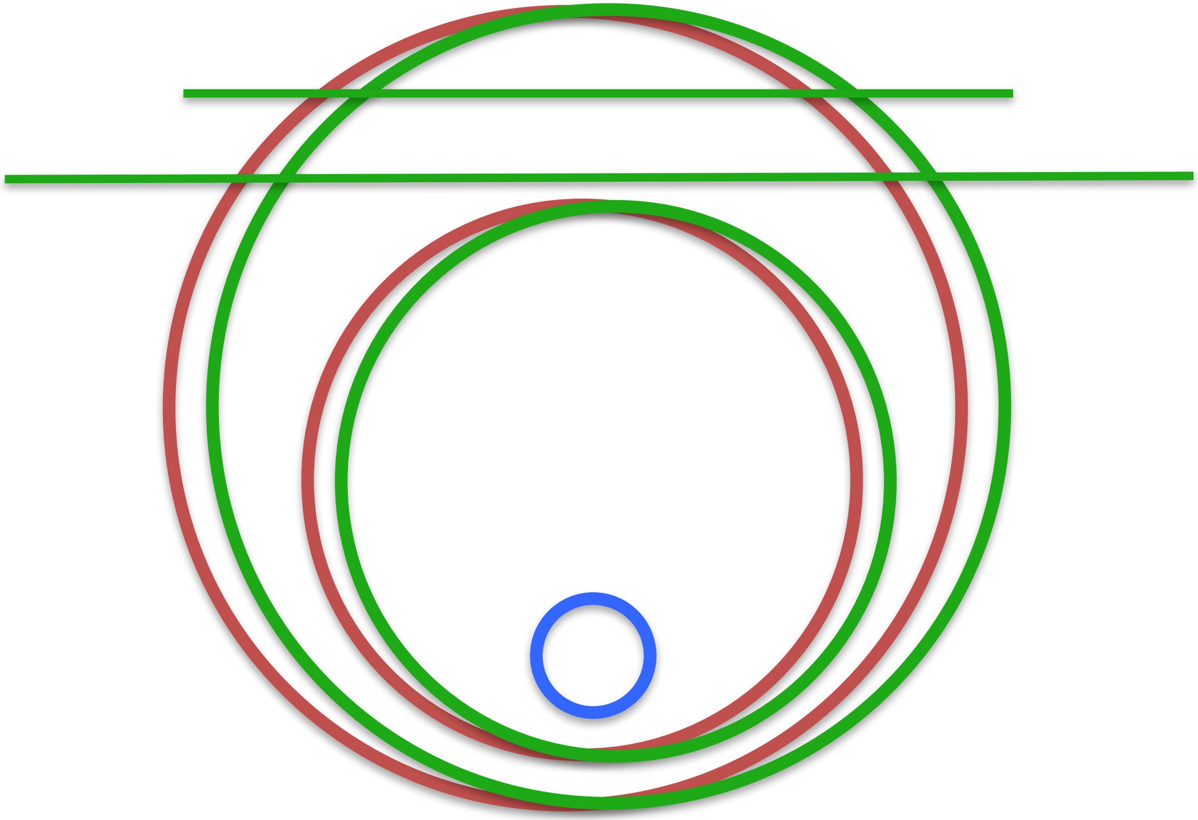
# Particle Physics



Klaus Desch
University of Bonn

Perspectives for Accelerators and Technology

Darmstadt - 16/02/2017

# Particle physics & Accelerators

Particle physics: probe shortest distances, produce heavy particles

$\lambda = h/p$ $m=E/c^2$

Particle accelerators are
- the driving tool for particle physics

Particle physics has been (and is)
- a driving application for accelerator physics

Discovery at

- hadron accelerator
- hadron collider
- $e^+e^-$ collider

# The scene: where do we stand?

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)

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

→ we have to rely on experimental exploration!
(T.Hänsch: „look where noone looked before“)

This „experimental exploration“ has started with LHC run1/2
We should be prepared for break-through discoveries every day....

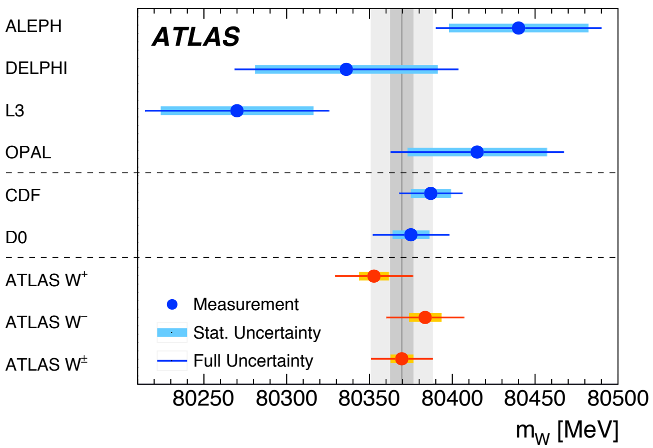
# Experimental exploration at work

→ look for deviations from SM predictions in as many signatures as possible

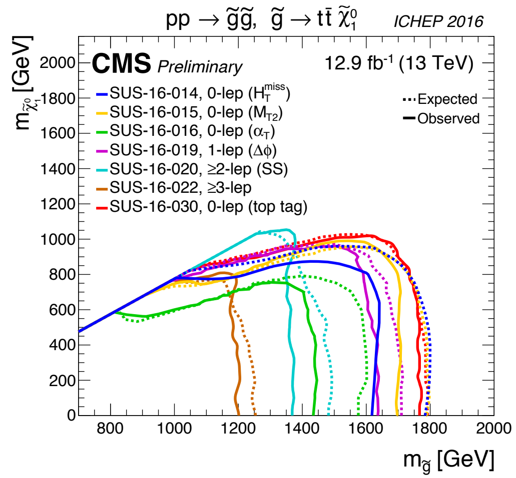
→ measure the degree of agreement of SM and data to exclude theoretical models (and make room in the heads of theorists...)

→ characterize the „known stuff“ to best possible precision (H,t,W)s

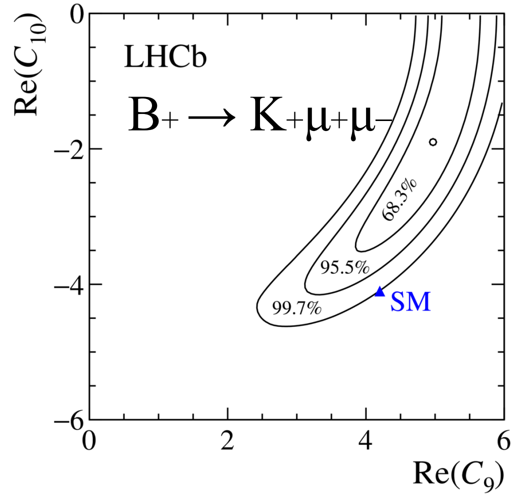
precision measurements




model exclusions




anomalies?



# The driving fundamental questions (KD selection)

| | |
|---|---|
| What is the Higgs boson? | Fundamental or composite?<br>Only one Higgs? |
| What makes it so light? | Fine tuning/Hierarchy? |
| What particles are carrying the Dark Matter? | WIMPs? WISPs? or BHs??? |
| How did anti-matter disappear? | CP violation (Higgs, Neutrinos, BSM ?) |
| Can all forces be unified? | SUSY?<br>Proton decay? |
| Are there more than 3 generations? | |
| Why is there no dipole moment of n/p? | Absence of CPV – symmetry? |

*(Add your favourite puzzle here)*

Accelerators play a vital role for all these questions

# Where to go from here?

European strategy update 2013
prepared by the
European Strategy Group for
Particle Physics
and was adopted by CERN council

Update foreseen ~2019/20
Preparatory process beginning soon

## The European Strategy for Particle Physics

Update 2013

Prepared by the European Strategy Group for Particle Physics for the special European Strategy Session of Council in Brussels on 30 May 2013.

### Preamble

Since the adoption of the European Strategy for Particle Physics in 2006, the field has made impressive progress in the pursuit of its core mission, elucidating the laws of nature at the most fundamental level. A giant leap, the discovery of the Higgs boson, has been accompanied by many experimental results confirming the Standard Model beyond the previously explored energy scales. These results raise further questions on the origin of elementary particle masses and on the role of the Higgs boson in the more fundamental theory underlying the Standard Model, which may involve additional particles to be discovered around the TeV scale. Significant progress is being made towards solving long-standing puzzles such as the matter-antimatter asymmetry of the Universe and the nature of the mysterious dark matter. The observation of a new type of neutrino oscillation has opened the way for future investigations of matter-antimatter asymmetry in the neutrino sector. Intriguing prospects are emerging for experiments at the overlap with astroparticle physics and cosmology. Against the backdrop of dramatic developments in our understanding of the science landscape, Europe is updating its Strategy for Particle Physics in order to define the community's direction for the coming years and to prepare for the long-term future of the field.

