Physics at Future Colliders

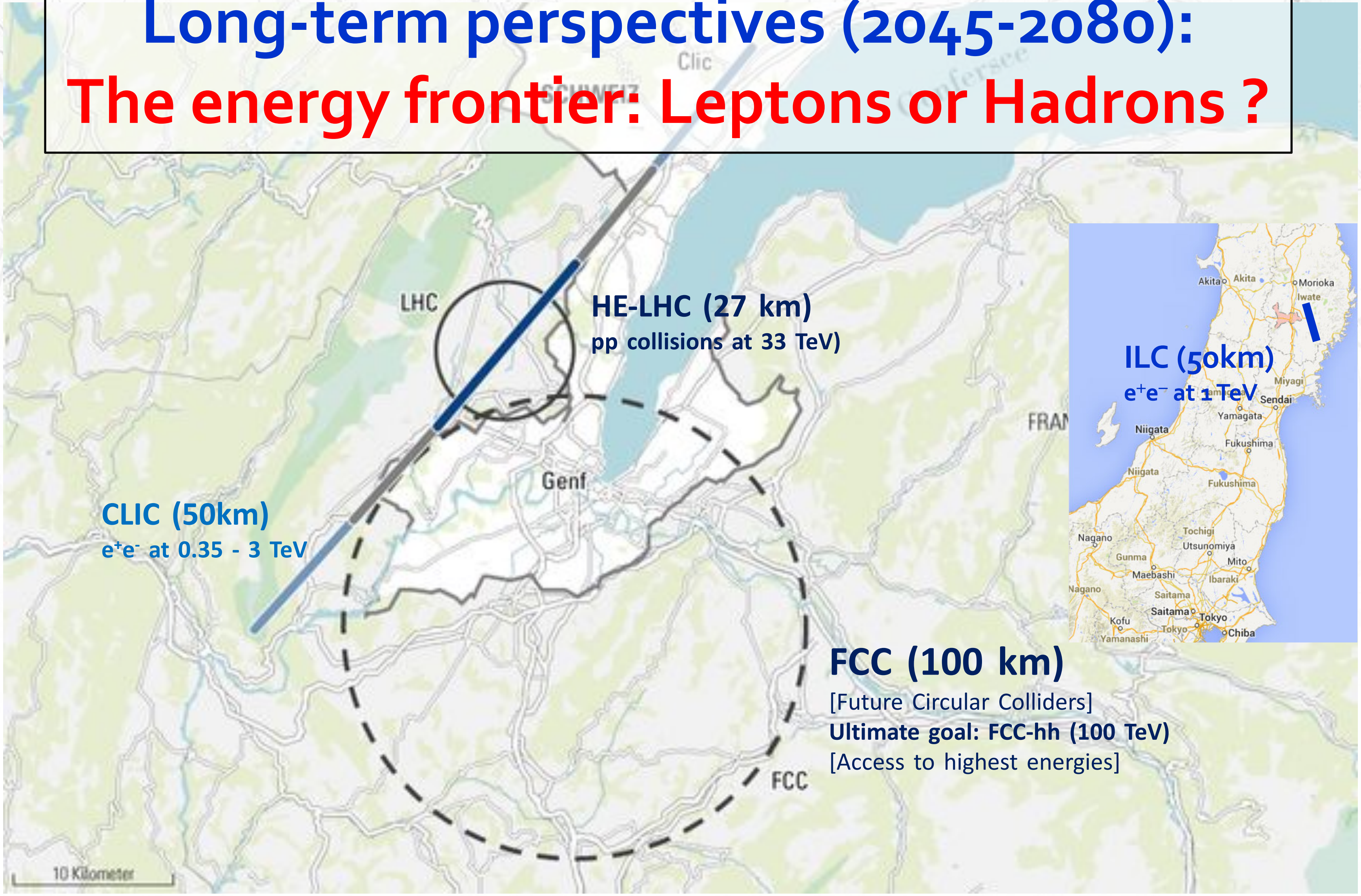
- **Lecture 1 (Wednesday 2 August, 10:25)**
  - ☐ An historical perspective (1964-2017): The need for precision and energy
  - ☐ A strategy for the future: Towards the precision and energy frontier
  - ☐ The short-term perspectives (2020-2035): The HL-LHC

- **Lecture 2 (Thursday 3 August, 10:25)**
  - ☐ The quest for precision (2030-2050): Linear or circular?

- **Lecture 3 (Thursday 3 August, 11:35)**
  - ☐ The energy frontier (2045-2080): Leptons or hadrons?
  - ☐ Thinking out of the box: Muon collider
  - ☐ Towards the next European Strategy update (2019-2020)

Lecture 3 (1st part)

Long-term perspectives (2045-2080): The energy frontier: Leptons or Hadrons ?



HE-LHC (27 km)
pp collisions at 33 TeV)

ILC (50km)
e^+e^- at 1 TeV

CLIC (50km)
e^+e^- at 0.35 - 3 TeV

FCC (100 km)
[Future Circular Colliders]
Ultimate goal: FCC-hh (100 TeV)
[Access to highest energies]

Reminder: The big questions (1)

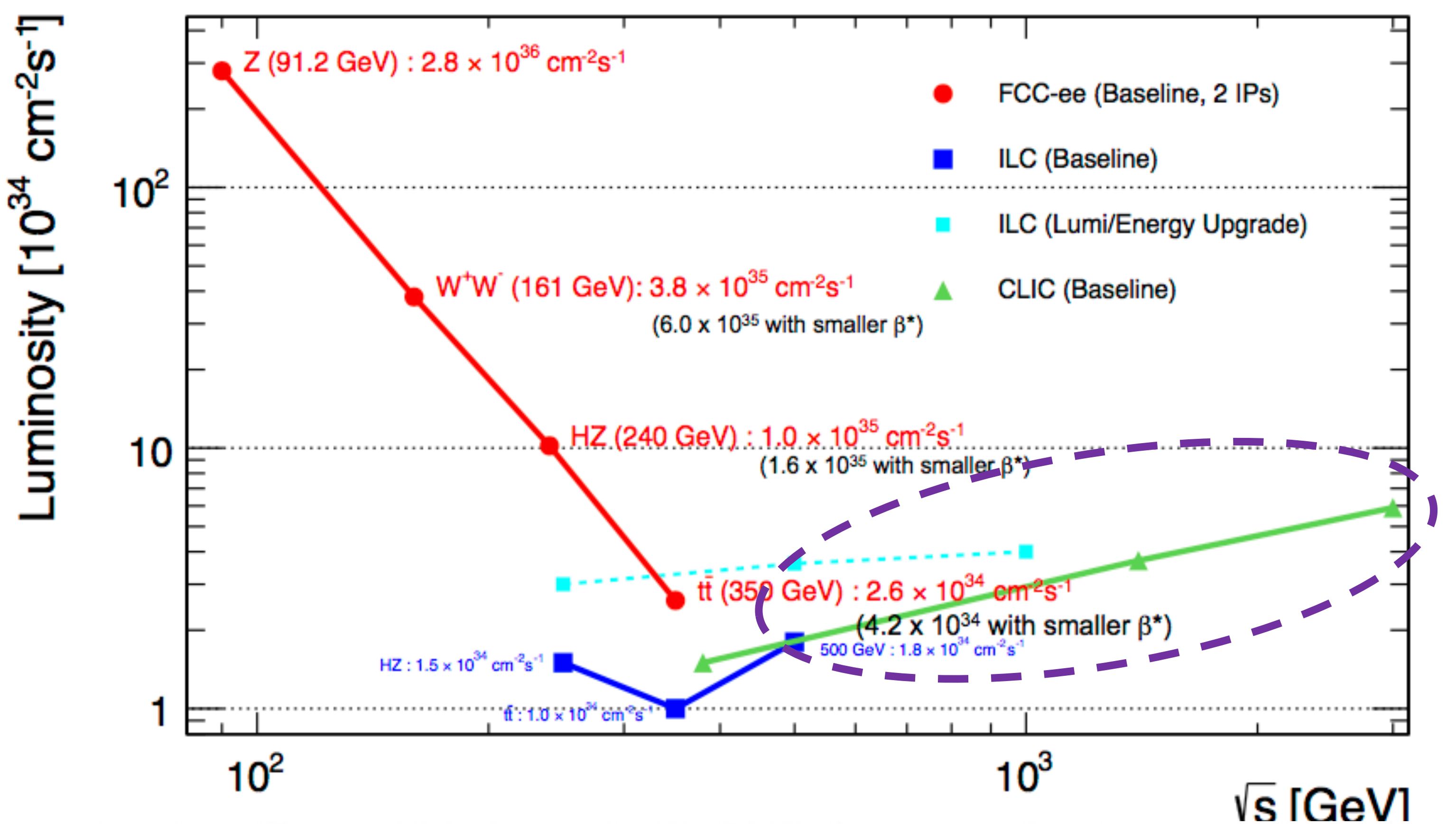
- The days of “guaranteed discoveries” are over …
  - … but the fundamental questions remain :
    - Why three generations and why the observed masses ?
    - What’s the origin of dark matter ?
    - What’s the origin of baryon asymmetry in the Universe ?
    - What’s the origin of the neutrino masses ? Why are they so light ?
    - What’s the origin of electroweak symmetry breaking ?
    - What’s the solution to the hierarchy problem ?
- The future of HEP will be mostly driven by experimental exploration
  - Rather than by deeply-rooted theoretical motivations

Reminder: The big questions (2)

- Key issue after LHC Run1 (and, hopefully not, but possibly after Run2)
  - Why don't we see new physics ?
    - Is the new physics mass scale beyond the LHC reach ?
    - Is the mass scale within LHC reach, but final states are elusive ?
      - Swamped by large backgrounds ?
      - Very weak couplings ? Very rare decays ?
      - …
  - These two scenarios are a priori equally likely
    - Future colliders must be ready to address both, with
      - Precision for indirect hints at new physics (see also Lecture 2)
      - Sensitivity to elusive signatures (see also Lecture 2)
      - Extended energy / mass reach for direct discovery (today)

Precision requires statistics (1)

- Reminder: Luminosity targets of e^+e^- colliders at high energy



  - Luminosity targets for CLIC at 1.4 and 3 TeV: ~2 ab^{-1}
  - Design of ILC kept compatible with a later energy upgrade to 1 TeV
    - Luminosity target for ILC at 1 TeV: ~2 ab^{-1}

Precision requires statistics (2)

- **Preliminary parameters for FCC-hh**
  - Compared to LHC and HL-LHC

Parameter	LHC	HL-LHC	FCC-hh
$\sqrt{s}$ (TeV)	14		**100**
Circumference (km)	26.7		**100 (80)**
Dipole field (T)	8.3		**16 (20)**
Luminosity (10^{34} cm^{-2}s^{-1})	1	5	5 [→ **30**]
Integrated Lumi (ab^{-1})	0.3	3	3 [→ **30**]
Bunch spacing (ns)	25		25 {**5**}
Events / bunch crossing	35	140	170 {34} [→ **1020** {**204**}]
Total SR Power (MW)	0.007	0.015	**5** [→ **30**]

- **Ultimate luminosity target: 30 ab^{-1} at $\sqrt{s}$ = 100 TeV**
- **Cross sections increase significantly from $\sqrt{s}$ = 14 TeV to $\sqrt{s}$ = 100 TeV**
  - **In general, statistical precision will not be an issue at FCC-hh**

Precision: Higgs properties at high energy (1)

- Why would we continue to do precision Higgs physics at high √s?
  - Precision achieved with e^+e^- colliders at √s=240-350 GeV : 0.1% - 1%
    - Superior to what can be done at higher energy
      - σ_{HZ} decreases, kinematics less favourable, backgrounds increase, …
    - Superior to what can be done at pp colliders
      - HL-LHC will already be limited by systematic uncertainties

