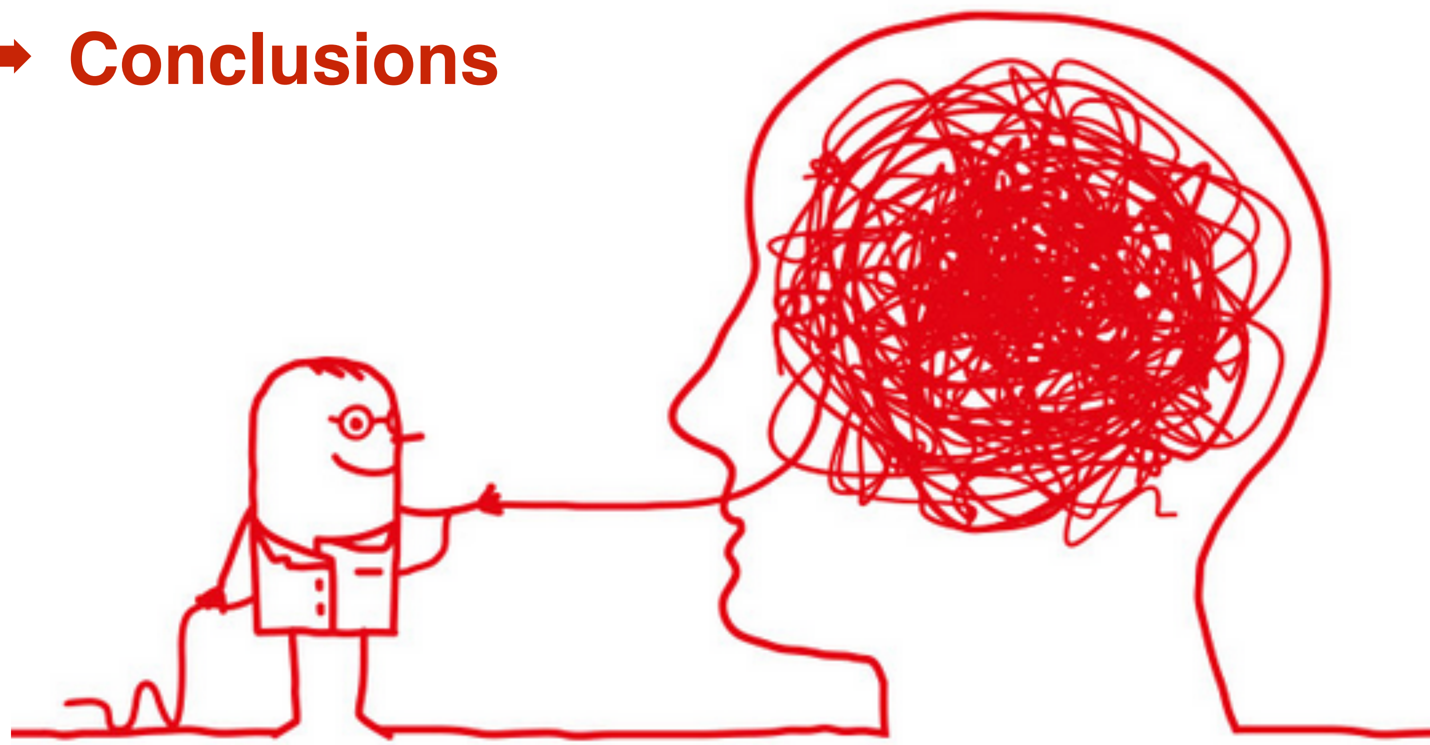
Higgs Bosons at Future Lepton Colliders

Markus Klute (MIT)
October 15th, 2015
Higgs Couplings 2015 - Lumley Castle, UK

Outline

- **Introduction**
  - Case for precision Higgs physics
  - Future lepton collider projects in a nutshell
- **Higgs Production at Lepton Colliders**
  - Processes
  - Energy
  - Luminosity
- **Higgs studies at lepton collider**
  - Couplings
  - Mass
  - Total width
  - BSM Higgs
- **Conclusions**



Case for precision Higgs physics

➡ **How large are potential deviations from BSM physics?**

➡ **How well do we need to measure Higgs couplings?**

- To be sensitive to a deviation δ, the measurement needs a precision of at least δ/3, better δ/5
- Implications of new physics scale on couplings from heavy states or through mixing

$$g = g_{\mathrm{SM}}\,[1+\Delta] \quad : \quad \Delta = \mathcal{O}(v^2/\Lambda^2)$$

$\frac{\Gamma_{\mathrm{2HDM}}[h^0 \to X]}{\Gamma_{\mathrm{SM}}[h \to X]}$	type I	type II	lepton-spec.	flipped
VV^*	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$
$\bar{u}u$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$
$\bar{d}d$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$
$\ell^+\ell^-$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$

arXiv:1310.8361

➡ **Percent-level precision needed to test TeV scale**

➡ **There is no strict limit to the precision needed!**

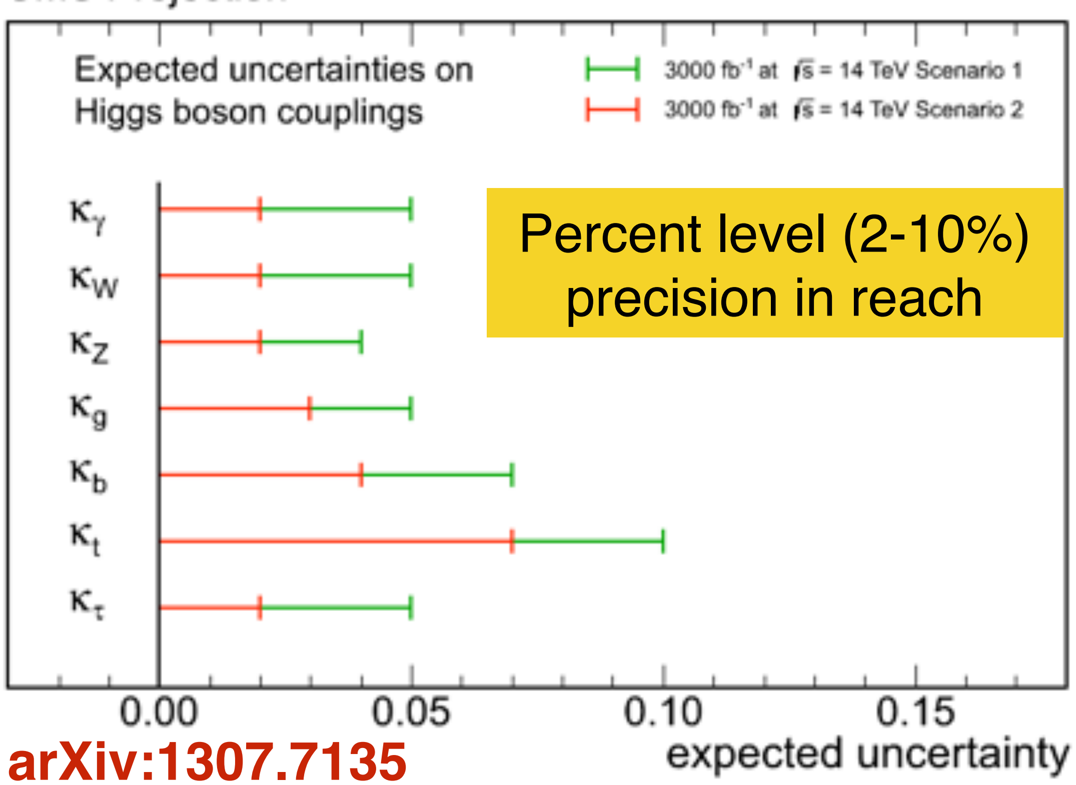
Why Lepton Colliders?

Parameter	ATLAS+CMS Measured	ATLAS+CMS Expected uncertainty	ATLAS Measured	CMS Measured
Parameterisation assuming $BR_{BSM} = 0$				
κ_Z	$1.03^{+0.11}_{-0.11}$	$^{+0.10}_{-0.11}$	$1.00^{+0.14}_{-0.14}$	$1.07^{+0.17}_{-0.18}$
κ_W	$0.91^{+0.10}_{-0.10}$	$^{+0.10}_{-0.11}$	$0.92^{+0.13}_{-0.13}$	$0.90^{+0.15}_{-0.15}$
κ_t	$1.43^{+0.23}_{-0.22}$	$^{+0.26}_{-0.32}$	$1.31^{+0.30}_{-0.32}$	$1.56^{+0.34}_{-0.32}$
κ_τ	$0.88^{+0.13}_{-0.12}$	$^{+0.16}_{-0.15}$	$0.97^{+0.19}_{-0.17}$	$0.82^{+0.19}_{-0.17}$
κ_b	$0.60^{+0.18}_{-0.18}$	$^{+0.25}_{-0.24}$	$0.61^{+0.26}_{-0.26}$	$0.61^{+0.27}_{-0.26}$
κ_g	$0.81^{+0.11}_{-0.10}$	$^{+0.17}_{-0.14}$	$0.94^{+0.18}_{-0.15}$	$0.70^{+0.15}_{-0.13}$
κ_γ	$0.92^{+0.11}_{-0.10}$	$^{+0.12}_{-0.12}$	$0.88^{+0.15}_{-0.14}$	$0.96^{+0.17}_{-0.15}$

ATLAS-CONF-2015-044 CMS-PAS-HIG-15-002

Fantastic performance already today

CMS Projection



Percent level (2-10%) precision in reach

arXiv:1307.7135

Scenario	Status 2014	Deduced size of uncertainty to increase total uncertainty by ≤10% for 300 fb^{-1}			by ≤10% for 3000 fb^{-1}				
Theory uncertainty (%)	[10–12]	κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \to H$									
PDF	8	2	-	-	1.3	-	-	-	-
incl. QCD scale (MHOU)	7	2	-	-	1.1	-	-	-	-
p_T shape and 0j → 1j mig.	10–20	-	3.5–7	-	-	1.5–3	-	-	-
1j → 2j mig.	13–28	-	-	6.5–14	-	3.3–7	-	-	-
1j → VBF 2j mig.	18–58	-	-	-	-	-	6–19	-	-
VBF 2j → VBF 3j mig.	12–38	-	-	-	-	-	-	6–19	-
VBF									
PDF	3.3	-	-	-	-	-	2.8	-	-
$t\bar{t}H$									
PDF	9								3
incl. QCD scale (MHOU)	8								2

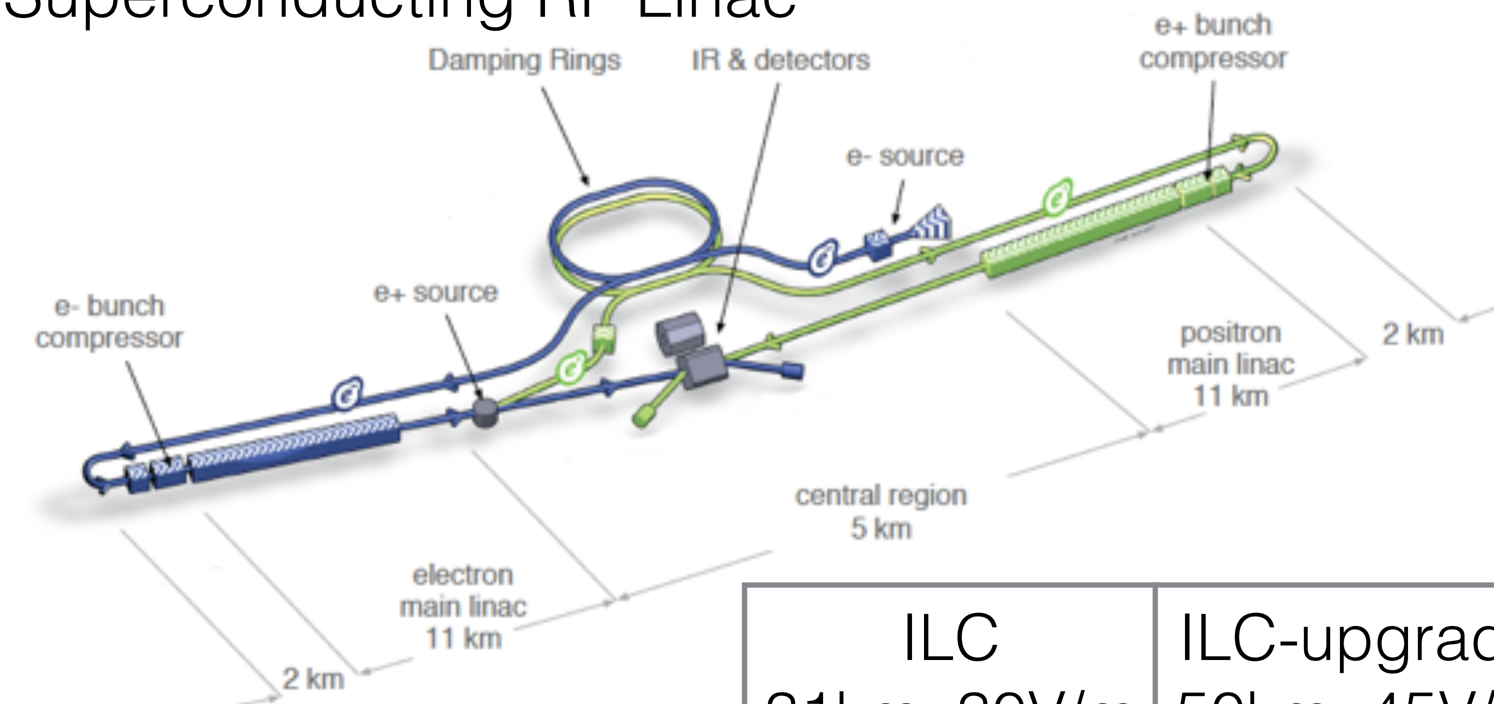
Key question is the evolution systematic uncertainty

ATL-PHYS-PUB-2014-016

Future Lepton Collider Projects

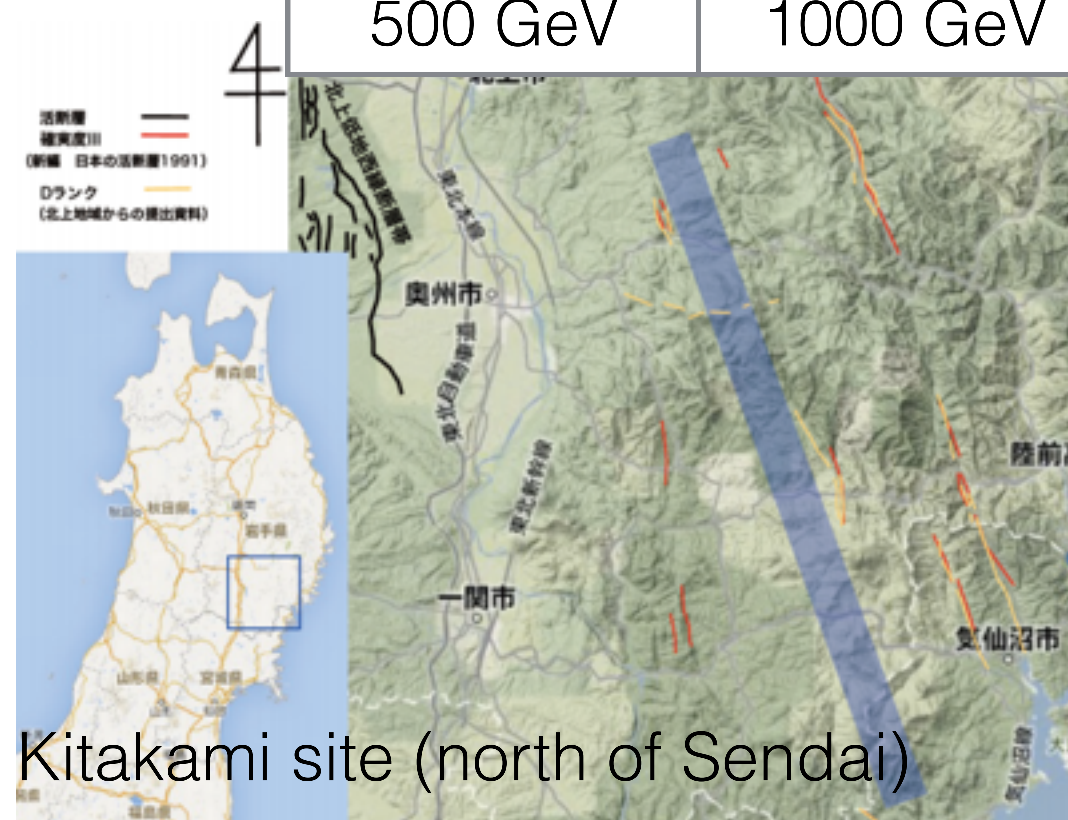
- ➡ **International Linear Collider (ILC)**
- ➡ Compact Linear Collider (CLIC)
- ➡ Circular Electron Positron Collider (CEPC)
- ➡ Future Circular Collider (FCC-ee)
- ➡ Muon Collider

Superconducting RF Linac



ILC	ILC-upgrade
31km, 30V/m	50km, 45V/m
500 GeV	1000 GeV

TDR delivered June 2013



Kitakami site (north of Sendai)

Future Lepton Collider Projects

arXiv:1506.05992

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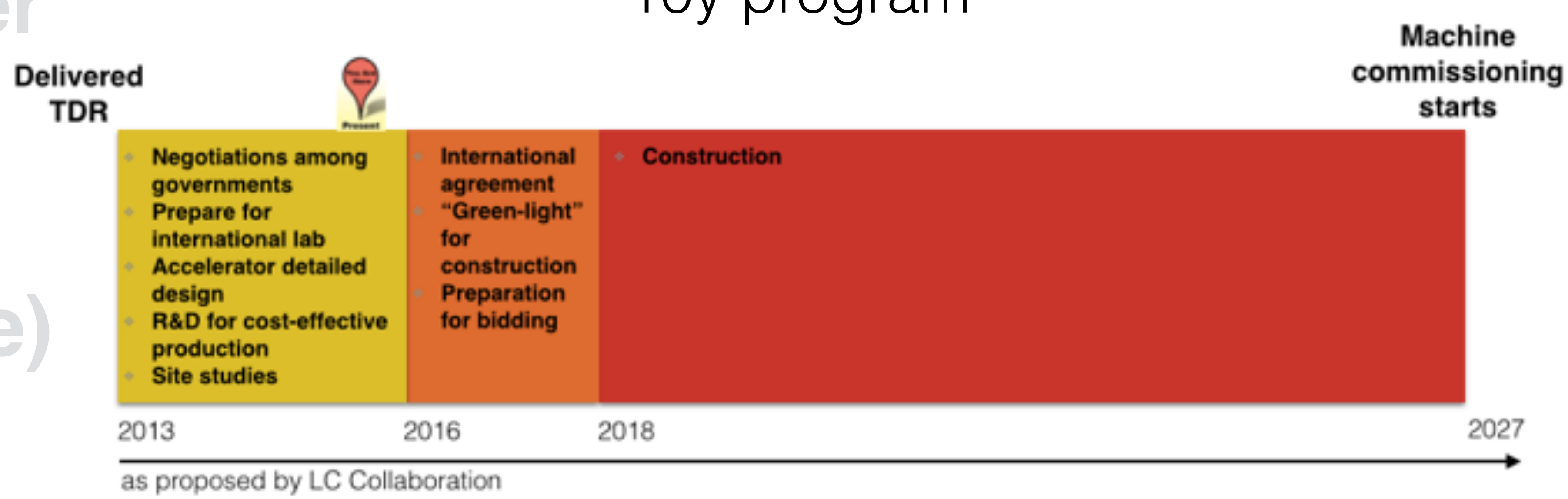
	Stage	500			500 LumiUP		
Scenario	$\sqrt{s}$ [GeV]	500	350	250	500	350	250
G-20	$\int \mathscr{L} dt$ [fb^{-1}]	1000	200	500	4000	-	-
	time [years]	5.5	1.3	3.1	8.3	-	-
H-20	$\int \mathscr{L} dt$ [fb^{-1}]	500	200	500	3500	-	1500
	time [years]	3.7	1.3	3.1	7.5	-	3.1
I-20	$\int \mathscr{L} dt$ [fb^{-1}]	500	200	500	3500	1500	-
	time [years]	3.7	1.3	3.1	7.5	3.4	-
	Stage	500			500 LumiUP		
Scenario	$\sqrt{s}$ [GeV]	250	500	350	250	350	500
Snow	$\int \mathscr{L} dt$ [fb^{-1}]	250	500	200	900	-	1100
	time [years]	4.1	1.8	1.3	3.3	-	1.9

