Challenges and Opportunities in Higgs Physics at Future Colliders*

Selected Topics

Pisa School on Future Colliders 2018

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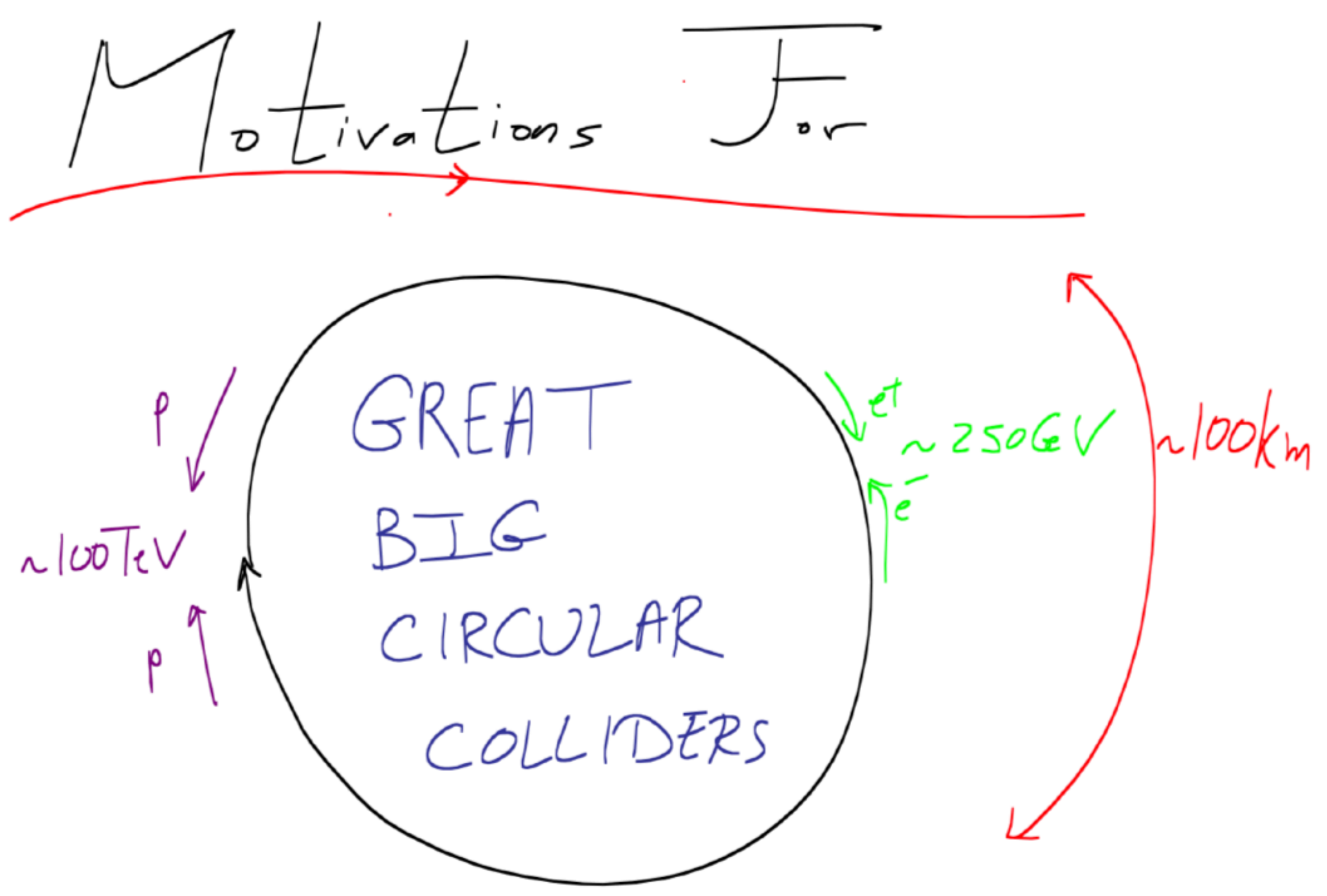
With a lot of input from P. Janot

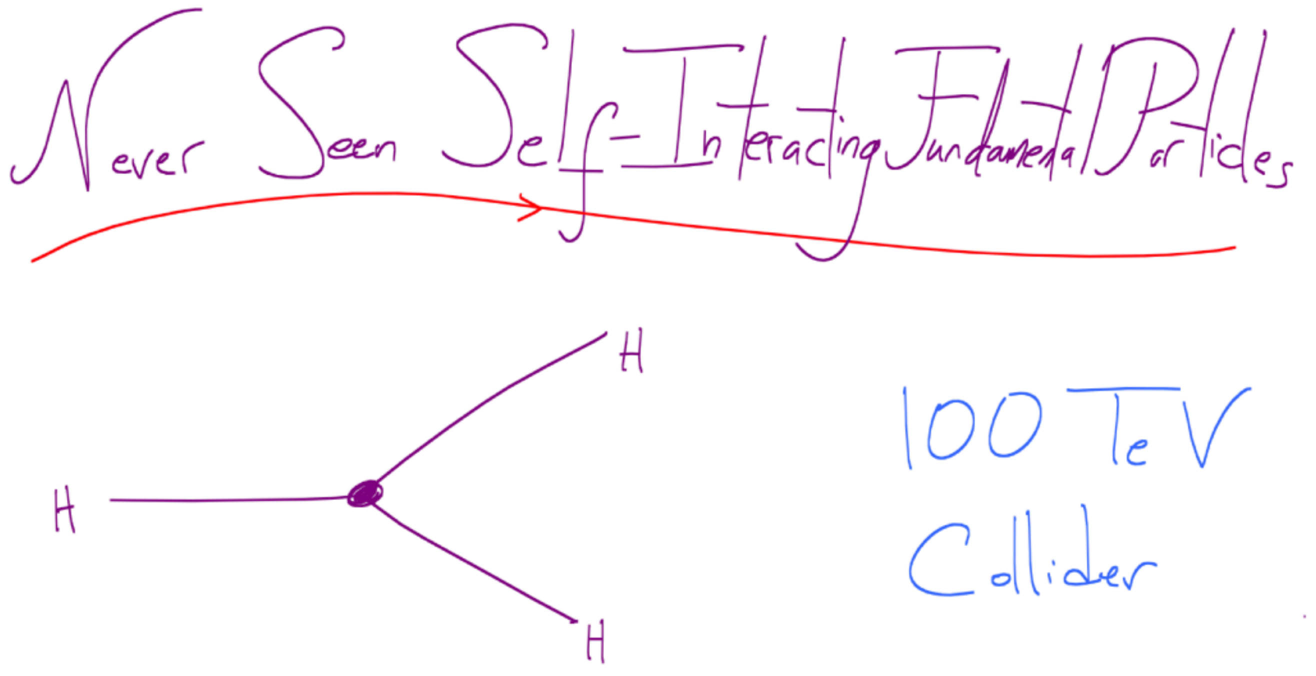
Preamble

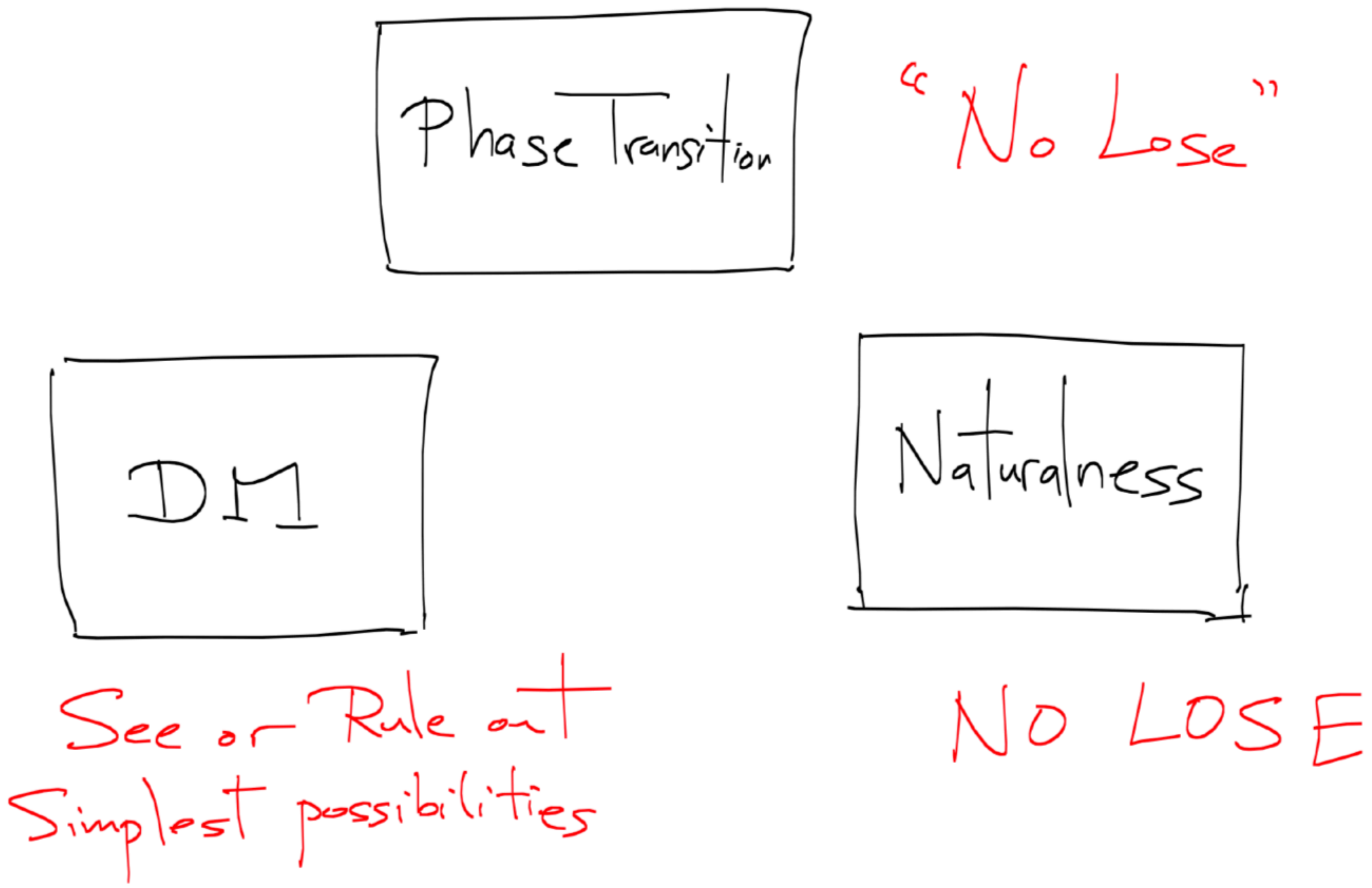
- The LHC is in its Run 2 phase and has gathered nearly 150 fb-1 per experiment.
- The bulk of the analysed data is approximately 36 fb-1 per experiment, i.e. 1% of the foreseen entire dataset of 3 ab-1.
- The LHC (and HL-LHC) is already an immense success with the discovery of the Higgs, precision measurements and a vast campaign of searches - nothing else was found. **However** may still have surprises which could reveal what is beyond the Standard Model.
  - Until the next leap in energy, the time of potential spectacular (i.e. timely) discoveries is gone - the doubling time of the luminosity is now several years.
  - The time of guaranteed discoveries (charm, top, tau neutrino and Higgs) is gone - there is no no-loose theorem anymore.
- There are however guaranteed deliverables of fundamental importance in measurements of Higgs properties and precision EW observables.
- In absence of indications of new physics these are among the most important benchmarks for the design and choice of all future collider projects.

Higgs Physics in the bigger picture

From Nima Arkani Ahmed (IAS-HKUST 2015)







Higgs physics

Is essential in all these main areas of the physics motivations for a « great big circular colliders » and more…

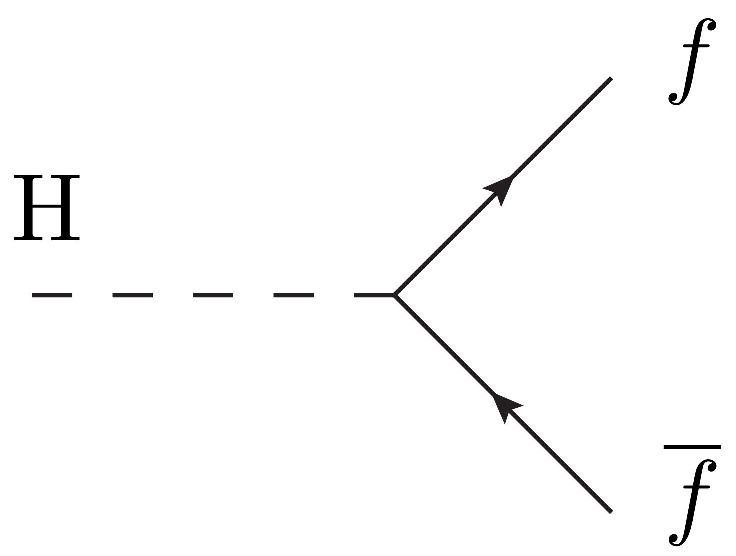
MUST LOOK AT IT CLOSELY

Rule of thumbs

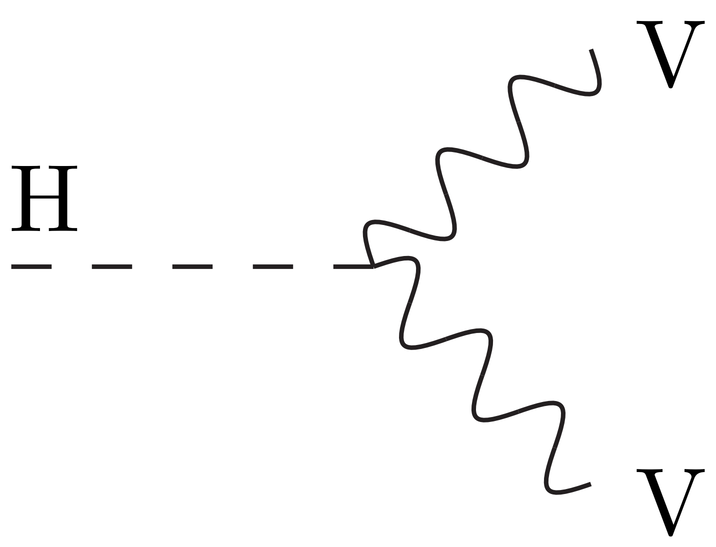
In order to investigate a scale Λ with Higgs data, the level of precision should be of the order v^2/Λ^2 i.e. **sub-percent level** to reach ~10 TeV!

Higgs boson couplings (within the Standard Model)

All the couplings of the Higgs boson to Standard Model particles (except itself) were known before the discovery of the Higgs boson!

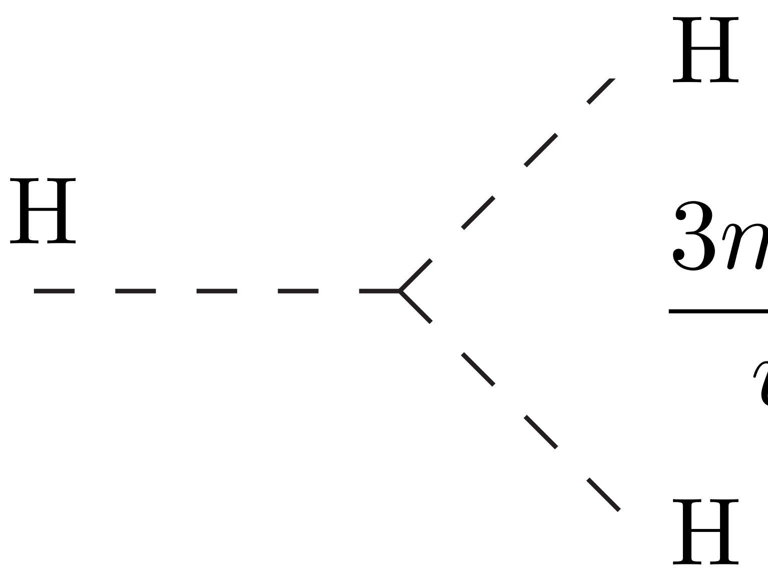


$$\frac{m_f}{v} \qquad + \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

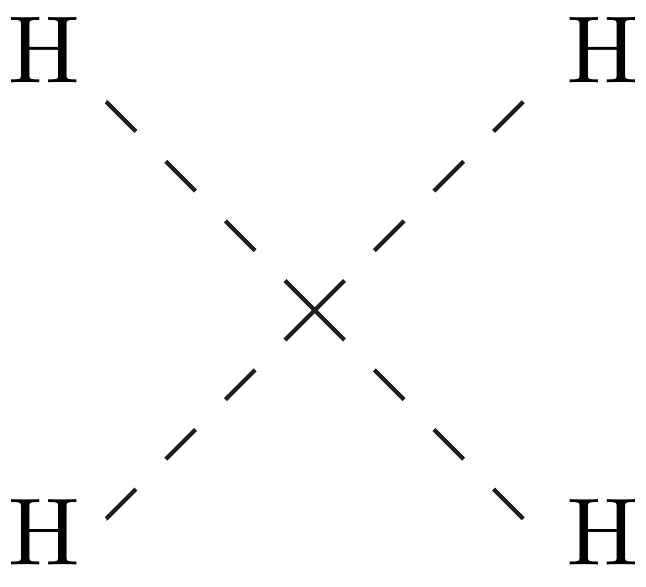


$$\frac{2m_V^2}{v} \qquad + |D_\mu \phi|^2$$

This term could not exist without a vev



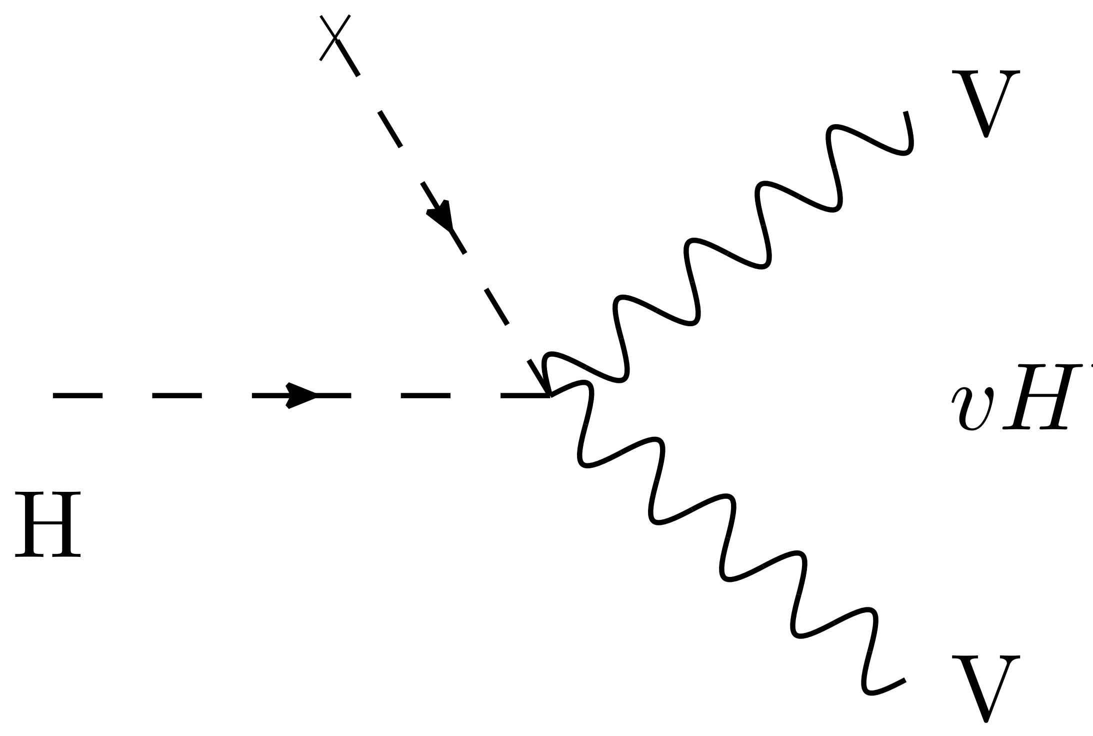
$$\frac{3m_H^2}{v}$$



$$\frac{3m_H^2}{v^2} \qquad V(\phi)$$

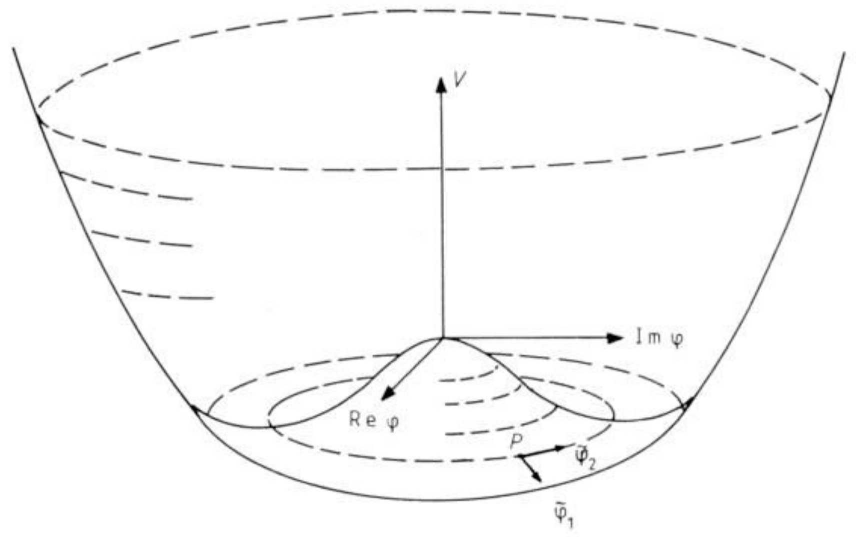
Is the Higgs boson responsible for the EW symmetry breaking also responsible for the masses of fermions?

