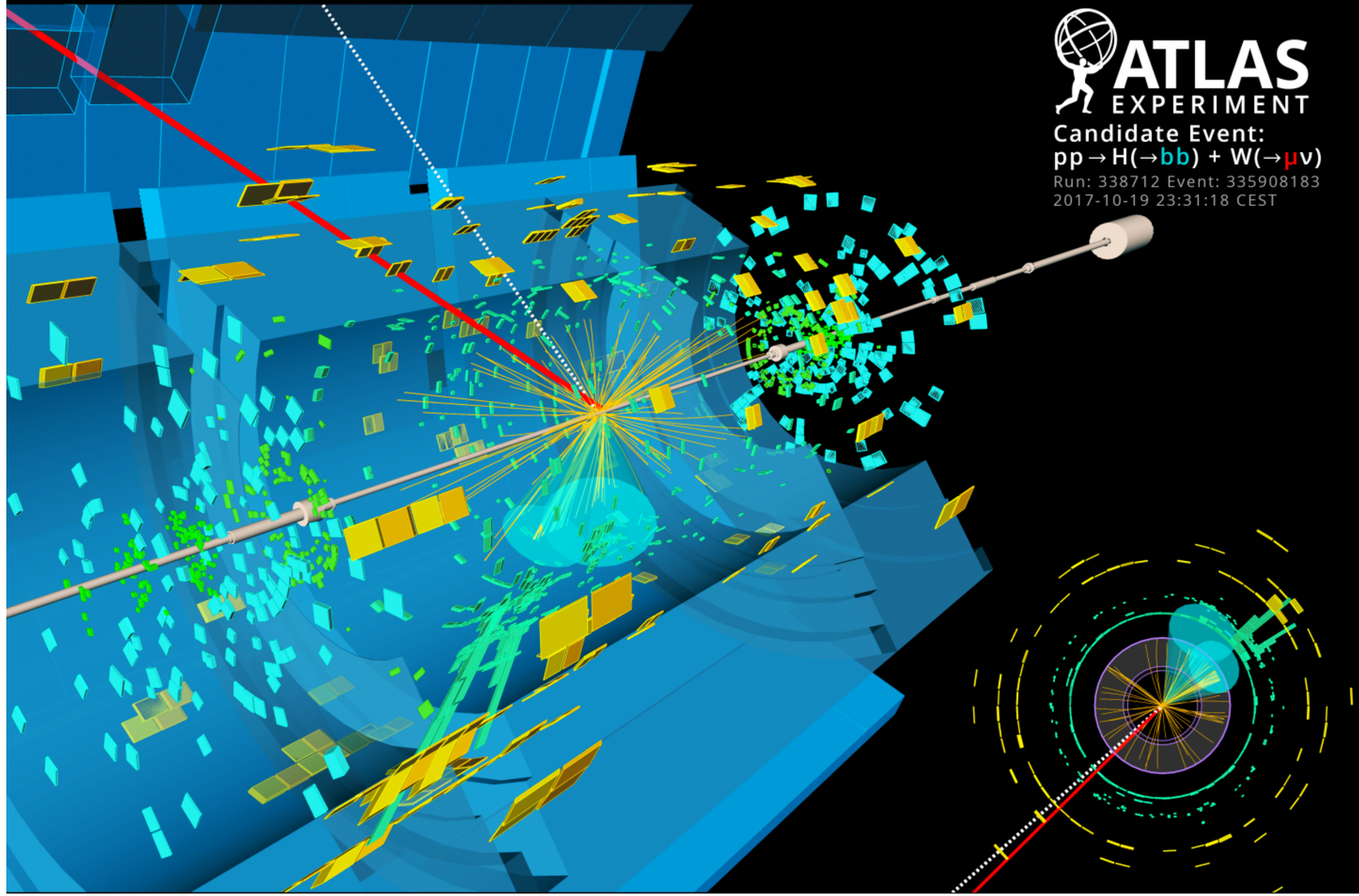
Higgs Boson Legacy in ATLAS

Its coupling to b & c quarks: State-of-the-art and perspectives

Seminars 16/02/2022

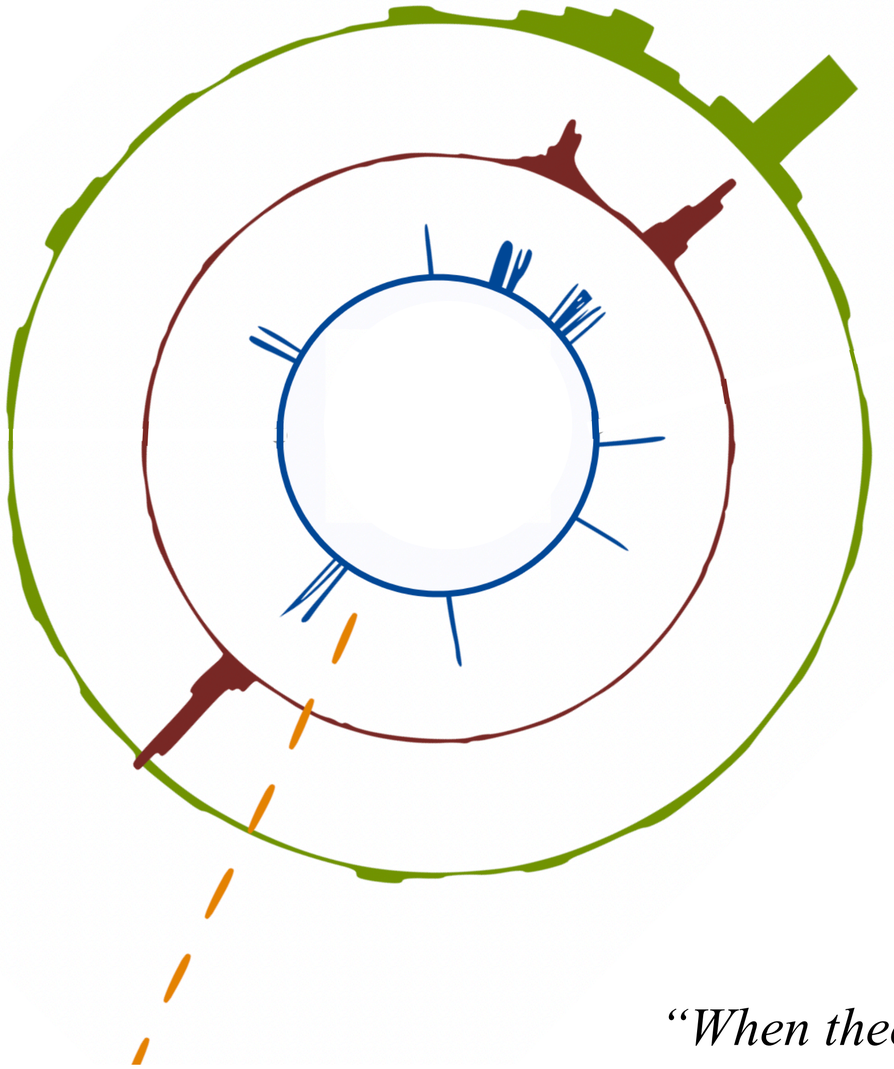
Lorenzo Santi



SAPIENZA
UNIVERSITÀ DI ROMA

ATLAS
EXPERIMENT

INFN
Istituto Nazionale di Fisica Nucleare



Overview

"When theorists are more confused, it's time for more, not less, experiments"
Nima Arkani-Hamed

Overview

Overview of the talk

1. CERN & LHC foundations
2. ATLAS Experiment
3. Physics at Colliders
4. **Higgs Boson**
5. Outlook and Conclusions

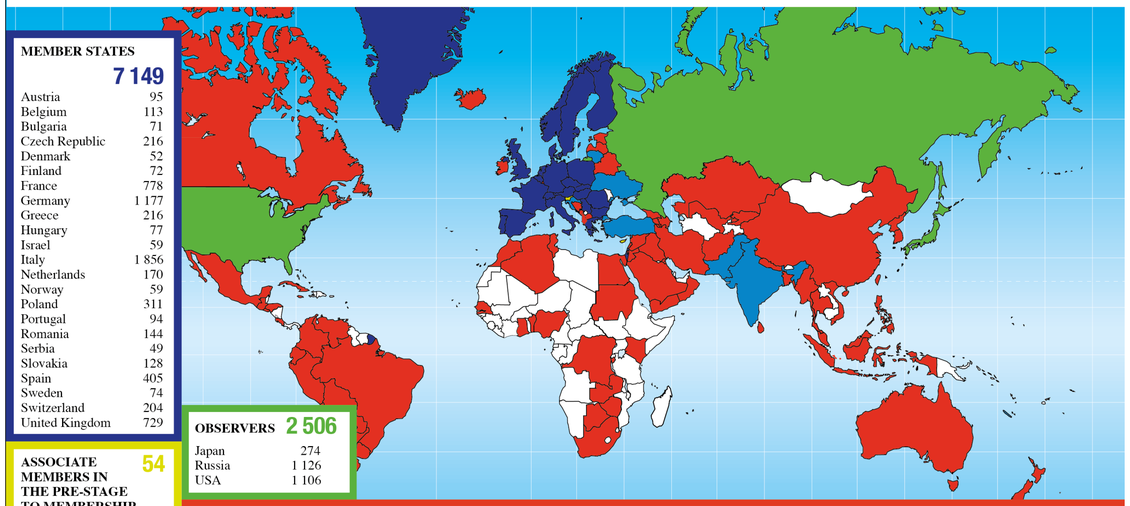
CERN & LHC

CERN (1954-pres.): EU organization

➡ Based in Geneva

➡ Affiliation from all over the world

Distribution of All CERN Users by Nationality on 27 January 2020



MEMBER STATES 7 149

Austria	95
Belgium	113
Bulgaria	71
Czech Republic	216
Denmark	52
Finland	72
France	778
Germany	1 177
Greece	216
Hungary	77
Israel	59
Italy	1 856
Netherlands	170
Norway	59
Poland	311
Portugal	94
Romania	144
Serbia	49
Slovakia	128
Spain	405
Sweden	74
Switzerland	204
United Kingdom	729

OBSERVERS 2 506

Japan	274
Russia	1 126
USA	1 106

ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP 54

Cyprus	21
Slovenia	33

ASSOCIATE MEMBERS 770

Croatia	47
India	367
Lithuania	31
Pakistan	63
Turkey	162
Ukraine	100

OTHERS

Albania	4	Bolivia	2	Egypt	26	Ireland	14	Montenegro	8	Saint Kitts		Uzbekistan	3
Algeria	8	Bosnia & Herzegovina	2	El Salvador	1	Jamaica	1	Morocco	26	and Nevis	1	Venezuela	10
Argentina	22	Bostwana	1	Estonia	16	Jordan	2	Myanmar	1	Saudi Arabia	2	Viet Nam	10
Armenia	18	Brazil	121	Georgia	54	Kazakhstan	12	Nepal	8	Senegal	1	Yemen	1
Australia	28	Burundi	1	Ghana	1	Kenya	1	New Zealand	6	Singapore	4	Zambia	1
Azerbaijan	7	Canada	155	Gibraltar	1	Korea	161	Nigeria	2	South Africa	54	Zimbabwe	1
Bahrain	3	Chile	21	Guatemala	1	Kyrgyzstan	1	North Korea	3	Sri Lanka	6		
Bangladesh	5	China	569	Hong Kong	1	Latvia	4	North Macedonia	2	Sudan	2		
Belarus	49	Colombia	35	Honduras	1	Lebanon	23	Oman	1	Syria	2		
Benin	1	Congo	1	Iceland	5	Luxembourg	3	Palestine	7	Taiwan	47		
		Costa Rica	1	Indonesia	11	Malaysia	19	Paraguay	1	Thailand	24		
		Cuba	16	Iran	46	Malta	5	Peru	6	Tunisia	5		
		Ecuador	11	Iraq	1	Mexico	80	Philippines	4	Uruguay	1		

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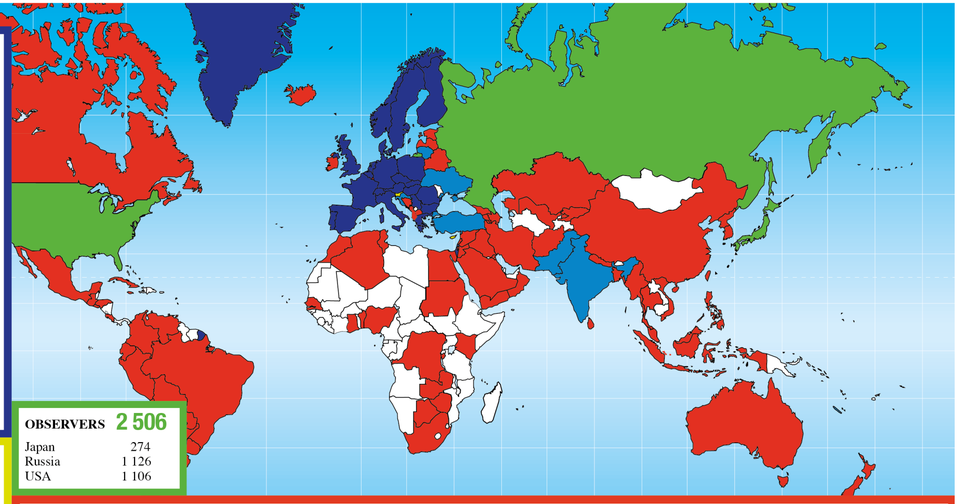

