Institut national de
physique nucléaire et de
physique des particules

10 ans découverte du boson de HIGGS

COLLOQUE BOSON DE HIGGS
10 ans après, l'aventure continue

Un avenir lumineux : facteurs 2, 20 et au-delà

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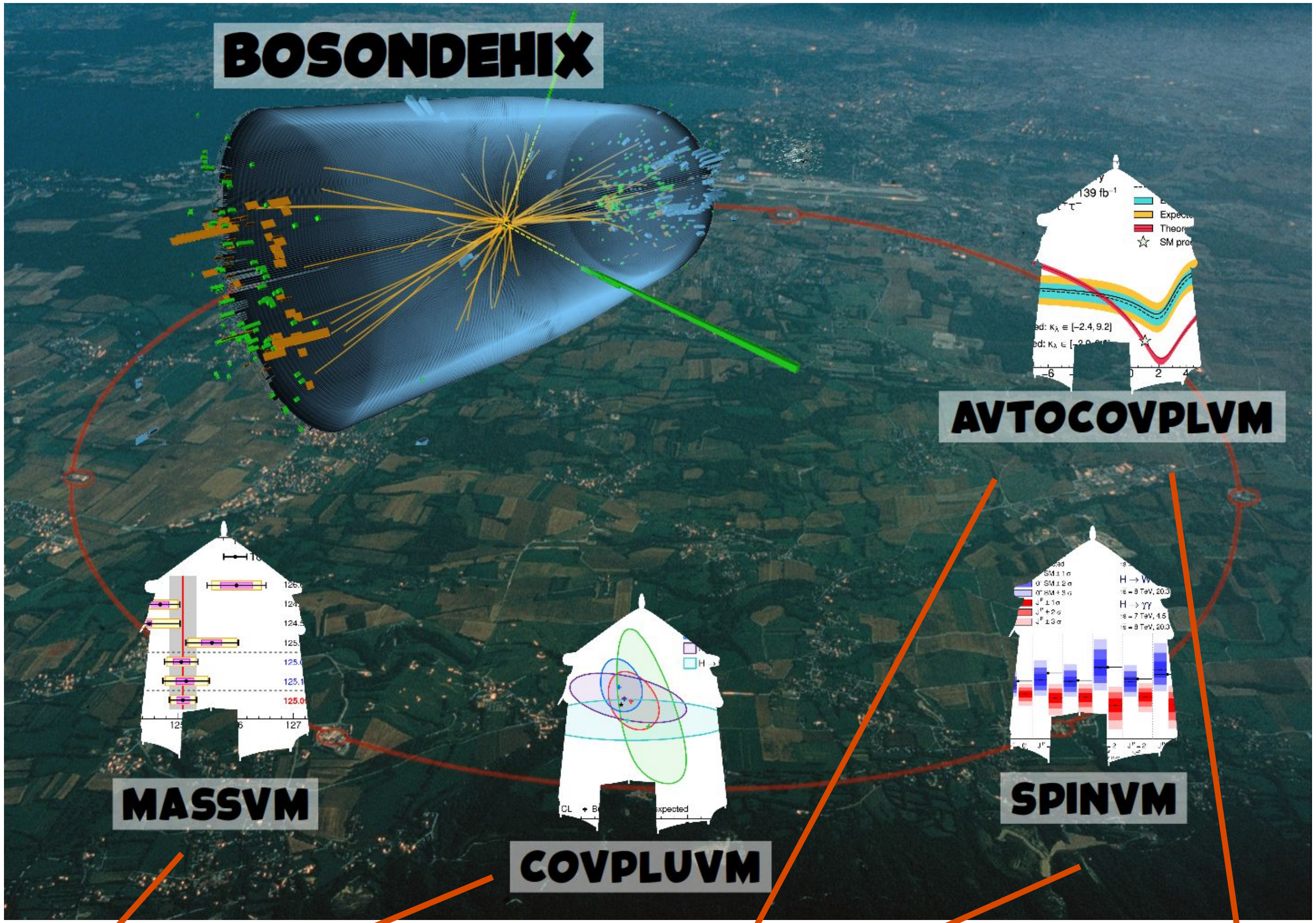
6 juillet 2022

Introduction



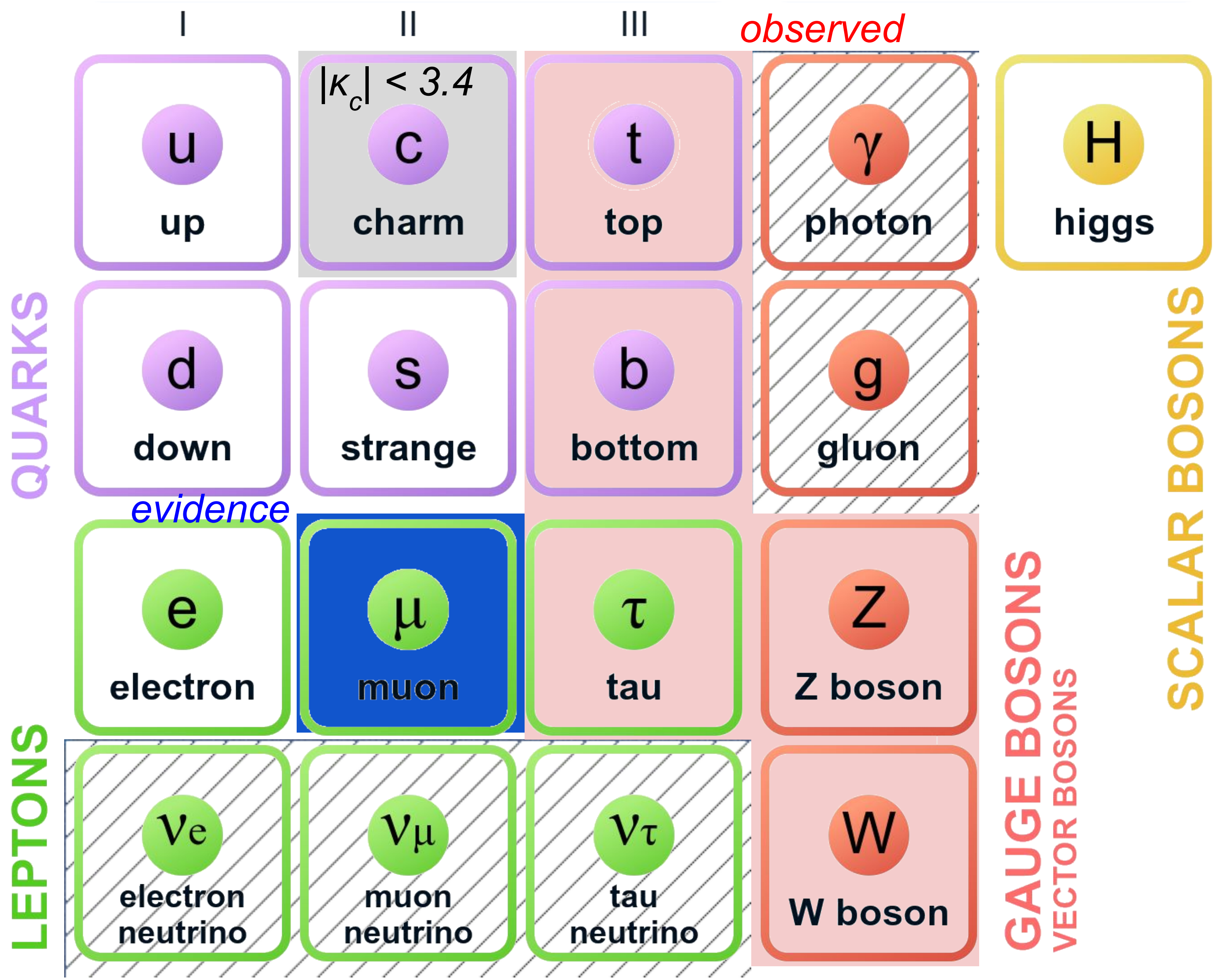
Dark Matter

Matter-antimatter asymmetry

Origin and hierarchy of masses

Where we stand today

- Mass: 0.1% precision



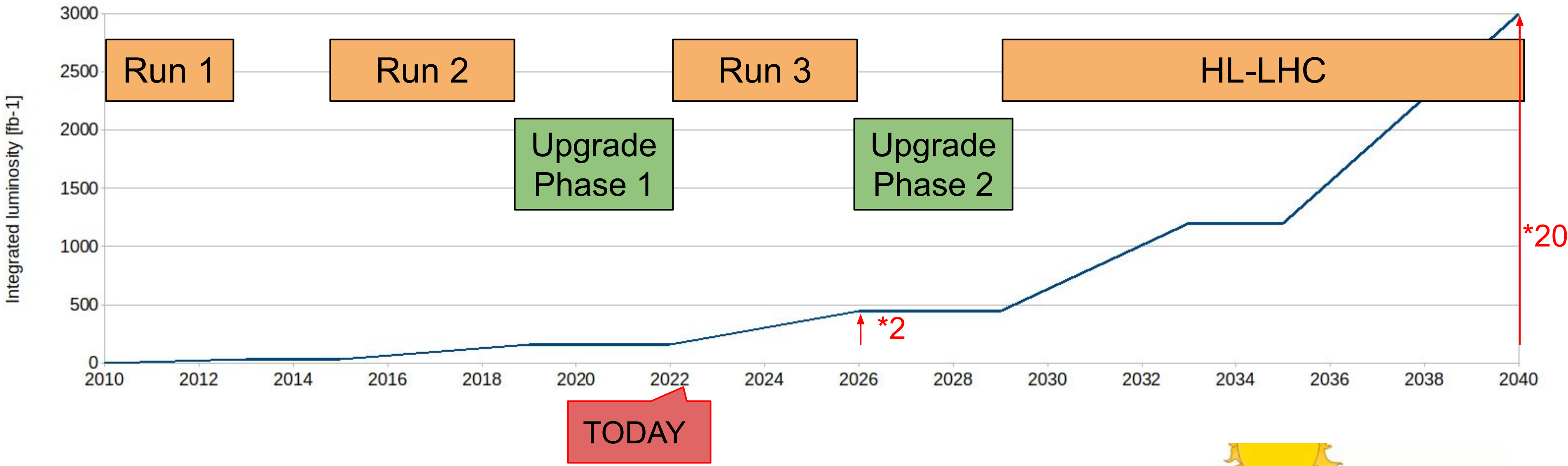
Why more data

- **~8 millions** Higgs bosons
- Recorded so far:

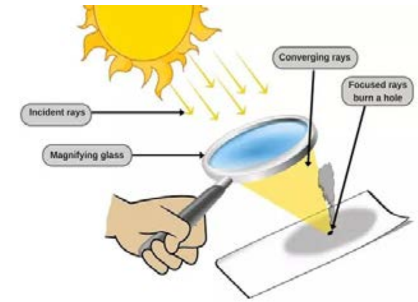
	Produced	**Selected**
$H \to \gamma\gamma$	20000	6000
$H \to ZZ^*$	200000	200
$H \to WW^*$	2e6	6000
$H \to \tau\tau$	500000	2000
$H \to bb$	5e6	9000
$H \to \mu\mu$	1500	900
$HH \to bb\gamma\gamma$	11	1

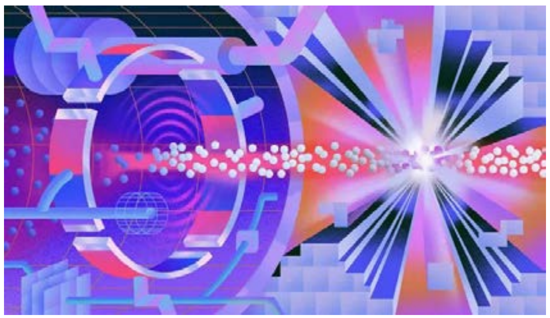
- Many measurements still statistically limited
  - mass in $H \to 4l$ channel
  - differential cross-sections
- Some decays/couplings not observed yet
  - $H \to \mu\mu$, $H \to Z\gamma$
  - u, d, s, c quarks, e, μ leptons, self-coupling

The LHC timeline and luminosity

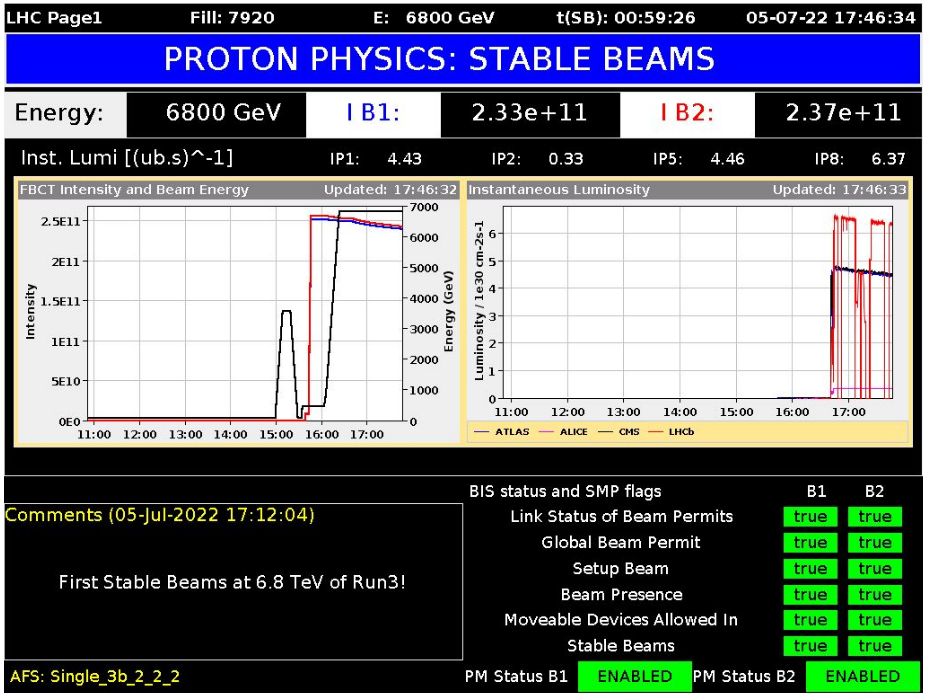


- Luminosity L: ~collision rate (in $cm^{-2}.s^{-1}$):
  - $dN/dt = \sigma * L$
  - proportional to the number of collisions that occur in a given amount of time
  - dependent on the proton beam parameters