Baseline -
10y program



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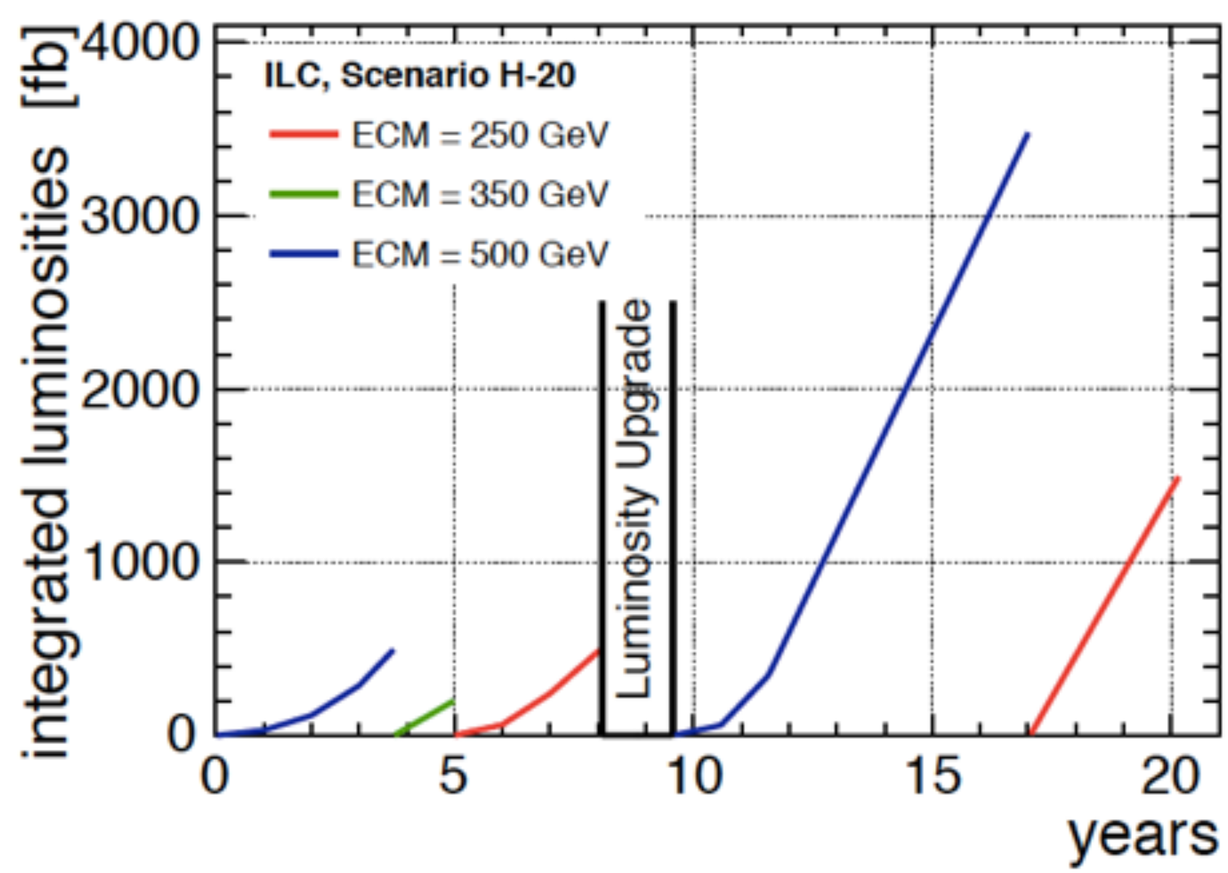
	Baseline ILC	Lumi Upgrade
Collision rate [Hz]	5	10
Electron linac rate [Hz]	10	10
Number of bunches	1312	2625
Estimated power [MW]	129	200
Luminosity [x10^{34}cm^{-2}s^{-1}]	0.75	3.0

Integrated Luminosities [fb]



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CDR Vol 2: Physics and Detectors - arXiv:1203.5940
CDR Vol 3: The CLIC Programme - arXiv: 1209.2543
CLIC Snowmass White Paper - arXiv: 1307.5288

CLIC
50km, 100V/m
3000 GeV

- ➡ Normal conducting accelerator structures operated at room temperature
- ➡ Two beam acceleration technique provides 100MV/m gradient
- ➡ Implementation in energy stages, driven by physics and technical considerations
- ➡ Each stage correspond to 4-5 years of data taking

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Center-of-mass energy	$\sqrt{s}$	GeV	350	1400	3000
Integrated luminosity	$\mathscr{L}_{\mathrm{int}}$	ab^{-1}	0.5	1.5	2.0

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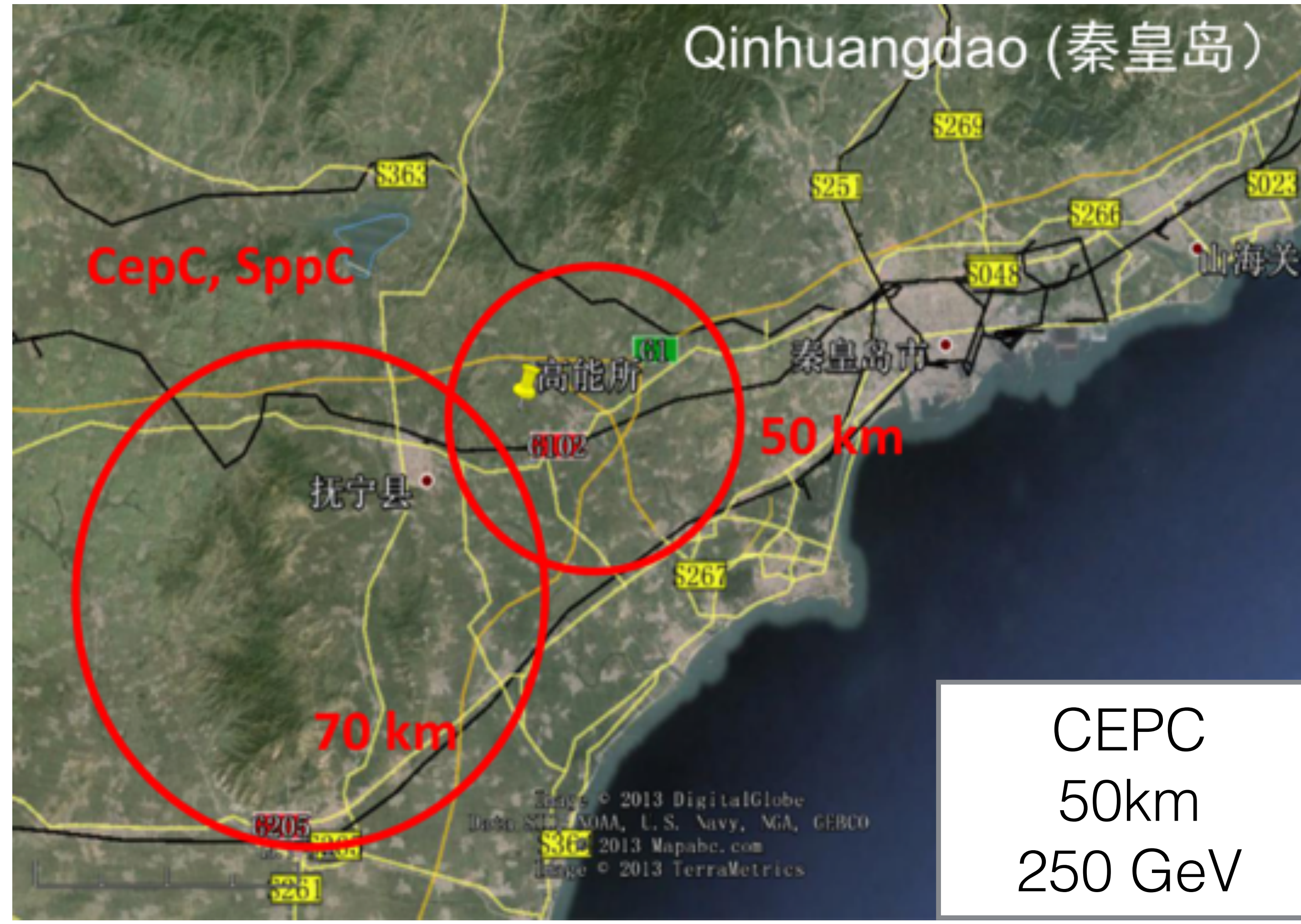

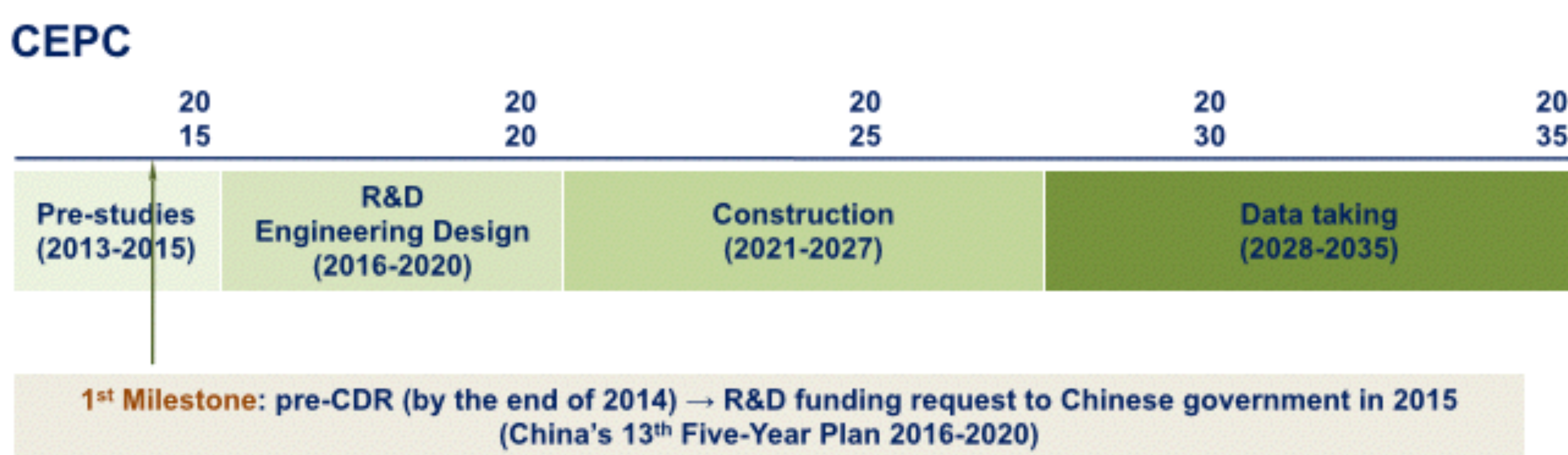

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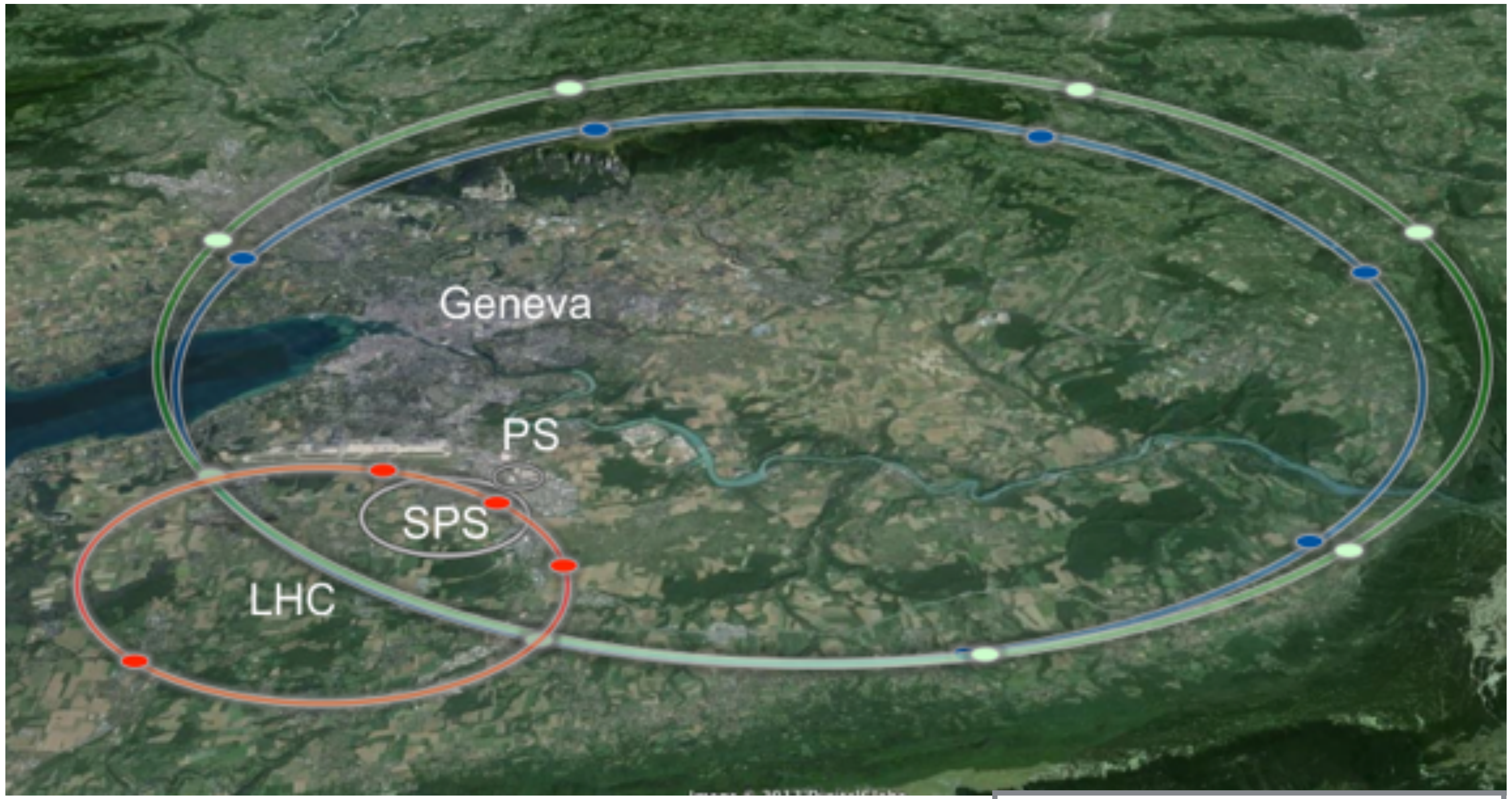

TLEP (FCC-ee) Physics case - arXiv:1308.6176
CDR in preparation for 2018

FCC-ee
100km, 200MV
350 GeV

$\sqrt{s}$ (GeV)	90	160	240	350	350+
$\mathscr{L}$(ab^{-1}/year)	86.0	15.2	3.5	1.0	1.0
Events/year	3.6×10^{12}	6.1×10^{7}	7.0×10^{5}	4.2×10^{5}	2.5×10^{4}
Event type	Z	WW	HZ	$t\bar{t}$	$WW \rightarrow H$
Years	0.3 (2.5)	1	3	0.5	3

crab-waist configuration with four interaction points

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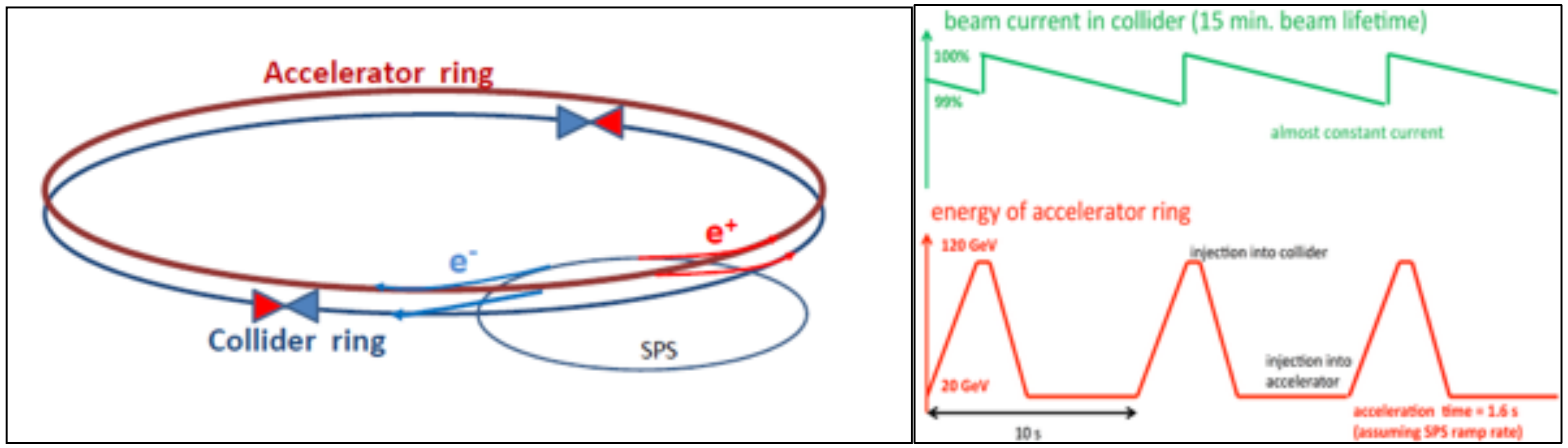
- Luminosity and energy are limited by the power budget, i.e. amount of synchrotron radiation (50MW per beam)
- One finds that ideally, all charge should be in a few single bunches at max energy
- Lifetime of beams very limited
- Solution: top-up injection scheme



