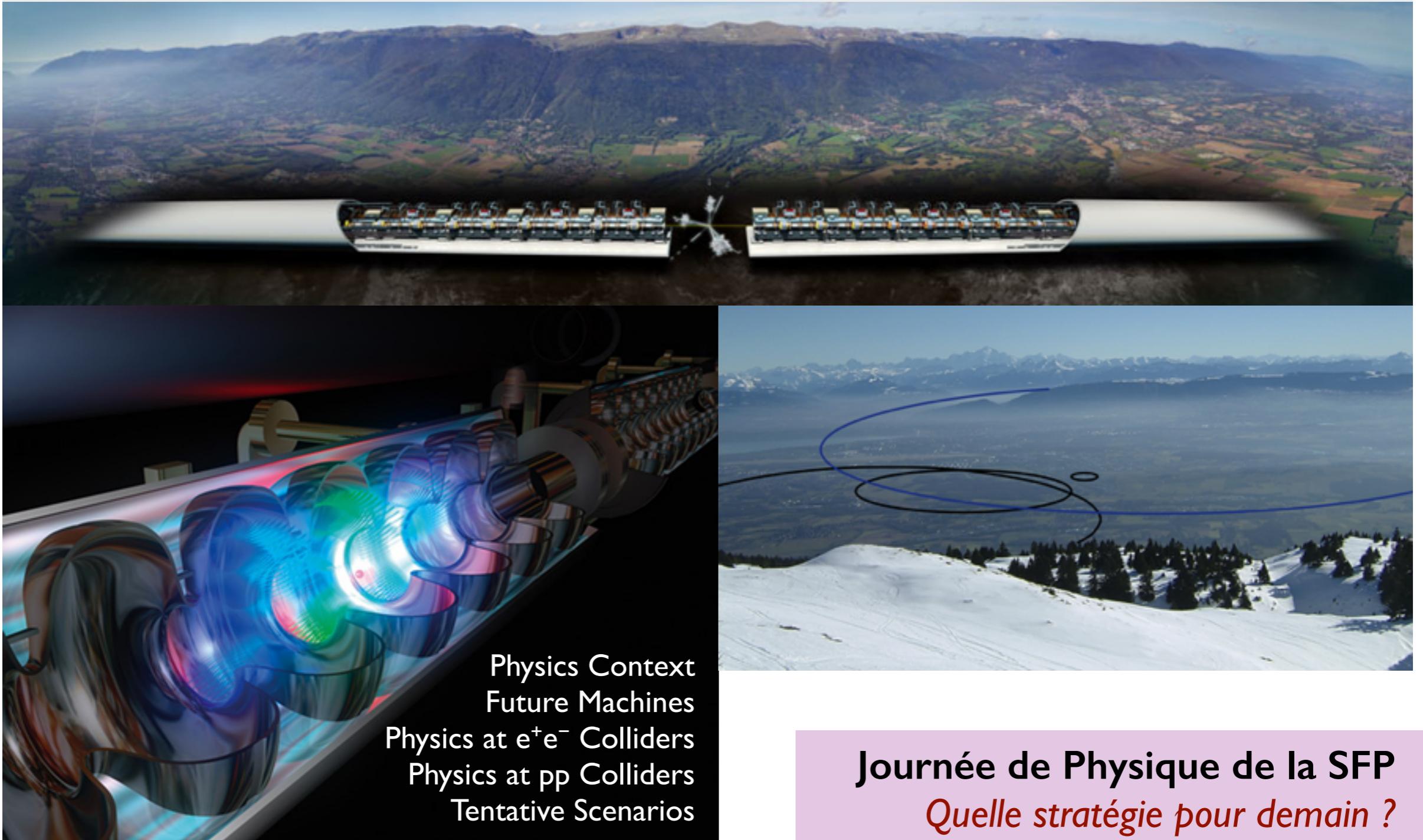


Physics Opportunities at Future Colliders



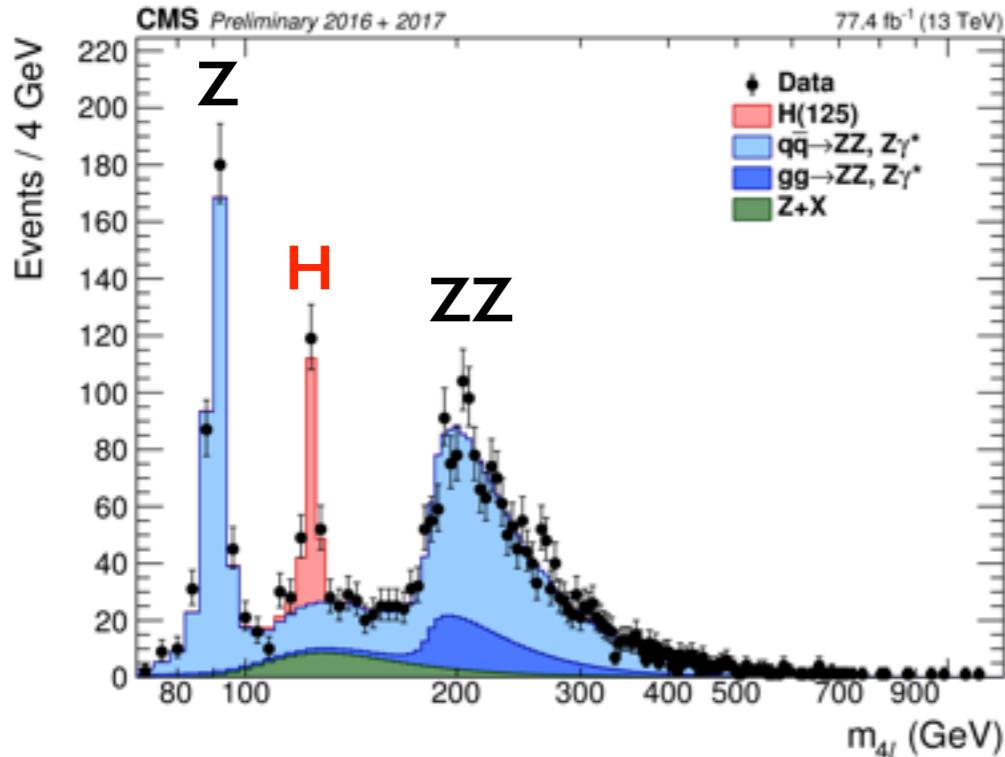
Gautier Hamel de Monchenault
avec la contribution de Roman Pöschl

Journée de Physique de la SFP
Quelle stratégie pour demain ?

22 novembre 2018
LPNHE, France

Standard Model

The beauty of the Higgs boson



$M_H = 125 \text{ GeV}$

- optimum of the product of decay probabilities
- near criticality of the quantum vacuum

Naturalness

- is there a symmetry (SUSY?) protecting the Higgs mass and linking the Z and H bosons?

So far no hint of SUSY at the LHC

- how much fine tuning can we bare?
→ HL-LHC (no NP) $\approx 1\%$ fine tuning

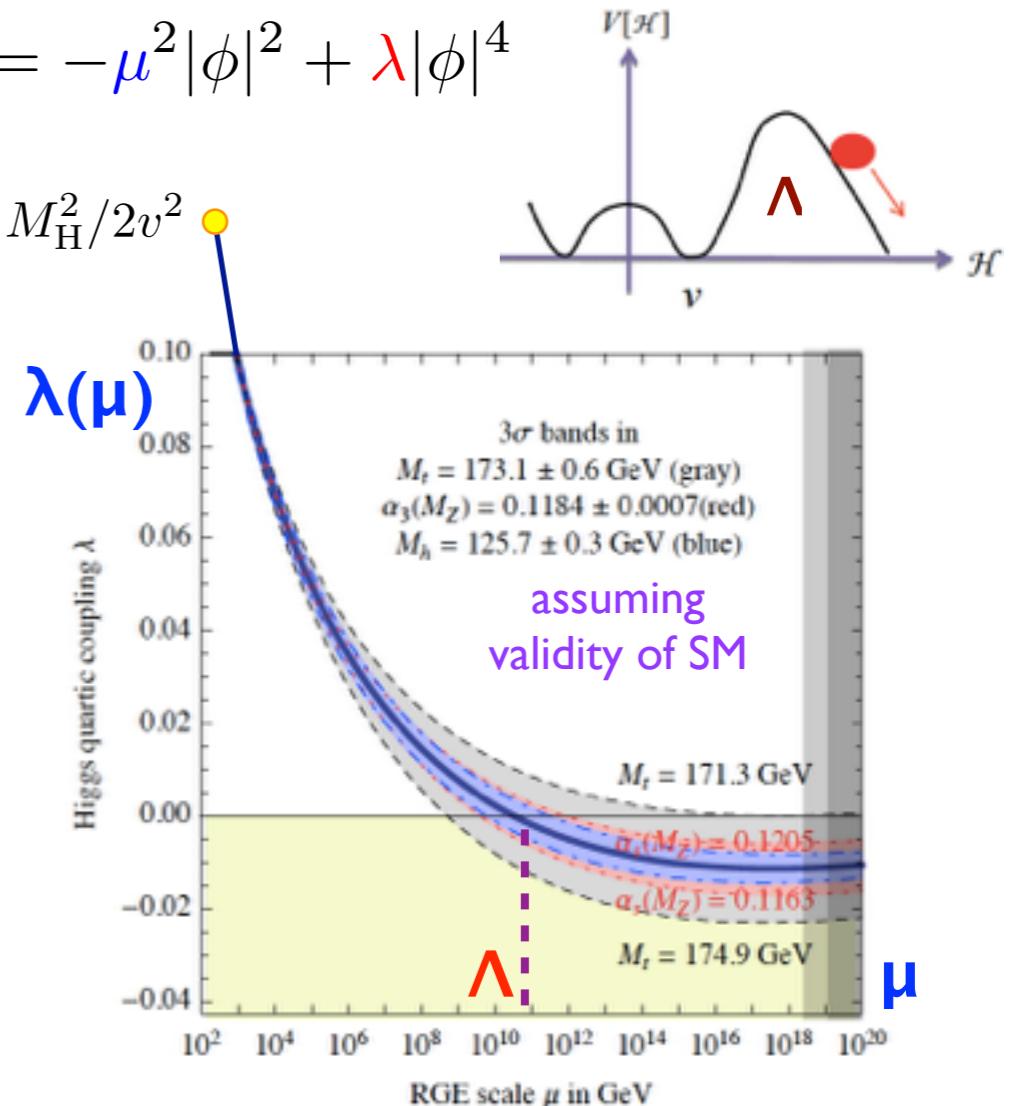
It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong.



Higgs potential

$$V_H = -\mu^2 |\phi|^2 + \lambda |\phi|^4$$

$$\lambda(v) = M_H^2 / 2v^2$$



The “instability scale” depends on M_{top} , M_H and α_s : $\log_{10} \Lambda(\text{GeV}) \approx 11$

The Standard Model (SM) may remain valid up to very high energy

Beyond SM?

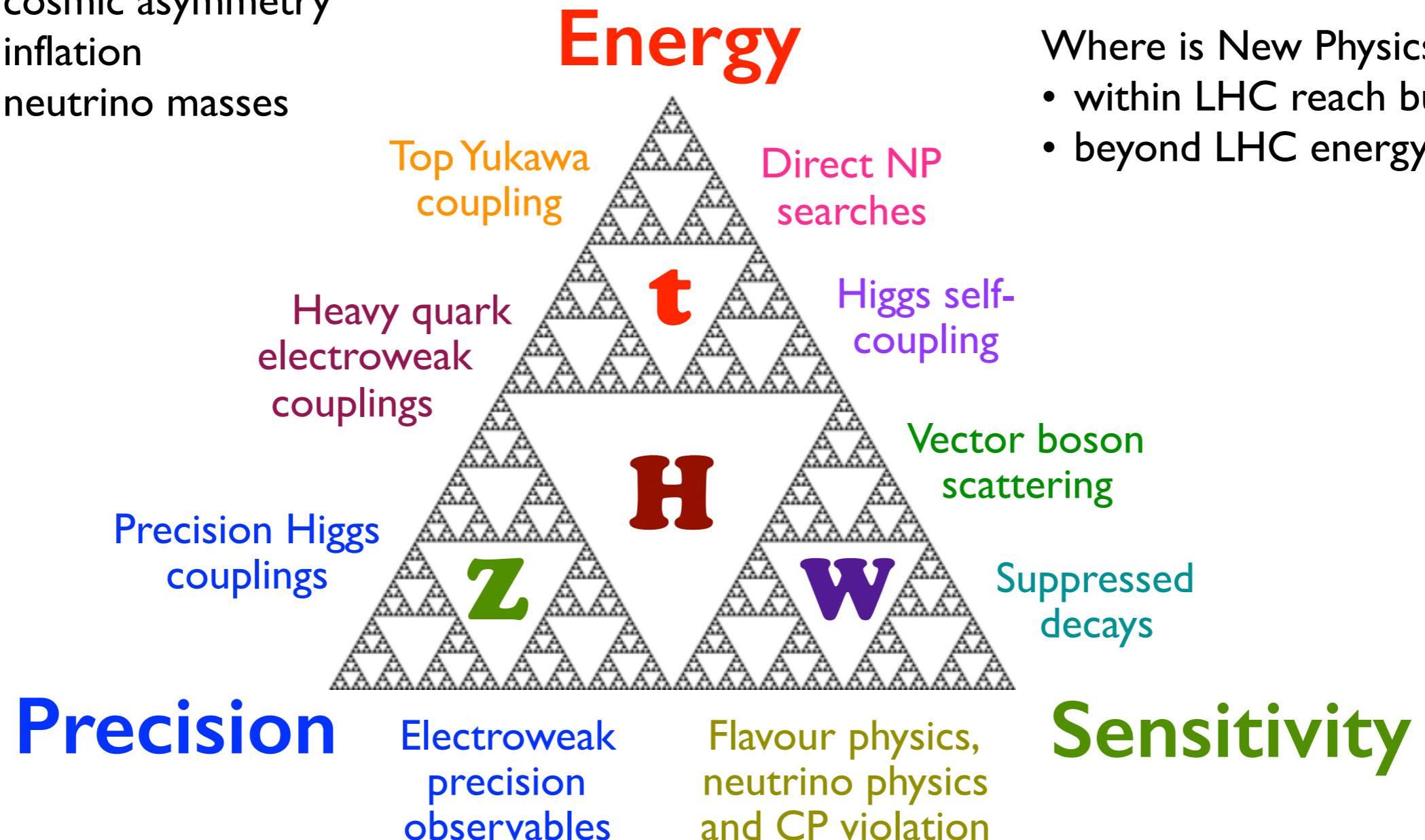
...there is no experiment/facility, proposed or conceivable (...) which can guarantee discoveries beyond the SM, and answers to the big questions of the field



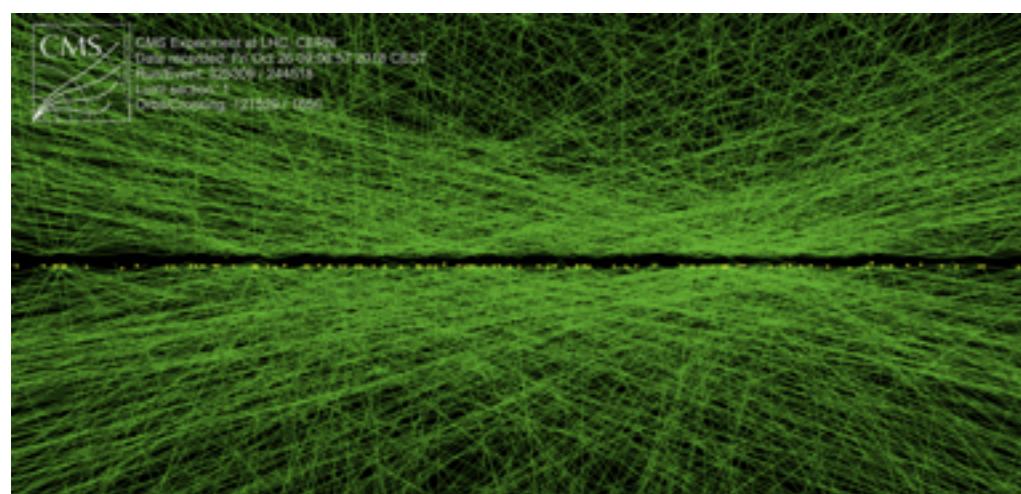
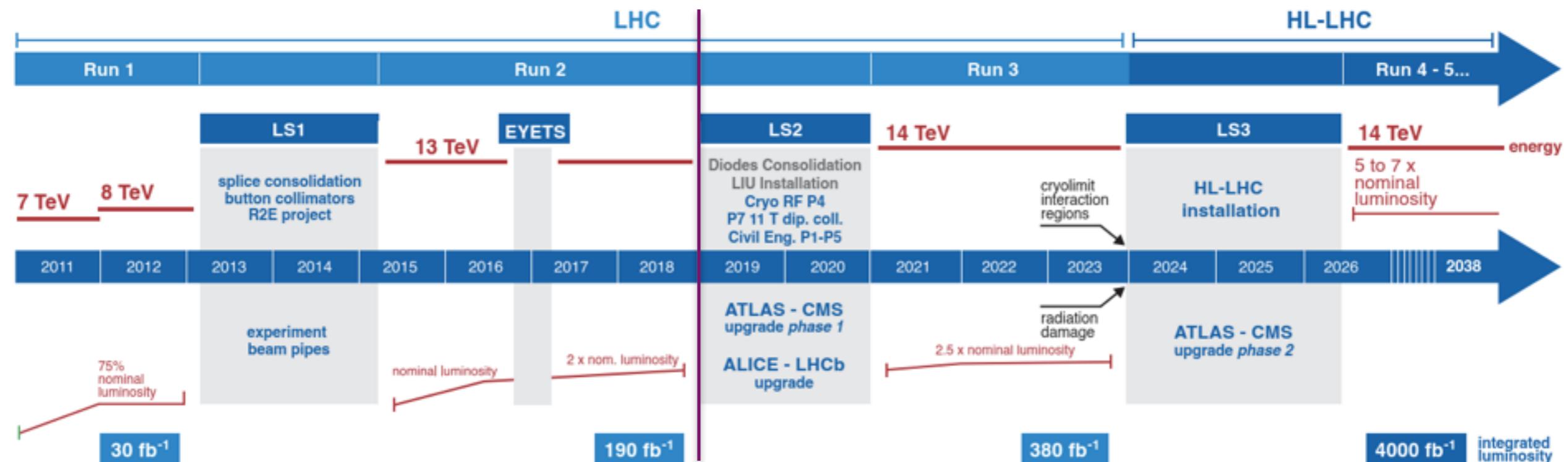
M. Mangano

Known departures from SM

- dark matter / energy
- cosmic asymmetry
- inflation
- neutrino masses



Timeline of LHC



136 pile-up event BX
(CMS, October 2018)

cf presentation by Marumi Kado

→ Run-2 (pp)

- just completed
- $>150 \text{ fb}^{-1}$ @ 13 TeV / exp.

from F. Bordry, RRB CERN 29/10/2018

→ Experiments preparing for Run-3

- $2.5 \times$ nominal luminosity @ 14 TeV
- double the statistics by 2023

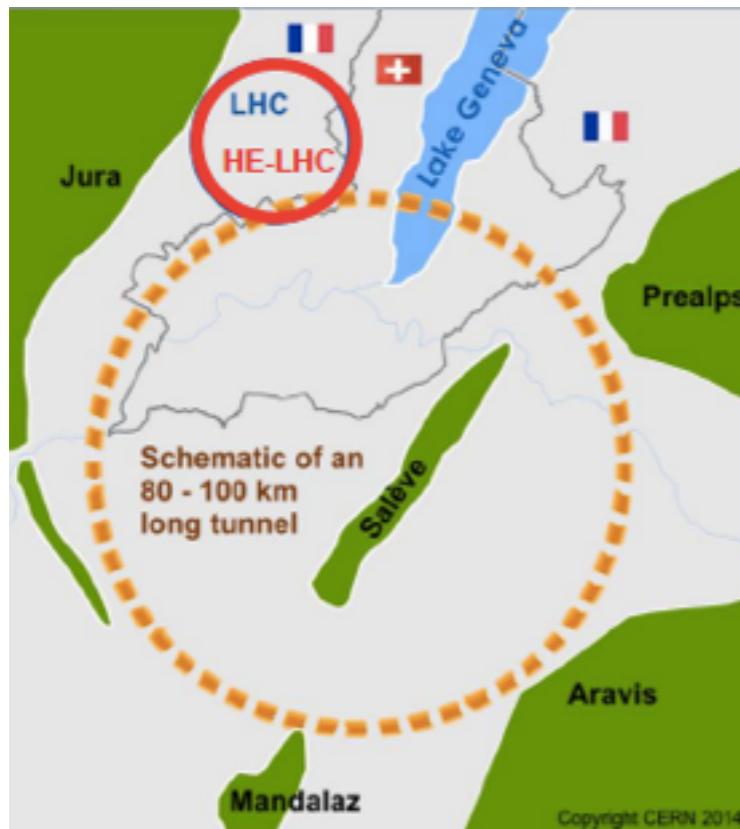
→ HL-LHC nominal

- starts 2026
- $>3 \text{ ab}^{-1}$ @ 14 TeV in 10 years

→ LHeC: an $e^\pm p$ option at HL-LHC?

- $1/x$ and $Q^2 = \text{HERA} \times 20$
- luminosity = HERA $\times 100/1000$

FCC: Future Circular Colliders



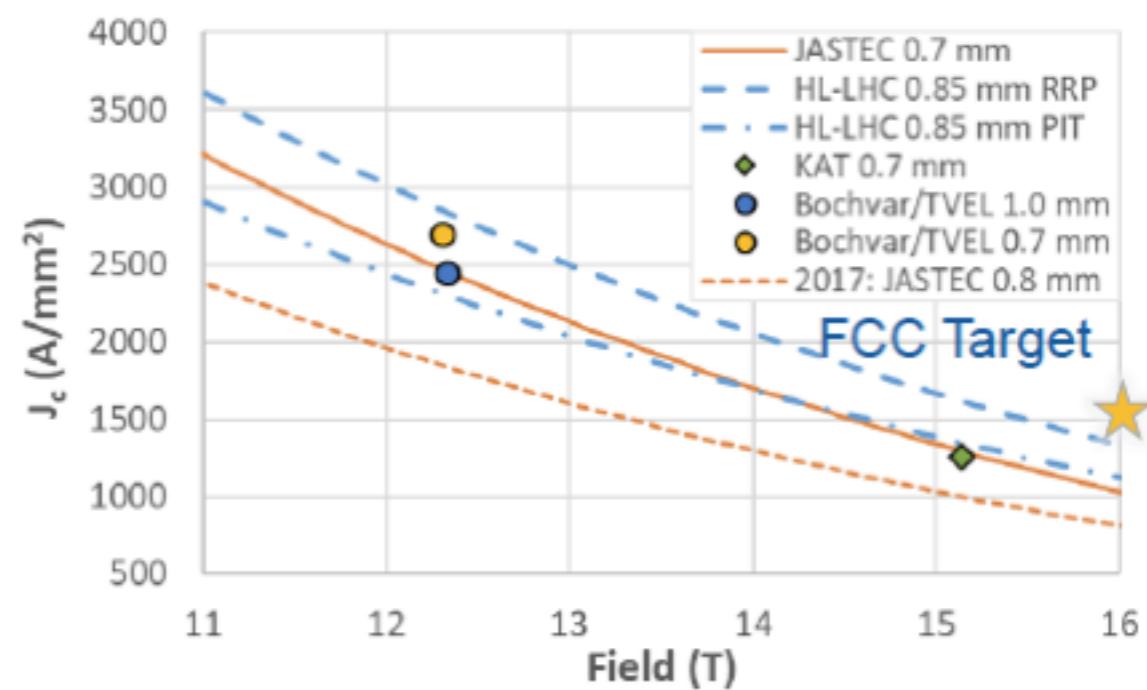
	\sqrt{s}	\mathcal{L} ($\text{cm}^{-2}\text{s}^{-1}$)	first beams (technically)	tunnel
HE-LHC	27 TeV	1.6×10^{35}	2040	LHC
FCC-ee	90-365 GeV	$200-1.5 \times 10^{34}$	2039	
FCC-eh	3.5 TeV	1.5×10^{34}	2043	100-km
FCC-hh	100 TeV	3×10^{35}	2043	cf backup slide

100-km tunnel in Geneva area

	\sqrt{s}	L (ab^{-1})	years
HE-LHC	27 TeV	12	20
FCC-hh	100 TeV	30	25

Major focus at CERN:
development of 16-T Nb₃Sb SC magnets

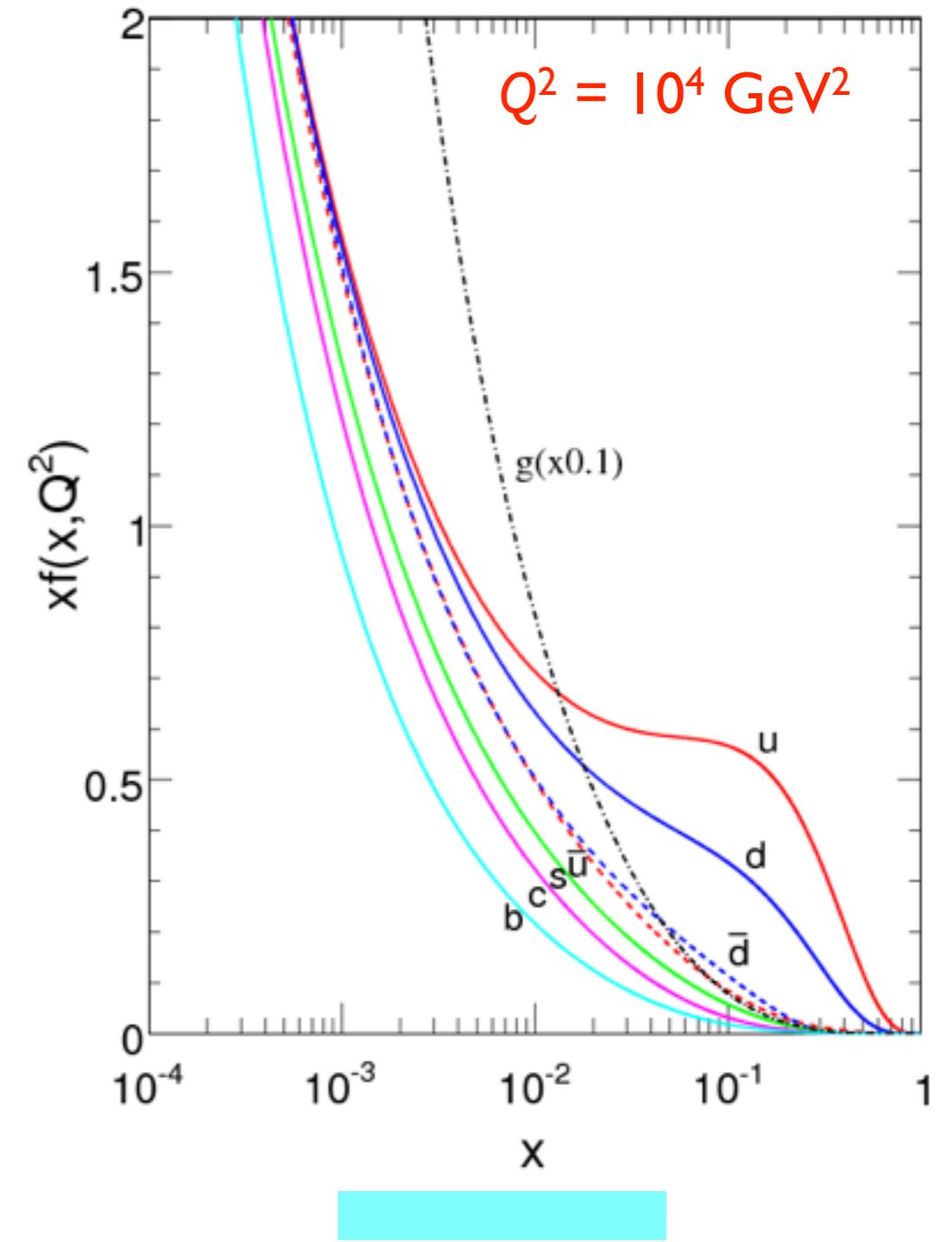
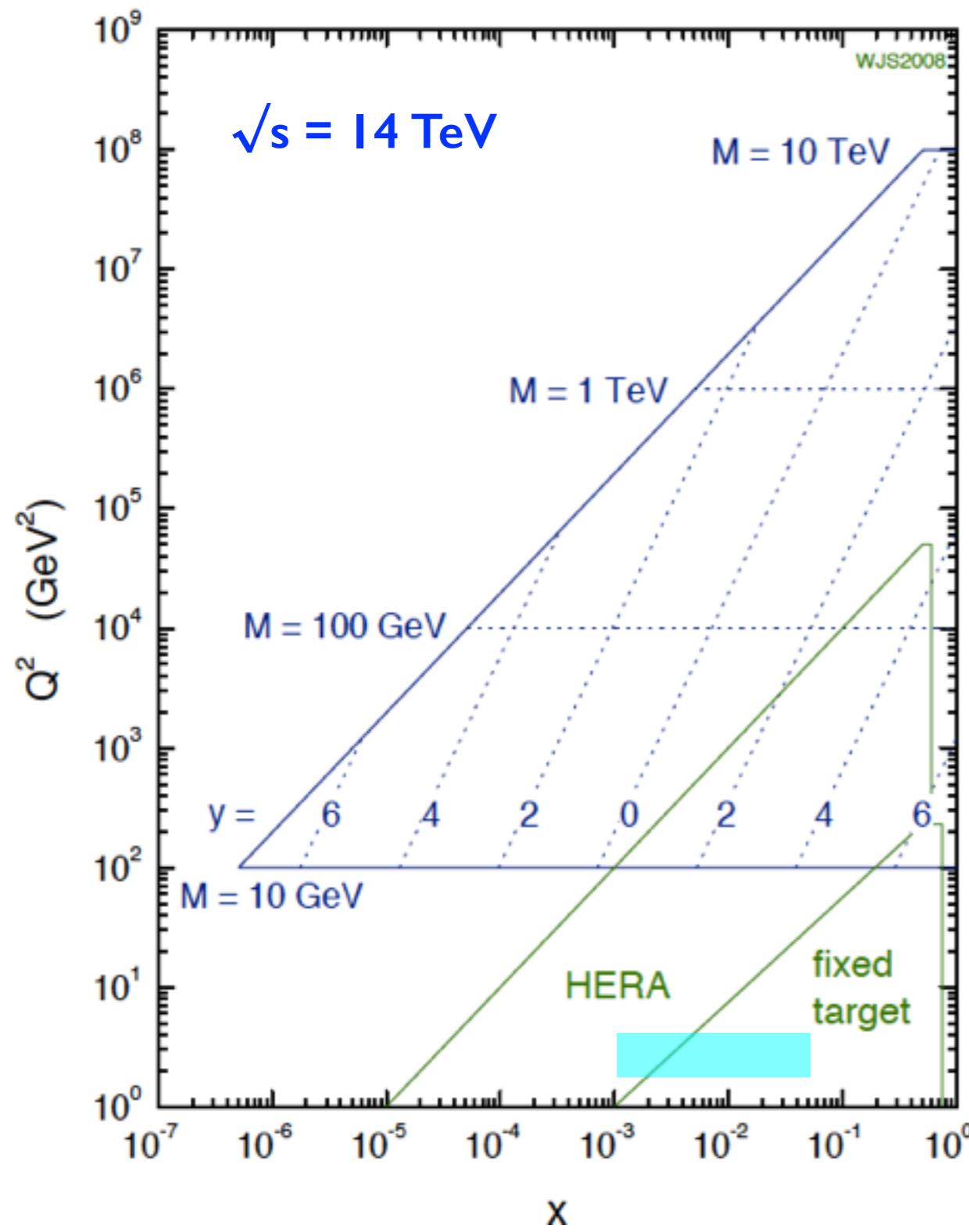
- on-going R&D on SC high-field magnets
- prepare industrialisation



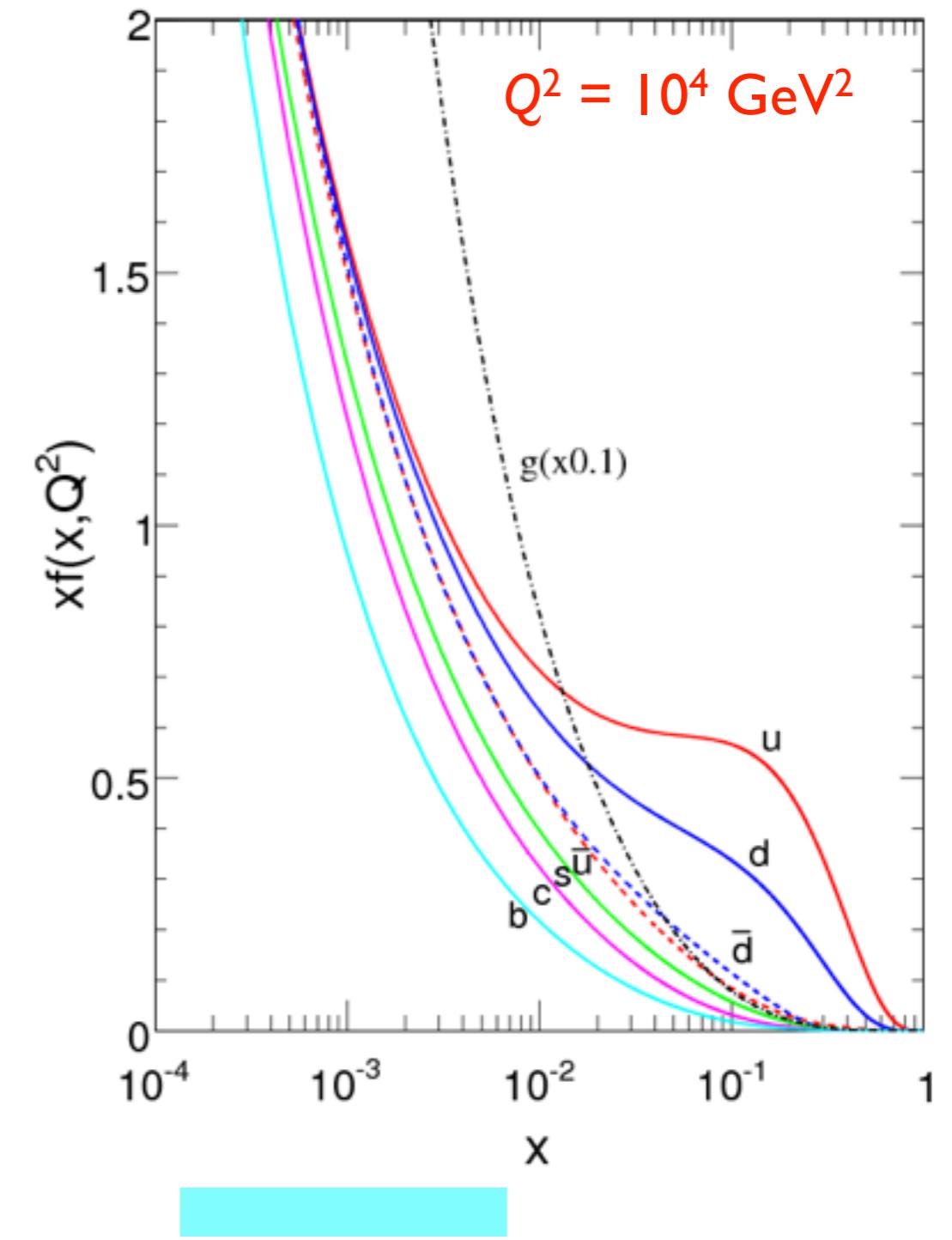
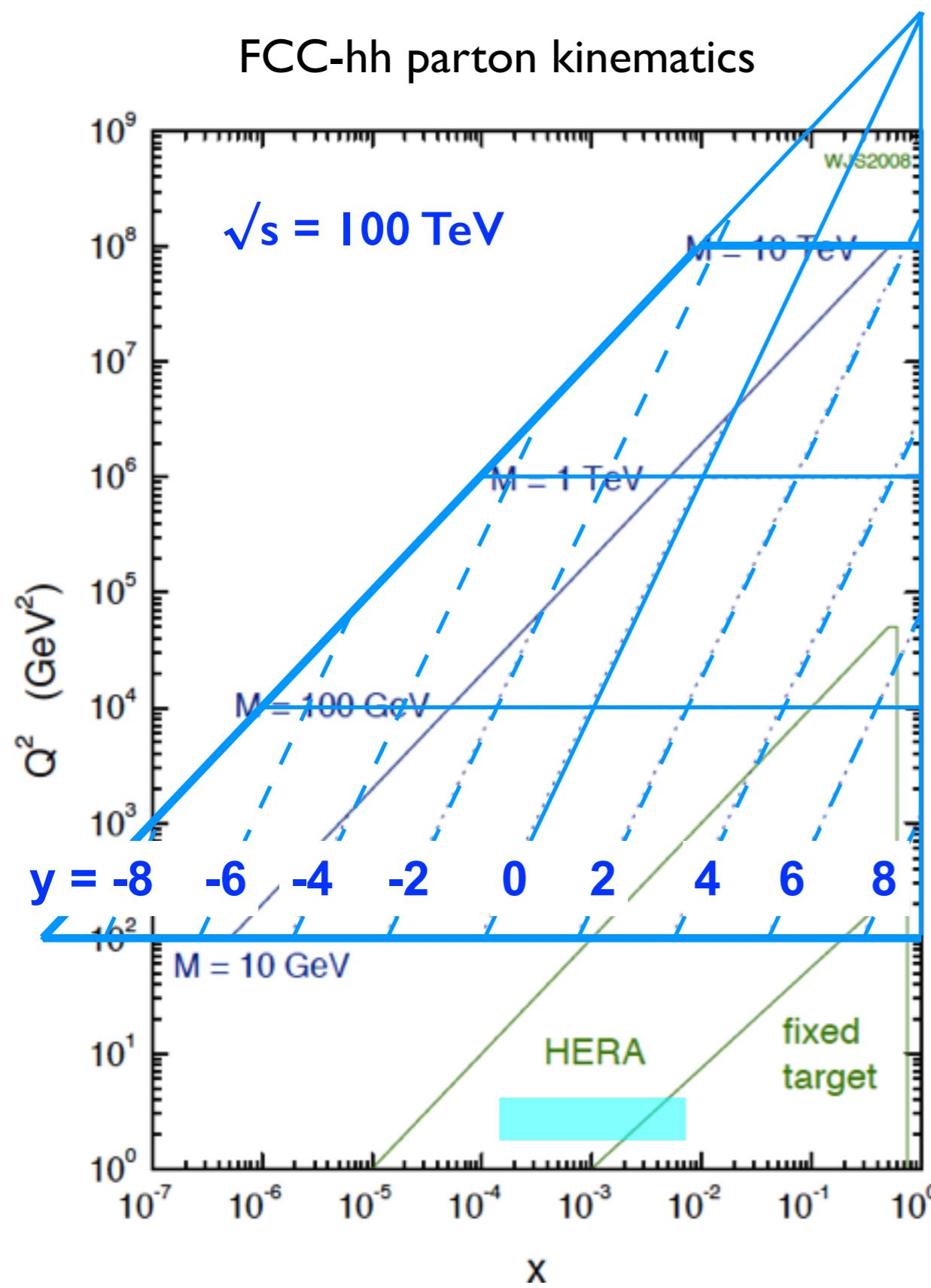
Parton Kinematics: LHC



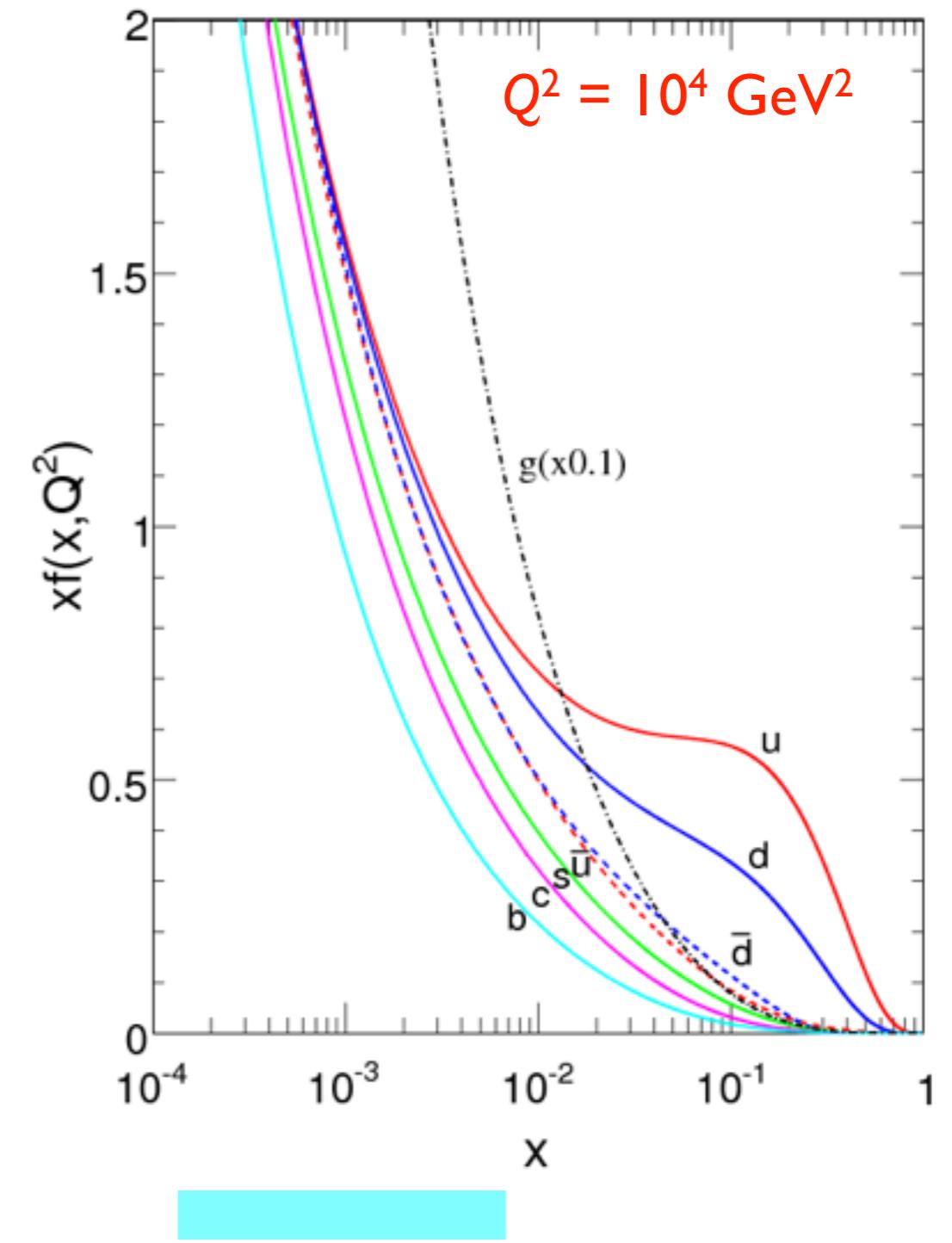
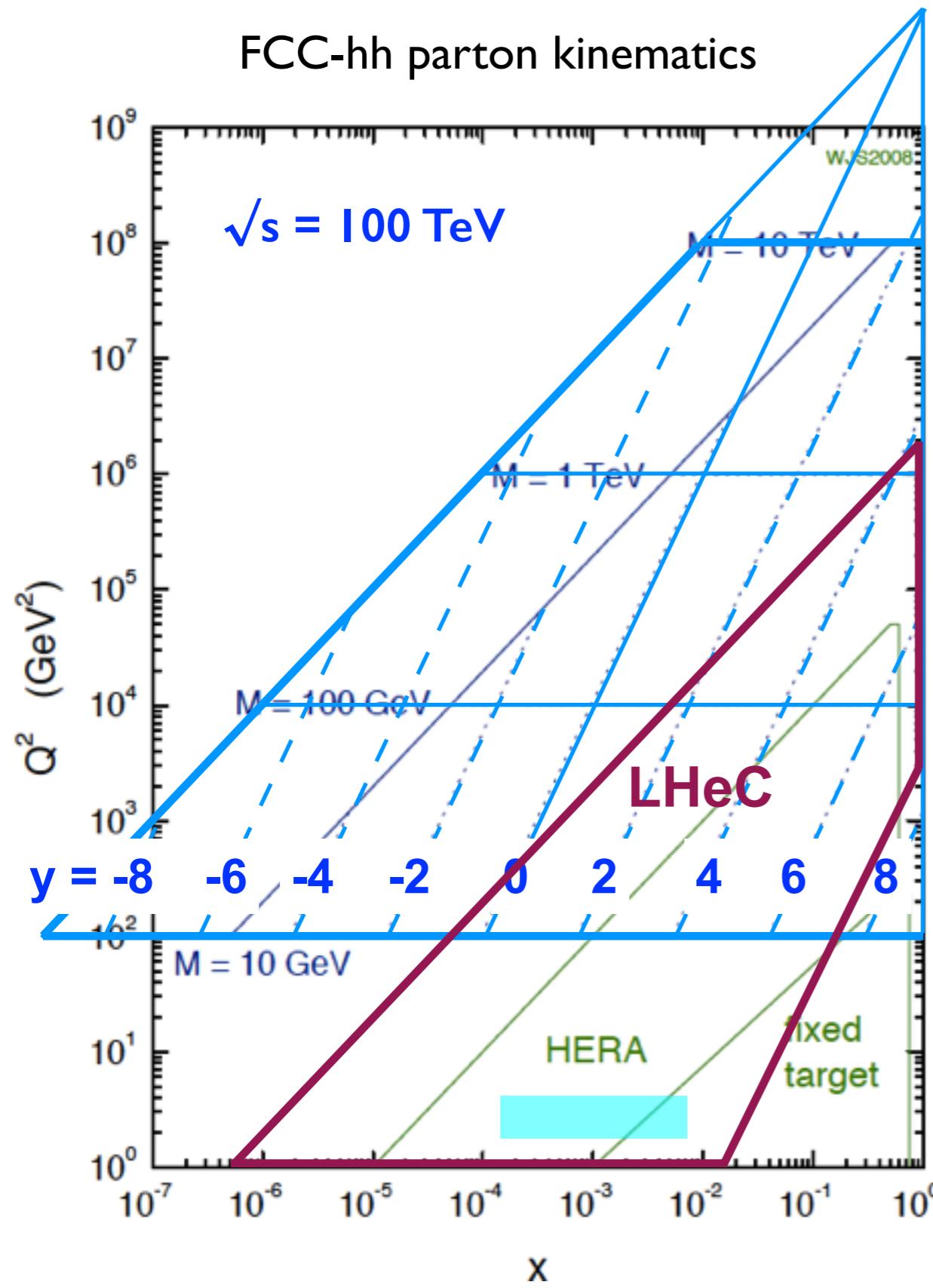
LHC parton kinematics



Parton Kinematics: FCC-hh

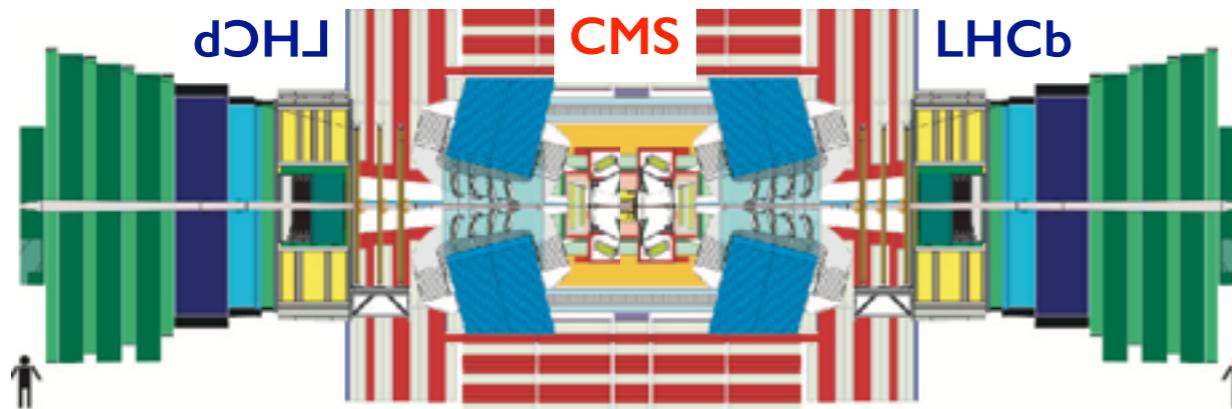


Parton Kinematics: FCC-hh



FCC-hh Reference Detector

Starting point

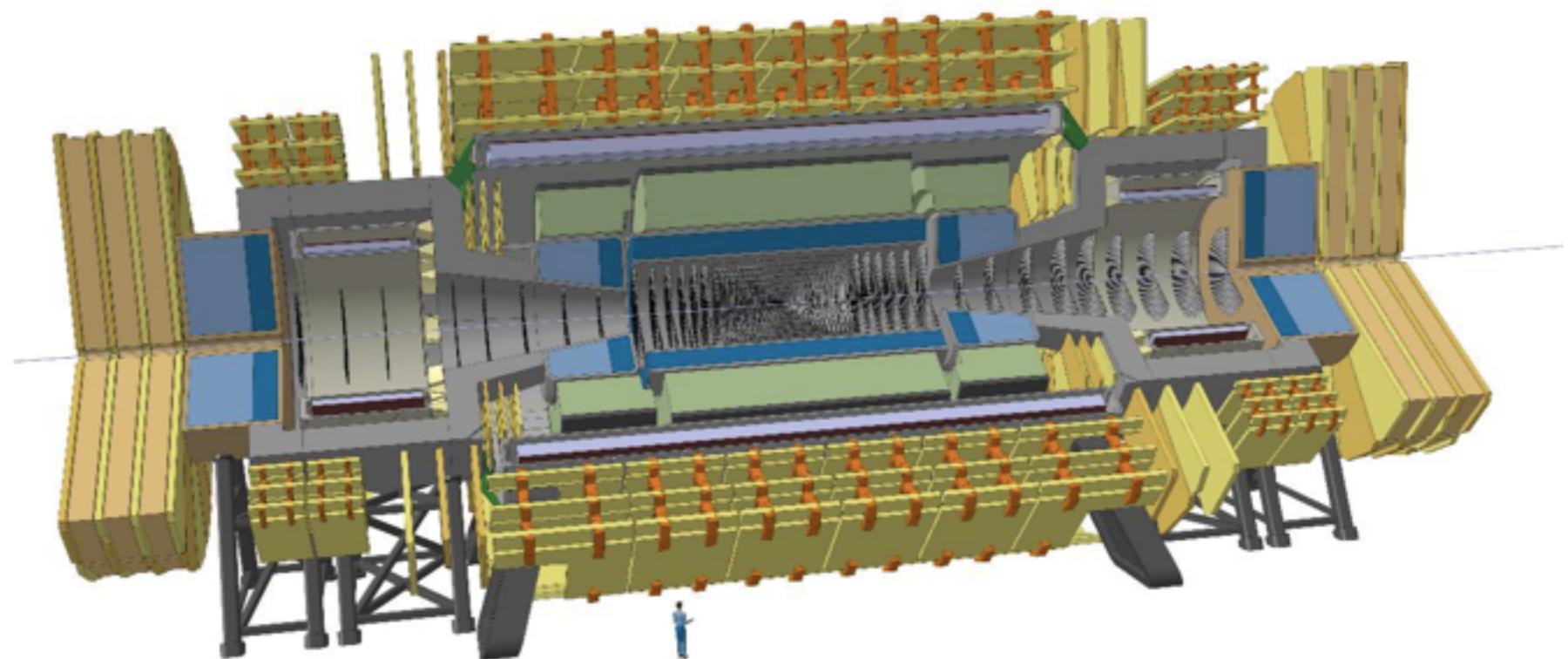


Main features

- 4T solenoid, 10-m bore solenoid
- Two forward 4T, 5-m bore solenoids
- no shielding
- ~ 14 GJ stored energy
- EM and H calorimetry up to $\eta = 6$
- high granularity ($\times 4$ ATLAS or CMS)
- trigger includes muon system

