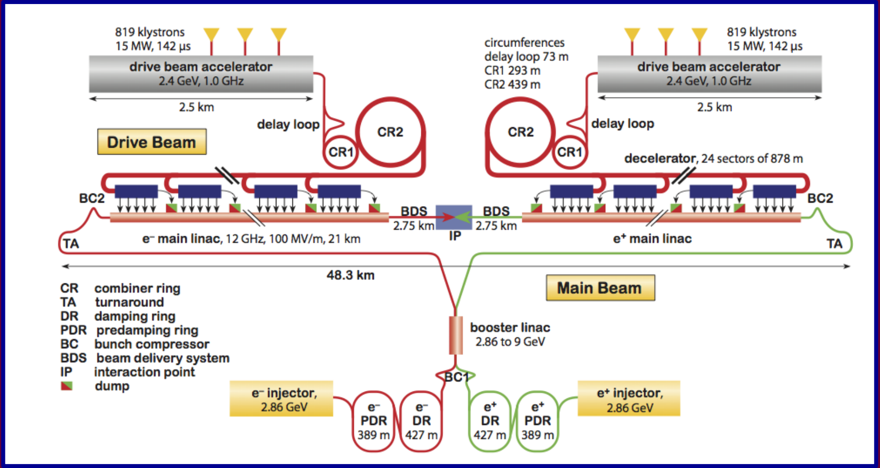
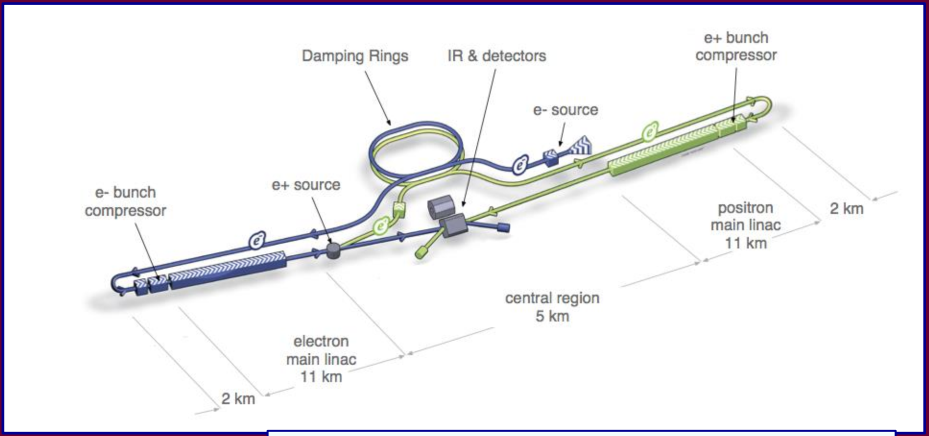
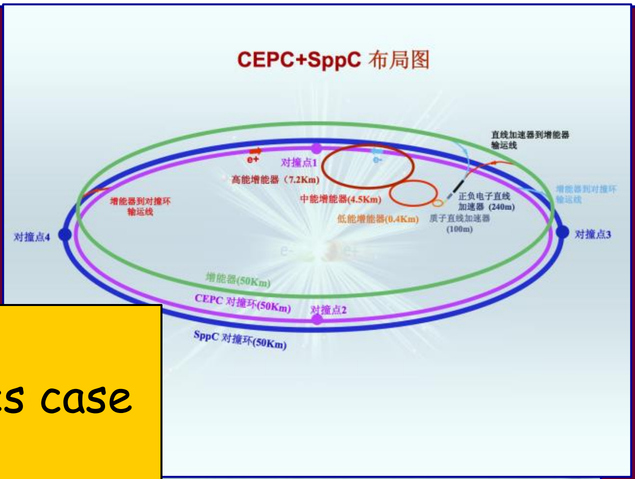
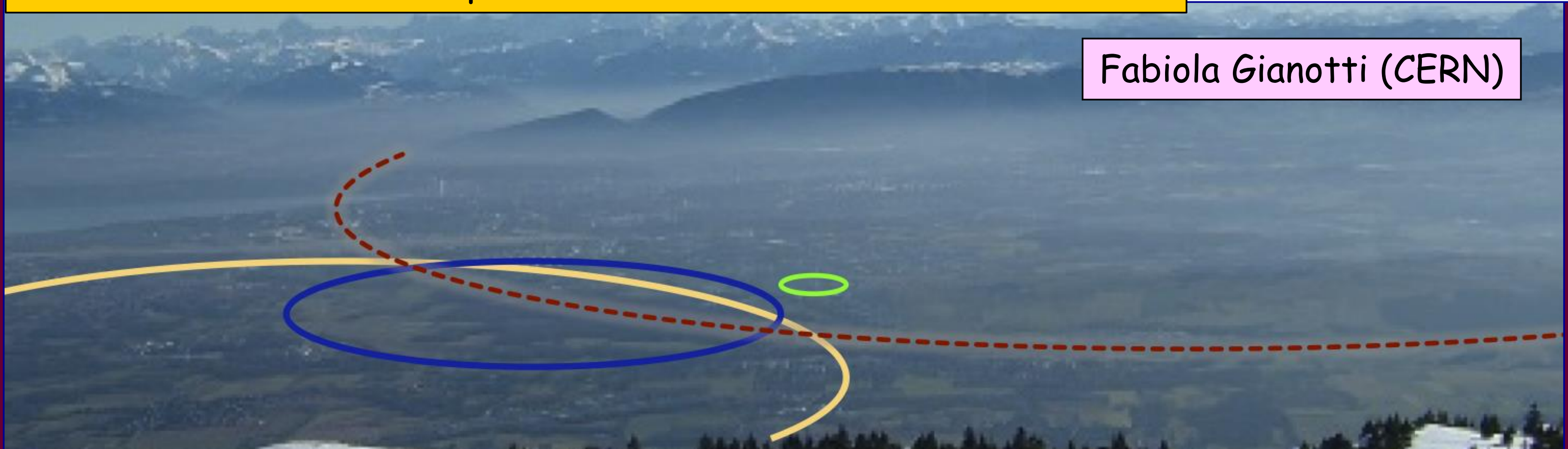






Opportunities and prospects for future high-E colliders

- ❑ The present questions in particle physics
- ❑ The main options for high-E colliders and their physics case
- ❑ Final remarks as an input to the discussion



Fabiola Gianotti (CERN)

The present questions in particle physics

With the discovery of a Higgs boson (a triumph for particle physics and high-E colliders), the SM has been completed.

However: the SM is not a complete theory of particle physics as several outstanding questions, raised also by experimental observations that cannot be explained within the SM, remain.

These questions require NEW PHYSICS

Main outstanding questions in today's particle physics

Higgs boson and EWSB
☐ m_H natural or fine-tuned ?
→ if natural: what new physics/symmetry?
☐ does it regularize the divergent V_LV_L cross-section at high $M(V_LV_L)$? Or is there a new dynamics ?
☐ elementary or composite Higgs ?
☐ is it alone or are there other Higgs bosons ?
☐ origin of couplings to fermions
☐ coupling to dark matter ?
☐ does it violate CP ?
☐ cosmological EW phase transition (is it responsible for baryogenesis ?)

Neutrinos:
☐ ν masses and and their origin
☐ what is the role of H(125) ?
☐ Majorana or Dirac ?
☐ CP violation
☐ additional species → sterile ν ?

Dark matter:
☐ composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
☐ one type or more ?
☐ only gravitational or other interactions ?

The two epochs of Universe's accelerated expansion:
☐ primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
☐ today: dark energy (why is Λ so small?) or gravity modification ?

Quarks and leptons:
☐ why 3 families ?
☐ masses and mixing
☐ CP violation in the lepton sector
☐ matter and antimatter asymmetry
☐ baryon and charged lepton number violation

Physics at the highest E-scales:
☐ how is gravity connected with the other forces ?
☐ do forces unify at high energy ?

At what E scale(s) are the answers ?

These questions are compelling, difficult and intertwined → require all approaches we have in hand (made possible also thanks to strong advancements in accelerator and detector technologies): high-E colliders, neutrino experiments (solar, short/long baseline, reactors 0νββ decays), cosmic surveys (CMB, Supernovae, BAO), dark matter direct and indirect detection, precision measurements of rare decays and phenomena, dedicated searches (WIMPS, axions, dark-sector particles), …

Main questions and main approaches to address them

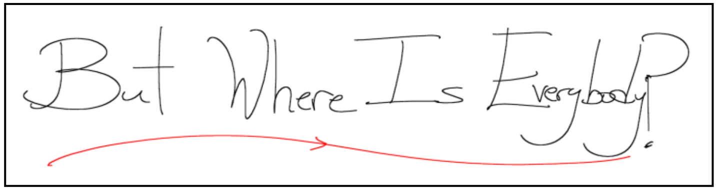
	High-E colliders	High-precision experiments	Neutrino experiments	Dedicated searches	Cosmic surveys
Higgs , EWSB	x				
Neutrinos	?		x	x	x
Dark Matter	x			x	
Flavour, CP-violation	x	x	x	x	
New particles and forces	x	x	x	x	
Universe acceleration					x

These complementary approaches are ALL needed: their combination is crucial to explore the largest range of E scales, properly interpret signs of new physics, and build a coherent picture of the underlying theory.

Two main outcomes from LHC Run 1

We have discovered a new (profoundly different from the others) particle
→ detailed precise measurements of the Higgs boson are mandatory

We have NO evidence of new physics (yet …)



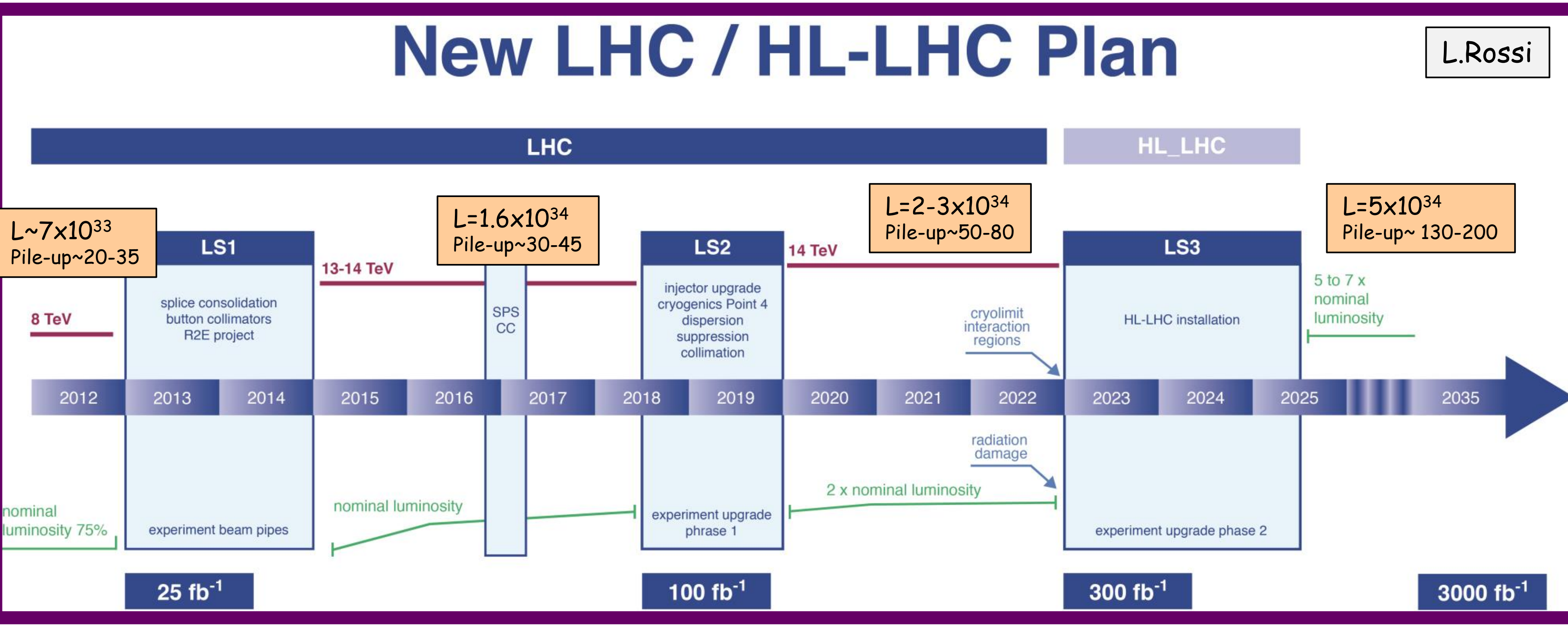
This last point implies that, if new physics exists at the TeV scale and is discovered at LHC at √s ~ 14 TeV in 2015++, its mass spectrum is quite heavy (unless part of it has escaped detection at present LHC)
→ it will likely require high energy and luminosity to study it fully and in detail
→ implications on future machines

Options for future high-energy colliders

- ☐ Linear and circular e^+e^- colliders
- ☐ Very high-E proton-proton colliders

Disclaimer: due to time limitation, I will not discuss other options: μμ, ep, γγ colliders

The present and near/medium-term future: LHC and HL-LHC



Full exploitation of LHC project with HL-LHC (√s ~ 14 TeV, 3000 fb^{-1}) is MANDATORY
(Europe's top priority per European Strategy, US highest-priority near-term large project per P5)

- Present highest-E accelerator, allowing:

→ detailed direct exploration of the TeV scale up to ~ 10 TeV

→ measurements of Higgs couplings to few percent

- Results will inform the future
- Cost of upgrade: ~ 1.5 BCHF (machine + experiments, material)

Future e^+e^- colliders

$L \sim 10^{34}$-10^{35} cm^{-2} s^{-1}

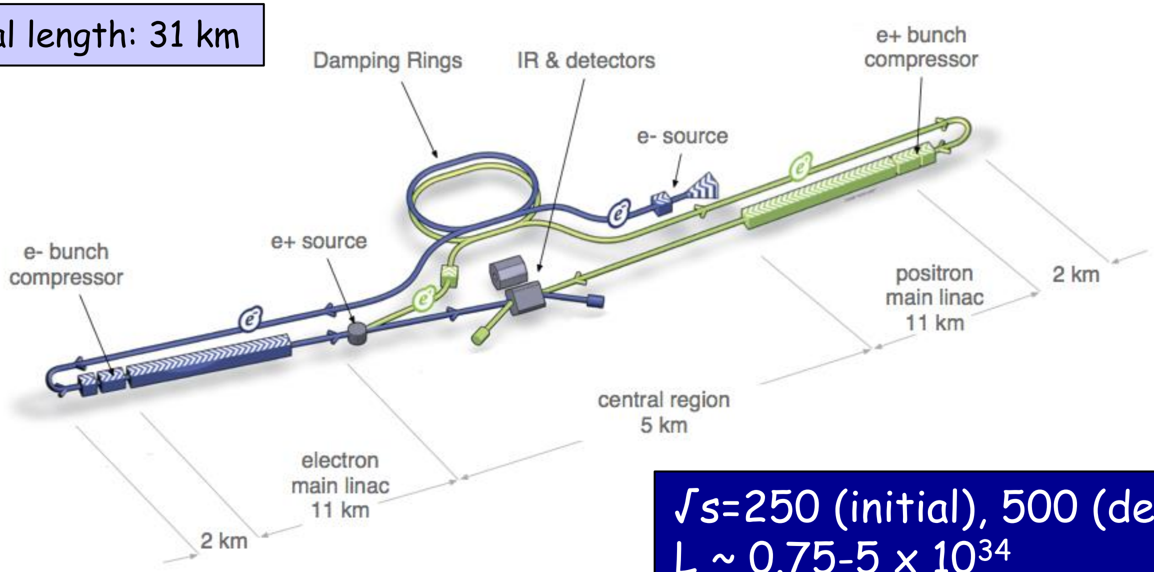
$\sqrt{s}$ (GeV)	Main physics goals
90	Z-pole precision EW measurements beyond LEP, SLC
180	WW precision physics (mass at threshold)
250	Higgs precision physics (HZ)
350	Higgs precision physics (HZ, Hvv), top precision physics (mass at threshold)
500-3000	ttH, HH (including self-couplings), direct searches for new physics

