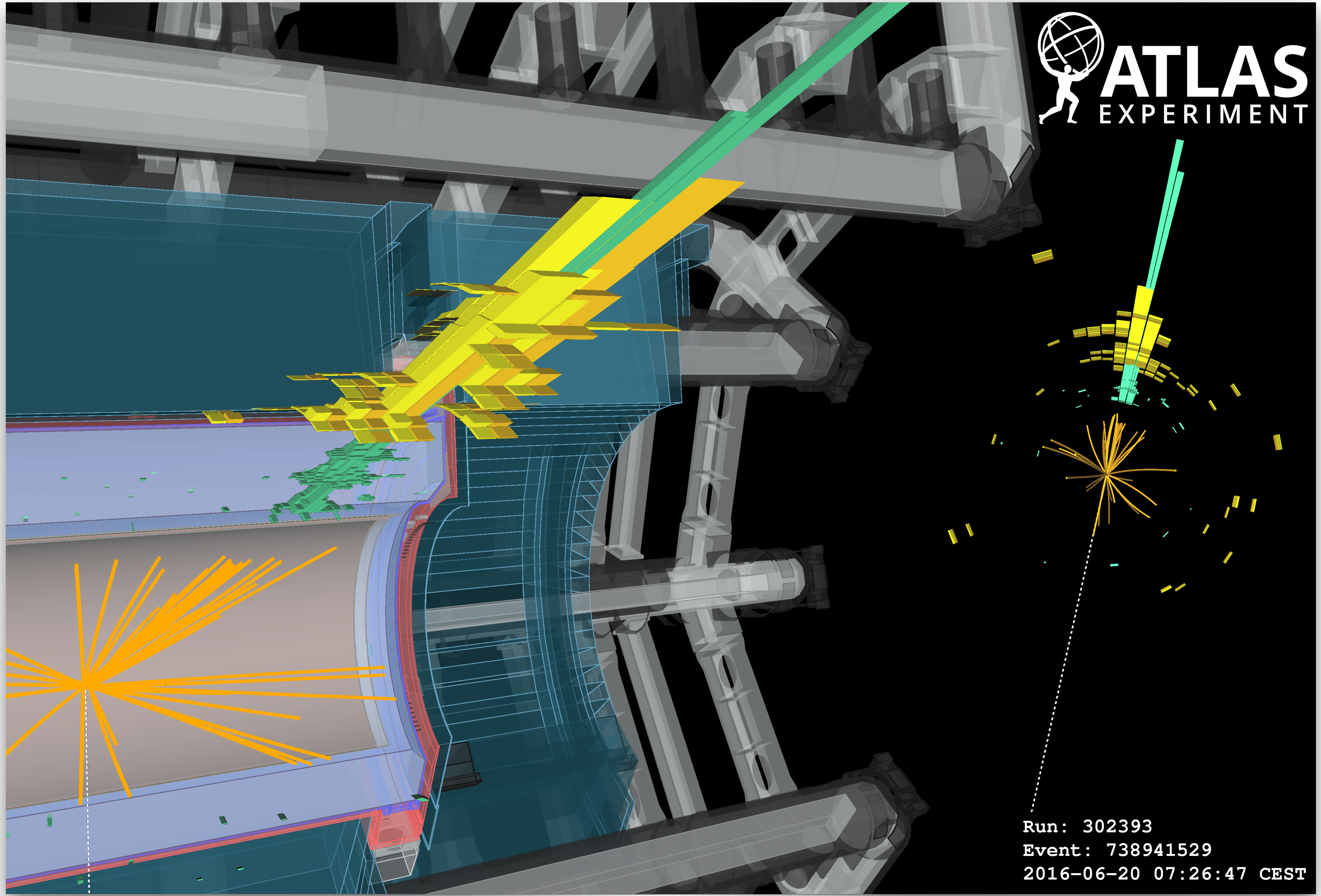
Experimental Physics at Hadron Collider



Lecture 4

Searches for New Physics

Conclusions and Outlook

Marumi Kado
Sapienza, Roma and LAL, Orsay

CERN Summer Students Lectures

July 22-25, 2019

CMS diphoton event

Outline

***Lecture 1**: Basic concepts, cross sections and QCD results*

- Preamble
- Context and mission of the LHC
- Fundamentals of hadron collisions
- Luminosity and total cross section
- Cross sections measurements
- Jet production measurements
- Measurement of the strong coupling constant

***Lecture 2**: SM Measurements*

- The electroweak sector in a tiny nutshell
- Measurement of the weak mixing angle
- W mass measurement
- Top mass measurement
- Diboson production
- Global fit of the Standard Model

***Lecture 3**: Higgs physics*

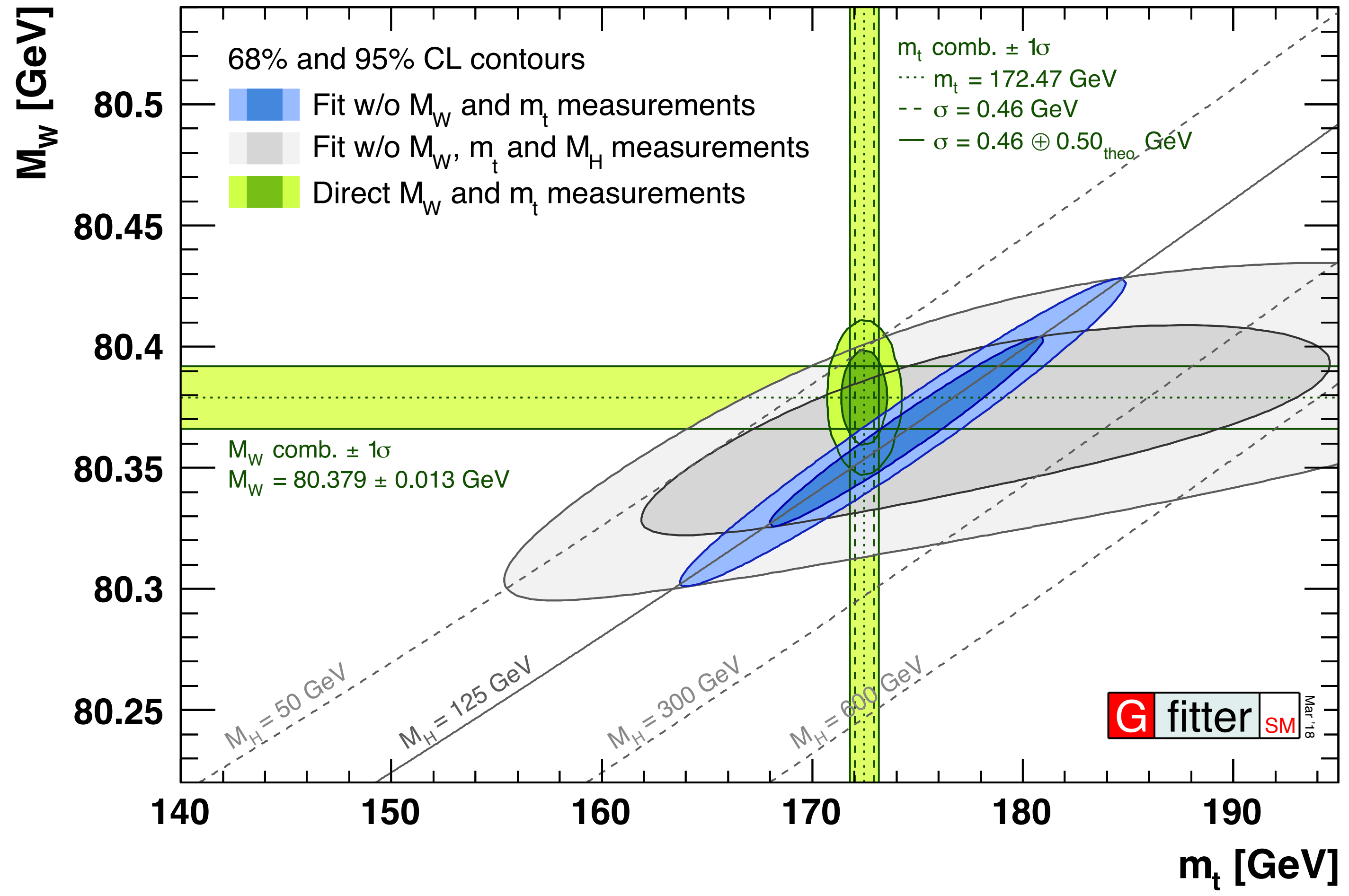
- The Higgs mechanism and Higgs production
- The discovery of the Higgs boson
- Precision Higgs physics with diboson channels
- Measuring the Yukawa couplings
- Measurement of Higgs properties
- Rare production and decays
- Global fit of the Standard Model (revisited)

***Lecture 4**: Searching for new physics BSM and future Hadron Colliders*

- Introduction
- Searches for supersymmetry and Dark Matter
- Searches in non SUSY theories
- Searches for unconventional signatures
- EFT and high energy observables
- Outlook on future colliders
- Conclusions

Direct Searches for New Physics

From Lectures 2 and 3:

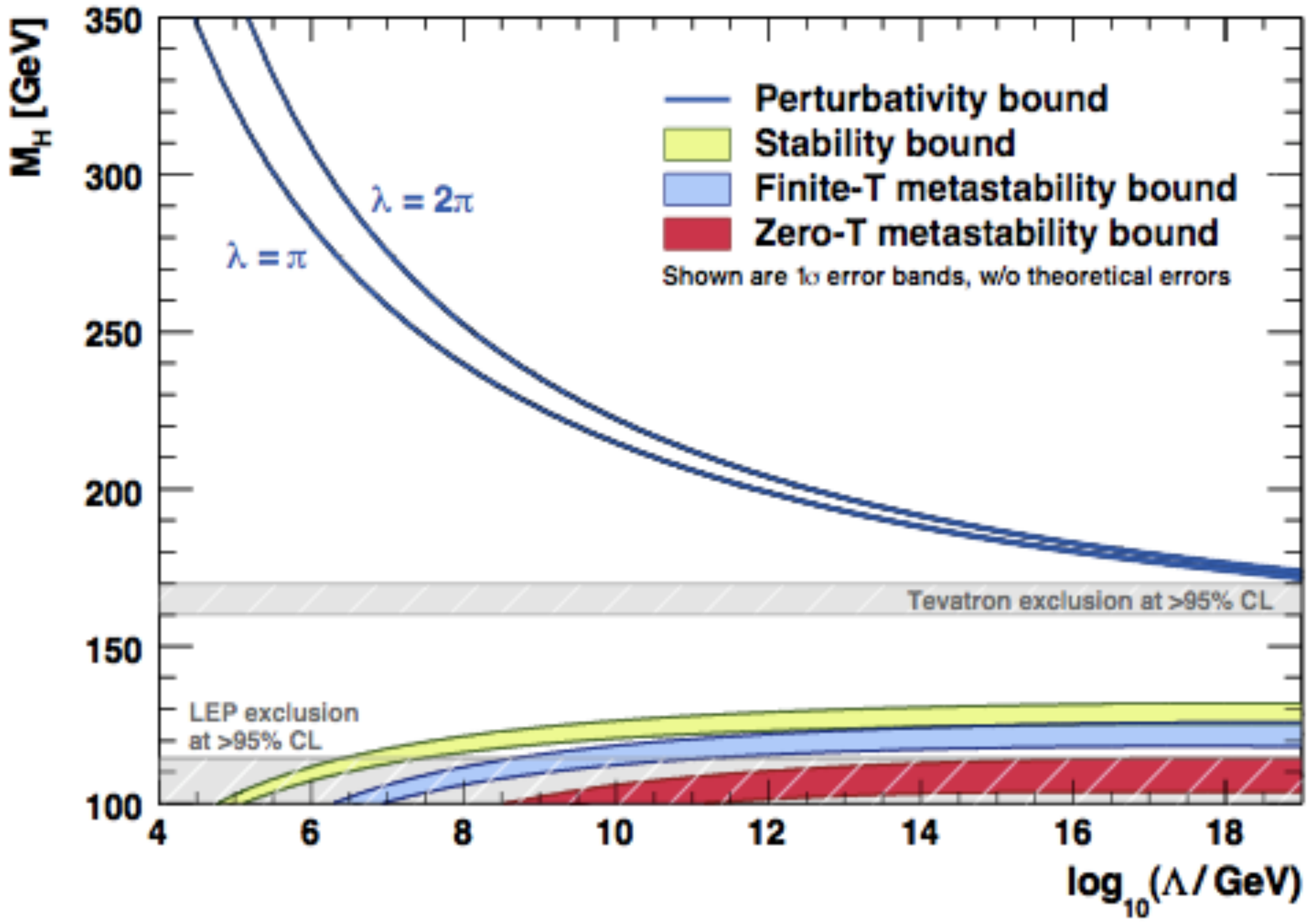


Global fit of the Standard Model: fully consistent!

In lectures 2 and 3 we have discussed how important it is to probe new physics through precision measurements of Standard Model parameters.

Within the current precision all measurements are consistent with the Standard Model

To further probe the Standard Model it is also extremely important to search directly for new phenomena which would yield different predictions than the Standard Model.



No indication of new physics scale.

With the discovery of the Higgs, for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.

Nima Arkani Hamed

The Standard Model still raises a large number of open questions and there are important unexplained phenomena that are very important guidelines to search directly for new physics scenarios.

The *Unsatisfactory* Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \psi + h.c.$$

The elegant gauge sector (tree parameters for EWK and one parameter for QCD)

$$\theta \frac{\alpha_s}{8\pi} F^A_{\mu\nu} \tilde{F}^{A\mu\nu} \qquad \theta < 10^{-10}$$

From neutron electric dipole moment measurements

The strong CP problem

$$+ \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

The less elegant Higgs sector:

- Carries the largest number of parameters of the theory
- Not governed by symmetries

- Gauge Hierarchy (and Naturalness)
- Flavour hierarchy (includes neutrino masses)

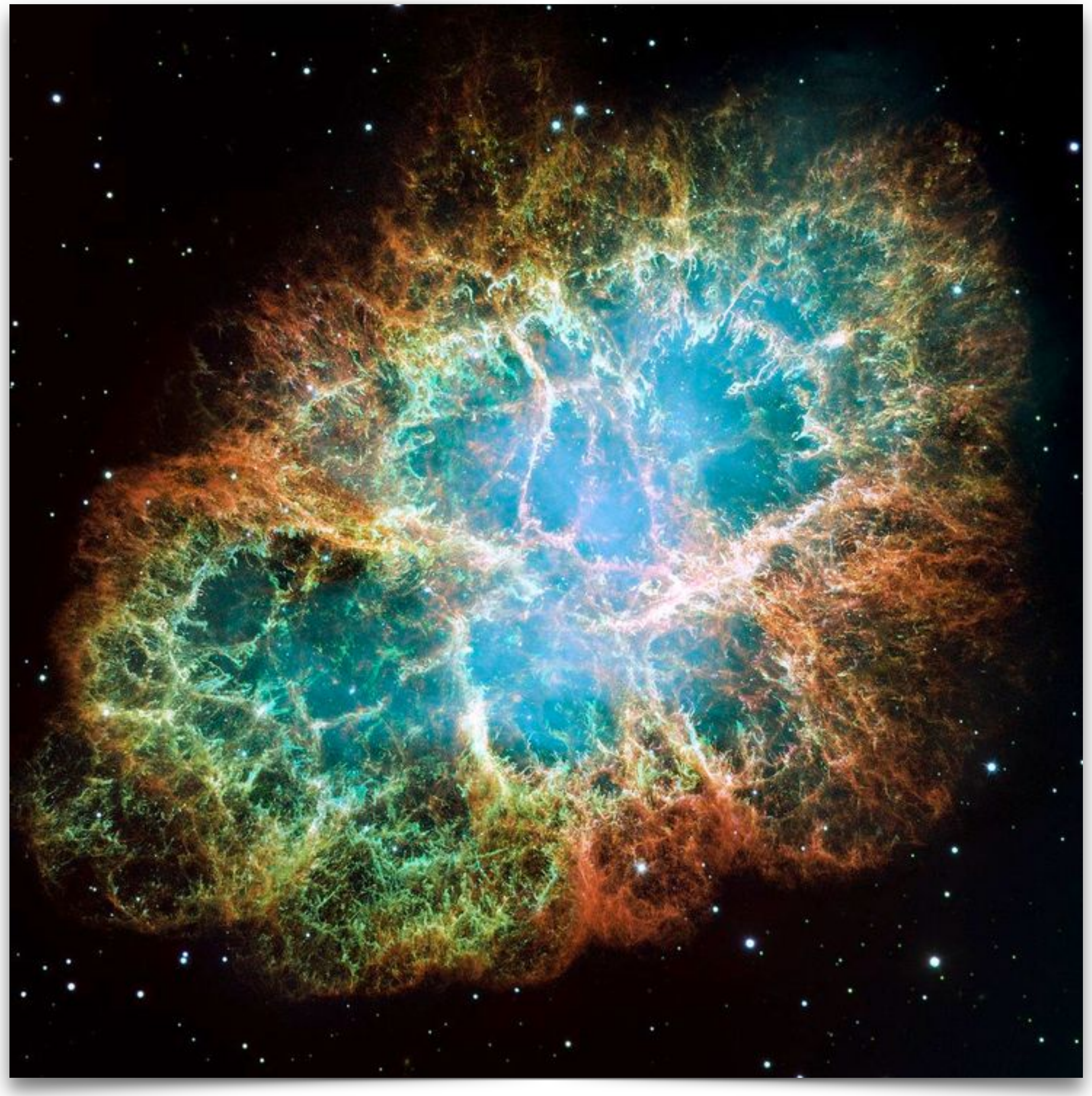
More fundamental questions (not explained by the SM):

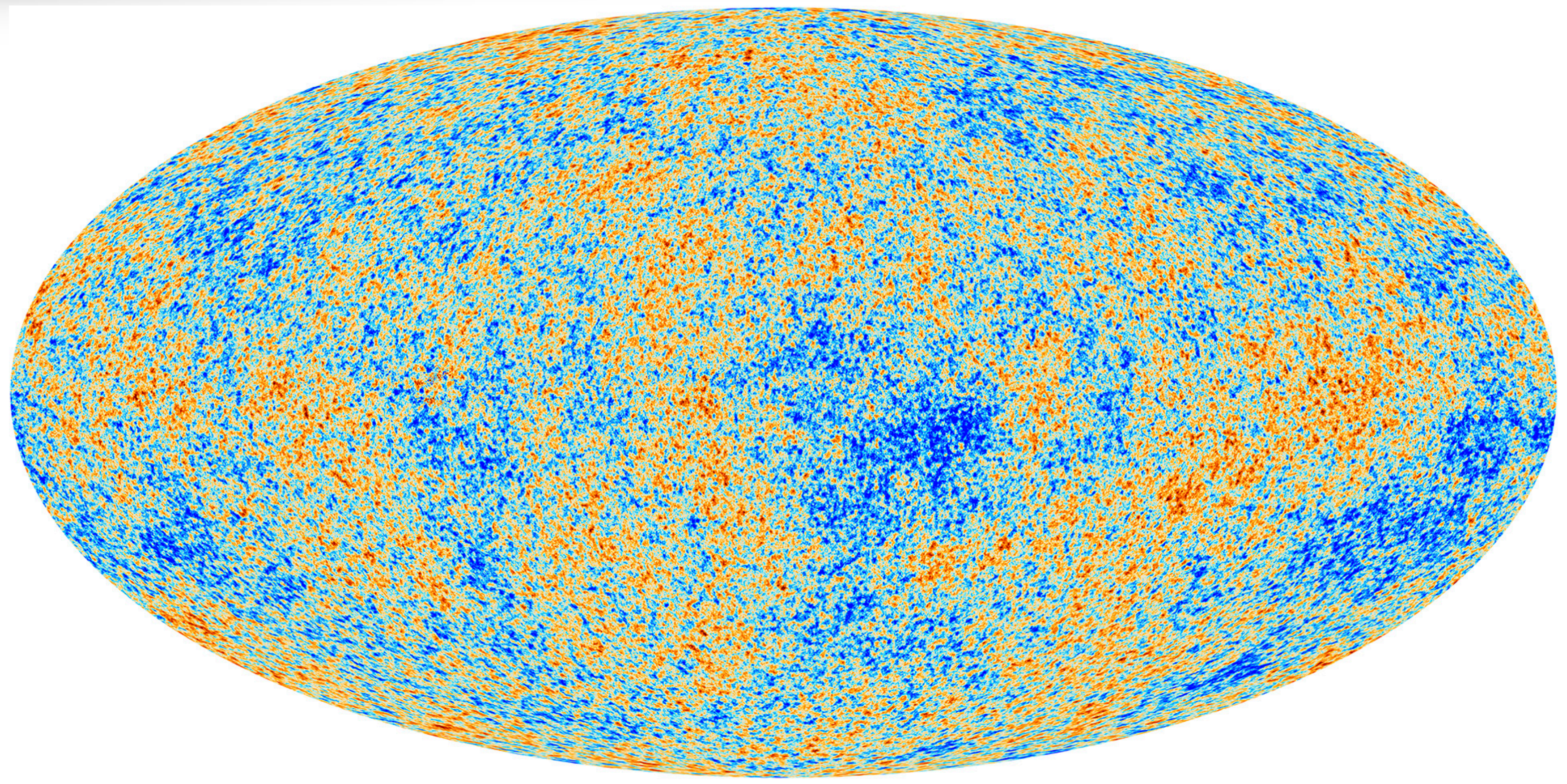
- Description of gravity at small distant scales?
- Why is the mu parameter in the Higgs potential negative?
- Why is the charge quantised and the charge of the electron equal that of the proton (grand unification)?
- … and many more!

Experimental observations (not explained by the SM):

- Anomalous magnetic moment of the muon (experiment currently taking data at FERMILAB (muon g-2, results coming soon) over 3σ discrepancy with expectation.
- B Lepton Flavor anomalies (see secures by Mark)
- and of course…

Unexplained Observed Phenomena





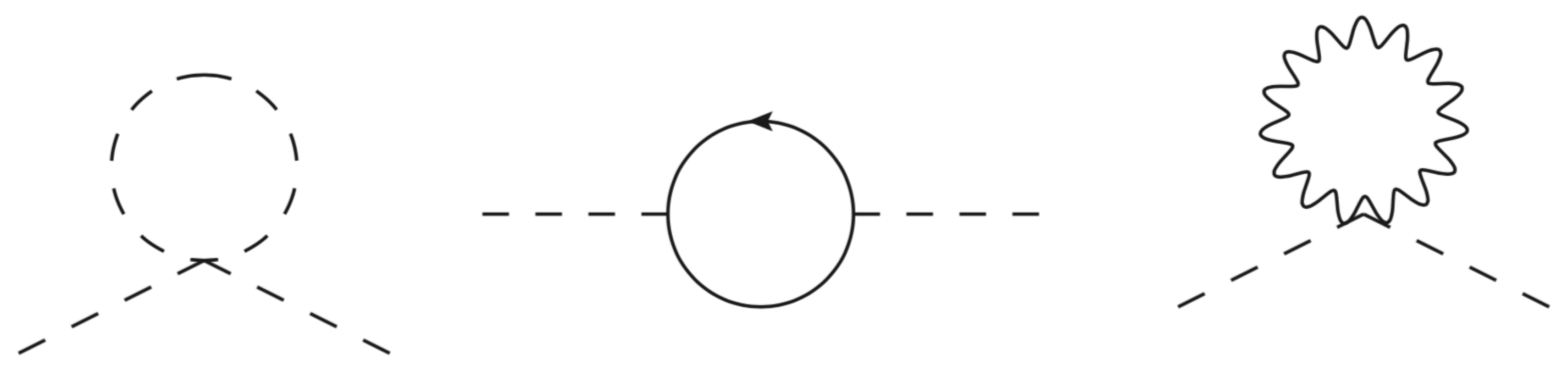
Astrophysical and cosmological observations:

- The mere existence of the universe and the matter/anti-matter balance?
- The nature of Dark Matter?
- The nature of Dark Energy?

Why is the Hierarchy an Issue?

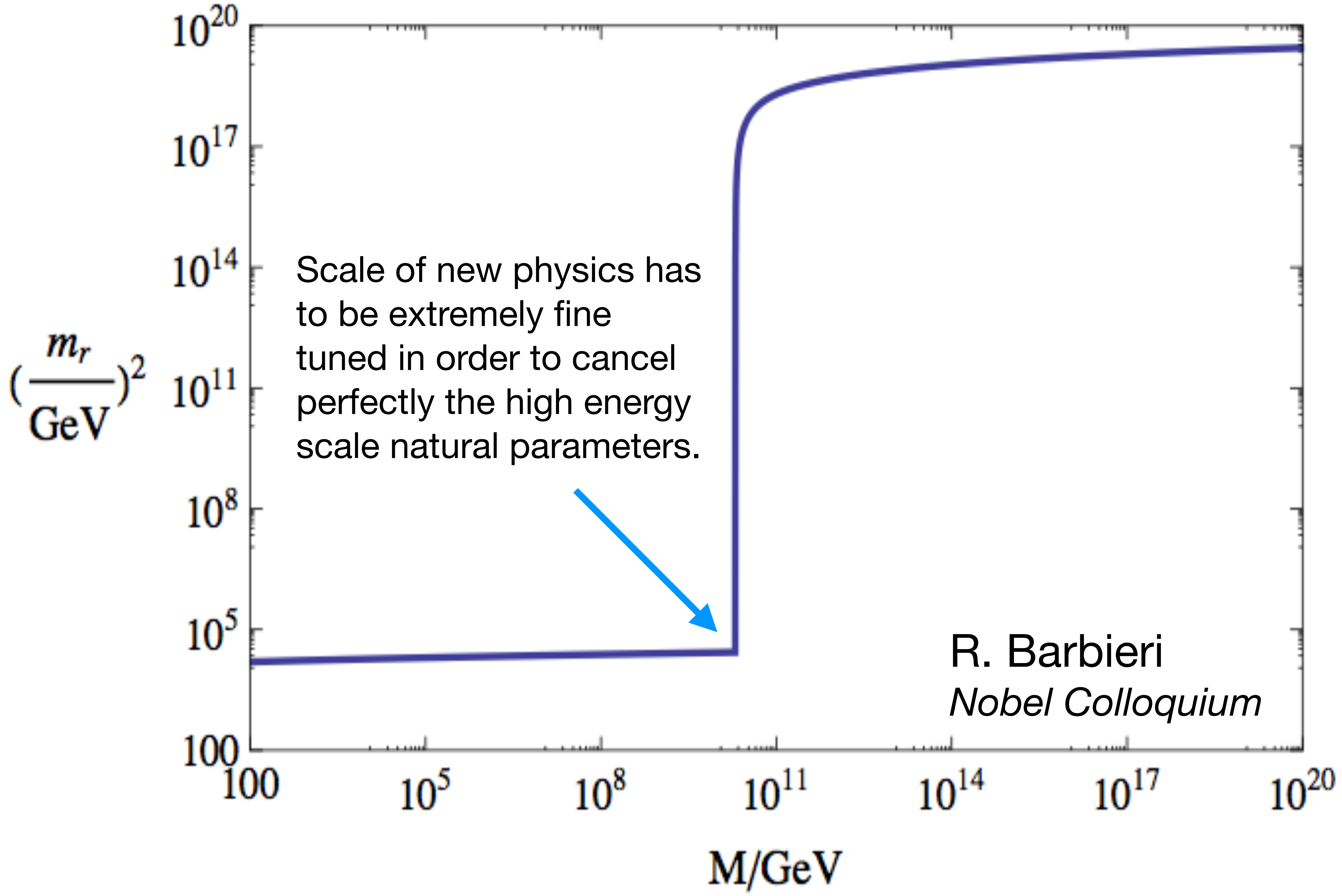
Naturalness

If the Higgs boson is an elementary scalar, loop corrections to its mass are quadratically divergent:



$$\Delta m^2 \propto \int^{\Lambda} \frac{d^4k}{(2\pi)^4}\frac{1}{k^2} \sim \frac{\Lambda^2}{16\pi}$$

The Standard Model is a renormalisable theory quadratic divergences are not a problem per se, but if we look at the running of the Higgs boson mass:



Solutions:

- **Weakly coupled**: introduce fields in the theory that can cancel the quadratic divergence and alleviate the fine tuning (e.g. SUSY)
- **Strongly coupled** (Composite): in this case the above does not apply. The Higgs could be either a generic bound state or a pseudo goldstone boson (similarly to the pion in Chiral perturbation theory).
- **Warped extra dimensions**: Difference between scales generated by warping.
- **Anthropic principle**: fine tuning is acceptable since it is a condition for existence of the universe as it is.

Supersymmetry

Supersymmetry

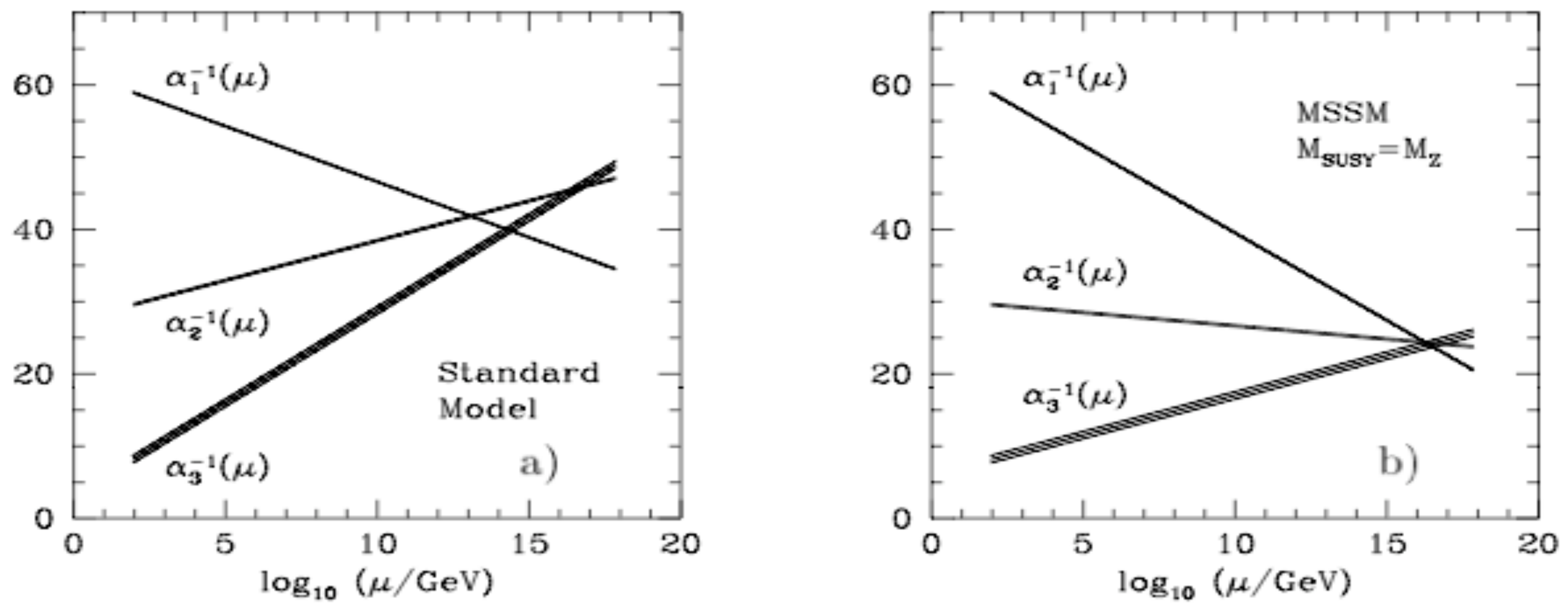
An elegant, simple and complete solution…

Nutshell description:

- For all fermions degree of freedom SUSY adds a boson degree of freedom
- To all bosons degree of freedom, SUSY adds a fermions

What SUSY addresses:

- It resolves the gauge hierarchy (naturalness problem)
- It allows unification of gauge couplings
- Local SUSY requires gravitino and therefore via SUSY naturally brings the graviton and is an essential ingredient in string theory
- It provides a natural candidate for dark matter



The only few (non negligible) **issues:**

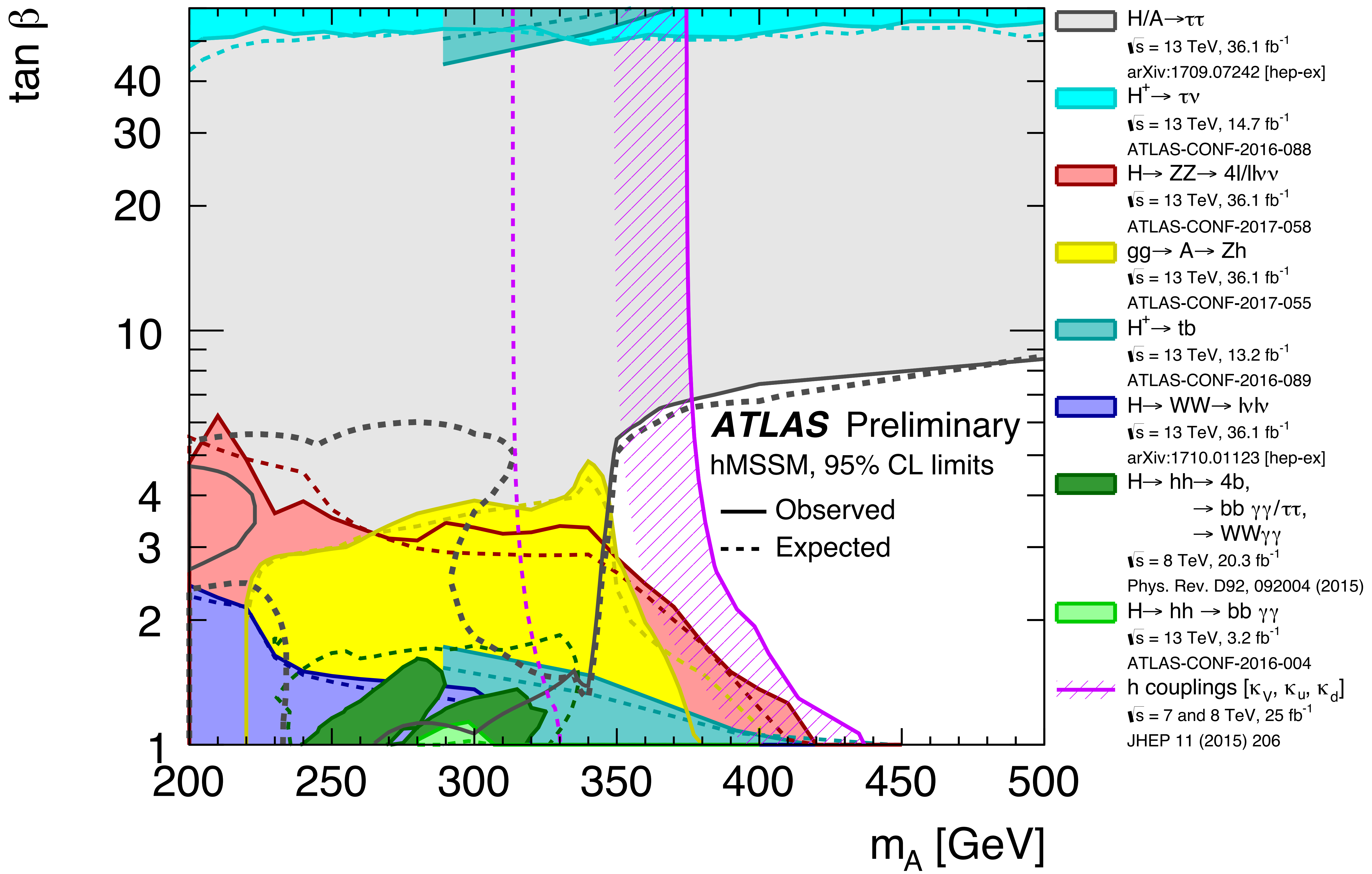
- It has not been found! If it exists it has to be broken
- If the super-partners are too heavy fine tuning re-emerges and one of the main issues (naturalness) reappears).
- With a much larger number of fields come a much larger number of parameters!

