Status and perspectives of BSM searches at the LHC

Maurizio Pierini

CERN

European Research Council

For decades physicists have been working on a beautiful theory that has promised to lead to a deeper understanding of the quantum world. **Now they stand at a crossroads:** prove it right in the next year or confront an epochal paradigm shift

By Joseph Lykken and Maria Spiropulu

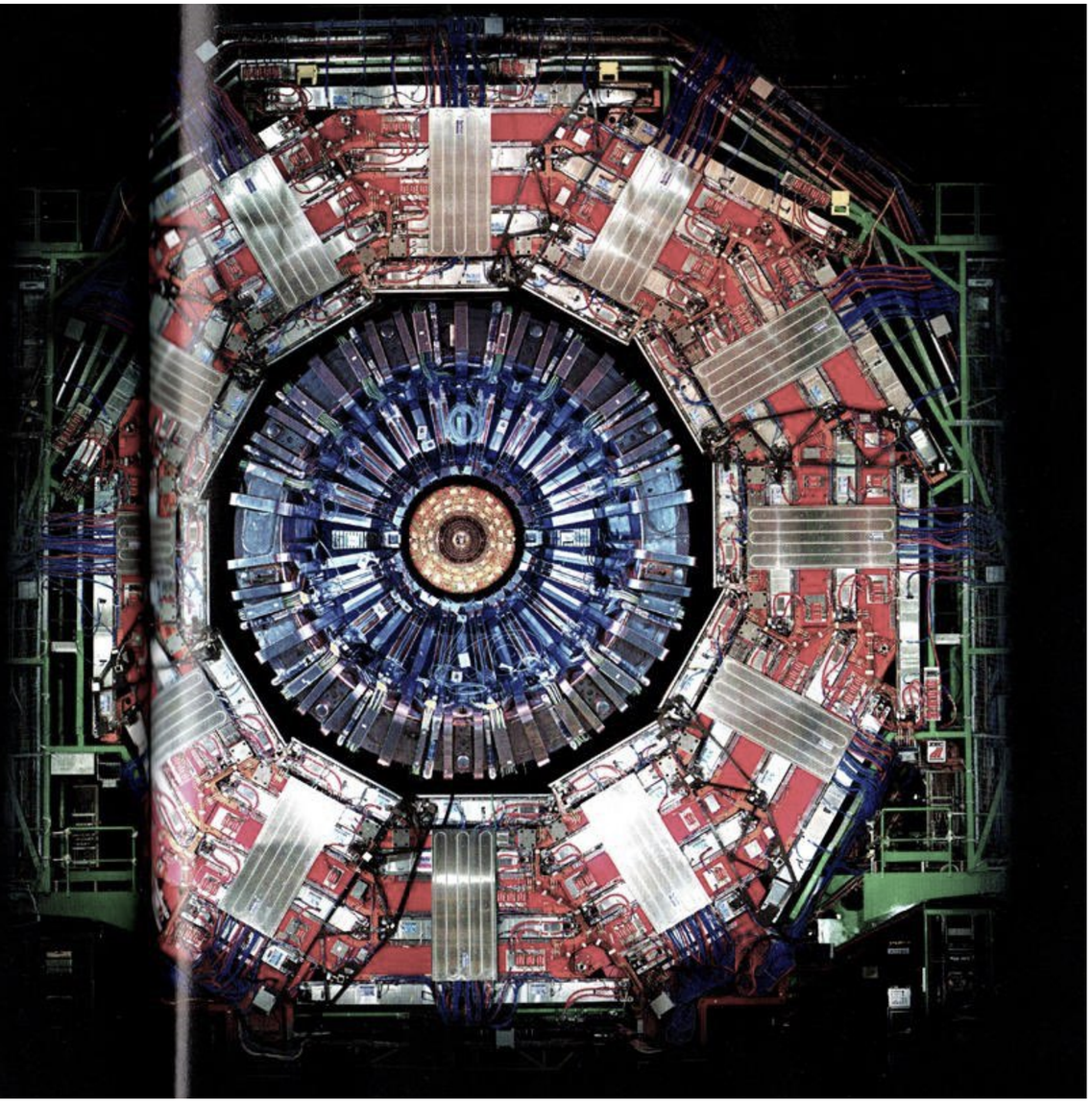
PARTICLE PHYSICS

Supersymmetry and the Crisis in Physics

IN BRIEF

Supersymmetry postulates that every known particle has a hidden superpartner. Physicists love supersymmetry because it solves a number of problems that crop up when they try to extend our understanding of quantum mechanics. It would also potentially solve the mystery of the universe's missing dark matter.

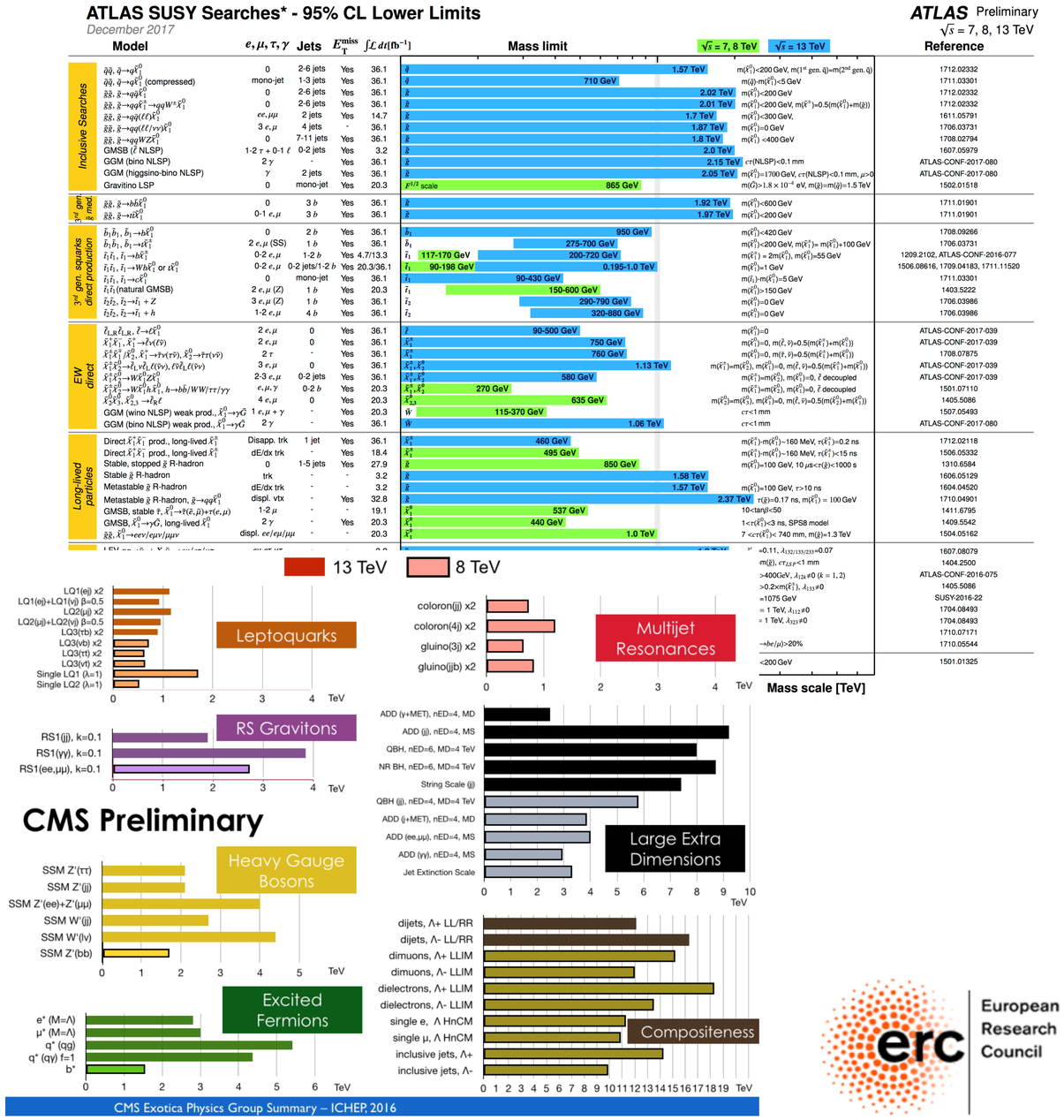
Physicists hoped to find evidence of supersymmetry in experiments at the Large Hadron Collider (LHC). To date, they have not. If no evidence arises in the next run of the LHC, supersymmetry will be in trouble. **The failure to find** superpartners is brewing a crisis in physics, forcing researchers to question assumptions from which they have been working for decades.



The big picture

Eight years of searches…

- *Extensively searched in all possible directions*
- *Done more than expected, with new ideas and original approaches to data taking*
- *Our new-physics target evolved towards more complicated scenarios*
  - *EXAMPLE: the SUSY we search for today is very different than what is in the ATLAS/CMS TDRs*



SUSY: a moving target

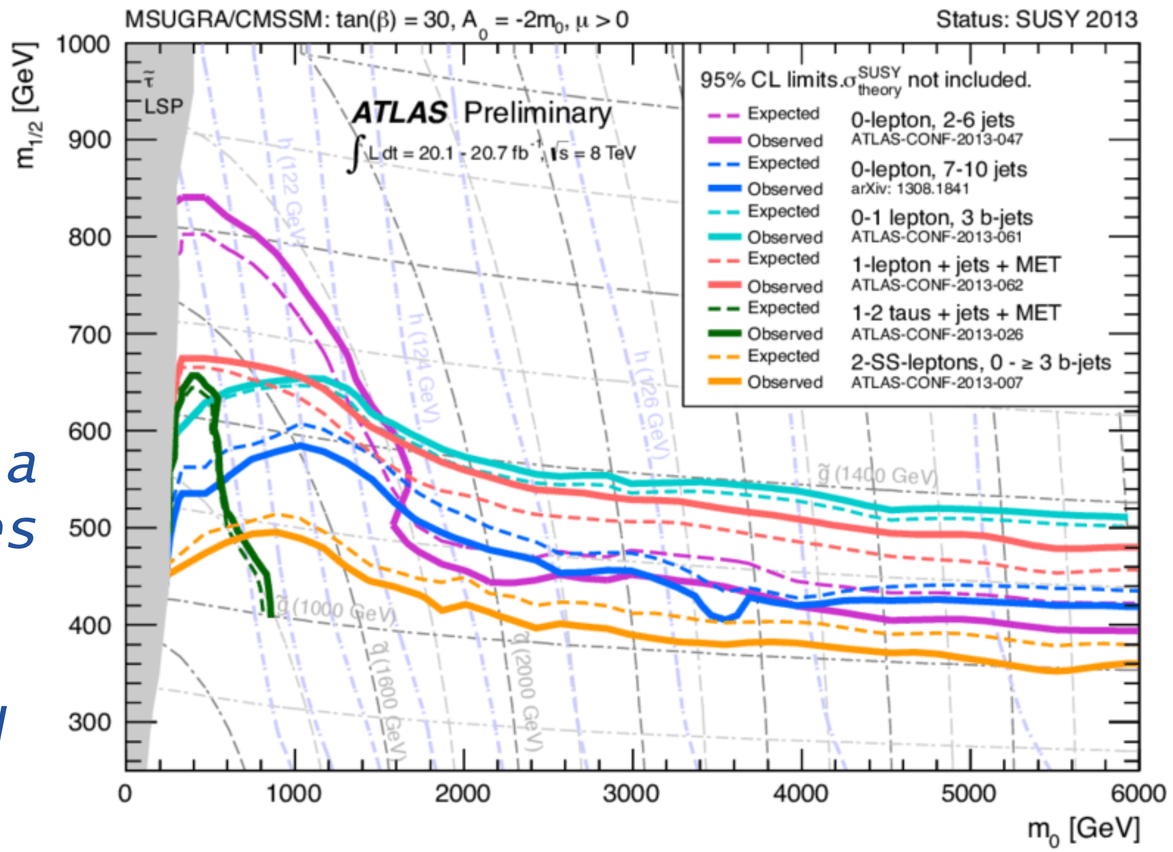
- ***We started looking for mSugra-inspired models. Thanks to large gluino and squark cross sections, exclusions became soon very strong***

- *We then moved to Natural-SUSY scenarios, with focus on t and b squarks*

- *We moved to simplified models as a generalization of search strategies (with 100% BR assumptions)*

- *We recently generalized simplified models to BR-independent results*

- *And we extended model interpretation to large-dimensional scans (pMSSM)*



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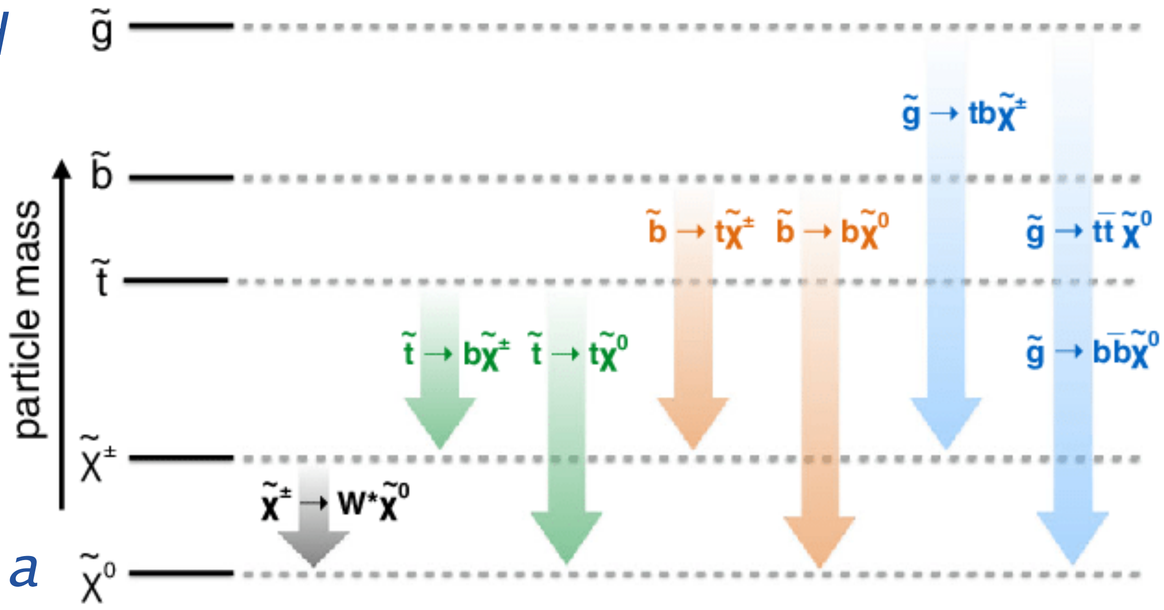

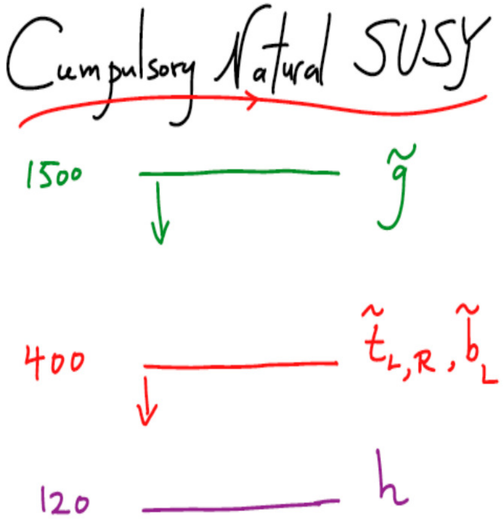

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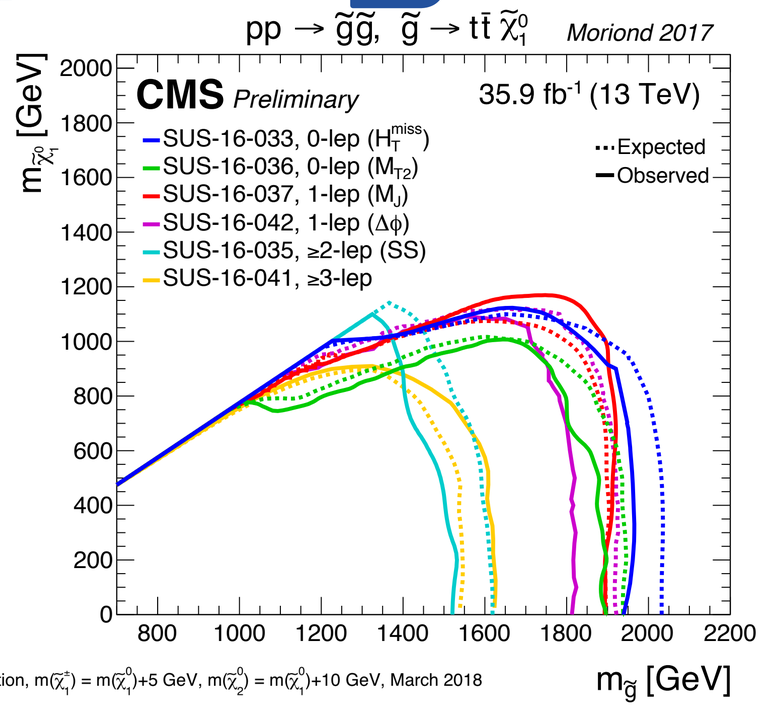

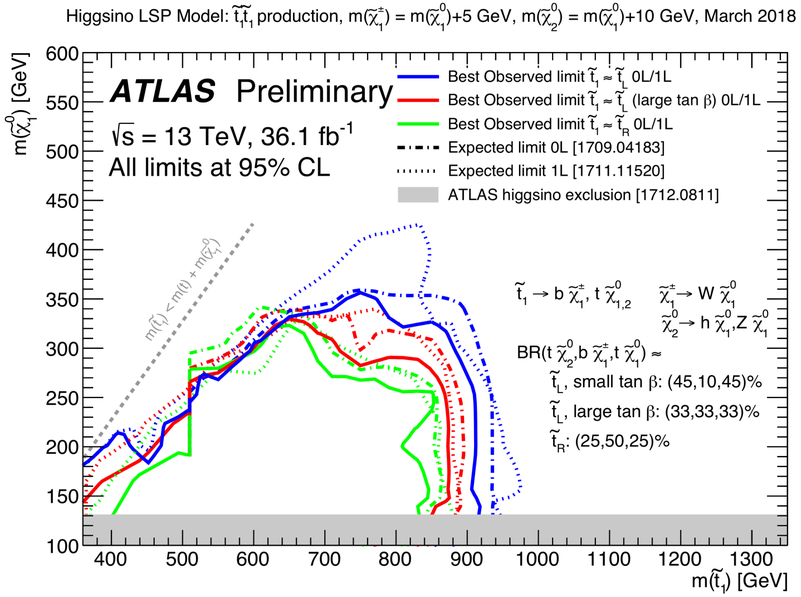

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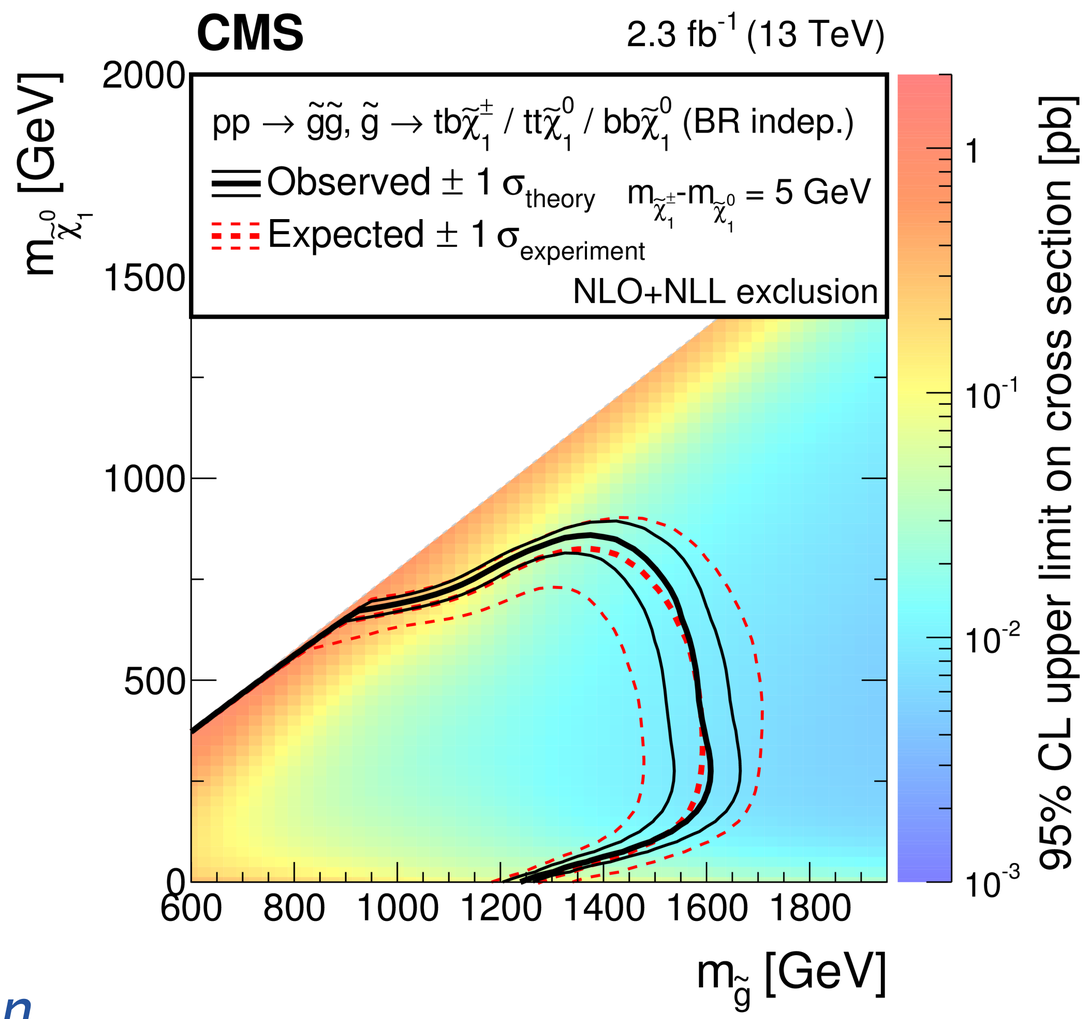

