Electroweak and Higgs physics

Some disclaimers:
** A very biased introduction from an experimentalist!*
** Will focus mostly on LHC physics, its already immense successes and the great opportunities ahead*
** Detailing only few specific but hopefully representative examples, an overview of what has been accomplished*

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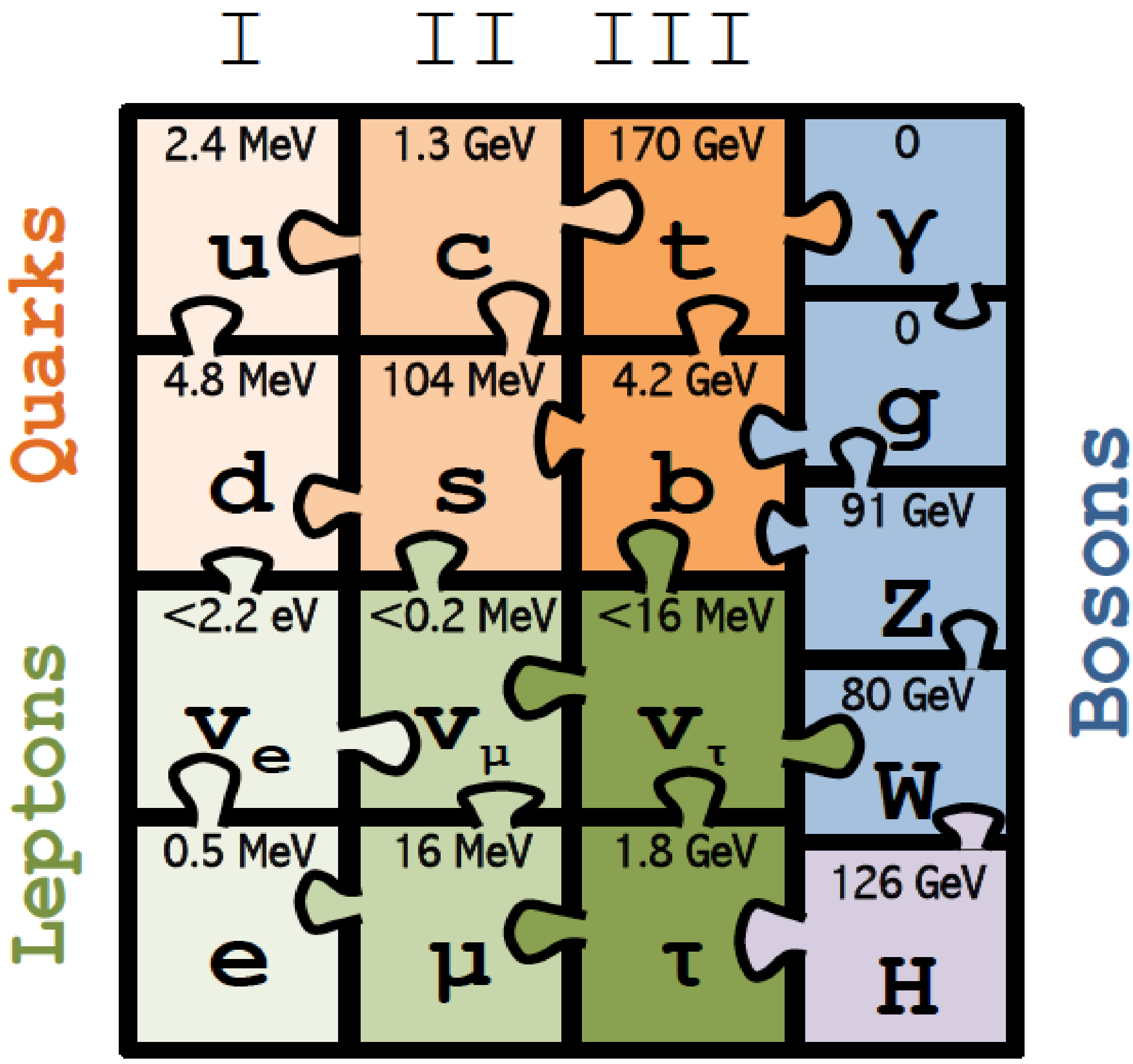
IDPASC 2015
IJCLab/Université Paris Saclay, 15-25 July 2015

The Standard Model (SM)
Reminder

- A successful model (from the experimental point of view) that describes the interactions between known fundamental particles of matter



The Standard Model (SM)
Reminder

- The particle physics world in 1975

- The **local gauge symmetry** that defines the SM is

QCD ⟶ SU(3) x SU(2) x U(1) ⟵ Electro weak

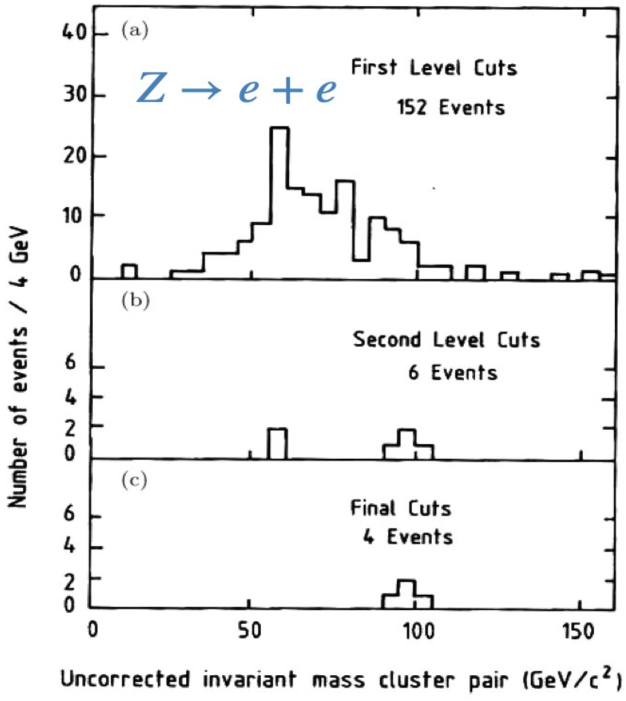
- The group representation determines the interaction form
  - Leptons: SU(3) singlets → do not interact strongly
  - Quarks: SU(3) triplets → interact with gluons

- Parity violation → Separation of the left and right SU(2) representations:
  - Left fermions: SU(2) doublets → interact weakly
  - Right fermions: SU(2) singlets → not interact weakly
  - **No mass terms for fermions**

- Also, **no mass terms for bosons W and Z**

- In 1983 UA1 and UA2 experiments at SPS announced the discovery of a massive W boson

Phys. Lett. B 126, 398 (1983).



The Standard Model (SM)

And the Higgs physics was born…

SM solution to the mass problem

Add scalar field with spontaneous symmetry breaking → **W, Z boson masses**

Add Yukawa couplings → **Fermion masses**

- Separately in 1964 (Brout and Englert), (Higgs) and (Guralnik, Hagen and Kibble) utilised the concept of symmetry breaking through the phase transition of a new scalar field φ, causing a non trivial Vacuum Expected Value (v.e.v. noted ν)

- The great success of this theory is when linearising the field around this v.e.v. You can get several terms:
  - 3 massive gauge bosons → W± (degenerate in mass) and Z with $m_W < m_Z$
  - 1 massless gauge boson → photon
  - A new boson (now called Higgs boson) with unique properties: it can couple to itself !

- Mass is not an intrinsic property of particles, but results from an interaction with the Higgs field that fills the space

• *ABEGHHK'tH mechanism (known commonly as Higgs mechanism) proposed by three independent groups in 1964*

• *Yukawa interaction, was not formalized in first seminal papers (introduced by S. Weinberg)*

The electroweak sector in a tiny nutshell

- Expanding a bit on the EWK sector:

SU(2) x U(1) (from the Higgs mechanism)

g g' ν

- The one-to-one relation between the couplings and the masses of gauge bosons (at Tree level) introducing the week mixing angle (θ_W)!

$$\tan\theta_W = \frac{g'}{g}$$

$$m_W = \frac{gv}{2}$$

$$m_Z = \frac{gv}{2\cos\theta_W}$$

$$m_\gamma = 0$$

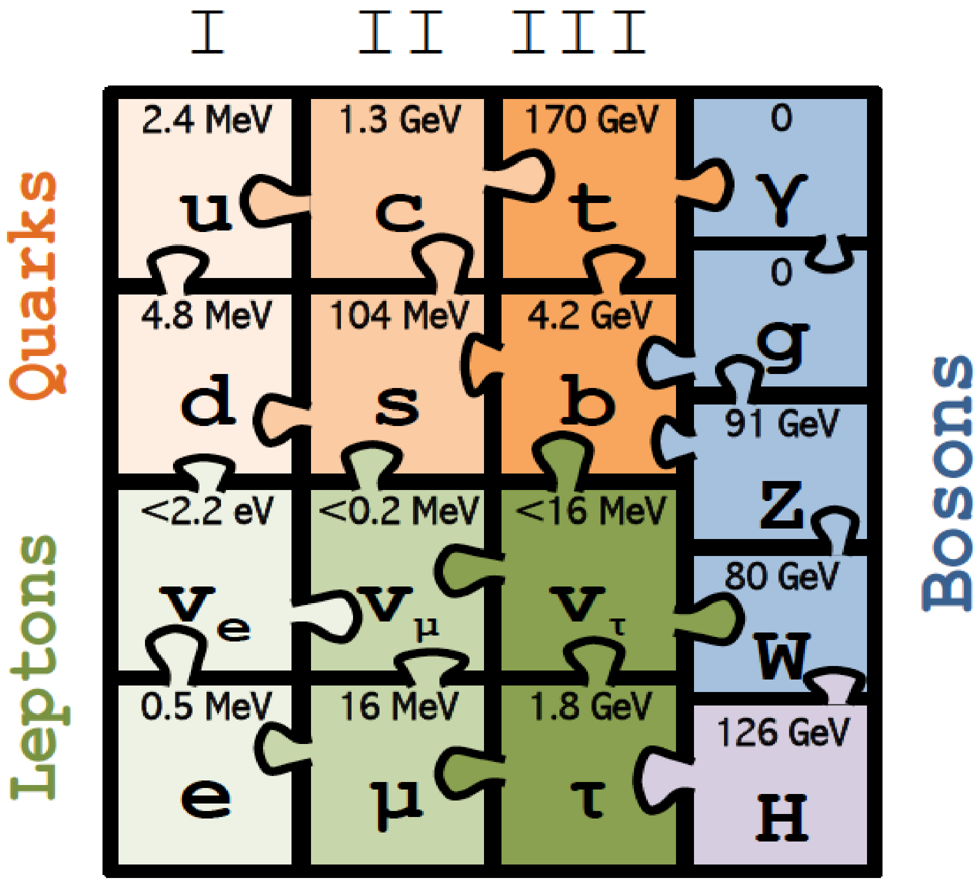
- As a consequence, at tree level:

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W}$$

Mass of electroweak gauge bosons and interactions strength predicted precisely from g, g', ν. LHC offers unique environment to test the EWK theory

The Standard Model (SM)

Global overview



Electroweak physics:

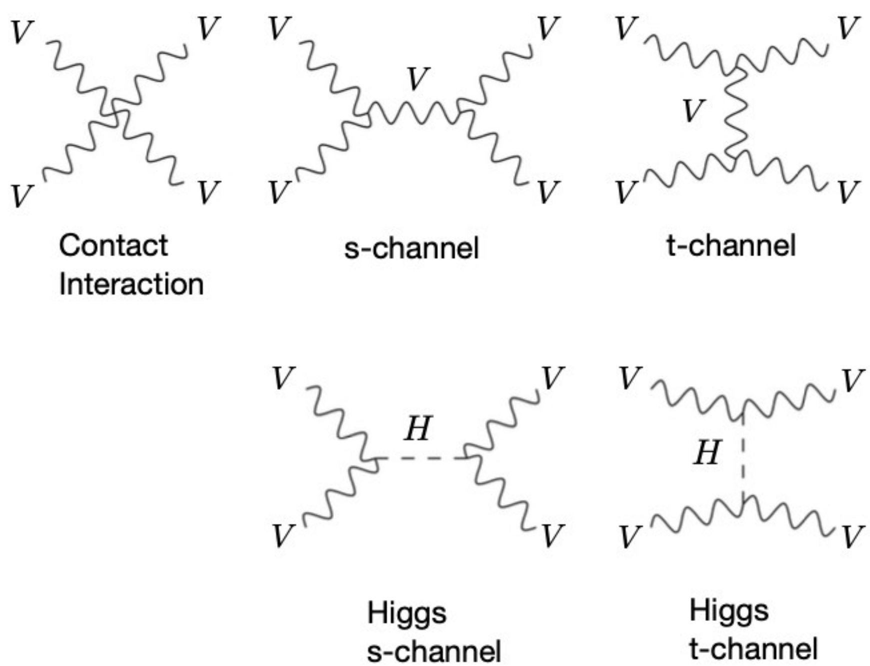
- Mostly related with boson measurements: W,Z,photons
- Precise tool to probe the gauge structure of EWK sector in the SM: diboson and triple gauge couplings

The Higgs sector in a tiny nutshell

- Less elegant Higgs sector wrt the electroweak one
  - Carries the largest number of parameters of the theory
  - Not governed by symmetries

- But the Higgs mechanism is absolutely necessary both for gauge boson and fermion masses
  - The Higgs mechanism also predicts the relation between the gauge boson masses and their couplings
  - The Higgs mechanism also predicts the existence of a Higgs boson

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \psi_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$



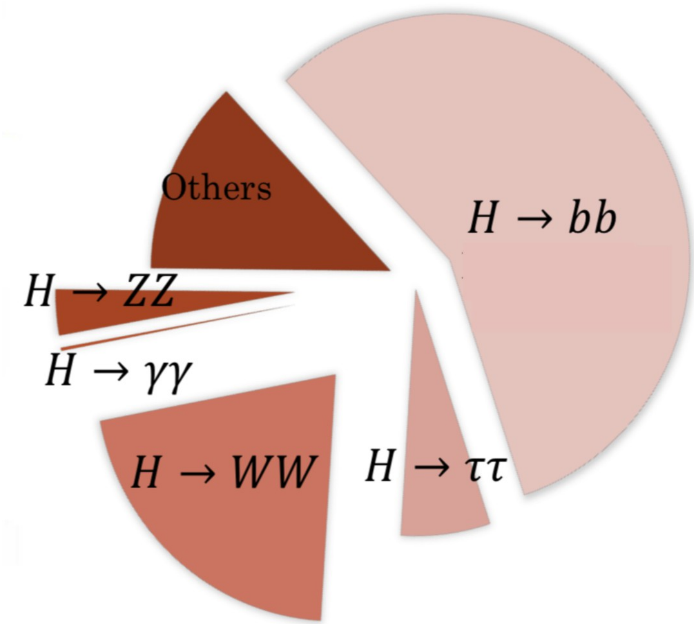
$$\mathcal{M} = g^2\left(\frac{E}{M_W}\right)^2$$

$$\mathcal{M} = -g^2\left(\frac{E}{M_W}\right)^2$$

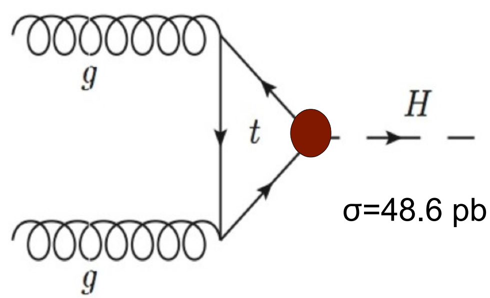
- The presence of a Higgs boson also solves another important issue, the unitarity of the longitudinal vector boson scattering **(no loose theorem)**
- The preservation of the perturbative unitarity of the WW scattering, imposes an upper limit on the Higgs boson of ~O(1 TeV).

The Higgs sector in a tiny nutshell

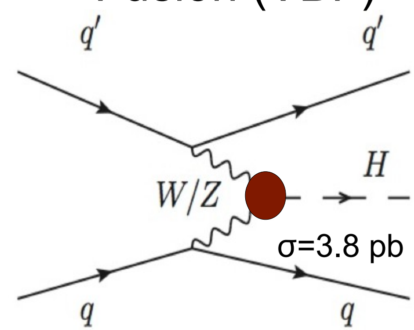
- **7M Higgs boson** produced by LHC during **Run-2 (2015-2018)** and **18M per experiment** expect by the end of **Run-3 (2022-2026)**!
- LHC experiments are making the most of this dataset!
- Which production mode or/and decay is the best?
  - There is an interplay between production and decay based on the backgrounds



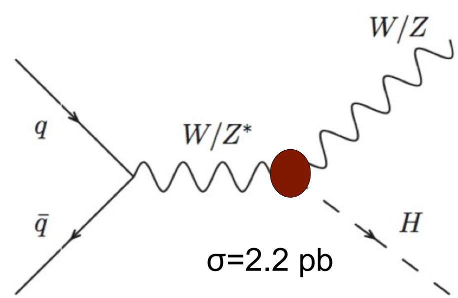
Gluon fusion (ggF)



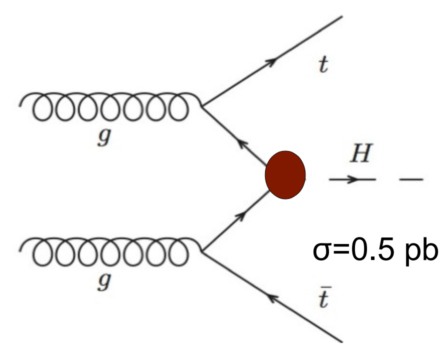
Vector Boson Fusion (VBF)



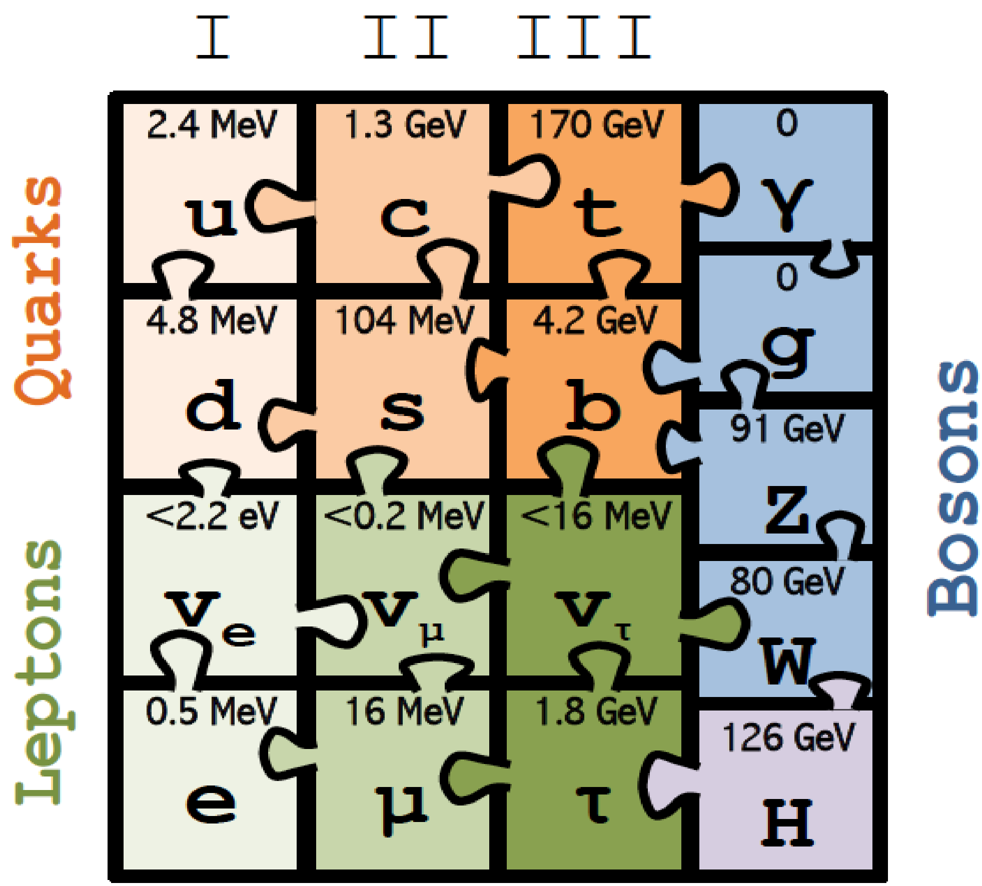
W/Z associated production (VH)



Top associated production (ttH)



The Standard Model (SM)
Global overview



Electroweak physics:

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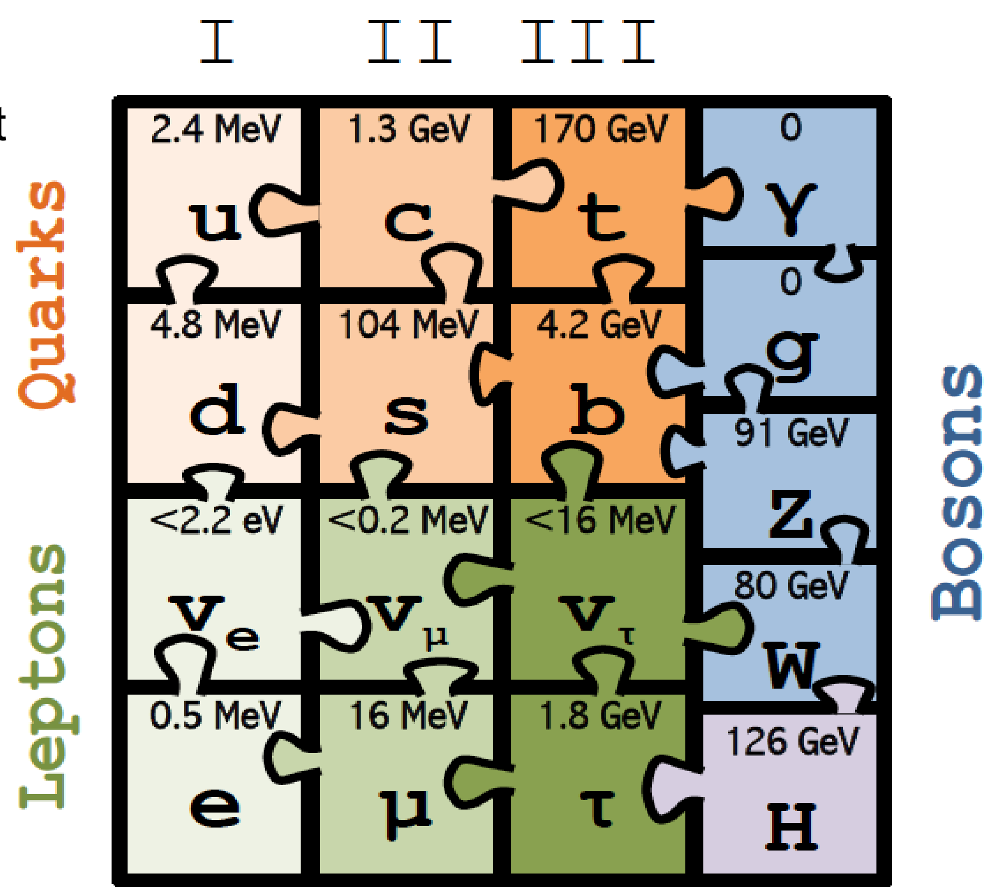
Higgs physics:
- Is the discovered particle the one predicted by the SM?
- Is the shape of the Higgs potential that predicted by the Standard Model?

The Standard Model (SM)

Global overview

QCD physics:
- Strong interaction
- 8 gluons, 6 quarks
- Asymptotic freedom weakly interaction at high E) and confinement (strong at low E)
- In experiment → jets

Top physics:
- A special kind of quark
- Decays before hadronizing t → Wb



Flavour physics:
- Quark and lepton flavor physics: mixings and couplings, symmetry principles violation
- Understanding the matter-antimatter asymmetry

Electroweak physics:
- Mostly related with boson measurements: W,Z,photons
- Precise tool to probe the gauge structure of EWK sector in the SM: diboson and triple gauge couplings

Neutrino physics:
- Weak interaction
- Tiny mass
- Sources: solar, nuclear reactors and accelerators

Higgs physics:
- Is the discovered particle the one predicted by the SM?
- Is the shape of the Higgs potential that predicted by the Standard Model?

Question #1

Does the Higgs boson couple to photons?

1) Yes, the Higgs boson couples directly to all gauge bosons

2) Yes, but only through quantum loops including charged particles

3) No, photons are massless and do not couple to Higgs bosons

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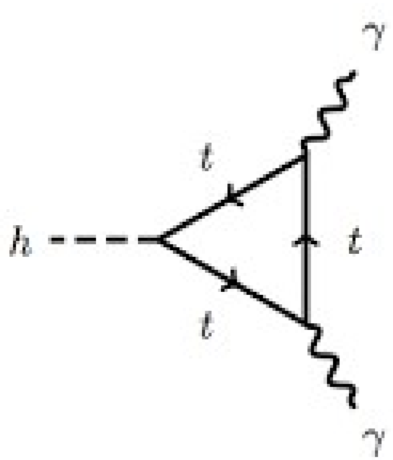
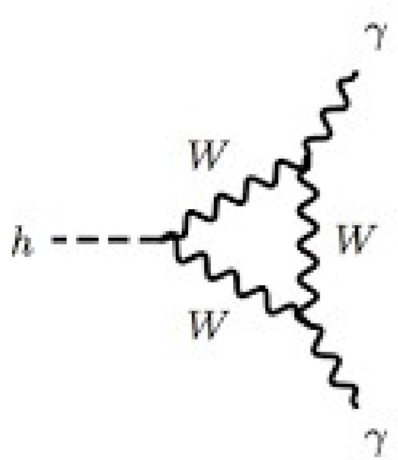




Since the photon's mass is zero, the Higgs really ought not to decay to photons at all. And indeed it does not, directly. It has to go through a loop of some other particle*, as in the cartoon above.

This is fine. In quantum mechanics, anything that can happen does.

Outline

- Some reminders:
  - Fundamentals of hadron collision
  - Luminosity and total cross section

- Electroweak measurements
  - Measurements of SM parameters
  - Investigation of EW gauge structure

- Higgs physics
  - Couplings to other particles
  - Other Higgs boson properties
  - Higgs self-coupling
  - Global fit of the Standard Model

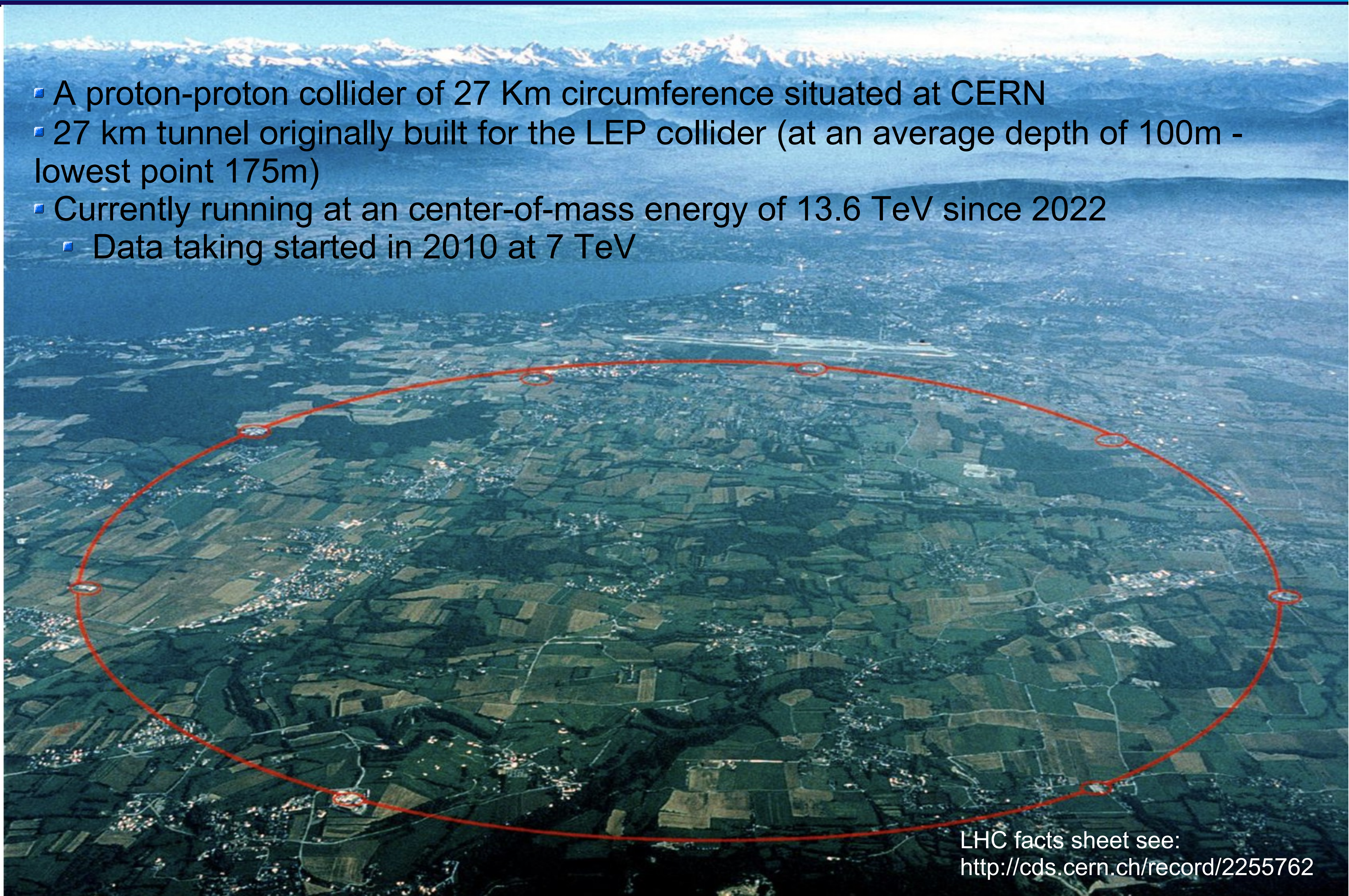
- Searching for new physics BSM

- A brief outlook on future colliders

So how do we study all these particles?

The current tools: The Large Hadron Collider (LHC)

- A proton-proton collider of 27 Km circumference situated at CERN
- 27 km tunnel originally built for the LEP collider (at an average depth of 100m - lowest point 175m)
- Currently running at an center-of-mass energy of 13.6 TeV since 2022
  - Data taking started in 2010 at 7 TeV



LHC facts sheet see:
http://cds.cern.ch/record/2255762

So how do we study all these particles?
The current tools: The Large Hadron Collider (LHC)

Few interesting facts

9300 Magnets (among which 1232 bending dipoles) reaching 8.3T with current of 11,400 A.

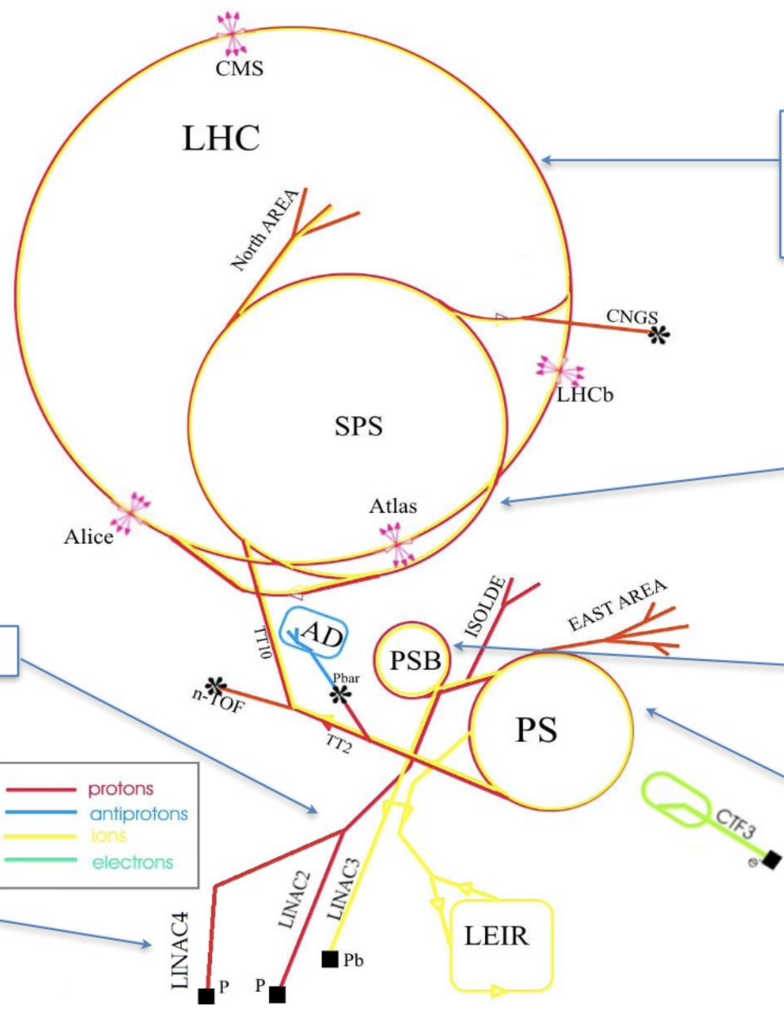
Beams are made of trains with a total nominal number of bunches of 2808 each containing approximately 100 Billion protons. Bunches are separated within trains by 25ns (approximately 7m).

Each proton has the kinetic energy of a mosquito and the total energy of the beams is 350 MJ ~ 1 TGV à 150 km/h.

Accelerated at 50 MeV in a LINAC

Hydrogen (gas) is ionized in a duoplasmotron.

First accelerated with a RF quadrupole at 750 keV.