Is the Higgs boson responsible for the masses of all fermions?



$$vHV^\mu V_\mu$$

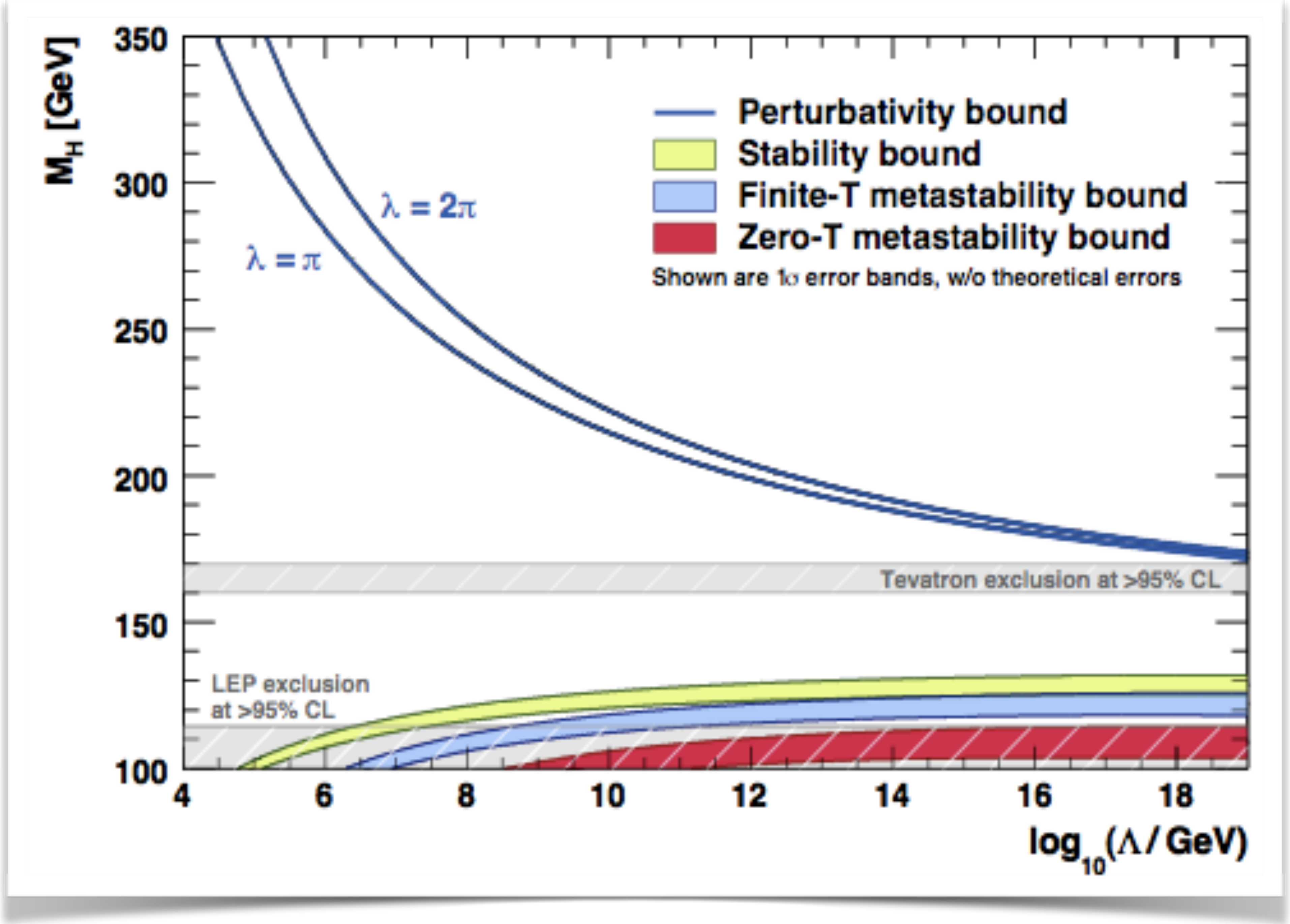
Proof of condensate !

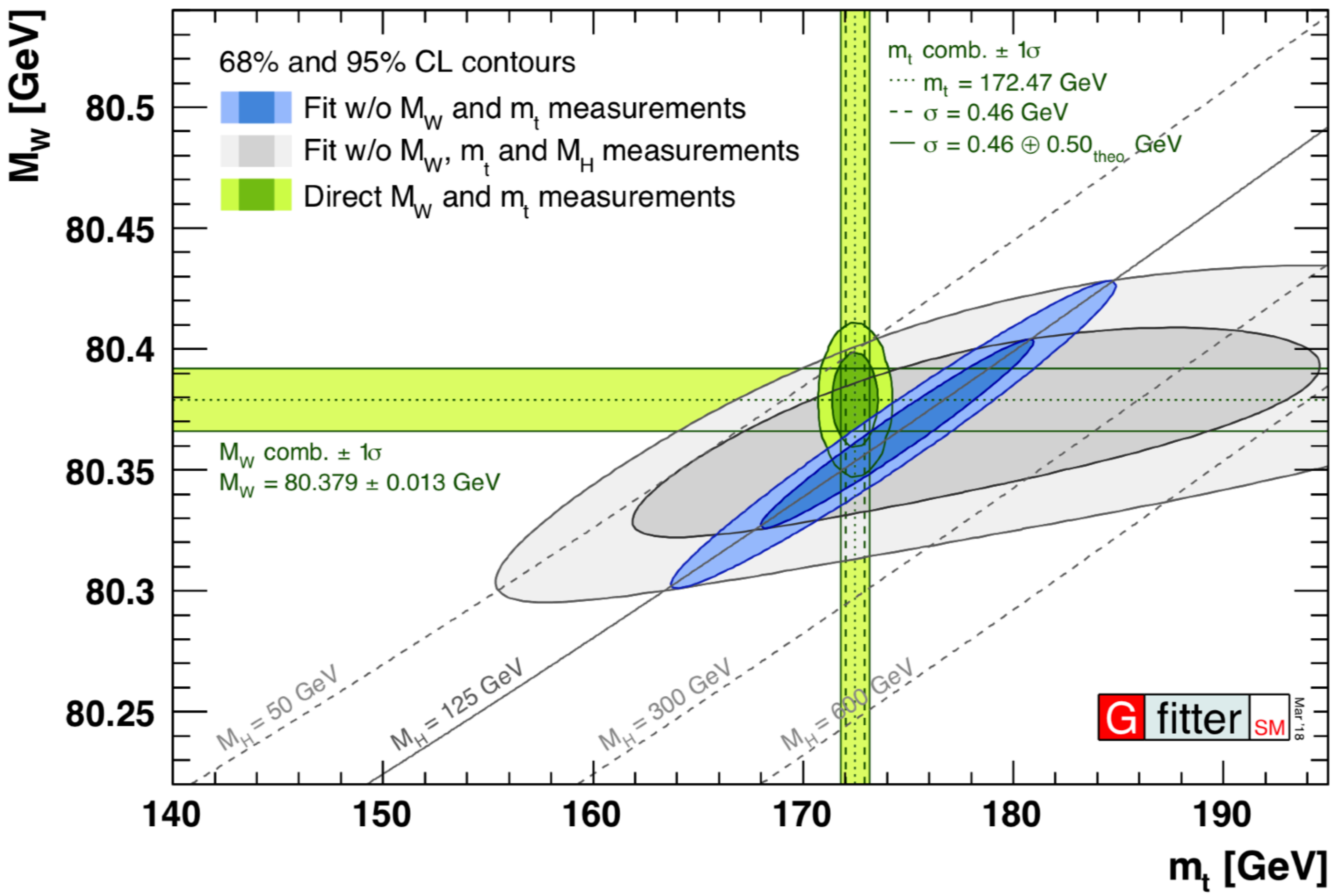


Is the shape of the Higgs potential that predicted by the Standard Model?

Higgs Discovery Implications

Running of the Higgs self coupling:





With the discovery of the Higgs, for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.

Nima Arkani Hamed

- Knowing the Higgs boson mass has a radical effect on global analysis of precision data.
- Knowing the Higgs boson mass precisely has little impact.

Triumph of the SM ?

A quick word on the kappa formalism

Introducing simple scale factors of the Standard Model couplings in a « naive » effective Lagrangian (assumes that the tensor structure of is that of the SM).

$$\mathcal{L} \supset \kappa_Z \frac{\mathrm{m}_{\mathrm{Z}}^2}{v} Z_\mu Z^\mu + \kappa_W \frac{\mathrm{m}_{\mathrm{W}}^2}{v} W_\mu W^\mu + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} + \sum_f \kappa_f \frac{\mathrm{m}_f}{v} f \overline{f}$$

Not gauge invariant and partial but very useful to illustrate coupling measurement concepts.

More complete EFT and rigorous framework exists but beyond the scope of this lecture.

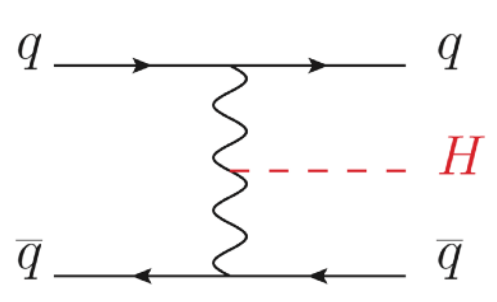
Very Brief Review of Where we Stand

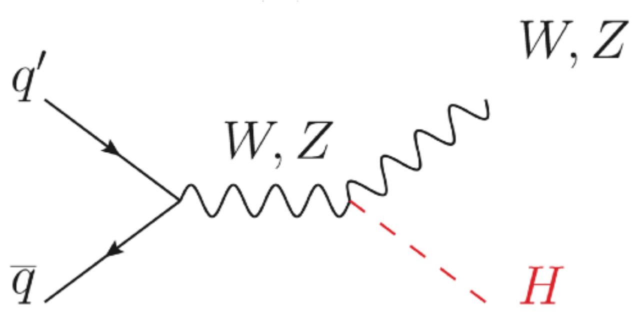
Run 2 Higgs Physics Milestones Reached Very Recently!

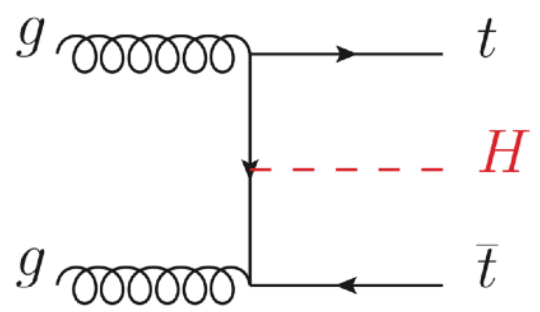
Yukawas at LHC		tau	b	top
ATLAS	Exp. Sig.	5.4 σ	5.5 σ	5.1 σ
	Obs. Sig.	6.4 σ	5.4 σ	6.3 σ
	mu	1.09 ± 0.35	1.01 ± 0.20	1.34 ± 0.21 *
CMS	Exp. Sig.	5.9 σ	5.6 σ	4.2 σ
	Obs. Sig.	5.9 σ	5.5 σ	5.2 σ
	mu	1.09 ± 0.27 *	1.04 ± 0.20	1.26 ± 0.26 **

* 13 TeV only derived from cross section measurements

** Lower uncertainty (upper uncertainty 31)



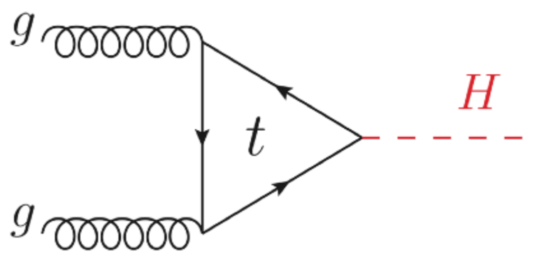
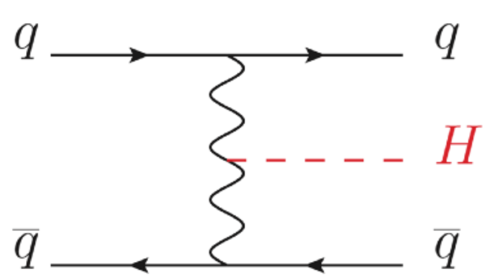
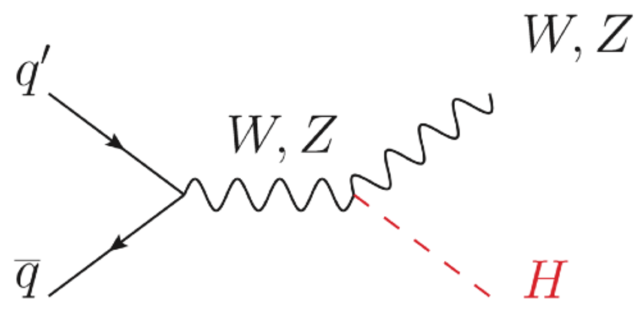
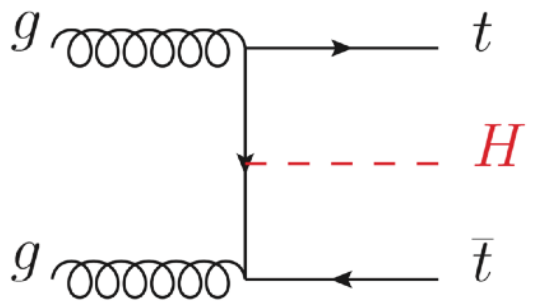




All measurements compatible with the SM Higgs boson

Nano Overview of Main Higgs Analyses at (HL) LHC

Most channels already covered at the LHC Run 1 and Run 2 with only 3% (80 fb-1) of the foreseen full HL-LHC dataset!

	Channel categories	ggF  ~4 M vets produced	VBF  ~300 k vets produced	VH  ~200 k vets produced	ttH  ~40 k evts produced
Observed decay modes	γγ	✓	✓	✓	✓
	ZZ (llll)	✓	✓	✓	✓
	WW (lνlν)	✓	✓	✓	✓
	ττ	✓	✓	✓	✓
	bb	✓	✓	✓	✓
Remaining to be observed	Zγ and γγ*	✓	✓	✓	✓
	μμ	✓	✓	✓	✓
Strong limits will be sufficient	Invisible	✓ (monojet)	✓	✓	✓

Nano Overview of Main Higgs Analyses at (HL) LHC

What is done in Higgs boson couplings analyses is to count number of signal events in specific production and decay channels.

$$n_s^c = \mu \sum_{i \subset \{\text{prod}\}} \sum_{f \subset \{\text{decay}\}} \mu^i \sigma^i_{SM} \times \mu^f Br^f \times \mathcal{A}^{ifc} \times \varepsilon^{ifs} \times \mathcal{L}$$

- At the LHC or any **hadron collider** primarily cross sections times branching ratios are measured: implies that only ratios of couplings can be measured and there is **no constraint on the total width**!

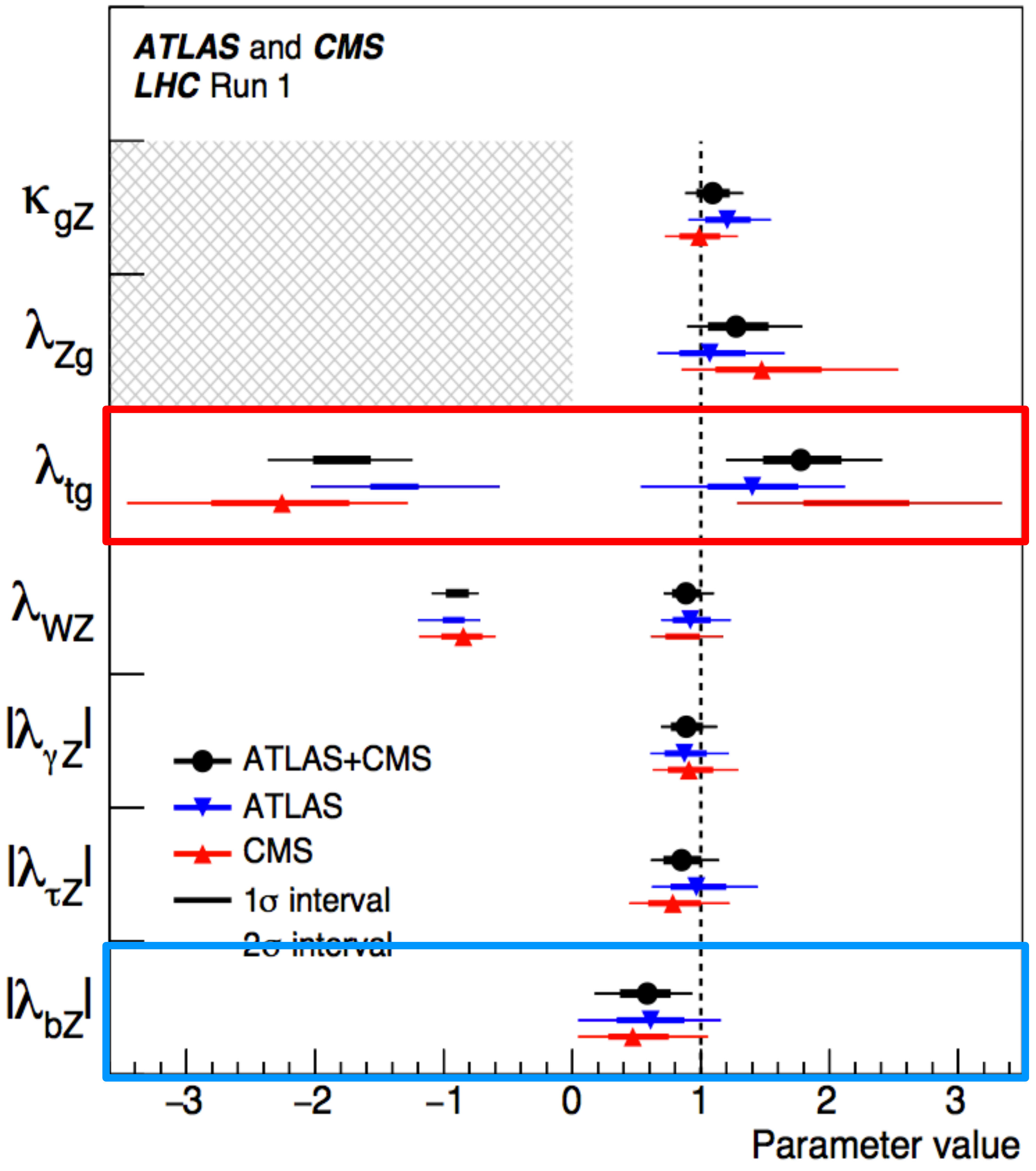
- Absolute measurements of couplings are possible with assumptions (e.g. no BSM width) or with indirect measurements of the width through Off-Shell couplings of the Higgs boson to vector bosons.

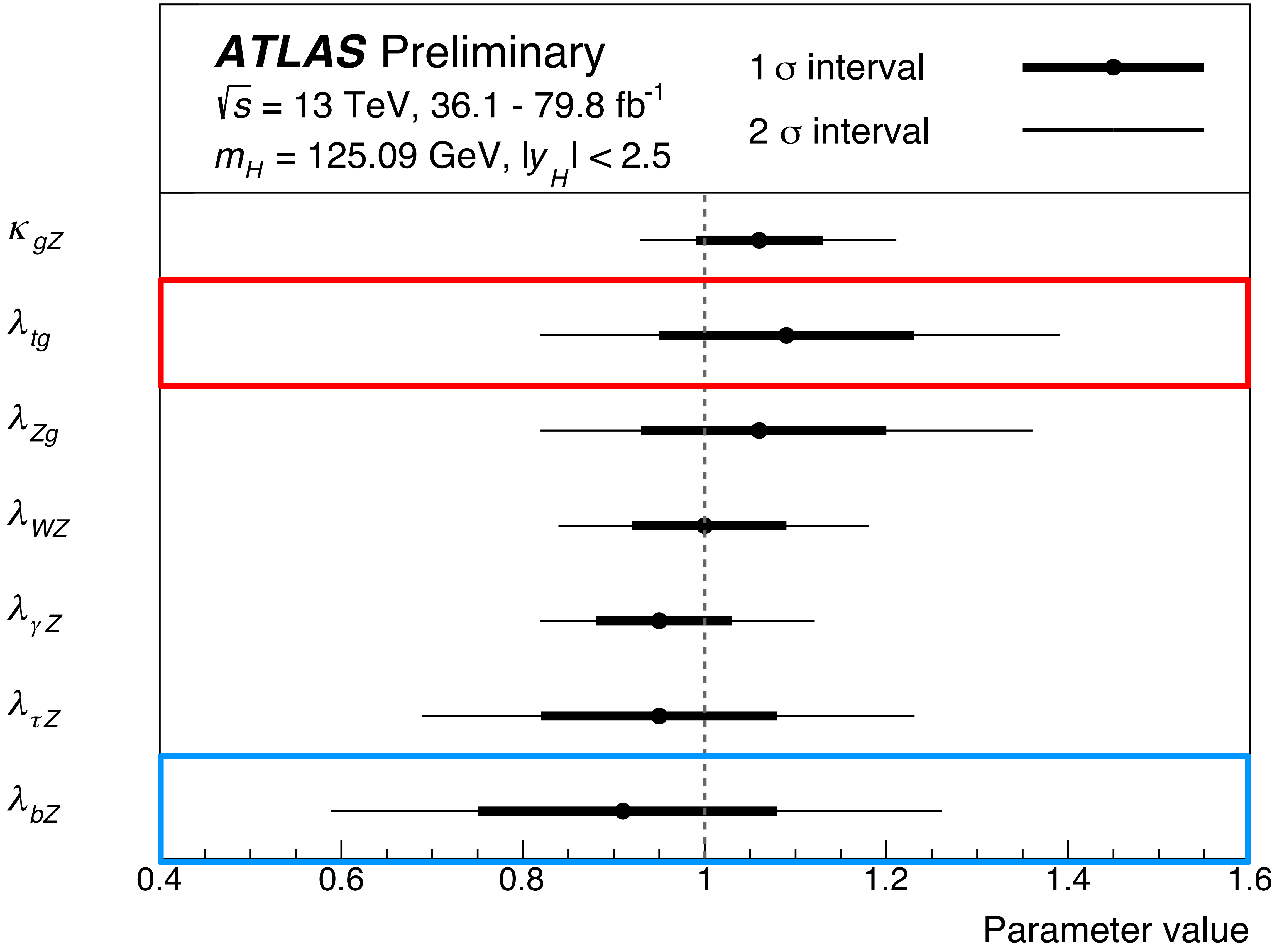
Decay mode	ggH	VBF	VH	ttH
$\gamma\gamma$ (A)	0.81 ± 0.18	2.0 ± 0.6	0.7 ± 0.8	1.4 ± 0.4
$\gamma\gamma$ (C)	1.10 ± 0.19	0.8 ± 0.6	2.4 ± 1.1	2.3 ± 0.8
4ℓ (A)	1.04 ± 0.17	2.8 ± 0.95	0.9 ± 1.0	< 1.8 68% CL
4ℓ (C)	1.20 ± 0.22	0.05 ± 0.04	0.0 ± 1.5	< 1.3 68% CL
WW^* (A)	1.21 ± 0.22	0.62 ± 0.36	3.2 ± 4.3	1.50 ± 0.61
WW^* (C)	1.38 ± 0.23	0.29 ± 0.48	3.27 ± 1.84	1.97 ± 0.67
$\tau^+\tau^-$ (A)	1.14 ± 0.44	0.98 ± 0.46	2.3 ± 1.6	1.36 ± 1.11
$\tau^+\tau^-$ (C)	1.2 ± 0.5	1.11 ± 0.34	-0.33 ± 1.02	0.28 ± 1.02
$b\bar{b}$ (A)	–	-3.9 ± 2.8	0.9 ± 0.27	0.83 ± 0.63
$b\bar{b}$ (C)	2.3 ± 1.66	2.8 ± 1.5	1.2 ± 0.4	0.82 ± 0.43
$\mu^+\mu^-$ (A)	$< 3.0\,(3.1)$	Incl.	–	–
$\mu^+\mu^-$ (C)	$< 2.6\,(1.9)$	–	–	–
$Z\gamma$ (A)	$< 6.6\,(5.2)$	Incl.	–	–
$Z\gamma, \gamma^*\gamma$ (C)	$< 3.9\,(2.9)$	Incl.	Incl.	–
Inv. (A)	–	<28% (31%)	<67% (39%)	–
Inv. (C)	Incl.	<24% (23%)	–	