The main predictions of SUSY

- Superpartners that should be at a reachable scale!
- A candidate dark matter particle: the neutralino (typically).
- An extended Higgs sector. Its minimal realisation is the MSSM (2 Higgs doublets so 5 Higgs bosons, 3 neutral and 2 charged).

Reaching SUSY from an extended Higgs sector

The MSSM Higgs sector at tree level is governed by only two parameters (mA and tan β).



SUSY could modify the couplings of the Higgs

From the combination of all channels presented in Lecture 3, from constraints on up versus down Yukawa and coupling to vector bosons, limits in the MSSM parameter space can be set.

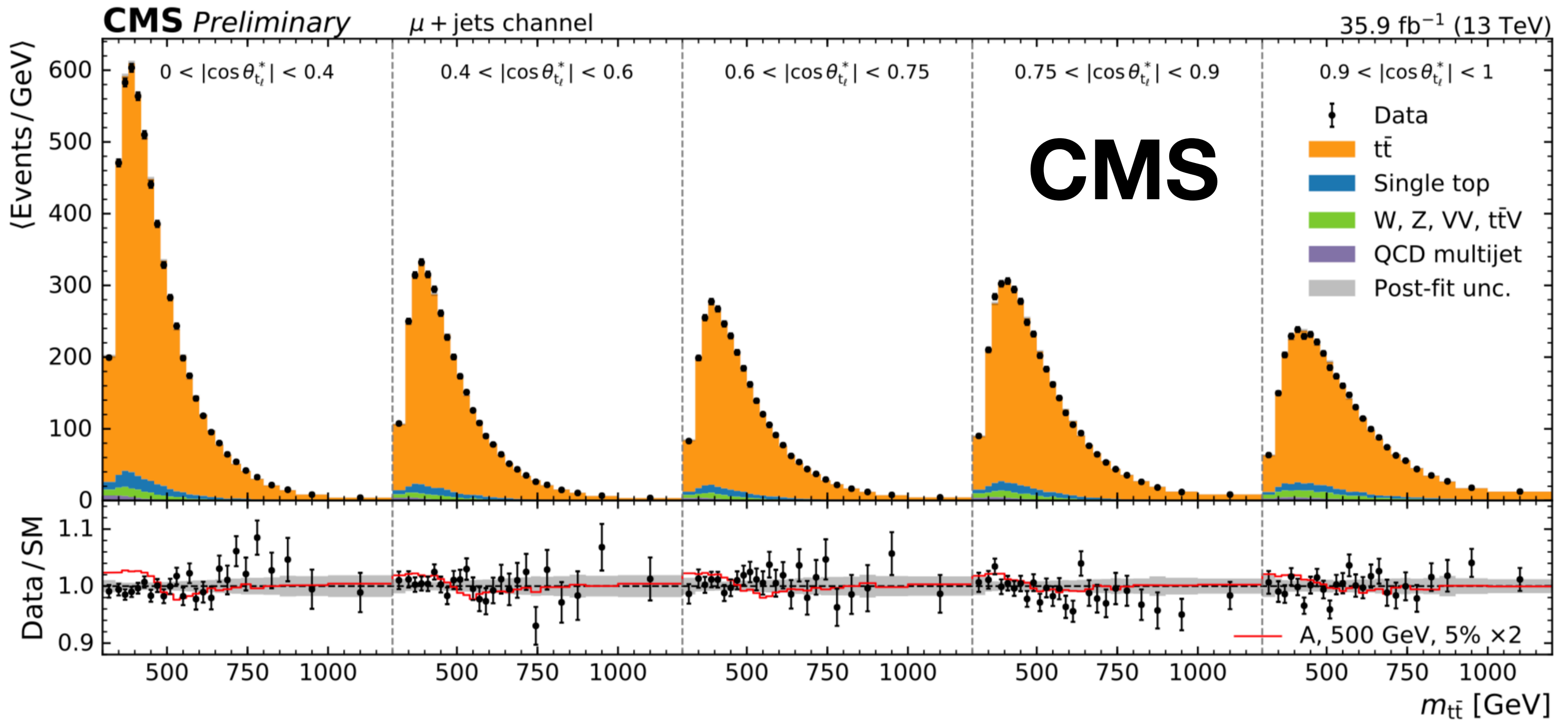
Direct searches for additional Higgs bosons (neutral and charged) have been performed:

- Neutral heavy Higgs to tau tau
- Charged Higgs to tau neutrino
- Heavy neutral Higgs to ZZ
- Charged Higgs to tb
- Heavy neutral Higgs to ZH
- Heavy Higgs boson to HH

Search for Higgs to top pair

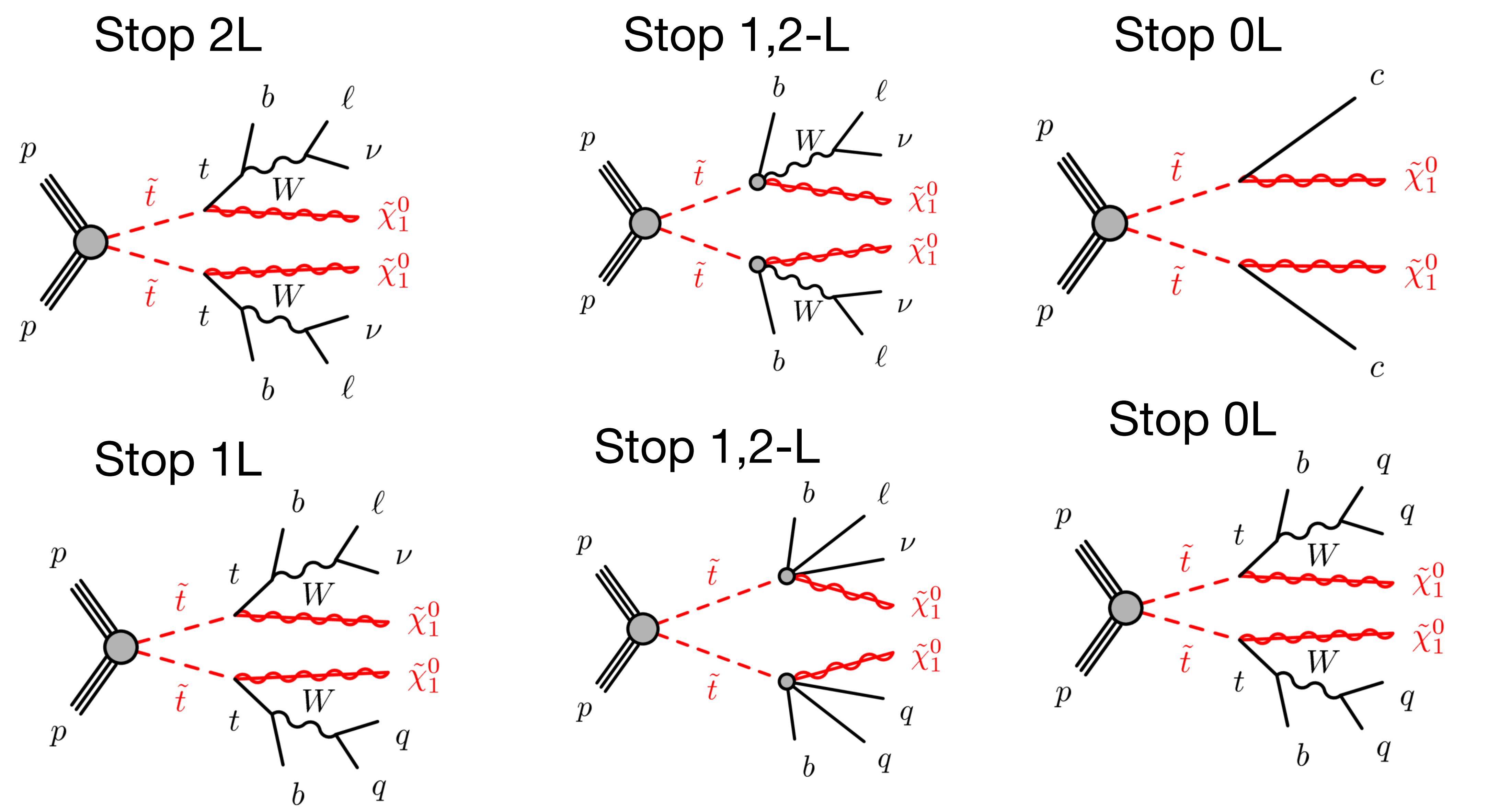
μ -jets channel

Intricate search for a non trivial interference pattern in ttbar mass.

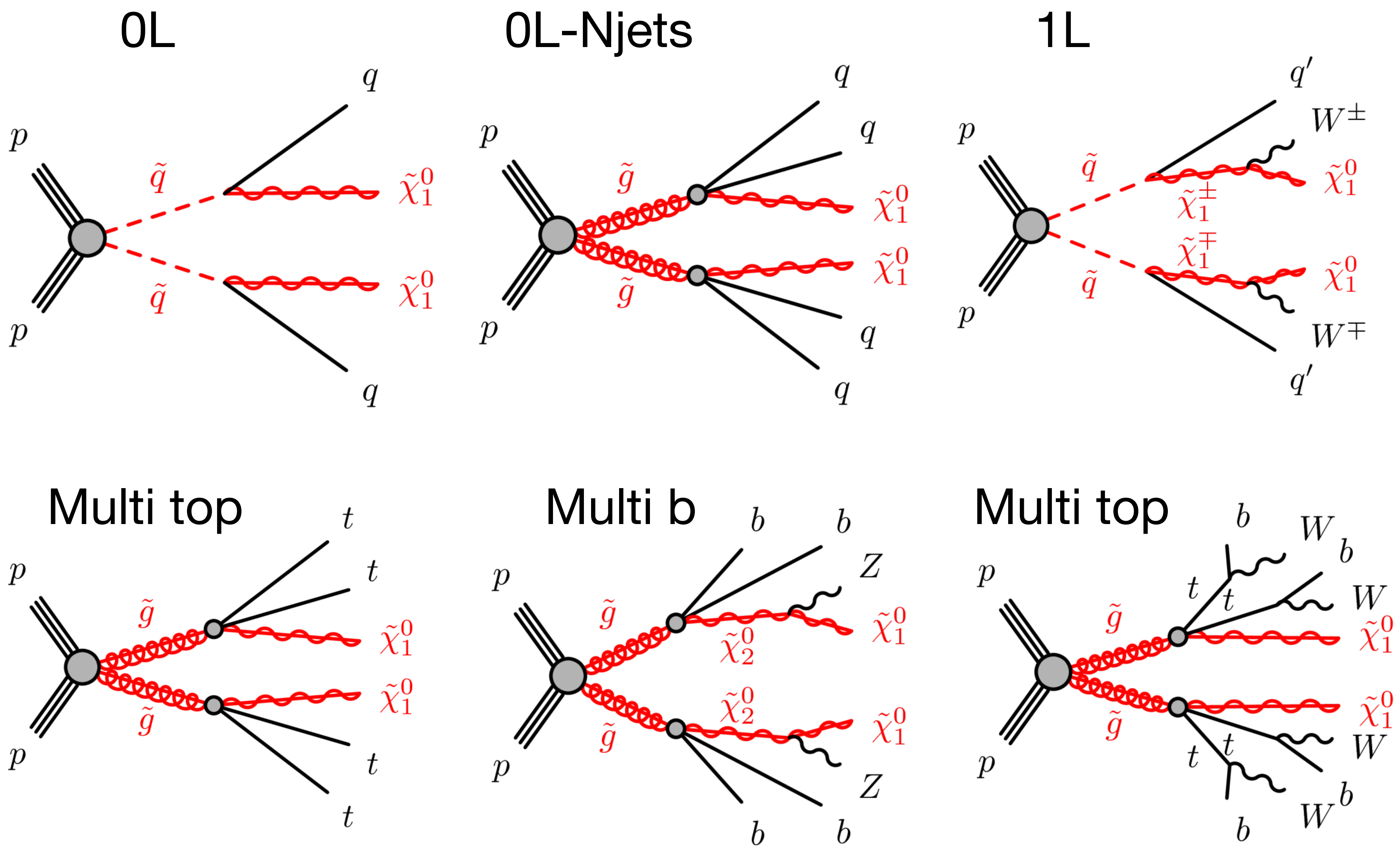


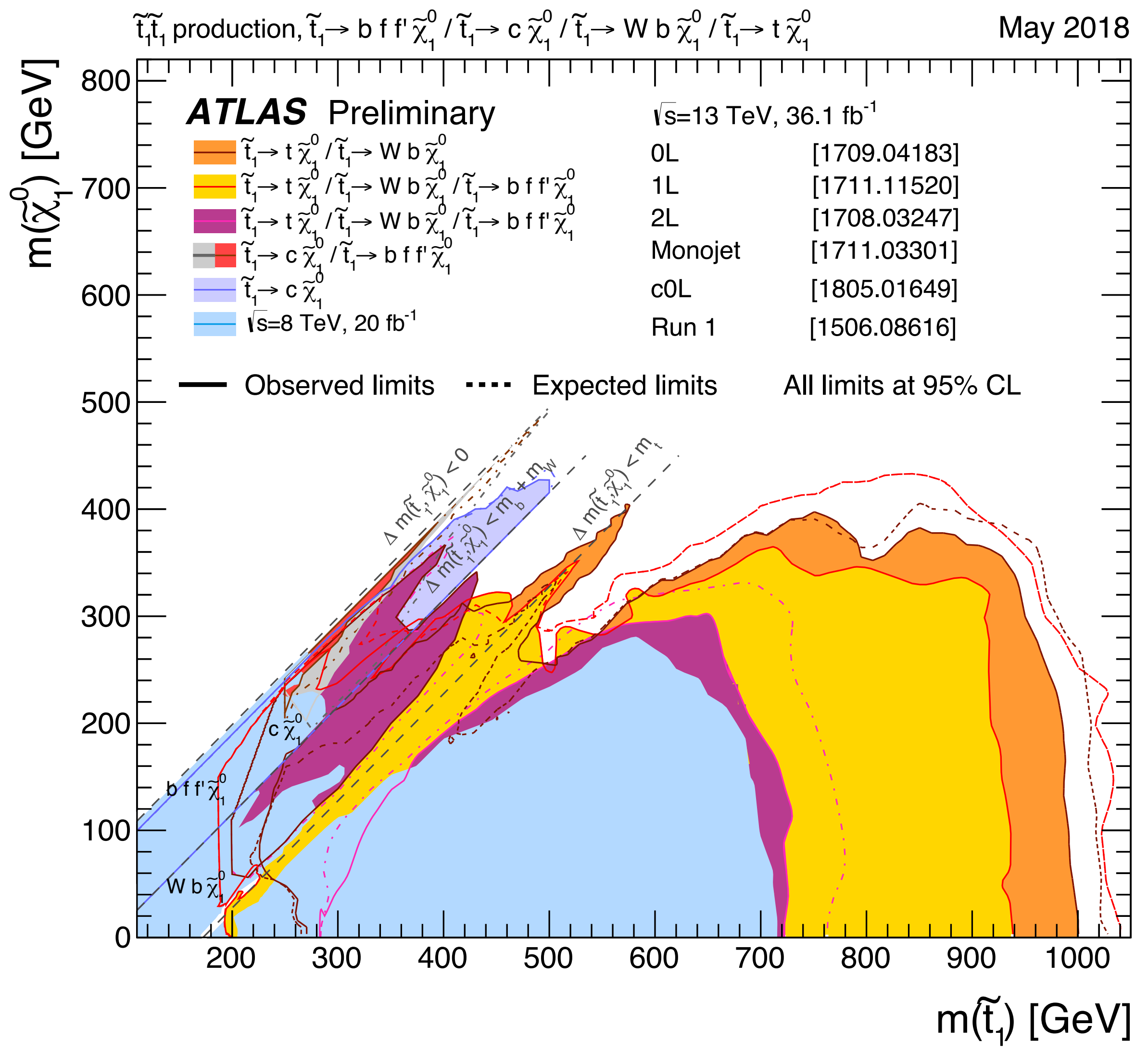
Searches for Natural and Strongly Produced SUSY

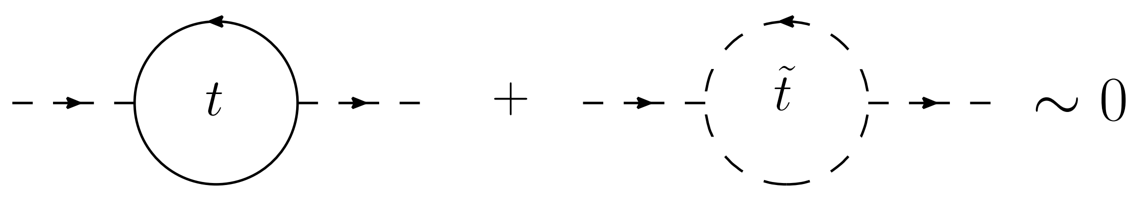
Stop



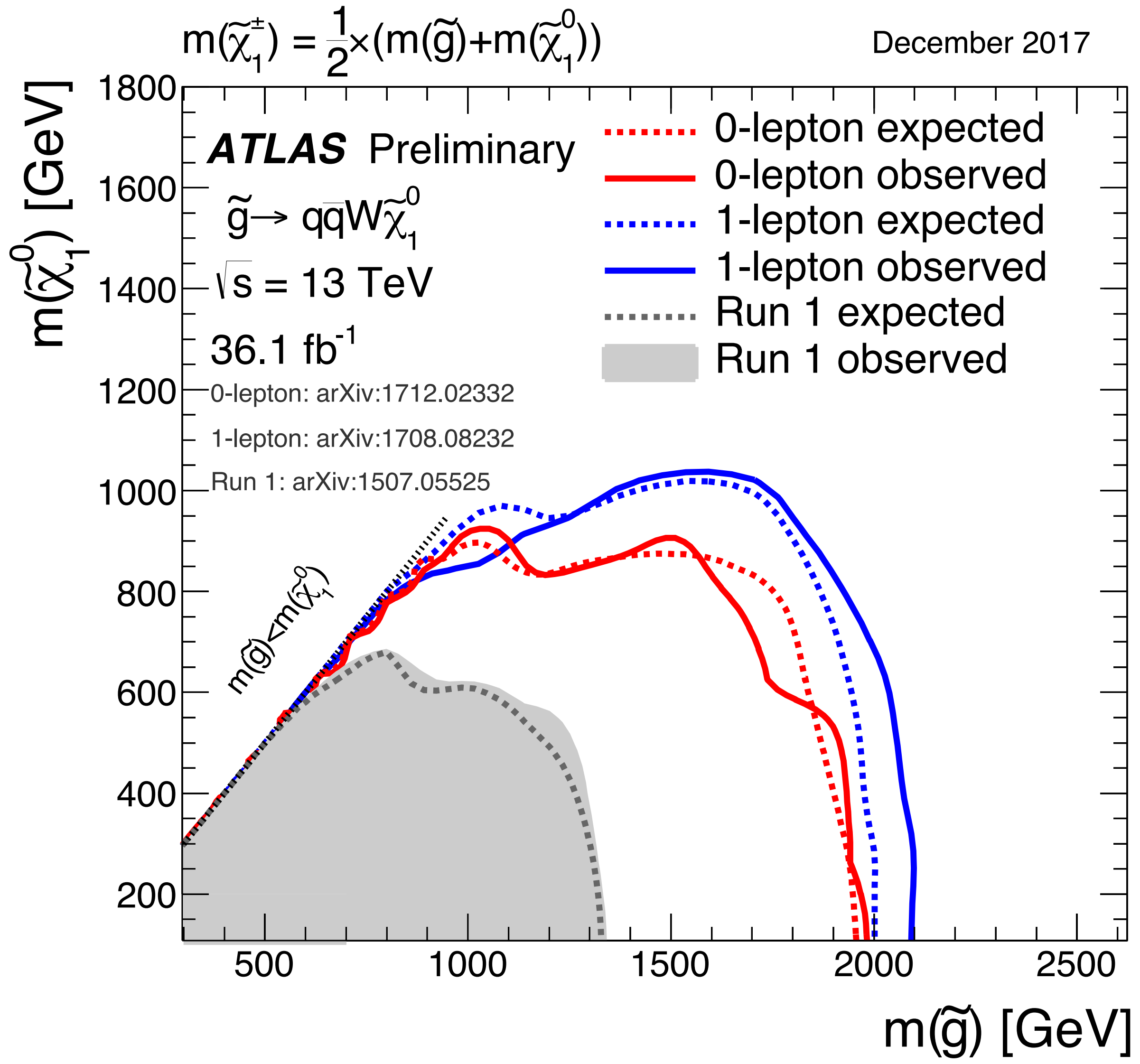
Squarks and gluinos

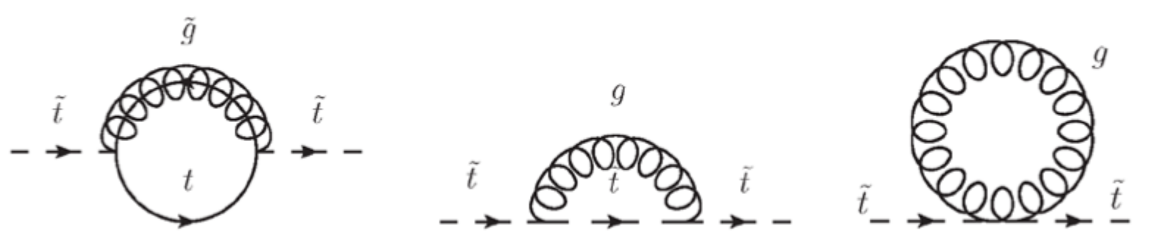






Not so natural SUSY: Stops > 1 TeV ~Tuning of factor **20**, but these exclusions are under specific conditions, and there are unexcluded corridors.





Stop also a scalar requires light gluinos to be light enough: for gluinos > 2 TeV ~tuning of Factor of **30**