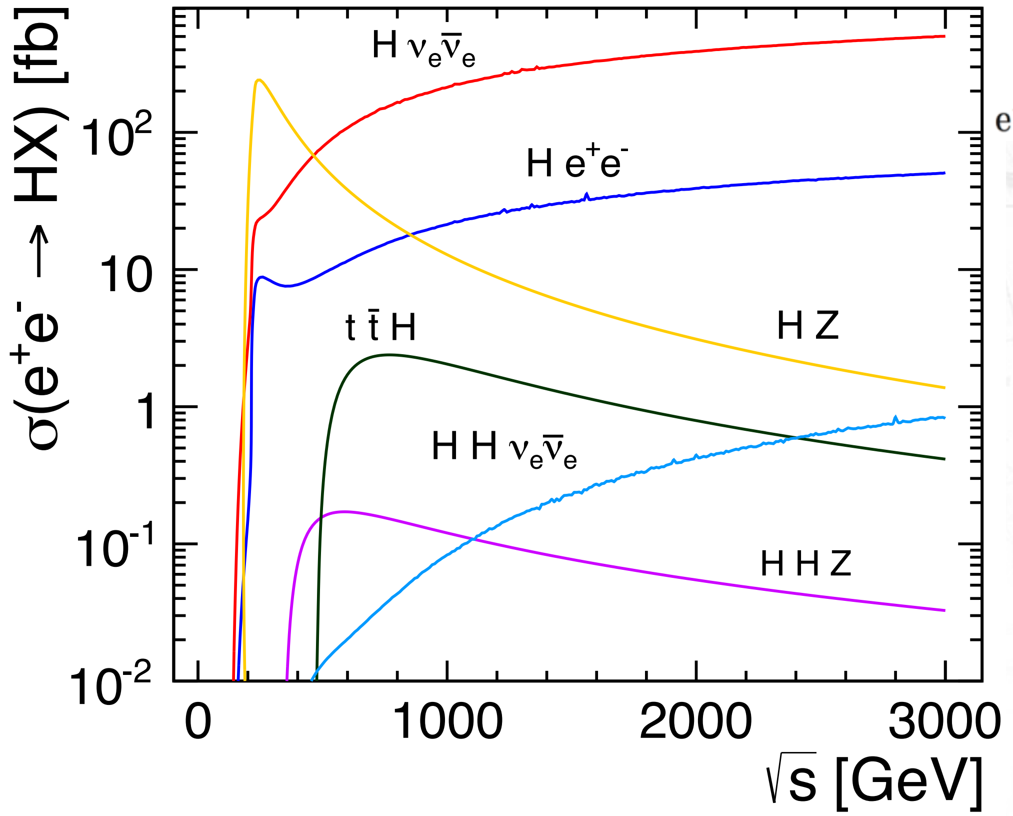
- However …
  - Some production processes are not directly accessible at low-energy e^+e^- colliders
    - Hence more couplings might become measurable at larger energy
      - e.g., Htt, HHH, HHHH, …

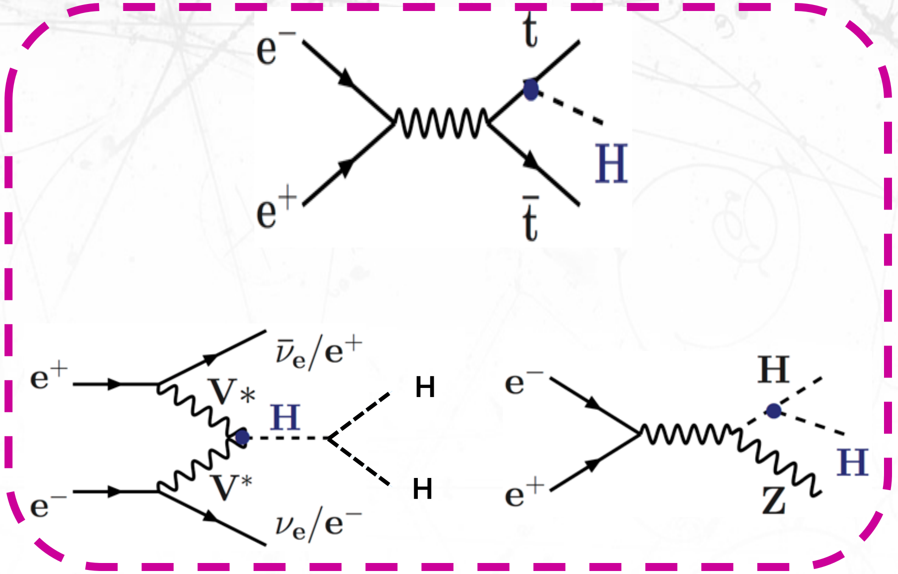
  - Some decay channels have very small branching fractions
    - Hence need more than 2×10^6 Higgs bosons to be measured with precision
      - e.g., $H \rightarrow \mu\mu, \gamma Z$, …

  - Systematic uncertainties at FCC-hh can be reduced by using ratios
    - Normalized to the precise measurements made in e^+e^- collisions

Precision: Higgs properties at high energy (2)

- Production in e^+e^- collisions

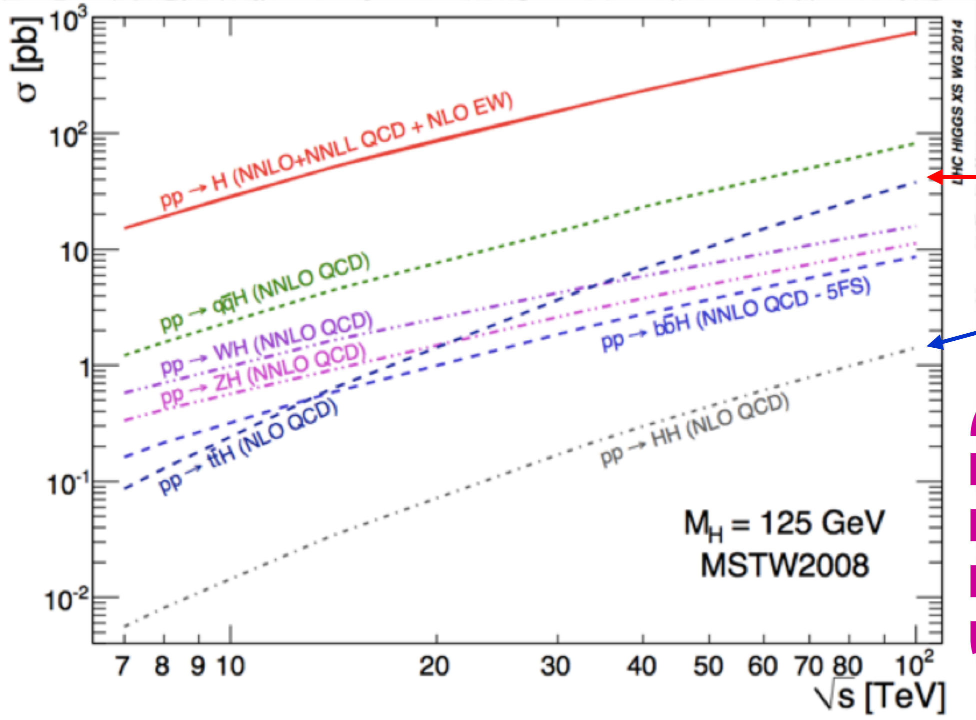




- Access to direct ttH coupling and Higgs self coupling measurements
  - Luminosity (at and) above 500 GeV essential for ttH
  - Larger energies essential for HHH

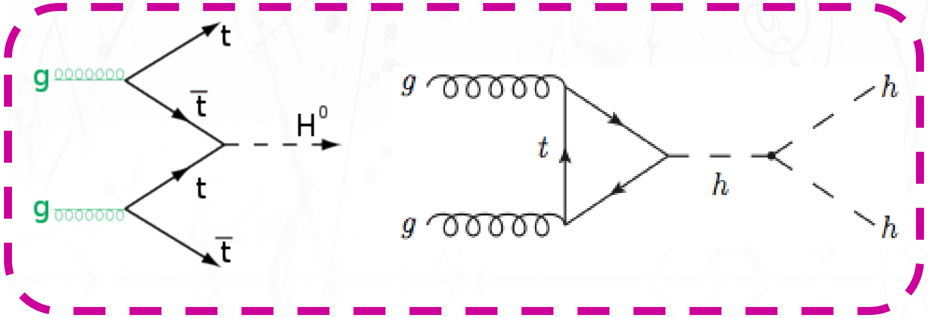
Precision: Higgs properties at high energy (3)

- **Production in pp collisions**



Large cross-section increase with √s

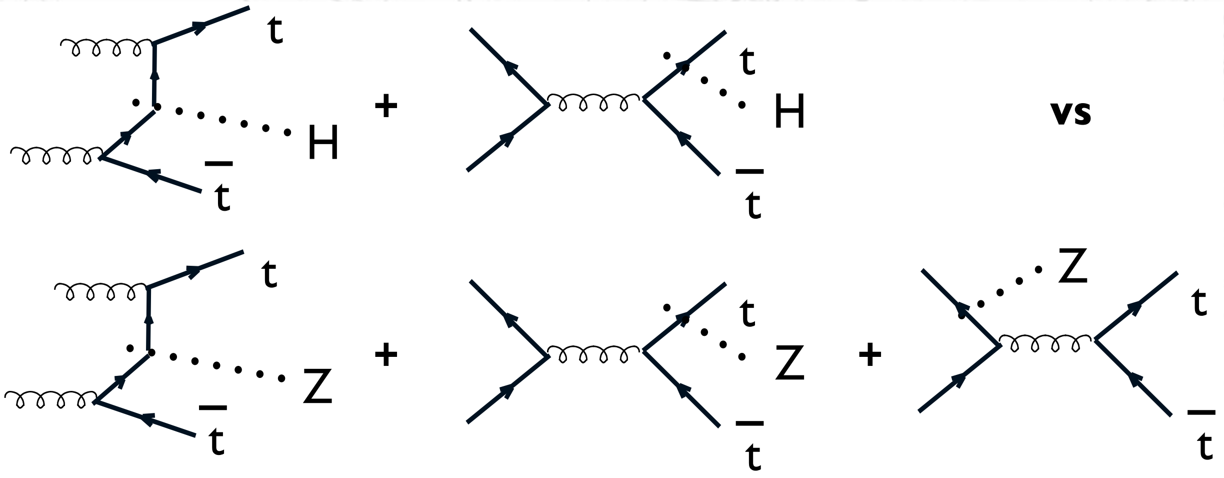
Process	14 TeV	33 TeV	100 TeV
gg → ttH	0.62 pb	4.5 pb × 7.3	37.8 pb × 61
gg → HH	33.8 fb	206 fb × 6.1	1.41 pb × 42



- **With 30 ab^{-1} at FCC-hh**
  - 2.5×10^{10} Higgs events in total; viz. 5×10^6 pp → H → μμ
  - 10^9 pp → ttH events, 5×10^7 pp → HH events
    - Statistical precision won't be much of a problem, even after selection

Precision: Higgs properties at high energy (4)

- **Example: ttH coupling @ FCC-hh**
  - ❑ **Measurement of λ_t with σ(ttH) / σ(ttZ), with H → ZZ, WW, ττ → leptons (+H → bb, γγ)**
    - ❖ **Very similar production mechanism, gg production dominant**



$$\frac{\sigma(ttH)}{\sigma(ttZ)} \approx \frac{\lambda_t^2}{\left(g_L^{ttZ}\right)^2 + \left(g_R^{ttZ}\right)^2}$$

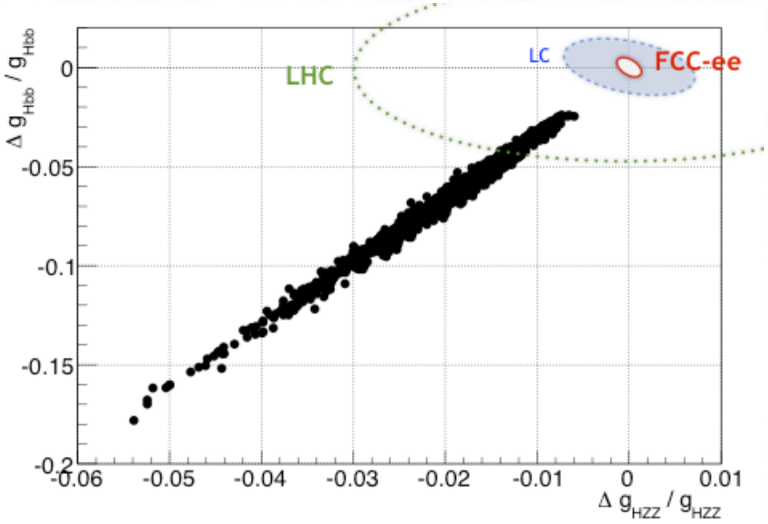
- ❖ **Most theory uncertainties cancel: < 1% precision possible on σ(ttH) / σ(ttZ)**
  - ▪ **Denominator given by FCC-ee with a precision of 1.5%**
  - ▪ **Higgs boson BR's given by FCC-ee with a precision of a few 0.1%**

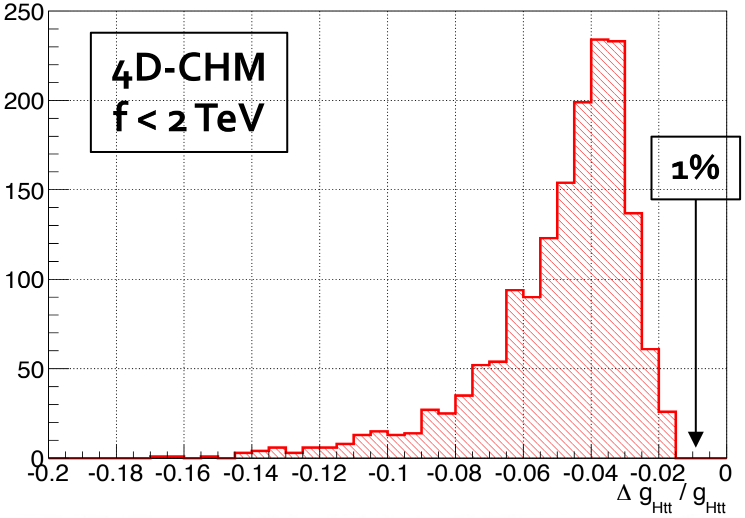
Precision: Higgs properties at high energy (5)

- **Achievable precisions**

Collider	HL-LHC	LC	LC 1-3 TeV	FCC-ee+hh
λ_t	4%	14%	2-4%	**<1%**
λ_H	50%	83%	10-15%	**5-10%**