A. Blondel & F. Zimmermann

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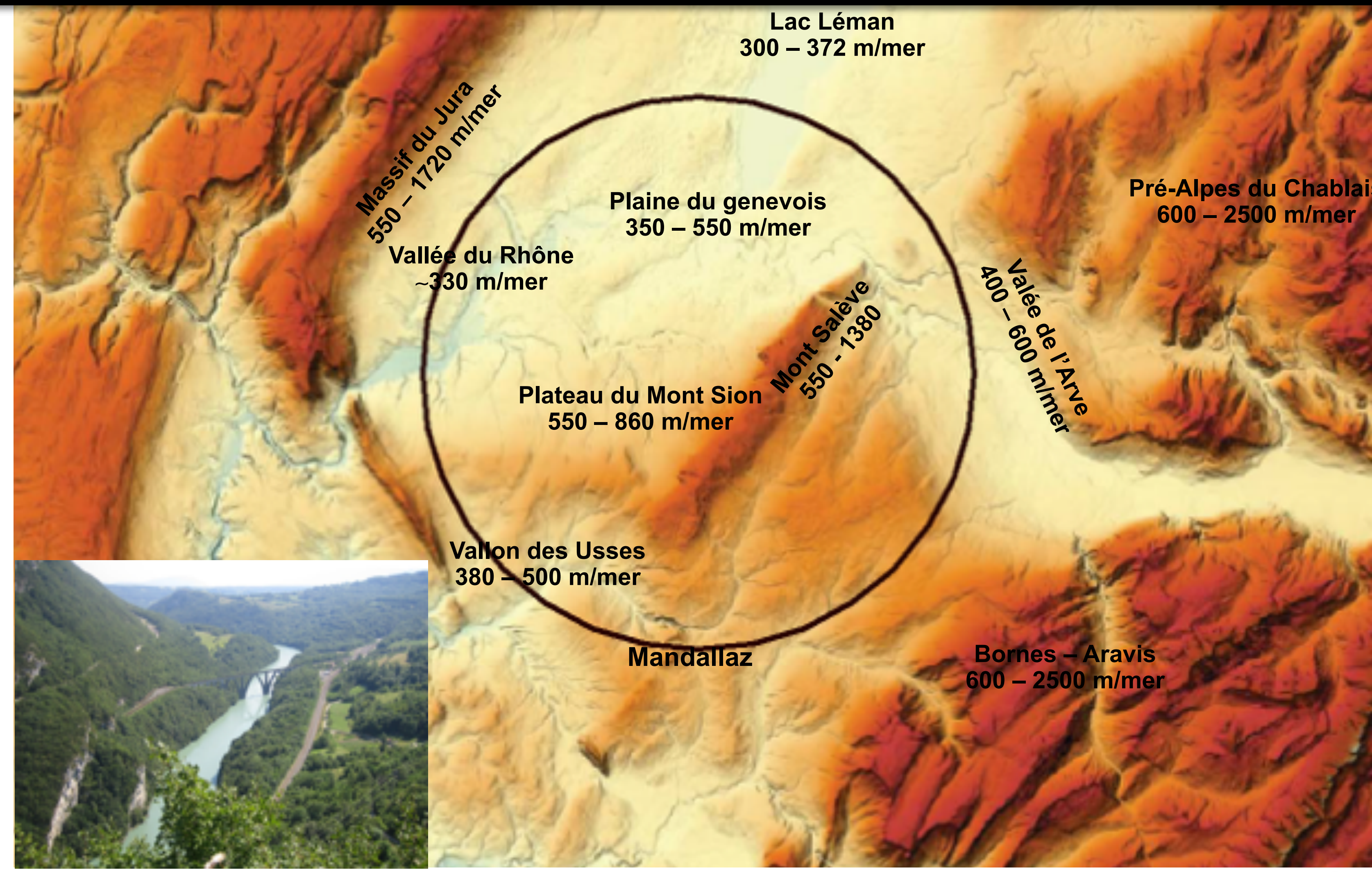

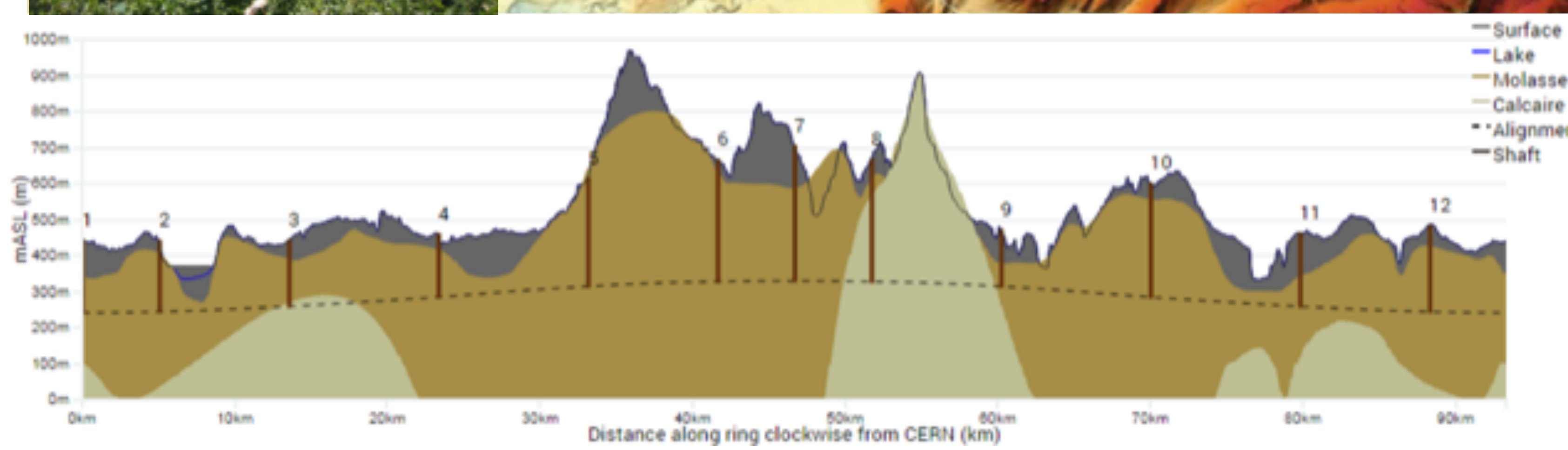

Ph. Lebrun

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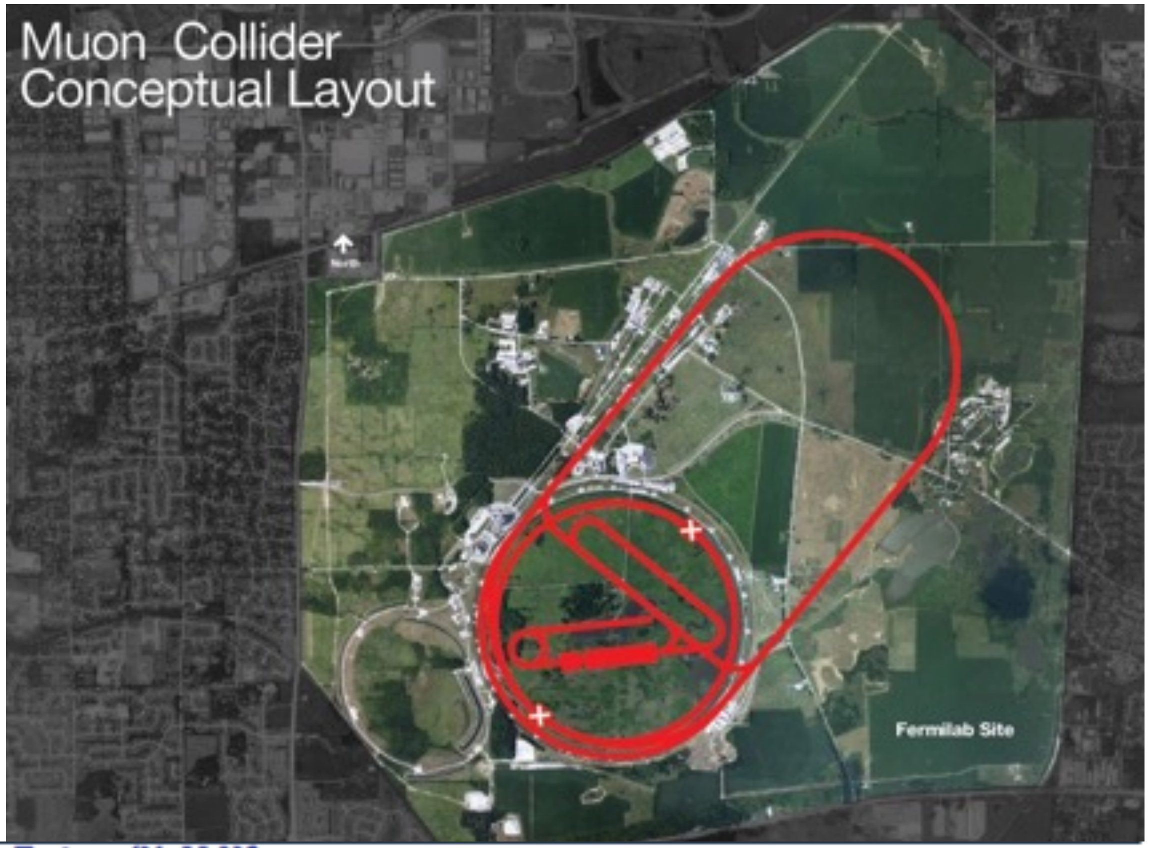
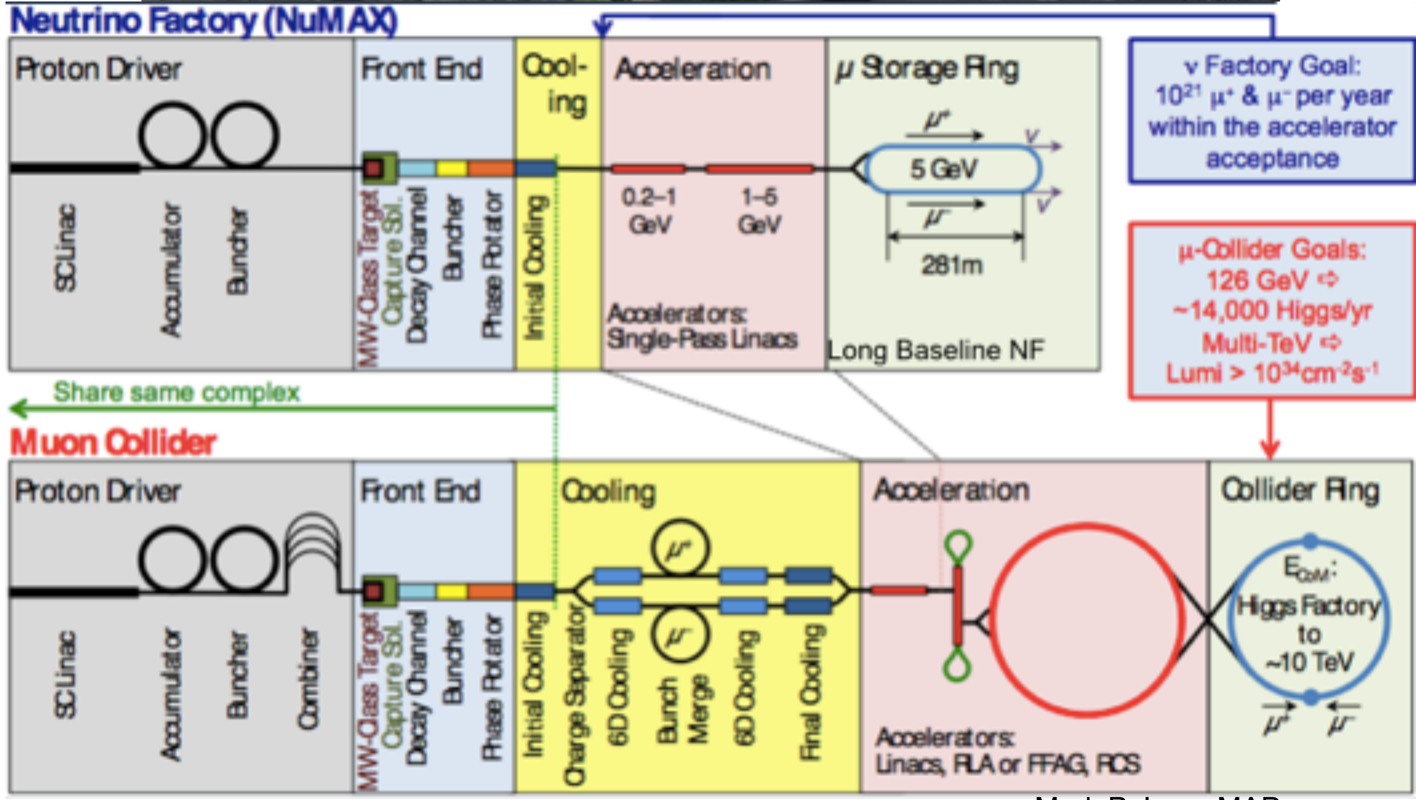
- ➡ **Muon Collider**

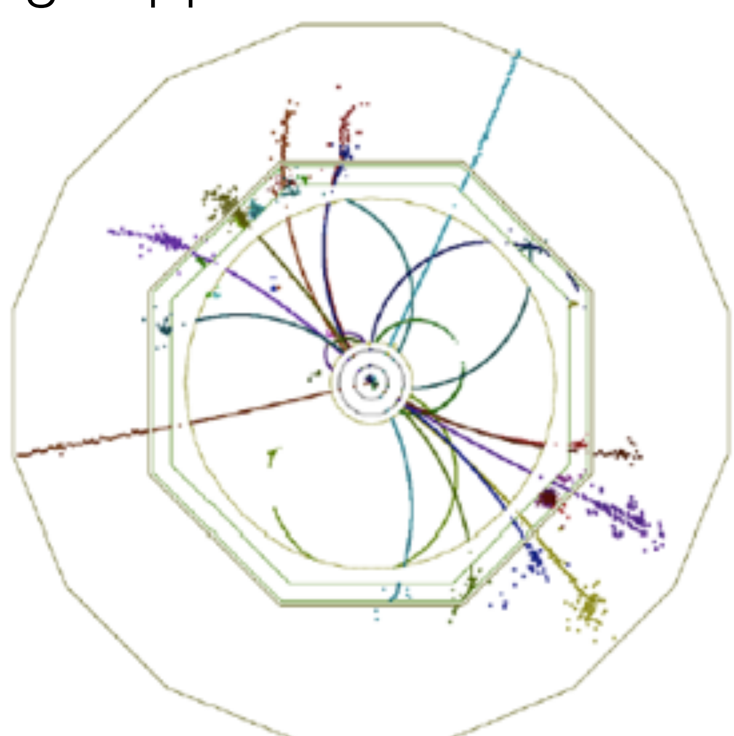




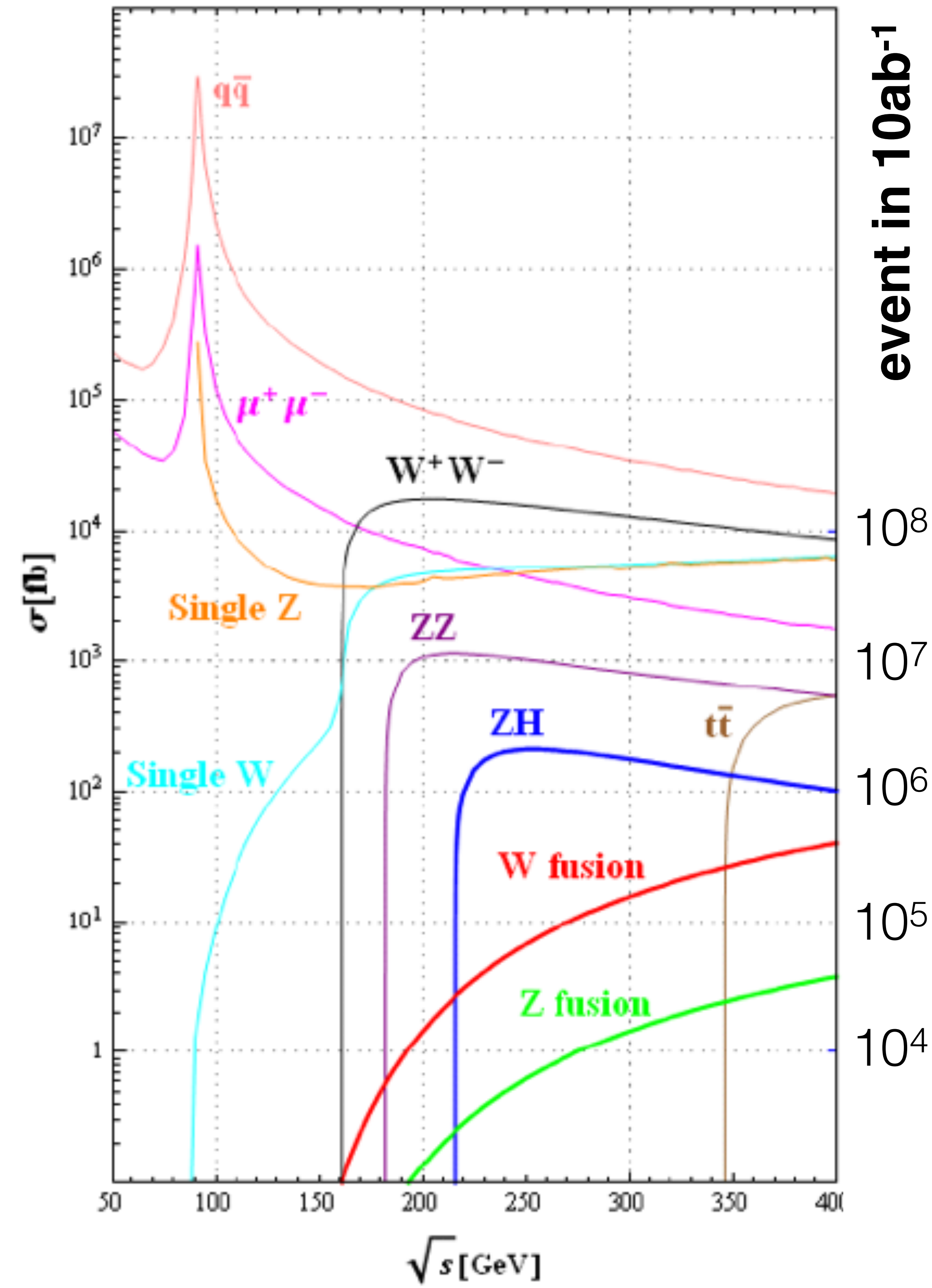
Mark Palmer: MAP program

Physics at Lepton Colliders

- **Electroweak production**
  - cross sections are predicted with (sub)percent precision
- **Lepton here really means electrons and muons**
- **Relative low rate**
  - trigger on every event
- **Well defined collision rate**
  - missing mass reconstruction
- **Clean events, smaller backgrounds**
  - comparing to pp machine



Example ILD event display



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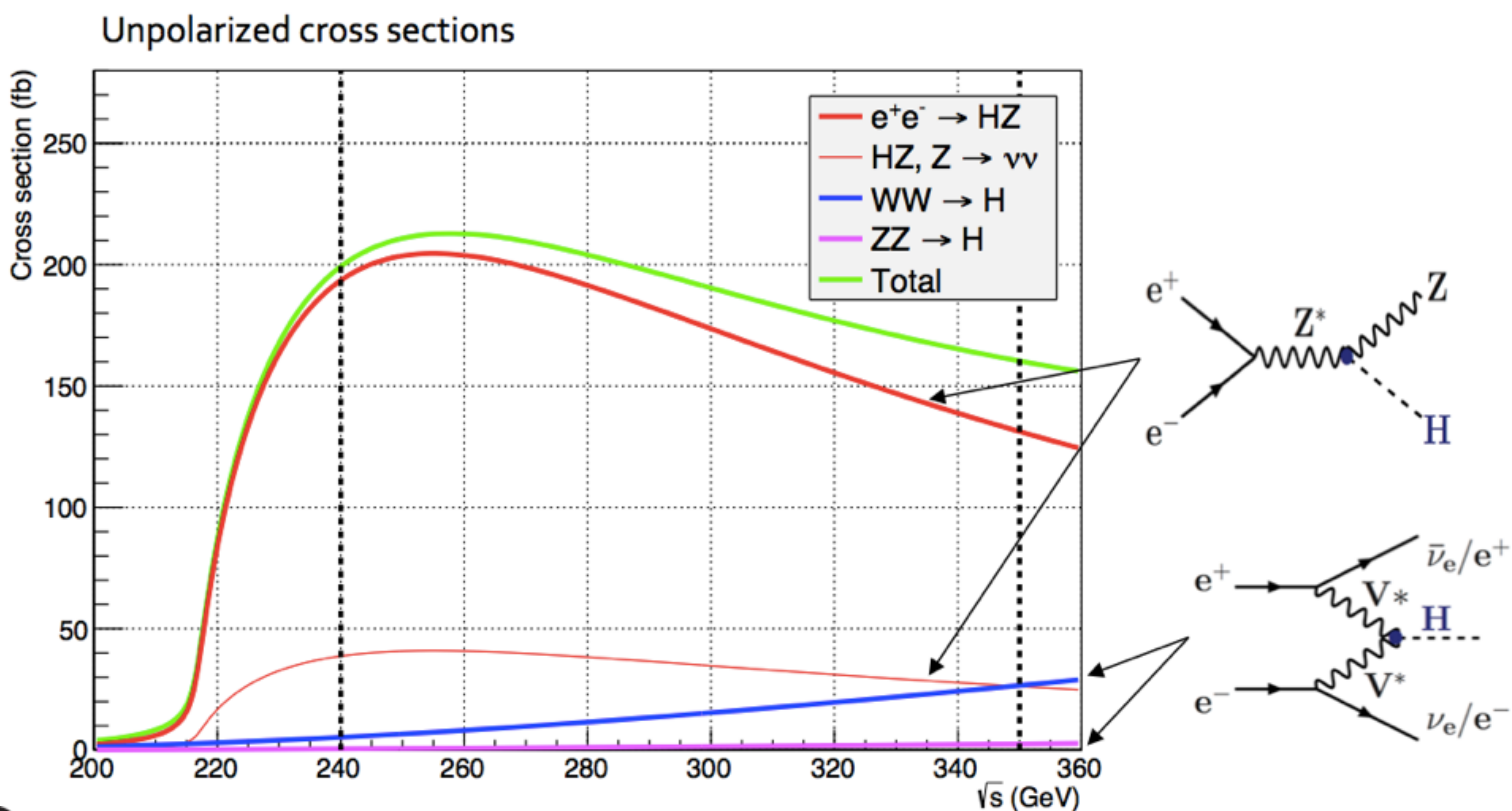
Higgs Production at Lepton Collider