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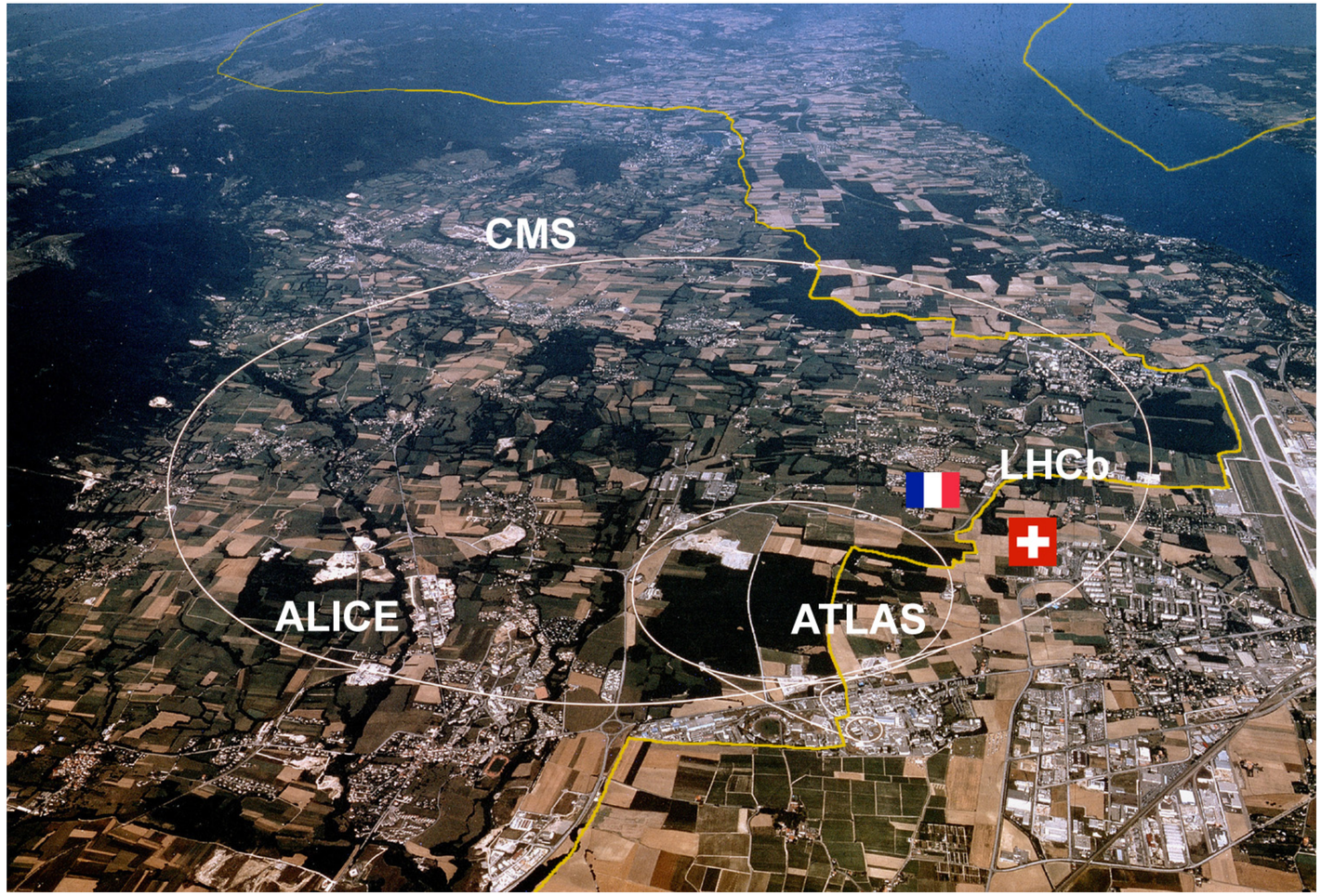
CERN & LHC



Large Hadron Collider (2008-pres.)

Highest energy ever reached in pp colisions:

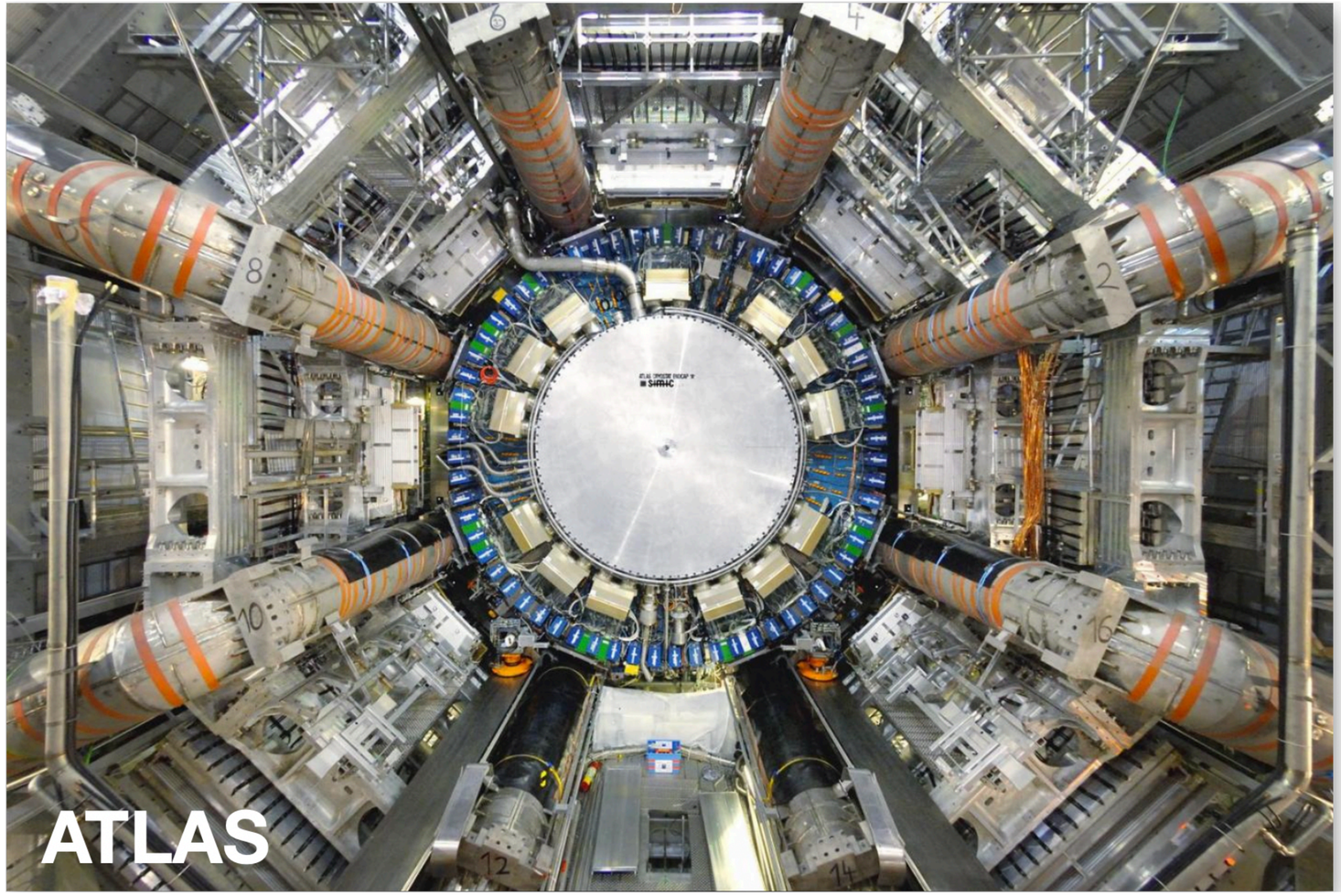
$$\sqrt{s} = 13\ TeV = 13 \times 10^{12}\ eV$$

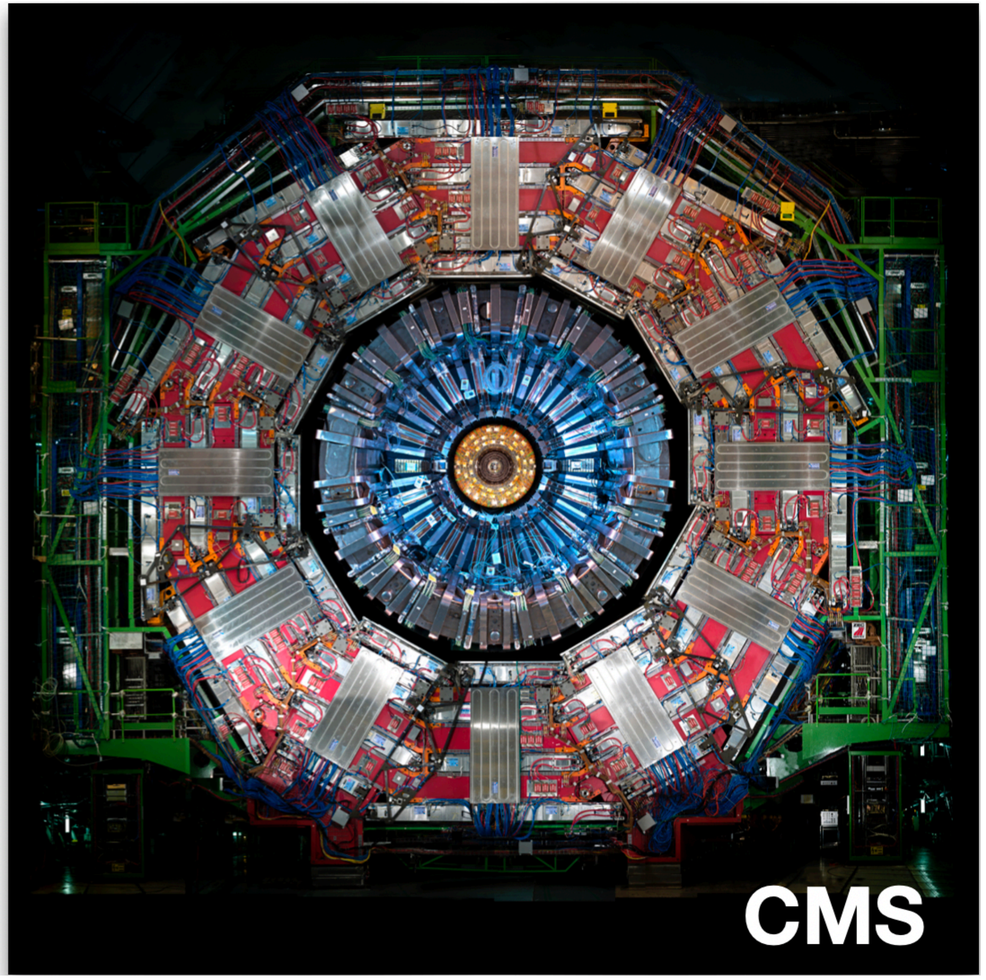
probing $\lambda \sim 10^{-19} m$

proton radius: $r_p \sim 10^{-15}\ m$

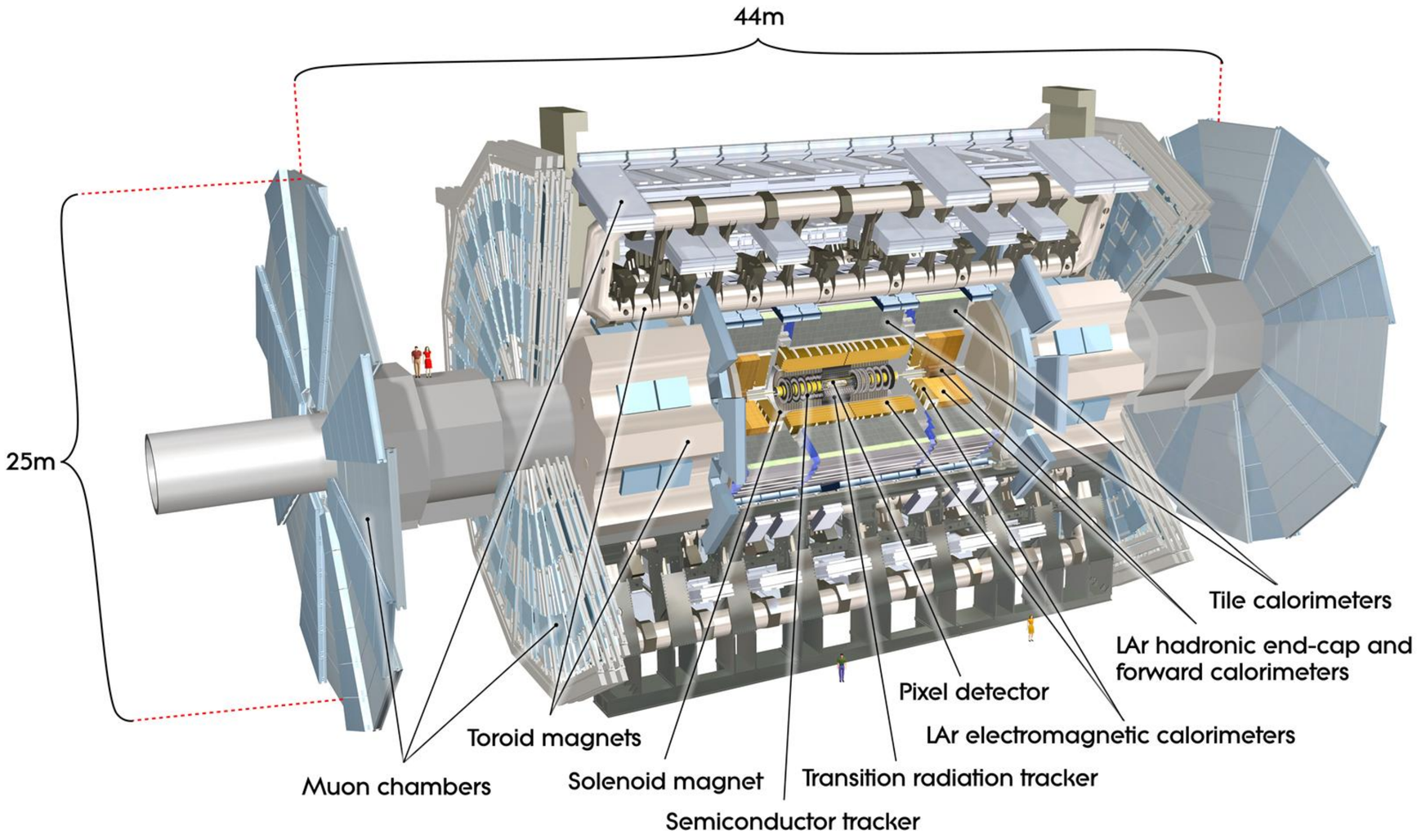
Hydrogen binding energy $E_I^H \sim 13.6\ eV$

