Unravelling the mysteries of the Universe through Higgs: now and future of the energy frontier

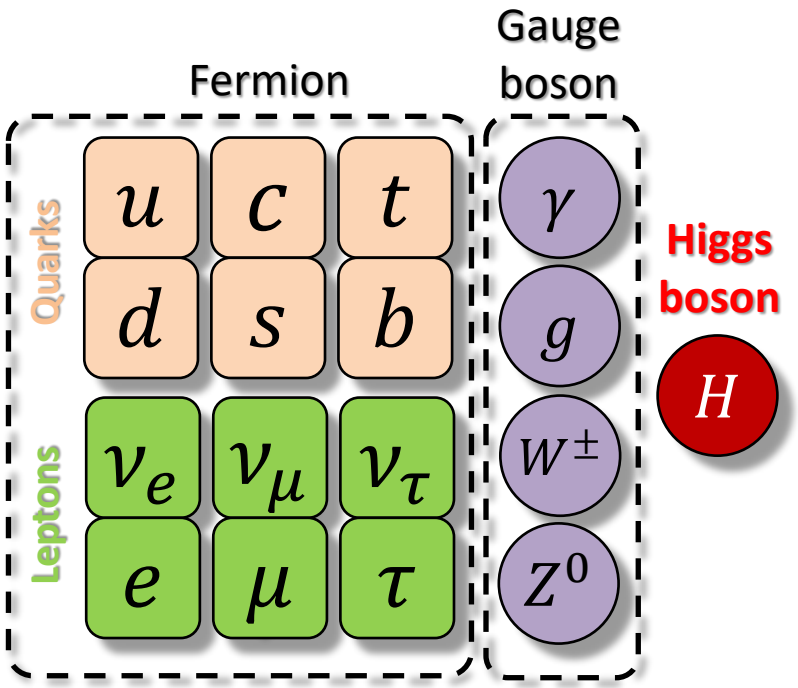
Shigeki Hirose (U. Tsukuba)

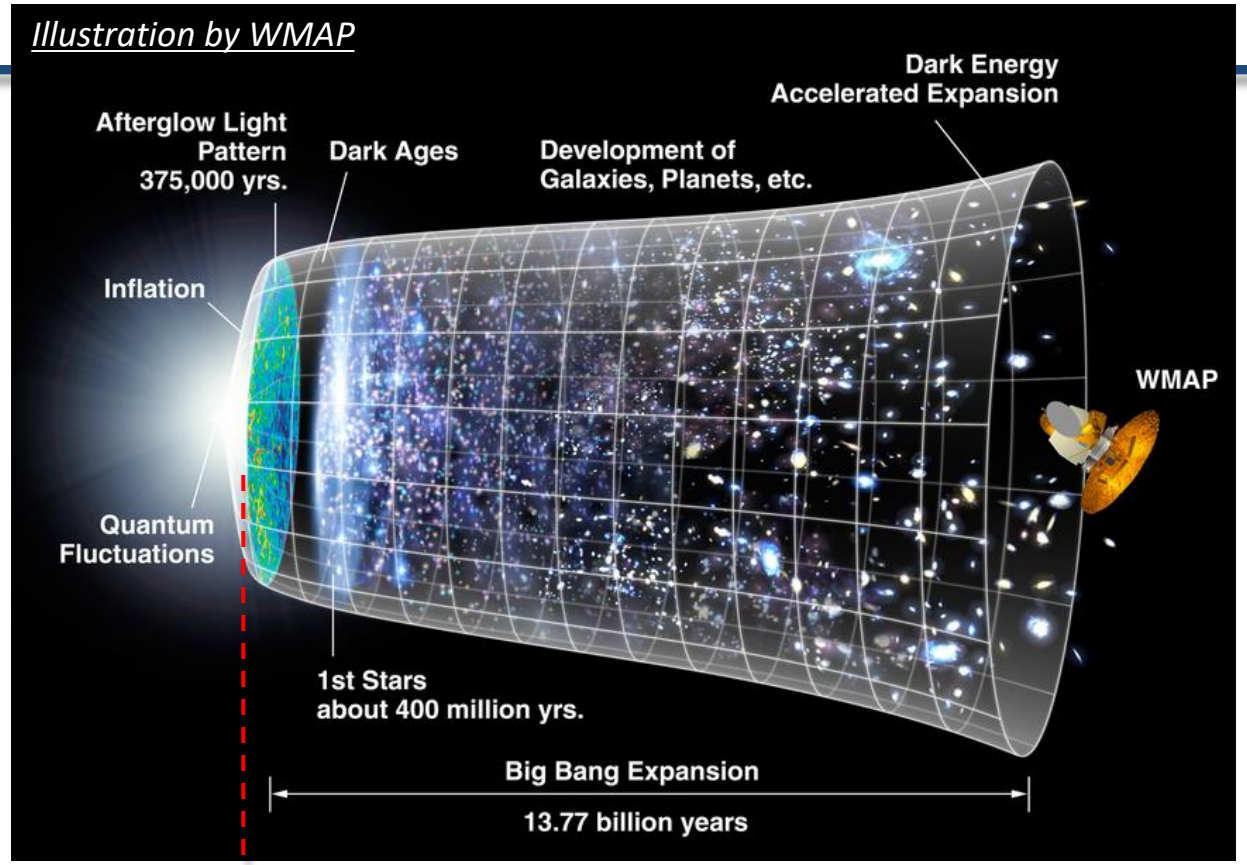
30 September 2024

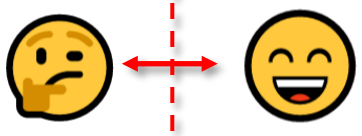
Tsukuba Global Science Week:

Evolution of the Universe and origin of matters session

Elementary particles



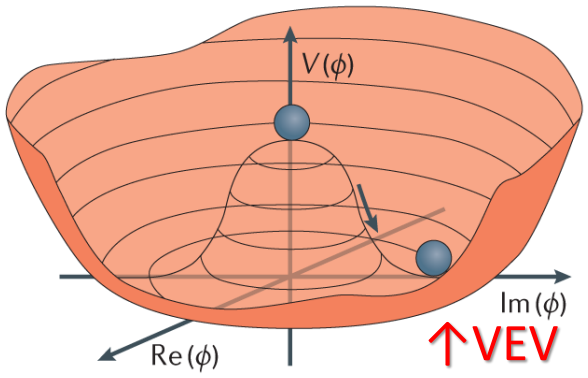




- Key element of the Universe
  - Fermions compose matters
  - Gauge bosons mediate forces
  - Higgs boson ← **special particle** connected to the vacuum
- Standard model (SM) of the elementary particle can describe evolution of the Universe **only 10^{-11} secs. after** the Big Bang

■ Special role of Higgs field

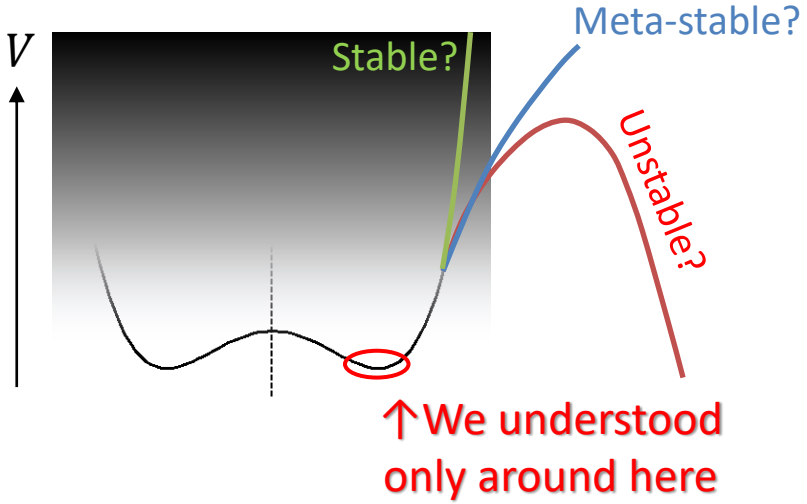
- Origin of the mass through the Higgs mechanism
  - After the symmetry breaking, the vacuum acquired the expectation value (i.e. energy)
    → Seed of the mass to weak bosons and fermions



- Special interaction that only the Higgs field can have
  - If there is a fermion-type family of the BSM particles, the Higgs boson is only an SM particle that can have a coupling to them

$$y\bar{\psi}_L\phi\psi_R$$

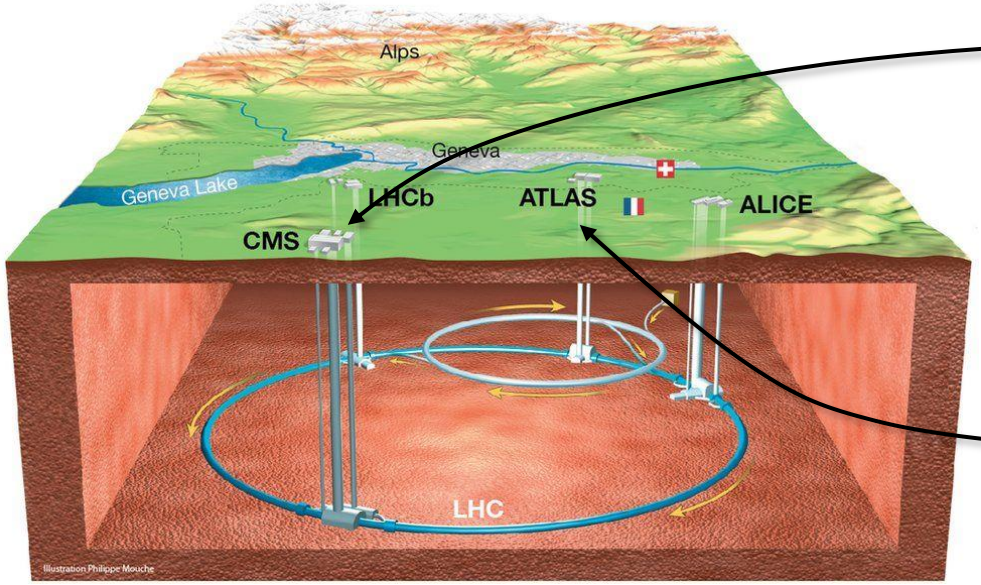
- Interaction with 'vacuum'
  - Higgs field may govern the vacuum stability at high energy

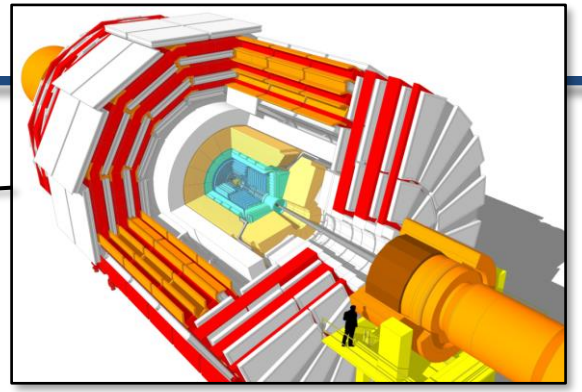


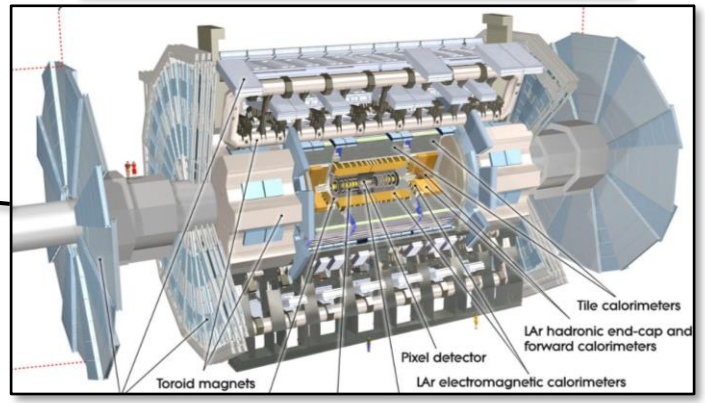
- The Higgs terms in the Lagrangian are all artificially introduced with no guiding principle

Is this just a convenient theory, or a real mechanism?