Ramped to 7.5 TeV in the LHC
The maximum number of bunches (2808) not reached at Run 2 is limited by the injection kickers (~1 μs) and by the beam dump extraction (~3 μs)

SPS accelerates protons to 450 GeV, bunches before injection in the LHC.

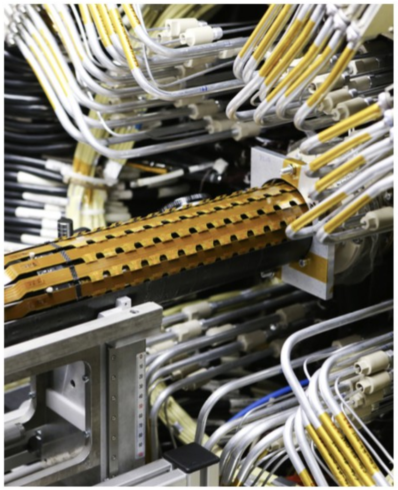
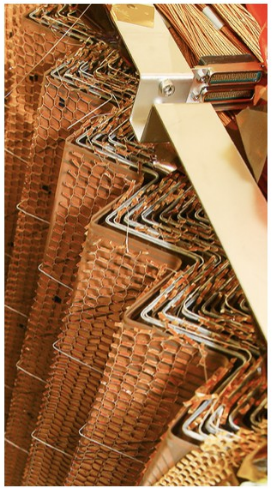
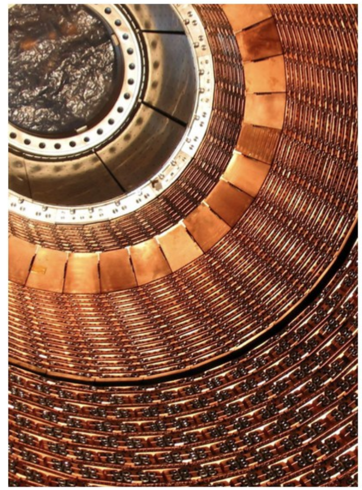
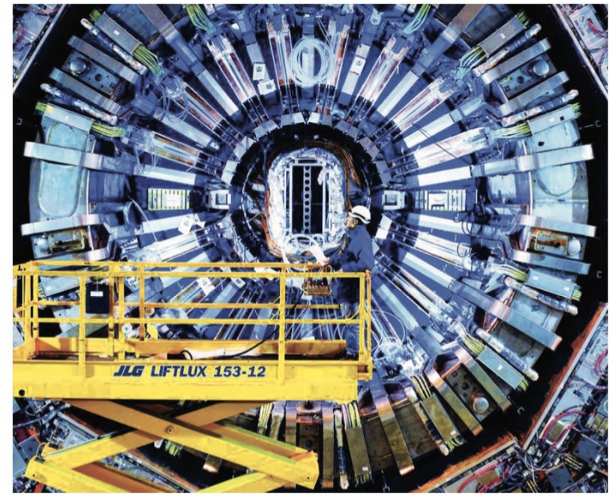
The booster accelerates protons at 1.4 GeV.

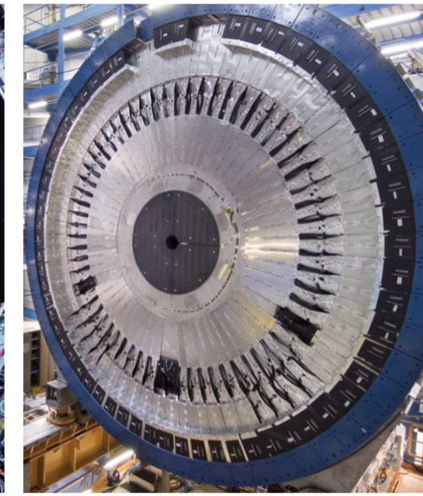
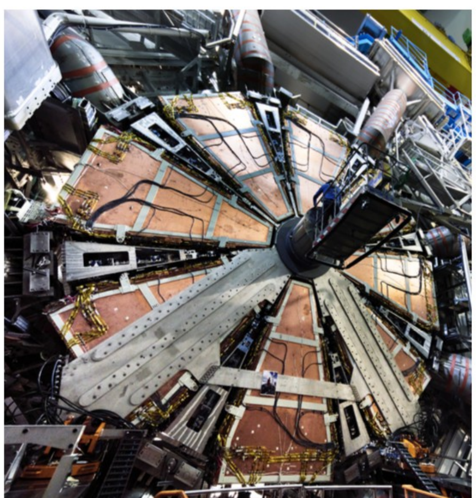
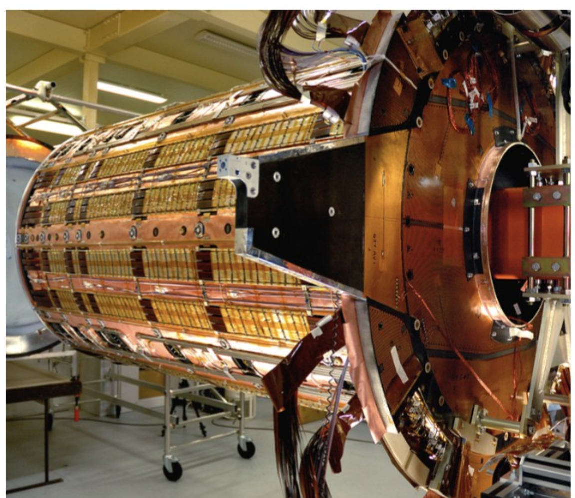
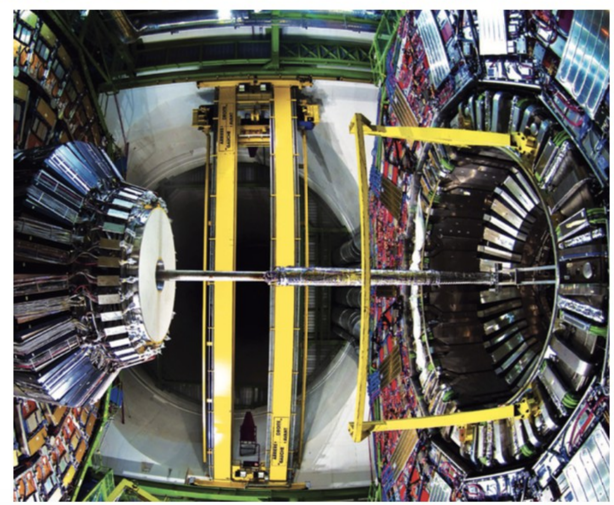
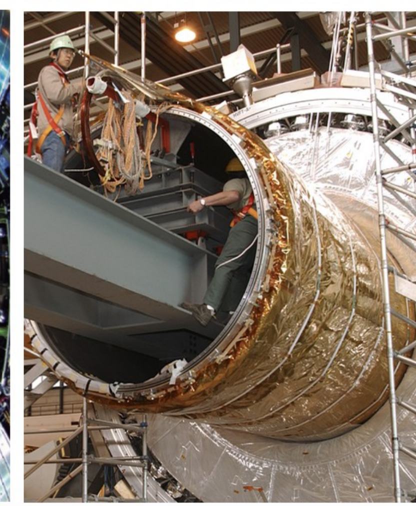
PS brings them to 26 GeV, it is in the PS that bunches are formed with a 25ns spacing.

So how do we study all these particles?

The particle detectors

10 years of construction

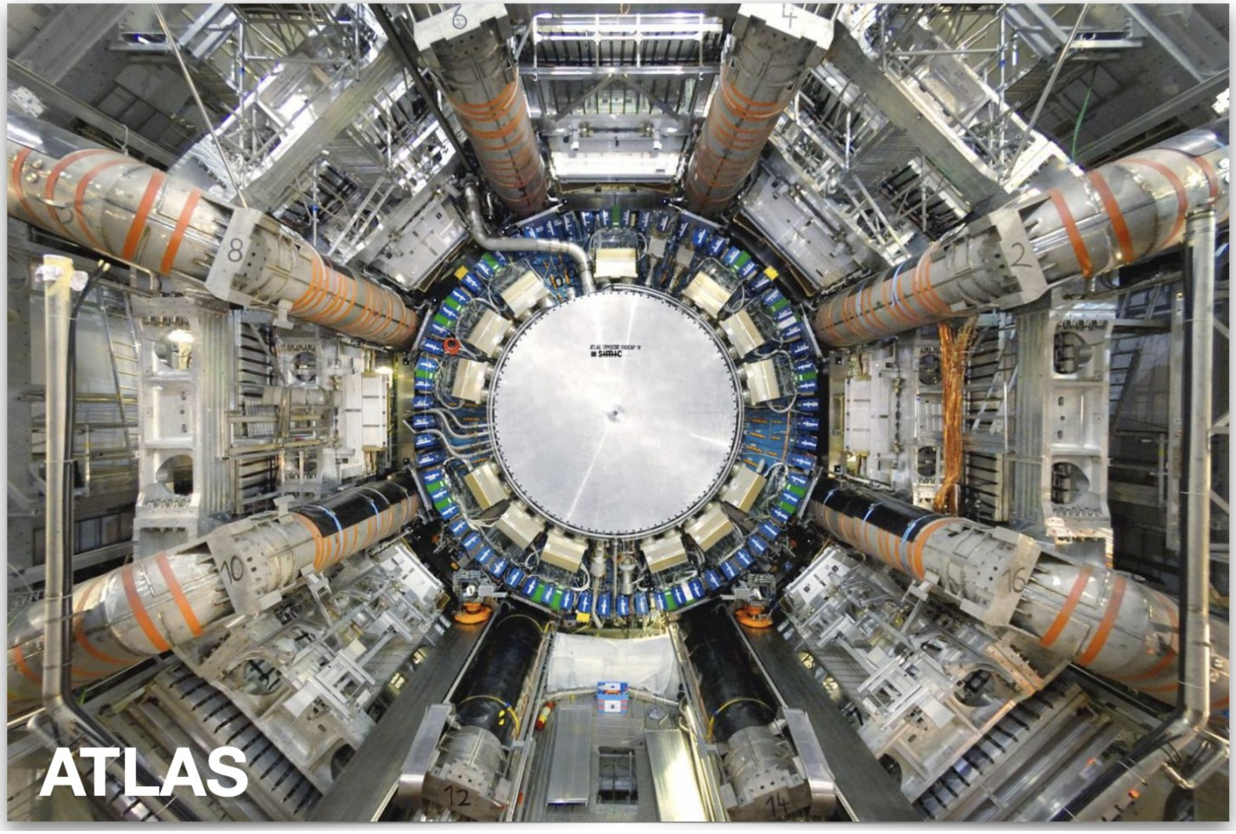





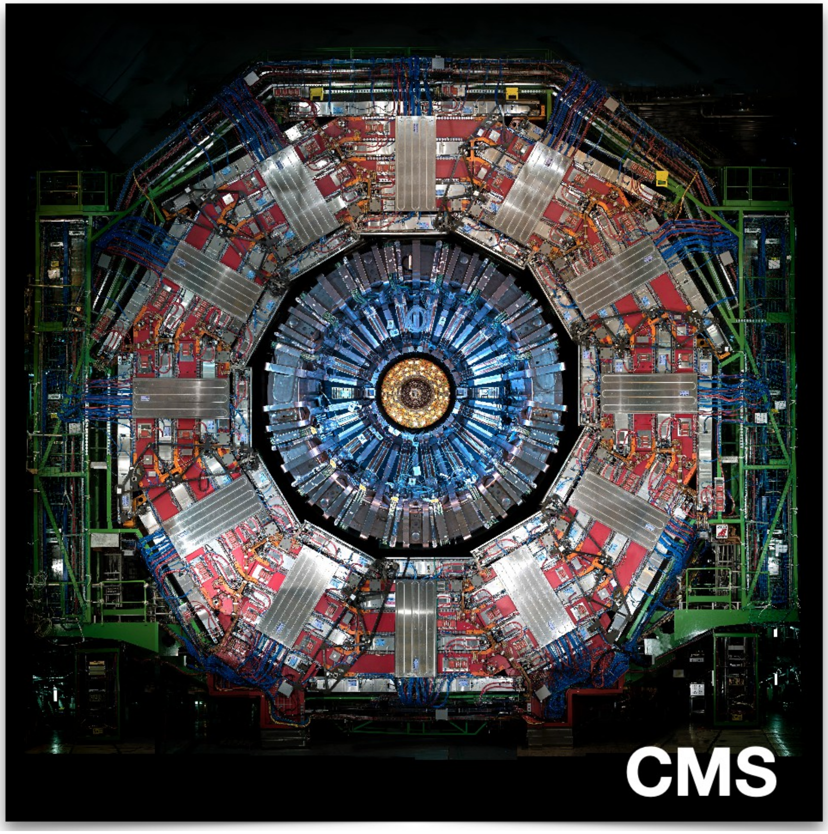






So how do we study all these particles?

The particle detectors

General purpose detectors

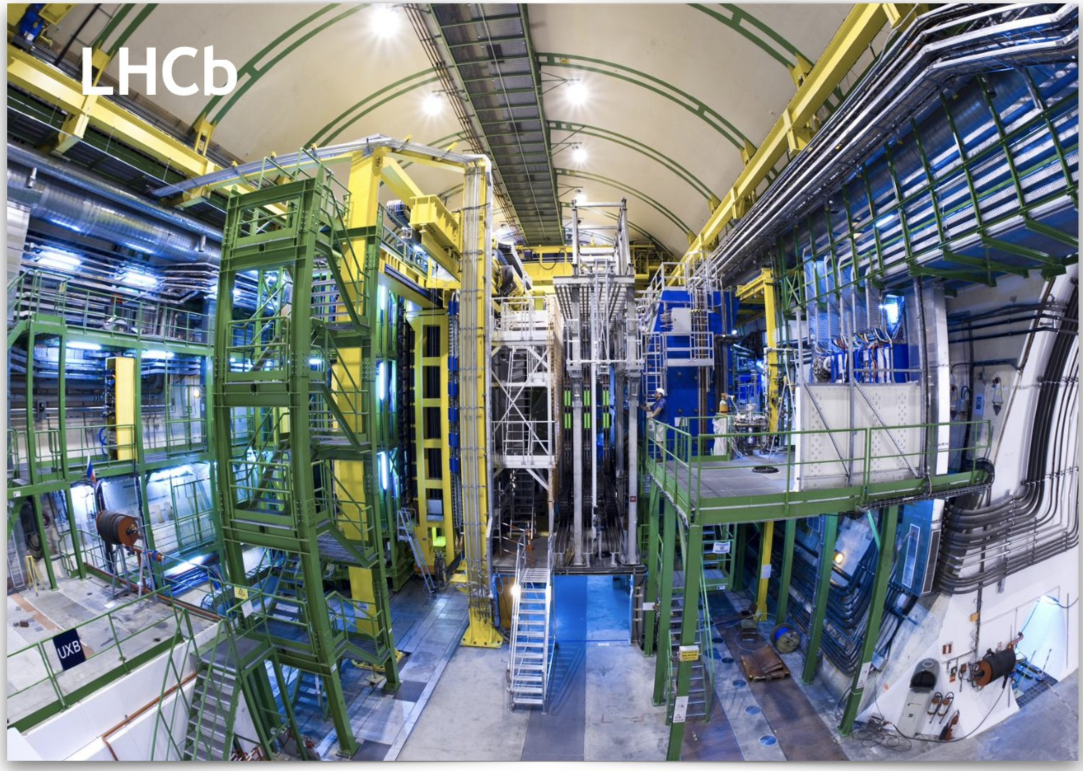


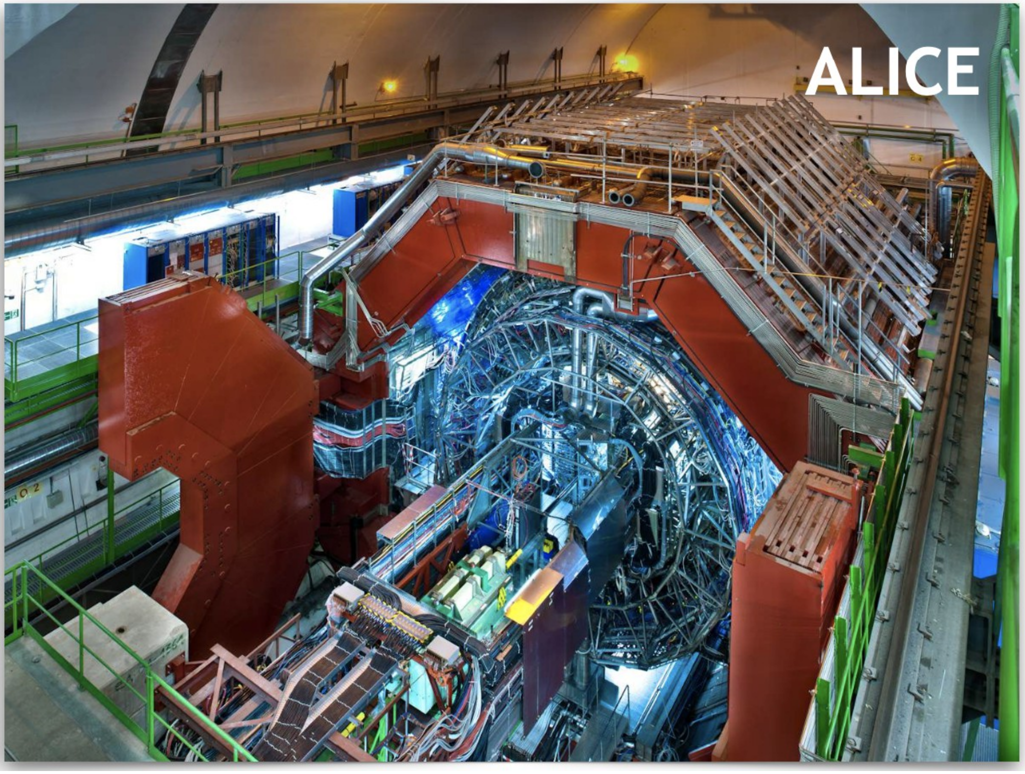


So how do we study all these particles?

The particle detectors

Specialized detectors





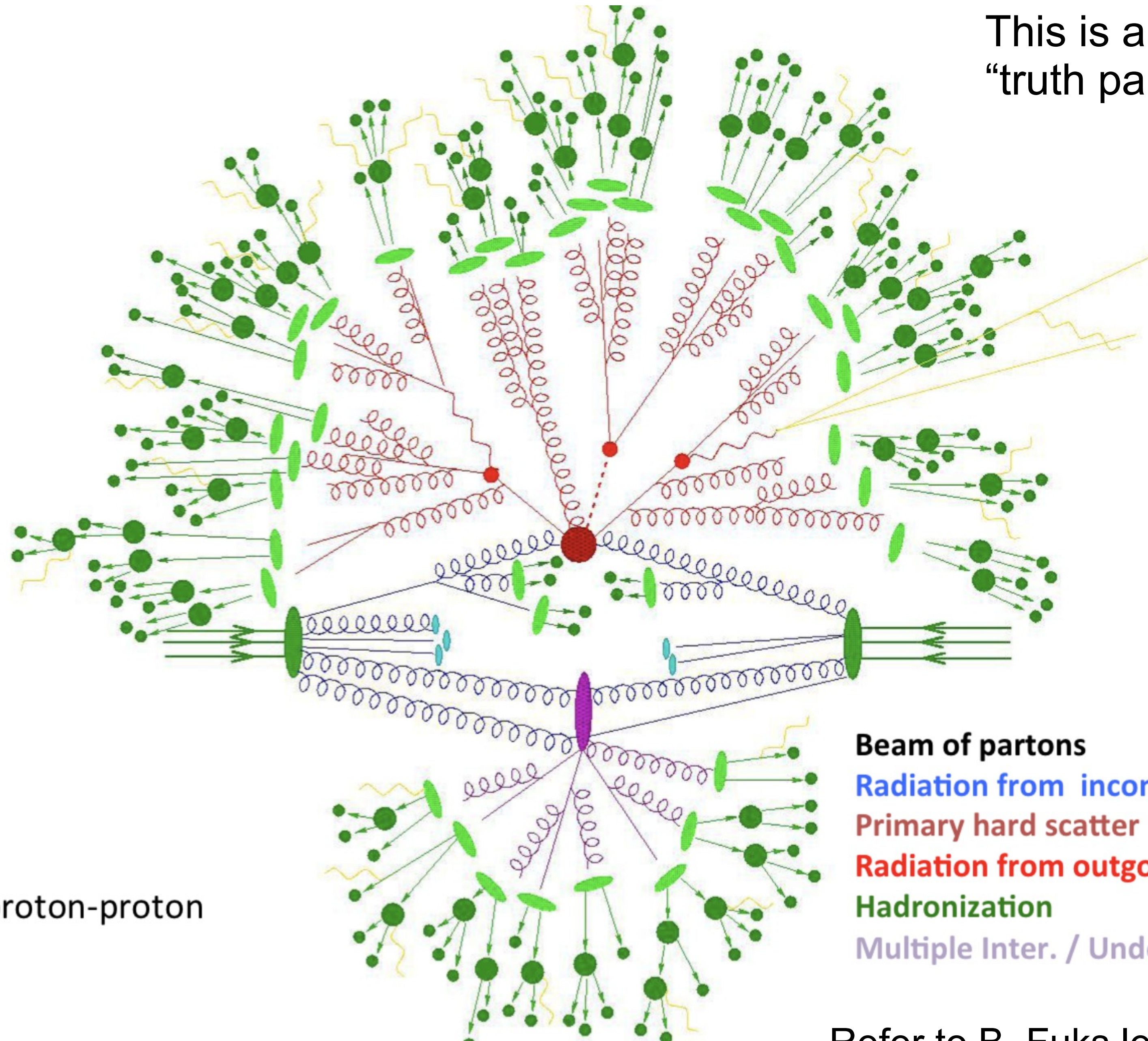
Flavour physics lecture by Yasmine Amhis

Click here to learn about other LHC specialized detectors!

So how do we study all these particles?

pp collisions phenomenology

This is an event at the "truth particle" level!



Beam of partons

Radiation from incoming partons

Primary hard scatter

Radiation from outgoing partons

Hadronization

Multiple Inter. / Underlying event

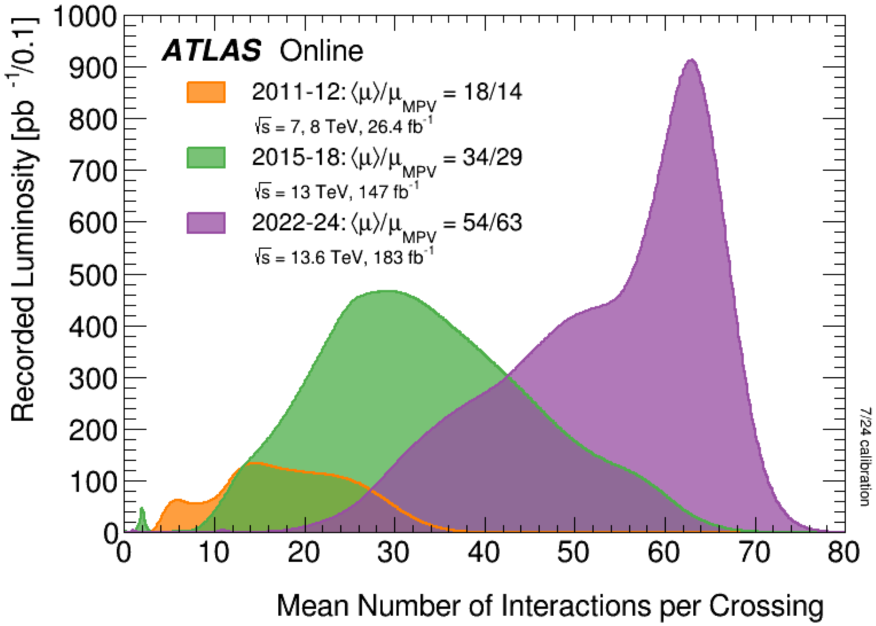
Typical proton-proton collision

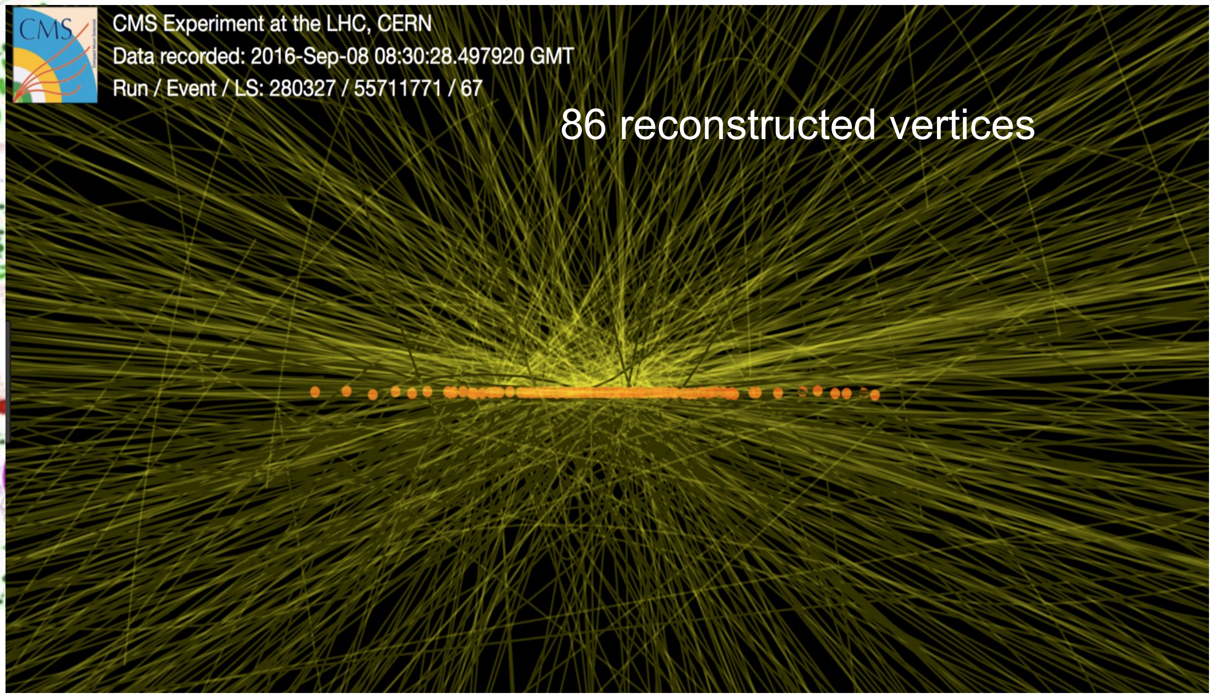
Refer to B. Fuks lecture!

So how do we study all these particles?

The collisions

High Lumi
=
high pileup

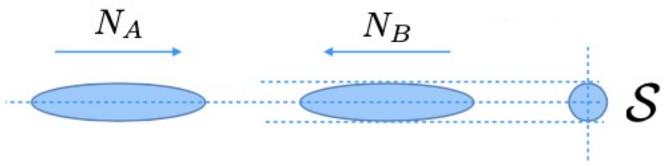




Impressive
detectors

Luminosity and event rates

- In LHC experiments: measure the rate of events of a defined type N_{evt}
- The rate of events can be predicted by:
  - knowing the beam conditions
  - Estimating the (hard scattering) cross section
  - Estimating the reconstruction (experimental) efficiency



- The probability for a random particle A to collide with a random particle B yielding the defined type of event is: σ/S

- If N_A and N_B particles crossing each other per second within *dt*:

$$\frac{dN_{evts}}{dt} = N_A N_B \frac{\sigma}{\mathcal{S}} = \sigma \mathcal{L}$$

- When beam collide with a revolution frequency f, the luminosity for two bunches colliding (always the same)
  - σ_x and σ_y are the transverse dimensions of the beam at the interaction point
  - At the LHC the beams are symmetric with a size of 16 μm
  - For bunches with equal average number of protons per bunch (N_p)
  - *f* is precisely known
  - N_p is known precisely through beam current measurements

$$\mathcal{L} = \frac{f N_p^2}{4\pi \sigma_x \sigma_y}$$

Luminosity and event rates

- Therefore, luminosity is a pure machine parameter. Its measurement and monitoring are crucial for all the physics we do at LHC

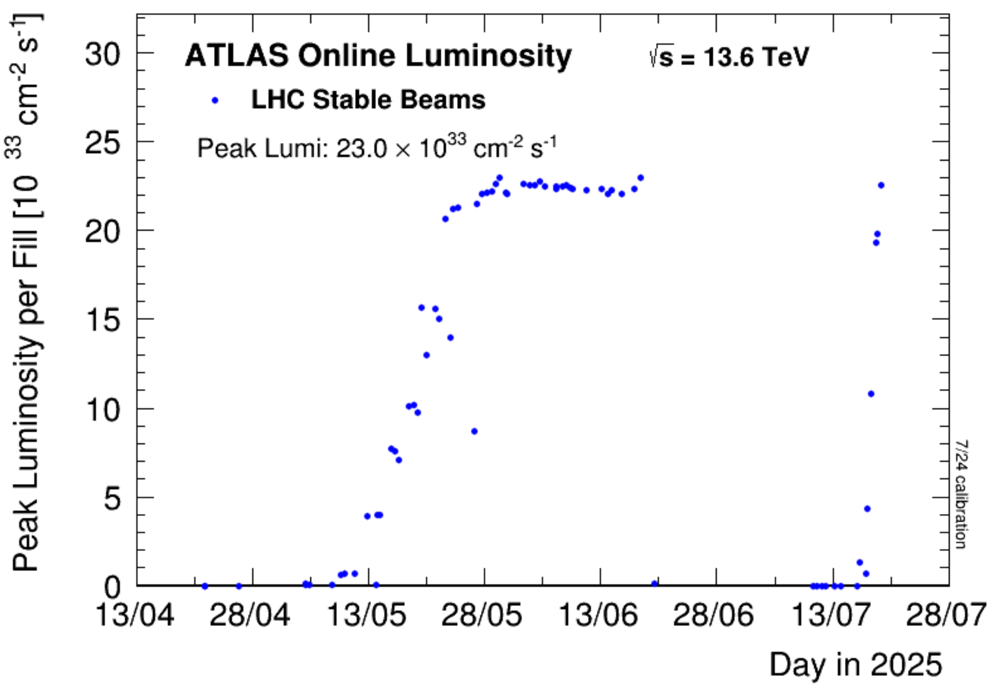
$$\mathscr{L} = \frac{N_{\text{bunch}} \cdot N_1 \cdot N_2 \cdot f_{\text{LHC}}}{4\pi \cdot \sigma_x \cdot \sigma_y}$$

N_{bunch} = number of bunches = 2808

N_1, N_2 = number of protons = 10^{11}

f_{LHC} = revolving frequency = c/26.7 km = 89 μs

σ_x, σ_y = Gaussian beam profile ≈ 50 μm



Parameter	2010	2011	2012	2016	2017	2018	Nominal	HL-LHC
CoM Energy	7 TeV	7 TeV	8 TeV	13 TeV	13 TeV	13 TeV	14 TeV	14 TeV
N_p	1.1 10^{11}	1.4 10^{11}	1.6 10^{11}	1.2 10^{11}	1.2 10^{11}	1.2 10^{11}	1.15 10^{11}	2.2 10^{11}
Bunches k	368	1380	1380	2300	2450	2500	2808	2760
Spacing	150 ns	50 ns	50 ns	25 ns	25 ns	25 ns	25 ns	25ns
ε (mm rad)	2.4-4	1.9-2.3	2.5	2.6	2.3	2.6	3.75	2.5
β* (m)	3.5	1.5-1	0.6	0.4	0.3-0.4	0.4	0.55	0.15
L ($cm^{-2}s^{-1}$)	$2x10^{32}$	$3.3x10^{33}$	~$7x10^{33}$	$1.5x10^{33}$	$2.0x10^{34}$	$2x10^{34}$	10^{34}	$8x10^{34}$
PU	~2	~10	~30	~30	~50	~50	~25	~130

Peak luminosity twice larger than LHC design luminosity!

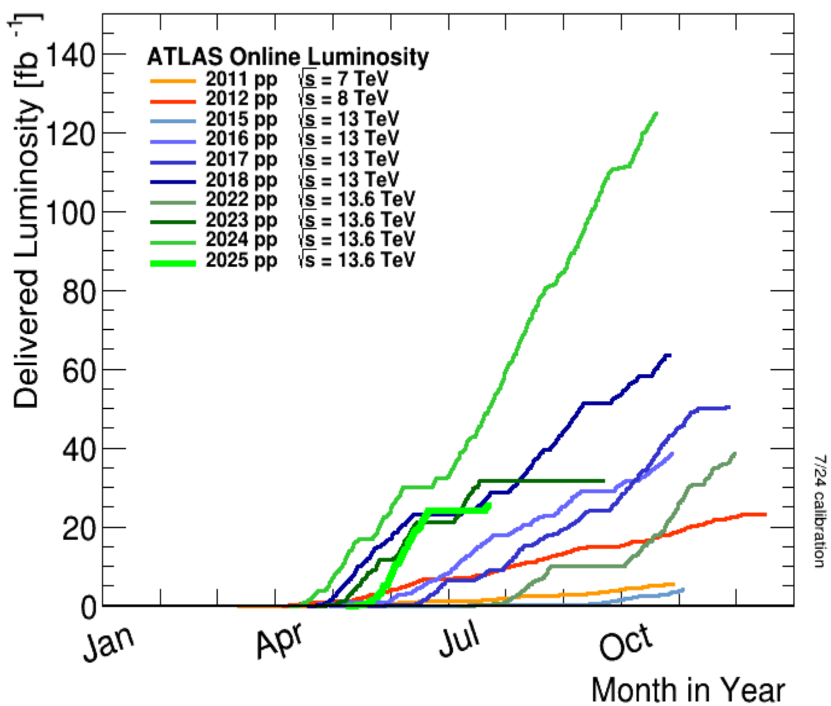
So how do we study all these particles?