Complementary	Linear colliders	Circular colliders
$\sqrt{s}$ reach	multi-TeV	limited to < 500 GeV by synchrotron radiation SR ~ E^4_{beam}/R
Luminosity	low repetition rate → L from squeezing beams to ~ nm size → large beamstrahlung	large number of continuously circulating bunches → larger beam size → smaller beamstrahlung → cleaner environment, smaller E spread
Injection	fresh bunches need to be injected at each cycle	short L lifetime (~ 30′) due to burn-off → continuous top-up $e^\pm$ injection
L vs $\sqrt{s}$	increases at high E (beam emittance decreases)	increases at low E (less SR → RF power accelerates more bunches)
Number of interaction regions	1 (shared by 2 detectors push/pull?)	several

International Linear Collider (ILC)

Technical Design Report released in June 2013

Total length: 31 km



$\sqrt{s}$=250 (initial), 500 (design), 1000 (upgrade) GeV
L ~ 0.75-5 x 10^{34}
(running at $\sqrt{s}$=90, 160, 350 GeV also envisaged)

Main challenges:

- ~ 15000 SCRF cavities (1700 cryomodules), 31.5 MV/m gradient
- 1 TeV machine requires extension of main Linacs (50 km) and 45 MV/m
- Positron source; suppression of electron-cloud in positron damping ring
- Final focus: squeeze and collide nm-size beams

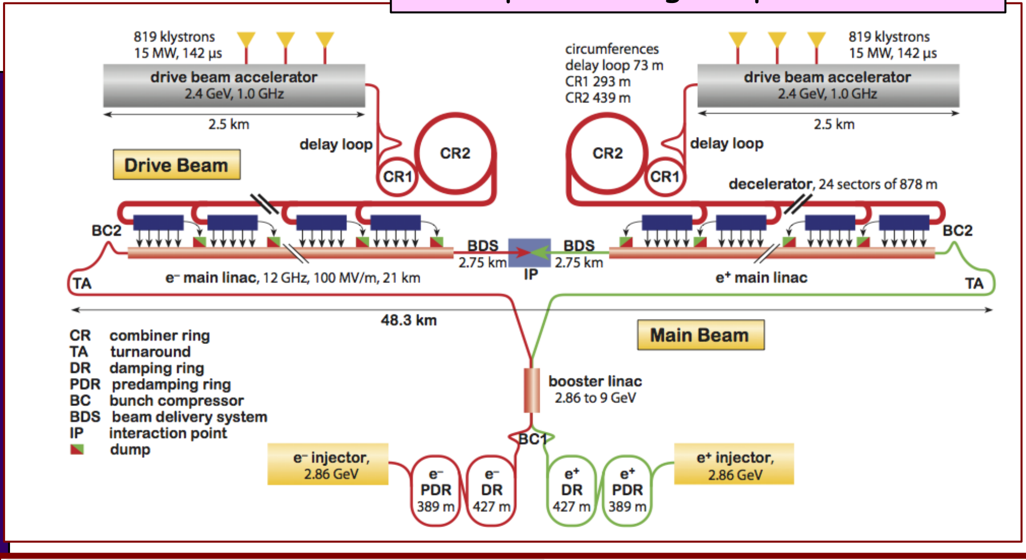
- Japan interested to host → decision ~2018 based also on ongoing international dicussions
  Mature technology: 20 years of R&D experience worldwide
  (e.g. European xFEL at DESY is 5% of ILC, gradient 24 MV/m, some cavities achieved 29.6 MV/m)

→ Construction could technically start ~2019, duration ~10 years → physics could start ~2030

- Cost of 500 GeV accelerator: ~ 8 B$ (material)

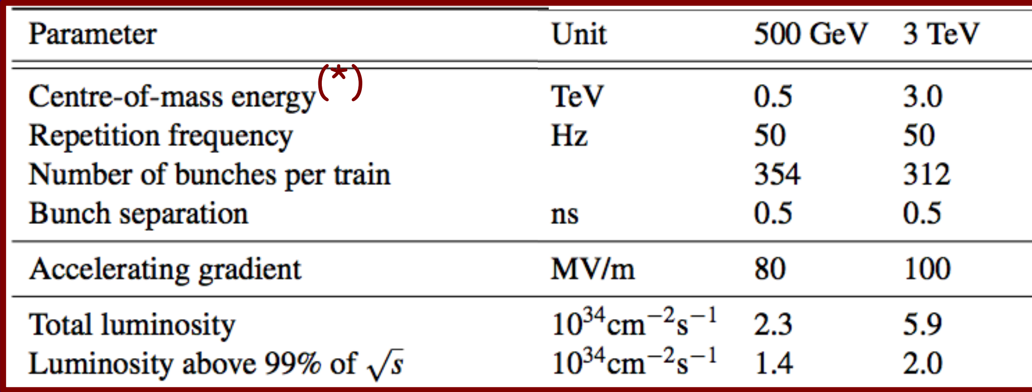
Compact Linear Collider (CLIC)

Conceptual Design Report end 2012



Main challenges:

- 100 MV/m accelerating gradient needed for compact (50 km) multi-TeV (up to 3 TeV) collider
- Short (156 ns) beam trains → bunch spacing 0.5 ns to maximize luminosity
- Keep RF breakdown rate small
- 2-beam acceleration (new concept): efficient RF power transfer from low-E high-intensity drive beam to (warm) accelerating structures for main beam
- Power consumption (~600 MW !)
- Preservation of nm size beams and final focus
- Detectors: huge beamstrahlung background (20 TeV per beam train in calorimeters at √s=3 TeV) → 1-10 ns time stamps needed



Parameter	Unit	500 GeV	3 TeV
Centre-of-mass energy(*)	TeV	0.5	3.0
Repetition frequency	Hz	50	50
Number of bunches per train		354	312
Bunch separation	ns	0.5	0.5
Accelerating gradient	MV/m	80	100
Total luminosity	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	2.3	5.9
Luminosity above 99% of $\sqrt{s}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.4	2.0

(*) Currently optimizing for initial stage at √s=350 GeV

- If decision to proceed in ~2018 → construction could technically start ~2024, duration ~6 years for √s ≤500 GeV, (26 km Linac) → physics could start 2030++
- Cost (material): ~8 BCHF for 500 GeV machine, +~4 BCHF/TeV for next E step

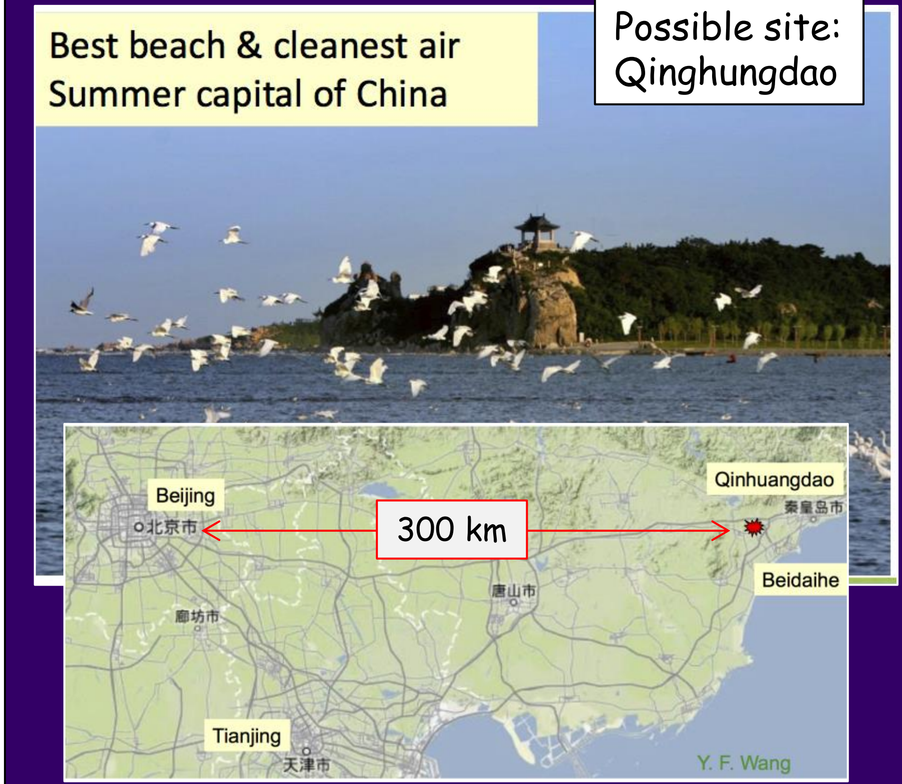
Future high-energy circular colliders

Parameters are indicative and fast evolving, as no CDR yet

China: 50-70 km e^+e^- $\sqrt{s}$=240 GeV (CepC) followed by 50-90 TeV pp collider (SppC) in same tunnel

50 km e^+e^- machine + 2 experiments:

- ☐ pre-CDR: end 2014
- ☐ construction: 2021-2027
- ☐ data-taking: 2028-2035
- ☐ cost (material): ~3 B$

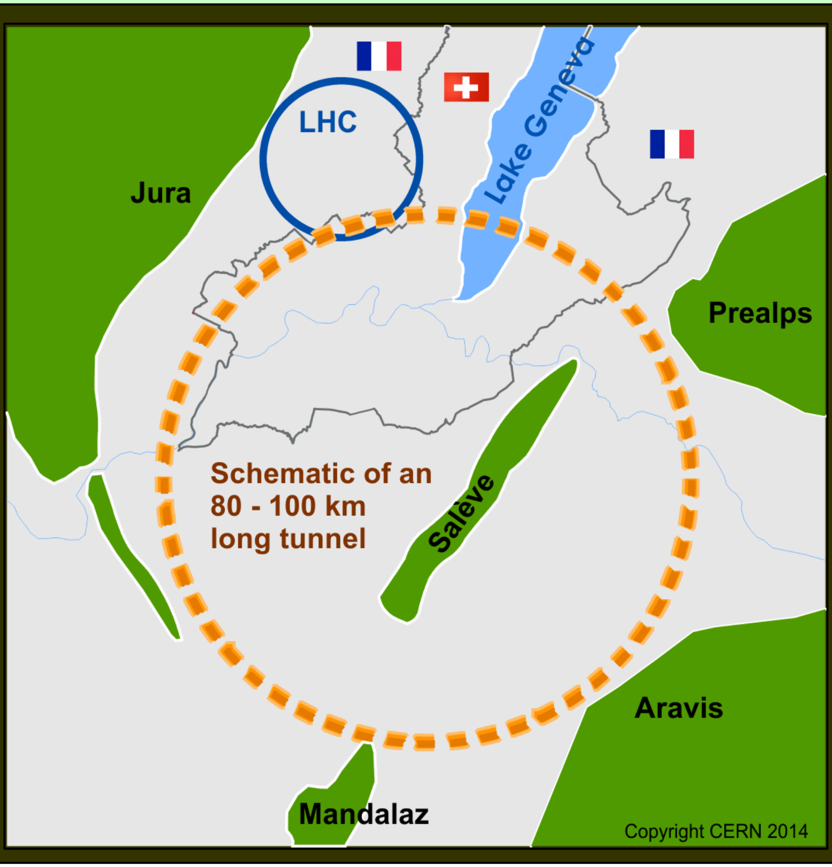

Best beach & cleanest air
Summer capital of China

Possible site: Qinghungdao

CERN FCC: international design study for Future Circular Colliders in 80-100 km ring:

- ☐ 100 TeV pp: ultimate goal (FCC-hh)
- ☐ 90-350 GeV e^+e^-: possible intermediate step (FCC-ee)
- ☐ $\sqrt{s}$= 3.5-6 TeV ep: option (FCC-eh)

Goal of the study: CDR in ~2018.



	CepC	FCC-ee		
Ring (km)	53.6	100		
$\sqrt{s}$ (GeV)	240	240	350	90
E loss per turn (GeV)	3	1.7	7.5	0.03
Total RF voltage (GV)	6.9	5.5	11	2.5
Beam current (mA)	16.6	30	6.6	1450
N. of bunches	50 (one ring!)	1360	98	16700
L (10^{34} cm^{-2} s^{-1})/IP	1.8	6	1.8	28
$e^{\pm}$/bunch (10^{11})	3.7	0.46	1.4	1.8
σ_y/σ_x at IP (μm)	0.16/74	0.045/22	0.045/45	0.25/121
Interaction Points	2	4	4	4
Lumi lifetime (min)	60	21	15	213
SR power/beam	50 MW	50 MW		

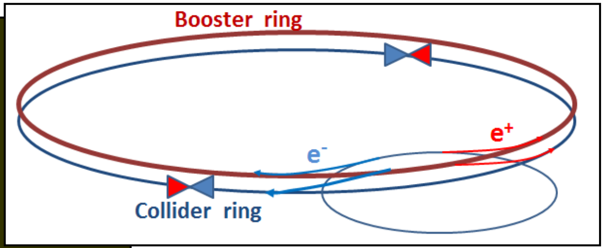
Main challenges:

☐ FCC ring size

☐ Synchrotron radiation → 100 MW RF system with high efficiency

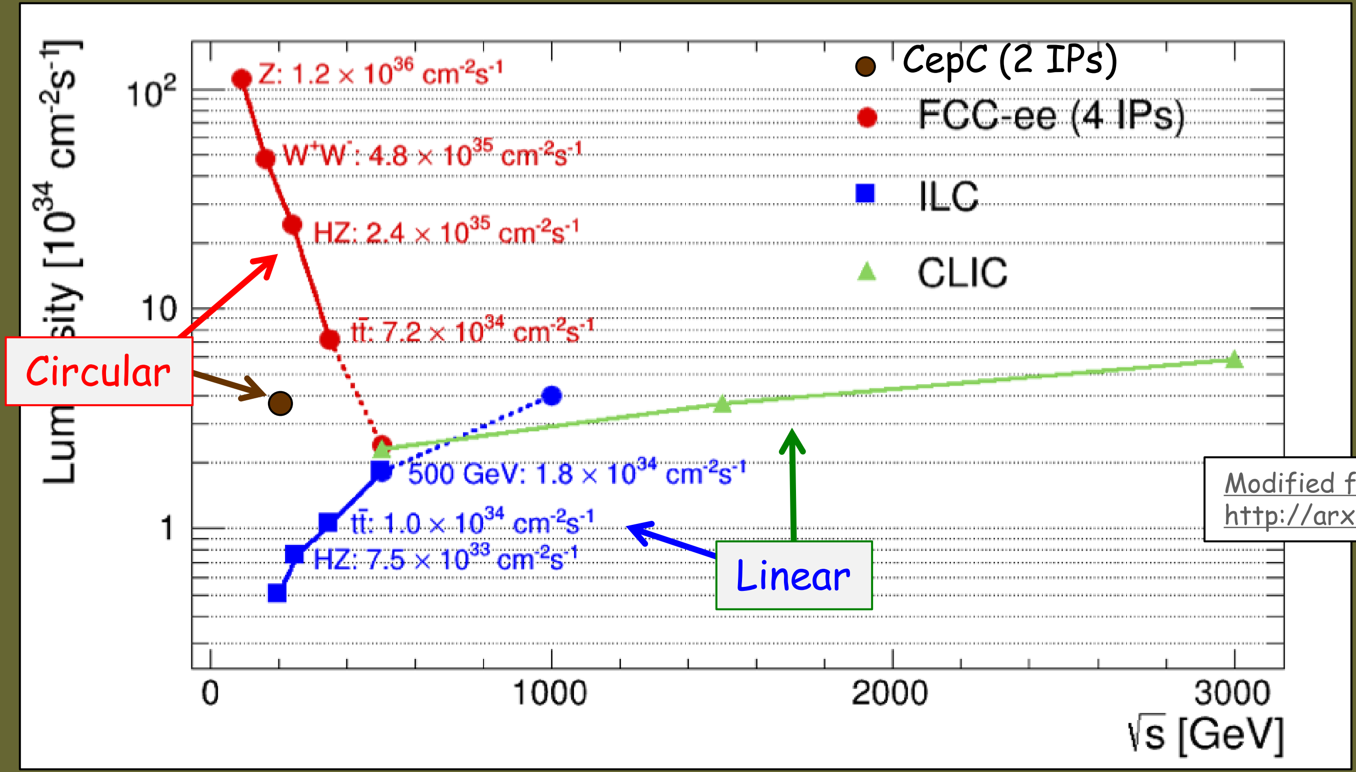
☐ Beam polarization for beam energy calibration at Z-pole and WW threshold to <100 keV to measure m_Z, m_W to < MeV at FCC-ee

