Present and Future of the Higgs Boson

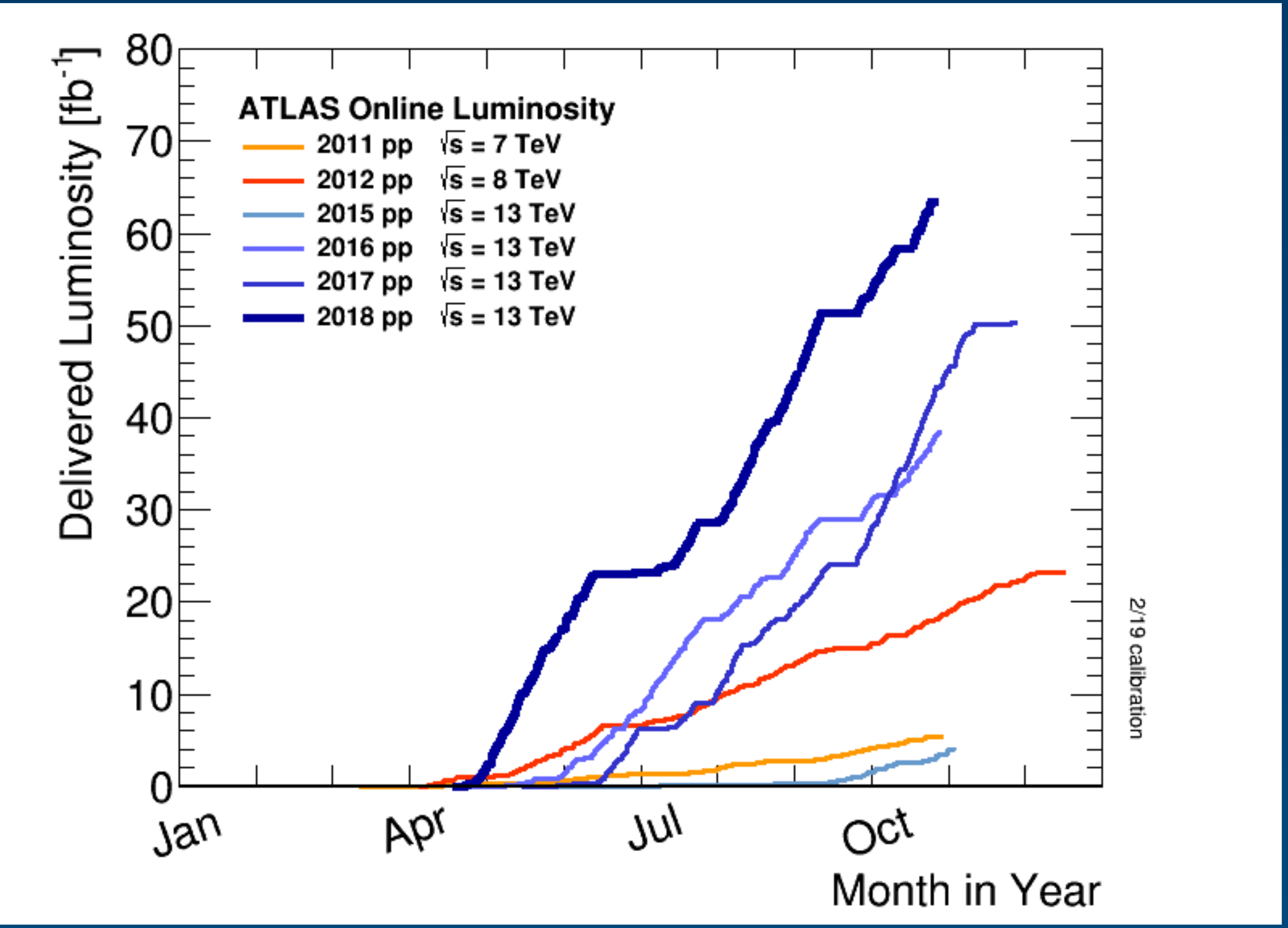
- Part 1: What we have learned since the discovery (Henri Bachacou)
- Part 2: What we hope to learn at High-Luminosity LHC and beyond (Christophe Ochando)
- Part 3: Detector challenges at High-Luminosity LHC and beyond (Laurent Serin)

Part 1
What we have learned since the discovery of the Higgs Boson

Henri Bachacou

LHC timeline in the past decade

- Run 1: 2011 at 7 TeV and 2012 at 8 TeV
  - Discovery with 2011 and part of 2012 data
- Run 2: 2015-2018 at 13 TeV.
  - Higher center-of-mass energy and luminosity → a much larger dataset allowing to study the Higgs boson in great detail.

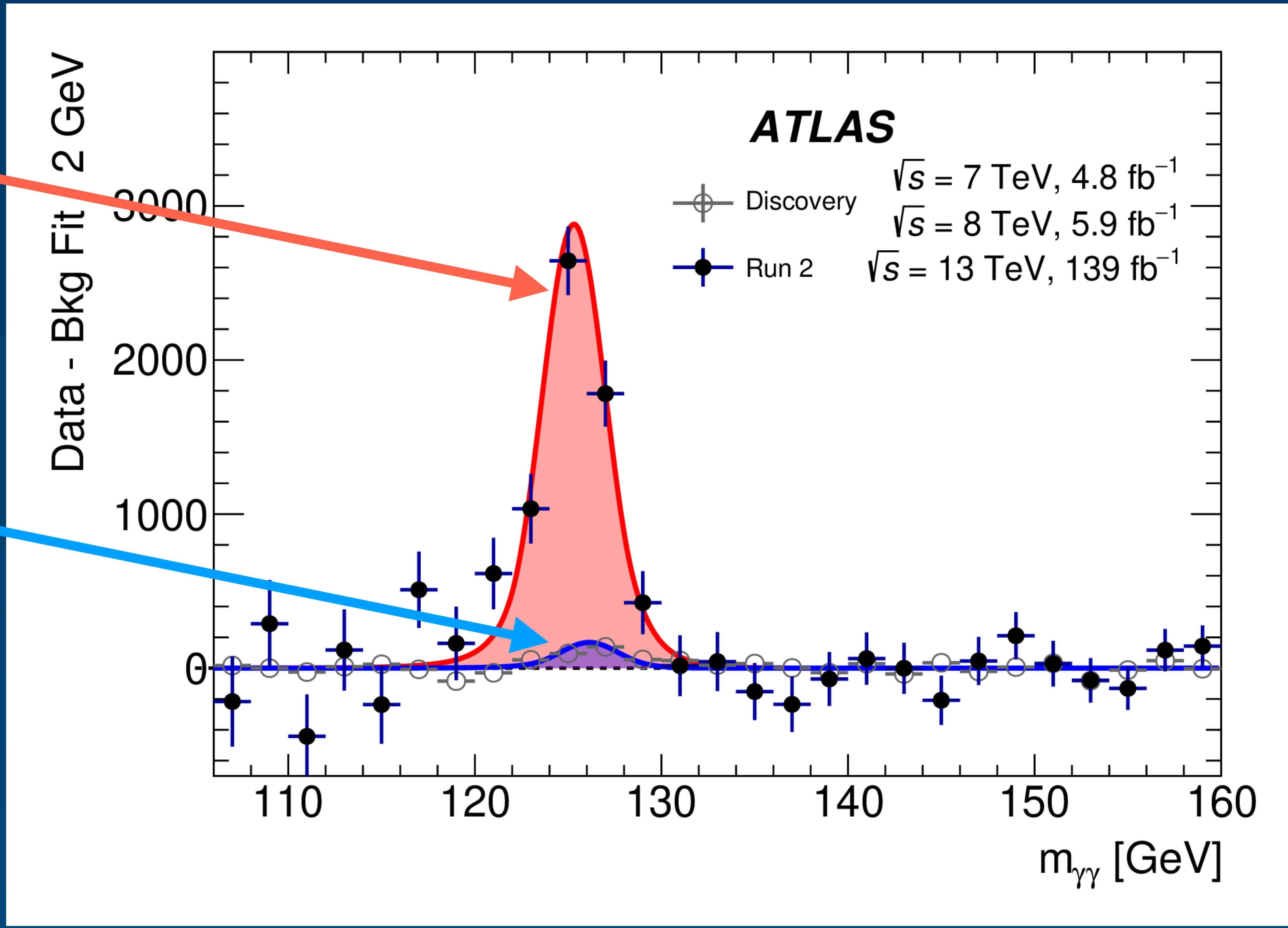


The Discovery Channels
Past and Present

- The Higgs boson was first observed in:
  - **The Diphoton channel (H→γγ)**
  - The 4-lepton channel (H→ZZ→4l)

Today (Run 2 data)

At the time of discovery (2012)



- LHC Run 2 offers much larger Higgs samples:
  - thousands of diphoton Higgs candidates

The Discovery Channels
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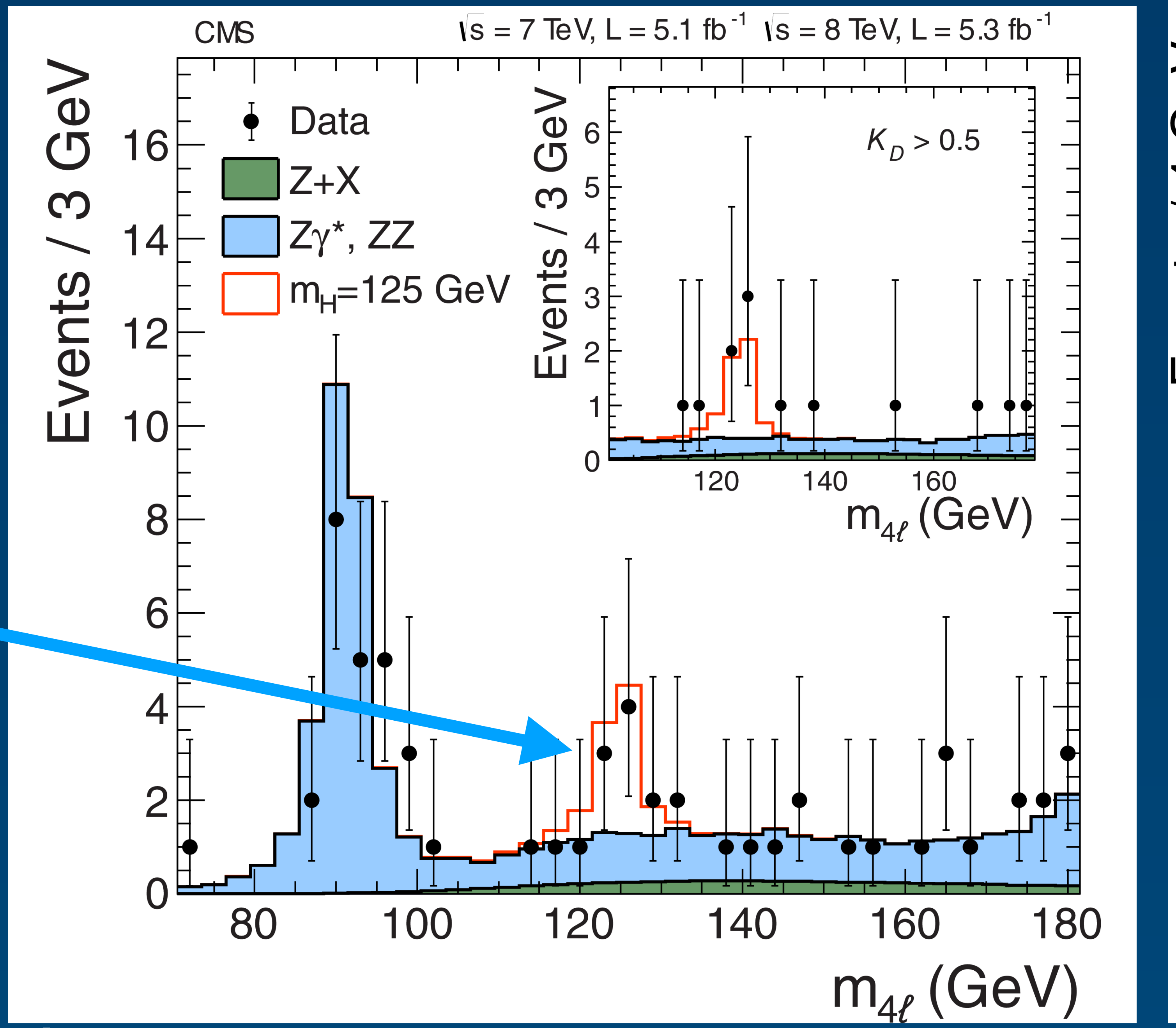

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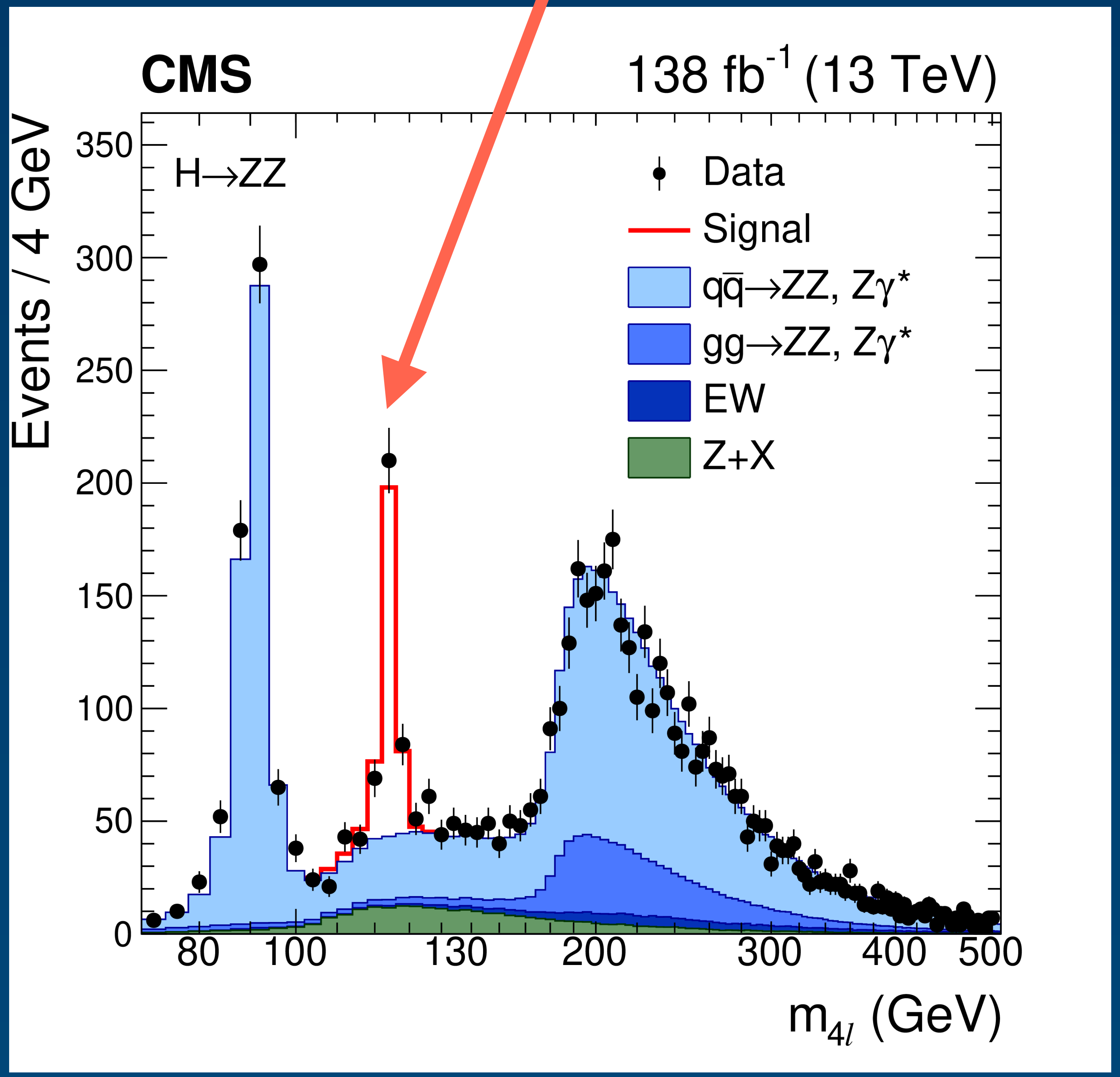
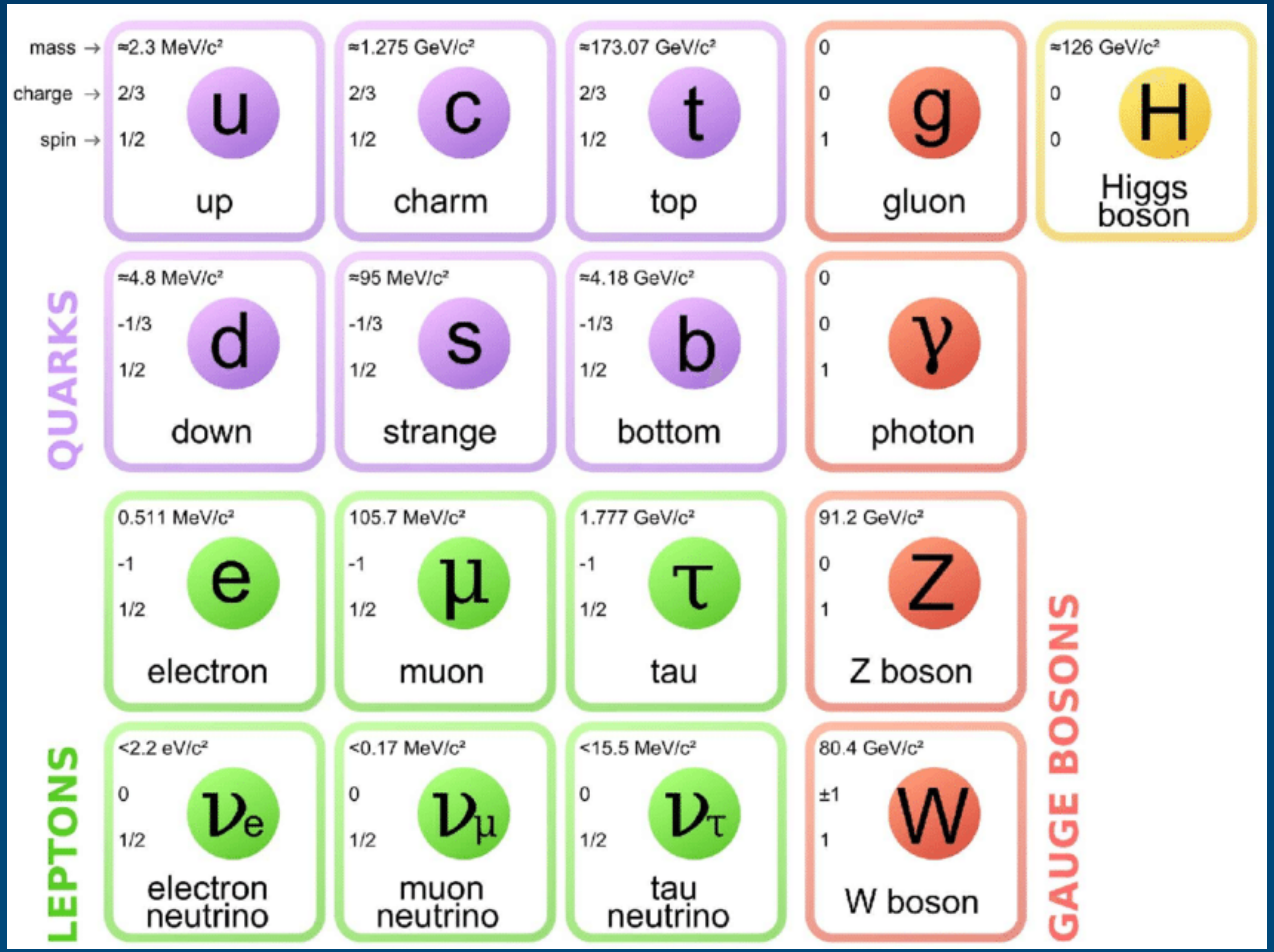


