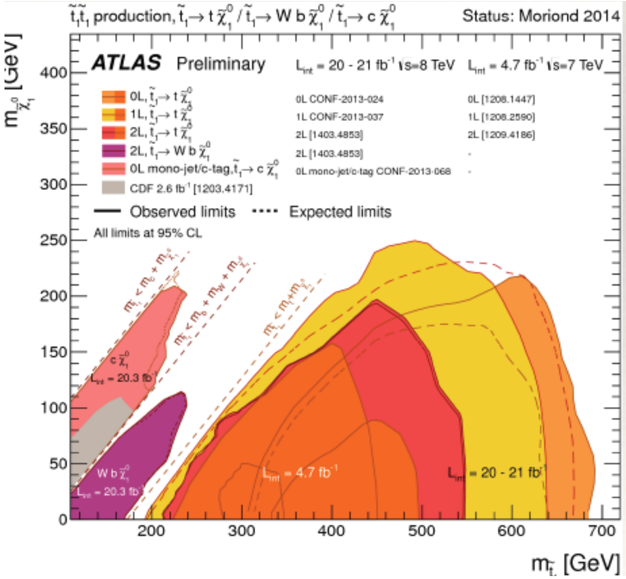
Direct search of BSM particles @100TeV

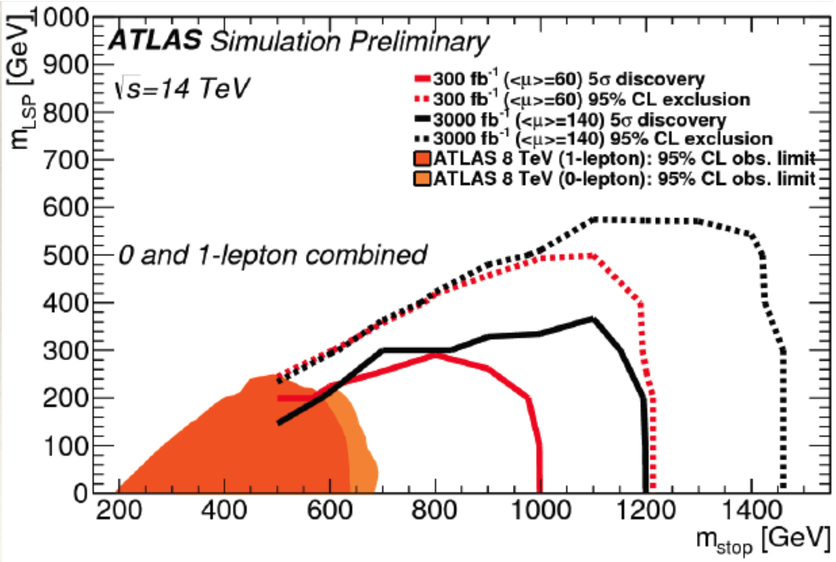
- The new energy regime allows looking for particles of 30 TeV and heavier.
- High statistics for a detailed exploration of the ~TeV regime.
- Access to very rare processes (including some stealth decay-modes) in the subTeV region