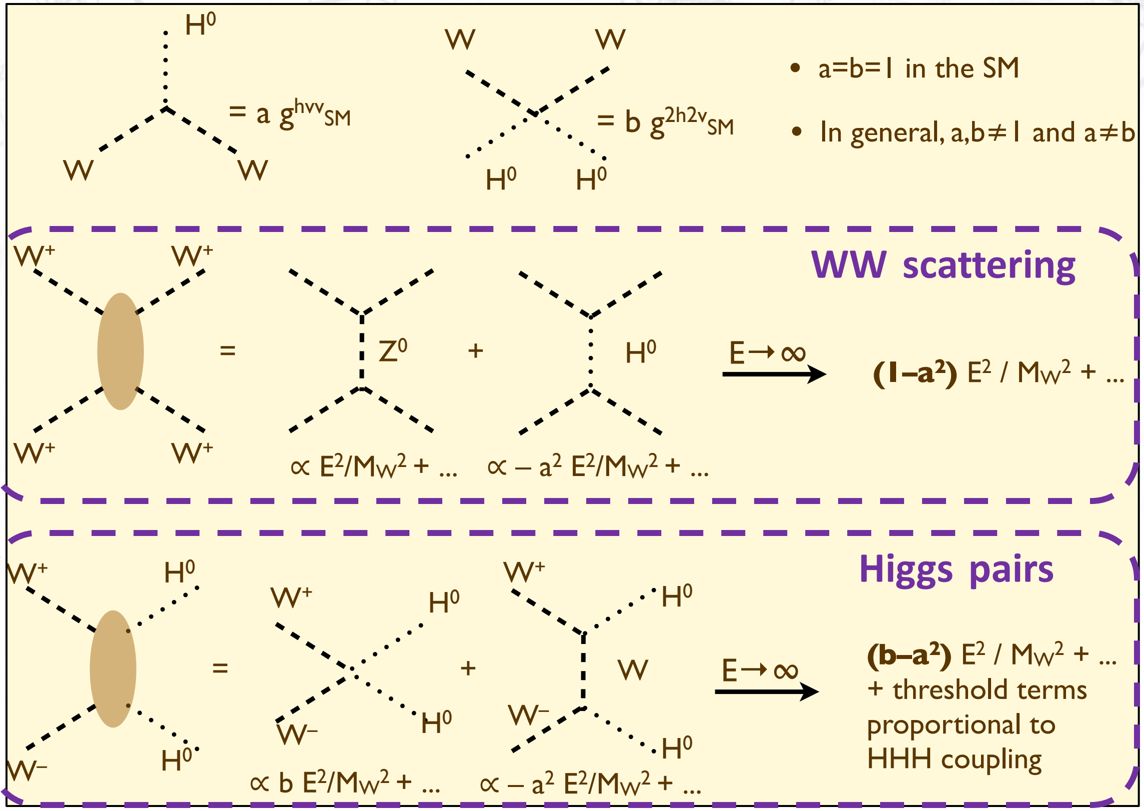
  - **Higgs self-coupling @ FCC-hh estimated with gg → HH → bbγγ so far (10^5 events!)**
    - **Other channels are under study**
- **Sensitivity to new physics (example)**
  - **ttH less sensitive than bbH+ZZH@FCC-ee**
    - **Improves sensitivity when combined**





Precision: WW scattering at high energy

- **Why WW scattering (and Higgs pair production) ?**
  - **In the SM, Z and H exchange diagrams diverge, but exactly cancel each other**
    - **Anomalous couplings, as relics of new physics, would have dramatic effects**
      - **Total WW scattering / Higgs pair cross section diverge with $m^4_{WW,HH}$**



$= a\, g^{hvv}_{SM}$

$= b\, g^{2h2v}_{SM}$

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

WW scattering

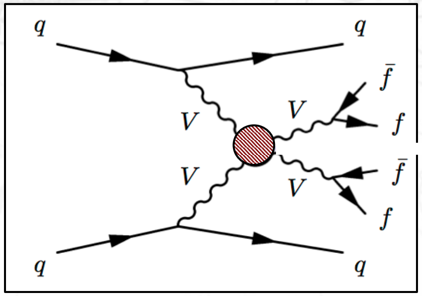
$= \; + \; \xrightarrow{E\to\infty}$ $\mathbf{(1-a^2)}\, E^2 / M_W^2 + \ldots$

$\propto E^2/M_W^2 + \ldots$ $\quad \propto -\, a^2\, E^2/M_W^2 + \ldots$

Higgs pairs

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

$\propto b\, E^2/M_W^2 + \ldots$ $\quad \propto -\, a^2\, E^2/M_W^2 + \ldots$



Precision on a and b

~ 30% at HL-LHC

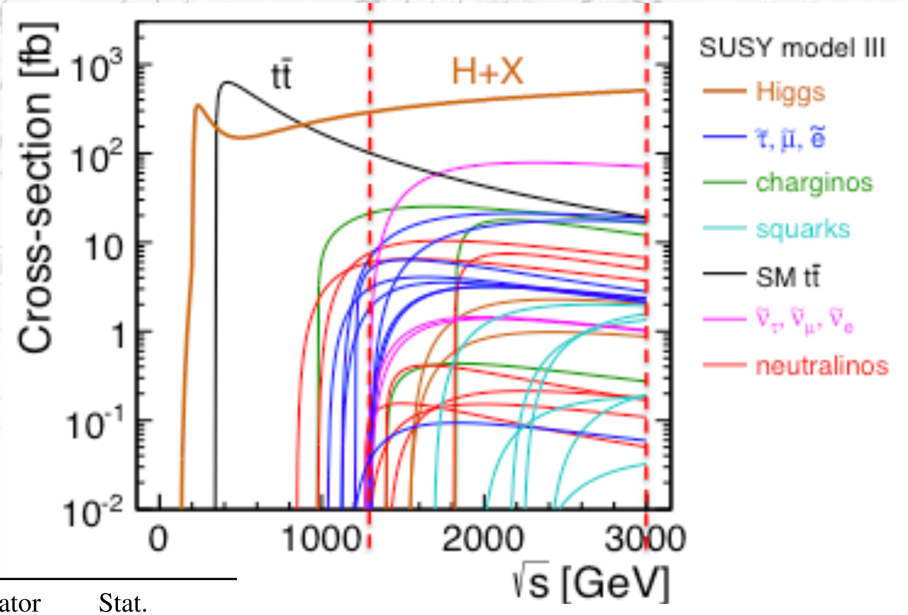
~ 30% with CLIC 3 TeV

~ 1% with FCC-hh 100 TeV

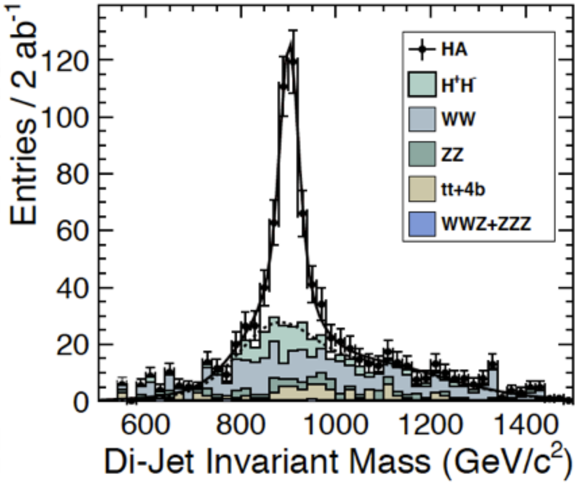
NB. “a” can be measured with 0.2% (0.8%) precision with FCC-ee (ILC)

Extended mass reach: Supersymmetry (1)

- **Production in e^+e^- collisions**
  - ***If* the SUSY spectrum is light enough**
    - **CLIC can produce a whole bunch of new particles (+Dark Matter) with masses below 1.5 TeV**
    - **And measure the masses with per-cent precision**
  - **Unique opportunity to probe the supersymmetry breaking mechanism**



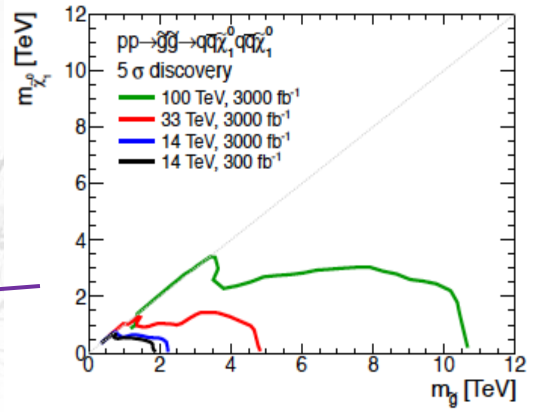
$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Generator value (GeV)	Stat. uncertainty
3.0	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	II	$\tilde{\ell}$ mass	1010.8	0.6%
				$\tilde{\chi}_1^0$ mass	340.3	1.9%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	1010.8	0.3%
				$\tilde{\chi}_1^0$ mass	340.3	1.0%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	1097.2	0.4%
				$\tilde{\chi}_1^\pm$ mass	643.2	0.6%
3.0	Chargino Neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$ $\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$	II	$\tilde{\chi}_1^\pm$ mass $\tilde{\chi}_2^0$ mass	643.2 643.1	1.1% 1.5%
3.0	Squarks	$\tilde{q}_R\tilde{q}_R \to q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$	I	$\tilde{q}_R$ mass	1123.7	0.52%
3.0	Heavy Higgs	$H^0A^0 \to b\bar{b}b\bar{b}$ $H^+H^- \to t\bar{b}b\bar{t}$	I	H^0/A^0 mass $H^\pm$ mass	902.4/902.6 906.3	0.3% 0.3%



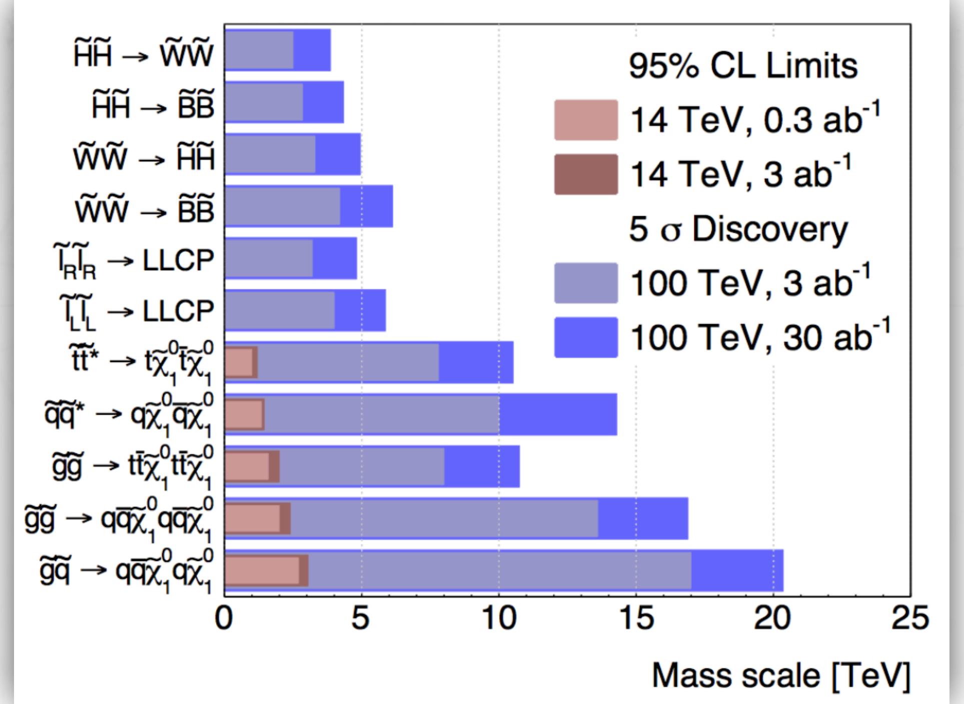
Example: Heavy Higgses

Extended mass reach: Supersymmetry (2)

- Production in pp collisions
  - If the spectrum is heavier
    (as hinted at by the so-far negative LHC searches)
    - Higher energy will be needed
      - Example: Gluino discovery reach with 3 ab^{-1}
        - 5 TeV at HE-LHC / 11 TeV at FCC-hh