# European strategy in brief

1. LHC + HL-LHC
2. Prepare ambitious post-LHC accelerator project at CERN
3. Look forward to proposal from Japan on ILC
4. Develop a neutrino program to enable European participation
5. Theory…
6. Quark+Lepton flavour physics
7. Detector & Computing R&D
8. Non-accelerator particle physics (coordingate with astro-particle ph.)
9. Coordinate at boundary between particle and nuclear physics

implementation fully underway

# German landscape

German Particle Physics strategy documented

in KET brochure (2014)

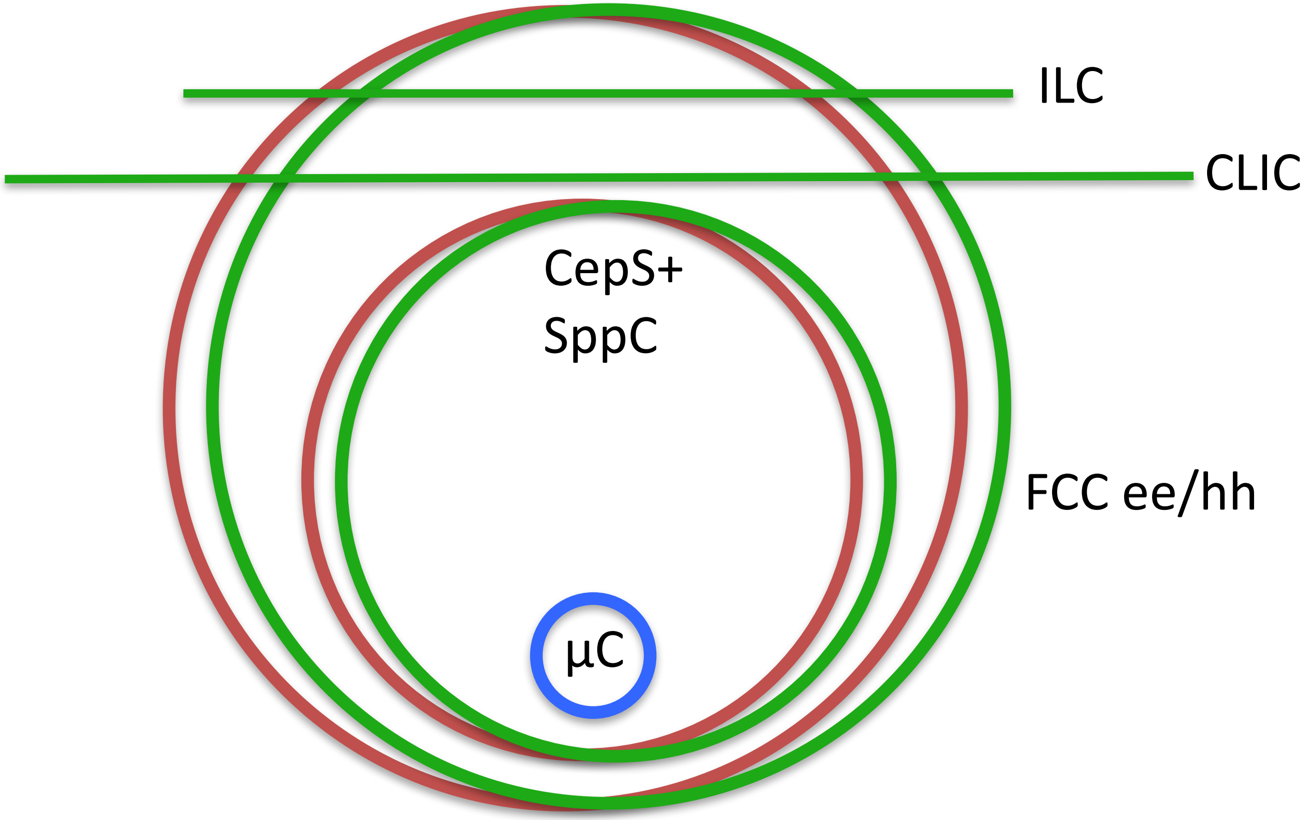
largely in-line with European Strategy

KET-workshops to prepare German input

next European strategy update:

1. $e^+e^-$ (2.-3.5.2016, MPP Munich) ✓
2. Neutrinos (23.-24.2.2017, MPK Heidelberg)
3. Beyond colliders (27.-28.4., Mainz)
4. Hadron machines (t.b.d.)
5. Summary workshop (t.b.d.)

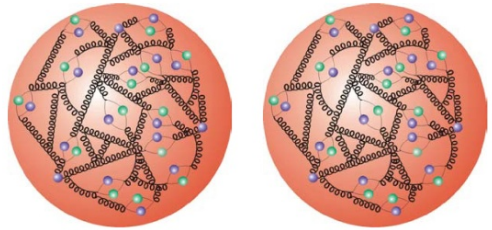
# (Major) Projects




Will comment mainly on physics case – technical implementation: O Brüning´s talk

# Lepton and Hadron collisions

$e^+$ • • $e^-$

p  p

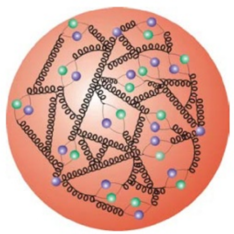
discovery through precision
study known particles

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)

What about p  • $e^-$ ?

# $e^+e^-$ collisions

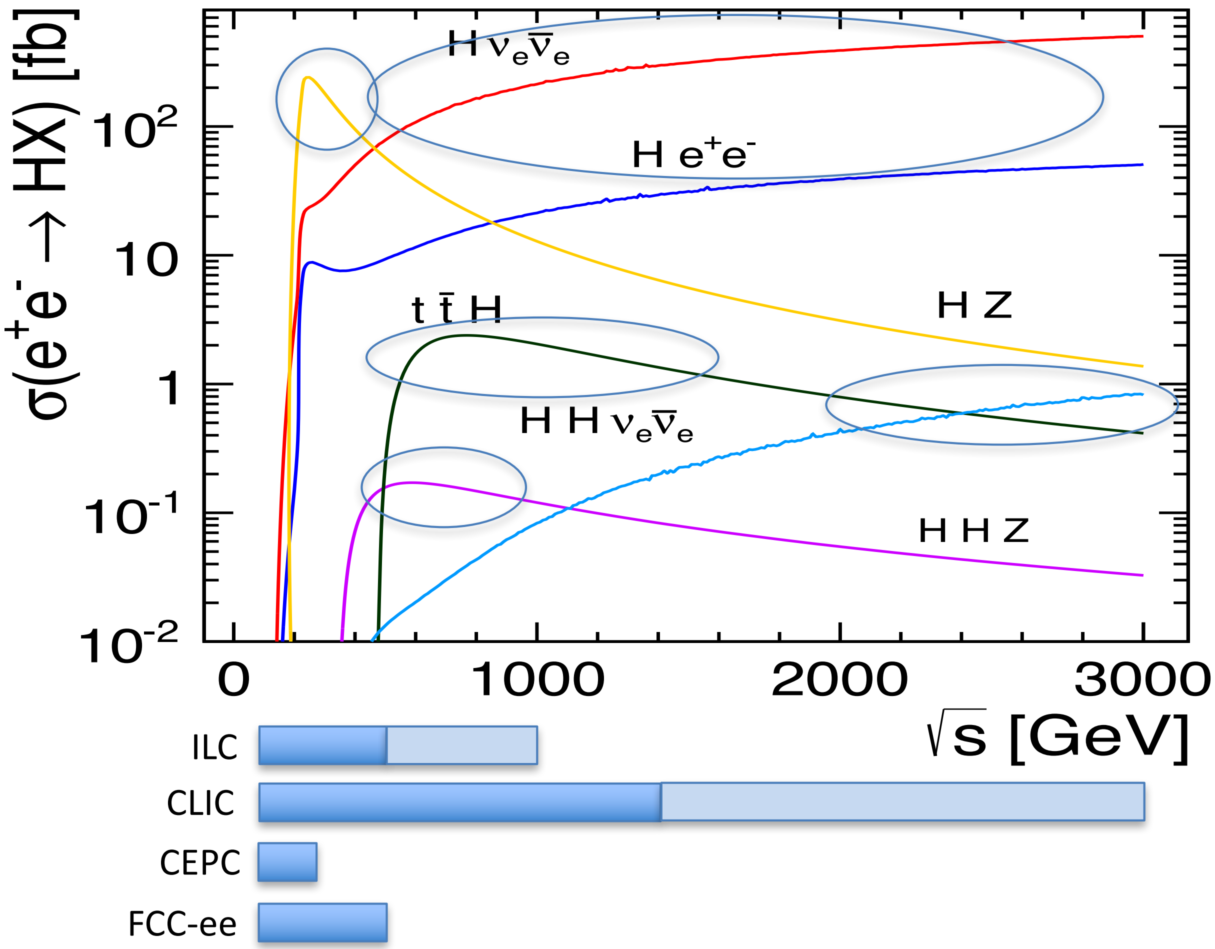
For $e^+e^-$ collisions (90-1000 GeV) there is a very strong physics case already now (i.e. without waiting for new LHC results):

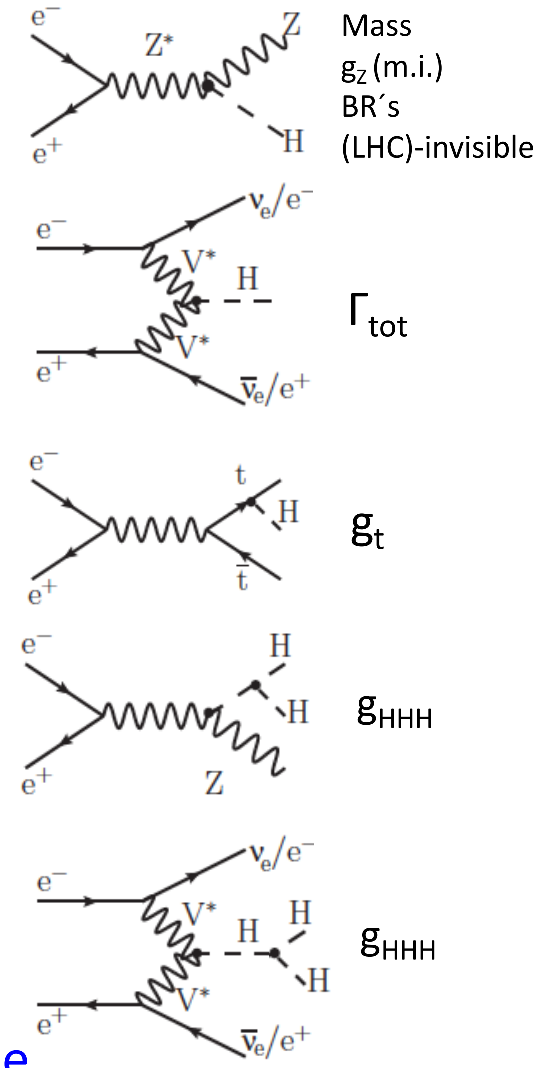
- Precision Higgs physics beyond LHC precision and quality
- Precision Top physics
- Precision EW measurements
- Complementary searches (where LHC is less/not sensitive)
- Polarized beams are a big asset!