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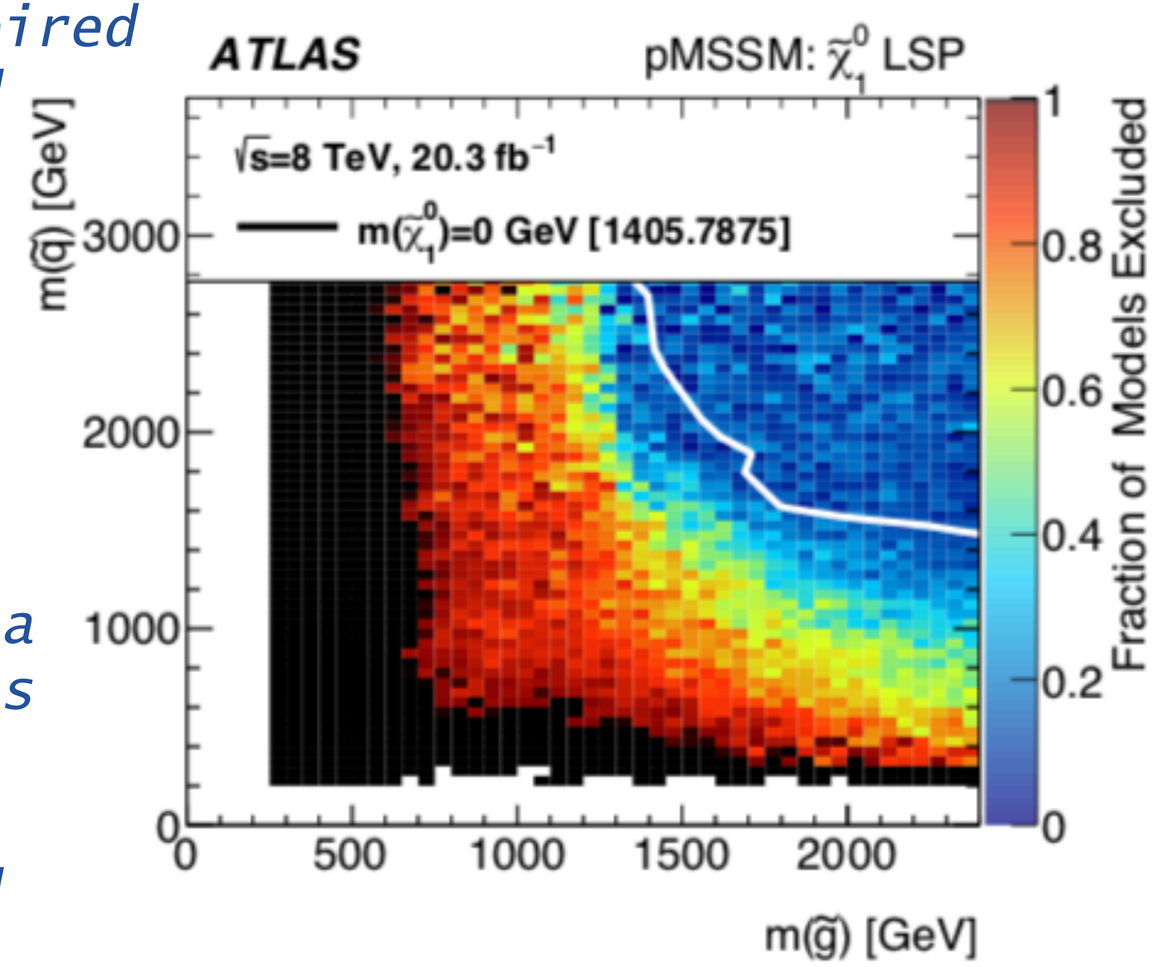
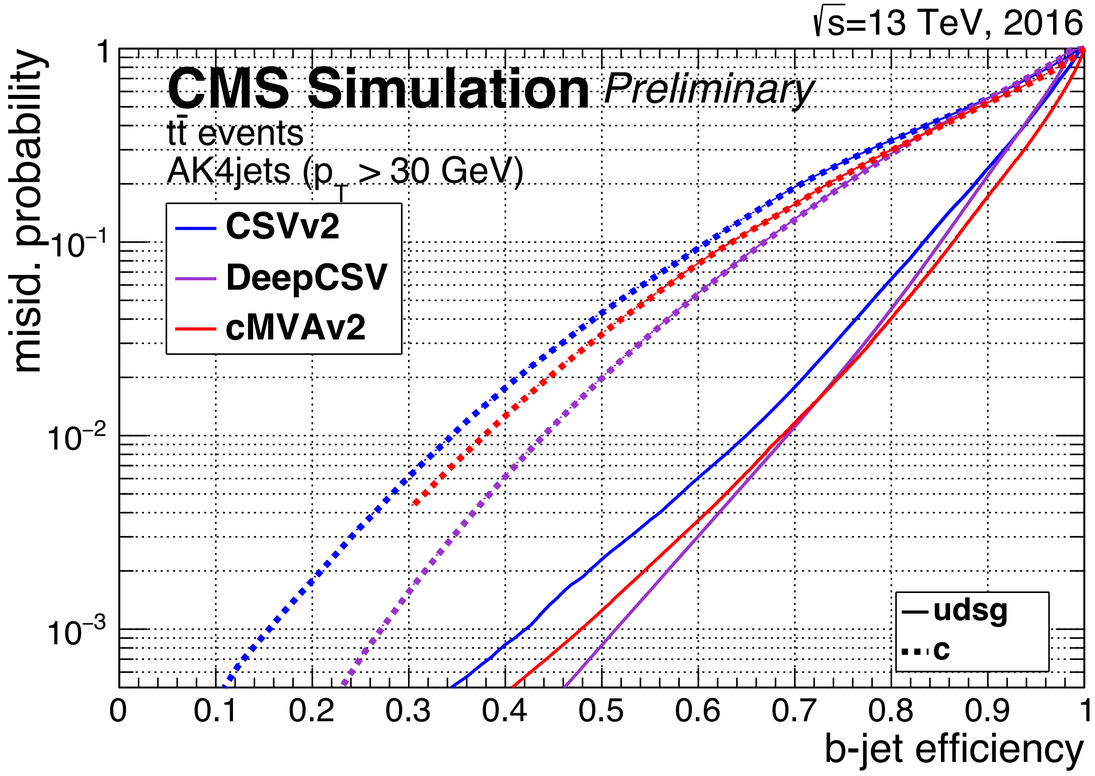


(a) All LSP types

New search tools

- *Today's BSM search today expanded in many new directions*
  - ***Better identification of complex objects (e.g., tau leptons, b-jets)***
  - *New Standard Model candles (e.g., the Higgs boson)*
  - *New reconstruction strategies (e.g., boosted jets)*
  - *Better understanding of the detector → better sensitivity to soft particles*
  - *More and more exotic signatures: displaced vertices, disappearing tracks, heavy stable charged particles, etc*



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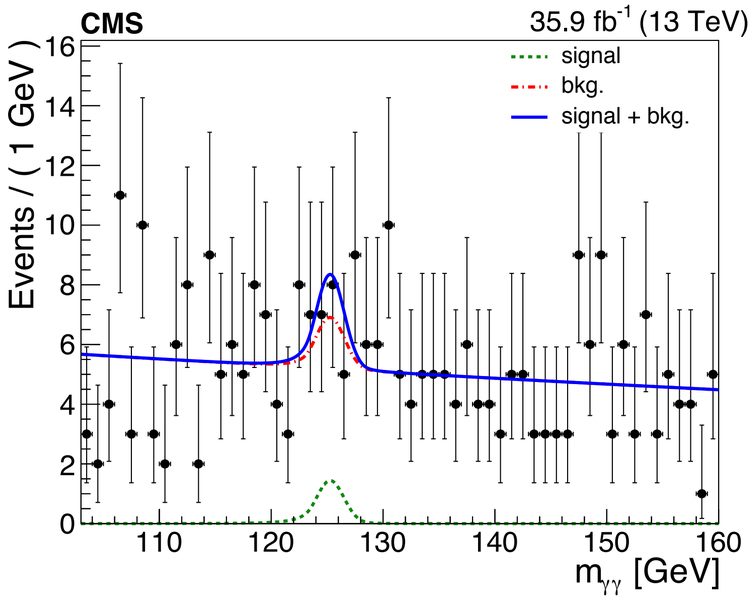

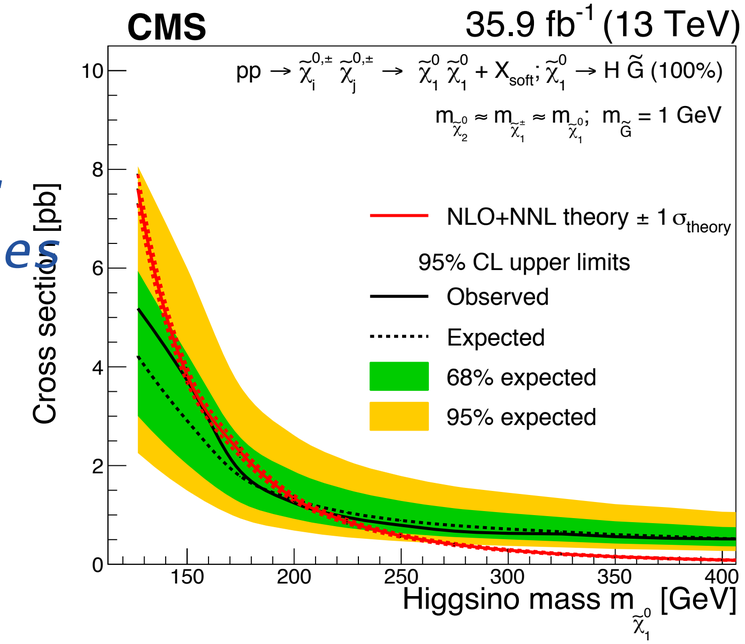

CMS-SUS-16-045

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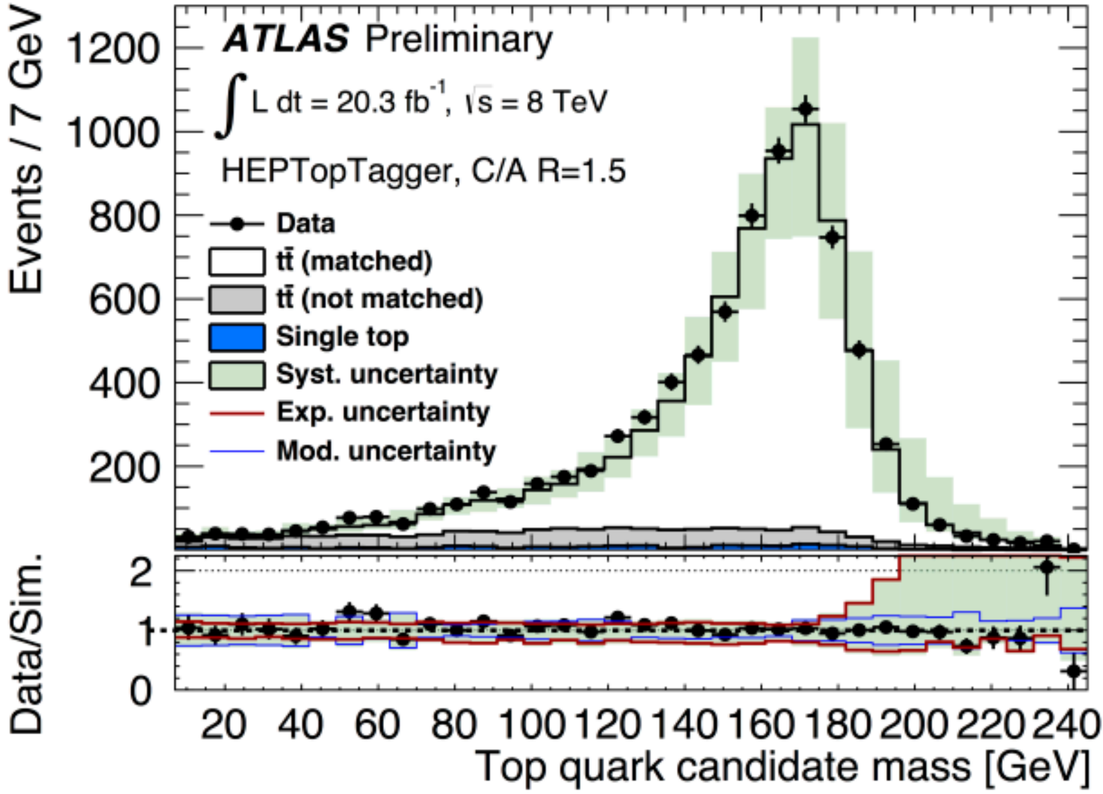

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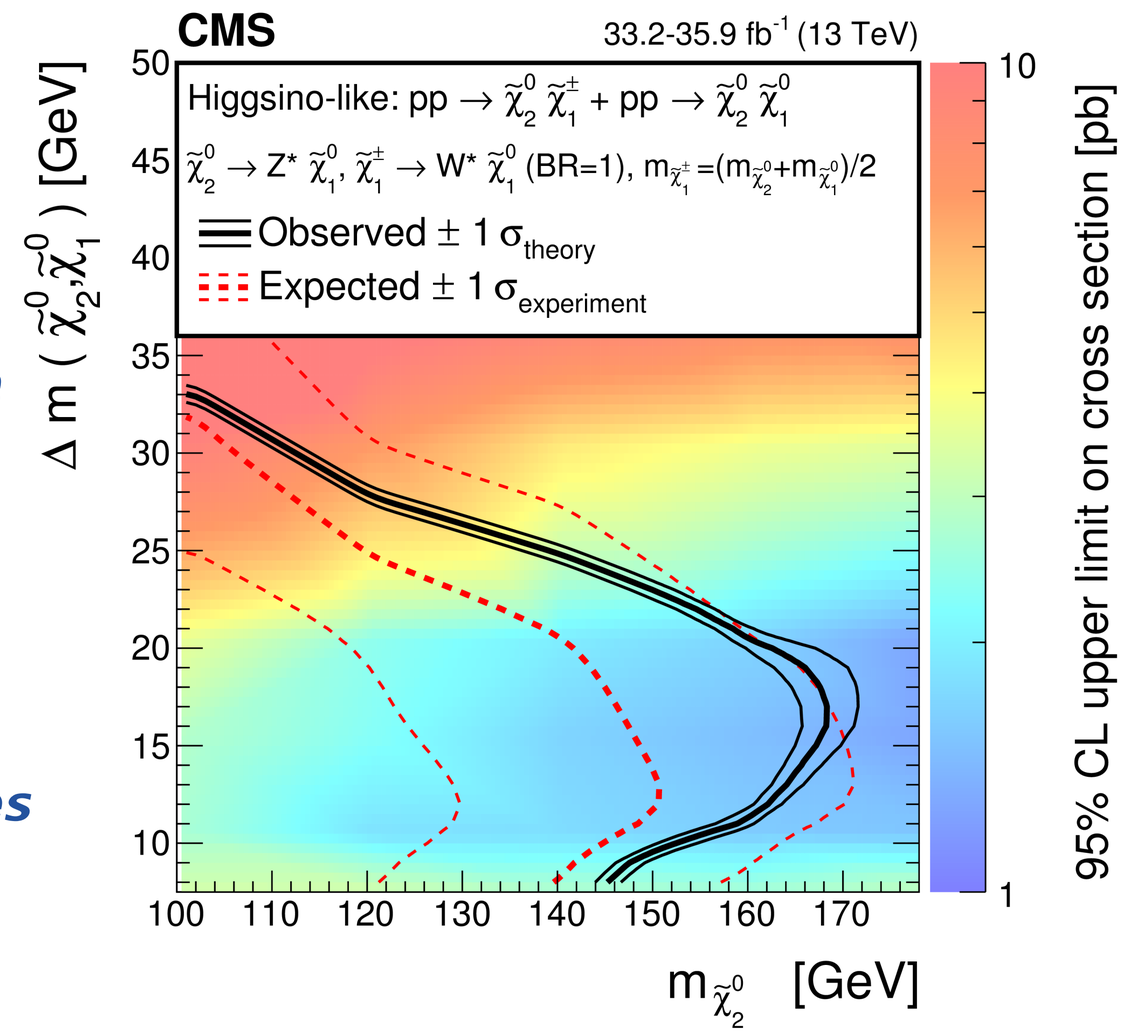

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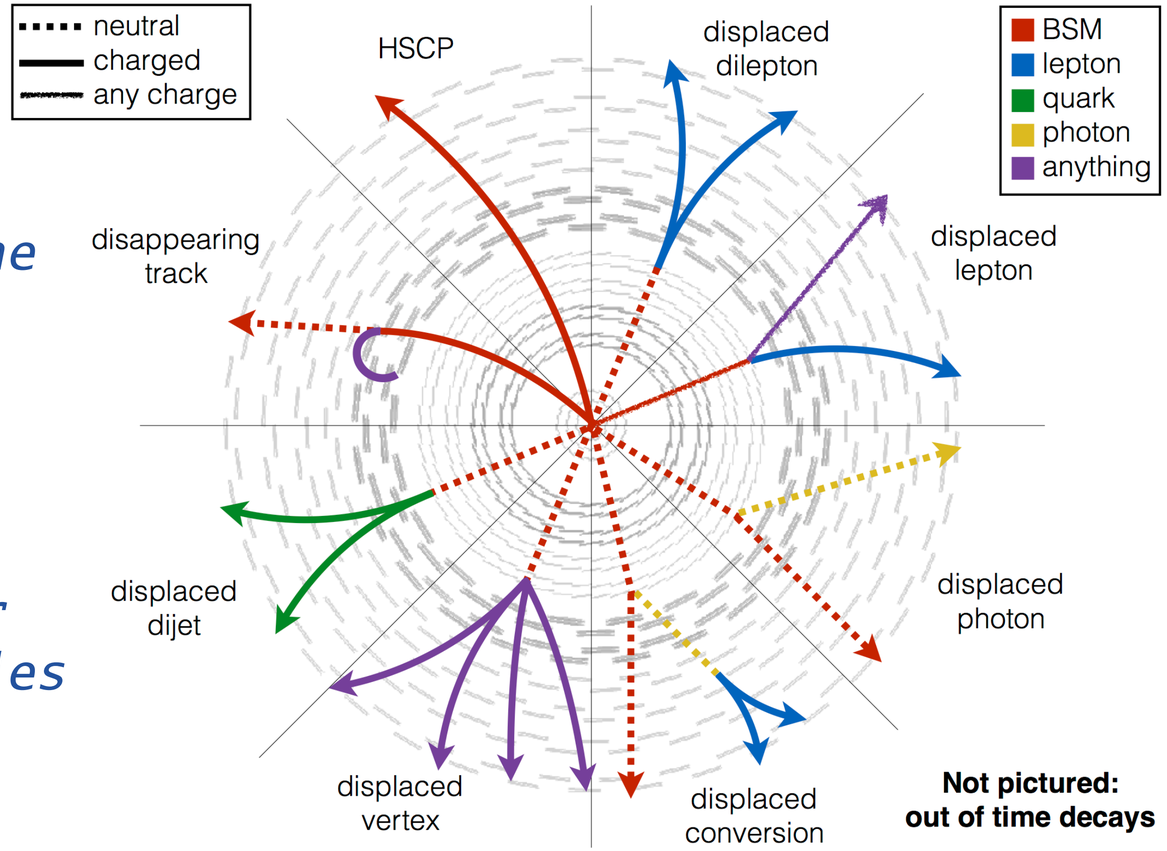
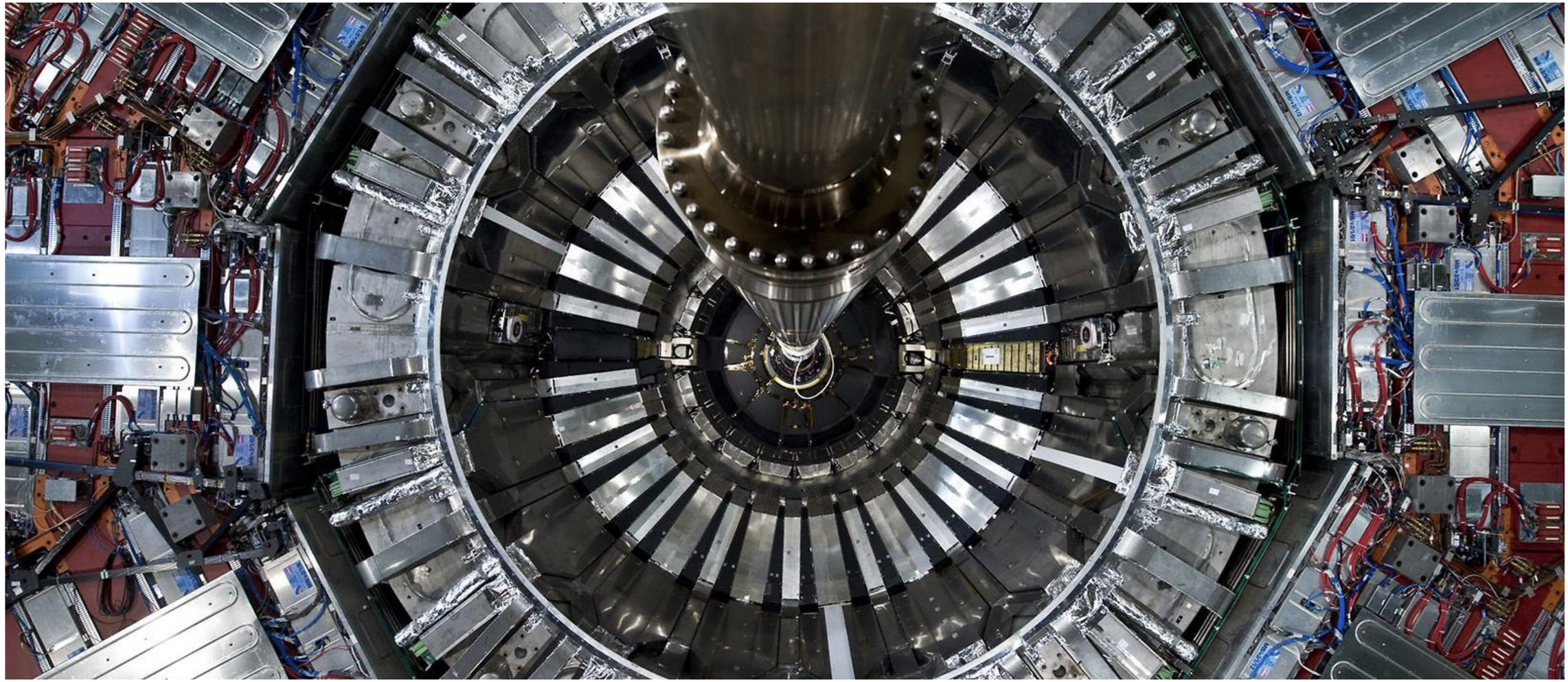


Talk Outline

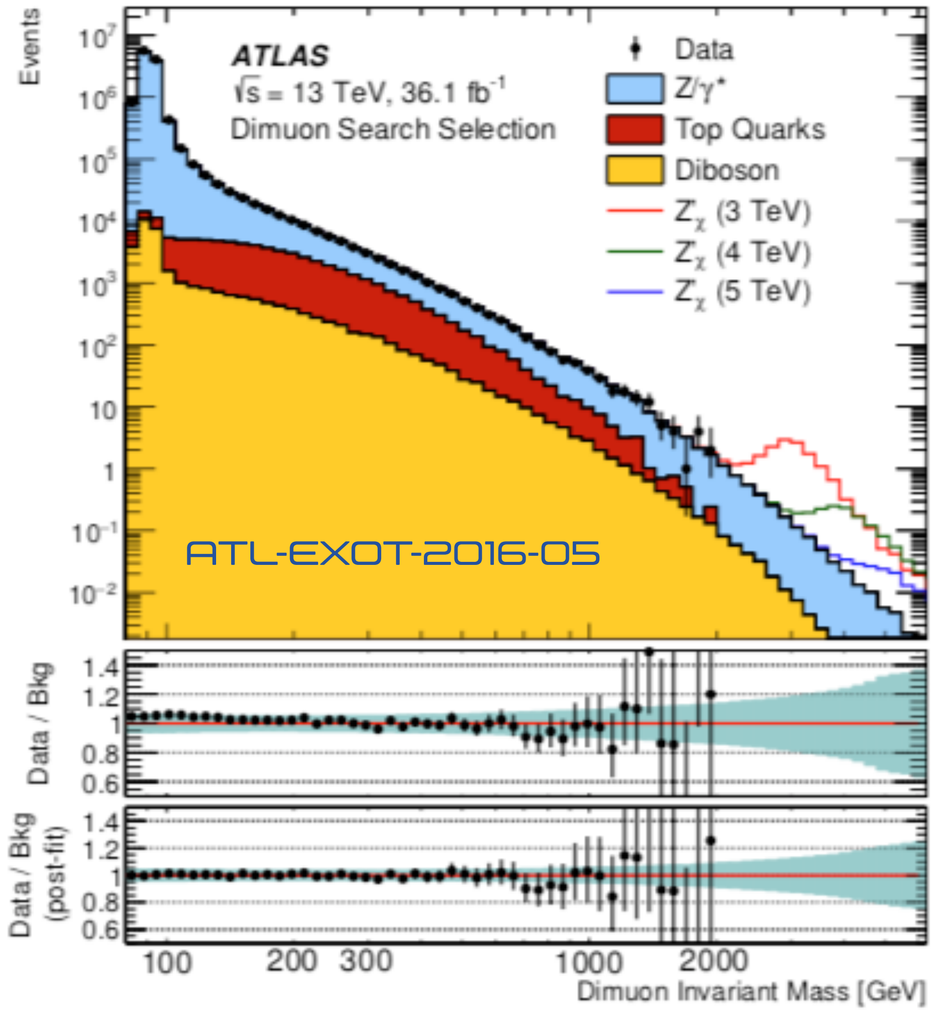
- *In the rest of this talk, I will give some highlight example of how BSM searches @LHC evolved*
- *I will not discuss the implications of LHCb anomalies (dedicated flavor session)*
- *I will then cover new strategies to extend our reach, to give you a sense of what is happening and could happen in the future*
- *CAVEAT: the picture is much broader than what I can discuss in 30 minutes*