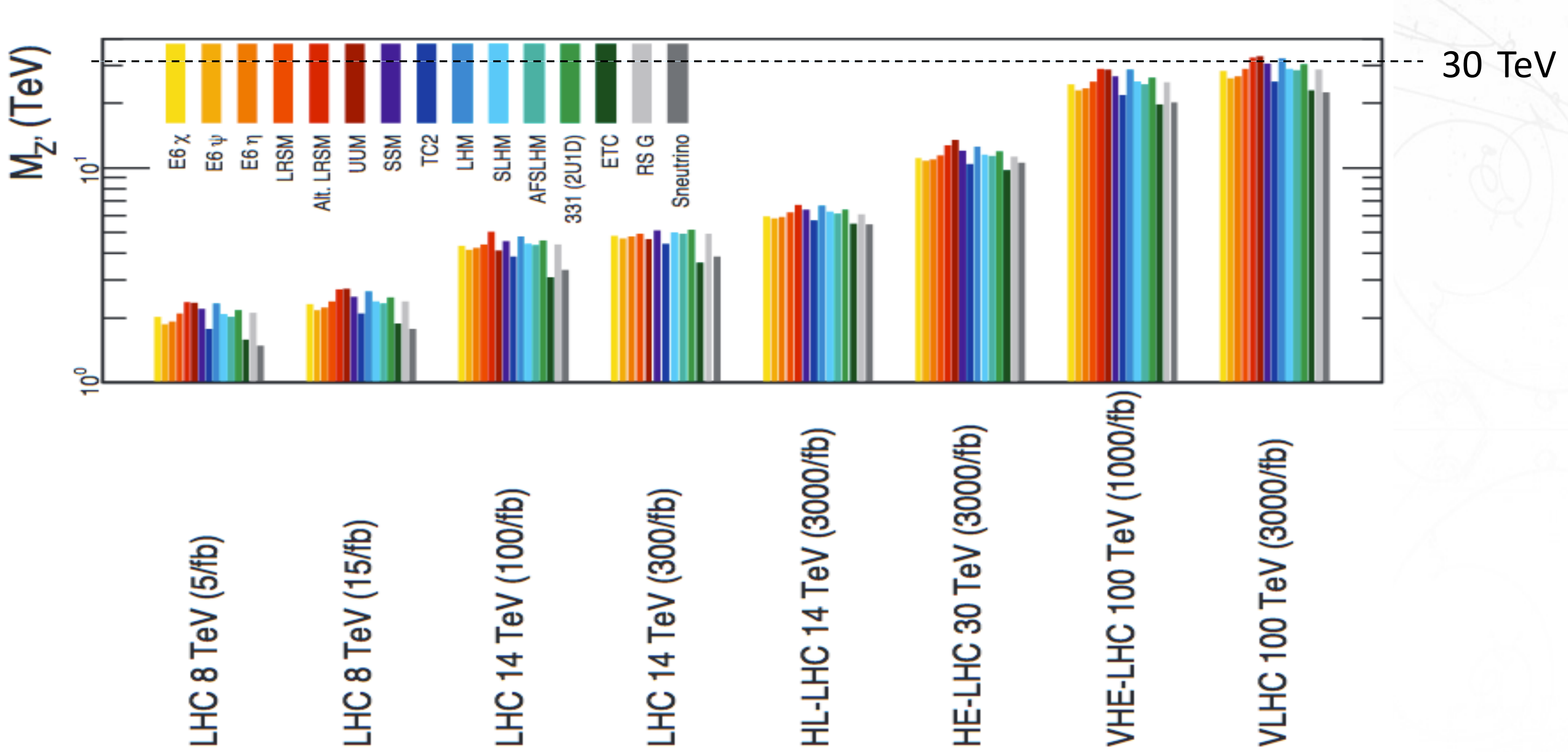


  - Super-summary:



Extended mass reach: New gauge bosons (1)

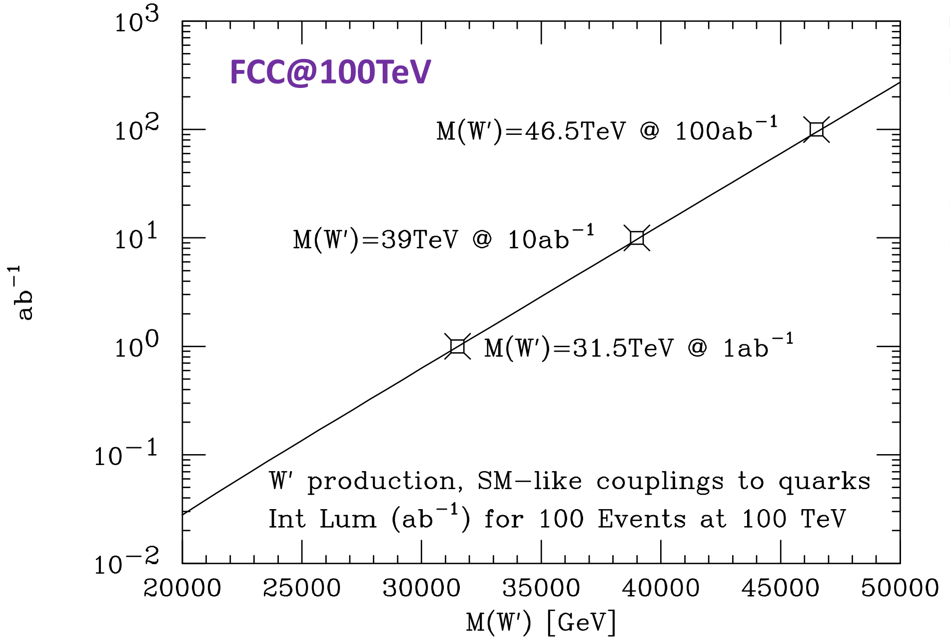
- Example 1: Searches for new Z' bosons
  - FCC-hh directly sensitive up to $m_{Z'}$ ~ 30-35 TeV (vs. ~ 3TeV for CLIC)
    - By looking for di-lepton resonances
  - CLIC 3-TeV indirectly sensitive up to $m_{Z'}$ ~ 15-20 TeV
    - By looking for deviations in the angular distribution of leptons

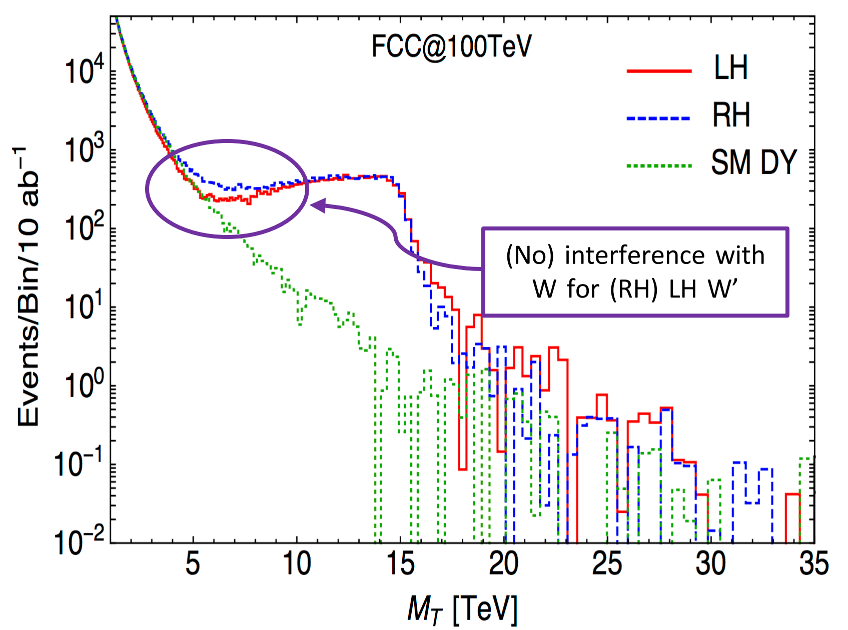


Extended mass reach: New gauge bosons (2)

- **Example 2: Searches for new W' bosons**
  - ❑ e.g., as a resonance in the di-jet mass (or l + E_T^{miss} distribution) at FCC-hh

Sensitivity as a function of integrated luminosity





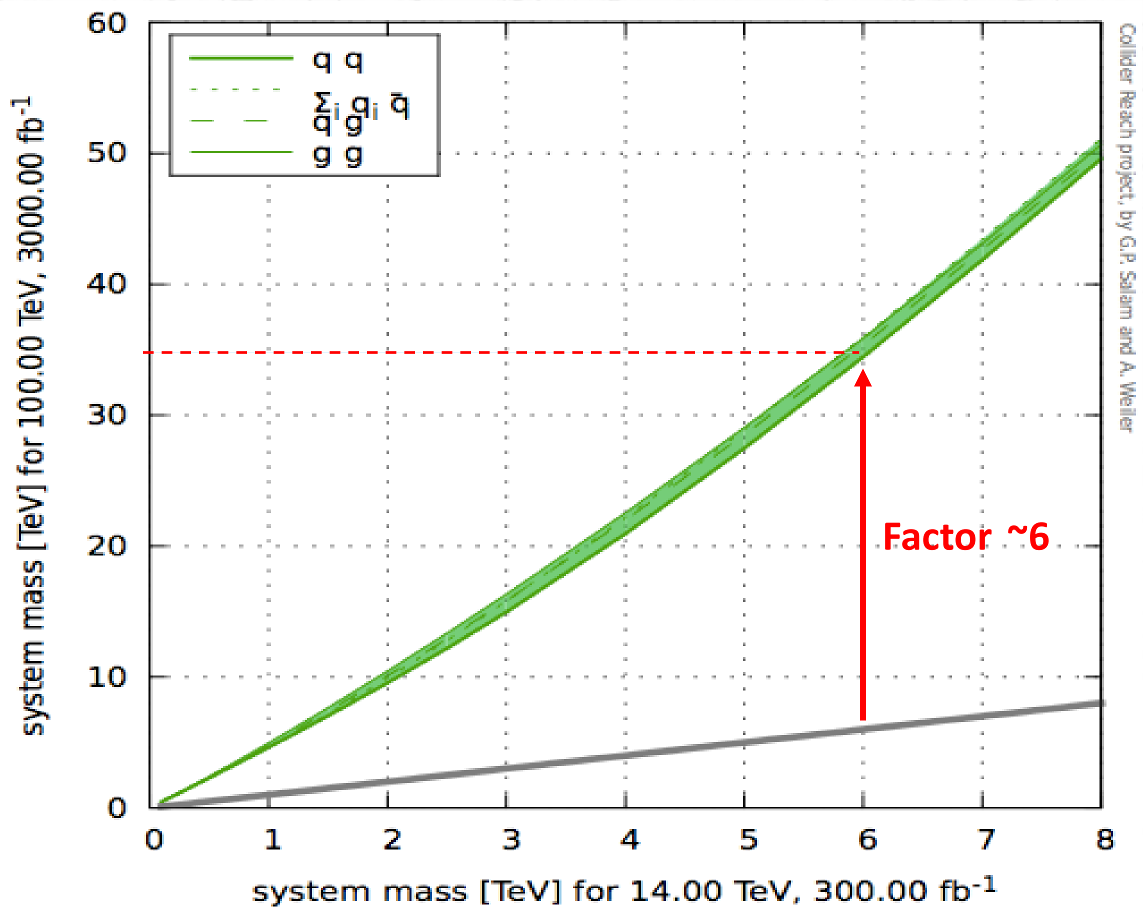
(No) interference with W for (RH) LH W'

Extend the mass reach by ~ 7 TeV for each factor 10 in luminosity

May be possible to disentangle left-handed and right-handed W'

Extended mass reach : Other exotica @ FCC-hh

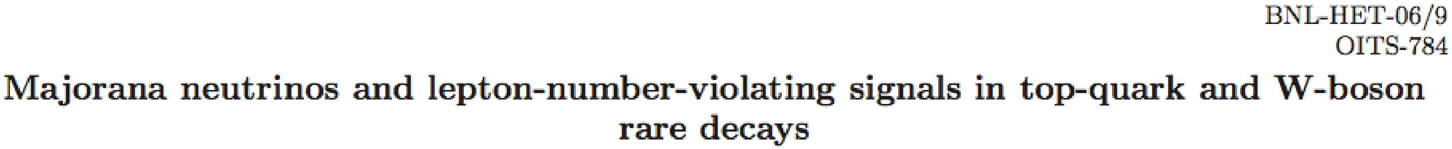
- 14 TeV (300 fb^{-1}) → 100 TeV (3 ab^{-1}) with pp collisions
  - Rule of thumb: a factor 5 in mass reach from LHC to FCC-hh
    - Then add to this factor one unit for each factor 10 in luminosity



Not just a mere extrapolation: Rare decays

- At FCC-hh, 30 ab^{-1} at 100 TeV imply
  - ❑ 2.5×10^{10} Higgs bosons = 10^4 × today's statistics, 10^4 × FCC-ee statistics
    - ❖ More precision measurements
    - ❖ Rare decays, FCNC probes, e.g., $H \rightarrow e\mu$ …

  - ❑ 2×10^{12} top quarks = 10^4 × today's statistics, 10^6 × FCC-ee statistics
    - ❖ Rare decays, FCNC probes, e.g., $t \rightarrow cZ$, cH
    - ❖ CP violation
    - ❖ 10^{12} W and 10^{12} b from top decays
    - ❖ 10^{11} τ from $t \rightarrow W \rightarrow \tau$
      - ▪ Rare decays, e.g., $\tau \rightarrow 3\mu, \mu\gamma$, CP violation …
    - ❖ BSM decays : any interesting channels to consider ?
      - ▪ Example: Majorana neutrino search in top decays