LHC@CERN





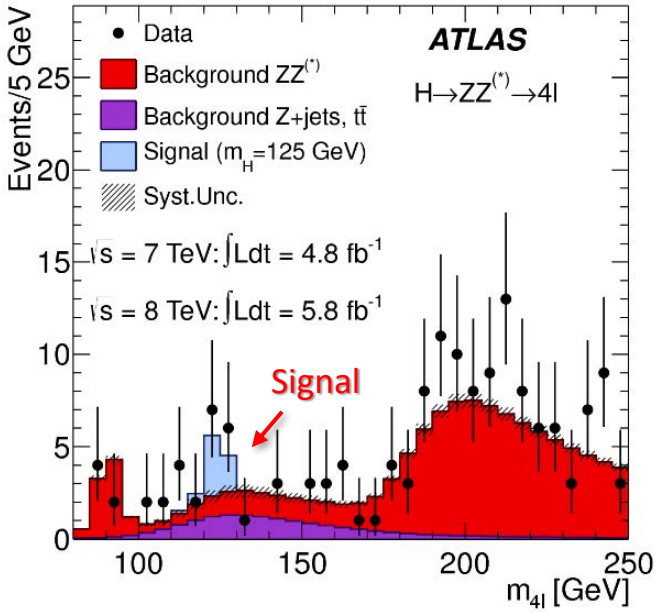


- World largest proton-proton collider with 27-km circumference
  - Centre-of-mass energy = 13.6 TeV at Run 3
  - Four main experiments: **ATLAS**, **CMS**, LHCb, ALICE
- ATLAS & CMS: detect final-state objects from heavy particle decays efficiently
  - ATLAS (diameter = 25 m): longer lever-arm
  - CMS (diameter = 15 m): 3.8 T solenoidal field: twice stronger than that of ATLAS

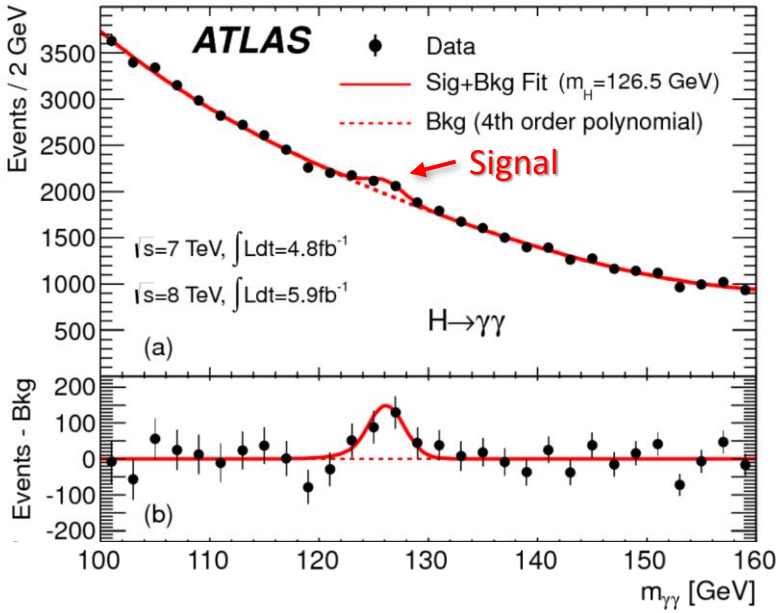
Discovery of the Higgs boson in 2012

ATLAS, Phys. Lett. B 716 (2012) 1

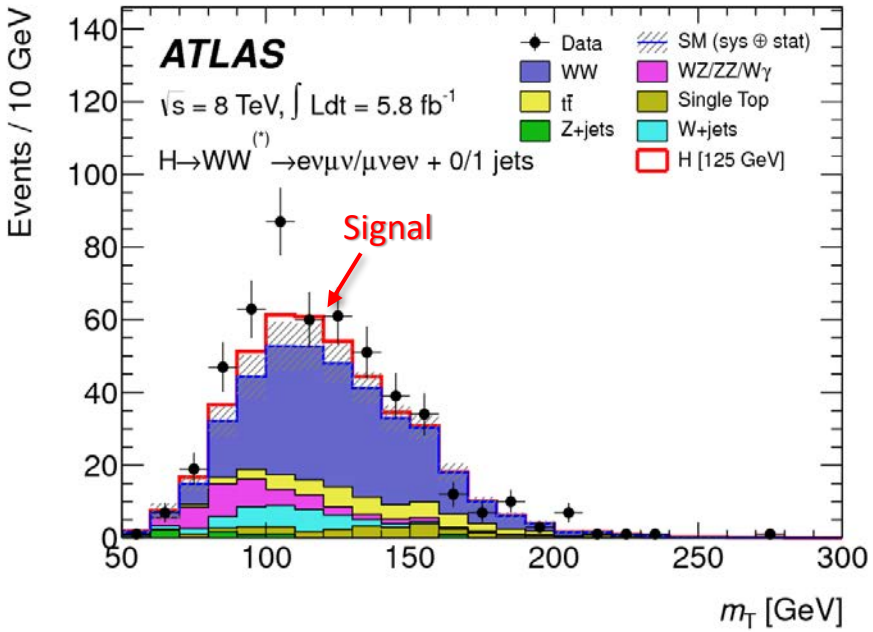
$H \to ZZ \to 4\ell$



$H \to \gamma\gamma$



$H \to WW \to \ell\nu\ell\nu$



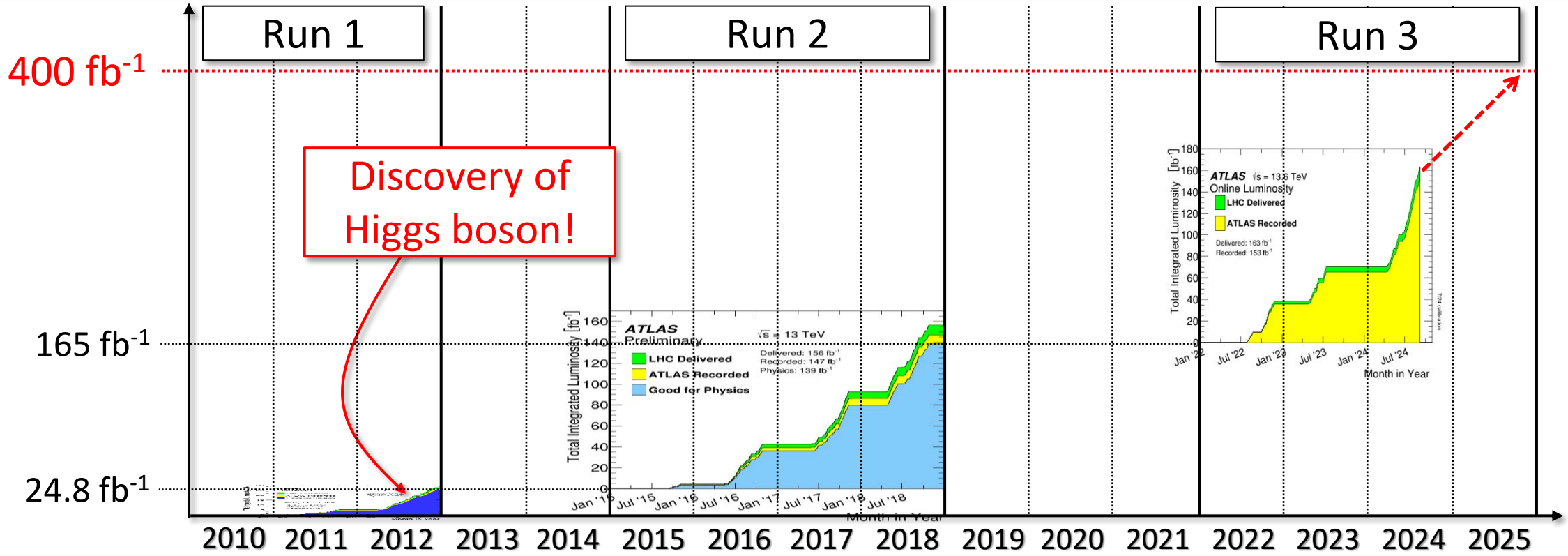
- Discovery of 'a new boson' was reported by ATLAS and CMS on 4th July 2012
  - ATLAS: 5.0σ @ 126.5 GeV
  - CMS: 4.9σ @ 125.3 GeV

This is just the BEGINNING !

F. Gianotti, CERN Seminar 4 Jul 2012

We are entering the era of "Higgs" measurements
First question: is the observed excess due to the production of a SM Higgs boson ?

■ Data-taking (ATLAS experiment)



CoM energy	7 TeV → 8 TeV	13 TeV	13.6 TeV
Peak lumi.	0.7×10^{15}/cm^2/s	1-2 $\times 10^{34}$ /cm^2/s	2×10^{34} /cm^2/s

- LHC continues to provide more data with increasing energy and luminosity
  - Peak lumi. reached 2x higher than its original design!

LHC is being a high energy & high luminosity machine!