Main Experiments





ATLAS Dimensions

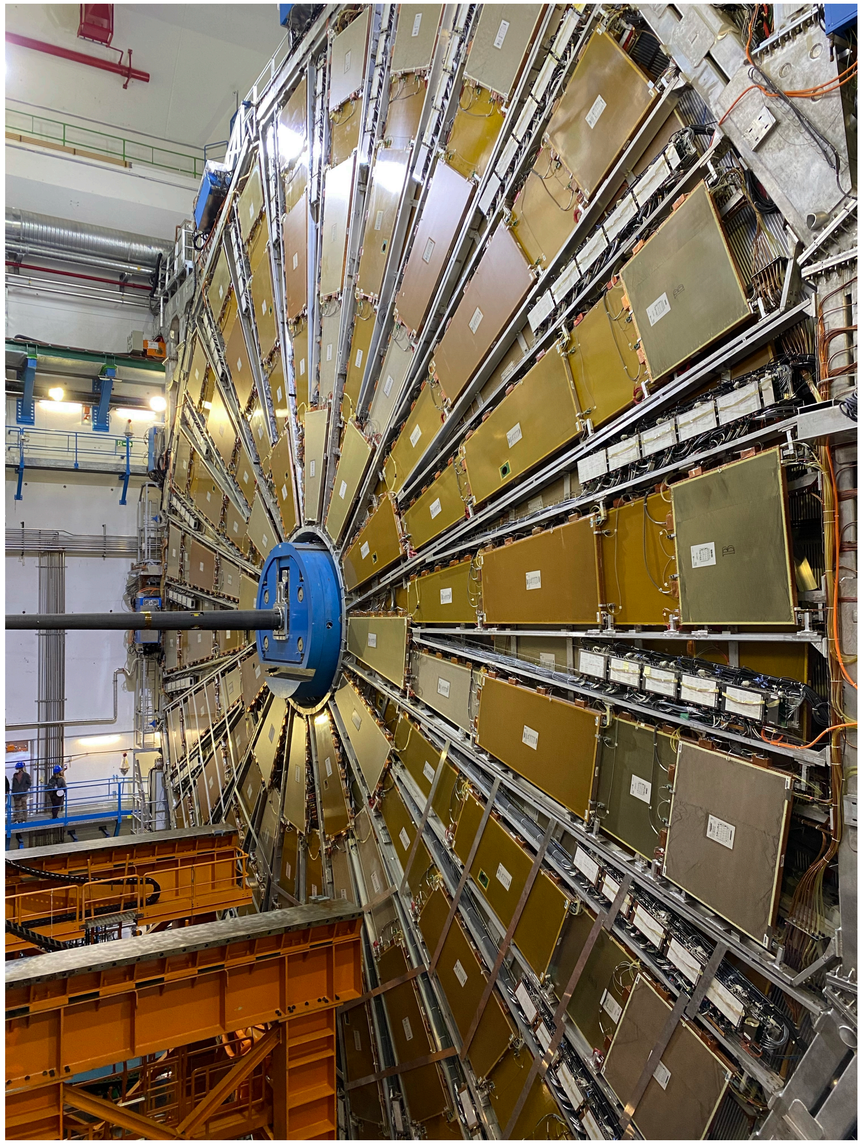


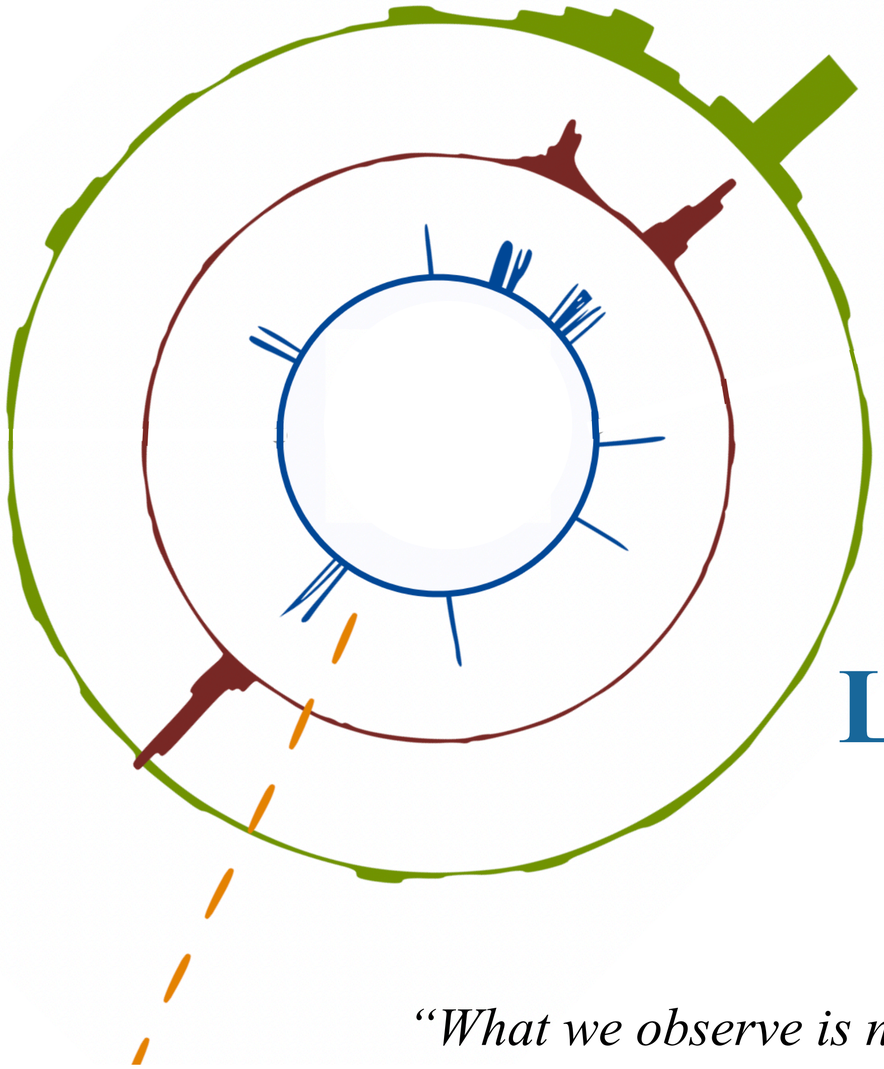
Detector sub-parts:

- Tracker:
  Charged particles
- EM Calorimeters:
  γ, $e^{\pm}$
- Hadronic Calorimeter
- Muon Spectrometer

ATLAS Dimensions

The New **Small** Wheel

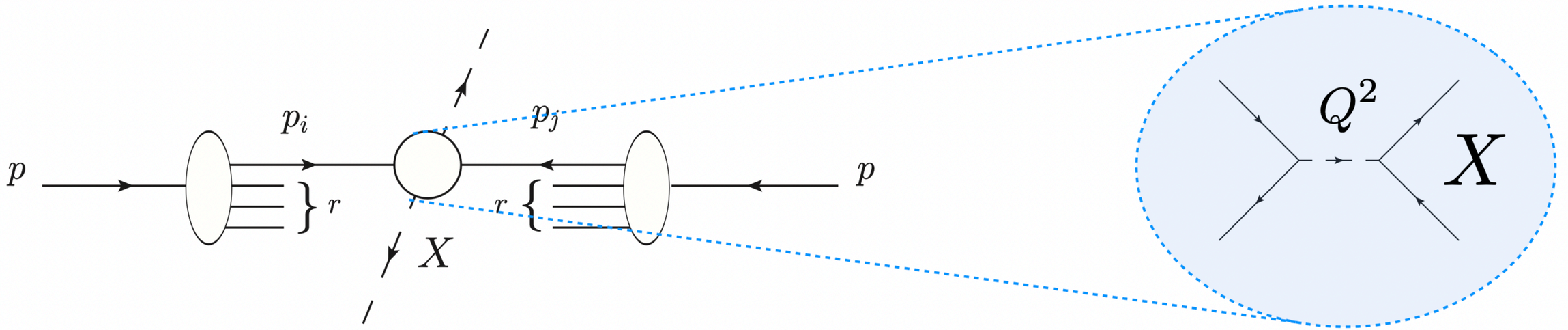




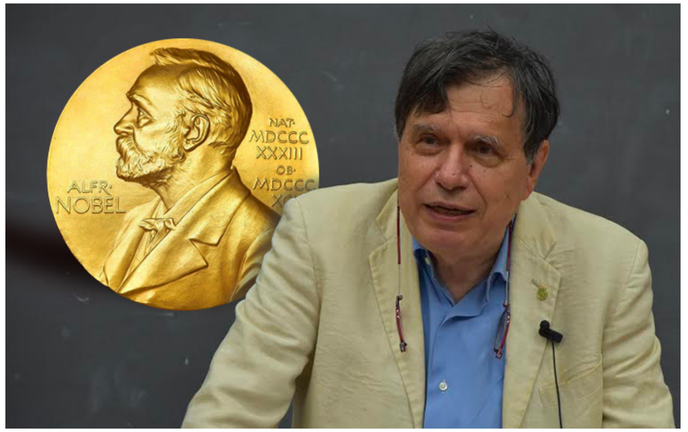
LHC Physics

"What we observe is not nature itself, but nature exposed to our method of questioning."
Werner Heisenberg

Basic concepts



Protons are composite objects → quarks and gluons **(partons)**
Probability to pick a parton → parton distribution functions **(PDF)**
Probability of a given "process" → **Feynman diagrams**



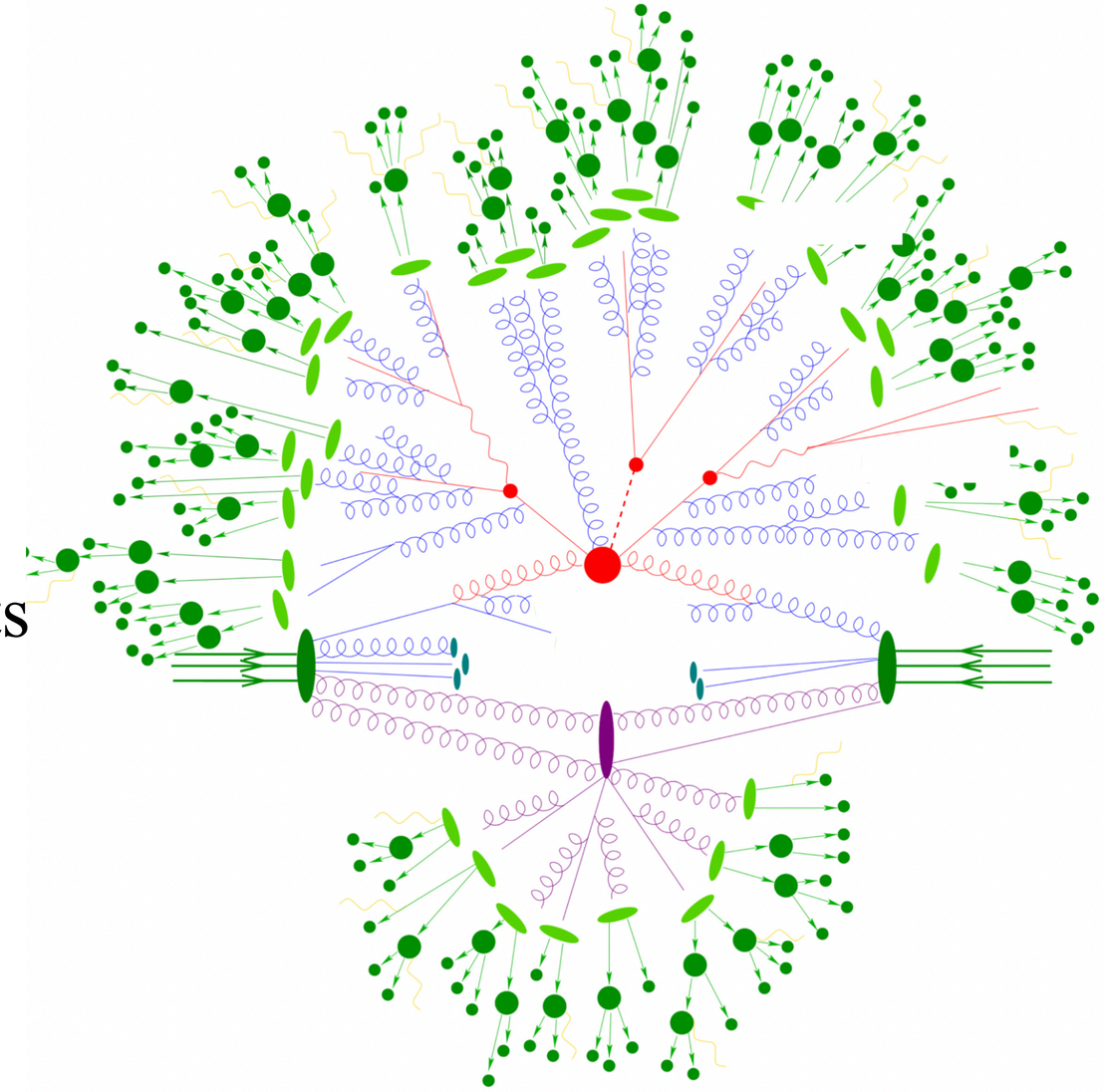
Predictions in terms of cross-sections $\sigma(pp \to X)[cm^2]$
cross-section → probability

Basic concepts

What's next?