Searches for Natural and Strongly Produced SUSY

Stop

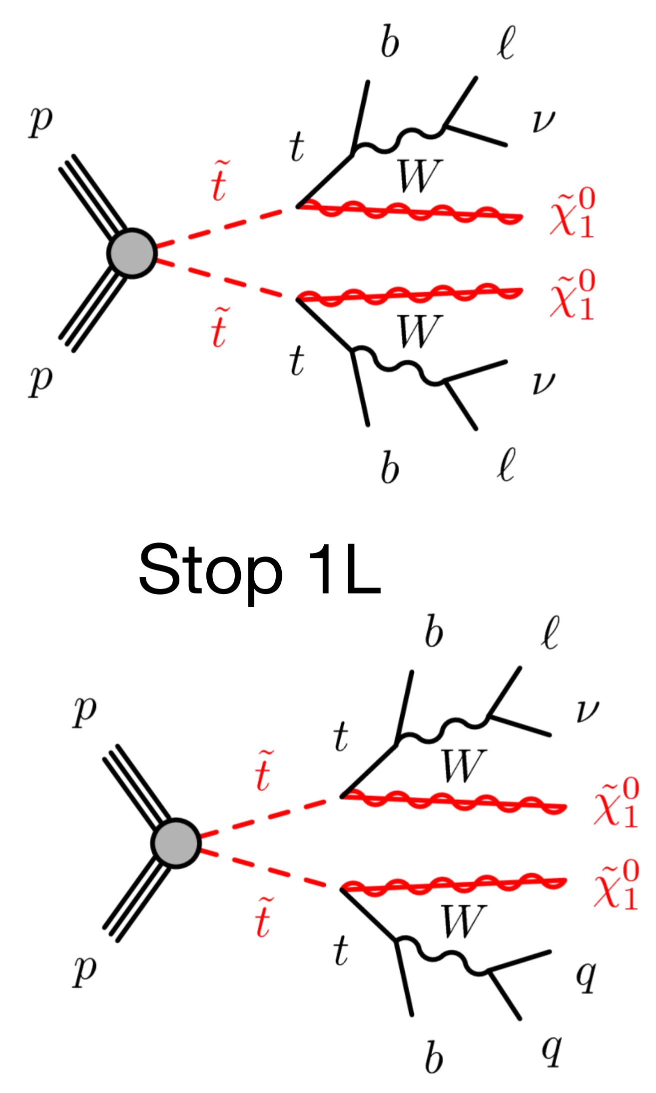
Stop 2L

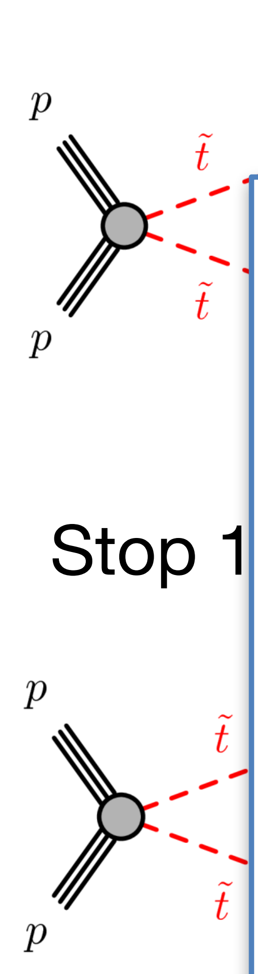
Stop 1,2-L

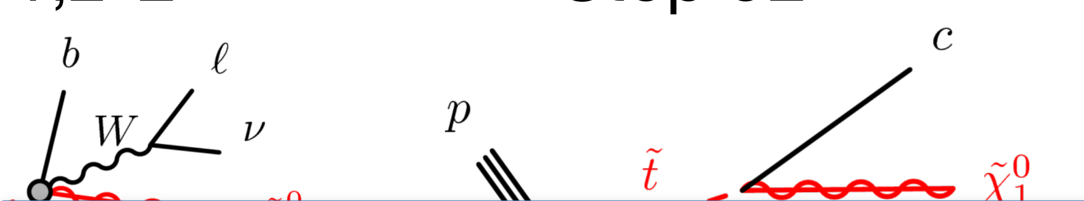
Stop 0L

Stop 1L

Stop 1







Squarks and gluinos

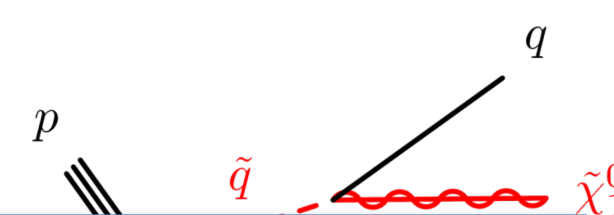
0L

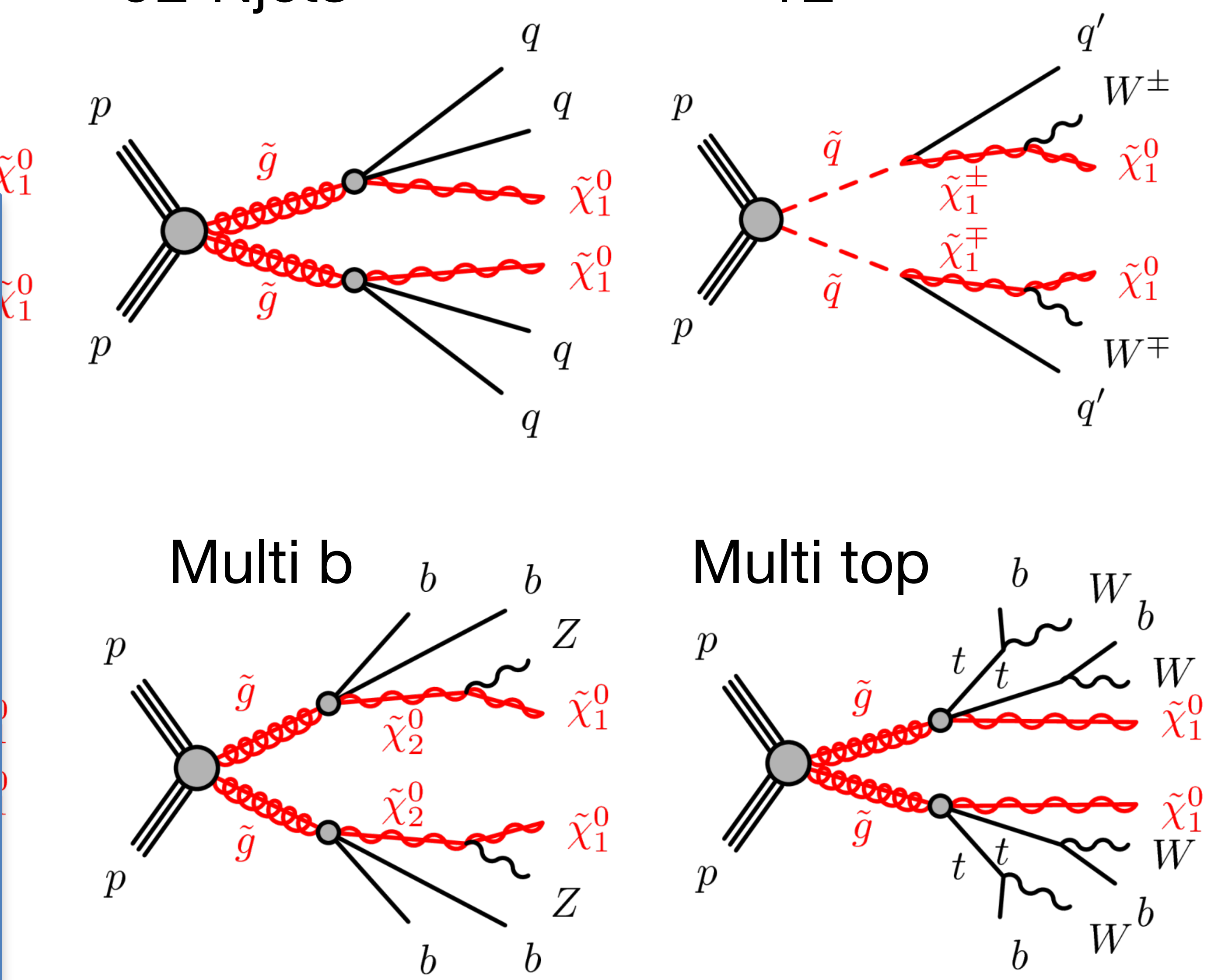
0L-Njets

1L

Multi b

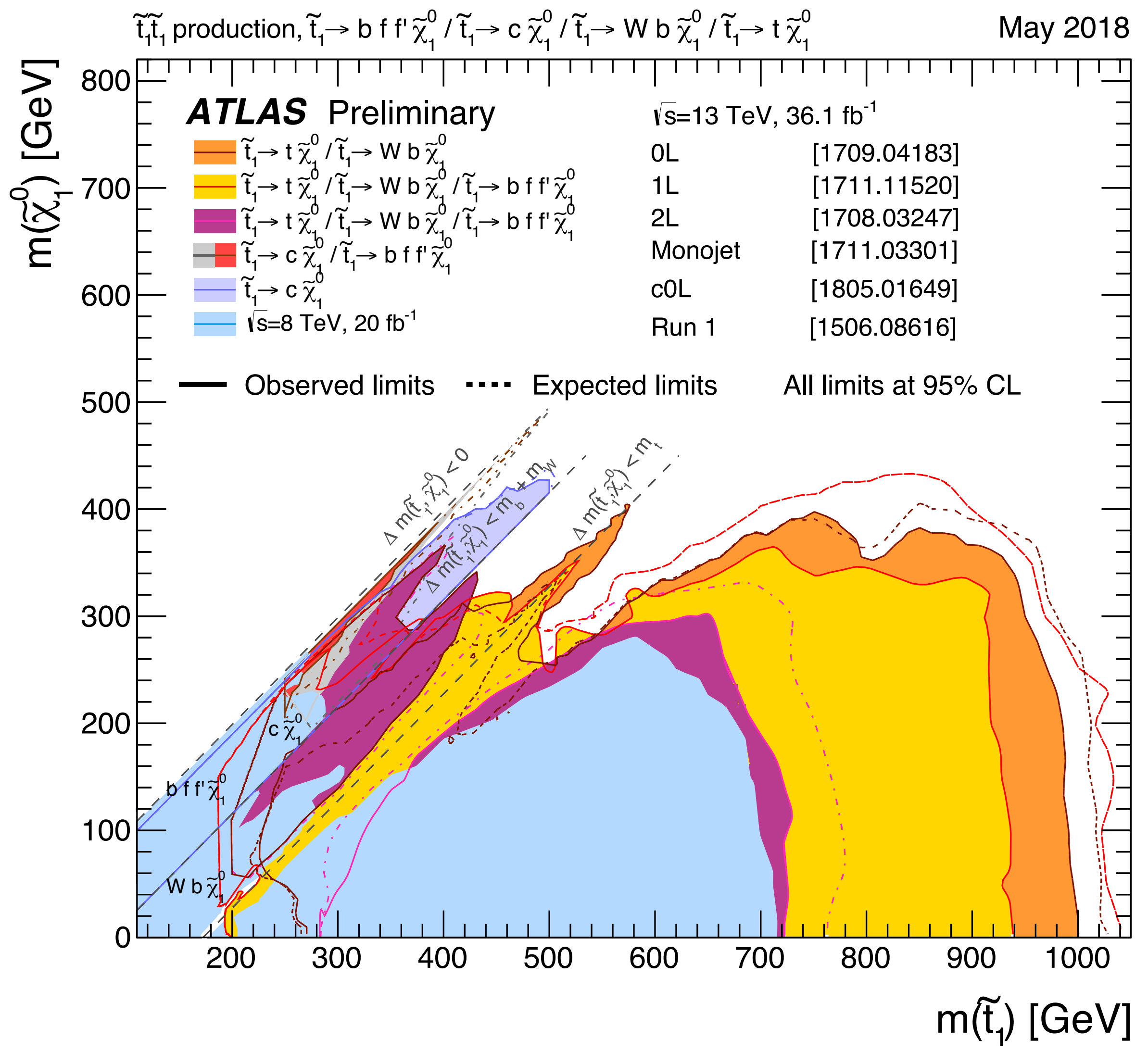
Multi top

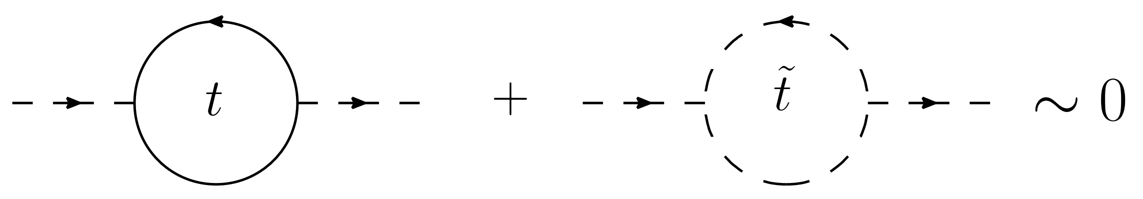




Large number of topologies which can cover different SUSY or other new physics scenarios

All signatures feature missing transverse energy are searches for Dark Matter (in this case the lightest SUSY particle)!





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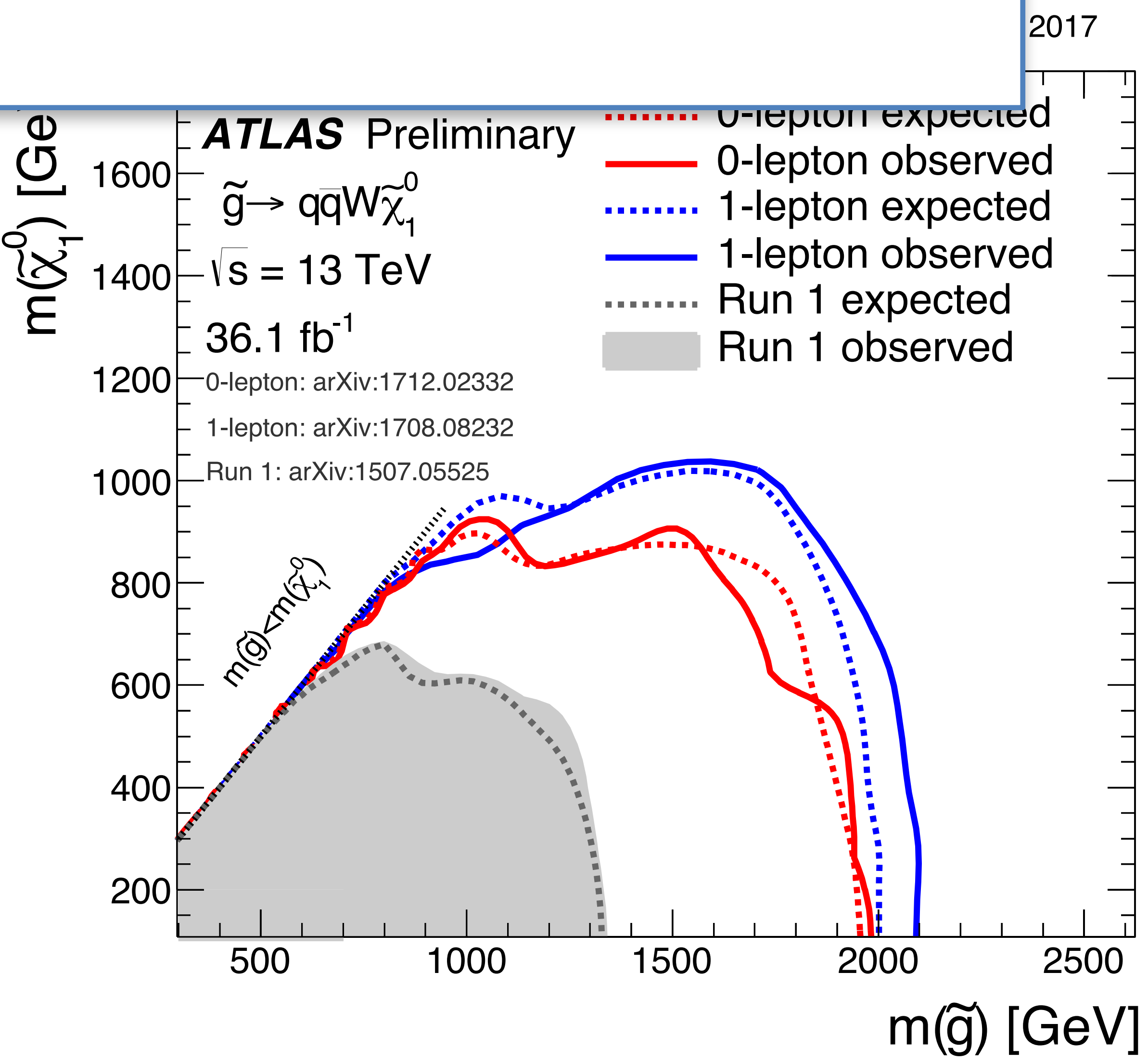
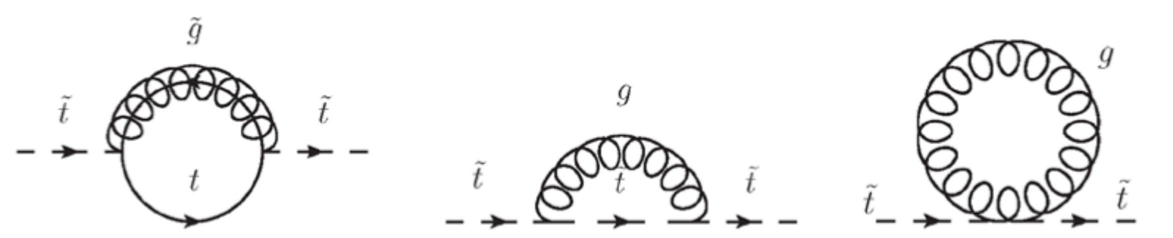
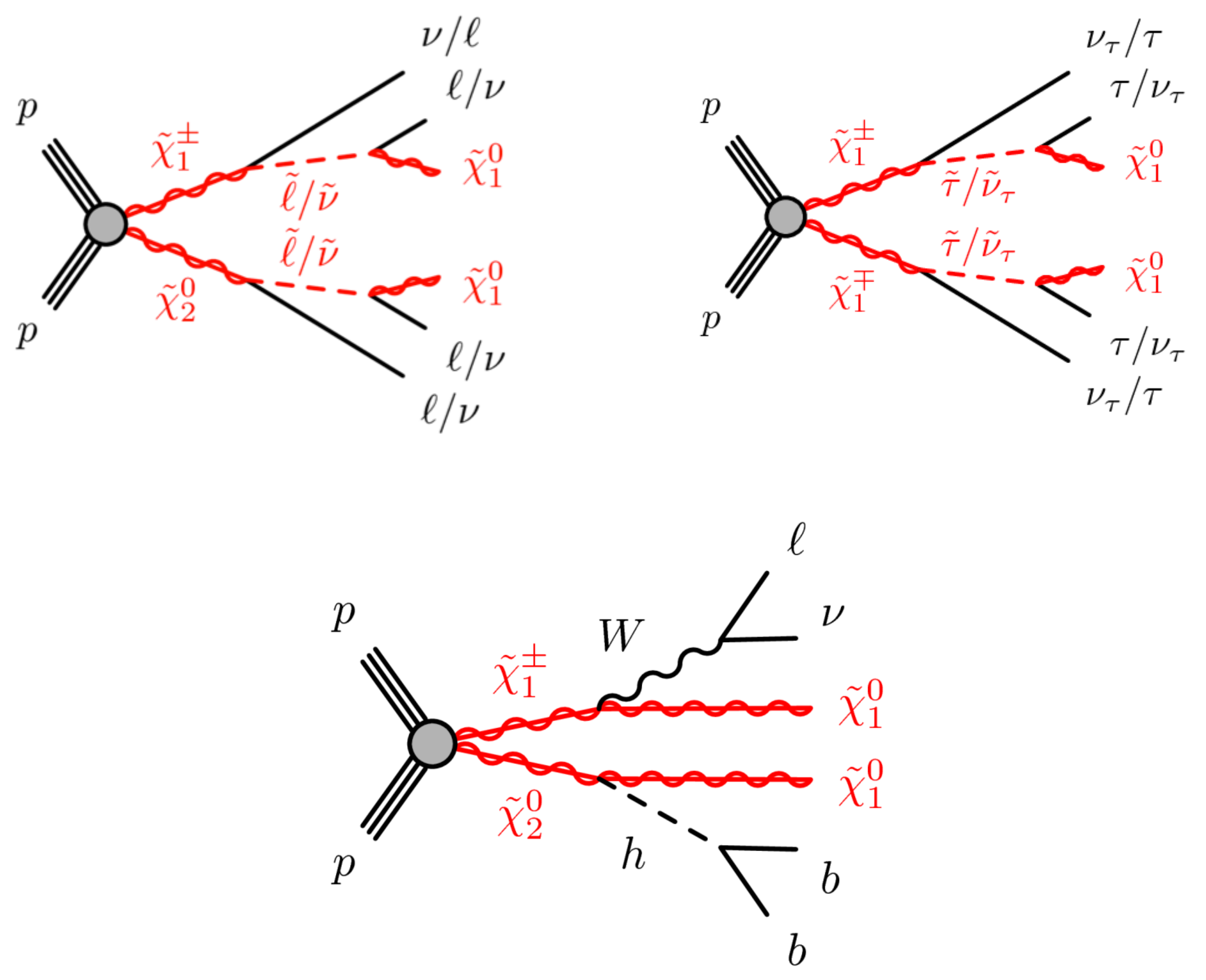




Stop also a scalar requires light gluinos to be light enough: for gluinos > 2 TeV ~tuning of Factor of **30**

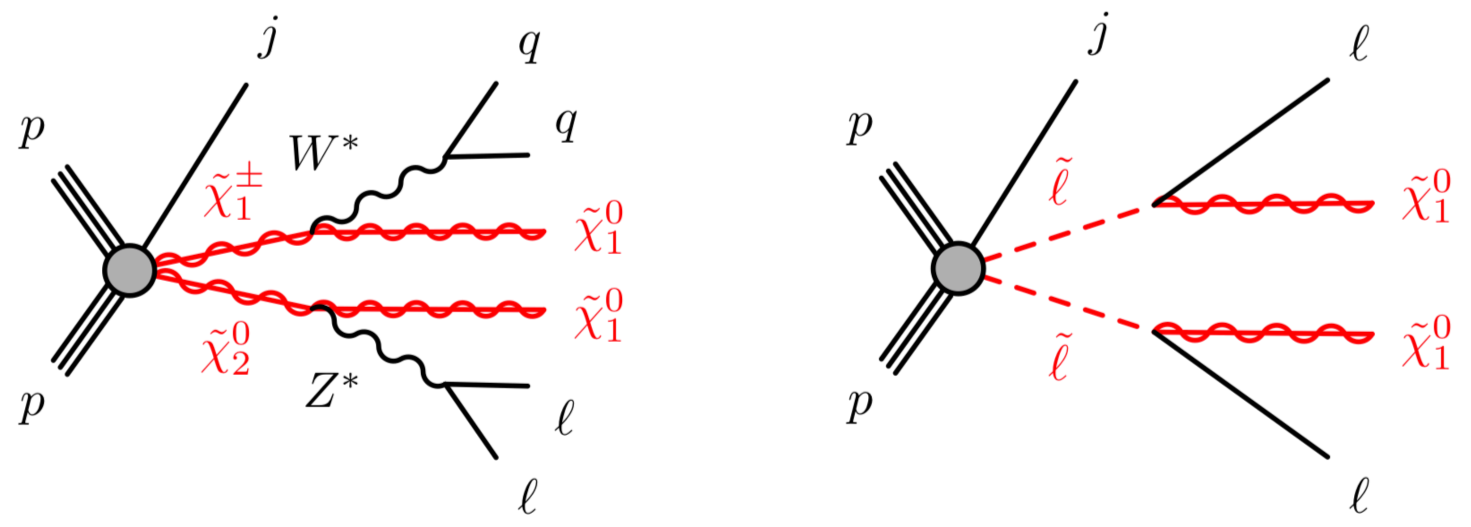
More intricate scenarios

Weak production of charginos, neutralinos and sleptons



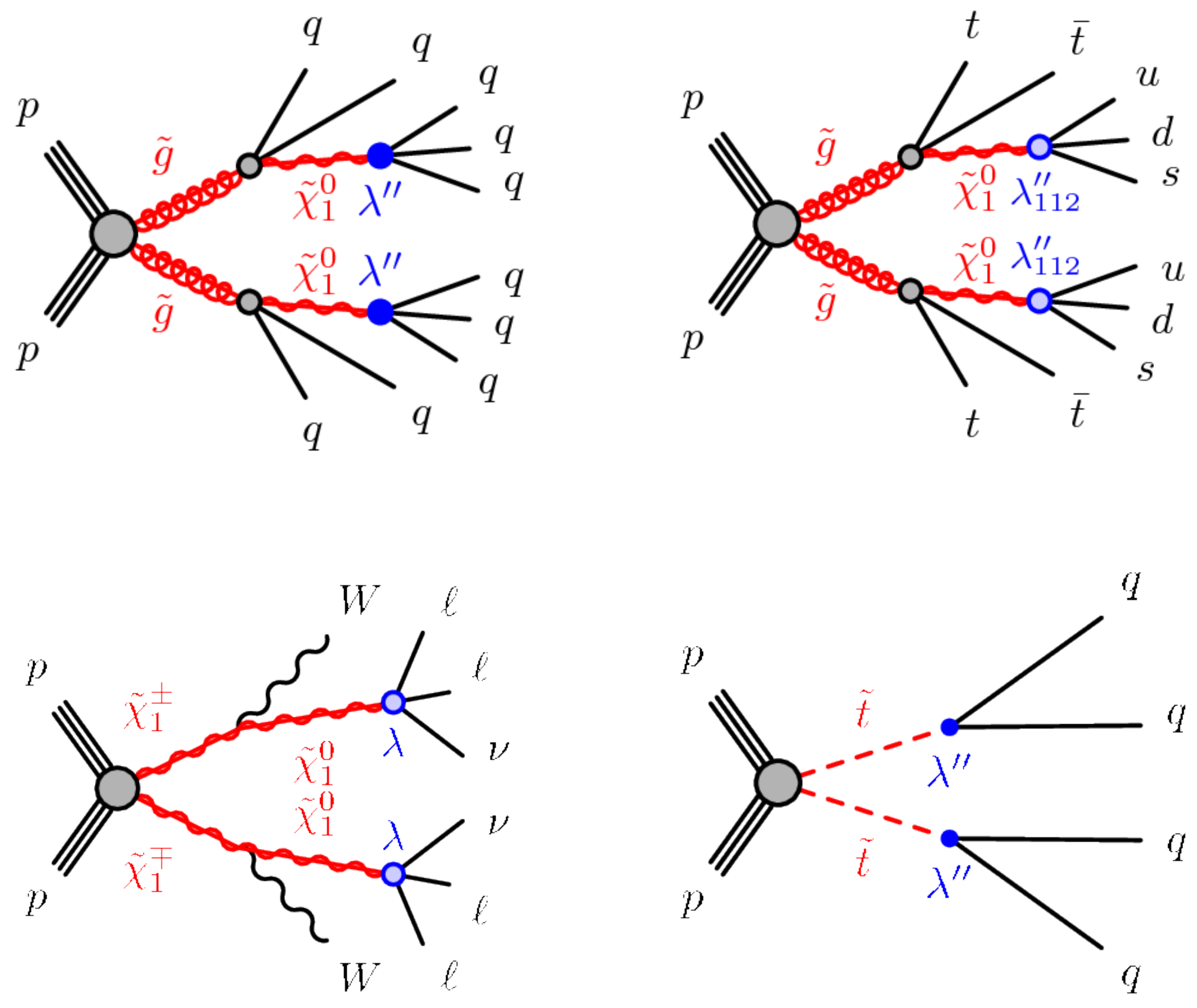
1 to 4 leptons (including taus) in the final state. Including decays to electroweak bosons.

Weak production in compressed scenarios



Scenarios where the charginos, neutralinos or sleptons are close to mass degenerate with the lightest SUSY particle (LSP).

R-Parity violating SUSY



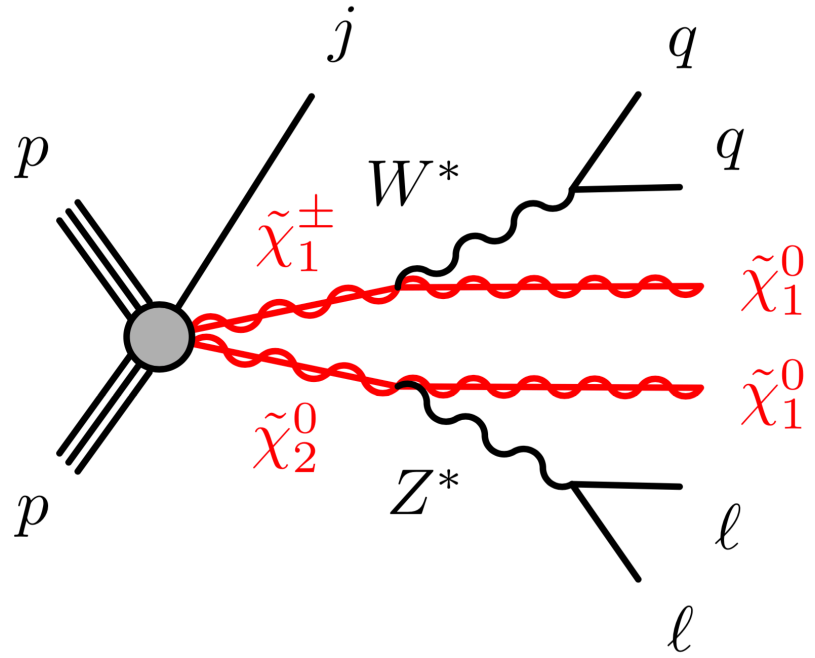
Resulting in topologies without LSP in the final state and therefore no MET.

$$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_iL_iH_2$$

RPV components of superpotential

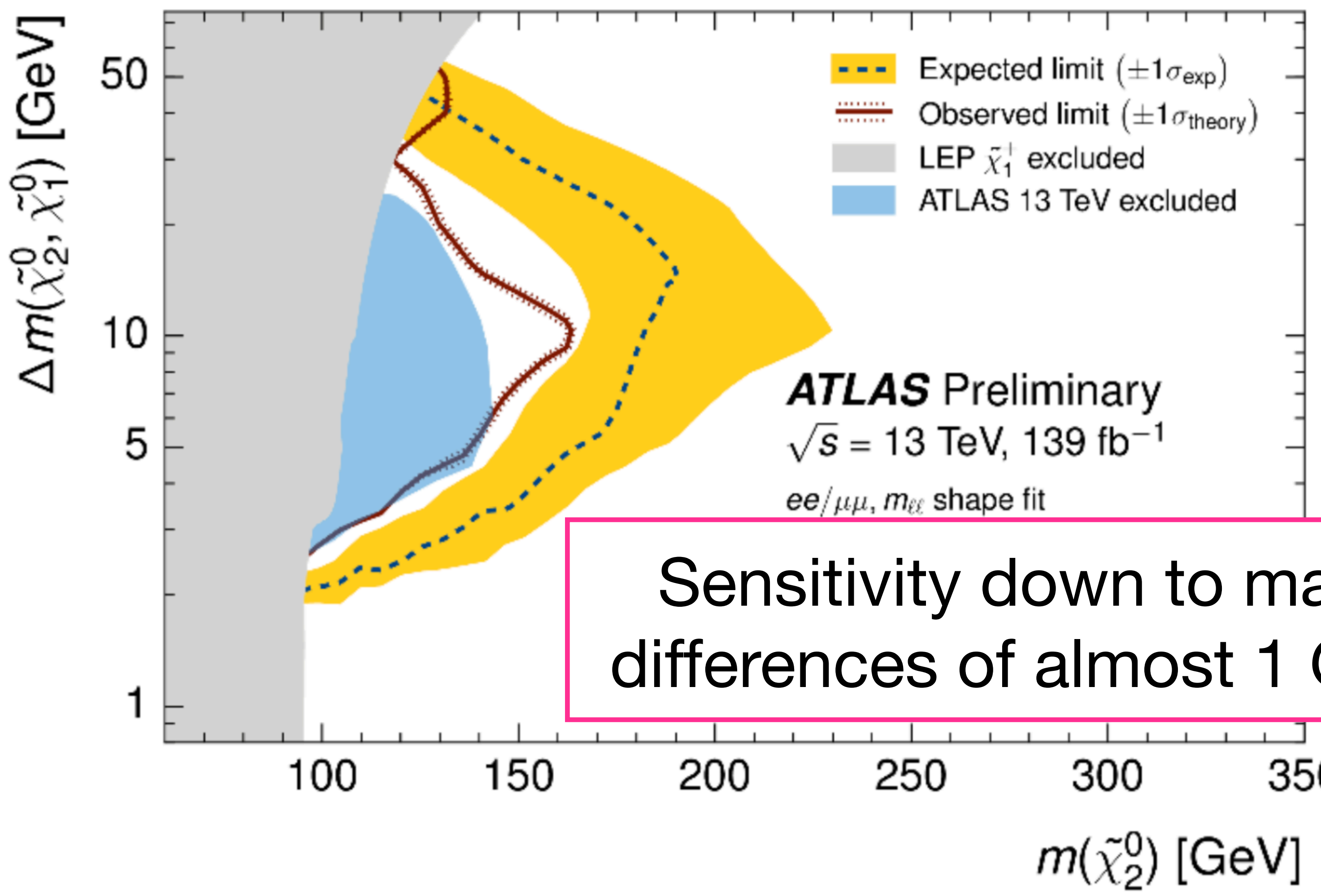
Searches for Charginos and Neutralinos (Examples)

Weak production of charginos and neutralinos

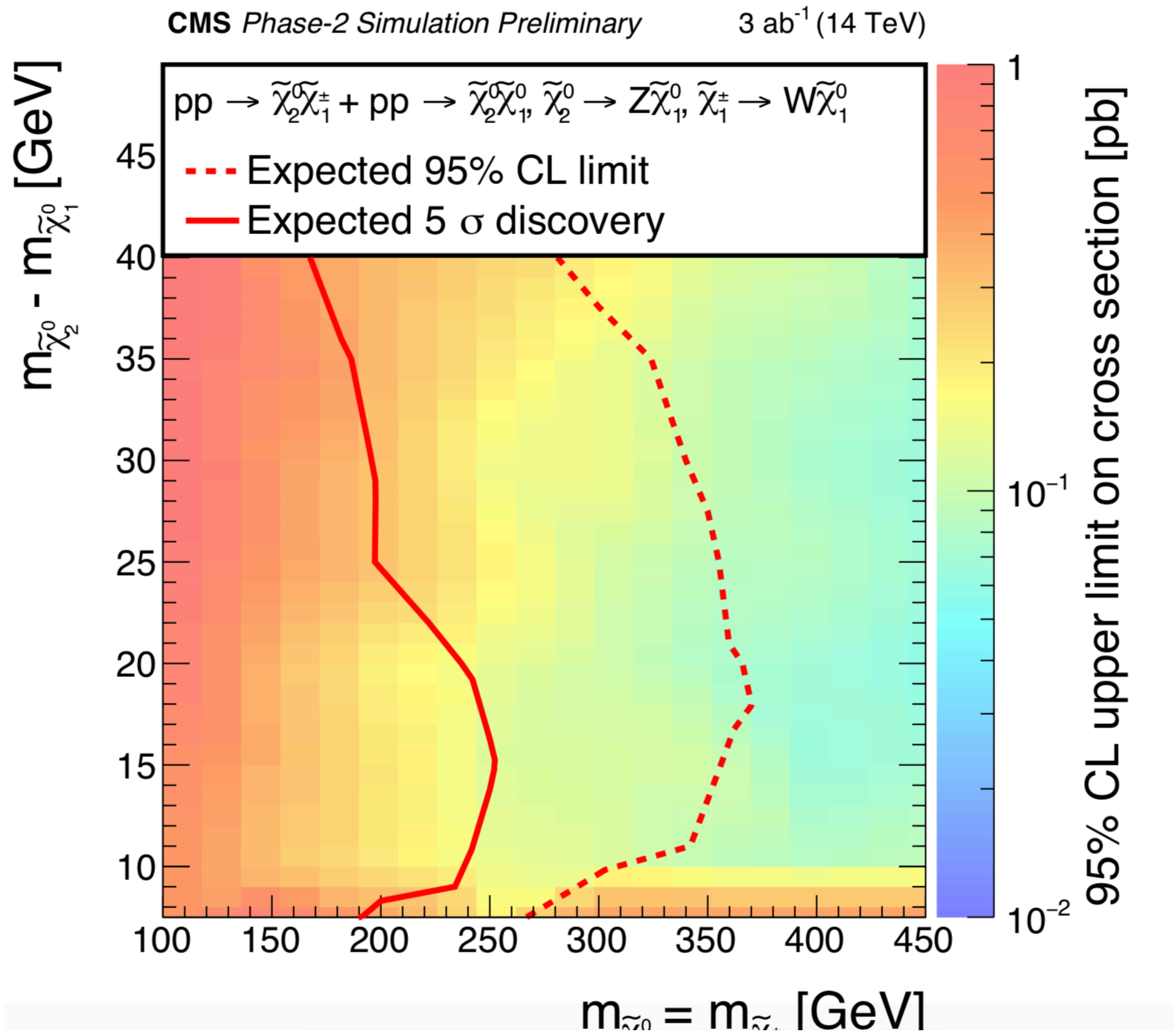


Example of boosting to find small mass differences.

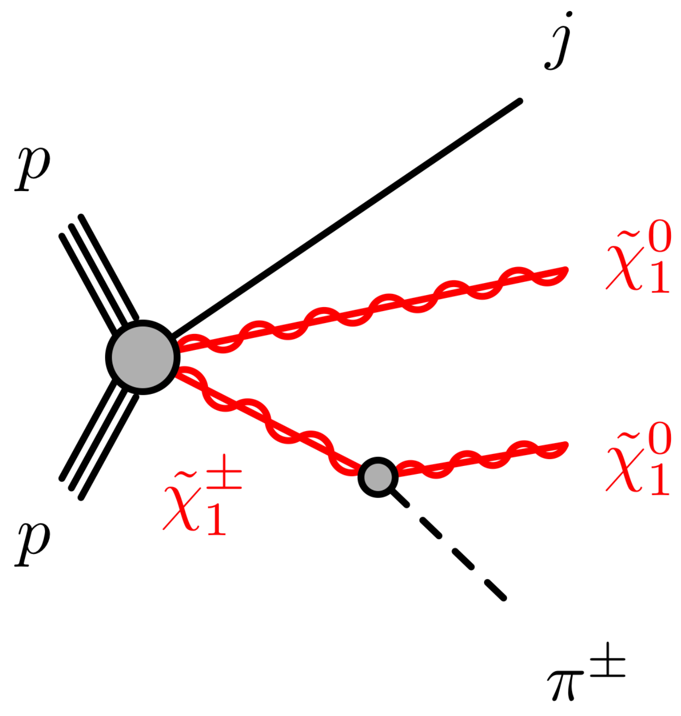
ATLAS-CONF-2019-014



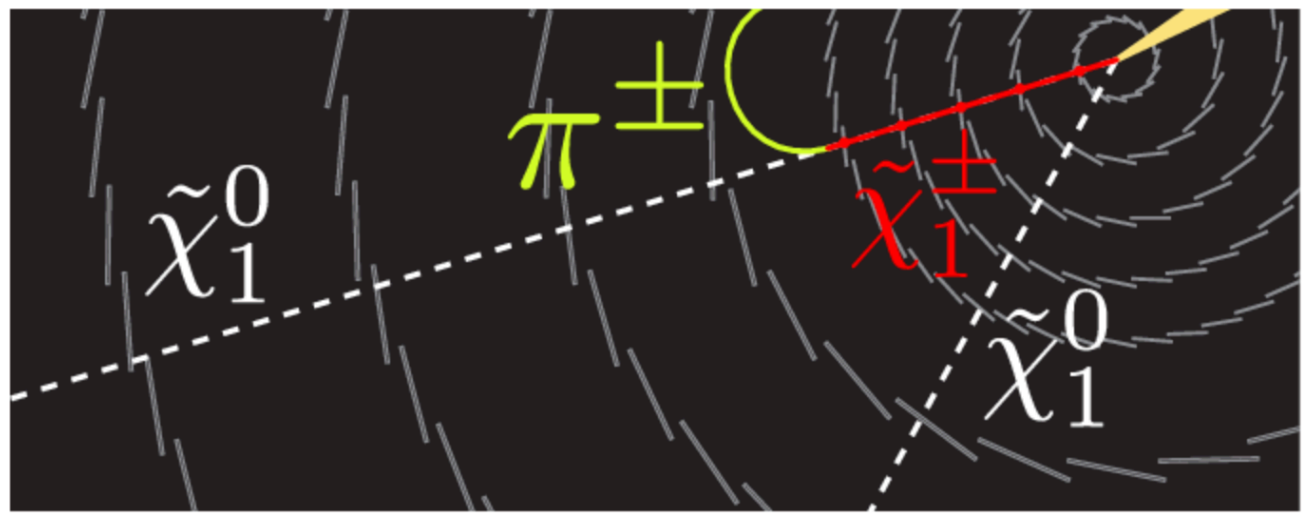
Sensitivity down to mass differences of almost 1 GeV!



