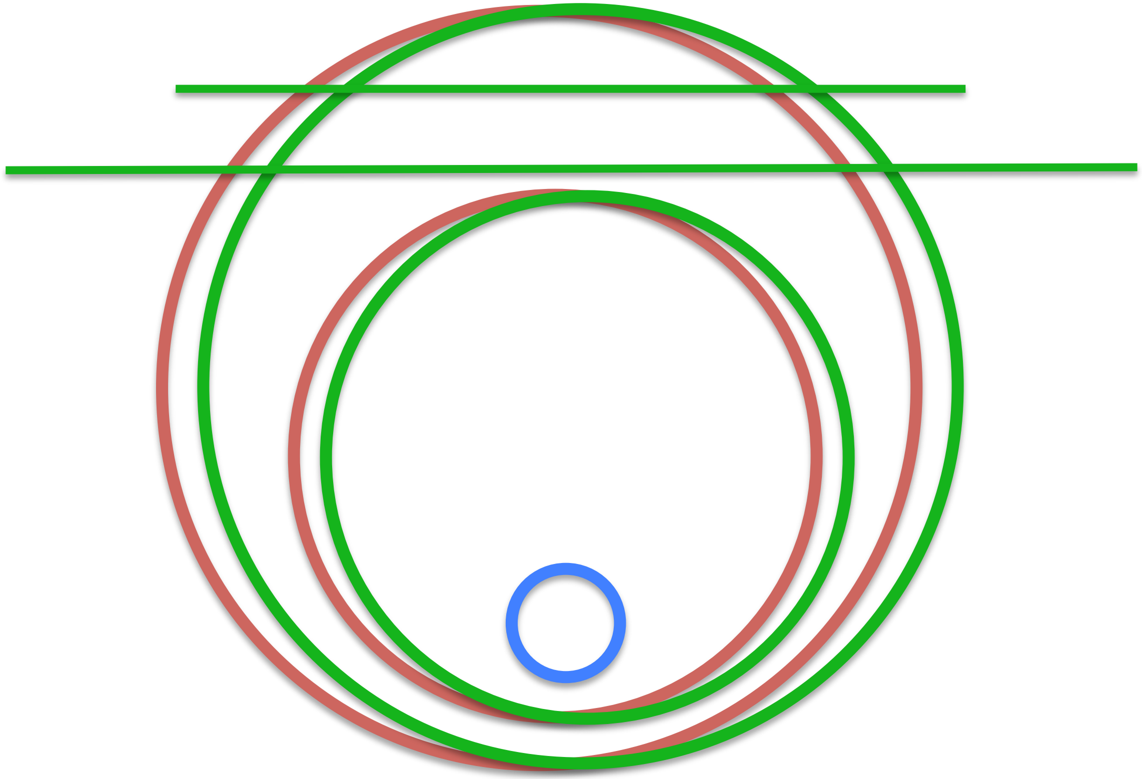
Future Colliders

Challenges and Opportunities



Klaus Desch
University of Bonn

DESY Theory Workshop 2015

02/10/2015

The scene

Higgs discovery at LHC: breakthrough in our understanding of SM

Higgs discovery is part of the LHC „no-lose“ theorem:

- if no Higgs -> breakdown of SM in $V_L V_L \rightarrow V_L V_L$
- LHC sensitive to either (although at different time scales and precision)

In spite of many fundamental open questions and puzzles:
there is no next-no-lose theorem (NNLT) (to my knowledge...)

> - This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

M. Mangano (2014)

This „experimental exploration“ has started with LHC run1/2
and we should be prepared for break-through discoveries
every day.... (→Pippa Wells)

Experimental exploration at work

Since we have LHC and will have HL-LHC (most likely),

shoudn´t we rather wait and see ?

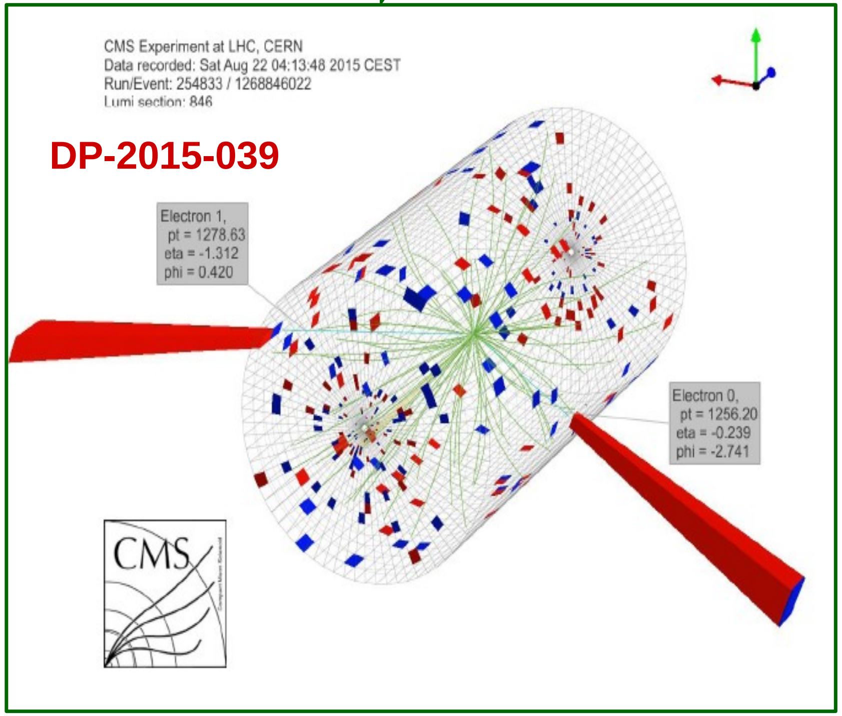
Almost any signficant deviation from the SM („discovery“) at LHC would allow us much better to evaluate where to go.

Examples:

Experimental exploration at work

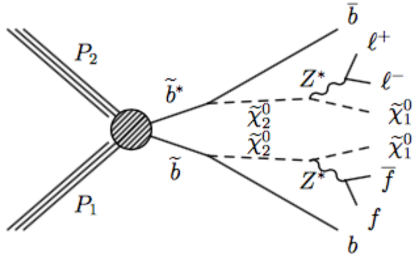
[CMS, TOP2015 (J. Andrea)]

– e+e- of m_{ll}=2.9 TeV (1.3,1.3 TeV)



10 more of these until christmas 2015 will likely make a strong case for e^+e^- collisions at 2.9 TeV

