Beyond the Standard Model Searches at Colliders

Katharine Leney
Southern Methodist University, Dallas, Texas, US

24th May 2022

Outline

Today: Why and how we look for BSM physics

- Why are we looking beyond the Standard Model?
- How do we search for new physics?
- Anomaly-driven searches.

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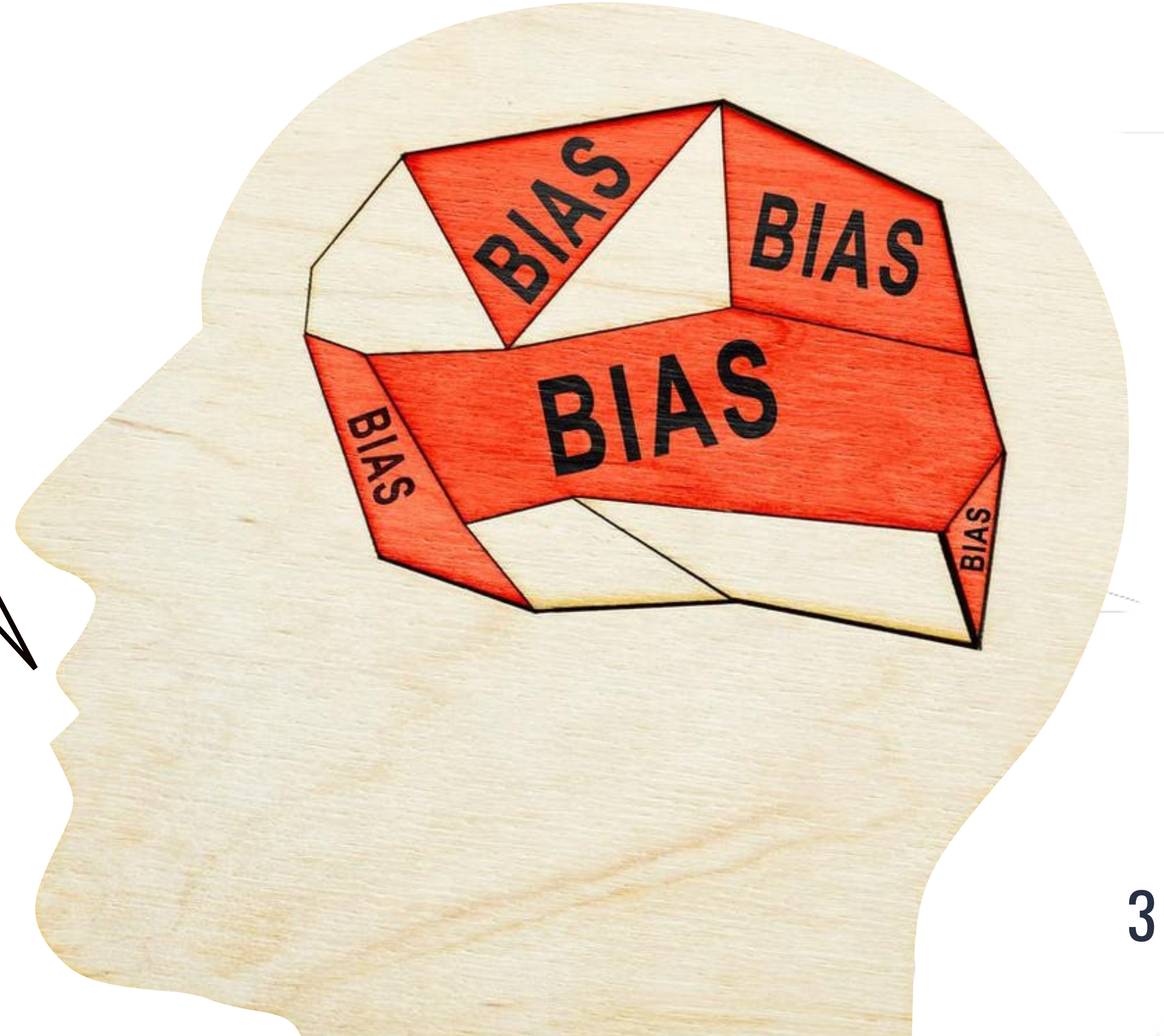
There is also a lot of personal bias in this talk! Due to the limited time I have chosen to focus more on areas I personally find interesting (and/or have expertise in).



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- Why are we looking beyond the Standard Model?
- How do we search for new physics?
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Tomorrow: New physics in the scalar sector

- Additional Higgs bosons.
- Using the Standard Model Higgs boson as a tool to search for new physics.
  - Exotic decays of the Higgs boson
  - Higgs self-coupling as a probe of new physics.

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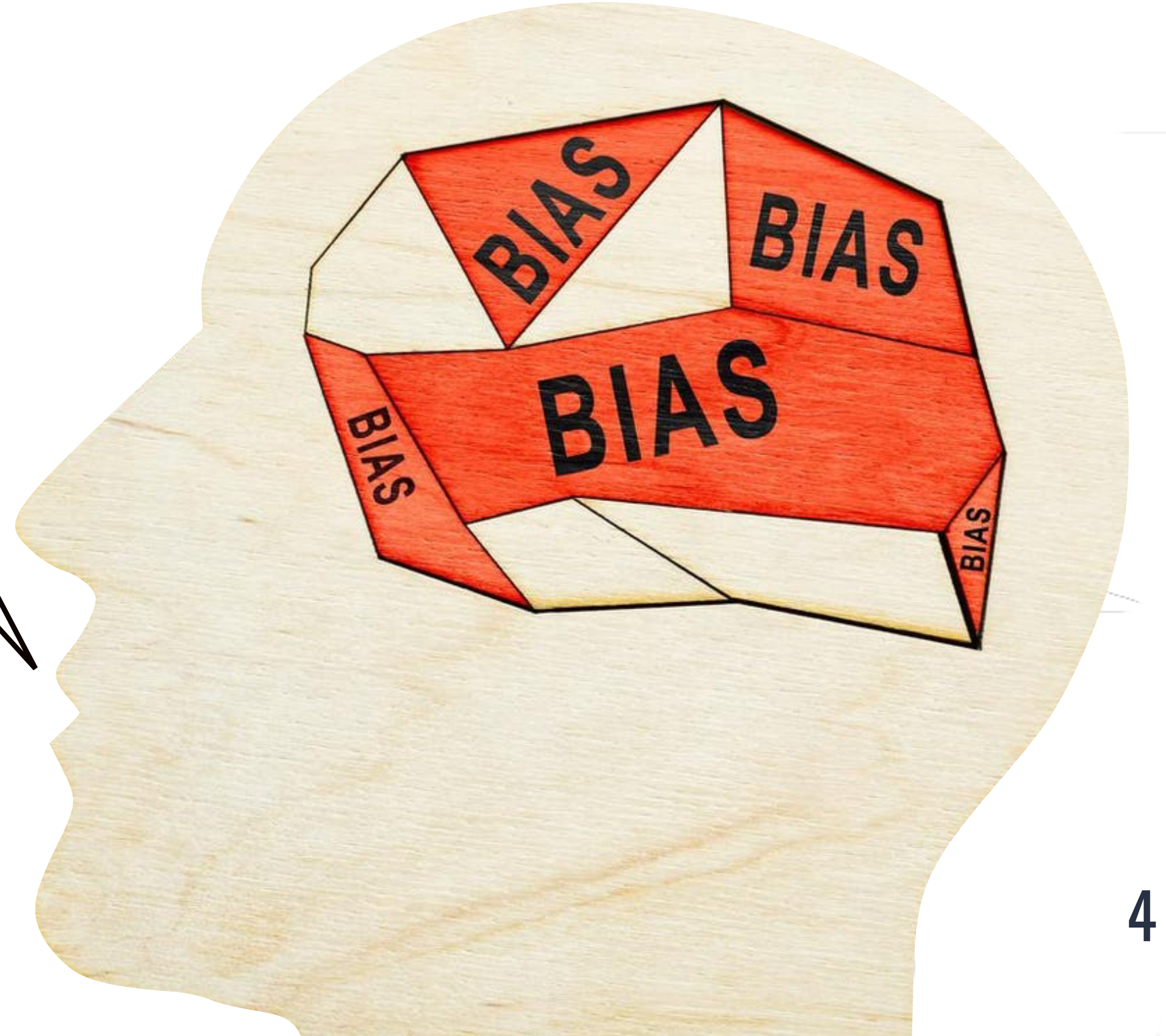
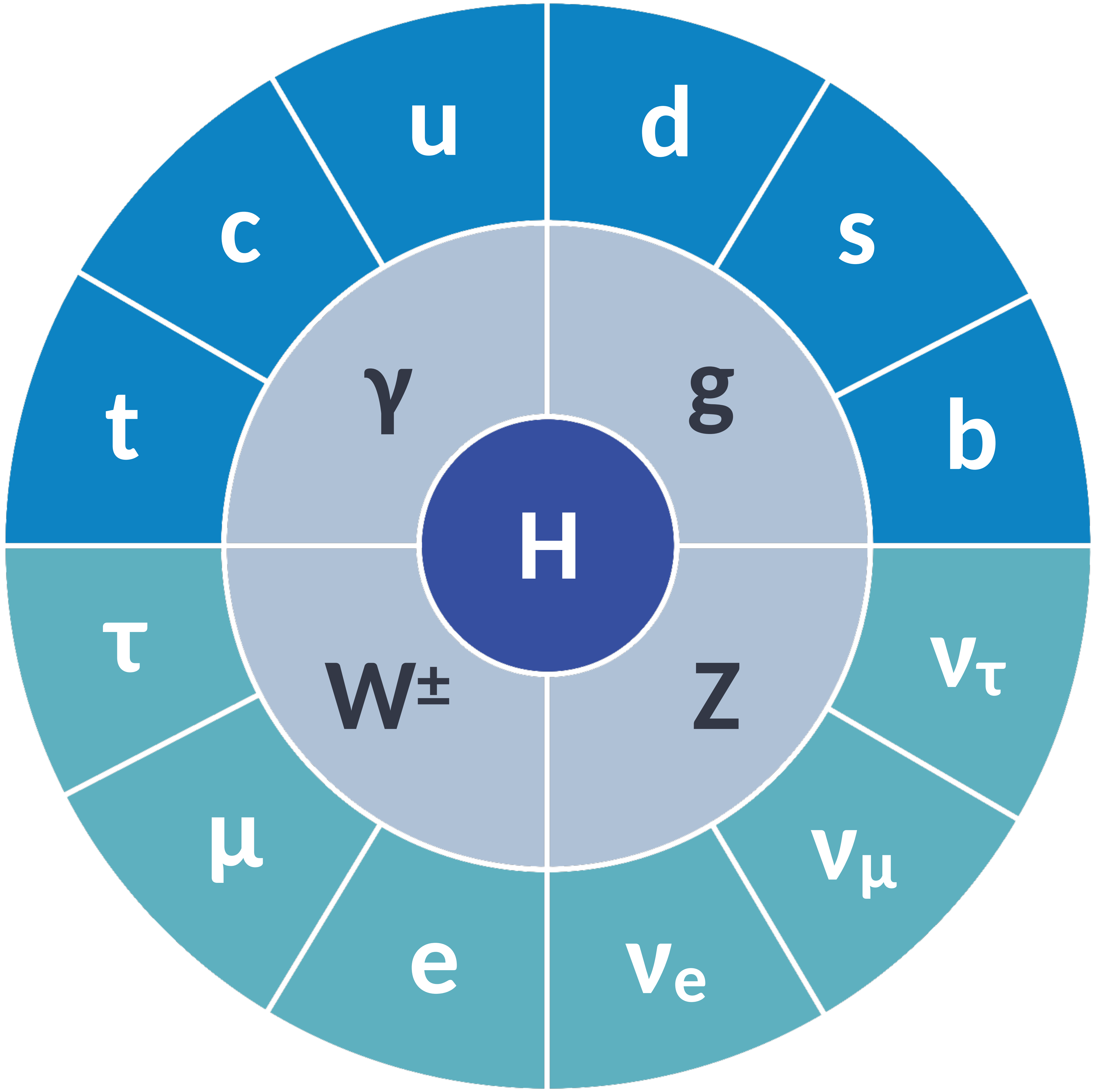
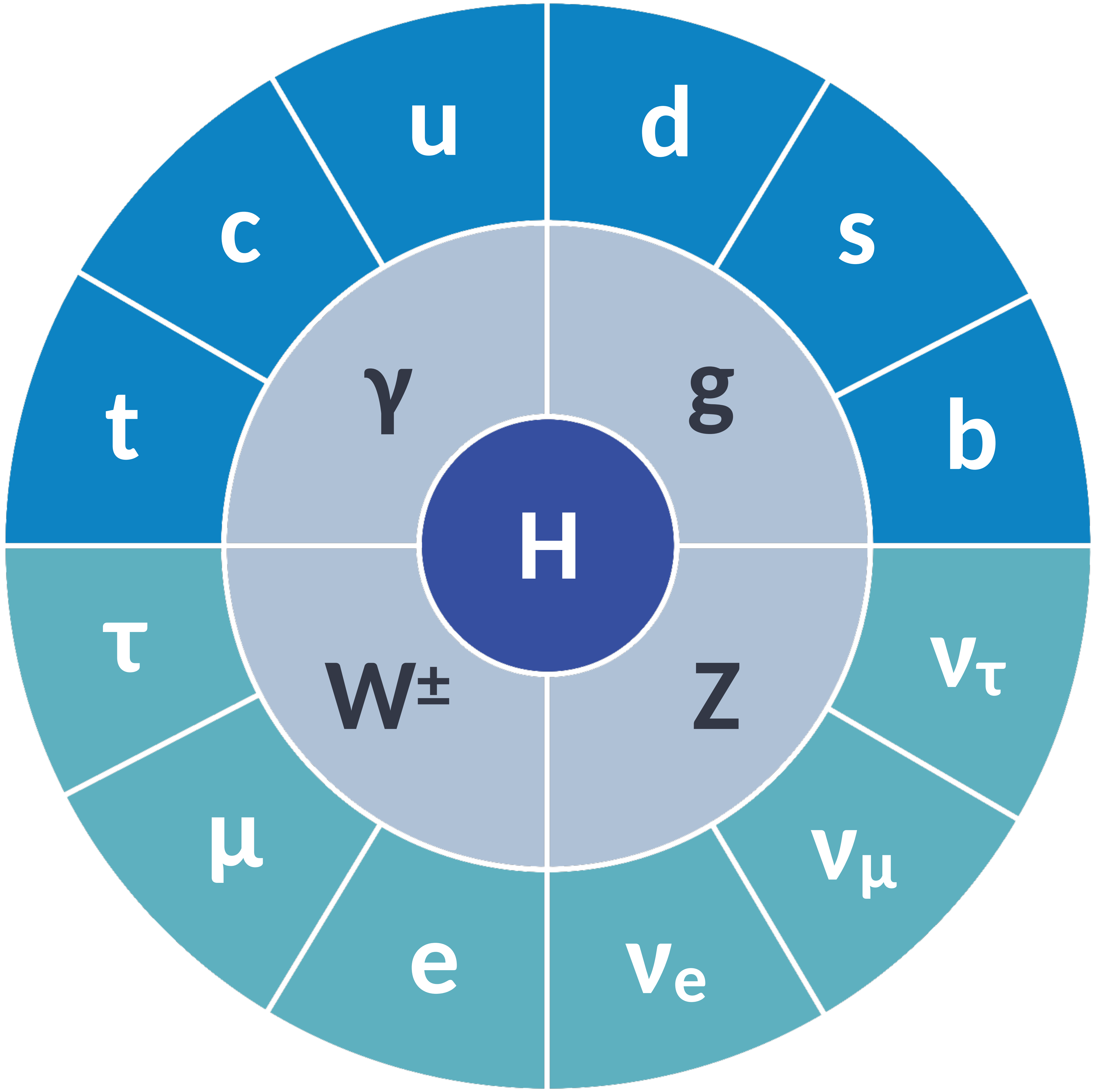


The Standard Model



The Standard Model

Fermions
3 generations of
quarks and **leptons**
- spin ½ particles



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Spin 1 particles
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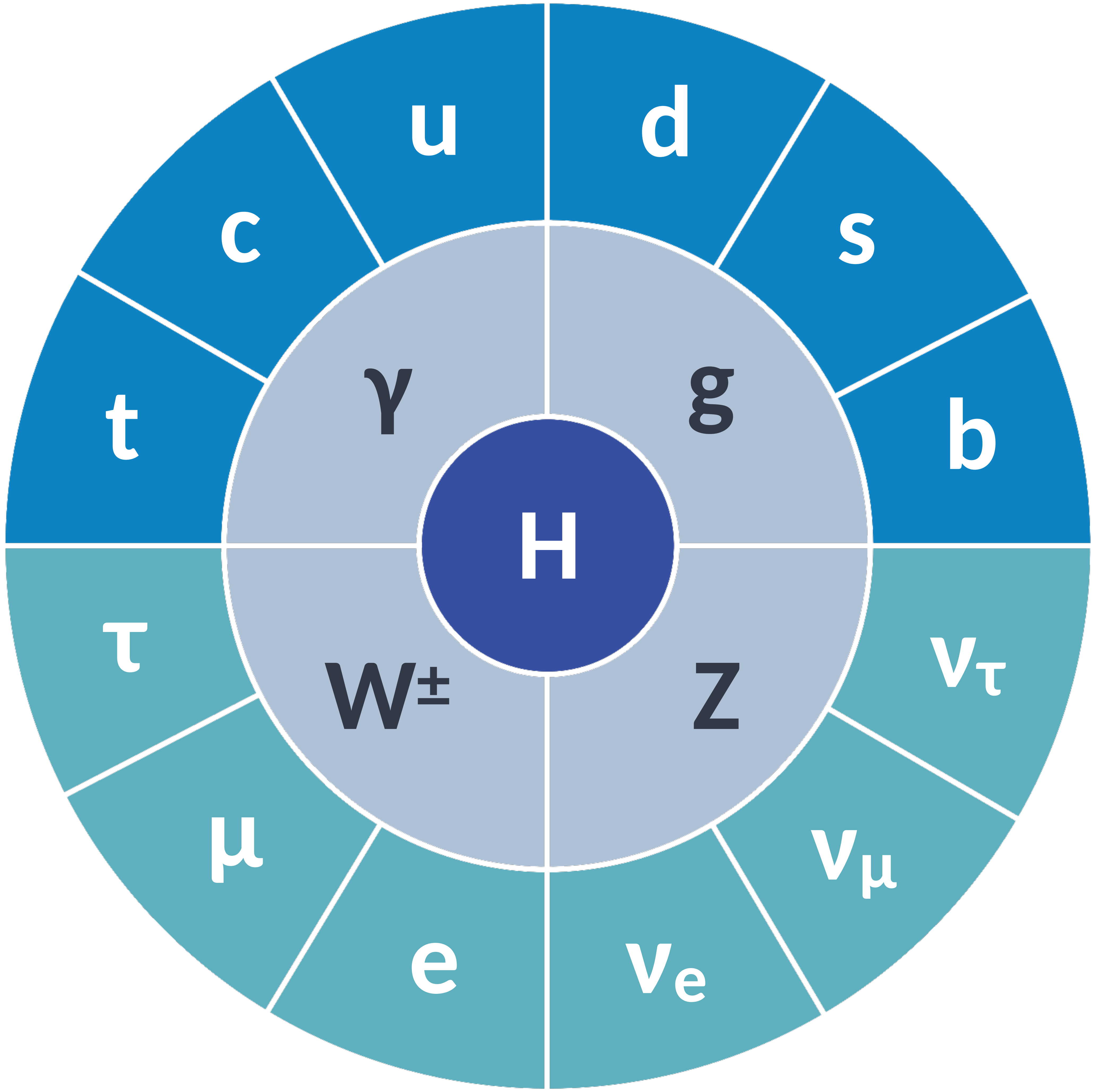

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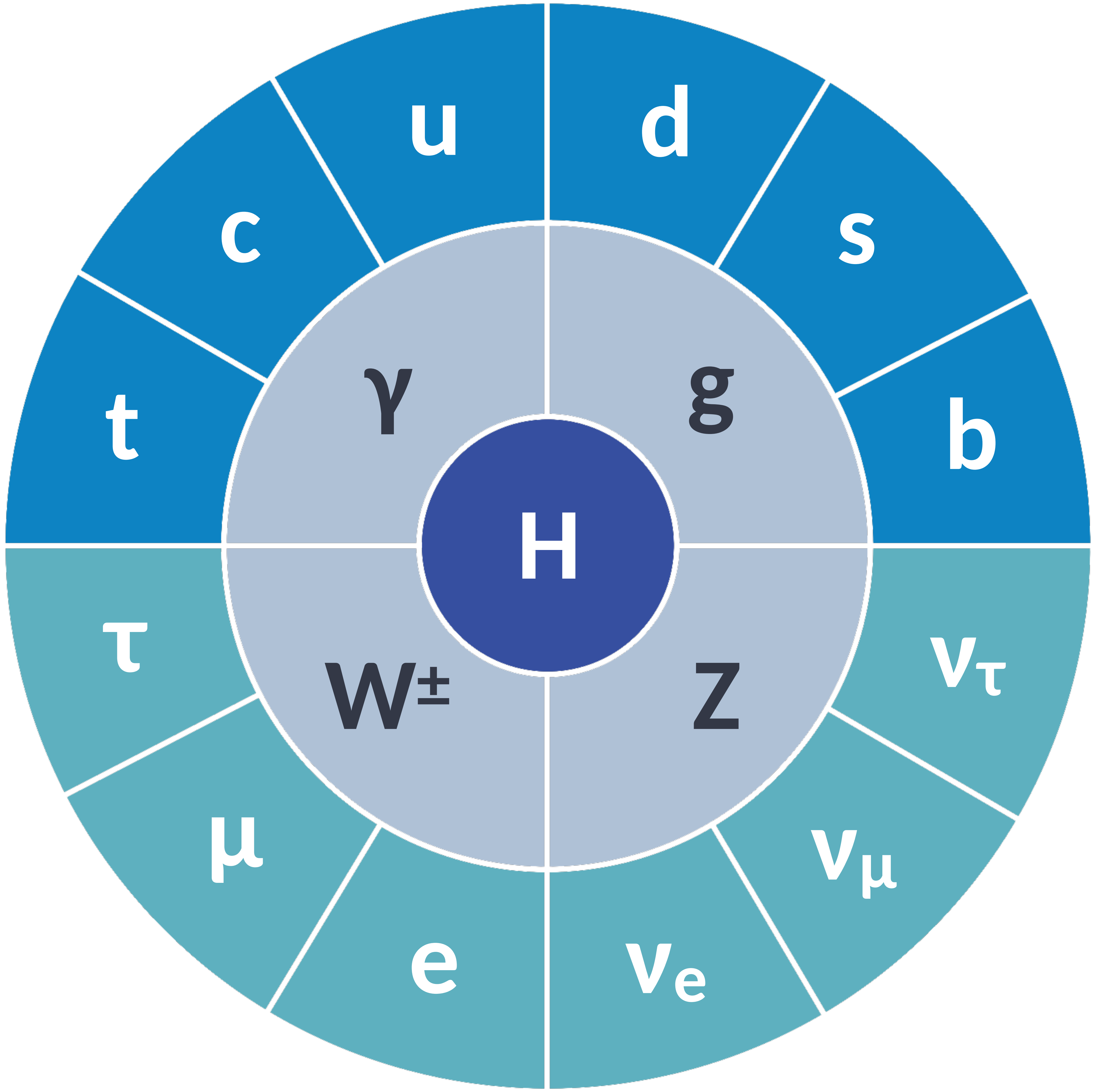
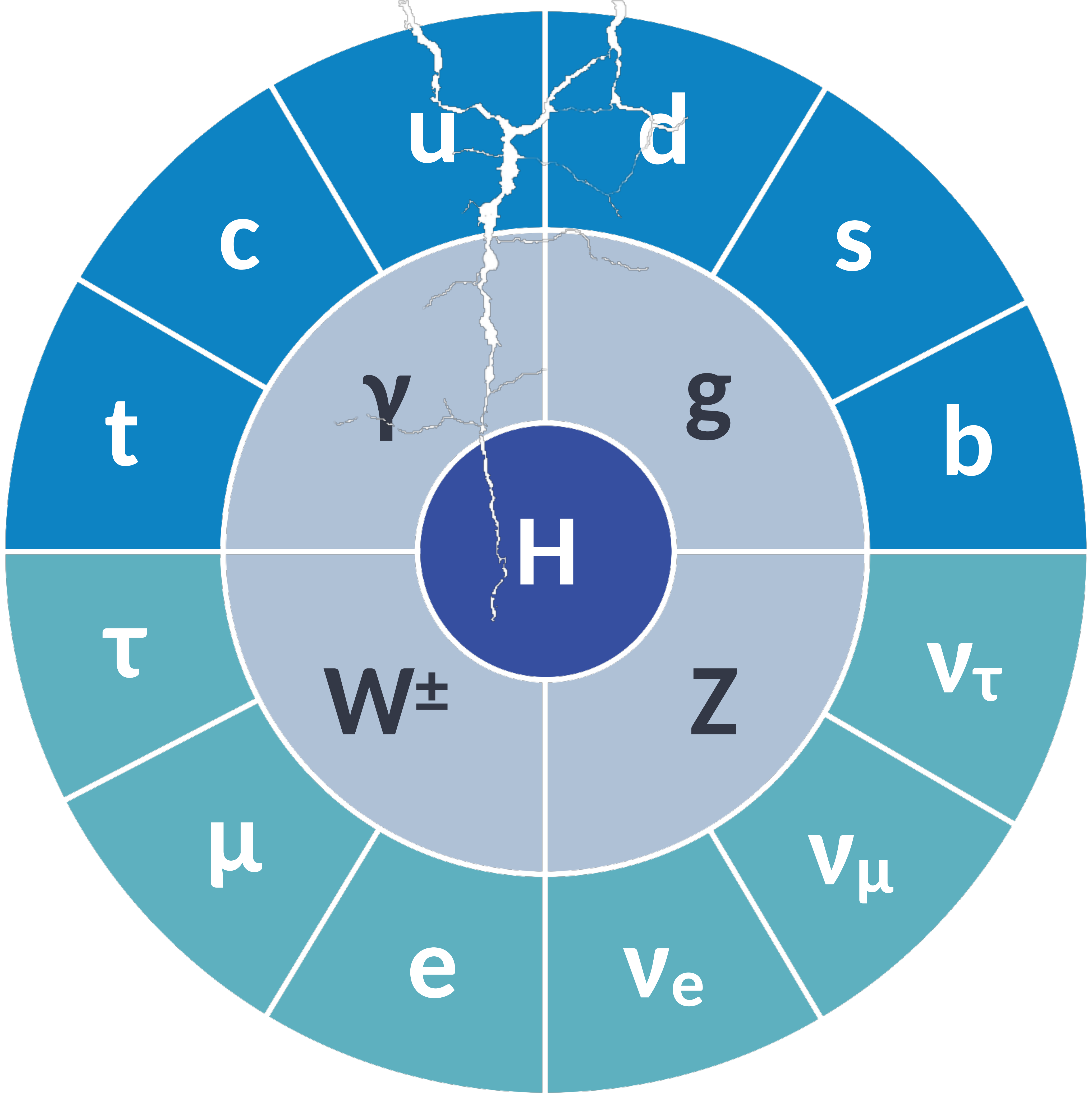
Higgs boson
Spin 0 particle
responsible for mass
generation



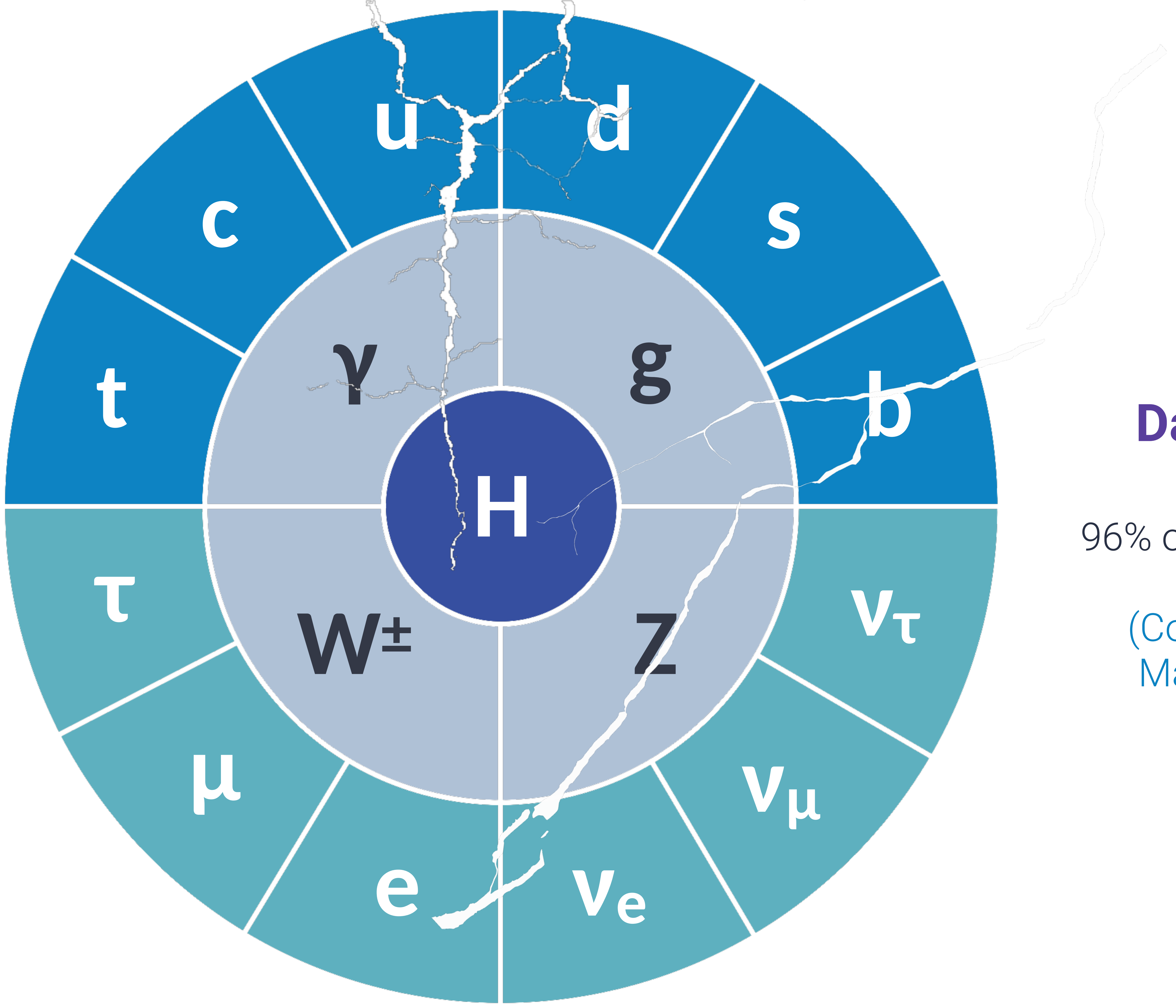
24th May 2022

Breaking the Standard Model

Gravity?
Mediated by the "graviton"?



Breaking the Standard Model



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Dark matter and dark energy?
96% of the universe is unaccounted for - what is it made of?
(Covered in C. Doglioni's "Dark Matter at colliders" lectures.)

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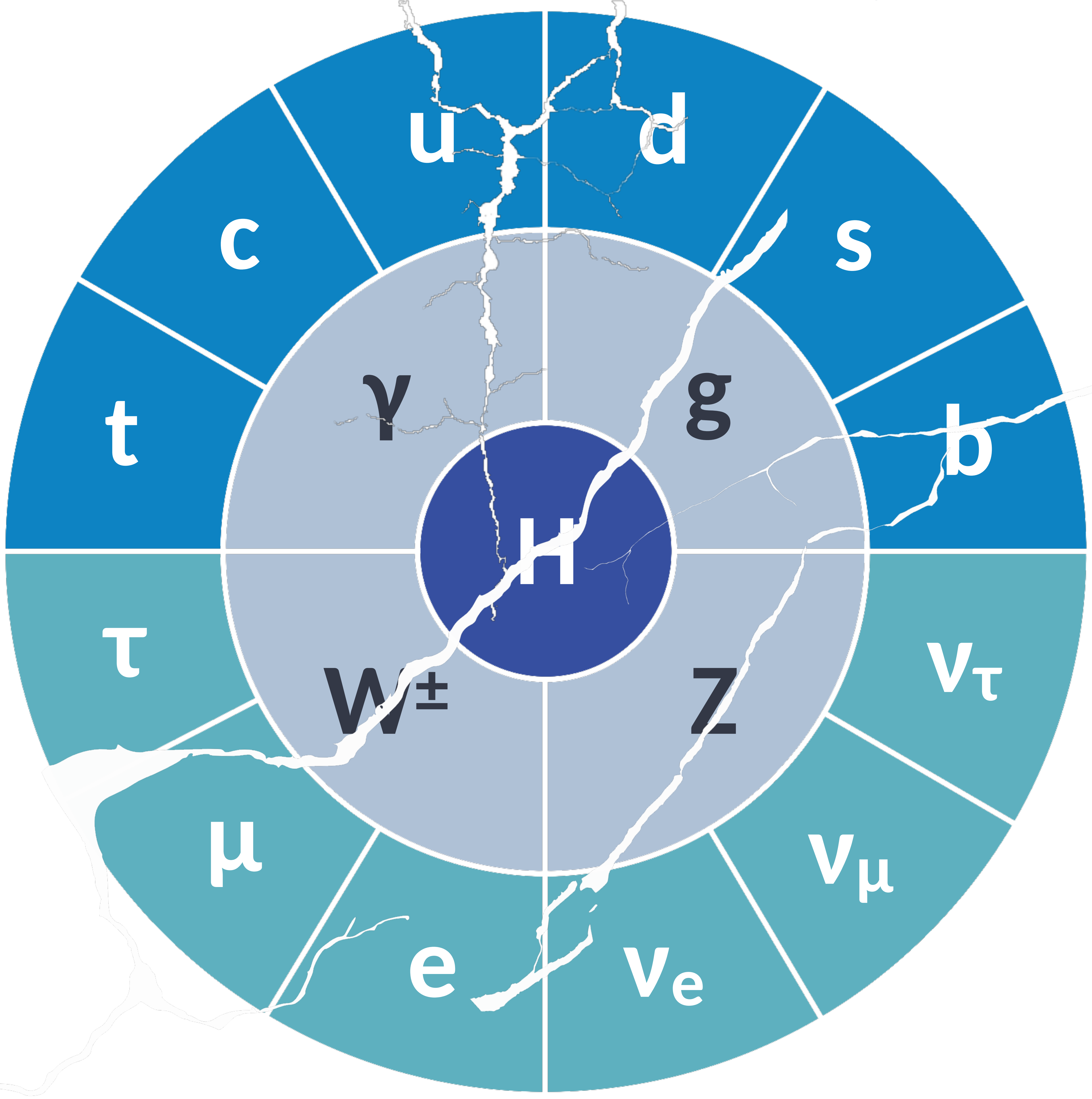

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Why is the Higgs boson so light? Is excessive fine-tuning a real problem, or just aesthetics?

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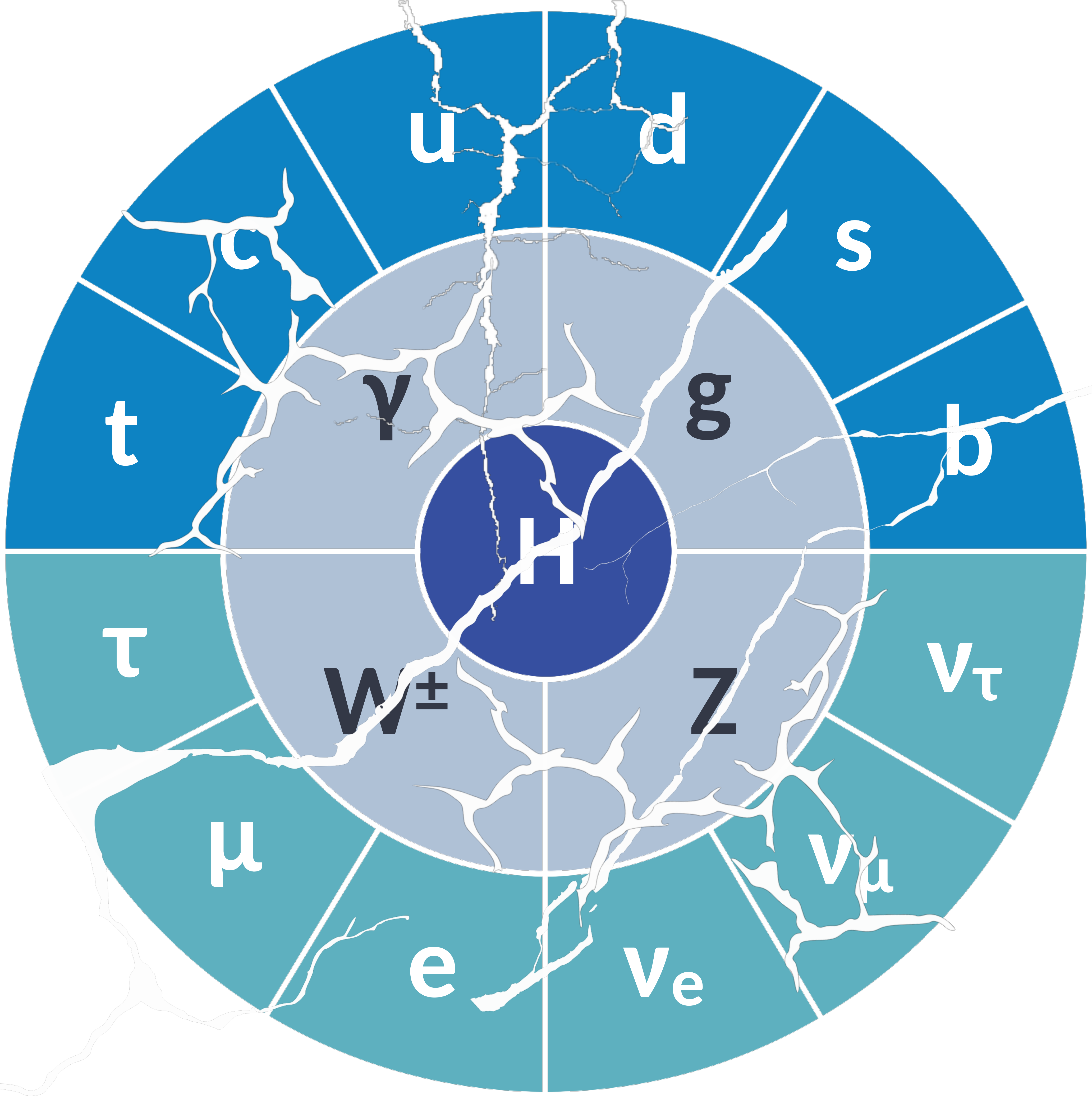

Gravity?

Mediated by the "graviton"?

Matter-antimatter asymmetry

Why do we live in a matter-dominated universe? Not enough CP violation in the quark sector for baryogenesis.

