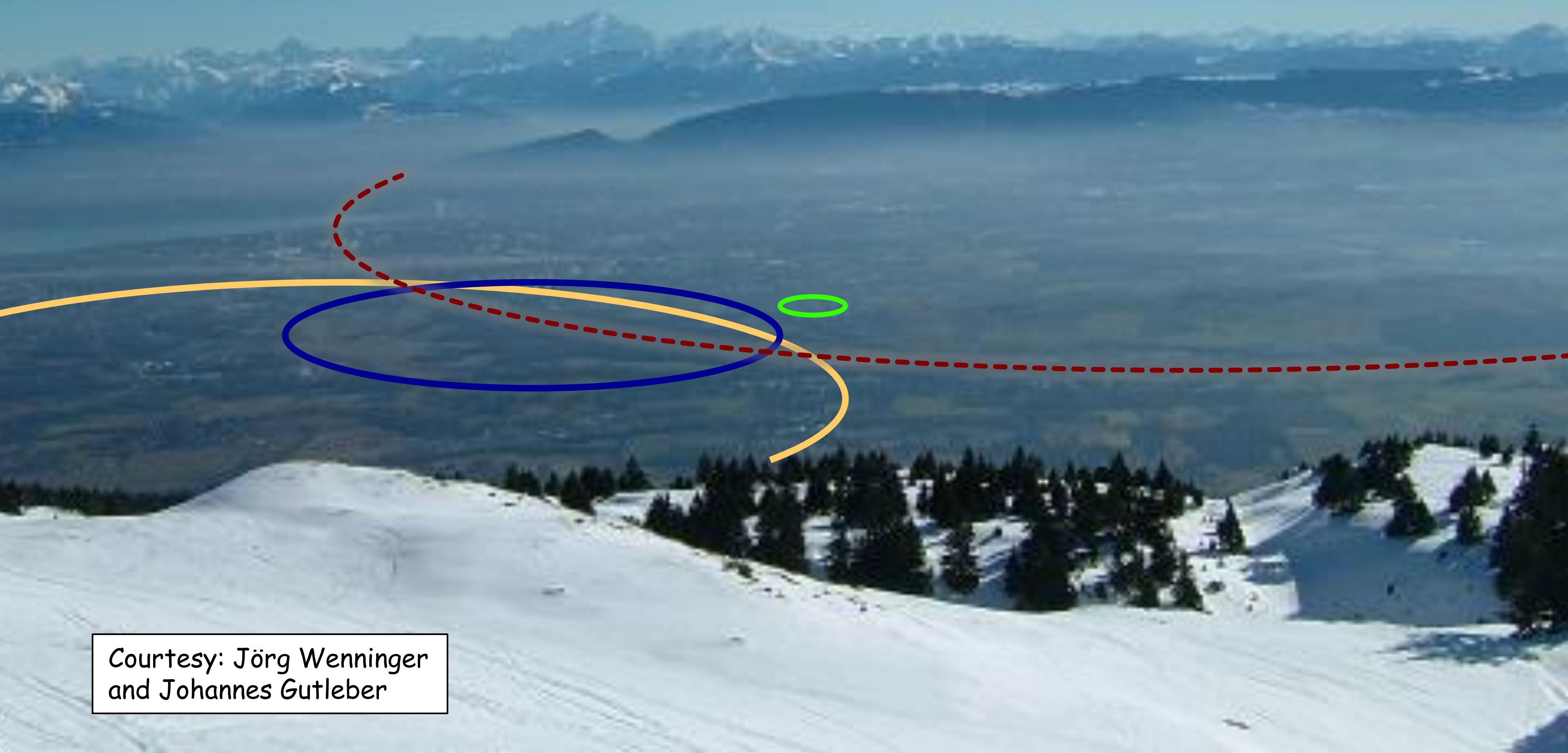
FCC hadron collider option: experiments and physics

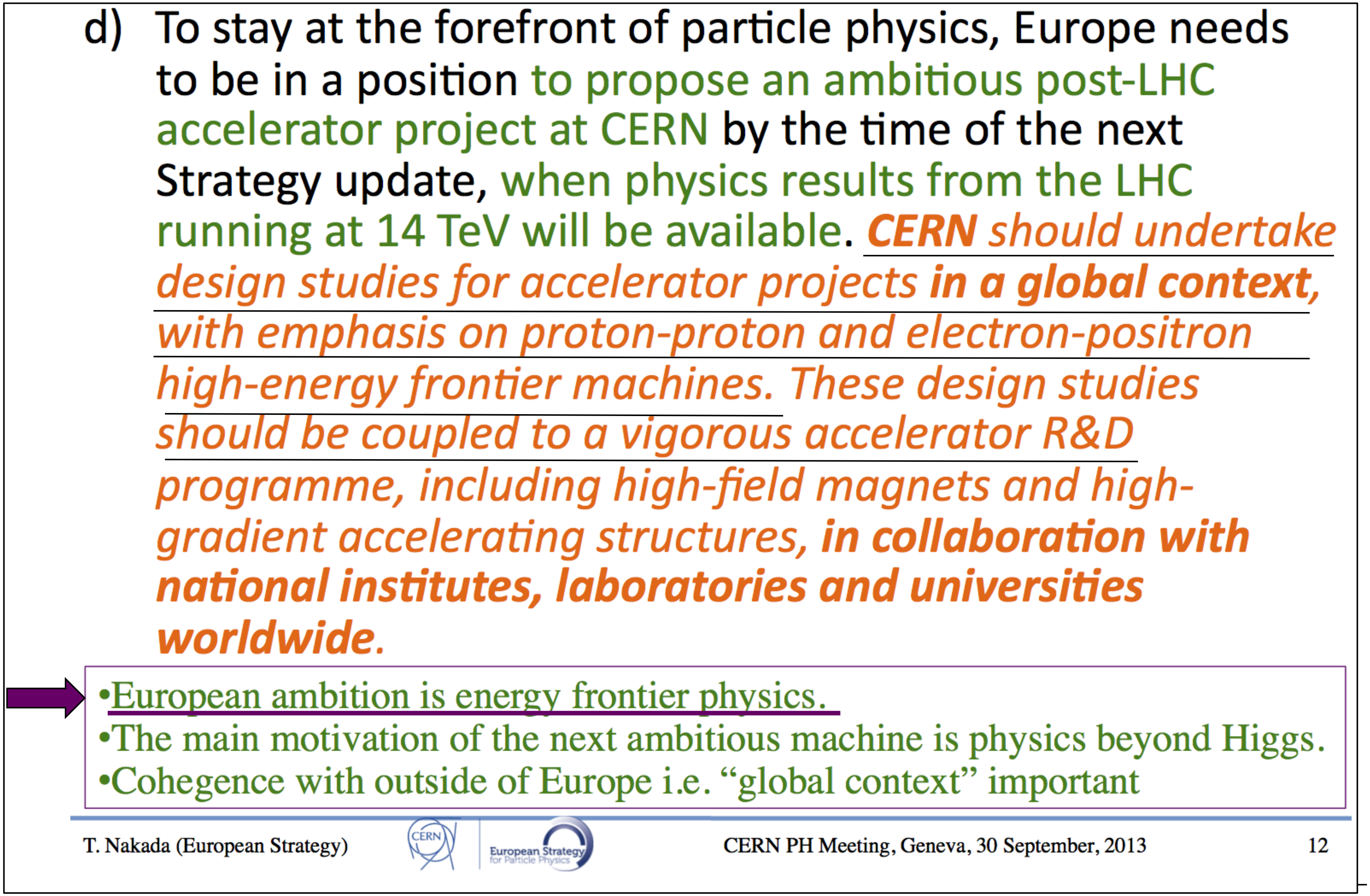
Fabiola Gianotti, CERN, Physics Department

LHCb general meeting, 1 April 2014



Courtesy: Jörg Wenninger
and Johannes Gutleber

From European Strategy deliberations



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**.*

- European ambition is energy frontier physics.
- The main motivation of the next ambitious machine is physics beyond Higgs.
- Cohegence with outside of Europe i.e. "global context" important

T. Nakada (European Strategy) CERN European Strategy for Particle Physics CERN PH Meeting, Geneva, 30 September, 2013 12

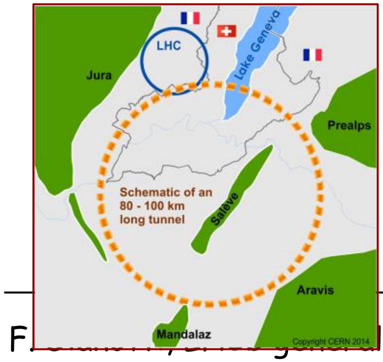
In September 2013, CERN Management set up a FCC project, with the main goal of preparing a Conceptual Design Report by the time of the next ES (~2018)

CDR main scope is to describe physics motivations, technical feasibility (e.g. tunneling, magnets), design (machine, experiments, ..), cost

Project Leader: Michael Benedikt (CERN, Beam Department)

Emphasis on (and design driven by) high-energy pp collider requirements.
An e^+e^- machine (FCC-ee, former "TLEP") and/or an ep machine (FCC-he) in the same tunnel are also considered and studied.
Note: China's emphasis is on 50-70 km e^+e^- machine

A kick-off meeting took place on 12-15 February 2014 at University of Geneva
http://indico.cern.ch/event/282344/timetable/#20140212.detailed
Very successful, almost 350 participants, strong international interest



FCC WEB site:
http://cern.ch/fcc


Future Circular Colliders Study Kickoff Meeting

12-15 February 2014
University of Geneva, Geneva
Europe/Zurich timezone

Future Circular Collider Kickoff Meeting

This meeting is the starting point of a five-year international design study called "Future Circular Colliders" (FCC) with emphasis on a hadron collider with a centre-of-mass energy of the order of 100 TeV in a new 80-100 km tunnel as a long-term goal. The design study includes a 90-400 GeV lepton collider, seen as a potential intermediate step. It also examines a lepton-hadron collider option. The international kick-off meeting for the FCC design study will be held at the University of Geneva, Unimail site, on 12–15 February 2014. The scope of this meeting will be to discuss the main study topics and to prepare the groundwork for the establishment of international collaborations and future studies. The formal part of the meeting will start at noon on Wednesday 12 February and last until noon on Friday 14 February. It will be followed by break-out sessions on the various parts of the project on the Friday afternoon, with summary sessions until noon on Saturday 15 February.

Main areas for design study

Preparatory group
for a kick-off meeting
=> Steering committee

Machines and infrastructure conceptual designs	**Technologies R&D activities Planning**	**Physics experiments detectors**
Infrastructure	High-field magnets	Hadron physics experiments interface, integration
Hadron collider conceptual design	Superconducting RF systems	$e^+ e^-$ coll. physics experiments interface, integration
Hadron injectors	Cryogenics	e^- - p physics and integration aspects
Lepton collider conceptual design	Specific technologies	
Safety, operation, energy management environmental aspects	Planning	

FHC-hh: represented in FCC Steering Committee by A.Ball, F.G., M.Mangano

- ❑ Work started in November 2013
- ❑ > 200 people subscribed to the FCC-hh mailing list, but small number (~30) active so far at tiny fraction of their time (LHCb contact: Tim Gershon)

Three main outcomes from LHC Run 1

We have consolidated the SM with detailed studies at √s = 7-8 TeV
(including measurement of 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 √s ~ 14 TeV in 2015++, its mass spectrum is quite heavy
→ it will likely require a lot of luminosity and energy to study it fully and in detail
→ implications on energy of future machines

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 current 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, e.g.:
naturalness, dark matter, matter/antimatter asymmetry, the flavour/family problems, unification of coupling constants, etc.

- ❑ Answers to some of the above (and other) questions expected at the ~TeV scale, whose study JUST started at the LHC → imperative necessity of exploring this scale as much as we can with the highest-E facility we have today
- ❑ Higgs sector (Higgs boson, EWSB mechanism): less known component (experimentally) of the SM → lot of work needed to e.g. understand if it is the minimal mechanism or something more complex

↓

Full exploitation of the LHC → HL-LHC ($\sqrt{s}$ ~ 14 TeV, up to 3000 fb^{-1}) is a MUST
Europe's top priority, according to the European Strategy

HL-LHC potential in a nutshell

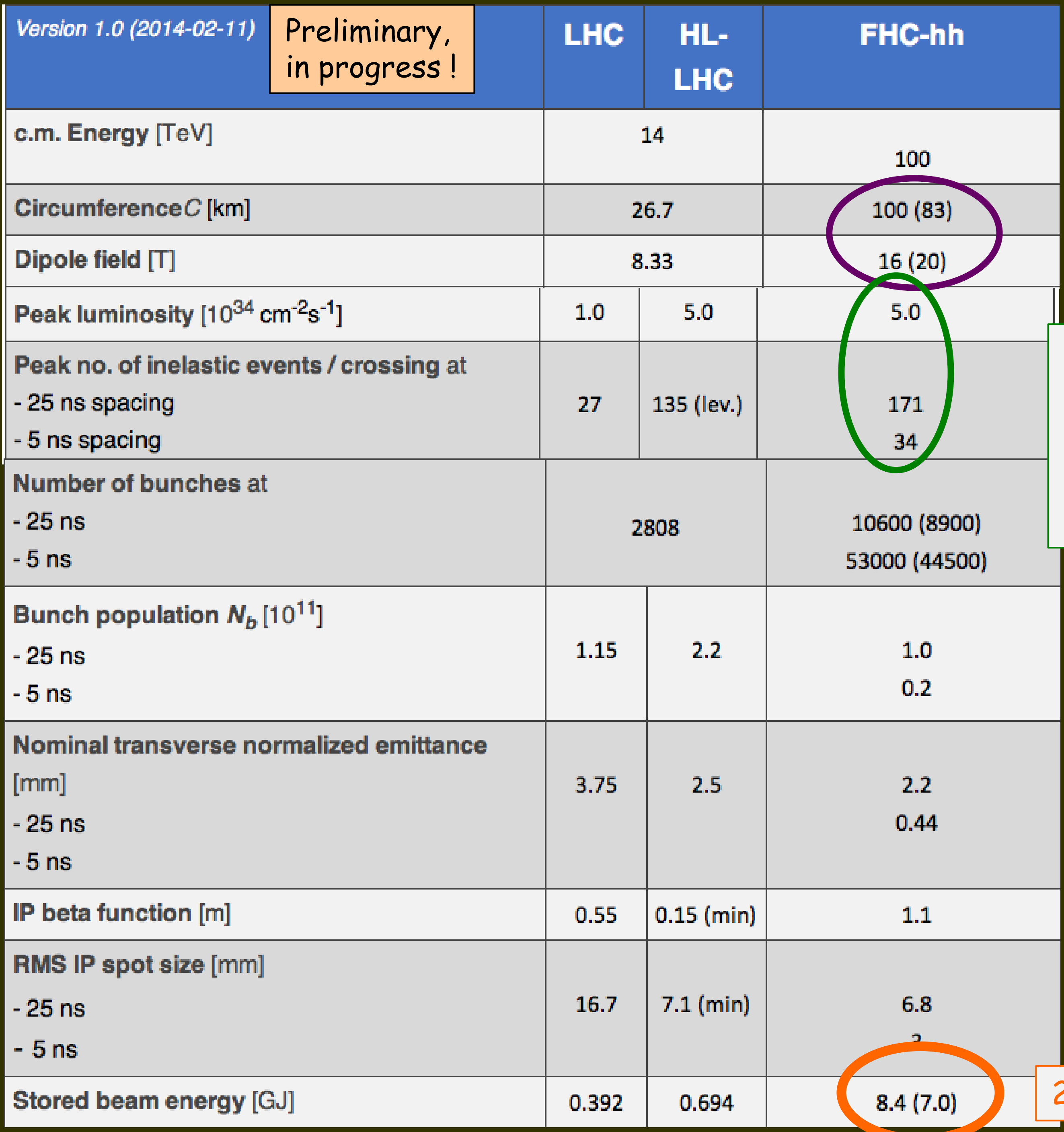
❑ Higgs couplings (assuming SM Γ_H):
-- 2-5% in most cases, 10% for rare processes (H→ μμ, ttH → ttγγ)
-- access for first time to 2nd generation fermions through (rare) H → μμ decay
-- direct access for first time to top Yukawa coupling through (rare) ttH → ttγγ
-- may measure Higgs self couplings to 30% ?