- LHC Run 2 offers much larger Higgs samples:
  - thousands of diphoton Higgs candidates
  - hundreds of 4-lepton Higgs candidates (with an excellent signal-over-background)
  - and much more…

What we would like to know about the Higgs boson

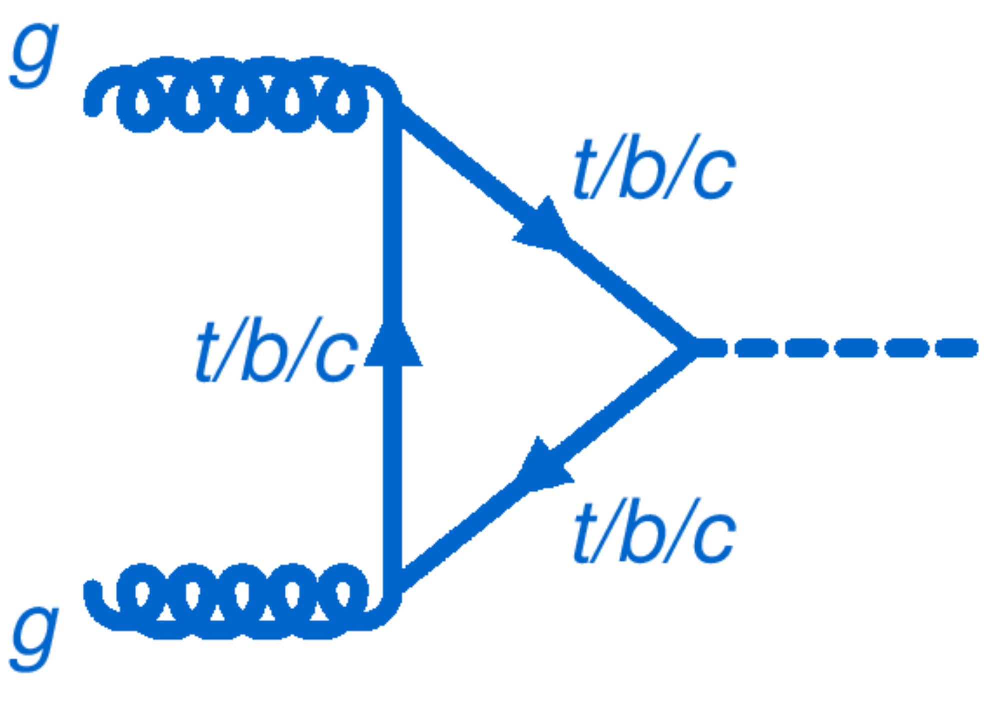
- Is it really the Higgs boson ?
  - Does it interact with the other Standard Model particles as expected?
    - With the W and Z vector of the weak force
    - With the fermions (quarks & leptons) proportionally to their mass
  - Is it a scalar (spin-0) elementary particle?
- Are there other Higgs bosons?
  - Some models (e.g. Supersymmetry) predict the existence of several Higgs bosons.
- Does the Higgs boson interact with non-Standard Model particles (e.g. Dark Matter)?



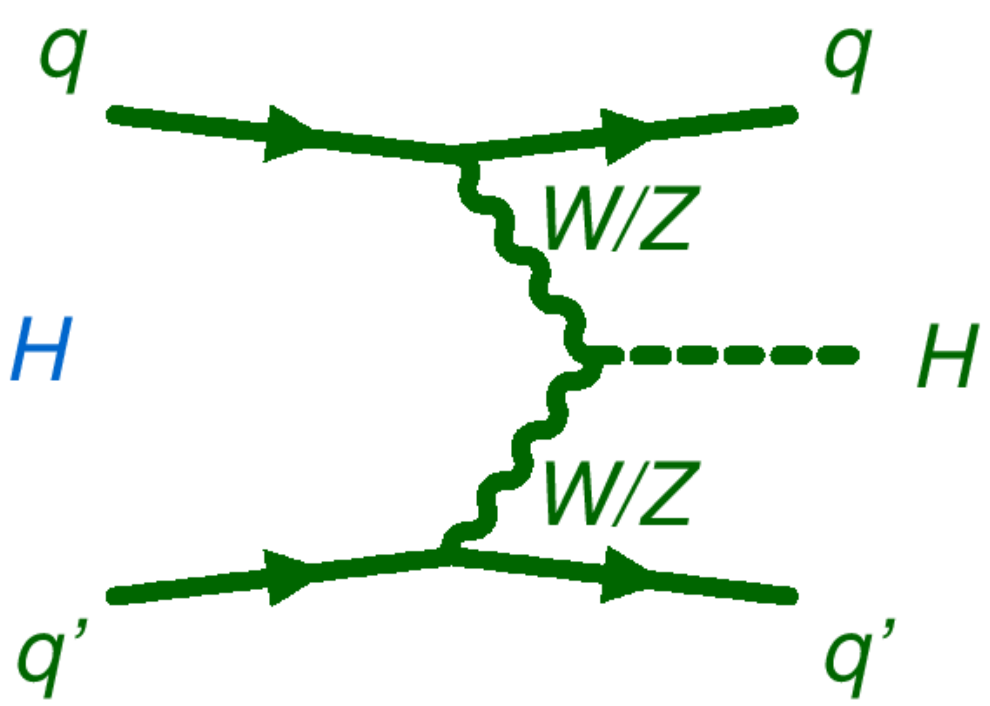
Higgs Production and Decay

Production Mechanisms:

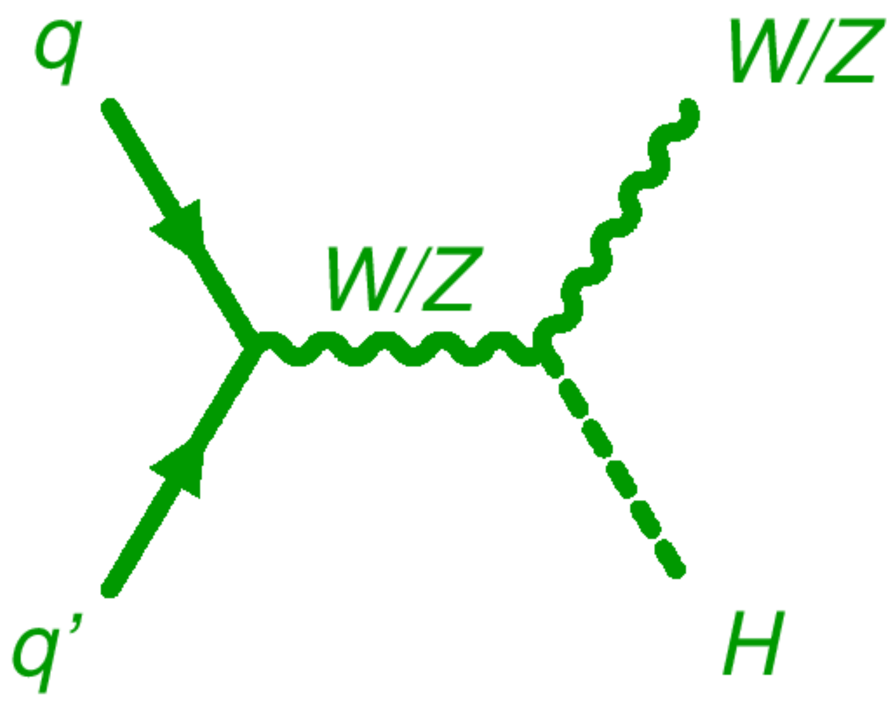
Gluon fusion



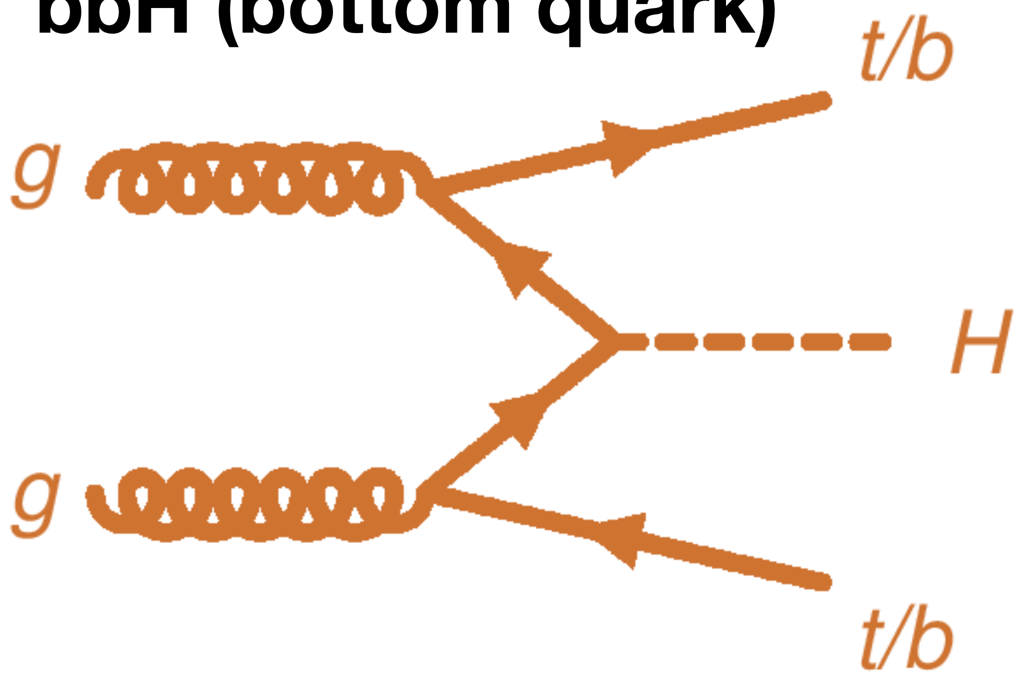
Vector Boson Fusion



W/Z Associated Prod.



ttH (top quark)
bbH (bottom quark)



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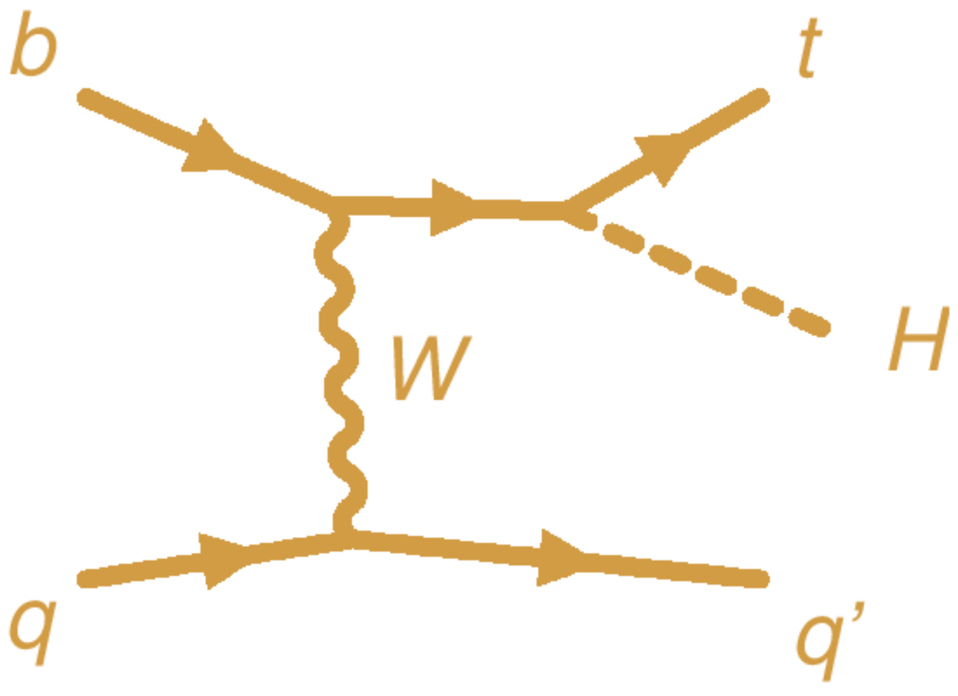
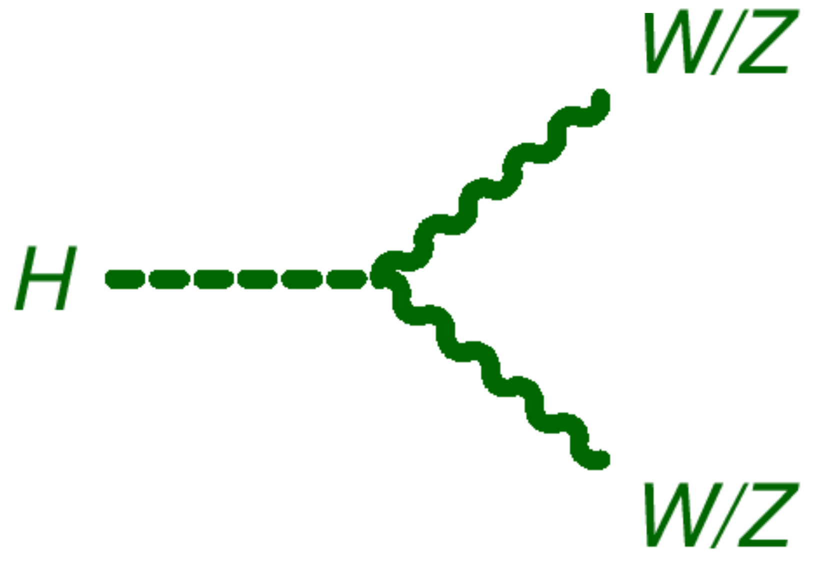
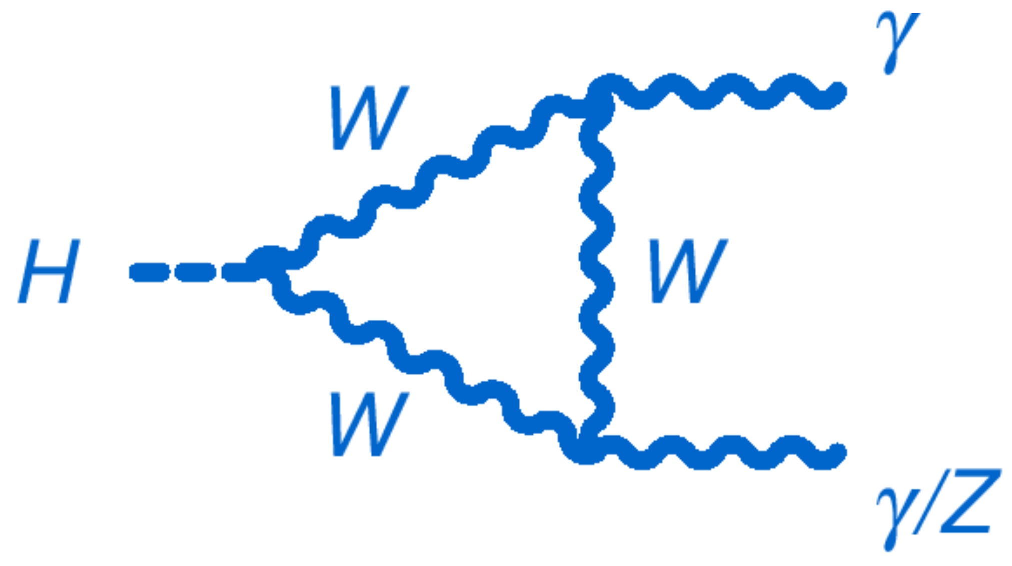


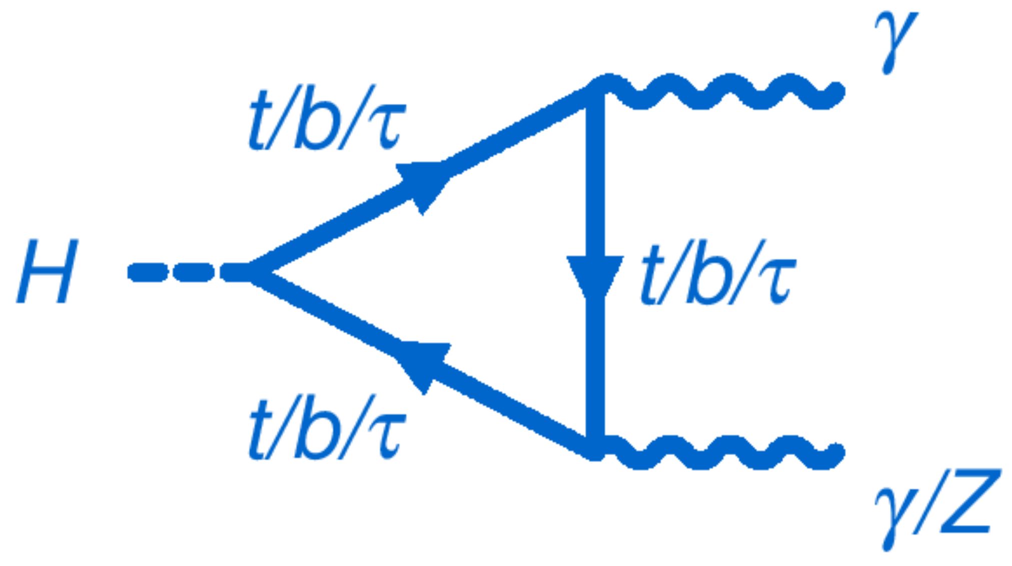
Decays:

Vector Boson pair

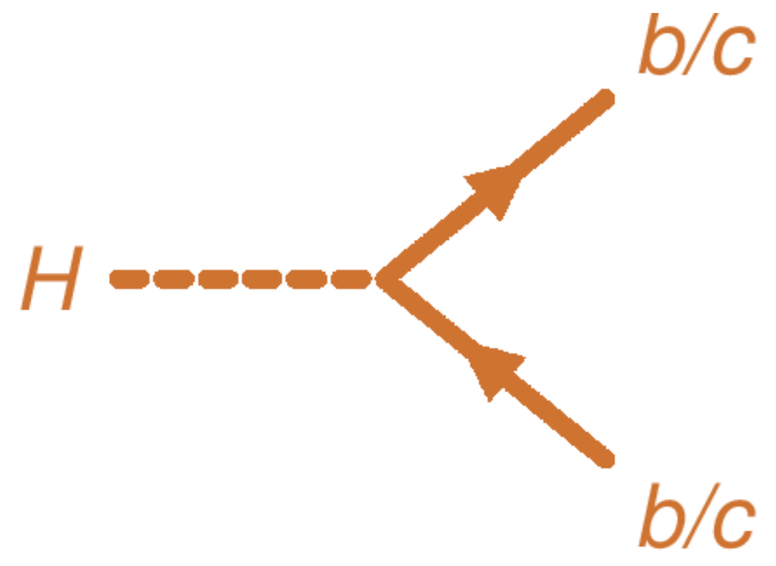


Diphoton

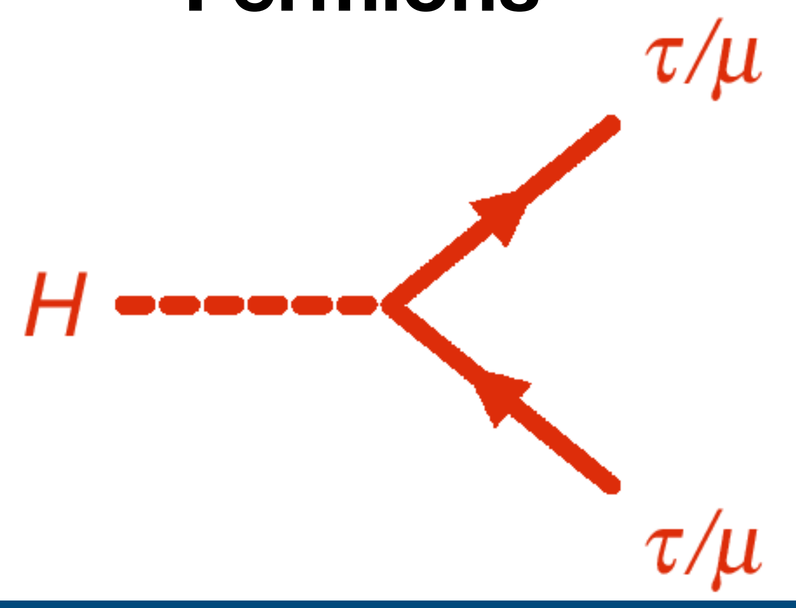




Bottom or charm quarks



Fermions



Each production and each decay tells us something about the <u>interaction</u> (coupling) between the Higgs and the other particles of the Standard Model