Run II Highlights: Resonances

From heavy to light

- ***ATLAS and CMS were designed (also) to probe the TeV scale***
- *We did very well in searching for TeV objects*
- *Even if we often assume narrow width, mass-peak searches have potential to wide resonances*
- *Other techniques allow to probe wide resonances beyond the bump-hunt scenario*



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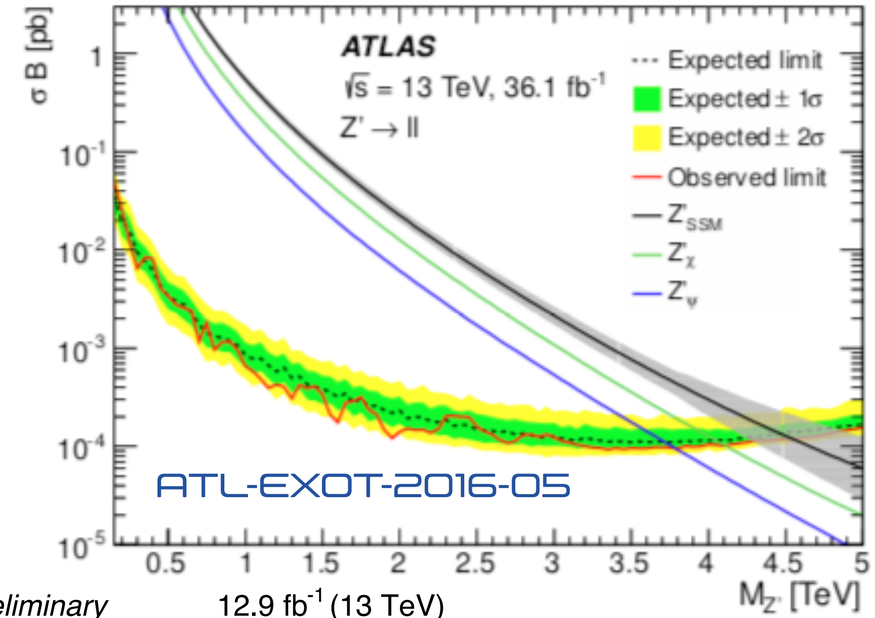

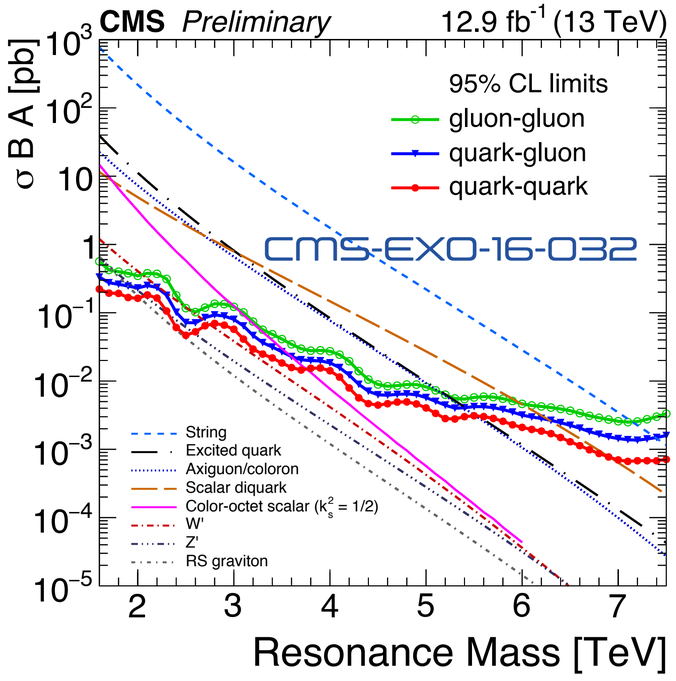

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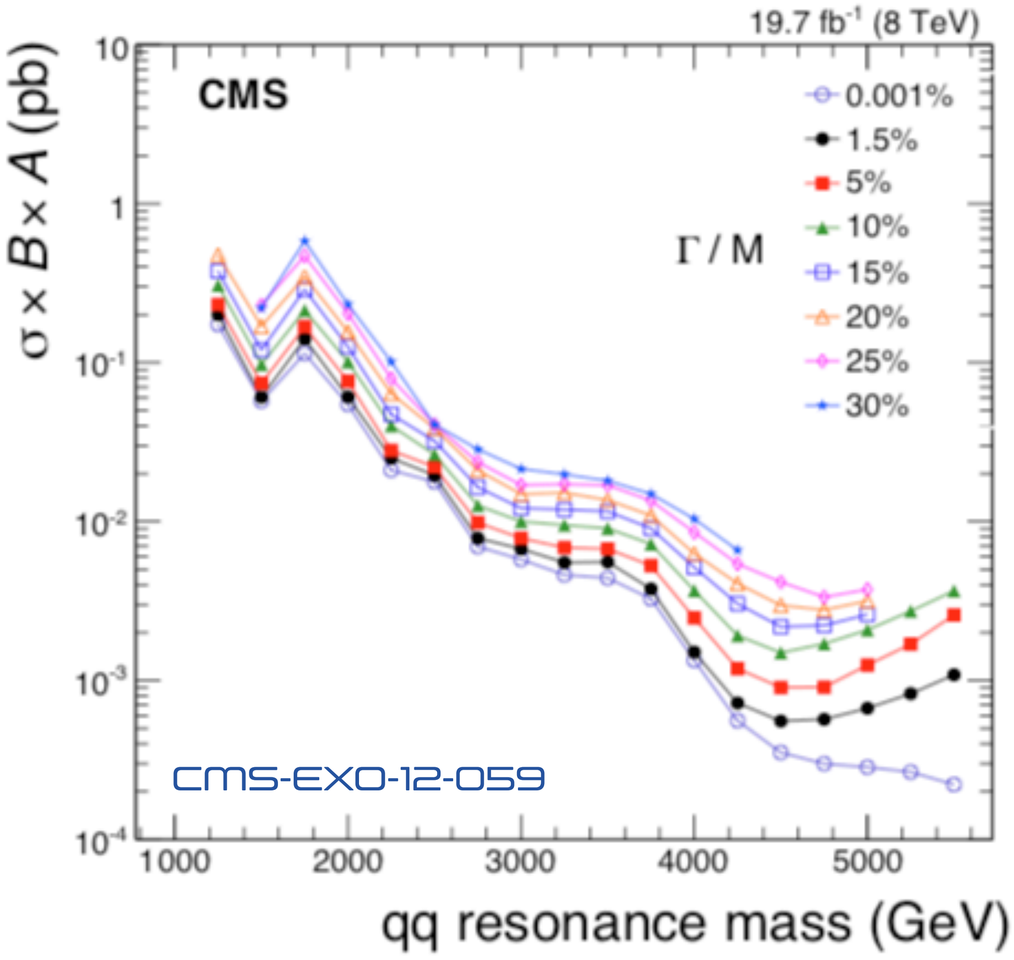
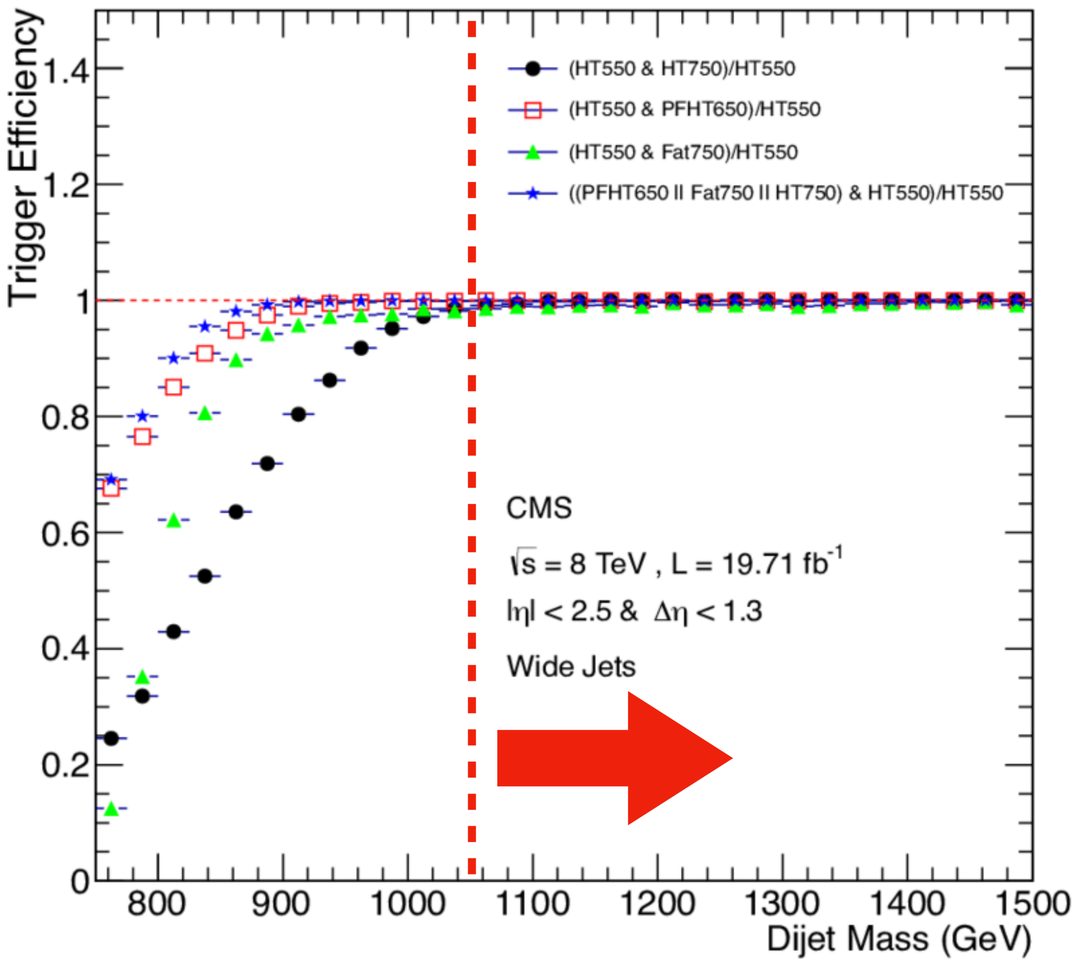


Factor ~5 sensitivity loss for 30% width. Still, some sensitivity retained

light Z'→qq with ISR recoil

- ***Extending these searches to the small-mass/small-coupling regime implies dealing with trigger constraints***
- *To overcome this, analyses are moved to X+ISR final states (e.g., jet, γ)*
- *Selecting high-pT ISR recoil allows to use standard triggers*
- *Forcing the X→qq system in a boosted regime allows better S/B thanks to jet substructure*



These days, we run HT triggers with threshold ~ 900 GeV

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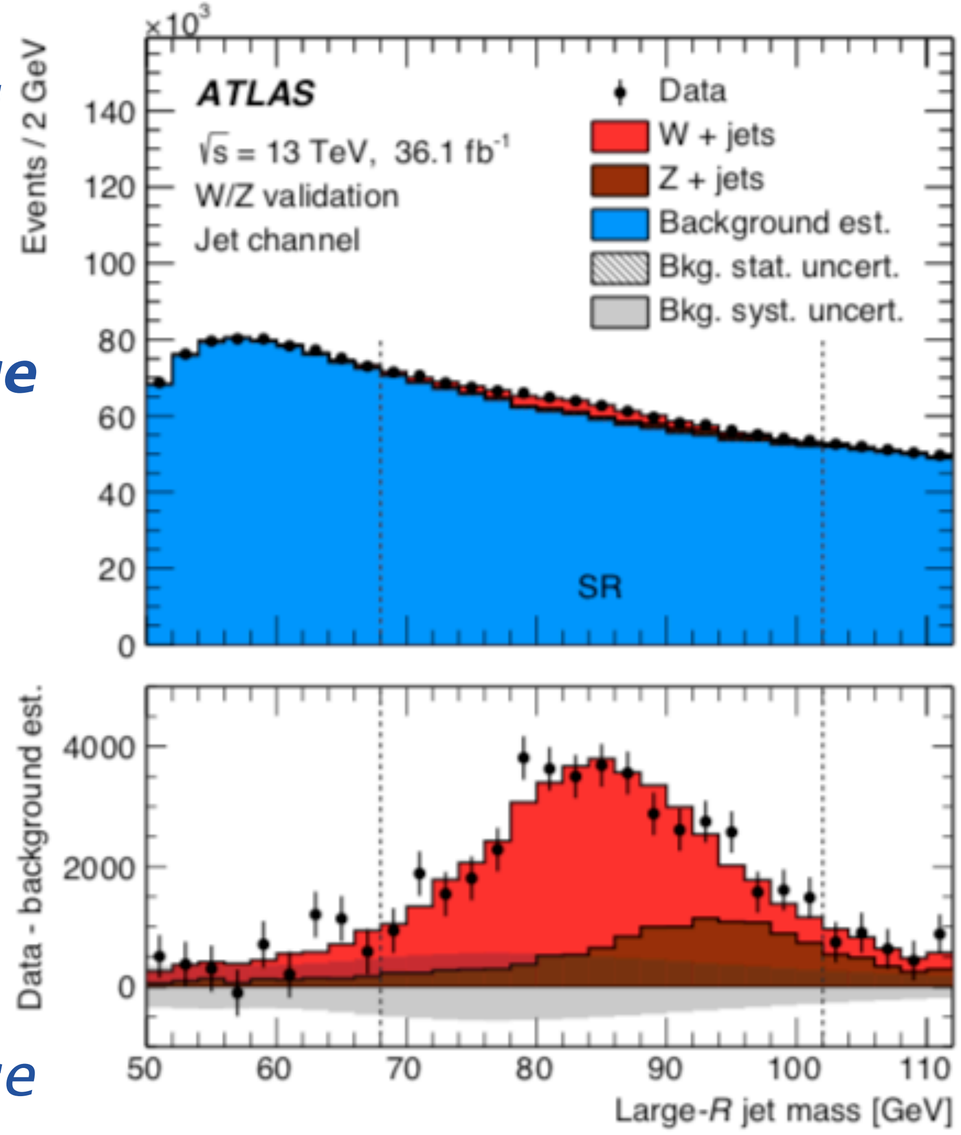

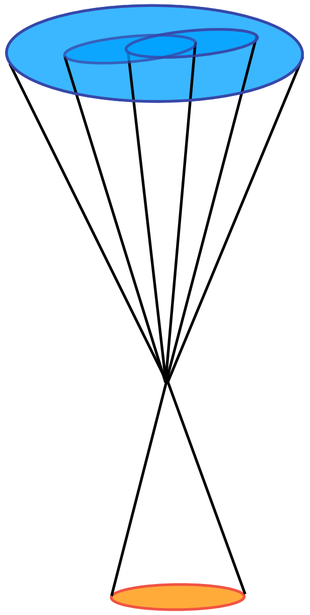

ATL-EXOT-2017-01

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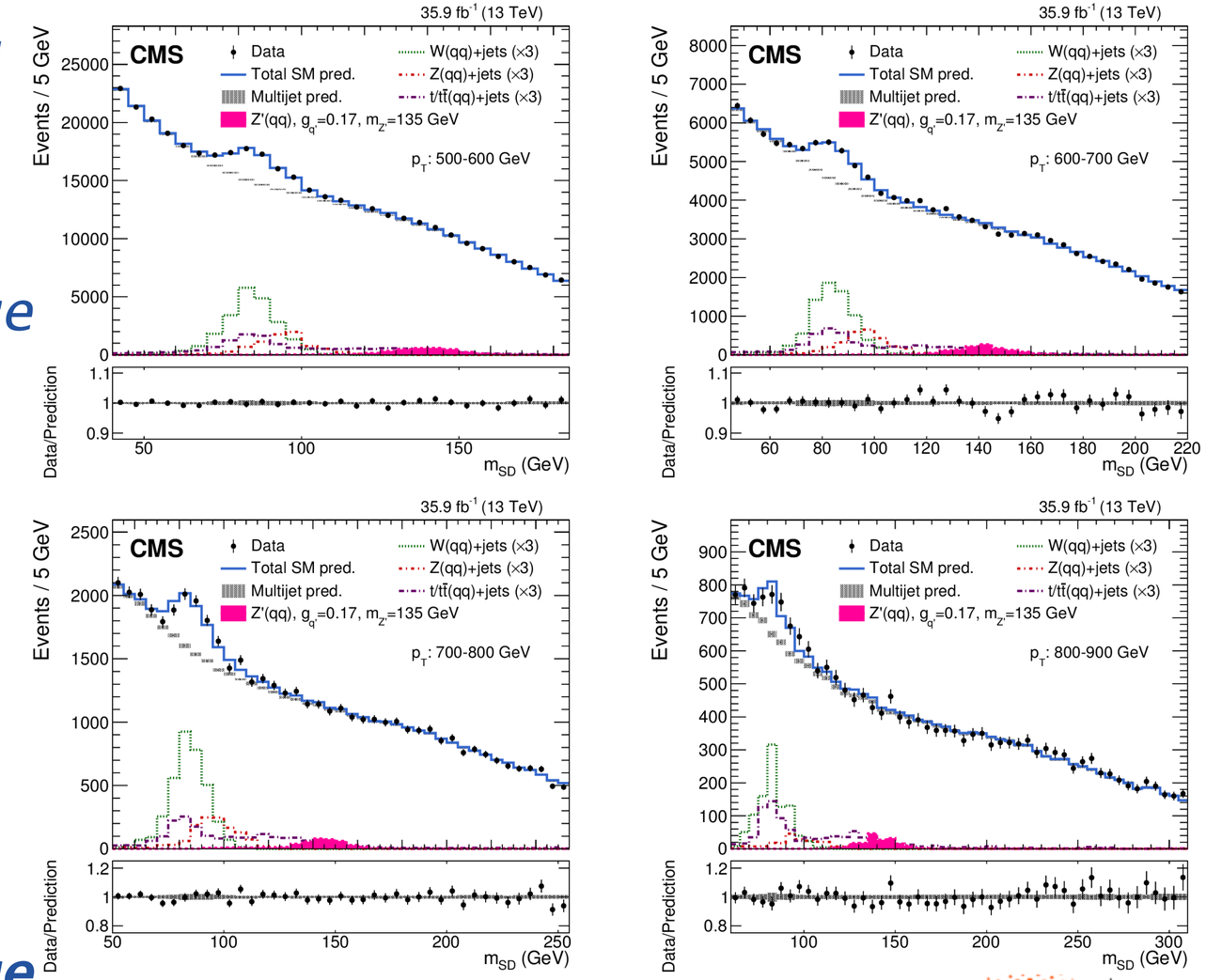
CMS-EXO-17-001