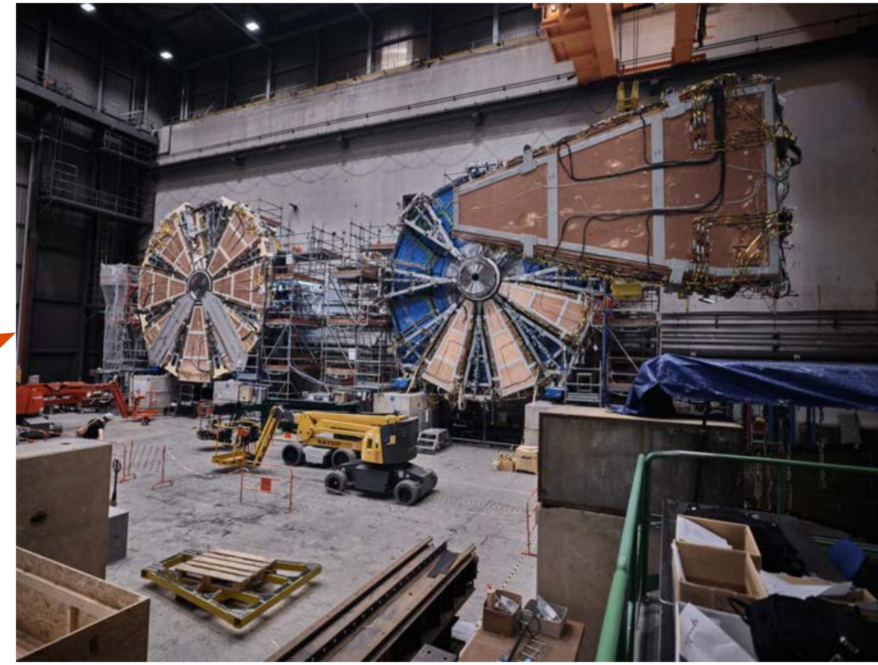
LHC Run 3: data*2

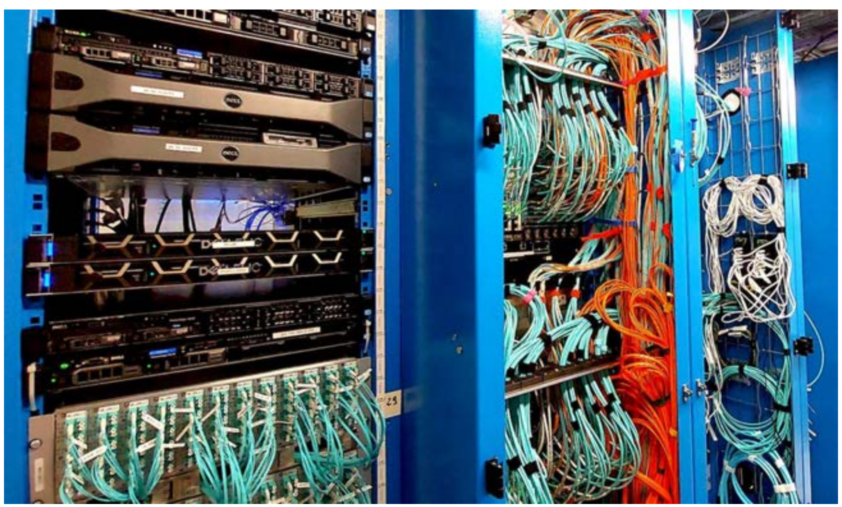


Detector upgrades for Run 3: not that simple !

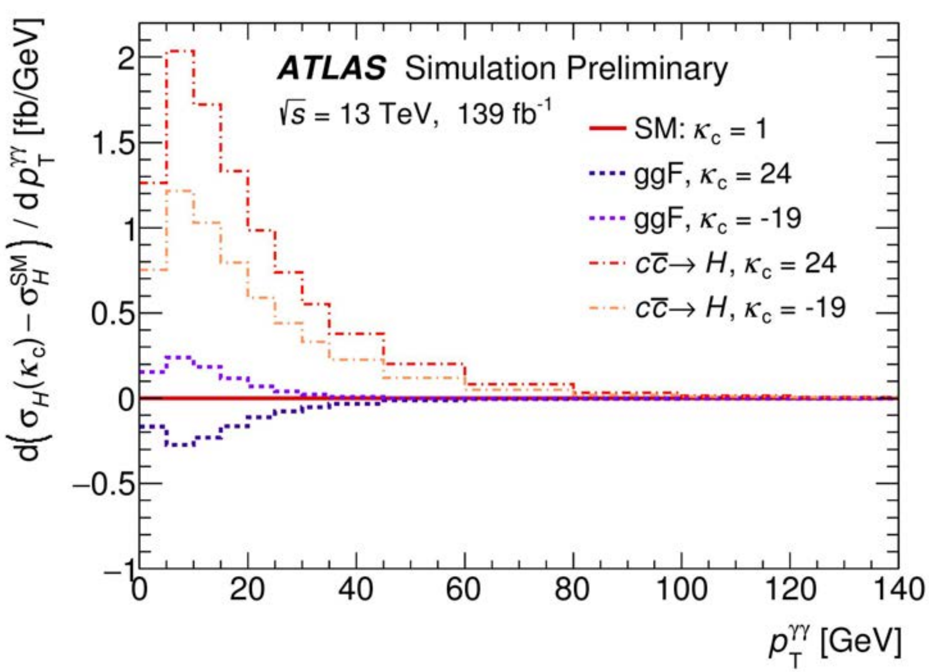
- Future-proof upgrades
  - Useful for Run-3 physics programme
  - Will stand through HL-LHC

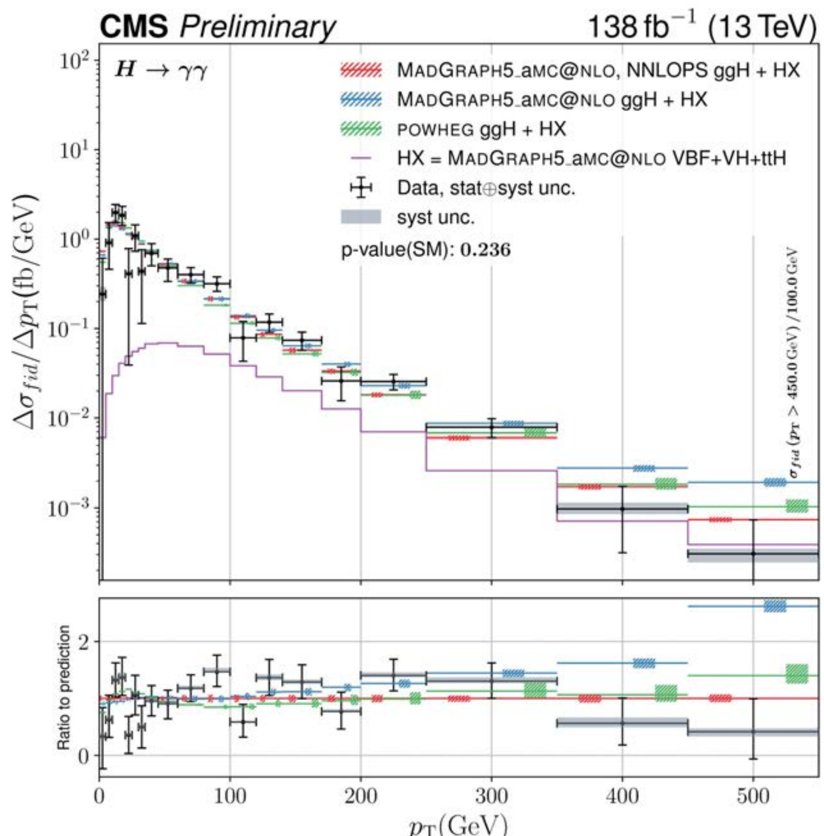
- ATLAS New Small Wheel
- LAr digital L1 trigger
  - + Construction/installation during Covid





- Increase in production cross-section (→13.6 TeV): +7.5% ggF, +12.6% ttH, +11% HH
- Differential cross-sections
  - sensitive to b-quark/c-quark at low p_T^H and top-quark/BSM at high p_T^H



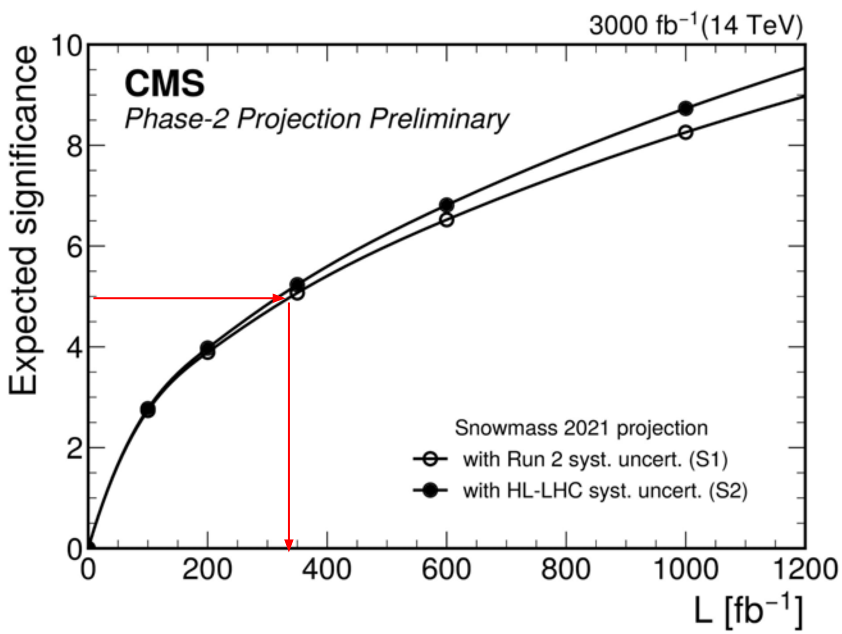


Higgs physics at Run 3 (2)

- **Rare decay**: $H \to Z(\to ee/\mu\mu)\gamma$: $BR = 0.1\times10^{-3}$
  - full Run 2 significance:
    - ATLAS: 2.2σ (expected 1.2σ)
    - CMS: 2.7σ (expected 1.2σ)

    } combined >3σ (evidence)
  - 3σ/exp. by the end of Run 3?

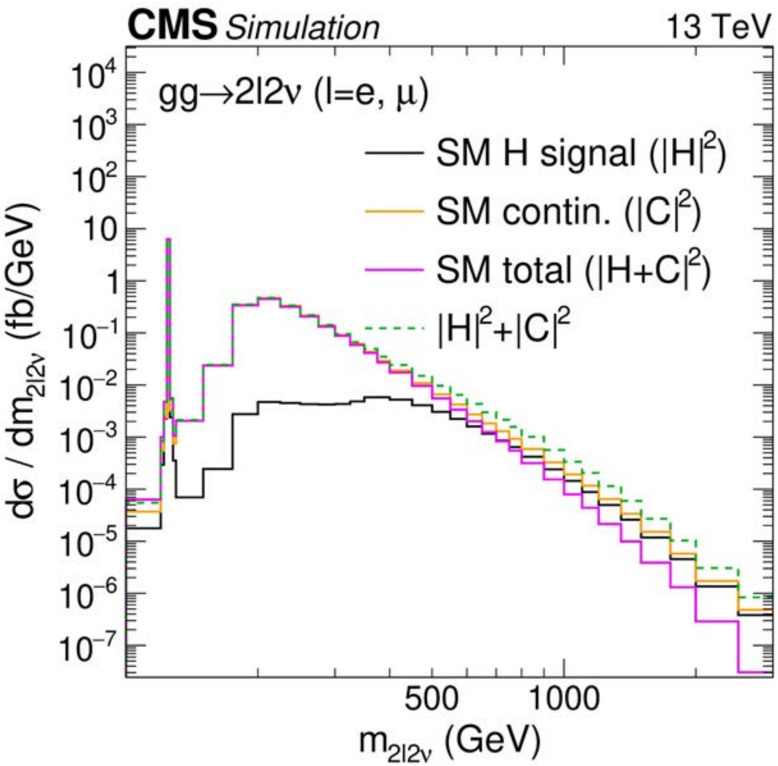
- **2^{nd} generation**
  - $H \to \mu\mu$
    - first evidence (3σ) at Run 2
    - 5σ can be achieved at Run 3
  - c-quark
    - sensitivity from $VH(\to cc)$