Higgs Production and Decay

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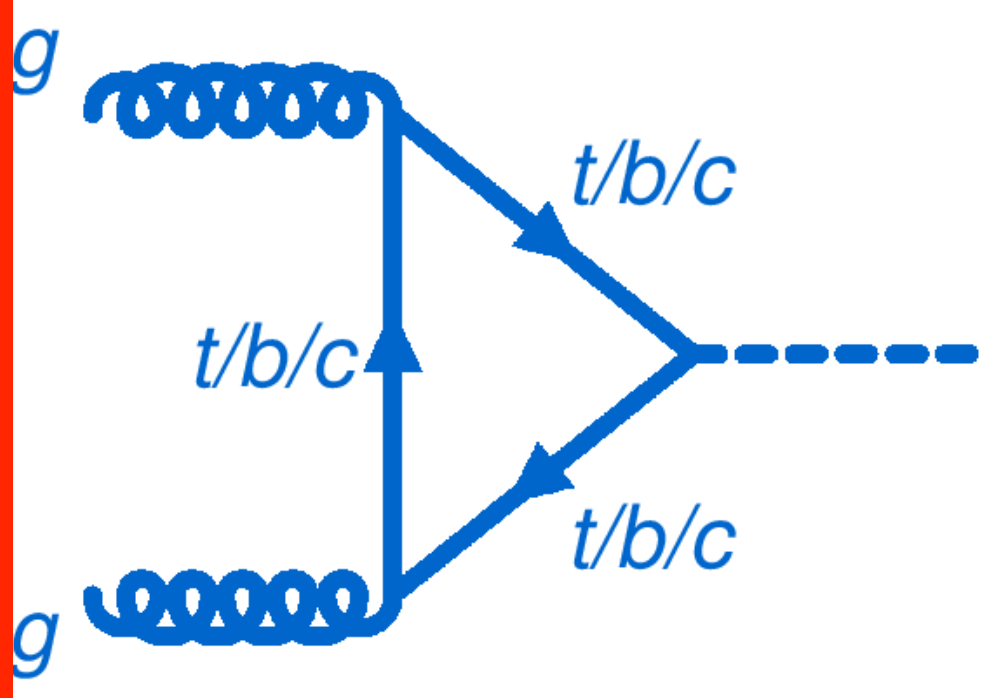
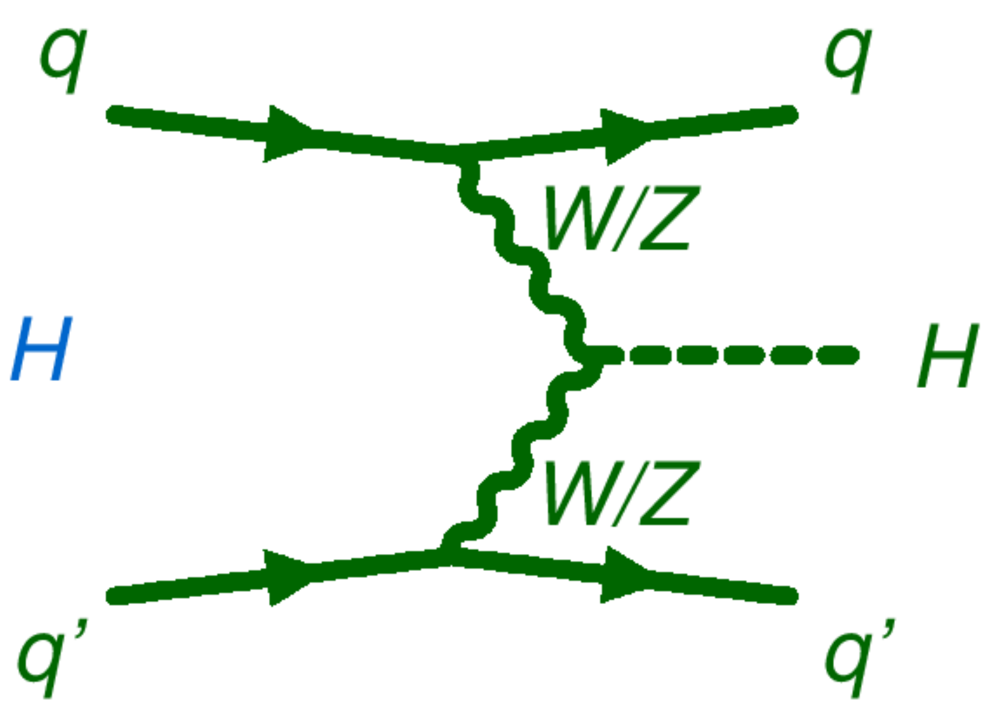


Vector Boson Fusion



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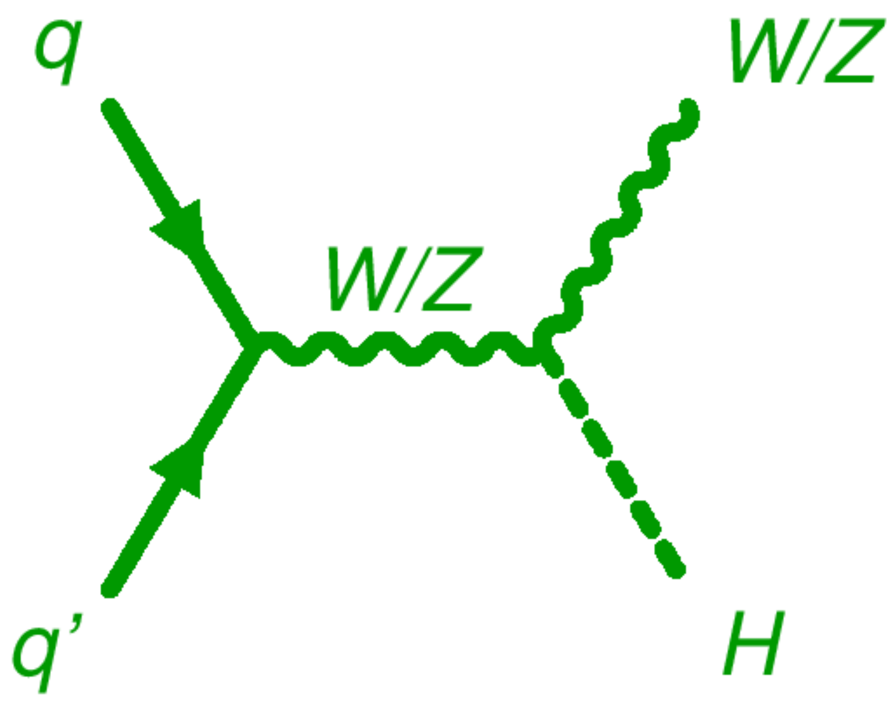

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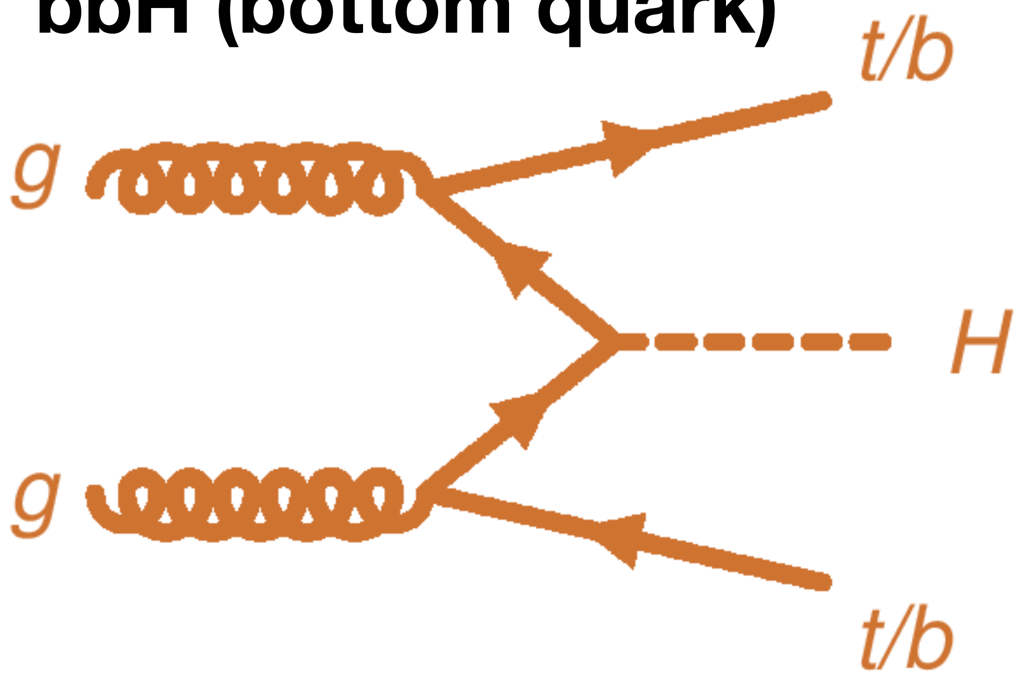

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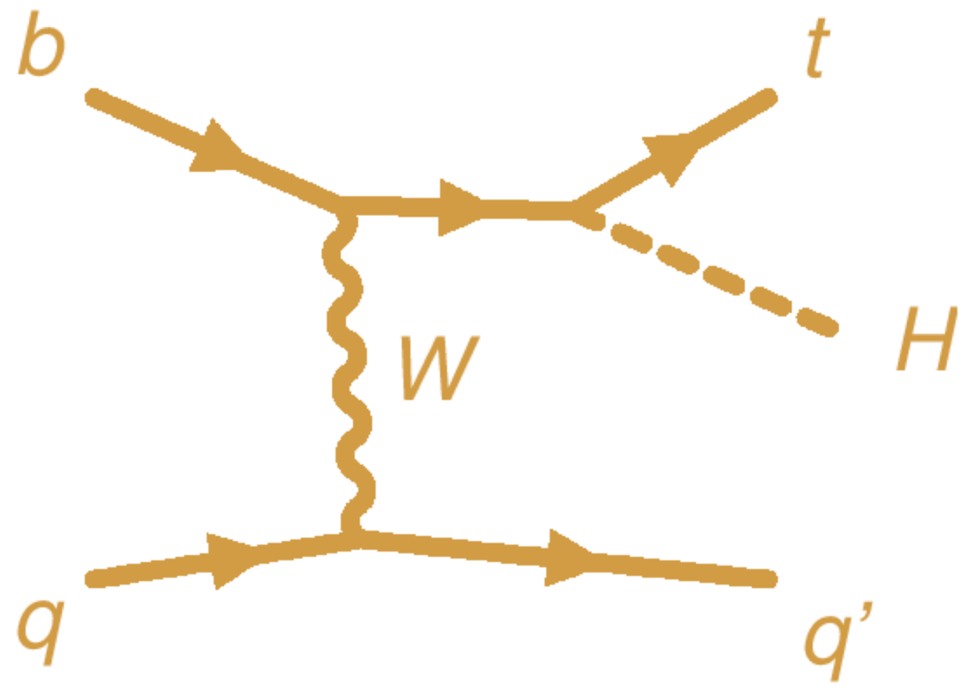

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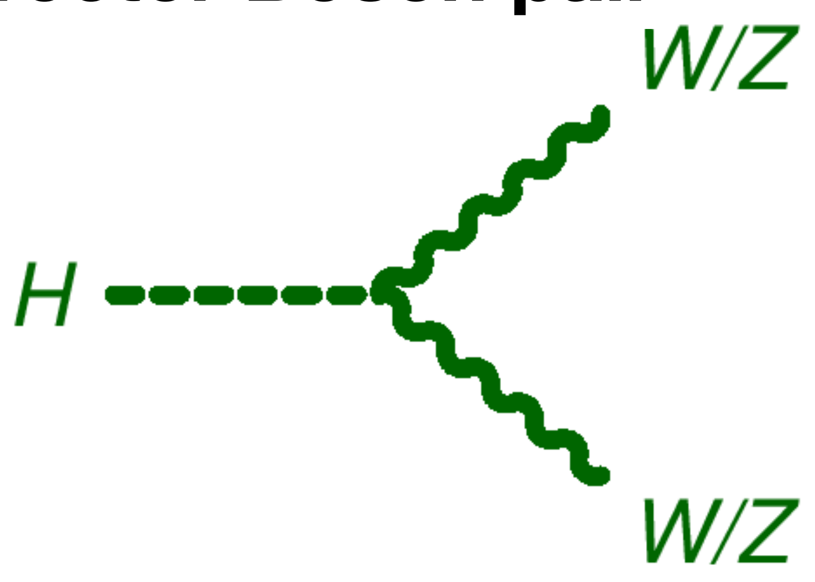
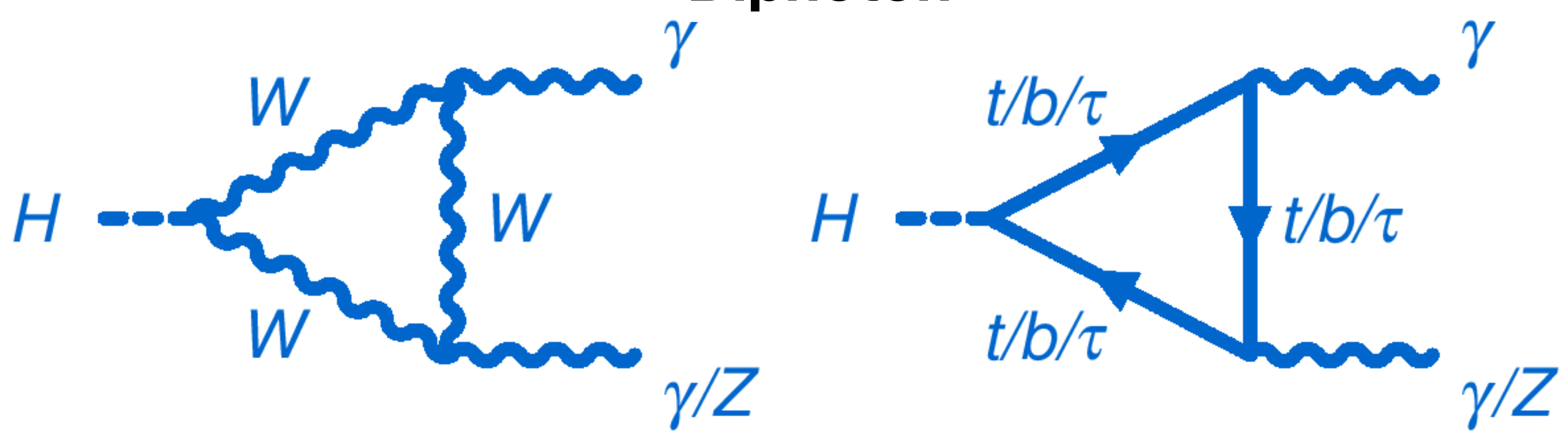


Diphoton



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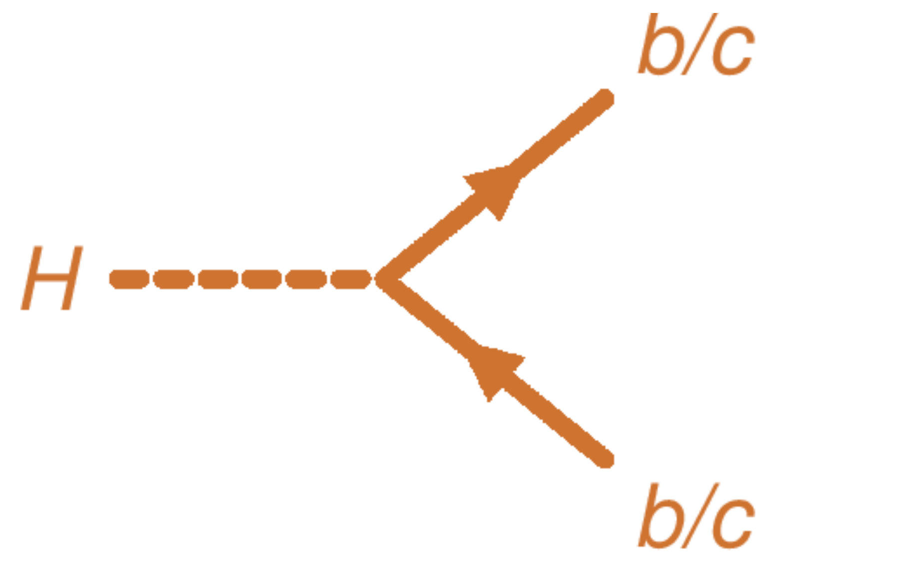

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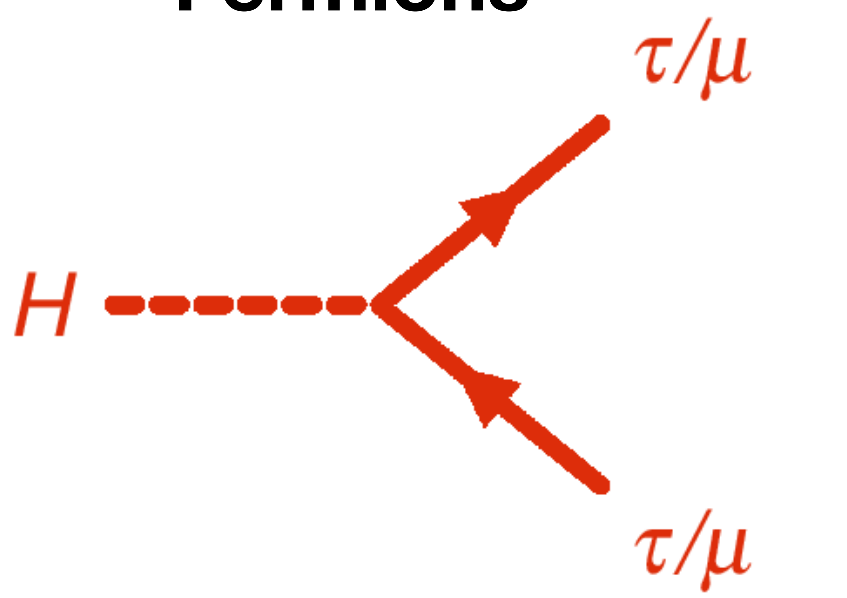
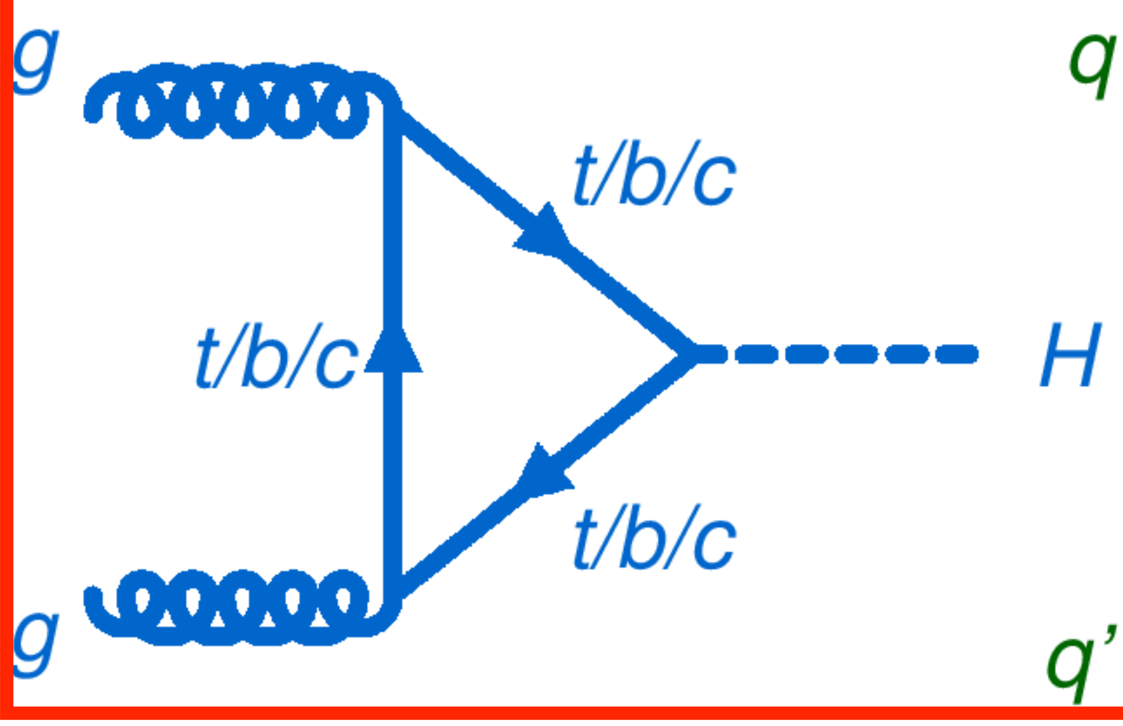


