LHC: what we have learned

CMS en el LHC (20 años en la frontera de la física)

J. Alcaraz, 17 September 2026

Expectations on new physics (Altarelli, 2008)

Summarizing

- SUSY remains the Standard Way beyond the SM

- No compelling, realistic alternative with less fine tuning so far developed (not an argument! Int. models explored)

- Extra dim.s is a complex, rich, attractive, exciting possibility.

- Little Higgs or composite models are just a postponement
  (both interesting to pursue)

Get the LHC ready fast; we badly need exp input!!!

Expectations on the Higgs (Altarelli, 2008)

Is it possible that the LHC does not find the Higgs particle?

Yes, it is possible, but then must find something else

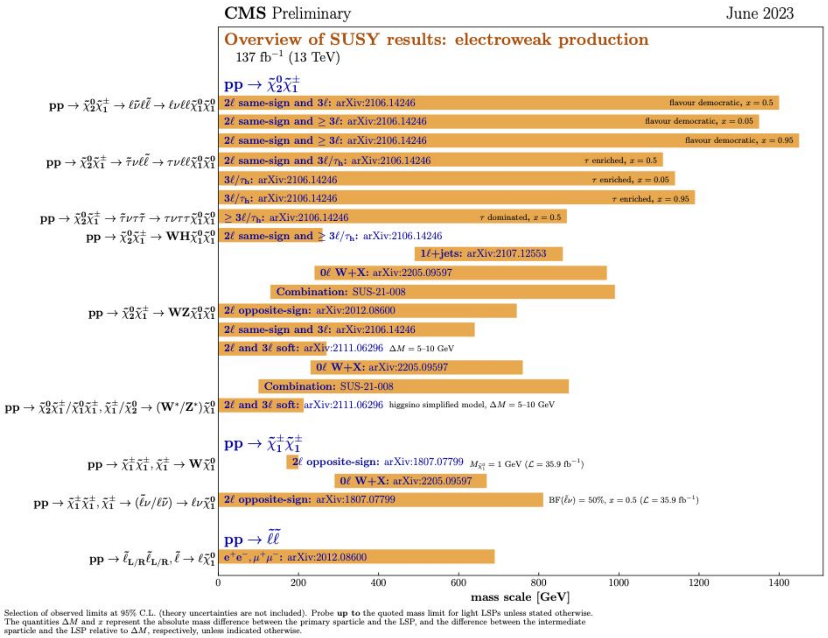
Is it possible that the LHC finds the Higgs particle but no other new physics (pure and simple SM)?

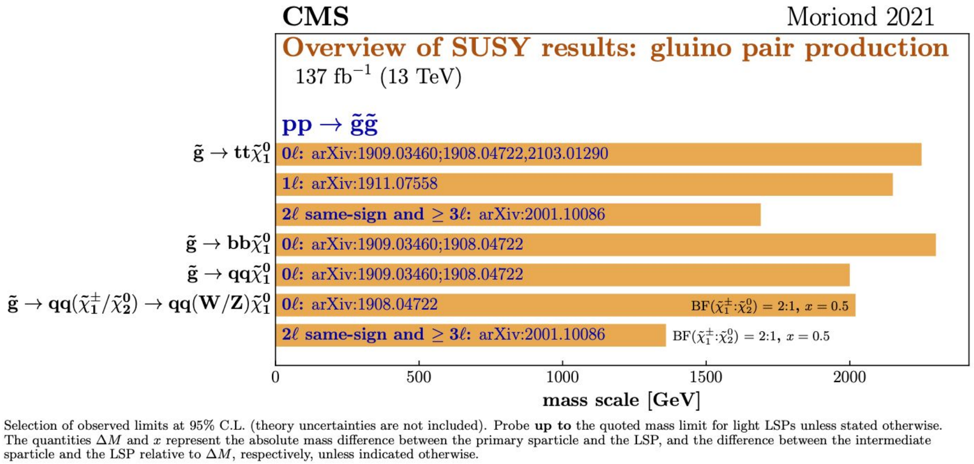
Yes, it is technically possible but it is not natural

Is it possible that the LHC finds neither the Higgs nor new physics?

No, it is essentially impossible

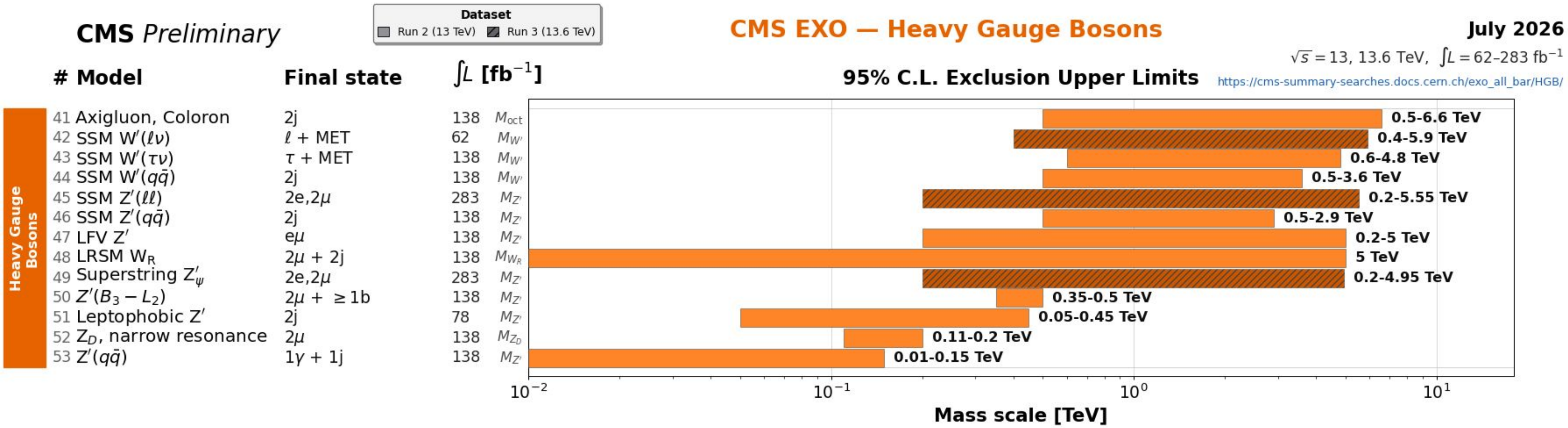
Looking for new physics then: SUSY?





