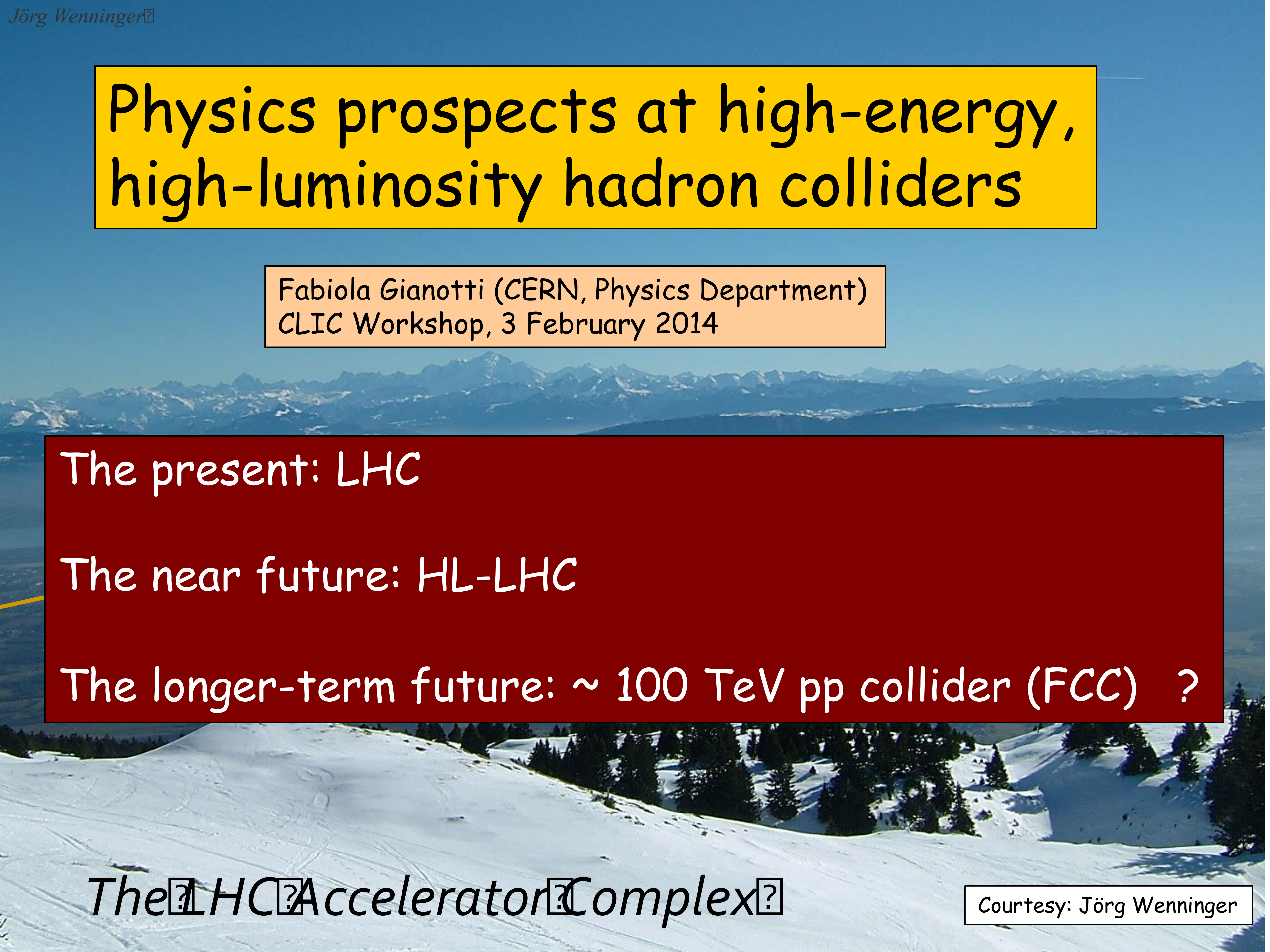
Physics prospects at high-energy, high-luminosity hadron colliders

Fabiola Gianotti (CERN, Physics Department)
CLIC Workshop, 3 February 2014

The present: LHC

The near future: HL-LHC

The longer-term future: ~ 100 TeV pp collider (FCC) ?



Courtesy: Jörg Wenninger

Three main outcomes from LHC Run 1

We have consolidated the Standard Model
(wealth of measurements at 7-8 TeV, including the rare, and very sensitive to New Physics, $B_s \rightarrow \mu\mu$ decay)
→ it works BEAUTIFULLY ...

We have completed the Standard Model: Higgs boson discovery
(almost 100 years of theoretical and experimental efforts !)

We have NO evidence of new physics (yet ...)

Note: the last point implies that, if New Physics exists at the TeV scale and is discovered at $\sqrt{s} \sim 14$ TeV in 2015++, its spectrum is quite heavy
→ it will require a lot of luminosity and energy to study it fully and in detail
→ implications for future machines (e.g. most likely this New Physics not accessible at a 0.5 TeV ILC)

F. Gianotti, CLIC WS, 3/2/2014

The present paradox ….

On one hand, the LHC results imply that the SM technically works up to scales much higher than the TeV scale, and present limits on new physics seriously challenge the simplest attempts (e.g. minimal SUSY) to fix its weaknesses

On the other hand: there is strong evidence that the SM must be modified with the introduction of new particles and/or interactions at some E scale to address fundamental outstanding questions, including: naturalness, dark matter, matter/antimatter asymmetry, the flavour/family problems, unification of coupling constants, etc.

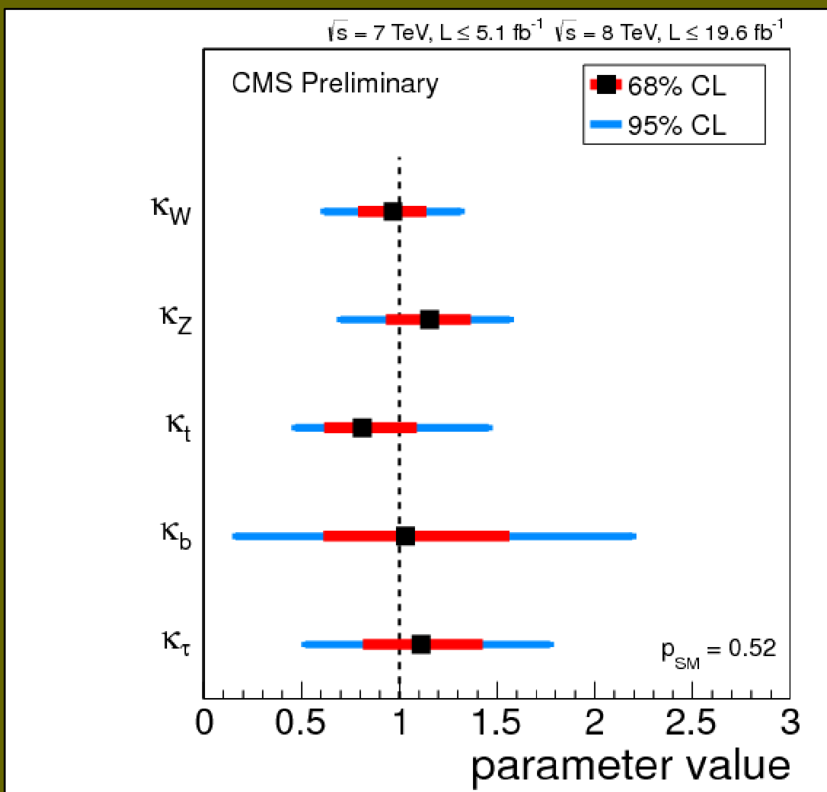
- Answers to some of the above questions expected at the TeV scale whose exploration JUST started.
- Higgs sector (Higgs boson, EWSB mechanism): less known component (experimentally) of the Standard Model → lot of work needed to e.g. understand if it is the minimal SM mechanism or something more complex

→ Full exploitation of the LHC (→ HL-LHC: $\sqrt{s} \sim 14$ TeV, 3000 fb^{-1}) is a MUST

→ Here only a few examples …

Today (25 fb^{-1} per experiment):

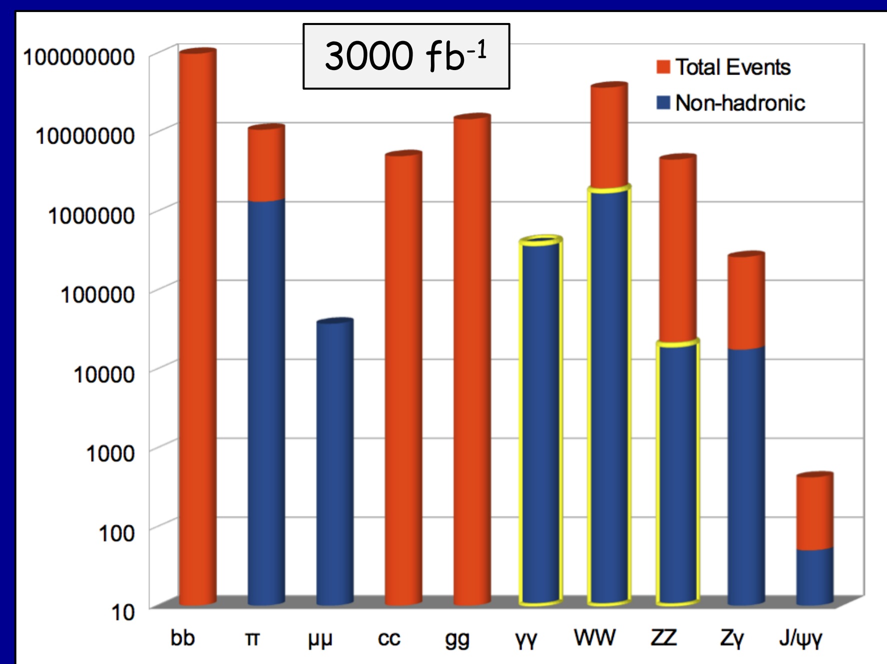
- ATLAS+CMS: 1400 Higgs events after selection cuts (1M at production)
- Observed/measured so far: couplings to W, Z and 3rd generation fermions t, b, τ (ttH: indirectly through gg-fusion production loop)
- Typical precision: ~ 20%