❑ Extend reach for stop quarks (naturalness !) up to m ~ 1.5 TeV

❑ Extend mass reach for singly-produced particles by 1-2 TeV compared to design LHC (300 fb^{-1}) → push energy frontier close to ~10 TeV

→ significant step forward in the knowledge of the Higgs boson
(though not competitive with ultimate reach of FCC-ee, ILC, CLIC)
→ detailed exploration of the TeV scale

Parameters of a ~ 100 TeV pp collider



Version 1.0 (2014-02-11) Preliminary, in progress !	LHC	HL-LHC	FHC-hh
c.m. Energy [TeV]	14		100
Circumference *C* [km]	26.7		100 (83)
Dipole field [T]	8.33		16 (20)
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	5.0	5.0
Peak no. of inelastic events / crossing at - 25 ns spacing - 5 ns spacing	27	135 (lev.)	171 34
Number of bunches at - 25 ns - 5 ns	2808		10600 (8900) 53000 (44500)
Bunch population N_b [10^{11}] - 25 ns - 5 ns	1.15	2.2	1.0 0.2
Nominal transverse normalized emittance [mm] - 25 ns - 5 ns	3.75	2.5	2.2 0.44
IP beta function [m]	0.55	0.15 (min)	1.1
RMS IP spot size [mm] - 25 ns - 5 ns	16.7	7.1 (min)	6.8 3
Stored beam energy [GJ]	0.392	0.694	8.4 (7.0)

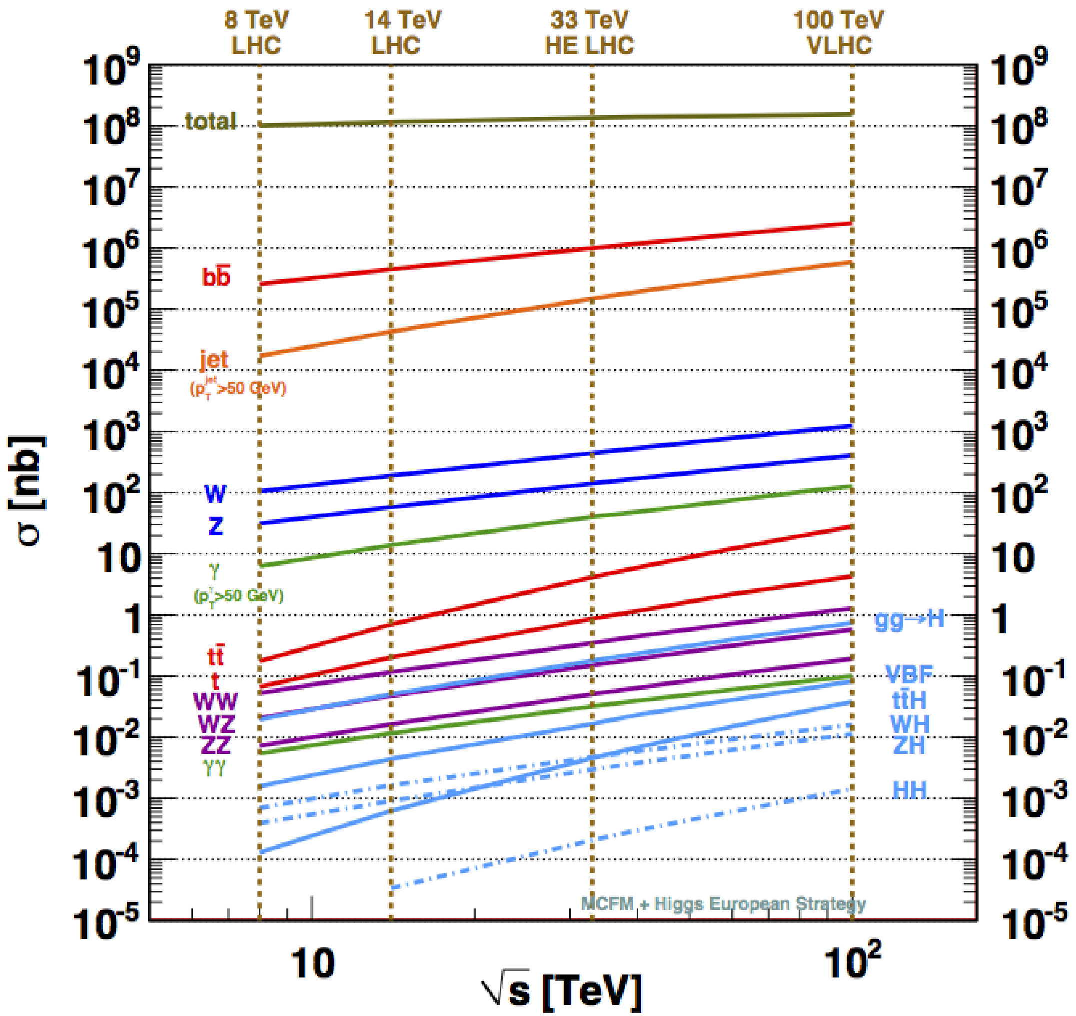
Nb_3Sn ok up to 16 T; 20 T needs HTS

Largest integrated luminosity needed for heavy physics
→ L=10^{35} may be reached
→ bunch-spacing 5 ns to mitigate pile-up and e-cloud

25 x LHC !

Cross sections vs √s

Snowmass report: arXiv:1310.5189



Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3

Studies will be made vs √s:

- ❑ comparison with HE-LHC
- ❑ if cost forces machine staging

Physics case: two scenarios

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

☐ LHC and/or HL-LHC find new physics:
the heavier part of the spectrum may not be fully accessible at $\sqrt{s} \sim 14$ TeV
→ strong case for a 100 TeV pp collider: 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 1 TeV ILC); access unbroken regime of EW symmetry; baryon asymmetry from EW phase transition ?
☐ 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

Although there is no theoretical/experimental preference today for new physics in the 10-50 TeV region, the outstanding questions are major and crucial, and we must address them. This requires concerted efforts of all possible approaches: intensity-frontier precision experiments, astroparticle experiments, dedicated searches, neutrino physics, high-E colliders, …

Among the main targets for the coming months: identify experimental challenges, in particular those requiring new concepts and detector R&D

The two main goals

- ☐ Higgs boson measurements beyond HL-LHC (and any e^+e^- collider)
- ☐ exploration of energy frontier

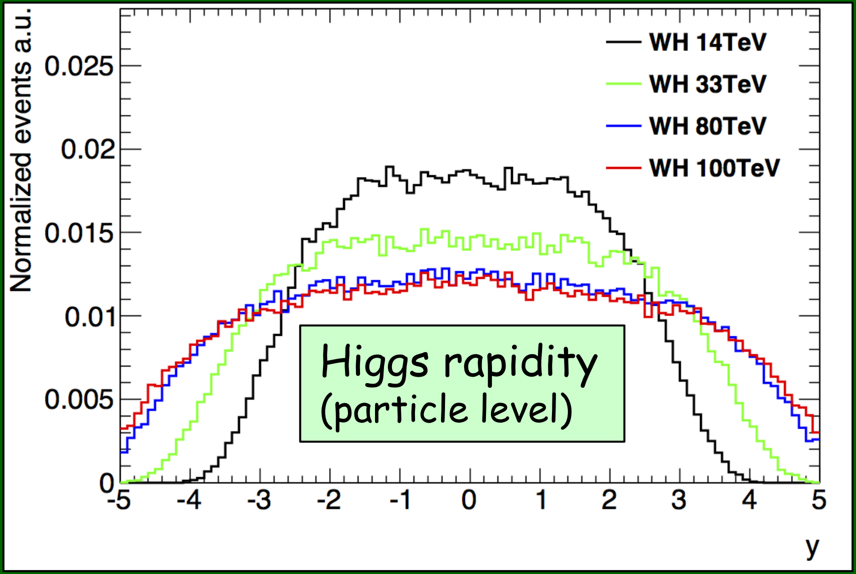
are quite different in terms of machine and detector requirements

Exploration of E-frontier → look for heavy objects up to m ~30-50 TeV, including high-mass V_LV_L scattering:

- ☐ requires as much integrated luminosity as possible (cross-section goes like 1/s)
- → 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 object → production becomes flatter in rapidity with increasing $\sqrt{s}$
- ☐ main experimental challenges: larger acceptance for precision physics than ATLAS/CMS
- → tracking/B-field and good EM granularity down to $|\eta|$~4-5; forward jet tagging; pile-up



Higgs rapidity (particle level)

H. Gray, C. Helsens

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

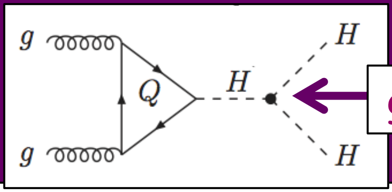
	14 TeV		100 TeV	
	2.5	4	2.5	4
ggF	0.74	0.99	**0.56**	0.88
WH	0.66	0.97	**0.45**	0.77
ZH	0.69	0.98	**0.48**	0.80
ttH	0.84	1	**0.56**	0.90
VBF	0.75	0.98	**0.55**	0.87

→ 30-50% acceptance loss for H→ 4l at 100 TeV wrt 14 TeV if tracking and precision EM 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 (note: ttH→ ttμμ, ttZZ "rare" and particularly clean)

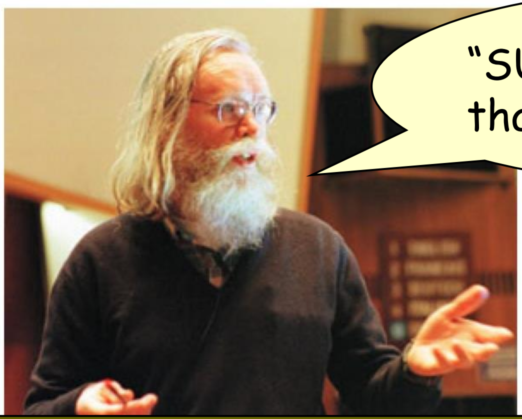


$g_{HHH} \sim \lambda v$

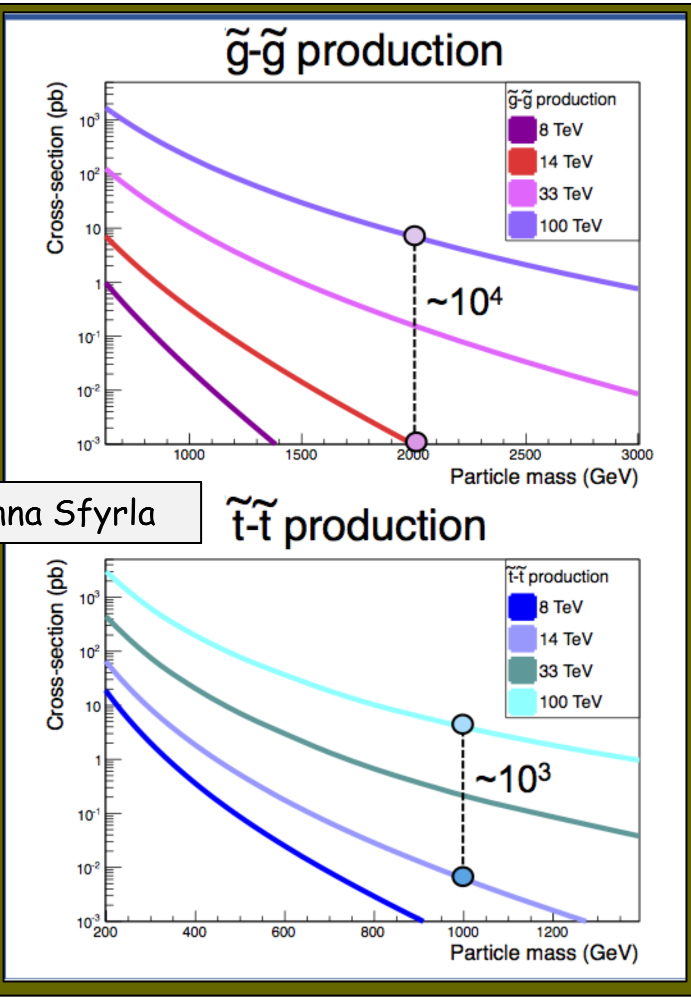
	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000	500	1600‡	500/1000	1600/2500‡	1500	+2000	3000	3000
λ	[redacted]	83%	46%	21%	13%	21%	10%	20%	8%

Why still SUSY in 2040++ ?

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

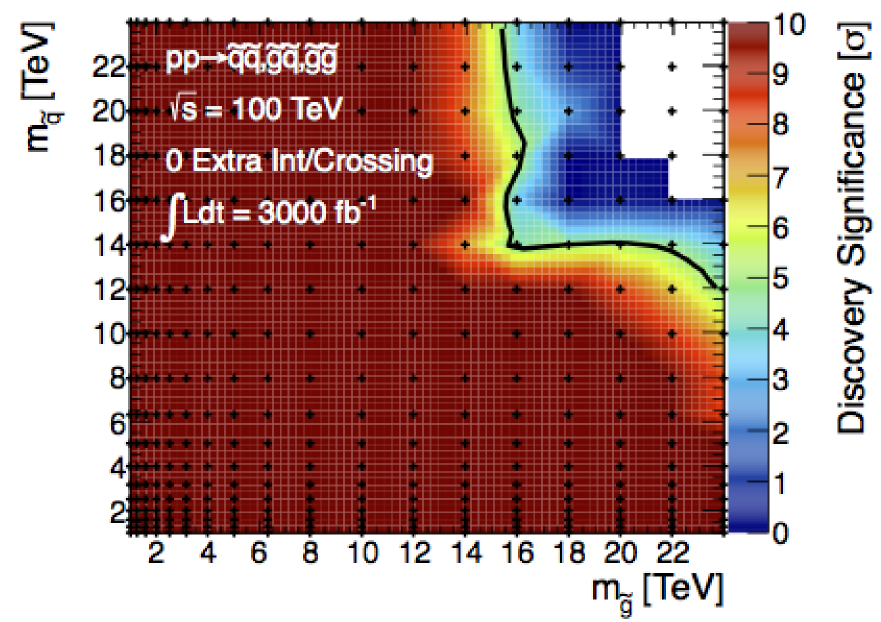


"SUSY anywhere is better than SUSY nowhere"