→ This programme justifies timely implementation

→ ILC

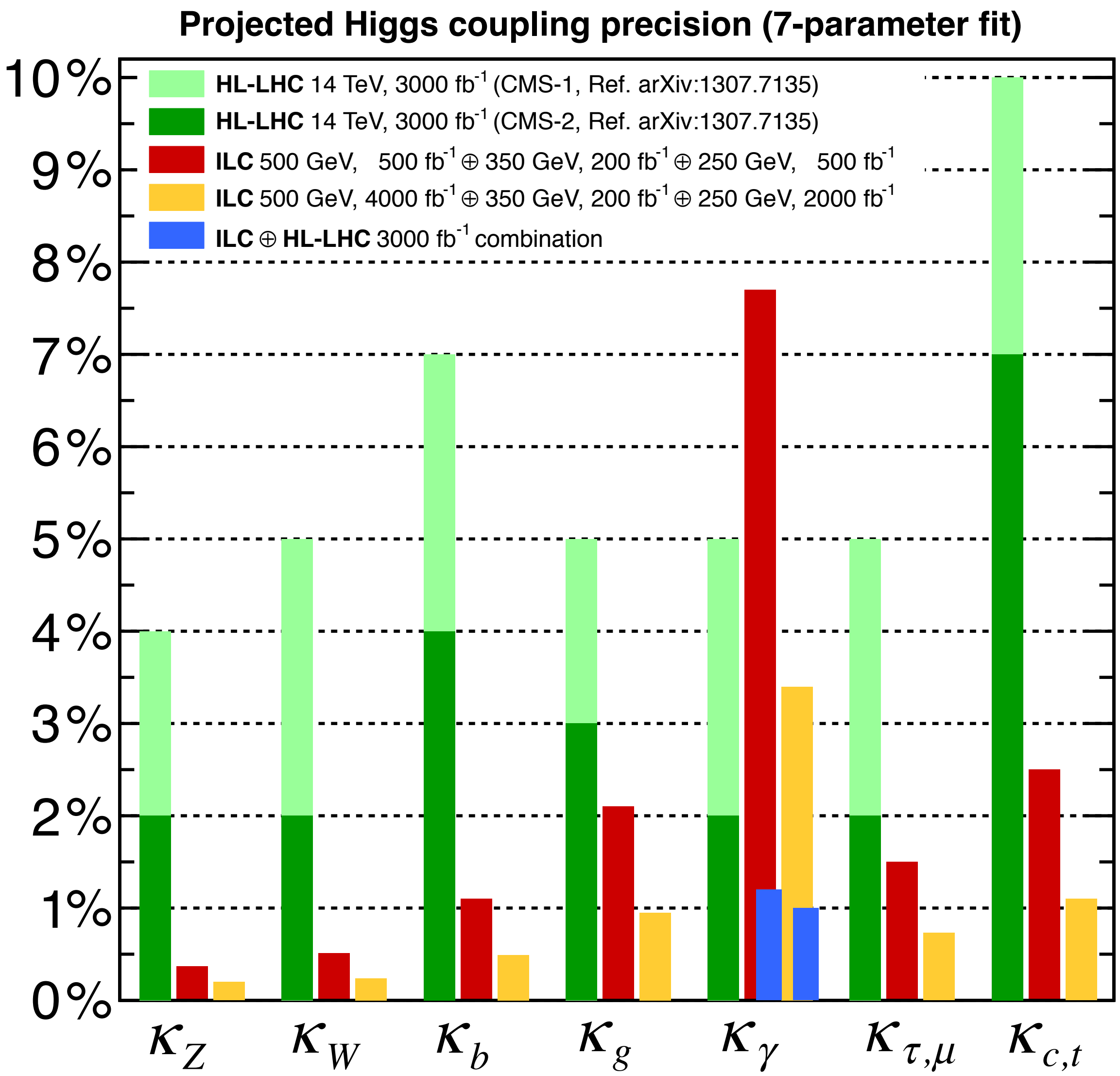
# $e^+e^-$ Higgs processes




- Many processes at different √s needed & accessible

# LHC vs ILC: model-dep. couplings (κ)



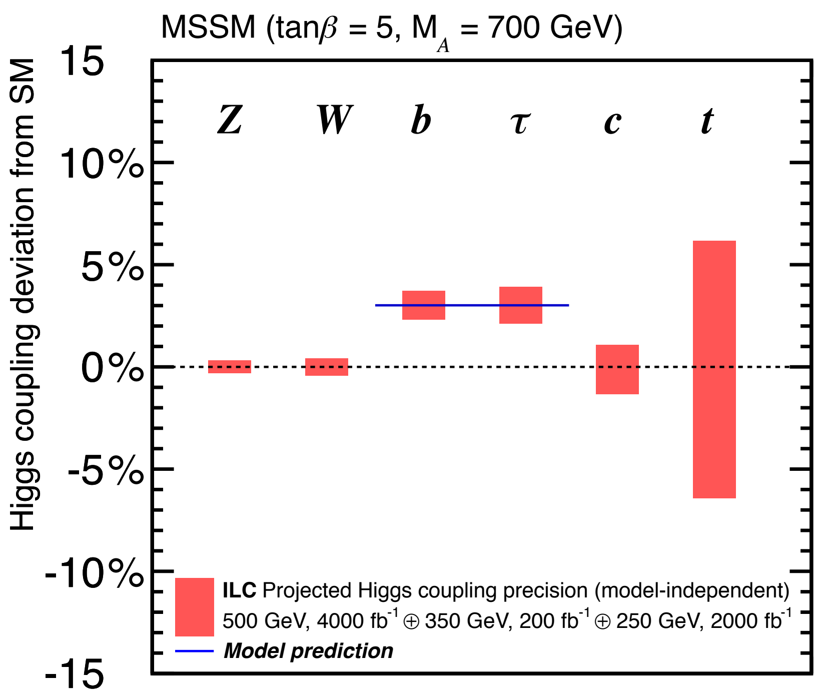

typically factor 5-10 improvement w.r.t. HL-LHC

important:
in $e^+e^-$, model-independent coupling can also be derived (not possible at hadron collider)

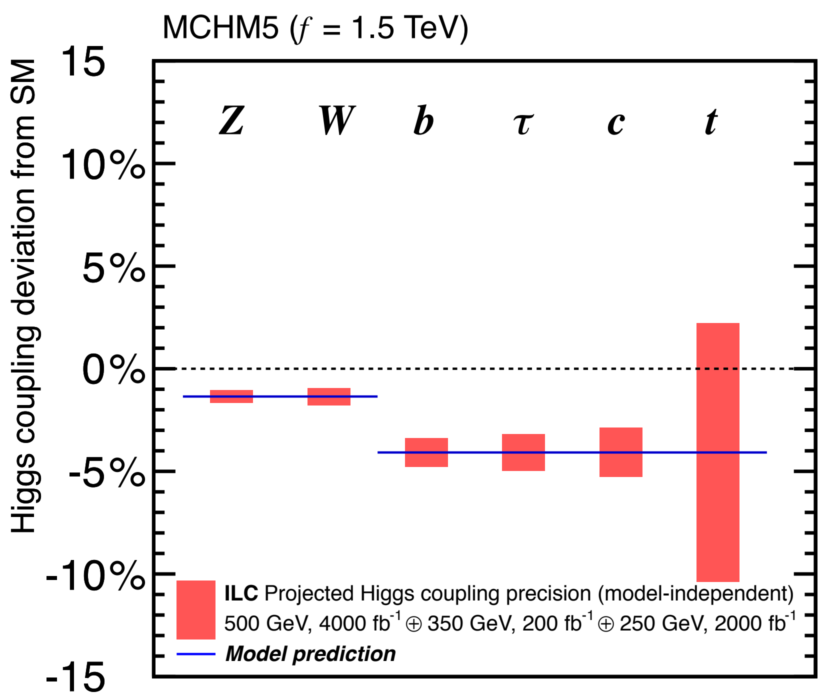
[LCC Physics Group arxiv:1506.05992]