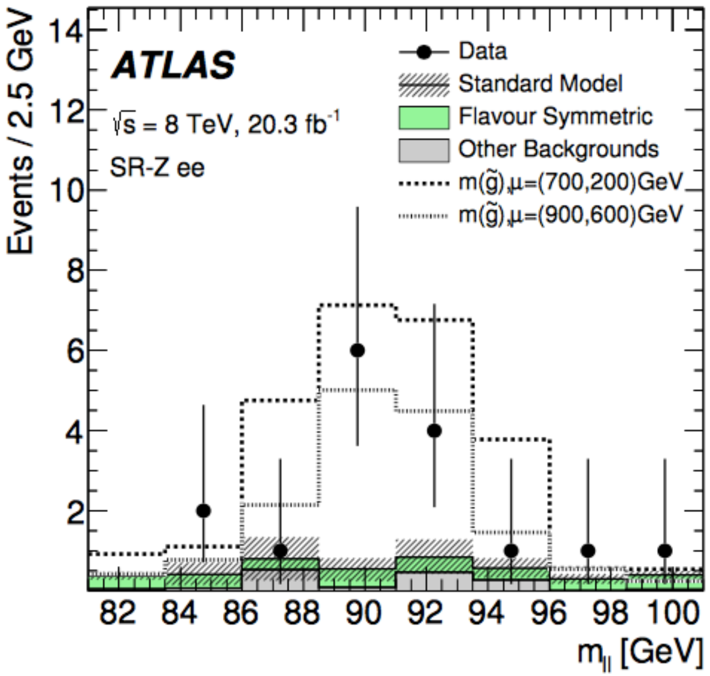
Experimental exploration at work



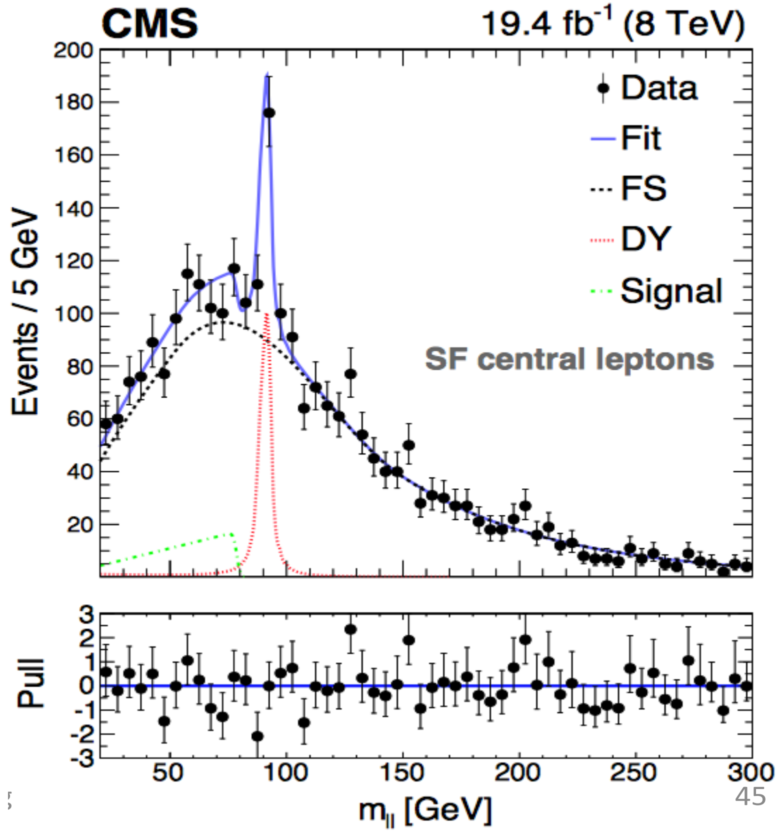
Di-Leptons with jets+MET

ATLAS: on-shell Z   CMS: off-shell Z

Z mass excess: 3.0σ for ee, 1.7σ for μμ

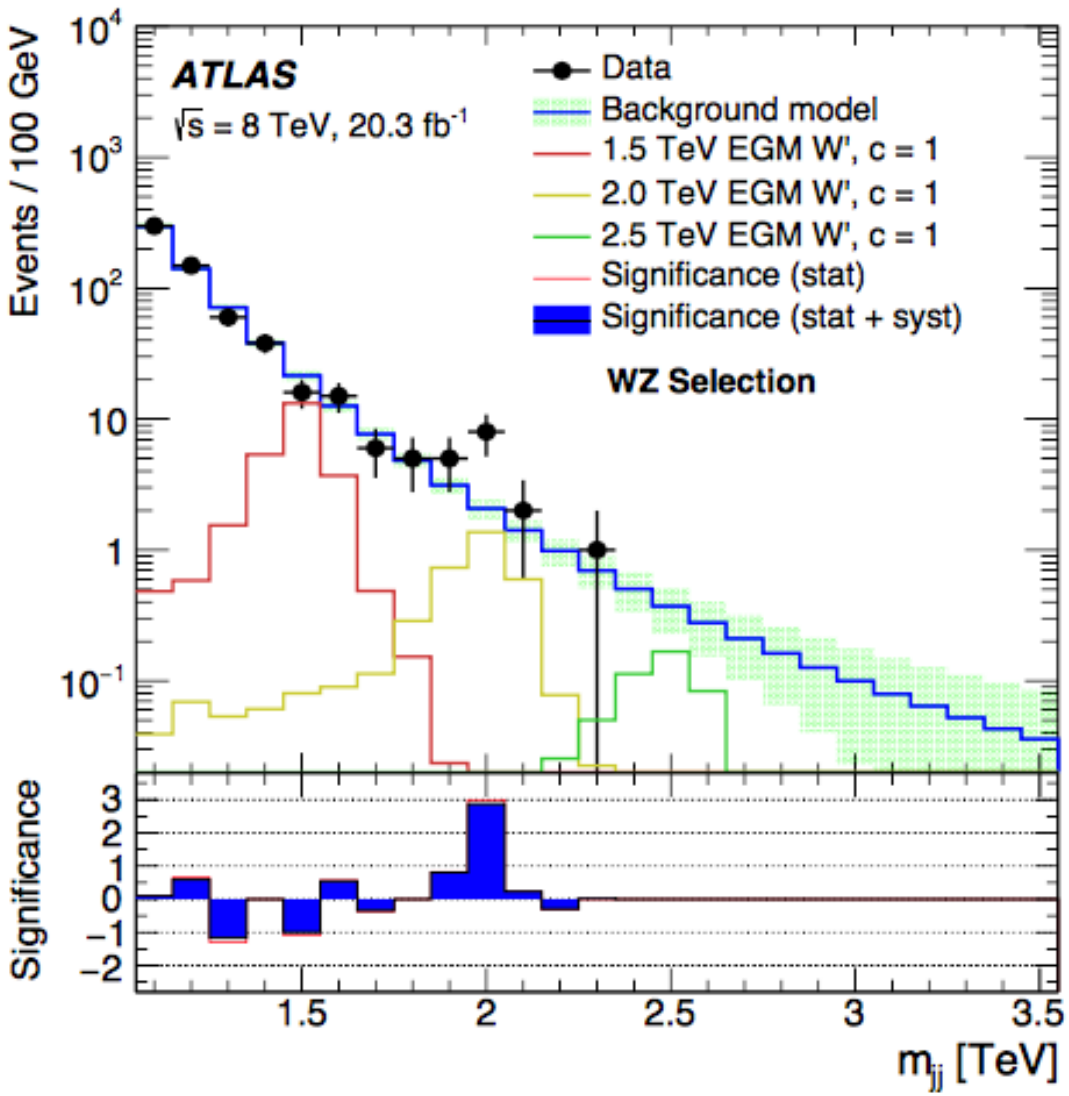


Edge excess: 2.6σ



Watch out – so far neither excess confirmed by the other experiment

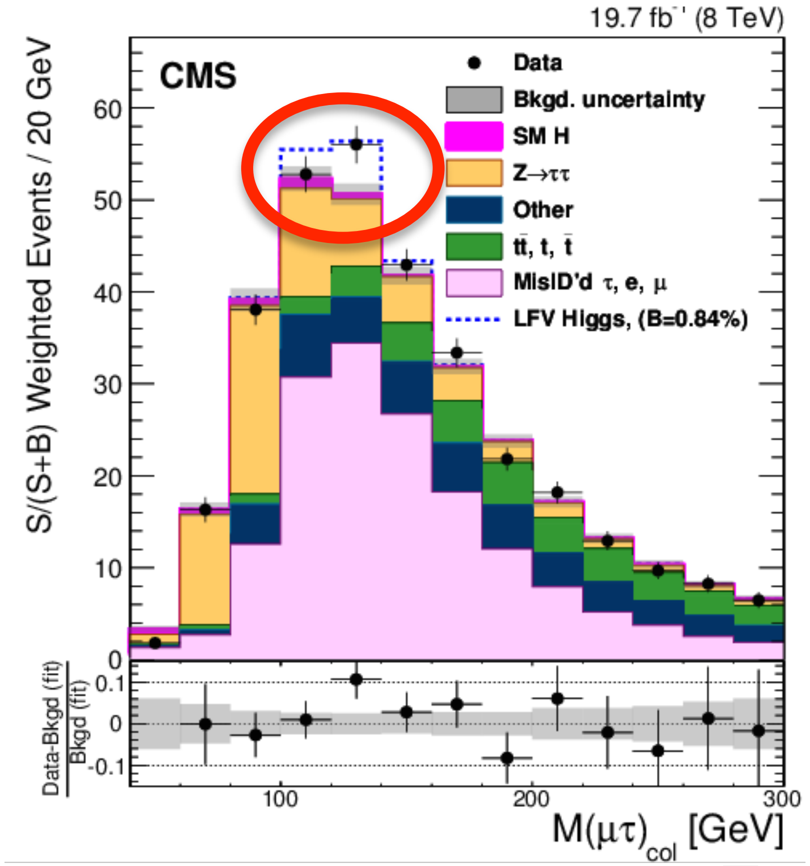
Experimental exploration at work



Di - „Fat Jets“

and what´s this?

Experimental exploration at work



and what´s this?

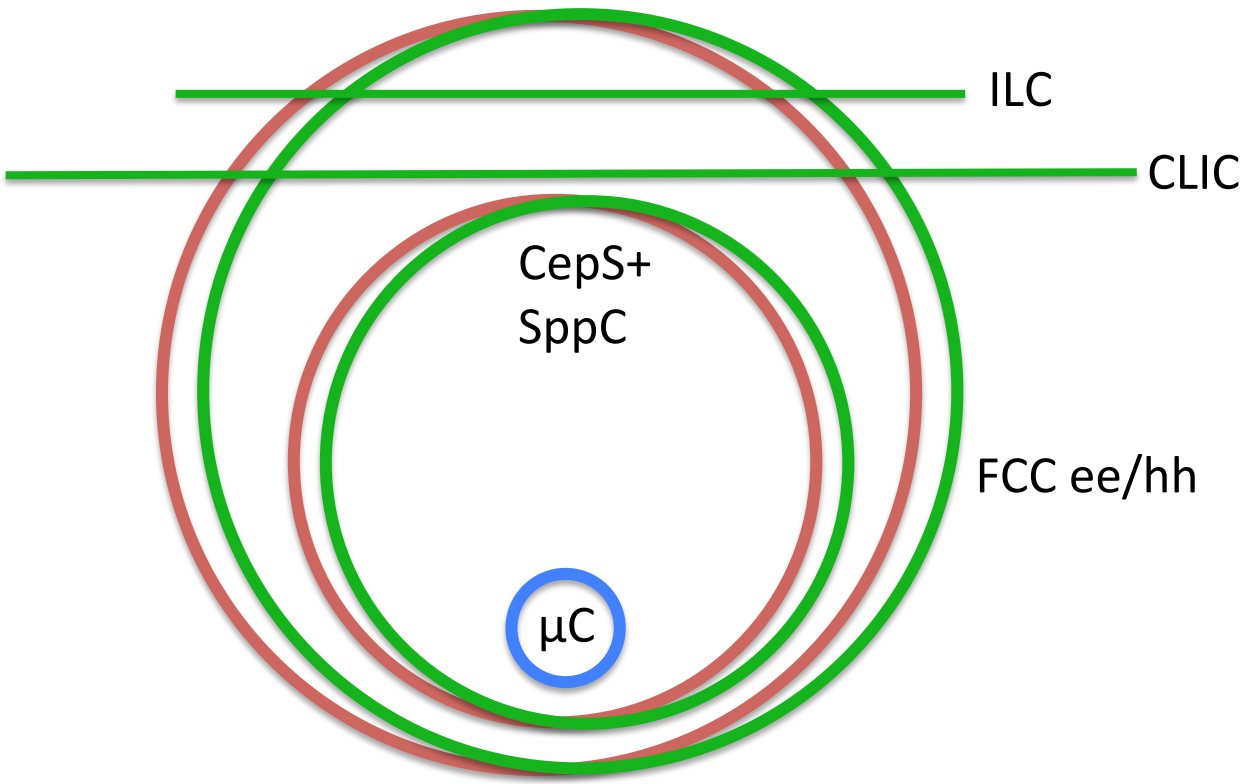
(and threre a few more...)

While it is true that 5x2σ is much less than 2x5σ (Dobrescu),

we do have all reasons to be excited and optimistic!!!

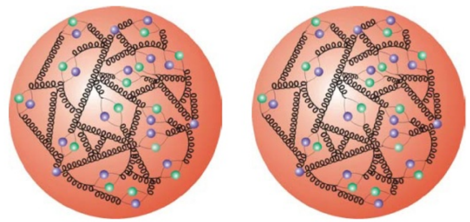
... and to prepare the next big machine(s)

The Menu



Lepton and Hadron collisions

e^+ • • e^-

p  p

discovery through precision

study known particles

discovery through

broadband + highest energies

too simple

also:
discover new particles
not visible in hadron collider environment

also:
impressive performance of modern detectors allows for remarkable precision also in pp (however limitations remain)

e^+e^- collisions

For e^+e^- collisions (90-1000 GeV) there is a very strong physics case already now (i.e. without waiting for new LHC results):

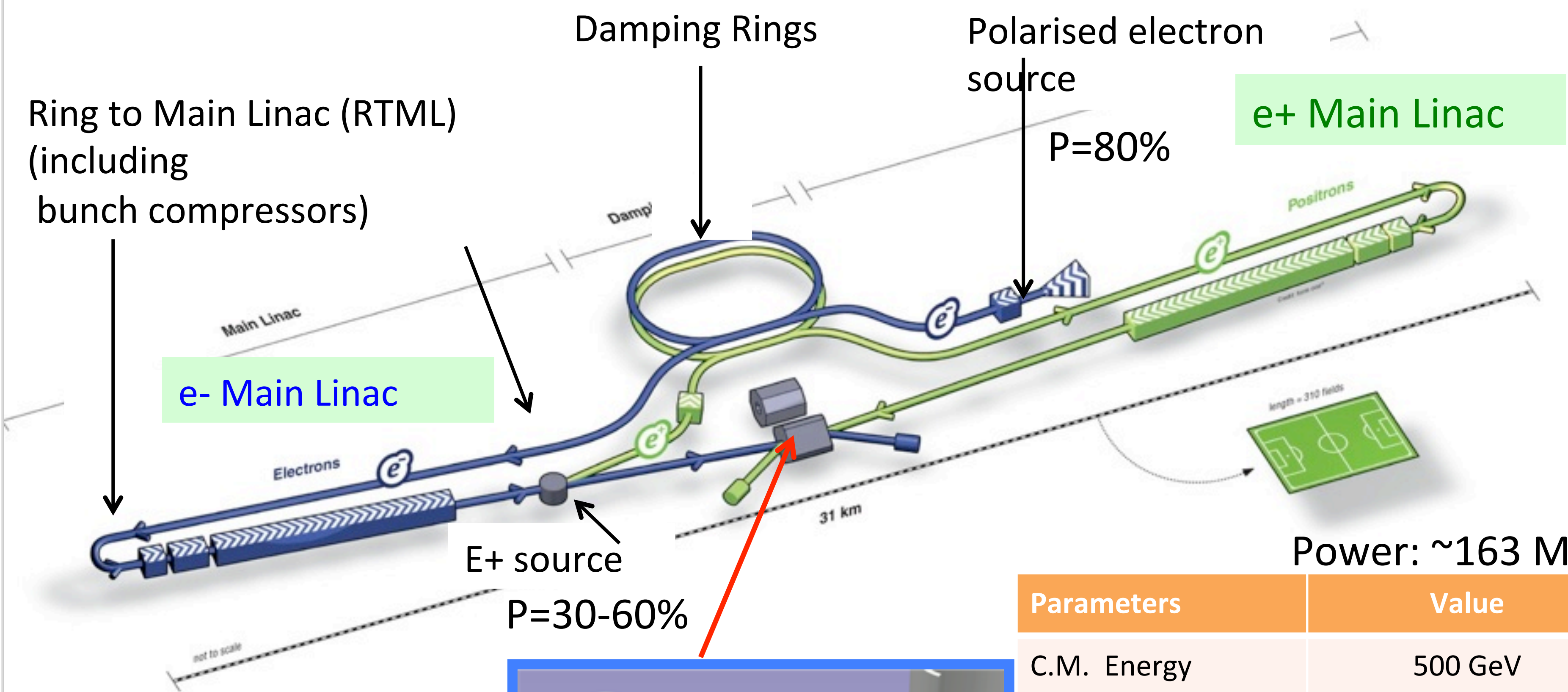
- Precision Higgs physics beyond LHC precision and quality
- Precision Top physics
- Precision EW measurements
- Complementary searches (where LHC is less/not sensitive)

