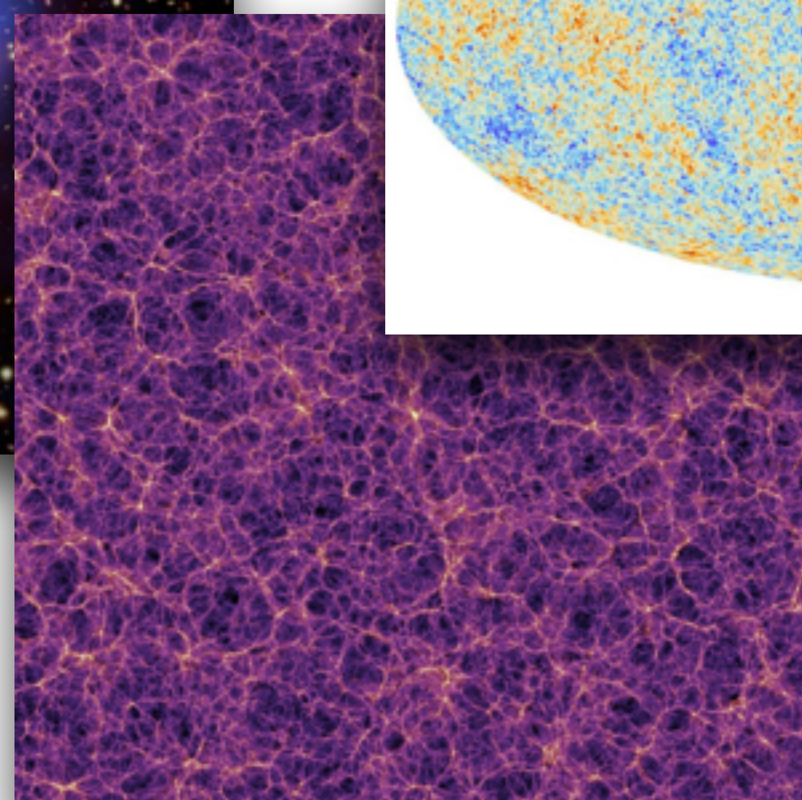
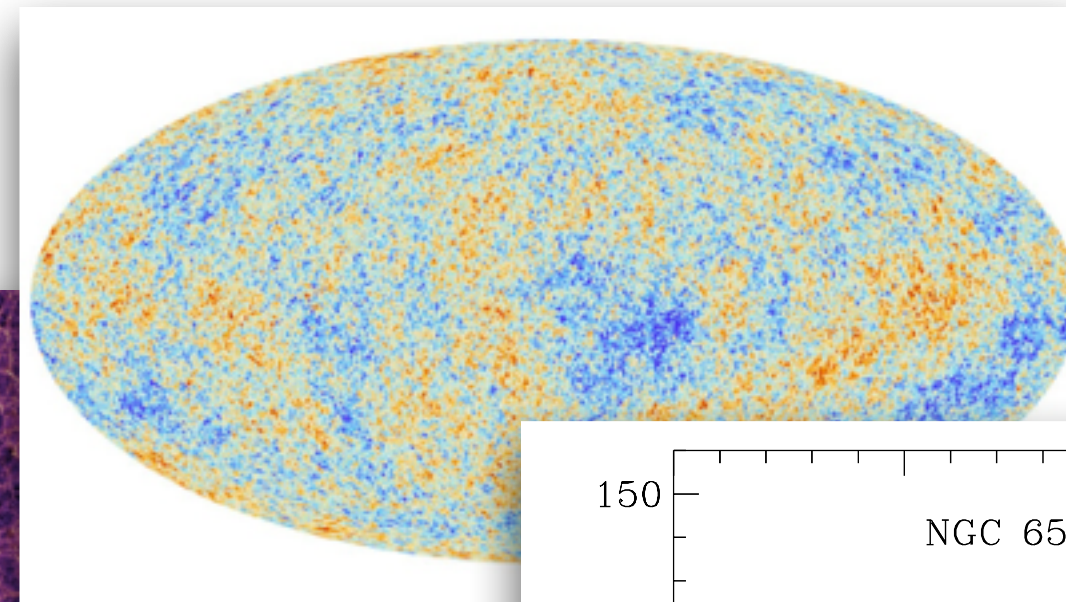
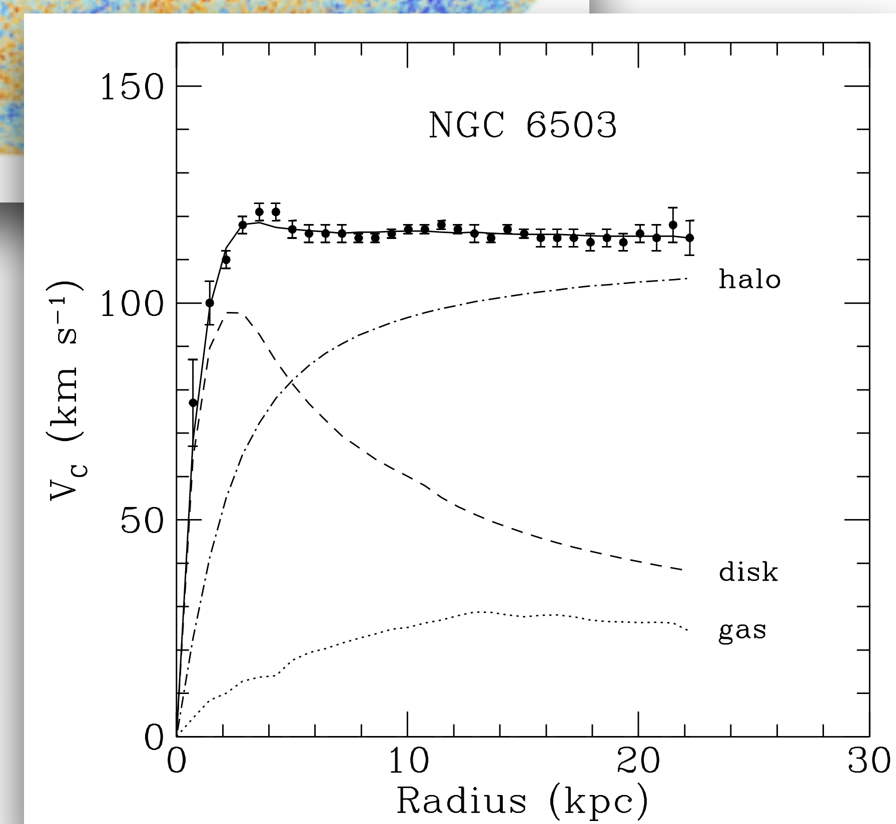
Dark Matter at 13 TeV and Data Interpretation

David Šálek

Dark Matter

- unequivocal gravitational evidence for Dark Matter in the Universe

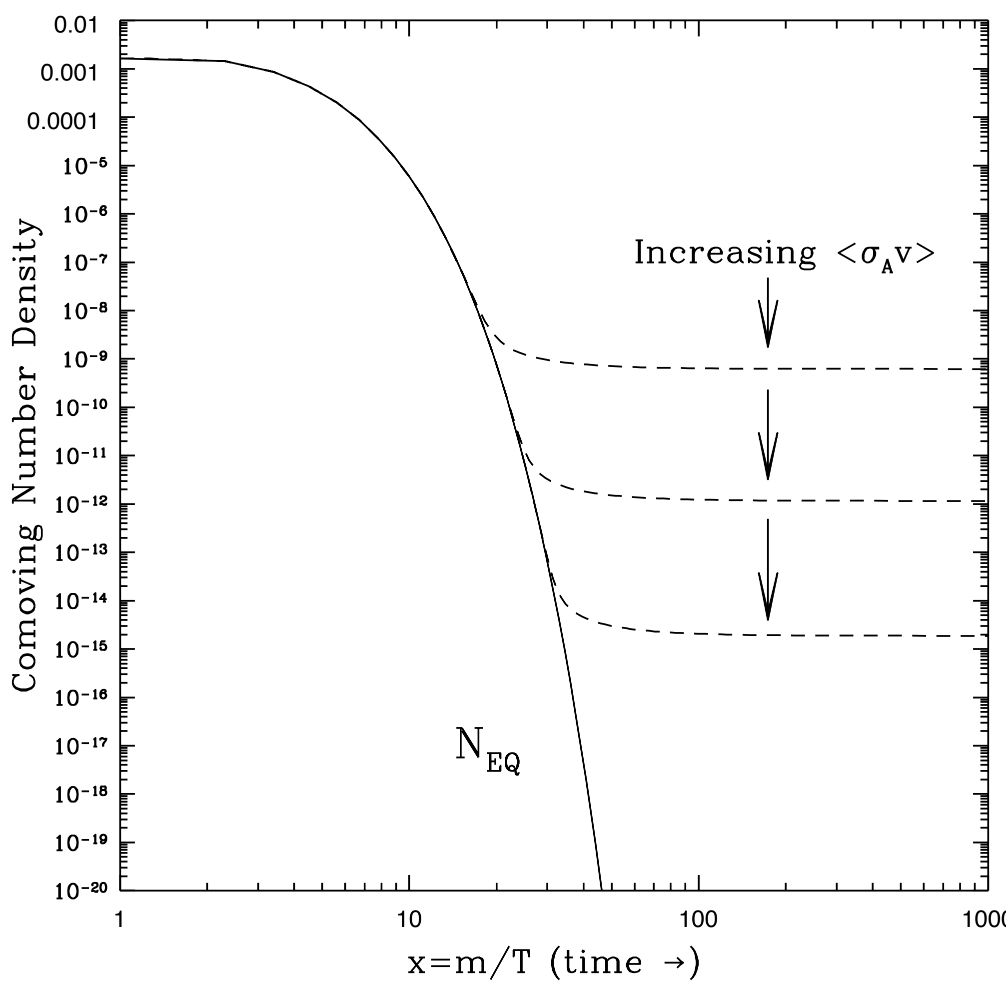
- Why do we expect to see it at the LHC?