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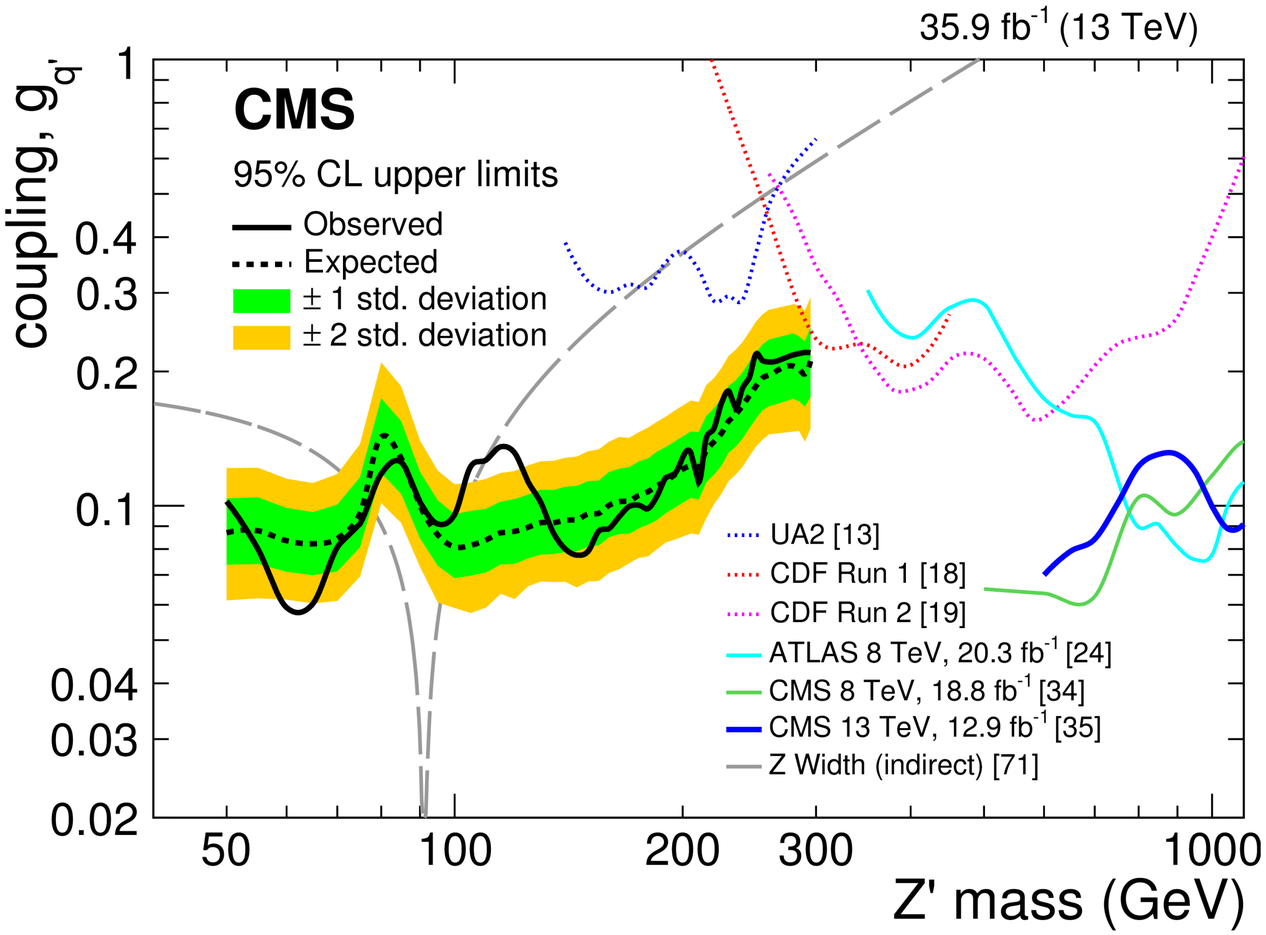
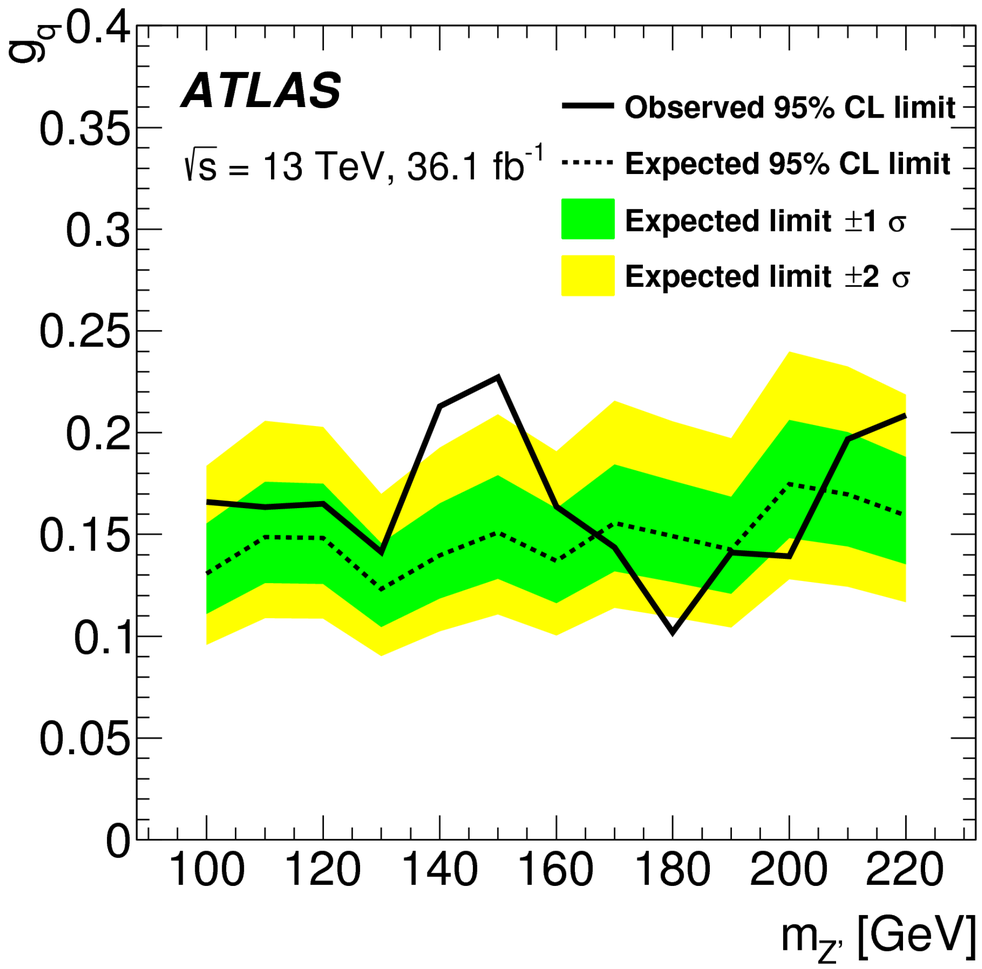
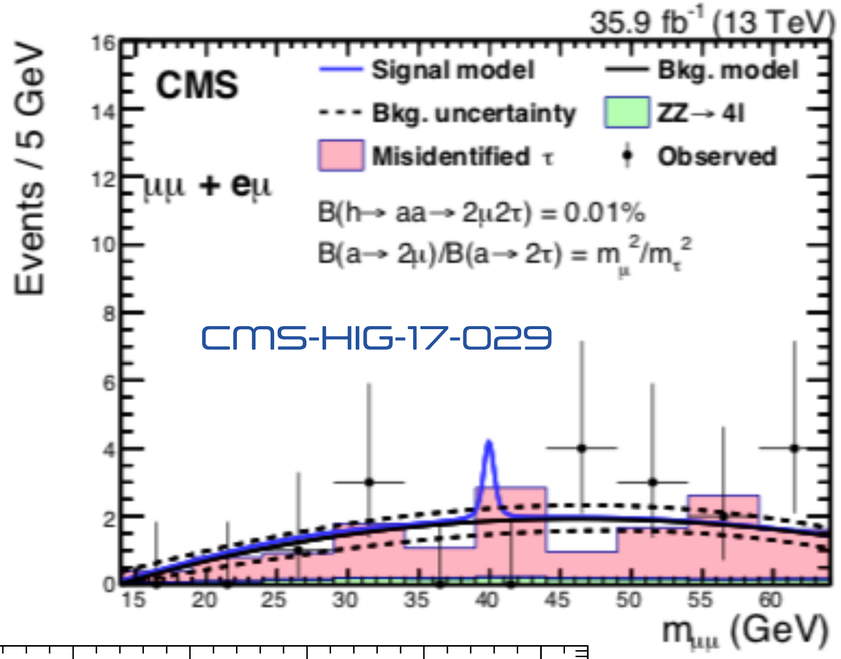
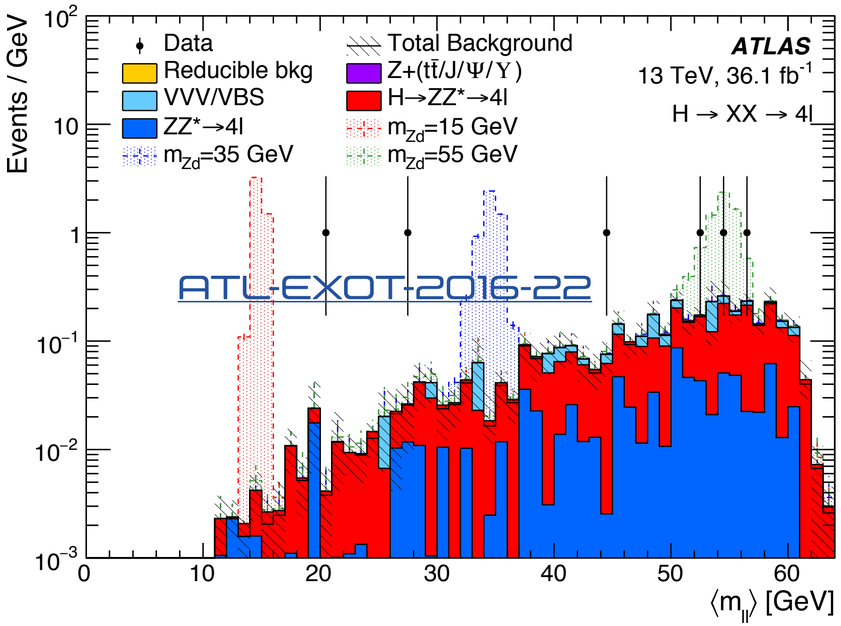




Dark Photons

- ***With muons, one can even go lower in momentum, exploiting multiple production mechanisms (e.g., for dark photons)***
  - *at ATLAS/CMS, looking for pair production, production from H decays, etc*
  - *at LHCb, looking for prompt production, thanks to detector geometry, rapidity region, high-rate trigger capabilities, and the sensitivity to displaced objects*





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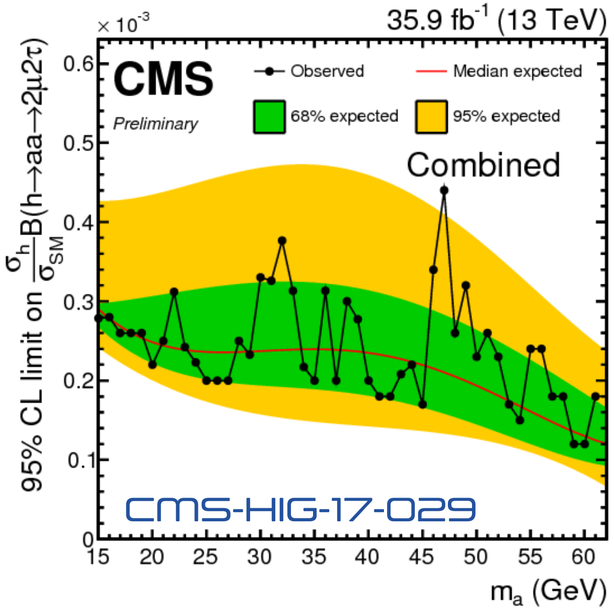

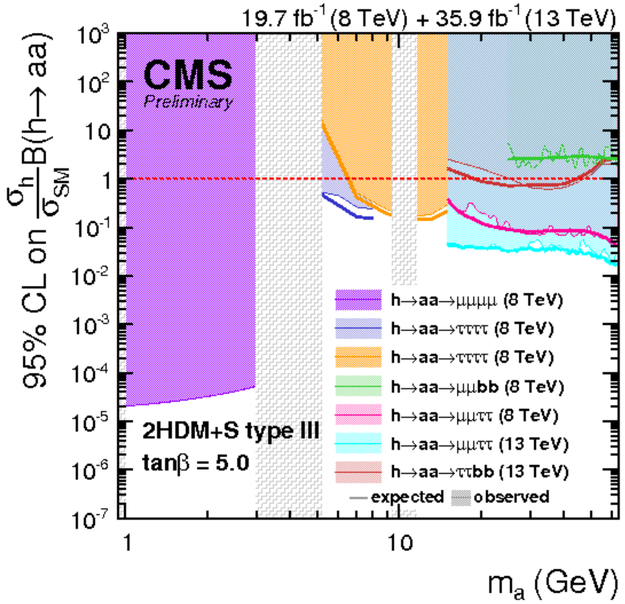

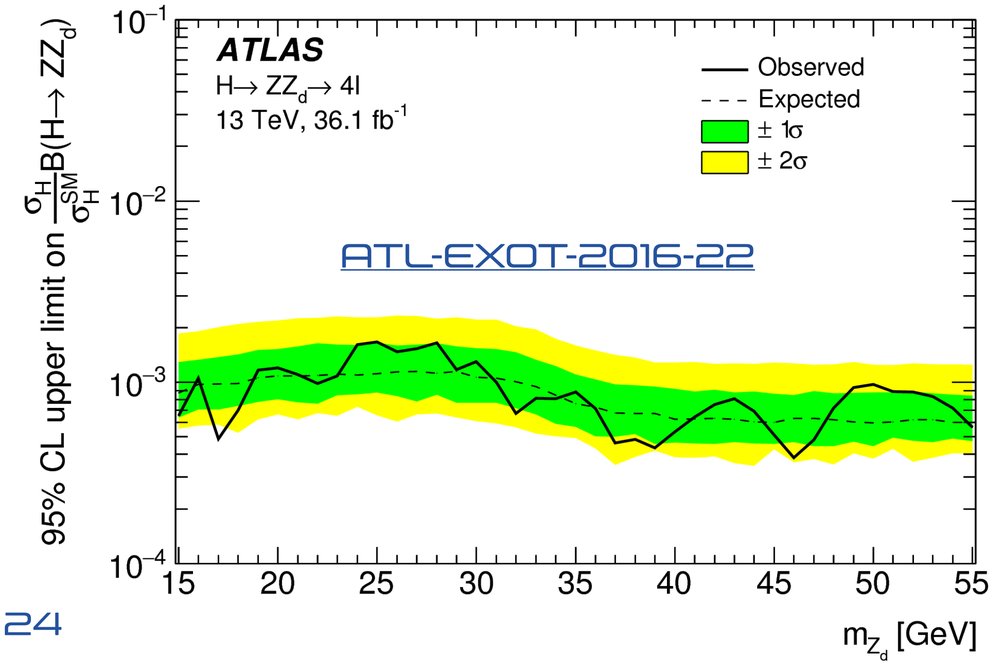

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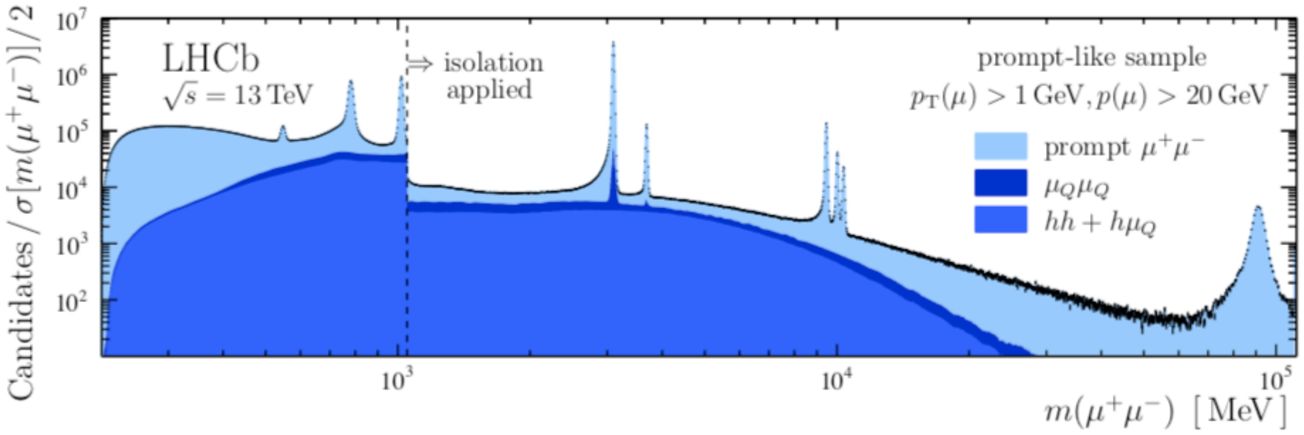
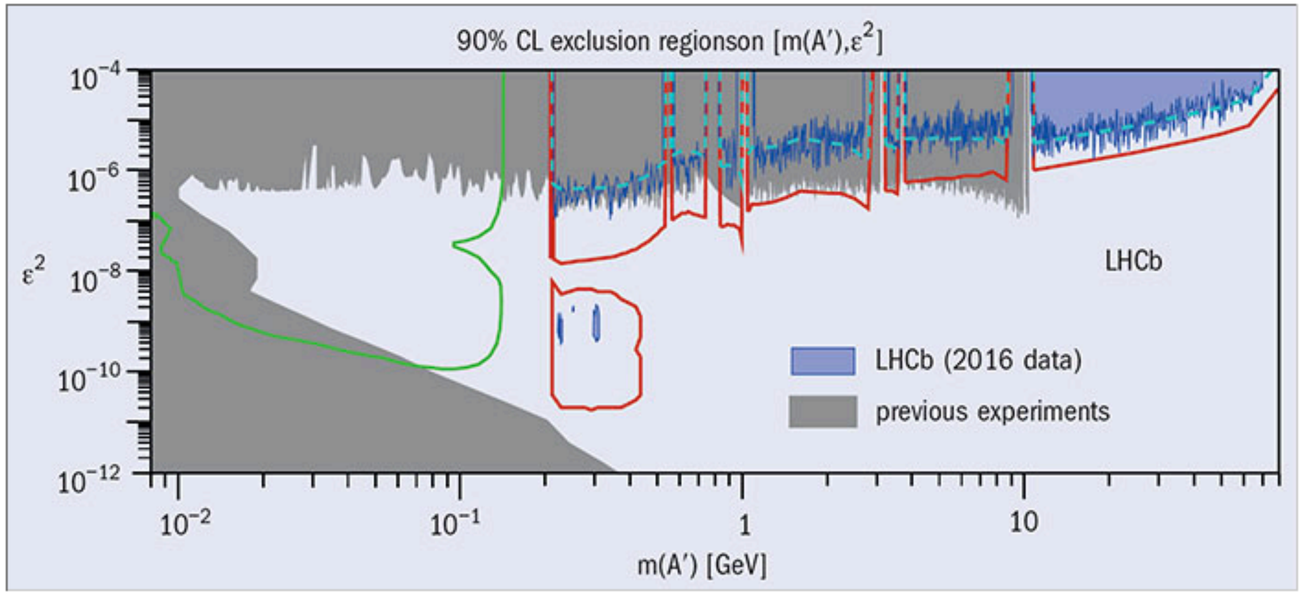
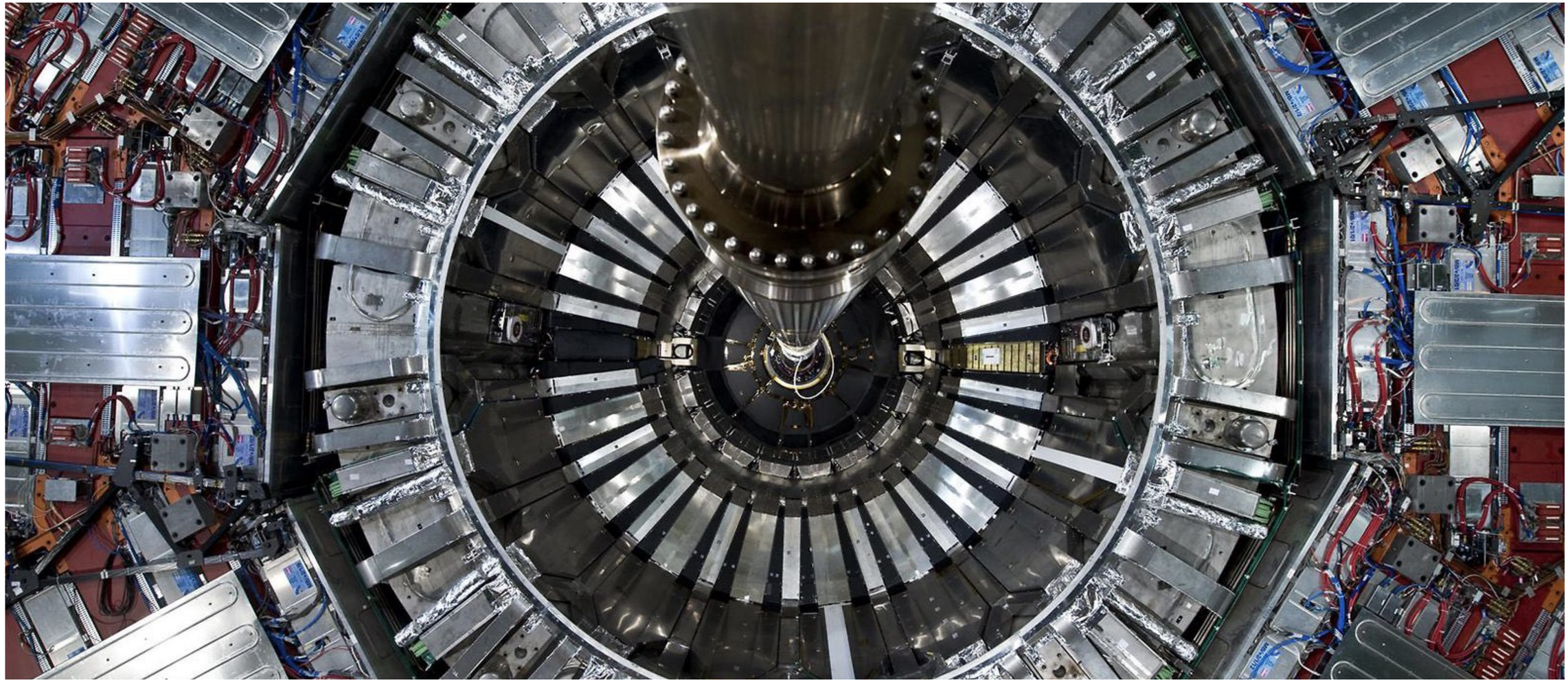




Comparison of the new LHCb results to existing constraints from previous experiments. Red and green curves show the predictions from LHC Run 3, while the dashed cyan curve is the prediction rescaled to the 2016 data sample.

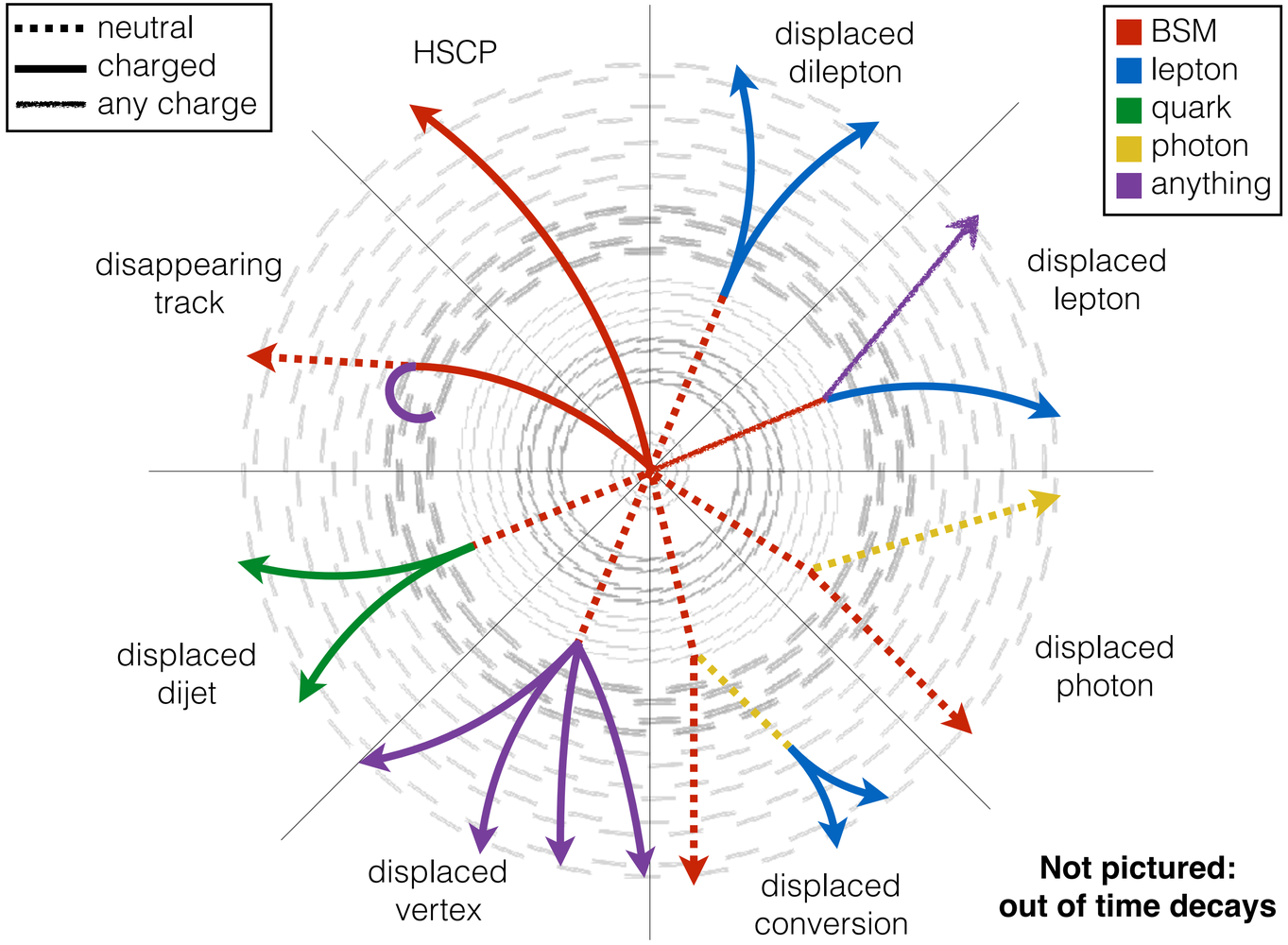
LHCb-PAPER-2017-038



Run II Highlights: long-living particles

What a LLP looks like in a detector

- ***Signatures can be very tricky***
- *Depending on the lifetime, different detector components are involved*
- *Some of these detectors cannot be operated in L1 trigger (and sometimes also at HLT)*
  - *Trigger can be a challenge*
  - *More than one analysis is needed for a given model, depending on the parameter space*