Integrating luminosity and pile-up

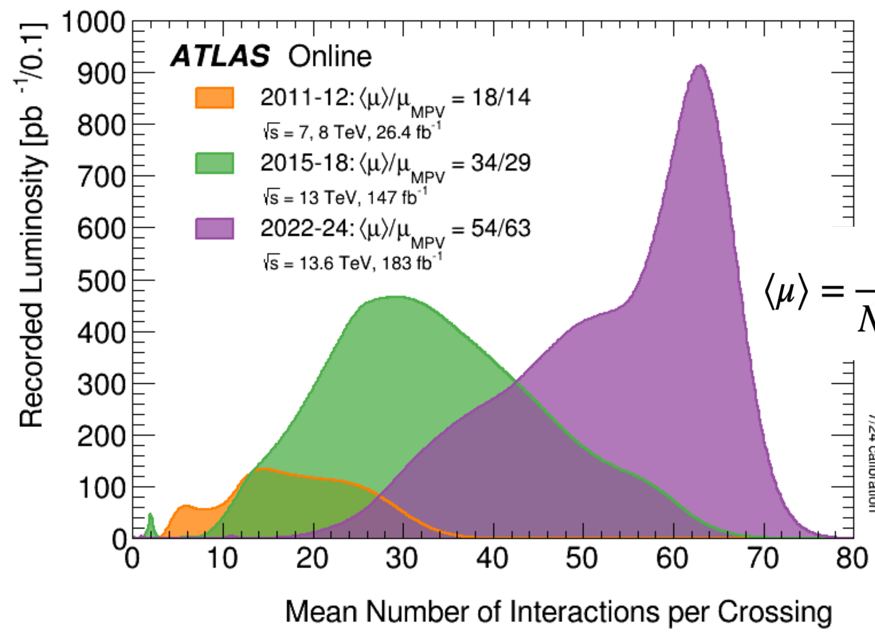
- The goal is to have the highest possible integrated luminosity in the best possible conditions for experiments (not just the highest possible instantaneous luminosity).

Luminosity comes at a cost for experiments: Pile-Up.

Pile Up: Number of inelastic interactions per bunch crossings!
So far reached mean number of PU events of approximately 40-60.
Future operations foresee scenarios with 200 PU events.



Outstanding performance over time!



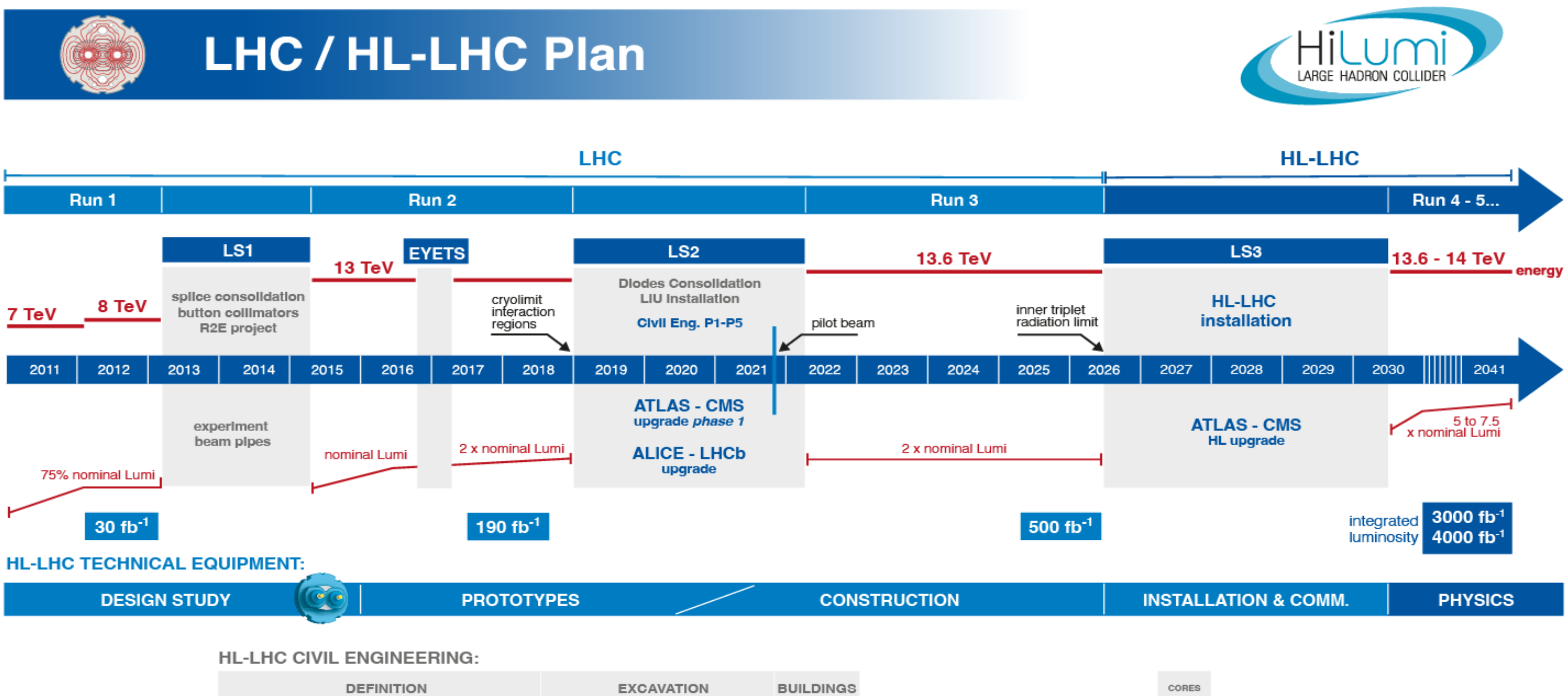
$$\langle \mu \rangle = \frac{\mathscr{L} \cdot \sigma_{\text{inel.}}}{N_{\text{bunch}} \cdot f_{\text{LHC}}}$$

fb^{-1} is a measure of the amount of data collected =~10^{12} proton-proton collisions. Used to translate σ into a total number of events. For the SM Vh with h→bb process, σ~1305 fb → in 100/fb of collected data, we expect a total of 130500 events

So how do we study all these particles?

15 years of the LHC

- The goal is to have the highest possible integrated luminosity in the best possible conditions for experiments (not just the highest possible instantaneous luminosity).



Run 2 is now completed with approximately 150 fb-1 delivered to each experiment

Future integrated luminosity goals:

- 500 /fb until mid-2026
- >3000 /fb at the end or the HL-LHC to start in 2030

Cross section measurements

- **σ is a measure of the probability of a certain kind of event happening**
- The detector can measure photons, charged leptons, hadrons, and missing transverse momentum only within its detector/ trigger capabilities (limited in pseudo rapidity and in transverse momentum/energy of the particles)
- How to derive the cross section from the counted number of events with specific analysis selection criteria?

Total cross section

$$\sigma_{tot} = \frac{N_{evts}}{\mathcal{A} \times \varepsilon \times \int \mathcal{L} dt}$$

- *A* the acceptance of the process, defined by the ratio of number of events produced in the fiducial volume to the total number of events and usually derived from simulation
- ε is experimental selection efficiency (objects, kinematics, binning)
- *L* is the integrated luminosity

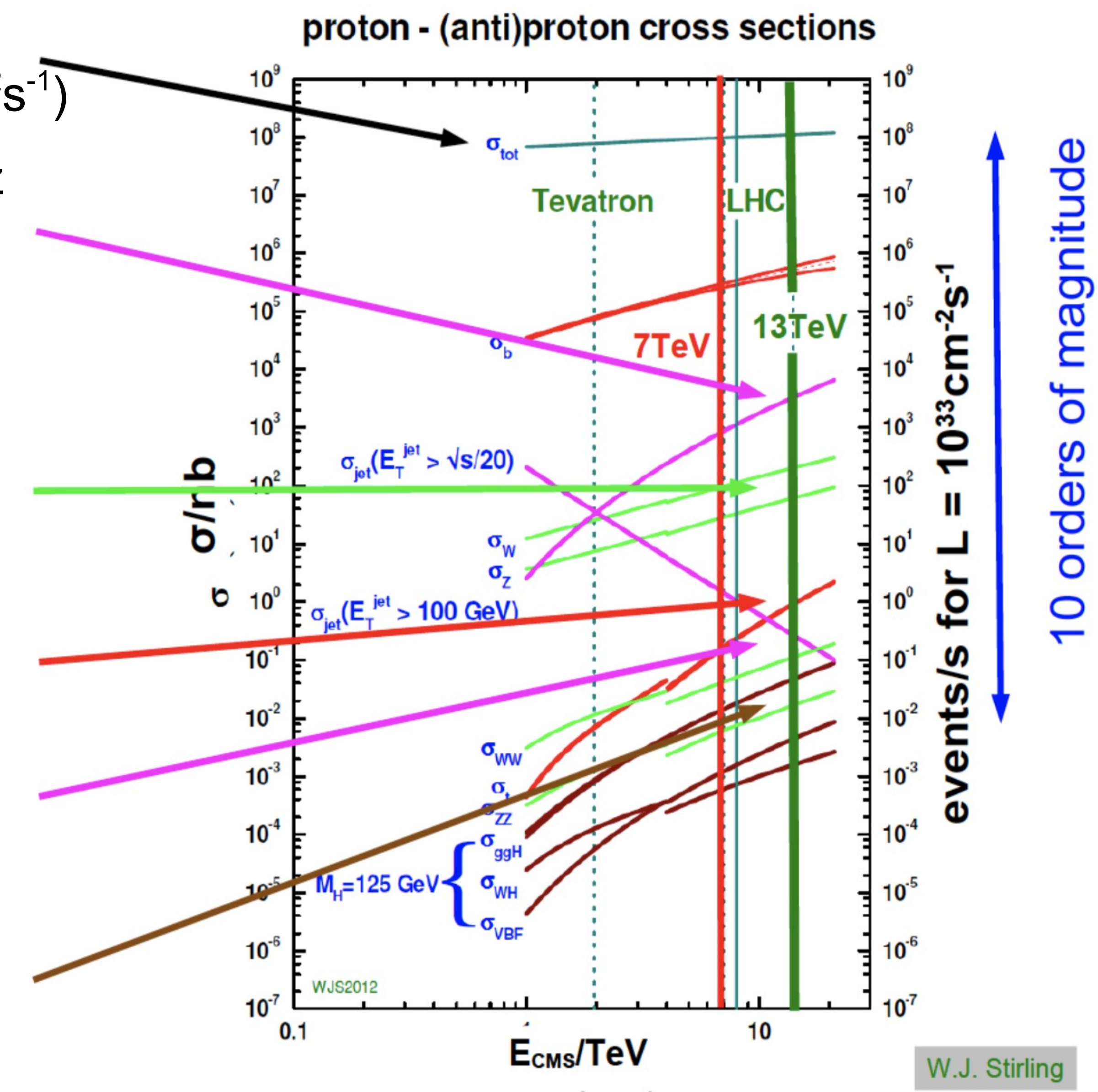
Fiducial cross section

$$\sigma_{fid} = \frac{N_{evts}}{\varepsilon \times \int \mathcal{L} dt}$$

- With a definition of the fiducial region, ε should be large and the fiducial cross section bear little model dependence

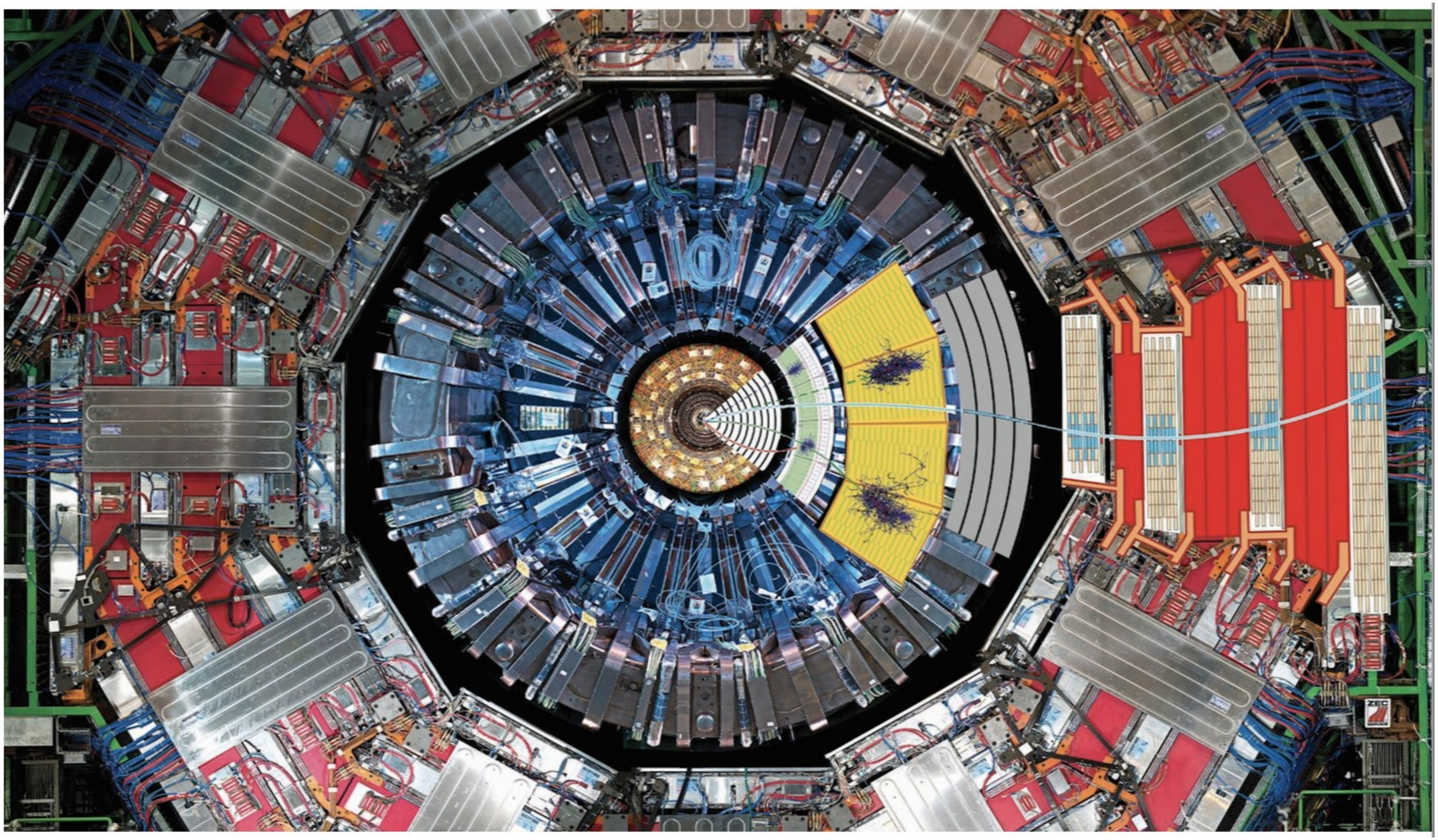
Event rates at the LHC

- **Total cross sections**
  - ~1.6*10^9 /s (80 mb, 2*10^34 cm^-2 s^-1)
  - Bunch crossing rate of 40MHz
- **Jets (E_T^{jet} > 100 GeV)**
  - ~40000 Hz
- **W & Z bosons**
  - ~4000 Hz, ~1000 Hz
- **Top quarks**
  - ~20 Hz
- **Jets (E_T^{jet} > 650 GeV)**
  - ~6 Hz
- **Higgs bosons**
  - ~1 Hz (50 pb, 2*10^34 cm^-2 s^-1)



What do we actually reconstruct from collisions?

- Energy and momenta of “stable” particles
  - Electrons, positrons, muons, anti- muons, charged hadrons
  - Photons, neutral hadrons
- Identify particle species
  - Including reconstruction of “unstable” particles from decay products
- Assign proton-proton collisions (pile-up removal)



Data and analysis chain

Detector

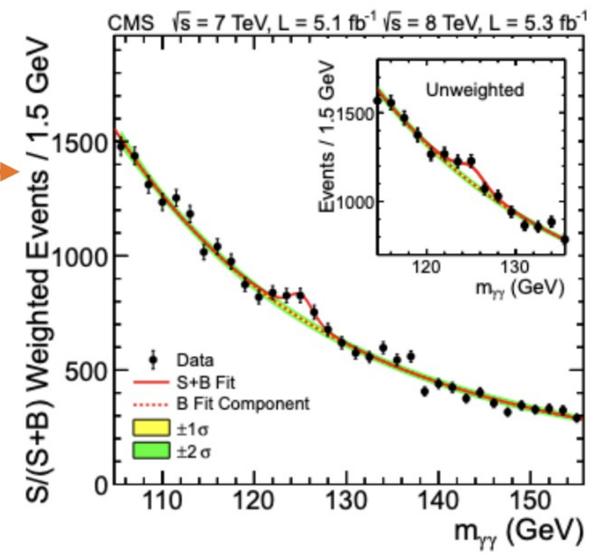
Trigger system: selection of rare events out of high background. Realised in a multi-level trigger, e.g.from 40 MHz to 100 kH to ~1 kH for ATLAS

Off-detector Trigger Computing farm

On-detector Trigger Electronics

Collision Data

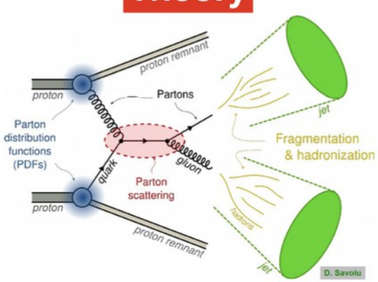
Reconstruction & Data reduction



Statistical analysis

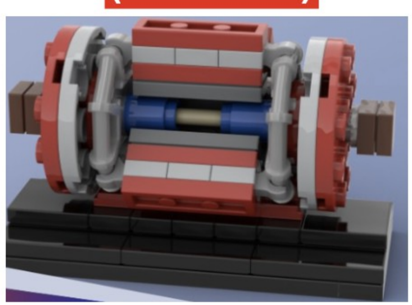
Calibration & alignment

Theory



Calculation of physics processes including hadronization

Digital twin (Simulation)



Simulated Data

Event reconstruction: tracking and clustering + combined reconstruction (jet finding, electron/photon/muon identification)

Machine learning/AI permeating all different steps in the chain!

Detector challenges

- **Read out and reconstruct** approximately **O(100M)** electronics channels at ~1 kHz
- **Trigger Challenge** : select ~400-1000 out of 20M events per second while keeping the interesting (including unknown) physics
- **Computing Challenge** : reconstruct, store and distribute 1000 complex events per second and the very large amount of simulation (over 100 PB per experiment - Several farms of over 200k Cores)
- **Analysis Challenge** : Maintain high (and as much as possible stable) reconstruction and identification efficiency
- **Machine Learning** : Ideal environment to develop Machine Learning techniques: in particular in areas such as trigger, reconstruction, object identification, calibration and pile up mitigation

CERN Computing Center

Question #2

How many proton-proton collisions does the LHC produce every 25 ns?

1) Between 40-60

2) Only one! That's more than enough

3) Around 200, what a challenge!

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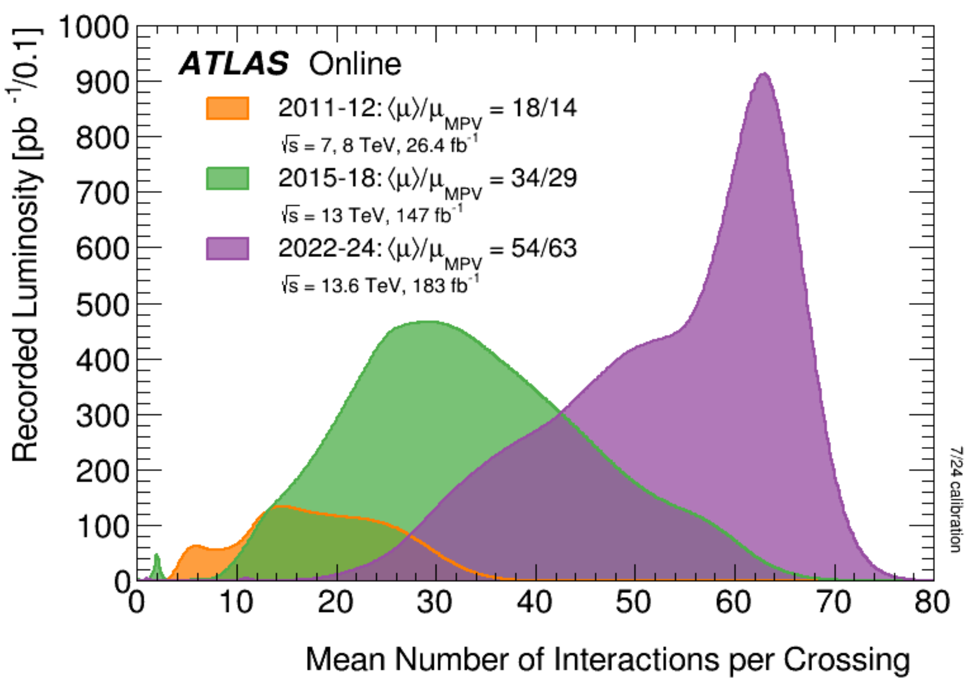

Outline

- Some reminders:
  - Fundamentals of hadron collision
  - Luminosity and total cross section
- Electroweak measurements
  - Measurements of SM parameters
  - Investigation of EW gauge structure
- Higgs physics
  - Couplings to other particles
  - Other Higgs boson properties
  - Higgs self-coupling
  - Global fit of the Standard Model
- Searching for new physics BSM
- A brief outlook on future colliders

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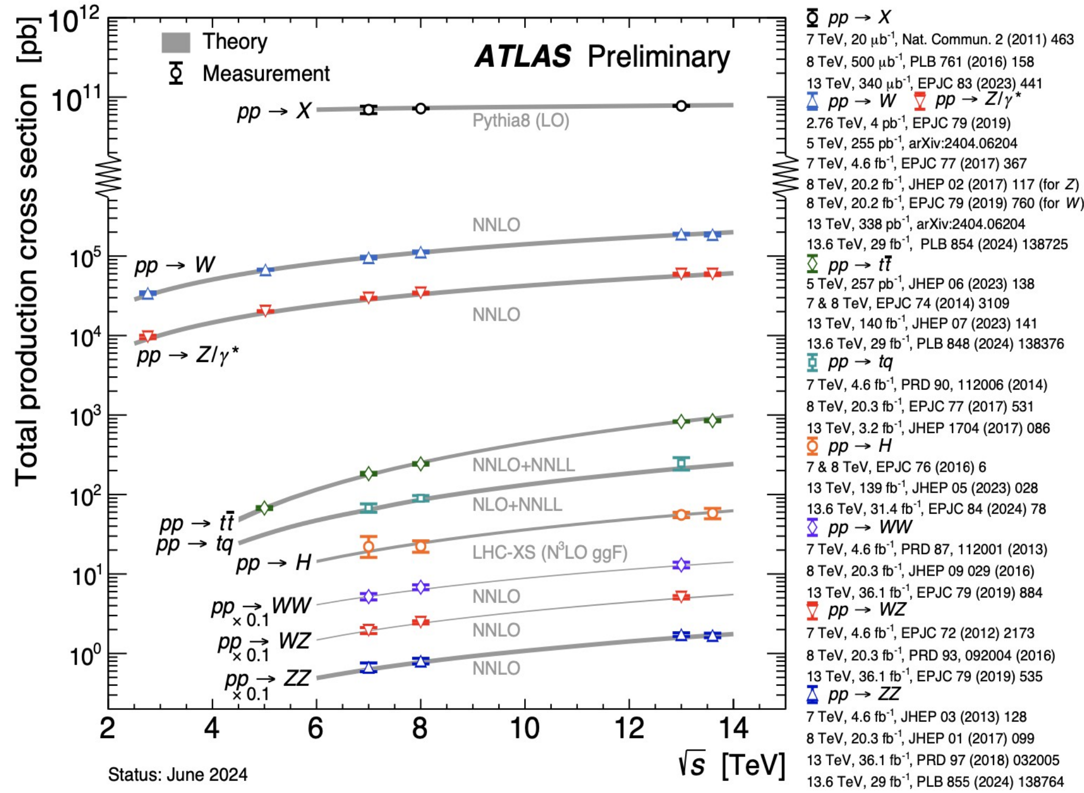


Electroweak tests at LHC

The precision frontier
i.e. measurements of SM parameters

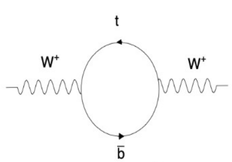
- W boson mass at LO $m_W = \left(\frac{\pi\alpha_{EM}}{\sqrt{2}G_F}\right)^{1/2} \frac{1}{\sin\theta_W}$

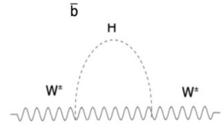
- Radiative corrections modify propagators and decay vertices

$$m_W = \left(\frac{\pi\alpha_{EM}}{\sqrt{2}G_F}\right)^{1/2} \frac{1}{\sin\theta_W} \frac{1}{\sqrt{1-\Delta r}}$$

$$\sin^2\theta_W \longrightarrow \kappa_f \sin^2\theta_W = \sin^2\theta_{eff}^f$$

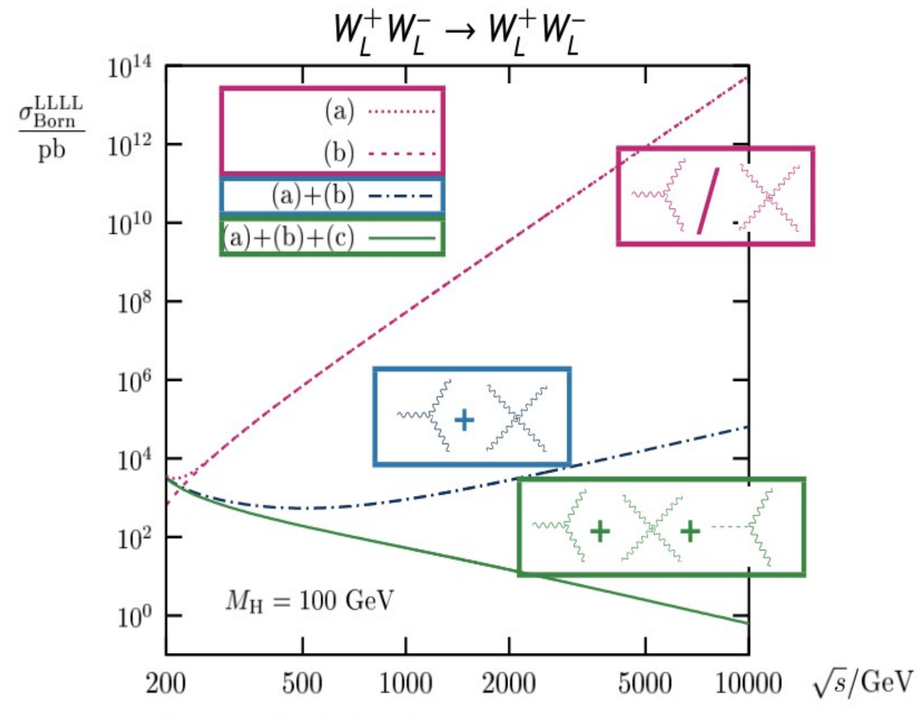
- Dominant radiative corrections:

fermion loops  $\Delta r \propto m_t^2$

Higgs boson loops  $\Delta r \propto \ln(m_H)$

- Measurement of EW parameters (e.g. the W boson mass) probes the radiative corrections and the relation between the top quark, Higgs boson and W boson masses

The energy frontier
i.e. investigation of EW gauge structure



from Nucl. Phys. B525 (1998) 27-50

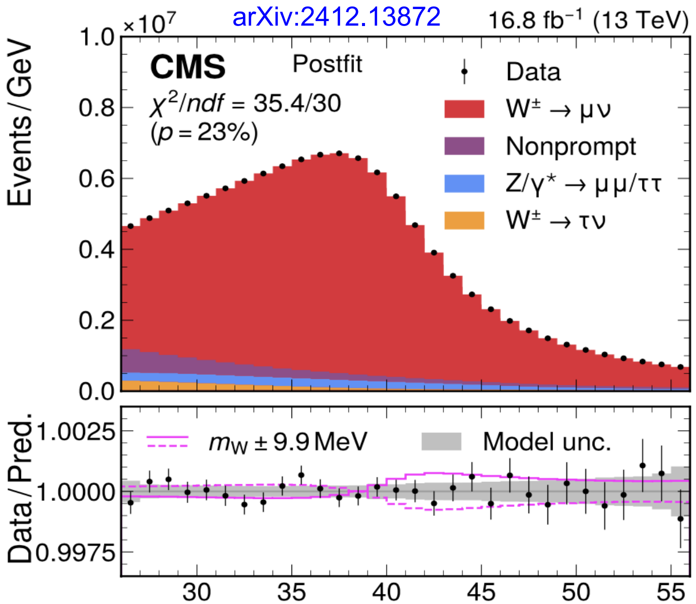
- Tests of the electroweak theory through delicate gauge cancellations at high energy
- Deviations can lead to potentially large effects

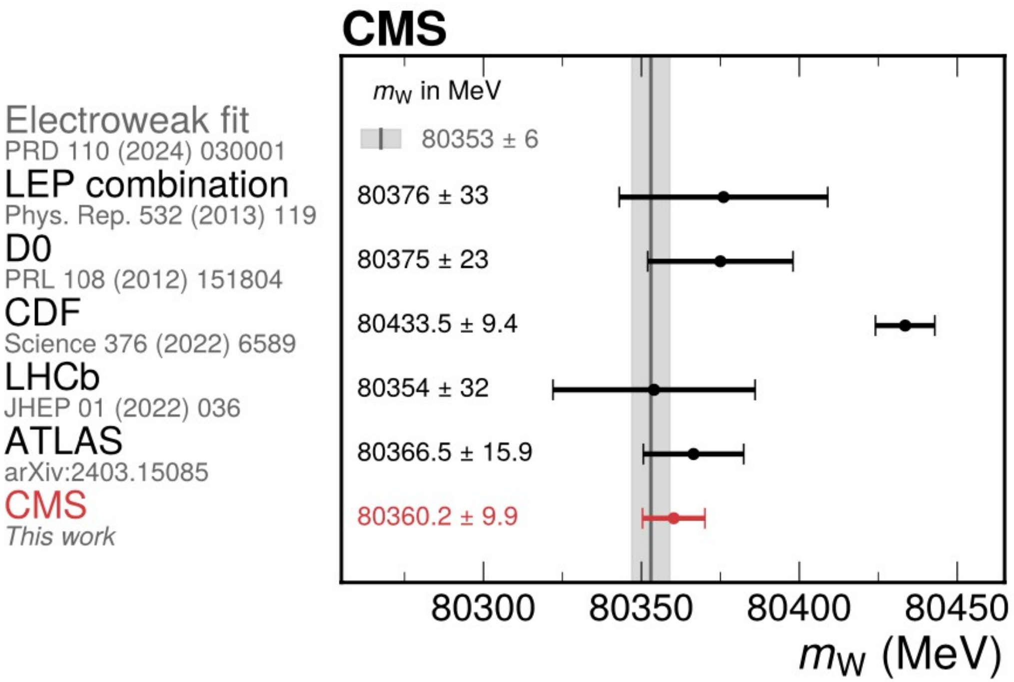
W mass and width

- **Observables**
  - Lepton transverse momentum
  - Transverse missing energy
  - Transverse mass

$$m_T = \sqrt{2p_T^{\ell}p_T^{miss}(1 - cos\Delta\phi)}$$

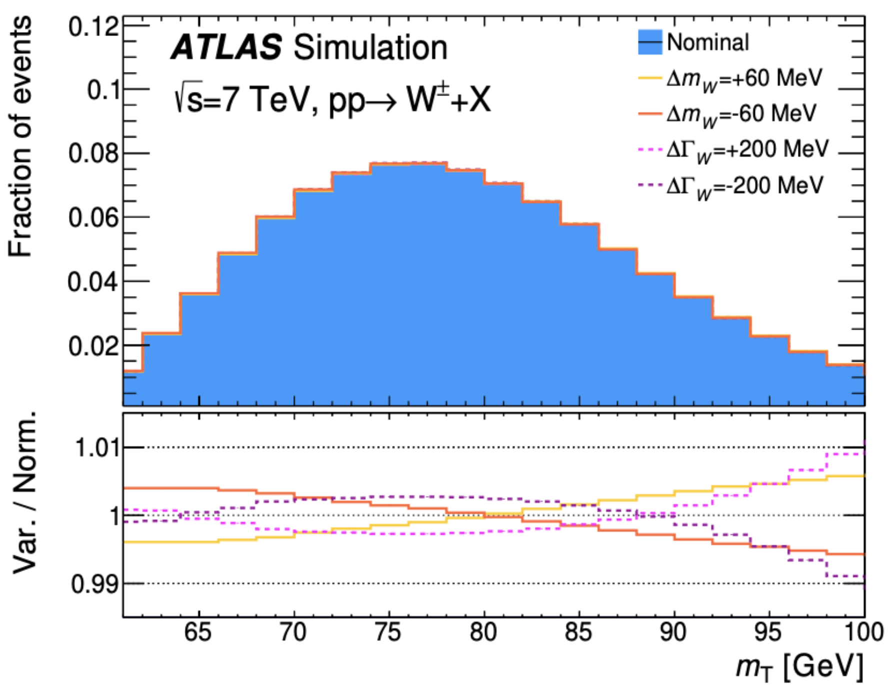
- **Challenges**
  - Experimental: lepton energy scale; missing transverse energy; pile-up conditions
  - Theoretical: W transverse momentum; PDFs
- **Strategy (in hadron colliders)**
  - Exploit lepton transverse momentum and transverse mass
  - Usually use templates to extract the W boson mass

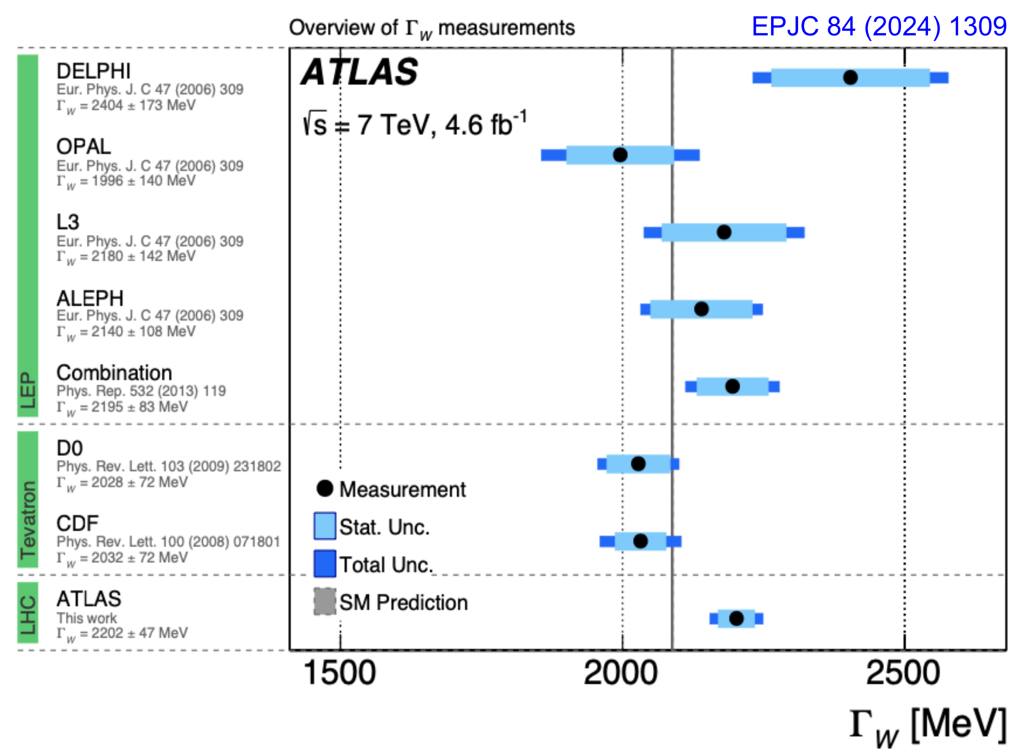




W mass and width

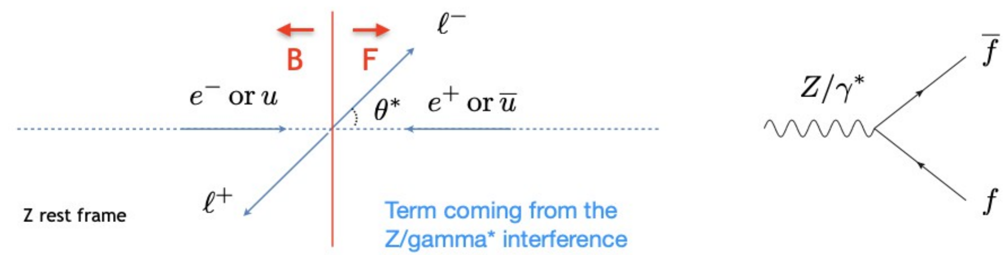
- The strategy followed for the ATLAS m_W measurement, in particular the usage of the m_T distribution, allows to also either determine $_W$ for fixed m_W , or (m_W, $_W$) simultaneously
  - With a dataset of only 4.6 fb^{-1} at 7 TeV, approximately 15.5 M W^+ events and 10.4 M W^- events (electrons and muons) with low pile-up, which is a favorable environment for this kind of measurements!