# Impact of BSM on Higgs Sector

**Supersymmetry**
**(MSSM)**




**Composite Higgs**
**(MCHM5)**




ILC (or better) precision required to discriminate models

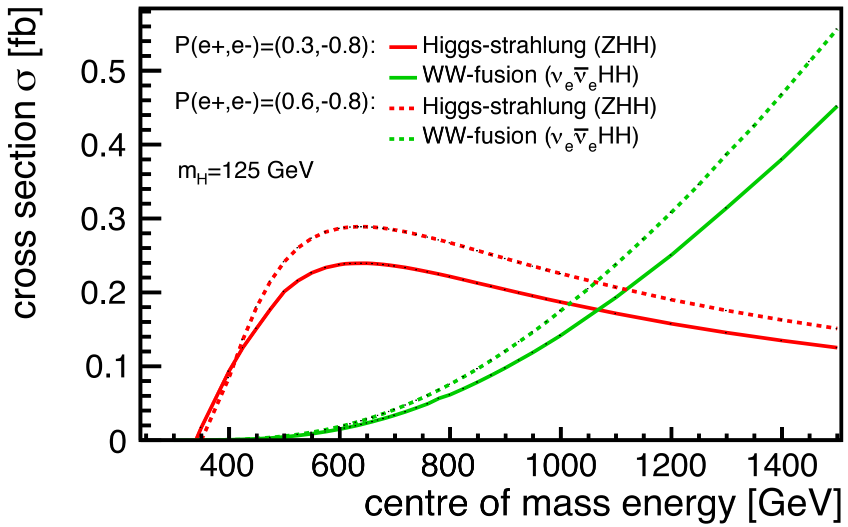
[LCC Physics Group]

# The Higgs self coupling

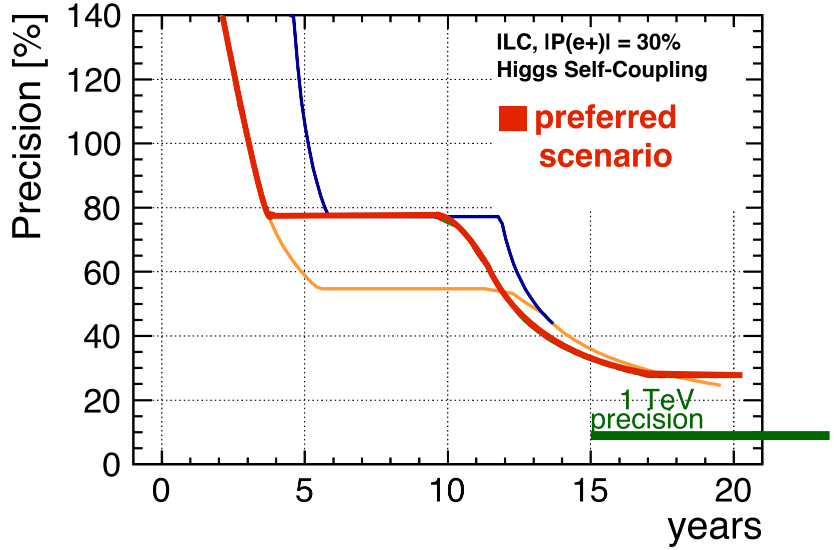
two choices:

$e^+e^- \rightarrow ZHH$
(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 $\lambda_{HHH}$ (can be mitigated by phase space weighting)

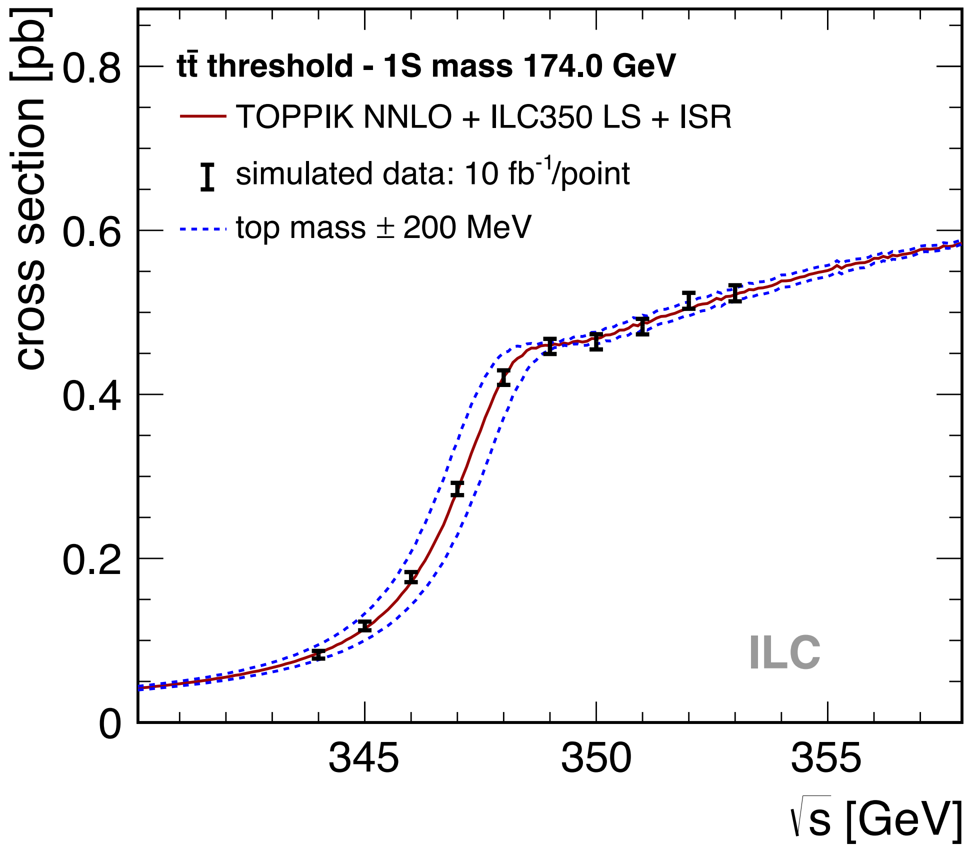



[Dürig, EPS 2015]

# Top Quark Mass

Top Quark mass from cross section at tt production threshold

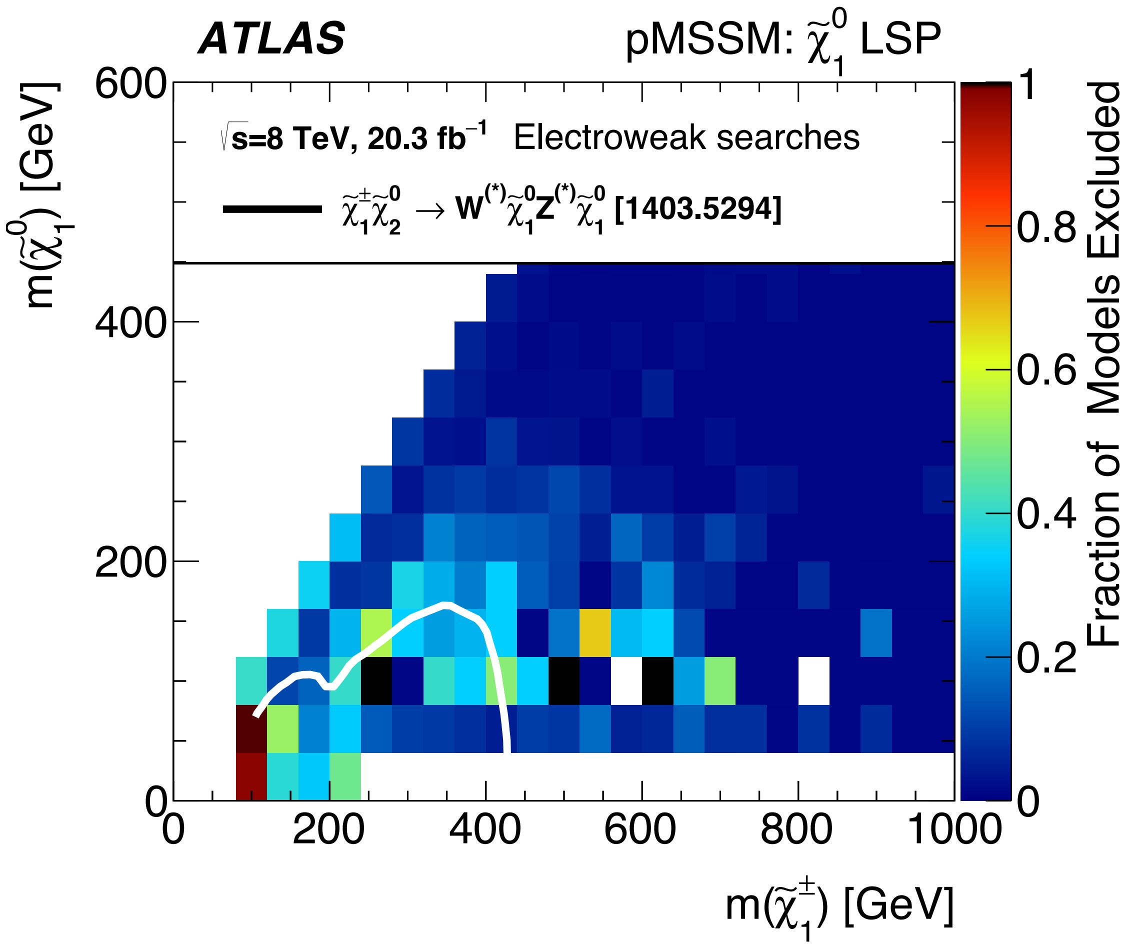
- theoretically well-defined, recent progress NNNLO, $y_t$ dependence
- – precision 50 MeV on $m_{t\ from}$ threshold scan




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

# Discovery at $e^+e^-$: there (still) is plenty of room for SUSY

ATLAS, pMSSM scan arxiv:1508.06608




(b) Chargino–neutralino

# $e^+e^-$ : CLIC

- Two-beam acceleration scheme
- Normal conducting cavities (power: 600 MW@3 TeV)

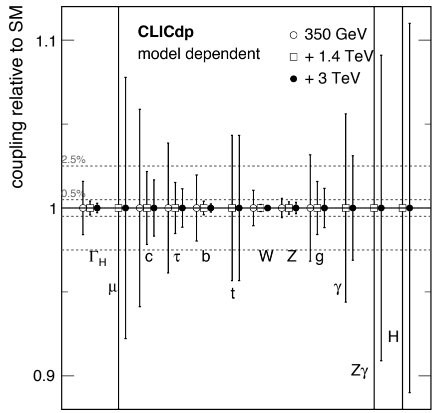
Significant R&D ongoing
Technical readiness in some years?