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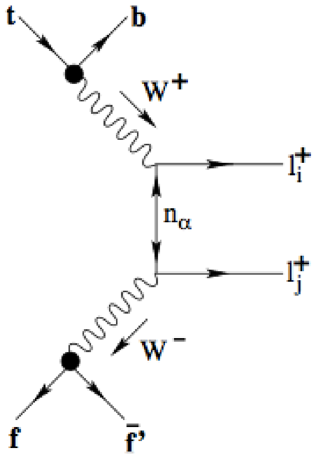
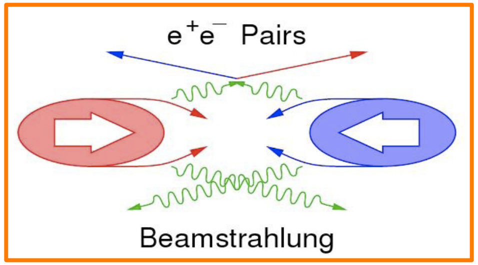
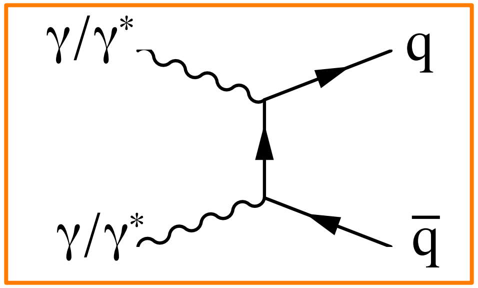
Majorana neutrinos and lepton-number-violating signals in top-quark and W-boson rare decays

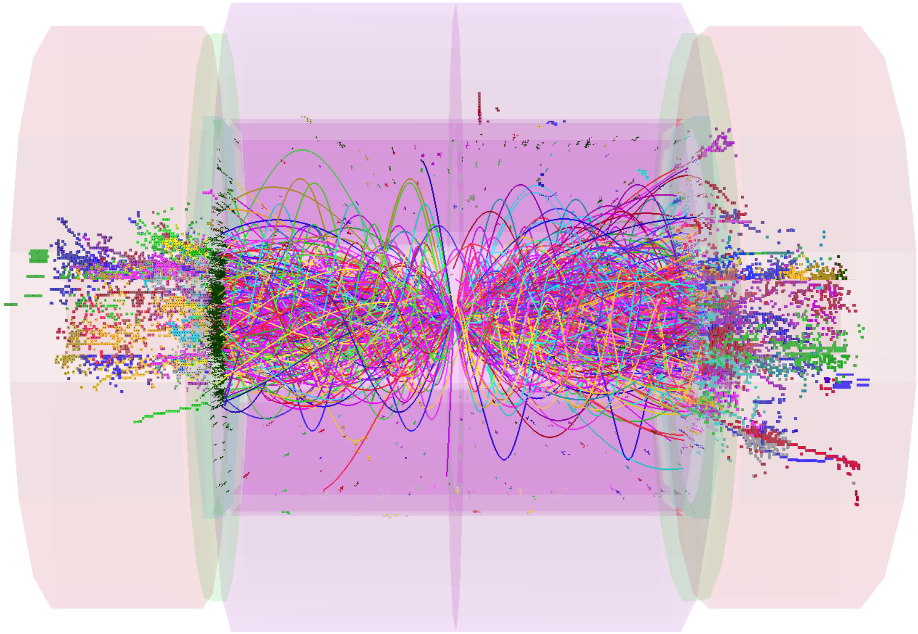


Not just a mere extrapolation: Detectors (1)

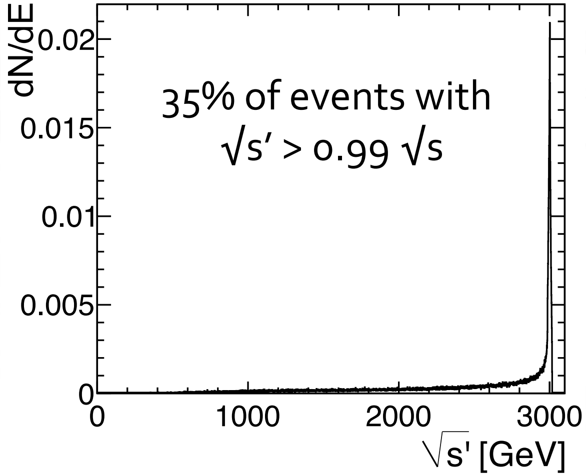
- Experimental conditions at CLIC
  - **Important beamstrahlung due to bunch charge density**
    - Caused by the extremely strong focusing
    - Radiated photon and electron-pair background
    - Pile-up of photon-photon collisions (mini-jets)
    - Reduction of effective centre-of-mass energy







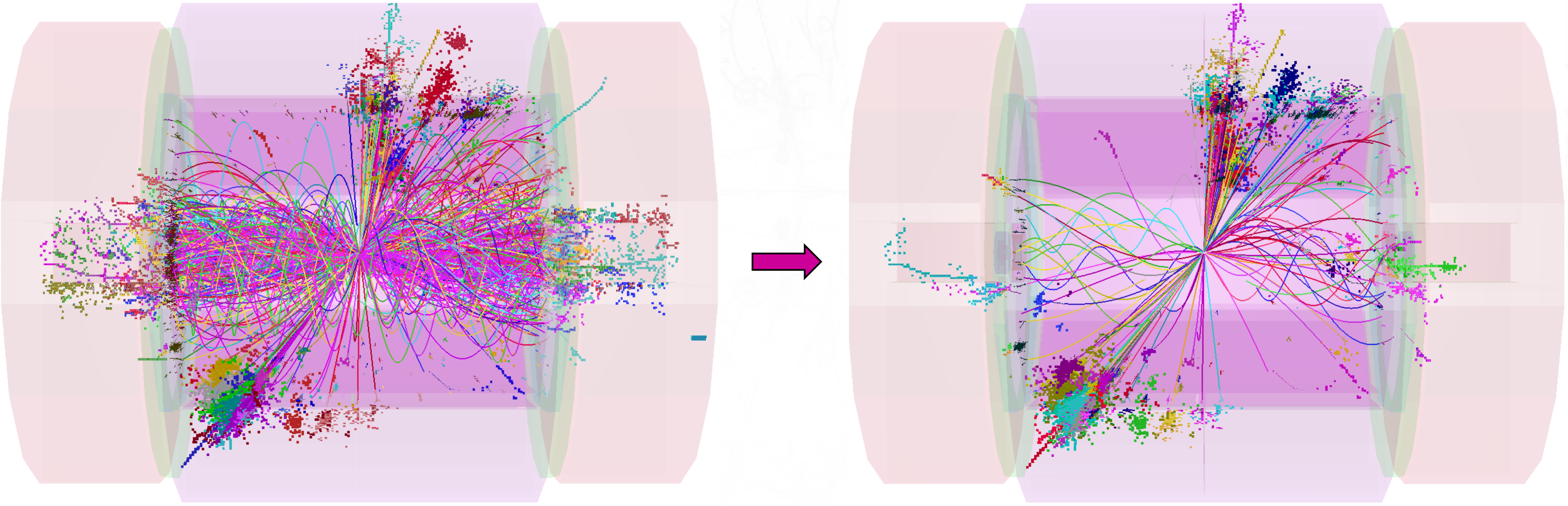
20 BX = 10 ns of $\gamma\gamma$ piled up



Not just a mere extrapolation: Detectors (2)

- Experimental conditions at CLIC, cont'd
  - Detectors will have to deal with these conditions
    - High-granularity calorimeter and tracker
      - for ultimate jet-energy resolution (no $\sqrt{s}$ constraint)
      - for individual particle characterization (timing)
    - Excellent timing resolution
      - to mitigate $\gamma\gamma$ pile-up interactions

Example: $e^+e^- \rightarrow H^+H^- \rightarrow$ 8 jets



Not just a mere extrapolation: Detectors (3)

- Detectors for FCC-hh: a formidable challenge, well beyond HL-LHC
  - Up to 1000 in-time pile-up events with 25 ns bunch spacing, bunch length 5 cm
    - High-granularity calorimetry, tracking and vertexing required
  - Reduced to 200 in-time pile-up events with 5 ns bunch spacing
    - Ultra fast detectors required (out-of time pile-up)

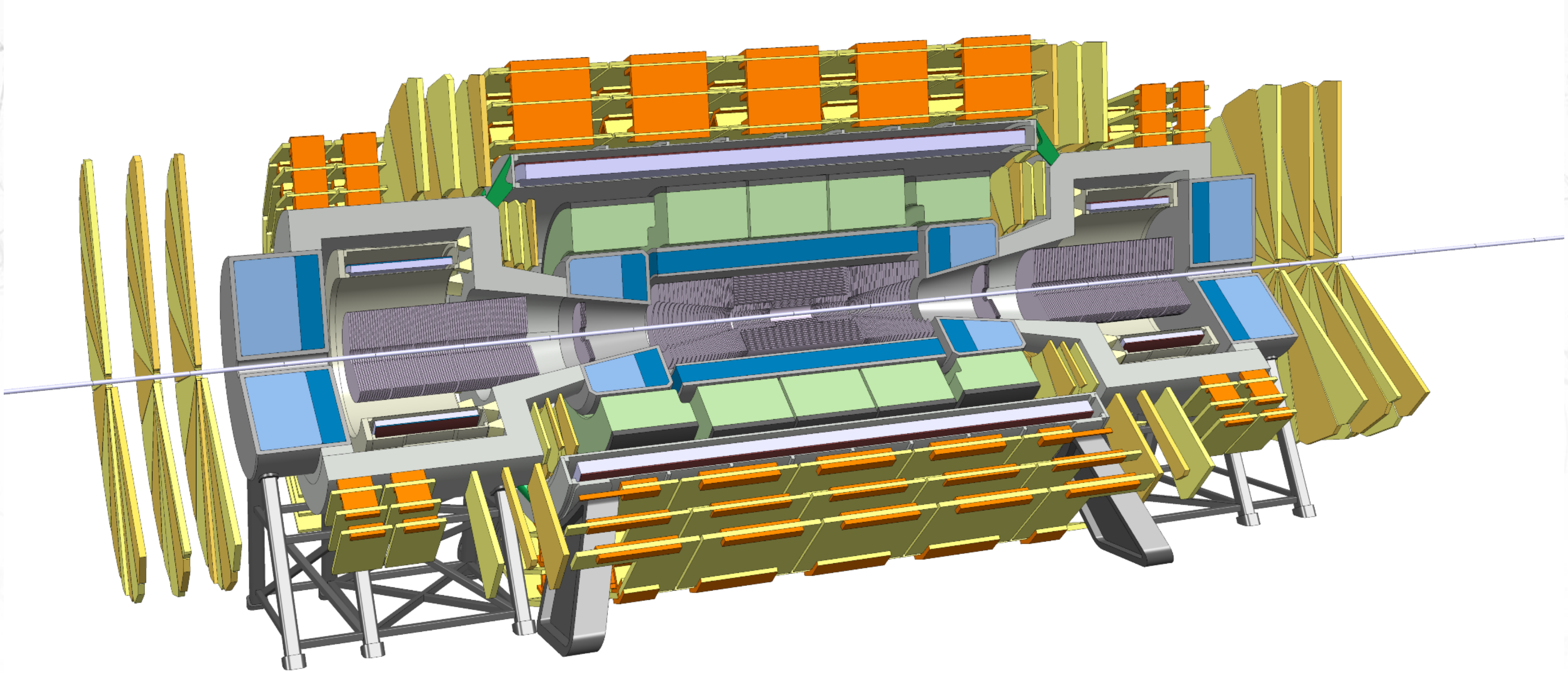
  - Large longitudinal event boost
    - Enhanced coverage at large rapidity required (with tracking and calorimetry)
      - Also need for forward-jet tagging in boson fusion production
  - Everything will be highly boosted also Zs, Ws, Higgses, tops
    - Again, high-granularity detectors needed

  - Very energetic charged particles
    - Precise momentum measurement up to 10 TeV: strong B field (4-6T) and large tracker
  - Very energetic jets
    - Energy containment require thicker calorimeter

Bigger, thicker, faster, stronger, more clever detectors

Not just a mere extrapolation: Detectors (4)

- **FCC-hh Detector Reference Design [as of May 17]**



4T, 10m bore solenoid, 4T forward solenoids, no shielding coil

→ 14 GJ Stored Energy
→ 20m Diameter (≈ ATLAS)
→ ≈ 1 Billion€ project

Summary at this point (1)

- Two very ambitious visions for the future
  - PLAN A

ILC [*]

250-500 GeV
SC 1.3 GHz
klystrons
31.5 MV/m
31 km

[*] Can also be CLIC wiith $\sqrt{s}$ = 0.38 & 1.4 TeV

Precision studies
of Higgs and top
10 B$, 2030 / 2035 ?

ILC [*]

1 TeV
SC 1.3 GHz
Klystrons
45 MV/m?
50 km

ttH (HHH) couplings
+10B$, 2045 ?