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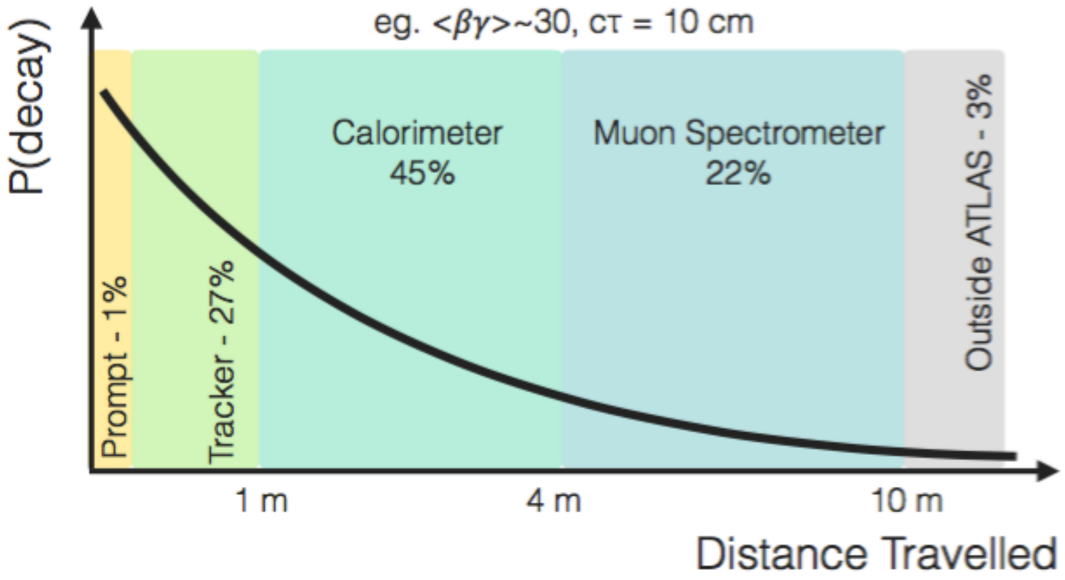
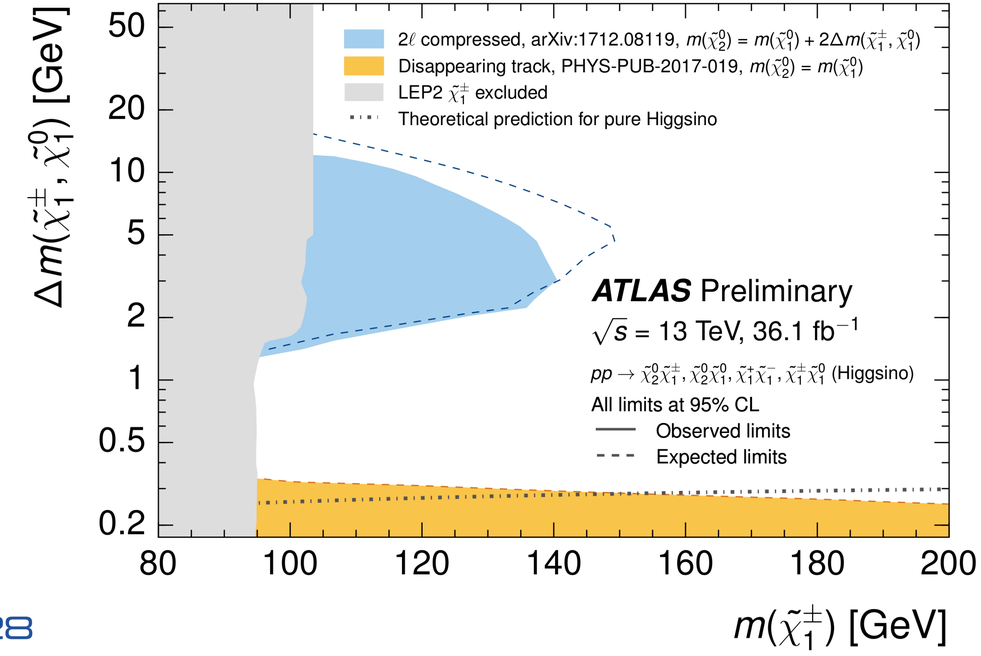
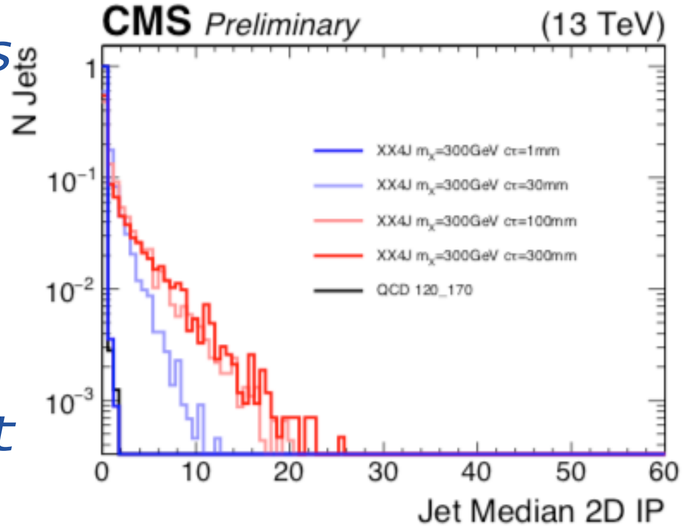


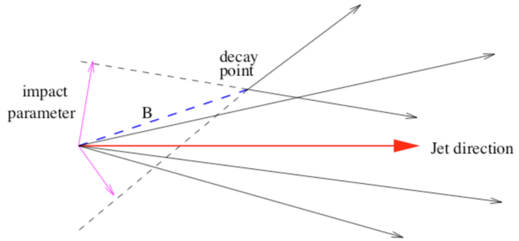


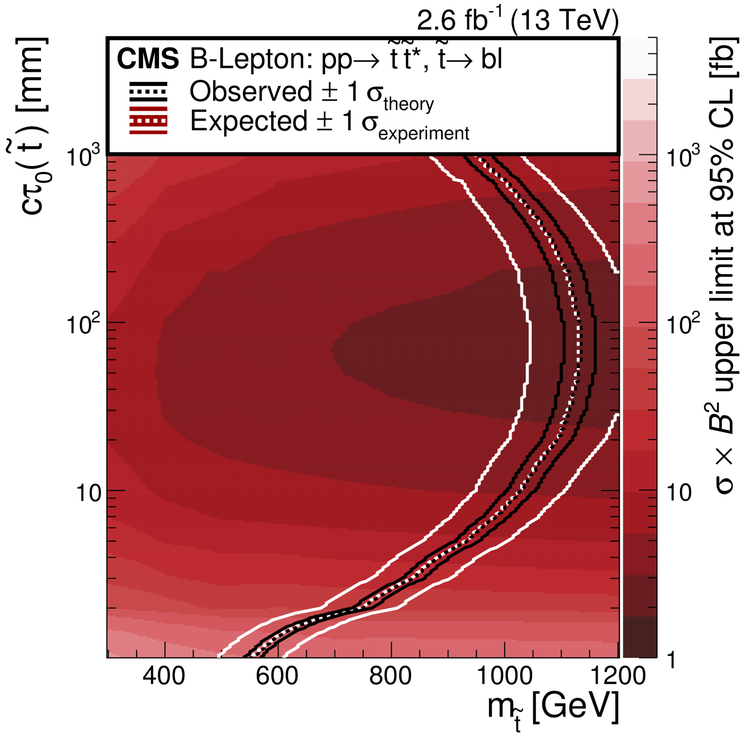
Displaced Jets

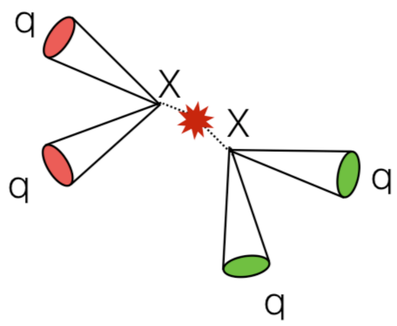
- Reconstruction of displaced jets has very specific challenges
  - physics background from b and τ jets
  - Projective geometry of the jet compromised (problematic e.g. for association of tracks to jets in particle flow)
  - Displacement exploitable in trigger only starting from HLT
- Despite these difficulties, several analyses exist that probe this scenario. Example: inclusive search for displaced-jets events



CMS-EXO-16-003

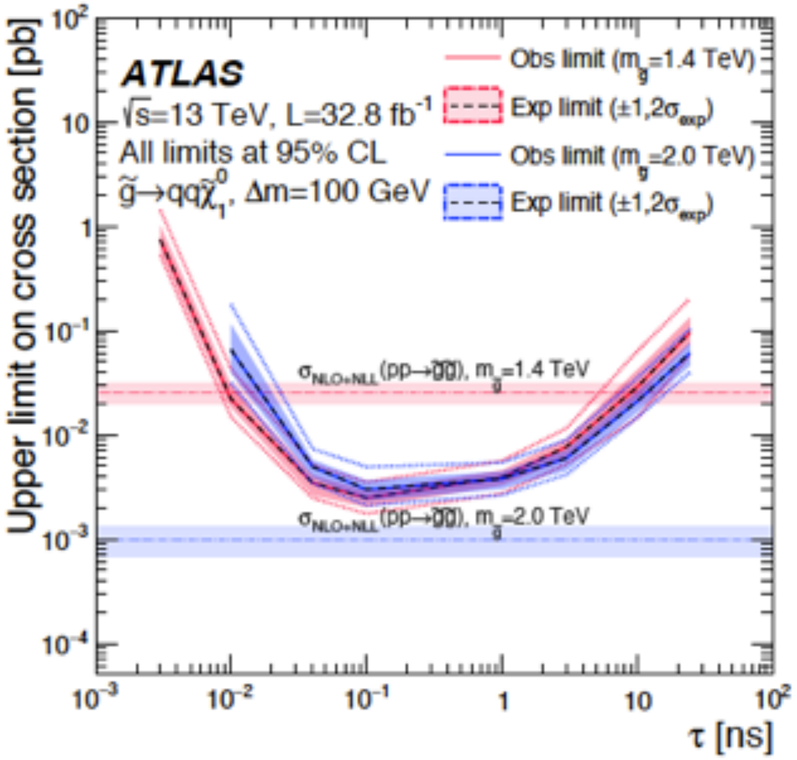


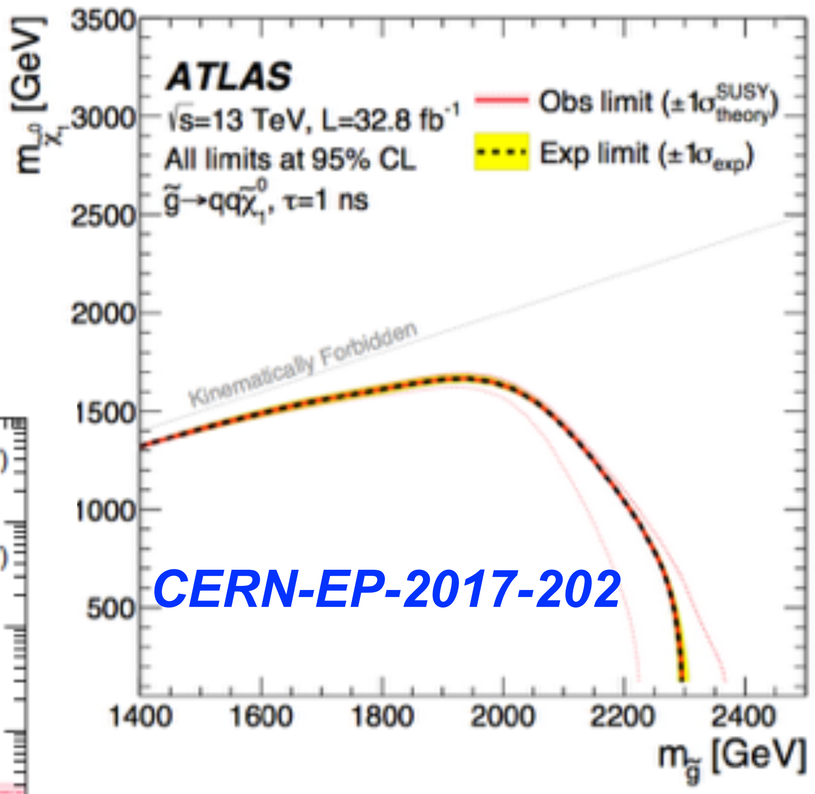




Displaced Vertices

- For smaller lifetimes, displacement becomes typically small
- NP particles would decay in the inner tracker
  - can use pixel vertexing in all its power
  - have physics-induced SM backgrounds to deal with



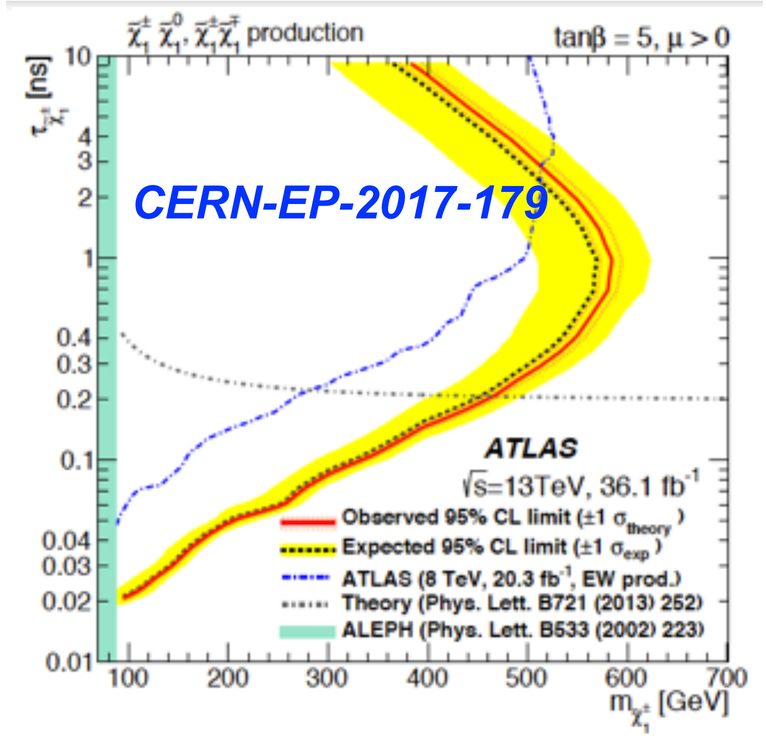


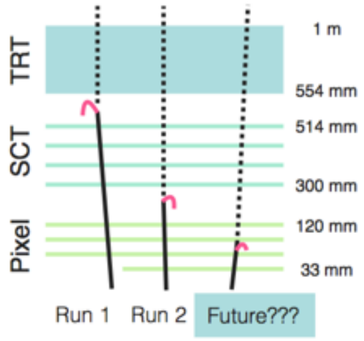
Disappearing Tracks

- *Disappearing tracks happen when*
  - *the LLP comes with charge*
  - *it decays to an invisible particle*
  - *the mass difference is small (i.e., any other decay product is undetectable)*
- *Can be exploited with different detectors, depending on lifetime*
- *That's why it is important to go closer and closer to the beam*

Very clean signature->can be ~ background-free search

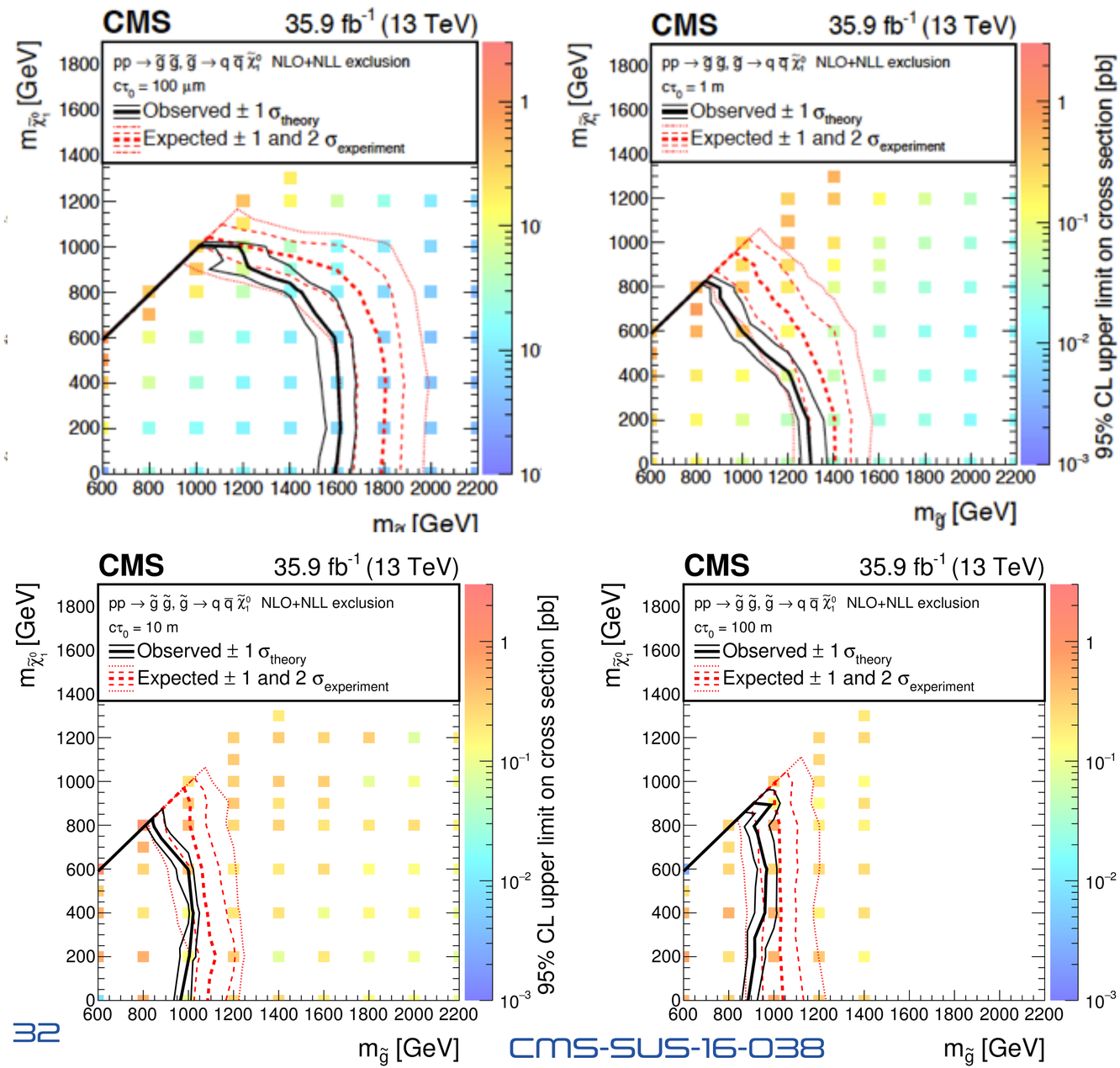
run period	est. event count leptons	fake tracks	total	observation
2015	$0.12^{+0.11}_{-0.08} \pm 0.01$	$0^{+0.079}_{-0}{}^{+0.025}_{-0}$	$0.12^{+0.14}_{-0.08}{}^{+0.03}_{-0.01}$	1
2016B+C	$1.99 \pm 0.42 \pm 0.11$	$0.38 \pm 0.19^{+0.41}_{-0.38}$	$2.38 \pm 0.46^{+0.43}_{-0.40}$	2
2016D-H	$3.07 \pm 0.63 \pm 0.22$	$0.91 \pm 0.35 \pm 0.91$	$3.98 \pm 0.71^{+0.93}_{-0.94}$	4
total	$5.18 \pm 0.76 \pm 0.25$	$1.3 \pm 0.4 \pm 1.0$	$6.48 \pm 0.86 \pm 1.03$	7



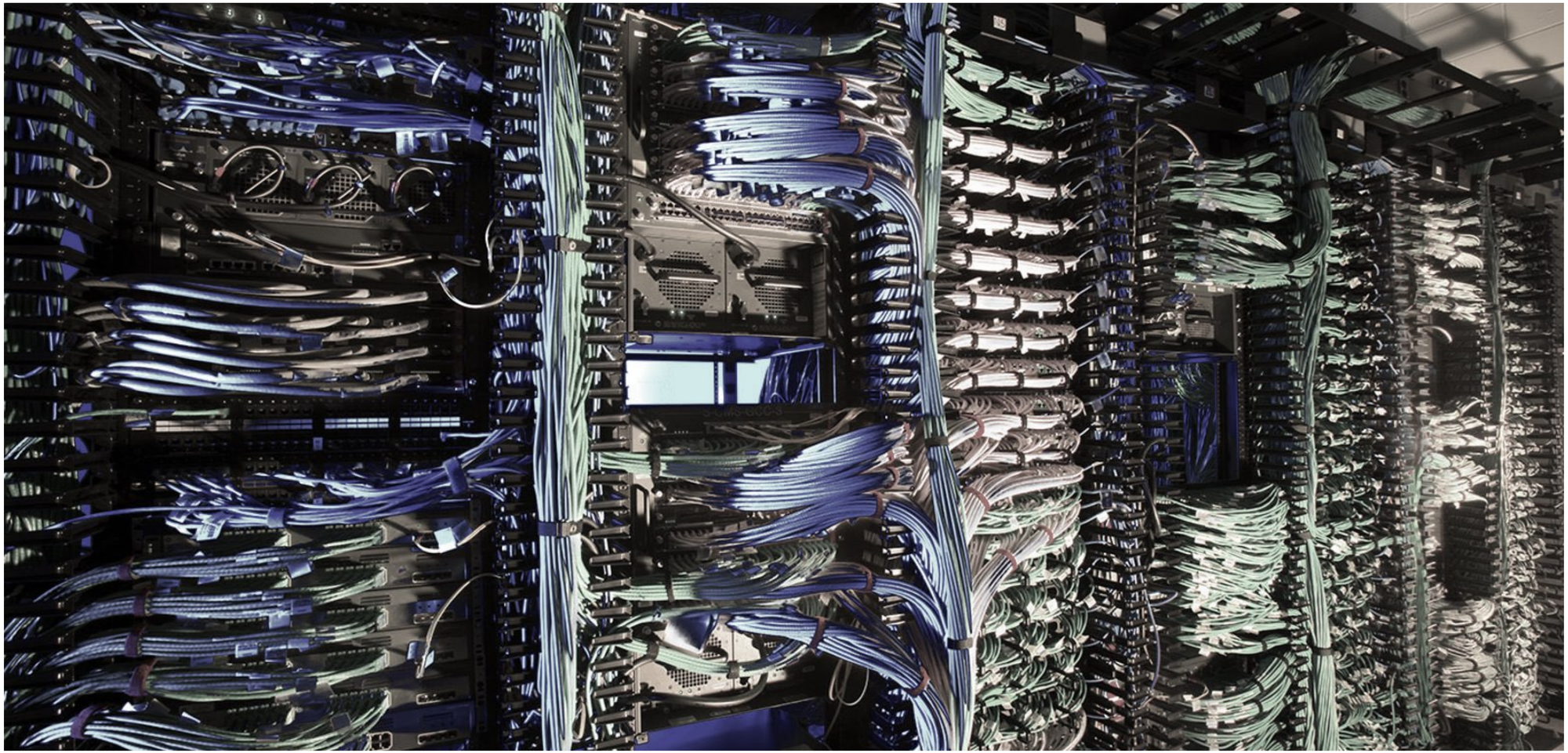


Reinterpreting Prompt Searches

- *Prompt analyses are sensitive to small displacements (i.e., to small lifetime)*
- *This is why some traditional prompt analysis was recasted to long-living particle scenarios*
- *The result is already good in probing large portion of parameter space*
- *The deterioration of sensitivity with lifetime is less pronounced than what would expect*