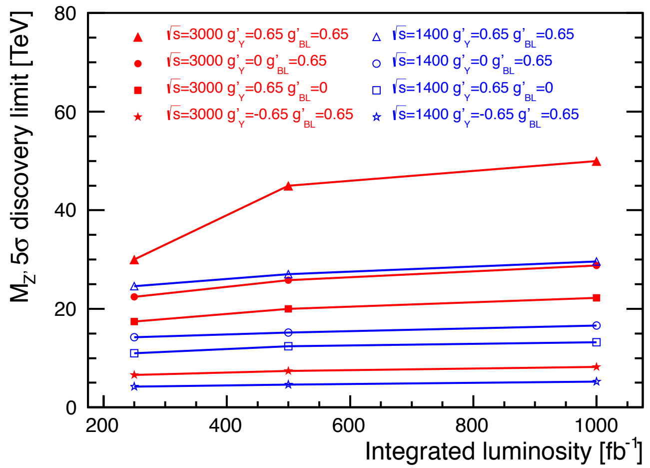
| **Parameter** | **Unit** | **380 GeV** | **3 TeV** |
|---|---|---|---|
| Centre-of-mass energy | TeV | 0.38 | 3 |
| Total luminosity | $10^{34}cm^{-2}s^{-1}$ | 1.5 | 5.9 |
| Luminosity above 99% of √s | $10^{34}cm^{-2}s^{-1}$ | 0.9 | 2.0 |

Physics:

380 GeV stage:
(late) alternative to ILC (if not built)

3 TeV stage:
energy frontier machine



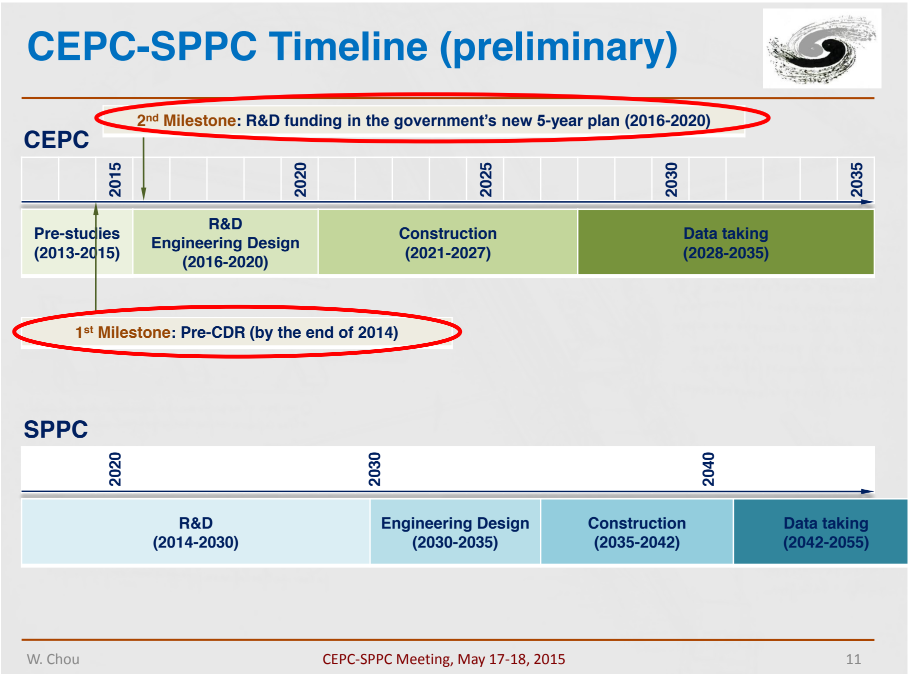



# $e^+e^-$ : CepC

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

- 54 km ring
- CepC: √s=240 GeV e+e- ; L=2x$10^{34}$; 2 IP
- possibly followed by SppC: √s = 70 TeV pp collider; L=1.2x$10^{35}$; 2 IP
- if more funding: 100 km ring and/or separate pipes for e+/e- beams)

pre-CDR published in 03/15

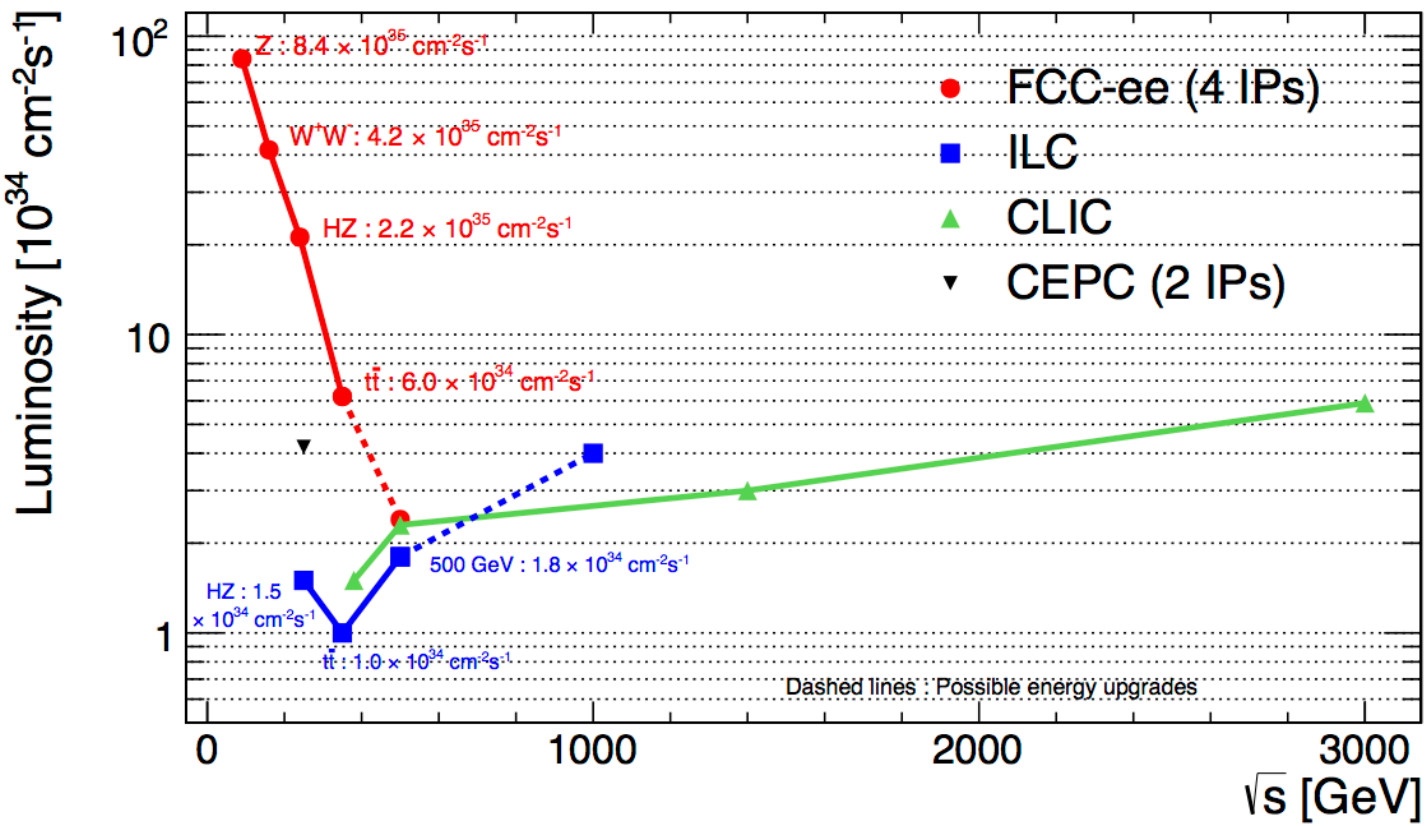



240 GeV energy reach
limits physics potential:

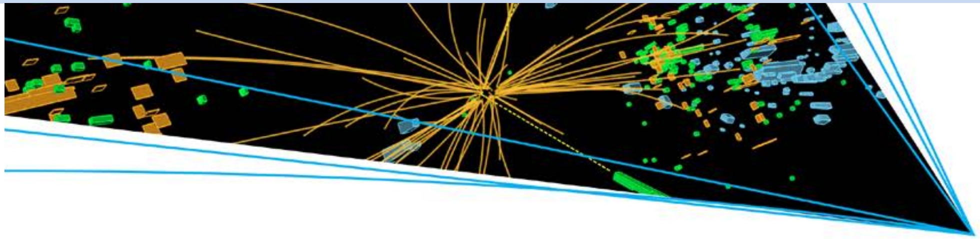
- mainly HZ programme
- no tth, HH,
- no ttbar
- almost no discovery potential for NP (only 30 GeV more than LEP2)