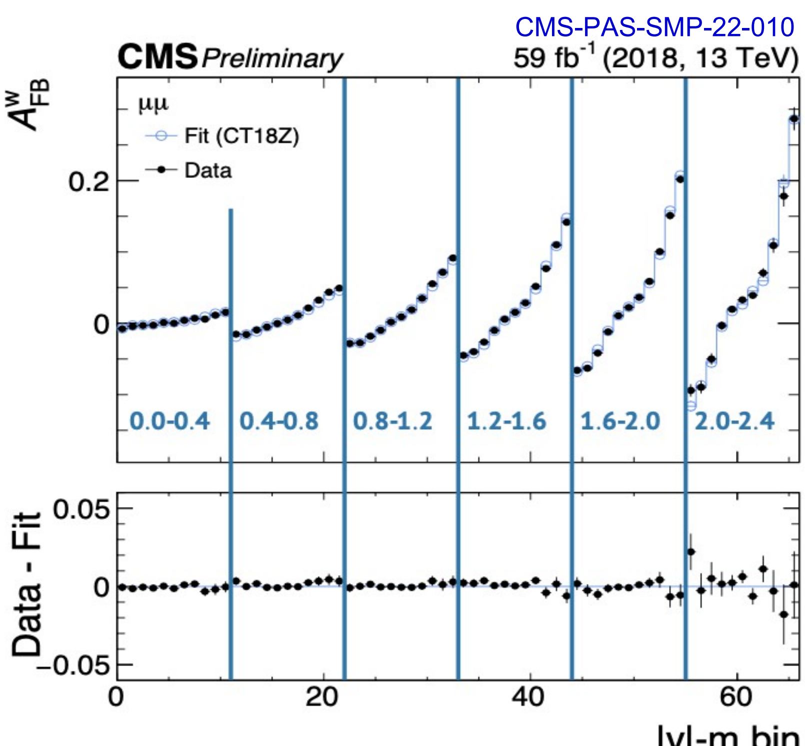
Measurement of the Effective Weak Mixing Angle

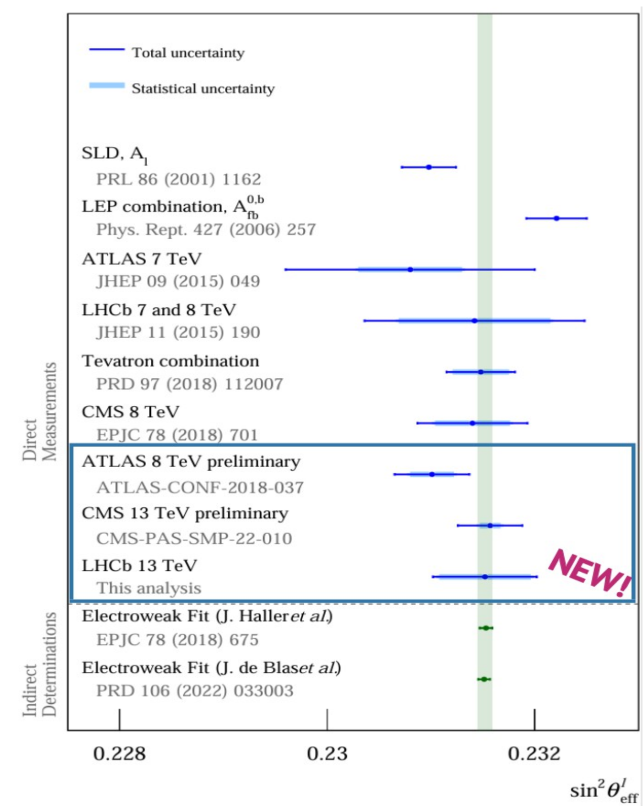
- Measurement of $pp \to l^+l^-$ forward-backward asymmetry can be used to determine $\sin^2\theta^l_{eff}$
- Once the reference frame is defined, the forward backward asymmetry can be straightforwardly measured, however defining the reference frame and expressing the asymmetry in terms of the effective mixing angle is less straightforward but done



$$\frac{d\sigma}{d\cos\theta^*} = \frac{4\pi\alpha^2}{3\hat{s}}\left[\frac{3}{8}A(1+\cos^2\theta^*) + B\cos\theta^*\right] \qquad B \propto \; A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

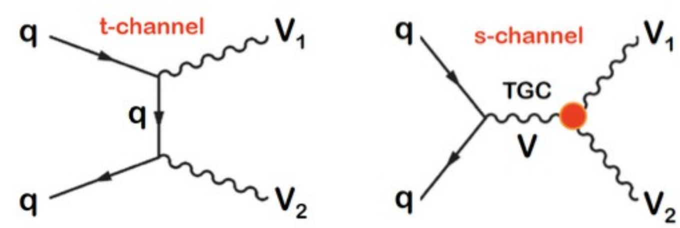
$$\frac{d\sigma}{d\cos\theta^*} \propto \left((g_{ve}^2 + g_{ae}^2)(g_{vf}^2 + g_{af}^2)(1+\cos^2\theta^*) + 8 g_{ve} g_{ae} g_{vf} g_{af} \cos\theta^*\right)$$



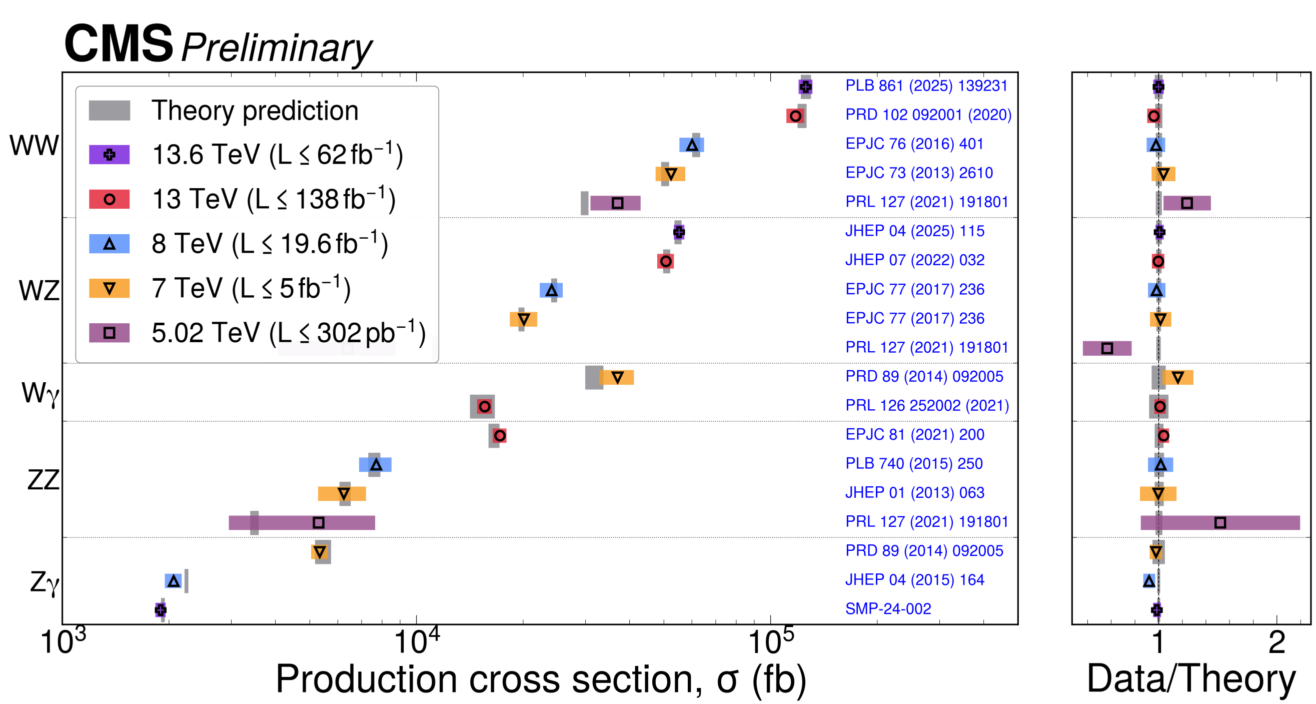


Multiboson production: dibosons

- Large number of diboson processes cross-sections measured
  - First measurements of diboson (*WW*, *ZZ*, *WZ*) processes in run-3 data taken in 2022! *arXiv:2406.05101*, *PLB 855 (2024) 138764* and *CMS-PAS-SMP-24-005*



- And used to put constraints on the theories beyond the Standard Mode
  - Anomalous couplings which lead to an excess in diboson events at high m_T or high p_T
- Generally good agreement between experiment and theory



Quartic Electroweak Couplings

- Quartic electroweak coupling experimentally accessible in vector-boson scattering and triboson production
  - Some of the rarest processes experimentally accessible at LHC
- Vector-boson scattering observed in all major channels
  - Exploiting characteristic signature
  - In agreement with theoretical predictions
- Triboson production experimentally more difficult

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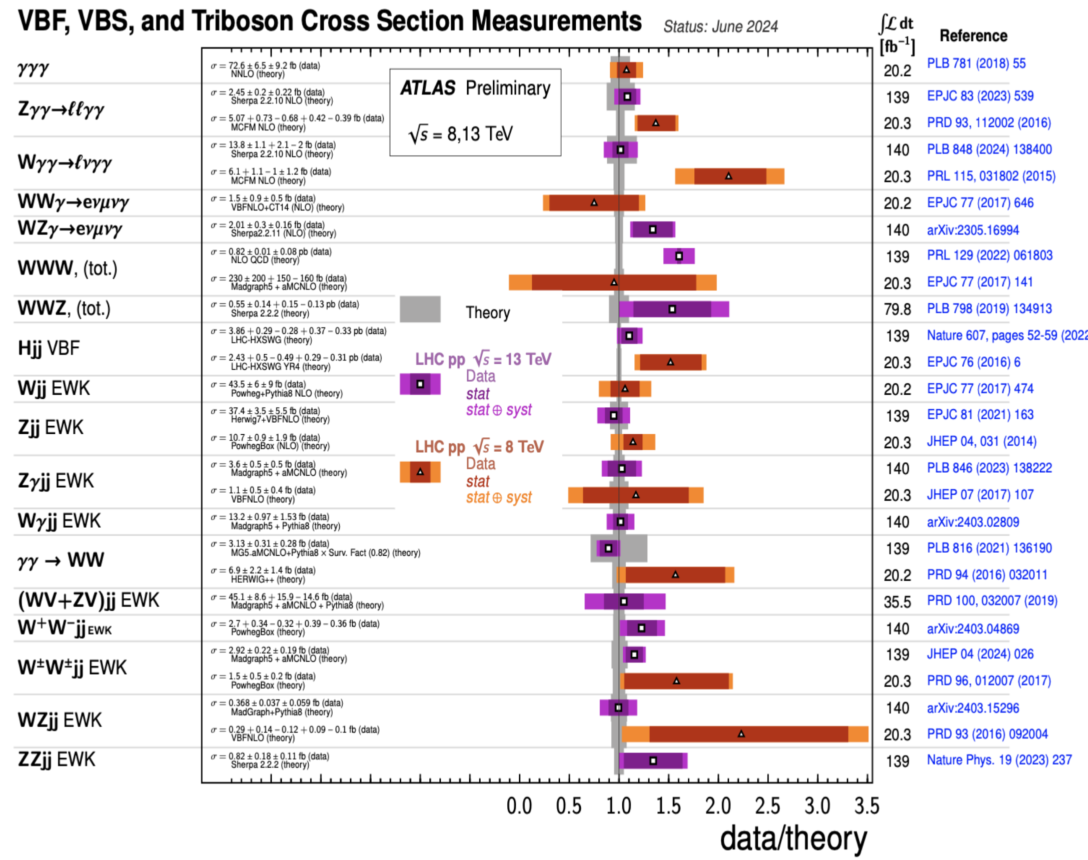
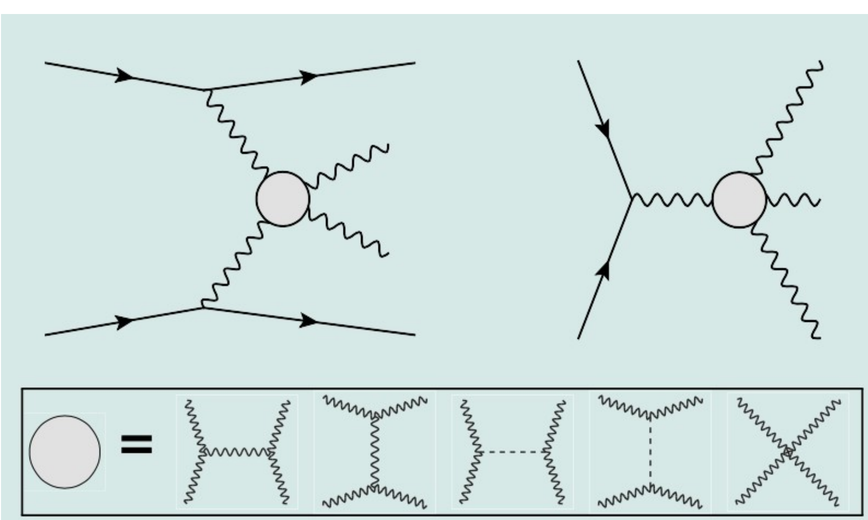
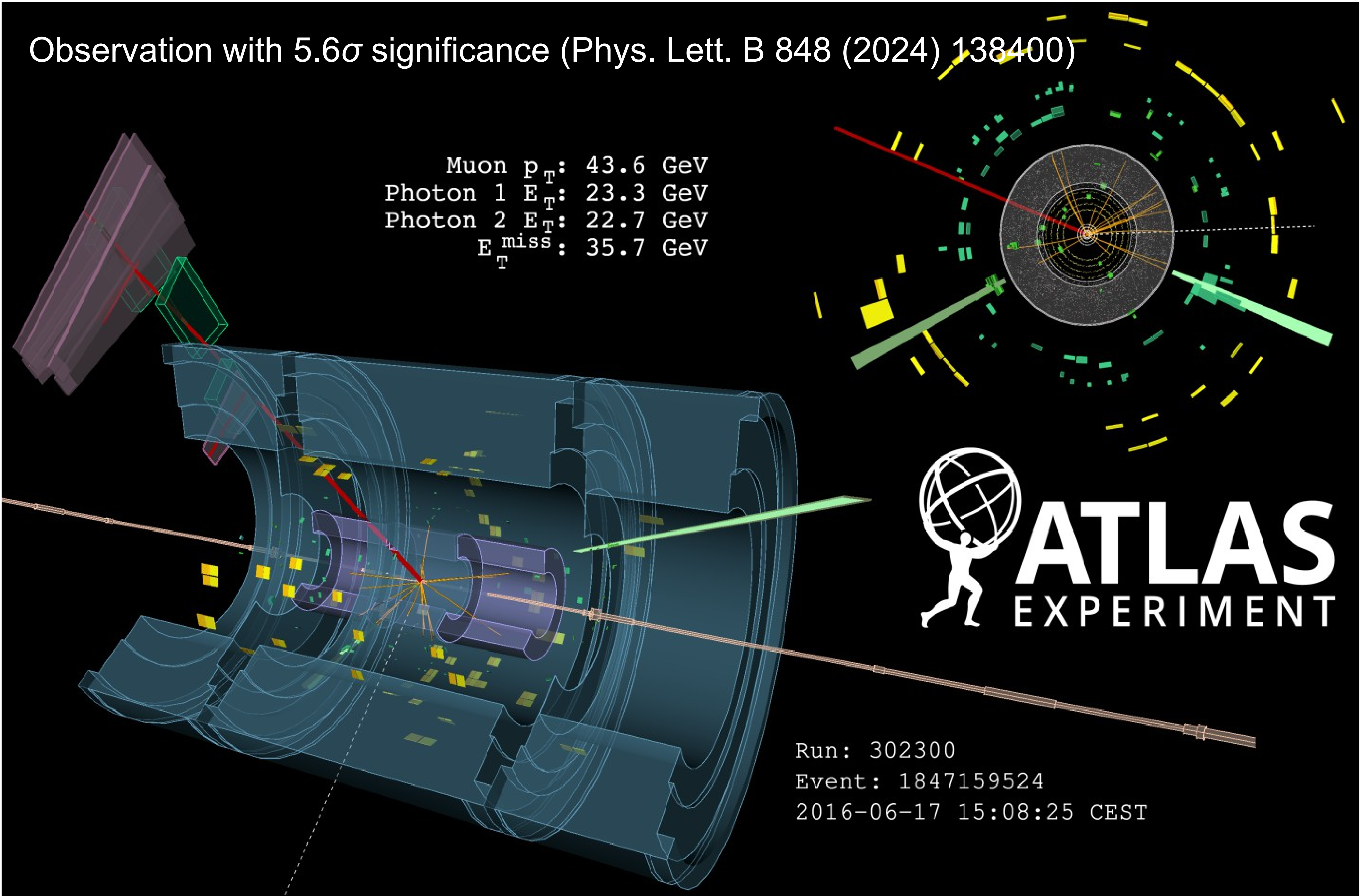




Triboson: recent observation of Wγγ

Observation with 5.6σ significance (Phys. Lett. B 848 (2024) 138400)



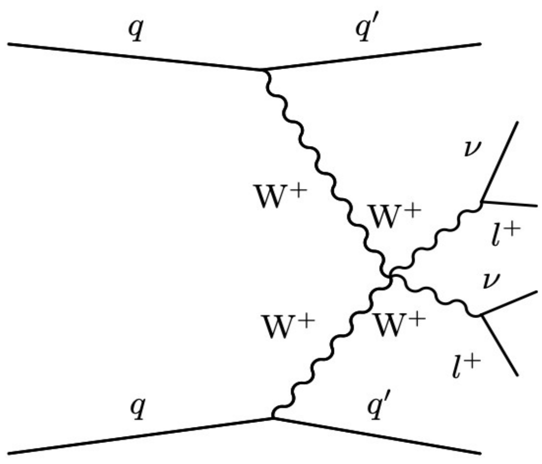
ATLAS EXPERIMENT

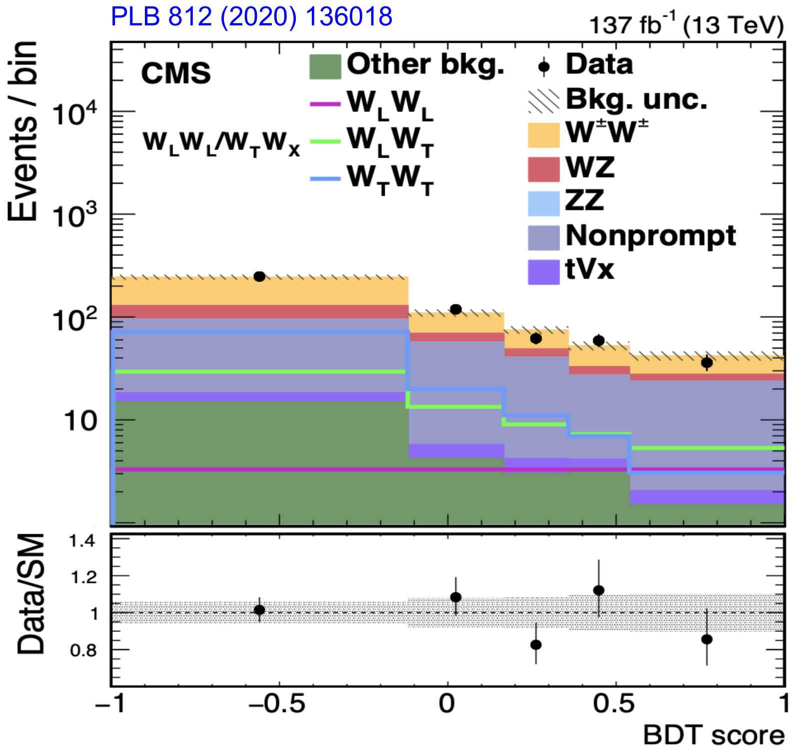
A word on diboson polarisation

- Study of diboson polarization is an important additional check of the EWSB
  - Longitudinal polarisation generated by Goldstone bosons in EWSB
  - Unitarity of V_LV_L scattering cross section at high energies guaranteed by gauge asymmetry

- Experiments gaining sensitivity to V_LV_L production and starting to study energy dependence of cross-section. Active field on both theoretical and experimental side!

- E.g. Analysis of VBS $W_L^\pm W_X^\pm jj$ and $W_L^\pm W_L^\pm jj$ by CMS
  - Three contributions in W±W± channel: $W_L^\pm W_L^\pm$, $W_L^\pm W_T^\pm$, and $W_T^\pm W_T^\pm$
  - A BDT used, with polarisation sensitive variables as inputs
  - Significance of the $W_L^\pm W_X^\pm$ process (where at least one of the W bosons is longitudinally polarized) is 2.6 σ observed





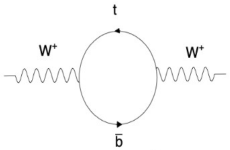
Global fit of the SM

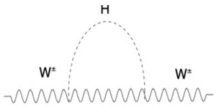
- As mention before: at loop level all other fields enter the game through loop corrections which can be parametrized. Creating a relation between the top quark, Higgs boson and W boson masses!

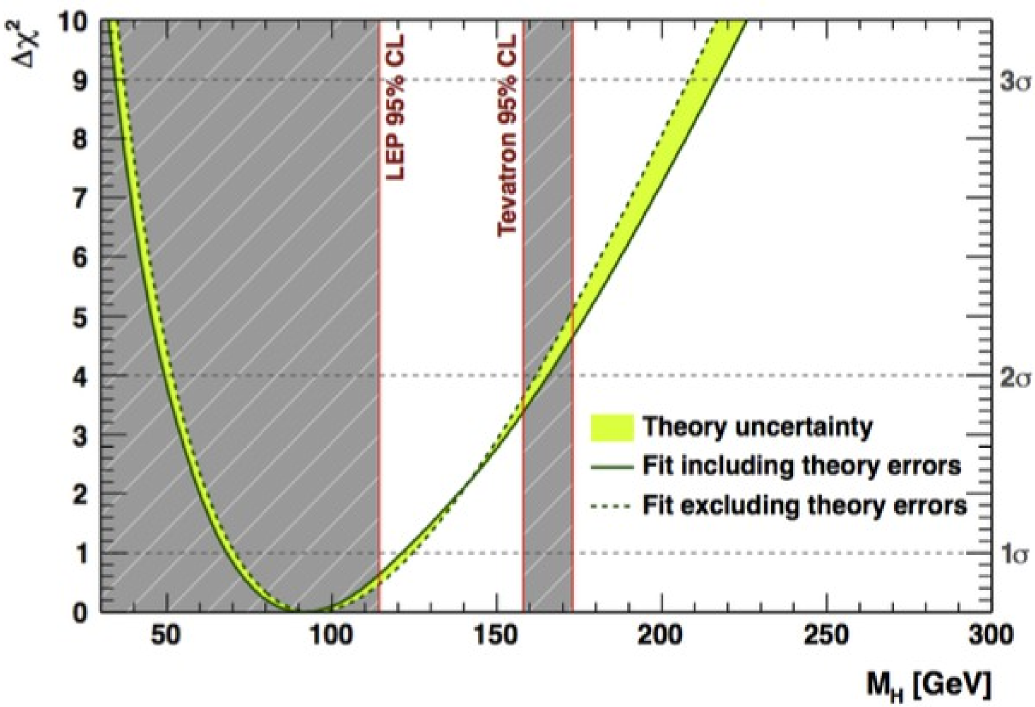
- A global fit of all relevant measurements can be then done to check the consistency of the Standard Model and predict parameters that are unknown: **Higgs boson mass!**

$$m_W = \left(\frac{\pi\alpha_{\text{EM}}}{\sqrt{2}G_F}\right)^{1/2} \frac{1}{\sin\theta_W} \frac{1}{\sqrt{1-\Delta r}}$$

$$\sin^2\theta_W \longrightarrow \kappa_f \sin^2\theta_W = \sin^2\theta_{\text{eff}}^f$$

fermion loops  $\Delta r \propto m_t^2$

Higgs boson loops  $\Delta r \propto \ln(m_H)$



Indirect measurement of the Higgs boson mass through its quantum effect on the precision observables.

mH = 91+30 GeV 23

Before the discovery of the Higgs boson!

Question #3

- The LHC is competing with previous machines in electroweak precision
- The LHC tests the electroweak theory at highest energies in multiboson measurements and measurement of the SM EWK parameters
    - Facilitated by large datasets, detailed understanding of the detectors, dedicated reconstruction techniques and state-of-the-art theory predictions
- They are precision probes improving our understanding of EWSB!

Why is important to study triboson topologies?

1) To measure the top quark charge

2) To obtain the most precise W measurement ever

3) To test quartic electroweak couplings

Outline

- Some reminders:
  - Fundamentals of hadron collision
  - Luminosity and total cross section

- Electroweak measurements
  - Measurements of SM parameters
  - Investigation of EW gauge structure

- Higgs physics
  - Couplings to other particles
  - Other Higgs boson properties
  - Higgs self-coupling
  - Global fit of the Standard Model

- Searching for new physics BSM

- A brief outlook on future colliders

A Higgs boson was discovered in 2012

A Nobel prize in Physics 2013 for Francois Englert and Peter W. Higgs:

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

The Standard Model (SM)

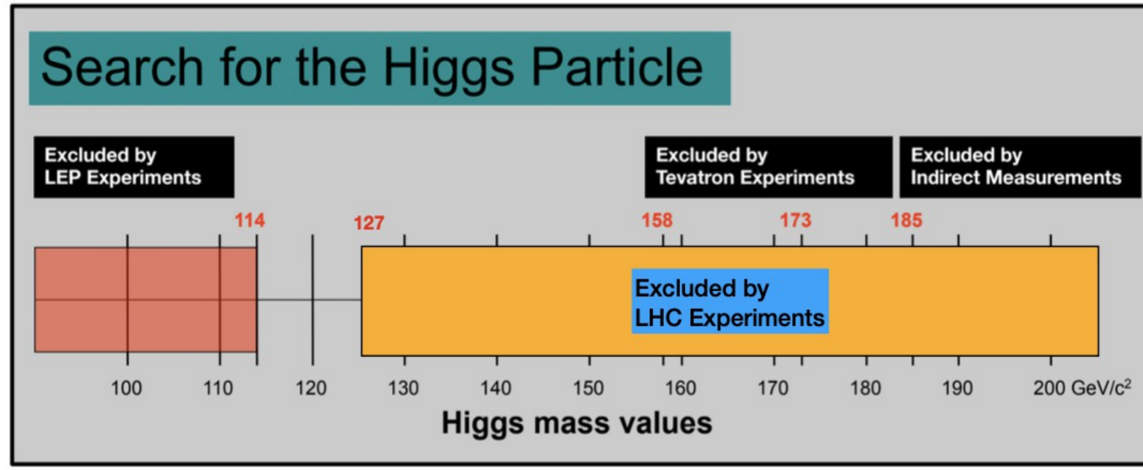
And the Higgs physics was born…

Standing ovation in the CERN auditorium at the end of the seminar announcing the discovery of the Higgs boson. (Image: Maximilien Brice, Laurent Egli/CERN)

The road to discovery

And the Higgs physics was born…

- **1964** R. Brout, F. Englert, and, independently, P. Higgs “theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles”
- **1989** the search for the Higgs Boson started to gain momentum at LEP
- **2001** the Tevatron at Fermilab continued the search
- **2010** the LHC entered the game
- Very quickly ATLAS and CMS excluded the existence of a SM Higgs in a very large mass range, spanning up to ~600 GeV... with the exception of a very narrow window ~125 GeV
- **Discovery in 2012!**



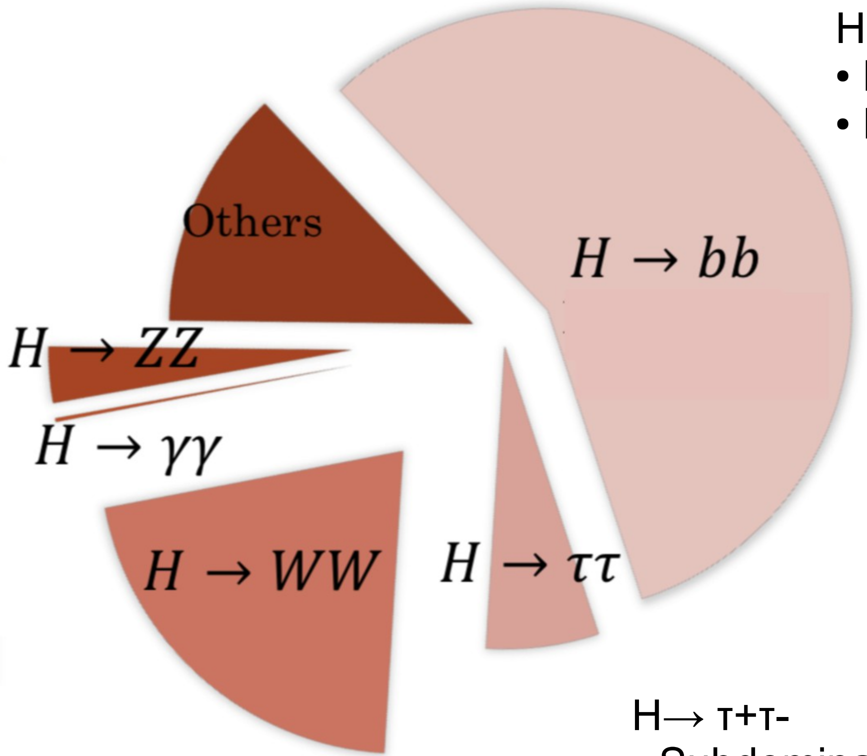
The buzz around the announcement was like that of a Lord of the Rings movie premiere, or the final Harry Potter book, with people queuing from the early hours to guarantee their seat to witness history. The queue wound its way from the auditorium on the first floor, down the main building staircase, through the cafeteria and out to the dining hall. (Image: Maximilien Brice/CERN)

Identifying the Higgs boson at the LHC: decay

Which production mode or/and decay is the best?