Excluding SUSY from a few hundreds of GeV (EWK production) to ~ 2 TeV (strong production)

Looking elsewhere then: resonances



- **Reach: up to ~ 2-4 TeV GeV with diboson decays, up to ~ 5-6 TeV with dilepton decays**
- **LHC is extensively exploring the TeV scale (10 TeV scale to be explored at FCC)**

- **Also exploring extensively regimes with too weak couplings at lower masses (Feebly Interacting Particles (FIPs), sometimes long-lived)**
- **Strong contribution from CIEMAT in dilepton and long-lived searches (see Begoña's and Alberto's talks)**

LHC is a very successful project

- We are victims of our success: we have discovered the Higgs 😅

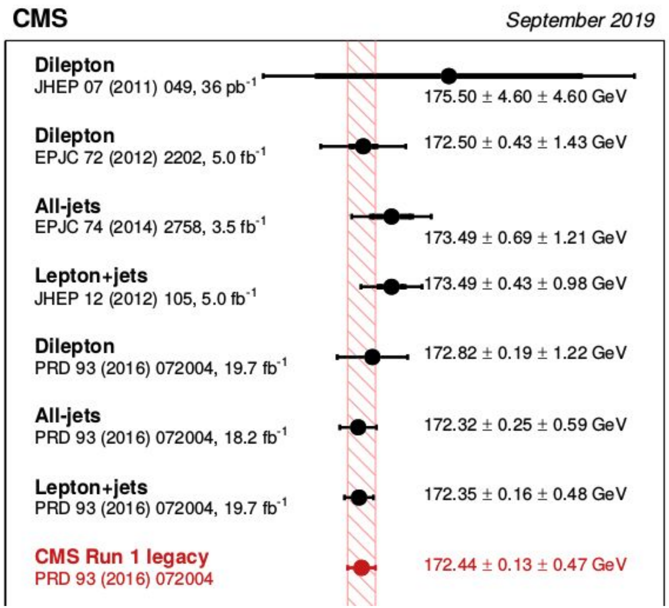
- LHC has outperformed all previous collider experiments, in terms of reach, precision and variety of physics scopes (generic, heavy ion physics, a B factory, top factory, a Higgs factory, QCD at low scales, …)

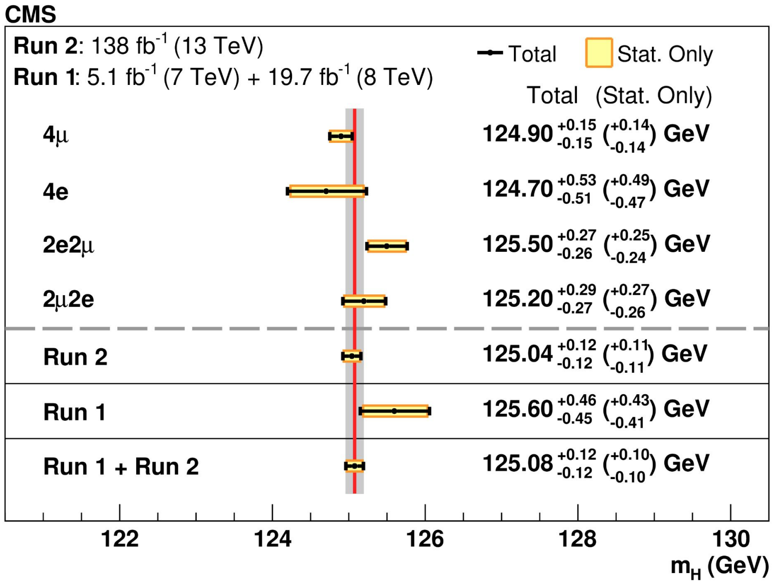
    - Comments of the type "LHC has not made anything relevant after the Higgs discovery" are just wrong

    - See LEP, for instance. LEP has not discovered any fundamental particle of the SM or any new interaction. Nevertheless it is considered to be an extremely successful project in the history of High Energy Physics

Stringent tests of validity of the SM

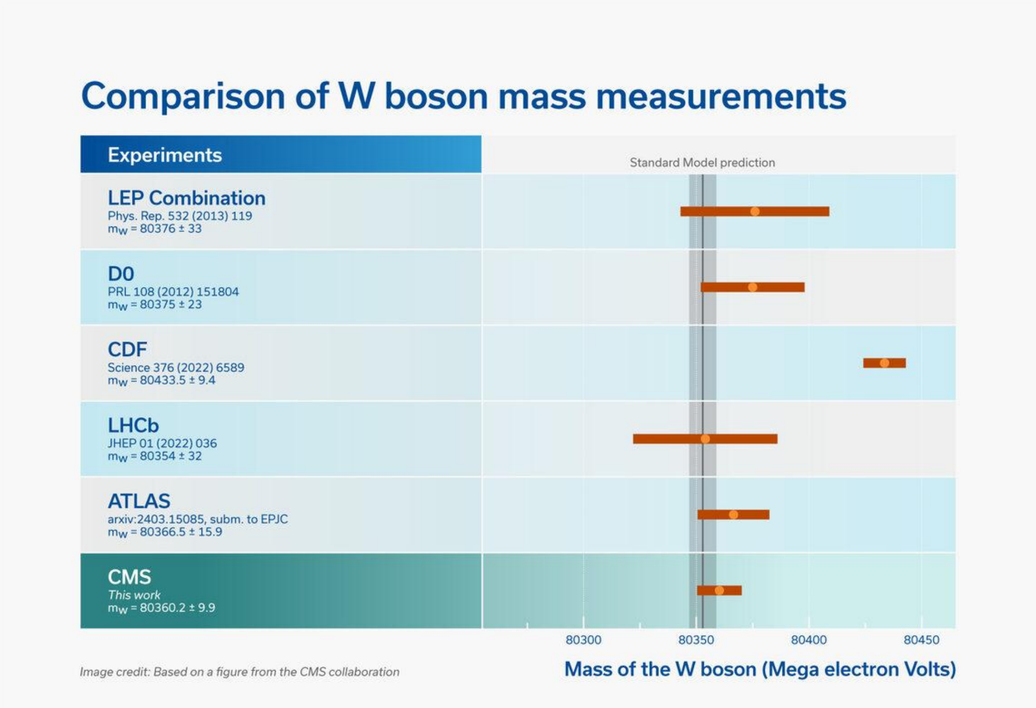
- **ALL LHC measurements of fundamental parameters of the SM are now better (or similar in just a couple of cases) than those of LEP**
- **Note: these measurements are major windows to search for new physics**
- **Obvious cases are top and Higgs masses:**