CLIC

3 TeV
drive beam
NC 12 GHz
100 MV/m
50 km

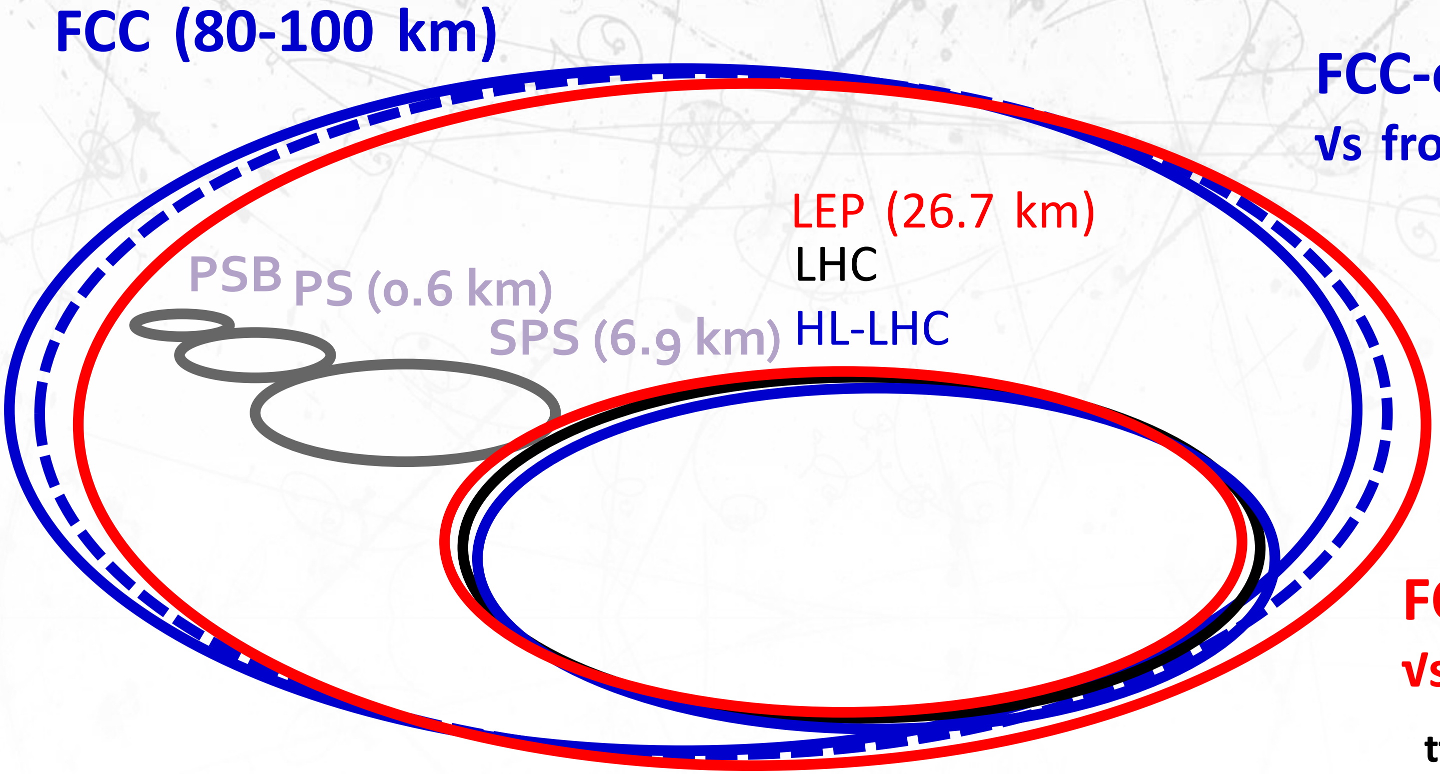
Plasma acceleration?
> 1 GV/m
4 km + final focus

Energy Frontier
20 B$, 2060 ?

≥ 50 years of e^+e^- (e^-e^-, $\gamma\gamma$) collisions up to $\sqrt{s}$ ~ 3 TeV

Summary at this point (2)

- **Two very ambitious visions for the future (cont'd)**
  - ❑ **PLAN α**



FCC-ee: e^+e^-,
$\sqrt{s}$ from 88 to 370 GeV)

Precision studies
of Z, W, H, top
4+3 B$, 2035 ?

FCC-hh: pp
$\sqrt{s}$ up to 100 TeV

ttH, HHH couplings
Energy frontier
20 B$, 2055 ?

& **FCC-he, $e^{\pm}p$ collisions**
$e^{\pm}$ (50-175 GeV) – p (50 TeV)

≥ 50 years of e^+e^-, pp and ep collisions at highest energies

Summary at this point (3)

- Two very ambitious visions for the future (cont'd)
  - Both visions have different, but solid, technological maturity
    - The linear collider vision is the most advanced from the design point-of-view
      - Many test facilities have proven the acceleration technology to work
        - But the associated risks are still non-negligible (final focus, positron source, …)
    - The circular collider vision is much younger
      - But is strongly backed up by 50 years of experience, by historical successes
        - And by projects that will prove its feasibility (SuperKEKB, HL-LHC)
  - The scientific case is obvious
    - Precision studies for new physics at high mass or with small couplings
    - Energy frontier for new physics at high mass and with large couplings
  - My own impression
    - Beyond the LHC Run2, the combination of FCC-ee and FCC-hh offers, for a great cost/infrastructure effectiveness, the best precision and the best search reach

Summary at this point (4)

- This impression will have to be reviewed
  - After the LHC Run2
  - After 5 years of FCC study

- A whole set of new discoveries may be waiting for us in LHC Run2
  - … or it may be decades before the next big discovery
    - Meanwhile, the LHC will set the scene for precision physics and rare decay searches

- Future options will need a long time to materialize
  - None of the options is cheap (from ~5 B$ to 20 B$)
    - Clear and global planning/funding are probably needed
  - Criteria for choice include
    - Scientific potential
    - Cost, funding availability, sociology
    - Technological maturity

    - Remember: We cannot afford to make a wrong choice…

Lecture 3 (2nd part)

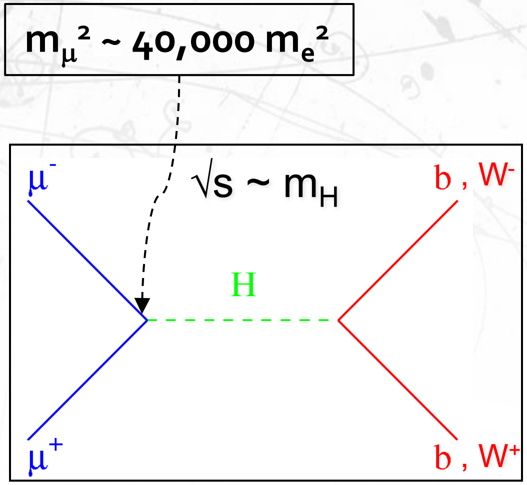
Thinking out of the box
Muon Colliders

Note:

- Muon colliders were not identified as priority by the European Strategy update in 2013
- However, interest has recently grown with new ideas that may improve their relizability
- It is therefore important to understand the relevant ins and outs

Why muon colliders ?

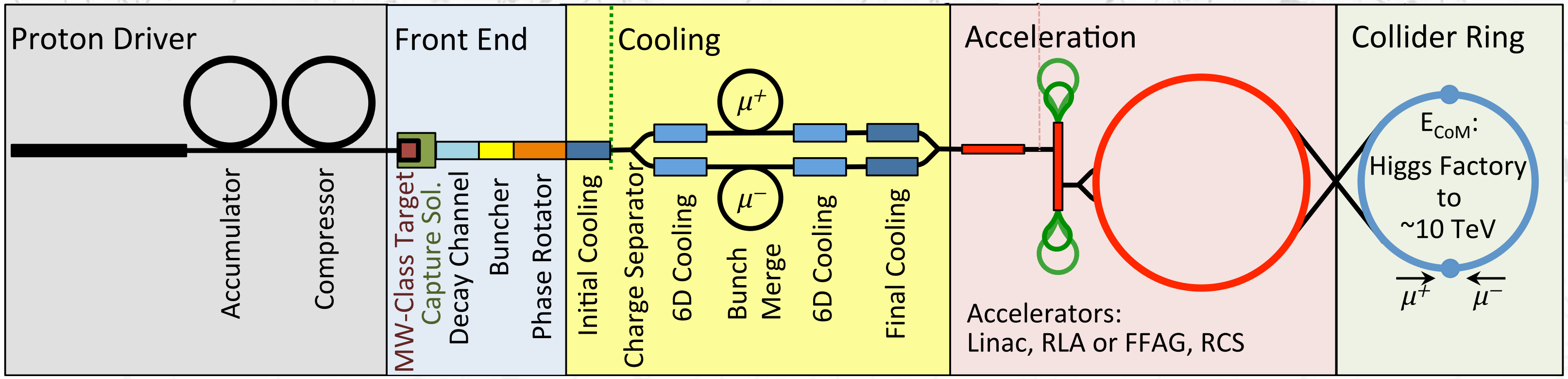
- **Muons are leptons (like electrons)**
  - Collisions at the full energy, small physics background, (E,p) conservation
    - Muons can *a priori* do all what electrons can do
- **Muons are heavy (like protons)**
  - Negligible synchrotron radiation, no beamstrahlung
    - Small circular colliders, up to large √s
    - Excellent energy definition (up to a few 10^{-5})
  - Large direct coupling to the Higgs boson
    - Unique Higgs factory at √s = 125.093 GeV


$m_\mu^2 \sim 40{,}000\, m_e^2$

- **Muons are naturally longitudinally polarized (100%)**
  - Because arising from $\pi^\pm$ decays to $\mu^\pm\nu_\mu$
    - Ultra-precise beam energy and beam energy spread measurement
- **Muons eventually decay (in 2.2 μs) to $e\nu_\mu\nu_e$**
  - Outstanding neutrino physics programme
    - Muon colliders could be the natural successors of neutrino factories ?

Muon colliders challenges

- Muons decay: Produce, Collect, Cool, Accelerate and Collide them *fast* !



- ☐ **Intense proton driver to get the adequate number of muons**
  - **At least 4 MW for the desired muon luminosities**
- ☐ **Robust target to not evaporate at the first proton bunch**
  - **Re-circulating liquid metal**
- ☐ **Efficient muon collector from pion decays**
  - **Magnetic fields of 20T**
- ☐ **Unique 6D muon cooling**
  - **To reduce beam sizes and beam energy spread**
- ☐ **Fast acceleration and injection into circular ring(s)**

All these aspects are at the level of intense R&D. Will require decades to demonstrate feasibility

Muon collider challenges since 2014 ?

- Clever alternative muon source

- Intense e^+ beam with $E \simeq 45$ GeV
  - 100 kW suffice for the desired muon luminosities
- Non-destructive target for $e^+e^- \to \mu^+\mu^-$
  - Keep the e^+ beam in a ring
    - Possible synergy with FCC-ee
    - Energy Recovery Linac is also a possibility
- Production at $\mu^+\mu^-$ threshold ($\sqrt{2} \simeq 2\,m_\mu$)
  - Quasi-monocromatic muons, much less need for cooling
    - Except for a Higgs factory
- Fast acceleration and injection into circular ring(s) remain as in the proton-driver option

If feasible, this design would probably be faster, cheaper, and easier then the proton-driver option

Muon collider optimal circumference(s)

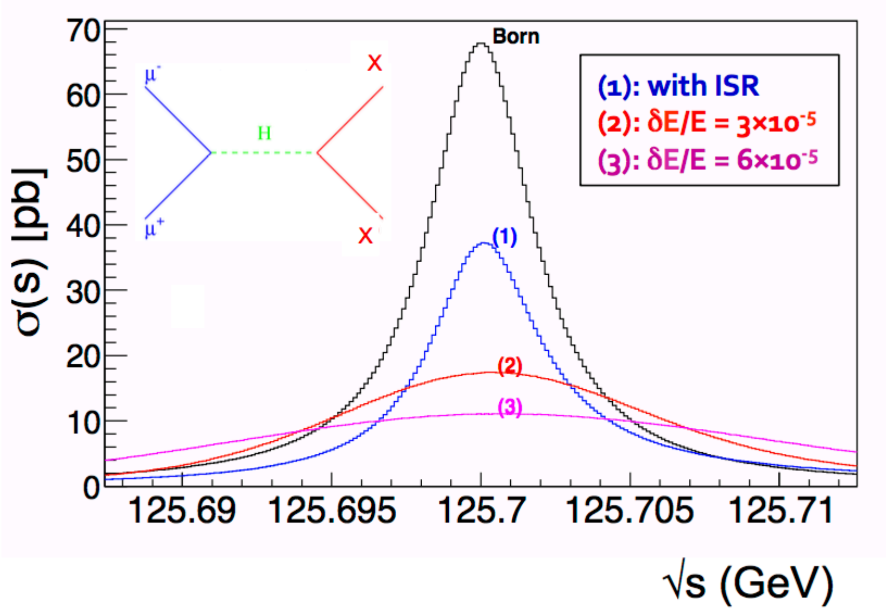
- Muon decay: Minimize the ring circumference
  - To allow the produced muons to collide as many times as possible before they decay
    - With 14T state-of-the-art dipoles, the optimal ring size is proportional to E_μ

$\sqrt{s}$	91 GeV	125 GeV	161 GeV	350 GeV	6 TeV	24 TeV
$t = \gamma\tau_\mu$	0.94 ms	1.30 ms	1.67 ms	3.64 ms	62.3 ms	249 ms
$L = \gamma\beta c\tau_\mu$	283 km	389 km	501 km	1090 km	18700 km	74000 km
Ring	100 m	140 m	180 m	390 m	6.6 km	27 km
N_{turns}	~2800 turns					