➡ $e^+e^- \to ZH$ production maximal at 240-260 GeV



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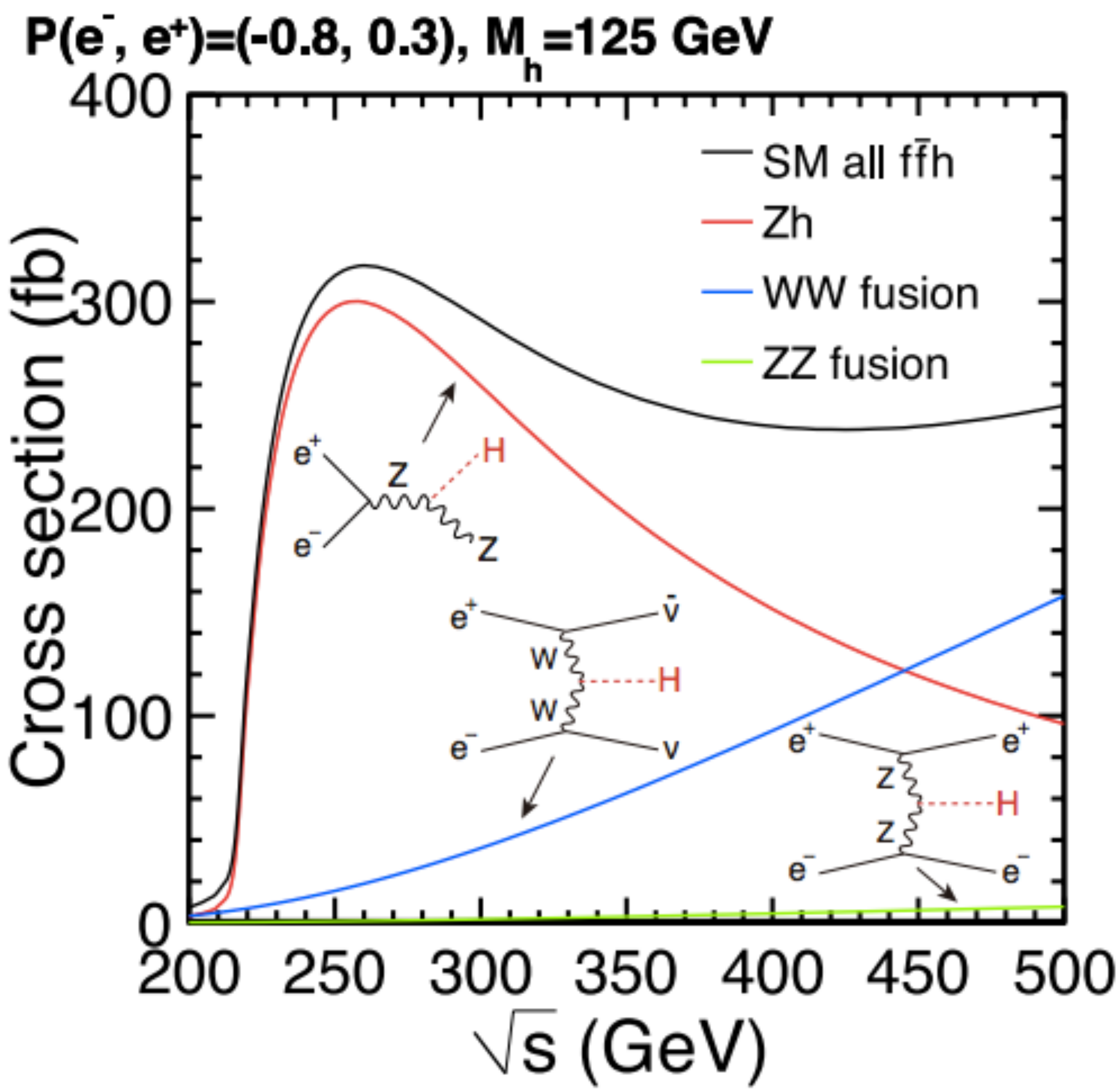
Higgs Production at Lepton Collider

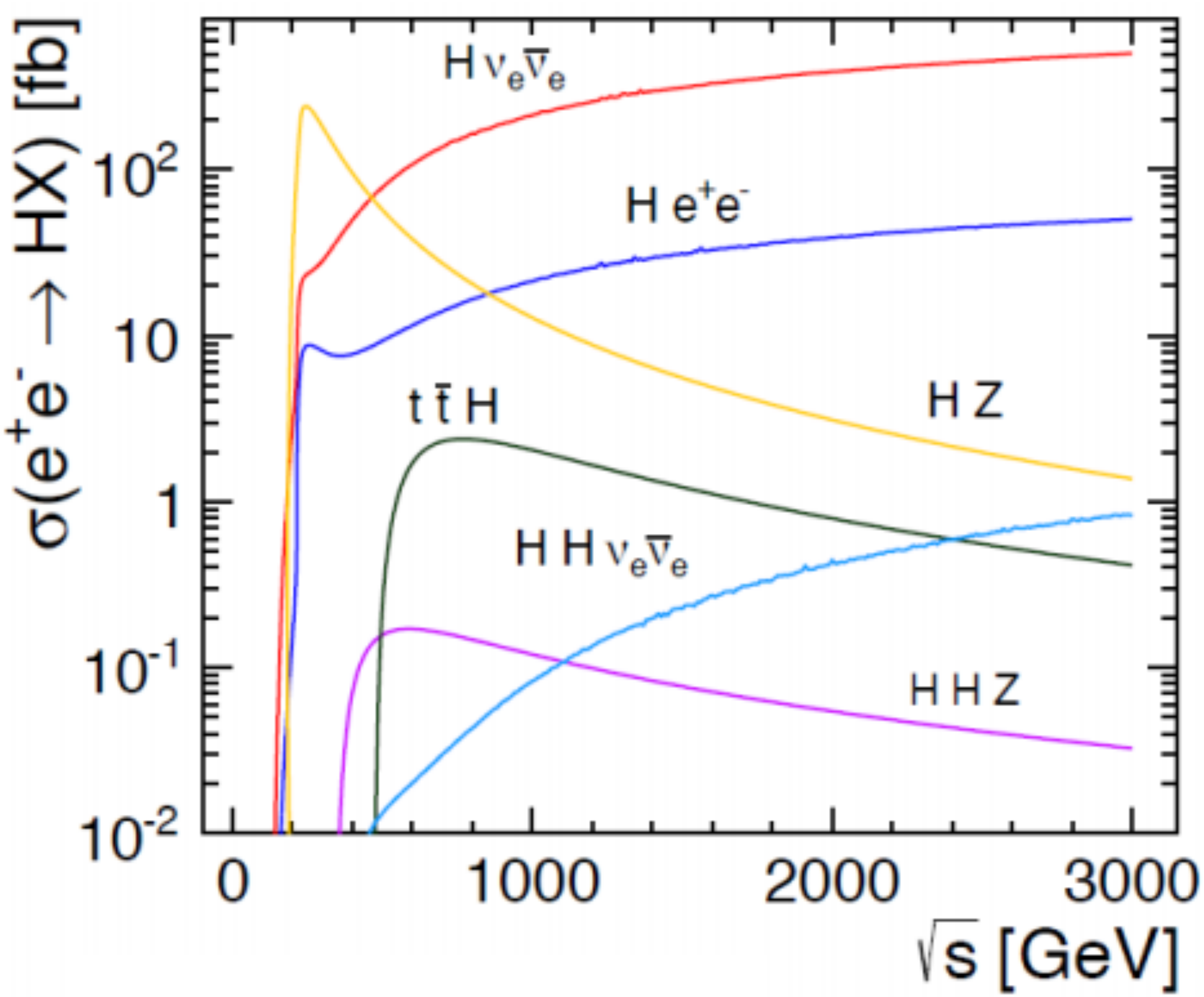
- ➡ $e^+e^- \to ZH$ production maximal at 240-250 GeV
- ➡ Beam polarization increases Higgs cross sections



44% increase in cross section

Higgs Production at Lepton Collider

- ➡ $e^+e^- \to ZH$ production maximal at 240-250 GeV
- ➡ Multi-TeV collider Higgs production



Higgs Production at Lepton Colliders

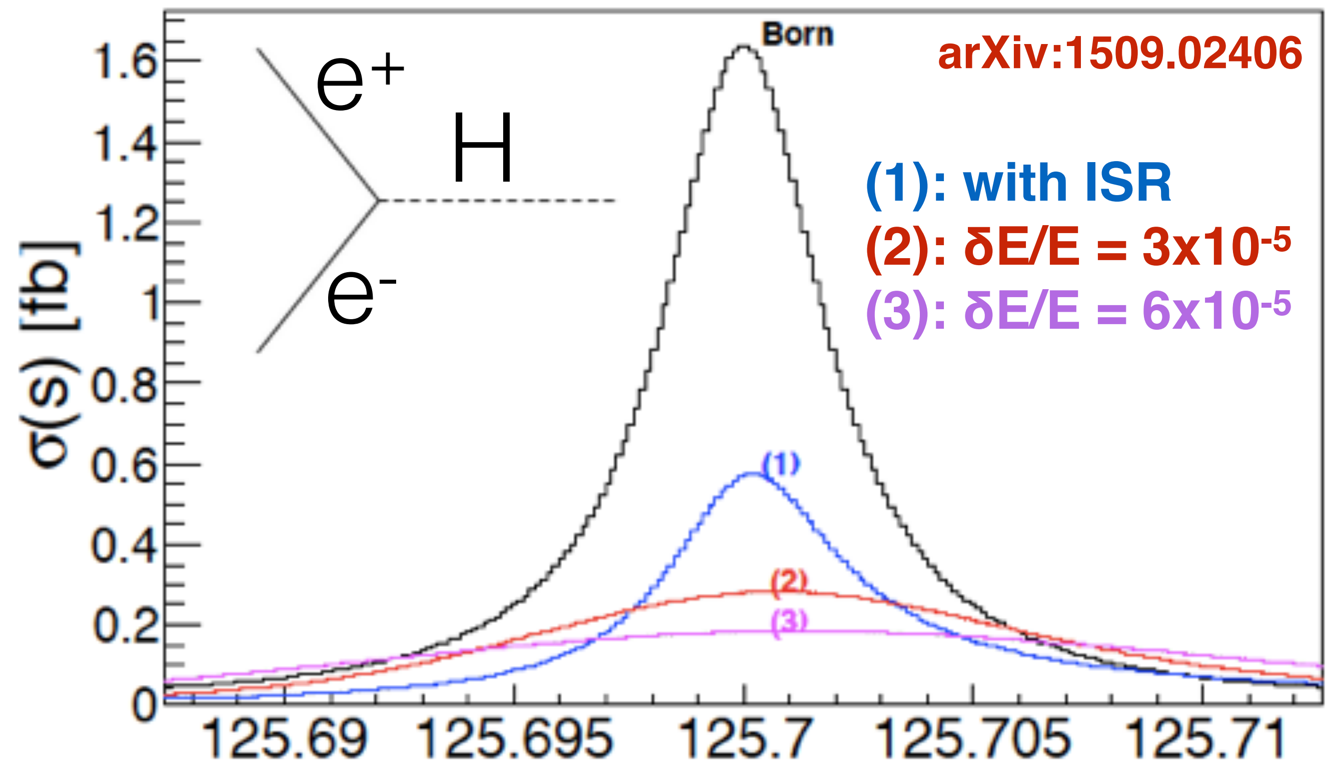
➡ s-channel production

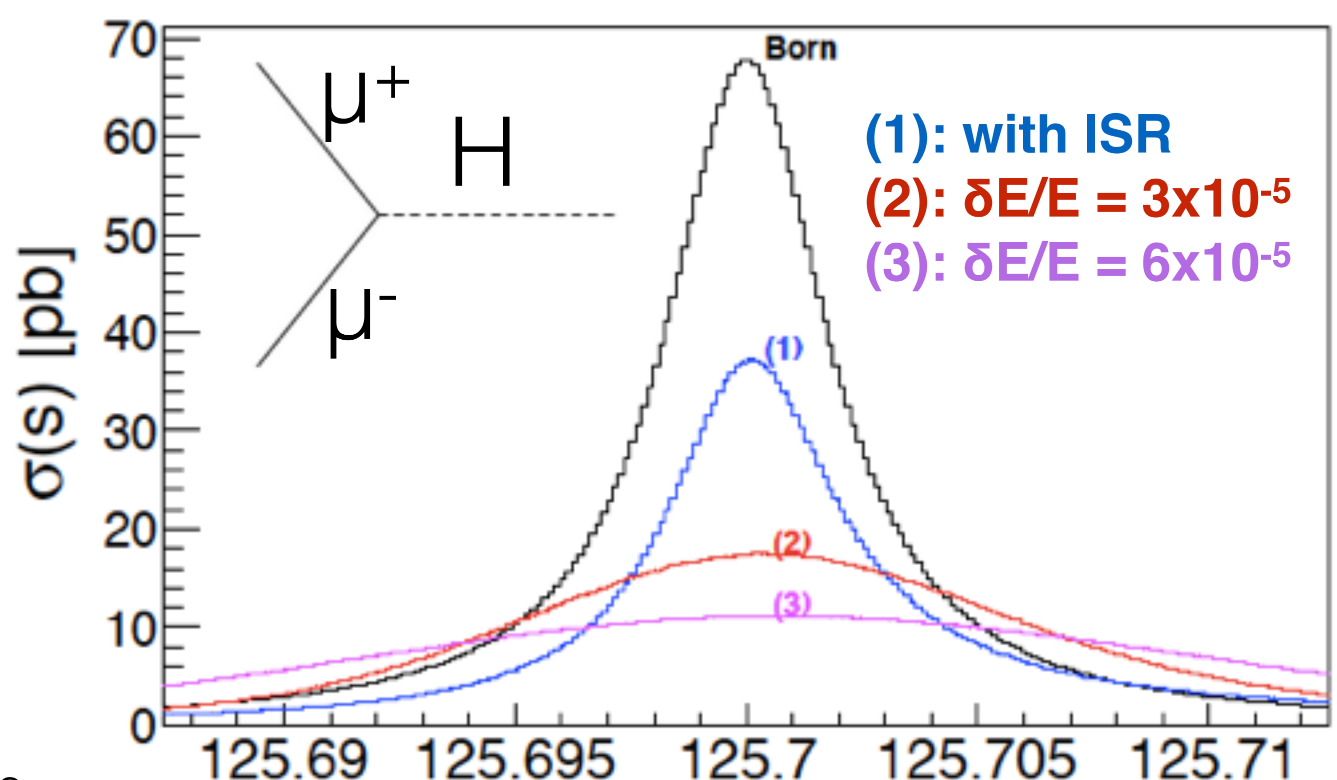
- very small cross section
- reduced by ISR and beam spread
- $\sigma^{born}(\mu^+\mu^- \rightarrow H) \approx 40.000\ \sigma^{born}(e^+e^- \rightarrow H)$
- $\sigma(e^+e^- \rightarrow H)$ = 50ab (nominal $\delta E/E$)
- $\sigma(\mu^+\mu^- \rightarrow H)$ = 15pb (nominal $\delta E/E$)

➡ Beam-spread improvements

- FCC-ee via monochromators
- Muon collider via improved cooling
- Feasibility and impact on luminosity need study

➡ Polarization





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Energy and Luminosity

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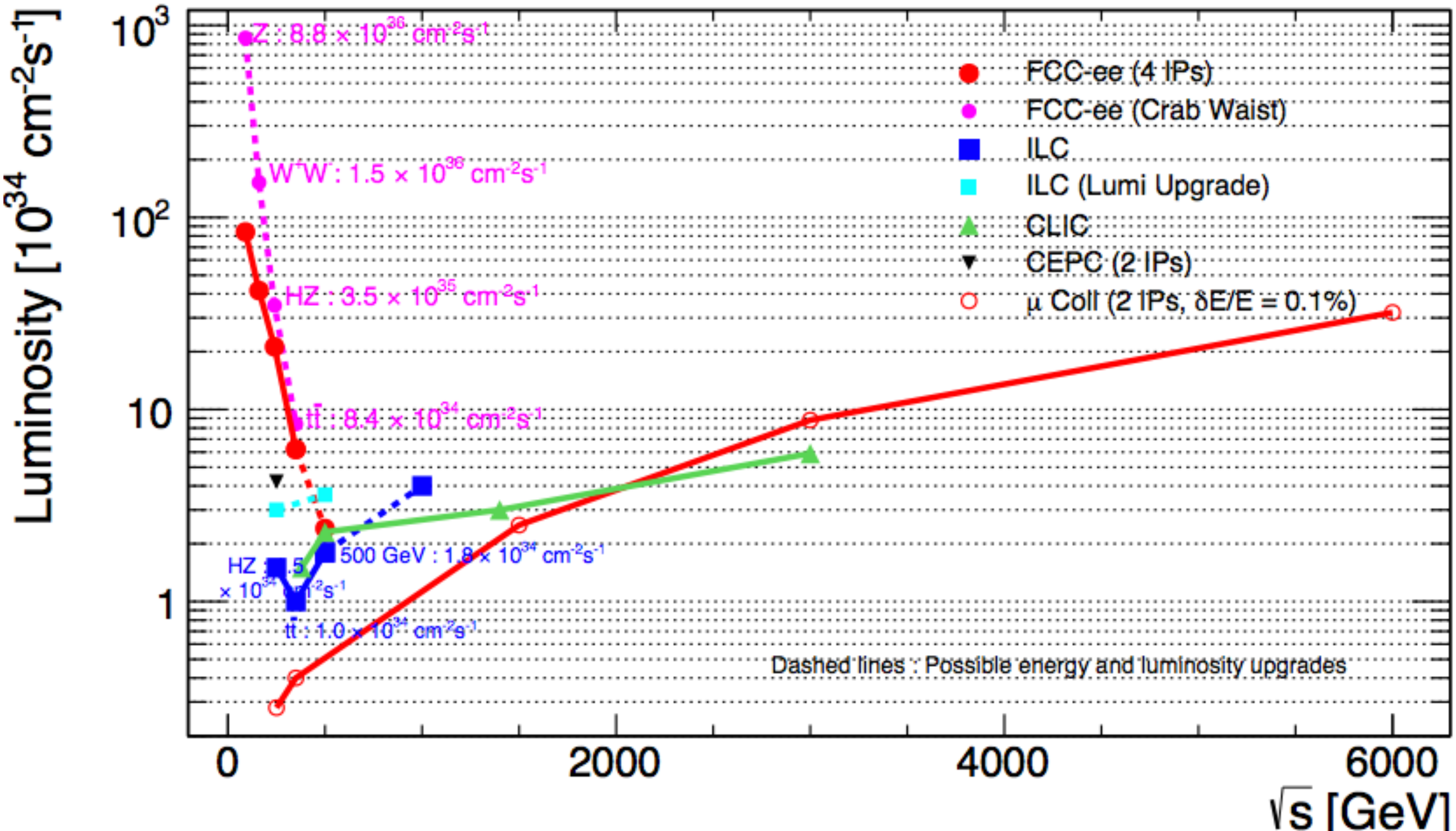

