Higgs physics at HL-LHC

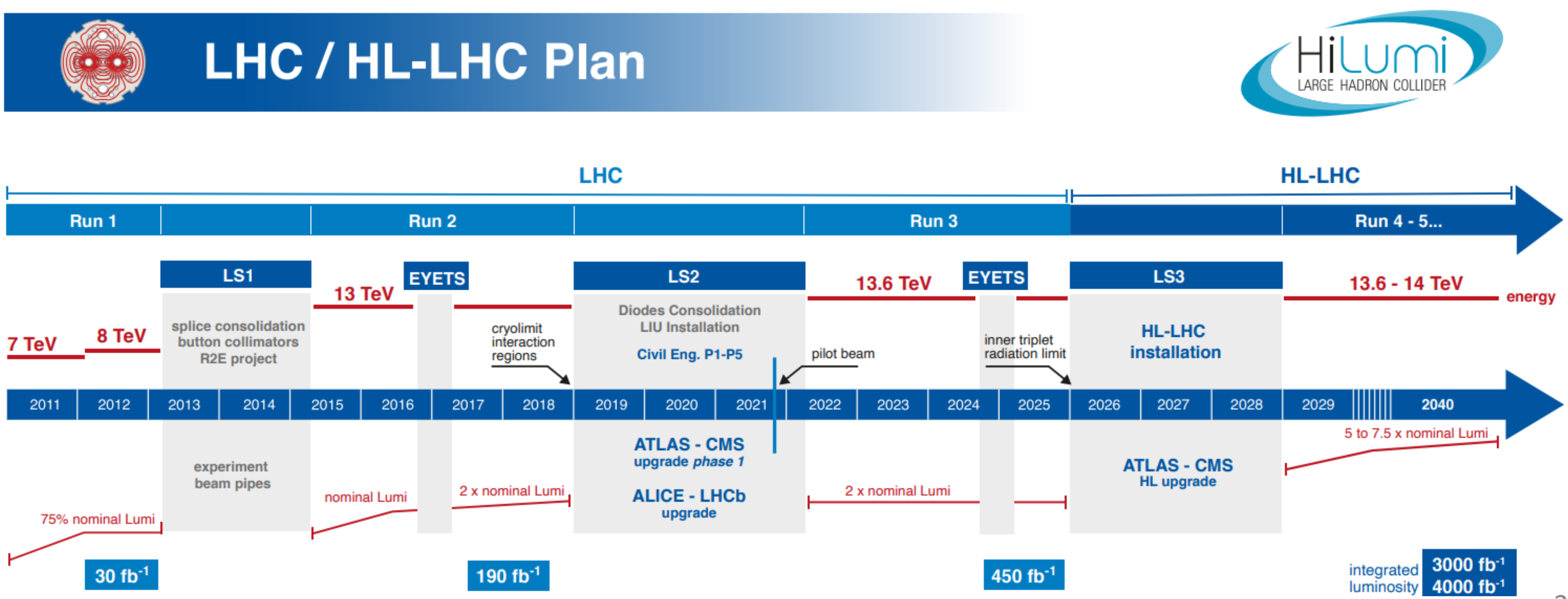
Lei Zhang (张雷)

On behalf of ATLAS and CMS collaboration

XXX Cracow EPIPHANY Conference on Precision Physics at High Energy Colliders, 8-12 Jan. 2024

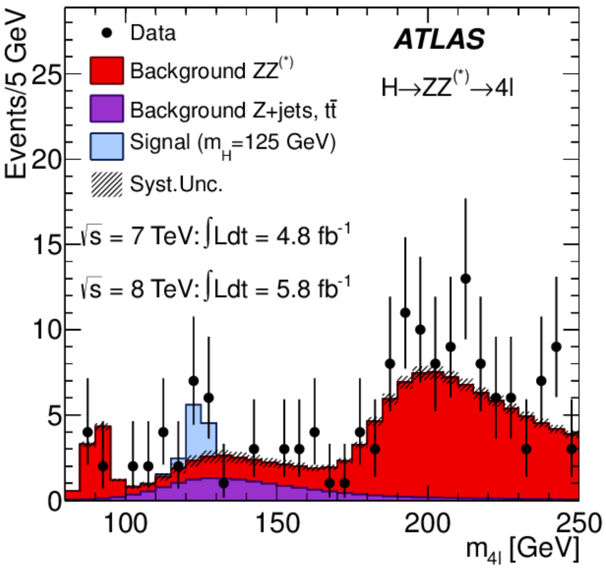
Outline

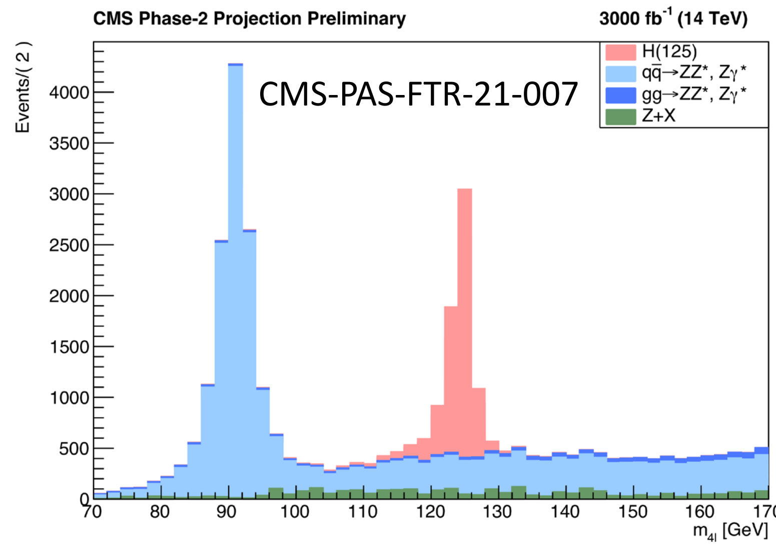
- HL-LHC, and ATLAS and CMS upgrade
- Higgs property measurement
- Di-Higgs search prospect
- Higgs rare decay and BSM processes



Physics potential

- Up to 3000 fb^{-1} Integrated luminosity at HL-LHC

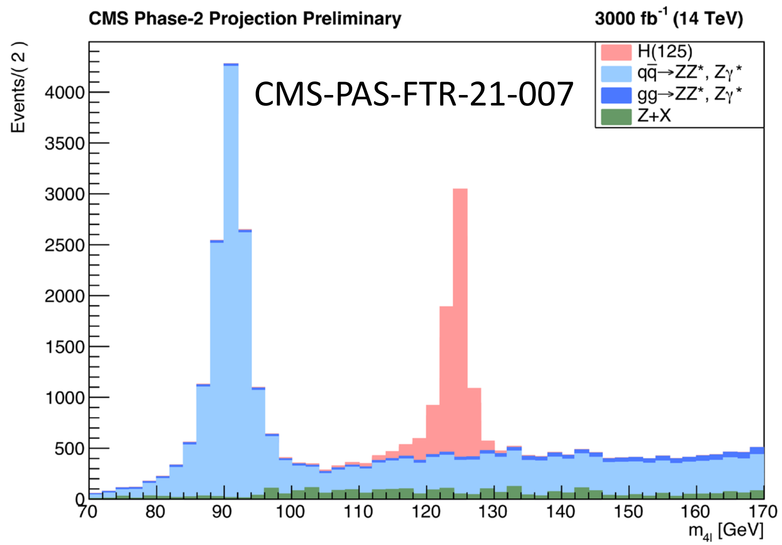




Physics potential

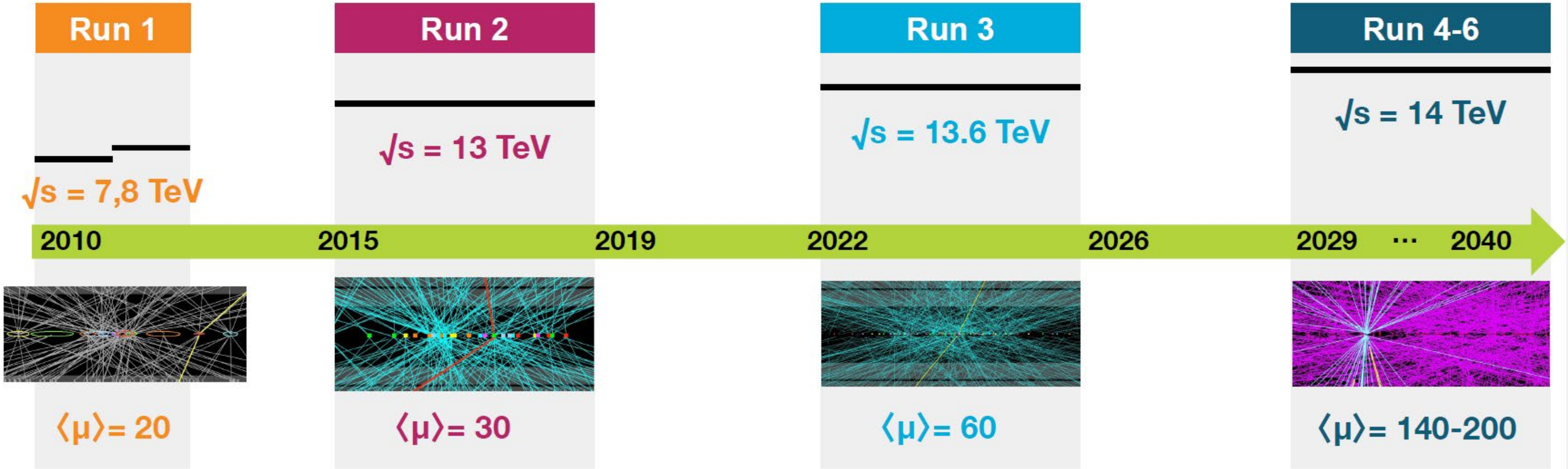
- Up to 3000 fb^{-1} Integrated luminosity at HL-LHC

  - $m_H = 125.38 \pm 0.03$ GeV
  - $\Gamma_H < 0.18$ GeV at 95% C. L.



- Understand electroweak symmetry breaking through Higgs
  - Couplings, mass and width, and trilinear self-coupling
  - Connections to new physics through Higgs sector?