HL-LHC: data*20

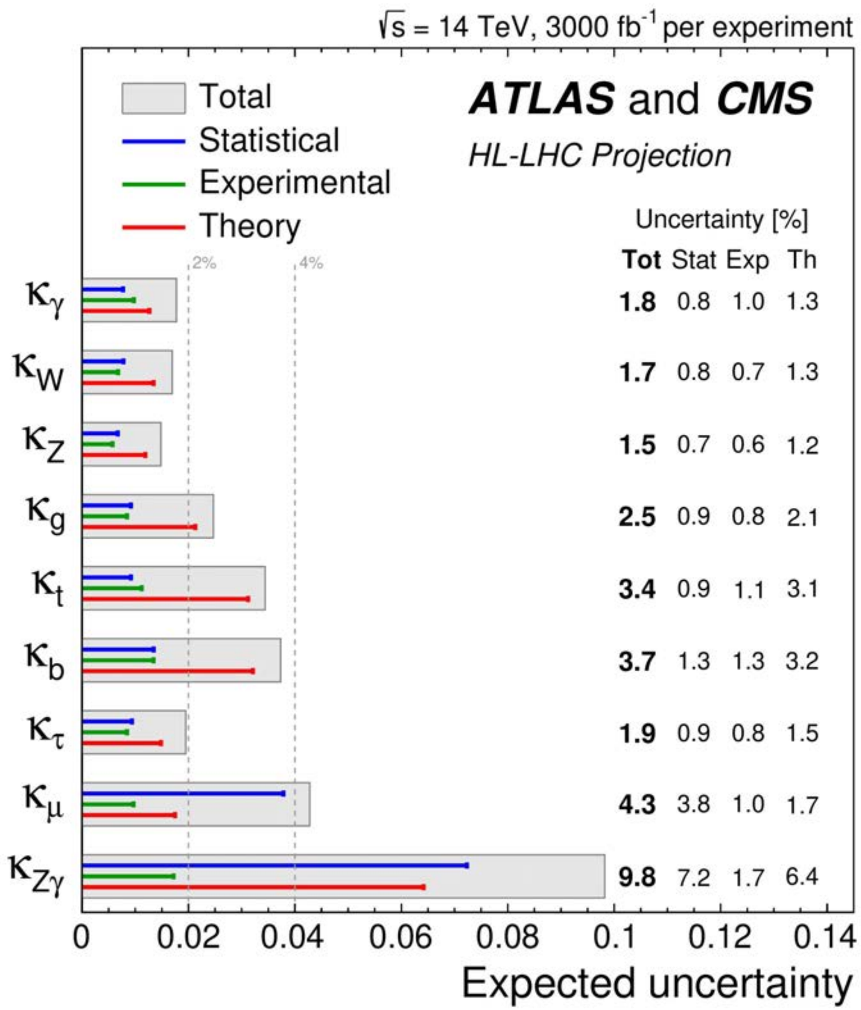
Higgs physics at HL-LHC: mass and width

- Mass
  - latest projection ($H \to 4l$): precision of 30 MeV (= 22 stat $\oplus$ 20 syst)
  - 10-20 MeV plausible, will dependent on future improvements of muon momentum measurements
- Width Γ_H (SM = 4.07 MeV)
  - thought to be impossible
  - $H \to ZZ$ on-shell and off-shell: 20% precision (assumption that ratio from SM)



Higgs physics at HL-LHC: Couplings (1)

$$\mu_i^f \equiv \frac{\sigma . BR}{\sigma_{SM} . BR_{SM}} = \frac{\kappa_i^2 . \kappa_f^2}{\kappa_H^2}$$



- Precision: 2-4%
  - limited by experimental and (mostly) theoretical systematics

Higgs physics at HL-LHC: Couplings (2)

- 2nd generation: coupling to charm through VH(→cc)
  - thought to be impossible not so long ago…

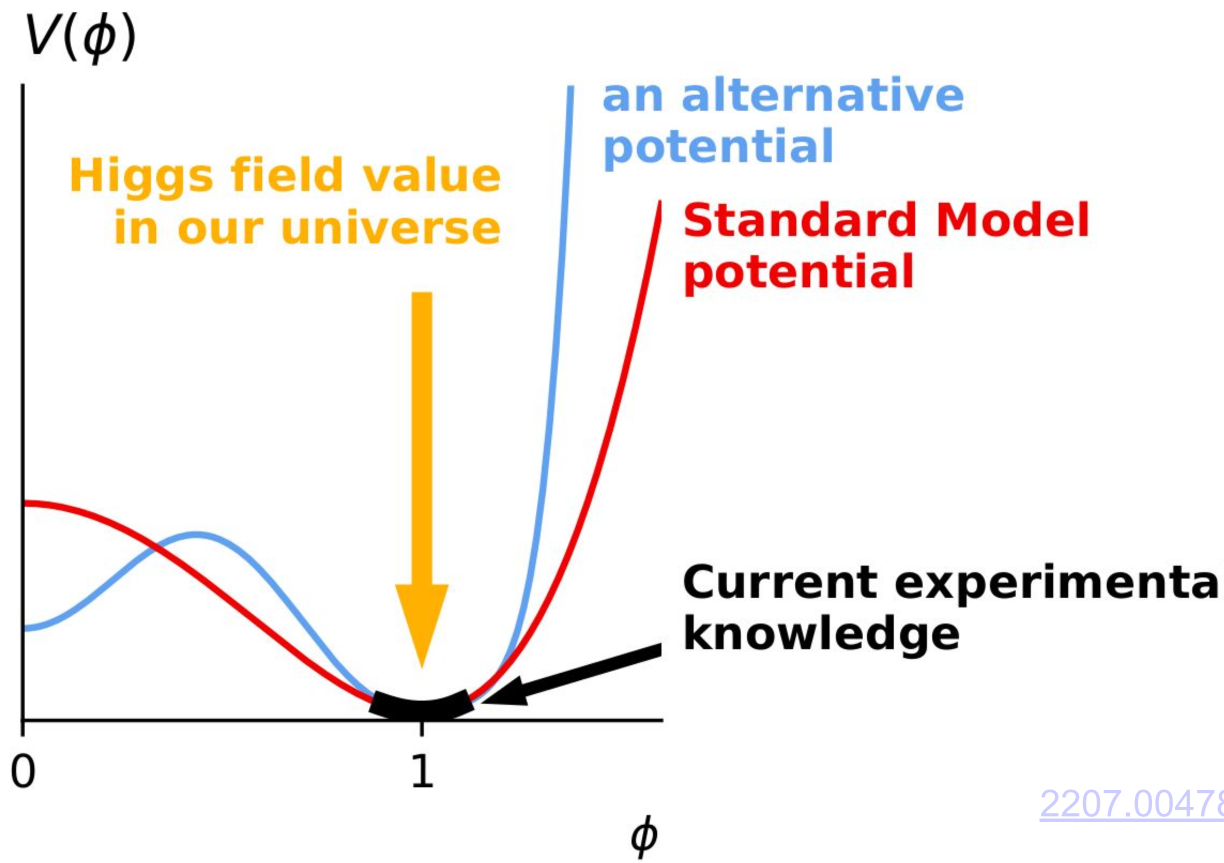
- 2nd generation: coupling to muons through H→μμ
  - improvement thanks to the extension of the coverage of the CMS muon system ($|\eta| < 2.8$) and ATLAS inner tracker ($|\eta| < 4$)
  - expected precision on signal strength:

	Statistical	Experimental	Theoretical	Total
ATLAS YR2018	$^{+12\%}_{-13\%}$	2.00%	$^{+5\%}_{-4\%}$	**13%**
CMS Snowmass2013				**14%**
CMS YR2018	9%	2%	3%	**10%**
CMS Snowmass2021	6%	2%	2%	**7%**

factor 2 in 8 years!

- Higgs potential:

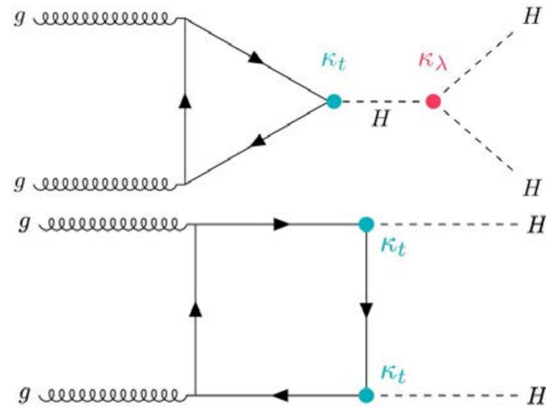
$$V(\Phi)=\frac{1}{2}\mu^2\Phi^2+\frac{1}{4}\lambda\Phi^4$$



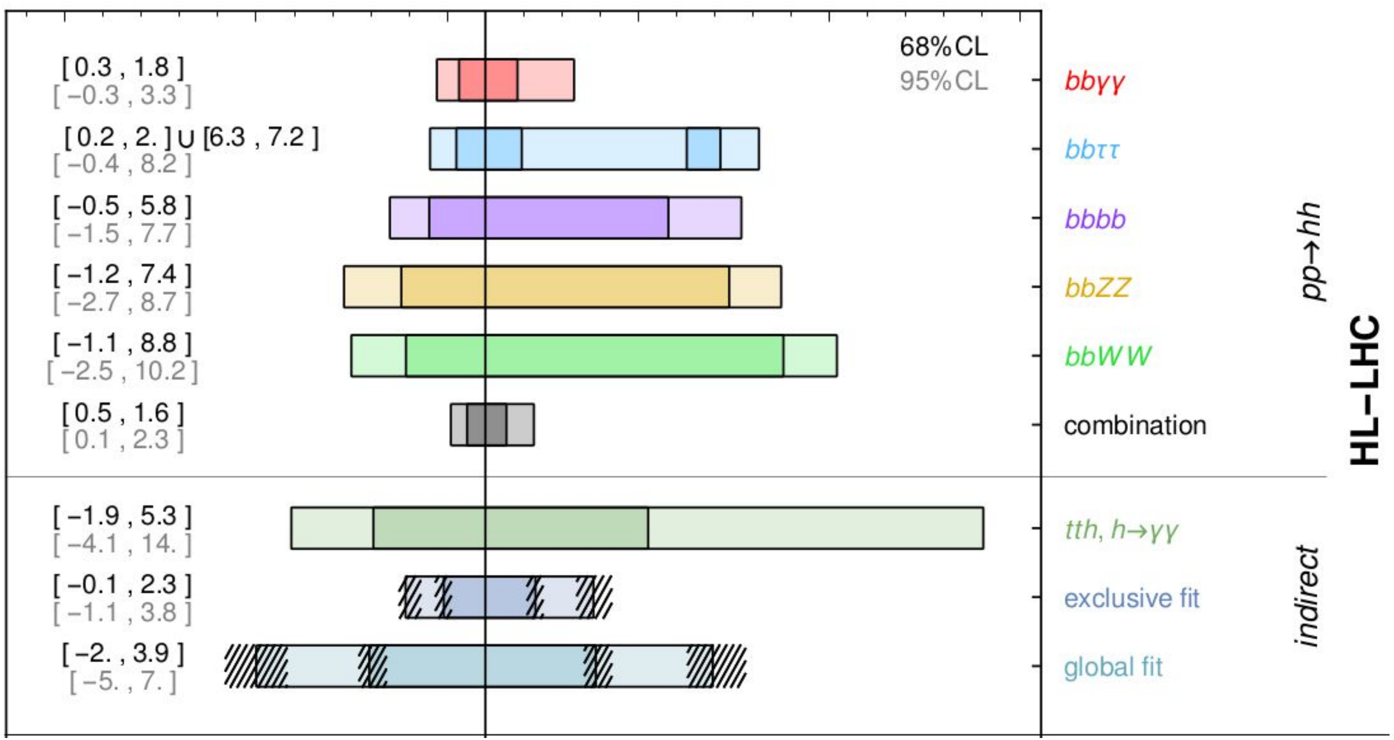
2207.00478

- BSM effects could change λ, ie Higgs self-coupling
- Relationship to electroweak phase transition: matter-antimatter asymmetry, gravitational waves, etc

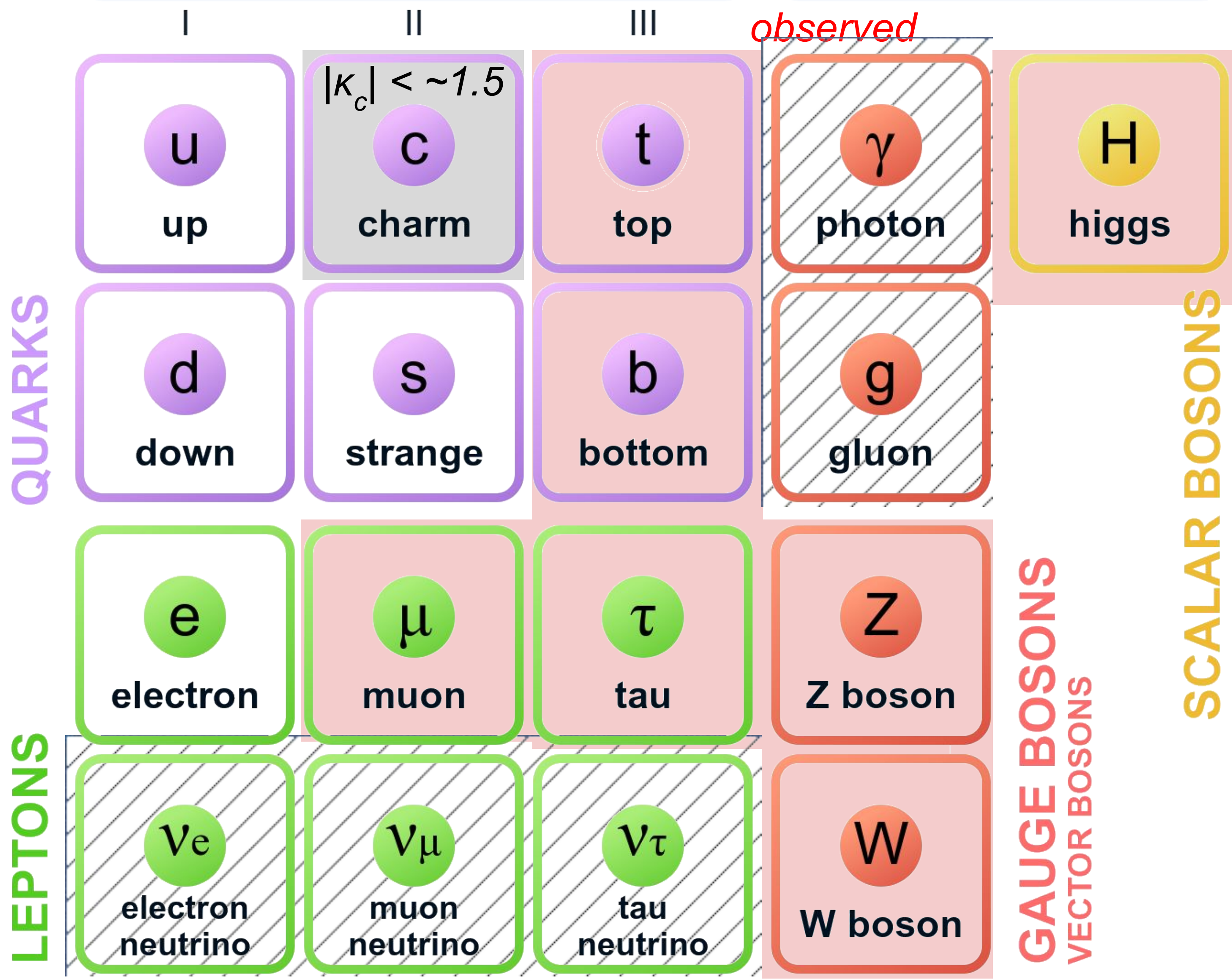
Higgs physics at HL-LHC: self-coupling (2)



