International School of Subnuclear Physics
«Gravity and matter in the subnuclear world»

ATLAS and CMS Highlights

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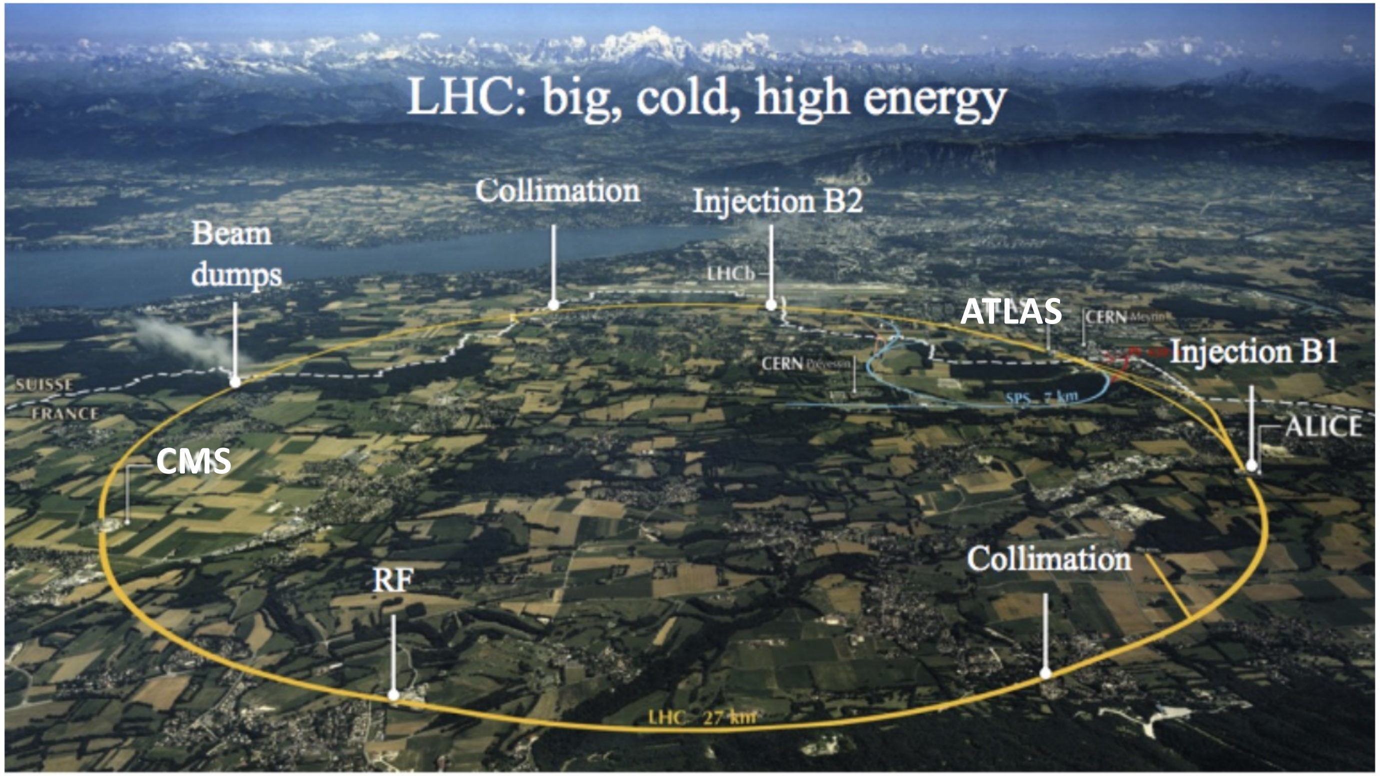
The LHC machine in Run 2



27 km ring
100 m underground
p-p collisions
E_{cm} =13.6 TeV

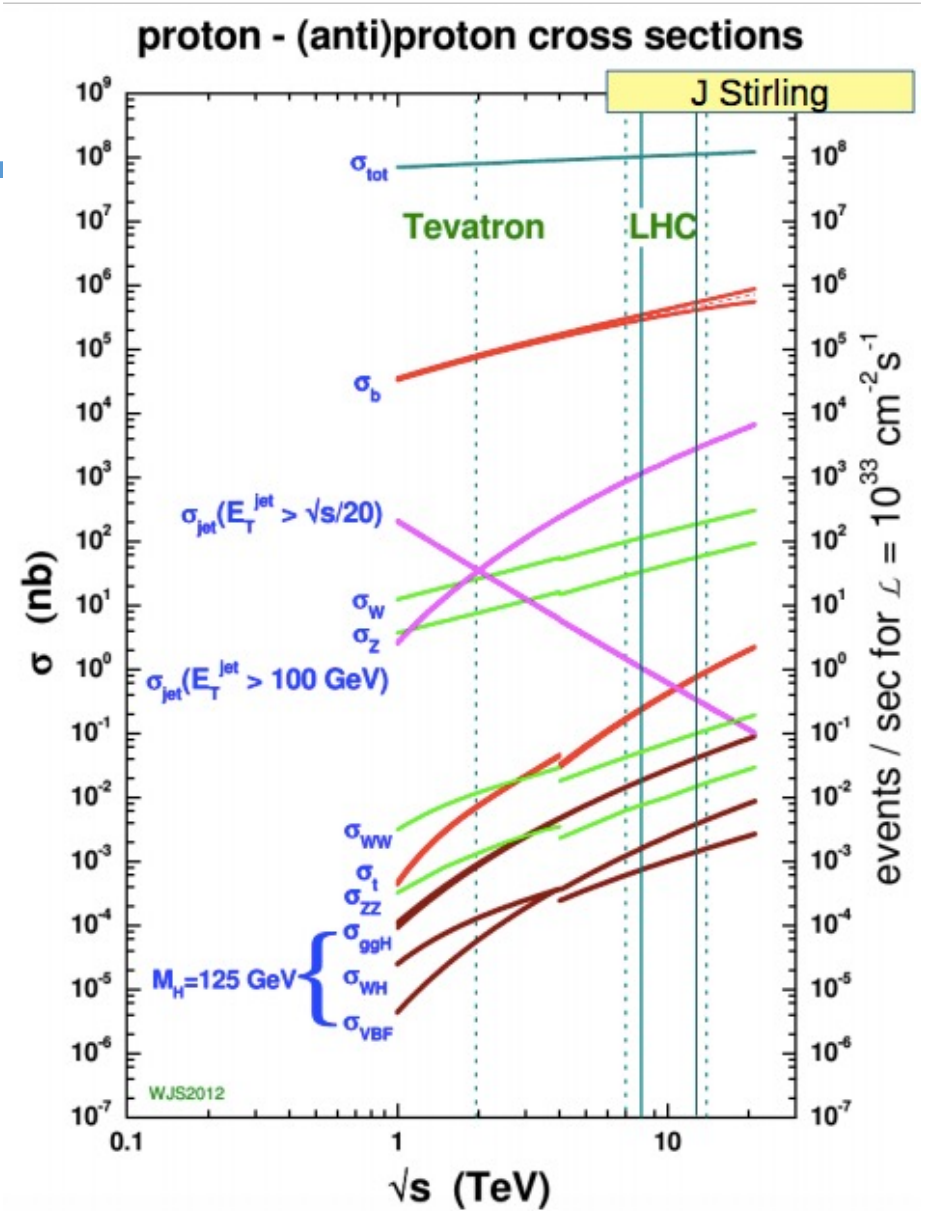
v_p = 99.999991% of c

1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
~4000 Beam loss monitors

150 tonnes helium, ~90 tonnes at 1.9 K
350 MJ stored beam energy in 2016
1.2 GJ magnetic energy per sector at 6.5 TeV

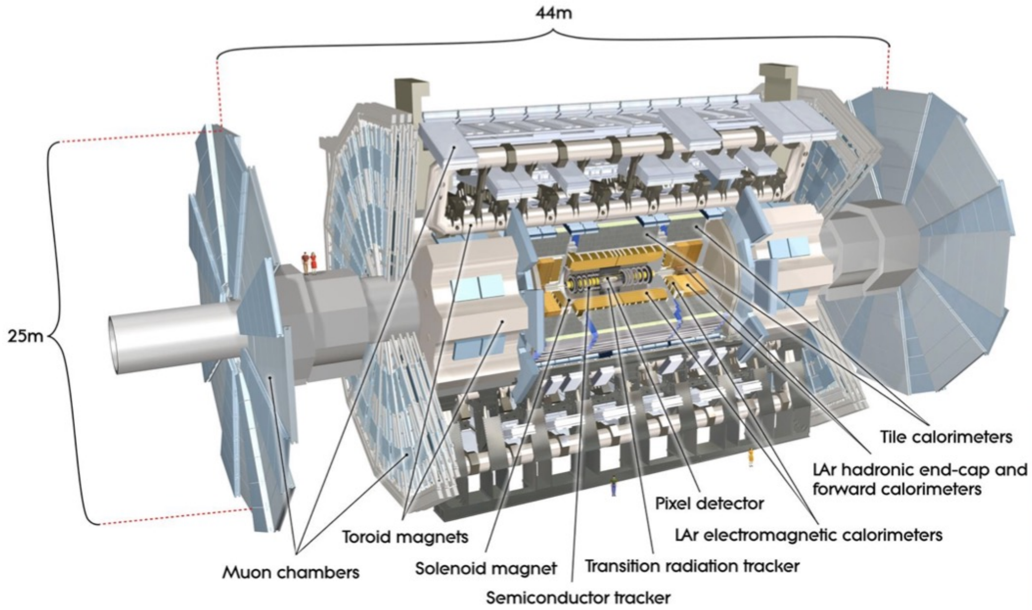
Key parameters

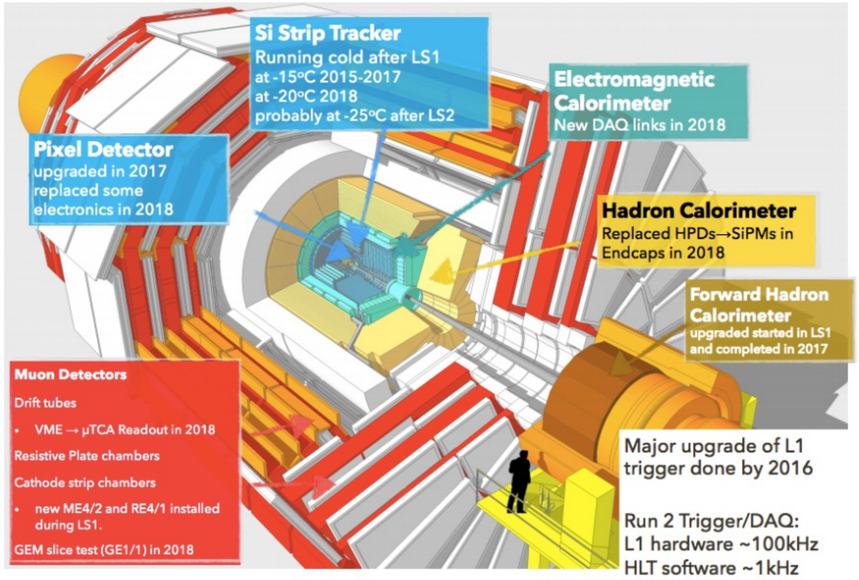
- Key parameters at a collider:
  - **Collision energy**
    - Set by dipole bending magnets (1232)
  - **Luminosity**
    - How many collisions occur
  - **Number of events for a given process**:
    - N = cross-section x luminosity
      cross-section depends on collisions energy



ATLAS/CMS Detectors

Same physics goals,
different design choices,





Magnets

- ATLAS Solenoid (2T) + 3 Toroids (muon system)
- CMS: Large Solenoid (3.8T)

Calorimeters

- ATLAS: LAr ECAL(longitudinal granularity), outside solenoid
- CMS: Crystal ECAL, inside solenoid

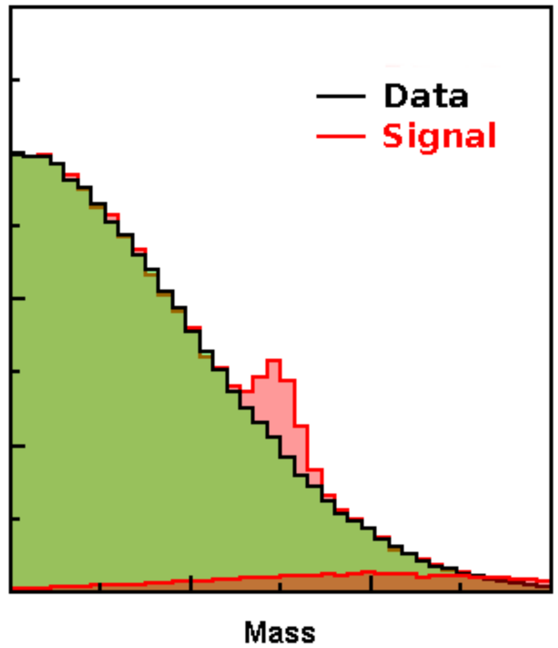
LHC physics program

- Physics@LHC is **most ambitious** and farthest reaching HEP program ever
- Huge dataset + well understood detector performance
- Only place to produce key SM particles: **8M Higgs, 0.1G Top, 0.5G W, Z**

- **Precision measurements**
  - ✓ Determine fundamental parameters, probe higher order QCD and EW effects
- Access to **rare processes** (eg: production of WWW and tttt)
  - ✓ Probe poorly or untested corners of the SM
- Broad **search program @ TeV scale** (high energy frontier) & feeble interactions
- Study of **new state of matter** (quark-gluon plasma)

New physics at collider experiments

- SM successful for particle collisions
- Discrepancies may indicate new physics ≡ new particles/fields



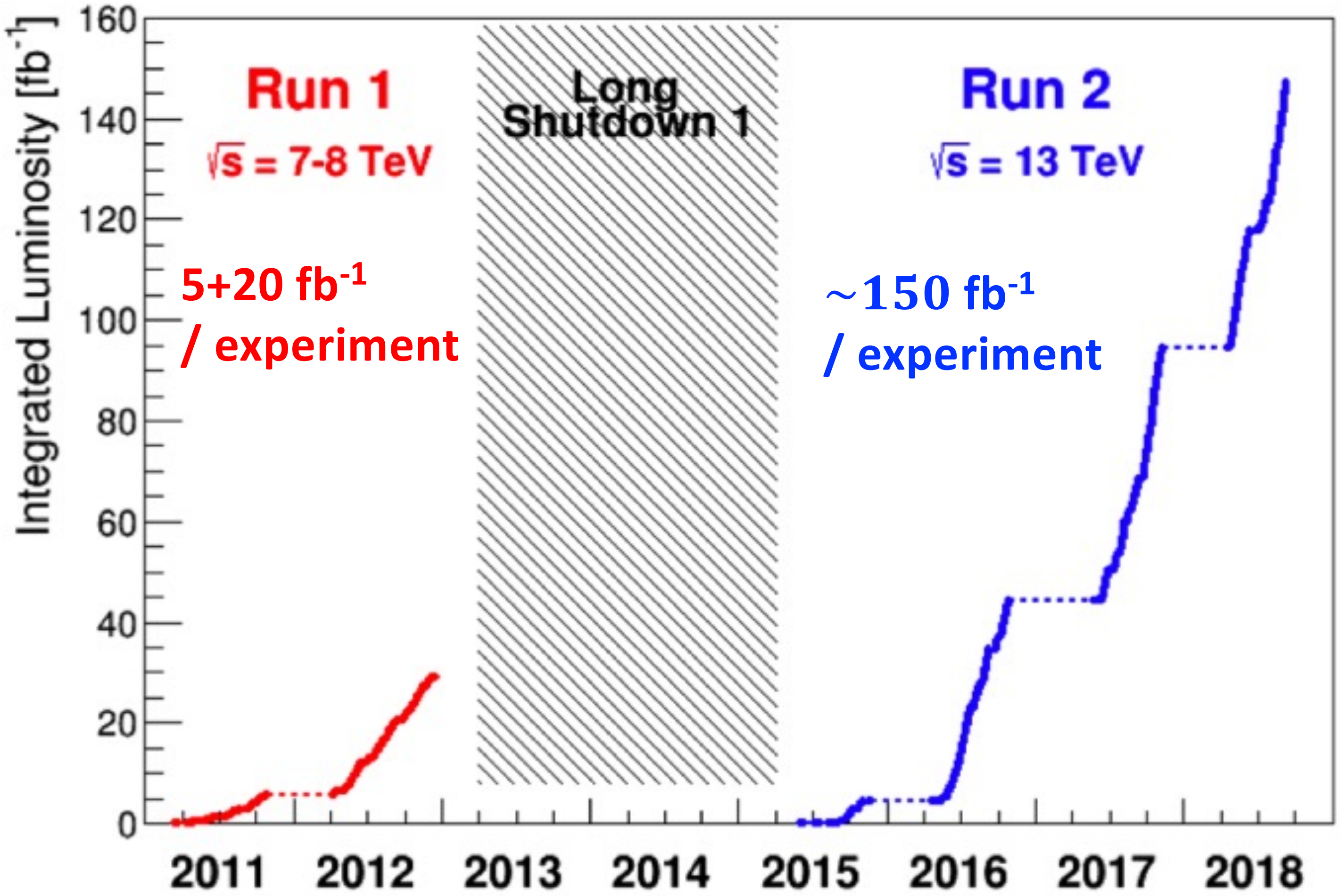
Direct observations of new particles

- Combine known particles to create “invariant masses” & search for “resonance” enhancements above background
- Observe through unusual signatures in detectors (anomalously high dE/dx tracks…)