Some of the challenges

- pileup = 1000
($\times 10$ / HL-LHC)
- radiation =
 10^{18} part (1MeV)/cm²
($\times 100$ / HL-LHC)
- forward SM physics
- high-pT jets
and leptons
- 1-1.5 PB/s



one billion € project

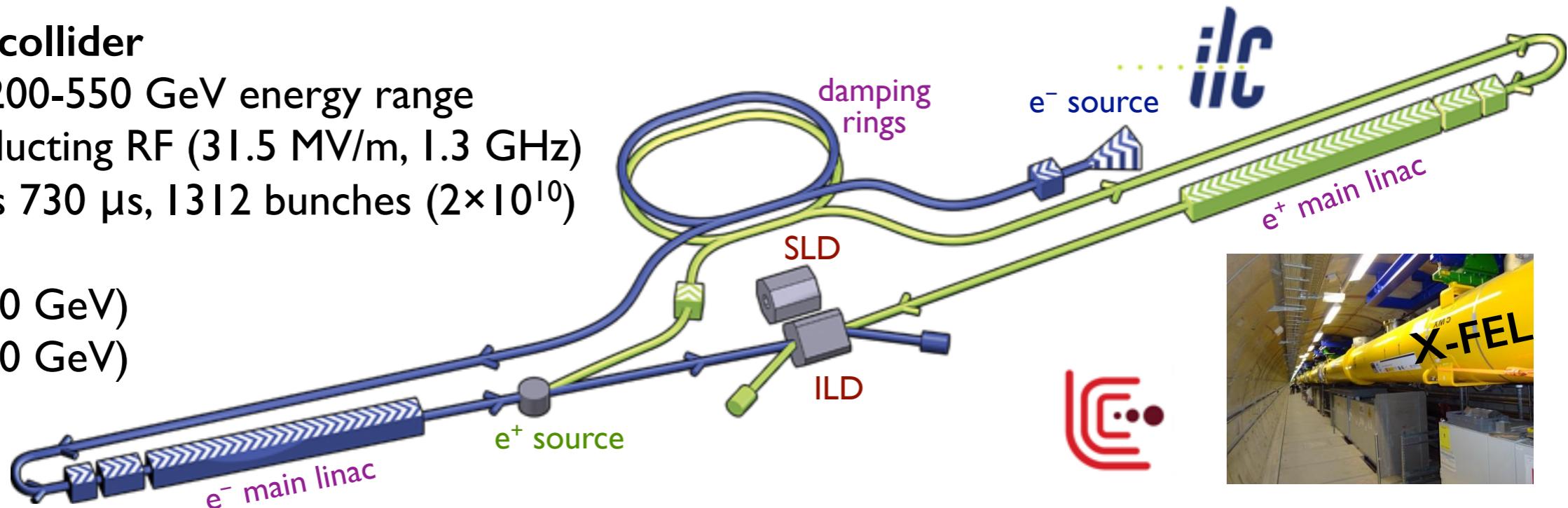
cf. presentation by Christophe Ochando

ILC: International Linear Collider

Linear e^+e^- collider

in the 200-550 GeV energy range

- super conducting RF (31.5 MV/m, 1.3 GHz)
- 5 Hz, trains 730 μ s, 1312 bunches (2×10^{10})
- footprint:
 - 20 km (250 GeV)
 - 31 km (500 GeV)

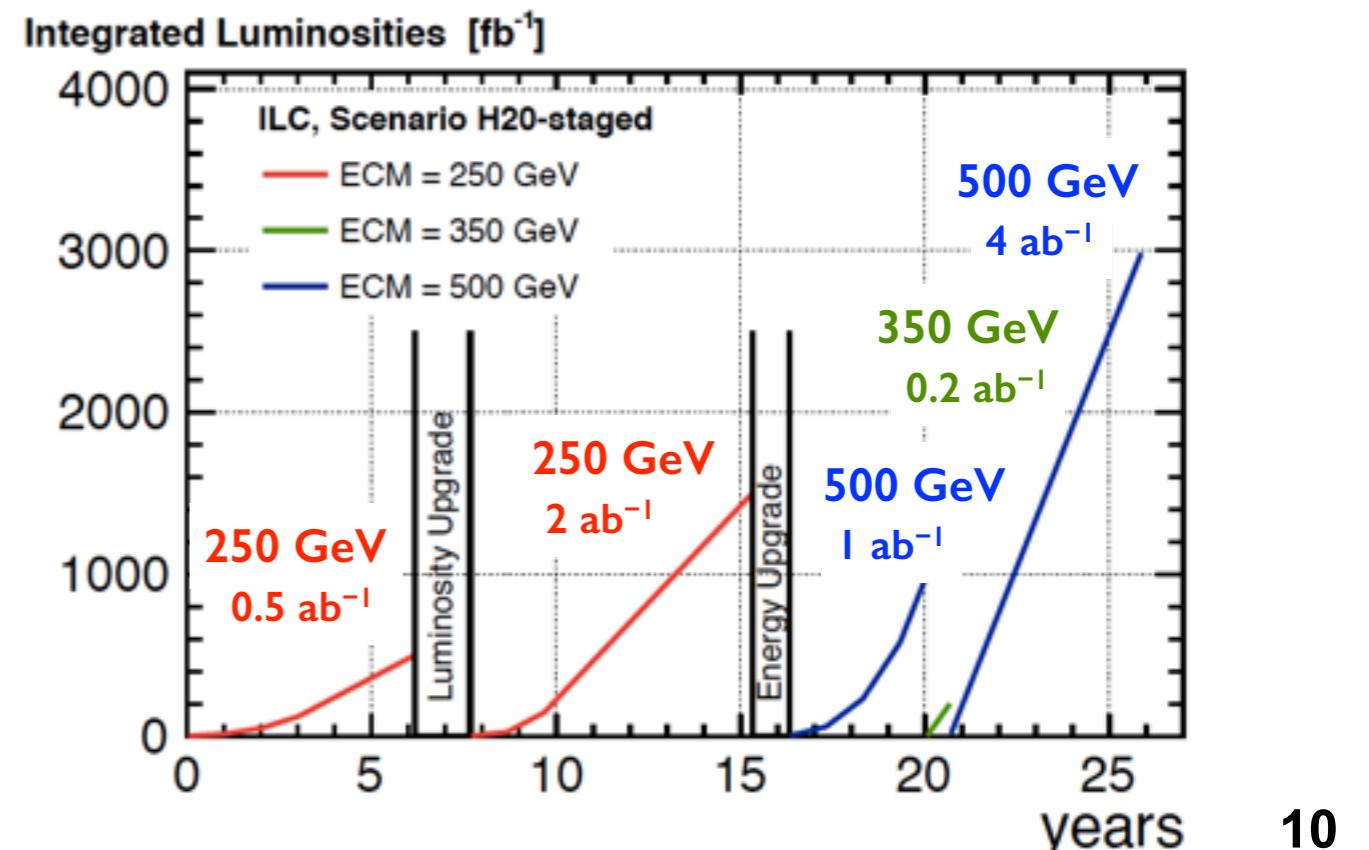


Staging scenario

ILC TDR (2013)
ILC-250 Physics Case (2017)

- $\sqrt{s} = 250$ GeV
- optimised luminosity: $\mathcal{L} = 1.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- $\pm 80\%$ ($\pm 30\%$) e^- (e^+) beam polarisation
- (LR, RL, LL, RR) = (45%, 45%, 5%, 5%)

Strong effort by Japanese
community to host ILC
➡ political decision expected
by end of 2018

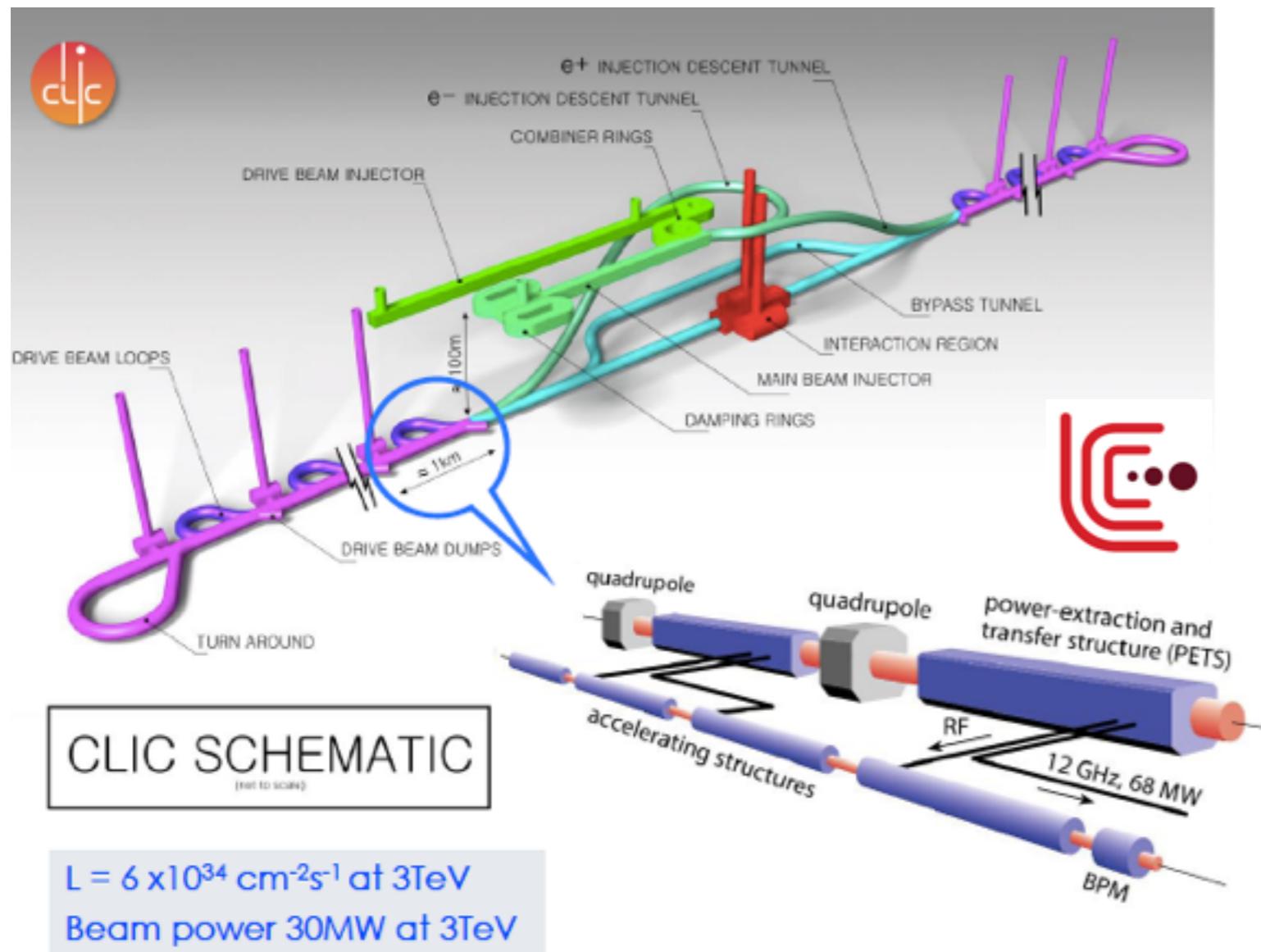


CLIC: Compact Linear Collider

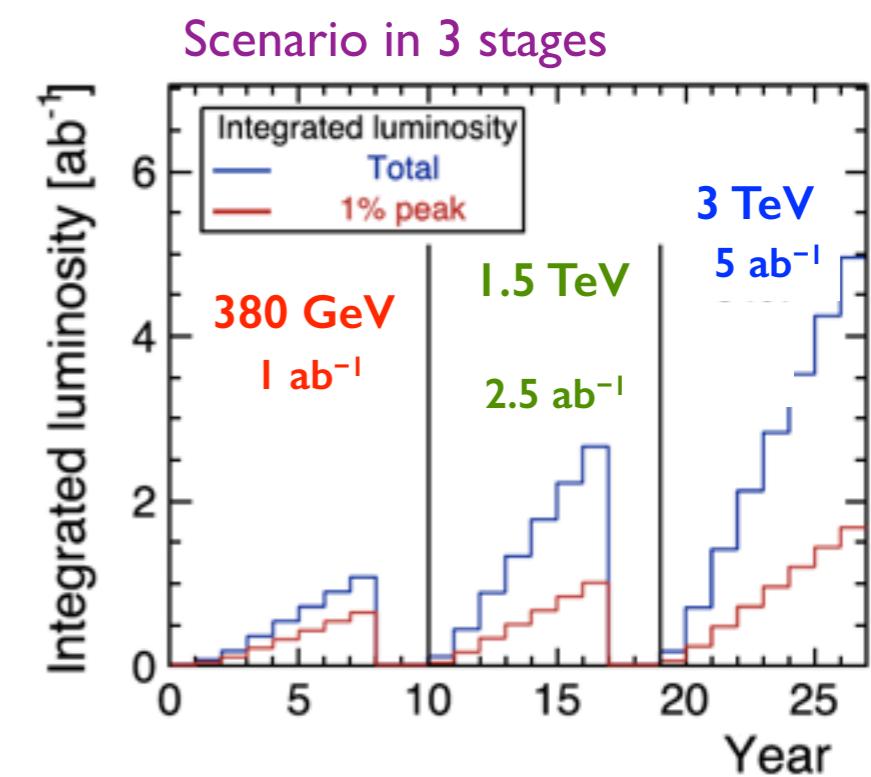
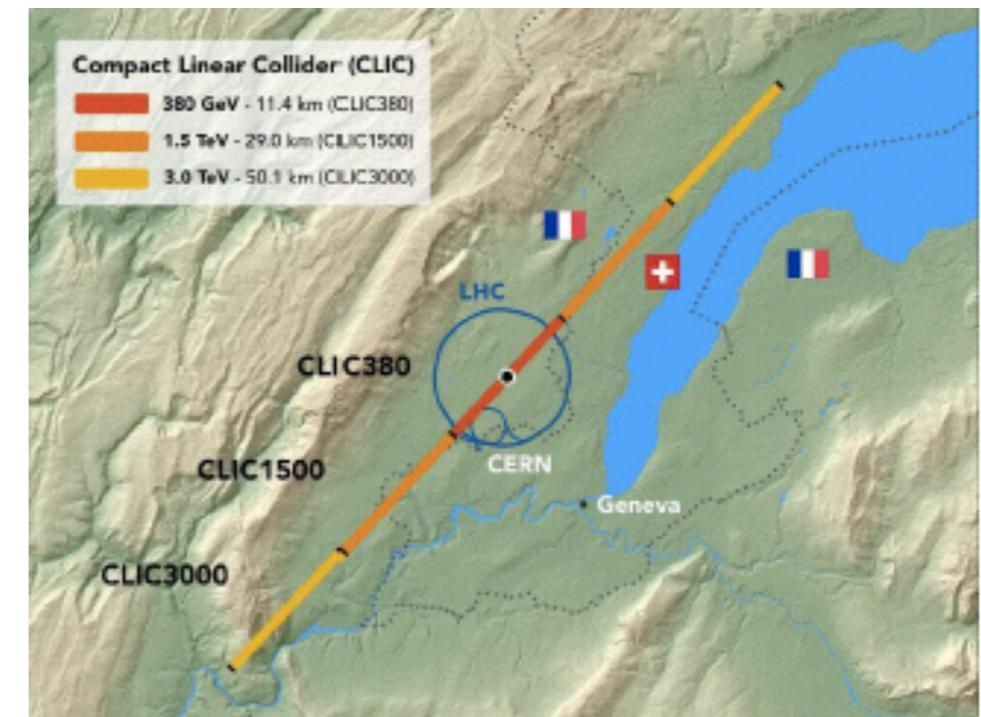
Linear e^+e^- collider at CERN

in the up-to multi-TeV energy range

- normal conducting high-frequency RF (X-band, 12 GHz)
- e^- drive beam for RF power generation

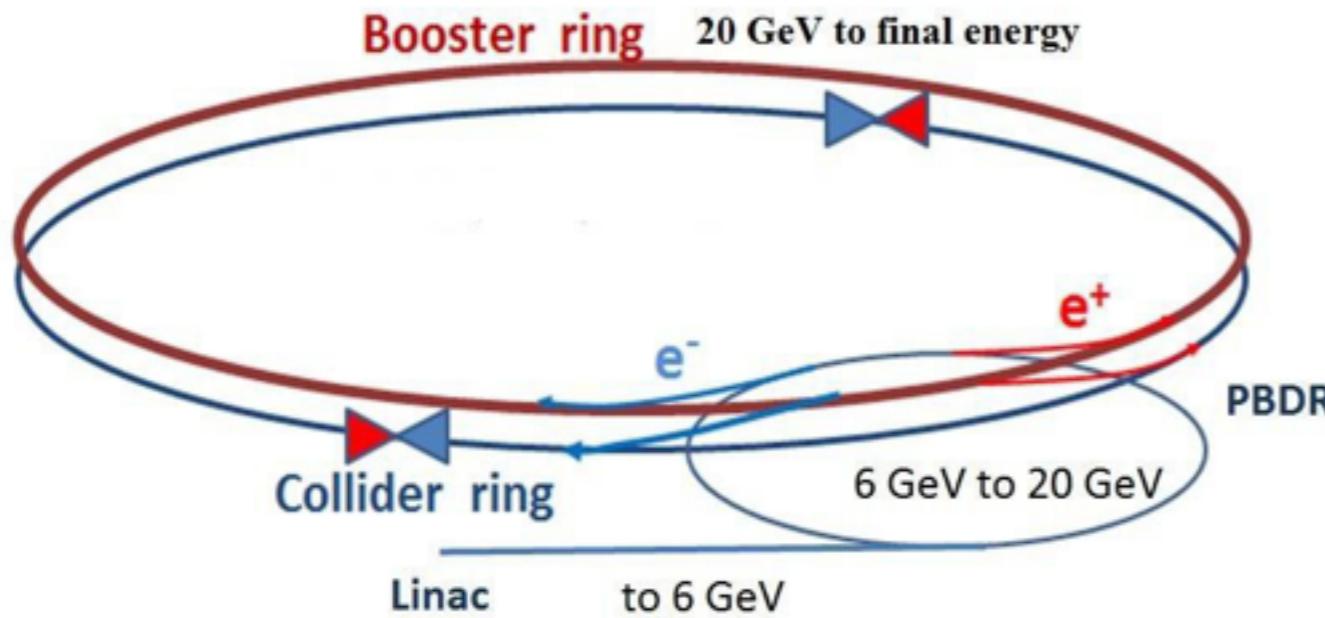


Beam polarisation: ($\pm 80\%$, $\mp 80\%$)
LR / RL = 50% / 50%



CERN/SPC/1114 (2018)

FCC-ee: e^+e^- Circular Collider



RF system: high-current \rightarrow high gradient
3 sets of RF cavities

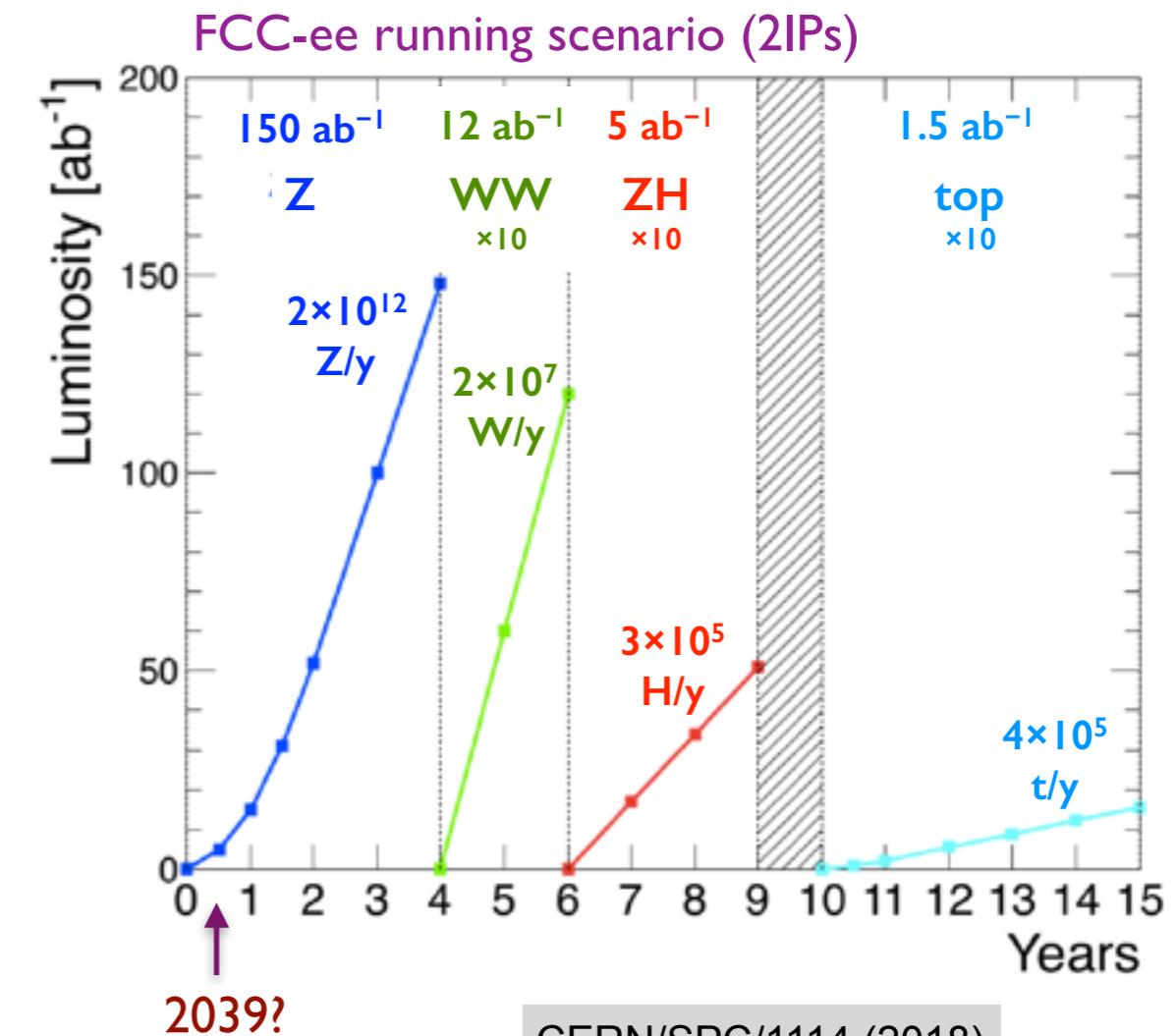
	V _{rf} [GV]	#bunches	I _{beam} [mA]
Z	0.1	16640	1390
WW	0.44	2000	147
ZH	2.0	393	29
top	10.9	48	5.4

Asymmetric optics with beam crossing angle of 30 mrad

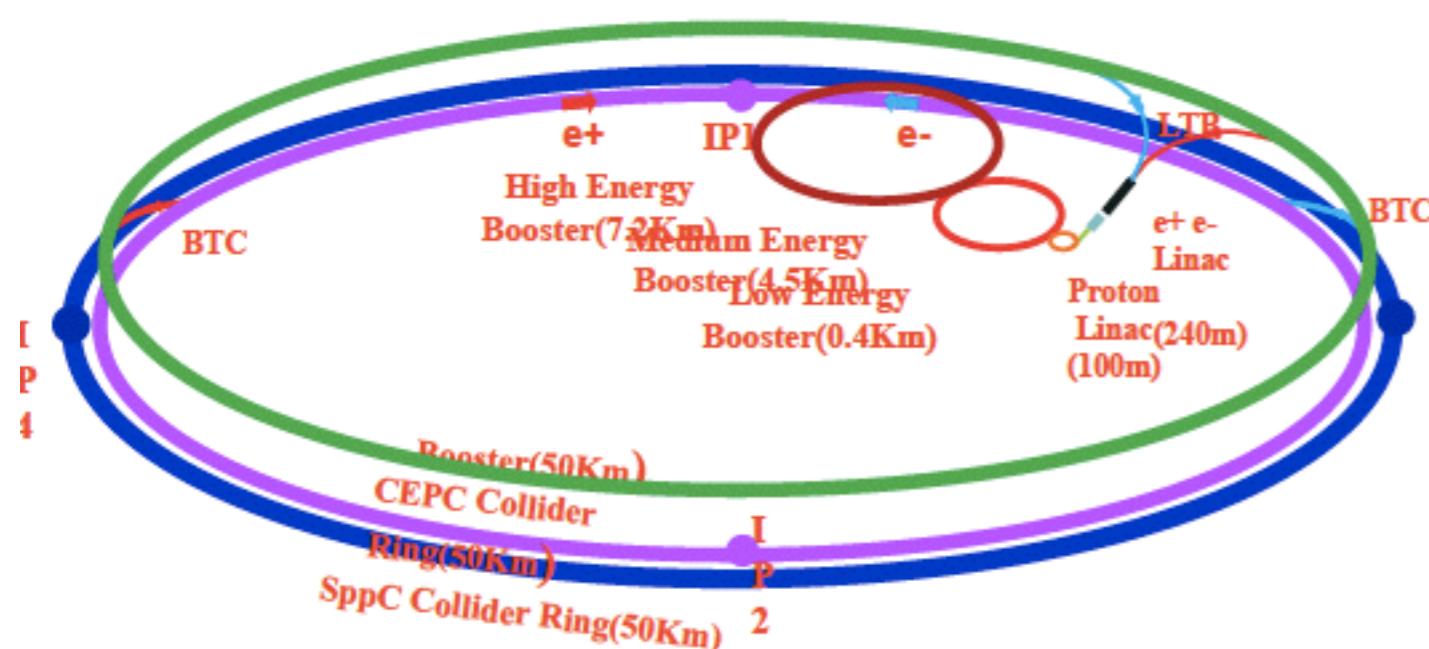
First-phase machine in the 100-km tunnel built to host eventually FCC-hh

Luminosity limited by SR

- top-up injection (once per minute)
- 50 MW power/beam
- 2 interaction points



CEPC: Chinese e⁺e⁻ Collider



Project similar to FCC-ee in China

- two colliding rings and a booster
- $\sqrt{s} = 90\text{-}240 \text{ GeV}$

- Hosted in a 100-km tunnel which could eventually host a 70-TeV pp collider
- several possible sites

Peak luminosity (2 IPs) (CDR parameters)

- at the Z: $1.7 \times 10^{35} \text{ cms}^{-2}\text{s}^{-1}$ (3T)
- at the W: $1.0 \times 10^{35} \text{ cms}^{-2}\text{s}^{-1}$
- at the H: $3 \times 10^{34} \text{ cms}^{-2}\text{s}^{-1}$

Physics goals:

- $>3 \times 10^{11}$ Z bosons (8 ab^{-1})
- 2×10^7 W pairs (2.6 ab^{-1})
- 10^6 Higgs bosons (5.6 ab^{-1})

Timeline

2013-2015	pre-studies
2016-2022	R&D Engineering Design
2022-2030	Construction
2030-2040	data taking

- Starts before the end of the HL-LHC
- possibly concurrent with the ILC

Detector Concepts

Particle Flow Detectors

- high hermiticity
- high granularity
- momentum resolution
- high separation power

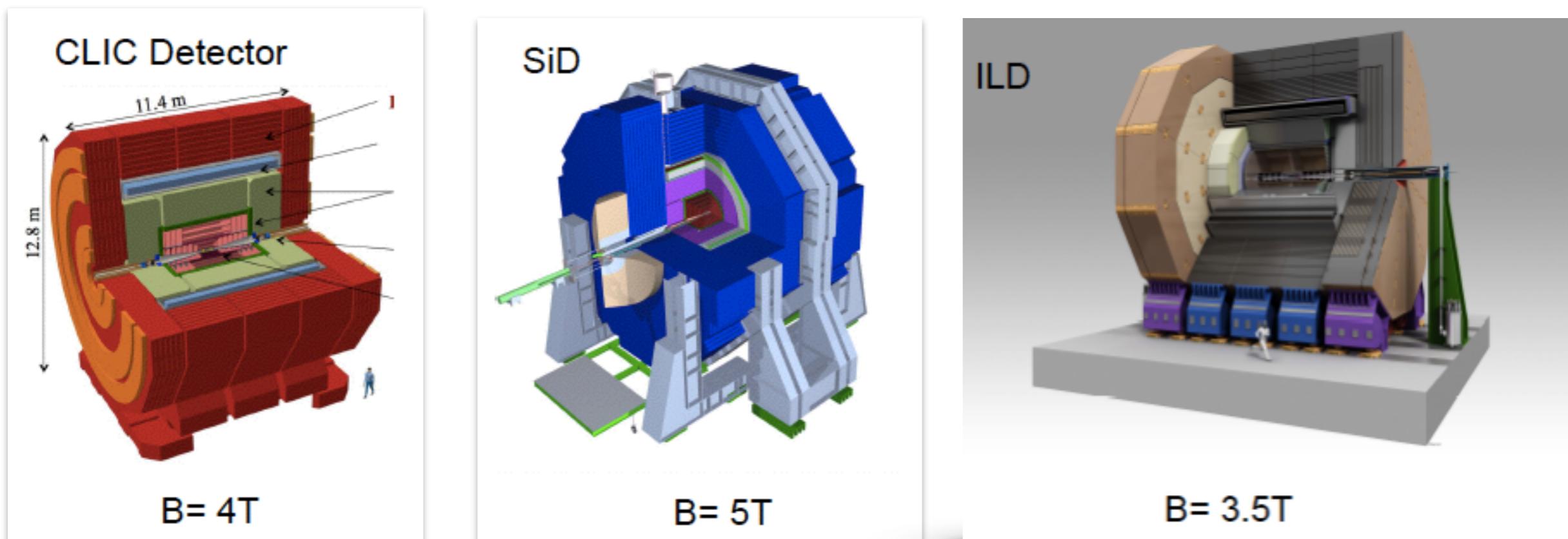
FCC-ee 2 detector concepts

- CLD: inspired from CLIC detector
- IDEA: from present state-of-the-art

cf. presentation by **Christophe Ochando**

CEPC 2.5 detector concepts

- baseline: ILD/SiD concept (3T)
- IDEA concept (2T)

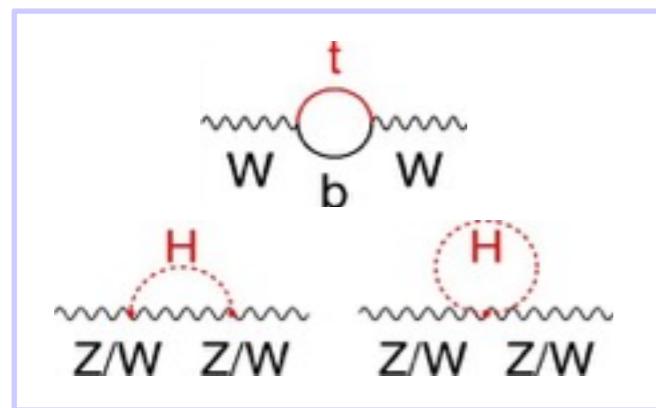


CLIC CDR (2012)
(revised since)

highly-granular calorimeters

ILC DBD (2013)

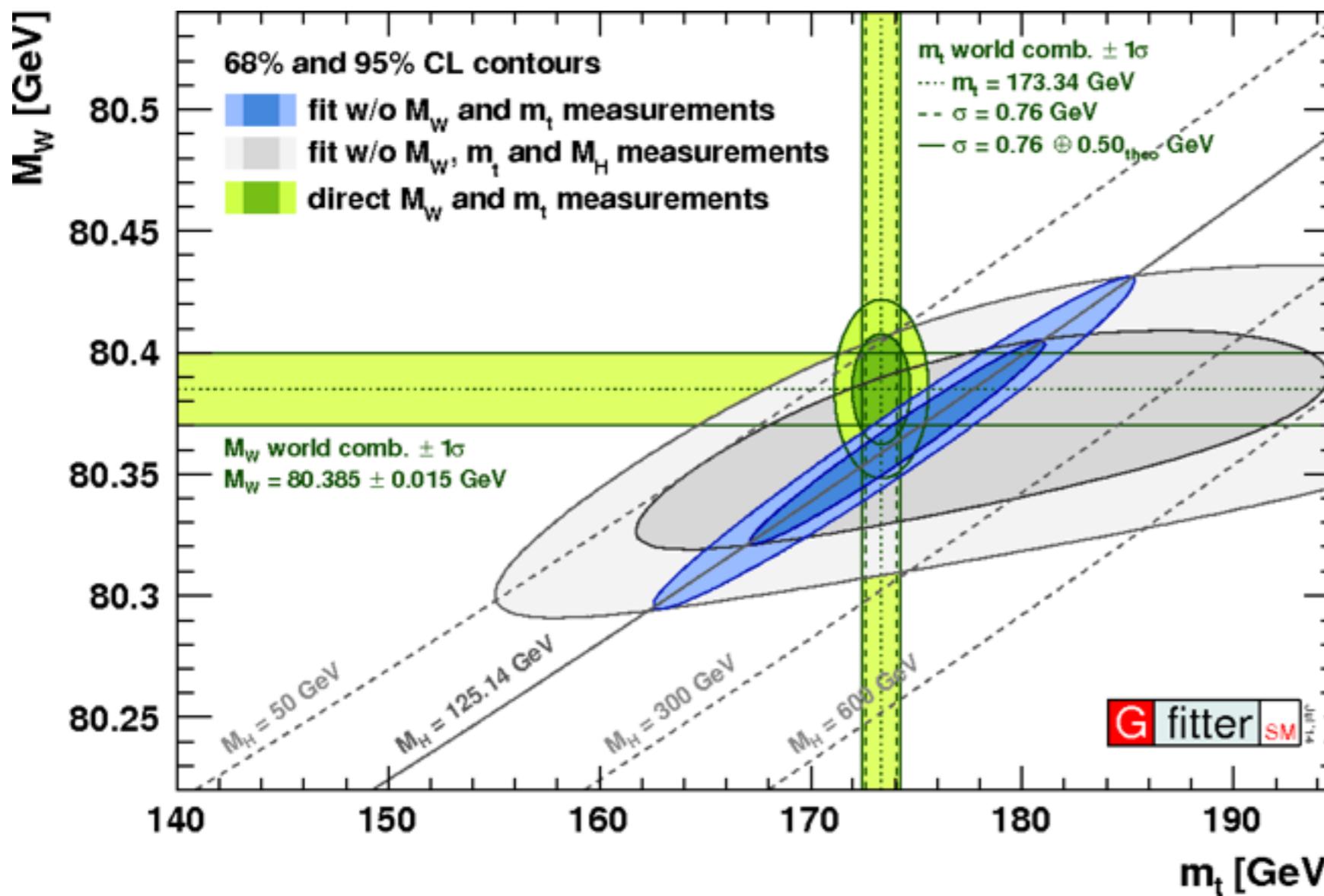
The Electroweak Fit



Through quantum corrections, the theory establishes relations between measurable parameters

$$M_W^2 = (1 + \Delta\rho) M_Z^2 (1 - \sin^2 \theta_{\text{eff}})$$

with $\Delta\rho = f(M_{\text{top}}^2, \ln M_H)$
(of order 1%)



Successful experimental strategy

- precision at e^+e^- machines
- discoveries at hadron machines

M_W : Parametric Errors

Experimental

$$M_W = 80.385 \pm 0.015 \text{ GeV}$$

Electroweak Fit

$M_W = 80.3584 \text{ GeV}$	$\pm 8.0 \text{ MeV}$	●
$\pm (\delta M_W)_{\text{th}}$	4.0 MeV	●
$\pm (\delta M_W)_{\text{top}}$	$(\delta M_{\text{top}}/0.76 \text{ GeV}) \times 5.5 \text{ MeV}$	●
$\pm (\delta M_W)_H$	$(\delta M_H/0.24 \text{ GeV}) \times 0.1 \text{ MeV}$	●
$\pm (\delta M_W)_Z$	$(\delta M_Z/2.1 \text{ MeV}) \times 2.5 \text{ MeV}$	●
$\pm (\delta M_W)_\alpha$	$(\delta \alpha/10^{-4}) \times 1.8 \text{ MeV}$	●
$\pm (\delta M_W)_{\alpha_s}$	$(\delta \alpha_s/3 \times 10^{-3}) \times 2.0 \text{ MeV}$	●

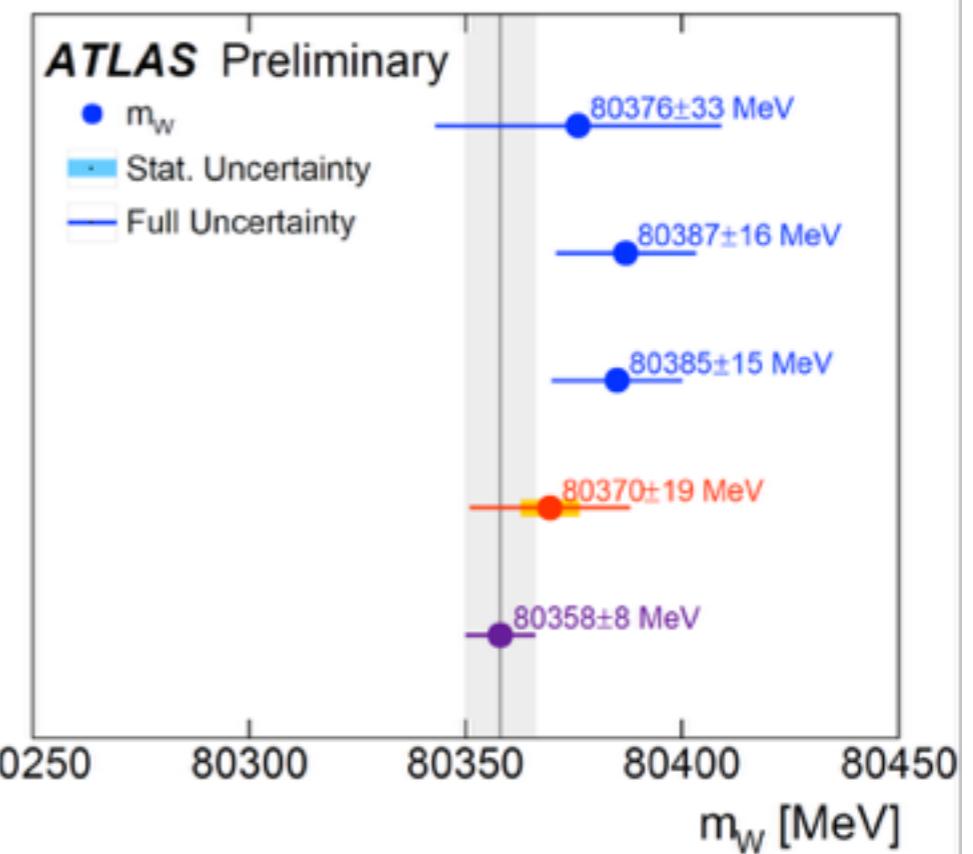
LEP Comb.

Tevatron Comb.

LEP+Tevatron

ATLAS 2017

Electroweak Fit

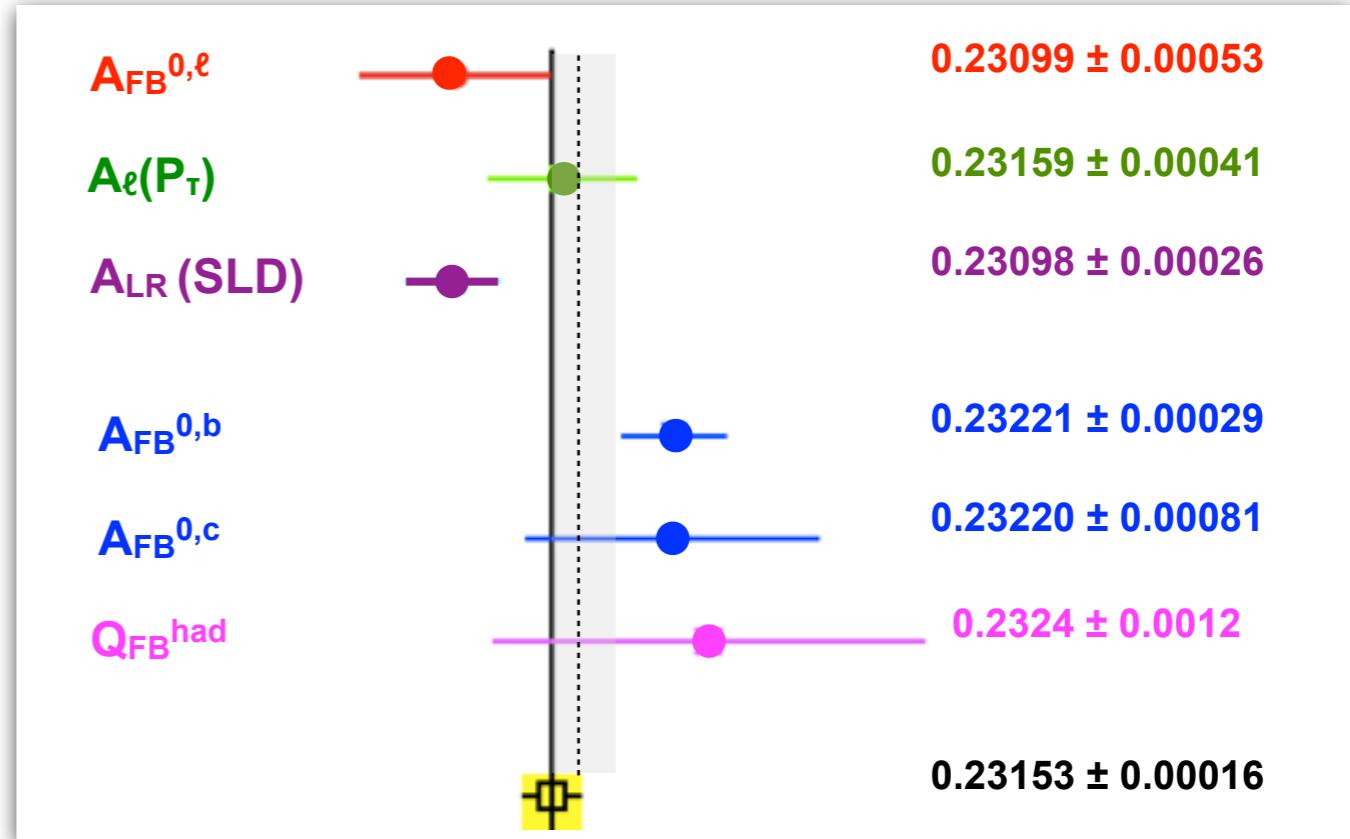


- Main parametric errors:
- top mass
 - theory
 - Z boson mass
 - α
 - α_s
 - Higgs mass

$\sin^2\theta_{\text{eff}}$: Parametric Errors

Experimental

$$\sin^2 \theta_{\text{eff}}^\ell = 0.23153 \pm 0.00016$$



Electroweak Fit

$$\sin^2 \theta_{\text{eff}}^\ell = 0.231488$$

$$\pm (\delta \sin^2 \theta_W^{\text{eff}})_{\text{th}}$$

$$\pm (\delta \sin^2 \theta_W^{\text{eff}})_{\text{top}}$$

$$\pm (\delta \sin^2 \theta_W^{\text{eff}})_H$$

$$\pm (\delta \sin^2 \theta_W^{\text{eff}})_Z$$

$$\pm (\delta \sin^2 \theta_W^{\text{eff}})_\alpha$$

$$\pm (\delta \sin^2 \theta_W^{\text{eff}})_{\alpha_s}$$

$$\pm 7.0 \times 10^{-5}$$

$$4.7 \times 10^{-5}$$

$$(\delta M_{\text{top}}/0.76 \text{ GeV}) \times 2.9 \times 10^{-5}$$

$$(\delta M_H/0.24 \text{ GeV}) \times 0.1 \times 10^{-5}$$

$$(\delta M_Z/2.1 \text{ MeV}) \times 1.5 \times 10^{-5}$$

$$(\delta \alpha/10^{-4}) \times 3.5 \times 10^{-5}$$

$$(\delta \alpha_s/3 \times 10^{-3}) \times 1.0 \times 10^{-5}$$



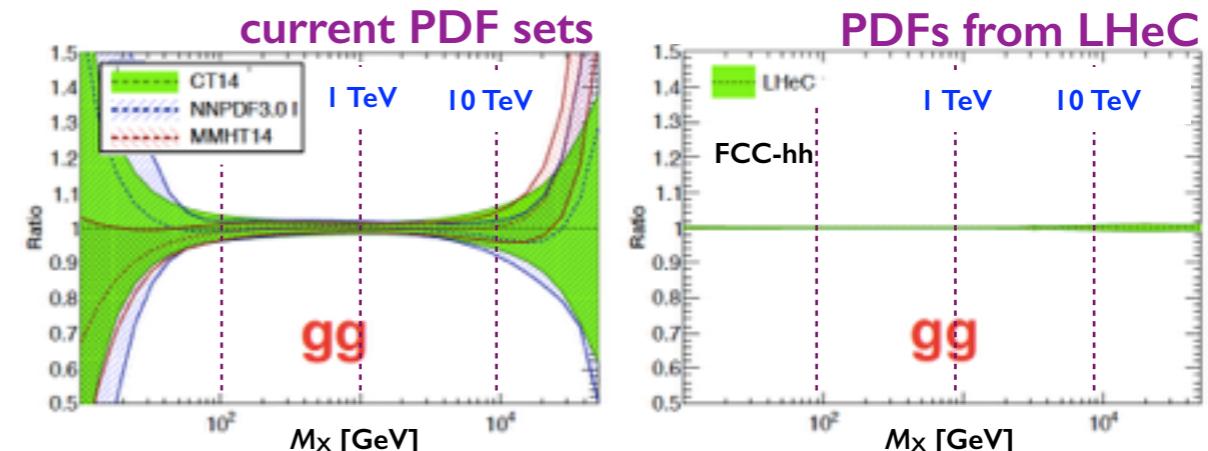
Main parametric errors:

- theory
- α
- top mass
- Z mass
- α_s
- Higgs mass

LHeC: Getting More from pp

Electrons for the LHC

- Energy Recovery Linac (ERL)
- 10-60 GeV e^- vs 1-7 TeV p
 $\rightarrow \sqrt{s} = 200 \text{ GeV}-1.3 \text{ TeV}$
- concurrent ep and pp (Run 5-6): 225 fb^{-1}
- dedicated $e^\pm p$ (4 years): $+650 \text{ fb}^{-1}$



⇒ PDFs with unprecedented precision in extended kinematic range

Many measurements at the LHC are limited by PDF uncertainties

M_W at ATLAS (2017)

- total = 19 MeV
- stat. = 7 MeV
- PDF = 9 MeV
- QCD = 8 MeV

$\sin^2\theta_{\text{eff}}$ at CMS (2018)

- total = $53 \cdot 10^{-5}$
- stat. = $36 \cdot 10^{-5}$
- PDF = $31 \cdot 10^{-5}$
- theory = $16 \cdot 10^{-5}$