- Through the HH production
  - rare process: σ(HH)/σ(H) = 0.1%
- Expected significance (ATLAS+CMS): 4σ
- Precision on $\kappa_\lambda = \lambda/\lambda^{SM}$: 50%
  - latest projections show that this value could be achieved with bbττ+bbγγ ATLAS-only

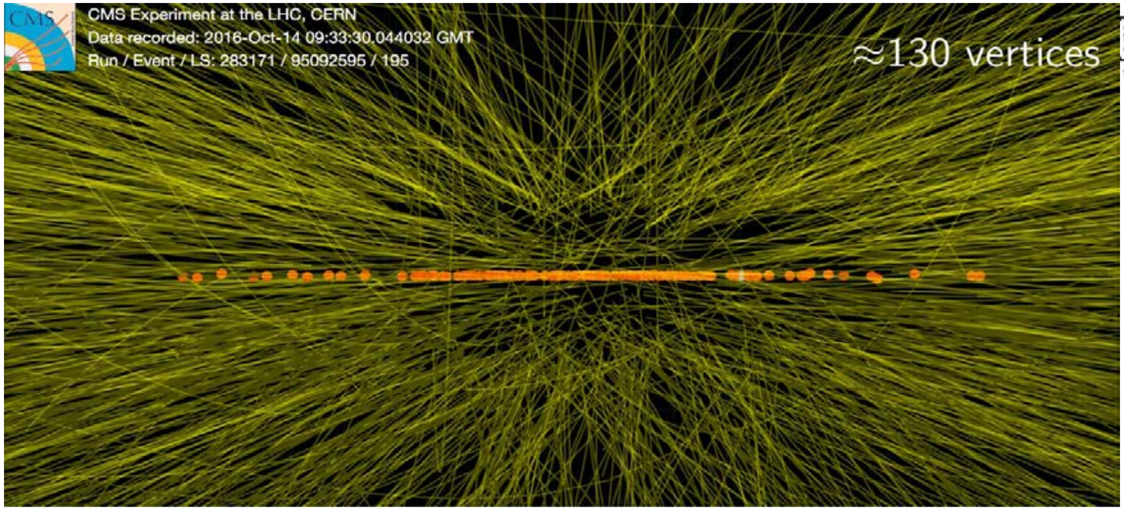


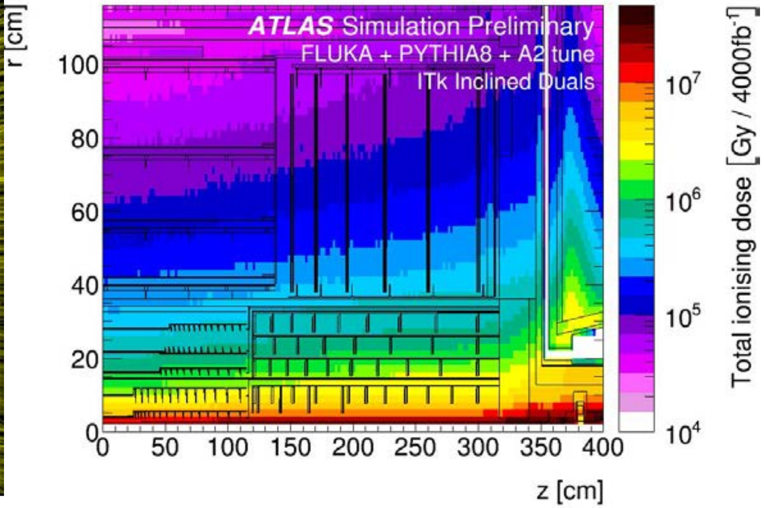
- Mass: 0.02% precision



HL-LHC: a luminosity challenge for detectors

- Achieving the HL-LHC Higgs programme is not guaranteed !
- HL-LHC: up to 200 collision vertices / bunch-crossing !
  - Trigger/readout rate challenge
  - Reconstruction challenge
  - Radiation hardness challenge



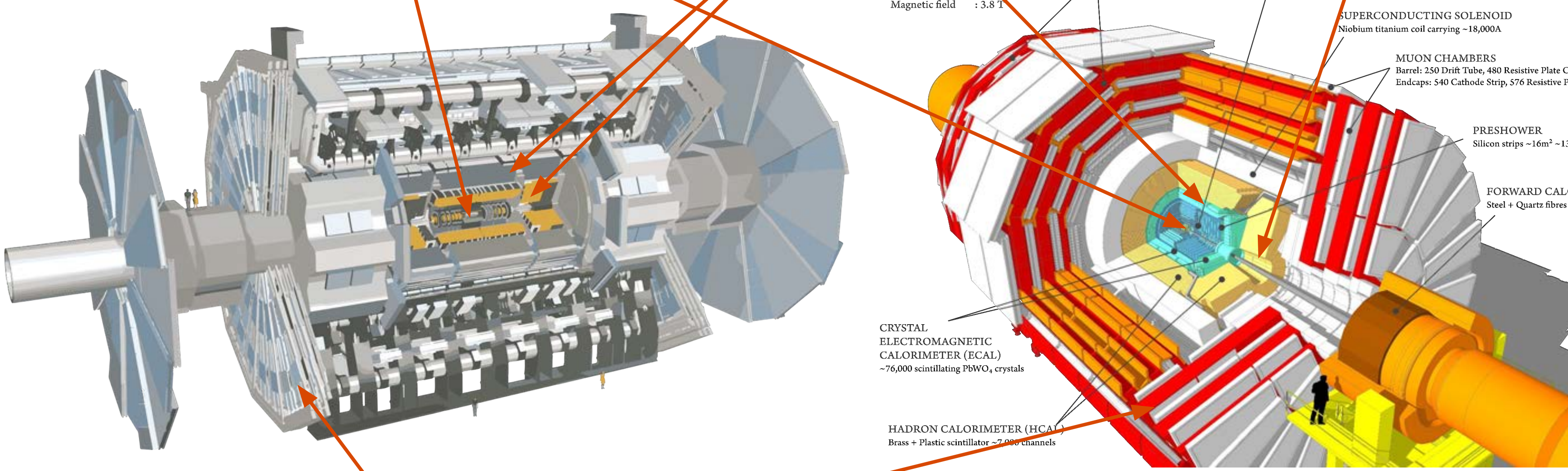


A construction-scale upgrade project

New trackers

New calorimeter readout electronics

New endcaps calorimeters



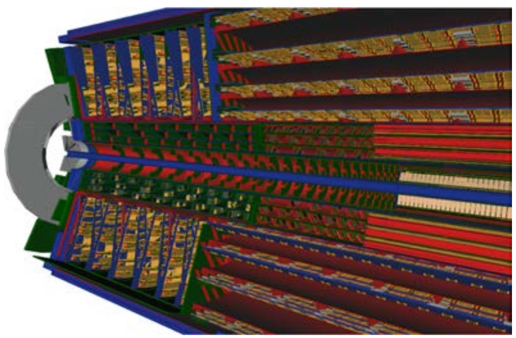
Upgraded muon detectors

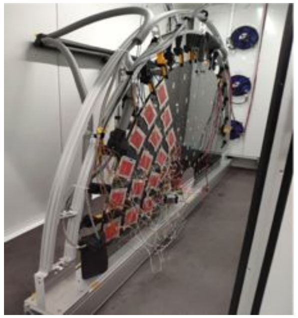
+ new timing detectors

+ new trigger / DAQ

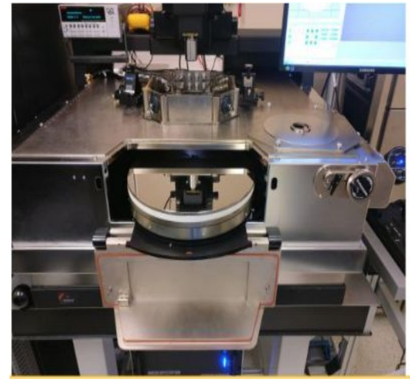
Brand new trackers

- Very challenging new detectors
  - Large size with small pixels
    - + Extended coverage
  - Radiation hard
  - CO_2 cooling
  - All services and mechanical structure as light as possible

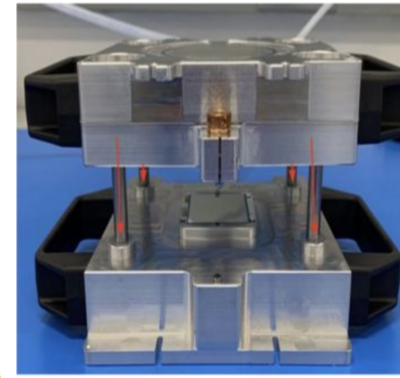




CMS Outer tracker endcap disks



Sensor QA



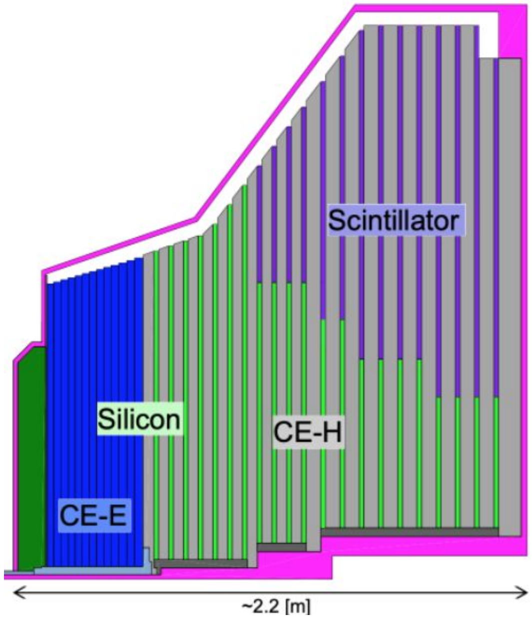
Module gluing

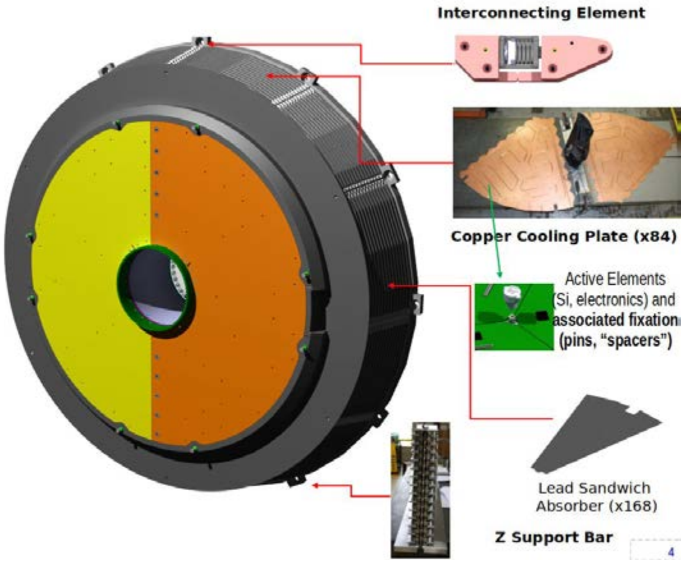
Staves

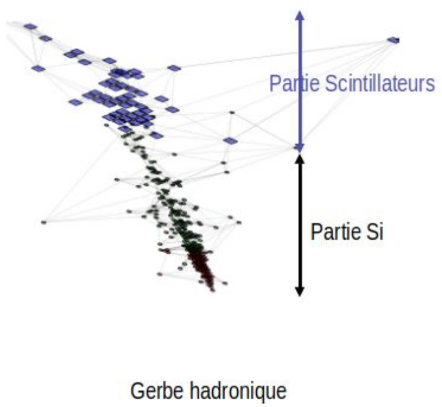
Services / cables

Replacing CMS endcap calorimeters

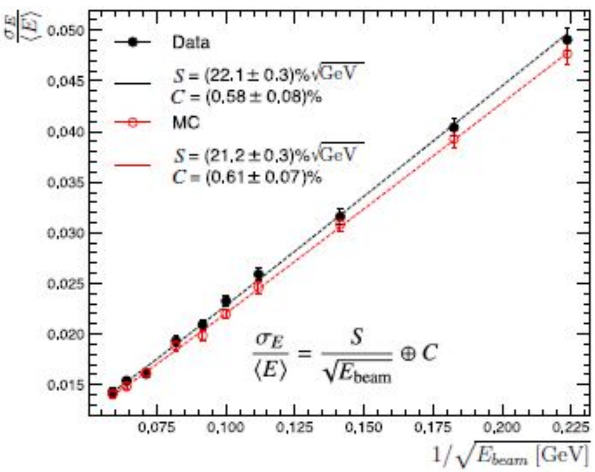
- Endcap ECAL crystals cannot survive HL-LHC
- New calorimeter using recent high-granularity technologies
  - 6 million channels
  - Challenge for trigger and readout
  - But also new opportunities