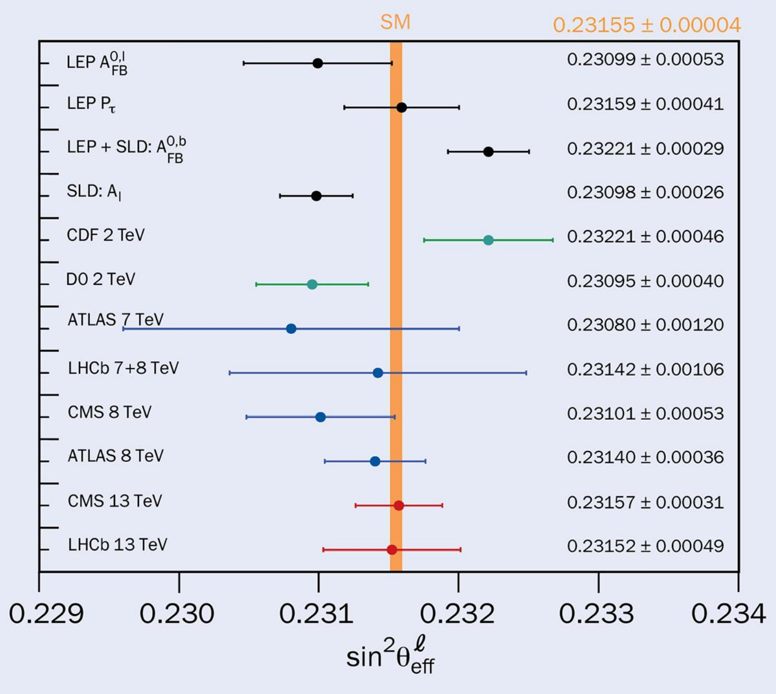




Stringent tests of validity of the SM

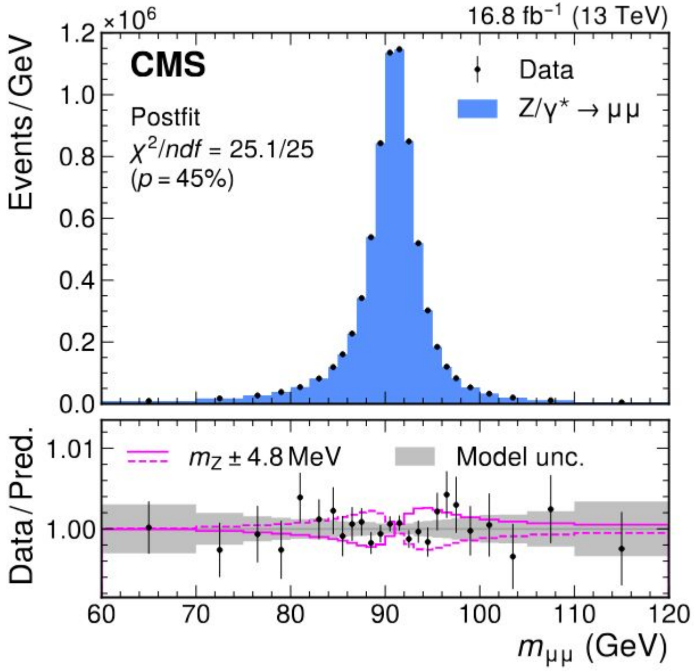
- **W mass and electroweak mixing angle: now most precise at LHC**





Stringent tests of validity of the SM

- **Even the precision on the Z mass is now challenging LEP !!**

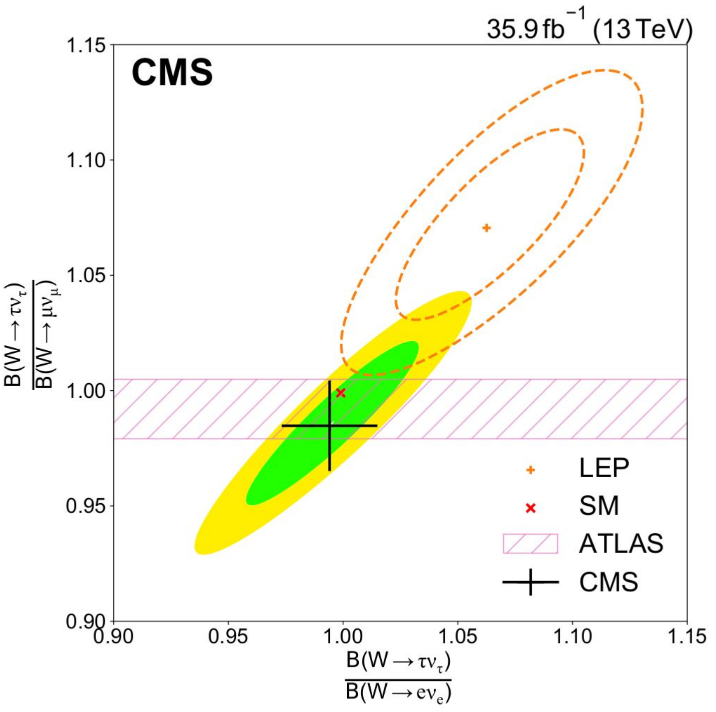


- **LEP precision is 2 MeV**

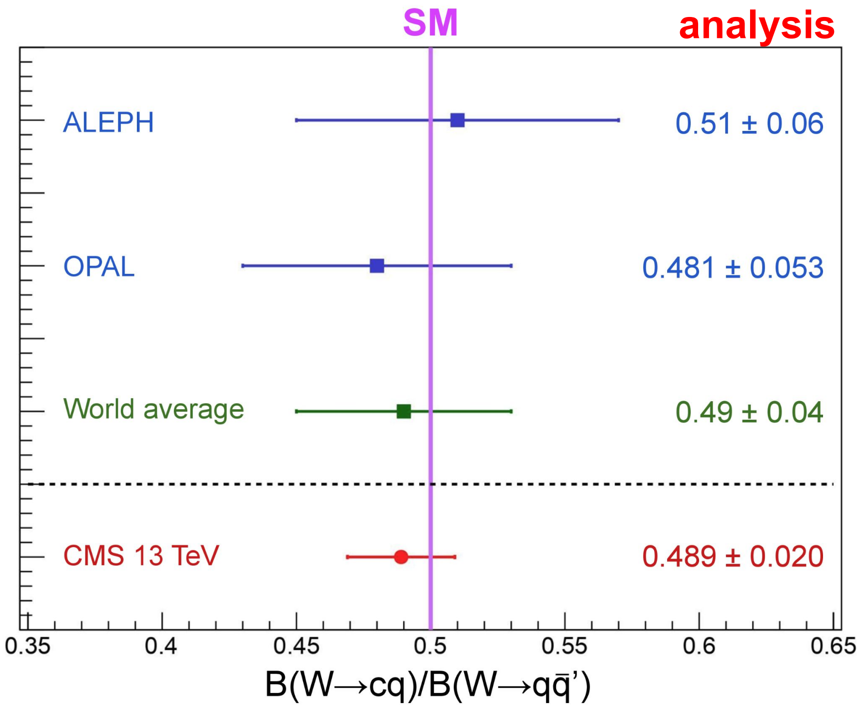
- **(This measurement is not yet promoted as such because it is part of the W mass measurement analysis and some calibration assumptions were partially based on the PDG Z mass value itself.)**