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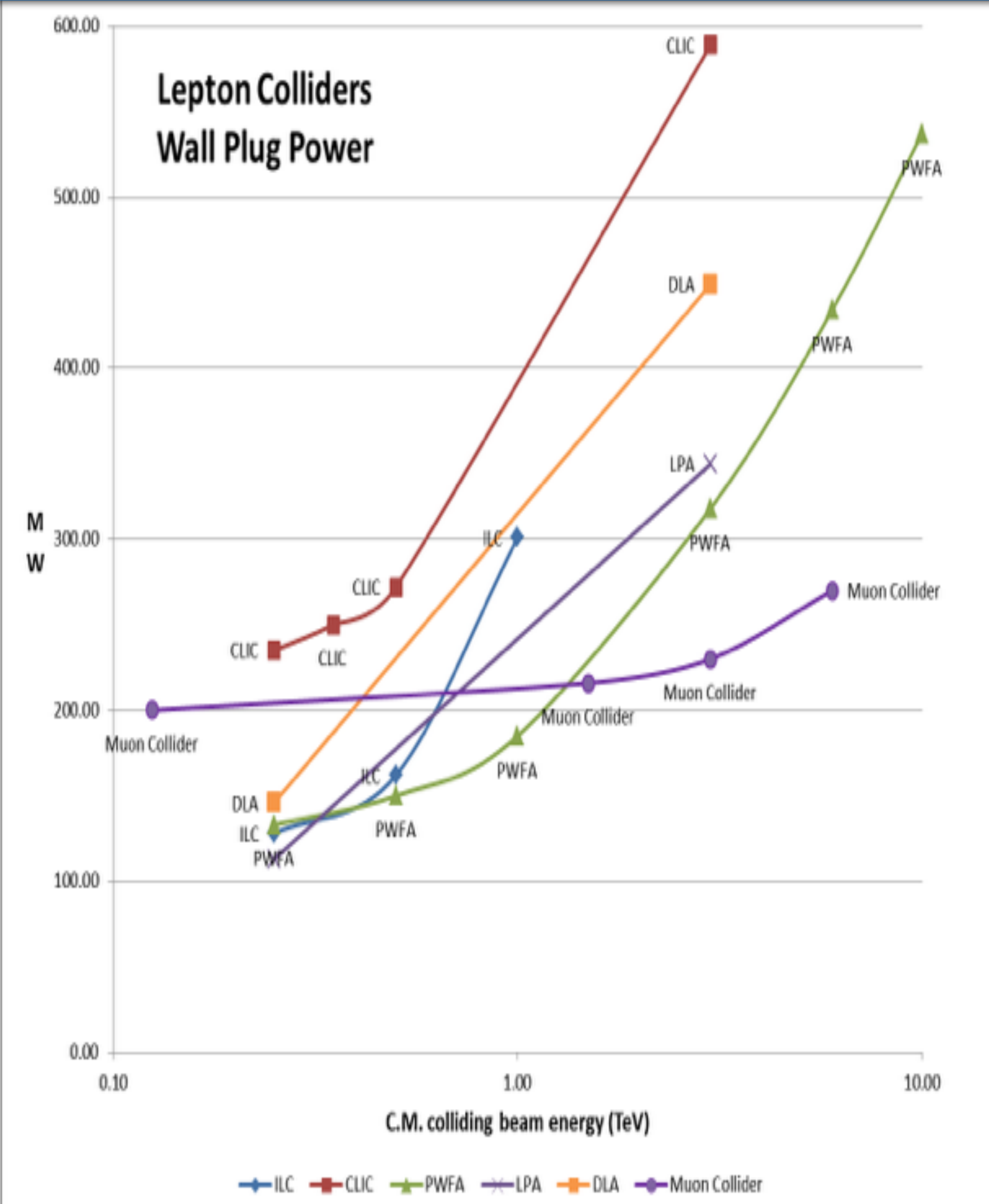
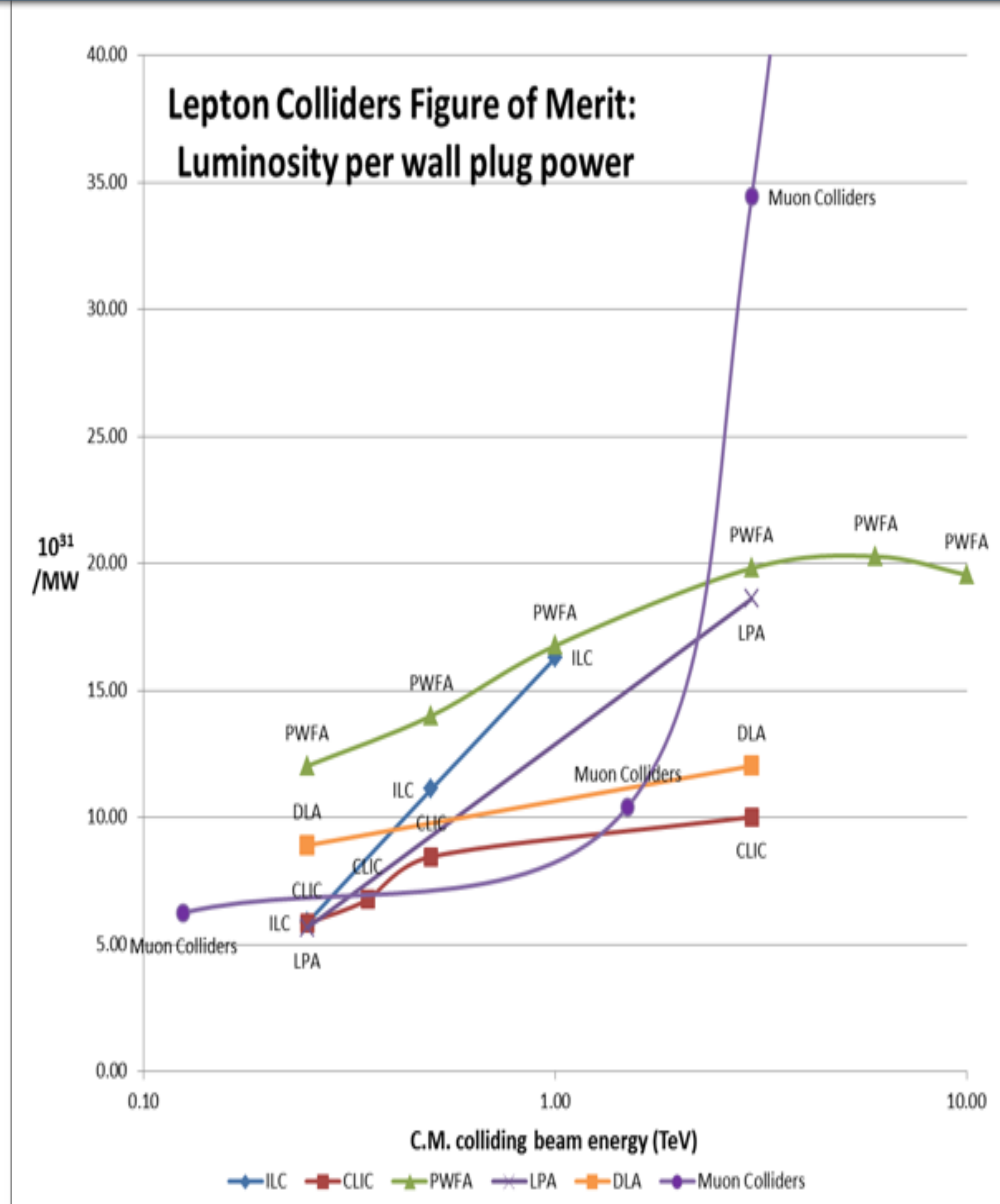
Multi-TeV Lepton Collider Figure of Merit





Higgs Related Physics at Lepton Colliders

$\sqrt{s}$ [GeV]	$\sqrt{s}$	Measurements (incomplete list)
90	m_Z	m_Z, Γ_Z, α_s, α_{QED}
125	m_H	s-channel Higgs production
160	$2m_W$	m_W, α_s
240-250	$m_H+m_Z+\ldots$	m_H, Γ_H, J^{PC}, g_{HXX}, BSM decays
340-355	$2{*}m_{top}$	g_{HWW}, Γ_H, indirect g_{Htt}, m_{top}
500	$2{*}m_{top}+m_H+\ldots$	g_{HHH}, g_{Htt}
> 500	m_{NP}	g_{Htt}, g_{HHH}, BSM Higgs

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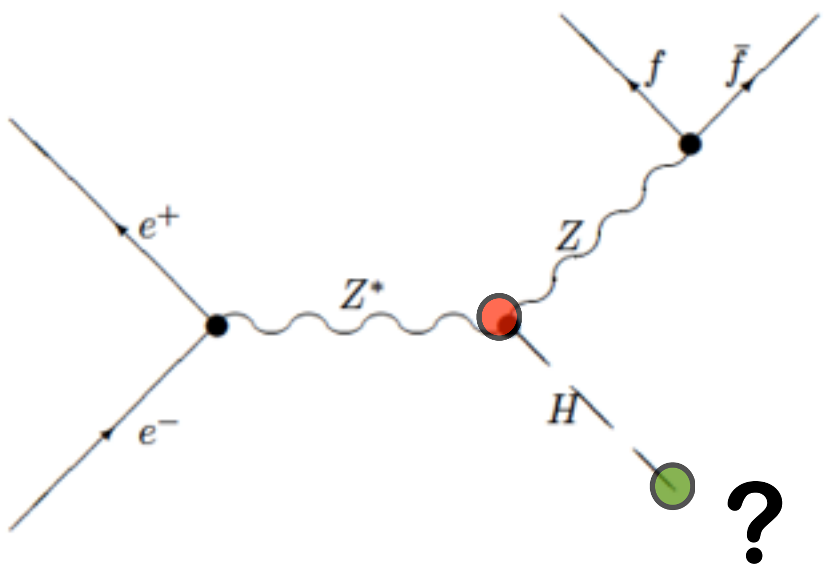
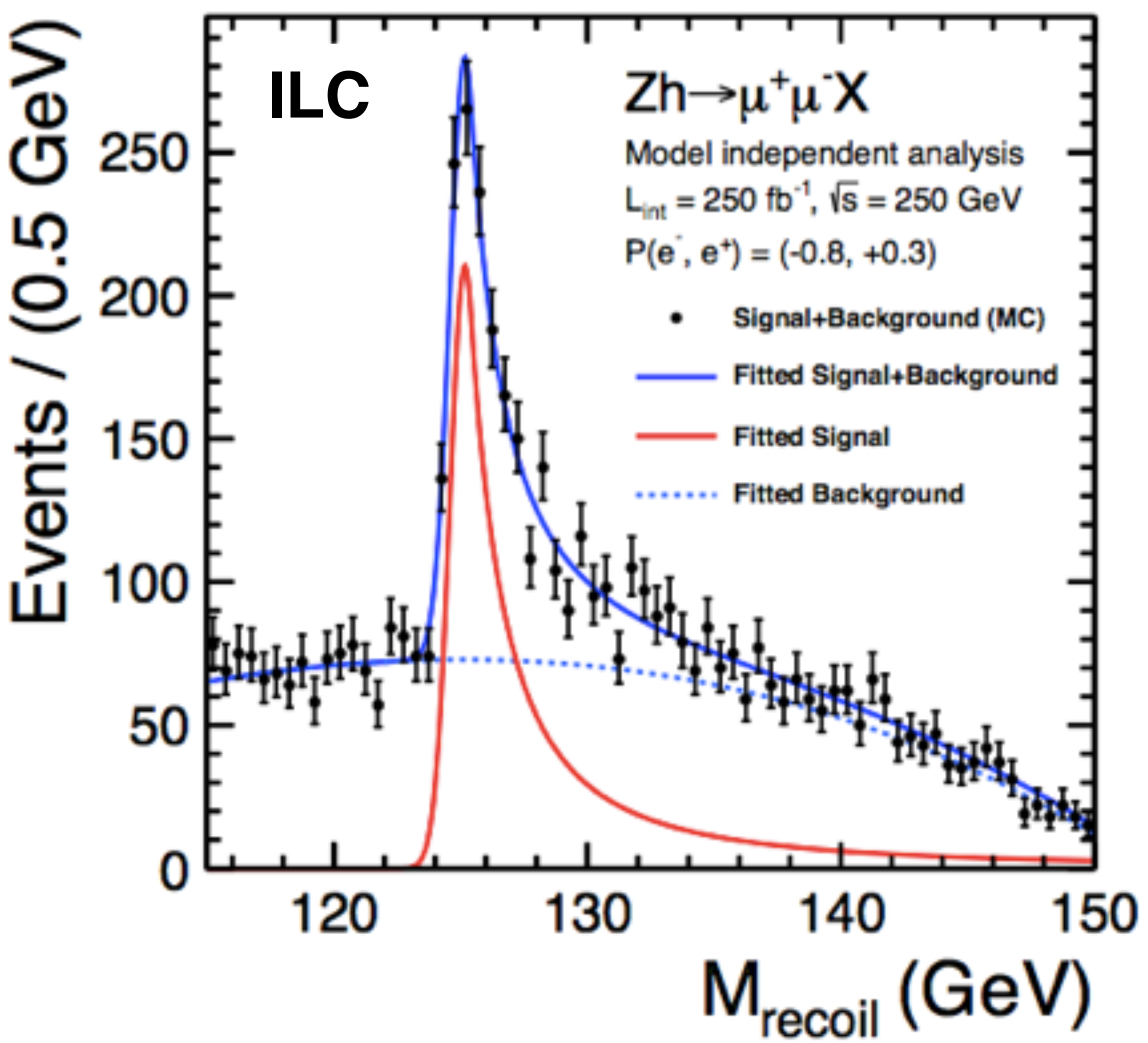
Higgs Precision Measurements

- ➡ Recoil method unique to lepton collider
- ➡ Tag Higgs event independent of decay mode
- ➡ Provides precision and model independent measurements of
  - ◉ $\sigma(ee \rightarrow ZH) \propto g_{HZZ}^2$
  - ◉ m_H
- ➡ Key input to Γ_H



$$m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$

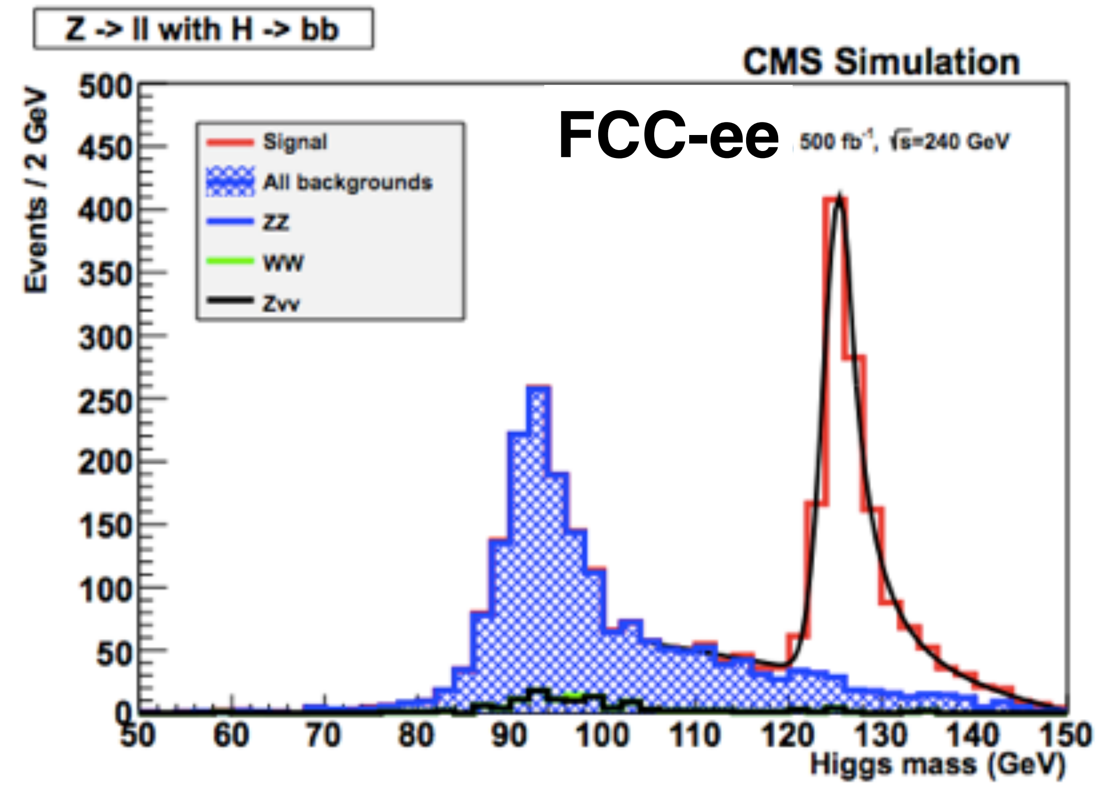


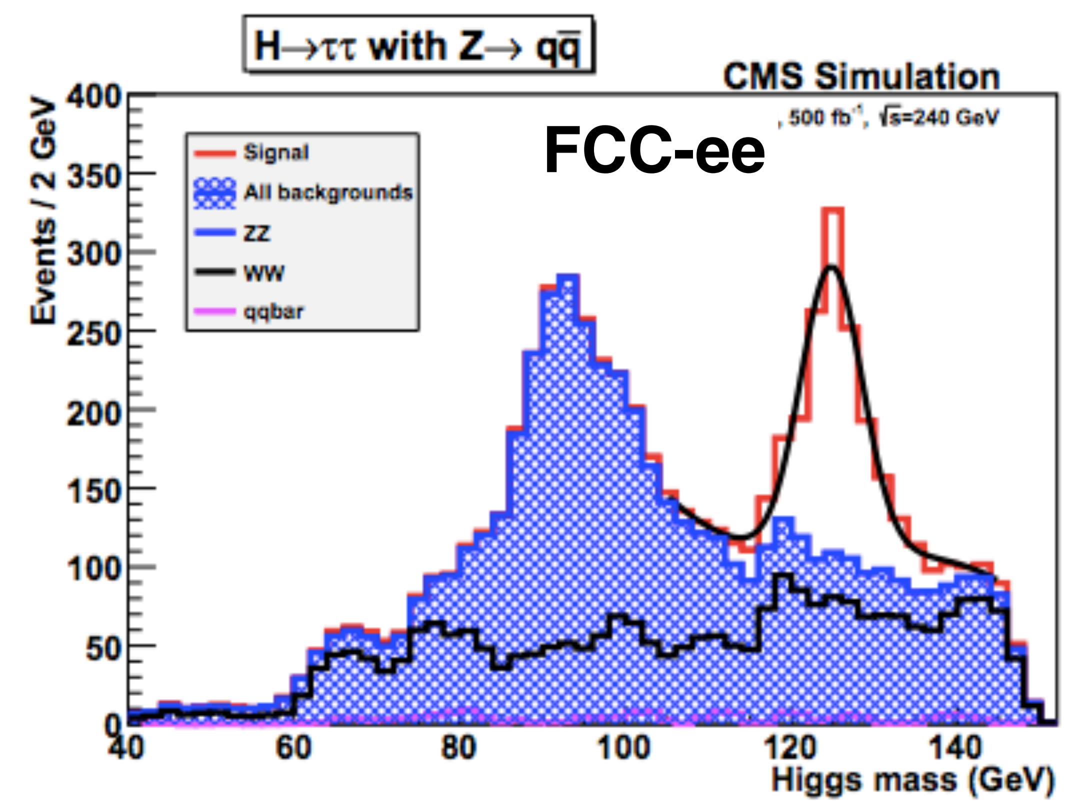
Precision Higgs Couplings

- Measure σ(ee→ZH) * BR (H→X) by identifying X
- Example: σ(ee→ZH) * BR (H→ZZ) $\propto g_{HZZ}^4/\Gamma_H$
- Total width from combination of measurements or fit - $\delta\Gamma_H$ = 0.04 MeV (FCC-ee)
- Hadronic and invisible Z decays increase precision
- Branching fraction to invisible tested directly to 0.19% @ 95% CL