The <u>discovery</u> was achieved with only one production mechanism (gluon fusion) and two decays (diphoton, ZZ)

Higgs Production and Decay

Production Mechanisms:

Gluon fusion



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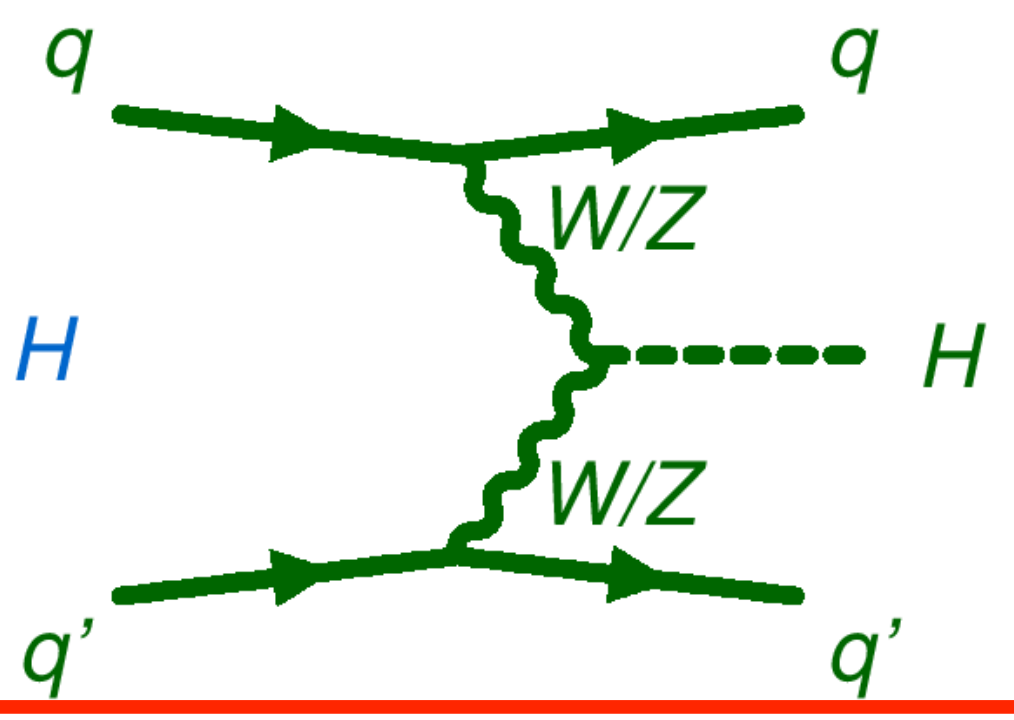

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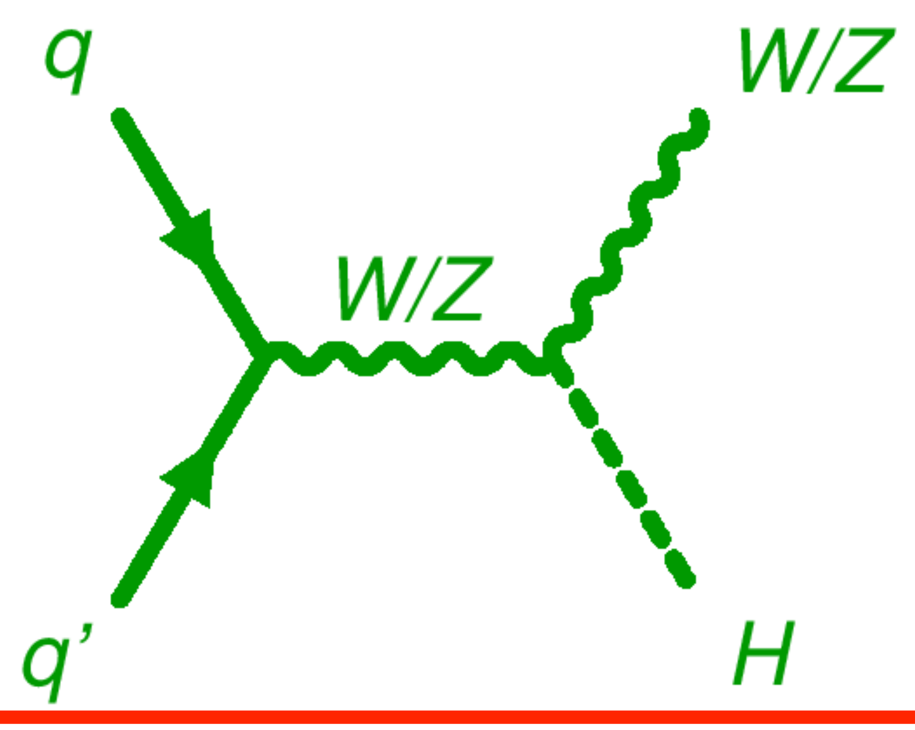

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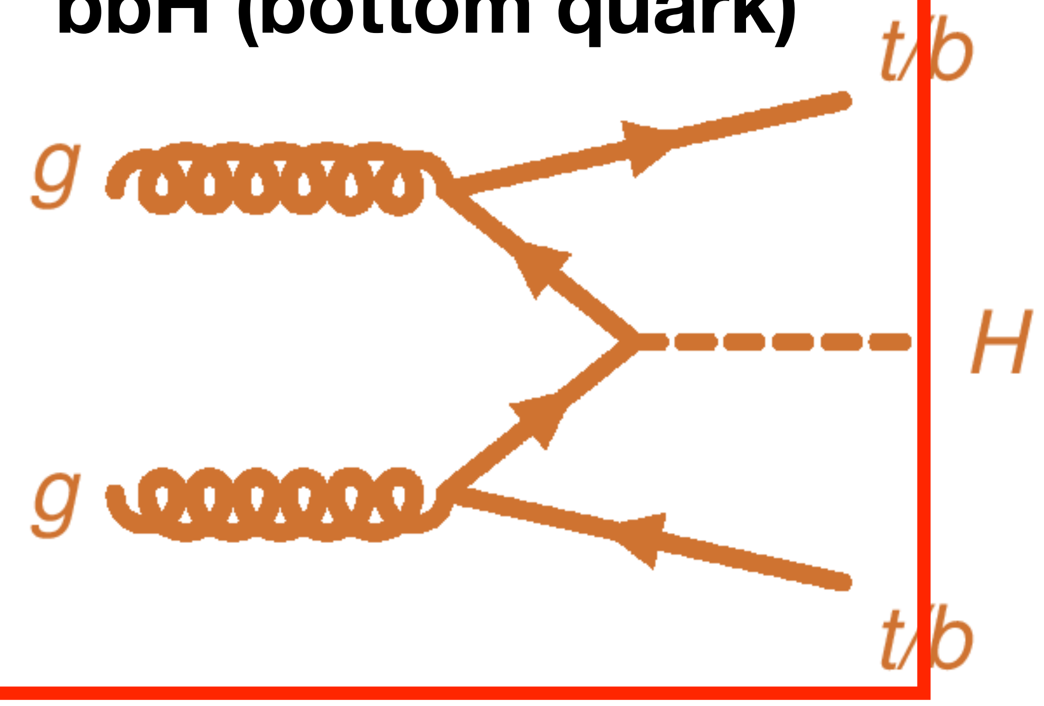

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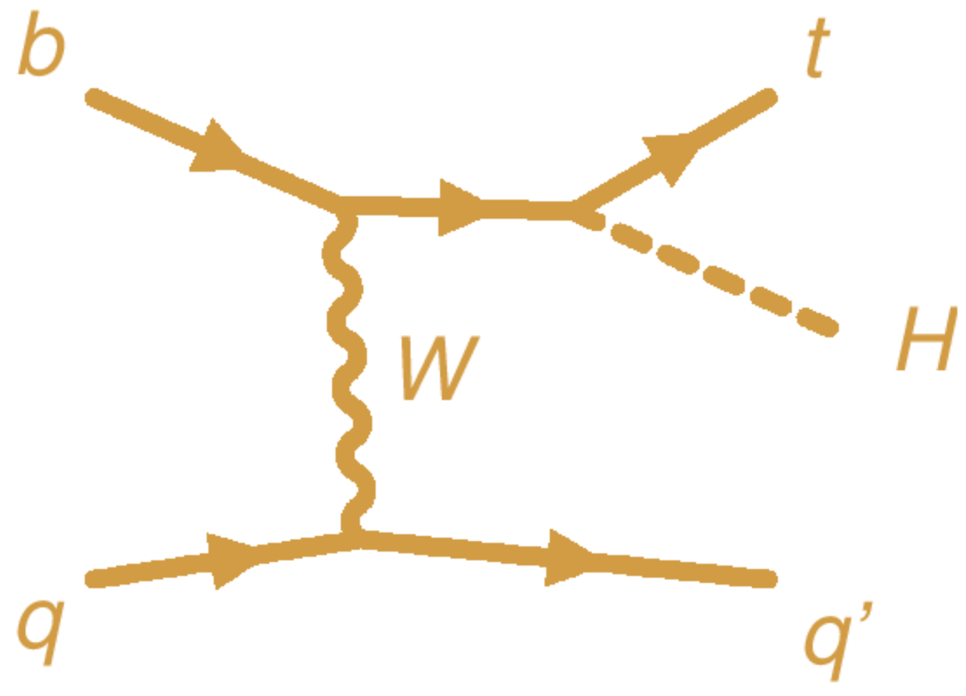

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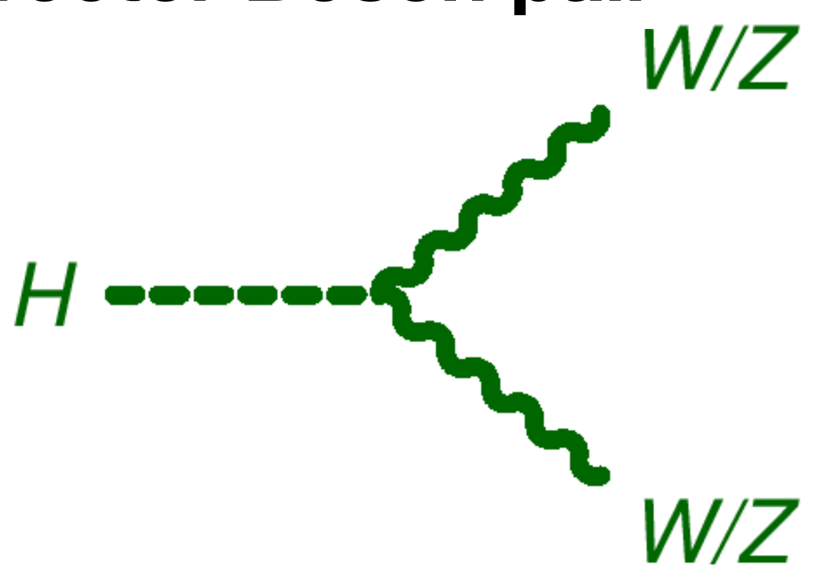

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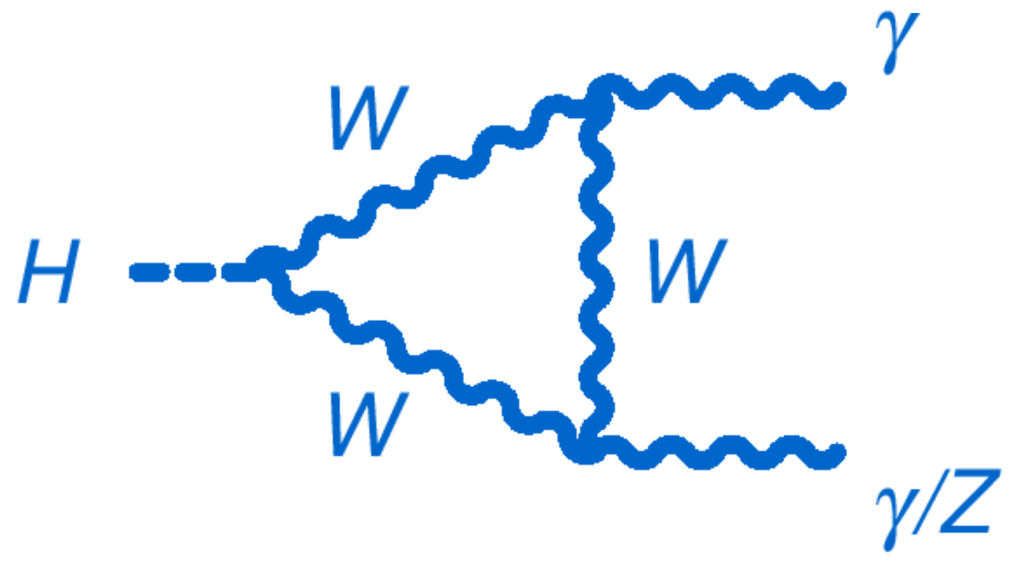

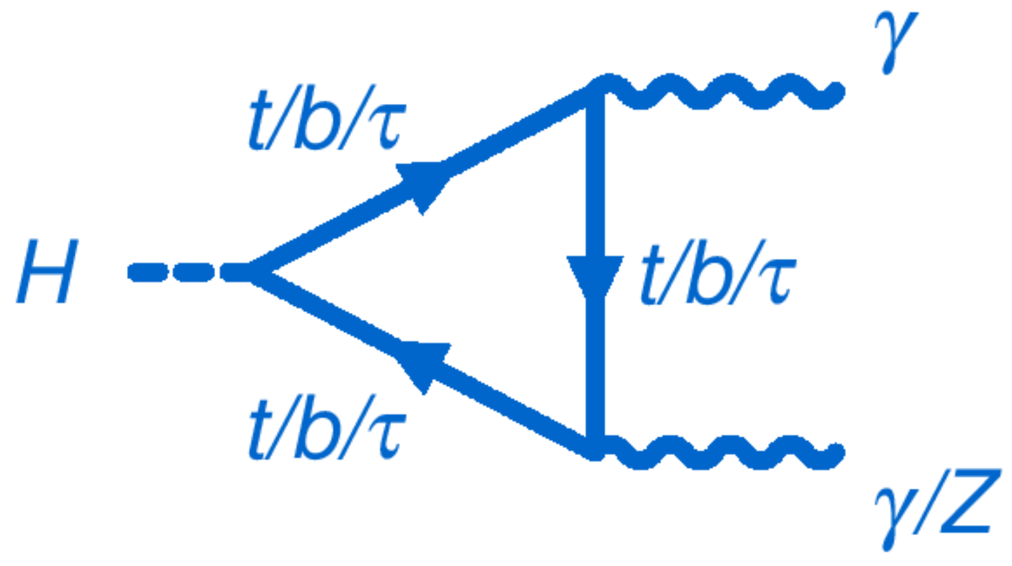

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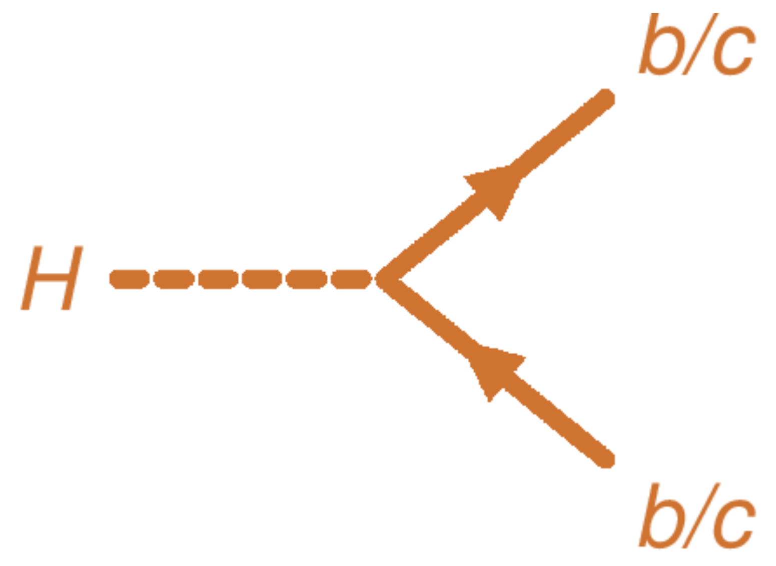