HL-LHC overview



Elizabeth Brost
Higgs@10 Symposium

- Instantaneous luminosity: 5–7.5 times higher
  - Pile up will increase from 60 (now) to 140-200 (levelled)
  - Beam induced cavern background increases linearly
  - Much larger radiation to detectors
  - Larger data sample: big challenges for computing and data storage
- Require improvements for experiments in all areas
  - Detectors, Electronics & Trigger, Software and computing

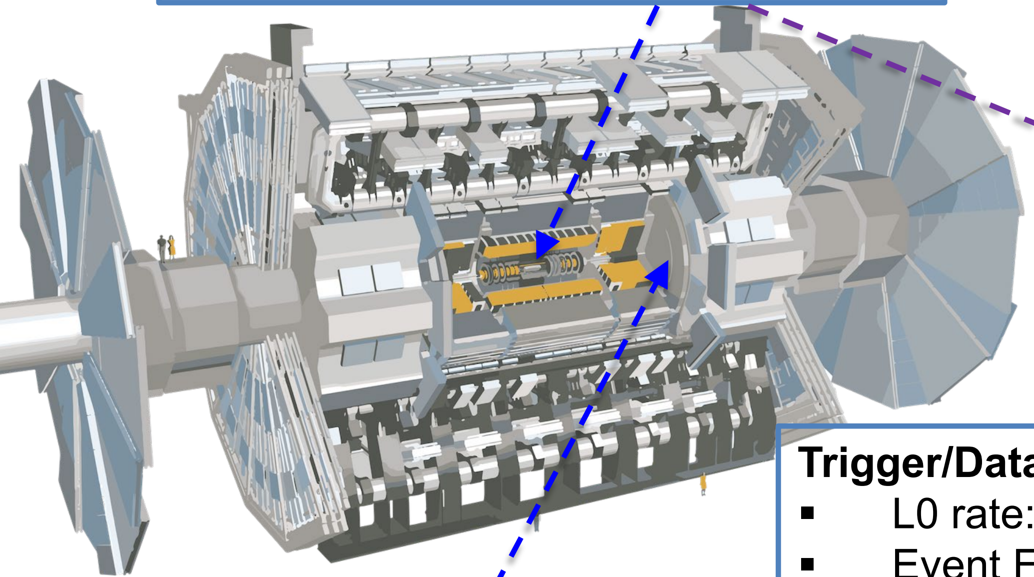
Upgrade at ATLAS and CMS

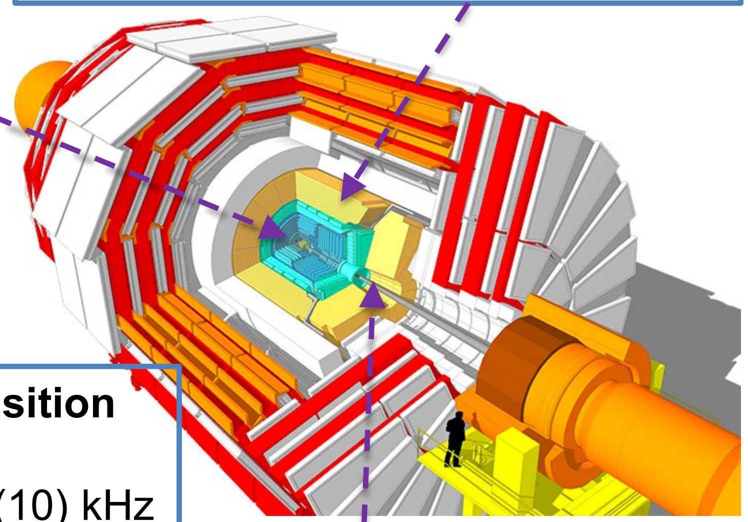
(Both) New Inner Tracker (ITk)

- All silicon up to |n]=4
- Less material, finer segmentation

MIP timing detector (MTD)

- Barrel: LYSO crystals + SiPMs
- Endcap: LAGD
- 30 ps timing resolution
- Full coverage to |η|~ 3





Trigger/Data Acquisition

- L0 rate: 1 MHz
- Event Filter: O(10) kHz

High Granularity Timing Detector (HGTD)

- 30 ps timing resolution with LGAD
- Coverage: 2.4 < |η| < 4.0
- Suppress pile-up and measure bunch-by-bunch luminosity

High-Granularity Endcap Calorimeter (HGCAL)

- Imaging calorimeter
- Si, Scint+SiPM in Pb/Cu-W/SS
- 3D showers and precise timing

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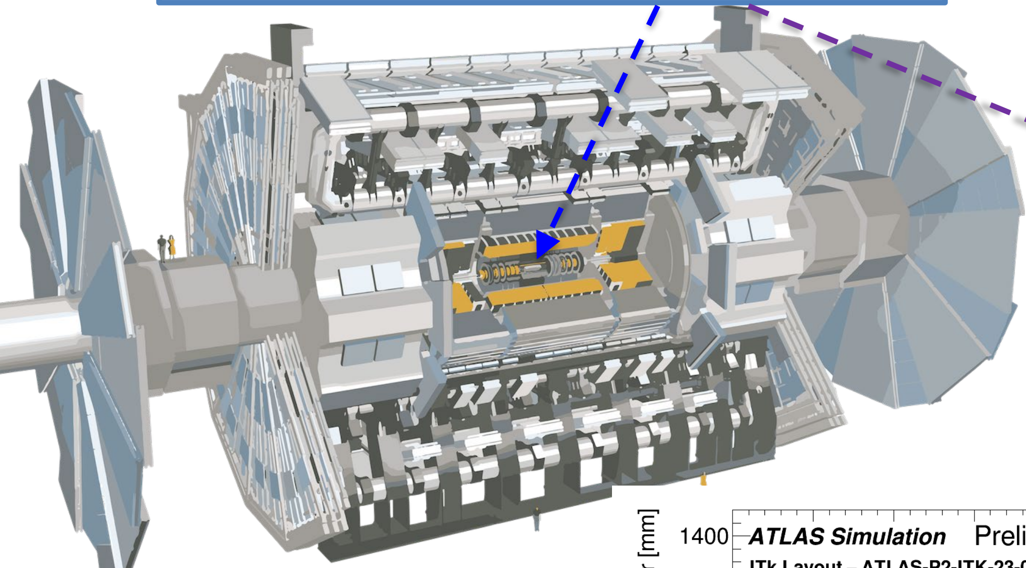

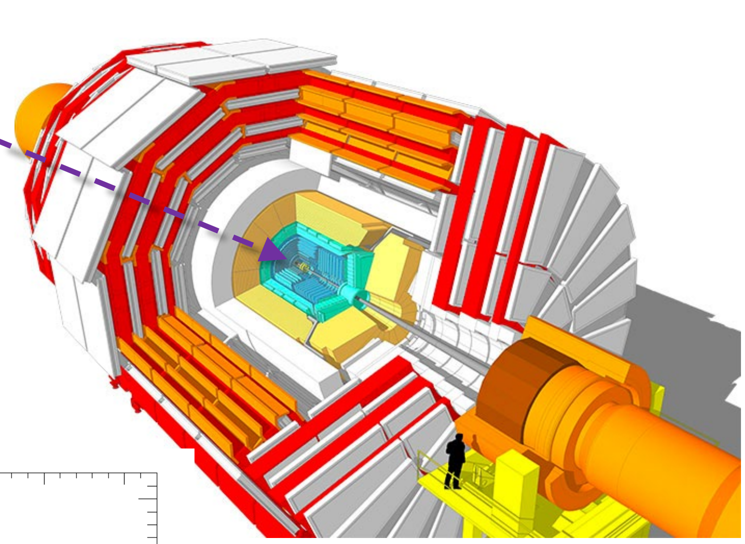

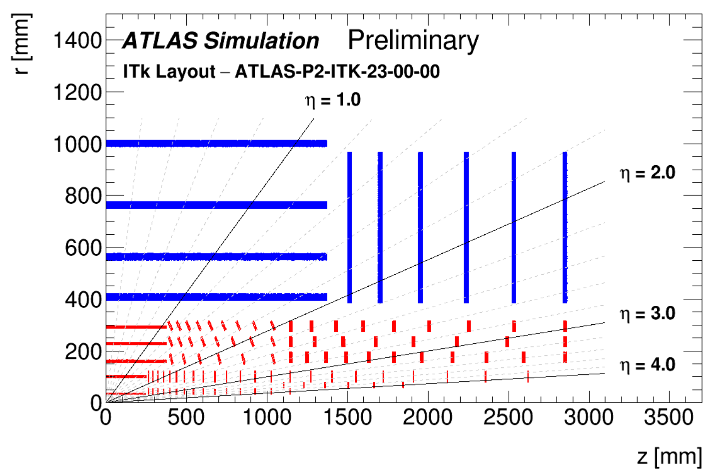

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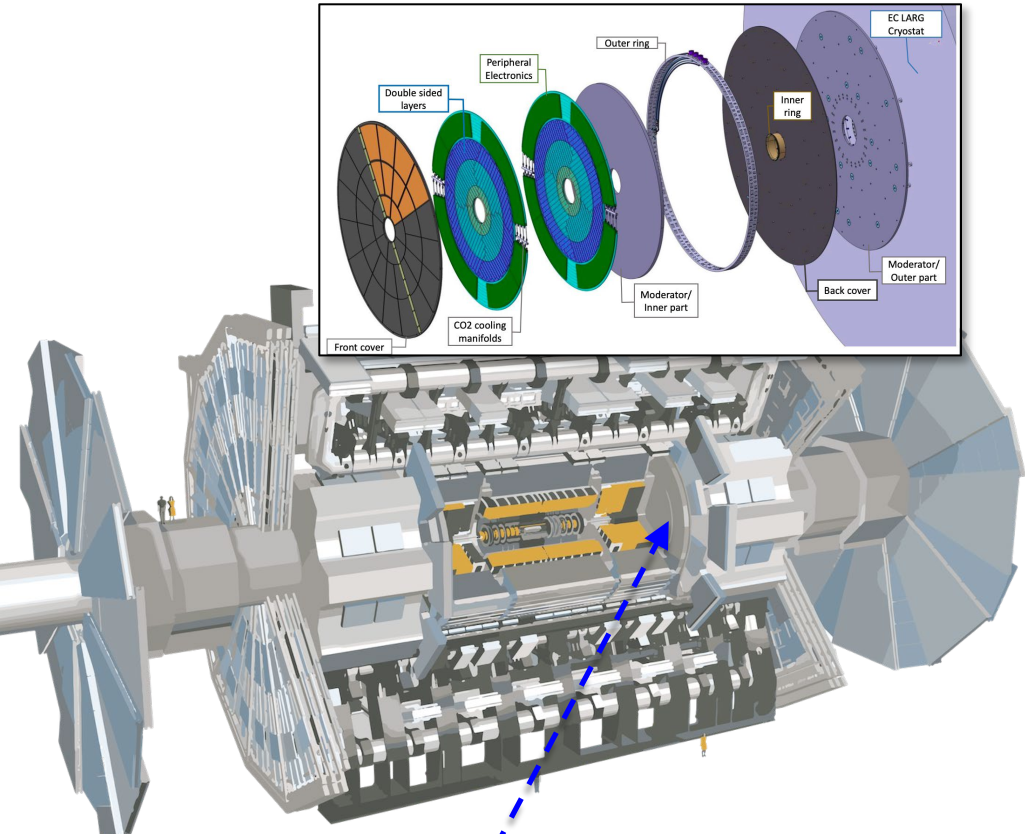

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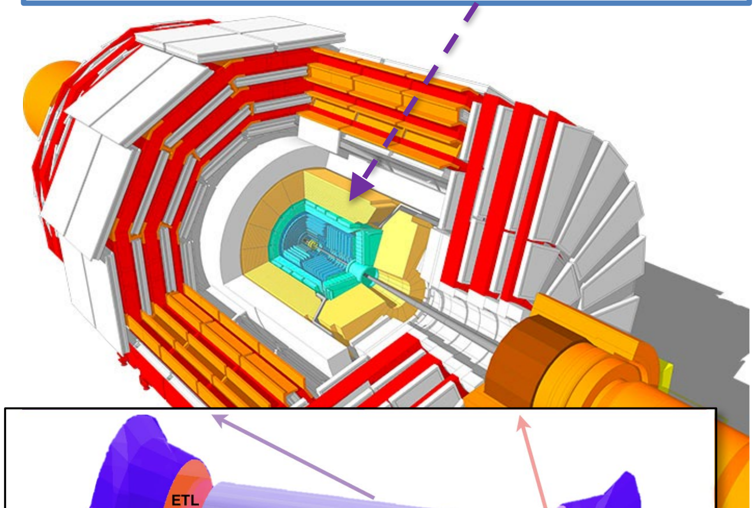