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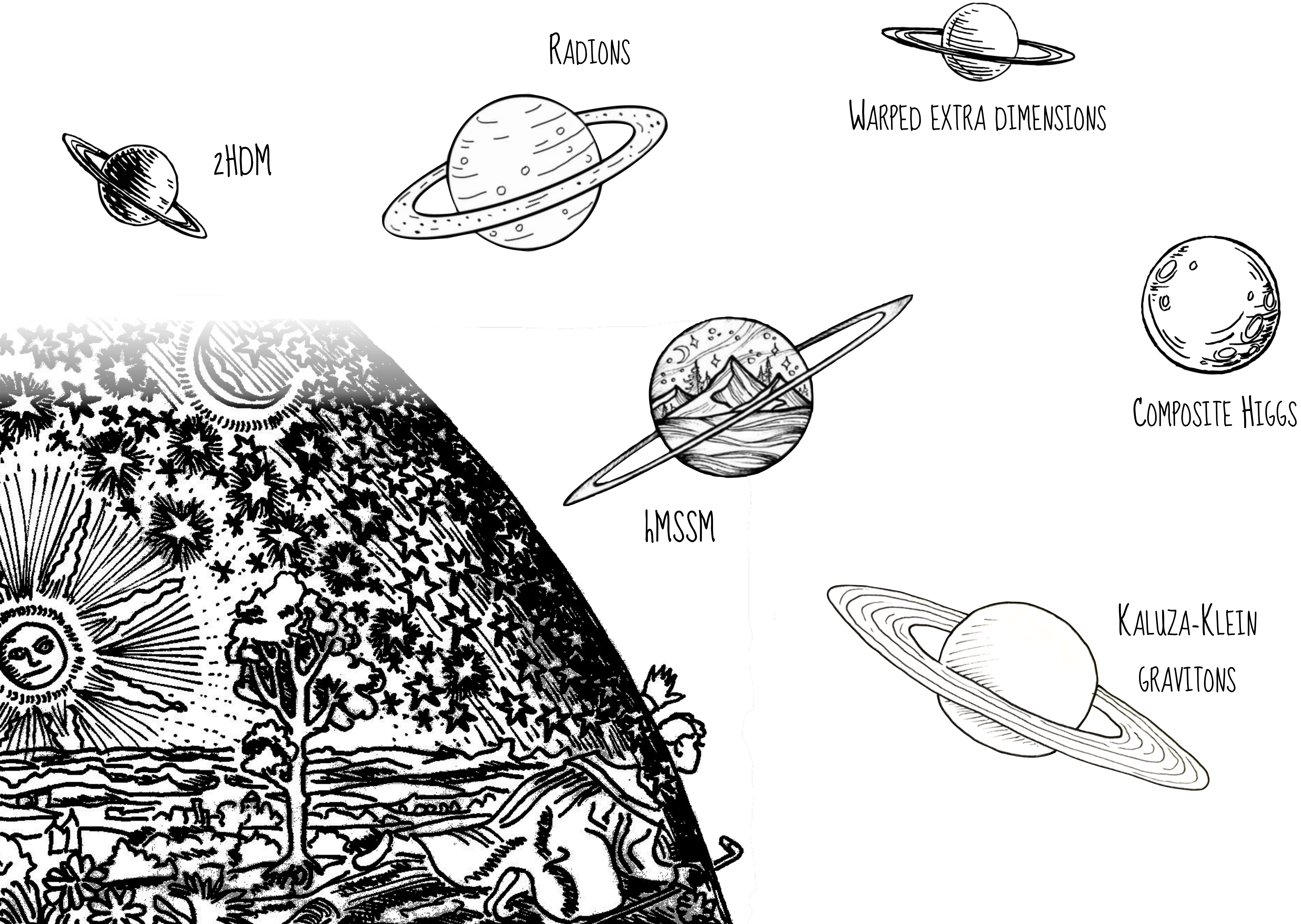
Beyond the Standard Model

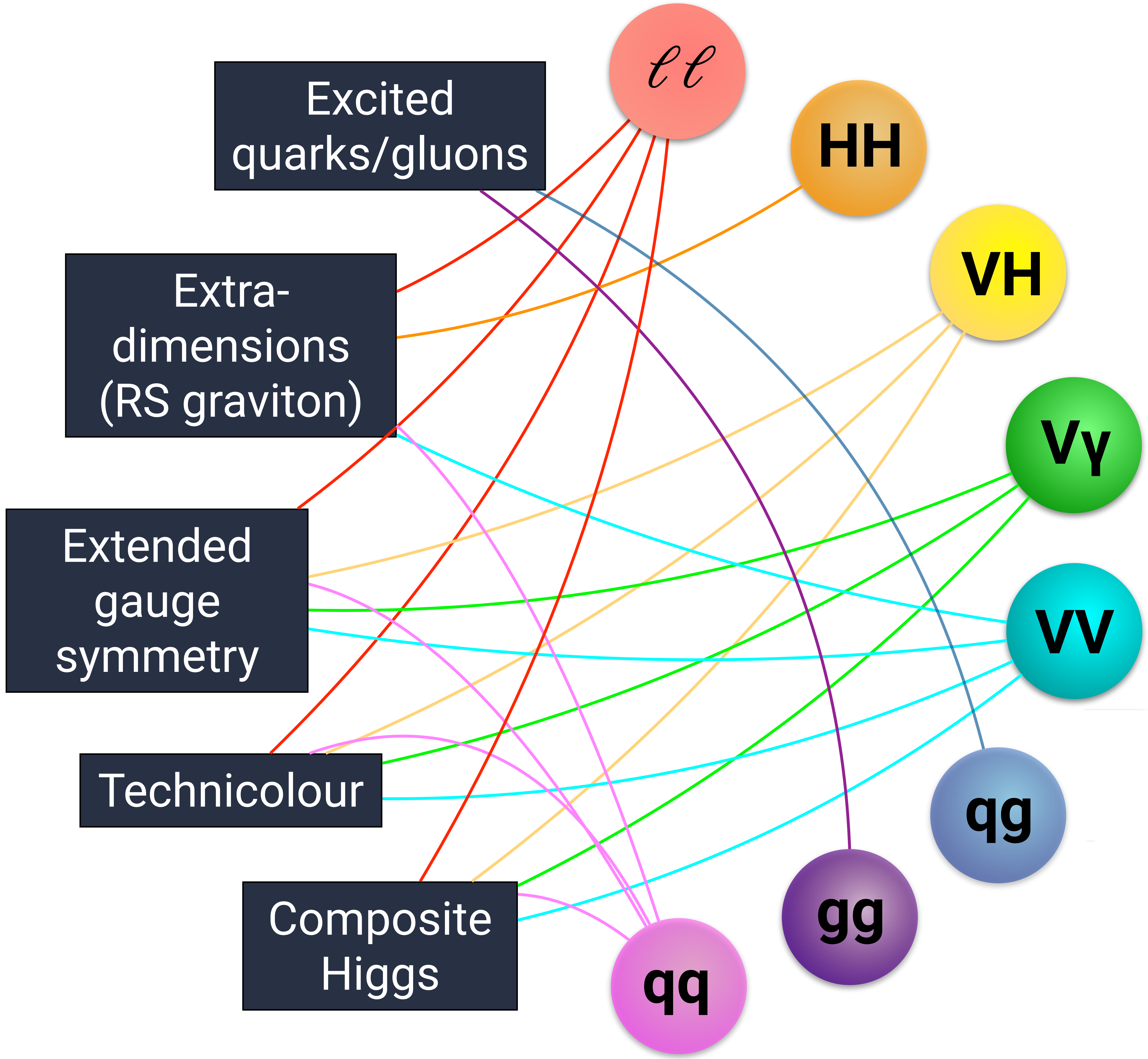


Models for new physics try to explain these phenomena by introducing new particles or interactions → search for evidence of these at colliders

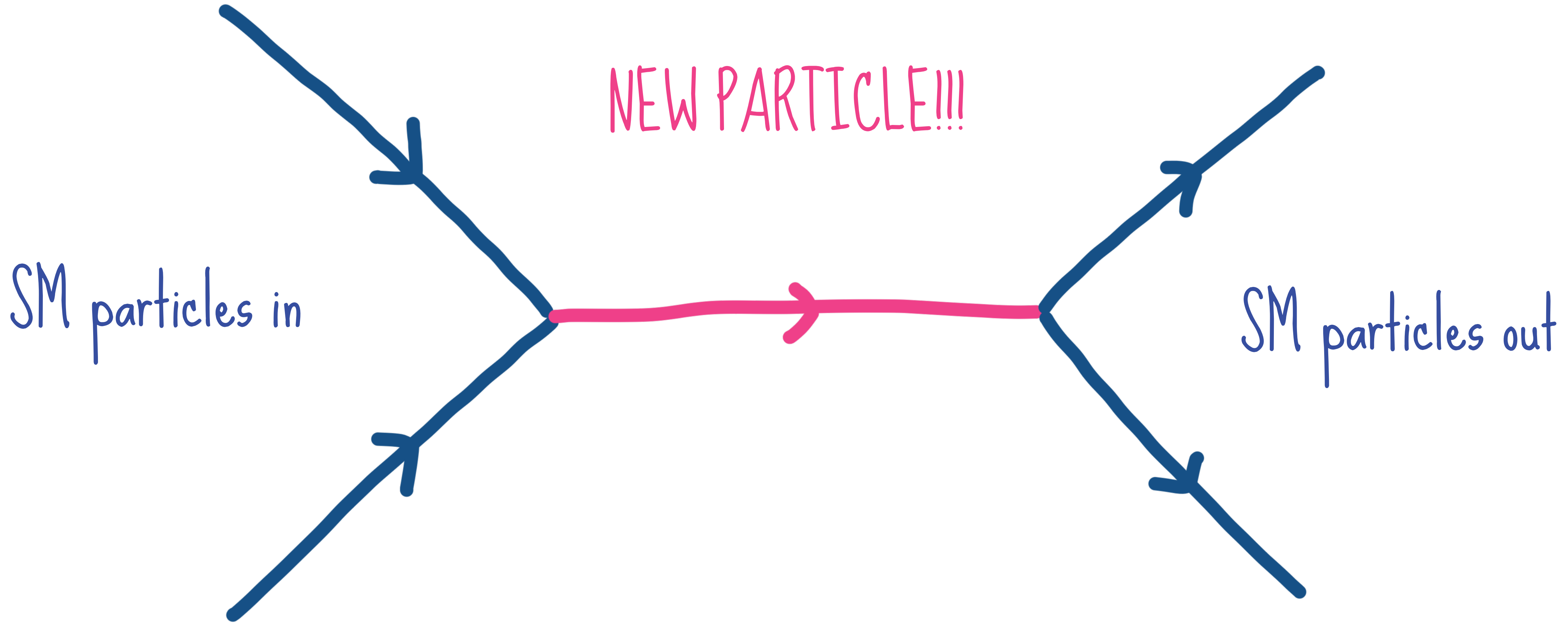
Resonance searches

Many BSM theories predict narrow resonances at the TeV mass scale.

- Clear `bump' over SM background.
- Almost any combination of 2 SM particles can form a resonance in BSM models.



Resonance search - simple example



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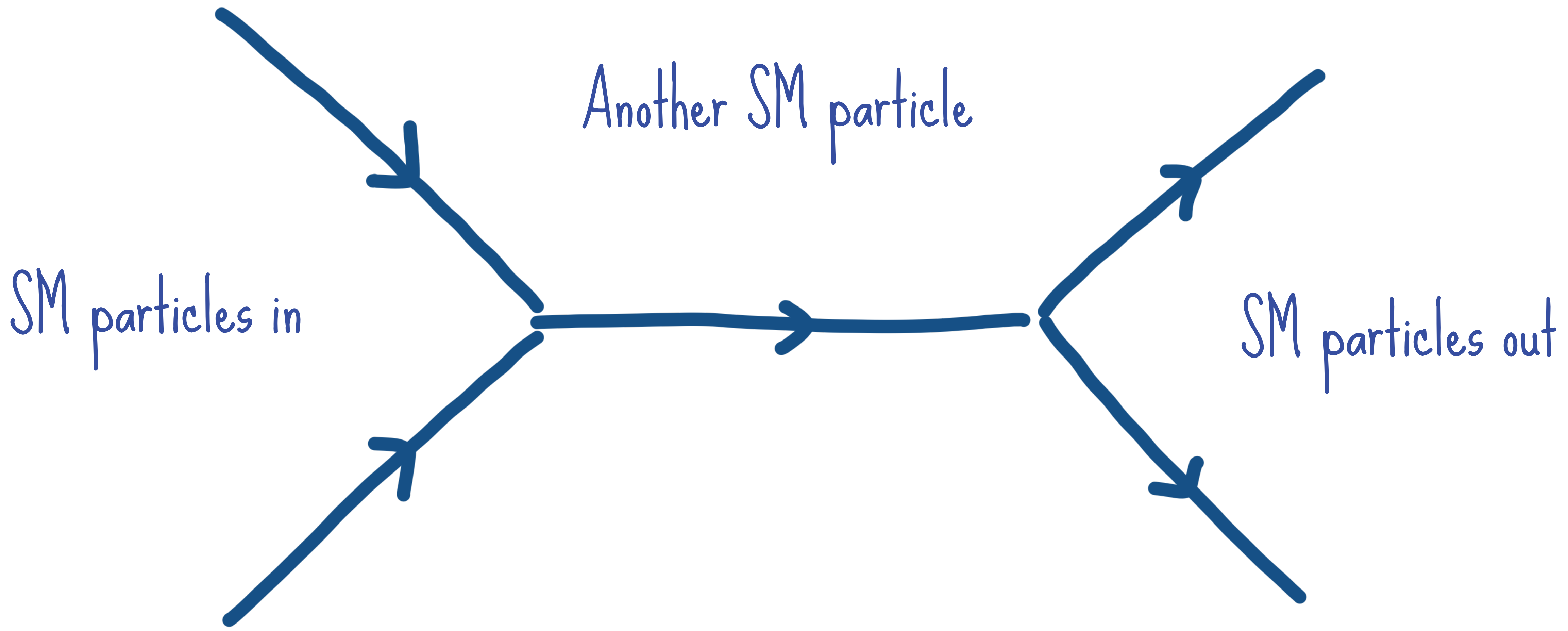

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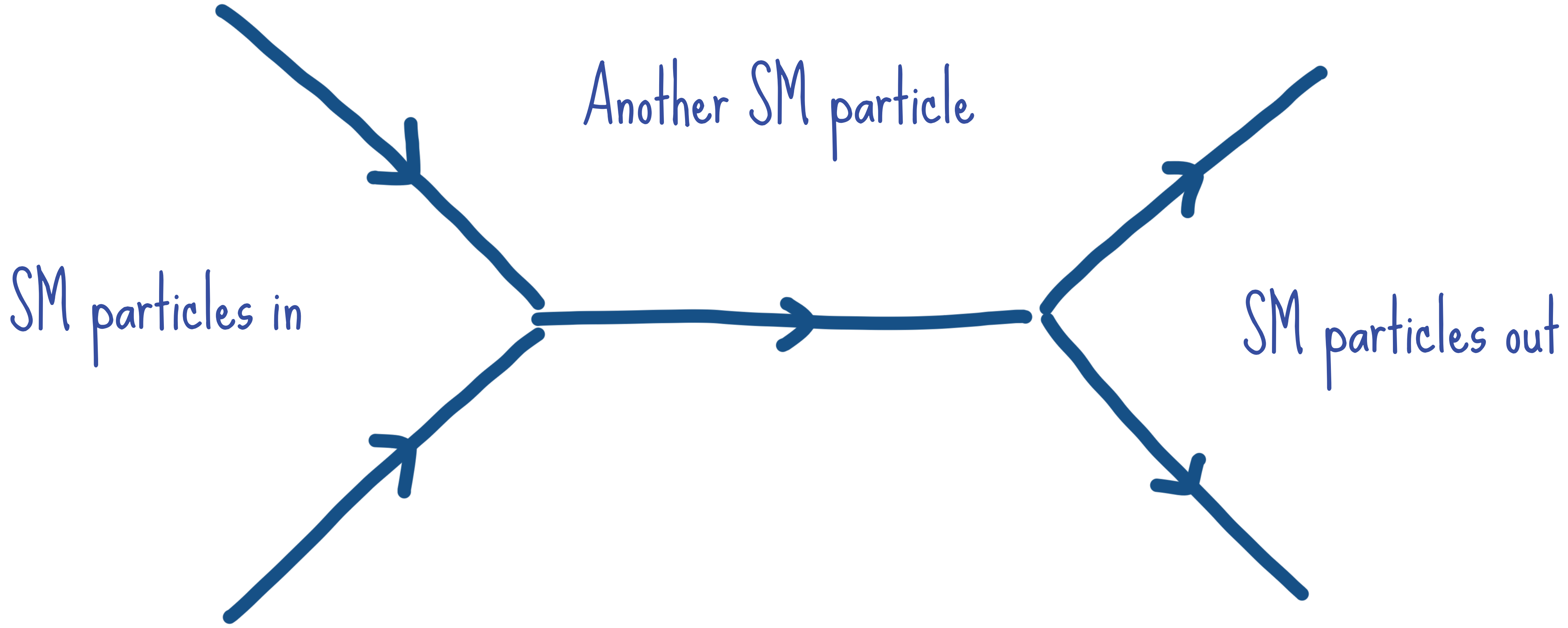

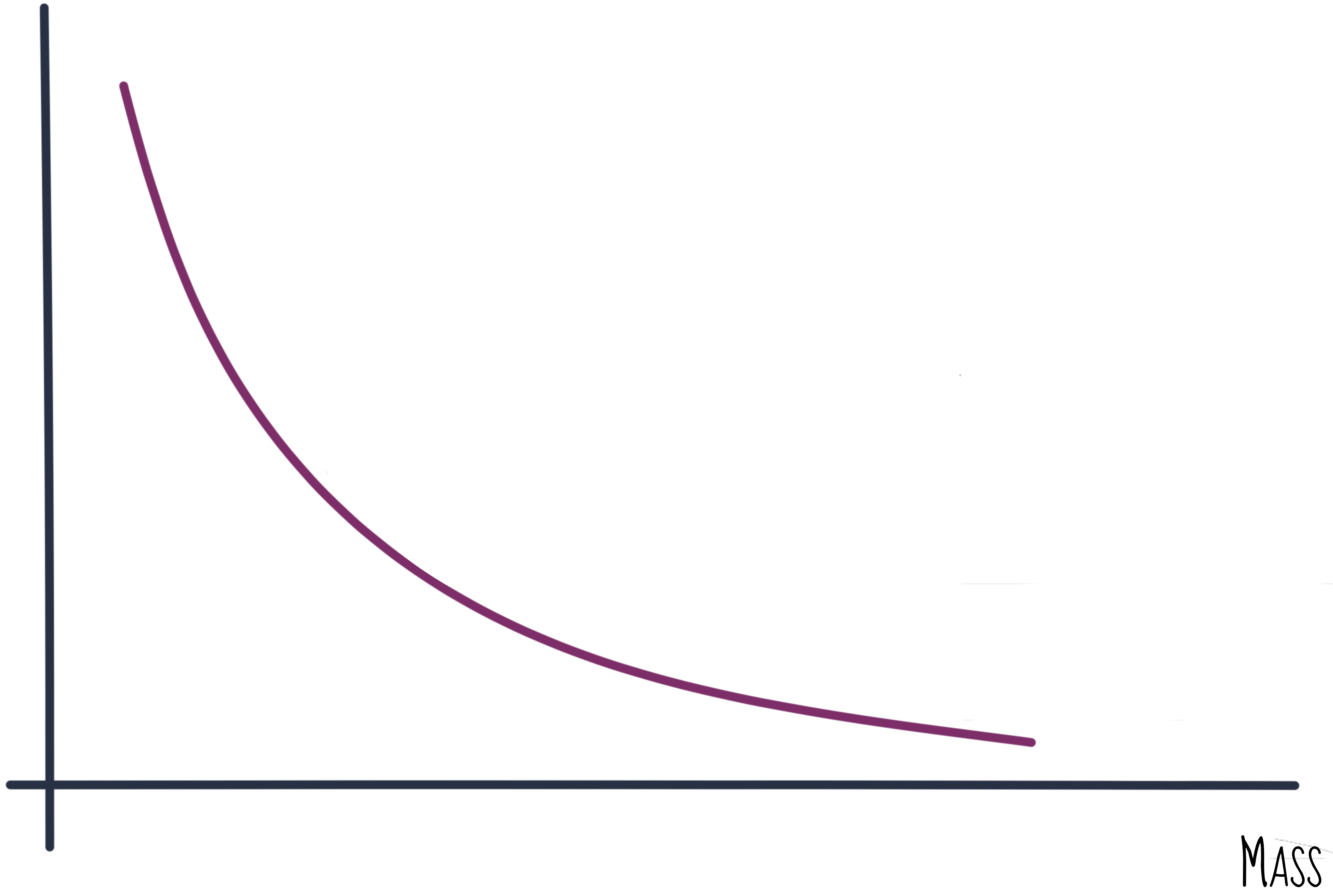

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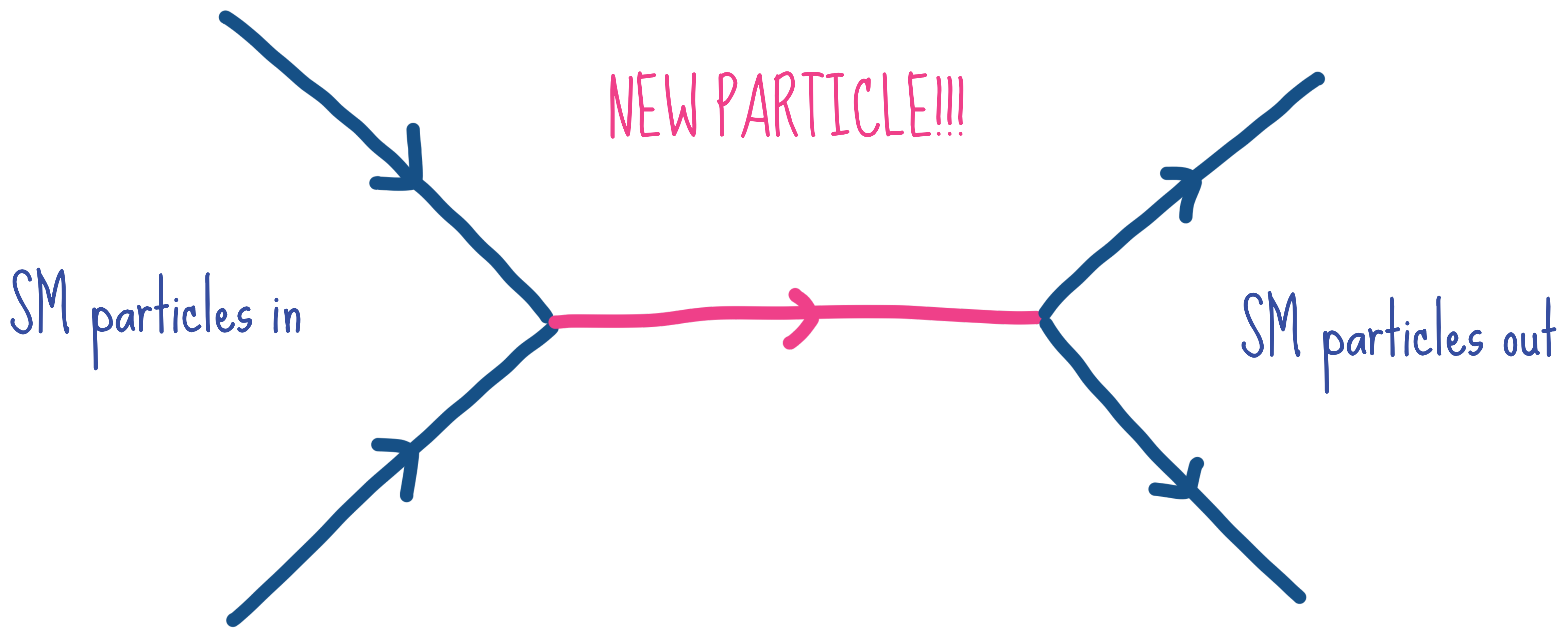

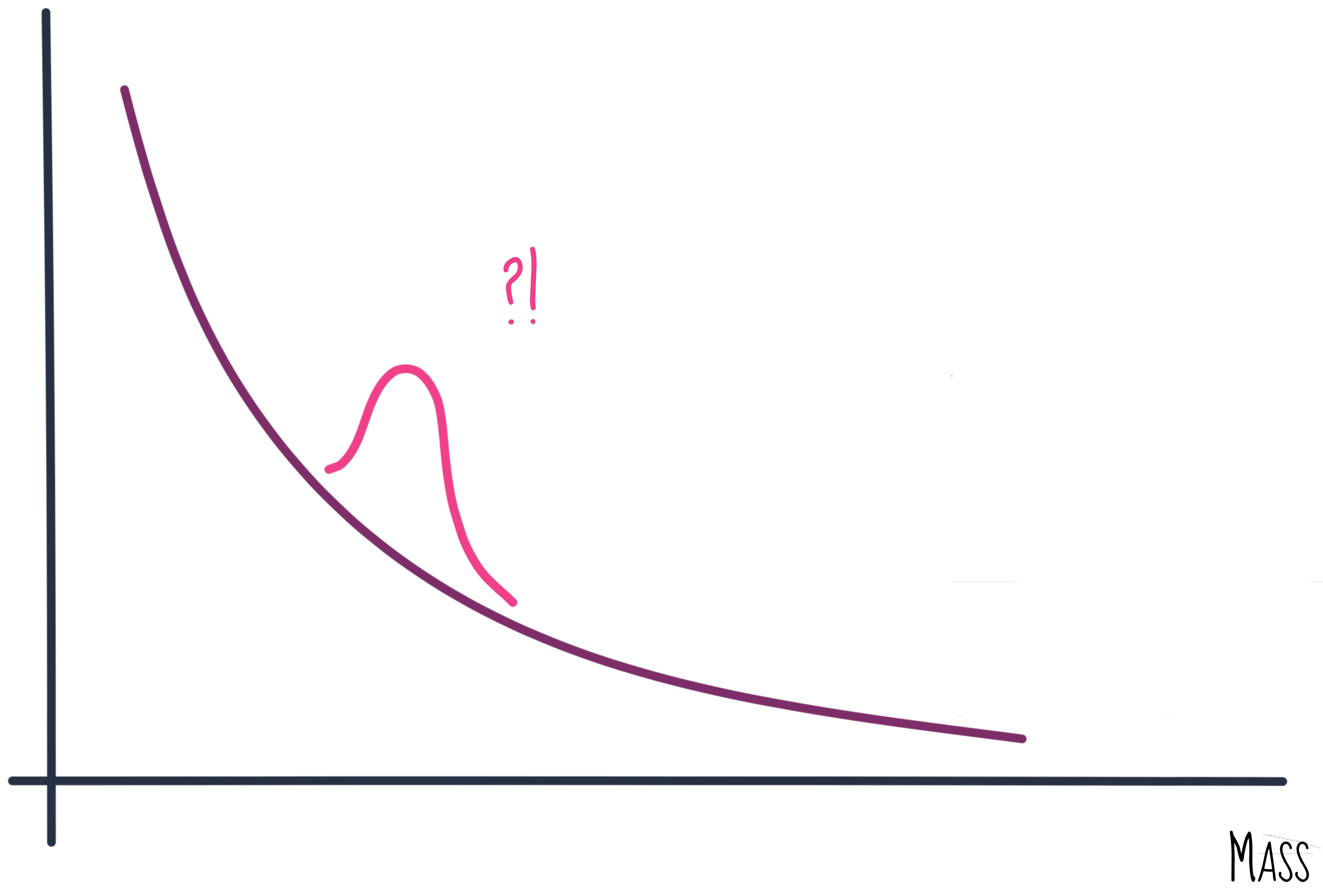

Steps in a BSM search analysis

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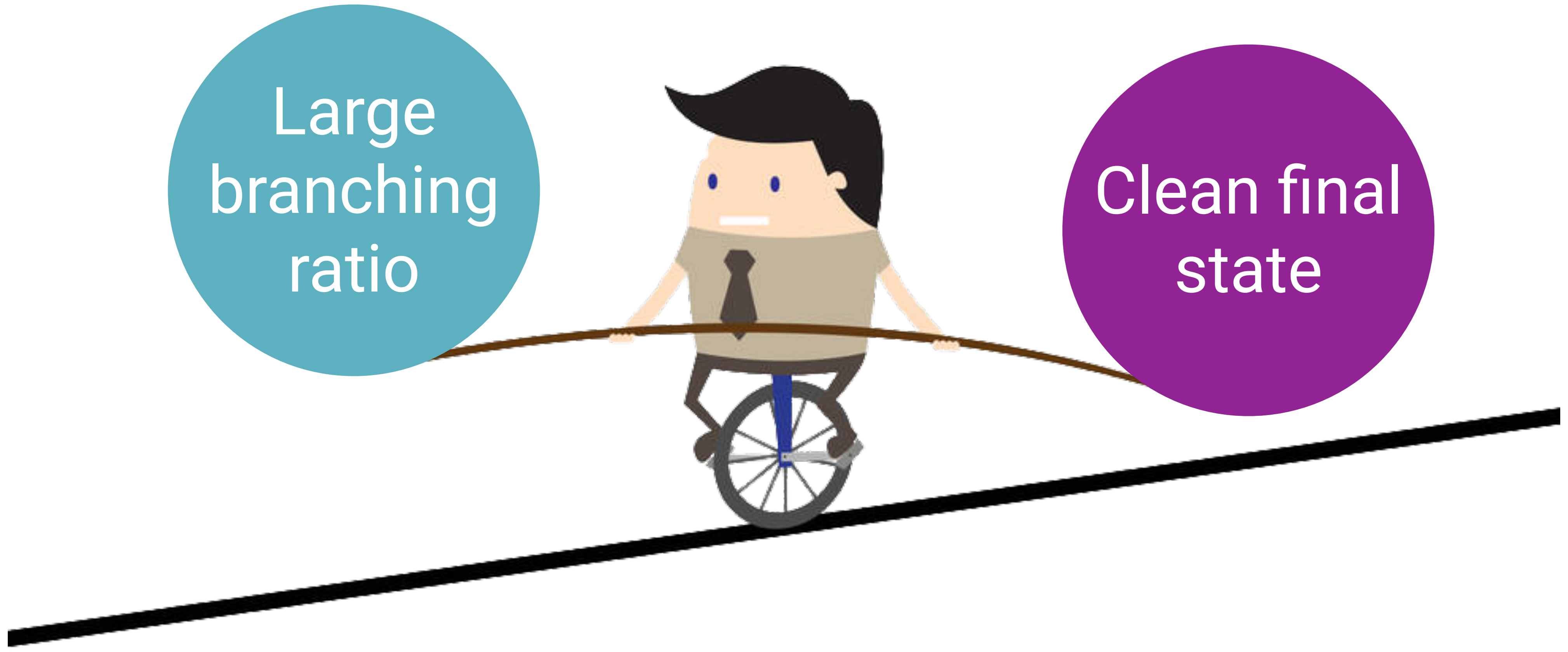


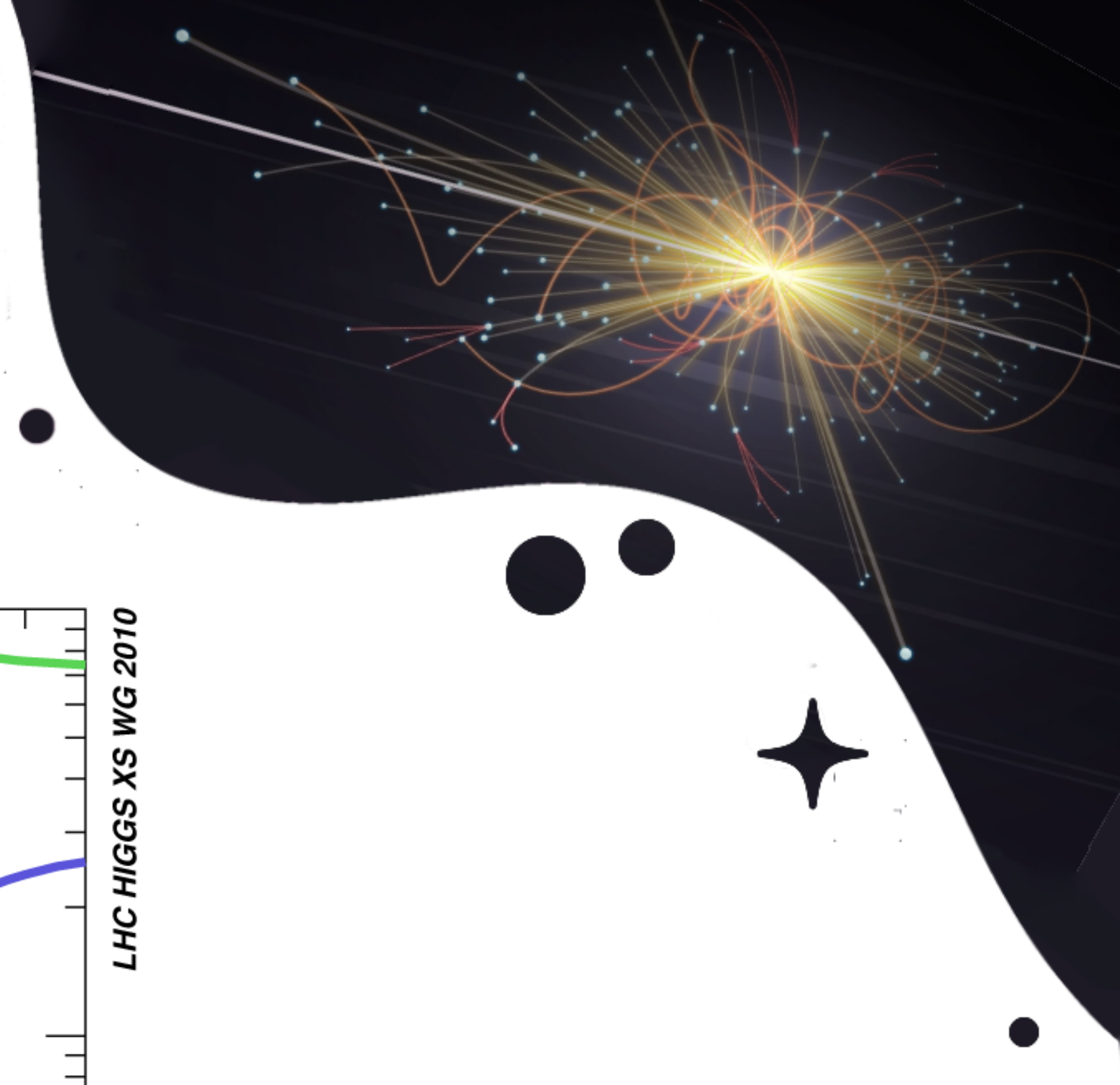

THE
♪ THE SIMPSONS ♪

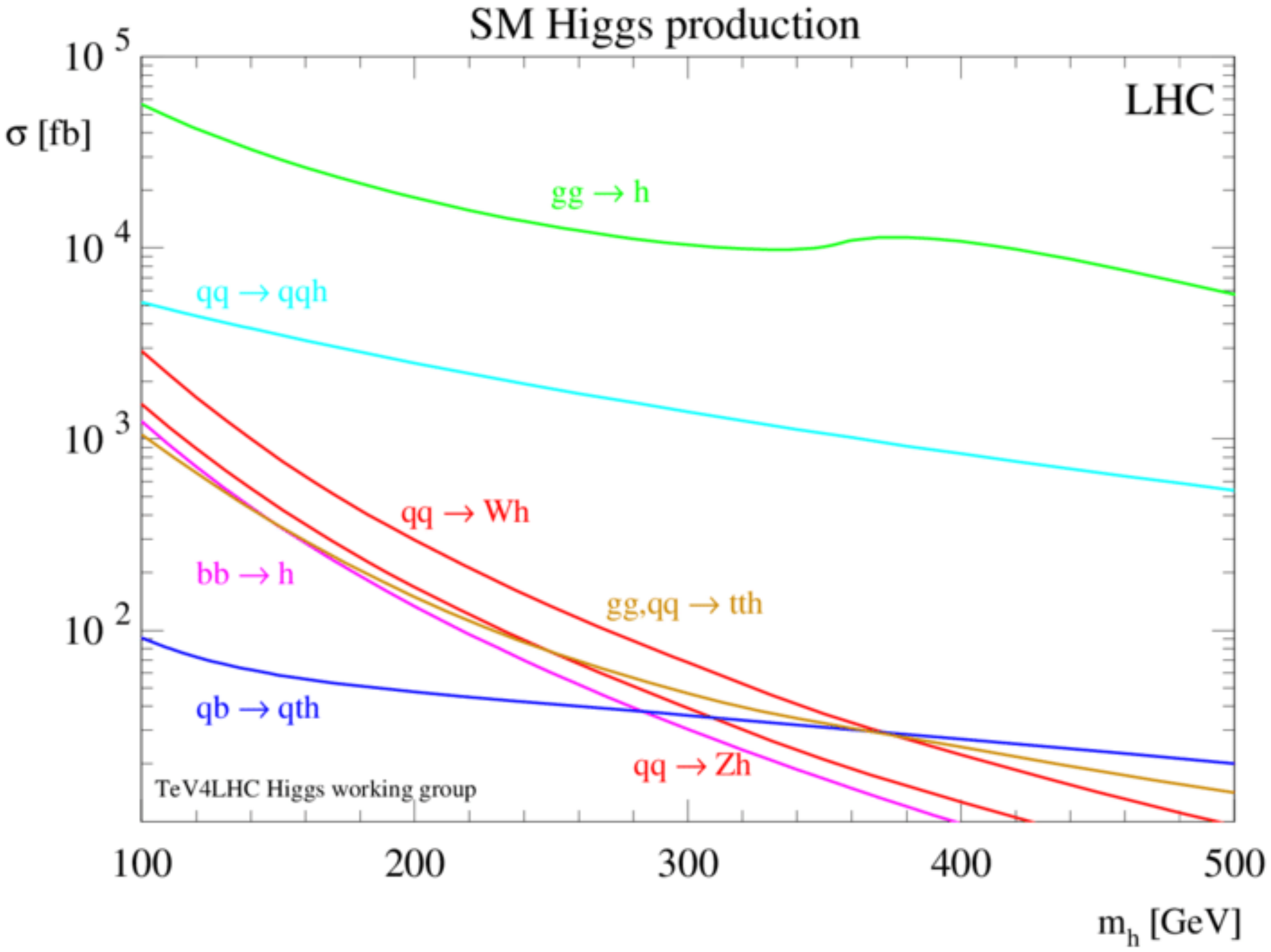
Case study

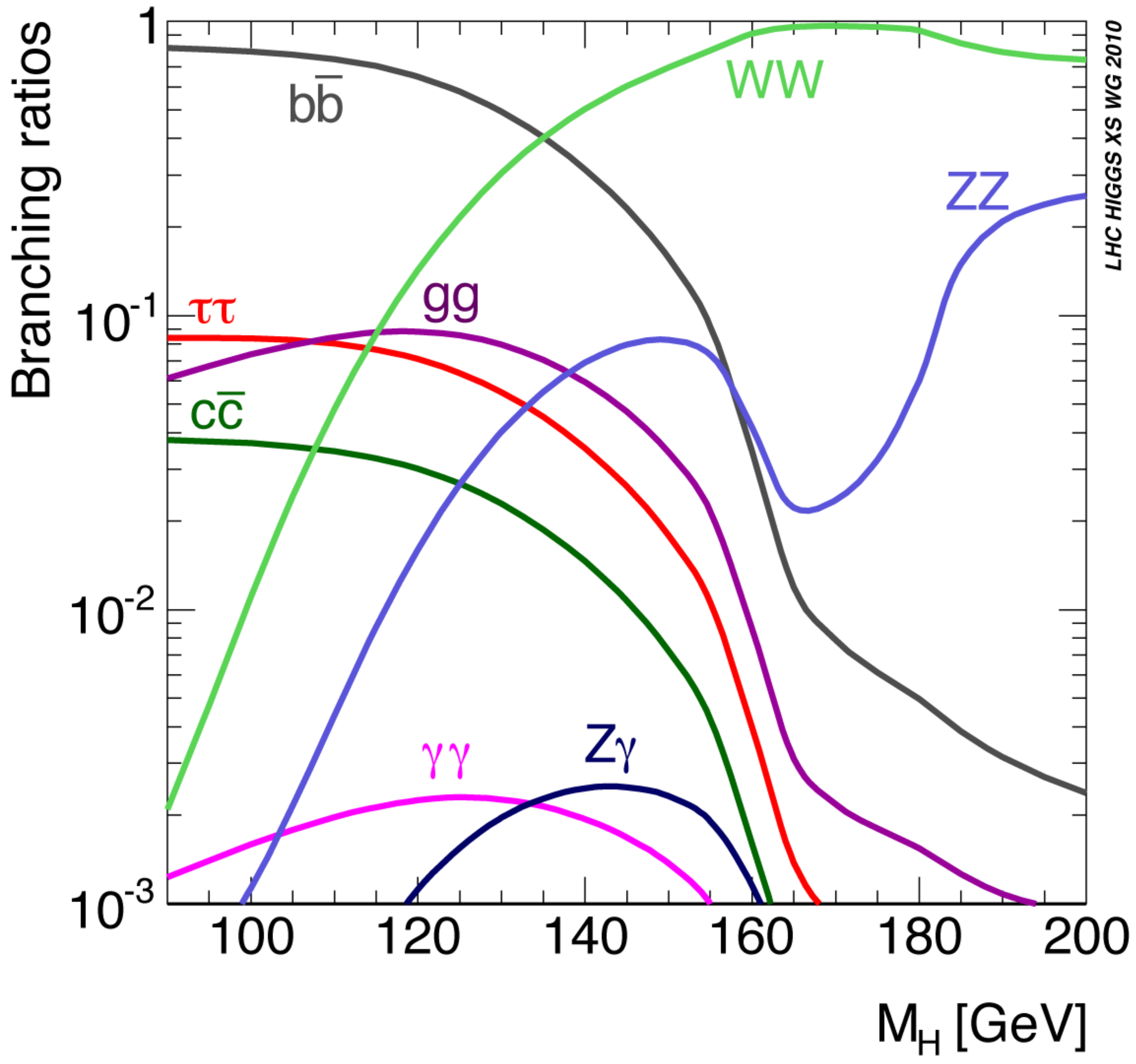
In season 21, episode 16 of The Simpsons, Homer has decided to do a PhD in particle physics on the ATLAS experiment at CERN. He needs to pick a thesis topic.