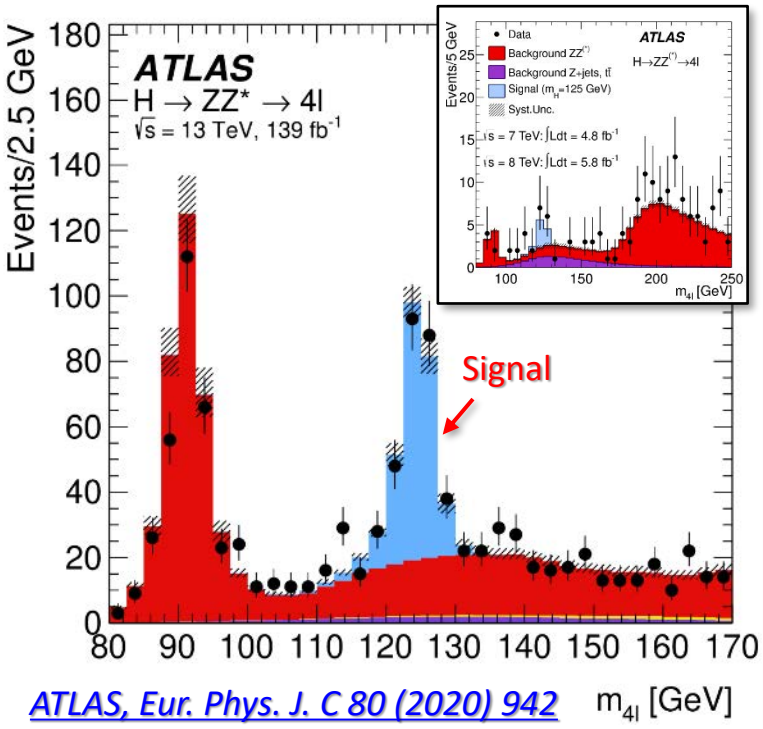
Higgs measurement: now

- High statistics analysis has become possible

As of CERN seminar 2012
N_{Higgs} = 0.23M

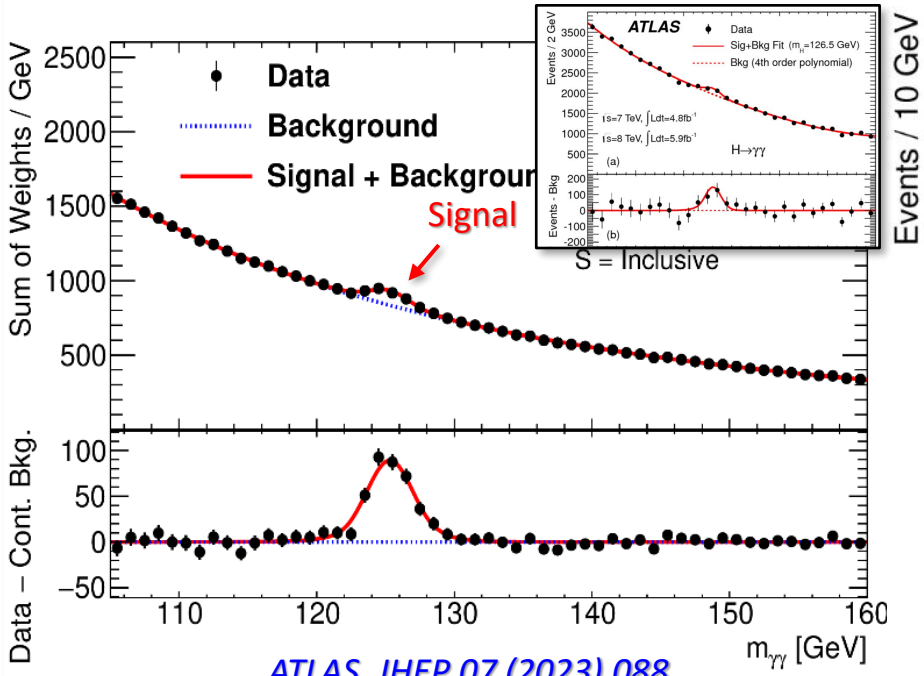
Today
N_{Higgs} = **19M**

$H \to ZZ \to 4\ell$



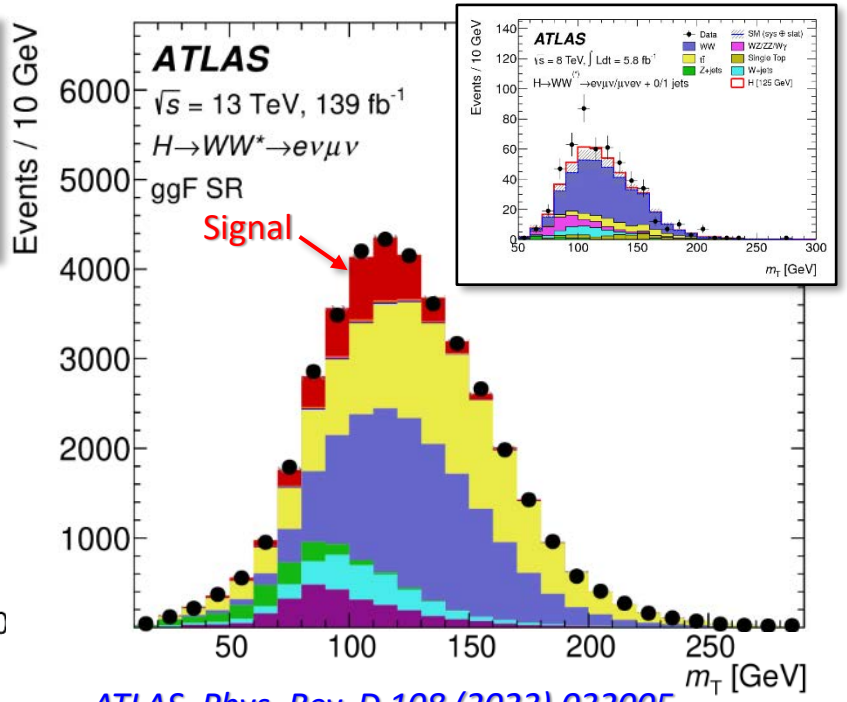
ATLAS, Eur. Phys. J. C 80 (2020) 942

$H \to \gamma\gamma$



ATLAS, JHEP 07 (2023) 088

$H \to WW \to \ell\nu\ell\nu$



ATLAS, Phys. Rev. D 108 (2023) 032005

Higgs peaks are very clear; no doubt that the Higgs boson exists

Higgs measurement: now

- High stat. data allows us to probe the Higgs terms in the Lagrangian

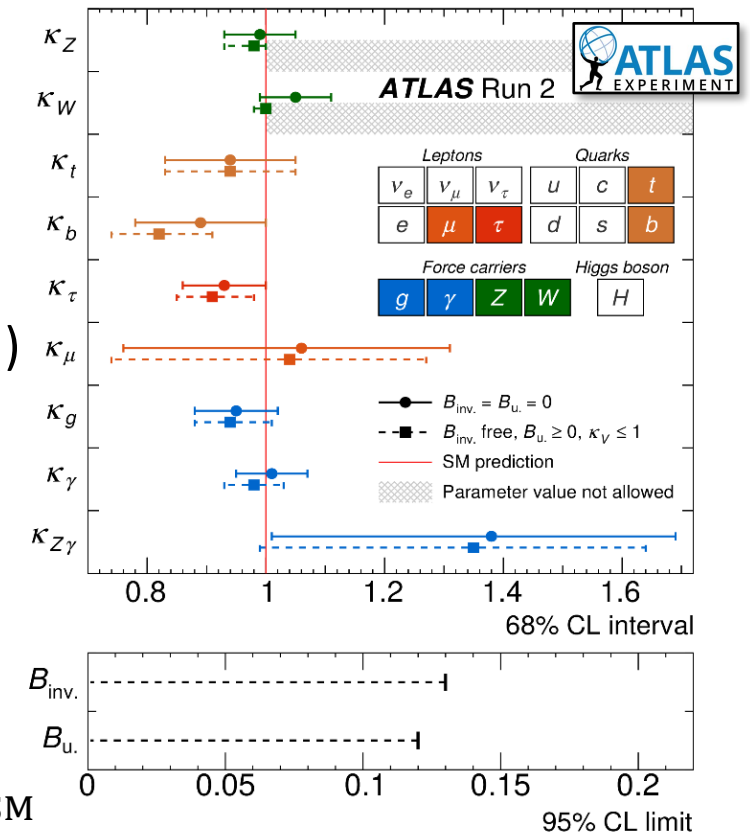
$$L_{\text{Higgs}} = \boxed{(D_\mu \Phi)^\dagger (D^\mu \Phi)} + \boxed{\bar{\psi}_L Y \Phi \psi_R} - \boxed{V(\Phi)}$$

$H \to VV$ $\quad$ $H \to f\bar{f}, t\bar{t}H$ $\quad$ Higgs pair production

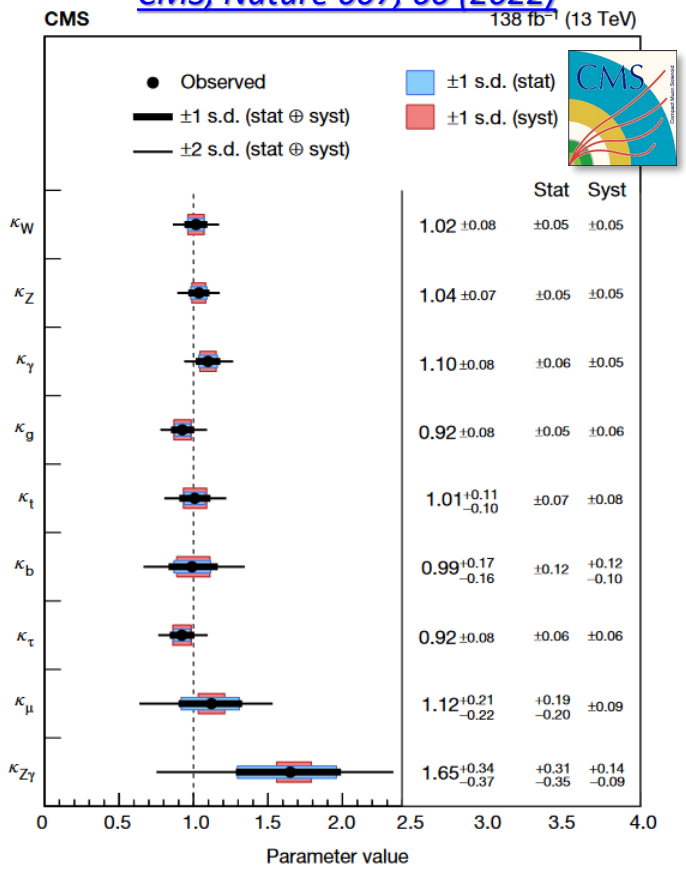
- Coupling to gauge bosons and 3-gen fermions have been established
- Important next-steps
  - Coupling to the **2nd-gen fermion** (κ_μ)
    → Understanding of the 'generation' structure
  - Search for the Higgs pair-production process
    → Direct probing on the Higgs potential

$$\kappa_p^2 = \Gamma_p / \Gamma_p^{\text{SM}}$$

ATLAS, Nature 607, 52 (2022)



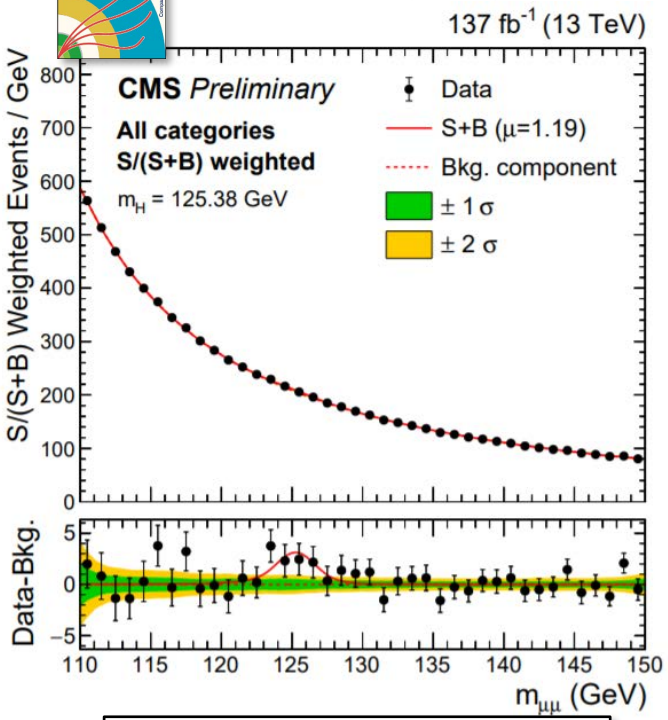
CMS, Nature 607, 60 (2022)



Higgs coupling to 2nd generation

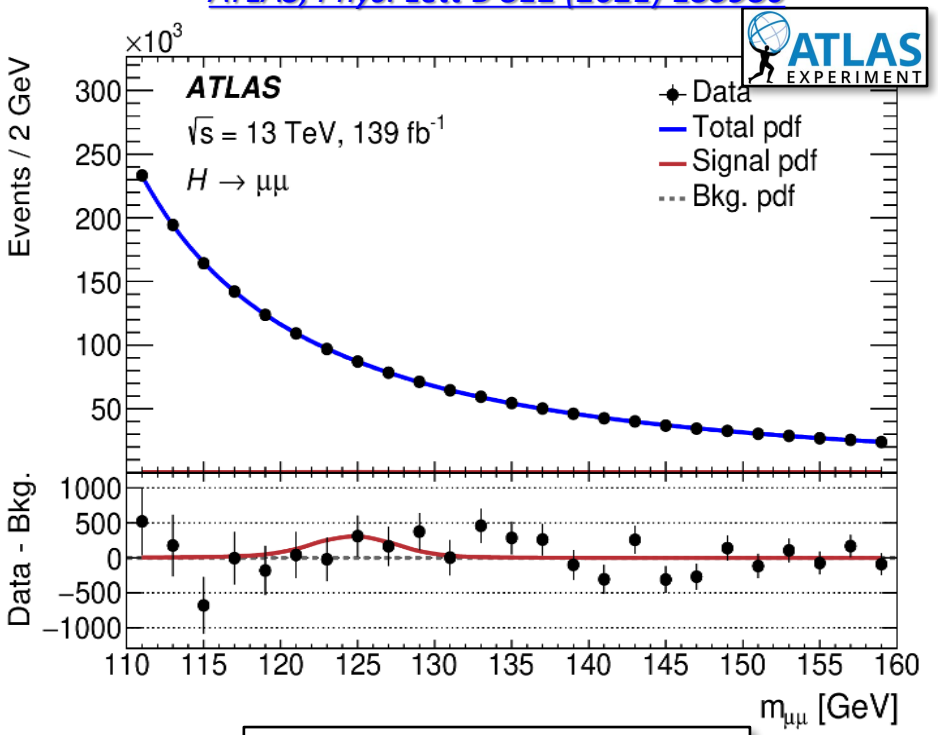
- $H \to \mu^+\mu^-$ is the most promising channel for the second generation
  - Clean, but very small BR (BR = 0.022%) → Overwhelmed by $Z \to \mu^+\mu^-$

CMS, JHEP 01 (2021) 148



CMS: $\mu = 1.21^{+0.43}_{-0.41}$ (3σ)

ATLAS, Phys. Lett B 812 (2021) 135980



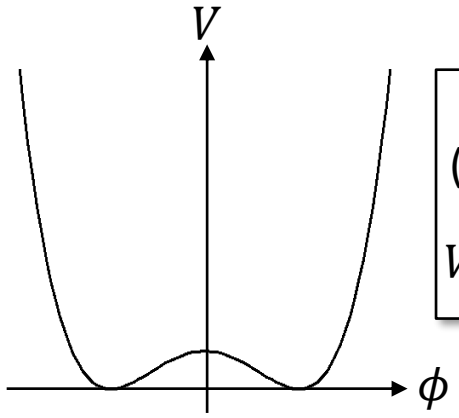
ATLAS: $\mu = 1.2 \pm 0.6$ (2σ)

- $m_{\mu\mu}$ resolution is the key: advantage in CMS with high B-field
- ATLAS attempts to include FSR to $m_{\mu\mu}$ calculation

Observation of $H \to \mu^+\mu^-$ may be possible in Run 3!

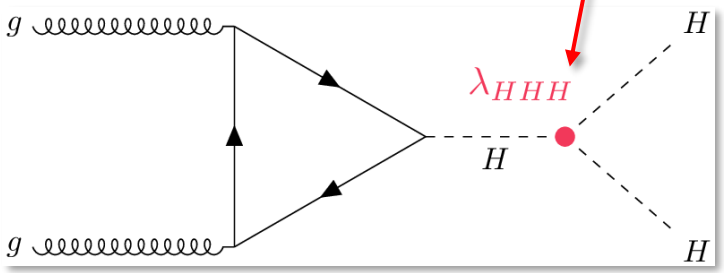
■ Higgs pair production

- Process sensitive to the self-coupling constant λ



Higgs potential
(SM; after phase transition)

$$V(h) = \frac{m_H^2}{2} h^2 + \lambda v h^3 + \cdots$$



$\sigma_{HH}^{\mathrm{SM}}$ = 34.4 fb

Only ~10,000 events
in the current dataset

$H \to \gamma\gamma$ is clean while small BR

	H→bb	H→WW	H→ττ	H→ZZ	H→γγ
H→γγ	0.26%	0.10%	0.03%	0.01%	0.001%
H→ZZ	3.1%	1.1%	0.33%	0.07%	
H→ττ	7.3%	2.7%	0.39%		
H→WW	24%	4.6%			
H→bb	34%				