Anna Sfyrla

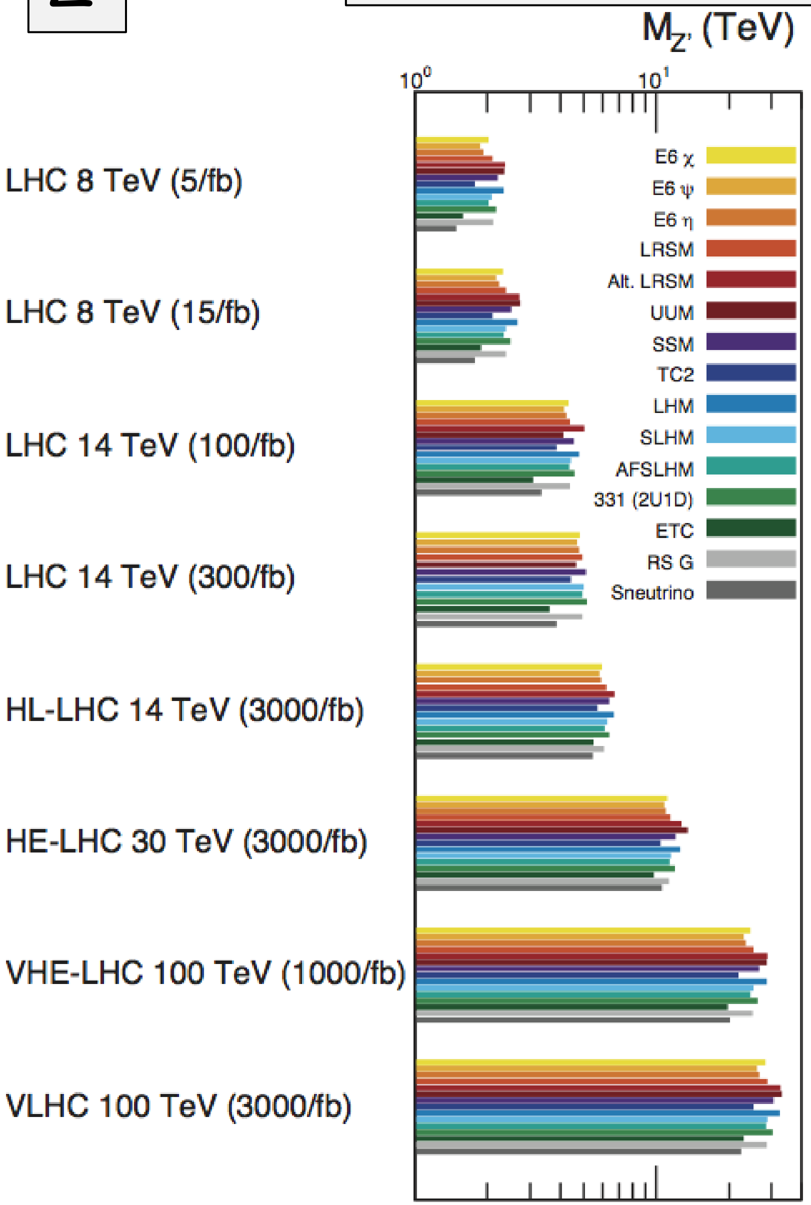
Snowmass report: arXiv:1311.6480



Squarks and gluinos discovery up to ~ 14 TeV

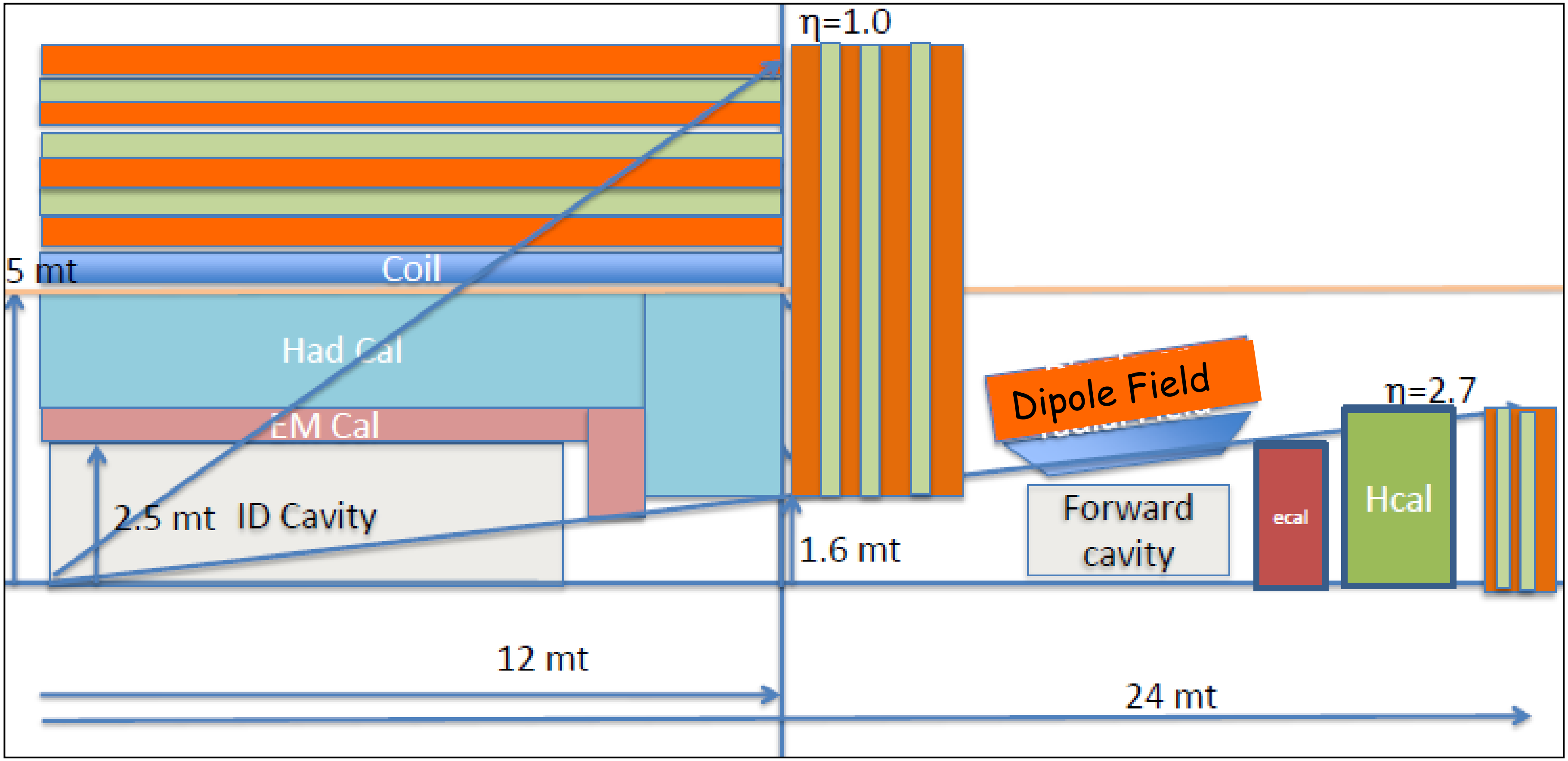
Z'

Snowmass report: arXiv:1309.1688



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

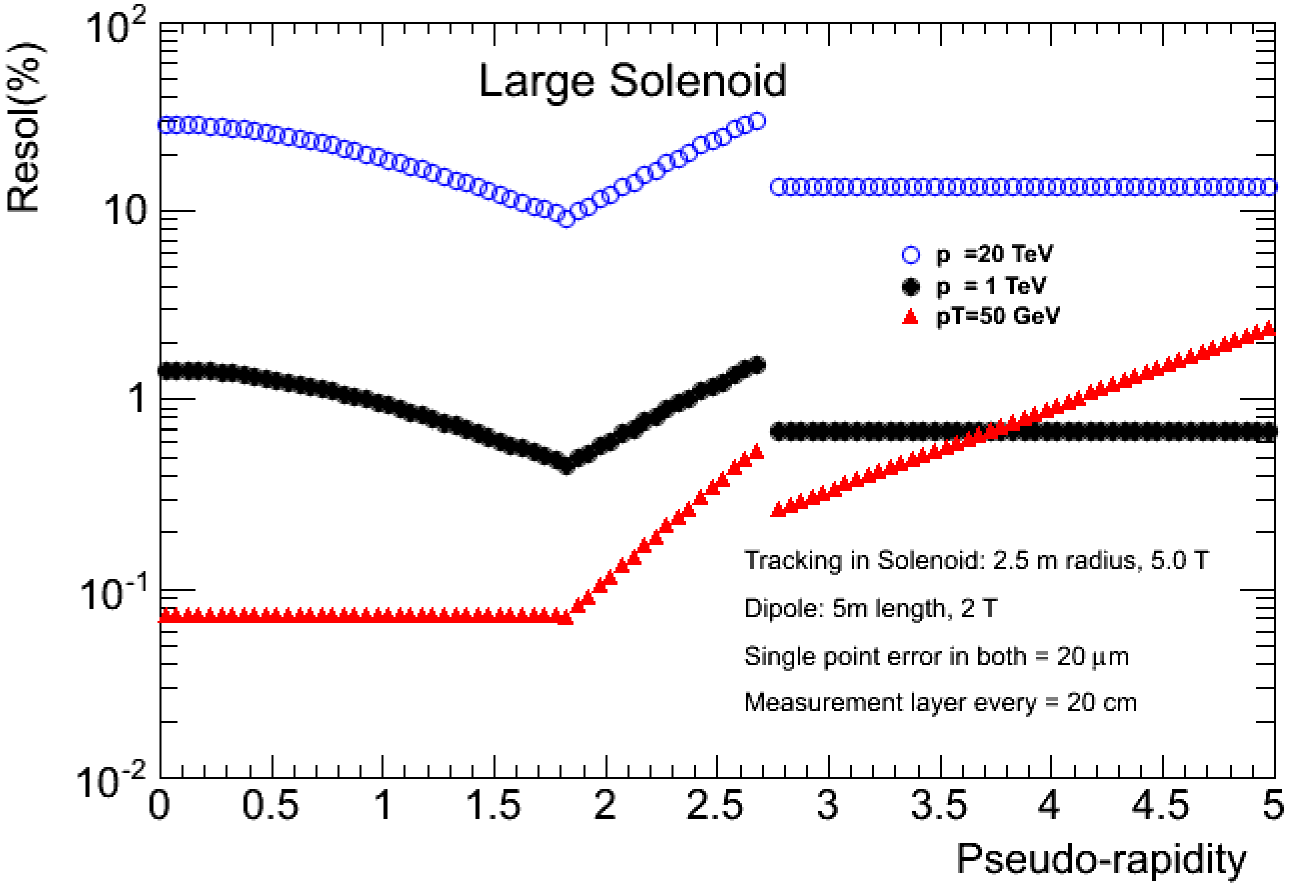
First ideas about detector layout: solenoid option



- Need BL^2 ~10 x ATLAS/CMS to achieve 10% muon momentum resolution at 10-20 TeV
- Solenoid: B=5T, R_{in}=5-6m, L=24m → size is x2 CMS. Stored energy: ~ 50 GJ
- > 5000 m^3 of Fe in return joke → alternative: thin (twin) lower-B solenoid at larger R to capture return flux of main solenoid ?
- Forward dipole à la LHCb: B~10 Tm
- Calorimetry: ≥ 12 λ for shower containment; W takes less space but requires 50ns integration for slow neutrons; speed for 5ns option (→ Si as active medium ?)

Muon momentum resolution

Note: ideal resolution: no multiple scattering, no misalignment



Tracking in Solenoid: 2.5 m radius, 5.0 T

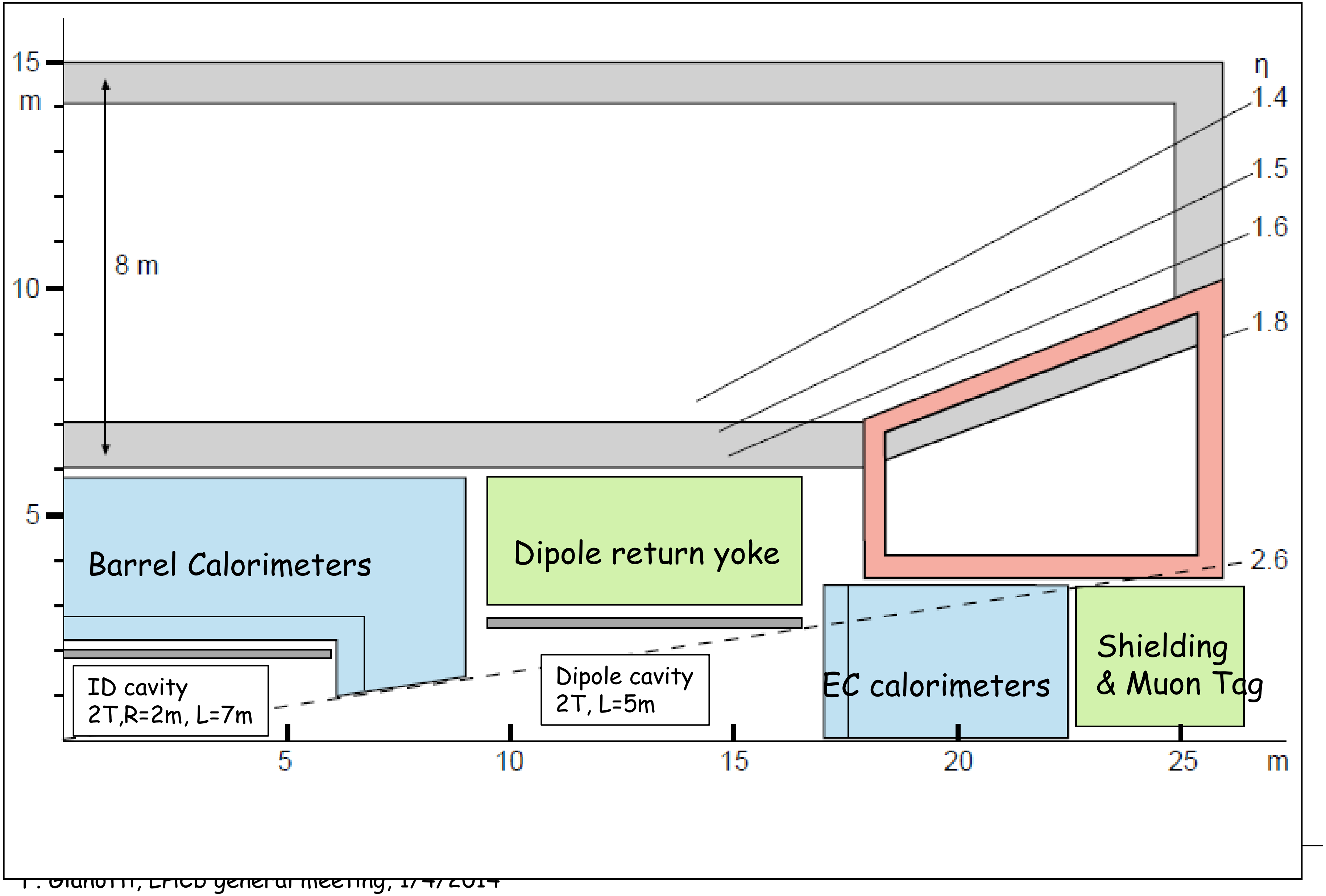
Dipole: 5m length, 2 T

Single point error in both = 20 μm

Measurement layer every = 20 cm

CMS:
12% at 1 TeV

First ideas about detector layout: toroid option



Additional remarks

- ☐ Given complexity of these detectors (e.g. access), alternative would be to decouple new physics (i.e. big, mainly central, detector) from Higgs studies (smaller, forward coverage). The former could still do large part of the (high-p_T) Higgs physics.

- ☐ Likewise, "bread-and-butter" SM physics: W, Z, top, QCD could be addressed more specifically by dedicated experiments.

- ☐ Physics case for (dedicated) HI experiment is being studied

- ☐ "Intensity-frontier" type (LFV, etc.) smaller-scale (collider or fixed-target) experiments beyond present worldwide program could be envisaged with SPS or LHC extracted beams

→ FCC could become a facility … → room for ideas

FCC-hh work organization

In the coming months: continue with one working group (plus already-existing HI group):
- ☐ at this early stage we benefit from discussions in one forum
- ☐ we want to give opportunity to more people to join and give their input before defining a WG structure and assigning coordination roles

Meetings: typically every 3 weeks (alternating emphasis on detector, SW, and physics) at a fixed time slot: Thursday at 3:30PM

In a few months: set up a WG structure for SW, detectors and physics, starting with macro-groups and increasing granularity with time

Note: intellectually very-stimulating activity:
- ☐ establishing the physics potential
- ☐ conceiving challenging experiments at a challenging machine from scratch
- ☐ developing/improving (new) detector technologies

→ hope to attract many (young) people

- ☐ Meeting page: http://indico.cern.ch/category/5258/
- ☐ Mailing list: fcc-experiments-hadron@cern.ch

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JOIN !

Conclusions

The extraordinary success of the LHC is the result of the ingenuity, vision and perseverance of the worldwide HEP community, and of more than 20 years of talented, dedicated work → the demonstrated 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 many outstanding questions remain.

The full exploitation of the LHC, and more powerful future accelerators, will be needed to address them and to advance our knowledge of fundamental physics.

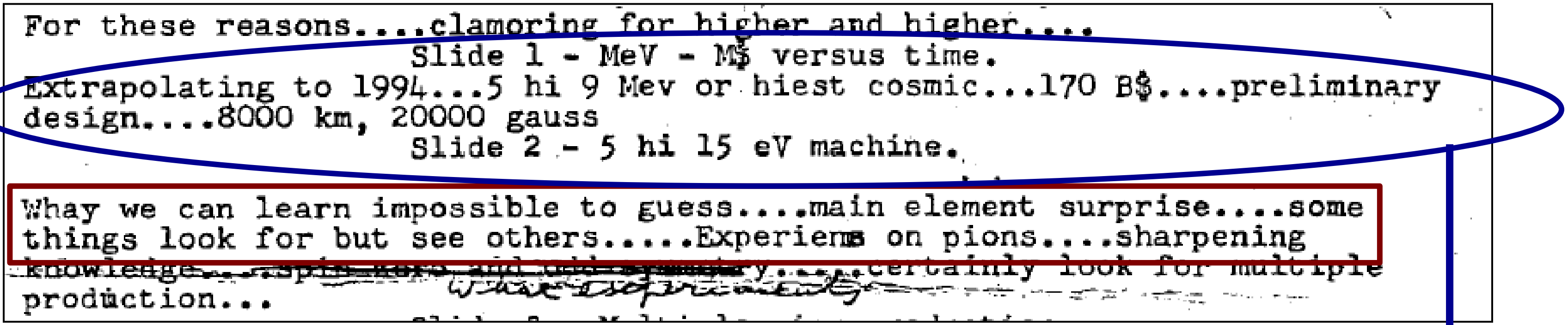
No doubt a future 100 TeV pp collider is an extremely challenging project.