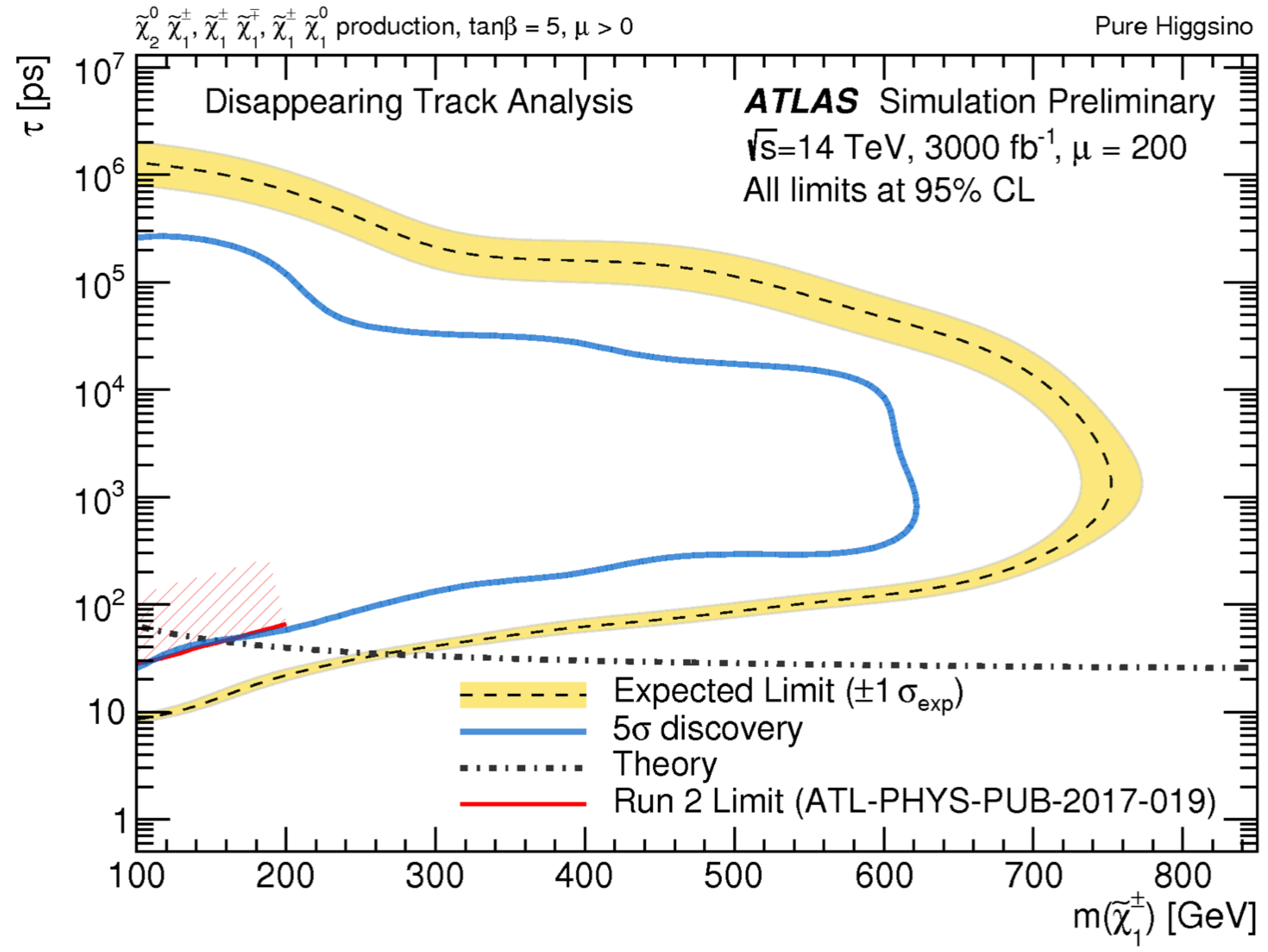
SUSY in highly compressed scenarios



Disappearing tracks topologies
(Uses MET Trigger - requires ISR jet)
ATLAS-PHYS-PUB-2018-031

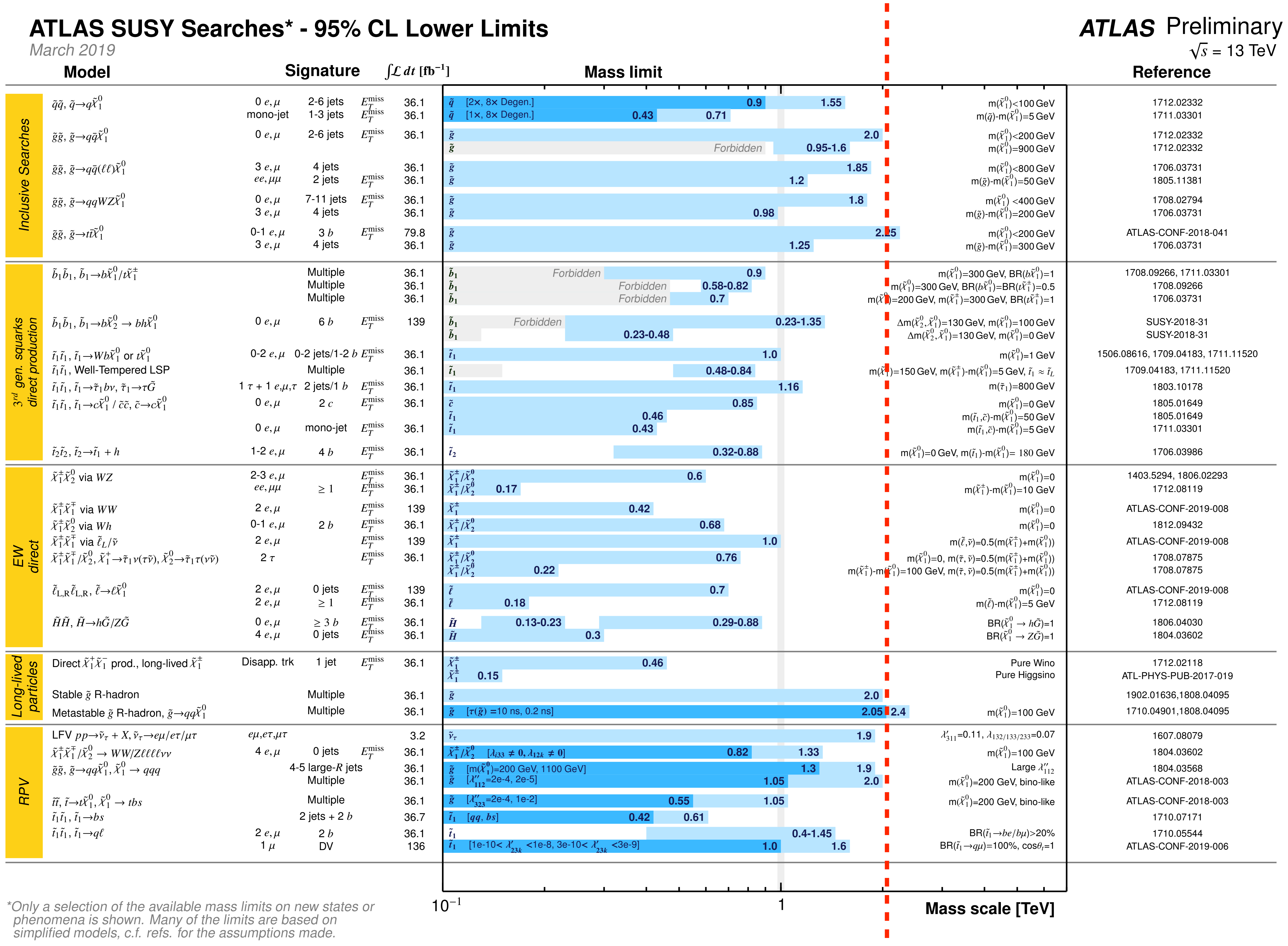


Scenario where the charginos and neutralinos are almost degenerate (chargino has significant lifetime and is seen in the first layers of the ID).



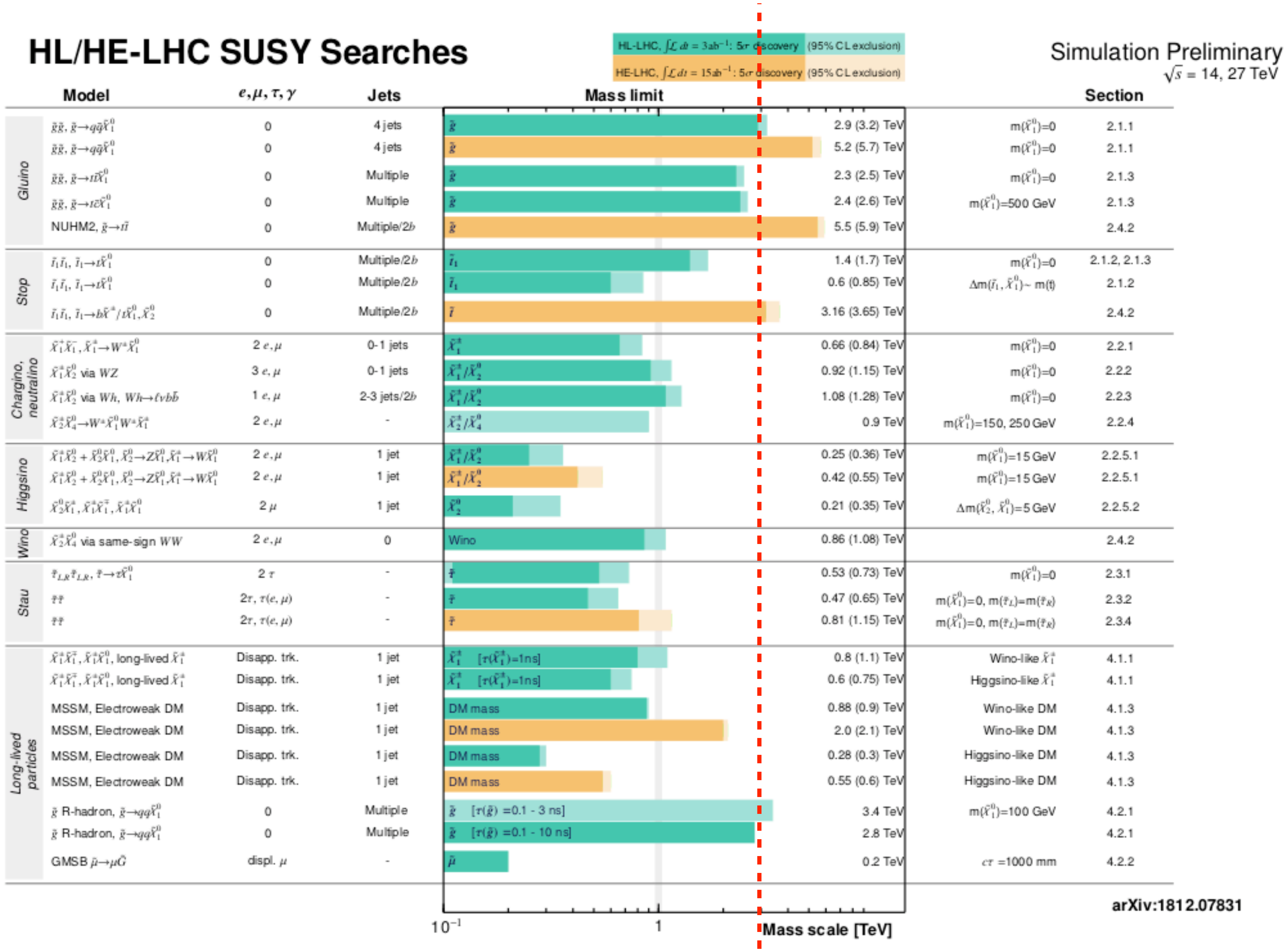
Very Large Number of SUSY Searches

(in large variety of topologies and models)



2 TeV

Example from ATLAS (same for CMS)

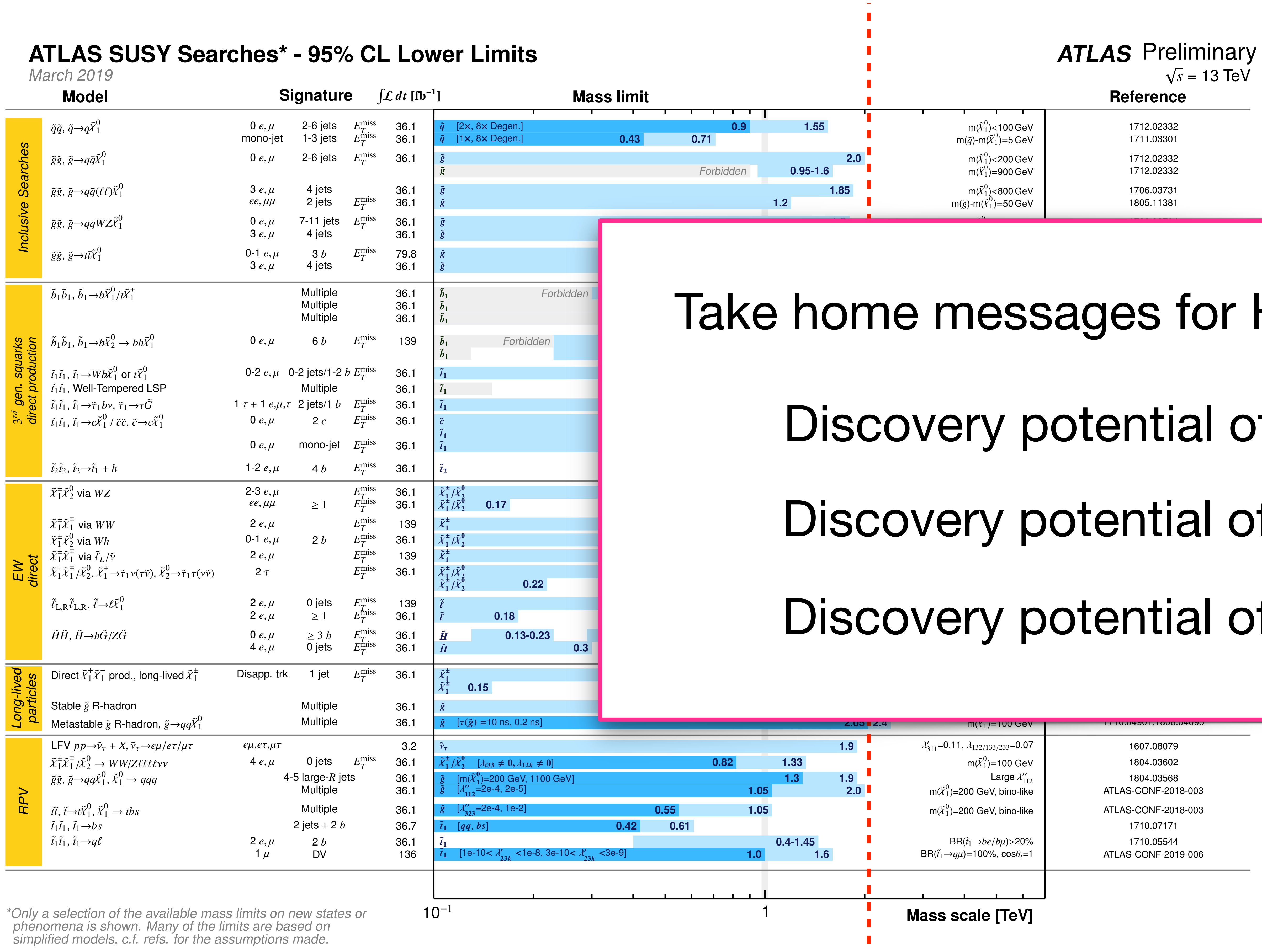


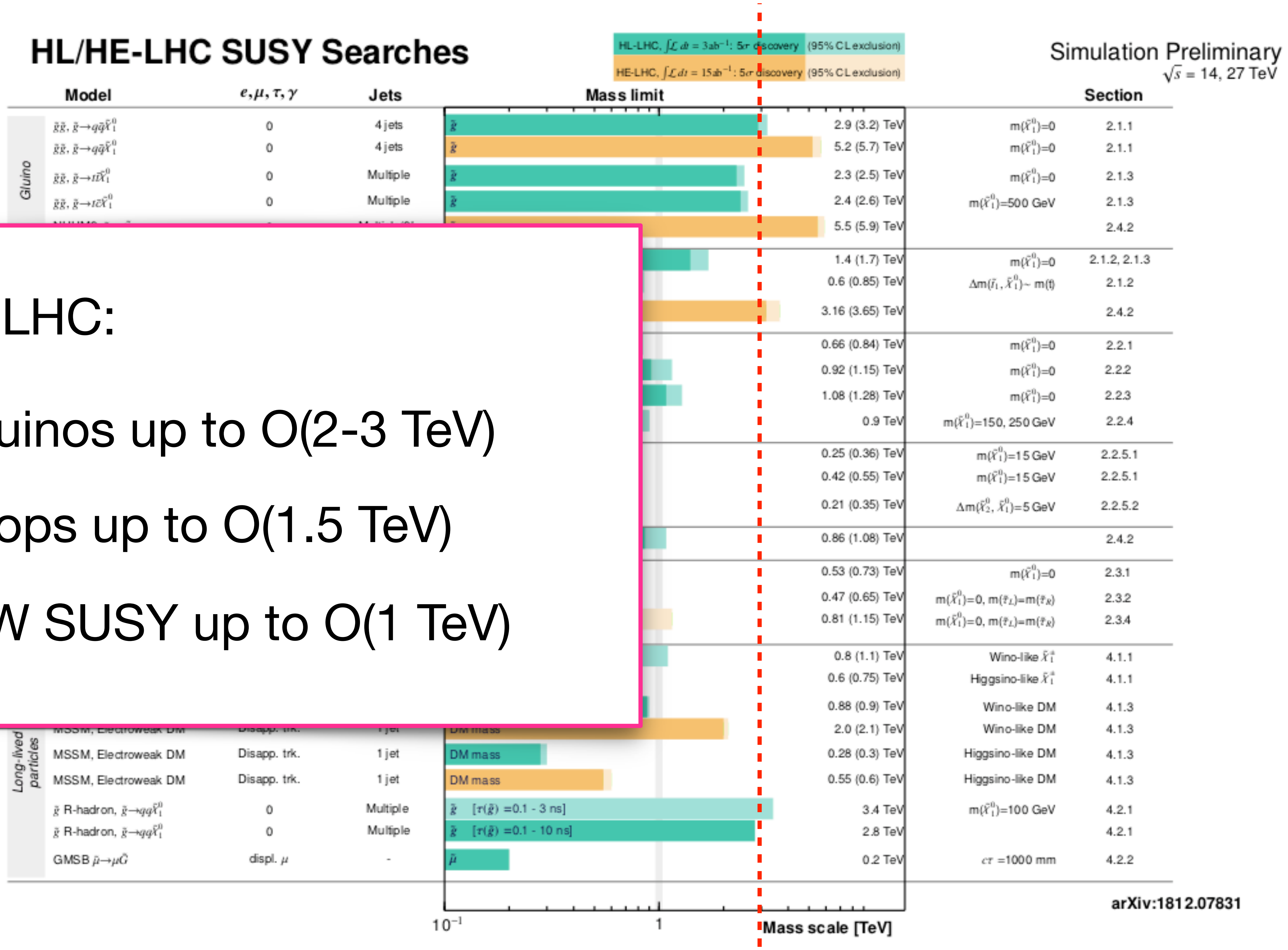
3 TeV

HL-LHC YR
1812.07831

Very Large Number of SUSY Searches

(in large variety of topologies and models)





Take home messages for HL-LHC:

- Discovery potential of gluinos up to O(2-3 TeV)
- Discovery potential of stops up to O(1.5 TeV)
- Discovery potential of EW SUSY up to O(1 TeV)

2 TeV

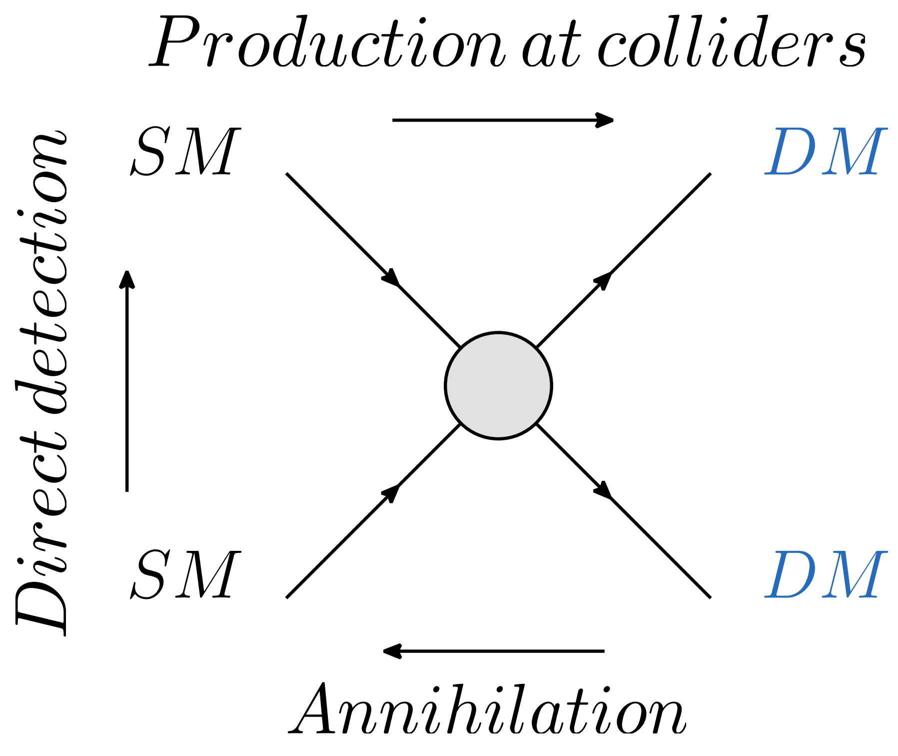
3 TeV

Example from ATLAS (same for CMS)

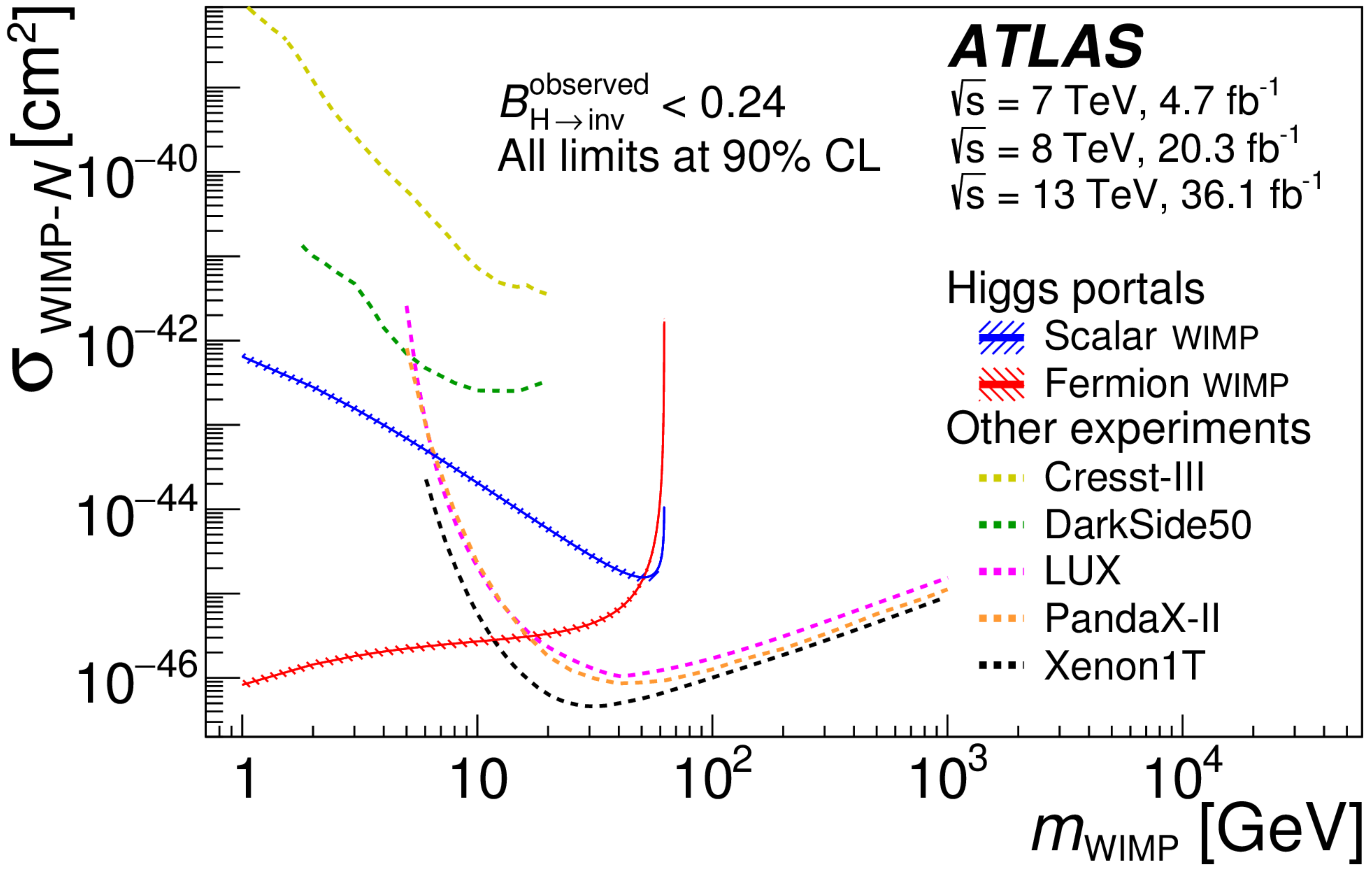
HL-LHC YR 1812.07831

Generic Search for Dark Matter

Generic Searches for Dark Matter



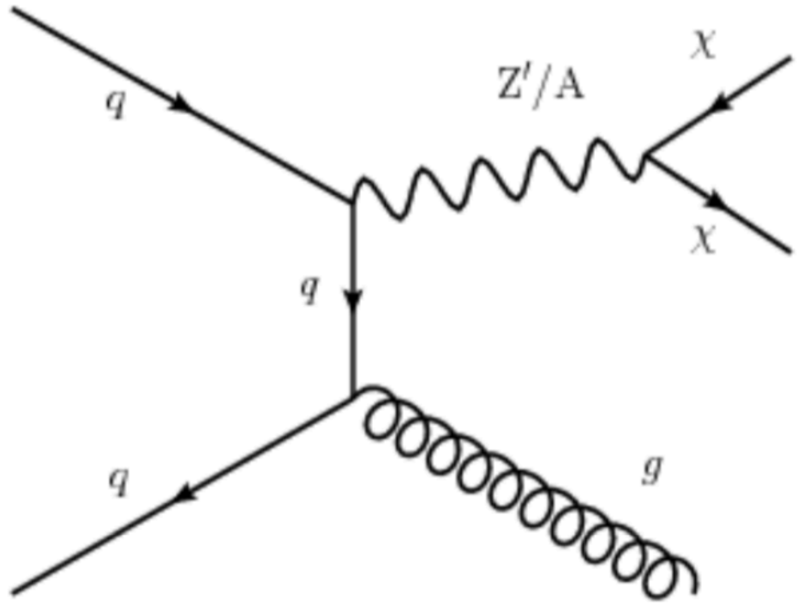
Complementarity of searches at colliders, direct and indirect searches!



Searches for Dark Matter at the LHC

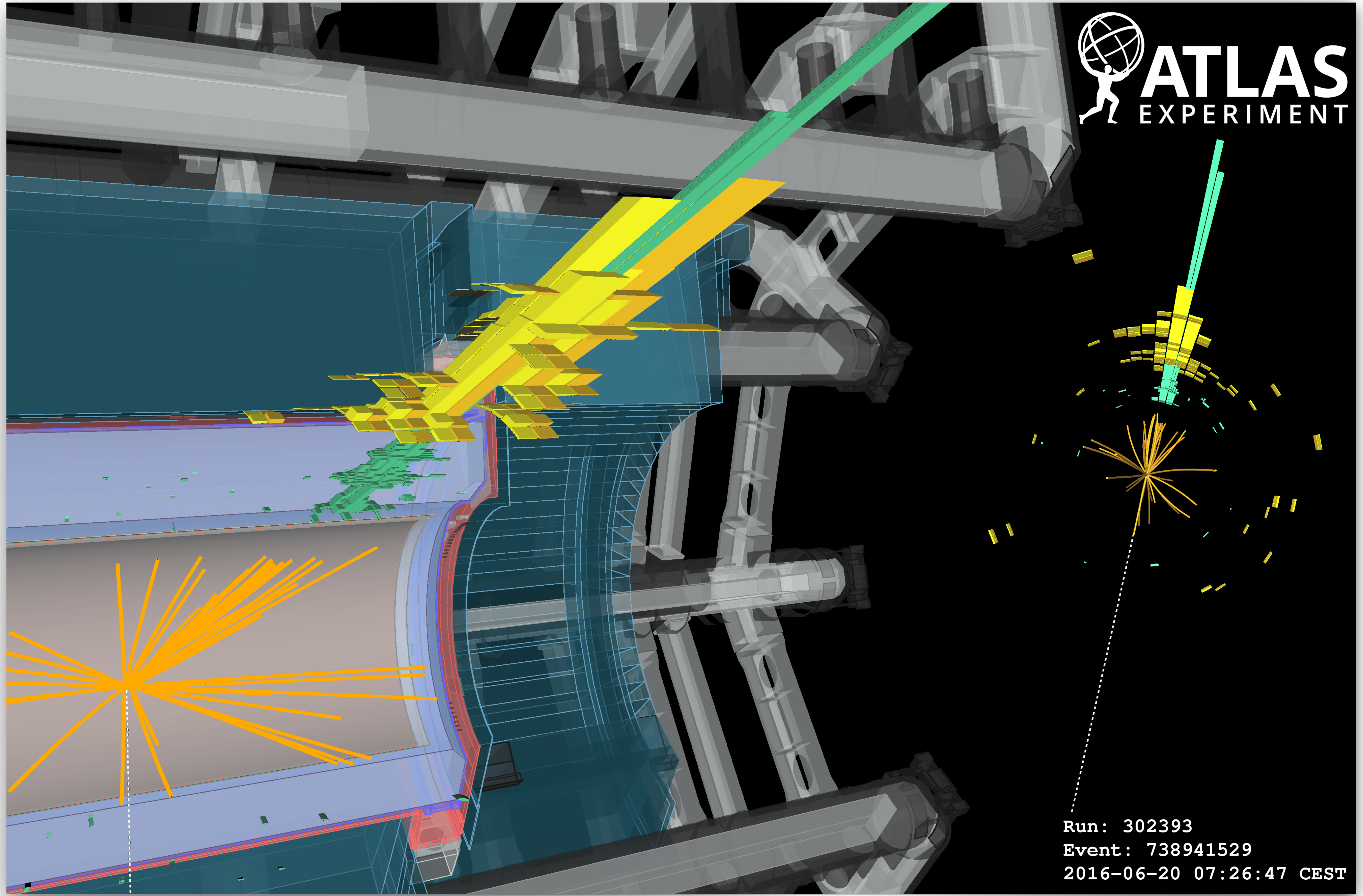
- Invisible Higgs searches (Lecture 3).