Just between $bbbb$ and $bb\tau\tau$

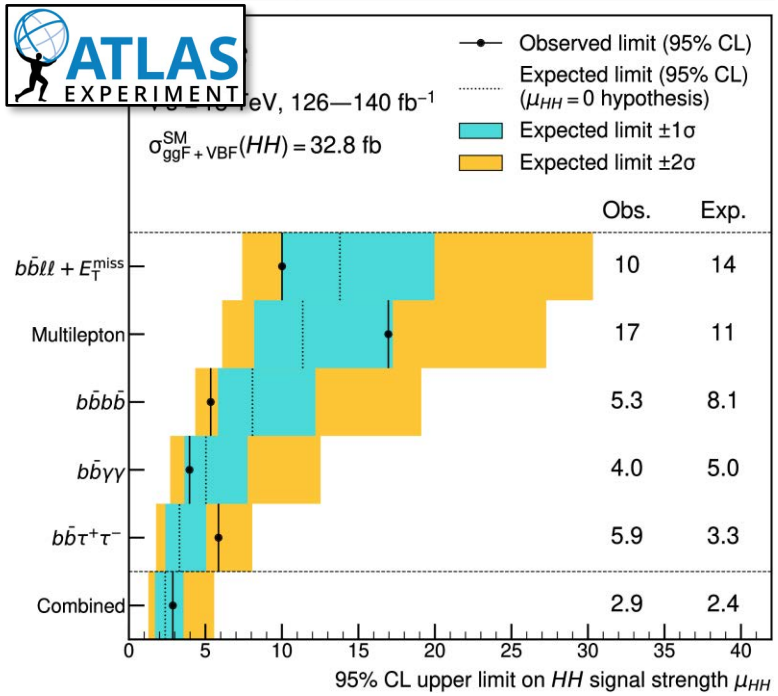
Large BR

Three golden channels:
$bbbb, bb\tau\tau, bb\gamma\gamma$

Measuring the HH process at LHC is still challenging, but important

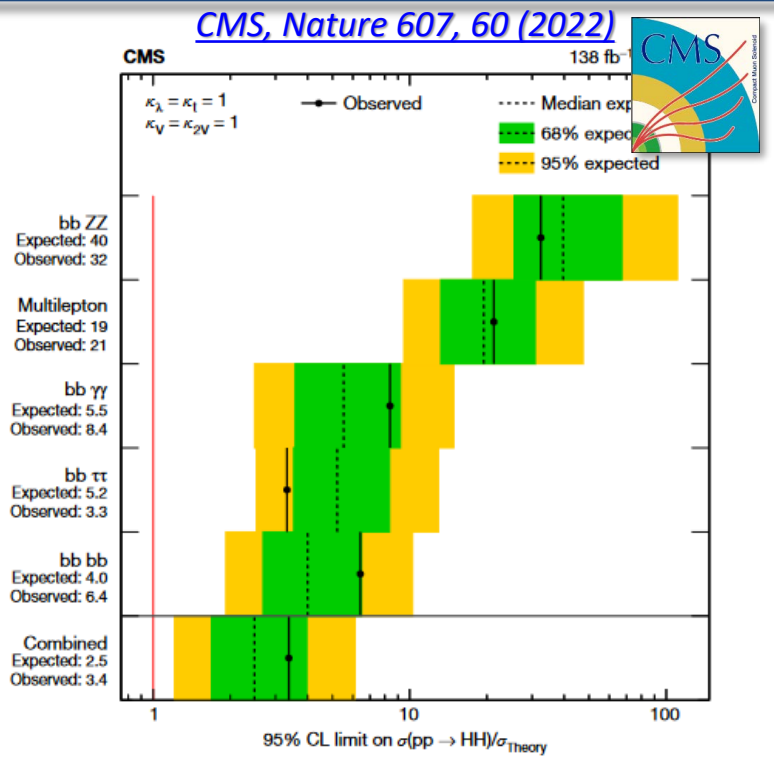
Status of Higgs pair-production searches

ATLAS, Phys. Rev. Lett. 133 (2024) 101801

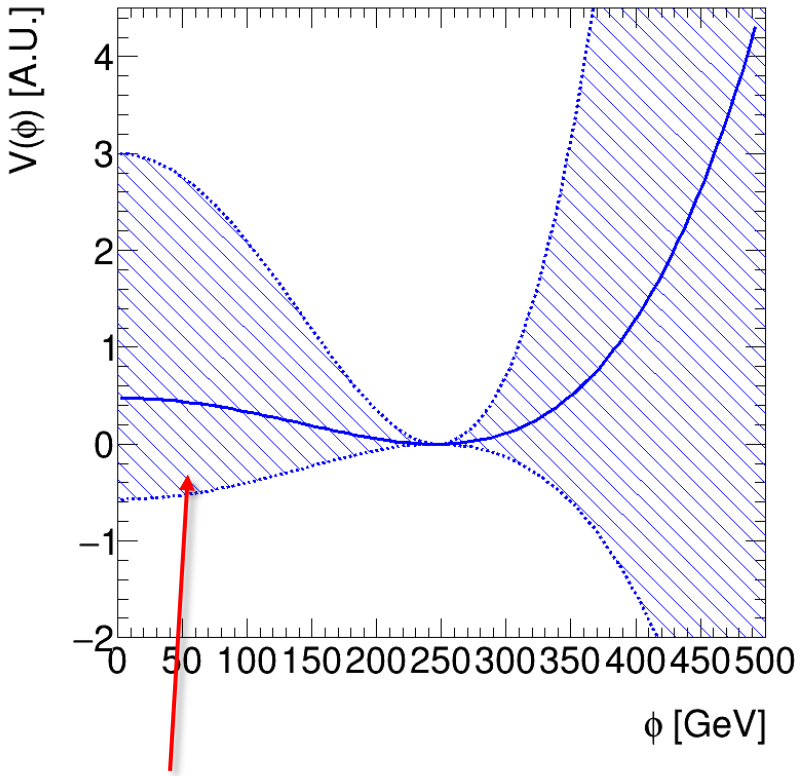


$\sigma/\sigma_{SM} < 2.9$
$-1.2 < \lambda/\lambda_{SM} < 6.3$

CMS, Nature 607, 60 (2022)



$\sigma/\sigma_{SM} < 3.4$
$-1.24 < \lambda/\lambda_{SM} < 6.4$

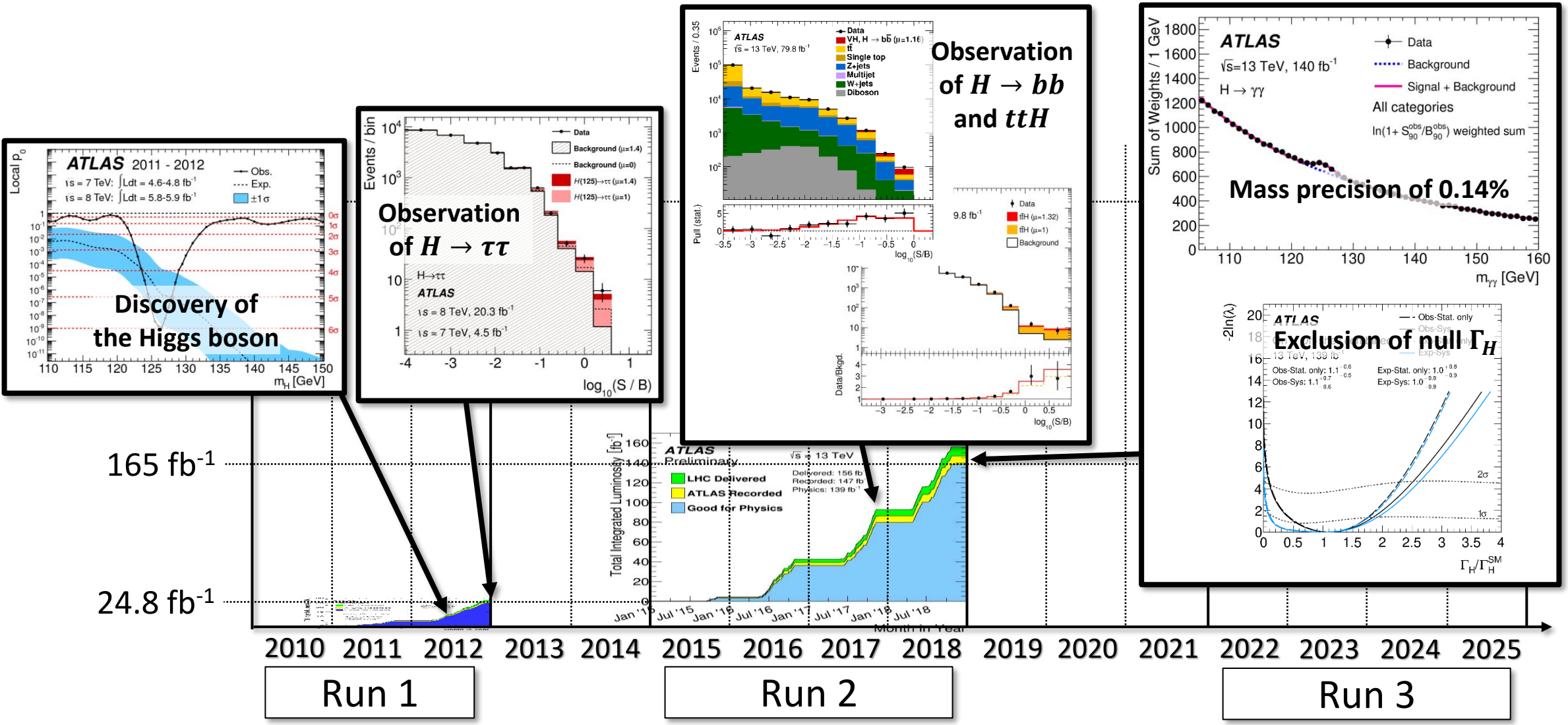


Uncertainty on the potential shape

- Both ATLAS and CMS set the upper limits at ~3x σ_{SM}
  - Signal significance is around 1σ → May reach 2σ at Run 3 in comb. of ATLAS and CMS!?
- Our knowledge on the Higgs potential is still marginal...
  - **Important to improve analysis further + accumulate more statistics**

Achievements at LHC

- Various achievements have been realised to date!



Analysis on the dataset from Run 3 is now on the full throttle!

Next step: High-Luminosity LHC

- HL-LHC starts in 2029

	Run 3 (2022-2025)	HL-LHC (2029-2041)
CM energy	13.6 TeV	14 TeV
Peak lumi.	2×10^{34} cm^{-2}s^{-1}	5×10^{34} cm^{-2}s^{-1}
Int. lumi.	~400 fb^{-1} (Incl. Run 1 and 2)	3000 fb^{-1}

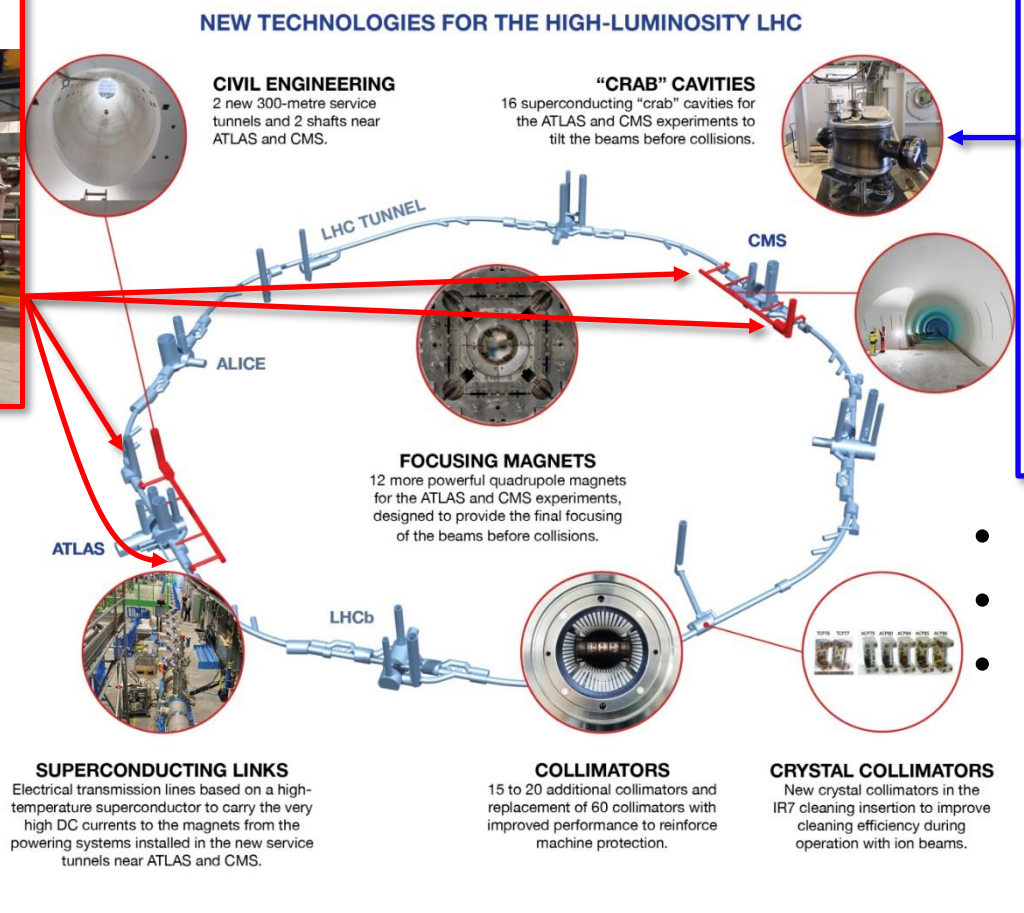
- Only an approved next-generation energy-frontier project today
  - **Thorough investigation** up to TeV-scale using the abundant statistics

