Strings 2024

CERN, 3 - 7 June 2024

Particle physics at colliders: status and prospects

Michelangelo L. Mangano CERN TH

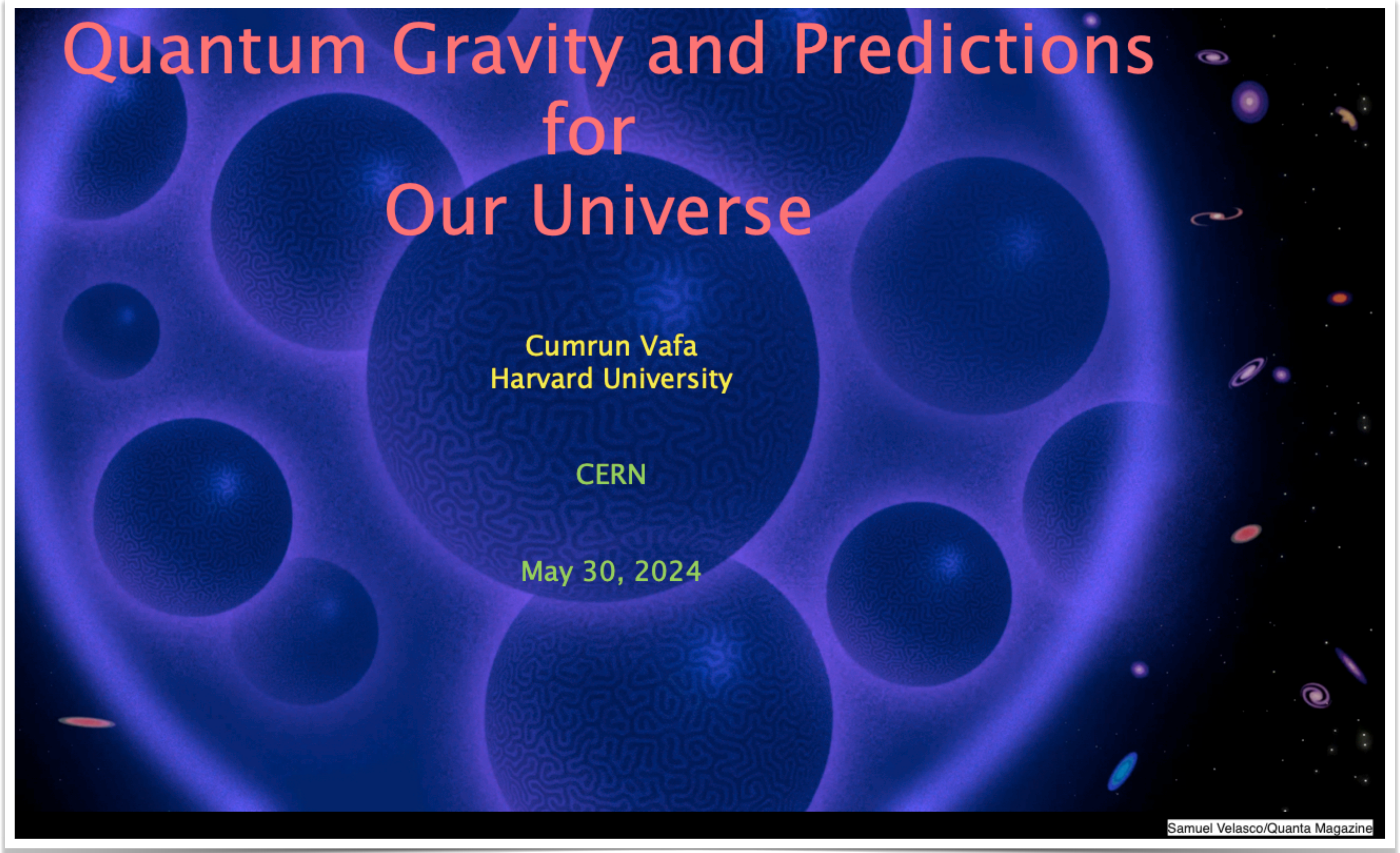
Preface:

I havent realized until recently that accepting to give this talk I was being tricked into a trap …

I was initially asked to talk about status of the LHC and future CERN programmes, like the Future Circular Collider etc. Which I happily agreed to … 10 days ago I discovered this was a set up to discuss connections and implications to string theory !! that's a challenge of different nature !!

I had a already a talk ~ ready , to give an overview of interesting recent results and future prospects, and the organizers allowed me to stick to it … so I was happy again …

But last Thursday I saw Cumrun colloquium at CERN (link) :



C. Vafa, CERN May 30, slide 4:

> String theory is believed to be a fundamental theory of nature leading to a consistent theory of quantum gravity.
>
> Yet, it is believed that we have no concrete predictions based on it. In this talk I would like to present some concrete predictions from string theory, testable by current experiments.

and this is when I realized the mess I got myself into …

busy with other urgencies till last night, I only started rewriting the talk at 4am this morning … apologies !

50 years ago, 1974 signalled the greatest before/after discontinuity in particle physics since its birth

before:

<1973:
- GWS model — Glashow Weinberg Salam
- GIM — Glashow Iliopulos Maiani
- renormalizability of gauge interactions — 't Hooft Veltman

1973:
- Discovery of neutral currents ⇒ SU(2)xU(1) gauge structure for weak interactions — Gargamelle @ CERN
- Asymptotic freedom ⇒ SU(3) gauge structure for strong interactions — Gross&Wilczek, Politzer
- Kobayashi-Maskawa CP violation with 3-generations ⇒ CKM flavour structure

1974:
- Discovery of charm ⇒ SU(2)xU(1) gauge structure for quarks and leptons — Richter@SLAC, Ting@BNL

In 1974 the SM gets firmly established as the framework to understand all known phenomena in particle physics … we just needed a few Nobel prizes to be distributed, and further experimental exploration to work out the details …

after:

1974:
- SU(5) and GUTs — Georgi Glashow, Pati Salam
- Supersymmetry — Wess Zumino

and the avalanche build-up ever since:

>1974
- Naturalness and EWSB, composite Higgs, etc — WIlson,
- Composite leptons and quarks — Pati Slam, Glashow, Neeman, 't Hooft, Harari …
- …

➡ explosion of BSM model building, phenomenology and exptl searches

By 1974 the SM is declared history, BSM searches become the new virgin territory of exploration, with theory providing guidance to experiments, rather than the opposite

1974 is also a transition point for string theory

the “before”

Nuclear Physics B74 (1974) 365–377. North-Holland Publishing Company

REGGE INTERCEPTS AND UNITARITY IN PLANAR DUAL MODELS *

G. VENEZIANO
Weizmann Institute of Science, Rehovot, Israel
and
CERN, Geneva

Received 4 February 1974

Abstract: We argue that unitarization of planar dual models should follow an “order of summation” different from the usual one according to powers of the coupling constant.

If one sums instead “per topology” i.e. planar diagram first, cylinders next and so on, a new perturbation expansion emerges, similar in structure to the one presently employed in analyzing multiparticle processes at ISR and NAL energies.

Yet no reference to QCD (1973) as the new possible framework to understand hadron phenomena and their relations to strings/dual models

(of course the relation of hadron physics and dual models remains today a hot topic … but the challenge is not to describe data, it’s to connect QCD and 4-d strings)

ISR: Intersecting storage ring, the first proton-proton collider in history (CERN)

NAL: National Accelerator Laboratory, to become FNAL/Fermilab shortly after

the "after"

DUAL MODELS FOR NON-HADRONS

Nuclear Physics B81 (1974) 118–144.

J. SCHERK and John H. SCHWARZ
California Institute of Technology, Pasadena, California 91109 †

Received 14 May 1974

Abstract: The possibility of describing particles other than hadrons (leptons, photons, gauge bosons, gravitons, etc.) by a dual model is explored. The Virasoro-Shapiro model is studied first, interpreting the massless spin-two state of the model as a graviton. We prove that in the limit of zero slope (with $g_{VS}^2\alpha'$ held fixed) one obtains the Einstein theory of gravitation accompanied by a massless scalar field. Next, the Veneziano model is studied for small slope as an expansion in powers of α'. It is known from previous work that the zeroth order term is precisely the Yang-Mills theory of a multiplet of massless vector bosons. We show that there are order α' terms arising both from the dual tree and loop graphs. The former constitutes a relatively unimportant modification of the Yang-Mills theory, whereas the latter involves the coupling of the massless scalar and graviton states of the Virasoro-Shapiro model. Thus one may take the point of view that gravity arises as a unitarization effect in a dual unified theory of electromagnetism and weak interactions. In order to obtain the correct values for the electric charge and Newton's constant it is necessary that $\alpha' \sim 10^{-34}$ GeV^{-2}. The coupling of massless scalar states is also studied.

back to:

By 1974 the SM is declared history, BSM searches become the new virgin territory of exploration, with theory providing guidance to experiments, rather than the opposite

None of these explorations has led anywhere as yet.

Open experimental puzzles remain open:

- what is dark matter?
- what is the origin of neutrino masses?
- what is the origin of CP violation?
- what is dark energy?

Contrary to the times leading to 1974, there is no dominant theoretical framework to be taken as obvious default or benchmark

Example 1

In the SM, the relation between M_W , M_Z and $\sin^2\theta_W$ is fixed at tree level. At the quantum level, the relation depends on input param's like m_{top} and m_H.

Precision measurements of M_W , M_Z and $\sin^2\theta_W$ at LEP/SLAC/Tevatron confirmed the deviation from tree level:

- *is this BSM or a manifestation of radiative corrections to the SM prediction?*
  - ➡ *calculate m_{top} and m_H that describe data, use/build a collider to search for top and Higgs with these mass values, and check if SM is ok*

The moral of the story:

the SM provided a framework to interpret the results of precision EW measurements, giving direct guidance as to how dedicated experiments (in this case Tevatron and LHC for top and Higgs resp) could confirm its consistency, or expose new phenomena

Example 2

In the SM, a prediction exists for the anomalous magnetic moment of the muon, $a_\mu = (g-2)_\mu$ … all SM parameters enter here via radiative corrections. All SM parameters are known today with sufficient precision to calculate a_μ with the accuracy required to challenge the SM with experimental data (FNAL, BNL).

Current data indicate that the SM prediction is off by 5.2σ … Options:

(A) the uncertainty of the SM result is underestimated (see eg recent lattice predictions)

(B) there is new physics

if (B), there is no BSM model, among the many considered, which can be singled out as a benchmark framework to interpret the origin of the a_μ anomaly, and plan for confirmation experiments/facilities

Example 3

A jets+ missing ET signal is observed at the LHC

In the 90's this would have been immediately interpreted as a supersymmetric neutralino, calling for discovery of SUSY and DM

Today, many options could be on the table:

(A) SUSY

(B) invisible H decay (eg to axions, dark photons, etc)