Indirect observations of new particles

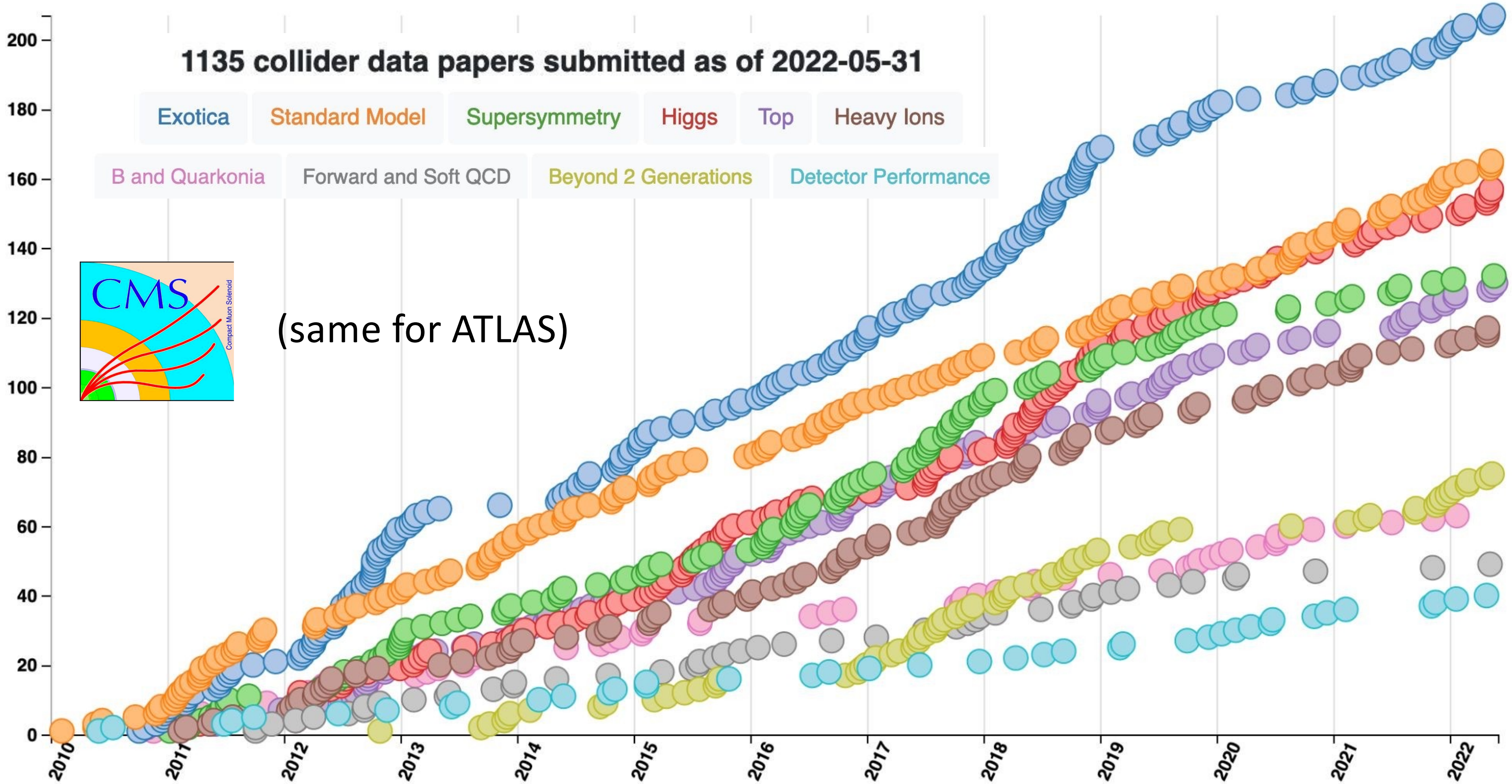
- Compare SM predictions with data
- Search for any discrepancy with SM background
- Explain using theoretical frameworks beyond SM (BSM)

LHC



Integrated Luminosity [fb^{-1}]
160
140
120
100
80
60
40
20
0
Run 1
$\sqrt{s}$ = 7-8 TeV
5+20 fb^{-1}
/ experiment
Long
Shutdown 1
Run 2
$\sqrt{s}$ = 13 TeV
~150 fb^{-1}
/ experiment
2011
2012
2013
2014
2015
2016
2017
2018

Huge scientific production



(same for ATLAS)

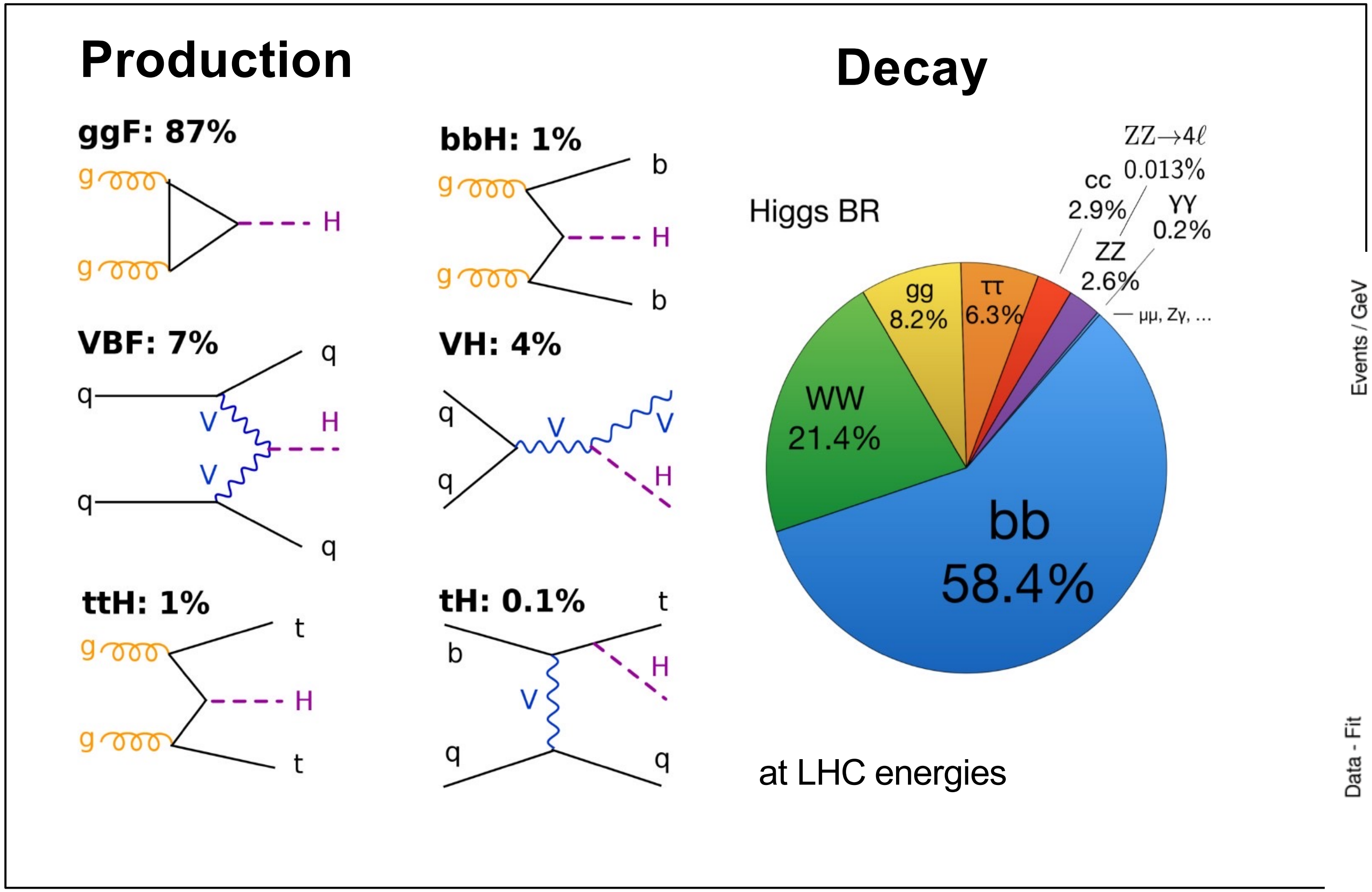
Run 2 Breakthroughs

- **Higgs**
  - Observation of all **main production mechanisms**
  - Observation of **Yukawa interactions** w/ 3rd generation fermions
  - Constraints on **Higgs self-interaction** via HH cross section
  - Evidence for H→ $\mu\mu$ and H→ $ll\gamma$
- **Rare processes**
  - Observation of weak boson scattering modes (incl. $W^{\pm}W^{\pm}$)
  - Observation of ttW, ttZ and tZq
  - Evidence for **tttt production**
- **Searches**
  - Excluded a wide range of BSM parameter space with a broad search program
    - **SUSY & resonances**: gluino, squark, stop and Z' exclusions* up to m= 2.3, 2.0, 1.3 and 5.0 TeV
    - **Dark matter** constraints, incl. H → invisible <~10%
    - Challenging signatures such as compressed spectra, displaced vertices, **long-lived particles** etc..

Precision Measurements

- Stringent tests of **Higgs Mechanisms**
- Measure **Yukawa Couplings**
- Stringent Tests of **SM self-consistency**

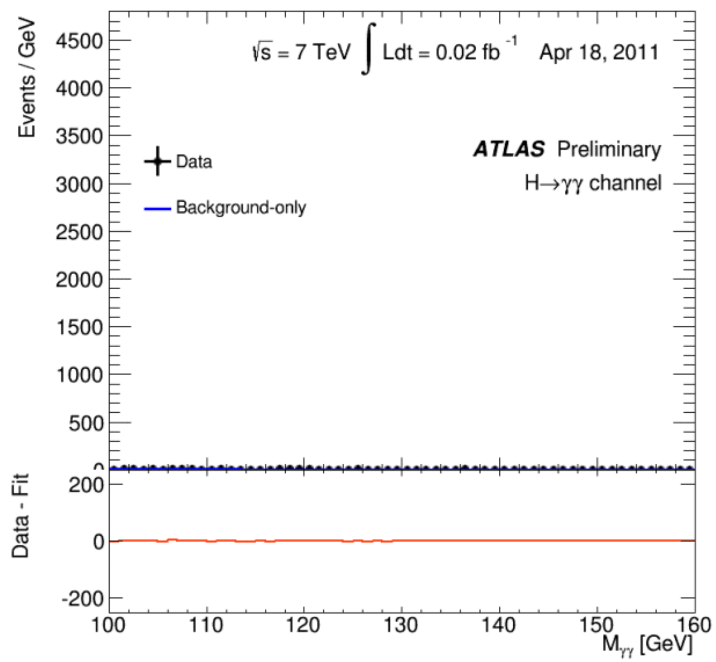
Higgs



Production
ggF: 87%
bbH: 1%
VBF: 7%
VH: 4%
ttH: 1%
tH: 0.1%
Decay
Higgs BR
bb 58.4%
WW 21.4%
gg 8.2%
ττ 6.3%
cc 2.9%
ZZ 2.6%
γγ 0.2%
ZZ→4ℓ 0.013%
μμ, Zγ, ...
at LHC energies

ANNIVERSARY
CELEBRATING

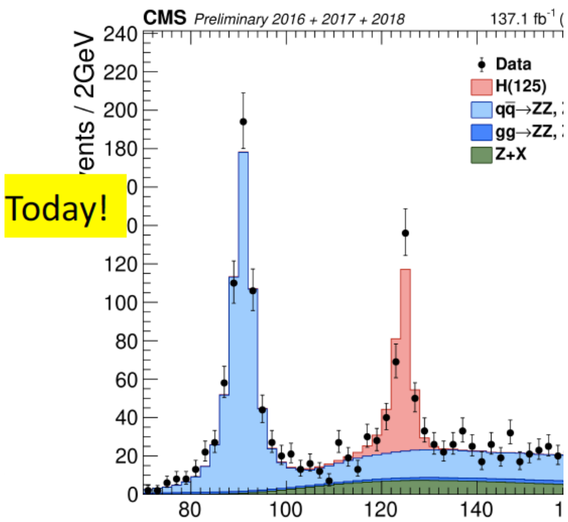
H→ γγ



√s = 7 TeV ∫ Ldt = 0.02 fb⁻¹ Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
Data - Fit
M_γγ [GeV]

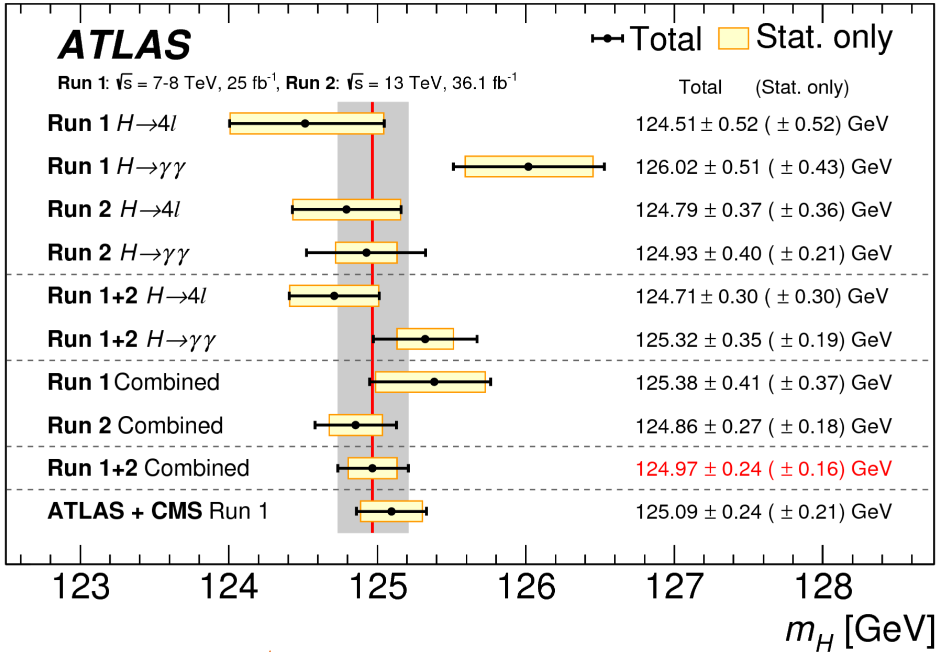
SM Higgs nowadays

Higgs signal



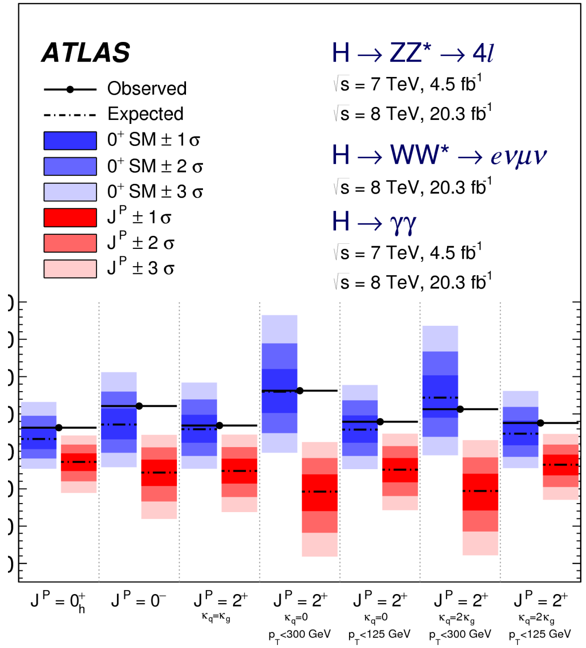
M(4l)

Higgs mass



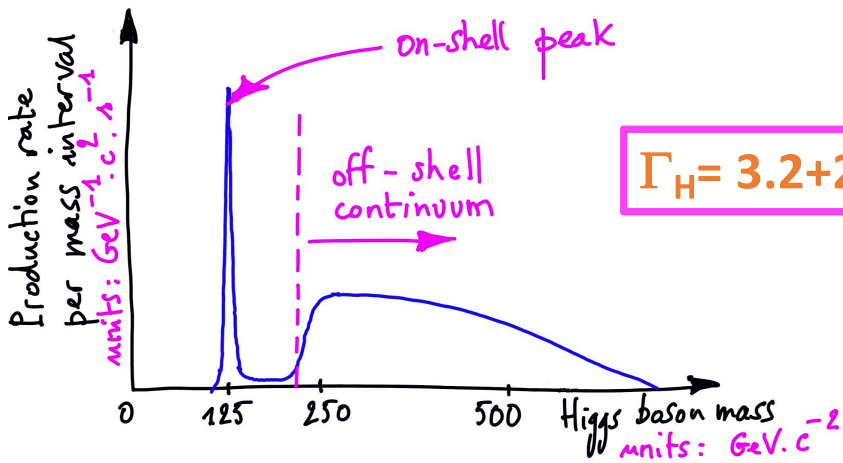
$\Delta m_H = 0.2\%$

Spin/CP

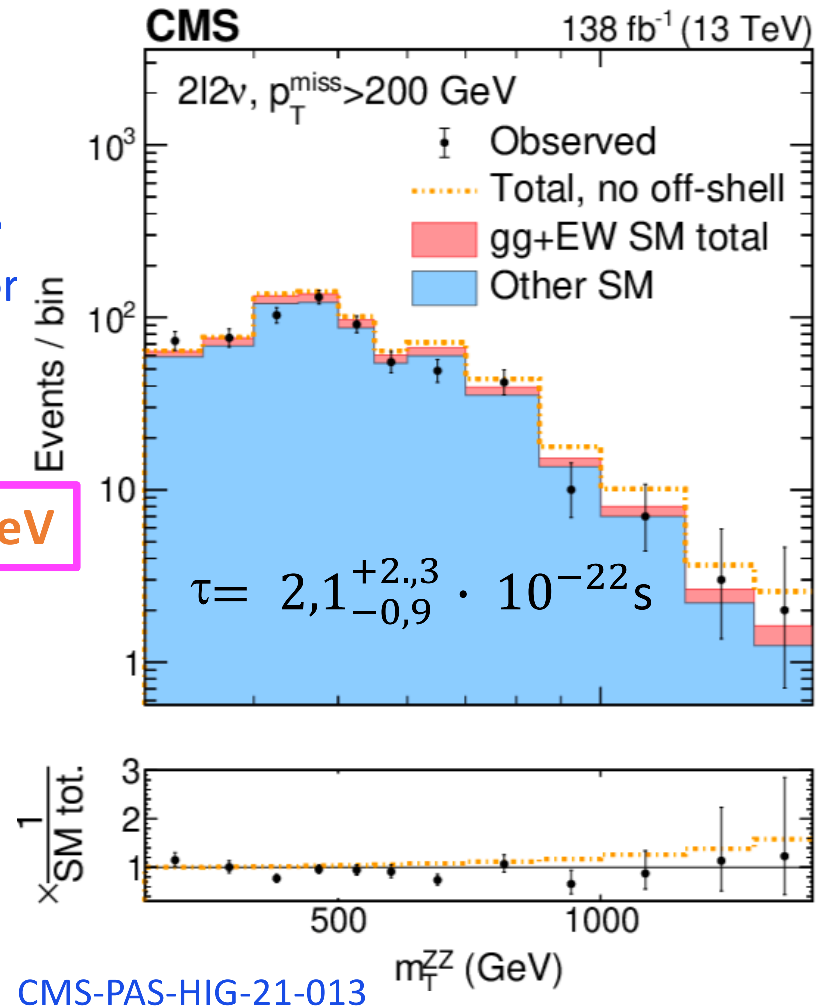


Higgs width

- Predicted $\tau_{Higgs} = 1{,}6 \cdot 10^{-22}$ s
  - 10^{12} times too short for the boson to fly a measurable distance
  - $\Gamma_{Higgs:}$ (~ 4 MeV) 200 times too small to be resolved by detector