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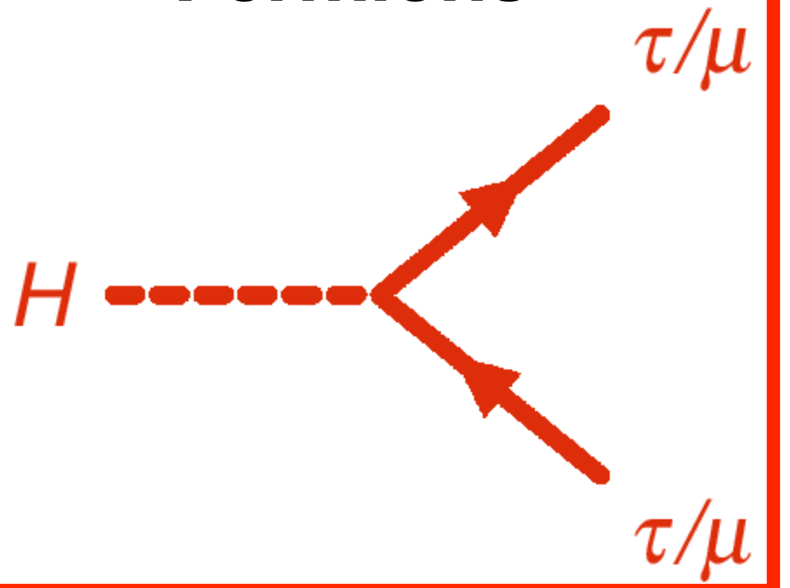
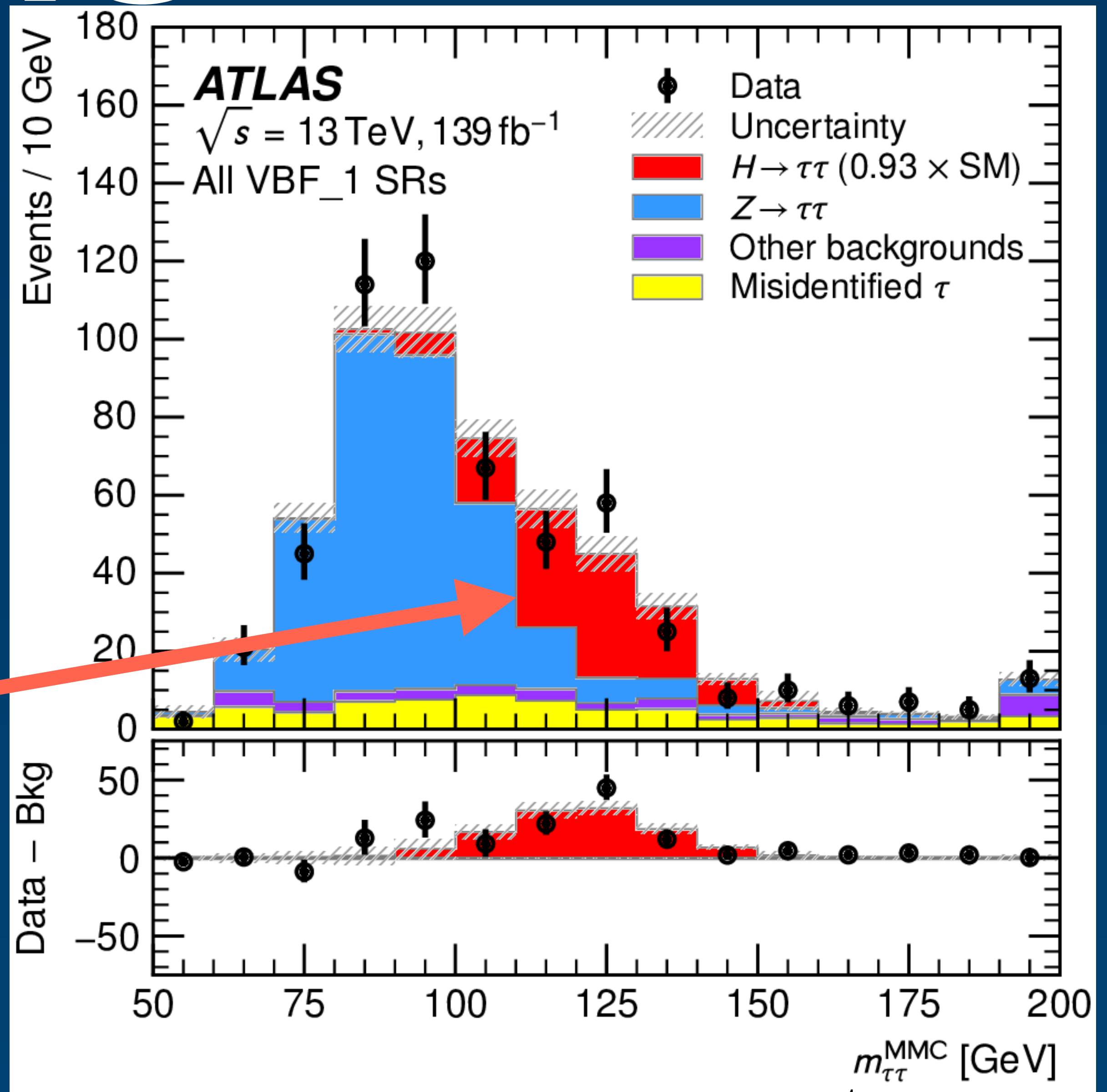
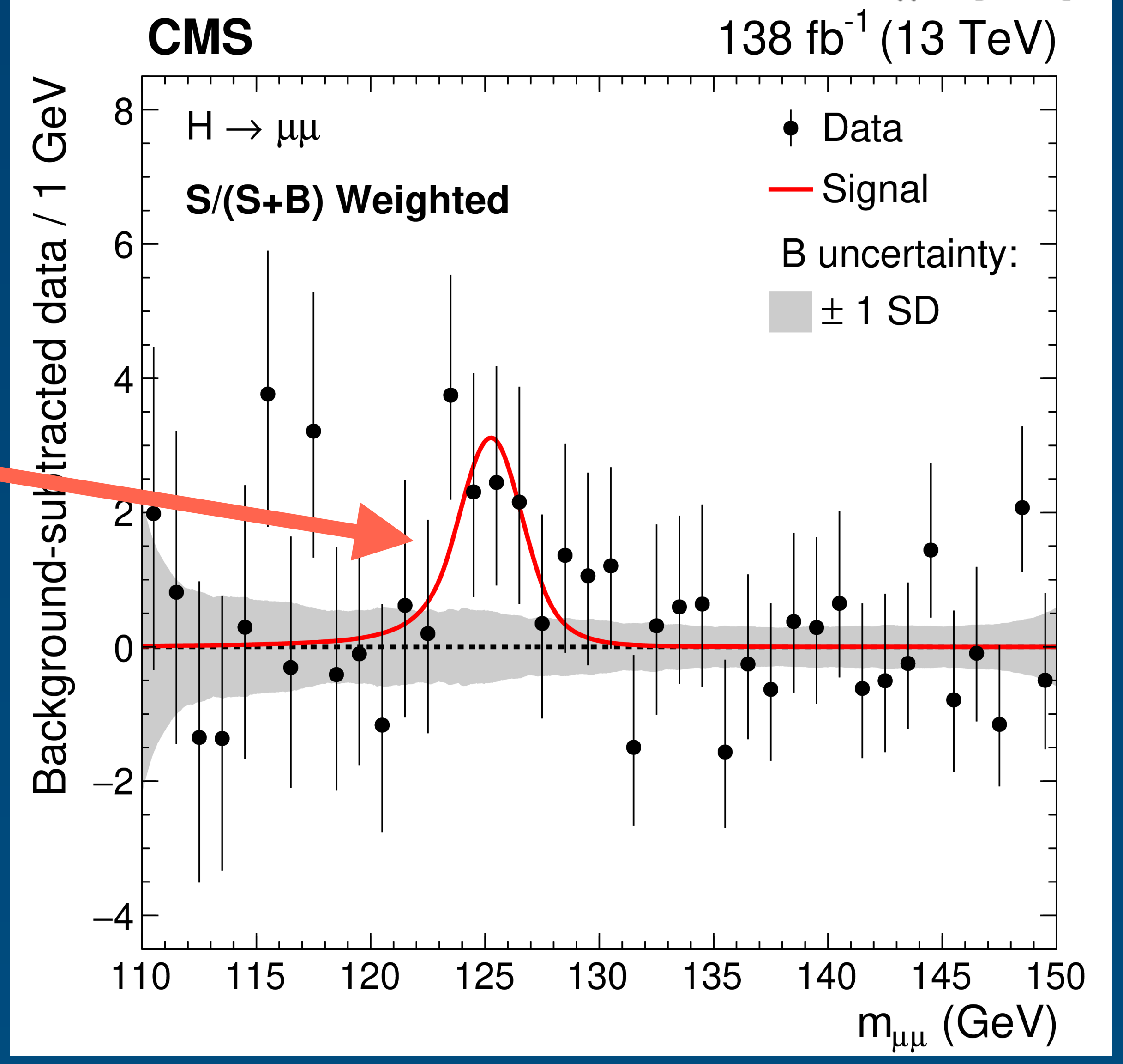


Today: most production mechanisms and decays have been observed and measured!
(and limits have been set on the other ones: bbH and tH production, H->cc decay)

Higgs and Leptons

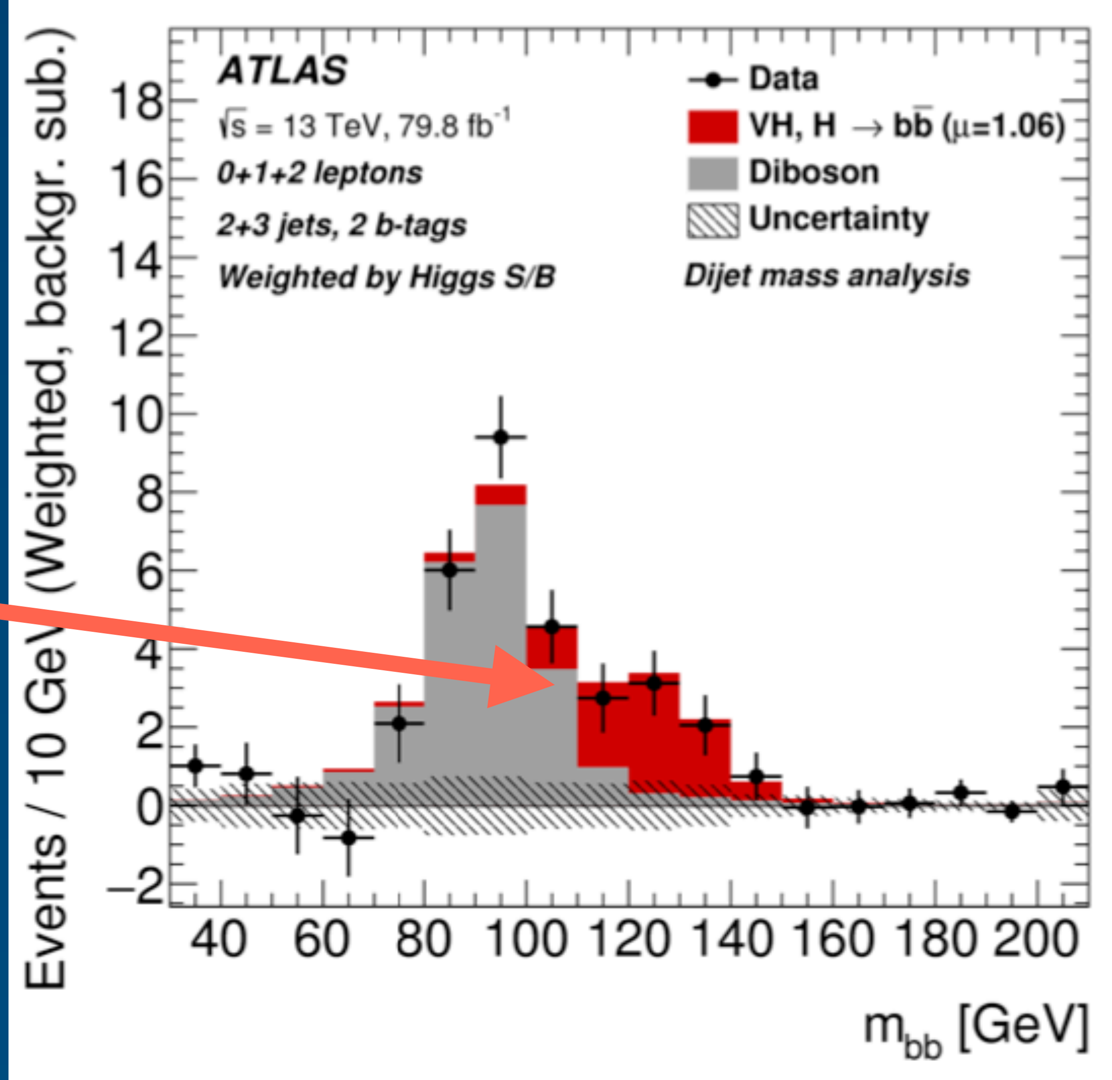
- The Higgs couples to fermions proportionally to their mass
  - m_top >> m_bottom ≈ m_tau >> m_mu
- In 2016, ATLAS and CMS observed the H → tau tau decay:
  - First direct observation of the Higgs coupling to fermions!
- Due to the muon very small mass, H → mu mu has a very small branching ratio:
  - Not yet observed, but almost…
    - 3 standard-deviation significance by CMS
    - 2 standard-deviation significance by ATLAS.

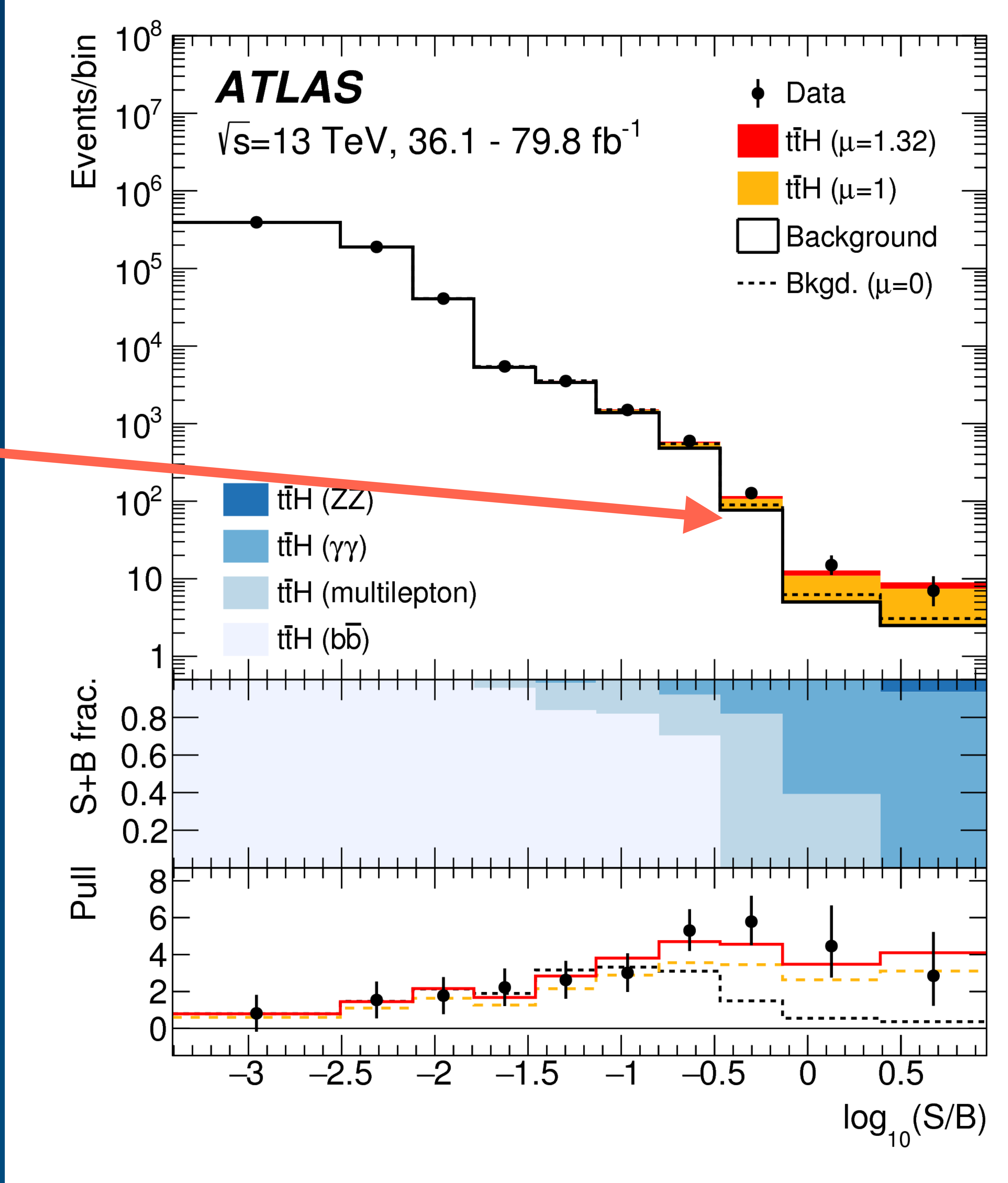




Higgs and Quarks

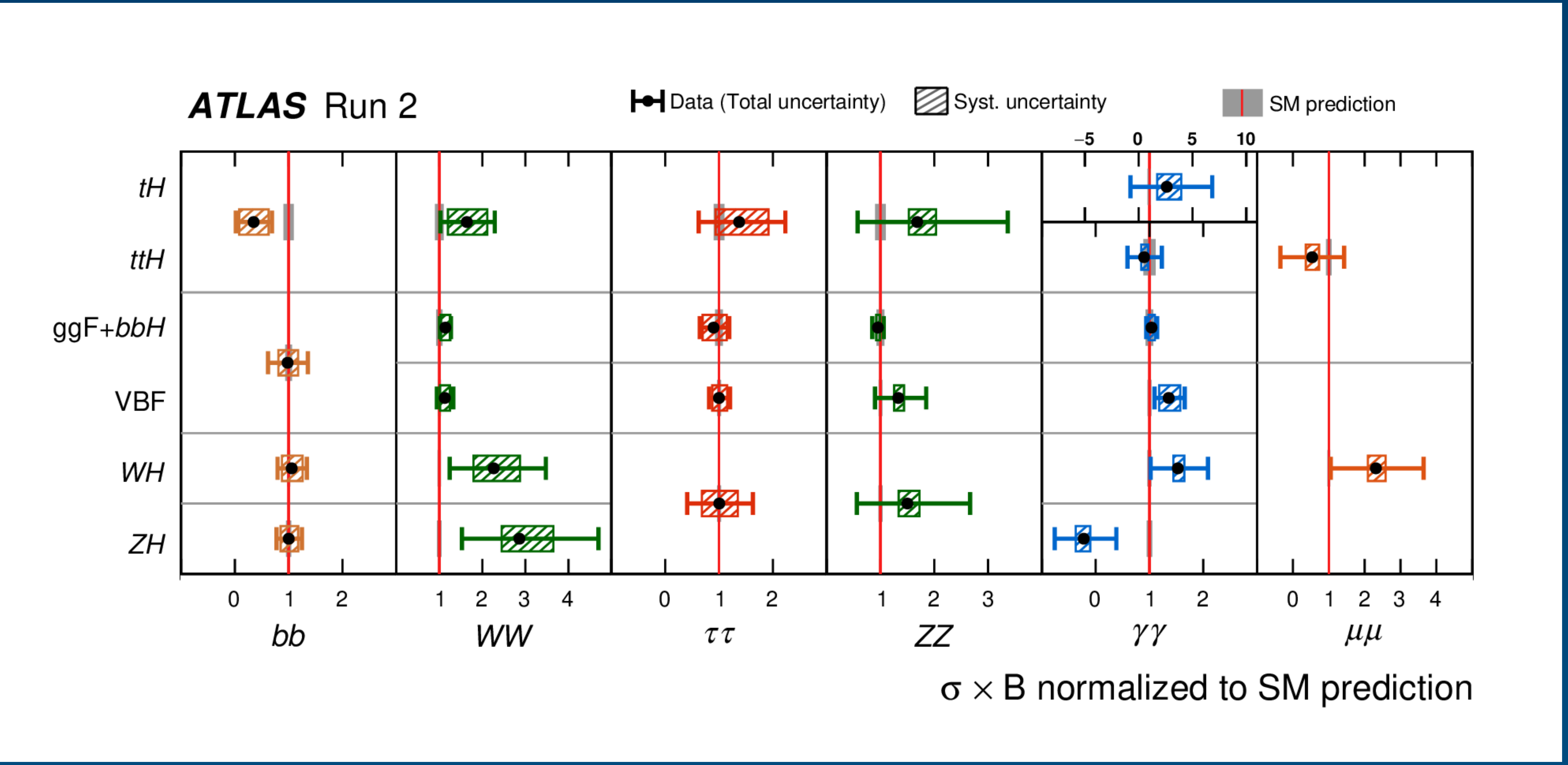
- ttH production and VH(H→bb) were the most challenging to observe:
  - Complex events
  - Backgrounds difficult to model
- ttH: Observation of ttH production with data from 2011-2016 (2017) by combining many Higgs and top decay channels.
  - ‣ Now observed with 5 s.d. significance in the H→yy channel alone!
- H → bb: Observation of VH(H→bb) in with 2011-2017 data.