■ Accelerator upgrade

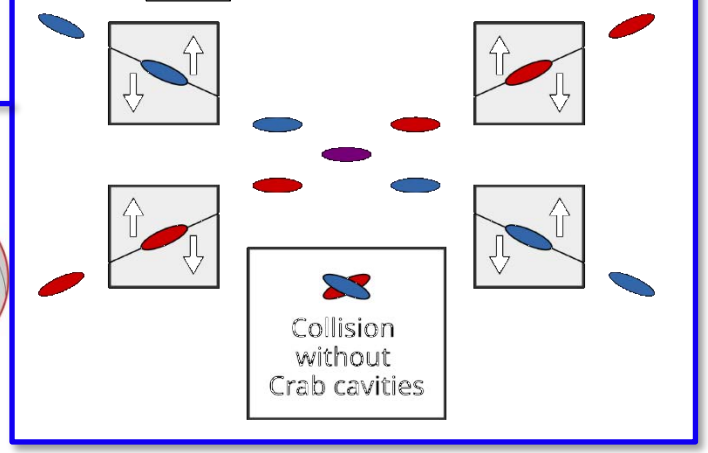
- The accelerator complex will be thoroughly upgraded in 2026-2028
  - Significant contributions from Japan

D1 magnet

- Separate beams around the IP with keeping low β^*
- 11.4 T is achieved by Nb_3Sn
- 3 magnets out of 6 from Japan have been produced
  → 11.4 T is reached



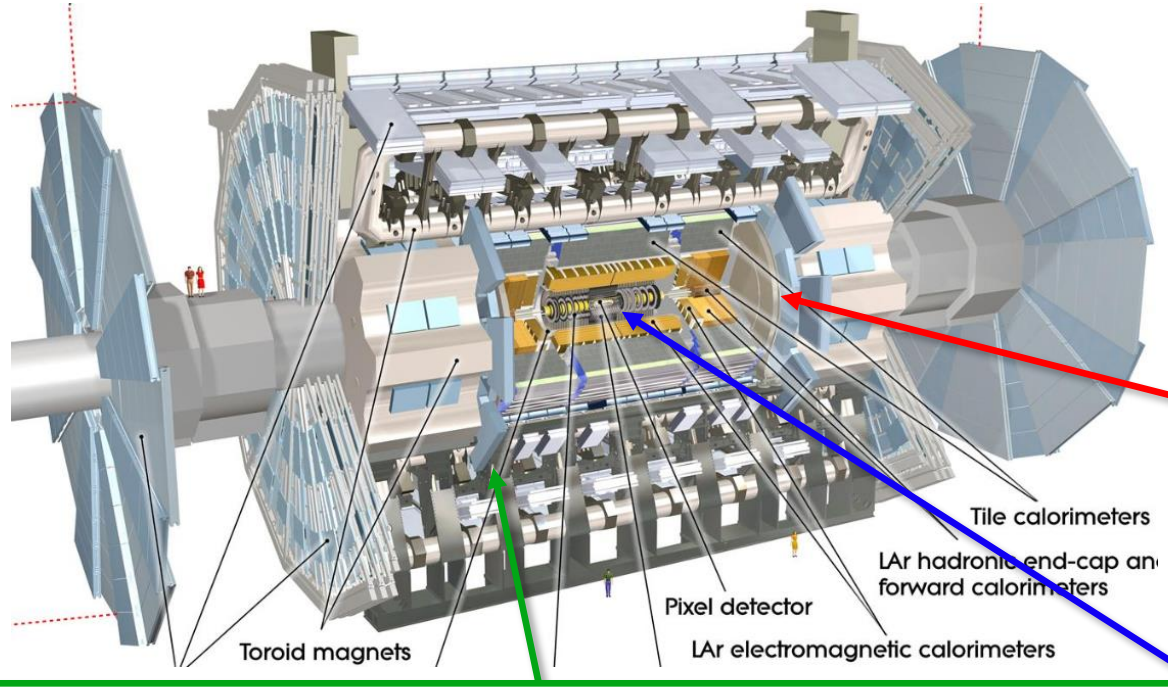
Crab cavity



- Suppress the hour-glass effect
- First introduced to KEKB!
- Production for 20 units of the RF system have been launched

■ ATLAS detector upgrade

- Upgrade the detector to fully exploit the high luminosity



Trigger and DAQ

- Reformation to a completely new scheme to handle 10x higher data rate
- More efficient trigger-level object identification

High Granularity Timing Detector

- Timing silicon detector (low-gain avalanche diode) on the endcap
- Determine track timing with $\sigma_t \sim 30$ ps → Precise mapping between forward tracks and vertices

Muon detector

- Place new RPCs to reduce inefficient region
  → Improve acceptance of muon trigger from 78% to 96%
- Introduce new muon-trigger system

Silicon tracker (Inner TracKer; ITk)

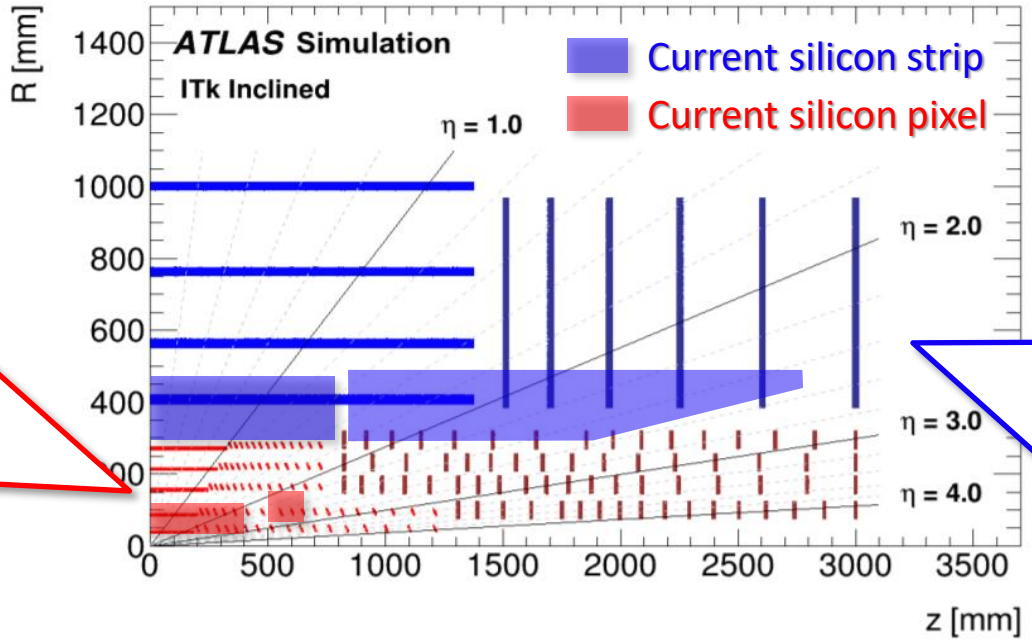
- Replace silicon + gas complex to all-silicon tracker
- Expand the acceptance from $|\eta| < 2.5$ to $|\eta| < 4.0$
  → Associate tracks from forward jets to vertices

- ATLAS Japan strongly drive upgrades of the silicon tracker and endcap muon trigger
  - Component R&D has been mostly completed → Started mass production

■ Inner Tracker (ITk)

ITk Pixel module

4 cm (50x50 μm^2 pixels)



ITk Strip module

9.8 cm (75.5 μm pitch strips)

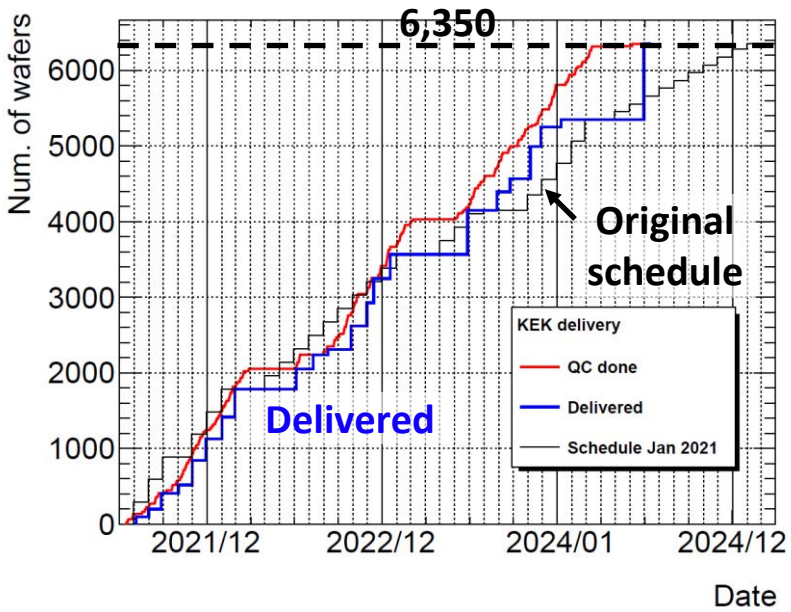
- ITk is the extreme silicon tracker
  - Surface area ~180 m^2 ← 3x larger than the current detector
  - Number of readout channels ~5G ← 50x more than the current detector

International project with ~1,000 people from 20 countries

U. Tsukuba group is also one of the key contributors!

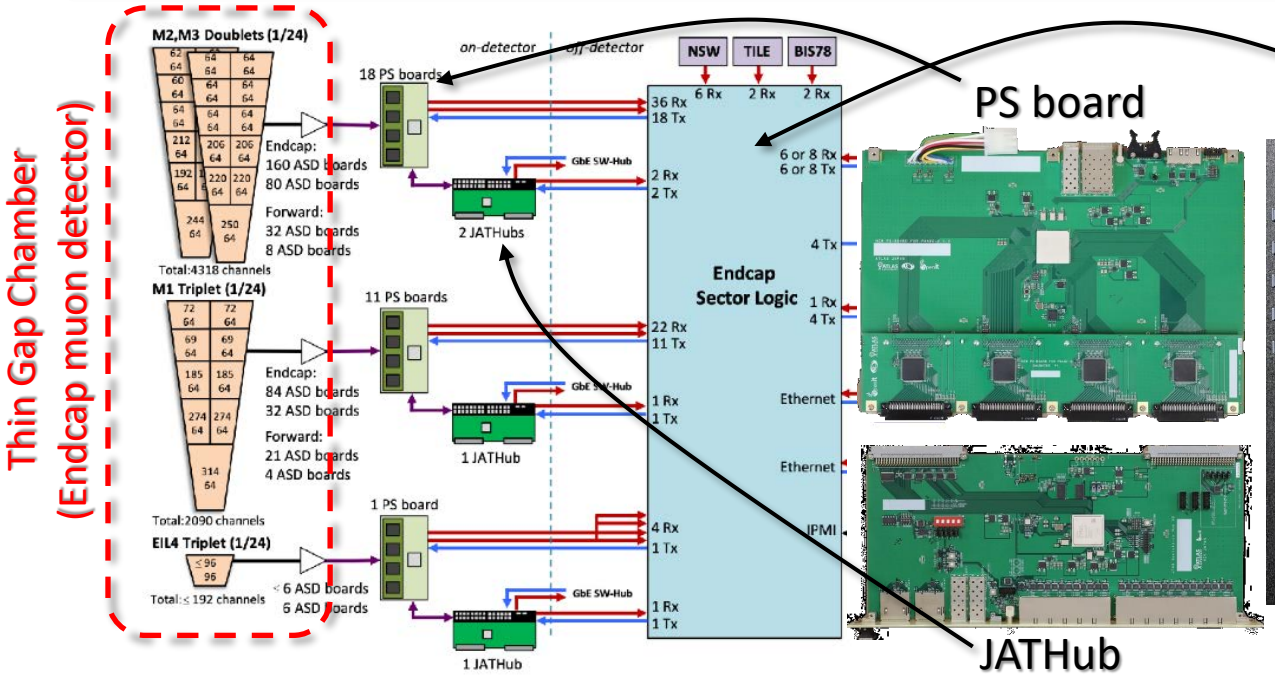
- Japan plays a key role in this project
  - For ITk Pixels: production of 2,800 modules (~25% to the total)
  - For ITk Strips: QC for 6,350 sensors (~30% to the total)