☐ Machine design with large energy acceptance over full $\sqrt{s}$ span



Note: Super-KEKB is an excellent "prototype", with more stringent requirements on positron rate, momentum acceptance, lifetime, β_y^*

Summary of e^+e^- colliders main parameters



Modified from original version:
http://arxiv.org/pdf/1308.6176v3.pdf

Some typical energy points only

	Size km	$\sqrt{s}$ GeV	RF MV/m	L per IP 10^{34}	Bunch/train x-ing rate(Hz)	σ_x μm	σ_y nm	Lumi within 1% of $\sqrt{s}$	Polarisation e^-/e^+
CEPC	54	240	20	1.8	4×10^5	74	160	>99%	considered
FCC-ee	100	240	20	6	2×10^7	22	45	>99%	considered
ILC	31	250	14.7	0.75	5	0.7	7.7	87%	80%/30%
ILC	31	500	31.5	1.8	5	0.5	5.9	58%	80%/30%
CLIC	48	3000	100	6	50	0.04	1	33%	80%/considered

Future pp colliders

Pioneering work in the US as of 1998 with VLHC: http://vlhc.org/vlhc/

	Ring (km)	Magnets (T)	$\sqrt{s}$ (TeV)	L (10^{34})
LHC	27	8.3	14	up to 5
HE-LHC	27	16-20	26-33	5
SppC-1	50	12	50	2
SppC-2	70	19	90	2.8
FCC-hh	100	16	100	≥ 5

Nb_3Sn ok up to 16 T; HTS needed for 20 T

May reach ~10^{35}

More parameters of 100 TeV FCC-hh

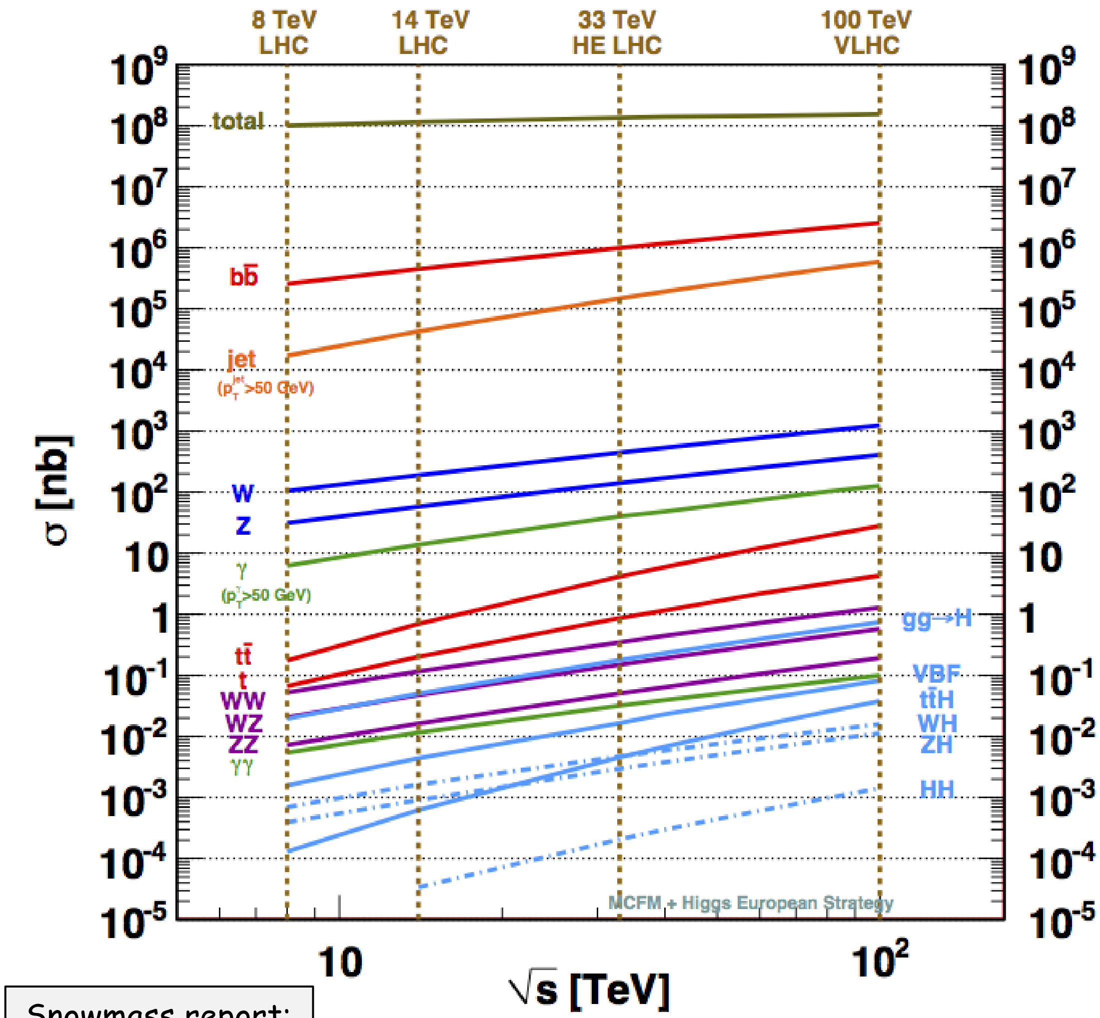
	HL-LHC	FCC-hh
Bunch spacing	25	25
N. of bunches	2808	10600
Pile-up	140	170
E-loss/turn	7 keV	5 MeV
SR power/ring	3.6 kW	2.5 MW
Interaction Points	4	4
Stored beam energy	390 MJ	8.4 GJ

5 ns also considered to mitigate e-cloud

Challenges (many, daunting, ...): magnet technology, tunnel excavation, stored beam energy, ...

As an Airbus 380 at full speed

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
$t\bar{t}$	~30
H	~15 ($t\bar{t}H$ ~60)
HH	~40
stop (m=1 TeV)	~10^3

→ With 10000/fb at √s=100 TeV expect: 10^{12} top, 10^{10} Higgs bosons, 10^8 m=1 TeV stop pairs, …

Physics motivations and potential

- ☐ Higgs boson coupling measurements
- ☐ Direct and indirect sensitivity to new physics
- ☐ Studies of EWSB through $V_L V_L$ scattering

How precisely do we need to know the Higgs boson ?

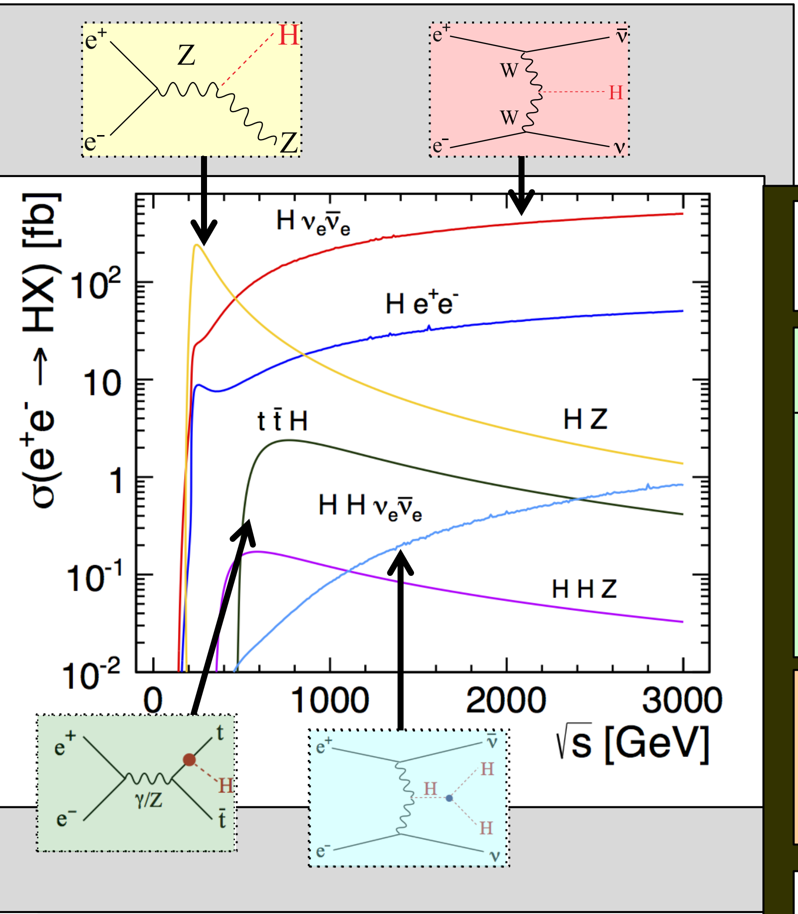
Effect of New Physics on couplings:

$\Delta\kappa/\kappa \sim 5\%/\Lambda^2_{NP}$ (Λ_{NP} in TeV)

→ 0.1-1% precision needed for discovery

Scenarios with no new particles observable at LHC

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



Integrated luminosities correspond to 3-5 years of running at each √s for e⁺e⁻ and 5 years with 2 experiments for pp

	√s (TeV)	L (ab^{-1})	N_H (10^6)	N_{ttH}	N_{HH}
FCC-ee*	0.24+0.35	10	2	--	--
ILC	0.25+0.5	0.75	0.2	1000	100
ILC-1TeV	0.25+0.5+1	1.75	0.5	3000	400
CLIC	0.35+1.4+3	3.5	1.5	3000	3000
				→ ttγγ, tt4l	→ bbγγ
HL-LHC	14	3	180	3600 ttγγ	250
FCC-hh	100	6	5400	12000 tt4l	20000

* 4 IP

<10% of events usable

F. Gianotti, LHCP 2014, 6/6/2014

Coupling	HL-LHC	FCC-ee	ILC (500)	ILC (1000)	CLIC
$\sqrt{s}$ →	14000	240 +350	250+500	250+500+1000	350+1400+3000
Int. L →	6000	10000+2600	250+500	250+500+1000	500+1500+2000
K_W	2-5%	0.19%	1.2%	1.2%	2.1%
K_Z	2-4%	0.15%	1.0%	1.0%	2.1%
K_g	3-5%	0.80%	2.3%	1.6%	2.2%
K_γ	2-5%	1.5%	8.4%	4.0%	<5.9%
K_μ	~7%	6.2%	--	16%	5.6%
K_c	--	0.71%	2.8%	1.8%	2.2%
K_τ	2-5%	0.54%	2.4%	1.8%	<2.5%
K_b	4-7%	0.42%	1.7%	1.3%	2.1%
BR_{invis}	<10 %	<0.19%	<0.9%	<0.9%	na
K_t	~5%	13%indirect	14%	3.2%	<4.5%
K_{HH} (self)	?	--	--	26% (13% ultimate)	10%

rare decays → HL-LHC is competitive

FCC-hh:
K_t: few percent ??
K_{HH} ~ 8%

- ☐ LHC: ~20% today → 5-10% in ~2020 (14 TeV, 300 fb^{-1})
- ☐ HL-LHC:

-- factor ~ 2 better than LHC @300 fb^{-1}
-- first direct observation of couplings to top (ttH) and 2nd generation fermions (H→ μμ)
-- model dependent measurements: Γ_H and σ (H) from SM

- ☐ e^+e^-:

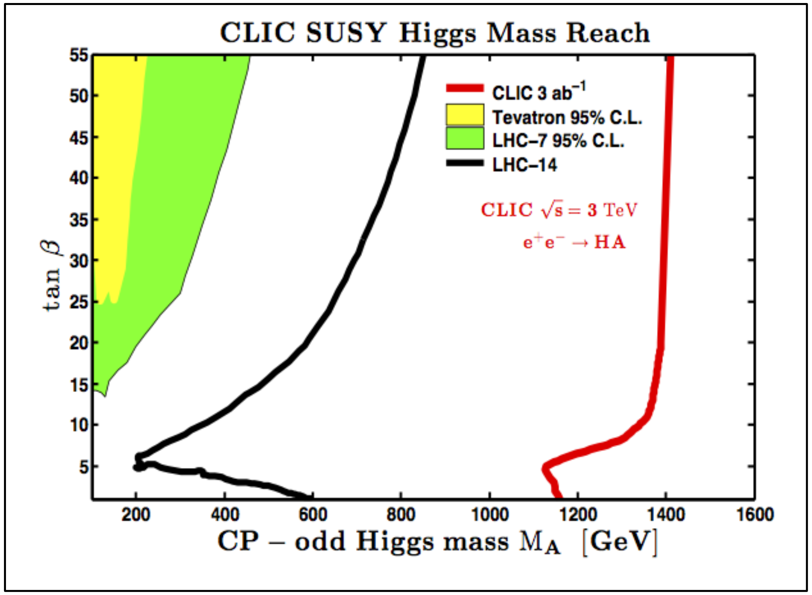
-- model-independent: σ(HZ) and Γ_H from data: ZH → μμX recoil mass (σ, Γ_H), Hνν → bbνν (Γ_Z)
-- all decay modes accessible (fully hadronic, invisible, exotic)

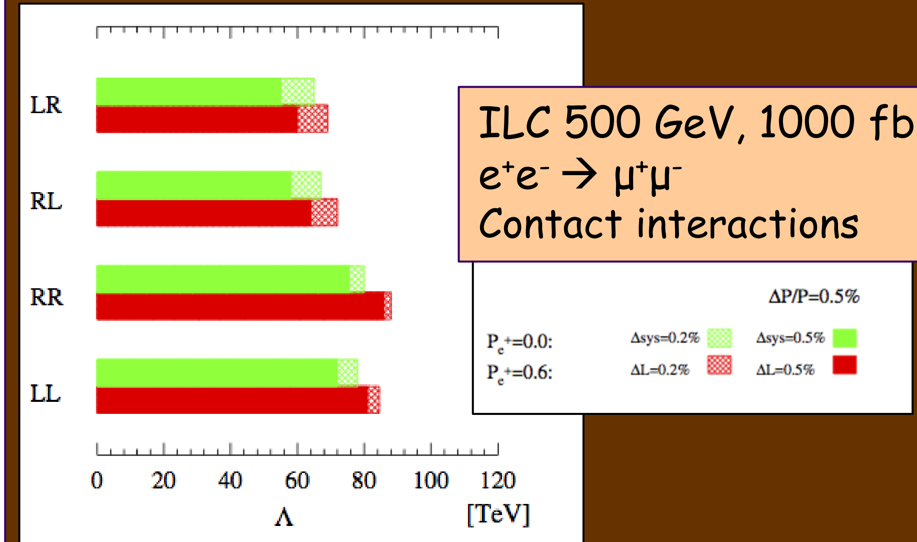
- ☐ Best precision (few 0.1%) at circular colliders (luminosity !), except for heavy states (ttH and HH) where high energy (linear colliders, FCC-hh) needed

Note: theory uncertainties, e.g. presently O(1%) on BR, need to be improved to match expected superb experimental precision and sensitivity to new physics

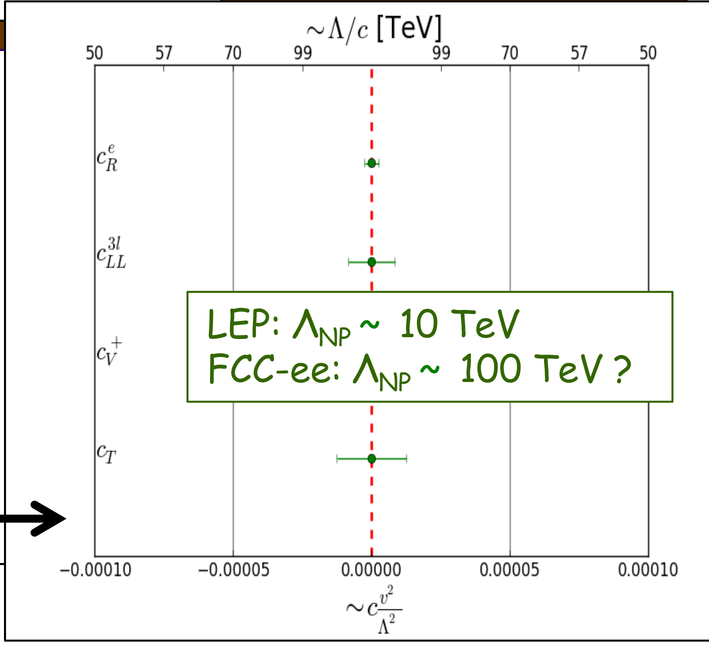
Direct and indirect sensitivity to high-scale new physics at e^+e^- colliders

- ❑ Direct: model-independent searches for new particles coupling to Z/γ* up to: $m \sim \sqrt{s}/2$
- ❑ Indirect: via precise measurements → ILC/CLIC/FCC-ee can probe up to Λ~O(100) TeV





ILC 500 GeV, 1000 fb^{-1}
$e^+e^- \to \mu^+\mu^-$
Contact interactions



LEP: $\Lambda_{NP} \sim$ 10 TeV
FCC-ee: $\Lambda_{NP} \sim$ 100 TeV ?