The LHC has just started taking data, and everyone's excited about finding a new particle called the Higgs boson.

Choose a channel



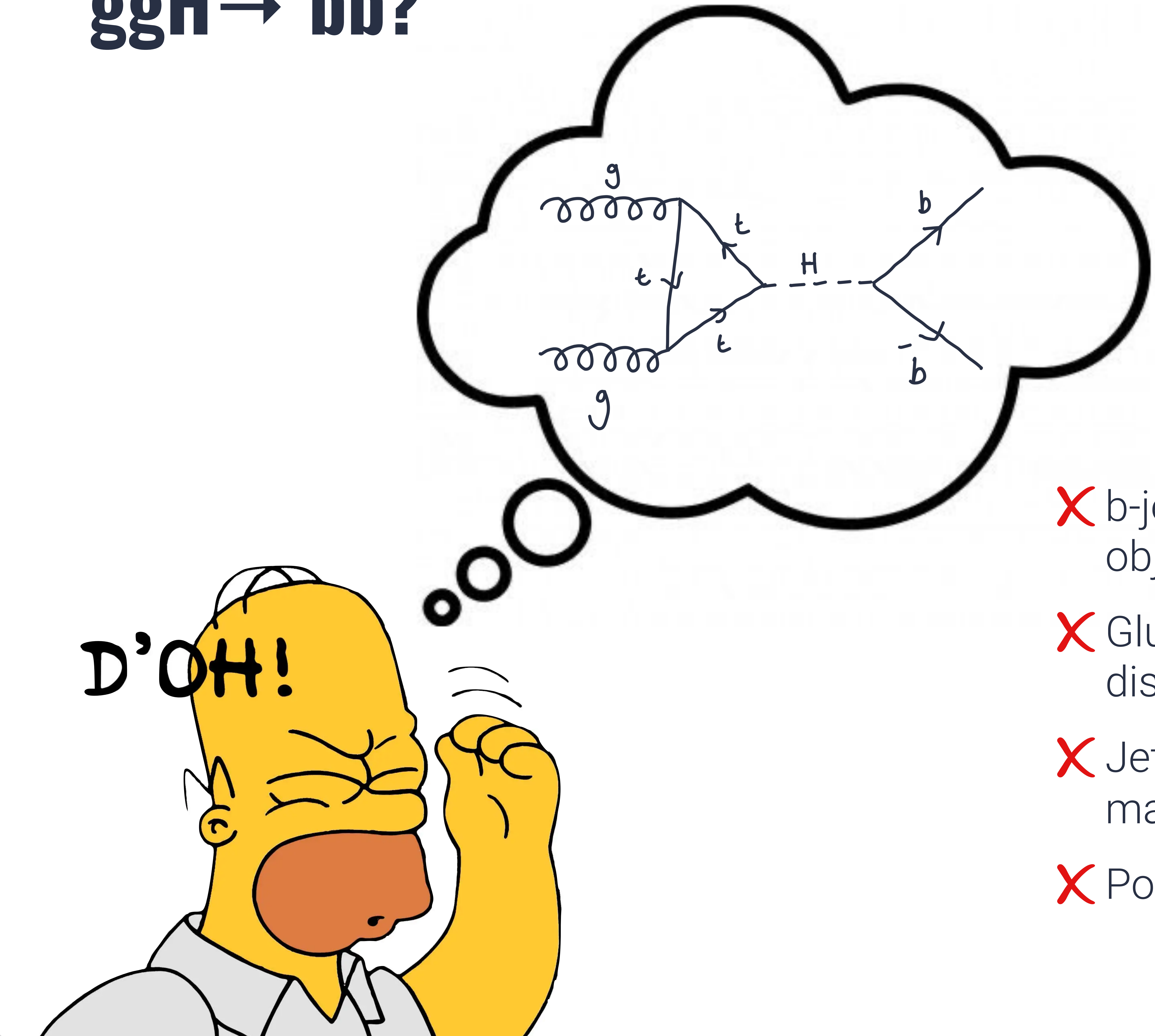




Choose production and decay modes that maximise the number of Higgs bosons?

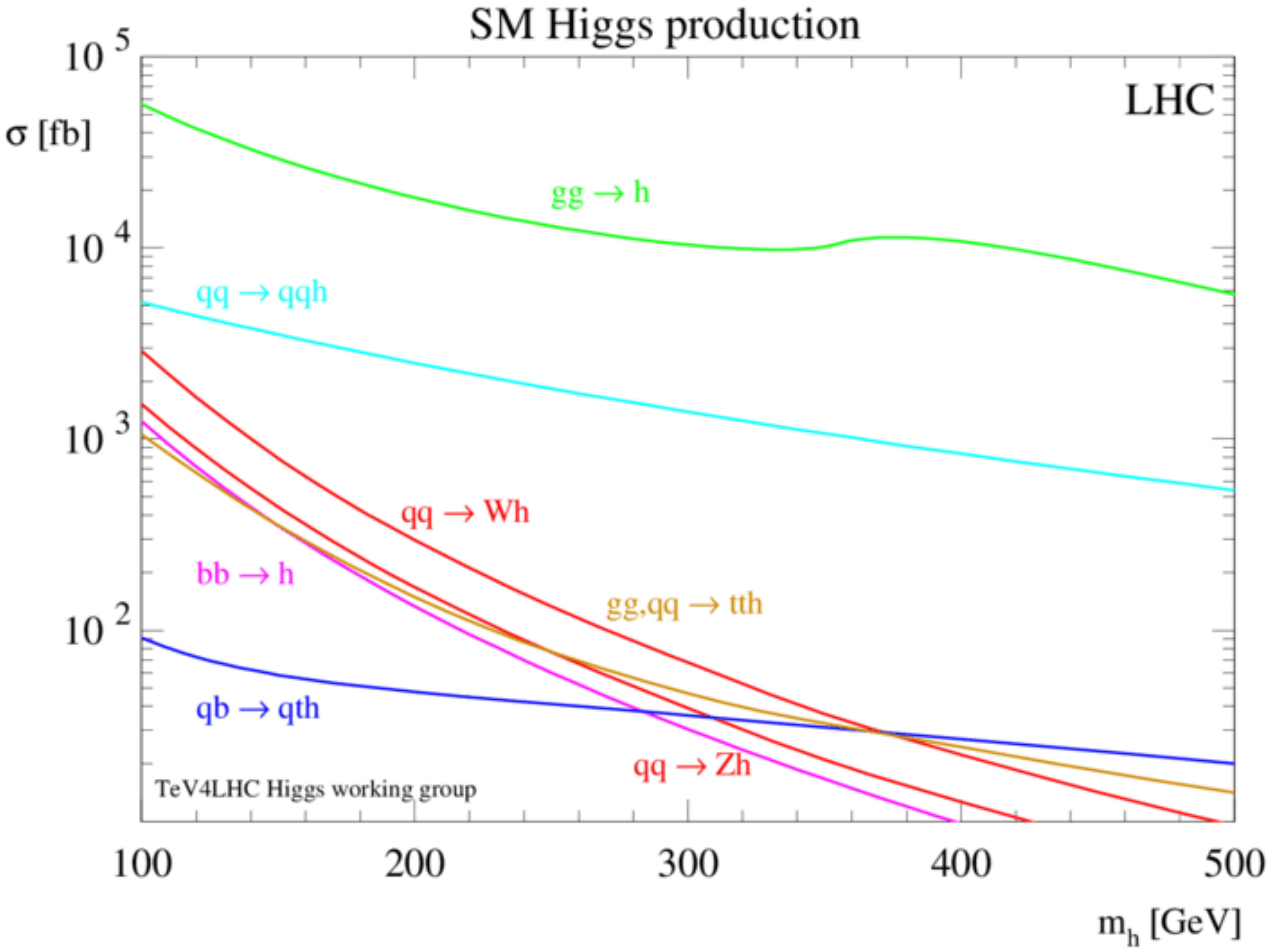
→ Gluon-fusion production, decay to b-quarks (Homer has a hunch that the Higgs will be light ;-)).

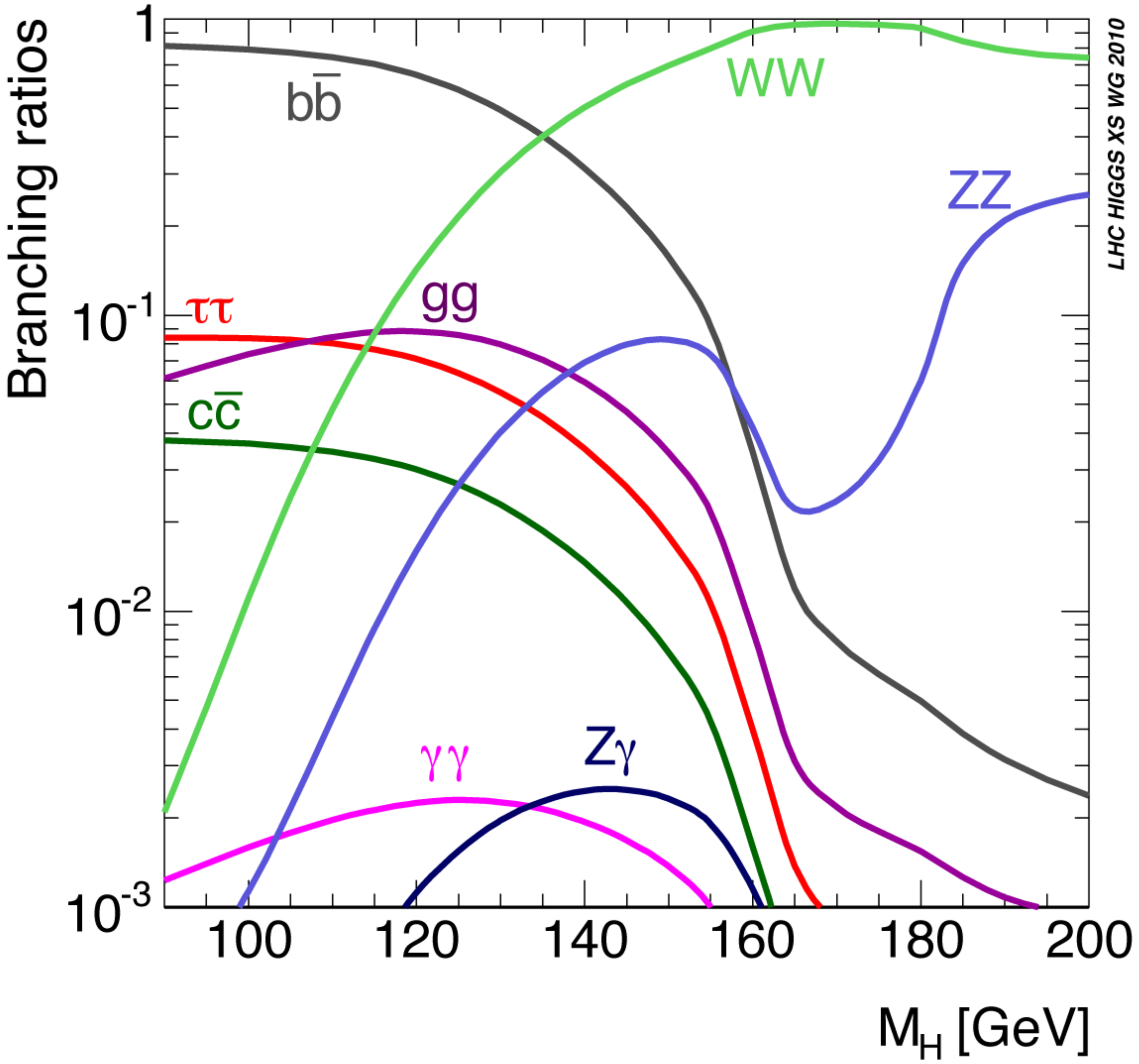
ggH→ bb?



- ✗ b-jets are probably the most difficult objects to identify in the detector.
- ✗ Gluon-fusion doesn't really provide any distinctive signature.
- ✗ Jet backgrounds are many orders of magnitude larger than your H→bb signal.
- ✗ Poor mass resolution of the bb pair.

Choose a channel

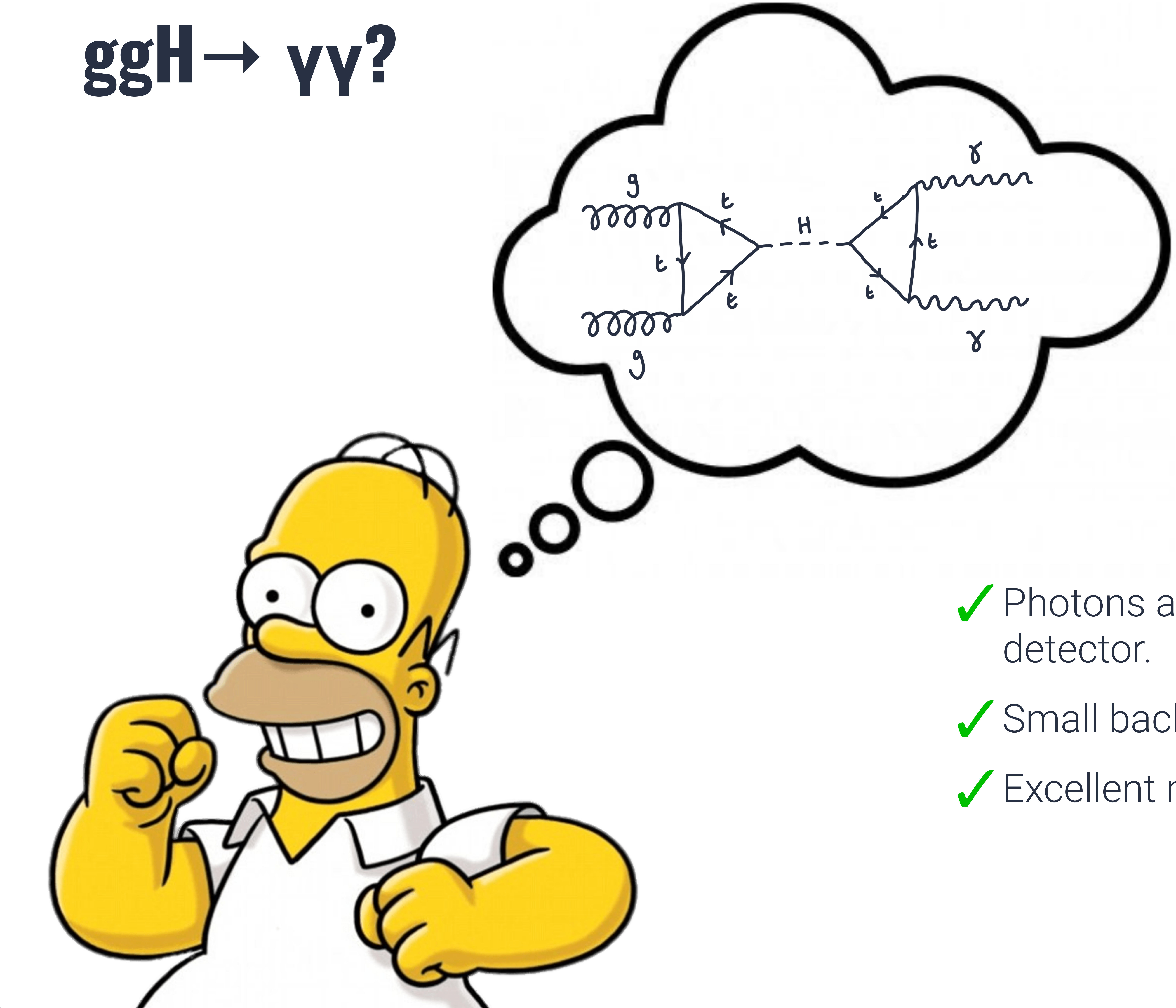




Need more “distinctive” signature…

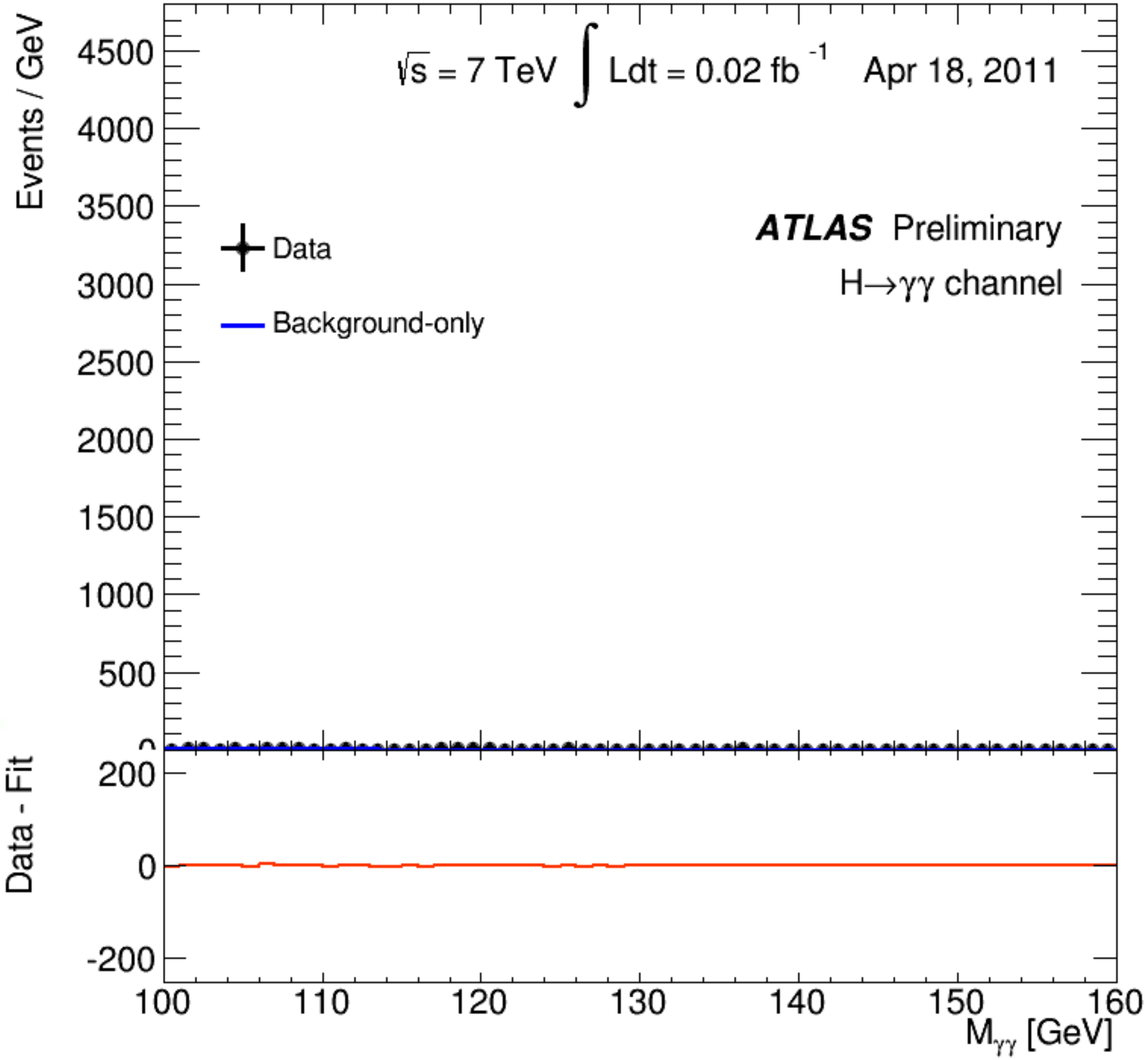
→ Gluon-fusion production to keep large cross-section, but decay to photons.

ggH→ γγ?



- ✓ Photons are “easy” to identify in the detector.
- ✓ Small backgrounds.
- ✓ Excellent mass resolution.

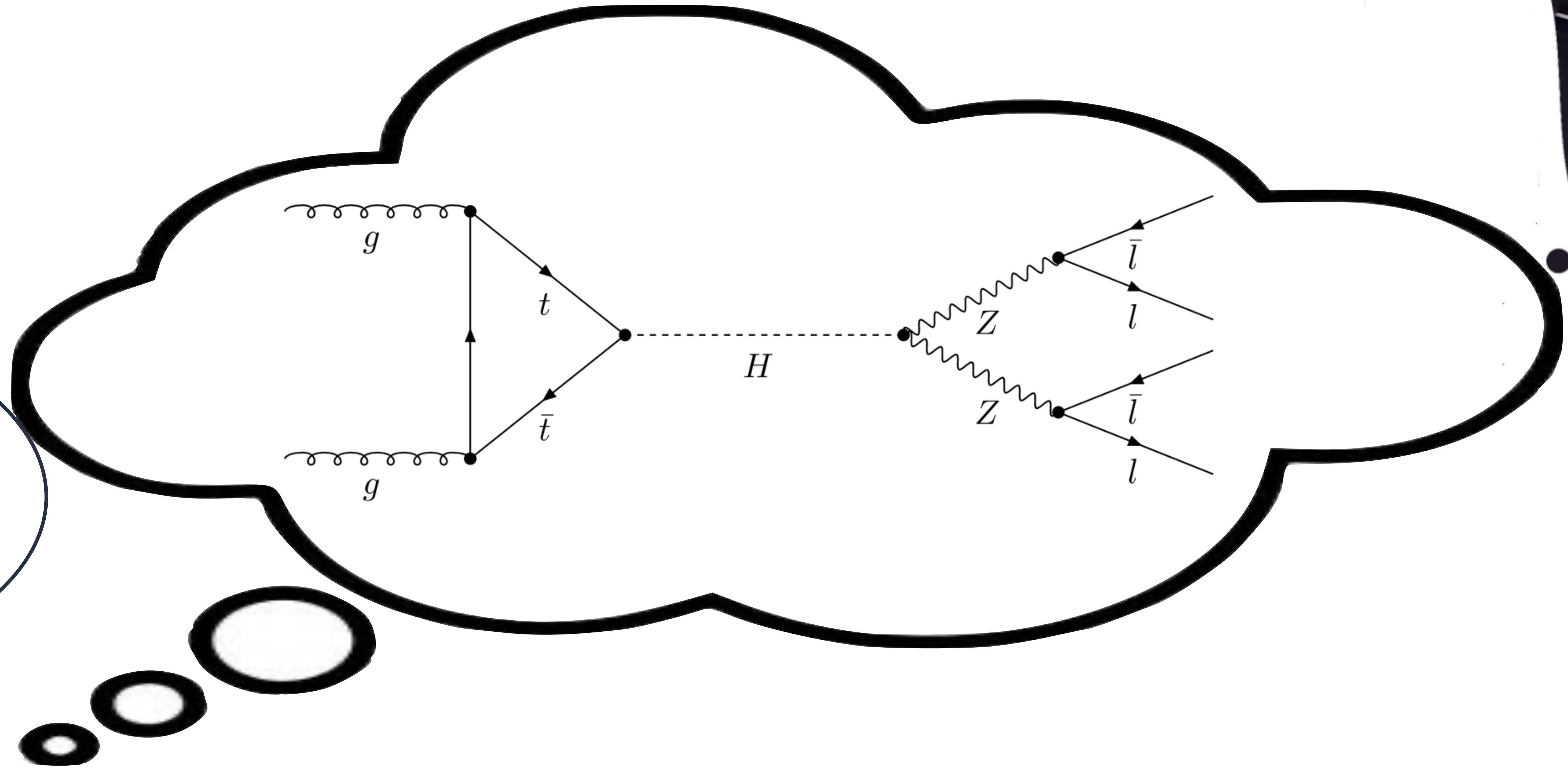
ggH→ γγ : a winning combination!



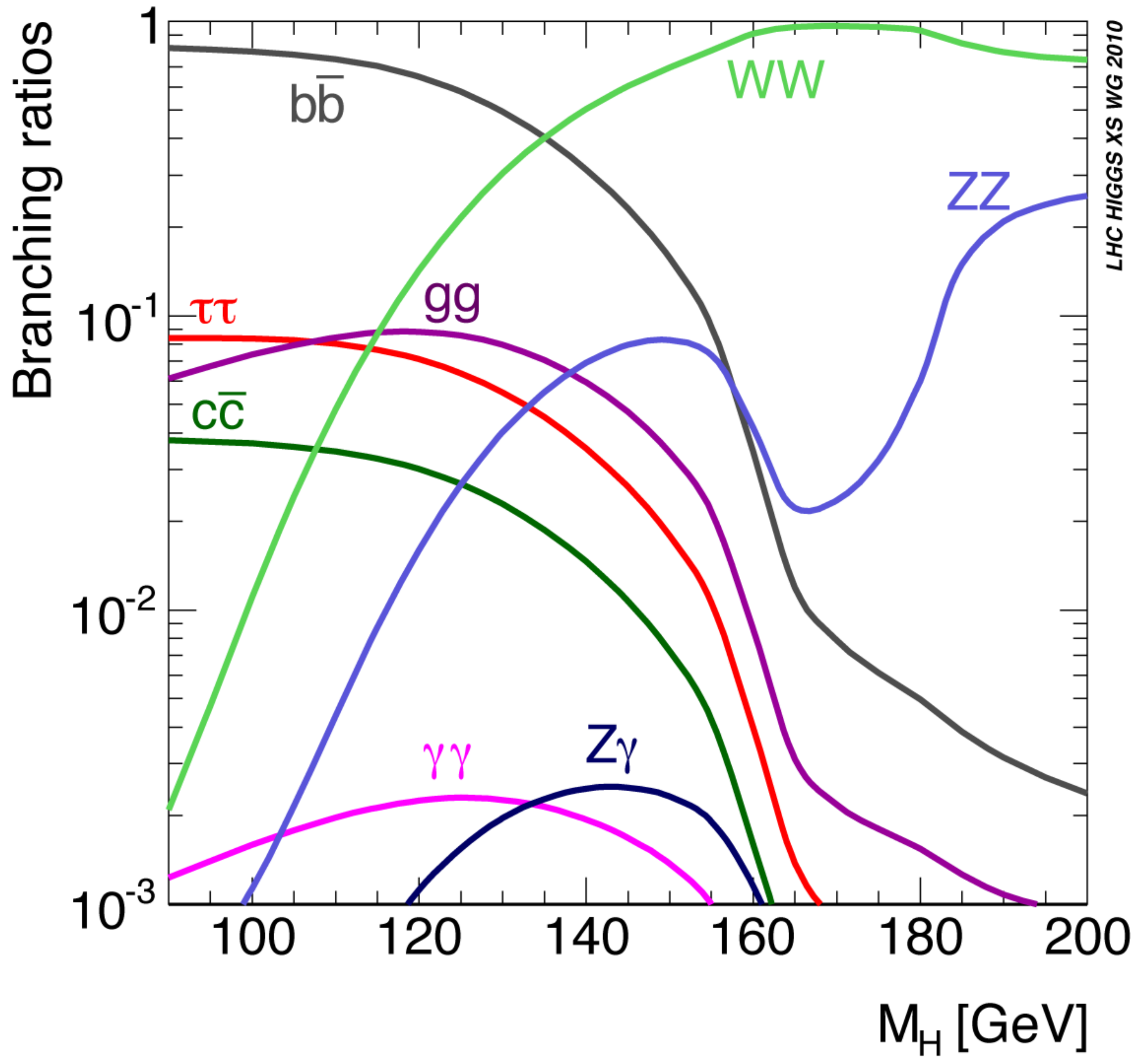
Dr Homer Simpson

H→ZZ?

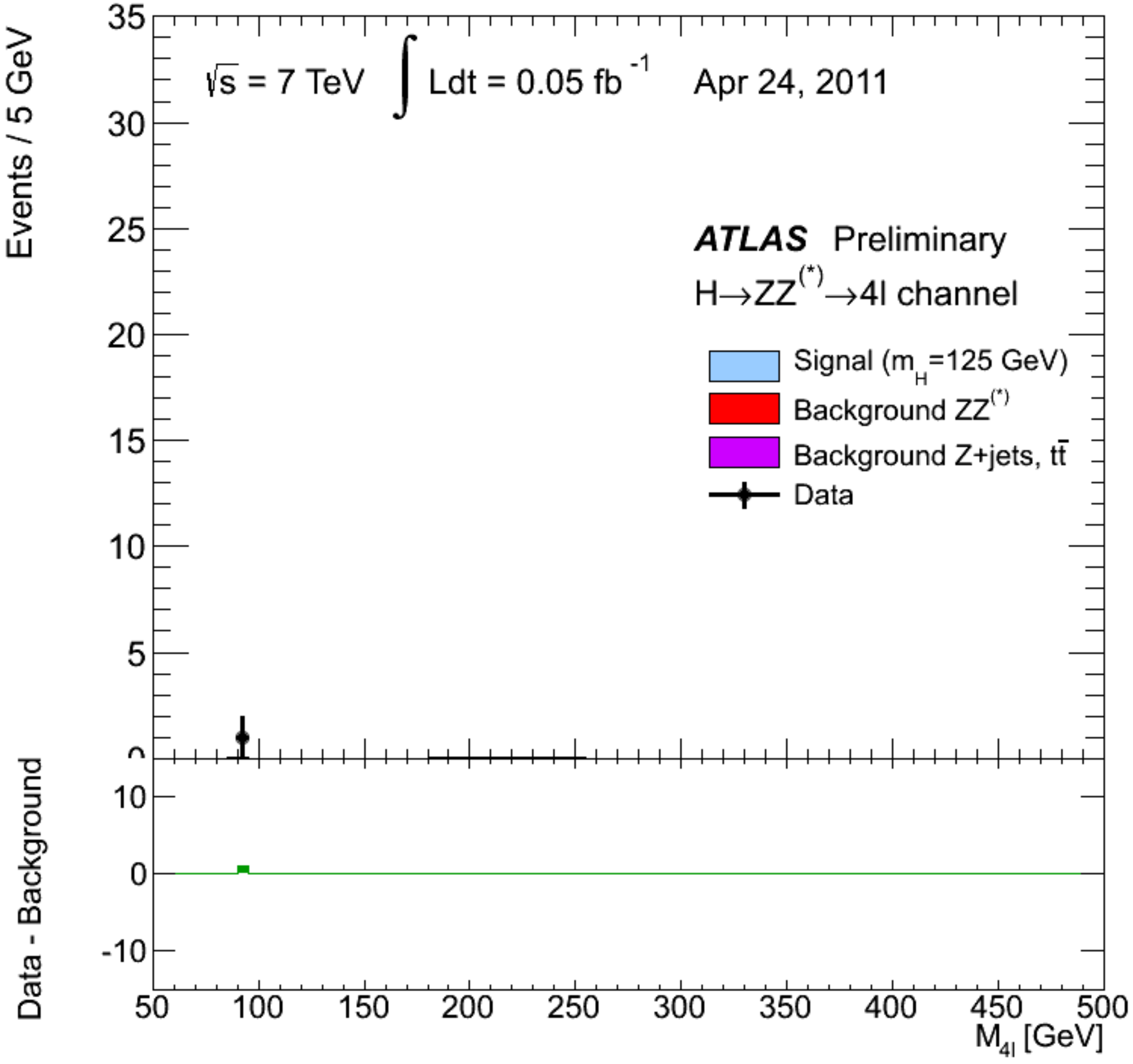
What about
H→ZZ→4e/eeμμ/4μ?



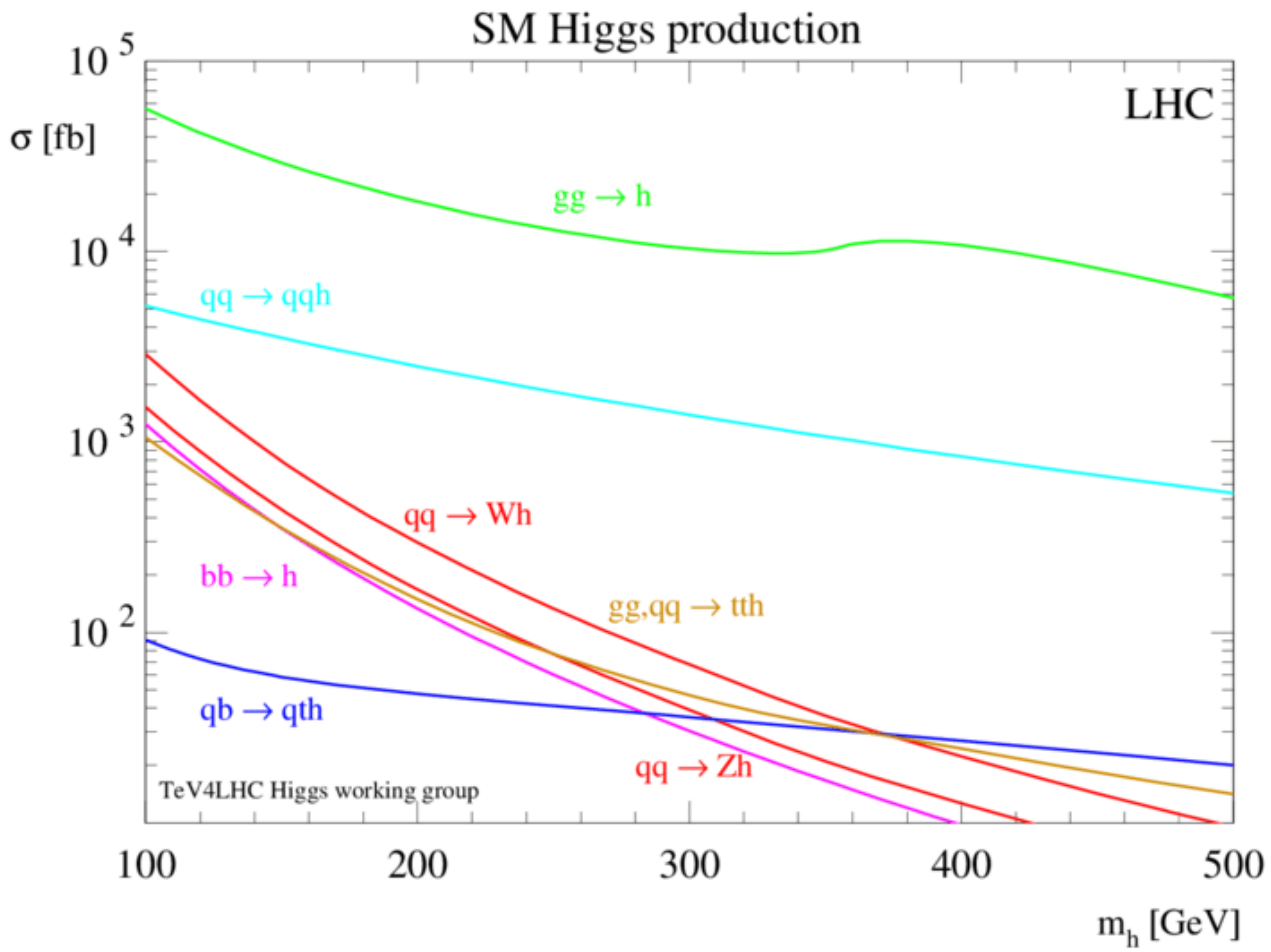
- ✓ Moderate branching ratio to ZZ.
- ✓ Z bosons can decay to electrons and muons that are easy to identify.
- ✓ Small backgrounds.
- ✓ Good mass resolution.
- ✗ BR(Z→ee/μμ) = 3.3% → BR(ZZ→4e/eeμμ/4μ) = 0.5%



H→ZZ : another winner!



But… what about H→bb?