Thermal relic

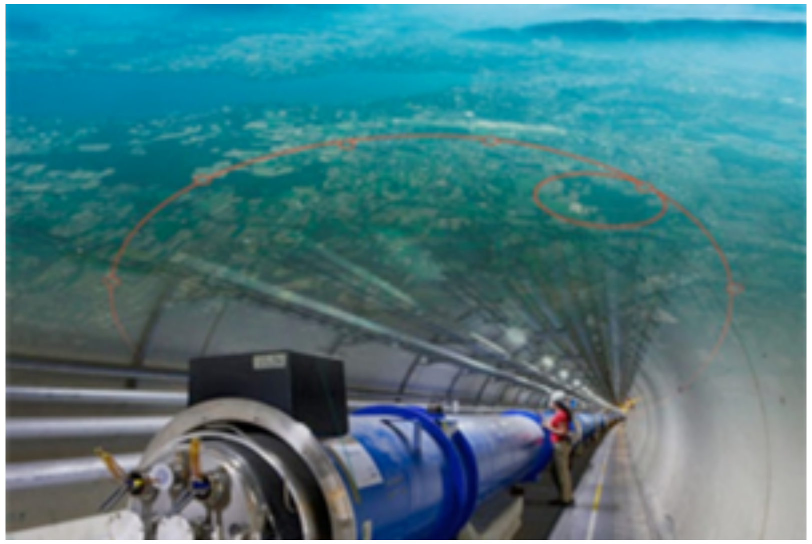
1) DM and SM in thermal equilibrium
2) Universe cools (DM annihilates)
3) Freeze-out

$$\langle \sigma v \rangle \gtrsim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

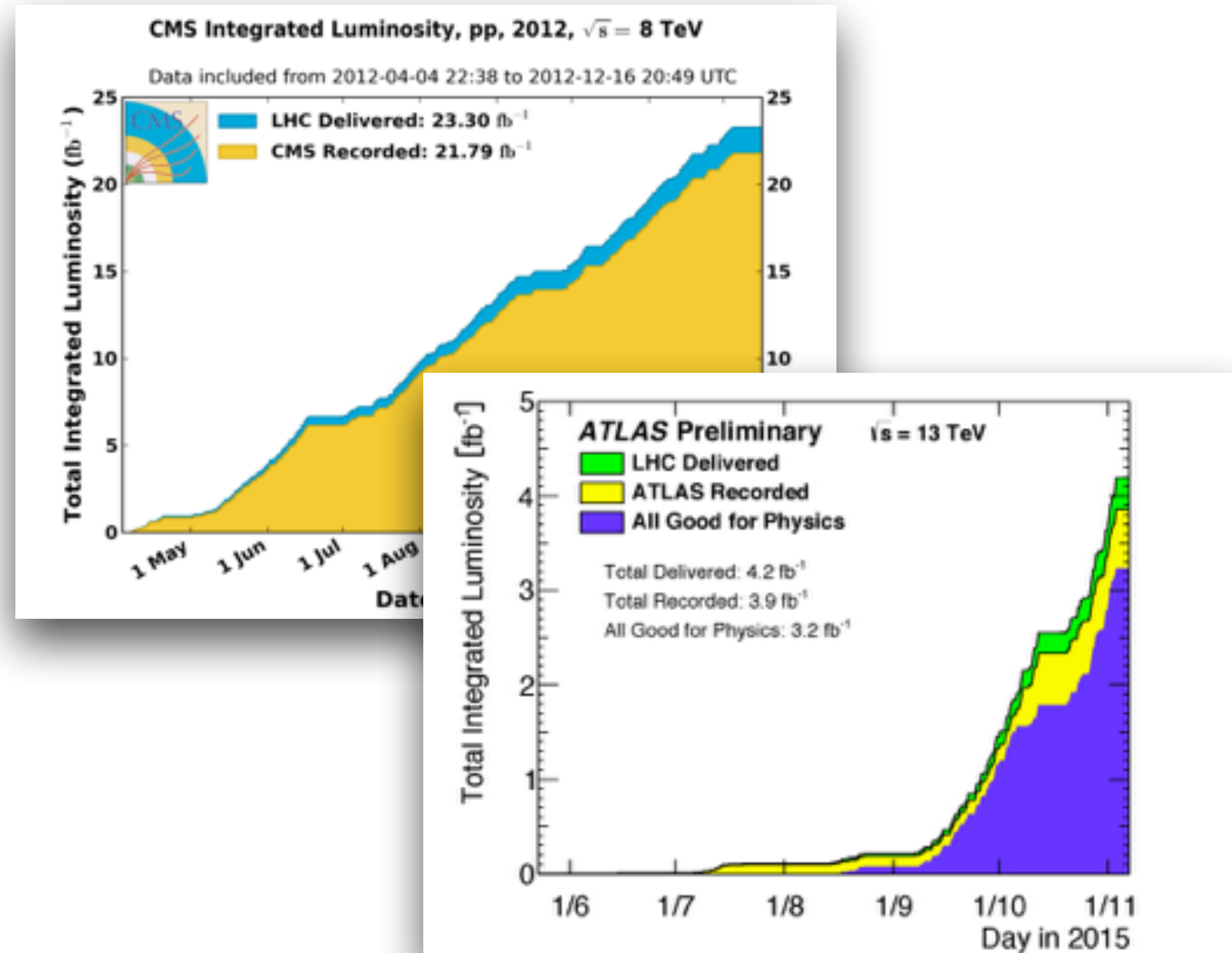
$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

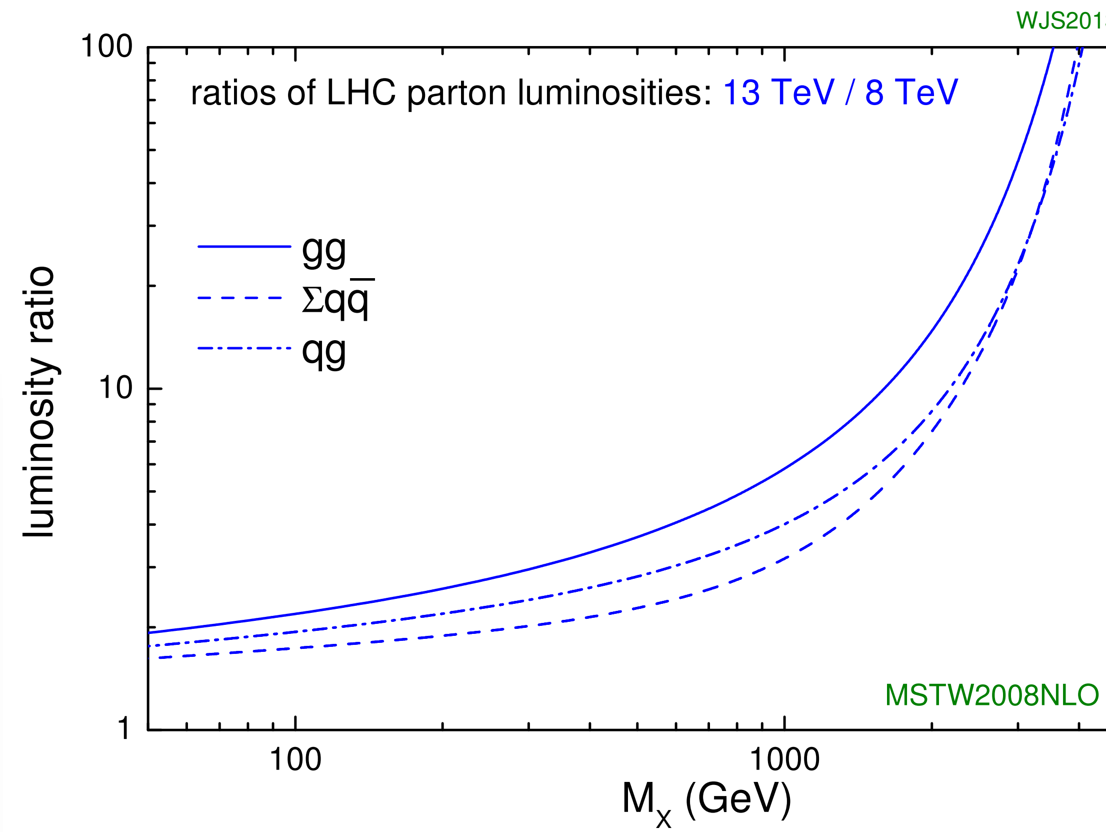


- The abundance is determined by the annihilation cross section.
- Works well for weak scale masses and couplings. → WIMP miracle
- DM could be produced at the LHC.