CMS-SUS-16-038

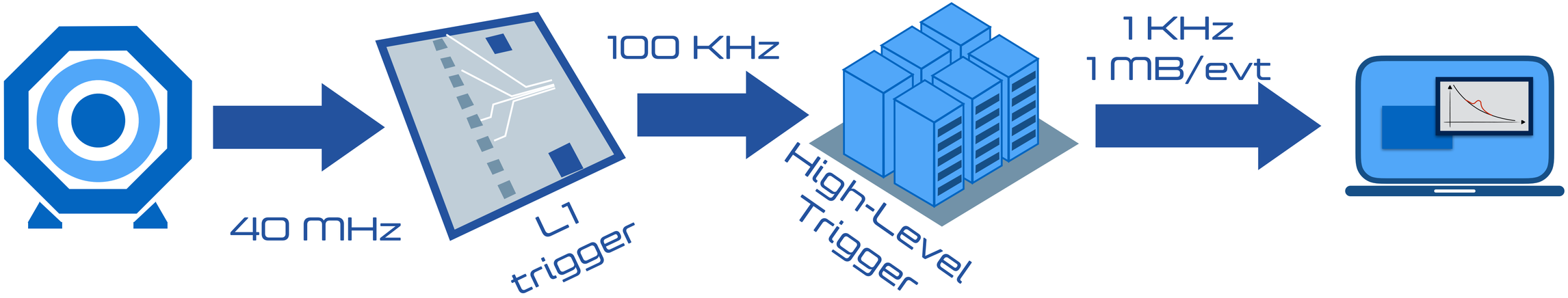


Searching for New Physics in the trigger system

European Research Council

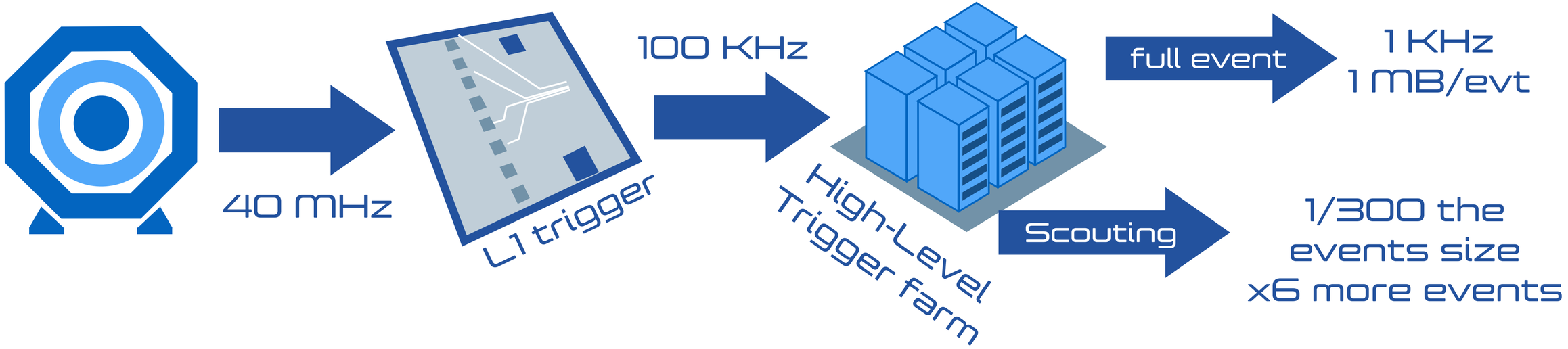
The Trigger Problem

- *Too many data, too large data → need to filter online*
- *Filters based on pheno bias: **we might be loosing good events***



- *L1 trigger: local, hardware based, on FPGA, @experiment site*
- *HLT: local/global, software based, on CPU, @experiment site*
- *Offline: global, software based, on CPU, @CERN T0*
- *Analysis: user-specific applications running on the grid*

Doing more with less



Real-time new physics search with large datasets

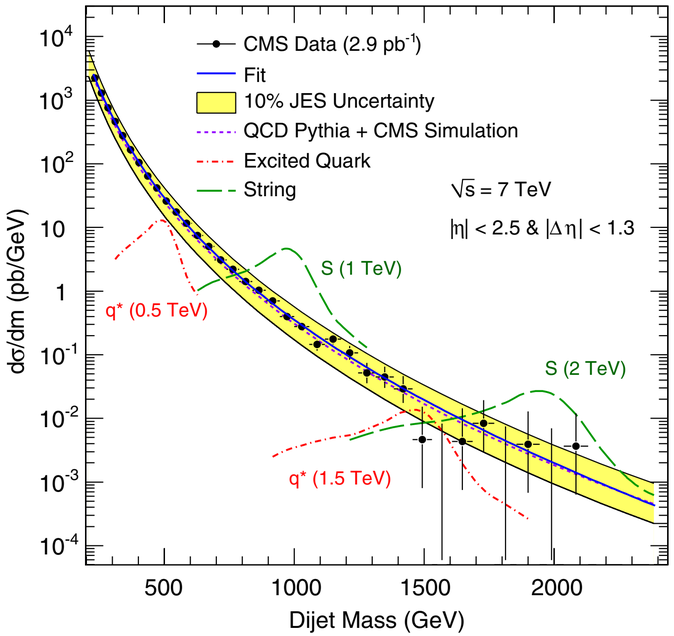
- *Run reconstruction in the trigger farm*
- *Avoid resource limitations: write less information (a few floats) for more events*
- *Probes unexplored territory, previously left behind*

Problem: practical (so far) only for specific topologies

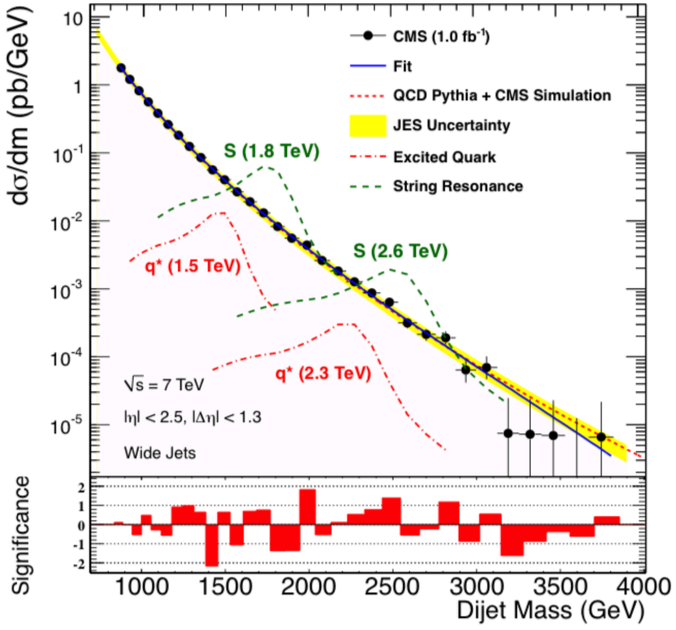
Why did we do this?

- In Run I, dijet search was the first BSM analysis published by CMS
  - Quick improved results from Tevatron in a wide range of mass spectra
  - Quickly forced to reduce mass range under investigation, due to increasing trigger rates vs limited resources
- Scouting was introduced to recover the lost territory (500 to 1100 GeV)

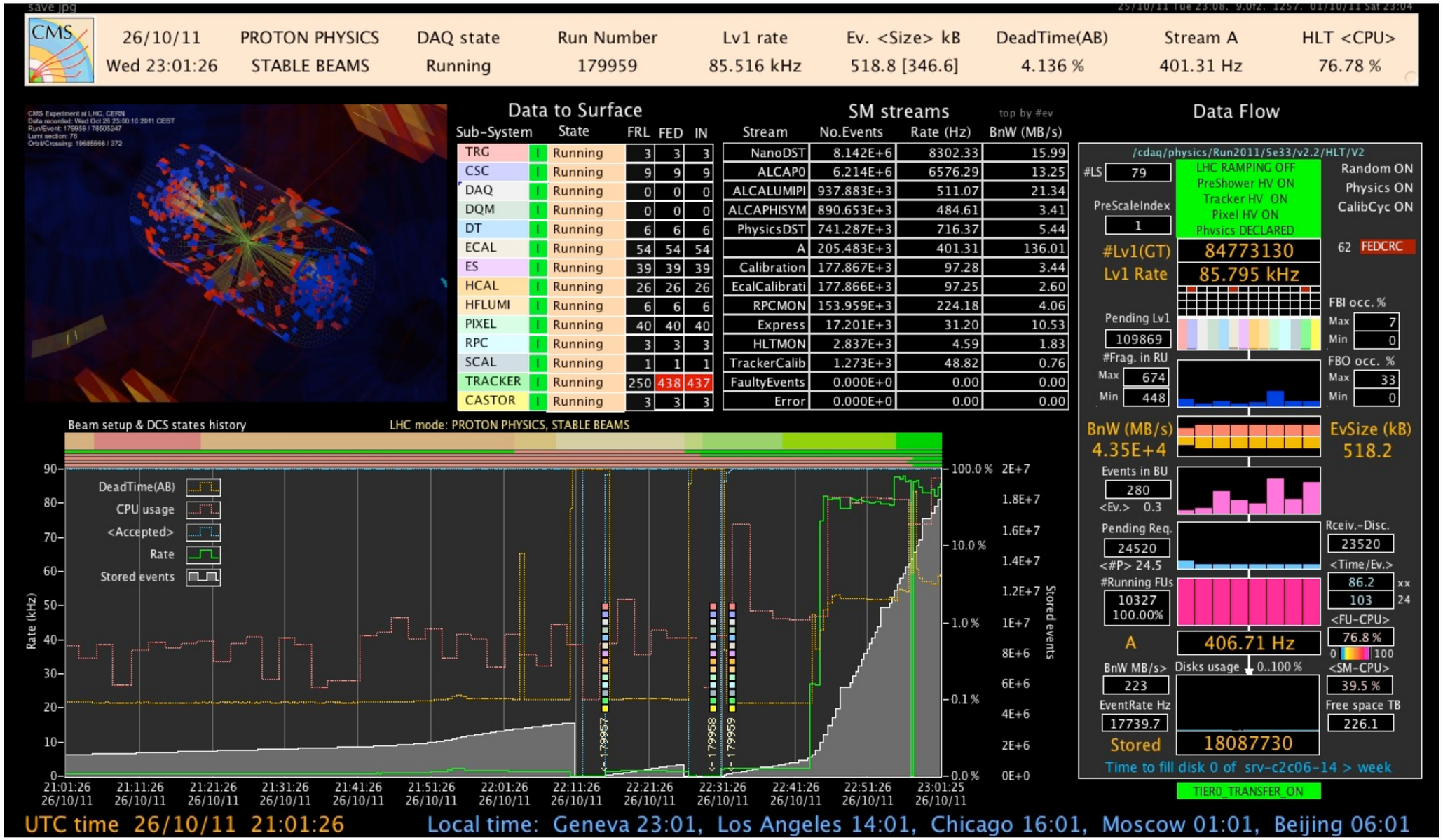
3 pb^{-1} @7 TeV in 2010



1 fb^{-1} @7 TeV in 2011



The first attempt



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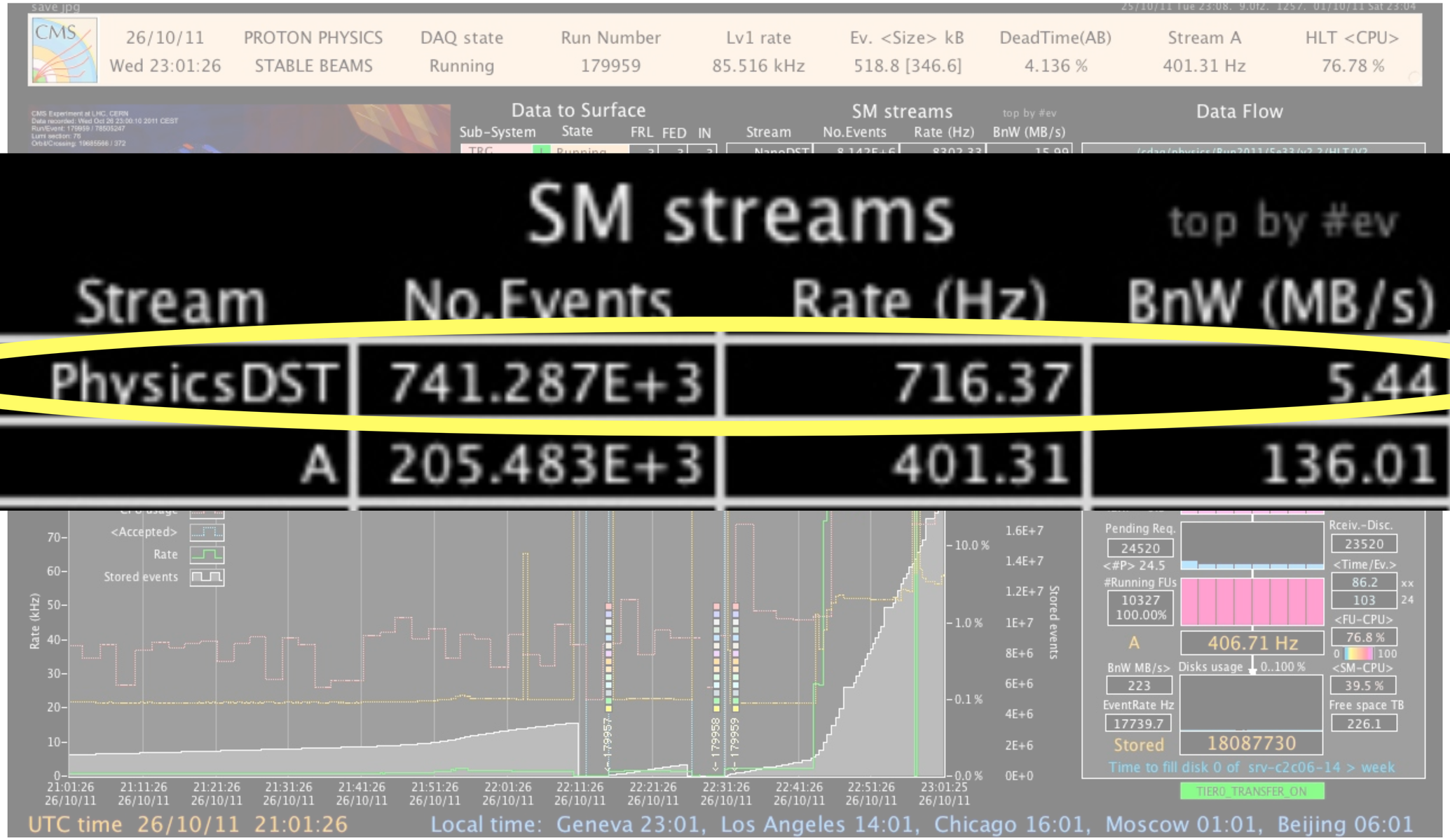
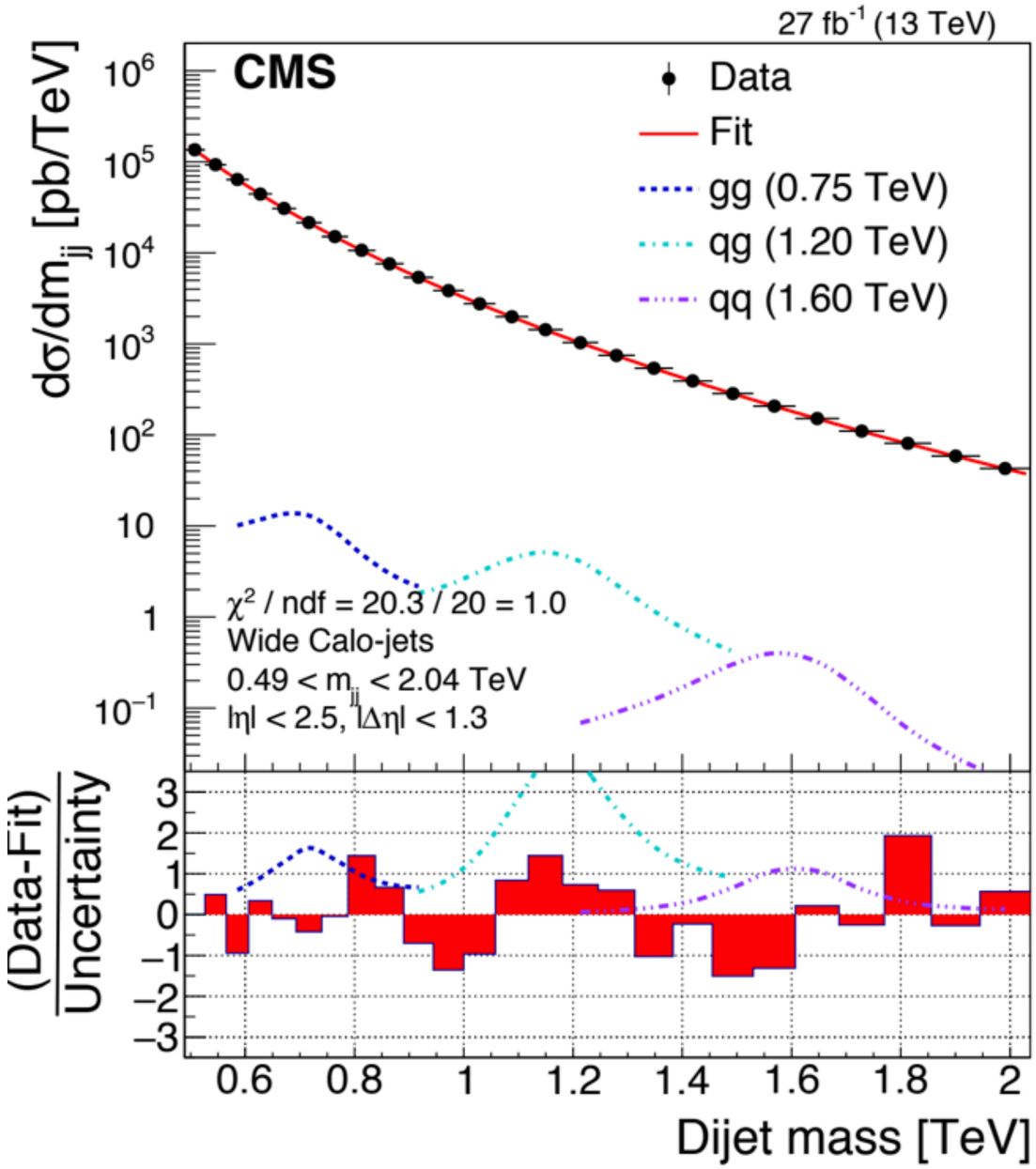


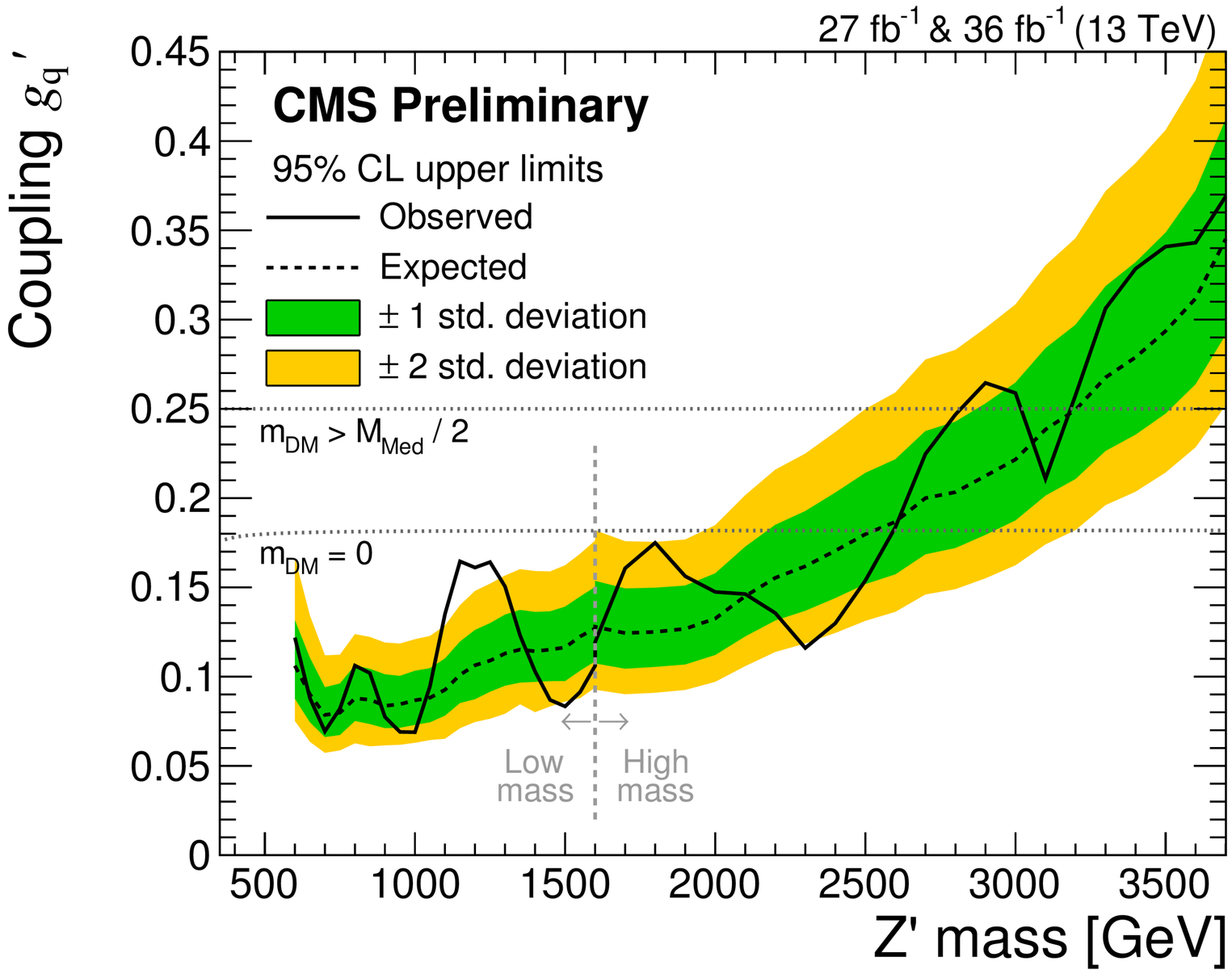
What we accomplished

- *Recovered sensitivity to 500 GeV resonances*
- *Reached limitation of L1 seed-> need to improve our hardware trigger (more on this later)*
- *Now extending the method to more final states (collected x3 more data than the rest of CMS in 2017)*



What we accomplished

- Kept sensitivity to 500-1500 GeV resonances
- Current limitation is L1 efficiency
- Can probe lower couplings by collecting more data