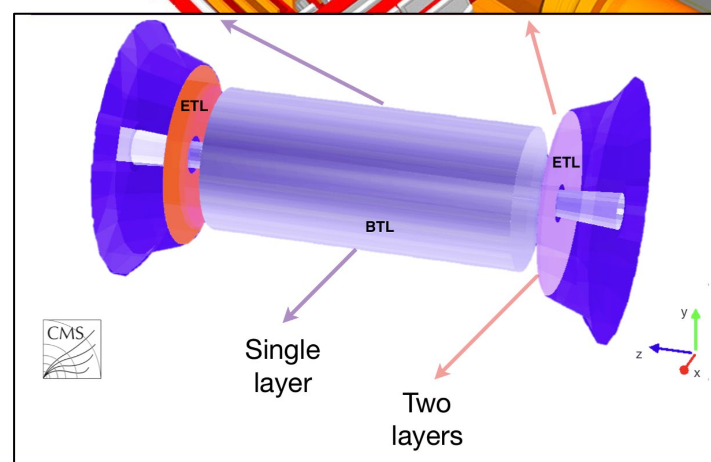

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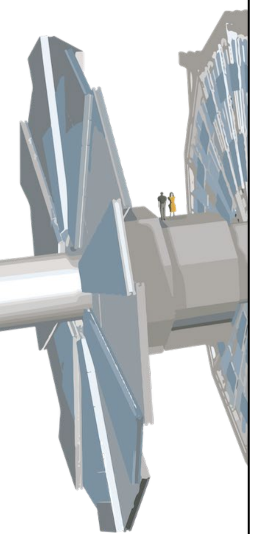

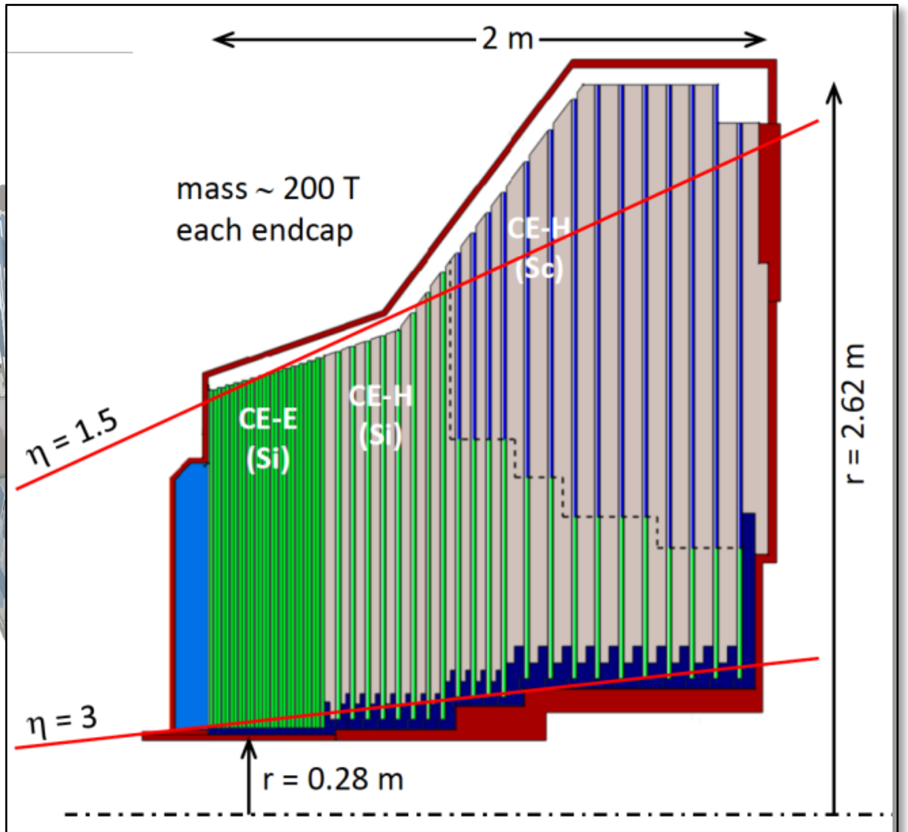

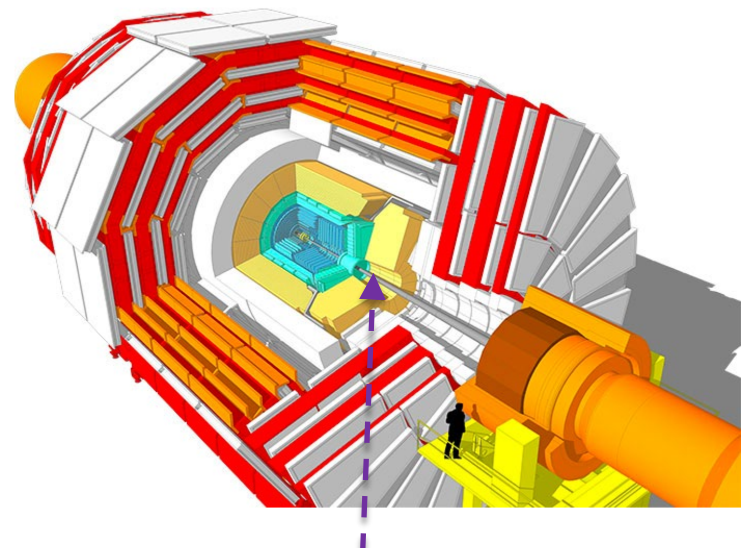

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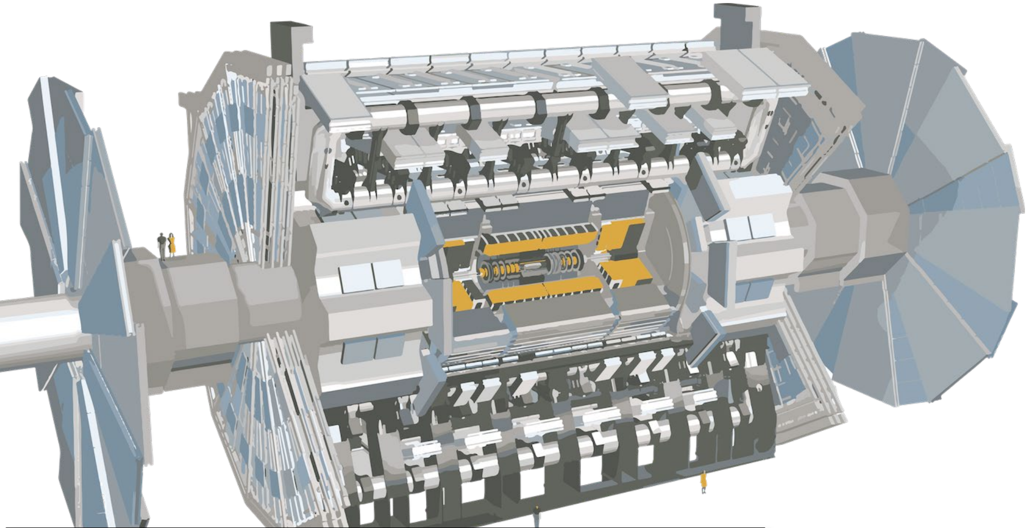
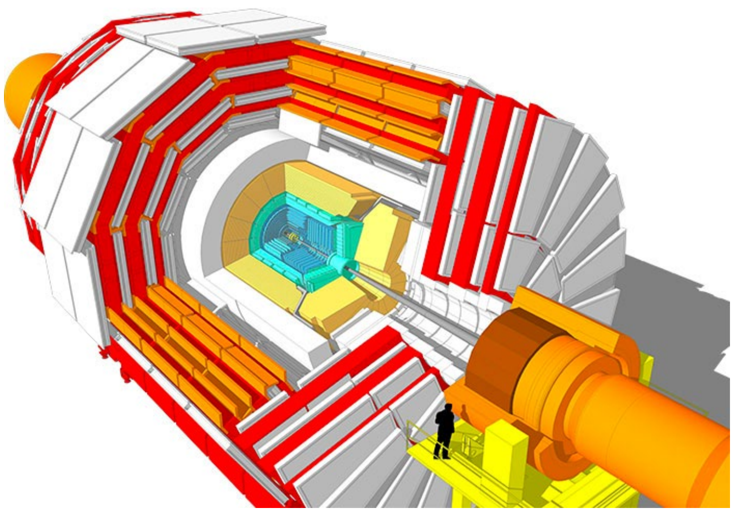
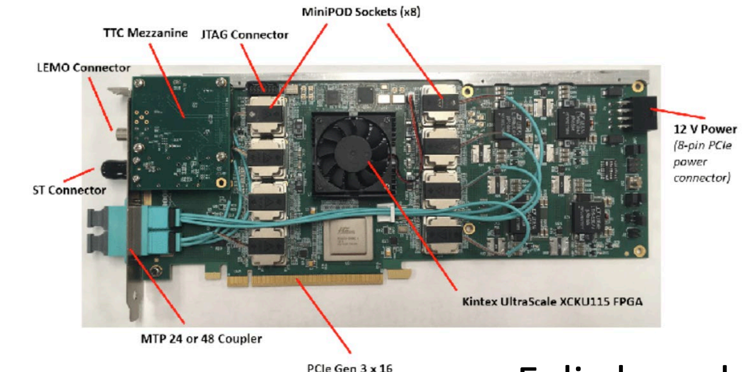
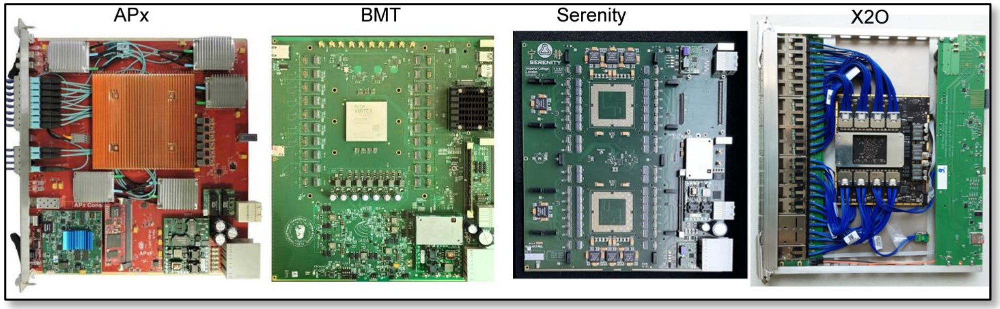