	Model-independent fit		
Coupling	FCC-ee -240	FCC-ee	
g_{HZZ}	0.16%	**0.15%**	(0.18%)
g_{HWW}	0.85%	**0.19%**	(0.23%)
g_{Hbb}	0.88%	**0.42%**	(0.52%)
g_{Hcc}	1.0%	**0.71%**	(0.87%)
g_{Hgg}	1.1%	**0.80%**	(0.98%)
$g_{H\tau\tau}$	0.94%	**0.54%**	(0.66%)
$g_{H\mu\mu}$	6.4%	**6.2%**	(7.6%)
$g_{H\gamma\gamma}$	1.7%	**1.5%**	(1.8%)
BR_{exo}	0.48%	**0.45%**	(0.55%)

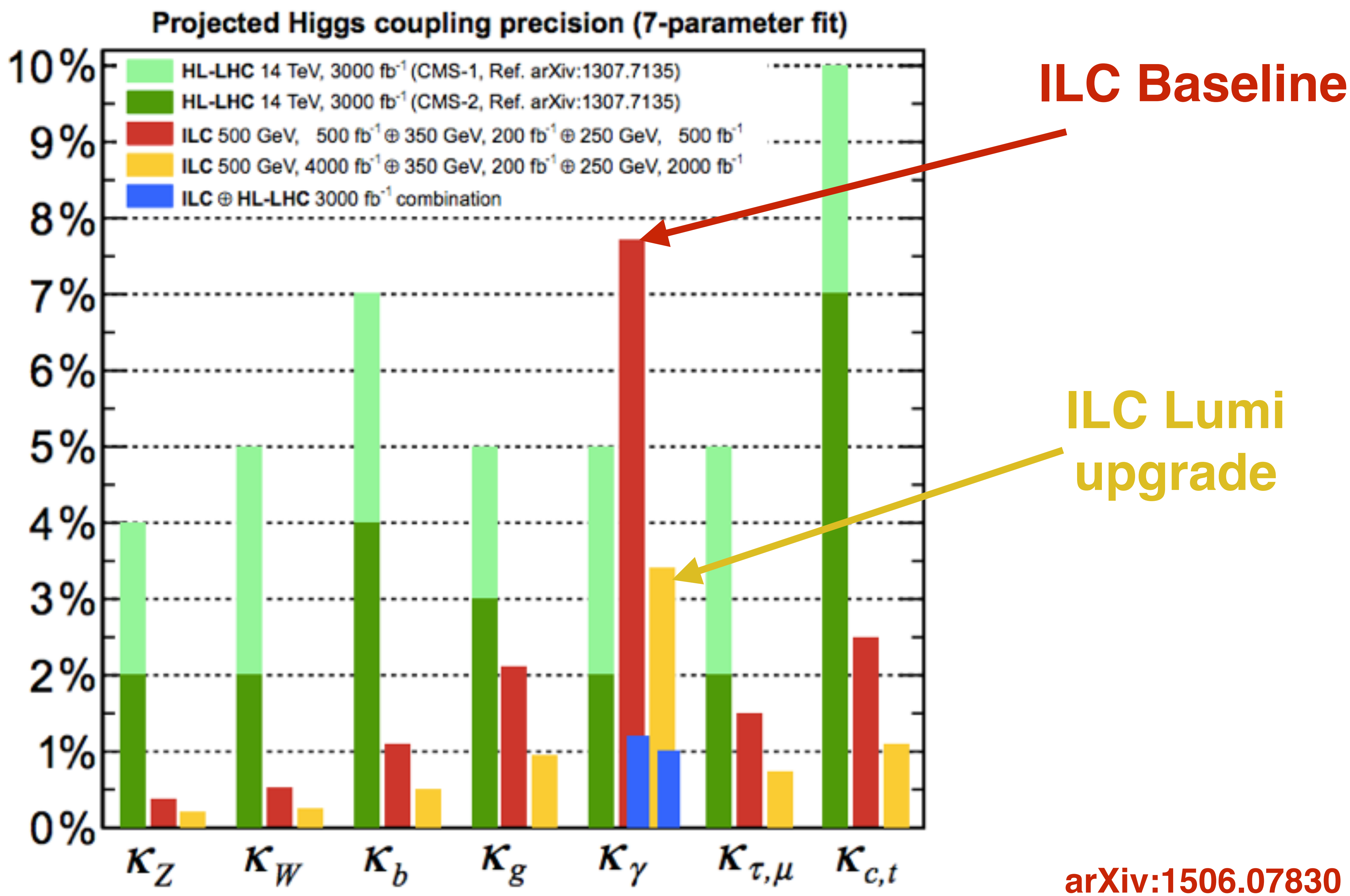
stat. uncertainties





Precision Higgs Couplings

➡ Measurements will built on, complement, and supersede LHC results



arXiv:1506.07830
arXiv:1506.05992

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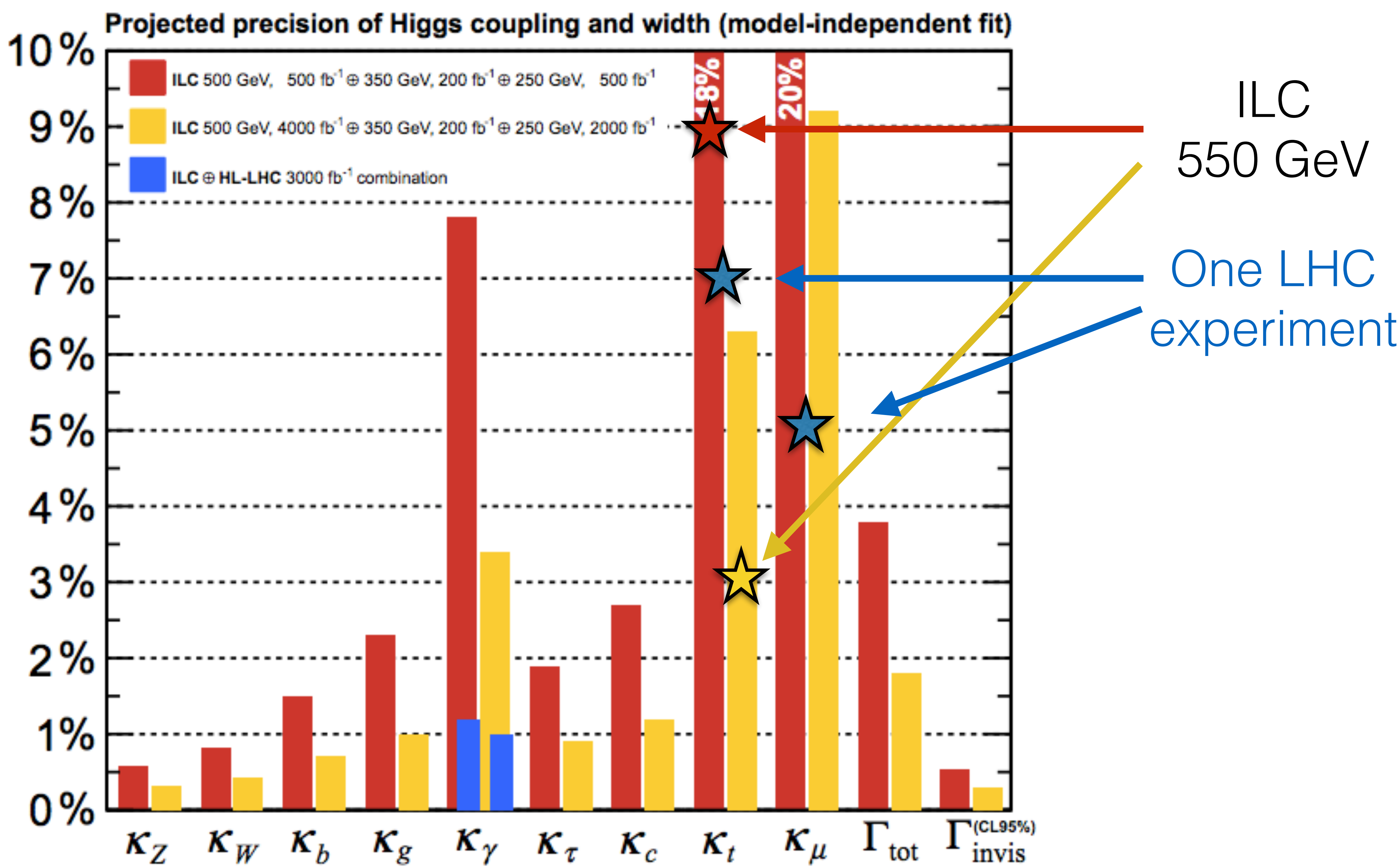
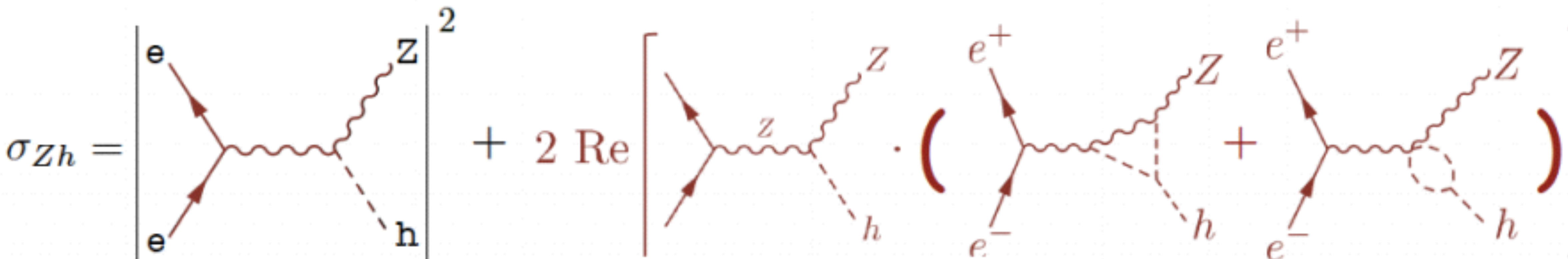
Precision Higgs couplings



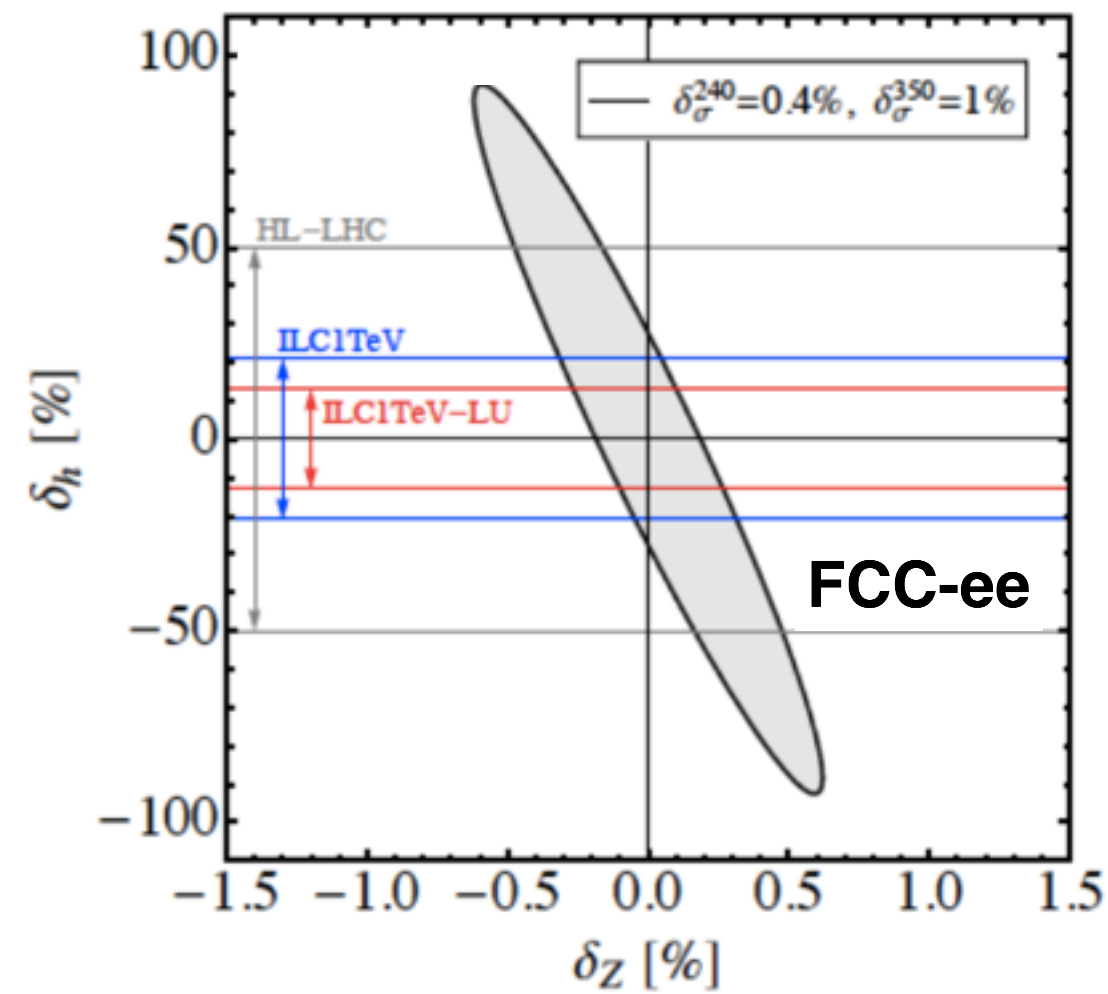
Higgs self-coupling through loop corrections



$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

➡ Very large datasets at high energy allow extreme precision g_{ZH} measurements

➡ Indirect and model-dependent probe of Higgs self-coupling



Matthew McCullough

arxiv:1312.3322

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Expected Precision on Higgs Parameters

Uncertainties	μ-Collider	CLIC	ILC	CEPC	FCC-ee
m_H [MeV]	**0.06**		30	5.5	8
Γ_H [MeV]	0.17	8.5	0.16	0.12	**0.04**
g_{HZZ} [%]	-	2.1	0.6	0.25	**0.15**
g_{HWW} [%]	2.2	2.1	0.8	1.2	**0.2**
g_{Hbb} [%]	2.3	2.2	1.5	1.3	**0.4**
$g_{H\tau\tau}$ [%]	5	2.5	1.9	1.4	**0.5**
$g_{H\gamma\gamma}$ [%]	10	5.9	7.8	4.7	1.5
g_{Hcc} [%]	-	2.4	2.7	1.7	**0.7**
g_{Hgg} [%]	-	2.3	2.3	1.5	**0.8**
g_{Htt} [%]	-	**4.5**	18	-	-
$g_{H\mu\mu}$ [%]	**2.1**	11	20	8.6	6.2
g_{HHH} [%]	-	24	-	-	-

for ~10y operation
lots of “!,*,?” in this table

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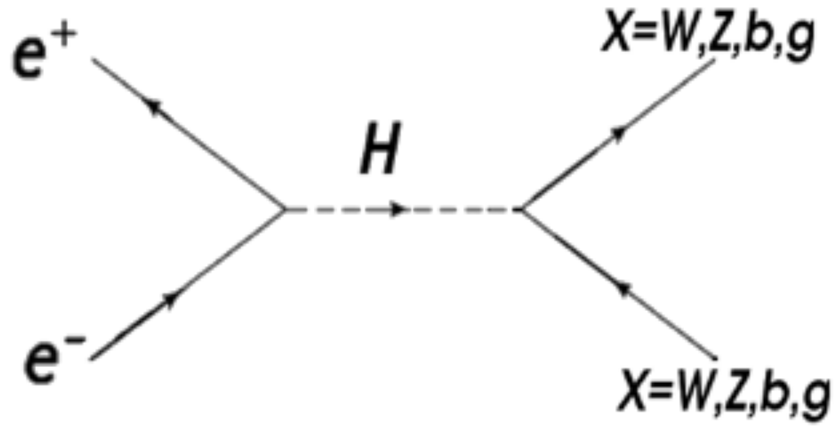
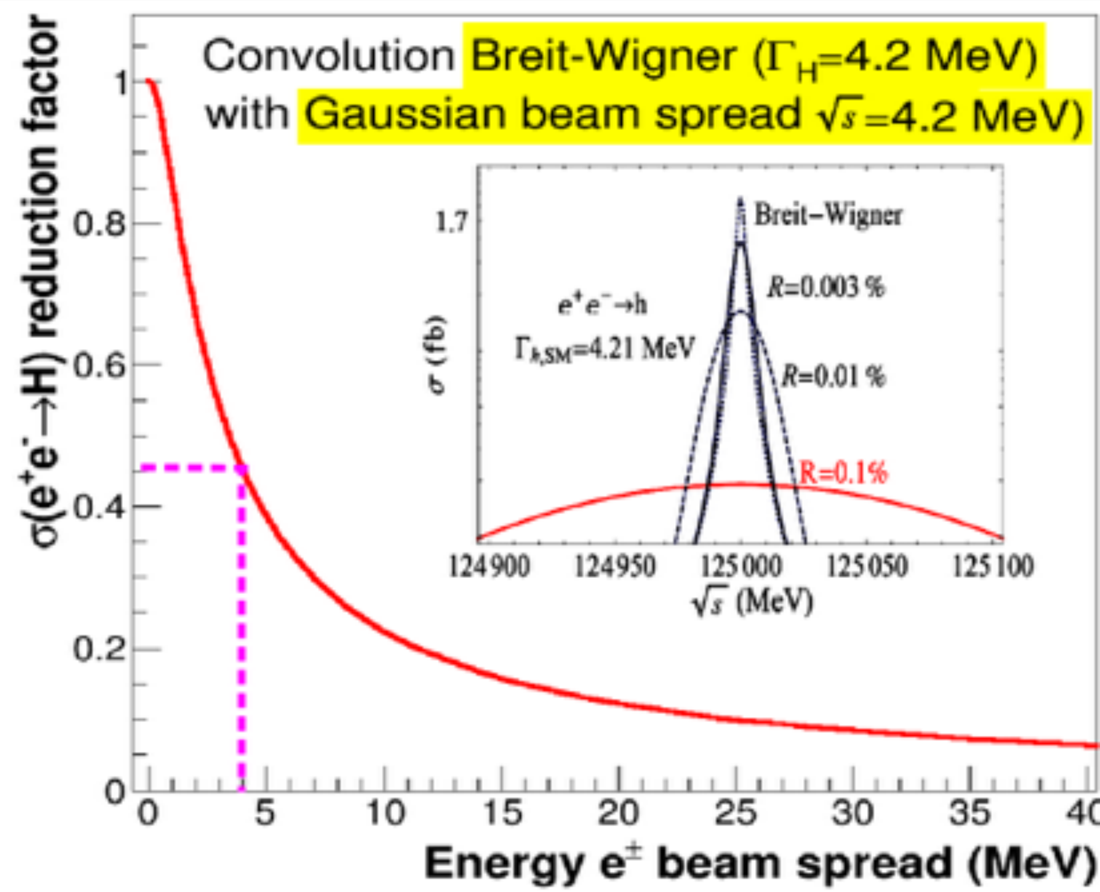
First generation couplings

➡ **s-channel Higgs production**

- Unique opportunity for measurement close to SM sensitivity
- Highly challenging; σ(ee→H) = 1.6fb; σ(e^+e^-→H) = 50ab (nominal δE/E)
- various Higgs decay channels studied





➡ **Work in progress**

- Can monochromators yields energy spread of Higgs width or smaller? At what luminosity cost?
- Energy scan O(10MeV) around mH will be needed to locate exact sqrt(s)
- Polarization increases cross section (e.g. by x2 at P=70%). At what luminosity cost?