Γ_H= 3.2+2.4−1.7 MeV

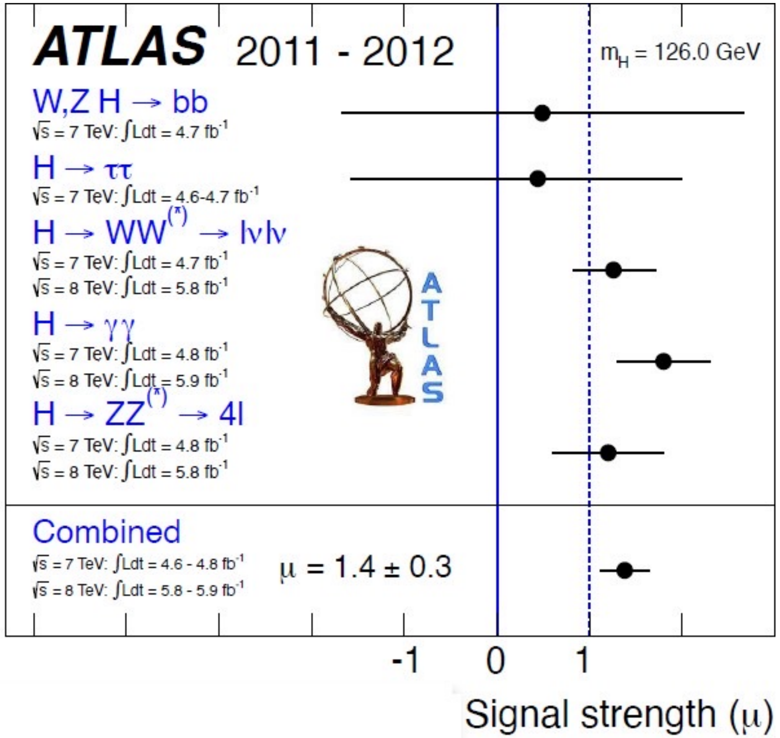


$\tau = 2{,}1^{+2.,3}_{-0,9} \cdot 10^{-22}$s

CMS-PAS-HIG-21-013

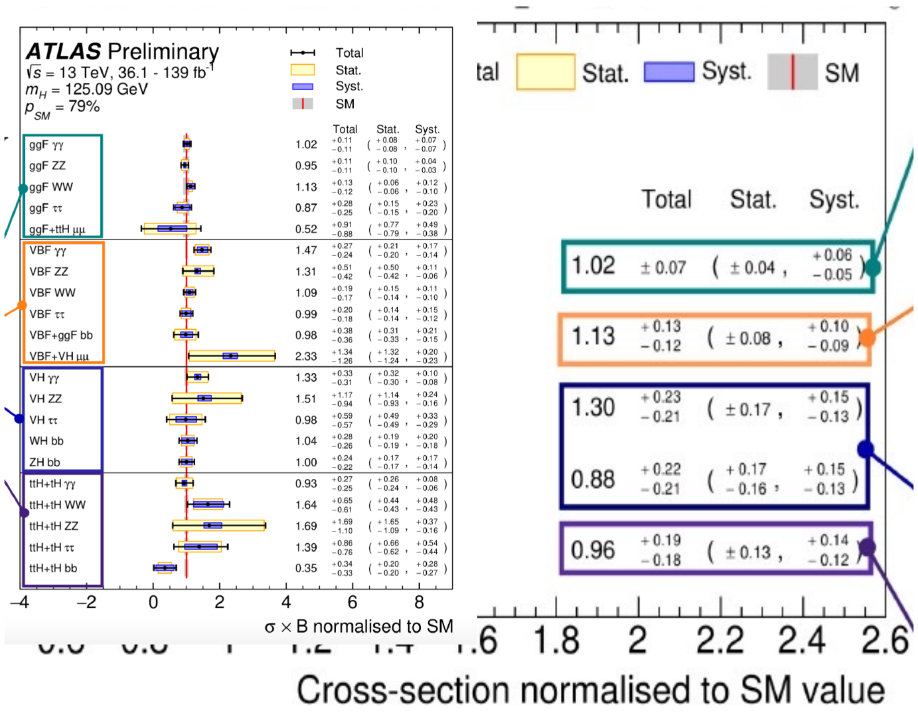
- Evidence for off-shell Higgs production (10% of on-shell)
- Extract Γ_{Higgs} from $\frac{off\ shell\ production}{on\ shell\ production}$

Higgs Signal strenght: Precision!



$\mu = \sigma / \sigma_{SM}$

10 years later.



$\mu = 1.4 \pm 0.3$

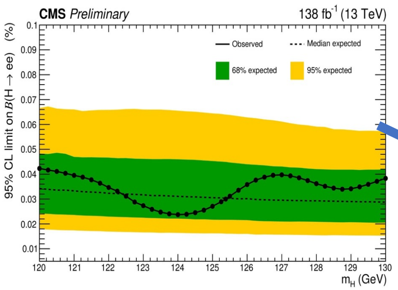
$\Delta\mu = 5.6\%$

$\mu = 1.08 \pm 0.06$

$\Delta\mu = 2.1\%$

Higgs Couplings: Precision!

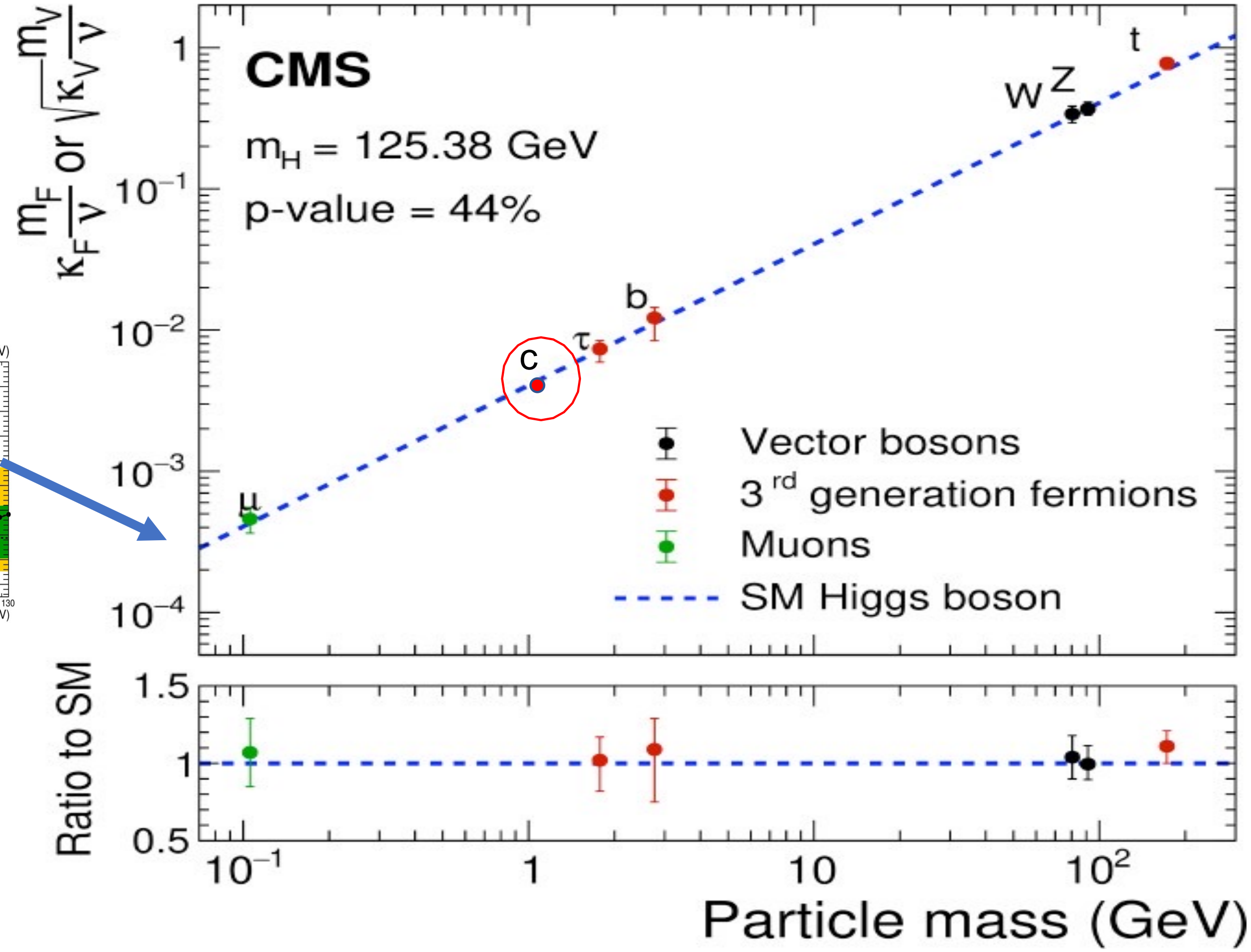
$H \rightarrow e^+ e^-$



HIG-21-015

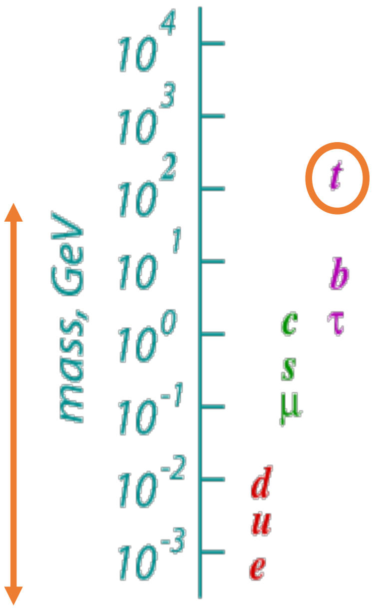
BR < 3.0×10^{-4}

Coupling vs mass



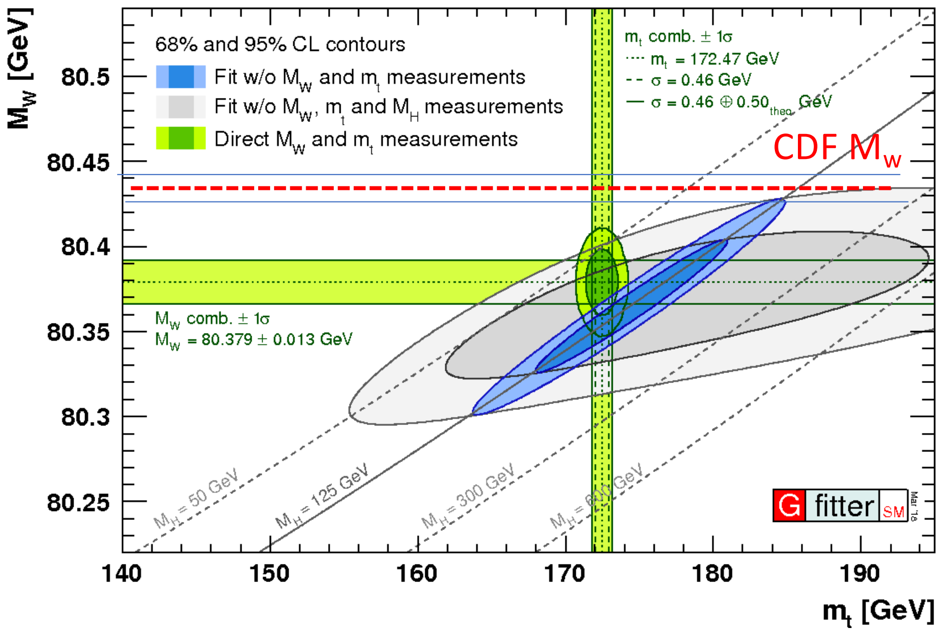
Top quark

- Heaviest SM particle



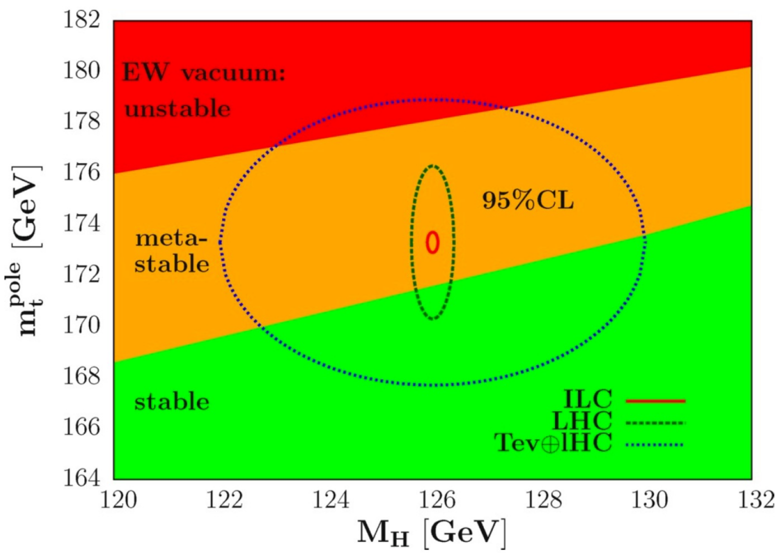
5 orders of magnitude

- Key to electroweak precision fits



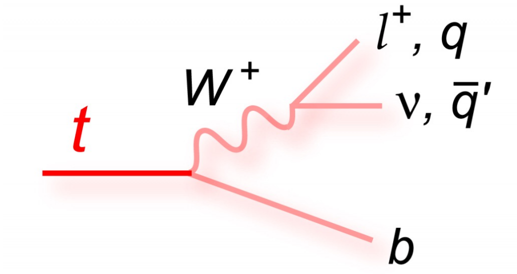
EW Precision fit from 2018

- Large top mass implies meta-stable universe



m_{top} vs m_H

Top quark mass best measurement

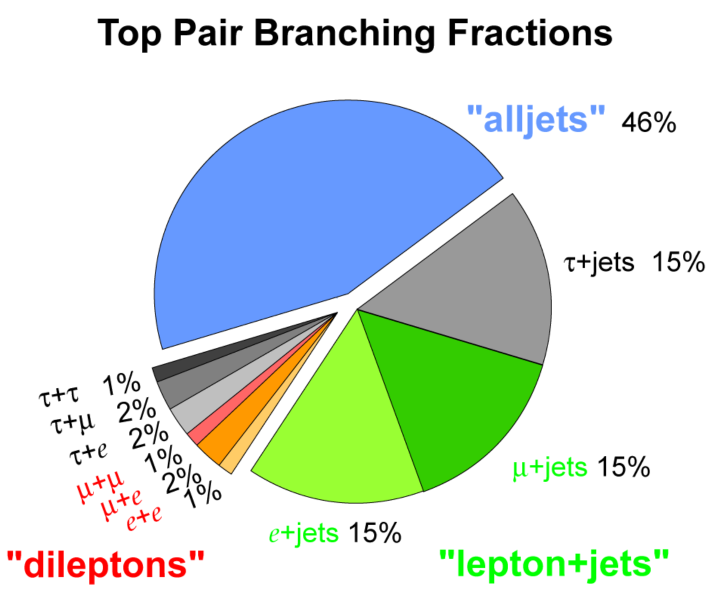


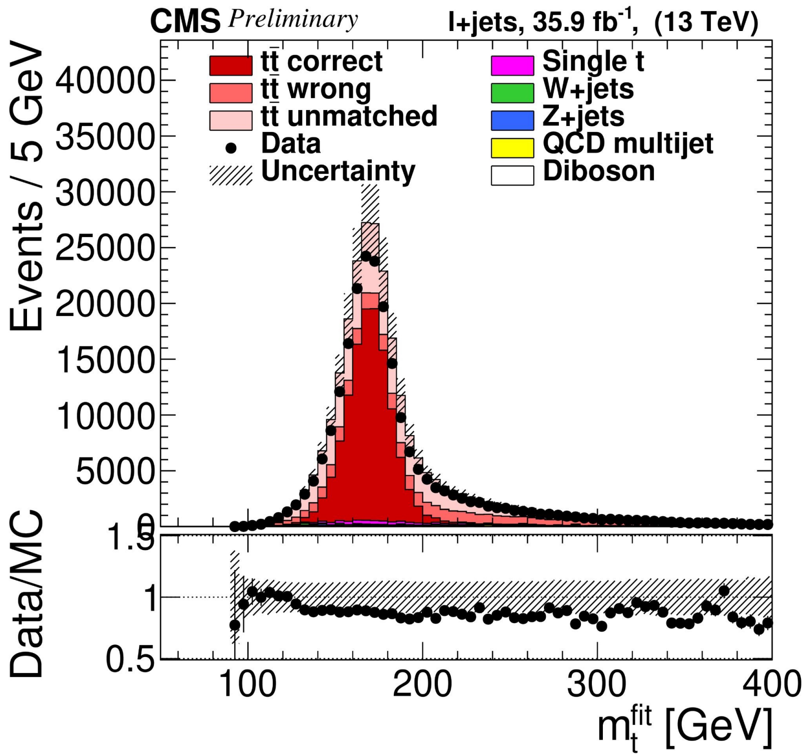
- Direct measurement in tt (ℓ + 2b+≥2j)
  - Recontruct mass from kinematic fit
  - Constrain jet uncertainty with '

TOP-20-008

$$m_t = 171.77 \pm 0.38 \text{ GeV}$$

Δm_t = 0.22%





Top mass definition

- Direct measurement:
  - rely on parton shower simulation
  - build templates dependent on m_{top} (parameter in the simulation)
  - yield small uncertainties
  - relation to a theoretically well defined mass has an uncertainty of O(0.1–1 GeV)

theoretical m_{top} depends on renormalization scheme. Choice is the pole mass m_{pole}