However: as scientists we have the duty to examine it.

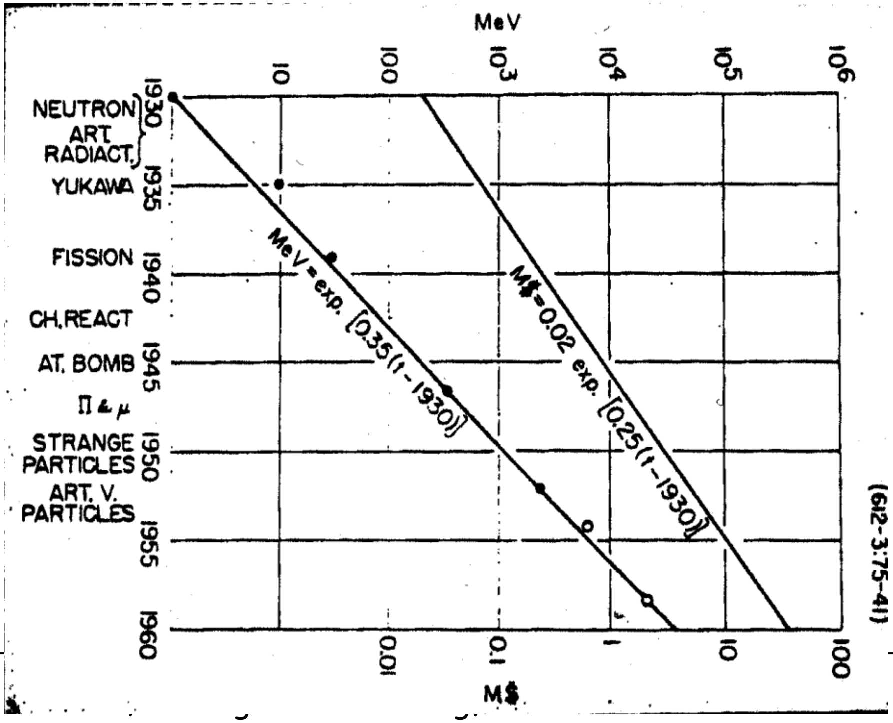
In the meantime, the correct approach is not to give up to financial and technical challenges, but to use our creativity to develop the technologies needed to make it financially and technically affordable

We did so many times in the past … →

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... [illegible]



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

Was that hopeless ??

NO !

We have found the solution:
we have invented colliders
and superconducting magnets ...
and built the Tevatron and the LHC

F.

Only if we are

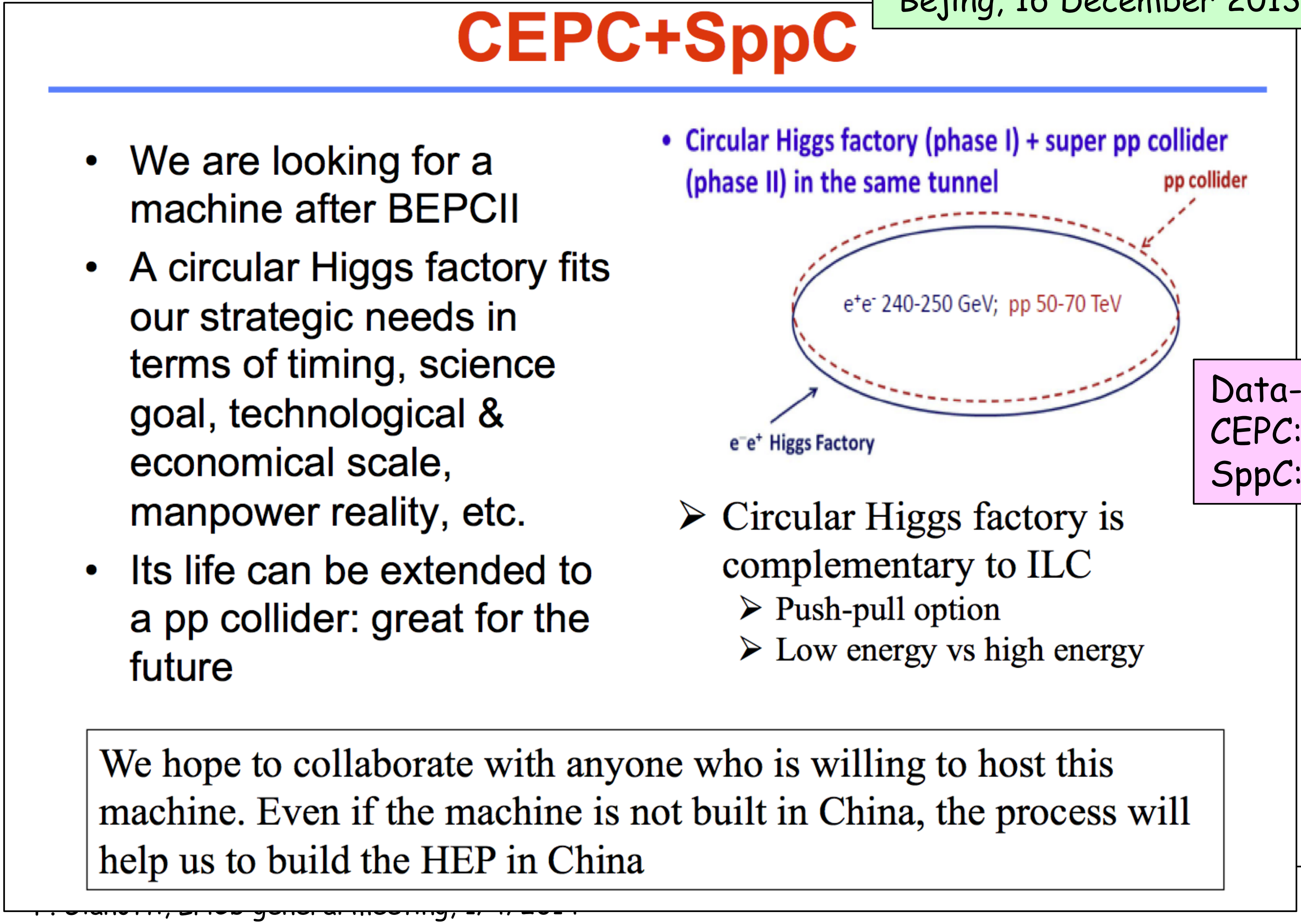
AMBITIOUS
BRAVE
CREATIVE
DETERMINED

can we also hope to be lucky, and continue to play a leading role in the advancement of knowledge

SPARES

The Chinese plans

Yifang Wang, Director of IHEP Bejing,
Future High-Energy Circular Colliders WS,
Bejing, 16 December 2013



CEPC+SppC

- We are looking for a machine after BEPCII
- A circular Higgs factory fits our strategic needs in terms of timing, science goal, technological & economical scale, manpower reality, etc.
- Its life can be extended to a pp collider: great for the future

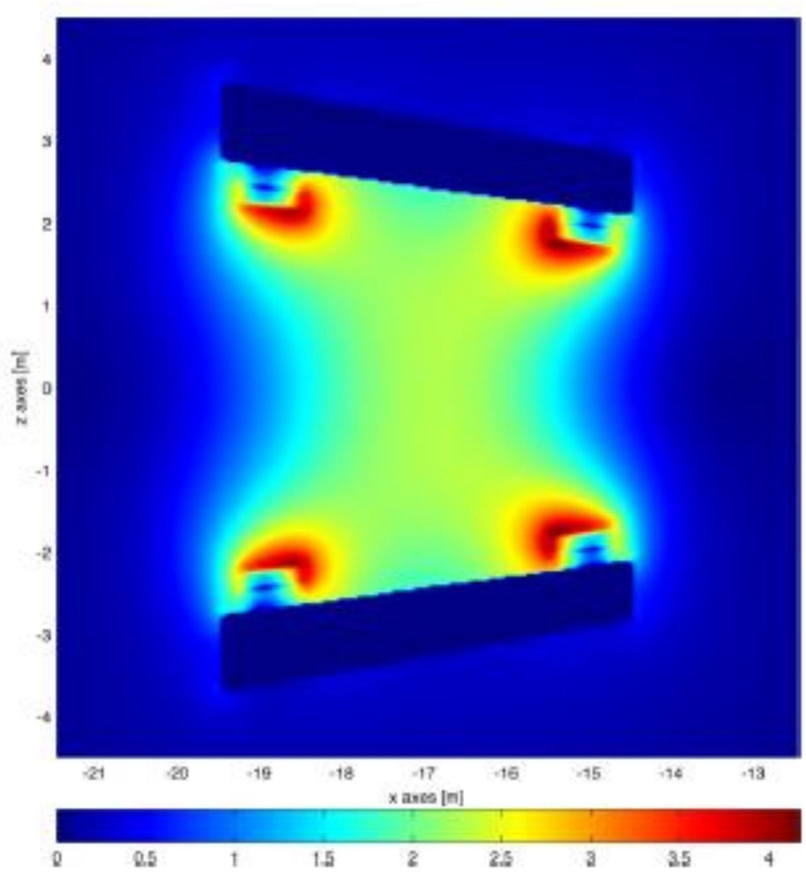
- Circular Higgs factory (phase I) + super pp collider (phase II) in the same tunnel

- ➤ Circular Higgs factory is complementary to ILC
  - ➤ Push-pull option
  - ➤ Low energy vs high energy

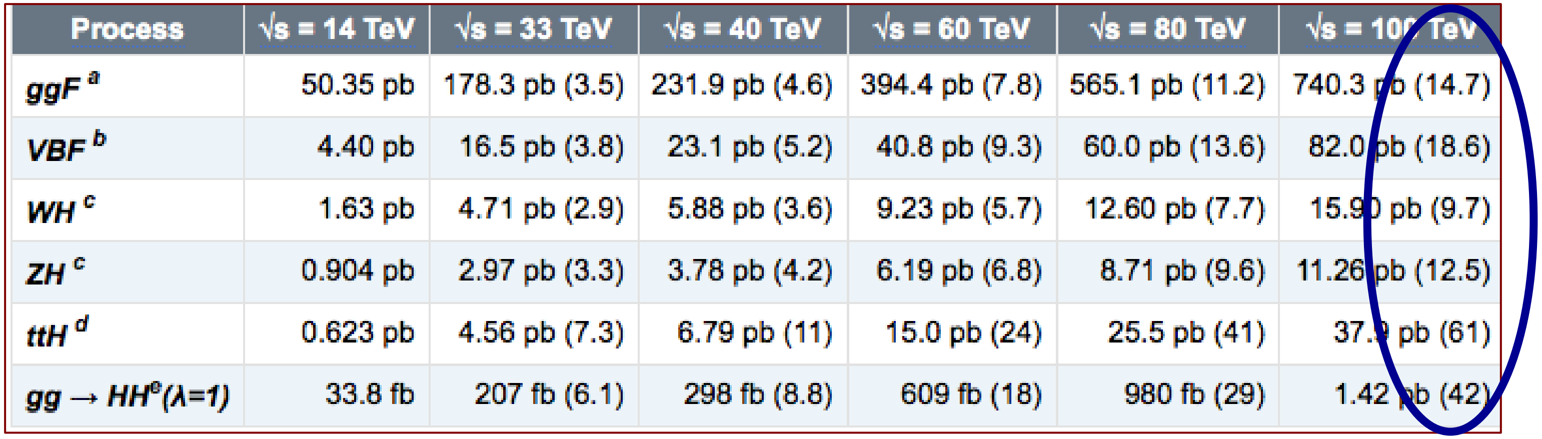
We hope to collaborate with anyone who is willing to host this machine. Even if the machine is not built in China, the process will help us to build the HEP in China

Data-taking:
CEPC: 2028-2035
SppC: 2042 -

Dipole magnet: wedge option



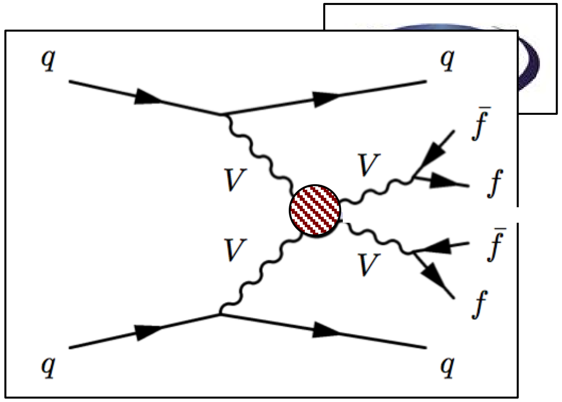
- 2 Decks with each 0.08 m^2 cross section
- 30 A/mm^2 current Density in conductor block
- 5.6 T peak field on conductor
- 0.2 GJ stored energy (without iron)
- 2.2 T central bending field

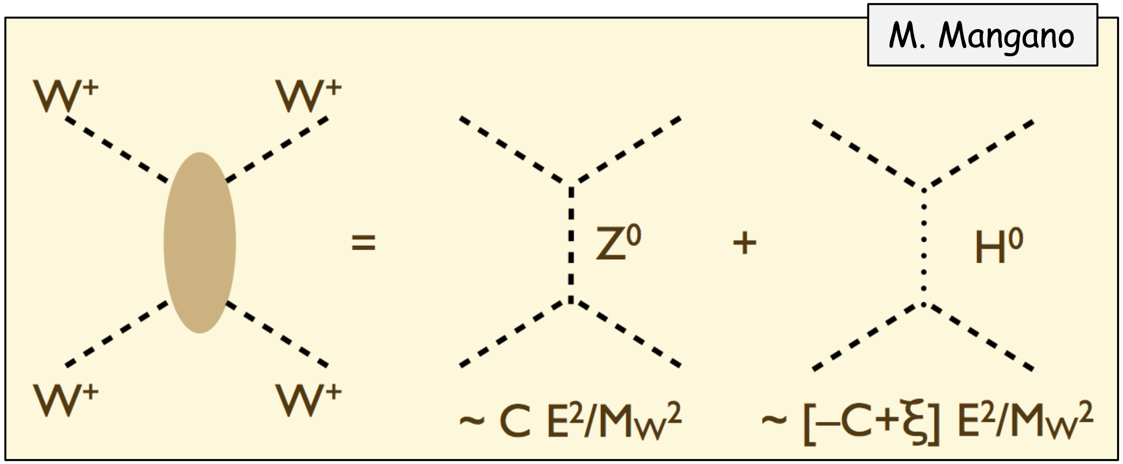


Process	√s = 14 TeV	√s = 33 TeV	√s = 40 TeV	√s = 60 TeV	√s = 80 TeV	√s = 100 TeV
ggF [a]	50.35 pb	178.3 pb (3.5)	231.9 pb (4.6)	394.4 pb (7.8)	565.1 pb (11.2)	740.3 pb (14.7)
VBF [b]	4.40 pb	16.5 pb (3.8)	23.1 pb (5.2)	40.8 pb (9.3)	60.0 pb (13.6)	82.0 pb (18.6)
WH [c]	1.63 pb	4.71 pb (2.9)	5.88 pb (3.6)	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 → HH[e]***(λ=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:

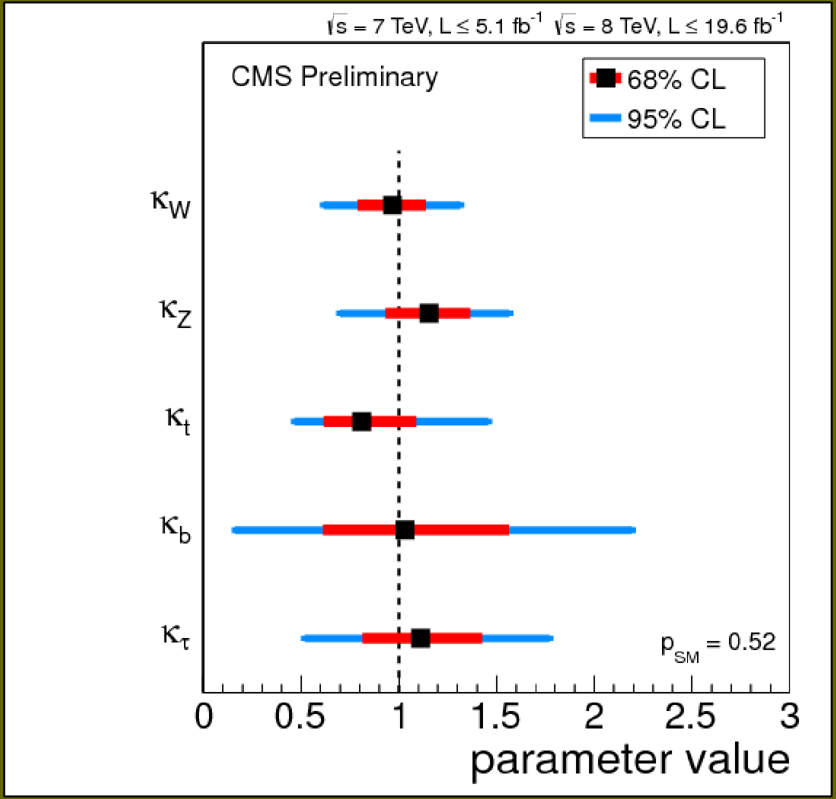
- ☐ Verify that Higgs boson accomplishes the job of canceling the divergences
- ☐ Does it accomplish it fully or partially ? I.e. is $\xi = 0$ or $\xi \neq 0$?