Preliminary Results

L = 10 ab^{-1}

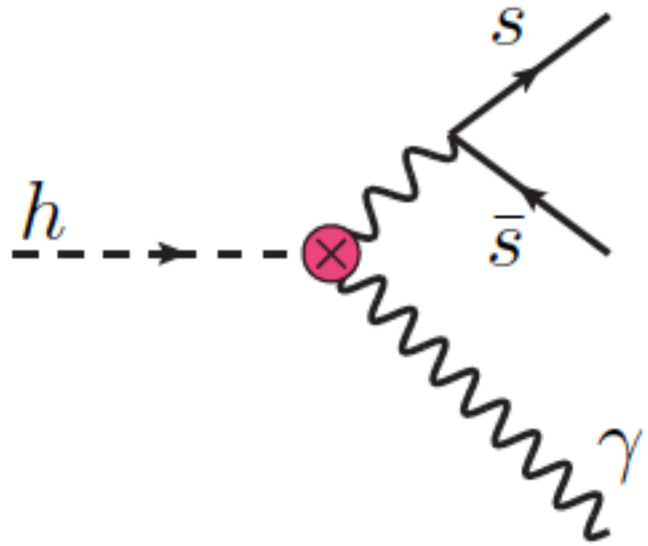
κ_e < 1.75 at 95% CL

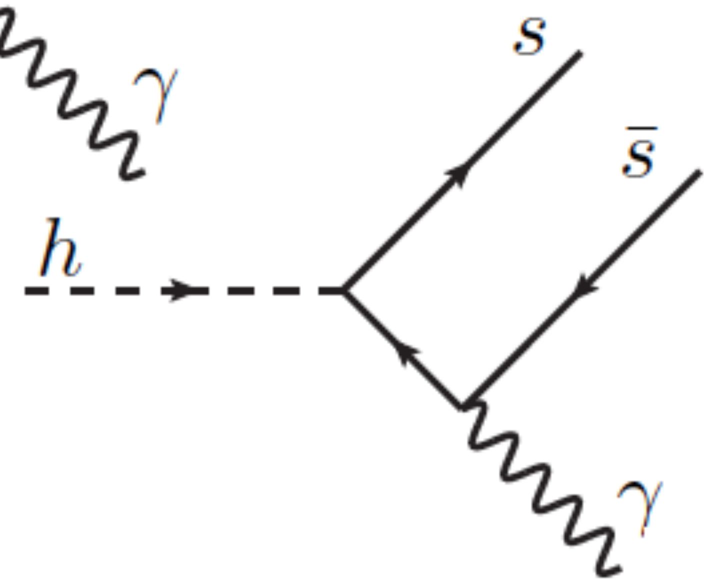
d'Enterria-Wojcik-Aleksan

Exclusive Higgs boson decays

- ➡ First and second generation couplings accessible
  - Sensitivity to u/d quark Yukawa coupling
  - Sensitivity due to interference

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9\pm 0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\right]}{0.57\bar{\kappa}_b^2} \times 10^{-5}$$





- ➡ Also interesting to FCC-hh program
- ➡ Alternative H→MV decays should be studied (V= γ, W, and Z)

$H \to J/\Psi\,\gamma$ ➡ y_c

$H \to \phi\,\gamma$ ➡ y_s

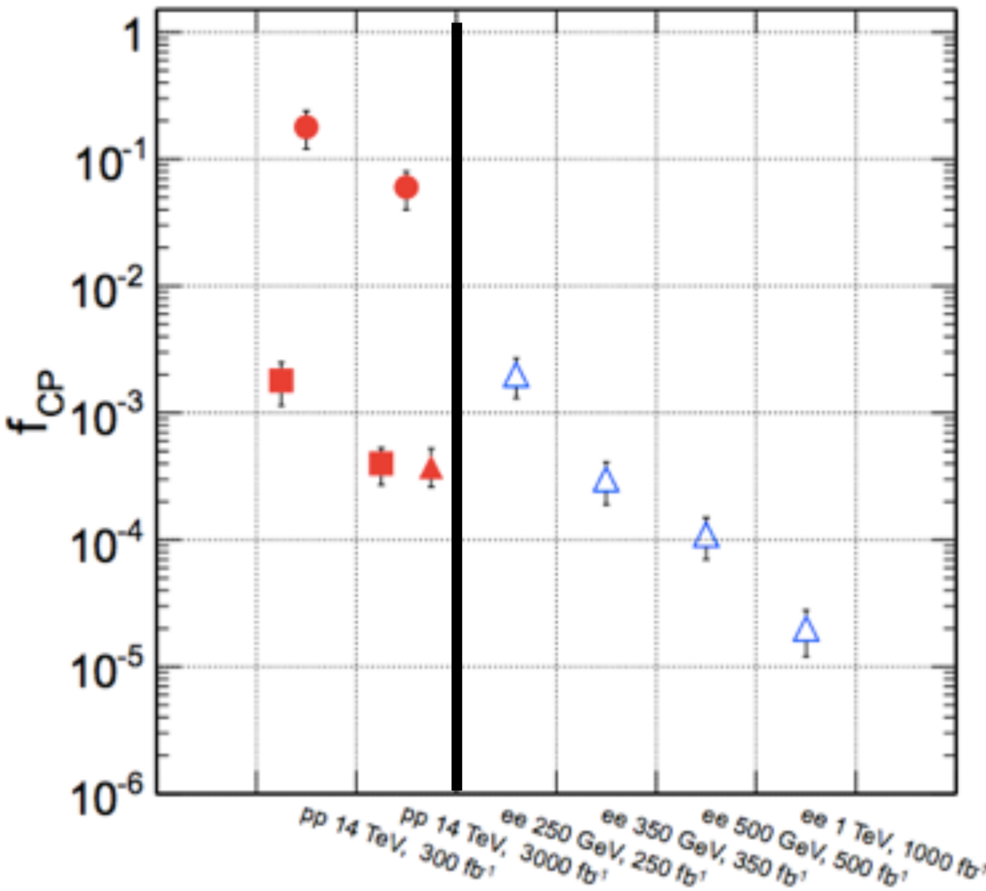
$H \to \rho\,\gamma$

$H \to \omega\,\gamma$ ➡ y_u, y_d

CP Measurements

- ➡ CP violation can be studied by searching for CP-odd contributions; CP-even already established
- ➡ Snowmass Higgs paper http://arxiv.org/abs/1310.8361
- ➡ Higgs to Tau decays of interest
- ➡ Studies consider intermediated resonances (ρ,a1)

for HVV couplings



$$\mathcal{L}_{hff} \propto h\bar{f}(\cos\Delta + i\gamma_5 \sin\Delta)f$$

Colliders	LHC	HL-LHC	FCCee (1 ab^{-1})	FCCee (5 ab^{-1})	FCCee (10 ab^{-1})
Accuracy(1σ)	25°	8.0°	5.5°	2.5°	1.7°

http://arxiv.org/abs/1308.1094

Rare and Exotics Higgs Bosons

- Largely unexplored!
- ZH events allow for detailed studies of rare and exotic decays
  - improved with hadronic and invisible Z decays
  - set requirements for lepton collider detector
- Coupling measurements have sensitivity to BSM decays
- Dedicated studies using specific final states improve sensitivity
- Example: Higgs to invisible, flavor violating Higgs, and many more
- Modes with of limited LHC sensitivity are of particular importance to lepton collider program
  - currently under study
- Detailed discussion of exotic Higgs decays at Phys. Rev. D 90, 075004 (2014)

$h \to \not{E}_T$

$h \to 4b$

$h \to 2b2\tau$

$h \to 2b2\mu$

$h \to 4\tau, 2\tau 2\mu$

$h \to 4j$

$h \to 2\gamma 2j$

$h \to 4\gamma$

$h \to ZZ_D, Za \to 4\ell$

$h \to Z_D Z_D \to 4\ell$

$h \to \gamma + \not{E}_T$

$h \to 2\gamma + \not{E}_T$

$h \to$ 4 ISOLATED LEPTONS $+ \not{E}_T$

$h \to 2\ell + \not{E}_T$

$h \to$ ONE LEPTON-JET $+ X$

$h \to$ TWO LEPTON-JETS $+ X$

$h \to b\bar{b} + \not{E}_T$

$h \to \tau^+\tau^- + \not{E}_T$

Muon Collider as Higgs Factory

- ➡ **A muon collider at $\sqrt{s}$ = mH is a *charming* Higgs factory**
  - but not competitive with other e^+e^- collider options
  - Higgs width better measured at e^+e^- colliders
  - Precision on $g_{H\mu\mu}$ compatible with HL-LHC performance
- ➡ **Case for muon collider**
  - if H(125) has nearby (a few to a few hundred MeV) peaks
  - allows study of heavy H and A (also a case for CLIC), but masses have to be known
- ➡ **Muon collider may be the best way to achieve multi-TeV lepton collider**
  - substantial R&D remains

Complementarity to Hadron Collider Program

setup for Tilman's talk

gH_{XY}	ZZ	WW	γγ	Zγ	tt	bb	ττ	cc	ss	μμ	uu,dd	ee	Γ_H	HH	BR_{exo}
FCC-ee	0.15	0.19	1.5			0.42	0.54	0.71	H→Vγ	6.2	H→Vγ	ee→H	0.9		0.45
HL-LHC	2	2	2	~10	~5	4	2	-	-	~5	-	-	-	~30	< 5%
FCC-hh			< 1?	1 ?	1					2 ?				5 ?	?

- ➡ Uncertainty in %.
- ➡ Almost perfect complementarity between lepton and hadron collider Higgs program
- ➡ In some cases the complementarity is obvious, in others more subtle

Conclusion

➡ **Exploration of Higgs Physics at the LHC on its way**

- We have seen impressive Run-I results this week
- HL-LHC will set a high bar for Higgs physics

➡ **Lepton Colliders offer impressive precision Higgs program**

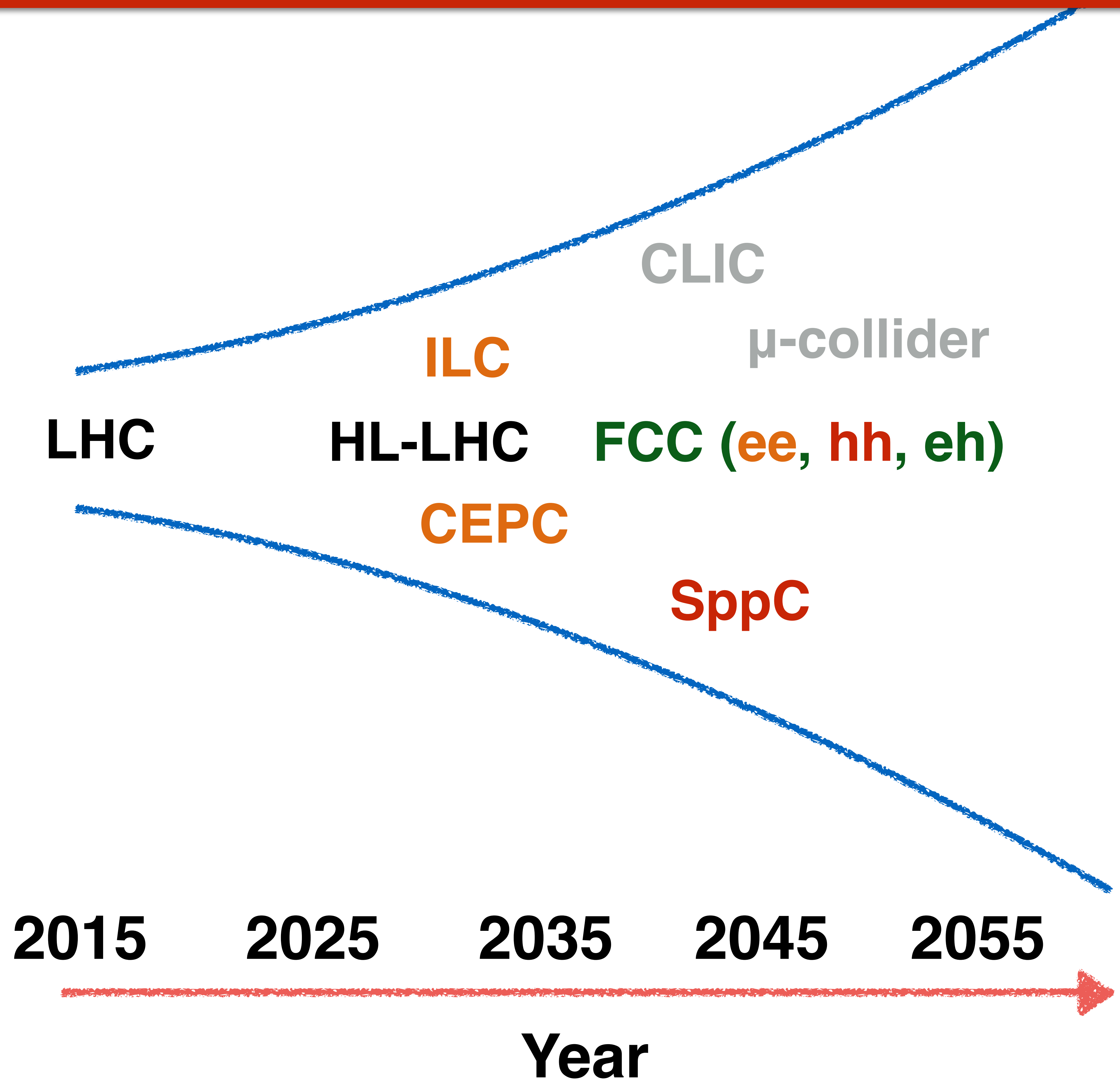
- Complementarity to hadron collider program

➡ **FCC-ee promises largest Higgs dataset**

- and path to next generation hadron collider (FCC-hh)

➡ **Muon collider is not a competitive Higgs factory**

Colliders of the 21st Century



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References / Input from

- s-channel Higgs production: D.d’Enterria, R.Aleksan, G.Wojcik
- CMS: Snowmass report, ECFA report
- ATLAS: ATL-CONF-15-007, ATL-PHYS-PUB-2014-016, 019
- TLEP/FCC-ee: TLEP Case Study http://arxiv.org/abs/1308.6176 JHEP 01 (2014) 164
- Prospective Studies for LEP3 with the CMS detector http://arxiv.org/abs/1208.1662
- CP measurement: http://arxiv.org/abs/1308.1094, Felix Xu’s meeting in the meeting
- Implications of new physics scales: http://arxiv.org/abs/1403.7191
- Luminosity needs for FCC-hh and Higgs @ 100 TeV: M.Mangano, Plehn, et al
- Exclusive Higgs decays: Y. Soreq
- …

Higgs prospects for the HL-LHC

CMS Projection for precision of Higgs coupling measurement

Rare-decays

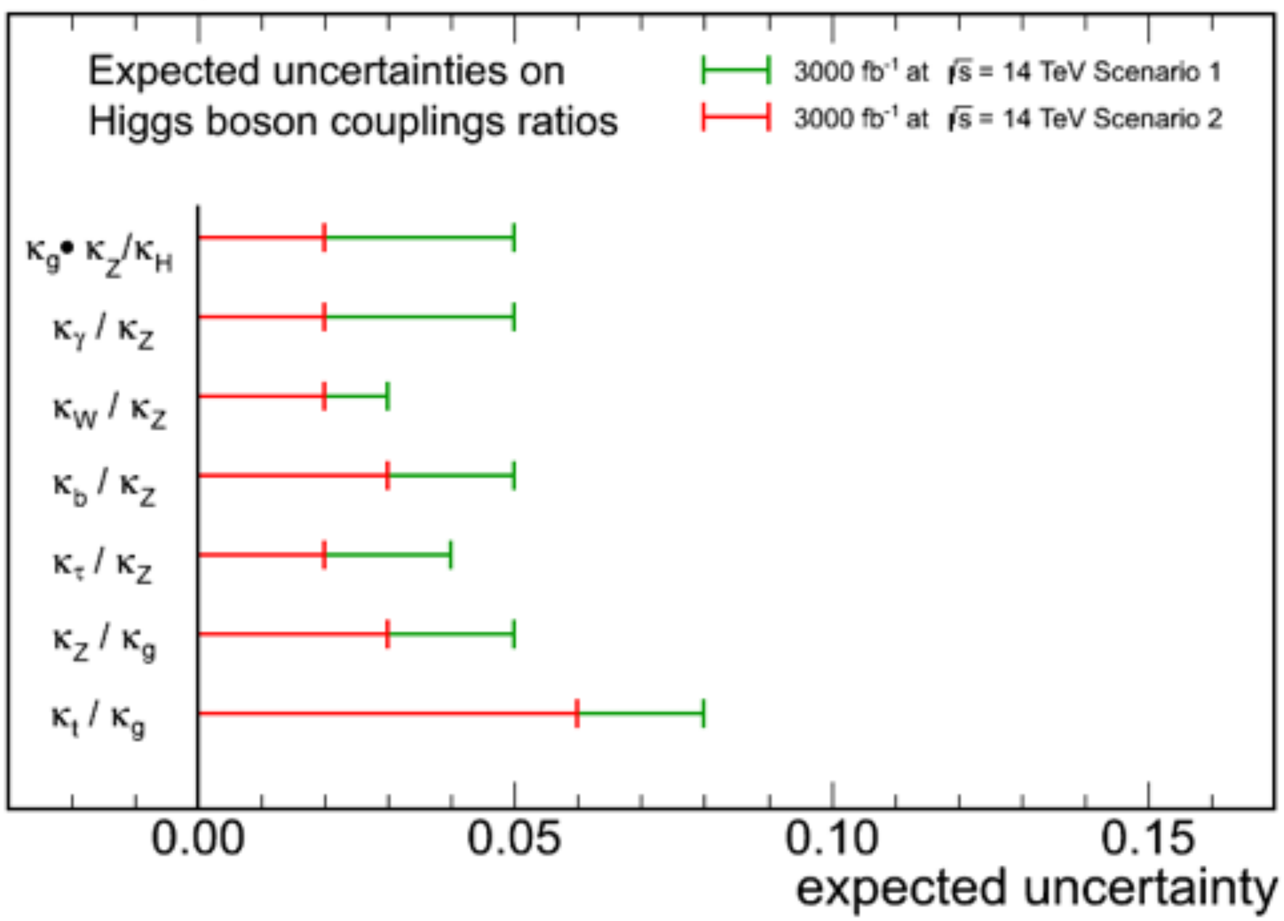
L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

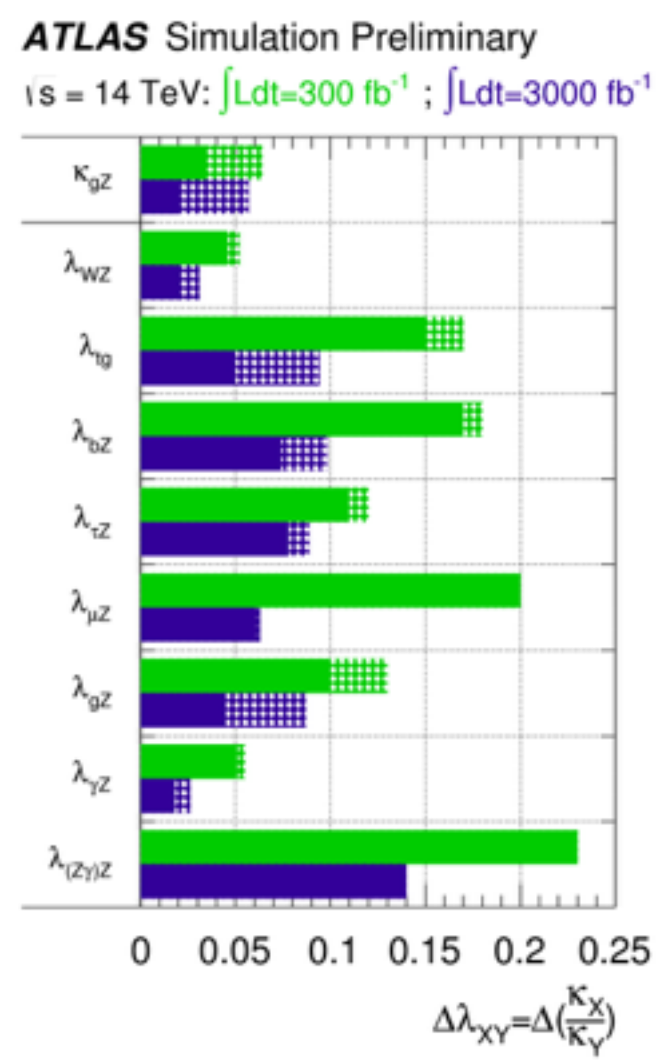
Coupling precision 2-10 %
factor 2-3 improvement from HL-LHC