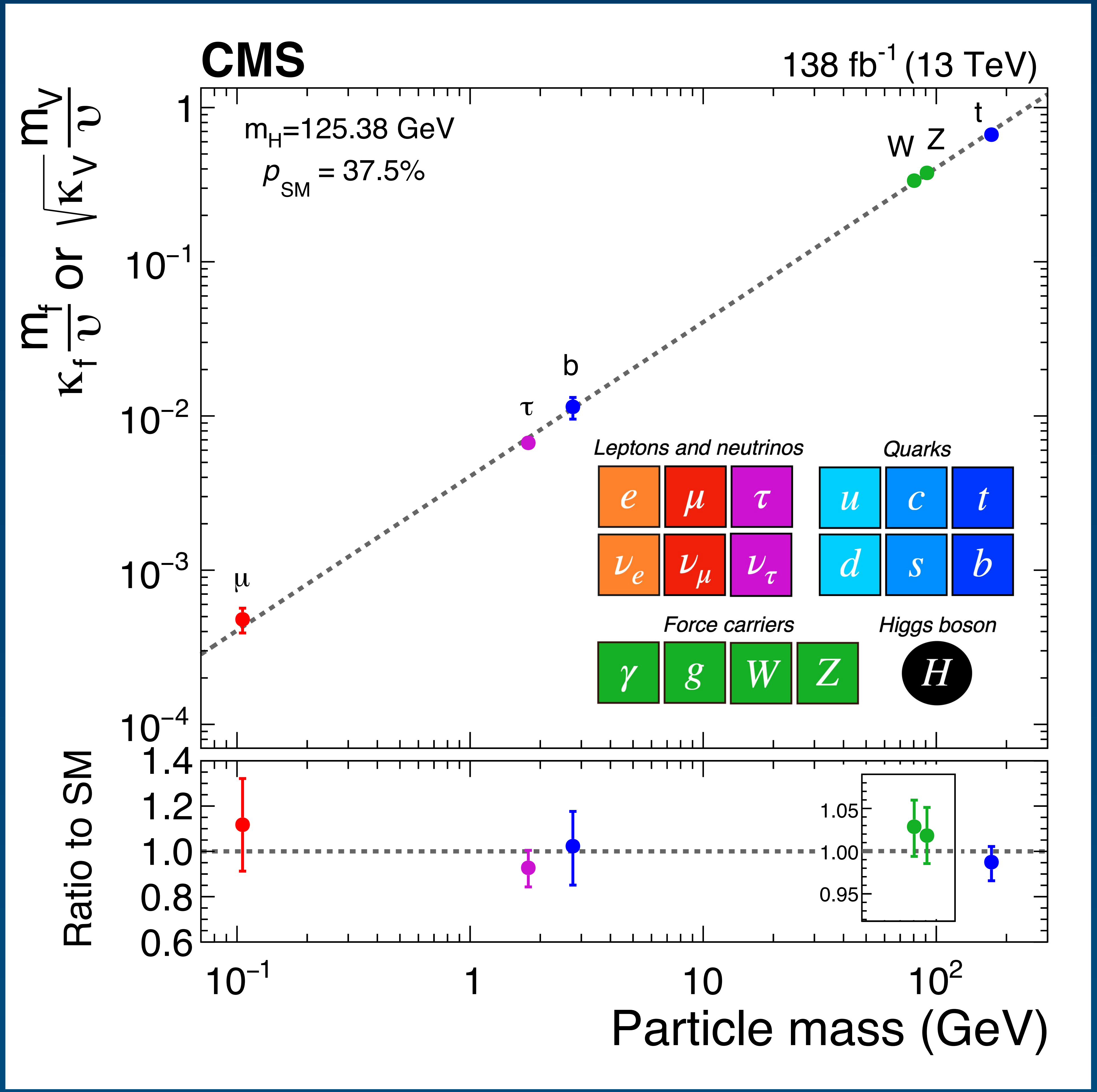




The Big Picture

- Measurement of production and decay rates allow to measure couplings between Higgs and other particles





What we know today:
A Summary

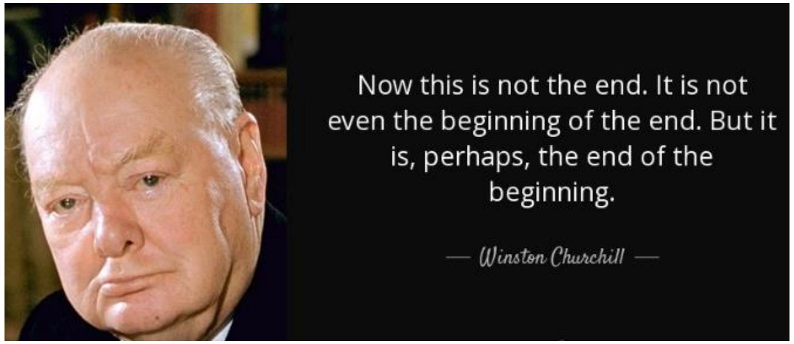
- Since its discovery in 2012, a lot of progress has been made in our knowledge of the Higgs boson thanks to the LHC Run 2 data:
  - All main production mechanisms and decays to W/Z vector bosons and 3rd generation fermions have been observed.
  - Main interaction couplings measured with a precision of O(10%). Several others are starting to be constrained.
  - Spin and symmetry properties have been tested.
  - Event kinematics: differential measurements.
- Limits have been set on some non-Standard Model phenomena:
  - Higgs decay to non-Standard Model particles (e.g. "invisible Higgs", decaying to Dark Matter).
  - Additional Higgs (e.g. from Supersymmetry).
- So far, the Higgs boson looks exactly as predicted by the Standard Model, but a lot more can be done at the HL-LHC and at future colliders…

Part 2
What we hope to learn at High-Luminosity LHC and beyond

Christophe Ochando

Introduction

The Higgs boson discovery is not the end of the story…
… it's rather the beginning of a new era in High Energy Physics.

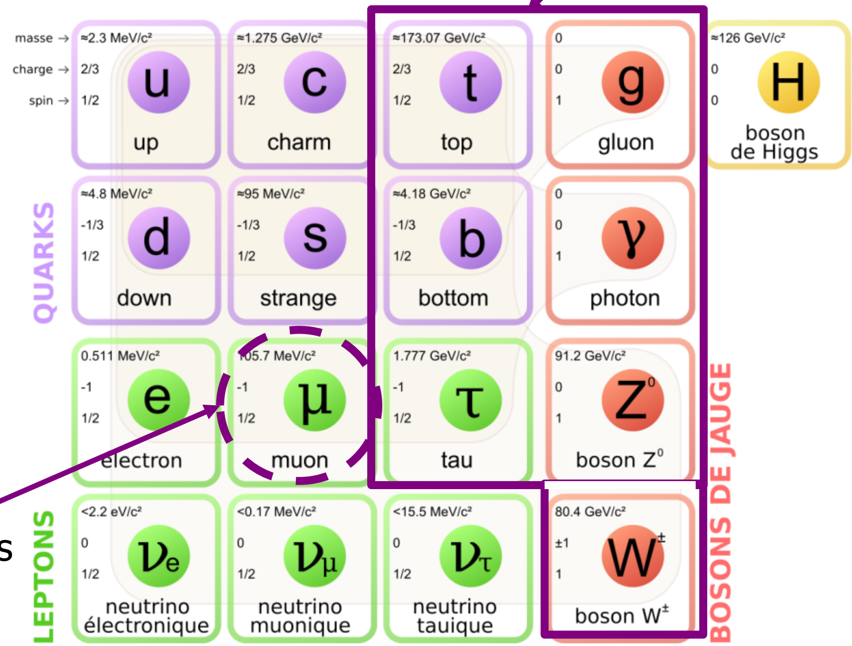


- Run 1 and Run 2 data taking allowed to start the exploration, but a LOT is still to be done.

- The Higgs is at the root of several problems of the Standard Model…
  ... It may be a **portal towards New Physics** !

We MUST study it in all possible details.

Observed
(although with limited precision)



Will be observed in the next years

(some) Open Questions related to the Higgs boson

- In addition to the questions mentioned before:
  - Does it couple to known particles as expected from the Standard Model ?
  - Does it couple to **Dark Matter** ?
  - Is there an extended scalar sector (i.e., are there **other Higgs**) ?
- Is it a fundamental or **composite** (ie, made of other, new, particles) ?
- Are there “forbidden” decays ($H \rightarrow \tau^+ \mu^-$) ?
- Are there charge-parity (CP) violating Higgs decays ?
  <=> connection to **matter-antimatter asymmetry**
- Is it connected to the mechanism at the origin of the cosmic **inflation** ?

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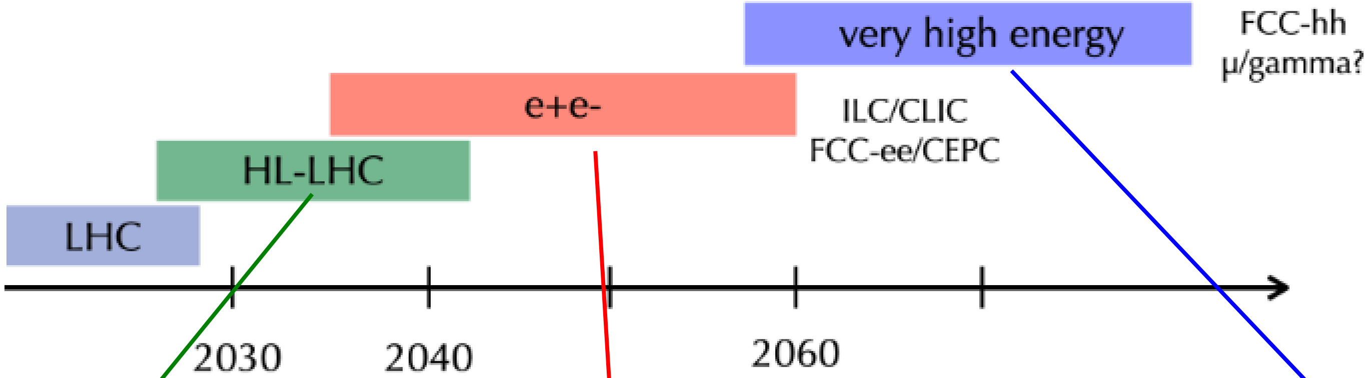
  - Is ther ... gs) ?
- Is it a fund ... les) ?
- Are there "
- Are there charge-parity (CP) violating Higgs decays ?
  <=> connection to **matter-antimatter asymmetry**
- Is it connected to the mechanism at the origin of the cosmic **inflation** ?

Answers to these questions may come from:

- **Very high precision measurements**
  - Any deviations wrt calculations may be New Physics
  - Need more statistics
    + progress on both theory calculations
    and experimental techniques
- **Higher energy scale exploration**

Future Machines

Requires new machines / new detectors
(beyond the current LHC & on-going Run 3 data taking)

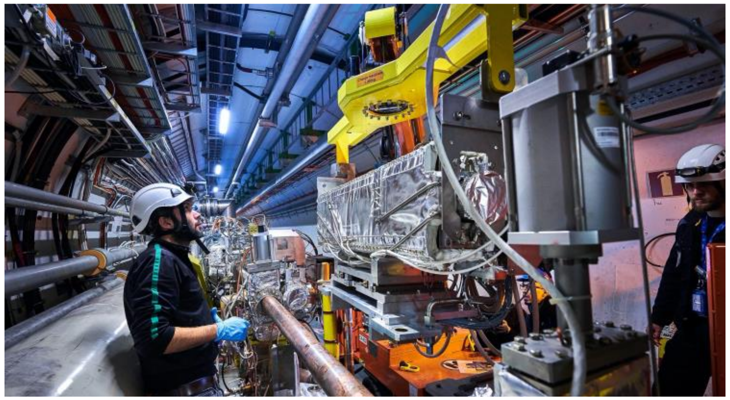


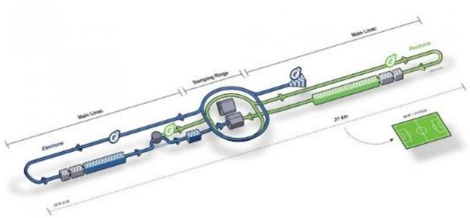
Tentative timeline

"Higgs Factory"

Very High Energy Colliders

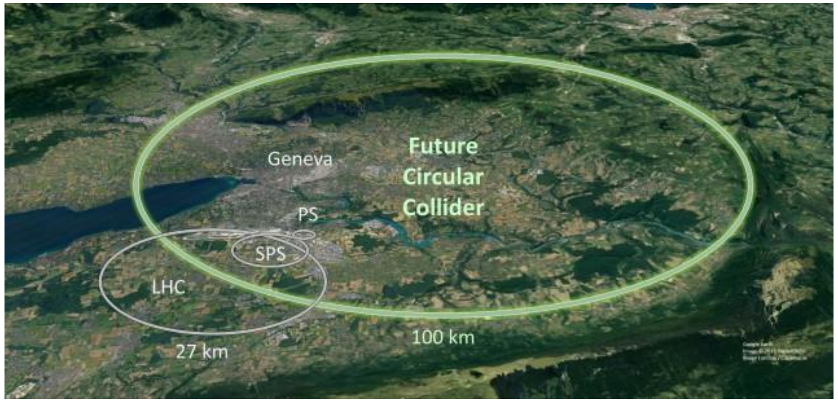
High-Luminosity LHC
Statistics x 20 wrt LHC





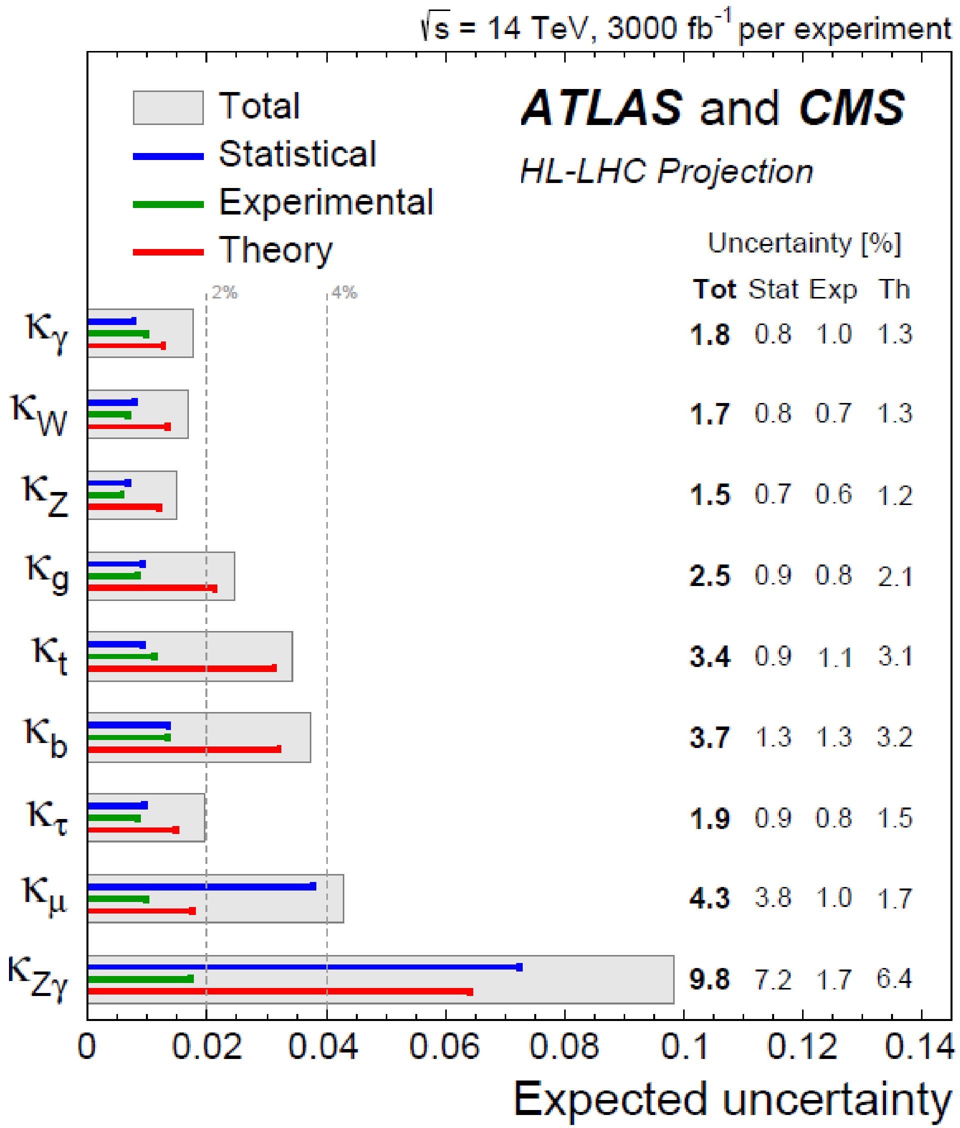
International Linear Collider

Future Circular Collider (FCC)
100 km tunnel (CERN)



FCC-ee: Higgs factory
FCC-hh: High Energy (100 TeV) proton collisions

Higgs Couplings @ HL-LHC



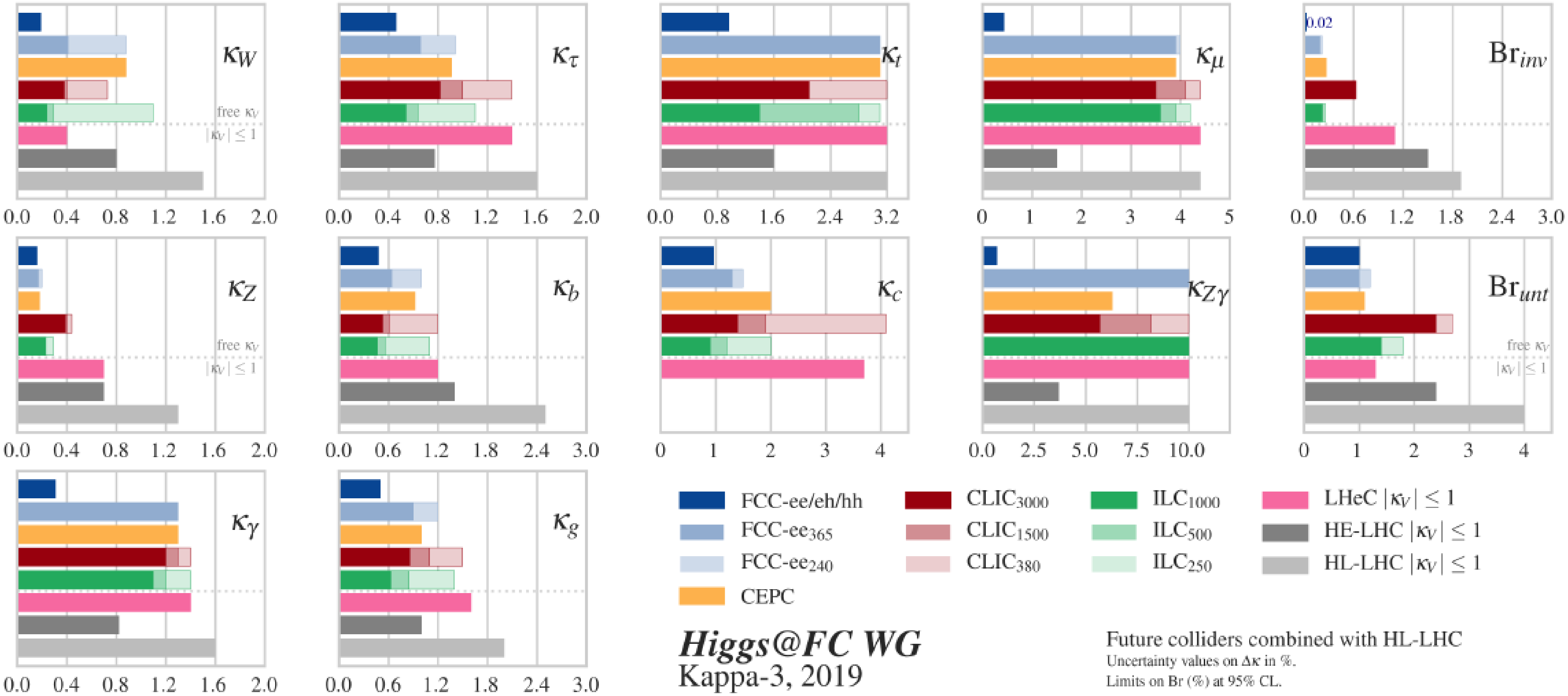
Most couplings to the Higgs boson known to 2-4% at the end of HL-LHC