Search for the third generation squarks



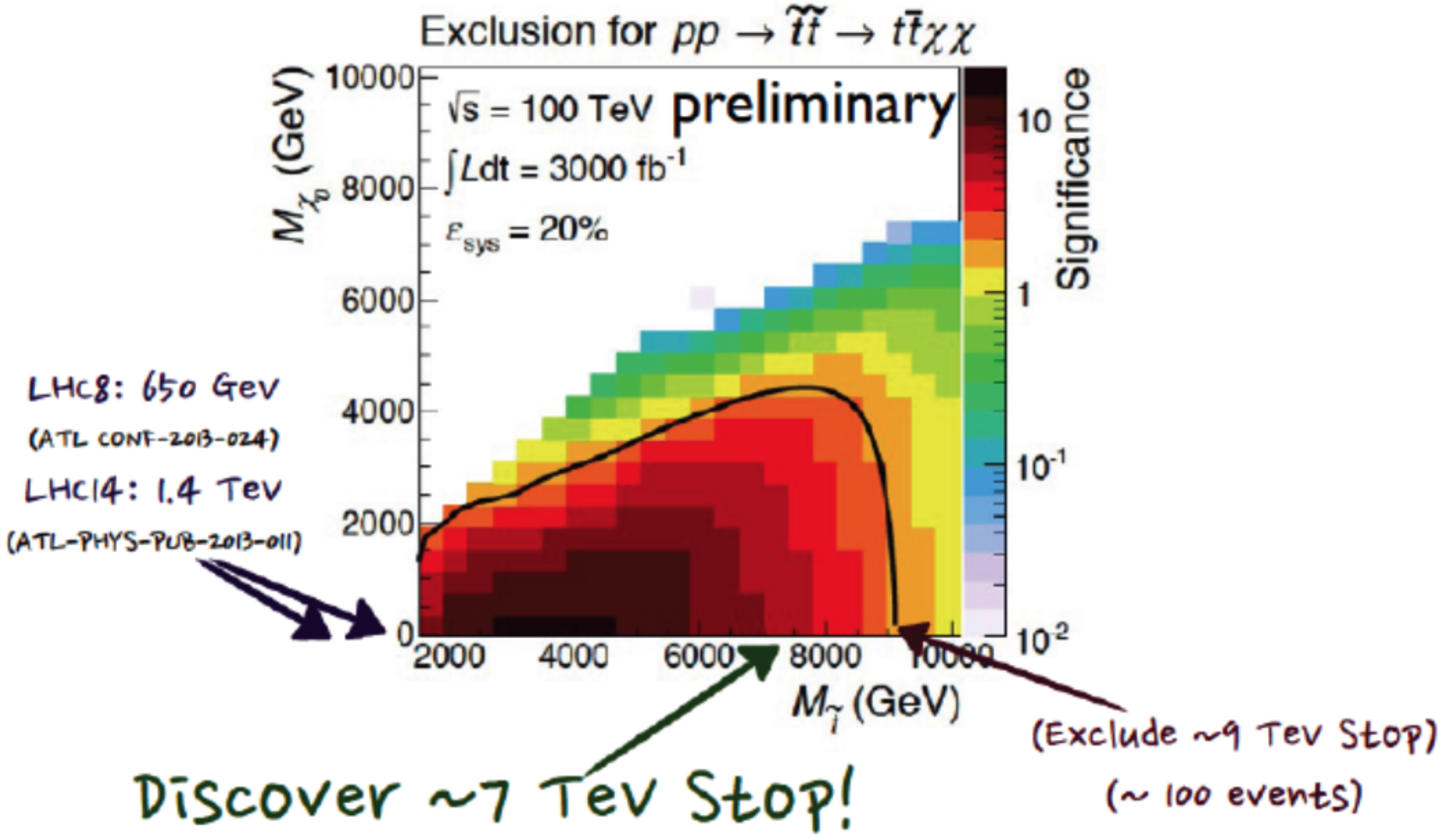


With LHC at 13/14TeV and 300 fb^{-1}the current limits could gain a factor 2 and pass the 1TeV mark.

With 3000fb^{-1}the additional gain will be marginal (~20%).

