Physics at Future Colliders

- **Lecture 1 (Thursday 28 July, 10:20)**
  - An historical perspective (1964-2014): 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

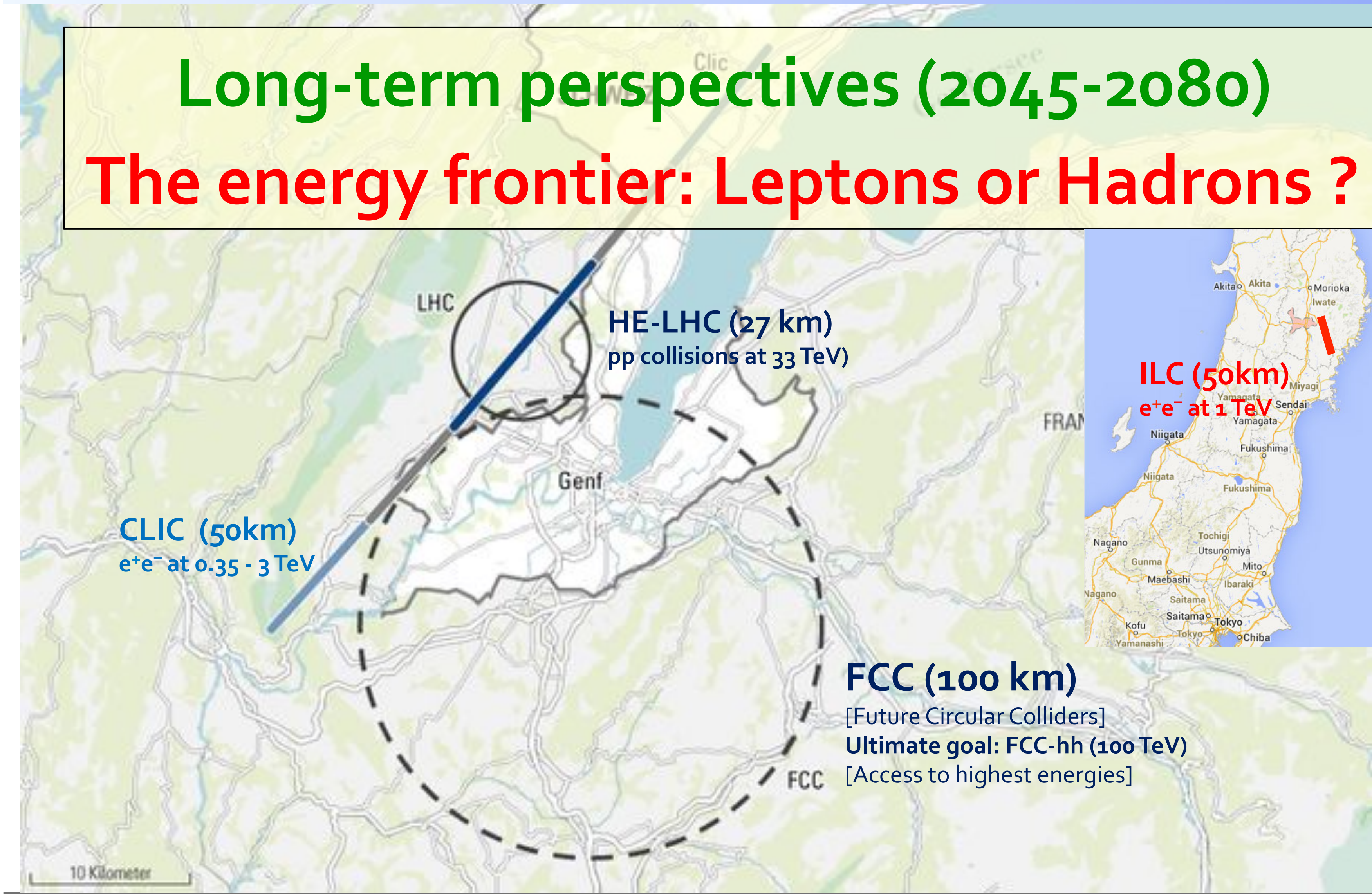
- **Lecture 2 (Friday 29 July, 9:15)**
  - The quest for precision (2030-2050): Linear or Circular ?

- **Lecture 3 (Friday 29 July, 10:20)**
  - 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 ?



Reminder: The big questions (1)

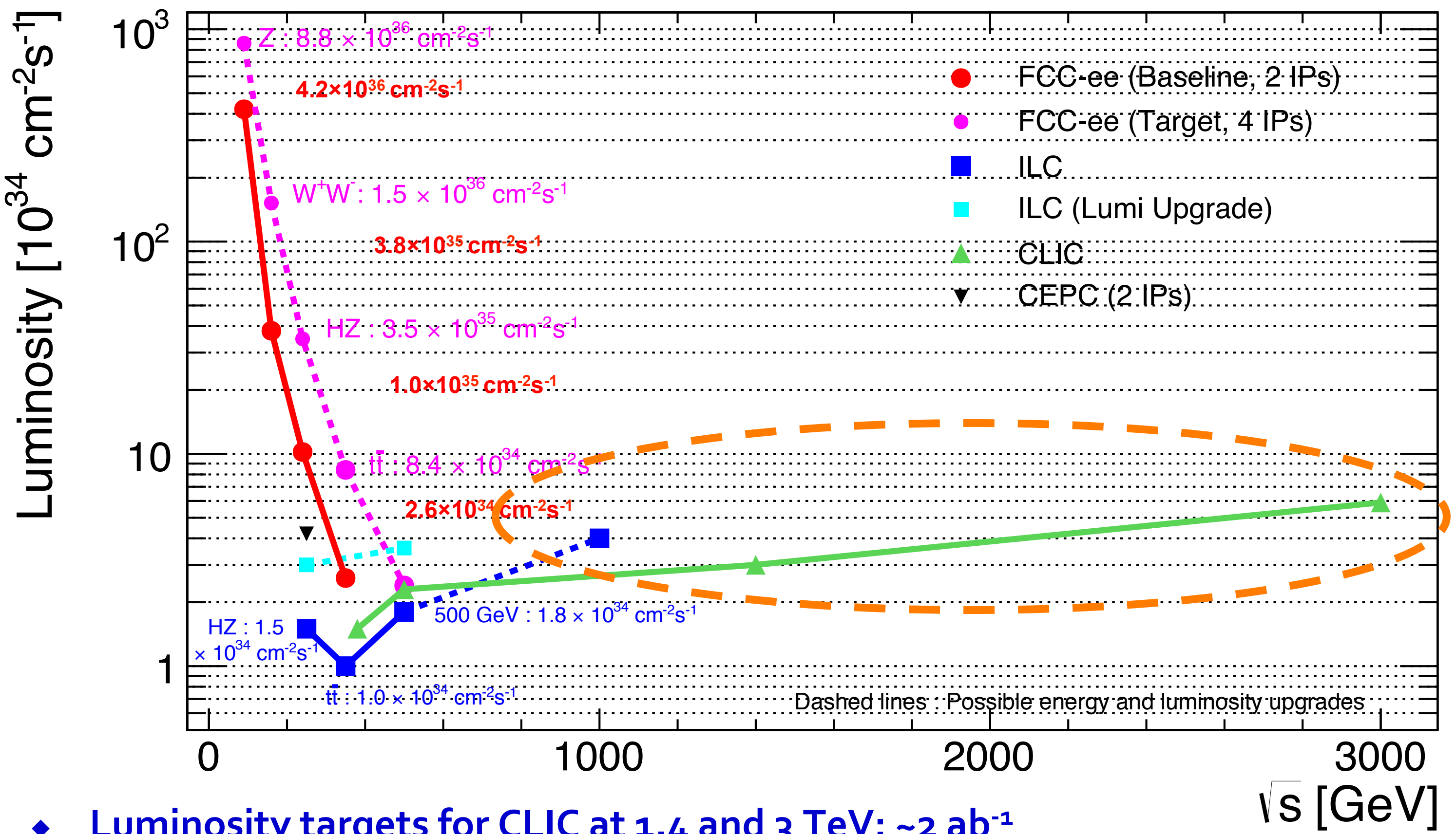
- The days of "guaranteed discoveries" are over …
  - … but the big questions remain :
    - What's the origin of dark matter ?
    - What's the origin of baryon asymmetry in the Universe ?
    - What's the origin of the neutrino masses ? Why are they so light ?
    - What's the origin of electroweak 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 (now)

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
√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 √s = 100 TeV**
- **Cross sections increase significantly from √s = 14 TeV to √s = 100 TeV**
  - ➨ **In general, statistical precision will not be not an issue at FCC-hh**

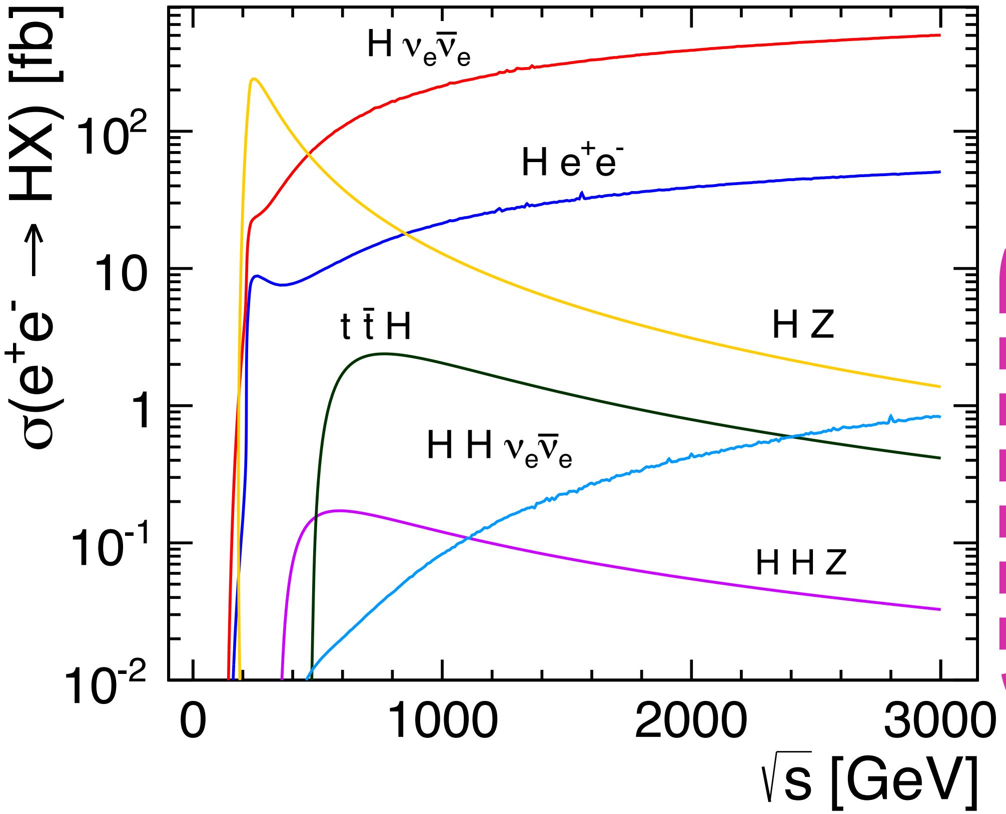
Precision: Higgs properties at high energy (1)