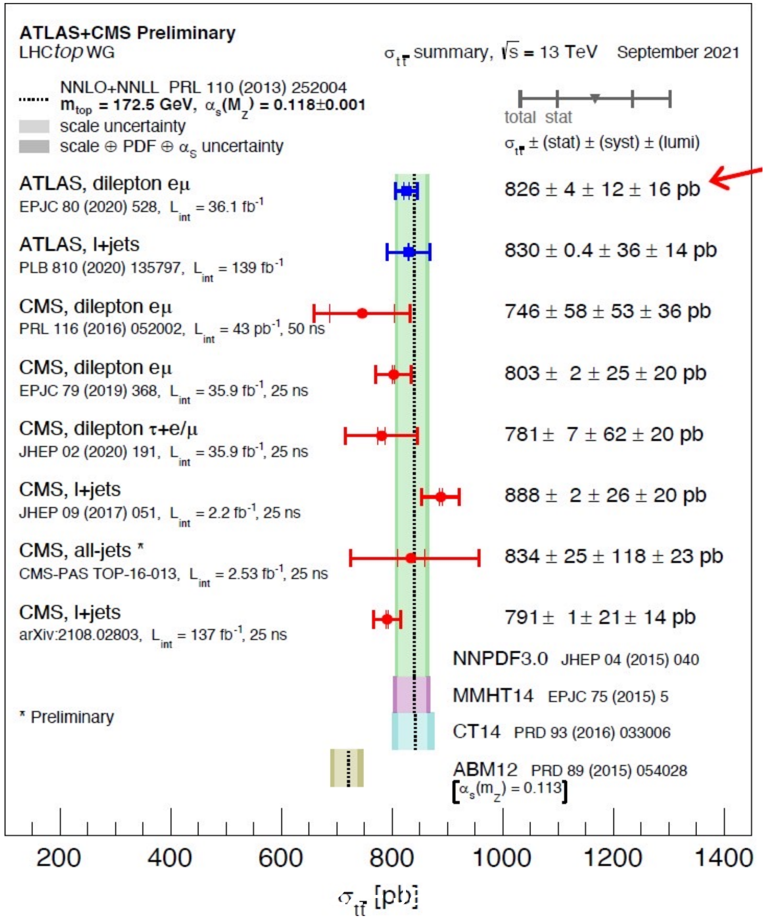
$$\frac{i}{\not{p} - m_0} \Rightarrow \frac{i}{\not{p} - \underbrace{m_0(\Lambda)}_{\text{'bare' mass}} - \underbrace{\delta m_0(\Lambda)}_{\text{divergent}} - \underbrace{\Sigma' m_0(\Lambda)}_{\text{finite}}} := \frac{i}{\not{p} - m^{\text{pole}}}$$

- Extracted via differential cross sections
  - unfolding procedure yield typically bigger uncertainty than direct measurement

Top mass & cross section: Precision

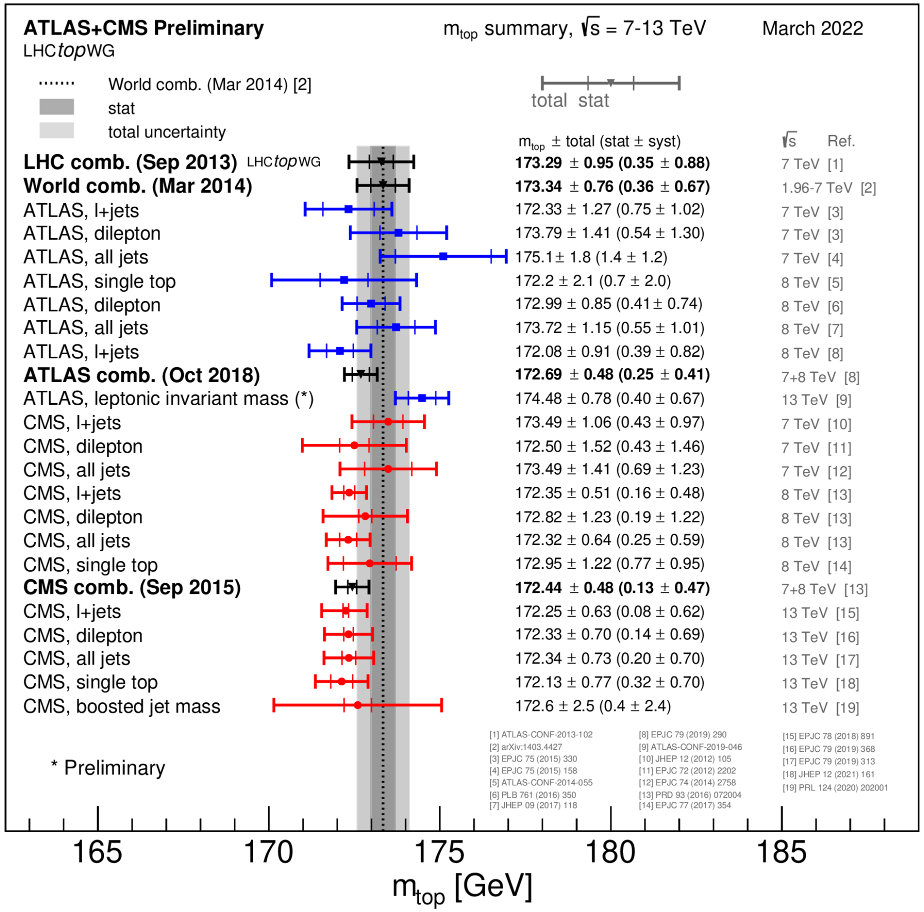
assess if (only) SM or deviations?

DIrect Mass measurement



Relative precision:
2.4% in eμ
(twice better than theory uncertainty

Relative precision:
0.28% on m_{top}
(SM parameter)



Top mass & cross section: Precision

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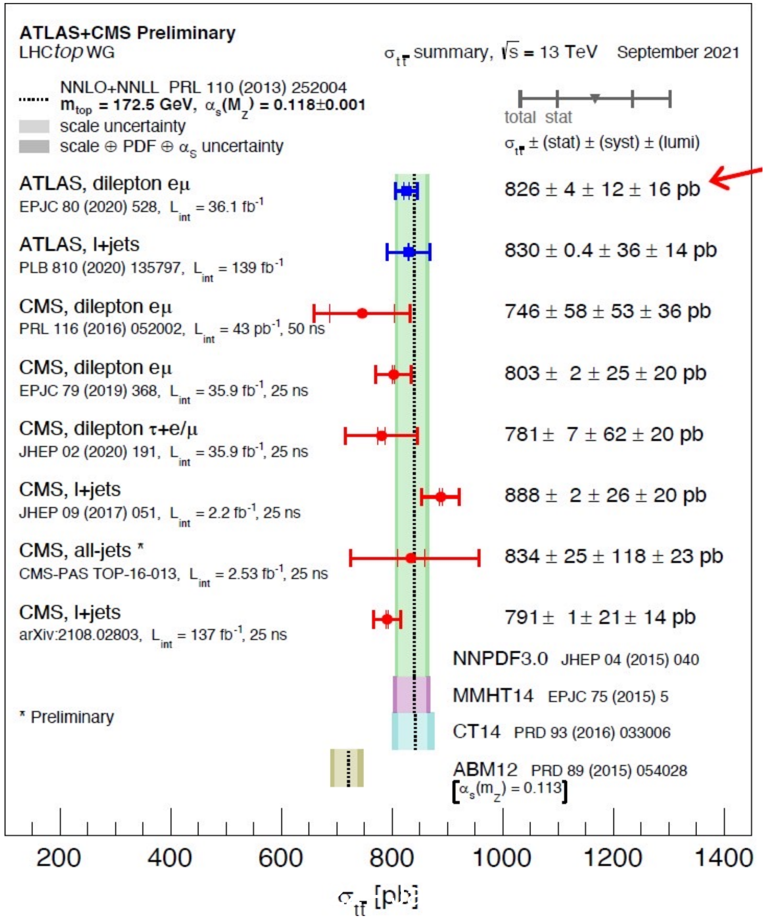

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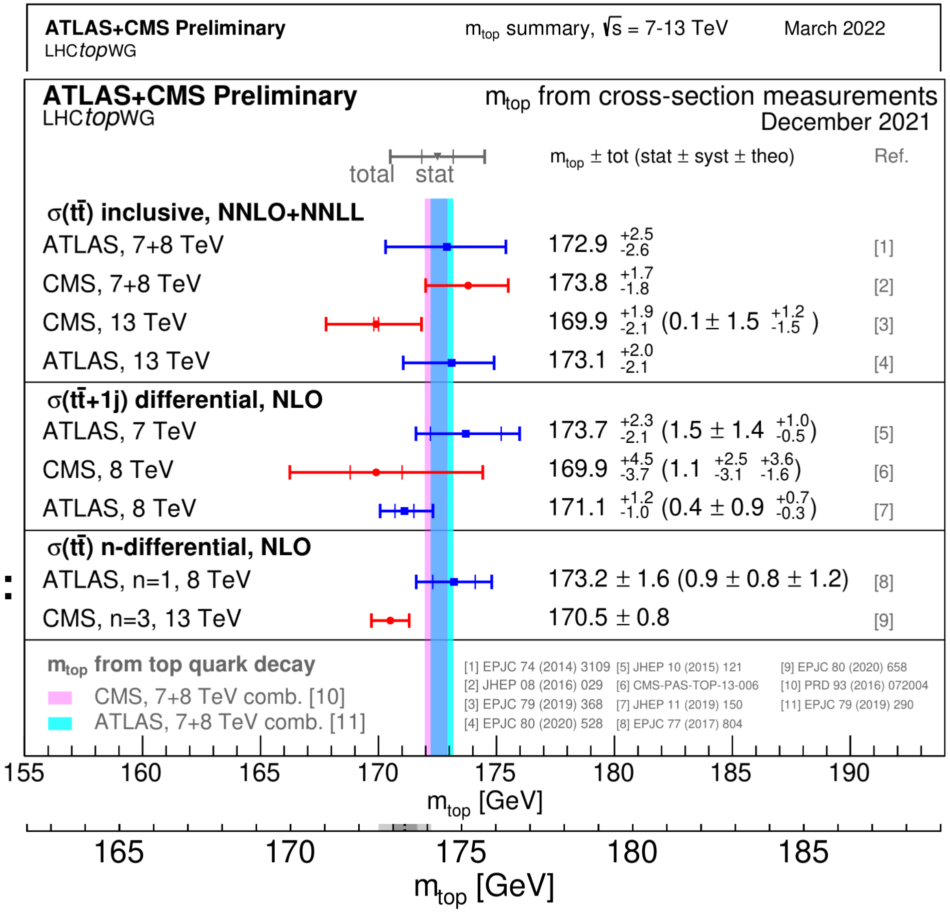
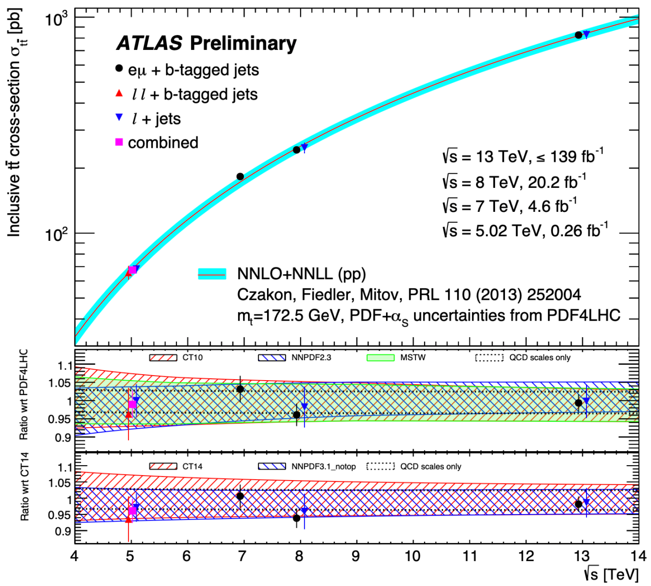
Pole Mass measurement

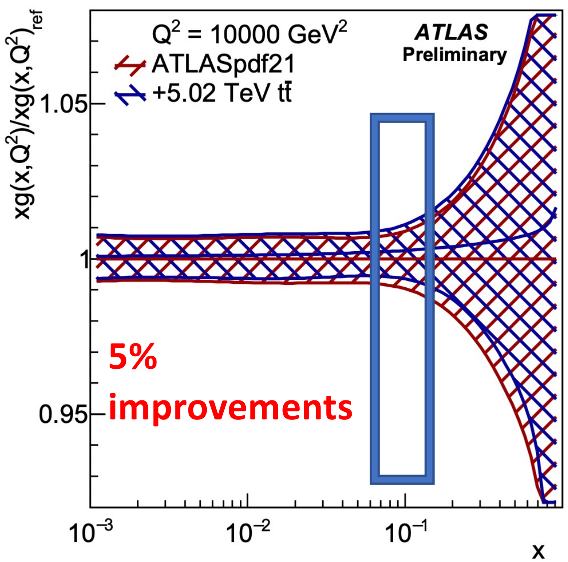


Top pair production at 5.02 TeV

- Just 1 week of data taking at 5.02 TeV in 2017 (small dataset of 0.26 fb^{-1})!
- Excellent precision reached (single+di-lepton decays and combination), similar to the one obtained @ 13 TeV with 500 times more data!
- X-sec value more than **a factor of ten smaller** than @ 13 TeV

ATLAS-CONF-2022-030





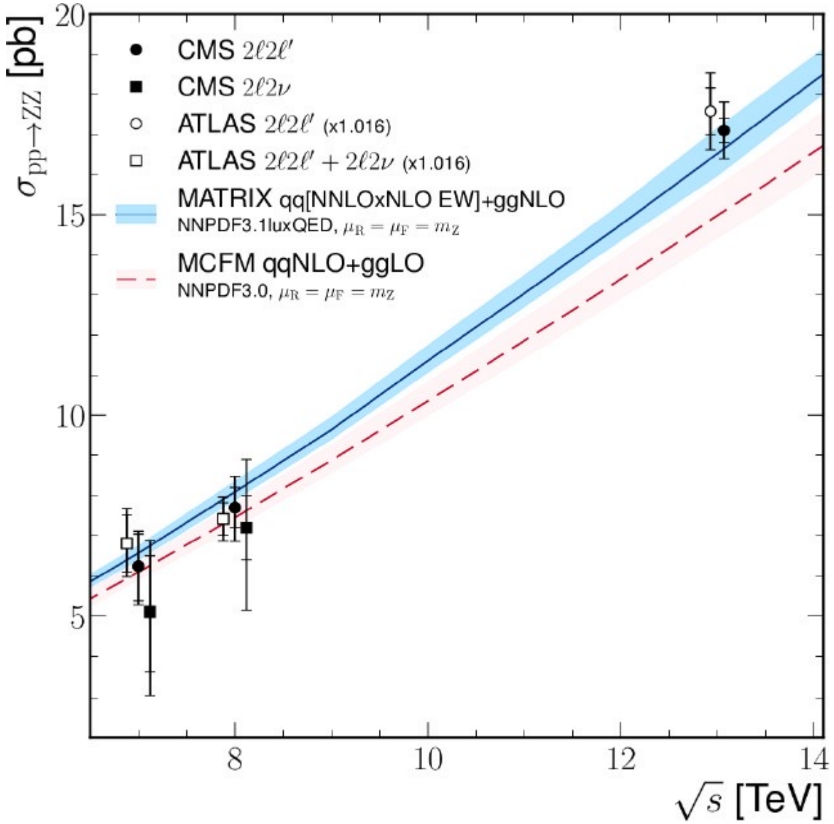
gluon pdf constraint improves prediction of ggF Higgs production

ATLAS-CONF-2022-031

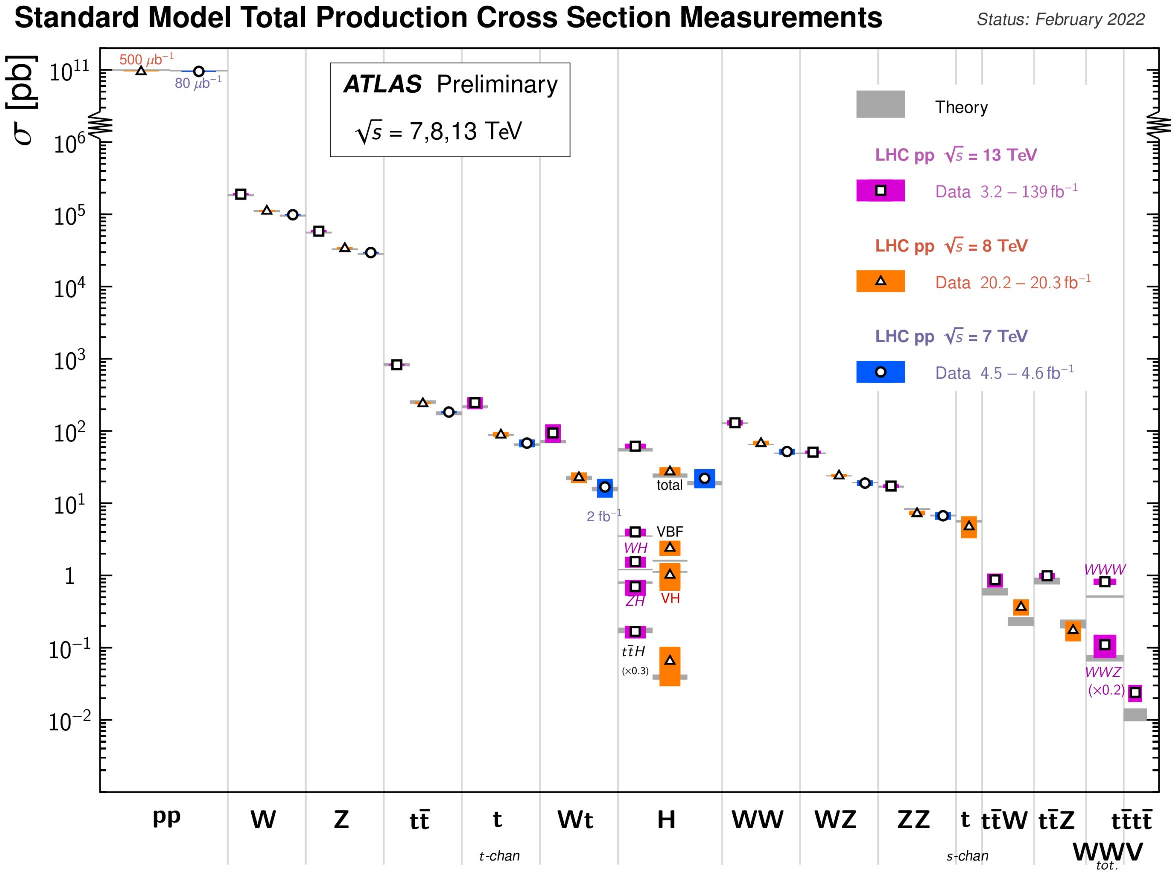
$$\sigma_{t\bar{t}} = 67.5 \pm 0.9(\text{stat.}) \pm 2.3(\text{syst.}) \pm 1.1(\text{lumi.}) \pm 0.2(\text{beam})\ \text{pb}$$