Stringent tests of validity of the SM

- **W leptonic branching fractions, V_{cq} coupling**

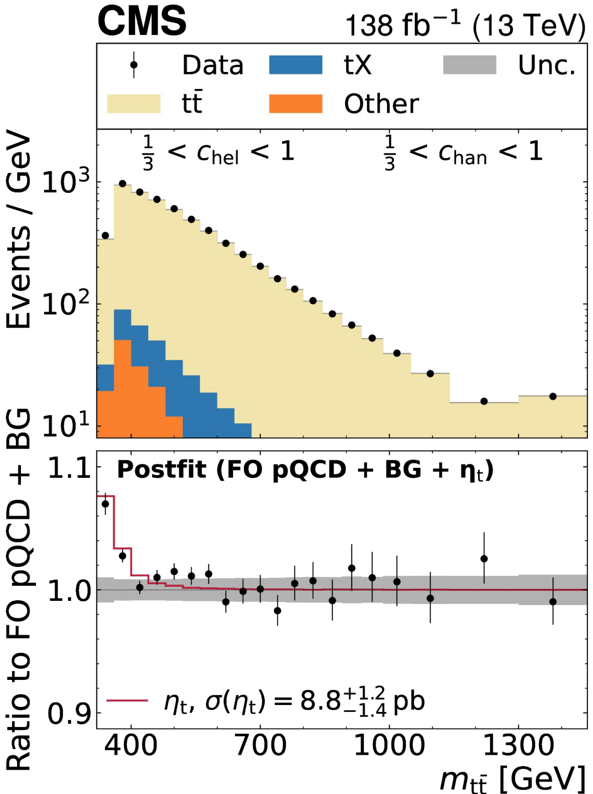


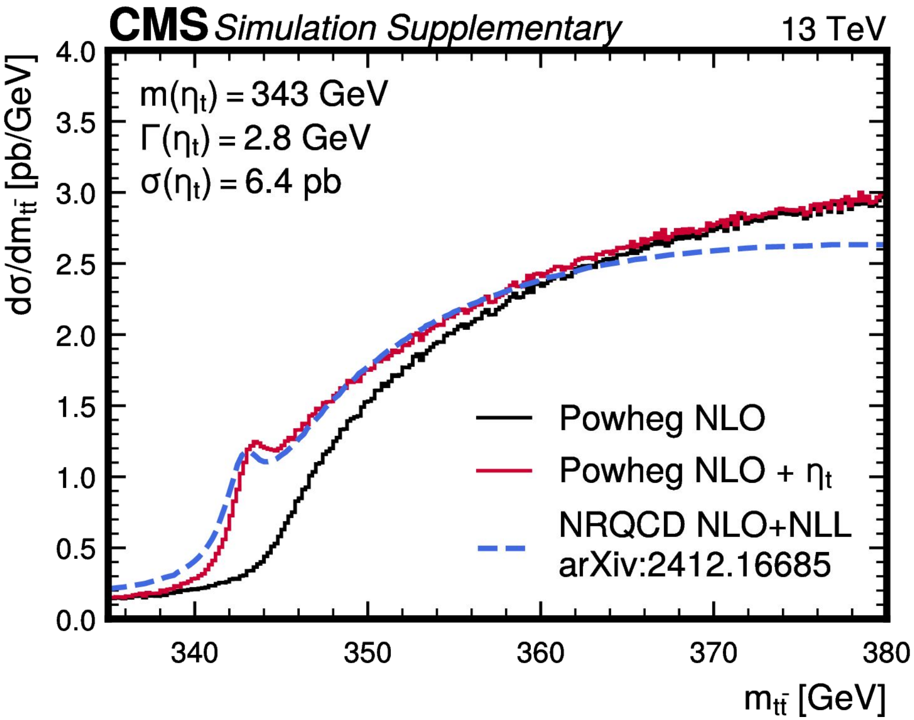
- **CIEMAT analysis**



Pushing SM limits: “toponium”

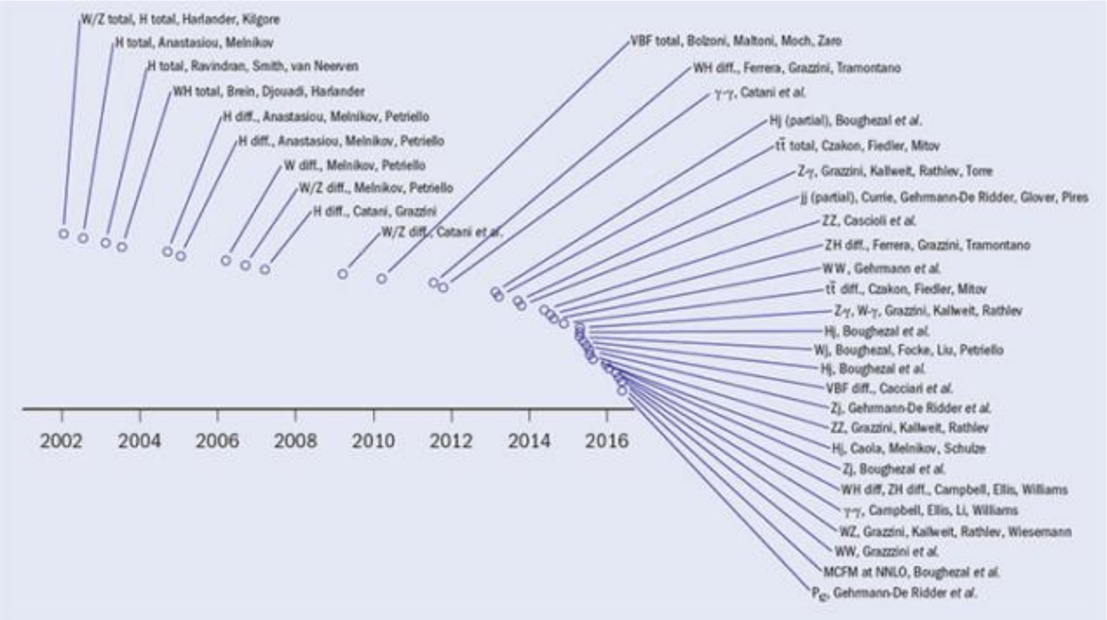
- **Exploring unaccounted QCD features, challenging SM predictions:**





What we have also learned with LHC

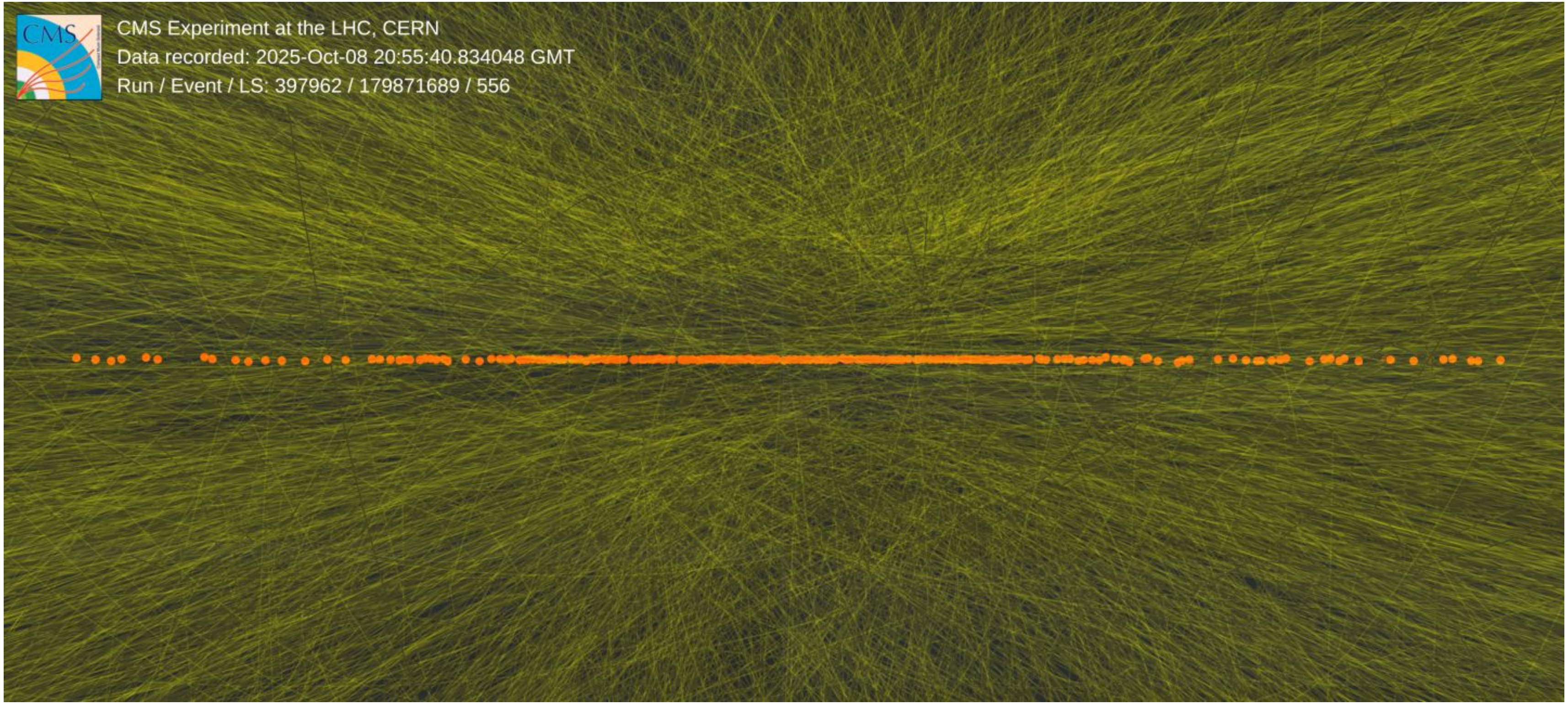
- **Hadron colliders are nowadays high precision machines. This is due to:**
  - **Theoretical predictions with percent level precision**
  - **Outstanding detectors, trigger, reconstruction and data acquisition capabilities**