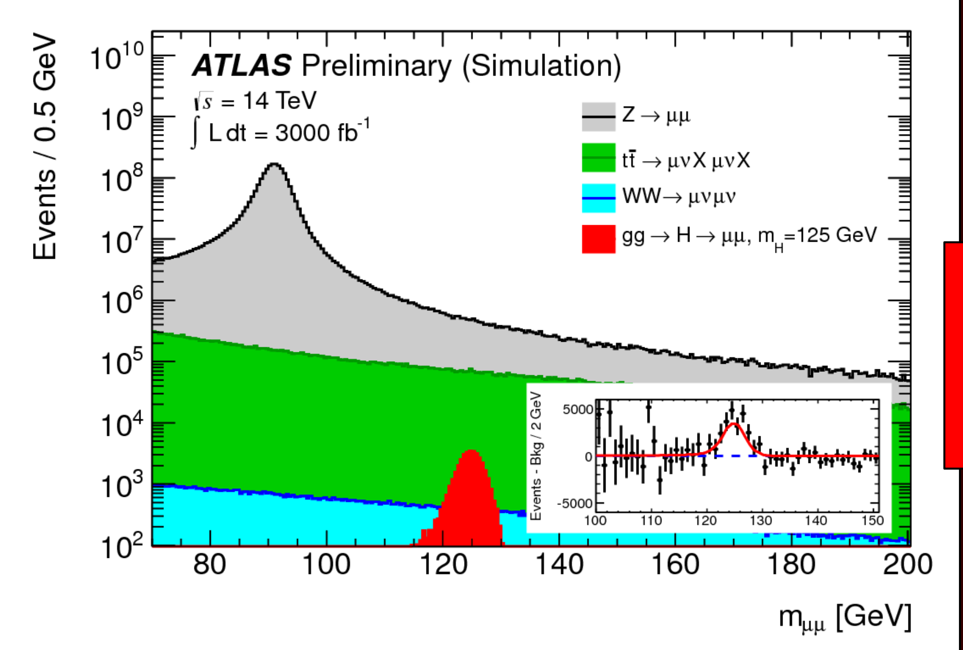
HL-LHC (3000 fb^{-1})

- > 170M Higgs events/expt at production
- > 3M useful for precise measurements, more than (or similar to) ILC/CLIC/TLEP

HL-LHC is a Higgs factory !
→ Access to rare processes
→ 4-10 times better precision on couplings than today



Several rare processes become accessible with 3000 fb^{-1} , e.g.: <u>direct coupling</u> to 2^{nd} generation fermions (H→ μμ) and to top quark (mainly through ttH→ ttγγ)



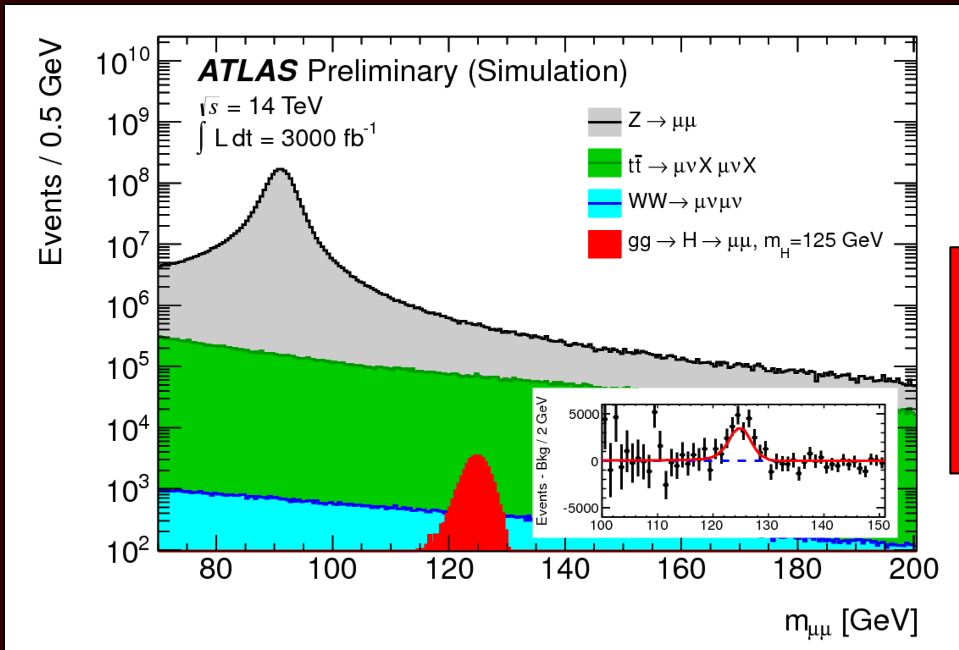
H →μμ

- Today's sensitivity: 8xSM cross-section
- With 3000 fb^{-1} expect 17000 signal events (S/B ~ 0.3%) and ~ 7σ significance
- Hμμ coupling can be measured to about 10%

Compilation from Snowmass 2013

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%	0.13%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.44%	0.22%	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%
κ_d	10 – 13%	4 – 7%	0.93%	0.51%	0.51%	0.31%	1.7/0.32/0.19%	0.39%
κ_u	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.76%	3.1/1.0/0.7%	0.69%

Several rare processes become accessible with 3000 fb^{-1}, e.g.: direct coupling to 2nd generation fermions (H→ μμ) and to top quark (mainly through ttH→ ttγγ)



H →μμ

- Today's sensitivity: 8xSM cross-section
- With 3000 fb^{-1} expect 17000 signal events (S/B ~ 0.3%) and ~ 7σ significance
- Hμμ coupling can be measured to about 10%

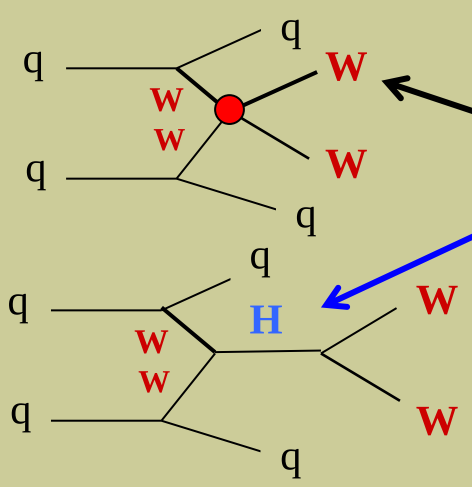
mass 2013

Facility	LHC	HL-LHC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	10,000+2600
κ_γ	$5-7\%$	$2-5\%$	1.45%
κ_g	$6-8\%$	$3-5\%$	0.79%
κ_W	$4-6\%$	$2-5\%$	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.05%
κ_ℓ	$6-8\%$	$2-5\%$	0.51%
κ_d	$10-13\%$	$4-7\%$	0.39%
κ_u	$14-15\%$	$7-10\%$	0.69%

Some sensitivity to physics beyond SM manifesting itself only through deviations to Higgs couplings

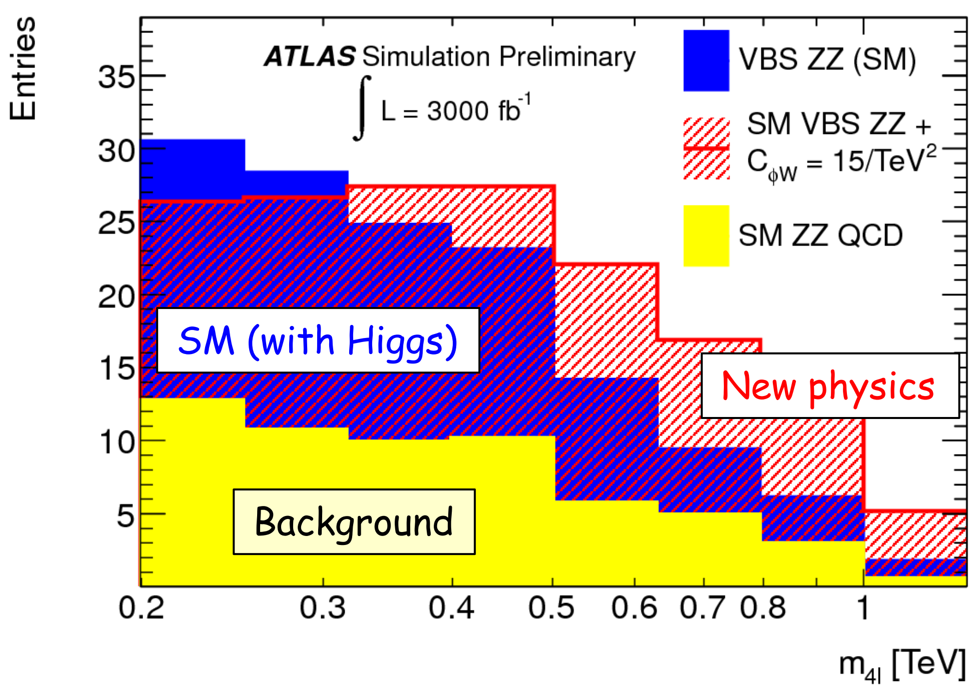
	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

Q1: Does the new particle fix the SM "nonsense" at large m_{VV} ?



This process violates unitarity: $\sigma \sim E^2$ at $m_{WW} \sim$ TeV (divergent cross section → unphysical)
if this process does not exist

→ Important to verify that the new particle accomplishes this task → a crucial "closure test" of the SM
→ Need $\sqrt{s} \sim 14$ TeV and ~3000 fb^{-1}

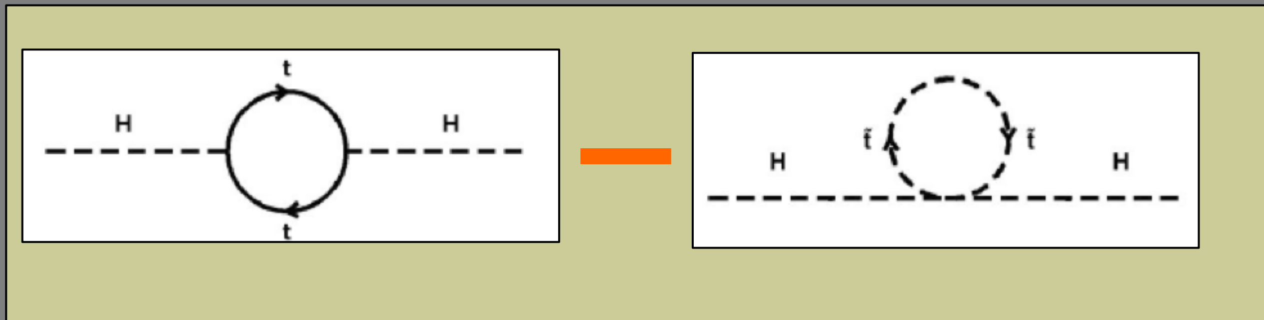


If no new physics: good behaviour of SM cross section can be measured to 30% (10%) with 300 (3000) fb^{-1}