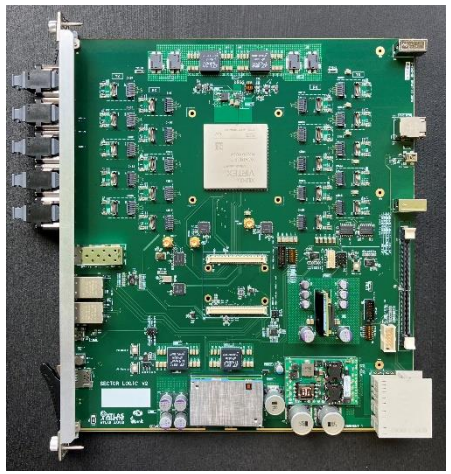
Status of upgrade: silicon tracker

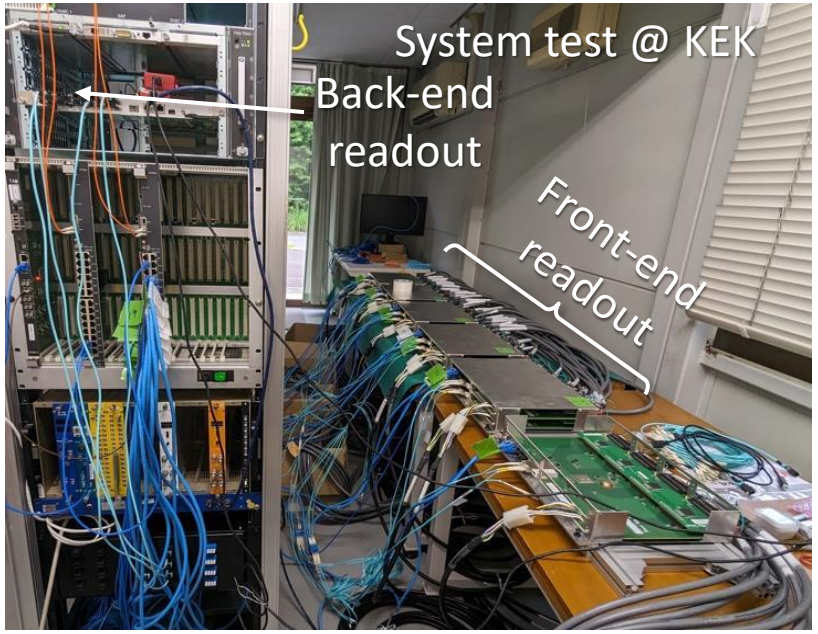


- ITk Strips
  - Production for the Japan's share has been completed in June 2024! (Took 3 years in total)
  - Periodical irradiation campaign to evaluate performance of irradiated sensors in sampling basis
- ITk Pixels
  - Pre-production last FY for 130 modules → Established the robust flow for assembly and QC
  - The pre-production modules are to be used for the ITk Pixel system test at CERN
  - Preparation of detector integration at CERN is underway

Status of upgrade: muon trigger





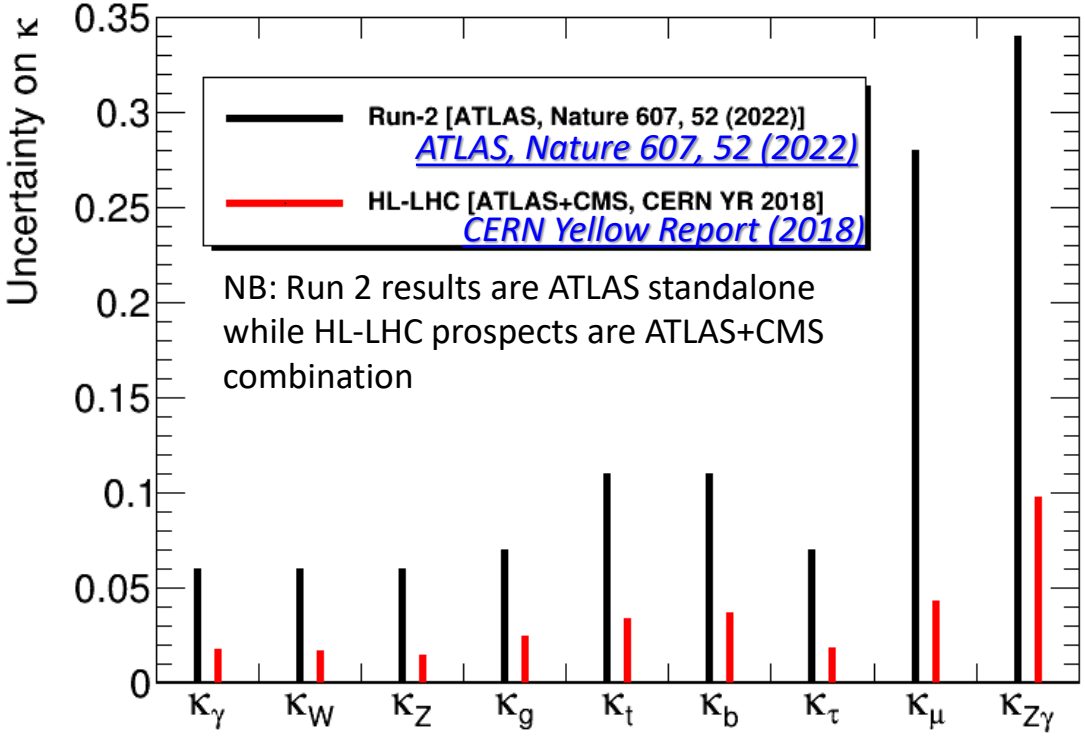


- Japan team is fully responsible for the front-end electronics of the endcap part
  - Mass production of the PS board: QC for 1,540 underway
    → Rad-hardness on ASIC/FPGA has been confirmed (γ: 180 Gy max.; n: 1.6×10^{12} $n_{\mathrm{eq}}/\mathrm{cm}^2$ max.)
- Sector Logic is also at the final stage of R&D → Production will start soon
  - Realise on-board fast tracking using UltraRAM
- System test with front-end + back-end electronics is ongoing at KEK

More details:
T. Nakagawa, 16aWB208-04 and various other talks

■ Prospects for HL-LHC: Higgs coupling

- Extrapolate to expected statistics of HL-LHC based on Run 2 results
  - 3,000 fb^{-1} is assumed
  - Not a full simulation; better performance of upgraded detectors is not taken into account



$H \to cc$ @ ATLAS, CMS
(First evaluation in 2022)

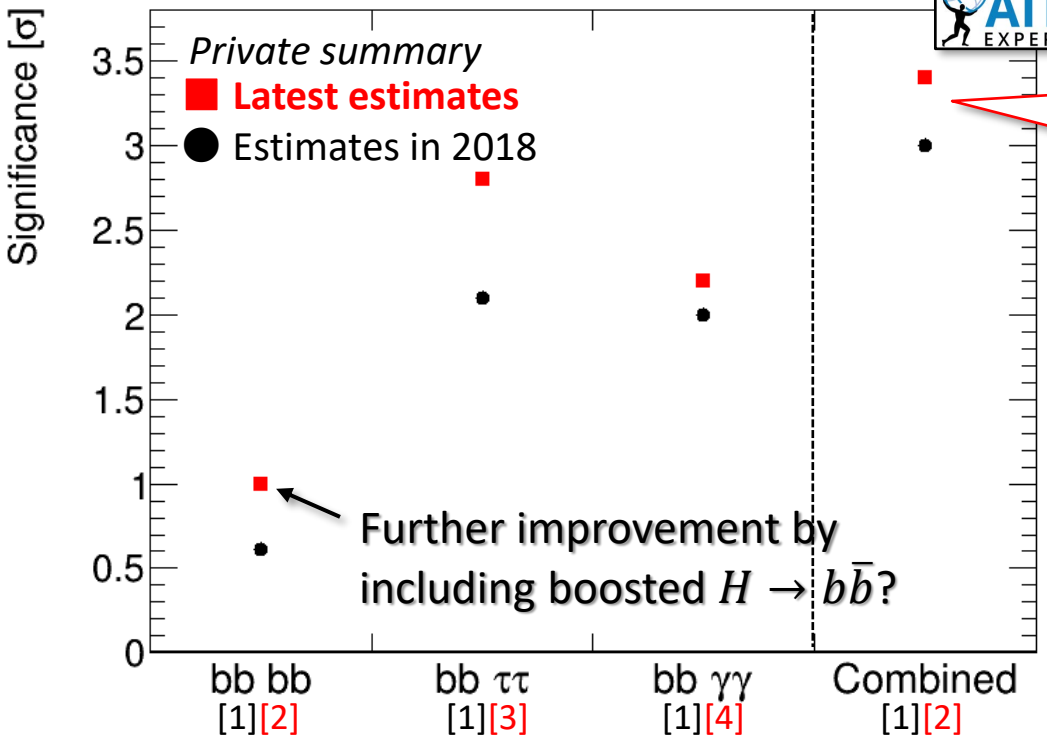
	ATLAS [1]	CMS [2]
$\lvert\kappa_c\rvert$	< 3.0	< 2

[1] ATLAS-PHYS-PUB-2021-039
[2] CMS-PAS-FTR-22-001

NB: $H \to cc$ is being significantly improved!

- Main Higgs couplings (i.e. gauge bosons and 3-gen) will be measured at 2-3% precision
  - 2nd-gen coupling (κ_μ) reaches ~4%!
  - Recent developments have not been included in many of the channels → Further improvements!

Prospects for HL-LHC: Higgs pair production



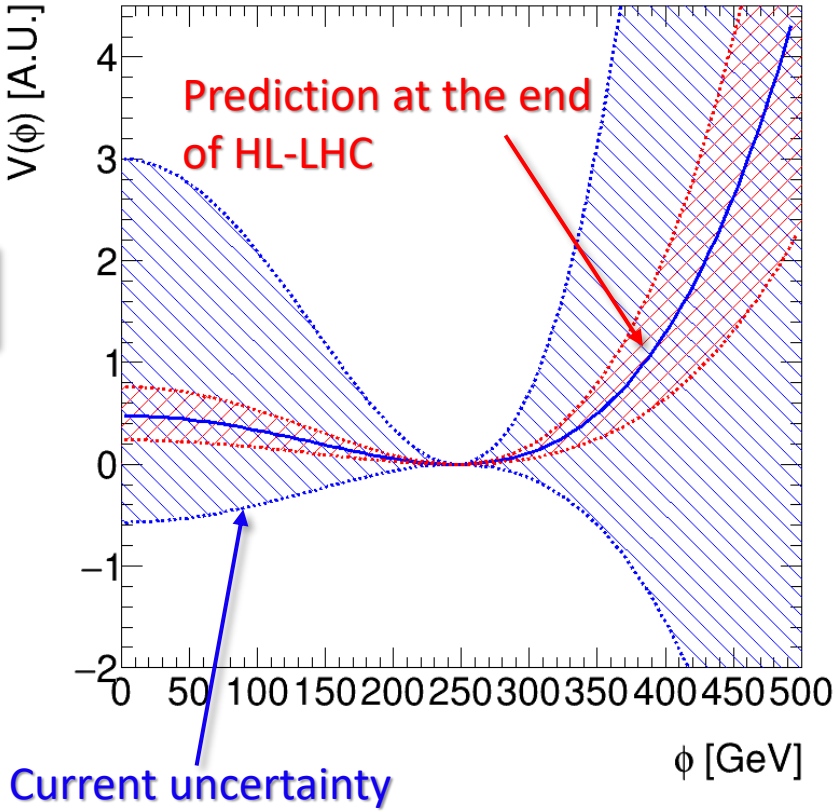
$0.5 < \lambda/\lambda_{SM} < 1.6$
(68% C.I.)

CMS (2018)
CMS-FTR-18-019

- 2.6σ
- $0.35 < \lambda/\lambda_{SM} < 1.9$

No recent update

[1] *ATL-PHYS-PUB-2018-053*
[2] *ATL-PHYS-PUB-2022-053*
[3] *ATL-PHYS-PUB-2021-044*
[4] *ATL-PHYS-PUB-2022-001*

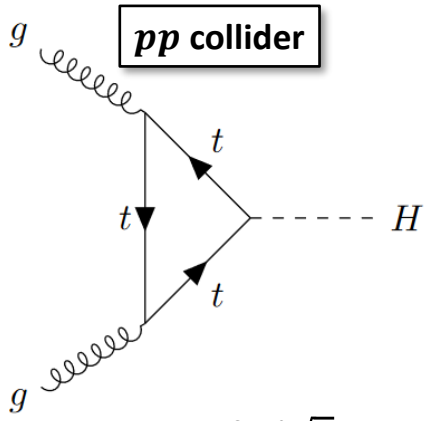


- Various improvements in the Run 2 analyses
  - The latest estimate shows **>10% improvements** with respects to that in 2018
  - Taking statistical combination from CMS improves sensitivity further by $\sim\sqrt{2}$

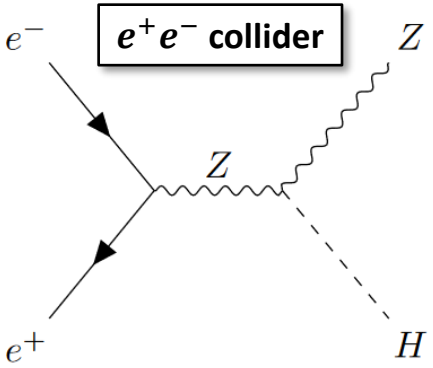
Observation of the Higgs pair production is one of the most important subjects at HL-LHC

■ Higgs Factory

- e^+e^- collider has an advantage of its clean environment
  - Less background from QCD events
  - Initial state is well defined