→ This programme justifies timely implementation

→ ILC

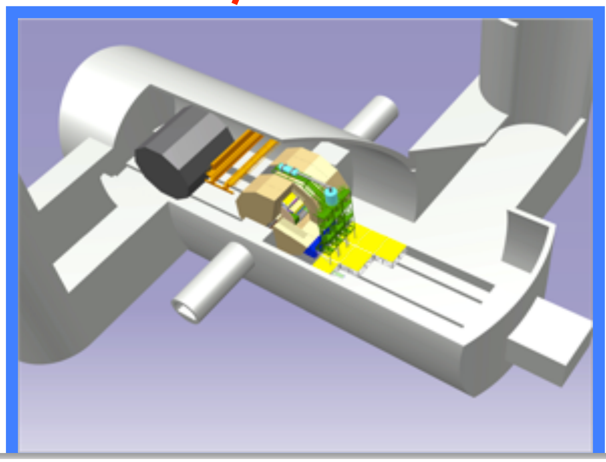
ILC Layout

[A.Seryi]



Power: ~163 MW

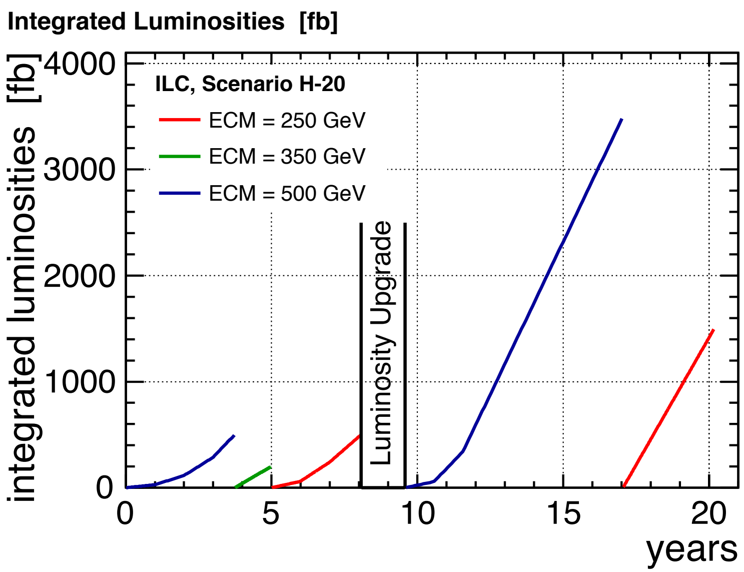
Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
E gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10



ILC luminosity and running scenario

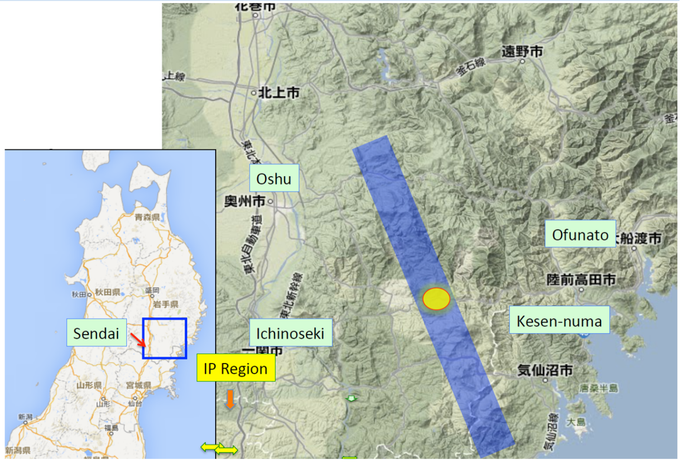
[ILC Parameters Joint WG arXiv:1506.07830]

Stage	ILC500			ILC500 LumiUP		
$\sqrt{s}$ [GeV]	500	350	250	500	350	250
$\mathcal{L}$ [fb^{-1}]	500	200	500	3500	-	1500
time [a]	3.7	1.3	3.1	7.5	-	3.1



possible 20 year running scenario

ILC status



- technically ready to be built
- site chosen (Kitakami, northern Japan)
- interest from Japanese government to host ILC as international project
- internal expert review at MEXT (Japanese science ministry)
  - Physics – Cost – International Sharing
  - Final report: spring 2016
  - Behind the scenes: a lot...

Any reason to be optimistic:

- Japan very interested in large international lab (political top theme – far beyond physics)
- Strong statements in regional strategies (EU, US, Asia, ICFA)
- Strong physics case – even if no additional LHC discovery in near future

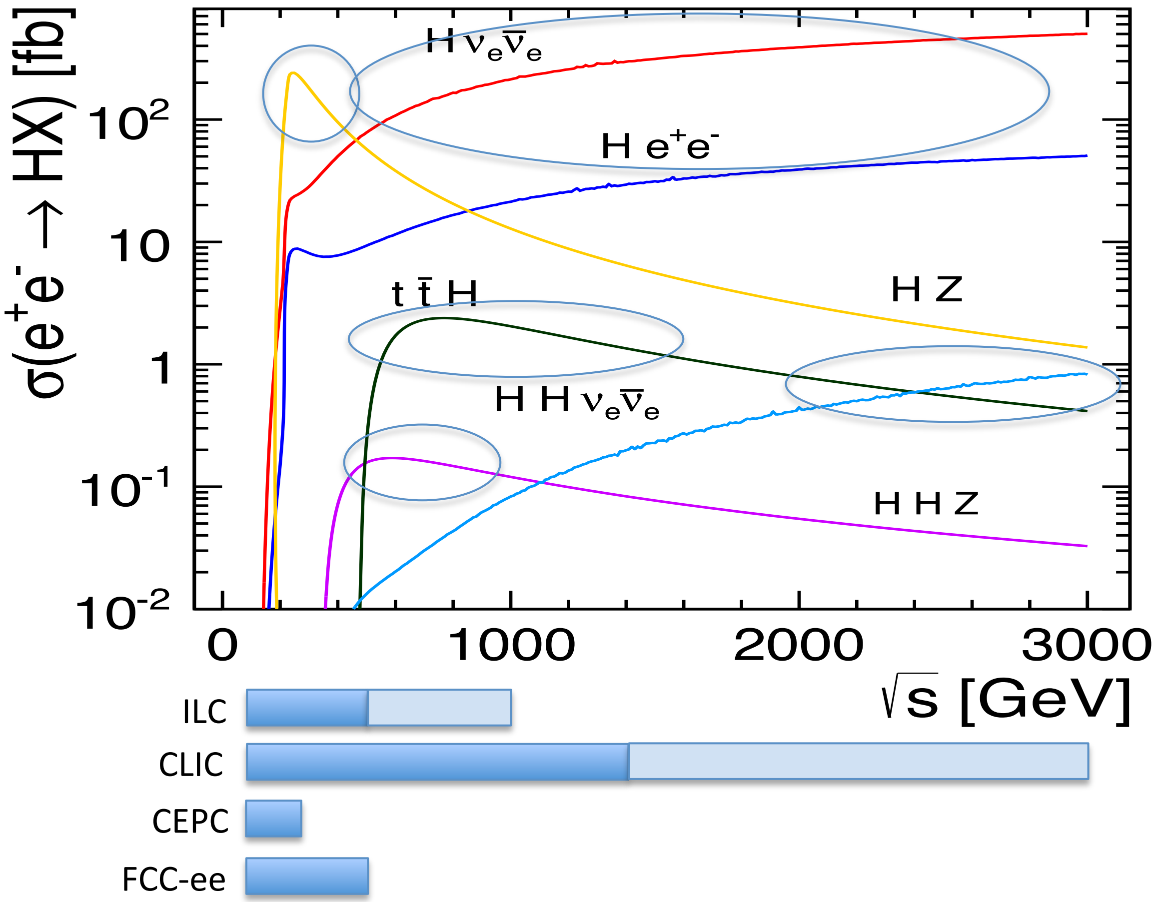
Higgs physics

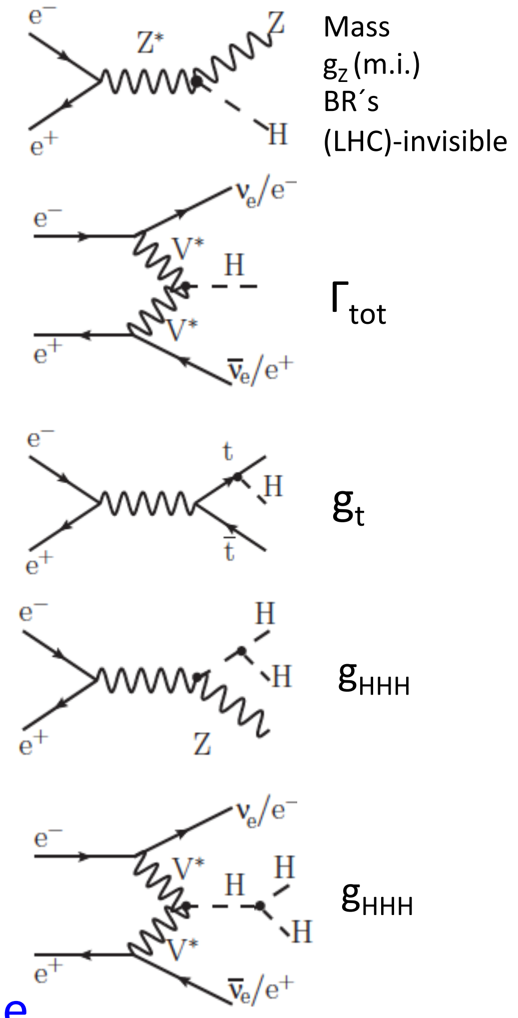
	(HL)LHC	ILC
Mass		
Spin		
CP		
boson couplings		
fermion couplings		
new decays		
self coupling		

legend:

- sufficiently precise for N.P. sensitivity/unambigous
- not precise enough for N.P. sensitivity/model-dependent
- challenging

e^+e^- Higgs processes



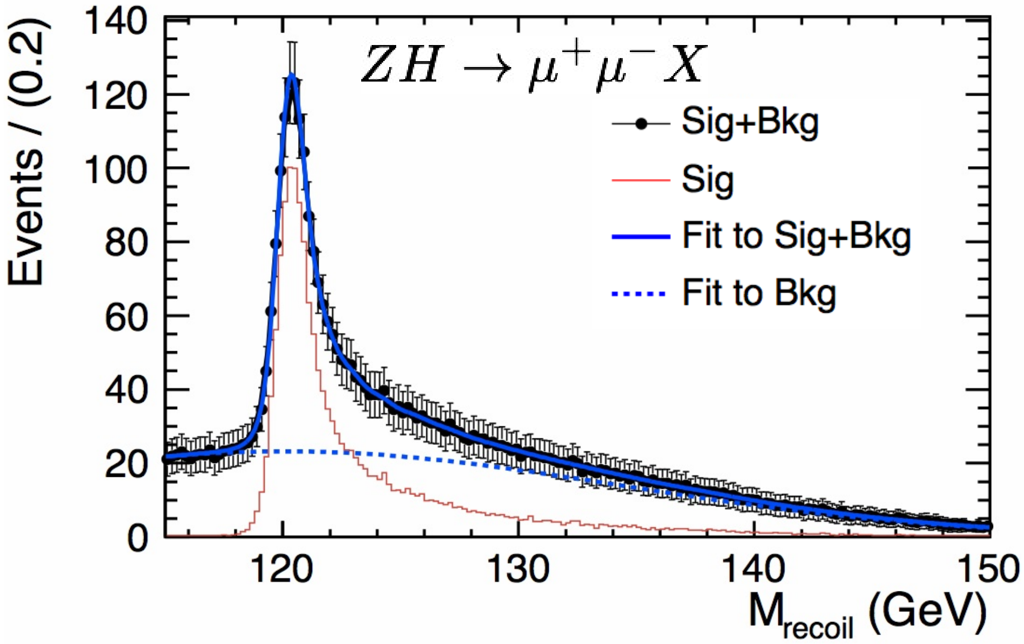


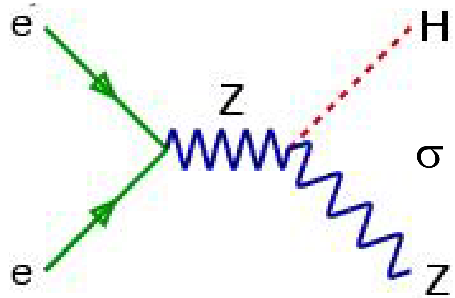
- Many processes at different √s needed & accessible

The LC flagship measurement

LHC: no known (to me) method to extract absolute Higgs BRs

LC: Recoil mass technique in $e^+e^- \rightarrow HZ$ allows us to measure σ_{HZ} indep. of H-decay





Higgsstrahlung

$\sigma \propto\sim 1/s$

$$m_H^2 = (p_{\ell\ell} - p_{initial})^2$$

$250\,\mathrm{fb}^{-1}@250\,\mathrm{GeV}$

$\Delta\sigma_{ZH}/\sigma_{ZH} = 2.6\%$

$\Delta m_H = 30\,\mathrm{MeV}$

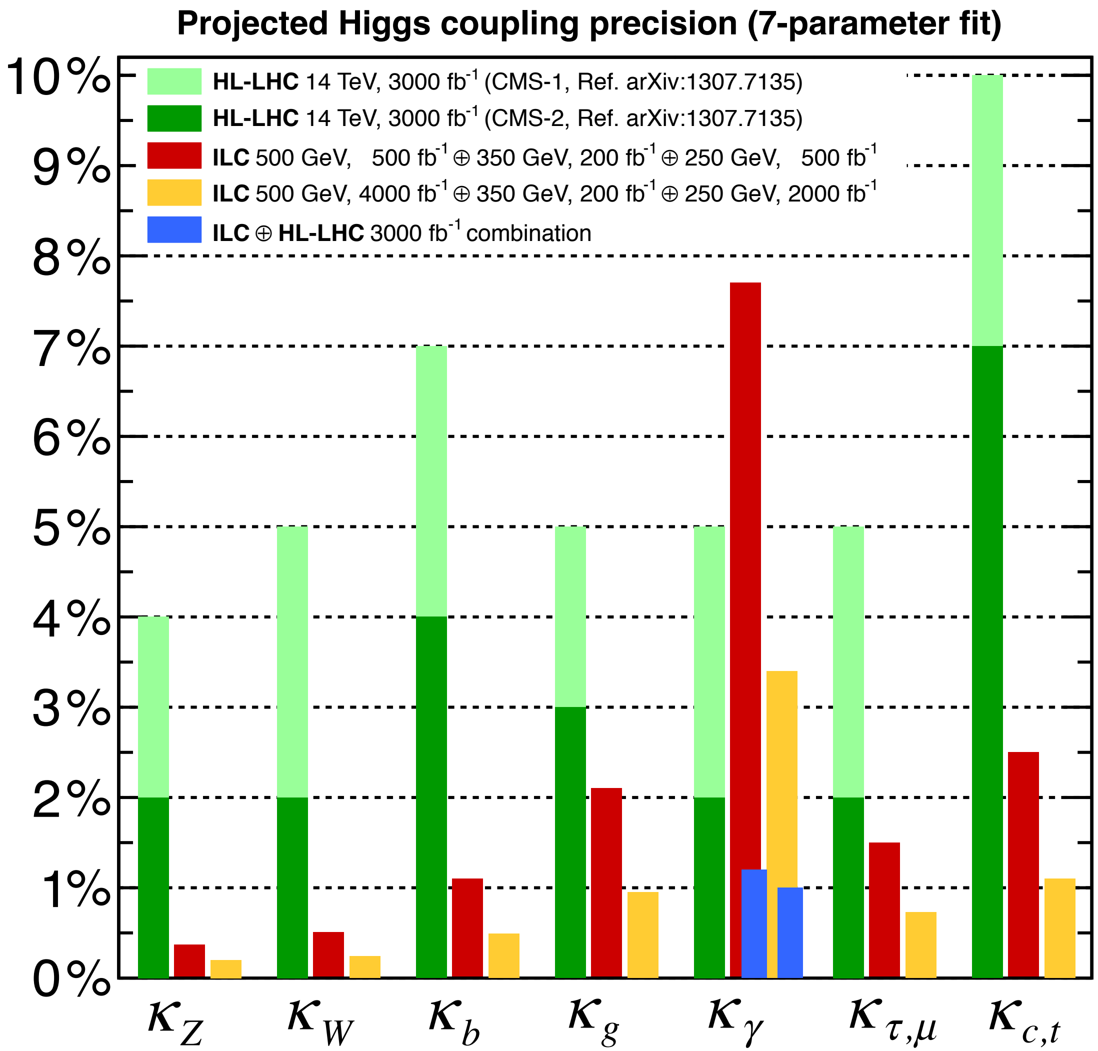
1/10 LHC

Once σ_{HZ} is known, any signal strength measurement can be turned into absolute BR´s measurement: $BR_X = (\sigma \times BR_X)_{meas} / \sigma(tot)_{meas}$

unique to lepton colliders (needs (E,p) constraint from initial state)

[Li, Poeschl]

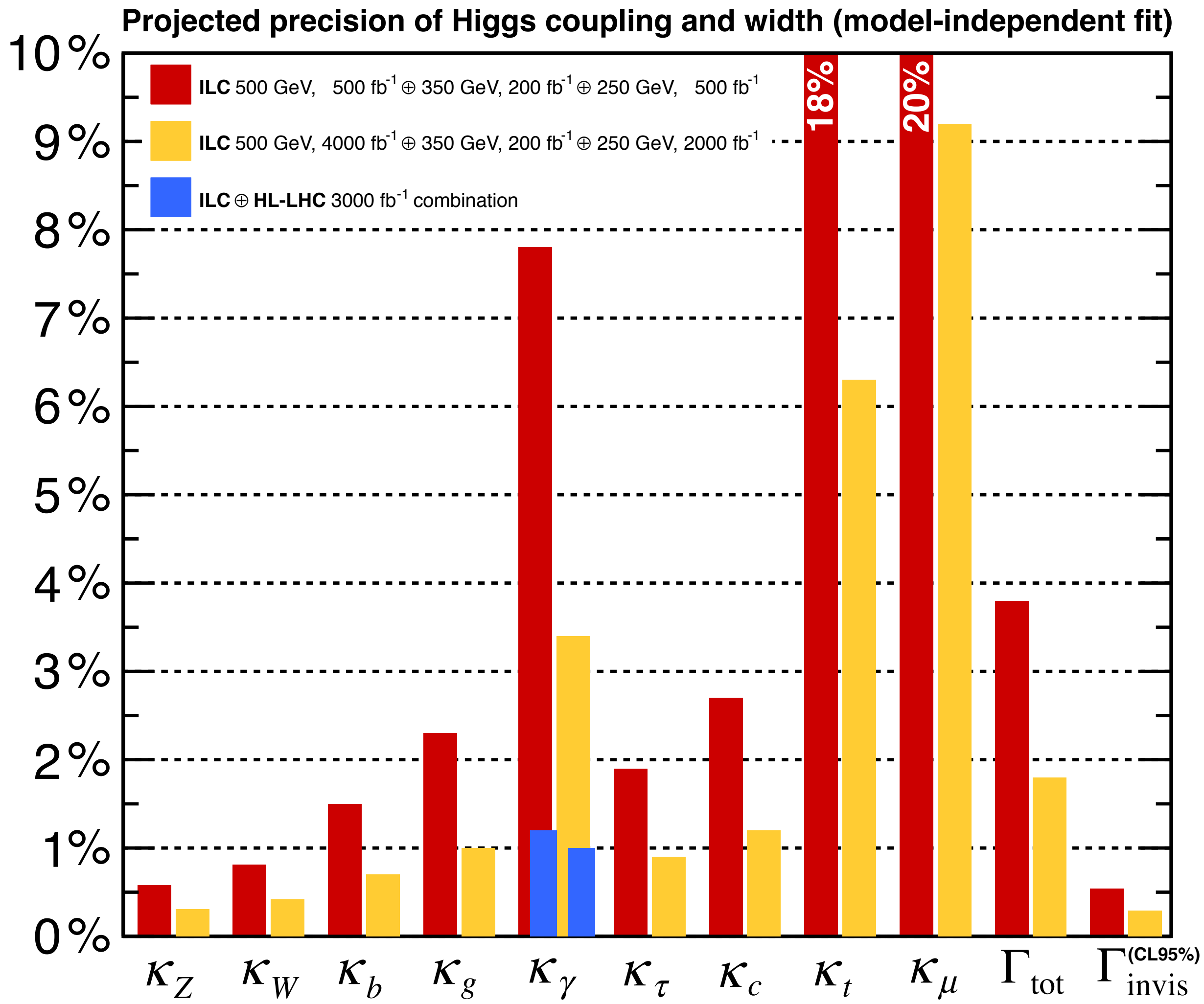
LHC vs ILC: model-dep. couplings (κ)



typically factor 5-10 improvement w.r.t. HL-LHC

[LCC Physics Group arxiv:1506.05992]