LHC data





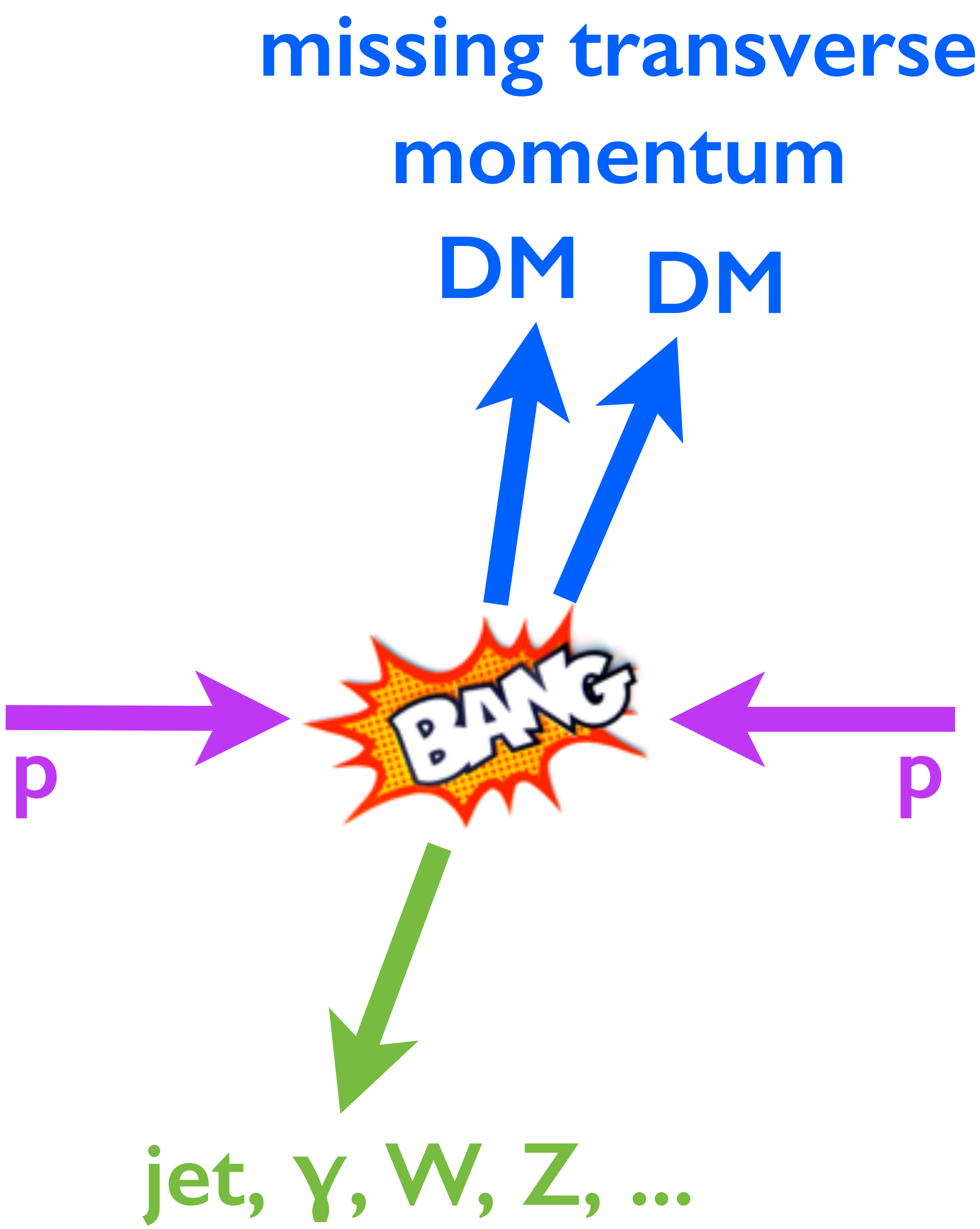
- No signs of BSM physics have been observed in the 8 TeV collisions from Run-1.
- Run-2 has provided around 3 fb^{-1} at 13 TeV already.
- Higher centre-of-mass energy promises better sensitivity to BSM physics especially at higher mass scales.

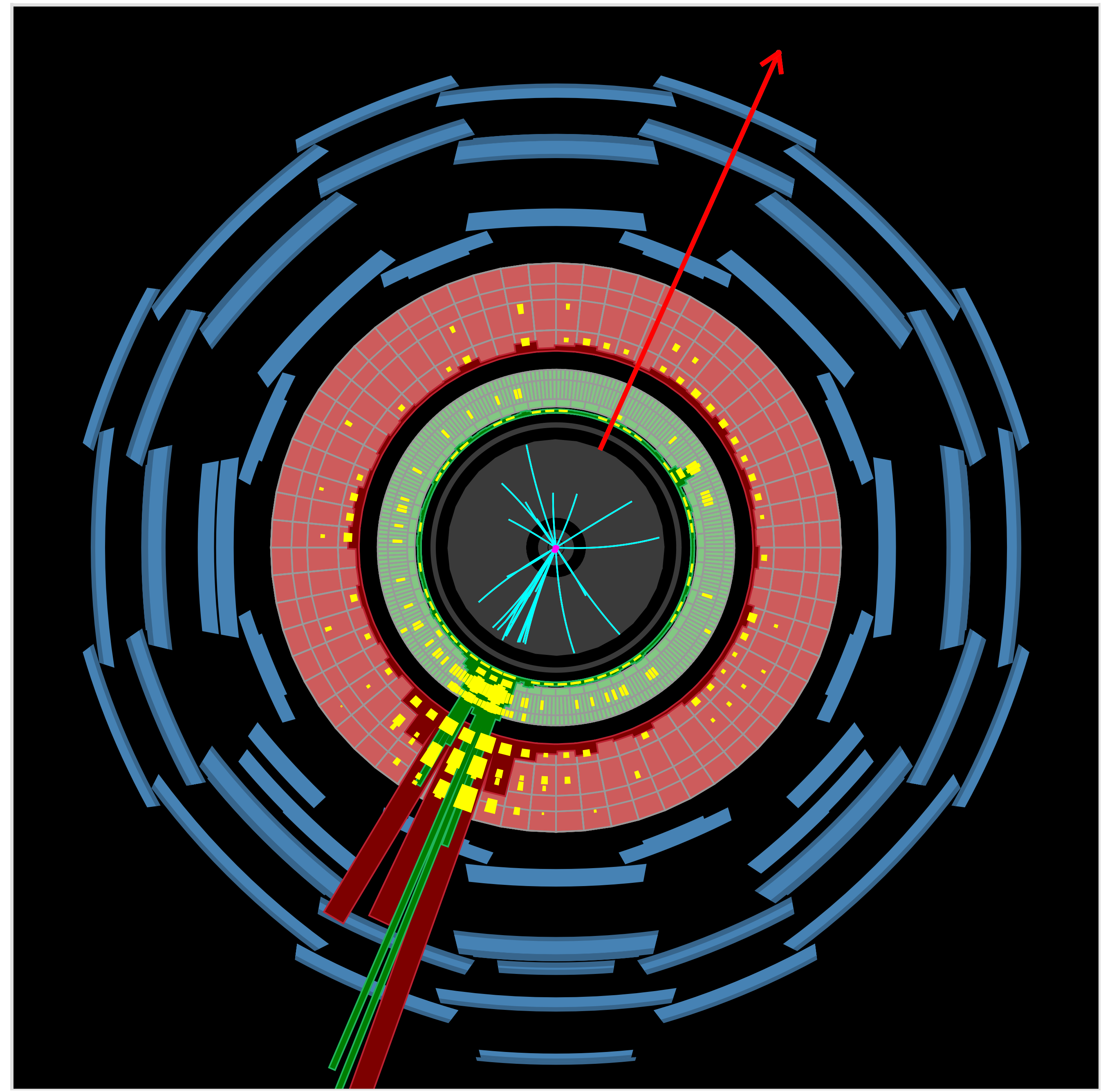
DM signatures

- mono-X → see the talks by Dan Levin and Manfred Jeitler
    - monojet
    - mono-W/Z/γ/H
    - DM + heavy flavor
- dijet
- SUSY
- Higgs portal
- BSM Higgs → see the talk by Zinonas Zinonos
- long-lived particles (composite dark sector)
- indirect constraints from SM precision measurements