$H \rightarrow bb$
- Dominant decay (~58% BR)
- Huge backgrounds from QCD jets

$H \rightarrow Z(*)Z$
- Penalty from $Z \rightarrow l^+l^-$
- BR very clean, fully reconstructed



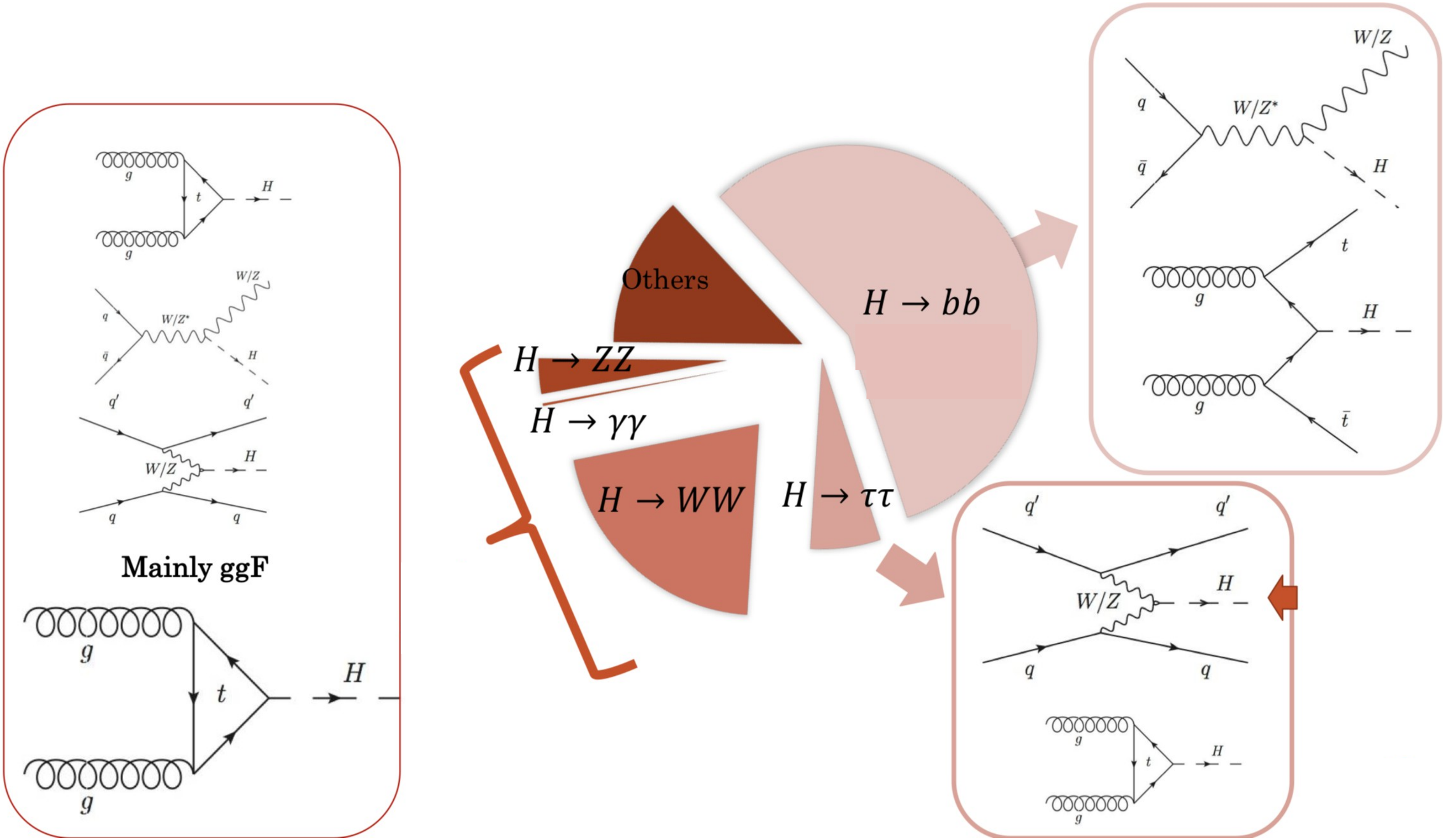
$H \rightarrow \gamma\gamma$:
- Very small BR
- Huge bkgs. from QCD photons and jets
- Fully reconstructed, clean mass measurement

$H \rightarrow W^+W^-$
- Subdominant (~22%)
- Incomplete reconstruction

$H \rightarrow \tau^+\tau^-$
- Subdominant (~6%)
- Incomplete reconstruction

There is an interplay between production and decay based on the backgrounds

Identifying the Higgs boson at the LHC: Interplay between production and decay



• Slide from George Aad's JRJC 2014 talk

Question #4

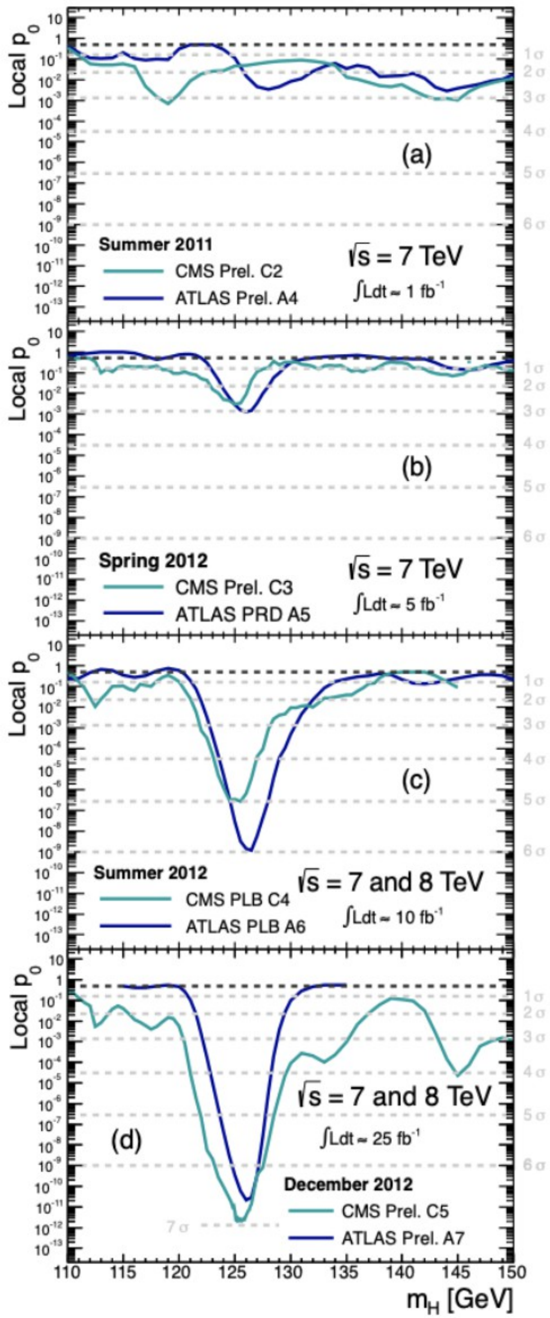
What does "observation of a new particle" mean?

1) the background plus signal hypothesis agrees with the data better than the hypothesis without new particle (background only)

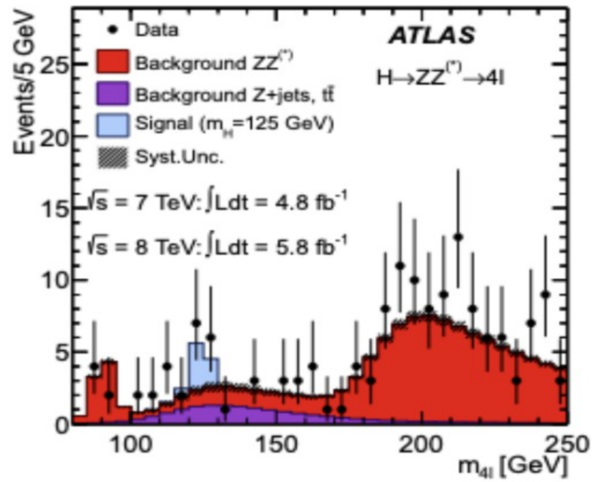
2) the background only hypothesis does not agree with the data

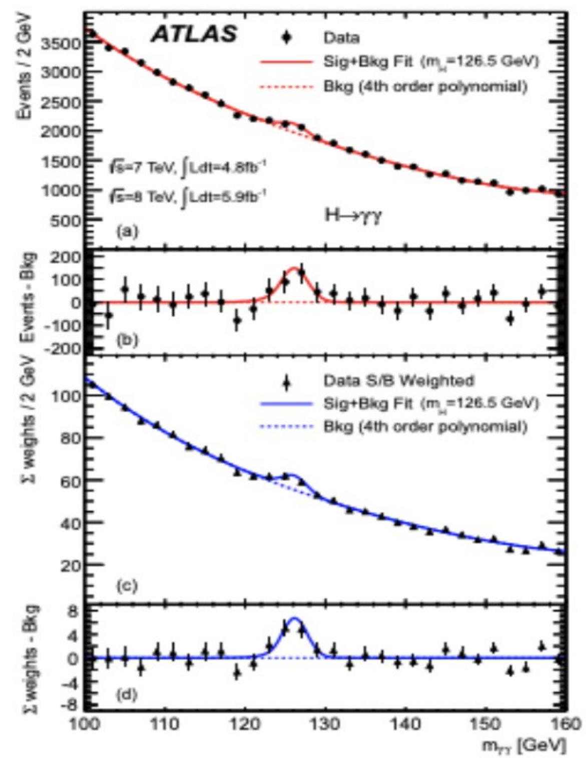
3) the background hypothesis agrees with the data

Textbook discovery



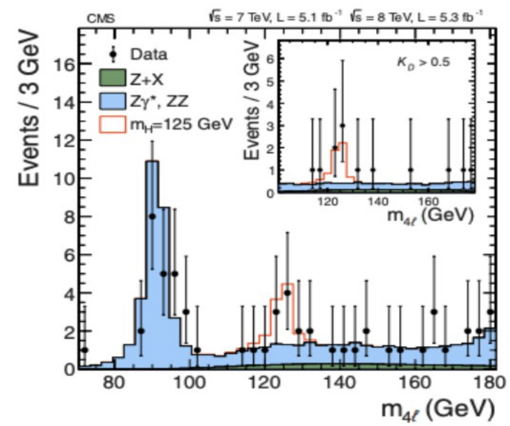
ATLAS

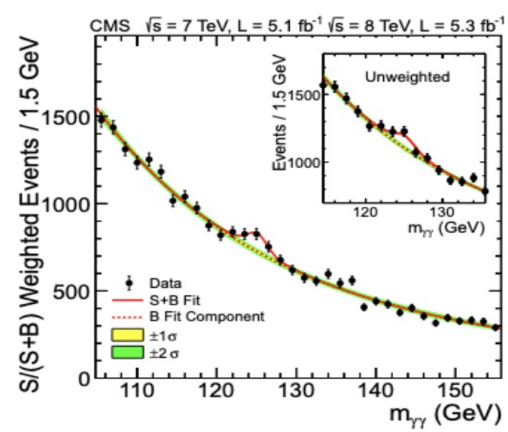




- Two independent experiments
- Two experimental signatures each
- Overall consistent picture
- ZZ and γγ were the first ones to be observed! Now we are doing precision measurements with them!

CMS





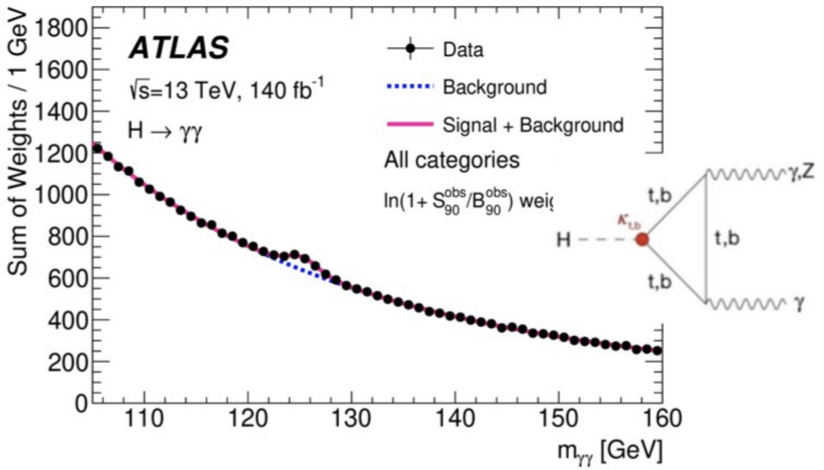
Higgs precision measurements: its mass

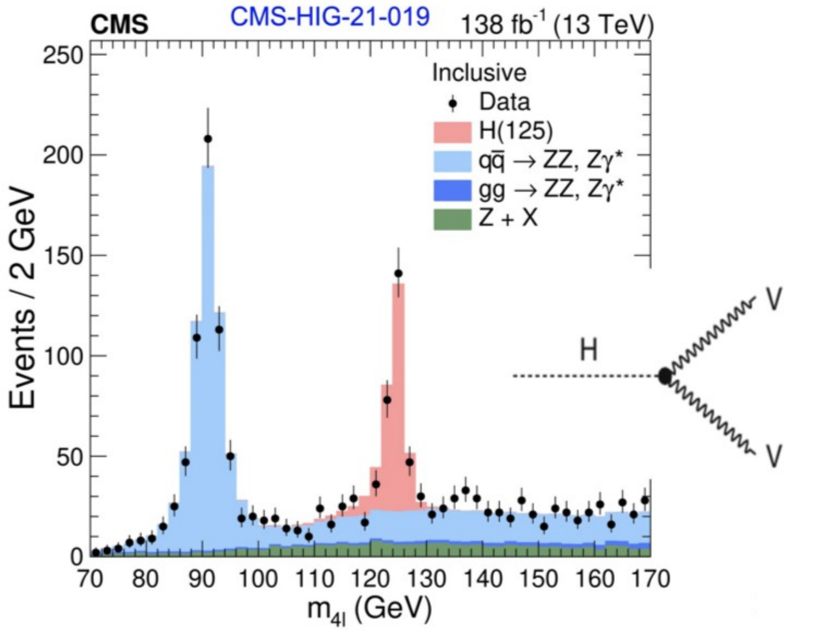
- Leading precision channels for mass measurements:
  - **H→ZZ→4l (e/μ):** Low statistics but clean final state, high signal/bkg. Still dominated by statistical uncertainties
  - **H→γγ:** High statistics and good $m_{\gamma\gamma}$ resolution. Smoothly falling background in $m_{\gamma\gamma}$. Large effort put to reduce uncertainties on photon energy calibration.

- **ATLAS uses a combination of both channels**
  - m_H = 125.08 ± 0.10 (stat.) ± 0.05 (syst.) GeV
  - Most precise measurement to date

- **CMS results comes from H→ZZ→4l**
  - M_H = 125.04 ± 0.11 (stat.) ± 0.12 (syst.) GeV
  - Most precise single measurement (< 1%)

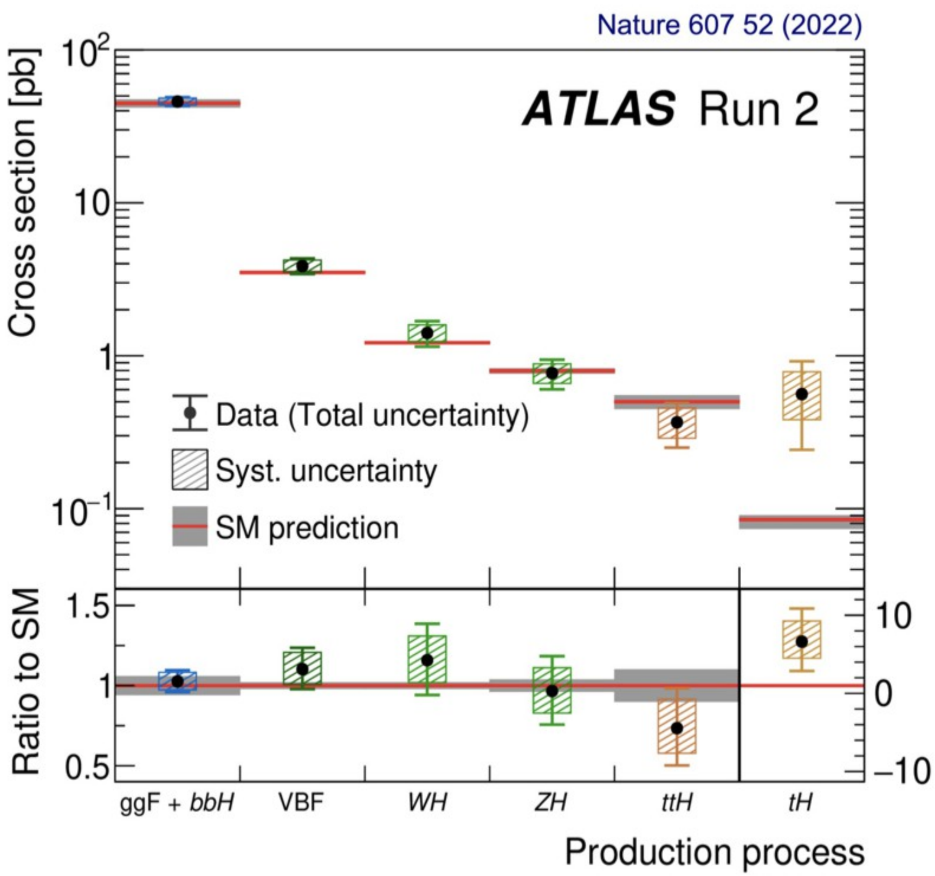
Phys. Lett. B 847 (2023) 138315
Phys. Lett. B 843 (2023) 137880

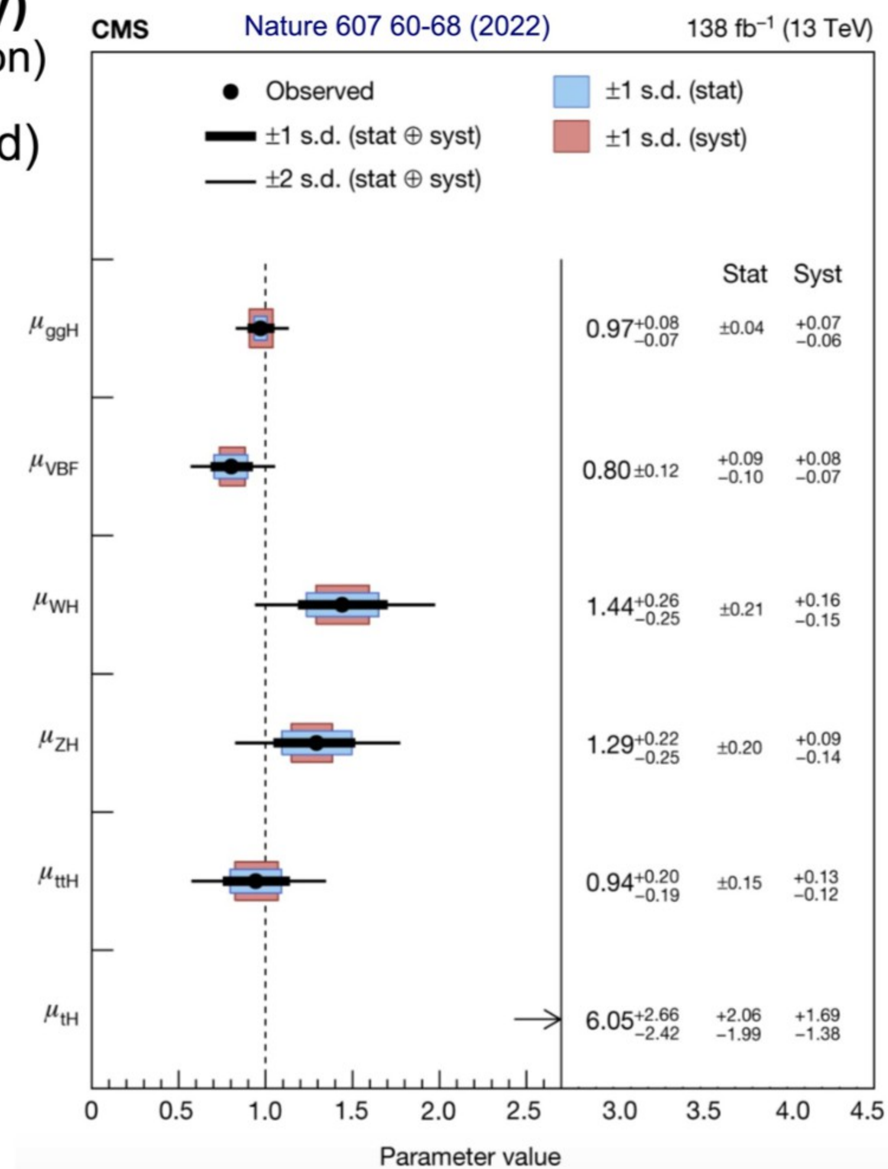




Let's talk about the Higgs production

- **Most dominant production modes observed (updated in 2022, 10th Higgs discovery anniversary)**
  - Results agree with SM prediction (no significant deviation)
- Upper limit on tH production 7xSM (15xSM expected)
- Let's also take a look at more recents results

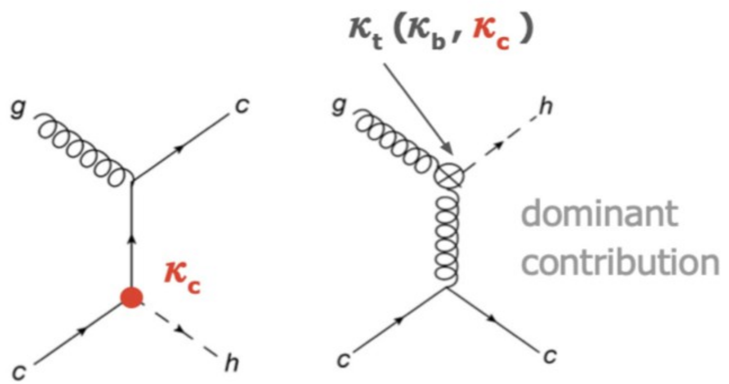


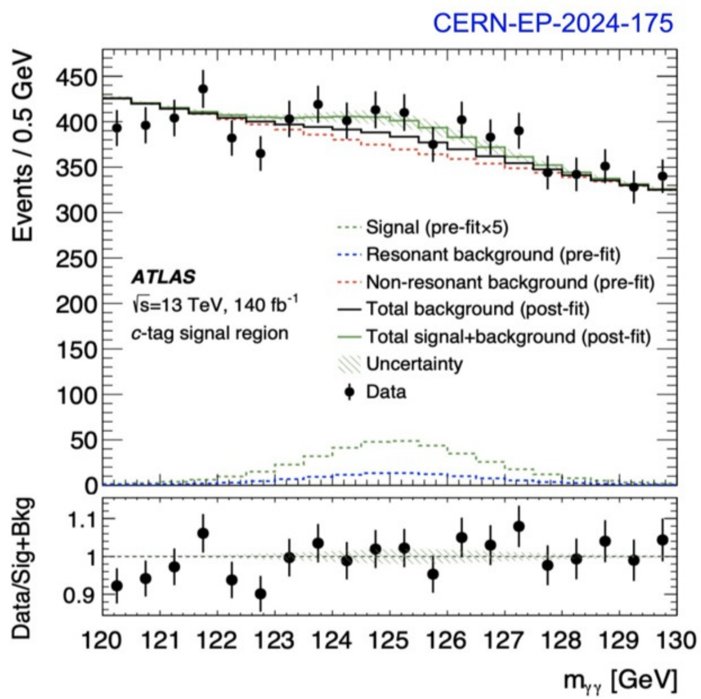


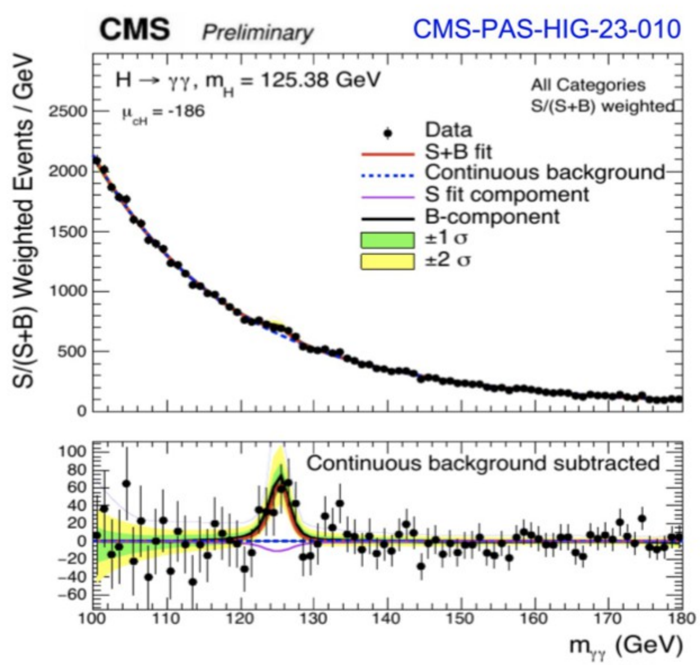
Signal strengths ($\mu=\sigma\cdot BR/\sigma\cdot BR_{SM}$)

Very rare production processes: H(→γγ)+c

- **Proving the c-coupling via the production**
- **Analysis strategy:**
  - Exploits the clean decay of H →γγ
  - Challenges: c-tagging, dominant contributions not sensitive to κ_c (~99%) in particular ggH backgrounds
  - Non-resonant bkg $pp \rightarrow \gamma\gamma + n$ is data-driven estimated





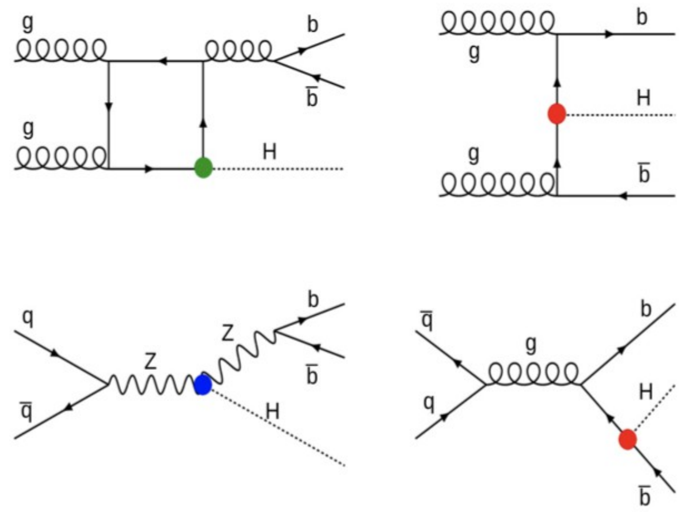


- ATLAS target inclusive H+c
- σ(H+c) = 5.2 ± 3.0 pb (SM: 2.9 pb), < 10.4 pb @ 95% CL

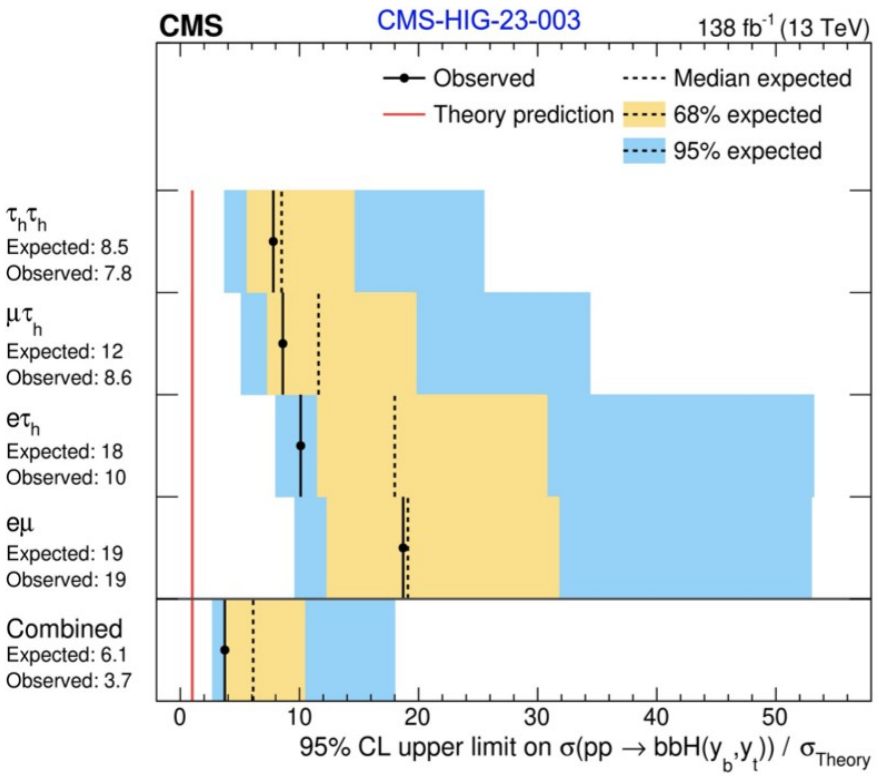
- CMS target κ_c-dependent part
- $\mu < 243\ (355) \Rightarrow |\kappa_c| < 38.1\ (72.5)$ @ 95% CL

Very rare production processes: bbH(→WW/ττ)

- **bbH cross-section ~ ttH cross-section**
- Sensitive to Higgs-b-quark and Higgs-top coupling
  - Quark loop dominates cross-section +destructive interference



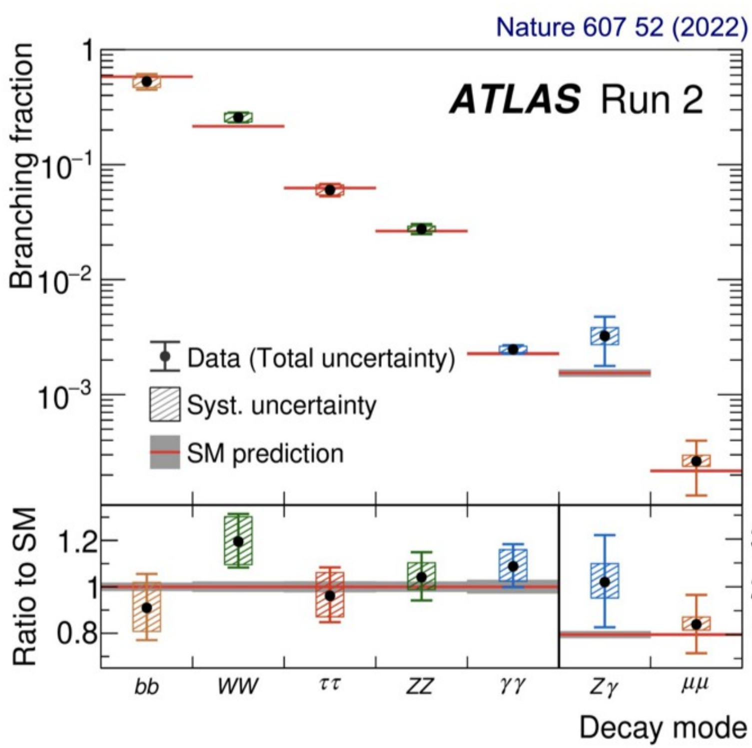
- **Analysis strategy:**
  - Decays to pairs of tau leptons and pairs of leptonically decaying W bosons are considered
  - BDT classifiers used in each of the studied channels
  - **Main challenges:** large backgrounds from Z+jets, tt, jet →τhad mis-ID
- μ <3.7 at 95% CL (exp. 6.1)

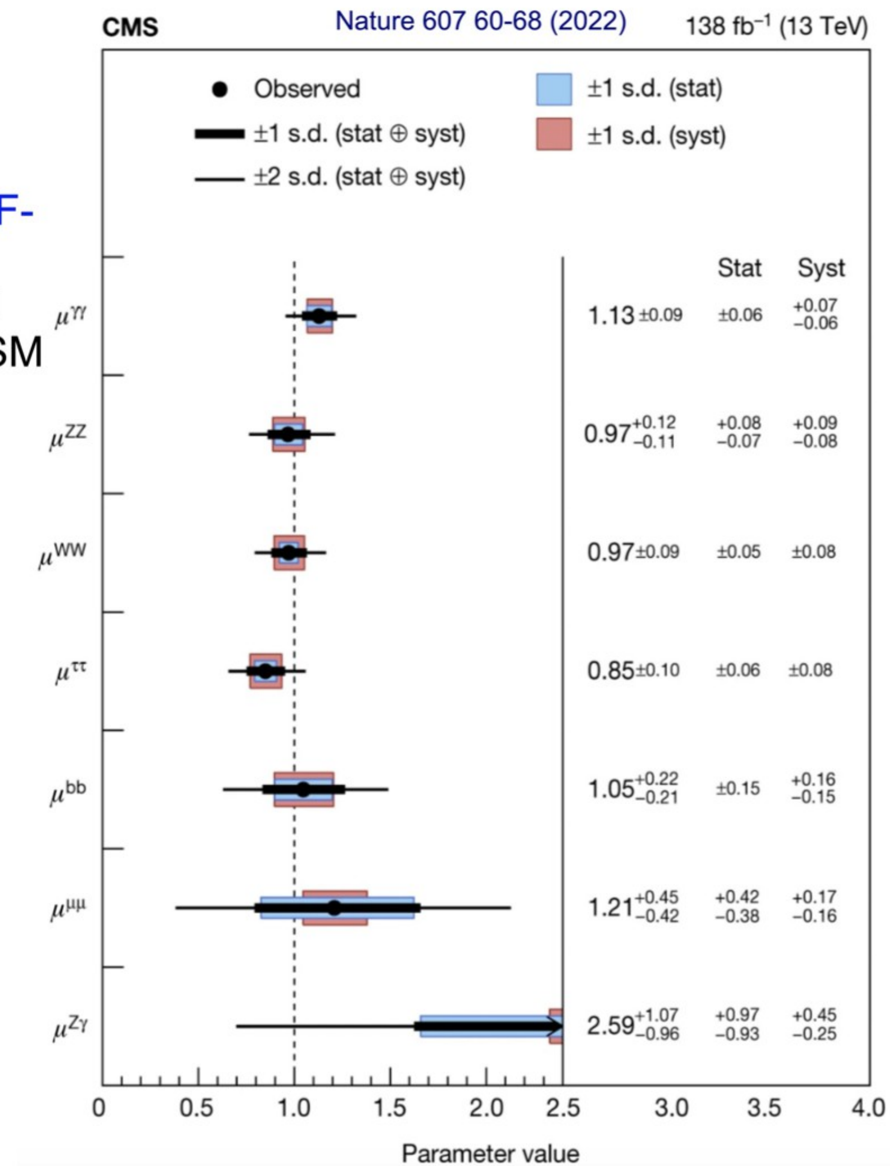


Let's talk about the Higgs decays

- **> 88% of potential SM decays observed and measured with < 10-20% precision (updated in 2022, 10th Higgs discovery anniversary)**
  - No observation of H→μμ, cc, gg...