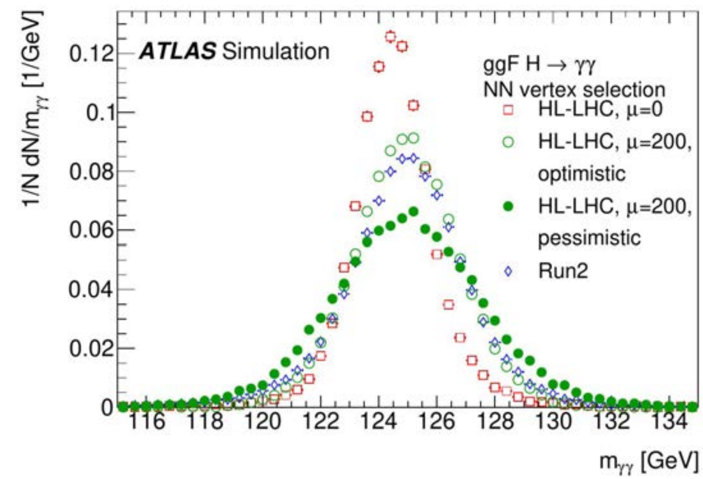


Graph neural networks for reconstruction

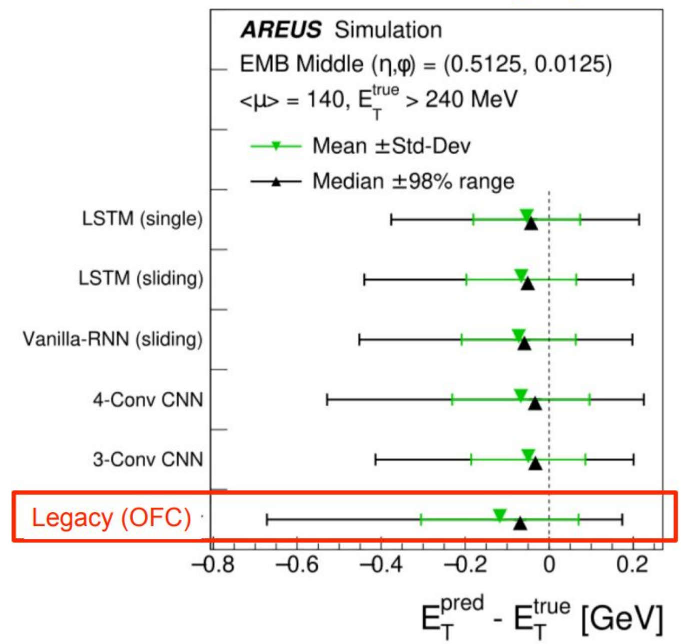


Readout electronics upgrades

- Maintaining Run-2 performance despite high pile-up
- More data sent off-detector
  - Offline-like information at trigger level
  - Use of ML algorithms in readout electronics

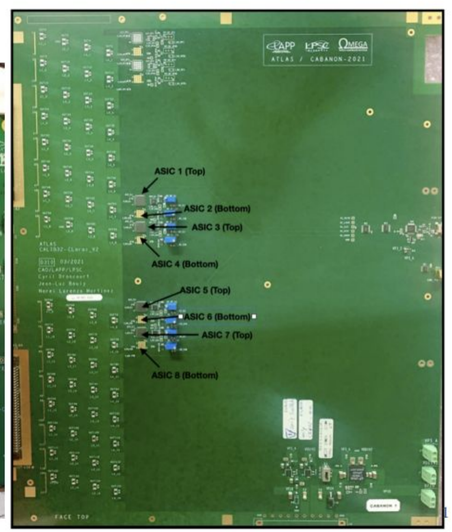


ML Vs. Legacy



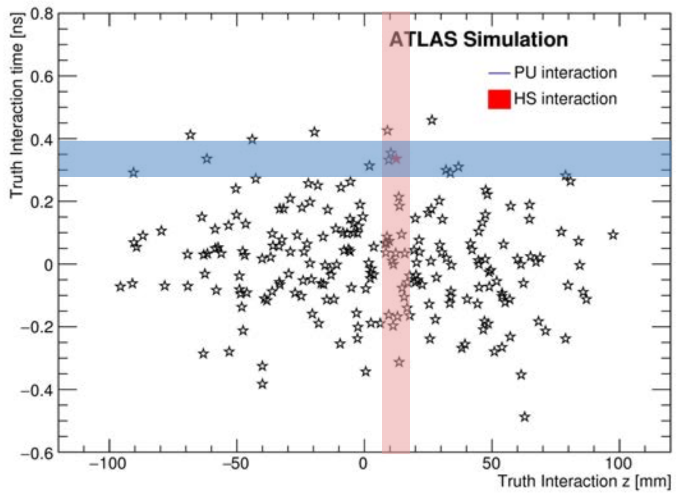
ASICs

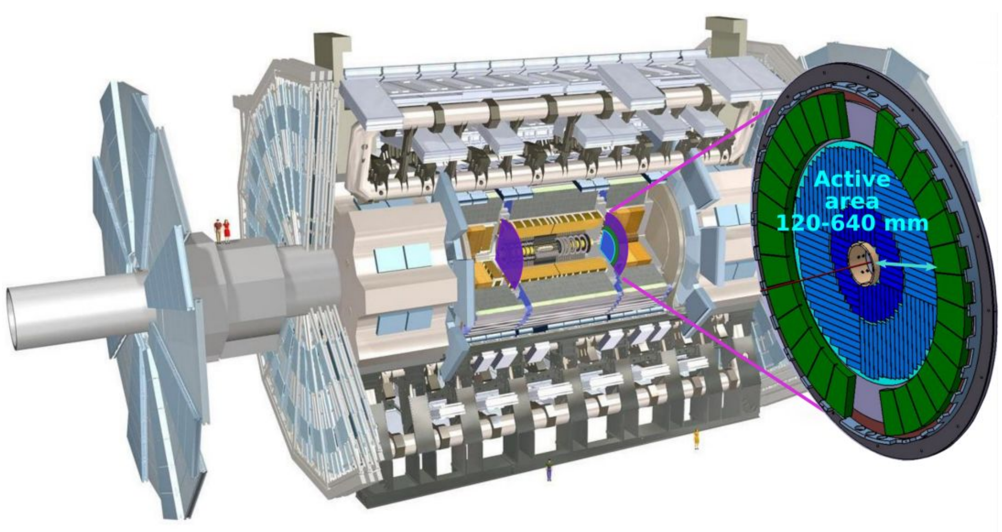
CABANON

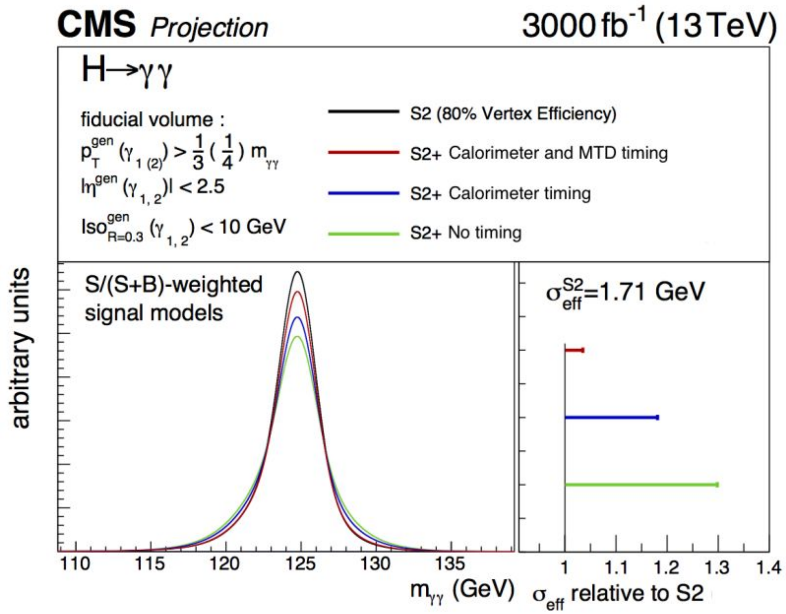


Embrace the 4th dimension

- Timing detectors (30ps): new technologies (LGAD) to reduce pile-up effects
  - Especially in forward region
  - Challenges in electronics, integration, radiation tolerance…

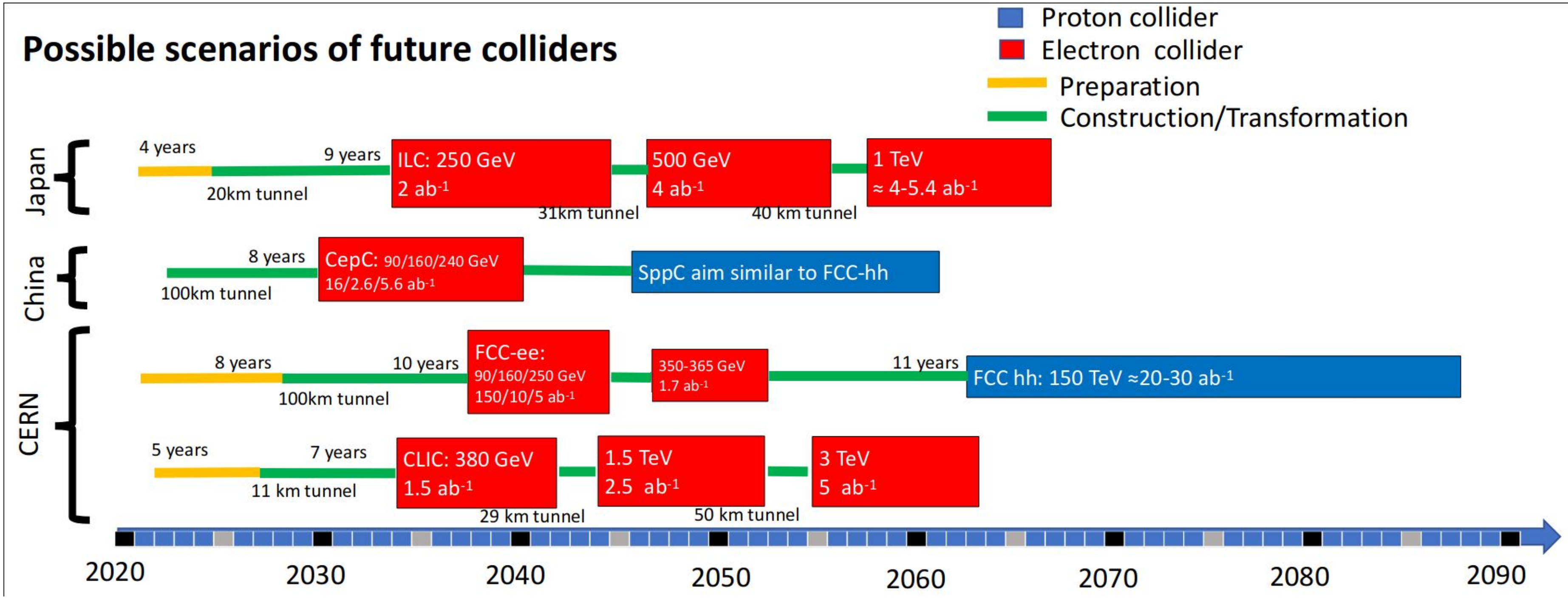






After LHC: to infinity and beyond

Beyond the LHC



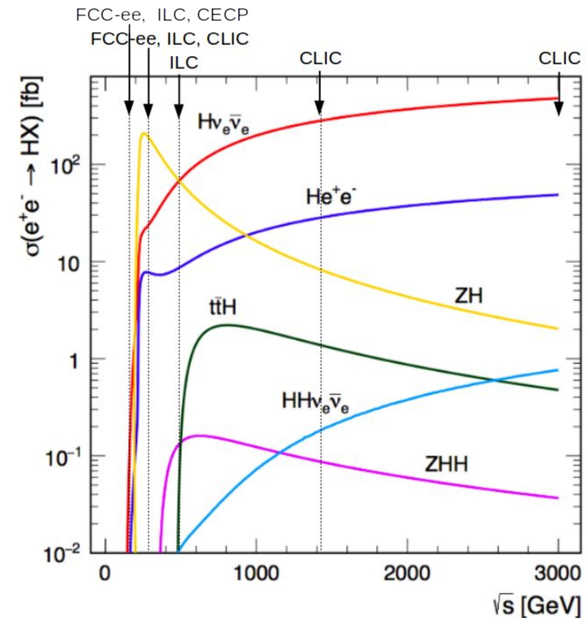
adapted from S. Bethke, ESPP symposium 2019

- IN2P3 Prospects 2021-2030, "The energy frontier" group:

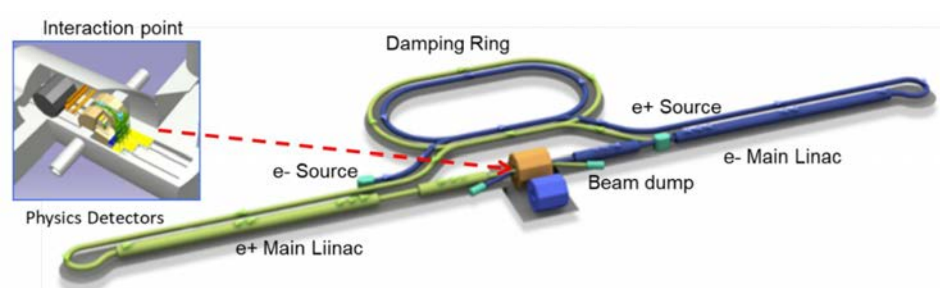
2. Support the construction of an e^+e^- collider running at the Higgs production resonance upgradable to higher energies. Support the theoretical effort to reach the expected precision of the measurements as well as the phenomenological studies.
3. Support the studies of the physics potential and performance requirements for a future high energy proton–proton machine.

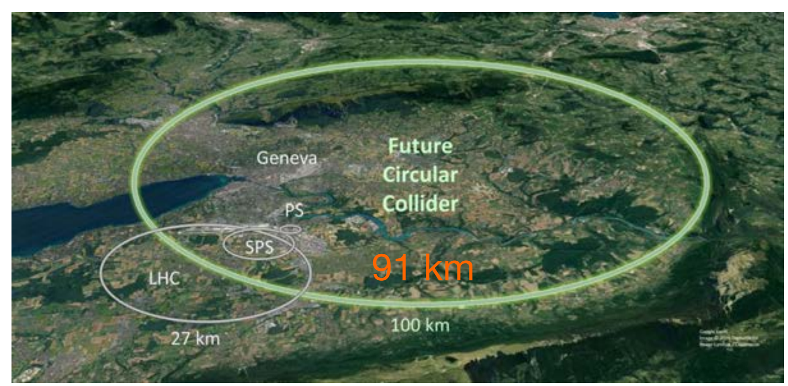
Higgs factories ?