Review of current results

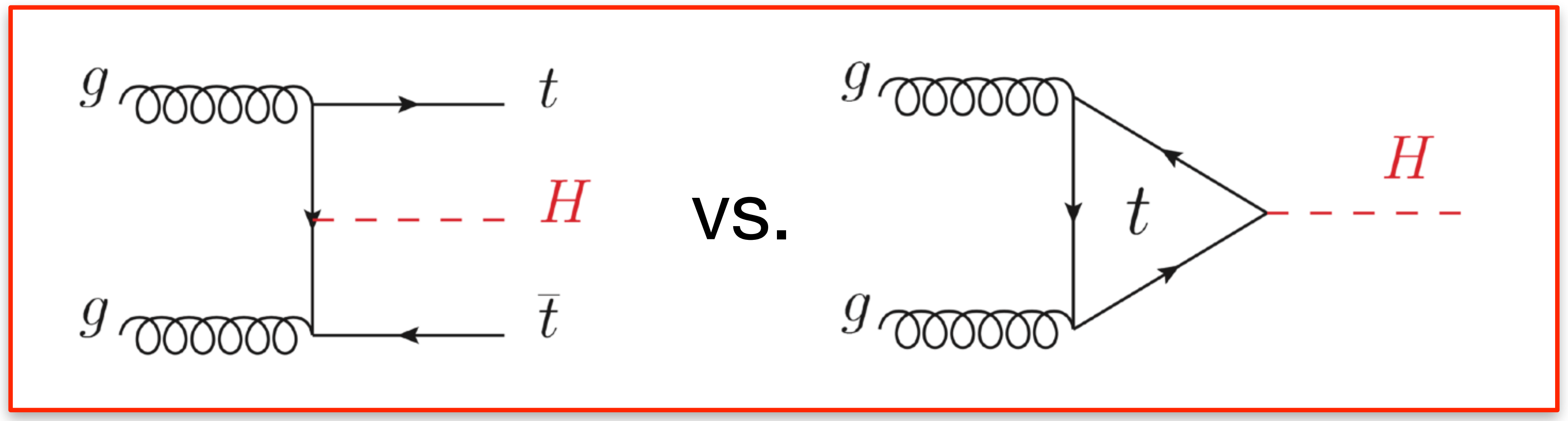
Run 1 versus (partial) Run 2

Δκ/κ ~ 11%
Δλ/λ ~ 23%
Δλ/λ ~ 30%
Δλ/λ ~ 11%
Δλ/λ ~ 12%
Δλ/λ ~ 16%
Δλ/λ ~ 34%





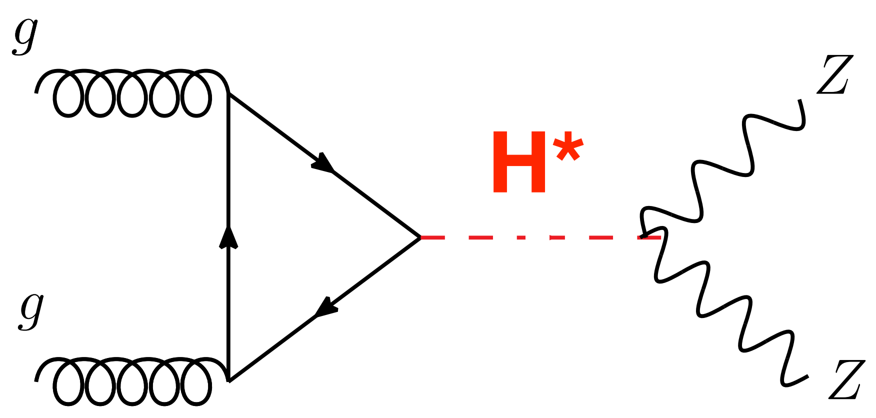
Δκ/κ ~ 7%
Δλ/λ ~ 15%
Δλ/λ ~ 15%
Δλ/λ ~ 9%
Δλ/λ ~ 8%
Δλ/λ ~ 13%
Δλ/λ ~ 18%

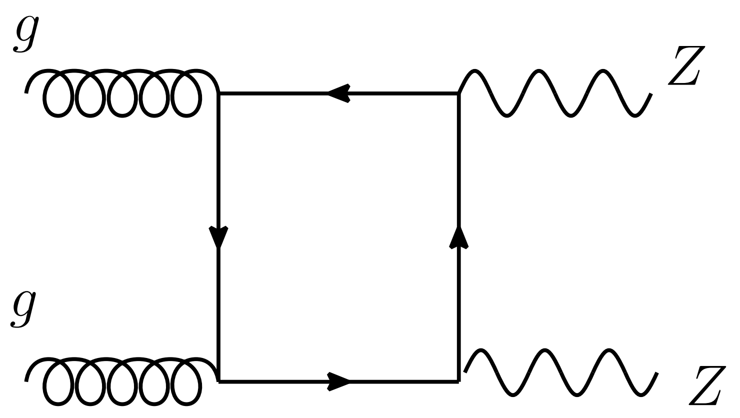


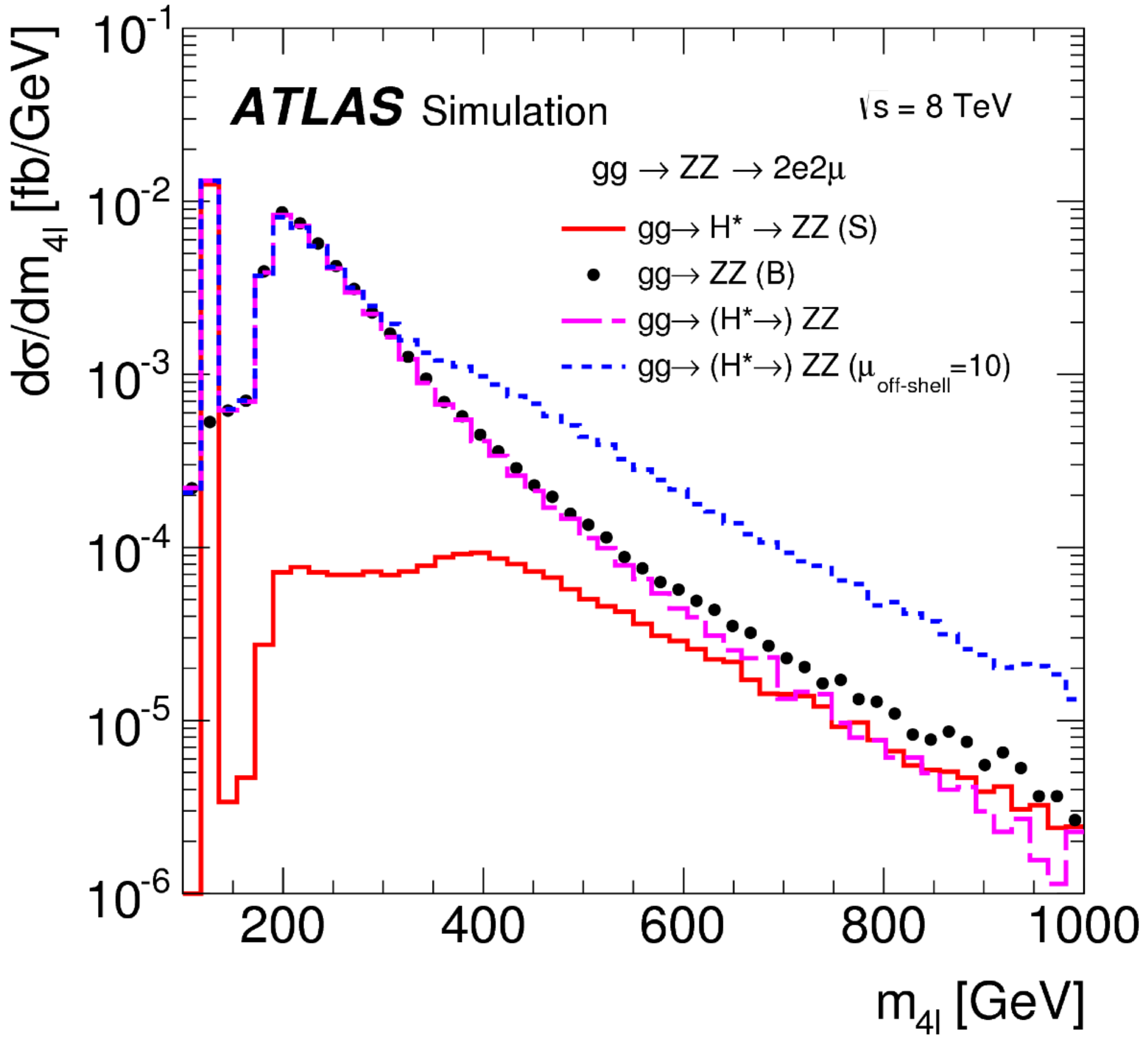
Off Shell Higgs

Study the Higgs boson as a propagator

Study the 4-leptons spectrum in the high mass regime where the Higgs boson acts as a **propagator**







Measuring the Higgs contribution is then independent of the total width of the Higgs boson (sensitive to the product off shell of the Higgs boson to the coupling to the top and Z)

Assuming that the couplings run as in the Standard Model, measuring them on shell allows for a measurement of the width of the Higgs boson!

$$\mu_{off\ shell} = (\kappa_t^2 \kappa_V^2)_{off\ shell}$$

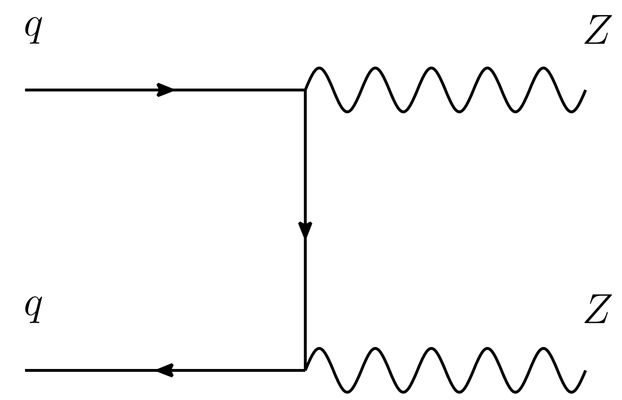
$$\mu_{on\ shell} = \frac{(\kappa_t^2 \kappa_V^2)_{on\ shell}}{\Gamma_H / \Gamma_H^{SM}}$$

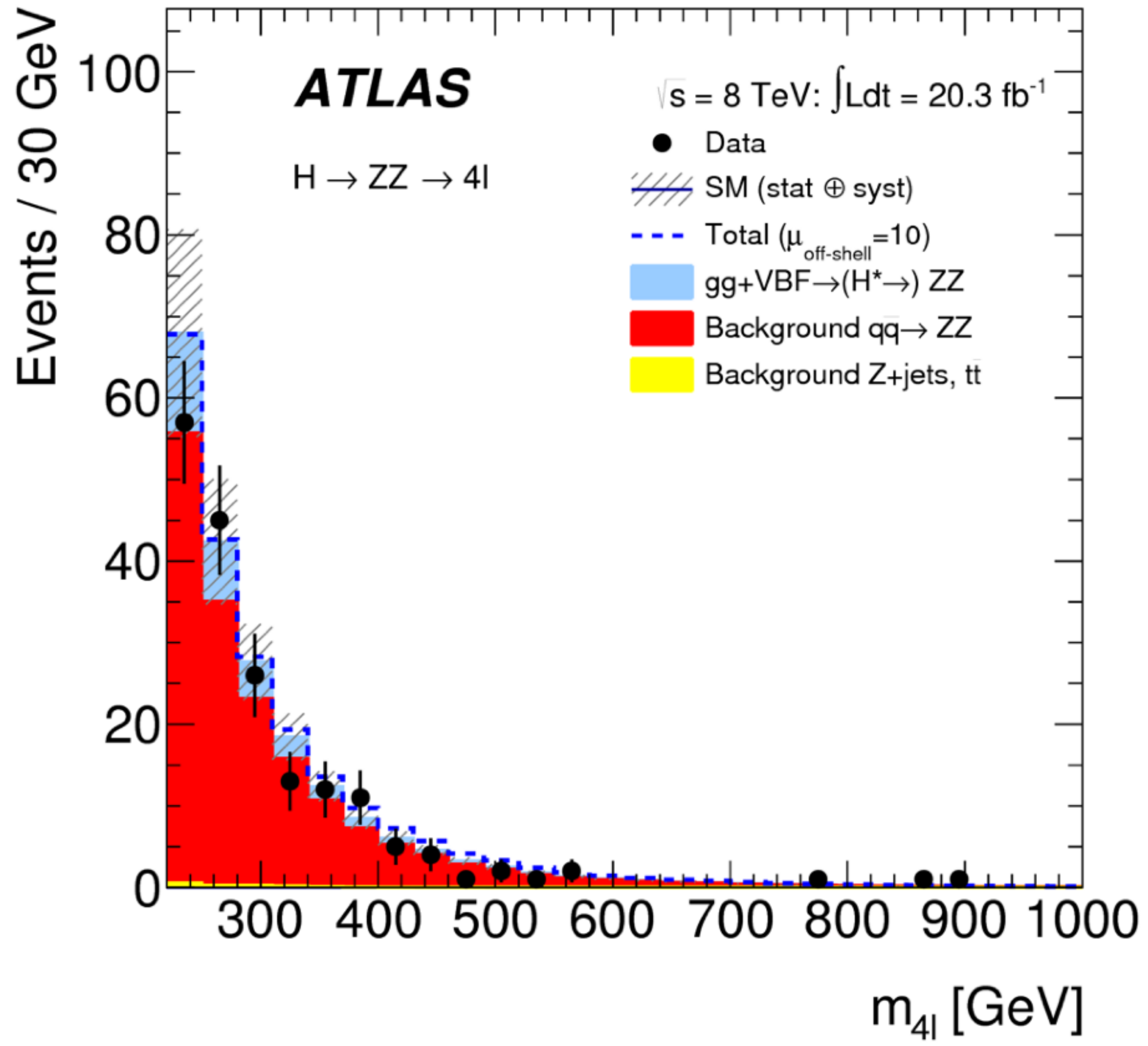
$$(\kappa_t^2 \kappa_V^2)_{on\ shell} = (\kappa_t^2 \kappa_V^2)_{off\ shell}$$

$$\Gamma_H = \frac{\mu_{off\ shell}}{\mu_{on\ shell}} \times \Gamma_H^{SM}$$

Highly non trivial due to:

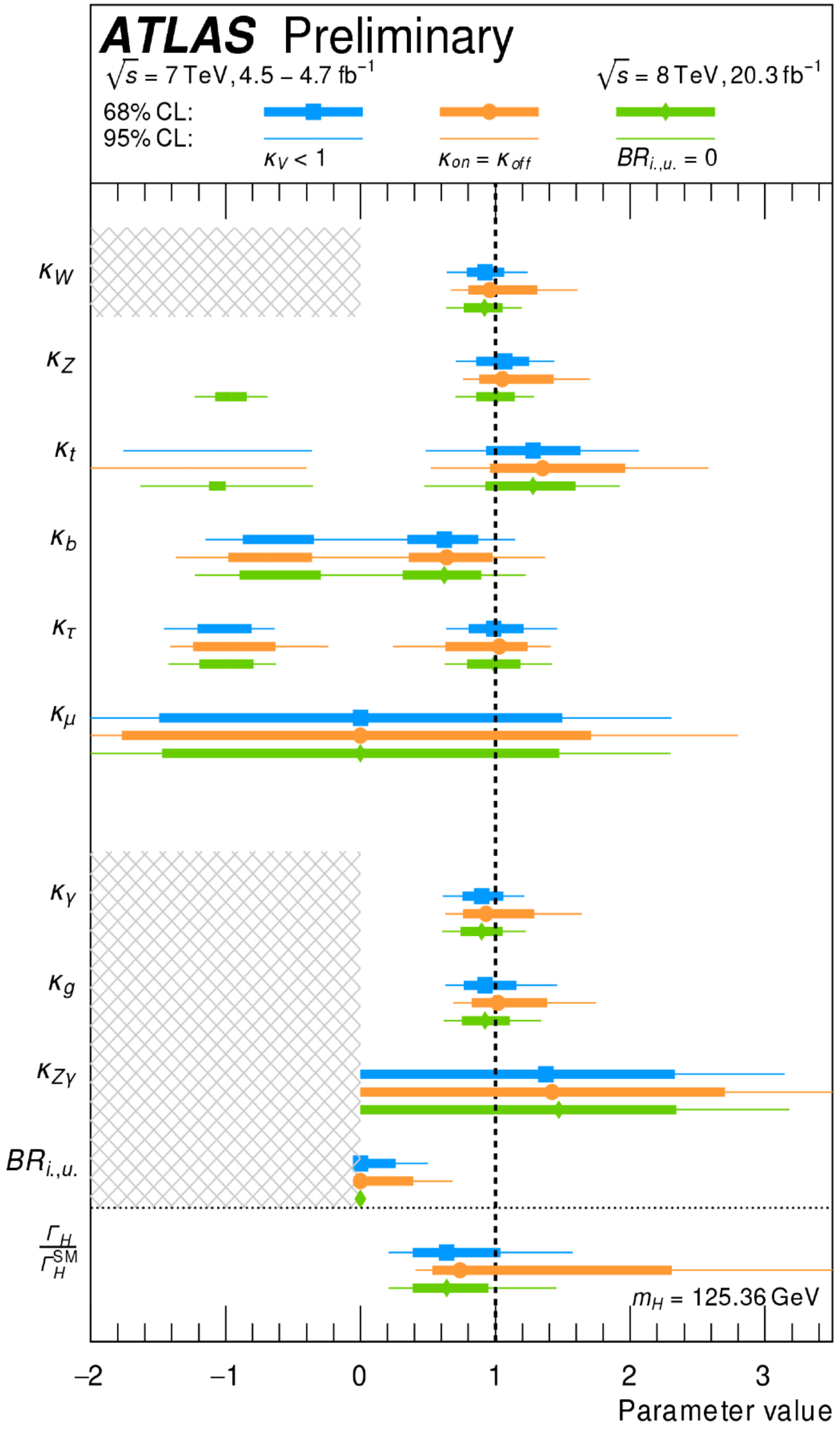
- The negative interference
- The large other backgrounds





Limits on the total width are currently at approximately 15 MeV

Absolute Measurement of Couplings at LHC?



Absolute couplings measurements under specific conditions:

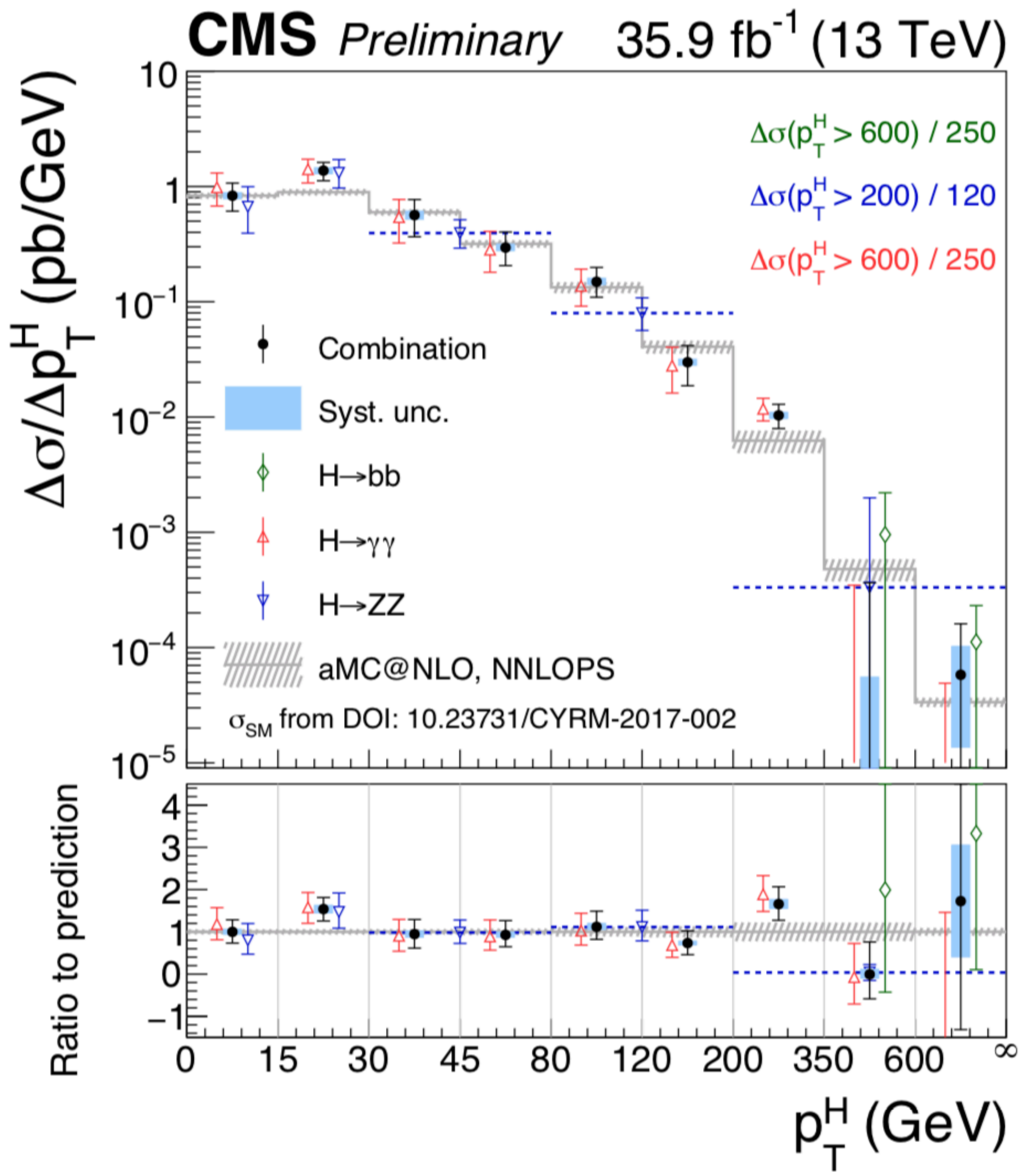
- **Green**: Constrain the width to SM field content only.
- **Blue**: Unitarity inspired constraint $k_V < 1$
- **Orange**: Use Run 1 constraints from Off-Shell coupling

$$\Gamma_{tot} < 22.7 \text{ MeV}$$

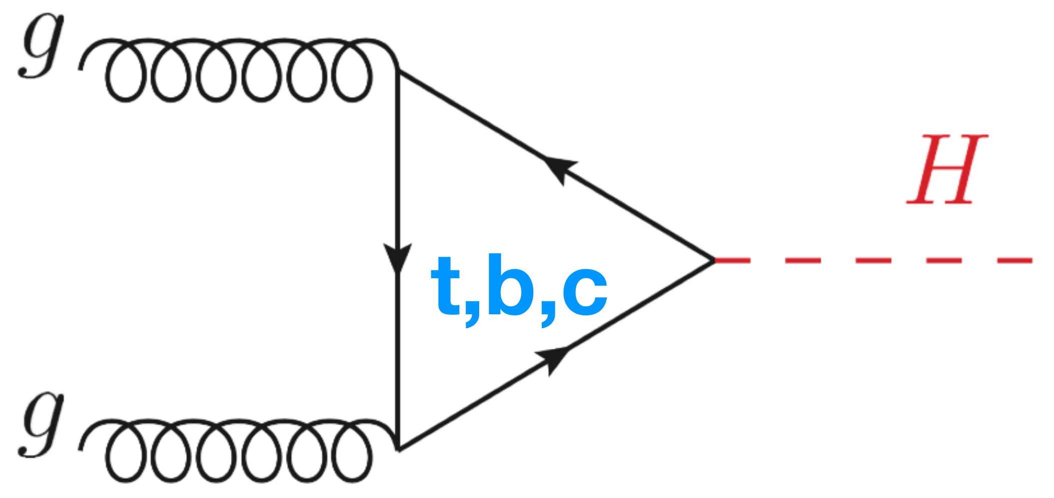
Limit using three channels ZZ(4l and llvv) and WW(lvlv).