Once particles are produced:

— produced partons must hadronize:
Confinement
— "stable" particles will cross the Detectors
— In the end we observe Reconstructed objects



Collision Detector

$pp \rightarrow$ Truth Particles → Reco Objects

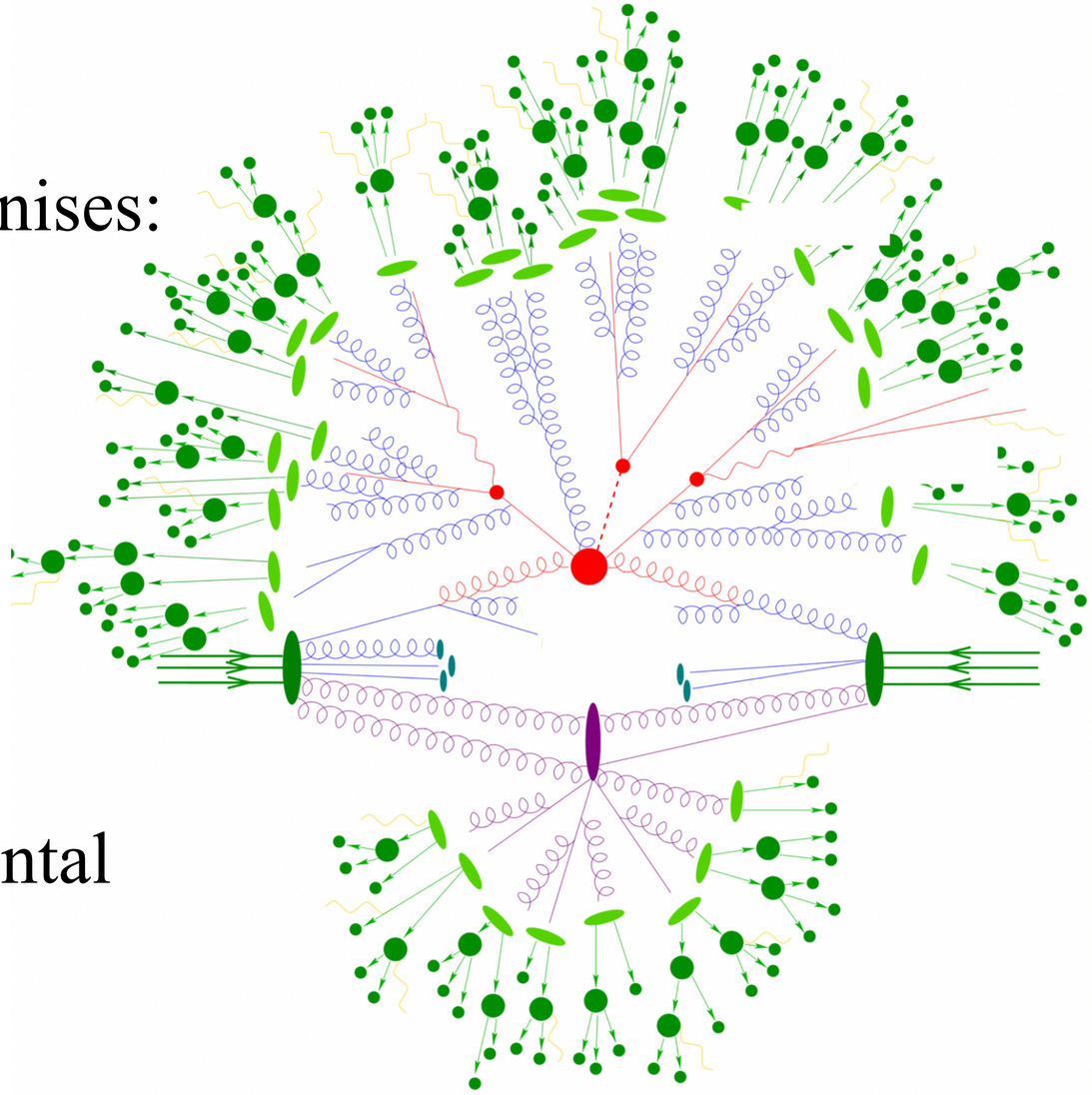
Basic concepts

Jets

When a parton (g, q=l,c,b) is produced it hadronises:

It produces a bunch of hadrons called jet

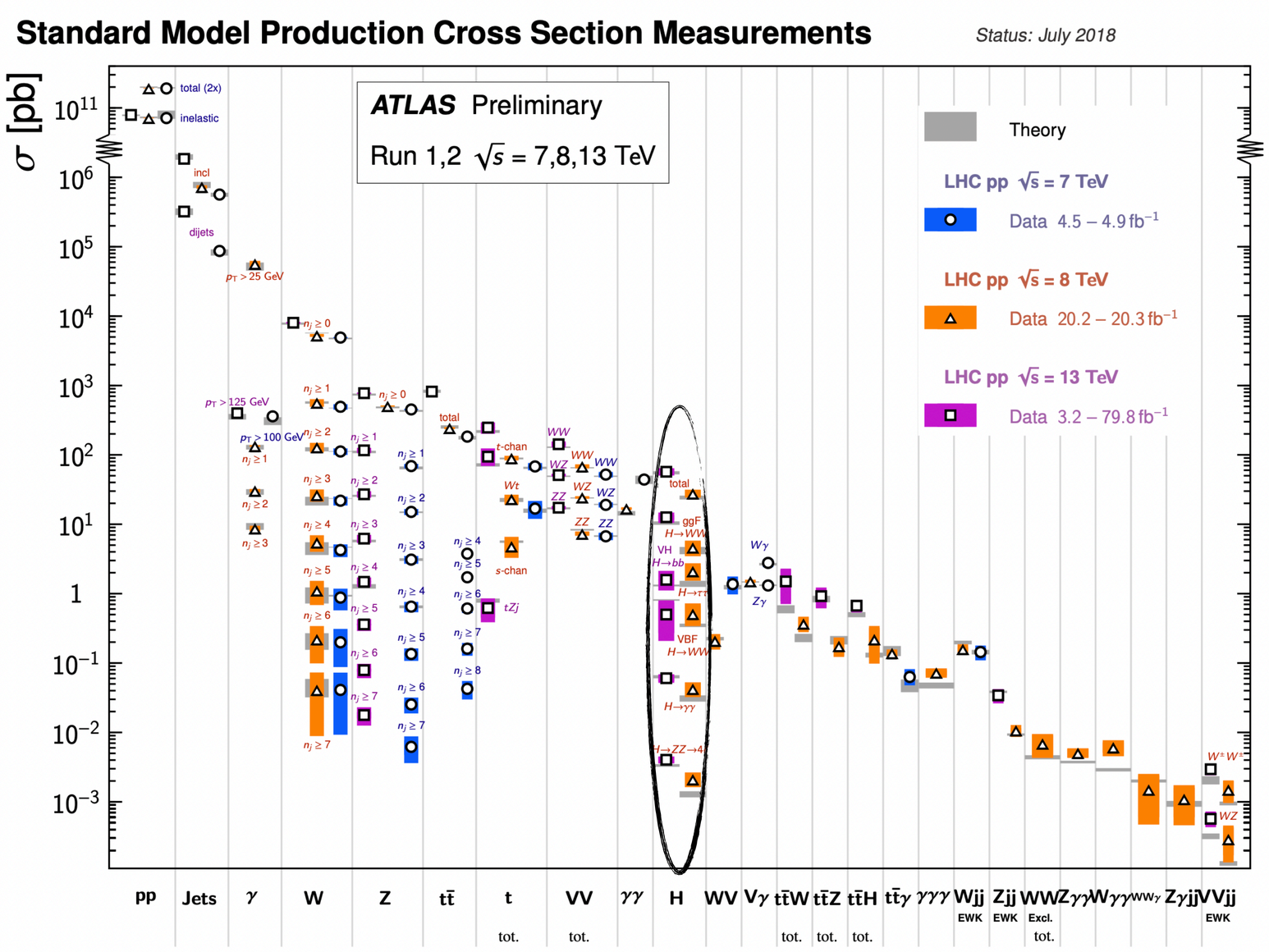
Jet initiated from different partons have different characteristics!



— Algorithm for jet identification are fundamental

What about the TOP quark?