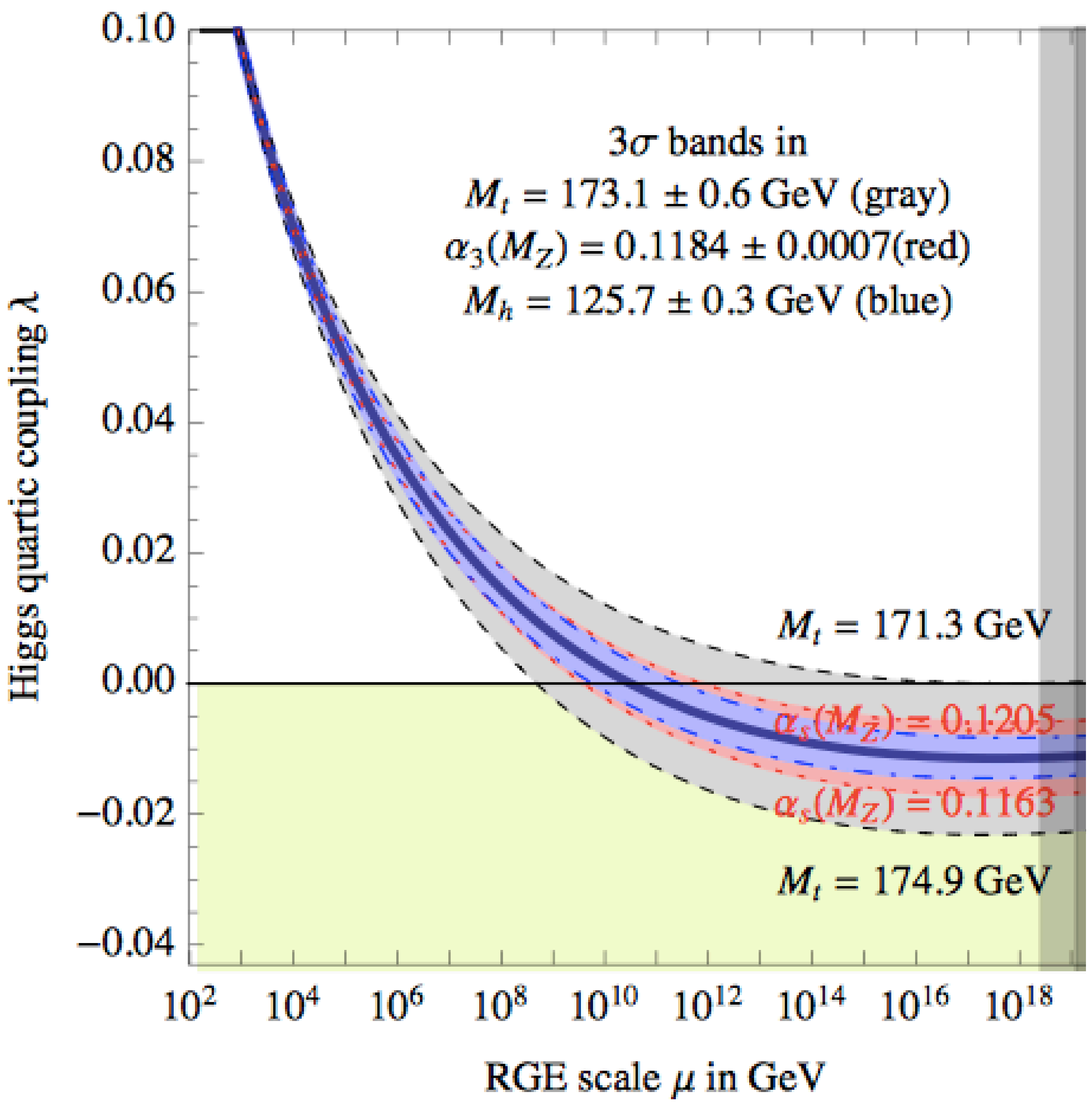
(C) extra dimensions

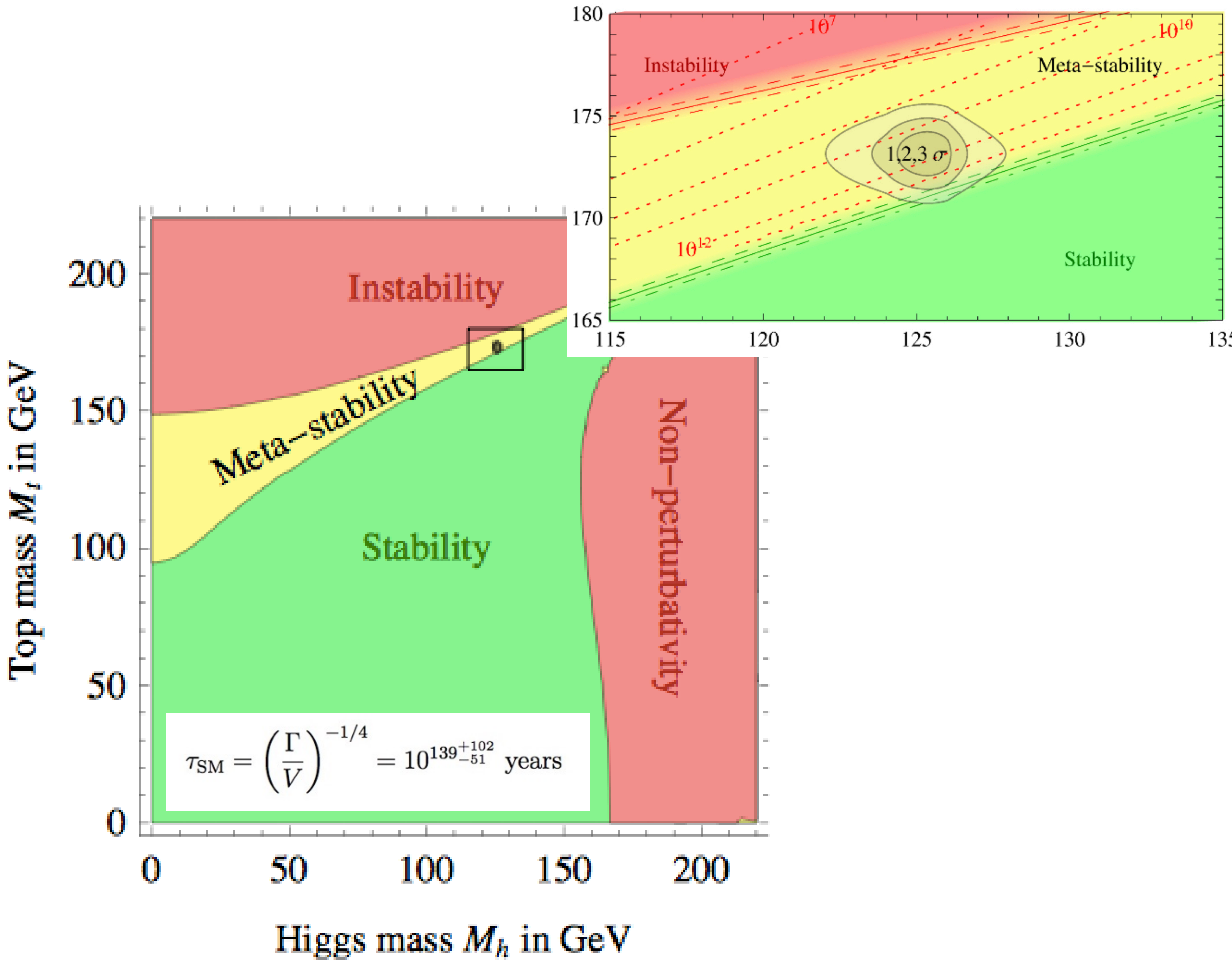
(D) …

After the SM, interpreting discoveries and pinning down their origin is harder than just predicting possible manifestations of BSM models … even if we work with a specific class of BSM scenarios in mind

Higgs vacuum metastability

Degrassi et al, arXiv:1205.6497



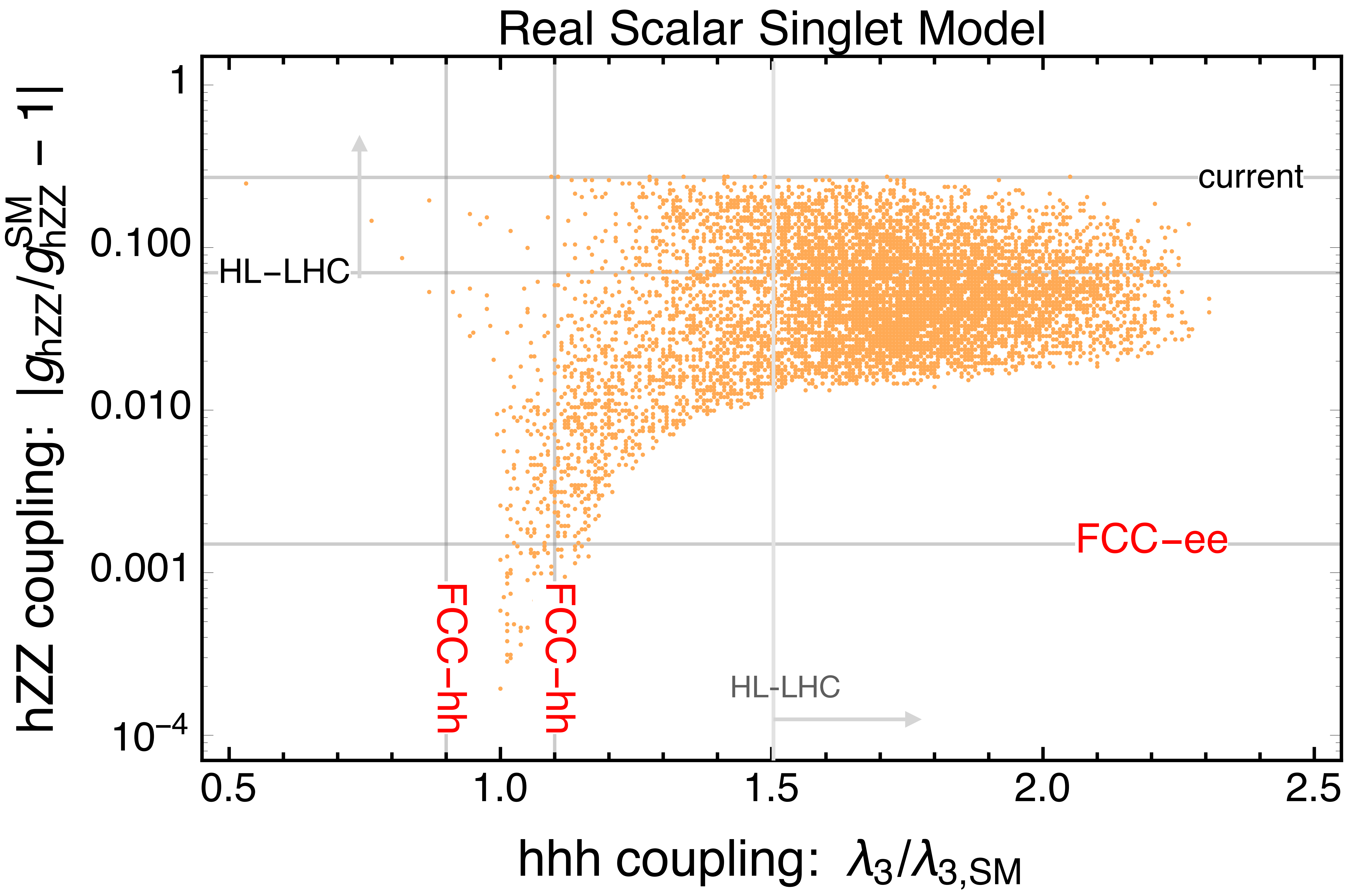


Where do we go from here, in terms of deciding which facility to build next to find out whether this is an accident or a hint?

Impact of extended Higgs sectors on nature of the EW phase transition

Extra-singlet models with potential strong 1st order phase transition

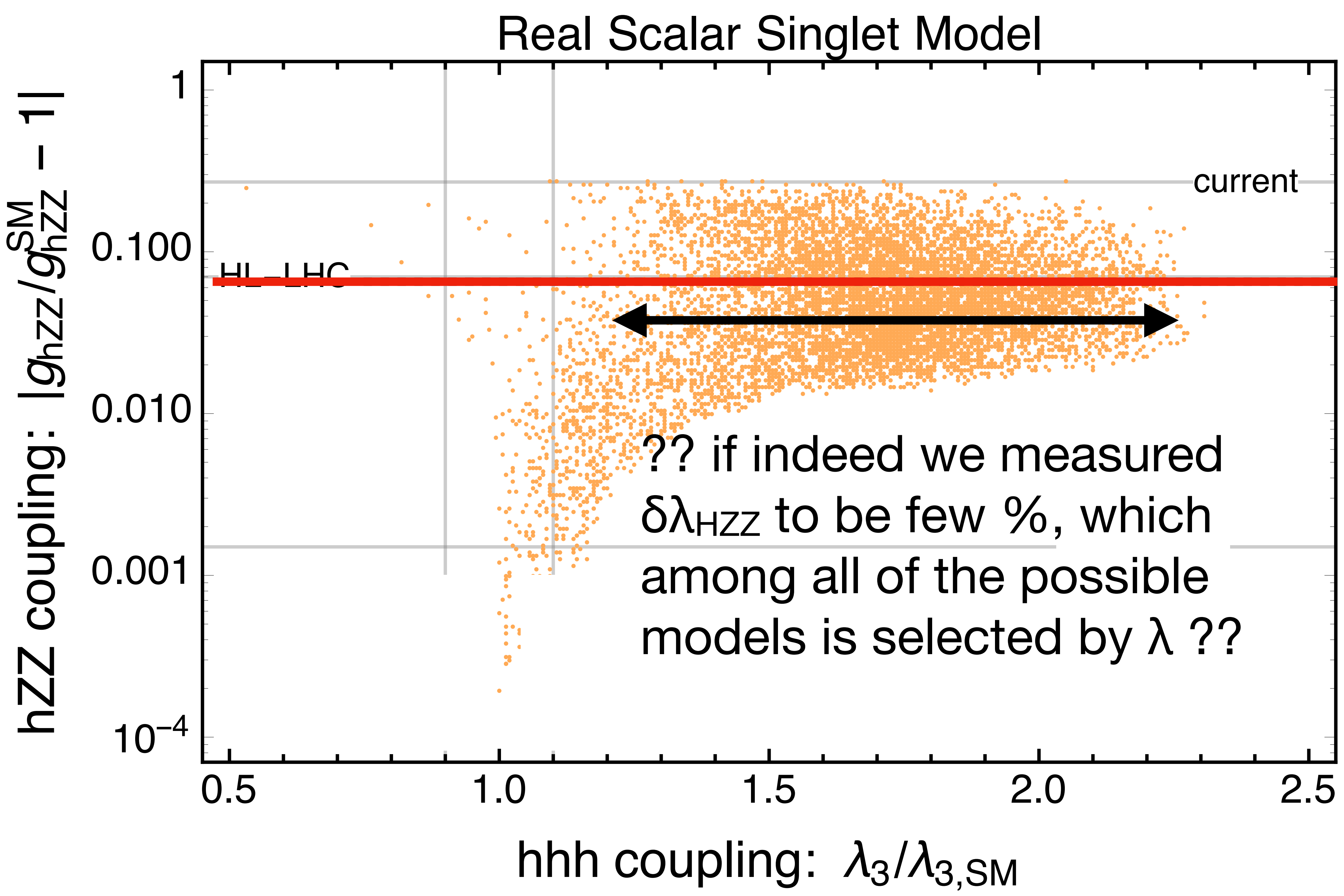
$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$



Experimental signature:
deviation in the Higgs coupling to the Z (g_{hZZ}) and in the Higgs self-coupling λ_3

Scan of model parameters a_i and b_i, and impact on g_{hZZ} and λ_3 for parameter points with strong FOPT

- The LHC might discover a deviation in the hZZ coupling, eg at the red-line level shown here:



- By itself an hZZ coupling deviation could arise from many other sources.
- Even for these models, multiple parameters are possible …
- … the measurement in addition of the Higgs selfcoupling could help limit further, or rule out, the interpretation…

The message:
redundancy, and precision, are be key features of current and future exploration at colliders

PRL

Are the New Particles Baryon-Antibaryon Nuclei?
Alfred S. Goldhaber and Maurice Goldhaber

Interpretation of a Narrow Resonance in e+ e- Annihilation
Julian Schwinger

Possible Explanation of the New Resonance in e+ e- Annihilation
S. Borchardt, V. S. Mathur, and S. Okubo

Model with Three Charmed Quarks **R. Michael Barnett**

Heavy Quarks and e+ e- Annihilation **Thomas Appelquist and H. David Politzer**

Is Bound Charm Found? **A. De Rújula and S. L. Glashow**

Possible Interactions of the J Particle
H. T. Nieh, Tai Tsun Wu, and Chen Ning Yang

Is the 3104-MeV Vector Meson the psi - Charm or the W0?
G. Altarelli, N. Cabibbo, R. Petronzio, L. Maiani, G. Parisi
Charm, EVDM and Narrow Resonances in e^+e^- Annihilation
C. A. Dominguez and M. Greco

Fig. 15. Immediate interpretations of the J/ψ, with their titles. PRL is Phys. Rev. Lett. **34**, Jan. 6th, 1975. The last two papers[88, 89] are in Lett. Nuovo Cim.

Figure from A. de Rujula, https://arxiv.org/abs/1910.13891

The physics programme of the LHC and future colliders builds on 3 pillars

- The guaranteed deliverables
  - improved measurements of fundamental constants and parameters
  - deeper exploration of dynamics of SM interactions, eg
    - EW symmetry breaking and flavour phenomena
    - QCD non perturbative dynamics
  - *push further the boundary between established facts (e.g. quarks are pointlike at the scale of (10 TeV)–1) and conjectures (e.g. quarks are pointlike)*
- The exploration and discovery potential
  - higher and higher energy !!
- Conclusive answers to important questions, like
  - Is DM a thermal WIMP ?
  - What was the nature of the EW phase transition ?
  - Does the origin of neutrino masses lie at the TeV scale ?
  - Are the Higgs potential and mass defined by physics at the few-TeV scale ?
  - are there BSM sources of CPV below the few-TeV scale ?

<u>Examples</u> of concrete questions/tasks we're addressing today with colliders

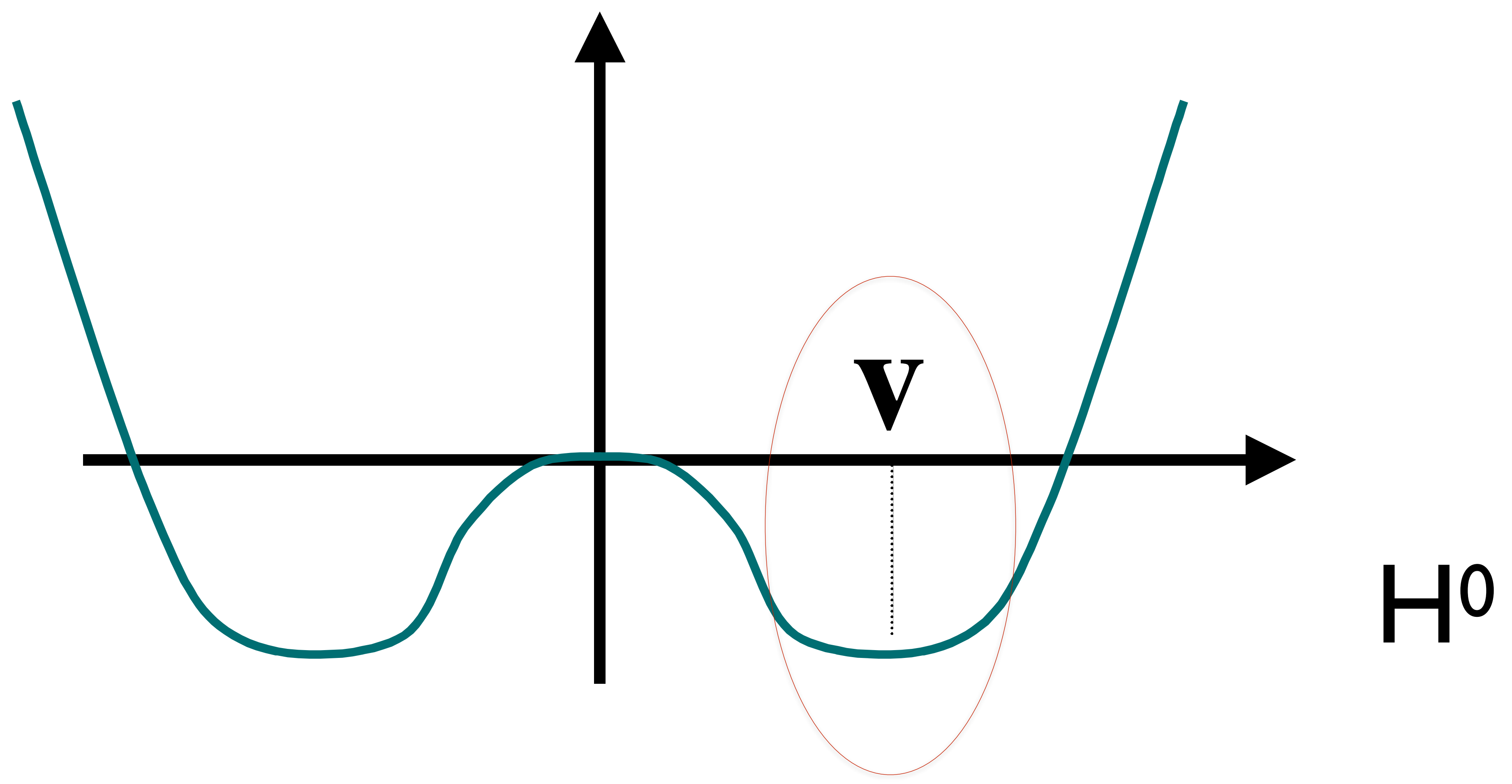
BSM:

- What's the origin of EW symmetry breaking (a broader way of defining the "hierarchy problem" puzzle)? In particular, is the Higgs elementary or composite?
- Are there flavour phenomena (including CPV) beyond CKM? What is the origin of the flavour structure of the SM
- IS DM a thermal WIMP?
- Is the source of neutrino masses a TeV-scale phenomenon?
- plus the old bread-and-butter favorites: are quarks and leptons composite? are there new quark and lepton families? are there new gauge interactions ?