LHeC greatly empowers HL-LHC results

- NP exclusion limits
- cross section measurements
- precision measurements

HL-LHC predictions

- 8 MeV on M_W
- $20 \cdot 10^{-5}$ on $\sin^2\theta_{\text{eff}}$

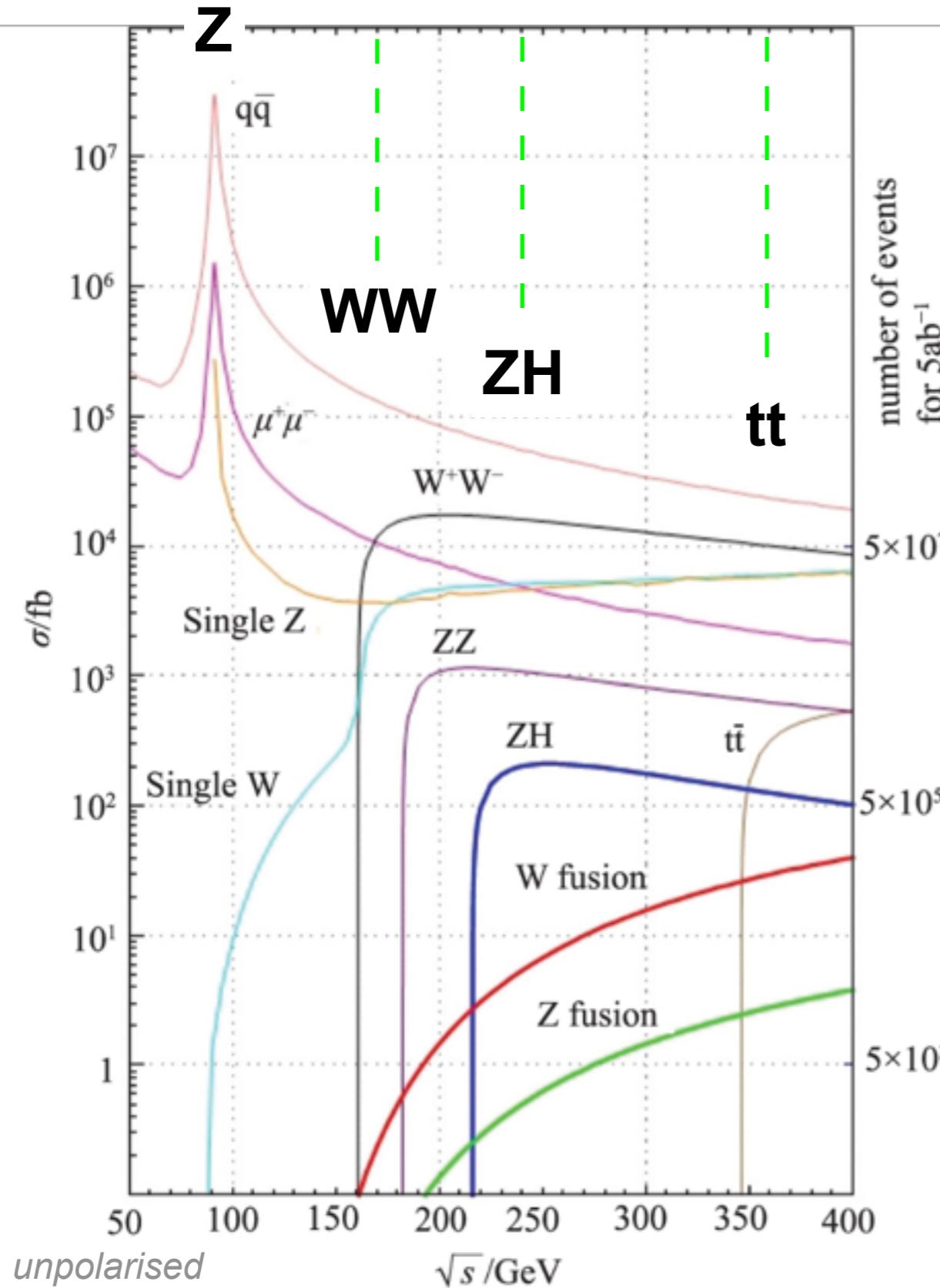
HL-LHC+LHeC

- 2 MeV on M_W
- $4 \cdot 10^{-5}$ on $\sin^2\theta_{\text{eff}}$

and also QCD, EWK, Higgs, BSM...

cf backup slides

Cross Sections in e^+e^-



At $\sqrt{s} = 250 \text{ GeV}$

- $e^+e^- \rightarrow ZH$ **200 fb** (*Higgsstrahlung*)
- $e^+e^- \rightarrow HvV$ **8 fb** (*W fusion*)

Cross sections decreasing as $1/s$:

- $e^+e^- \rightarrow qq(\gamma)$ **60 pb** (*incl. Z return*)
- $e^+e^- \rightarrow W^+W^-$ **16 pb**
- $e^+e^- \rightarrow ZZ$ **1 pb**

Slowly increasing cross sections:

- $\gamma\gamma \rightarrow qq, \ell\ell$ **30 pb** ($m > 30 \text{ GeV}$)
- $e\gamma \rightarrow Ze$ **3.8 pb**
- $e\gamma \rightarrow Wv$ **1.5 pb** ($WW\gamma$)
- $ee \rightarrow Zvv$ **32 fb** (WWZ)

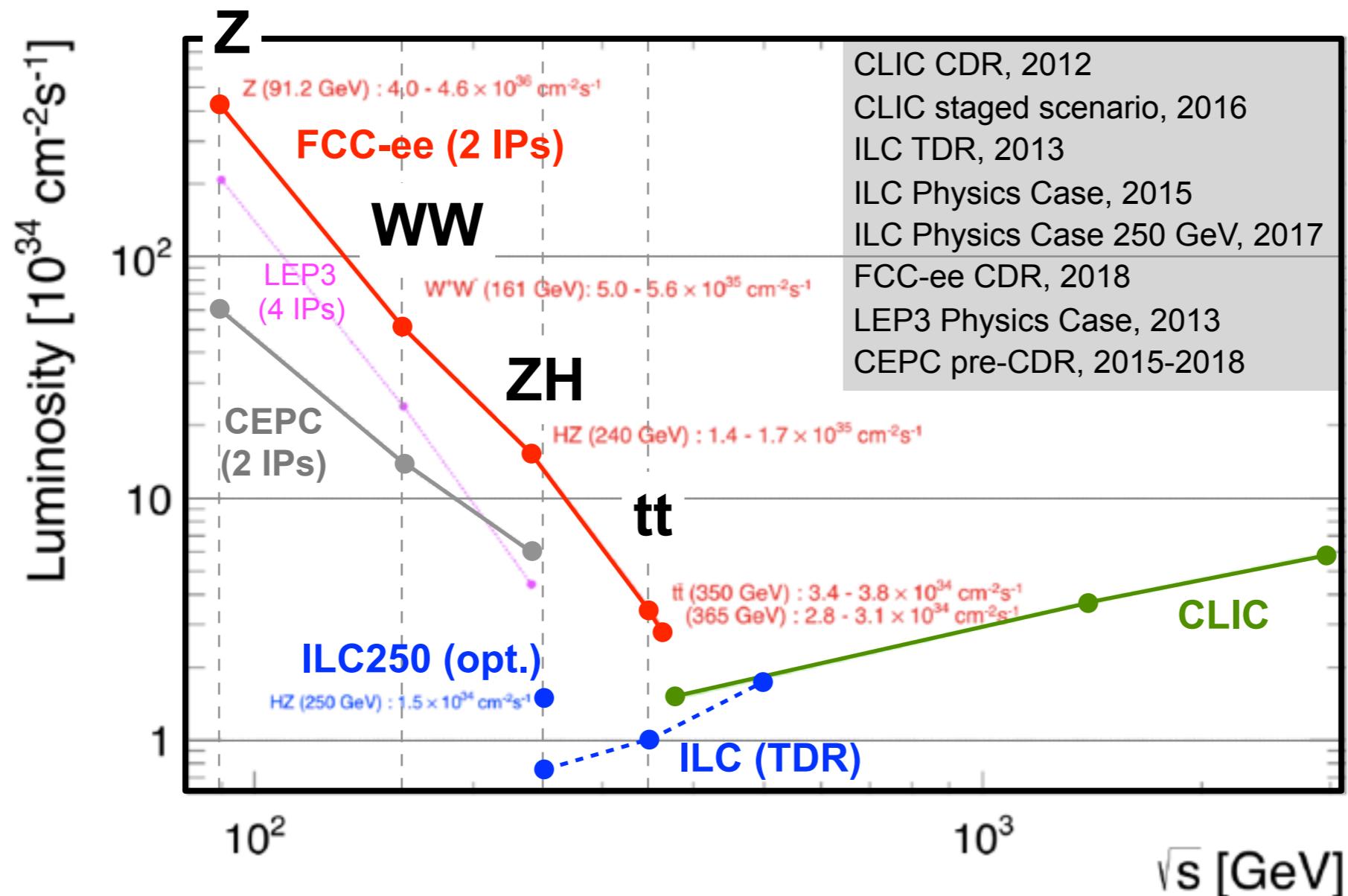
At $\sqrt{s} = 380 \text{ GeV}$

- $e^+e^- \rightarrow tt$ **500 fb**
- $e^+e^- \rightarrow ZH$ **100 fb**
- $e^+e^- \rightarrow HvV$ **40 fb**

Physics at e⁺e⁻ Colliders

\sqrt{s}	Processes	Physics Goals	Observables
91 GeV	• $e^+e^- \rightarrow Z$	ultra-precision EW physics	$\sin^2\theta_{\text{eff}}$ M_Z, Γ_Z, N_V α, α_s
125 GeV	• $e^+e^- \rightarrow H$	limit on s-channel H production?	y_e
160 GeV	• $e^+e^- \rightarrow W^+W^-$	ultra-precision W mass	M_W, Γ_W
>160 GeV	• $e^+e^- \rightarrow W^+W^-$ • $e^+e^- \rightarrow qq, \ell\ell (\gamma)$	precision W mass and couplings precision EW (incl. Z return)	M_W, a_{TGC} N_V
250 GeV	• $e^+e^- \rightarrow ZH$	ultra-precision Higgs mass precision Higgs couplings	M_H K_V, K_f, Γ_H
360 GeV	• $e^+e^- \rightarrow tt$	ultra-precision top mass	M_{top}
>360 GeV	• $e^+e^- \rightarrow tt$ • $e^+e^- \rightarrow ZH$ • $e^+e^- \rightarrow Hvv$	precision top couplings precision Higgs couplings	
500+ GeV	• $e^+e^- \rightarrow ttH$ • $e^+e^- \rightarrow ZHH$ • $e^+e^- \rightarrow Z' \rightarrow ff$ • $e^+e^- \rightarrow XX$ • $e^+e^- \rightarrow AH, H^+H^-$	Higgs coupling to top Higgs self-coupling search for heavy Z' bosons search for supersymmetry (SUSY) search for new Higgs bosons	y_{top} λ_{HHH}

Luminosity of e^+e^- Colliders



Circular colliders

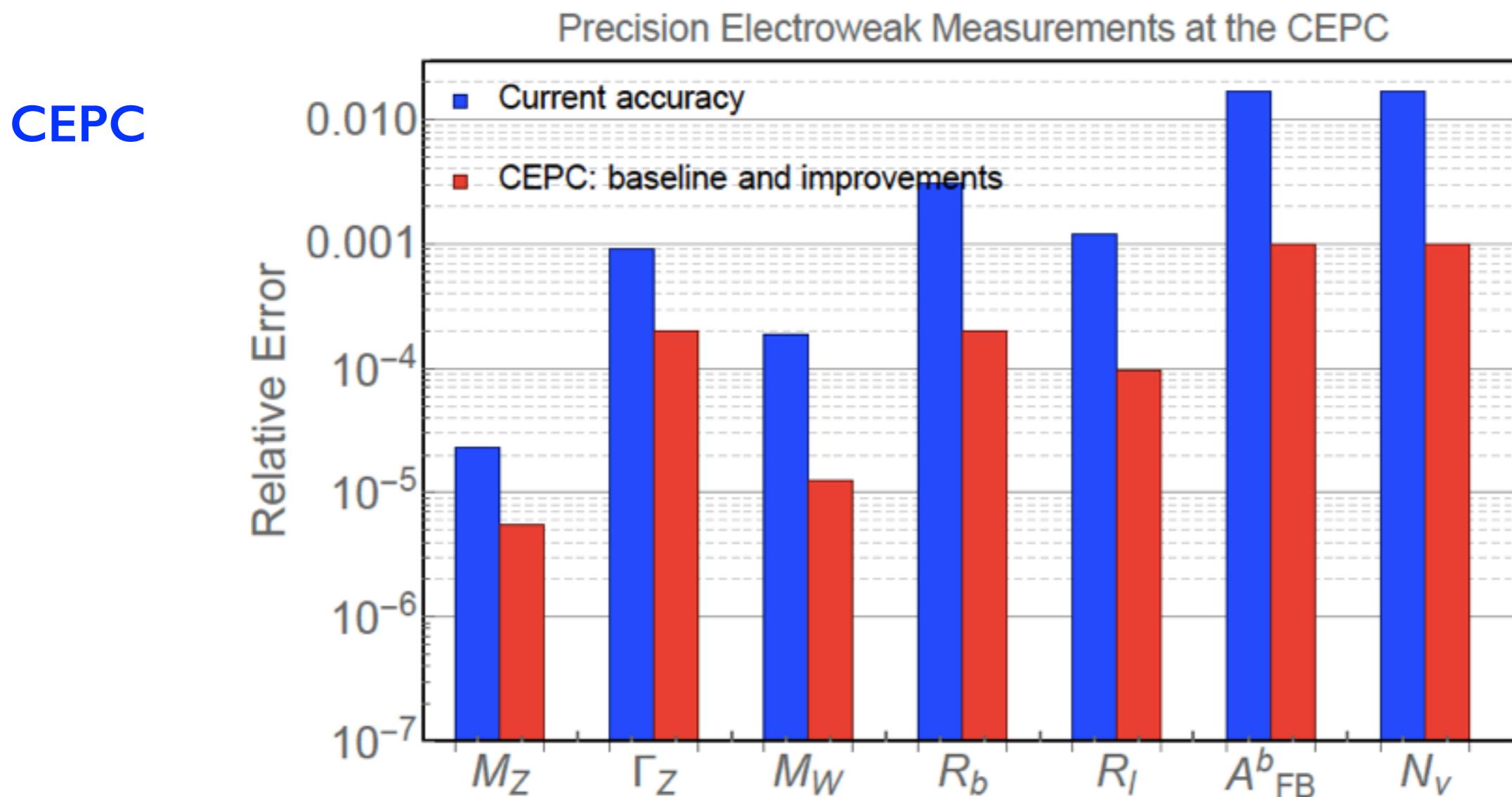
- 👉 high-luminosity from Z peak to top pair threshold

Linear colliders

- 👉 extendability at high energy and beam L-polarisation

Circular and linear Pros&Cons
see backup slide

Physics with 3×10^{11} Z Bosons



Jump by
factor 5 to 20
in relative precision

Physics with 5×10^{12} Z Bosons

FCC-ee

observable	present value	FCC-ee stat syst	from	main source of systematics
FCC-ee	M_Z (MeV)	91187.5 ± 2.1	0.005 ± 0.100	line shape beam energy calibration $A_{FB}^{\mu,0}$ b-quark asymmetry hadrons to leptons R_ℓ
	Γ_Z (MeV)	2495.2 ± 2.3	0.008 ± 0.100	
	$\sin^2\theta_{\text{eff}}$ ($\times 10^5$)	23153 ± 16	$0.3 \pm 0.2-0.5$	
	$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	$0.002 \pm 1-3$	
	R_ℓ ($\times 10^3$)	20767 ± 25	$0.06 \pm 0.2-1$	
	α_s ($\times 10^4$)	1990 ± 25	$0.1 \pm 0.4-1.6$	
cf backup slide	$1/\alpha$ ($\times 10^3$)	128952 ± 14	$4 \pm <1$	A_{FB}^{μ} off-peak
	σ_{had}^0 (pb)	41541 ± 37	0.1 ± 4	peak cross-sections
	N_V ($\times 10^4$)	29840 ± 82	0.05 ± 10	

- continuous \sqrt{s} calibration by RDP
 - 100 (500) keV at Z-pole (WW)
- energy spread (~ 60 MeV) at 1% from scattering angle of μ pairs
- W+Si luminometer

From asymmetries and partial width measurements, improvement by 1 to 2 orders of magnitude on Z vector and axial-vector couplings to leptons (e, μ and τ) and quarks (b and c)

Also a flavour factory

cf backup slide

W Mass at e^+e^- Colliders

ILC at threshold with polarisation

- use LR to enhance WW
- use RL to measure backgrounds
- use LL and RR to control polarisation
- $500 \text{ fb}^{-1} (\pm 80\%, \mp 30\%) \rightarrow \Delta M_W \approx 2.1 \text{ MeV (stat+syst)}$

A run at $\sqrt{s} = 160 \text{ GeV}$ not in the current staged running scenario at the ILC

Above threshold

- 1000 times LEP-2 statistics
- much better detectors

FCC-ee at threshold, unpolarised

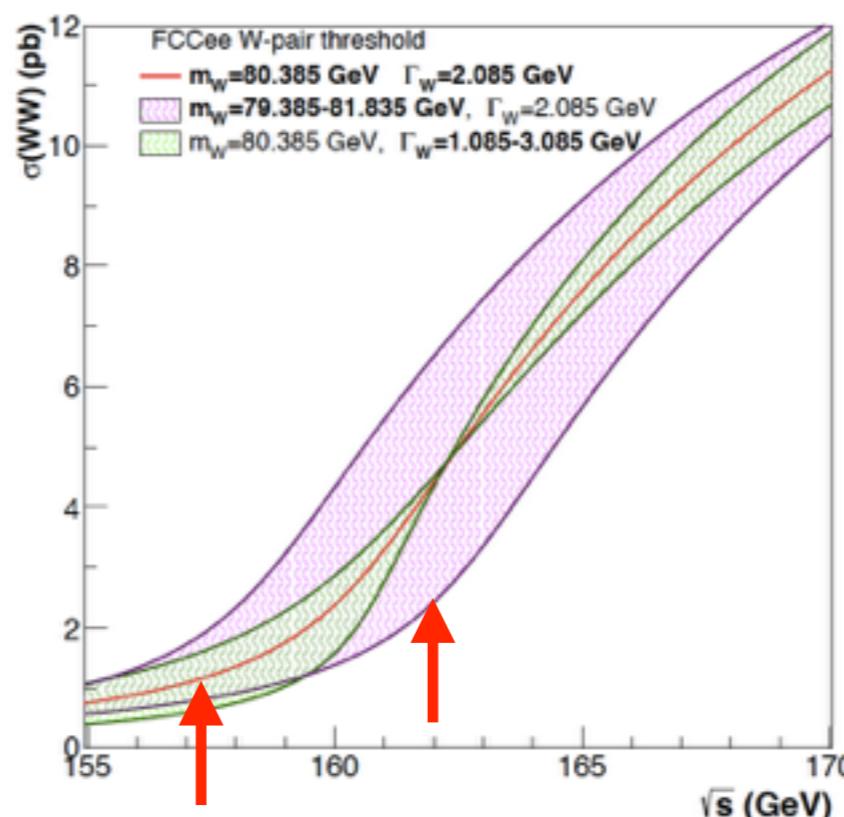
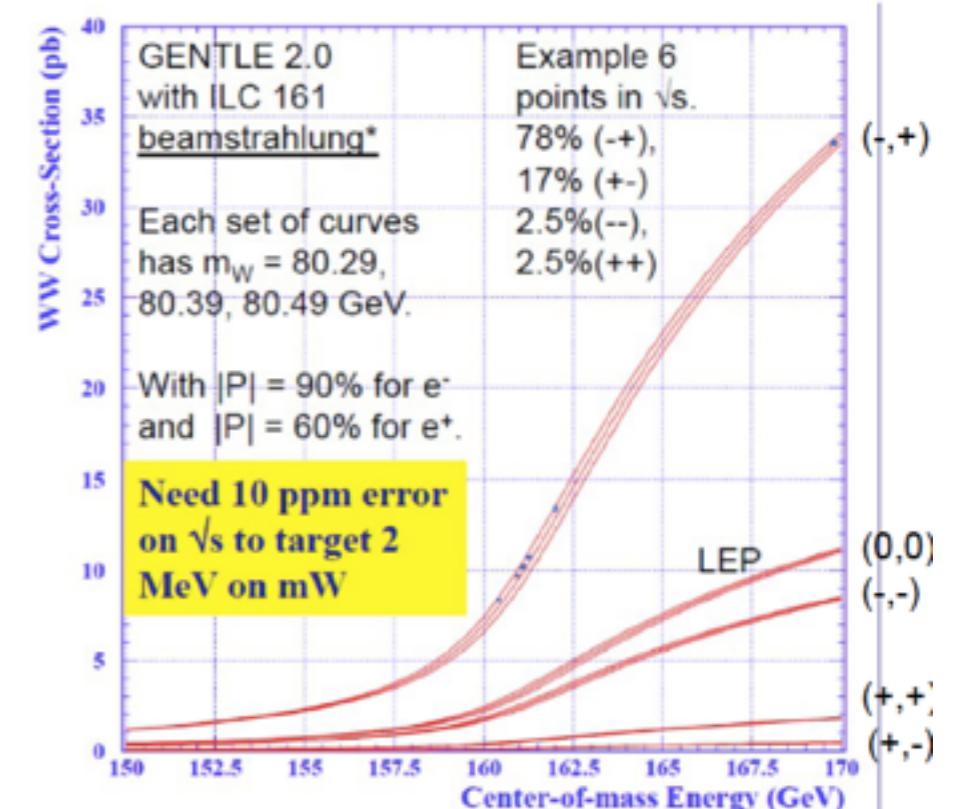
Center-of-mass energy (unc. 0.3 MeV)

- known by resonant depolarisation

Luminosity (unc. $< 2 \times 10^{-4}$)

- from Bhabha events

Carefully chosen energy points



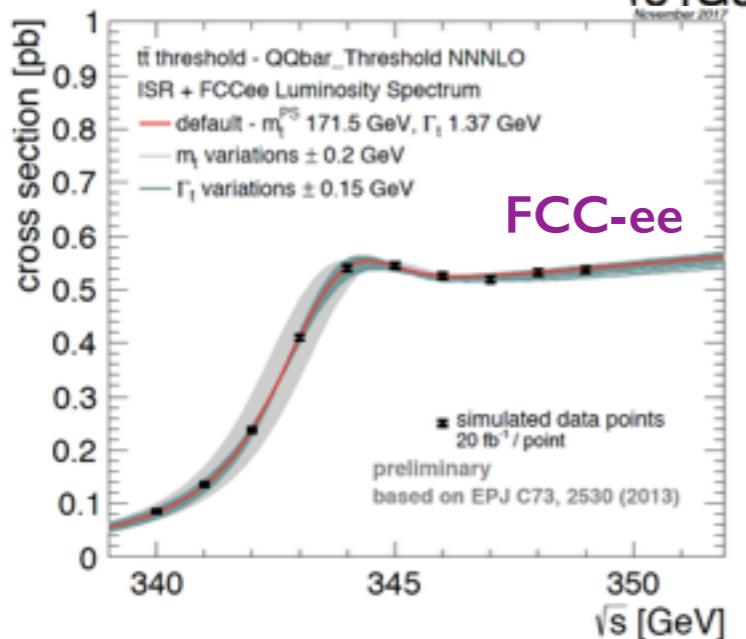
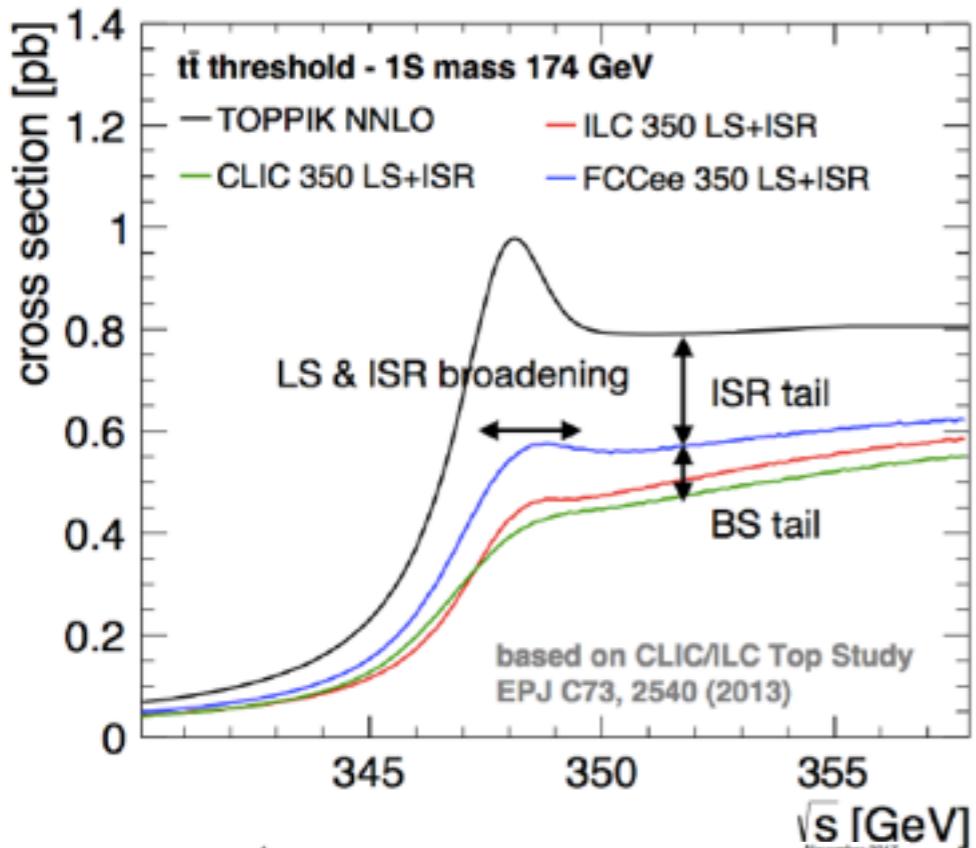
$$\Delta M_W = 0.7 \text{ MeV}$$

$$\Delta \Gamma_W = 1.5 \text{ MeV}$$

Top Mass at Pair Threshold

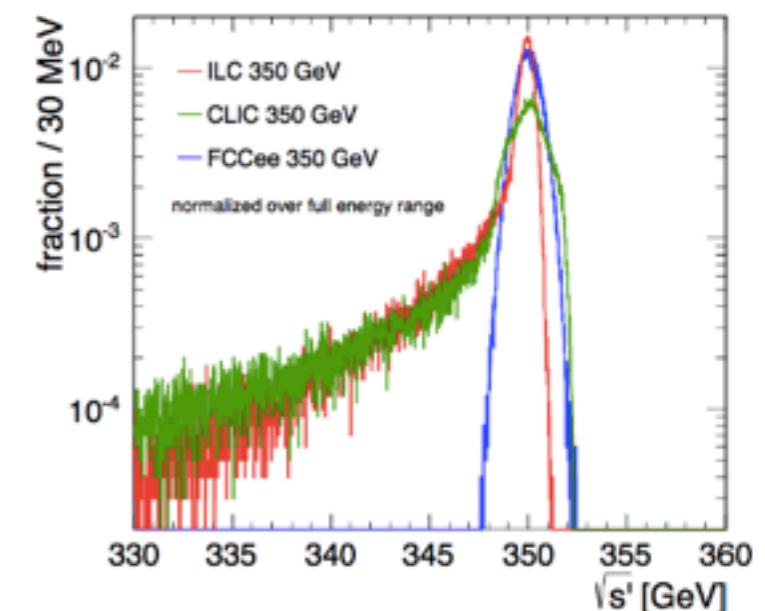
Which definition for the top quark mass?

- HL-LHC → MC mass with uncertainty <200 MeV
- can the *pole mass* be determined at better than $\mathcal{O}(\Lambda_{\text{QCD}})$?

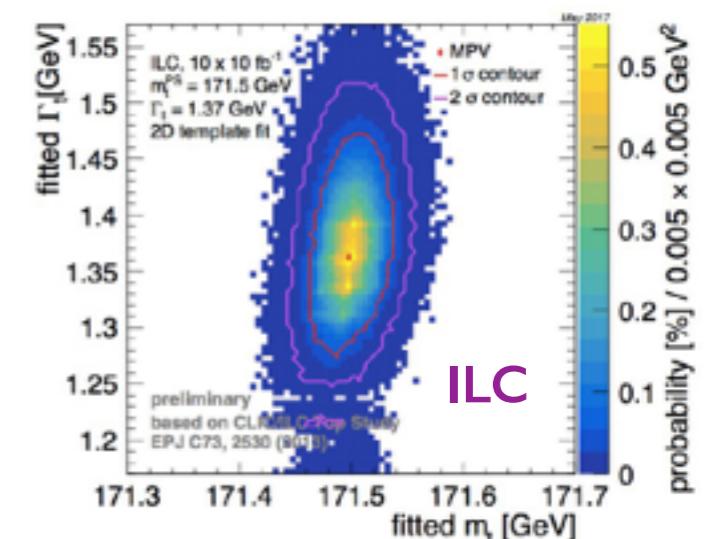


Threshold mass

- safe definition
- can be translated to *pole mass* with uncertainty <100 MeV



Different luminosity spectra at different machines



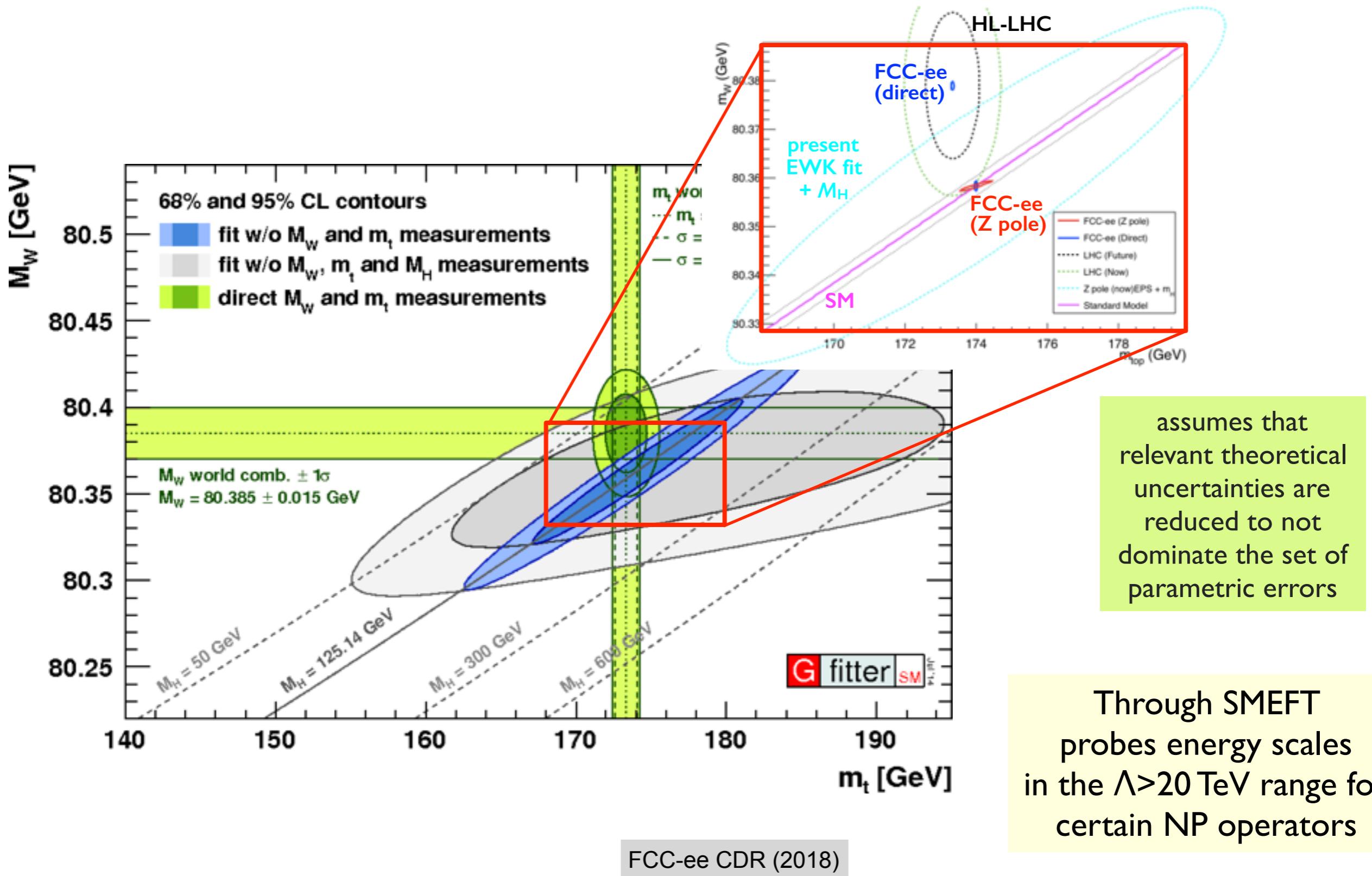
Energy scan

- optimal choice of points
- typically 20 fb^{-1} per point
- stat: 15-20 MeV on M_{top}
- theory (NNNLO): 40 MeV

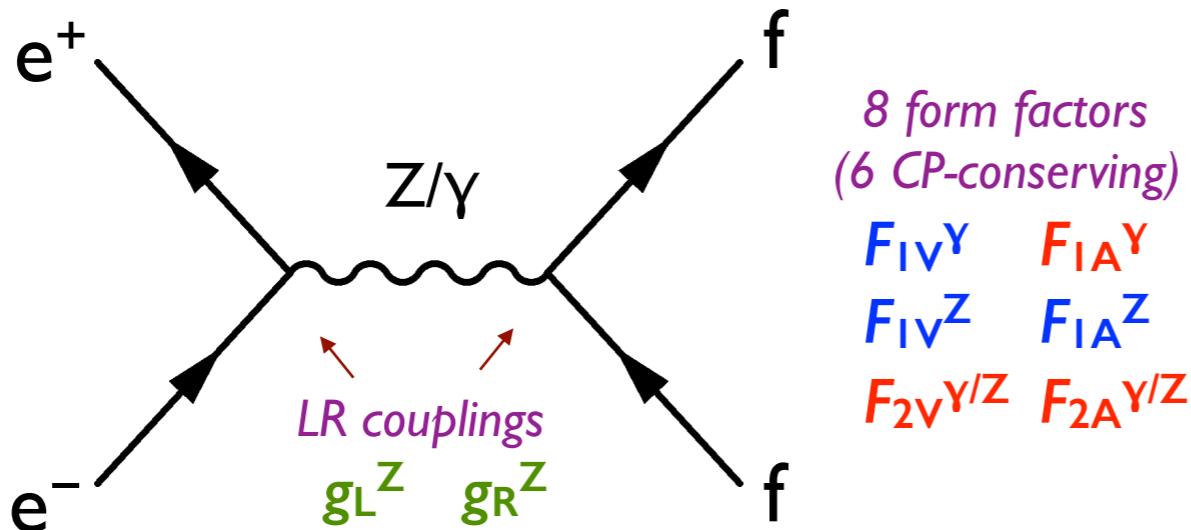
also:

- Γ_{top} at <100 MeV
- indirect y_{top} at 10%

The Ultimate Electroweak Fit



Fermion Pair Production



- $F_{1A}^Y = 0$ in SM
(QED gauge invariance)

Tensor couplings

- 0 in SM
- $F_{2A}^{Y/Z}$ are CP violating

At tree level in SM

$$\sin^2\theta_W \sim 0.234$$

	lepton	b quark	top quark
F_{1V}^Y	-1	-1/3	+2/3
F_{1V}^Z/F_{1A}^Z	$1 - 4\sin^2\theta_W$ +0.064	$1 - (4/3)\sin^2\theta_W$ +0.688	$1 - (8/3)\sin^2\theta_W$ +0.376
g_L^Z	-0.266	-0.422	+0.344
g_R^Z	+0.234	+0.078	-0.156

Third generation of quarks

☞ top quark

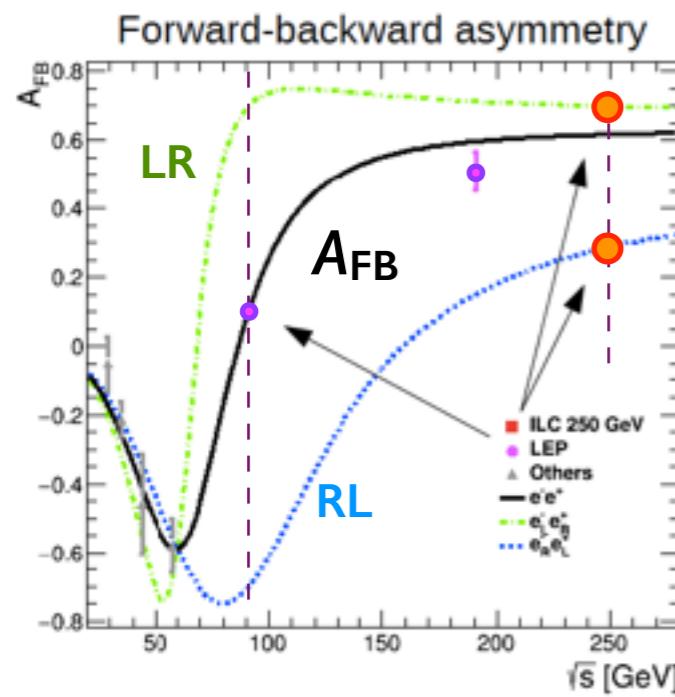
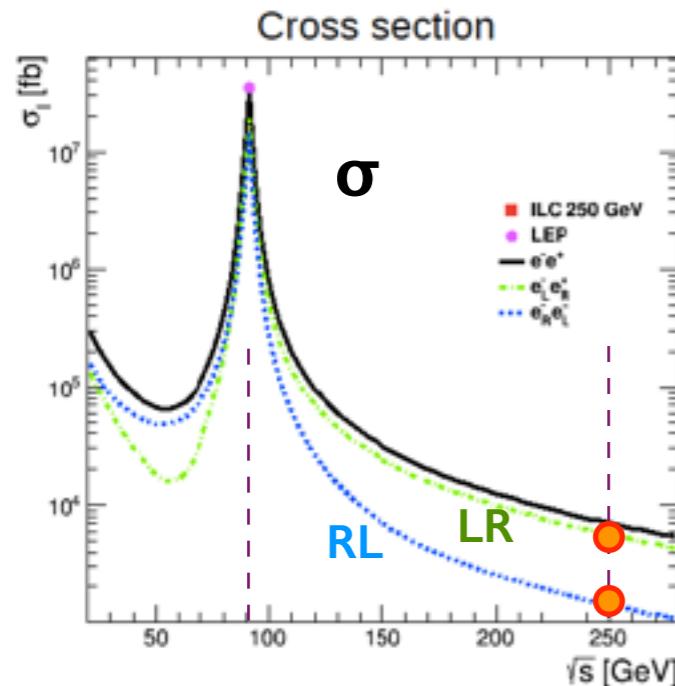
- related to the EWSB scale
- top Yukawa close to one

☞ (partially) composite?

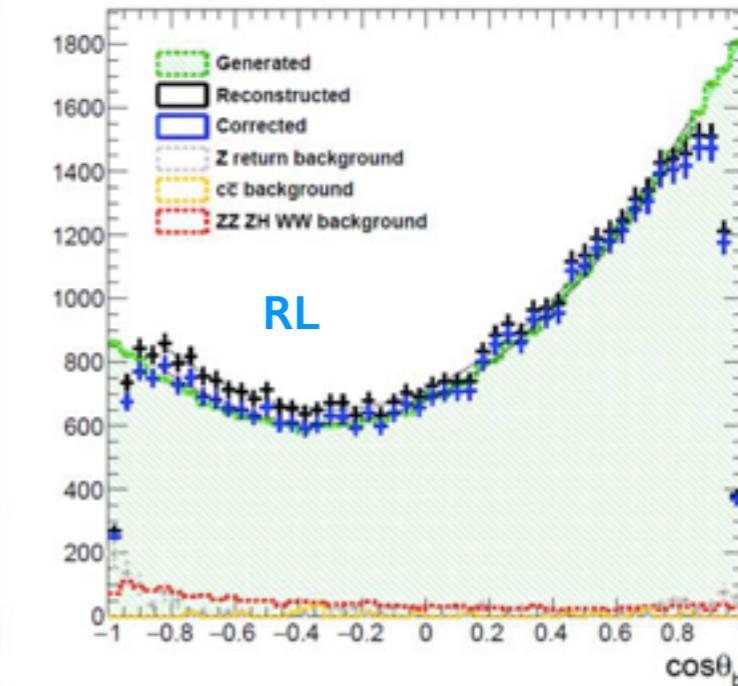
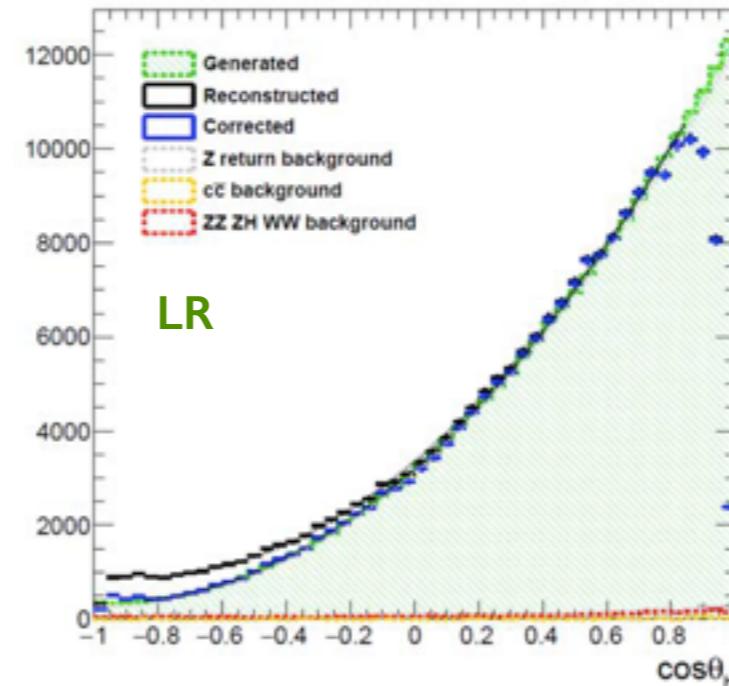
☞ b quark: top isospin partner

b-Quark EWK Couplings

Observables sensitive to chiral structure: σ and A_{FB}



Differential cross sections as a function of $\cos\theta_b$
 $S(1 + \cos^2\theta_b) + A \cos\theta_b$



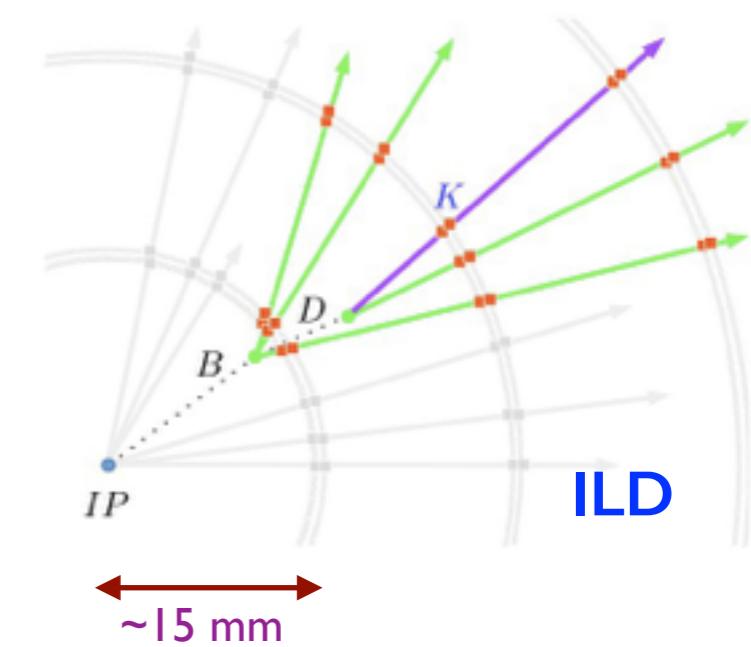
ILC-250
 250 fb^{-1}
 (ILD full sim)

blue:
 corrected
 for charge
 migrations
 (from data)

Excellent b- and c-tagging
 ↗ size of the beam spot
 ↗ particle identification

b-charge determination

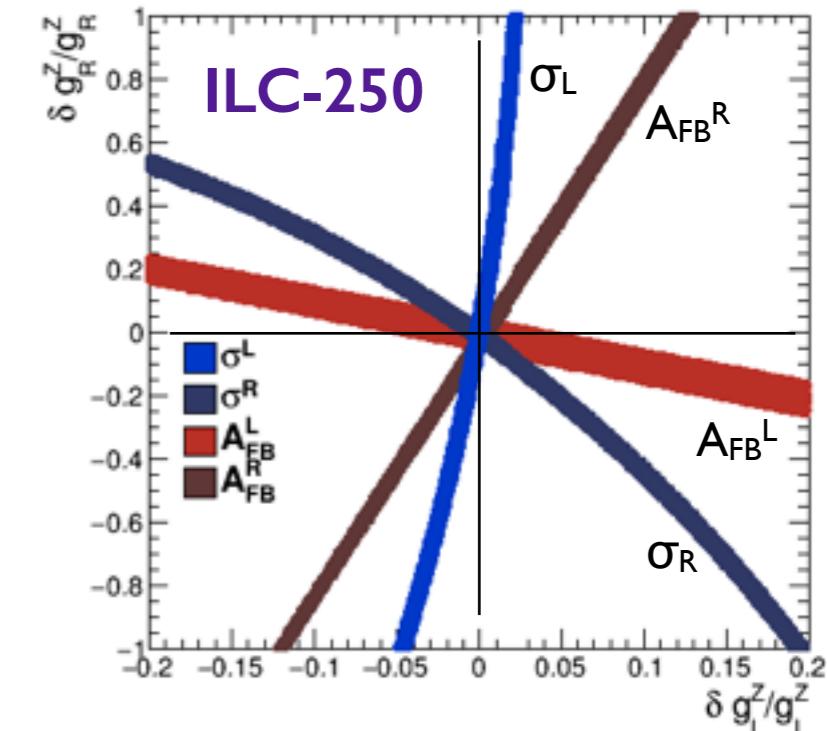
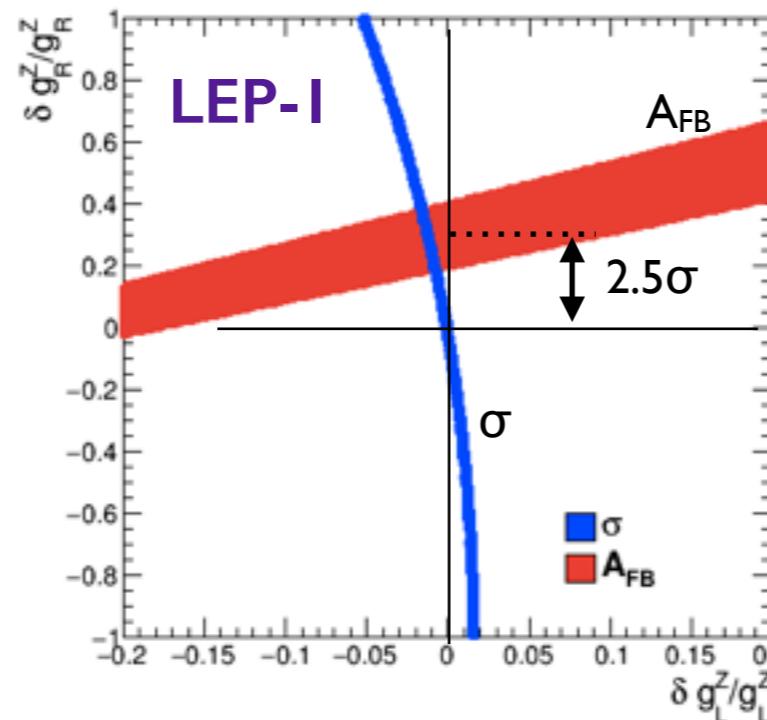
- on event-by-event basis
- sum of charges at secondary and tertiary vertices



Tackling the LEP Anomaly

Long-standing anomaly

- a 2.5σ tension between A_{FB}^L and A_{FB}^R
- 30% deviation of 30% of the g_R^Z coupling
- hint of heavy quark compositeness?