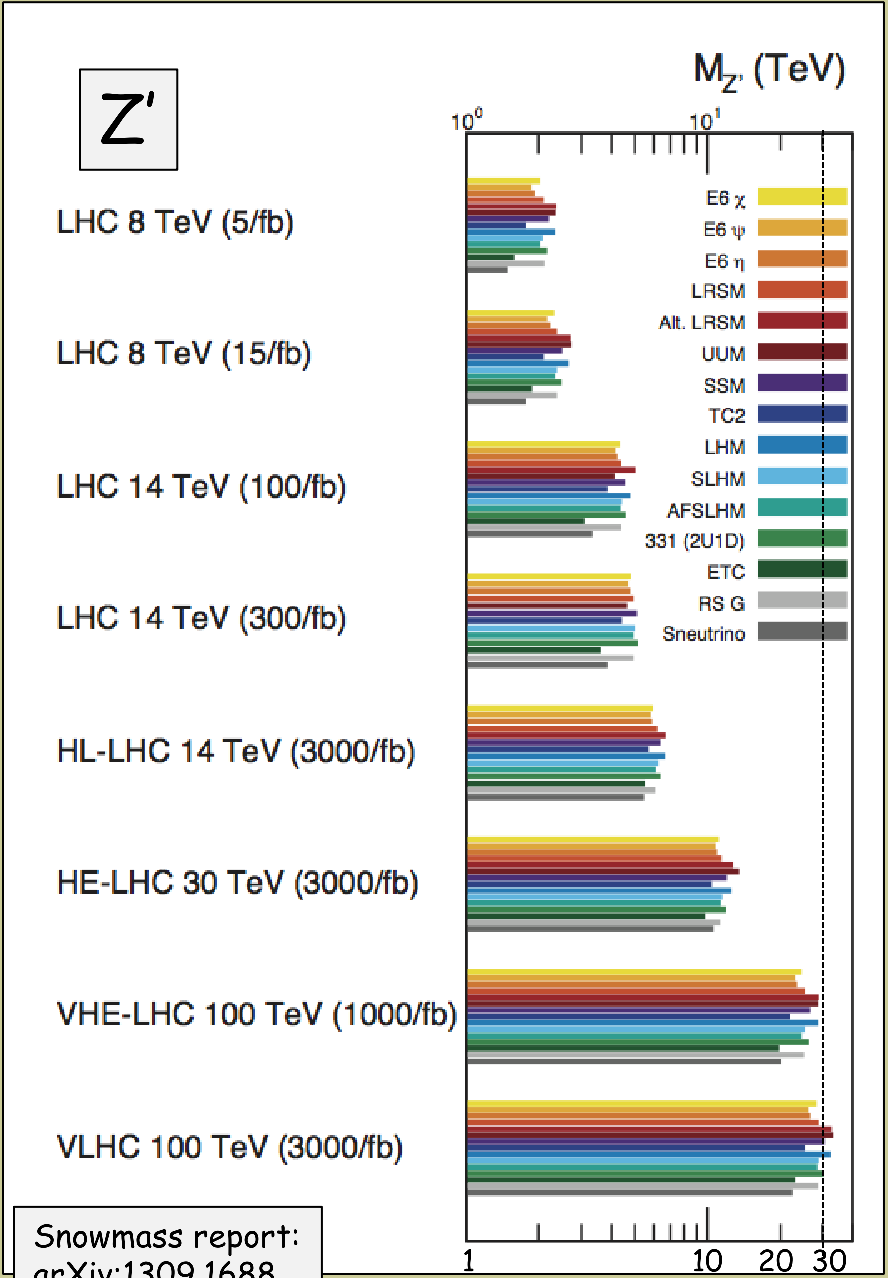
FCC-ee statistical power:

- ❑ 10^{12} Z (L= 2.8×10^{35} → full LEP1 dataset every 15')
  → x300 higher precision on EW observables
- ❑ 10^8 WW → $\Delta m_W < 1$ MeV
- ❑ 2×10^6 $t\bar{t}$ → $\Delta m_t \sim 10$ MeV

$$L_{\text{eff}} = \sum_n \frac{c_n v^2}{\Lambda^2} O_n$$

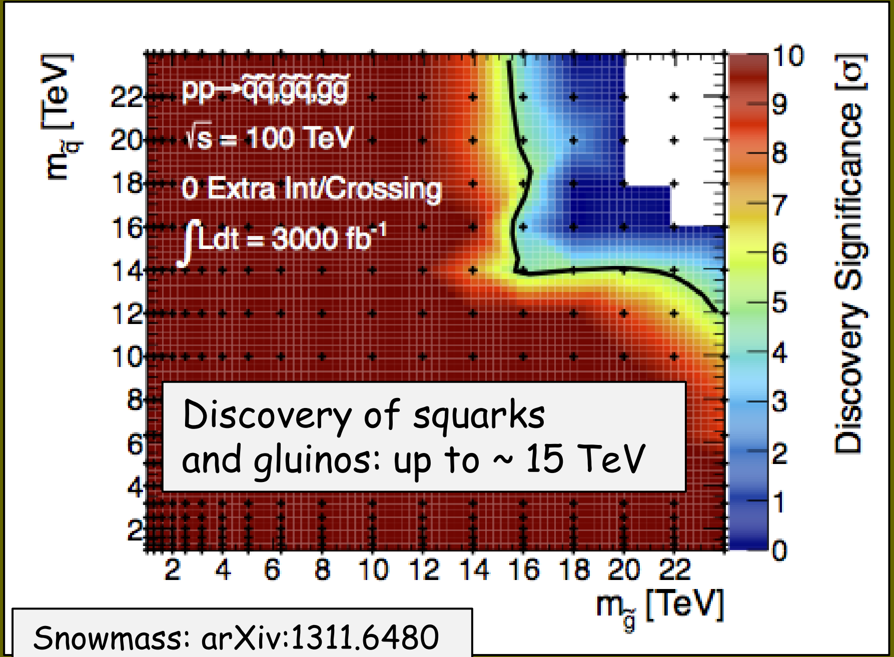
probe higher-dimensional operators from new physics

A 100 TeV pp collider is the instrument to explore the O(10 TeV) E-scale directly



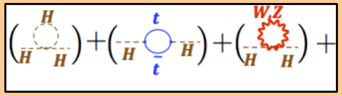
Snowmass report:
arXiv:1309.1688

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



Discovery of squarks and gluinos: up to ~ 15 TeV

Snowmass: arXiv:1311.6480



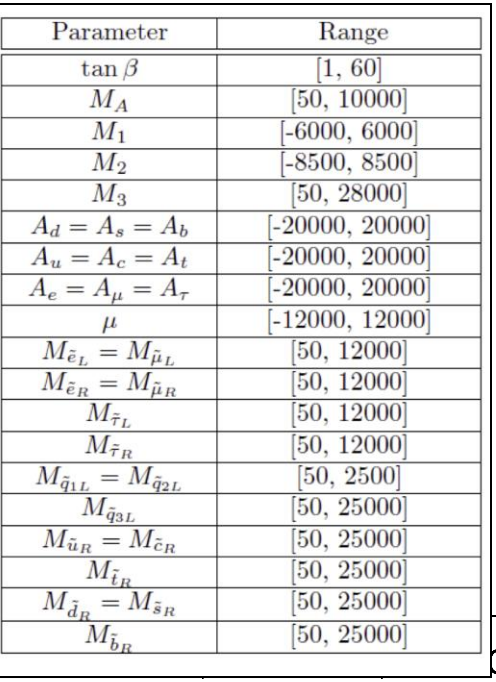
$\Delta M_H^2 \sim (\ldots)+(\ldots)+(\ldots)+\ \cdots \sim \Lambda^2$

- ☐ Only Higgs and nothing else at ~O(1 TeV) → 1% fine-tuning
- ☐ Only Higgs and nothing else at ~O(10 TeV) → 10^{-4} fine-tuning

(Distinguished) theorist 1: “Never seen 10^{-4} level of tuning in particle physics: qualitatively new, mortal blow to naturalness”

(Distinguished) theorist 2: “Naturalness is a fake problem”

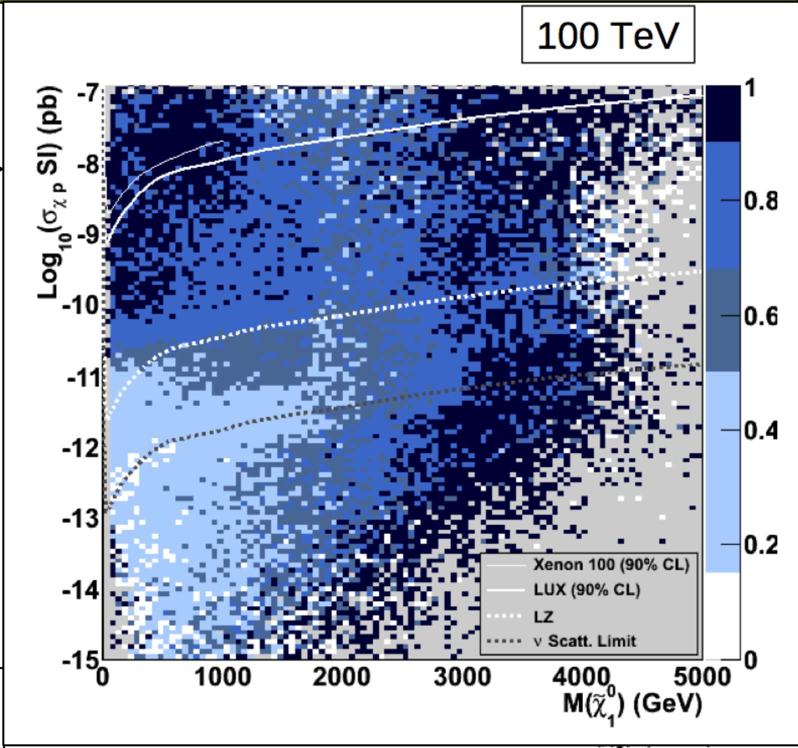
Dark Matter searches



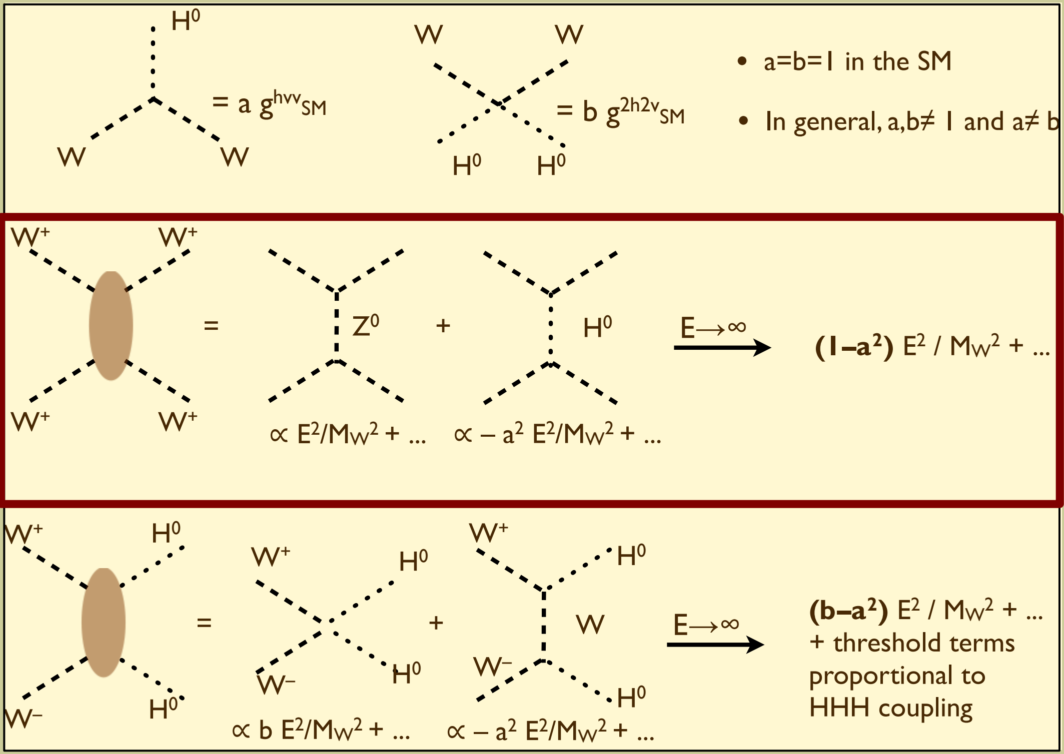
Parameter	Range
$\tan\beta$	[1, 60]
M_A	[50, 10000]
M_1	[-6000, 6000]
M_2	[-8500, 8500]
M_3	[50, 28000]
$A_d = A_s = A_b$	[-20000, 20000]
$A_u = A_c = A_t$	[-20000, 20000]
$A_e = A_\mu = A_\tau$	[-20000, 20000]
μ	[-12000, 12000]
$M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$	[50, 12000]
$M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$	[50, 12000]
$M_{\tilde{\tau}_L}$	[50, 12000]
$M_{\tilde{\tau}_R}$	[50, 12000]
$M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$	[50, 2500]
$M_{\tilde{q}_{3L}}$	[50, 25000]
$M_{\tilde{u}_R} = M_{\tilde{c}_R}$	[50, 25000]
$M_{\tilde{t}_R}$	[50, 25000]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[50, 25000]
$M_{\tilde{b}_R}$	[50, 25000]

Fraction of pMSSM parameter space that can be excluded at 95% CL by present experimental constraints and direct DM searches at HL-LHC (14 TeV, 3000 fb^{-1}) and 100 TeV pp collider (5000 fb^{-1})

Arbey, Battaglia, Mahmoudi



A 100 TeV pp collider would allow a definitive exploration of EWSB



- a=b=1 in the SM
- In general, a,b≠ 1 and a≠ b

$\propto E^2/M_W^2 + \ldots$ $\quad \propto -a^2 E^2/M_W^2 + \ldots$ $\quad \xrightarrow{E\to\infty}$ $(1-a^2)\, E^2 / M_W^2 + \ldots$

$\propto b\, E^2/M_W^2 + \ldots$ $\quad \propto -a^2 E^2/M_W^2 + \ldots$ $\quad \xrightarrow{E\to\infty}$ $(b-a^2)\, E^2 / M_W^2 + \ldots$ + threshold terms proportional to HHH coupling

By providing direct access to EW theory in the unbroken regime ($\sqrt{\hat{s}} \gg v=246$ GeV)

$V_L V_L$ scattering violates unitarity at m_{VV} ~TeV without Higgs exchange diagrams

KEYWORD: ENERGY !

