Exotic searches at the LHC

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On behalf of the ATLAS, CMS, and LHCb collaborations

ATLAS EXPERIMENT

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Outline

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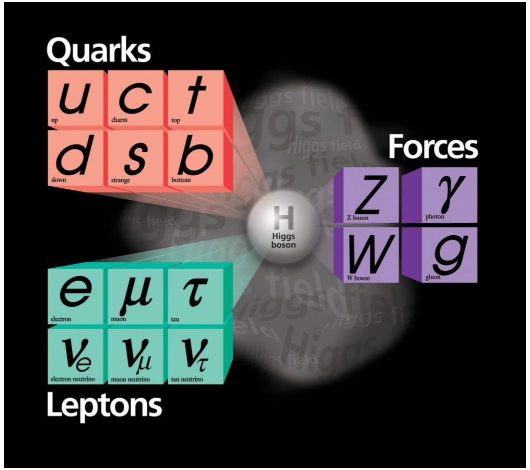
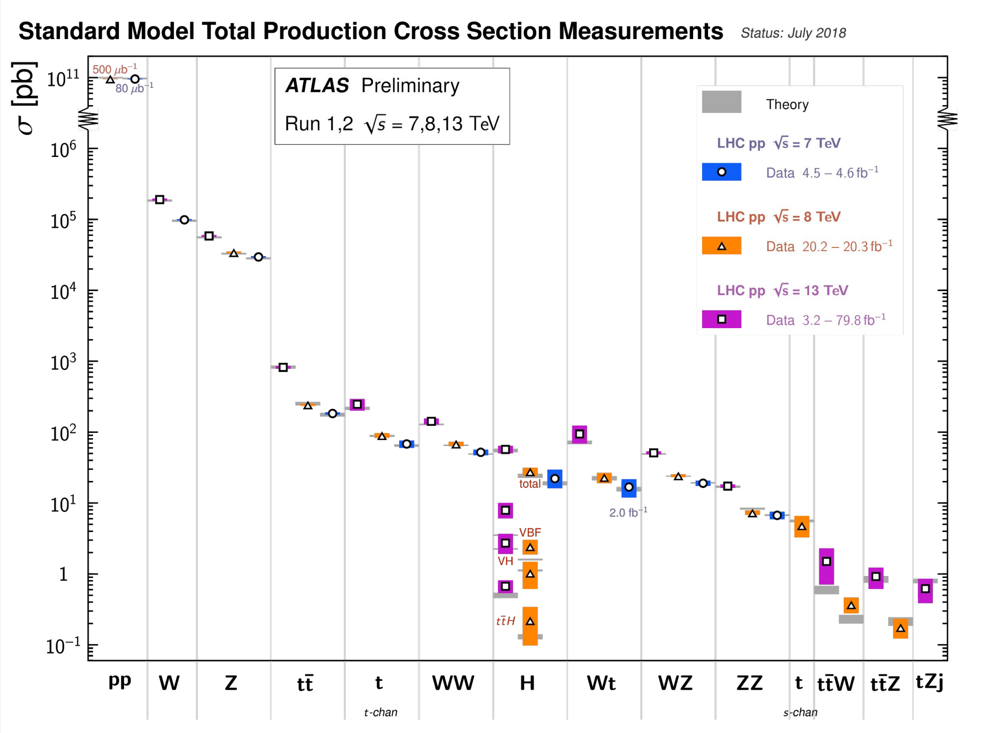
- Why do we need new physics?
- How are we searching for new results?
- Selection of a few **recently published analyses** from ATLAS, CMS, and LHCb are presented here.
  - Public results: ATLAS, CMS, and LHCb summary pages.

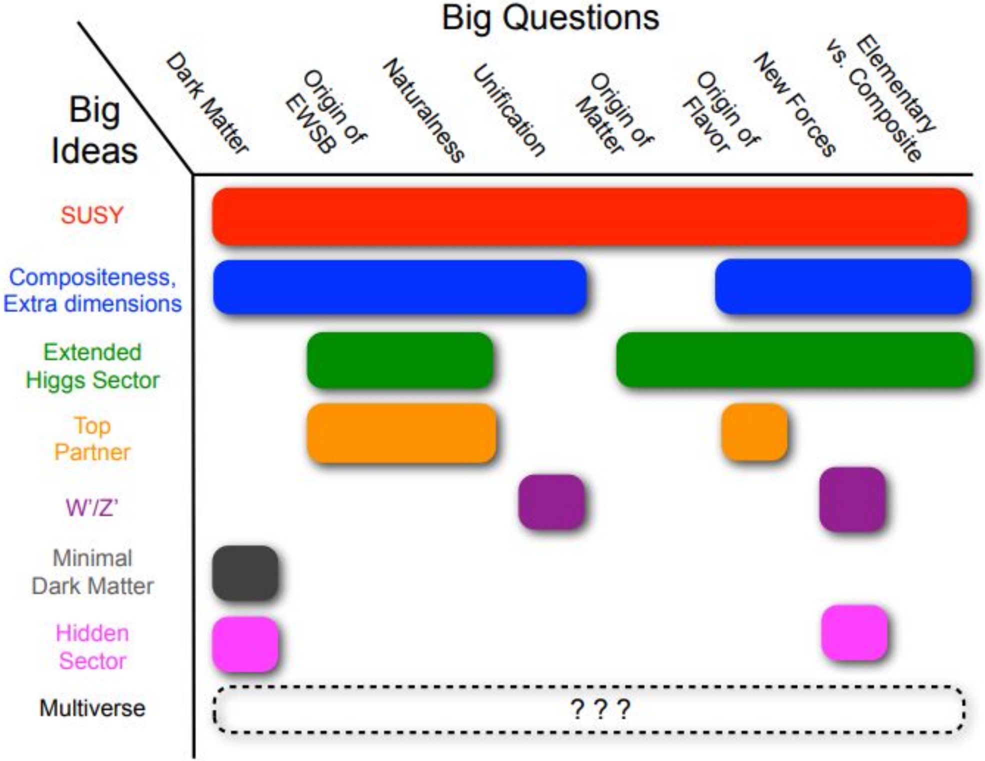
Why new physics?

- The Standard Model (SM) is a **complete framework of particles and their interactions**
- Tested at the LHC and several other experiments
- However, it has its limitations...





Why new physics?



Scope of this talk

Exotics = BSM physics without SUSY

Why new physics: Dark Matter

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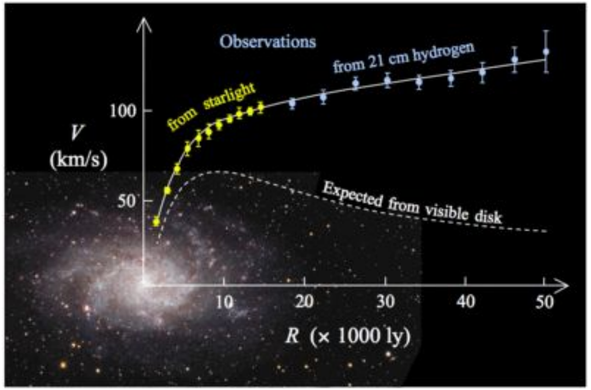
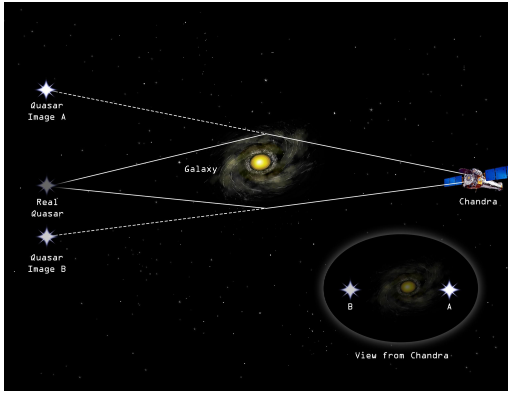
Galactic rotation curves



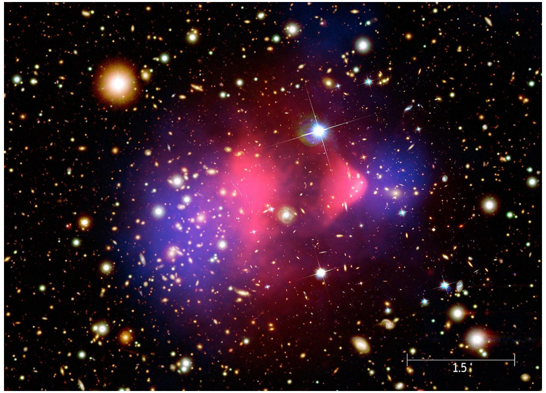
- **Discrepancy between measured rotation curves and theoretical predictions**.
- **Most mass** must be **invisible** to us.