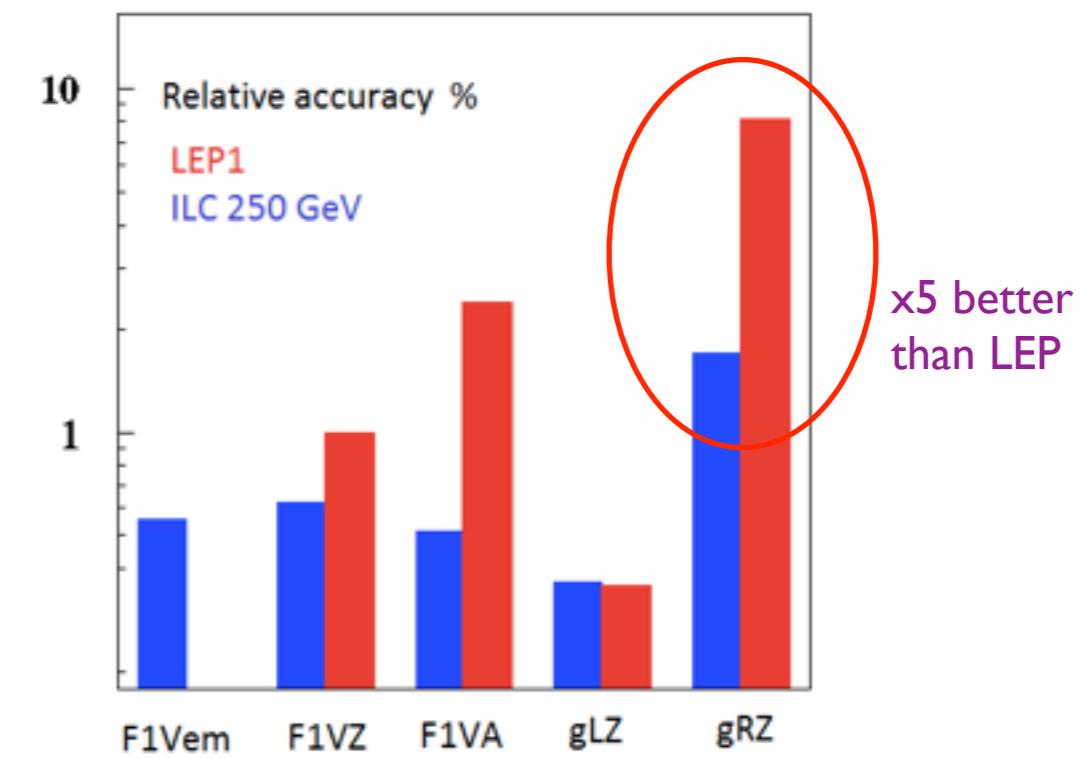
ILC-250 with beam polarisation provides access

to vector and axial couplings

- $\delta g_R^Z/g_R^Z \sim 2\%$ (10% at LEP)
- discard or confirm the anomaly with $>5\sigma$ confidence
- sign ambiguity in the anomaly can be resolved

also:

- constraints on tensor couplings
- sensitivity to BSM scenarios (e.g., Randall-Sundrum)



Top-Quark EWK Couplings

Focus on most sensitive channel:

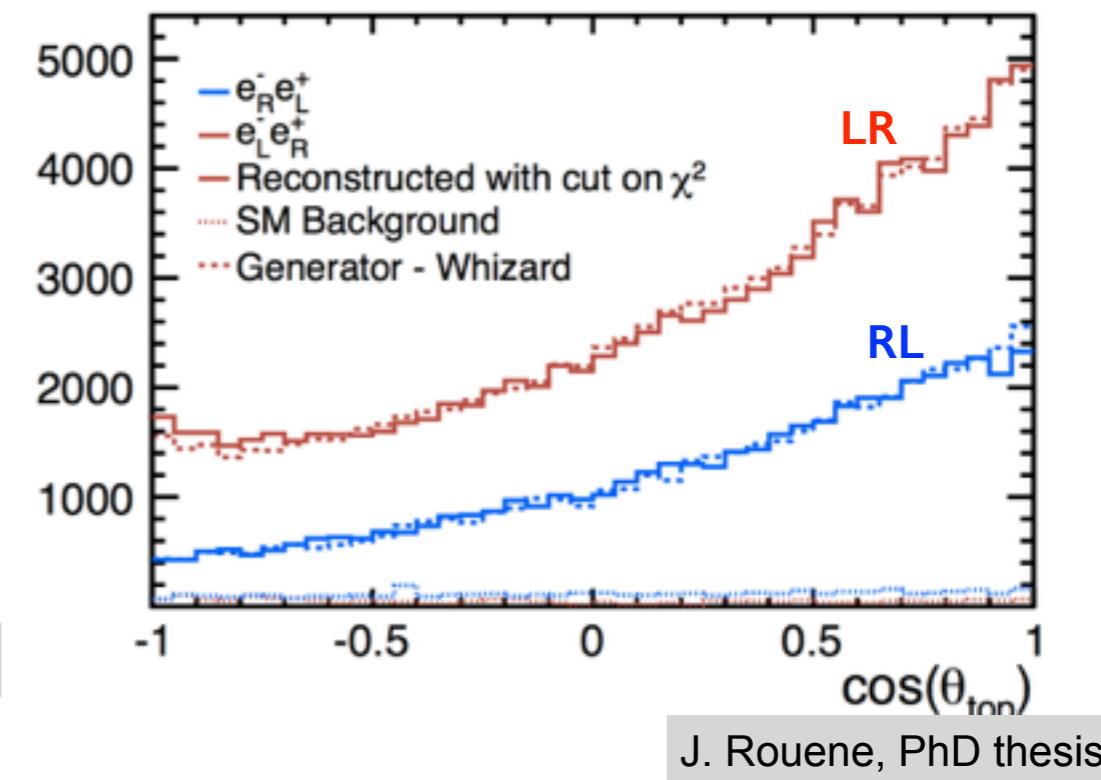
→ semileptonic (44%)

$$e^+e^- \rightarrow tt \rightarrow \ell\nu qq\bar{b}\bar{b} (\ell = e, \mu)$$

ILC 500 fb⁻¹@500 GeV

- precise reconstruction in both polarisations
- b-charge needed to solve ambiguities in LR
- 2% precision on A_{FB}
- improved precision with full statistics

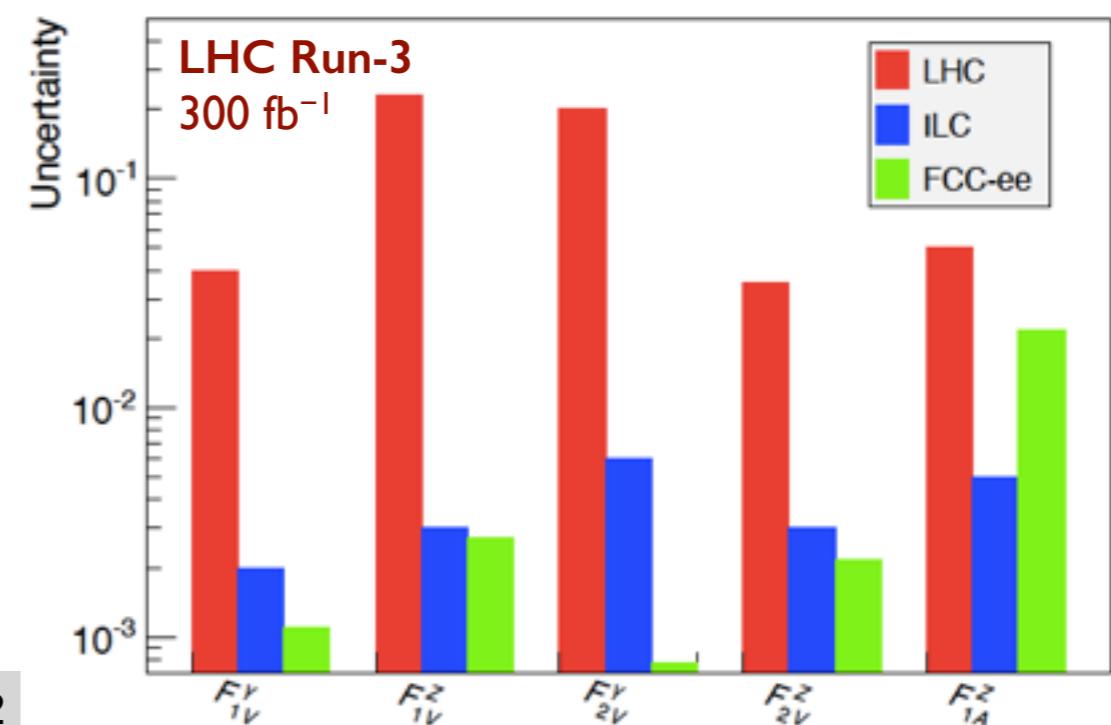
ILC TDR



FCC-ee 2.4 ab⁻¹@365 GeV

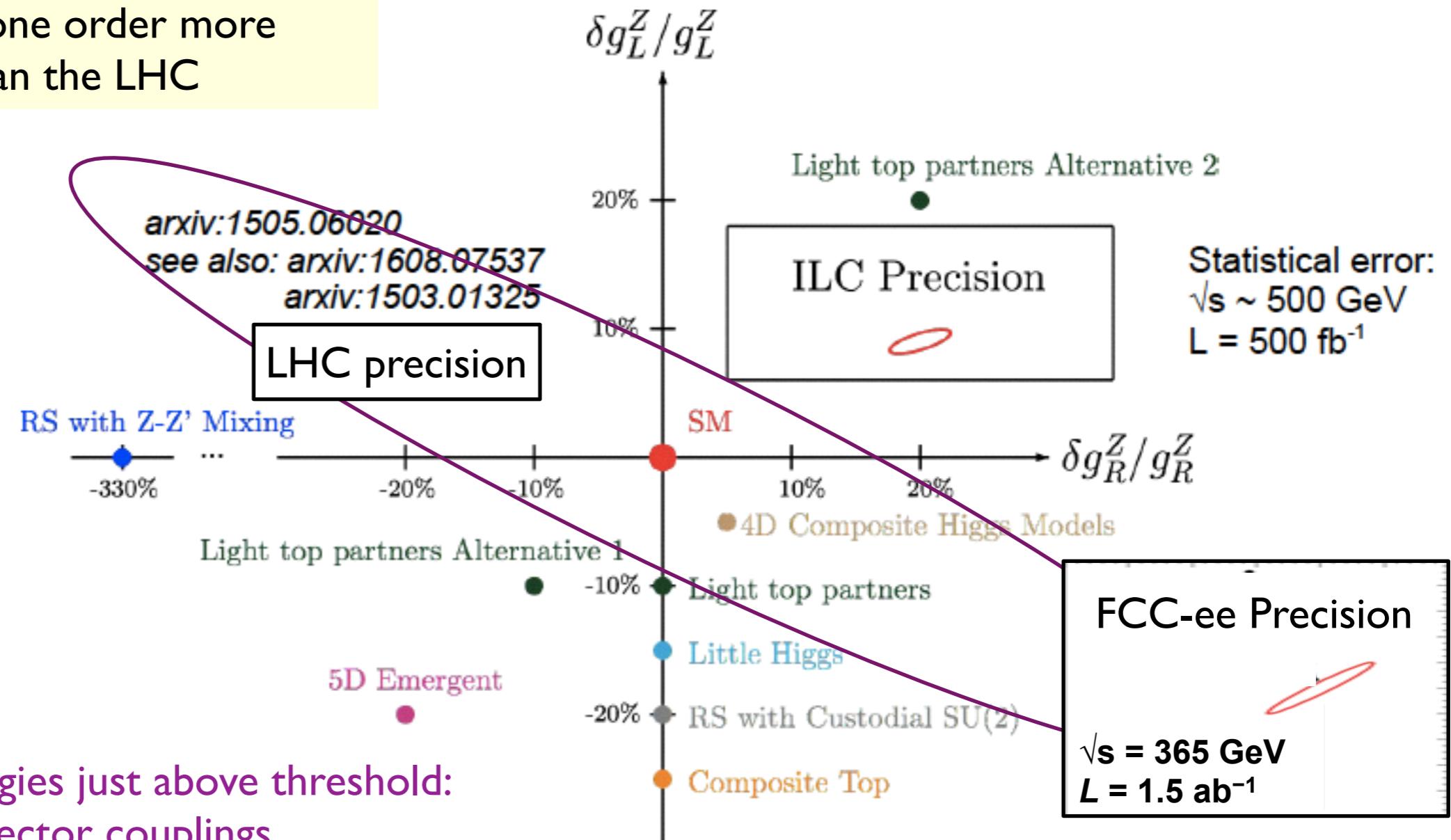
- compensates lack of polarisation with statistics (one million tt events)
- final state polarisation extracted statistically from 2D energy/angular distribution of the lepton (**polarisation transferred through the V-A decay of t → Wb**)

P. Janot, JHEP 04 (2015) 182



Top Quark: Sensitivity to NP

e^+e^- machines (ILC, CLIC, FCC-ee)
 ➔ more than one order more precise than the LHC



Limitation at energies just above threshold:

- vanishing axial-vector couplings
- large QCD uncertainties

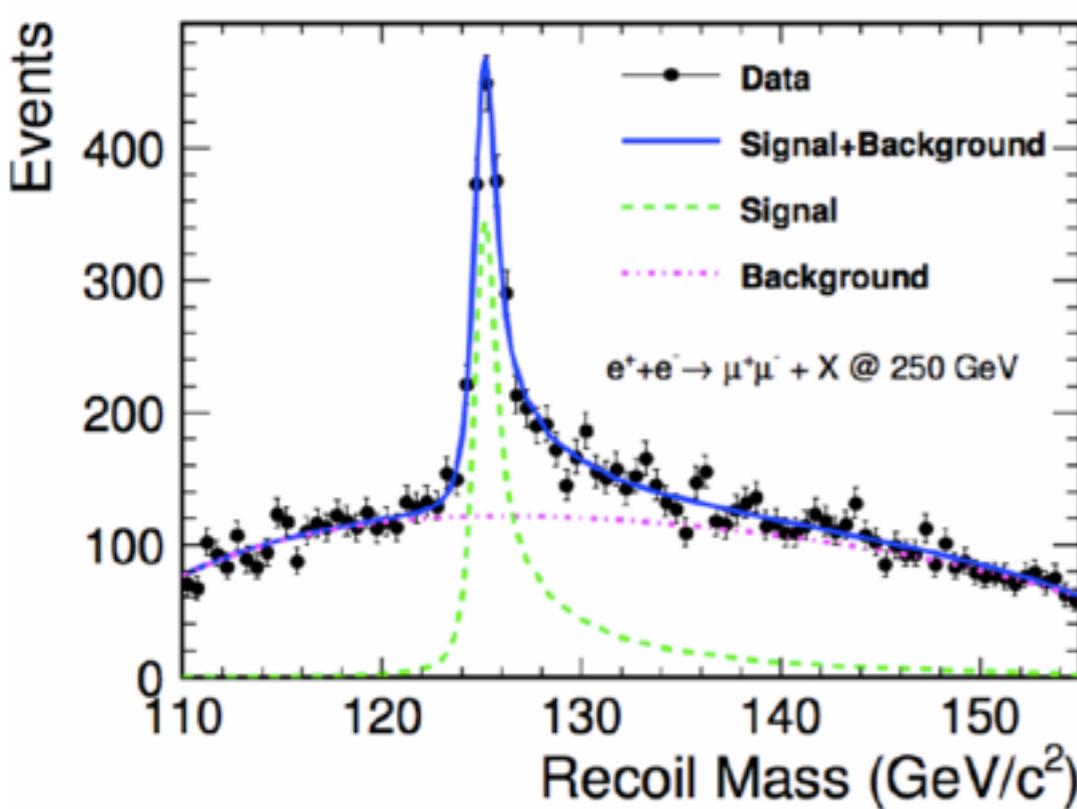
ILC optimal energy: $\sqrt{s} \sim 500 \text{ GeV}$

Higgs Recoil-Mass Analysis

Higgsstrahlung in leptonic mode

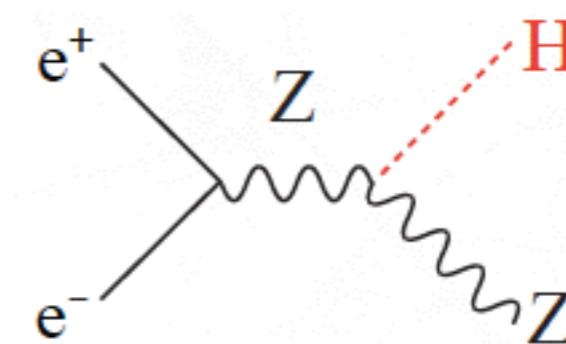
$$e^+e^- \rightarrow ZH \rightarrow \ell^+\ell^-H$$

- (selection and acceptance independent of Higgs decay channel)
- high signal purity
- major backgrounds: $Z\gamma$, ZZ , and WW



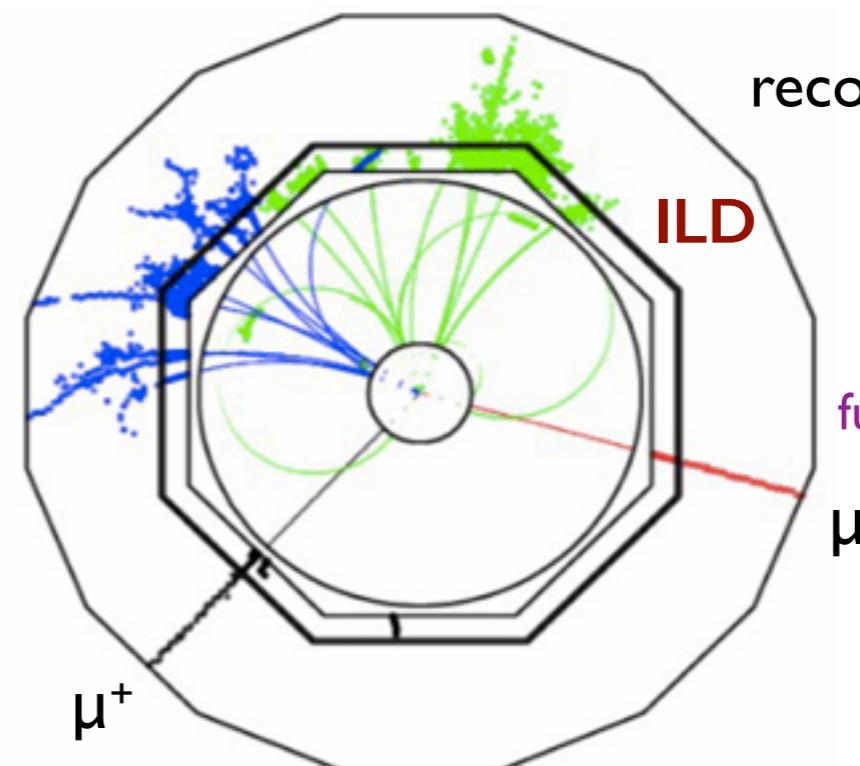
$Z \rightarrow qq$ (60% vs 3.5% for $Z \rightarrow \mu\mu$)

can also be exploited at the price of a small dependence on the Higgs decay



$$\sigma \approx 200 \text{ fb}$$

less than 3 orders of magnitude below $e^+e^- \rightarrow qq$



reconstruct Higgs events independently of the decay channel

full event reconstruction

See presentation by Christophe Ochando

Recoil mass:

$$M_X^2 = s + M_Z^2 - 2\sqrt{s}(p_{\mu^+} + p_{\mu^-})$$

with 500 fb^{-1} at $\sqrt{s} = 250 \text{ GeV}$

- $\delta M_H = 28 \text{ MeV}$

cf backup slide

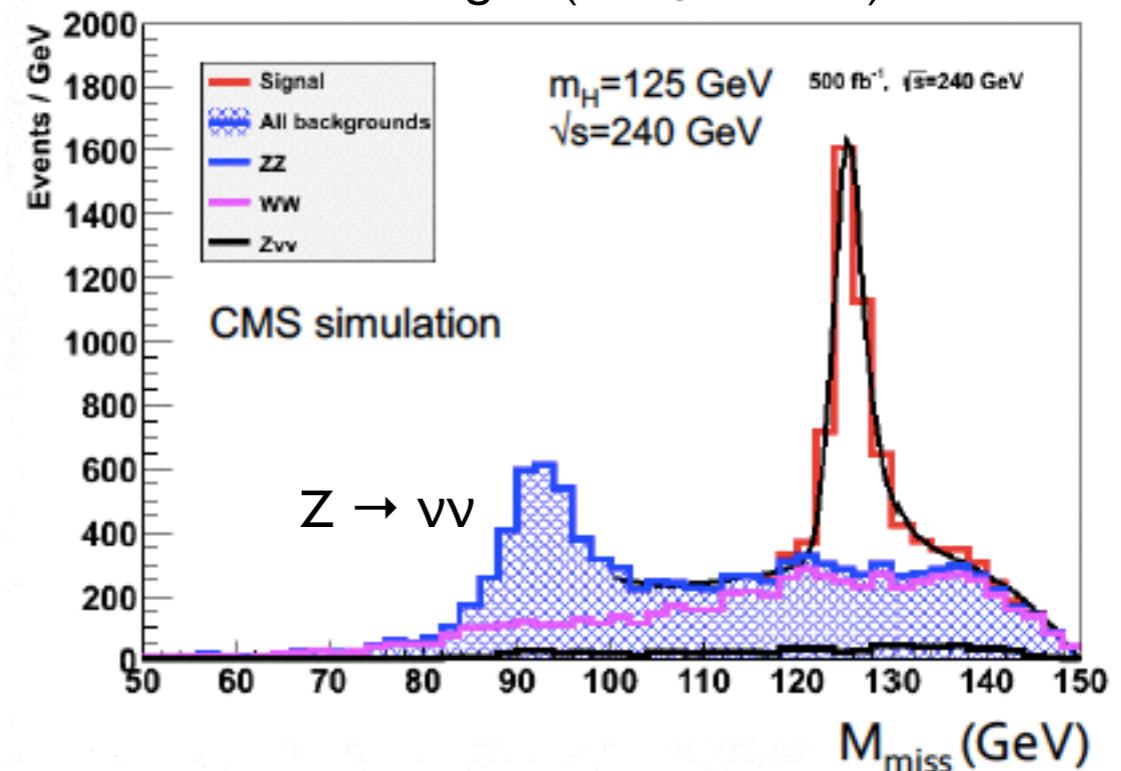
Higgs Decay Branching Ratios

Typical precision on $\sigma \times \text{BR}$ meas.
 ILC at 250 fb^{-1} at $\sqrt{s} = 250 \text{ GeV}$
 ($\sim 75\,000 \text{ ZH events with LR pol.}$)

ILC TDR Vol. 2 - Physics (2013)		$\delta\sigma_{\text{ZH}}/\sigma_{\text{ZH}}$
	BR (125 GeV)	$\delta(\sigma \times \text{BR})/(\sigma \times \text{BR})$
$H \rightarrow bb$	58.4%	1.1%
$H \rightarrow cc$	2.9%	7.4%
$H \rightarrow gg$	8.2%	9.1%
$H \rightarrow WW^*$	21.4%	6.4%
$H \rightarrow \tau^+\tau^-$	6.3%	4.2%
$H \rightarrow ZZ^*$	2.6%	19%
$H \rightarrow \gamma\gamma$	0.23%	34%
$H \rightarrow \mu^+\mu^-$	0.02%	--
$H \rightarrow \text{inv}$	0%	<0.9%

Neat, but still, statistics is an issue

$ZH \rightarrow \ell^+\ell^- + \text{nothing}$
 assuming $\text{BF}(H \rightarrow \text{invisible}) = 100\%$



$\sigma(ZH) \times \text{BF}(H \rightarrow ZZ^*)$ is proportional to g_{HZZ}^4/Γ_H
 ⇒ measurement of Γ_H

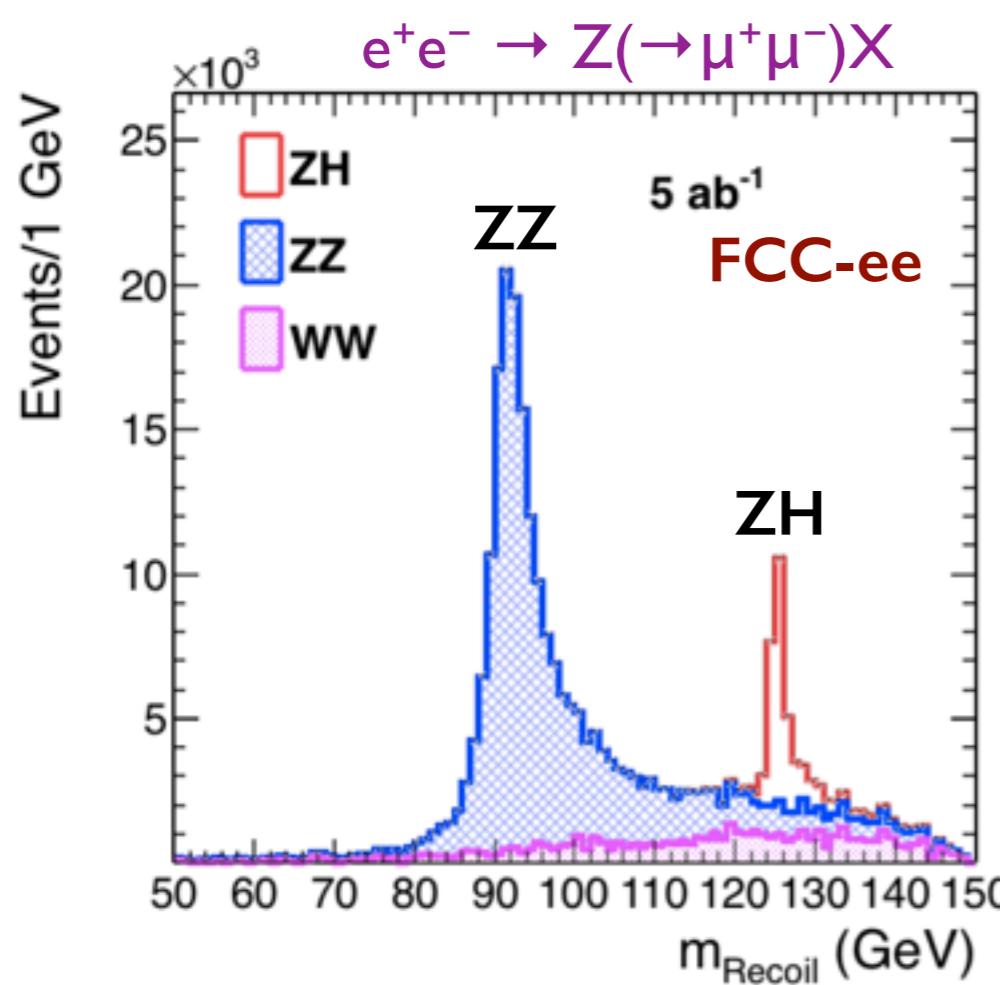
Also:
 Higgs spin determination from rise of
 HZ cross section near threshold
 (measurements at $\sqrt{s} = 215$ and 225 GeV)

Predicted Statistics of Higgs Events

now aiming at *much*
higher statistics

	integrated \mathcal{L} in ab^{-1} (\sqrt{s} in GeV)	# of years	# of H events
ILC-250	2 (250)	13	0.5M
ILC	2 (250) + 0.2 (350) + 4 (500)	25	1.6M
CLIC	1 (380) + 3 (1500) + 5 (3000)	25	1.5M
FCC-ee	5 (240) + 0.2 (350) + 1.5 (365)	8	1.2M
CEPC	5 (240)	10	1.0M

one “year” data-taking time between 0.5 and 1.6×10^7 s



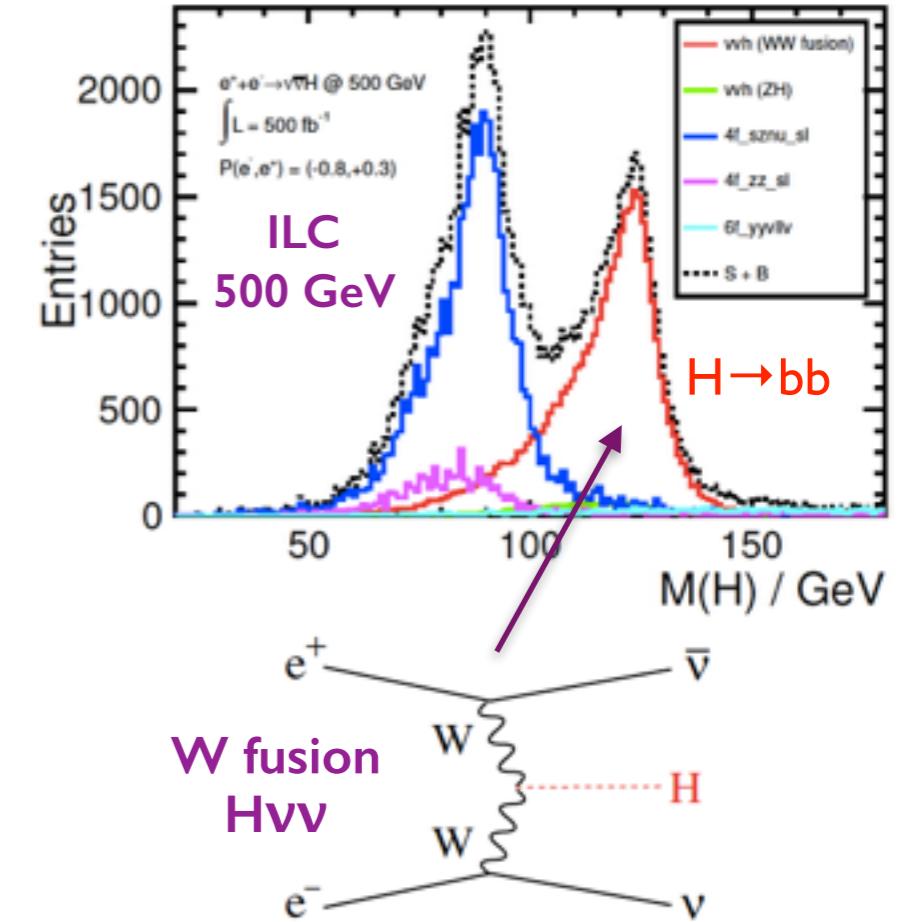
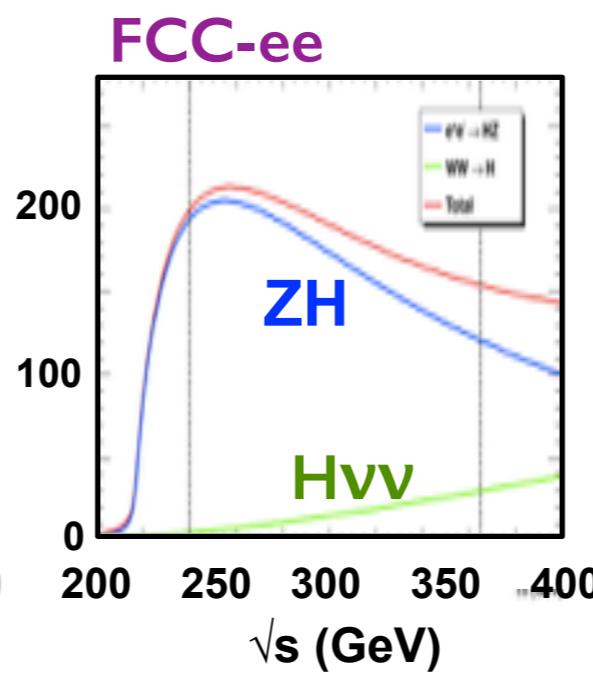
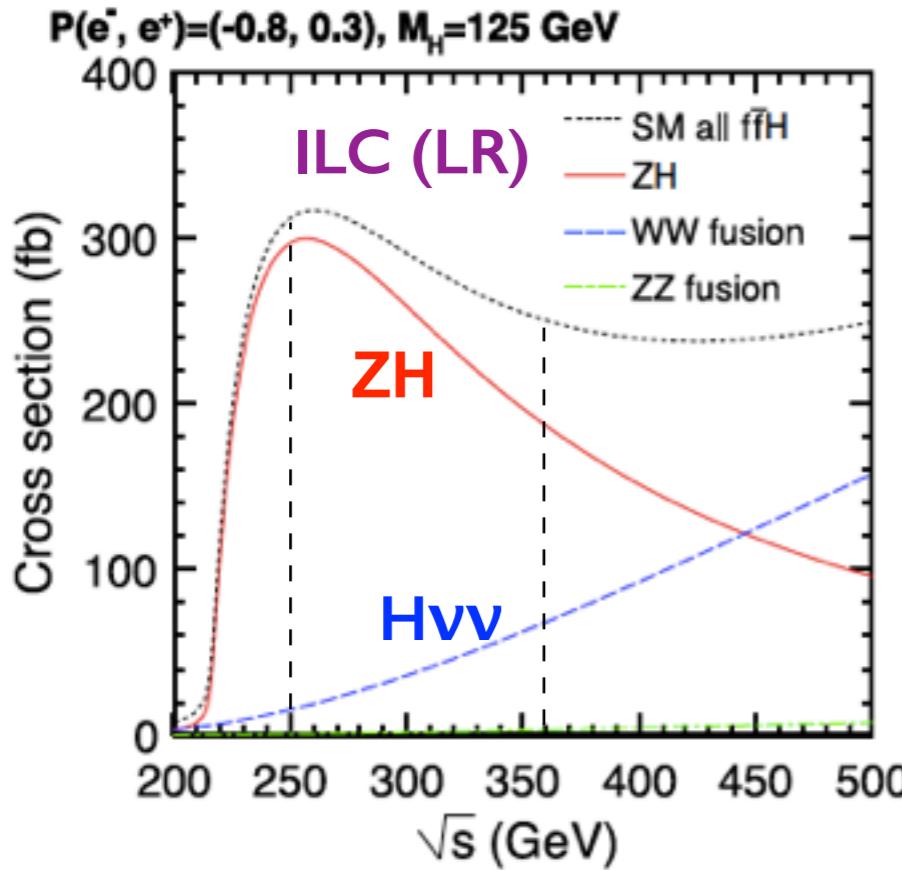
From the recoil analysis ($\sqrt{s} = 250$ GeV)
with of the order of 1M events, σ_{ZH} can be
determined at the 0.5% level

$$\sigma(e^+e^- \rightarrow ZH) = \sigma_{ZH} \propto g_{HZZ}^2$$

Note:
30 ab^{-1} at FCC-hh 100 TeV (25 y)
→ 40 billion Higgs boson produced!
(a small fraction usable due to backgrounds)

Higgs couplings

- to extract couplings from BR, one needs a measurement of the total width Γ_H
- to measure the total width, one needs at least one partial width and BR



At given energy ($> 250 \text{ GeV}$)

$$\frac{\sigma(WW \rightarrow H) \times \mathcal{B}(H \rightarrow XX)}{\sigma(ZH) \times \mathcal{B}(H \rightarrow XX)} = \frac{(g_{HWW}^2 \times g_{HXX}^2)/\Gamma_H}{(g_{HZZ}^2 \times g_{HXX}^2)/\Gamma_H} = \frac{g_{HWW}^2}{g_{HZZ}^2}$$

XX = $b\bar{b}$, W^+W^-

→ Measurements of g_{HWW} and Γ_H

Higgs Couplings

inspired from

FCC-ee TDR (2018)

	HL-LHC	ILC	CLIC	FCC-ee	CEPC		
\sqrt{s} (GeV)	14000	250	+500	380	90-240	+365	90-250
L (ab $^{-1}$)	3	2	+4	0.5	5	+1.5	5
Years	13	15	+10	7	3	+6	7
ZZ (%)	3.5	0.38	0.30	0.80	0.25	0.22	0.25
WW (%)	3.5	1.8	0.4	1.3	1.3	0.46	1.2
$\tau\tau$ (%)	6.5	1.9	0.8	4.2	1.4	0.8	1.4
tt (%)	4.2	—	—	—	—	3.3 ^(*)	—
bb (%)	8.2	1.8	0.6	1.3	1.4	0.7	1.3
cc (%)	—	2.4	1.2	1.8	1.8	1.2	1.8
gg (%)	—	2.2	1.0	1.4	1.7	0.9	1.4
$\gamma\gamma$ (%)	3.6	1.1 ^(*)	1.0 ^(*)	4.7	4.7	1.3 ^(*)	4.7
Γ_H (%)	50	3.9	1.7	6.3	2.8	1.5	2.6
exo (%)	—	<1.6	<1.3	<1.2	<1.2	<1.0	<1.2

(*) incorporating
HL-LHC results

ILC: using κ -framework

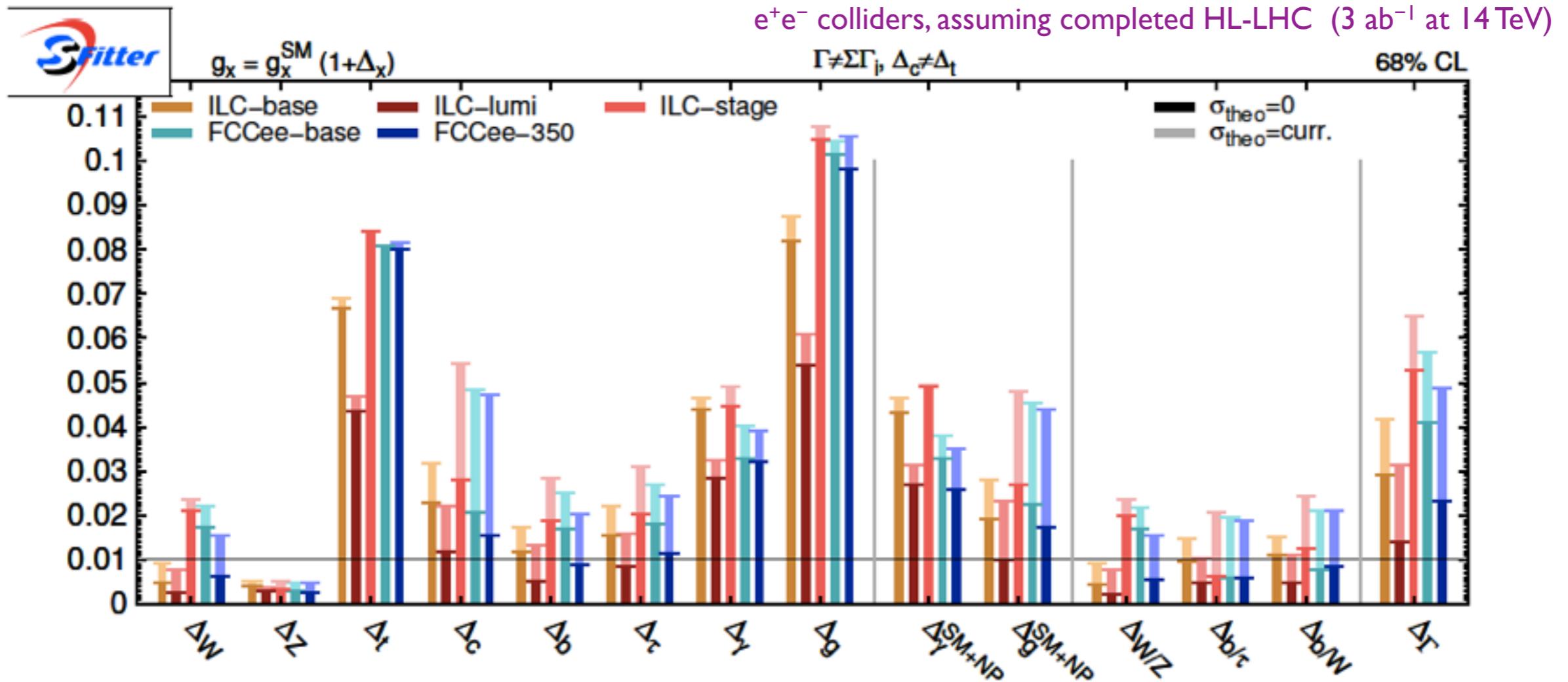
- simple scaling of the couplings
- no operator formalism
- no assumption on total width

HL-LHC measures σ_{ttH} but the extraction of g_{ttH} is model-dependent (through σ_{prod} and Γ_H)

- benefits from Γ_H at e^+e^- machines

sFitter e^+e^- Comparisons

R. Lafaye et al, arxiv:1706.02174



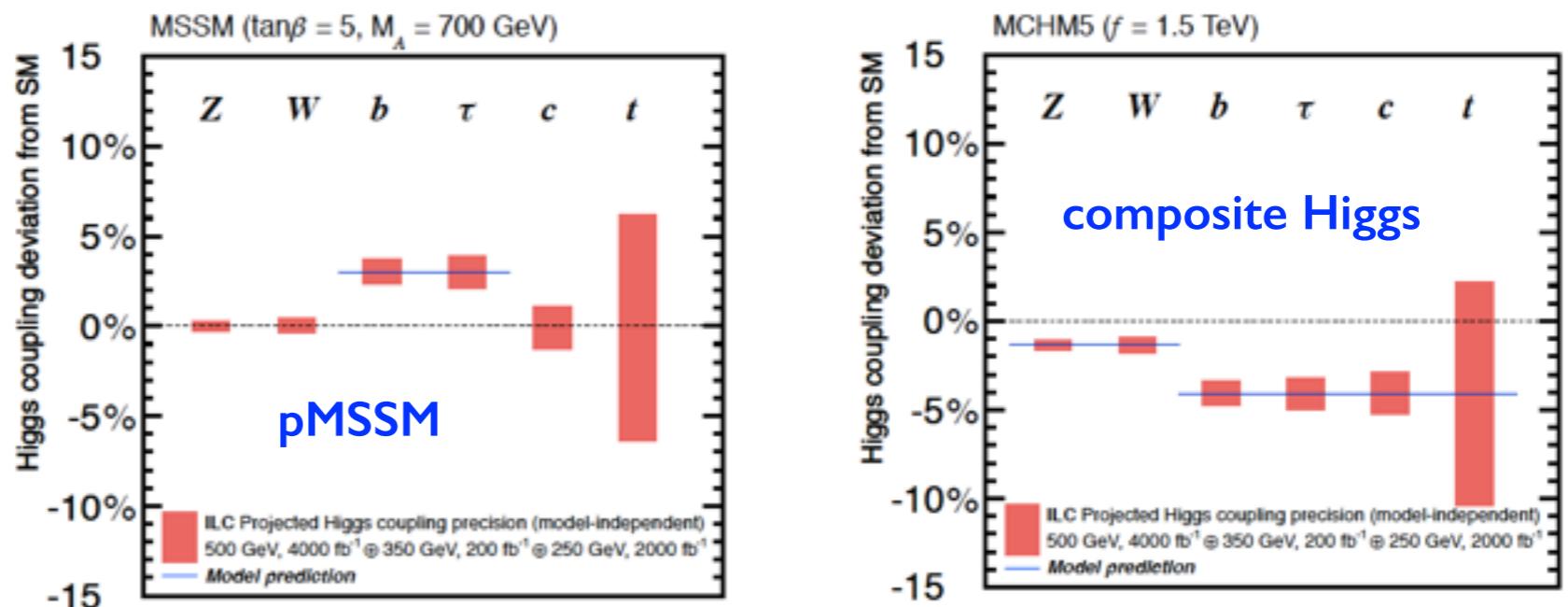
→ already powerful programme at 250 GeV

→ compelling reasons to reach higher energy

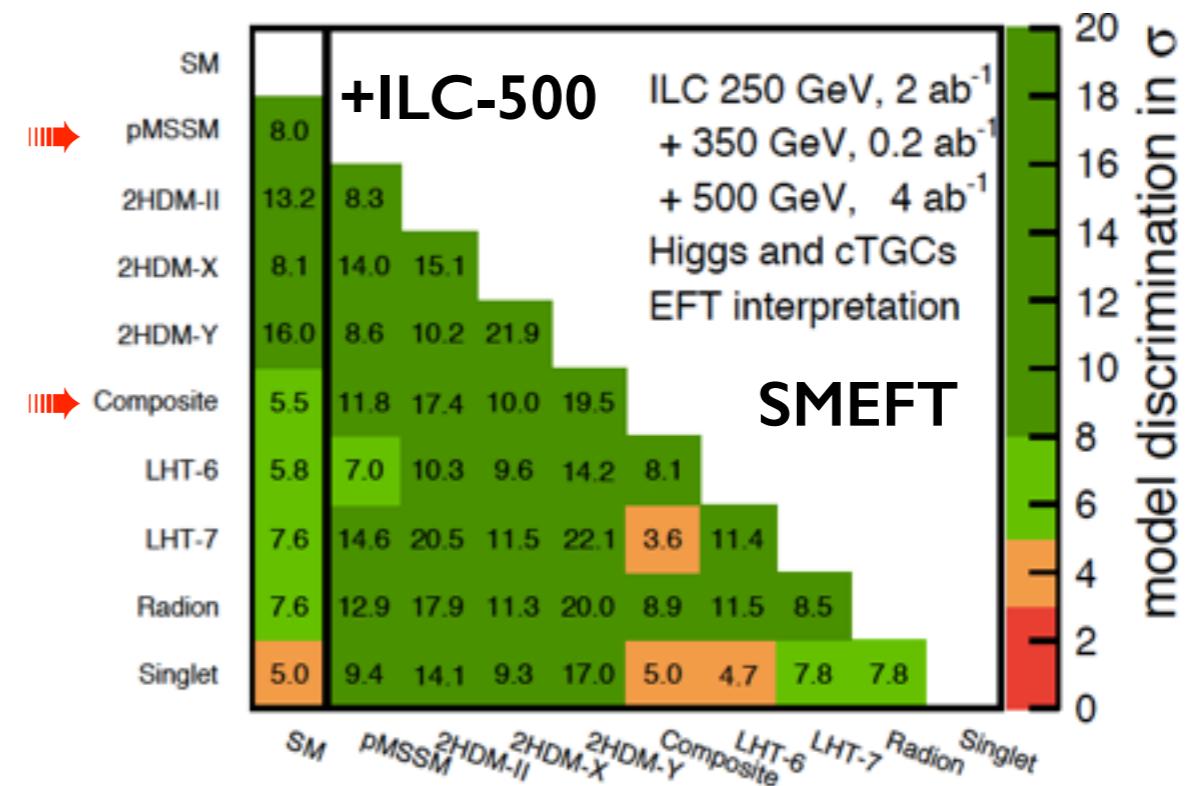
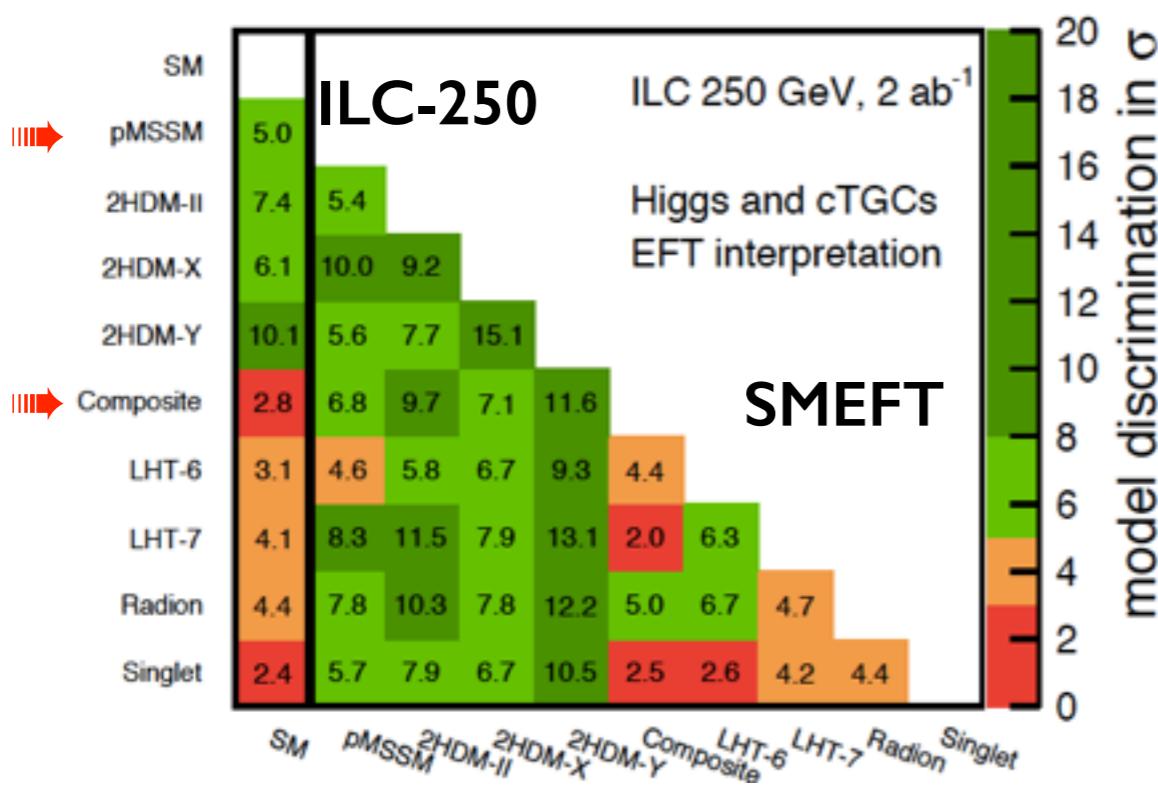
- access to W fusion production
- top physics (mass, couplings)
- constraints on λ
- BSM reach

Sensitivity to BSM Models

Different new physics (NP) models lead to different patterns of deviations



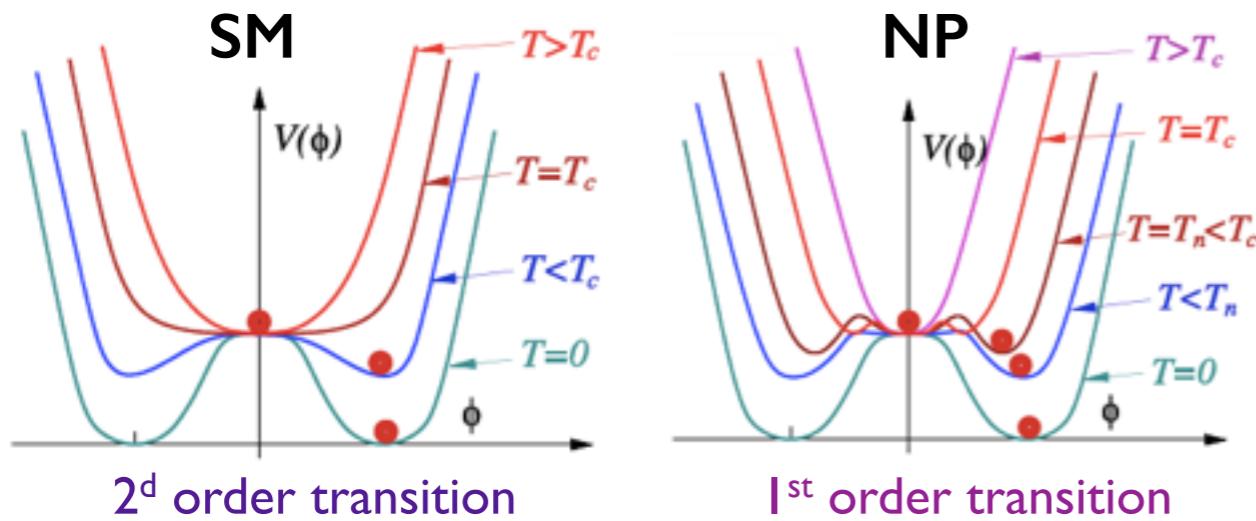
Percent level precision is required !