No hint @ 300 fb^{-1}→ no much fun@ 3000fb^{-1}

Stop exclusion limits @100TeV

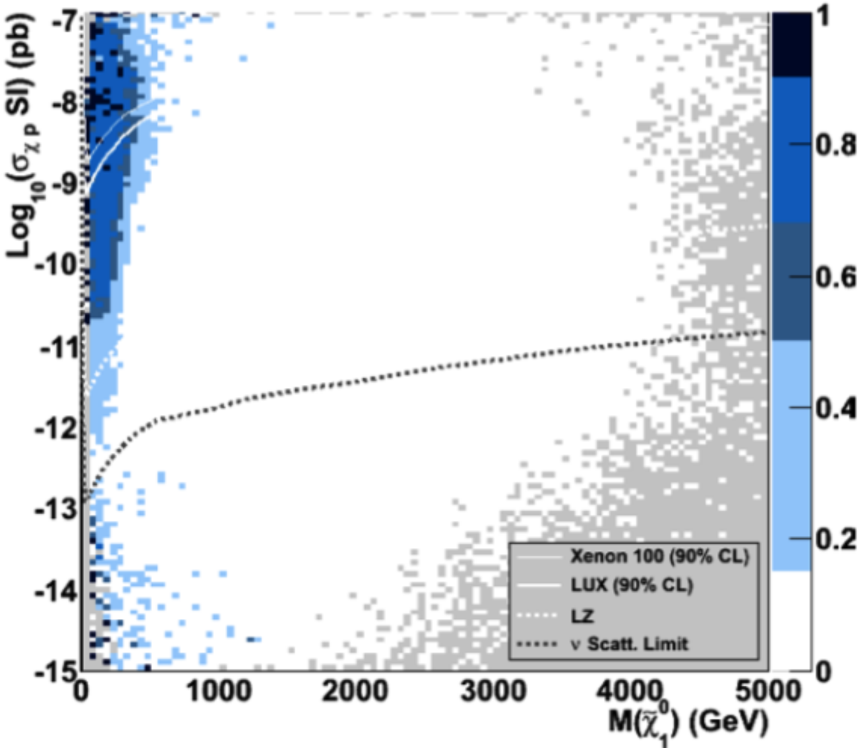


FCC-hh challenges SUSY model builders

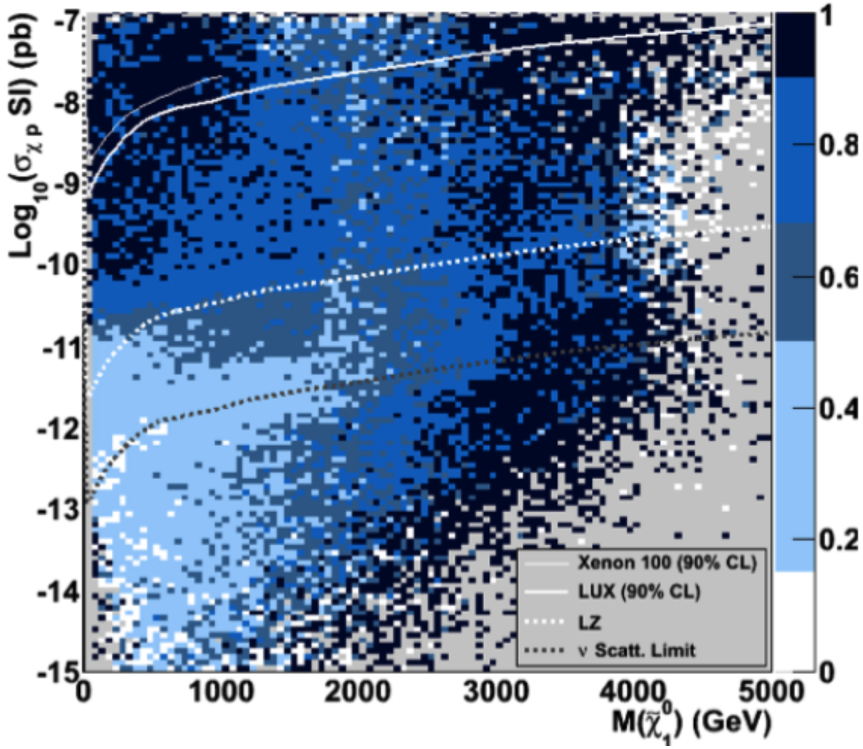
Fraction of pMSSM parameter space that can be explored by LHC14 and FCC-hh. Dark matter constrains are also included.