- One ring per centre-of-mass energy
  - Two very small rings for precision studies
    - One for Z and H factories (140 m circumference)
    - One for W and top pair thresholds (390 m circumference)
  - Larger ring(s) for the energy frontier
    - $\sqrt{s}$ = 6 TeV can fit, for example, in the Tevatron tunnel (6.6 km circumference)
    - $\sqrt{s}$ = 24 TeV can fit in the LHC tunnel
  - Plus a number of rings for first stages of fast acceleration

Muon collider as a Higgs factory (1)

- Challenges for the Higgs factory
  - Γ_H is small (4.2 MeV in the SM)
    - Similar or smaller beam energy spread is required (3×10^{-5})
      - Fast longitudinal cooling to reduce energy spread
    - Beam energy reproducibility must be at the same level or better



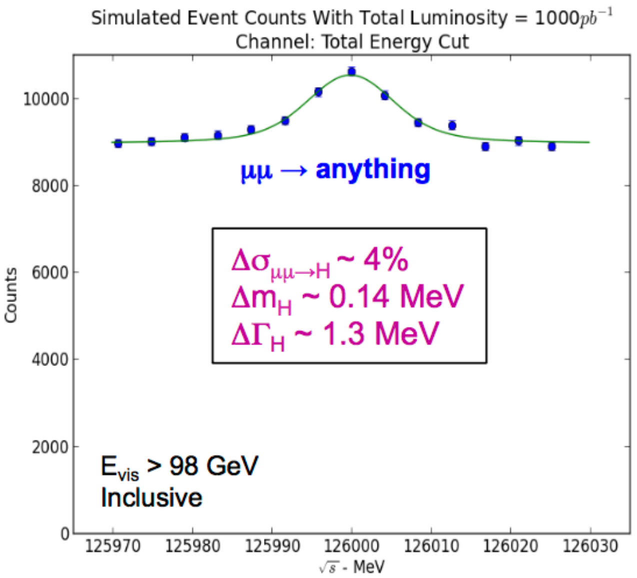
  - $\sigma(\mu^+\mu^- \rightarrow H)$ is about 20 pb
    - Luminosity must be at the level of 1.5×10^{32} cm^{-2}s^{-1} for the same number of Higgs bosons as ILC …
    - and at the level of 1.6×10^{33} cm^{-2}s^{-1} for the same number of Higgs bosons as FCC-ee
      - Fast transverse cooling to reduce beam spot dimensions

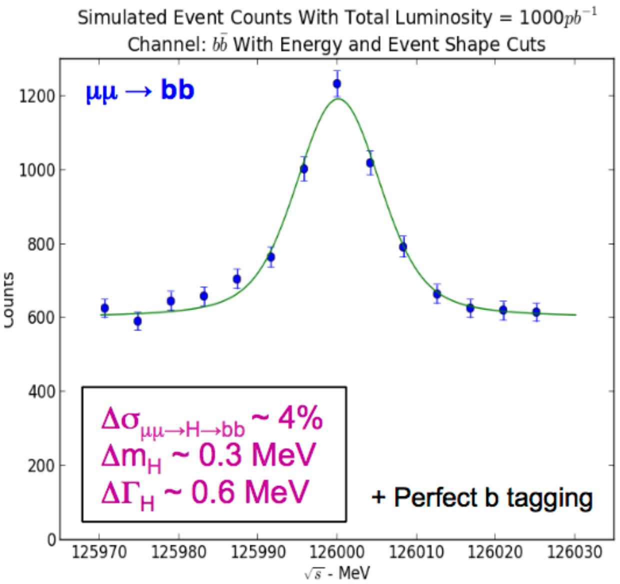
        And the Higgs bosons produced are not tagged with a Z anyway …
  - Problem
    - Longitudinal and transverse cooling are antagonistic
      - Luminosity is limited (as of today's knowledge) to a few 10^{31} cm^{-2}s^{-1}

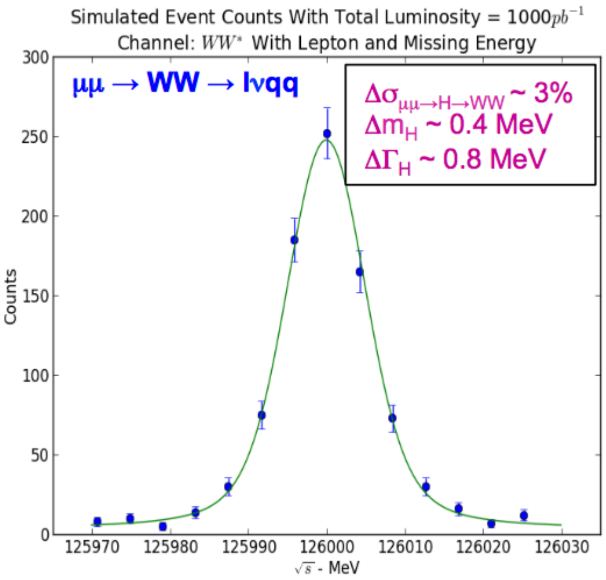
D. Schulte

Muon collider as a Higgs factory (3)

- Physics performance of a Higgs factory
  - Scan of Higgs resonance in the inclusive bb and WW final states
    - Ten years of data taking at 10^{31} cm^{-2}s^{-1}, just count events







- Measure Γ_H to 5% in 10 years (cf. 4% at ILC, <1% at FCC-ee)
  - Only way to see a structure in the resonance (several Higgs bosons?)
- Measure σ_{peak} ~ $BR_{\mu\mu}$ to 2-3% in 10 years
- Other expected measurement on the figures

Muon collider as a Higgs factory (4)

- Summary of precision measuremetns (after ~10 years of running)

Error on	μμ collider	ILC	FCC-ee
m_H (MeV)	0.06	30	8
Γ_H (MeV)	0.17	0.16	0.04
g_{Hbb}	2.3%	1.5%	0.4%
g_{HWW}	2.2%	0.8%	0.2%
$g_{H\tau\tau}$	5%	1.9%	0.5%
$g_{H\gamma\gamma}$	10%	7.8%	1.5%
$g_{H\mu\mu}$	2.1%	20%	6.2%
g_{HZZ}	-	0.6%	0.15%
g_{Hcc}	-	2.7%	0.7%
g_{Hgg}	-	2.3%	0.8%
BR_{invis}	-	<0.5%	<0.1%

Not obvious what is the practical use of such high precision on m_H

The Higgs width is best measured at ee colliders

These Higgs couplings are best measured at ee colliders

The Higgs coupling to muons is *the* added value of a μμ collider *)

These Higgs couplings are *only* measured at ee colliders *)

*) pp colliders have their say, too

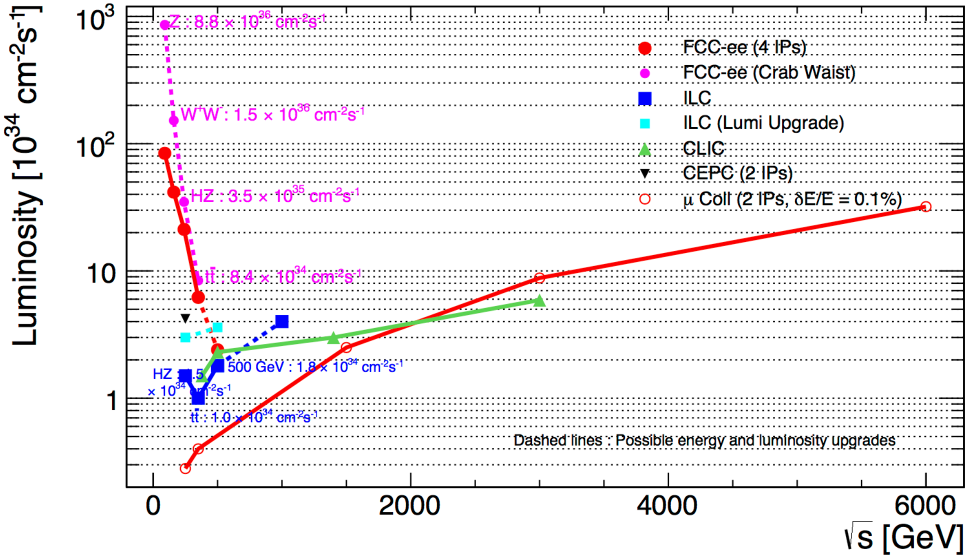
- Note: BR(H→μμ) can be also measured with % precision af FCC-hh (Will be already 10% after LHC)

Muon colliders at the energy frontier (1)

- Muon colliders might be a solution for high energy in the (far?) future
  - Many challenges to solve with sustained R&D and innovative thinking, as to
    - Increase luminosity for precision studies
    - Solve the radiation hazard at high energy (decay neutrino interactions in Earth)
- For the record, here are the current target performance

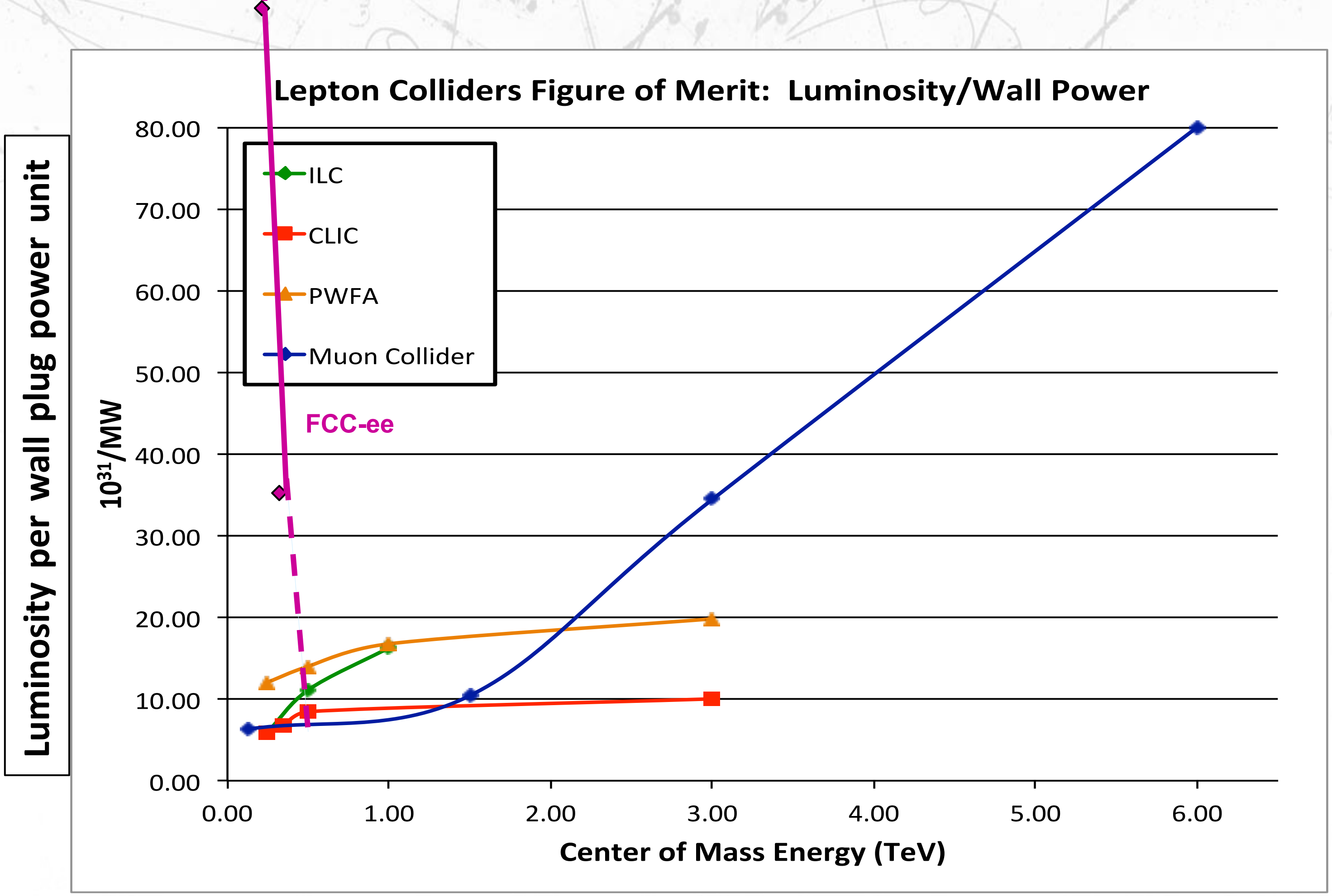
√s (TeV)	**0.091**	**0.125**	**0.3**	**1.5**	**3.0**	**6.0**
Lumi (10^{34} $cm^{-2}s^{-1}$)	**0.01**	**< 0.008**	**0.2**	**1**	**4**	**15**
R = Δp/p (%)	**0.1**	**0.003**	**0.1**	**0.1**	**0.1**	**0.1**

- Larger than CLIC above 1.5 TeV
  - With the possibility of several IPs



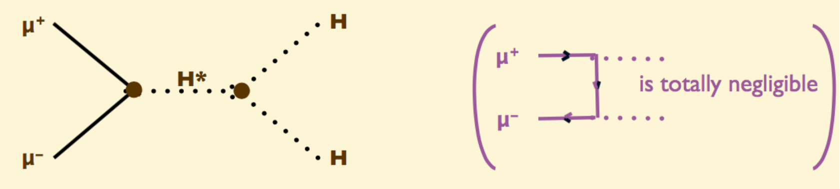
Muon colliders at the energy frontier (2)

- Muon colliders might be a solution for high energy in the (far?) future
  - With an acceptable power consumption



Muon colliders: Summary

- A muon collider may be the best way to get lepton collisons at $\sqrt{s} \geq 3$ TeV
  - Much R&D remain in, e.g., muon cooling/acceleration
- A muon collider at $\sqrt{s} = 125$ GeV is a very pretty Higgs factory ($\mu^+\mu^- \to H$)
  - But not necessarily the one we need
    - If H(125) is a single particle, the process $e^+e^- \to HZ$ @ 240 GeV is better suited
      - In particular, the Higgs width can be measured very well in e^+e^- collisions
    - A muon collider can also do that, but much higher luminosity would be necessary
      - At least two orders of magnitude – limited by the proton/positron source
- Several quasi-degenerate Higgs bosons is a strong case for μμ Higgs factory
  - If Δm is between 4 MeV (Γ_H) and ~100 MeV (LHC resolution)
    - Such a situation may occur with two Higgs doublets, and quasi-degenerate H & A
      - Isolate the two peaks and perform nice CP studies !
- A muon collider at $\sqrt{s} > 2\, m_H$ provides the only way to *cleanly* probe HHH coupling



- A muon collider is the natural second step of neutrino factories

- Conclusion: don't write them off completely, but don't oversell them !