Higgs Potential and BAU

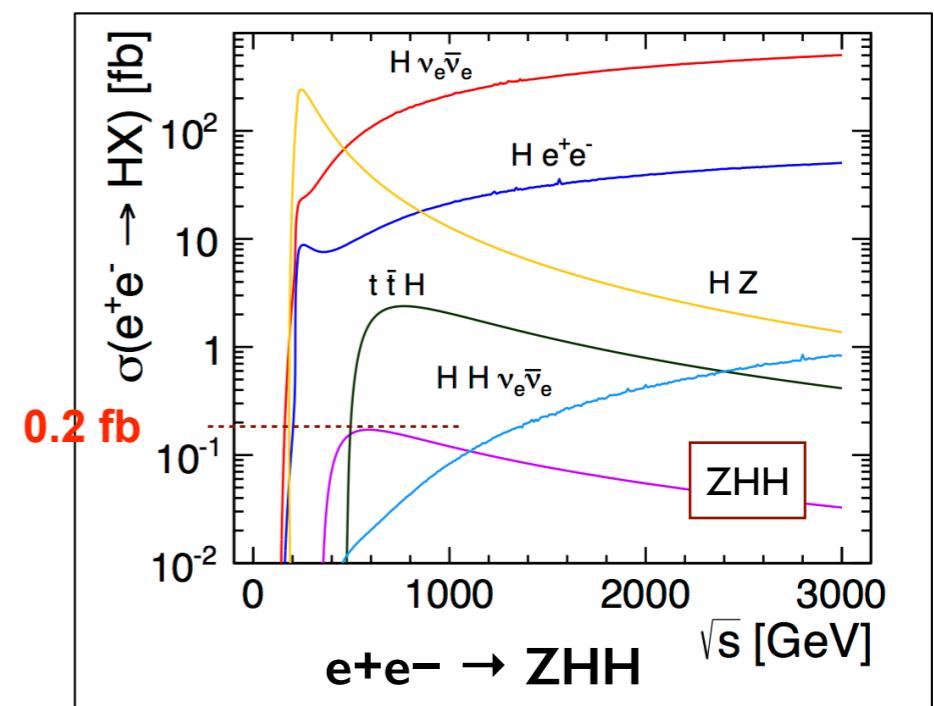
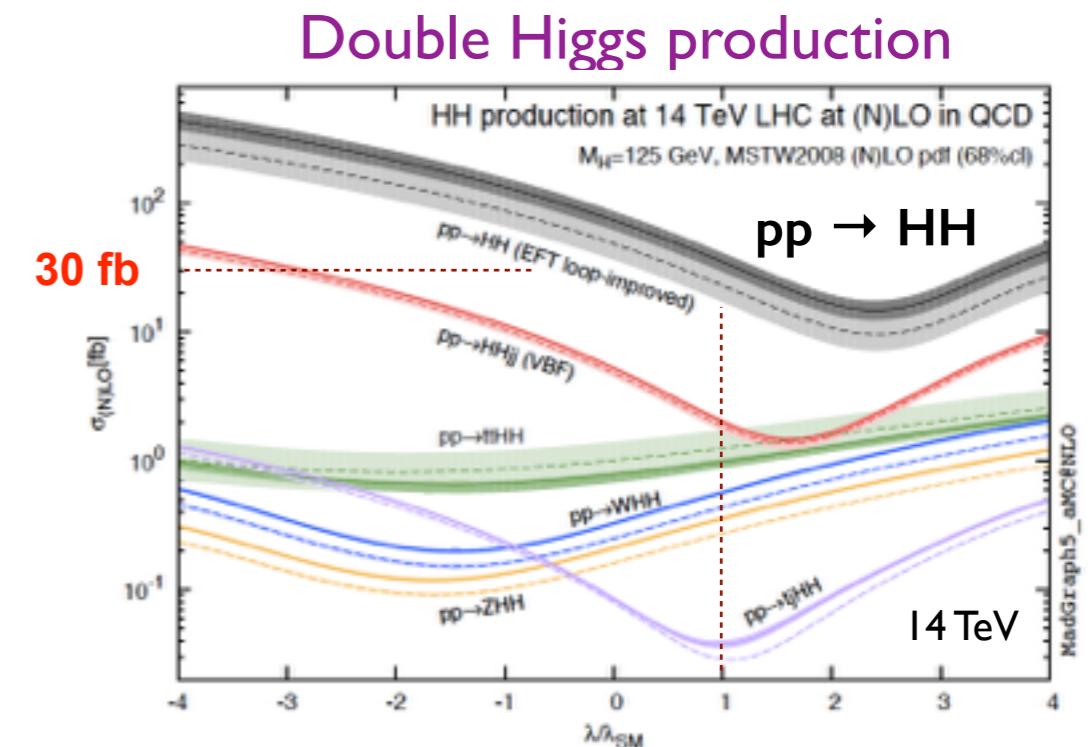
Higgs potential: $V_H = -\mu^2 |\phi|^2 + \lambda |\phi|^4$

NP: $M_H \neq \sqrt{2\lambda v^2}$



Baryon Asymmetry of the Universe (BAU)

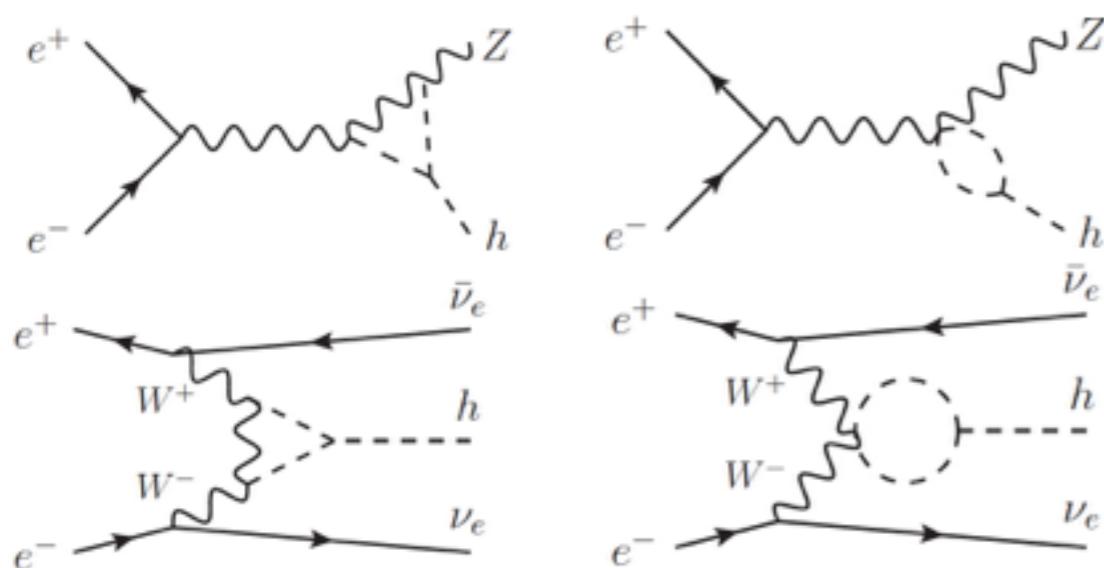
- electroweak (EWK) baryogenesis requires 1st order electroweak transition
- $M_H = 125 \text{ GeV} \rightarrow 2^{\text{d}} \text{ order}$
- EWK BAU implies a modification of the Higgs potential
- it takes $\mathcal{O}(1)$ deviations on λ to get 1st order



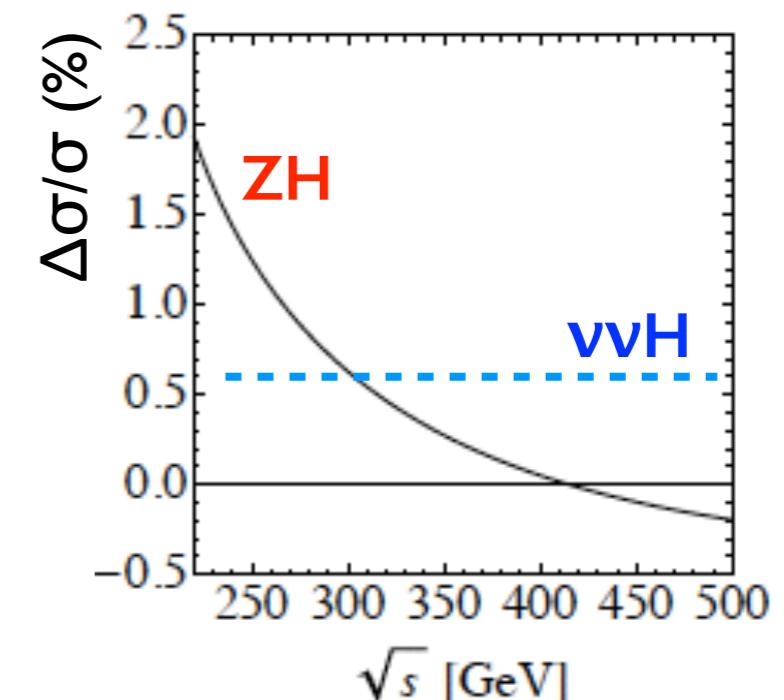
CLIC with 2.5 ab^{-1} @ 1.4 TeV + 5 ab^{-1} @ 3 TeV: $\Delta\lambda/\lambda = {}^{+11\%}_{-7\%}$

Self Coupling at e^+e^- Colliders

- σ_{ZH} and σ_{VvH} receive one-loop vertex corrections which depend on the Higgs self-coupling λ_{HHH} and vary with energy

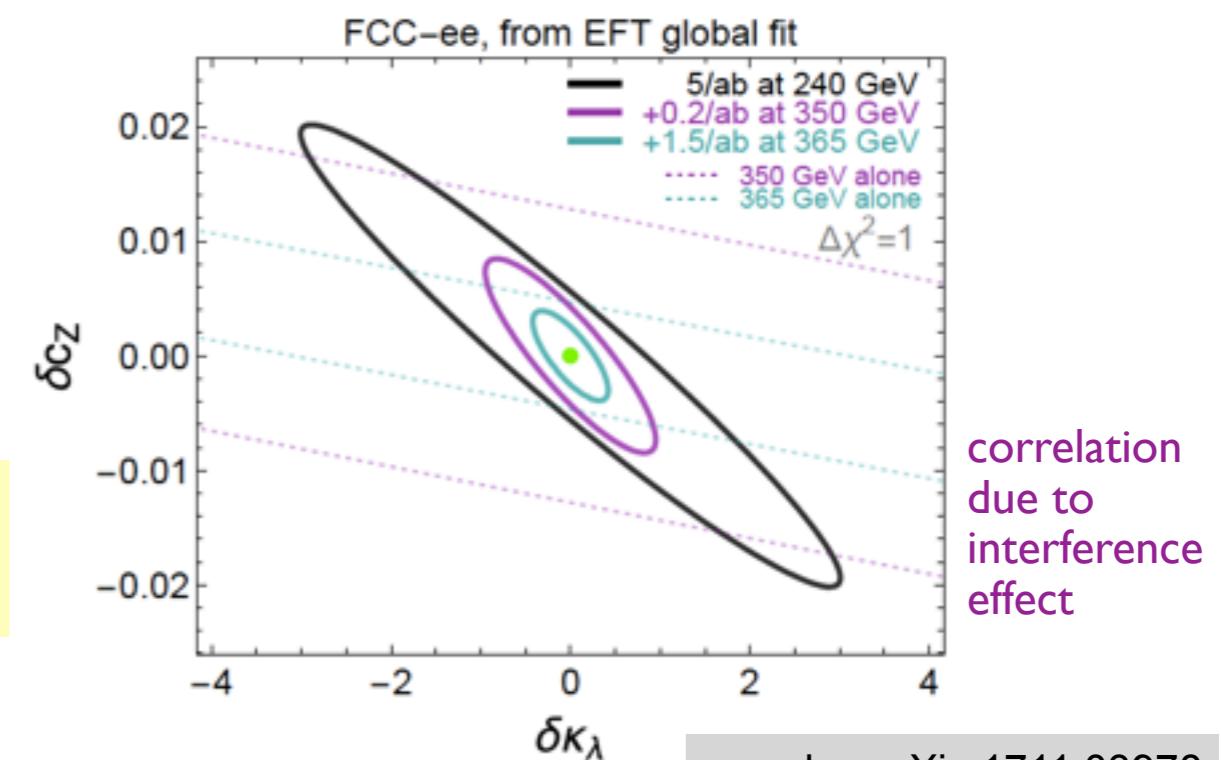


M. McCullough,
PRD 90 (2014)
015001



- Up to 1.5% effect on σ_{ZH} at $\sqrt{s} = 240$ GeV
 - σ_{ZH} with 0.5% accuracy
 - degeneracy between $\delta\kappa_\lambda$ and $\delta\kappa_Z$

Two energy points are necessary to break the degeneracy



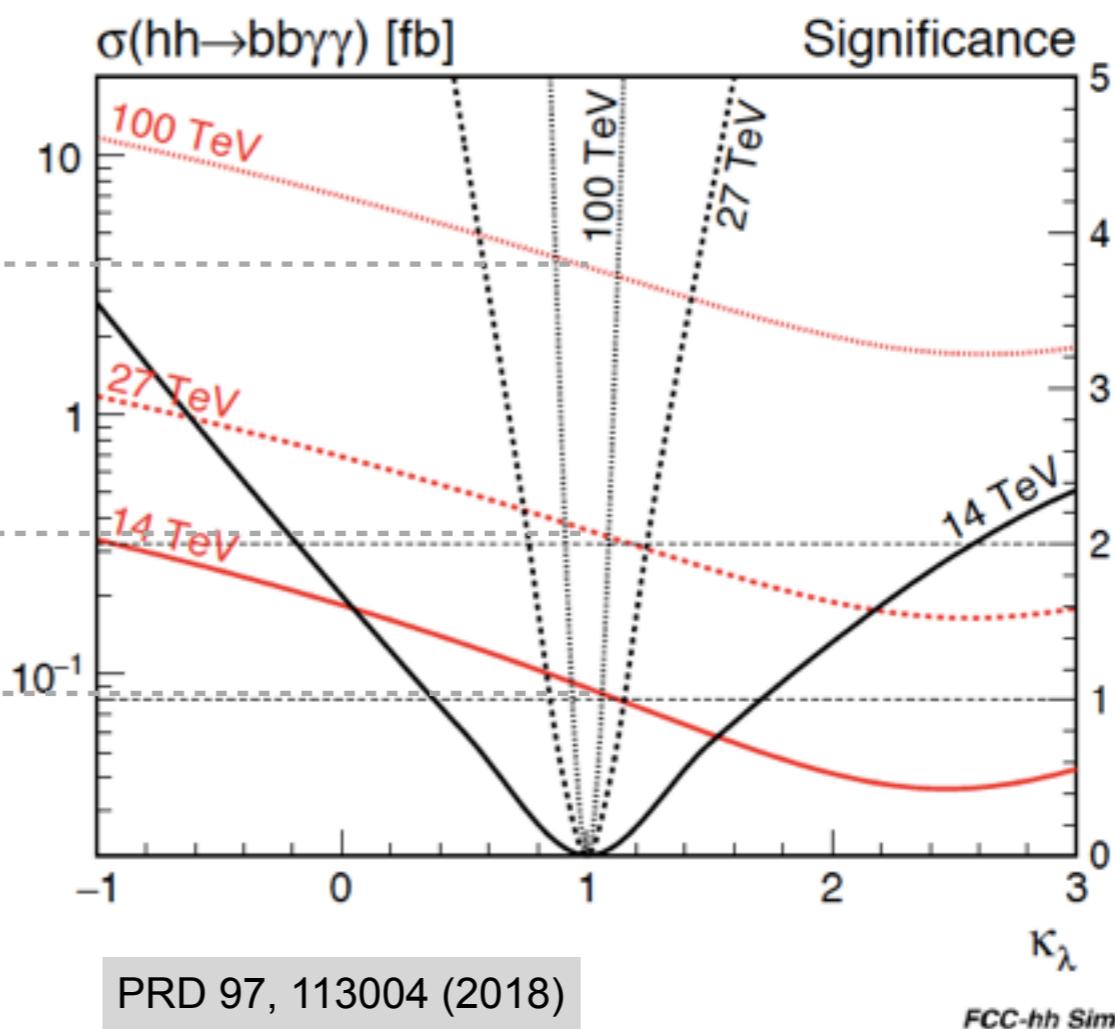
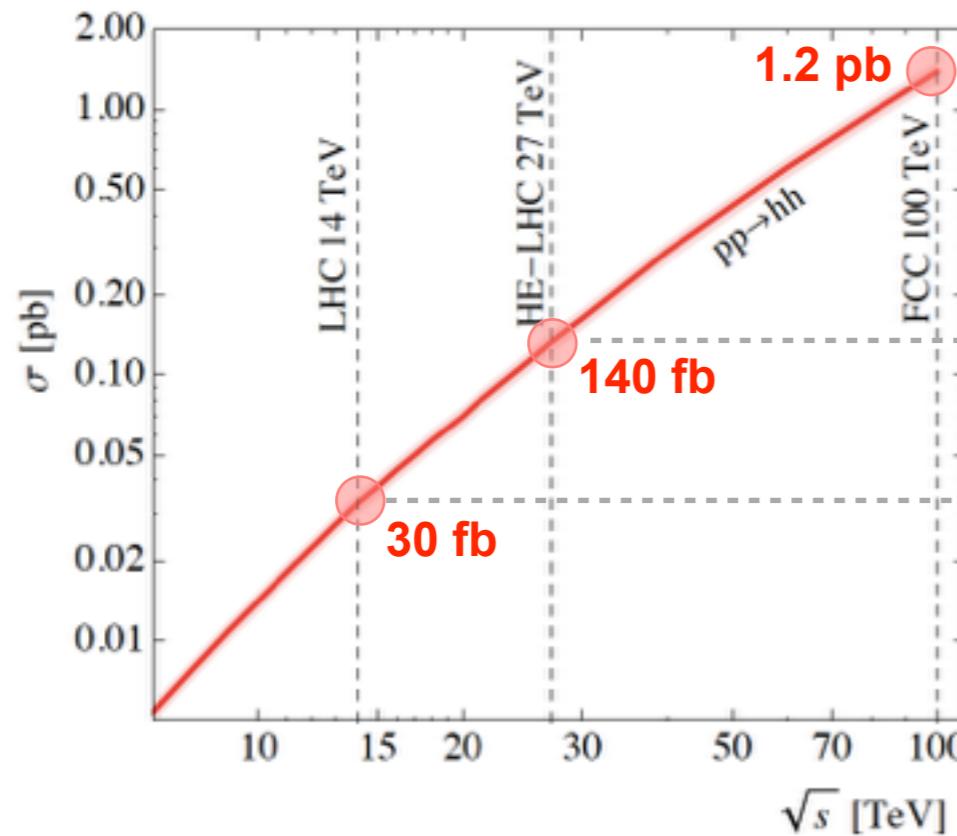
correlation
due to
interference
effect

FCC-ee (2IPs) : model-independent constraint on $\delta\kappa_\lambda$ at the ±35% level

see also arXiv:1711.03978

Self Coupling at the FCC-hh

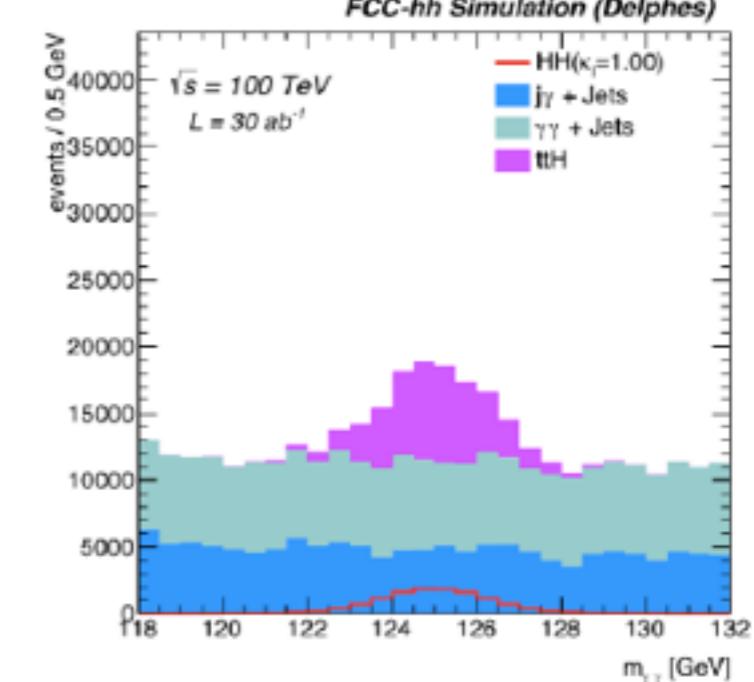
Factor 40 in cross-section / HL-LHC



- $HH \rightarrow bb\gamma\gamma$ is the Golden channel the FCC-hh
 - ttH is a resonant background

	$b\bar{b}\gamma\gamma$	$b\bar{b}ZZ^*[\rightarrow 4\ell]$	$b\bar{b}WW^*[\rightarrow 2j\ell\nu]$	4b+jet
$\delta\kappa_\lambda$	6.5%	14%	40%	30%

- Nature of the EW phase transition and the BAU
 - first order implies strong deviations from predictions



Higgs Couplings at 100 TeV

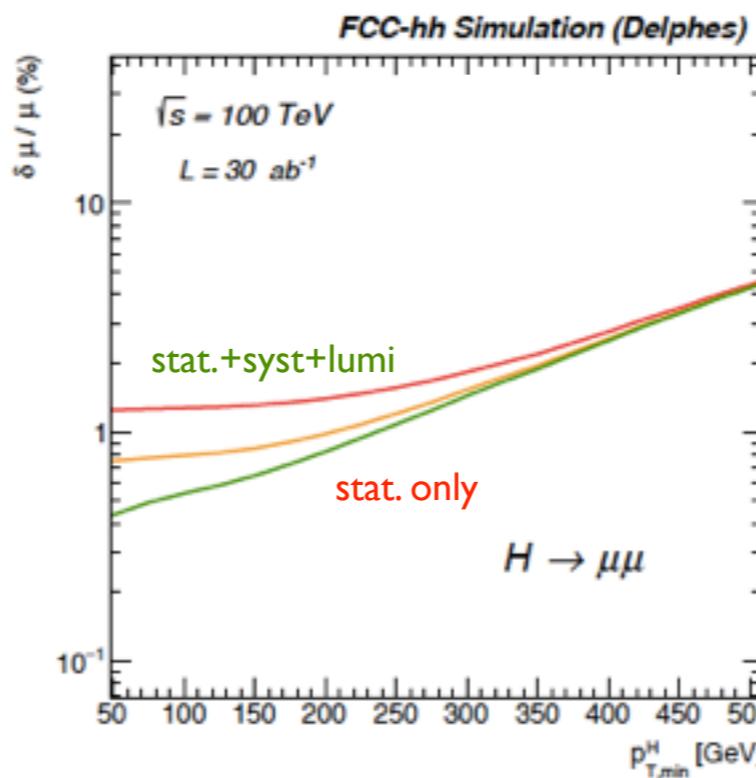
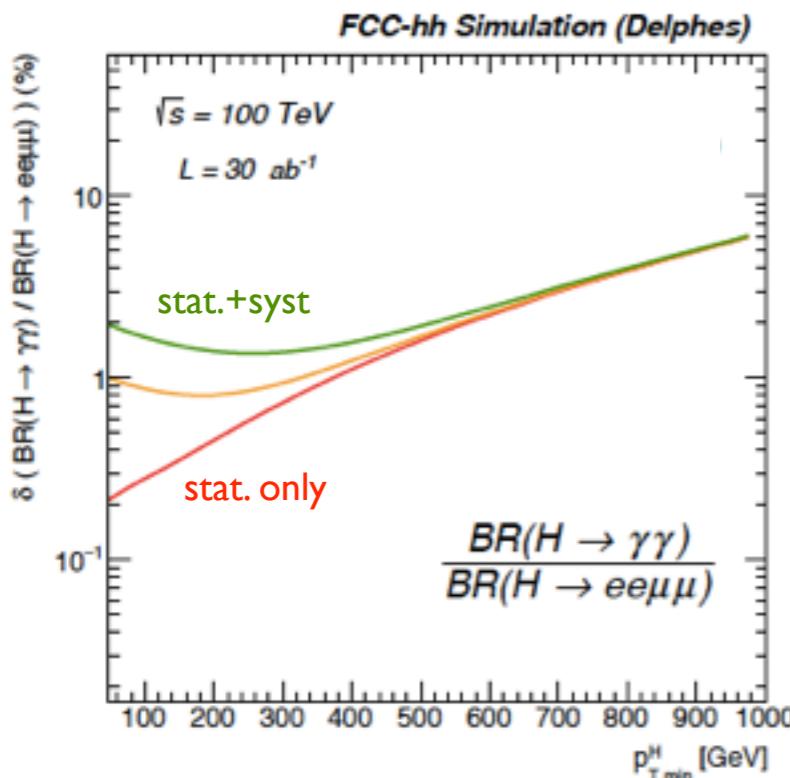
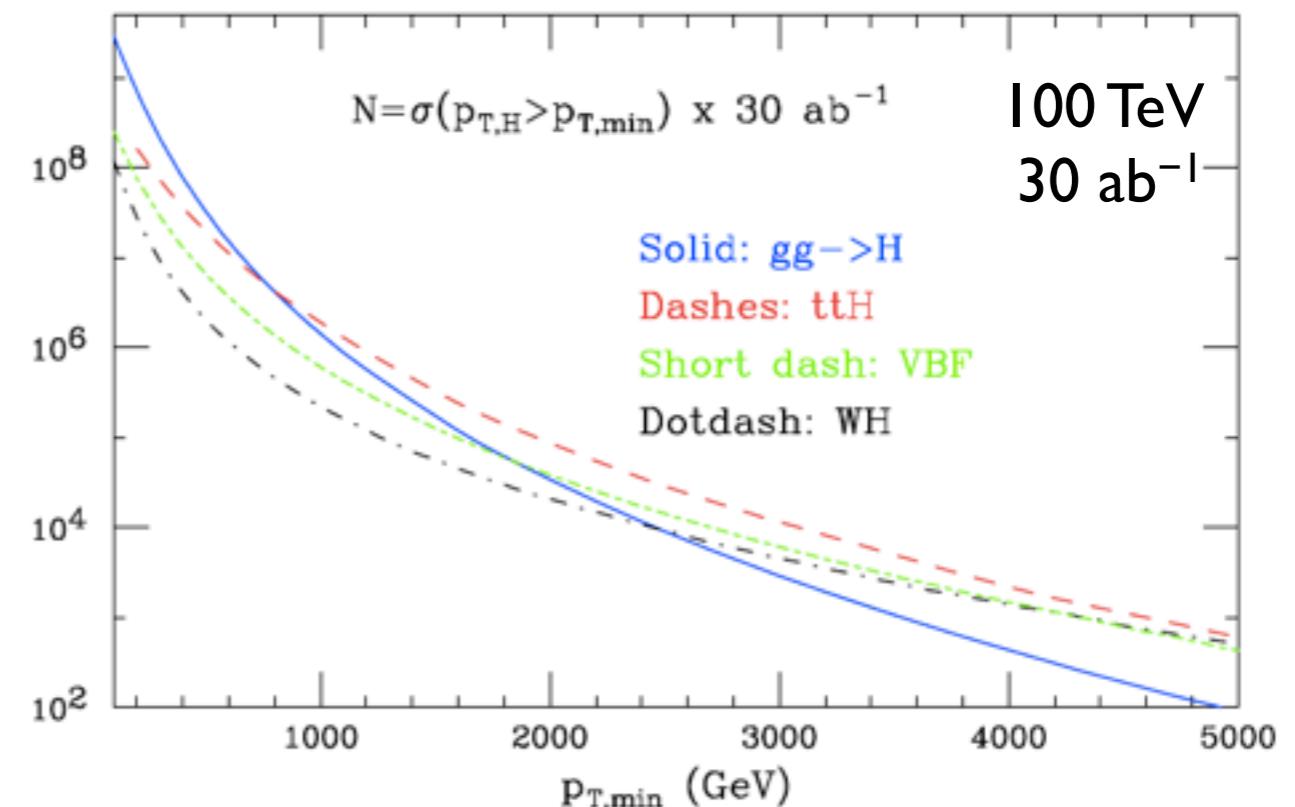
Large kinematic range for Higgs production

- different hierarchy of production processes
- sensitivity to effects at large Q^2

At $p_T > 800$ GeV

- millions of events
- ttH production becomes dominant

Complementary with e^+e^- precision

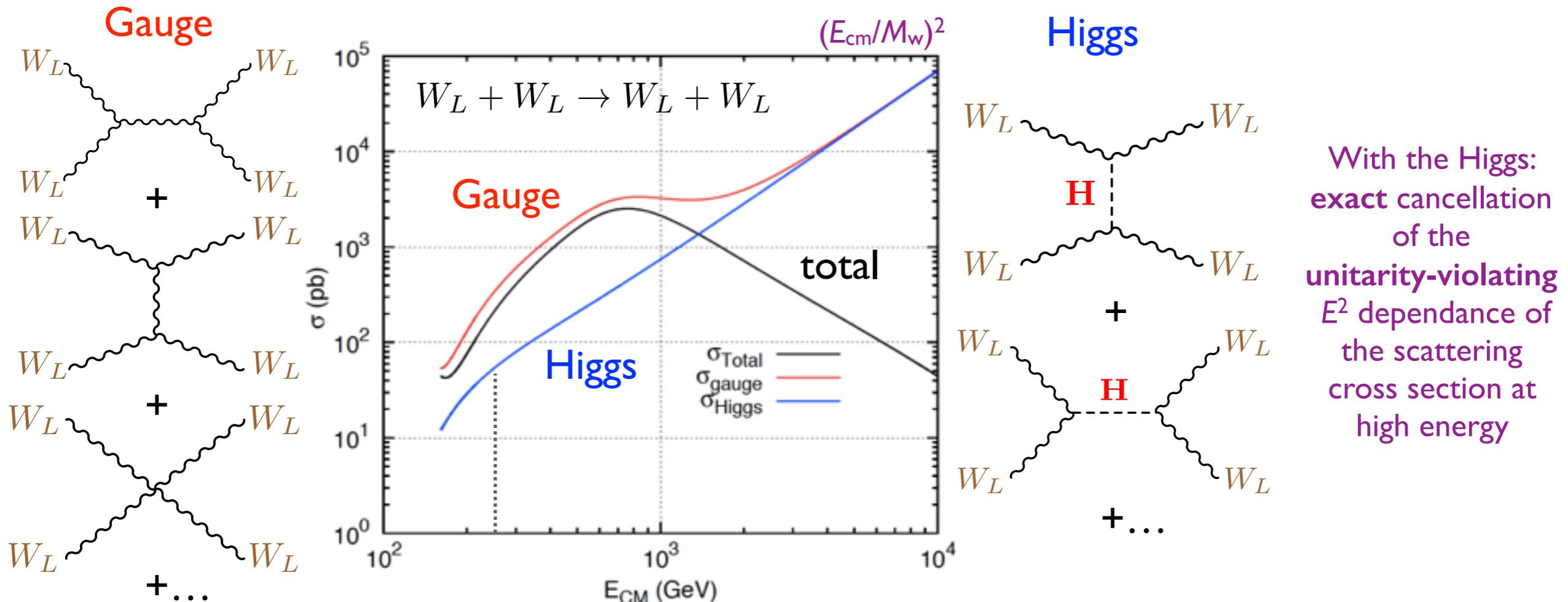


Rare decays

- absolute measurements
- ratio to known decay in fiducial region
- reduced systematic uncertainties at high p_T
- ➡ percent-level coupling measurements

Unitarity and the Higgs Boson

- In the SM, the Higgs boson “unitarises” the longitudinal W scattering amplitudes



Elucidation of the EWSB sector

- probe SM in regime where the EW symmetry is restored ($\sqrt{s} \gg v=246$ GeV) by studying longitudinal gauge boson scattering in the 1-5 TeV energy range

Crucial closure test of the SM

- either the Higgs regularises the theory fully
- or New Physics shows up at the TeV scale
 - anomalous TGCs and QGCs
 - new Higgs or gauge particles

FCC-hh: Selected Measurements

Scattering of longitudinal vector bosons (VBS)

- sensitive to the relation between gauge couplings and the VVH coupling
- large QCD and EWK backgrounds
- two jets at large backward and forward rapidities
- azimuthal correlations between the two leptons

A precise measurement necessitates
leptons down to $|\eta| = 4$ and
jets down to $|\eta| = 6$
in conditions of 1000 pile-up events!

Extraction y_{top} from $\sigma(\text{ttH}) / \sigma(\text{ttZ})$

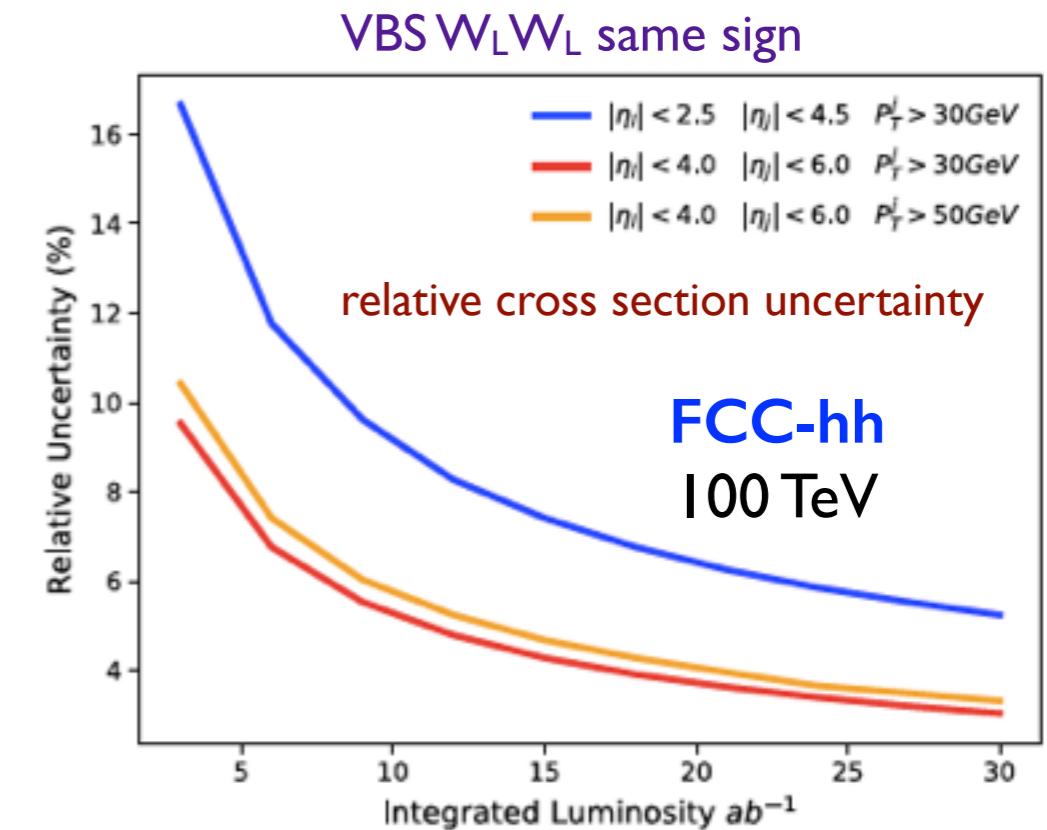
- most systematics cancel in the ratio

Use all possible combinations of final states

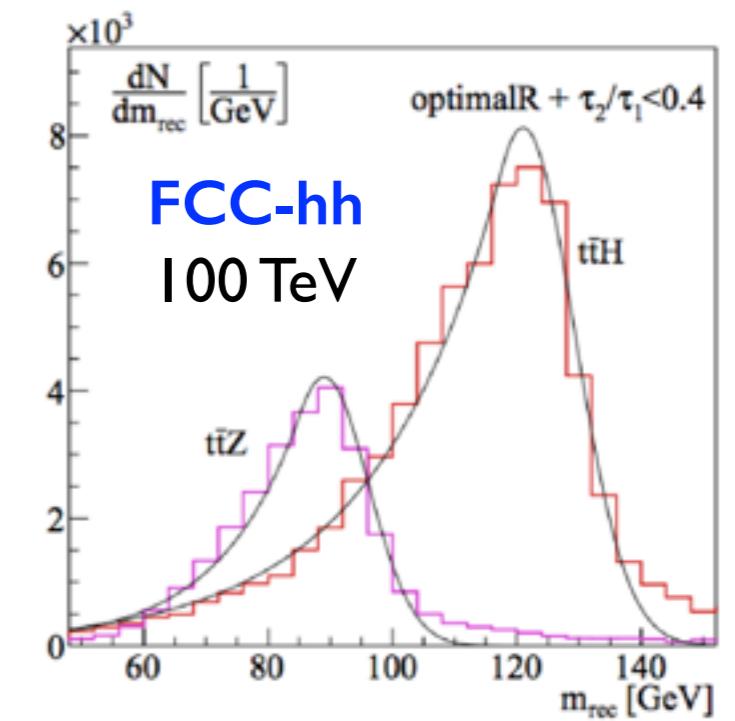
- exclusive and boosted Higgs and Z decays
- semileptonic and boosted hadronic top

Measurement of the N_H/N_Z ratio at the 1% level

$$\delta y_{\text{top}}/y_{\text{top}} \sim 1\% \text{ (stat+syst)}$$



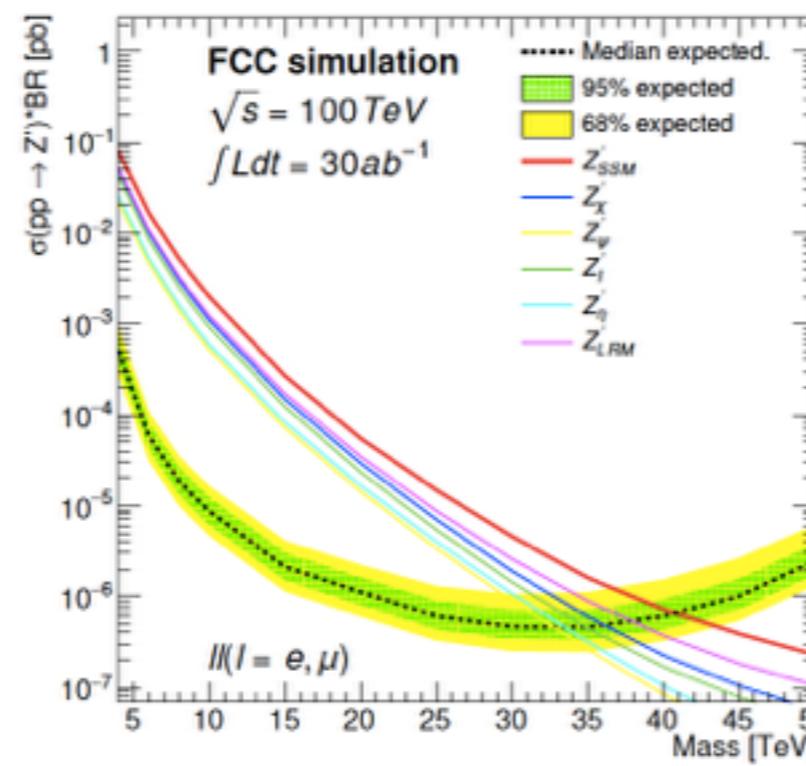
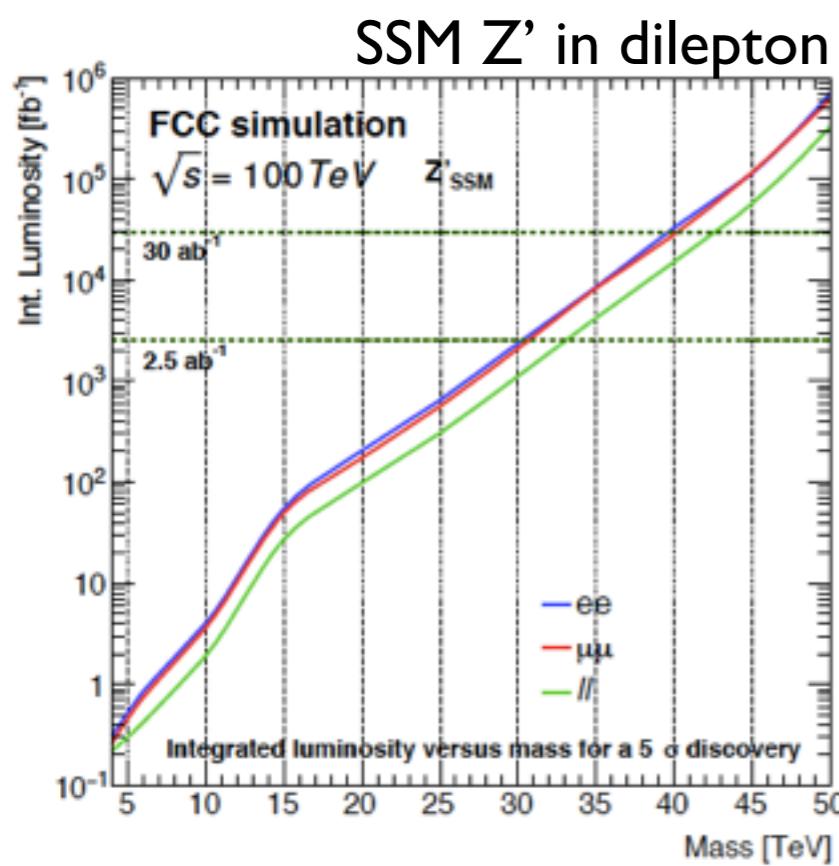
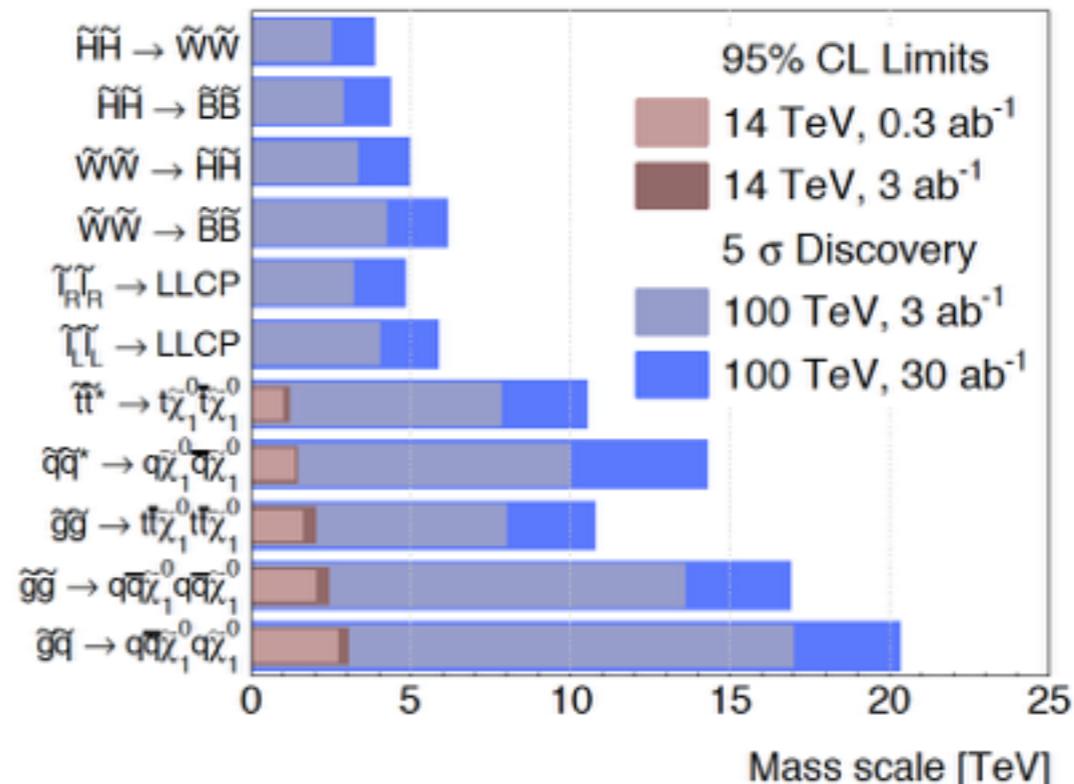
use Higgs
properties (Γ_H)
from e^+e^-



FCC-hh: Exploration Potential

→ Mass reach enhanced by factor 5-7 depending on luminosity

→ Sensitivity to rare processes enhanced by several orders of magnitude



→ FCC-hh can push the limit on fine-tuning to 10^{-4}

→ FCC-hh has the potential to discover new resonances in the $\mathcal{O}(10 \text{ TeV})$ range

Tentative Scenarios

- In the following we present a few selected scenarios
- Schedules are taken as advertised by the projects
 - some estimates may be more trustable than others
- Some level of common sense is unforced
 - avoid several major running machines in the same lab
 - avoid several 100-km class tunnels in the World
- Scenarios are evaluated on the basis of 7 physics criteria evaluated at date 20XX

Circa 20XX		
• Direct NP	New physics reach potential	★★★★★
• flavour, top	Potential in flavour and top physics	★★★★★
• Higgs	Sensitivity on Higgs boson couplings	★★★★★
• ttH, HH	Sensitivity on top Yukawa and Higgs self couplings	★★★★★
• EWK@TeV	Sensitivity on vector boson scattering at TeV scale	★★★★★
• EWK Fit	Sensitivity on electroweak precision observables	★★★★★
• EWK Vacuum	Sensitivity on top quark mass and Higgs boson mass	★★★★★

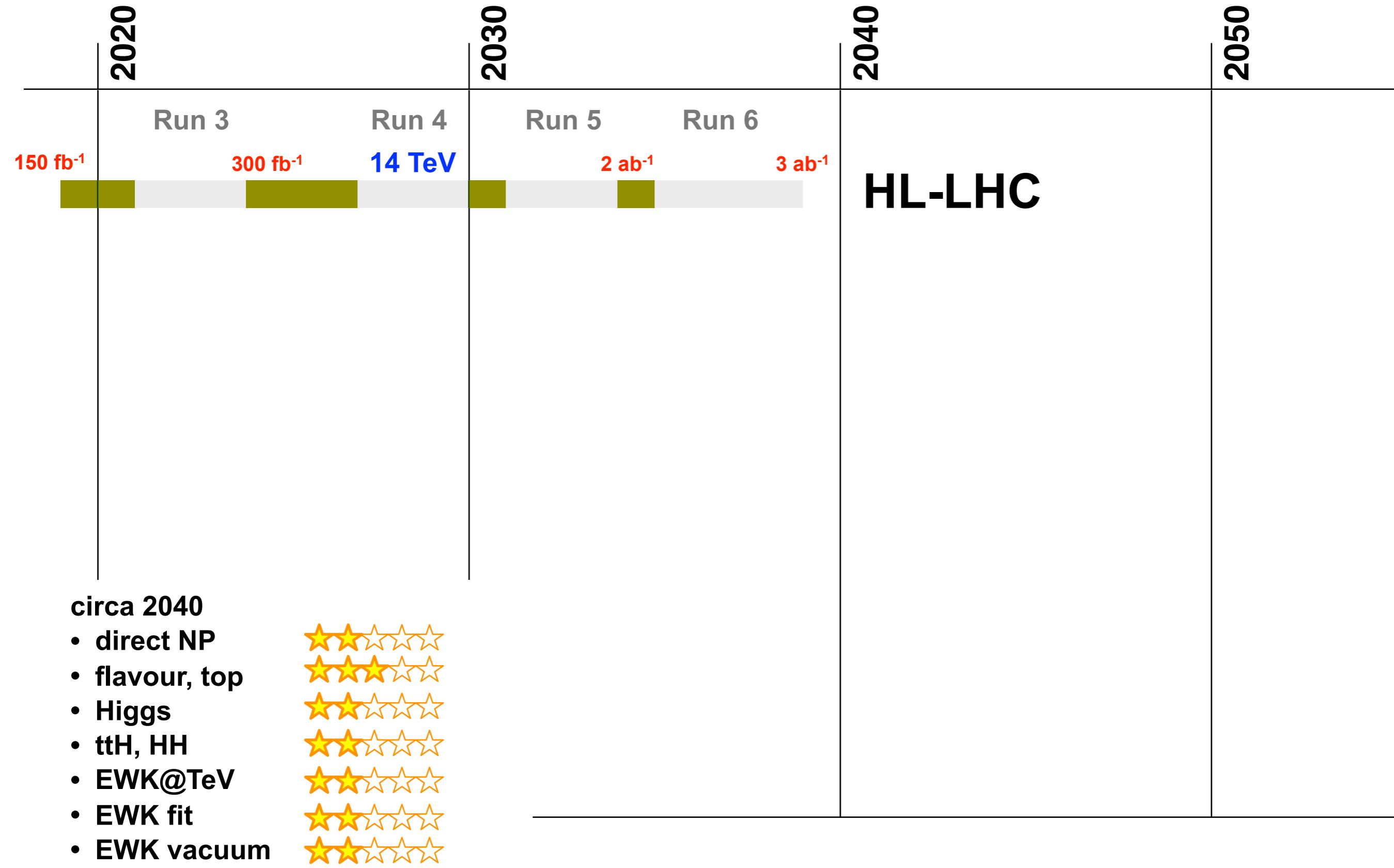
Ce sont les millions dépensés dans l'étude préalable démontrant que ce projet est foireux qui nous contraint à le poursuivre.