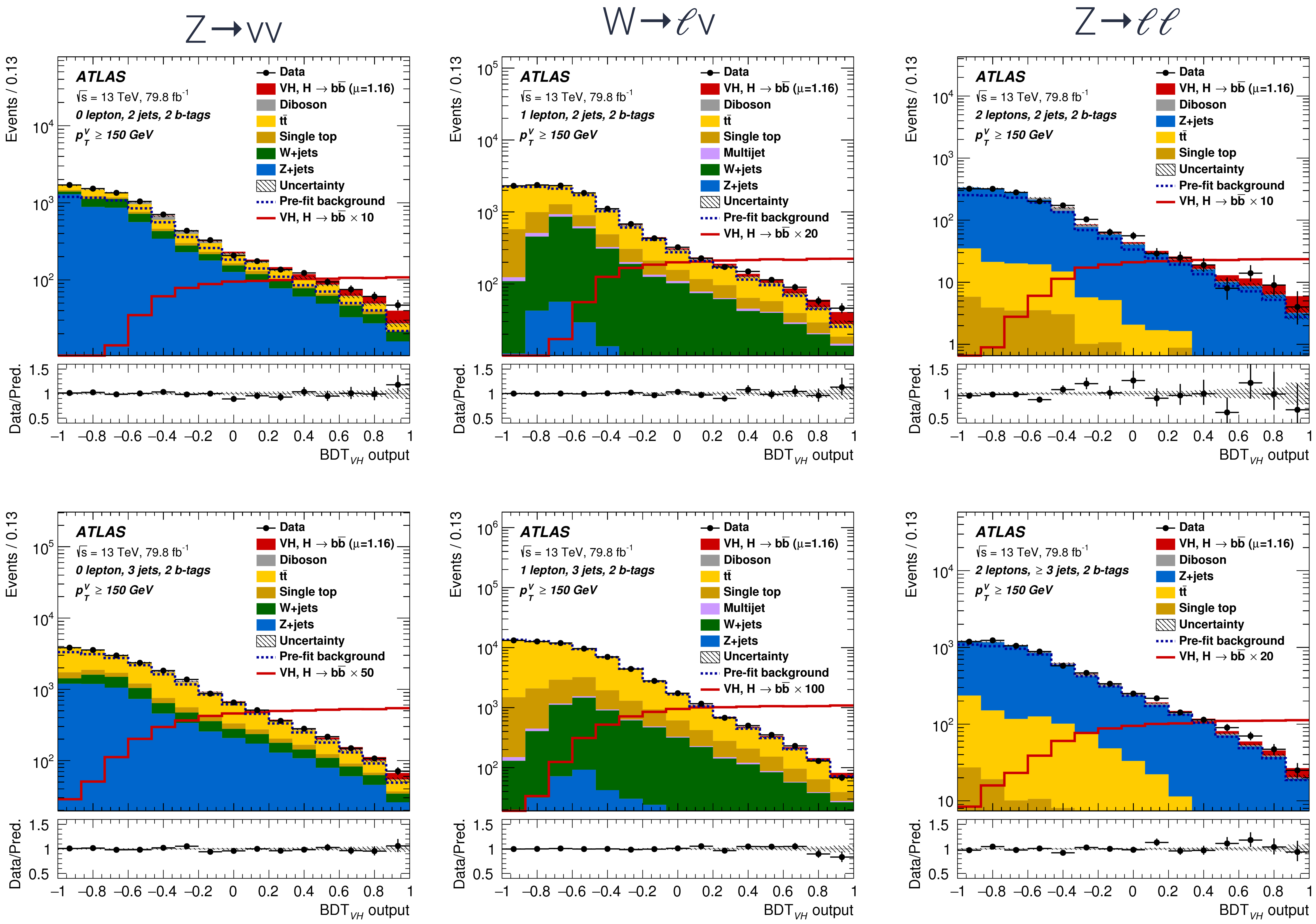


- Search for events where the Higgs is produced in association with a leptonically decaying W or Z boson to get an extra handle to reject backgrounds.
- Use BDTs to improve signal-background separation. (See T. Golling's lectures for more on machine learning.)

ggF
H→bb

VH (H→bb)
with machine
learning

H→bb



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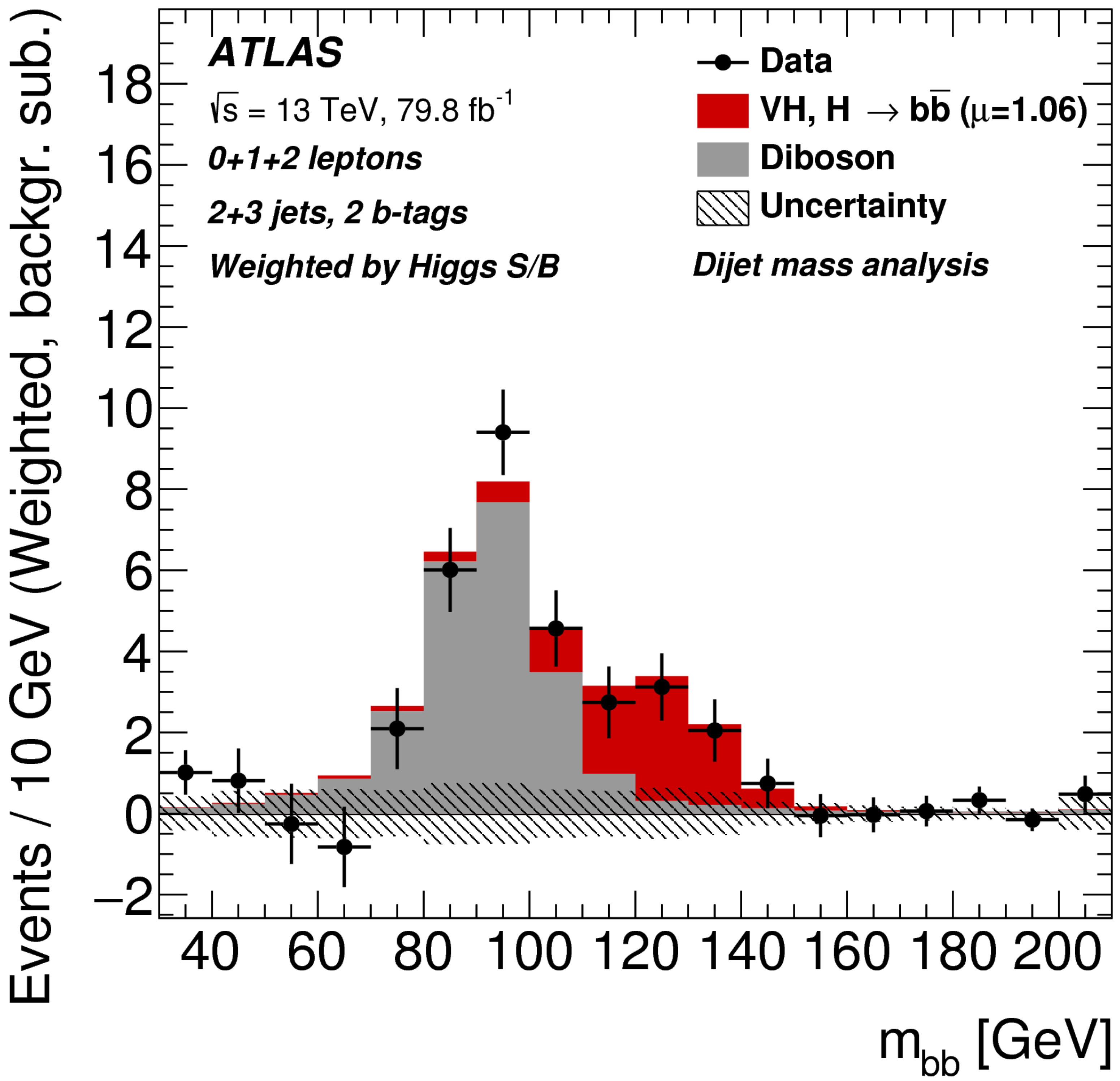


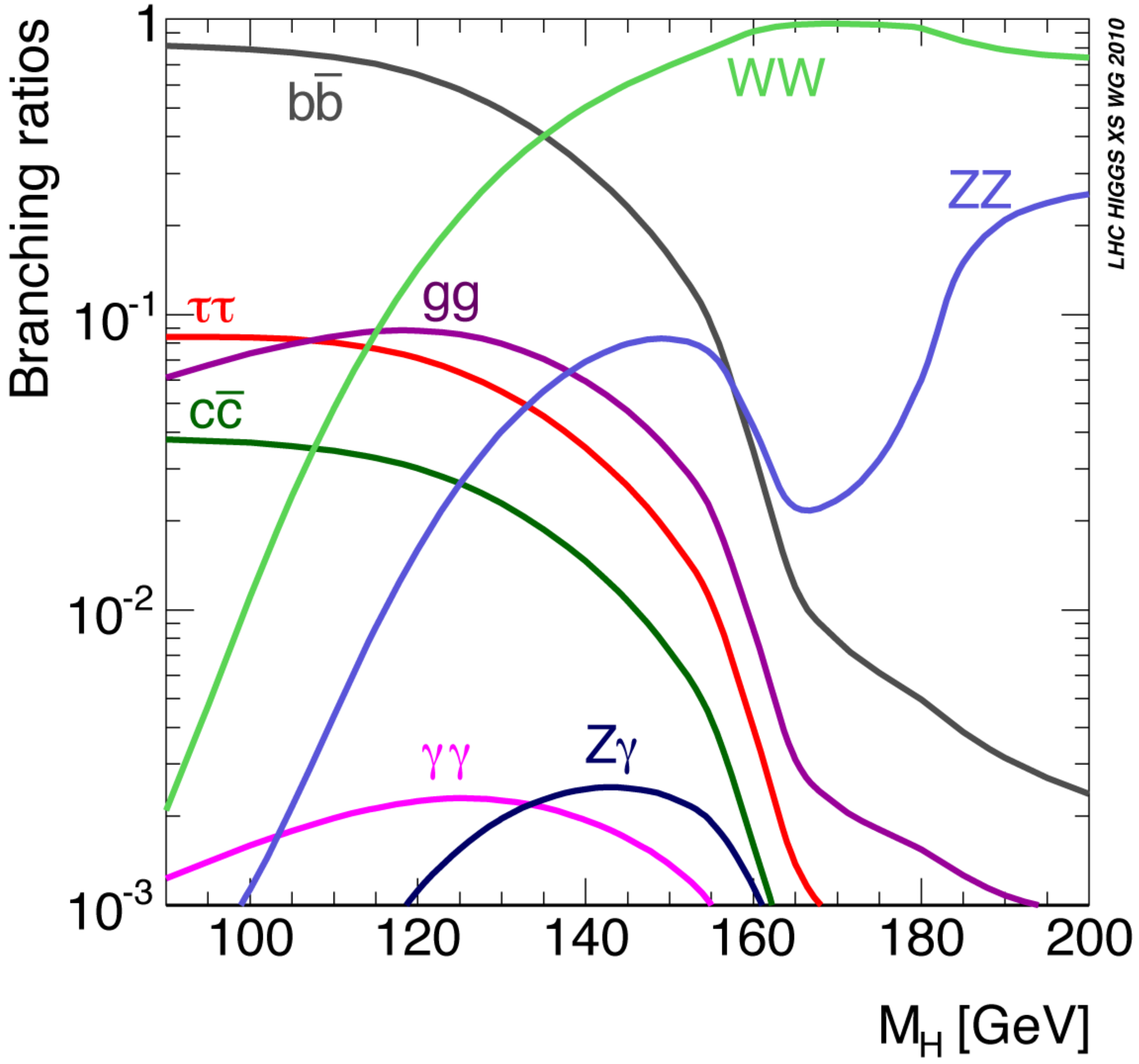
6 years after the Higgs discovery (γγ + ZZ channels), BDTs in 6 different signal regions, 3 x more data, √s increase from 7/8 TeV → 13 TeV.

Was it worth it?!

Yes!

During the Higgs “search phase”:

- We didn’t know its mass…
- …or if it would be SM-like…
- …or if it would even be there at all!



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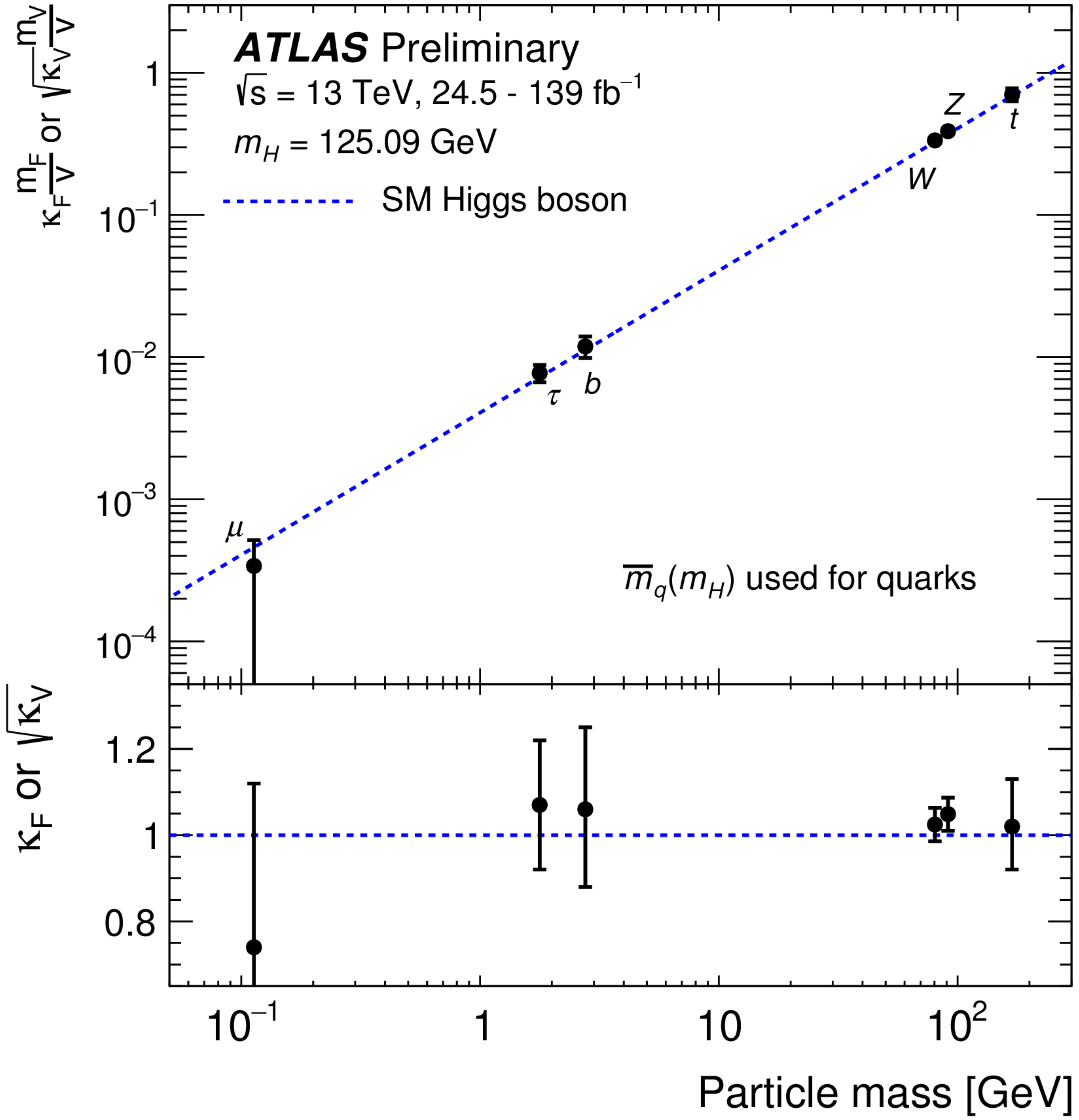
And later:

- Crucial to establish that the Higgs does decay to b-quarks (as predicted by the SM).
- Test mass hierarchy of Higgs couplings.



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3. What is the final state? Implement “Preselection” cuts.
   1. Typically demand that the events contain the same objects as you would expect in your signal that you can then use as a starting point for defining regions which are enriched in signal, and others that are enriched in backgrounds.
   2. Ensure the selection is loose enough that you can estimate background processes, but tight enough that your data volume is manageable.

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    i. Multijet background almost always extracted from data.
    ii. Also need to correct MC for real-life data conditions.

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   2. Also need to correct MC for real-life data conditions.
5. As statistics increase, more difficult, since mis-modelings not hidden by statistical uncertainties anymore
   1. Mis-modelings often show up in tails…

So what BSM physics should I look for?

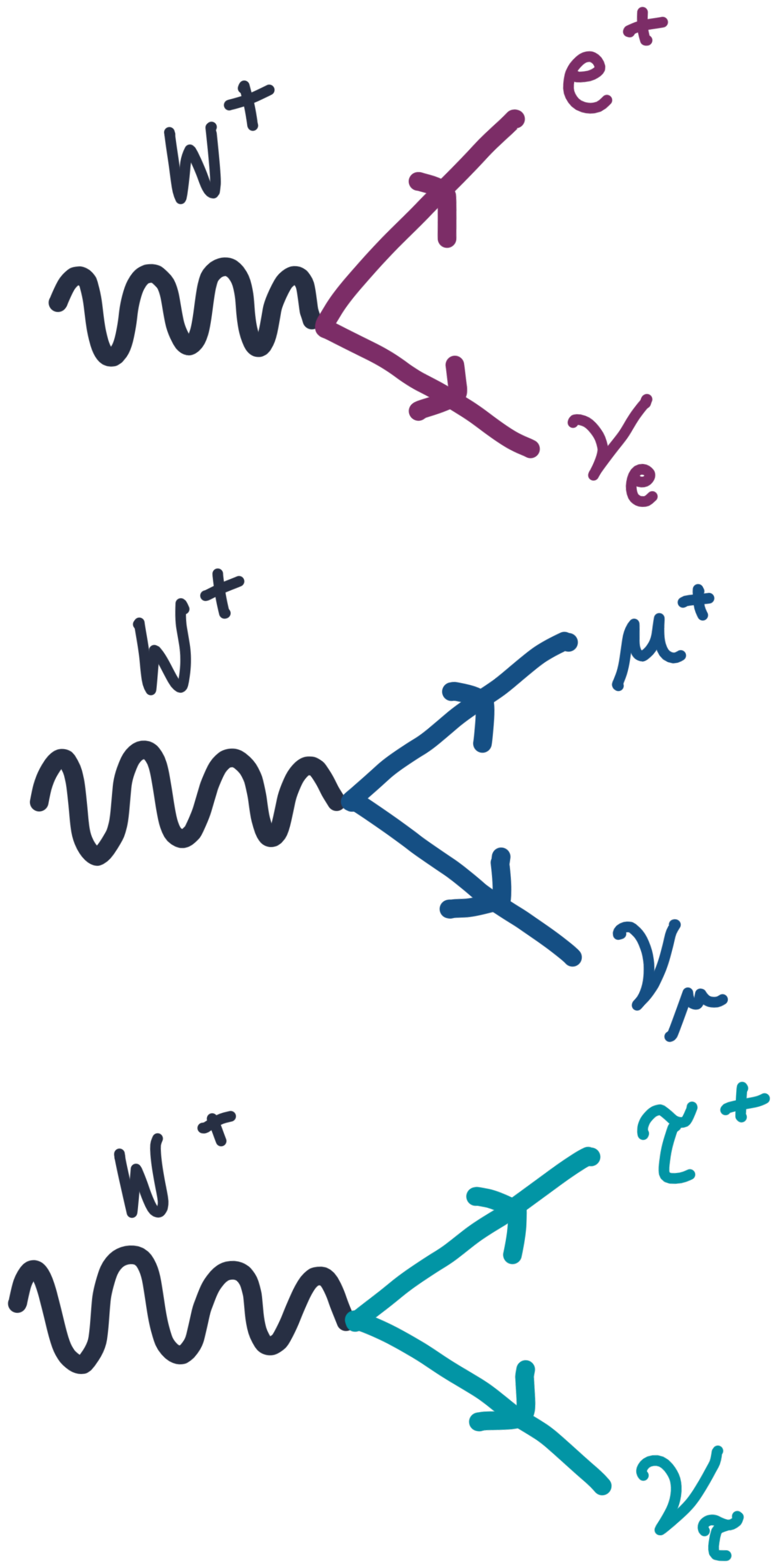
- Saw before that there are many phenomena still not understood - most searches are motivated by trying to address one (or more) of these problems.
- Additionally, precision measurements of SM processes often provide key insight into where new physics might be hiding.
  - Helps guide where to focus efforts for new physics searches.

CAUTION: Anomalies in measurements are not proof of new physics! But… they can provide useful clues about where to look.

Case study: lepton flavour universality

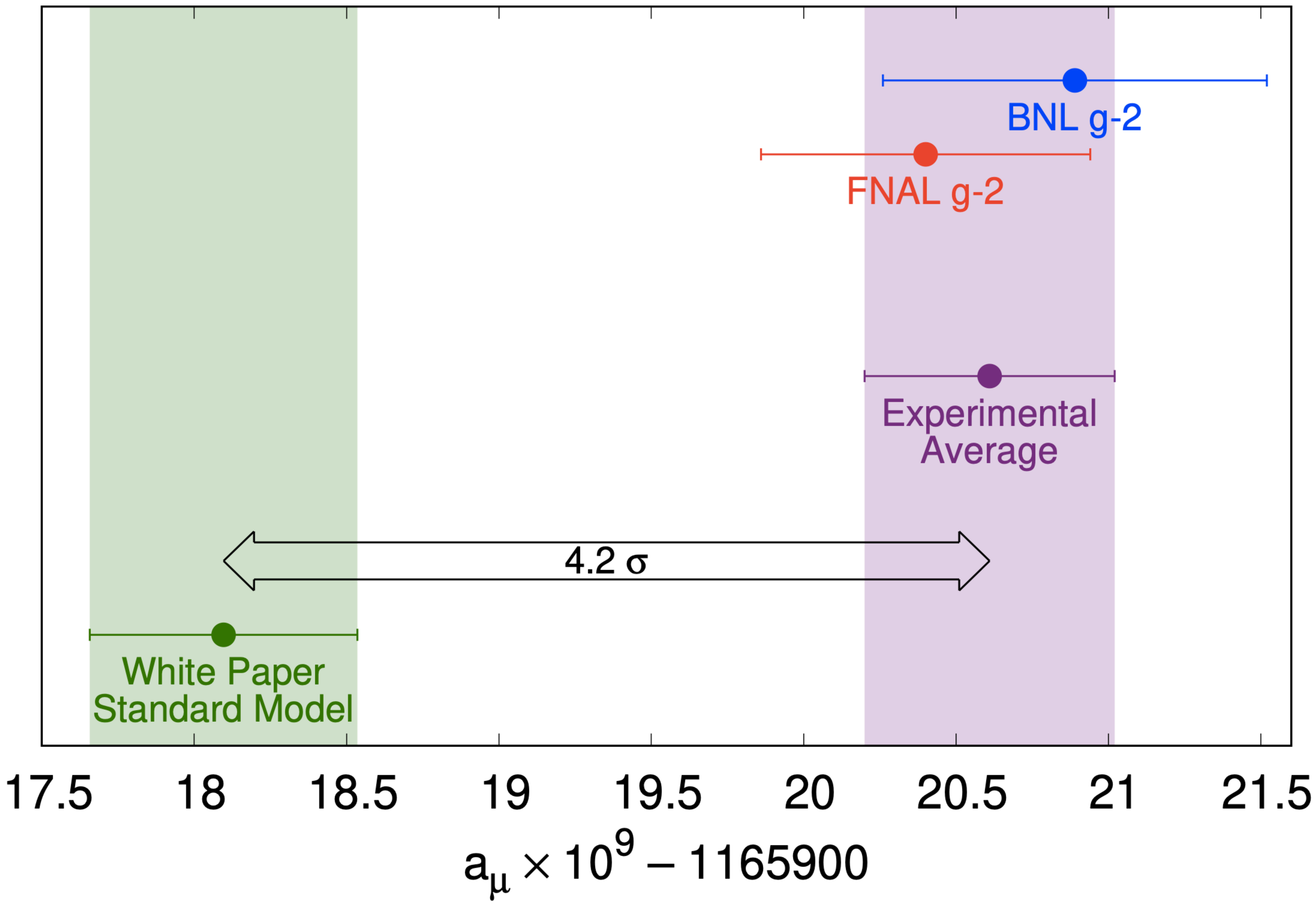
Lepton universality

- Standard Model predicts lepton universality, i.e. the coupling of leptons to all types of gauge boson are flavour-independent.
- Some experimental hints that this might not be the case.



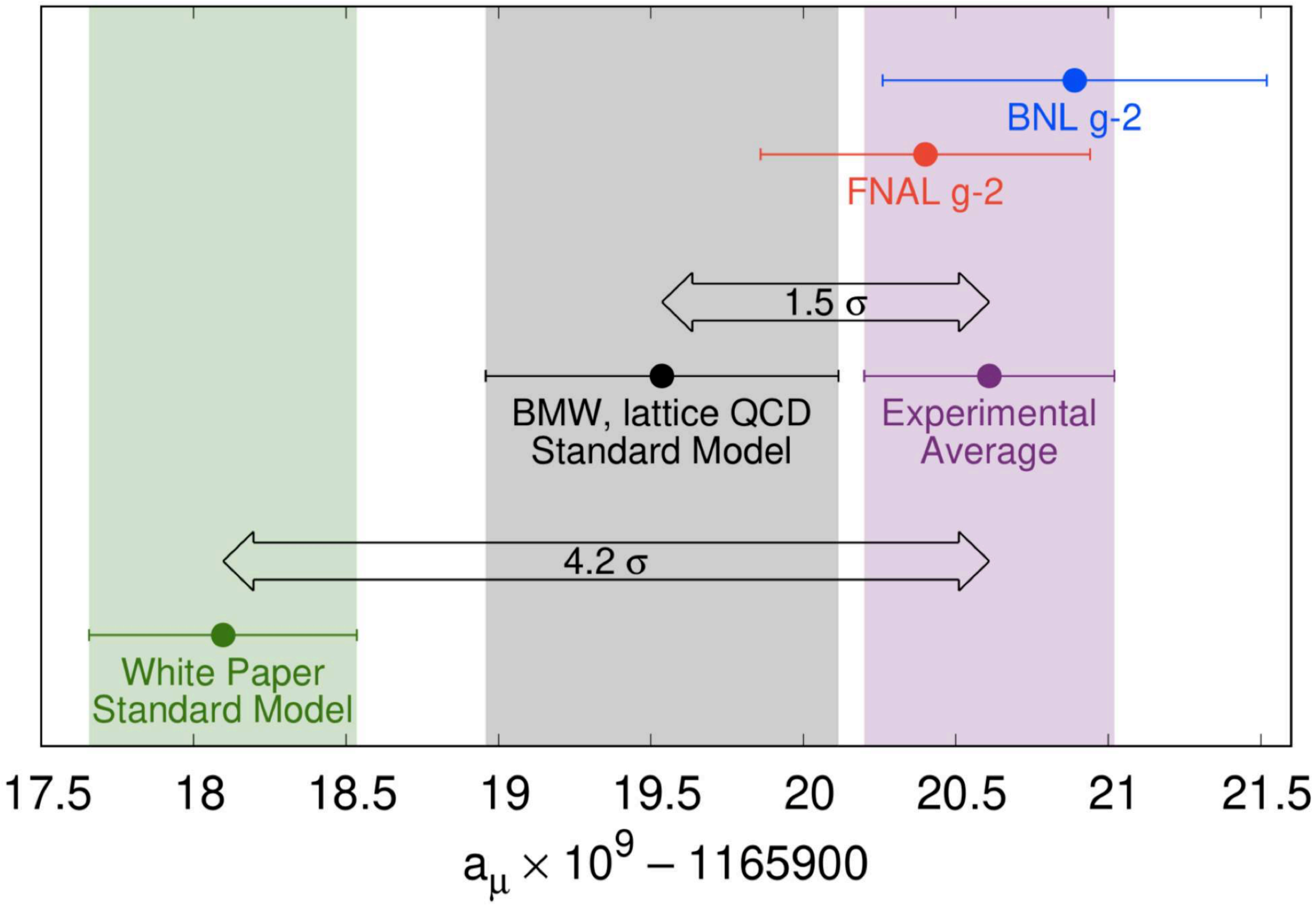
Muon g-2

Measurement of muon anomalous magnetic moment in 4.2σ tension with SM prediction…



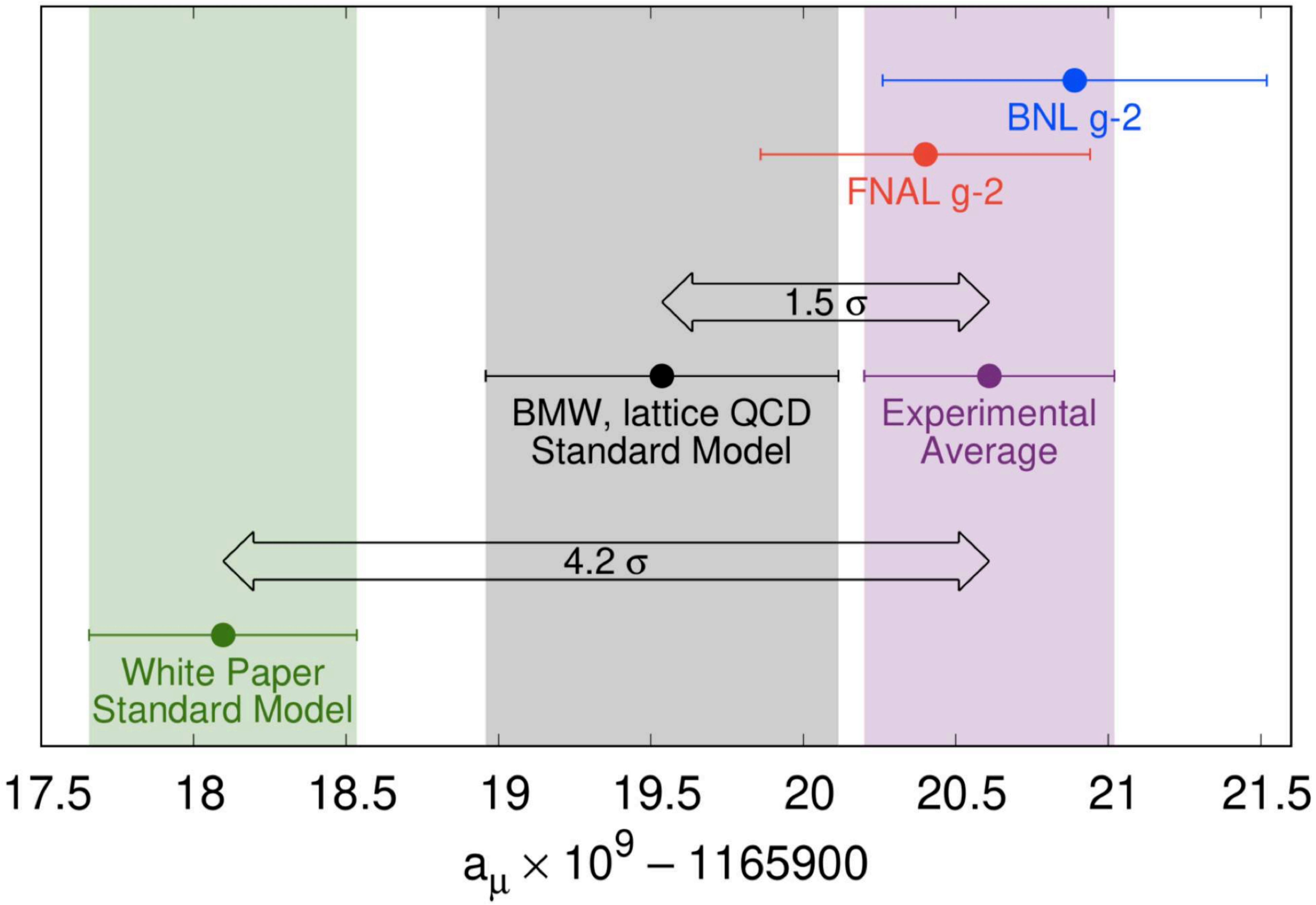
Muon g-2

… but newer theory prediction that uses a different approach is only 1.5σ away from measurement.



Muon g-2

… but newer theory prediction that uses a different approach is only 1.5σ away from experimental average.

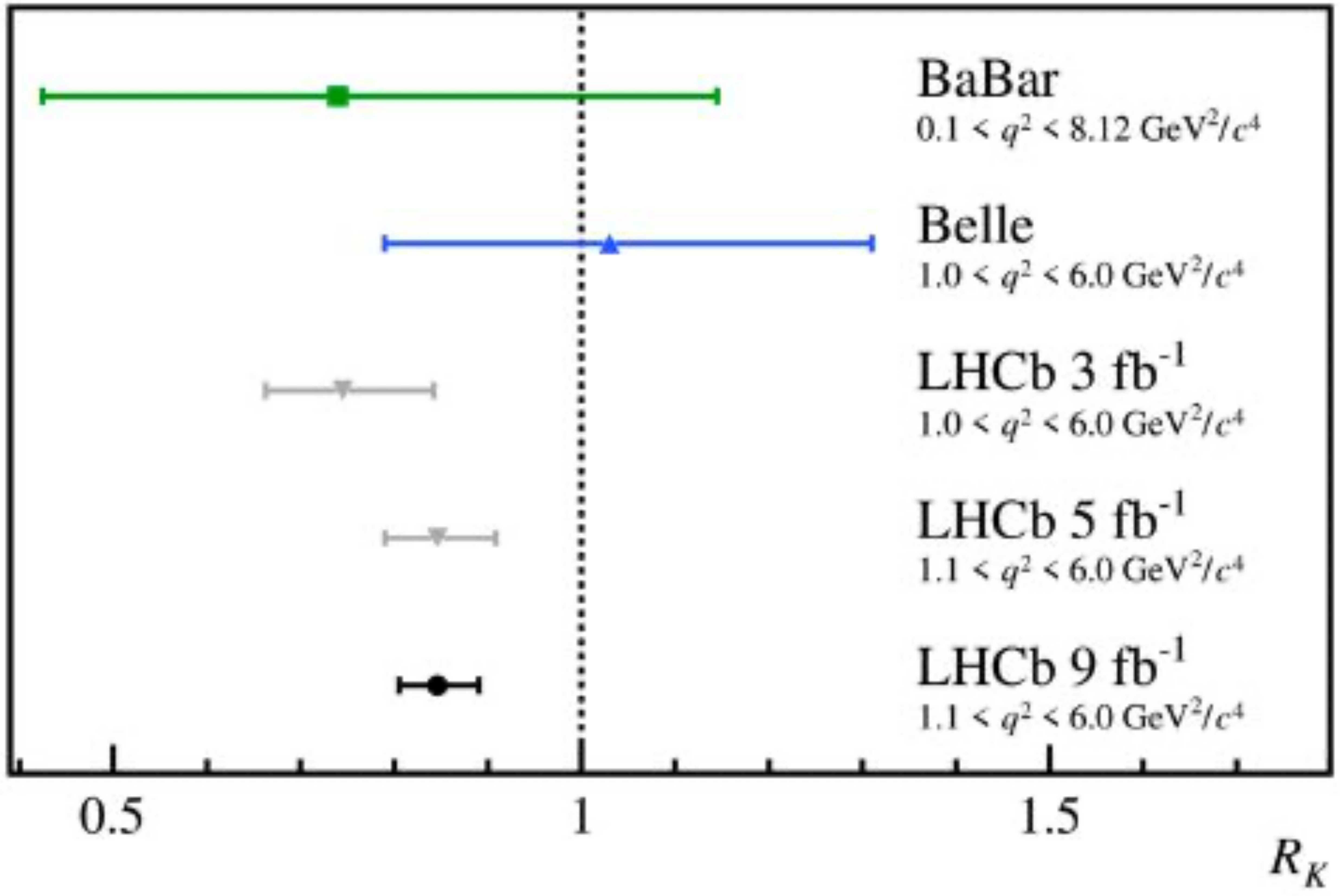


Too early to get excited, but intriguing when considered in context with the other flavour anomalies…

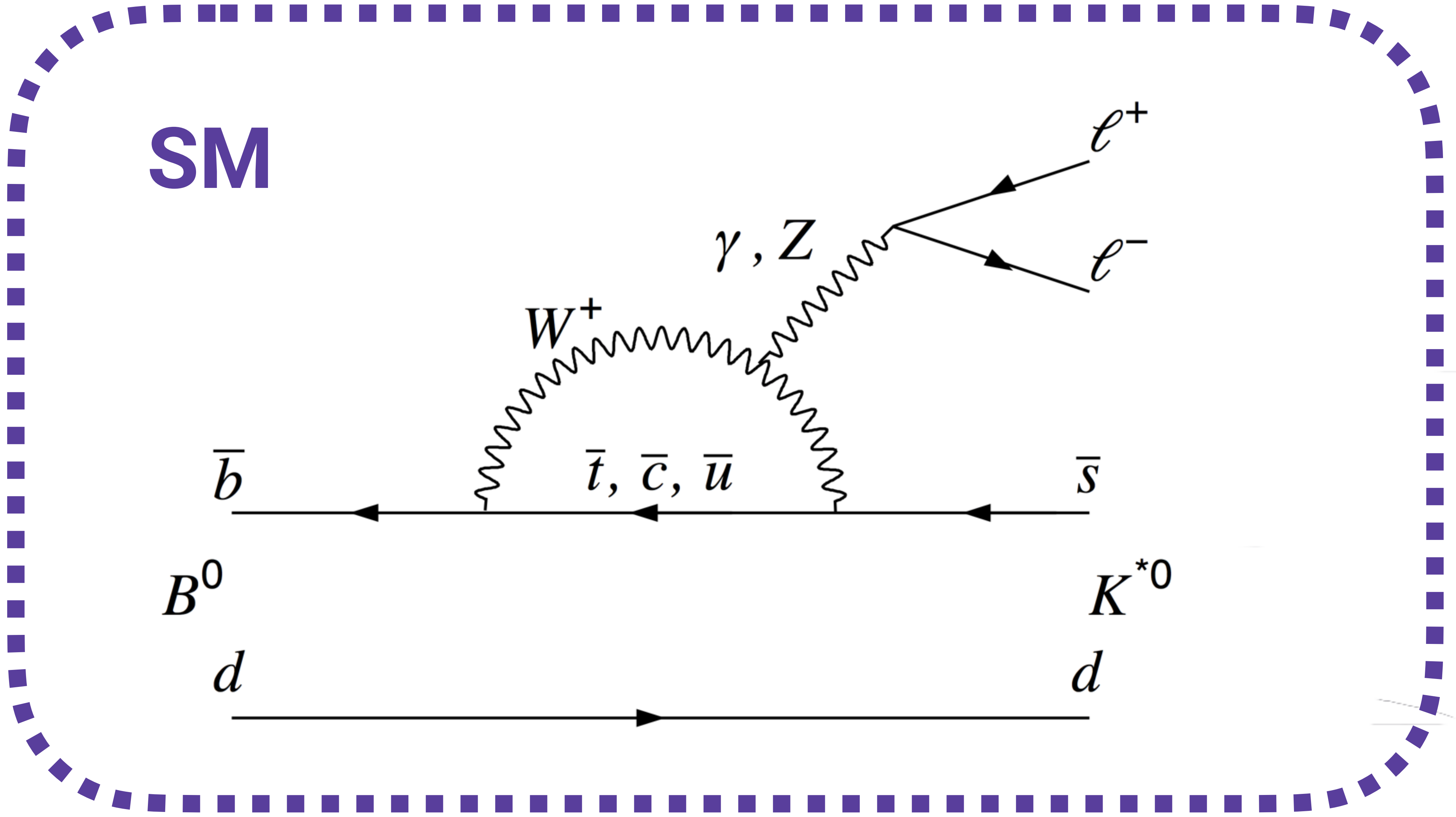
Interesting to see how this will develop in the coming years, with more data/improved experimental methods.

Flavour anomalies

- Small-to-moderate deviations from SM predictions in many measurements probing lepton universality.
- e.g. R(K),R(K*) combination deviates from SM by ~2−2.5σ.