# $e^+e^-$ : FCC-ee

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



# e+e- Statement



KET
Komitee für Elementarteilchenphysik

Conclusions of the

## KET Workshop on Future $e^+e^-$ Colliders[a]

Max-Planck-Institut für Physik Munich, May 2-3, 2016

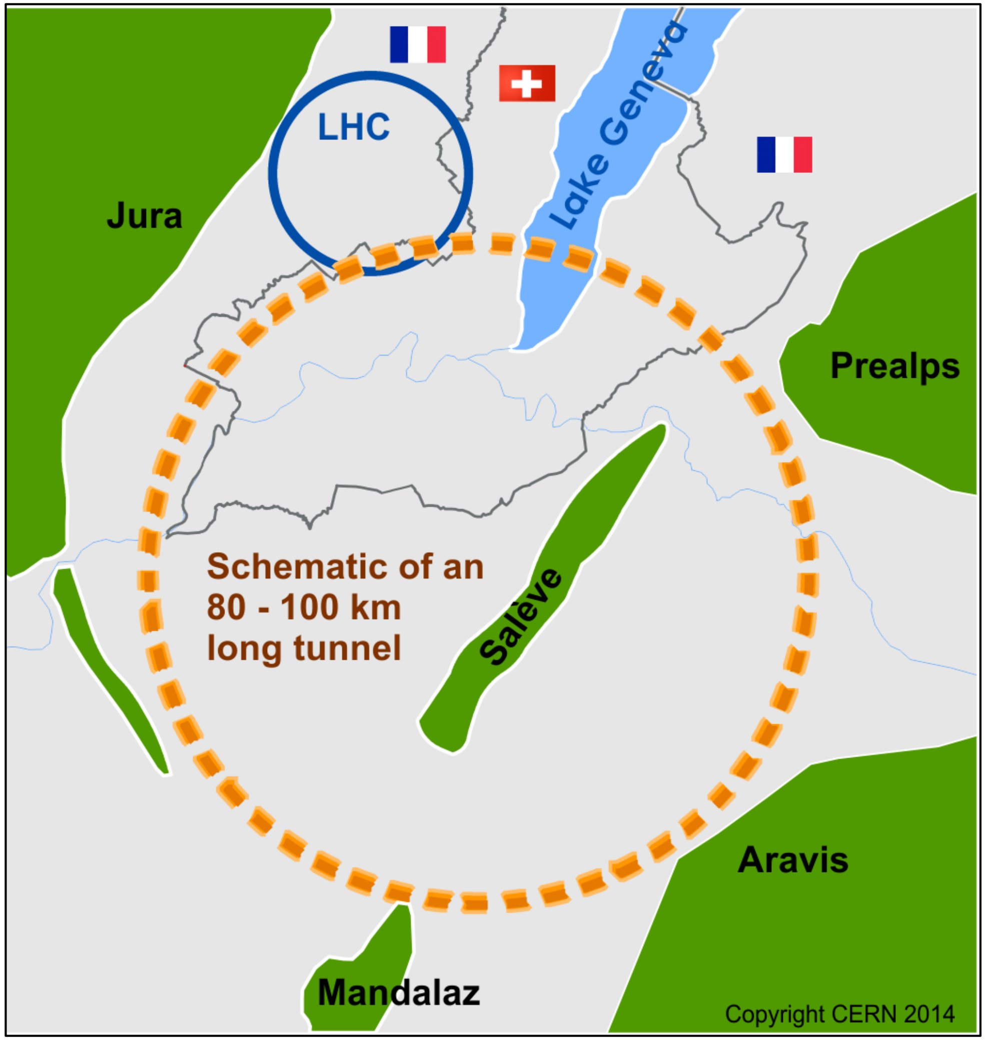
1. The physics case for a future $e^+e^-$ collider, covering energies from $M_Z$ up to the TeV regime, is regarded to be very strong, justifying (and in fact requiring) the timely construction and operation of such a machine.[i]

2. The ILC meets all the requirements discussed at this workshop.[ii] It is currently the only project in a mature technical state. Therefore this project, as proposed by the international community and discussed to be hosted in Japan, should be realised with urgency. As the result of this workshop, this project receives our strongest support.[iii]

3. FCC-ee, as a possible first stage of FCC-hh, and CEPC could well cover the low-energy part of the $e^+e^-$ physics case, and would thus be complementary to the ILC.[iv]

4. CLIC has the potential to reach significantly higher energies than the ILC. CLIC R&D should be continued until a decision on future CERN projects, based on further LHC results and in the context of the 2019/2020 European Strategy, will be made.

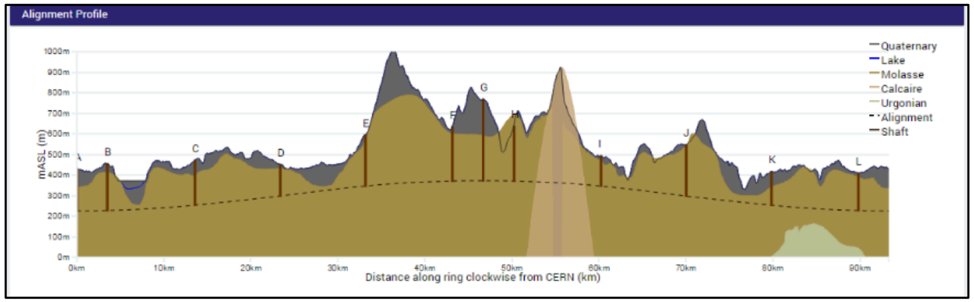
# Hadron Collider: FCC-hh



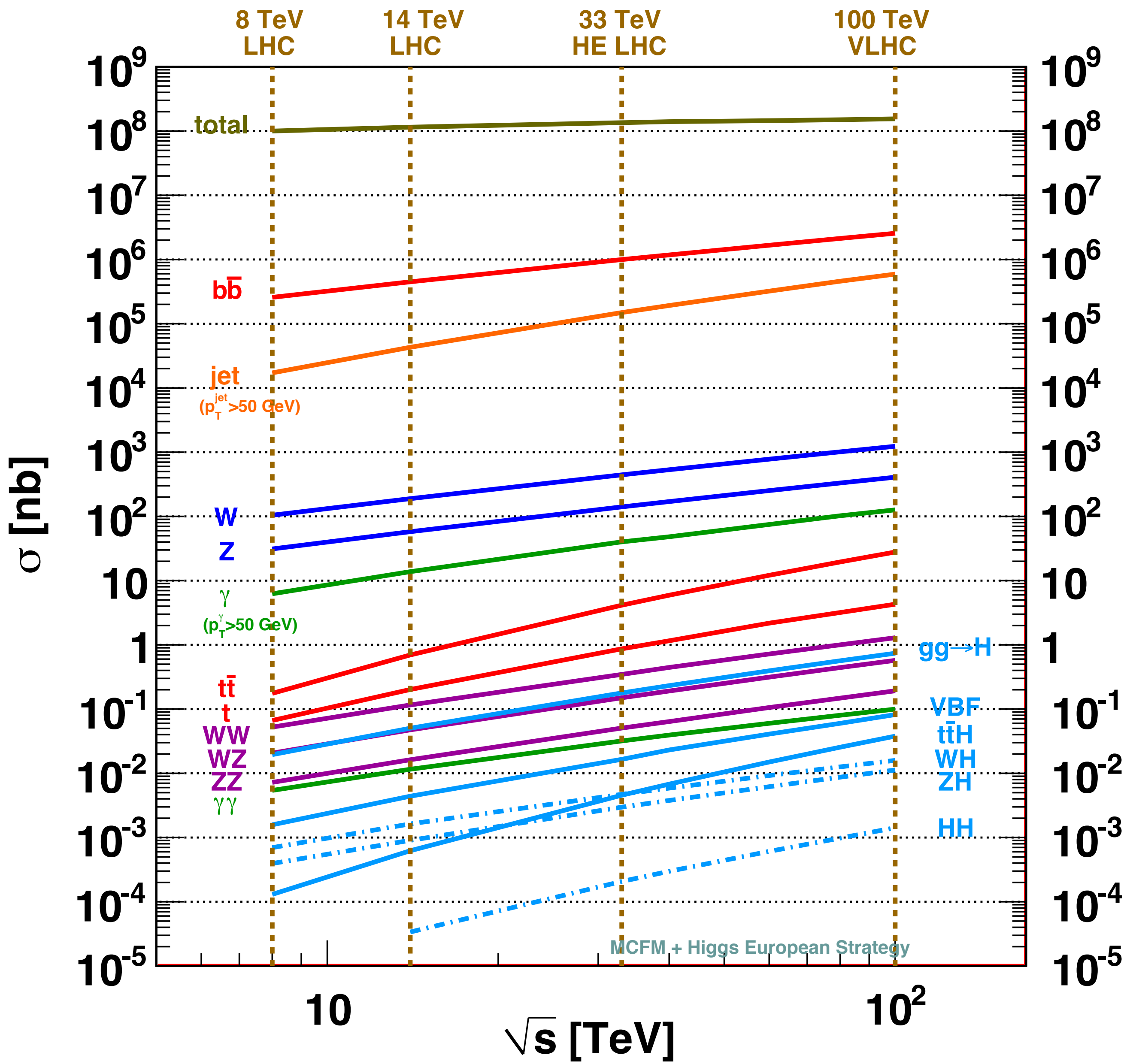

CERN launched international conceptual design study for 100 km ring in Geneva region

pp: √s = 100 TeV L=5-30x10$^{34}$ 2+2 IPs

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



# FCC-hh Cross Sections




New territory,
all we know:

SM cross sections
at 100 TeV

w.r.t. LHC:

W,Z x7
H x15
HH: x40

X (1 TeV) x$10^3$
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 rate 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?)