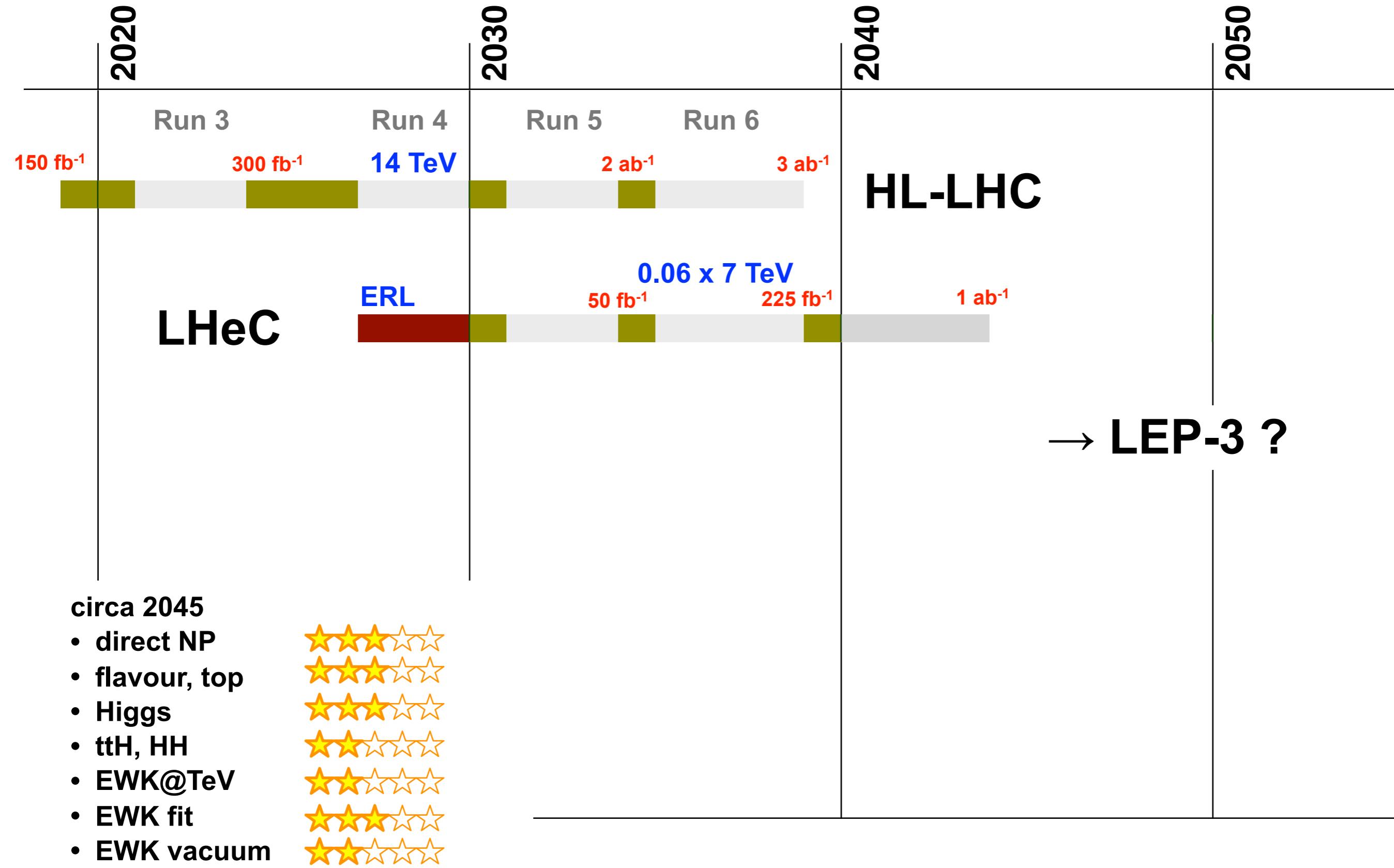
the scores are arbitrary, they are just meant as input to the afternoon discussion

- Let's first focus on CERN only scenarios...

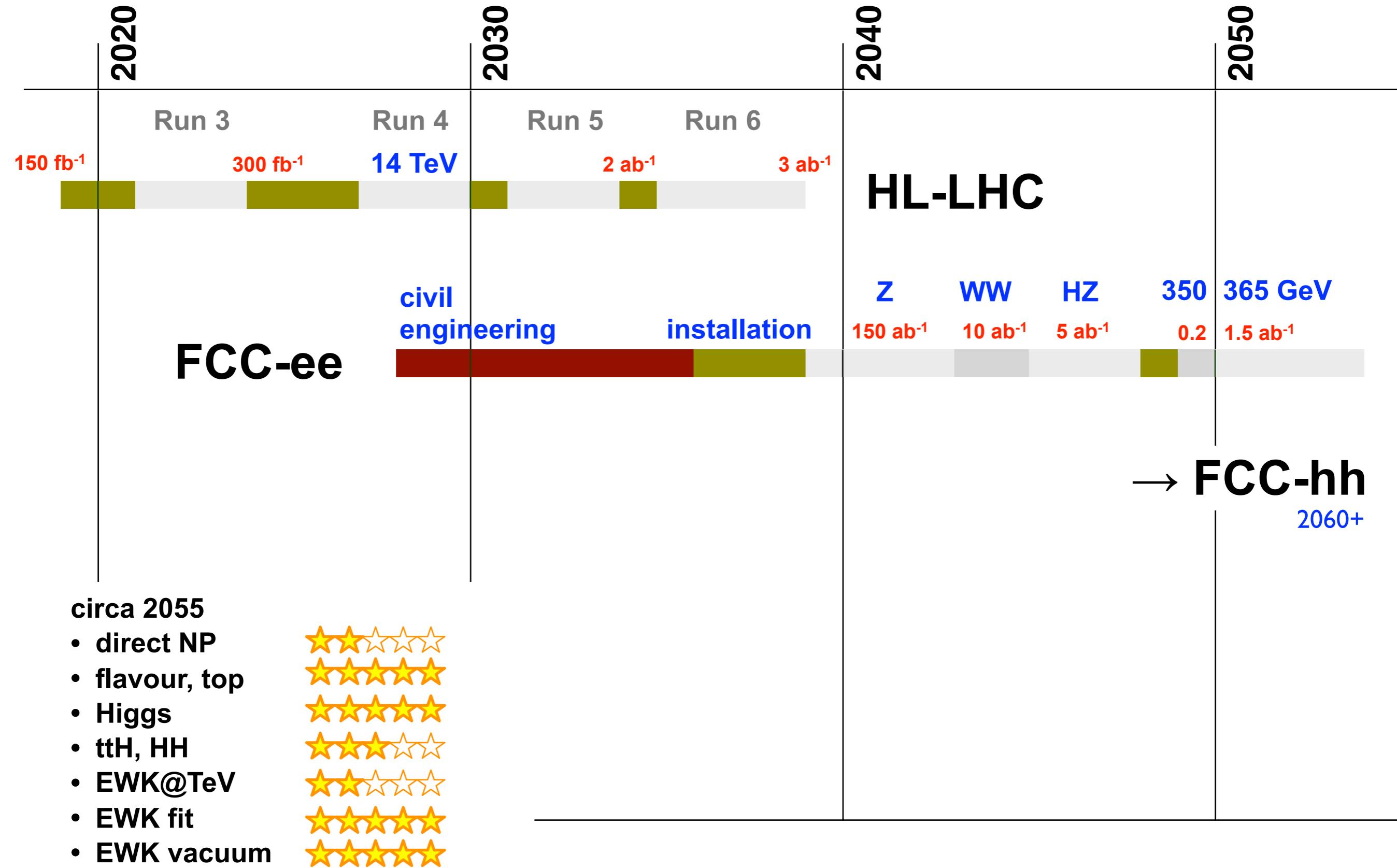
HL-LHC



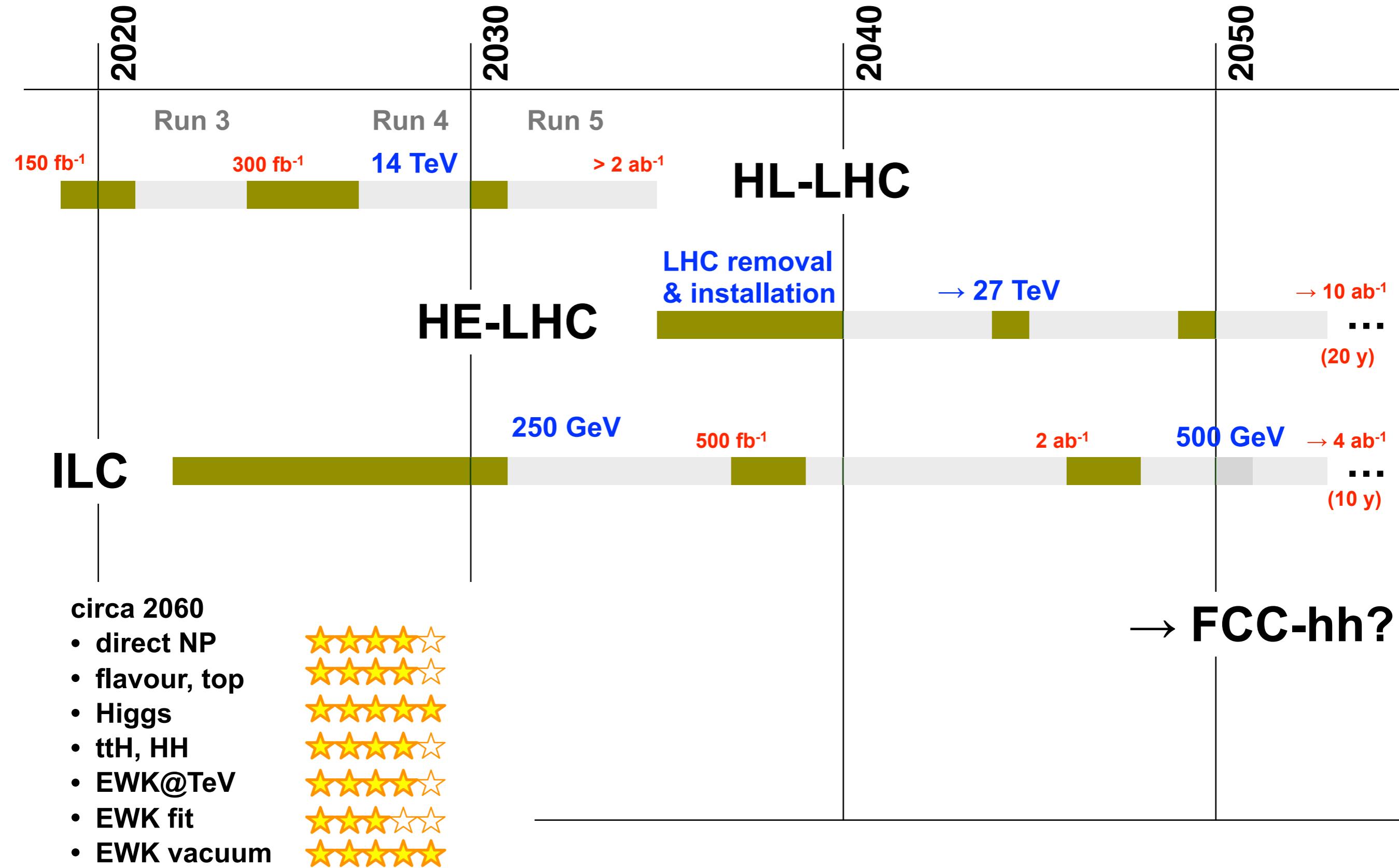
HL-LHC+LHeC



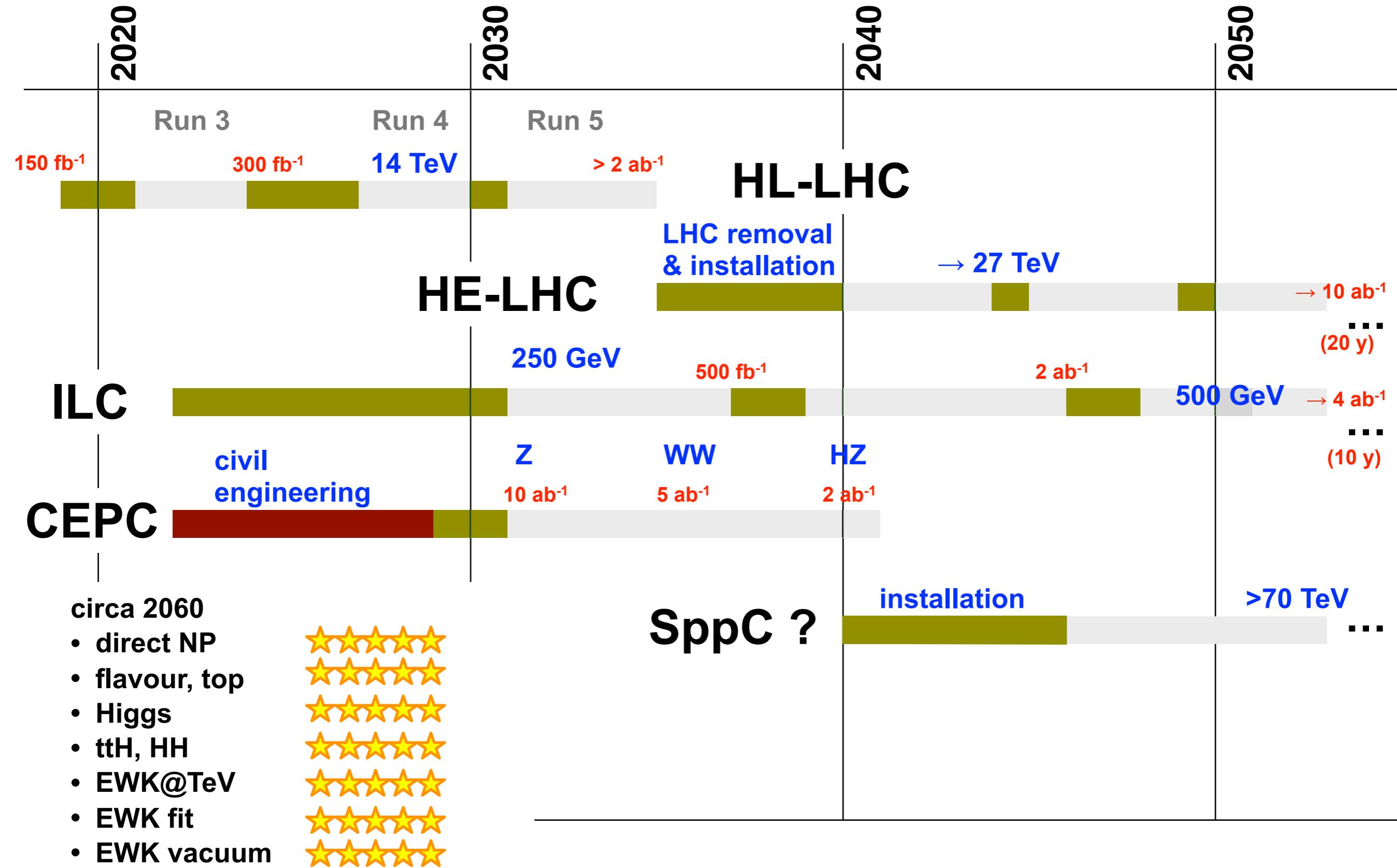
HL-LHC+FCC-ee



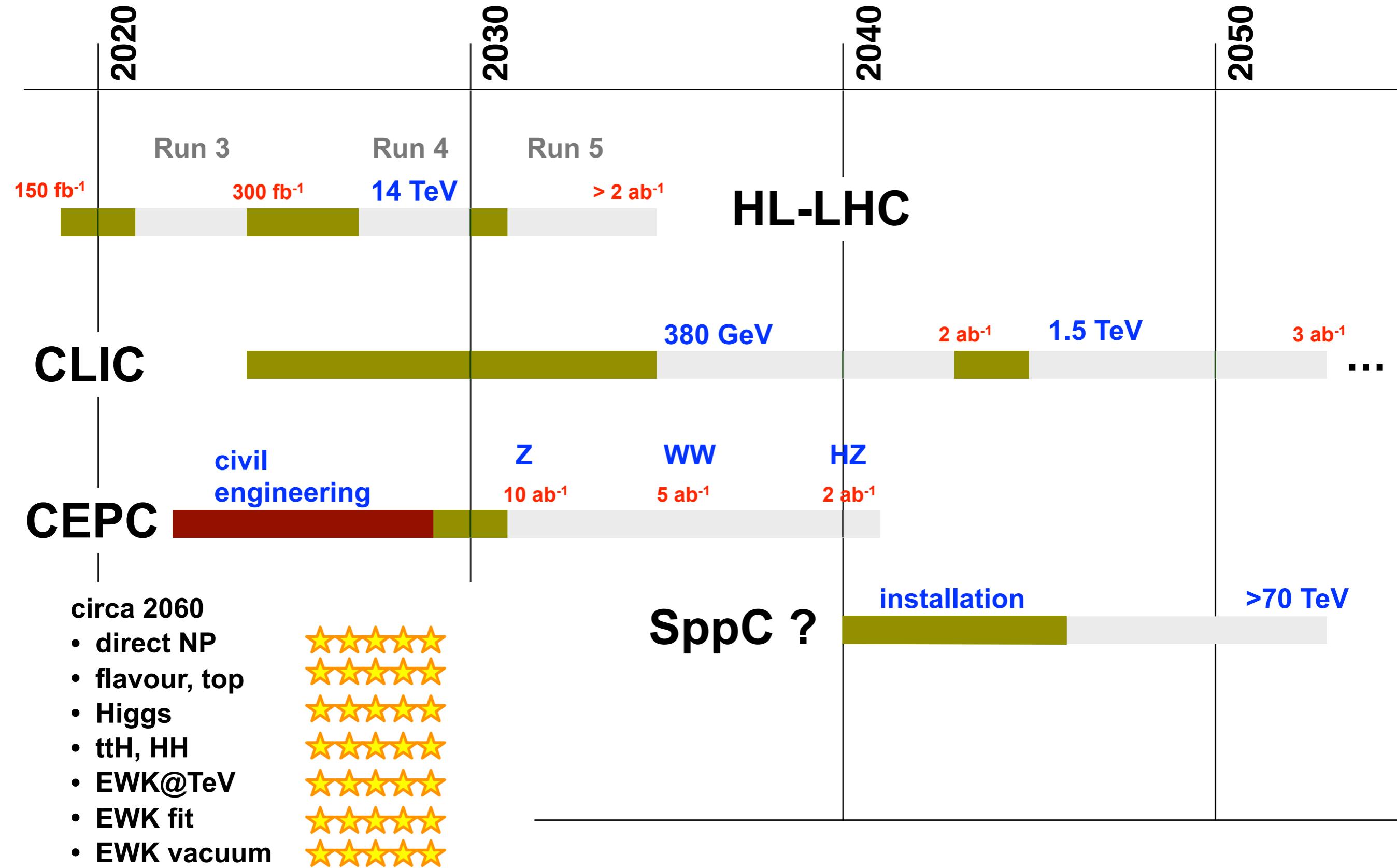
HL-LHC+HE-LHC+ILC



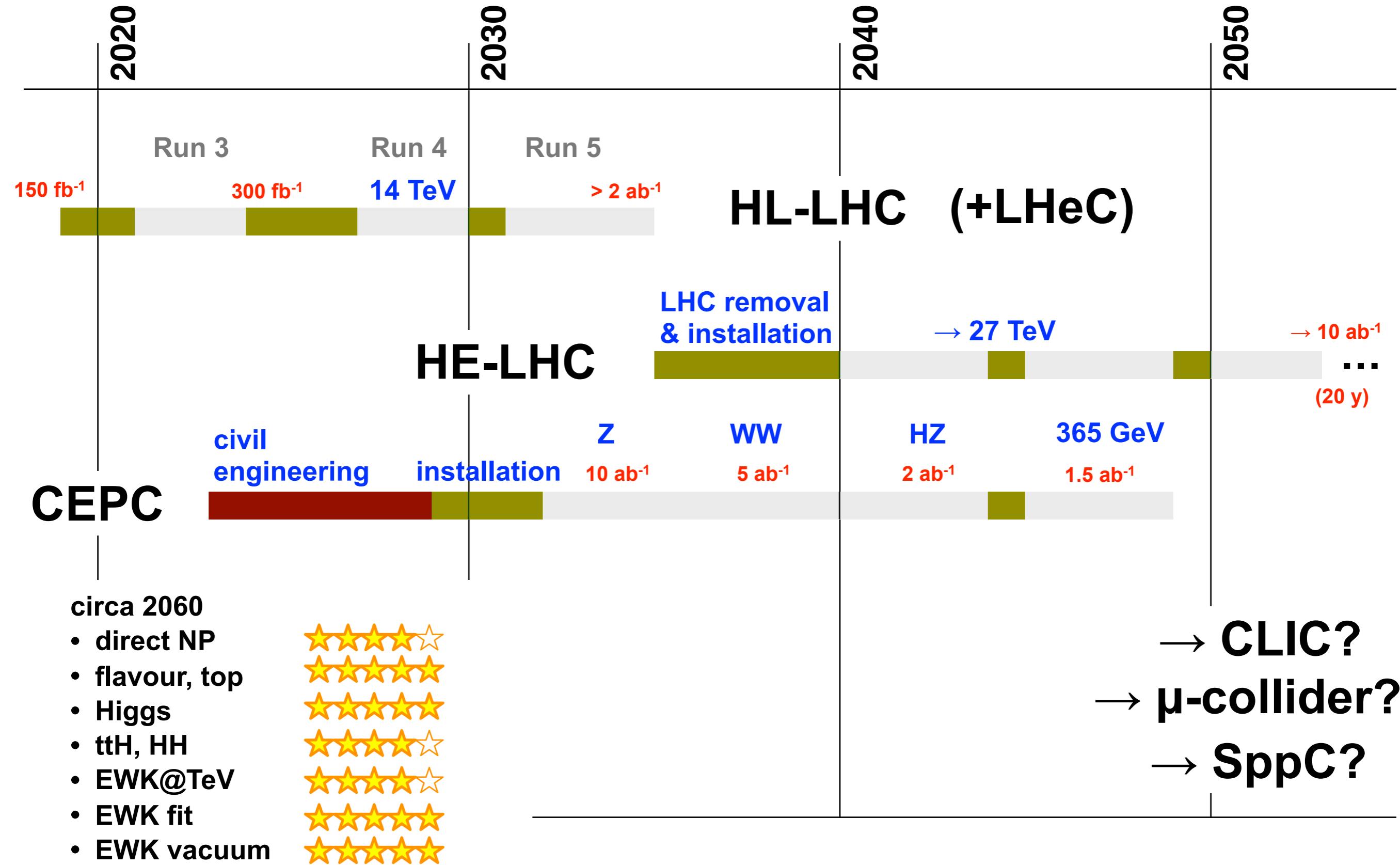
HL-LHC+HE-LHC+ILC+CEPC



HL-LHC+CLIC+CEPC+SppC



HL-LHC+HE-LHC+CEPC



En guise de conclusion

A few *personal* comments, as input for the discussion

Electron-positron collider

Following the results of the LHC, which indicate that the discovered Higgs boson is SM-like and that BSM spectroscopy is either not kinematically reachable at present LHC energies or weakly coupled to the SM sector, an electron-positron collider is imperative to perform precision (sub-percent level) Higgs coupling measurements.

Linear versus circular electron-positron collider

The case for a linear collider relies on polarisation and extendability at higher energies. The case for a circular collider relies on high luminosity in the energy range from the Z peak to the top pair production threshold.

The anticipated precisions on Higgs coupling measurements are similar.

Proton-proton colliders beyond the LHC

Going beyond 14 TeV in proton-proton collision is mandatory to extend the direct new physics reach, to elucidate the EWSB sector at the TeV scale, and to perform precision measurements of the Higgs self-coupling and the top Yukawa coupling.

Electron-Proton collider

In addition to a solid physics case, an electron-proton collider exploiting 7-TeV protons from the LHC can empower the physics output of present and future proton-proton colliders.

Selected References

CERN

- Machine parameters and project luminosity performance of proposed future colliders at CERN, [CERN/SPC/1114](#)

FCC

- Future Circular Collider Study, Volume I — Physics Opportunities — Conceptual Design Report, *in preparation*
- Physics at a 100 TeV pp collider: beyond the Standard Model phenomena, [arxiv:1606.00947](#)
- Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies, [arxiv:1606.09408](#)
- Physics at a 100 TeV pp collider: Standard Model processes, [arxiv:1607.01831](#)

LHeC

- A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector, [arxiv:1206.2913](#)

CLIC

- Updated baseline for a staged Compact Linear Collider, [arxiv:1608.07537](#)

ILC

- The International Linear Collider Technical Design Report - Volume I: Executive Summary, [arxiv:1306.6327](#)
- Physics Case for the 250 GeV Stage of the International Linear Collider, [arxiv:1710.07621](#)

CEPC

- Conceptual Design Report, Volume 2 — Physics and Detector, [IHEP-CEPC-DR-2018-02](#)

Un grand merci

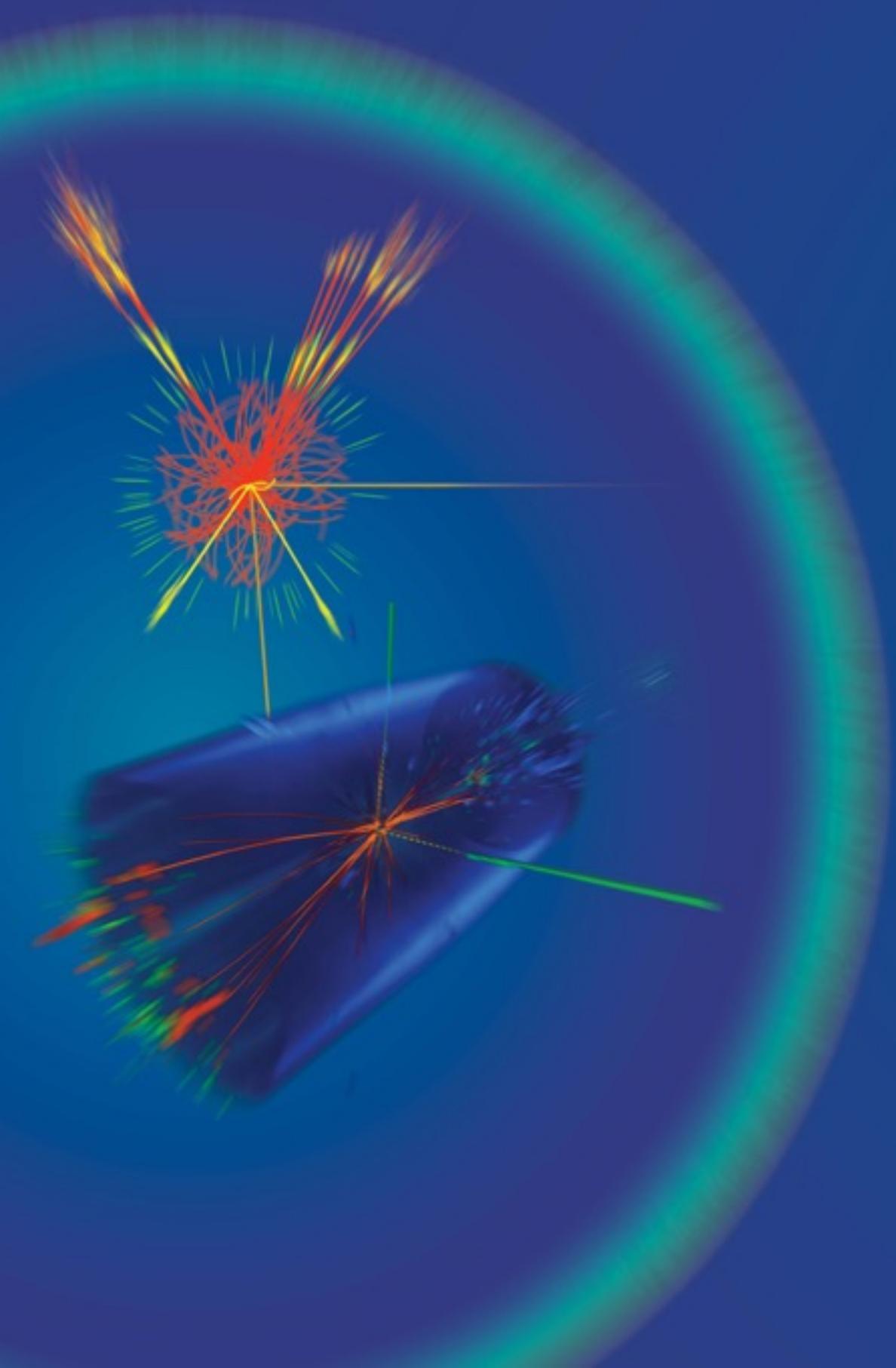
à la Société française de physique
aux organisateurs de la journée

à tous les participants

à Roman Pöschl

à Maarten Boonekamp

Back-up



LEP-I and SLD

e^+e^- colliders $\sqrt{s} = 91$ GeV

LEP-I at CERN

- 1989-1992
- circular
- ALEPH, DELPHI, L3, OPAL
- 20 million Z's



27 km \varnothing

1.2 mile long



SLC at SLAC

- 1989-1998
- linear
- e^- beam polarisation
- SLD
- 550,000 Z's

A fantastic legacy!

$$M_Z = 91187.5 \pm 2.1 \text{ MeV}$$

$$\Gamma_Z = 2495.2 \pm 2.3 \text{ MeV}$$

$$\sin^2\theta_{\text{eff}} = 0.23153 \pm 0.00016$$

$$\alpha_s = 0.1190 \pm 0.0025$$

$$N_v = 2.9840 \pm 0.0082$$

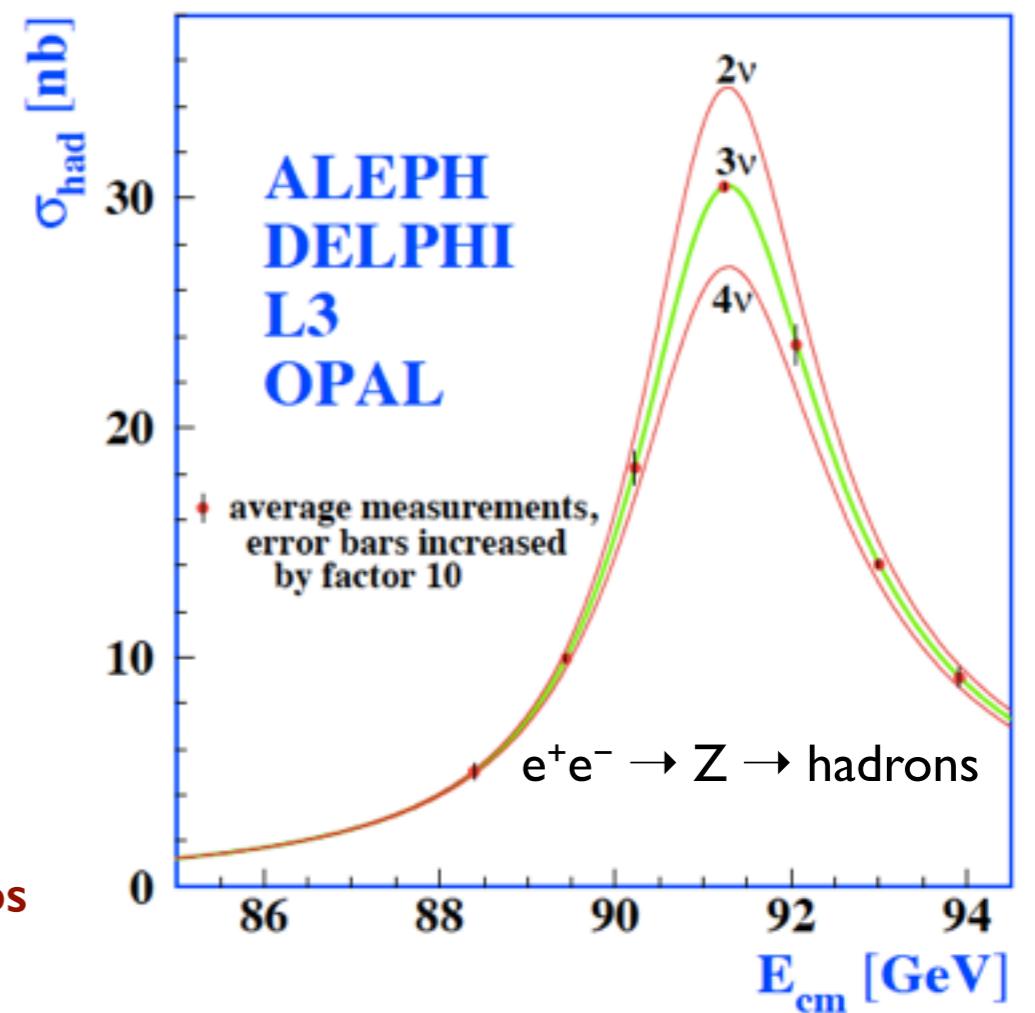
from Z line shape

from LR and FB asymmetries
(tension "leptons" vs "quarks")

from multi-jets

from peak cross -section
and ratio of partial widths
(2σ deficit)

Only three species of active, light neutrinos

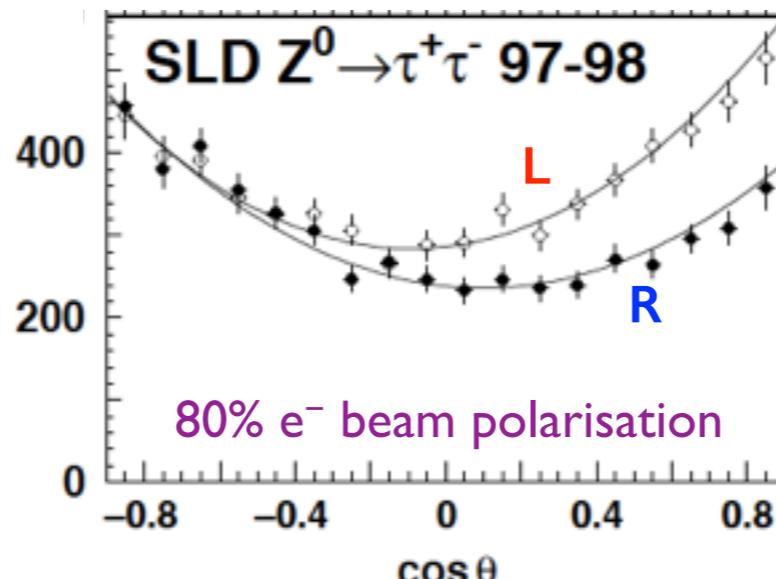
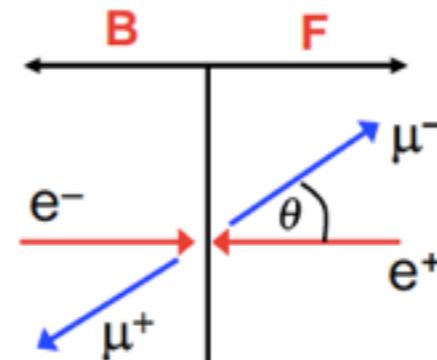


Asymmetries

Left-right (LR)

$$\mathcal{A}_f = \frac{L_f - R_f}{L_f + R_f} = 2 \frac{g_{Vf}/g_{Af}}{1 + (g_{Vf}/g_{Af})^2}$$

- small for leptons (15%)
- large for b quarks (93%)
- sensitive to $\sin^2\theta_{\text{eff}}$



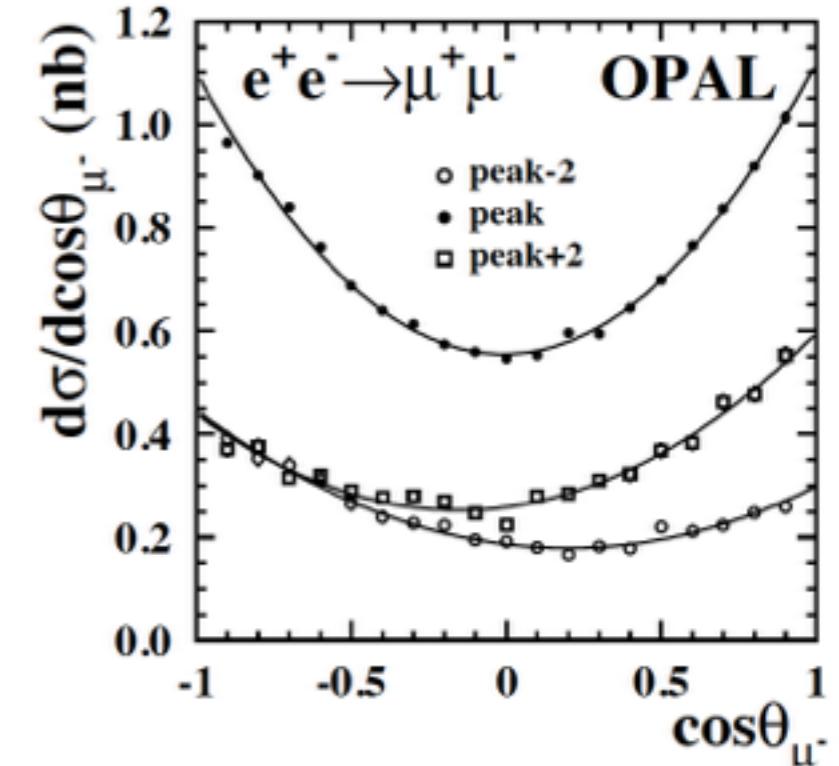
Forward-backward (FB)

$$\frac{d\sigma}{d\cos\theta} \propto 1 + \cos^2\theta + \frac{3}{8} A_{\text{FB}} \cos\theta$$

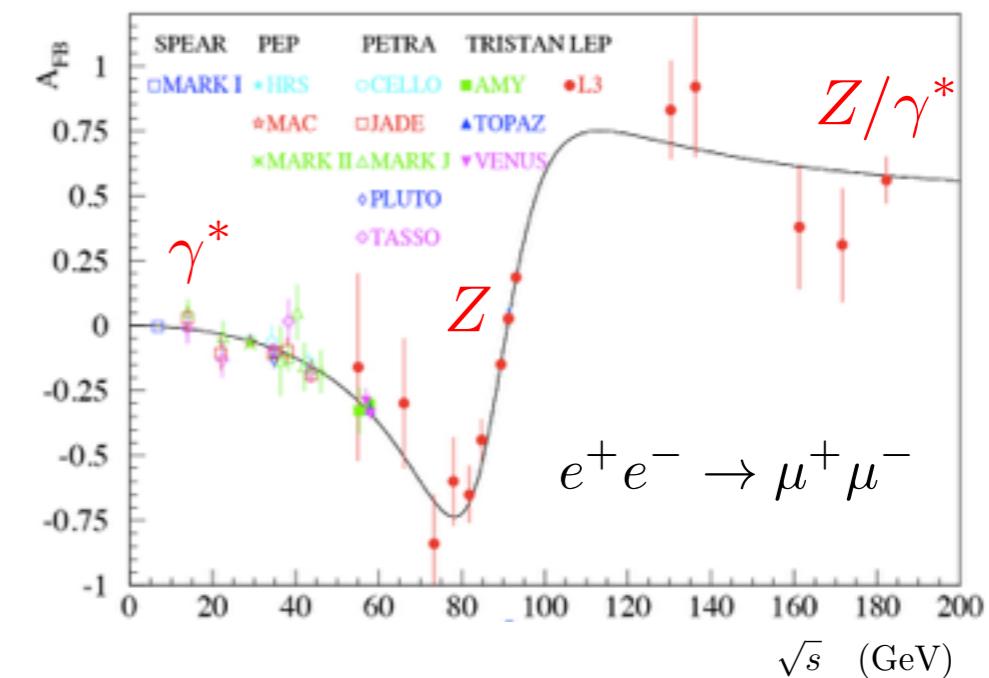
at the Z pole:

$$A_{\text{FB}}^{0f} = \frac{3}{4} \mathcal{A}_e \mathcal{A}_f$$

- **SLD**
 \mathcal{A}_e from LR Z cross-section
 \mathcal{A}_e , \mathcal{A}_μ and \mathcal{A}_τ
- **LEP**
 \mathcal{A}_e and \mathcal{A}_τ from τ polarisation
- **LEP (and SLD)**
 A_{FB} for leptons and heavy quarks



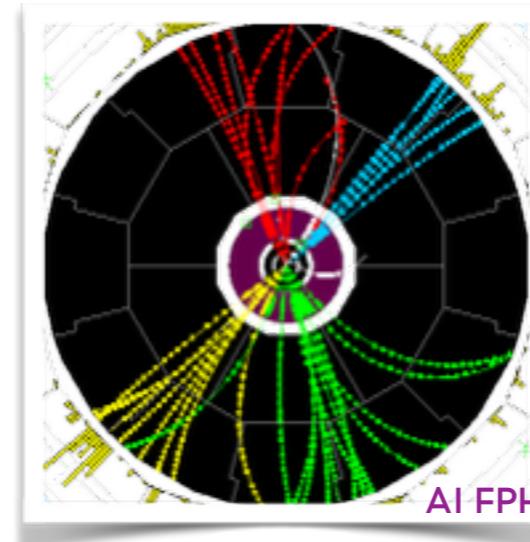
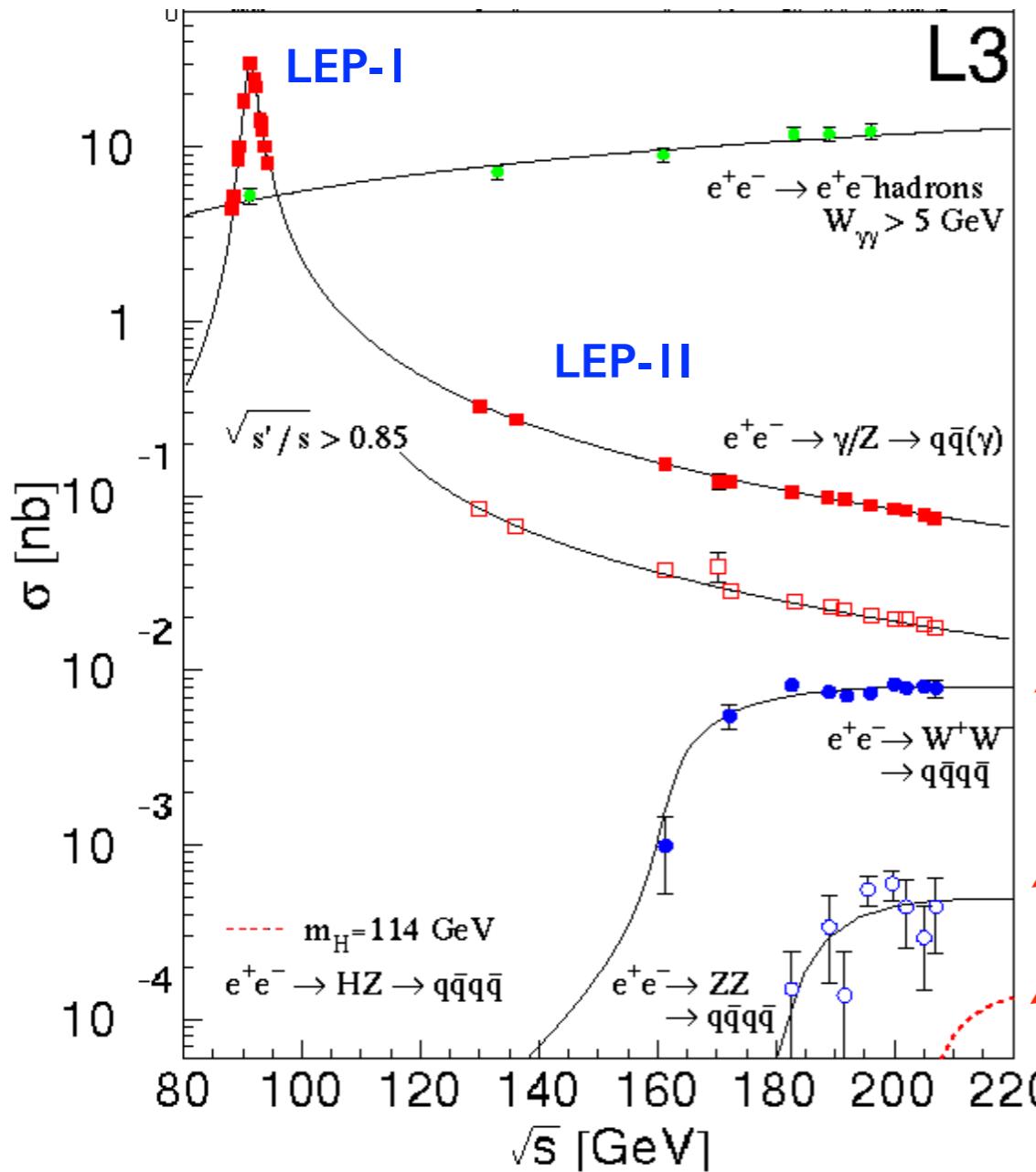
- A_{FB} \sqrt{s} dependance
- sensitivity to α



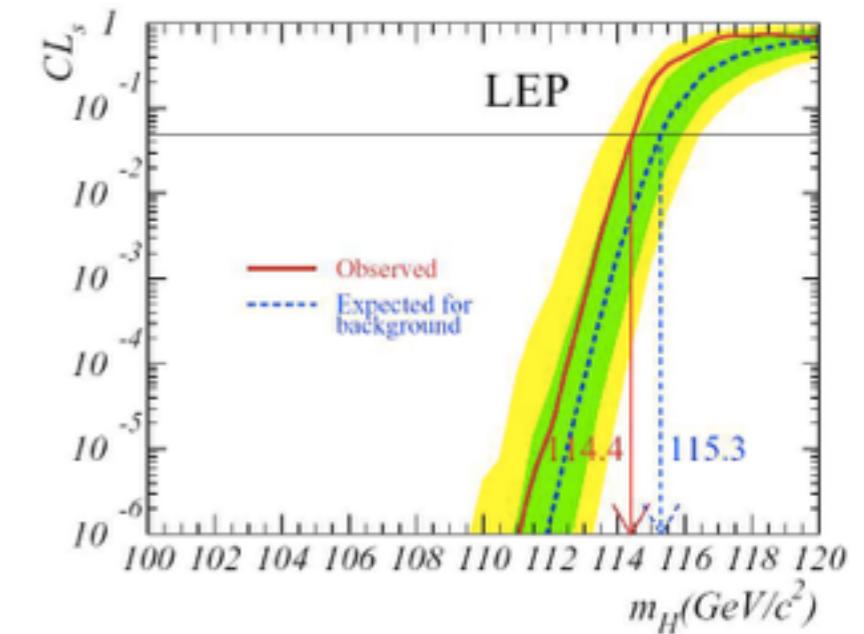
LEP-2 : Chasing Higgs and SUSY

LEP-2 at CERN 1992-2000

$\sqrt{s} = 120$ to 209.2 GeV



- 40,000 W pairs

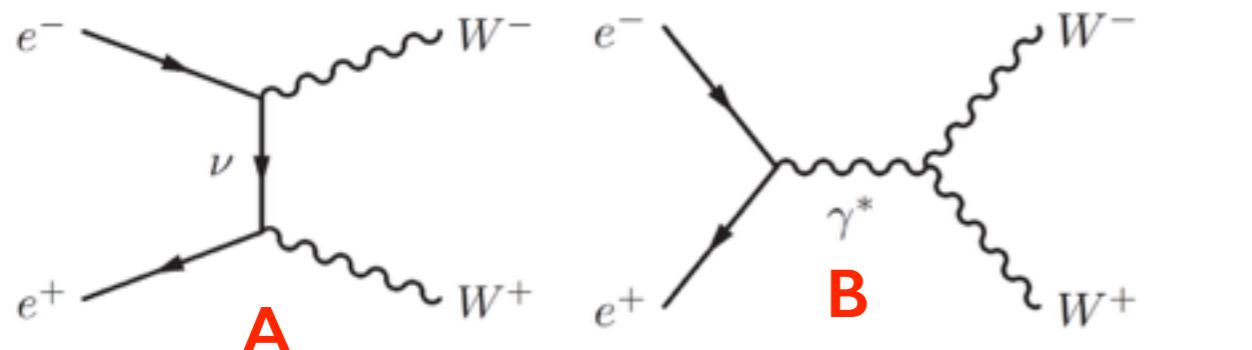


$M_H > 114.4 \text{ GeV} @ 95\% \text{ CL}$

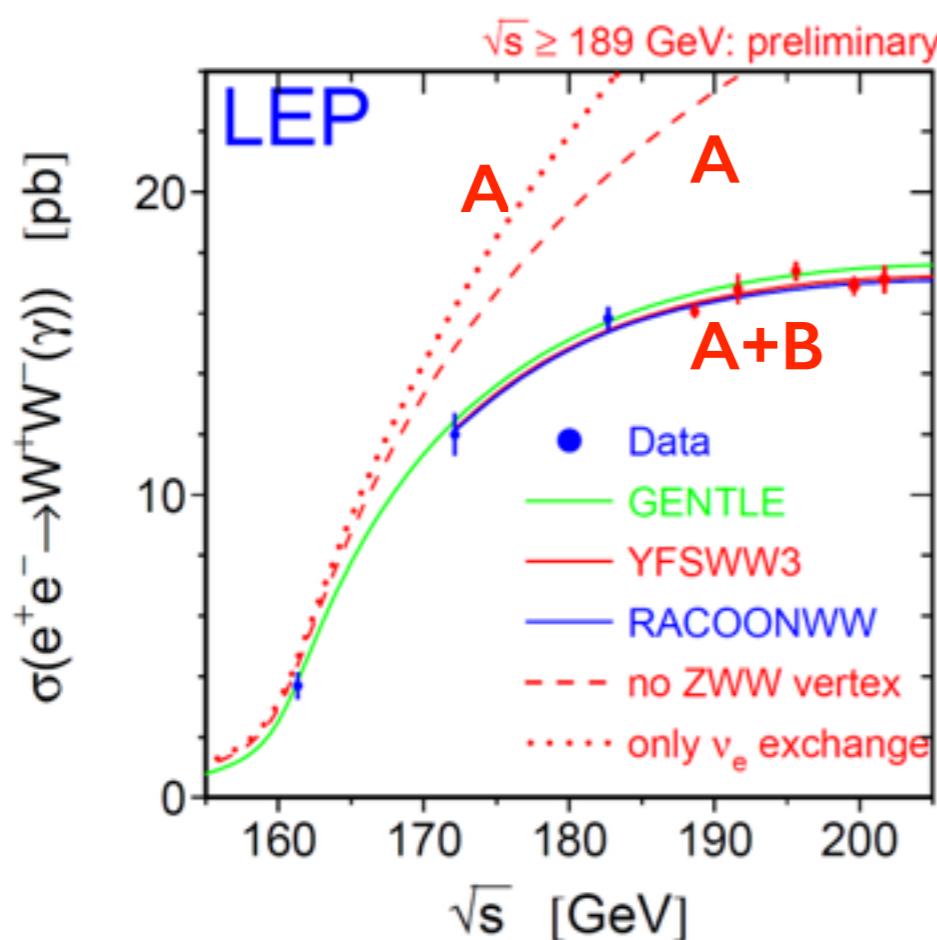
Note: importance of absolute beam energy and luminosity measurements