Important to verify that:

☐ H (125) regularizes the theory → a crucial "closure test" of the SM

☐ Or, else: observe deviations in VV production compared to SM expectation → anomalous quartic (VVVV) gauge couplings and/or new heavy resonances → new physics
(Note: several models predict SM-like Higgs but different physics at high E)

☐ ILC 1 TeV, 1 ab^{-1} : indirect sensitivity to new resonances up to m~6 TeV (exploit $e^{\pm}$ polarization)

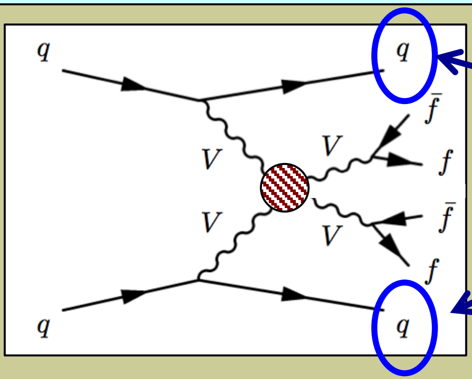
☐ CLIC 3 TeV, 1 ab^{-1} : indirect sensitivity to composite Higgs scale Λ~30 TeV from VV→ hh

☐ 100 TeV pp: huge cross-sections at high-mass: $\sigma \sim 100$ fb $m_{WW} > 3$ TeV; $\sigma \sim 1$ fb $m_{HH} > 2$ TeV

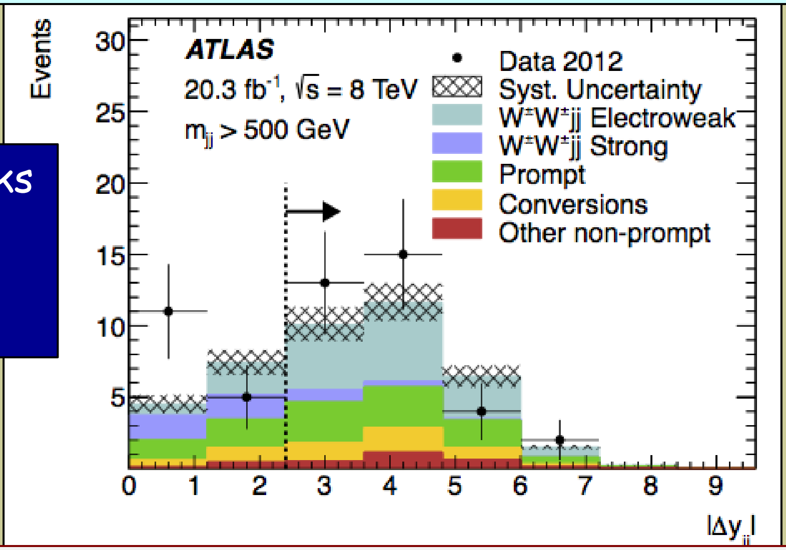
→ detailed <u>direct</u> studies

Evidence for EW VBS reported recently by ATLAS in pp → $W^\pm W^\pm$ jj channel giving 2 same-sign leptons and 2 high-mass jets (m_{jj} > 500 GeV)

Significance of EW VBS signal: ~3.6σ for large rapidity gap between 2 jets



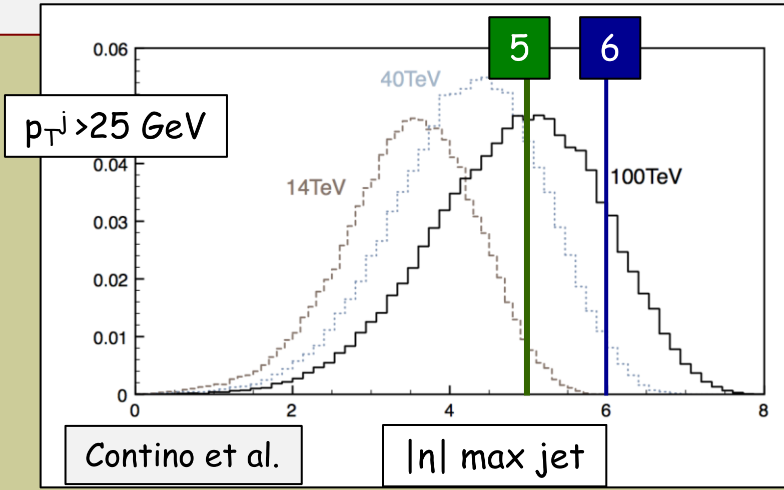
Tagging these forward quarks (jets) is crucial signature to distinguish EW VBS from the background



- ☐ HL-LHC: measure SM EW cross-section to 10%; x2 higher sensitivity to anomalous couplings than LHC@300 fb^{-1}, ~5% precision on parameters if new physics observed at LHC@300 fb^{-1}
- ☐ ILC 1 TeV, 1 ab^{-1}: indirect sensitivity to new resonances up to m~6 TeV (exploit $e^\pm$ polarization)
- ☐ CLIC 3 TeV, 1 ab^{-1}: indirect sensitivity to composite Higgs scale Λ~30 TeV from VV→ hh
- ☐ 100 TeV pp: huge cross-sections at high-mass: σ ~ 100 fb m_{WW}> 3 TeV; σ ~ 1 fb m_{HH} > 2 TeV

→ detailed direct studies

Maximum jet rapidity vs √s
→ calorimeter coverage over |η| ≥ 6 needed at 100 TeV pp collider (ATLAS, CMS: |η|< 5)
→ challenging: pile-up, radiation, … !!



Contino et al.

Where do we go from here ?

LHC Run-1 brought us a certitude: the Higgs boson as the key of EWSB

❑ H(125) needs to be studied with the highest precision → door to new physics ?

→ Low m_H makes H accessible to both circular and linear colliders, with different pros/cons

❑ complete exploration of EWSB needed (HH production, $V_L V_L$ scattering, look for possible new dynamics, etc.) → requires multi-TeV energies

LHC Run-2 and beyond may (hopefully !) bring additional no-lose theorems:

❑ if new (heavy) physics is discovered

→completion of spectrum and detailed measurements of new physics likely require multi-TeV energies

❑ if indications emerge for the scale of new physics in the 10-100 TeV region (e.g. from dijet angular distributions → Λ compositeness)

→ need the highest-energy pp collider to probe directly the scale of new physics

Regardless of the detailed scenario, and even in the absence of theoretical/experimental preference for a specific E scale, the directions for future high-E colliders are clear:

❑ highest precision → to probe E scales potentially up to O(100) TeV and smallest couplings

❑ highest energy → to explore directly new territories and get crucial information to interpret results from indirect probes

Thanks also to great technology progress, many scientifically strong opportunities are available: none of them is easy, none is cheap.

Decision on how to proceed, and the time profile of the projects, depends on science (LHC results), technology maturity, cost and funding availability, global (worldwide) perspective

There is challenging work for everybody to make the “impossible” possible !

Accelerator R&D (few examples …):

- High-field accelerator-quality Nb$_3$Sn superconducting magnets ready for massive industrial production starting mid-end next decade. Continue to push HTS (still in dreamland …) for farther-term future.
- Normal- and super-conducting high-Q RF cavities reaching higher field at lower cost (e.g. Nb$_3$Sn coating for SCRF; lower breakdown rates for NCRF)
- Higher-efficiency RF sources
- Novel ideas to reach GV/m acceleration gradients, allowing factor ~10 shorter Linacs: e.g. laser- and beam-driven plasma wakefield acceleration (FACET@SLAC, BELLA@LBNL, AWAKE@CERN, LAOLA@DESY, FLAME@LNF)
- MW-class proton sources and high-power targets for longer-term opportunities (muon colliders ?)

Detectors (few examples …):

- ultra-light, ultra-fast, ultra-granular, rad-hard, low-power Si trackers
- 10^8 channel imaging calorimeters (power consumption and cooling at high-rate machines,..)
- big-volume 5-6 T magnets (~2 x magnetic length and bore of ATLAS and CMS, ~50 GJ stored energy) to reach momentum resolutions of ~10% for p~20 TeV muons

Theory: improved theoretical calculations (higher-order EW and QCD corrections) needed to match present and future experimental precision on EW observables, Higgs mass and branching ratios. Work together with experiments on model-independent analyses in framework of Effective Field Theory (see S.Dittmaier’s talk)

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.

With the discovery of a Higgs boson, after 80 years of superb theoretical and experimental work the SM is now complete. However major questions remain.

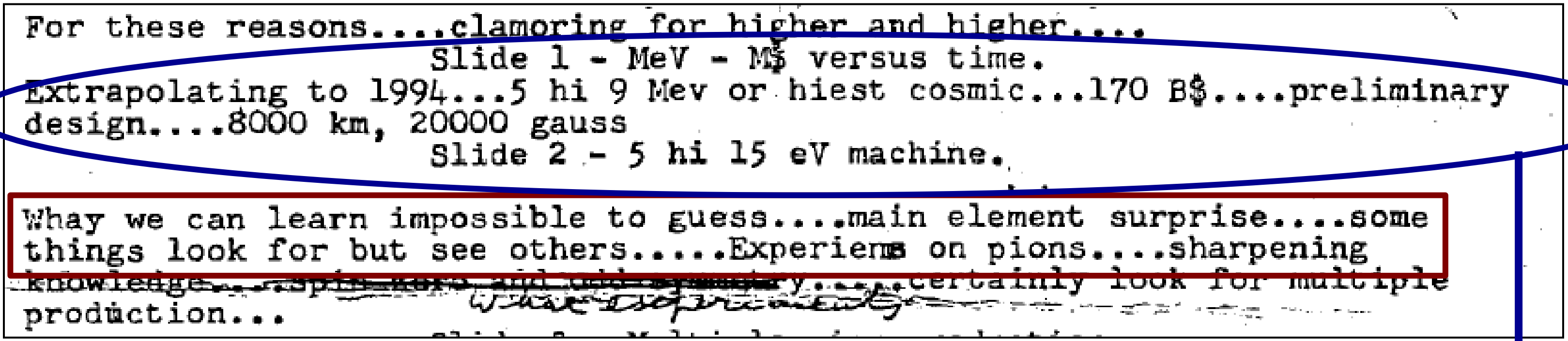
The full exploitation of the LHC, and more powerful future accelerators, will be needed to address them and to advance our knowledge of fundamental physics.

No doubt that future high-E colliders are extremely challenging projects
Didn't the LHC also look close-to-impossible in the '80s ??

However: the correct approach, as scientists, is not to abandon our exploratory spirit, nor give up to financial and technical challenges. The correct approach is to use our creativity to develop the technologies needed to make future projects financially and technically affordable

We already did so in the past … →

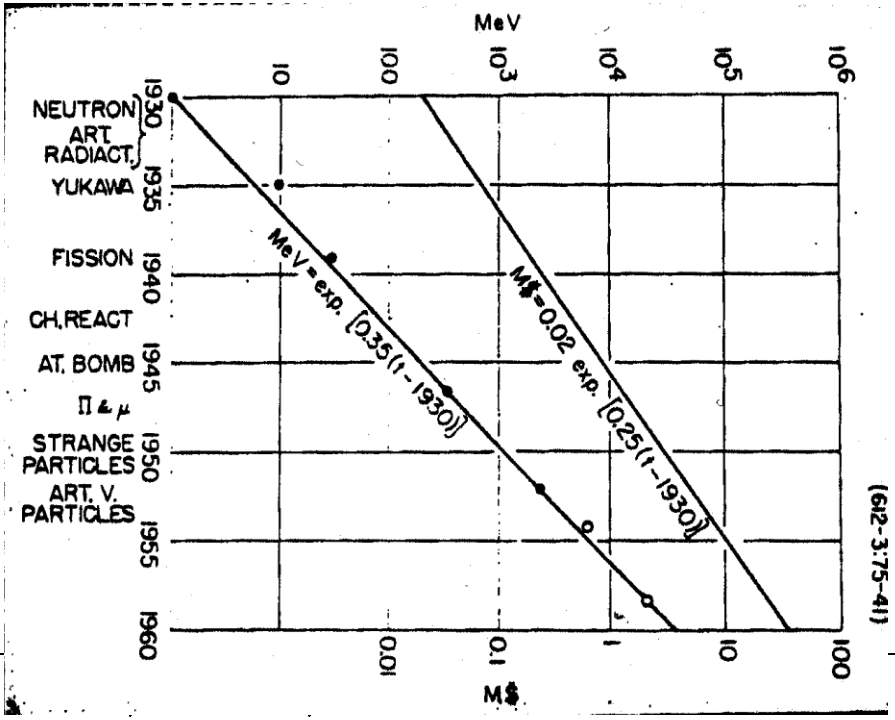
From E. Fermi, preparatory notes for a talk on
“What can we learn with High Energy Accelerators ? ”
given to the American Physical Society, NY, Jan. 29th 1954



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 kors 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 → √s ~ 3 TeV
Cost : 170 B$



F.

Was that hopeless ??

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

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

MANY THANKS TO …

THE ORGANISERS

and

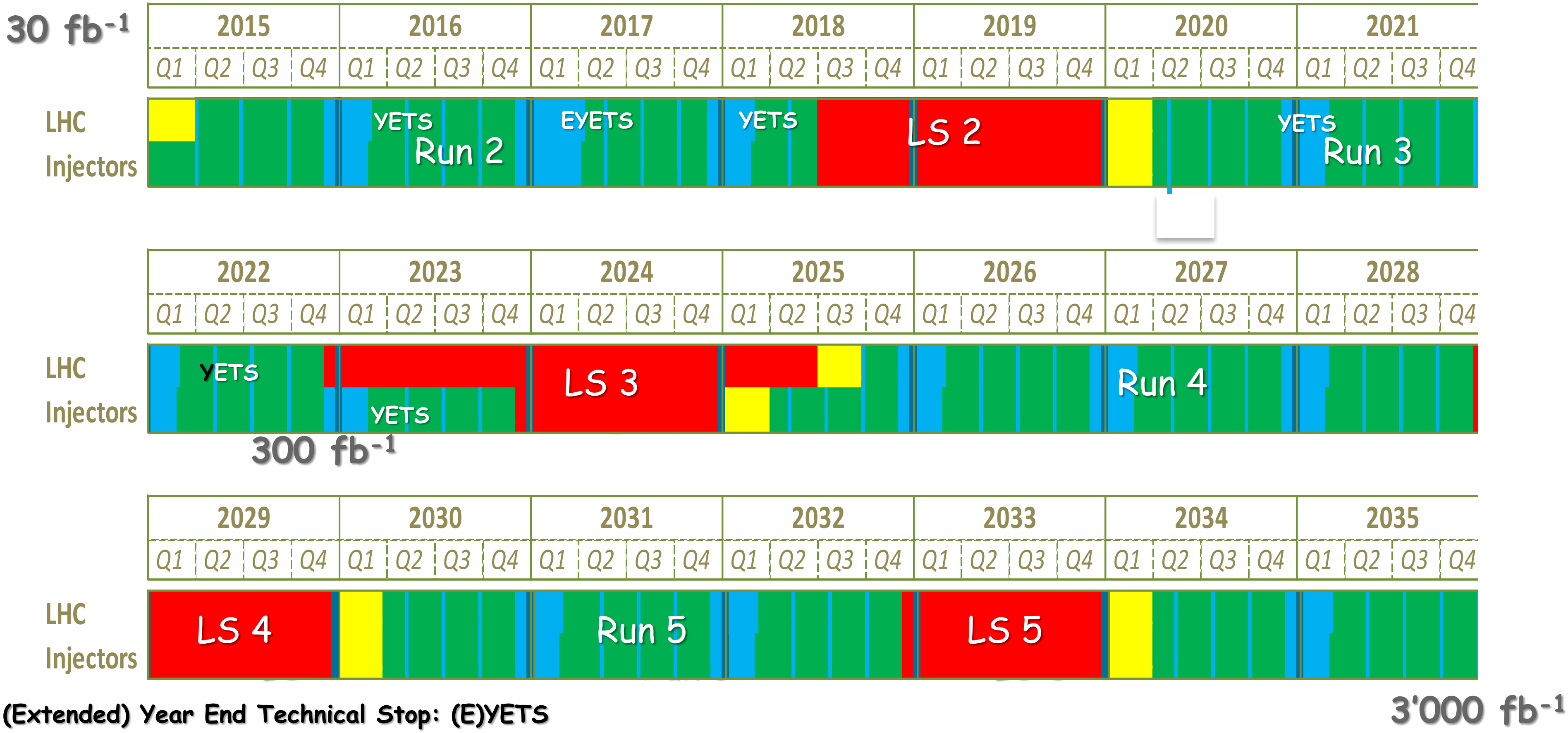
J.Ellis, L.Evans, D.Fournier, M.Harrison, P.Janot, P.Jenni, A.Lankford, L.Linssen, M.Mangano, Q.Qin, L.Rossi, S.Stapnes, Y.Wang, F.Zimmermann