Differential Cross Sections

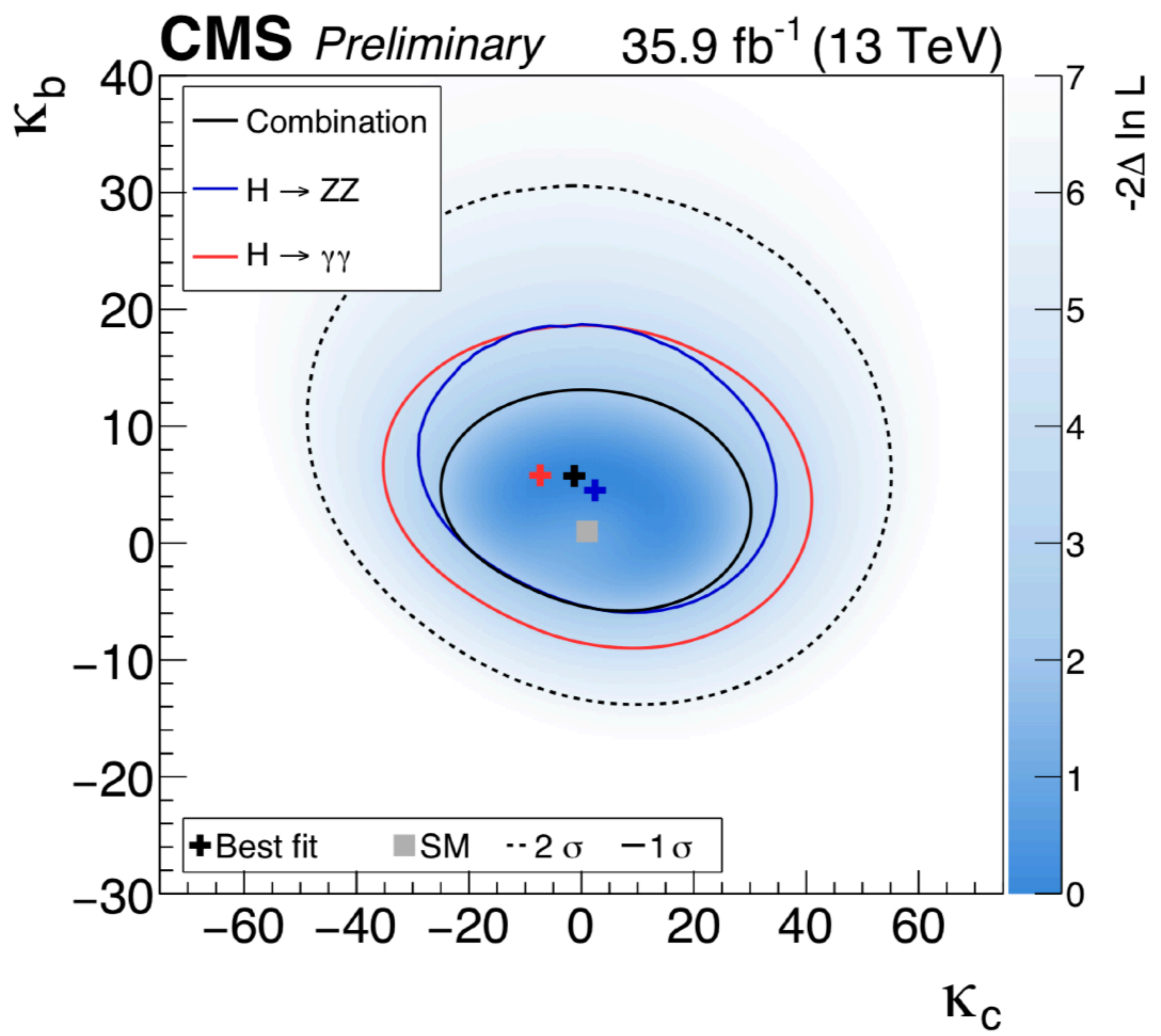
Couplings constraints through loop effects



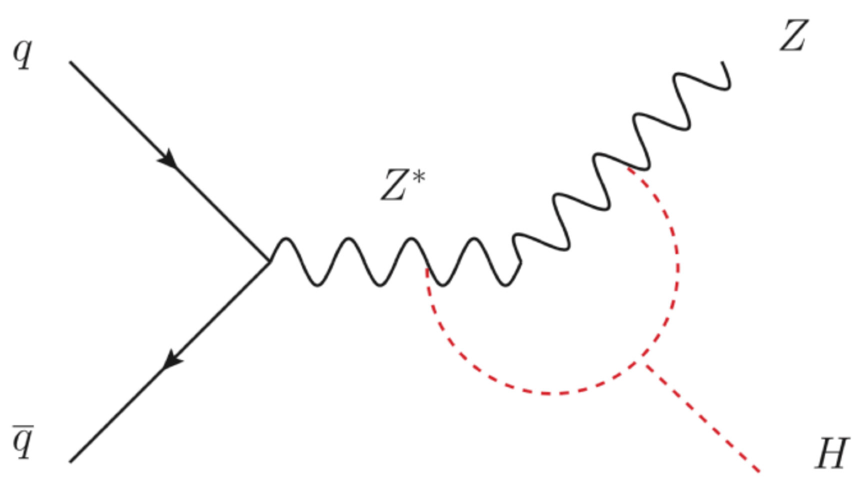
Fiduciall differential cross sections in transverse momentum are sensitive to the loop content in the gluon fusion production



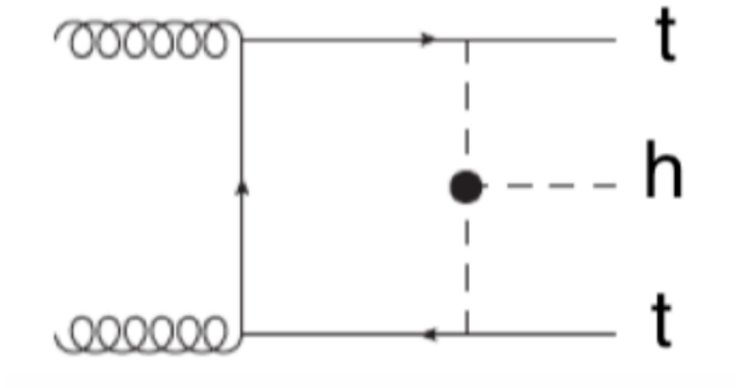
Recent indirect measurement of the b and c Yukawa couplings through their effecting the production loop.



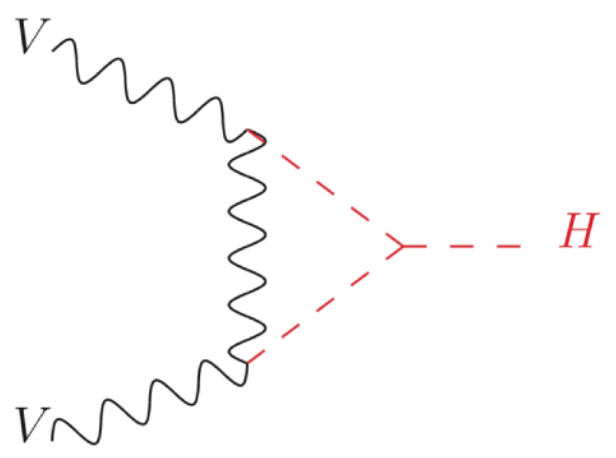
Similarly other processes can be used to gain sensitivity to the Higgs boson self couplings



VH Production at high VH mass



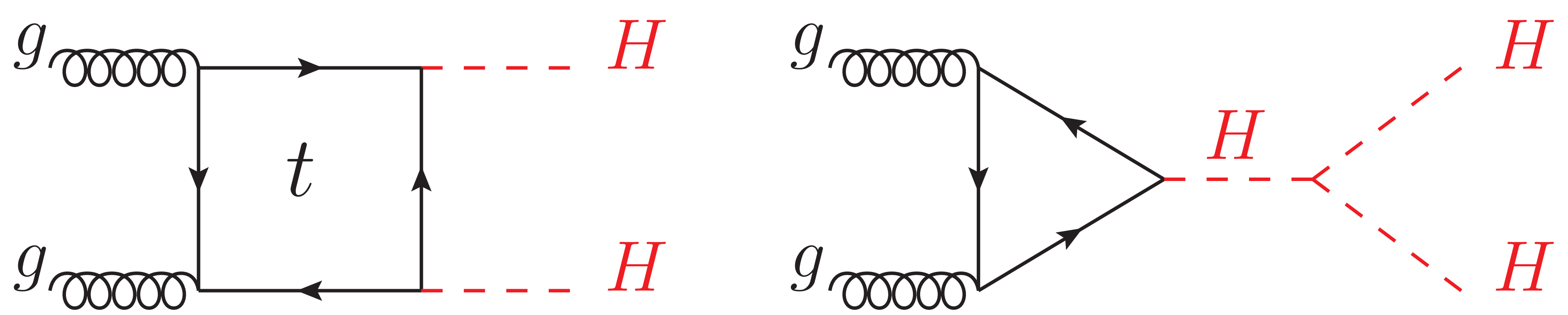
ttH Production



Higgs decays (e.g. 4l, etc…)

Current constraints not significant

Double Higgs Production and Higgs Self Coupling



- **Off Shell Higgs analysis**: Search very similar to the Off Shell couplings of the Higgs boson in the two vector bosons channels. It is also done far Off shell in mass.

- The total production cross section is very small. First step is a limit on HH production (**inclusively**).

Yellow: 12 fb-1   Orange: 36 fb-1

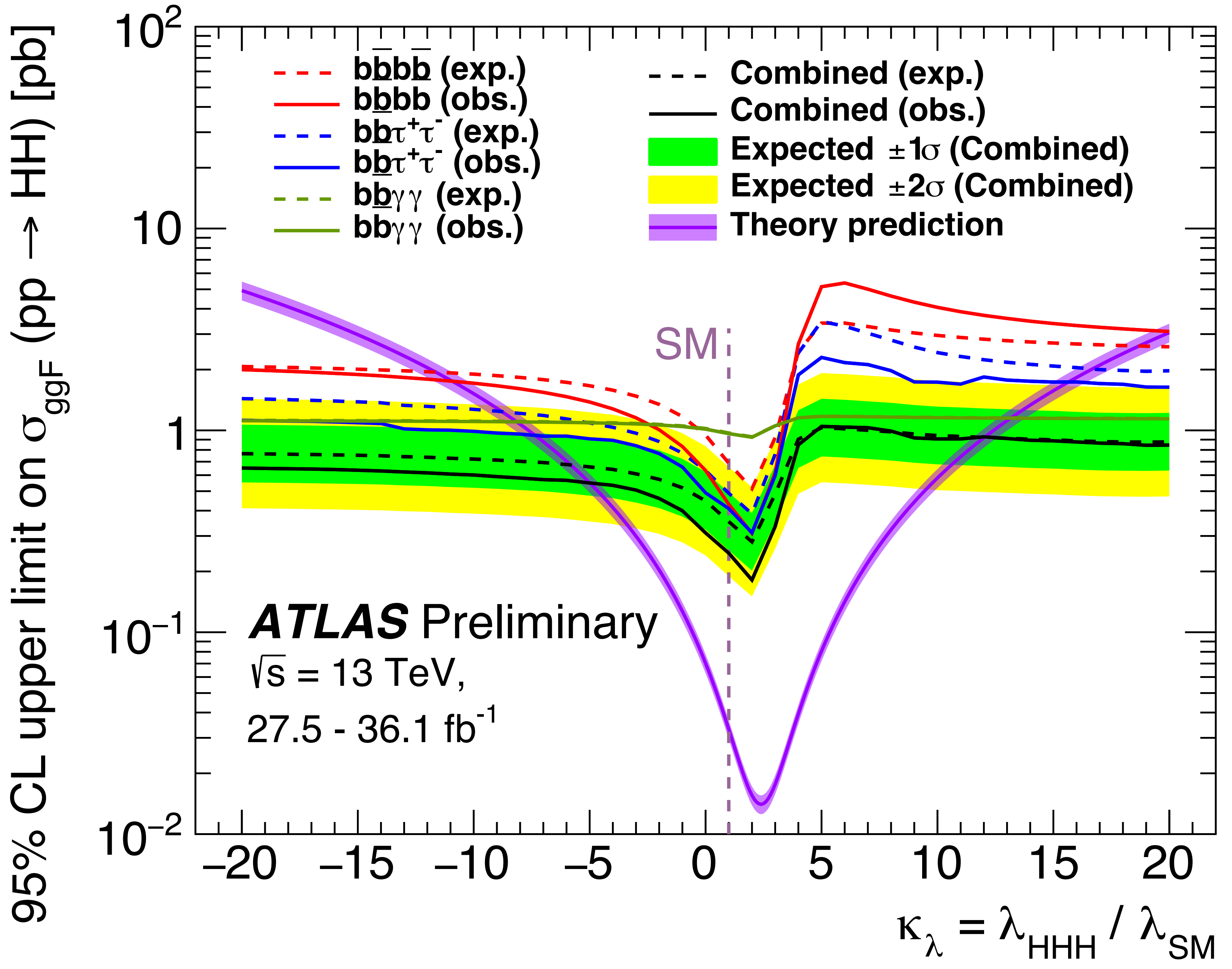
exp.	WW$\gamma\gamma$	bb $\gamma\gamma$	bb $\tau\tau$	bbWW	bbbb
$\sigma \times B$	0.1 %	0.26 %	7 %	25 %	34 %
ATLAS	<747 (386)	<22 (28)	**<13 (15)**	-	<13 (21)
CMS	-	<24 (19)	<30 (25)	<79 (89)	<75 (37)

CMS combination $\sigma_{HH} < 13 \times \sigma_{SM} \quad (15 \text{ exp.})$

- **Multiple channels investigated:** depending on the both Higgs decays considering (bb, yy, tautau, WW)

- Evolution of sensitivities has brought interesting surprises.

ATLAS combination $-5.0 < \kappa_\lambda < 12.1$



Higgs physics Landscape at LHC… and Beyond

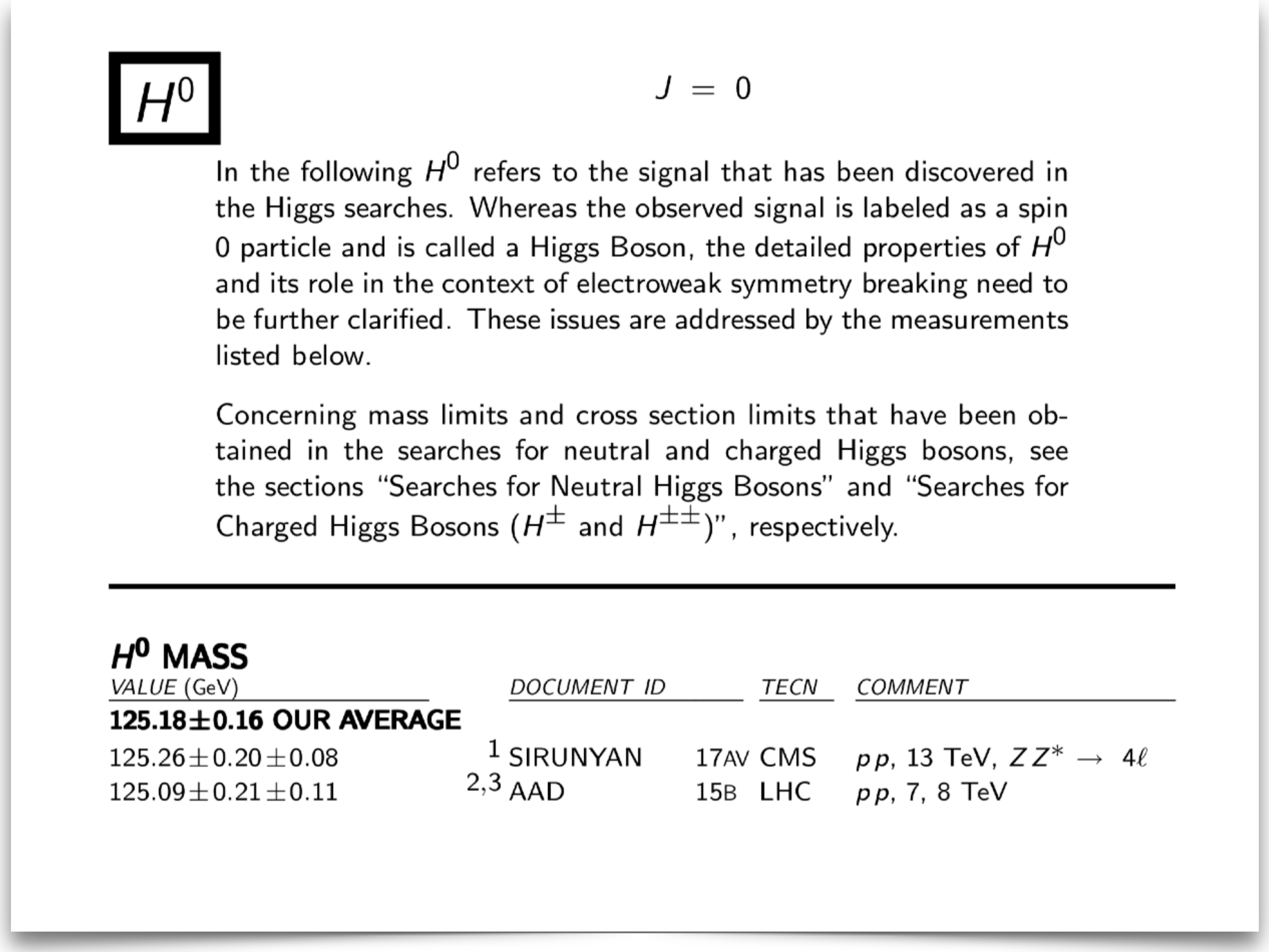
There is much more to it
… but no time to discuss it here

Precision
- Mass and width
- Coupling properties
- Quantum numbers (Spin, CP)
- Differential cross sections
- STXS
- EFT Interpretations
- Off Shell couplings and width
- Interferometry

Rare decays
- $Z\gamma$, $\gamma\gamma^*$
- Muons $\mu\mu$
- LFV $\mu\tau$, $e\tau$
- $J/\Psi\gamma$, ZY, WD
- Phiγ, rhoγ

Rare Production
- tH
- FCNC top decays
- Di-Higgs production (and trilinear couplings)

The Higgs particle



H^0 $J = 0$

In the following H^0 refers to the signal that has been discovered in the Higgs searches. Whereas the observed signal is labeled as a spin 0 particle and is called a Higgs Boson, the detailed properties of H^0 and its role in the context of electroweak symmetry breaking need to be further clarified. These issues are addressed by the measurements listed below.

Concerning mass limits and cross section limits that have been obtained in the searches for neutral and charged Higgs bosons, see the sections "Searches for Neutral Higgs Bosons" and "Searches for Charged Higgs Bosons ($H^{\pm}$ and $H^{\pm\pm}$)", respectively.