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

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

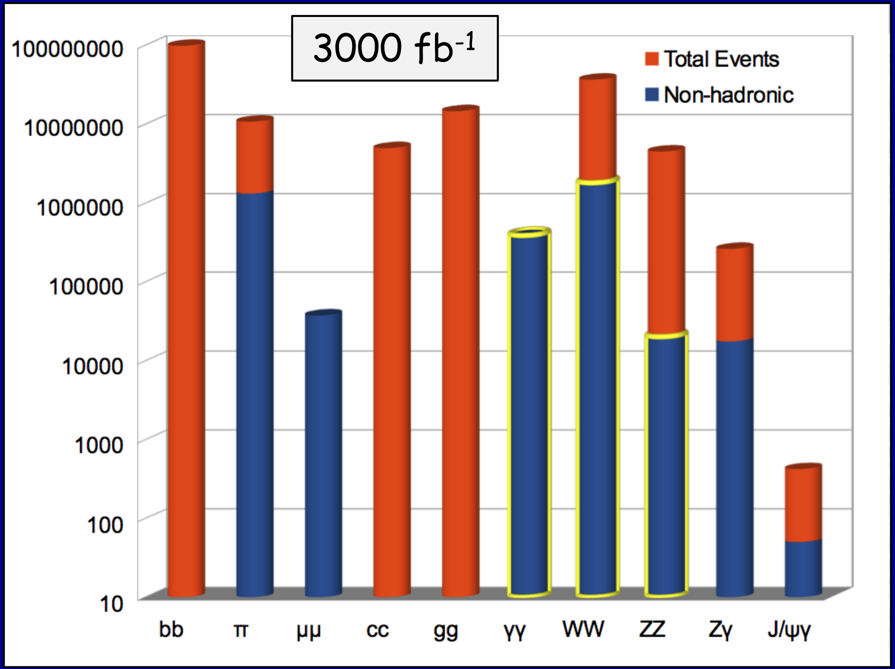
- ATLAS+CMS: 1400 Higgs events after selection cuts (1M at production)
- Observed/measured so far: couplings to W, Z and 3rd generation fermions t, b, τ (ttH: indirectly through gg-fusion production loop)
- Typical precision: ~ 20%



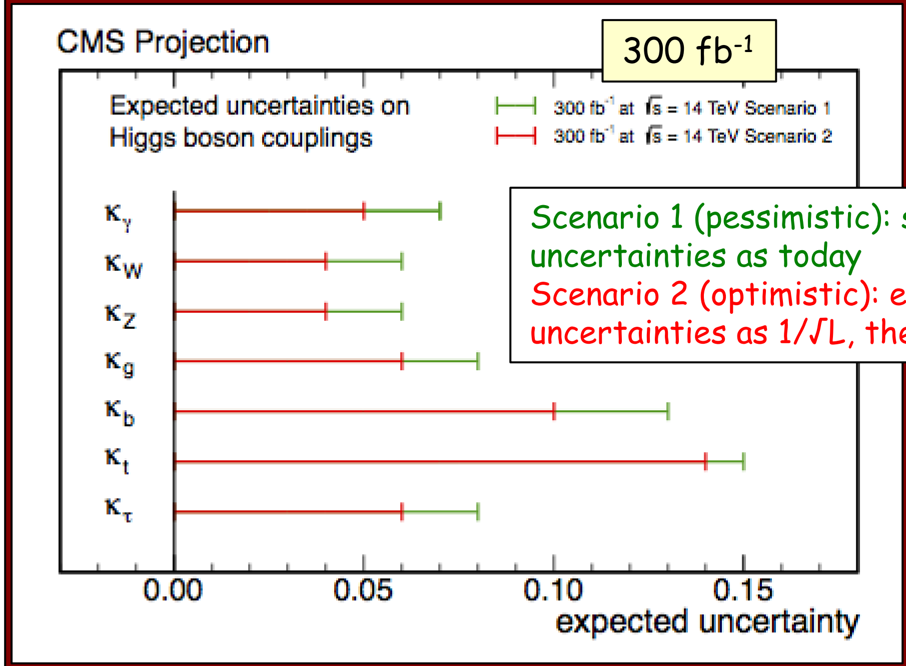
HL-LHC (3000 fb^{-1})

- > 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



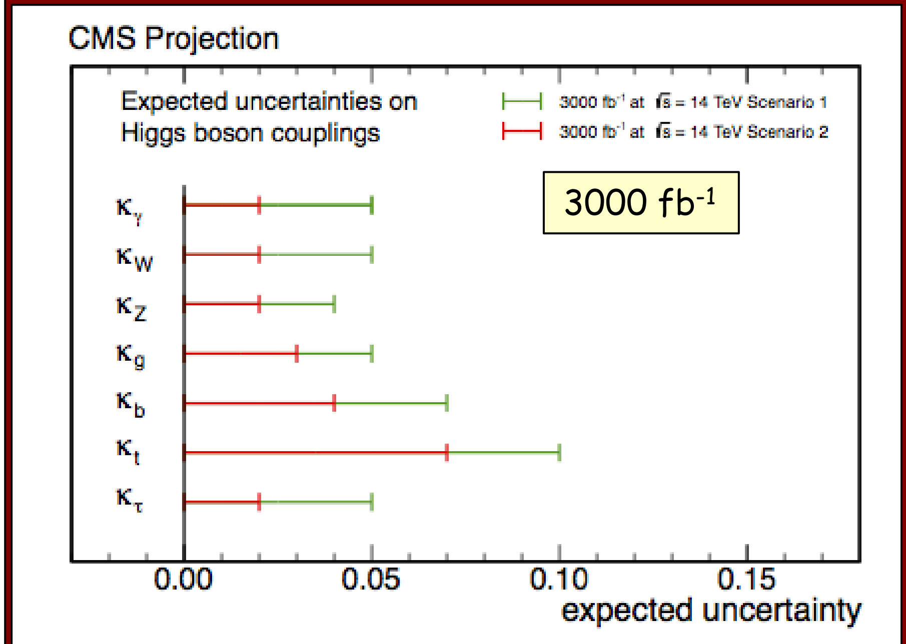
Measurements of Higgs couplings



300 fb^{-1}

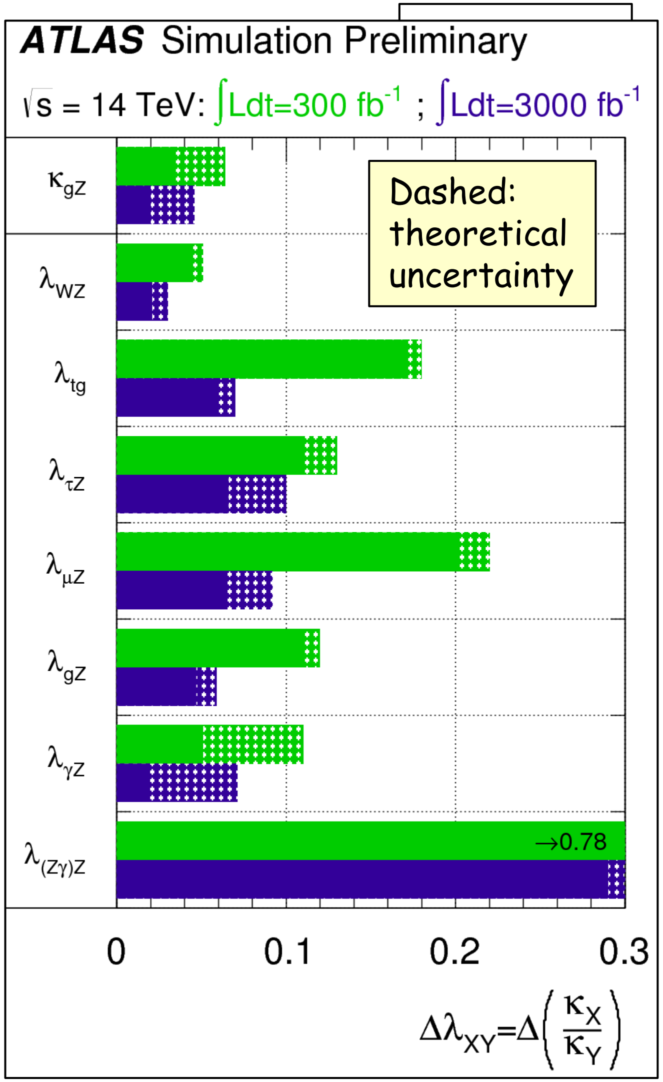
Scenario 1 (pessimistic): systematic uncertainties as today

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



3000 fb^{-1}

k_i= measured coupling normalized to SM prediction $\Lambda_{ij}=k_i/k_j$

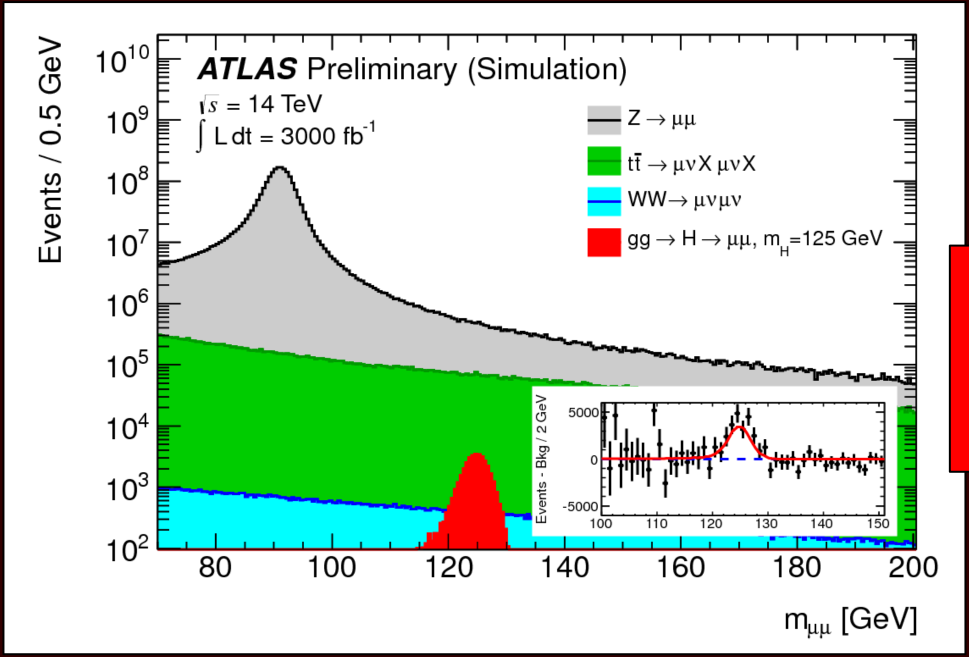


Dashed: theoretical uncertainty

Main conclusions:

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

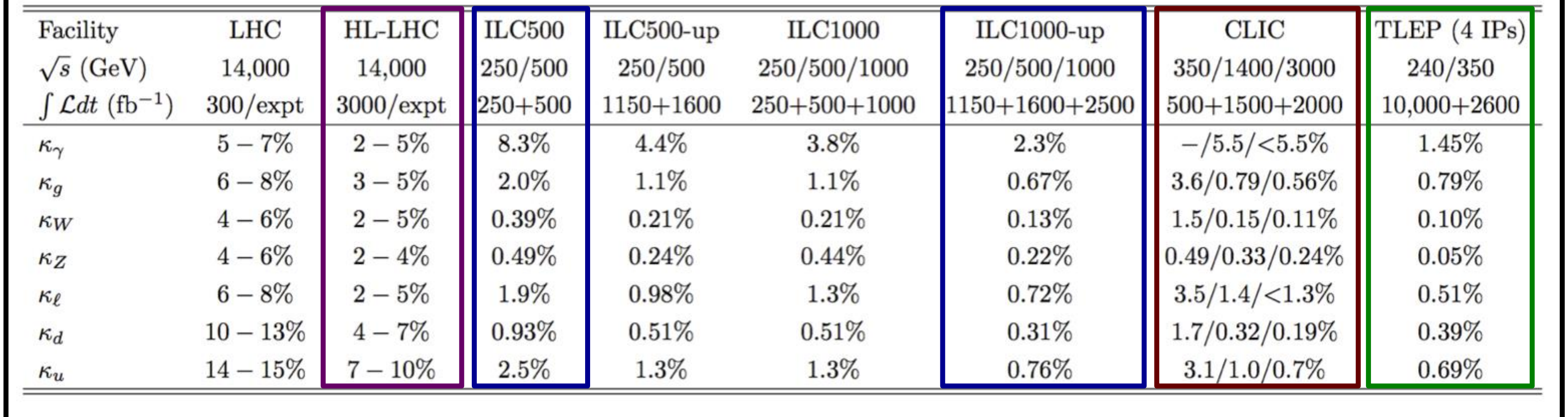
Several rare processes become accessible with 3000 fb^{-1} , e.g.: direct coupling to 2nd generation fermions (H→ μμ) and to top quark (mainly through ttH→ ttγγ)



H →μμ

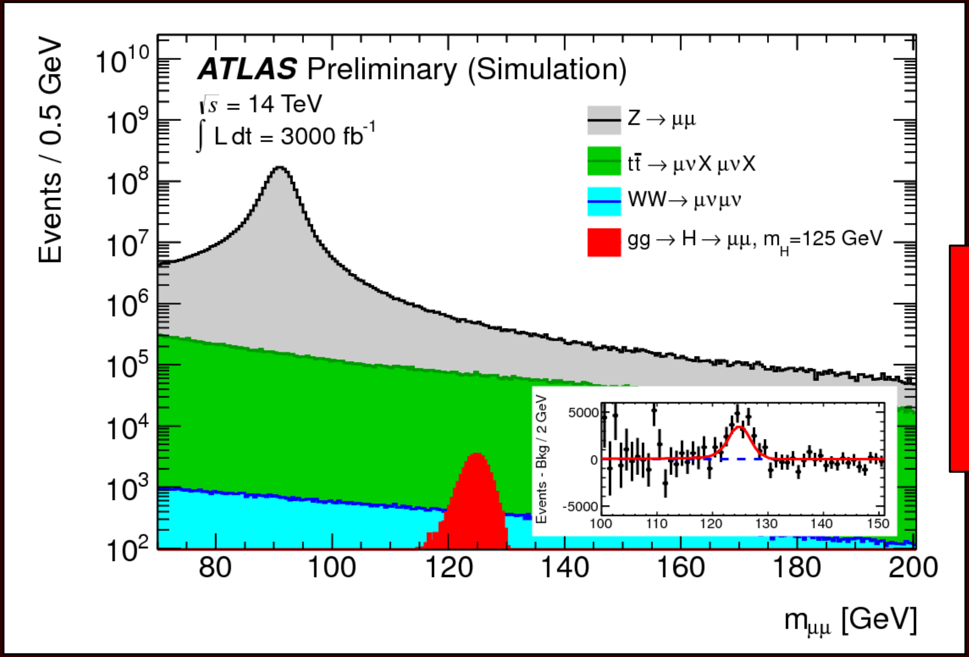
- ☐ Today's sensitivity: 8xSM cross-section
- ☐ With 3000 fb^{-1} expect 17000 signal events (S/B ~ 0.3%) and ~ 7σ significance
- ☐ Hμμ coupling can be measured to about 10%

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.: <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%