N_{Higgs} produced per experiment

Ex: Coupling to W/Z bosons known to < 10% (now)… 8.10^6

< 2% (HL-LHC) 180.10^6

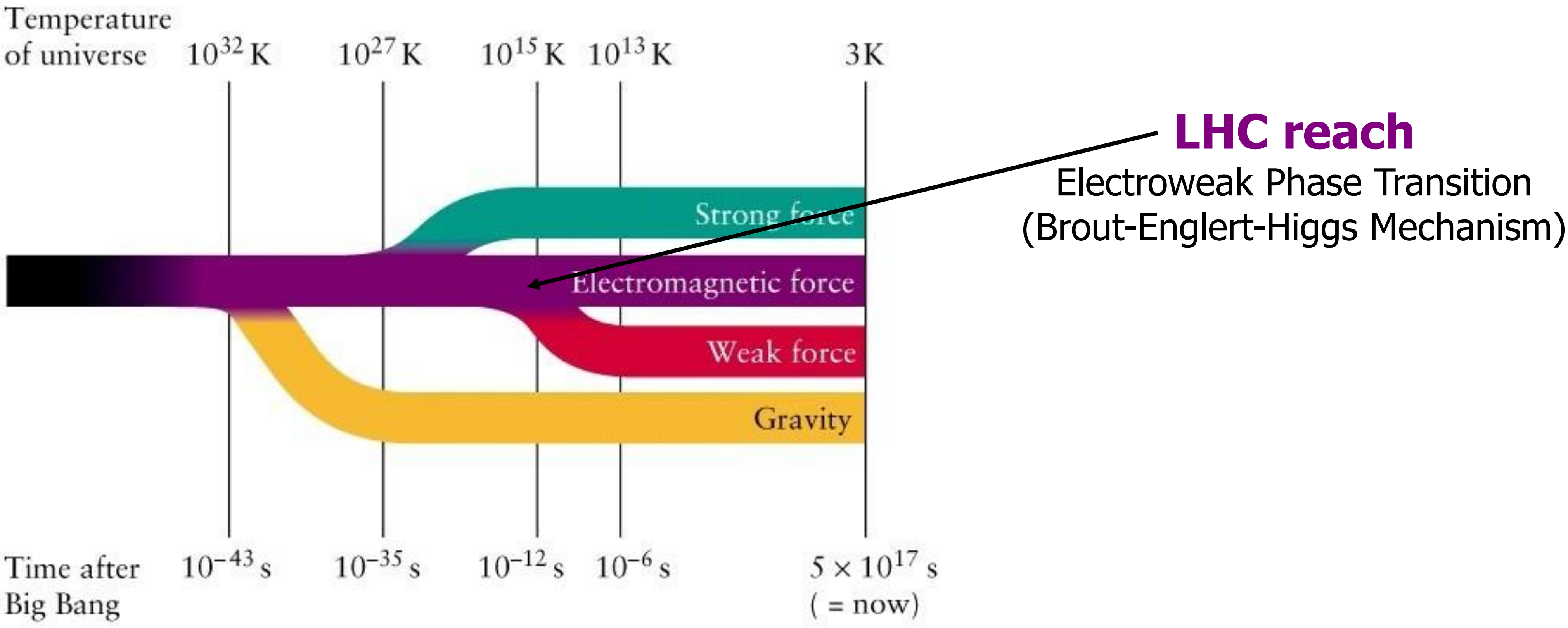
Higgs couplings @ Higgs factories (and beyond)



Most couplings to the Higgs boson known to 0.2-2% at the end of Higgs Factories

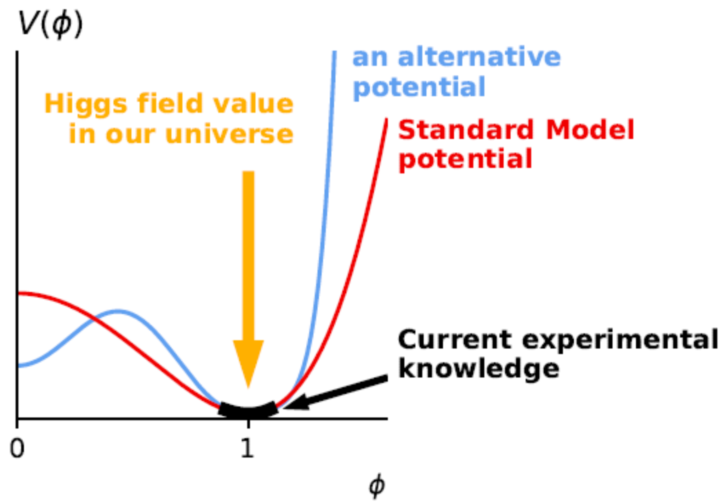
		N_{Higgs} produced per experiment
Ex: Coupling to W/Z bosons known to	< 10% (now)…	8.10^6
	< 2% (HL-LHC)	180.10^6
	~ 0.2-0.3% (Higgs Factories)	10^7

Higgs Self-Coupling

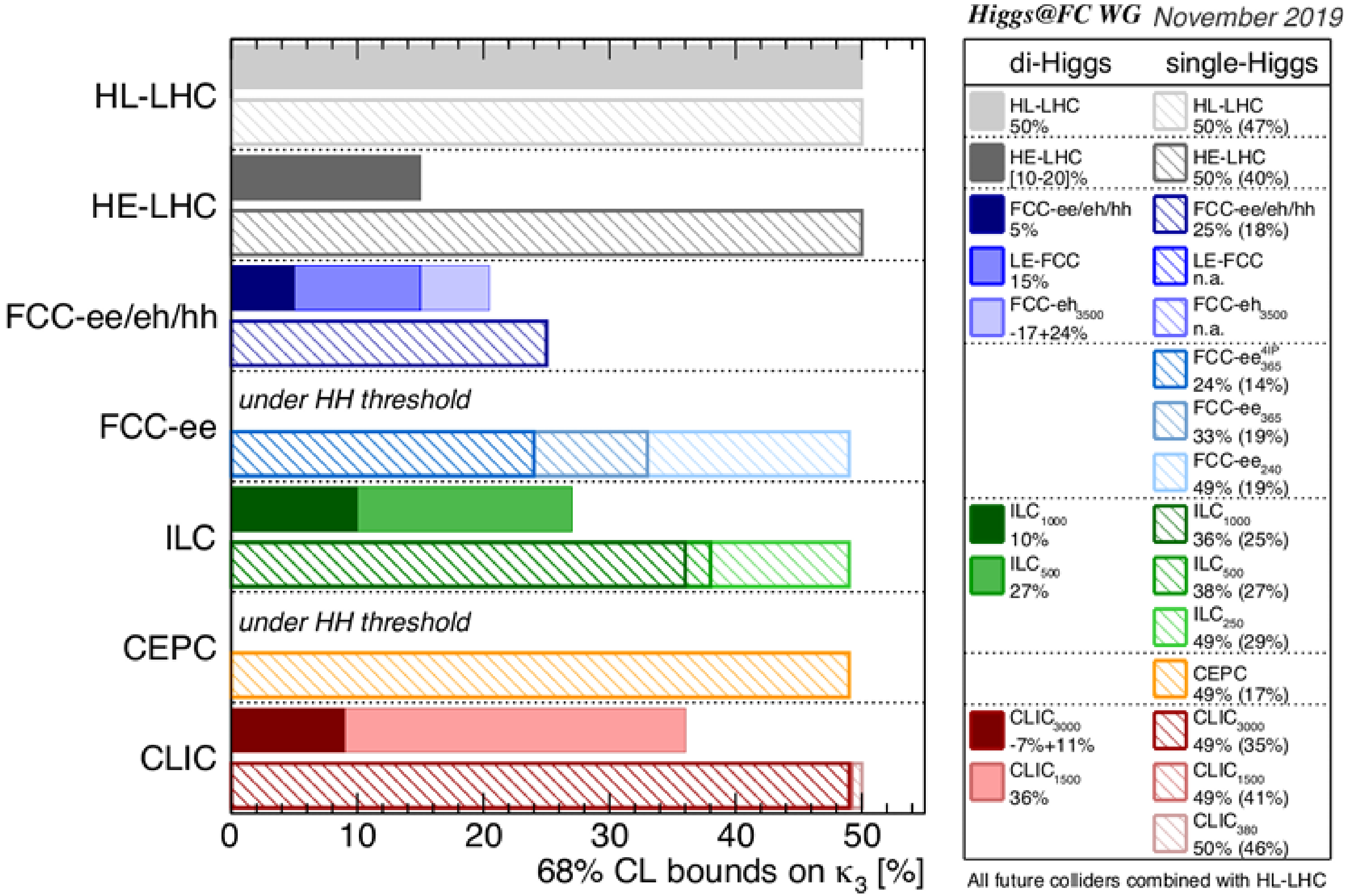


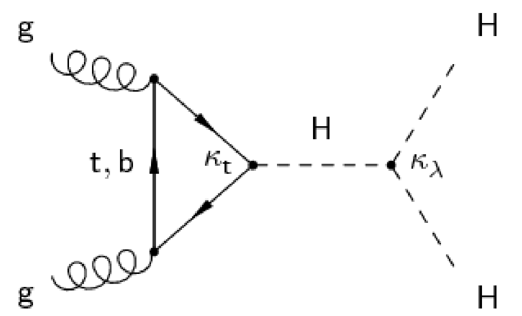
➢ Phase transition dynamics is dictated by the "Higgs potential"

- How to access it ? Measure "Higgs self-coupling" (λ_{HHH})
- How ? **Study Double-Higgs production !**
  (Very rare process… 3 orders of magnitude rarer than single H)
- **New physics can have huge impact…**



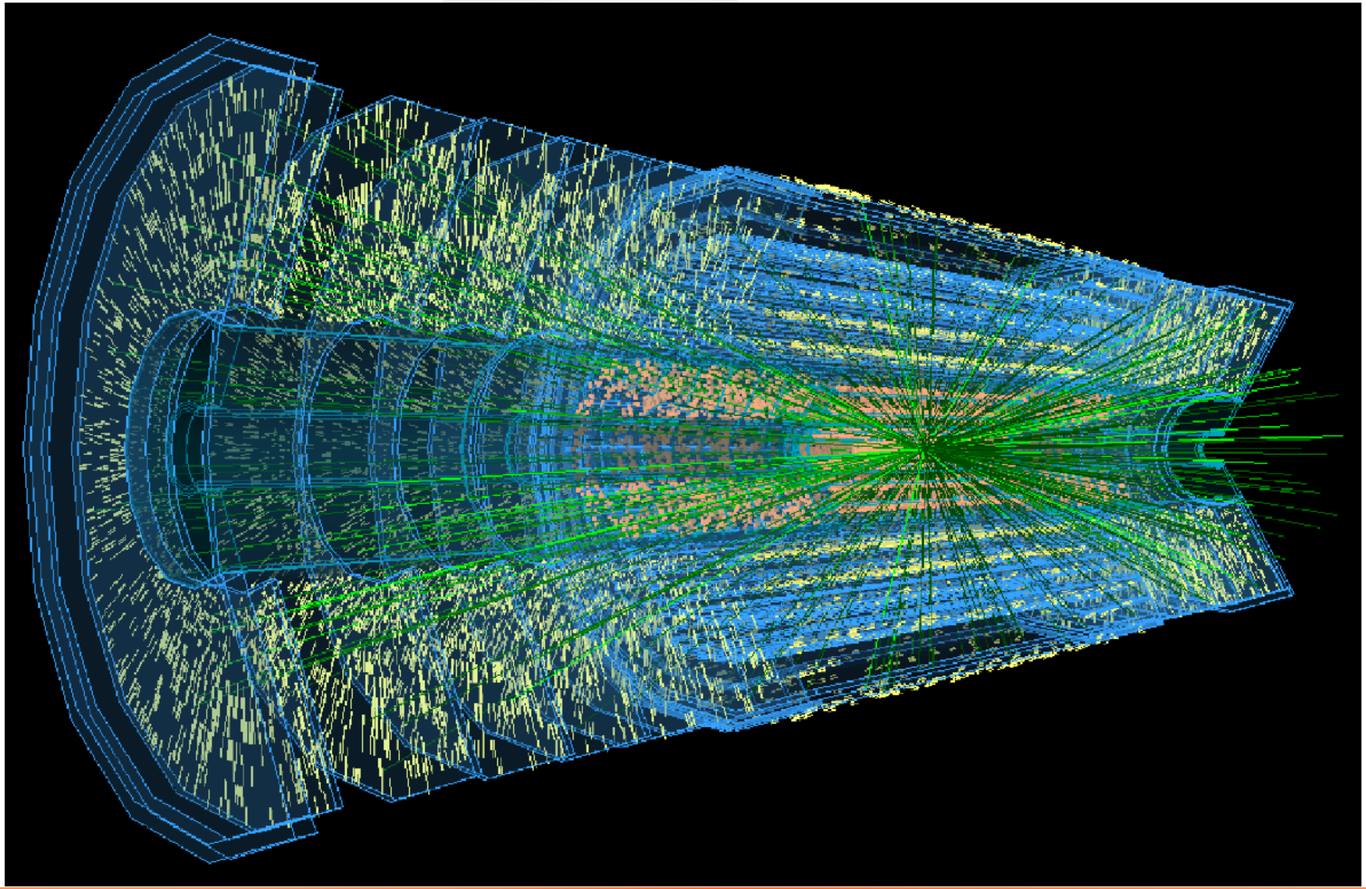
Higgs Self-Coupling @ colliders



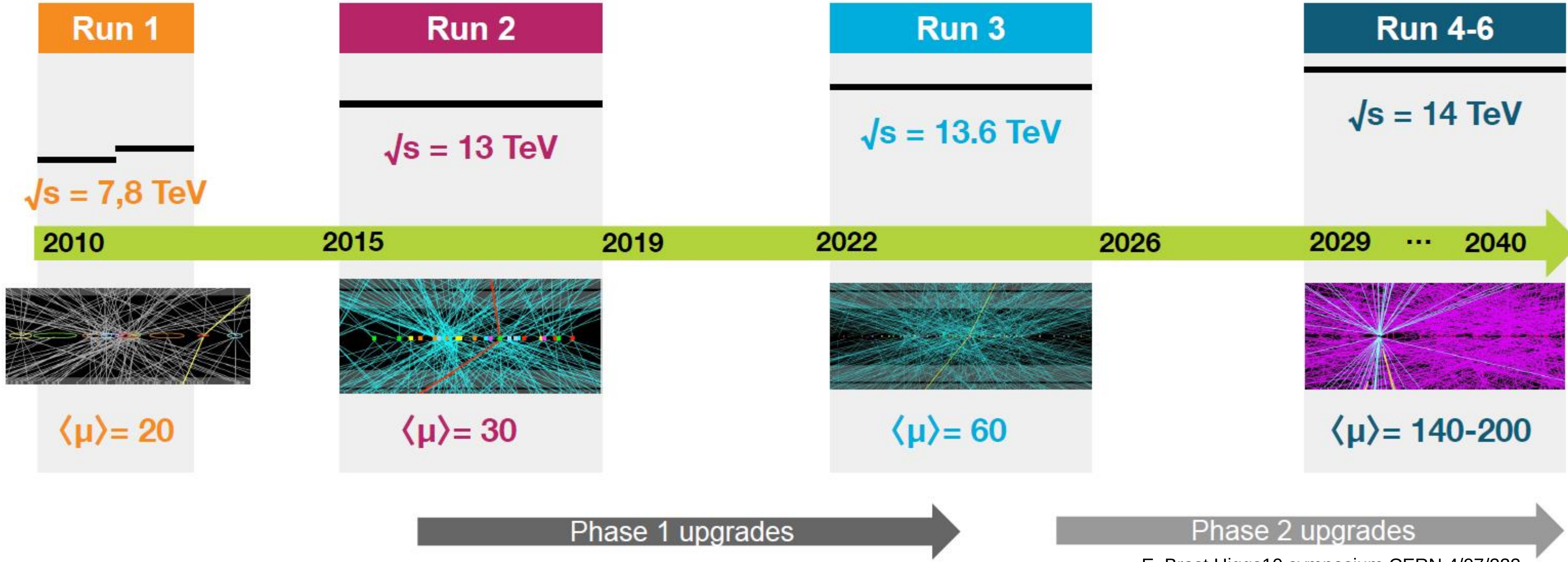


Higgs Self-coupling: 1st Observation requires HL-LHC
~ 50% precision (HL-LHC)
~ 5% precision (Higgs Factories+FCC-hh)

Detector challenges at HL-LHC and beyond



New challenges for detectors at HL-LHC



E. Brost Higgs10 symposium CERN 4/07/222

Radiation hardness

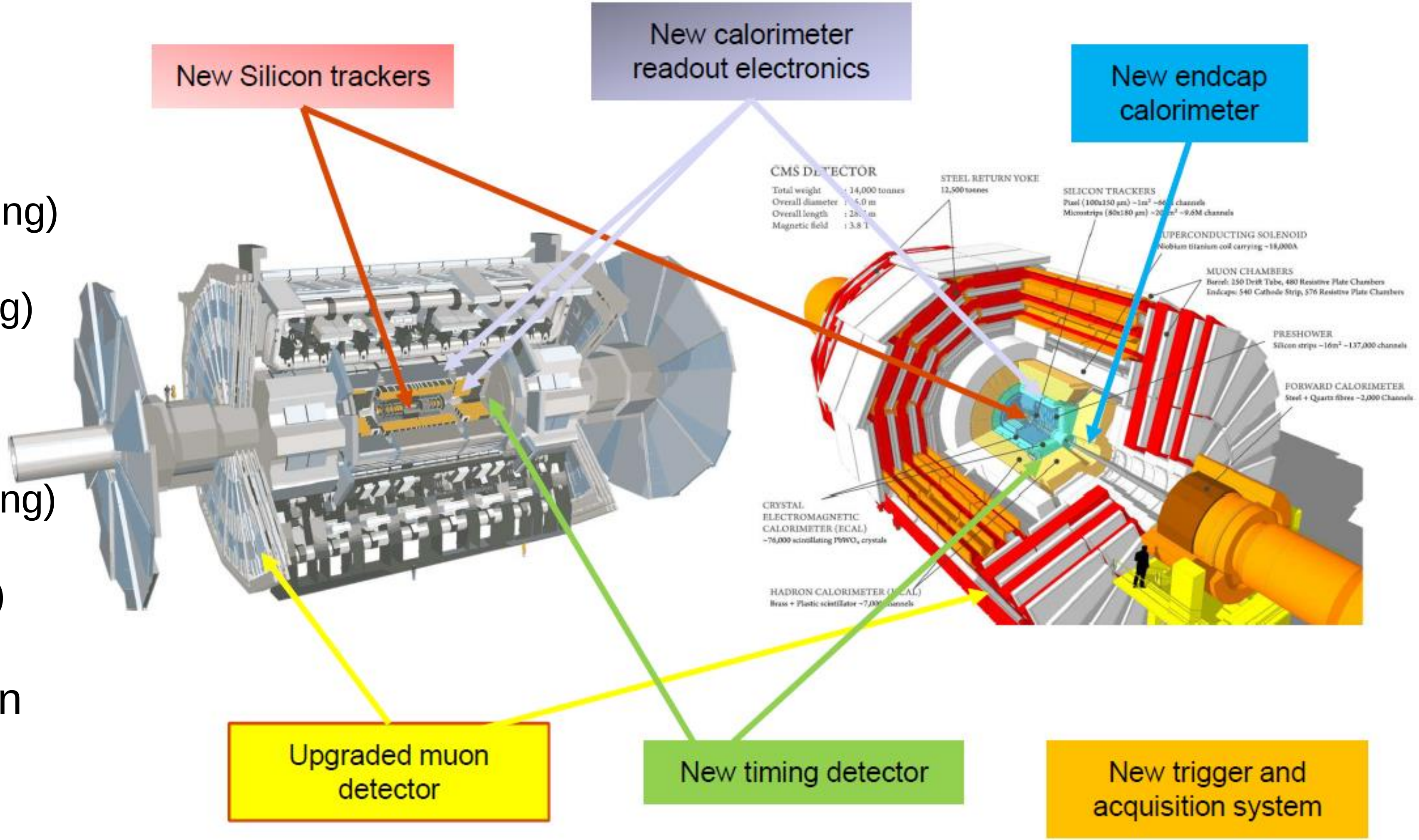
Trigger/readout

Reconstruction/software

New detectors for HL-LHC

ATLAS@IJCLAb
46 (19 phys, 9 PhD, 28 Ing)
ATLAS@Irfu
40 (16phys , 6PhD, 18 ing)
ATLAS&CMS@ omega
10 (3 PhD, 7 Ing)
CMS@LLR
37 (17phys, 10 PhD, 10 ing)
CMS@irfu
27(14 phys, 3 Phd, 9 ing)

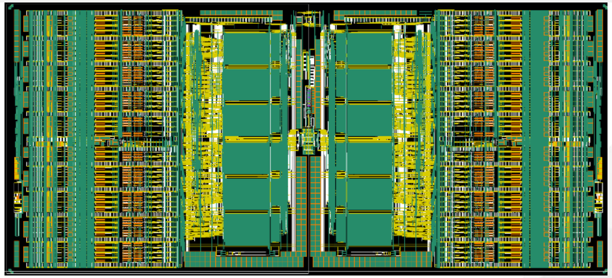
→ about 2/3 involved in upgrade (~120)



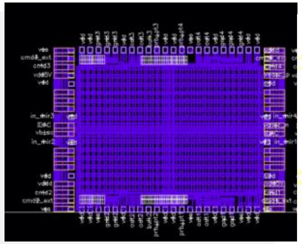
Micro-electronics circuit at the forefront of Phase II (Irfu/Omega)

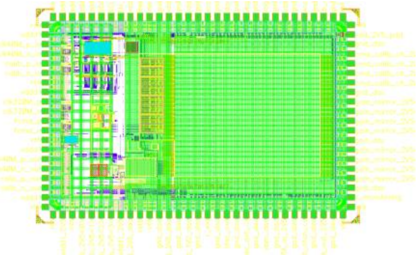
Conception of new asics for calorimetry and timing measurements : new CMOS technology and quite difficult layout with analog and digital while targeting low noise, low jitter, low power….