Mono-X signatures

- simple idea…

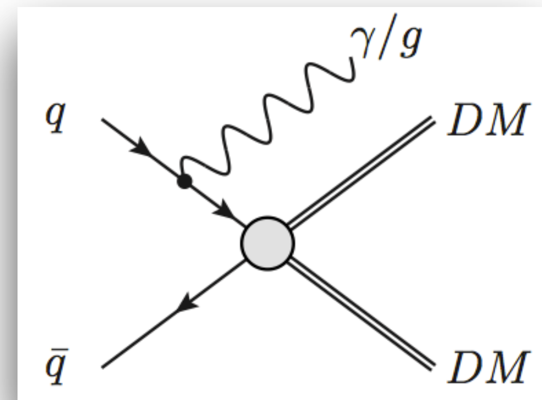




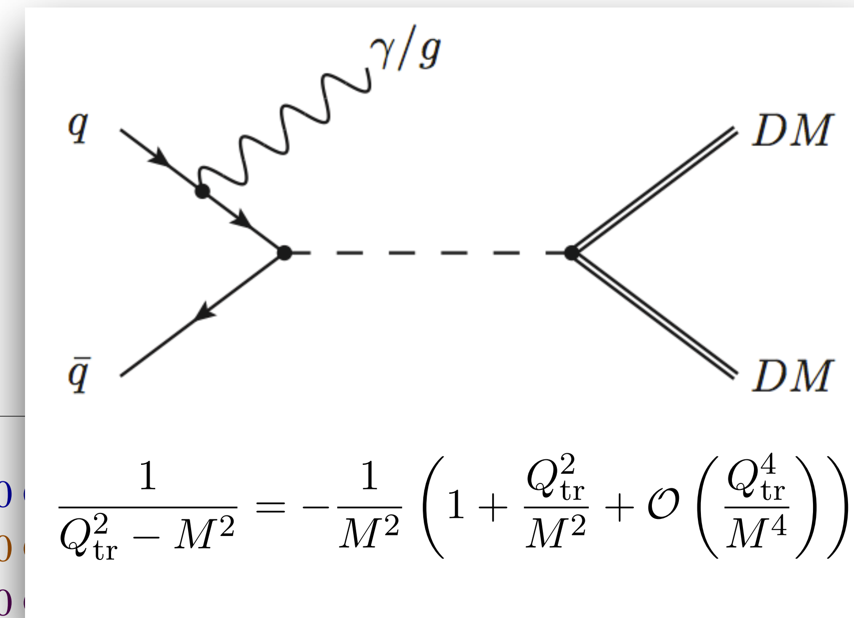
highest pT (~970 GeV) single-jet event observed in the ATLAS 13 TeV data

Effective Field Theories

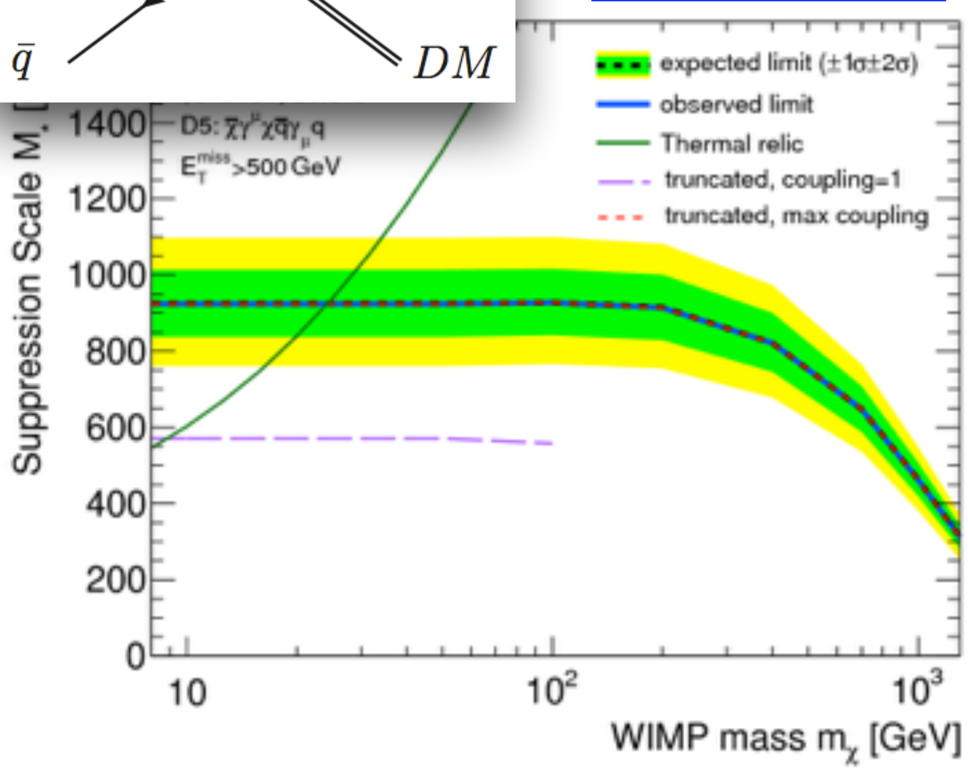
- Effective Field Theory models provide a simple framework to compare collider and non-collider experiments.
- However, it needs to be used with caution at the LHC.

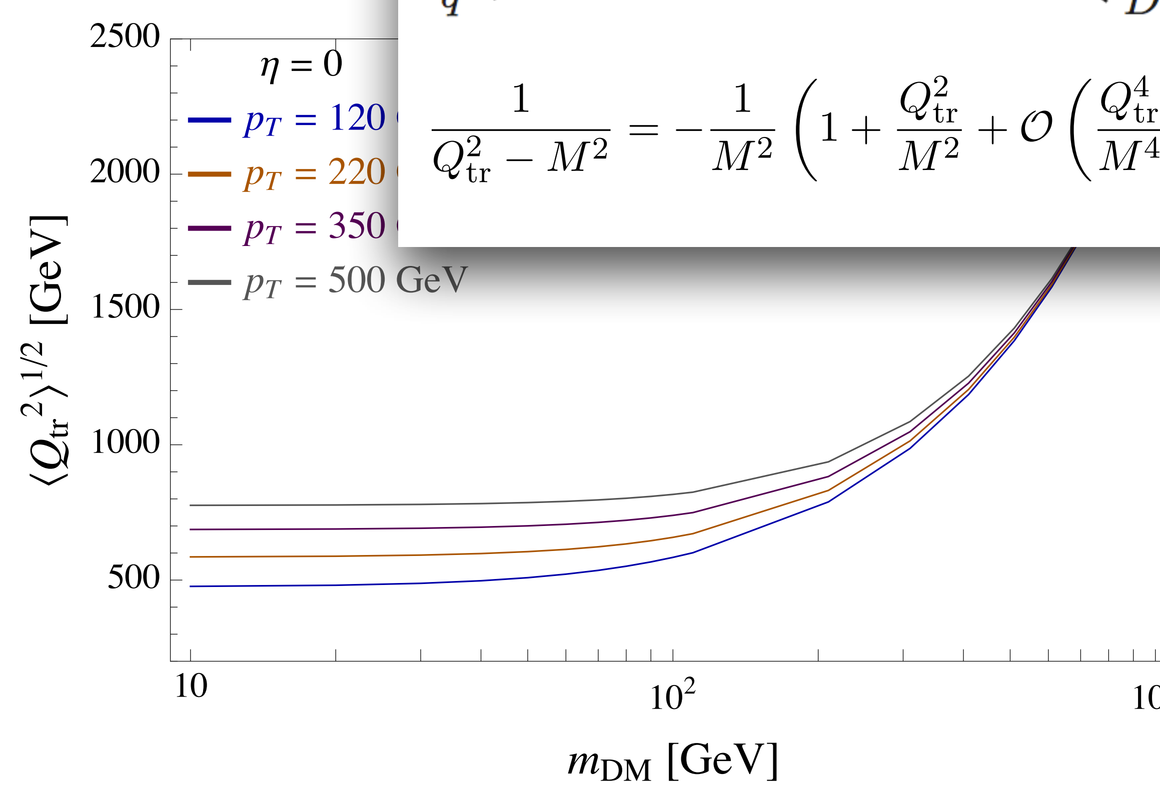


$Q^2_{\text{tr}} \ll M^2$



EXOT-2013-13





- The average momentum transfer is comparable to the inferred EFT interaction scale!