Lecture 3 (3rd part)

Towards the future

The 2019-2020 strategy update

What have we learnt since 2013 ? (1)

- LHC accelerator
  - Successful refurbishment for √s ≳ 13 TeV operation
  - Run2 at √s = 13 TeV proceeds extremely well:
    - ~40 fb^{-1} in 2016; likely equivalent this year [11.4 fb^{-1} as of today]
- LHC detectors
  - The experiments continue to perform very well
- LHC Physics
  - No hints of strong deviations from Standard Model just as yet
    - Direct BSM searches, Higgs properties, SM & HF measurements
- Policy / Politics
  - The FCC design study has started at CERN, with financial support
    - All configurations are pursued: ee, hh, eh
  - The P5 process has come to an end in US in 2015
    - Strong support for HL-LHC as the highest global priority
    - Long-term US-domestic accelerator-based particle physics program (ν's @ LBNF)
  - China
    - Discussions of possible circular machine(s)
      - Size has been increasing from 50-70 km to now 100 km
      - Current focus on 250 GeV e^+e^- machine, followed by 50+ TeV pp collider

What will we know after LHC Run2 ?

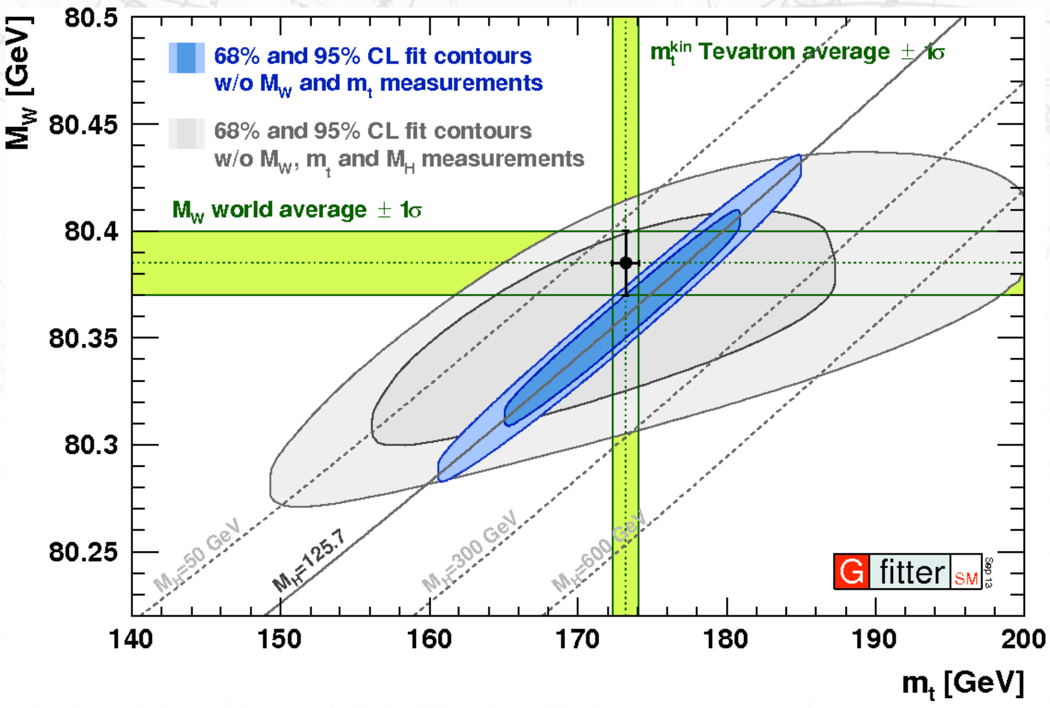
- If new physics is found in LHC Run2
  - It will (hopefully) point to best new accelerator to build
    - Which in turn will make it easier to get financial / political / societal support for this accelerator

- Much greater challenge if no new physics is found in Run2
  - Cannot continue indefinitely with R&D towards all possible future facilities
    - A choice will have to be made in 2019-2020
    - However, it is impossible for the LHC to rule out all possible new particles with m < 1 TeV (say)
      - In a model independent fashion

    - Some very difficult and painful judgment calls will have to be made
      - HL-LHC duration
        - → 2035, 2037, 2039 ? Possibility to speed up ?
      - Required energy / luminosity for a hadron / lepton collider

Personal views

- Very clear physics case for an e^+e^- collider with $90 < \sqrt{s} < 350\text{-}500$ GeV
  - Precision Higgs and electroweak physics (Z pole and WW/tt thresholds)
    - Precision measurements at the Z pole start to look like the poor relation in this plot



      - Calls for much more precise measurements
      - Also calls for significant theoretical progress in this areas
    - Measurements of W, H, top properties will give orders of magnitude improvements

Personal views

- Very clear physics case for an e^+e^- collider with $90 < \sqrt{s} < 370$-500 GeV
  - Precision Higgs and electroweak physics

- Much harder to make physics case for e^+e^- colliders with $\sqrt{s} > 370$-500 GeV
  - At least without clear evidence for accessible new particles
    - Produced copiously in e^+e^- or $\gamma\gamma$ collisions

- Need serious assessment of relative merits of ILC and FCC-ee
  - As precision machines – as we have done in this series of lectures
  - … plus some RealPolitik, of course
    - Funding situations, strengths of the collaborations, … etc
  - The above may be already taking place. From this summer, it seems that
    - ILC is zooming in on running at $\sqrt{s} = 250$ GeV only (at least as a start…)
    - Similarly, CLIC is zooming in on $\sqrt{s} = 380$ GeV running

- Exploration of energy frontier seems best done with a hadron collider
  - e.g., FCC-hh

Even more personal views

- Will China be in a position to build an e^+e^- Higgs factory ?
  - Maybe followed by a hadron collider ?
    - Financially, yes ! But …
    - … size of the community, expertise, scientific and organizational structure
      - In both accelerator and particle physics

- There will be, most probably, only one such machine in the world

- Don't underestimate the value of CERN
  - … and its 60-years track record and treaty in comparison

- Continue CERN's geographic expansion
  - With new associate member states
  - With financial contributions of associate members
  - … maybe even persuade China to make in-kind contributions to a new accelerator ?

Conclusions of this series of lectures

- The journey towards the future of HEP will probably be long and tortuous
  - You can make it enjoyable for yourself:
    - Always keep your passion for science
    - Apply healthy practical common sense
    - Follow your dreams

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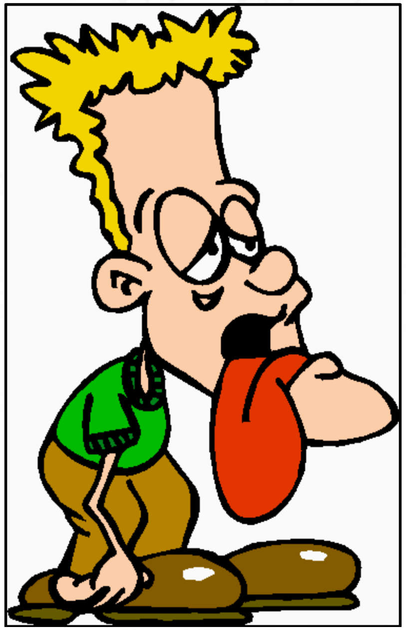

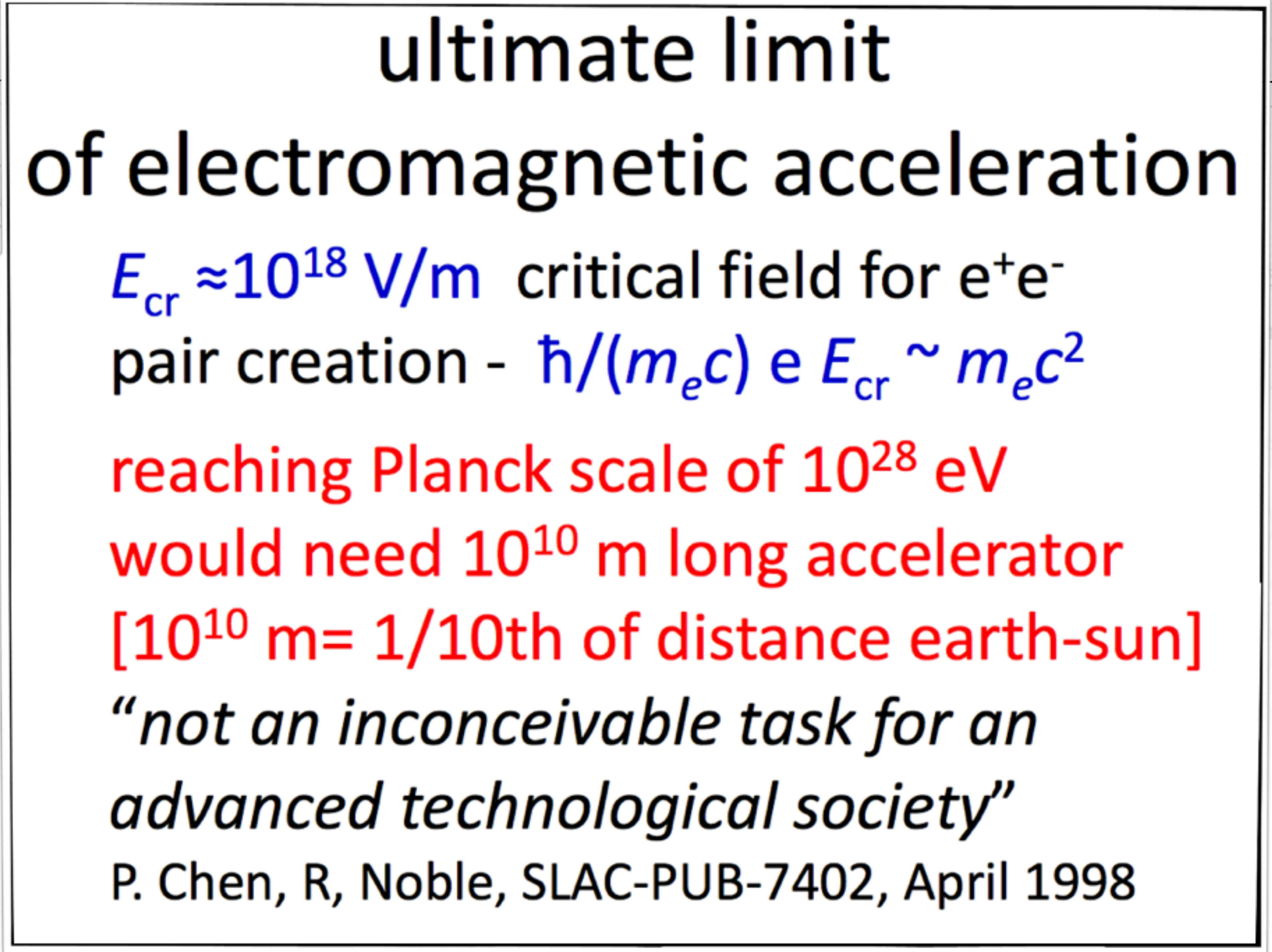

ultimate limit of electromagnetic acceleration

$E_{cr} \approx 10^{18}$ V/m critical field for e^+e^- pair creation - $\hbar/(m_e c)\, e\, E_{cr} \sim m_e c^2$

reaching Planck scale of 10^{28} eV would need 10^{10} m long accelerator [10^{10} m= 1/10th of distance earth-sun]

"*not an inconceivable task for an advanced technological society*"

P. Chen, R, Noble, SLAC-PUB-7402, April 1998