Gravitational lensing



- The **observed galaxy mass is not enough** to account for the extent of the lensing.

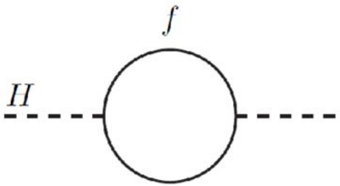
Bullet cluster

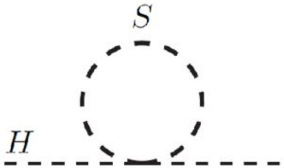


- **Dark matter interacts presumably only weakly** and bypassed the colliding gas. Visible by gravitational lensing of background objects (blue).

Why new physics: Hierarchy problem

- Problem: m_H^2 receives very **large quantum corrections** from every particle coupling to Higgs field, i.e. from a loop containing a Dirac fermion *f* or a Scalar *S*.





- The fermion loop yields a correction:

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV} + ...$$

- If SM was correct for all energies → $\Lambda_{UV} = \infty$, $m_H = \infty$
  - Obviously not true → **SM cannot be completely right**.

Why new physics: Neutrino oscillations

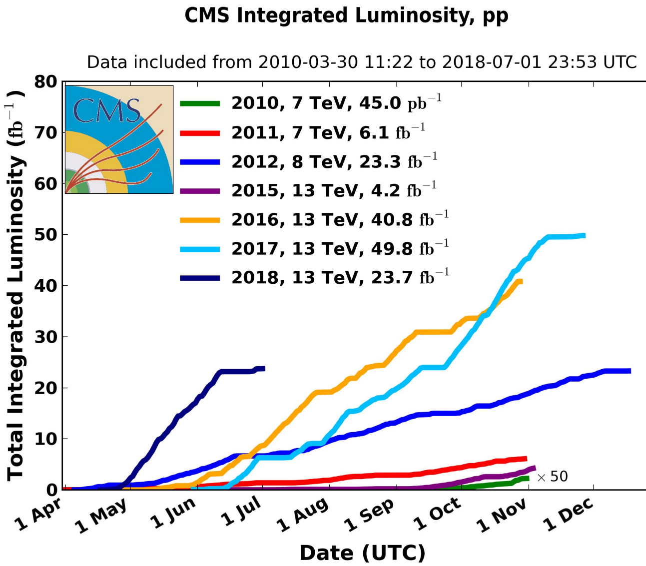
- **Neutrino oscillations** (mixing between neutrino flavors) established that at least two of the SM neutrinos have non-zero masses.

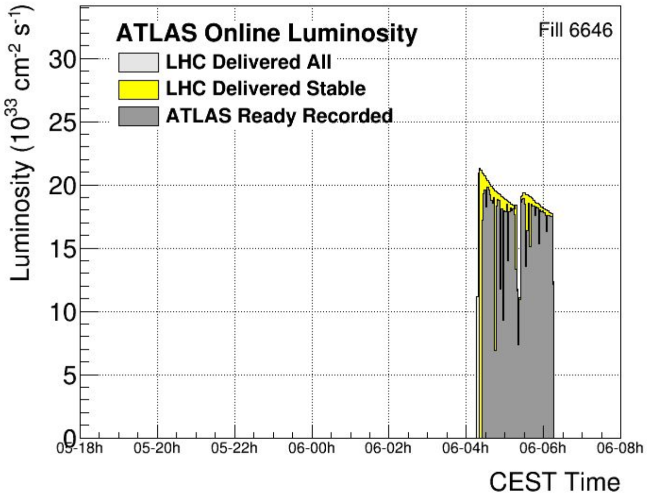
- One of the first indications of BSM physics.

- **Seesaw mechanism** one of leading theoretical explanations. Heavy neutrino N is postulated that explains the small masses m_v of the other neutrinos.
    - $m_v \sim y_v^2 v^2 / m_N$
    - y_v Yukawa coupling, v Higgs vacuum expectation value, m_N mass of heavy neutrino
    - One obtains one light and one heavy neutrino.

How to look for new particles: The LHC

- The Large Hadron Collider (LHC) **collides protons and heavy ions**.
- 2010 - 2012: √s (proton-proton collisions) of 7-8 TeV, ATLAS and CMS collected ~30 fb^{-1} of data
- 2015 - 2018: √s = 13 TeV, accumulated data (as of ~July 2018): CMS ~113 fb^{-1} , ATLAS 136 fb^{-1}
- Target luminosity ~150 fb^{-1}



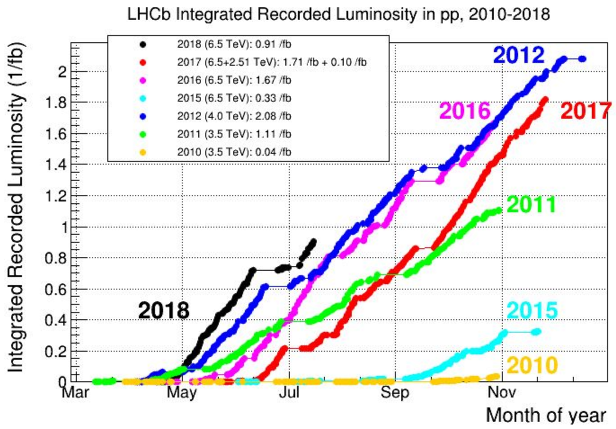


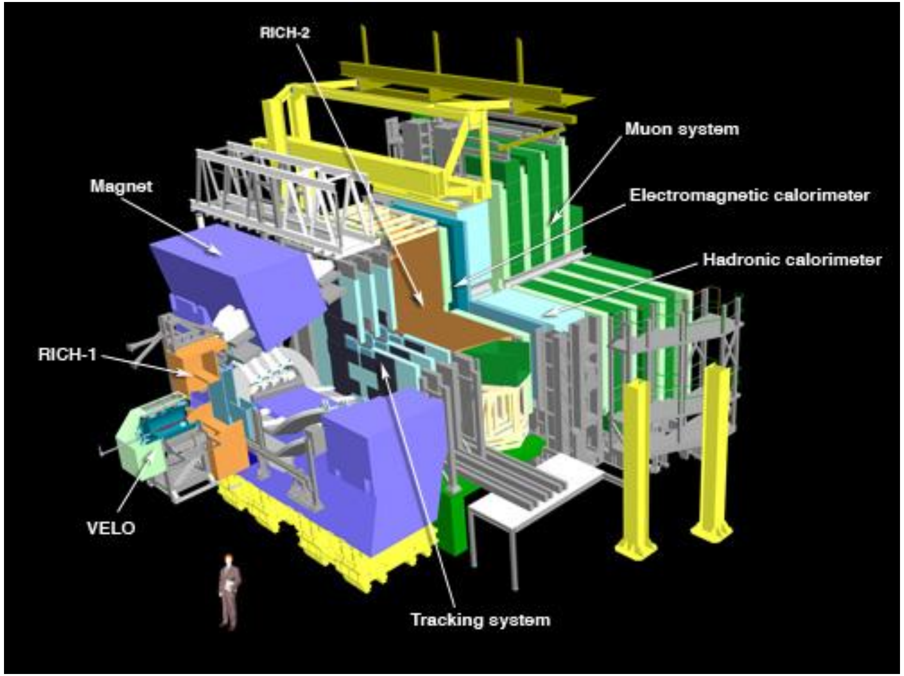
How to look for new particles: Experiments

- LHCb is a **specialized b-physics experiment** for primarily investigating CP violation in b-hadron interactions.