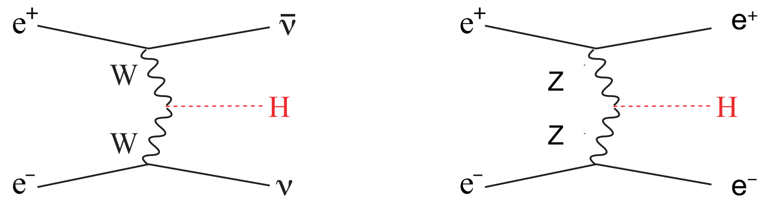
- Why would we continue to do precision Higgs physics at high √s?
  - Precision achieved with e^+e^- colliders at √s=240-350 GeV : 0.1% - 1%
    - Far superior than what can be done at higher energy
      - ➨ σ(HZ) decreases, kinematics less favourable, backgrounds increase, …
    - Far superior than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

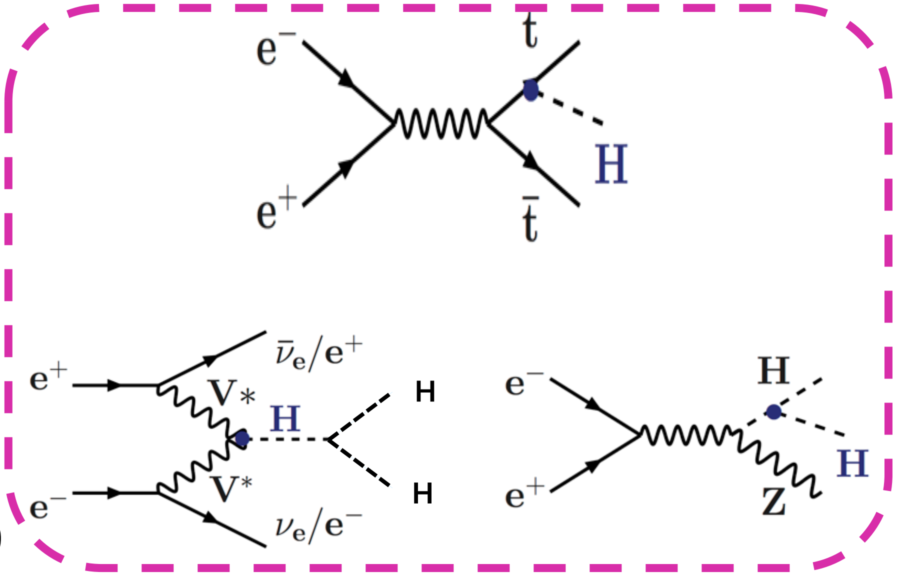
- However …
  - Some production processes are not directly accessible at low-energy e^+e^- colliders
    - Hence more couplings might become measurable at larger energy
      - ➨ e.g., Htt, HHH, HHHH, …
  - Some decay channels have very small branching fractions
    - Hence need more than 2×10^6 Higgs bosons to be measured with precision
      - ➨ e.g., $H \to \mu\mu, \gamma Z$, …
  - 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



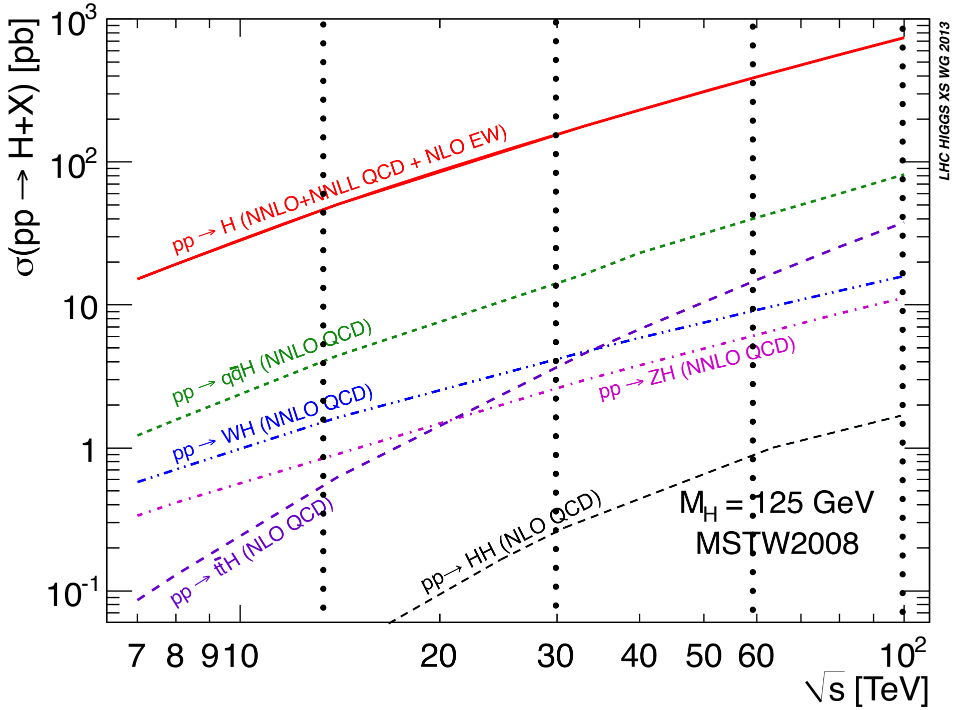




- Access to direct ttH coupling and Higgs self coupling measurements
  - Luminosity (at and) above 500 GeV essential for ttH
  - Larger energies essential for HHH

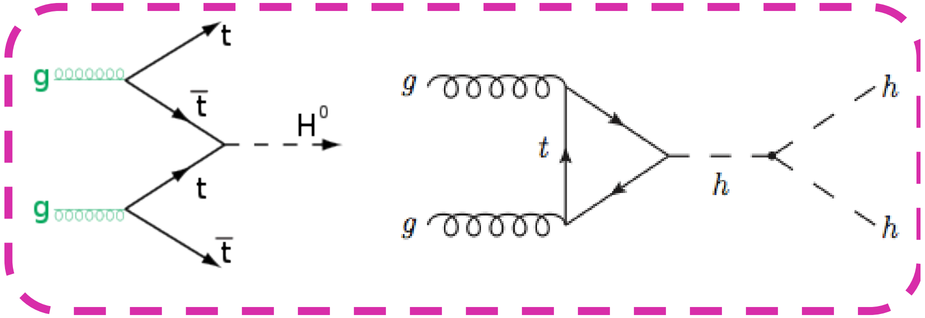
Precision: Higgs properties at high energy (3)

❑ Production in pp collisions



Large cross-section increase with √s

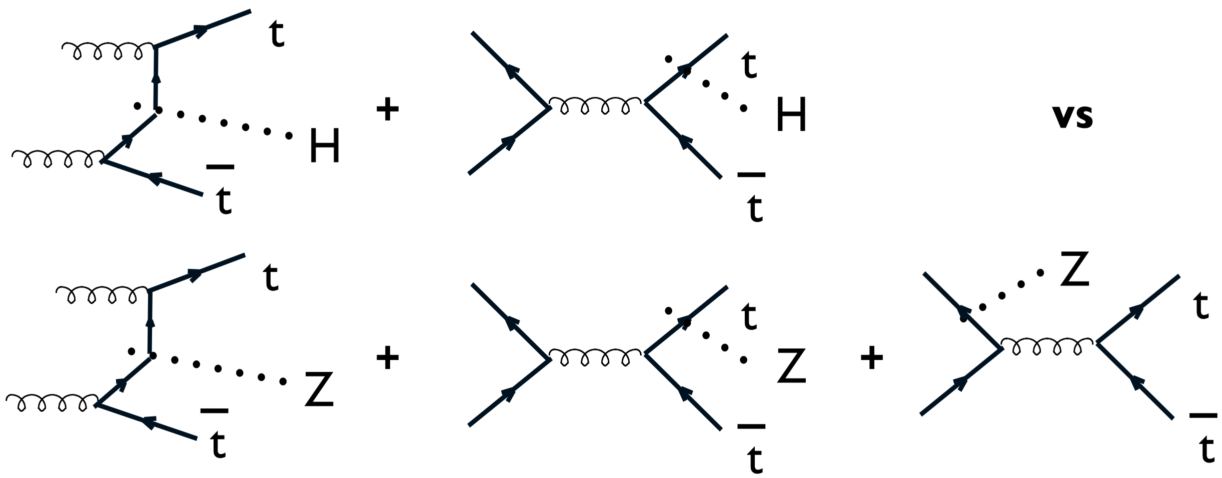
Process	14 TeV	33 TeV	100 TeV
gg → ttH	0.62 pb	4.5 pb × 7.3	37.8 pb × 61
gg → HH	33.8 fb	206 fb × 6.1	1.41 pb × 42



- With 30 ab^{-1} at FCC-hh
  - 10^9 gg → ttH events, 5×10^7 gg → HH events, 5×10^8 gg → H → μμ
    - ➨ 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%

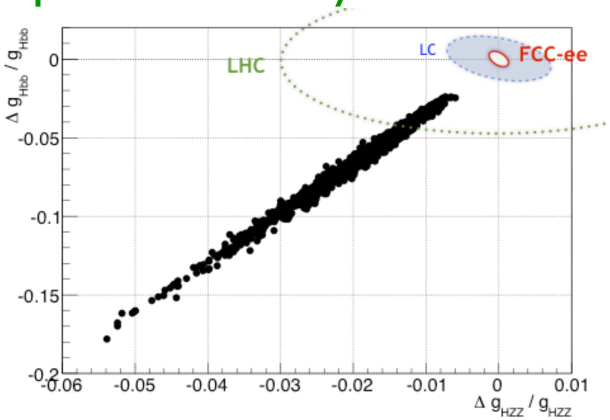
Precision: Higgs properties at high energy (5)