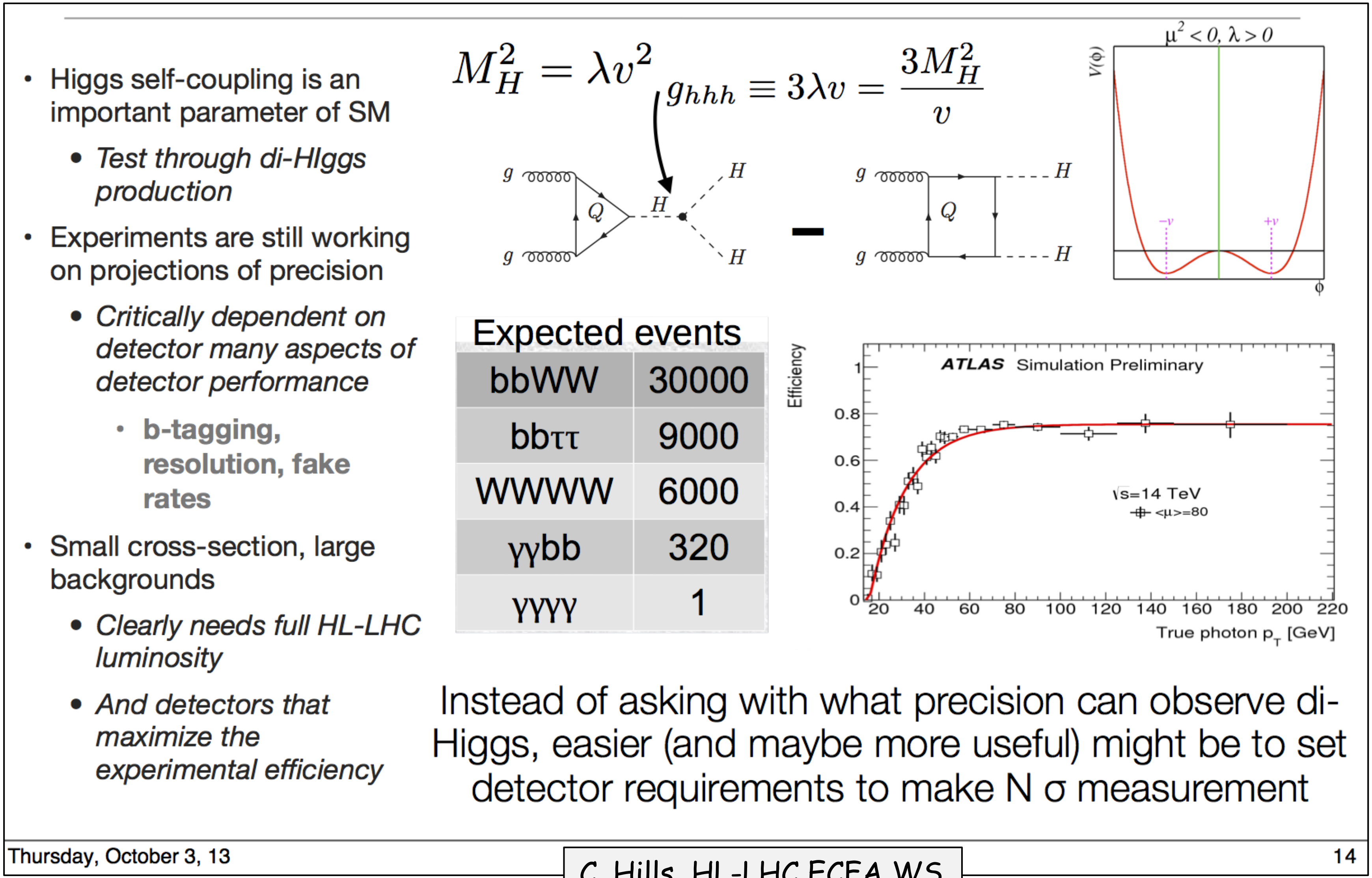
mass 2013

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	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

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

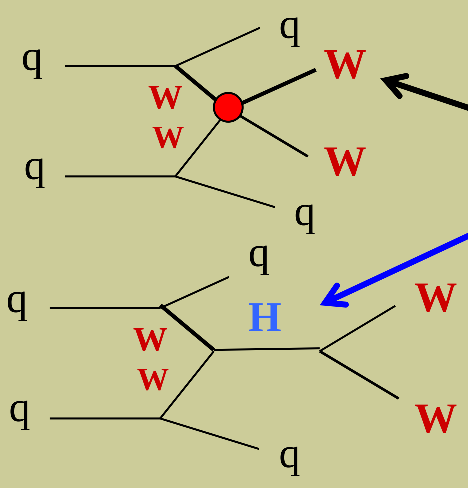
Instead of asking with what precision can observe di-Higgs, easier (and maybe more useful) might be to set detector requirements to make N σ measurement

Thursday, October 3, 13

14

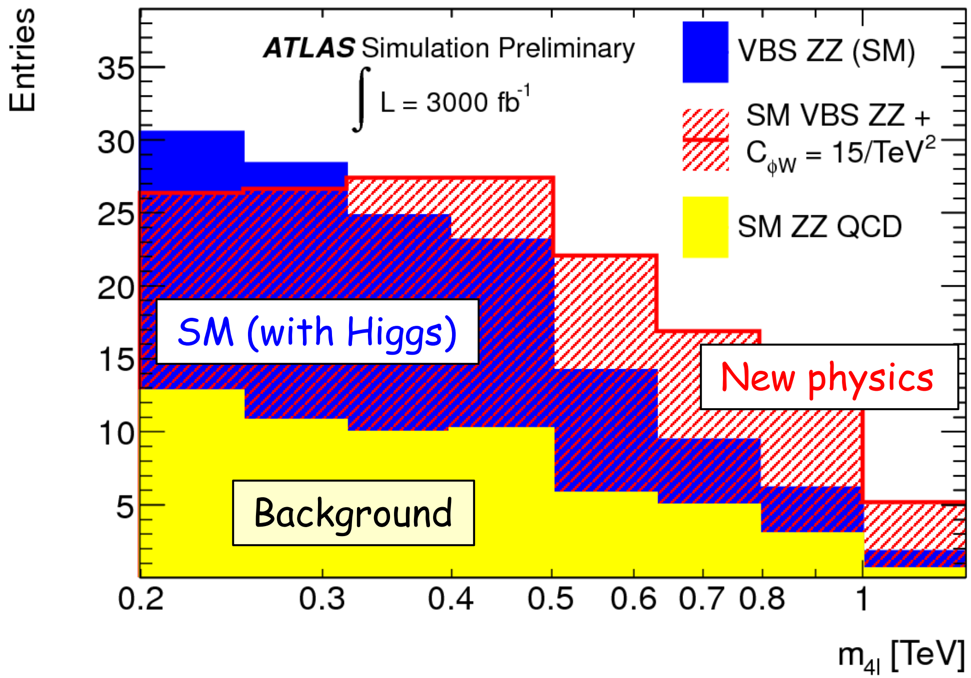
C. Hills, HL-LHC ECFA WS

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}

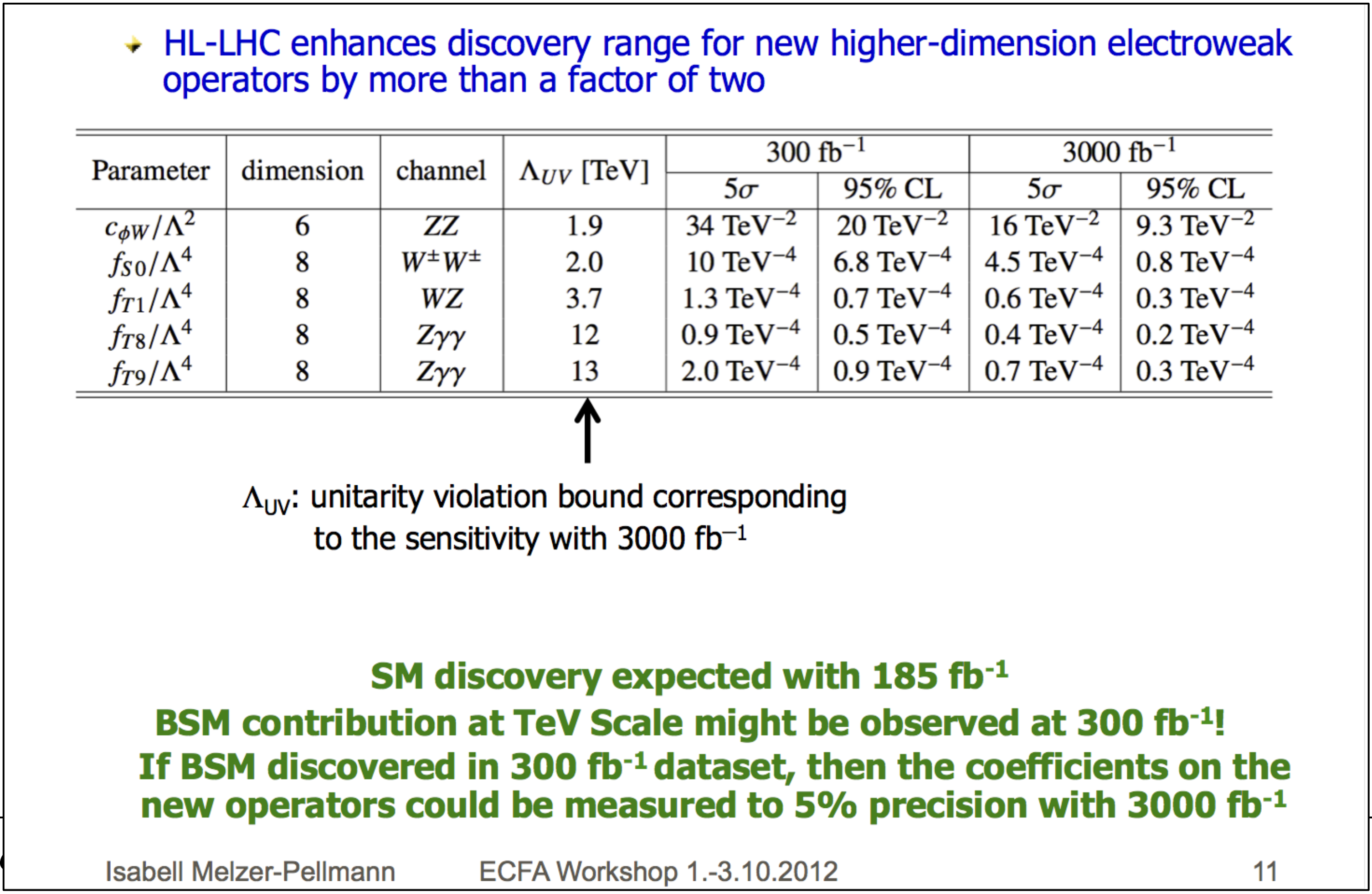
If new physics: sensitivity increases by ~ 2 (in terms of scale and coupling reach) between 300 and 3000 fb^{-1}

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

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}

$\uparrow$

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

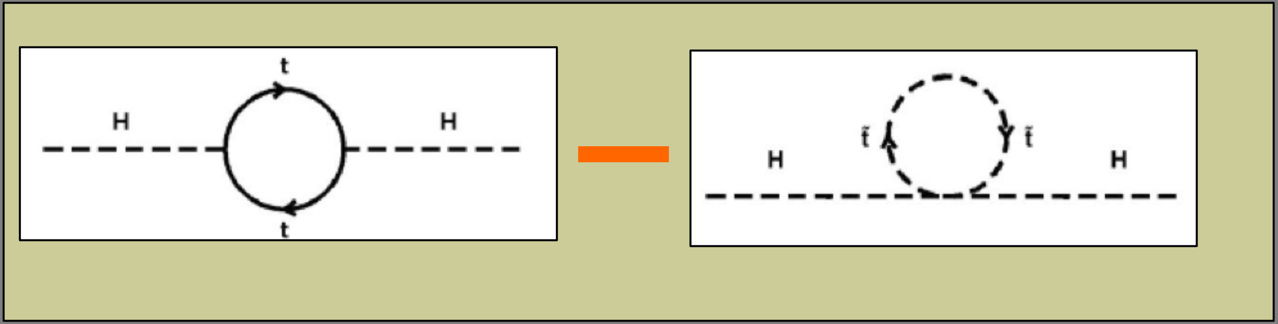
SM discovery expected with 185 fb^{-1}

BSM contribution at TeV Scale might be observed at 300 fb^{-1}!

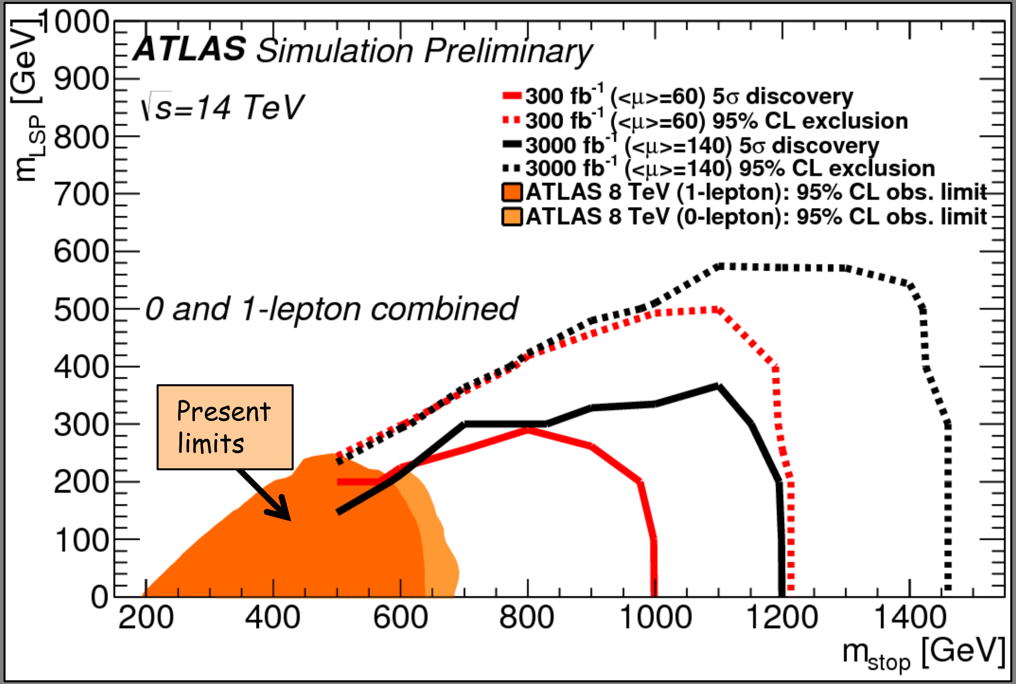
If BSM discovered in 300 fb^{-1} dataset, then the coefficients on the new operators could be measured to 5% precision with 3000 fb^{-1}

Isabell Melzer-Pellmann ECFA Workshop 1.-3.10.2012 11

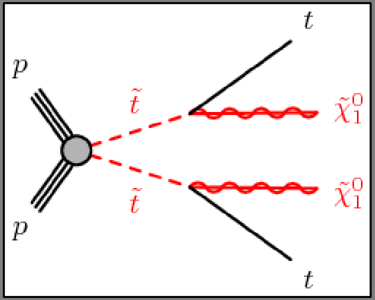
Q2: Is the Higgs mass "natural", i.e. stabilized by New Physics ?