$\Delta\sigma =$ 3.9%

Standard Model Summary

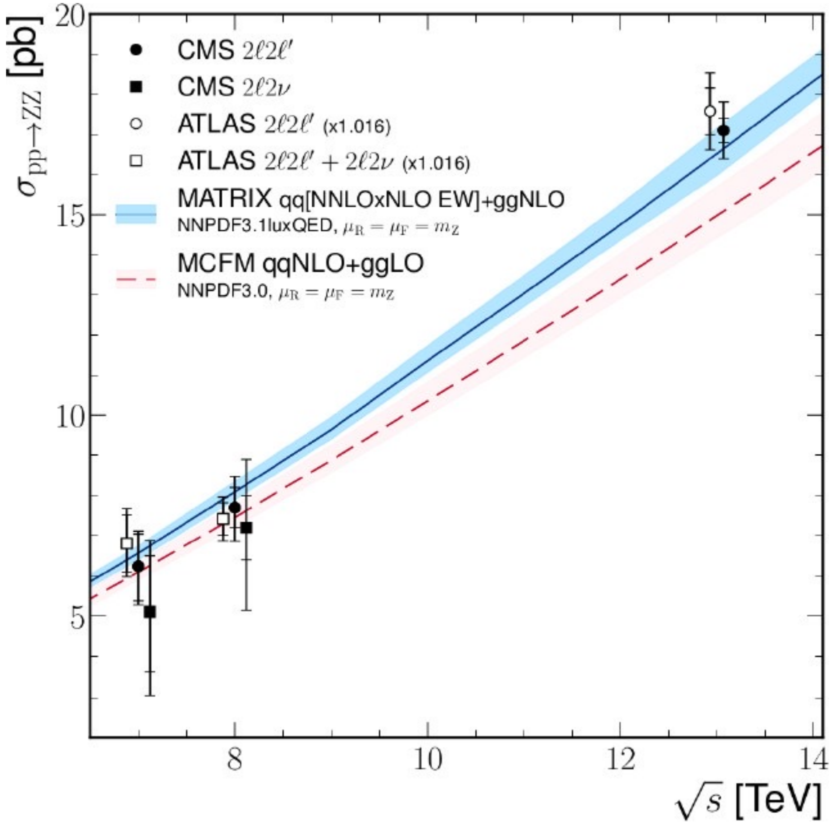


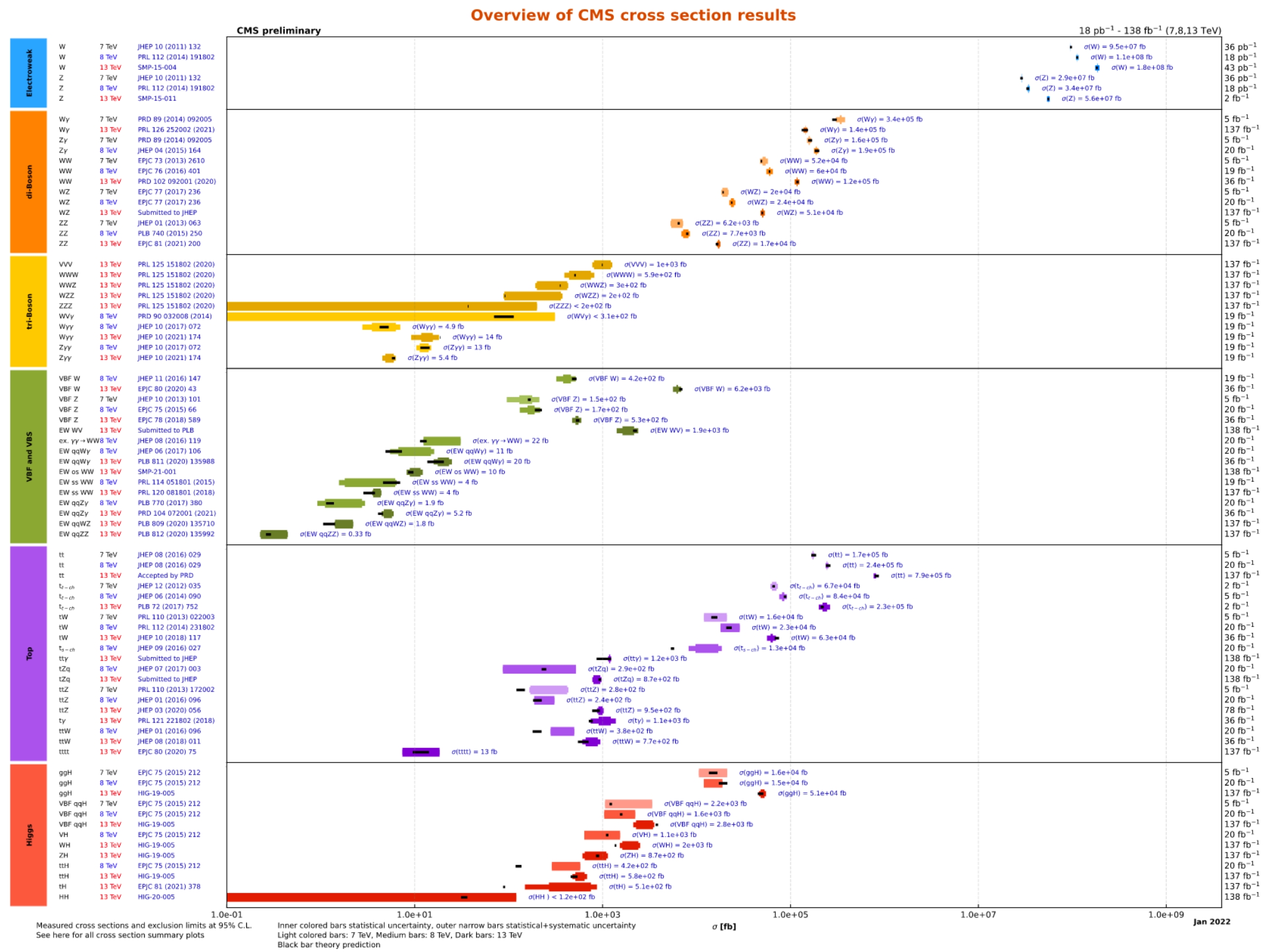
9 orders of magnitude



Electroweak Top Higgs

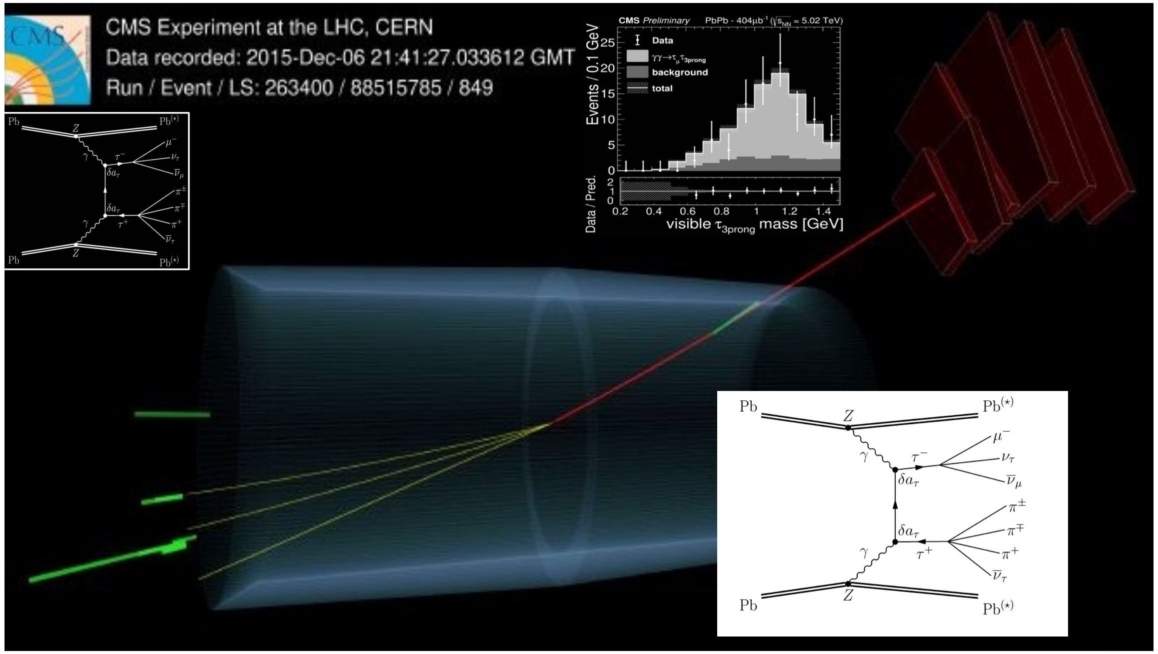
Standard Model Summary



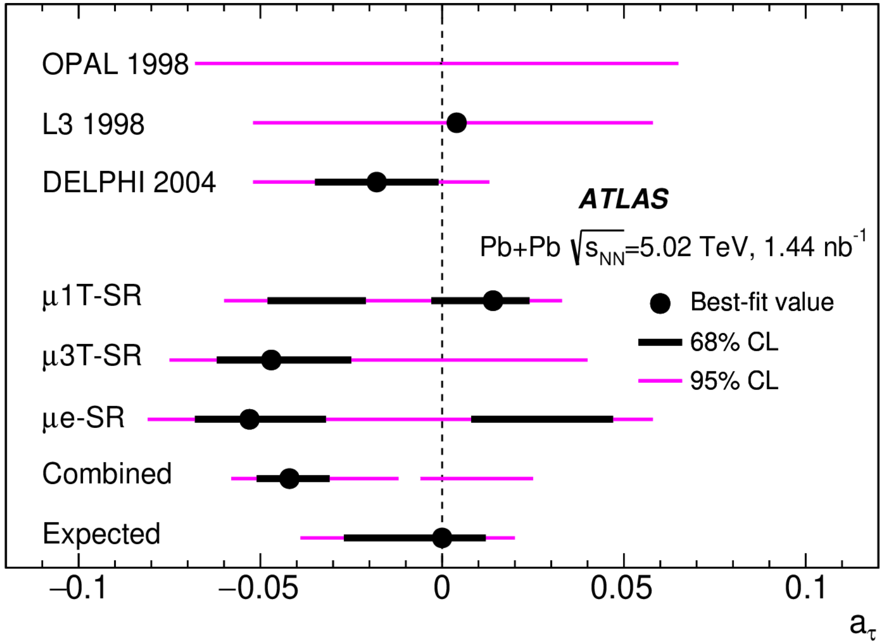


Observation of the γγ→ττ process in Pb+Pb collisions

- First observation of ττ lepton production in ultraperipheral nucleus-nucleus collisions.
- E_{cm} of 5.02 TeV, integrated luminosity 404 μb^{-1}



τ-lepton anomalous magnetic moment



σ(γγ→τ+τ−)= 4.8 ±± 0.6 (stat) ±± 0.5 (syst) μb

Muon p_T sensitive to a_τ. As at LEP, templates with distributions of p_T are used in the fit to determine a_τ.

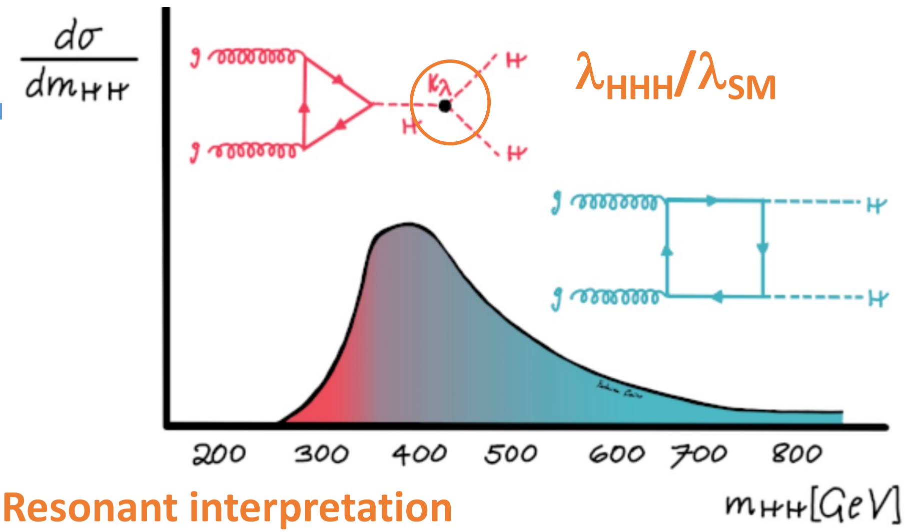
Rare SM Processes

- Measure **parameters of EW symmetry** breaking
- Sensitive to many models of **new physics**

Higgs self-coupling

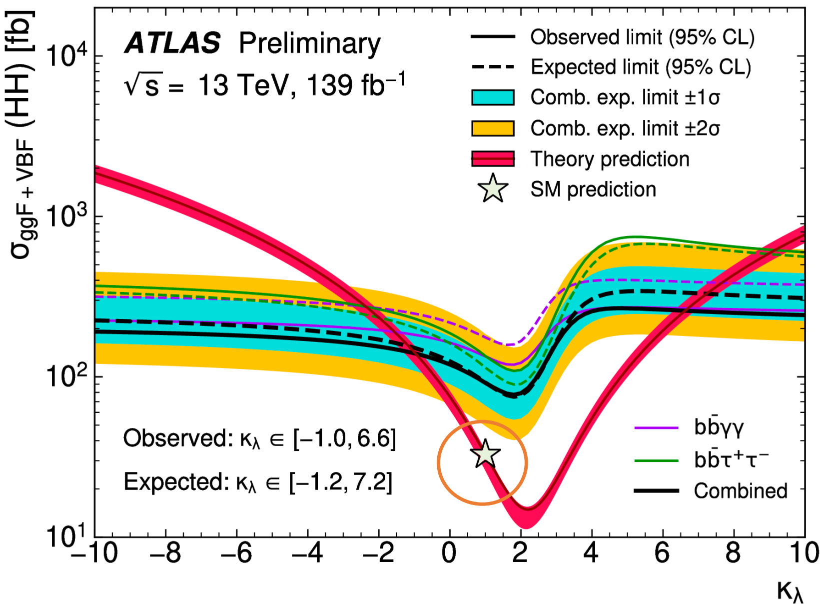
- Searches for di-Higgs production allow to probe new physics e.g. resonances decaying to HH as well as the Higgs boson self-coupling
- Similar CMS recent search (CMS-PAS-B2G-22-003)