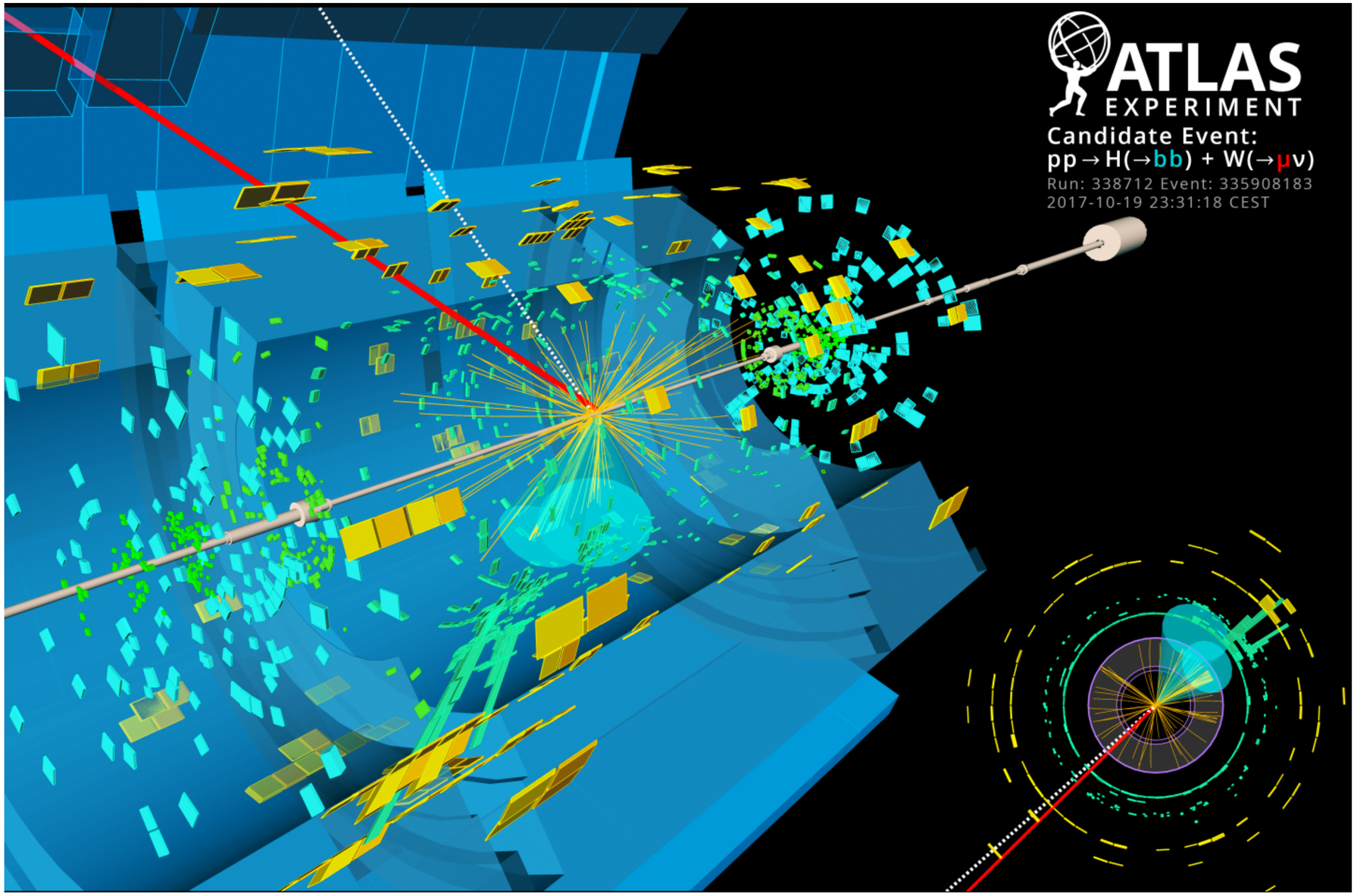
Basic concepts



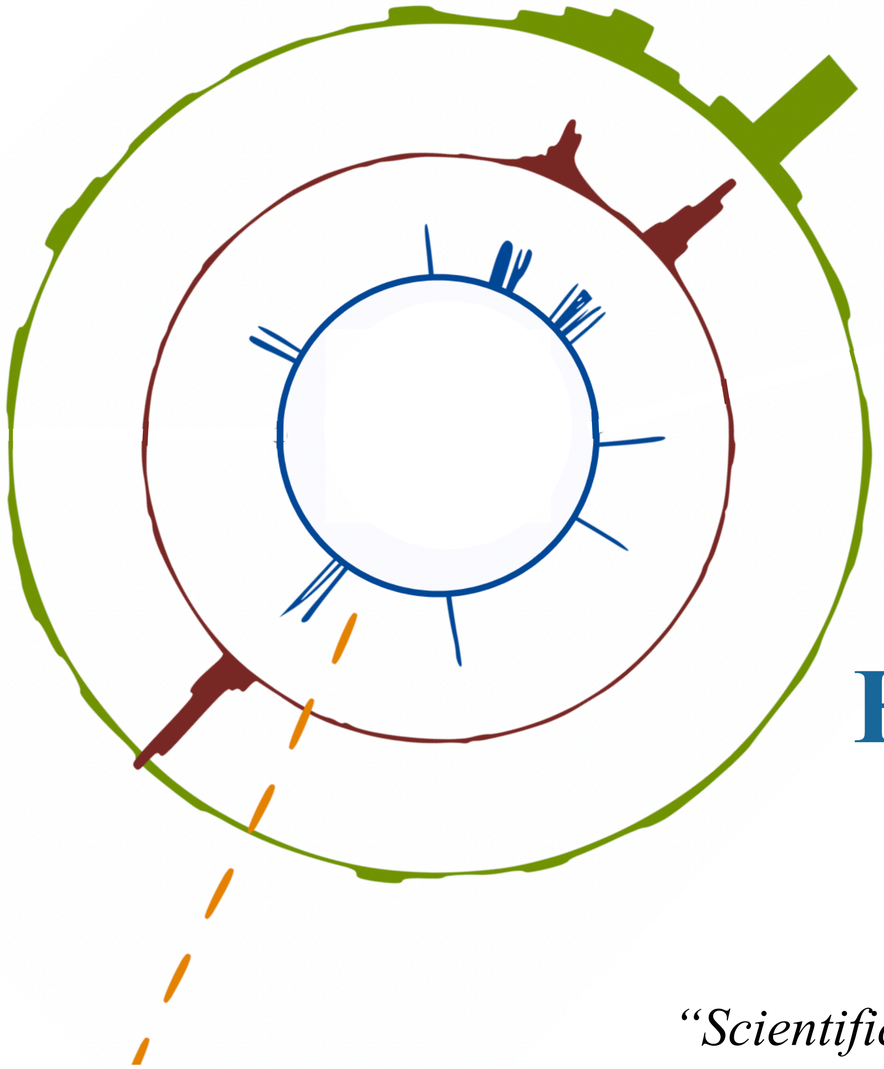
Today we'll talk about

Higgs Boson production

Basic concepts



Event Display
Higgs produced with
aVector Boson (W)



A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John Ellis, Mary K. Gaillard *) and D.V. Nanopoulos +)
CERN -- Geneva

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Higgs Boson

"Scientific theories cannot be deduced by purely mathematical reasoning."
Steven Weinberg

Higgs Physics

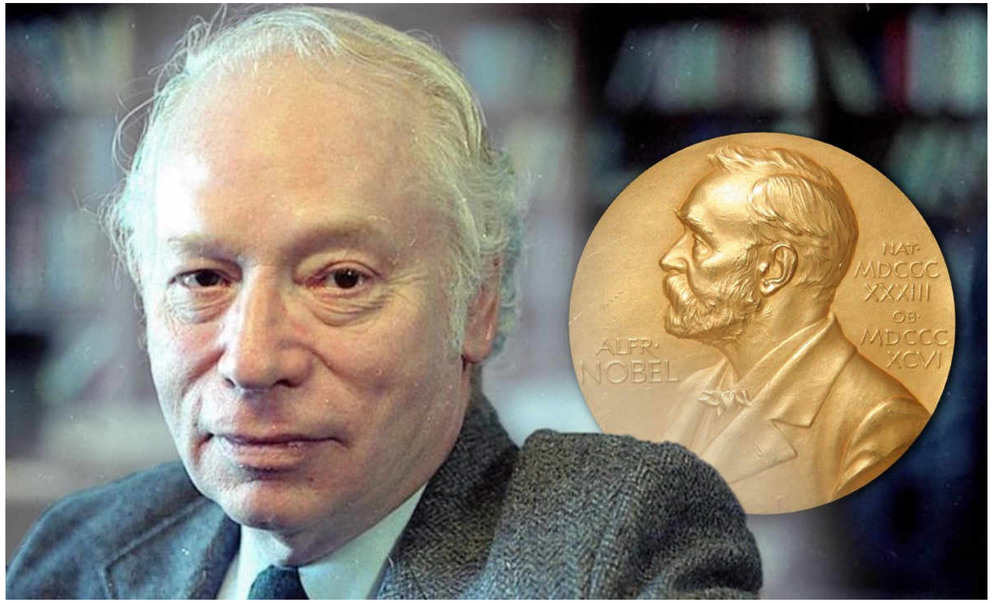
Higgs mechanism of Spontaneous Symmetry Breaking solves:

— Mass to gauge vector bosons

— Mass to fermions

— Standard Model Couplings

Introducing: **Scalar Massive Particle**



A Model of Lepton - Weinberg (1967)

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\Psi} \not{D} \Psi + h.c.$$

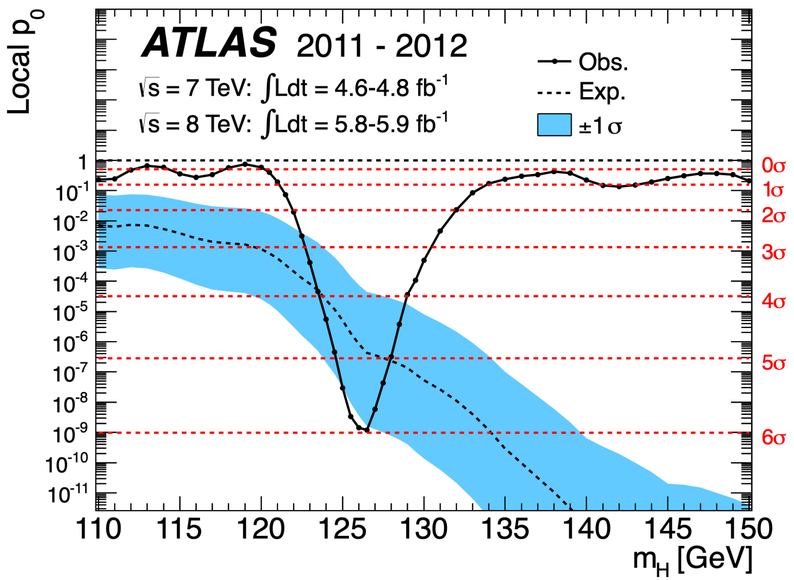
$$+ \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c.$$

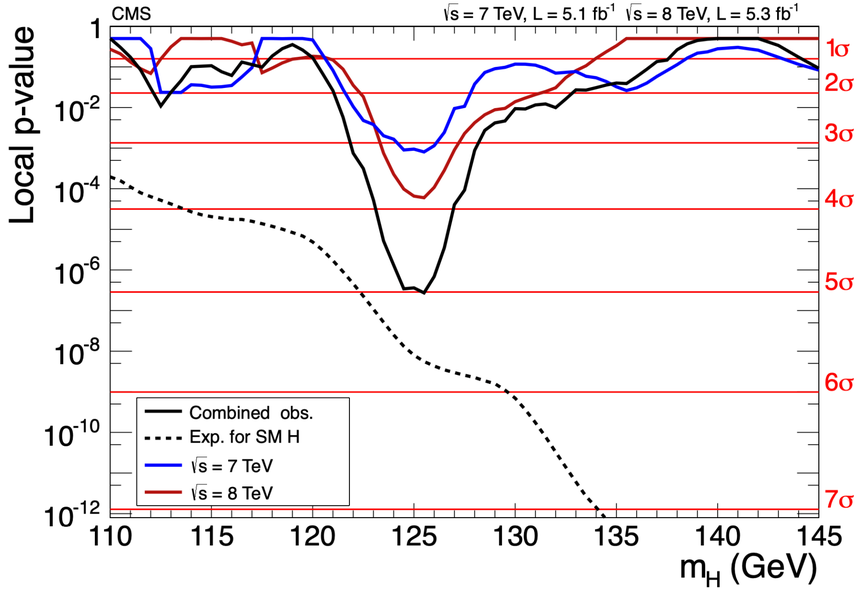
$$+ |D_\mu \phi|^2 - V(\phi)$$

Higgs Physics

No Loose Theorem of LHC:

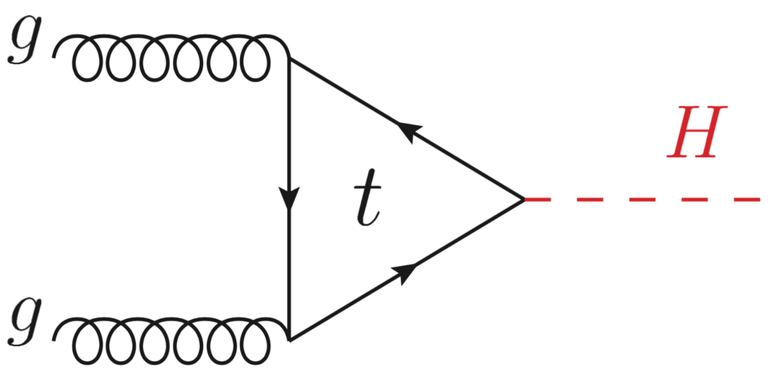
"Either you observe the Higgs Boson or new phyisics is required at the *TeV* scale"