Examples of concrete questions/tasks we're addressing today with colliders

SM:

- Further improve the precision of measurements, to expose possible deviations, in all sectors, from EW to flavour
- Deepen our understanding of strong interactions in all dynamical regimes: energy, density, temperature, collective environments, …, perturbative and non-perturbative
    - The challenge goes beyond "formally proving confinement": new data keep emerging that contradict assumptions judged until now to be "obvious" and "robust"



$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

Where does this come from?

The SM Higgs mechanism (*á la Weinberg*) provides the *minimal* set of *ingredients* required to enable a consistent breaking of the EW symmetry.

Where these *ingredients* come from, what possible additional infrastructure comes with them, whether their presence is due to purely anthropic or more fundamental reasons, we don't know, the SM doesn't tell us …

How do we calculate m_H?

a historical example: superconductivity

- The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.
- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and **we must look beyond.**

examples of possible scenarios

- **BCS-like**: the Higgs is a composite object
- **Supersymmetry**: the Higgs is a fundamental field and
  - $\lambda^2 \sim g^2+g'^2$, it is not arbitrary (MSSM, w/out susy breaking, has one parameter less than SM!)
  - potential is fixed by susy & gauge symmetry
  - EW symmetry breaking (and thus m_H and λ) determined by the parameters of SUSY breaking
- …

Other important open issues on the Higgs sector

- Is the Higgs the only (fundamental?) scalar field, or **are there other Higgs-like states** (e.g. $H^{\pm}$, A^0, $H^{\pm\pm}$, ... , EW-singlets, ...) ?
  - Do all SM families get their mass from the **same** Higgs field?
  - Do $I_3=1/2$ fermions (up-type quarks) get their mass from the **same** Higgs field as $I_3=-1/2$ fermions (down-type quarks and charged leptons)?
  - Do Higgs couplings conserve flavour? $H\to\mu\tau$? $H\to e\tau$? $t\to Hc$?
- Is there a deep reason for the apparent metastability of the Higgs vacuum?
- Is there a relation among Higgs/EWSB, baryogenesis, Dark Matter, inflation?
- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?

➡ the Higgs discovery does not close the book, it opens a whole new chapter of exploration, based on precise measurements of its properties,
which can only rely on the LHC and on a future generation of colliders

Diversity and guaranteed deliverables of the 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 are appearing by the new experiments started in Run 3 (FASER, SND@LHC)

Of these:

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

~30% on searches for new physics (35% if ATLAS+CMS only)

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

Some examples of the diversity of the programme next …

Not only Higgs and exotic searches !

Flavour physics

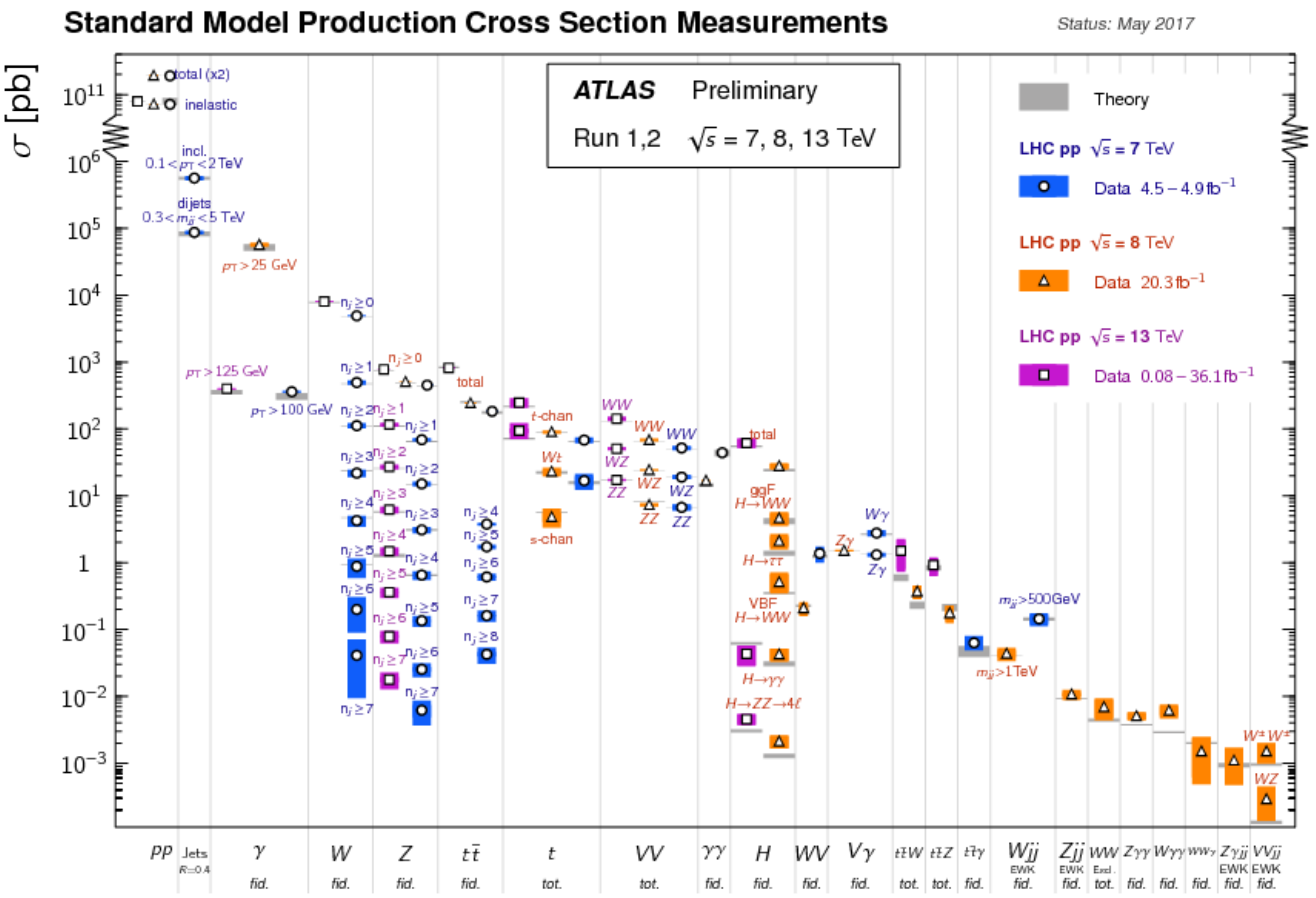
- B(s) $\to \mu\mu$
- D mixing and CP violation in the D system
- Measurement of the γ angle, CPV phase ϕ_s, …
- Lepton flavour universality in charge- and neutral-current semileptonic B decays => possible anomalies ?

QCD dynamics

- Countless precise measurements of hard cross sections, and improved determinations of the proton PDF
- Measurement of total, elastic, inelastic pp cross sections at different energies, new inputs for the understanding of the dominant reactions in pp collisions
- Exotic spectroscopy: discovery and study of new tetra- and penta-quarks, doubly heavy baryons, expected sensitivity to glueballs
- Discovery of QGP-like collective phenomena (long-range correlations, strange and charm enhancement, …) in "small" systems (pA and pp)

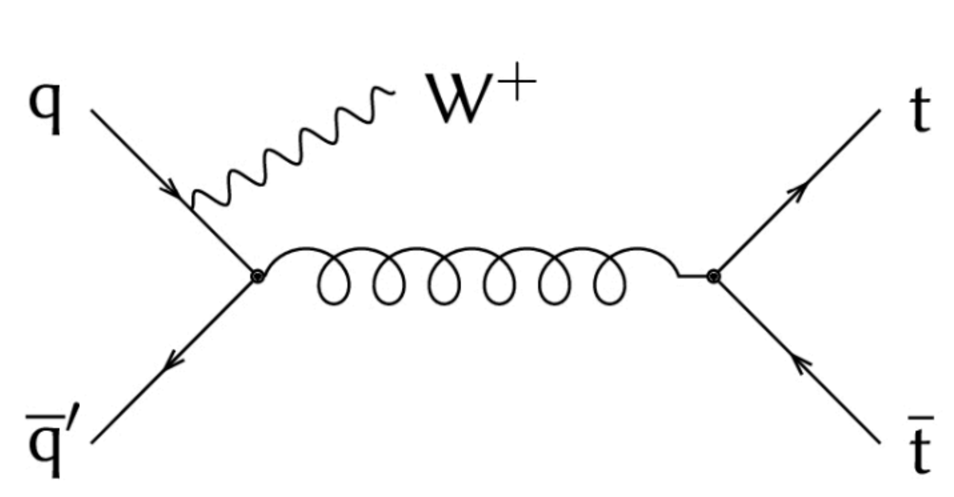
EW param's and dynamics

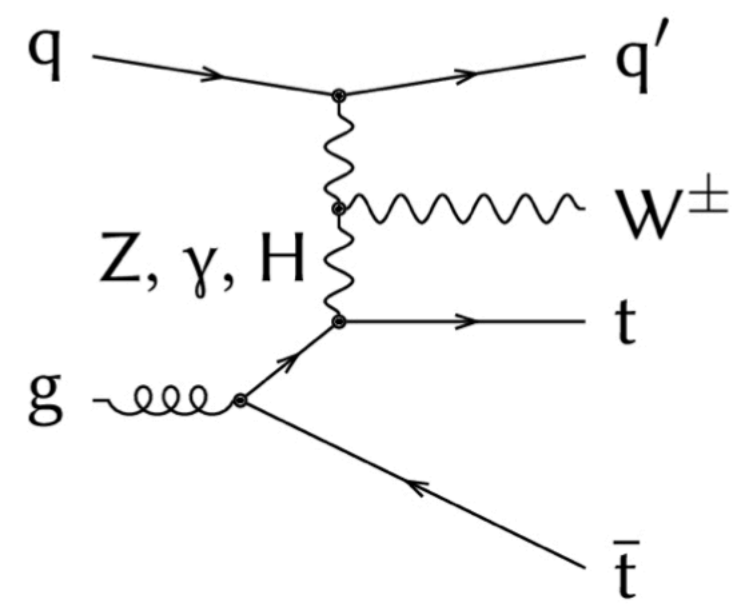
- m_W, m_{top} 171.77 ± 0.37 GeV, $\sin^2\theta_W$
- EW interactions at the TeV scale (DY, VV, VVV, VBS, VBF, Higgs, …)