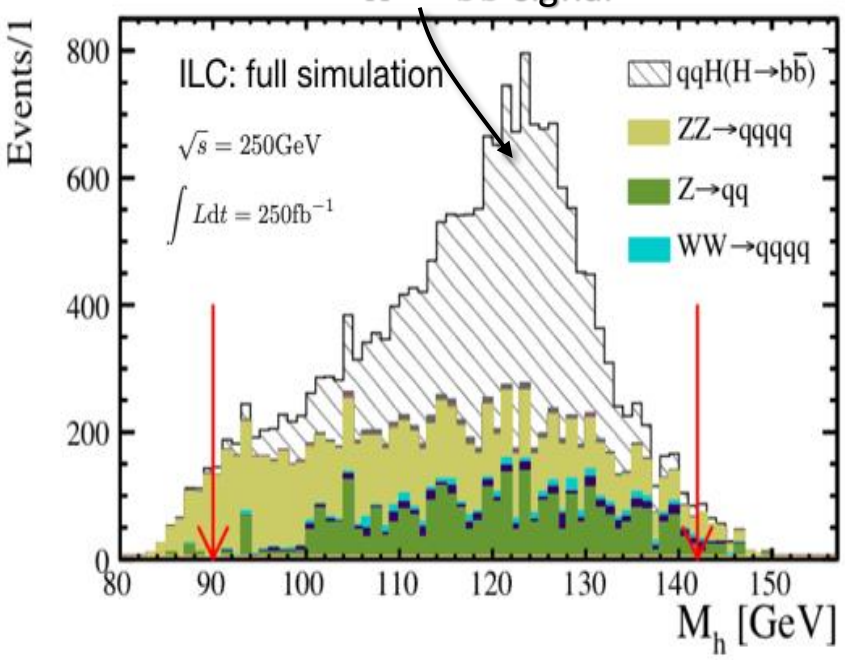
σ_{Higgs} = 55,000 fb ($\sqrt{s}$ = 14 TeV)



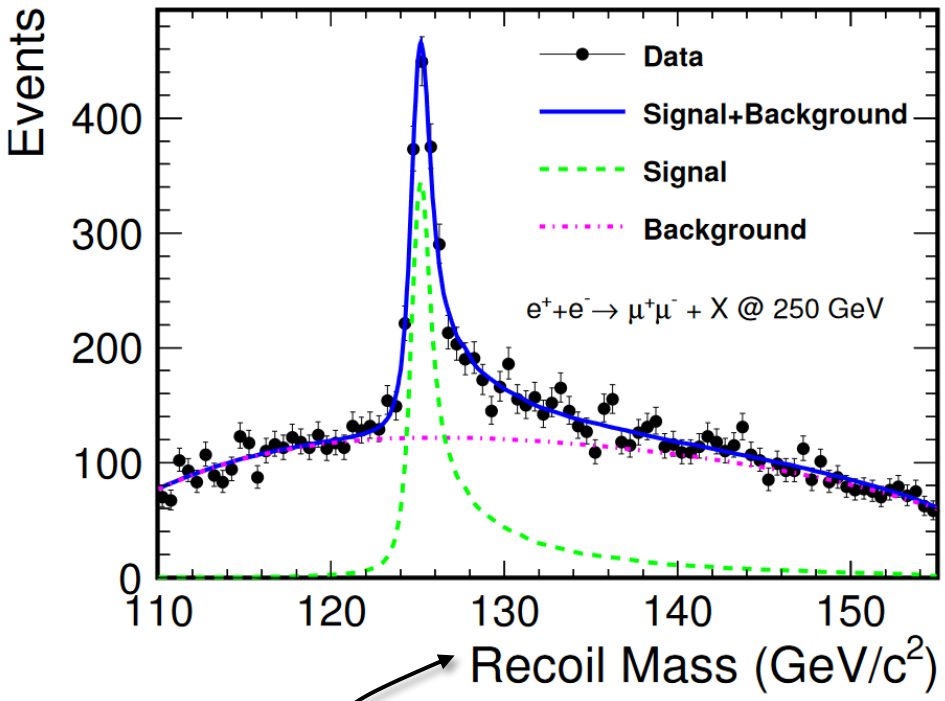
σ_{Higgs} = 320 fb ($\sqrt{s}$ = 250 GeV)

A. Aryshev et al., ILC Report to Snowmass 2021

$H \to b\bar{b}$ signal



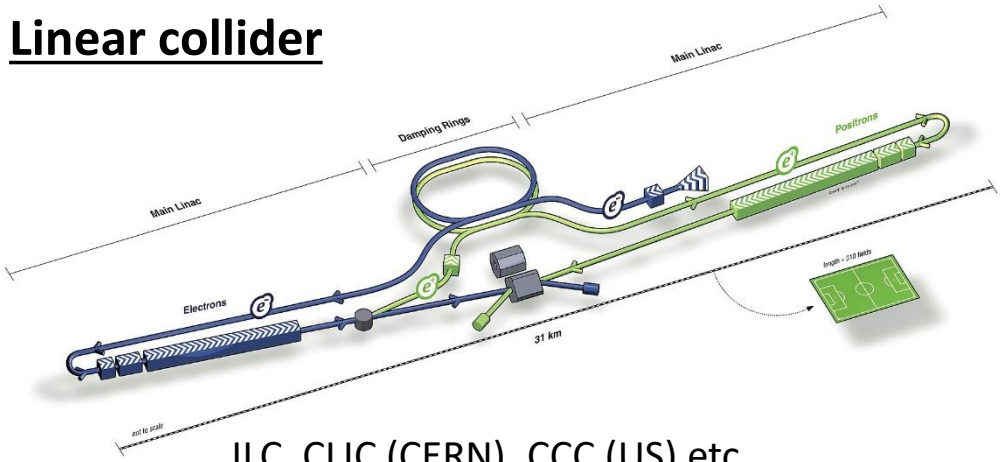
J. Yan et al., Phys. Rev. D 94 (2016) 113002



Calculated from $p_{e^+e^-} - p_{Z\to\mu^+\mu^-}$

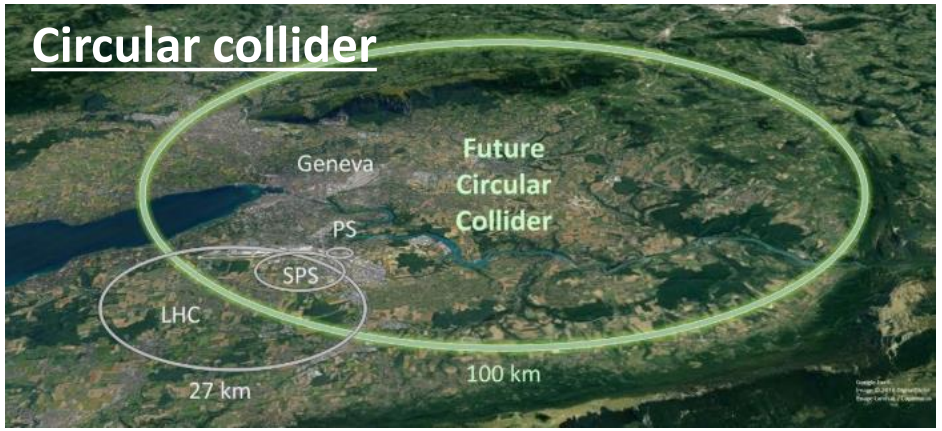
Linear vs Circular

Linear collider



ILC, CLIC (CERN), CCC (US) etc.

Circular collider

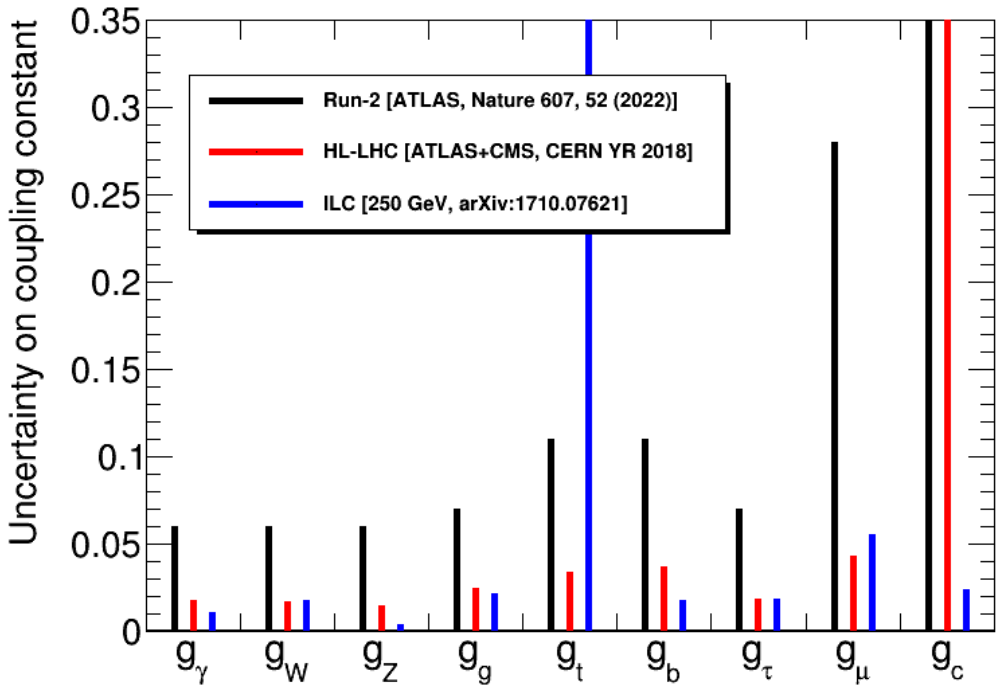


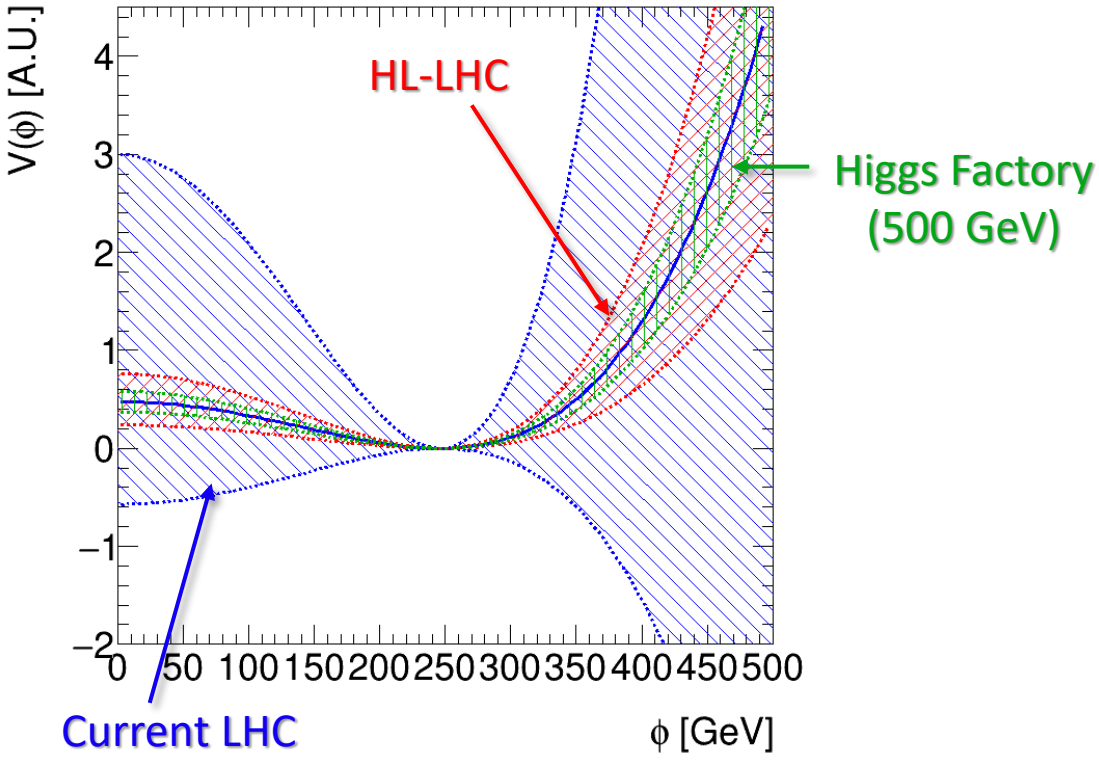
FCC (CERN), CEPC (China) etc.