Arbey, Battaglia, Mahmoudi

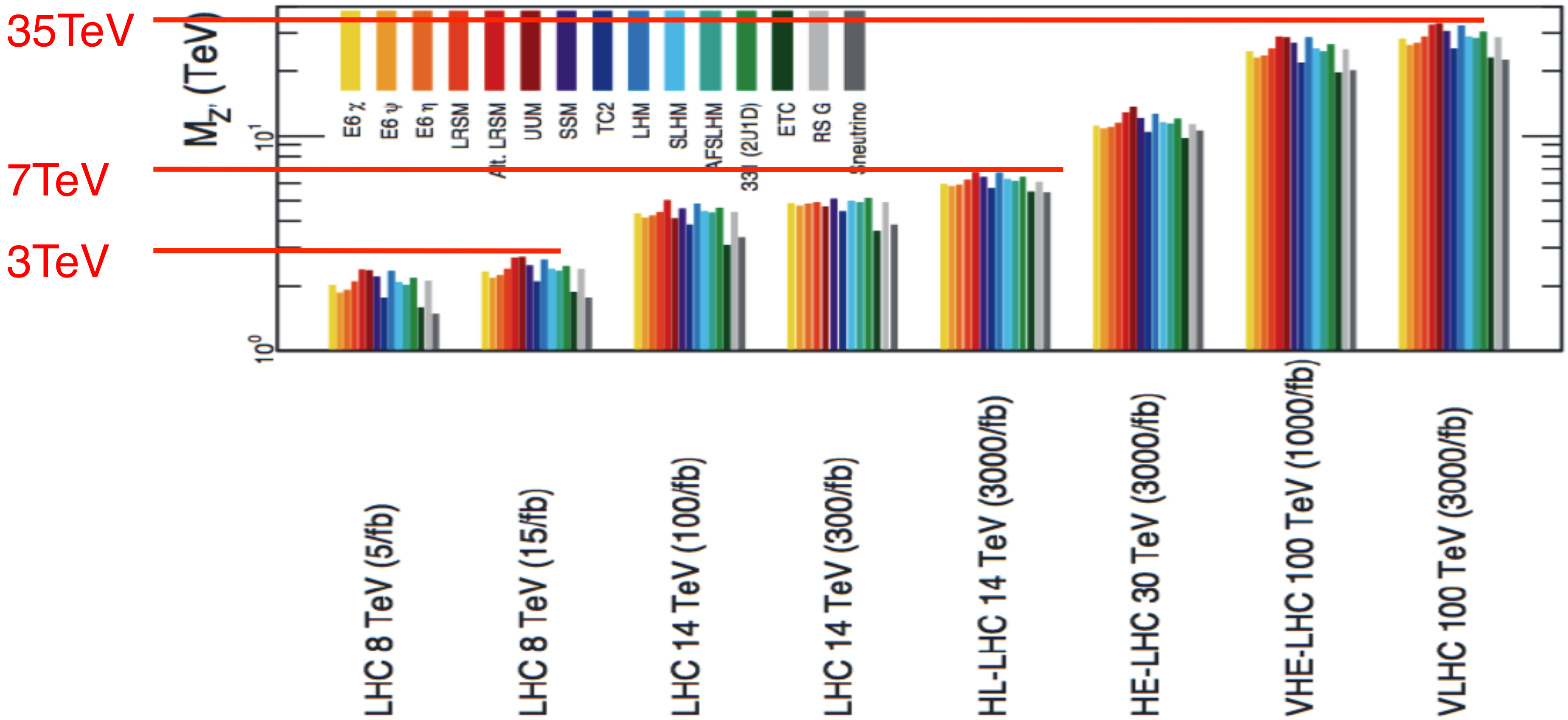
14TeV



100TeV



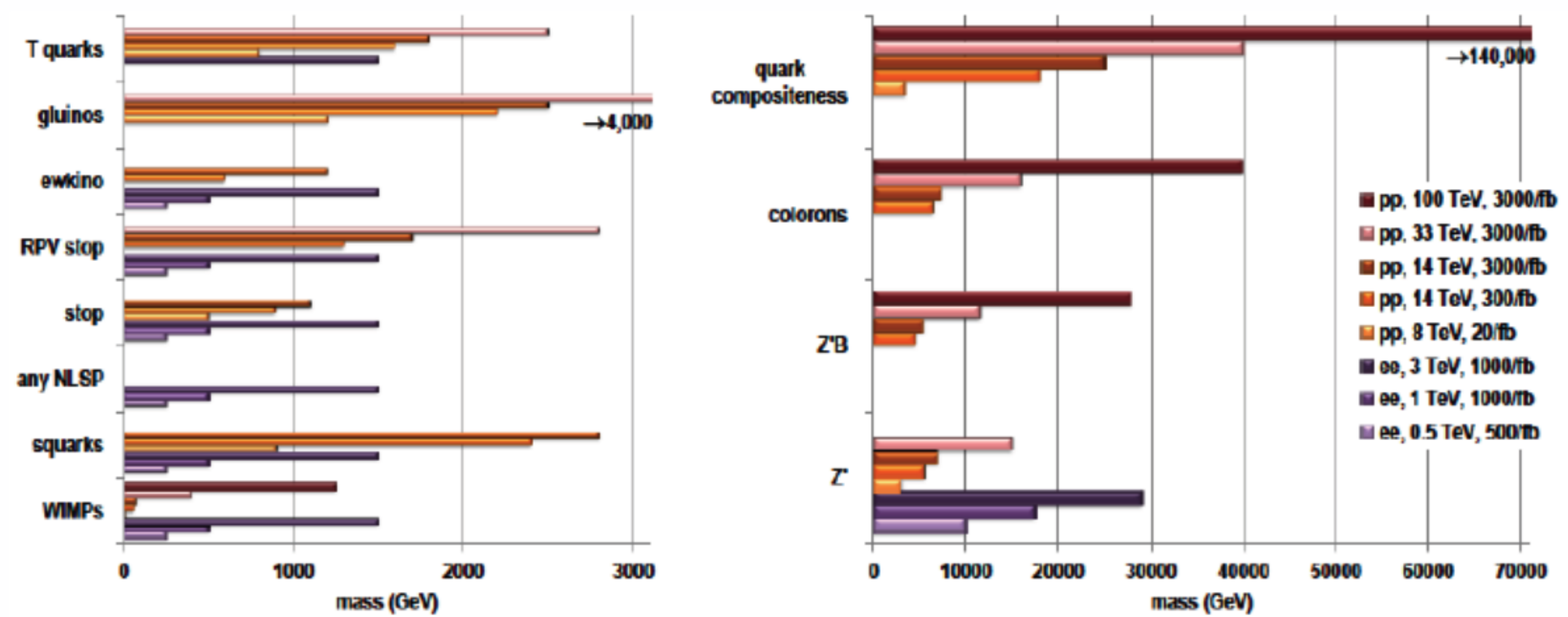
Search for Heavy Resonances



Rule of thumb: factor 5 in mass reach for FCC-hh @ 3000fb^{-1} wrt LHC14 3000fb^{-1}

FCC-hh sensitive to Z' in dileptons up to 30-35TeV

Other exotic states



Energy Frontier Snowmass study (1311.0299)