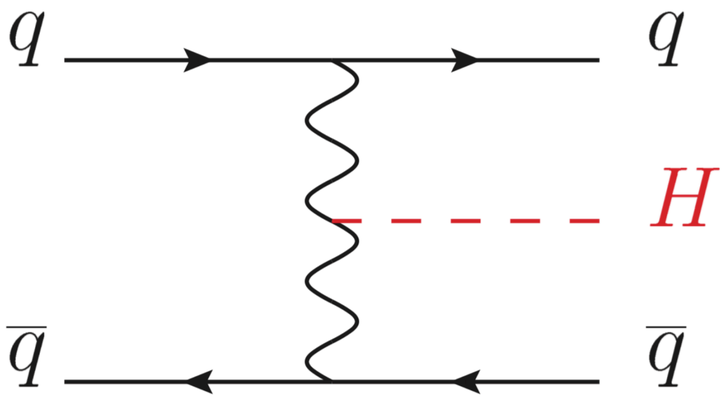
Higgs found in 2012
at $m_H = 125\ GeV$

Production $\sqrt{s} = 13\ TeV$



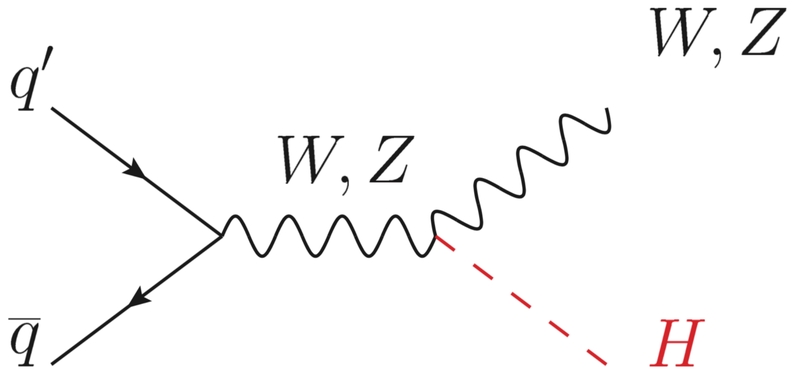
gluon-gluon Fusion **(ggF)**

$\sigma_{ggF} \sim 50\ pb$



Vector Boson Fusion **(VBF)**

$\sigma_{VBF} \sim 3.8\ pb$



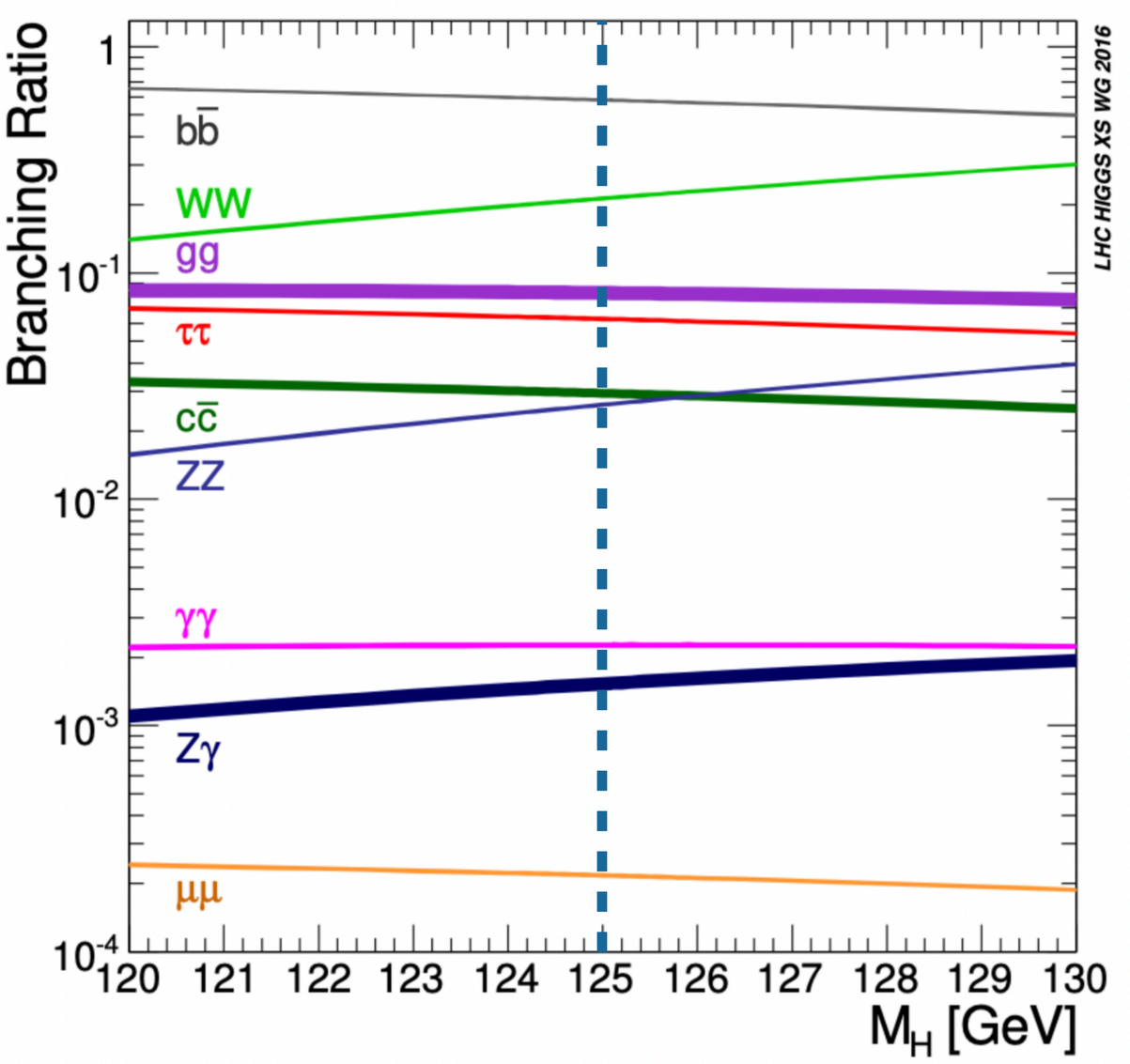
Higgs-strahlung **(VH)**

$\sigma_{ZH} \sim 0.9\ pb$

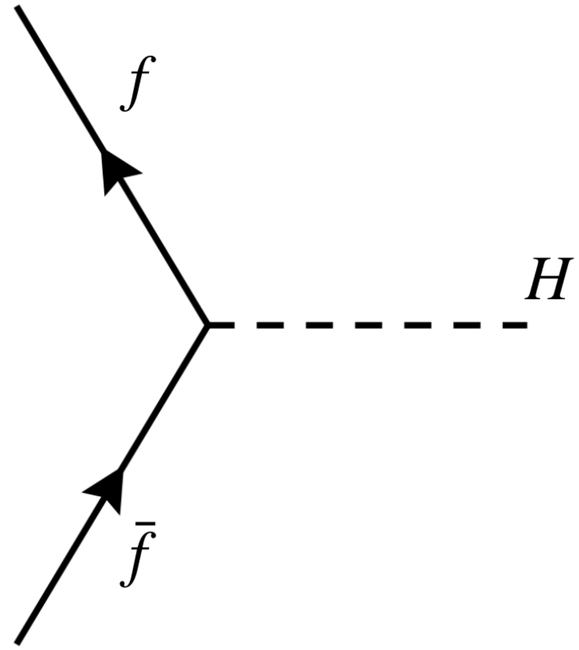
$\sigma_{WH} \sim 1.4\ pb$

$*1b = 10^{-24} cm^2$ $\sigma =$ probability of production

Decaying $m_H = 125\ GeV$



Channel	Branching Ratio (BR)
bb	57%
WW	22%
gg	8,3%
ττ	6,3%
cc	3%
ZZ	3%
γγ	0,2%
Zγ	0,2%
μμ	0,02%



*BR = prob. of decay

*observed

*not observed

$H \to bb$

Despite $BR(H \to bb) \sim 57\,\%$ it's **difficult** to measure it in **ggF** and **VBF**

too much background

Best channel is **VH:** First observation in 2018 of VH production and H(bb)

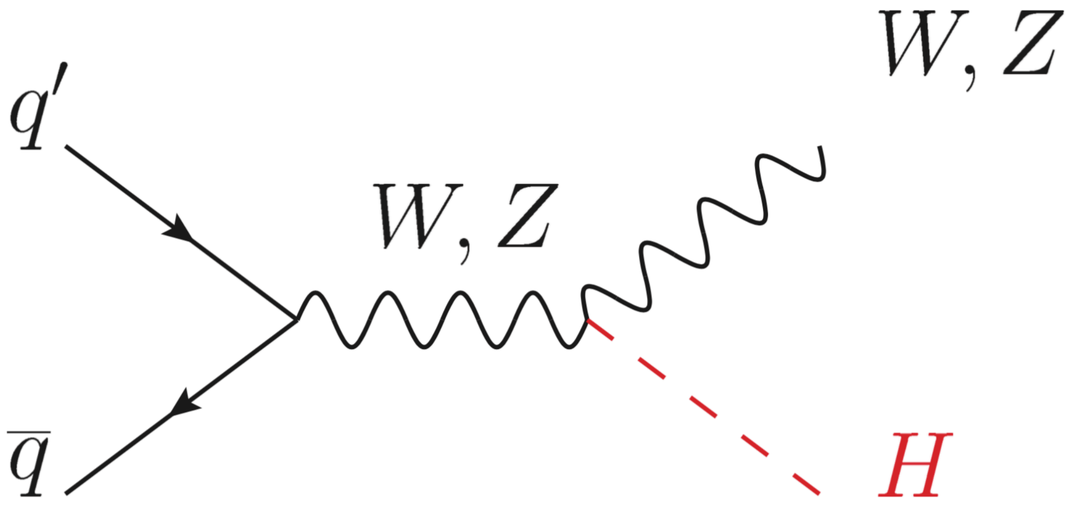
Why?

W,Z decay to **leptons**:

0L: $Z \to \nu_l \bar{\nu}_l$ (High Missing Energy, $\not{E}$)

1L: $W \to l\nu_l$ (1 Prompt lepton + $\not{E}$)

2L: $Z \to l^+ l^-$ (2 Prompt lepton at Z mass)



much more clear signature of the event

b-tagging

VH(bb) signature: 2 b-quarks → 2 b-jets:

b-tagging: algorithms identify a b-jet → ϵ_b

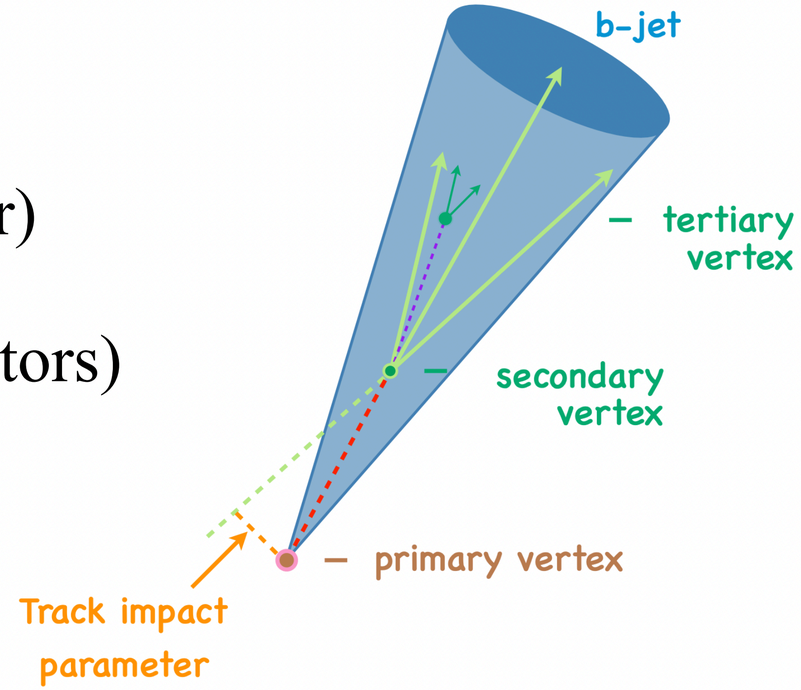
Exployting b-quark will hadronize in a B-hadron (e.g. B^0) that have a long lifetime

→ $c\tau_b \simeq 0.45\ mm$

Machine Learning techniques for identification (DL1r)

Delicate calibrations of ϵ_b on data (data-MC scale factors)

Calibrations on orthogonal (pure) samples as $t\bar{t}$



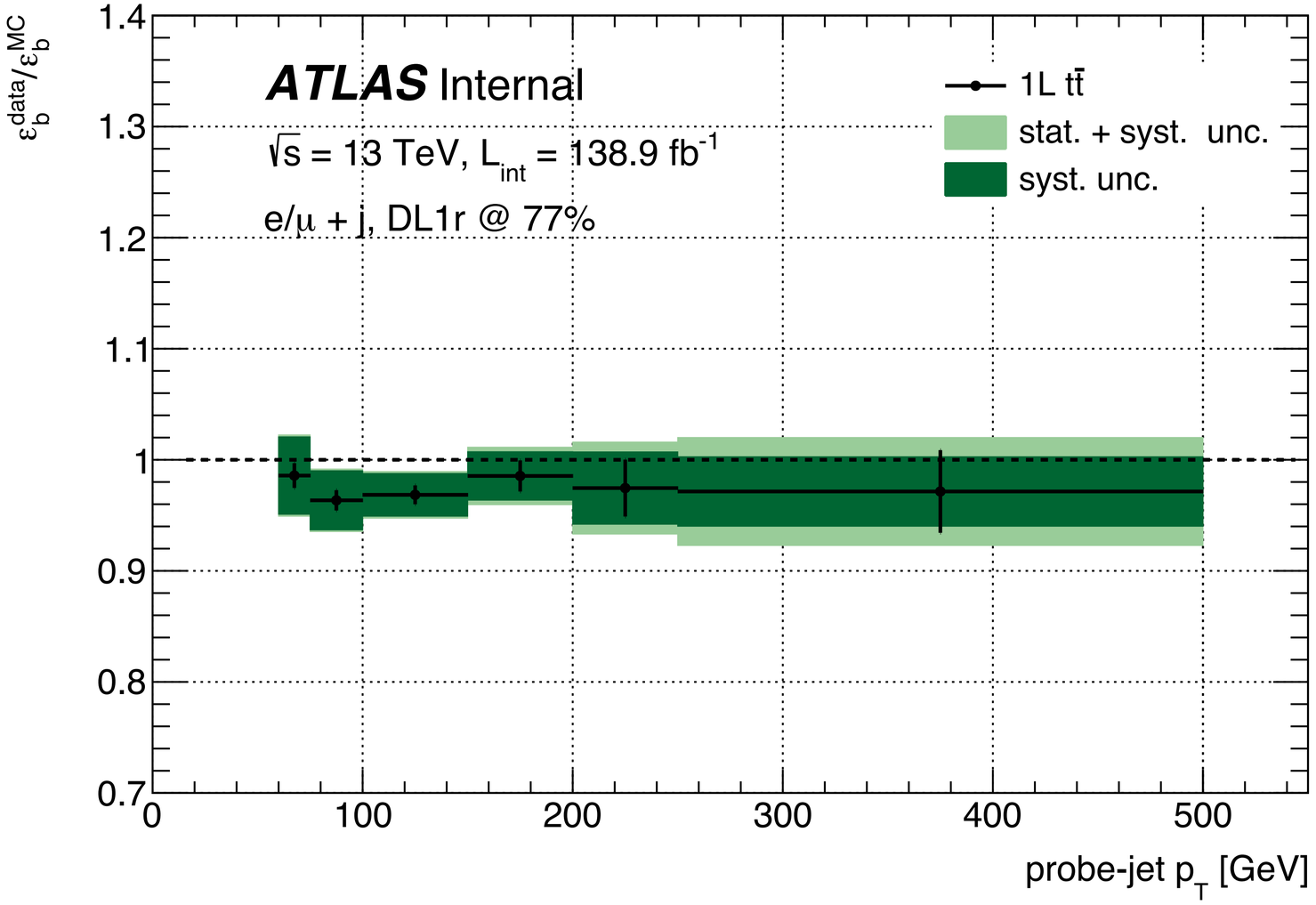
b-tagging

Small differences between data-MC since algorithms are optimized on MC simulations