- Goal: O(few) million Higgs bosons
  - Detect and classify each one !
  - Complementary of different √s



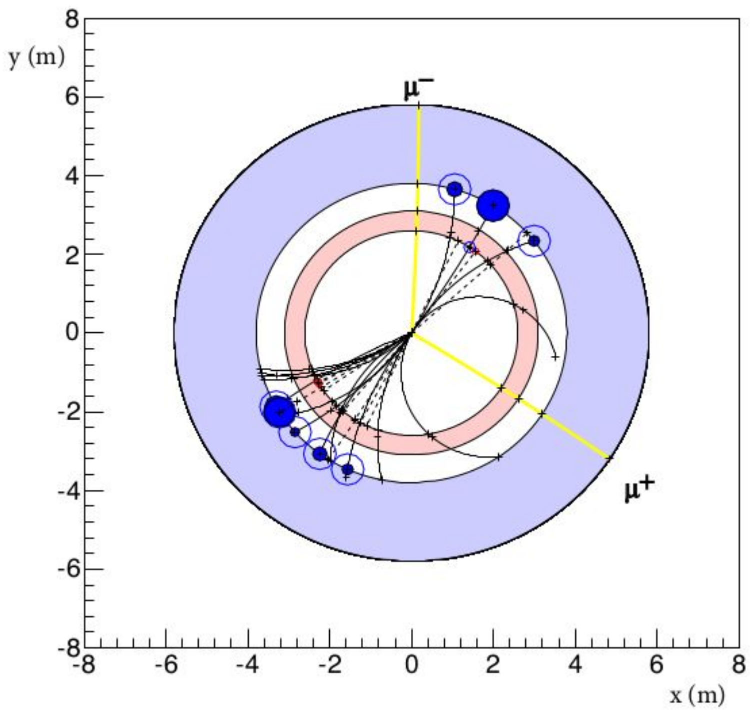
- Linear collider (ILC)
  - Mature design
- Circular colliders (FCC, CEPC)
  - Concept design phase
  - Z / EW physics programme

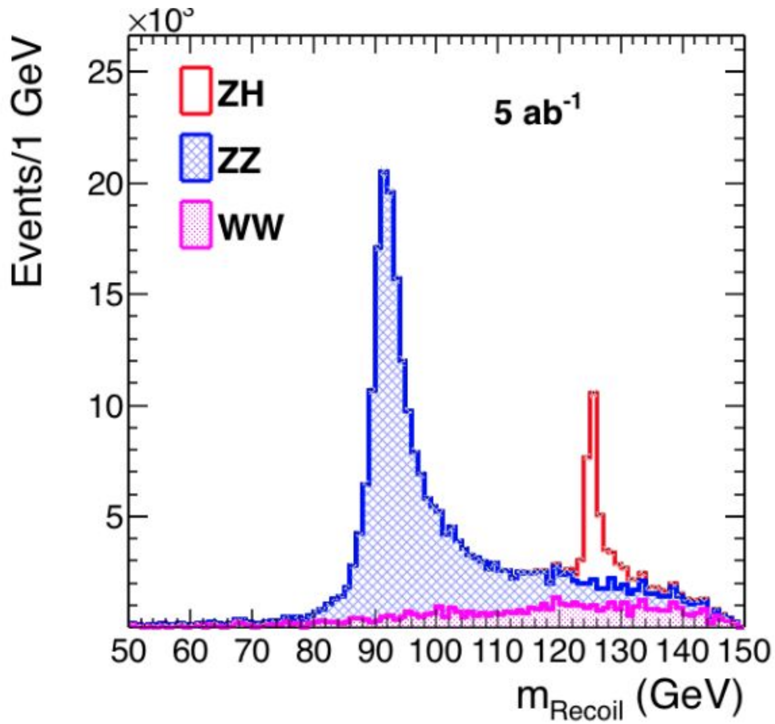




Higgs physics beyond LHC (e^+e^-): mass and width

- Directly measurable at ee colliders
  - mild model dependence

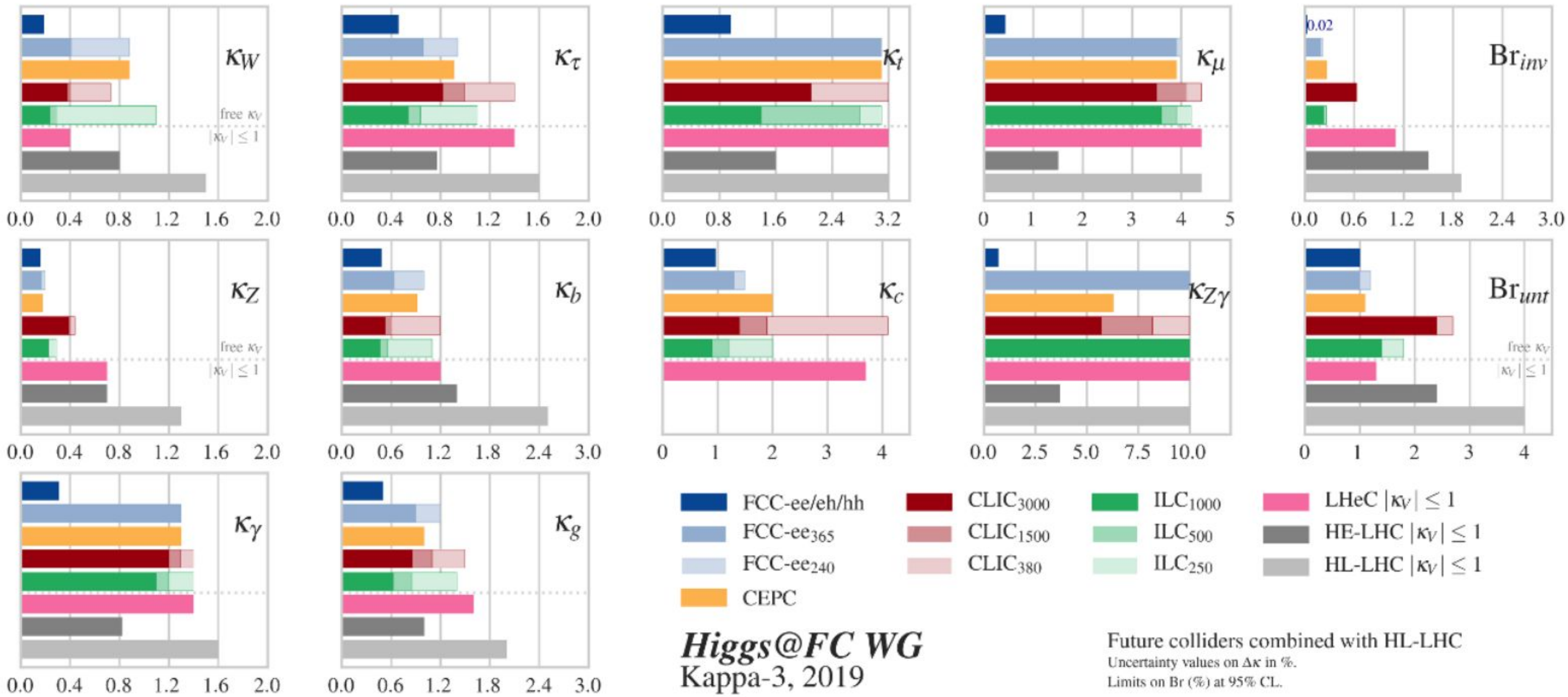




- Mass:
  - ≲10 MeV achievable
- Width:
  - 1-2% precision

Higgs physics beyond LHC: couplings

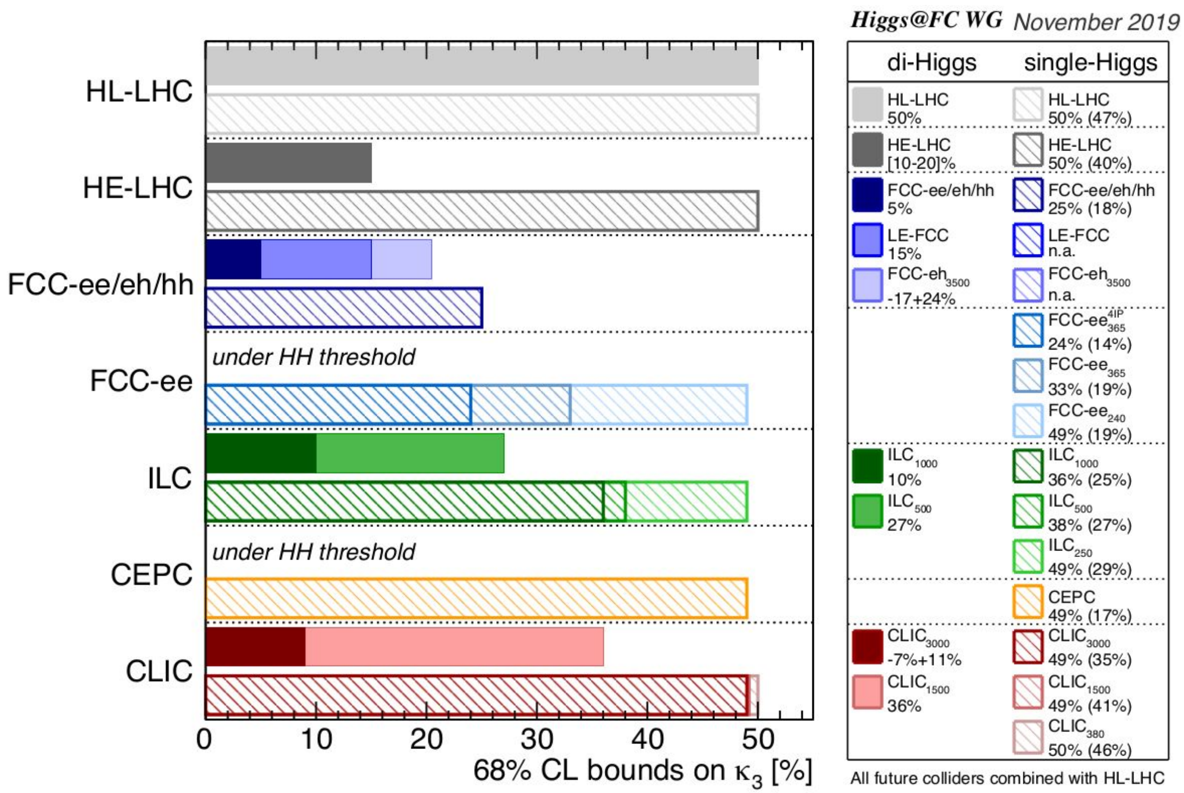
- All results combined with HL-LHC



- Sensitivities of ee colliders in their initial stages are rather comparable
- The most precise coupling measurements (to Z and W bosons) can measured to 0.2-0.3%

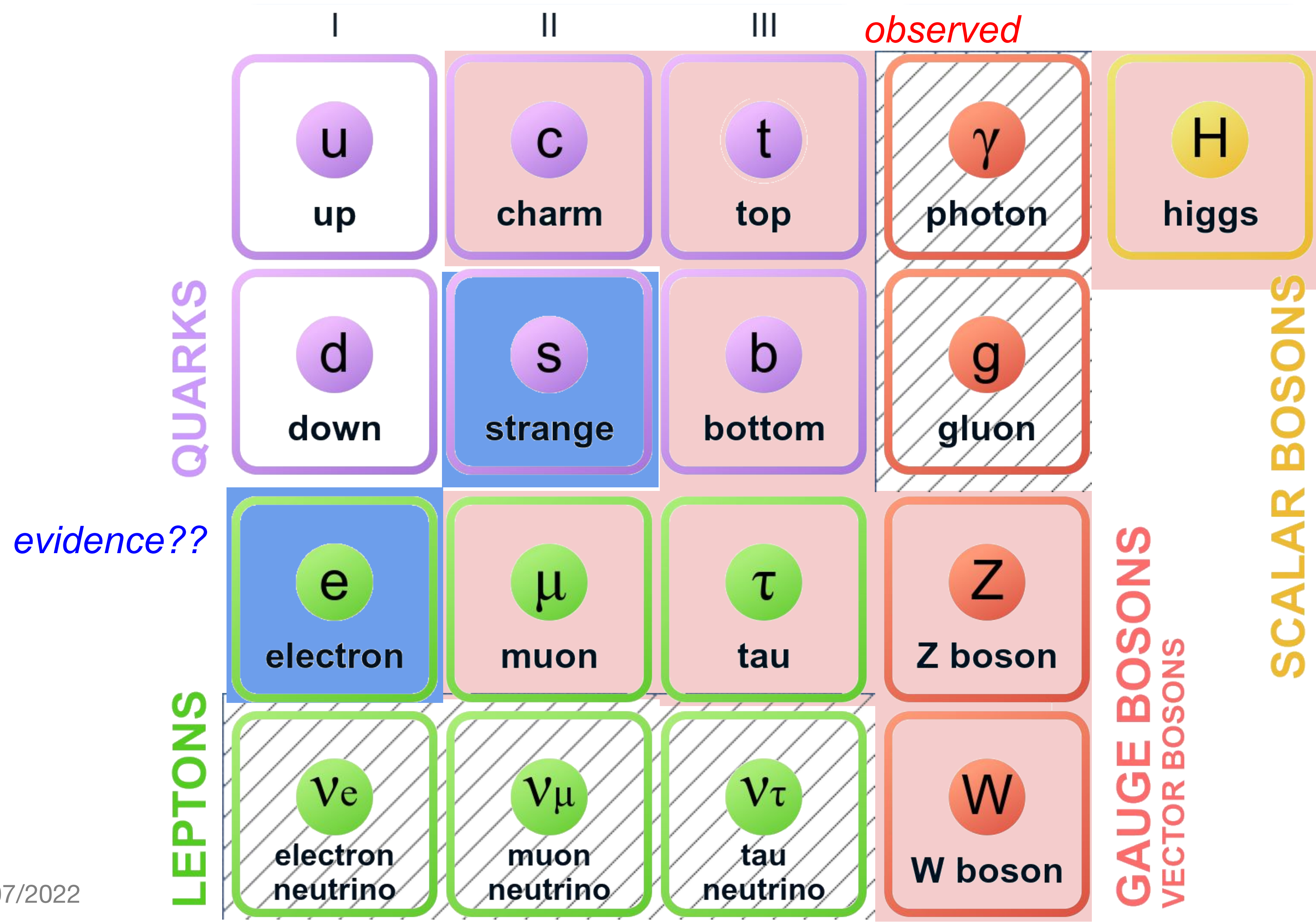
Higgs physics beyond LHC: self-coupling

- Direct production (ZHH and ννHH): √s > 500 GeV
- One-loop corrections of the single-Higgs production
- 68% CL uncertainties on κλ:
  - all combined with HL-LHC