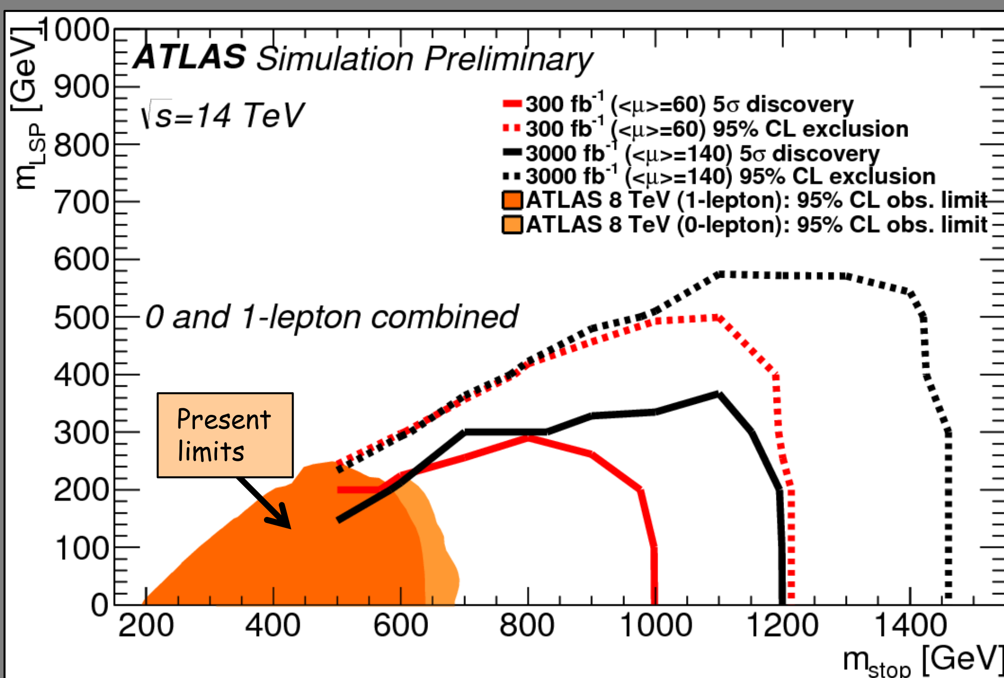
If new physics: sensitivity increases by ~ 2 (in terms of scale and coupling reach) between 300 and 3000 fb^{-1}

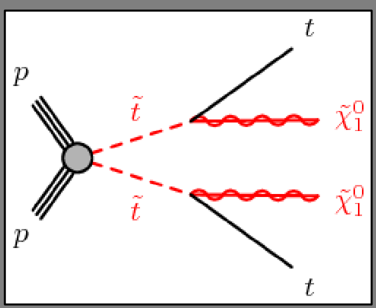
→ HL-LHC is crucial for a sensitive study of EWSB dynamics

Q2: Is the Higgs mass "natural", i.e. stabilized by New Physics ?

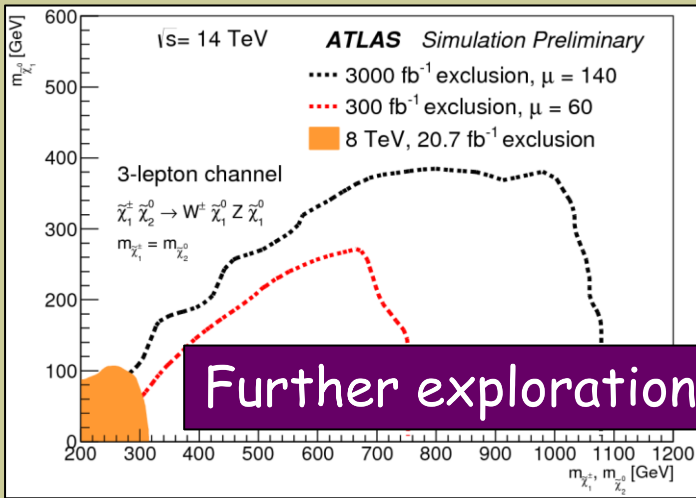


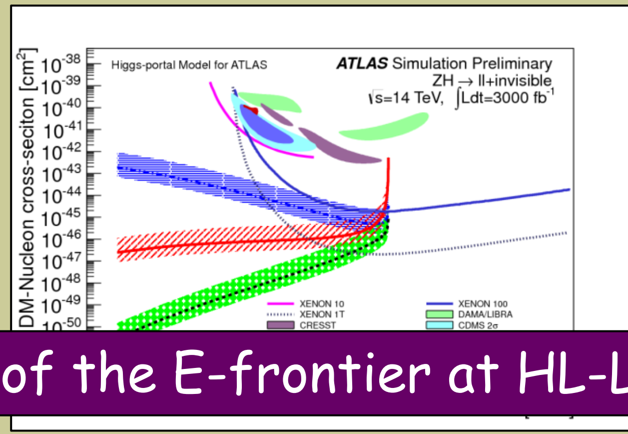
To stabilize the Higgs mass (without too much fine-tuning), the stop should not be much heavier than ~ 1-1.5 TeV (note: the rest of the SUSY spectrum can be heavier)

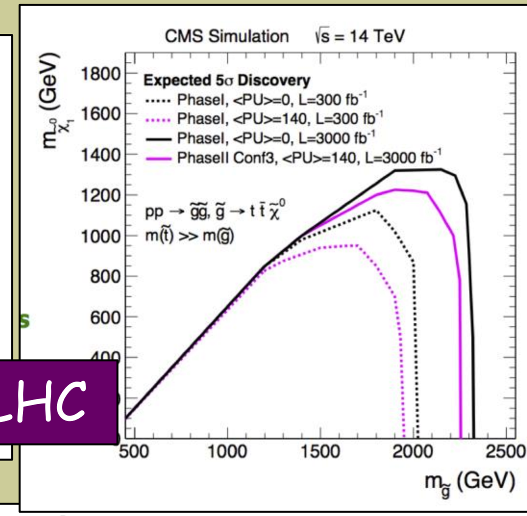




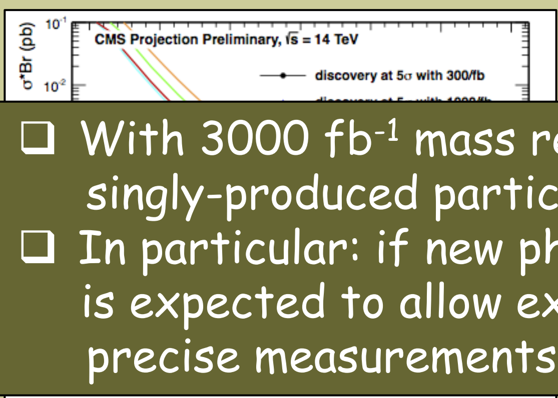
Mass reach extends by ~ 200 GeV from 300 to 3000 fb^{-1}
→ most of best motivated mass range will be covered at HL-LHC

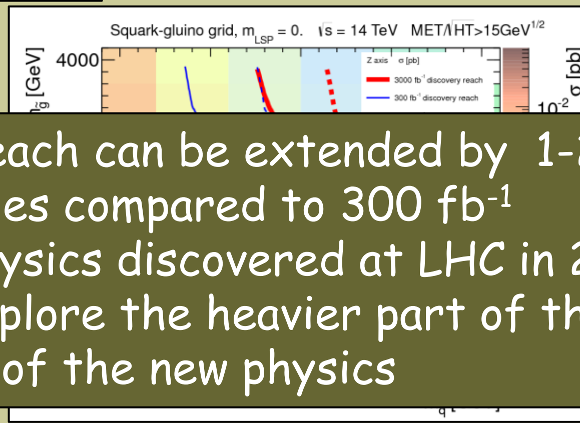


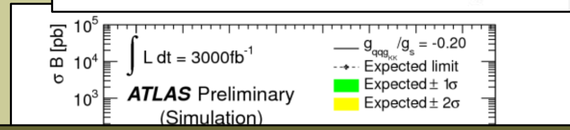




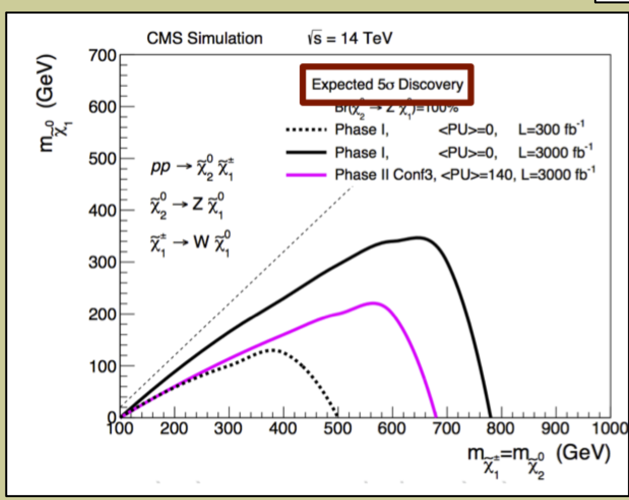
Further exploration of the E-frontier at HL-LHC

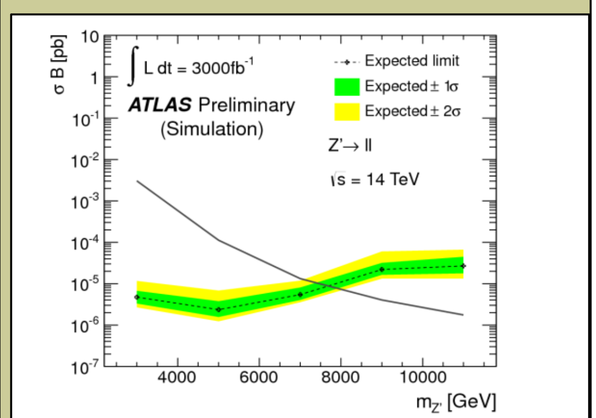


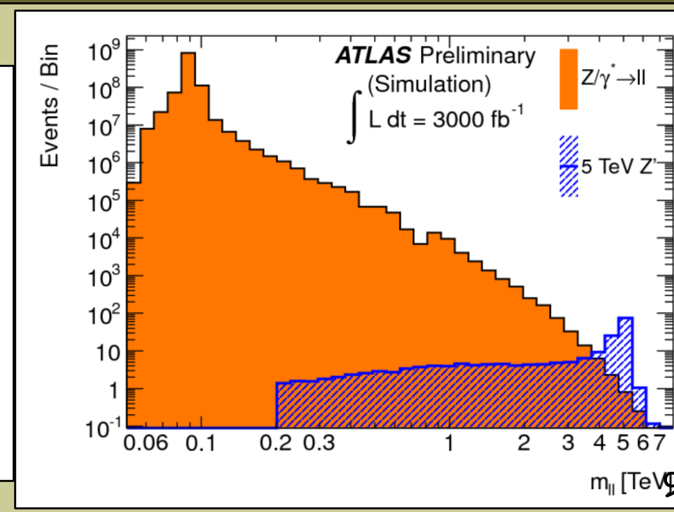




- With 3000 fb^{-1} mass reach can be extended by 1-2 TeV for singly-produced particles compared to 300 fb^{-1}
- In particular: if new physics discovered at LHC in 2015++ → HL-LHC with 3000 fb^{-1} is expected to allow explore the heavier part of the spectrum and perform precise measurements of the new physics