- In order to be observed invisible final states need additional objects to be associated with. Mono-anything searches: Mono-jet, mono-V (leptonic and hadronic), Mono-Higgs (various modes), Mono-photon, Mono-top.



Monojet signature! One of the most sensitive channels!

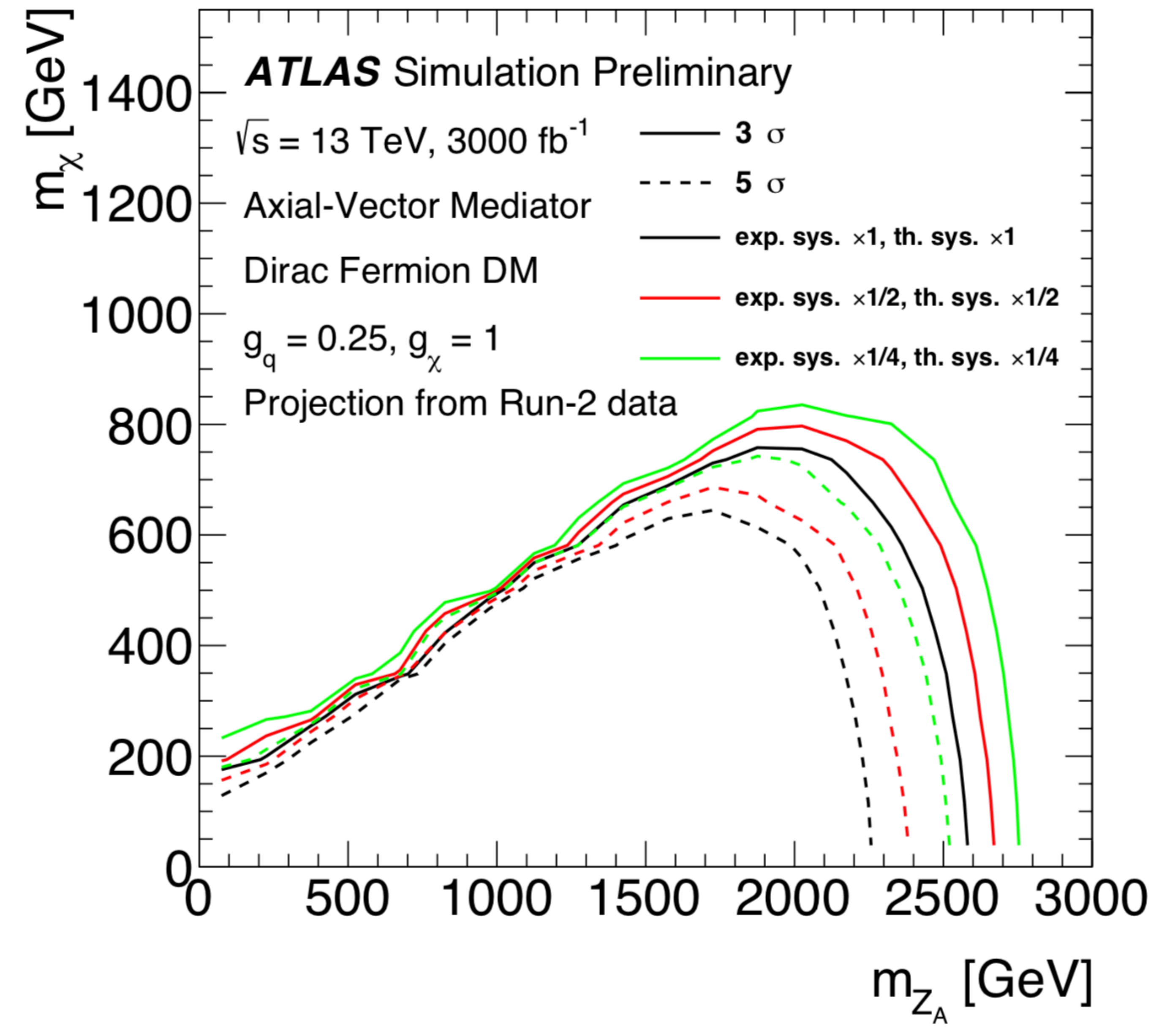
Generic Searches for Dark Matter



A jet with pT of 1707 GeV. The ETmiss of 1735 GeV is shown as the white dashed line. No additional jets with pT above 30 GeV is found.

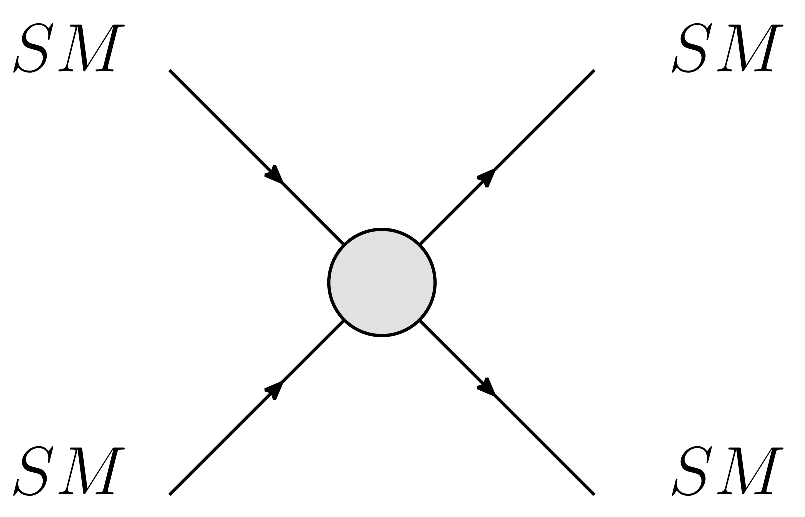
Mono jet search prospects

Reach close to TeV range at HL-LHC (model dependent)



Generic Searches for Dark Matter

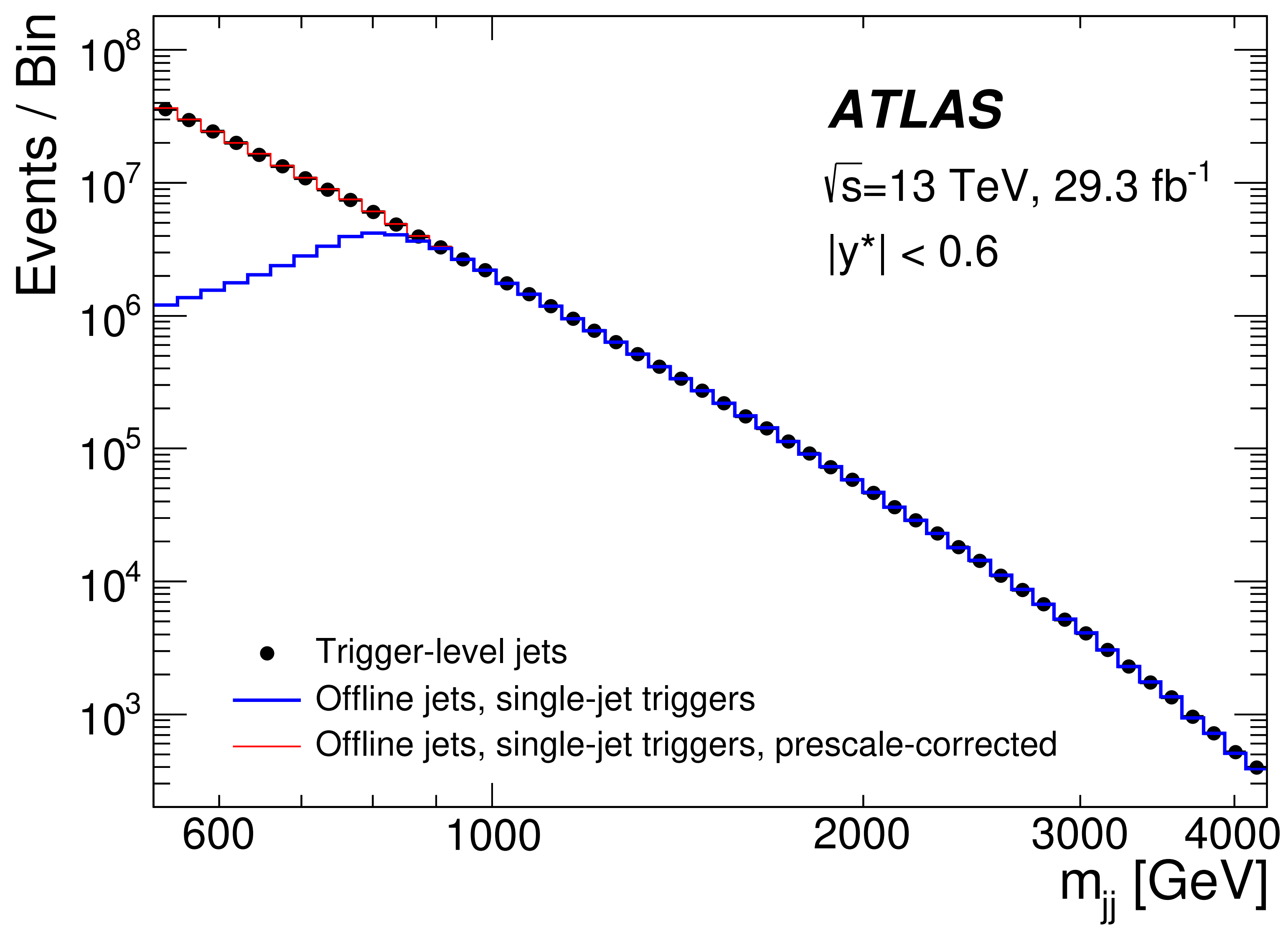
Searches for the dark matter mediator
in e.g. in dijet events extending at low masses

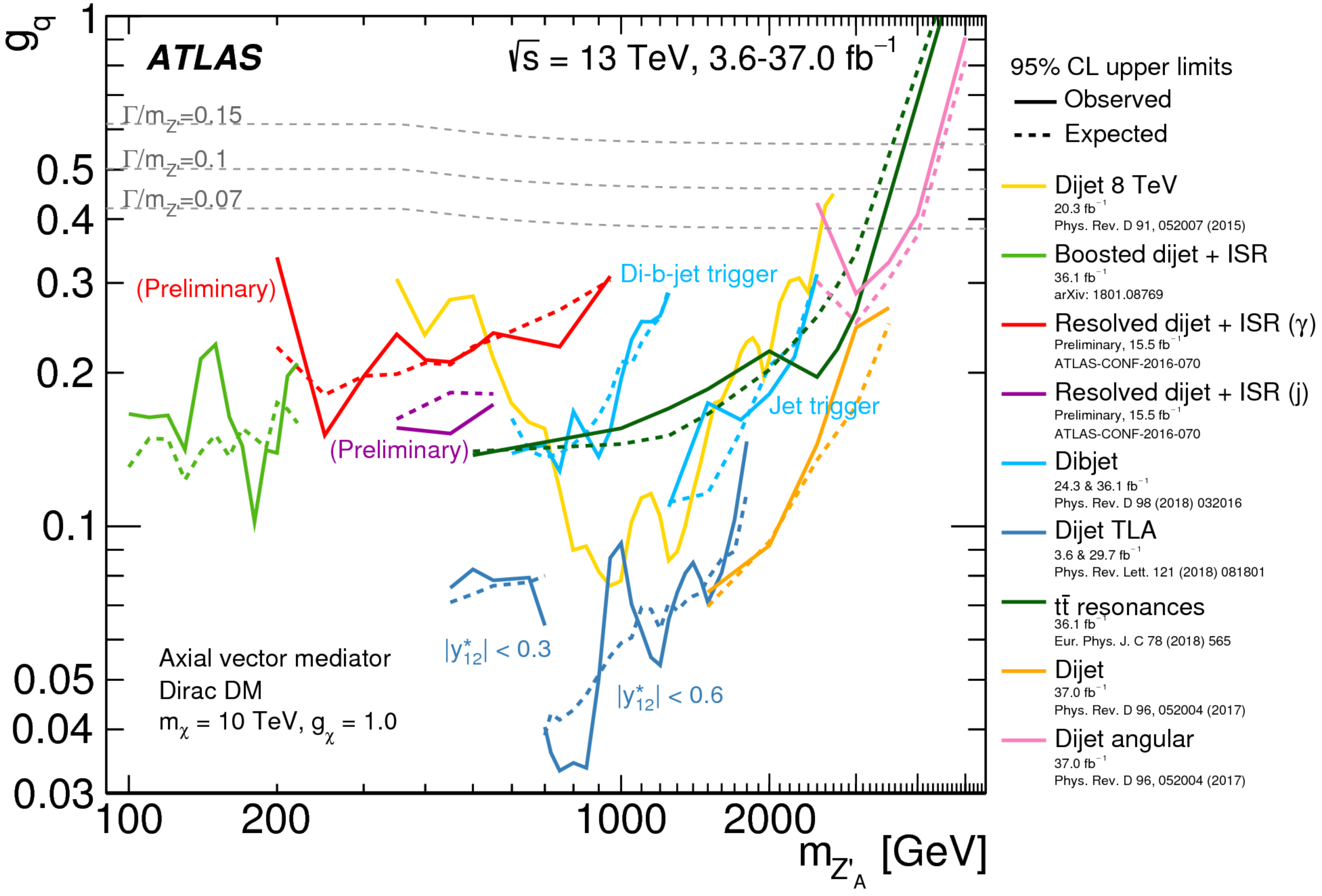


Numerous strategies to also cover lower masses e.g.:

- boosting (ISR photon/jet)
- Trigger level analyses

Dijet Trigger level analysis





Searches for new Physics Beyond the Standard Model in non SUSY theories

Panorama of Searches for Conventional Signatures

Searches for Vector Like Quarks

Simple additional chiral fermions are essentially ruled out by Higgs data.

Fermions that are not Chiral

- The L and R components transform the same way under SM symmetries.
- Interact with SM through mixing with SM quarks.
- Present in models where the Higgs is a pseudo Goldstone boson (e.g. in Composite Higgs and little Higgs models).
- Present in Warped Extra dimension models.

Large variety of possible states and complex channels

- Heavy quark partners with charges -1/3, 2/3, 4/3 and 5/3.
- Complex channels looking for T(2/3), B(1/3): Ht+X, Wt+X, Wb+X, Zb+X, Zt+X (Performed at Run 2) so far and T(5/3) 4tops final state.

And still many more !!

Searches for W'and Z'

High mass states motivated in many theories e.g. Grand Unified and additional gauge symmetries.

- electrons, muons, taus, jets, b-jets and tops.
- di-bosons including vector bosons and Higgs bosons

Searches for high mass states of spin 0 and 2

Motivated in Randall Sundrum models (Graviton and radion)

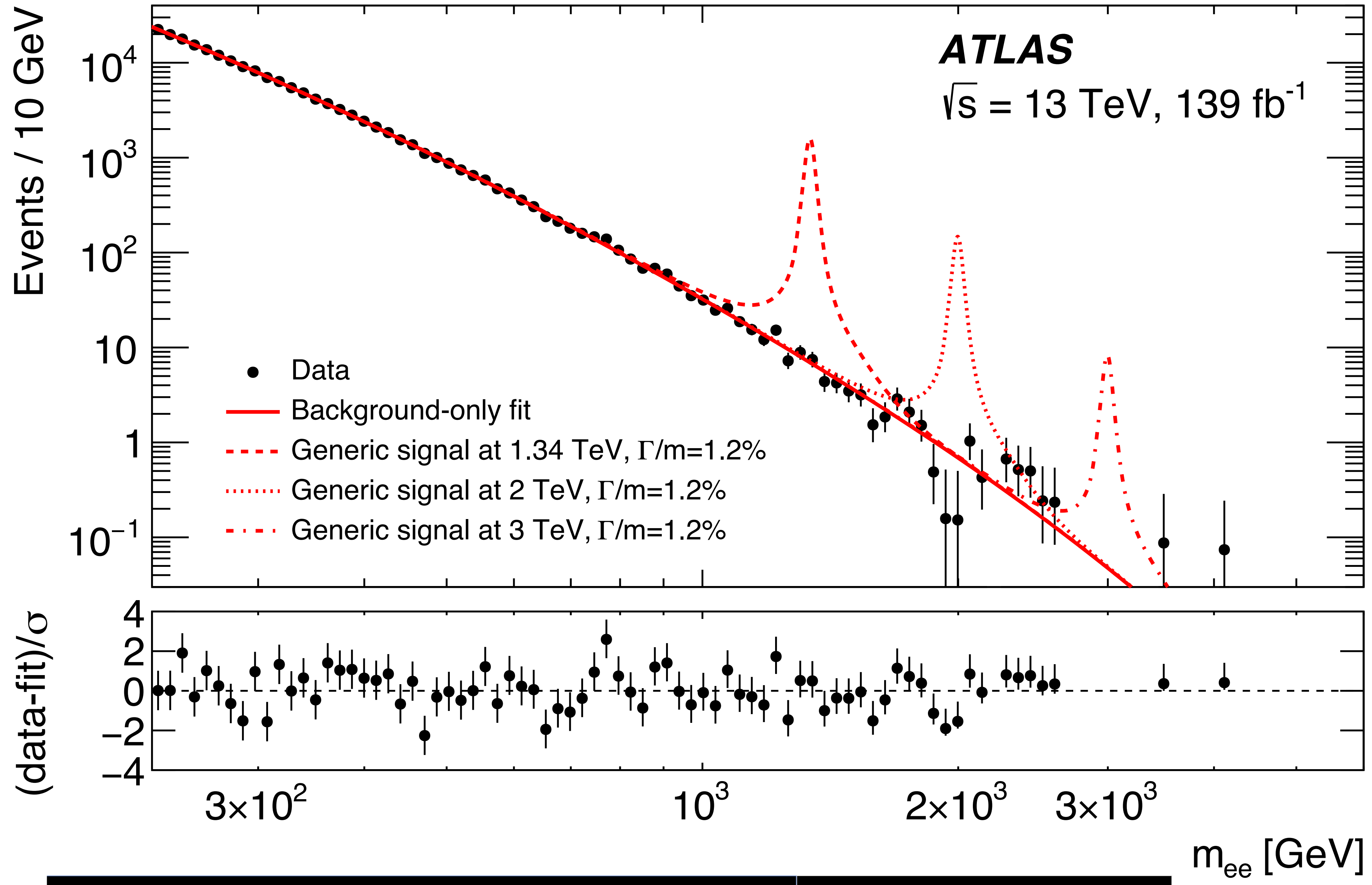
Searches in various channels dijet, diphoton and di-leptons

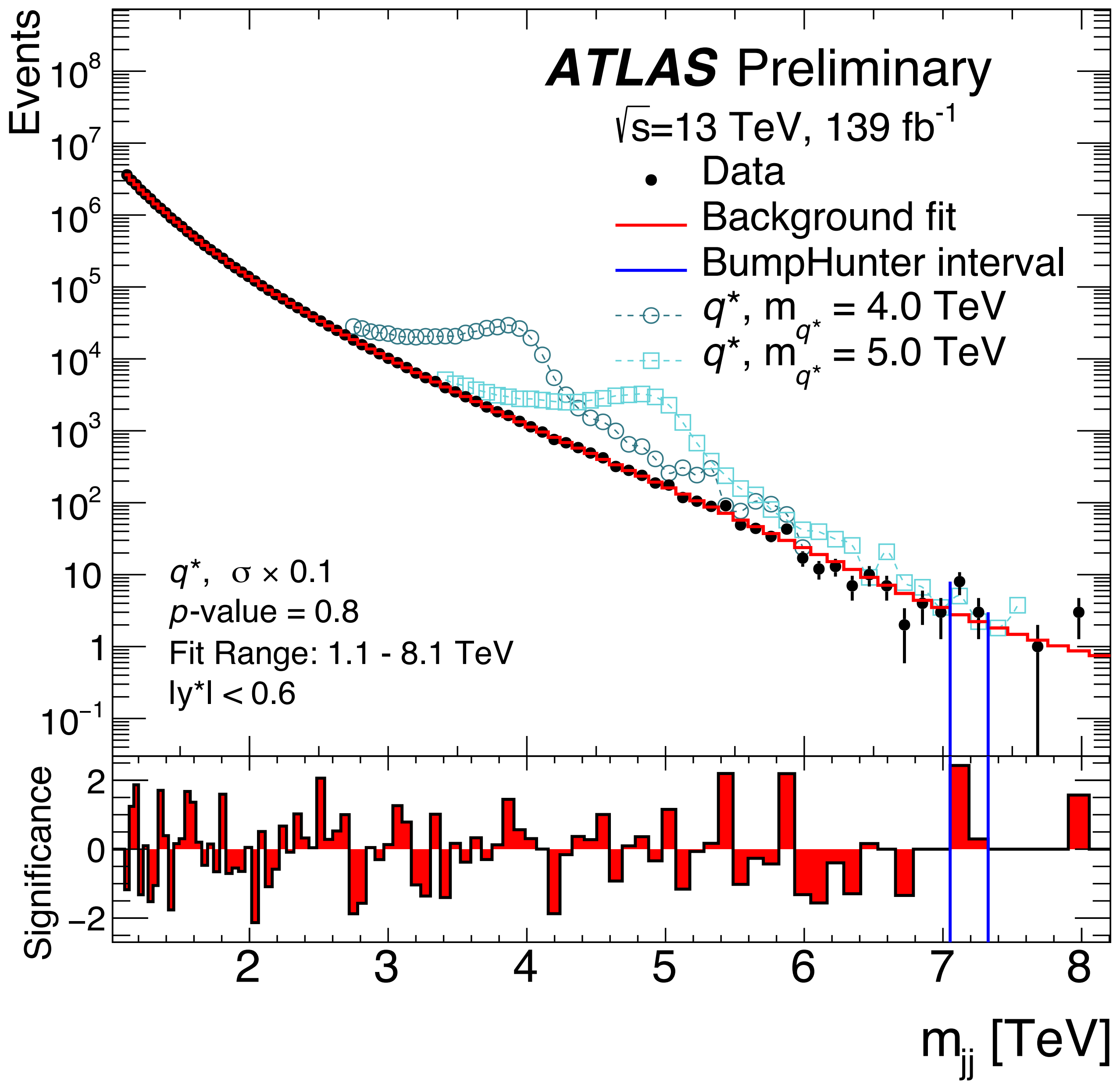
Any many more

- **Quark compositness**
- **Leptoquarks**: predicted in grand unified theories and interest raised by lepton flavor universality anomalies
- **Heavy neutrinos**: produced in theories for neutrino masses (e.g. Seesaw)
- **High mass and high activity events**: strong gravity (from extra dimension theories), mini black holes, quantum black holes…
- **Searches for low mass states.**