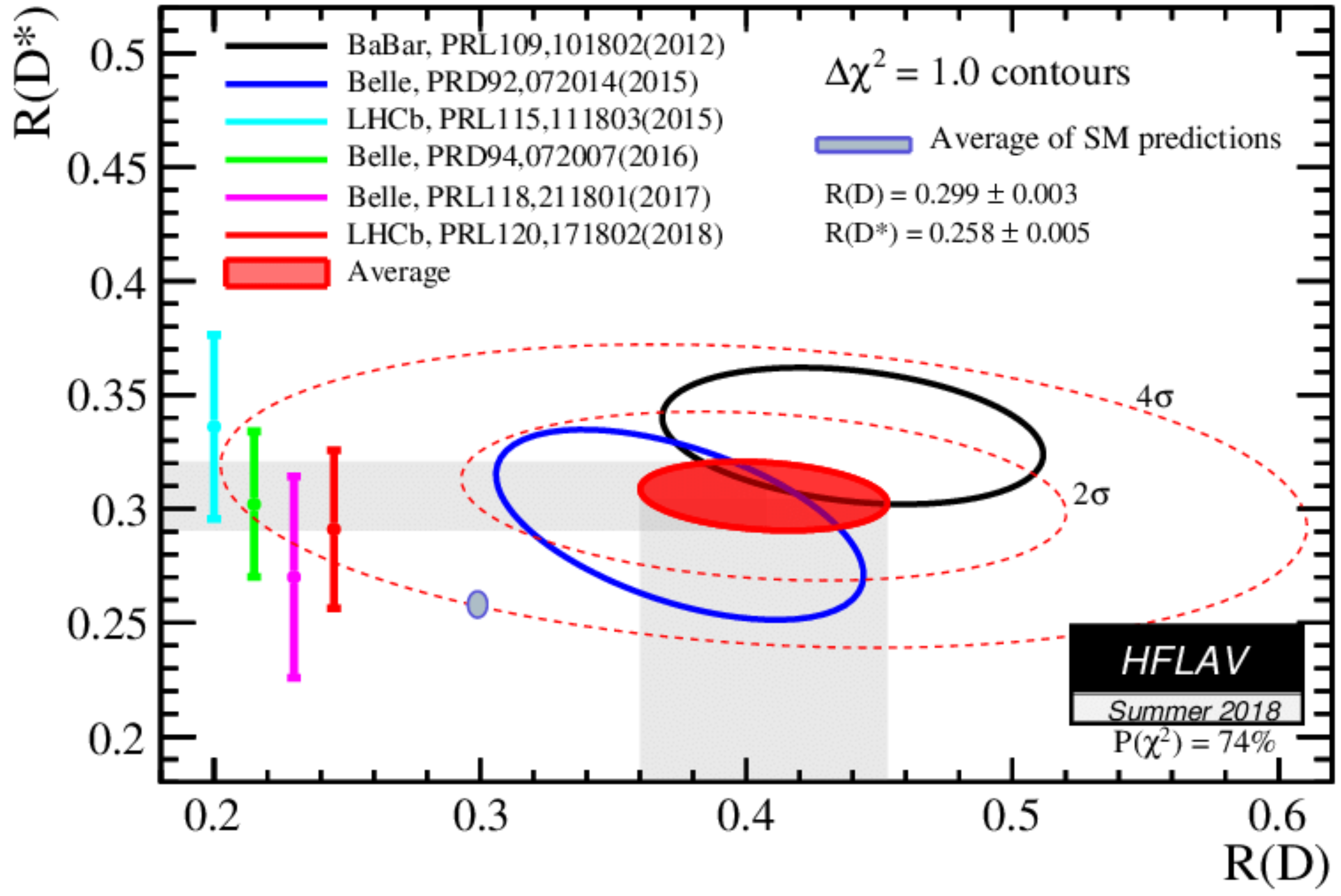


$$R(K^{(*)}) = \frac{BR(B \to K^{(*)}\mu^+\mu^-)}{BR(B \to K^{(*)}e^+e^-)}$$

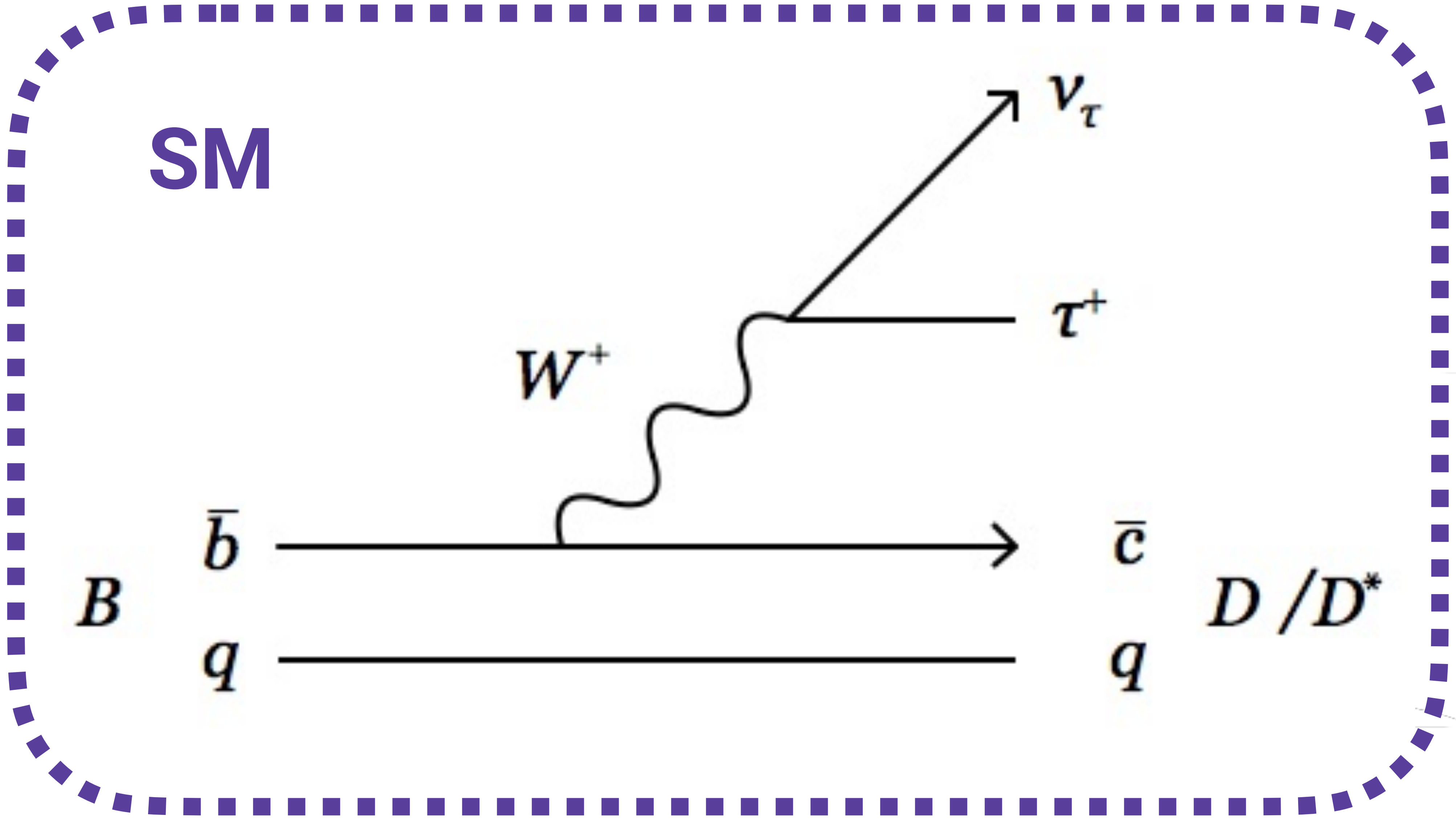


Flavour anomalies

- R(D),R(D*) combination deviates from SM by ~4σ.



$$R(D^{(*)}) = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\mu\nu)}$$



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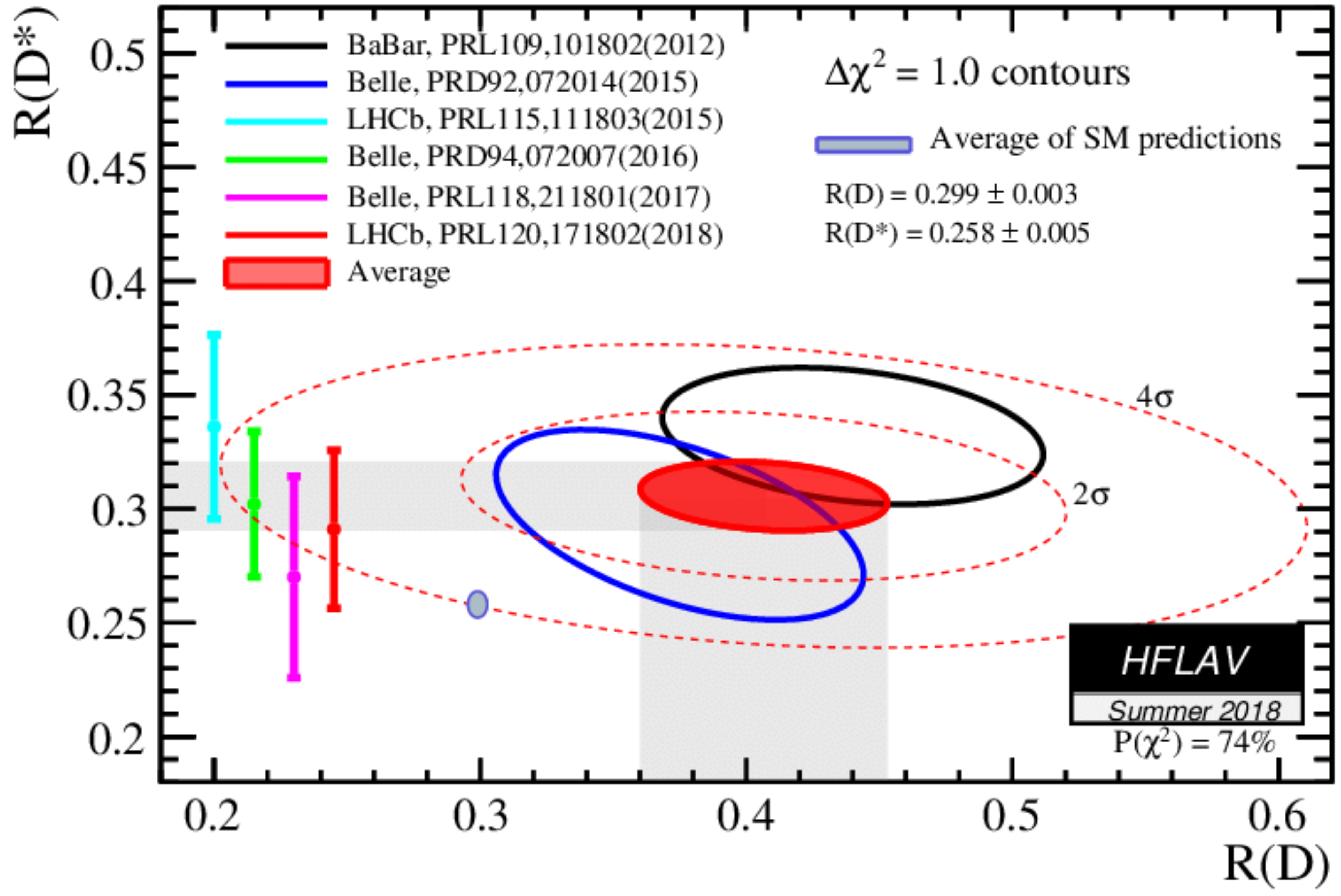

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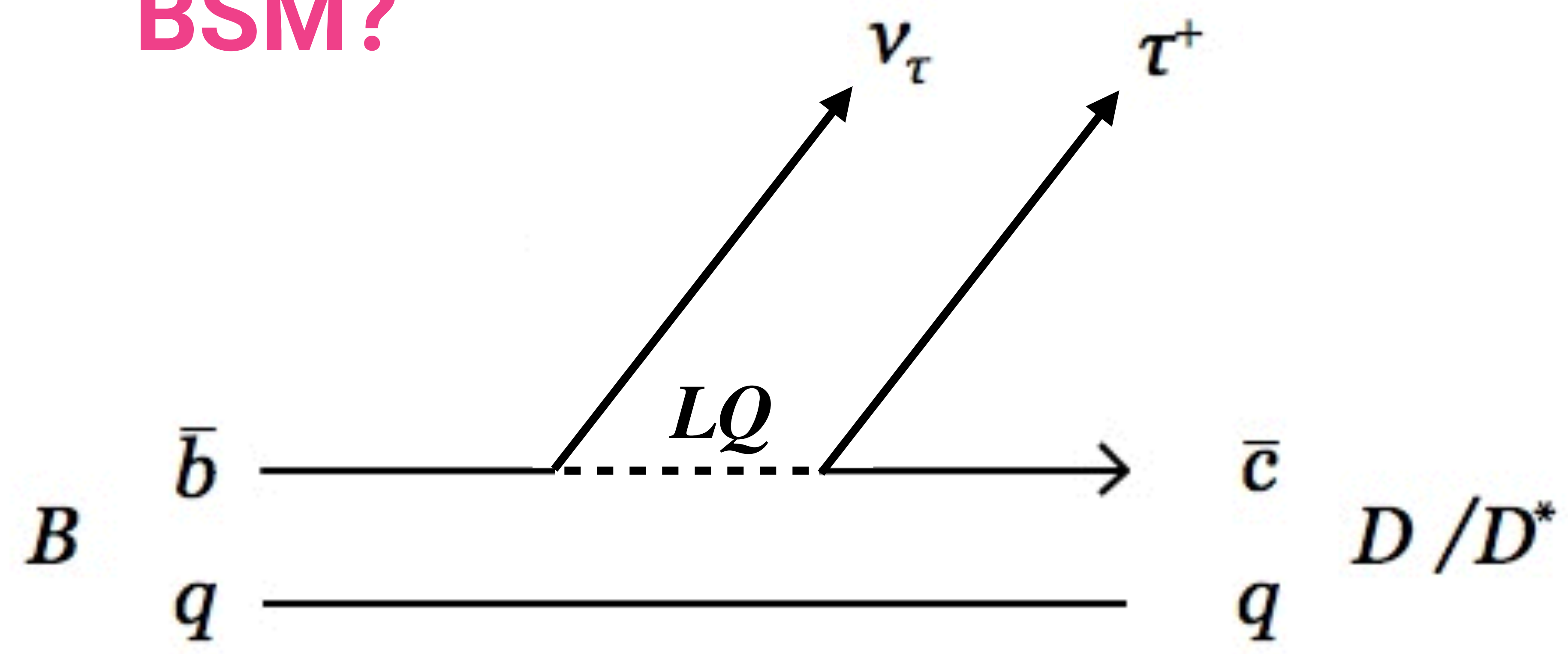
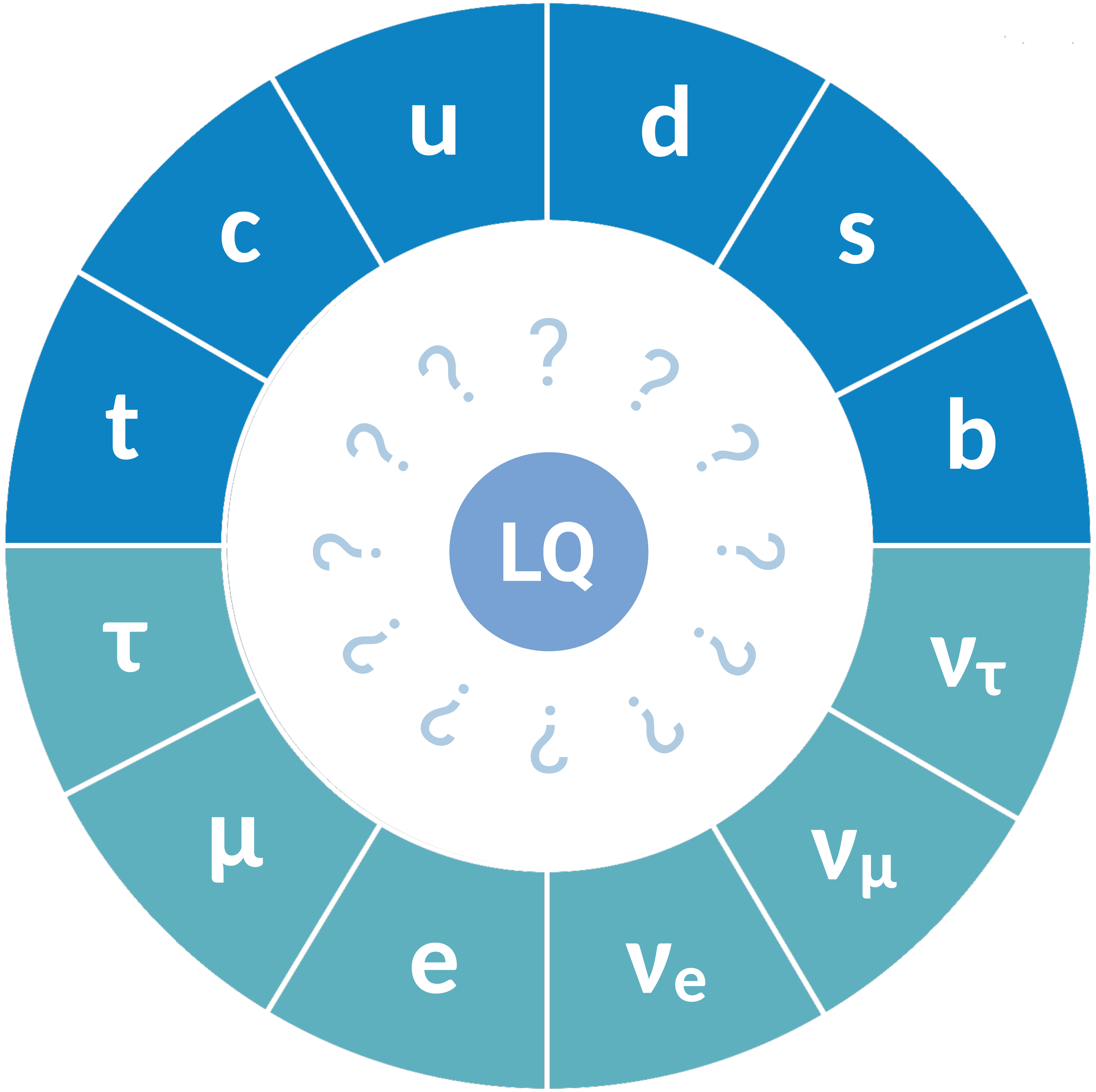
BSM?



Possible explanation: Leptoquarks

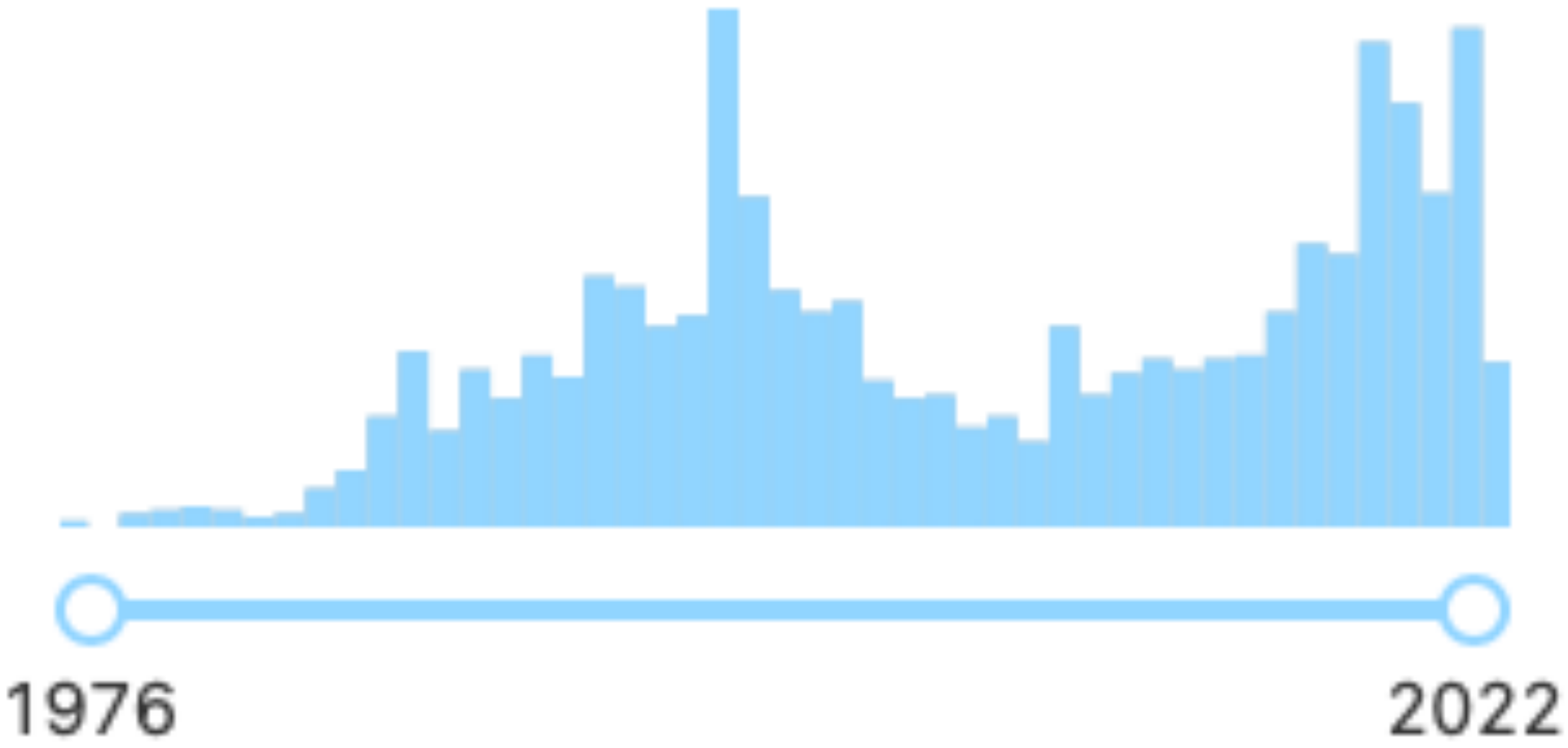
- Motivated by many similarities between quarks and leptons (mass hierarchy, charge cancellation etc).
- Similarities between quarks and leptons suggest a possible link between the two sectors.

→ Leptoquarks: Hypothetical particles which mediate quark-lepton transitions.



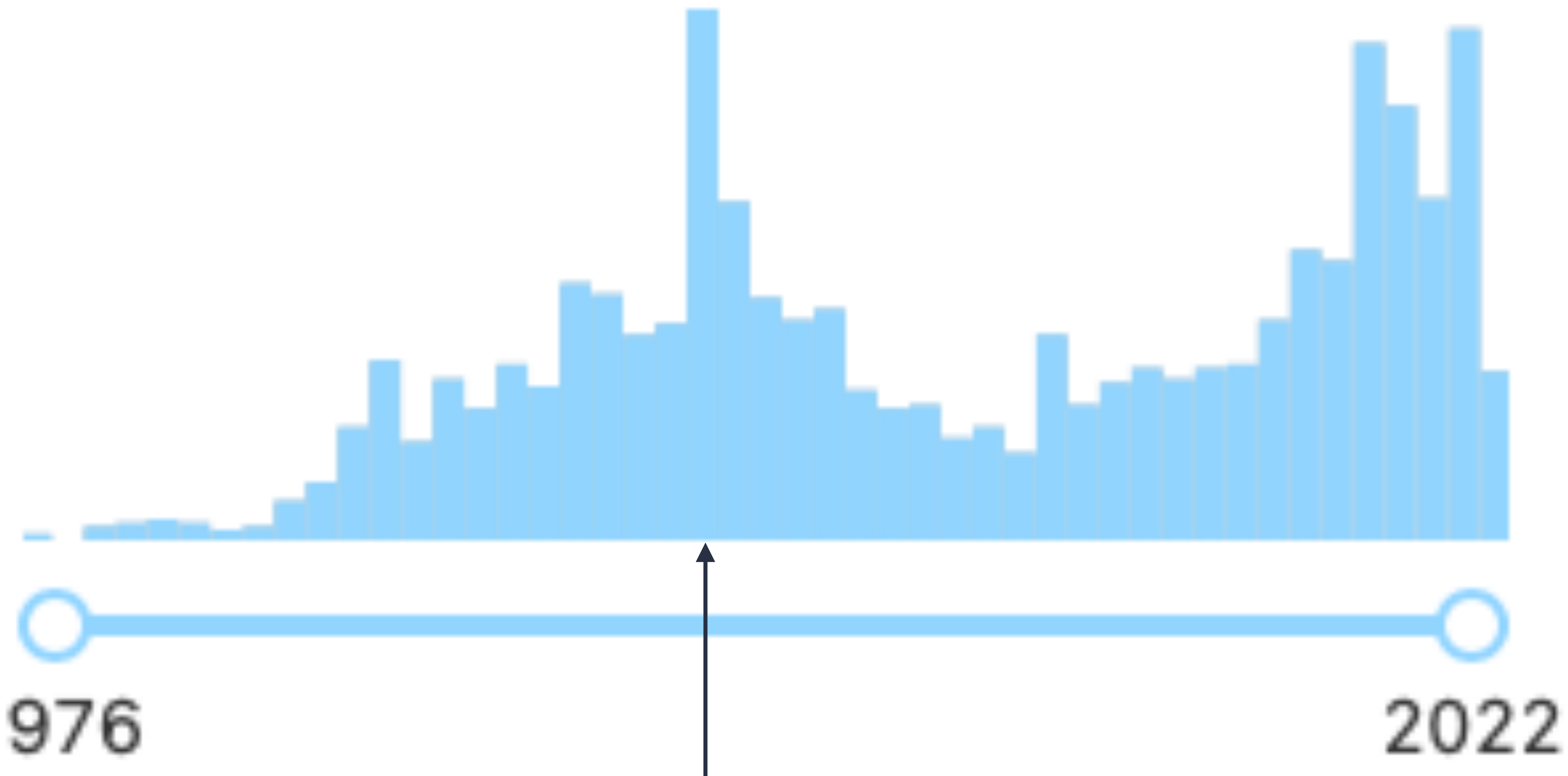
Leptoquarks à la mode

Search results for "leptoquark" papers on Inspire, by year



Leptoquarks à la mode

SEARCH RESULTS FOR "LEPTOQUARK" PAPERS ON INSPIRE, BY YEAR



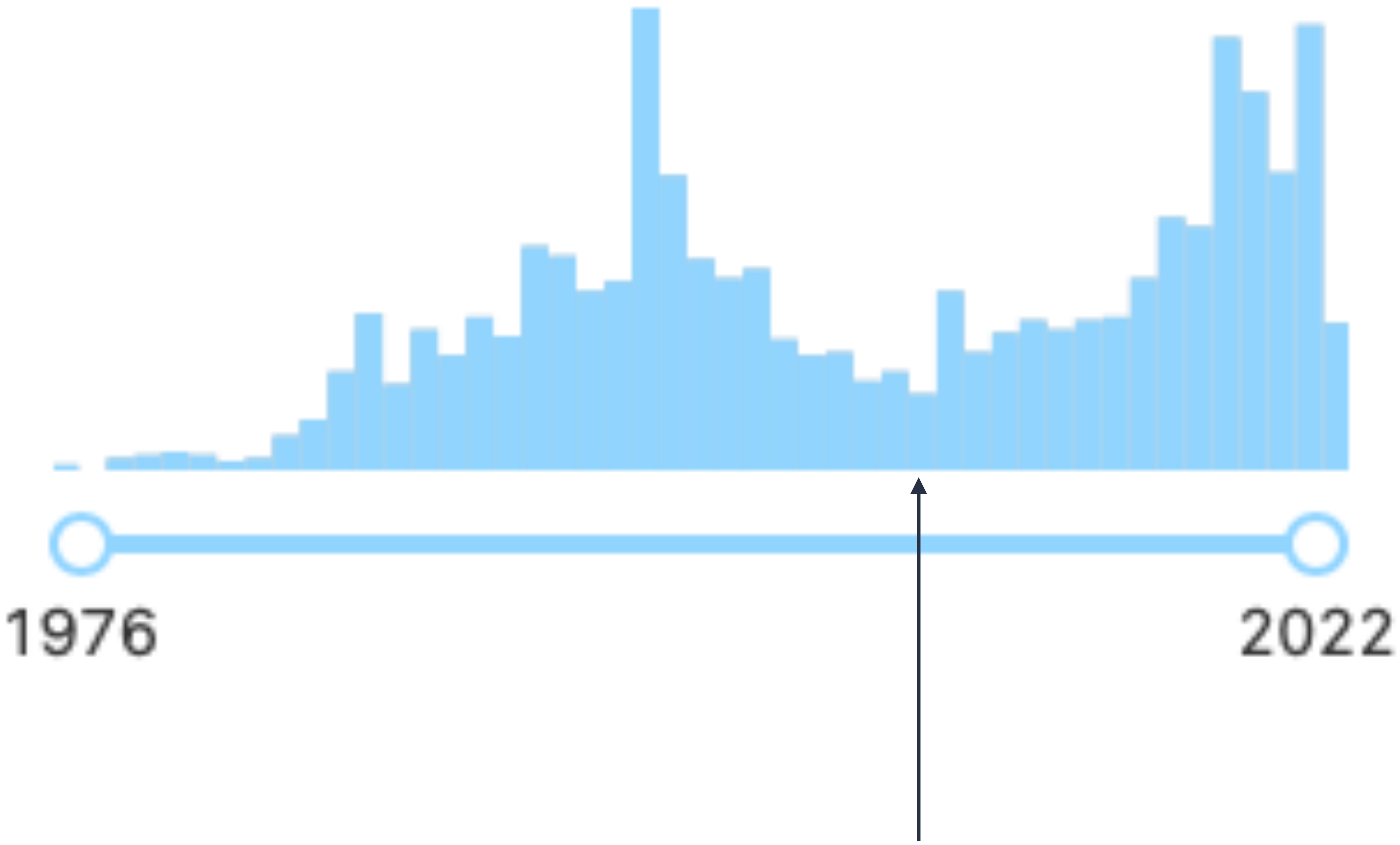
1997: H1 and ZEUS collaborations (HERA accelerator) make measurements of electron-proton scattering and both see (mild) excesses of events with large Q^2.

Z.Phys.C74:191-206,1997

Z.Phys.C74:207-220,1997

Leptoquarks à la mode

SEARCH RESULTS FOR "LEPTOQUARK" PAPERS ON INSPIRE, BY YEAR



Excesses are diluted/disappear once more data is analysed.
Direct searches for leptoquarks at HERA and the Tevatron yield null results.

Leptoquarks à la mode

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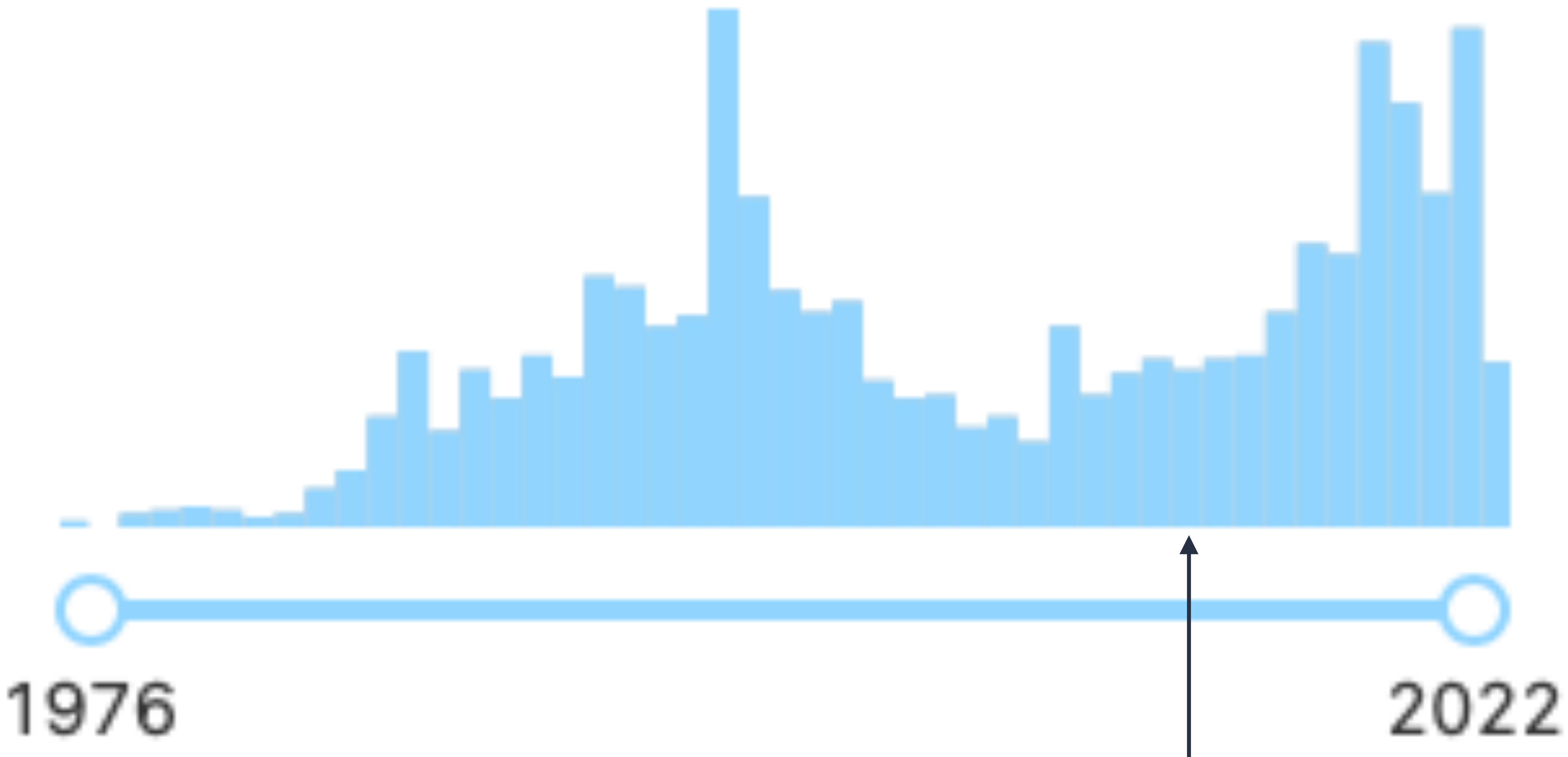
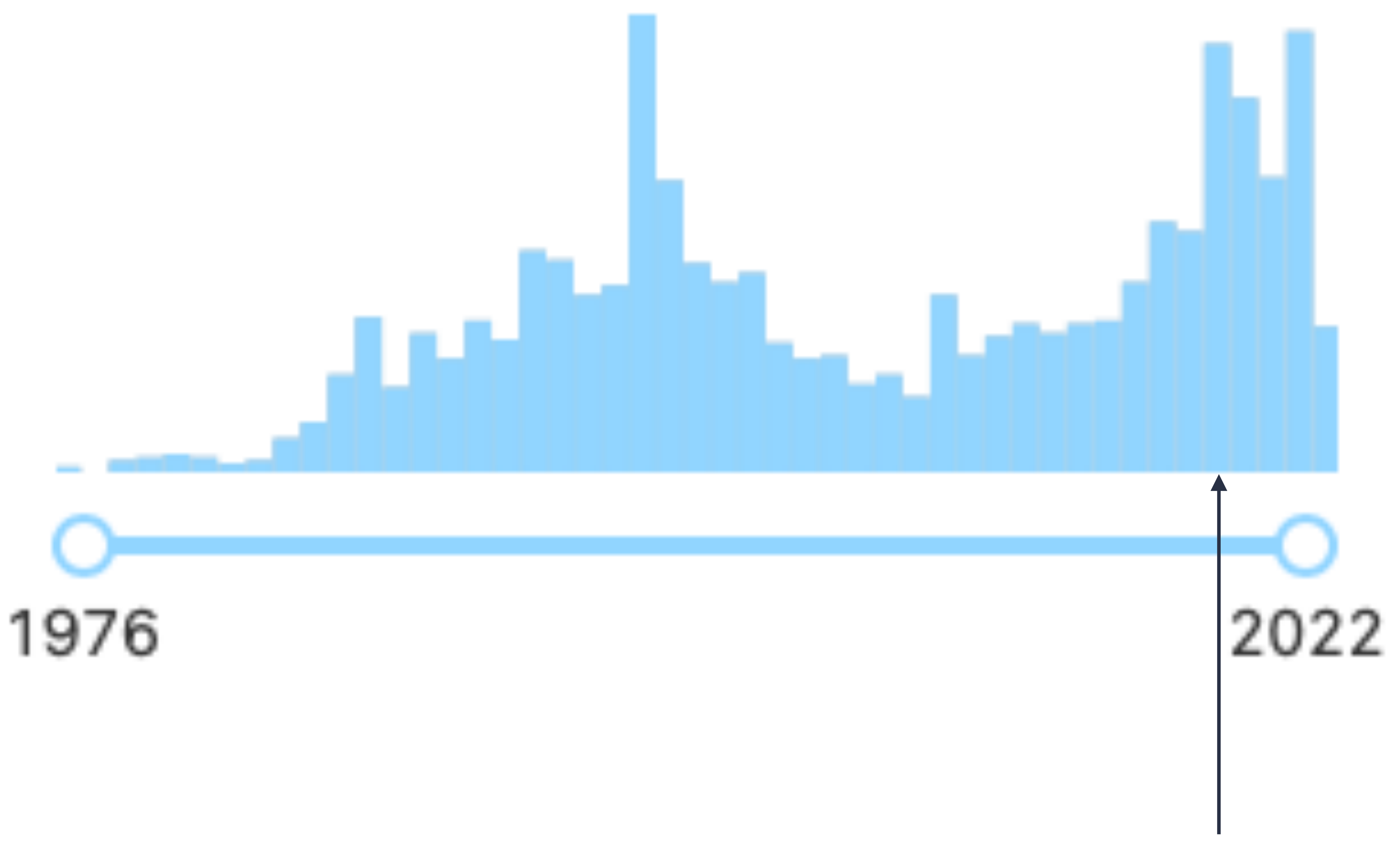


Belle and BaBar observe ~3σ deviations from SM predictions in measurements of $R_{D^{(*)}}$

Leptoquarks à la mode

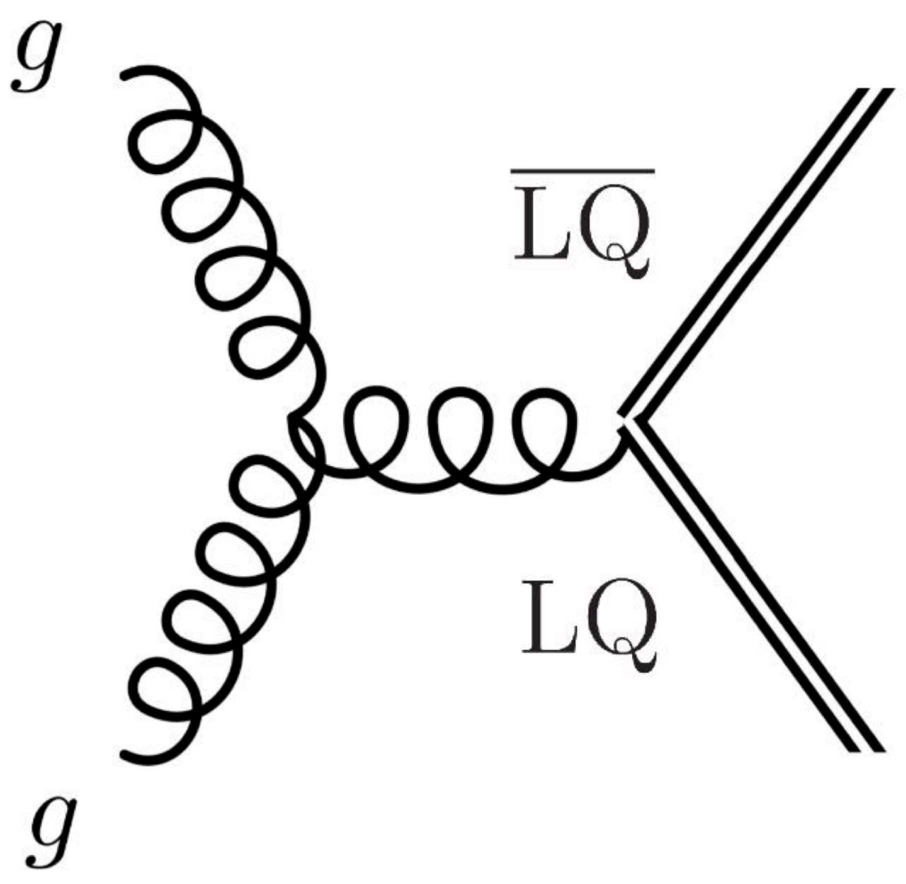
Search results for "leptoquark" papers on Inspire, by year

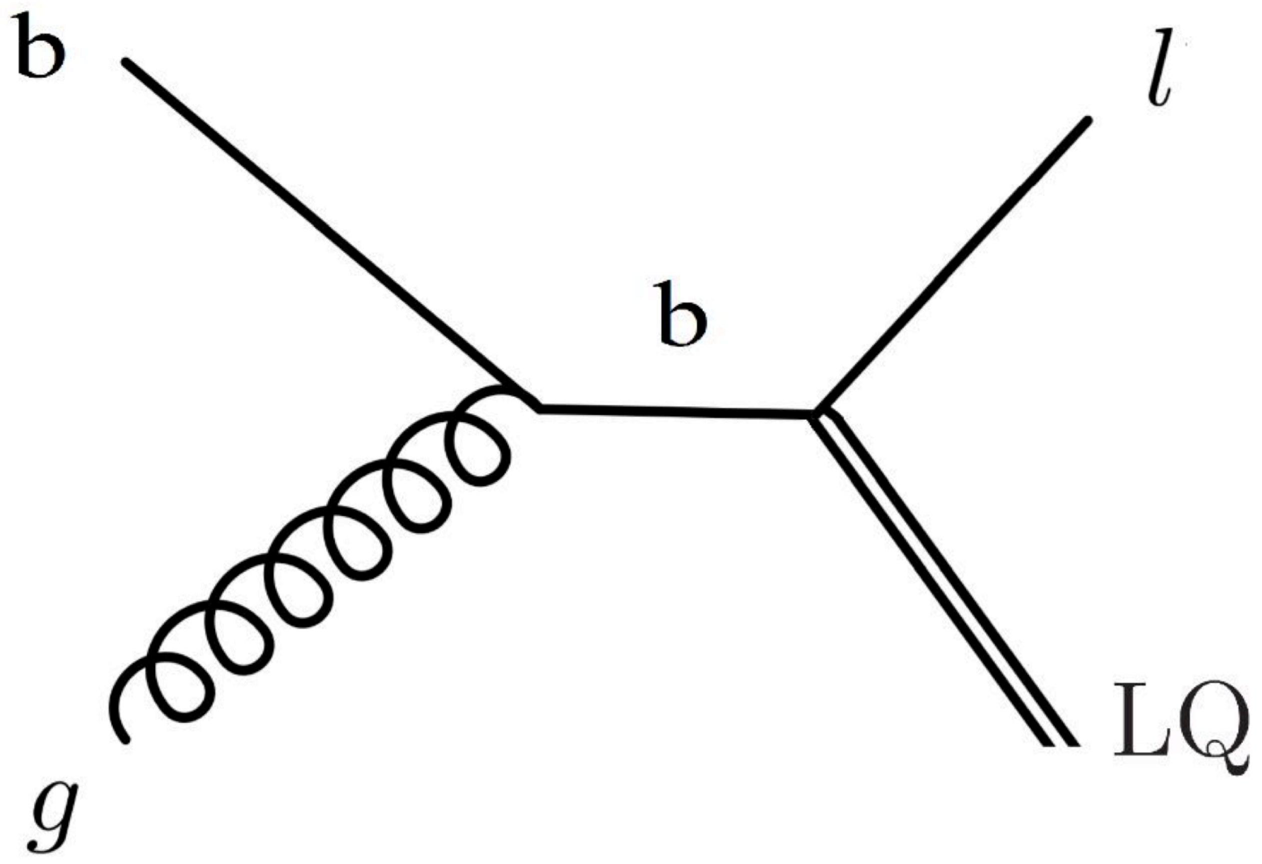


More measurements from LHCb, providing even stronger evidence for lepton non-universality.