H^0 MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
125.18±0.16 OUR AVERAGE				
125.26±0.20±0.08	[1] SIRUNYAN	17AV	CMS	pp, 13 TeV, $ZZ^* \to 4\ell$
125.09±0.21±0.11	[2,3] AAD	15B	LHC	pp, 7, 8 TeV

PDG Listing entry for the Higgs boson

Is the SM minimal?
- 2 HDM searches
- MSSM, NMSSM searches
- Doubly charged Higgs bosons

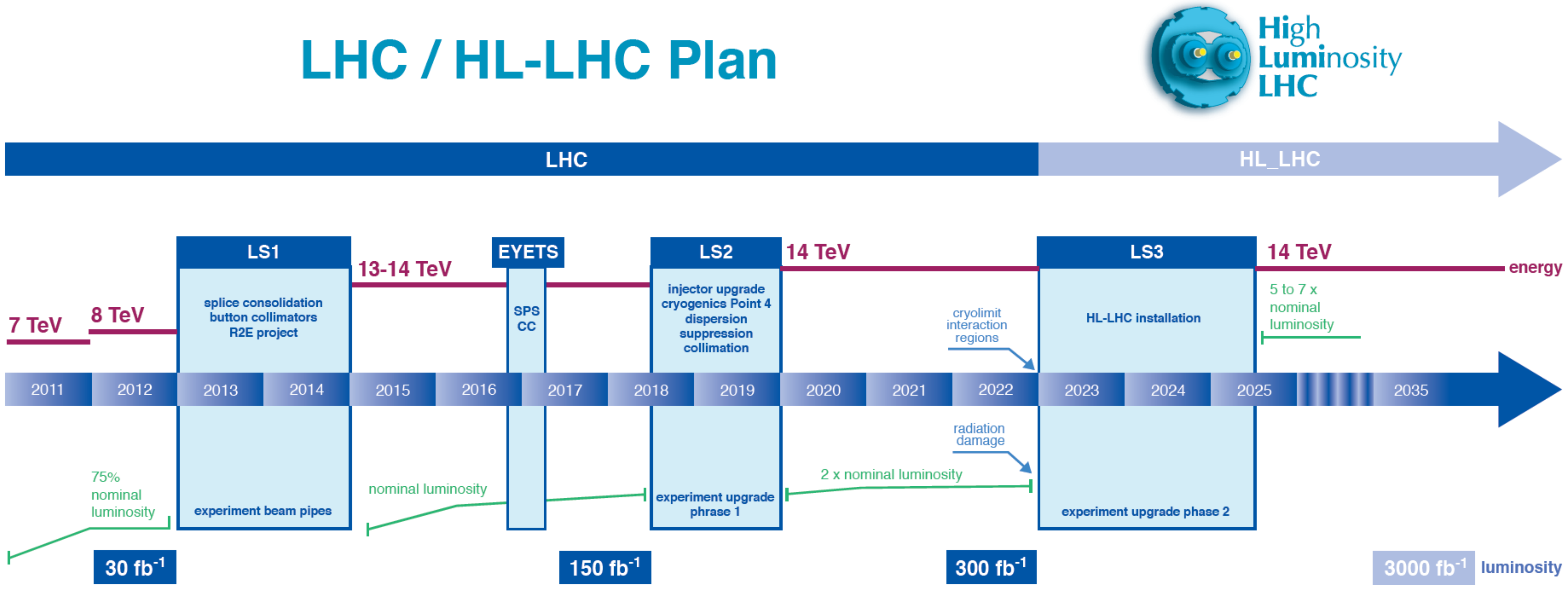
Tool for discovery
- Portal to DM (invisible Higgs)
- Portal to hidden sectors
- Portal to BSM physics with H^0 in the final state (ZH^0, WH^0, H^0H^0)

Covered by Claudio

Most of these topics extend to future colliders (not detailed in this lecture)

Extrapolations to HL-LHC

Project	HL-LHC
Location	CERN
Circ.	27 km
COM energy	14 (15?) TeV
Luminosity	2 x 3 ab-1
PU	140-200
Field	8T



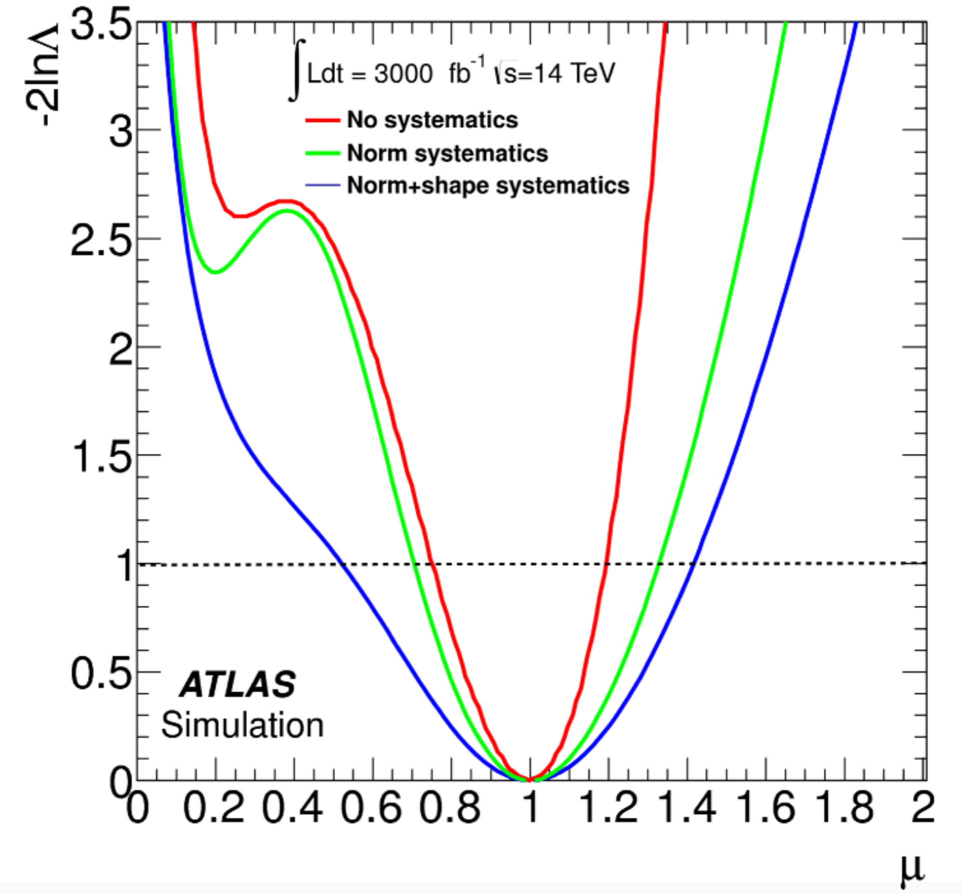
- A lot has been learned from the current LHC analyses.
- Approaching the Update of the European Strategy for Particle Physics Update in 2020, all projections are being updated.
- Only have new numbers for a very recent update of the main couplings measurements.

Nano Overview of Main Higgs Analyses at (HL) LHC

- Projections of made in 2013 for the last update of the European strategy.
- Preliminary more recent projections including recent analysis improvements (from CMS).

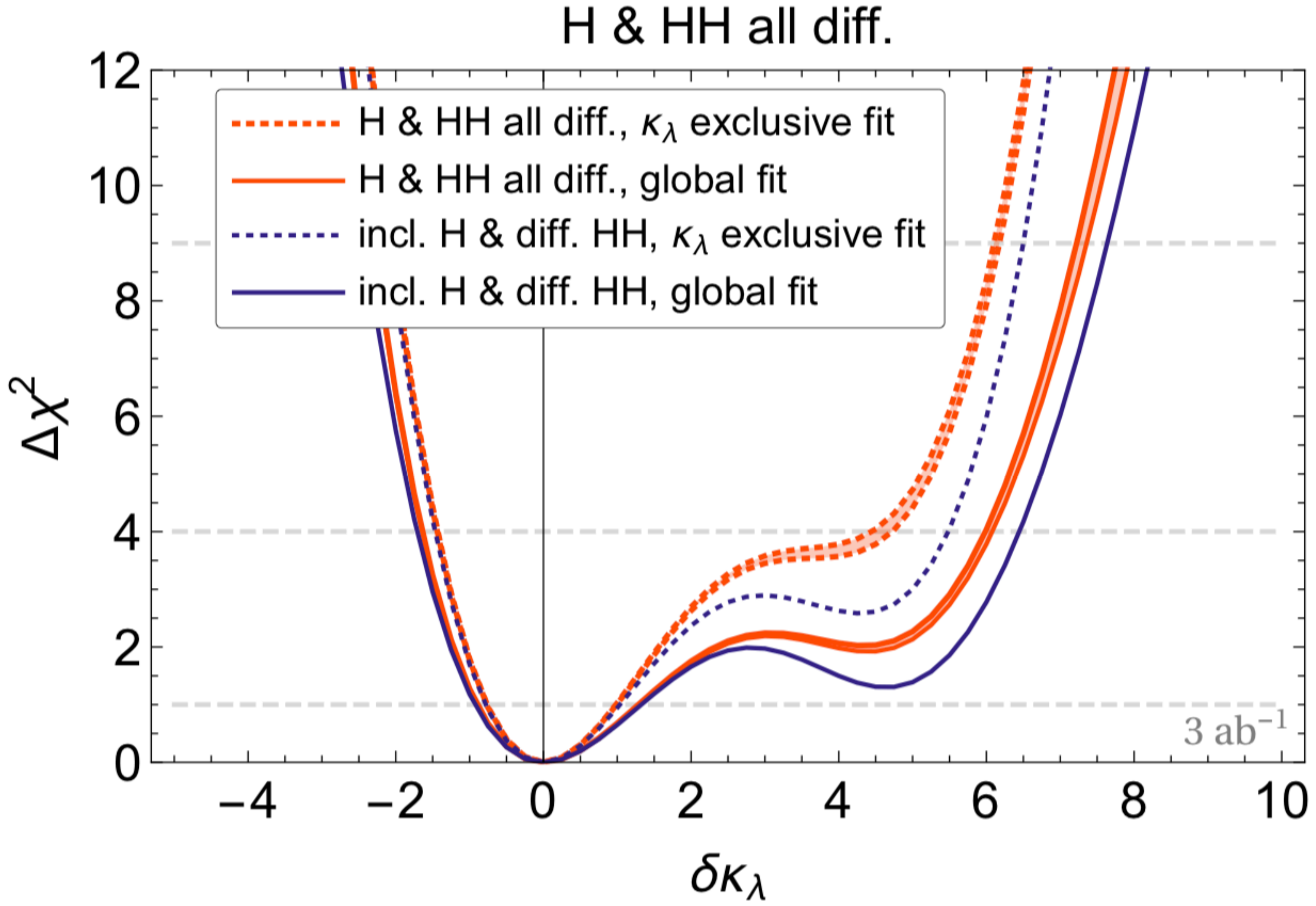
Coupling	LHC*	ES 2013	HL-LHC
ZZ	~10 %	2-4%	1.6-2.2%
WW	~10%	2-5%	1.7-2.3%
bb	~15 %	4-7%	3.4-4.8%
cc	-	-	-
gg	~10%	3-5%	2.3 - 3.6%
$\tau\tau$	~15 %	2-5%	1.9-2.6%
$\mu\mu$	-	5-8%	5.0-6.6%
$\gamma\gamma$	~10%	2-5%	2.0-2.7%
$Z\gamma$	<3.9		
tt	~10 %	7-10%	2.8-4.7%
HH	<15 x SM	60 %	30-40%
uu, dd	-	-	-
Binv	<20%	-	<5%
Γ_{tot}	-	-	~30%
λ	-	-	~100%

For one LHC experiment



Preliminary HL-LHC results show that a reasonable sensitivity can be obtained with 3 ab-1:

$$\Gamma_H = 4.2^{+1.5}_{-2.1}\,MeV$$



- With a global fit impact of single Higgs observable limited.
- Projections being reappraised with more channels and new analyses.

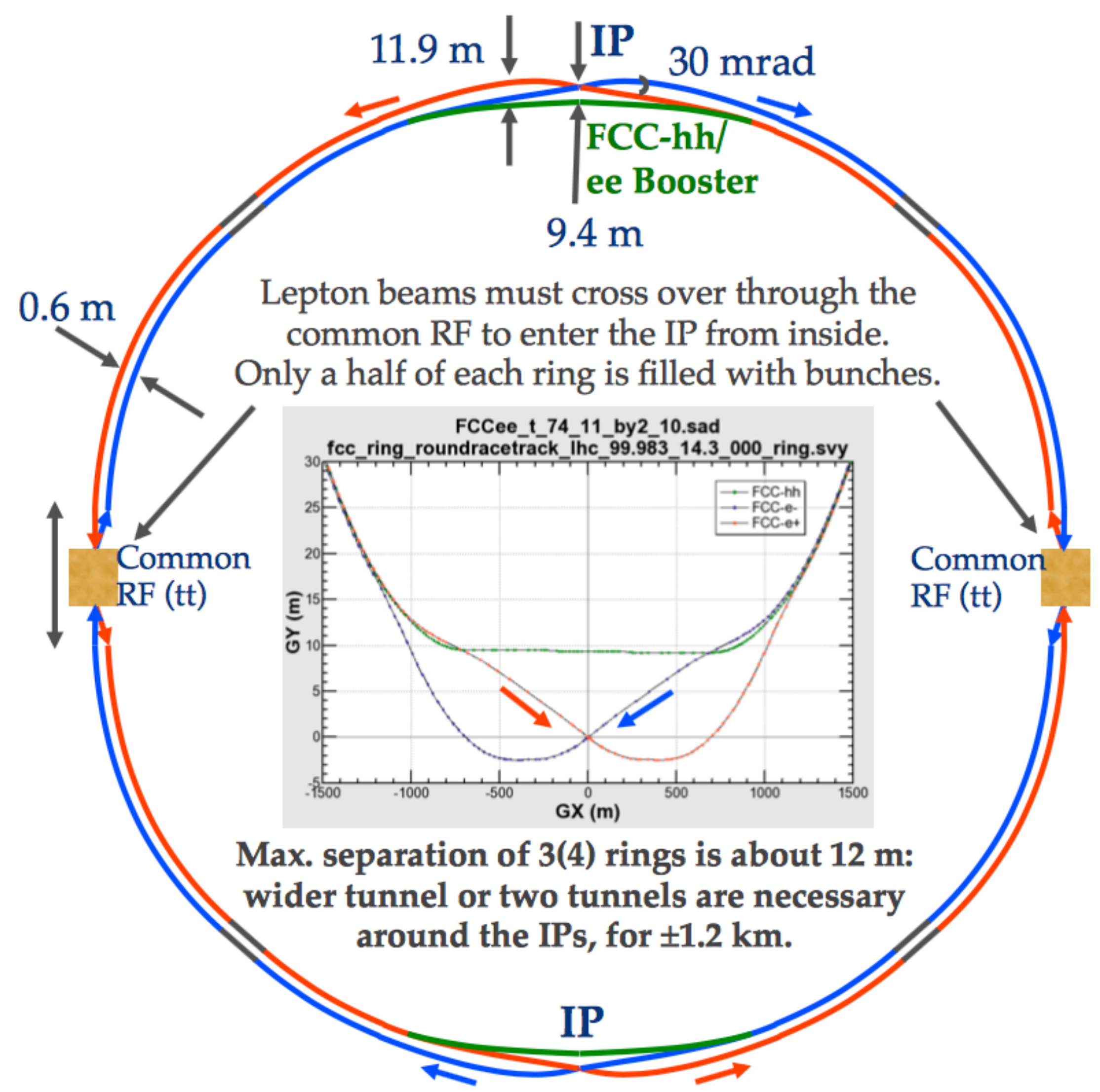
Higgs Factories and Beyond

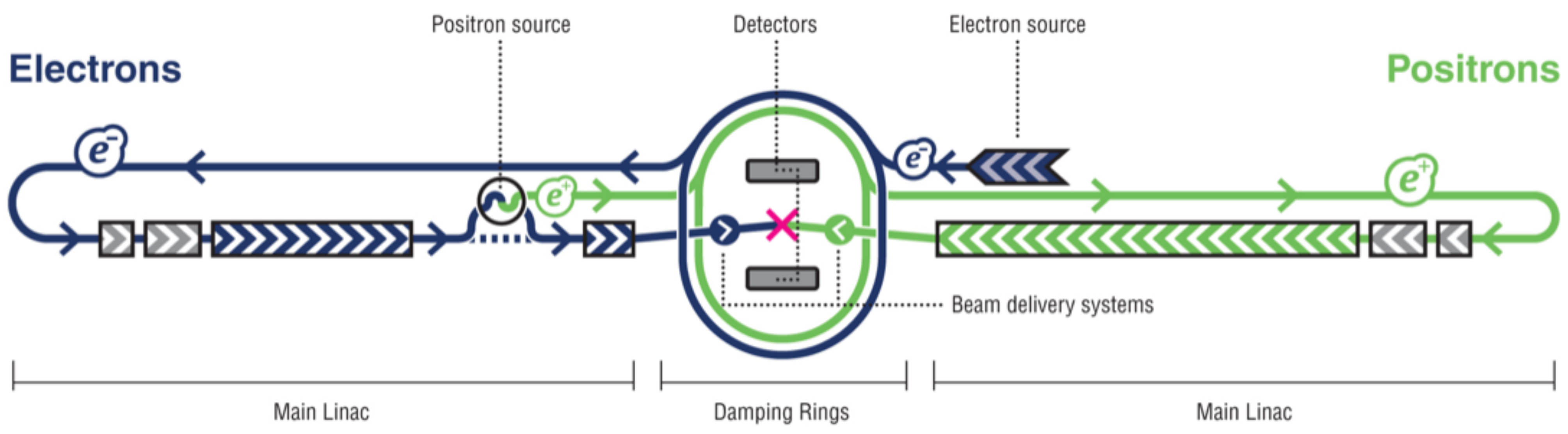
Lepton Collider Projects: Higgs Factories and beyond

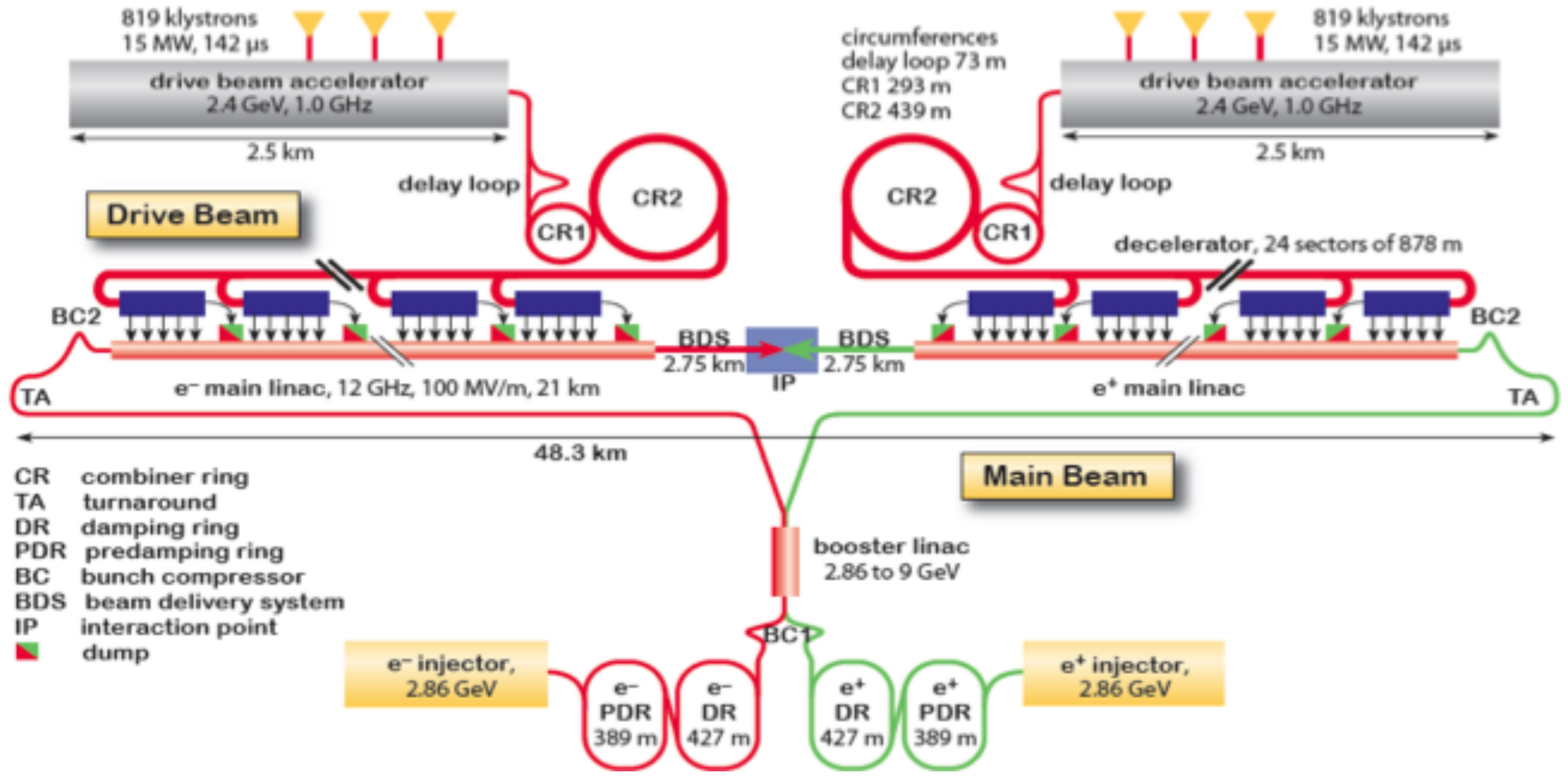
The e+e- candidate machines in a tiny nutshell

Project	ILC	CLIC	FCC-ee	CepC
Location	Kitakami - JP	CERN	CERN	China TBD
Length	20.5 km	50 km	100 km	100 km
COM energy	250 GeV	0.35, 0.5, 3 TeV	90-365 GeV	90 -250 TeV
Lumi*	1.35 10^{34} $cm^{-2}s^{-1}$	1-2 10^{34} $cm^{-2}s^{-1}$	7 10^{34} $cm^{-2}s^{-1}$	2x2 10^{34} $cm^{-2}s^{-1}$
Int. Lumi*	2 ab^{-1}	0.5, 1.5, 3 ab^{-1}	2x 5 ab^{-1}	2x 3 ab^{-1}

*At 250 GeV



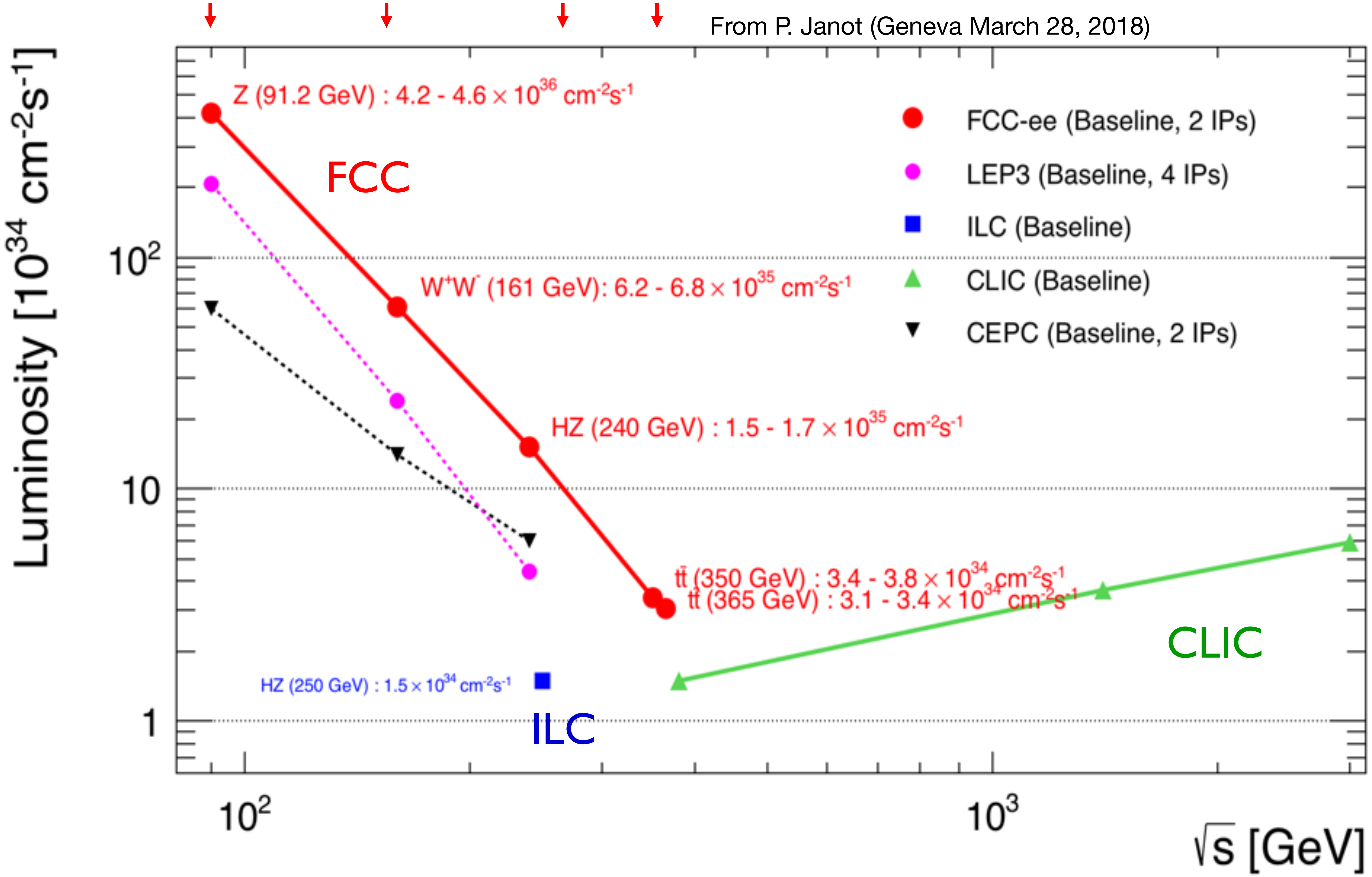




The FCC-ee Project

LEP × 10^5 !