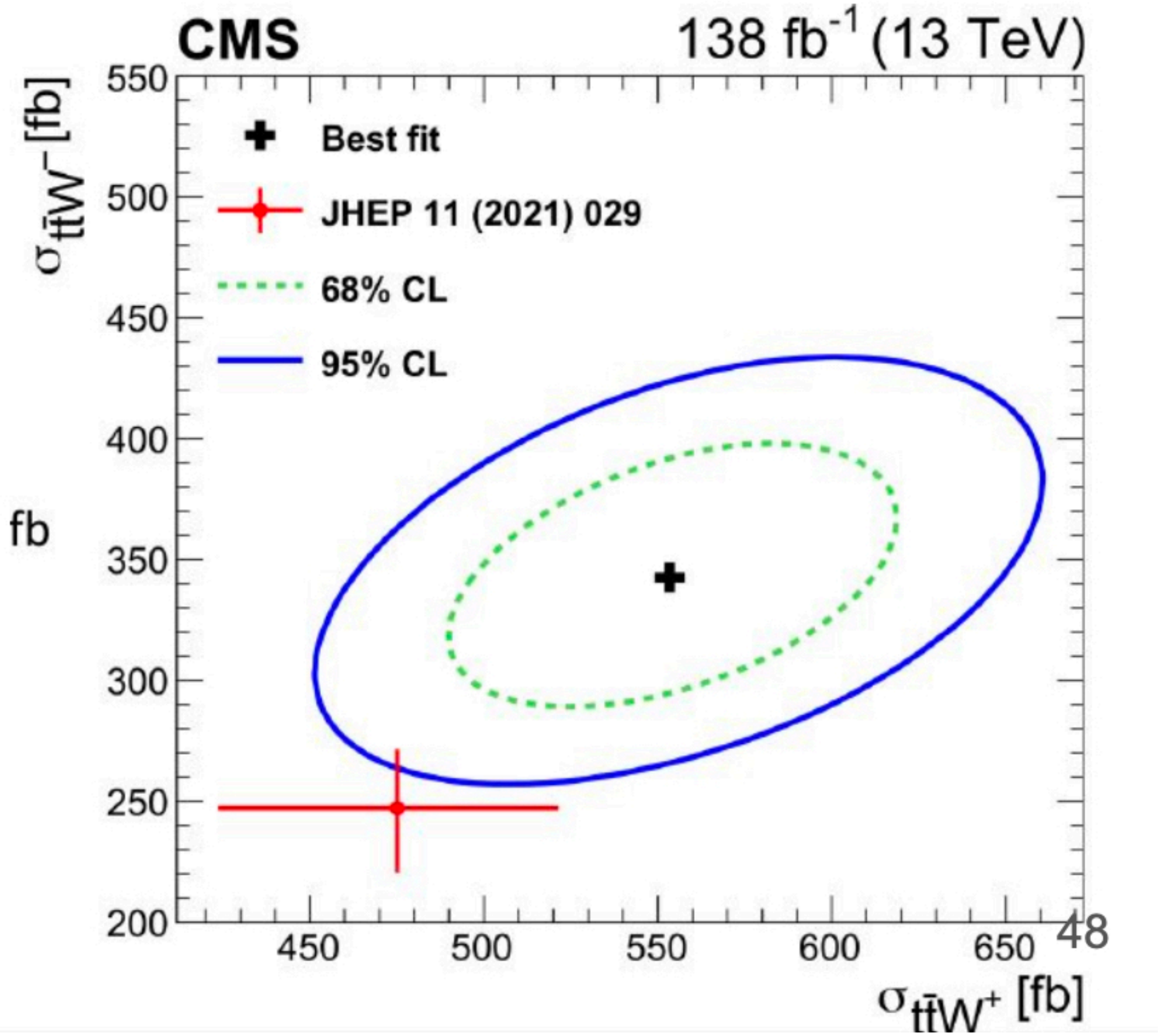


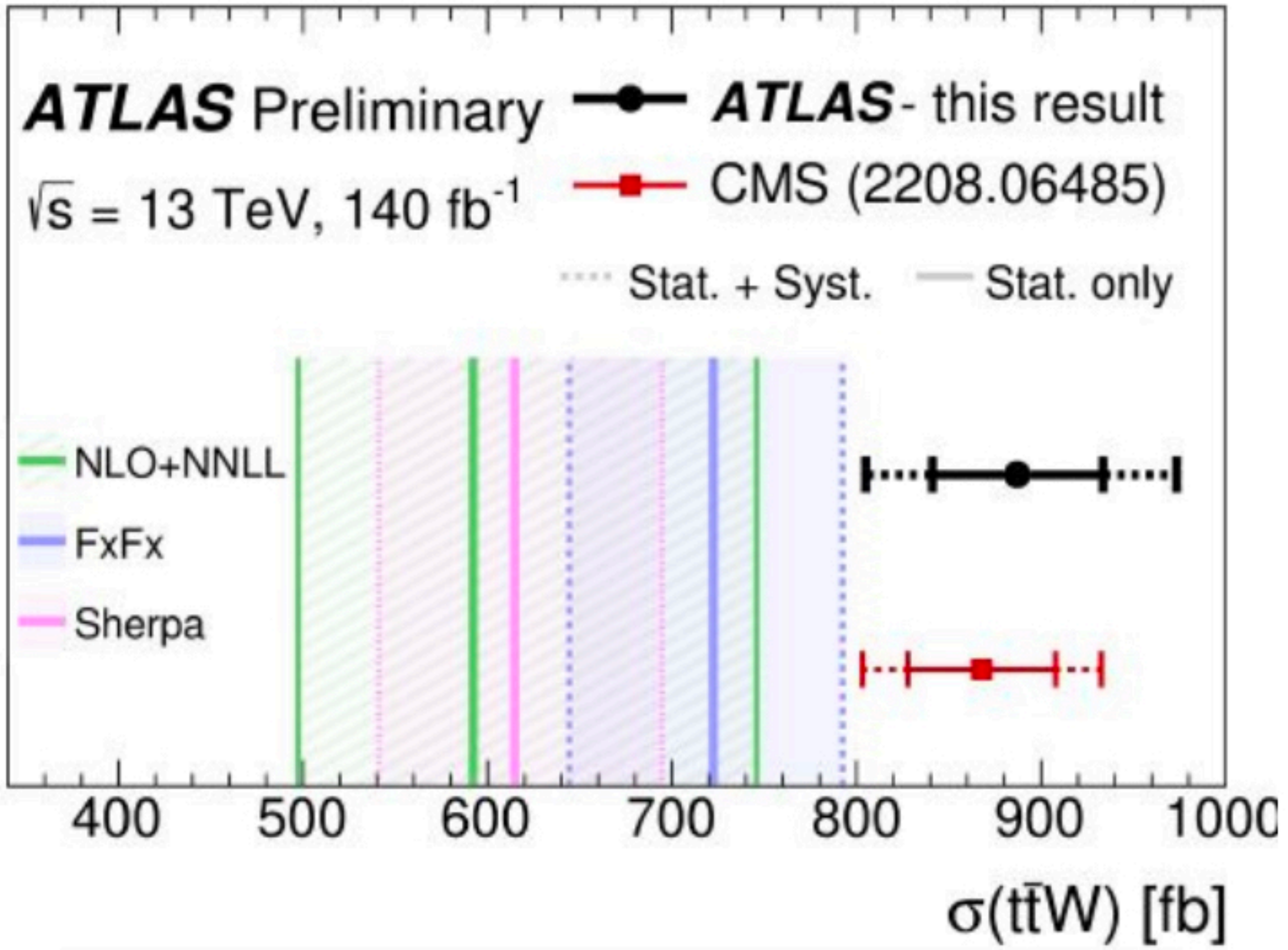
Excellent agreement between data and theoretical predictions, over 10 orders of magnitude, culminating 30 years of progress in higher-order perturbative calculations, which have now reached next-to-leading order as routine, NNLO as benchmark for most processes, and NNNLO available for only some (very important!) cases, but rapidly expanding beyond ==> see F.Caola's talk

Not everything is perfect though!
Ex: ttW cross section….