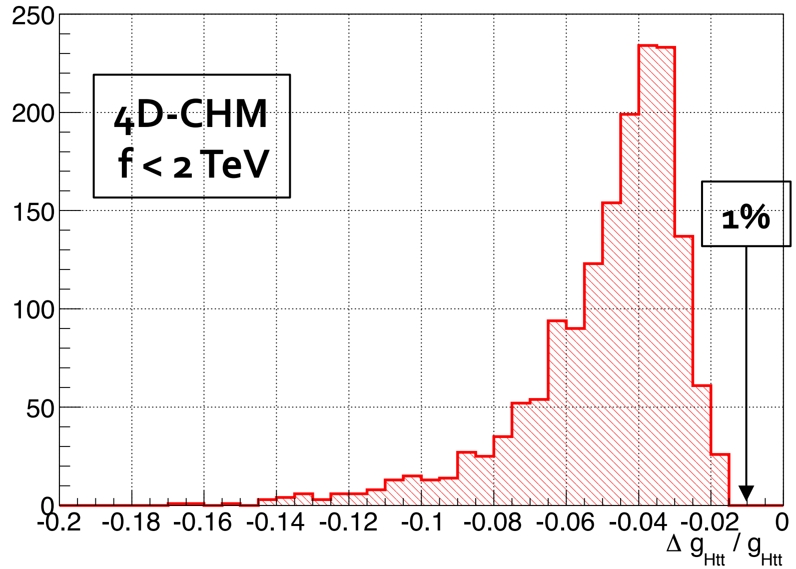
- Achievable precisions

Collider	HL-LHC	LC 500 GeV	LC 1-3TeV	FCC-ee+hh
λ_t	4%	7-14%	2-4%	<1%
λ_H	50%	30-80%	10-15%	<5%

- Higgs self-coupling @ FCC-hh estimated with gg → HH → bbγγ so far (10^5 events!)
  - Other channels are under study

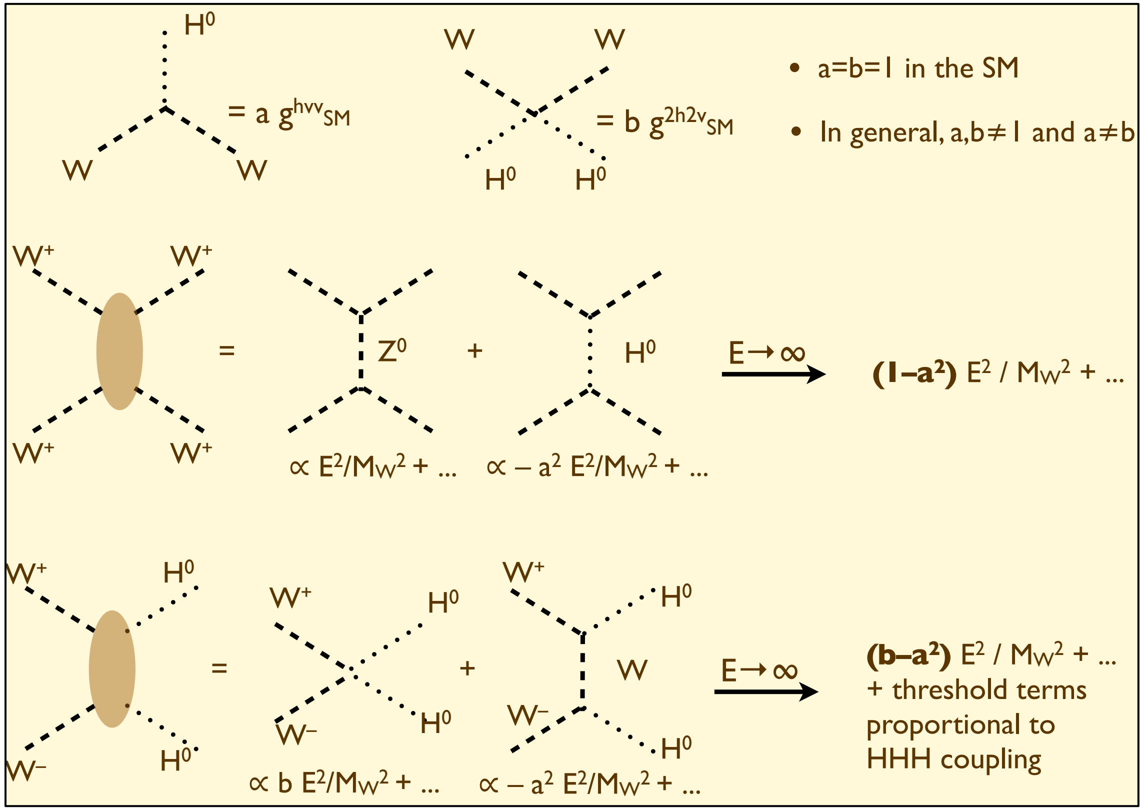
- Sensitivity to new physics (example)
  - ttH less sensitive than bbH+ZZH@FCC-ee
    - Improves sensitivity when combined

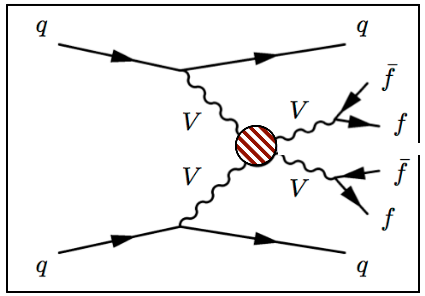




Precision: WW scattering at high energy

- **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 $m^4_{WW,HH}$





Precision on a and b

~30% at HL-LHC

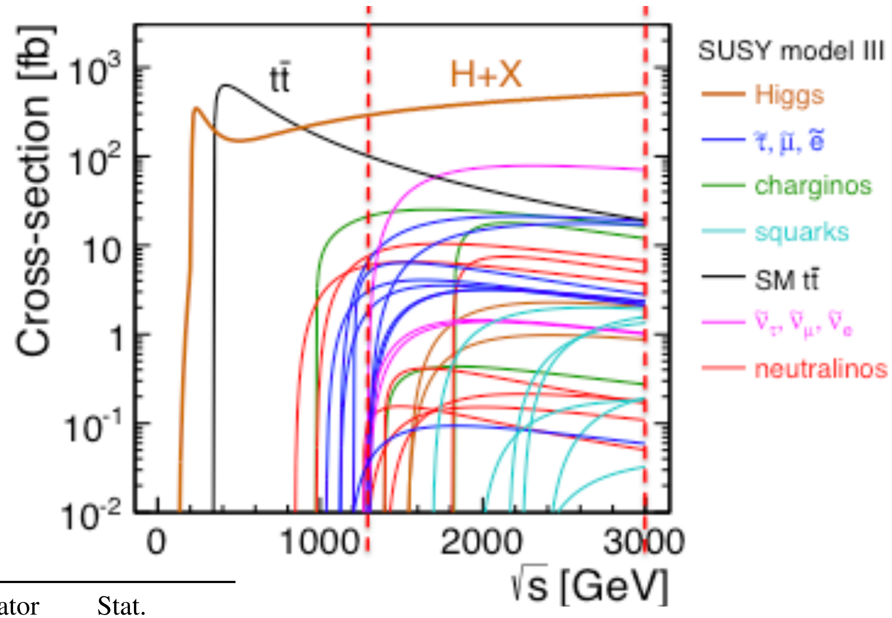
~30% with CLIC 3 TeV

~1% with FCC-hh 100 TeV

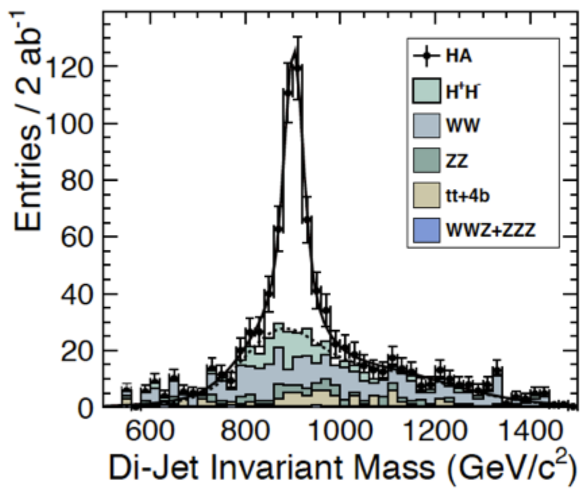
NB. "a" can be measured with 0.1% (1%) precision with FCC-ee (ILC)

Extended mass reach: Supersymmetry (1)

- **Production in e^+e^- collisions**
  - If the 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



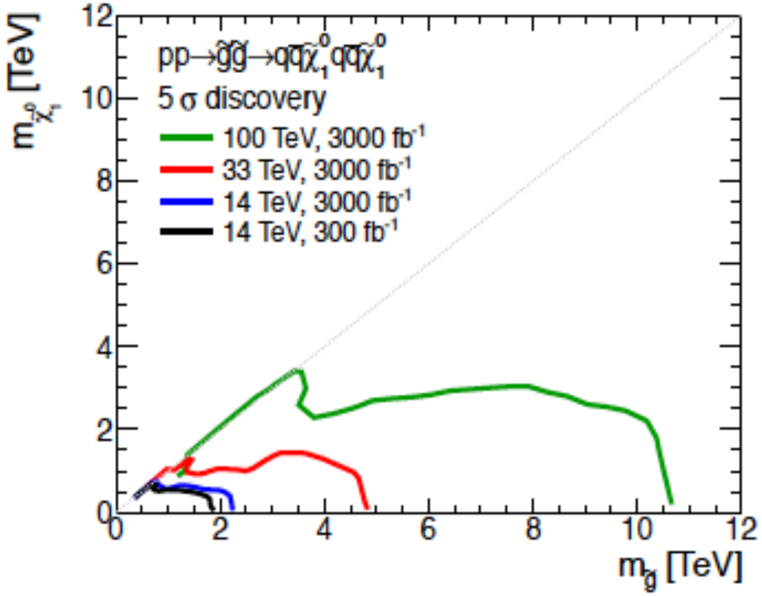
$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Generator value (GeV)	Stat. uncertainty
3.0	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	II	$\tilde{\ell}$ mass	1010.8	0.6%
				$\tilde{\chi}_1^0$ mass	340.3	1.9%
		$\tilde{e}_R^+\tilde{e}_R^-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

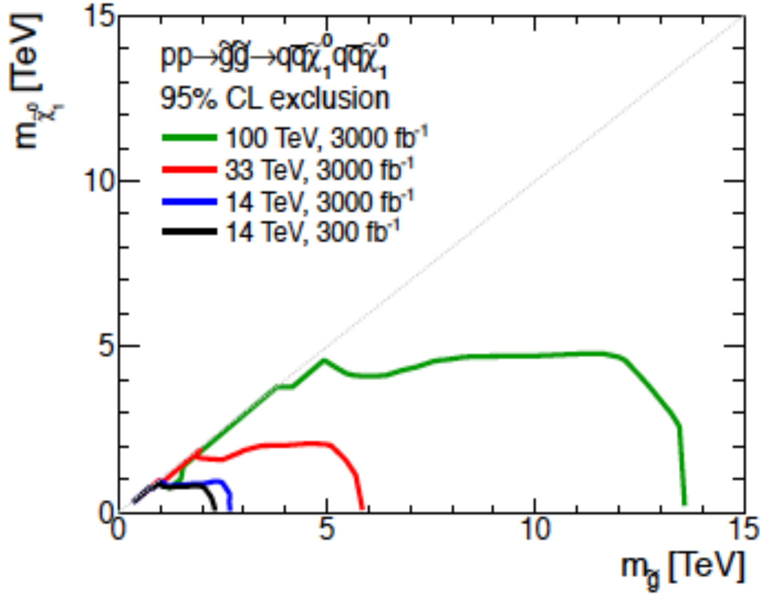


Example: Heavy Higgses

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 ~ (5) 11 TeV with 3 ab^{-1} @ (HE-LHC) FCC-hh