ILC: model-independent couplings



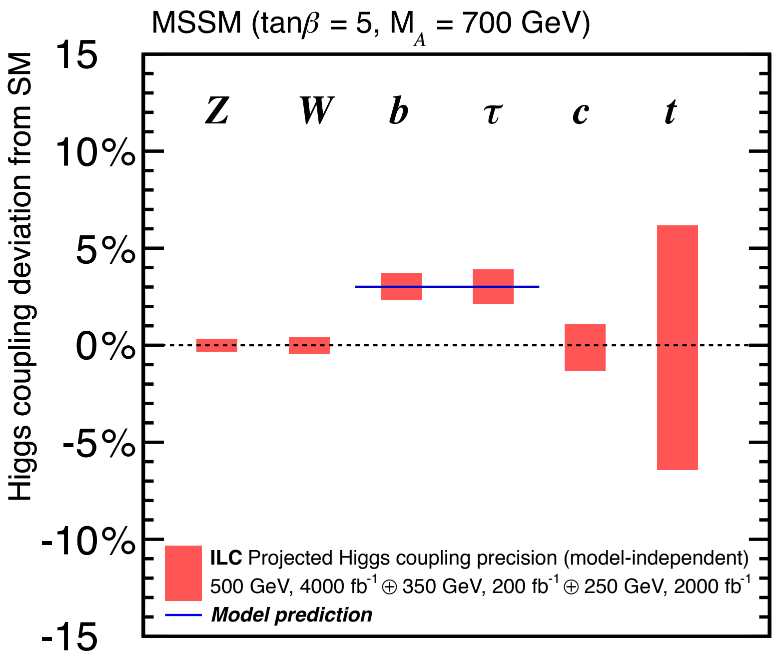
this cannot be done at LHC

At ILC:
only possible due to
a) recoil method g_{HZ}
and
b) total width measurement

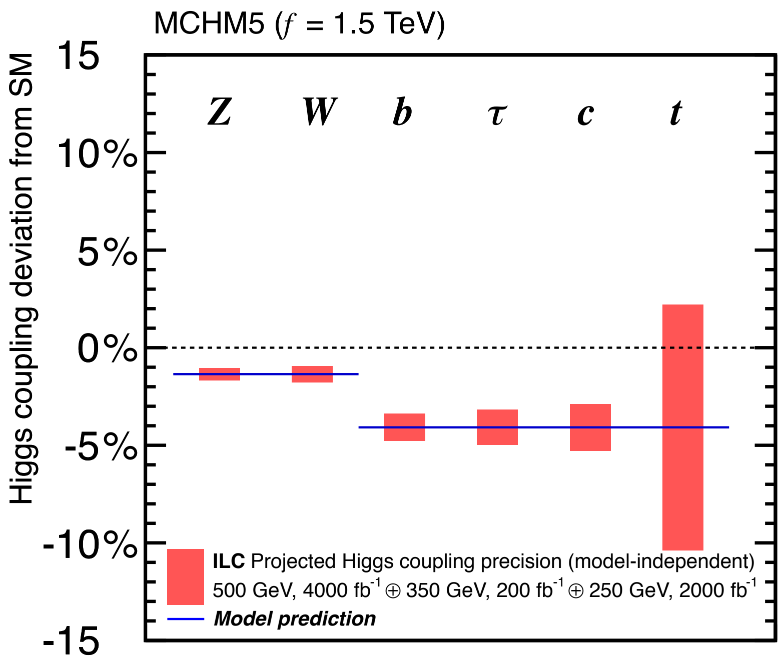
[LCC Physics Group arxiv:1506.05992]

Impact of BSM on Higgs Sector

Supersymmetry
(MSSM)



Composite Higgs
(MCHM5)

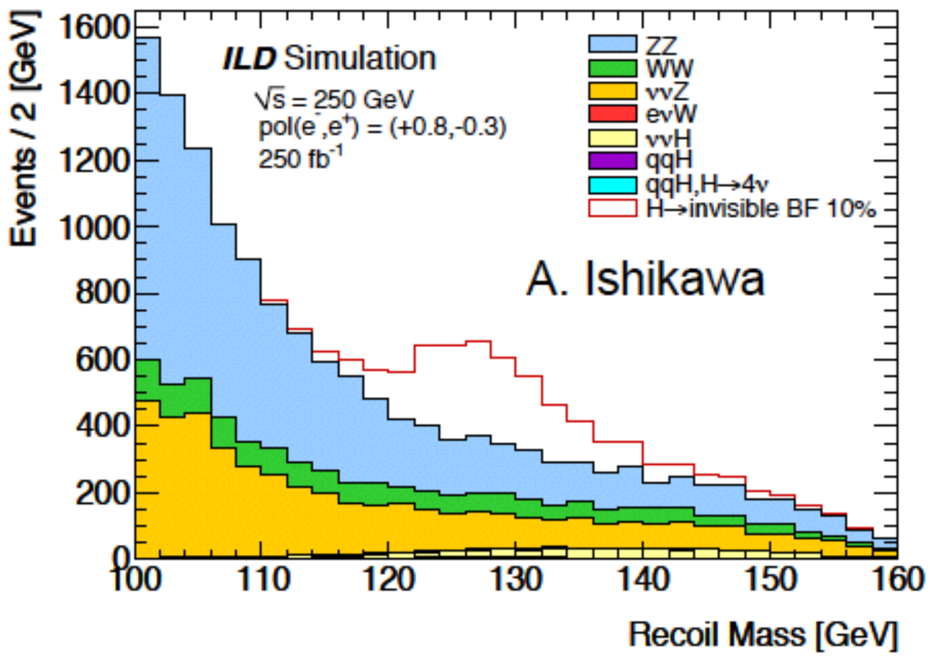


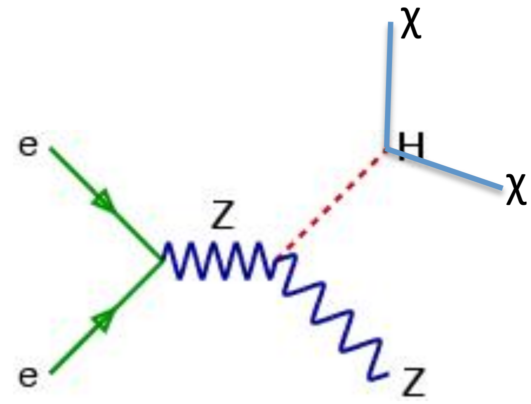
ILC (or better) precision required to discriminate models

[LCC Physics Group]

Invisible Higgs

The recoil mass technique also allows for unbiased observation of any non-SM decay, e.g. H→invisible:





UL on BF [%]	"Left"	"Right"
250GeV	0.95	0.69
350GeV	1.49	1.37
500GeV	3.16	2.30

Exclusion for BR(H→inv.) < 0.69% (95%CL)

also (qualitatively) applies to „LHC-invisible" decays, e.g. H→gg, H→qq etc.

The Higgs self coupling

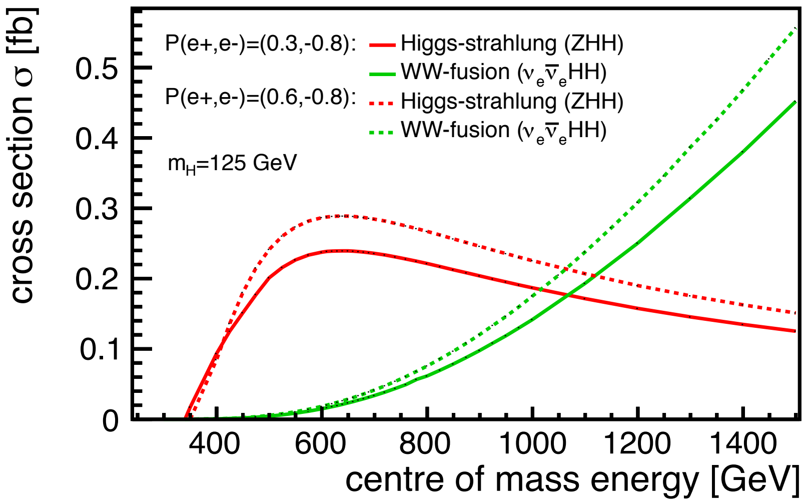
two choices:

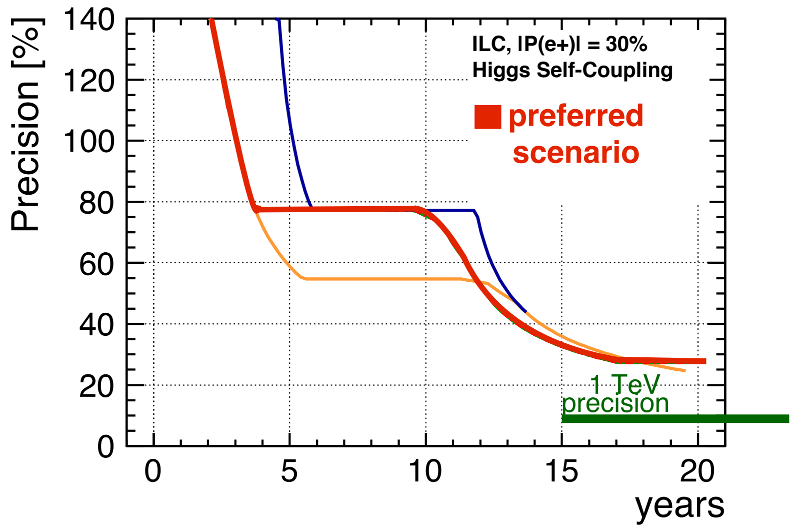
$e^+e^- \rightarrow ZHH$
(maximum of σ around √s ≈ 600 GeV)
→ ILC500 (~75 events in 500 fb^{-1})

$e^+e^- \rightarrow HH\nu\nu$
(log. rise of σ, need at least 1 TeV)

challenges:
- huge number of different final states
- „dilution" due to interference with non-HHH diagrams (not sensitive to λ_{HHH} (can be mitigated by phase space weighting)

analysis ongoing





[Dürig, EPS 2015]

Top Physics

	(HL)LHC	ILC
Mass	yellow	green
Width	yellow	green
EW (neutral) couplings	yellow	green
FCNC	green	yellow
tt resonances	green	yellow
rare decays	green	yellow