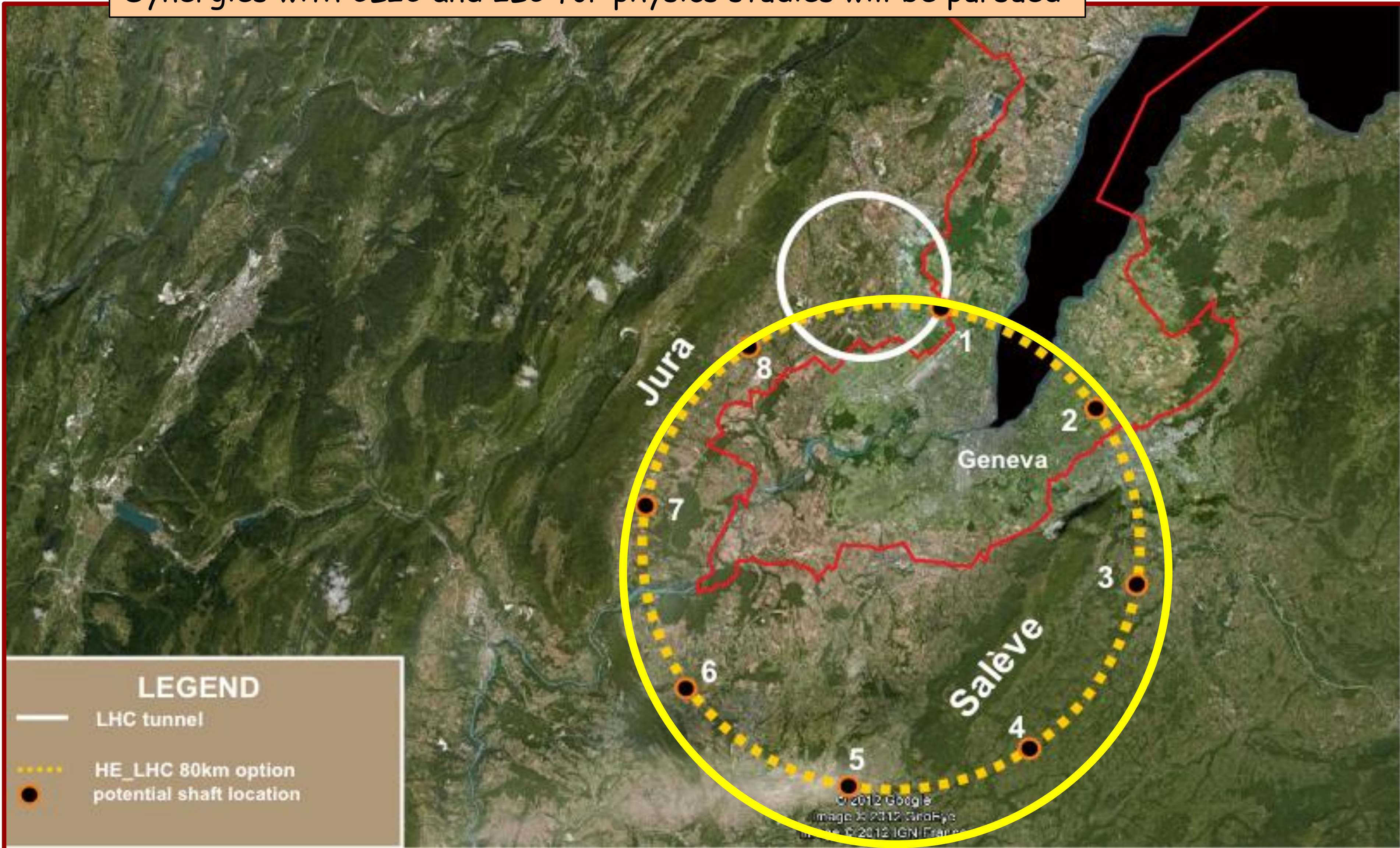






The longer-term future: a ~ 100 TeV pp collider ?

International initiative → see M. Benedikt's talk
Synergies with CLIC and ILC for physics studies will be pursued



Physics motivations

One of the main goals of the Conceptual Design Report (~ 2018)
→ will be studied in detail in the years to come …

Two scenarios:

- LHC and/or HL-LHC find new physics:
  the heavier part of the spectrum may not be fully accessible at $\sqrt{s}$ ~ 14 TeV
  → strong case for a 100 TeV pp collider (and CLIC): complete the spectrum and measure it in some detail
- LHC and/or HL-LHC find indications for the scale of new physics being in the 10-50 TeV region (e.g. from dijet angular distributions → Λ compositeness)
  → strong case for a 100 TeV pp collider: directly probe the scale of new physics

LHC and HL-LHC find NO new physics nor indications of the next E scale:

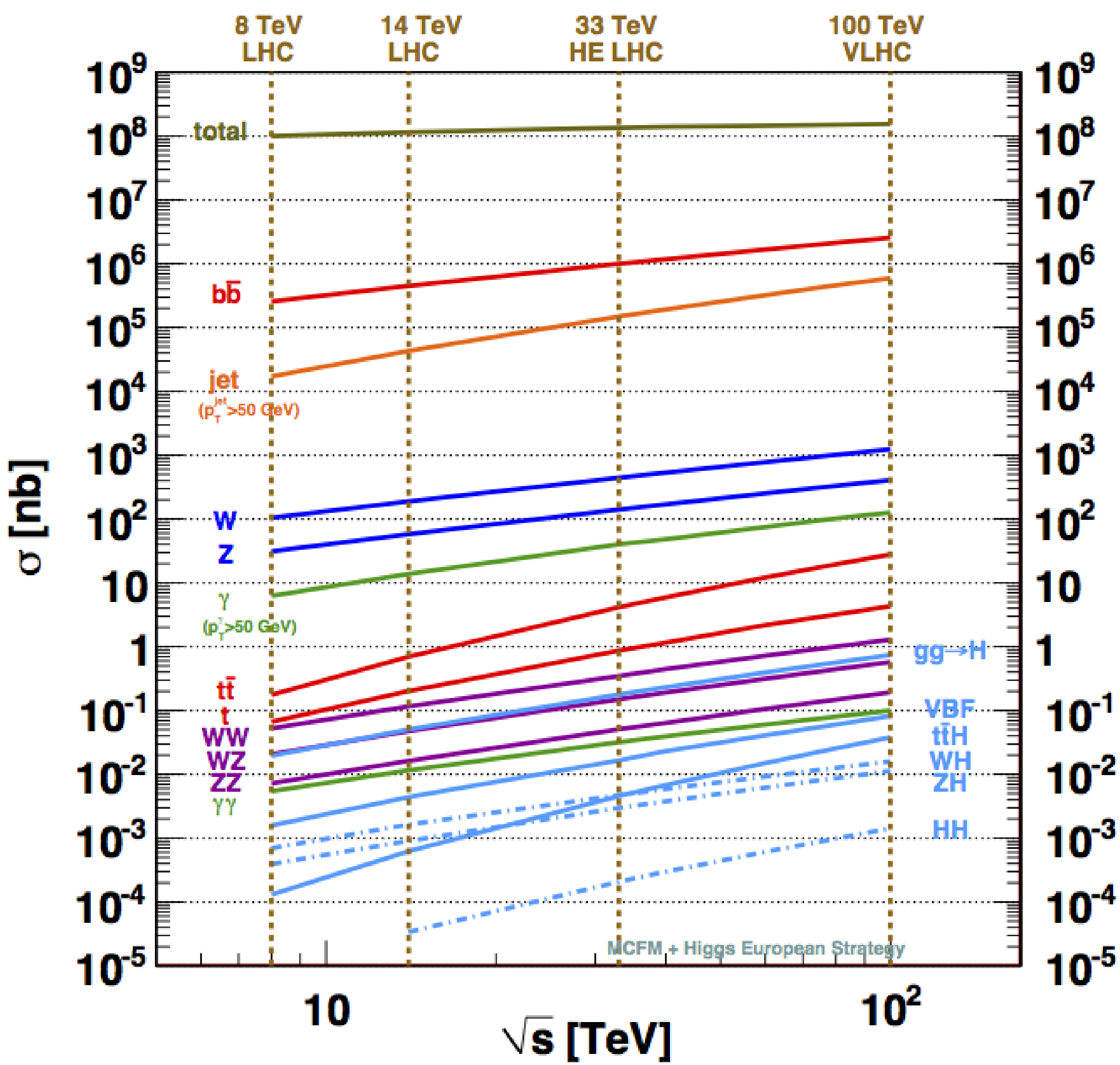
- several Higgs-related questions (naturalness, HH production, $V_L V_L$ scattering) may require high-E machines (higher than a 1 TeV ILC) → CLIC, 100 TeV pp
- a significant step in energy, made possible by strong technology progress (from which society also benefits), is the only way to look directly for the scale of new physics

No theoretical/experimental preference today for new physics in the 10-50 TeV region.

However: the outstanding MAJOR, CRUCIAL questions require concerted efforts in order to be addressed successfully, using all possible approaches: intensity-frontier precision experiments, astroparticle experiments, neutrino physics, high-E colliders, …

Cross sections vs √s

Snowmass report: arXiv:1310.5189



Process	R(100 TeV/14 TeV)
W	~ 7
Z	~ 7
WW	~10
ZZ	~10
tt	~30
H	~15
stop (m=1 TeV)	~ 10^3

Studies will be made vs √s:
- comparison with HE-LHC
- if cost forces machine staging

The two main goals

- ❑ Higgs boson measurements beyond HL-LHC (and future e^+e^- colliders)
- ❑ exploration of energy frontier

quite different in terms of machine and detector requirements

Exploration of E-frontier → look for heavy objects, including high-mass $V_L V_L$ scattering:

- ❑ requires as much integrated luminosity as possible (cross-section goes like 1/s)

→ maximizing reach may require operating at higher pile-up than HL-LHC (~140 events/x-ing)

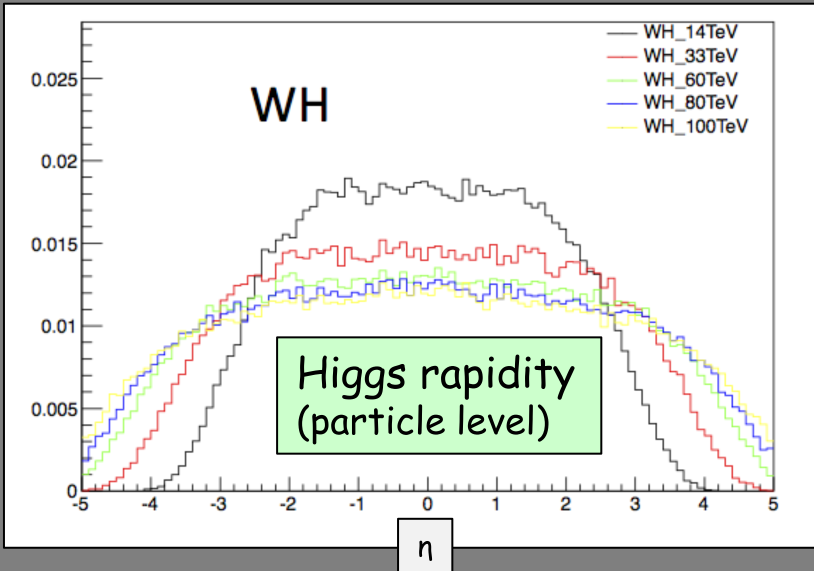
- ❑ events are mainly central → "ATLAS/CMS-like" geometry is ok
- ❑ main experimental challenges: good muon momentum resolution up to ~ 50 TeV; size of detector to contain up to ~ 50 TeV showers; forward jet tagging; pile-up

Precise measurements of Higgs boson :

- ❑ would benefit from moderate pile-up
- ❑ light-objects (Higgs !) production becomes flatter in rapidity with increasing $\sqrt{s}$
- ❑ main experimental challenges: higher acceptance for precision physics than ATLAS/CMS: tracking/B-field and good EM granularity down to $|\eta|$~4-5; forward jet tagging; pile-up

F. Gianotti, CLIC WS, 3/2/2014

H. Gray, C. Helsens



H→ 4l acceptance vs η coverage (e, μ p_T cuts applied)

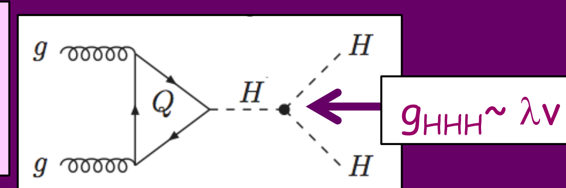
	14 TeV		100 TeV	
	2.5	4	2.5	4
ggF	0.87	1	**0.66**	0.91
WH	0.72	0.99	**0.52**	0.83
ttH	0.91	1	**0.70**	0.94

→ 20-30% acceptance loss for H→ 4l at 100 TeV (wrt 14 TeV) if tracking and precision calorimetry limited to |η|<2.5 (as ATLAS and CMS) → can be recovered by extending to |η|~ 4

Why still Higgs physics in 2040++ ?