- **Evolution of theoretical predictions:**

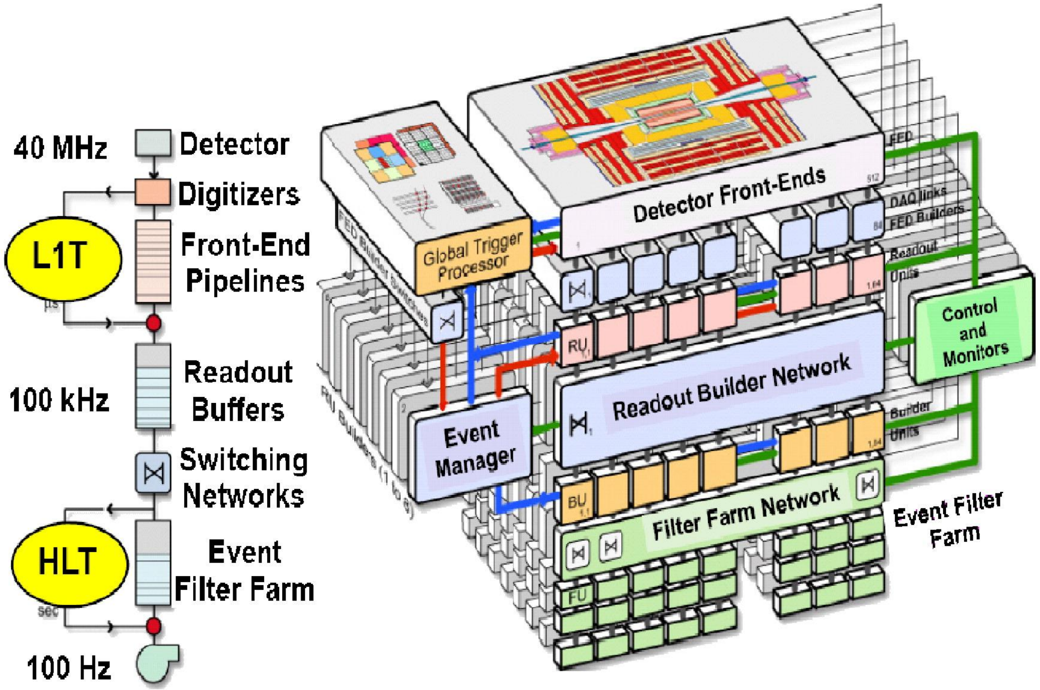
30%	Leading order (LO)
⇓	⇓
10%	Next-to-leading (NLO)
⇓	⇓
few %	Next-to-next (NNLO)

Outstanding detectors: huge pileup



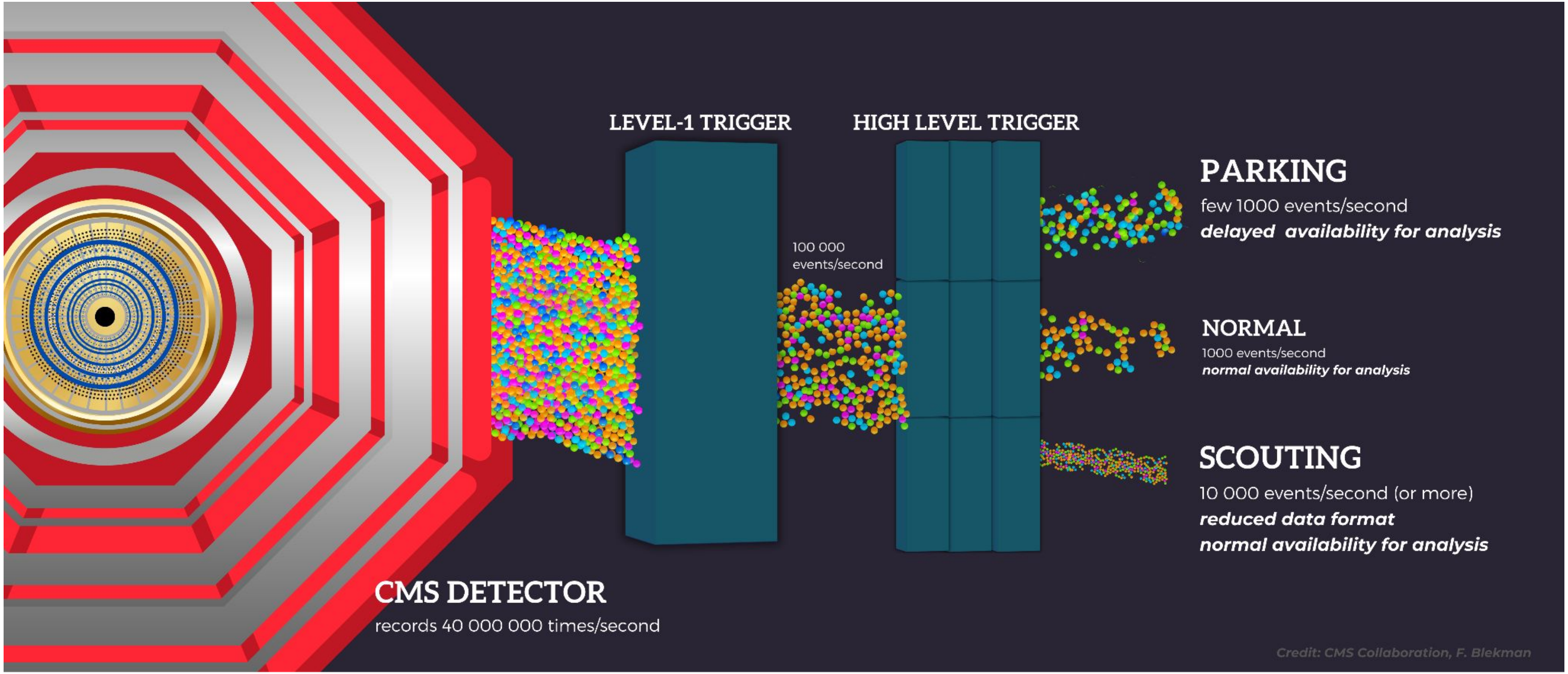
- **9381 tracks, 206 vertices, incredible reconstruction capabilities**

Outstanding CMS: high-level trigger (HLT)



- HLT: pioneering CMS bet → do full offline filtering just after L1T (in 40 ms per event)
- High-level processing also expanding also at L1T these days (unique CIEMAT contributions: see previous talks)

Outstanding CMS: scouting,parking



- **Able to analyze more data with relaxed thresholds**

Summary

- LHC has been (and still is, see next talk) an extremely successful project, at the physics frontier of precision and energy

- It is not only the Higgs discovery:
  - Searches, SM physics, a B-factory, a top factory, a Higgs factory, QCD and heavy ion systems, …
  - Extensive exploration of the TeV scale (not yet over)
  - Pioneering exploration of almost any possible new physics effects: low masses, dark matter, very weak couplings, CP violation, quark-gluon plasma, …
  - Ultraprecise measurement of almost all SM parameters
  - It has paved the way towards the next generation of ultraprecise experiments at colliders