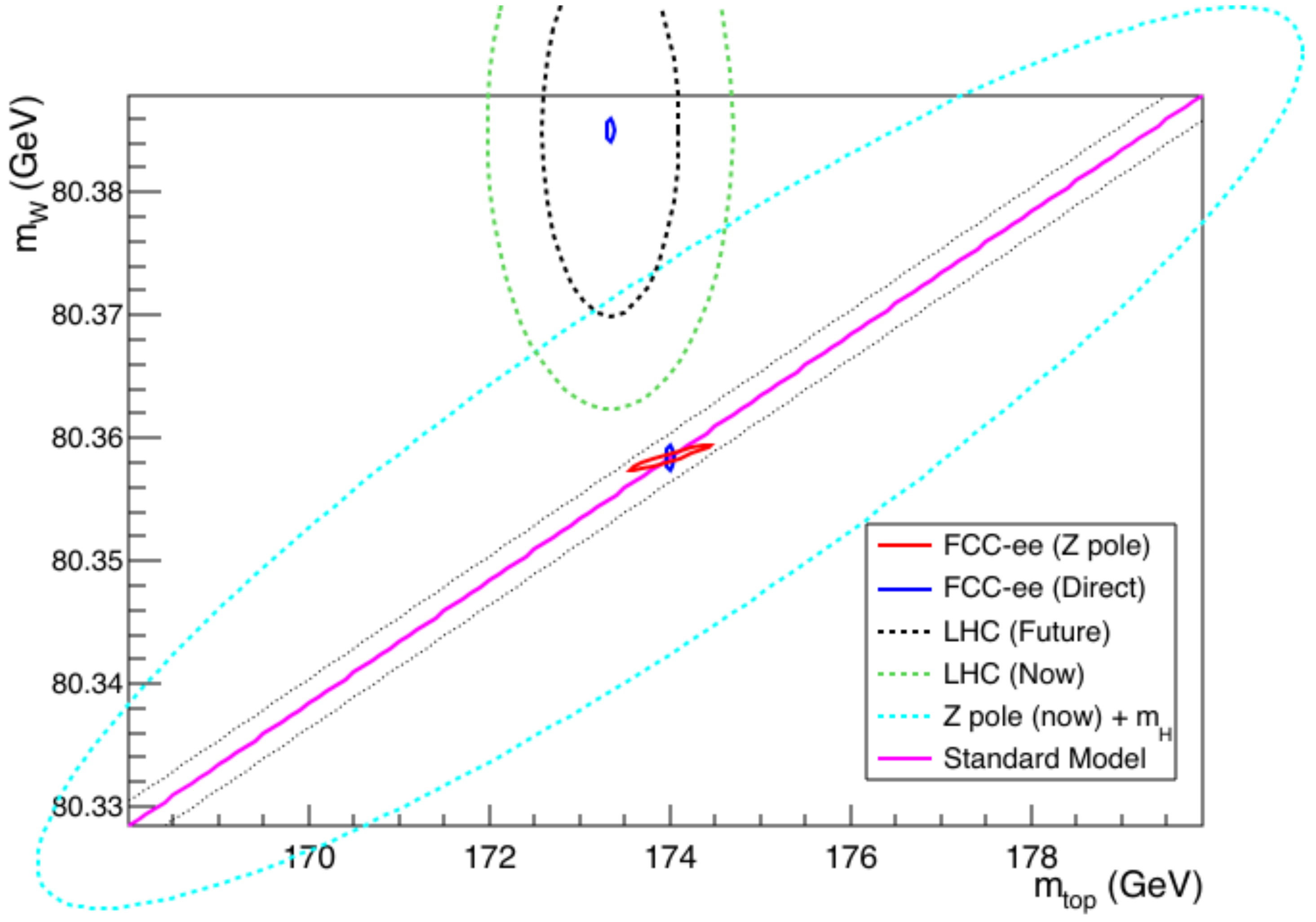
Z WW HZ $t\bar{t}$



Colossal amount of extremely useful data in a very clean environment!

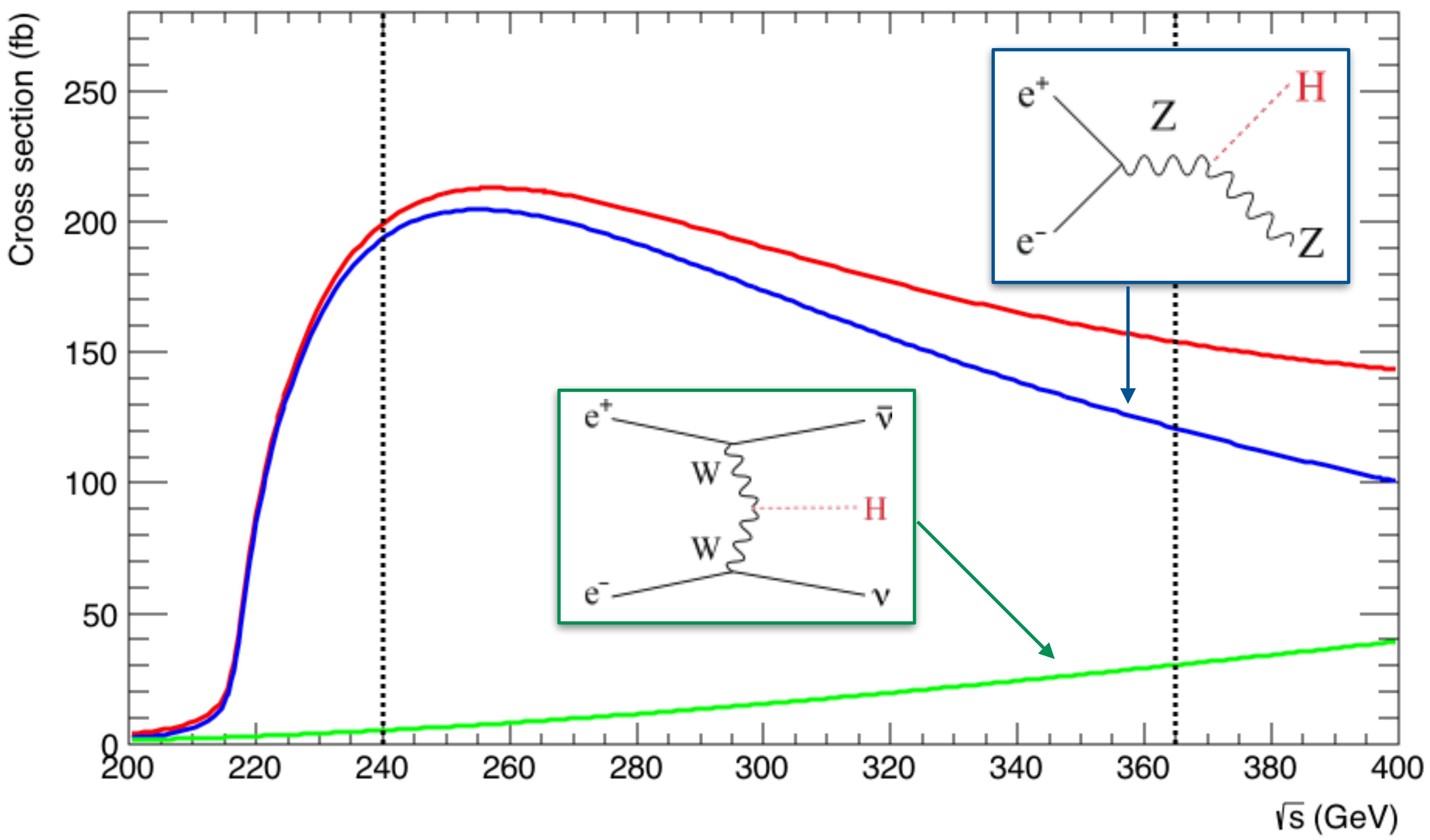
- No Pile up
- Centre-of-mass energy of the collision well known (full Energy and momentum conservation constraints).

- 100 000 Z / second
- 10 000 W / hour
- 1 500 Higgs bosons / day
- 1 500 top quarks / day



Requires 10-fold improved theory calculations

Higgs Physics at the FCC-ee



1M per IP very clean ZH events produced at threshold for 5 ab-1

Approximately 1/3 of the number of ZH events at HL-LHC but in a much cleaner environment!

All final states can be very cleanly reconstructed.

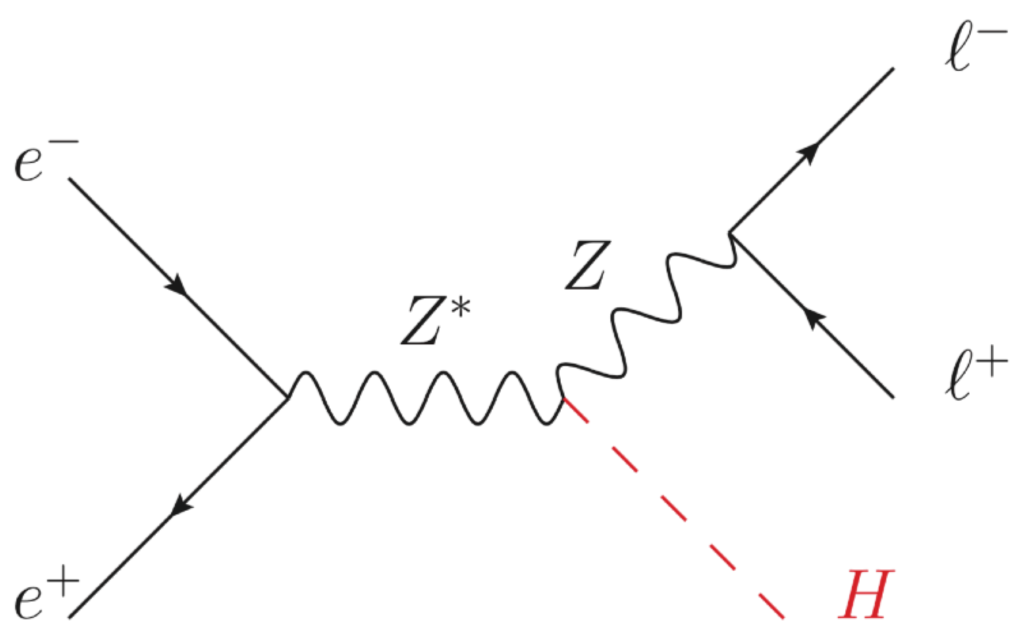
Additional 200k events at 350-365 GeV with approximately 30% from WW fusion which is interesting for the width measurement

- With 1M events precision ranges from 0.2% to 5%
- Measure $\sigma(e^+e^- \to HZ)$ x Br(H → bb, cc, gg, WW, ττ, γγ, μμ, Zγ, …) from each individual final state.
- Can also measure invisible decays from the reconstructed Z boson.

Fundamental difference with the LHC (and other hadron colliders): the width can be measured from the total HZ cross section!

Higgs Width at HZ Threshold

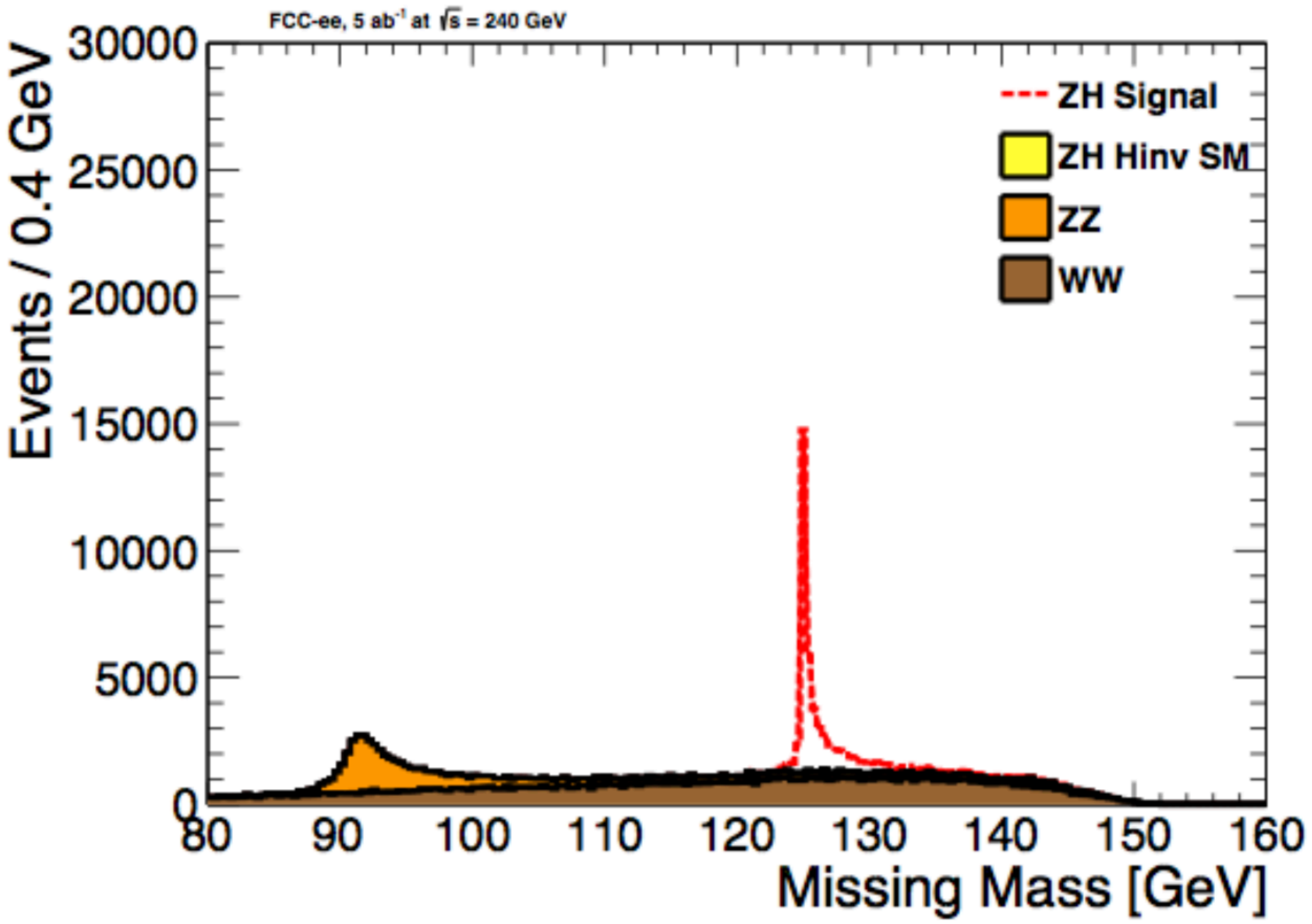
Threshold production of HZ at e+e- colliders provide a opportunity to measure the total HZ cross section through the recoil method



$$m^2_{\text{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |p_{\ell\ell}|^2$$

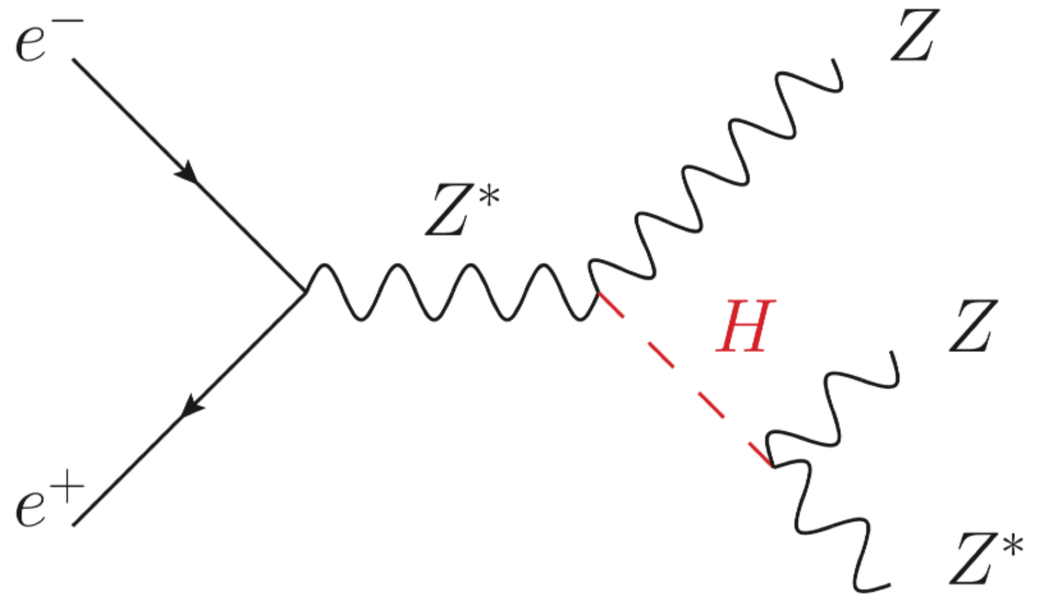
From conservation of energy and momentum, the energy and momentum of the Higgs is known from the Z without measuring the Higgs boson!

$$\sigma(e^+e^- \to HZ) \propto \kappa_Z^2$$



Measurement of the cross section at 240 GeV at 0.5% precision (0.9% at 365 GeV).

Then using the measurement of HZ with the Higgs to ZZ*:

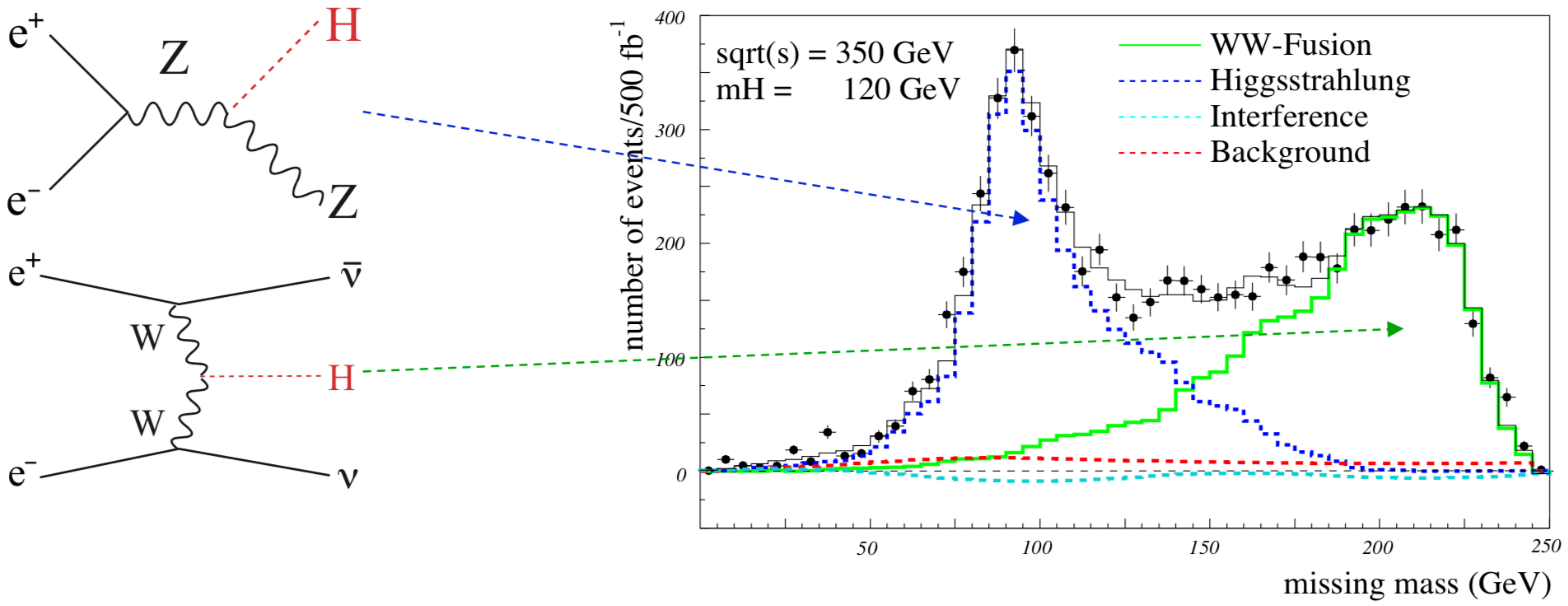


The total width of the Higgs can be measured at **2.8%** level with FCC-ee (240) alone.

$$\sigma(e^+e^- \to HZ) \times B(H \to ZZ^*) \propto \frac{\kappa_Z^4}{\Gamma_H}$$

Higgs Width at Higher Energies

Further measurements of the width can be obtained using the WW fusion process as follows:



The WW fusion can be disentangled from the HZ process from the missing mass (which will not be peaked at the Z, but in this case at sqrt(s)-mH.