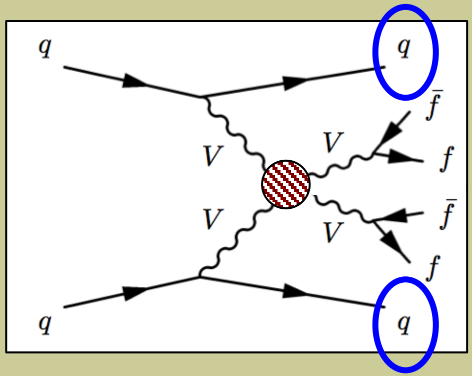
"Heavy" final states require high √s, e.g.:

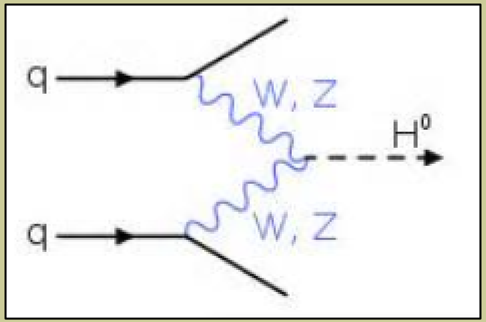
- HH production (including measurements of self-couplings λ)
- ttH (ttH→ ttμμ, ttZZ "rare" and particularly clean)



	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	[redacted]	83%	46%	21%	13%	21%	10%	20%	8%

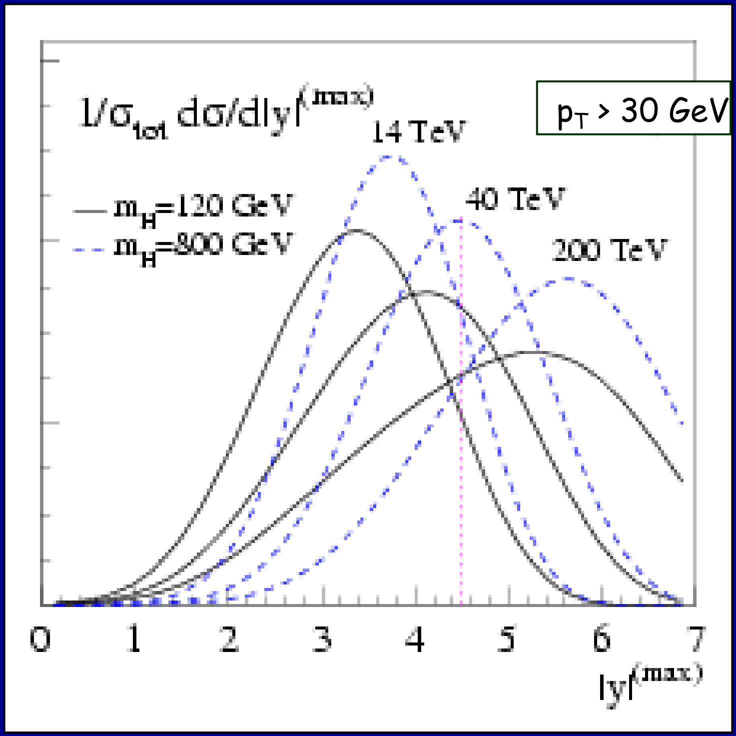
Forward jet tag expected to be crucial for both low-mass (Higgs) and high-mass VV scattering studies





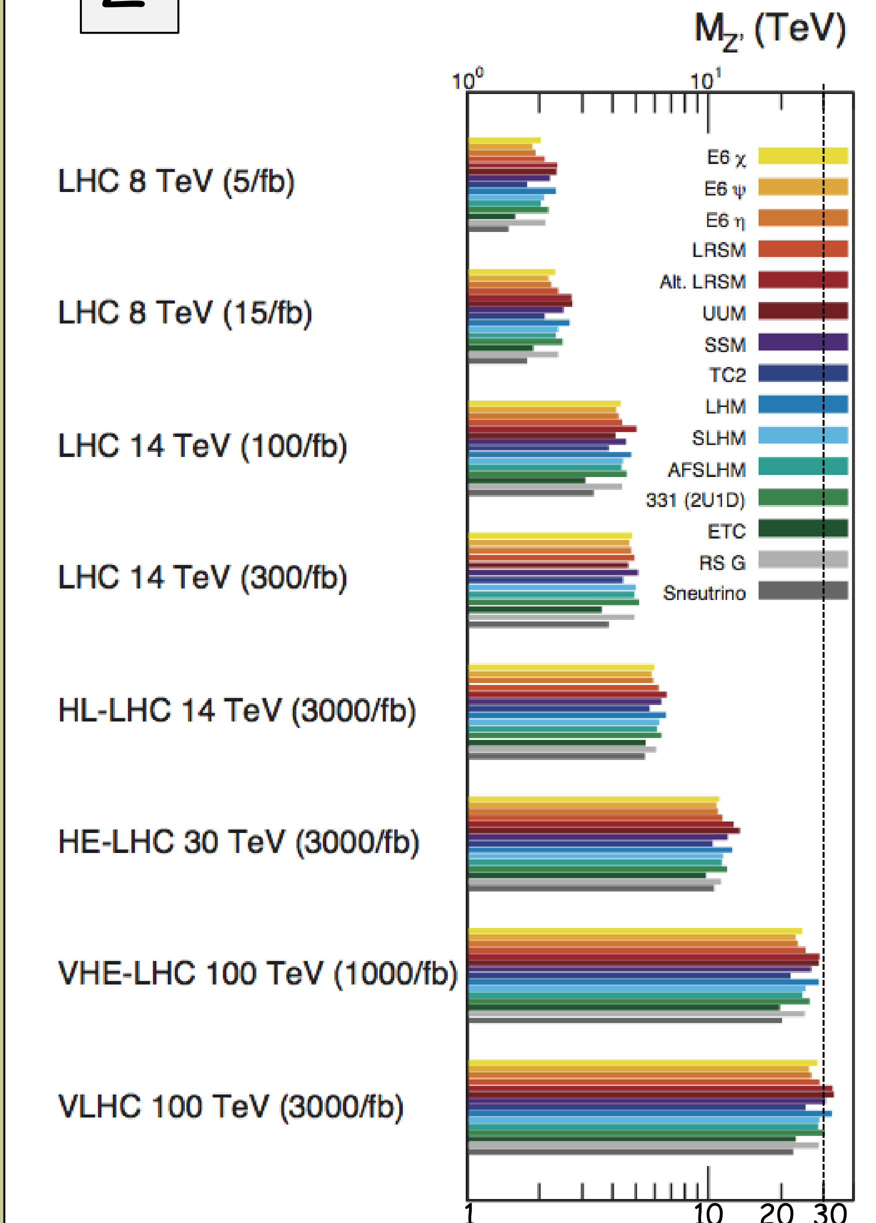
Maximum jet rapidity vs √s VBF "Higgs" production
(from an old US-VLHC study)

→ Calorimeter coverage up to |η| ~ 6 needed



Z′

Snowmass report: arXiv:1309.1688

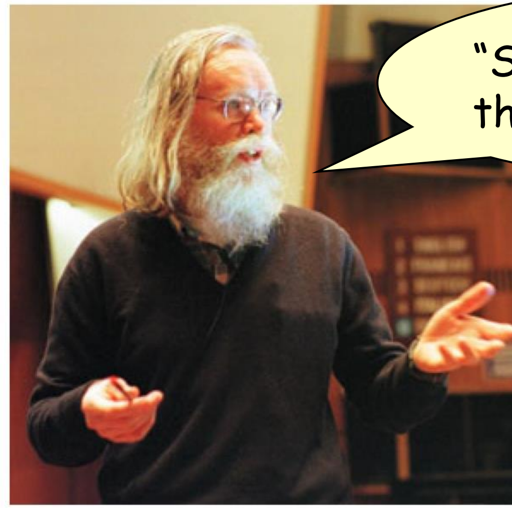


Expected reach in q*
(strongly produced):
M ~ 50 TeV

Expected sensitivity to
Compositeness scale:
Λ ~ 120 TeV

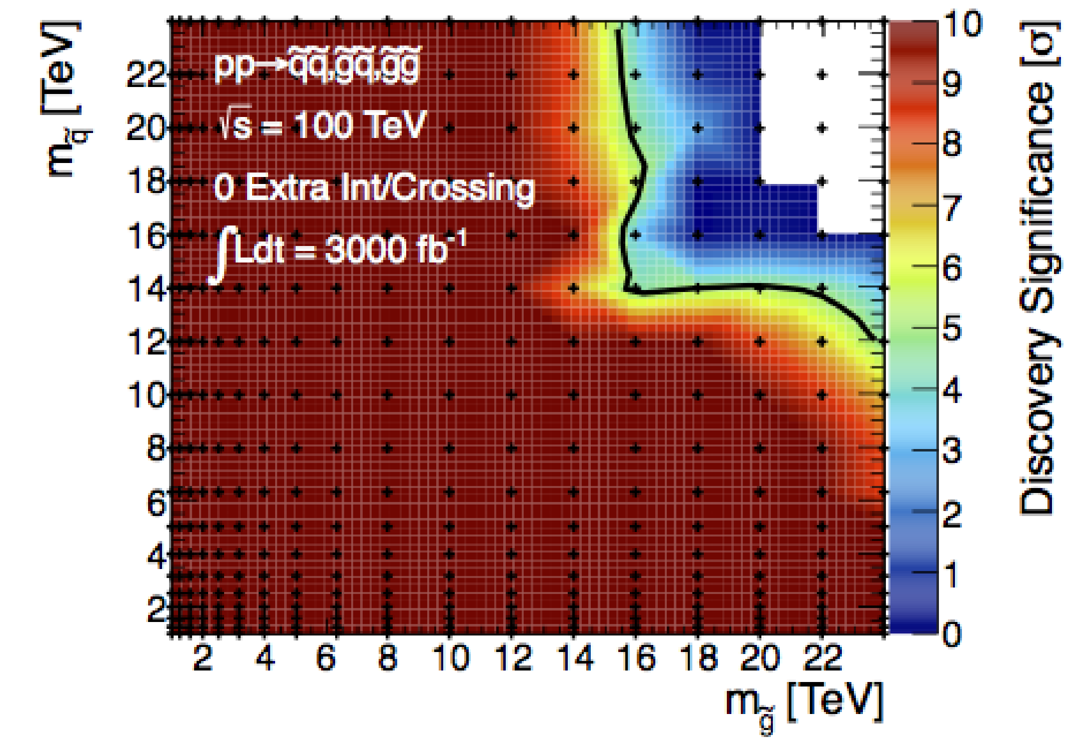
Why still SUSY searches in 2040++ ?