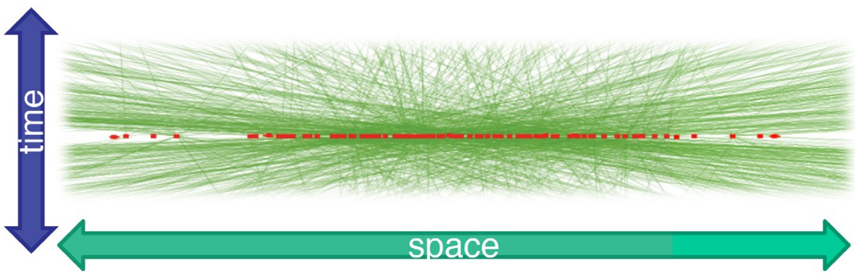


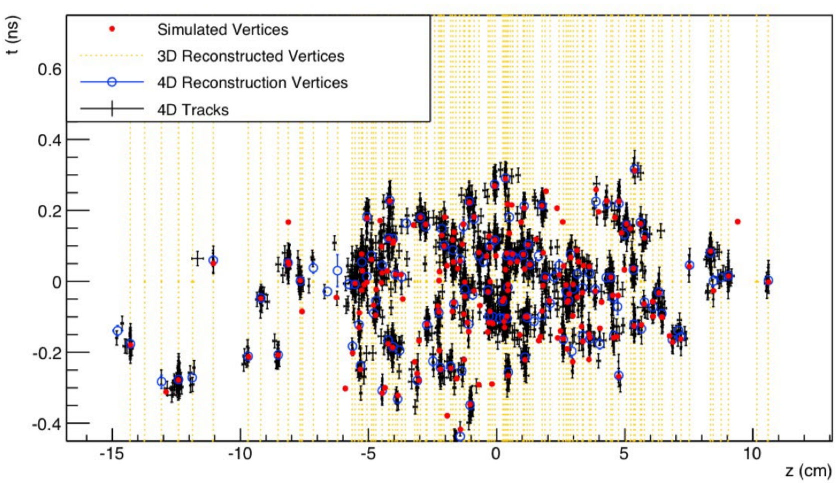
Felix board



Pileup and Timing

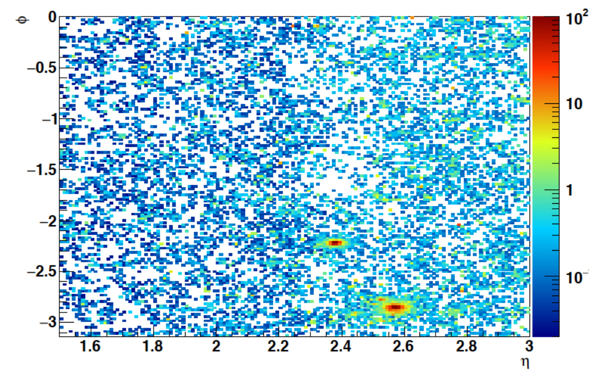
- Higher pileup: major challenge
- Timing: the new dimension to mitigate pileup



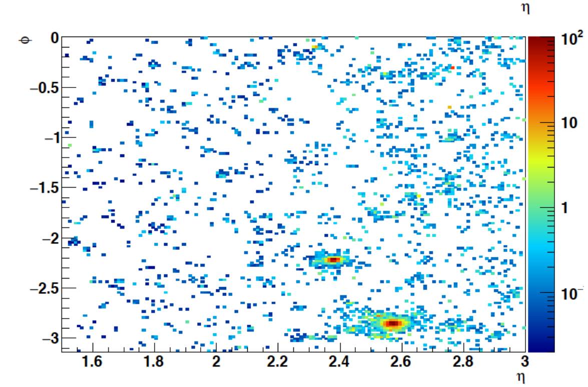


CERN-LHCC-2019-003

- VBF (H→γγ): (Pileup=200 events)
  - 1 γ and 1 VBF jet in HGCal



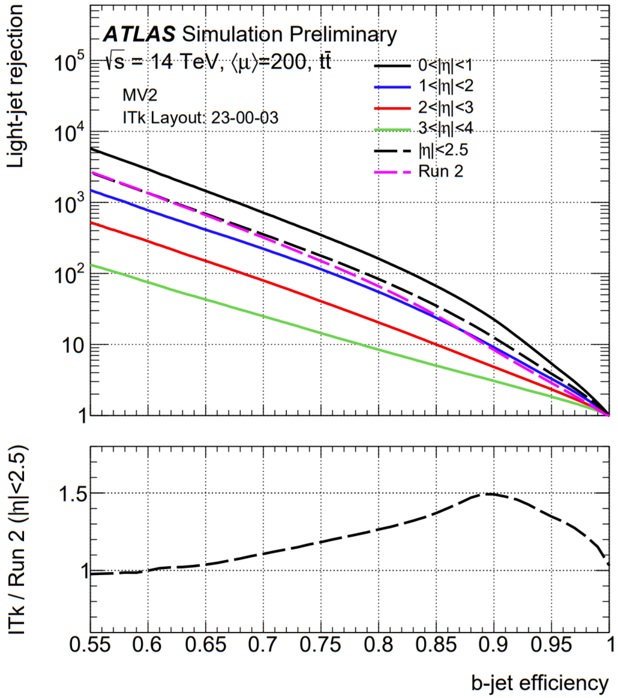
No timing cut



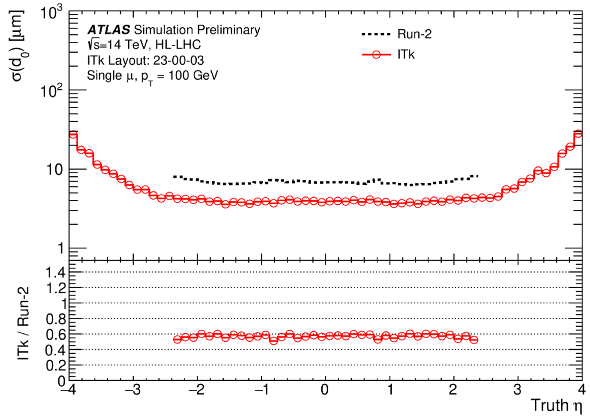
Cut Δt < 90ps (3σ at 30ps)

T. S. Virdee @Ioannina 23

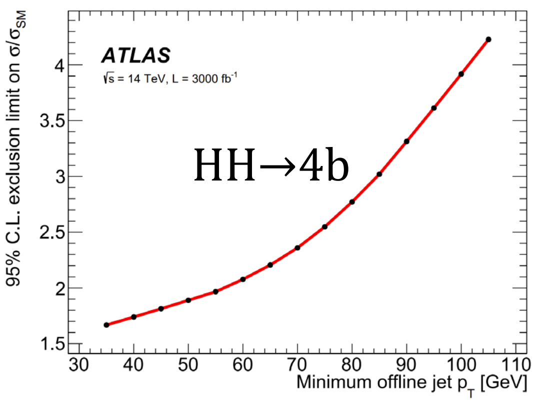
Expected performance (ATLAS as example)



Note: performance evaluated using dedicated simulations with HL-LHC conditions



ATL-PHYS-PUB-2021-024



ATLAS-TDR-029

- In this study, we assume to the detector at HL-LHC just maintain the same performance as Run 2-3
- Very conservative assumption
  - Wider coverage: extended to higher |η| range, higher granularity
  - Faster electronics and computing, same or lower trigger threshold

Methods for HL-LHC prospect studies

1. MC event Generator + Fast detector simulation
   - E.g. Madgraph, Pythia, Powheg + Delphes
   - Parameterized detector response

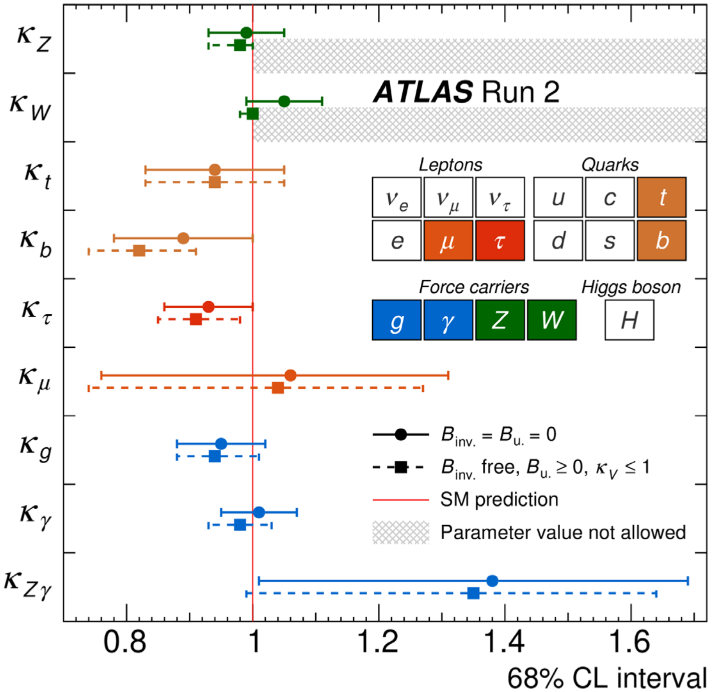
2. Start from published LHC Run 2 results, adapt to HL-LHC conditions
   - Center-of-mass energy: 13 TeV→14 TeV
   - Larger dataset: $140\ fb^{-1} \rightarrow 3000\ fb^{-1}$
   - Simulated detector and reconstruction performance
   - Assume the same detector efficiency as Run 2
   - Theory and experimental uncertainties: usually present a few scenarios

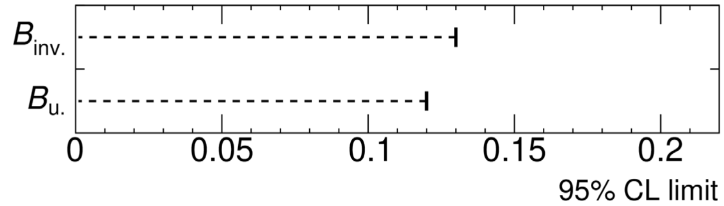
Systematic Uncertainties

- Baseline scenario in this talk, unless otherwise specified
  - Detector and trigger performance comparable to Run 2
  - Most experimental uncertainties scaled down according to luminosity
  - Theoretical uncertainties halved with respect to current values
  - Luminosity uncertainty: 1%

Higgs boson at Run 2-3

- Current Higgs couplings measurement at O(10%) level

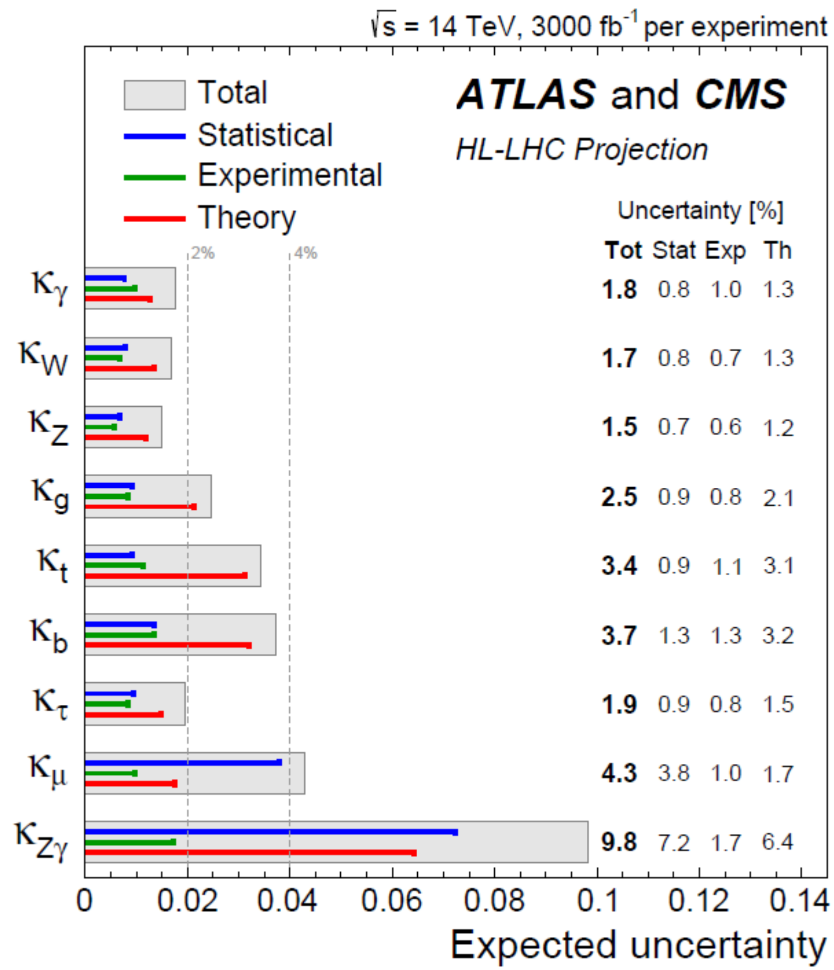




Michal's talk and Martina's talk in the previous session

Higgs boson at the HL-LHC

- Higgs couplings move into precision regime
  - Many known at O(%) level
  - Most dominated by theory uncertainties