HGCROC : CMS HGCAL (Irfu & Omega) , 120000 chips

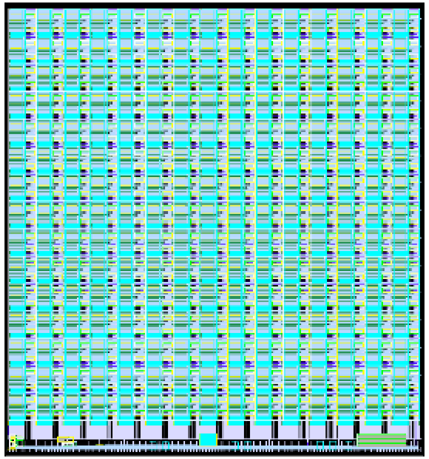


CLAROC & LADOC :ATLAS calo calibration
10000 chips (Omega)

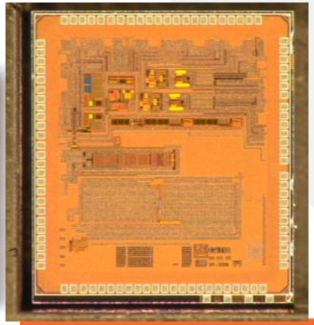




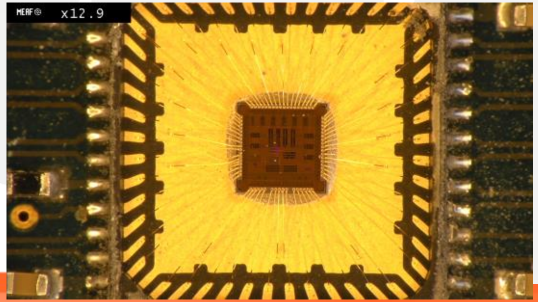
ALTIROC : ATLAS HGTD (Omega)
30000 chips



CATIA : CMS barrel ECAL readout
100000 chips (Irfu)



RAFAEL : precise clock distribution (Irfu) 40000 chips



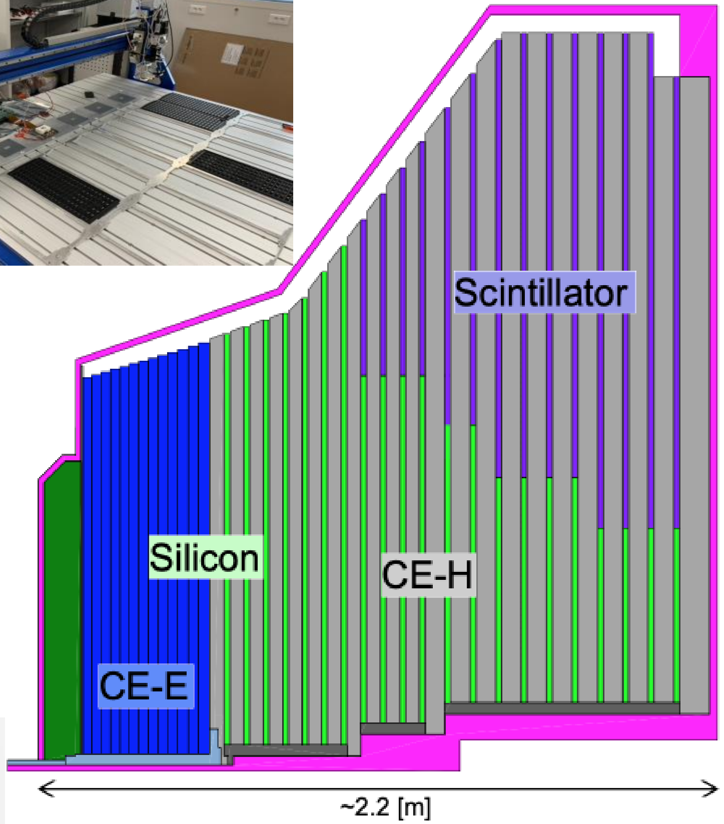
Asics still under validation, and large mass production over 2023-2025 and testing !

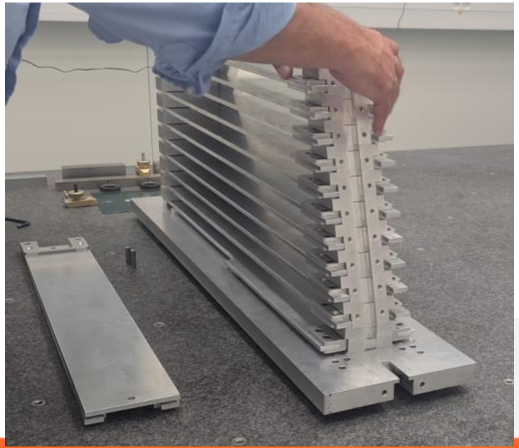
Board design and testing also for ATLAS calorimeter (IJCLAb) CMS calorimeter (Irfu)

Up to 6 millions of channels. New and challenging technology

- Sensors
- HGCROC ASIC design (Irfu/Omega) and test (LLR)
- Mechanical design (CE-E)+ cooling (LLR)
- Trigger and reconstruction with AI methods (LLR)

(R&D as major part of P2IO emblematic project HIGHTEC)



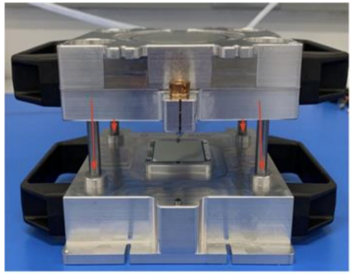


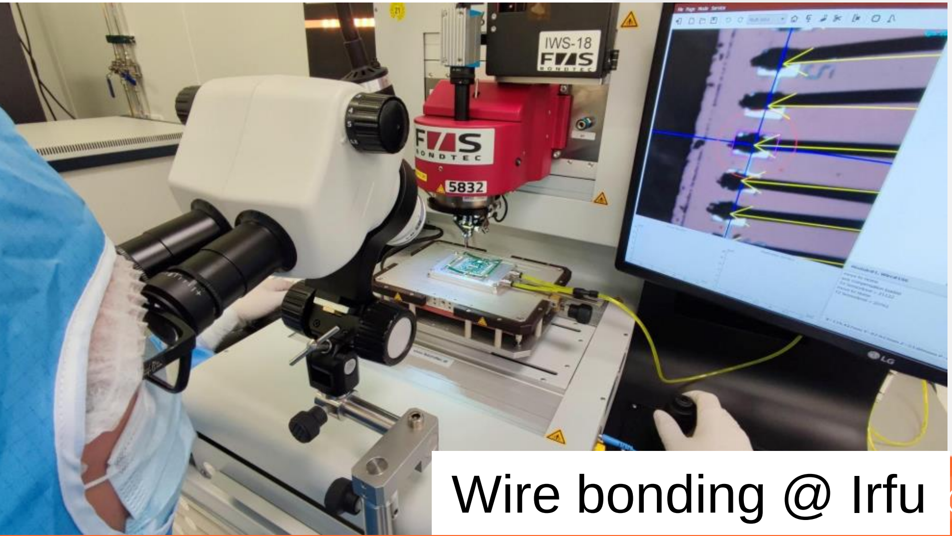
New vertex detector (IJCLAb/Irfu) in ATLAS

- Paris cluster (IJCLab, Irfu, LPNHE) : construction of 2000 pixel modules

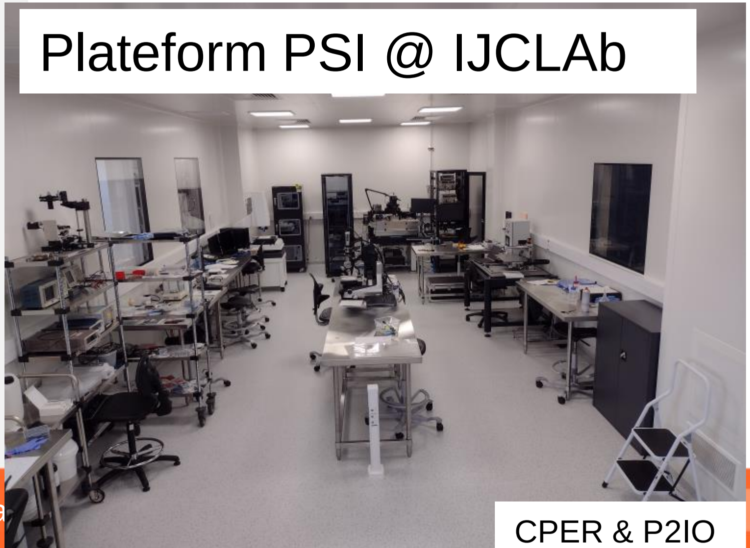
 Dedicated Infrastructures (funds from P2IO&CPER)

- Probe station for asic and sensor validation at wafer level
- Module assembly (Gluing, wire bonding) and metrology
- Electronics tests and thermal cycling

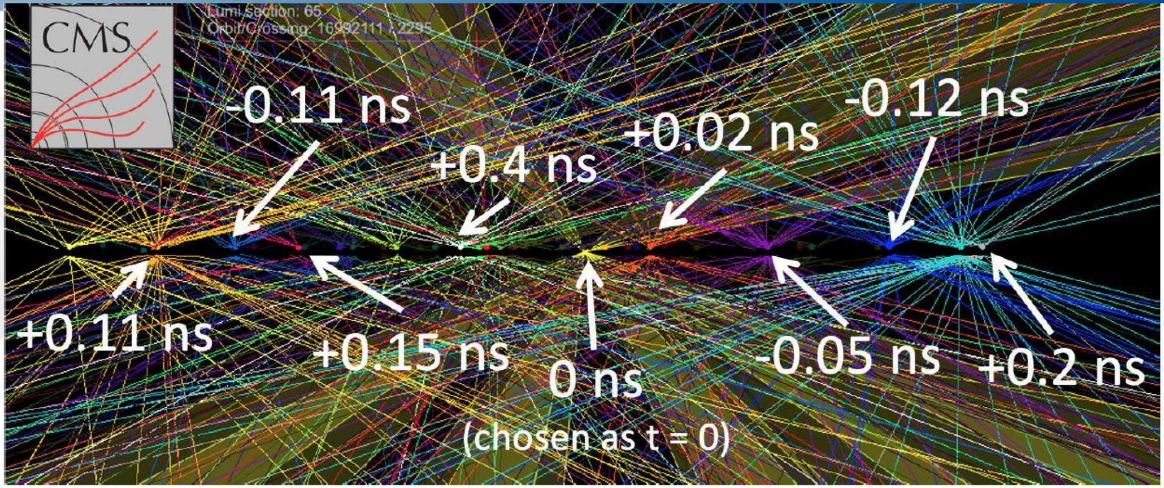




Wire bonding @ Irfu


Plateform PSI @ IJCLAb

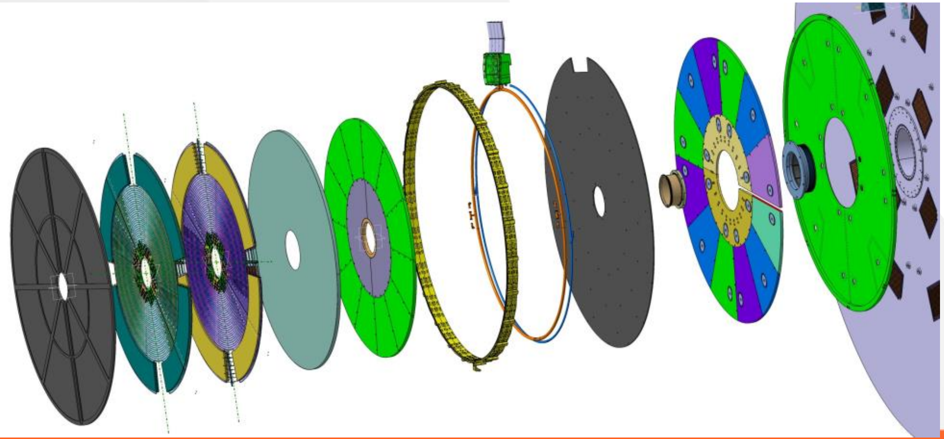
CPER & P2IO

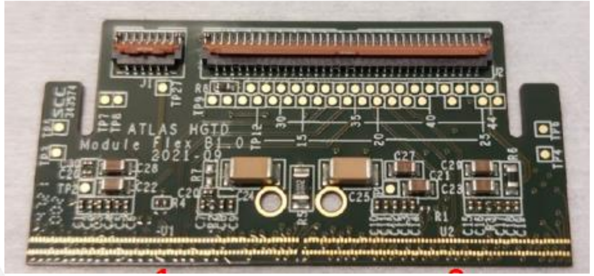


High Granular Timing Detector (HGTD)

Measuring track time to better than 50 ps !

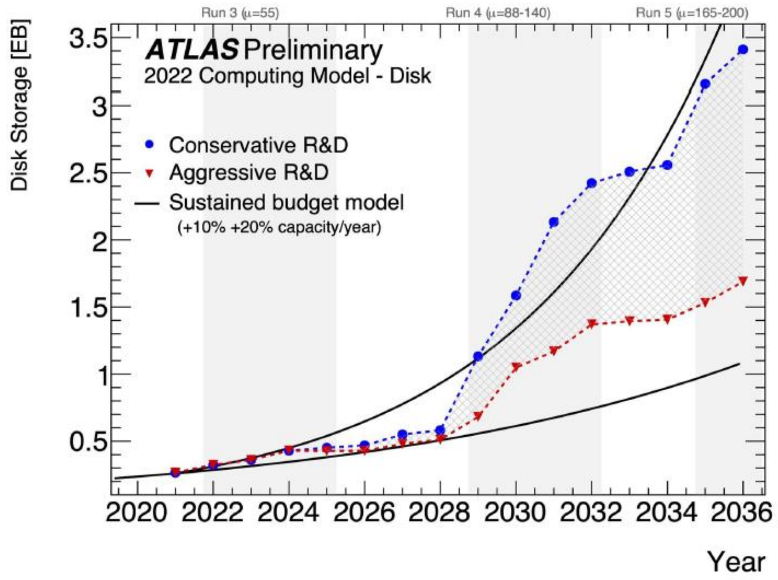
- Using new sensors (LGAD)
- Challenging readout asic (OMEGA & IJCLAb)
- Compact mechanical design and cooling (IJCLAb)
- Module assembly (2000) quite similar to pixel and share same infrastructures (IJCLAb & Irfu)





Initial studies funded by P2IO/HIGHTEC

Key success of HL-LHC : computing and software



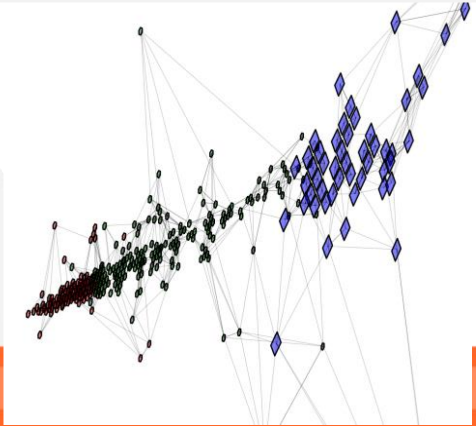
GRIF T2 : Computer centers at LLR, Irfu and IJCLab

Virtual data at IJCLAb (CPER&P2IO)

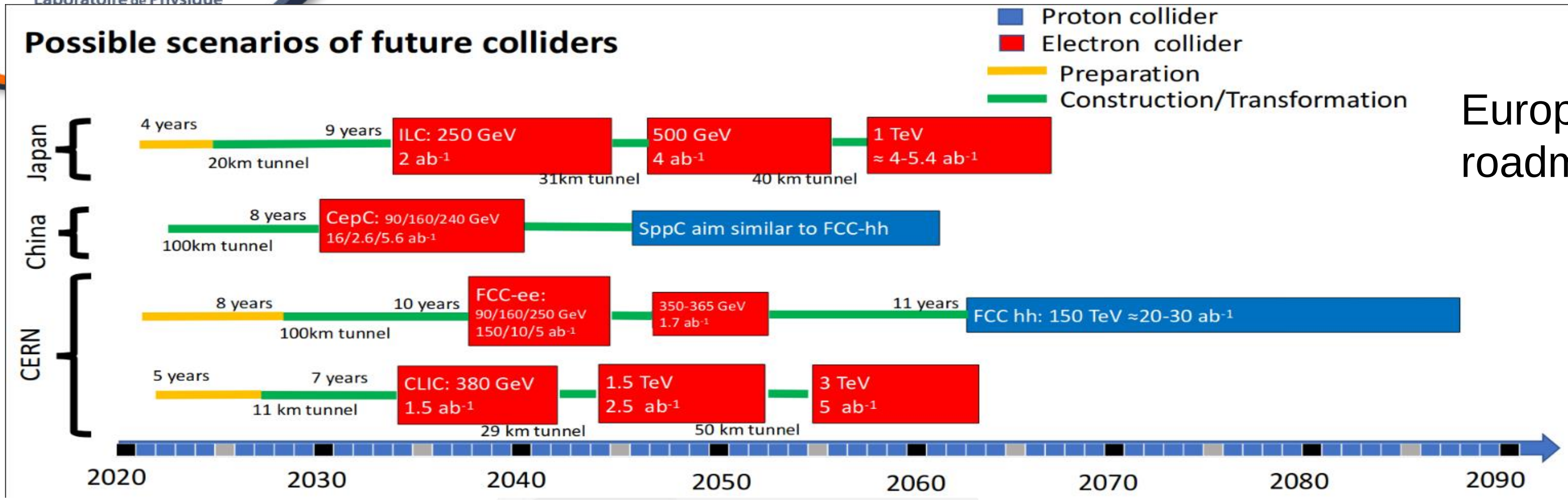
- Need continuous increase of T2 capability
- Development of new algorithm for data reconstruction including machine learning both online in FPGA and offline

(DATAIA @ Paris Saclay & “Learning to Discover” worskshop at Institut Pascal)

Graph Neural Network for HGCAL CMS



Beyond HL-LHC



European strategy roadmap in 2020

New generation of trackers and calorimeters

- Some R&D quite mature, targeting specifically ILC started one decade ago : CALICE (LLR, IJCLab, Omega) , TPC with microMegas (Irfu)
- Some R&D targeting FCC-ee started recently on calorimetry at IJCLab (Noble liquid, Liquido) and tracker at Irfu (CMOS)

→ increasing commitments/responsibilities expected from our labs in the next years