Simplified models

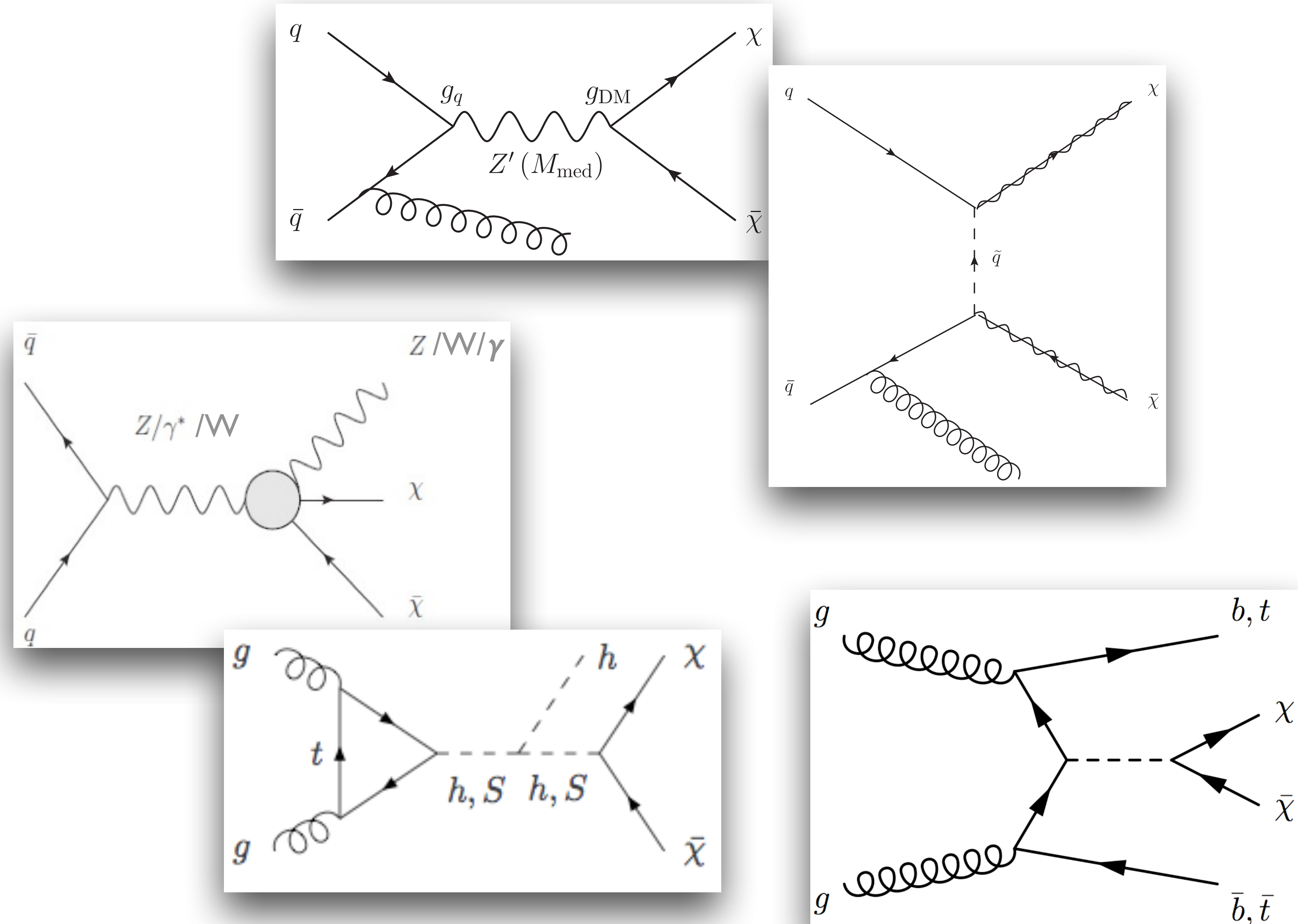
- The Dark Matter Forum report recommends the use of a common set of simplified models for early Run-2 searches by ATLAS and CMS.
- choice of the benchmark models:
  - based on the existing models in literature
  - Does the experimental signature (kinematics) change between models or model points?
  - Does the model add new experimental signature?
- standardised matrix element implementation

Grounding assumptions

- Dirac fermion DM
  - common in literature
  - easy to reinterpret in terms of Majorana fermion
- minimal mediator width
  - reduces the dimension of the parameter space
  - no room for coupling to other particles
  - but couplings to fermions are required by gauge invariance
- Minimal Flavour Violation
  - to ensure the models do not violate flavour constraints
- universal quark couplings
  - although isovector couplings ($g_u = -g_d$) for axial-vector model are also motivated (Z boson couples in this way; constructive coupling for direct detection)

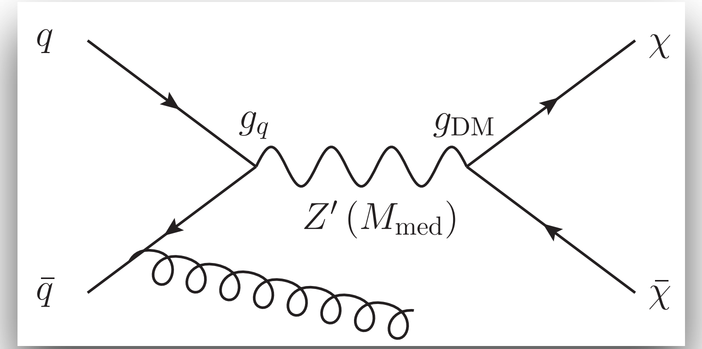
Simplified models

- mono-jet models
  - s-channel
  - t-channel
- electroweak models
  - mono-Z/W/γ
  - mono-H
- heavy flavour



- These benchmark models are only a starting point towards more complete models…
- ➡ future models?
- ➡ reinterpretations

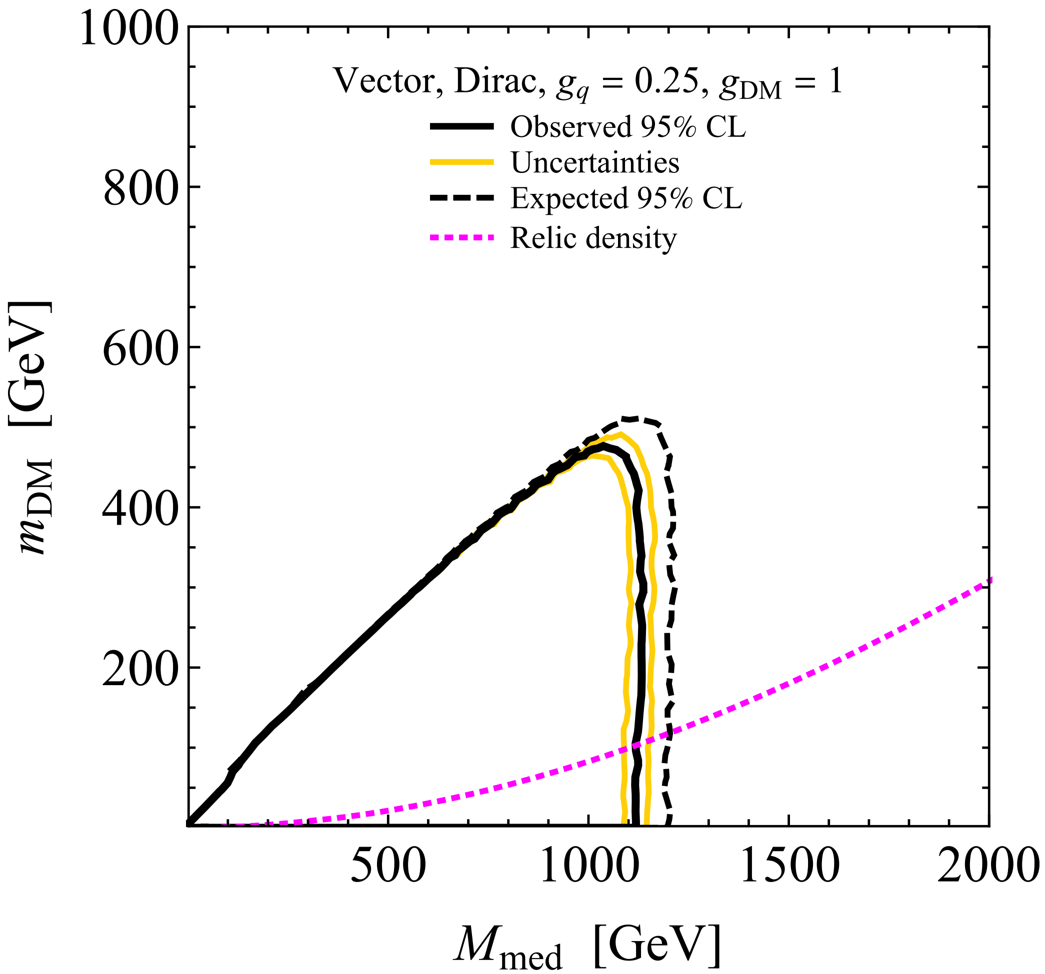
Interpretation



$$\mathcal{L}_{\text{axial-vector}} = -g_{\rm DM} Z'_\mu \bar{\chi}\gamma^\mu\gamma_5\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu\gamma_5 q$$

$$\Gamma^{\chi\bar{\chi}}_{\text{axial-vector}} = \frac{g^2_{\rm DM}\,M_{\rm med}}{12\pi}\,(1-4\,z_{\rm DM})^{3/2}$$

$$\Gamma^{q\bar{q}}_{\text{axial-vector}} = \frac{g^2_q\,M_{\rm med}}{4\pi}\,(1-4\,z_q)^{3/2}\ .$$