Non Resonant interpretation



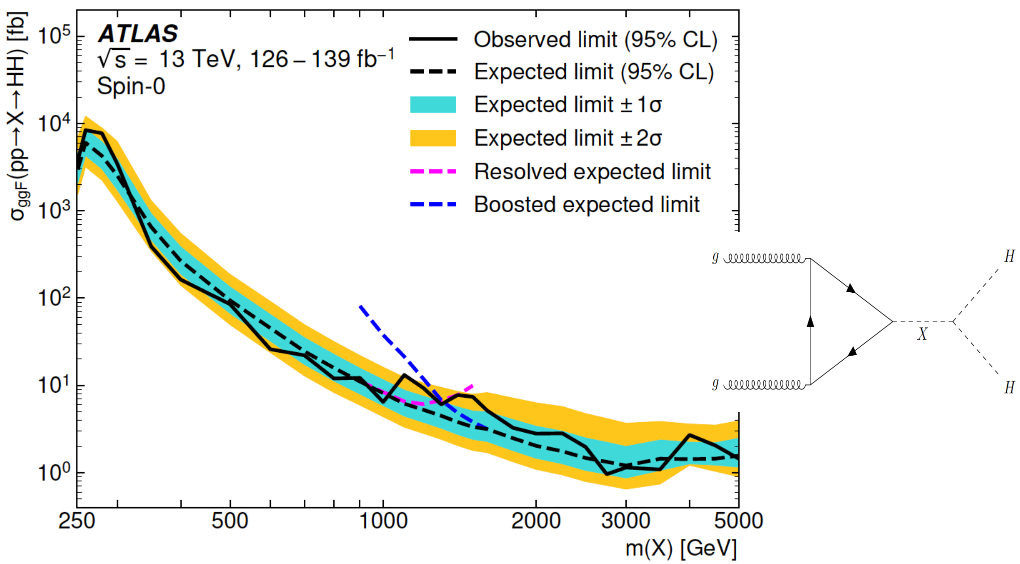
Combination

arXiv:2202.07288

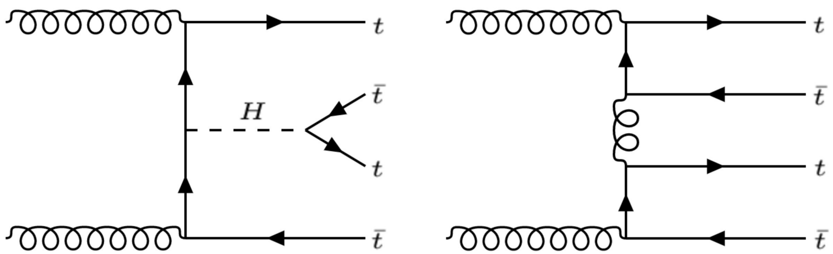


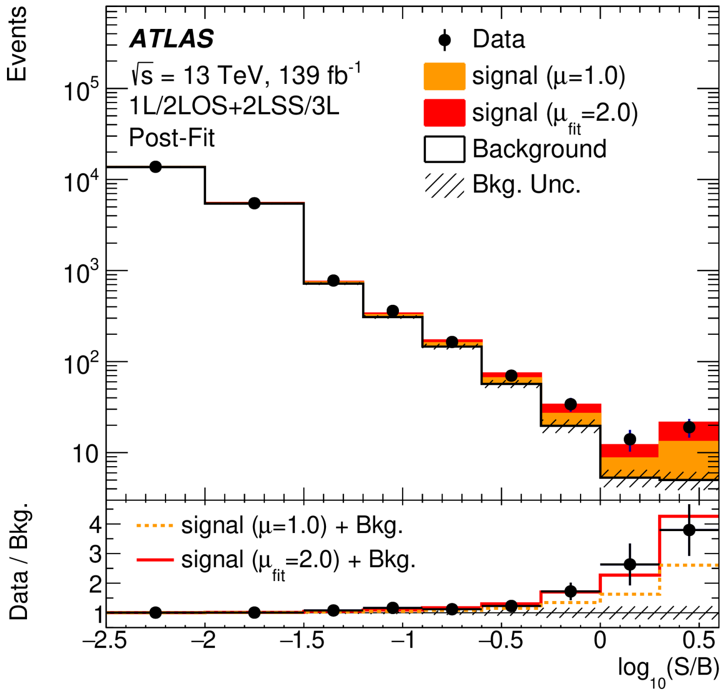
Resonant interpretation

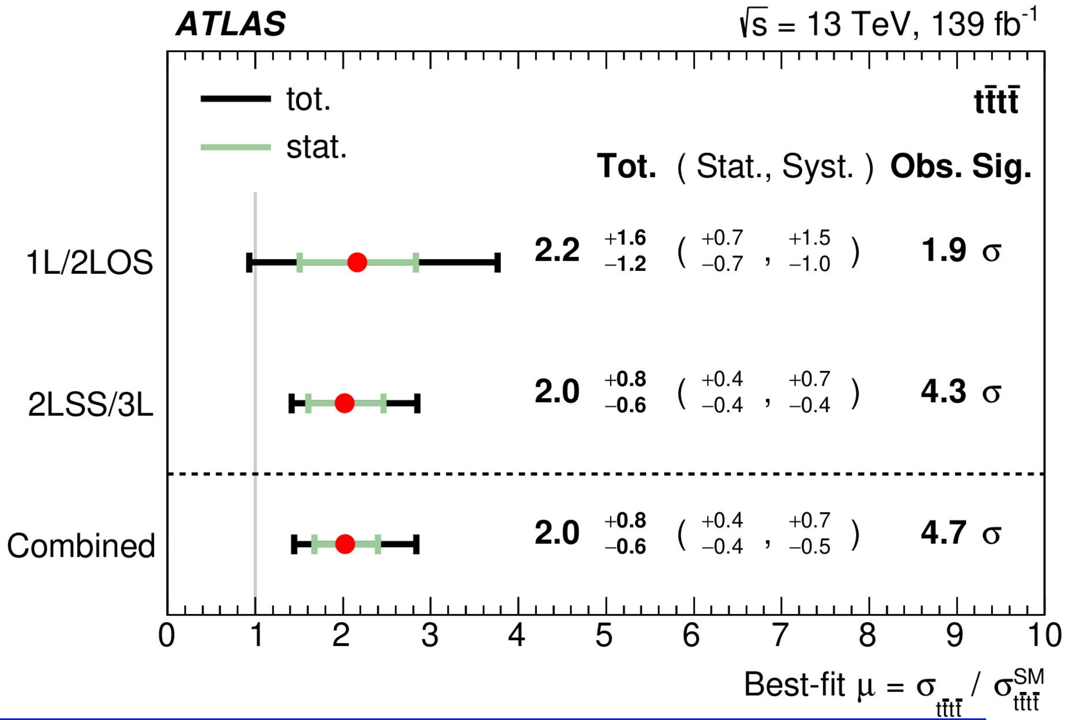
arXiv:2112.11876, ATLAS-CONF-2021-052



Four-top-quark production cross section







The ATLAS combined four-top-quark production cross section is measured to be $24^{+7}_{-6}\ fb$, with an observed (expected) signal significance of 4.7 (2.6) σ over the background-only prediction.

JHEP11(2021)118

New Physics

Standard Model Effective Field Theory

Consistent framework to parametrize possible deviations in a model independent way by encapsulating new physics effects in higher- dimensional operators involving the SM fields

Assume the SM Lagrangian **correct** but **incomplete**

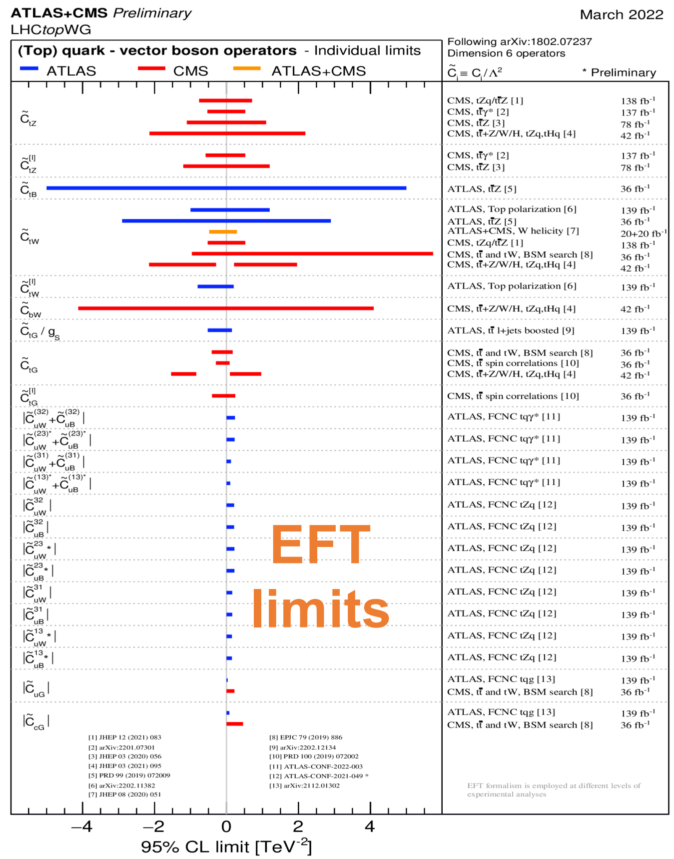
EFT **includes the appropriate degrees of freedom** to describe physical phenomena at a chosen energy scale, ignoring substructure/degrees of freedom at higher energies

Add to the SM Lagrangian higher dimensional operators weighted by a certain coefficient

Look for **additional interactions between SM particles** due to exchanges of heavier particles and put constraints on coefficients

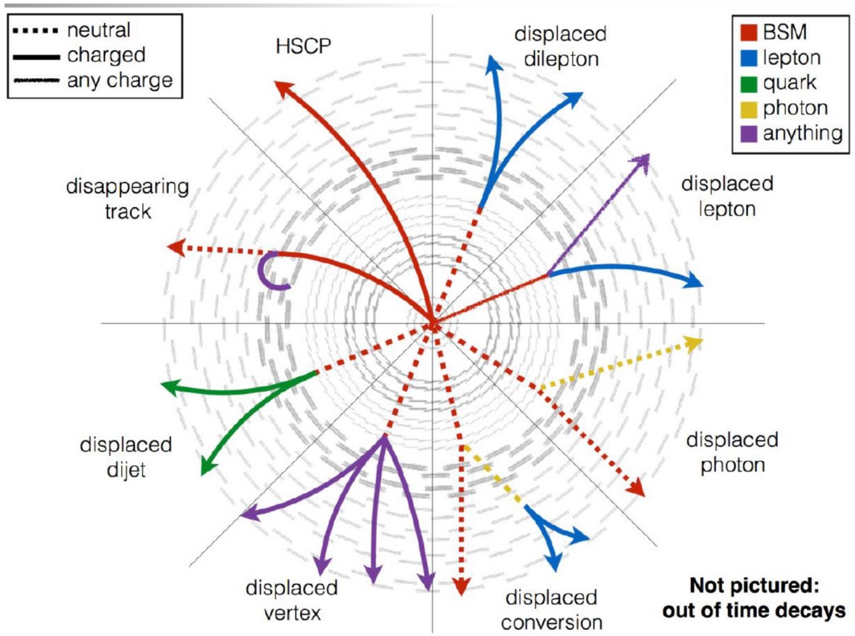
Most efficient way to extract largest amount of info from LHC/other experiments

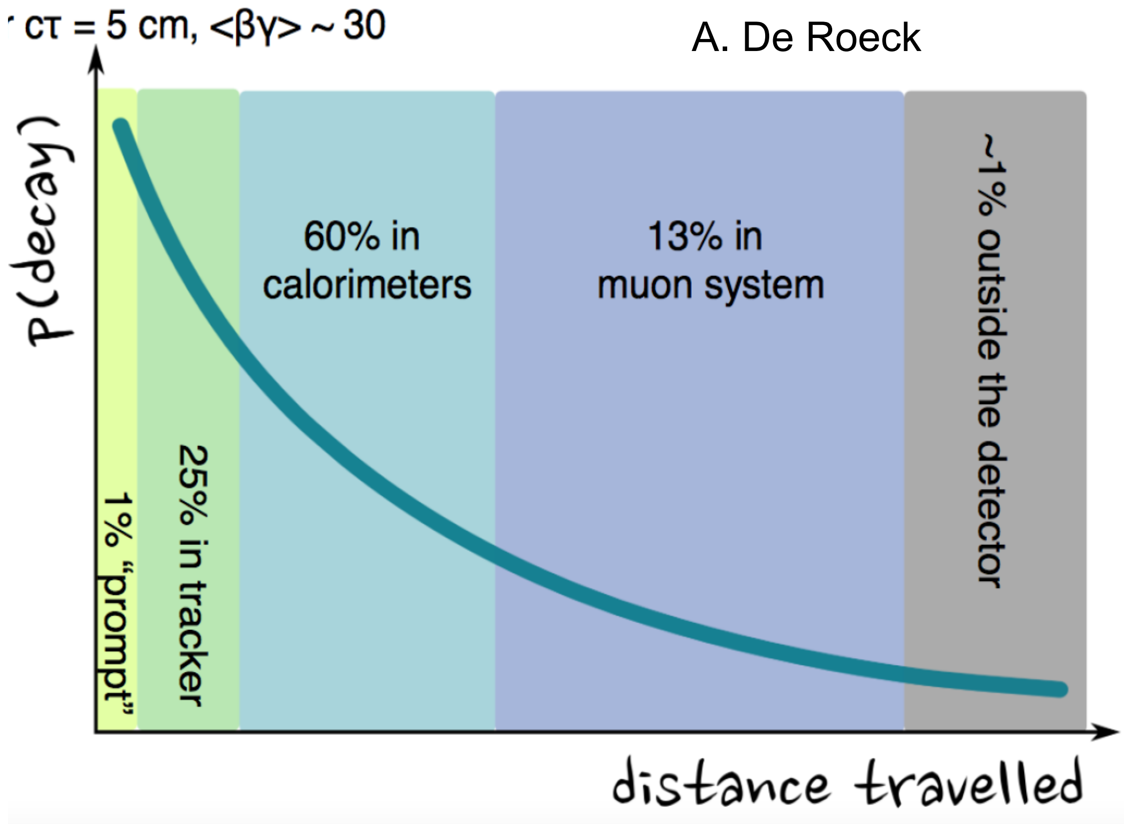
Model-independent way to look for physics beyond the SM



Long Lived Particles (LLP)

- From a hierarchy of scales or a small coupling (i.e. RP violating SUSY, Dark QED/Dark Photons…)
- Could travel sizeable distances through the detector before decay





- **Special reconstruction technique!**

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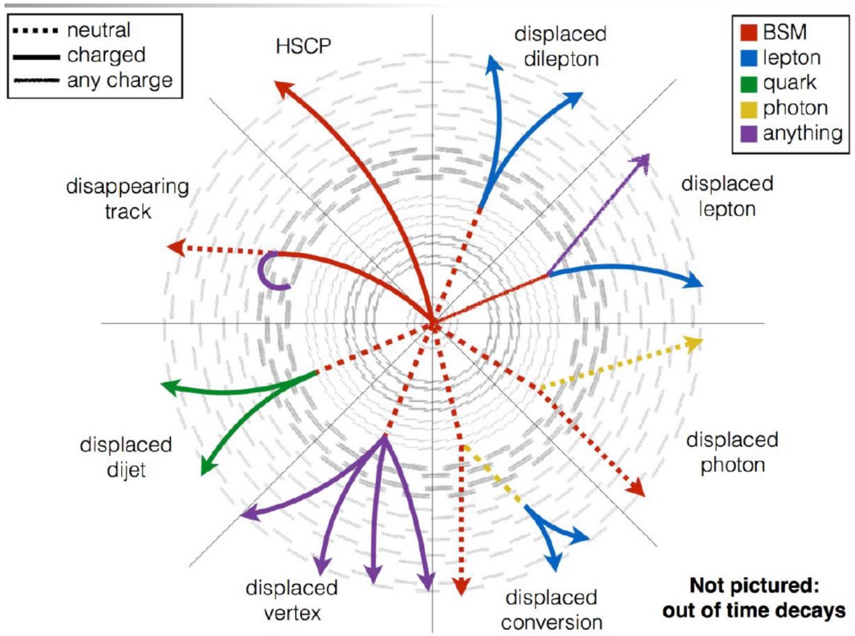
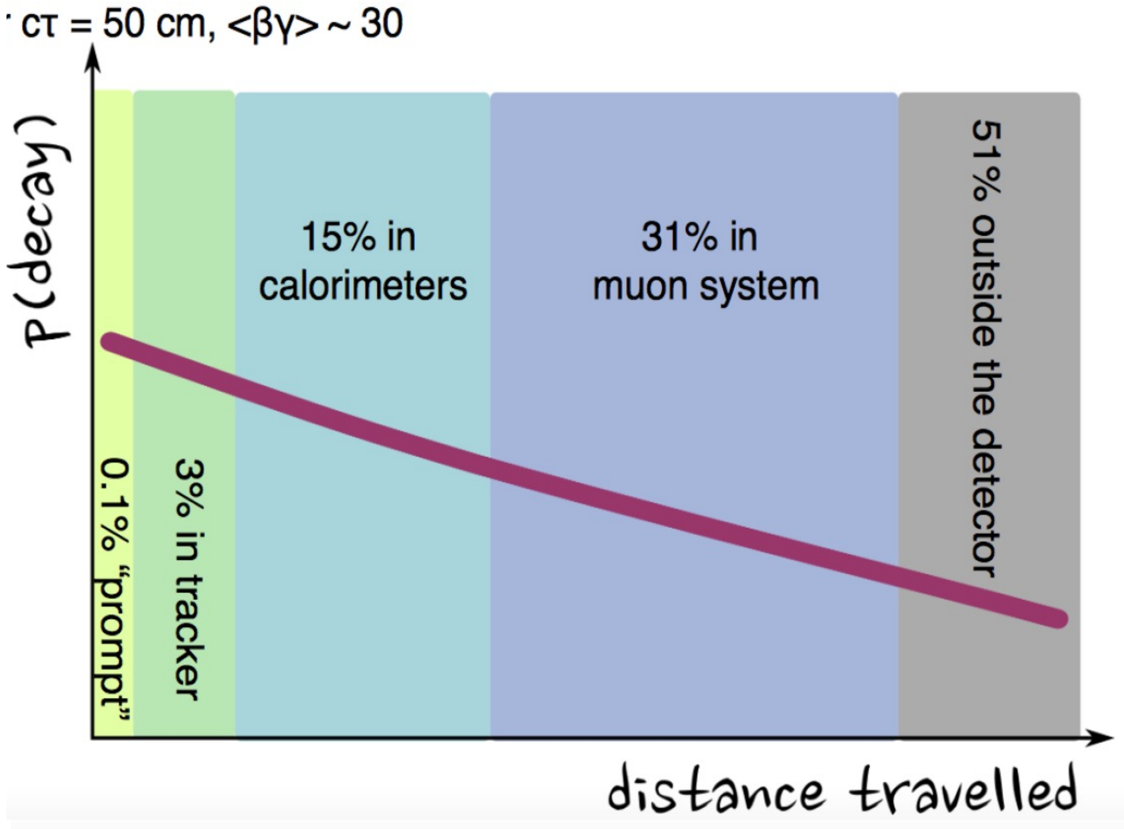




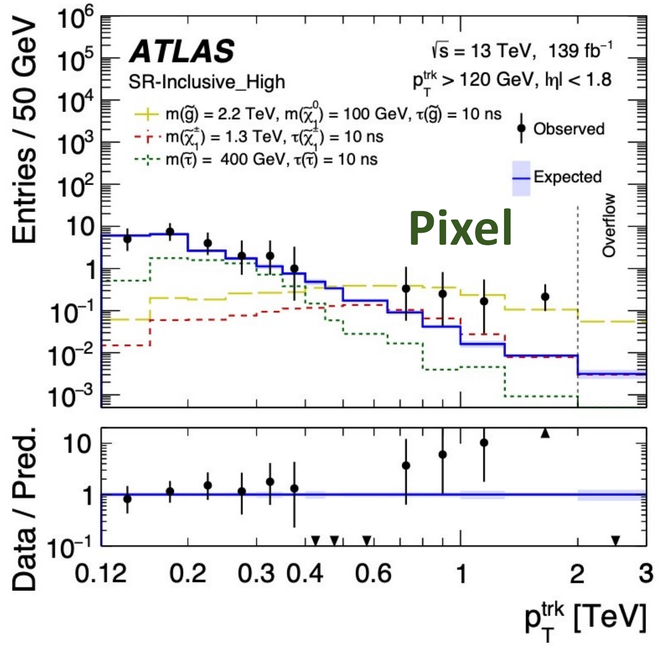
- **Special reconstruction technique!**

LLP different signatures

Heavy charged LLP, large ΔE/Δx

Slower than c, high p_T, large dE/dx. Probe τ O(1) ns , masses from 100 GeV to 3 TeV.