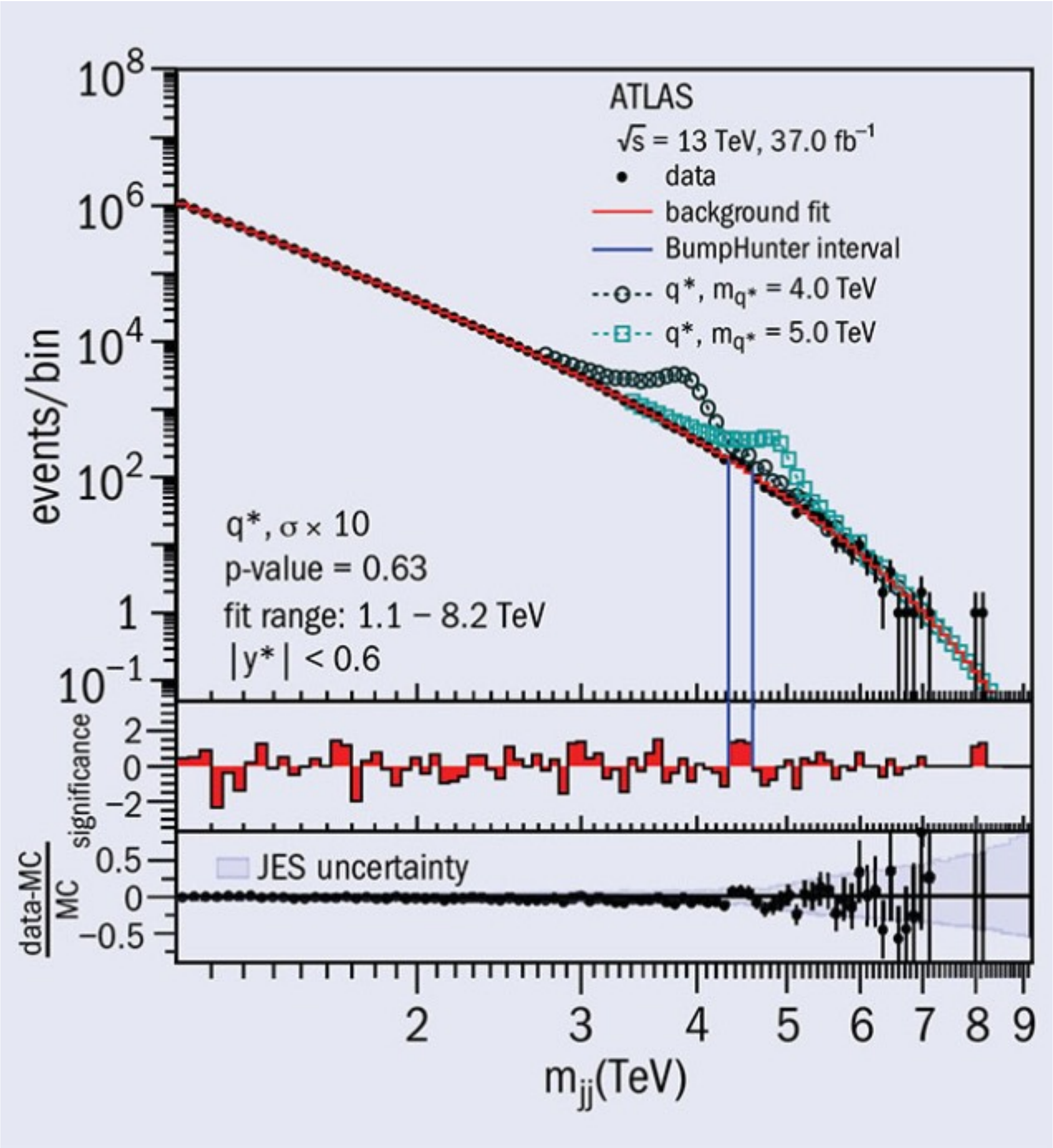


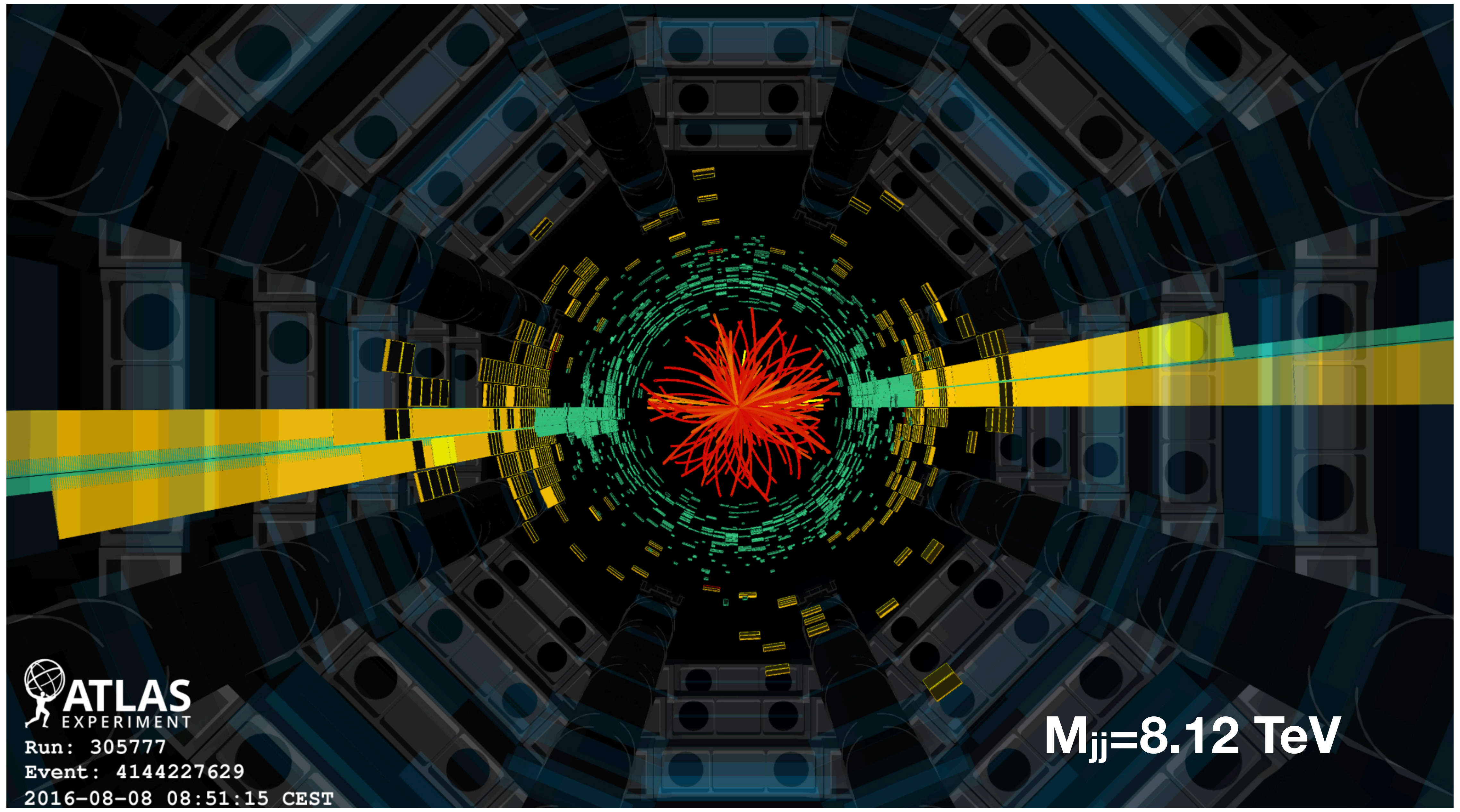


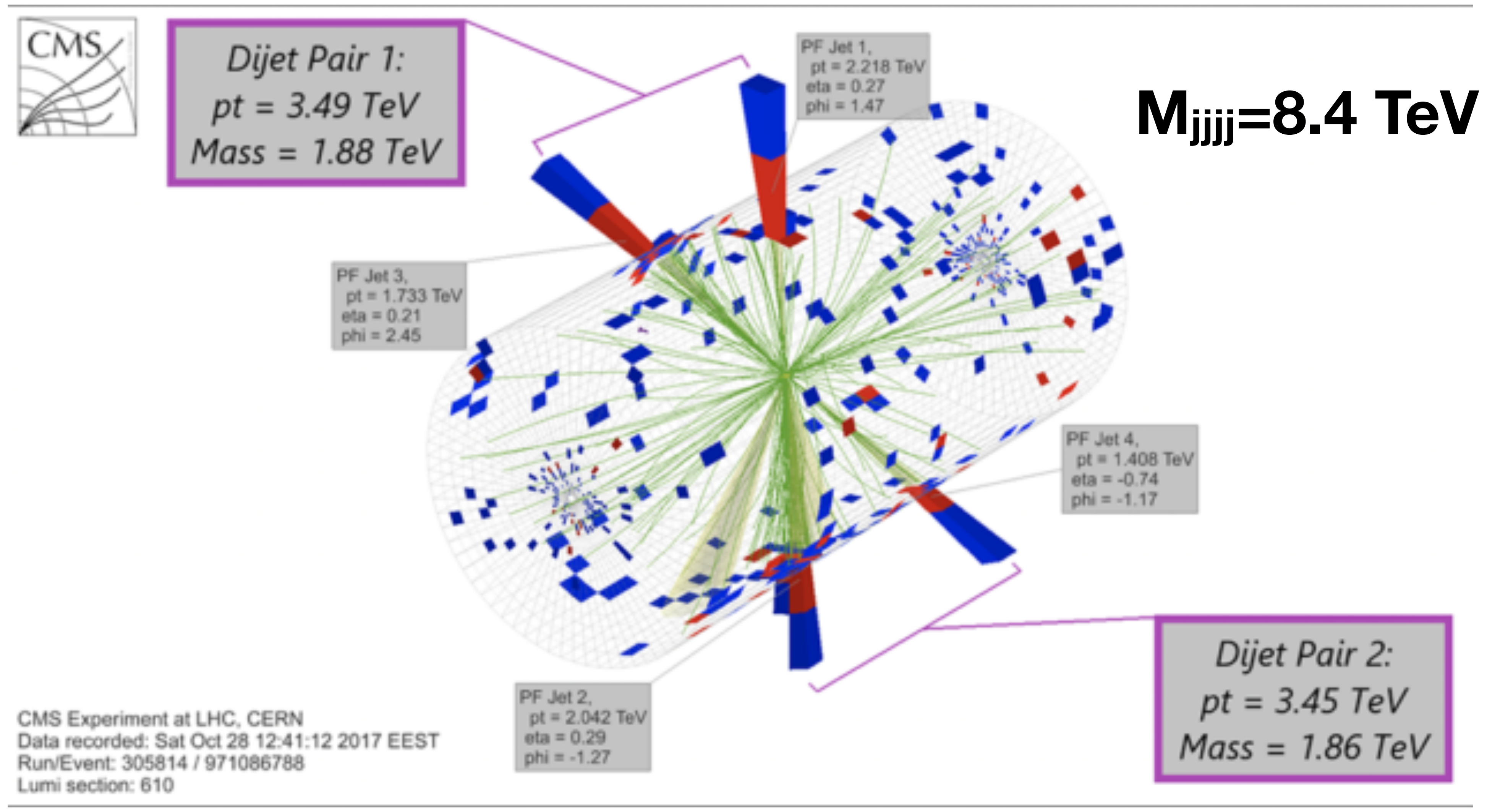
arXiv:2208.06485

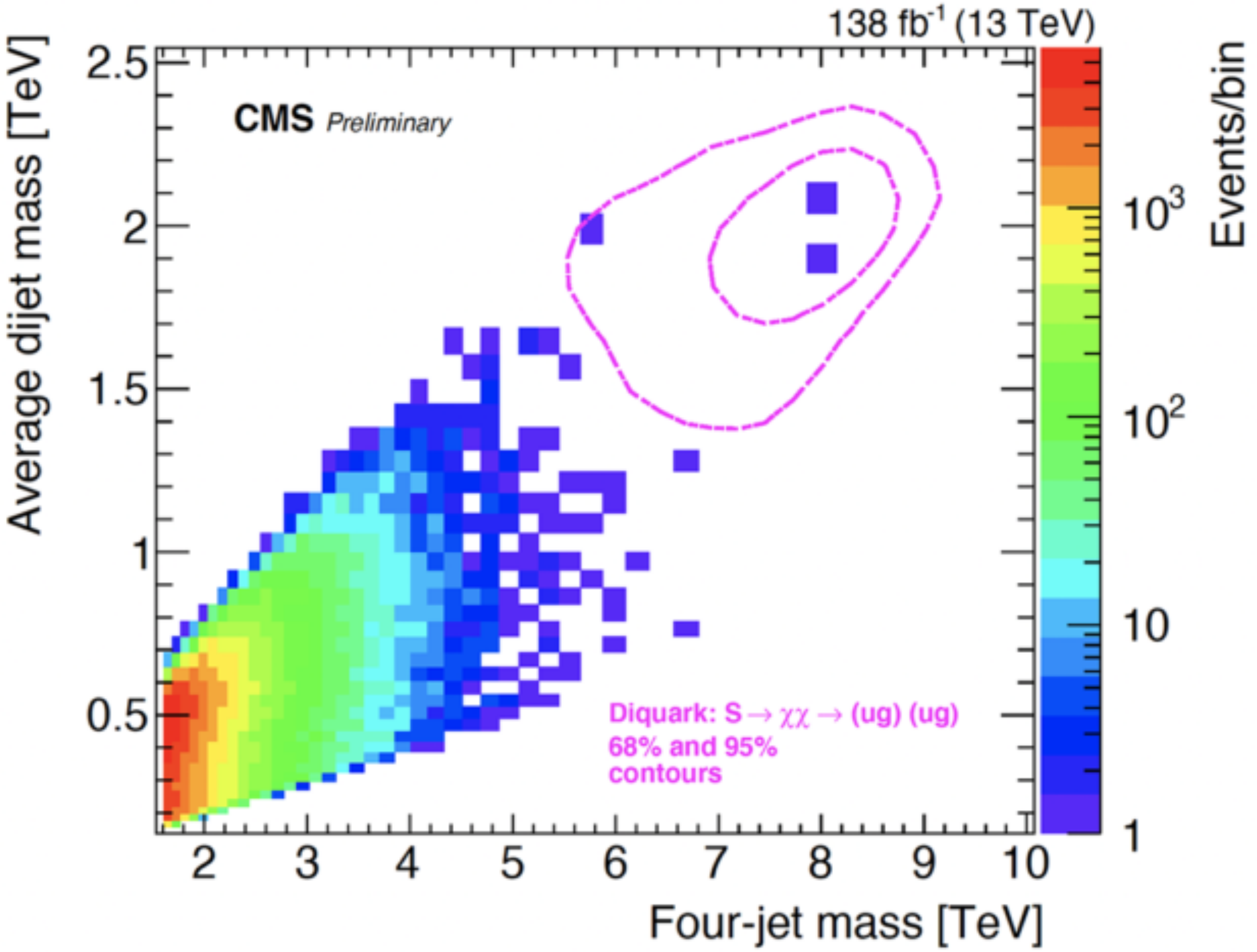
ATLAS-CONF-2023-019

Approaching the 10 TeV energy threshold





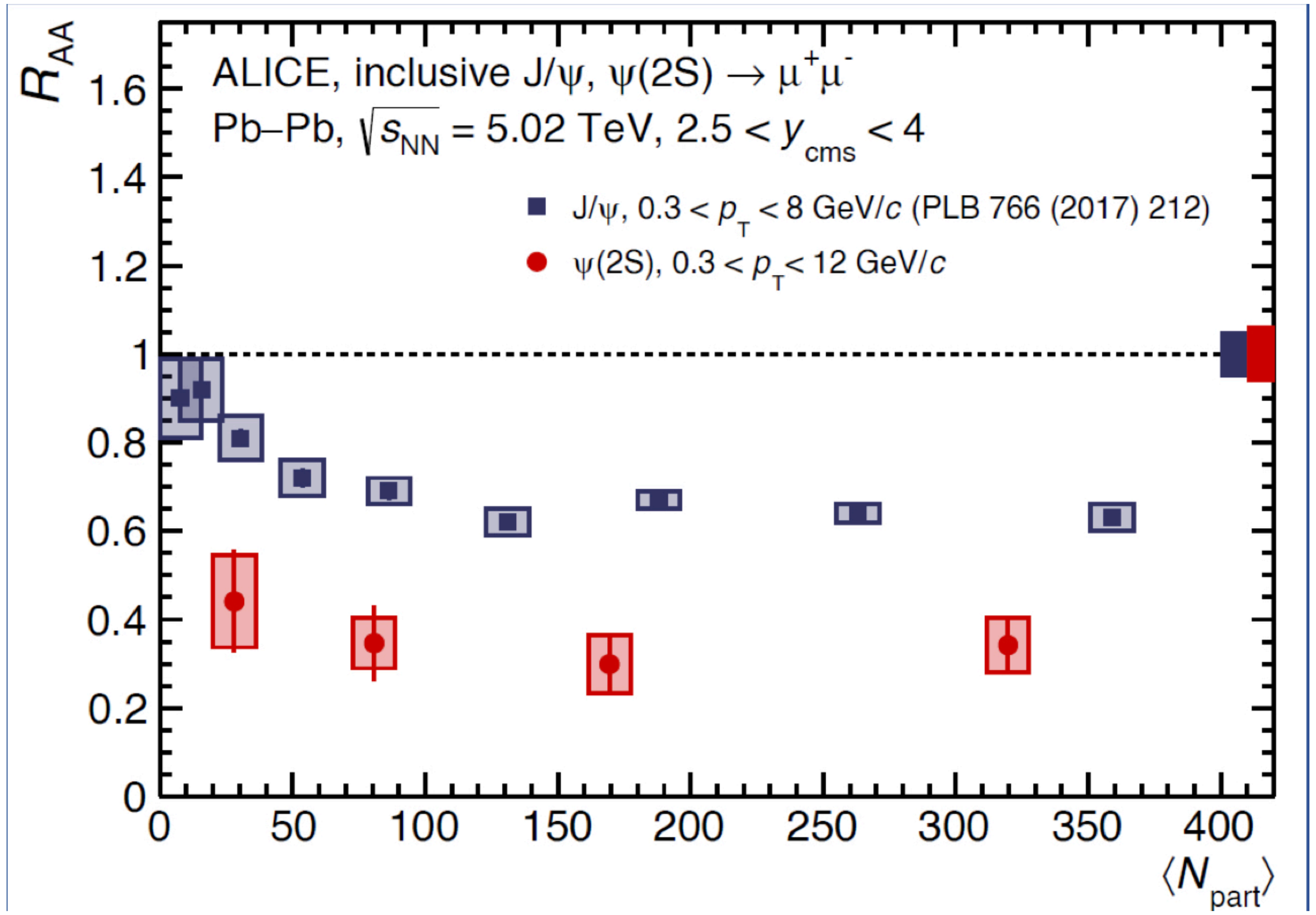




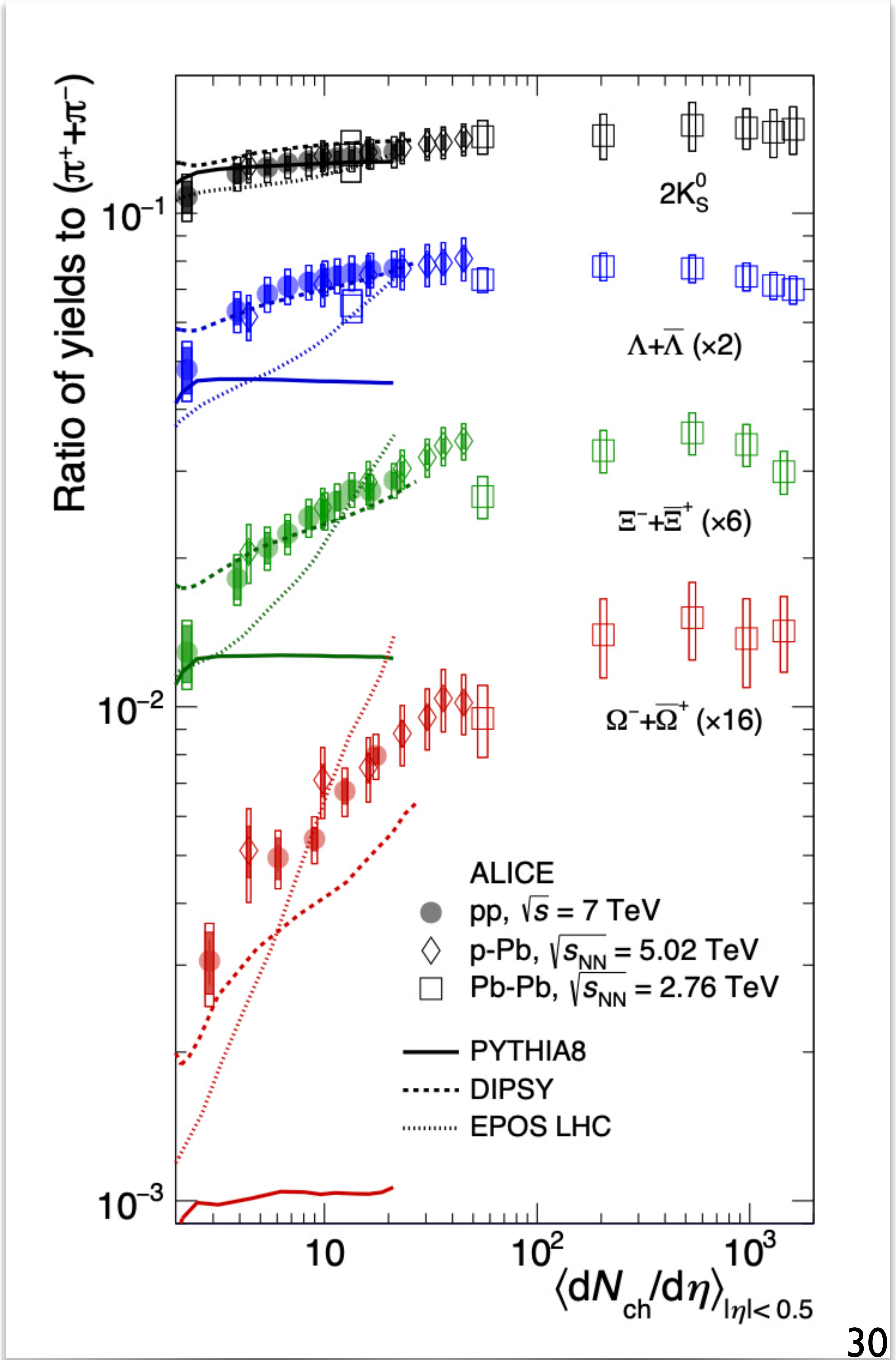
https://arxiv.org/abs/1911.03947

Collective QCD phenomena in high-T, high-density and other extreme environments

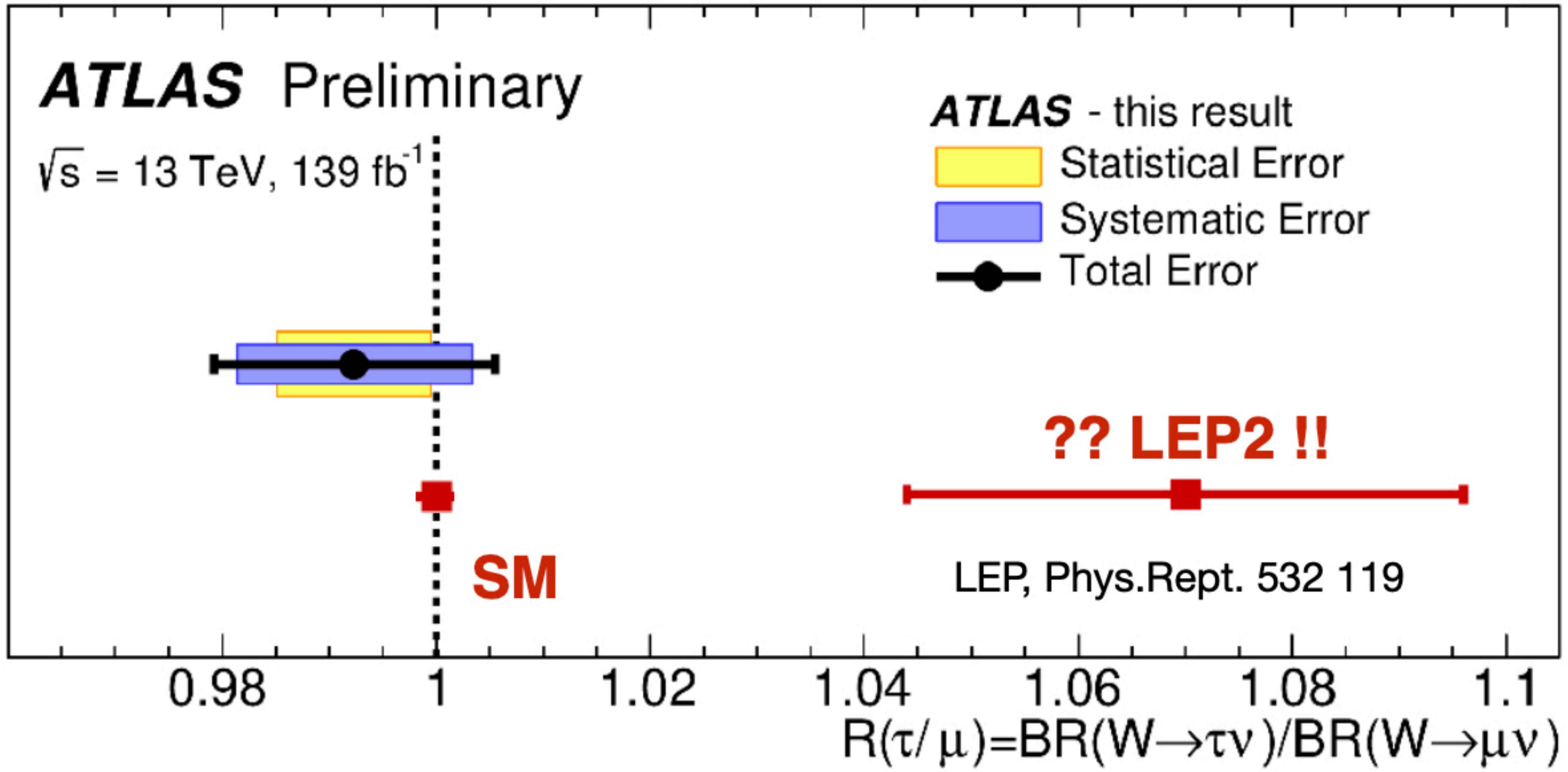
consolidation of known phenomena, with higher precision and broader coverage:
(ALICE, https://inspirehep.net/literature/2165947)



discovery of new dynamical behaviour, with collective phenomena typical of QGP appearing already in high-multiplicity final states of pp and pA