Then from the ratio of the following three measurements:

$$\frac{[\sigma(ZH) \times B(H \to WW)] \times [\sigma(ZH) \times B(H \to bb)]}{\sigma(\nu\nu H) \times B(H \to bb)}$$

$$\propto \frac{\kappa_Z^2 \kappa_W^2}{\Gamma_H} \times \frac{\kappa_Z^2 \kappa_b^2}{\Gamma_H} \times \frac{\Gamma_H}{\kappa_W^2 \kappa_b^2} = \frac{\kappa_Z^4}{\Gamma_H}$$

Substantial gain in sensitivity to the total width, combined **1.6%** - adding FCC-ee (365).

s-Channel Higgs production and e-Yukawa

Extremely challenging for several reasons:

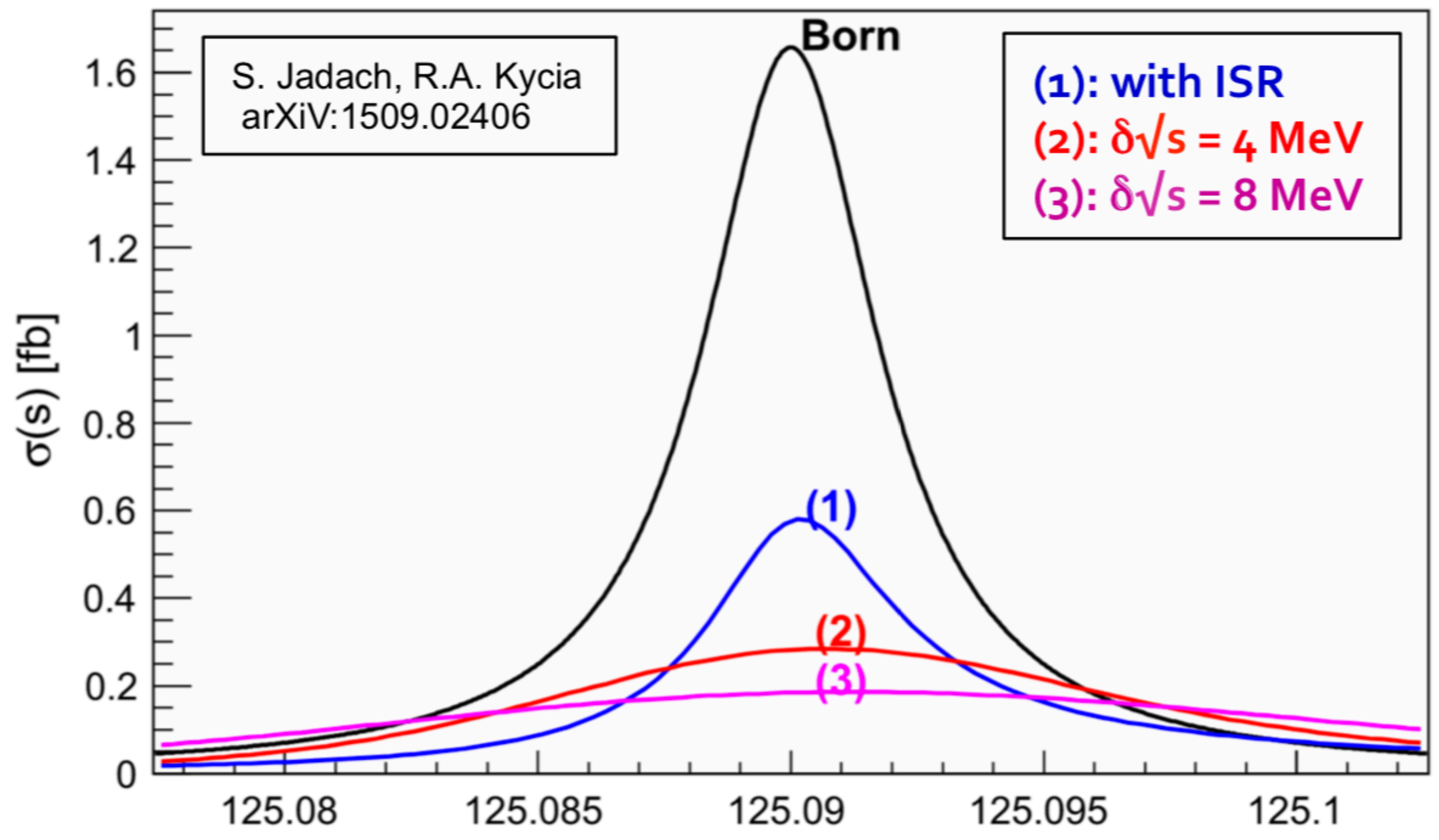
1.- The production cross section is $\sigma(ee \to H) = 1.6 \text{ fb}$ will require extremely large luminosities

2.- Given the very small Higgs width, and extremely small energy spread is necessary - require monochromatization.

- Default has delta ~ 100 MeV (no visible resonance)
- Monochromatization options

$$\delta \sim 10 \text{ MeV} \qquad \sigma(ee \to H) = 100 \text{ ab}$$
$$\delta \sim 10 \text{ MeV} \qquad \sigma(ee \to H) = 250 \text{ ab}$$

(Both options require huge luminosities 7ab-1 and 2ab-1)



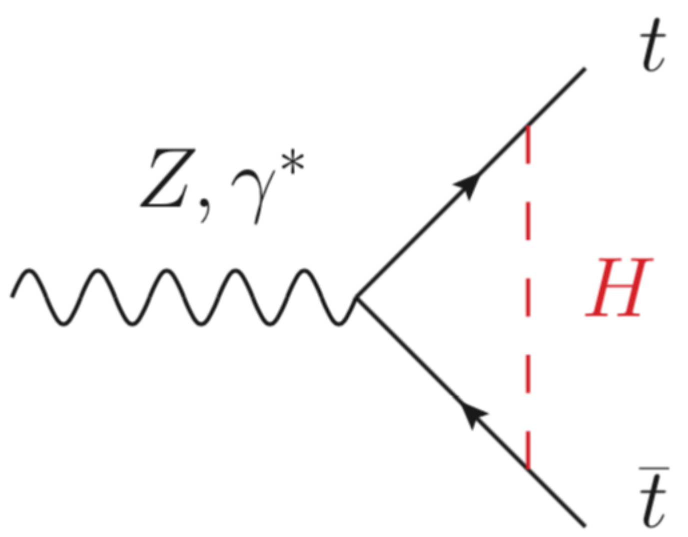
Expected signal significance for both options is a limit at 2.5 x SM !

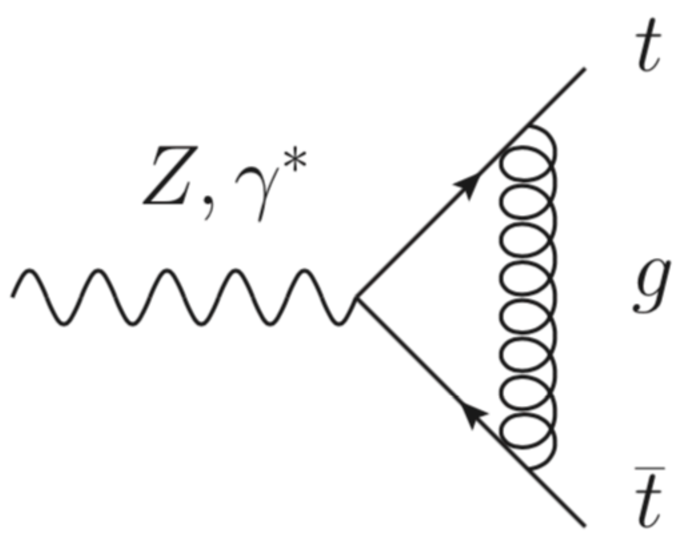
Monochromatization often considered but never used

Monochromatization uses opposite correlation between spatial position and energy.

FCC-ee and Model Dependent Measurements through Loops

Top pair cross section at threshold and above

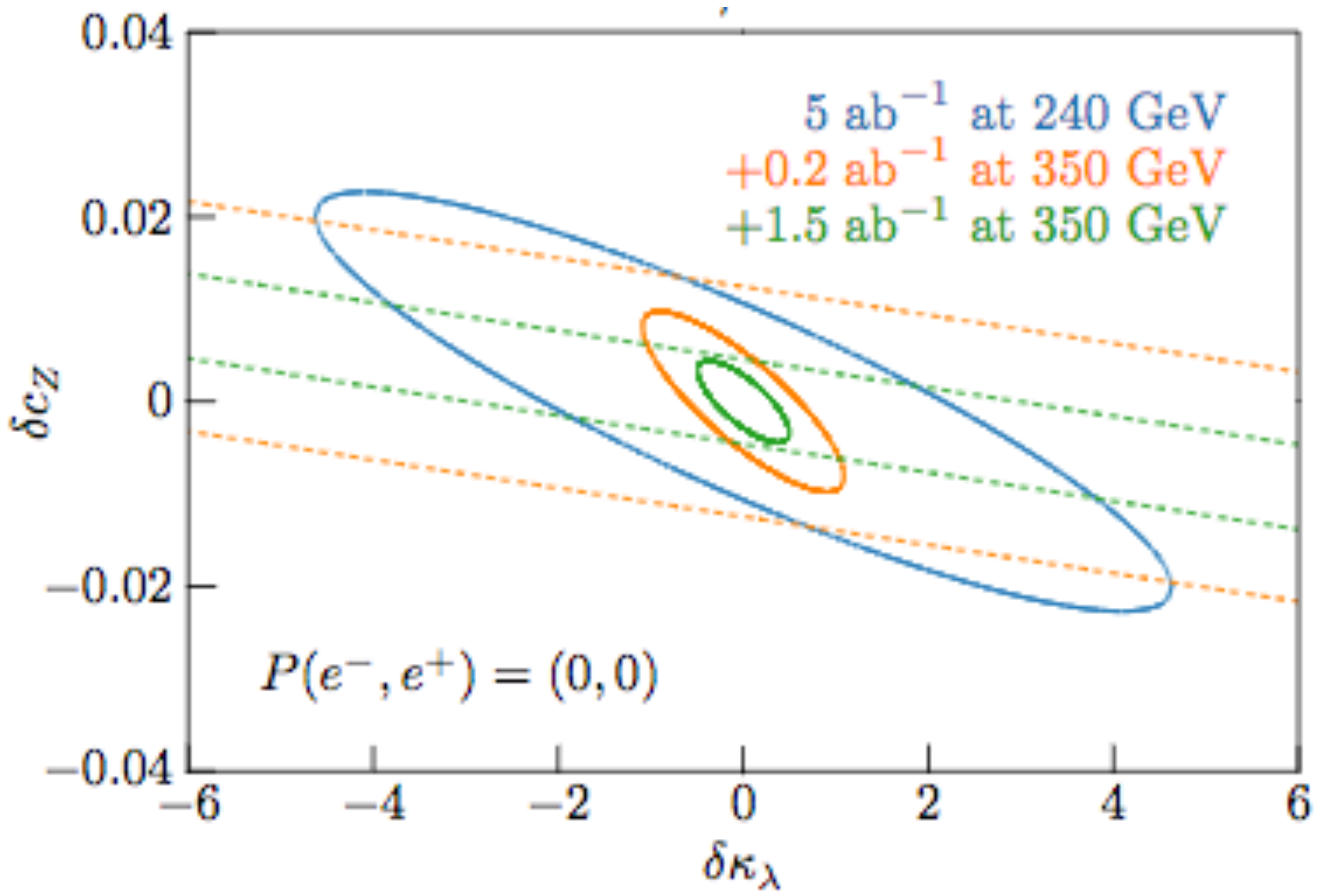




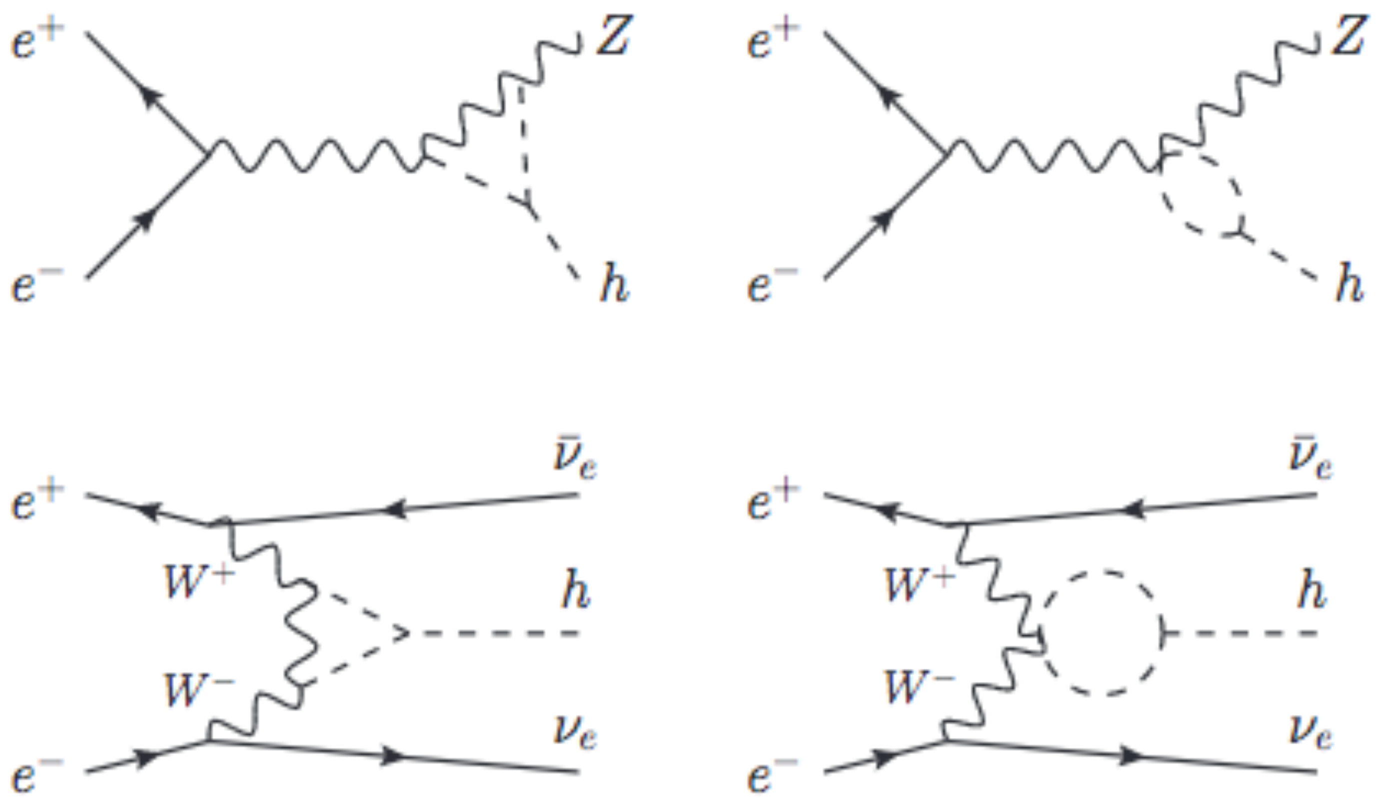
Precision on alphaS at FCC-ee will be important

Top Yukawa coupling precision from top pair cross section measurements **<10%**

https://arxiv.org/pdf/1711.03978.pdf



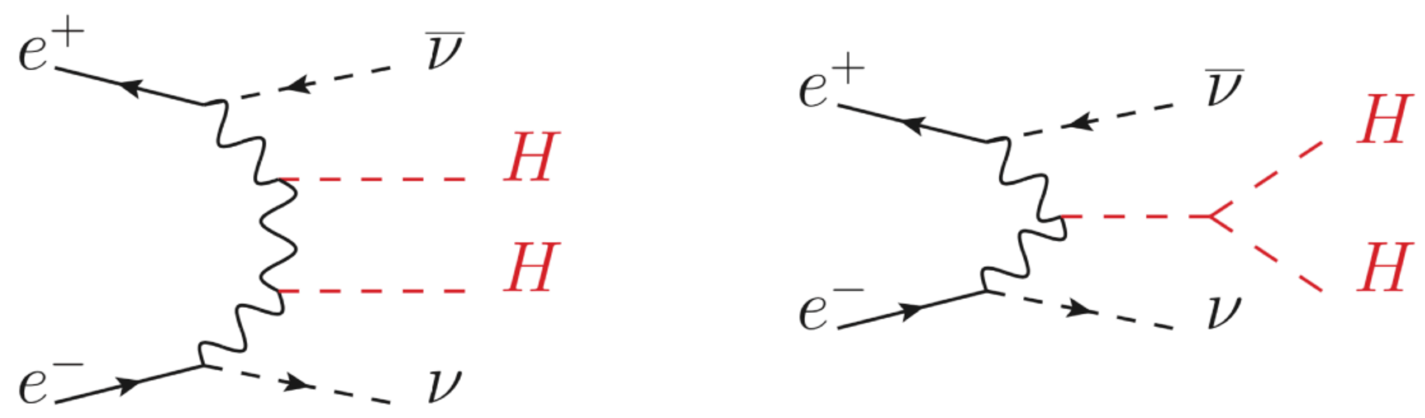
Higgs cross section at 240, 350, at 365 GeV



Similarly to what is done at LHC in VH channels and ttH.

Higgs self coupling precision ~30% - reduced to ~20% with kappaZ = 1 from SM

Similar precisions are obtained with double Higgs production at CLIC ($\sqrt{s}$ = 1.4 and 3 TeV)



Nano Overview of Main Higgs Analyses at (HL) LHC

Coupling	LHC*	ES 2013	HL-LHC	FCC-ee
ZZ	~10 %	2-4%	1.6-2.2%	0.15 %
WW	~10%	2-5%	1.7-2.3%	0.19 %
bb	~15 %	4-7%	3.4-4.8%	0.42 %
cc	-	-	-	0.71 %
gg	~10%	3-5%	2.3 - 3.6%	0.8 %
$\tau\tau$	~15 %	2-5%	1.9-2.6%	0.54 %
$\mu\mu$	-	5-8%	5.0-6.6%	6.2 %
$\gamma\gamma$	~10%	2-5%	2.0-2.7%	1.5 %
tt	~10 %	7-10%	2.8-4.7%	~10%*
HH	<15 x SM	60 %	30-40%	~30 %*
Binv	<20%	-	<5%	<0.45%
Γ_{tot}	-	-	~30%	1.6 %
λ	-	-	~100%	20-30%*

For one LHC experiment

*indirect

The goal of sub-percent level precision is reached in most of the channels at FCC-ee with 5 ab-1.

Still only weak or indirect constraints on the Higgs self coupling and the top Yukawa coupling.

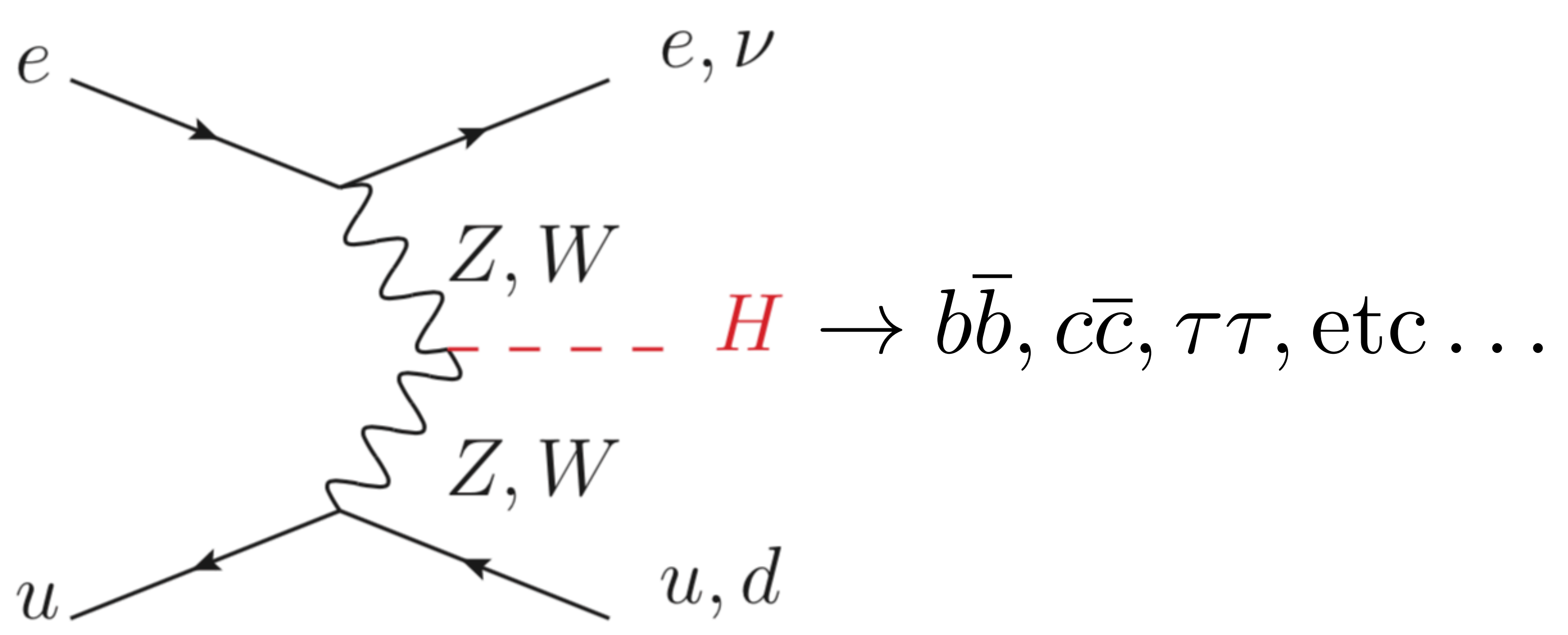
High Energy electron-proton Projects

The eh candidate machines

Project	LHeC	HE-LHeC	FCC-eh
Location	CERN	CERN	CERN
e energy	60 GeV	60 GeV	60 GeV
p energy	7 TeV	12.5	50 TeV
Lumi.	0.8 10^{34} $cm^{-2}s^{-1}$	1.2 10^{34} $cm^{-2}s^{-1}$	1.5 10^{34} $cm^{-2}s^{-1}$

Primary program to measure proton PDFs, but also nice additional potential in Higgs physics