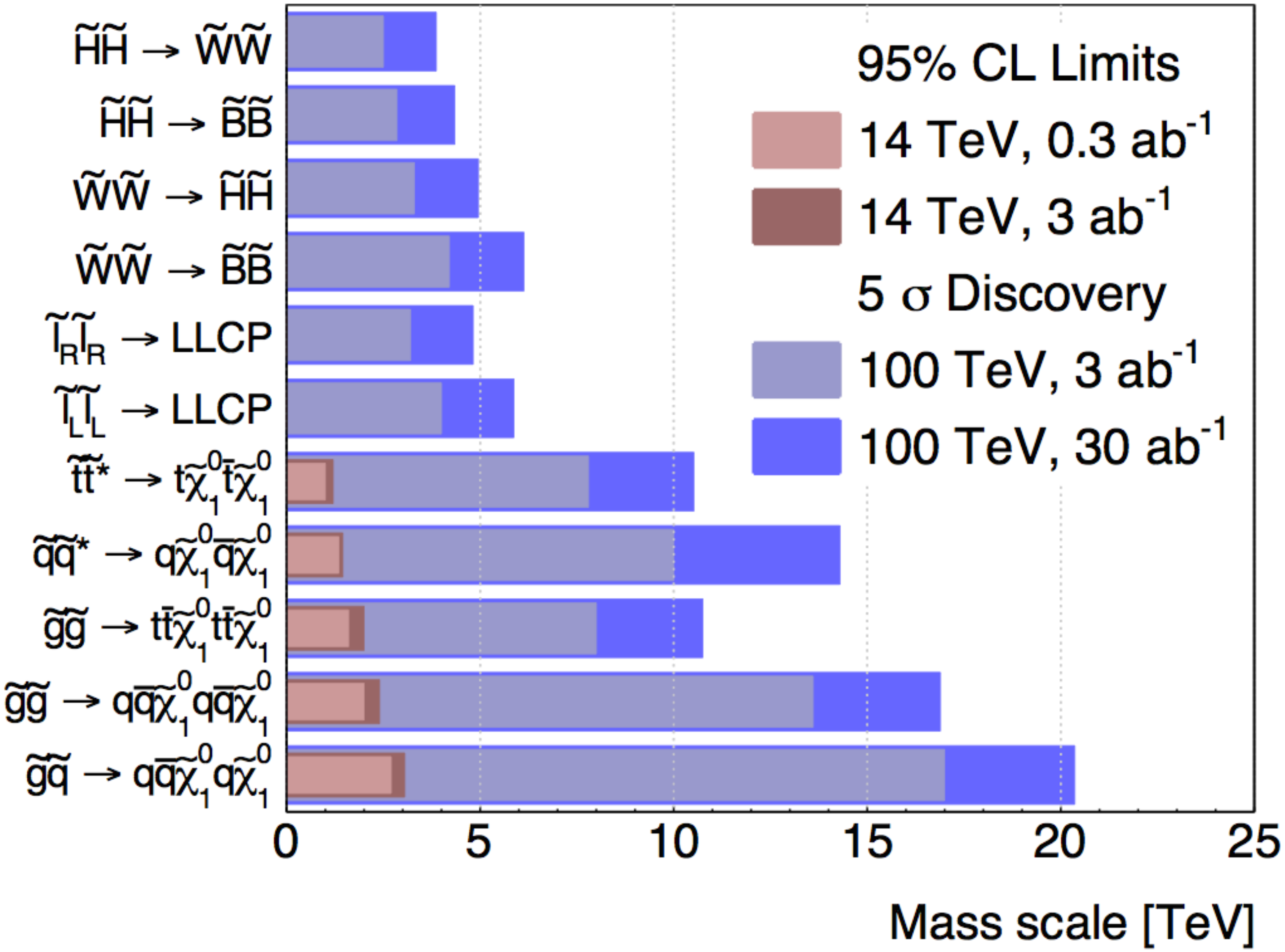
- Discovery reach of stop searches

  Up to 3 TeV with HE-LHC

  Up to 10 TeV with FCC-hh

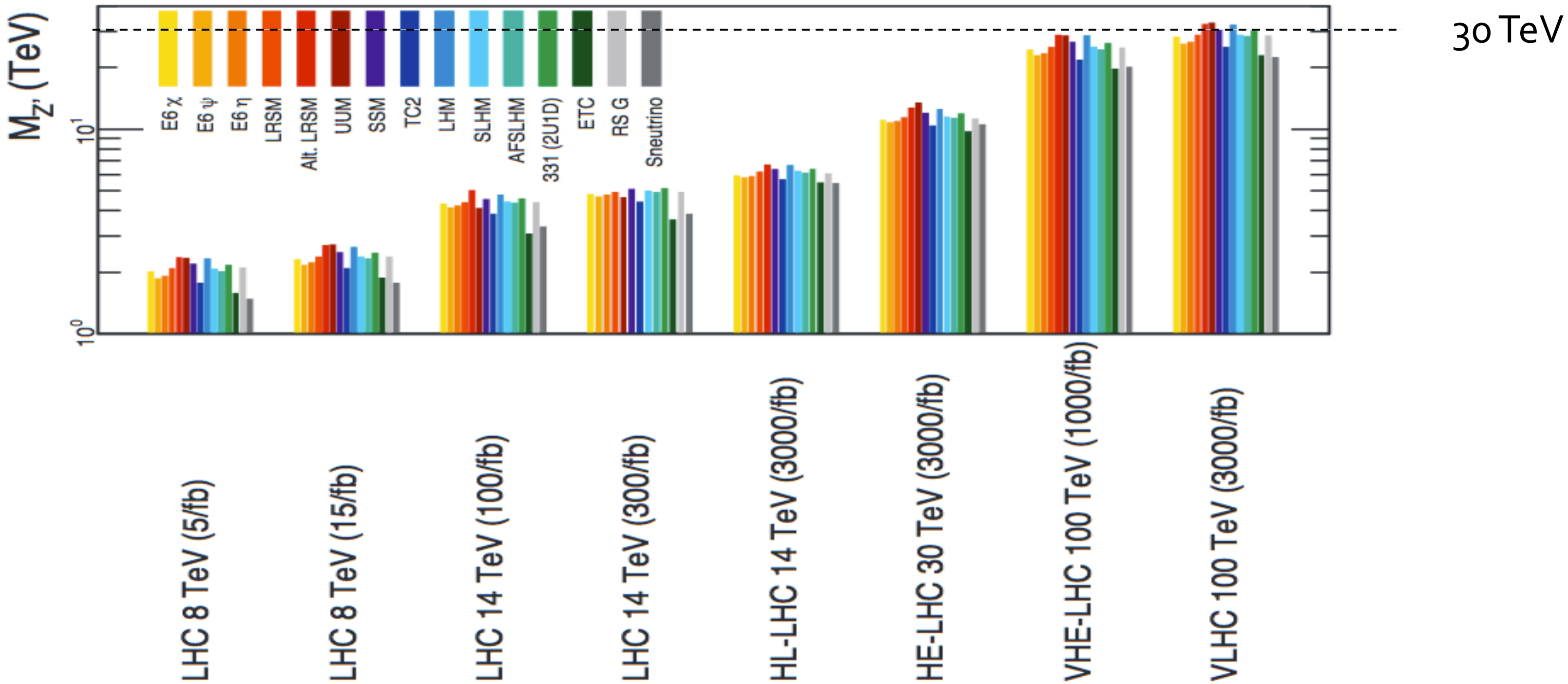
Extended mass reach: Supersymmetry (3)

- **Updated super-summary**



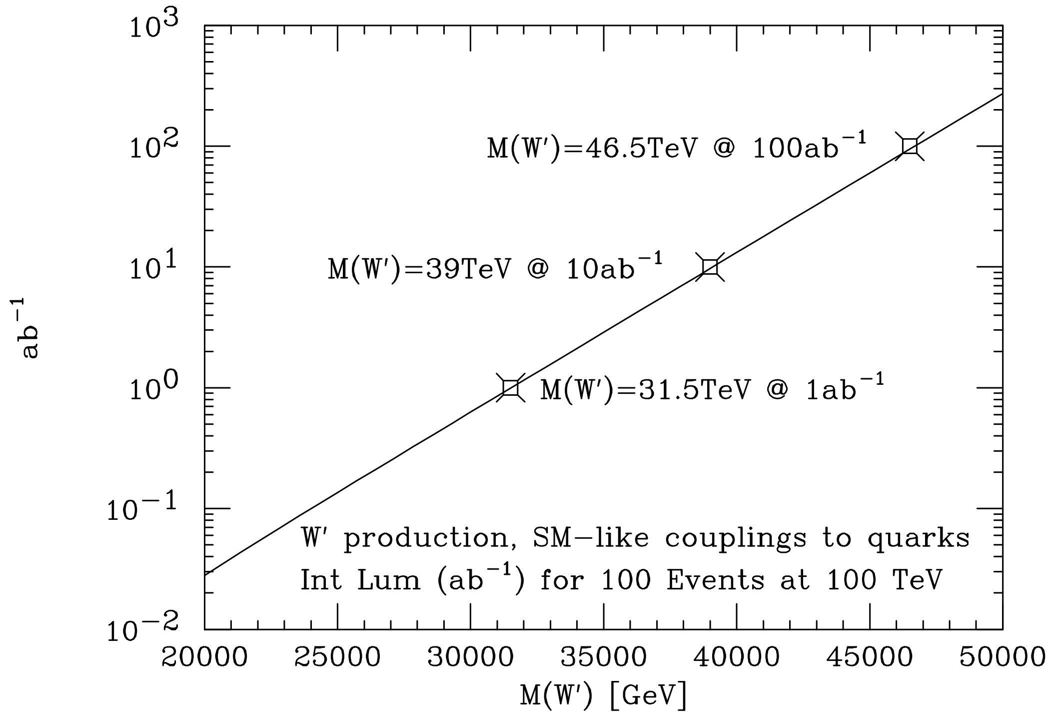
Extended mass reach: New gauge bosons (1)