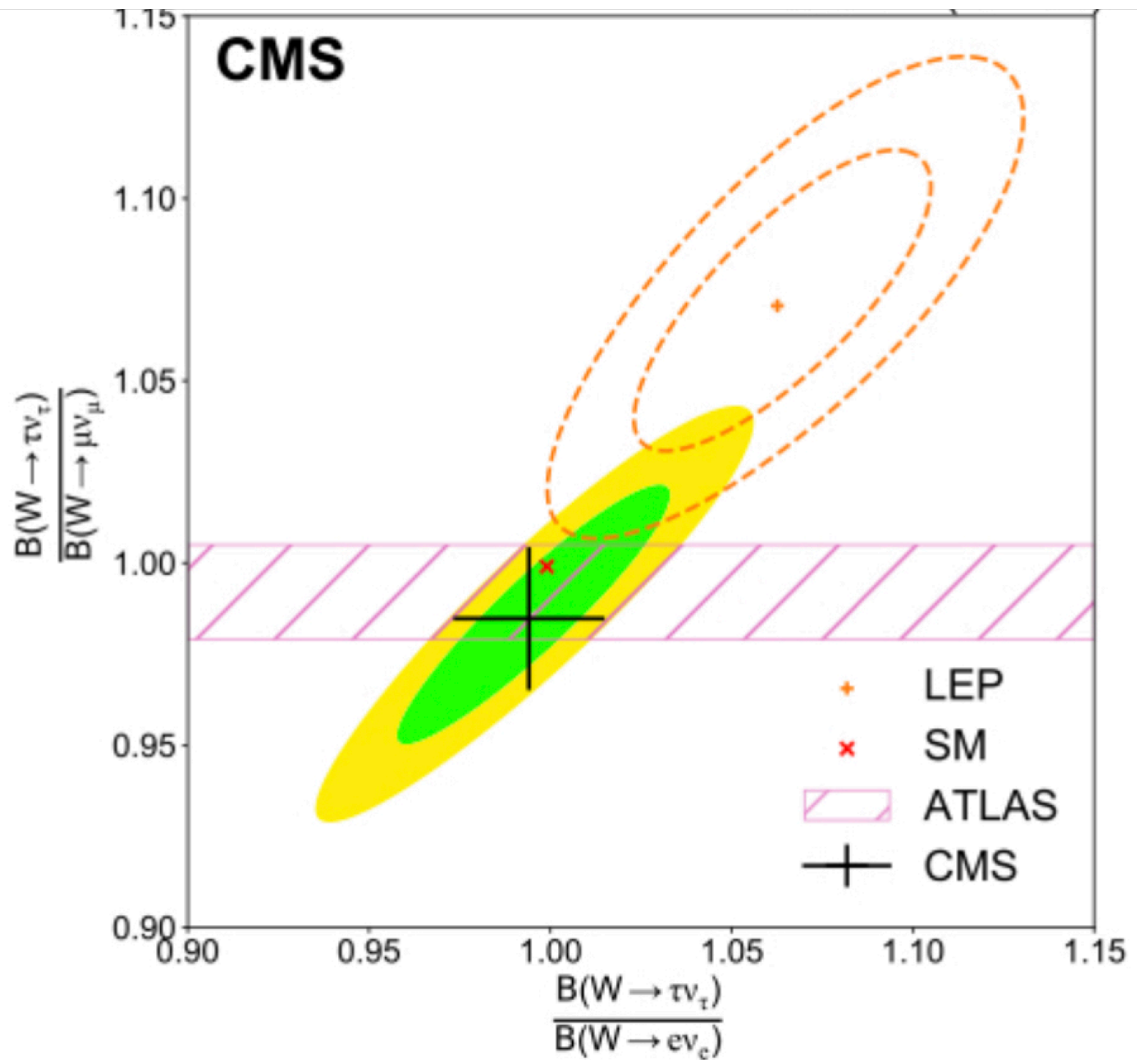


Exploring lepton universality of W couplings

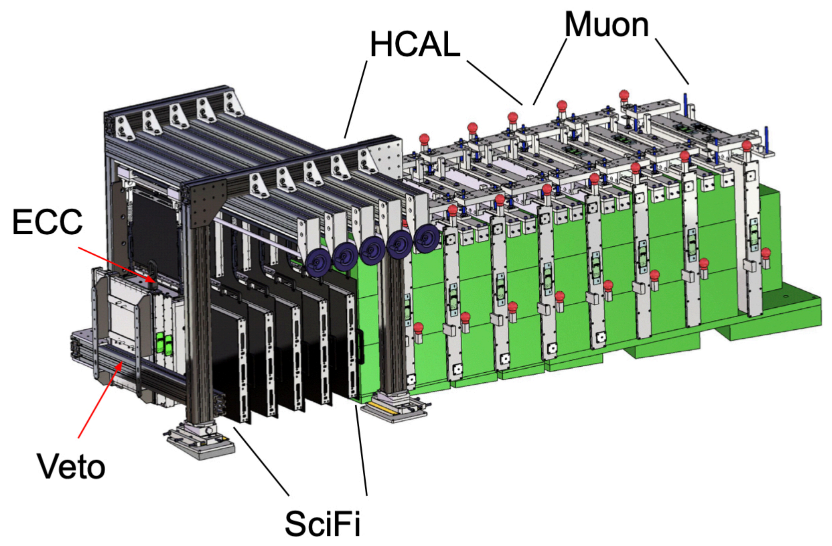


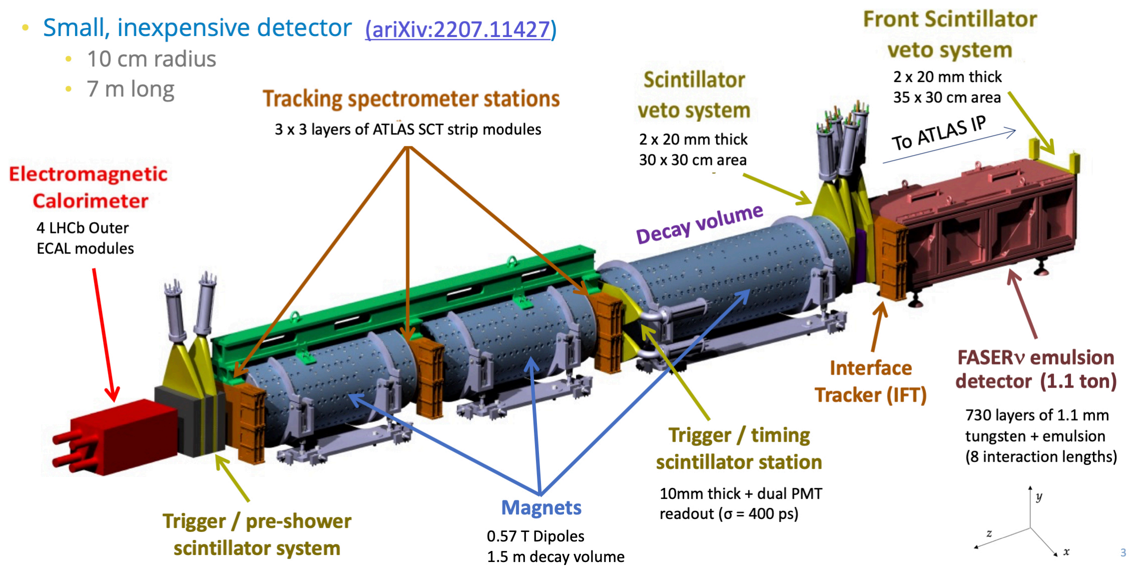
LEP:
***BR*(W→τν)/*BR*(W→μν) = 1.066 ± 0.025**

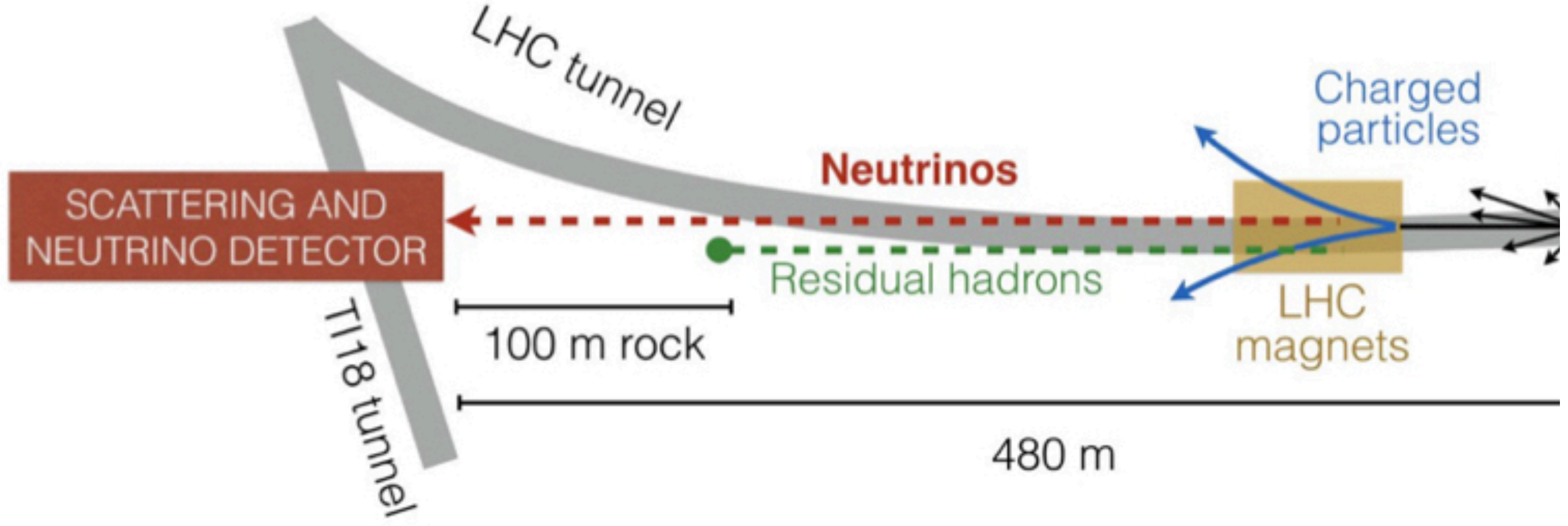
ATLAS:
***BR*(W→τν)/*BR*(W→μν) = 0.992 ± 0.013**