- 2010 - 2012: ~ 3.23 fb^{-1} at $\sqrt{s}$ = 3.5/4 TeV

- 2015 - 2018: ~4.62 fb^{-1} at $\sqrt{s}$ = 6.5 TeV





How to look for new particles: Experiments

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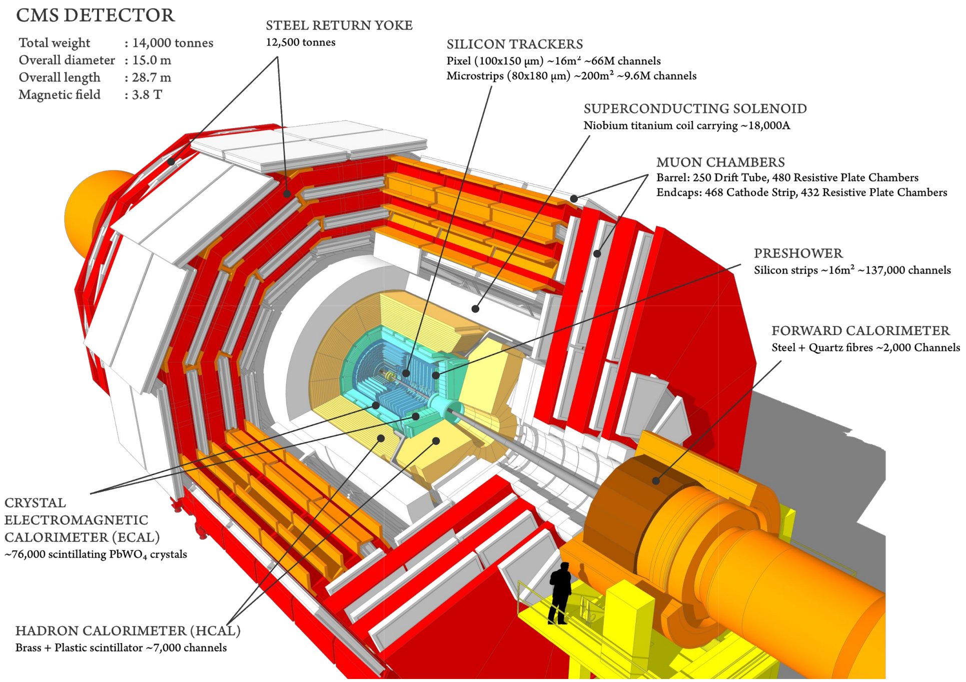
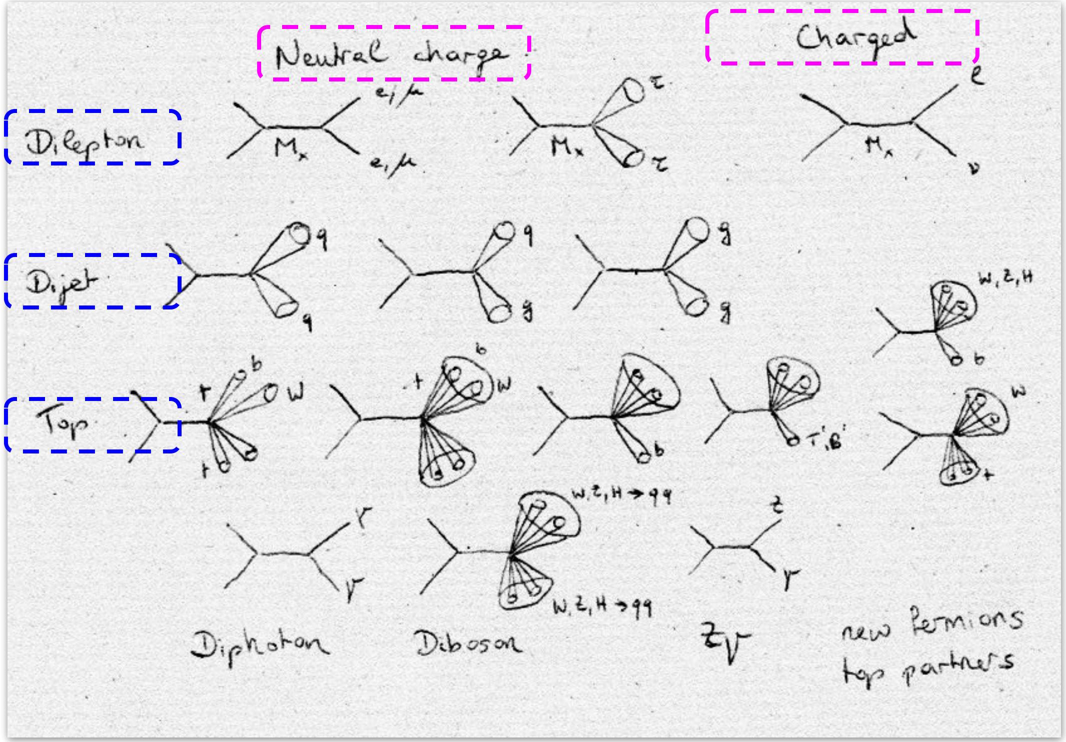
- ATLAS and CMS are **general-purpose detectors**, both consisting of several subsystems, designed to exploit the physics potential at the LHC.



Resonance searches

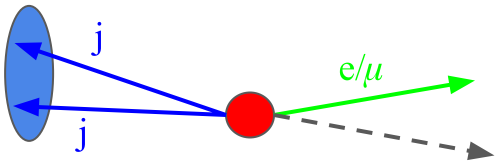
- Resonance = particle decaying into two other SM particles, creating a **bump in the invariant mass spectrum**.
- It is crucial to ensure **good resolution** on the reconstructed invariant mass (depends on the energy and momentum resolution of the objects).



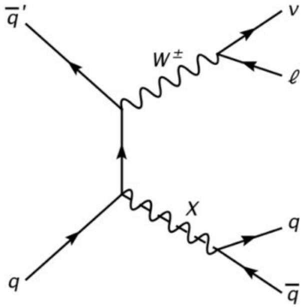
Resonance searches: Dijet + lepton (ATLAS)

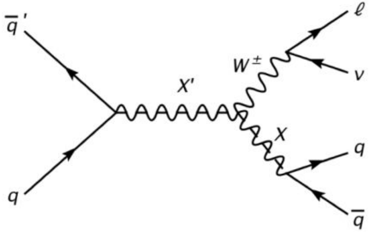
Dataset 79.8 fb^{-1}

- Main observable: **Invariant mass m_{jj}** of the selected jet pair
- Generic search covering various BSMs
- Lepton trigger allows:
  - Probing smaller dijet masses
  - Reduction of QCD background



Lepton only for triggering





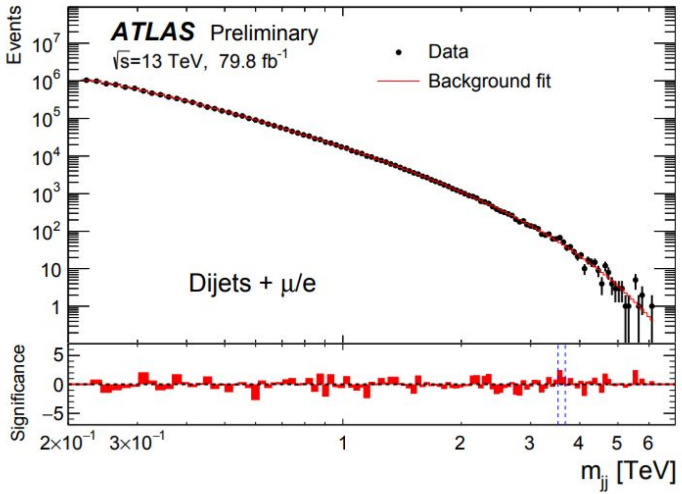
Generic resonance, X, decaying to two partons in association with a leptonically decaying W boson in the

- t-channel (left)
- s-channel (right)

ATLAS-CONF-2018-015

Resonance searches: Dijet + lepton (ATLAS)

- Very **loose SR requirements**
  - Isolated high-quality lepton + two jets
- Two different fit functions used for high and low mass region to establish shape of the estimated background.