Indeed, even if fine-tuned,
it makes our universe more likely



"SUSY anywhere is better than SUSY nowhere"

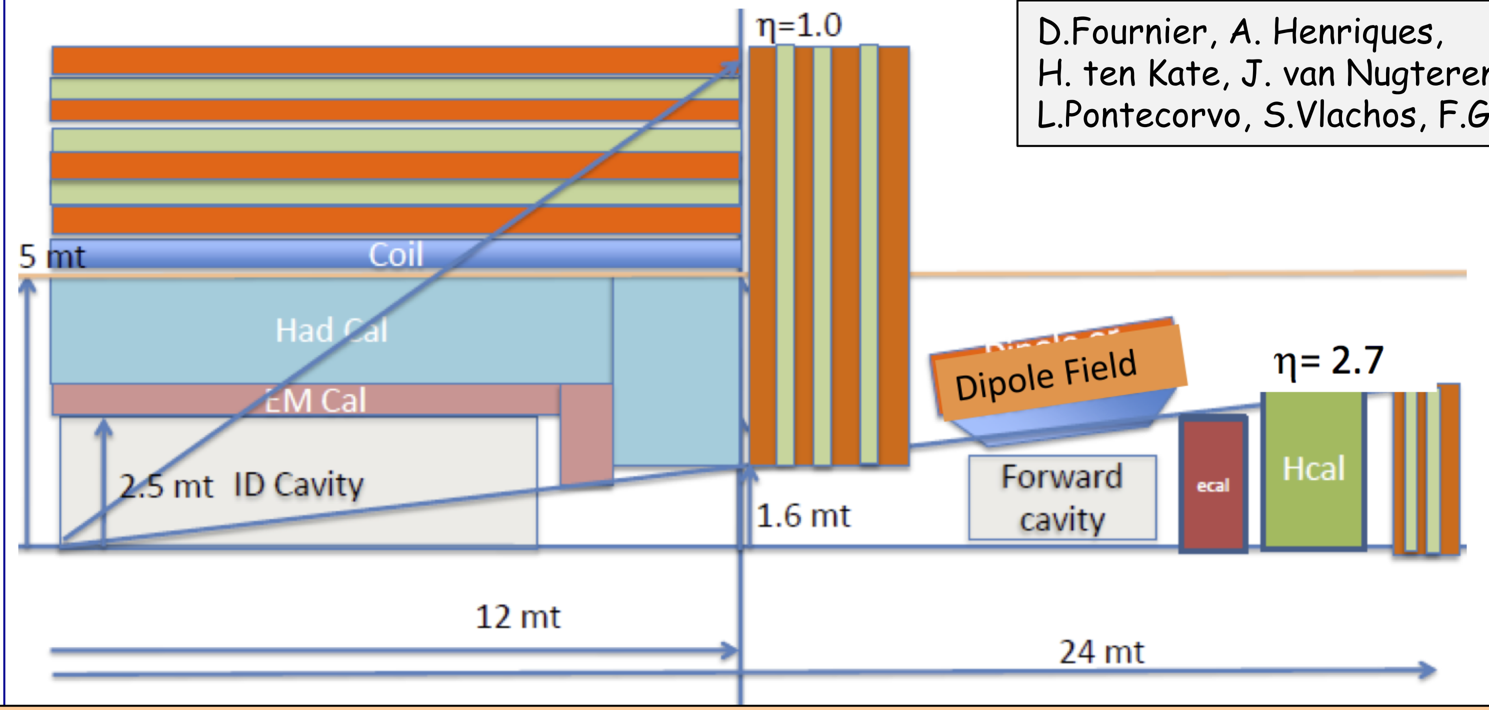
Snowmass report: arXiv:1311.6480



Discovery potential for squarks and gluinos at 100 TeV pp collider: up to ~ 14 TeV

Very first ideas about detector layout being developed

Here one example of a very preliminary exercise, for illustration purposes only …



D.Fournier, A. Henriques, H. ten Kate, J. van Nugteren, L.Pontecorvo, S.Vlachos, F.G.

- Large magnet system to achieve p resolution of ~ 20% for 20 TeV muons:
  -- central solenoid (B ≥ 5T) or toroid (bending ~ 20 Tm, x 7 ATLAS)
  -- size (R, L): ~ 2x ATLAS/CMS magnets
  -- stored energy: ~ 40-100 GJ !
  + forward dipole (~ 10 Tm) with tracking and calorimeters for low-mass physics up to $|\eta|$~4-5
- Alternative: decouple high-mass/E studies (big, mainly central, detector) from Higgs studies (smaller detector with forward coverage). Central detector could still do large part of high-p_T Higgs physics.
- Synergies with CLIC and ILC for detector design and R&D will be pursued

Conclusions

The extraordinary success of the LHC is the result of the ingenuity, vision and perseverance of the HEP community, and of > 20 years of talented, dedicated work
→ strength of the community is an asset also for future, even more ambitious, projects

After almost 100 years of superb theoretical and experimental work, the Standard Model is now complete. However: we know that it is not the <u>ultimate</u> theory of particle physics, because of the many outstanding questions

The full exploitation of the LHC, and more powerful future accelerators, will be needed to advance our knowledge of fundamental physics. Creativity, new ideas, developments and technologies will be essential to provide higher energy at affordable costs.

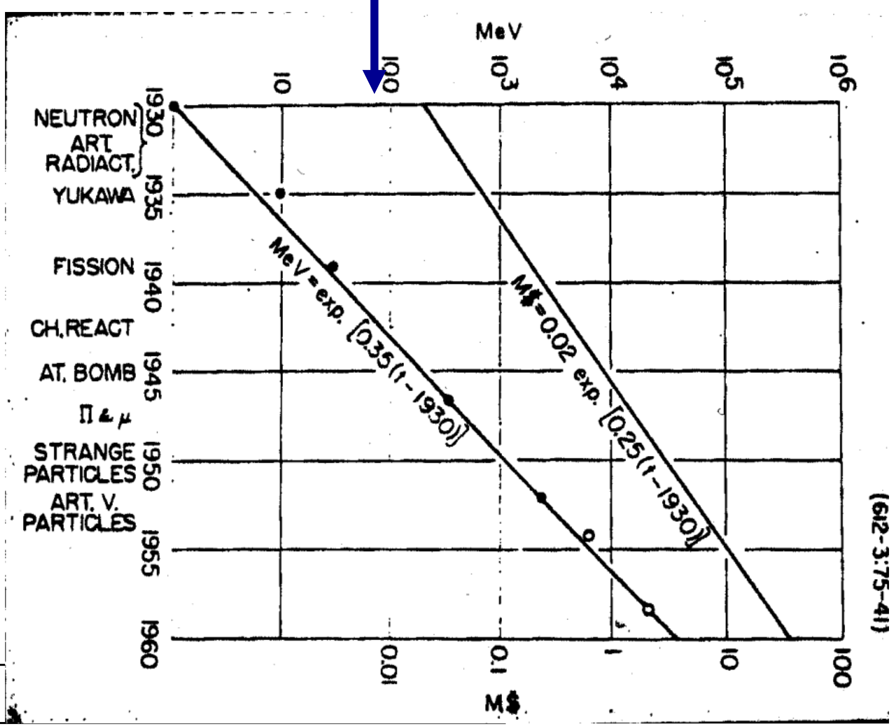
No doubt a future 100 TeV pp collider is an extremely challenging project.
However: it is one of the (few) options for the future of our discipline.
As researchers in this field we have the duty and the right to examine it and, if justified by physics, ….

.. to be **BRAVE** and **DREAM** ….

From E. Fermi, preparatory notes for a talk on
"What can we learn with High Energy Accelerators ? "
given to the American Physical Society, NY, Jan. 29th 1954

For these reasons....clamoring for higher and higher....
Slide 1 - MeV - M$ versus time.
Extrapolating to 1994...5 hi 9 Mev or hiest cosmic...170 B$....preliminary design....8000 km, 20000 gauss
Slide 2 - 5 hi 15 eV machine.

Whay we can learn impossible to guess....main element surprise....some things look for but see others.....Experiems on pions....sharpening knowledge....~~spin zero and odd symmetry~~....certainly look for multiple production...



Fermi's extrapolation to year 1994:
2T magnets, R=8000 km (fixed target !),
E_{beam} ~ 5×10^3 TeV, cost 170 B$

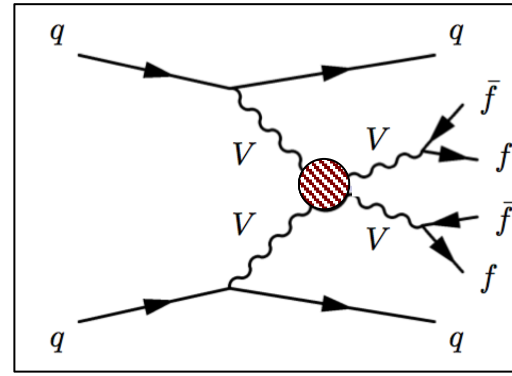
Fortunately we have invented colliders and superconducting magnets …