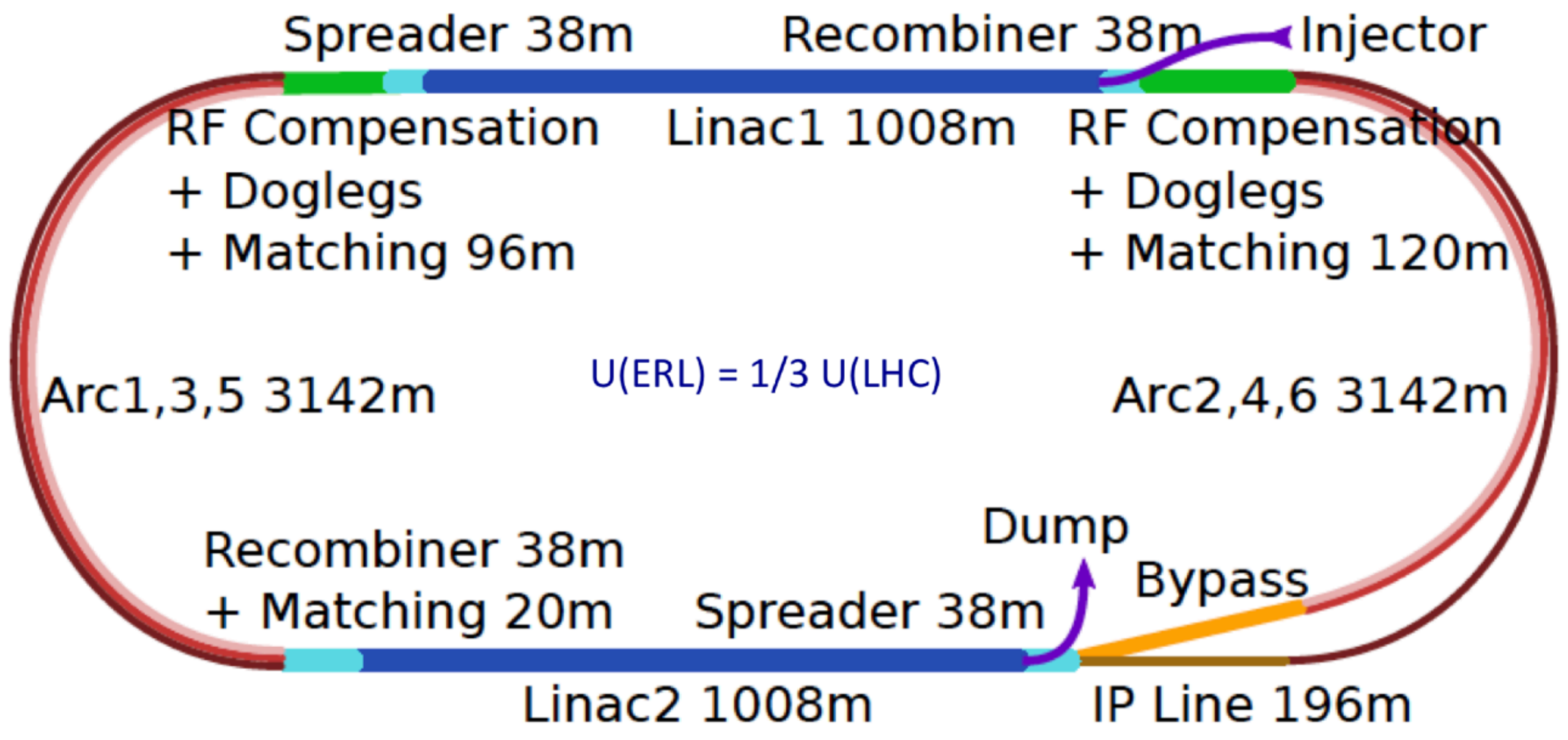
Main production process through vector boson fusion

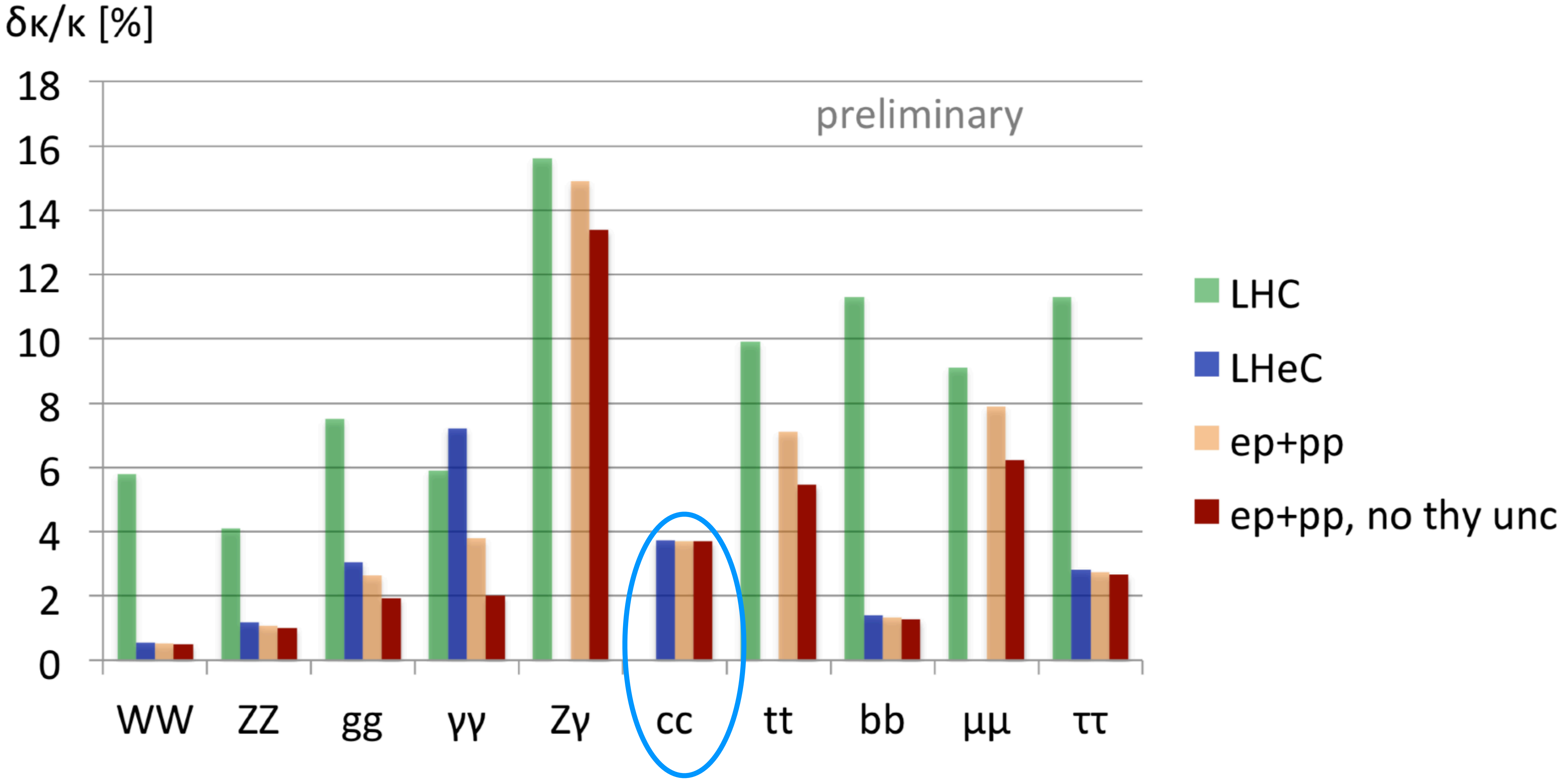


Much cleaner environment than pure hadron!

Good reach in the WW channel.

60 GeV Electron ERL added to LHC





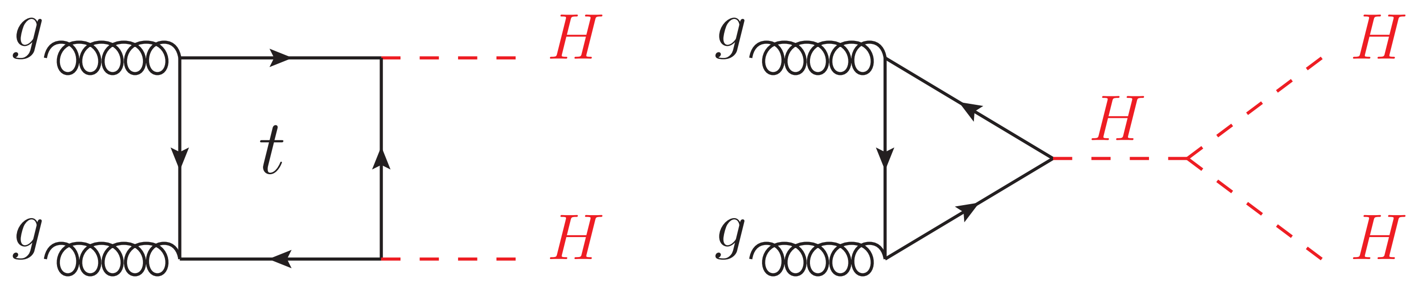
Clean enough to make charm Yukawa at good precision and improvement in the b Yukawa as well w.r.t. HL-LHC.

High Energy Hadron collider Projects

The candidate machines in a tiny nutshell

Project	HL-LHC	HE-LHC	FCC-hh	SppC
Location	CERN	CERN	CERN	China TBD
Circ.	27 km	27 km	100 km	55 - 100 km
COM energy	14 (15?) TeV	27 TeV	100 TeV	70 -140 TeV
Luminosity	2 x 3 ab-1	2 x 15 ab-1	2 x 20-30 ab-1	TBD
PU	200	800	1000	TBS
Field	8T	16T	16T	20T

- Back to more difficult environment with very high PU densities.
- Primary goal of higher energy collider would be the direct searches for new phenomena.
- Analysis techniques similar to LHC.



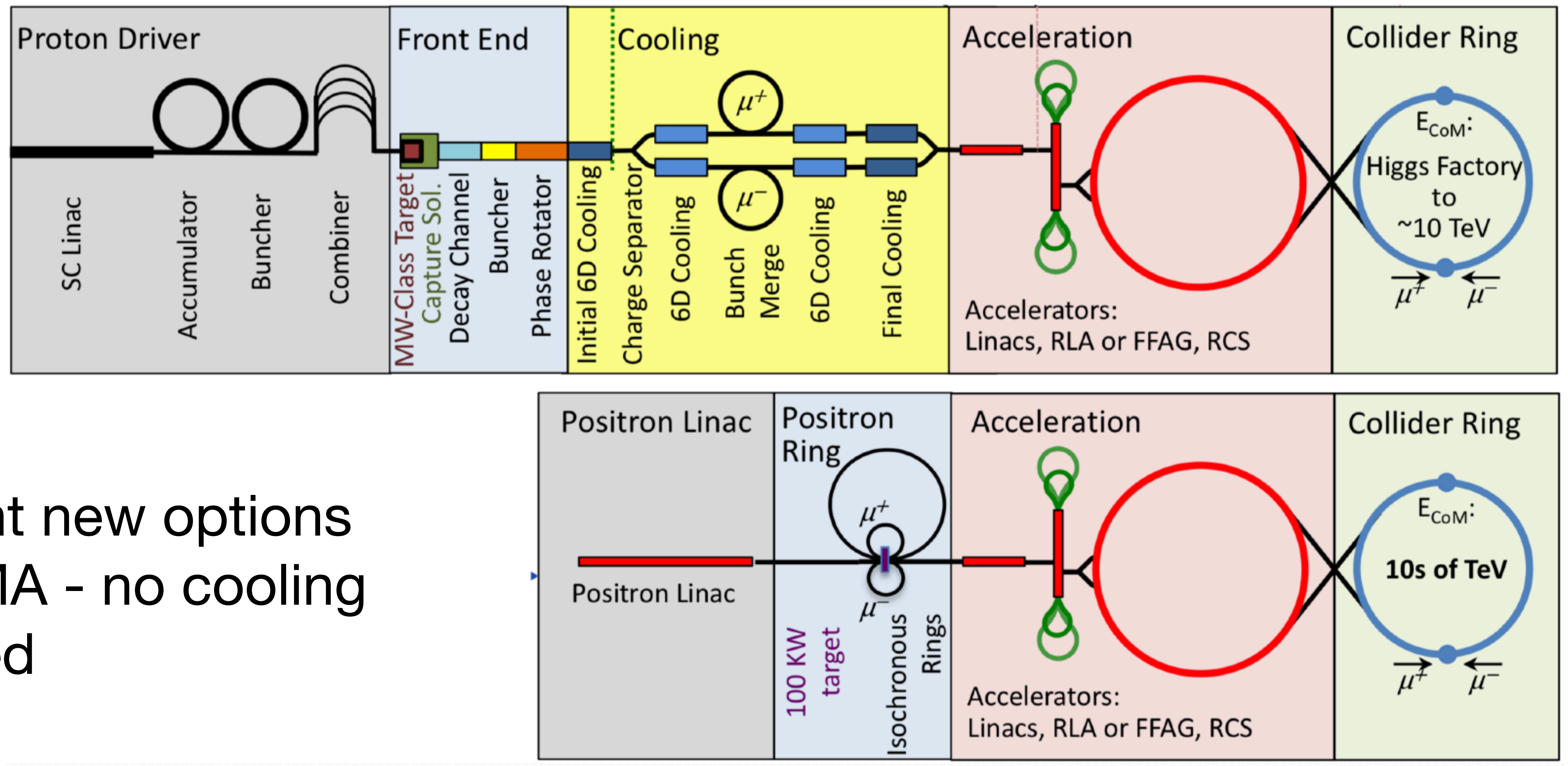
Collider	$\delta\kappa_t$	$\delta\kappa_\lambda$
CLIC 3	4 %	19 %
HE-LHC	O(1%)*	O(30%)*
FCC-hh	1 % or better	5 %

*Sensitivity being estimated for the European Strategy Update

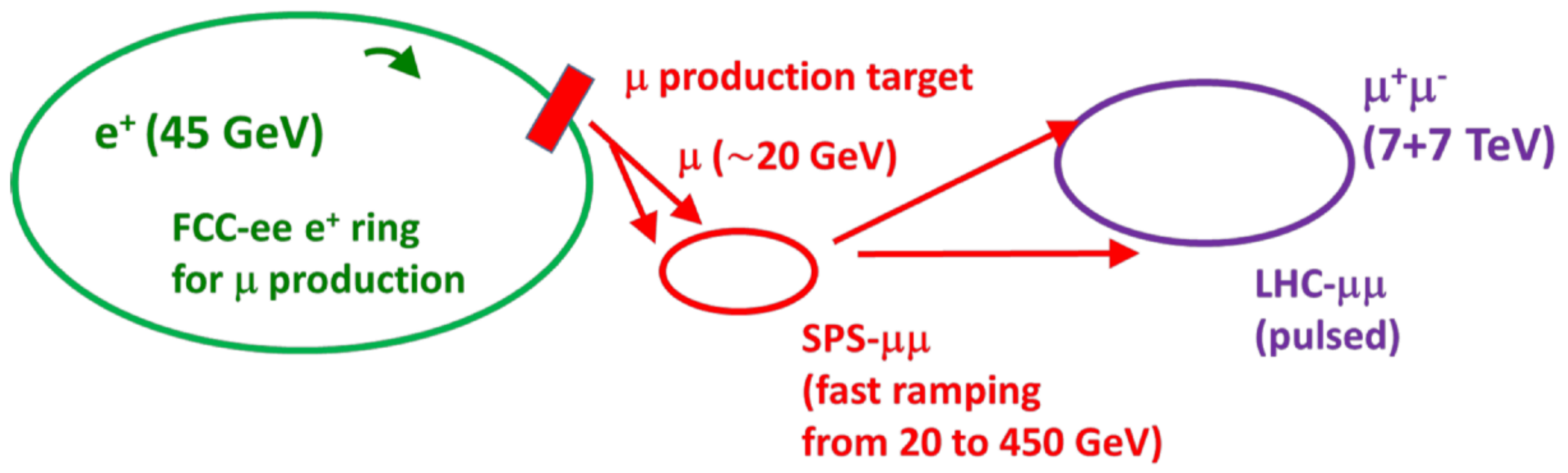
- HE-LHC and FCC-hh alone even with these extremely large statistics will be limited by TH uncertainties on cross sections and PDFs.
- The reach in sensitivity of the HE-LHC and FCC-hh is greatly improved with results from FCC-ee

Energy Frontier with FCC-hh splendidly complements the precision obtained at FCC-ee other projects do not seem competitive

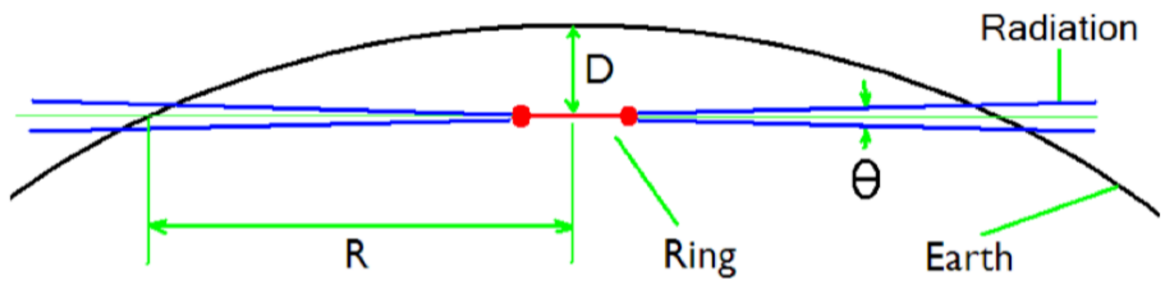
Muon Collider Projects



Recent new options
LEMMA - no cooling
needed



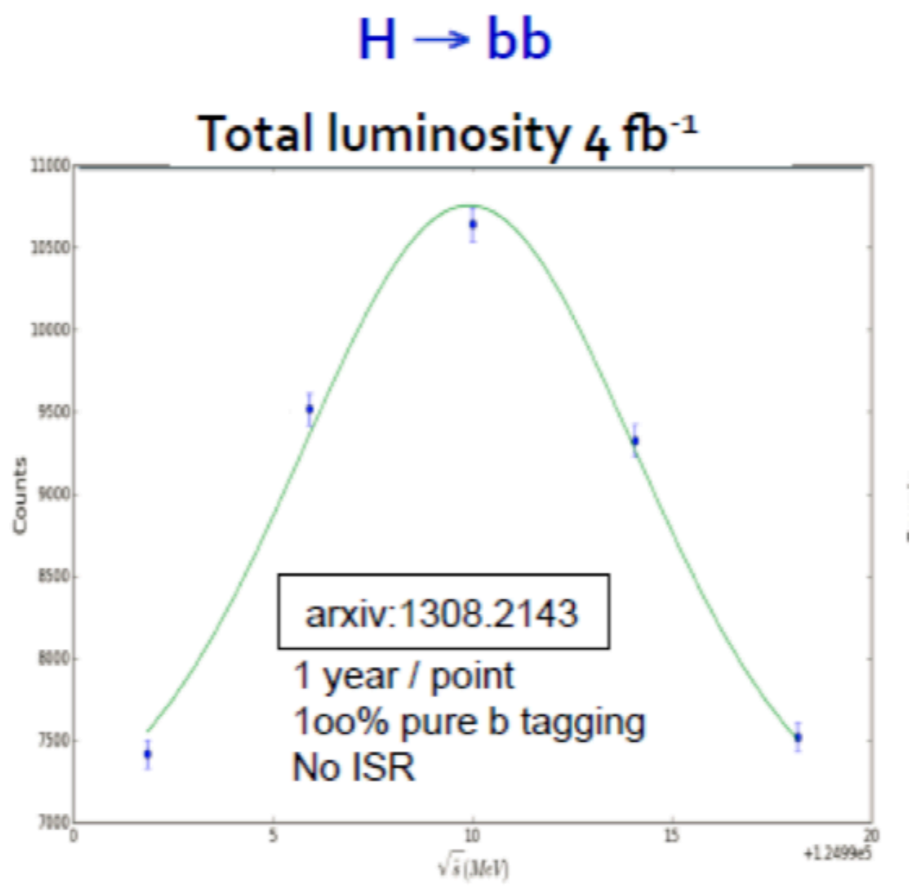
- Generating muons at 22 GeV (from collisions of ~45 GeV positrons on electrons ~at rest).
- Various options to reach 14 TeV (at LHC) or even 100 TeV at FCC-mumu.
- However very high energies are potentially problematic for radiation induced by neutrinos from the muon decays (so called the neutrino pancake).



- Extremely interesting for high energies (see Andreas' talk), but difficult (requires 0.003% resolution) for s-channel production but muons radiate less and can therefore have a « superb" energy definition:

$$\sigma(\mu^+\mu^- \to H) \sim 15 \text{ pb}$$

- With 5 years running at 8 10^{31} $cm^{-2}s^{-1}$:
  - **Best Precision of 0.1 MeV on the mass**
  - 0.25 MeV on the width



- As a Higgs factory precision on $B(\mu\mu) \times B(XX)$ in the few percent range (2.5% for bb and 10% for tautau). Not competitive with e+e- Higgs factories.

- Higher energies are more exciting and do also provide interesting possibilities to measure the Higgs self coupling.

Conclusions

- The LHC is an immense success with the Higgs discovery, a vast program of searches for new phenomena and a number of precision measurements.
- Its reach in precision for Higgs boson couplings is excellent, however not sufficient to reach the required sub-percent level precision.
- The required level of precision for most couplings can only be reached with lepton colliders.
- To reach the precision for the top Yukawa coupling and the Higgs self coupling a high energy hadron collider is ideal (in conjunction with a lepton collider)
- The FCC-ee and FCC-hh program fully and optimally addresses these reaching the required level of precision, and much much more!

Comparison lepton colliders up to 380 GeV

Collider	μ Coll$_{125}$	ILC$_{250}$	CLIC$_{380}$	LEP3$_{240}$	CEPC$_{250}$	FCC-ee$_{240}$	FCC-ee$_{365}$
Years	6	15	7	6	7	3	+4
Lumi (ab^{-1})	0.005	2	0.5	3	5	5	+1.5
δm_H (MeV)	0.1	14	110	10	5	7	6
$\delta\Gamma_H / \Gamma_H$(%)	6.1	3.8	6.3	3.7	2.6	2.8	1.6
$\delta g_{Hb} / g_{Hb}$ (%)	3.8	1.8	2.8	1.8	1.3	1.4	0.68
$\delta g_{HW} / g_{HW}$ (%)	3.9	1.7	1.3	1.7	1.2	1.3	0.47
$\delta g_{H\tau} / g_{H\tau}$(%)	6.2	1.9	4.2	1.9	1.4	1.4	0.80
$\delta g_{H\gamma} / g_{H\gamma}$ (%)	n.a.	6.4	n.a.	6.1	4.7	4.7	3.8
$\delta g_{H\mu} / g_{H\mu}$ (%)	3.6	13	n.a.	12	6.2	9.6	8.6
$\delta g_{HZ} / g_{Hz}$ (%)	n.a.	0.35	0.80	0.32	0.25	0.25	0.22
$\delta g_{Hc} / g_{Hc}$ (%)	n.a.	2.3	6.8	2.3	1.8	1.8	1.2
$\delta g_{Hg} / g_{Hg}$ (%)	n.a.	2.2	3.8	2.1	1.4	1.7	1.0
Br$_{invis}$ (%)$_{95\%CL}$	SM	< 0.3	< 0.6	< 0.5	< 0.15	< 0.3	< 0.25
BR$_{EXO}$ (%)$_{95\%CL}$	SM	< 1.8	< 3.0	< 1.6	< 1.2	< 1.2	< 1.1

HL-LHC
25
3
100
50
8.2
3.5
6.5
3.6
5.0
3.5
SM
3.9
< 3
SM

From P. Janot at Circular Lepton Colliders