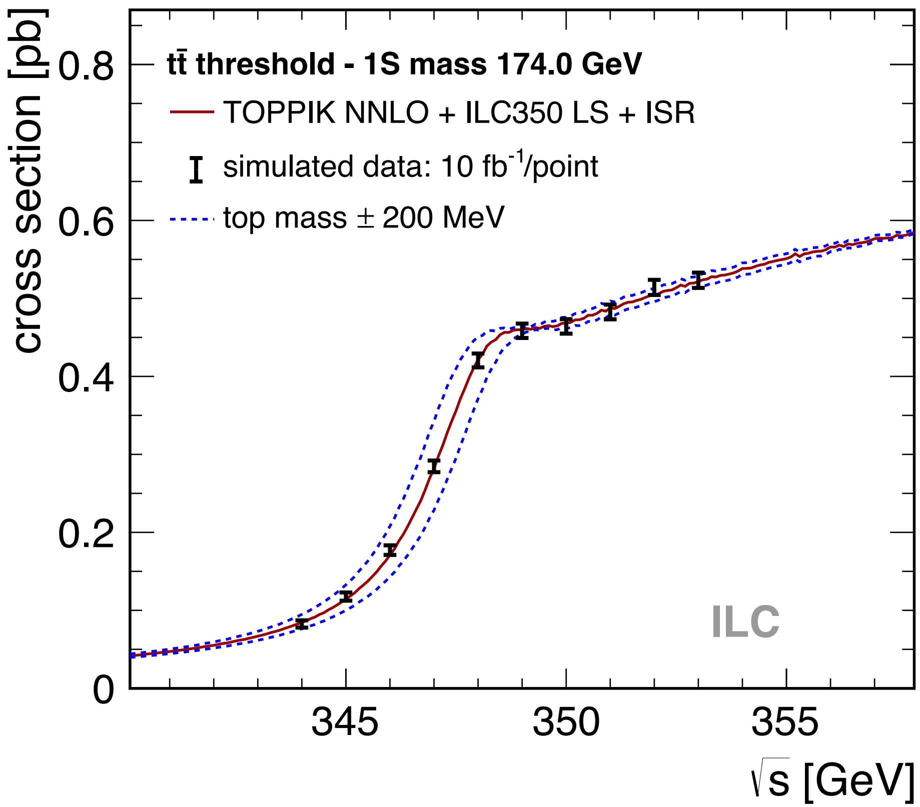
legend:

- green: sufficiently precise for N.P. sensitivity/unambiguous
- yellow: not precise enough for N.P. sensitivity/model-dependent
- orange: challenging

Top Quark Mass

Top Quark mass from cross section at tt production threshold

- theoretically well-defined, recent progress NNNLO, y_t dependence
- – precision 50 MeV on $m_{t\ from}$ threshold scan

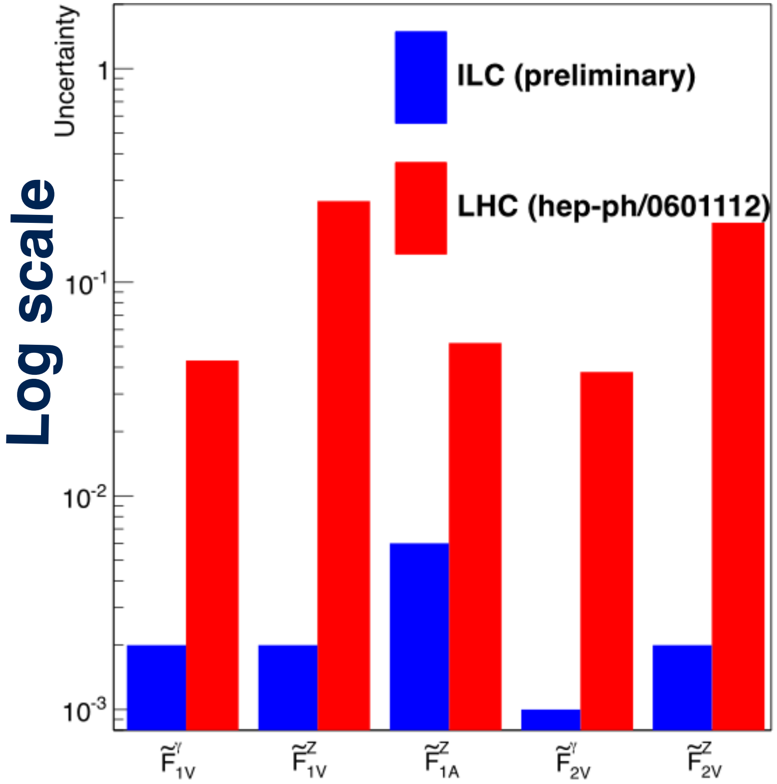


lots of theory progress!
[Hoang et al 2014]
[Bach et al 2014]
[Beneke et al 2015]
[Marquard et al 2015]

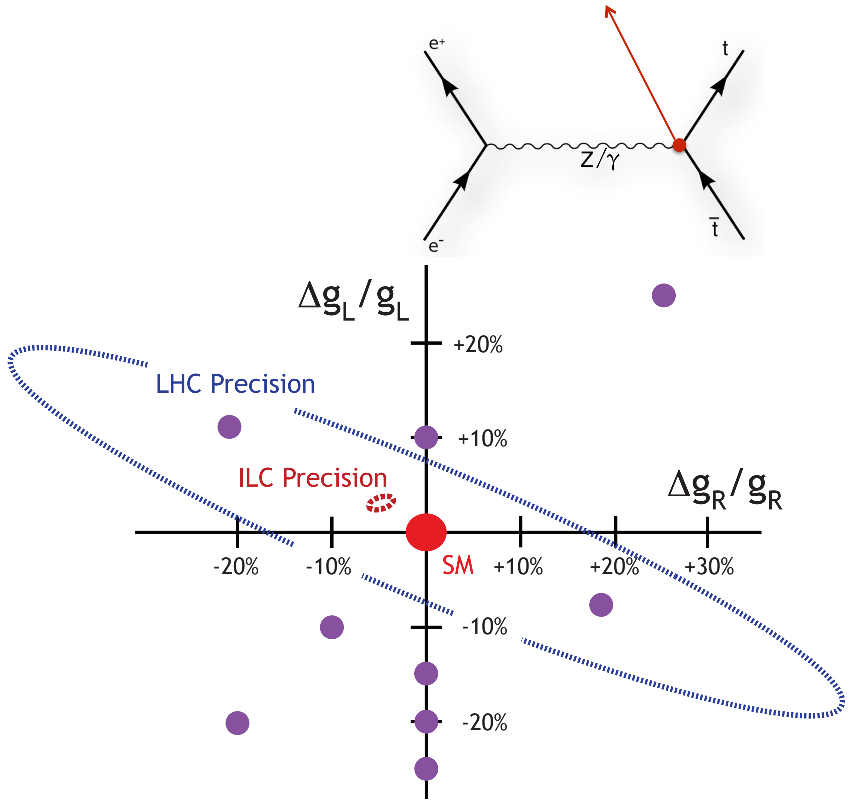
Top Quark at ILC

Top quark neutral EW couplings in effective operator approach

$$\Gamma_\mu^{ttX}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(\widetilde{F}_{1V}^X(k^2) + \gamma_5 \widetilde{F}_{1A}^X(k^2)\right) + \frac{(q-\bar{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^X(k^2) + \gamma_5 \widetilde{F}_{2A}^X(k^2)\right)\right\}$$



[Pöschl et al]



[Richard et al]

Discovery of new particles

	(HL)LHC	ILC
X	?	?
Y	?	?
Z	?	?
...	?	?

legend:

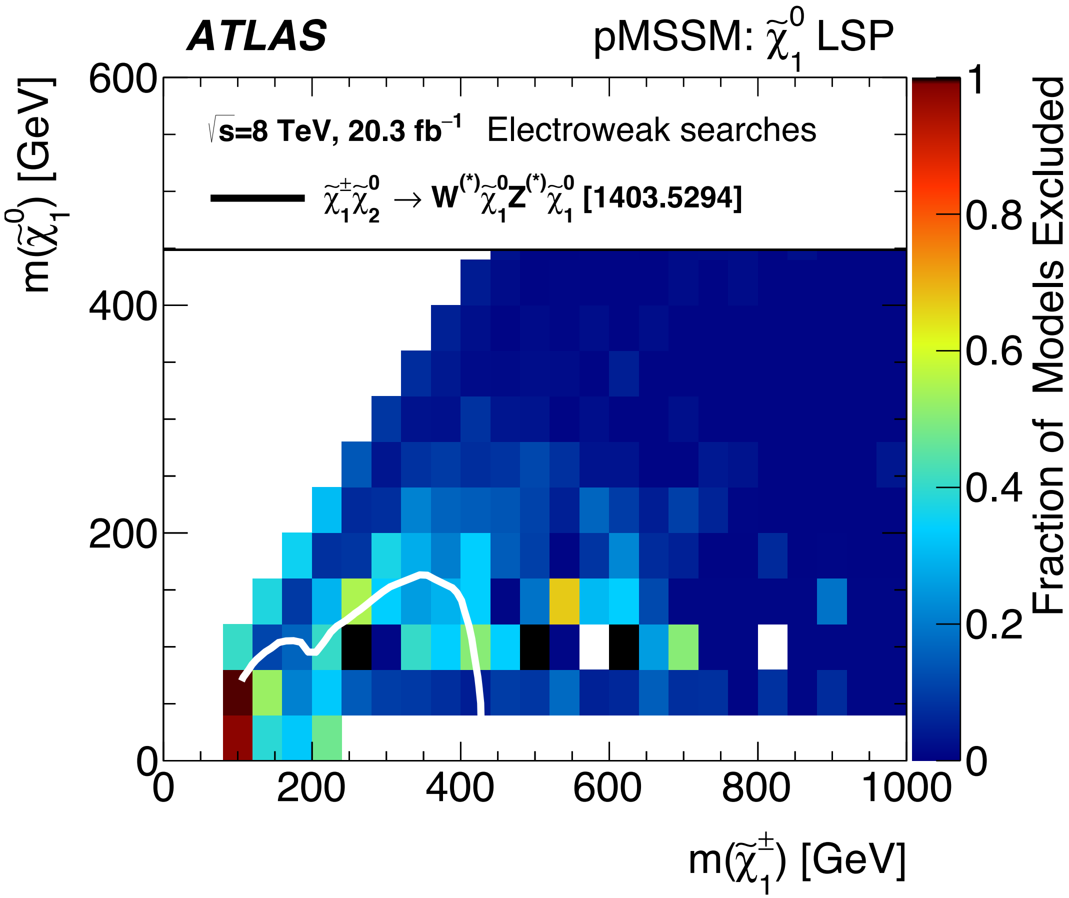
- discovery (green)
- 3σ effect (yellow)
- no discovery (red)