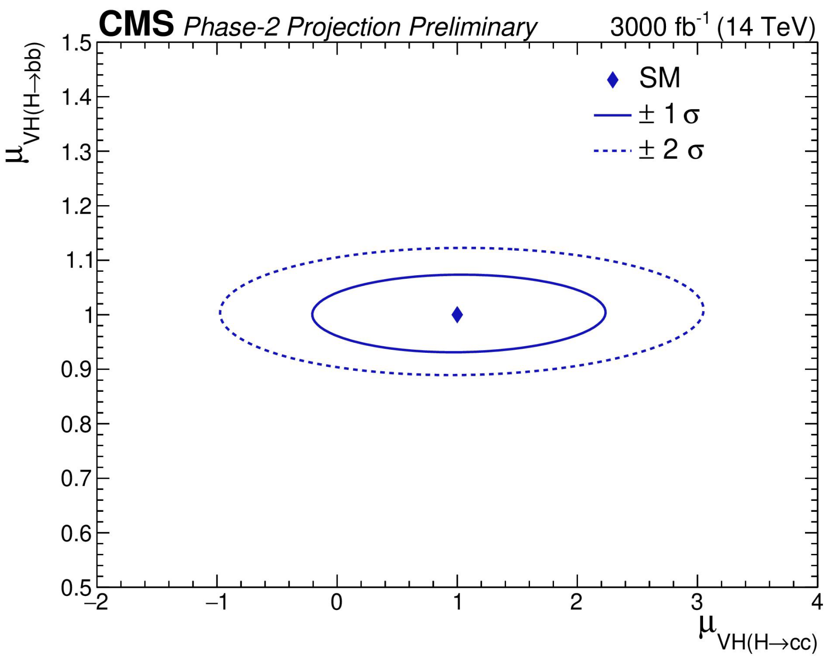


ATL-PHYS-PUB-2022-018, CMS PAS FTR-22-001

- New update
  - H→ττ: ATL-PHYS-PUB-2022-003
  - ttH(bb), dilepton: CMS-PAS-FTR-21-002

Higgs coupling to charm, bottom

- H(bb) and H(cc) couplings probed via VH production mode
  - $\mu(VH, H \rightarrow cc) = 1.0 \pm 1.2$



CMS-PAS-HIG-21-008
ATL-PHYS-PUB-2021-039

- Higgs to charm coupling still difficult to achieve at the HL-LHC
  - New analysis techniques, such as multivariate techniques and jet substructure variables, making great progress in this direction

Higgs coupling to charm, bottom

- H(bb) and H(cc) couplings probed via VH production mode

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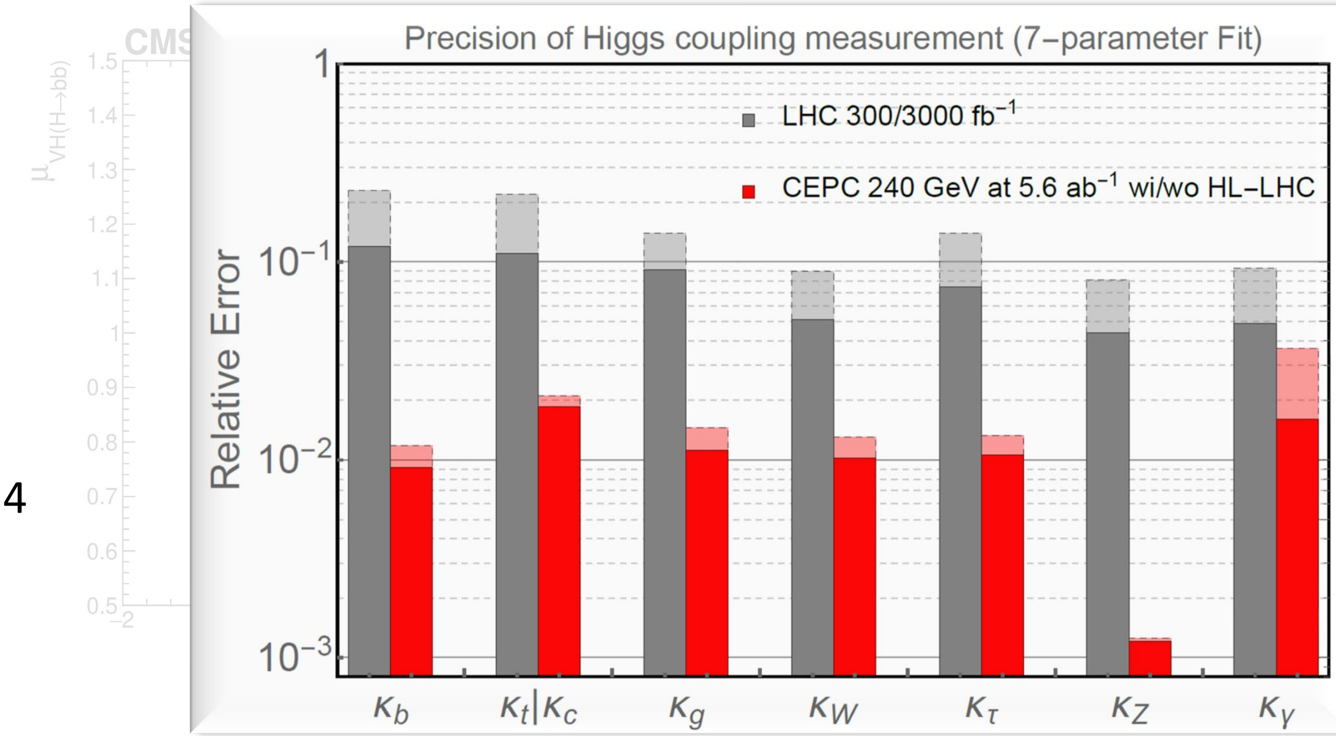


- Higgs to charm coupling still difficult to achieve at the HL-LHC

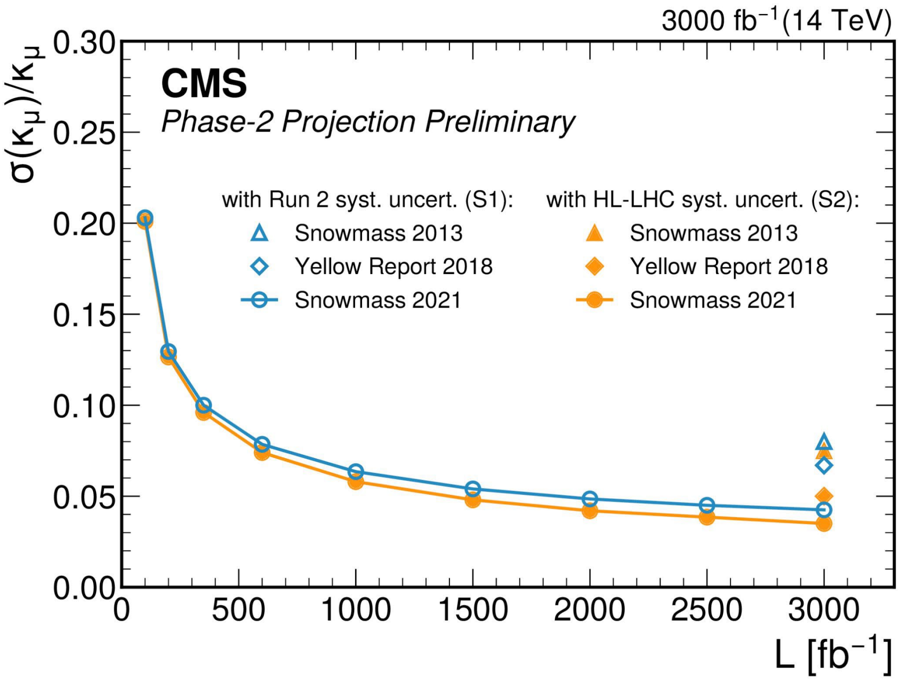
Yukawa sector to be clarified by the future Higgs factories, e.g. CEPC, FCC-ee, ILC, etc.

Alain Blondel's talk and Patrick Janot's talk

Higgs coupling to muons

- $H \rightarrow \mu\mu$ projection based on CMS Run 2 "3σ evidence" analysis
  - Precision better than 5%

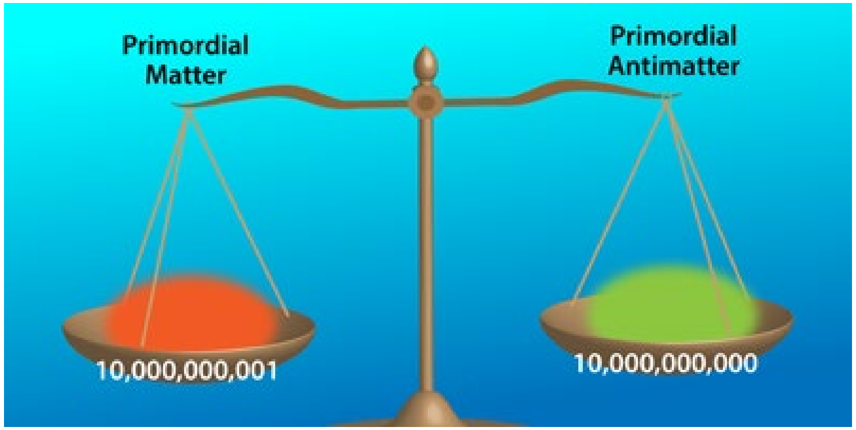
CMS-PAS-FTR-21-006



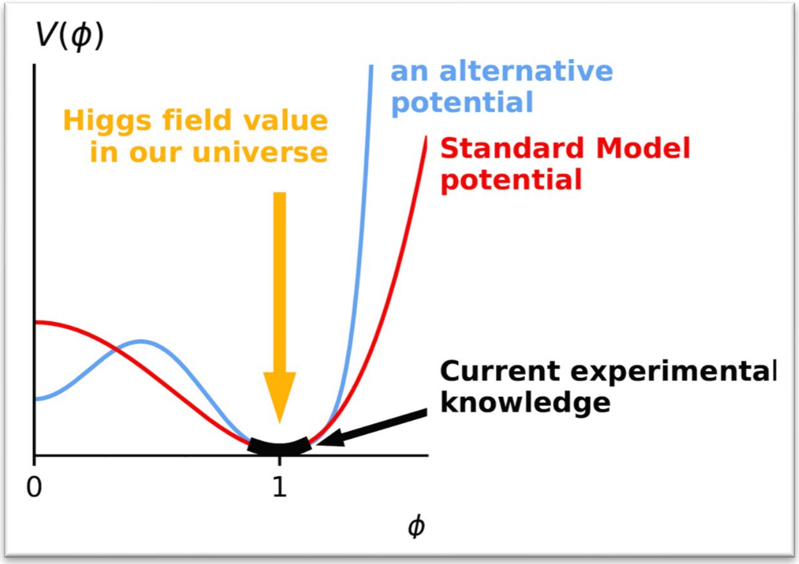
- Signal yield increased due to new detectors
  - Larger muon η acceptance, estimated via Delphes simulation