Key question is the
evolution systematic uncertainty

Snowmass Whitepaper for CMS - http://arxiv.org/abs/1307.7135

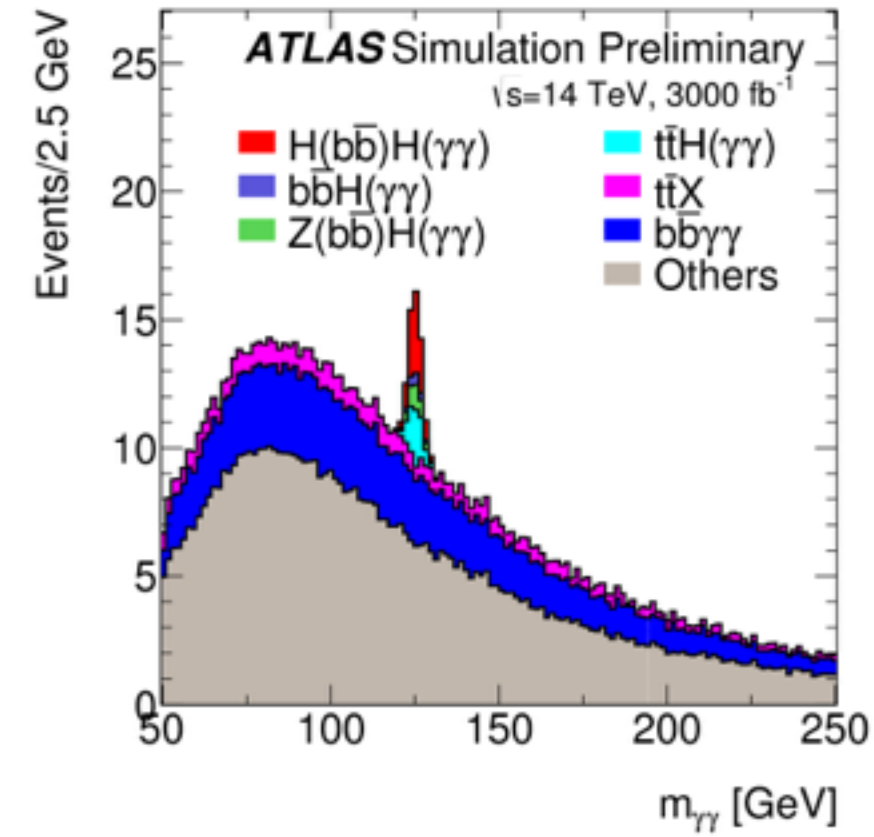
CMS Projection





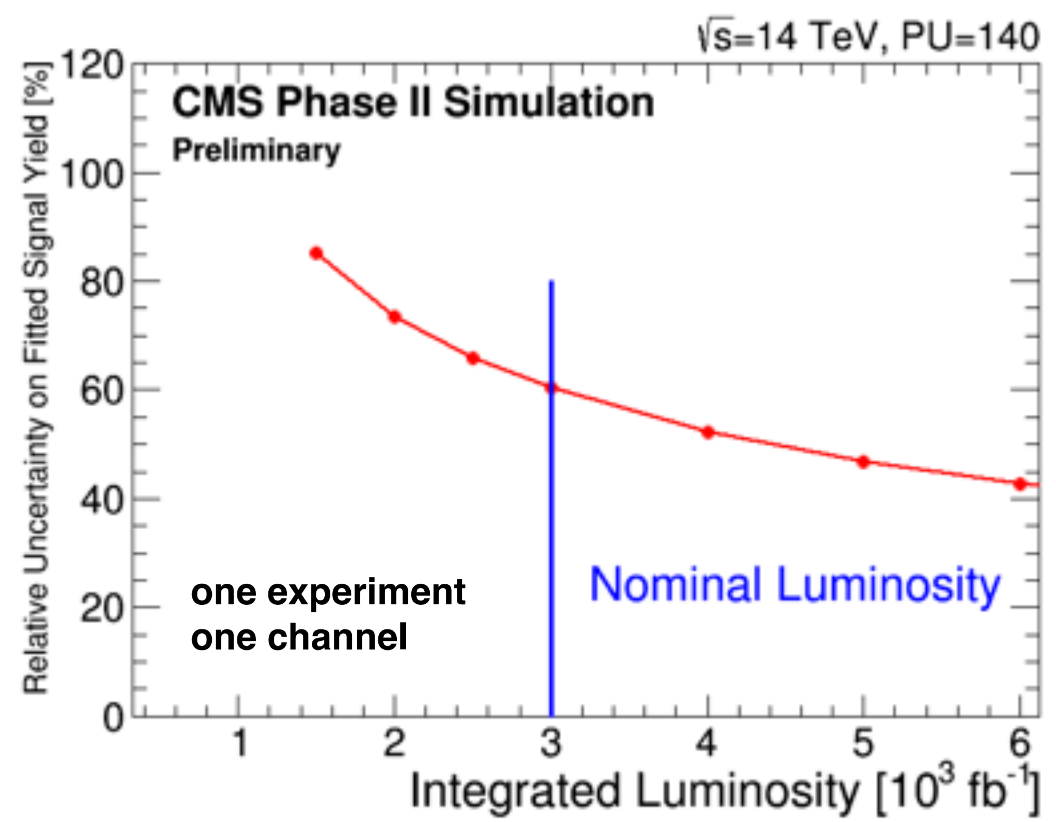
Higgs prospects for the HL-LHC

- **Di-Higgs production: exciting prospects of the HL-LHC**
  - Gluon fusion cross section is only **40.2fb** [NNLO] at 14 TeV
  - Vector boson fusion cross section is 2fb
- **Most interesting final states**
  - bb**γγ** [320 expected events in 3ab-1]
  - bb$\tau\tau$ [9000 expected]
  - bbbb [40k expected (2k in VBF)]
  - bbWW [30000 exp. events]
- **Goal is to reach minimum sensitivity of 3σ for SM production and with that to BSM scenarios**



Process / Selection Stage	HH	ZH	$t\bar{t}H$	$b\bar{b}H$	$\gamma\gamma$+jets	γ+jets	jets	$t\bar{t}$
Object Selection & Fit Mass Window	22.8	29.6	178	6.3	2891	1616	292	113
Kinematic Selection	14.6	14.6	3.3	2.0	128	96.9	20	20
Mass Windows	9.9	3.3	1.5	0.8	8.5	6.3	1.1	1.1

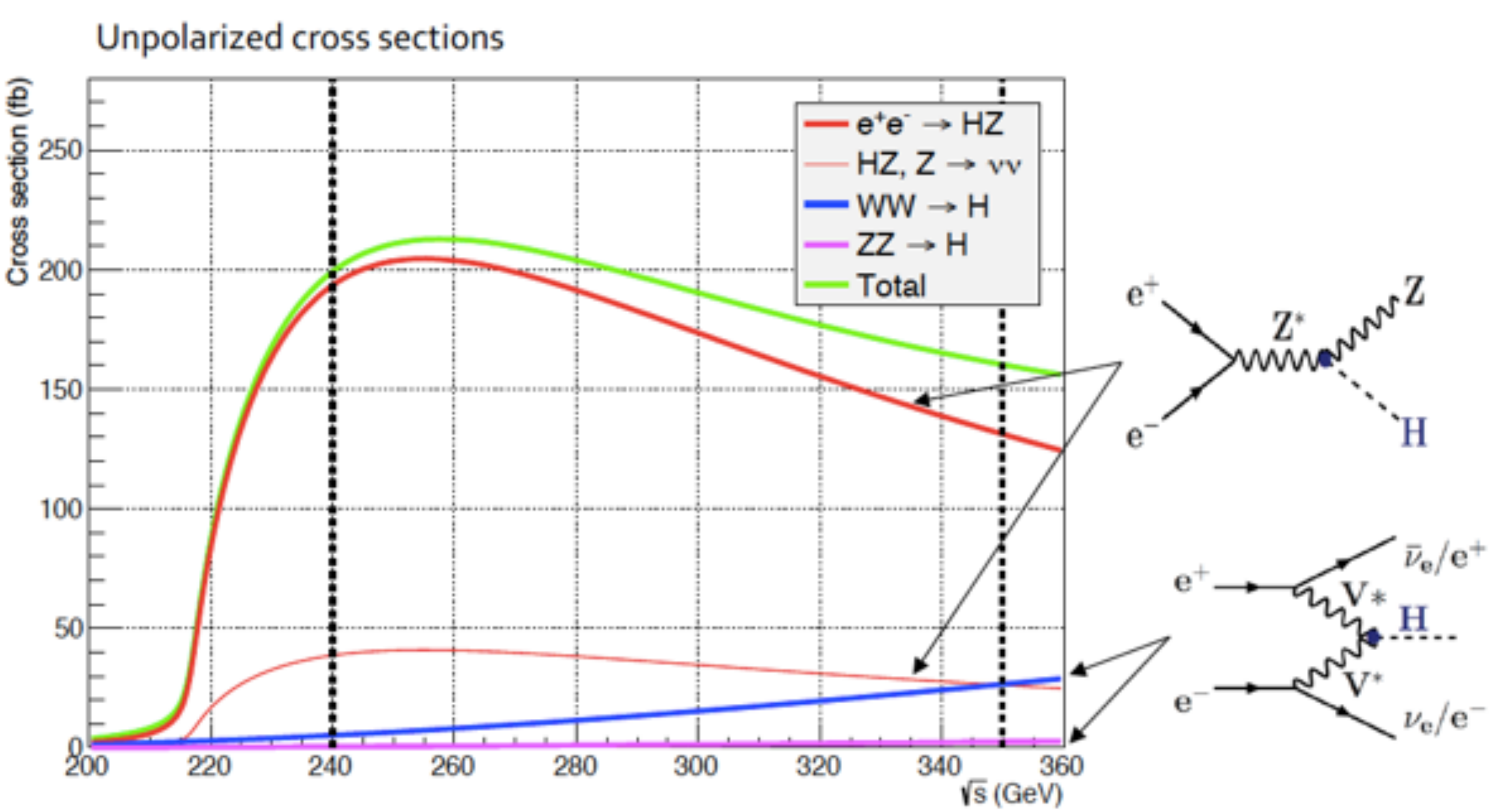
CMS - central photon yield



Higgs Physics at the FCC-ee

- ➡ Precision Higgs coupling studies and total width
- ➡ Higgs self coupling through loop corrections
- ➡ 1st and 2nd fermion generation couplings
- ➡ Rare and exotic decays (e.g. DM decays)
- ➡ Extra Higgs bosons
- ➡ Tensor structure
- ➡ …

	FCC-ee
Total Integrated Luminosity (ab^{-1})	**10**
Number of Higgs bosons from $e^+e^- \to HZ$	**2,000,000**
Number of Higgs bosons from boson fusion	**50,000**



	FCC-ee
σ_{HZ}	**0.4%**
$\sigma_{HZ} \times BR(H \to bb)$	**0.2%**
$\sigma_{HZ} \times BR(H \to c\bar{c})$	**1.2%**
$\sigma_{HZ} \times BR(H \to gg)$	**1.4%**
$\sigma_{HZ} \times BR(H \to WW)$	**0.9%**
$\sigma_{HZ} \times BR(H \to \tau\tau)$	**0.7%**
$\sigma_{HZ} \times BR(H \to ZZ)$	**3.1%**
$\sigma_{HZ} \times BR(H \to \gamma\gamma)$	**3.0%**
$\sigma_{HZ} \times BR(H \to \mu\mu)$	**13%**

stat. uncertainties

ILC Timeline

Delivered TDR

Machine commissioning starts

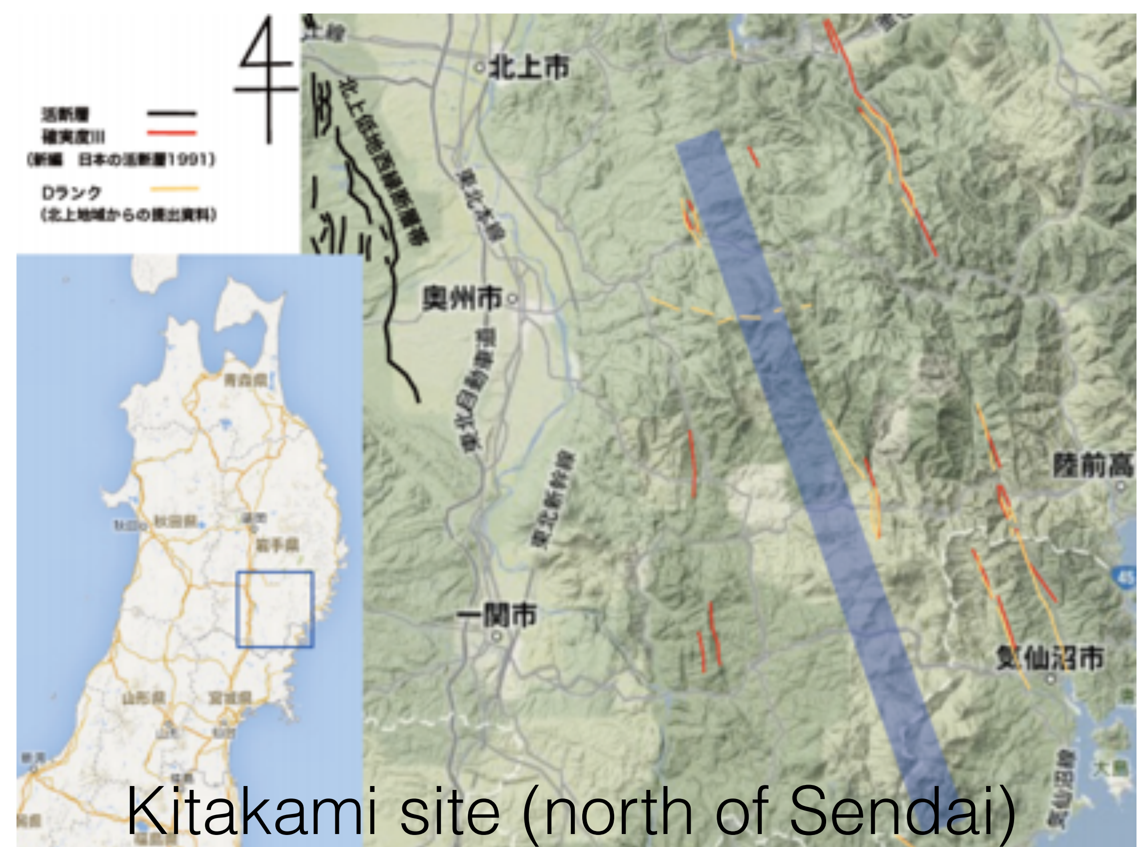
2013–2016
- Negotiations among governments
- Prepare for international lab
- Accelerator detailed design
- R&D for cost-effective production
- Site studies

2016–2018
- International agreement
- "Green-light" for construction
- Preparation for bidding

2018–2027
- Construction

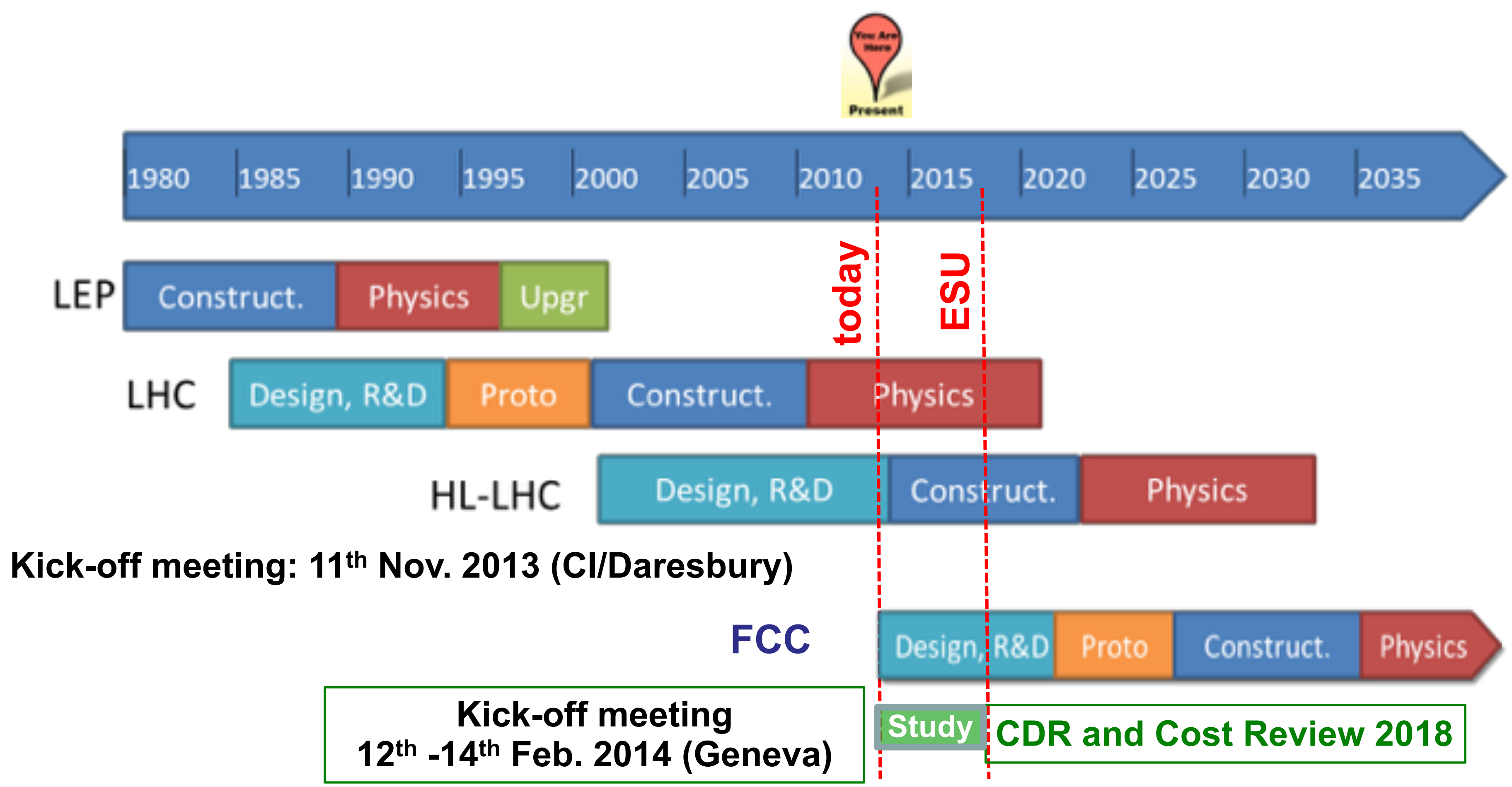
2013 2016 2018 2027

as proposed by LC Collaboration



Kitakami site (north of Sendai)

CERN (FCC) Timelines



- LHC and HL-LHC operation until ~2035
- Must start now developing FCC concepts to be ready in time

CEPC-SppC Timelines

CEPC

SppC