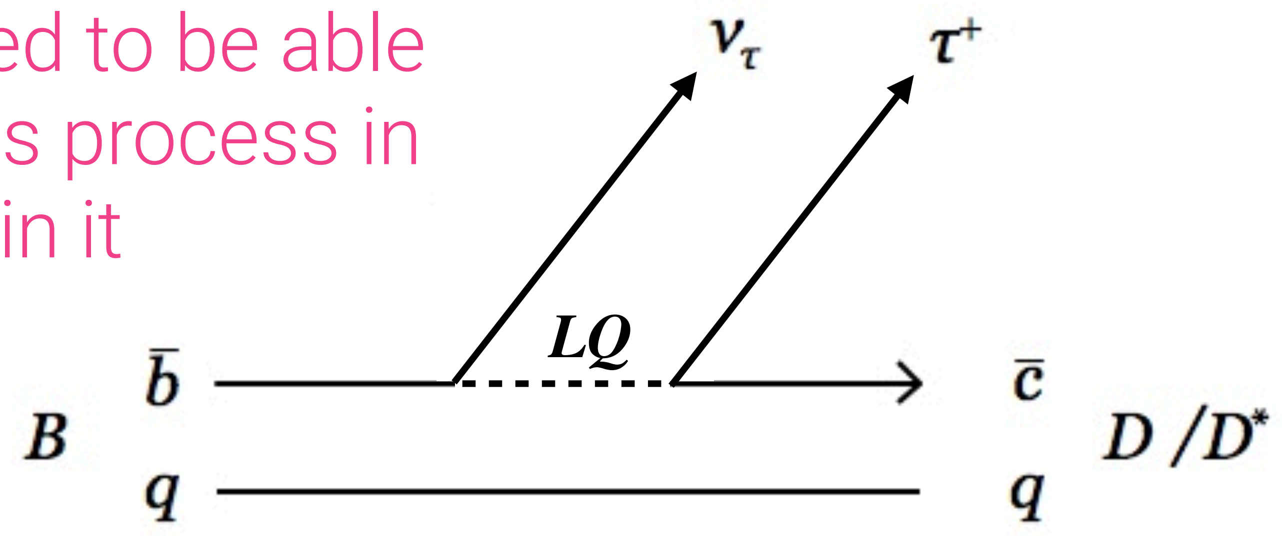
Leptoquarks searches at the LHC

- Can be scalar (spin 0) or vector (spin 1).
- Fractional electric charge: |q| = ⅔ (up-type) or ⅓ (down-type)
- Pair-production dominant at LHC, but single LQ production important at very high masses.
- Decays to a lepton and a quark: LQ→$\ell^{\pm}$q, LQ→νq
  - Models where the LQ decays to third generation particles (or cross-generational decays, e.g. LQ→μb) favoured theoretically.





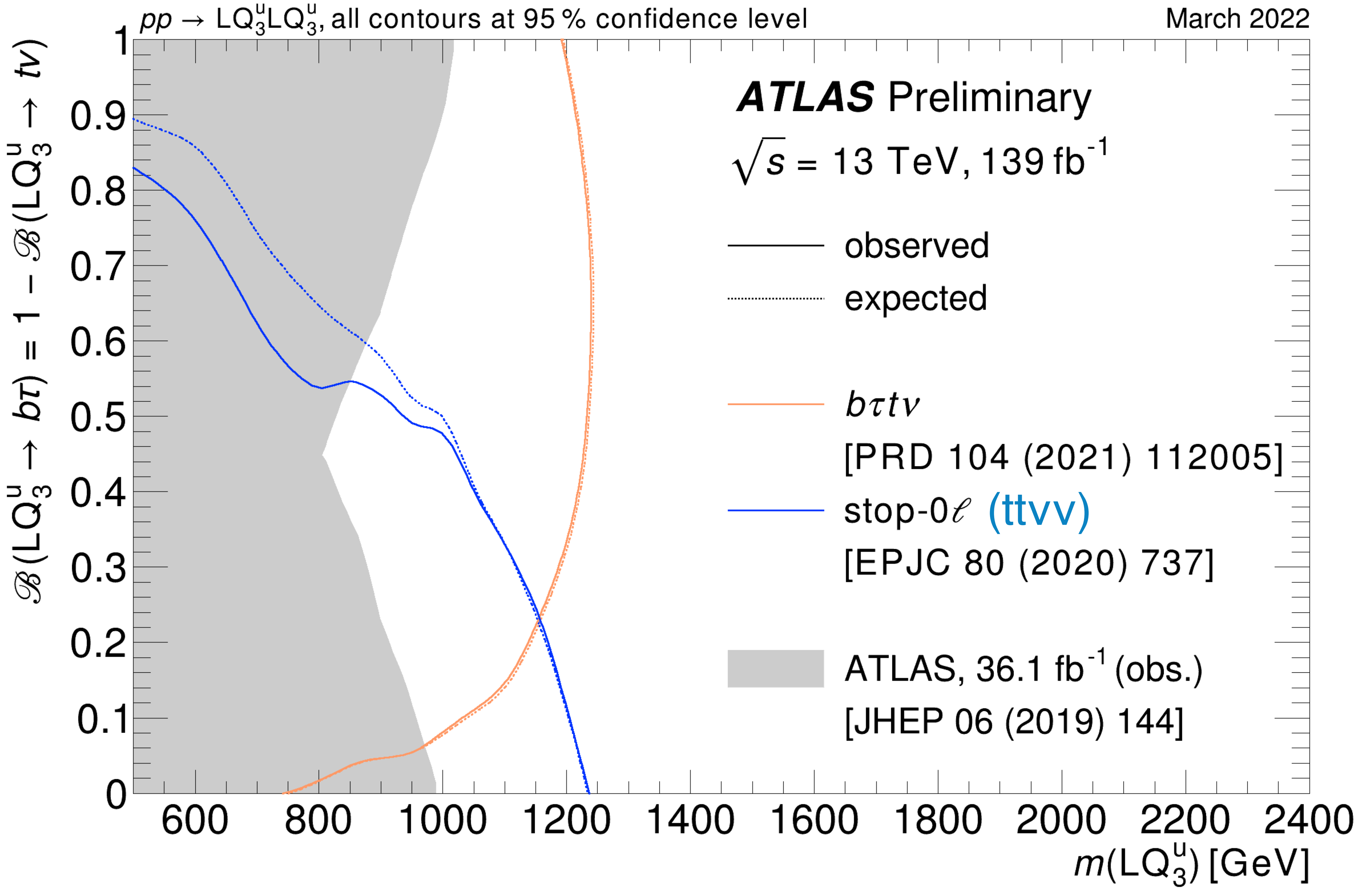
Reminder: need to be able to mediate this process in order to explain it

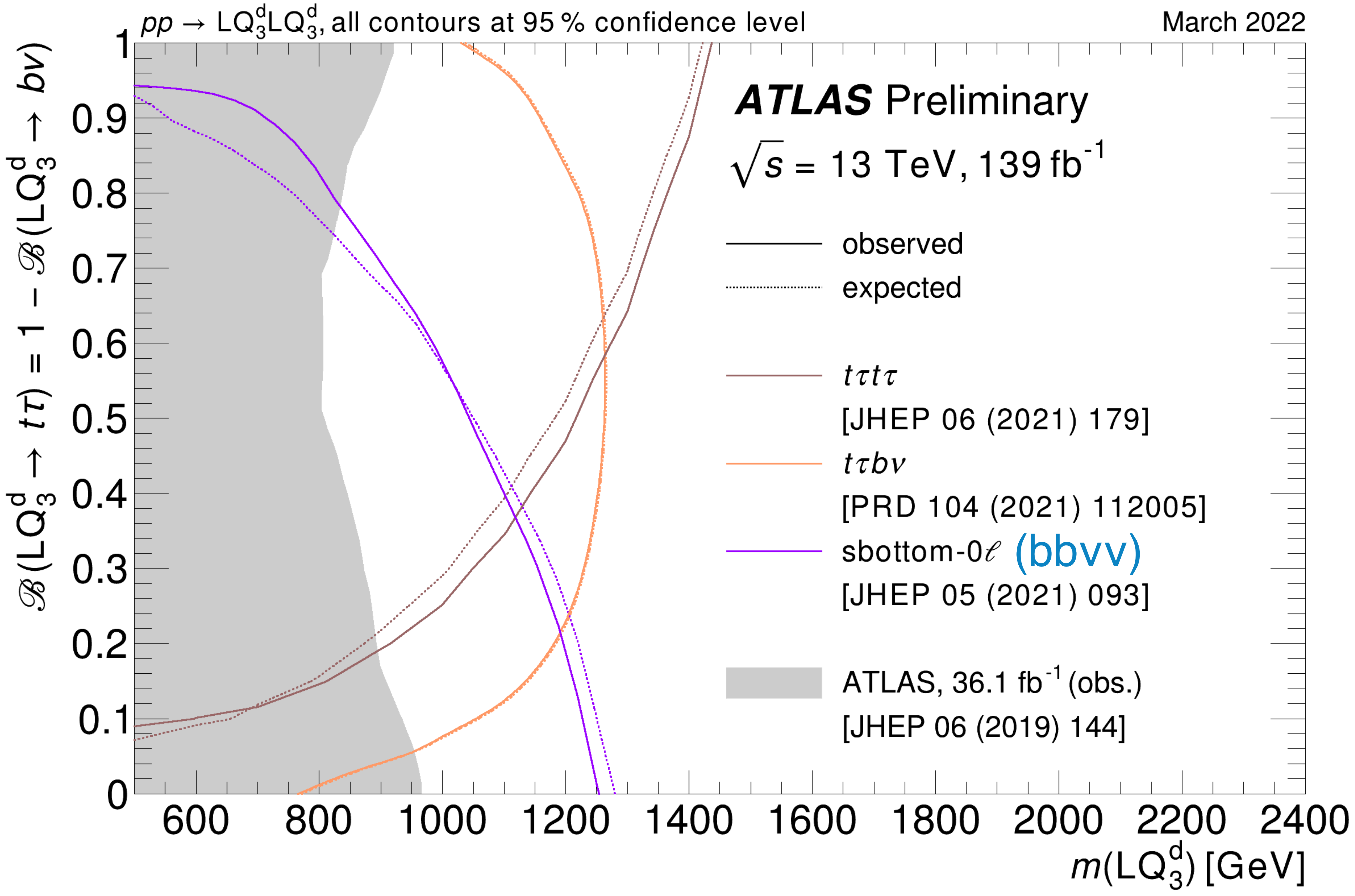


Leptoquarks searches at the LHC

Many different possible decays, depending on the charge of the leptoquark:

- Up-type 3rd generation: LQ→tν and/or LQ→bτ
- Down-type 3rd generation: LQ→tτ and/or LQ→bν





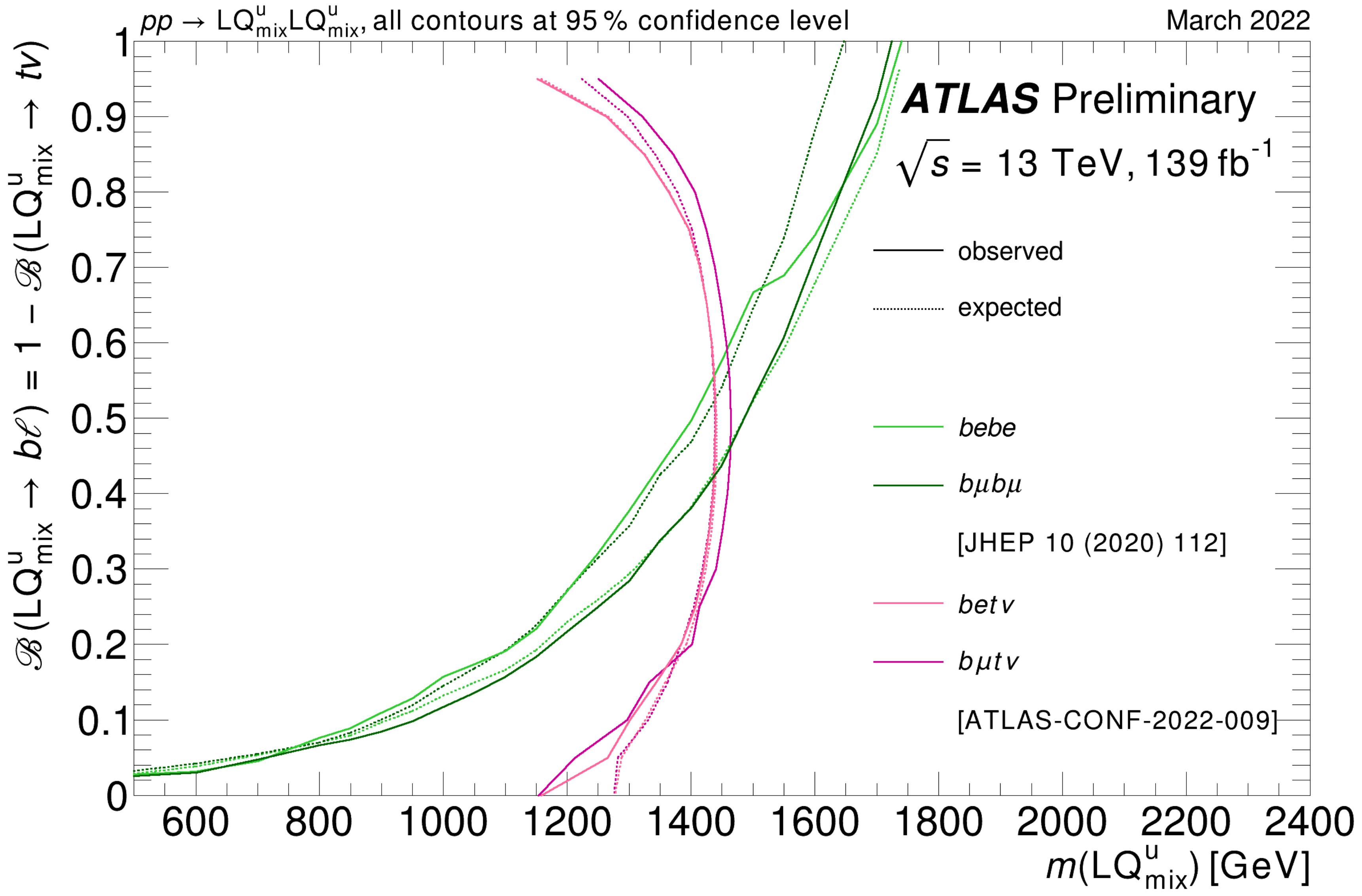
ATLAS results for illustration - CMS also has a rich LQ search programme!

Leptoquarks searches at the LHC

No interesting excesses in the data, but rich phenomenology:

- Single vs. pair-production
- Vector vs. scalar
- Coupling strength of LQ to lepton-quark
- Mass

… and considering all permutations of decays to $[e,\nu_e,\mu,\nu_\mu,\tau,\nu_\tau]$—[u,d,s,c,b,t] yields many different final states.



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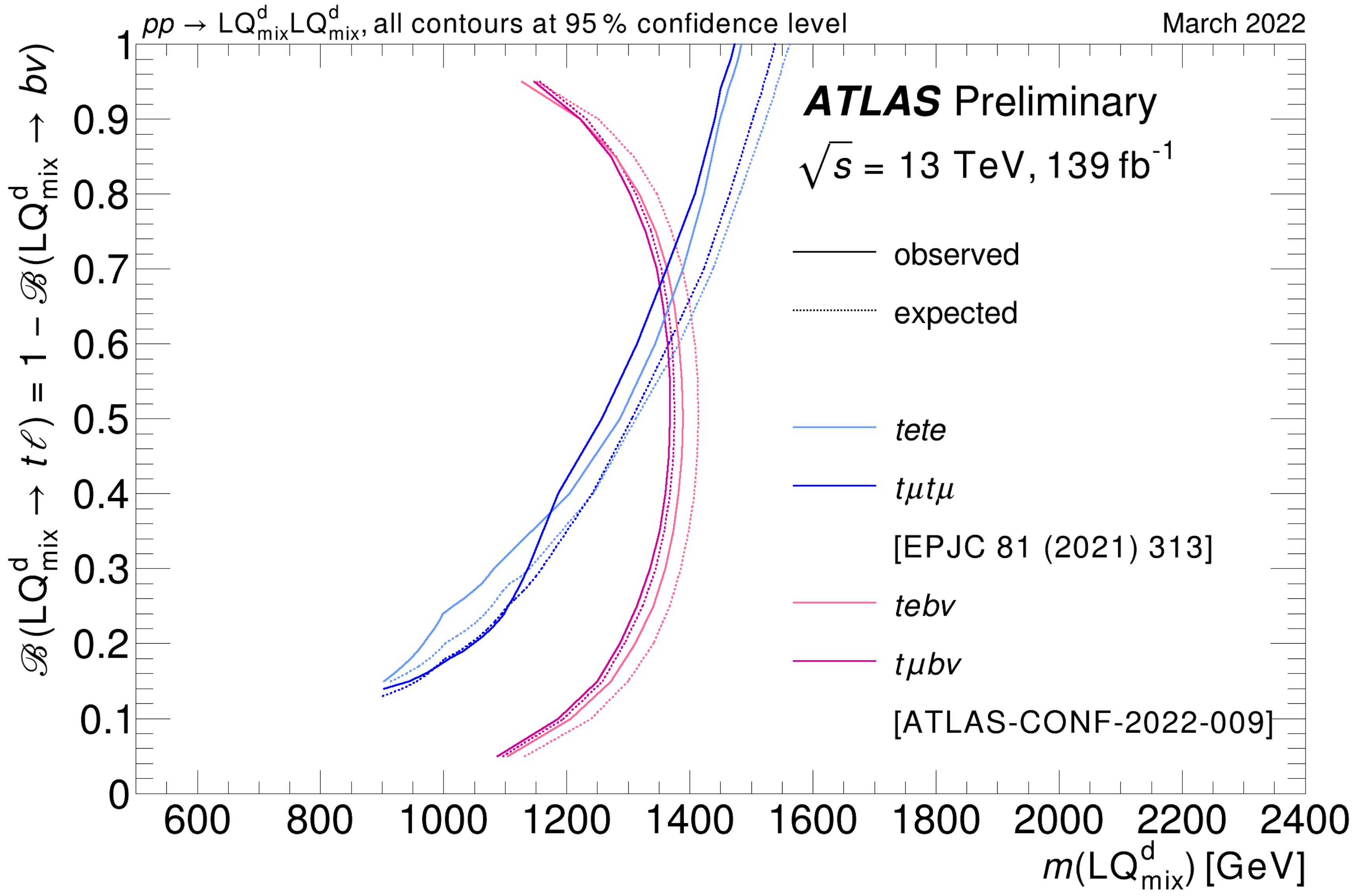

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IF YOU HAVEN'T FOUND IT YET, KEEP LOOKING

STEVE JOBS

PICTUREQUOTES.com

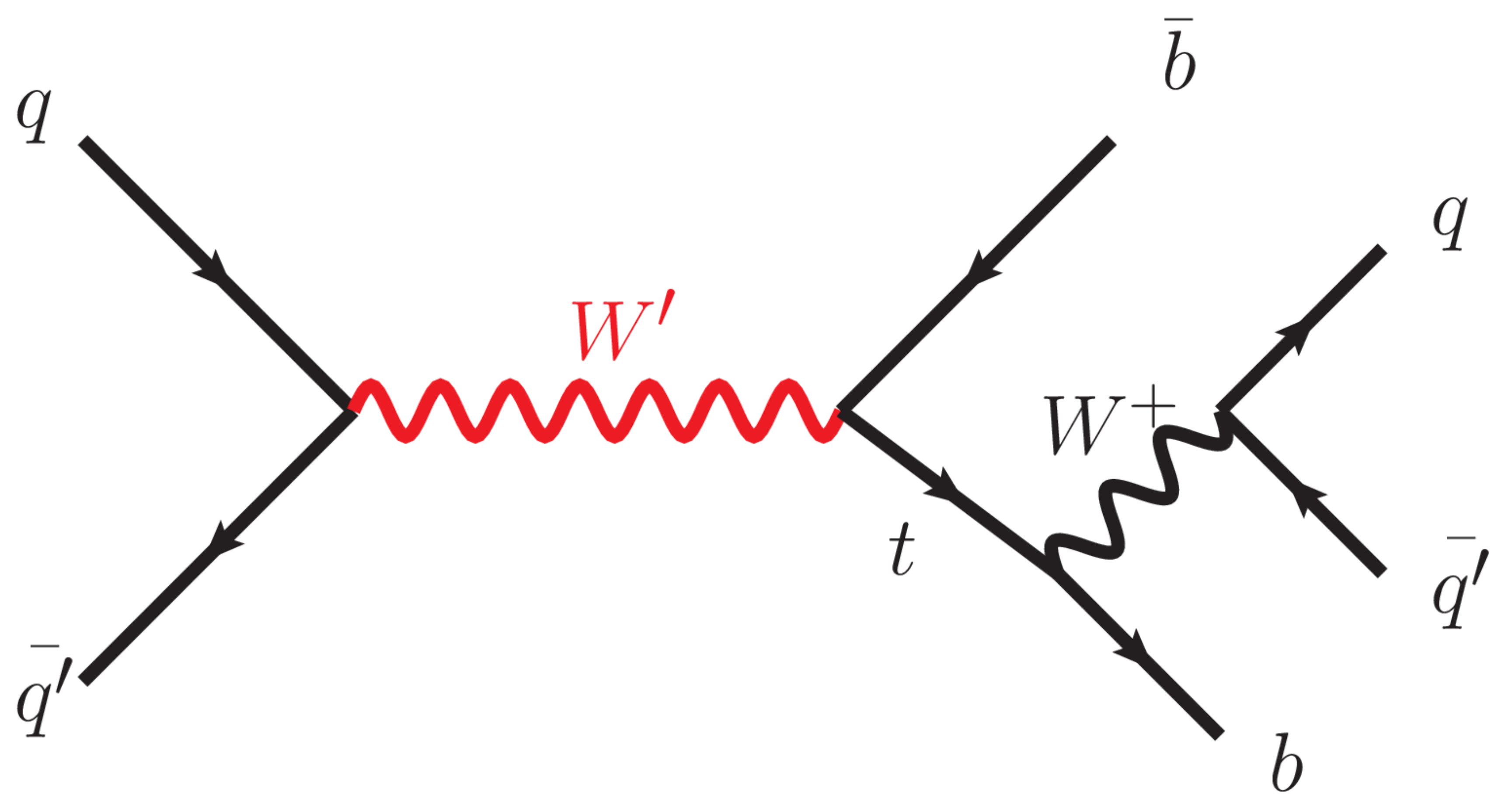
PICTUREQUOTES

Heavy gauge bosons

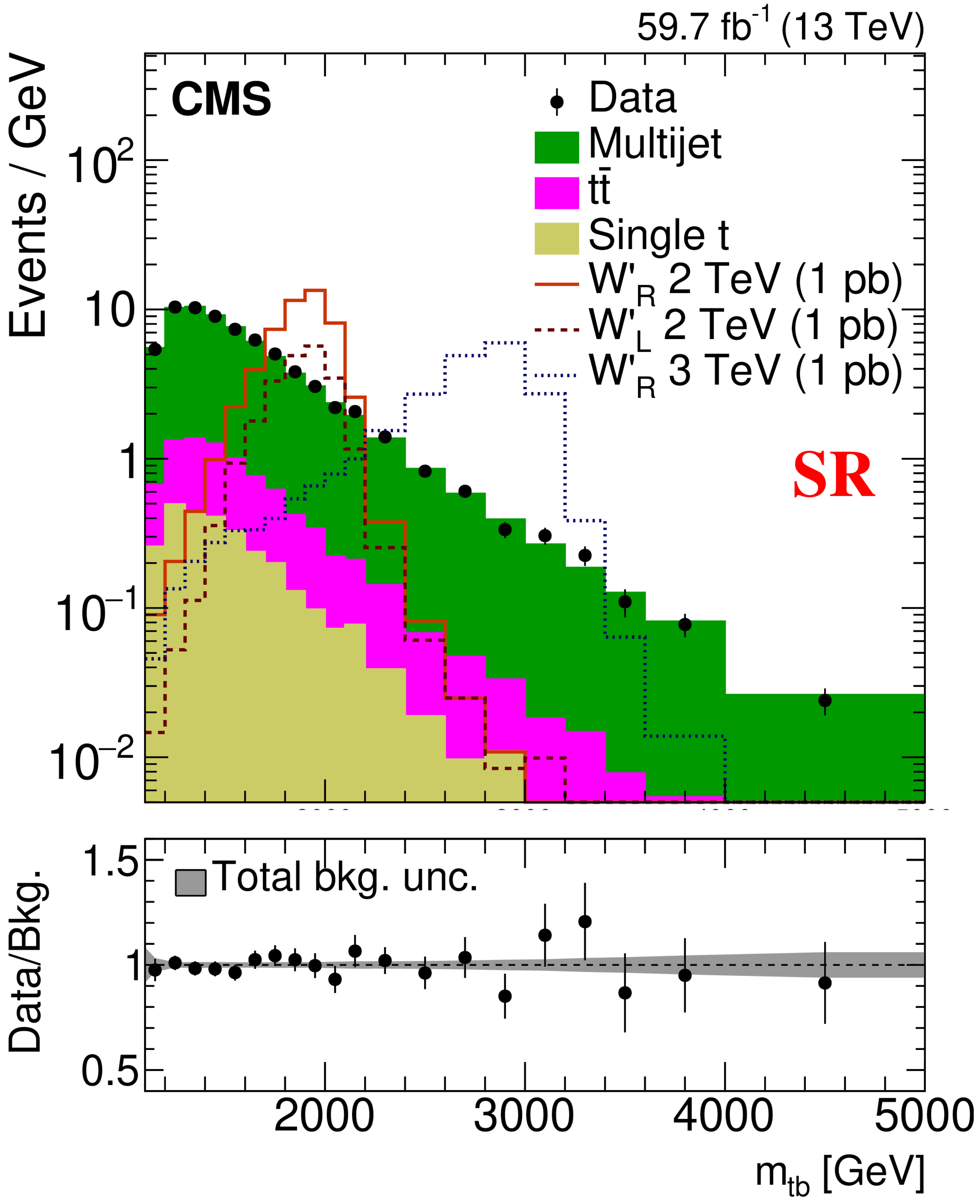
Flavour anomalies could also be explained by the existence of additional gauge bosons that have flavour-dependent coupling.

More generally, predicted by many models.