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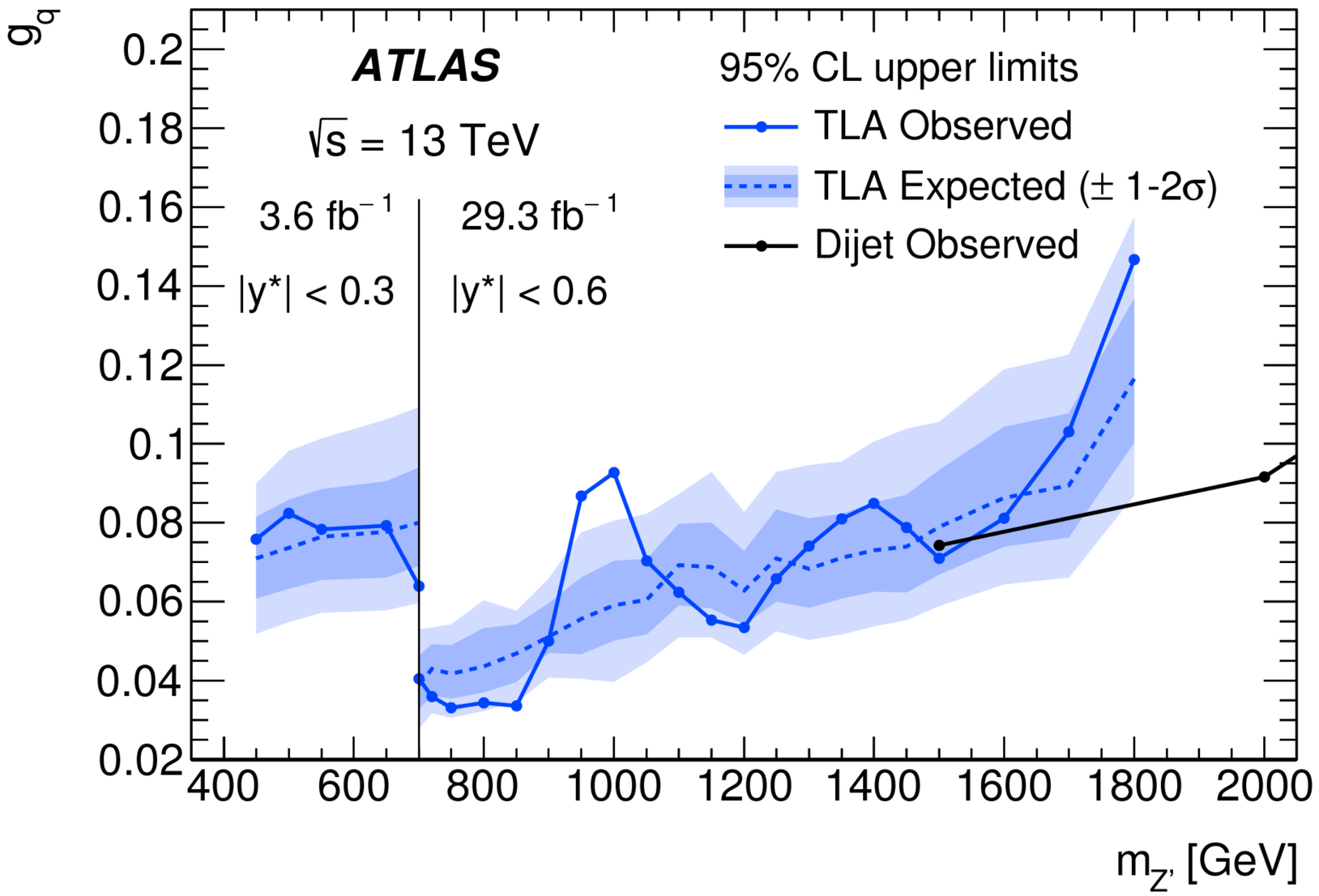

An established approach

International Journal of High-Energy Physics

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CERN COURIER

Nov 13, 2015

CMS data-scouting and a search for low-mass dijet resonances

Proton beams crossed inside each of the CMS and ATLAS detectors 20 million times a second during the 2012 LHC proton–proton run. However, the physics programme of CMS is based on only a small subset of these crossings, corresponding to

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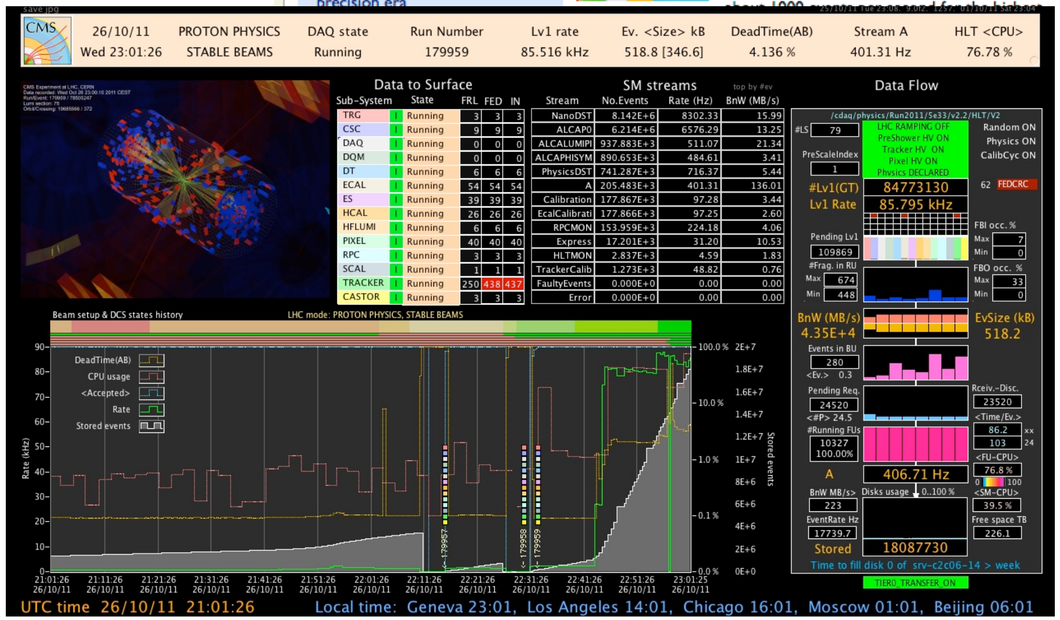


Available on the CERN CDS information server — **CMS PAS EXO-11-094**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-exotica@cern.ch — 2012/07/11

Search for Narrow Resonances using the Dijet Mass Spectrum in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CMS-EXO-14-005

CERN-EP/2016-090
2018/05/15

Search for narrow resonances in dijet final states at $\sqrt{s} = 8$ TeV with the novel CMS technique of data scouting

The CMS Collaboration*

Abstract

A search for narrow resonances decaying into dijet final states is performed on data from proton-proton collisions at a center-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 18.8 fb^{-1}. The data were collected with the CMS detector using a novel technique called data scouting, in which the information associated with these selected events is much reduced, permitting collection of larger data samples. This technique enables CMS to record events containing jets at a rate of 1 kHz, by collecting the data from the high-level-trigger system. In this way, the sensitivity to low-mass resonances is increased significantly, allowing previously inaccessible couplings of new resonances to quarks and gluons to be probed. The resulting dijet mass distribution yields no evidence of narrow resonances. Upper limits are presented on the resonance cross sections as a function of mass, and compared with a variety of models predicting narrow resonances. The limits are translated into upper limits on the coupling of a leptophobic resonance Z'_B to quarks, improving on the results obtained by previous experiments for the mass range from 500 to 800 GeV.

Submitted to Physical Review Letters

arXiv:1604.08907v1 [hep-ex] 29 Apr 2016

Abstract

r new particles decaying to a pair of jets in pp collisions at
ample for events with dijet invariant mass above 0.9 TeV cor-
ted luminosity of 5 fb^{-1} collected by the CMS detector at the
d the sensitivity in the 0.6–0.9 TeV range, a complementary
erformed employing a special dataset with reduced event con-
an integrated luminosity of 0.13 fb^{-1} and collected in the last
king period. We set specific lower limits on the mass of string
arks, axigluons, colorons, s8 resonances, E_6 diquarks, W′ and
itons in the 0.6–4.3 TeV range, most of which extend previous
et mass search technique.

European Research Council

An established approach

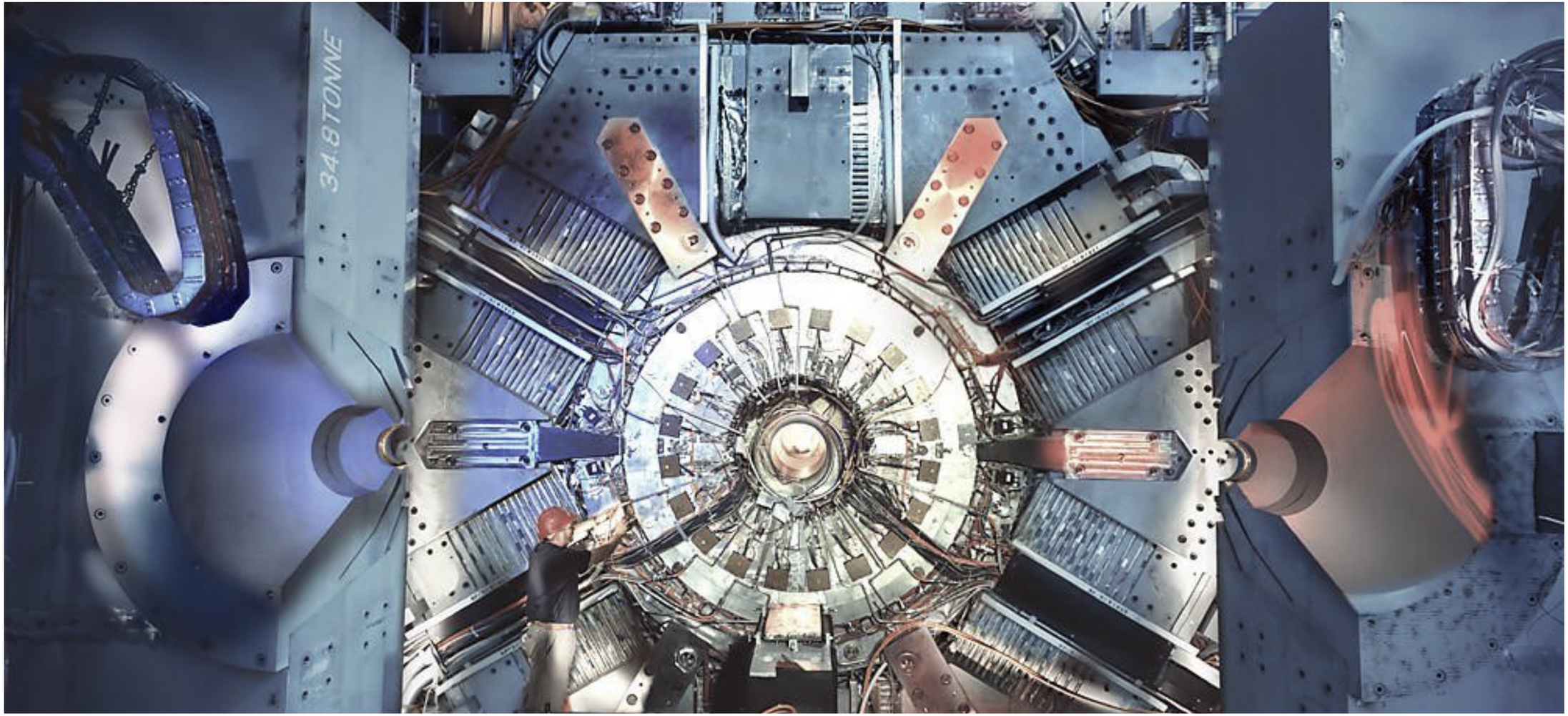
- *CMS uses Scouting since 2011 and now extended it to other final states*
- *LHCb planned during Run I a gradual move to online processing for the full physics program (TurboStream + HLT upgrade for Run III)*
- *ATLAS is producing trigger-level analyses since 2015 (start of Run II)*
- *ALICE is also moving to a real-time processing for Run III*

A direction to explore in order to push sensitivity to new physics beyond the current technical limitations

Conclusions

- *BSM searches deeply evolved since the LHC started*
- *With stringent bounds being put with early data, new analyses focused on more complicated scenarios*
  - *light resonances*
  - *weak couplings*
  - *exotic signatures*
- *So far, we manage to sustain the increasing challenges of the LHC experimental environment*
  - *recovered lost territory with new ideas (e.g., scouting)*
  - *not clear what will happen in the future (HL-LHC poses clear problems with scaling current techniques vs. foreseen computing power)*
- *LHCb flavor anomalies are opening the possibility to surprises*
  - *Synergy between direct searches and indirect constraints*
  - *Focus even more than in the past on 3rd generation*

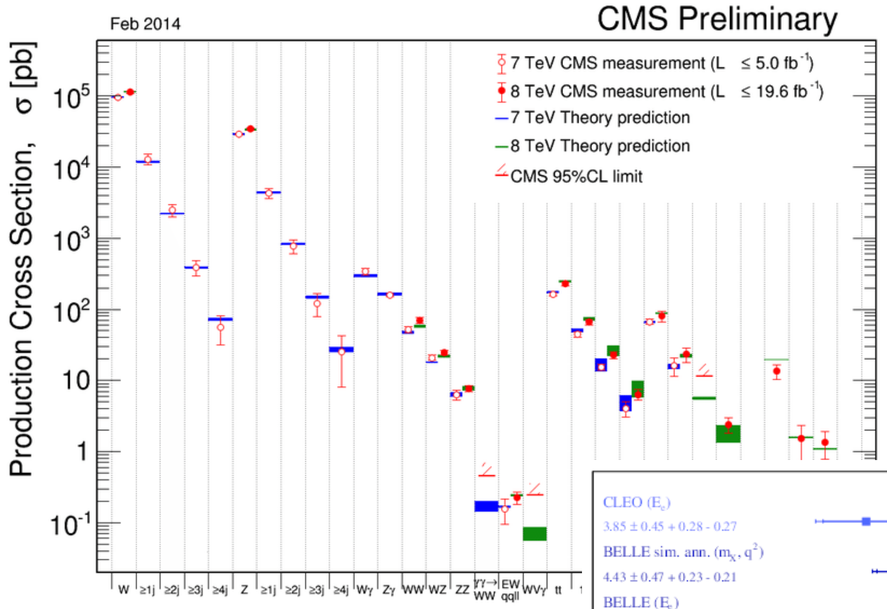
Backup

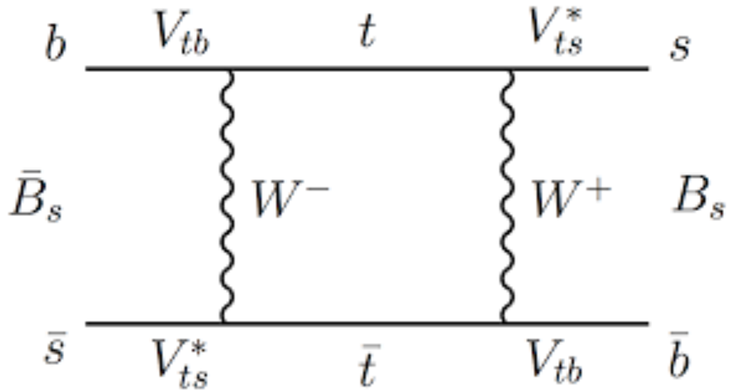


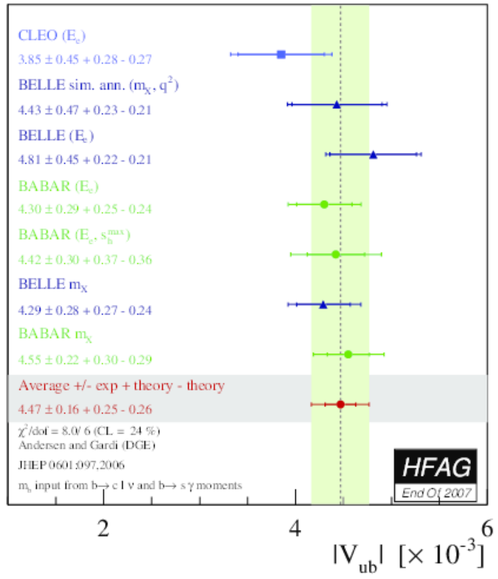
Final remark: the power of precision

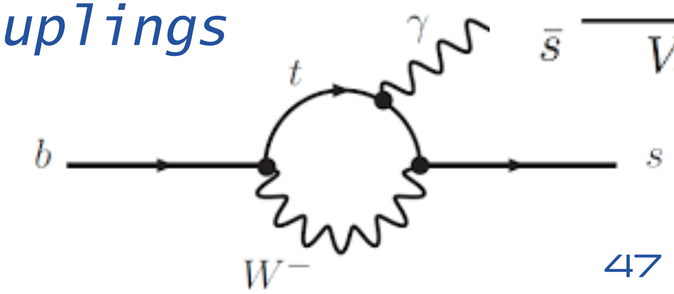
No New physics: surprised?

- *New physics at high scale could also be probed using quantum effects*
  - *heavy particles could "run" in the loops and shift observables vs SM expectation*
  - *This can happen at many levels*
    - *Flavor physics*
    - *EW physics*
    - *Higgs couplings*
    - *…*



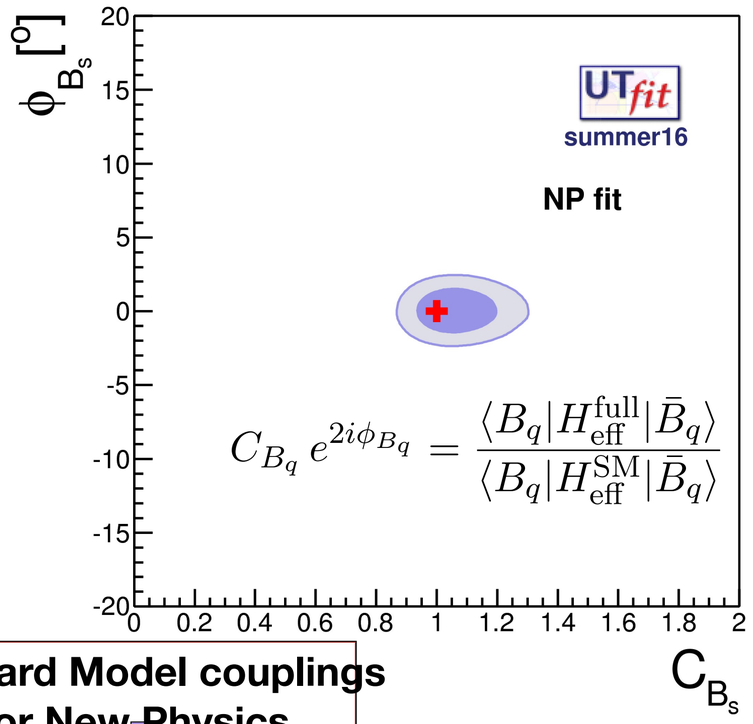


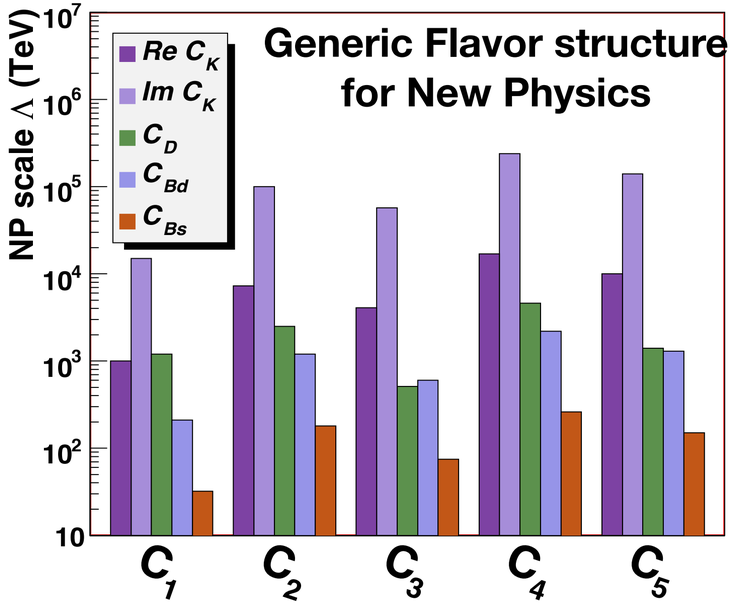


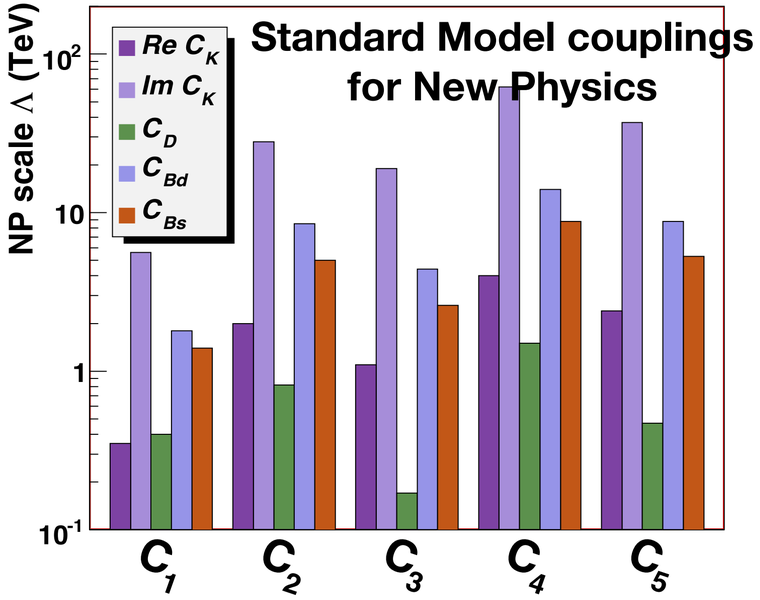


pre-LHC knowledge

- This approach was extensively used before LHC
- If no deviation observed → lower bound on new physics energy scale
  - e.g. Flavor physics (O(10) measurements for 4 parameters)

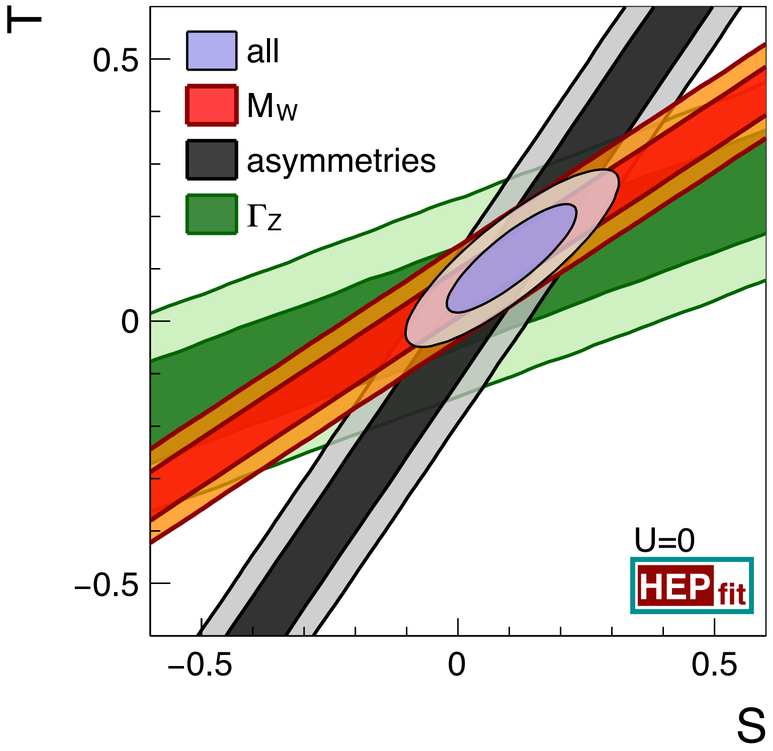


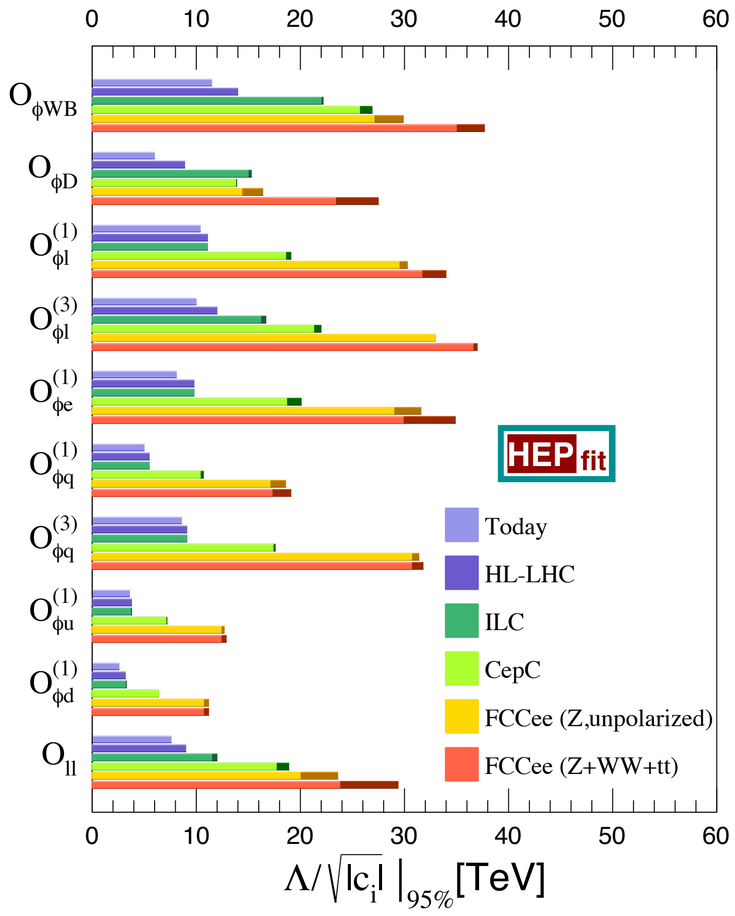




pre-LHC knowledge

- This approach was extensively used before LHC
- If no deviation observed → lower bound on new physics energy scale
  - EW precision: New Physics parameters parameterized in terms of effective form factors