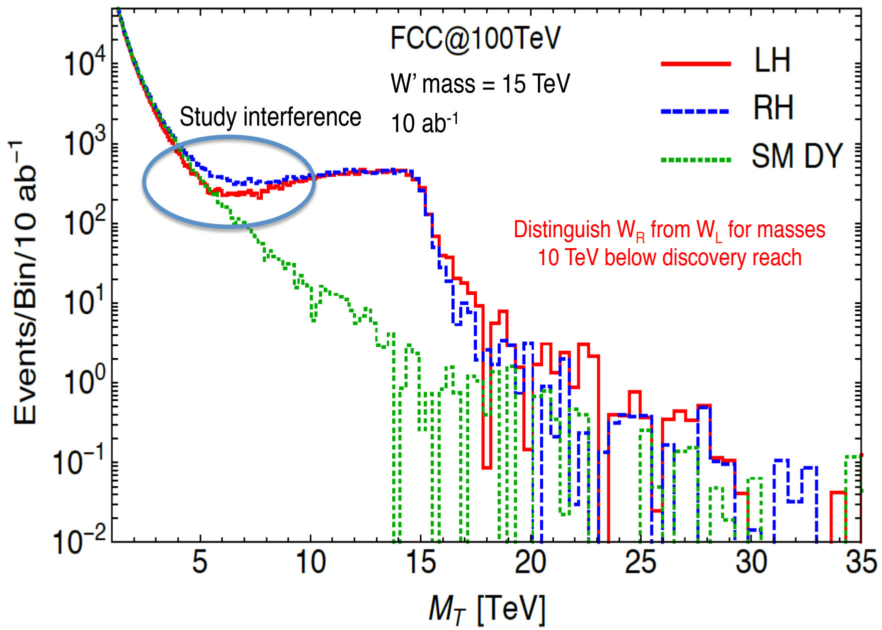
- **Example 1: Searches for new Z′**
  - **FCC-hh directly sensitive up to $m_{Z'}$ ~ 30-35 TeV (vs. ~ 3TeV for CLIC)**
    - **By looking for di-lepton resonances**
  - **CLIC 3-TeV indirectly sensitive up to $m_{Z'}$ ~ 15-20 TeV**
    - **By looking for deviations in the di-lepton mass distribution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



Extended mass reach: New gauge bosons (2)

- **Example 2: Searches for new W′**
  - **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**



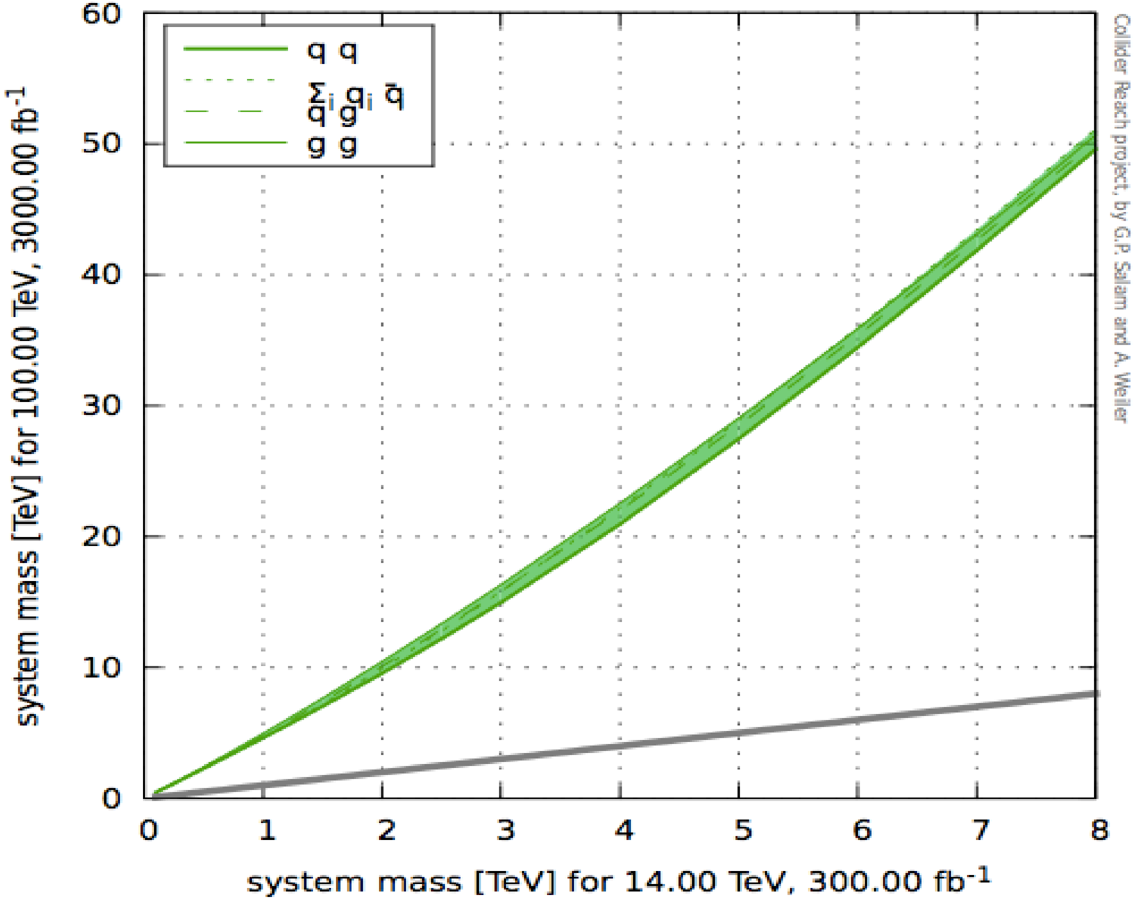


Extend the mass reach by ~ 7 TeV when L × 10

May be able 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 ad 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**
  - 3×10^{10} Higgs bosons = 10^4 today's statistics, 10^4 FCC-ee statistics
    - More precision measurements
    - Rare decays, FCNC probes, e.g., $H\to e\mu$ …
  - 3×10^{12} top quarks = 10^5 today's statistics, 3×10^6 FCC-ee statistics
    - Rare decays, FCNC probes, e.g., $t\to cZ$, cH
    - CP violation
    - 10^{12} W and 10^{12} b from top decays
    - 10^{11} τ from $t \to W \to \tau$
      - Rare decays, e.g., $\tau \to 3\mu$, $\mu\gamma$, CP violation …
    - BSM decays : any interesting channels to consider ?
      - Example: Majorana neutrino search in top decays

BNL-HET-
OITS

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

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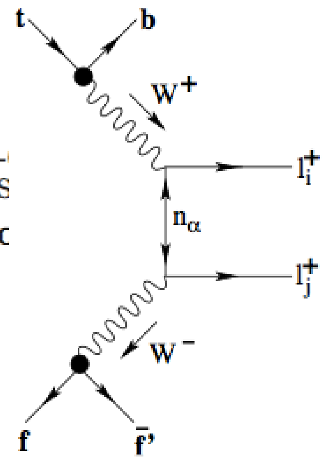
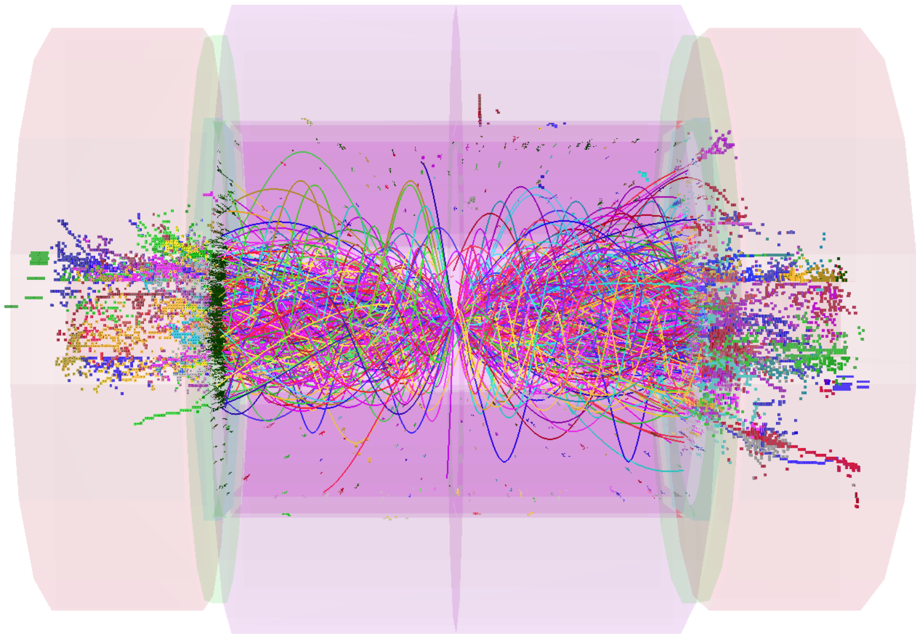
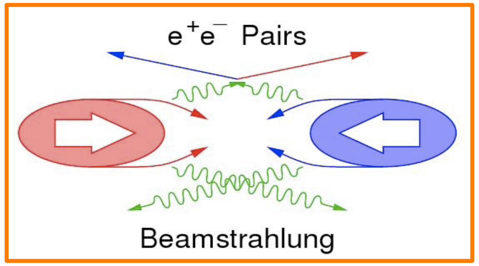


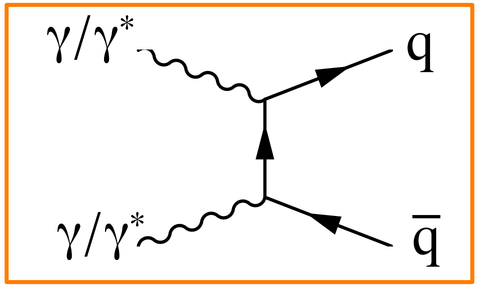
Not just a mere extrapolation: Detectors (1)

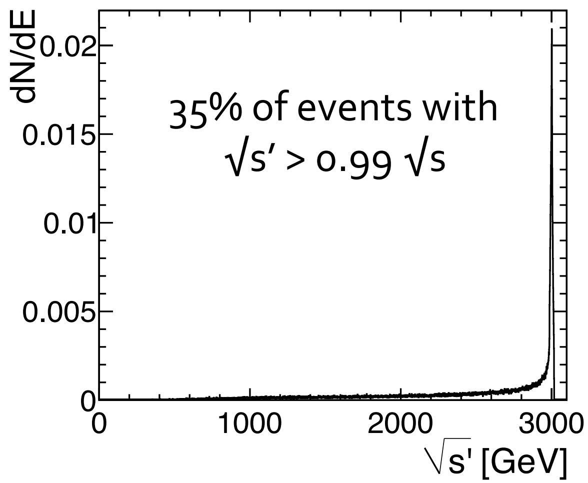
- **Experimental conditions at CLIC**
  - **Important beamstrahlung due to bunch charge density**
    - **Radiated photon and electron-pair background**
    - **Pile-up of photon-photon collisions (mini-jets)**
    - **Reduction of effective centre-of-mass energy**