- THE UNKNOWN...

FCC week Berlin 29/05-02/0617

# Muon collider

- physics case for a muon collider at sqrt(s) is identical to the one at $e^+e^-$ at same energy and luminosity (but no beamstrahlung)

→ if it would be easier and/or more cost efficient to build an x TeV muon collider than x TeV $e^+e^-$ machine we should do it 😀

- add-on of muon collider: s-channel Higgs production
- → measure decay width directly
  (KD: this add-on might be a bit over-stated, indirect methods in $e^+e^-$ work well)

# Electron proton collider (LHeC)

## The LHeC Physics Programme

arXiv:1206.2913 (CDR) 1211.4831 and 5102

| | |
|---|---|
| QCD Discoveries<br>Higgs<br>Substructure<br>New and BSM Physics<br>Top Quark | $\alpha_s < 0.12$, $q_{sea} \neq \bar{q}$, instanton, odderon, low $x$: (n0) saturation, $\overline{u} \neq \overline{d}$<br>$WW$ and $ZZ$ production, $H \rightarrow b\bar{b}$, $H \rightarrow 4l$, CP eigenstate<br>electromagnetic quark radius, $e^*$, $\nu^*$, $W$?, $Z$?, top?, $H$?<br>leptoquarks, RPV SUSY, Higgs CP, contact interactions, GUT through $\alpha_s$<br>top PDF, $xt = x\bar{t}$?, single top in DIS, anomalous top |
| Relations to LHC | SUSY, high $x$ partons and high mass SUSY, Higgs, LQs, QCD, precision PDFs |
| Gluon Distribution<br>Precision DIS | saturation, $x \approx 1$, $J/\psi$, $\Upsilon$, Pomeron, local spots?, $F_L$, $F_2^c$<br>$\delta\alpha_s \simeq 0.1\,\%$, $\delta M_c \simeq 3\,\mathrm{MeV}$, $v_{u,d}$, $a_{u,d}$ to $2-3\,\%$, $\sin^2\Theta(\mu)$, $F_L$, $F_2^b$ |
| Parton Structure<br>Quark Distributions<br>QCD | Proton, Deuteron, Neutron, Ions, Photon<br>valence $10^{-4} \lesssim x \lesssim 1$, light sea, $d/u$, $s = \overline{s}$?, charm, beauty, top<br>N$^3$LO, factorisation, resummation, emission, AdS/CFT, BFKL evolution |
| Deuteron<br>Heavy Ions<br>Modified Partons | singlet evolution, light sea, hidden colour, neutron, diffraction-shadowing<br>initial QGP, nPDFs, hadronization inside media, black limit, saturation<br>PDFs "independent" of fits, unintegrated, generalised, photonic, diffractive |
| HERA continuation | $F_L$, $xF_3$, $F_2^{\gamma Z}$, high $x$ partons, $\alpha_s$, nuclear structure, .. |

Ultra high precision (detector, e-h redundancy) - new insight
Maximum luminosity and much extended range - rare, new effects
Deep relation to (HL-) LHC (precision+range) - complementarity

[M.Klein,Nov16]

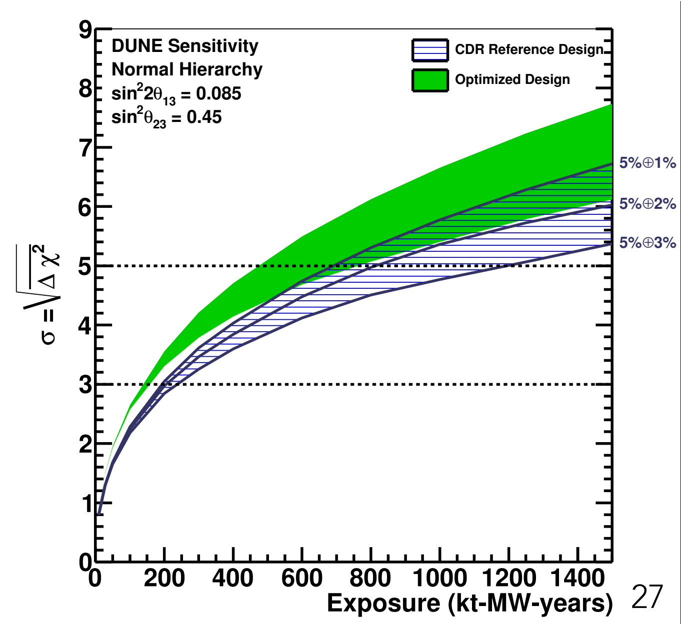
# Beyond colliders: Neutrino beams

Recent progress in neutrino physics was mainly driven by natural neutrinos sources + reactors but accelerators catching up (T2K, MINOS, NO$\nu$A)

Next steps (hierarchy, CP phase) likely need high-intensity neutrinos beams from accelerators (but competition from reactors/atm. on hierarchy)

CENF: CERN Neutrino facility → enable EU groups to participate (detectors)

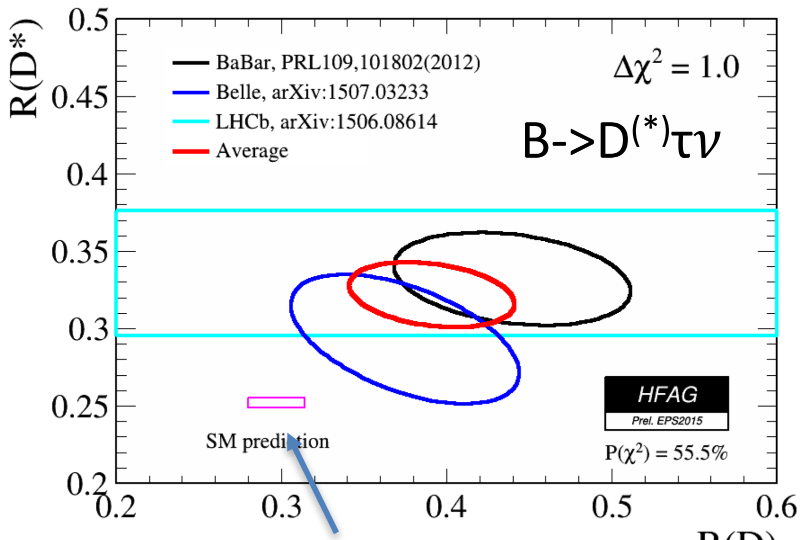
Projects:
US: DUNE (L=1300km, 2.3 MW, 40 kt LAr detector)
JP: T2HK (L=295 km, 1.3 MW, 500 kt $H_2O$-Č detector)



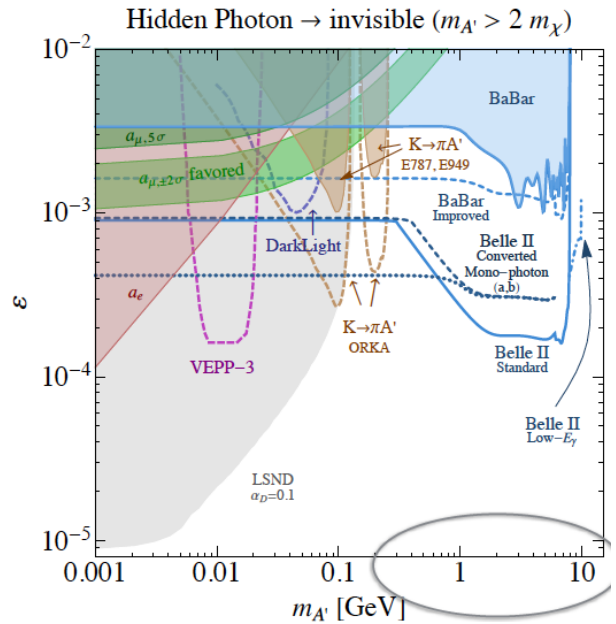

So far, limited engagement on accelerator-based neutrinos in Germany
→ KET workshop next week

# SuperKEKB – Belle II

B-factories: $e^+e^-$ collider at √s = m(Υ(4S)) = 10.6 GeV, asymmetric beams
Complementary to B-physics with LHCb (+CMS, ATLAS)
Ultimate luminosity $8 \times 10^{35}$ $cm^{-2}s^{-1}$, 50 $ab^{-1}$
Study (also) hadronic final states
Ultra-rare dacays ($<10^{-9}$) → BSM sensitvity in loops, CPV, (heavy) hadron physics
Examples:




= Belle II sens. with 50 $ab^{-1}$




Strong German involvement in Belle II

# Beyond colliders: dedicated low-E machines

Fixed target / high intensities:

Physics of "small couplings" – no law of nature that $\alpha_{em}$ is the smallest coupling in nature → look for new light fundamental particles (dark photons, heavy leptons, …)     (e.g. SHIP proposal)

Muons (PSI, Japan, Fermilab)

- Look for Lepton Flavour Violation in muon decays/$\mu \rightarrow e$ conversion
- $(g\text{-}2)_\mu$

Antiprotons (CPT tests etc.)

proton EDM

note: also non-accelerator particle physics experiments (WIMPs, Axions, ...)