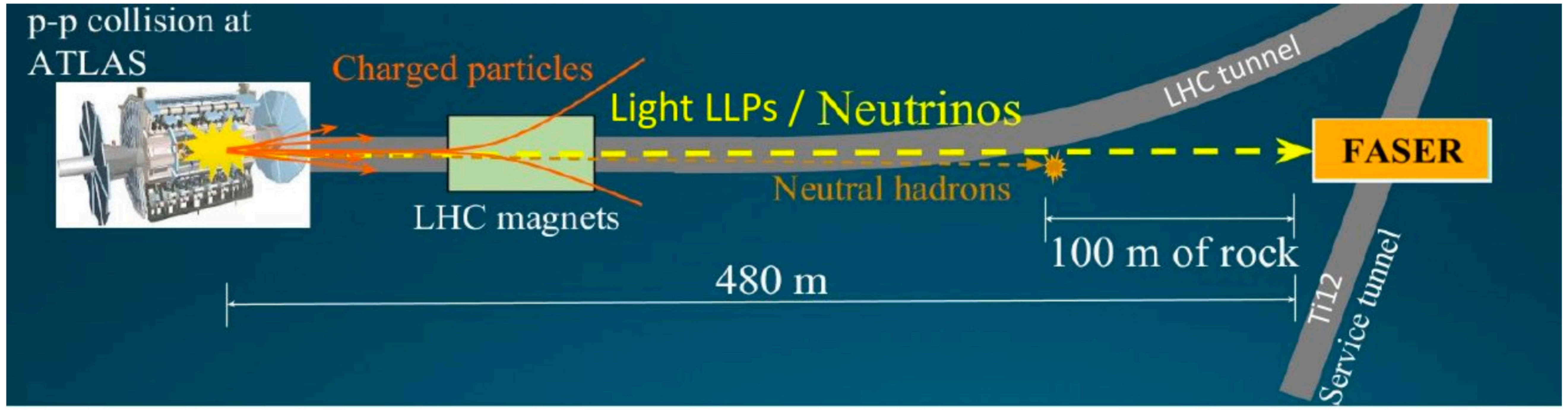


Neutrinos and LLPs: FASER & SND@LHC

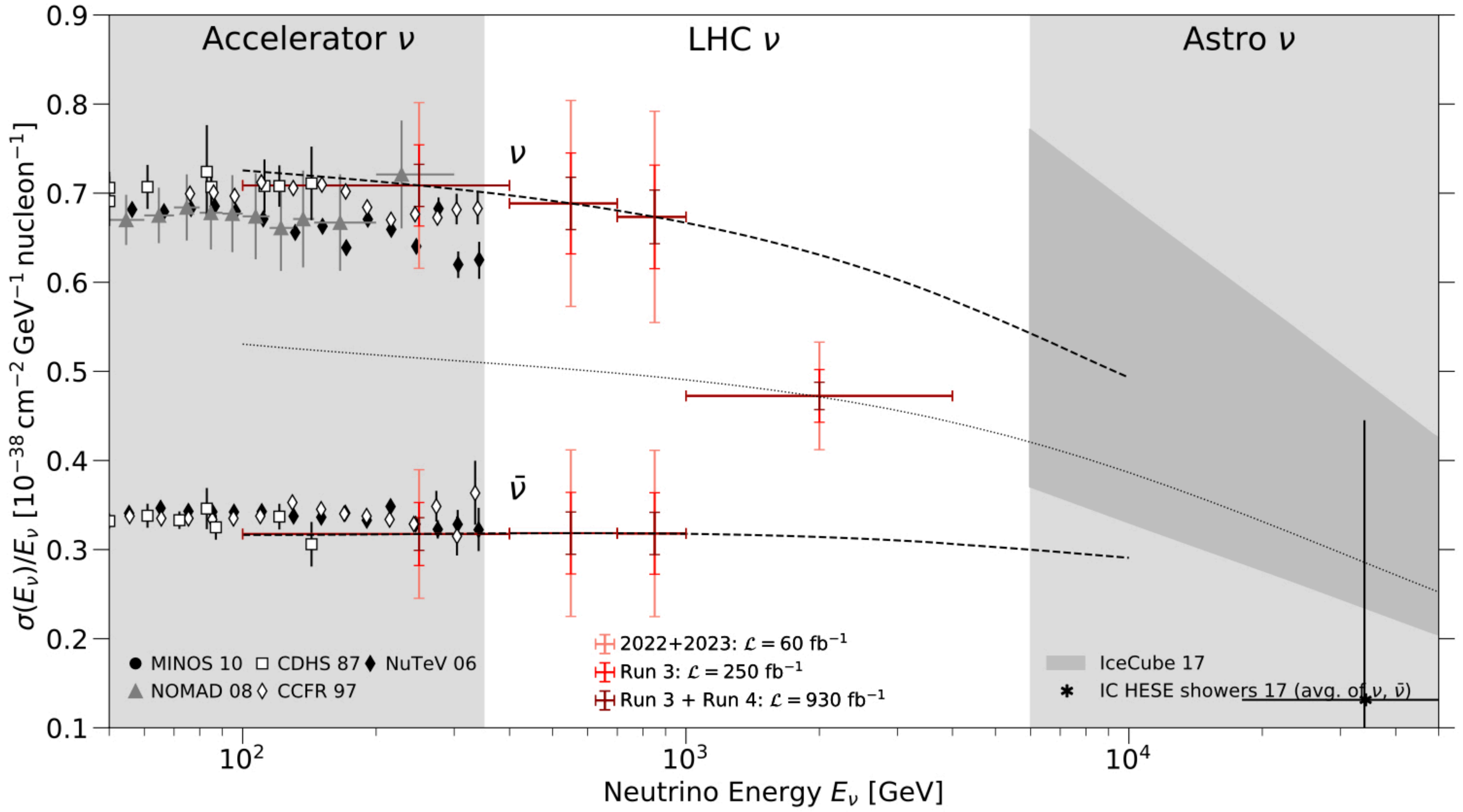




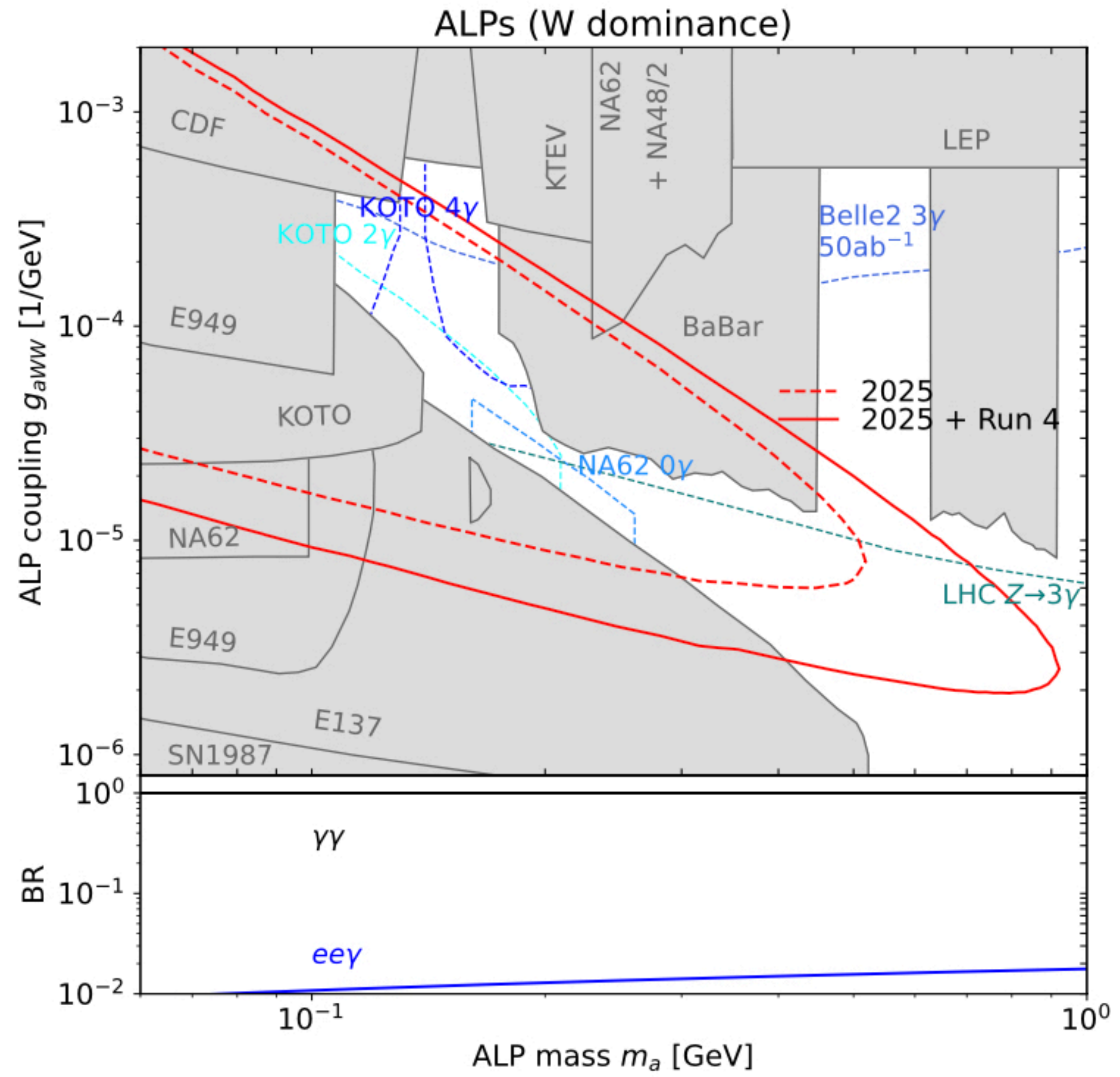


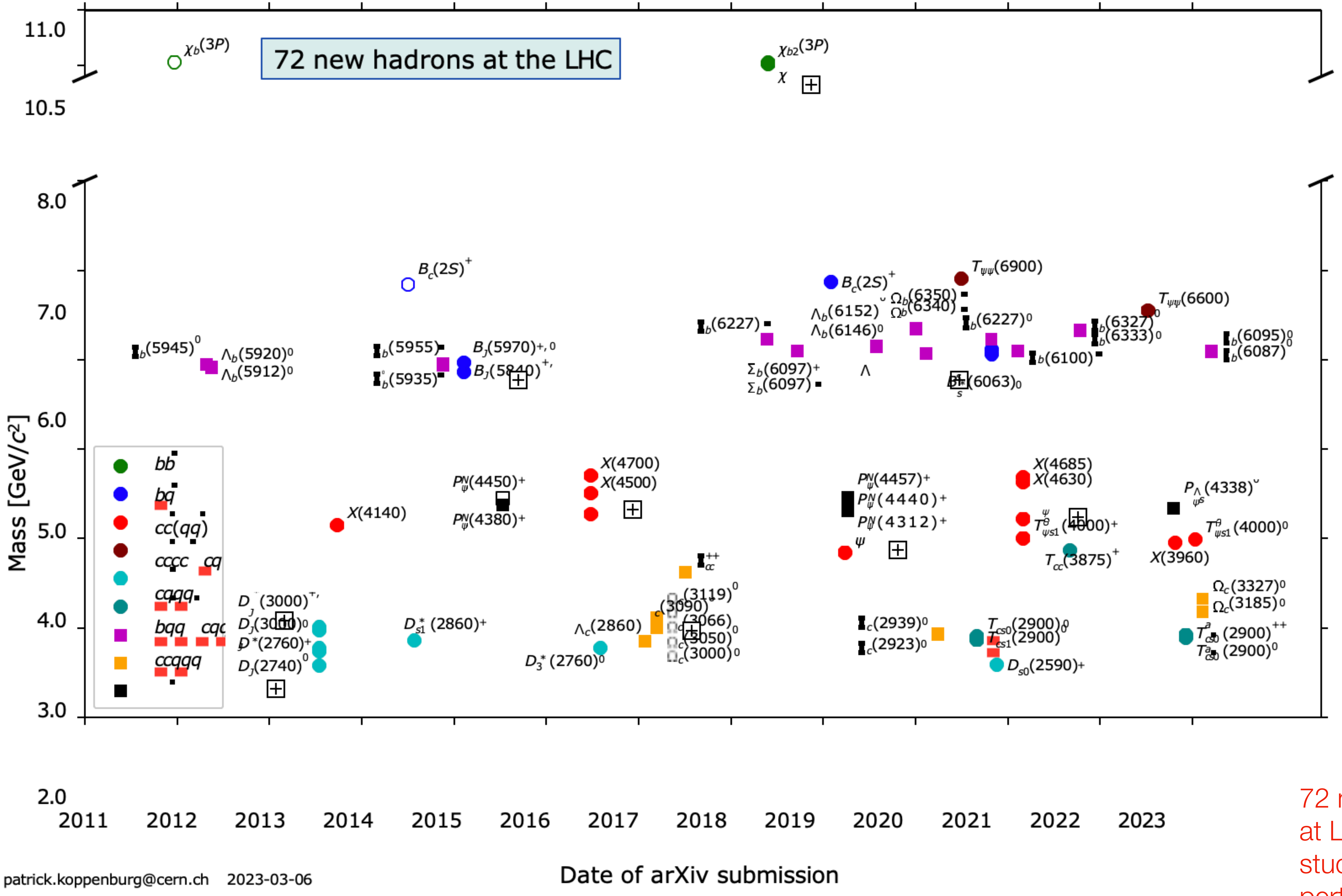


Measure ν cross sections in previously unchartered energy ranges



Explore BSM in unconstrained regions

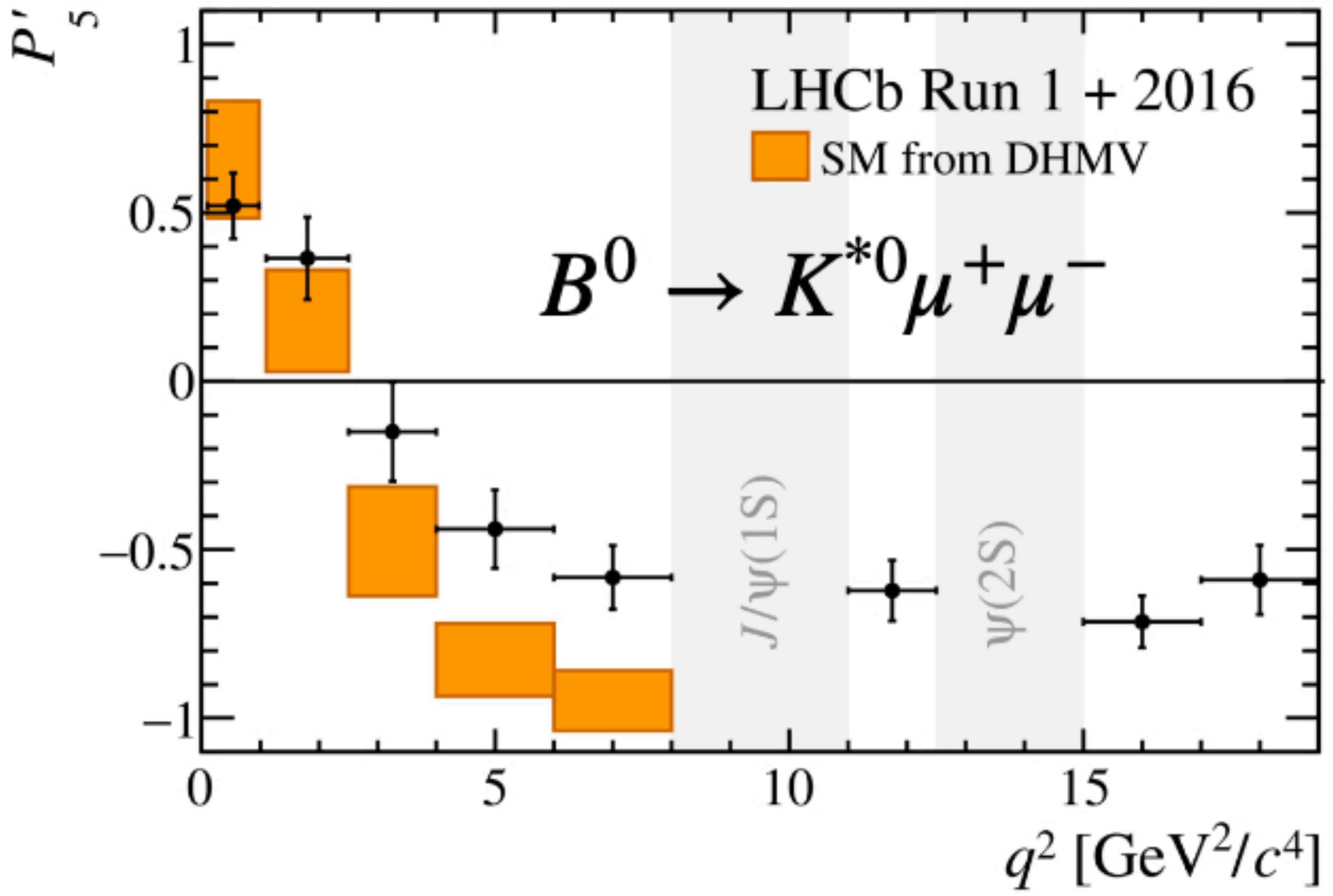




72 new hadrons discovered at LHC, opening a new era of studies of QCD non-perturbative dynamics

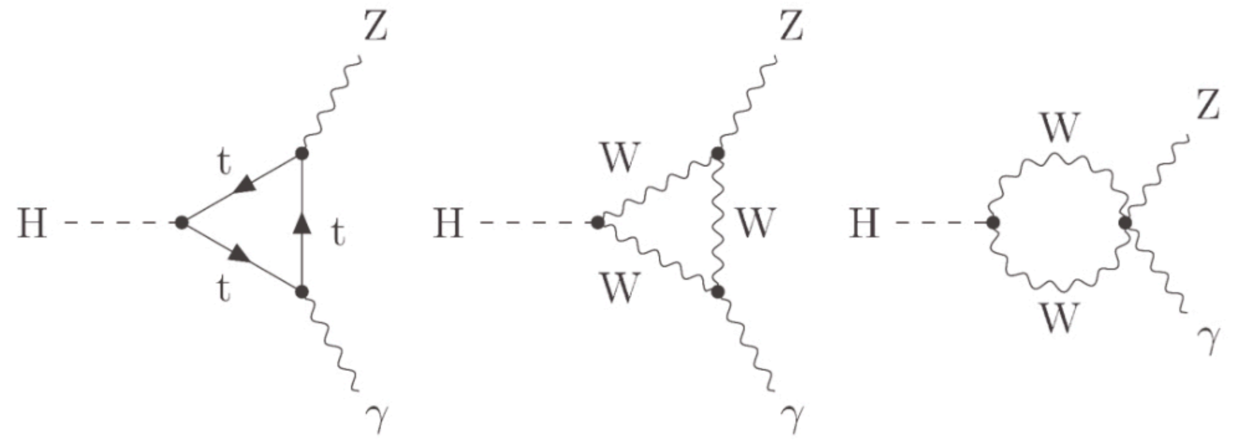
Hints of SM anomalies …

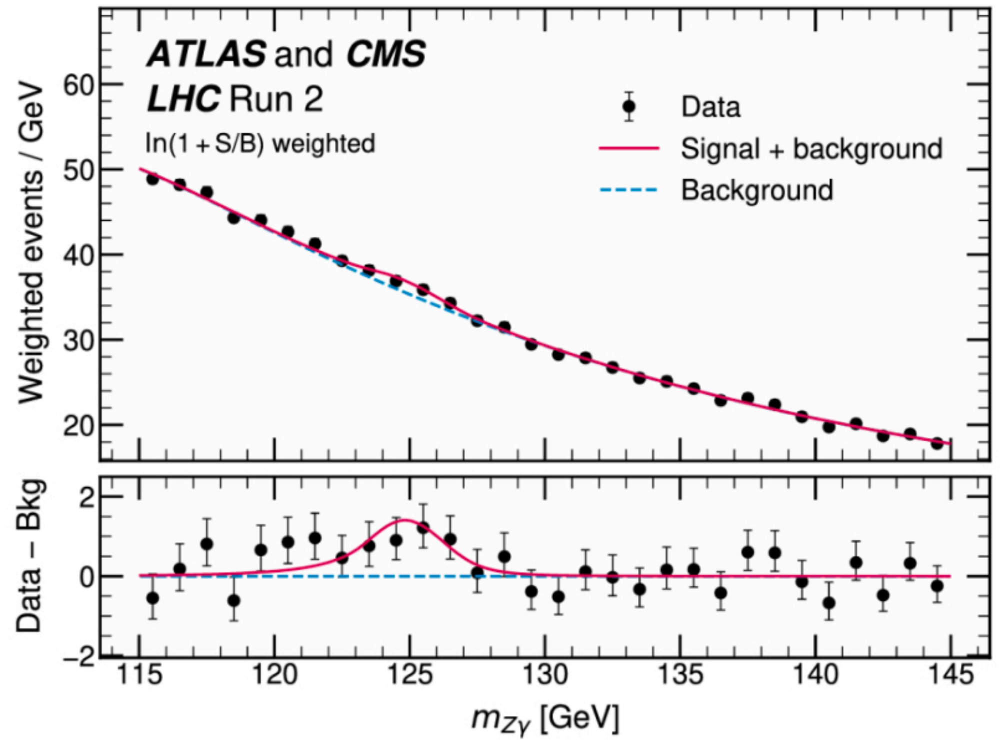
Anomaly in the $\mu^+\mu^-$ mass spectrum corroborated by further $b \to s\mu\mu$ channels such as $B_S \to \phi\mu\mu$