+ constraints on SUSY and New Physics

LEP-2 : W Boson Physics

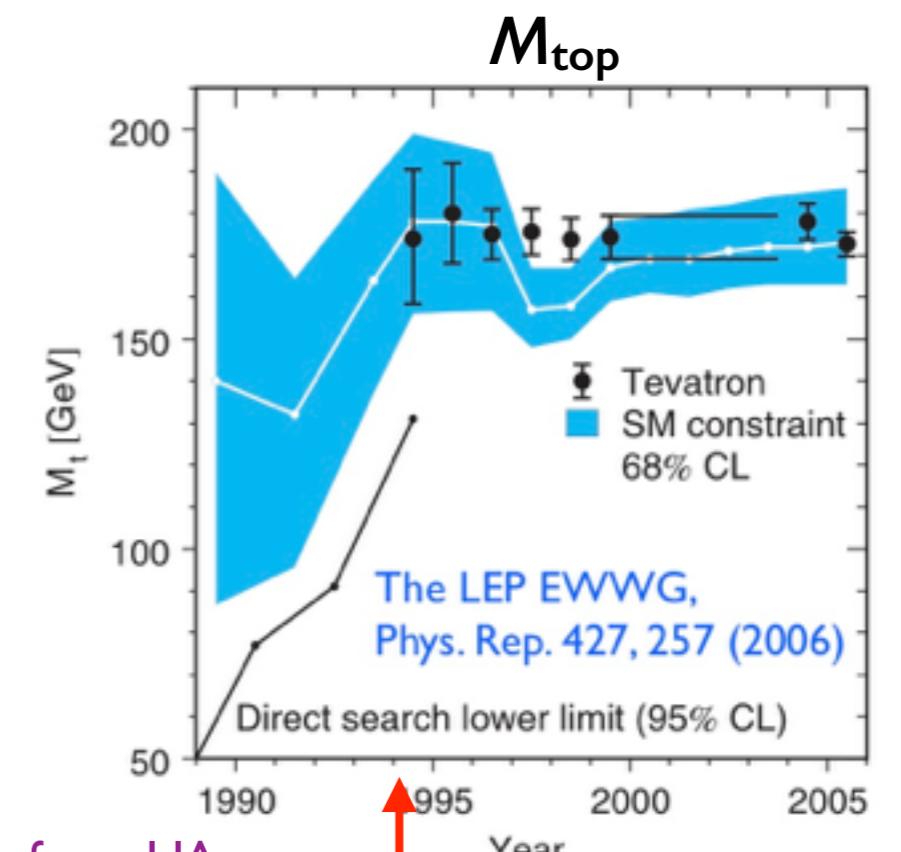


Clear observation of triple gauge couplings



M_W measurements

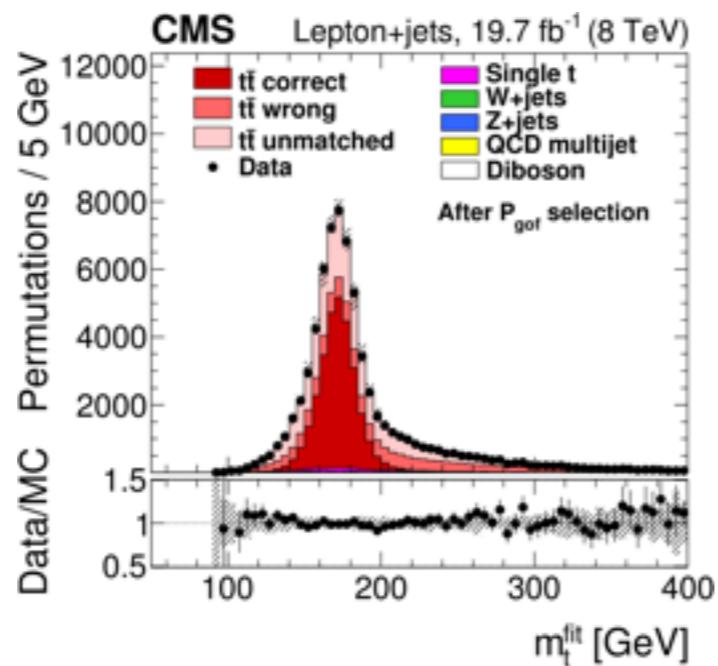
- threshold (11 pb^{-1})
210 MeV ($\pm 200 \text{ (stat)} \pm 70 \text{ (syst)} \text{ MeV}$)
- above threshold
36 MeV ($\pm 30 \text{ (stat)} \pm 20 \text{ (syst)} \text{ MeV}$)



M_W from UA + precision EW from LEP/SLD
top quark discovery (Tevatron)
 M_W from LEP-II

Mass Measurements

M_Z , M_W , M_{top} ,
and M_H
are known with
good precision



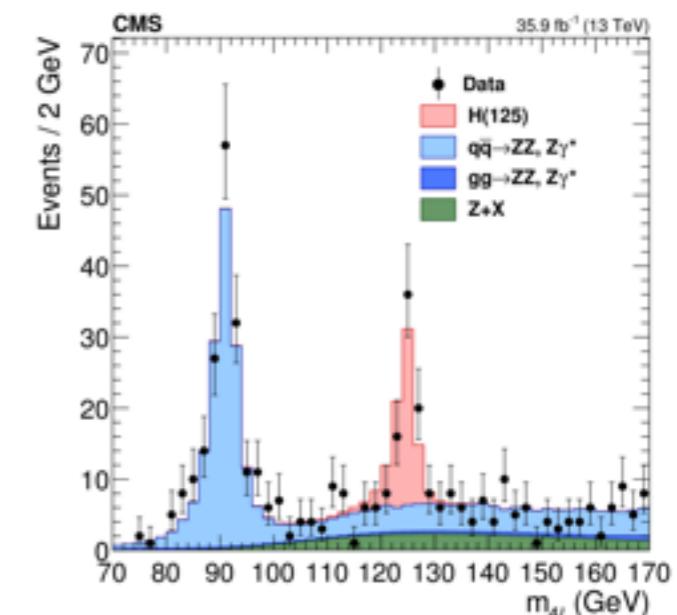
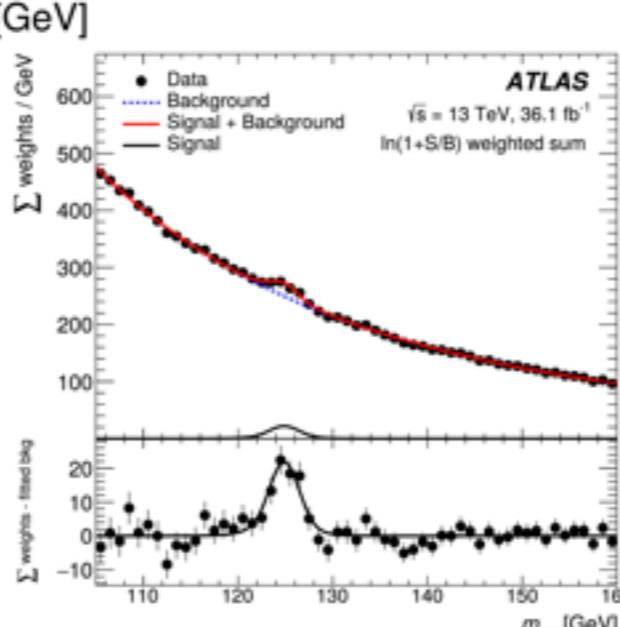
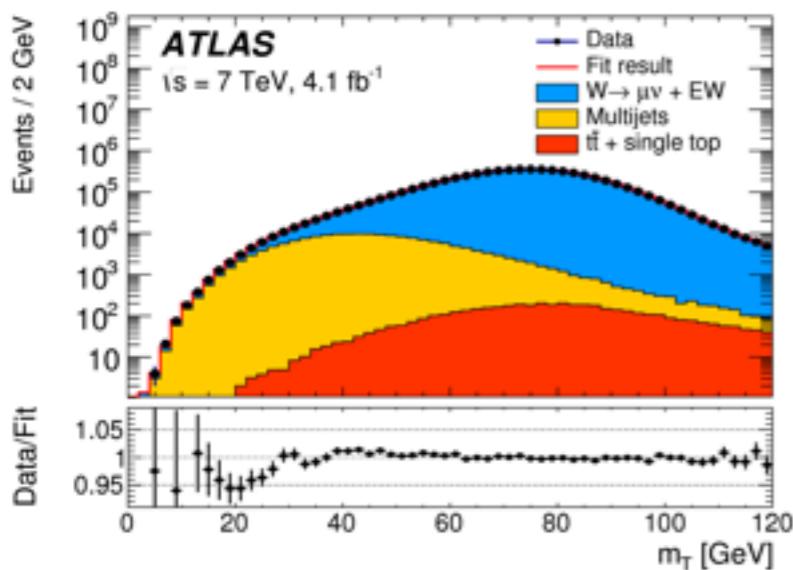
Tevatron (2014)
World (2014)
CMS (2015)
ATLAS (2017)

M_{top} (GeV)

174.34 \pm 0.64 ($\pm 0.37_{\text{stat}} \pm 0.52_{\text{syst}}$)
173.34 \pm 0.76 ($\pm 0.27_{\text{stat}} \pm 0.71_{\text{syst}}$)
172.44 \pm 0.48 ($\pm 0.13_{\text{stat}} \pm 0.47_{\text{syst}}$)
172.51 \pm 0.50 ($\pm 0.27_{\text{stat}} \pm 0.42_{\text{syst}}$)

M_W (MeV)

LEP-II (2006)	$80\ 376 \pm 33$
Tevatron (2012)	$80\ 387 \pm 16$
World (2012)	$80\ 385 \pm 15$
ATLAS (2017)	$80\ 370 \pm 19$

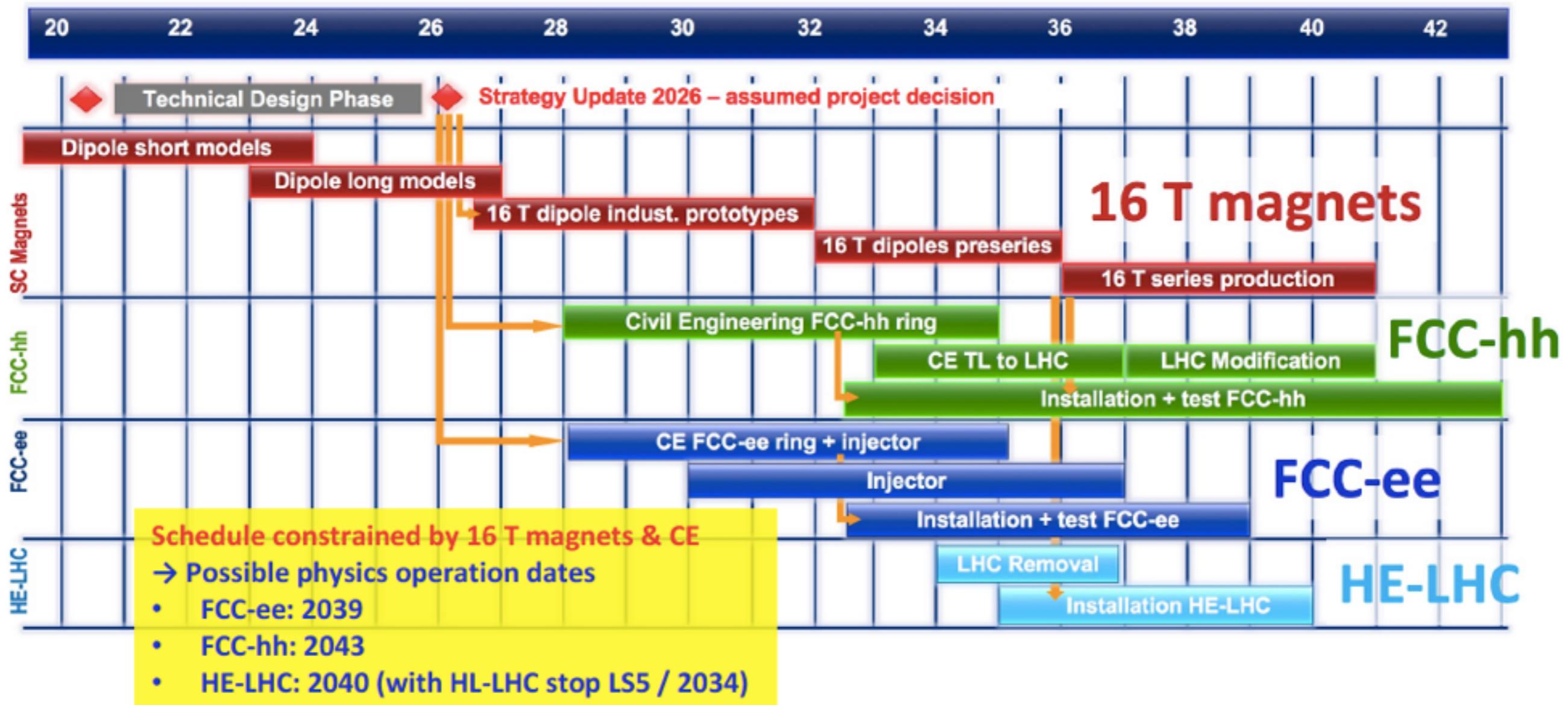


LHC (2015)
CMS (4ℓ) (2017)
ATLAS ($4\ell+2\gamma$) (2017)

M_H (GeV)

125.09 \pm 0.24 ($\pm 0.21_{\text{stat}} \pm 0.11_{\text{syst}}$)
$125.26 \pm 0.21 (\pm 0.20_{\text{stat}} \pm 0.08_{\text{syst}})$
$124.97 \pm 0.24 (\pm 0.16_{\text{stat}} \pm 0.17_{\text{syst}})$

FCC Technical Schedules



Colliding Muons?

Muon collider to extend lepton collisions to the multi-TeV range

- almost no synchrotron radiation nor beamstrahlung
- needs intense source of cold muons, followed by fast acceleration
- issues with radiation safety and backgrounds from muon decays
- neutrino induced hazard (!)

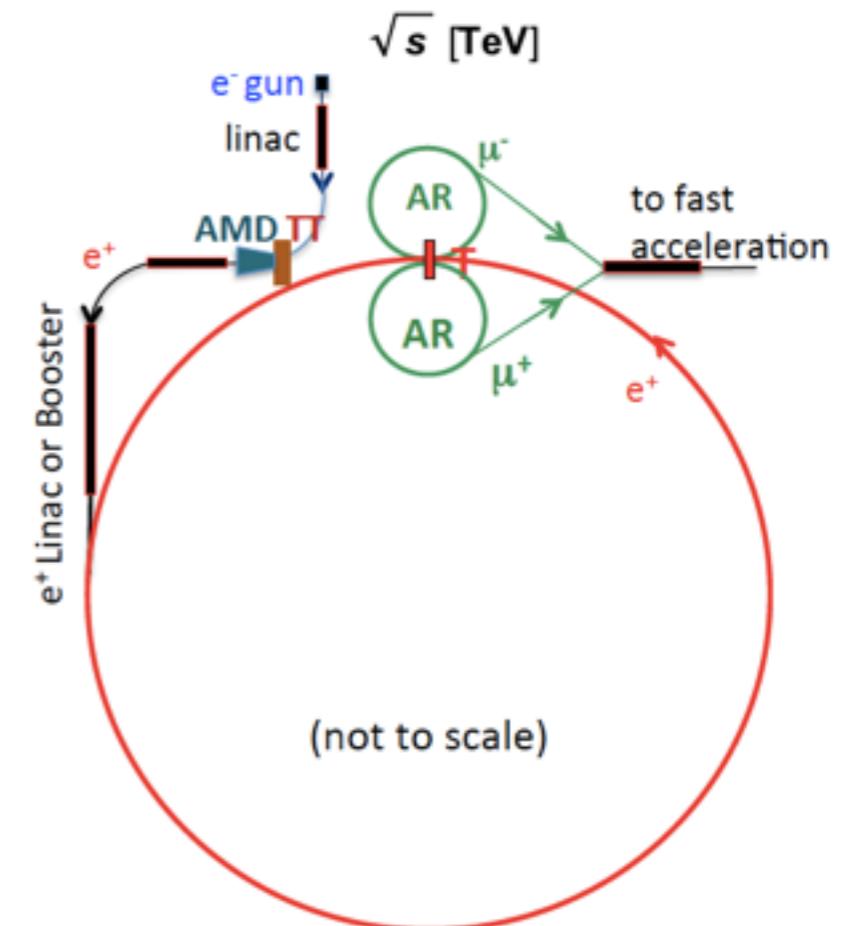
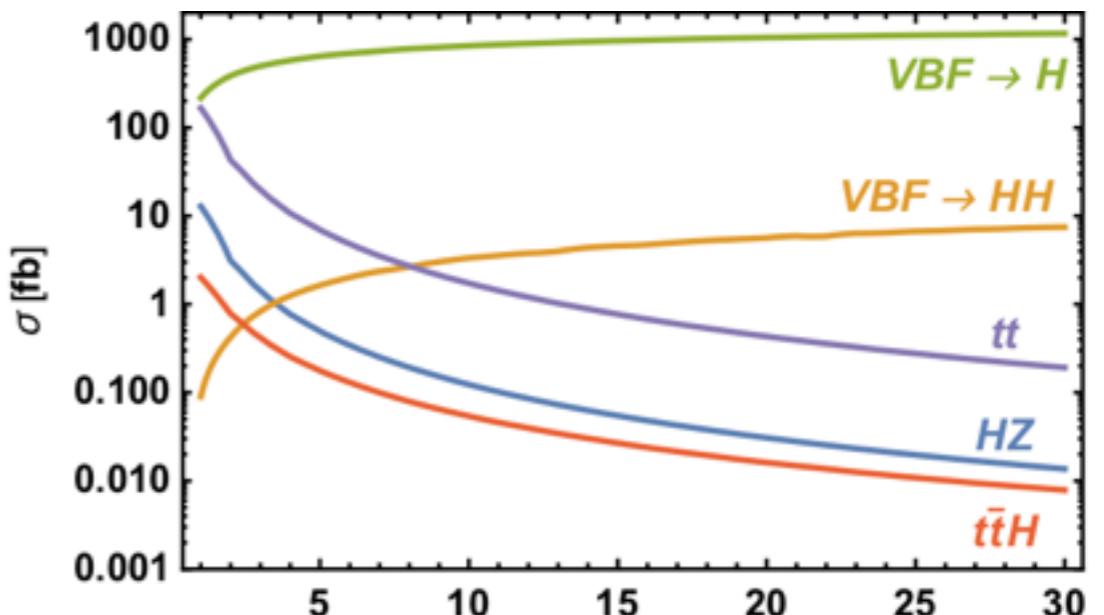
MAP (US)

JP. Delahaye et al, arXiv:1502.01647

- proton based production, μ as tertiary particles
- large μ production cross section (mb)
- cooling necessary

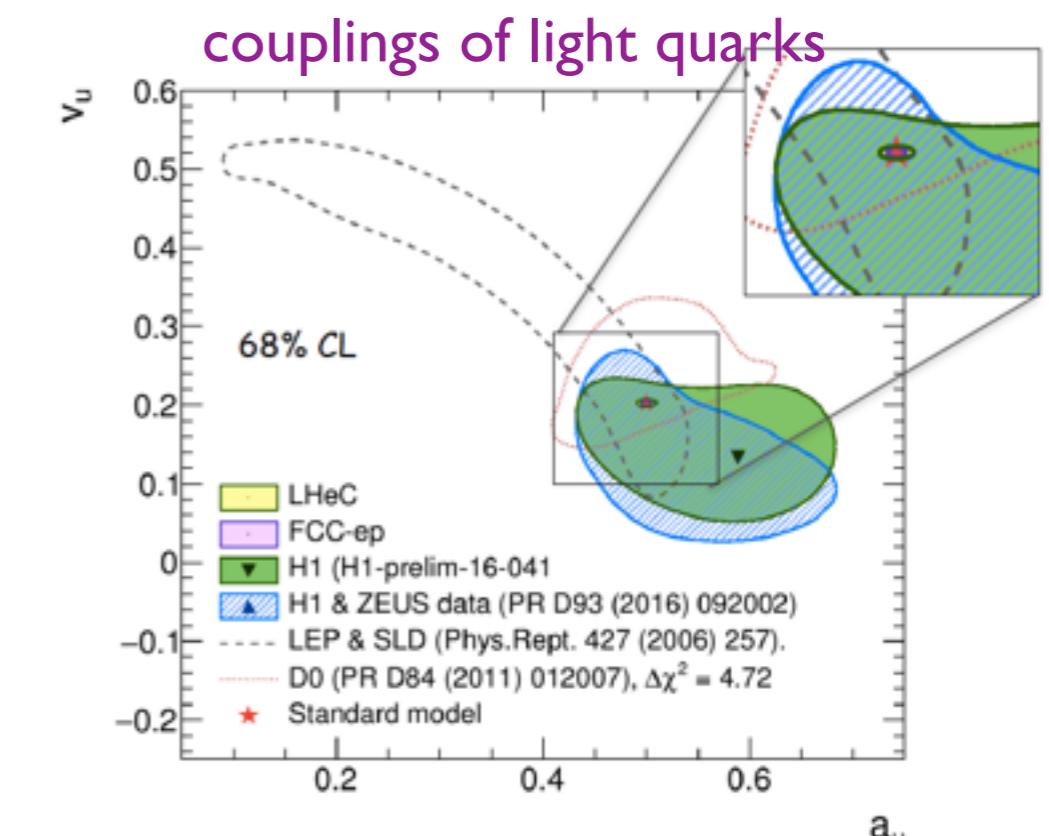
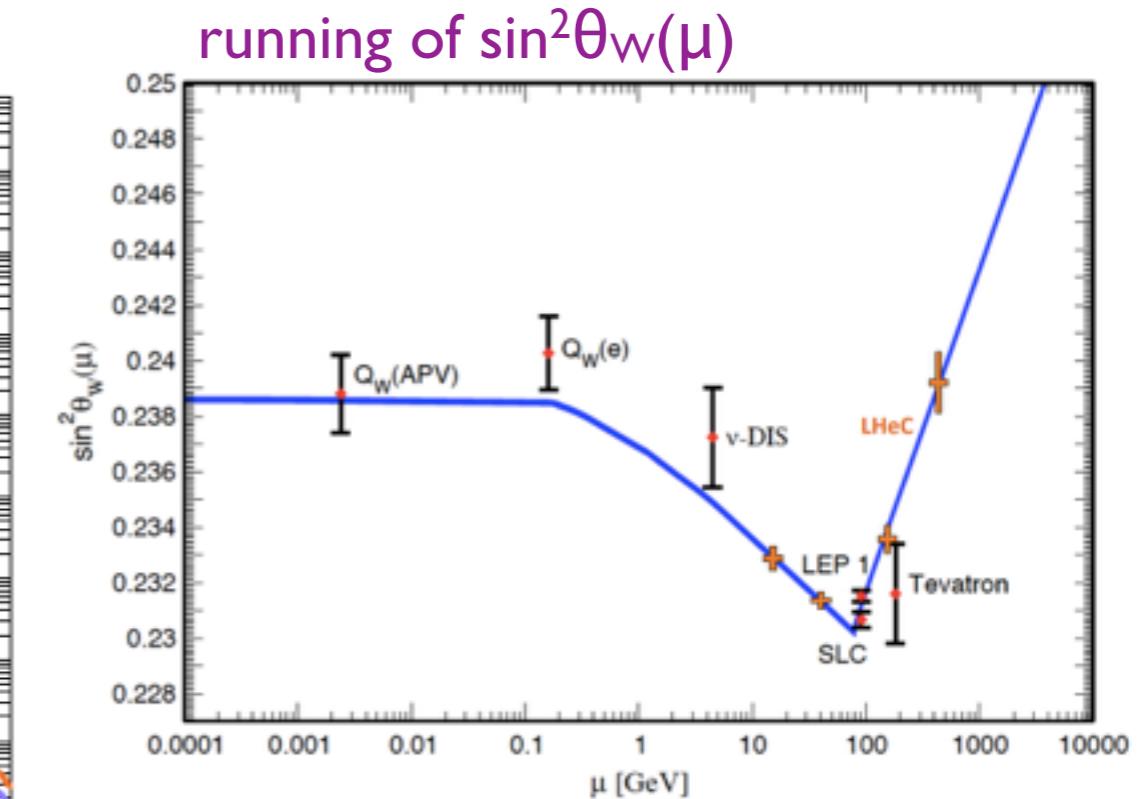
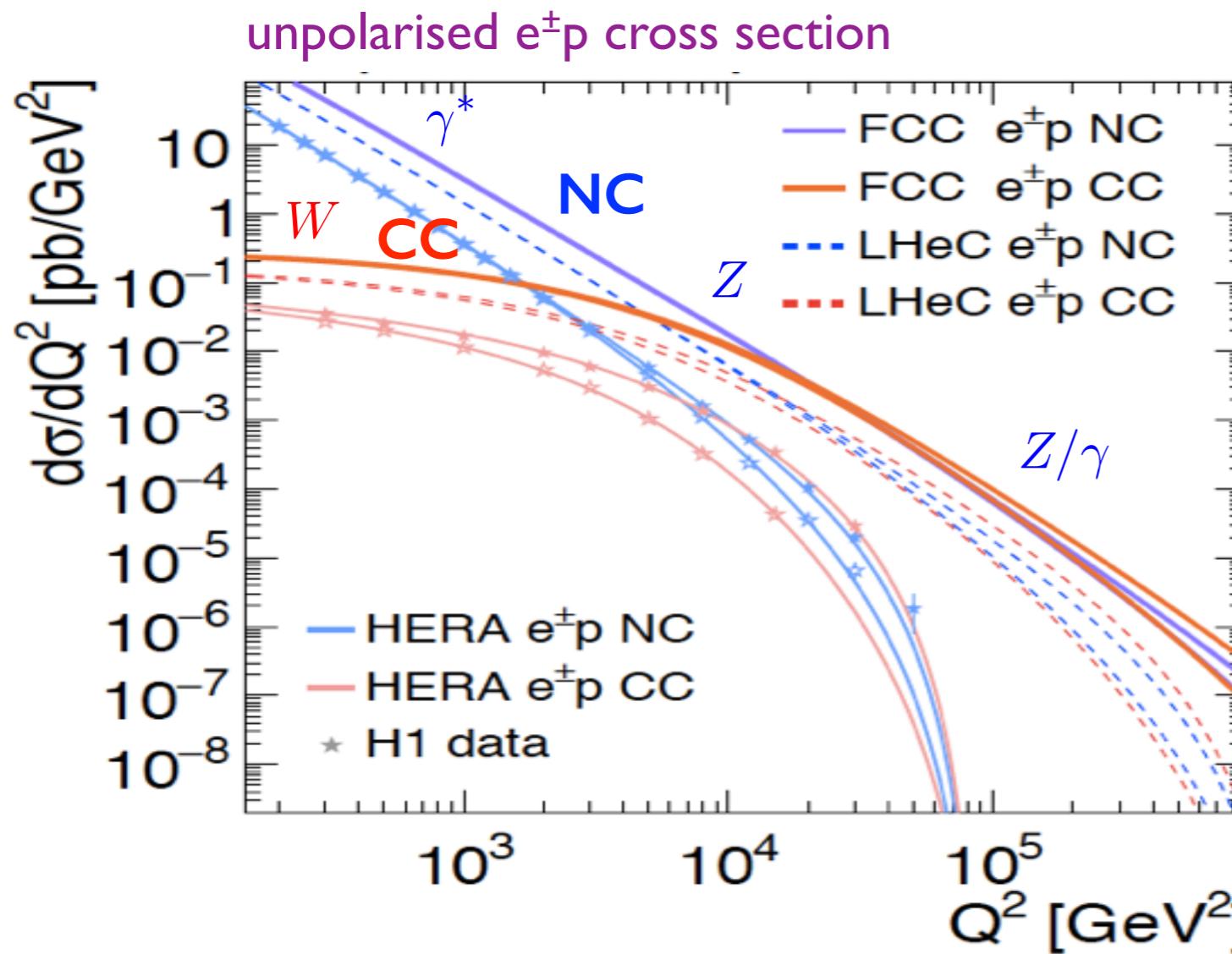
Muon cooling

- MICE experiment (RAL)
 - Ionisation cooling — promising results
- LEMMA (Low EMittance Muon Accelerator)
 - direct muon pairs at threshold ($\sqrt{s} = 212$ MeV) 45 GeV e^+ beam on thin target
 - large boost ($\gamma \sim 200$, $E \sim 22$ GeV)
 - small emittance possible, but low rates



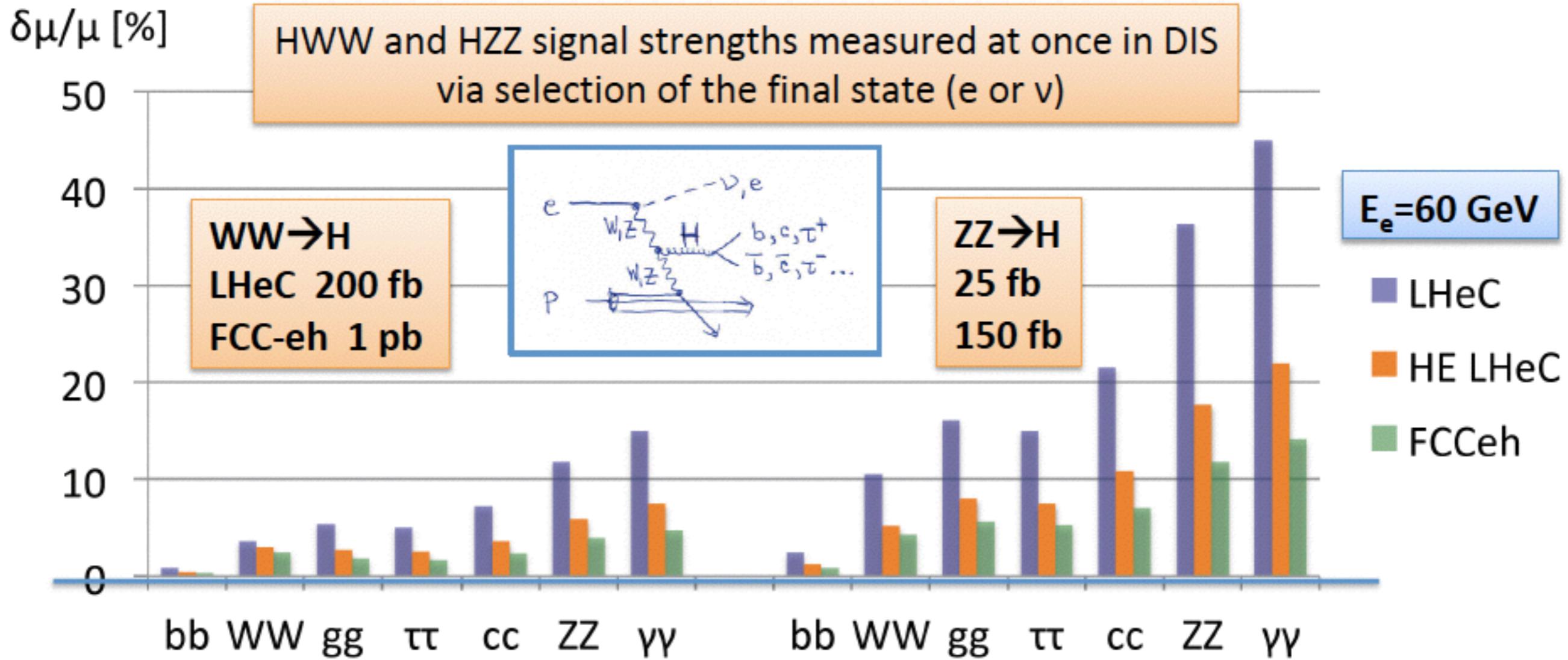
M. Antonelli et al, arXiv:1509.04454

Electroweak Physics in e-p



- NC cross sections at high Q^2 receive important Z boson and γ/Z interference contributions
- together with CC cross sections, they are sensitive to electroweak parameters
- also interesting Higgs and BSM physics

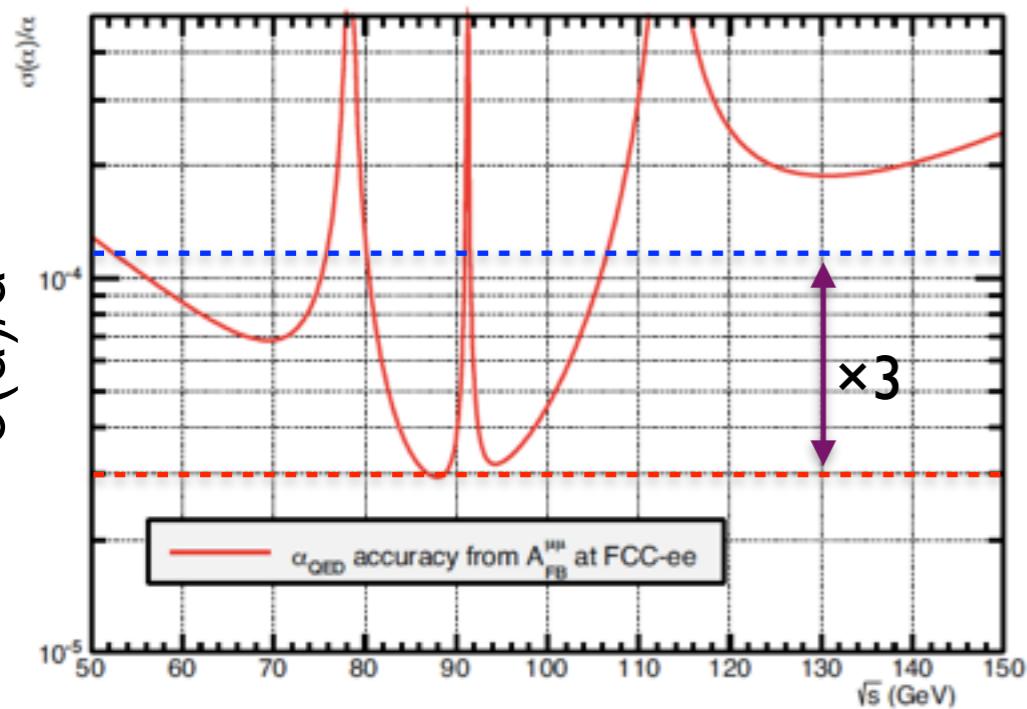
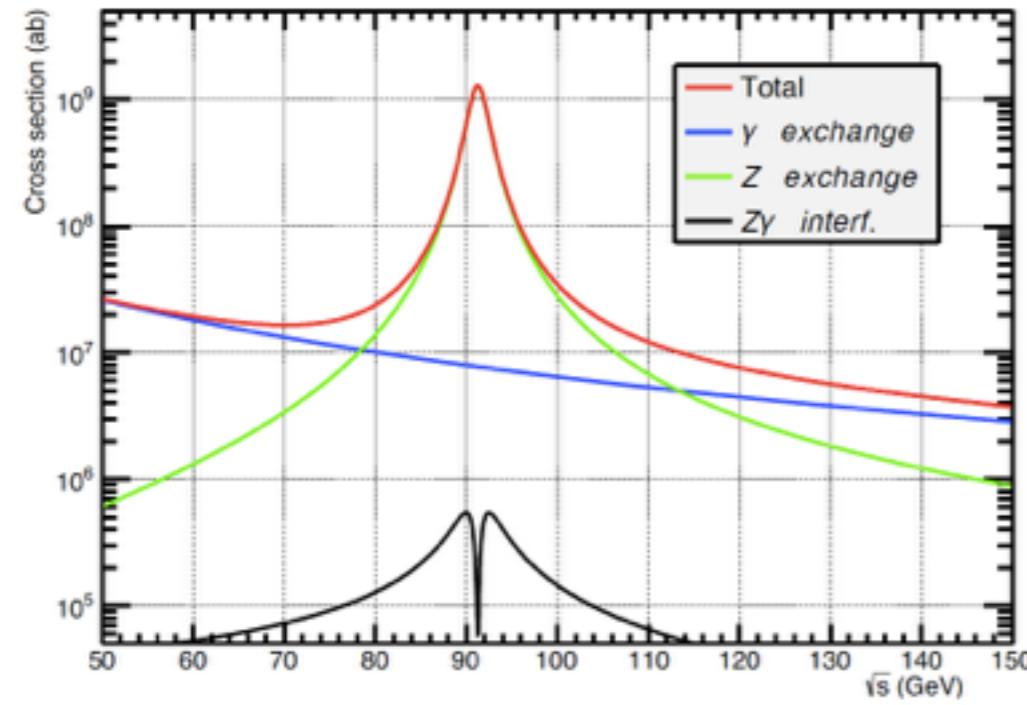
Higgs Physics in e-p



Future e^+e^- Colliders: Pros & Cons

Circular Colliders (FCC-ee)		Linear Colliders (ILC)		
	pros	cons	pros	cons
\sqrt{s}		<ul style="list-style-type: none"> limited by synchrotron radiation (SR), which increases as E_{beam}^4/R 100 km \rightarrow 365 GeV max 	<ul style="list-style-type: none"> extendable in energy large potential \sqrt{s} reach $250 \rightarrow 500 \rightarrow 1000$ GeV (access to ttH, ZHH, Hee) 	<ul style="list-style-type: none"> running at \sqrt{s} smaller than 250 GeV would require optimisation
beam-strahlung		<ul style="list-style-type: none"> strong: affects beam lifetime (typically 30 min.) top-up injection needed to compensate for fast \mathcal{L} burn-off 		<ul style="list-style-type: none"> strong due to beam size at interaction point (IP) increasing with energy
energy spread	<ul style="list-style-type: none"> small energy spread (<0.1% at 240 GeV) with top-up injection: mean $\mathcal{L} = 95\%$ of peak 			<ul style="list-style-type: none"> larger energy spread (86% within 1% of nominal at 250 GeV)
lumi	<ul style="list-style-type: none"> high-lumi obtained with large number of bunches increasing at lower \sqrt{s} due to less SR (spare RF used to accelerate more bunches) crab waist scheme several interaction regions possible 	<ul style="list-style-type: none"> limited by SR power at higher energies 	<ul style="list-style-type: none"> high-lumi obtained with nanometer-size beams increasing naturally with energy thanks to beam dynamics at IP luminosity upgrade ($1312 \rightarrow 2625$ bunches) 	<ul style="list-style-type: none"> low repetition rate only one interaction region (ILD and SLD detectors in push-pull)
L-polar		<ul style="list-style-type: none"> no L-polarisation, except perhaps at Z peak 	<ul style="list-style-type: none"> e⁻ beam: $\pm 80\%$ e⁺ beam: $\pm 30\% (\pm 60\%)$ 	
misc	<ul style="list-style-type: none"> precise E_{beam} from resonant depolarisation (Z peak and perhaps WW threshold) 		<ul style="list-style-type: none"> nm-beams at IP allow for very small beam pipe (superior for b/c tagging) 	

QED Coupling Constant $\alpha(M_Z^2)$



one year of running at any given \sqrt{s}

- $1/\alpha(M_Z^2) = 128.952 \pm 0.014$ ($\rightarrow \delta\alpha/\alpha \approx 1.1 \times 10^{-4}$)
- uncertainty dominated by hadronic vacuum polarisation (from low energy data)
 - currently second largest source of parametric error on $\sin^2\theta_{\text{eff}}$ (first=theory)
 - can be measured from the slope of the FB μ asymmetry in the vicinity of the Z pole

$$A_{\text{FB}}^{\mu}(s) \simeq A_{\text{FB}}^{0\mu} \left[1 + \frac{s - M_Z^2}{2s} \frac{8\pi\sqrt{2}\alpha}{M_Z^2 G_F (1 - 4\sin^2\theta_{\text{eff}})^2} \right]$$

FCC-ee

$1/\alpha(M_Z^2)$ at the 4×10^{-5} level
from 40 fb^{-1} at $\pm 3 \text{ GeV}$ of Z pole

- param. error $< 1.2 \times 10^{-5}$ on $\sin^2\theta_{\text{eff}}$
- param. error $< 0.6 \text{ MeV}$ on M_W

P. Janot, JHEP 02 (2016) 053

Note: computation of missing EW higher-order corrections is needed

Triple Gauge Couplings at 250 GeV

Measurements of γWW and ZWW TGCs: test of the $SU(2)_L \times U(1)_Y$ self-coupling structure
CP conserving and CP-violating effects are separately measurable

$$e^+ e^- \rightarrow W^+ W^-$$

$$e^- \gamma \rightarrow \nu W^-$$

ILC-250

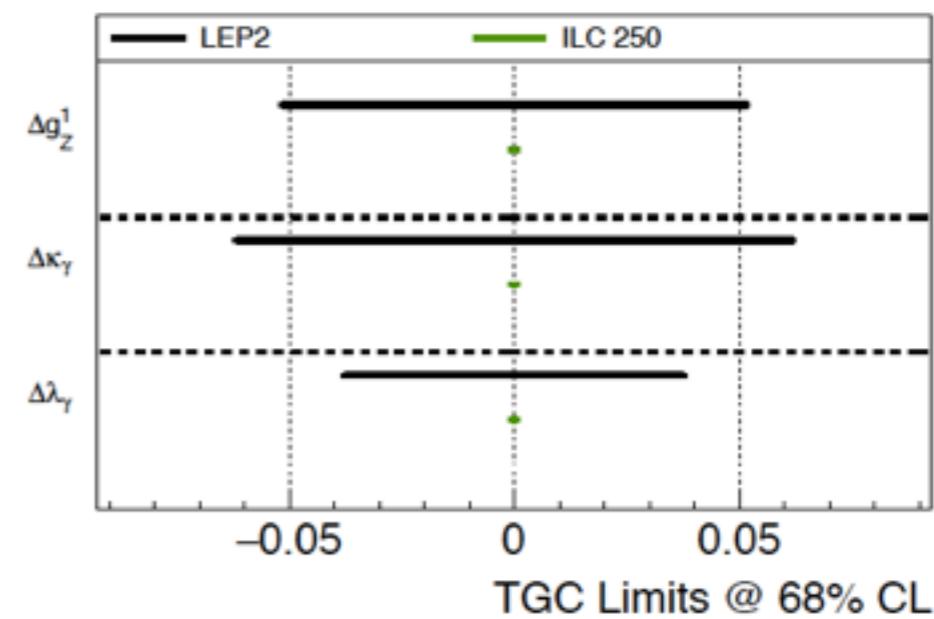
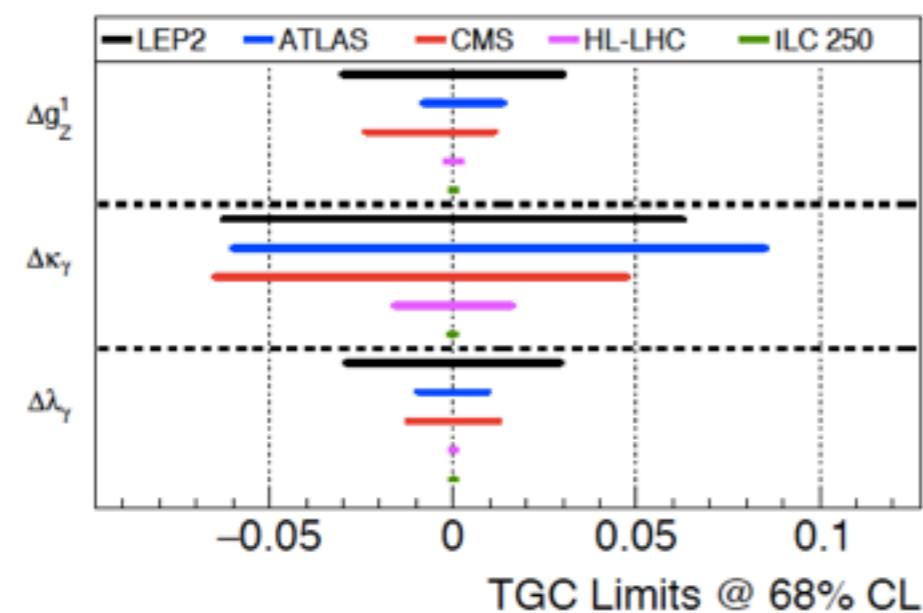
semileptonic channel only

Exp	N_{par}	total error ($\times 10^{-4}$)		
		g_1^Z	κ_γ	λ_γ
LEP 2	3	516	618	376
ILC 250	3	4.4	5.7	4.2
LEP 2	1	300	626	292
LHC	1	319	1077	198
HL-LHC	1	19	160	4
ILC 250	1	3.7	5.7	3.7

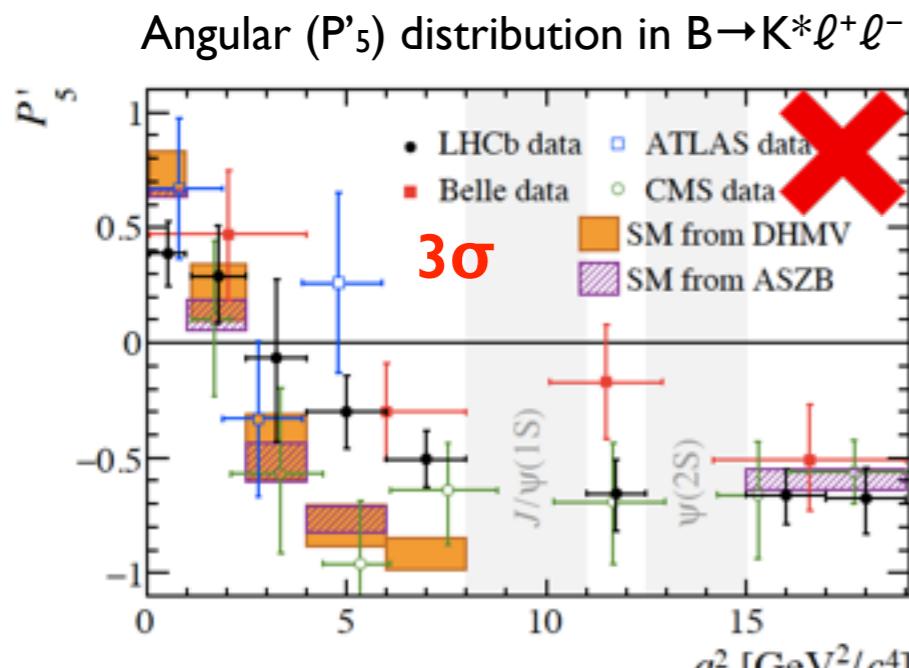
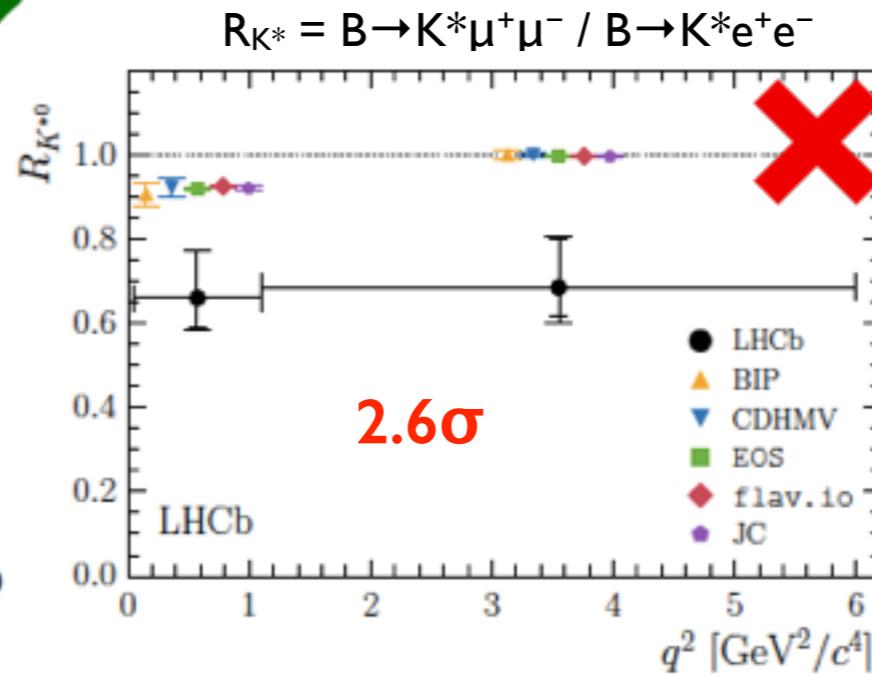
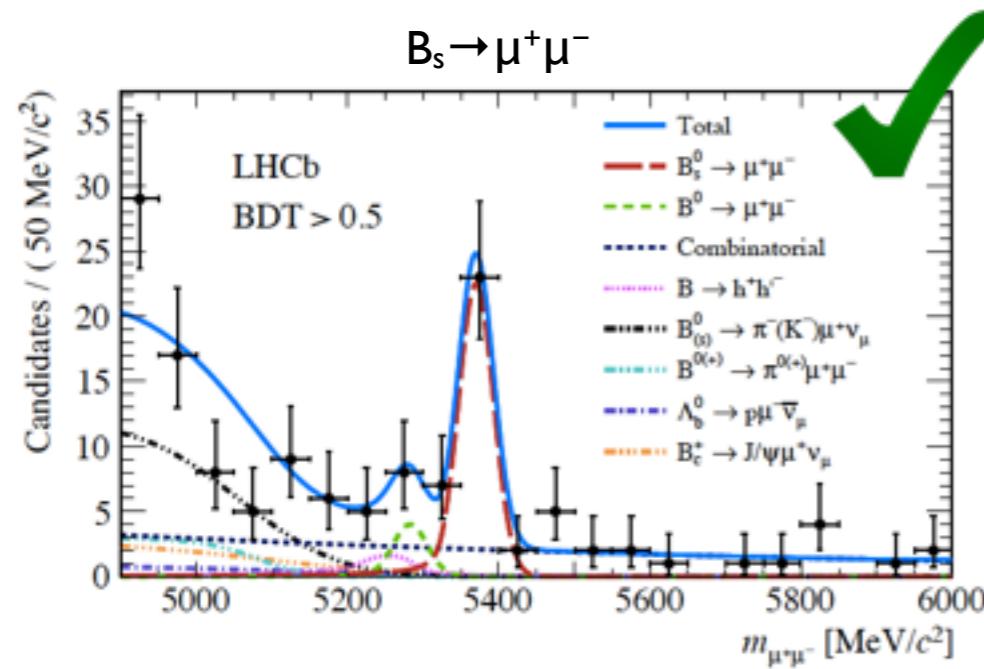
Uncertainties
of a few 10^{-4}
already at 250 GeV

Full angular analysis, five observable angles as polarisation analysers

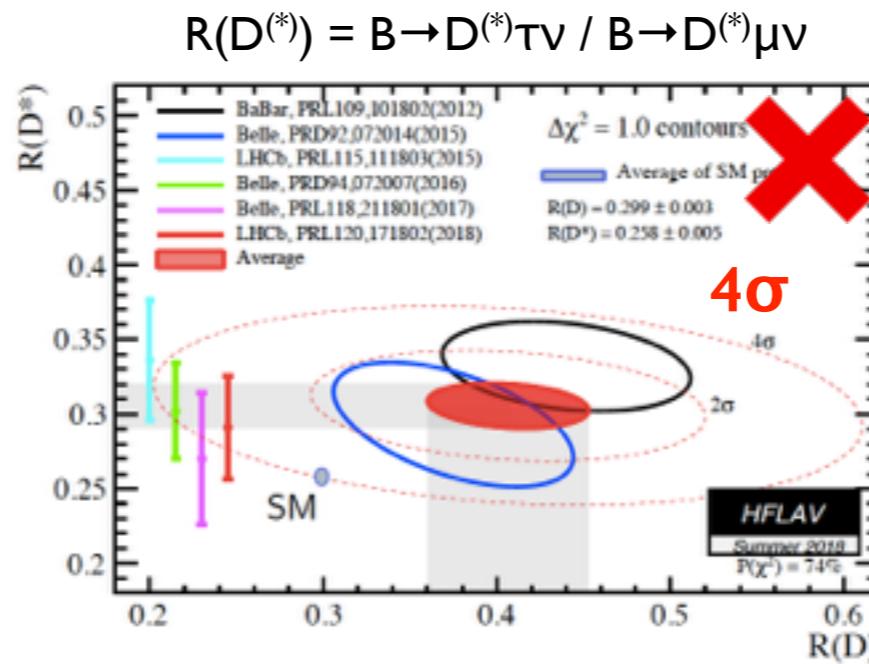
Beam polarisation used to disentangle γWW and ZWW couplings



Anomalies in Flavour Physics



New Physics in
flavour-changing neutral currents?