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



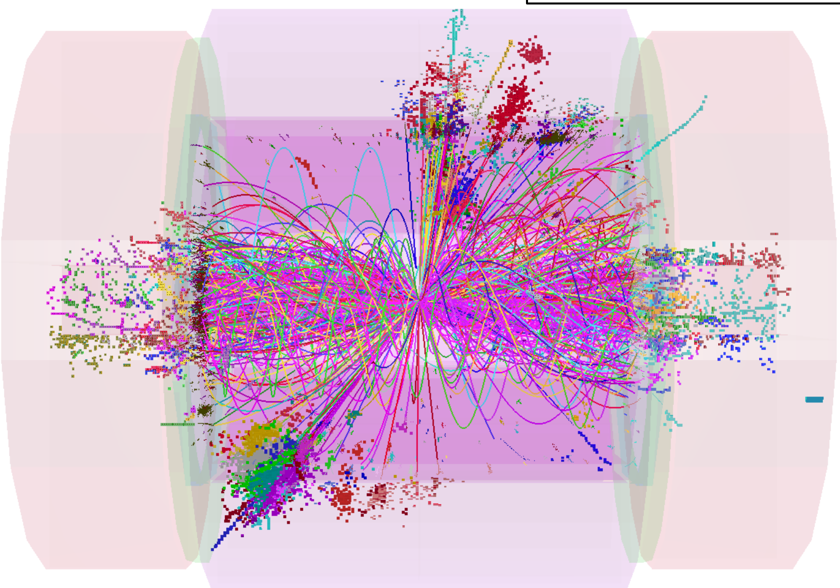


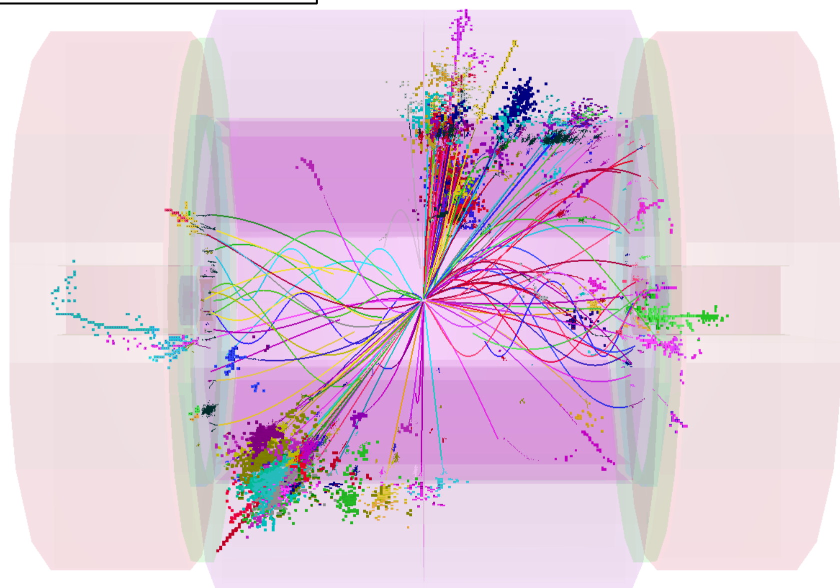


Not just a mere extrapolation: Detectors (2)

- **Experimental conditions at CLIC, cont'd**
  - To find elusive signatures, 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





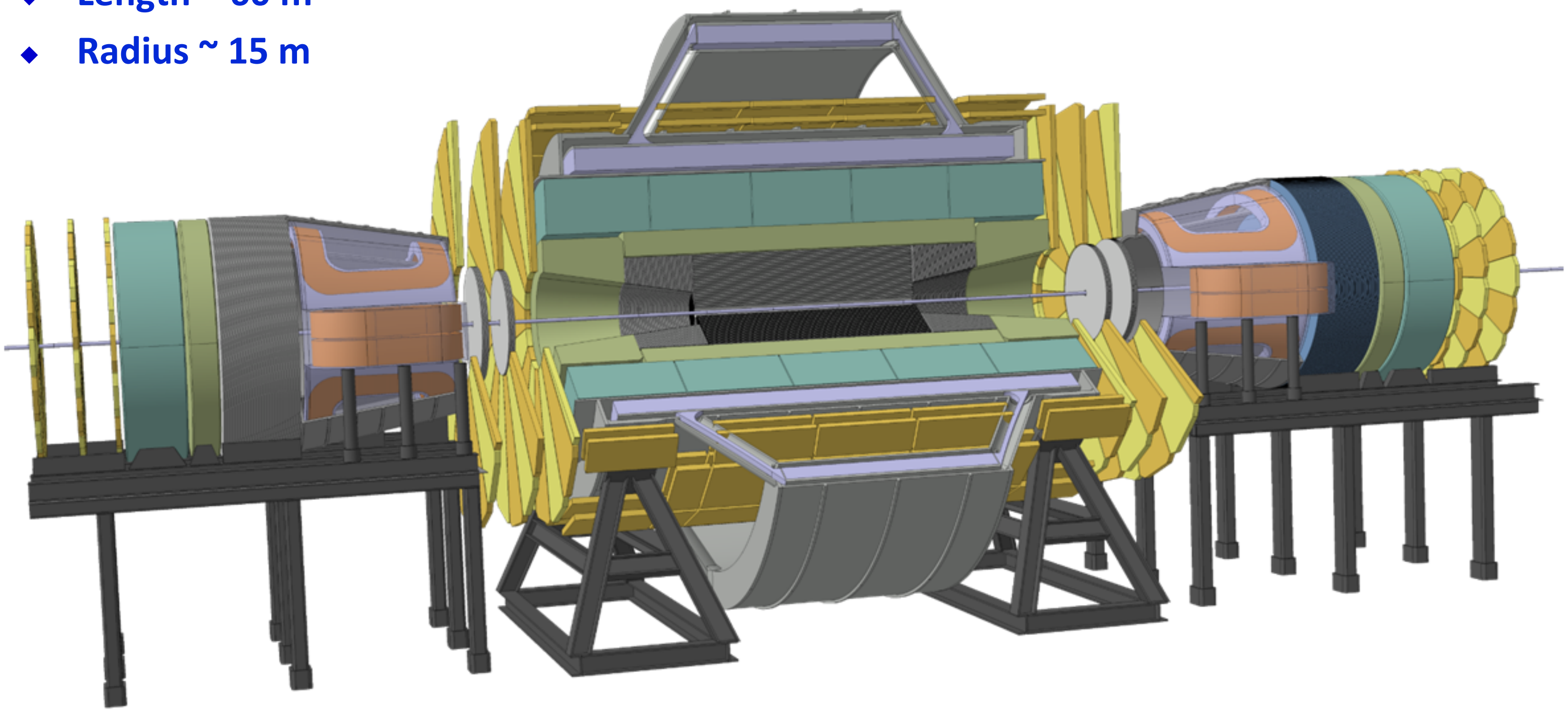
Not just a mere extrapolation: Detectors (3)

- **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
  - Zs, Ws, Higgses, tops, will also be boosted
    - Again, high-granularity detectors needed
  - Very energetic charged particles
    - Precise momentum measurement up to 10 TeV: strong B field (6T) and large tracker
  - Very energetic jets
    - Energy containment require thicker calorimeter

Bigger, thicker, faster, stronger, clever detectors

Not just a mere extrapolation: Detectors (4)

- **Initial option: Twin Solenoid 6T, 12m bore, Dipoles 10Tm**
  - Length ~ 60 m
  - Radius ~ 15 m



  - Cost ~ 2-3 BCHF – not entirely reasonable
    - Scale down magnet system to 10m, 4T solenoid and 4Tm dipoles
      - ➨ Reduces the cost by a factor 2.

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 √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

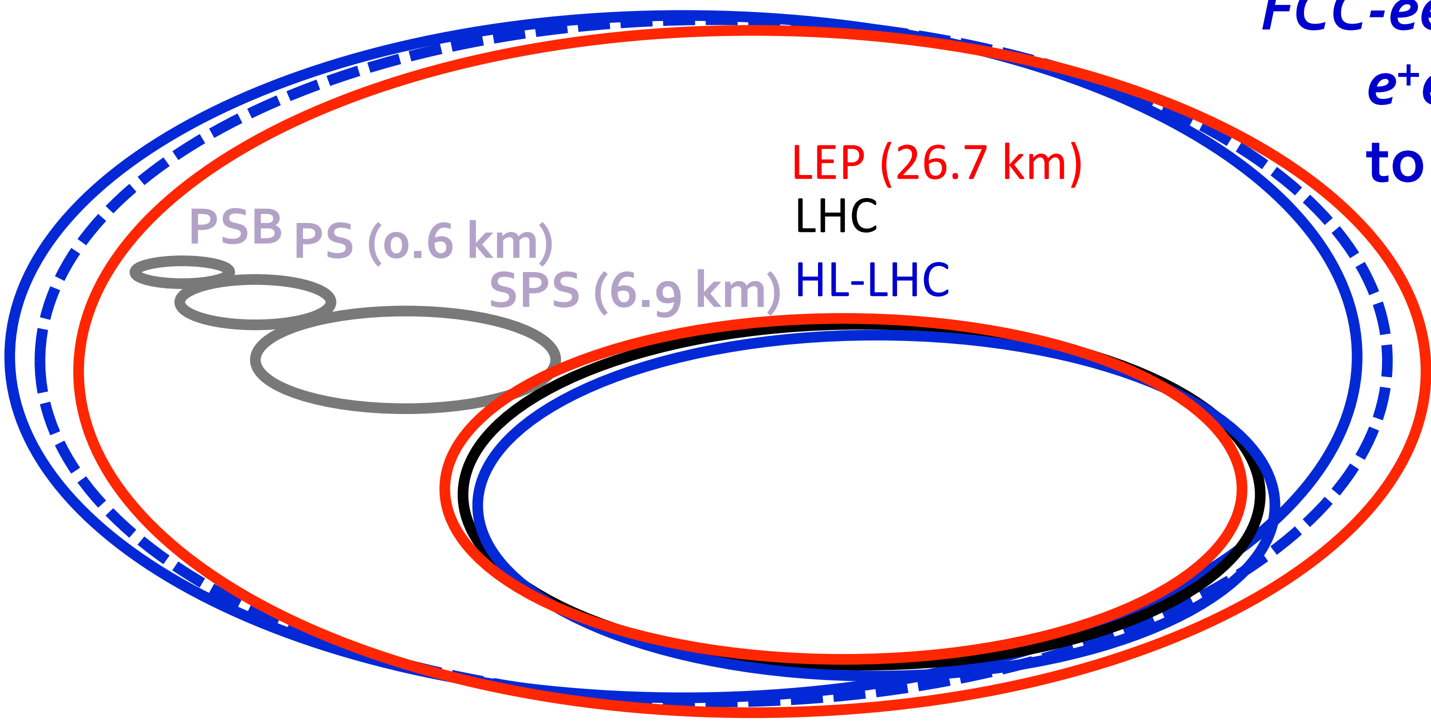
Plasma acceleration?
> 1 GV/m
4 km + final focus

Energy Frontier
20 B\$, 2060 ?