- Systematic uncertainties
  - Background model 30-100 %
  - Jet energy scale and resolution 1.0-1.4 %
  - Lepton energy scale < 0.05 %
  - Luminosity 2%

- Most significant deviation found at m_{jj} = 3.56 TeV (p-value = 0.7).
- Data **consistent with the background-only hypothesis**.

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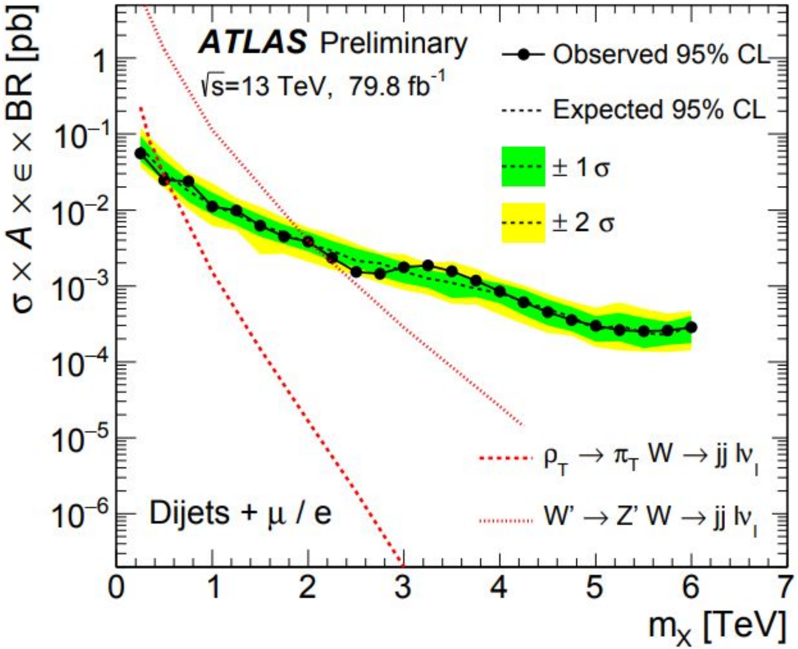
Resonance searches: Dijet + lepton (ATLAS)

- **Obtained limits** range from 50 fb to 0.1 fb for resonance masses between 0.25 and 6 TeV.

- These results exclude BSM models predicting resonances that **decay to dijets and an associated lepton** with cross-sections larger than the reported limits.



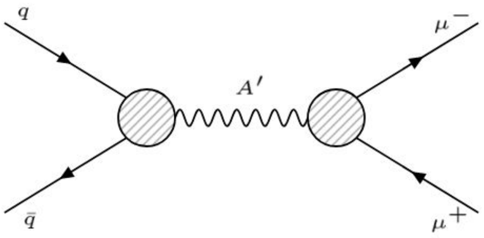
ATLAS-CONF-2018-015

Dark photons (LHCb)

Dataset 1.6 fb^{-1}

- Search for **massive dark photons** A', whose coupling to the EM current is **suppressed by factor of ε** in comparison to the ordinary photon γ.

- $A' \to \mu^+\mu^-$ decays analyzed.
  - For prompt A': di-μ < $m_{A'}$ < 70 GeV
  - For long-lived A': 214 MeV < $m_{A'}$ < 350 MeV



Backgrounds for prompt production

- Prompt $\gamma^* \to \mu^+\mu^-$ production (irreducible)
- Resonant decays to $\mu^+\mu^-$ (these mass-peak regions avoided)
- Various types of misreconstruction of hadron products of heavy-quark decays.

Backgrounds for long-lived production

- Photon conversions to $\mu^+\mu^-$
- b-hadron decays where two muons are produced in the decay chain
- Low-mass tail from $K_S^0 \to \pi^+\pi^-$ decays, where both pions are identified as muons

LHCb-PAPER-2017-038

Dark photons (LHCb)

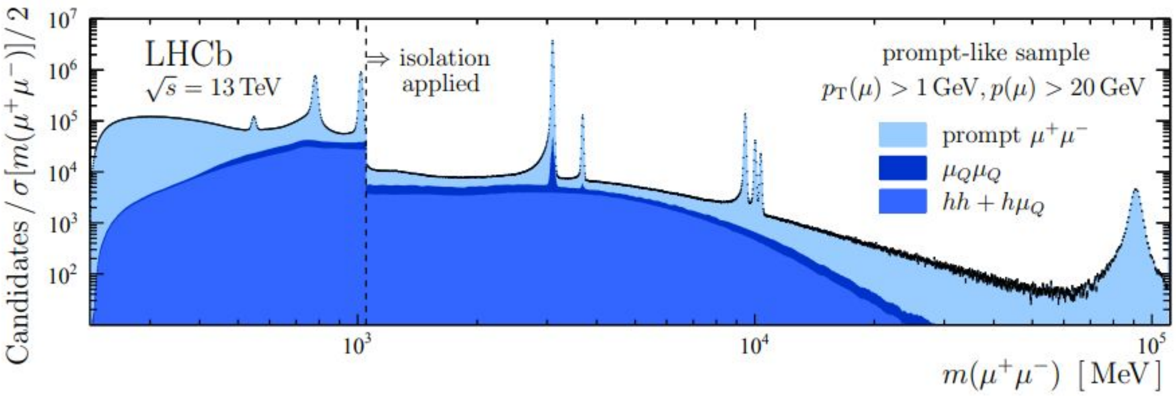
For masses < m_ϕ:

- A’ produced in meson-decays.

For masses > m_ϕ:

- A’ produced in Drell-Yan processes

Signal **sensitivity enhanced** by applying jet-based isolation requirement for m(A’) > m(ϕ).

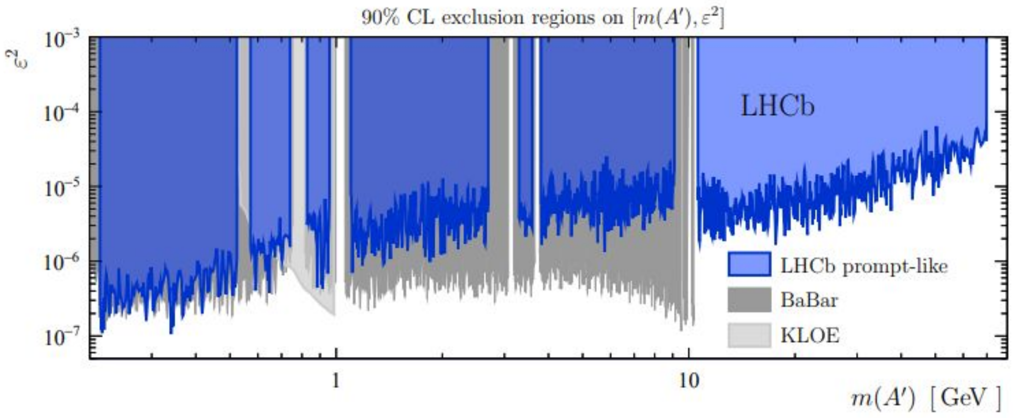


Prompt-like $m(\mu^+\mu^-)$ spectrum with Δm bins that are $\sigma[m(\mu^+\mu^-)]/2$ (mass resolution) wide.
Yields are obtained from fits applied to the spectrum, proportional to $\varepsilon^2 \rightarrow$ constraints set on ε^2.