Calibration of algorithms to correct the MC given trusted data

— SF_b

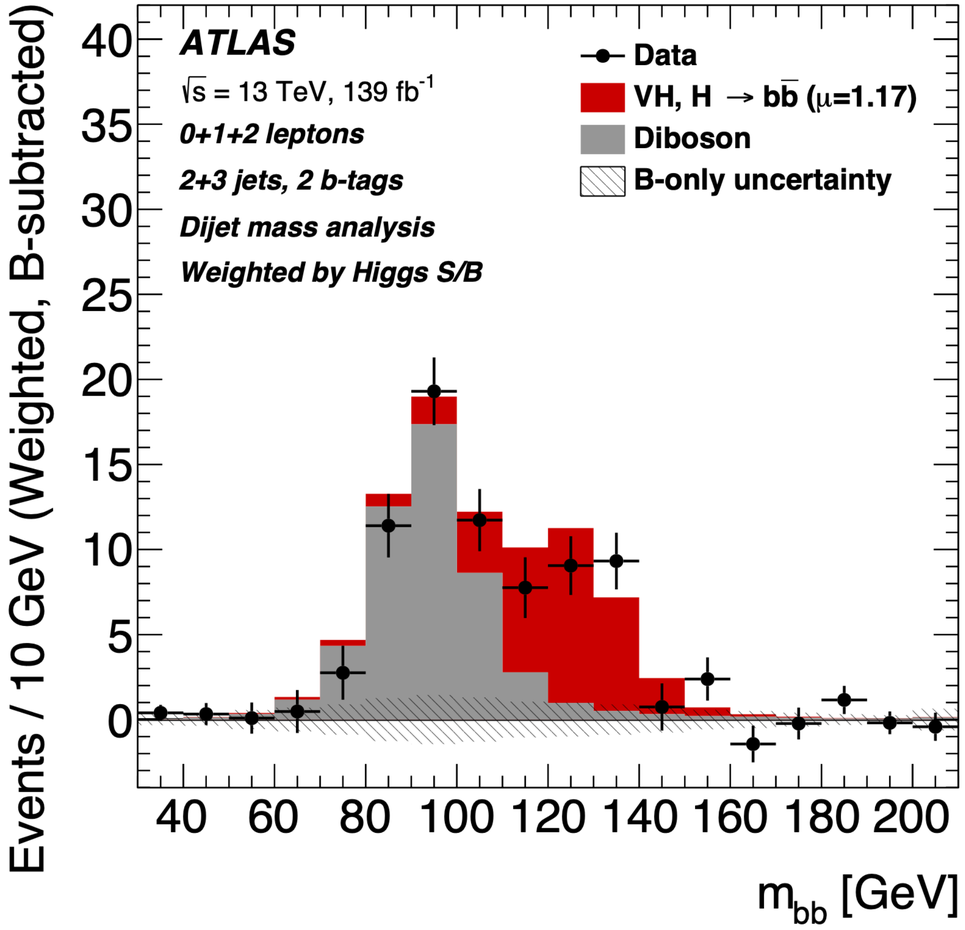
Multiple calibrations: combination

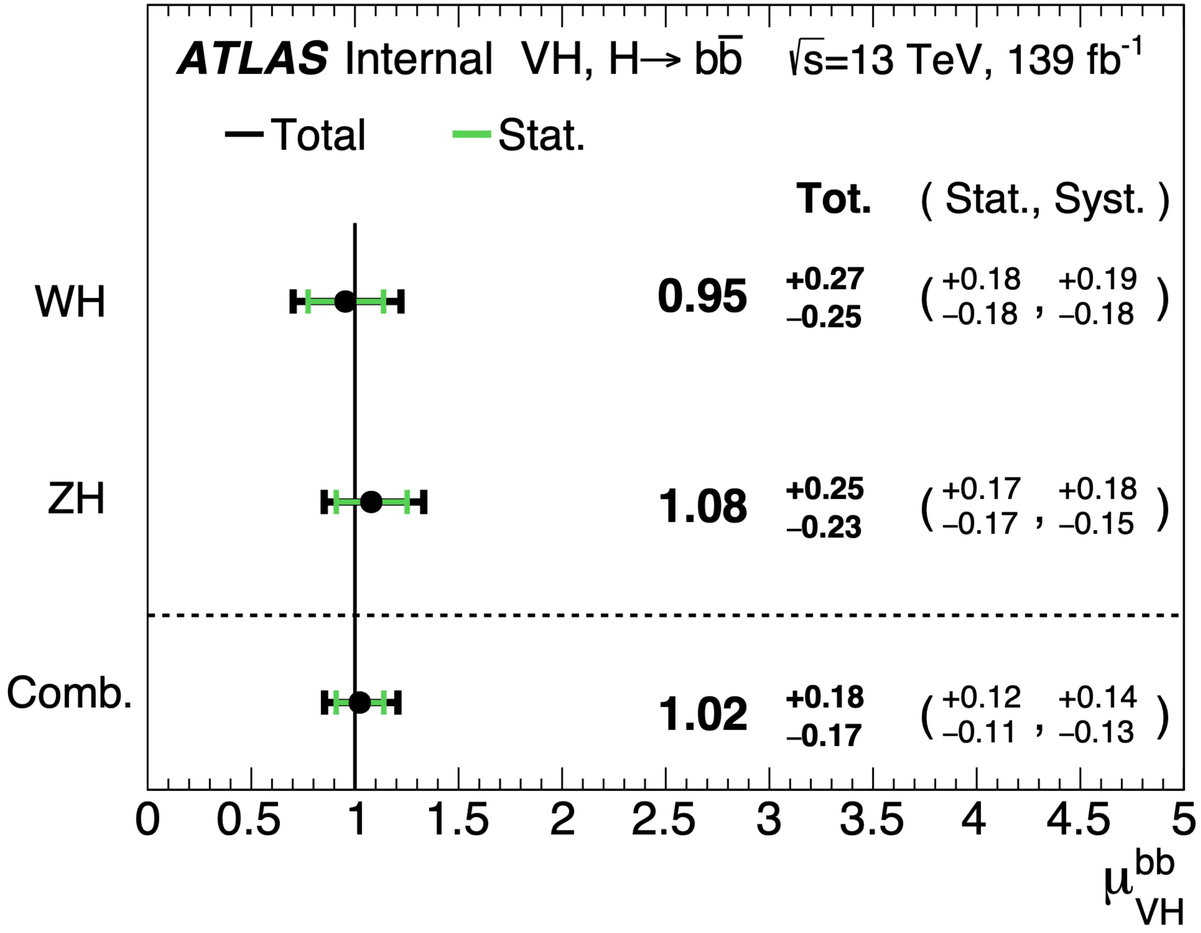


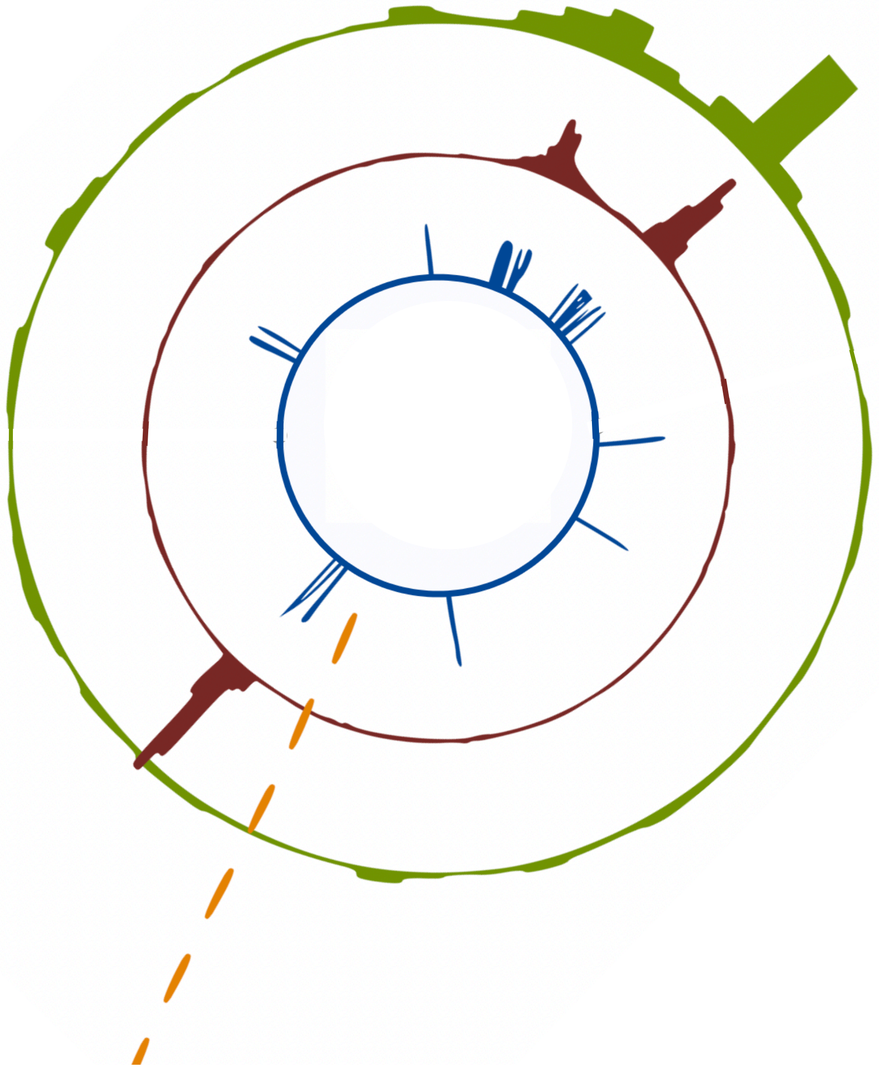
VH(bb) Results

Observation:
Expected (Observed): 6.7σ (6.7σ)

Results in terms of signal strength $\mu = \dfrac{\sigma \cdot BR}{\sigma_{SM} \cdot BR_{SM}}$



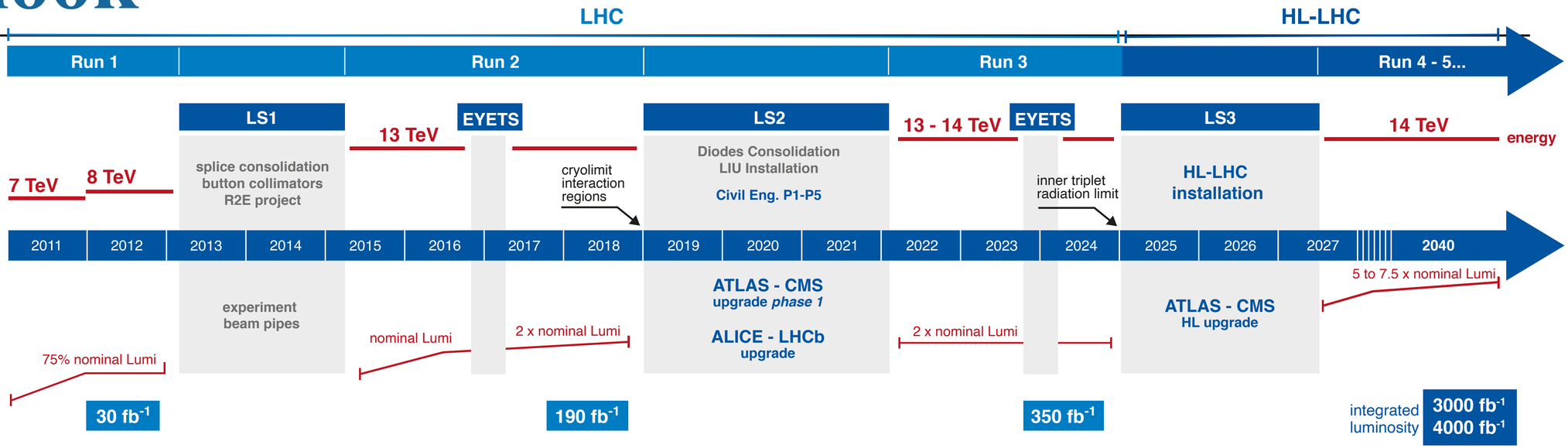




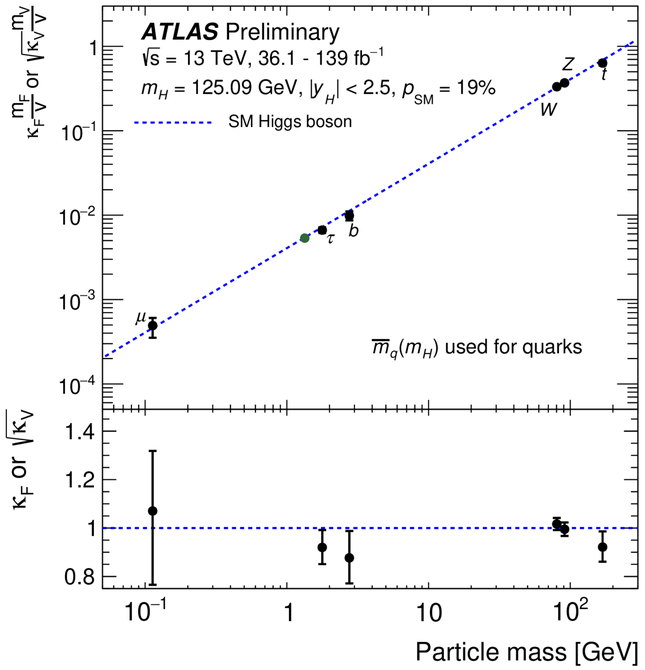
Outlook

"I am quite surprised that it happened during my lifetime.
It is nice to be right about something sometimes."
Peter Higgs