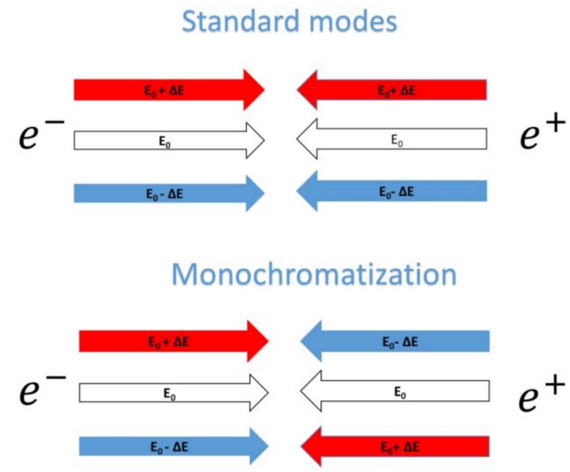
Where we will stand in the (rather far) future

- Mass: 0.005% precision

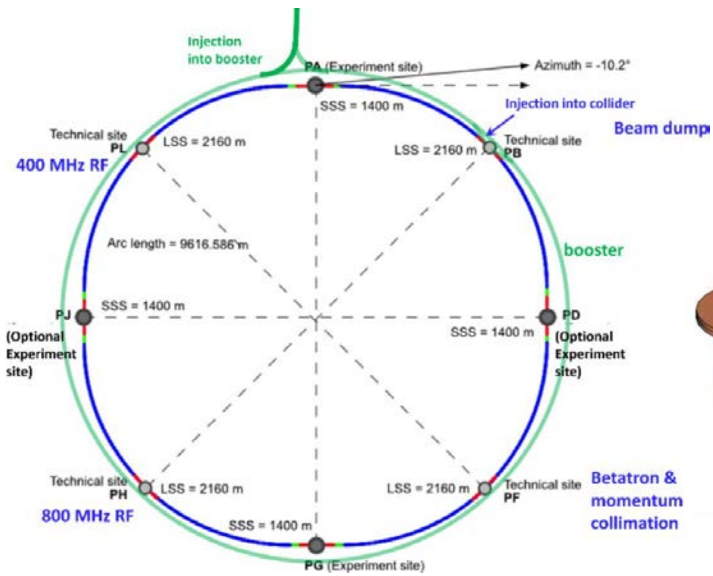


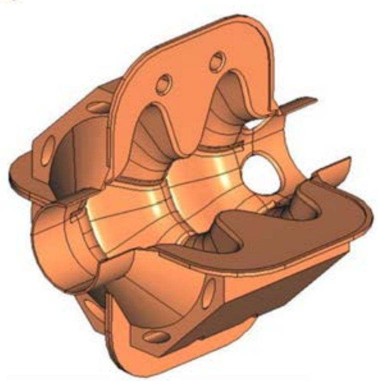
FCC: not ‘just as LEP, but bigger’

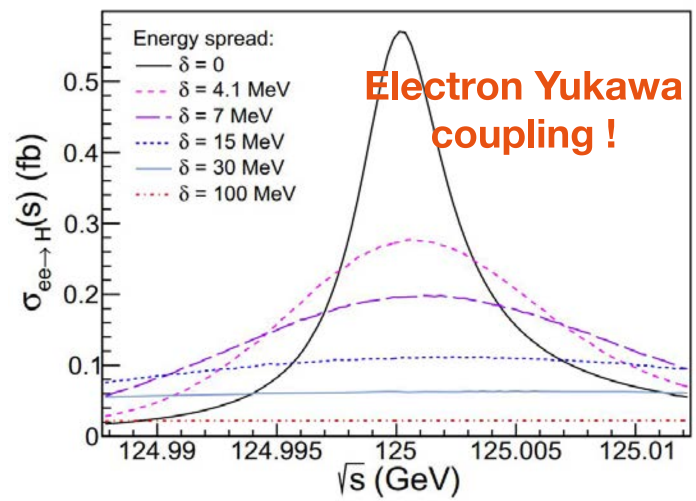
- Numerous challenges for the accelerator
  - Positrons source
  - Top-up injection
  - Focalisation
  - Mono-chromatization
  - Stability and positioning



Improving the CM energy resolution







Detectors for future colliders

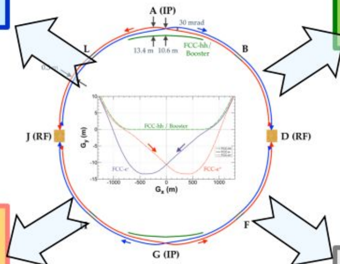
- Very different environment wrt LHC
  - Rates
  - Backgrounds, radiation levels
  - Number of particles in final state
- Stringent specifications
  - Linked to requirements of physics programme

"Higgs Factory" Programme

- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}\,\text{GeV}^{-1}$ commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme & QCD

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6} : stability of √s meast.



Heavy Flavour Programme

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ √E level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

Feebly Coupled Particles - LLPs

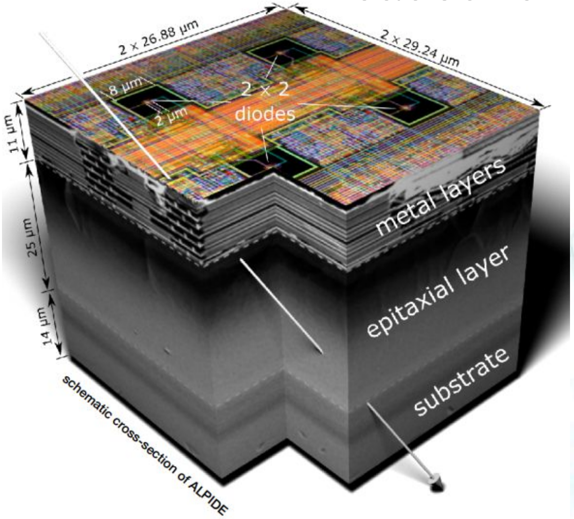
Benchmark signature: Z → νN, with N decaying late

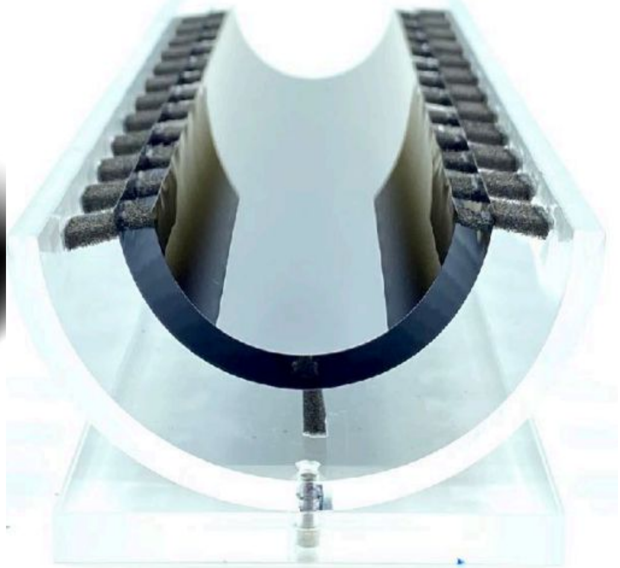
- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Precise timing for velocity (mass) estimate
- Hermeticity

Next generation of trackers

- Many stringent requirements
  - Position resolution (vertexing) => small pixels
  - Material budget => low power
  - PID capabilities (ToF, dE/dx)
- Silicium or gaseous detectors

MAPS
Bent sensors with readout embedded





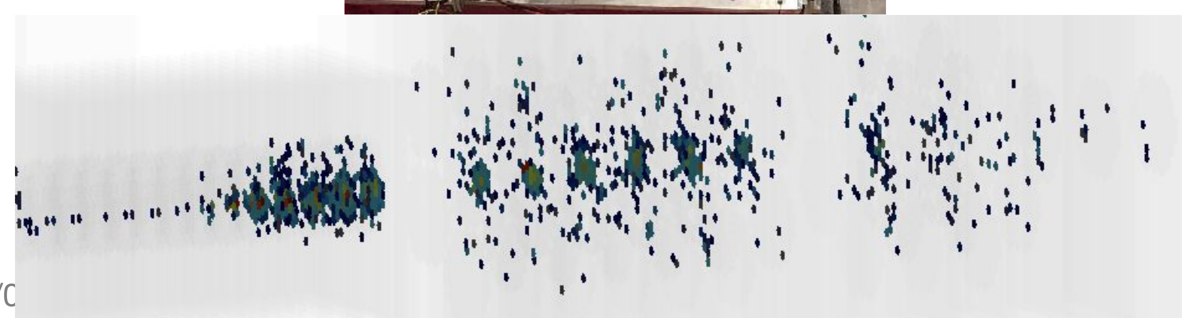
Drift chambers

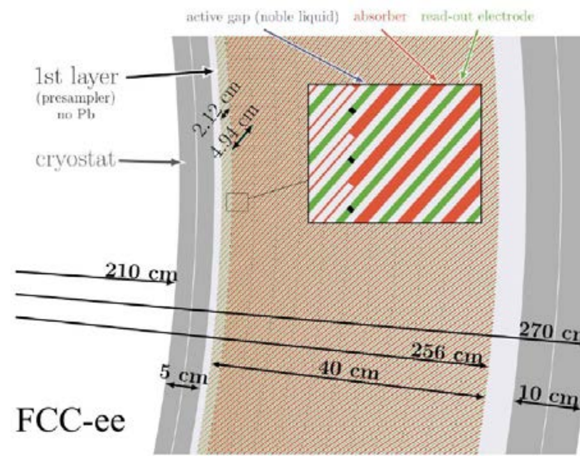
Next generation of calorimeters

- Main requirement for Higgs physics:
  - Unprecedented resolution for hadronic decays
  - Points towards high-granularity calorimeters
- Several calorimeter concepts
  - Very different degrees of maturity

Dual readout scintillation / Cerenkov fibres calorimeter

CALICE
EM + hadron
calorimeters



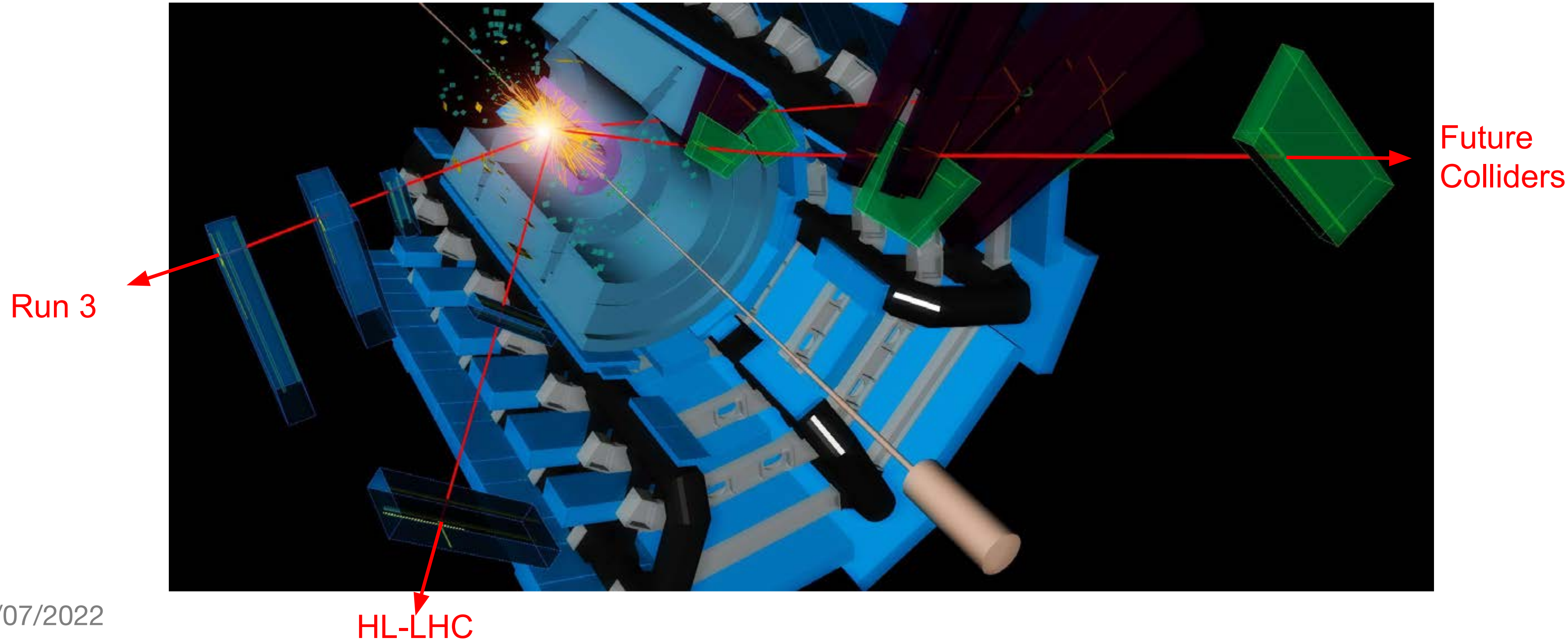


Noble Liquid calorimeter

Conclusions

- Studying the Higgs boson: trying to answer fundamental questions about our universe
  - Huge program for Higgs physics ahead of us !
  - Both HL-LHC and future Higgs factories necessary