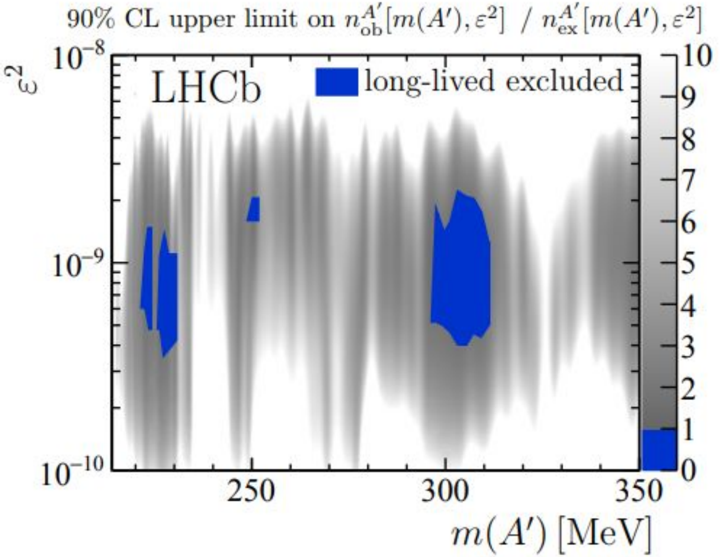
LHCb-PAPER-2017-038

Dark photons (LHCb)

Regions of the [m(A’), ε²] parameter space excluded at 90% CL by the prompt-like A’ search compared to the best existing limits.



Ratio of the observed upper limit on $n_{obs}^{A'}[m(A'), \varepsilon^2]$ at 90% CL to its expected value.



No evidence for a signal is found. 90% CL exclusion regions are set on the γ–A’ kinetic-mixing strength.

LHCb-PAPER-2017-038

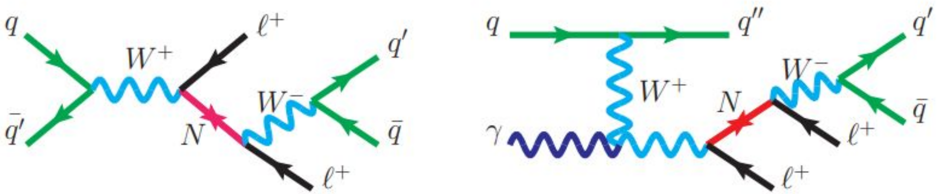
Search for heavy Majorana neutrinos (CMS)

Dataset 35.9 fb^{-1}

Signature

- Two same-sign leptons (low SM background)
- W decaying hadronically

Signal regions SR	$m_N < 80$ GeV	$m_N > 80$ GeV
W boson propagator	on-shell	off-shell
Invariant mass final state	m_{lljj} ~ W boson mass	W on-shell → m_{jj} ~ W boson mass



Drell-Yan production and photon-initiated production of a Majorana neutrino N.

Further splitting of SRs based on the **jet configuration** and the **flavor channels** ee, $\mu\mu$, and eμ.

CMS-EXO-17-028

Search for heavy Majorana neutrinos (CMS)

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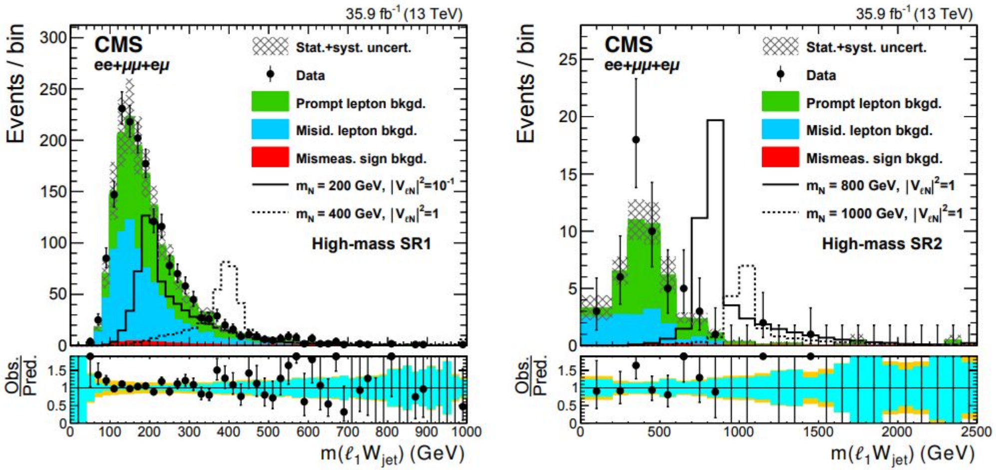
Backgrounds

- SM processes with multiple prompt leptons
- Misidentified leptons
- Sign mismeasurement

Major contribution to systematic uncertainties coming from

- Estimate of the SM cross-section
- PDF variations
- Misidentified leptons

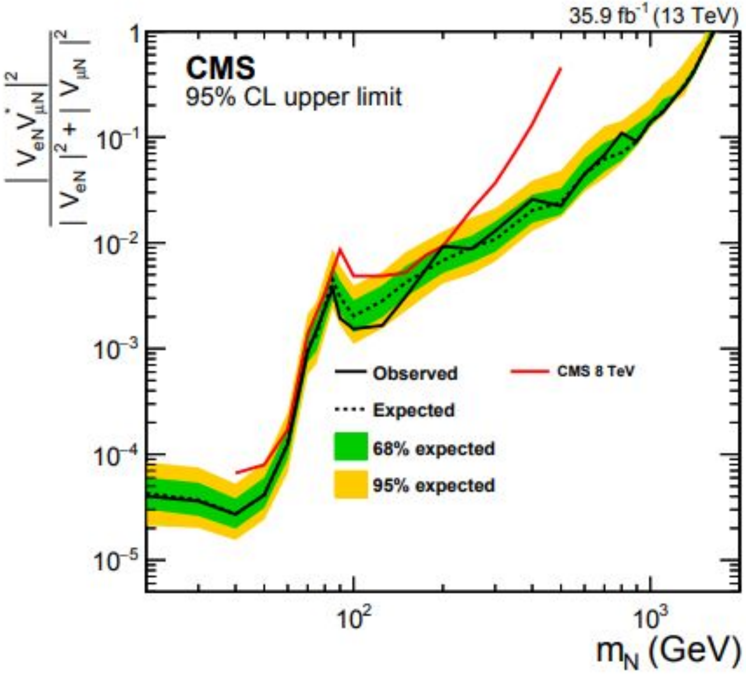


Observed distributions of the invariant mass of the leading lepton and jets for two high-mass regions.

CMS-EXO-17-028

Search for heavy Majorana neutrinos (CMS)

- The search is sensitive to 20 GeV < m_N < 1600 GeV.
- The limits set on the mixing parameters for m_N > 430 GeV are the most restrictive, and the first for masses greater than 1200 GeV.



No significant excess of events compared to the expected SM background prediction is observed.

Search for lepton-flavor violation (ATLAS)

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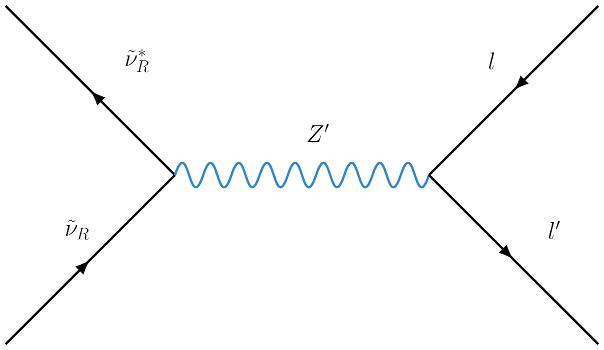
Dataset 36.1 fb^{-1}

- Search for **heavy particle** decaying into eμ, eτ or μτ.

- Analysis used for setting limits on
  - Z' of the extended SM
  - Supersymmetric τ-sneutrino
  - Threshold mass for quantum black hole production with interpretations based on the ADD and Randall-Sundrum model.