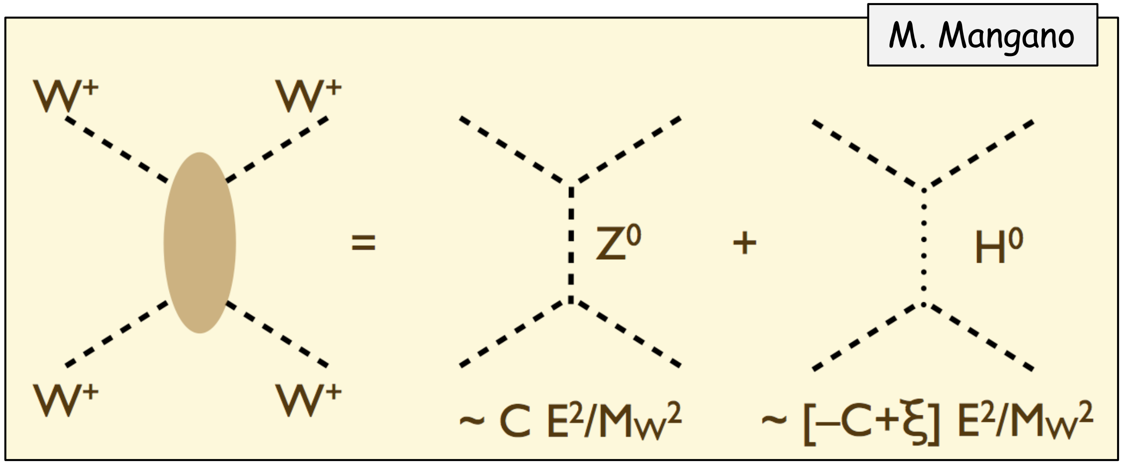
SPARES

Process	$\sqrt{s}$ = 14 TeV	$\sqrt{s}$ = 33 TeV	$\sqrt{s}$ = 40 TeV	$\sqrt{s}$ = 60 TeV	$\sqrt{s}$ = 80 TeV	$\sqrt{s}$ = 100 TeV
ggF [a]	50.35 pb	178.3 pb (3.5)	231.9 pb (4.6)	394.4 pb (7.8)	565.1 pb (11.2)	740.3 pb (14.7)
VBF [b]	4.40 pb	16.5 pb (3.8)	23.1 pb (5.2)	40.8 pb (9.3)	60.0 pb (13.6)	82.0 pb (18.6)
WH [c]	1.63 pb	4.71 pb (2.9)	5.88 pb (3.6)	9.23 pb (5.7)	12.60 pb (7.7)	15.90 pb (9.7)
ZH [c]	0.904 pb	2.97 pb (3.3)	3.78 pb (4.2)	6.19 pb (6.8)	8.71 pb (9.6)	11.26 pb (12.5)
ttH [d]	0.623 pb	4.56 pb (7.3)	6.79 pb (11)	15.0 pb (24)	25.5 pb (41)	37.9 pb (61)
$gg \rightarrow HH^{e}(\lambda=1)$	33.8 fb	207 fb (6.1)	298 fb (8.8)	609 fb (18)	980 fb (29)	1.42 pb (42)

Higgs cross sections (LHC HXS WG)

Vector-Boson (V=W, Z) Scattering at large m_{VV}
→ insight into EWSB dynamics





First process (Z exchange) becomes unphysical ($\sigma \sim E^2$) at $m_{WW} \sim$ TeV if no Higgs, i.e. if second process (H exchange) does not exists. In the SM with Higgs: $\xi = 0$

CRUCIAL "CLOSURE TEST" of the SM:

- ❑ Verify that Higgs boson accomplishes the job of canceling the divergences
- ❑ Does it accomplish it fully or partially ? I.e. is $\xi = 0$ or $\xi \neq 0$?

If $\xi \neq 0$ → new physics (resonant and/or non-resonant deviations) → important to study as many final states as possible (WW, WZ, ZZ) to constrain the new (strong) dynamics

Requires energy and luminosity → first studies possible with design LHC, but HL-LHC 3000 fb^{-1} needed for sensitive measurements of SM cross section or else more complete understanding of new dynamics

VBS

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \left[\frac{a_i}{\Lambda} \mathcal{O}_i^{(5)} + \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \frac{e_i}{\Lambda^4} \mathcal{O}_i^{(8)} \cdots \right]$$

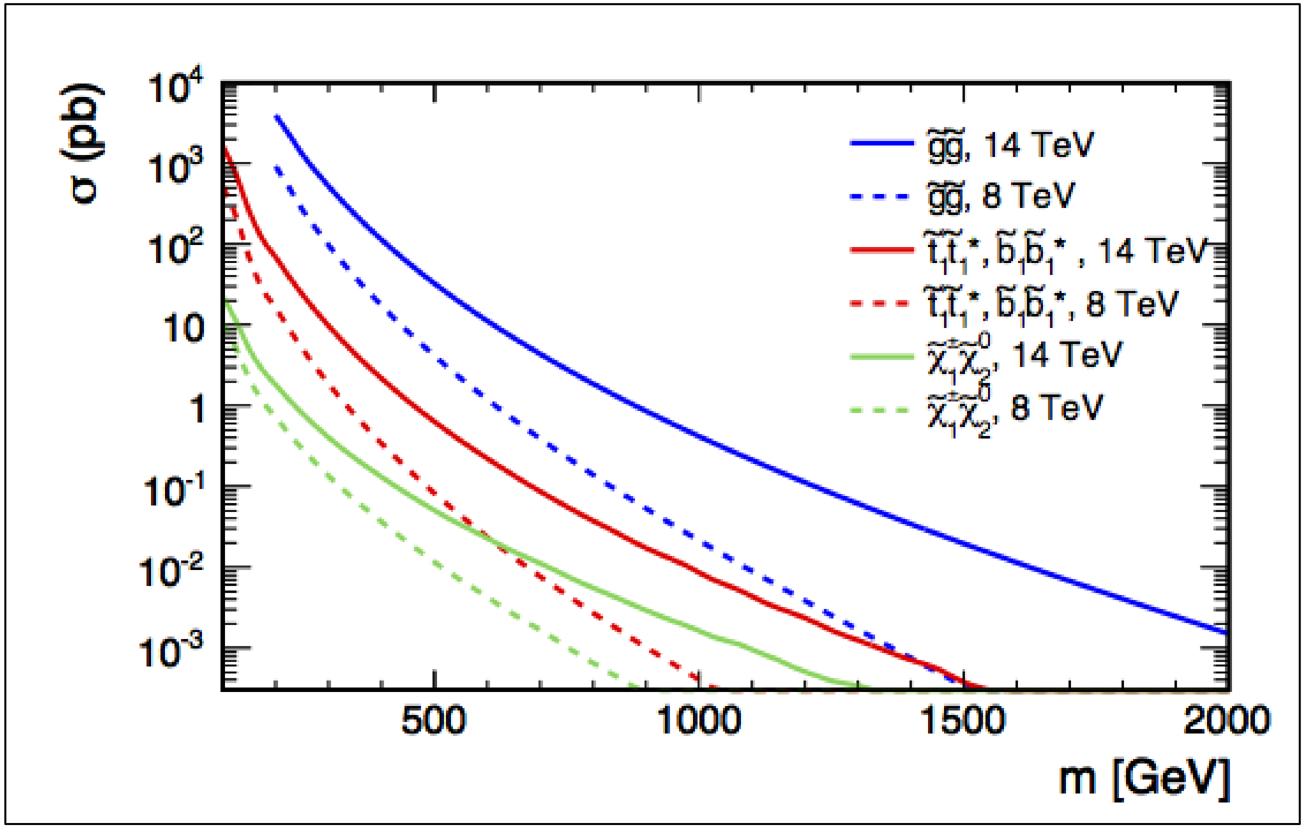
Observation of **anomalous quartic gauge coupling** would indicate **new physics in the electroweak symmetry breaking sector!**

- HL-LHC enhances discovery range for new higher-dimension electroweak operators by more than a factor of two

Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^\pm W^\pm$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}

Λ_{UV}: unitarity violation bound corresponding to the sensitivity with 3000 fb^{-1}

SM discovery expected with 185 fb^{-1}
BSM contribution at TeV Scale might be observed at 300 fb^{-1}!
If BSM discovered in 300 fb^{-1} dataset, then the coefficients on the new operators could be measured to 5% precision with 3000 fb^{-1}



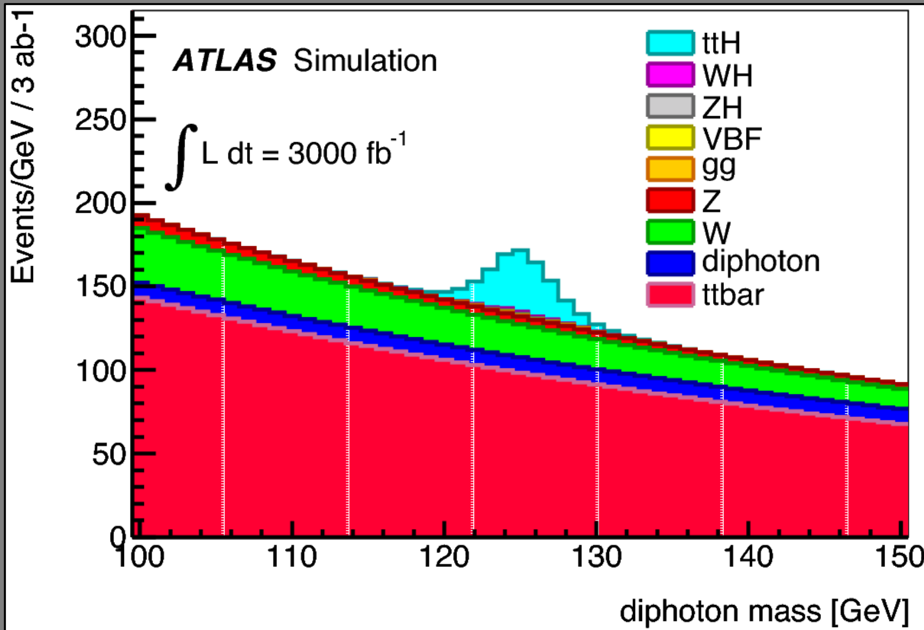
σ (pb)
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
500
1000
1500
2000
m [GeV]
g̃g̃, 14 TeV
g̃g̃, 8 TeV
t̃₁t̃₁*, b̃₁b̃₁* , 14 TeV
t̃₁t̃₁*, b̃₁b̃₁*, 8 TeV
χ̃₁±χ̃₂0, 14 TeV
χ̃₁±χ̃₂0, 8 TeV

Search for top-antitop resonances in the lepton + jet (dilepton) channel

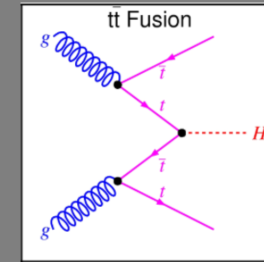
ATLAS simulation

model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
Z'_{topcolor}	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)