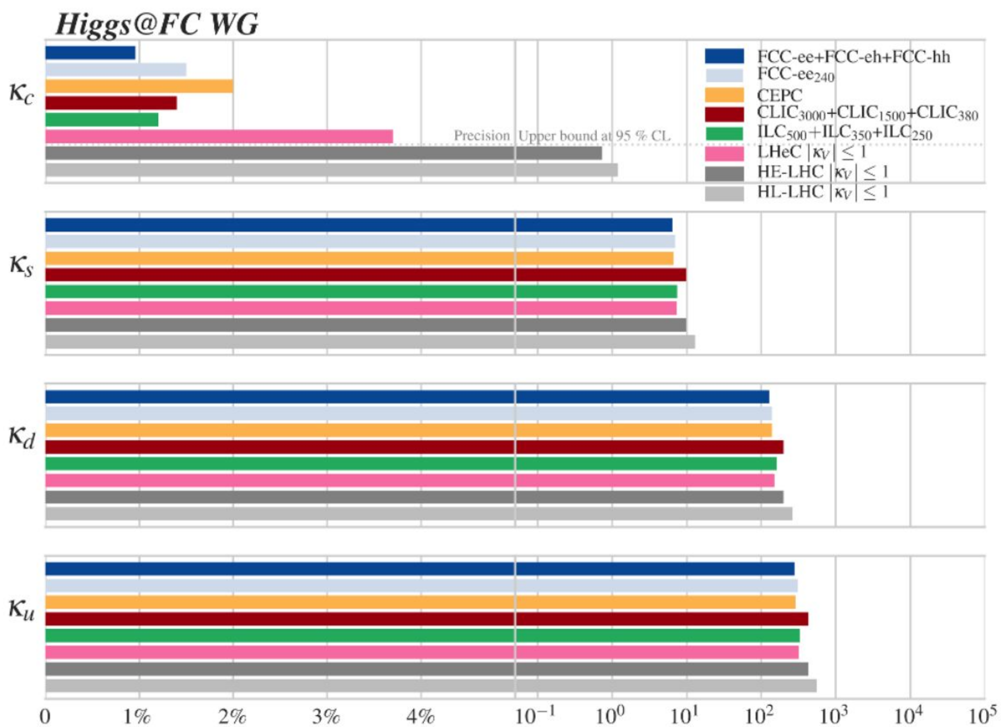
- Strong implications and recognised expertise of IN2P3
  - both on the analysis and detectors



Back-up slides

Couplings to rare quarks at Future Colliders

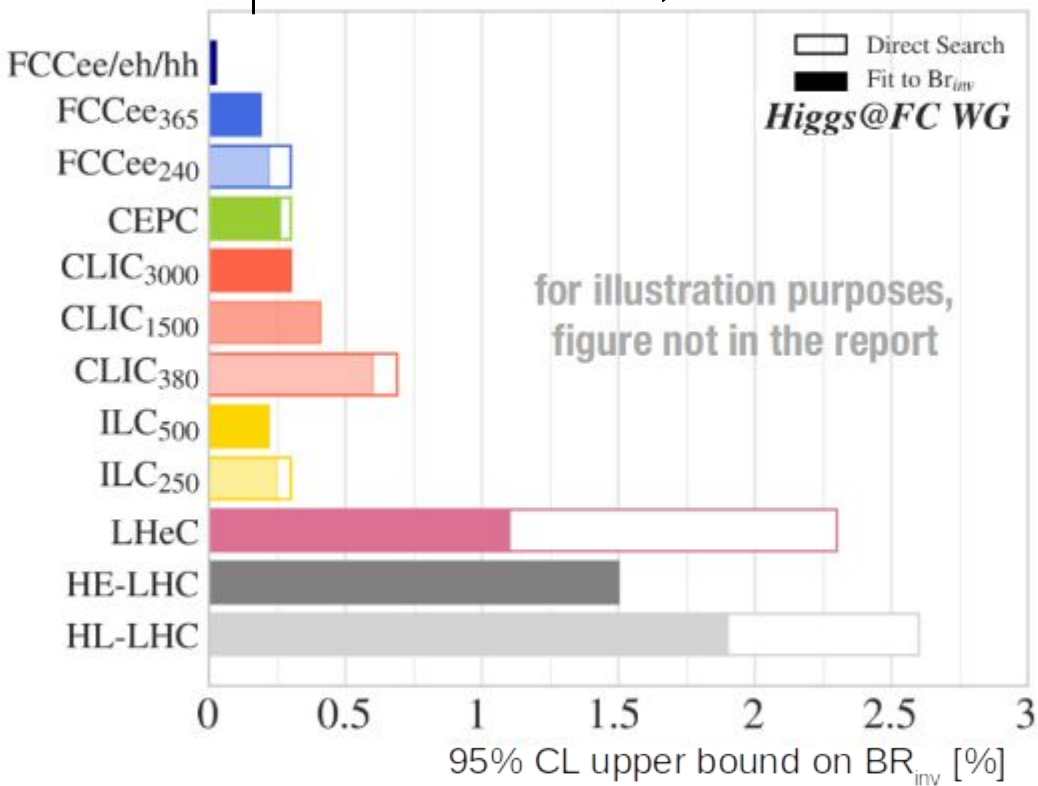
- Constraints on light Yukawa obtained from the upper limits on $BR_{untagged}$



- Hee: very challenging
  - FCC-ee: SM sensitivity could be reached in a five year run with a dedicated run at √s=mH

Invisible decays at Future Colliders

- Connection between the Higgs boson and dark matter
- In the SM, $BR^{SM, inv}$ = $BR(H \rightarrow 4\nu)$ = 0.11%
- Current LHC limits ~ 15-20% @ 95%CL
- Direct searches for invisible width
  - Lepton collider: Z recoil, would improve upon HL-LHC limits by an order of magnitude
  - Hadron collider: E_T^{miss} uncertainties, FCC-hh : values below the SM



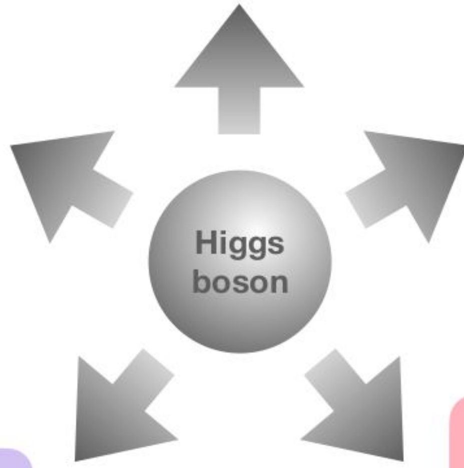
What can we learn from the Higgs boson?

What is the origin of the early-universe inflation?

- Is the Higgs connected to the mechanism that drives inflation?
- Are there any imprints in cosmological observations?

What is the origin of the vast range of quark and lepton masses in the Standard Model?

- Are there modified interactions to the Higgs boson and known particles?
- Does the Higgs decay into pairs of quarks and leptons with distinct flavours (for example, $H \to \mu^{+}\tau^{-}$)?



Why is the electroweak interaction so much stronger than gravity?

- Are there new particles close to the mass of the Higgs boson?
- Is the Higgs boson elementary or made of other particles?
- Are there anomalies in the interactions of the Higgs with the W and Z?

What is dark matter?

- Can the Higgs provide a portal to dark matter or a dark sector?
- Is the Higgs lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs?

Why is there more matter than antimatter in the universe?

- Are there charge-parity violating Higgs decays?
- Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-universe electroweak phase transition?
- Are there multiple Higgs sectors?

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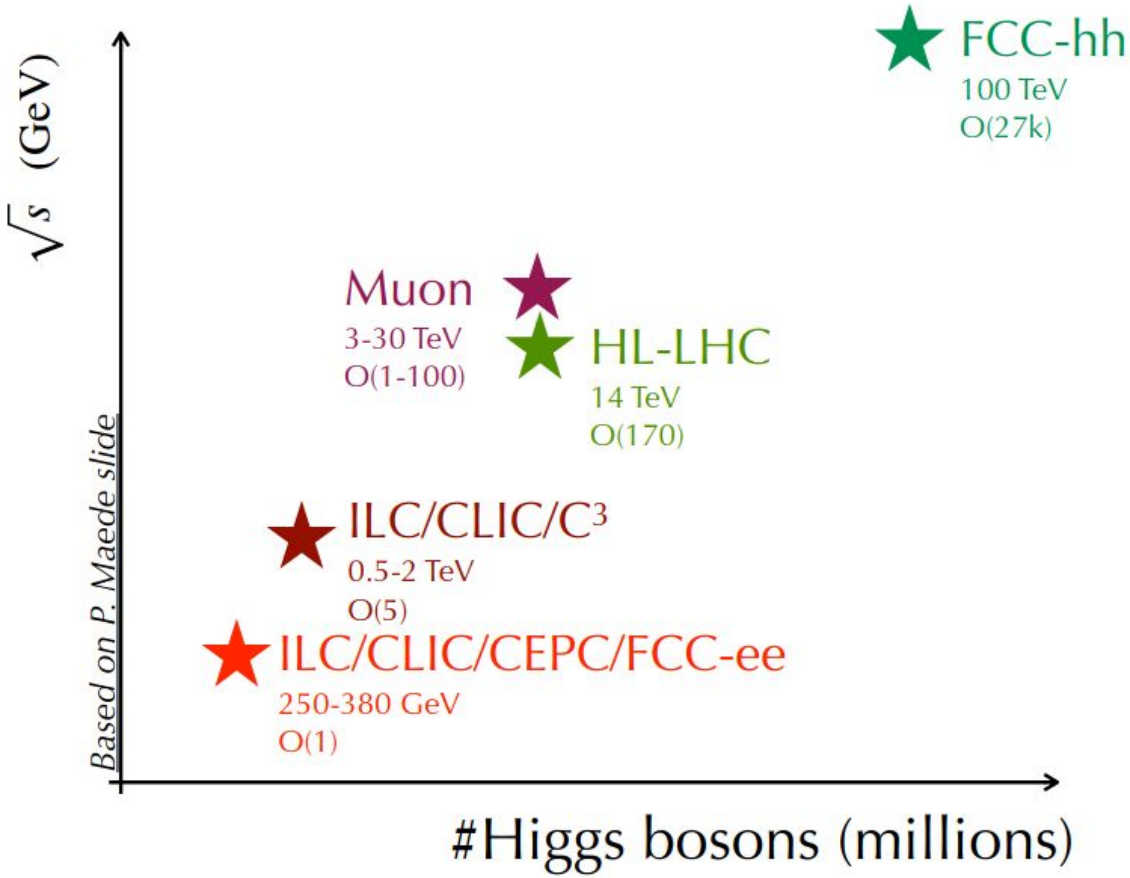
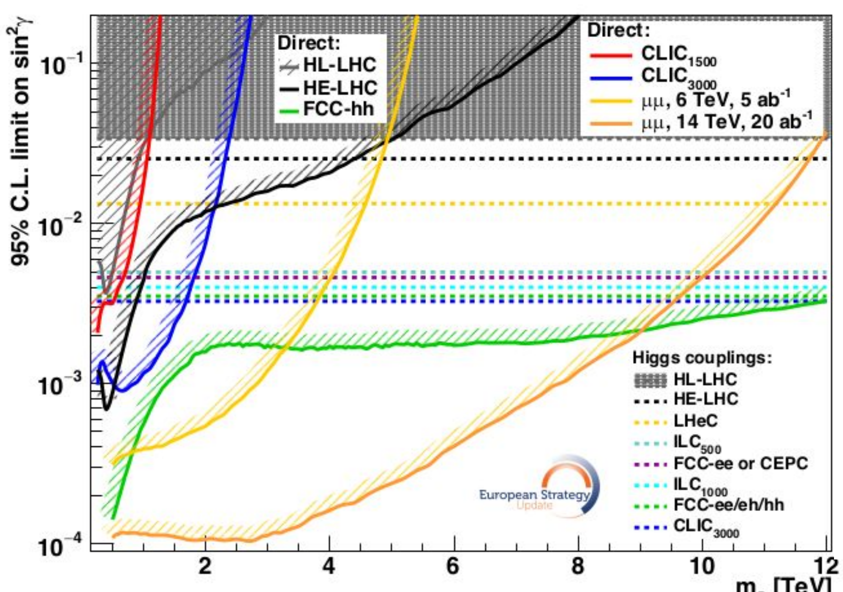
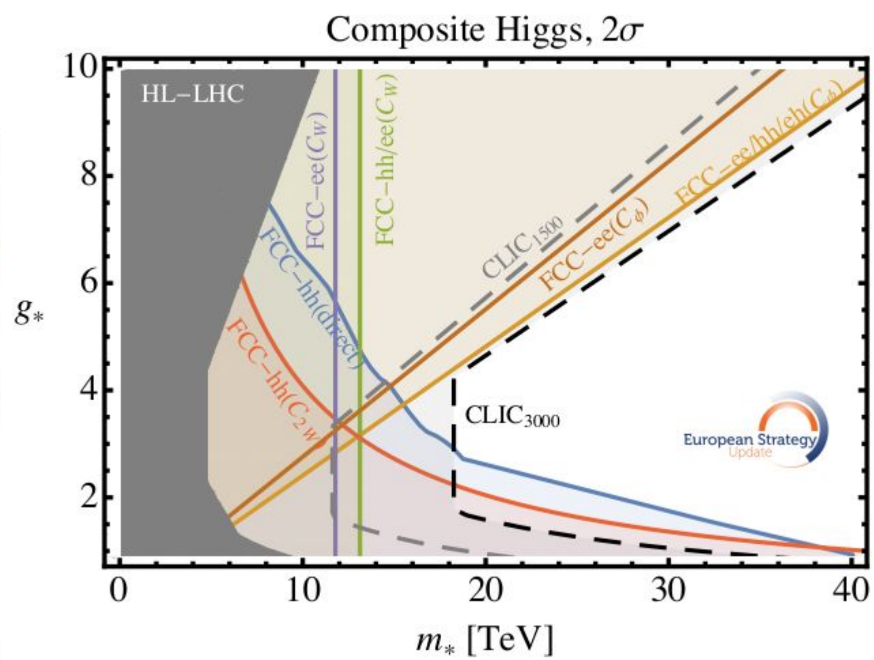
Random backup



Beyond SM Higgs physics

- Many BSM scenarios involving the Higgs boson
  - forbidden decays ($H \to \tau\mu$), exotic Higgs decays
  - dark-matter (invisible decays)
- Extended Higgs sectors
  - heavy MSSM ($\to\tau\tau$, $\to HH$, charged)
  - singlet massive scalar field
- Composite Higgs scenarios





Outline

- intro sur pourquoi on veut plus de données (3)
- ce qu'on va faire au Run 3 (E) (2)
- les upgrades pour le Run3 (N) -> (1)
- ce qu'on va faire au HL-LHC (E) (5)
- les upgrades pour le HL-LHC (N) (6)
- ce qu'on va faire avec un collisionneur e+e- (ou pp) (E) (5)
- les pistes de collisionneurs/détecteurs (N) (6)