Nature of EWSB

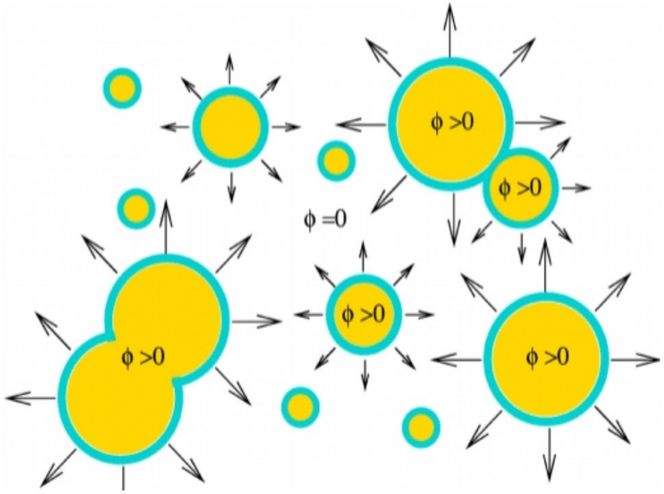
- Sakharov Conditions
  - B Violation
  - C/CP Violation
  - **Departure from Thermal Equilibrium**



- Electro-Weak Symmetry Breaking:



1st order or **2nd order** Phase Transition?



arXiv:2207.00478

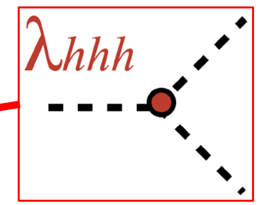
Probe Higgs potential

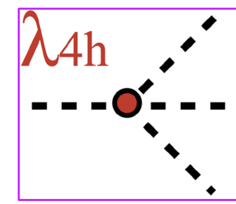
- Expand Higgs potential about the minimum

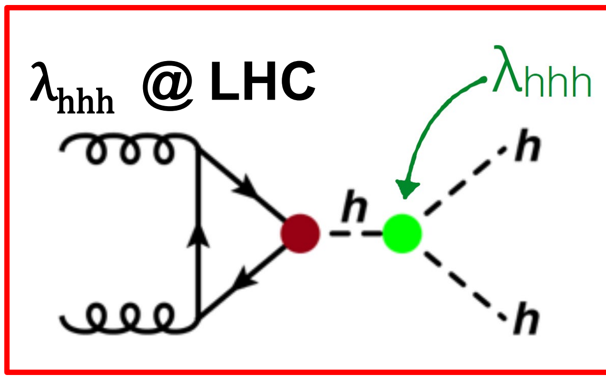
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4 \Rightarrow V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$

$$= V_0 + \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4}\frac{m_h^2}{2v^2} h^4$$

m_H







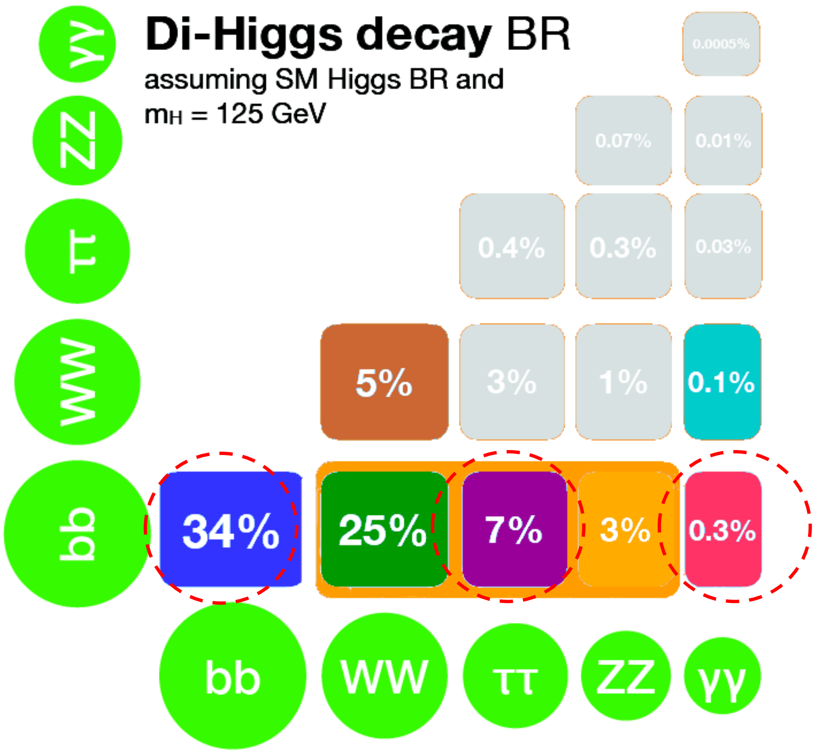
Standard Model:

$$\lambda_{hhh} = \frac{m_h^2}{2v^2}$$

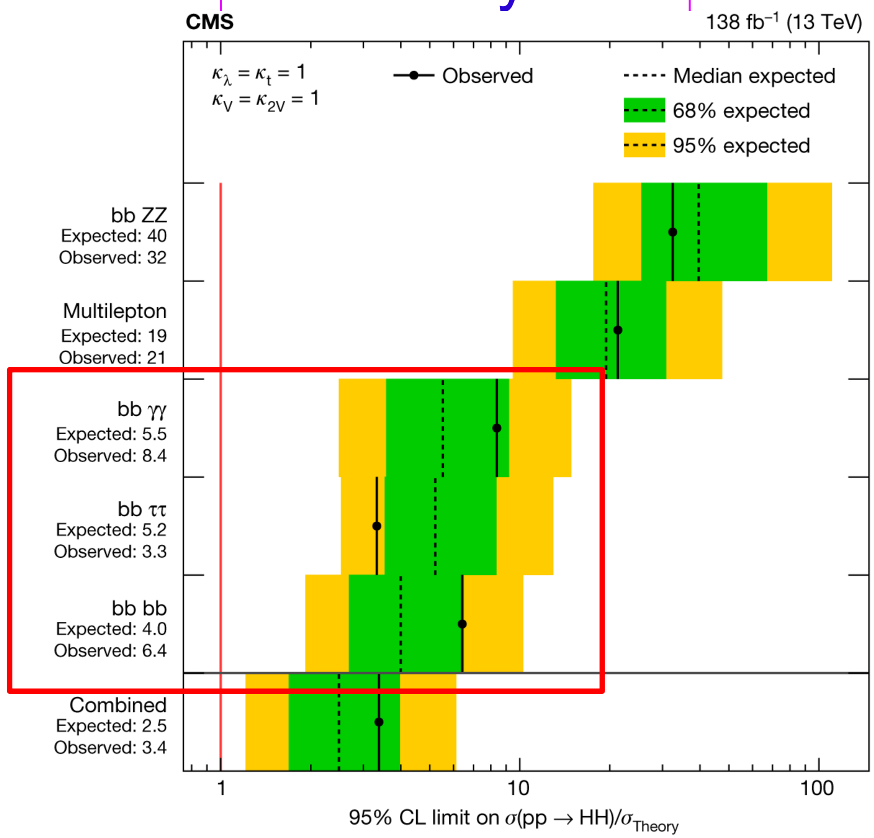
- Higgs-self coupling (λ_{hhh}) is crucial for probing Higgs potential
- λ_{hhh} can be measured in double Higgs production (di-Higgs) at LHC

Searching channels

- Various decay modes searched



Summary Plot

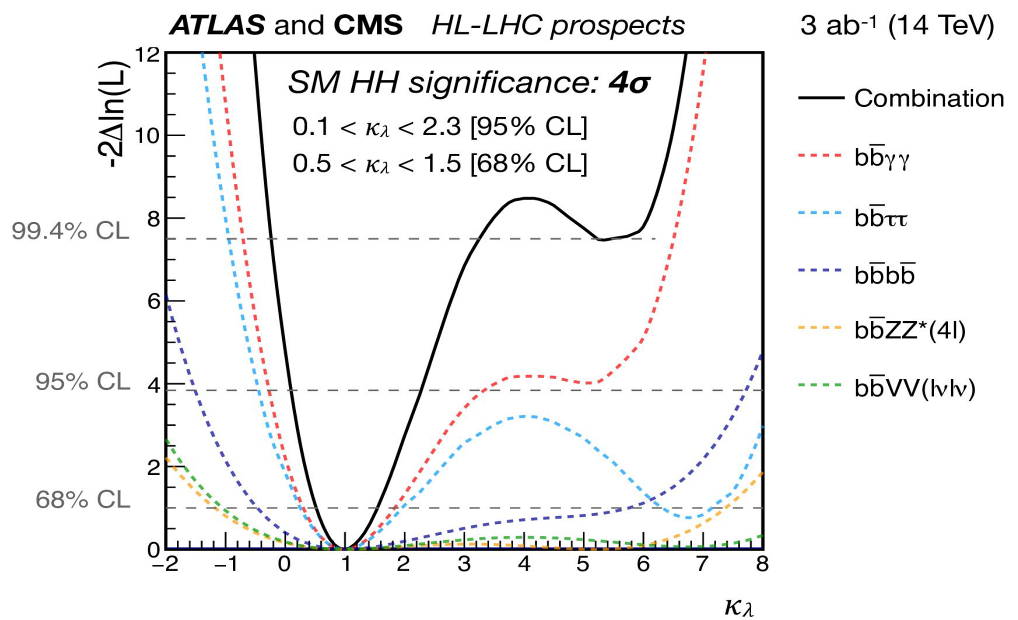


- Leading channels: **bbγγ, bbττ, bbbb**

Nature 607, pages60–68 (2022)

Higgs self-coupliing

European Strategy
CERN-2019-007



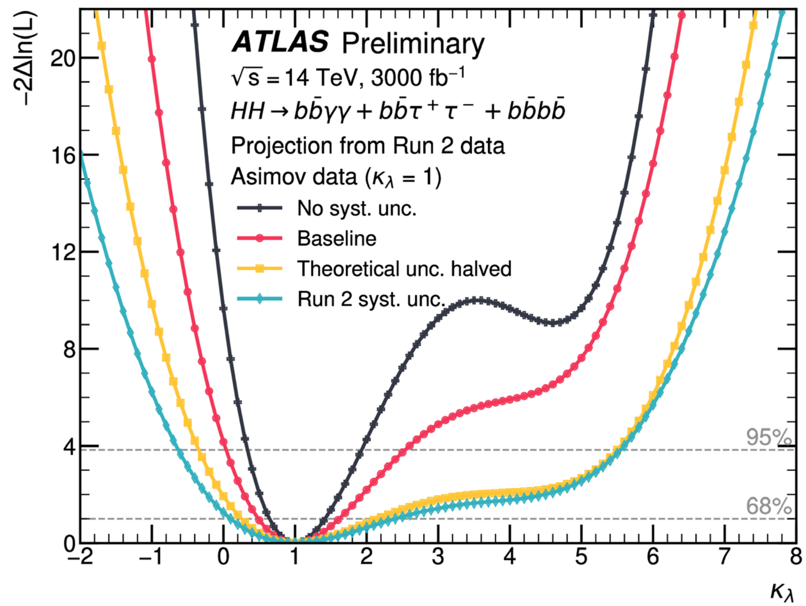
- Combination of 5 HH channels
  - Many based on partial Run 2 analysis strategy
- Self-coupling: 50% precision, SM HH significance: 4σ (ATLAS+CMS)

HH projections for the HL-LHC

Snowmass update (2022):