Backup

Hitoshi Murayama's talk (LHCP 2017)

M.L. Mangano slides (2026)

LHC scientific production

Over 4000 papers published/submitted to refereed journals by the 7 experiments that operated in Run 1 and 2 (ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM, MoEDAL)... and the first papers by the new experiments started in Run 3 (FASER, SND@LHC)

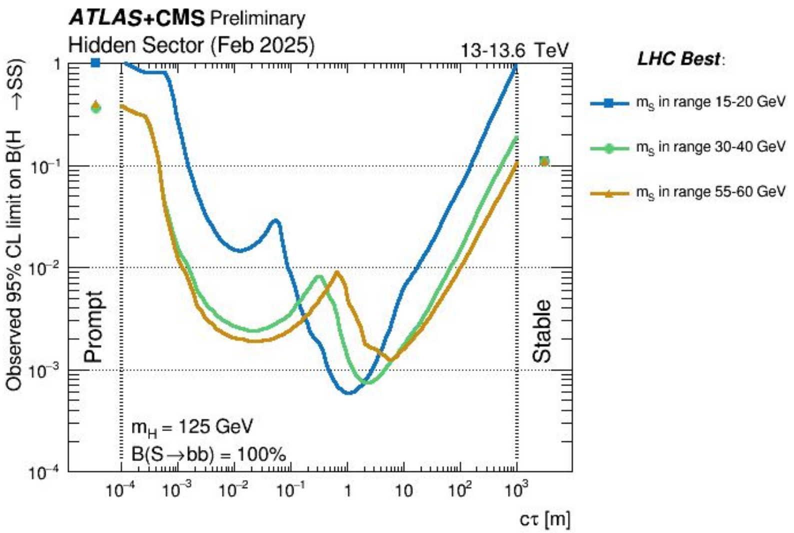
Of these:

~10% on Higgs (15% if ATLAS+CMS only)

~25% on searches for new physics (30% if ATLAS+CMS only)

~60% of the papers on SM measurements (jets, EW, top, b, HIs, …)

Current LHC reach: new resonances

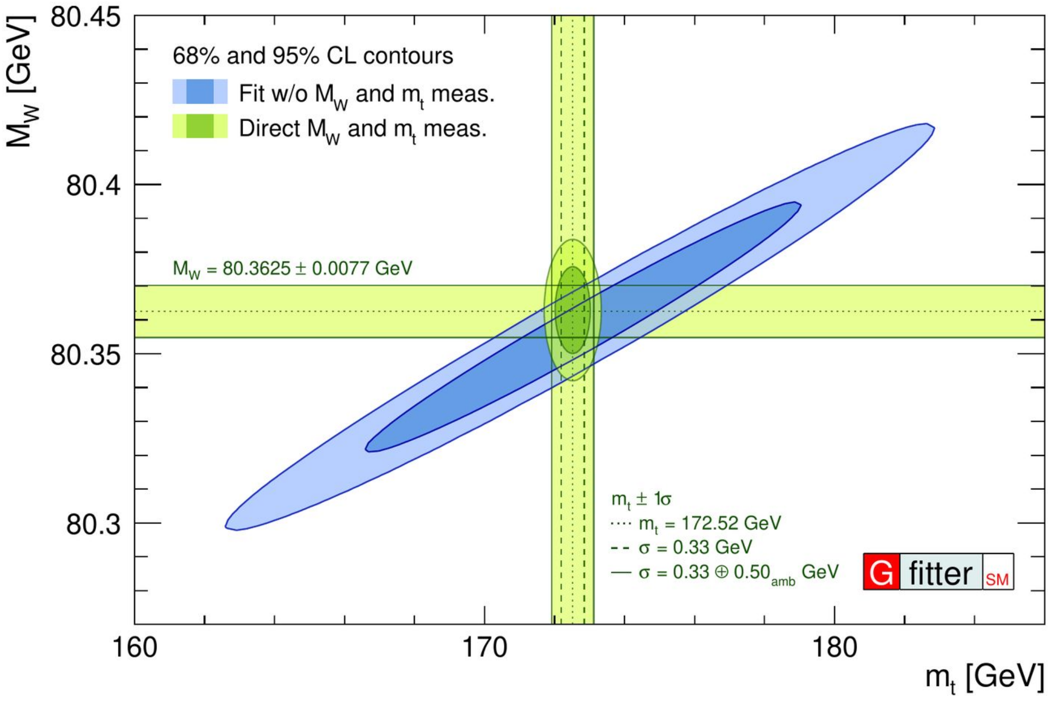


- **Also exploring regimes with too weak couplings tp SM particles, low masses, dark matter, …**

- **LHC has extensively explored the TeV scale. Note:**
  - **Any limits that you could see beyond 10 TeV are assuming extreme models or unlikely physics channels (technically: too strong couplings, too much flavour violation, necessarily “indirect” production, …)**
  - **The comprehensive “10 TeV” exploration will be done by the FCC**

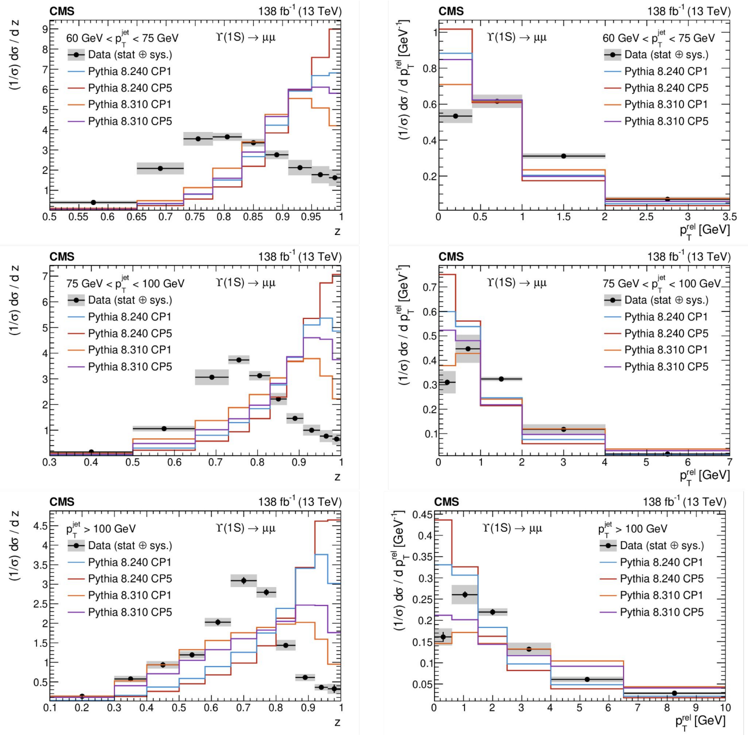
Stringent tests of validity of the SM

- **Top vs W mass relation: a key test for deviations of the SM**



QCD precision: fragmentation

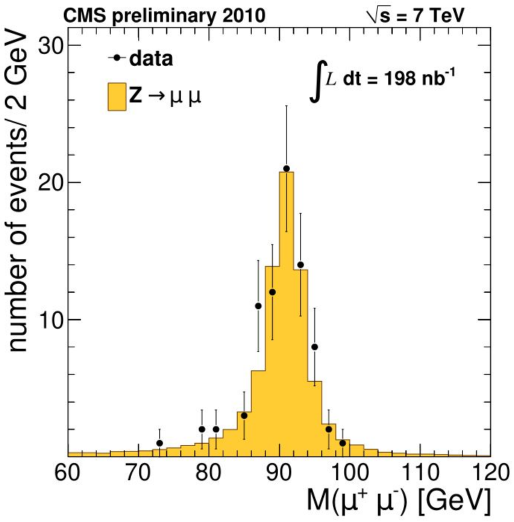
- **New QCD features, challenging SM predictions:**