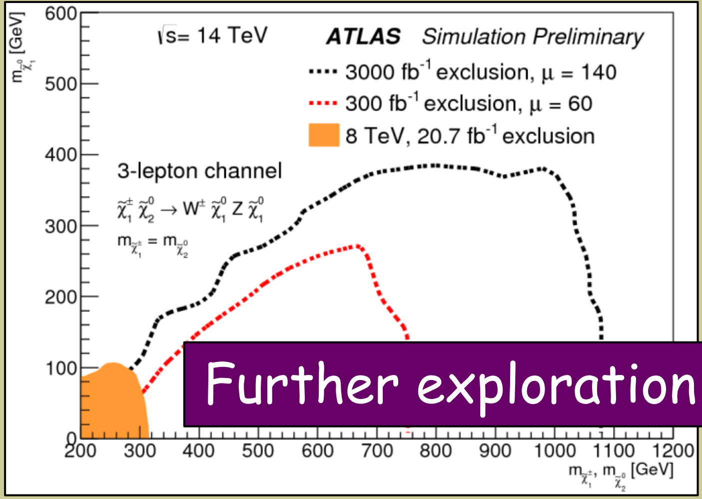
To stabilize the Higgs mass (without too much fine-tuning), the stop should not be much heavier than ~ 1-1.5 TeV (note: the rest of the SUSY spectrum can be heavier)

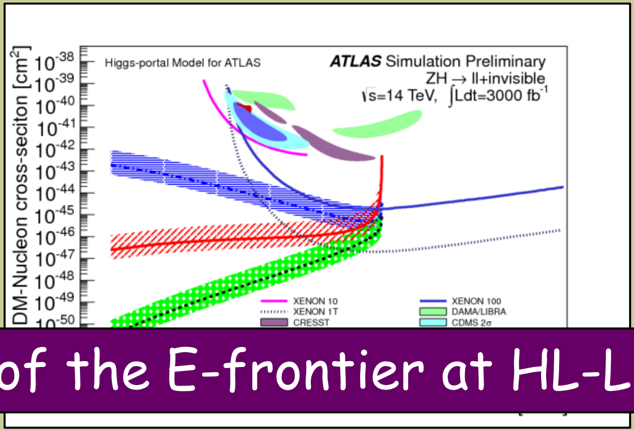


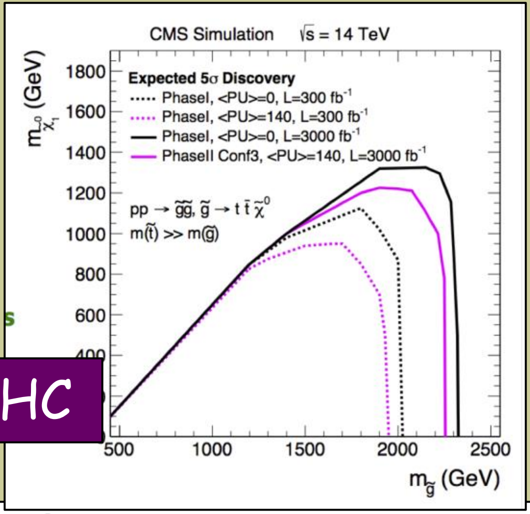
Present limits



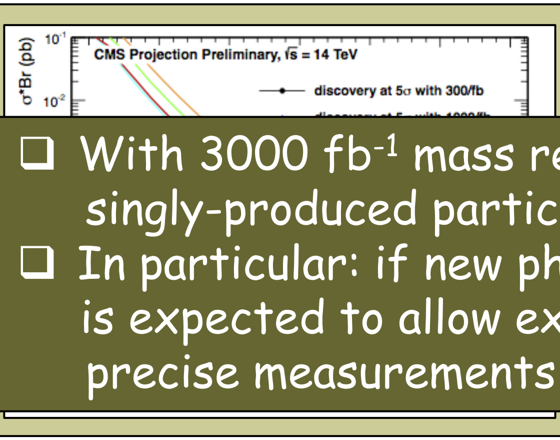
Mass reach extends by ~ 200 GeV from 300 to 3000 fb^{-1}
→ most of best motivated mass range will be covered at HL-LHC

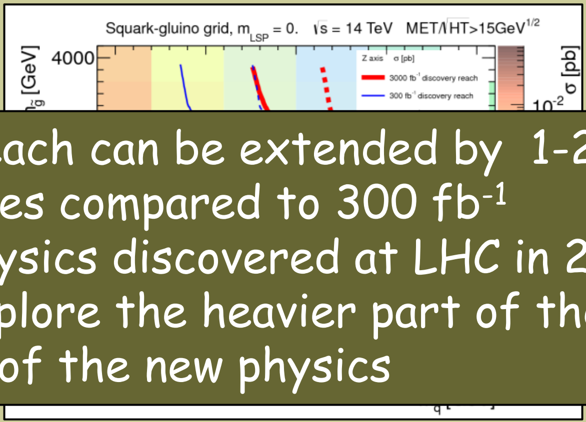


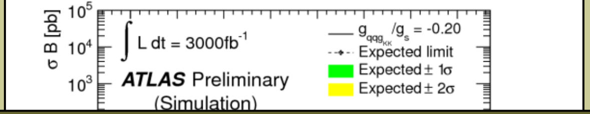




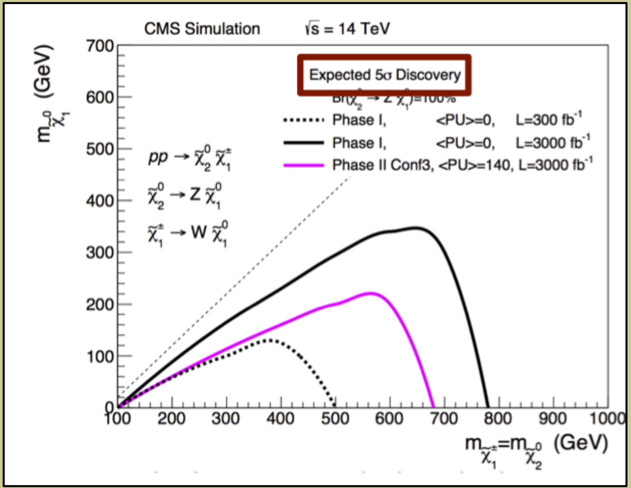
Further exploration of the E-frontier at HL-LHC

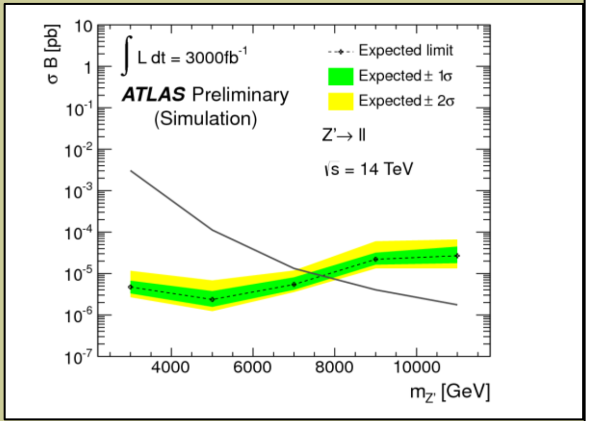


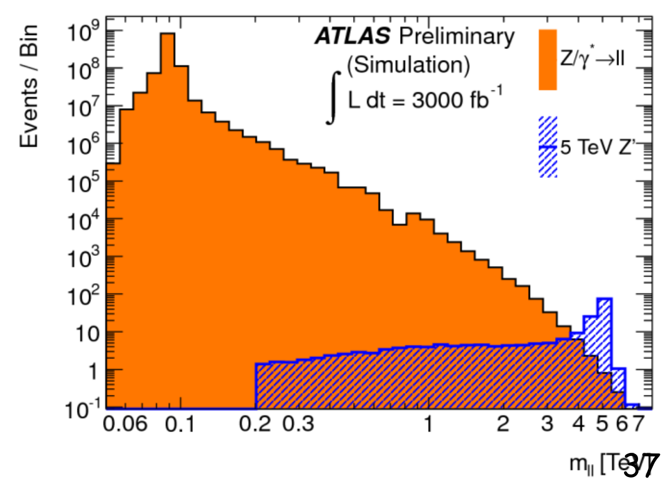




- ❑ With 3000 fb^{-1} mass reach can be extended by 1-2 TeV for singly-produced particles compared to 300 fb^{-1}
- ❑ In particular: if new physics discovered at LHC in 2015++ → HL-LHC with 3000 fb^{-1} is expected to allow explore the heavier part of the spectrum and perform precise measurements of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

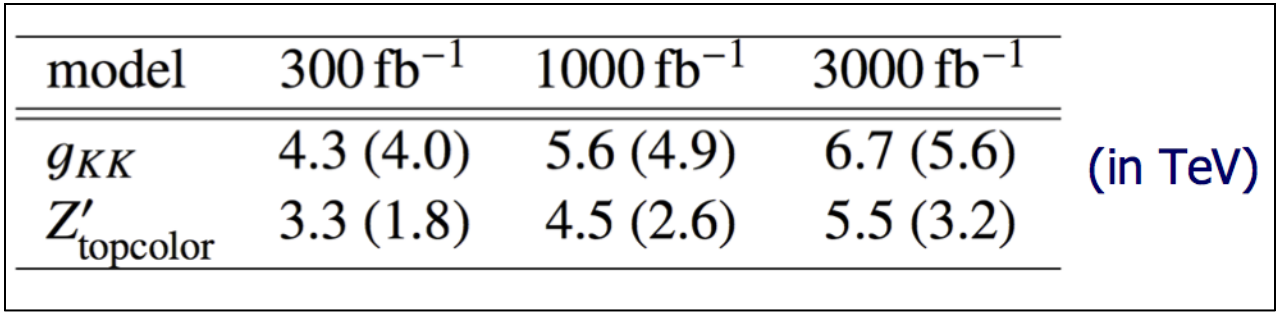






Search for top-antitop resonances in the lepton + jet (dilepton) channel

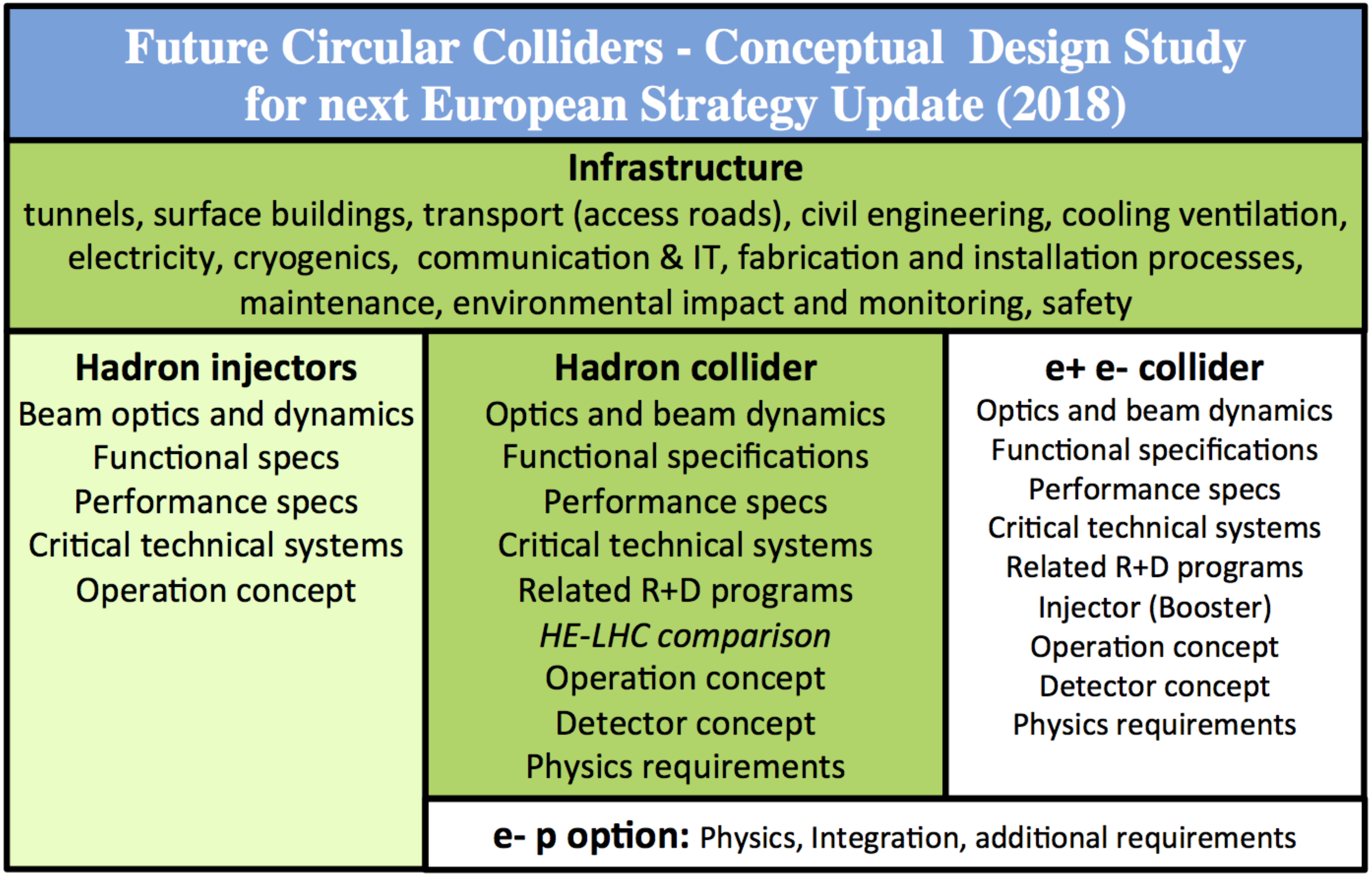
ATLAS simulation



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)

FCC Study Scope and Structure



Future Circular Colliders - Conceptual Design Study for next European Strategy Update (2018)

Infrastructure

tunnels, surface buildings, transport (access roads), civil engineering, cooling ventilation, electricity, cryogenics, communication & IT, fabrication and installation processes, maintenance, environmental impact and monitoring, safety

Hadron injectors

Beam optics and dynamics
Functional specs
Performance specs
Critical technical systems
Operation concept

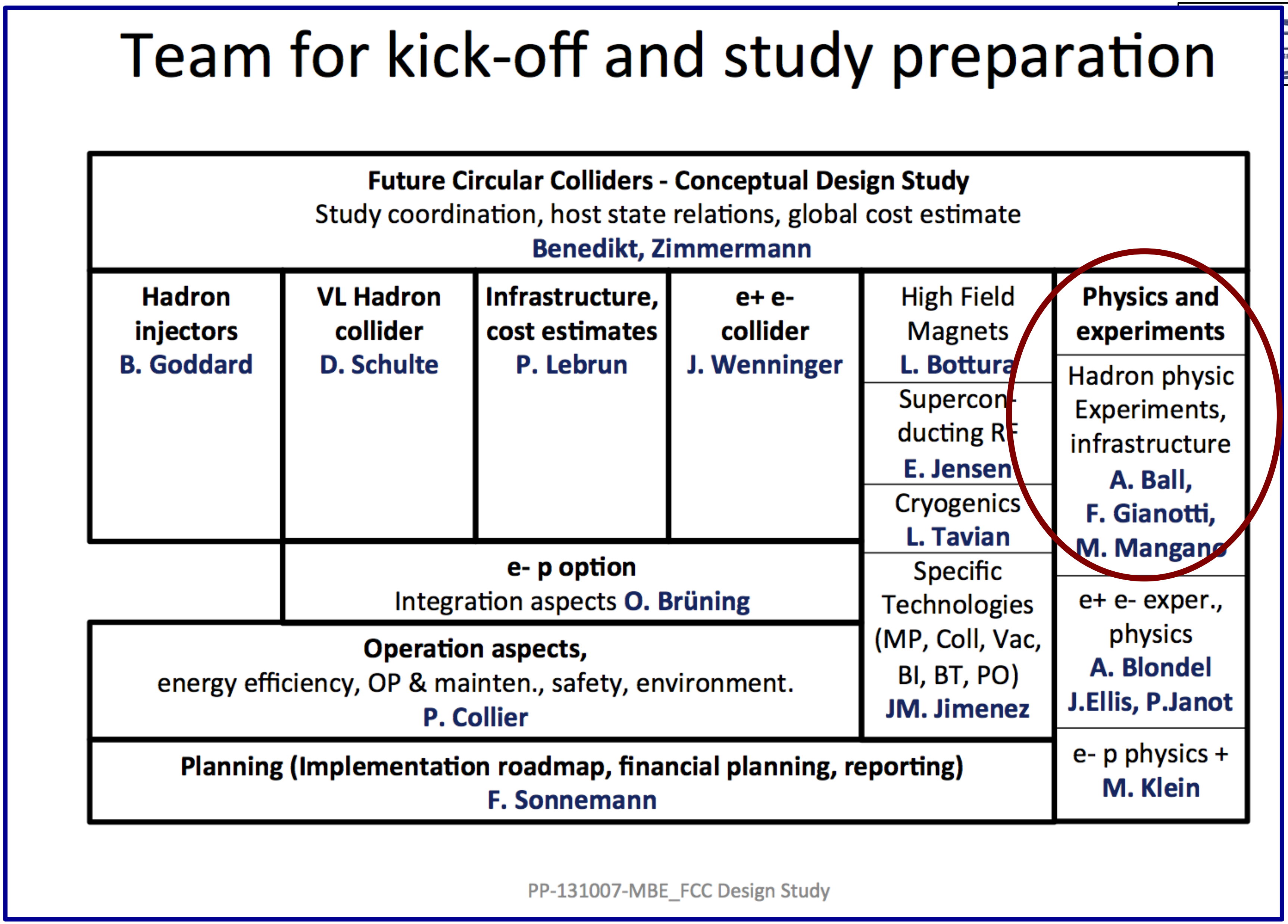
Hadron collider

Optics and beam dynamics
Functional specifications
Performance specs
Critical technical systems
Related R+D programs
HE-LHC comparison
Operation concept
Detector concept
Physics requirements

e+ e- collider

Optics and beam dynamics
Functional specifications
Performance specs
Critical technical systems
Related R+D programs
Injector (Booster)
Operation concept
Detector concept
Physics requirements

e- p option: Physics, Integration, additional requirements



Team for kick-off and study preparation

Future Circular Colliders - Conceptual Design Study
Study coordination, host state relations, global cost estimate
Benedikt, Zimmermann

Hadron injectors
B. Goddard

VL Hadron collider
D. Schulte

Infrastructure, cost estimates
P. Lebrun

e+ e- collider
J. Wenninger

High Field Magnets
L. Bottura

Supercon-ducting RF
E. Jensen

Cryogenics
L. Tavian

Specific Technologies (MP, Coll, Vac, BI, BT, PO)
JM. Jimenez

Physics and experiments

Hadron physic Experiments, infrastructure
A. Ball, F. Gianotti, M. Mangano

e+ e- exper., physics
A. Blondel J.Ellis, P.Janot

e- p physics +
M. Klein

e- p option
Integration aspects **O. Brüning**

Operation aspects,
energy efficiency, OP & mainten., safety, environment.
P. Collier

Planning (Implementation roadmap, financial planning, reporting)
F. Sonnemann

PP-131007-MBE_FCC Design Study

Here: focus on the pp part (FHC)

- Work started in November 2013
- > 200 people subscribed to the FCC-hh mailing list, but small number (~30) active so far at tiny fraction of their time

Only few very preliminary ideas shown here …

Hope for a strong international collaboration in the FCC-hh studies !