- Search optimized for looking at phenomena in high mass range
  - Events selected by single lepton trigger (p_T = 65 GeV).
  - Only events with exactly two different lepton flavors chosen.
  - Leptons required to be back-to-back → $\Delta\phi$ (l,l') > 2.7



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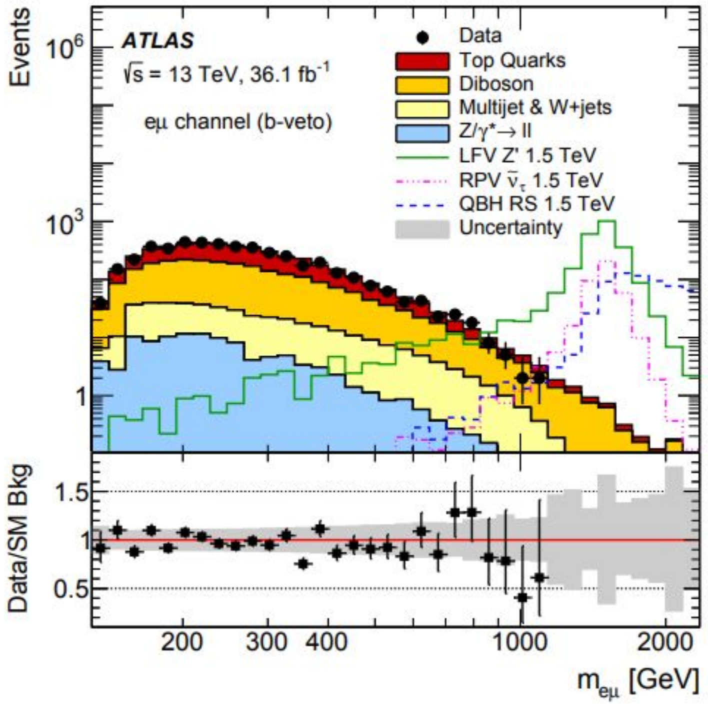
Search for lepton-flavor violation (ATLAS)

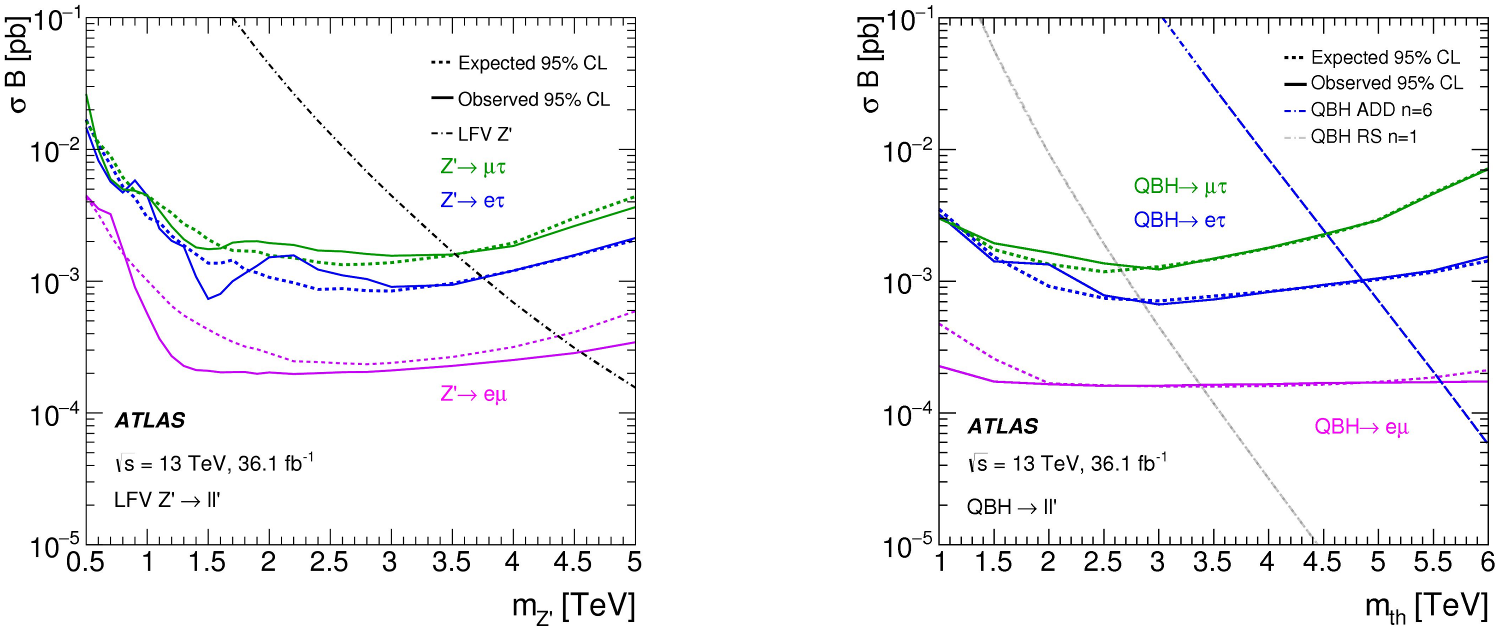
Channel	Main backgrounds
eμ	ttbar (suppressed by b-veto), diboson
eτ	W+jets, multijet
μτ	W+jets, multijet

- Systematic uncertainties
  - PDFs
  - Multijet estimation
  - m_{ll}, modelling in ttbar events
  - Jet efficiency and resolution



CERN-EP-2018-137

Search for lepton-flavor violation (ATLAS)

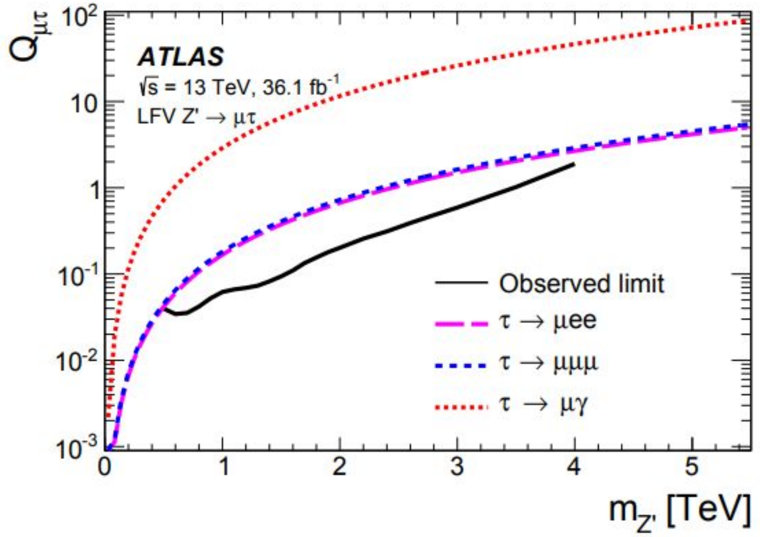


Bayesian lower limits at 95% CL are set for all three considered models.

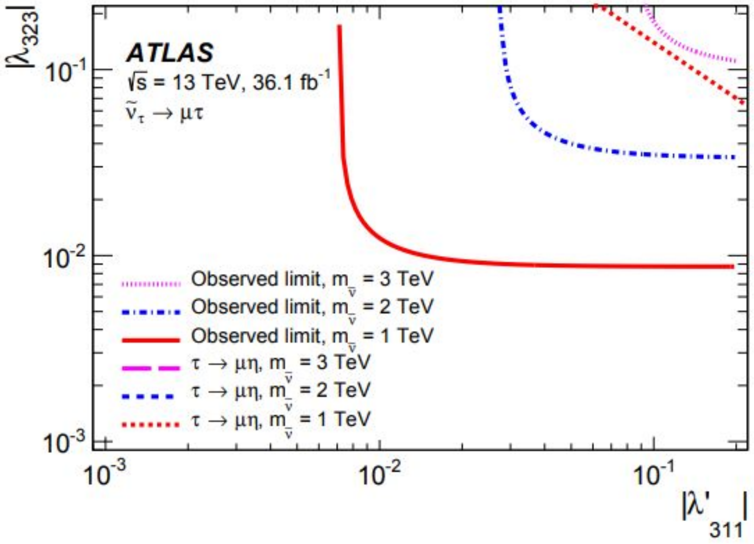
CERN-EP-2018-137

Search for lepton-flavor violation (ATLAS)

Coupling limits for the lepton-flavor-violating Z' and the τ-sneutrino are more stringent than those from low-energy experiments for the channels including a τ.



95% CL upper limits on the coupling $Q_{\mu\tau}$ as a function of $m_{Z'}$.