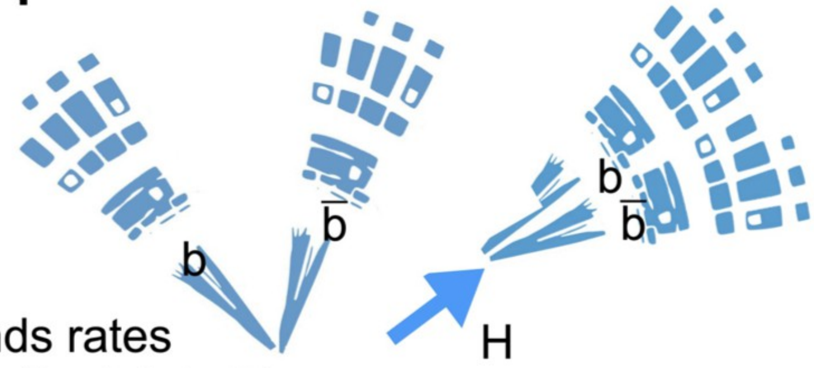
- Some recent results:
  - VH, H→ bb/cc, ATLAS Run-2 legacy [ATLAS-CONF-2024-010]
  - H→$\tau\tau$, ATLAS Run 2 legacy [HIGG-2022-07]. Total cross-section values computed and agreeing with SM





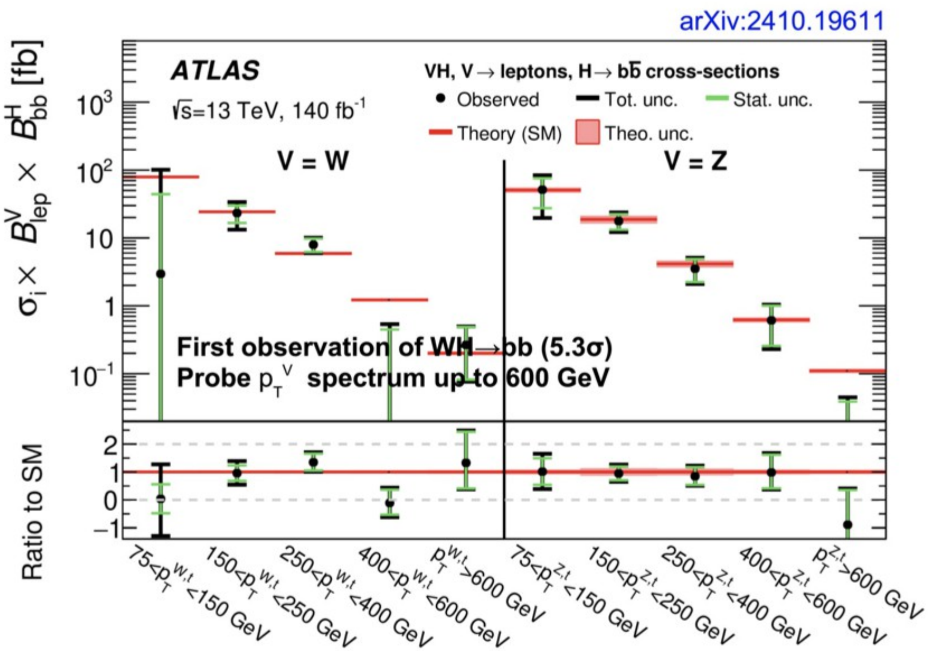
A challenging channel: H→bb/cc

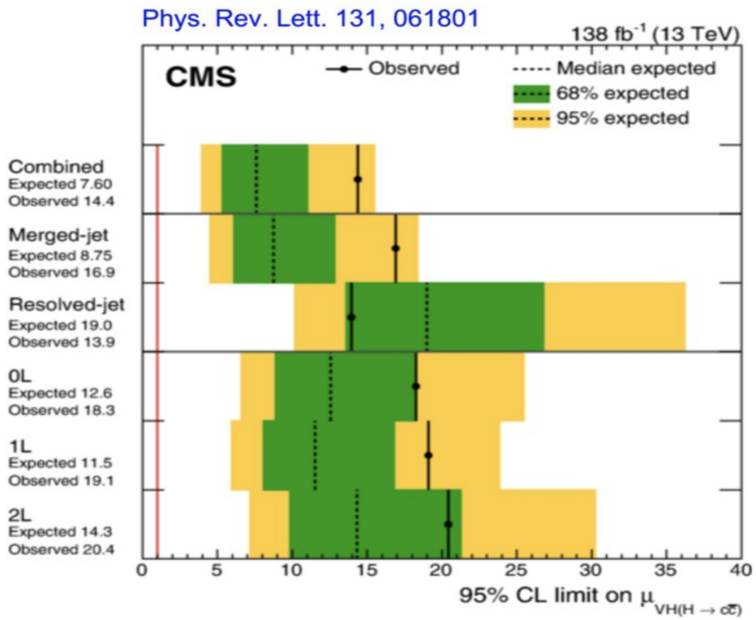
- **H → bb largest Higgs decay BR (58%) and H→cc probes coupling to 2nd generation quark**



- **Analysis strategy for VH, H→bb:**
  - Boosted (p_T^V > 250 GeV) and resolved topologies
  - Split signal according to number of leptons
  - **Challenges**: poor kinematic resolution, high backgrounds rates (V+jets and top) and requires excellent performance for the b-jets ID

- Observation of H→bb in 2018, now in full diffe measurements mode. Results compatible wit

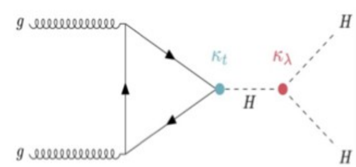




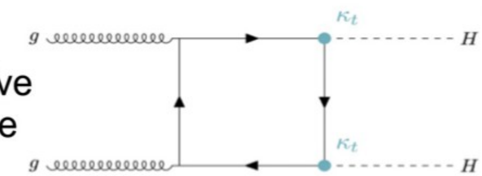
- Includes boosted H→cc (p_T^H > 300 GeV)
- μ<14(8)xSM obs.(exp.) @95% CL and 1.1<|κ_c| <5.5
- First observation of Z→cc in hadronic collisions

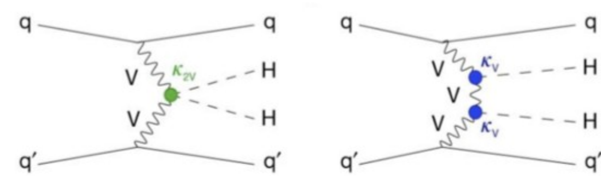
On the search side: HH production

- Another way of probing the EWSB mechanism: making progress towards **testing the shape of the Higgs potential through the Higgs self-coupling**
  - Rare process in SM: σ(gg→HH) ≈0.1%*σ(gg→H)
  - LHC has generated ~7.5 million Higgs boson but only 4500 Higgs-boson pairs in Run-2

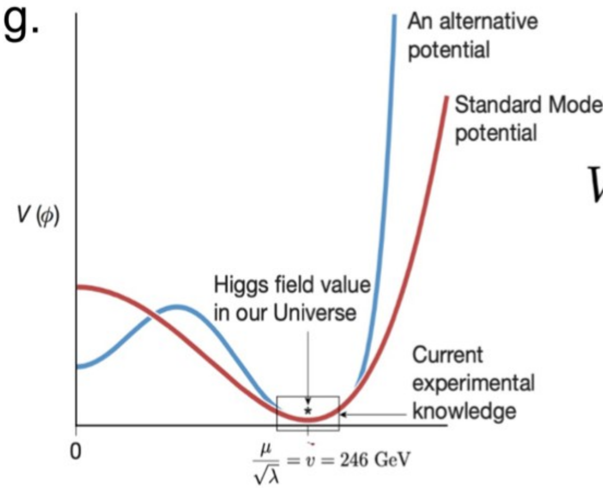


+ destructive interference





- Access the triple Higgs boson coupling (κ_λ)
  - Probe the shape of the Higgs potential
- Also access to other interactions, e.g. VVHH (κ_{2V})



$$V = V_0 + \frac{1}{2} m_H^2 h^2 + \boxed{\frac{m_H^2}{2v^2} v h^3} + \ldots$$

Higgs boson mass: know to 0.2%

Higgs boson self interaction

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

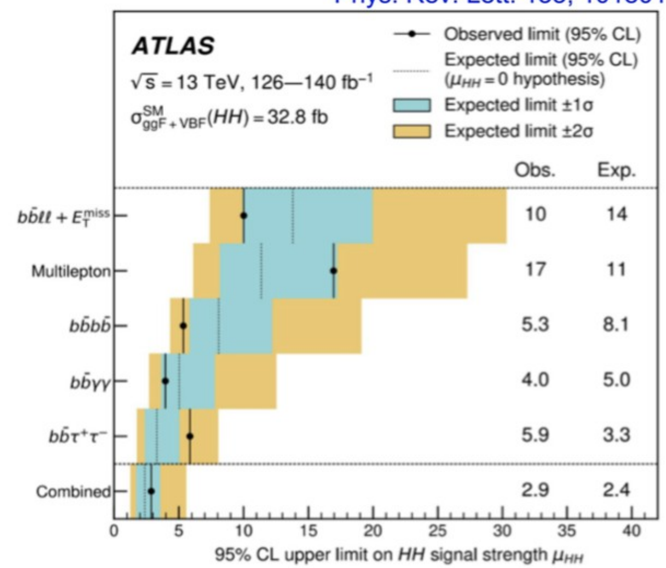
☐ = Existing results

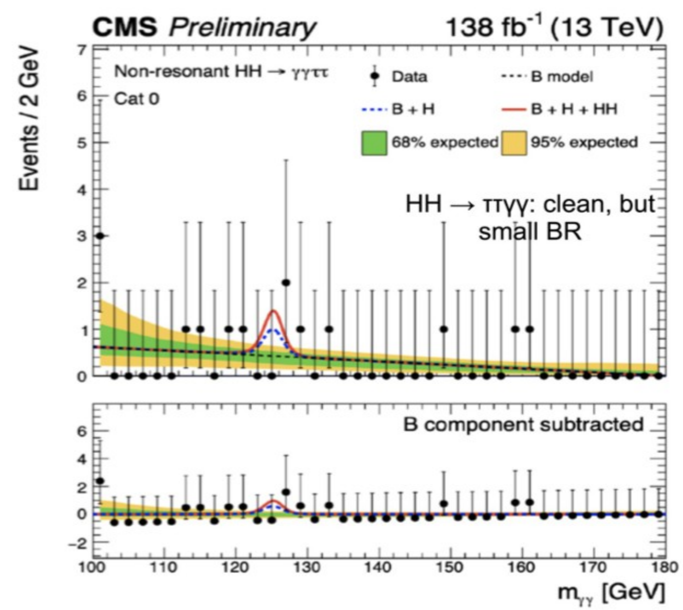
- No golden channel, therefore a combination is important to increase sensitivity!

On the search side: HH production

- **ATLAS Run-2 HH combination (bbττ + bbγγ + bbbb + multileptons + bbll+MET)**
  - Best (exp.) upper limit on σ(ggF HH): < 2.9 (2.4) × SM @95% CL
- **Similar result obtained by CMS** [Nature 607 (2022) 60] with same channels
- Observed limits on κ_λ:
  - ATLAS: [-1.2, 7.2]
  - CMS: [-1.24, 6.49]
- Hierarchy of channels depends on many things → not the same in ATLAS/CMS
- **Current constraints on κ_{2V}:**
  - ATLAS: [0.6, 1.5] Phys. Rev. Lett. 133, 101801
  - CMS: [0.67, 1.38] Nature 607 (2022) 60
  - Dominated by bbbb
- The following aspects are key to progress towards HH evidence:
  - Good detector performance
  - Improvements of analysis and object performance technique
  - Exploring new channels

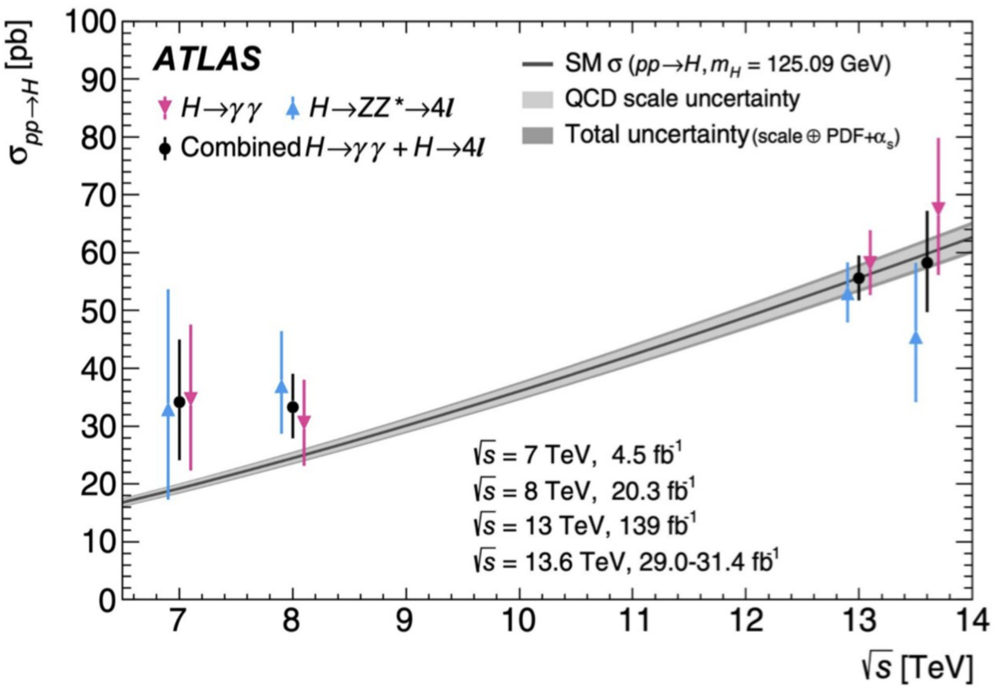
Phys. Rev. Lett. 133, 101801



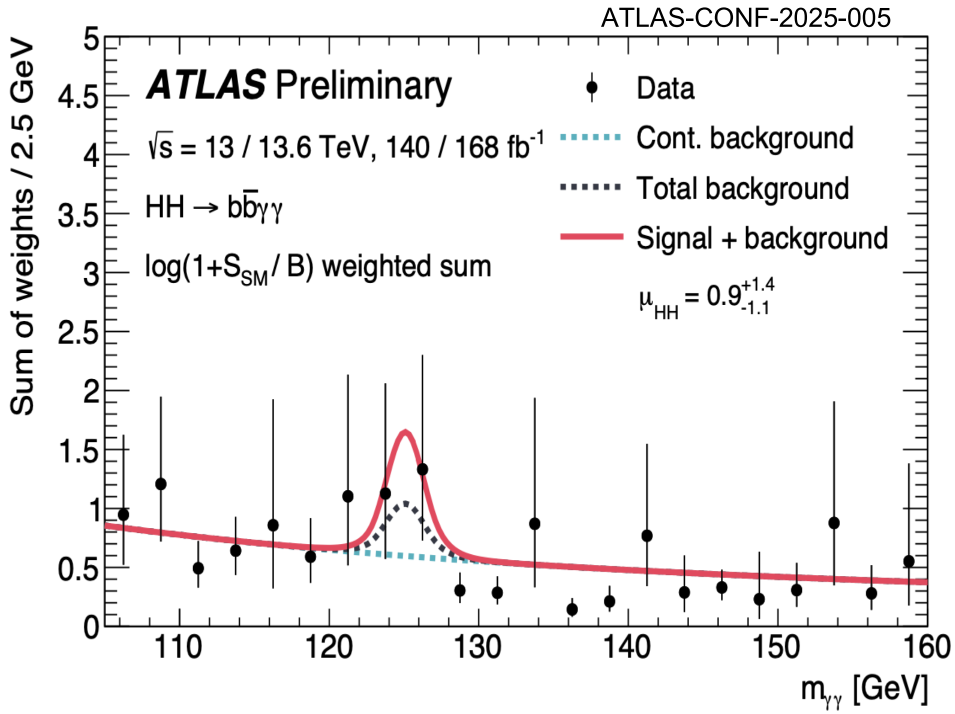


Analyzing the Run-3 data

- **Comparing 13.6 TeV measurements with Run-1 and Run-2 results**: good agreement with SM predictions! Expected trend predicted by the SM

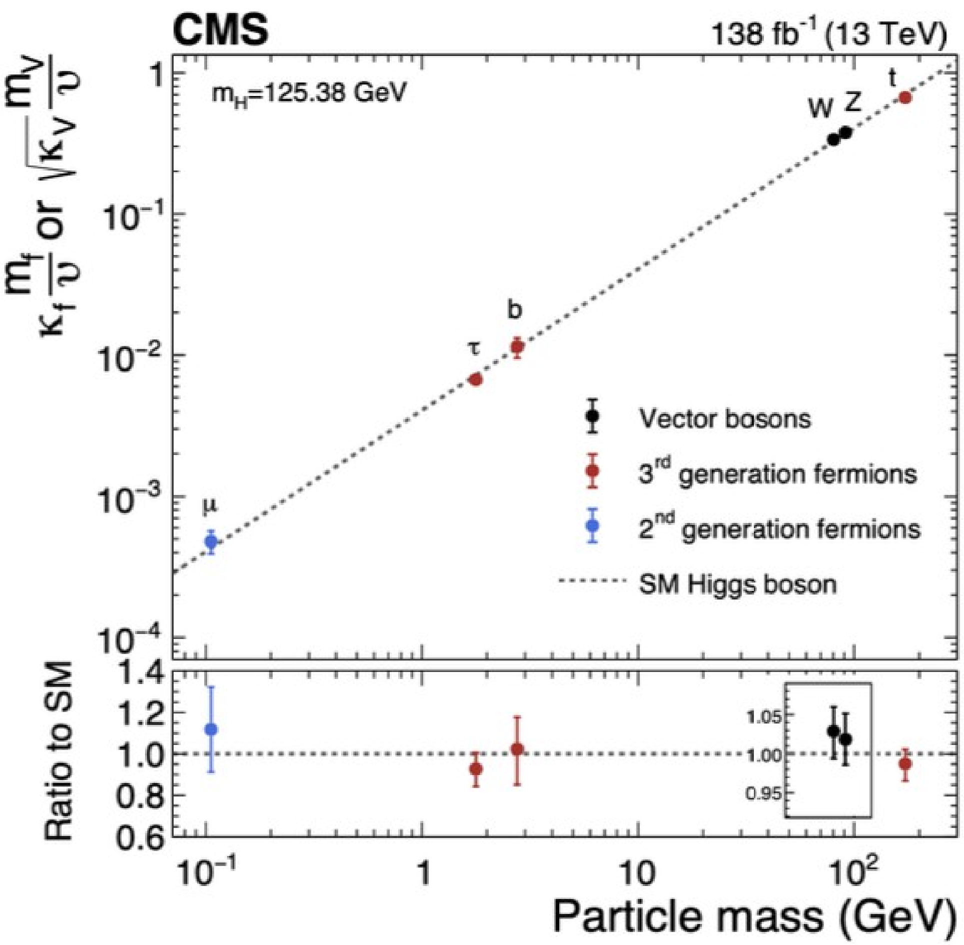


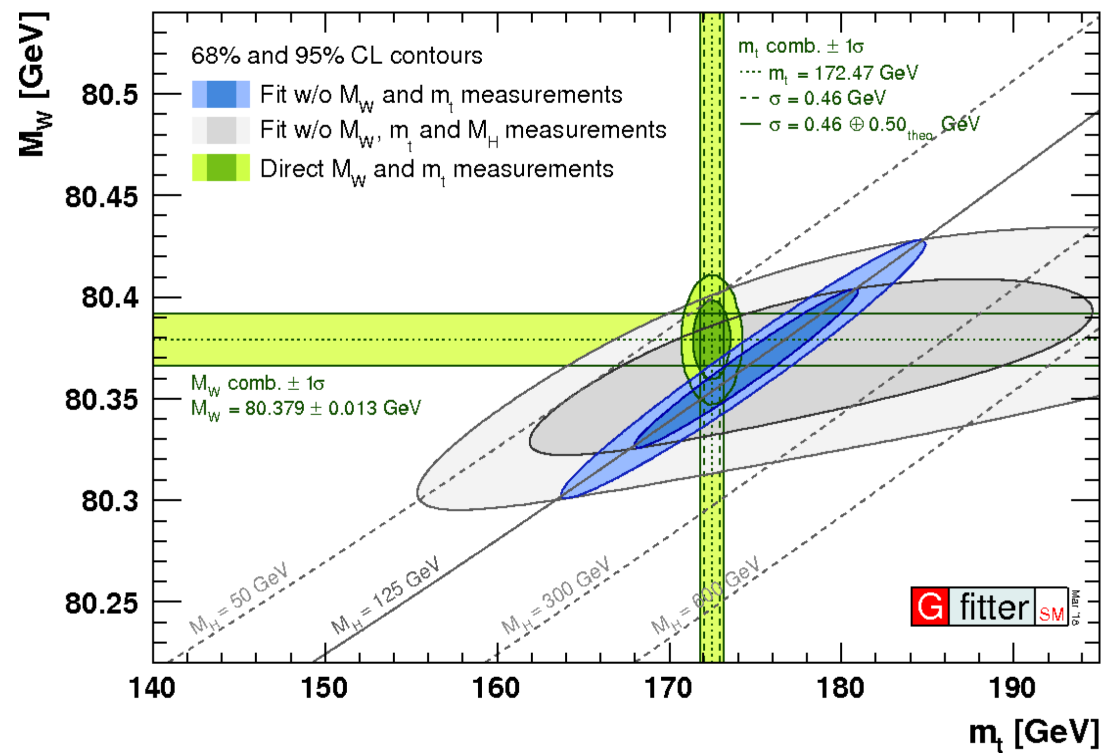
- **Run 3 HH→bbγγ**: First ATLAS result using 308 fb^{-1} data! 140 fb^{-1} Run 2 data (2015-2018, √s = 13 TeV) and 168 fb^{-1} Run 3 data (2022-2024, √s = 13.6 TeV)



Observed significance of SM HH: 0.8σ

Everything looking SM-like?

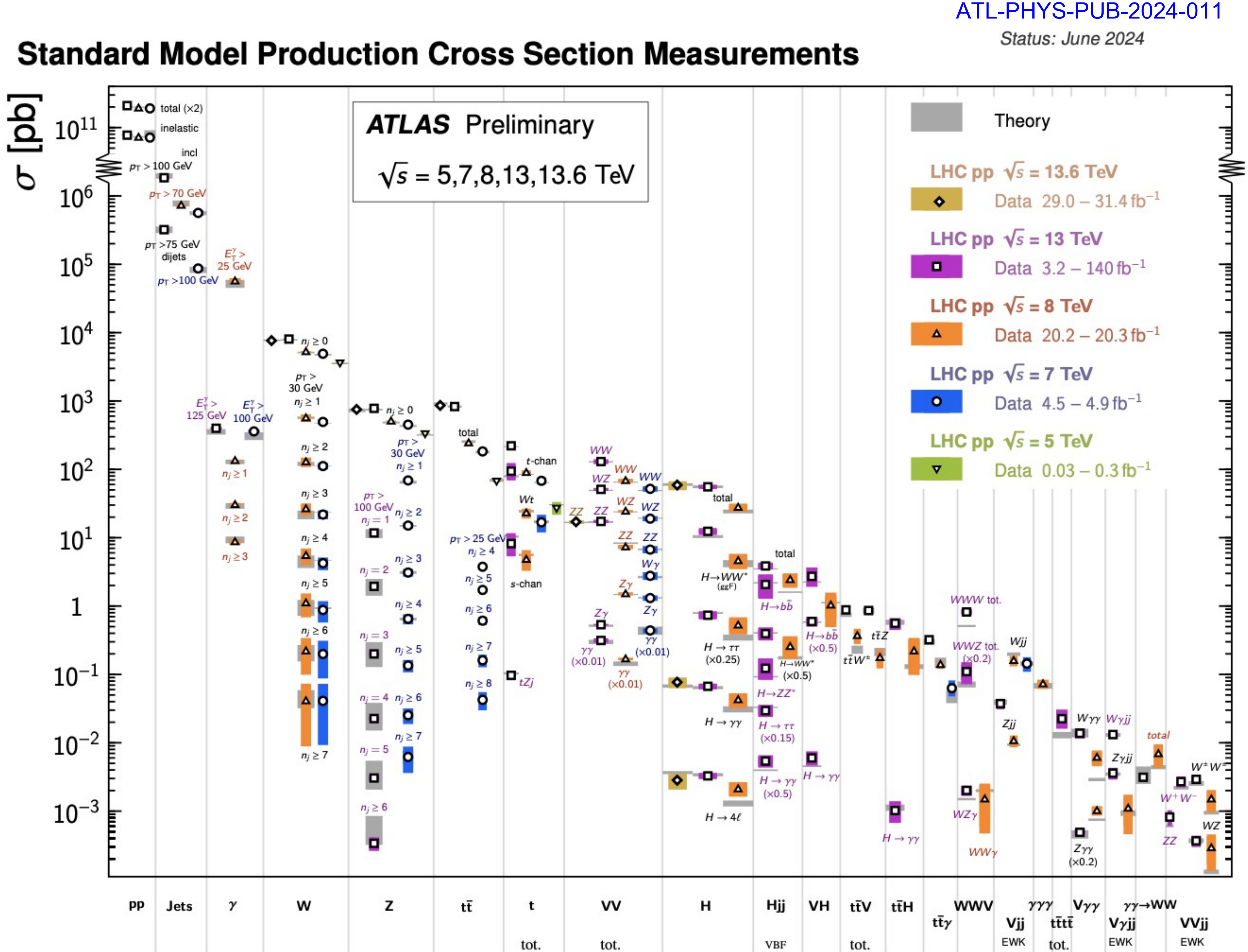




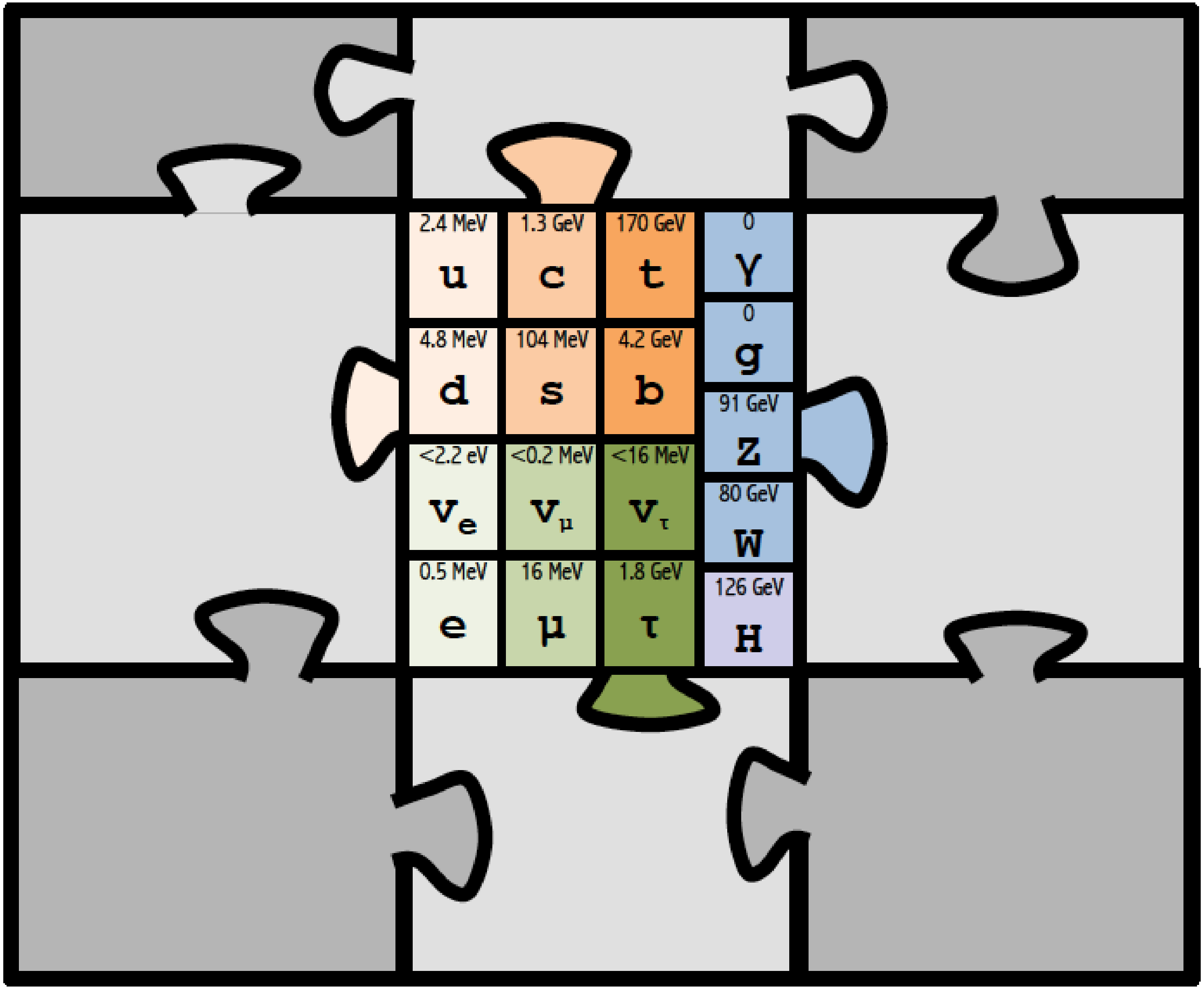
Knowing the Higgs boson mass has a large impact on global analysis

And a few more SM measurements

ATL-PHYS-PUB-2024-011



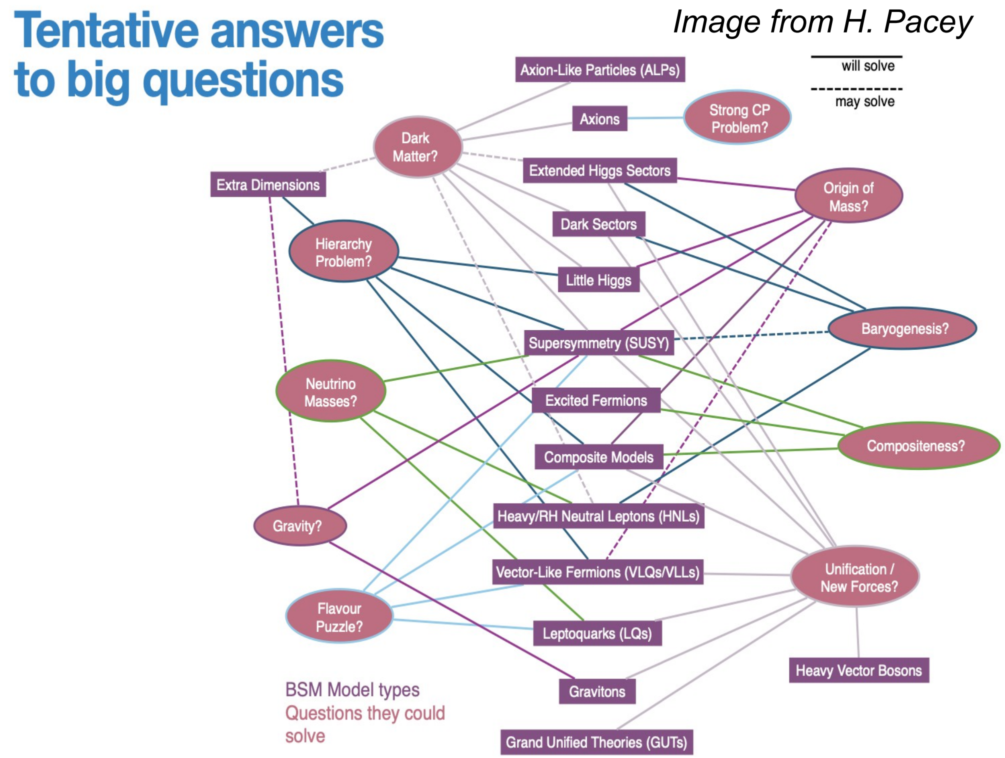
Is there something else beyond the SM?