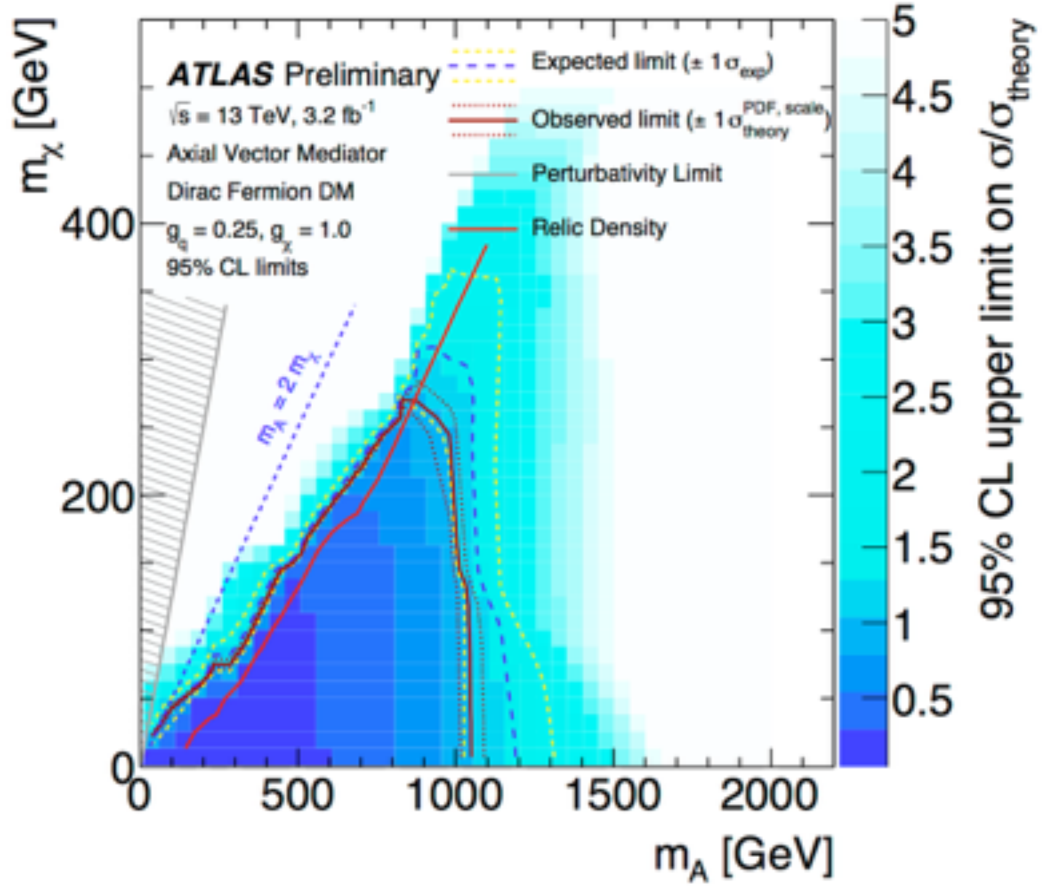


- mass-mass plane: 2-dimensional slice of the 4-dimensional parameter space
- Relic density indicates where this particular model explains the observed abundance.
- perturbative unitarity $m_{\rm DM} = \sqrt{\pi/2}\,M_{\rm med}$ 1510.02110

→ see the talk by Felix Kahlhoefer

Interpretation

EXOT-2015-03



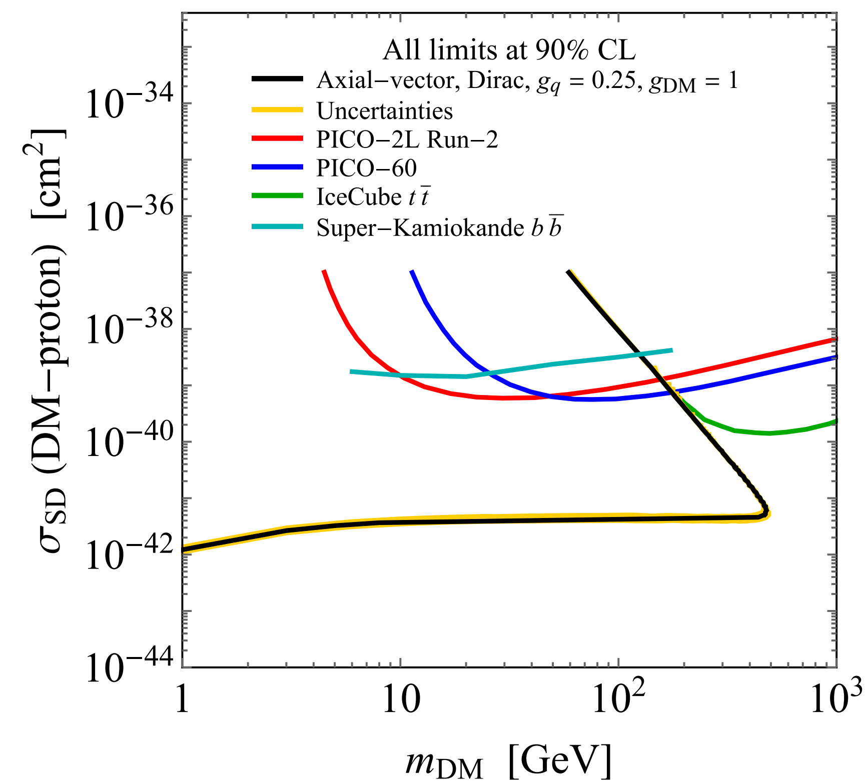
- In addition, auxiliary plot showing the limit on the signal strength μ may be shown.
- However, it should be made clear that μ must not be confused with a cross section rescaling factor.
- Usefulness of such bound on μ is limited to scenarios where kinematic distributions remain unaltered for different realisation of the simplified model.
- Narrow width approximation → $\sigma(pp\rightarrow\chi\chi+j) = \sigma(pp\rightarrow Z'+j)\ BR(Z\rightarrow\chi\chi)$

Comparison to non-collider results

- Direct detection

$$\sigma_{\rm SI} \simeq 6.9 \times 10^{-43}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{1}\right)^2 \left(\frac{125\ {\rm GeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$$

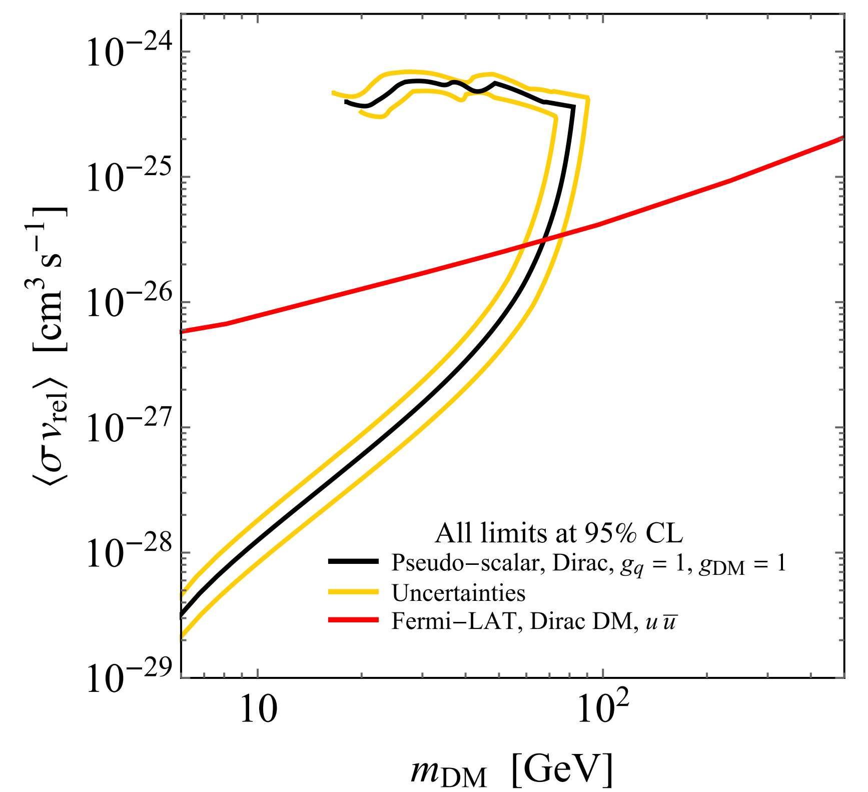
$$\sigma^{\rm SD} \simeq 2.4 \times 10^{-42}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$$



- Indirect detection

$$\langle \sigma v_{\rm rel}\rangle_q = \frac{3m_q^2}{2\pi v^2} \frac{g_q^2 g_{\rm DM}^2 m_{\rm DM}^2}{(M_{\rm med}^2 - 4m_{\rm DM}^2)^2 + M_{\rm med}^2\Gamma_{\rm med}^2} \sqrt{1 - \frac{m_q^2}{m_{\rm DM}^2}}$$

$$\langle \sigma v_{\rm rel}\rangle_g = \frac{\alpha_s^2}{2\pi^3 v^2} \frac{g_q^2 g_{\rm DM}^2}{(M_{\rm med}^2 - 4m_{\rm DM}^2)^2 + M_{\rm med}^2\Gamma_{\rm med}^2} \left|\sum_q m_q^2 f_{\text{pseudo-scalar}}\left(\frac{m_q^2}{m_\chi^2}\right)\right|^2$$