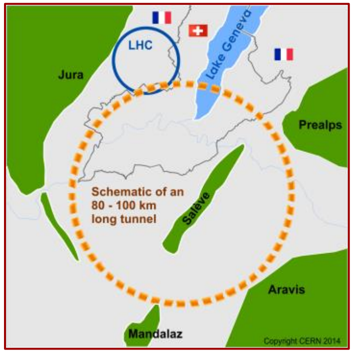
- We are benefitting from previous studies: e.g. SSC and VLHC efforts in the US (and Snowmass 2001 and 2013)

- Links established with similar activities in the world (e.g. cross attendance of workshops) → will be pursued and intensified

China:
- Future High-Energy Circular Colliders WS, Bejing, 16-17 December 2013: http://indico.ihep.ac.cn/conferenceDisplay.py?confId=3813
- 1st CFHEP (= Center for Future High Energy Physics) Symposium on Circular Collider Physics, Beijing, 23-25 February 2014: http://cfhep.ihep.ac.cn

US:
- Physics at a 100 TeV Collider, SLAC, 23-25 April 2014: https://indico.fnal.gov/conferenceDisplay.py?confId=7633
- Next steps in the Energy Frontier: Hadron Colliders, FNAL, 28-31 July 2014

Parameters of a ~ 100 TeV pp collider



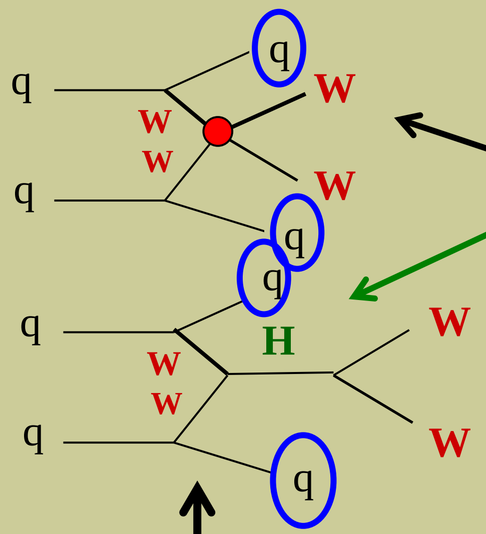
One of the main goals of the Conceptual Design Report (~ 2018)
→ will be studied in detail in the years to come …

Note:
-- Nb$_3$Sn ok up to 16 T
-- 20 T needs HTS

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

	Ring (km)	Magnets (T)	√s (TeV)
LHC	27	8.3	14
HE-LHC	27	16-20	26-33
"SSC-like" (not attractive, not considered)	80	8.3	42
FCC-hh	80 100	20 16	100 100

Forward jet tagging: crucial for both low-mass (Higgs) and high-mass (VV scattering)

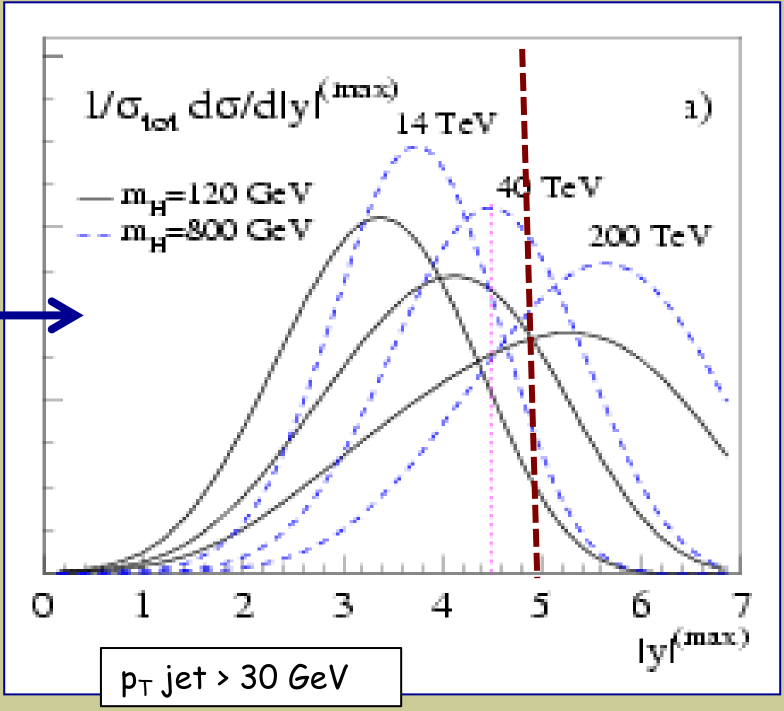


This process violates unitarity: $\sigma \sim E^2$ at $m_{WW} \sim$ TeV
(divergent cross section → unphysical)
if this process does not exist

Important to verify that H (125) accomplishes this task
→ a crucial "closure test" of the SM
Complete elucidation of EWSB: cross section measurements and searches for resonances
→ Likely requires high-E machine beyond HL-LHC and ILC

In addition: VBF Higgs production:
- ❑ ~10% of cross-section,
- ❑ information on couplings

Maximum jet rapidity vs √s for
VBF "Higgs" production
(from Snowmass 2001 US VLHC study: hep-ph/0201227)



ATLAS and CMS calorimeter coverage: |η|< 5
100 TeV detectors need to extend to |η| ≥ 6
→ pile-up is a big challenge !!

How our views of the experimental challenges change with time …..

From: “Report of High Luminosity Study Group to the CERN Long-Range Planning Committee”, CERN 88-02, 1988.

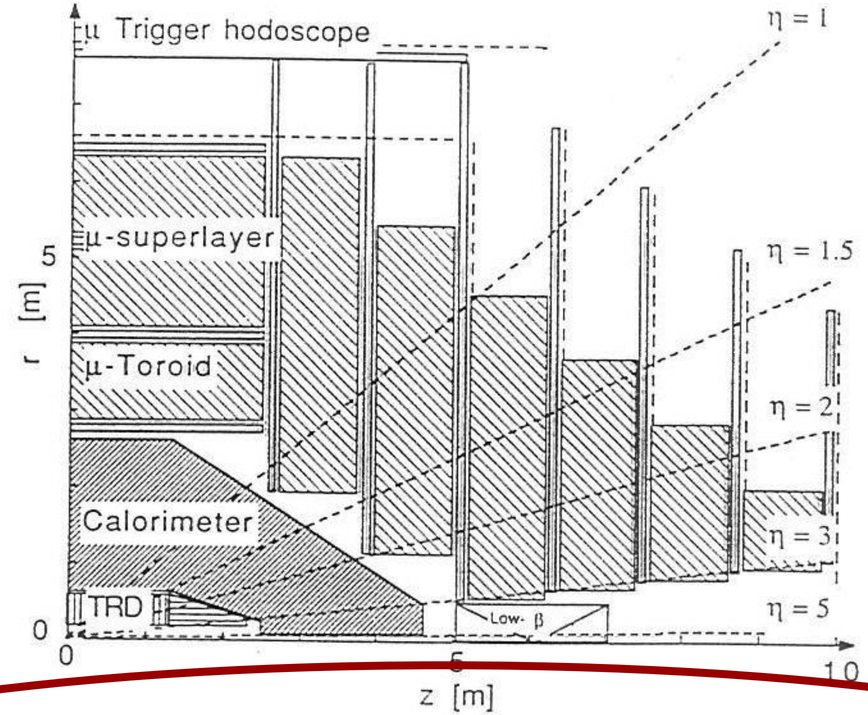
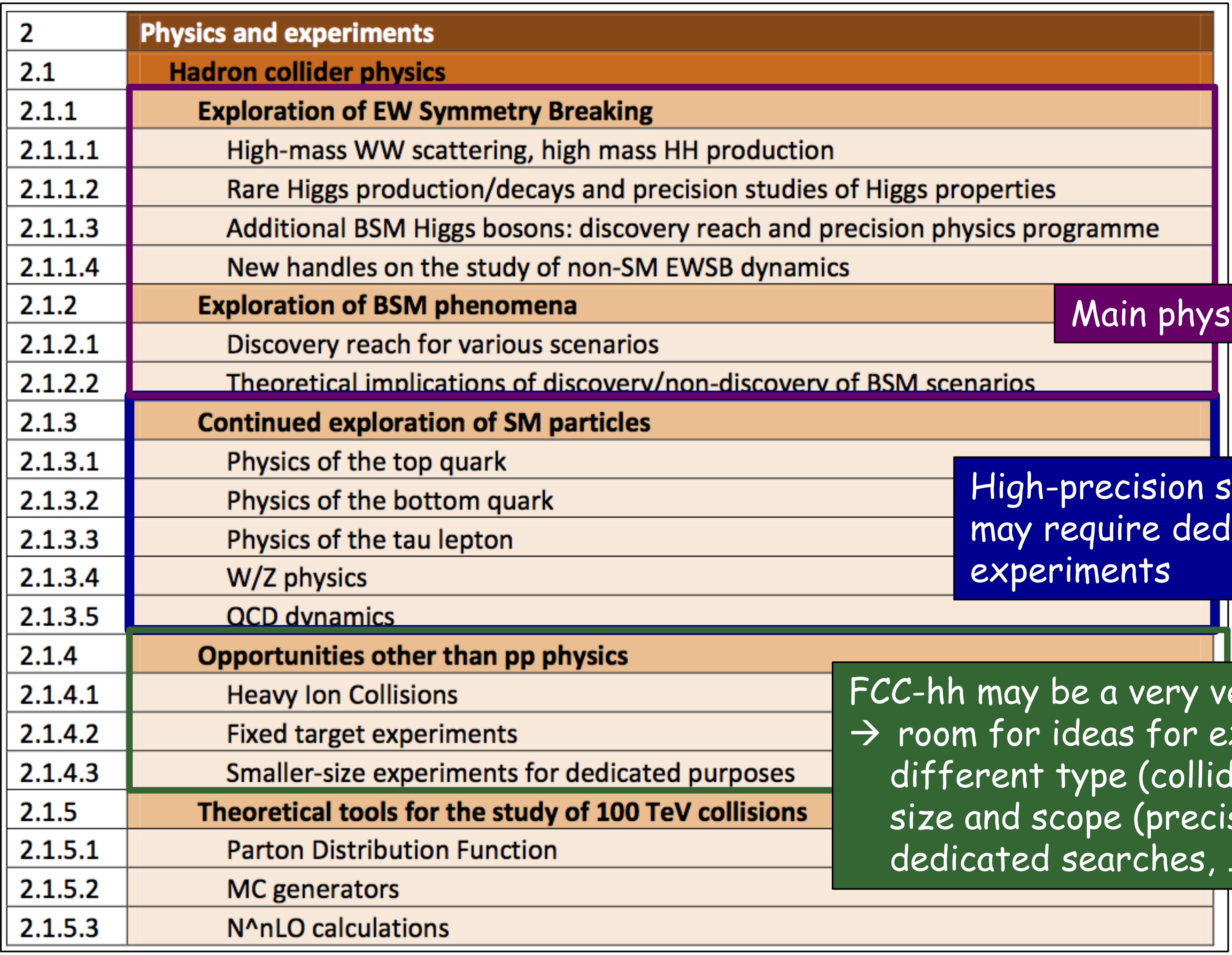


Figure 1. Conceptual design of ‘non-magnetic’ detector system. Calorimeter coverage for $3 < |\eta| \leq 5$ is not essential for luminosity $> 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

?

Work outline - I



2	**Physics and experiments**
2.1	**Hadron collider physics**
2.1.1	**Exploration of EW Symmetry Breaking**
2.1.1.1	High-mass WW scattering, high mass HH production
2.1.1.2	Rare Higgs production/decays and precision studies of Higgs properties
2.1.1.3	Additional BSM Higgs bosons: discovery reach and precision physics programme
2.1.1.4	New handles on the study of non-SM EWSB dynamics
2.1.2	**Exploration of BSM phenomena**
2.1.2.1	Discovery reach for various scenarios
2.1.2.2	Theoretical implications of discovery/non-discovery of BSM scenarios
2.1.3	**Continued exploration of SM particles**
2.1.3.1	Physics of the top quark
2.1.3.2	Physics of the bottom quark
2.1.3.3	Physics of the tau lepton
2.1.3.4	W/Z physics
2.1.3.5	QCD dynamics
2.1.4	**Opportunities other than pp physics**
2.1.4.1	Heavy Ion Collisions
2.1.4.2	Fixed target experiments
2.1.4.3	Smaller-size experiments for dedicated purposes
2.1.5	**Theoretical tools for the study of 100 TeV collisions**
2.1.5.1	Parton Distribution Function
2.1.5.2	MC generators
2.1.5.3	N^nLO calculations

Main physics goals

High-precision studies may require dedicated experiments

FCC-hh may be a very versatile facility
→ room for ideas for experiments of different type (collider, fixed target), size and scope (precise measurements, dedicated searches, …)

More in Michelangelo's talk

Work outline - II

2.2	**Hadron collider experiments**
2.2.1	**Detector performance**
2.2.1.1	Rapidity coverage for tracking, leptons, jets
2.2.1.2	Forward tracking and b-tag vs pile-up density
2.2.1.3	Electromagnetic calorimeter: dynamic range, forward granularity
2.2.1.4	Forward jet tagging
2.2.1.5	Muon resolution in the O(10 TeV) region
2.2.1.6	Optimisation of the bunch spacing (trigger and readout vs pile-up)
2.2.2	**Technical systems**
2.2.2.1	Technologies that require R&D
2.2.2.2	Detector technologies
2.2.2.3	Radiation effects
2.2.2.4	Shielding
2.2.2.5	ECAL
2.2.2.6	HCAL
2.2.2.7	Magnet system
2.2.2.8	Muon detection
2.2.2.9	Inner detector
2.2.2.10	Tracking
2.2.2.11	Trigger system
2.2.2.12	Data acquisition, detector controls and detector safety
2.2.3	**Detector machine Interface**
2.2.3.1	L*, TAS, TAN locations and specifications
2.2.3.2	Bunch structure, luminous region and crossing angle
2.2.3.3	Beam pipe and vacuum design
2.2.3.4	Fluencies, shielding, dose rates, activation, and radiological dose minimization
2.2.3.5	Physics and detector protection instrumentation in the long straight section

Performance requirements and experimental challenges

Detectors layout, R&D and technologies
→ synergies with FCC-ee, ILC and CLIC being established

Detector-machine interface issues

More in D. Fournier's talk and Friday afternoon's parallel session