- **Upsilon energies in total disagreement with predictions … (CIEMAT analysis)**

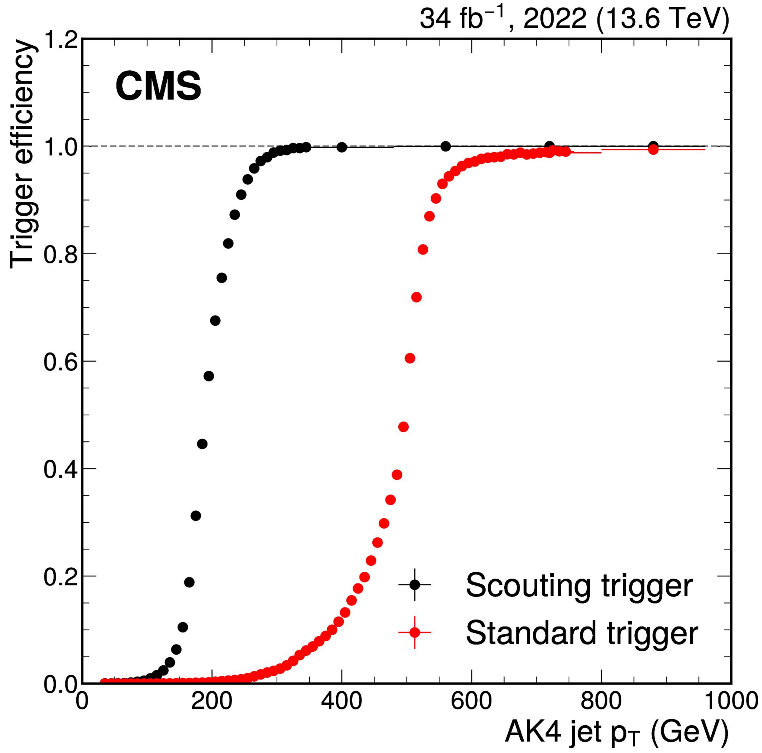
Early and well understood performance

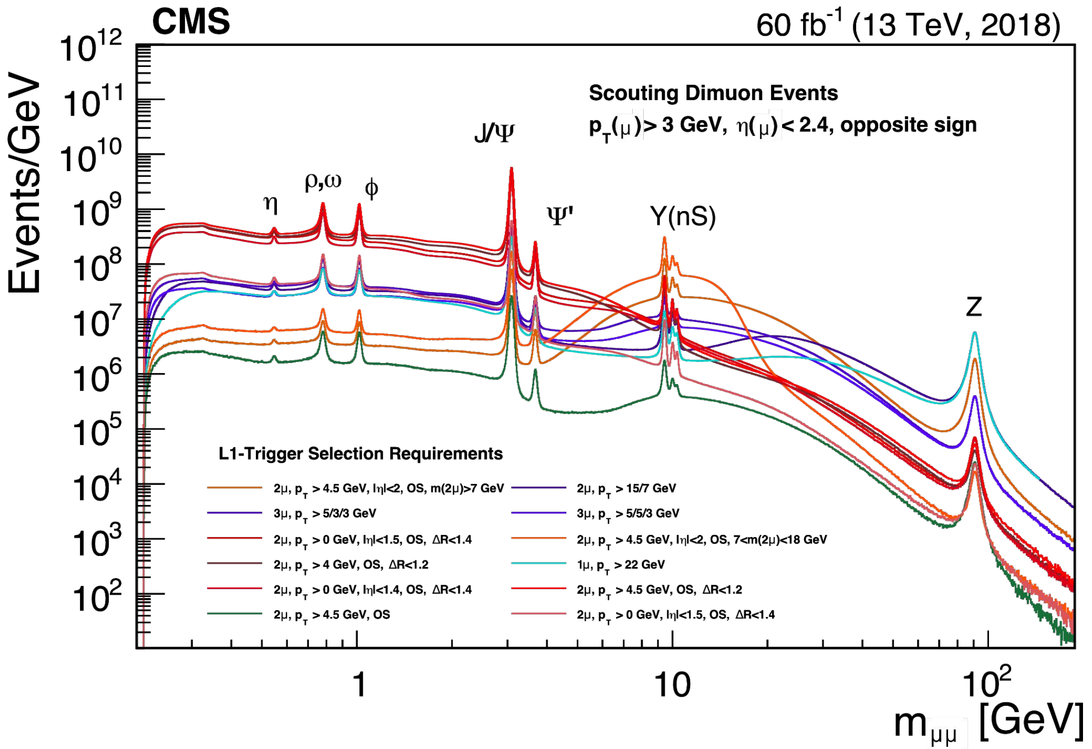
- ✓ There is the general assumption that detectors in hadronic colliders take too much time to calibrate and understand. This might not be the case at the LHC.
  - ✓ Note that at Tevatron top cross sections are small and collecting large EW samples for calibration took some time.
  - ✓ LHC detectors with an integrated luminosity of L ~ 100 pb^{-1} will have an enormous amount of dilepton events at resonances (J/Psi. Y, Z) and ttbar events to understand jet resolutions and b-tagging.
  - ✓ The challenge is rather on the organizational side: we need to process and analyze all these useful data as soon as possible.