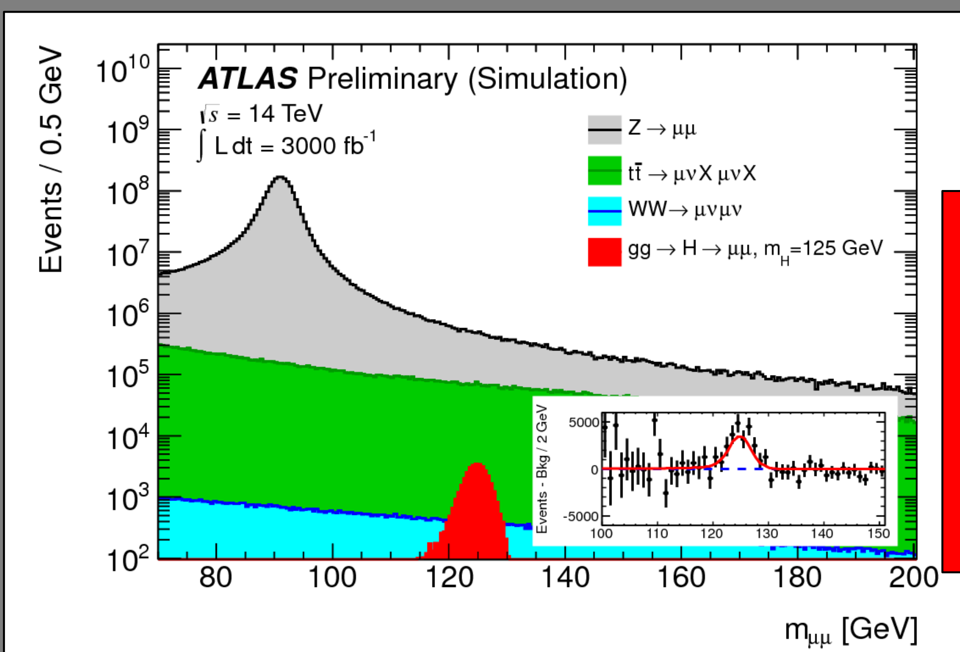
(in TeV)



ttH production with H → γγ



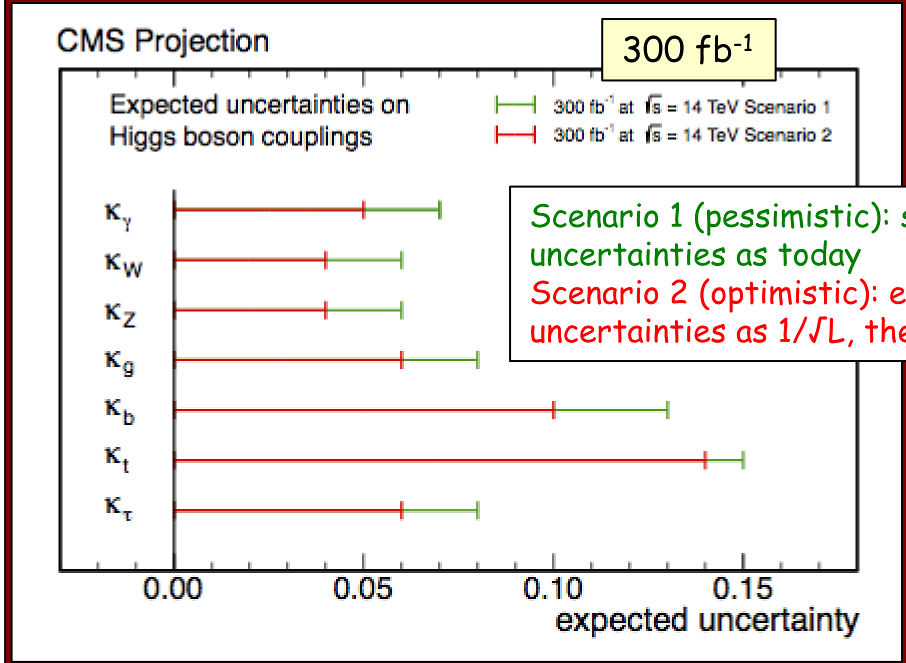
- Gives direct access to Higgs-top coupling (intriguing as top is heavy)
- Today's sensitivity: 6xSM cross-section
- With 3000 fb^{-1} expect 200 signal events (S/B ~ 0.2) and > 5σ
- Higgs-top coupling can be measured to about 10%



H → μμ

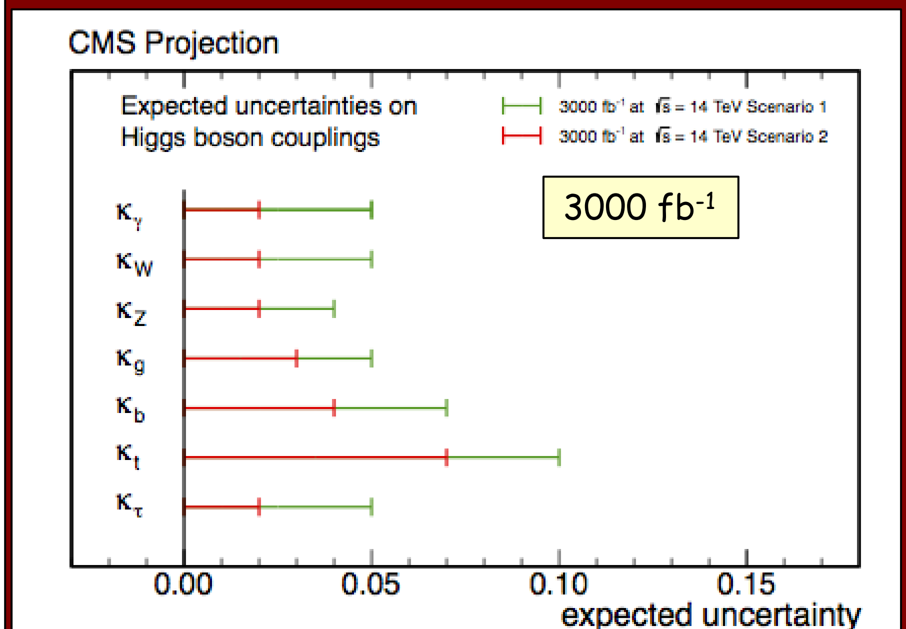
- Gives direct access to Higgs couplings to fermions of the second generation.
- Today's sensitivity: 8xSM cross-section
- With 3000 fb^{-1} expect 17000 signal events (but: S/B ~ 0.3%) and ~ 7σ significance
- Higgs-muon coupling can be measured to about 10%

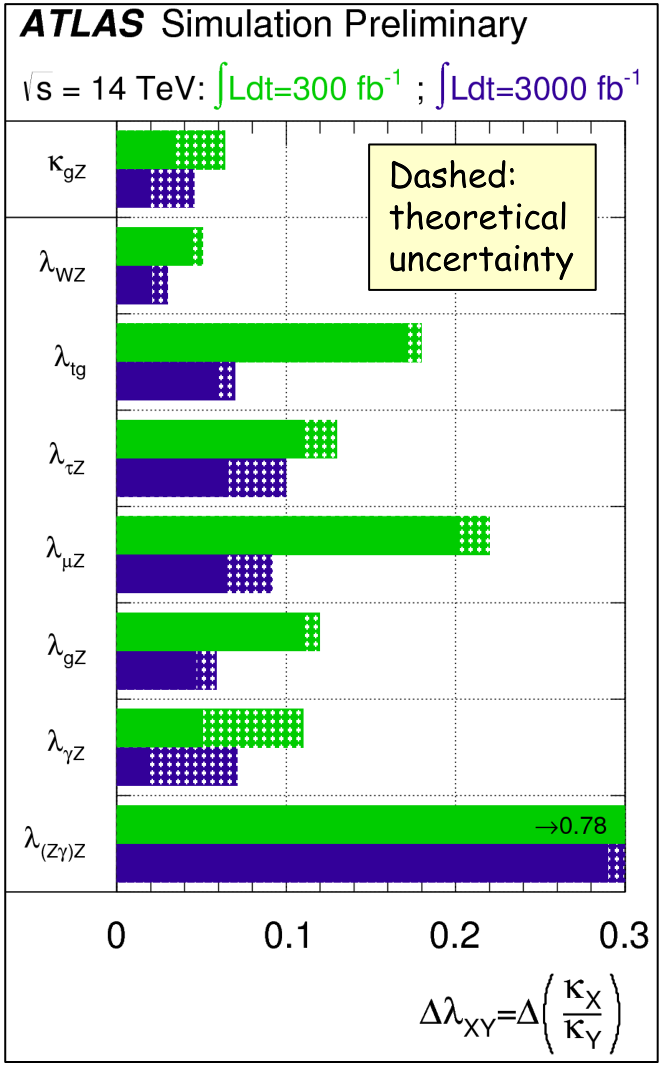
Measurements of Higgs couplings



Scenario 1 (pessimistic): systematic uncertainties as today

Scenario 2 (optimistic): experimental uncertainties as $1/\sqrt{L}$, theory halved





k_i= measured coupling normalized to SM prediction

$\Lambda_{ij}=k_i/k_j$

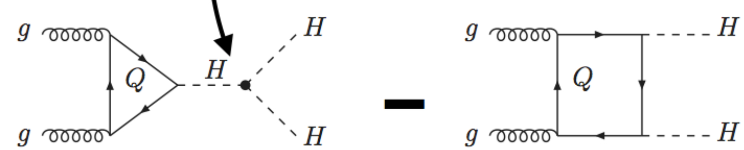
Main conclusions:

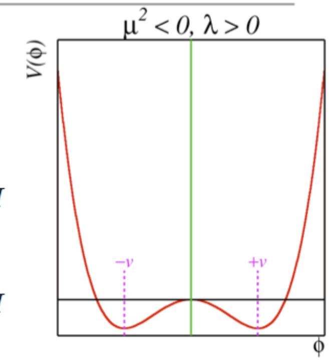
- 3000 fb^{-1}: typical precision 2-10% <u>per experiment</u> (except rare modes)
  → 1.5-2x better than with 300 fb^{-1}
- Crucial to also reduce theory uncertainties

Higgs pair production

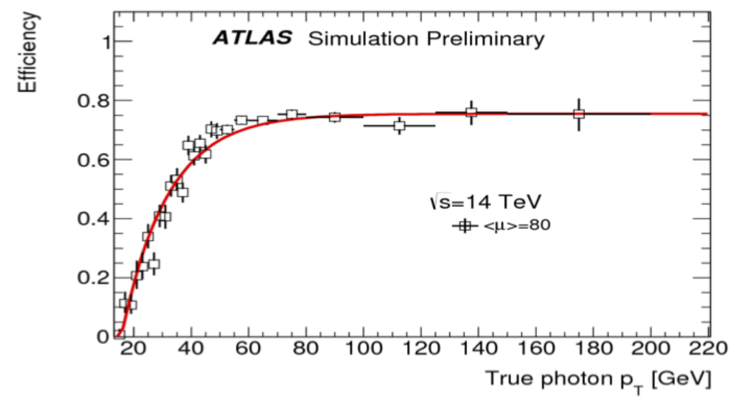
- Higgs self-coupling is an important parameter of SM
  - *Test through di-HIggs production*
- Experiments are still working on projections of precision
  - *Critically dependent on detector many aspects of detector performance*
    - **b-tagging, resolution, fake rates**
- Small cross-section, large backgrounds
  - *Clearly needs full HL-LHC luminosity*
  - *And detectors that maximize the experimental efficiency*

$$M_H^2 = \lambda v^2 \qquad g_{hhh} \equiv 3\lambda v = \frac{3M_H^2}{v}$$





Expected events	
bbWW	30000
bbττ	9000
WWWW	6000
γγbb	320
γγγγ	1



Instead of asking with what precision can observe di-Higgs, easier (and maybe more useful) might be to set detector requirements to make N σ measurement

C. Hills, HL-LHC ECFA WS

F. Gianotti, CLIC WS, 3/2/2014

Machine parameters: $\sqrt{s}$ vs ring size and magnets

Facility	Ring (km)	Magnets (T)	$\sqrt{s}$ (TeV)
(SSC)	87	6.6	40
LHC	27	8.3	14
HE-LHC	27	16-20	26-33
FHC	80 80 100	8.3 20 16	42 100 100

F. Gianotti, CLIC WS, 3/2/2014