# Saturation of Livingston Plot

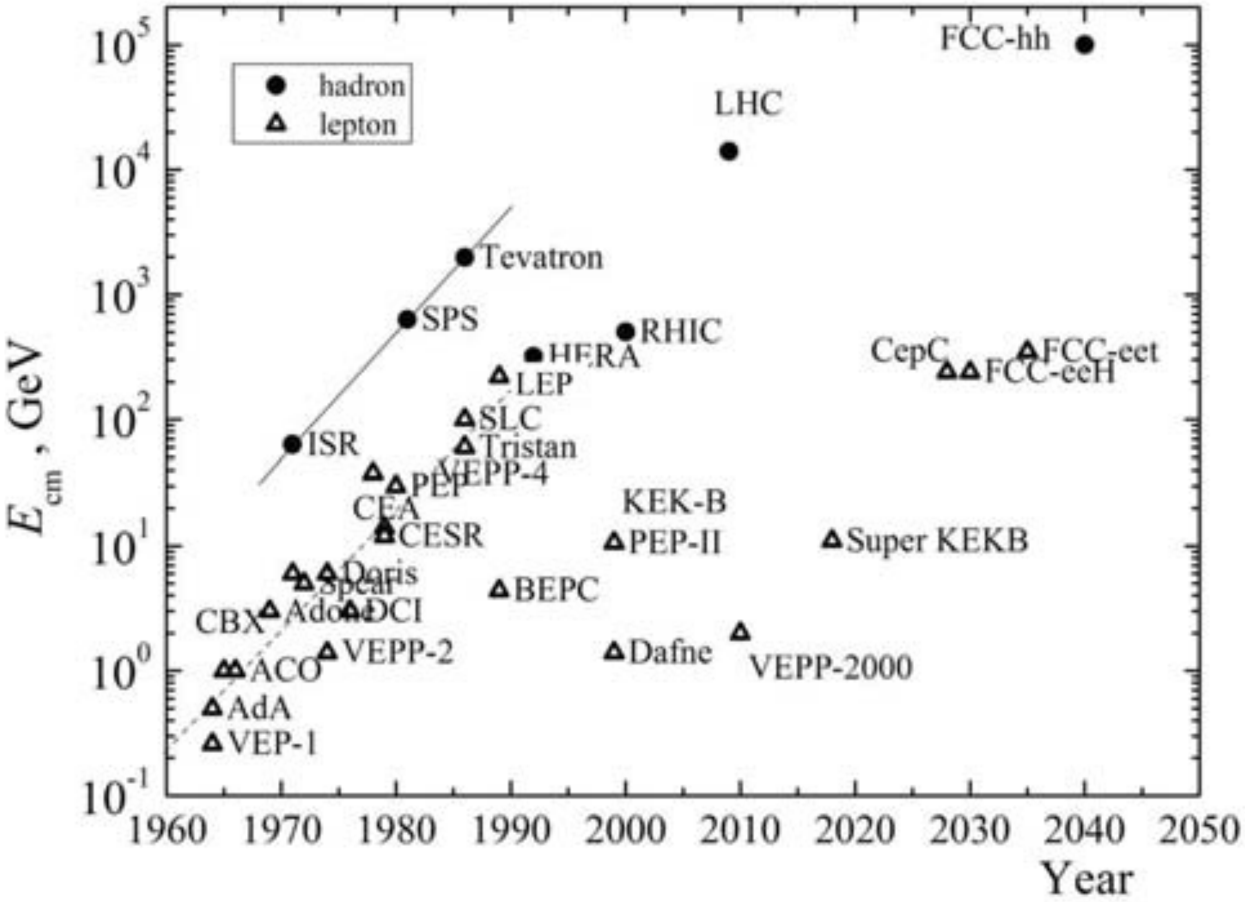



Figure 2: Collider energy vs. year [10] [V. Shiltsev].

[M. Benedikt, IPAC14]

# Beating scaling laws

Need to beat E ~ length (limited by B for circular hadron colliders
limited by SR for circular $e^+e^-$
limited $V_{acc}$/m for linear accelerators)

Need to beat E ~ $$$ (limited by public acceptance)

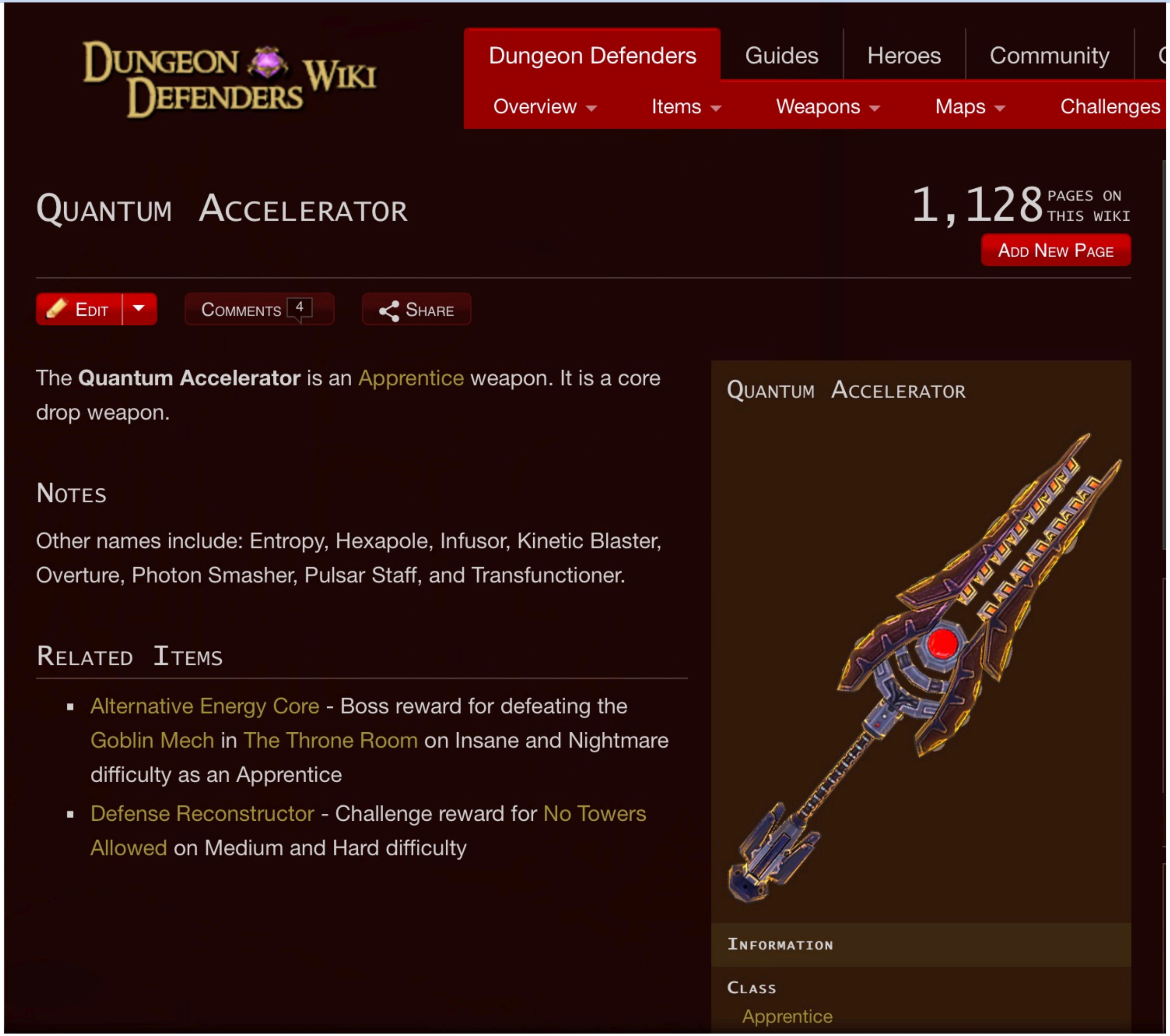
Need to beat $\int \mathcal{L} dt$ ~ GWy (running cost becomes a limiting factor)

Any R&D addressing these challenges is worth the effort!
We (particle physicists) strongly support such R&D!

- high-field low-power (SC) cavities
- high-field magnets
- plasma wakefield acceleration
- …

be courageous!

# Vision or non-sense?



# Conclusions

- Particle physics relies and will rely on high-energy accelerators
- Mid-term: 1-2 more big machines worldwide (ILC@JP, postLHC@CERN, China??)
  - many side-effects, spin-offs (SCRF, high-field magnets, ...)
- The (long-term) future has to start now – particle physics supports R&D towards fundamentally new and/or cost-saving technologies
- Exploit synergies with other fields (light sources, NP facilities, medical + mat. science applications, ...)
- The physics case for „particle physics“ will remain fascinating for us and for society → technological driver for accelerator physics