Searches for High Mass Resonances

ATLAS Dilepton search ATLAS 1903.06248

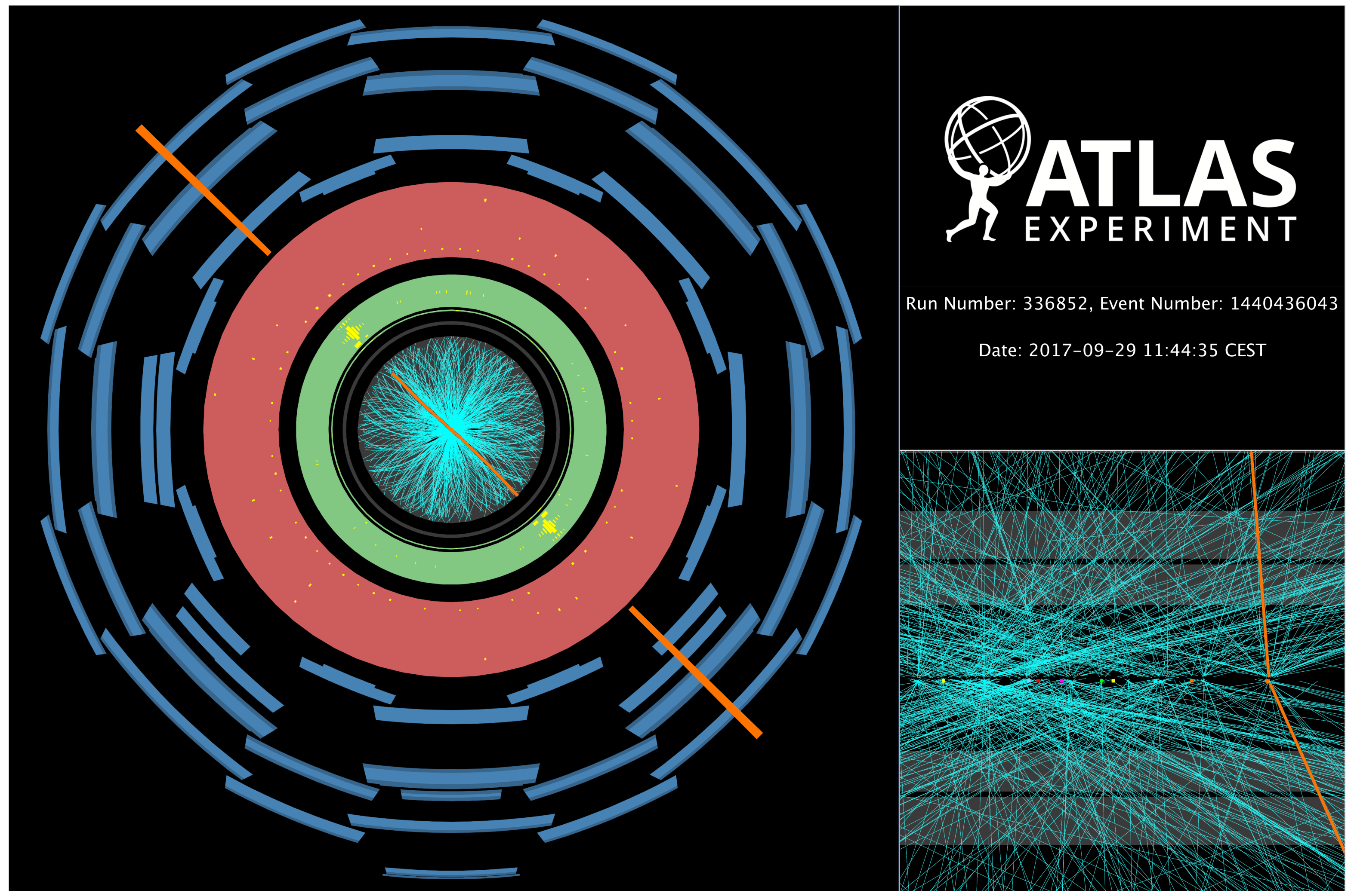




ATLAS Dijet search

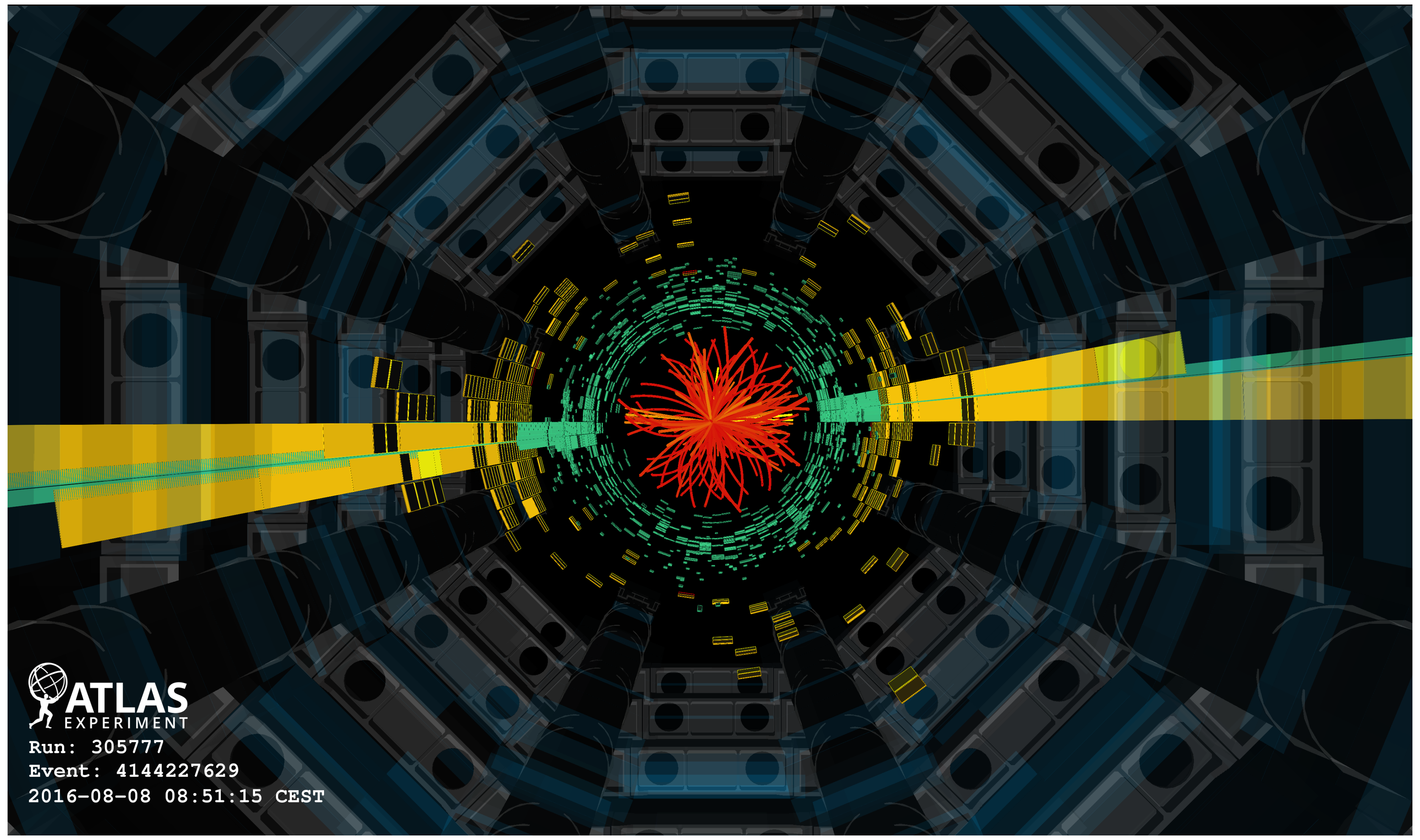
ATLAS-CONF-2019-007

Limits on excited quarks at 6.7 TeV

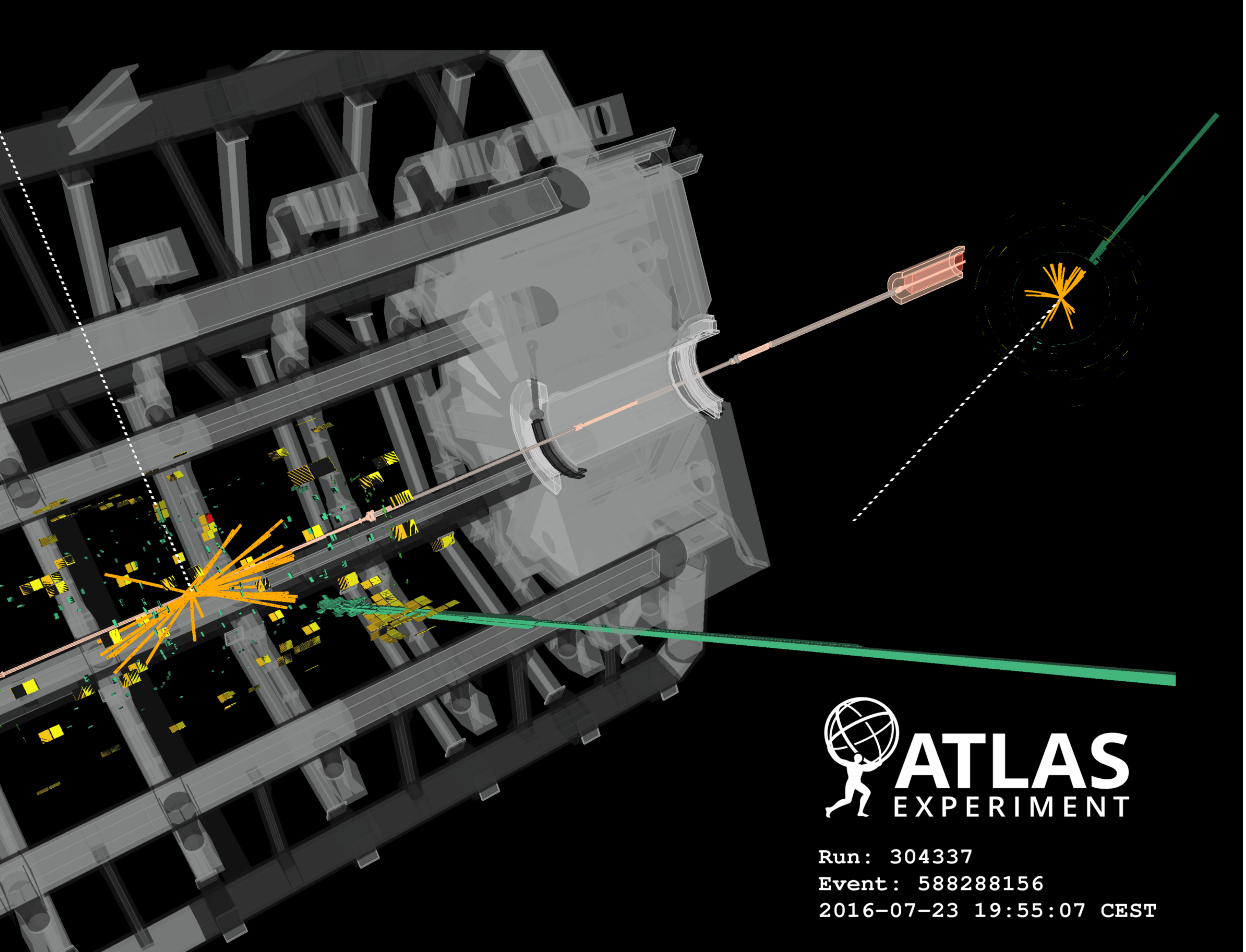


Exclusions up to ~5 TeV

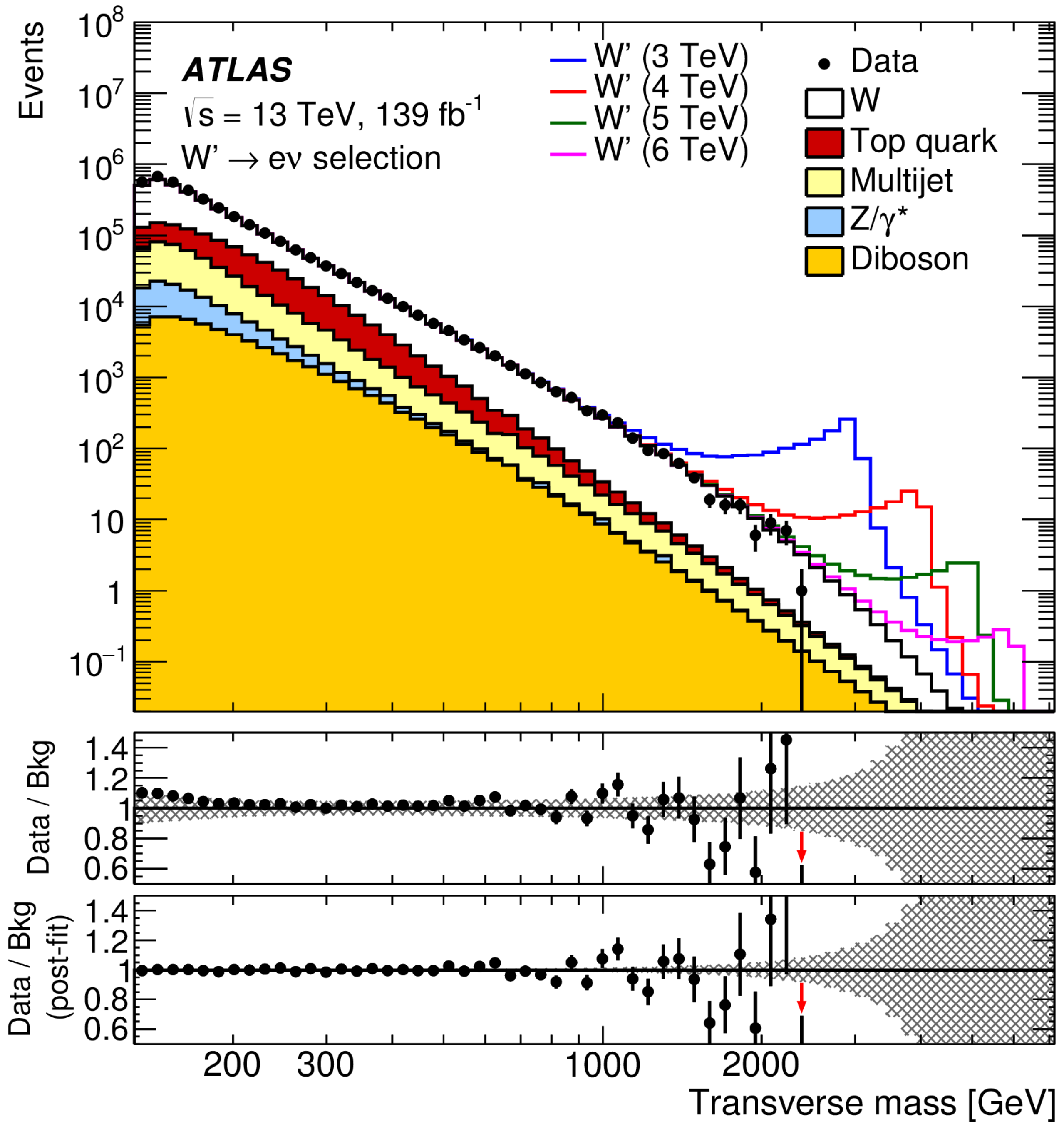
Highest mass di-electron event ~4 TeV



Highest mass (central) dijet event ~8 TeV



Transverse mass (in lepton-MET search)

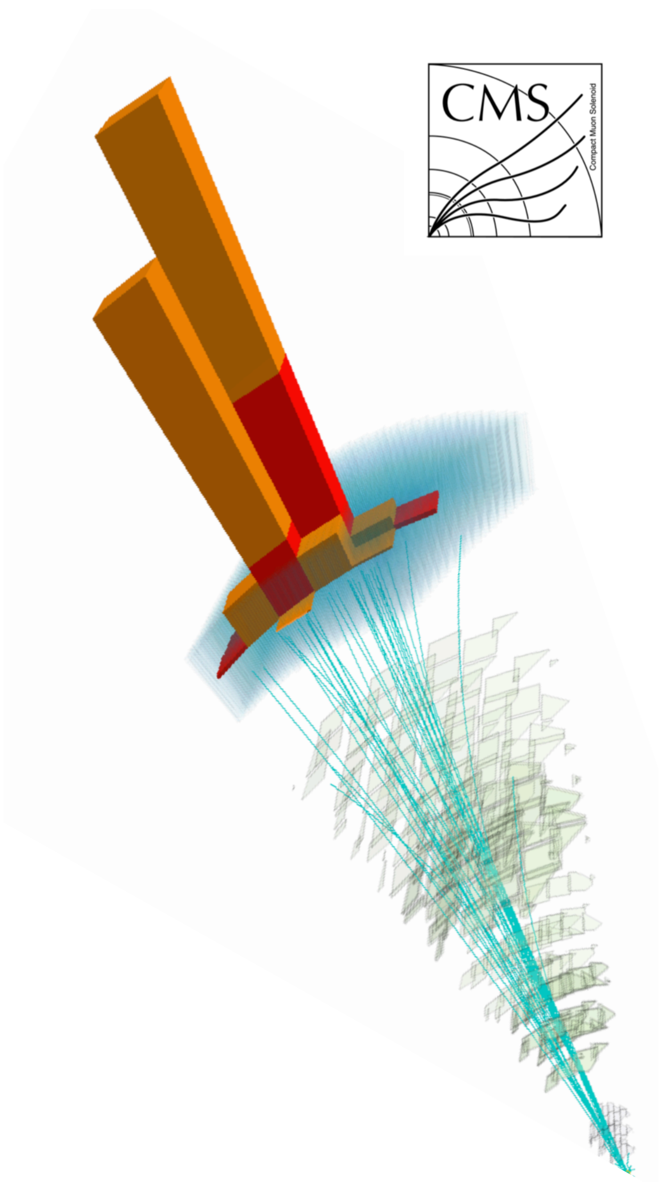


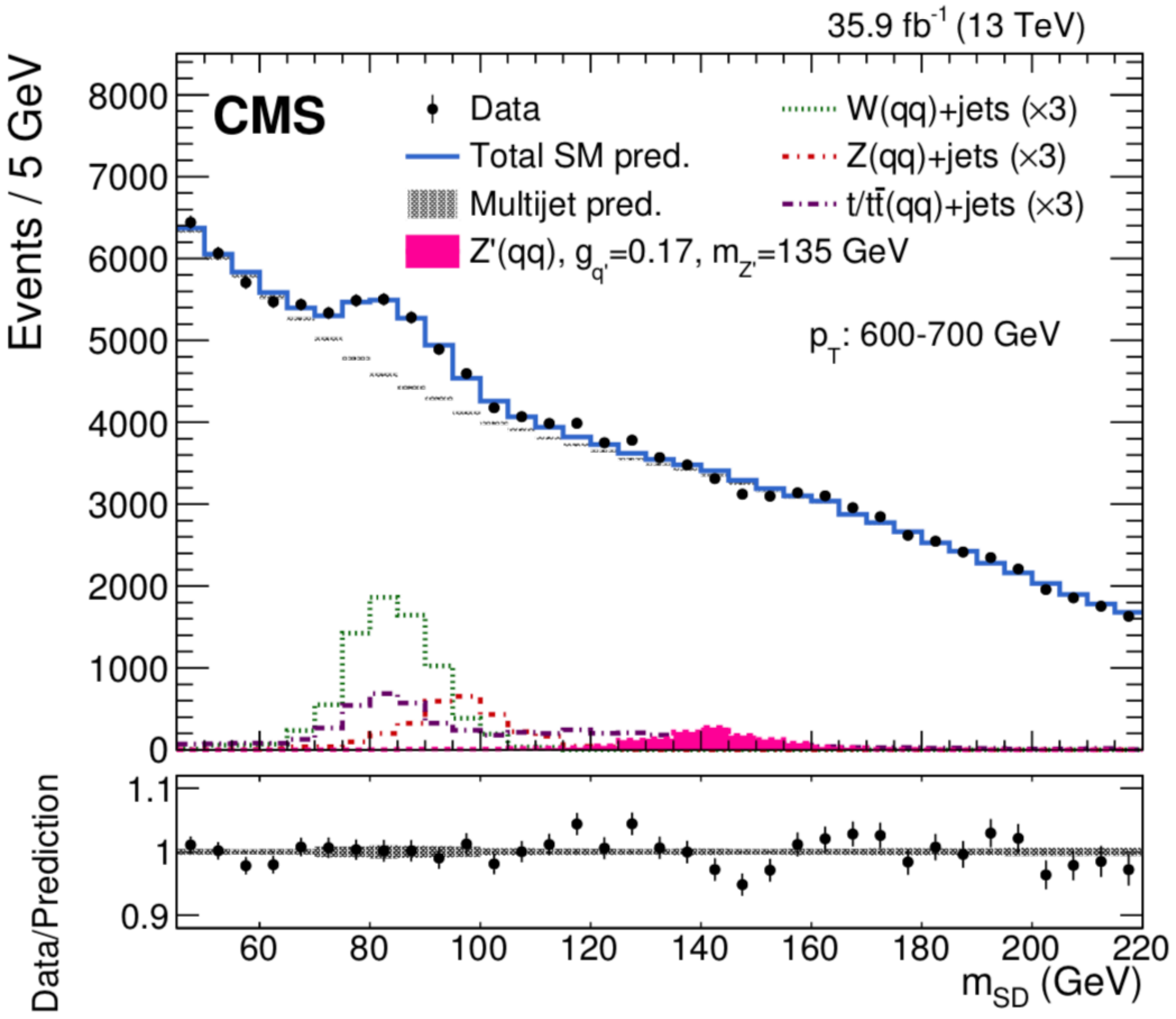
Drell Yan (and other processes) predictions and lepton calibration in the TeV energy range.

Electron pT = 1.1 TeV
MET = 1.16 TeV

Improving Reconstruction Techniques

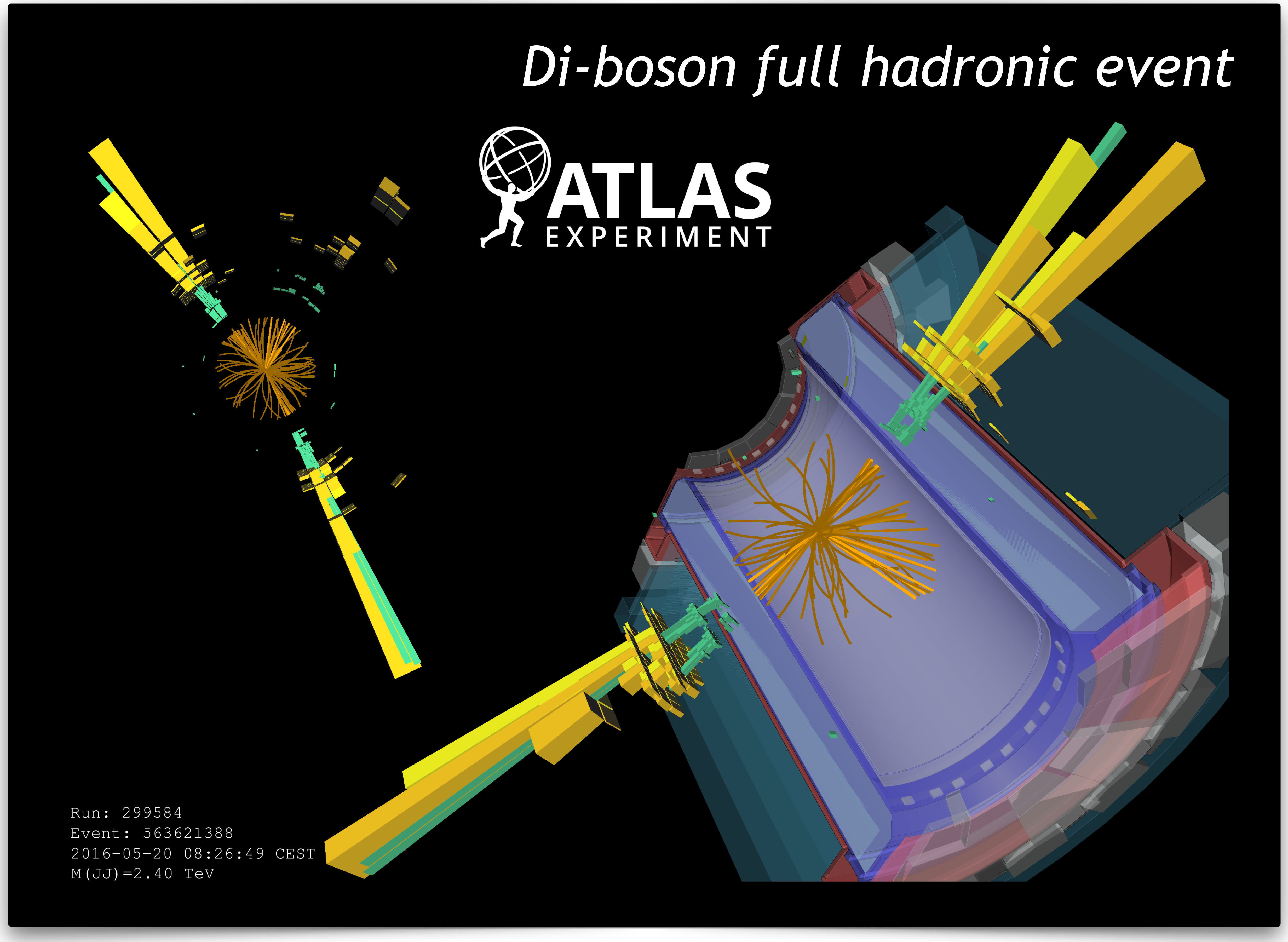
Jet substructure reconstruction improvements reconstructing a vector boson, a Higgs boson or a top quark.





Search for intermediate mass resonance as a single jet investigating its substructure.

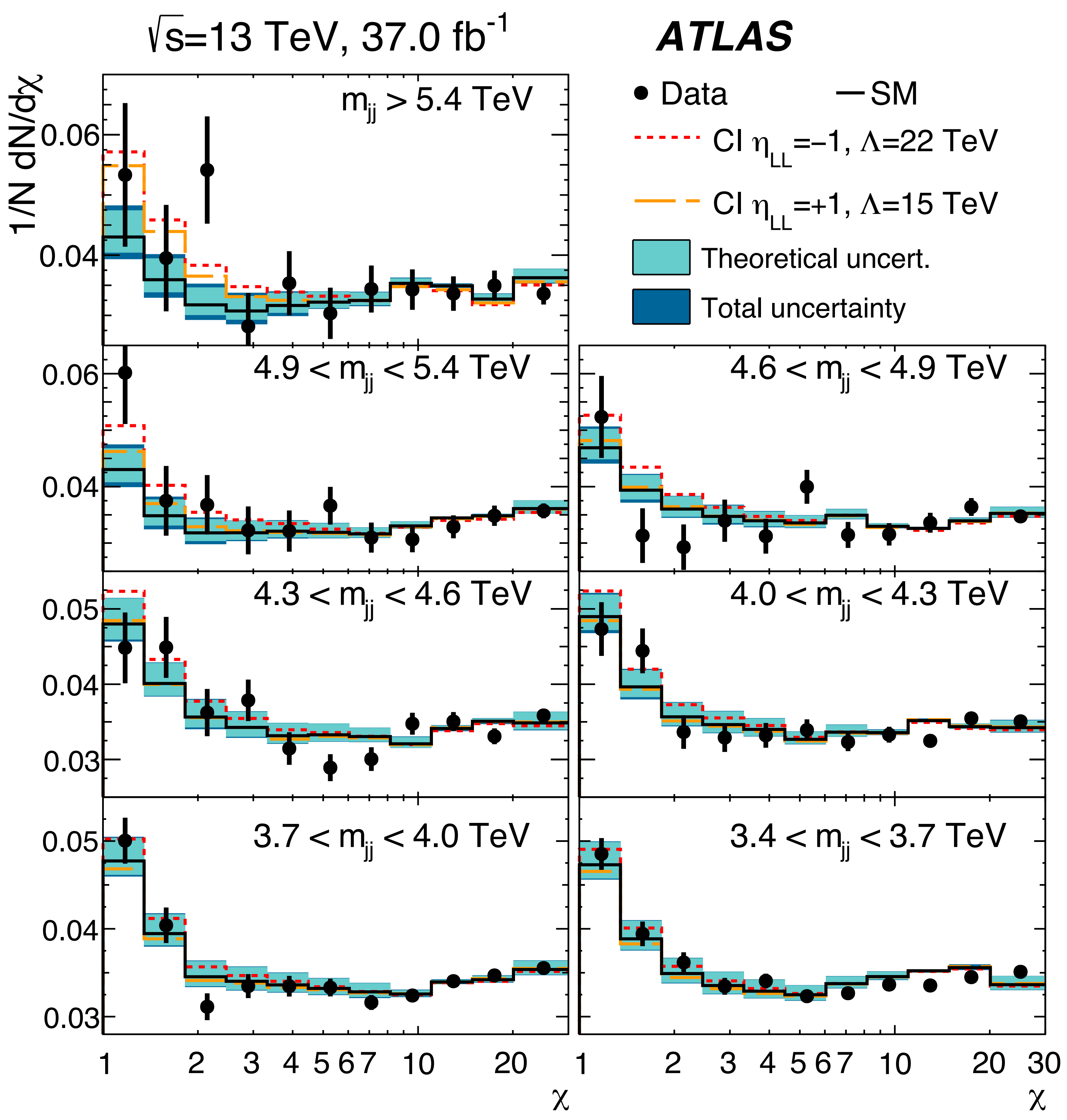
Searches for diboson in two boosted jets signatures



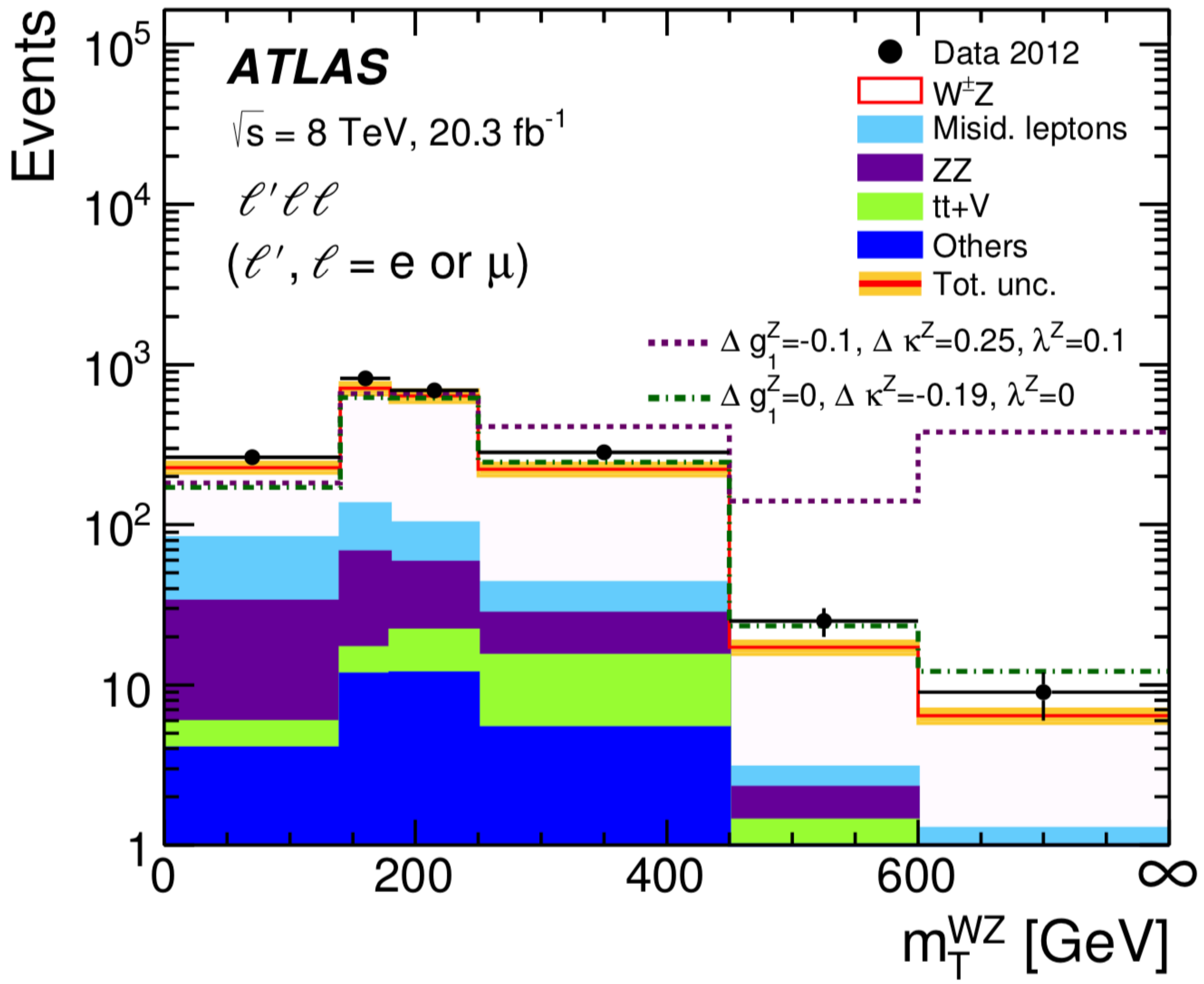
Di boson candidate event in a fully hadronic search, each jet has a mass compatible with a vector boson (W or Z).

Non Resonant Searches

Direct searches at the cross roads with Standard Model measurements in the high energy domain



Jet cross sections predictions and jet calibration with multi TeV jets



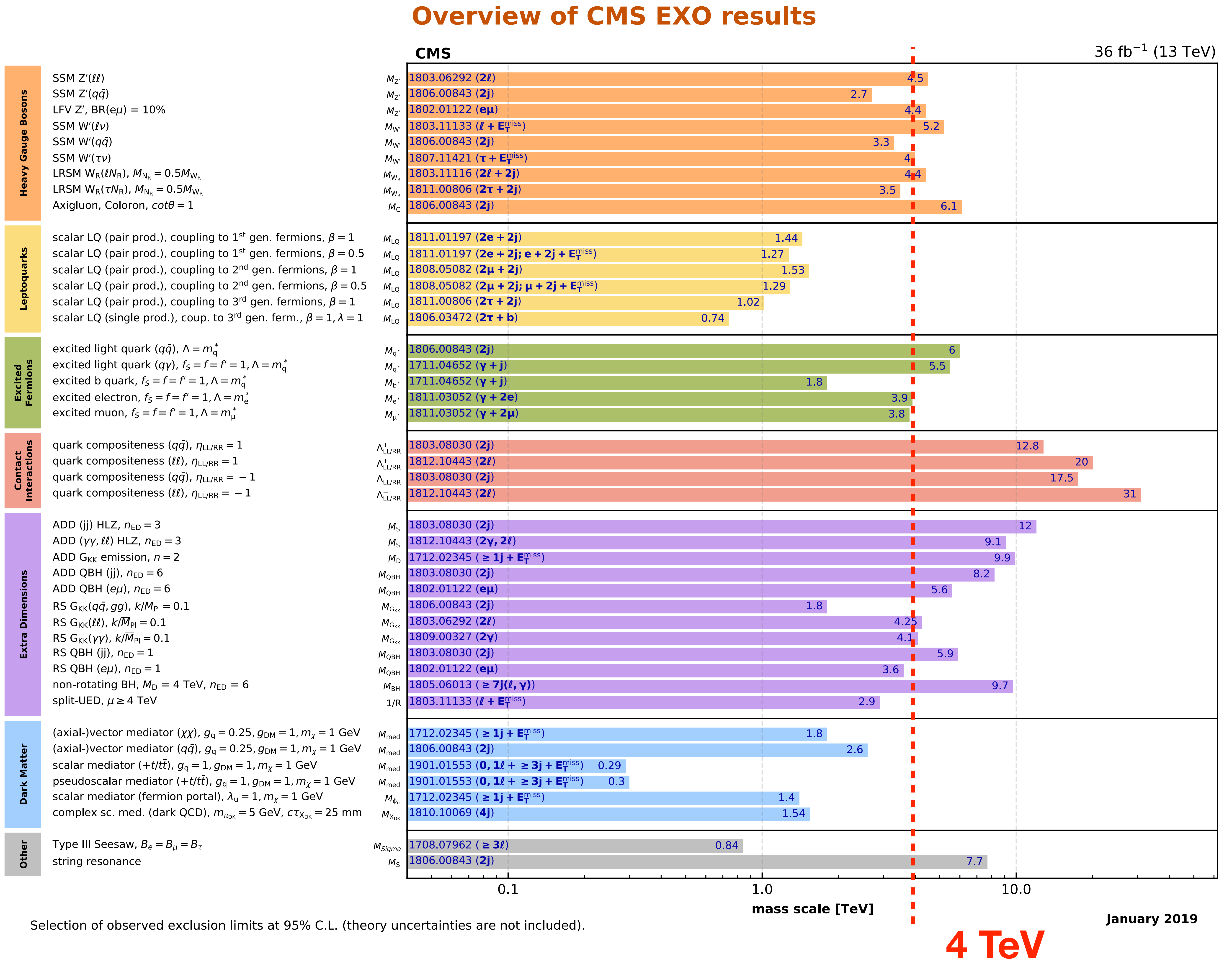
Measurement of di-boson in the high mass regime

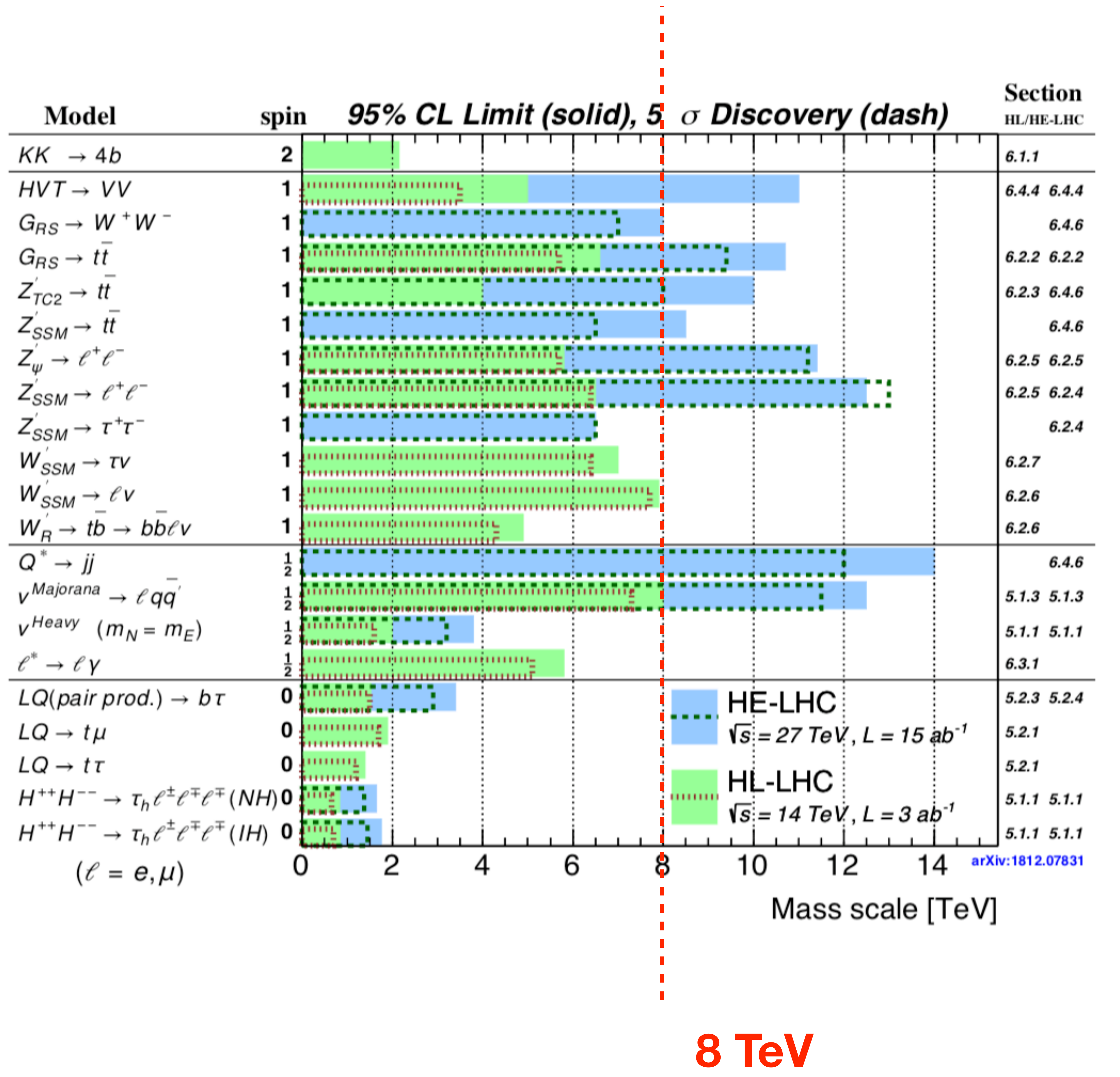
Any deviation in the measurements with a special attention to the high energy regime can be the manifestation of new higher energy domain new physics.

Powerfull and consistent framework to interpret the effect of higher energy new physics (above a higher scale): **Effective Field Theory**.