Outlook

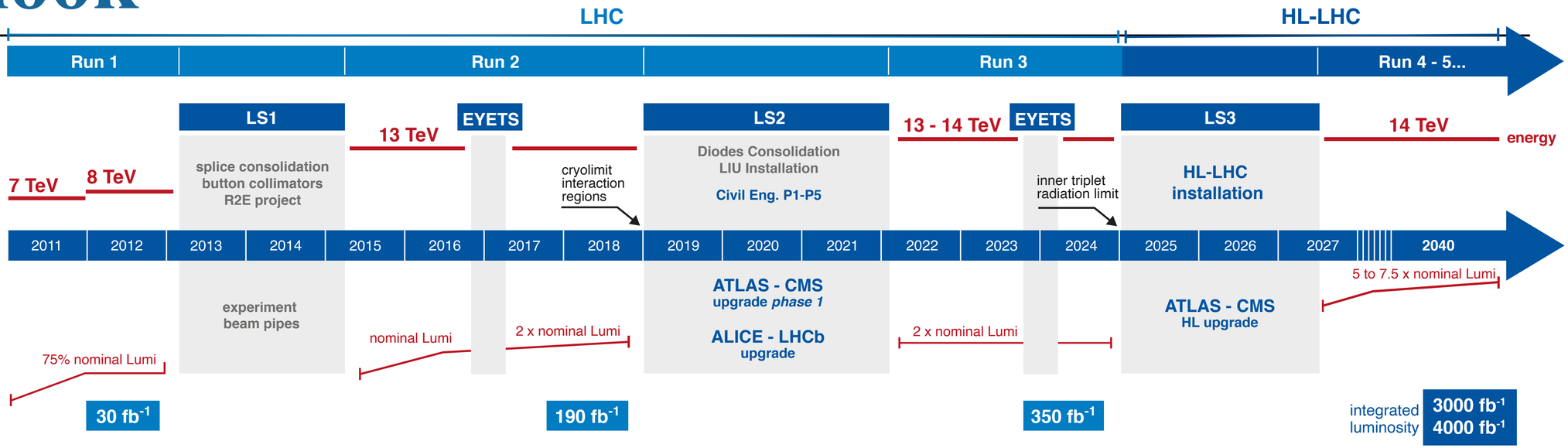


Now the **goal** is to give the **best measurement** of the VH production cross-section using upgraded algorithms and combining the analysis of $H \to b\bar{b}$ (observed) and $H \to c\bar{c}$ (not-observed)



c?

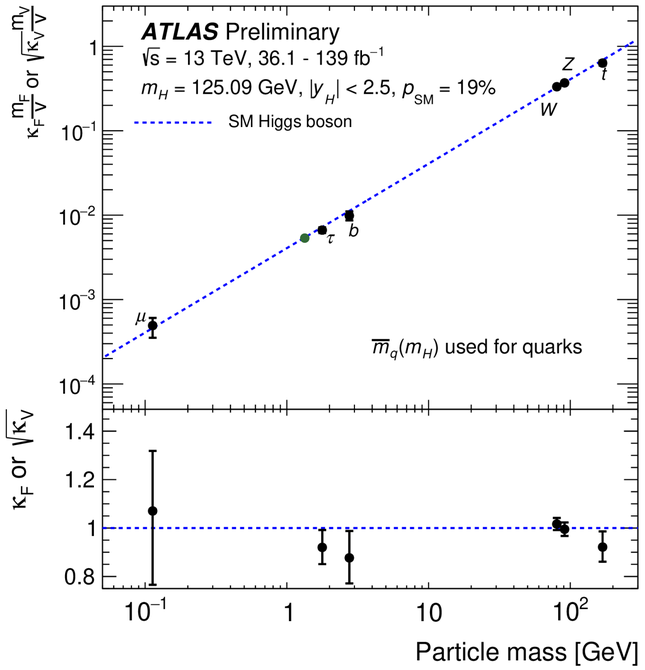
Outlook



Main Evidence/Observation purpose of Run-3 and beyond:

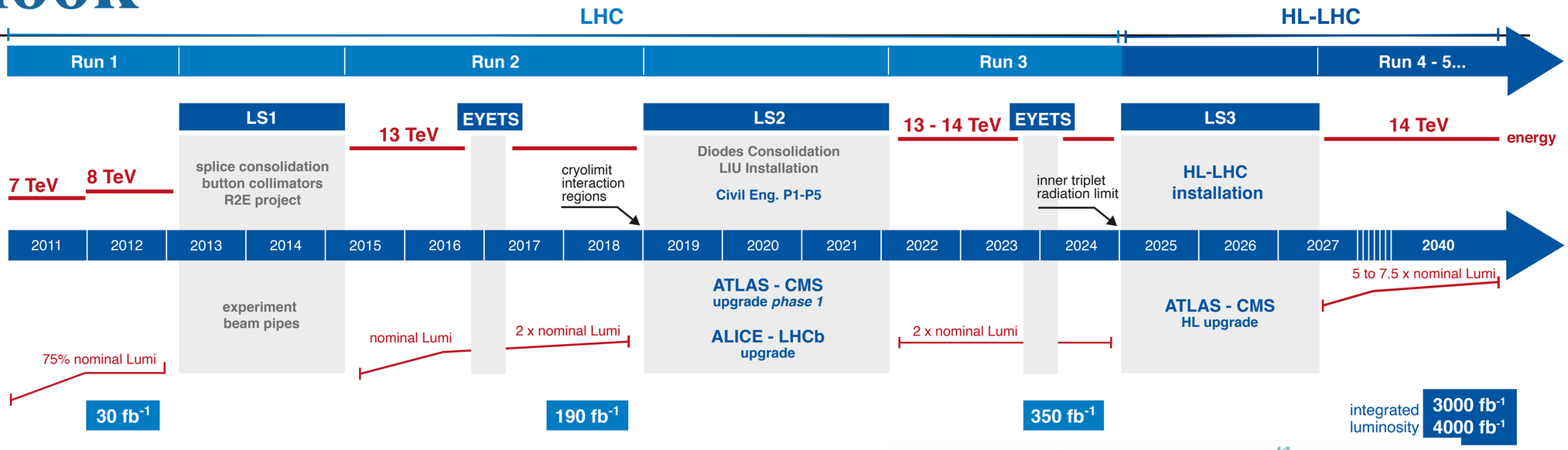
— Higgs coupling to 2nd generation:

$H \to c\bar{c}$ $H \to \mu^+\mu^-$



c?

Outlook



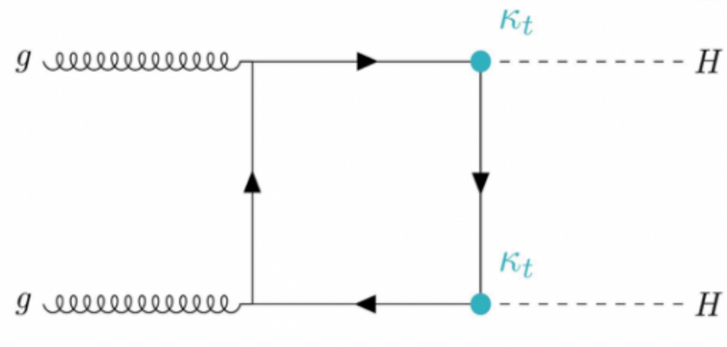
Main Evidence/Observation purpose of Run-3 and beyond:

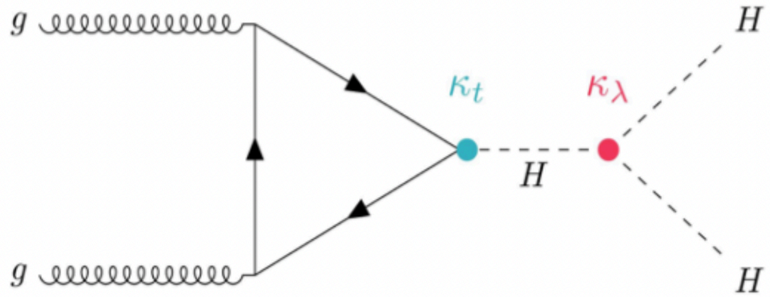
— Higgs coupling to 2nd generation:

$H \to c\bar{c}$ $H \to \mu^+\mu^-$

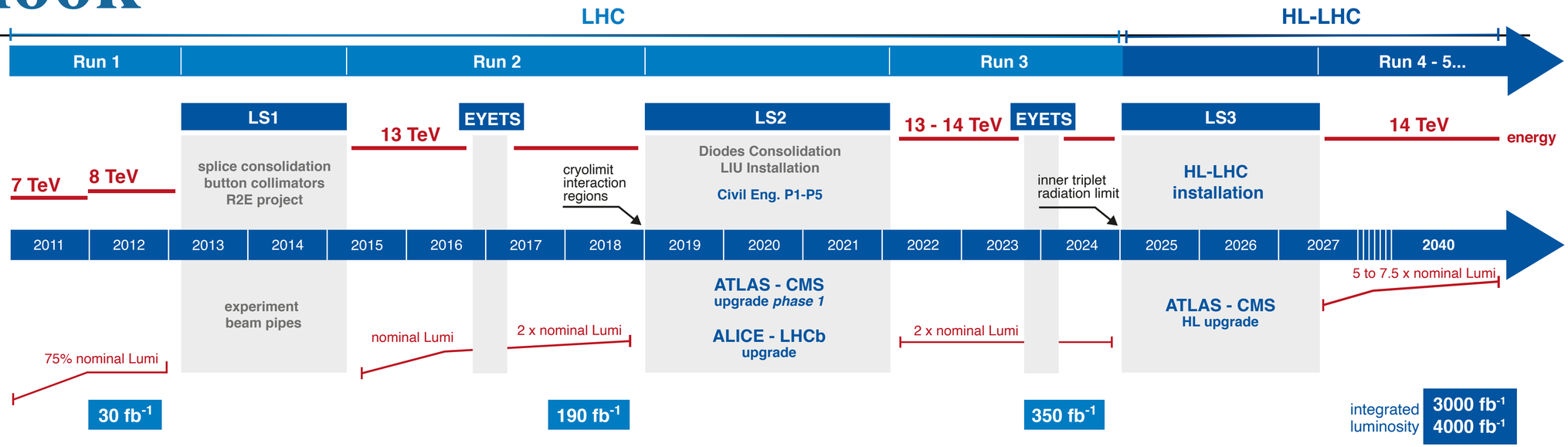
— Higgs self-coupling:

$pp \to HH$ (maybe another time 🙃)





Outlook



Main Evidence/Observation purpose of Run-3 and beyond:

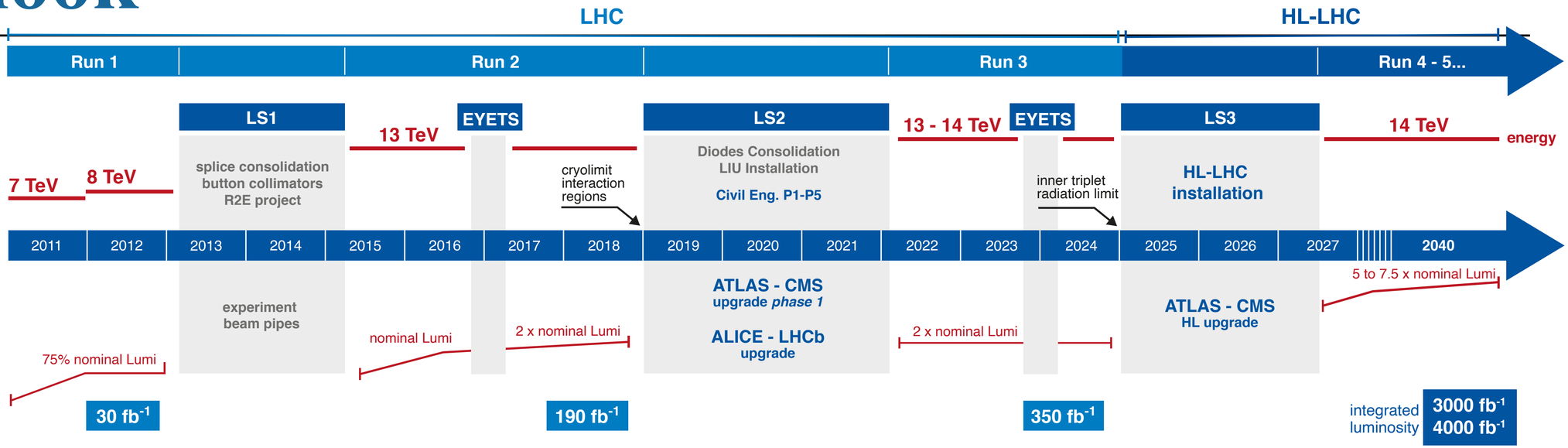
— Higgs coupling to 2nd generation:

$H \to c\bar{c}$ $H \to \mu^+\mu^-$

— Higgs self-coupling:

$pp \to HH$ (maybe another time 🙃)

Outlook



Thanks for the attention!