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

Summary at this point (2)

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



FCC-ee **(80-100 km, e^+e^-, √s from 90 to ~400 GeV)**

Precision studies of Z, W, H, top
3-5 B$, 2035 ?

FCC-hh **(*pp*, up to 100 TeV c.m.)**

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

& ***e*± (50-175 GeV) – *p* (50 TeV)** collisions (*FCC-he*)

≥ 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 risk is still quite high (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 might still 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

- Next update of the European Strategy in 2019-2020 : stay tuned !

Lecture 3 (2nd part)

Thinking out of the box

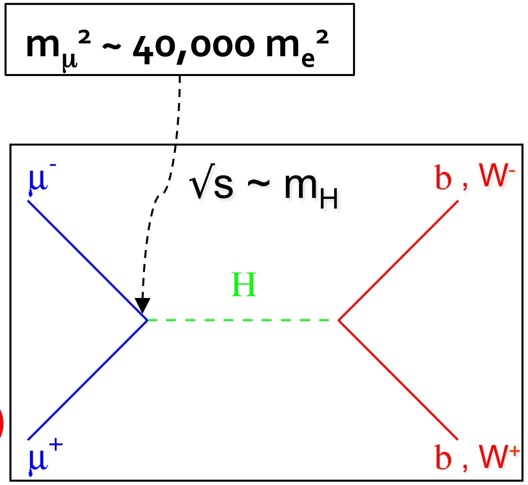
Muon Colliders

Note:

- **Muon colliders were not identified as priority by the European Strategy update in 2013.**
- **However, interest has recently with new ideas that may make them realizable**
- **It is therefore important to understand the relevant ins and outs**

Why muon colliders ?

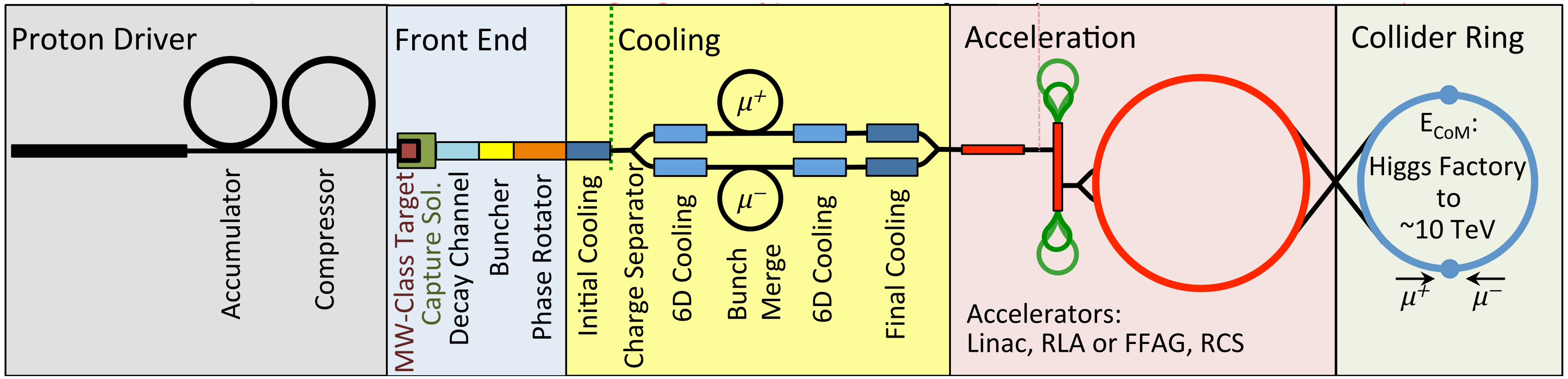
- **Muons are leptons (like electrons)**
  - Collisions at the full energy, small physics background, (E,p) conservation
    - Muons can a priori do all what electrons can do
- **Muons are heavy (like protons)**
  - Negligible synchrotron radiation, no beamstrahlung
    - Small circular colliders, up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



- **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 until 2014

- **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 colliders challenges since 2014 ?

Clever alternative

- Intense e^+ beam with E = 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
    - ➨ Unique synergy with FCC-ee
    - ➨ Energy Recovery Linac is also a possibility
- Production at threshold ($\sqrt{s} \sim 2\, m_\mu$)
  - Quasi monochromatic muons, almost no need for cooling
    - ➨ Except for the 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 than the proton-driver option

Muon collider optimal circumference(s)

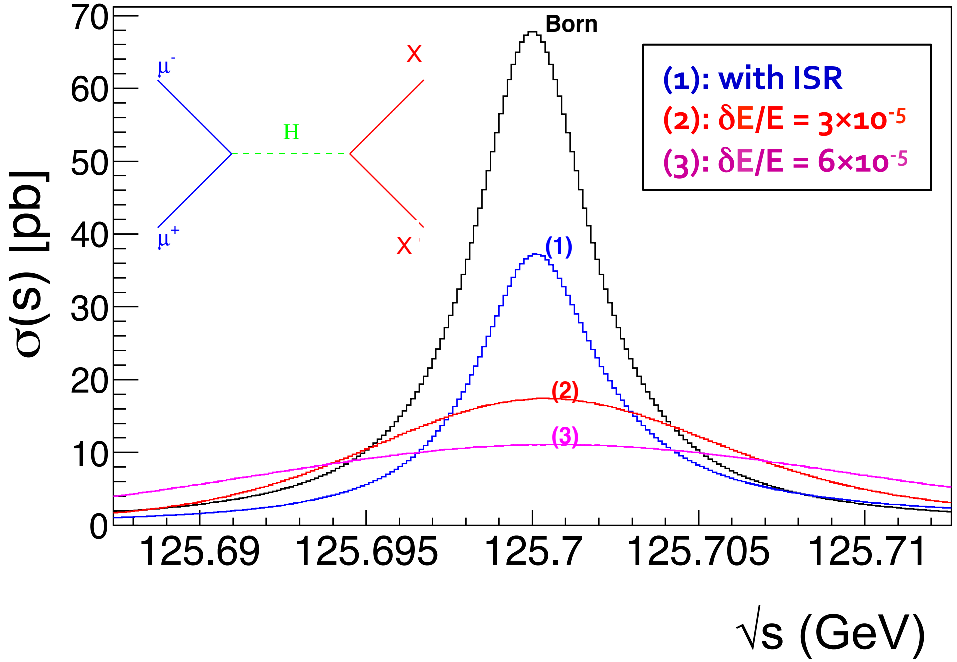
- **Muon decay: Minimize the ring circumference**
  - To allow the produced muons to collide as many times as possible before they decay
    - With 14T state-of-the-art dipoles, the optimal ring size is proportional to E_μ

$\sqrt{s}$	91 GeV	126 GeV	161 GeV	350 GeV	6 TeV	24 TeV
$t = \beta\gamma\tau_\mu$	0.94 ms	1.27 ms	1.67 ms	3.64 ms	68.7 ms	280 ms
$L = \beta\gamma c\tau_\mu$	284 km	383 km	502 km	1092 km	20600 km	84000 km
Ring	100 m	140 m	180 m	385 m	6.6 km	27 km
N_{turns}	~2840 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 (385 m circumference)
    - One larger ring for the energy frontier
      - $\sqrt{s}$ = 6 TeV can fit, for example, in the Tevatron (6.6 km circumference)
      - $\sqrt{s}$ = 24 TeV can fit in the LHC
    - Plus a number of rings for first stages of fast accelaration

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 3.5×10^{33} cm^{-2}s^{-1} for the same number of Higgs bosons as FCC-ee
      - ➨ Fast transverse cooling to reduce beam spot dimensions

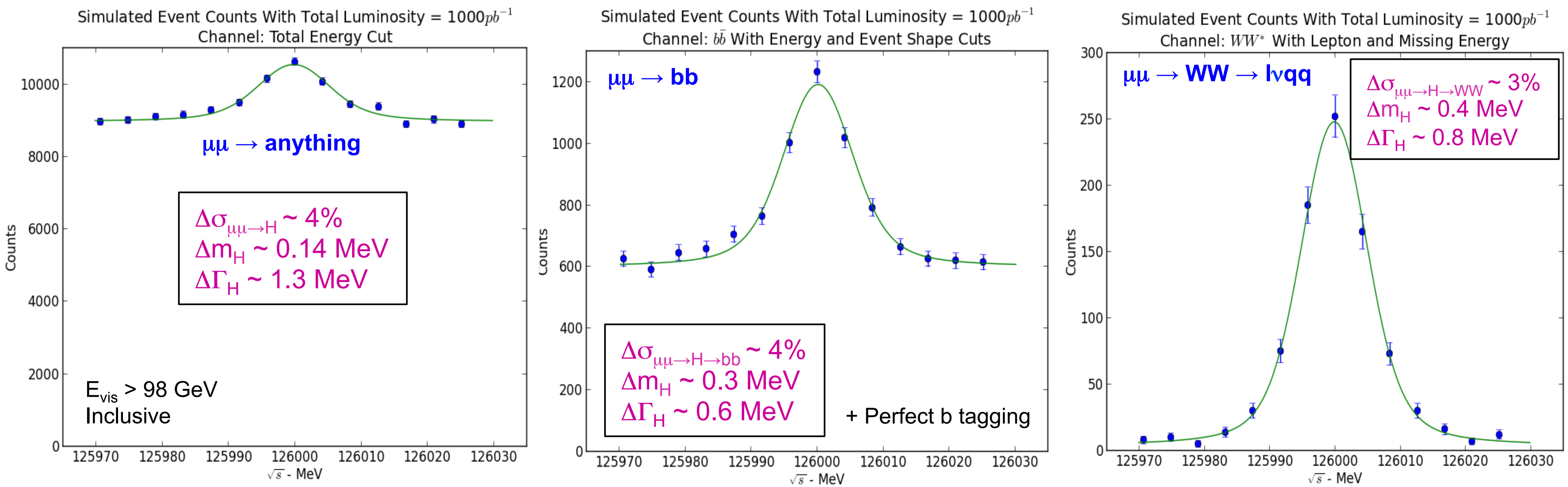
And the Higgs bosons produced are not tagged with a Z anyway …