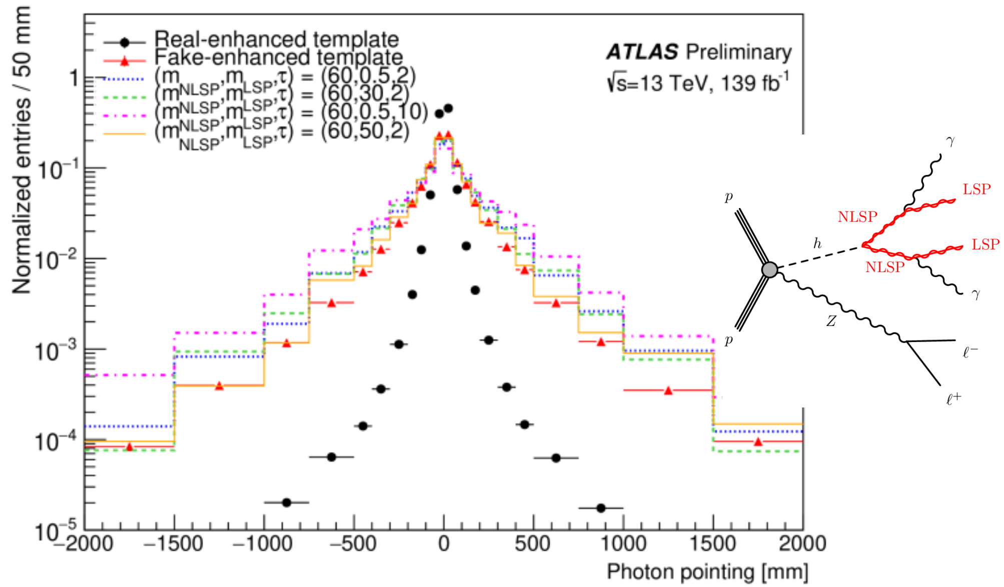
arXiv:2205.06013



- 3.3 σ excess in ~1.4 TeV mass hypothesis
- Tracks study shows no slow-moving

Displaced photons in Higgs exotic decays

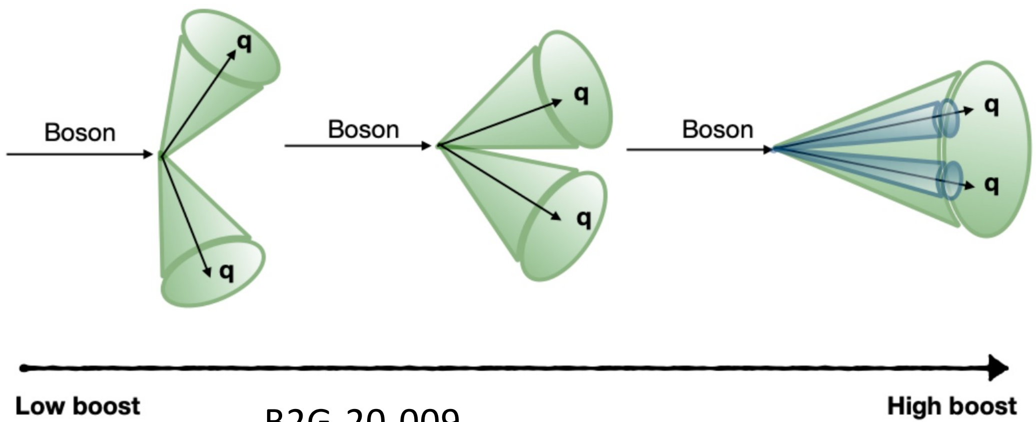
First LHC constraints, based on pointing and timing info..



- Data consistent with background
- Excluded various supersymmetric models

Boosted heavy diboson resonances

- WW, WZ; ZZ; WH, ZH
- New resonances predicted to be about 10 times heavier than W, Z and H bosons → "daughter" bosons emitted with high momentum, or "Lorentz boost"



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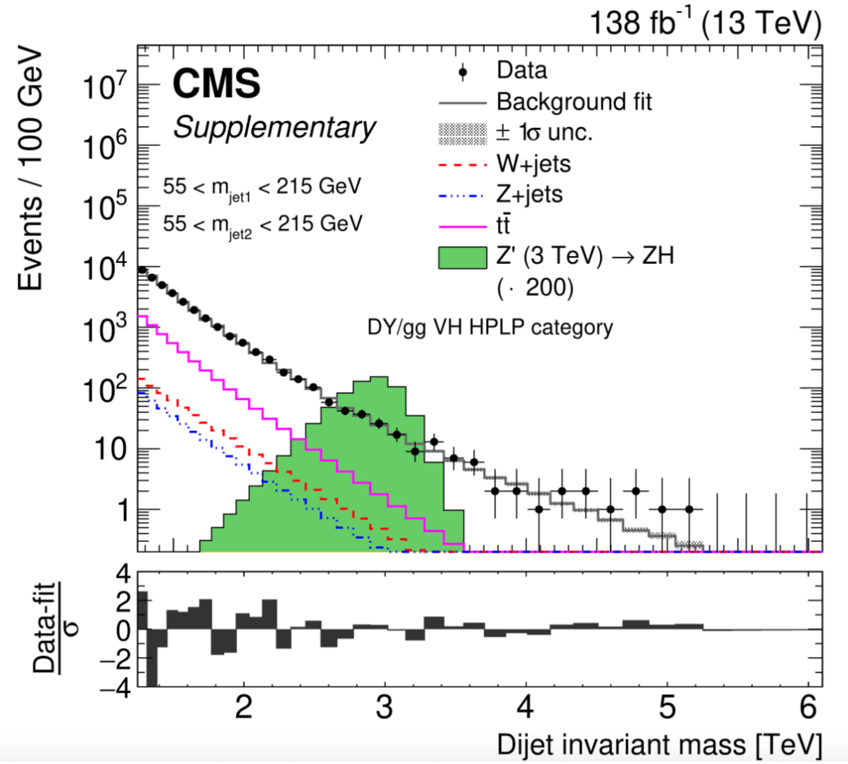
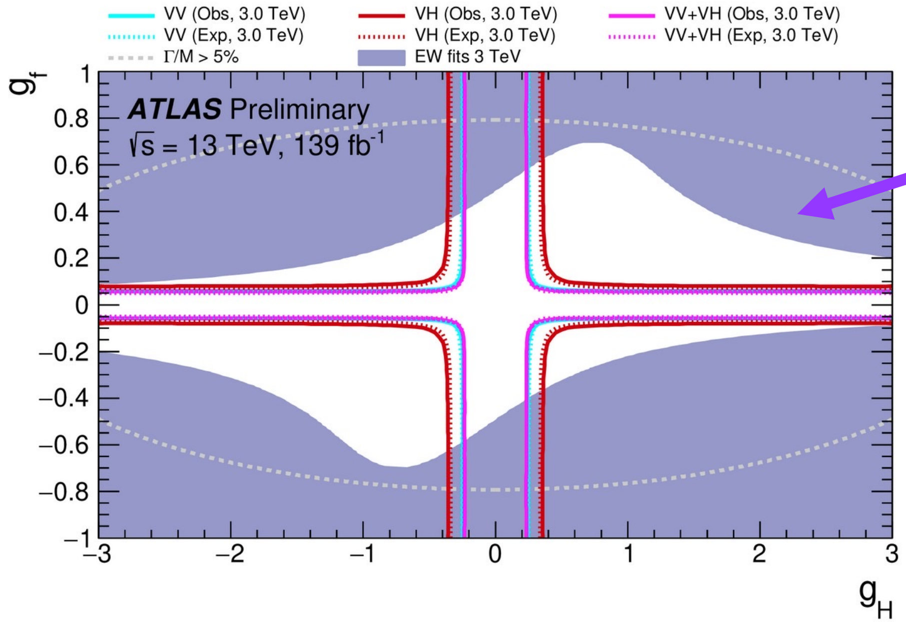


New particle excluded. up to **4.8 TeV** (most stringent constraint to date),
New graviton resonances (scenarios with extra space-time dimensions,) excluded up to 1.4 TeV

Combined search for heavy resonance

ATLAS-CONF-2022-028



Typical exclusions for
3 TeV for qq production mode

$WW/WZ/ZZ \to qqqq$	$WZ/ZZ \to$ llqq	$ZH \to \nu\nu bb$	lν
$WZ/ZZ \to \nu\nu qq$	$WZ \to$ lνll	$WH \to$ lνbb	$\tau\nu$
$WW/WZ \to$ lνqq	$WH/ZH \to qqbb$	$ZH \to$ llbb	ll

- 12 individual searches (2018 – 2022), each one optimized on its own
- Statistical combination for different bosonic decay modes
- Results in context of Spin-1 Heavy Vector Triplet (HVT) model
- Constraints expressed in terms of couplings to quarks, leptons and fermions
- HVT with **mass < 5.8 (4.5) TeV excluded in a weakly (strongly) coupled scenario**.

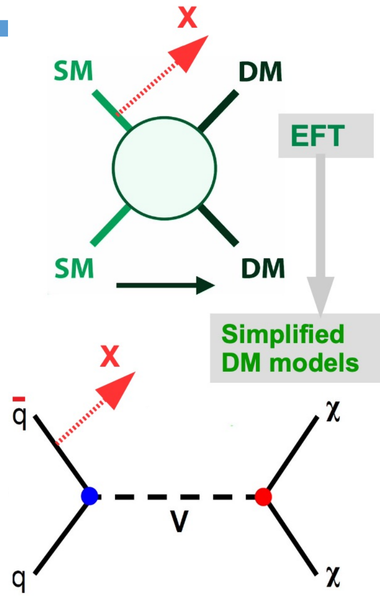
Searches for Dark Matter

IF new particles exist and **IF** at EW scale → within LHC energy reach

Production

Several models for production mechanism

- From **low energy/thermal interactions** with other SM particles in the early Universe → masses from few keV to hundreds of TeV
- through **more energetic collisions** (masses well below the eV)

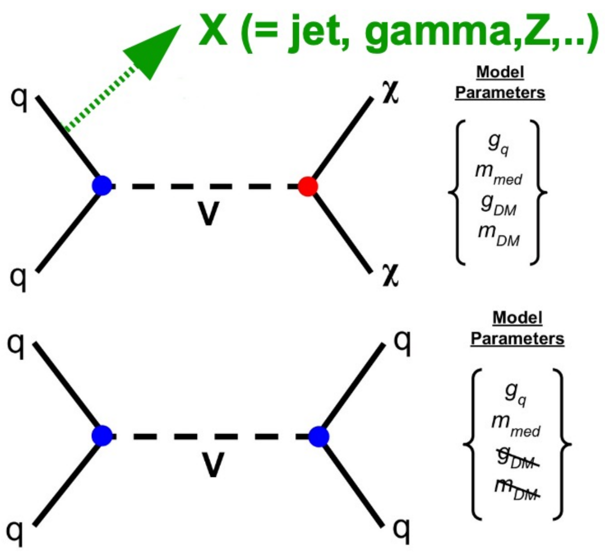


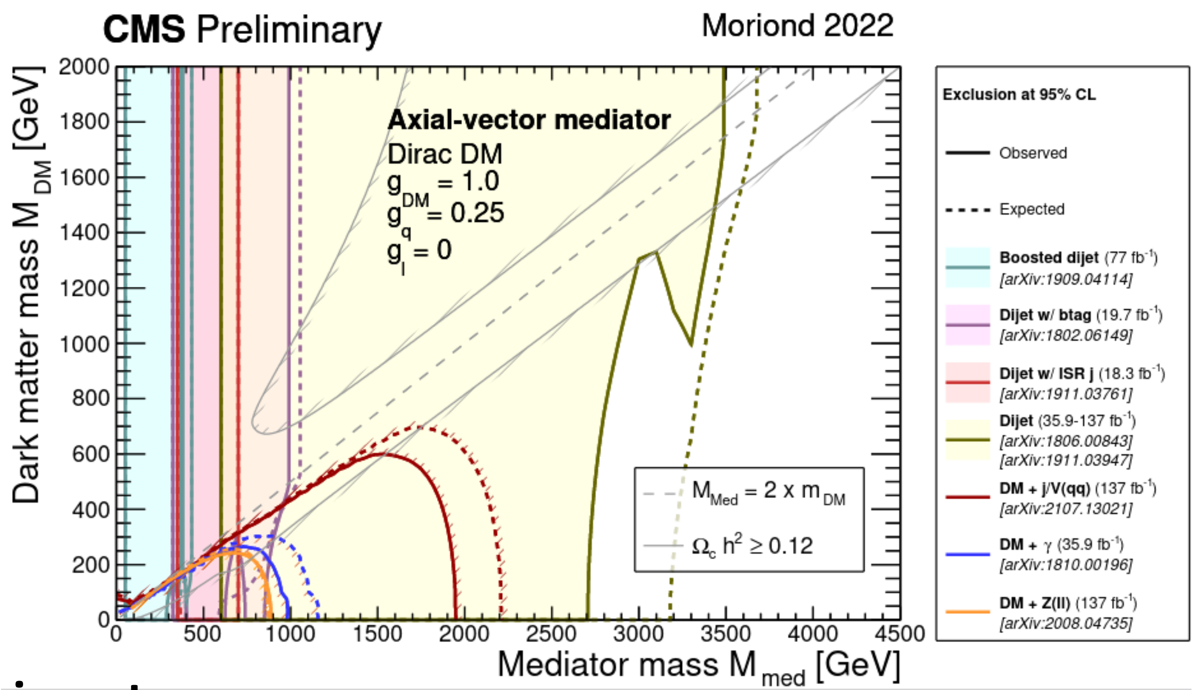
Searches classifications

Based on SM particles coming along in the final state

- With **single high p_T jet**: probe models with DM produced via exchange of a neutral mediator
- With **heavy flavor quarks**
- With only a **single photon** or **Z boson** (DM interactions with EW gauge bosons)

Dark Matter Summary





Complementary to direct detection experiments:

- Strong (model-dependent) limits for low mass
- Strong limits for spin-dependent DM- nucleons
- Comprehensive searches for DM-SM mediators

- Adopt simplified DM model with a "mediator" **V**
- g_q (g_{DM}) – mediator coupling to quarks (DM)
- m_{med} (m_{DM}) – mass of mediator (DM)
- ATLAS & CMS: **g_q=0.25 (S=1), g_q=1 (S=0), g_{DM} =1**

Leptoquarks

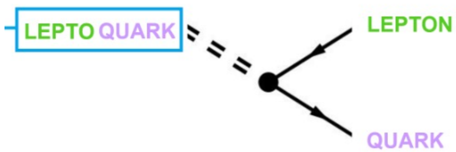
4321 Model:

- SM extension with an SU(4) × SU(3)′ × SU(2)L × U(1)′ gauge sector
- Leptoquark (LQ) predicted as primary source of lepton flavour, vector-like leptons are the lightest new particles

Leptoquarks

Vector LQ motivated by B-physics anomalies, e.g., lepton flavour (non-) universality in NC & CC B decays

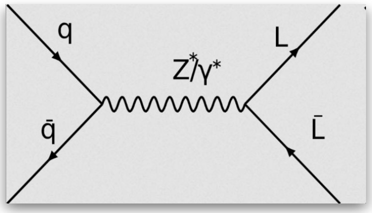
- New particles that would interact (and decay) with quark and leptons
- Color triplet bosons, carrying lepton and barion numbers
- In SM extensions as technicolor theories, theories of quark-lepton unification, or GUTs based on SU(5), SO(10).