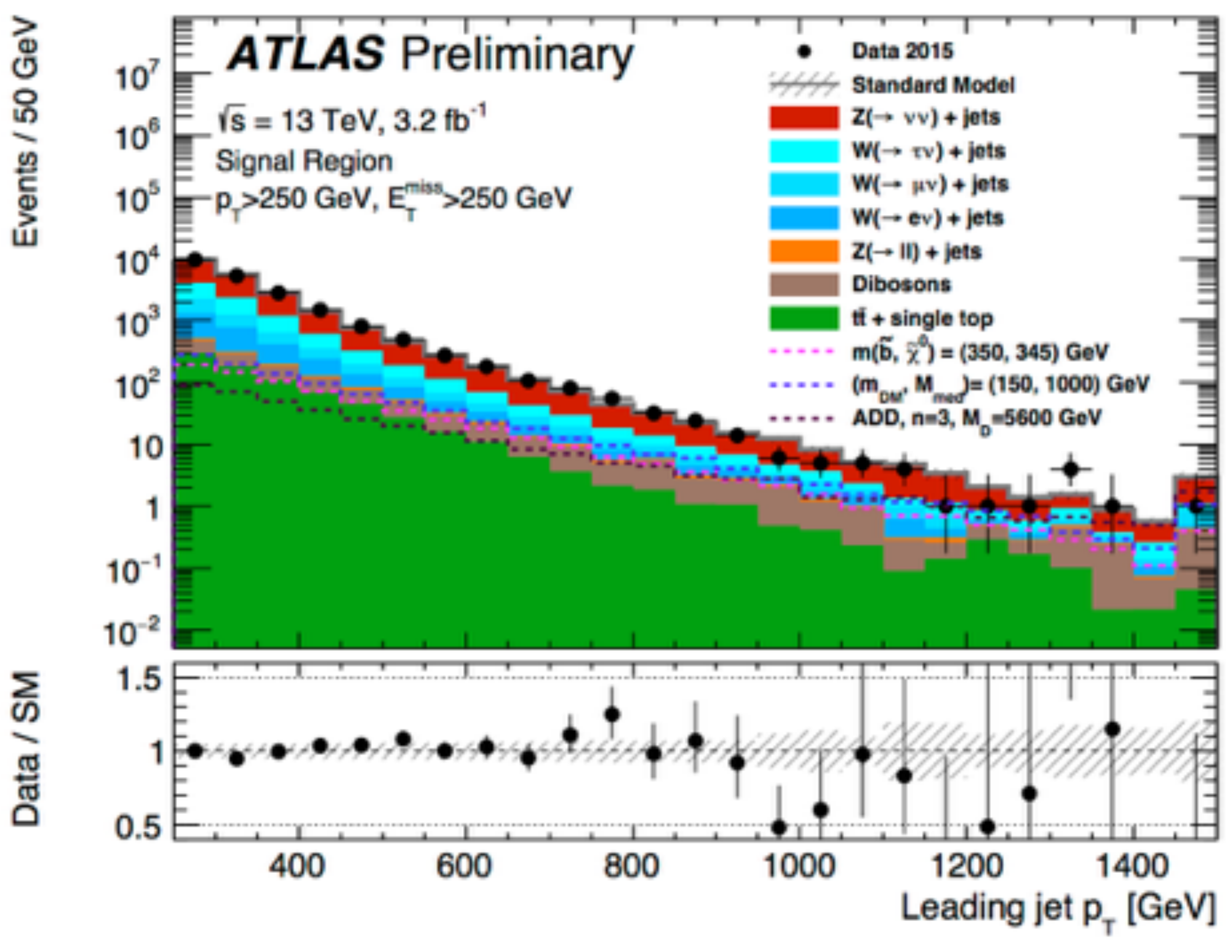


- These interpretations are valid within the context of these particular models only!