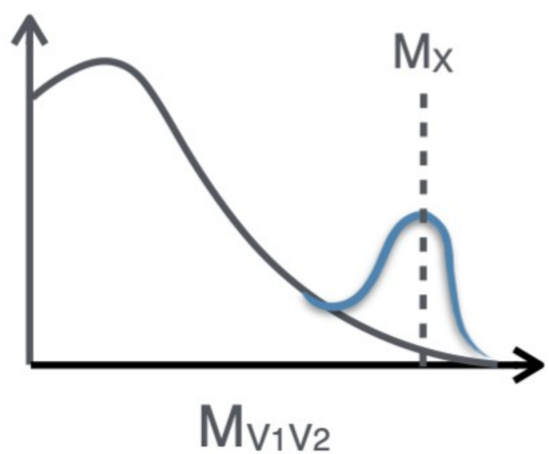
New physics portals?

- Many extended Higgs theories have over parts of their parameter space a lightest Higgs scalar with properties very similar to those of the SM Higgs boson
- Beyond measuring SM particle properties with precision, we can look for new particles, e.g. additional Higgs bosons Higgs boson decays to new particles

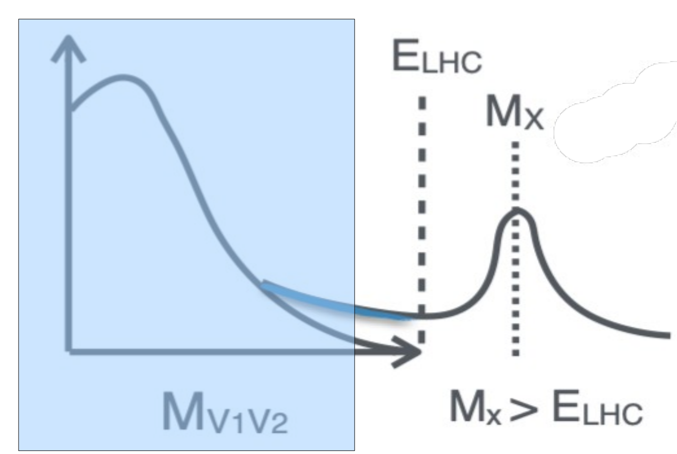
Image from H. Pacey



Direct searches: new resonances

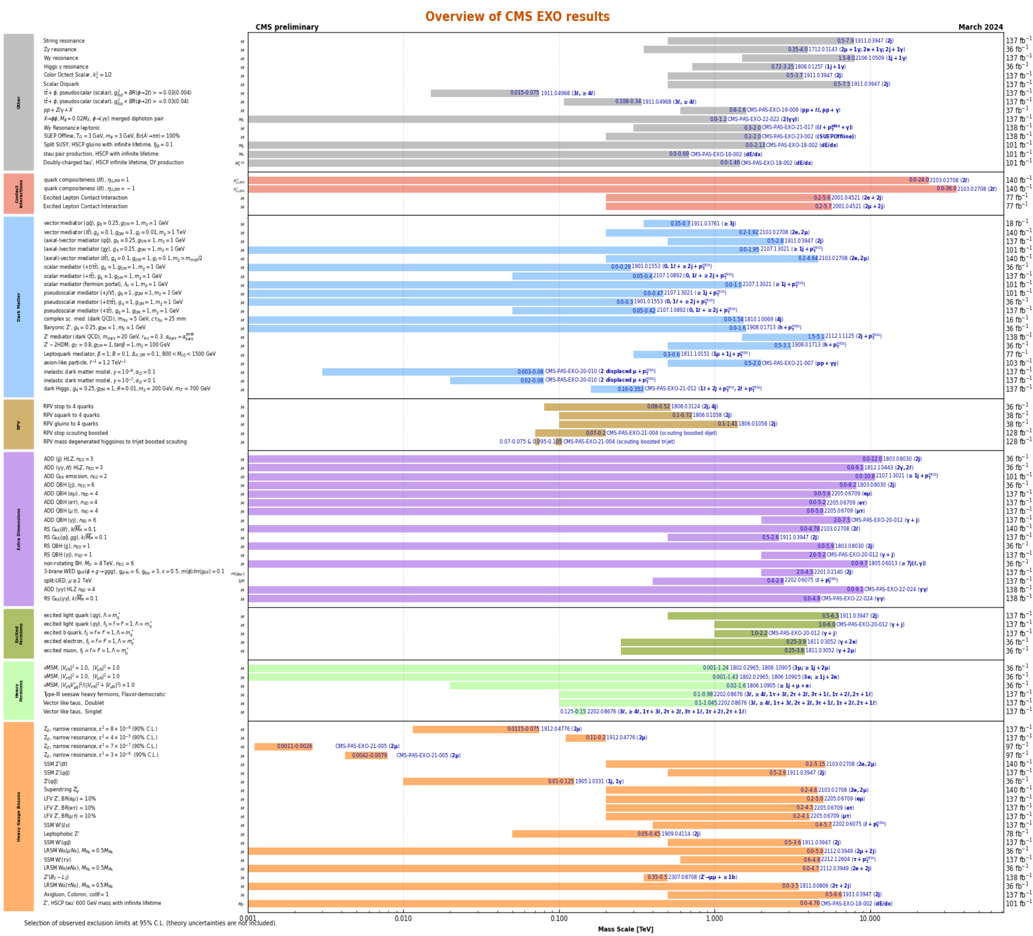


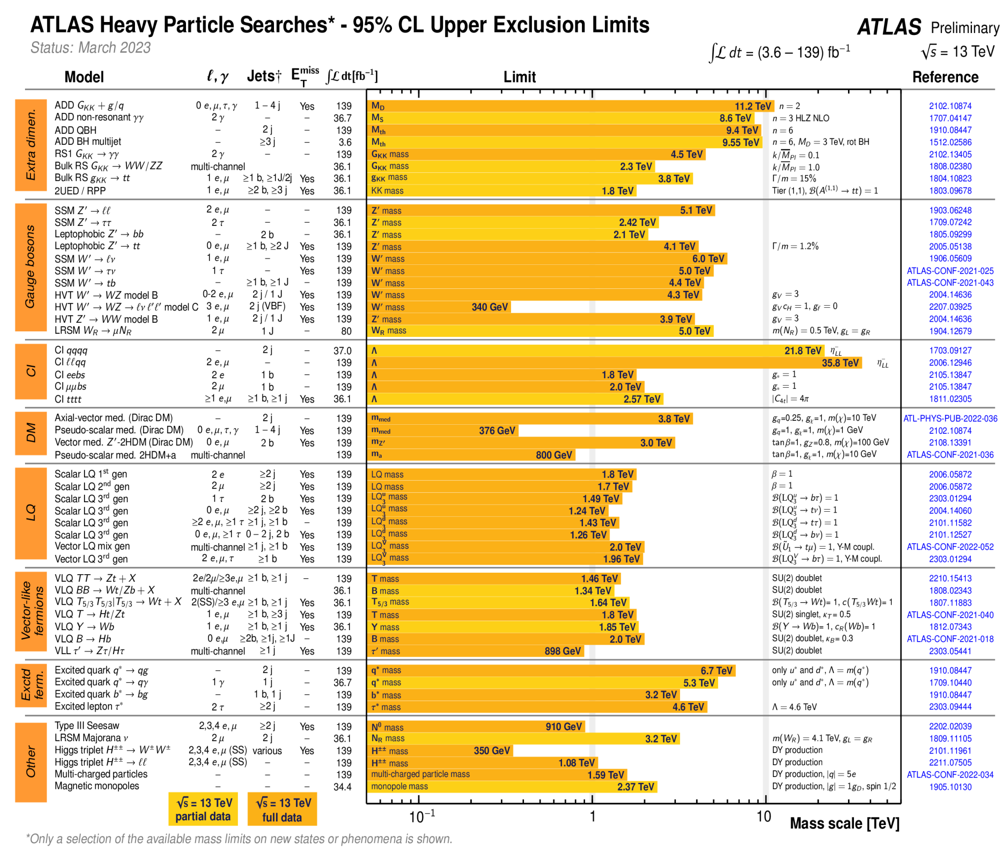
Indirect searches: beyond LHC reach can still leave measurable fingerprints



New physics portals?

- A huge BSM program at LHC!
  - Exploiting the strengths of our particle physics community to ensure deep but focused coverage of well-motivated models,
  - And also broad but shallow coverage for more speculative models, exploiting extra data and instrumental/tools/methods developments





Question #5

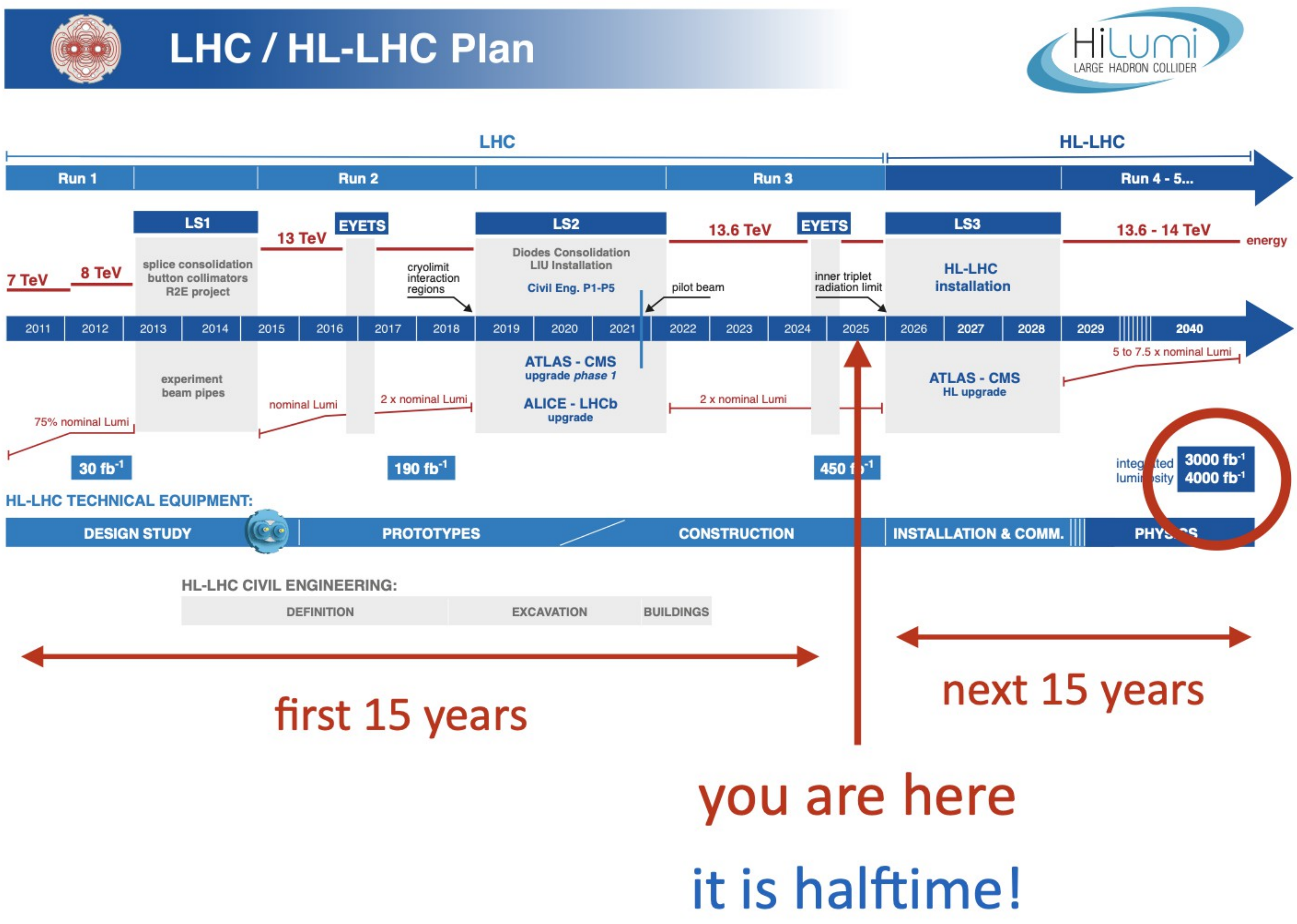
What is the most promising observation channel for HH?

1) HH → bbbb

2) Difficult to say, should pursue a combination

3) HH → bbχχ

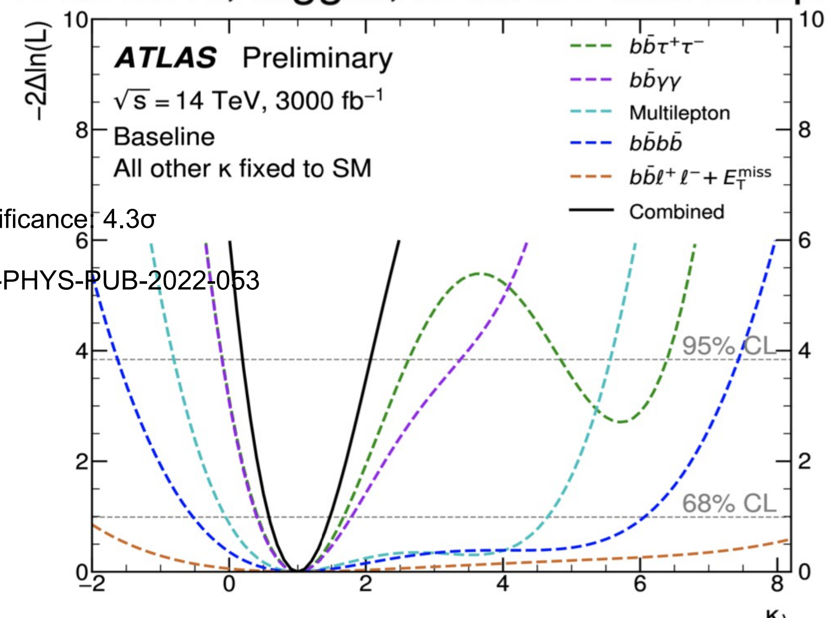
The near future: High luminosity (HL-) LHC



The near future: High luminosity (HL-) LHC

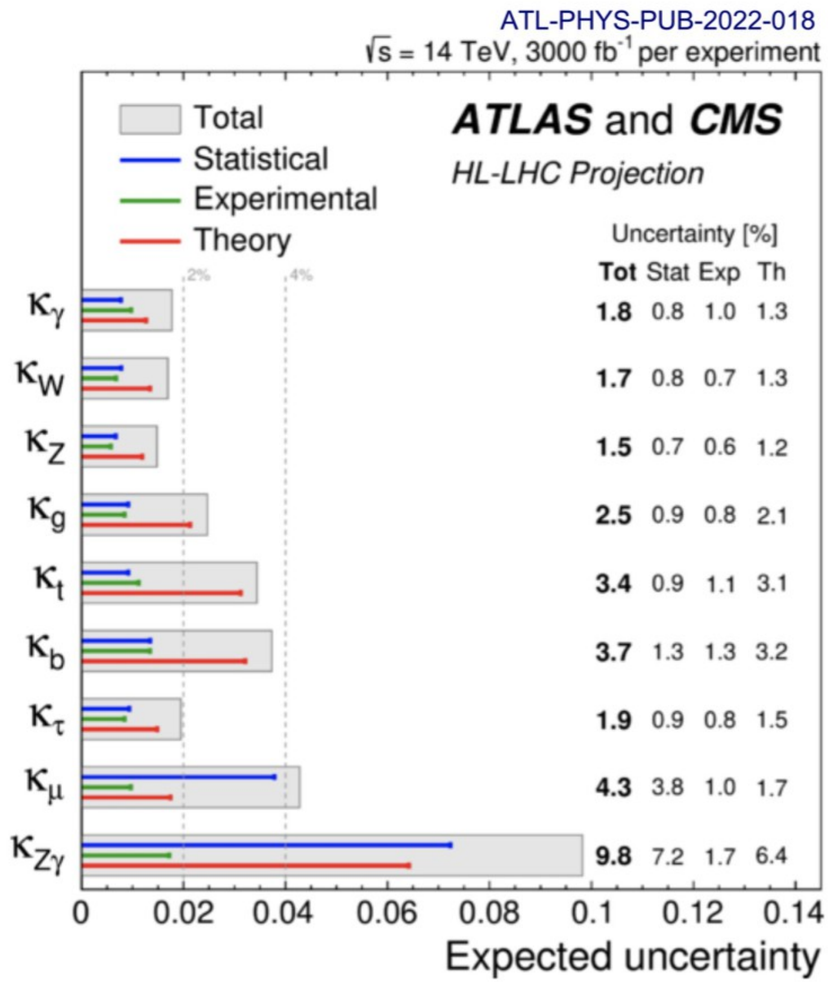
- **HL-LHC will dramatically expand the Higgs physics reach**
  - 170M Higgs bosons - 120k HH pairs for 3000/fb
- **But also challenging!**
  - More pile-up, beam induced cavern background, radiation to detectors
  - Big challenges for computing and data storage given the larger dataset

- **Requires improvements for experiments in all areas**
  - Detectors, trigger, software and computing



Significance: 4.3σ

ATL-PHYS-PUB-2022-053



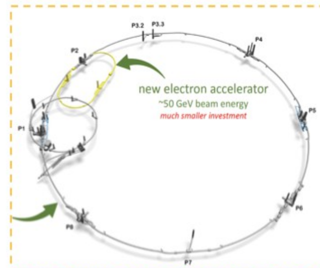
- 2-4% precision for many of the Higgs couplings. Theory uncertainty remains the largest component for most measurements
- Different uncertainties scenarios considered in these studies

Further along in time?

FCC-ee

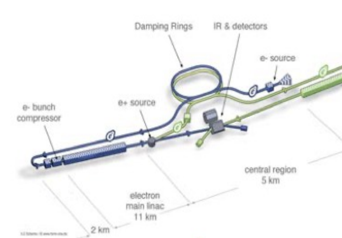
LEP3

LHeC

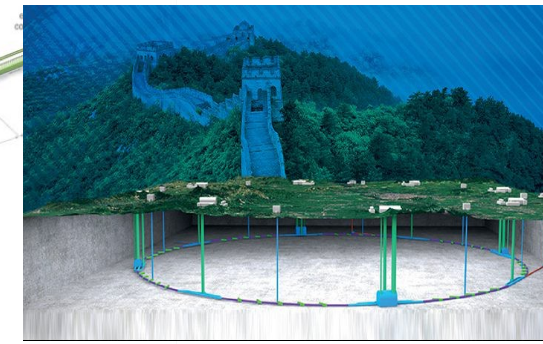


PERLE

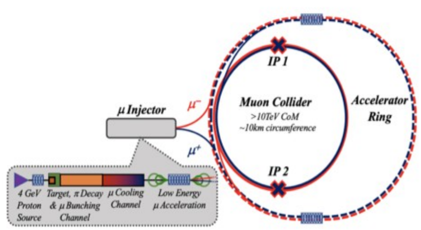
LCF, CLIC



Circular Electron Positron Collider (CEPC)



FCC-hh,
baseline 85 TeV (→ 120 TeV)



Muon Collider (3, 10 TeV)

R&D

e^+e^- with improved acceleration technologies
LCF, C^3 (→ 1 TeV), CLIC (1.5 TeV), HALHF, …

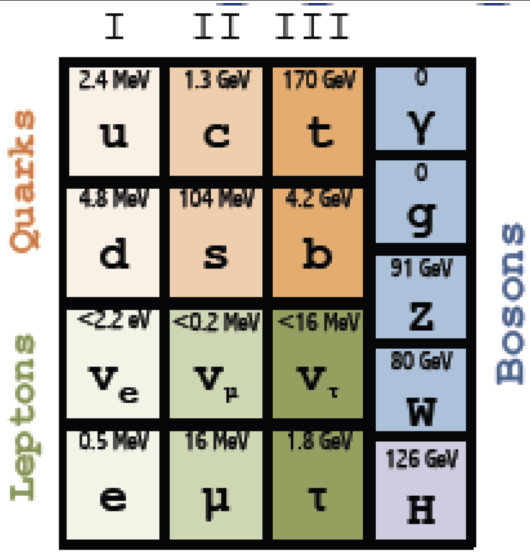
Suggest to check the ECFA session at EPS-HEP 2025

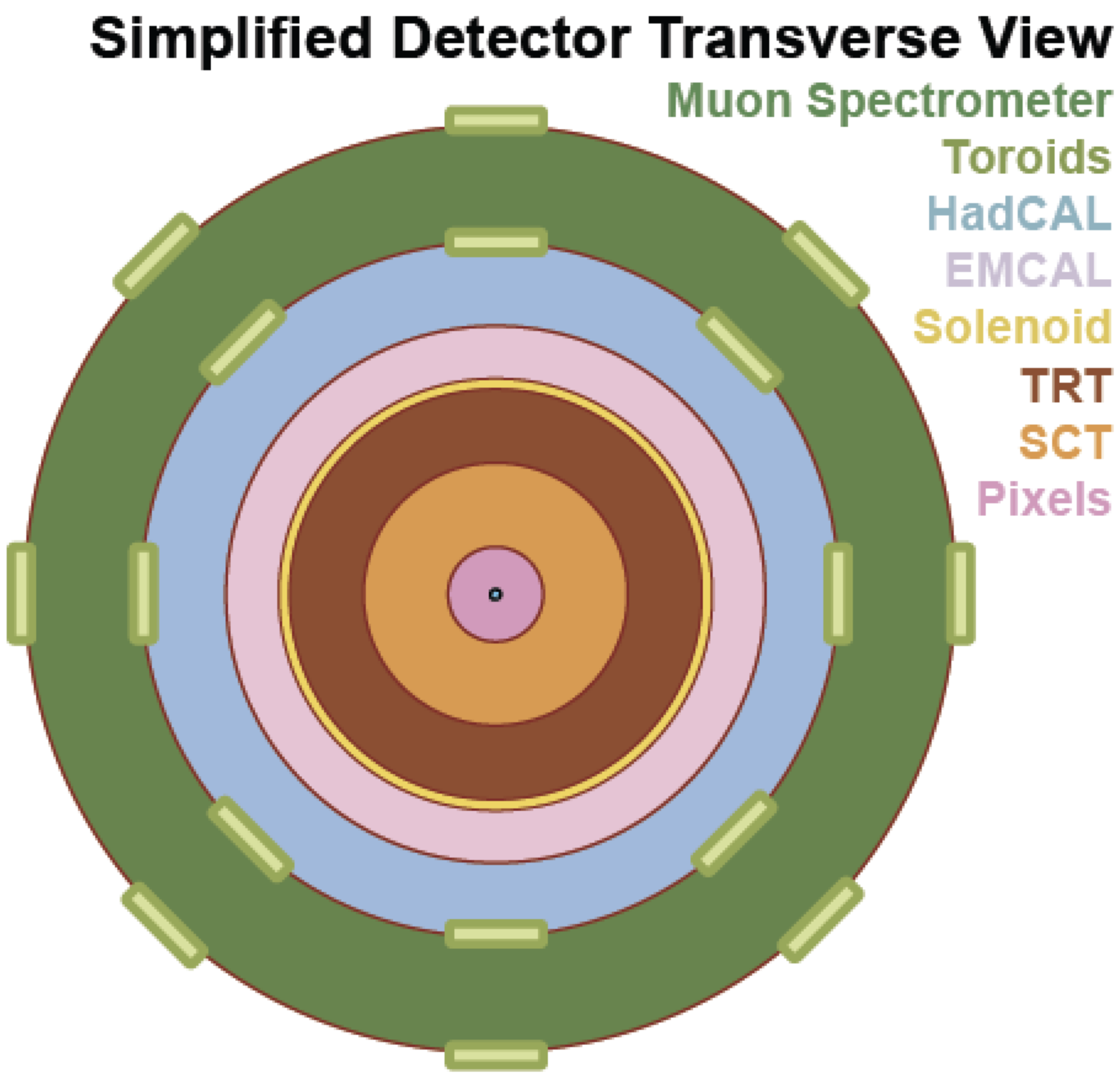
Thanks

Material/inspiration from lectures by Markus Klute, Tatjana Lenz, Katharine Leney and Marumi Kado

So how do we study all these particles?

How do we detect the particles?





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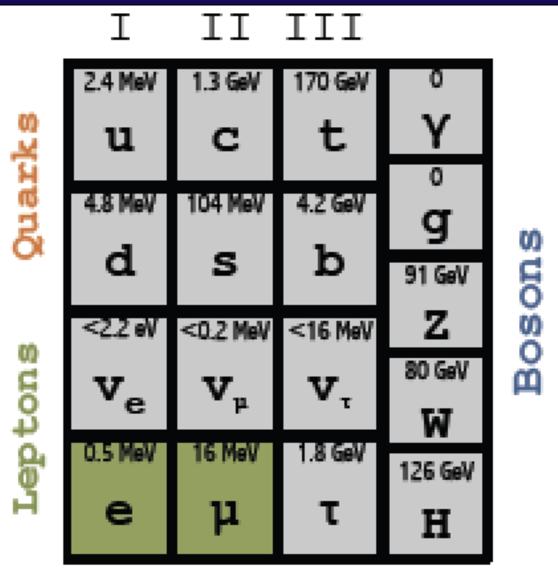

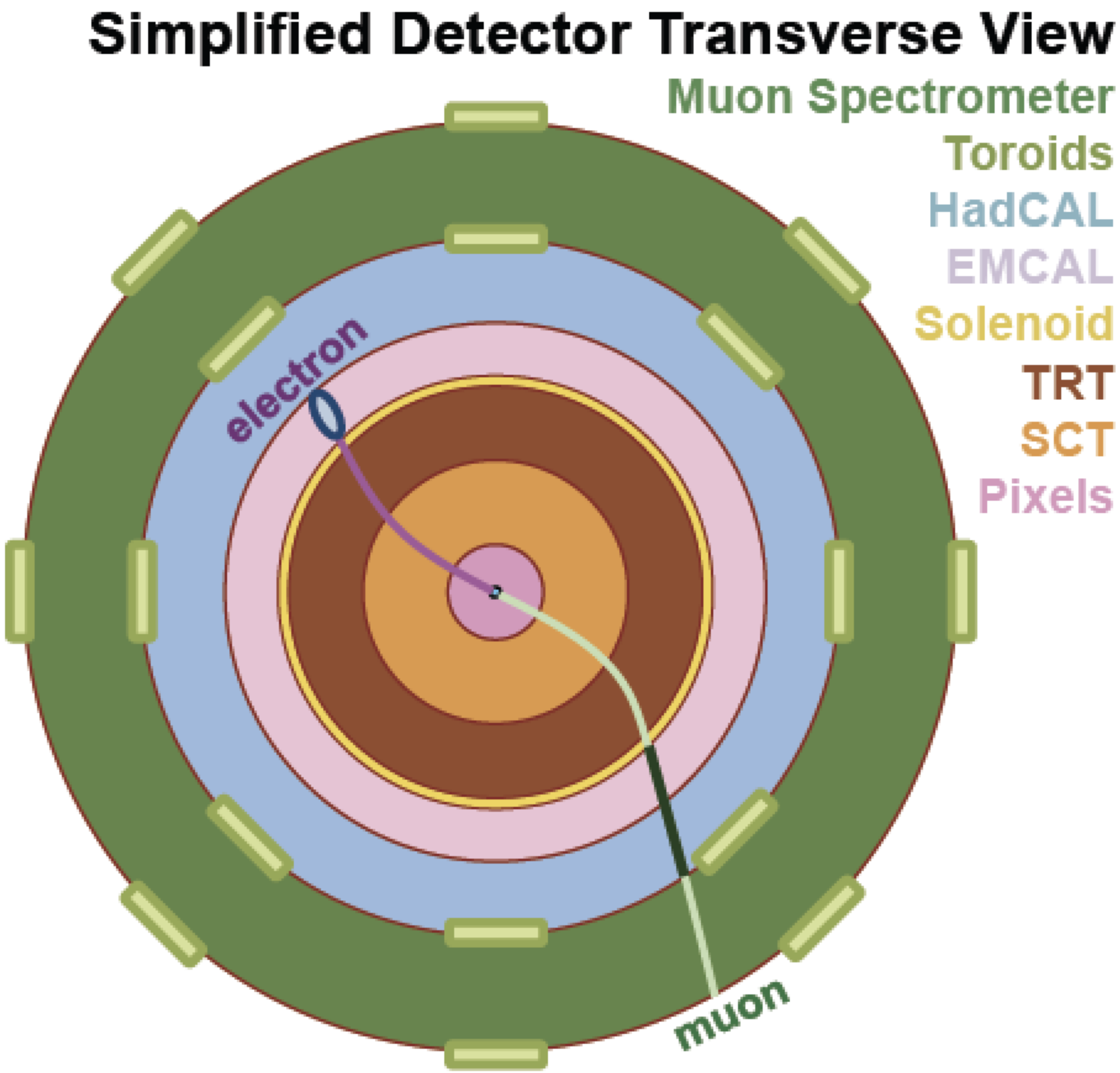

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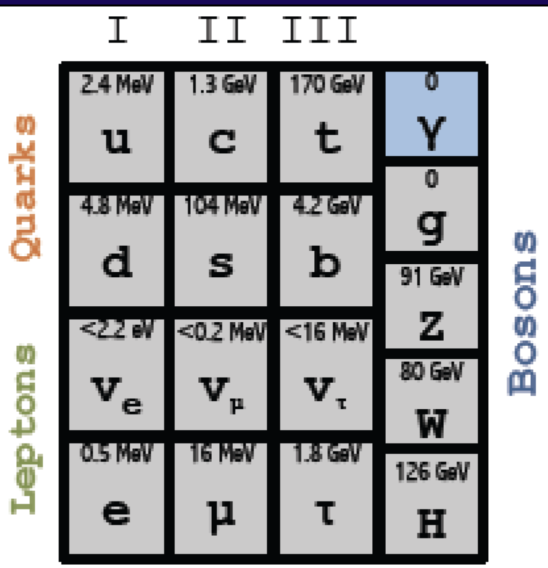
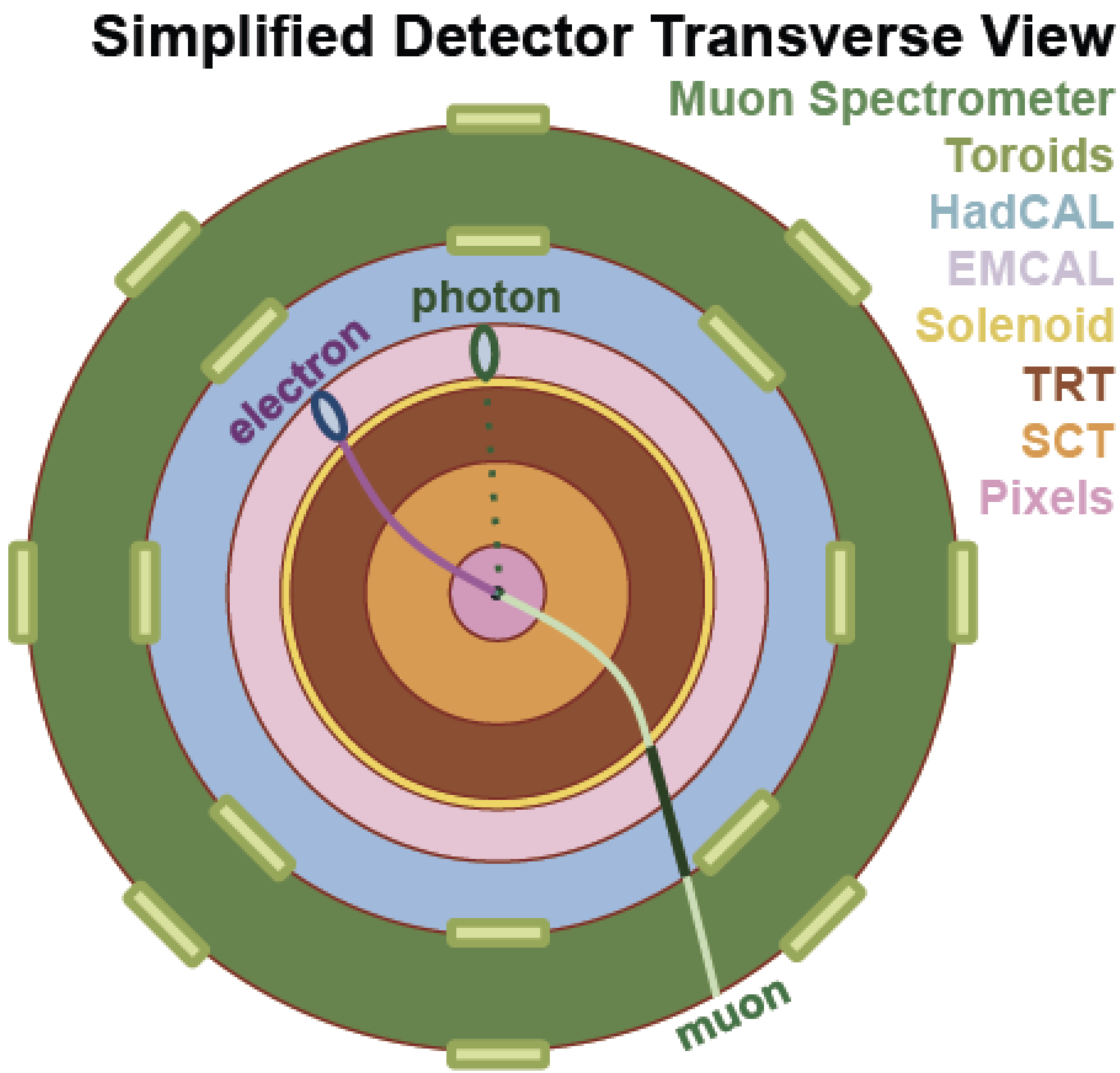
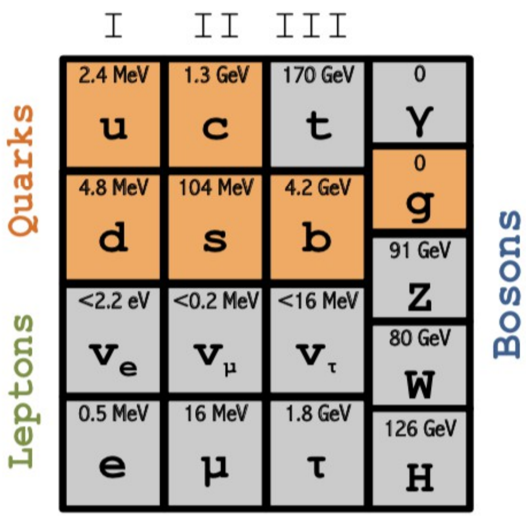
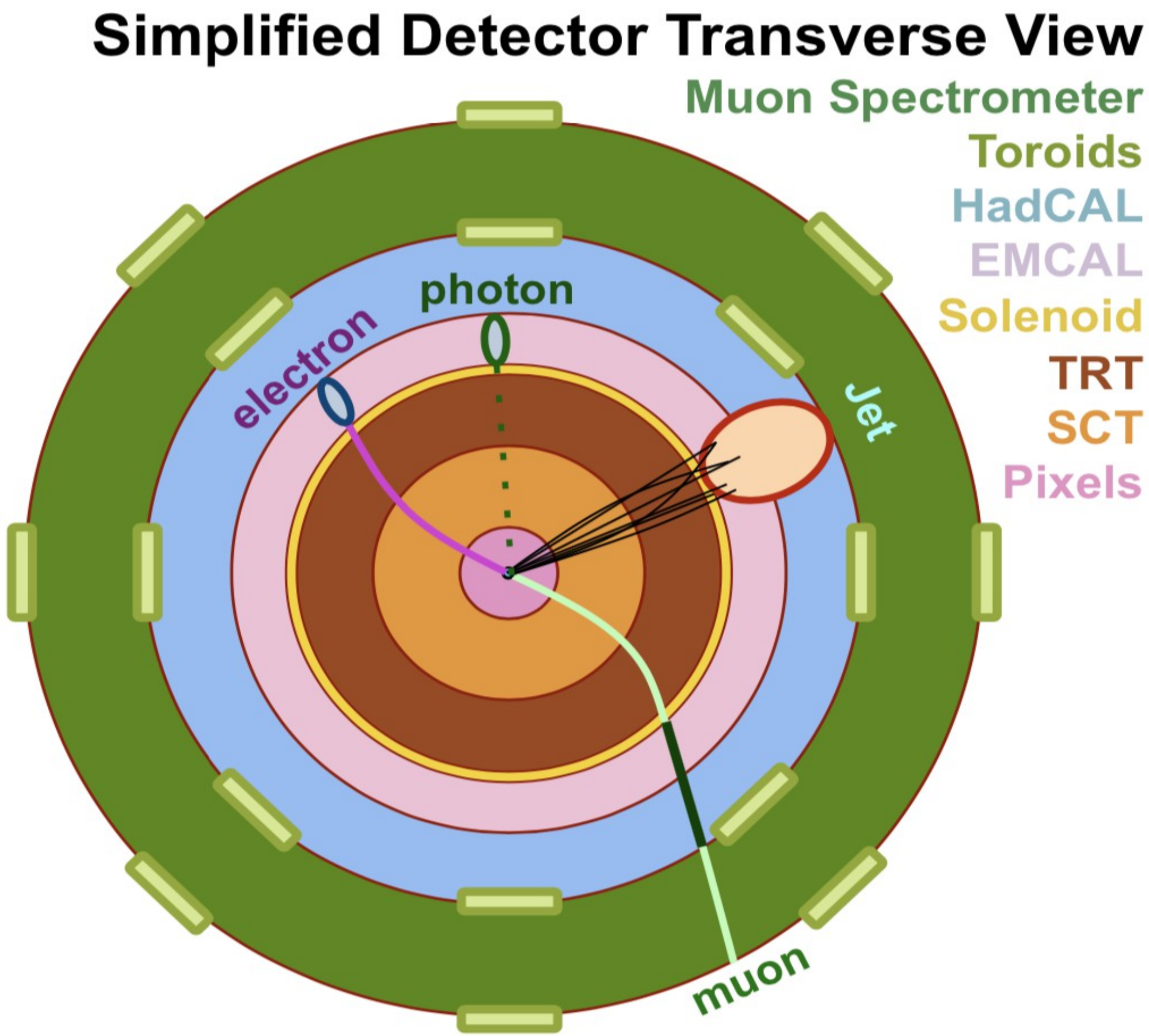




So how do we study all these particles?