there is ample complementarity between LHC and ILC in discovery reach

we simply don´t know which NP Nature has chosen

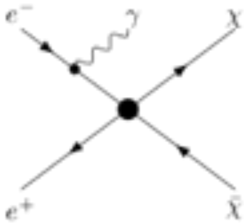
there is plenty of room for SUSY

ATLAS, pMSSM scan arxiv:1508.06608



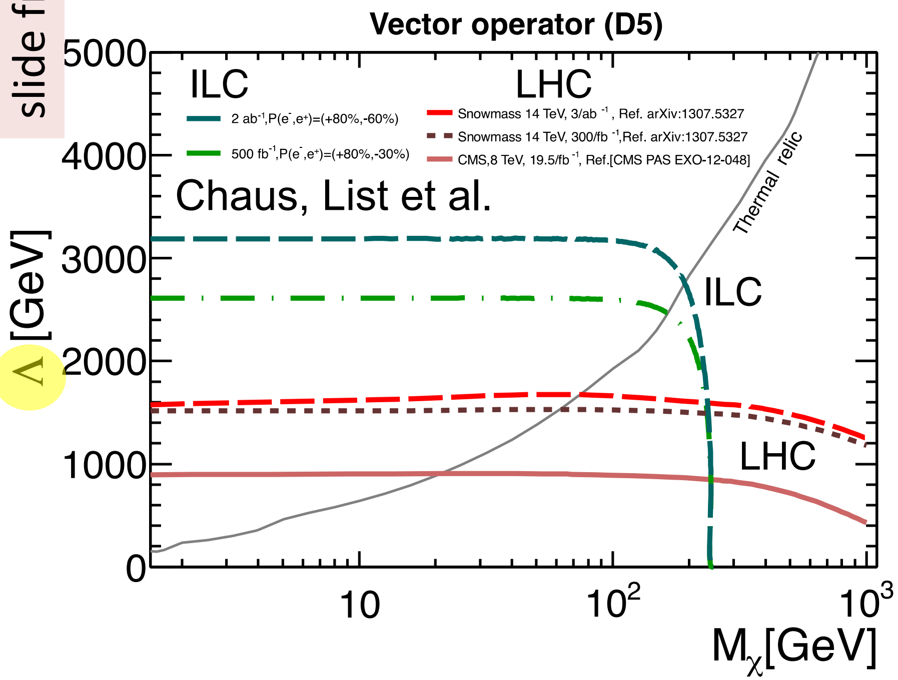
(b) Chargino–neutralino

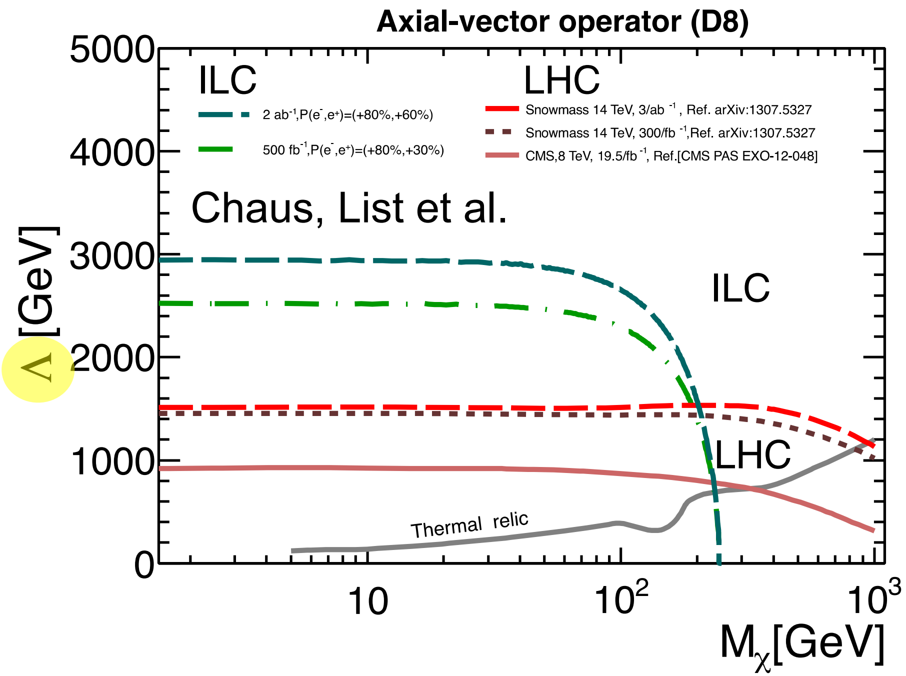
DM: Effective Operator Approach



$$\mathcal{L}_{\rm int} = \frac{1}{\Lambda^2}\mathcal{O}_i$$

$$\mathcal{O}_V = (\bar{\chi}\gamma_\mu\chi)(\bar{\ell}\gamma^\mu\ell) \qquad \mathcal{O}_A = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{\ell}\gamma^\mu\gamma^5\ell)$$





LHC sensitivity: Mediator mass up to Λ~1.5 TeV for large DM mass

ILC sensitivity: Mediator mass up to ***Λ~3 TeV*** for ***DM mass up to ~√s/2***

e^+e^- alternatives: CLIC

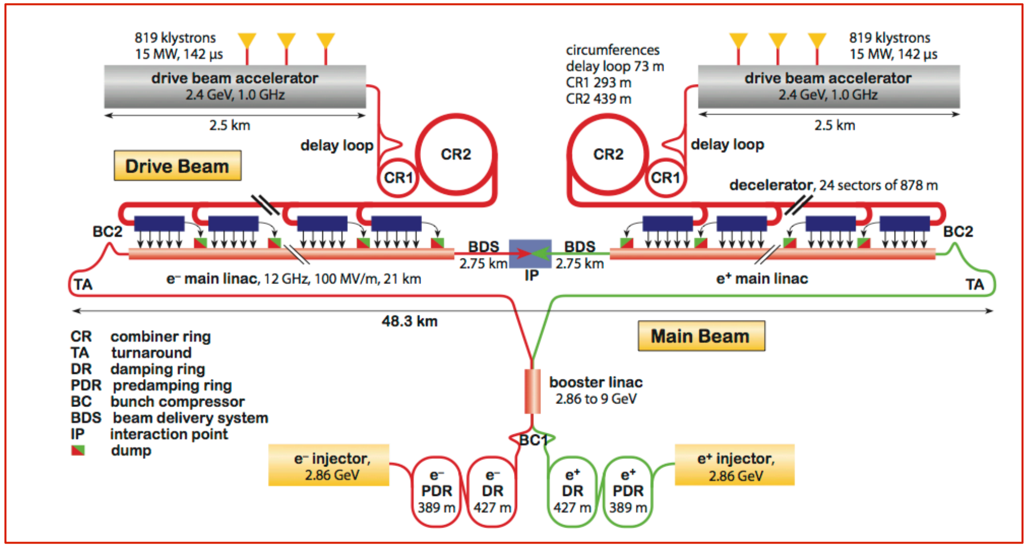
- Two-beam acceleration scheme
- Normal conducting cavities (power: 600 MW@3 TeV)
- aim at 100 MV/m for 50km/3 TeV machine

Significant R&D ongoing

Technical readiness in some years?

Higher energy reach than ILC – Alternative to ILC (if not built)

If at CERN, unlikely to operate before (end HL-LHC+some years) ~2040



Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	$10^{34}cm^{-2}s^{-1}$	1.5	5.9
Luminosity above 99% of √s	$10^{34}cm^{-2}s^{-1}$	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72	100

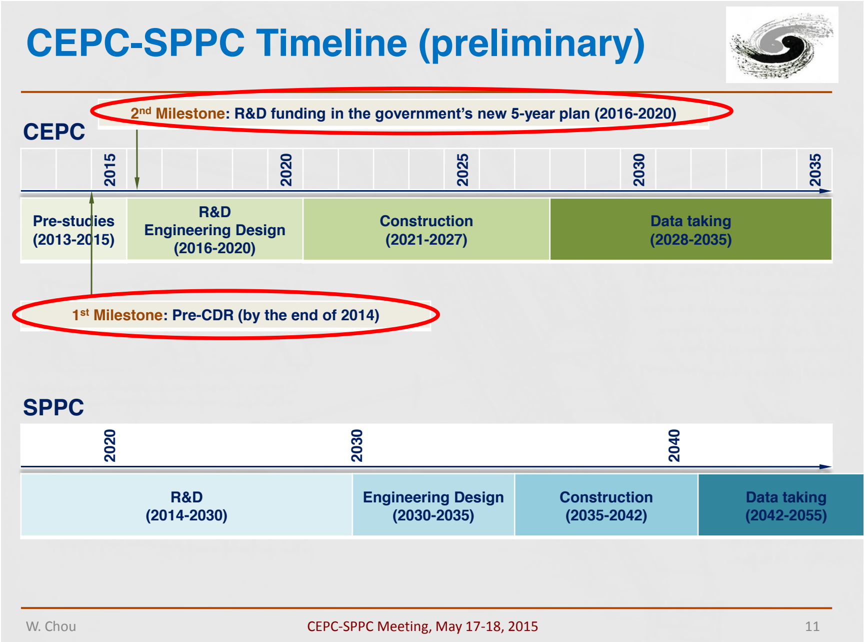
[Gianotti EPS15]

e^+e^- alternatives: CepS

http://cepc.ihep.ac.cn/preCDR/volume.html

- 54 km ring
- CepC: √s=240 GeV e+e- ; L=2x10^{34}; 2 IP
- possibly followed by SppC: √s = 70 TeV pp collider; L=1.2x10^{35}; 2 IP
- if more funding: 100 km ring and/or separate pipes for e+/e- beams)