95% CL upper limits on the RPV couplings $|\lambda_{323}|$ versus $|\lambda'_{311}|$ for a few values of m_{ν}.

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Summary

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- The performance of the LHC provides an **always increasing dataset** and allows the experiments to **improve their sensitivity** throughout Run 2.

- There is a **large variety of exotics searches** at the LHC, exploring
  - Various BSM models
  - Different experimental signatures
  - Broad kinematic regimes

- So far **all data consistent with SM** expectations in BSM searches. **No significant excess** was found.

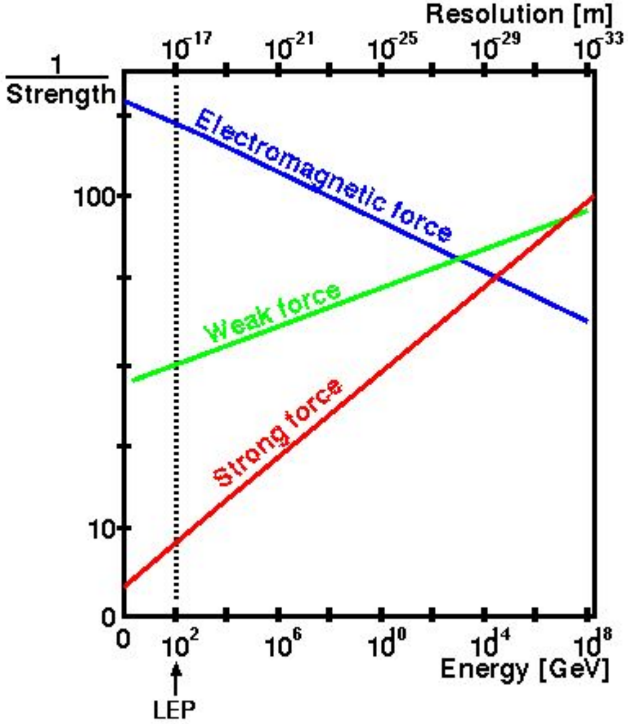
- However, **new limits** significantly extend the Run 1 results.

Backup

Why new physics: Gauge coupling unification

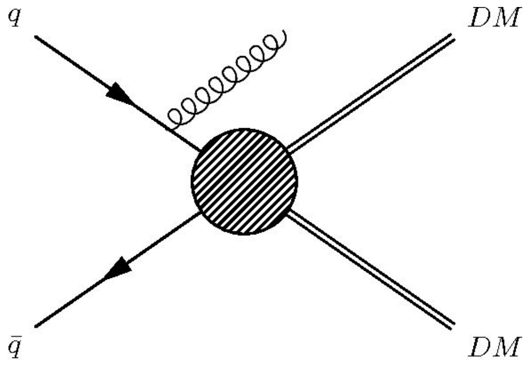
- If electroweak and strong force are unified:
  - Unification mass in **Grand Unified Theory (GUT)** must be large enough such that the lifetime of the proton is compatible with current limit (> 10^{31} years)

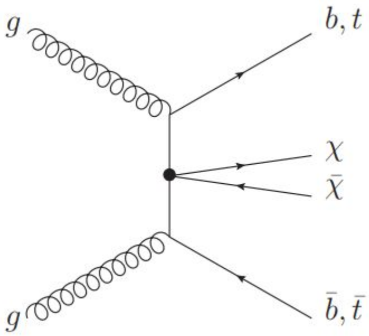
- Gravity 10^{-38} times weaker than the strong interaction → difficult to unify with other forces.
  - A possible solution for this hierarchy problem are **extra dimensions**.

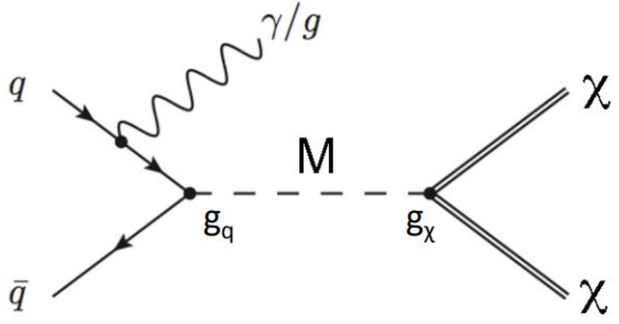


Dark matter searches

- Three search approaches
  - Mono-X signature: Look for initial state radiation
  - Associate production of dark matter with SM particles
  - Direct search for mediators that result in dijet resonance