- Pros and cons of each type of collider

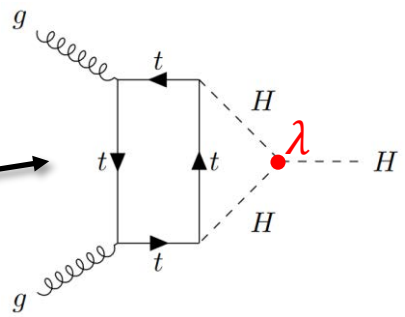
	Linear collider	Circular collider
Size for 250 GeV	Relatively compact (~20 km)	~100 km is necessary
Luminosity	Challenging because just one crossing possible for a bunch	High-L naturally possible as beam condition is adjustable in the MR
Energy extendibility	Higher energy is easily achieved by extending the length	Limited by RF power to recover energy loss due to intensive radiation
Maturity	Less precedents (only SLC)	Well-established technology
Concerns	High power e^+ source needs to be developed	RF system

■ Prospects of Higgs measurements at Higgs Factory



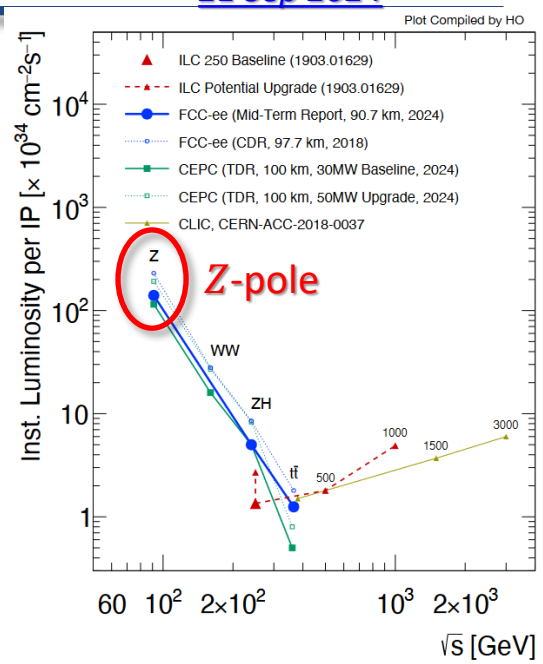


- Higgs coupling
  - LHC has advantage on the small couplings (g_μ) and $t\bar{t}H$ (g_t)
  - Higgs Factory has advantage on the large couplings (g_Z) and H-c coupling (g_c)
- Higgs self-coupling
  - At 250 GeV: Only indirect constraint is possible via higher-order diagrams
  - At 500 GeV: 22% measurement will be possible *J. de Blas et al., JHEP 01 (2020) 139*



Tera-Z at FCC-ee

H. Oide, JAHEP Town Hall Meeting 21 Sep 2024



- Low-energy run of the circular Higgs factory may achieve extreme luminosity
  - This is because synchrotron radiation power is highly suppressed
  - 2×10^{36} /cm^2/s may be possible at Z-pole

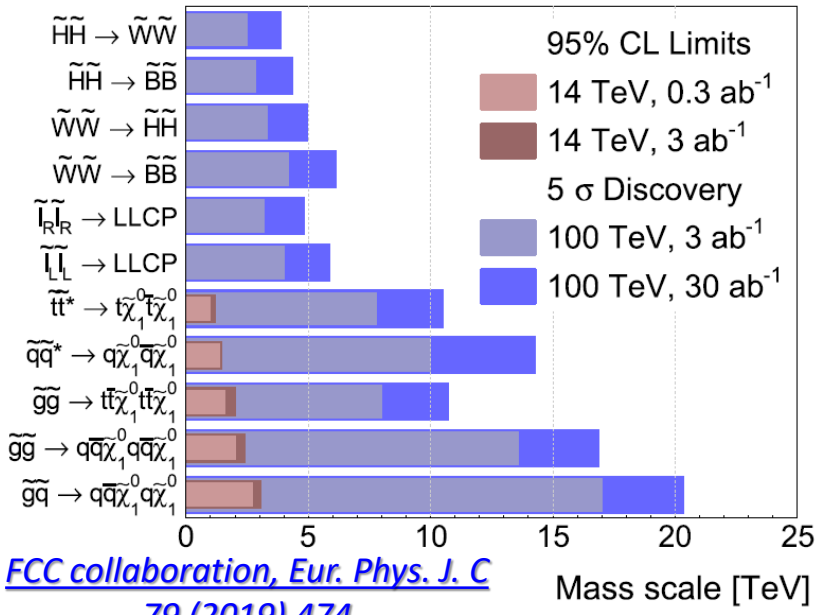
    50x higher than Super-KEKB!
- Tera-Z: O(10^{12}) Z bosons can be accumulated during 4-year Z-pole operation
  - Can provide an excellent opportunity for high-stat. flavour studies

[x10^9]	B^0	$B^\pm$	B_s^0	Λ_b	$B_c^\pm$
FCC at Tera-Z	310	310	75	65	1.5
Belle II	52	52	0.6	-	-

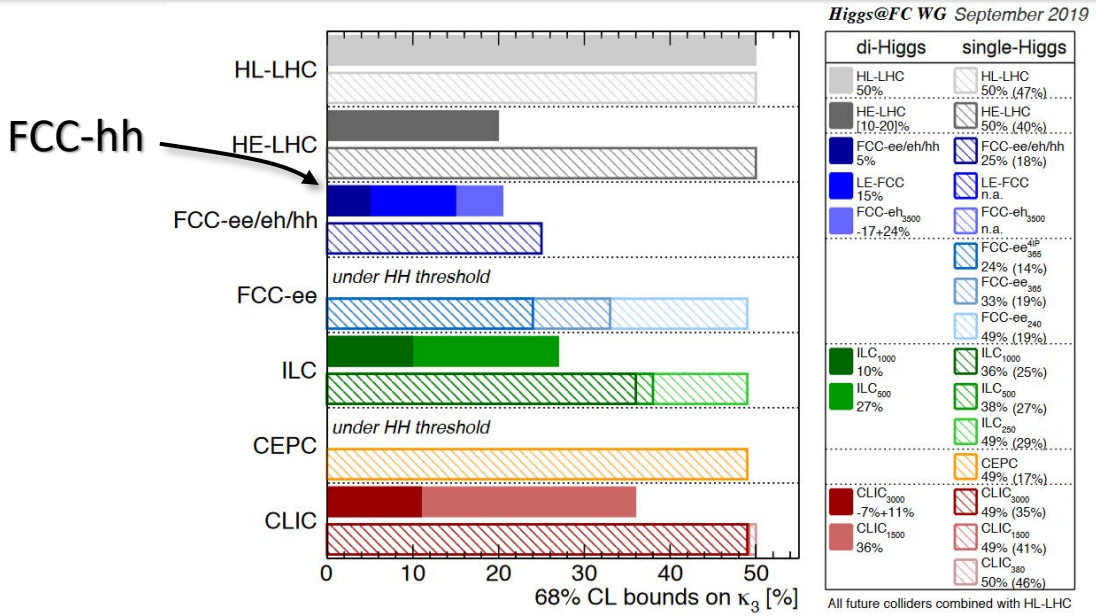
S. Monteil et al., Eur. Phys. J. C 136 (2021) 837

  - 10x more statistics than full Belle II data
- Challenge: signal rate will be ~100 kHz
  - DAQ system needs to handle such a huge data traffic
  - Gaseous tracker may not be operable? But a fully-silicon tracker has more materials

■ After Higgs Factory: ~100 TeV collider



FCC collaboration, Eur. Phys. J. C 79 (2019) 474



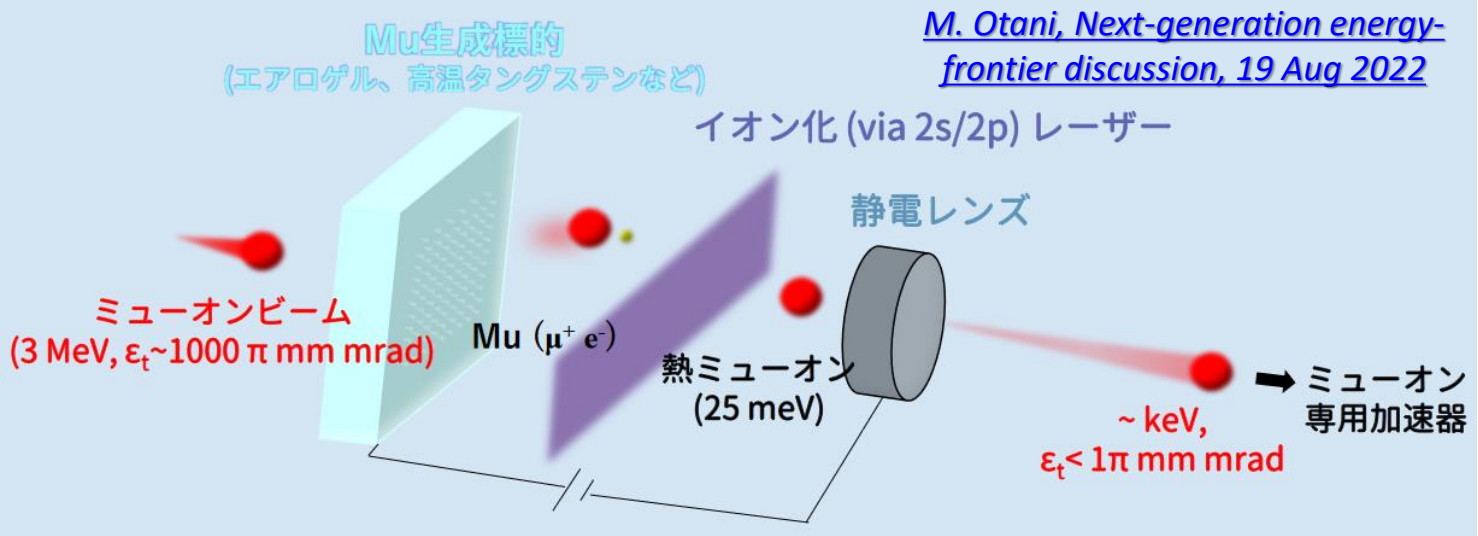
J. de Blas et al., JHEP 01 (2020) 139

- Circular Higgs Factories (FCC-ee and CEPC) can be renovated to be hadron machines
  - $p = 0.3BR$ with B = 16 T and R = 16 km → ~**100 TeV is possible**
- At 100-TeV hadron collider, O(10 TeV) BSM particles can be searched
  - E.g. 'natural SUSY' can be discovered or fully excluded
  - Much more Higgs pair-production events; **5% measurement on λ** may be possible
- Challenges
  - 16 T Nb_3Sn magnets need to be developed (not only base technology but also methods for mass production)
  - Cost is estimated to be higher than the entire construction cost of FCC-ee (~10B CHF / 1.6T JPY)

■ Ultimate dream: muon collider

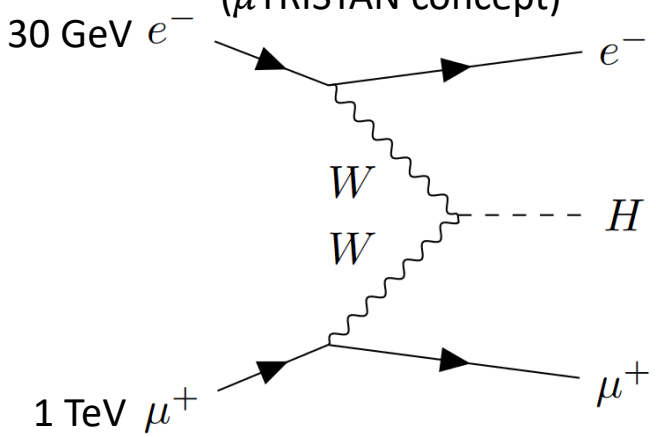
- Muon is an elementary particle with 106 MeV
  - 200x heavier than electrons → Less synchrotron radiation, so **10-TeV lepton collider may be possible**
  - Difficulties are:
    - Lifetime = 2.2 μs
    - Production by colliding protons

    } **Need to make low-emittance μ beams as quick as possible**
- First μ^+ beam is achieved at J-PARC (for the muon g-2 experiment) *G.A. Beer et al., Prog. Theor. Exp. Phys. 2014, 091C01 (2014)*
  - Smart idea by using 'muonium' = bound state of e^--μ^+ in a material
    → This cannot be used for μ^-



M. Otani, Next-generation energy-frontier discussion, 19 Aug 2022

$e^-\mu^+$ collider with asymmetric energy?
(μTRISTAN concept)



Y. Hamada et al., Prog. Theor. Exp. Phys. 2022, 053B02 (2022)

Muon collider is fantastic, but there are still many fundamental challenges: μ^- beam, high intensity p beam, ...

World-wide discussion for future projects

P5 process has been concluded last year (link)

- The panel endorses an **offshore** Higgs factory
- The panel recommends R&D ... a 10 TeV parton center-of-momentum (100 TeV pp collider / 10-TeV μ collider)

European strategy update process is going to start next year *More details in K. Jakobs, LCWS 2024*

- CERN is seeking realisation of the 91-km Future Circular Collider *F. Zimmermann, JPS Fall 2024*
- Feasibility study (incl. civil engineering, site selection etc.) is going to be concluded next year → Input to ESPPU

Japan is preparing for a community input to ESPPU *More details in Y. Nakahama, JPS Fall 2024*

- Community-wide discussion is ongoing, focusing on Higgs Factory: not only ILC but also FCC-ee etc.

China is proposing 100-km CEPC to the 15th five-year national plan

- If successful, start of operation in 2035 may be possible *More details in J. Gao, LCWS 2024*

All of the future project proposals are challenging, but some decisions are to be made in coming years

■ Summary

- LHC has been leading the energy frontier for >15 years
  - Various properties of the Higgs boson have been investigated; **so far** consistent with the SM
  - Higgs pair-production is now being measured; important test for the vacuum in the Universe

- Next step: HL-LHC starting in 2029
  - Target luminosity is 3000 fb^{-1}; we have **only 10% of data** with respect to the final goal!
  - Accelerator and detector upgrade activities are ongoing
    → ATLAS Japan is working on massive QC programme during the detector production

- Beyond LHC: discussions are being more serious
  - Higgs Factory may be consensus in the HEP community
    - US concluded the P5 process last year
    - ESPPU is starting early next year: main focus will be FCC-ee (with prioritised backup plans)
    - Japan is discussing next steps: not only ILC but also other options
    - China is aiming for the next five-year national plan

Understand the Higgs field first, and then discover BSM behind the Higgs sector is an ultimate goal