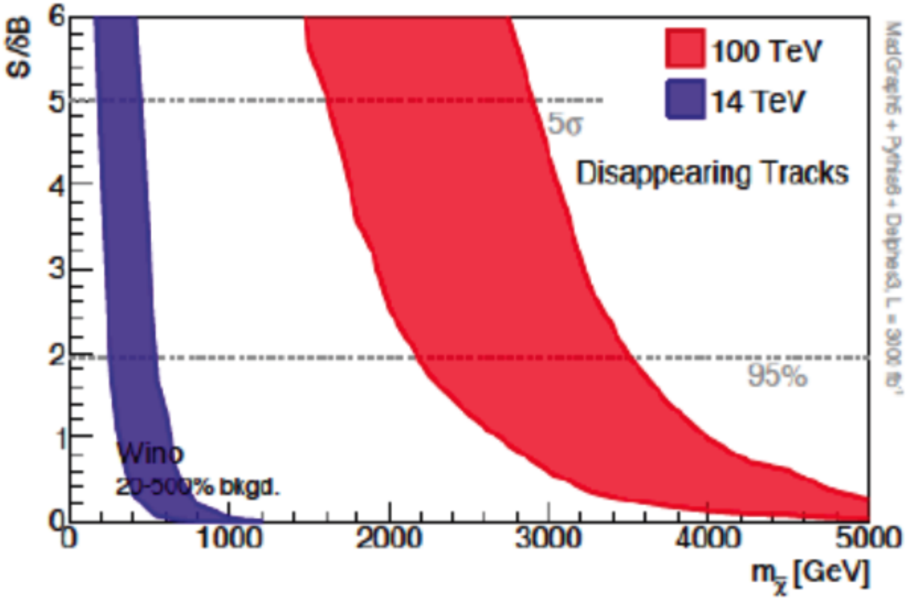
Search for WIMP candidates for dark matter

DM overclosure upper limits:

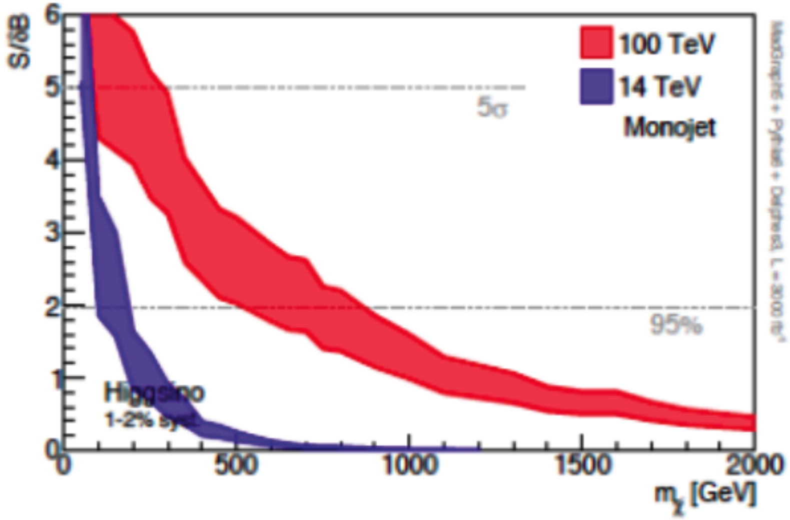
$M_{WIMP} < 1.8\,TeV\,(g^2/0.3) \Rightarrow$

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

Beware: dark matter could well be axions or other strange beasts that do not like to produce signals in our colliders.