Very Large Number of Searches

(in large variety of topologies and models)



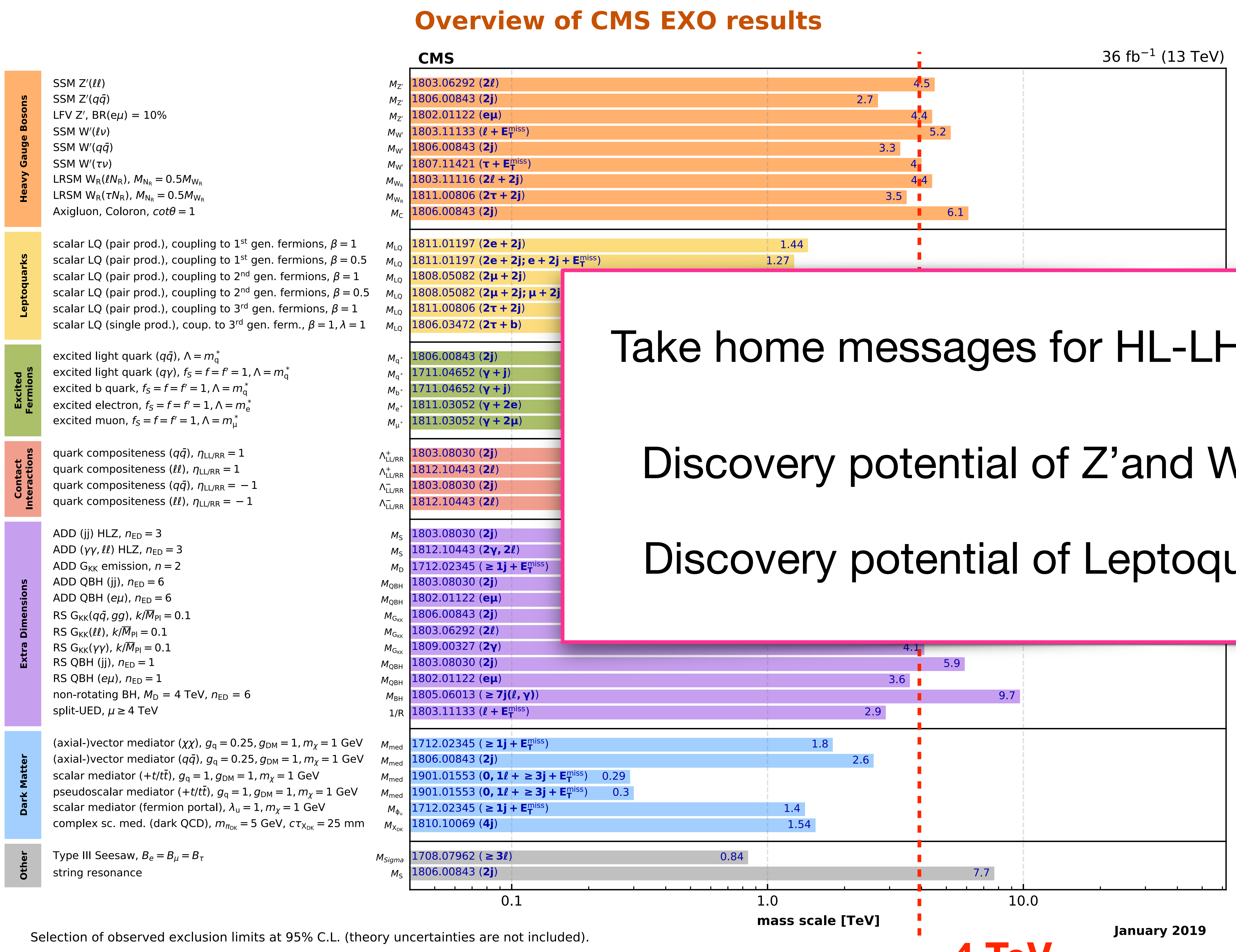


Example from CMS (similar for ATLAS)

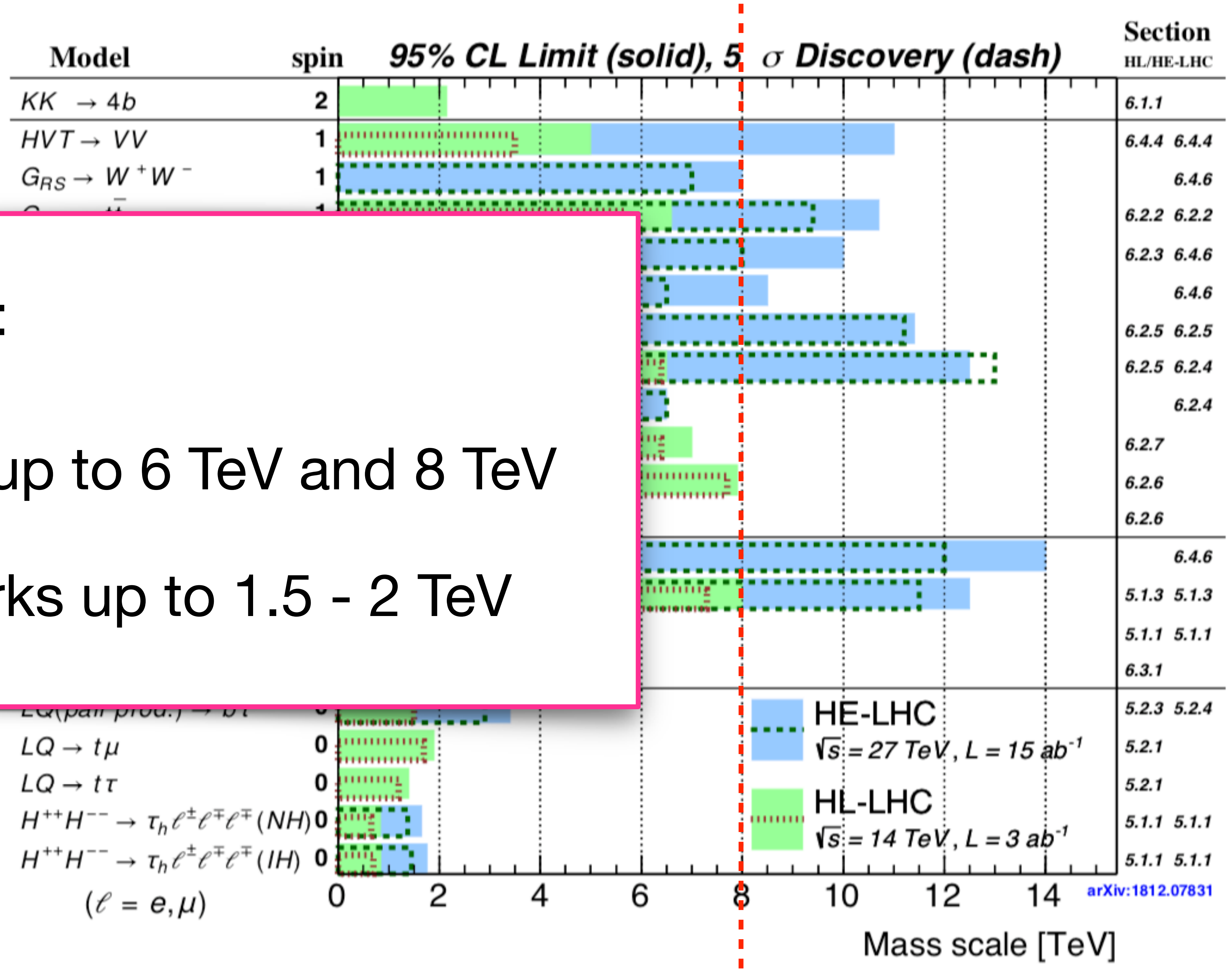
HL-LHC YR
1812.07831

Very Large Number of Searches

(in large variety of topologies and models)



4 TeV



8 TeV

Take home messages for HL-LHC:

Discovery potential of Z'and W' up to 6 TeV and 8 TeV

Discovery potential of Leptoquarks up to 1.5 - 2 TeV

HL-LHC YR 1812.07831

Example from CMS (similar for ATLAS)

Unconventional Signatures

Many extensions of the Standard Model predict new particles that are long lived heavy (neutral and charged) and can decay after several cm or even meters.

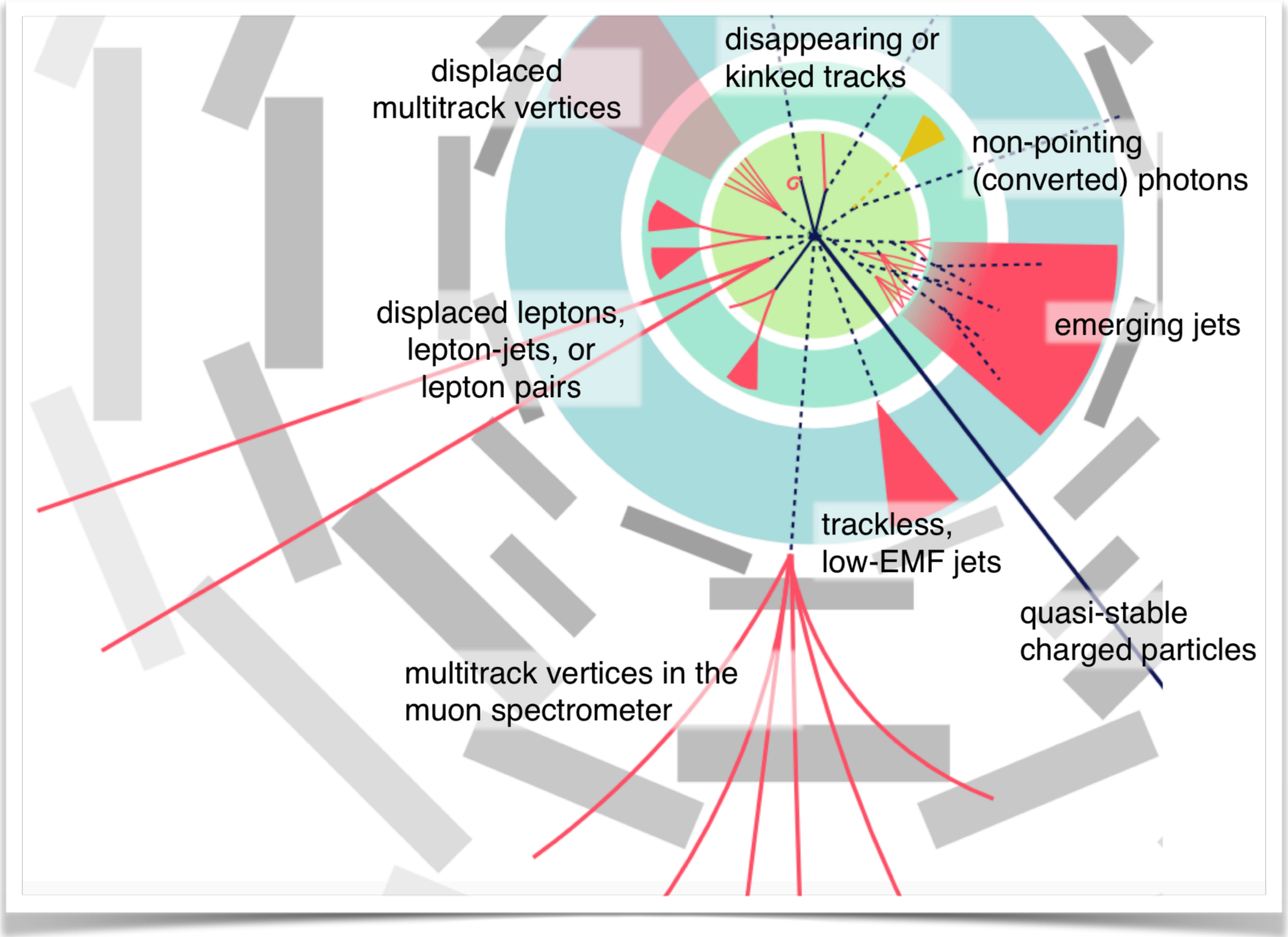
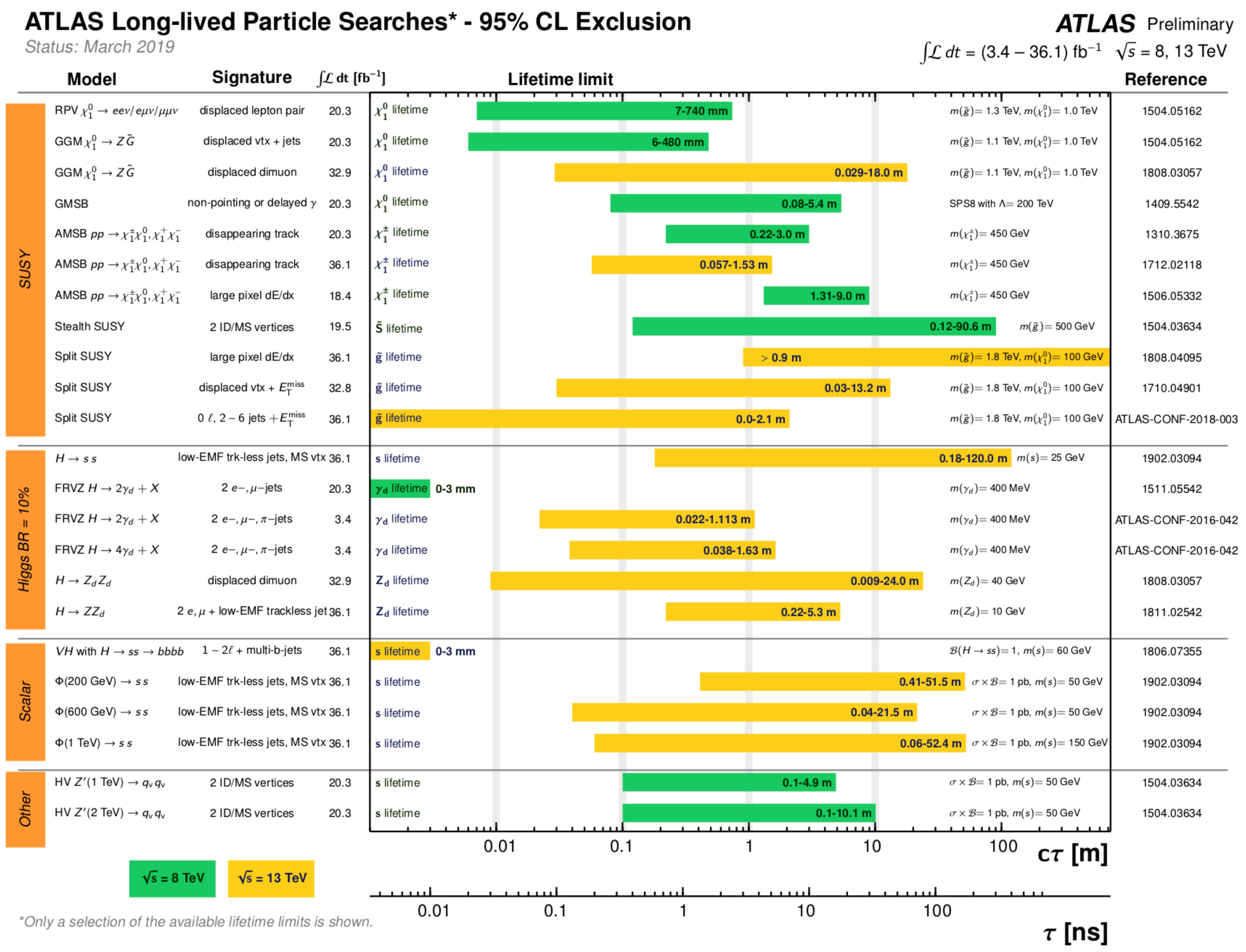


Image from H. Russel



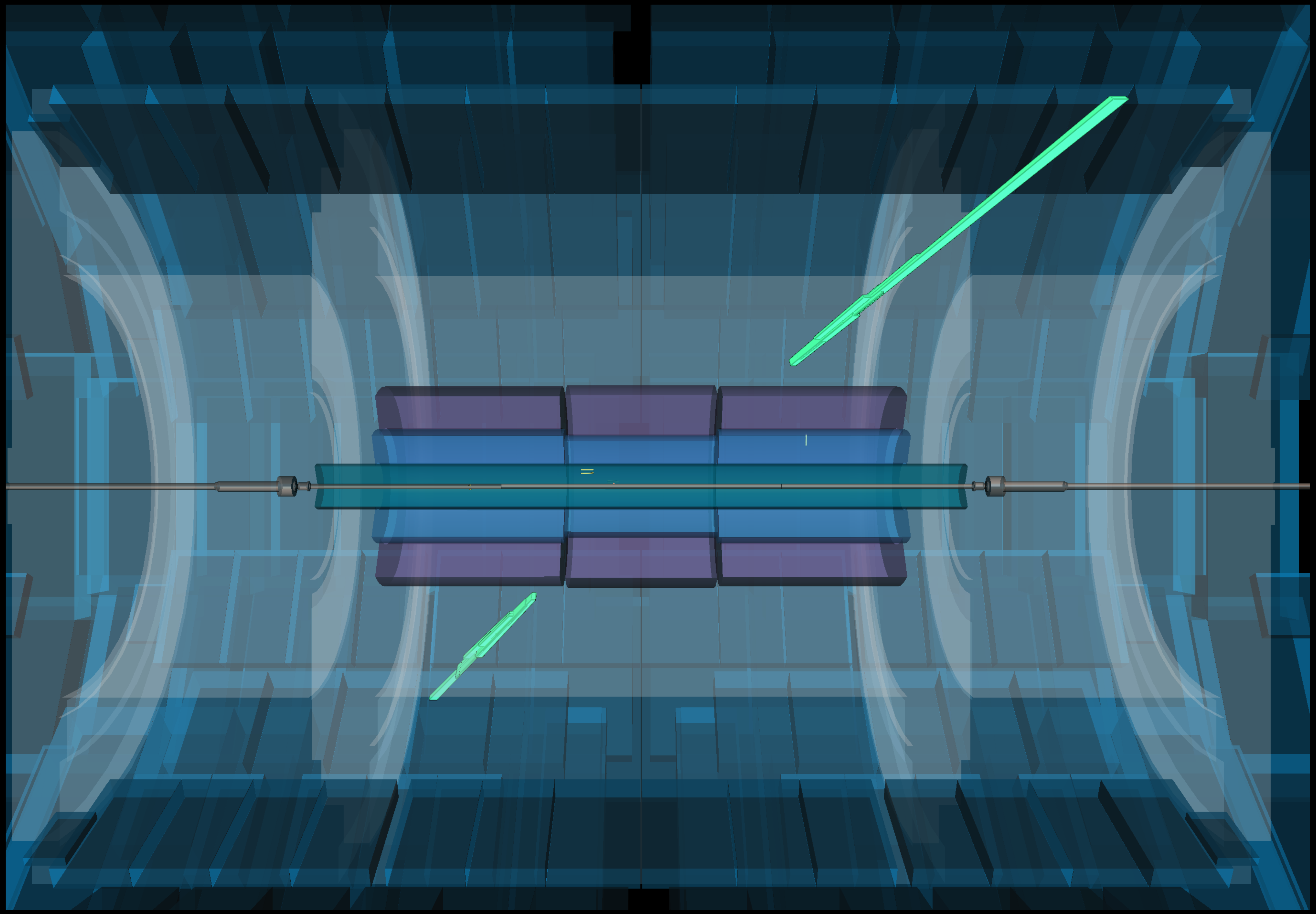
Sample for ATLAS (same for CMS)

Difficult signatures requiring specific complex reconstruction and trigger!

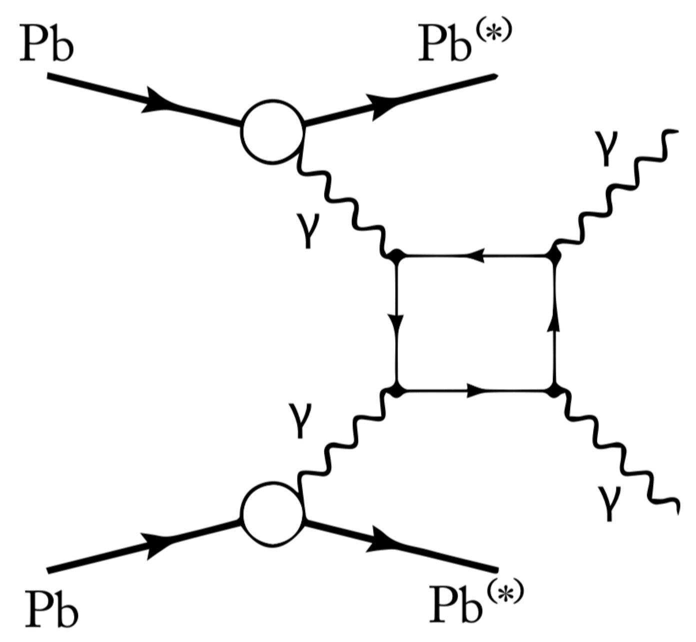
A Spectacular Heavy Ion Event

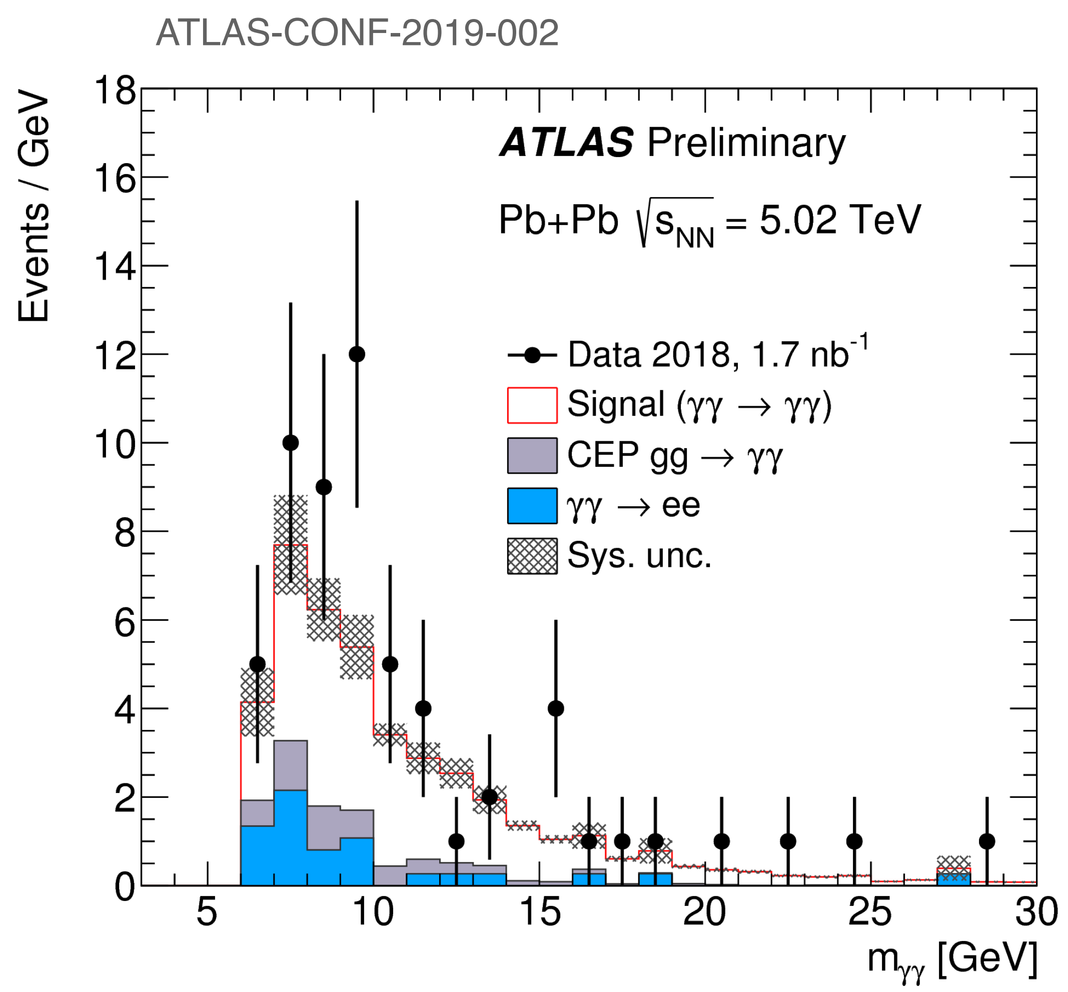
ATLAS EXPERIMENT

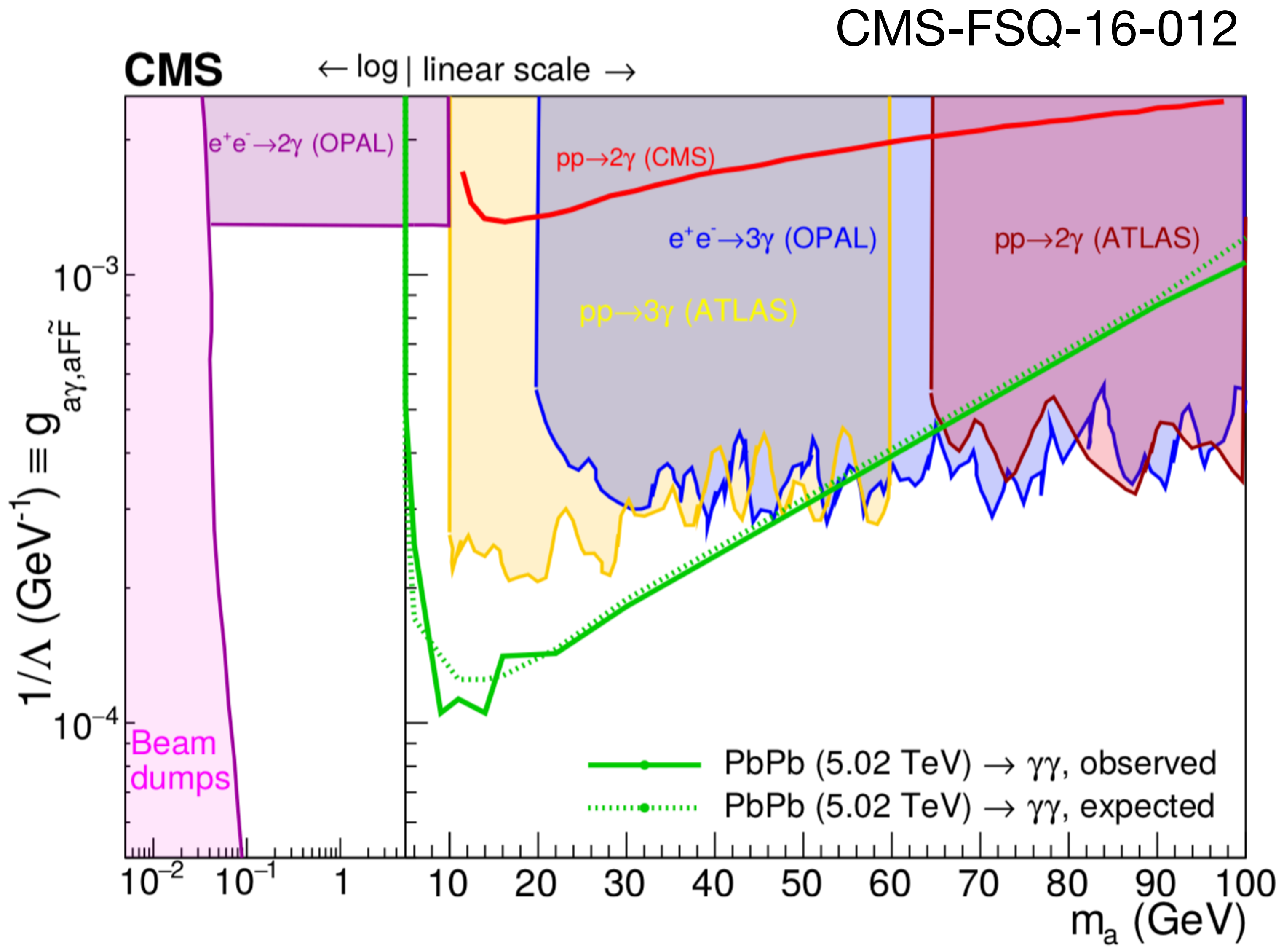
Run: 366994
Event: 453765663
2018-11-26 18:32:03 CEST



Observation of **Light-by-light scattering** (Central Exclusive Production)







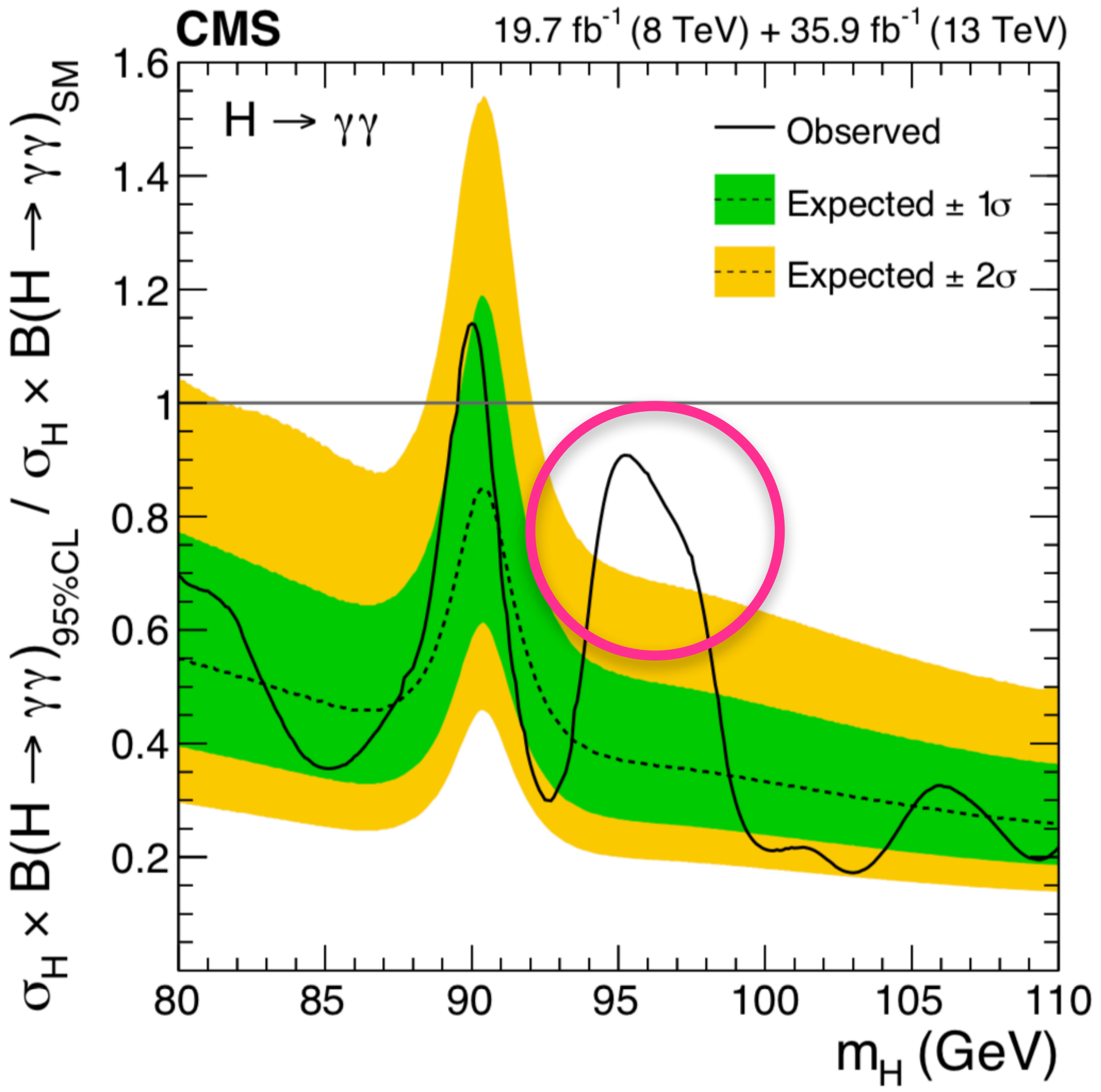
Constraints on ALP (Axion Like Particles) assuming sole coupling to photons.