SPARES

LHC schedule beyond LS1

LS2 starting in 2018 (July) => 18 months + 3 months BC
LS3 LHC: starting in 2023 => 30 months + 3 months BC
Injectors: in 2024 => 13 months + 3 months BC

- 🟩 Physics
- 🟥 Shutdown
- 🟨 Beam commissioning
- ⬛ Technical stop



(Extended) Year End Technical Stop: (E)YETS

LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators (December 2013)

F. Gianotti, LHCP 2014, 6/6/2014

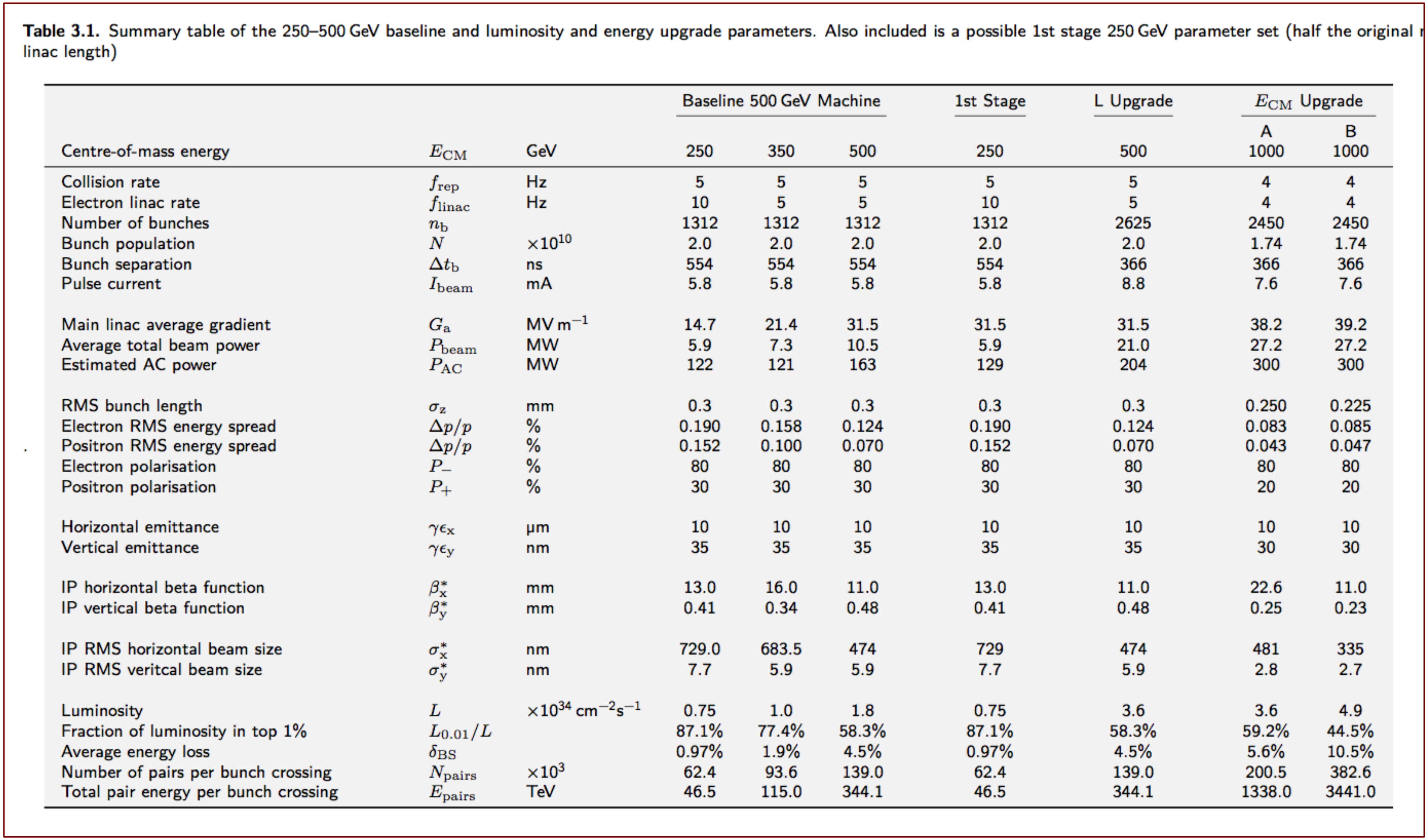


Table 3.1. Summary table of the 250–500 GeV baseline and luminosity and energy upgrade parameters. Also included is a possible 1st stage 250 GeV parameter set (half the original
linac length)

			Baseline 500 GeV Machine			1st Stage	L Upgrade	E_{CM} Upgrade	
								A	B
Centre-of-mass energy	E_{CM}	GeV	250	350	500	250	500	1000	1000
Collision rate	f_{rep}	Hz	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	5	5	10	5	4	4
Number of bunches	n_{b}		1312	1312	1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_{b}	ns	554	554	554	554	366	366	366
Pulse current	I_{beam}	mA	5.8	5.8	5.8	5.8	8.8	7.6	7.6
Main linac average gradient	G_{a}	MV m^{-1}	14.7	21.4	31.5	31.5	31.5	38.2	39.2
Average total beam power	P_{beam}	MW	5.9	7.3	10.5	5.9	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	122	121	163	129	204	300	300
RMS bunch length	σ_{z}	mm	0.3	0.3	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.190	0.158	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.152	0.100	0.070	0.152	0.070	0.043	0.047
Electron polarisation	P_{-}	%	80	80	80	80	80	80	80
Positron polarisation	P_{+}	%	30	30	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_{\mathrm{x}}$	µm	10	10	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35	35	35	35	30	30
IP horizontal beta function	β_{x}^{*}	mm	13.0	16.0	11.0	13.0	11.0	22.6	11.0
IP vertical beta function	β_{y}^{*}	mm	0.41	0.34	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ_{x}^{*}	nm	729.0	683.5	474	729	474	481	335
IP RMS veritcal beam size	σ_{y}^{*}	nm	7.7	5.9	5.9	7.7	5.9	2.8	2.7
Luminosity	L	$\times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.75	1.0	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		87.1%	77.4%	58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	δ_{BS}		0.97%	1.9%	4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^{3}$	62.4	93.6	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	46.5	115.0	344.1	46.5	344.1	1338.0	3441.0

CEPC 参数表

Number of IPs	2
Energy (GeV)	120
Circumference (km)	53.6
SR loss/turn (GeV)	3.01
N_e/bunch (10^{11})	3.71
Bunch number	50
Beam current (mA)	16.6
SR power /beam (MW)	50
B_0 (T)	0.065
Bending radius (km)	6.1
Momentum compaction (10^{-4})	0.415
β_{IP} x/y (m)	0.8/0.0012 (ratio:667)
Emittance x/y (nm)	6.8/0.02 (ratio:333)
Transverse σ_{IP} (um)	73.7/0.16 (ratio:470)
ξ_x/IP	0.104
ξ_y/IP	0.074
V_{RF} (GV)	6.87
f_{RF} (MHz)	700
Nature bunch length σ_z (mm)	2.26
Bunch length include BS (mm)	2.6
Nature Energy spread (%)	0.13
Energy acceptance RF(%)	5.4
Energy acceptance(%)	2
n_γ	0.22
δ_{BS} (%)	0.07
Life time due to beamstrahlung-Telnov (minute)	2028
Life time due to simulation (minute)	150
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	1.82

F. Gianotti, LHCP 2014, 6/6/2014

SppC参数表

Physics performance and beam parameters						
Peak luminosity per IP	1.0E34	5.0E34	5.0E34	5.0E34	1.2E+35	$cm^{-2}s^{-1}$
Beta function at collision	0.55	0.15	0.35	1.1	0.75	m
Circulating beam current	0.584	1.12	0.478	0.5	1.0	A
Max beam-beam tune shift perIP	0.01	0.015	0.01	0.01	0.0075	
Bunch separation	25	25	25	25 5	25	ns
Number of bunches	2808	2808	2808	10600（8900） 53000（44500）	5333	
Bunch population	1.15E11	2.2E11	1.0E11	1.0E11	2.0E+11	
Normalized rms transverse emittance	3.75	2.5	1.38	2.2	3.3	mm
Beam life time due to burn-off	45	15.4	5.7	19.1/15.9	8.7	hour
Total / inelastic cross section	111/85	111/85	129/93	153/108	140	mbarn
Reduction factor in luminosity（F）					0.85	
Full crossing angle	285	590	185	74	139	mrad
rms bunch length	75.5	75.5	75.5	80/75.5	75.5	mm
rms IP spot size	16.7	7.1	5.2	6.8	8.5	mm
Beta at the 1st parasitic encounter					19.5	m
rms spot size at the 1st parasitic encounter					43.3	mm
Stored energy per beam	0.392	0.694	0.701	8.4/7.0	5.4	GJ
SR power per ring	0.0036	0.0073	0.0962	2.4/2.9	1.5	MW
Arc SR heat load	0.17	0.33	4.35	28.4/44.3	45.8	W/m
Energy loss per turn	0.0067	0.0067	0.201	4.6/5.86	1.49	MeV

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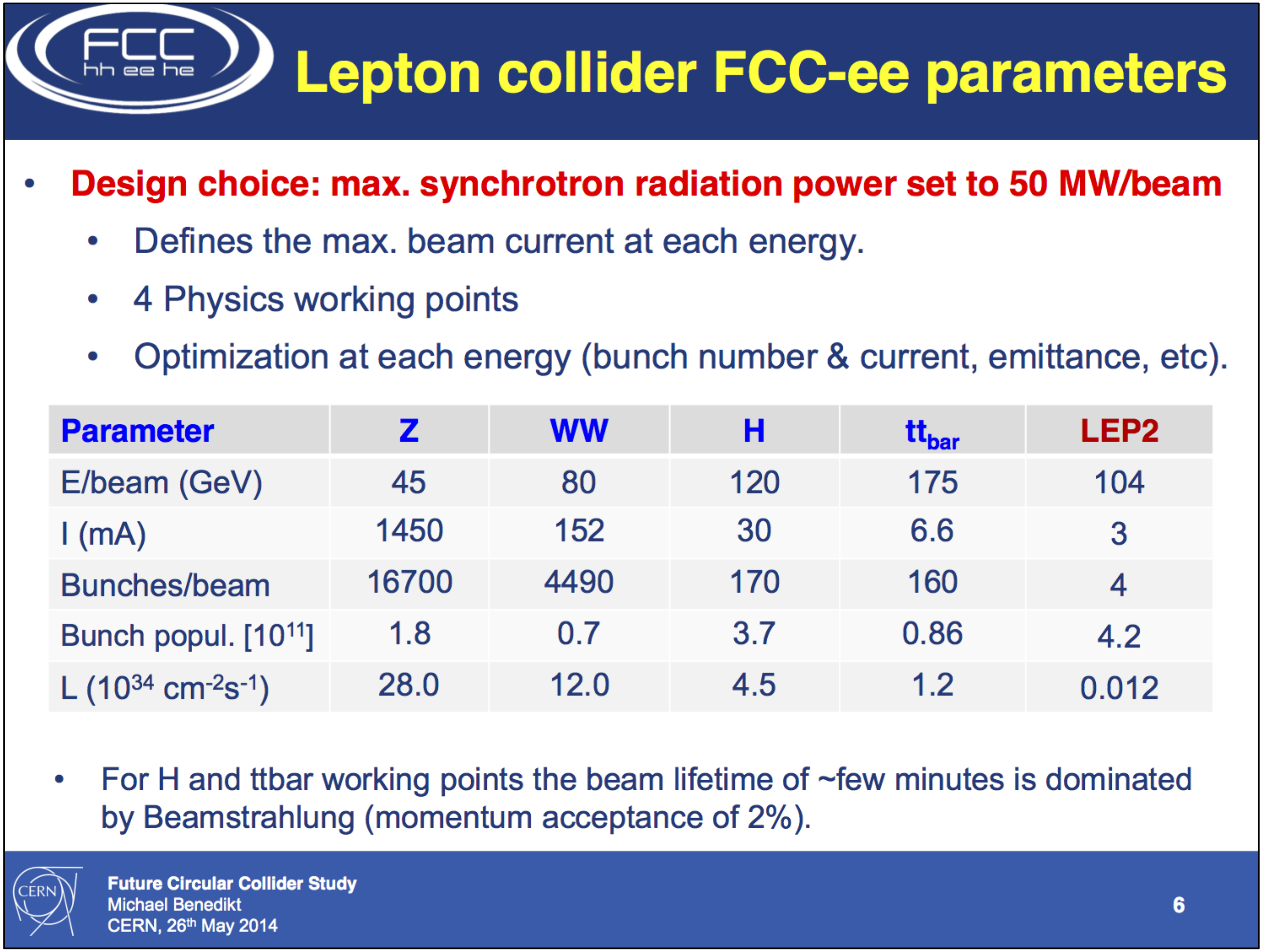
Circular e^+e^- colliders



Lepton collider FCC-ee parameters

- **Design choice: max. synchrotron radiation power set to 50 MW/beam**
  - Defines the max. beam current at each energy.
  - 4 Physics working points
  - Optimization at each energy (bunch number & current, emittance, etc).

Parameter	**Z**	**WW**	**H**	**tt_{bar}**	**LEP2**
E/beam (GeV)	45	80	120	175	104
I (mA)	1450	152	30	6.6	3
Bunches/beam	16700	4490	170	160	4
Bunch popul. [10^{11}]	1.8	0.7	3.7	0.86	4.2
L (10^{34} $cm^{-2}s^{-1}$)	28.0	12.0	4.5	1.2	0.012

- For H and ttbar working points the beam lifetime of ~few minutes is dominated by Beamstrahlung (momentum acceptance of 2%).