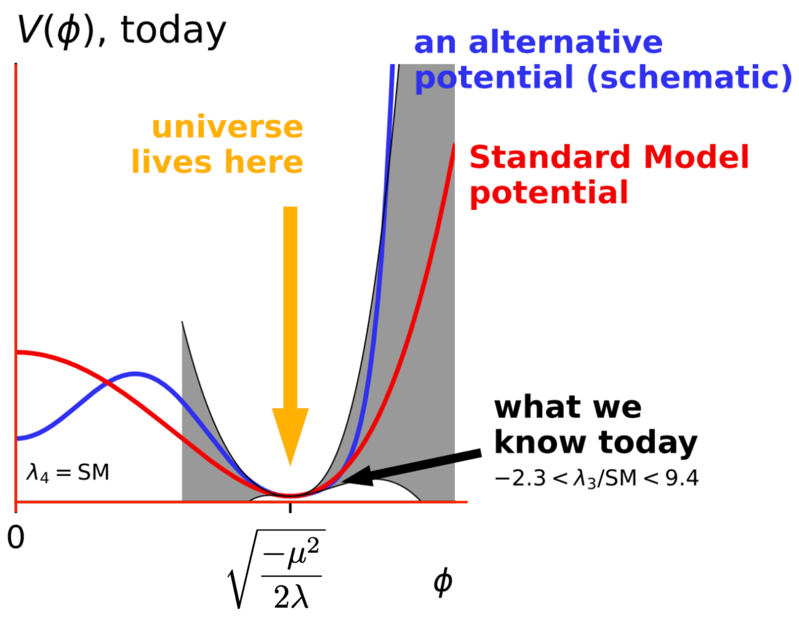
- ATLAS γγbb+bbττ (only) combination: 3.4σ

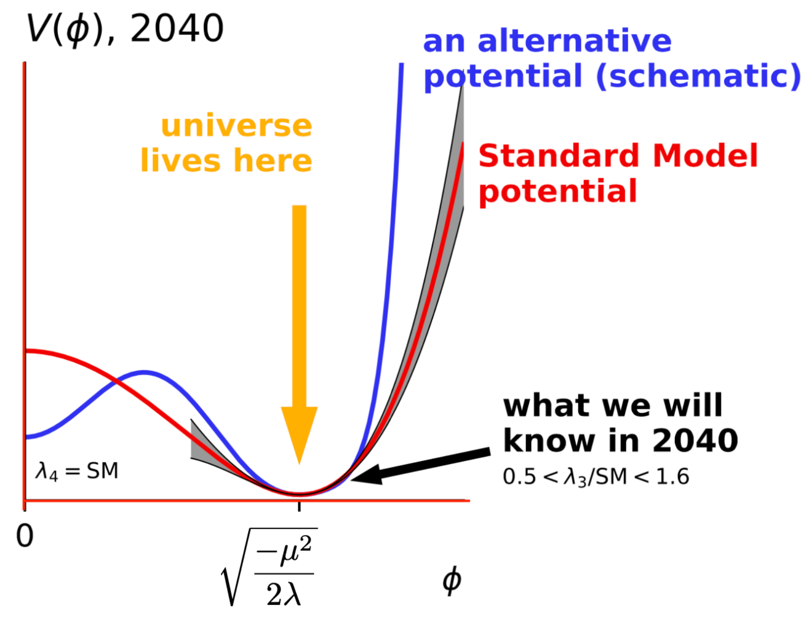
ATL-PHYS-PUB-2022-053



- Recent update from CMS
  - γγbb results(FTR-21-004-pas), γγWW+γγττ (FTR-21-003-pas), ttHH, HH→4b (FTR-21-002-pas), HH→4b (CMS PAS HIG-22-011)
- Reasonable belief
  - SM HH significance 5σ very likely by combining ATLAS and CMS at HL-LHC

Recap on Higgs potential





D. Florian, adapted from G. Zanderighi, Salam, Wang

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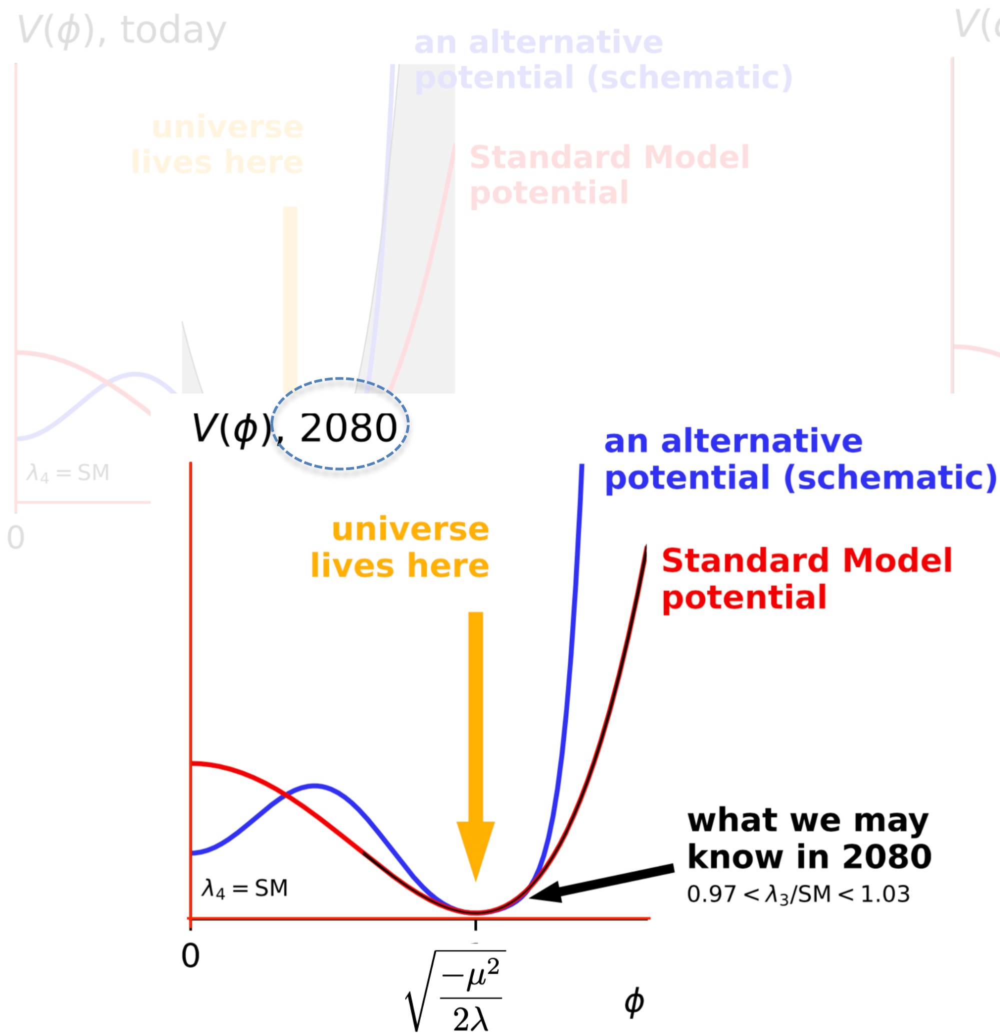
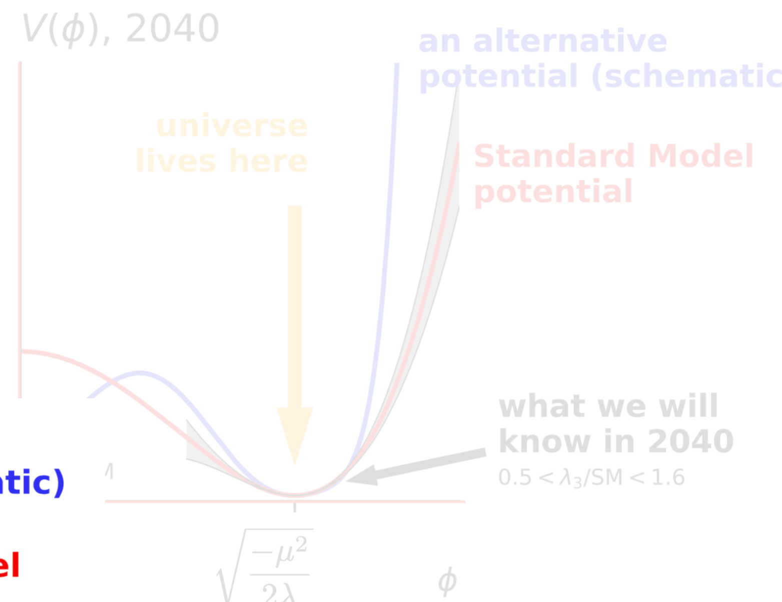
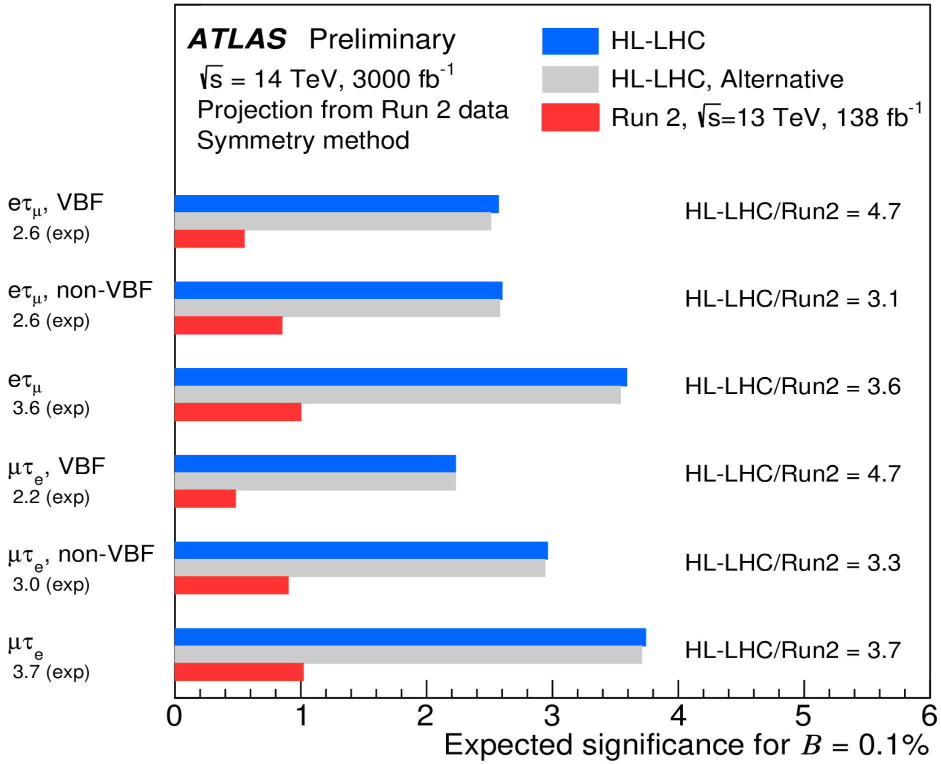




We should build FCC-hh and SppC !