  - 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 measurements on the next slide.**

Muon collider as a Higgs factory (4)

- **Summary of precision measurements (after ~10 years of running)**

Error on	$\mu\mu$ 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 sure of the practical use of such a precision on m_H

The Higgs width is best measured at ee colliders

These Higgs couplings are best measured at ee colliders

The SM Higgs coupling to muons is *the* added value of a $\mu\mu$ collider *

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

* pp colliders have their say, too

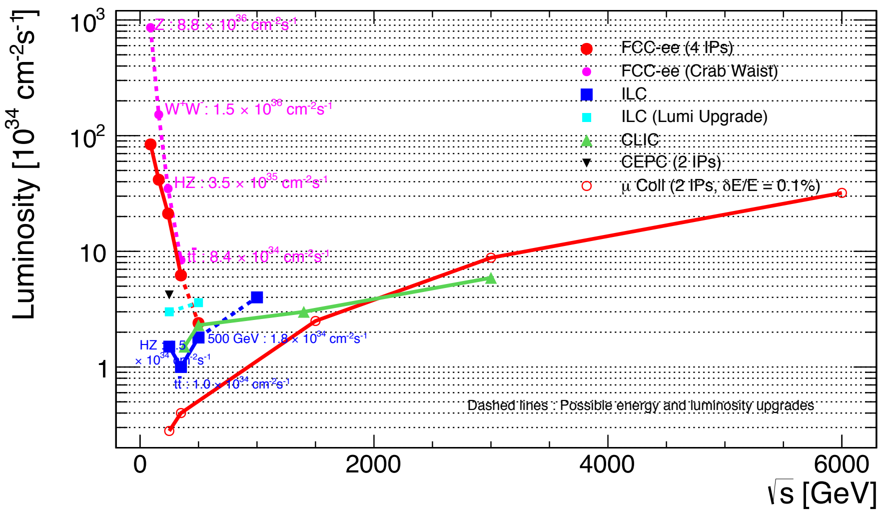
- **Note: BR(H→ $\mu\mu$) can also be measured with % precision at FCC-hh. (Will be already 10% after LHC.)**

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 with Earth)**
- **For the record, here are the current target performance**

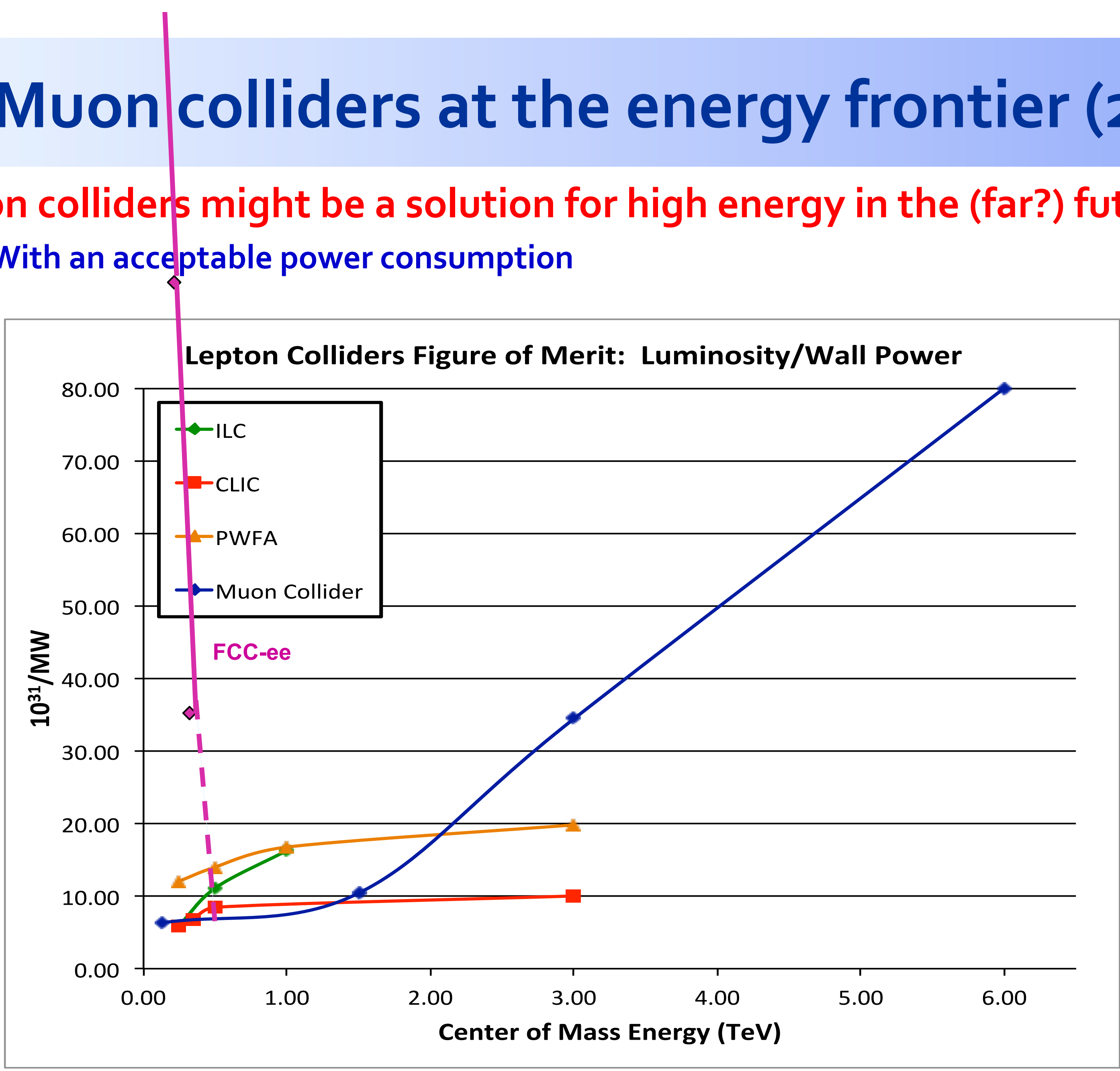
√s (TeV)	0.091	0.125	0.3	1.5	3.0	6.0
Lumi (10^{34} $cm^{-2}s^{-1}$)	0.01	< 0.008	0.2	1	4	15
R = Δp/p (%)	0.1	0.003	0.1	0.1	0.1	0.1

  - **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 (or not) / 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, e^+e^- can measure the Higgs width very well
    - A muon collider can also do that, but much higher luminosity would be necessary
      - ➨ At least two orders of magnitude – limited by the p/e^+ source.
- Several quasi-degenerate Higgs bosons is a strong case for muon colliders
  - 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 is the natural second step of neutrino factories / FCC-ee
- Conclusion: don't kill it, but don't oversell it !

Lecture 3 (3rd part)

Towards the next strategy update (2019)

Personal views

What have we learnt since 2013 ?

- **LHC accelerator**
  - Successful refurbishment towards $\sqrt{s}$ > 13 TeV in 2013-14
  - The Run2 at $\sqrt{s}$ = 13 TeV proceeds extremely well – possibly 50 fb^{-1} in 2016 !
- **LHC detectors**
  - The experiments continue to perform very well, too – see ICHEP results @ Chicago
- **LHC Physics**
  - No convincing 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 (50-70km – so far)
      - ➨ Current focus on 250 GeV e^+e^- machine, followed by 50 TeV pp collider

What will we know after LHC Run 2 ?

- If new physics is found in LHC Run 2
  - 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

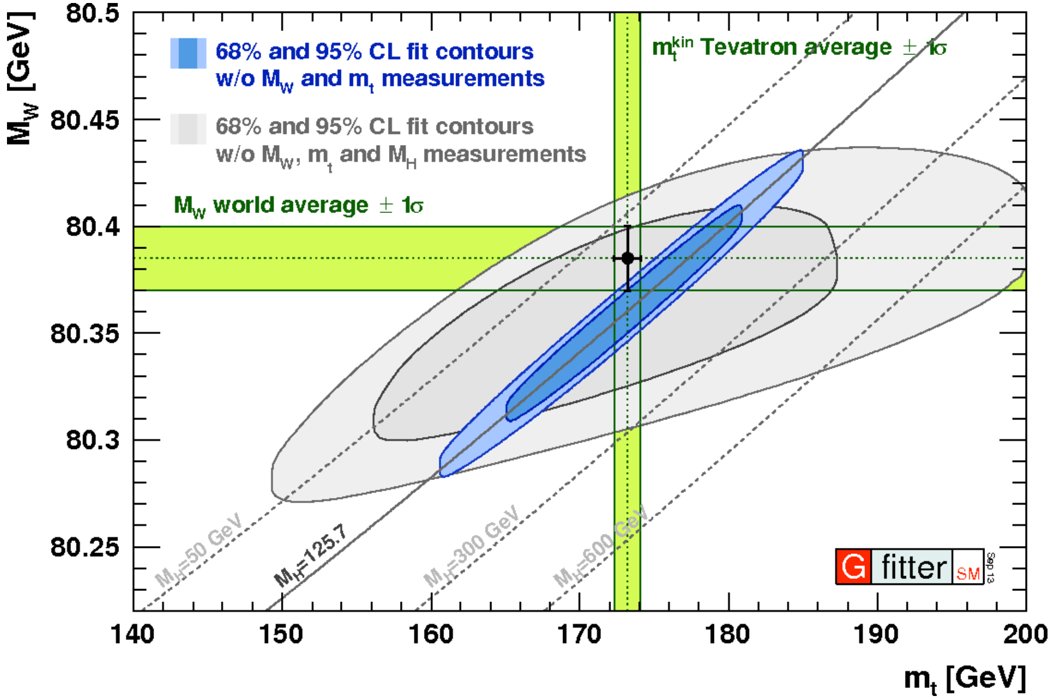
- Much greater challenge if no new physics is found in Run2
  - Cannot continue indefinitely with R&D towards all possible future facilities
    - A choice will have to be made in 2019-2020

    - However, it is impossible for the LHC to rule out all possible new particle 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
      - ➨ Minimal energy / luminosity for a lepton / hadron 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 at the Z pole

➨ Also calls for significant theoretical progress in this area

- 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 < $\sqrt{s}$ < 350-500 GeV**
  - Precision Higgs and electroweak physics
- **Much harder to make physics case for e^+e^- colliders with $\sqrt{s}$ > 350-500 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
    - T2K highest priority for Japan, strengths of the collaborations, … etc
- **Hard to imagine next major investment in R&D for CLIC (~300 MCHF)**
  - Without clear evidence of new physics to study
- **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
    - … and political progress not as fast as anticipated

- 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

- CERN should continue to expand geographically
  - With new associate member states
  - With financial contributions of associate members
  - … and maybe persuade China to make a large in-kind contribution to 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

DISCUSS !