Conclusion and next steps

The physics program of FCC-hh is absolutely magnificent.
Plenty of room for new ideas.
The exploration of the new energy regime will change in depth our current vision of matter and the Universe. Data will decide in which direction.

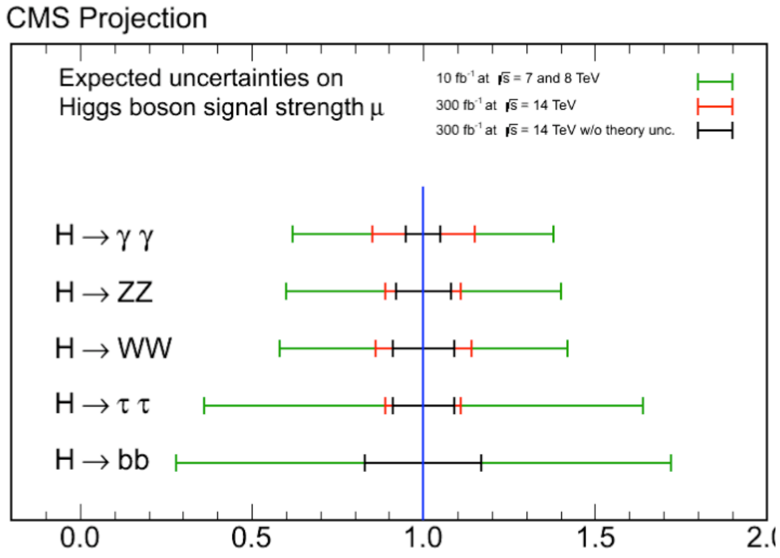
Next steps

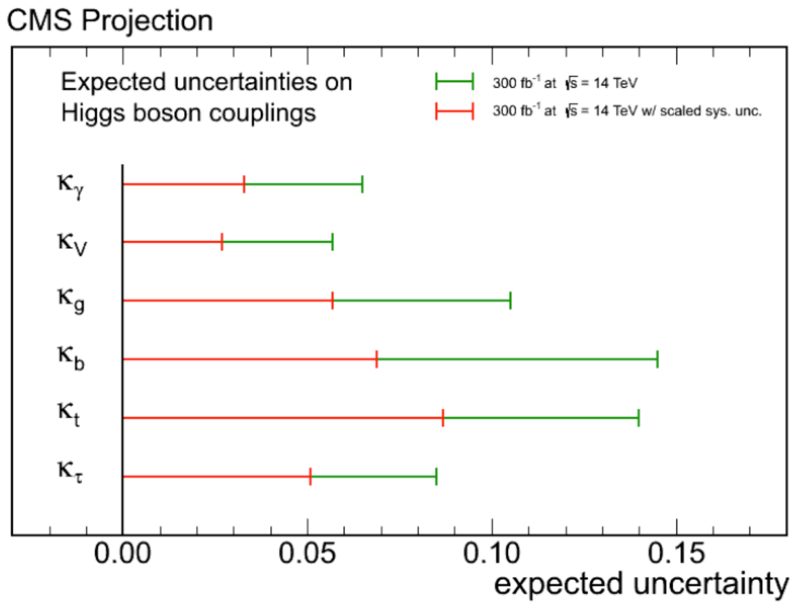
1. Study the properties of the main physics objects (jets, high p_T objects, b/tau/top/Higgs-tagging, VBF topologies etc in the new kinematical regime.

2. Study the implications at detector/trigger level: implement a series of requirements.

3. Improve the theoretical understanding of the new territory (PDFs, MCs generators, constrains on the new physics scenarios coming from precision measurements (including FCC-ee).

Projection on the couplings: $300fb^{-1}$-$3000\ fb^{-1}$





5-10%@LHC 14TeV and $300fb^{-1}$.

< 5%@LHC 14TeV and $3000fb^{-1}$, only if systematics can be drastically reduced.

Scenario 1: no improvements in systematics

Scenario 2: theory uncertainties halved and systematics scaling as 1/sqrt of the integrated luminosity.

Coupling	Uncertainty (%)			
	$300\ fb^{-1}$		$3000\ fb^{-1}$	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0