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  r
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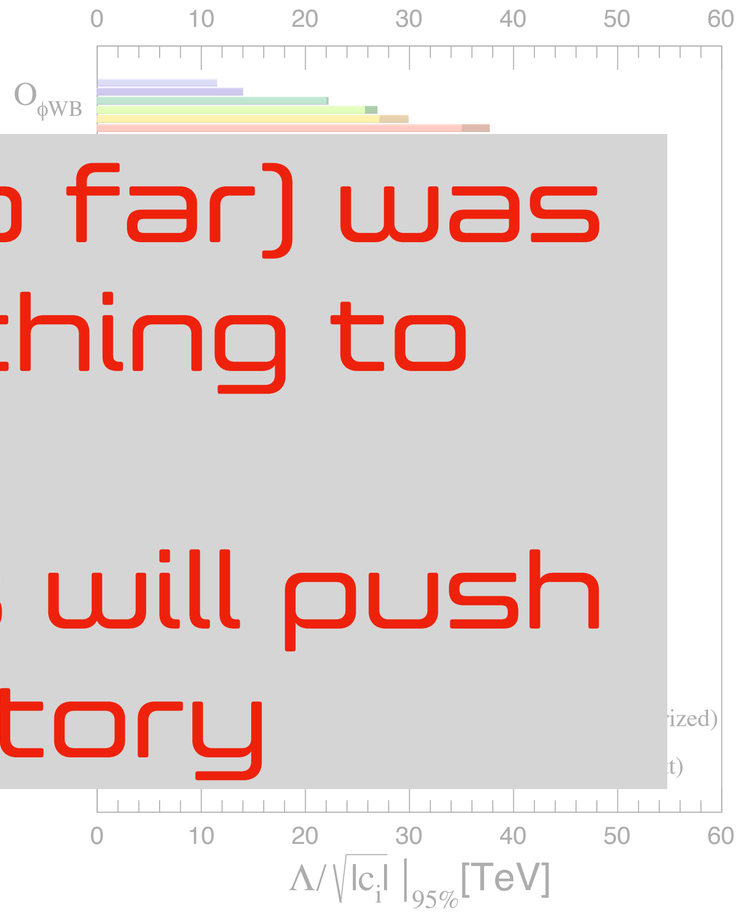
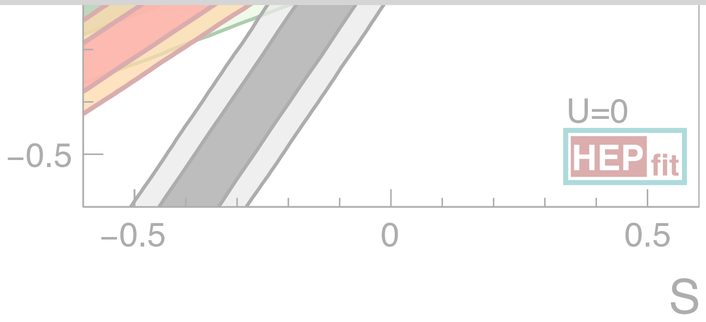


The LHC outcome (so far) was the most probable thing to expect

But the next 10 years will push us into new territory

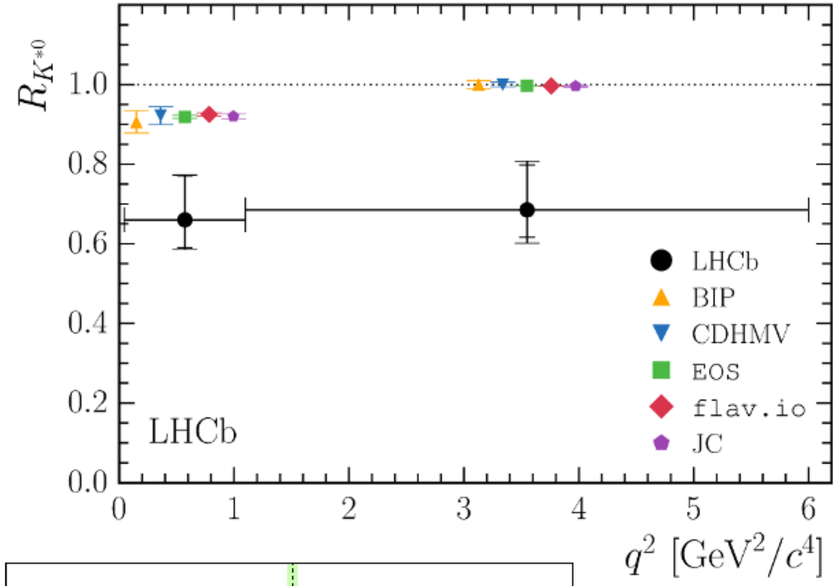


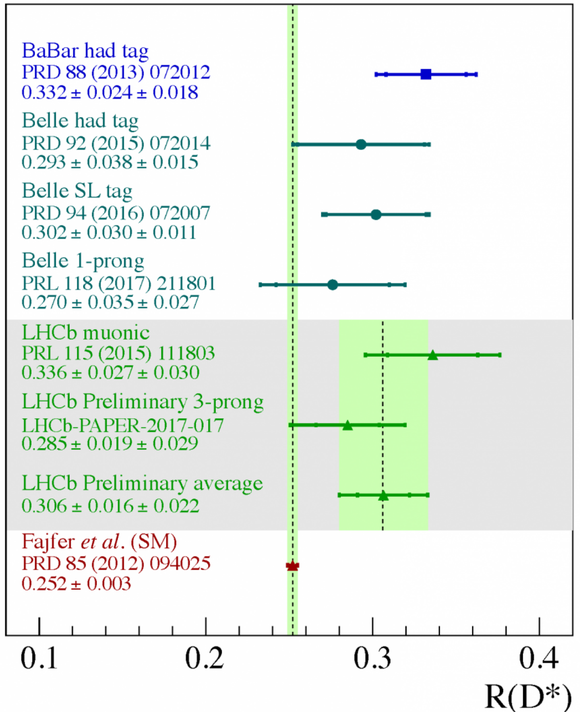
Flavor Anomalies

European Research Council

A surprise to come?

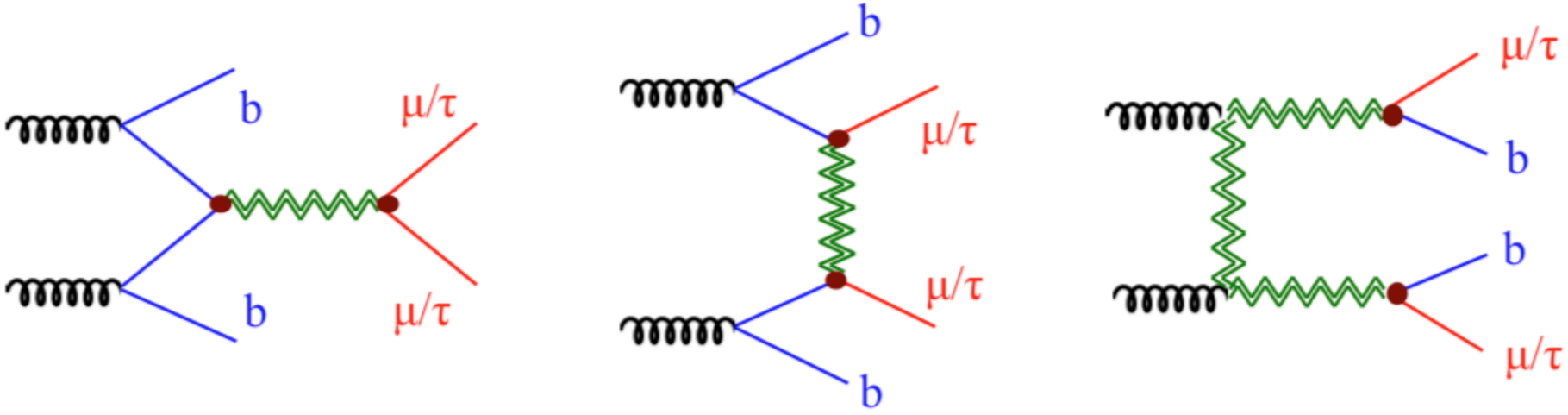
- LHCb reported very interesting anomalies, questioning lepton universality
- A confirmation at 5σ significance would change the picture above
  - would imply upper bound on the New Physics energy scale
  - would point the finger to a specific class of models (Z', fundamental or composite leptoquarks, …)
- Not all anomalies necessarily point to the same new-physics scale





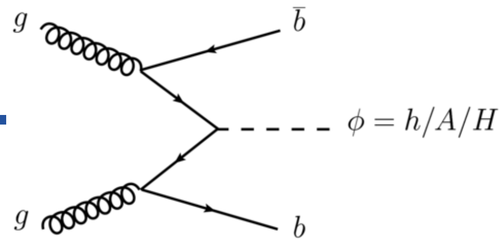
Implications for ATLAS and CMS

- *This is pushing ATLAS and CMS to investigate more 3rd-generation final states*
- *Much of these final states are already searched for*
- *Other bounds can be obtain re-interpreting existing analyses*

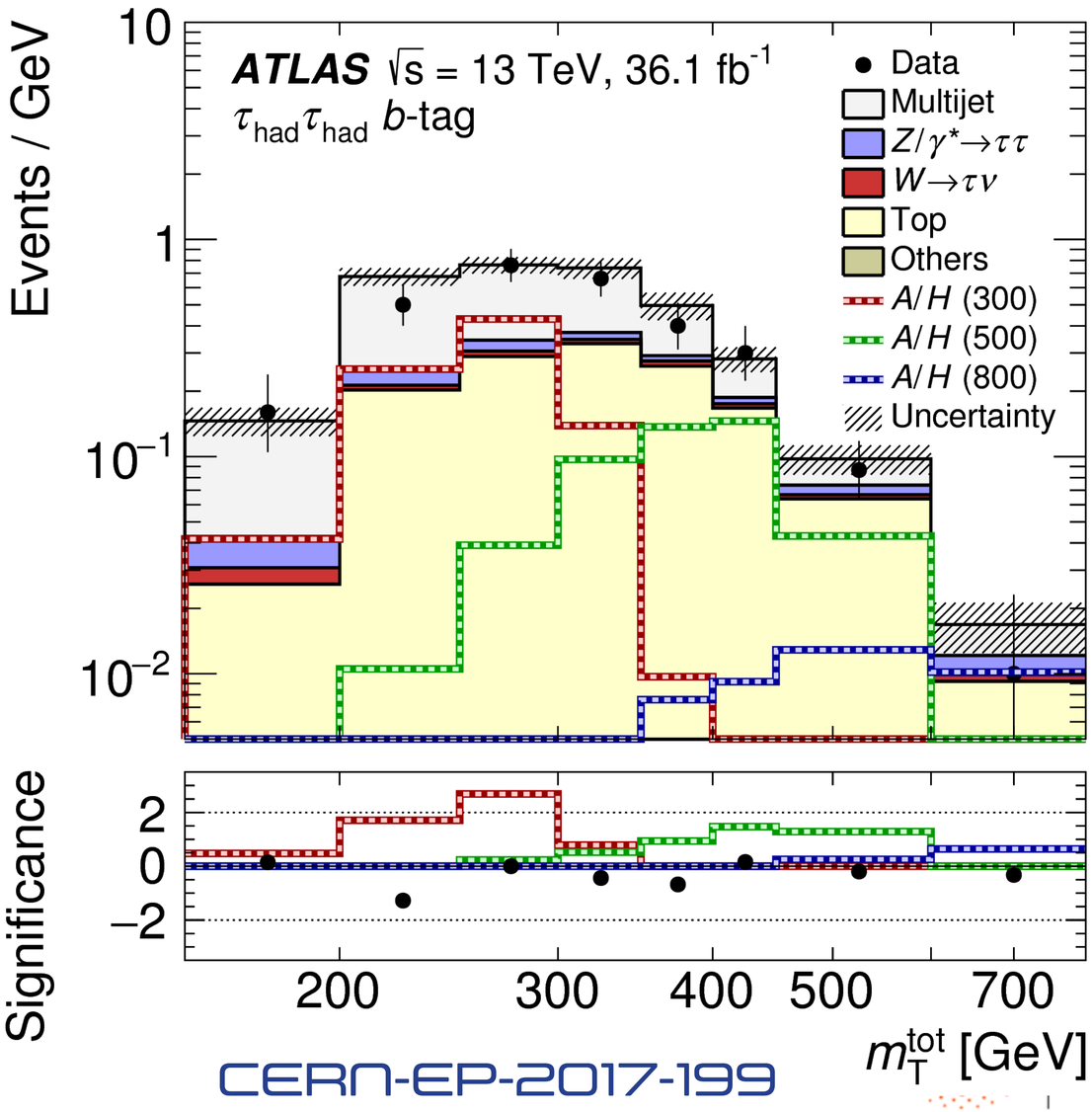


, etc etc

Z' Searches



- *Z' searches to tt final states already looked for (in the context of heavy Higgs searches)*
- *Production in association with bb also part of this model*
- *Direct translation of the result in terms of the Z' advocated for flavor anomaly*
- *Strong bound derived here, but much more data (and more collision energy?) needed to push search at tens of TeV*



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Z' Searches

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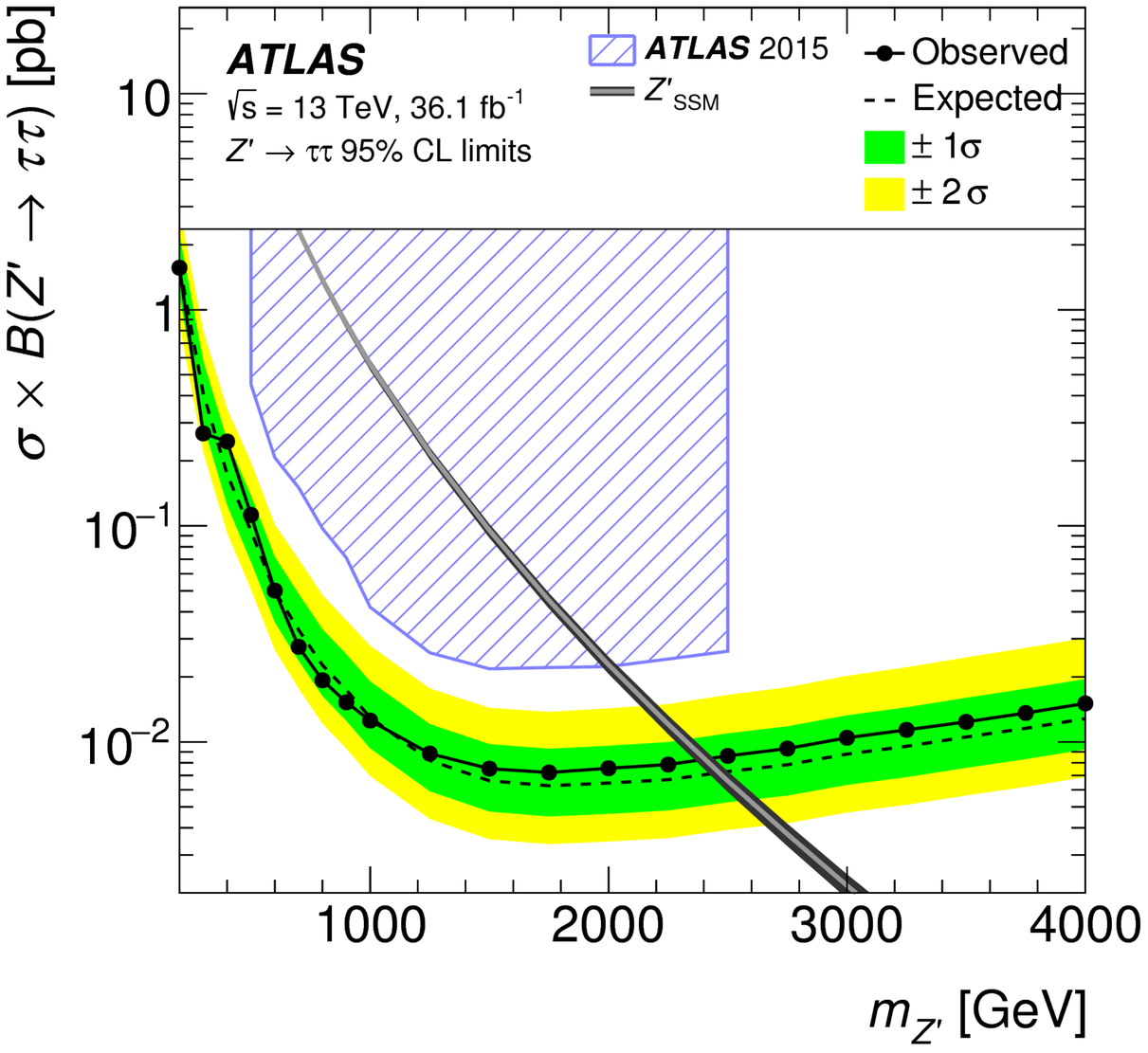

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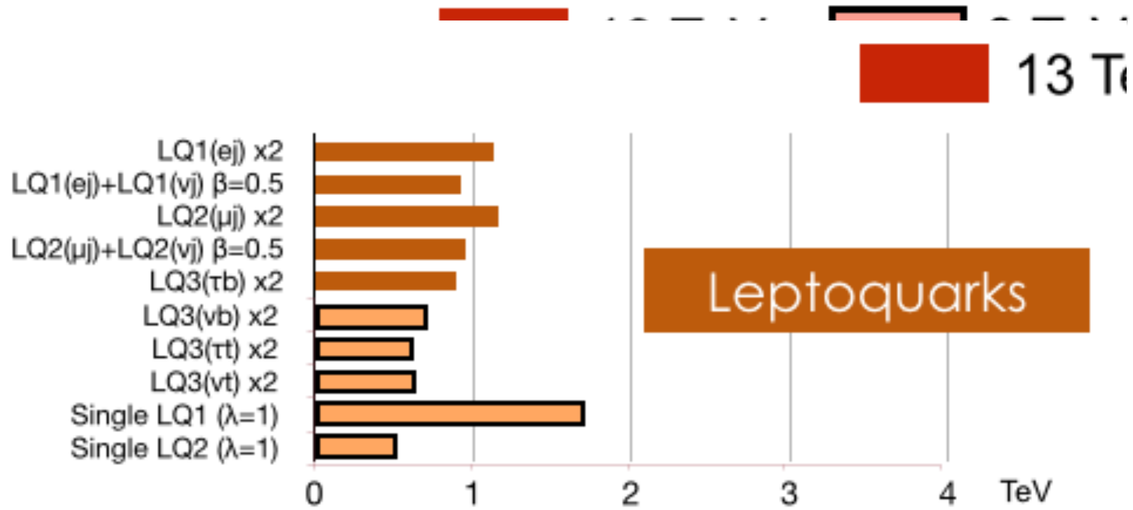
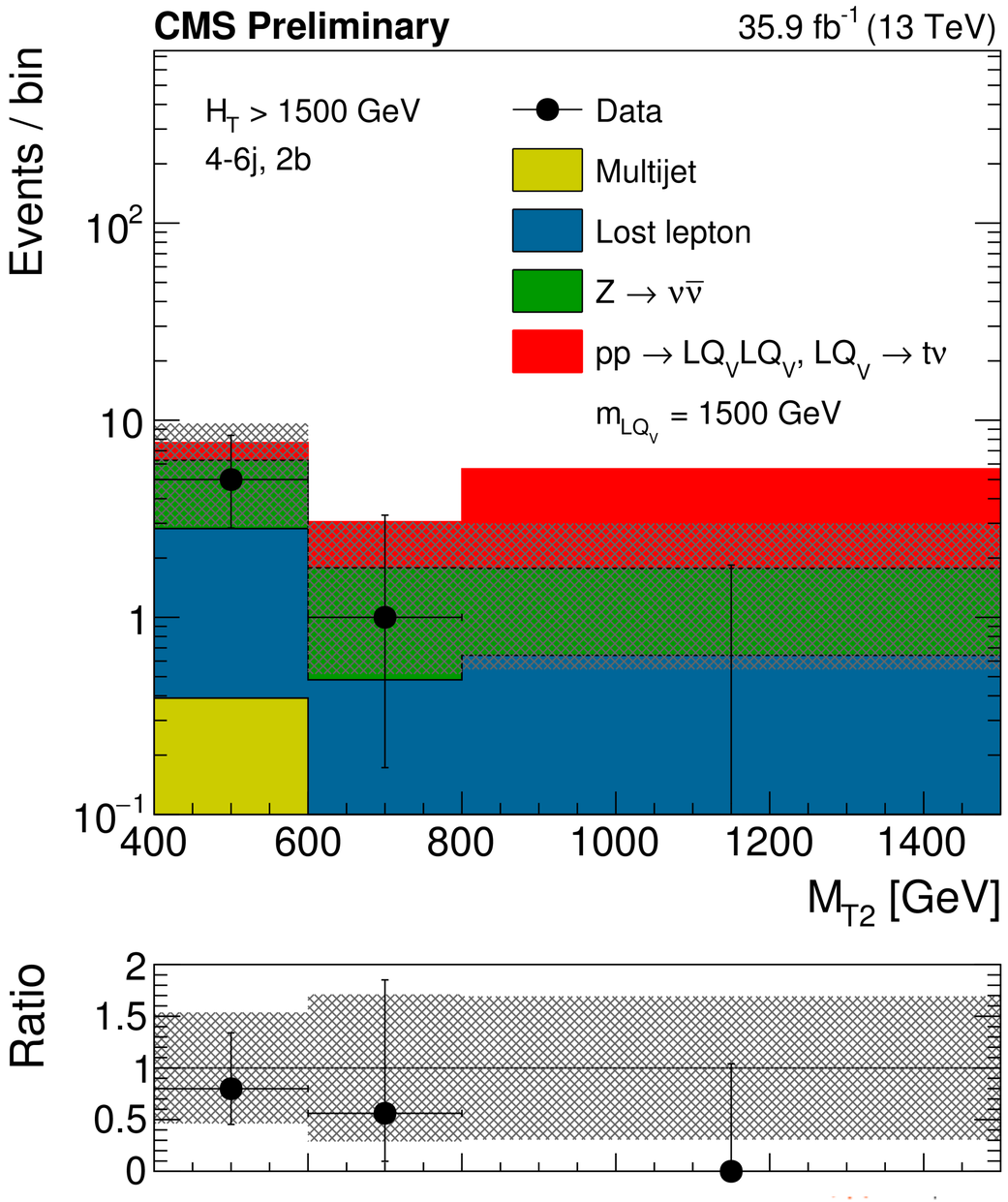
Leptoquarks

- *Leptoquarks extensively searched for in Run I*
- *Full exploration ongoing with Run II data*
- *In this sense, reinterpretation/ adaptation of SUSY searches is pushing sensitivity forward*





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