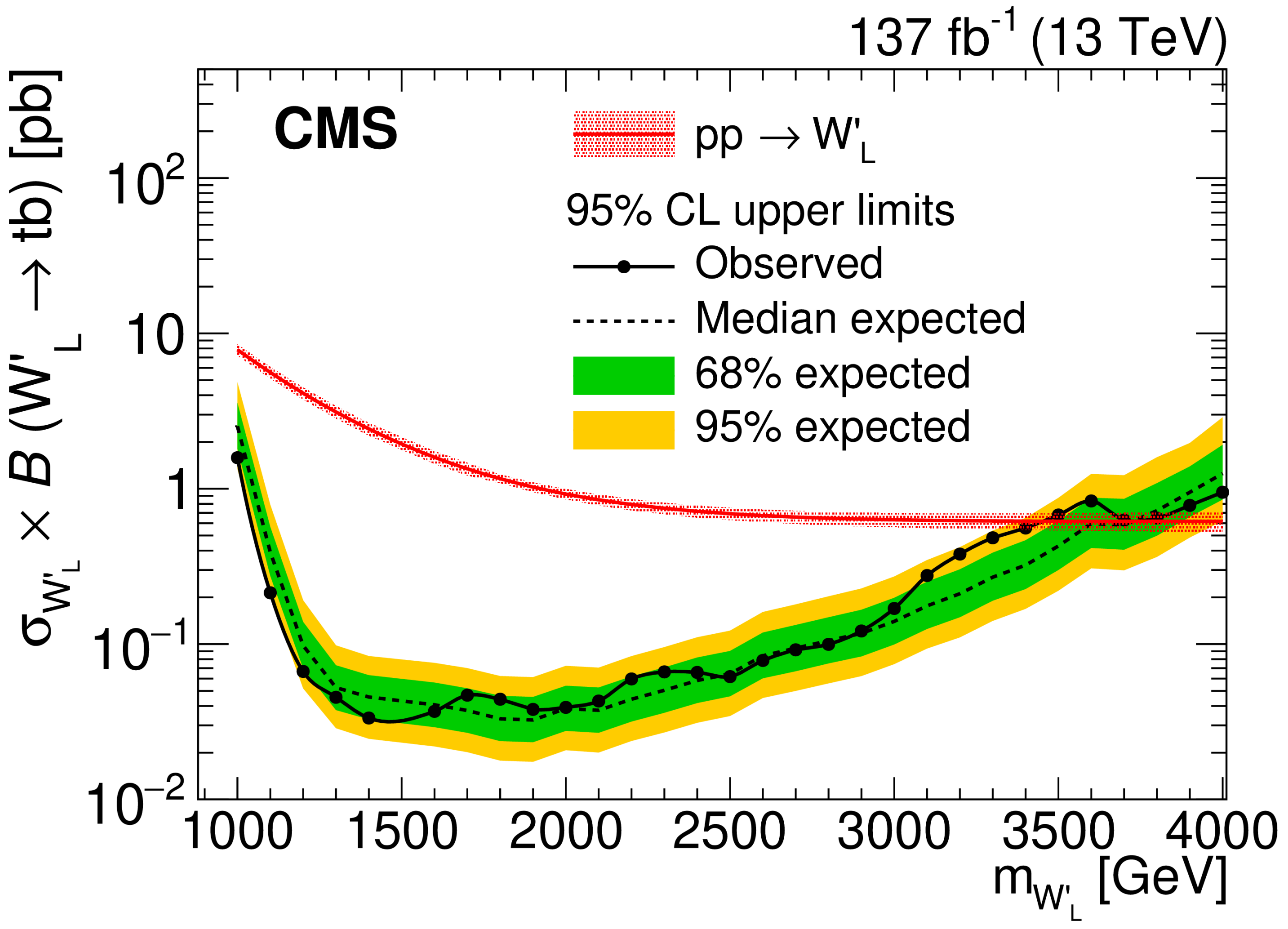
Search for W'→tb

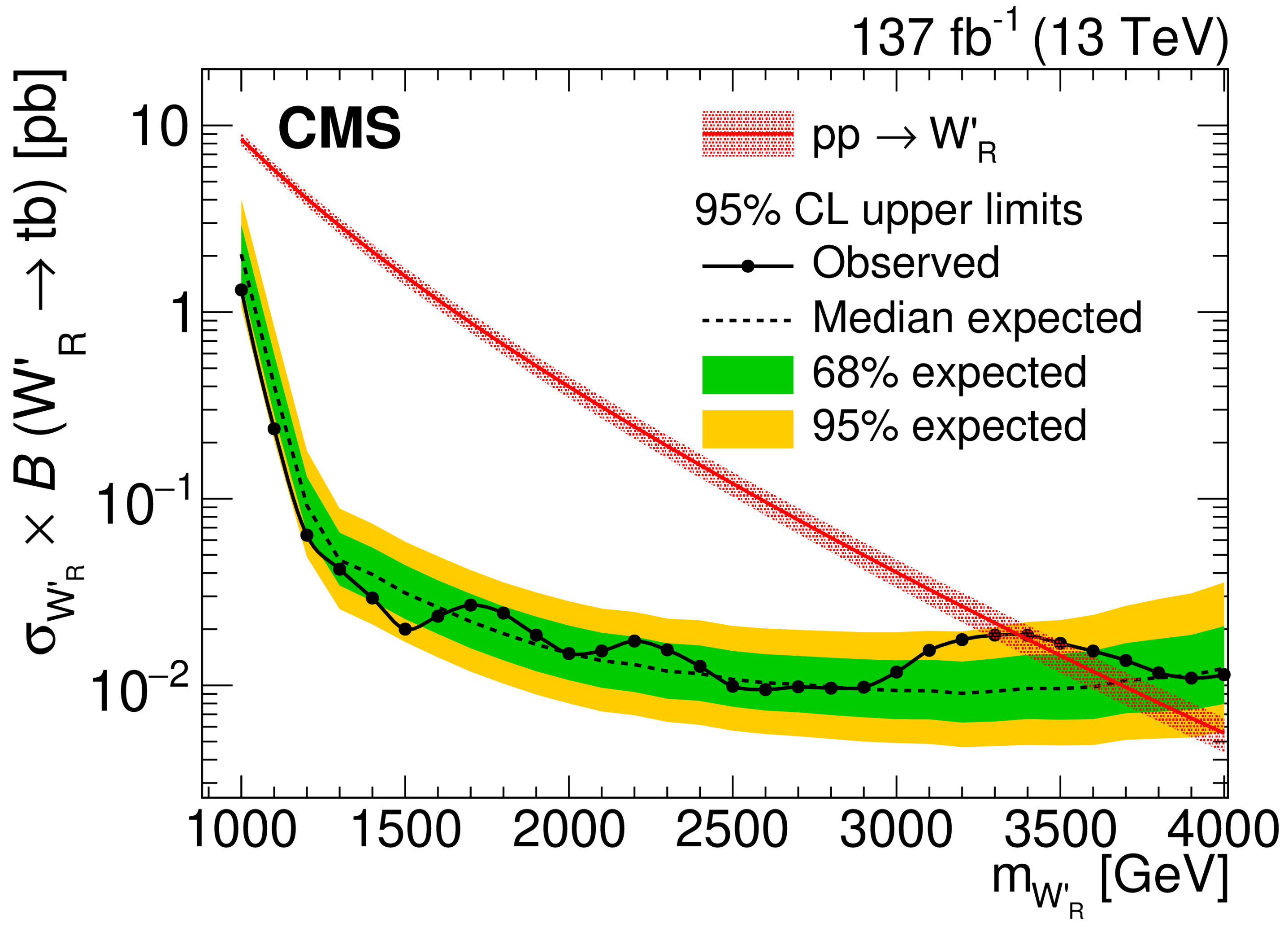


Reconstruct invariant mass of the tb system

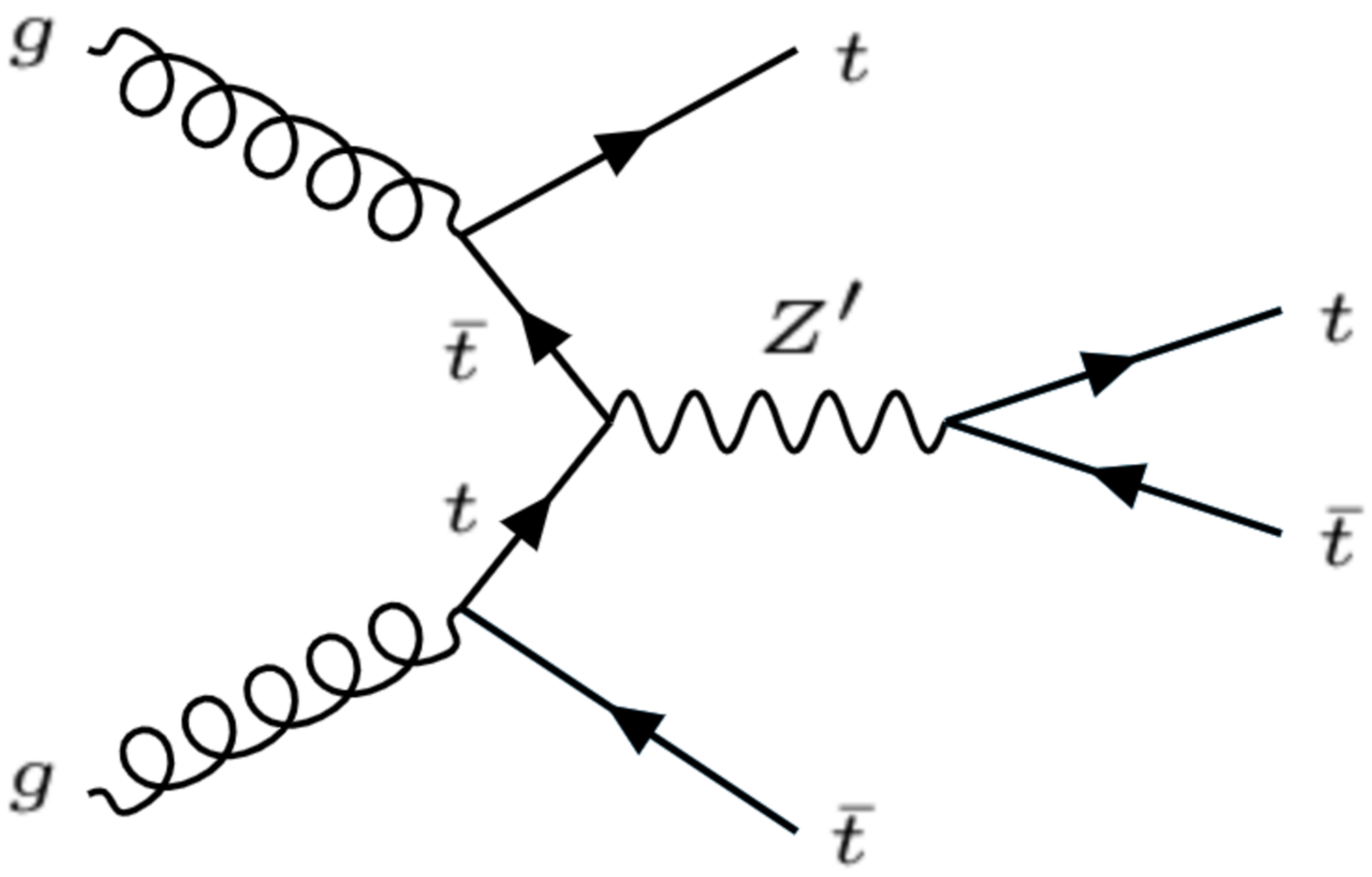


Phys. Lett. B 820 (2021) 136535

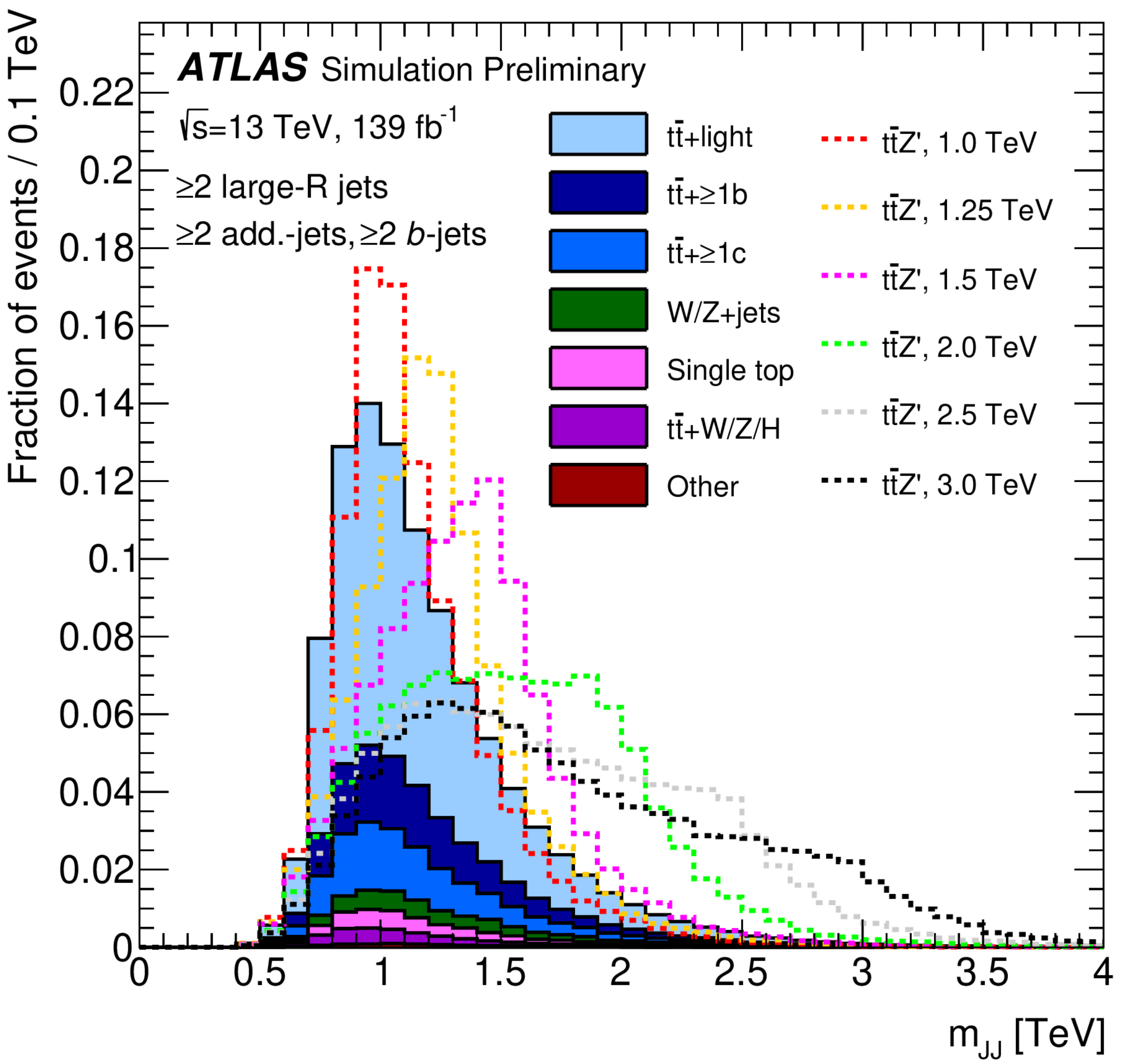




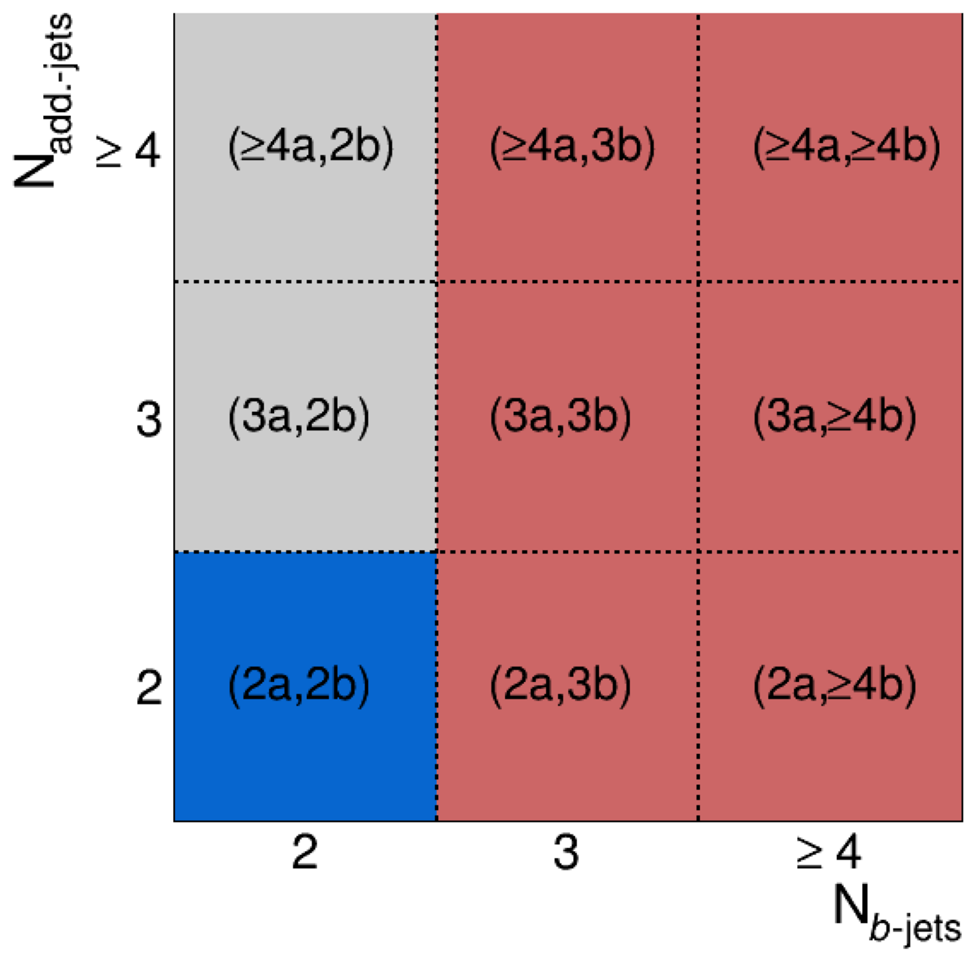
Search for Z’→tt



Top quarks from Z’ decay are highly boosted



ATLAS-CONF-2021-048

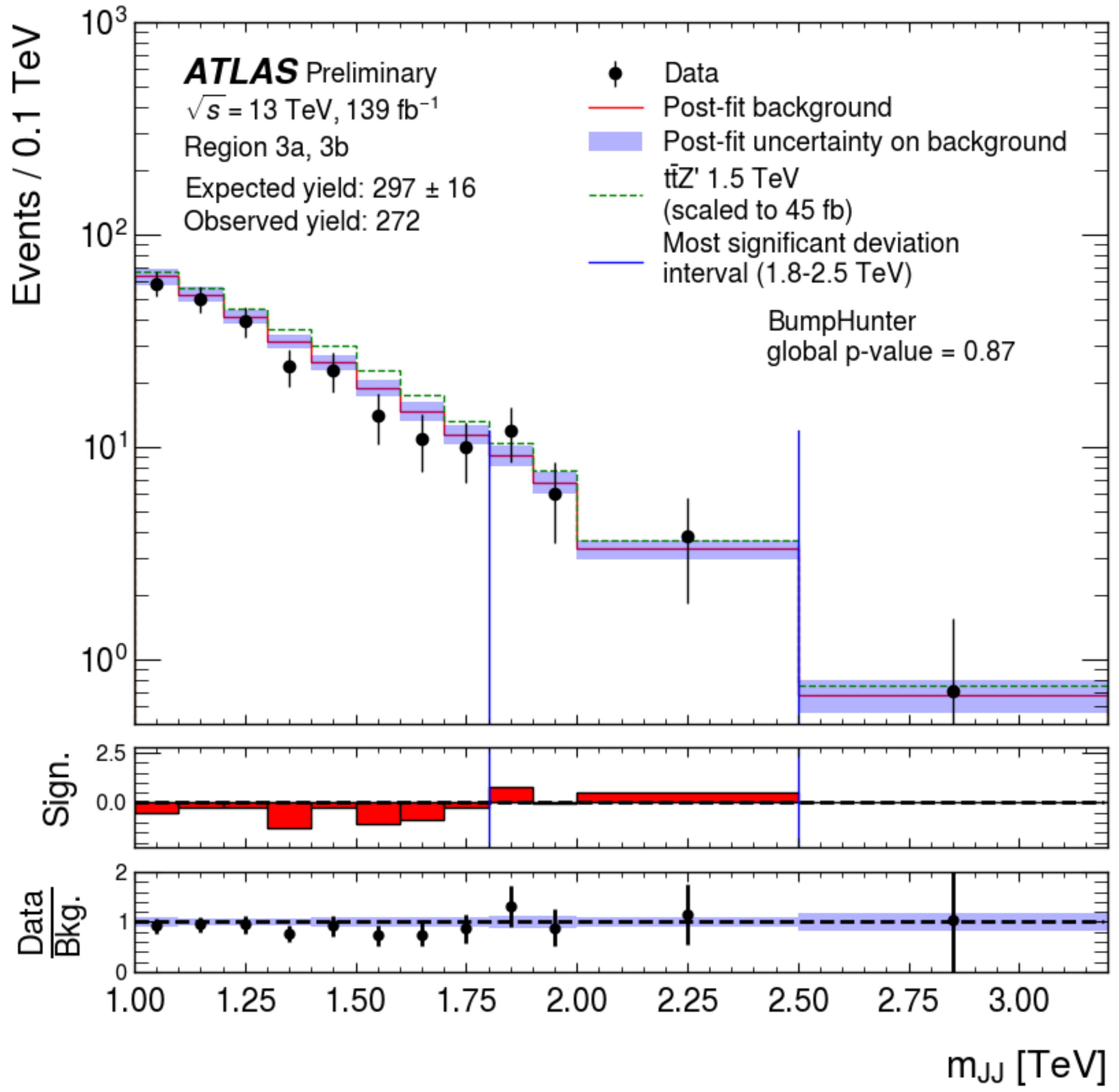


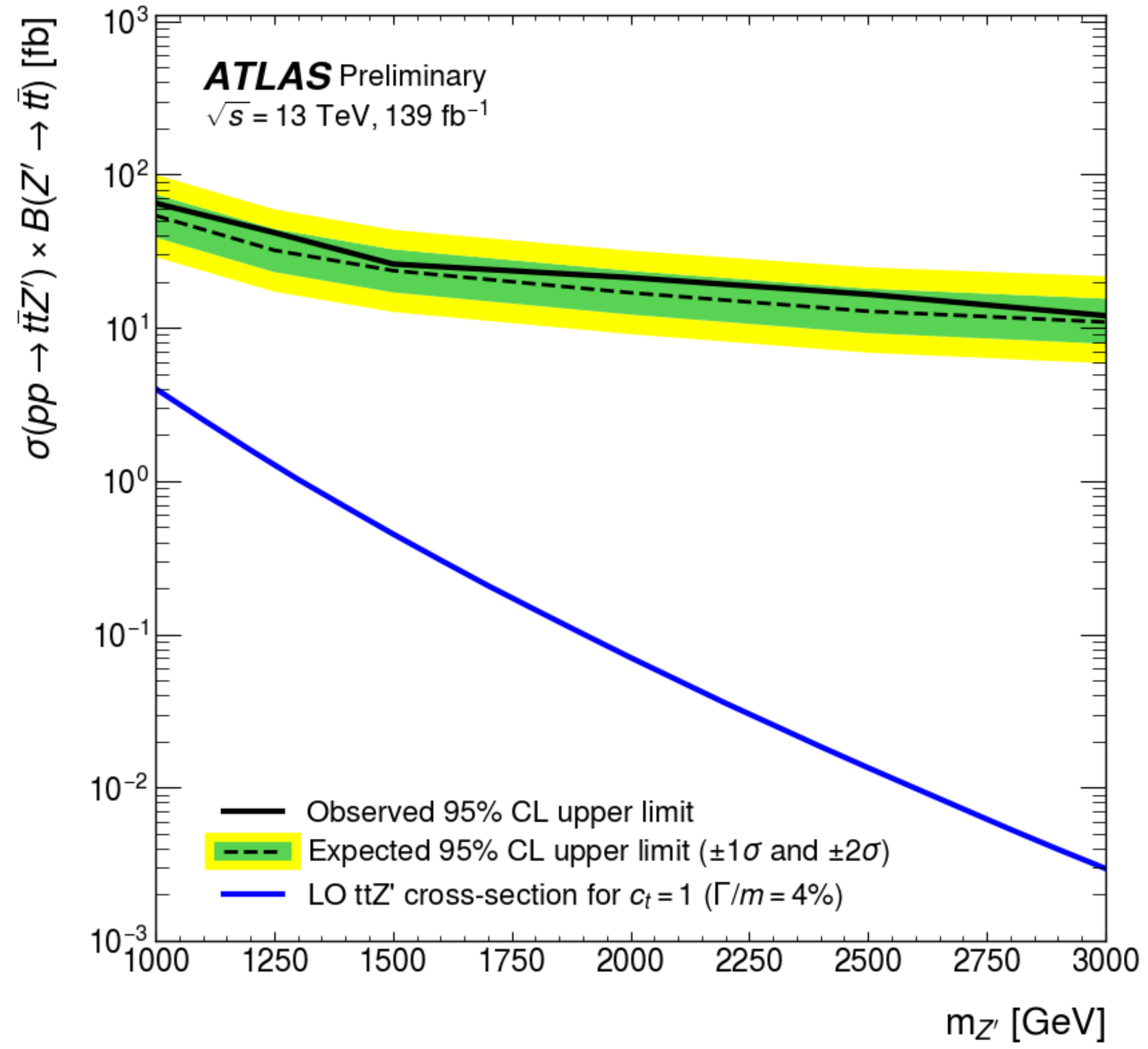
Not used

$N_{\text{add.-jets}}$ \ $N_{b\text{-jets}}$	2	3	≥ 4
≥ 4	(≥4a,2b)	(≥4a,3b)	(≥4a,≥4b)
3	(3a,2b)	(3a,3b)	(3a,≥4b)
2	(2a,2b)	(2a,3b)	(2a,≥4b)

Signal regions

Derive background estimate

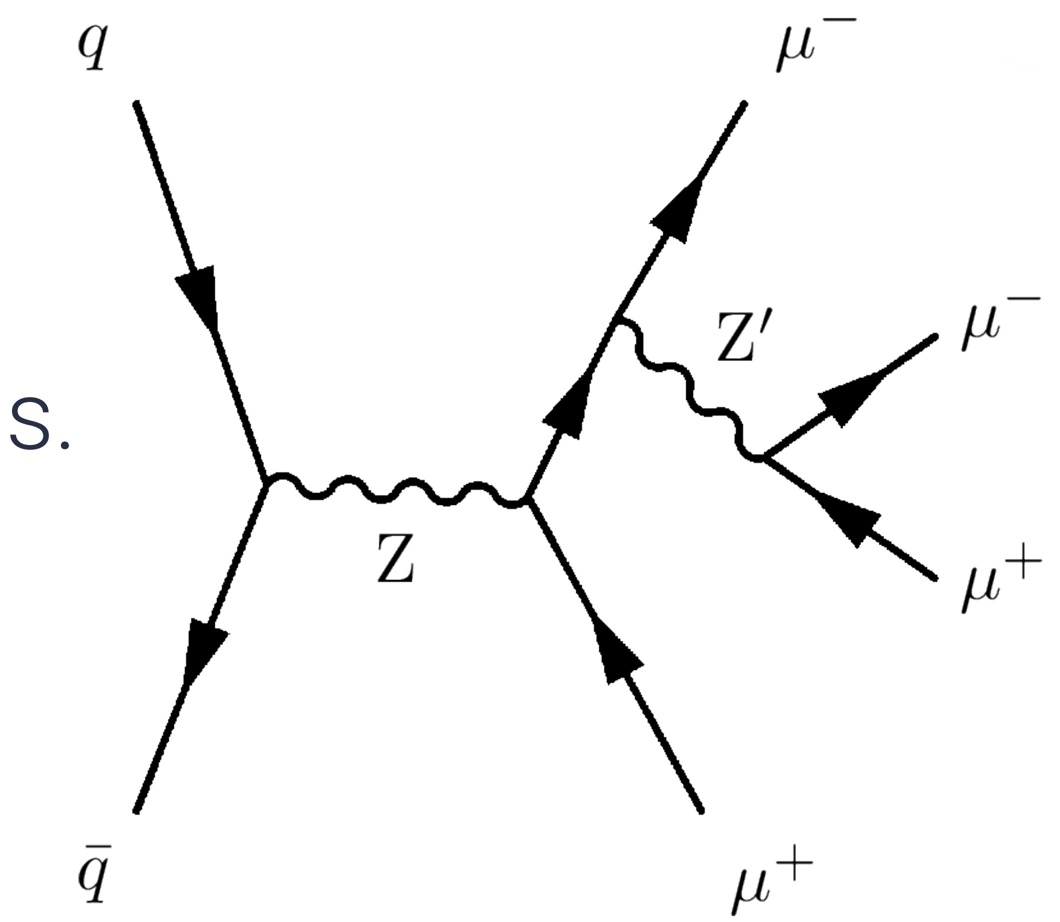




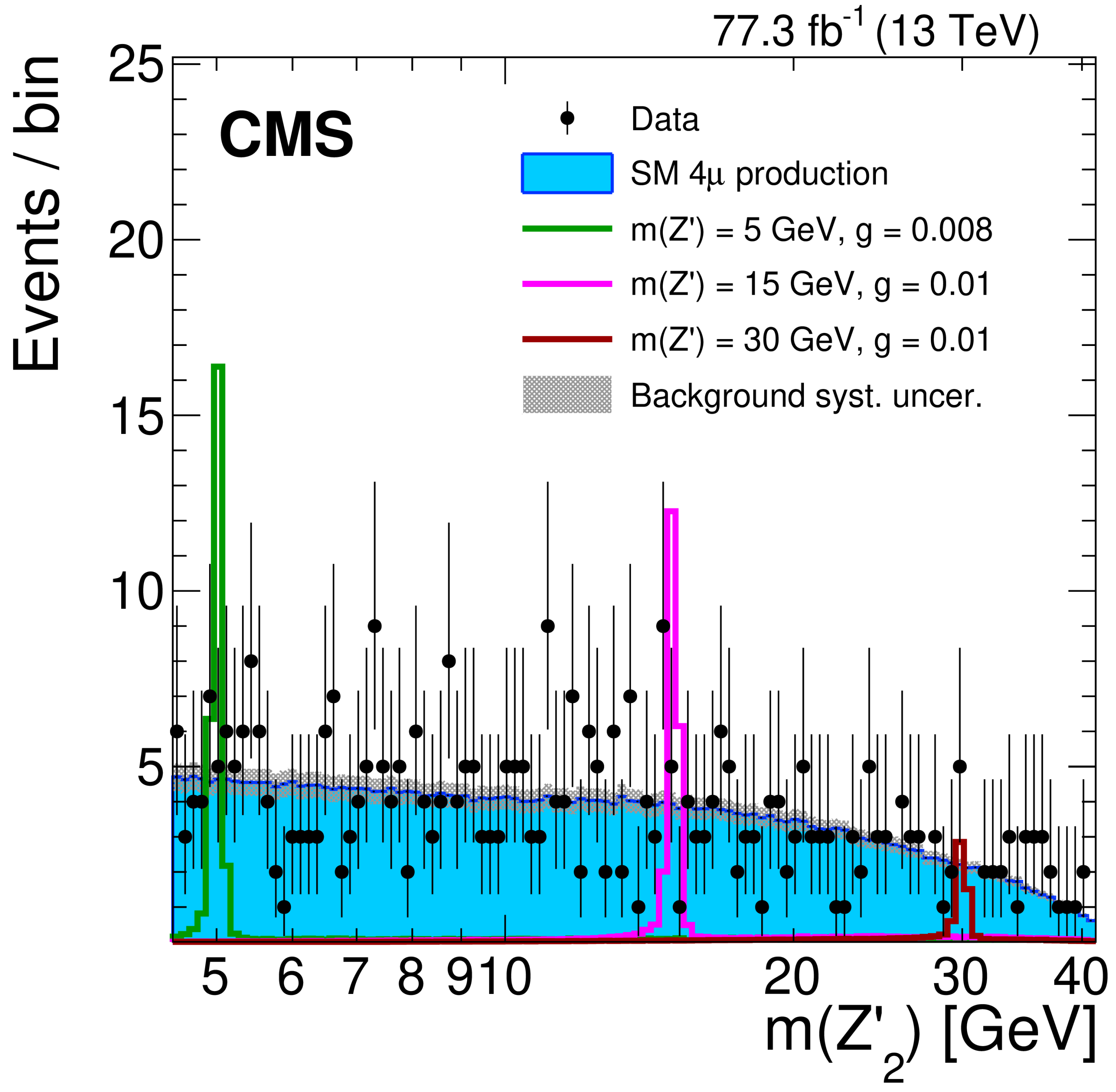
24th May 2022

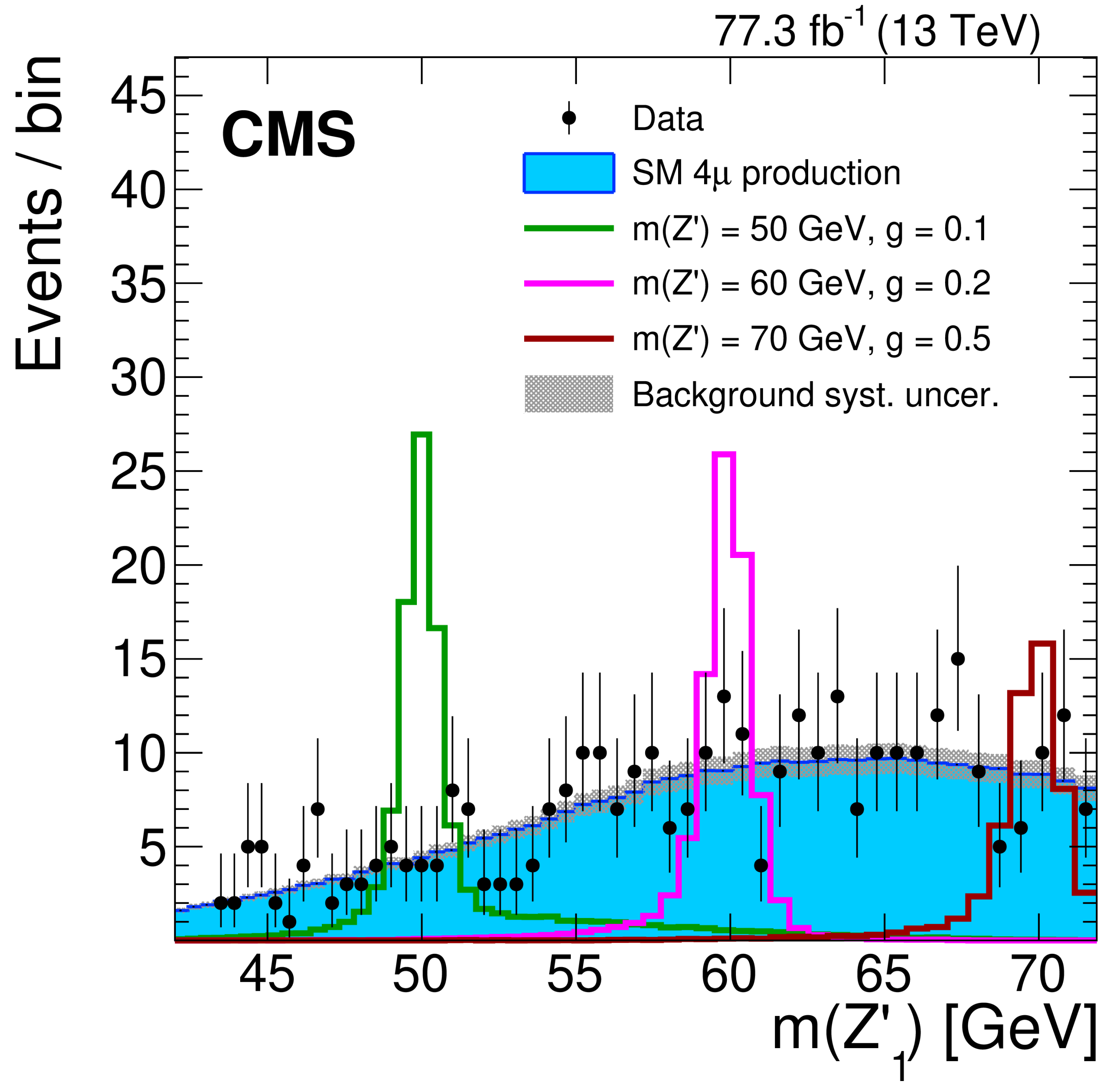
Low mass Z’→4μ

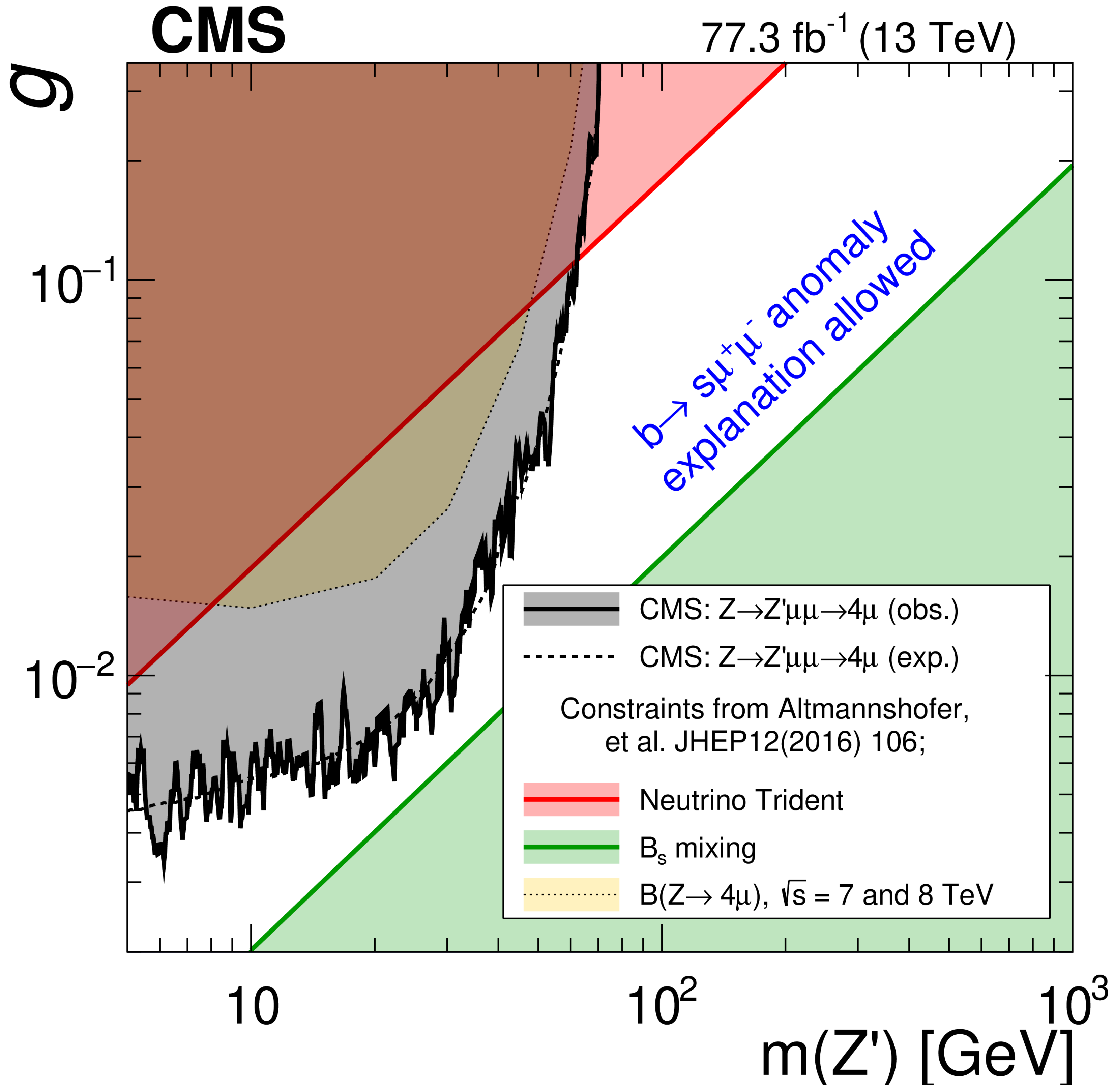
- Light Z’ boson couples only to 2nd and 3rd generation leptons.
  - Can explain flavour anomalies, μ(g-2), dark matter, neutrino masses, and more.
- Z’ produced through radiation in a Drell-Yan process.
- Search in 4 muon final state.
  - 4-μ invariant mass = Z mass.
  - Combinatorial challenge to choose which two muons coming from the Z’.



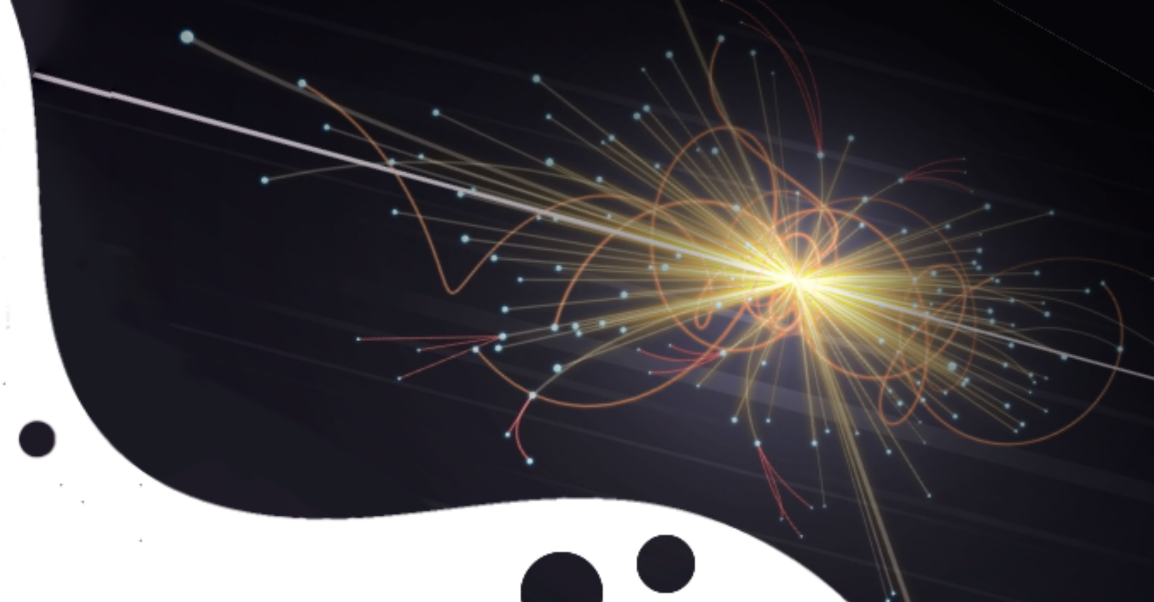
Phys. Lett. B 792 (2019) 345





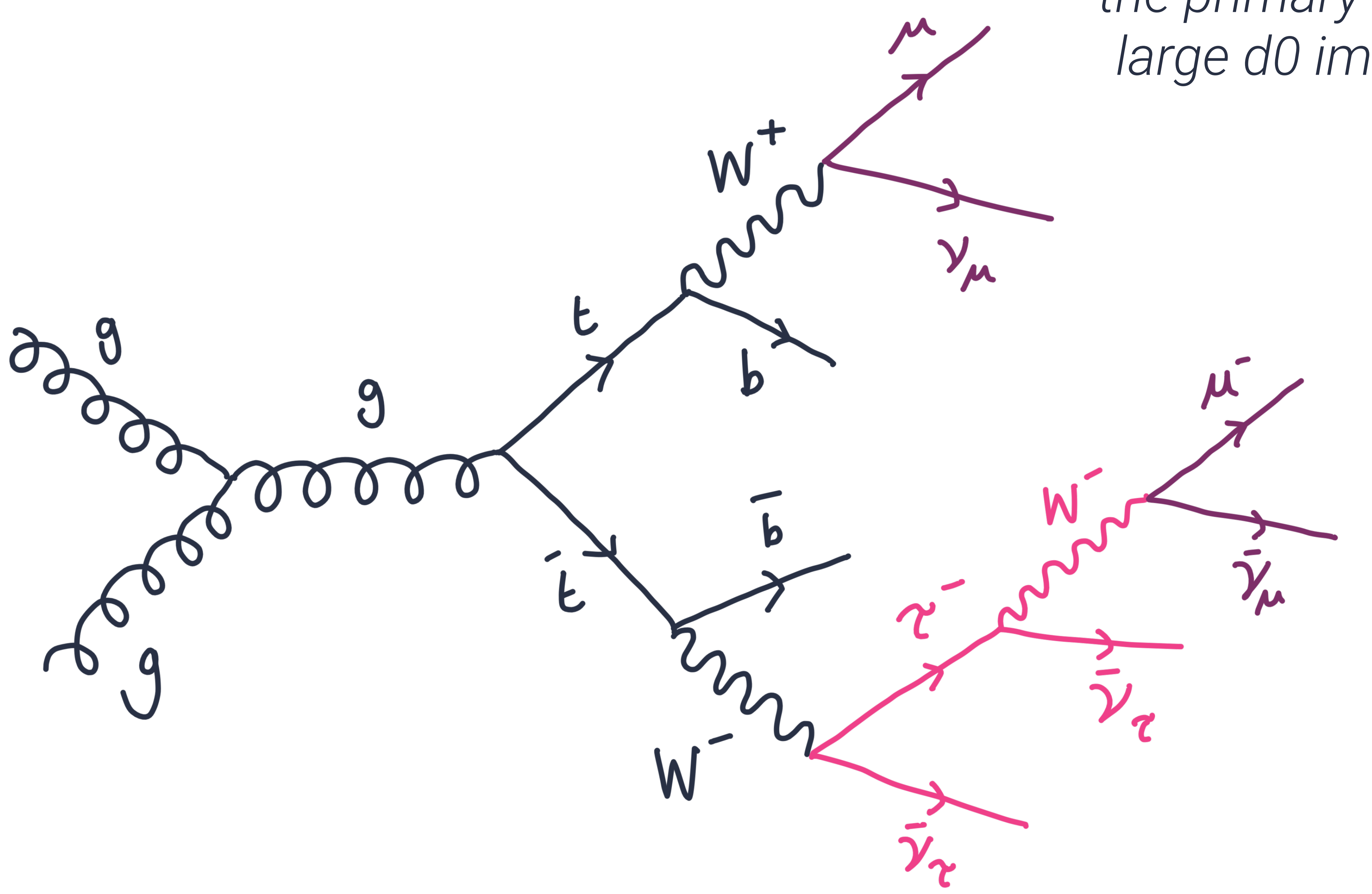


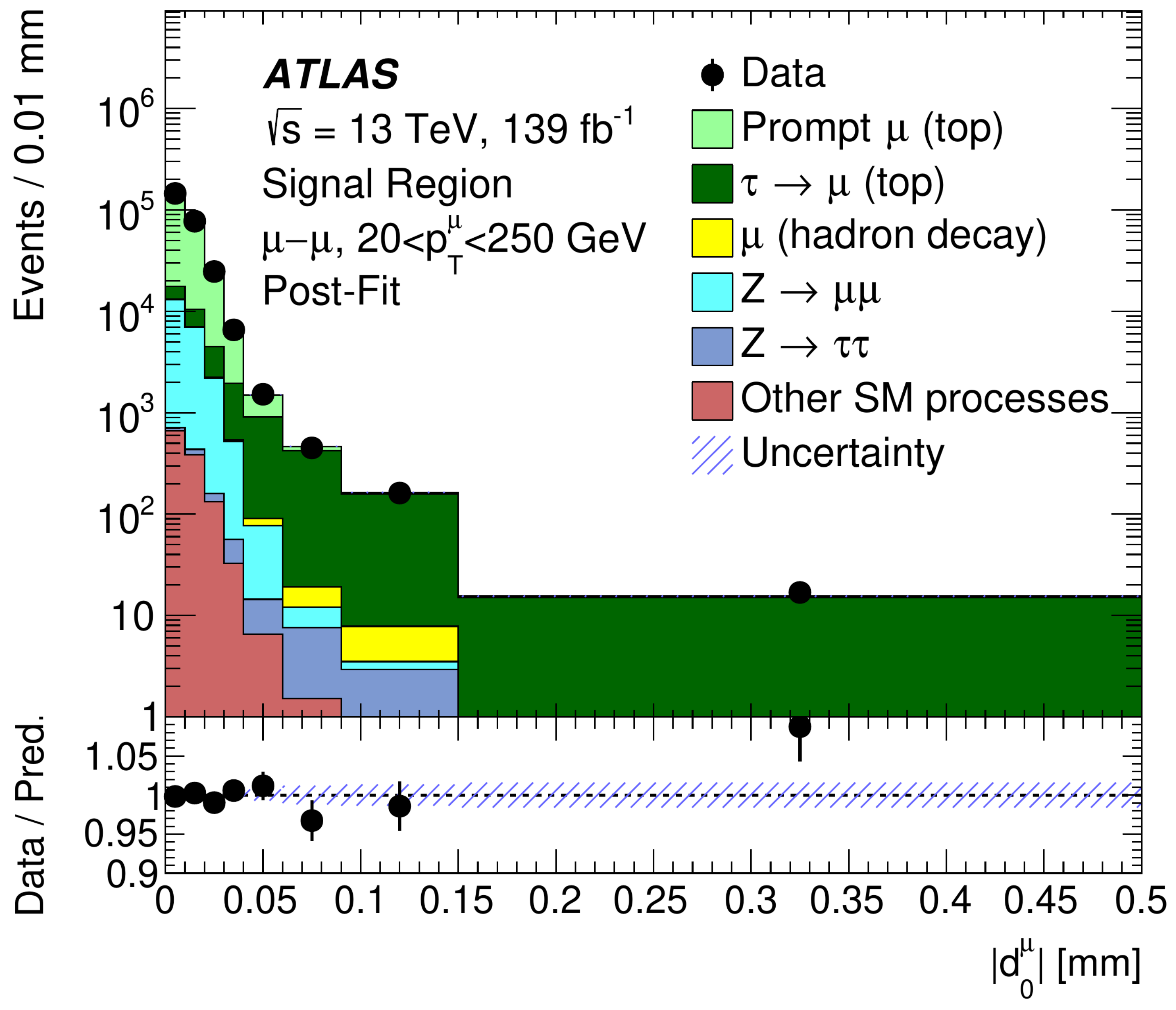
Testing lepton universality in W decays

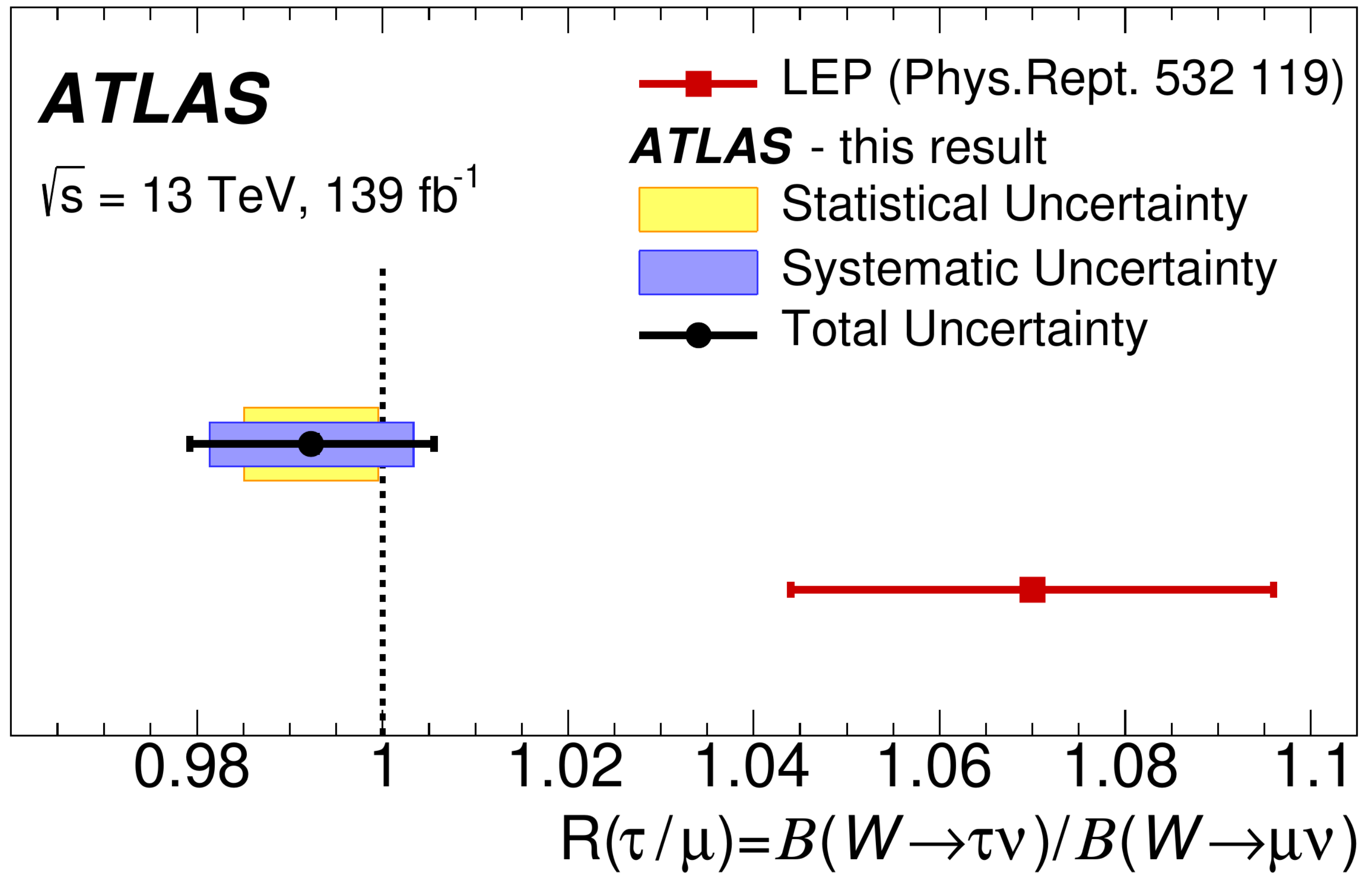


Nature Physics 17, 813–818 (2021)

Taus have a relatively long lifetime - muons originating from a tau decay will point away from the primary vertex (i.e. have a large d0 impact parameter).