Higgs decay with LFV

- LFV decays of Higgs boson, inspired by:
  - SUSY, extended Higgs sector, warped extra dimensions, as well as flavour anomalies measured by BaBar, Belle and LHCb
- Search for $H \to e\tau$ and $H \to \mu\tau$ processes

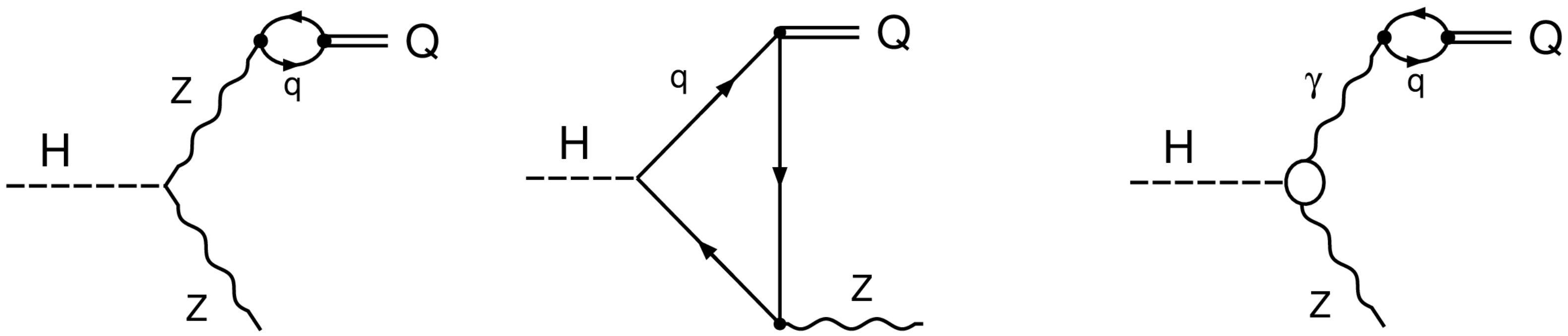


- Expected significance for $Br = 0.1\%$
  - A factor of 3-4 improvement comparing to Run 2 results

ATL-PHYS-PUB-2022-054

Higgs decays to mesons

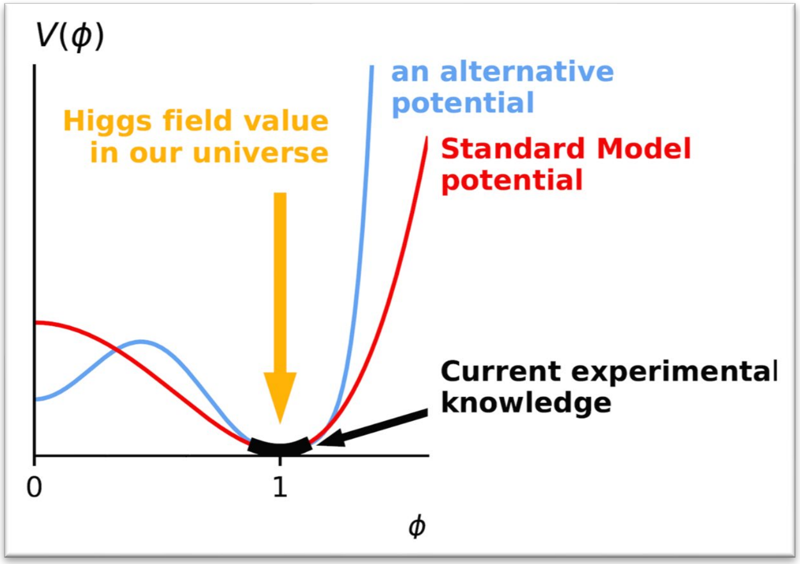
- Clean channel to probe Higgs Yukawa coupling to fermions
  - Especially, 1st and 2nd generation quarks, which BSM lead to enhanced branching fractions by up to 3 orders of magnitude.
- Four-lepton final state: $H \to ZJ/\psi$, $\to \Upsilon(nS)\Upsilon(mS)$ (n,m= 1,2,3)
- Upper limit at 95% CL
  - $B(H \to ZJ/\psi) = 2.9 \times 10^{-4}$, $B(H \to \Upsilon(nS)\Upsilon(mS) = 1.3 \times 10\text{-}5$



CMS PAS FTR-21-009

Extended Higgs sector

- Extension of Higgs sector could change the Higgs potential.
- For example, SM plus one singlet extension
  - Allow 1st order EW phase transition

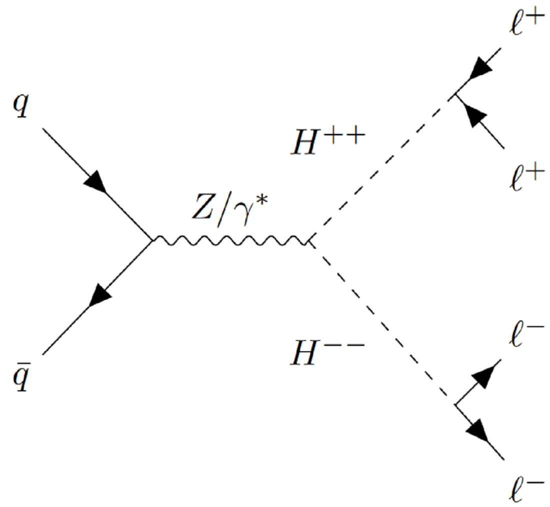


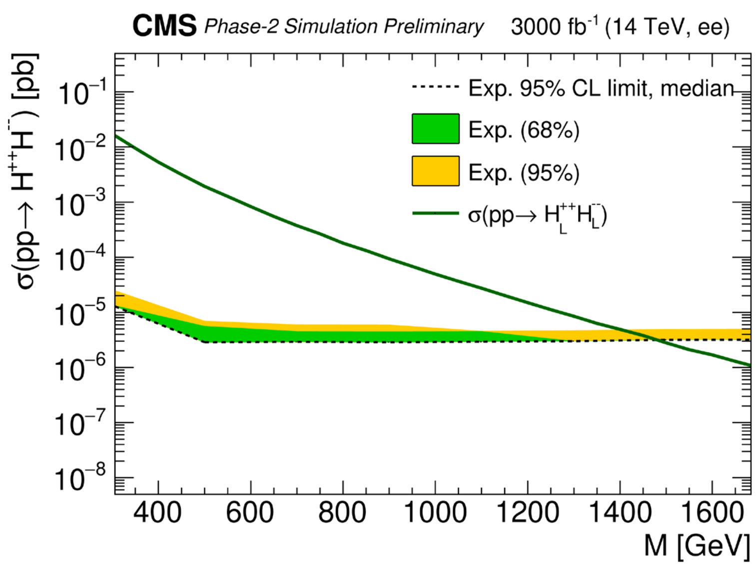
$$V_{\mathrm{CxSM}} = \frac{m^2}{2}\mathrm{H}^\dagger\mathrm{H} + \frac{\lambda}{4}(\mathrm{H}^\dagger\mathrm{H})^2$$

$$+ \frac{\delta_2}{2}\mathrm{H}^\dagger\mathrm{H}|\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4 + \left(\frac{b_1}{4}\mathbb{S}^2 + a_1\mathbb{S} + c.c.\right)$$

BSM Higgs searches

- Doubly charged Higgs: $h^{\pm\pm}, h^{\pm}, h^0, H^0, A^0$
- Motivated by many BSM theories
  - left-right symmetry (LRS)
  - Type II Seesaw model: explain neutrino mass
  - Models with Higgs fields must have a triplet representation



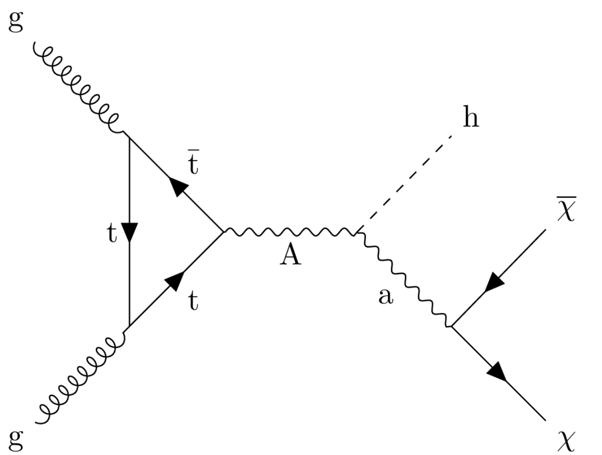


- HL-LHC rule out masses up to at least 1400 GeV at 95% CL

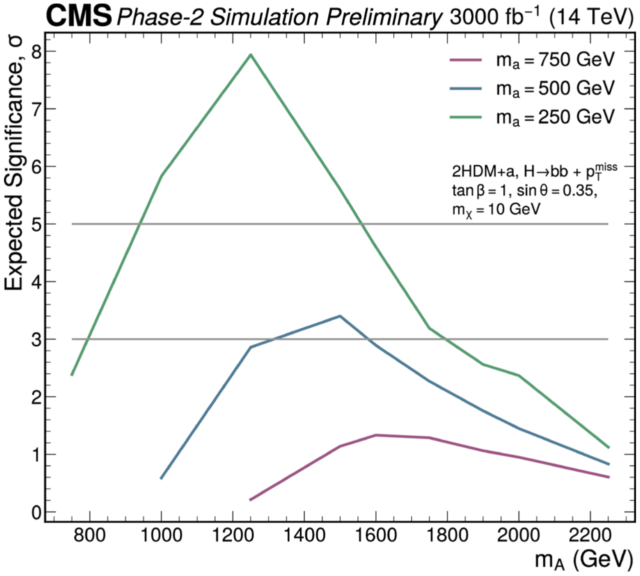
CMS PAS FTR-22-006

Dark matter associated

- Higgs associated produced with dark matter particles
  - In 2HDM+a model, a heavy new particle mediate Higgs and dark matter particle



- Signature:
  - Higgs ($H \rightarrow bb$) + large missing E_T
- Results:
  - m_a= 250 and m_A= 1000-1600 GeV, which are not yet excluded, could reach a significance near 5σ



CMS PAS FTR-22-005

Summary

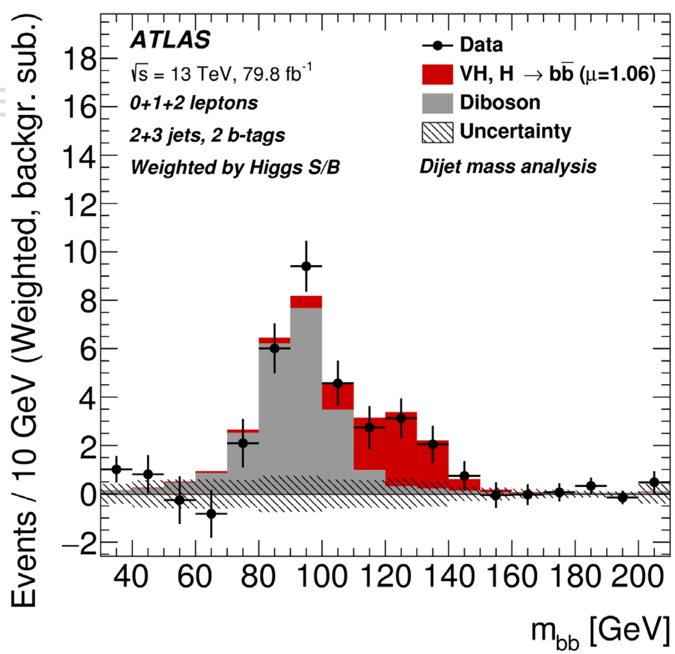
- HL-LHC will bring ~20 times more data
  - Huge physics potential, also leads higher pileup background
  - ATLAS and CMS upgraded to more sophisticated detectors and experimental methods
- Major physics program on Higgs sector:
  - Higgs precision measurement, Higgs potential via di-Higgs, exotic and rare Higgs decays, …
  - Many of results will be limited by the theory uncertainties, e.g. single Higgs or di-Higgs

Go beyond expectation

- ATLAS TDR II, page 685, 1999 e data

In conclusion, the extraction of a signal from $H \to b\bar{b}$ decays in the WH channel will be very difficult at the LHC, even under the most optimistic assumptions for the b-tagging performance and calibration of the shape and magnitude of the various background sources from the data itself.

- Major physics program on Higgs sector:
- Discovery of H→bb with 5.4σ significance Higgs, exotic
  - **PLB 786 (2018) 59**
  - Many of results will be limite e.g. single Higgs or di-Higgs



The end