How do we detect the particles?

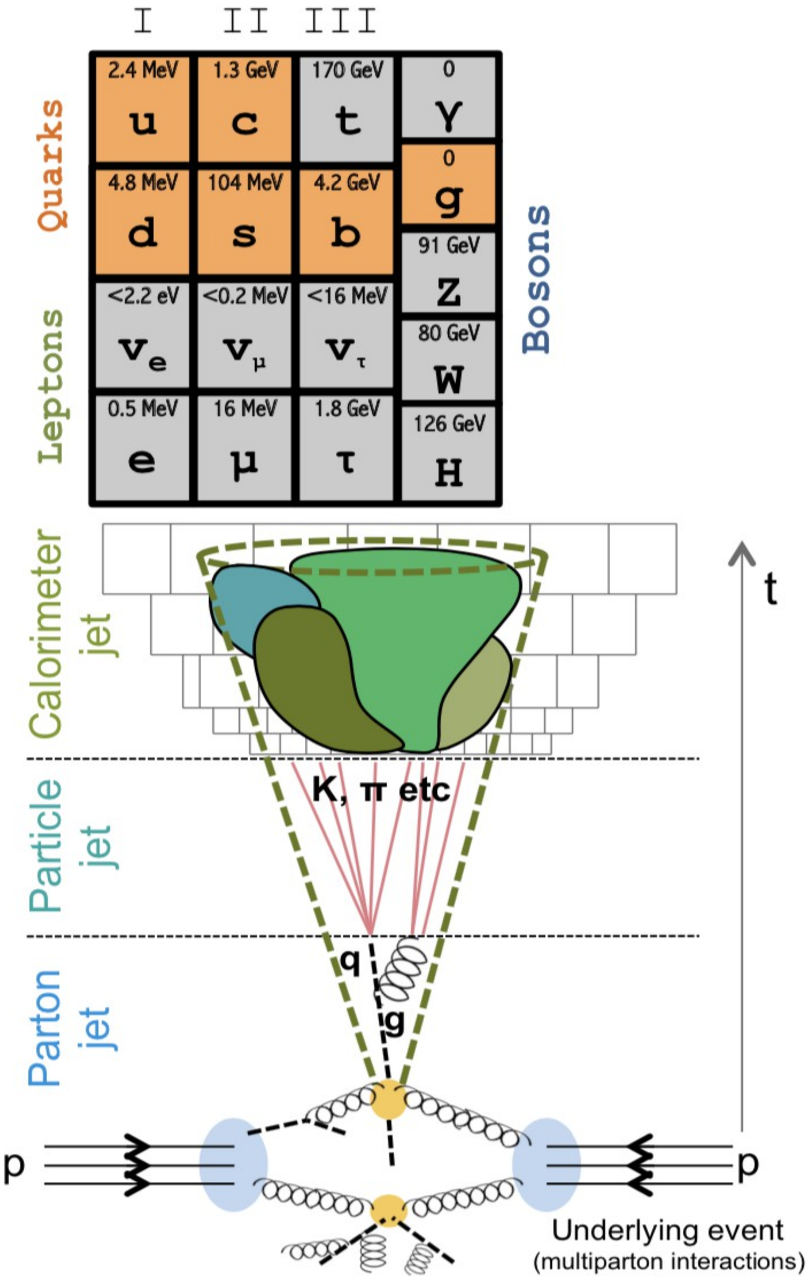


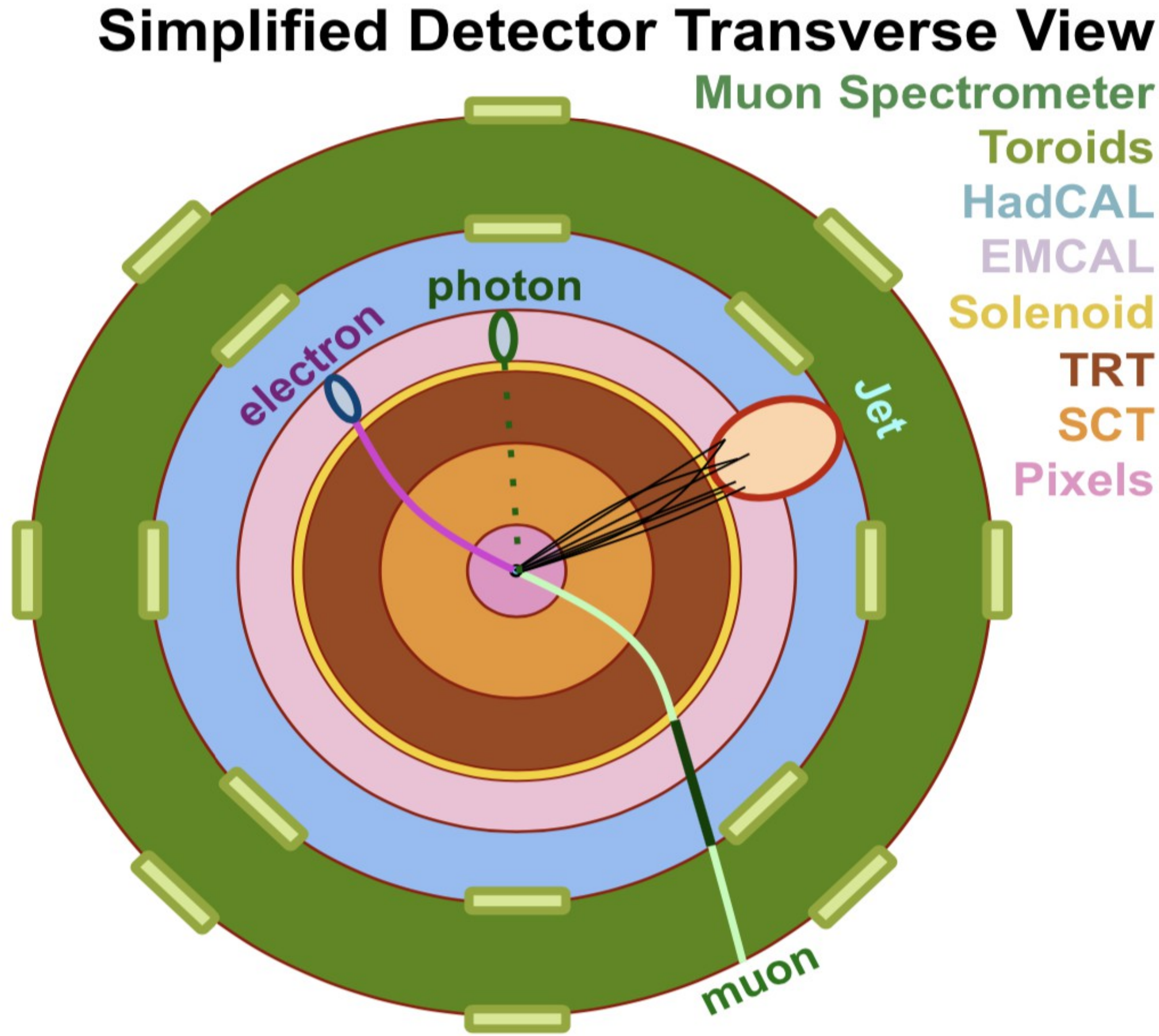


- Bare quarks,isolated gluons are colored objects and can't be observed isolated
- Radiate, eventually reconnect to the rest of the event evolve to create colorless final states
- end fragmenting to a directed flow of hadrons jet

So how do we study all these particles?

How do we detect the particles?



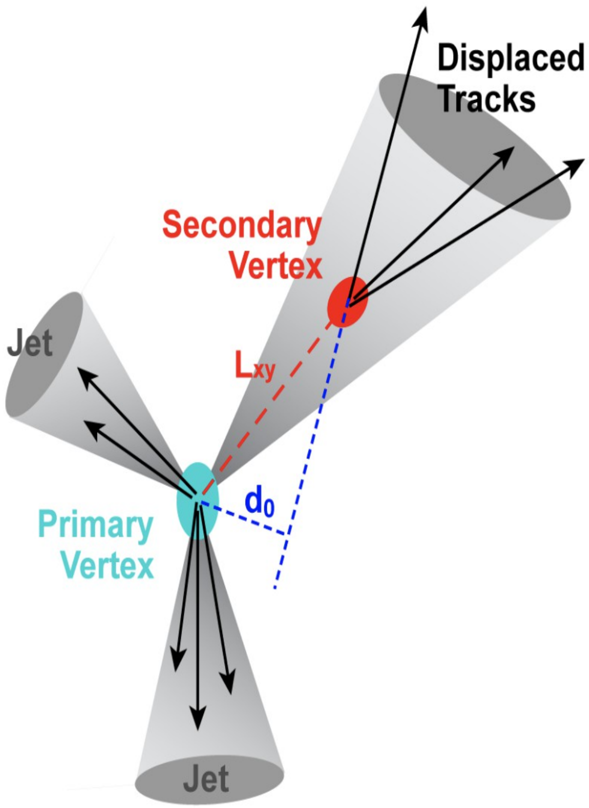


- Different algorithms used to combine inputs and reconstruct jets, eg. anti-kT, soft-drop
- Inputs can be from truth level, calorimeter, inner tracker and calorimeter+inner tracker (eg. PFlow)

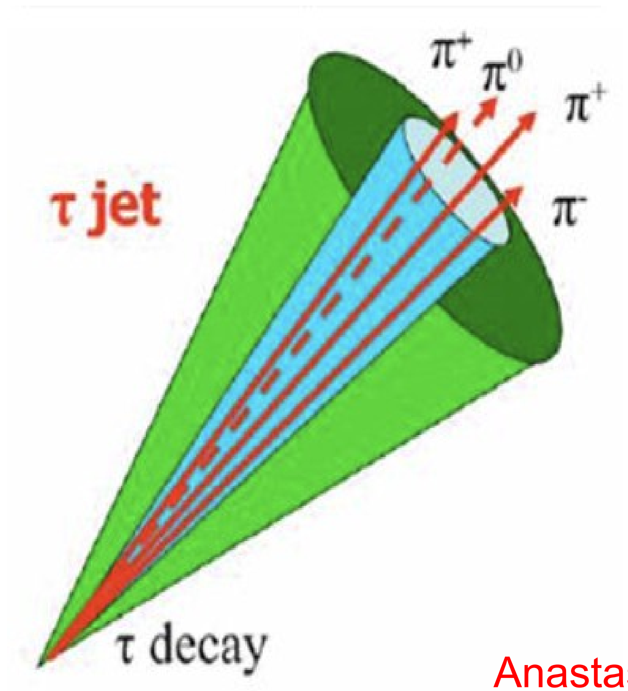
So how do we study all these particles?

Some of them are harder to identify/measure

Jets from b-quarks: b-hadrons fly before decaying this allow us to define advanced identification algorithms



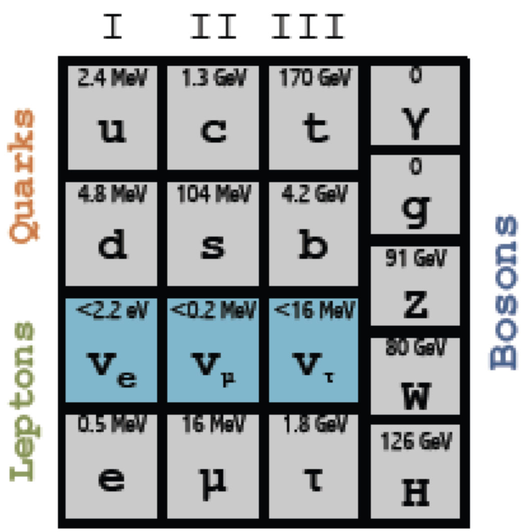
Tau leptons decay to hadrons and form jets: usually narrower jets with less tracks

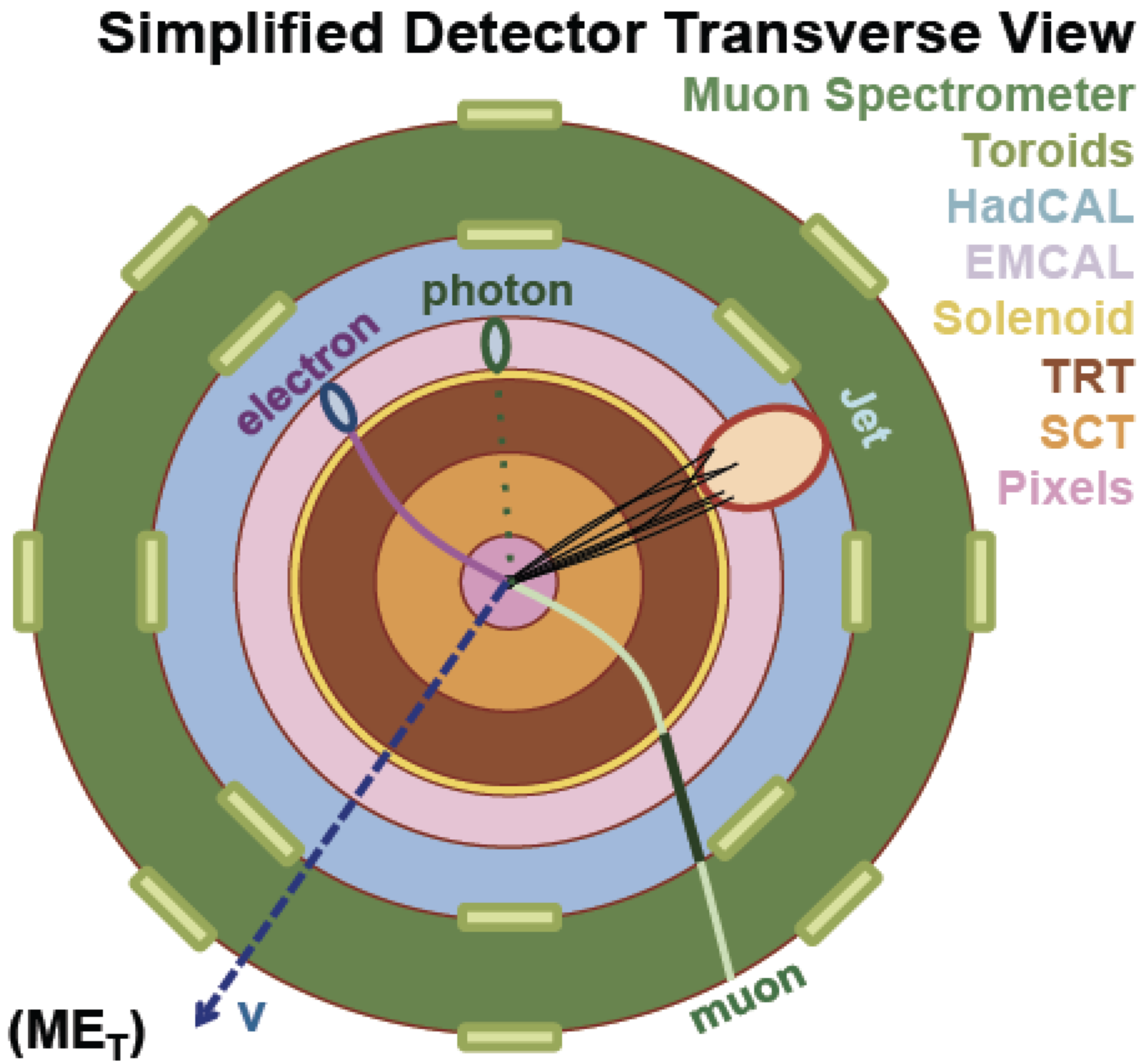


Anastasia will discuss about ways of identifying hard scatter jets in the forward region of the detector!

So how do we study all these particles?

How do we detect the particles?





In the transverse plane:

$$\sum \vec{p}_T = 0$$

Missing Transverse Momentum (ME_T)

Evolving Landscape

2015 — 2018 — 2022 — 2025

HH→bbγγ

Significance: 1.3σ

$-1.3 < \kappa_\lambda < 8.7$ (95% CI)

ATL-PHYS-PUB-2014-019

Simulation-based analysis

HH→bbττ

$\mu_{HH} < 4.3 \times$ SM

$-4 < \kappa_\lambda < 12$ (95% CI)

ATL-PHYS-PUB-2015-046

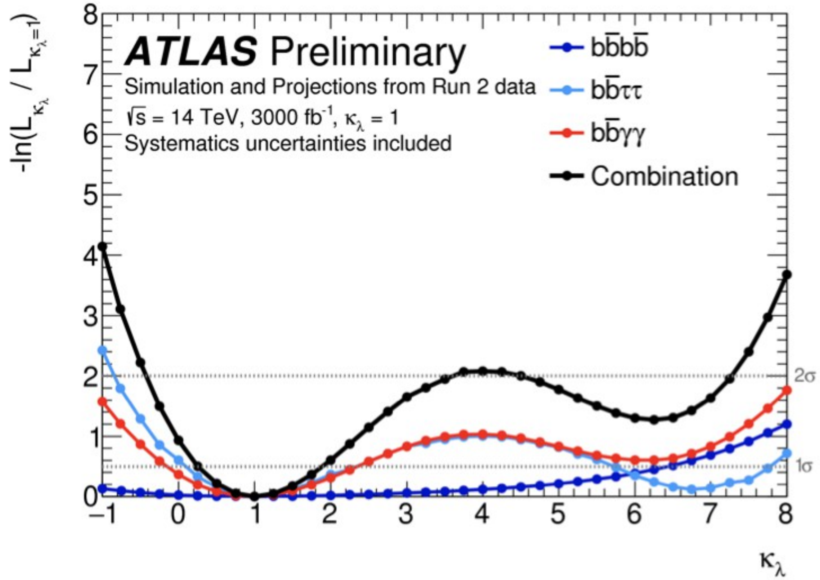
Simulation-based analysis

Evolving Landscape

2015 · **2018** · 2022 · 2025

Sig
-1.3 <
ATL
Sim

-4 <
ATL
Simu



Significance: 3.0σ

$-0.2 < \kappa_\lambda < 2.5$ (68% CI)

ATL-PHYS-PUB-2018-053

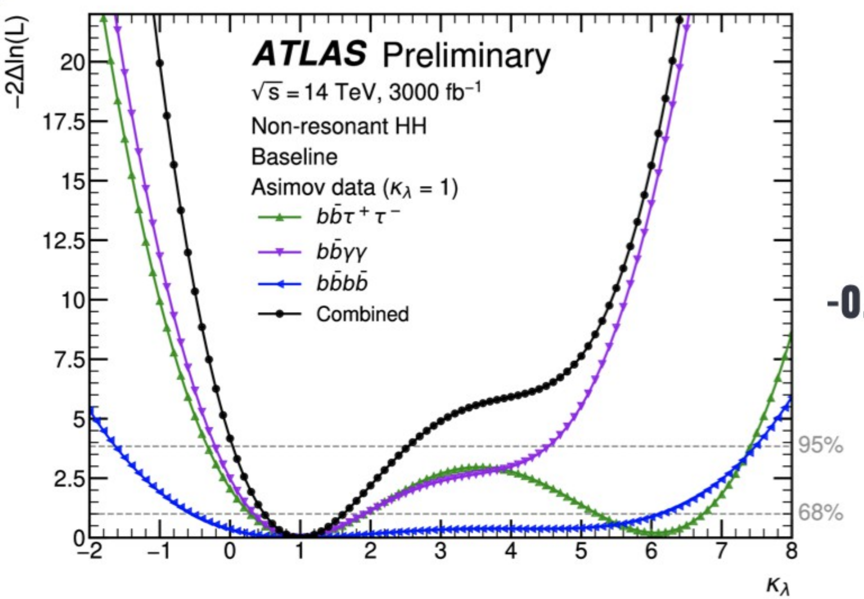
Extrapolations based on partial Run 2 analyses

Evolving Landscape

2015 — 2018 — 2022 — 2025

Sig
-1.3 <
ATL
Sim

-4 <
ATL
Simu



Significance: 3.4σ

$-0.5 < \kappa_\lambda < 1.6$ (68% CI)

ATL-PHYS-PUB-2022-053

Extrapolations based on first full Run 2 analyses

Evolving Landscape

2015 — 2018 — 2022 — 2025

Sig

-1.3 <

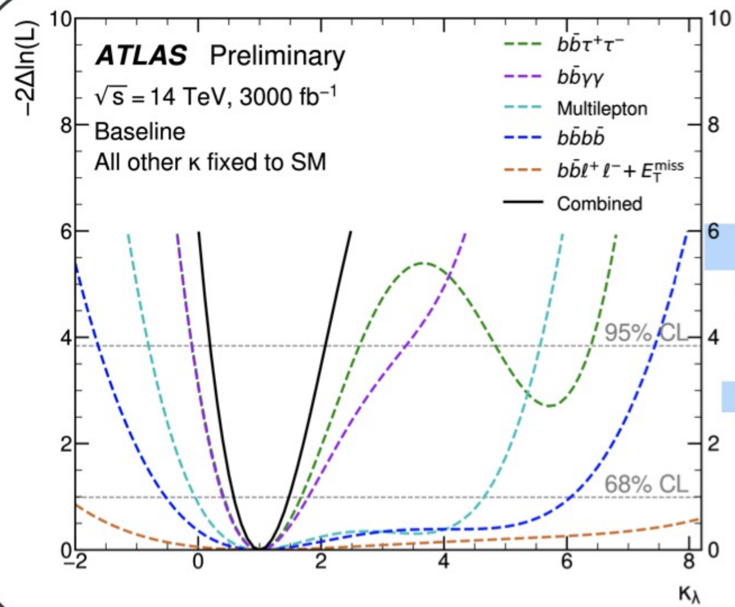
ATL

Sim

-4 <

ATL

Simul

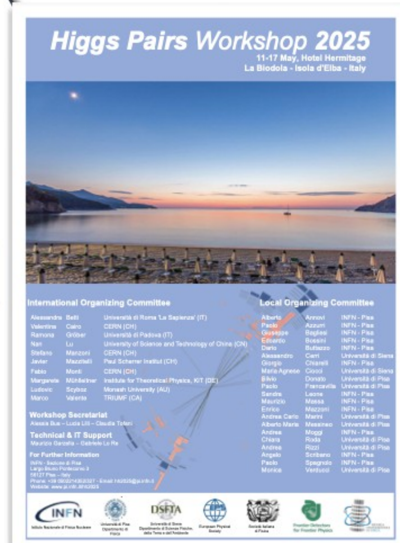


Significance: 4.3σ

$0.58 < \kappa_\lambda < 1.48$ (68% CI)

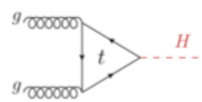
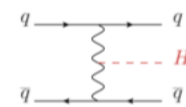
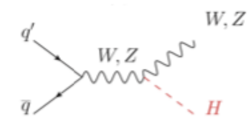
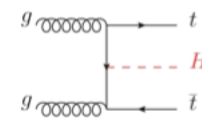
ATL-PHYS-PUB-2025-006

Extrapolations based on legacy full Run 2 analyses



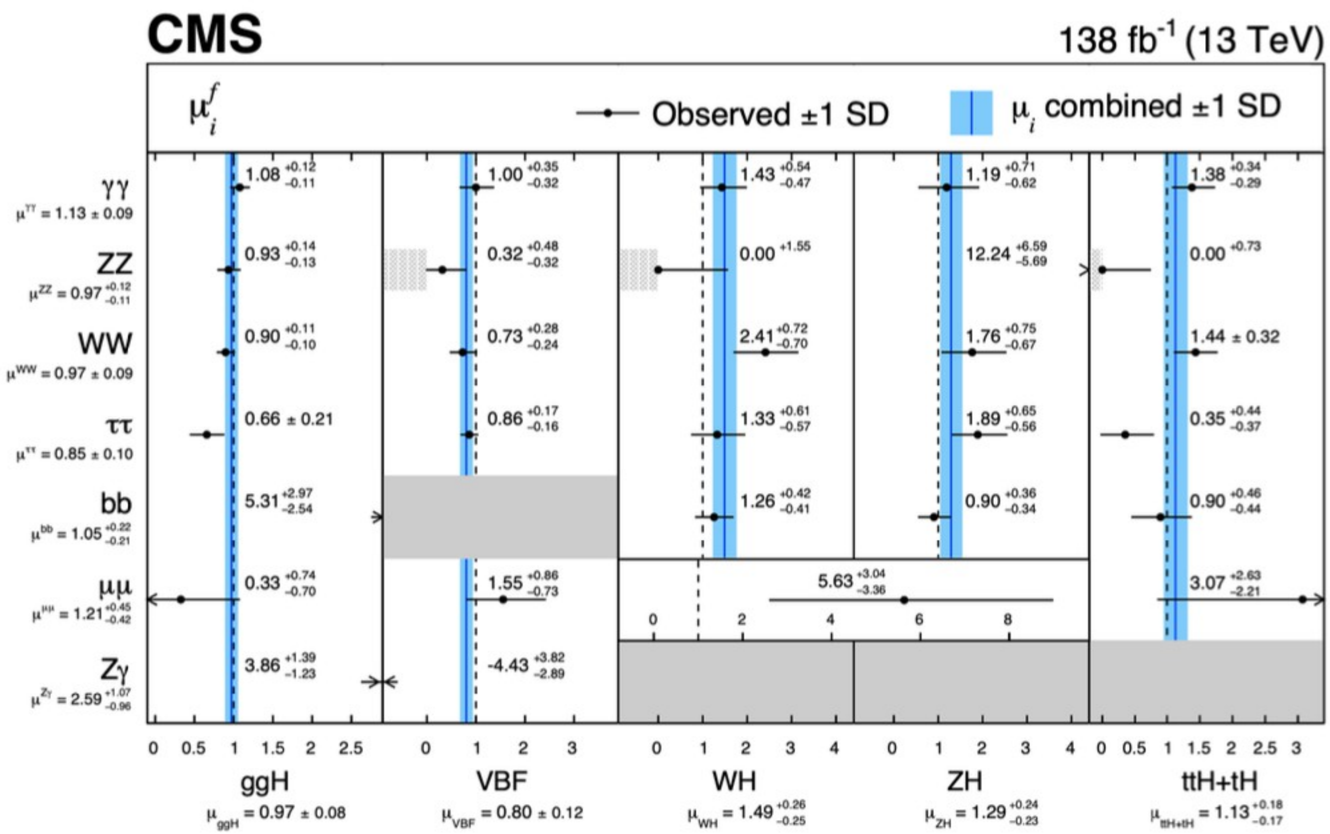
Nano Overview of Main Higgs Analyses at (HL) LHC

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

	Channel categories	Br	ggF  ~4 M vets produced	VBF  ~300 k vets produced	VH  ~200 k vets produced	ttH  ~40 k evts produced
	Cross Section 13 TeV (8 TeV)		48.6 (21.4) pb*	3.8 (1.6) pb	2.3 (1.1) pb	0.5 (0.1) pb
Observed modes	γγ	0.2 %	✓	✓	✓	✓
	ZZ	3%	✓	✓	✓	✓
	WW	22%	✓	✓	✓	✓
	ττ	6.3 %	✓	✓	✓	✓
	bb	55%	✓	✓	✓	✓
Remaining to be observed	Zγ and γγ*	0.2 %	✓	✓	✓	✓
	μμ	0.02 %	✓	✓	✓	✓
Limits	Invisible	0.1 %	✓ (monojet)	✓	✓	✓

*N3LO

Portrait of the Higgs Boson 10 Years after its Discovery



Portrait of the Higgs Boson 10 Years after its Discovery

	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2	Current precision
κ_γ	13%	1.04 ± 0.06	1.10 ± 0.08	6%
κ_W	11%	1.05 ± 0.06	1.02 ± 0.08	6%
κ_Z	11%	0.99 ± 0.06	1.04 ± 0.07	6%
κ_g	14%	0.95 ± 0.07	0.92 ± 0.08	7%
κ_t	30%	0.94 ± 0.11	1.01 ± 0.11	11%
κ_b	26%	0.89 ± 0.11	0.99 ± 0.16	11%
κ_τ	15%	0.93 ± 0.07	0.92 ± 0.08	8%
κ_μ	-	$1.06^{+0.25}_{-0.30}$	1.12 ± 0.21	20%
$\kappa_{Z\gamma}$	-	$1.38^{0.31}_{-0.36}$	1.65 ± 0.34	30%
B_{inv}		$< 11\,\%$	$< 16\,\%$	
		Nature 607, 52-59 (2022)	Nature 607, 60-68 (2022)	

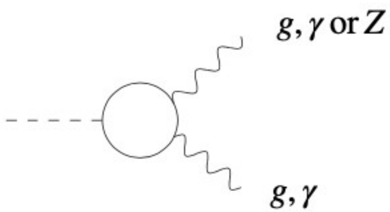
How elementary is the Higgs Boson?

Minimal Composite Higgs scenarios

$$g_{HVV} = \frac{2m_V^2}{v}\sqrt{1 - v^2/f^2}$$

$$4\pi f \gtrsim 9\,\mathrm{TeV}$$

Probing new particles through loops



Probing the **Flavour Hierarchy** through the Yukawa couplings!

Backup