Future Circular Collider Study
Michael Benedikt
CERN, 26th May 2014

6

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

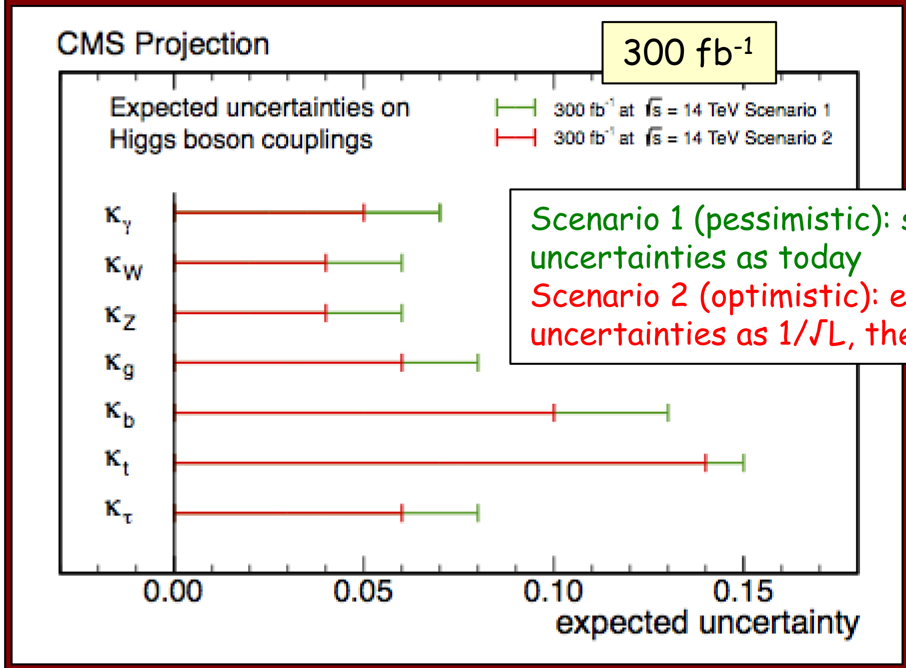
Exploration of E-frontier → look for heavy objects up to m ~30-50 TeV, including high-mass $V_L V_L$ scattering:

- ❑ 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

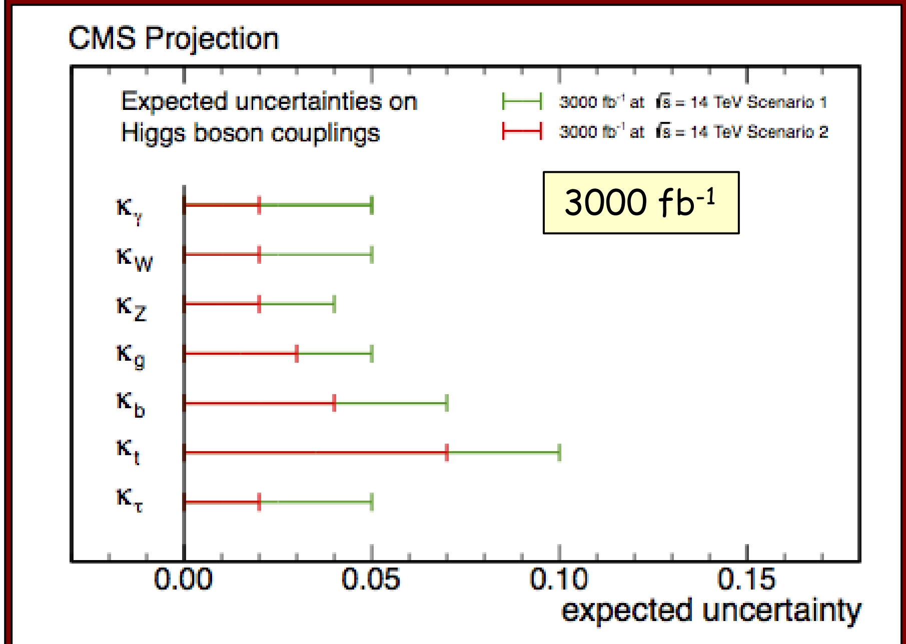
Measurements of Higgs couplings



300 fb^{-1}

Scenario 1 (pessimistic): systematic uncertainties as today

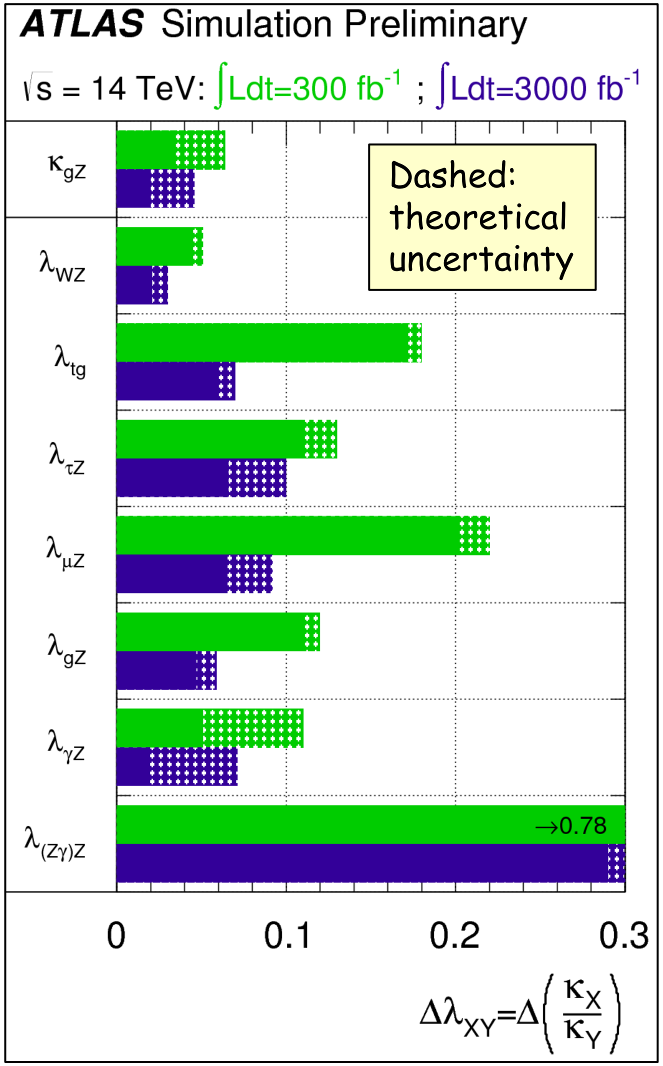
Scenario 2 (optimistic): experimental uncertainties as $1/\sqrt{L}$, theory halved



3000 fb^{-1}

k_i= measured coupling normalized to SM prediction

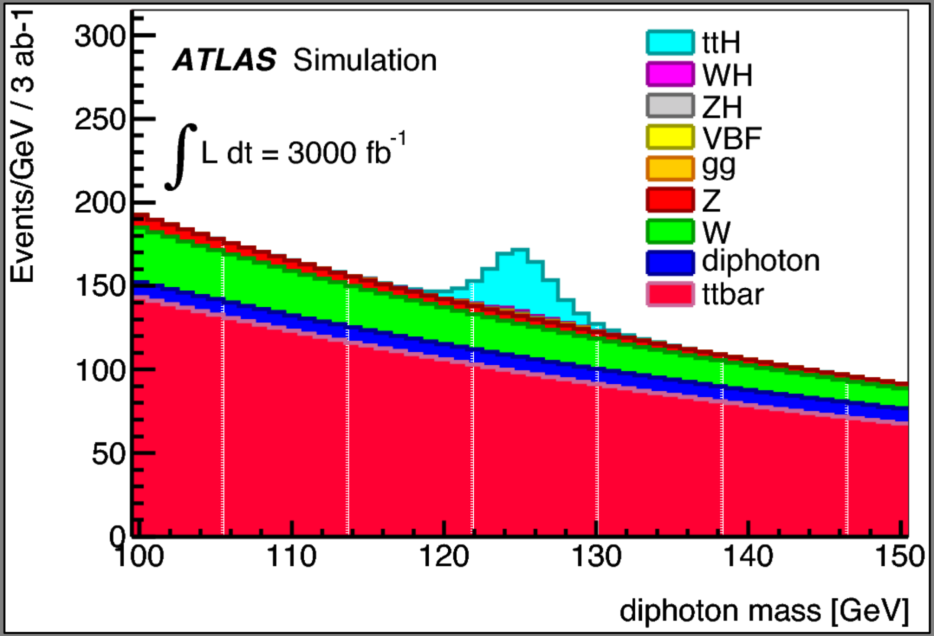
$\Lambda_{ij}=k_i/k_j$



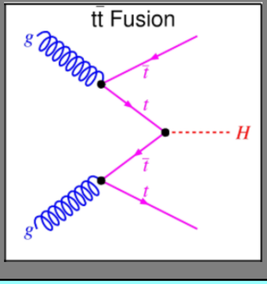
Dashed: theoretical uncertainty

Main conclusions:

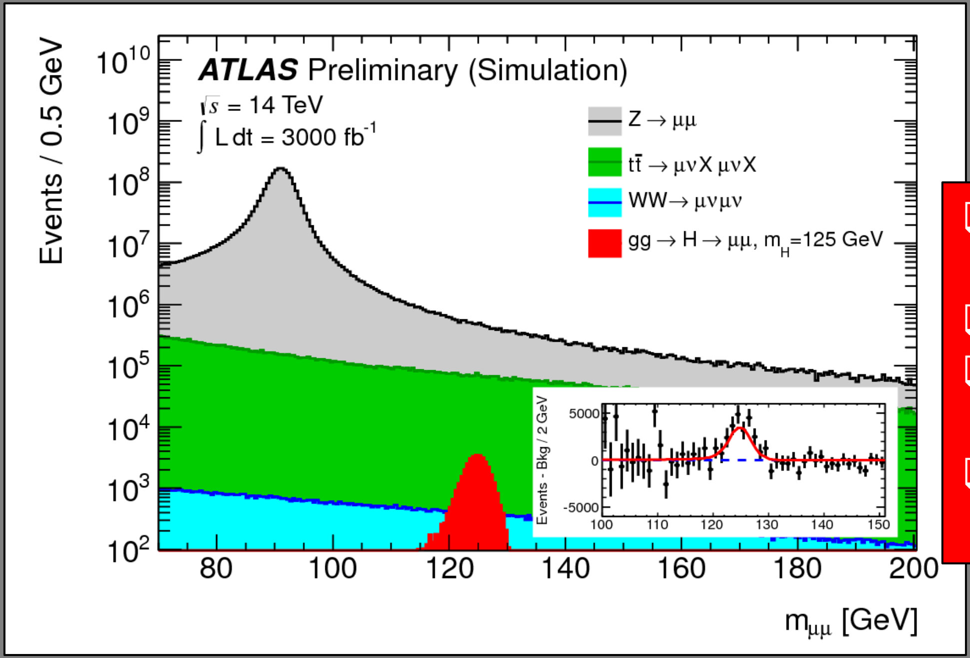
- ☐ 3000 fb^{-1}: typical precision 2-10% <u>per experiment</u> (except rare modes) → 1.5-2x better than with 300 fb^{-1}
- ☐ Crucial to also reduce theory uncertainties



ttH production with H → γγ

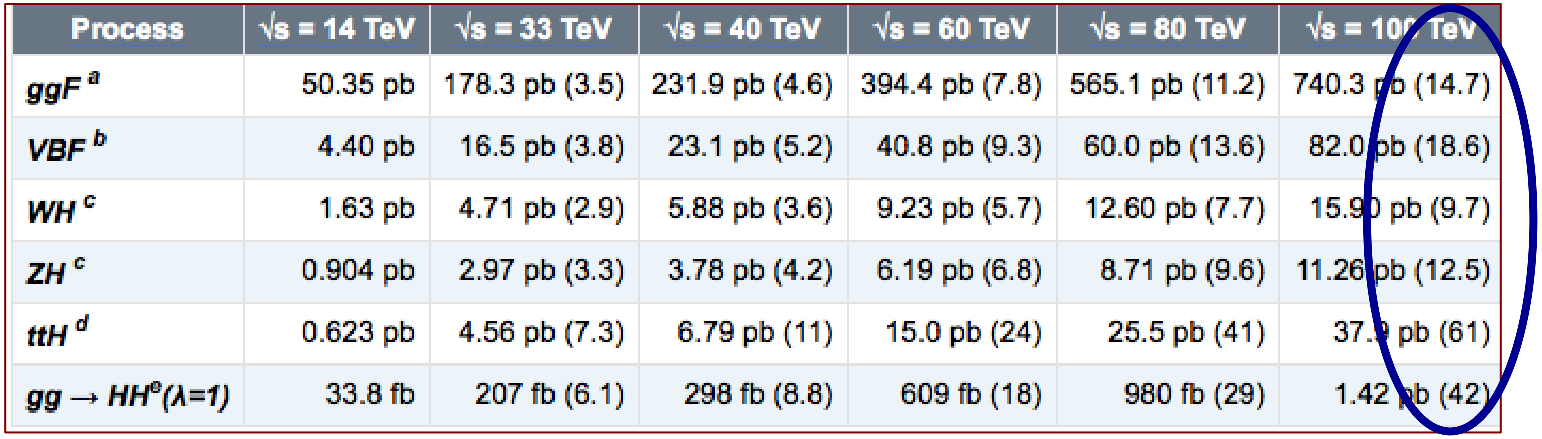


- Gives direct access to Higgs-top coupling (intriguing as top is heavy)
- Today's sensitivity: 6xSM cross-section
- With 3000 fb^{-1} expect 200 signal events (S/B ~ 0.2) and > 5σ
- Higgs-top coupling can be measured to about 10%



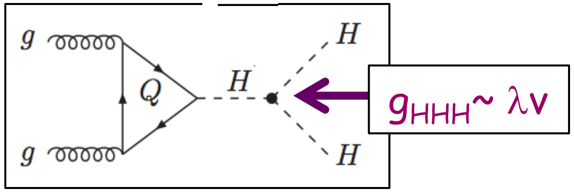
H →μμ

- 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%



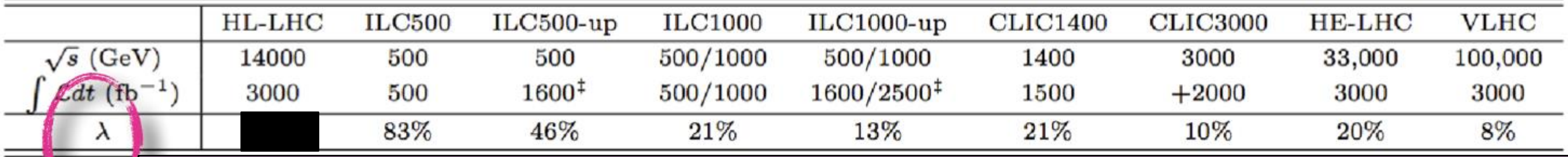
Process	√s = 14 TeV	√s = 33 TeV	√s = 40 TeV	√s = 60 TeV	√s = 80 TeV	√s = 100 TeV
ggF [a]	50.35 pb	178.3 pb (3.5)	231.9 pb (4.6)	394.4 pb (7.8)	565.1 pb (11.2)	740.3 pb (14.7)
VBF [b]	4.40 pb	16.5 pb (3.8)	23.1 pb (5.2)	40.8 pb (9.3)	60.0 pb (13.6)	82.0 pb (18.6)
WH [c]	1.63 pb	4.71 pb (2.9)	5.88 pb (3.6)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



$g_{HHH} \sim \lambda v$

Higgs self-couplings difficult to measure at any facility (energy is mainly needed ..)