Dark matter searches: Overview CMS & ATLAS

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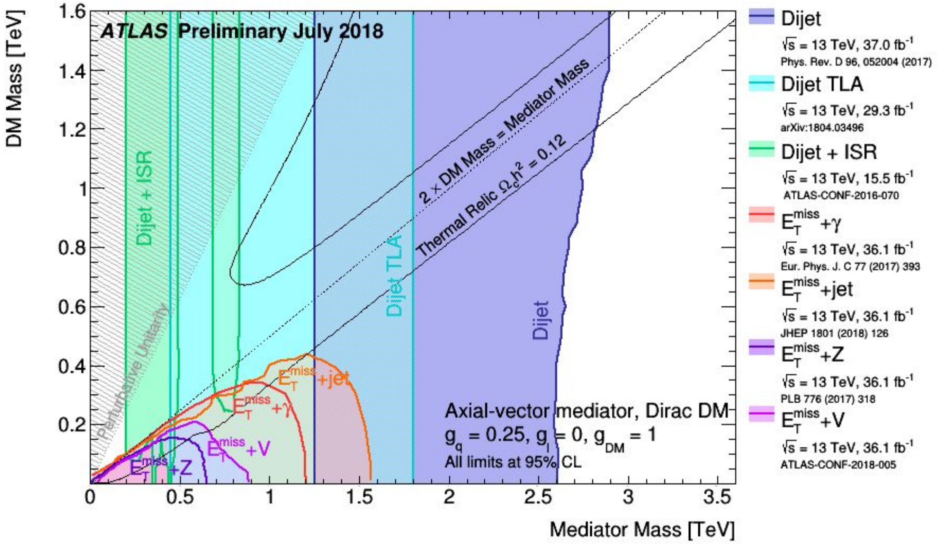
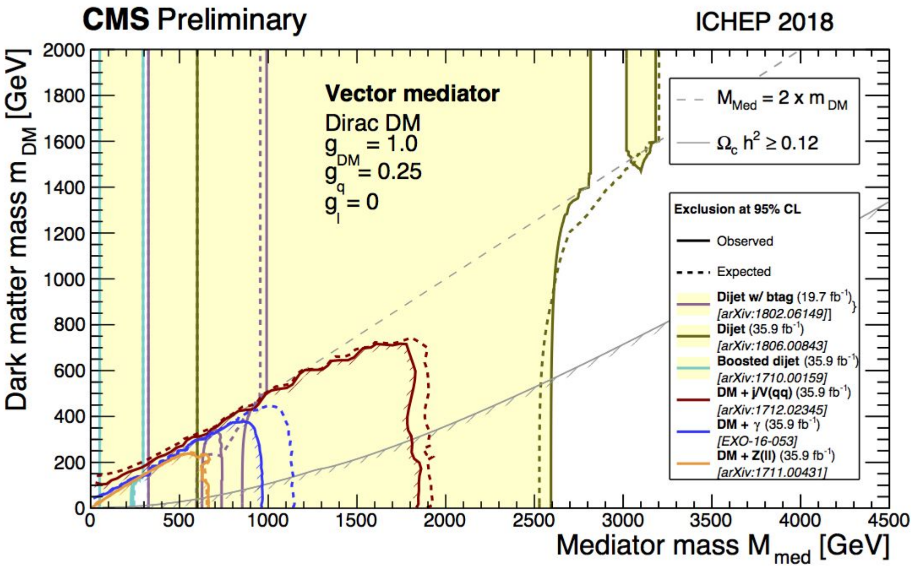
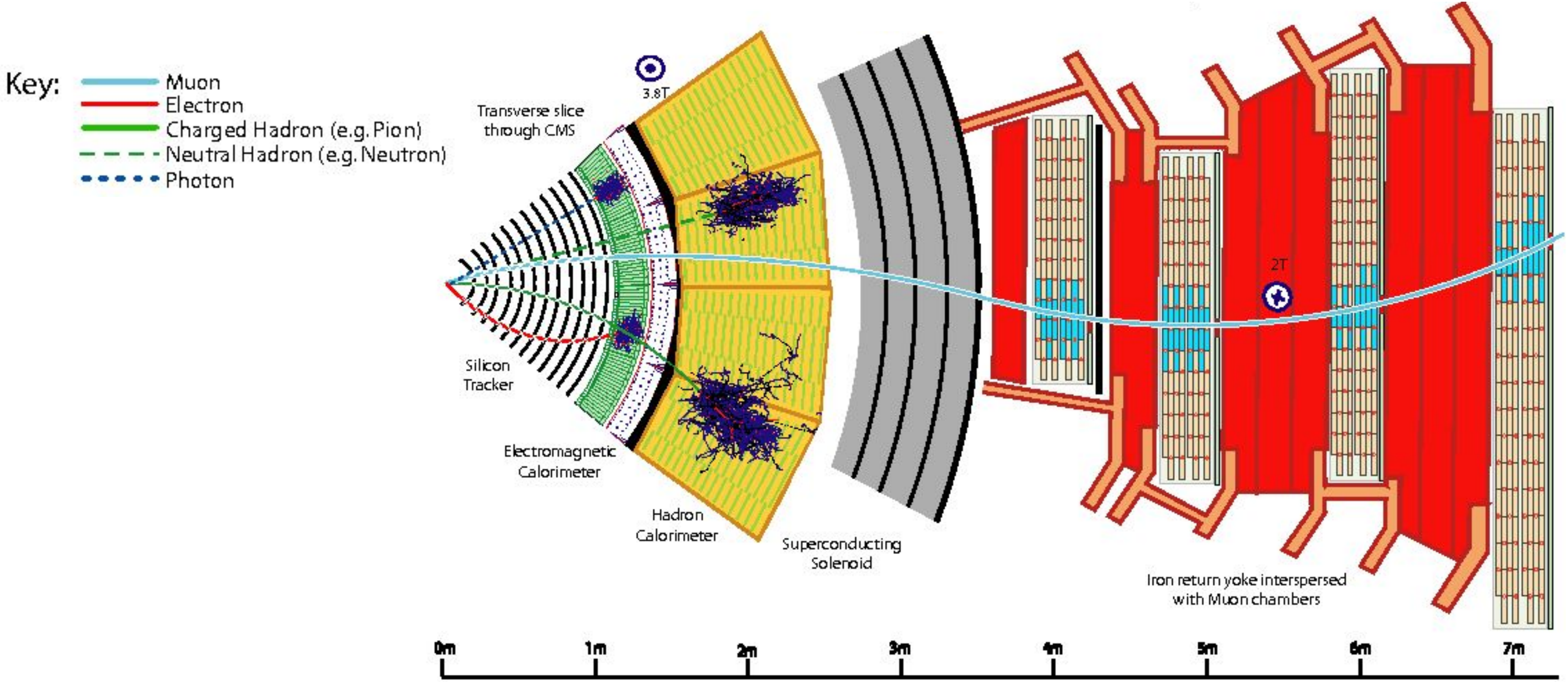
Regions in a dark matter mass-mediator mass plane excluded at 95% CL computed for a universal quark coupling $g_q = 0.25$ and for a DM coupling of $g_{DM} = 1.0$.

More in Vasiliki's talk on Friday





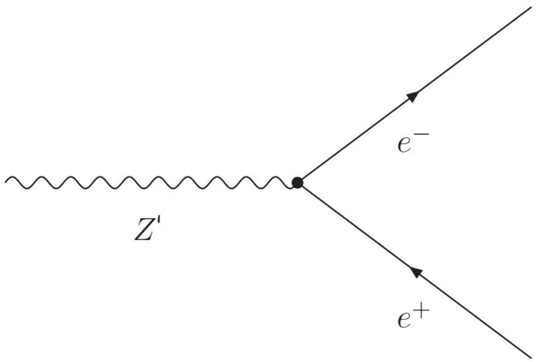
How to look for new particles: Particle reconstruction

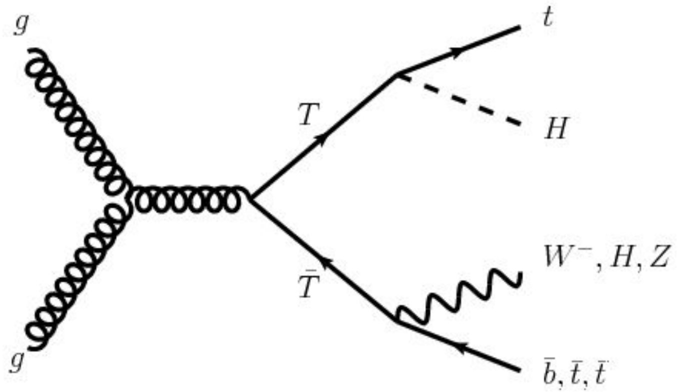


How to look for new particles: Expected signatures

- In most searches we assume that **new particles decay to SM particles** that can be detected.
  - Exception to that are Mono-X searches.

- These new particles are expected at high masses.
  - Final state objects must have a high p_T.
  - Often final state particles expected.





Search for lepton-flavor violation (ATLAS)

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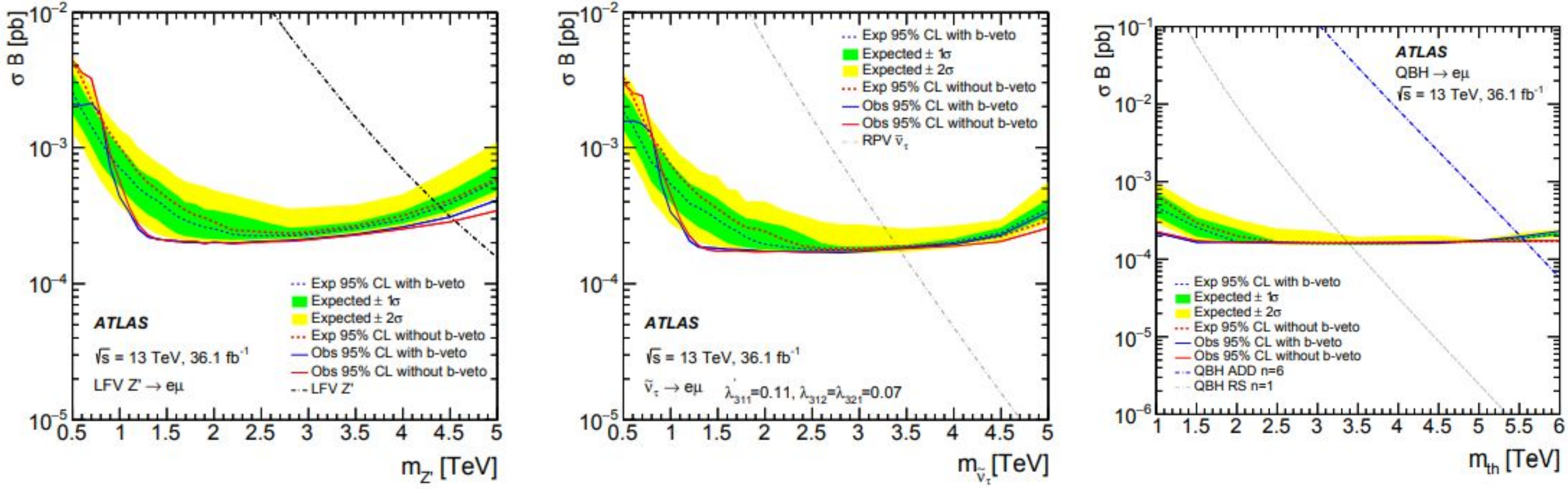

Bayesian lower limits at 95% CL are set for all three considered models.

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