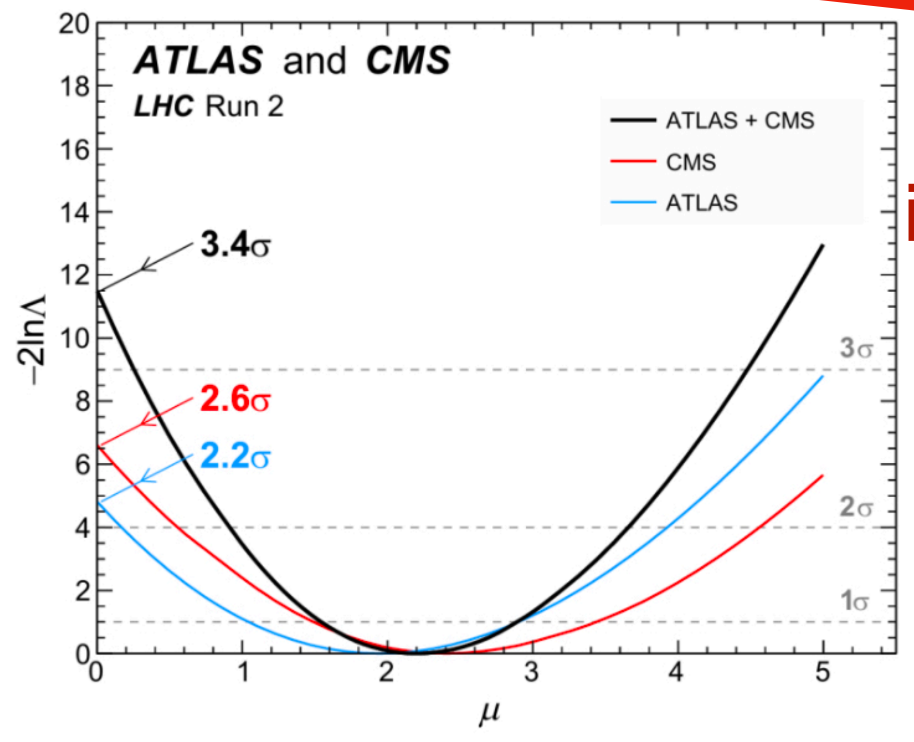
Higgs decays into $Z\gamma$

- $H \to Z\gamma$ decay has a small branching ratio (1.5×10^{-3}) in the Standard Model.
- Many BSM scenarios increase the branching ratio.
- ATLAS and CMS searched for $H \to Z\gamma$ where the Z decays into electrons or muons. Results combined.
  - observed event yield: 2.2 ± 0.7 times SM prediction
  - observed (expected) local significance: 3.4σ (1.6σ)



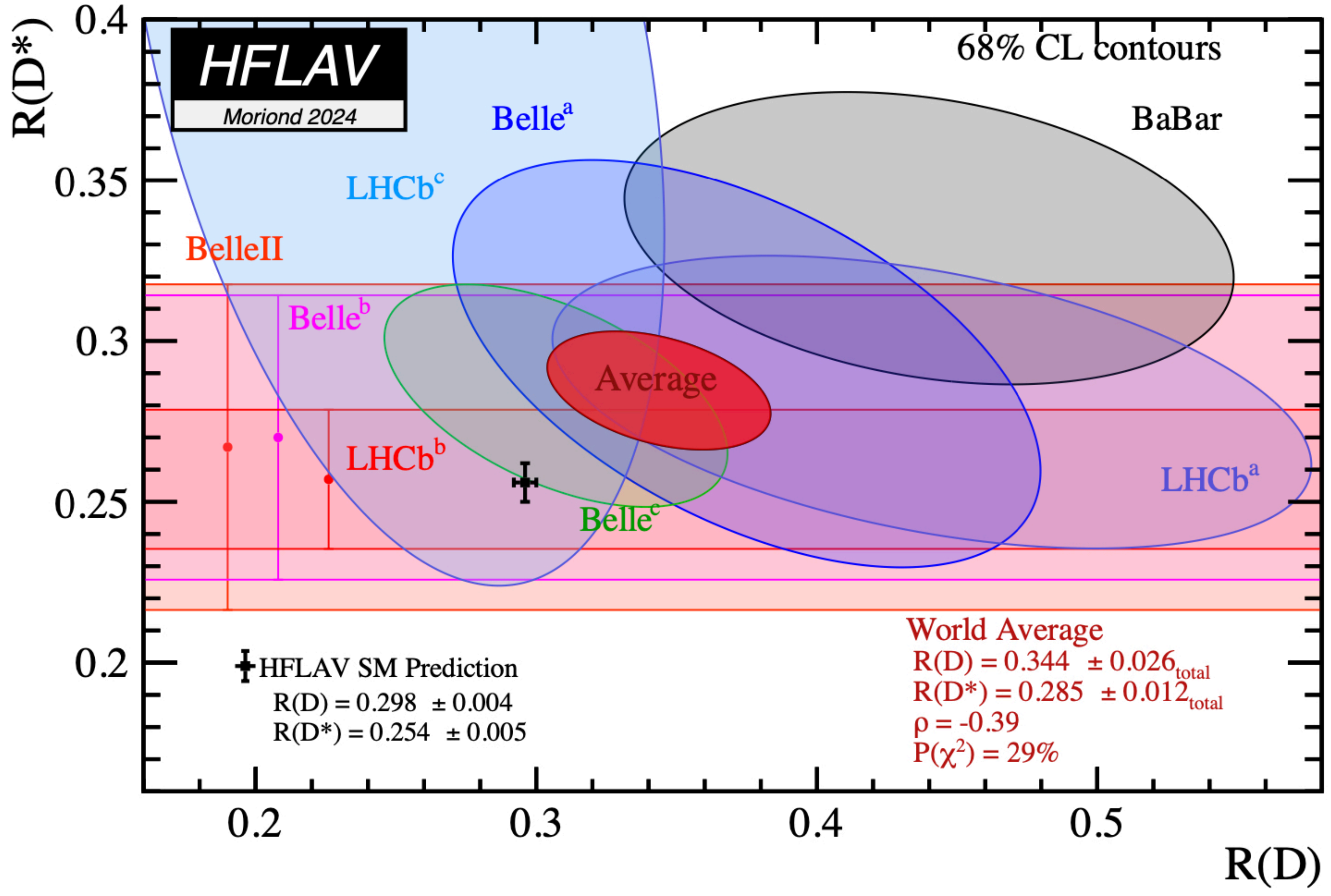


PhysRevLett.132.021803



PhysRevLett.132.021803

if this is real, HL-LHC will fully confirm it

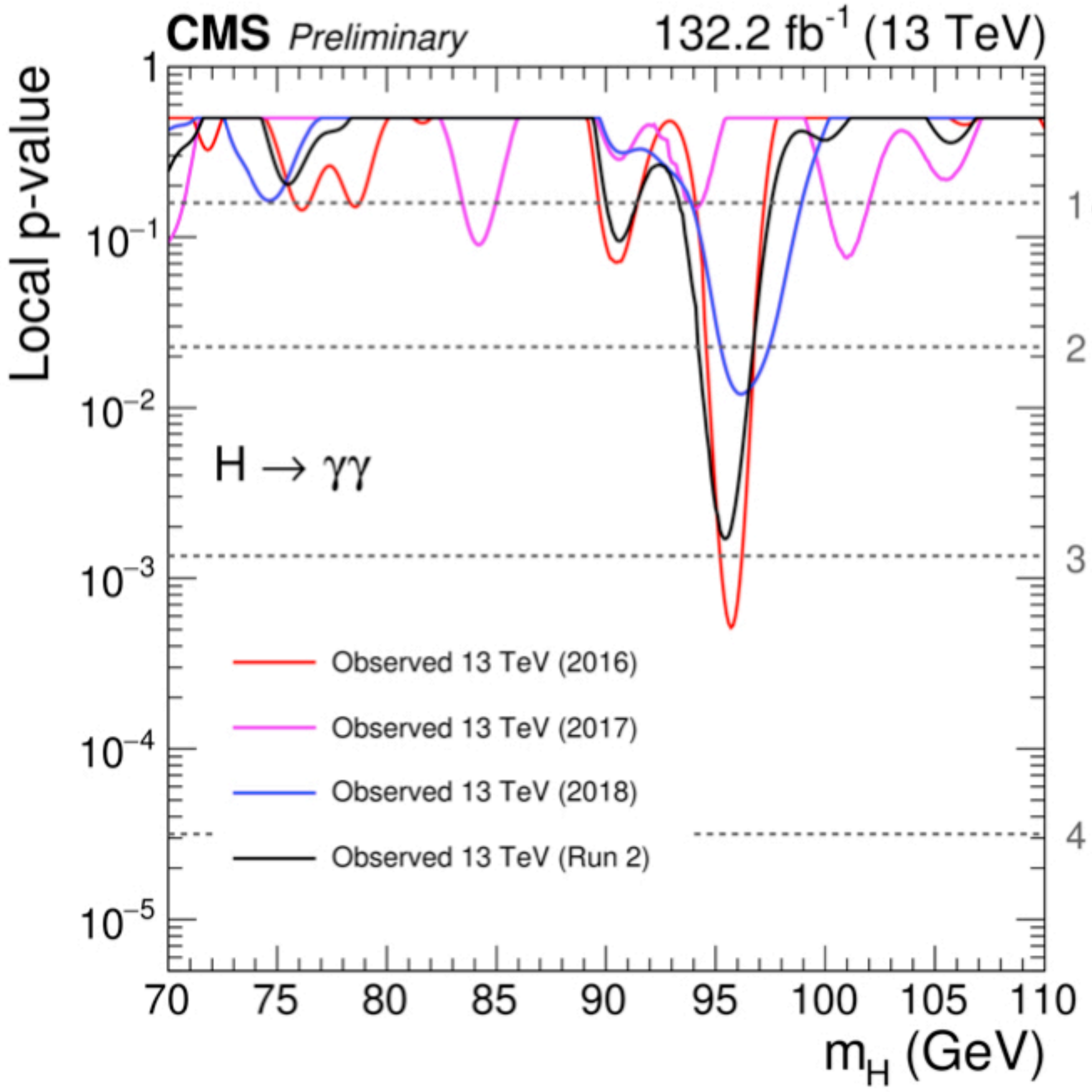


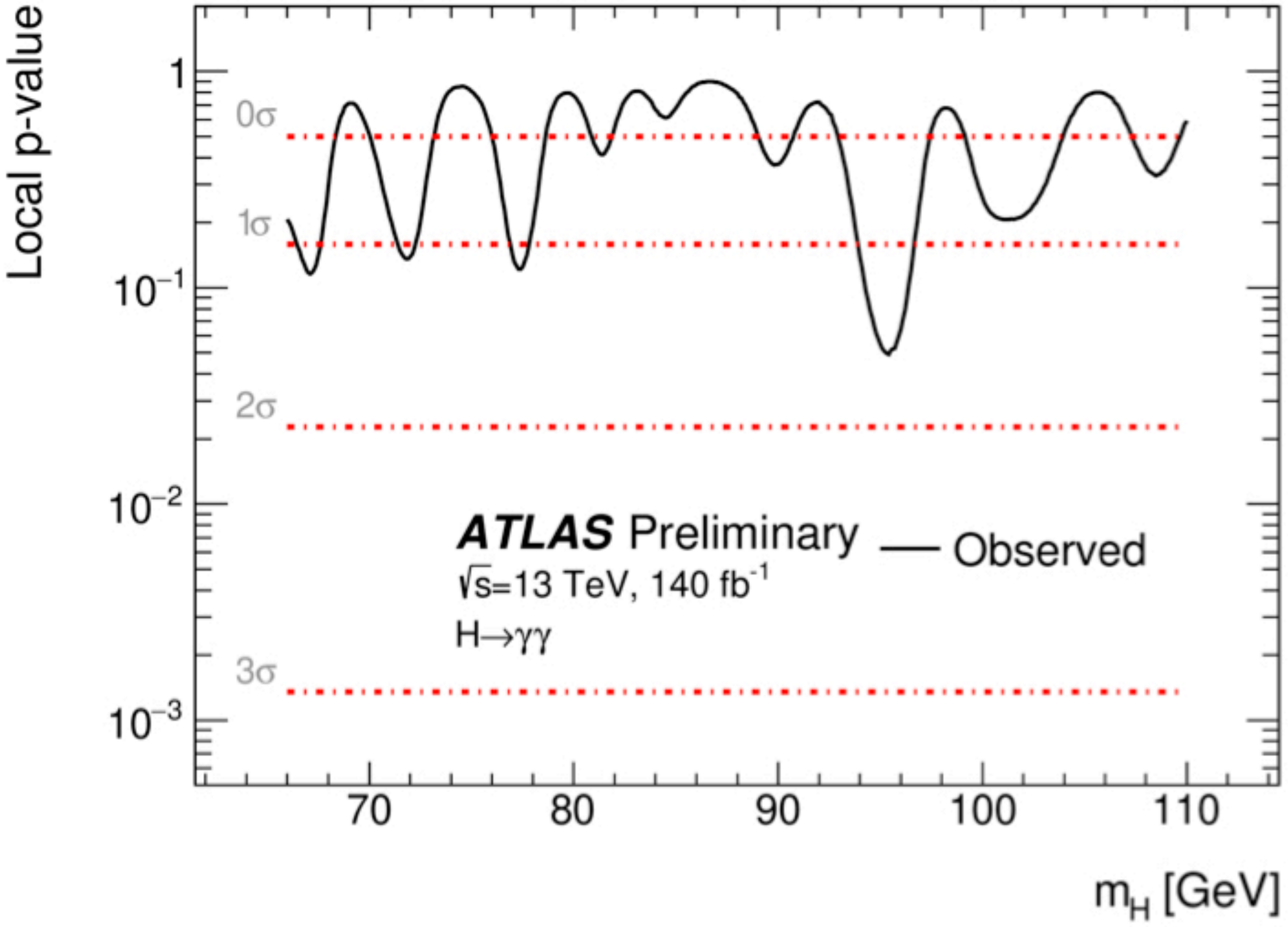
3.2 σ tension

HFLAV

Search for low-mass γγ (Higgs-like) resonances: from Run 2 excesses at ~m=95.4 GeV in both experiments …

CMS-PAS-HIG-20-002





Final words

- Understanding the origin of the Higgs and EWSB is a key task, which only colliders — to the best or our current knowledge — can undertake

- Firm and unambiguous exptl evidence of SM deviations in particle physics experiments are needed to define credible BSM scenarios around which to develop interpretations and plans for future colliders.

- Until then, reliance on precision, sensitivity and higher energy are the best means to extend our exploration

- The diverse collider phenomenology —particularly the hadronic one —probes a huge dynamical range of phenomena, challenging the theoretical understanding, both at the level of fundamental understanding and of computational complexity.

- The goal of measuring and theoretically describing “ SM data “ goes hand in hand with the search for BSM physics, whether directly or via precision SM tests.

It provides the motivational challenge and the intellectual reward to ensure the continued progress of collider physics for the next decades