	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%

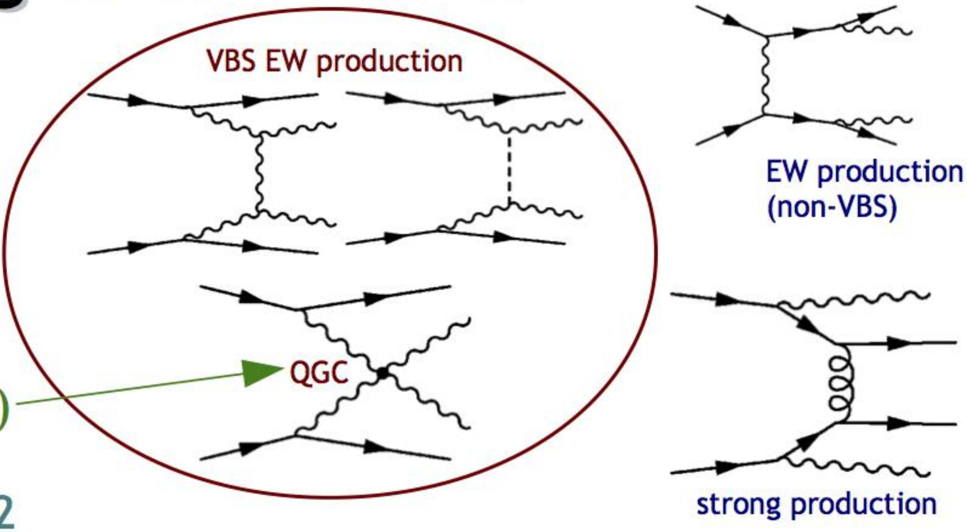
HL-LHC studies not completed yet … ~30% precision expected, but need 3000 fb^{-1}

Vector boson scattering $W^{\pm}W^{\pm} \rightarrow W^{\pm}W^{\pm}$

At high energies, WW → WW and ZZ → ZZ processes test if the Higgs fully explains electroweak symmetry-breaking: vector boson scattering (VBS) processes

Sensitive to anomalous four-gauge boson interactions (quartic gauge coupling, QGC)

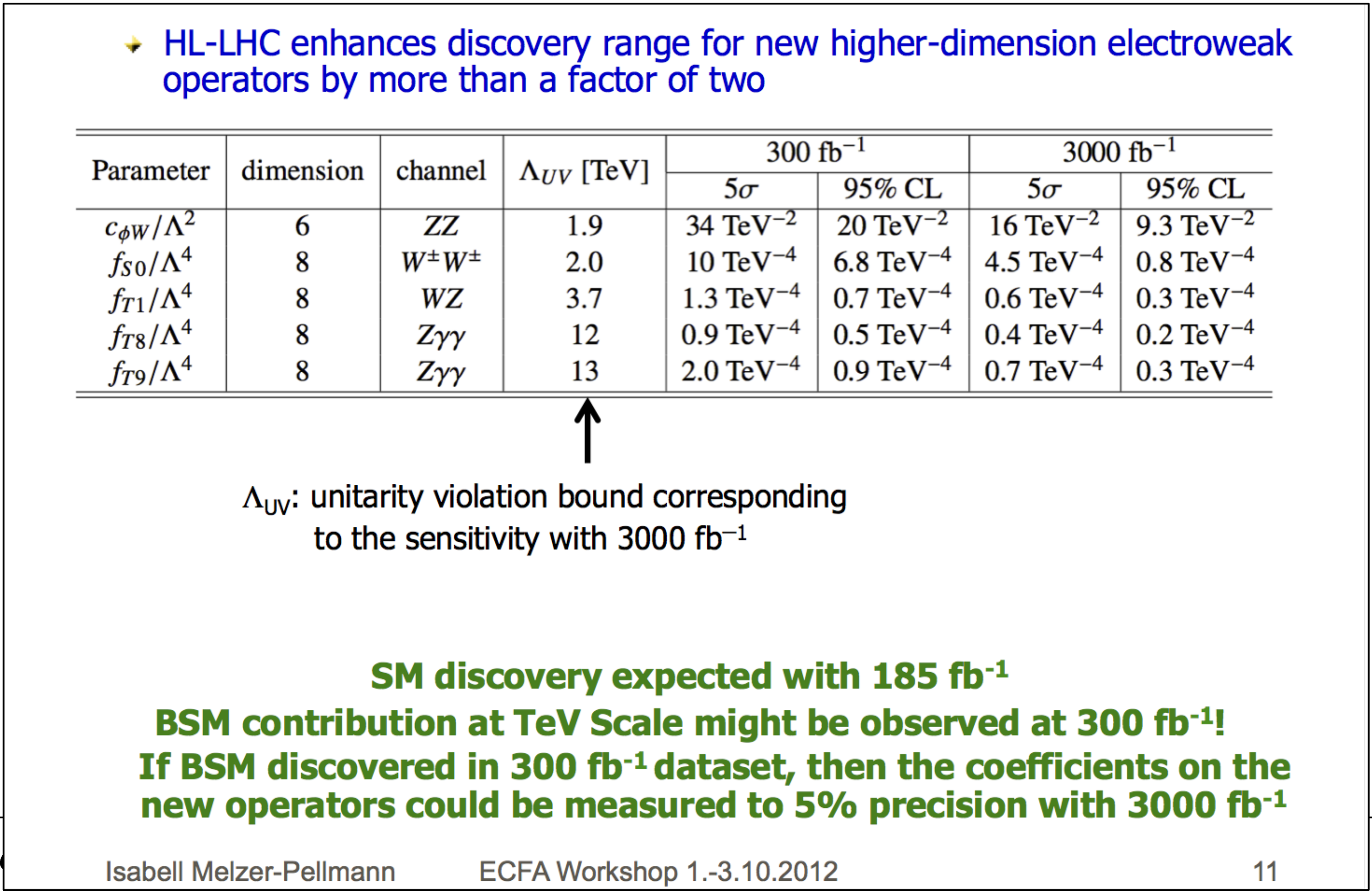
Search for $W^{\pm}W^{\pm}jj$ production in dilepton+2 jet final states, m(jj)>500 GeV



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}

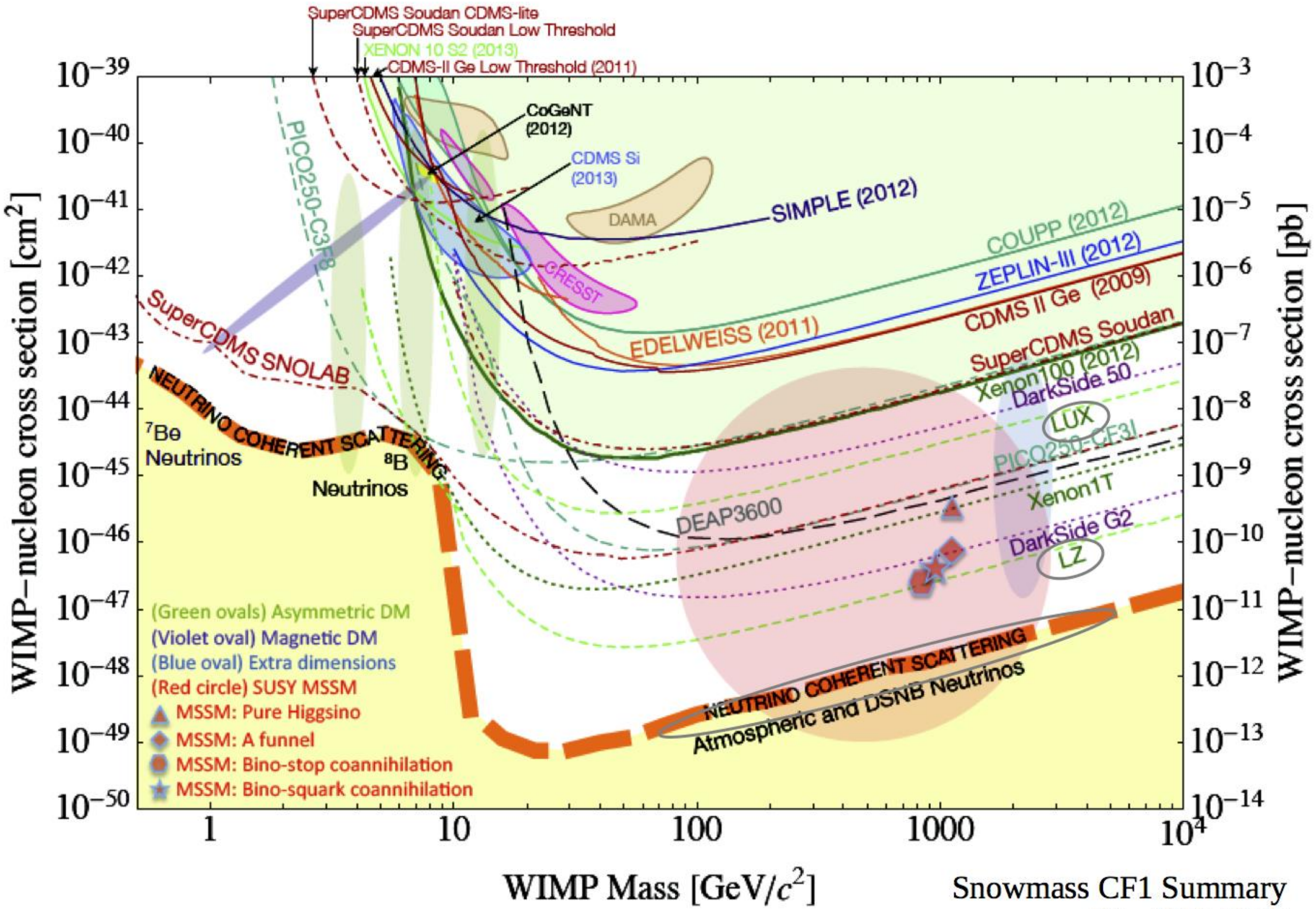
SM discovery expected with 185 fb^{-1}

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

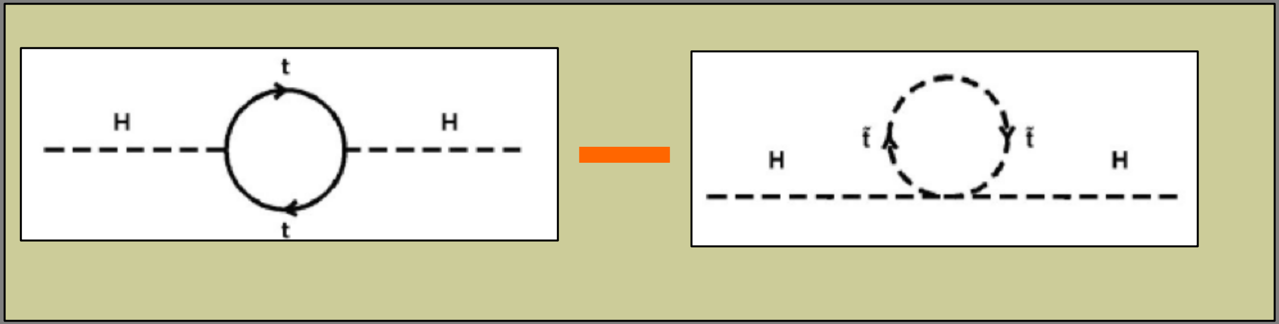
If BSM discovered in 300 fb^{-1} dataset, then the coefficients on the new operators could be measured to 5% precision with 3000 fb^{-1}

Isabell Melzer-Pellmann ECFA Workshop 1.-3.10.2012 11

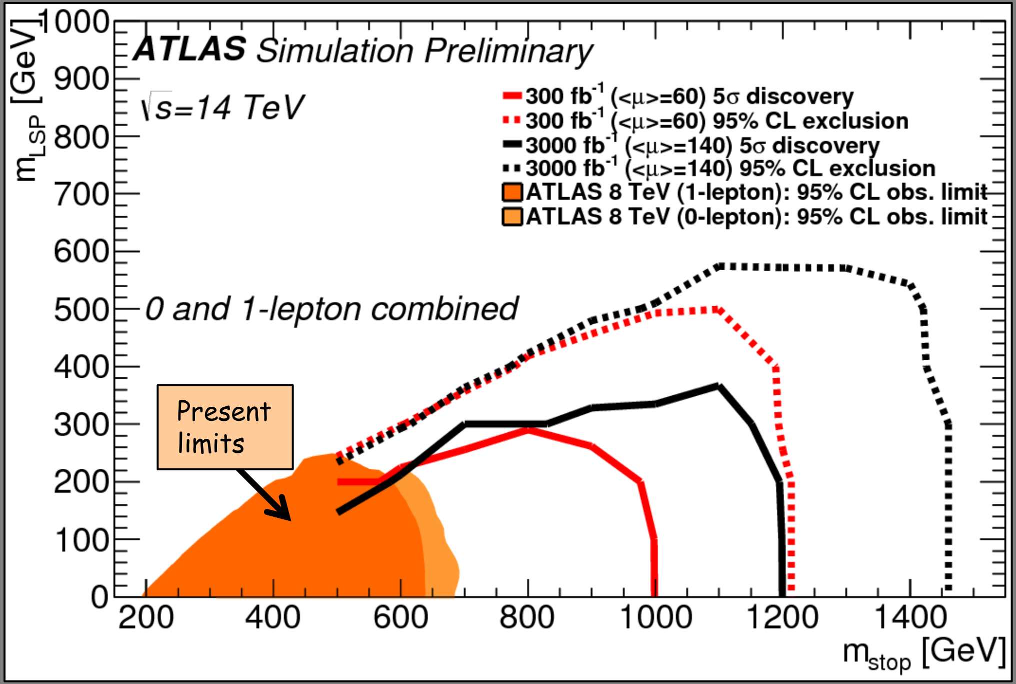
Dark Matter Direct Detection Experiments: Limits and Future Sensitivity



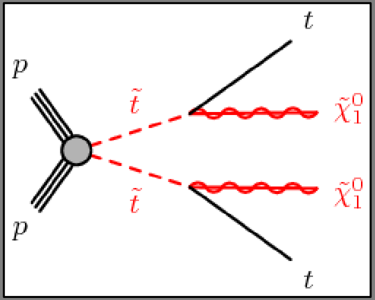
Snowmass CF1 Summary
arXiv:1310.8327



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)



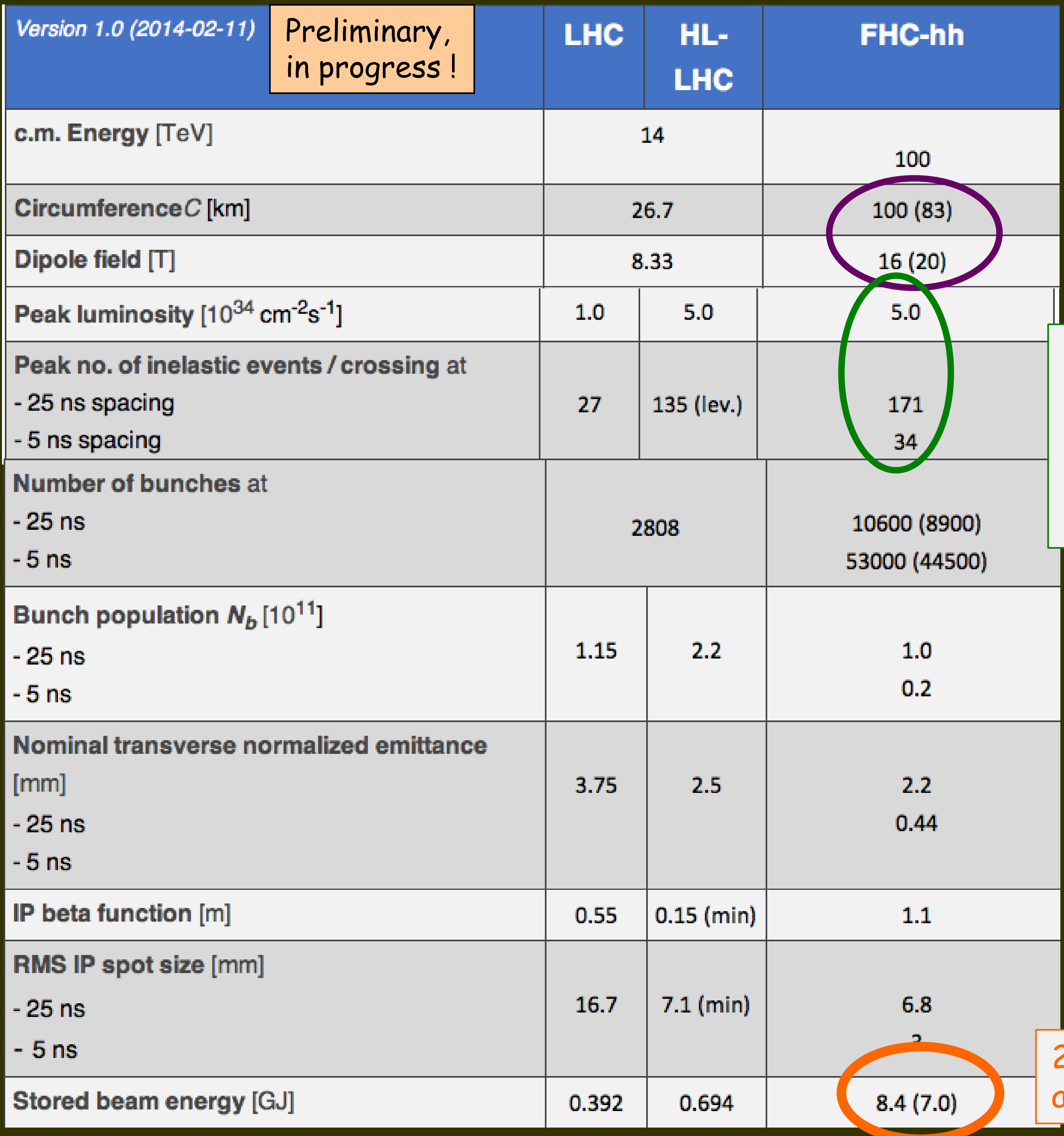
Present limits



Mass reach extends by ~ 200 GeV from 300 to 3000 fb^{-1}

→ most of best motivated mass range will be covered at HL-LHC

Parameters of a ~ 100 TeV pp collider



Preliminary, in progress !

Version 1.0 (2014-02-11)	**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 ! 1 Airbus 380 at full speed