Conclusion on Searches

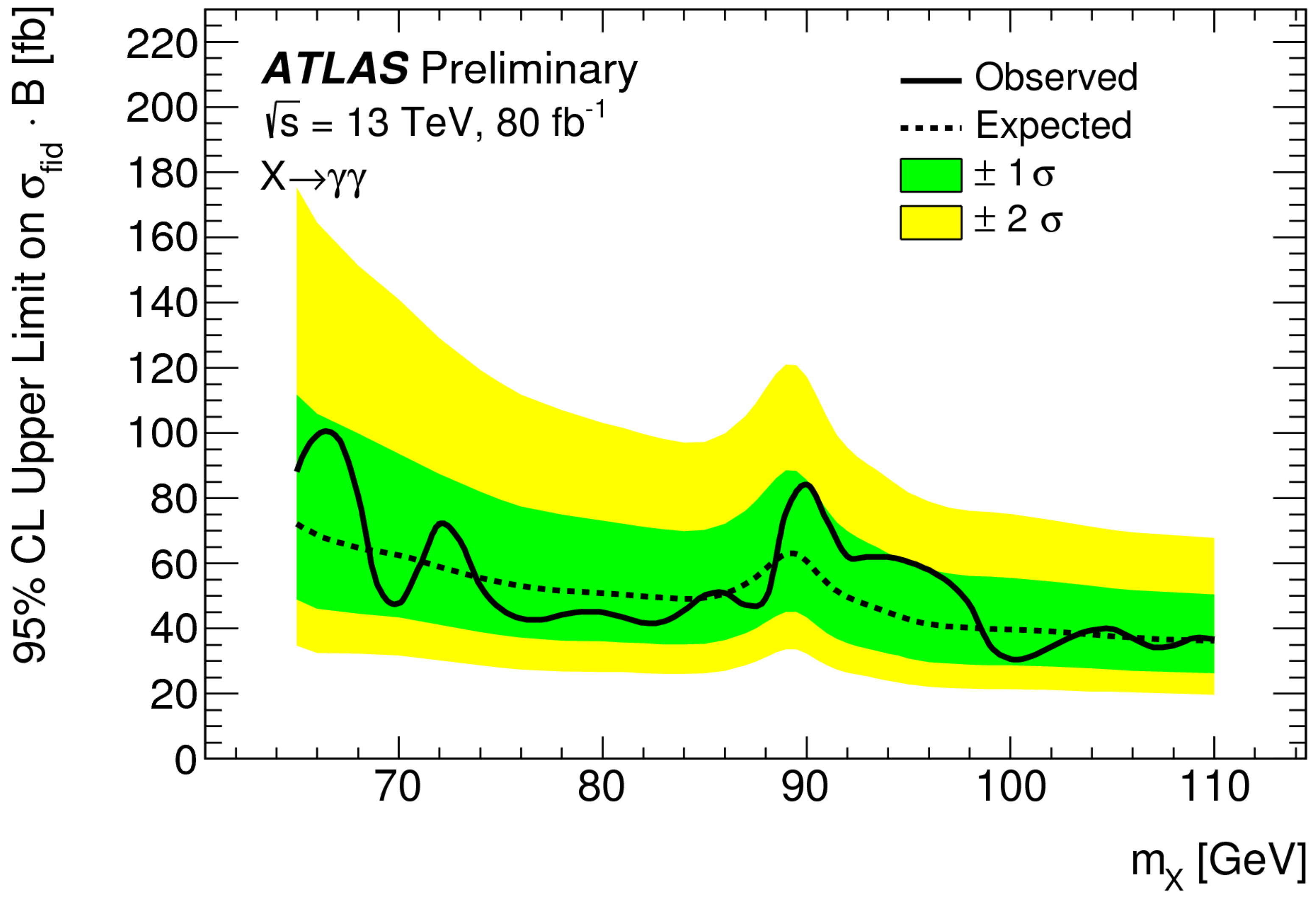
Are there any Anomalies in the Searches done so far?

$a \to \gamma\gamma$

Local (global) significance at 95.3 GeV : 2.90σ (**1.5σ**)



ATLAS-CONF-2018-025



Acceptance ~50%

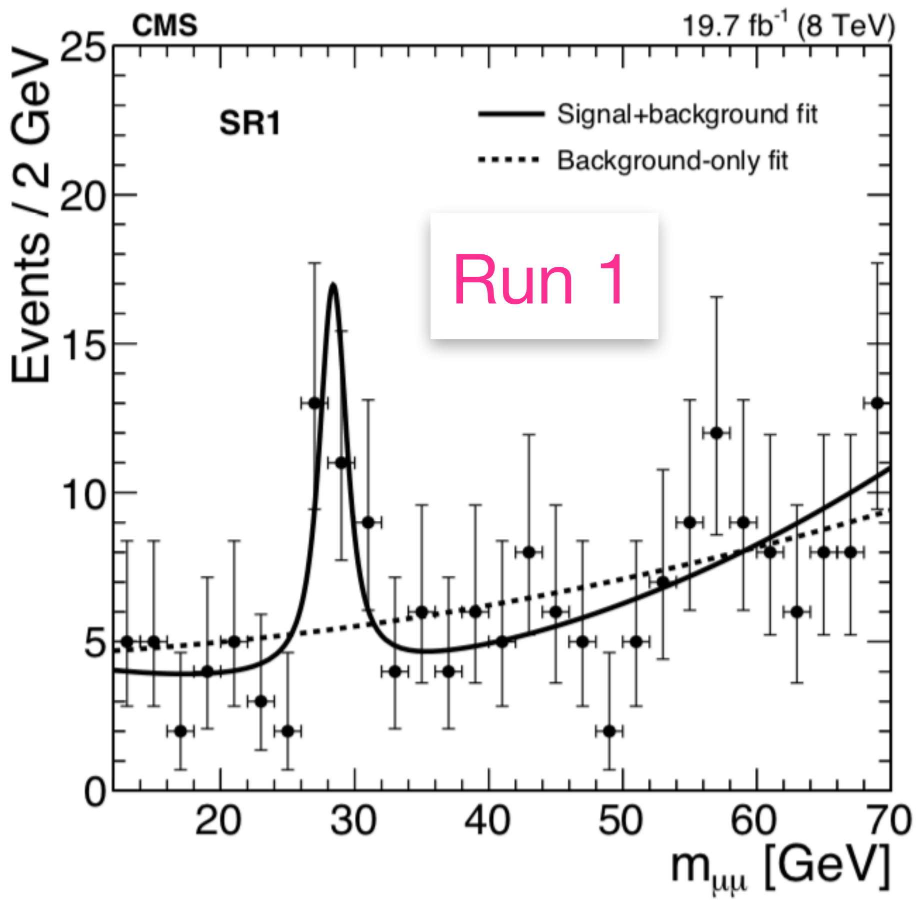
Limit on σxBR~120 fb

Not confirmed (but not conclusively excluded)

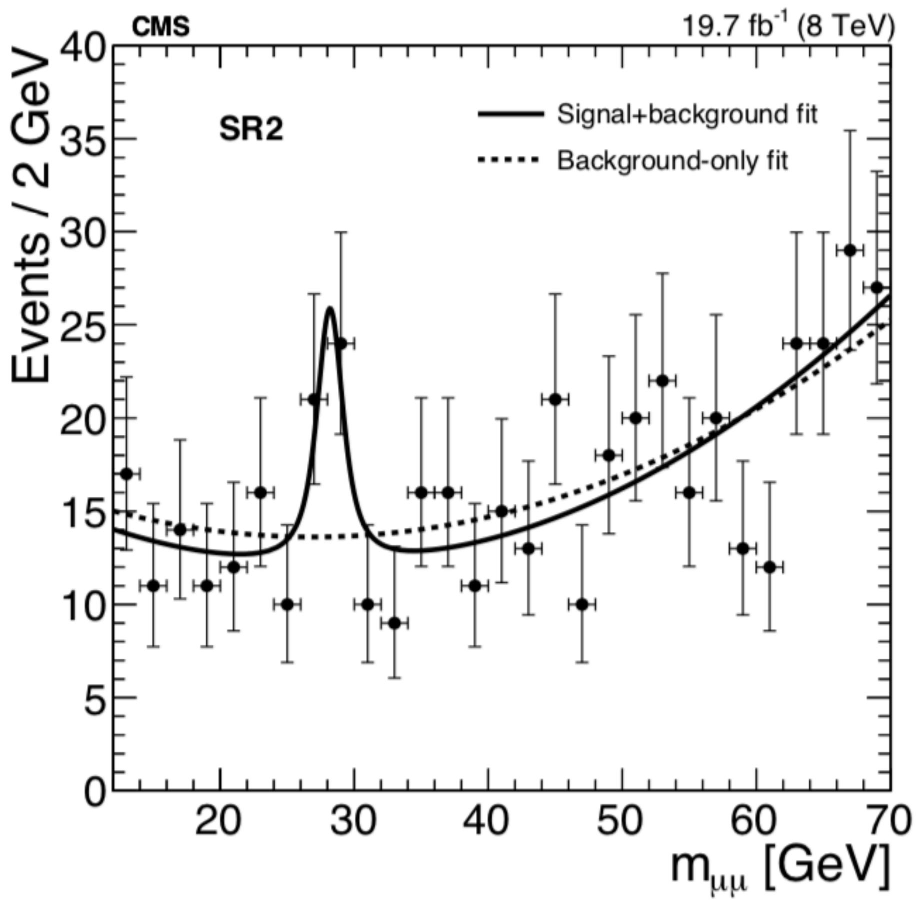
Astonishingly small (number of) anomalies given the number of analyses made at the LHC!

$b(a \to \mu\mu)$

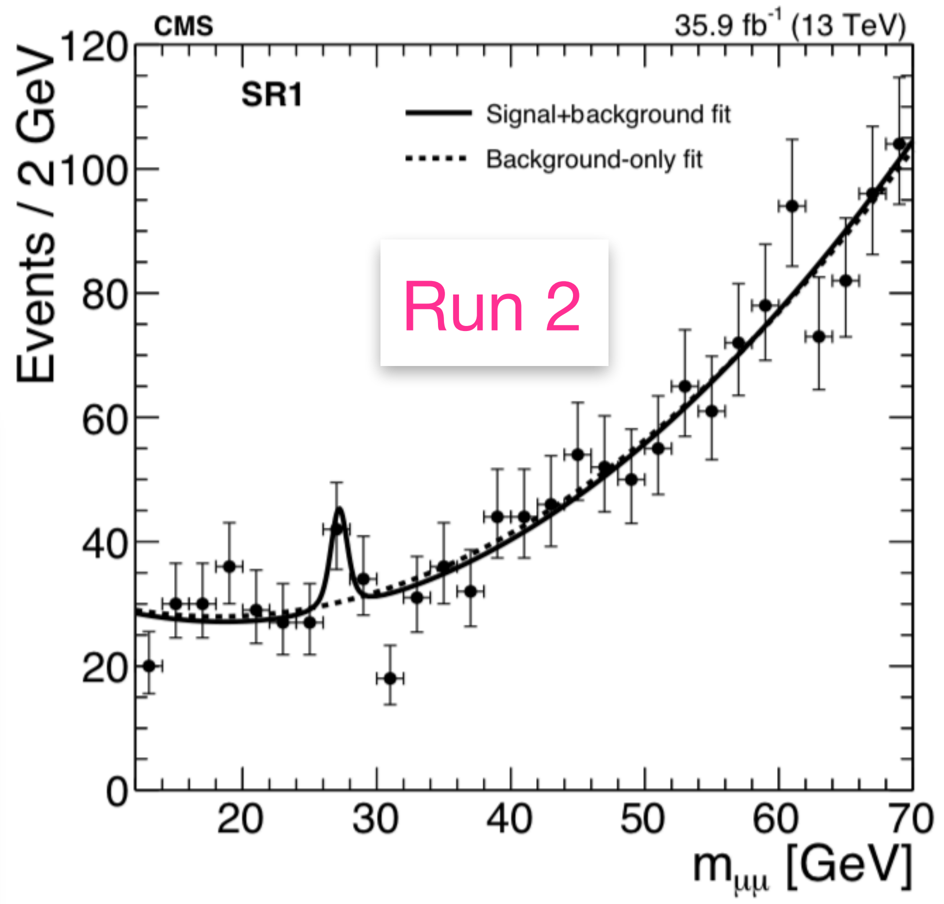
arXiv:1808.01890



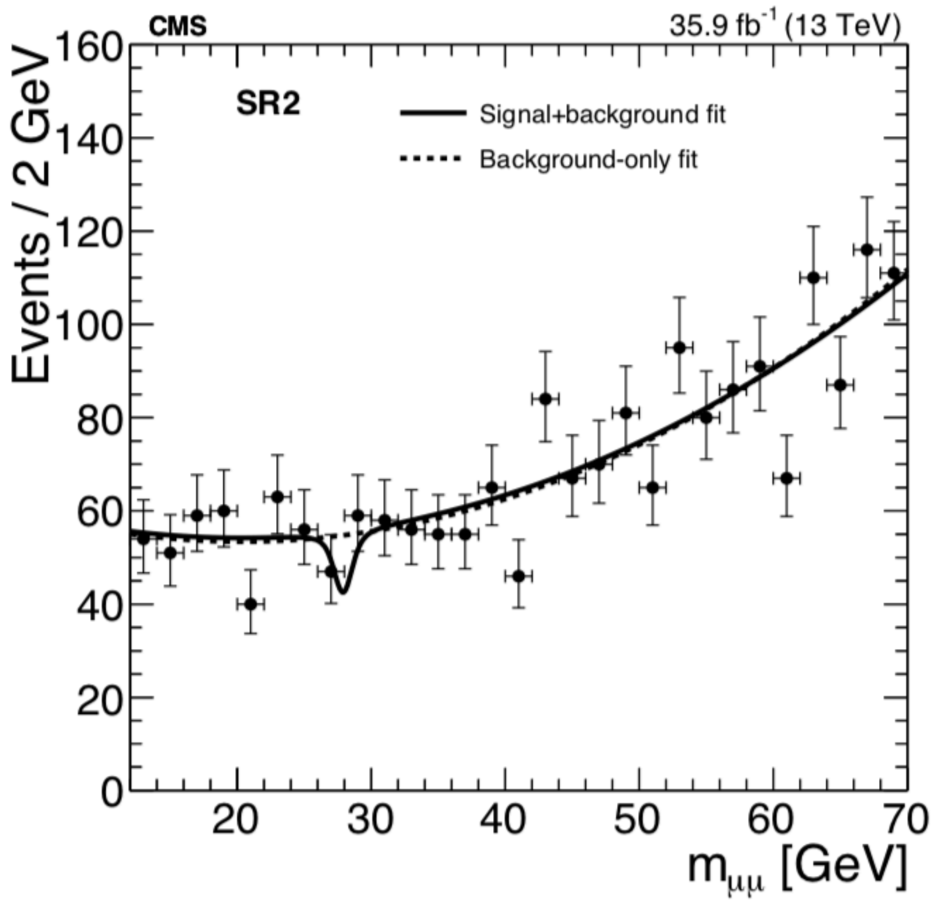
Local significance: **4.2σ**



Local significance: **2.9σ**



Local significance: **2.0σ**



Local significance: -**1.4σ**

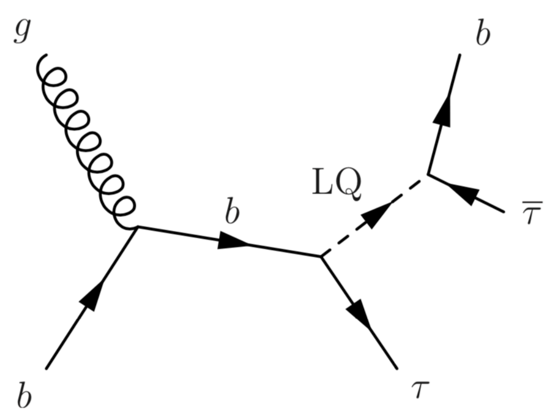
Conclusions of Searches

- A vast program of searches has been carried out at the Energy Frontier

- No stone was left unturned, and any significant deviation has been thoroughly verified (e.g. with the Lepton Flavor Universality anomaly in B decays - see M. Williams lectures)

Motivated Leptoquark and non universal V' bosons searches.

e.g. 3d generation Leptoquarks in CMS



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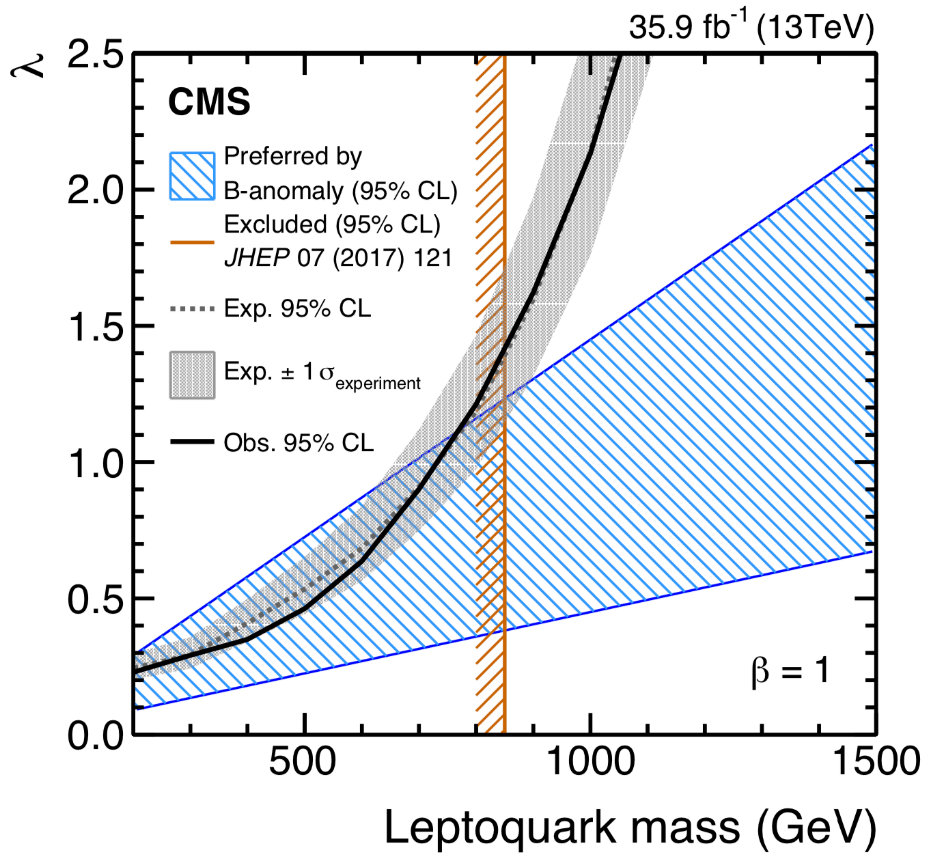
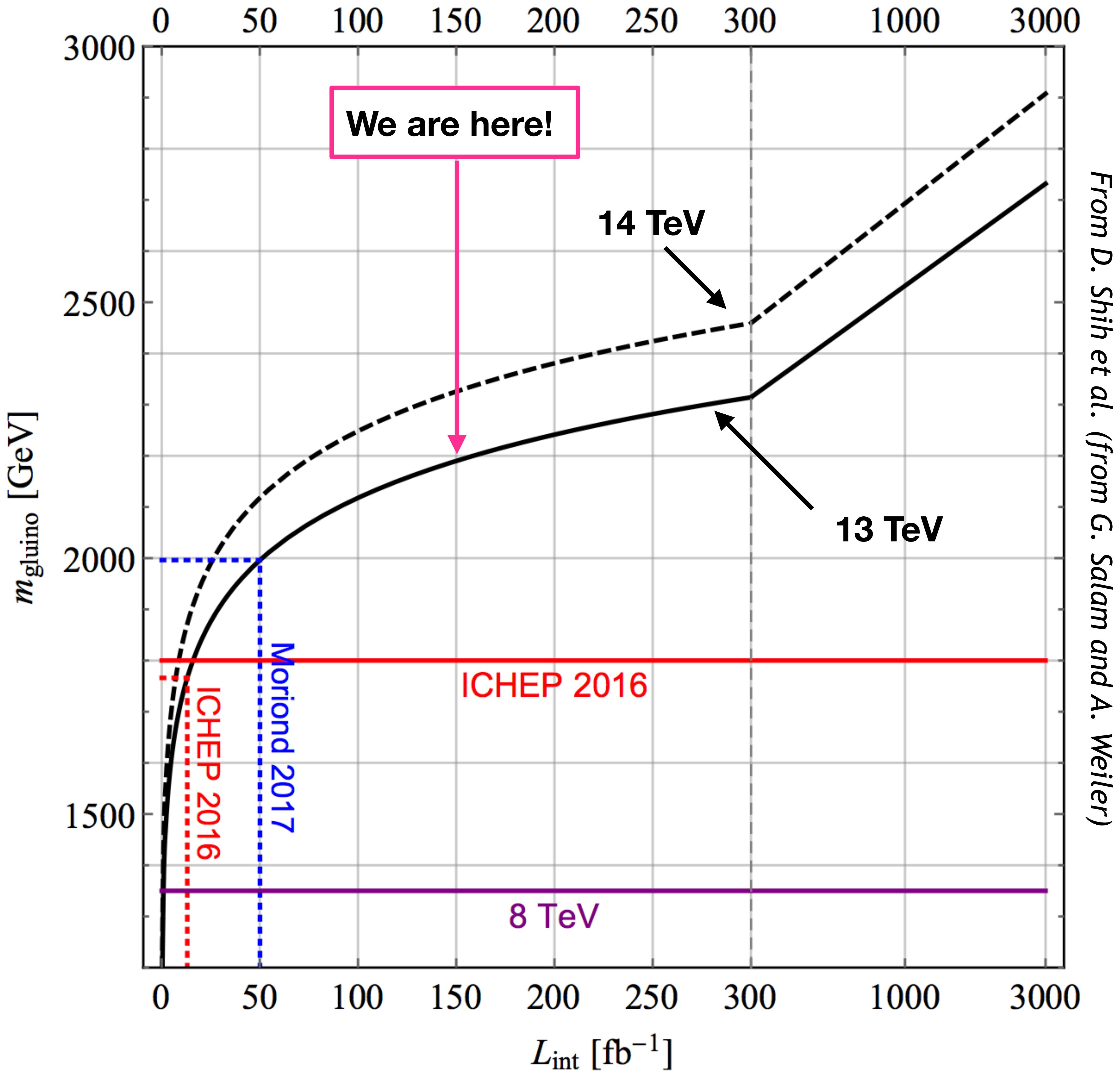


- A common effort with the Theory community that has provided fundamental benchmarks to be searched for at the LHC

No significant deviation from the Standard Model has been found so far

Towards HL-LHC and Precision Physics at LHC

Evolution of **exclusion** search sensitivity for generic strongly interacting particle (e.g. **gluino**)



http://collider-reach.web.cern.ch/collider-reach/

Towards HL-LHC still a **factor of 20** in luminosity:

- Still **room for discoveries!**
- Given that the **doubling time of the luminosity** is now counted in **several years**: discoveries will take time, and times for spectacular discoveries (in the sense of immediate) are over.
- Low hanging fruits typically have been (or are being) harvested! Immense amount of work in trying to expand search reach beyond the root-L:
  - With new ideas and developments at all levels.
  - **Improving precision (theoretical and experimental) will be key!**

Outlook and Conclusions

The LHC a « Marvel of Technology »

First mention of the LHC in 1977 by sir John Adams (former CERN director) as an option of a superconducting hadron collider to be hosted in the LEP tunnel (requesting that the LEP be made large enough to host a proton collider of at least 3 TeV beam energy). That was a period very busy with extremely important physics results.

- 1984: CERN and ECFA workshop in Lausanne.
- 1988: LEP tunnel completed (Europe's largest civil engineering project prior to the channel tunnel).
- 1992: ATLAS and CMS letters of intent.
- 1994: Approval of the LHC (1993 cancellation of 40 TeV SSC).
- 1995: LHC CDR published.
- 1997-98: ATLAS, CMS, LHCb and ALICE experiments approved.
- 2003-2005: Caverns completed installation started.
- 2007: LHC dipoles installed in LHC (after having been all individually checked at SM18).
- 2008: Experiments installed.
- 2008 September 10: Start of the LHC.
- 2008 September 19: Incident occurs between dipole and quadrupole.
- **2009** November: Beams are back in the LHC!

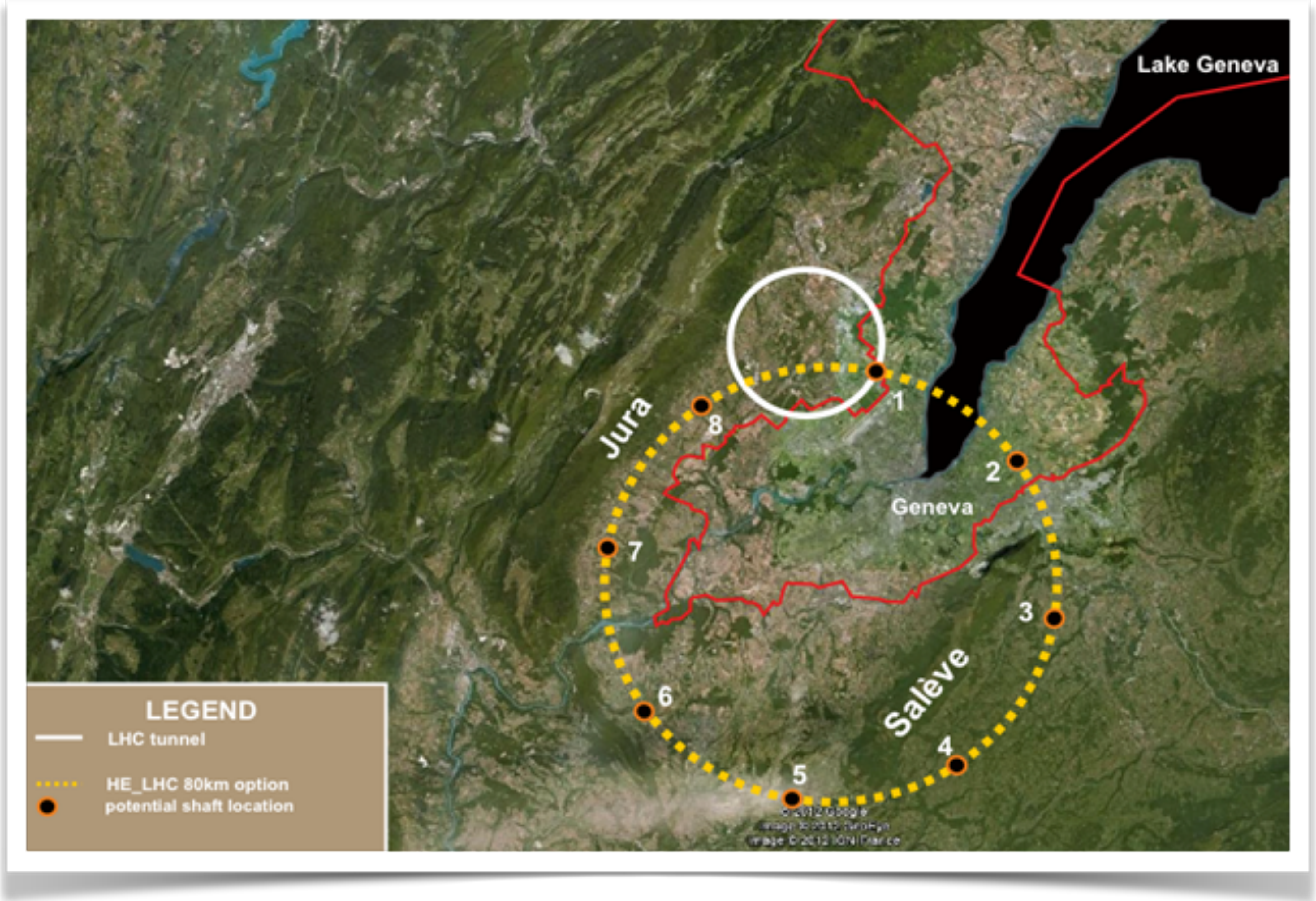
Since 2009: 10 years of successful operations and landmark results and 20 years of running ahead!

Glimpse at Future Hadron Colliders

The candidate machines in a tiny nutshell

Project	**HL-LHC**	**HE-LHC**	**FCC-hh**	**SppC**
Location	CERN	CERN	CERN	China TBD
Circ.	27 km	27 km	100 km	55 - 100 km
COM energy	14 (15?) TeV	27 TeV	**100 TeV**	70 -140 TeV
Luminosity	3 ab-1	15 ab-1	20-30 ab-1	TBD
PU	up to 200	up to 800	**up to 1000**	TBS
Bunch sp.	25 ns	25 ns	25 ns	25 ns
Field	8T	16T	16T	20T
When?	Until 2037	After 2037?	After 2037	TBS

Much much more in Lecture by R. Corsini



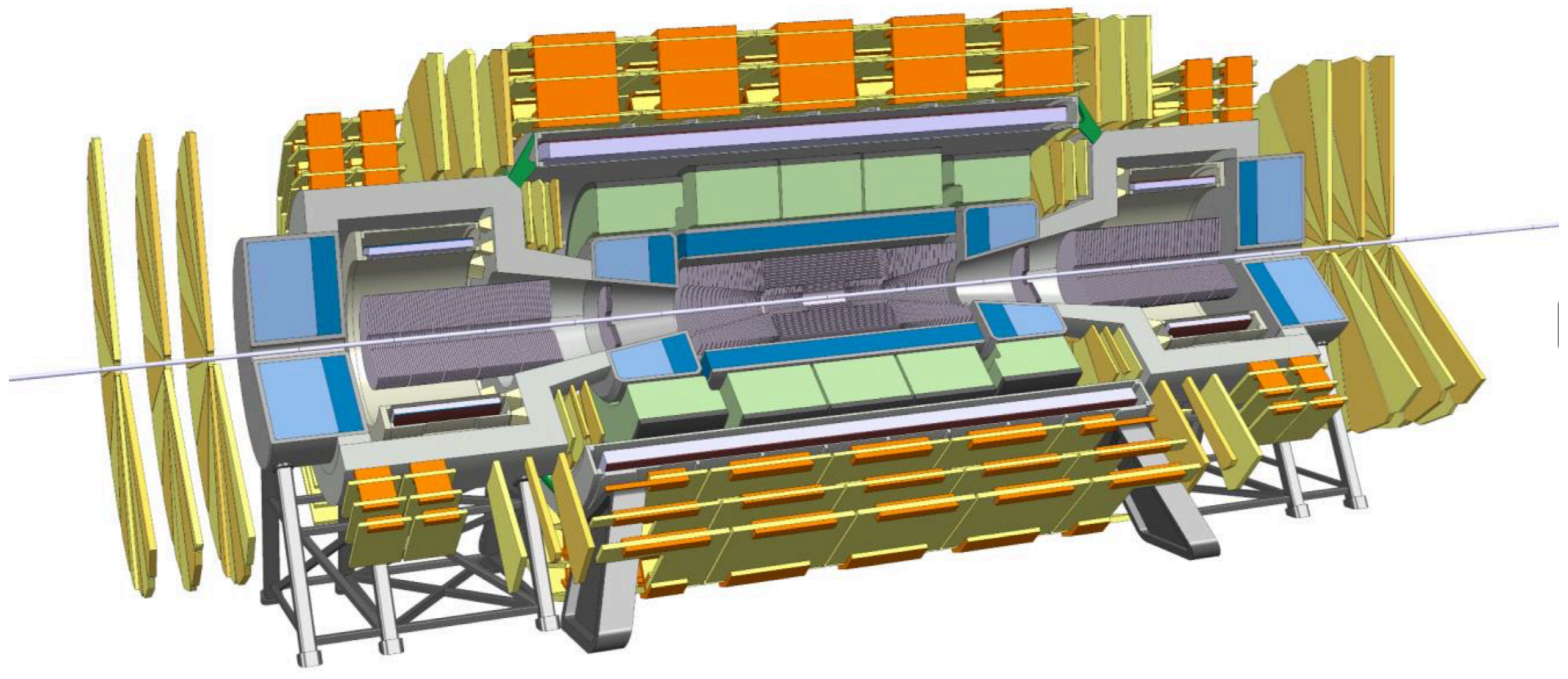
A b at 5 TeV can travel 50cm and a tau 10 cm

Decay products of a Z at 10 TeV are separated by $\Delta R = 0.01$

Detector, Trigger DAQ, Reconstruction challenges

Two challenges: higher PU (1000) higher pT

Answer: granularity and resolution



Conclusions of the Lectures

- Hadron colliders have been extremely successful to unveil many of the secrets of nature at the smallest scales.

- The first 10 years of the LHC running have been an immense success with major landmark results:

  - The discovery of the Higgs boson, and the measurement of its properties all compatible with the Standard Model Higgs boson.

  - A vast campaign of searches at the energy frontier leaving no stones unturned, which have so far revealed no signal of physics beyond the Standard Model.

  - The LHC has proved not to be only a discovery machine with a vast potential in direct searches, but also a precision measurements machine!

- However only 5% of the data has been collected so far, there is therefore still a vast potential for discoveries and interesting measurements!

- The level of precision reached in reconstruction and measurements is outstanding, but limits should continue pushed. It will be a common effort with the Theory community.

- **Very exciting program ahead with great opportunities for you at LHC and beyond!**