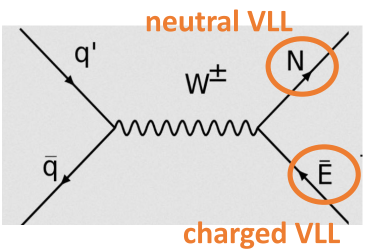


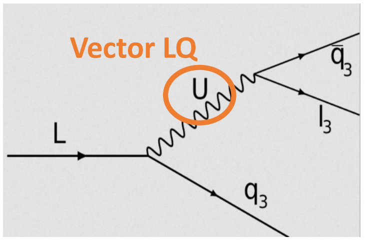
Leptoquarks

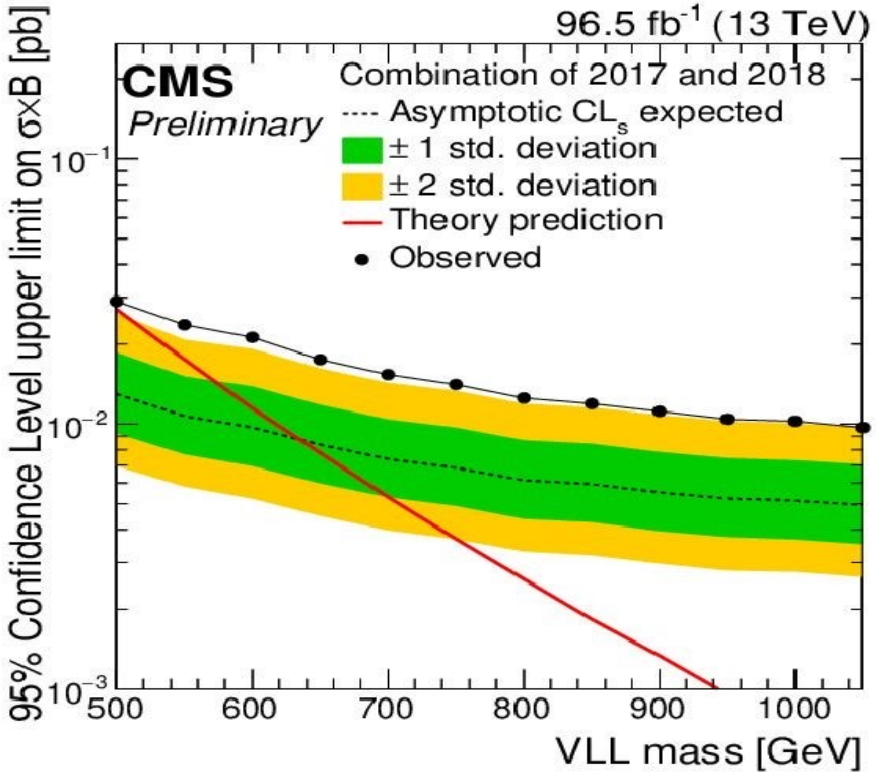
- Search for vector-like leptons in 4321 model
  - Final state 0-2τ + 4b jets + jets
  - Mild excess (2.8σ) @ 600 GeV

σxB **vs. VLL mass**









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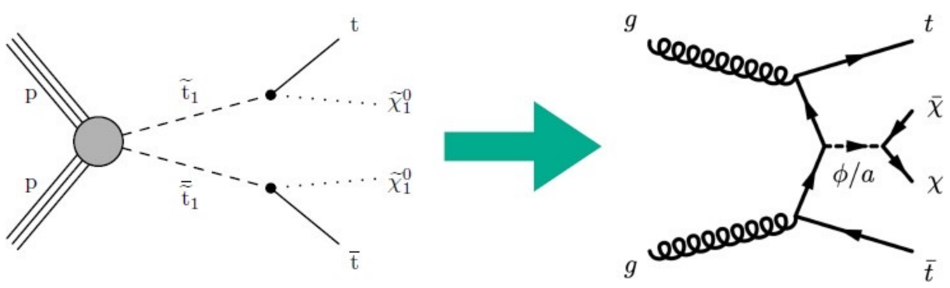
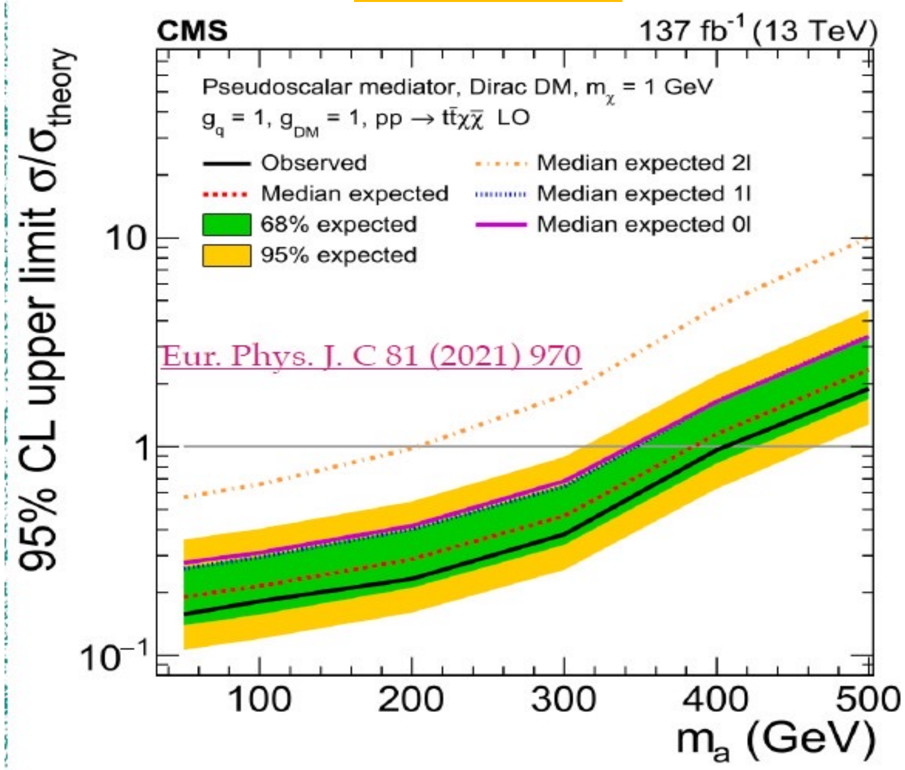
Reinterpretations

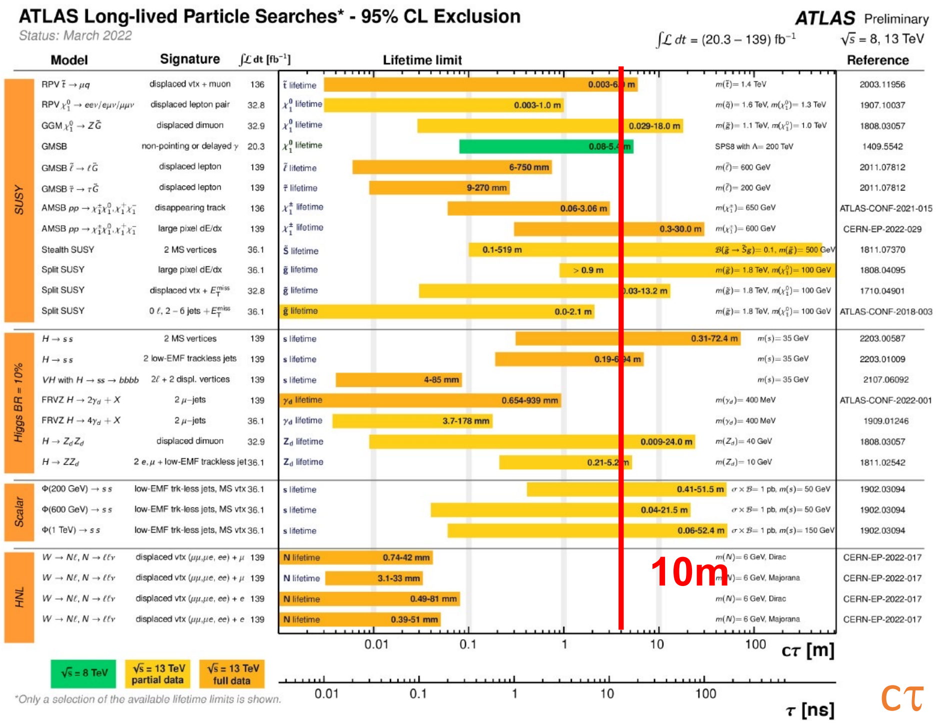
- SUSY search reinterpreted for DM
  - Stop pair production → ttbar+DM

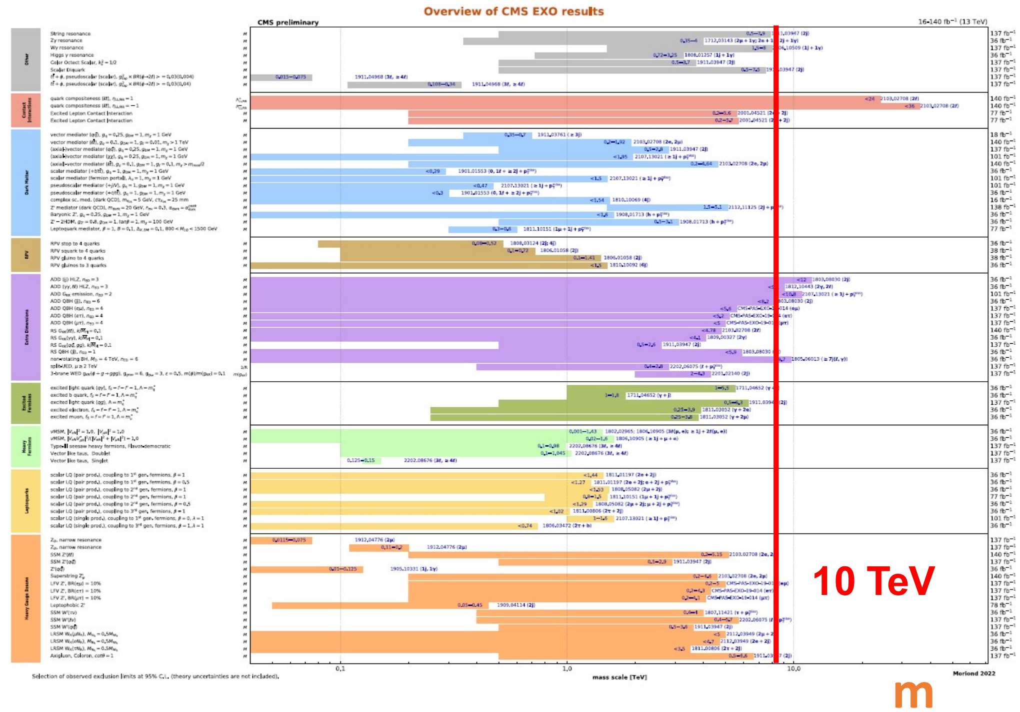


σ/σ_{SM} vs. m_a



LHC limits for direct and indirect BSM searches





- **~100 decay channels** with various models that predict certain production rate (extra dim., gauge bosons, contact interactions, dark matter, heavy quarks, excited fermions, LQ)
- Commonly **excluded masses ~ 0.4 – 12 TeV**
- But ..plenty of models that predict too small cross section for exclusion!

The future

Run 3 (13.6 TeV)

- LHC Run 3 is about to start
- Extension of Run 3 by one year and an extension of LS3 by six months,

overall shift of Run-4 by 18 months.

LHC L_{int}	Run 2	Run 3 (estimate delivered)
ATLAS/CMS pp	140 fb^{-1}	300 fb^{-1}

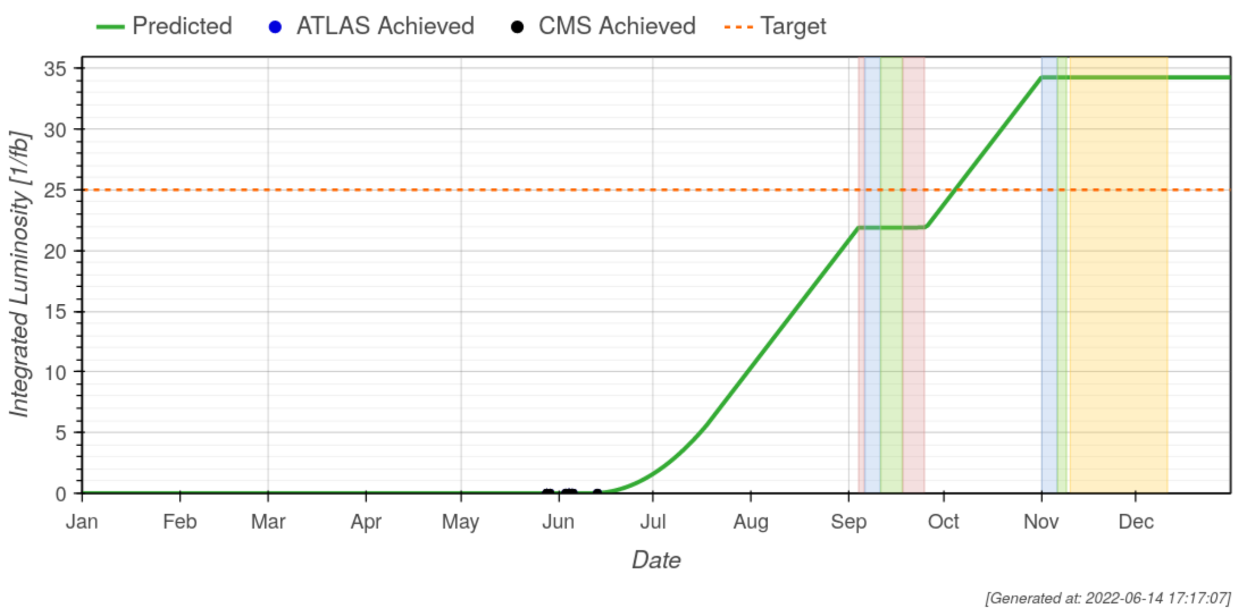
First 13.6 TeV stable beams:

1200 bunches collisions on July 5th

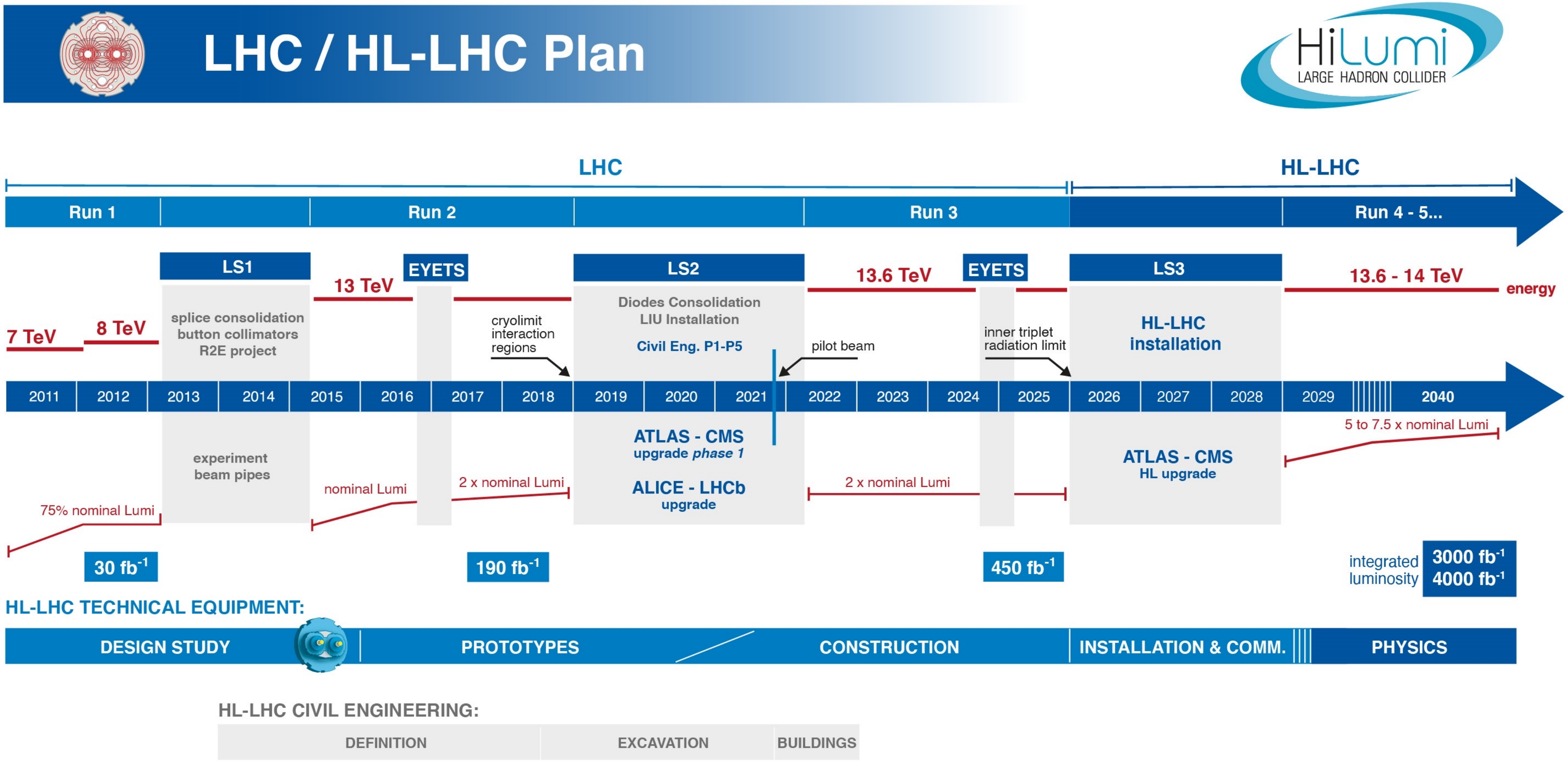
86 pp physics days (> 1200 bunches)

PbPb running:

- 27 HI physics days



Toward the future: HL-LHC



Physics potential @ HL-LH

- More powerful detectors (new trackers, new triggers, new timing info..)
- Much higher luminosity

SM

60 billions W

170 million H

3 billion tt

6 billions Z

Higgs

Higgs factory: 170 million of Higgs

Couplings: From precision of 8-10% to few %.

Self-coupling: : Evidence for, if not discovery

Dark Matter

Monojet searches: probe m_{DM} up to 800 GeV and mediator masses up to 2.5 TeV

Searches with HF quarks: sensitivity to m_{med} by a factor from 3 to 8

Searches via Interactions with EW bosons For example, in mono-Z searches, masses up to a factor of three larger than current limits ould be probed

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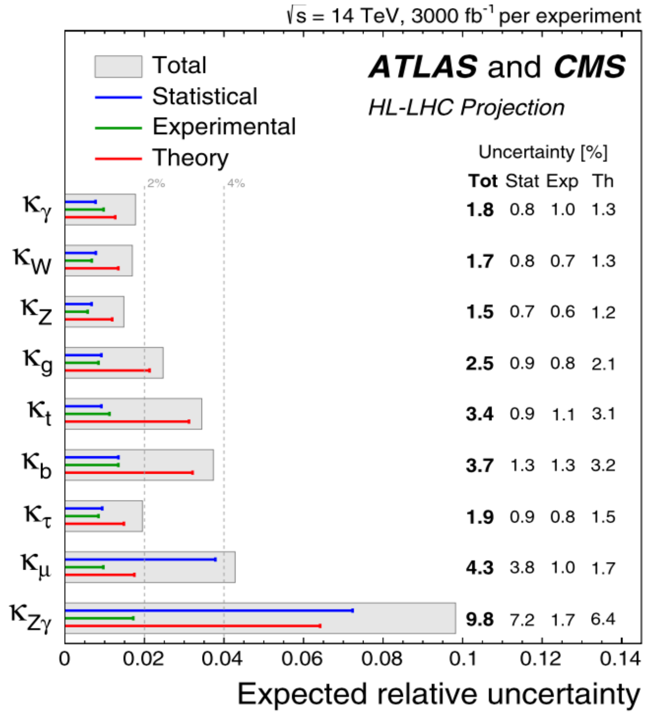

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:

Conclusions

- Continued stream of LHC run 2 publications
- Precise measurements in all areas
  - Including measurements of rare processes and in extreme phase spaces
  - Including heavy flavors and heavy ion collisions
- New physics searches in multi-TeV range
- And indirect limits from EFT fits
- LHC can probe many of the current puzzles
  - Probe NP related to heavy flavor anomalies
  - Searches for dark matter …
- Run 3 will more than double the dataset
  - At 13.6 TeV

List of Results

- All ATLAS Physics Analysis Public Results appear at
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ResultswithData2018
- All CMS Physics Analysis Summaries appear at:
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/CMS/index.html

- ATLAS Physics Briefings at
  - https://atlas.cern/updates/briefing
- CMS Physics Briefings at:
  - https://cms.cern/tags/physics-briefing