Combined results from LEP experiments showed a 2.7σ deviation from the SM expectation in R(τ/μ) measurements. ATLAS result compatible with the SM.

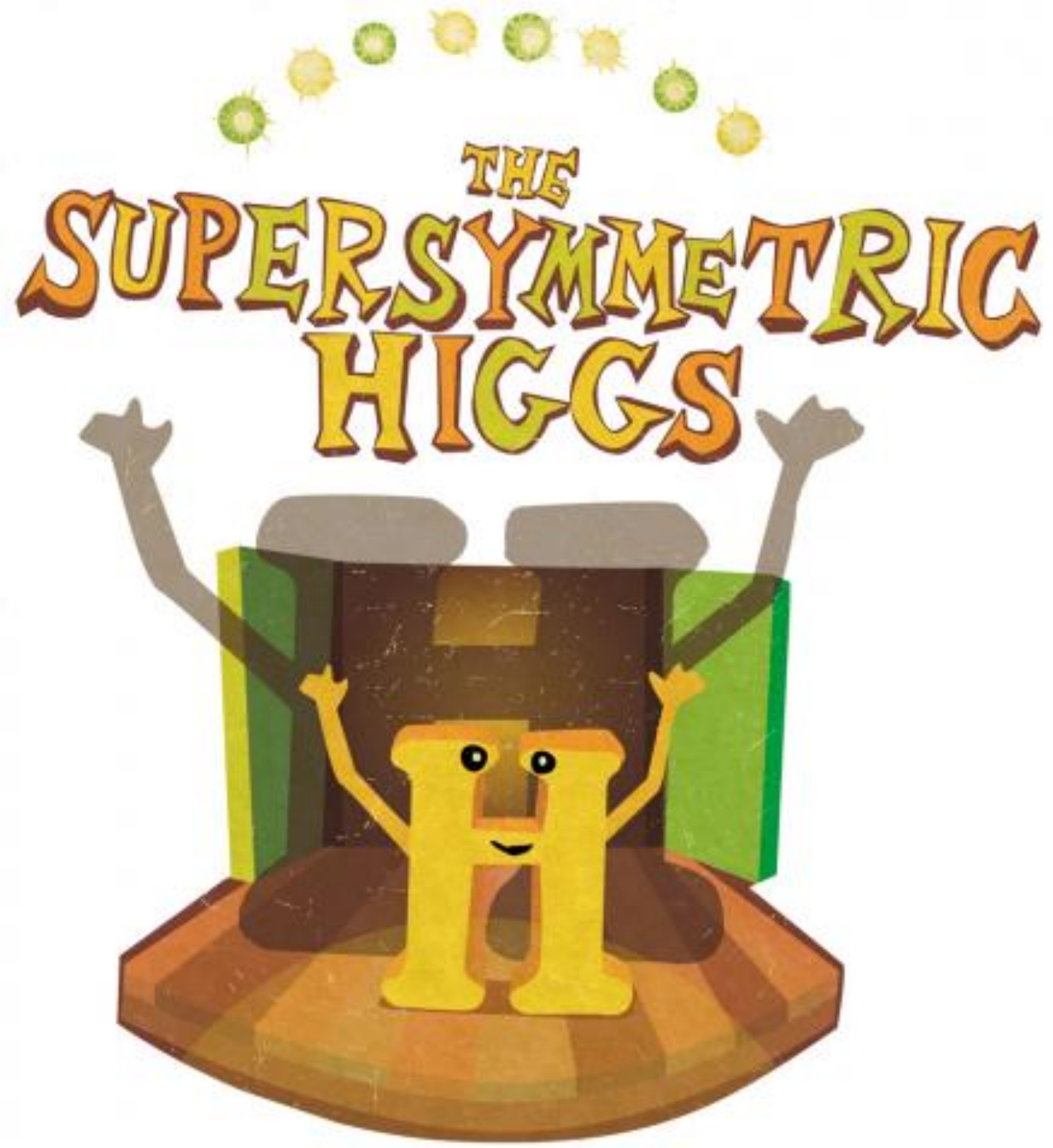
→ often anomalies just… disappear…

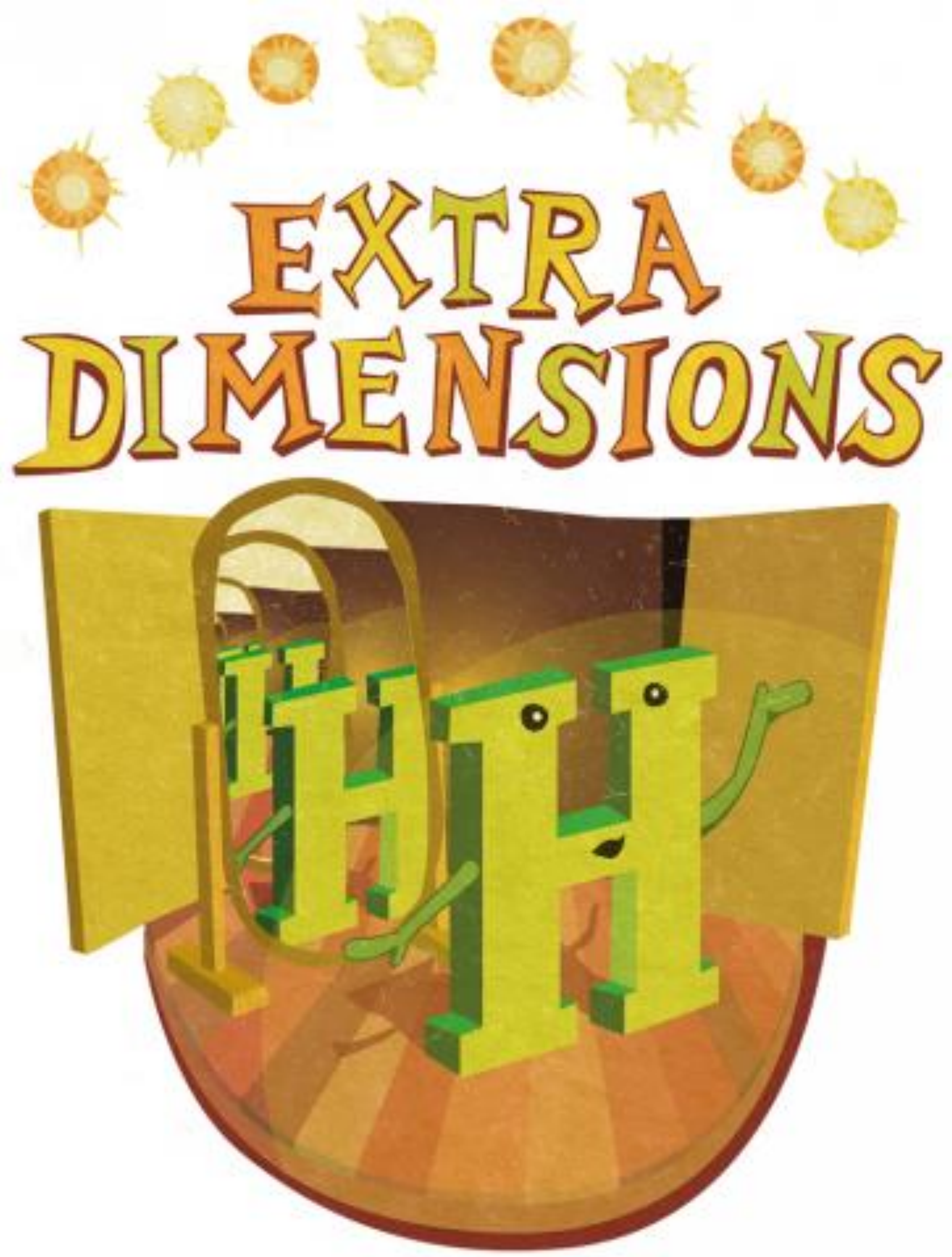
Extended Higgs sector

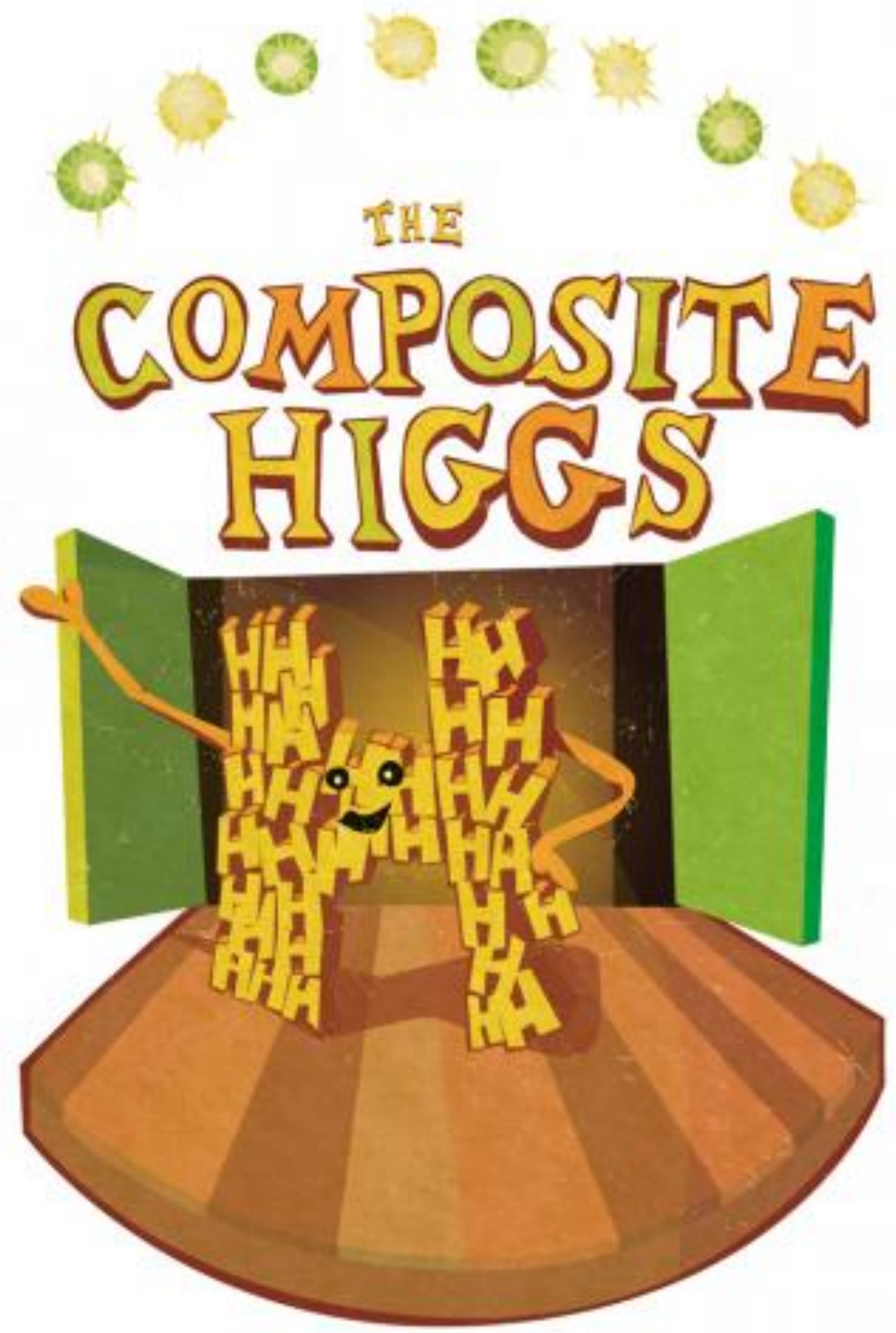
Higgs bosons interaction strength proportional to mass → possible link to flavour anomalies?

The Higgs boson is the only Spin 1 particle in the SM, but many BSM theories predict there should be additional Higgs bosons.

Higgs cross-section is small and many production/decay modes very challenging to probe → still plenty of room for new physics that interacts with the Higgs to be hiding.







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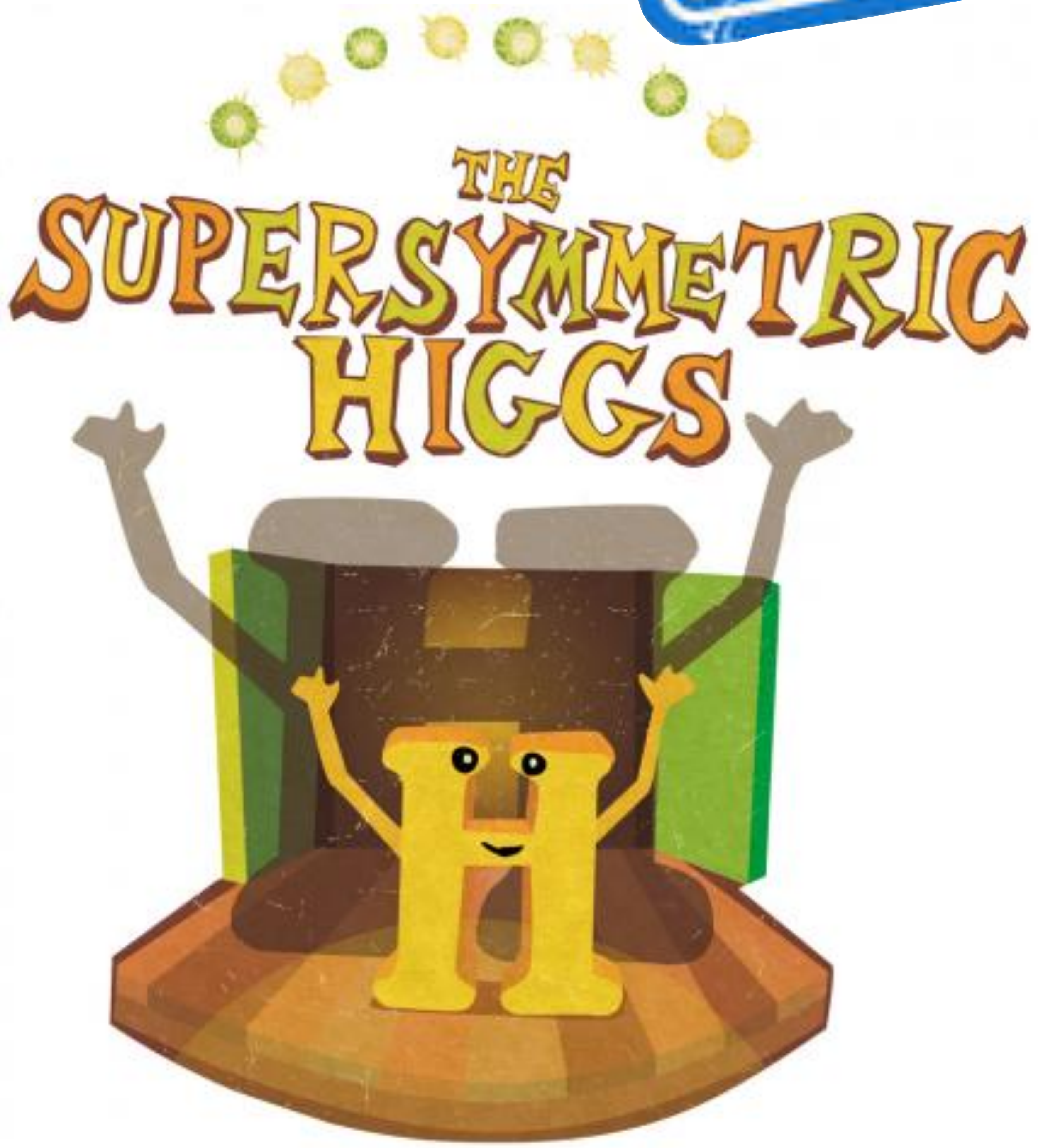
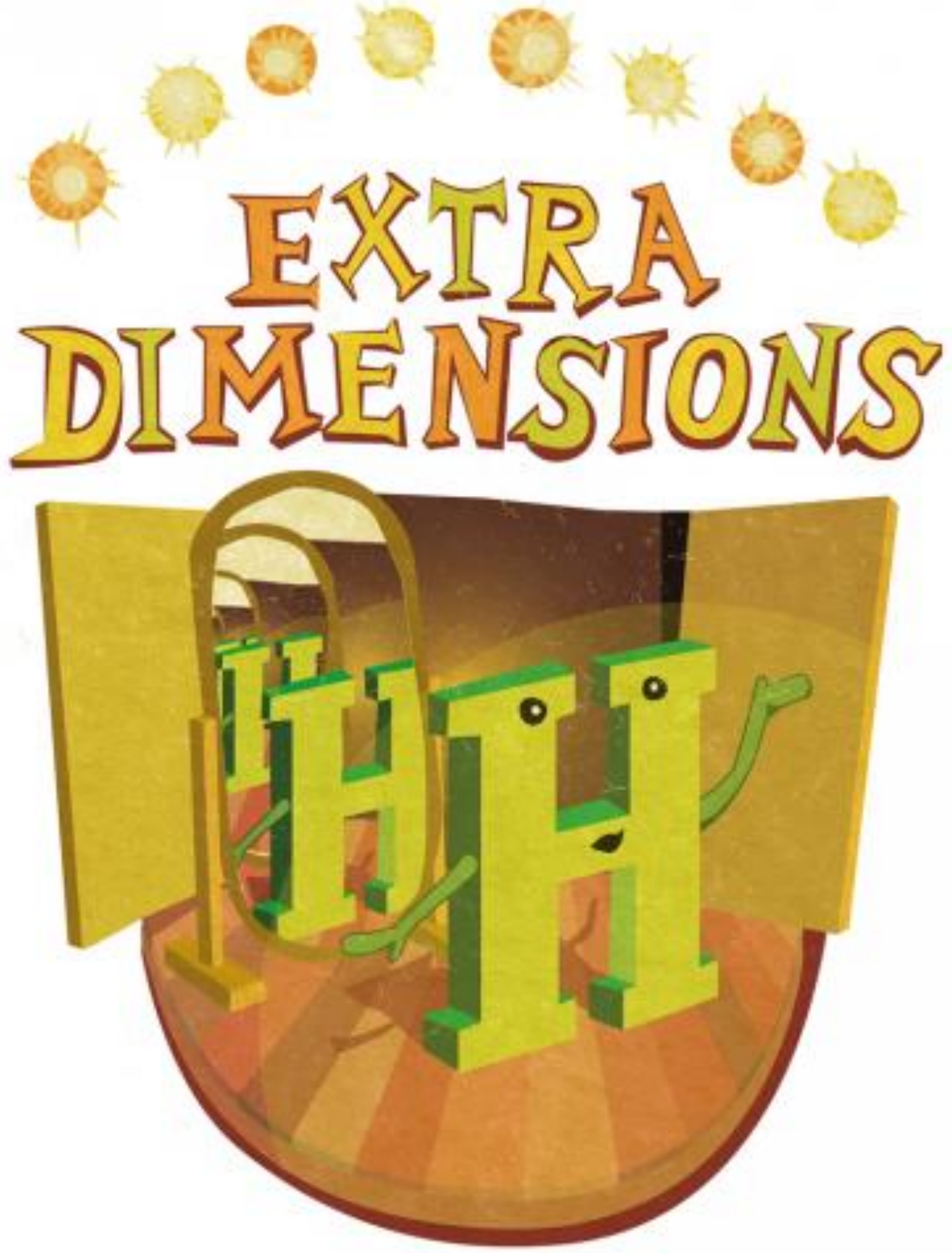
TOMORROW

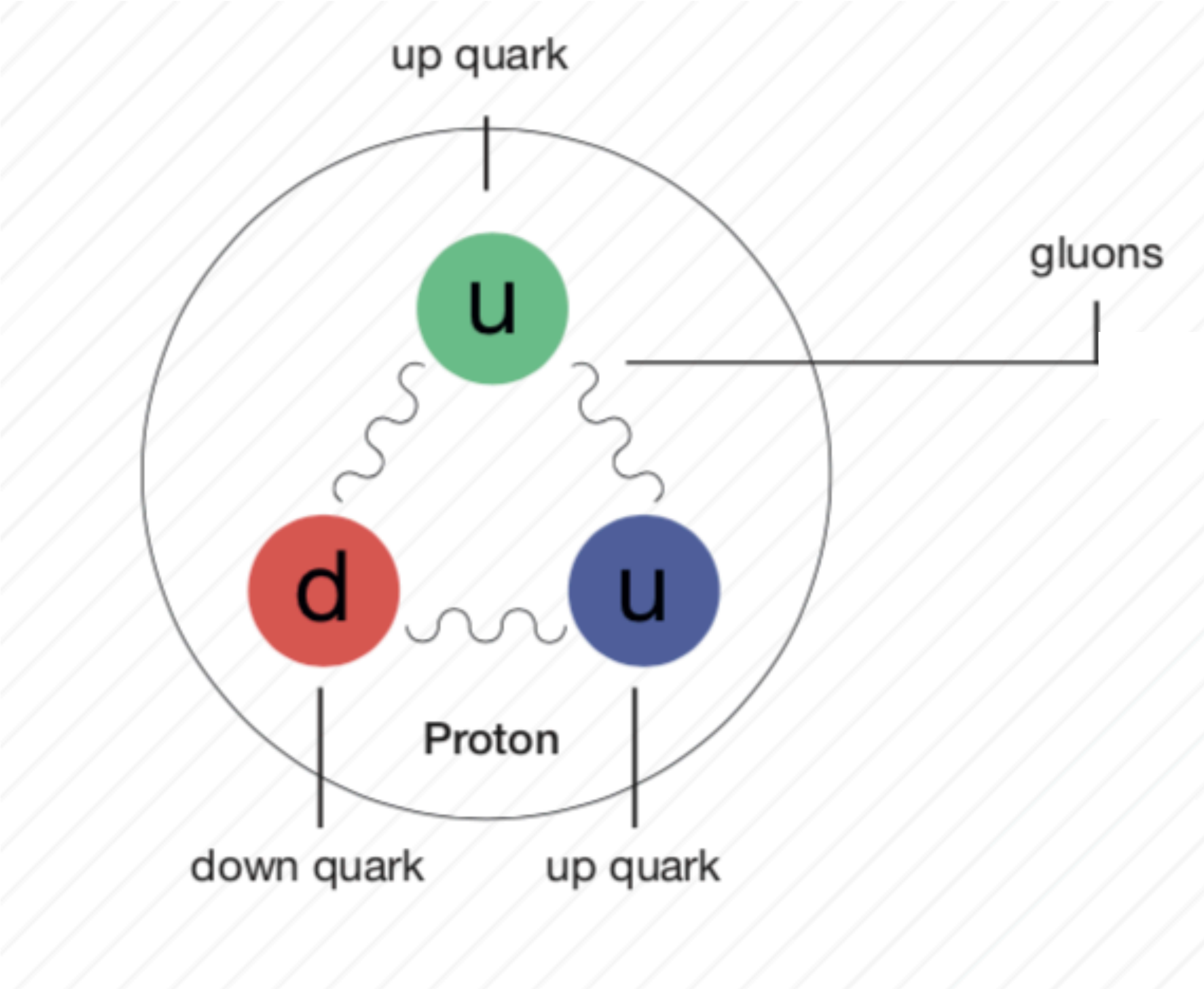




Back Up

Revisiting the proton

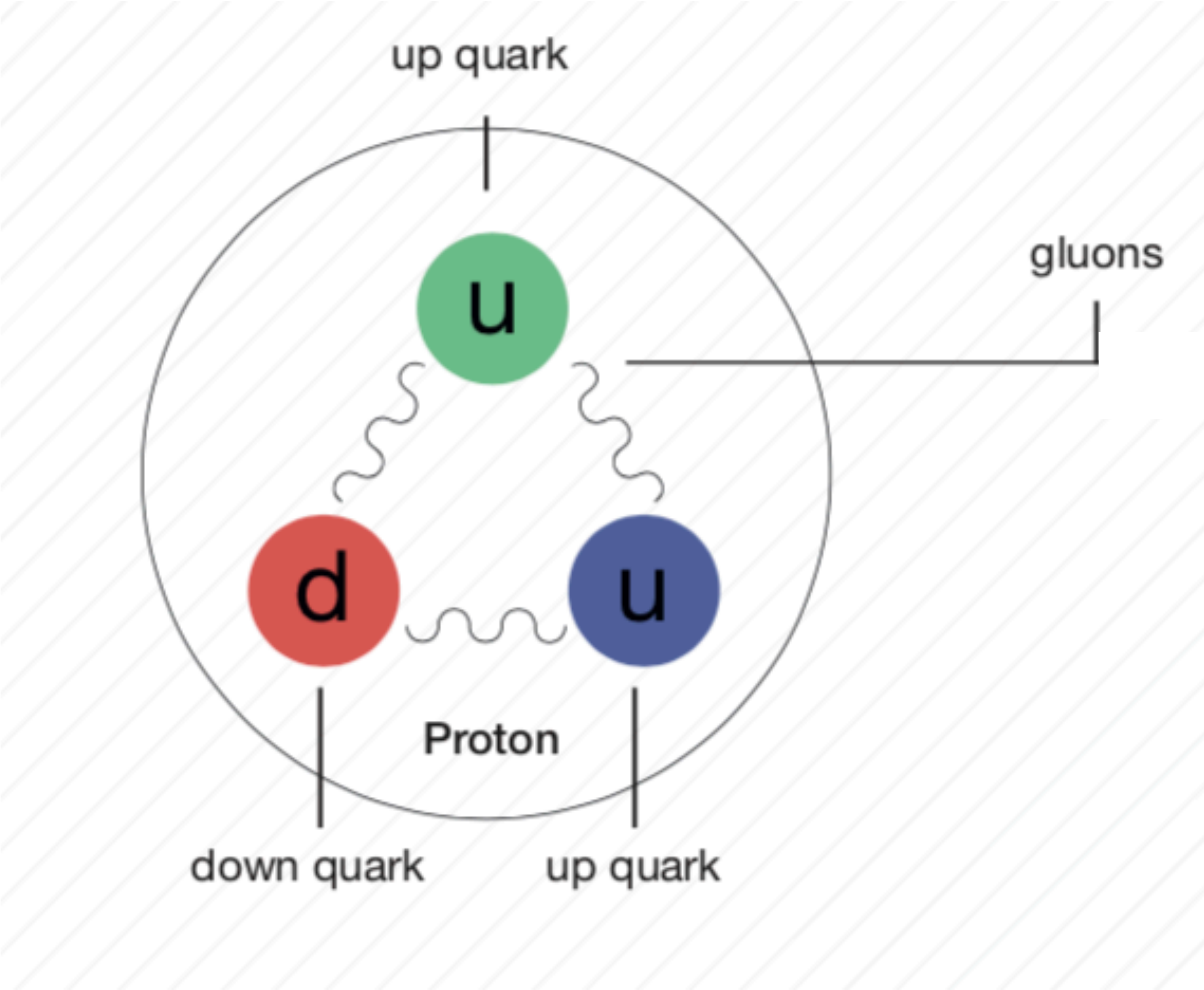
Simplified picture of a proton:



- 3 primary quarks
  - 2 up-quarks
  - 1 down-quark
- Quarks are bound together by the strong force (carried by gluons)

Revisiting the proton

Simplified picture of a proton:

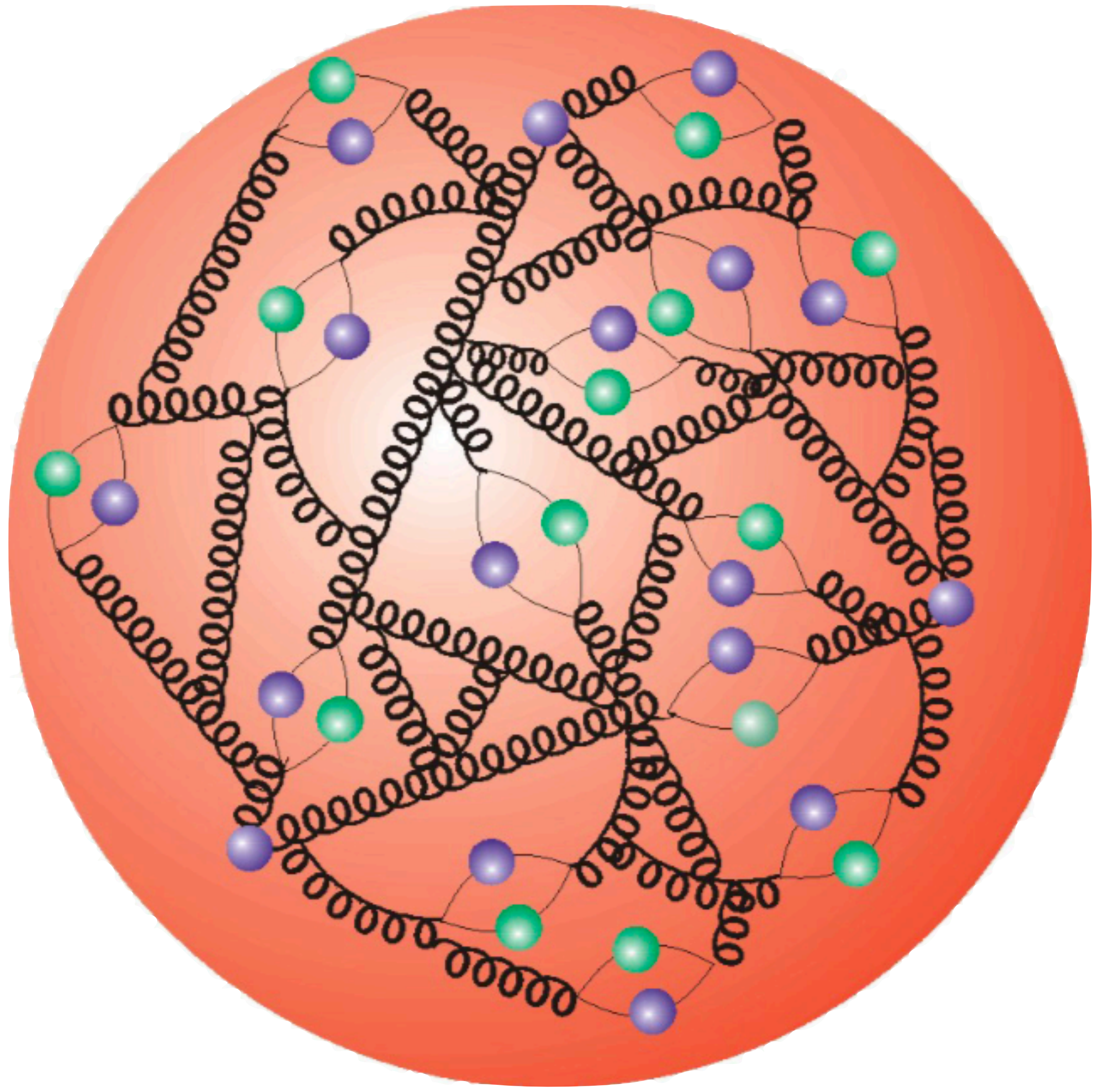


- 3 primary quarks
  - 2 up-quarks
  - 1 down-quark
- Quarks are bound together by the strong force (carried by gluons)

This picture is otherwise horribly wrong!

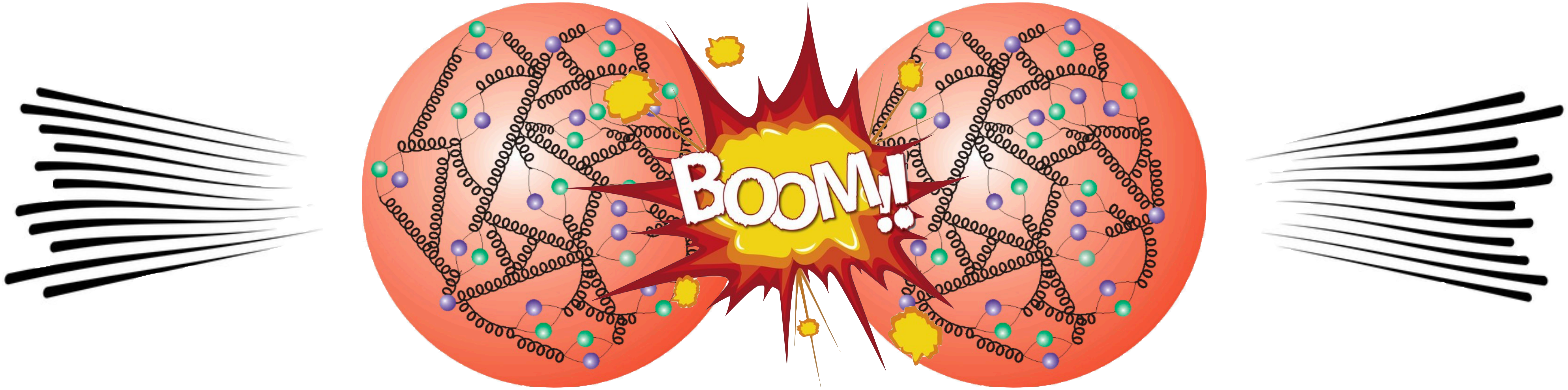
Revisiting the proton

(Slightly) more accurate picture of a proton:



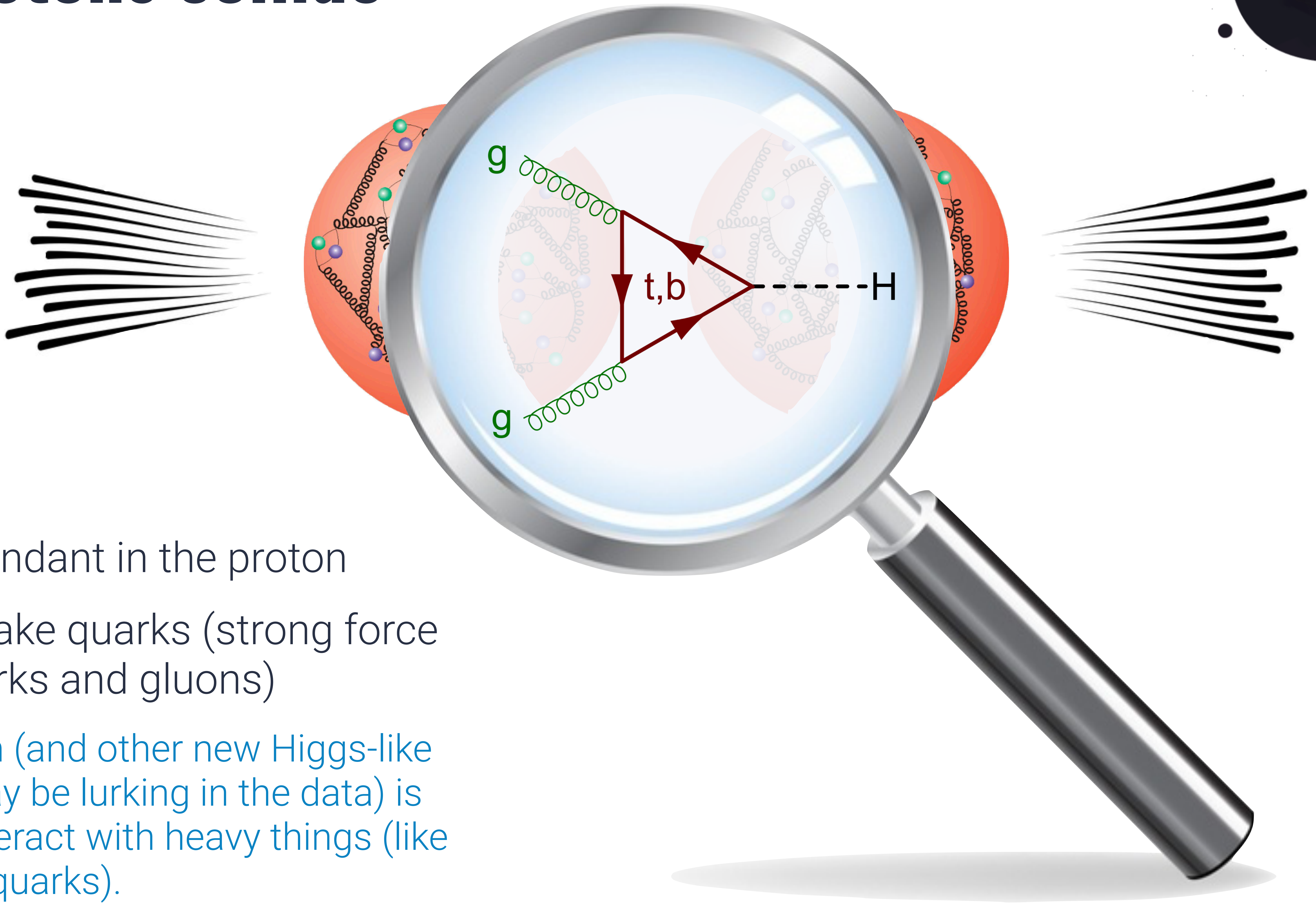
Most of the proton’s structure comes from the activity of the gluons, and the fact that virtual quark—anti-quark pairs are popping in and out of existence (thanks to the strong energy field).

When protons collide



The energy carried by all of the quarks and gluons inside the proton can be used to create new heavy particles.

When protons collide



Gluons are abundant in the proton

They love to make quarks (strong force couples to quarks and gluons)

The Higgs boson (and other new Higgs-like particles that may be lurking in the data) is most likely to interact with heavy things (like top and bottom quarks).

Jokes

Why can’t physicists prove a Grand Unified Theory?

Because it’s based on a GUT feeling.

Distance raptor over time raptor equals velociraptor

A photon checks into a hotel, where a bellhop asks where its suitcase is.

The photon replies, “I didn’t bring any luggage. I’m traveling light.”

What happens when electrons lose their energy?

They get Bohr’ed.