pre-CDR published in 03/15

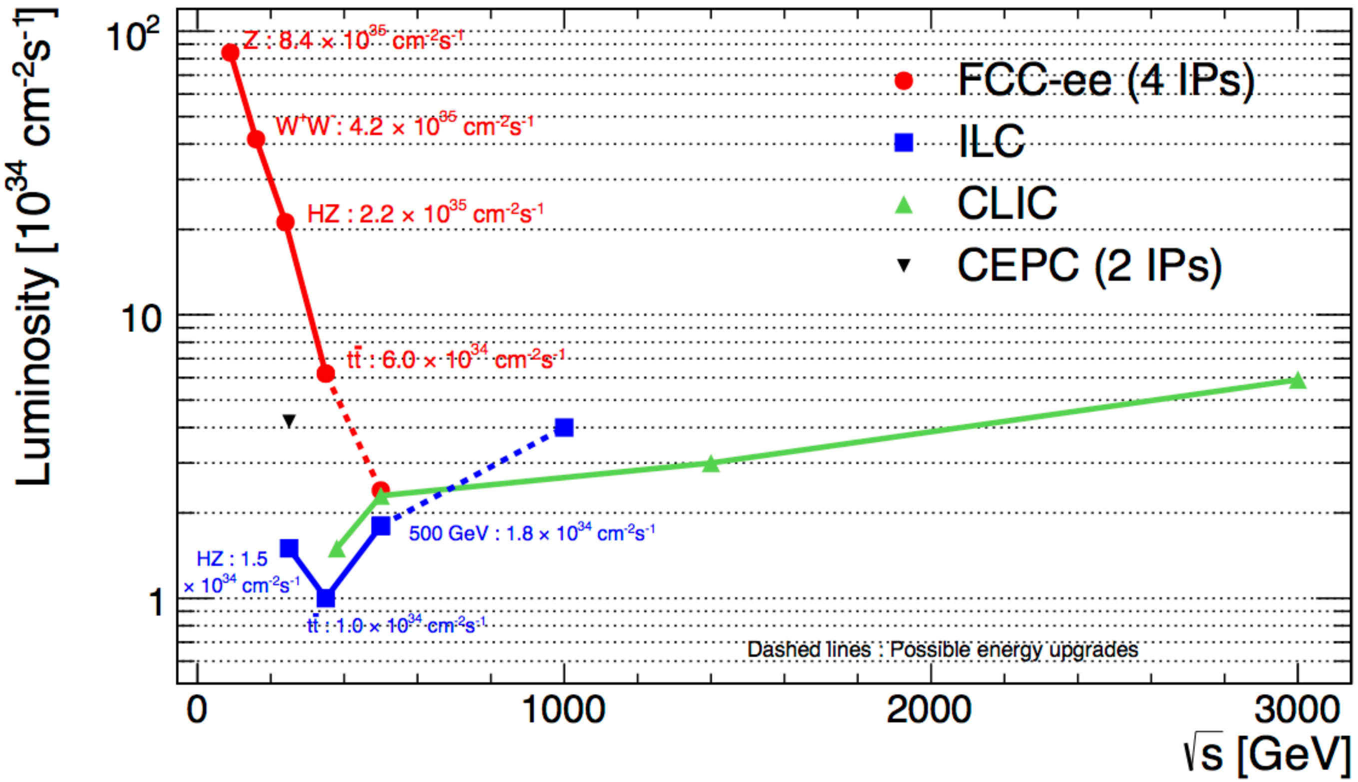


240 GeV energy reach limits physics potential:

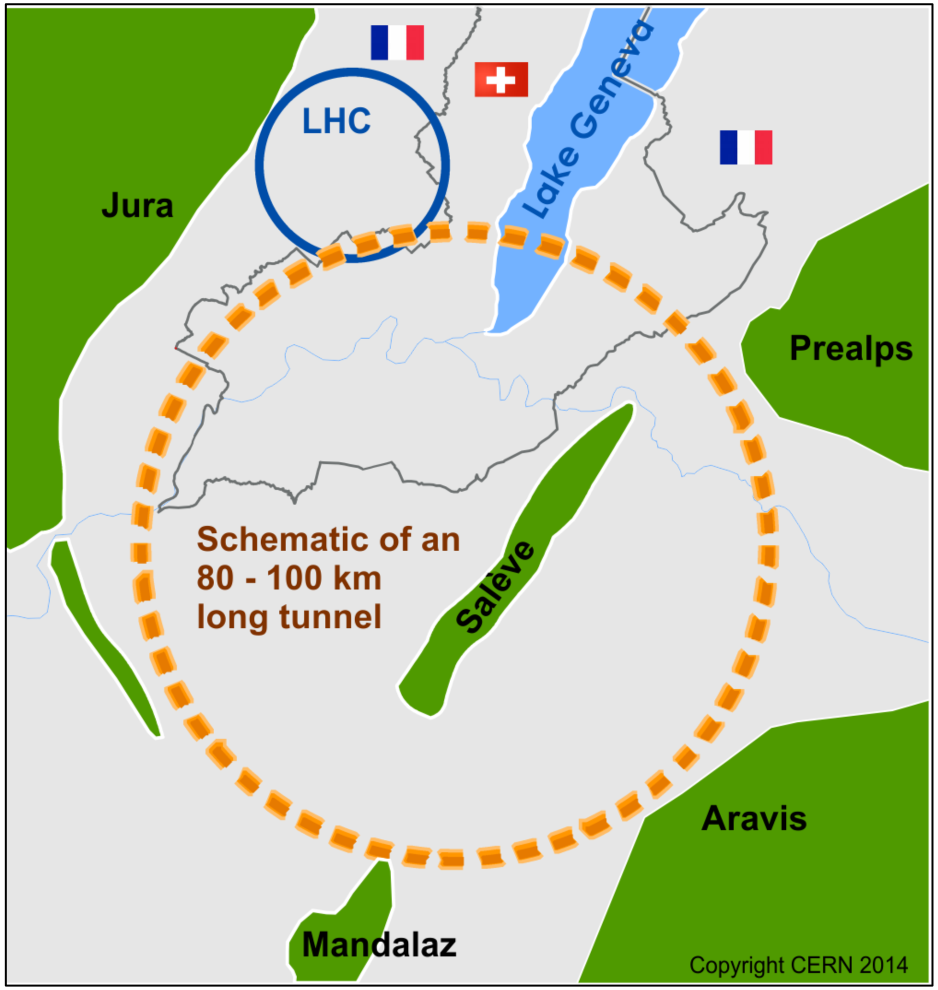
- mainly HZ programme
- no tth, HH,
- no ttbar
- almost no discovery potential for NP (only 30 GeV more than LEP2)

e^+e^- alternatives: FCC-ee

- Proposed as precursor to FCC-hh study for 100km/100TeV pp collider
- Huge luminosity at low energies promised (tempting), multiple IPs
- Need extra top-up ring due to low beam lifetime 30 min (luminosity)
- Limited √s (<= 500 GeV) due to SR – power consumption 500 MW?
- Timeline? If at CERN, probably not before (end HL-LHC+n years ~2040?)
- Delay of FCC-hh energy frontier machine



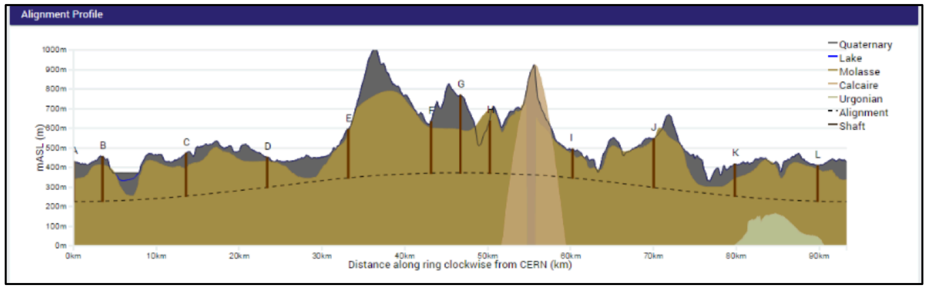
Hadron Collider: FCC-hh



CERN launched international conceptual design study for 100 km ring in Geneva region

pp: √s = 100 TeV L=2.5x10^{35} 4 IPs

Goal: CDR in 2017? Input to next European Strategy update



Key Parameters FCC-hh

W. Chou, EPS15

Parameter	FCC-hh	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP$_{main}$ [$cm^{-2}s^{-1}$]	5 - 30 x 10^{34}	1 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

Major FCC-hh Challenges

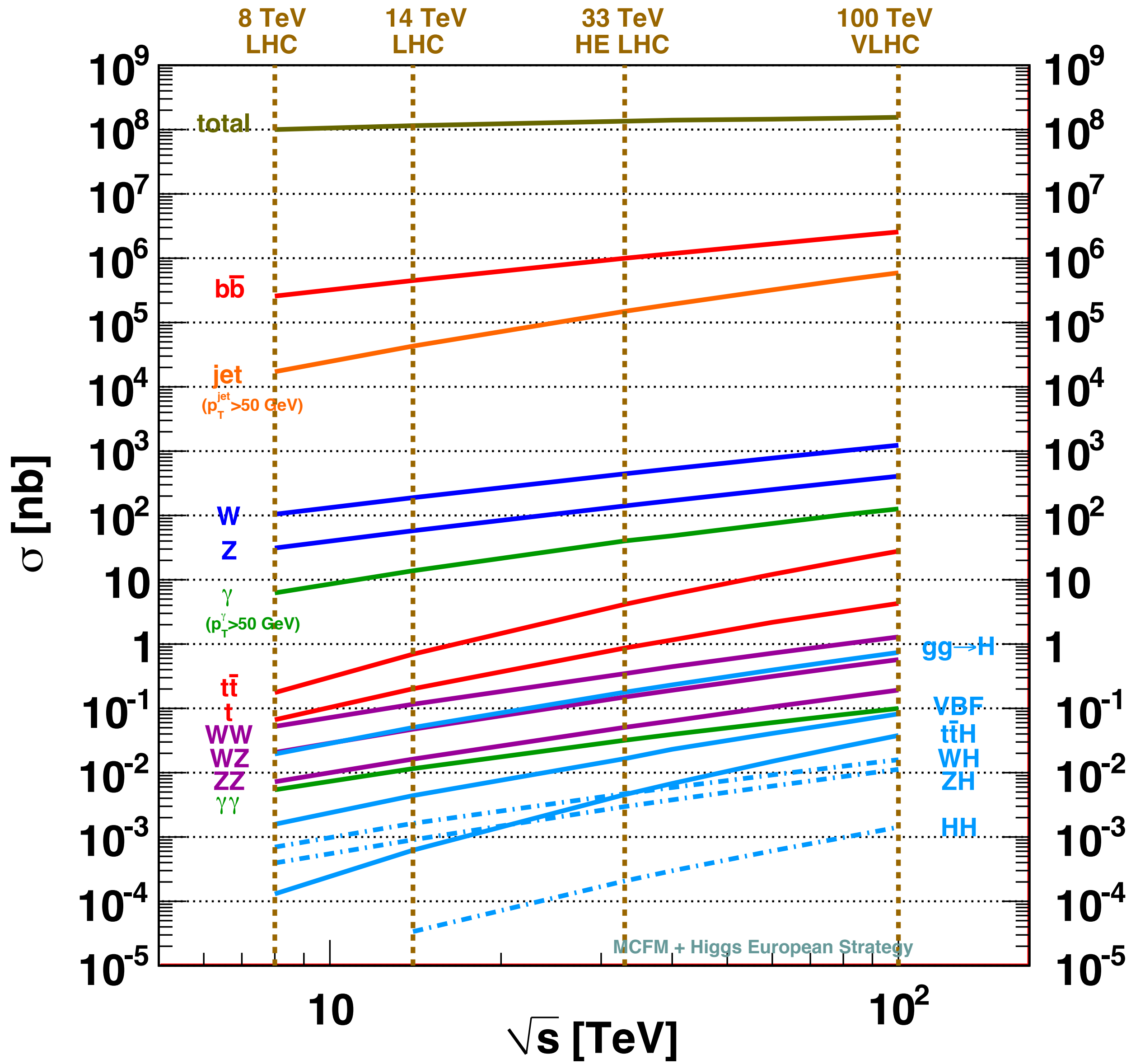
- Magnets:
  NbTi (LHC) will no longer work, need new SC material (Nb_3Sn or HTSC...)
  and new magnet design → significant R&D, takes time

- Stored beam energy
  8 GJ = 40xLHC = 2 tons TNT = 1 A380 (kin. energy)
  → machine protection

- Synchrotron radiation (sic!)
  28 W/m = 160xLHC needs to be efficiently shielded from SC magnets

Lots of R&D needed, has started within international FCC study

FCC-hh Cross Sections



New territory,
all we know:

SM cross sections
at 100 TeV

wrt. LHC:

W,Z x7
H x15
HH: x40

X (1 TeV) x10^3
X (14 TeV) x∞

Physics arguments for FCC-hh

- if new heavy particle(s) discovered at LHC/HL-LHC (possibly beyond CLIC reach) they can be produced with much higher than at LHC (e.g. 1 TeV stop: factor 10^3, even larger factor for higher masses)

- potentially complete the spectrum (if the new particle is not alone)

- study $V_L V_L \rightarrow V_L V_L$ with large statistics (ultimate EWSB closure test)

- Higgs self-coupling (HH cross section 40xLHC – enough?)

- interesting playground for novel ideas (your job...)

- THE UNKNOWN...

Conclusions

- We live in very exciting times,
  in the middle of exploring uncharted territory: LHC
- Great prospects to get answers on big questions and guidance how to ask even better questions
- Higgs, top, EW calls for a timely precision study
  to explore new physics → ILC
- Time to prepare the next big jump at the energy frontier
  → FCC-hh , CLIC, SppS?
  LHC needs to tell us where to jump

Conclusions

Unification and heavy RH neutrinos below the Planck scale). Clearly we are experiencing a very puzzling situation but, to some extent, this is good because big steps forward in fundamental physics have often originated from paradoxes. We highly hope that the continuation of the LHC experiments will bring new light on these problems.

Prof. Guido Altarelli, arxiv:1407.2122