- M. Cepeda, ICHEP 2010

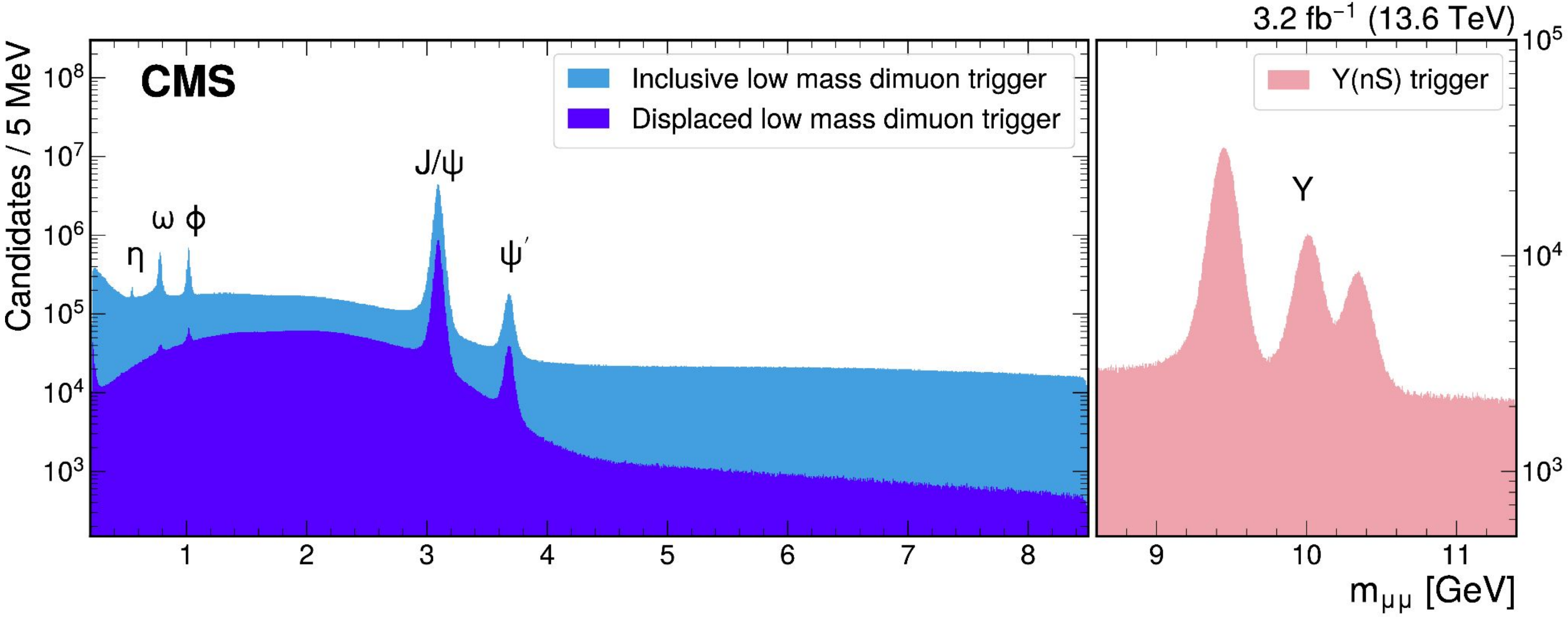
Outstanding detectors: scouting





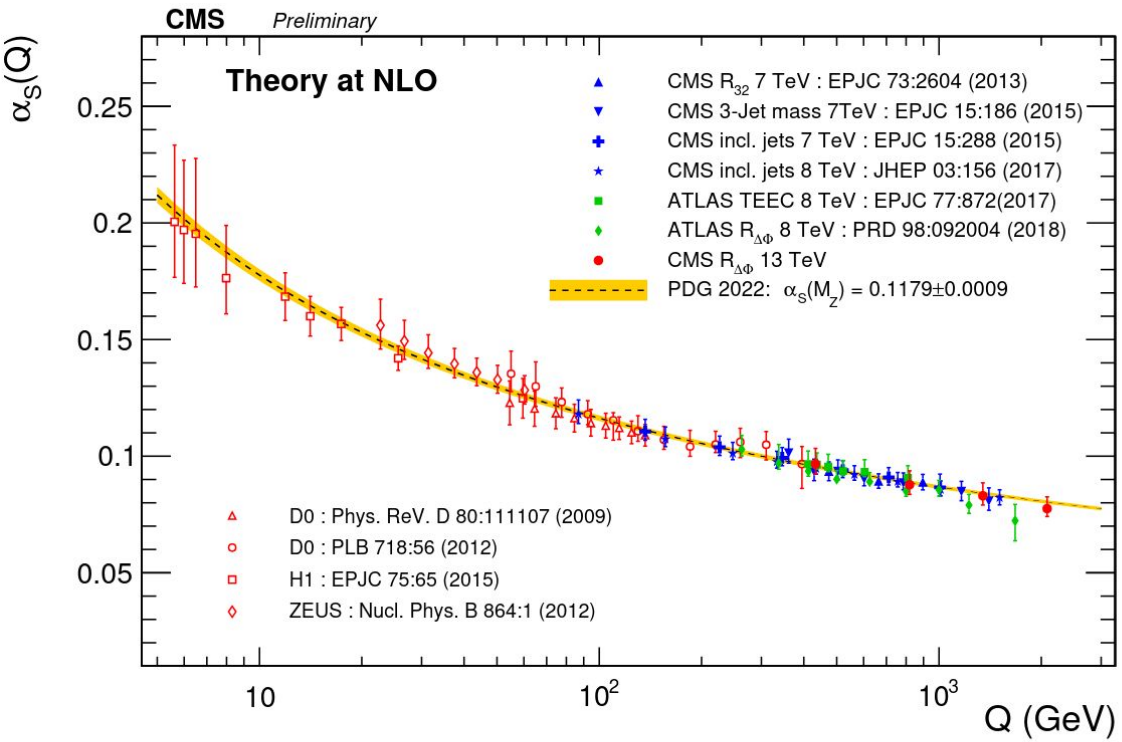
- **Able to analyze data with just trigger information and lower thresholds**

Outstanding detectors: parking



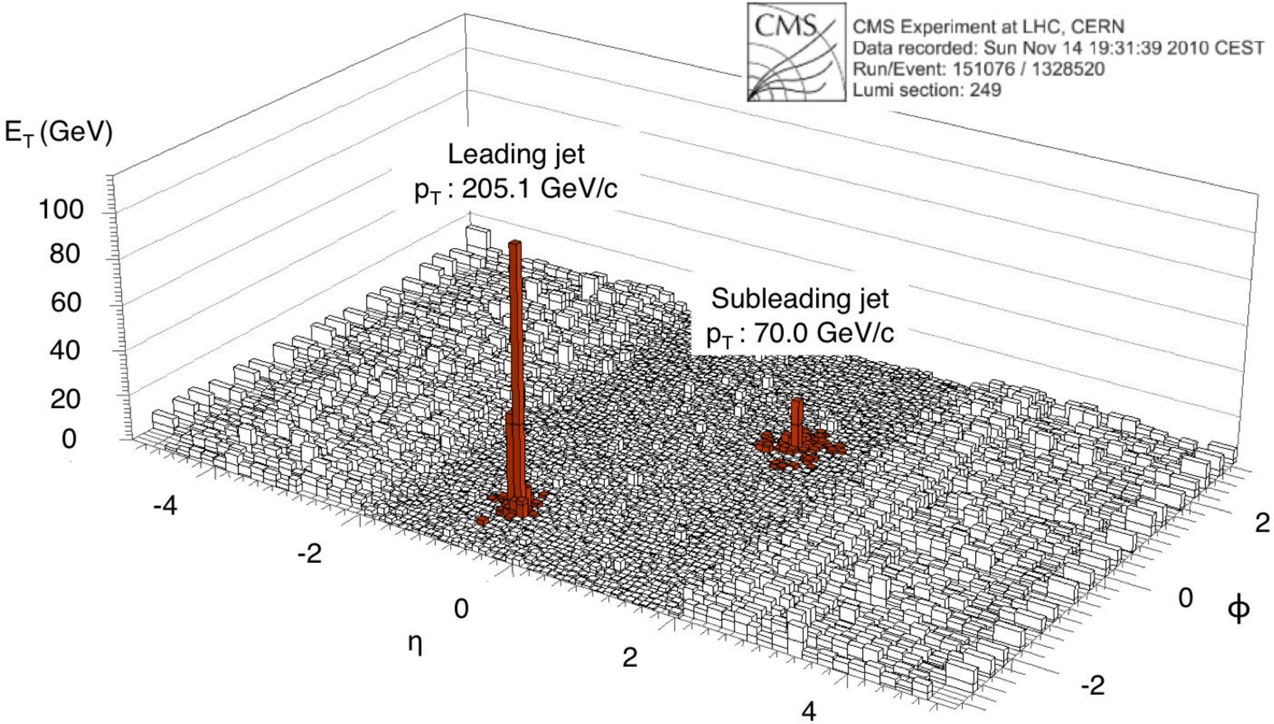
- **Able to delay the analyses of more data using lower thresholds**

QCD studies



- **Evolution of the strong coupling constant with energy**

Quark-gluon plasma evidences



- **Jet-quenching: jets “fade away” inside the plasma**