Lepton flavour non-universality?

- Remember:
- tension in SLD/LEP LR/FB asym. (2.5 σ)
 - tension in N_V (2 σ)

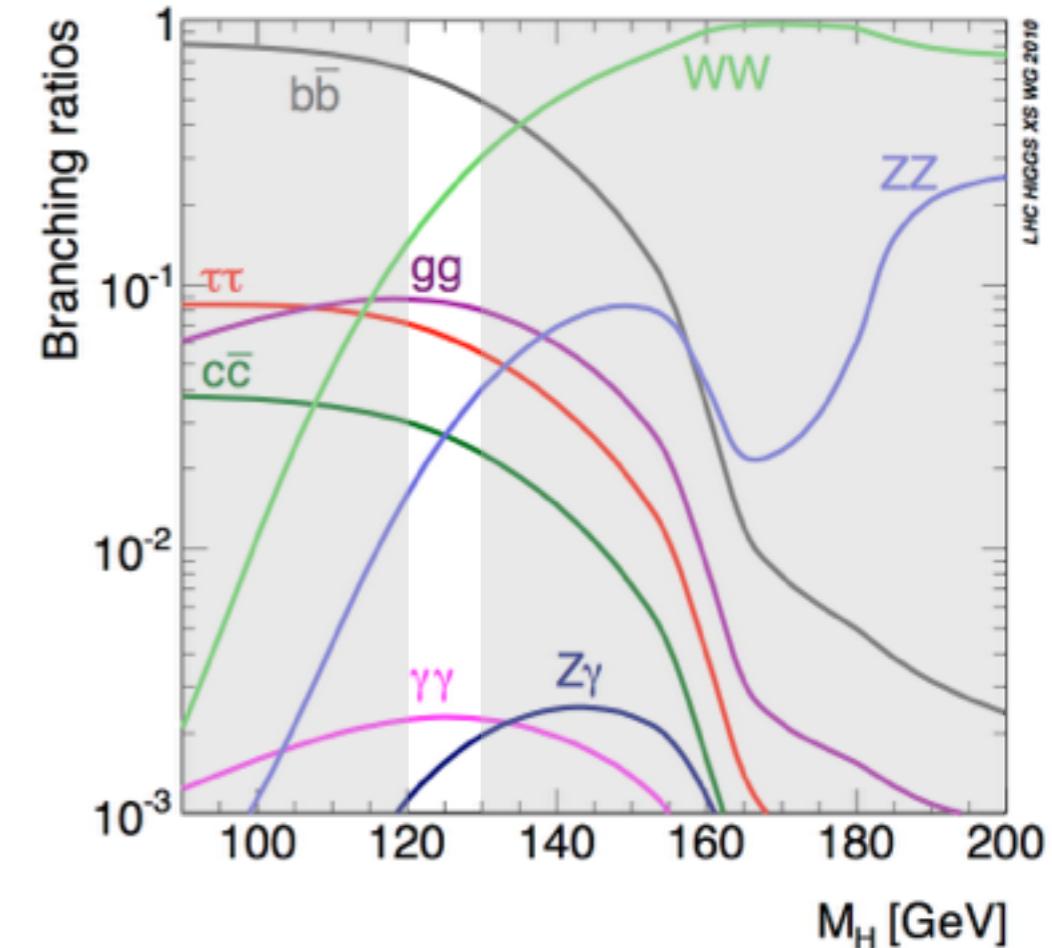
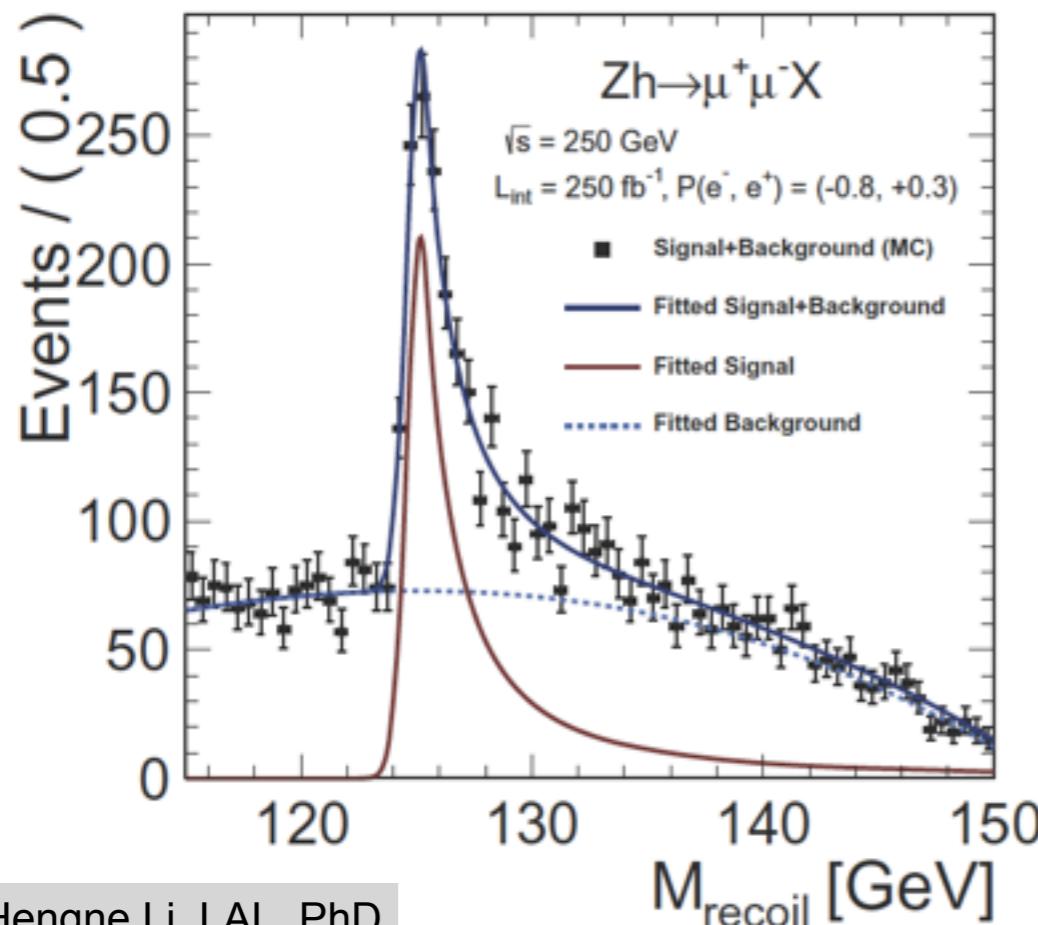
- Also:
- $\mu(g-2)$ anomaly (4 σ)
 - suppressed $B_s \rightarrow \phi \ell^+ \ell^-$ (3 σ)
 - tensions in inclusive/exclusive $|V_{ub}|$ and $|V_{cb}|$ (3 σ)

All flavour anomalies
to be probed
with high confidence
at LHCb and BELLE-2
in the next 5 years

Precision Higgs Boson Mass

Motivation: reduce theory uncertainty on VV^* partial widths (WW^* , ZZ^*)

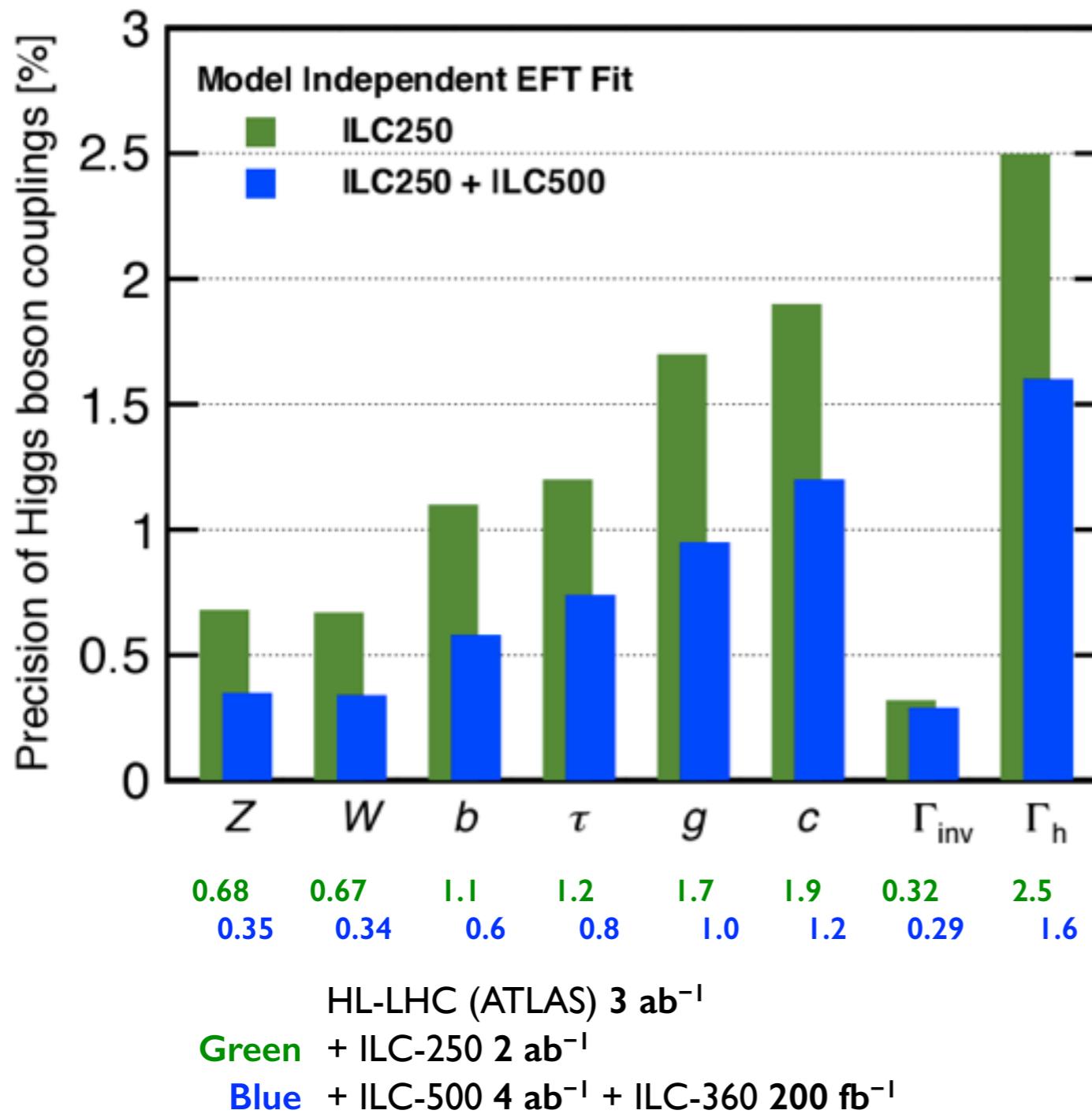
- Γ_V strongly depends on M_H
 $\delta(\sqrt{\Gamma_V}) \approx 7\text{-}8 \delta M_H$
- predictions at the 0.1% level
→ precision on M_H better than 20 MeV
- LHC current precision: ~ 200 MeV
- HL-LHC ultimate precision: < 100 MeV



- From leptonic recoil at the ILC
- 500 fb^{-1} at $\sqrt{s} = 250 \text{ GeV}$ (6y)
 - $\delta M_H = 28 \text{ MeV}$ (LR+LR)
 - 2 ab^{-1} at $\sqrt{s} = 250 \text{ GeV}$ (15y)
 - $\delta M_H = 14 \text{ MeV}$ (LR+RL)

ILC: Higgs Couplings with EFT

EFT = Effective Field Theory



EFT-based framework

- all dim-4 and dim-6 operators consistent with $SU(2)_L \times U(1)_Y$ (implies *custodial symmetry*)
- no new light particle
- invisible decay of H boson as new degree of freedom

Results obtained with the EFT for 2 ab^{-1} at 250 GeV already in the 1% range for most couplings

Still compelling reasons to pursue with higher energies

- access to W fusion production for independent g_{HWW} meas,
- top physics (mass, couplings)
- constraints on λ_{HHH}
- BSM reach

Patterns of Deviation

Different new physics (NP) models lead to different **patterns of deviations**

ILC TDR 2013

The size of deviations depends on the NP scale

MSSM and 2-Higgs doublets models (2HD)

- one light CP-even state (h) with SM couplings
- deviations induced through mixing with extra Higgs states
- types I, II, X and Y: discrete symmetries to protect FCNC

$$\frac{g_{hbb}}{g_{hbb}^{\text{SM}}} = \frac{g_{h\tau\tau}}{g_{h\tau\tau}^{\text{SM}}} \simeq 1 + 1.7\% \left(\frac{1 \text{ TeV}}{m_A} \right)^2$$

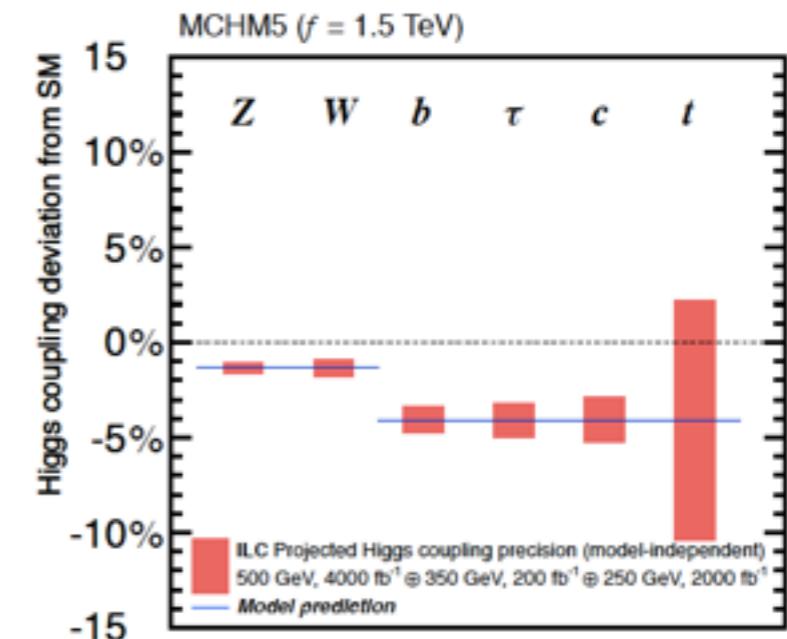
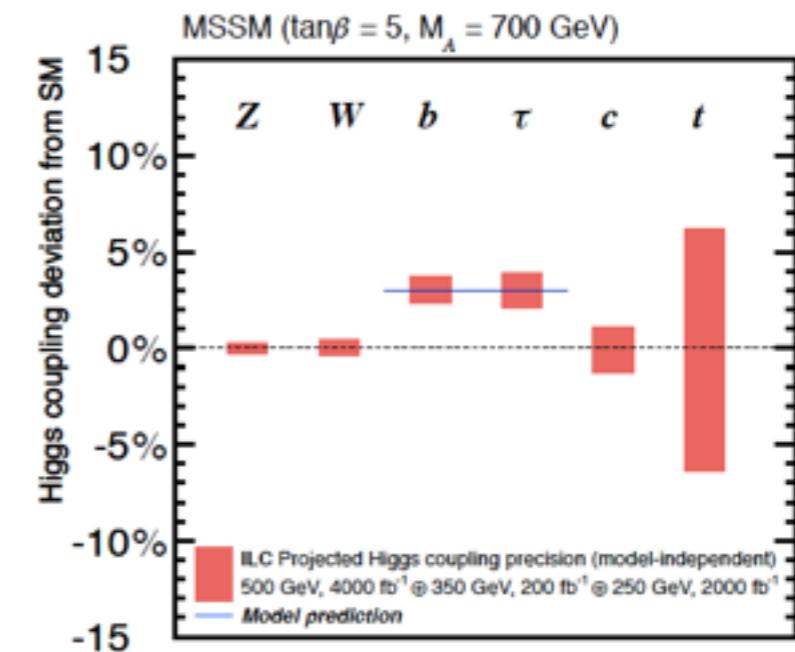
Composite Higgs

- solves hierarchy problem
- all coupling reduced according to composite scale f

$$\frac{g_{hff}}{g_{hff}^{\text{SM}}} = \frac{g_{hVV}}{g_{hVV}^{\text{SM}}} \simeq 1 - 3\% \left(\frac{1 \text{ TeV}}{f} \right)^2$$

Percent level precision is required !

credit: M. Mangano



Coupling precision
after full ILC running

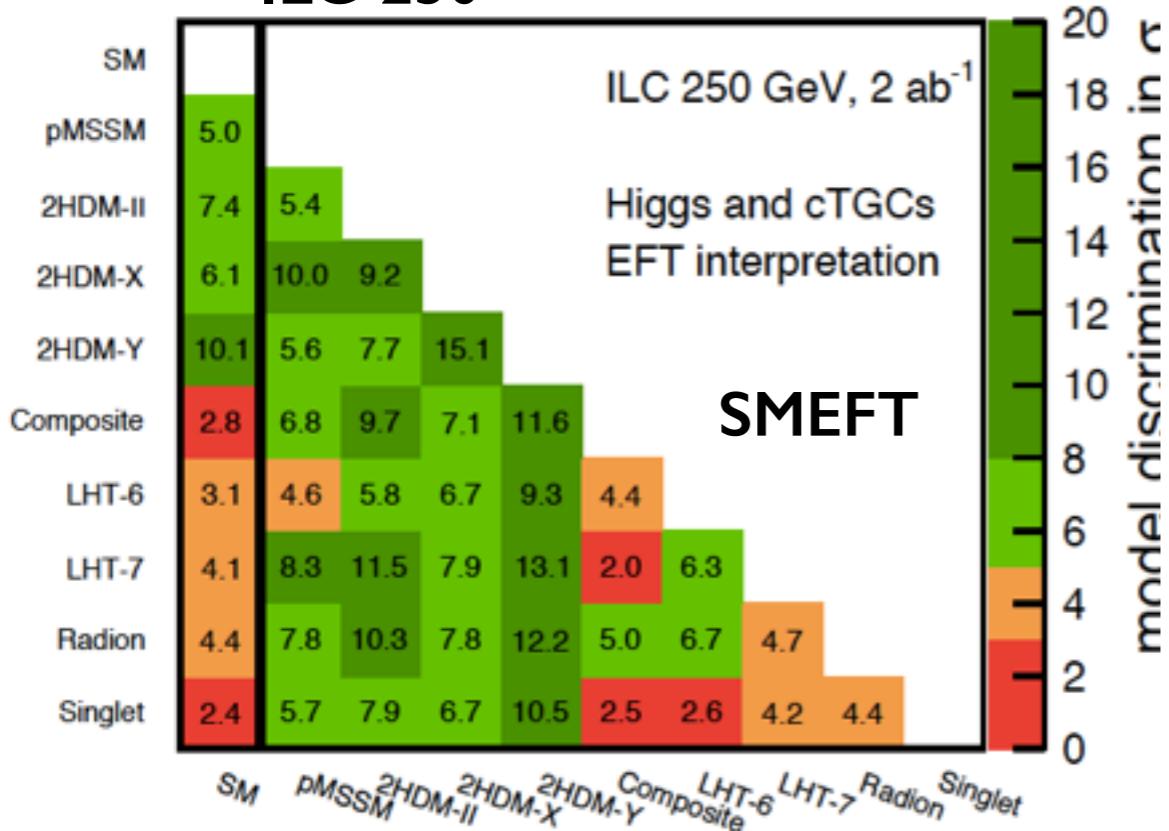
Sensitivity to BSM Models

Deviations to SM Higgs boson couplings (in %)

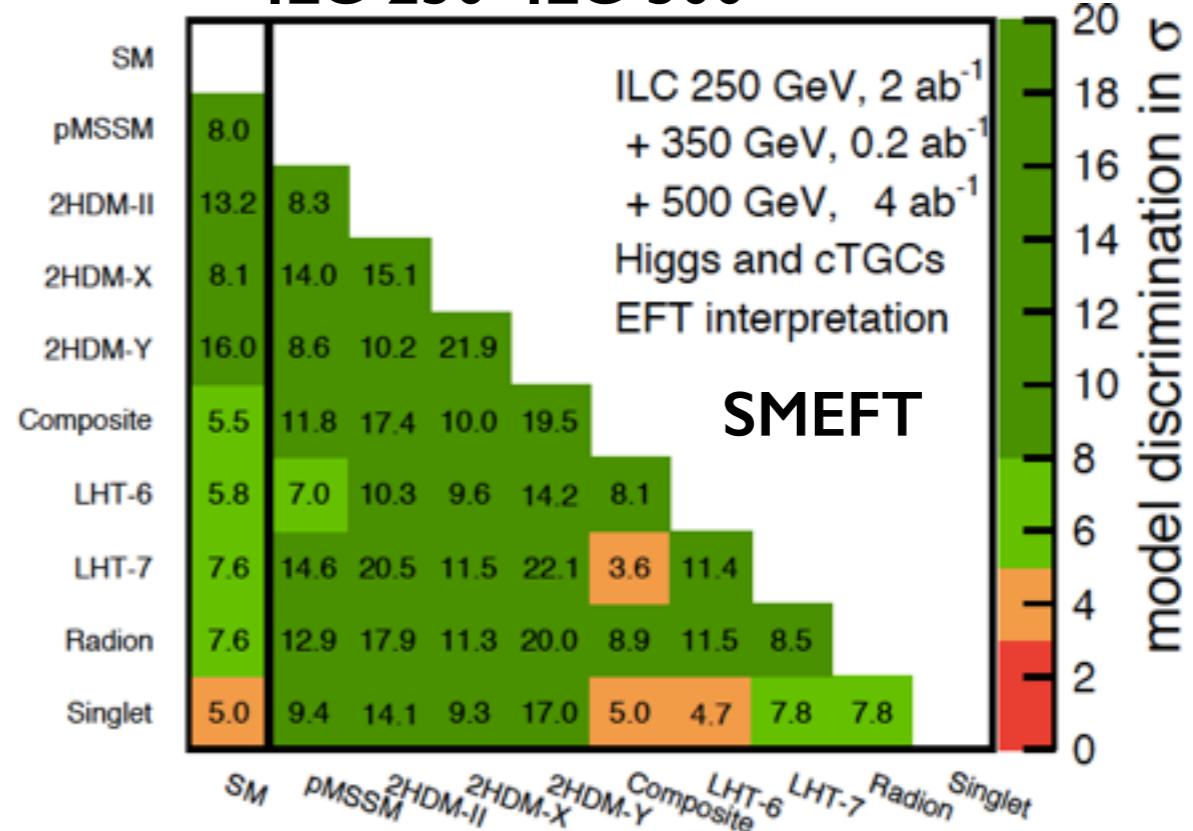
models consistent with no discovery at the HL-LHC
(incl. Higgs partners)

Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1 MSSM [38]	+4.8	-0.8	-0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2 Type II 2HD [39]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3 Type X 2HD [39]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4 Type Y 2HD [39]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5 Composite Higgs [40]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4

ILC-250



ILC-250+ILC-500



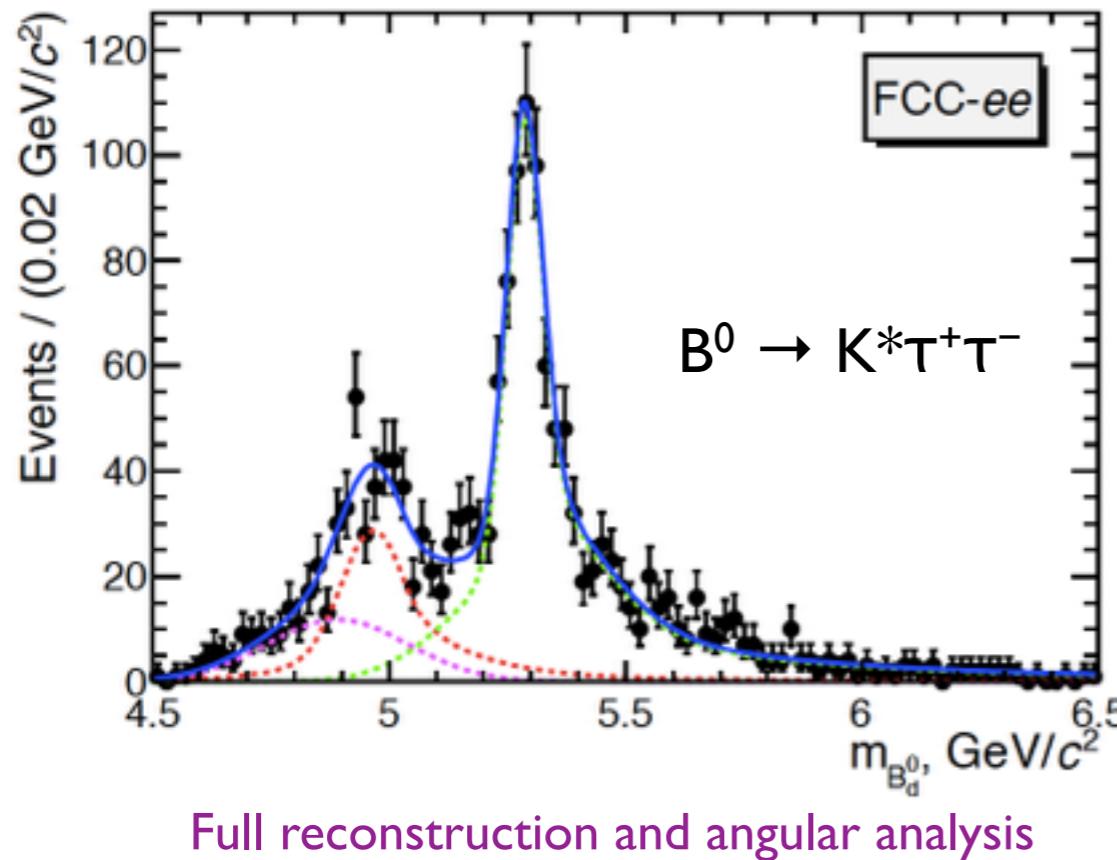
Flavour Physics at the FCC-ee

→ $10^{12} Z \rightarrow bb$

- the ultimate e^+e^- B factory
- access to B^0, B_s, B_c, B hadrons
- 100 000 $B_s \rightarrow \tau^+\tau^-$

→ example

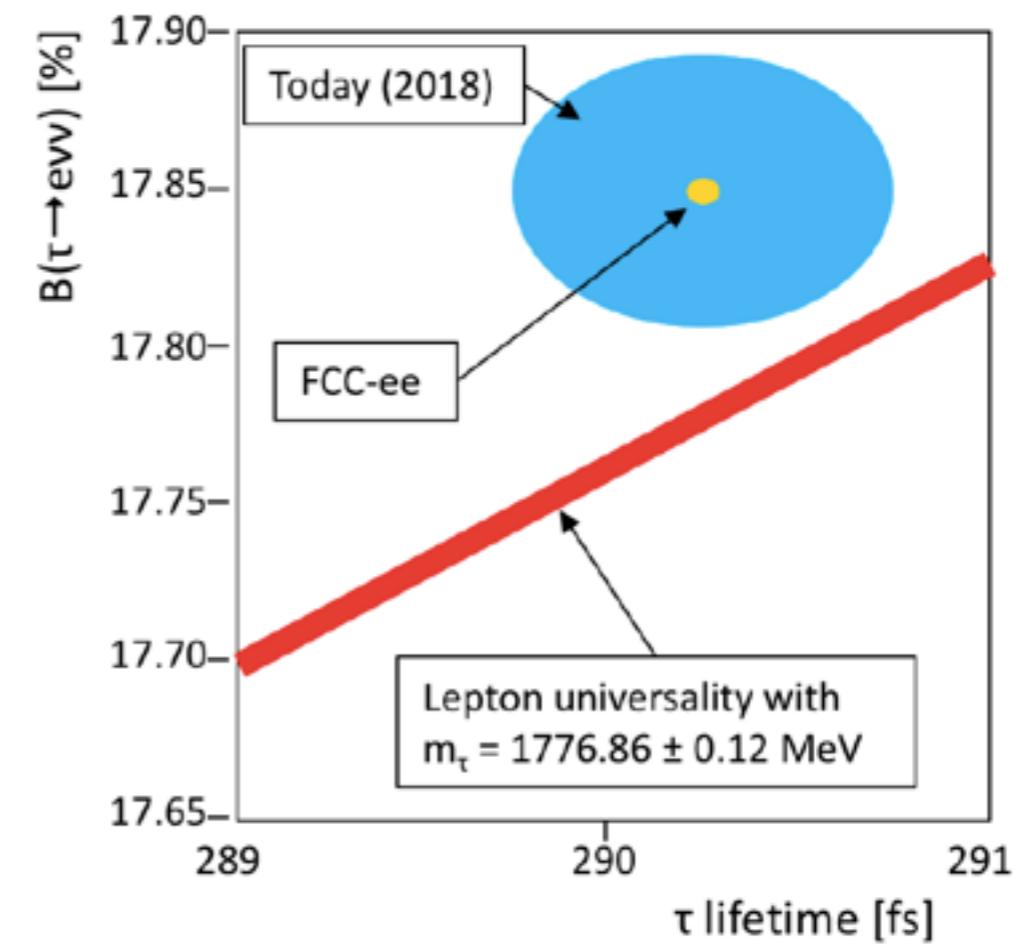
test of the $b \rightarrow s\ell^+\ell^-$ anomaly for $\ell = \tau$



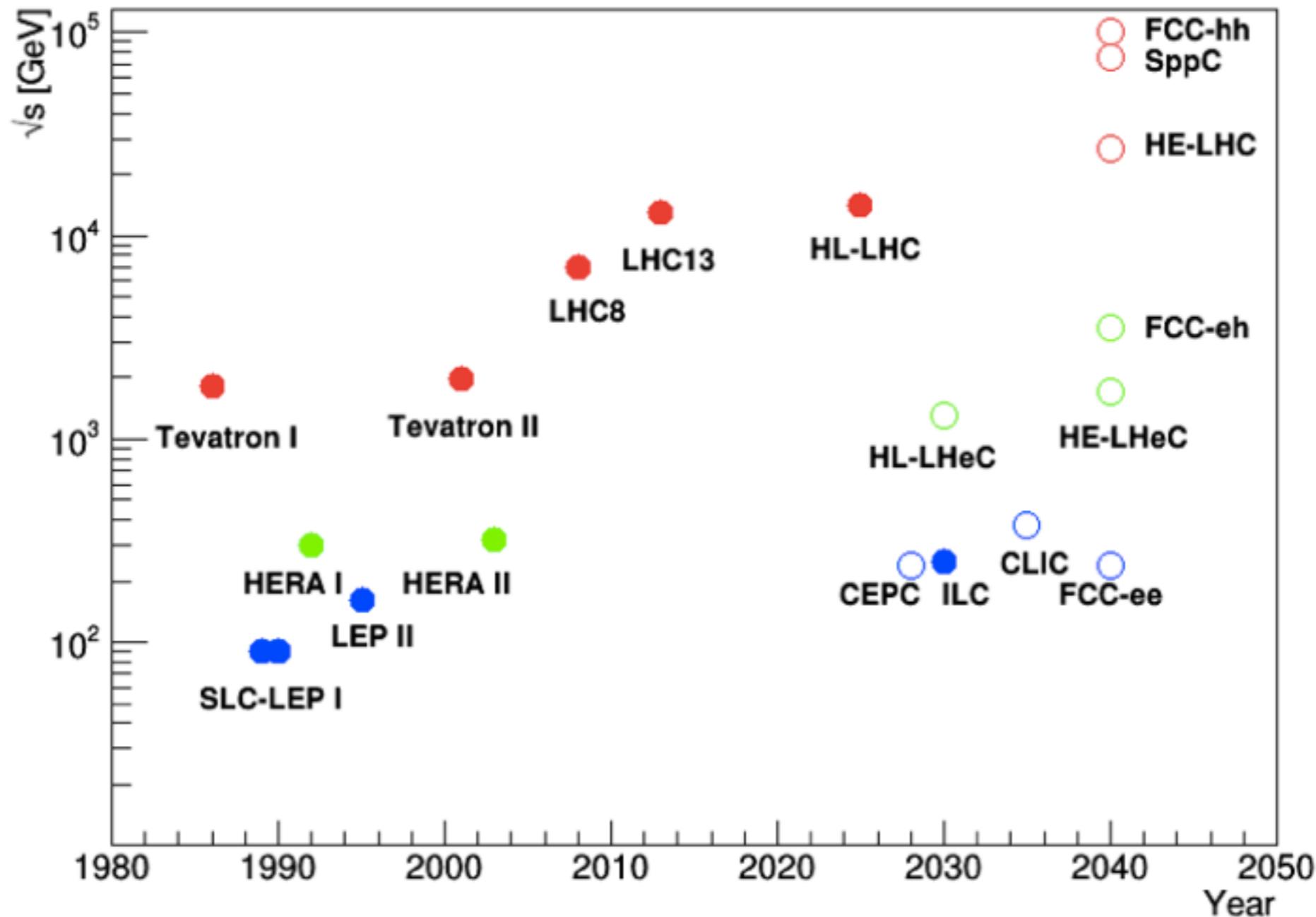
Complementarity with Belle-II and LHCb

→ another example

- test of lepton flavour universality in $BR(\tau \rightarrow e\nu\nu)$ versus τ lifetime

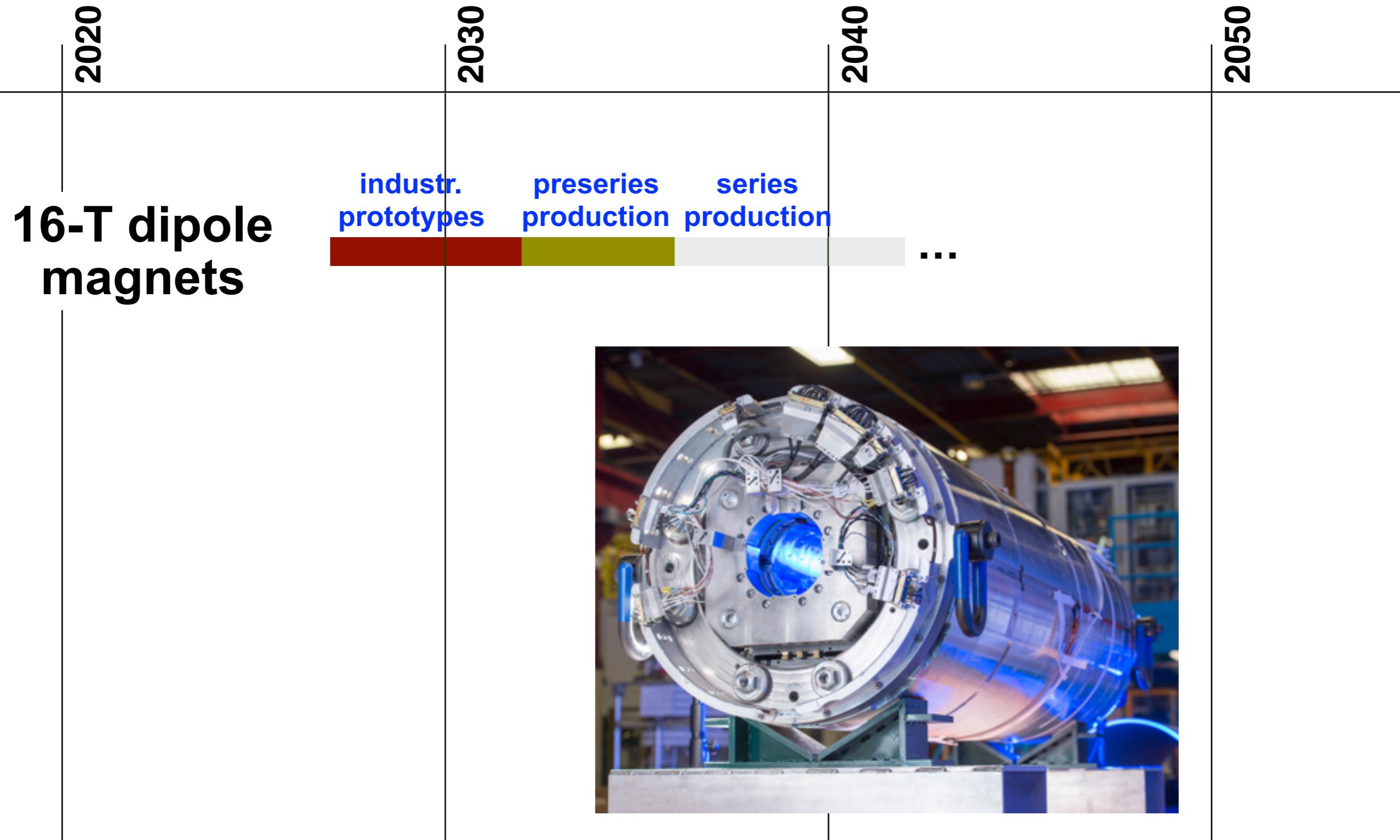


Past, Present & Future Projects

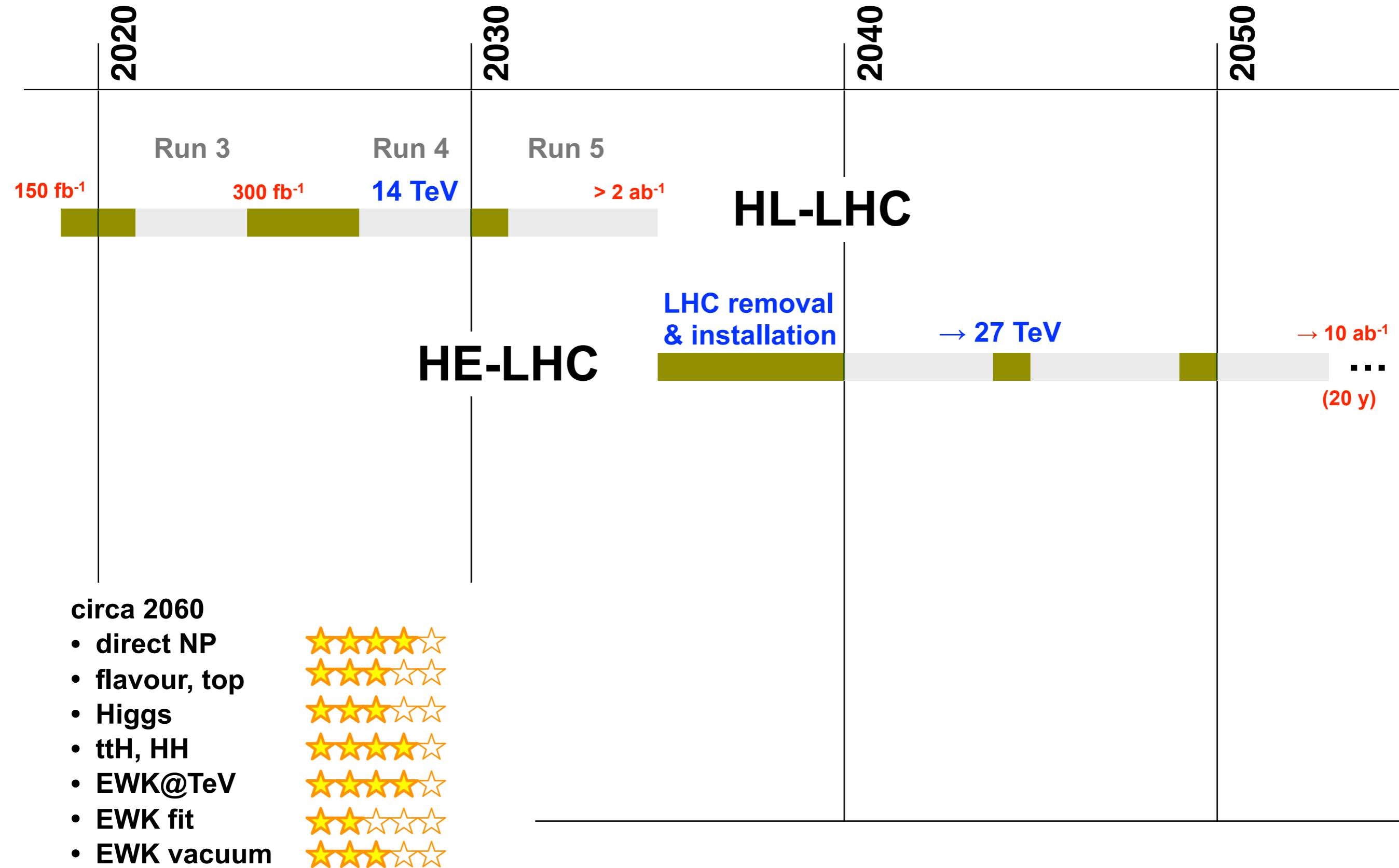


From R. Pöhl, Future Colliders — Linear and circular, arXiv:1809.10426

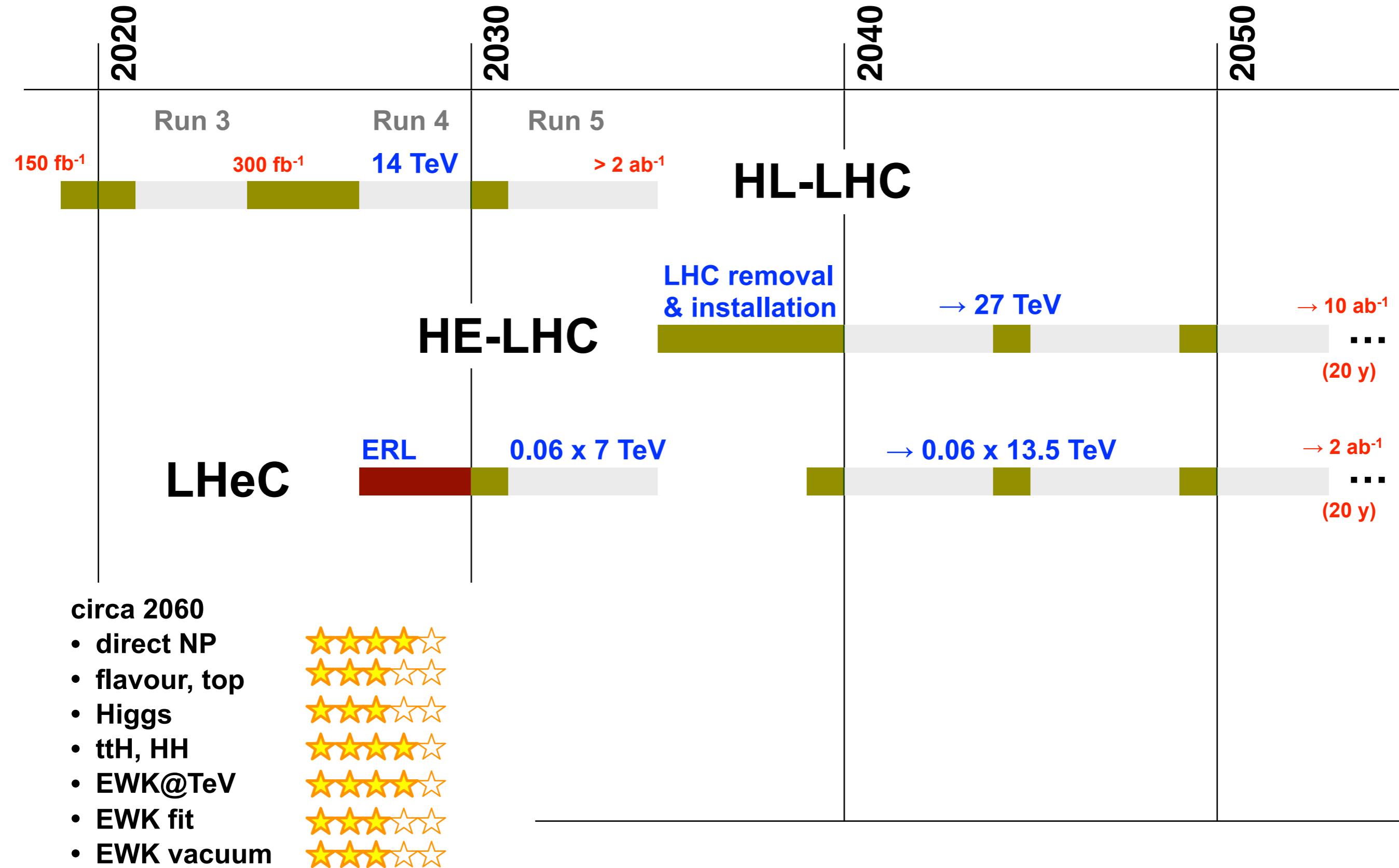
16-T SC Magnet Developments



HL-LHC+HE-LHC



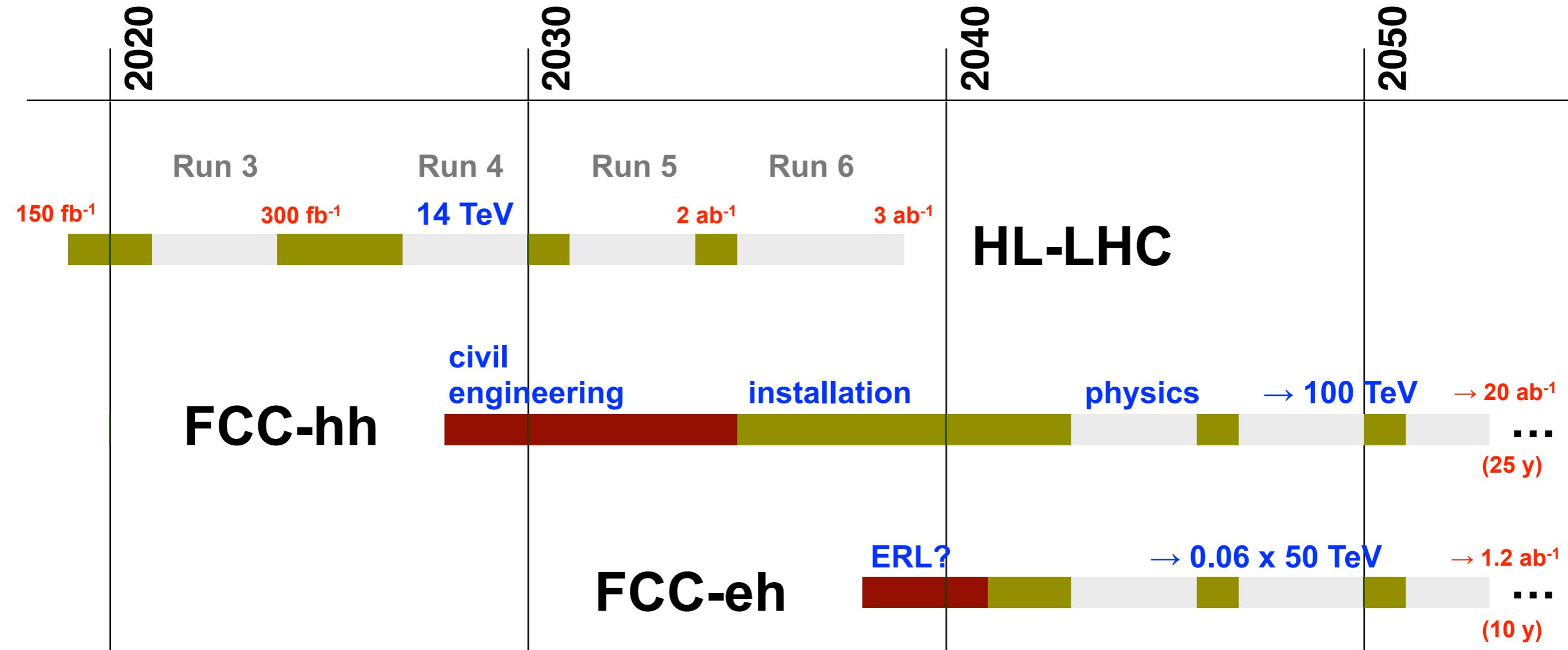
HL-LHC+HE-LHC+HE-LheC



HL-LHC+FCC-hh



HL-LHC+FCC-hh+FCC-eh



circa 2065

- direct NP
- flavour, top
- Higgs
- tth, HH
- EWK@TeV
- EWK fit
- EWK vacuum