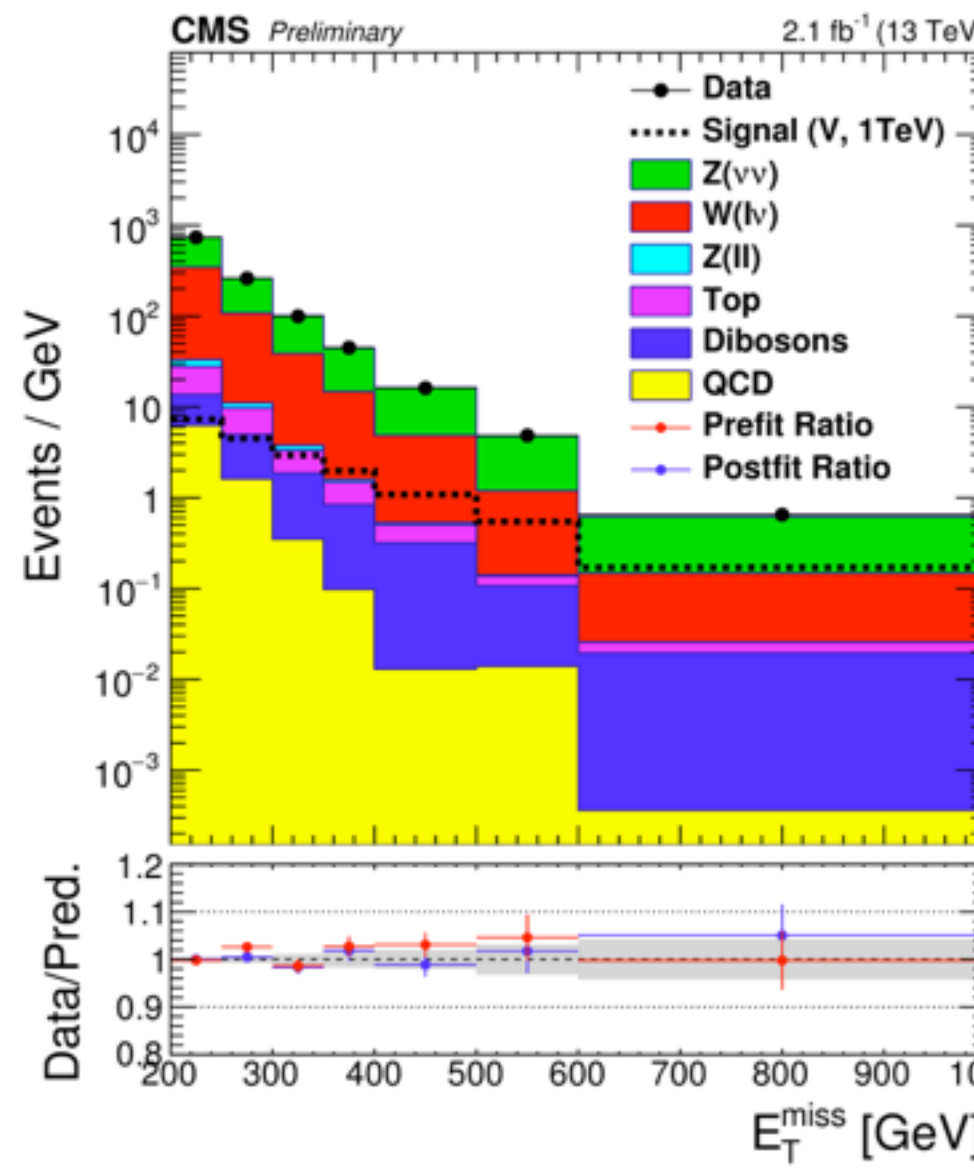
Monojet searches

- The mono-jet analysis is taken as the most sensitive generic DM search…

EXOT-2015-03



EXO-15-003



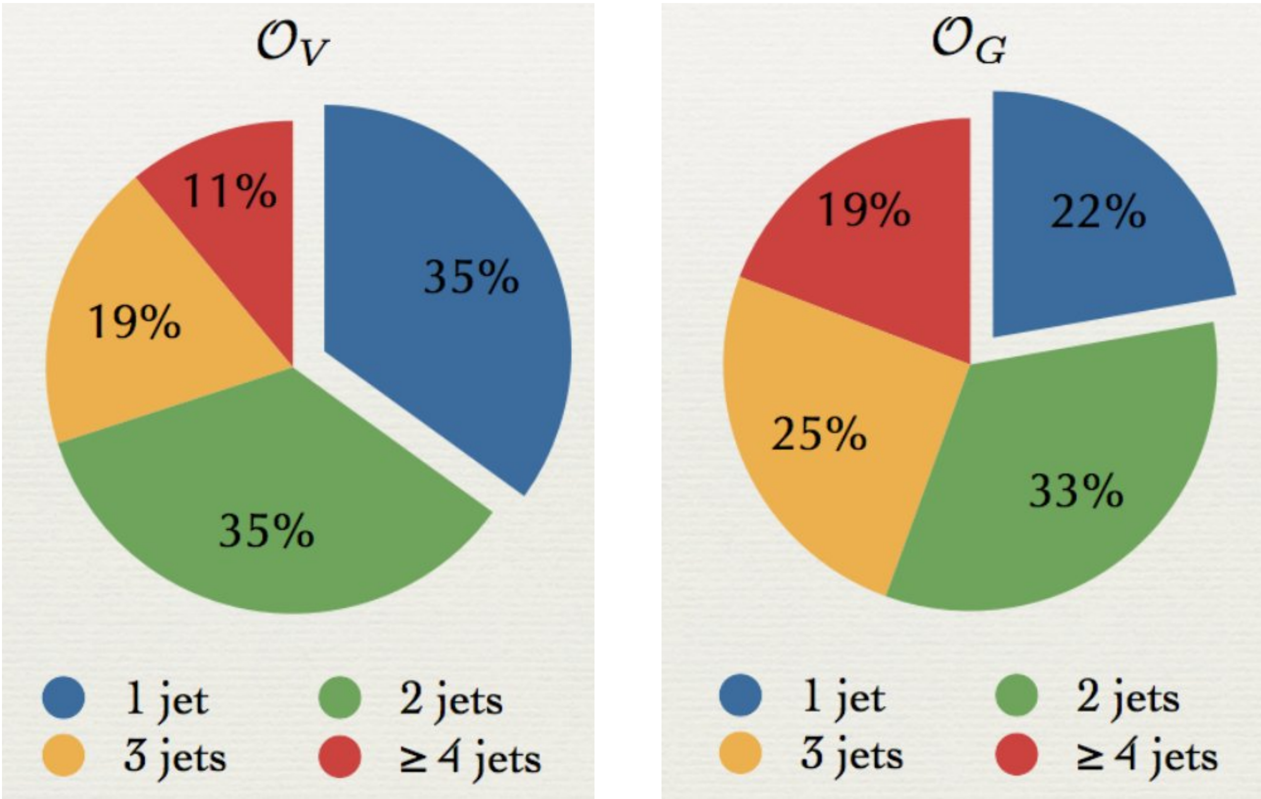
- … **Is it really the case?**

Jet multiplicity

- jet multiplicity in the monojet searches:
  - ATLAS 7 TeV: exactly 1 jet
  - CMS 7 and 8 TeV: up to 2 jets
  - ATLAS 8 TeV: monojet-like (pT/MET > 0.5)
  - ATLAS 13 TeV: up to 4 jets
  - CMS 13 TeV: fully inclusive search
- The jet multiplicity selection is driven by two factors:
  - orthogonality to other searches (e.g. SUSY starts with 2 jets)
  - sensitivity to DM models

- Large portion of the signal cross section comes from higher jet multiplicity final states.
- It is important to model the QCD effects precisely (NLO implementation)

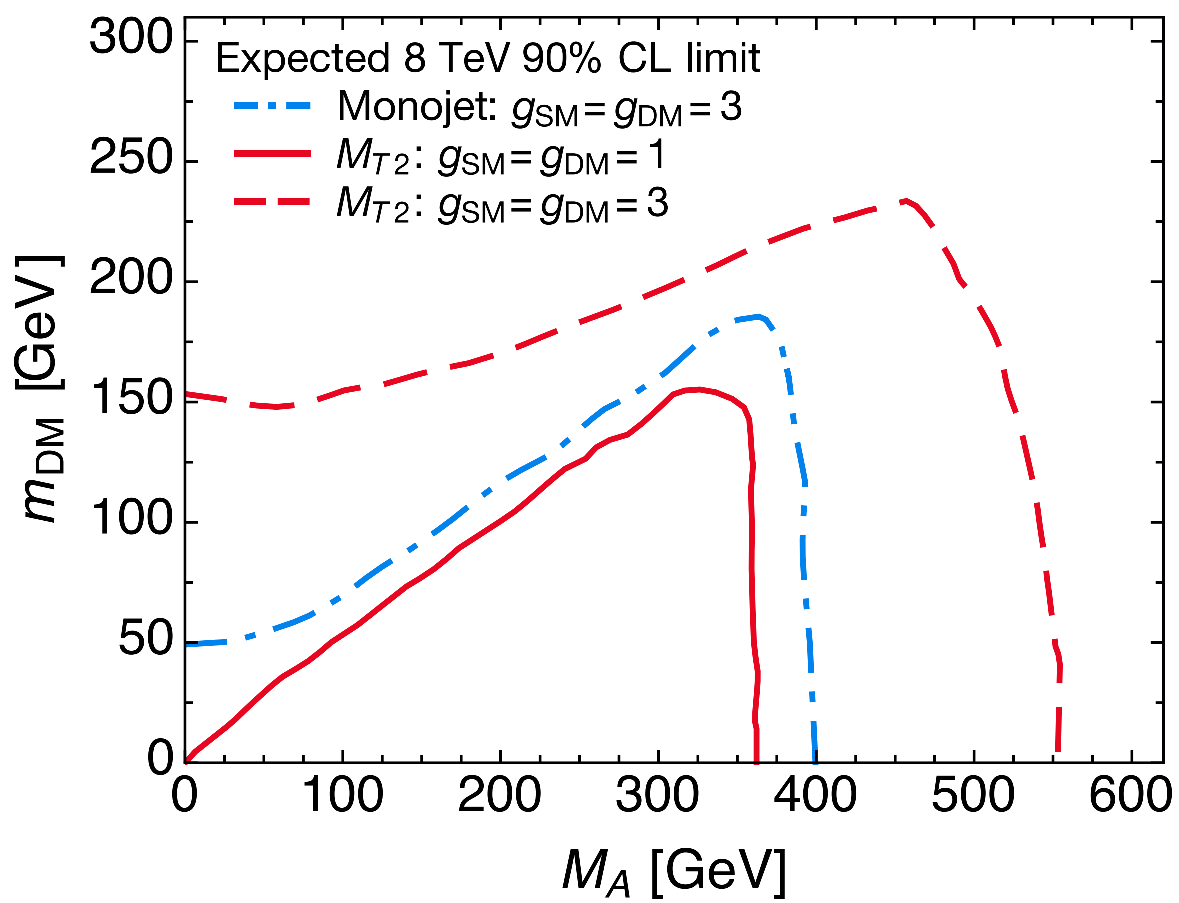
1310.4491



Jet multiplicity

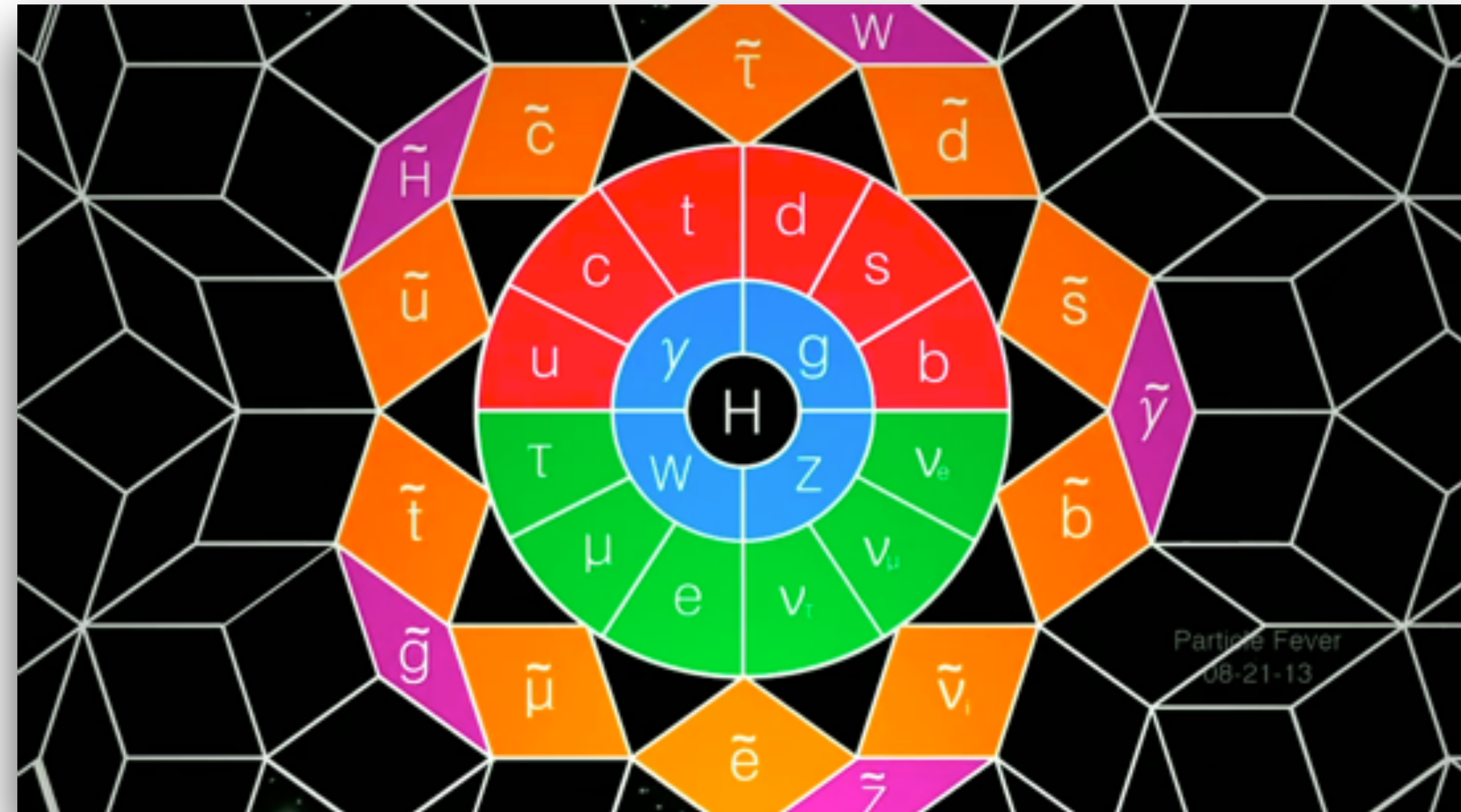
- Production of pseudo-scalar or scalar mediators is dominated by gluon fusion which in general leads to higher jet multiplicities.
- Multijet searches, such as M_{T2} search, may have stronger sensitivity to pseudo-scalar mediators than monojets.

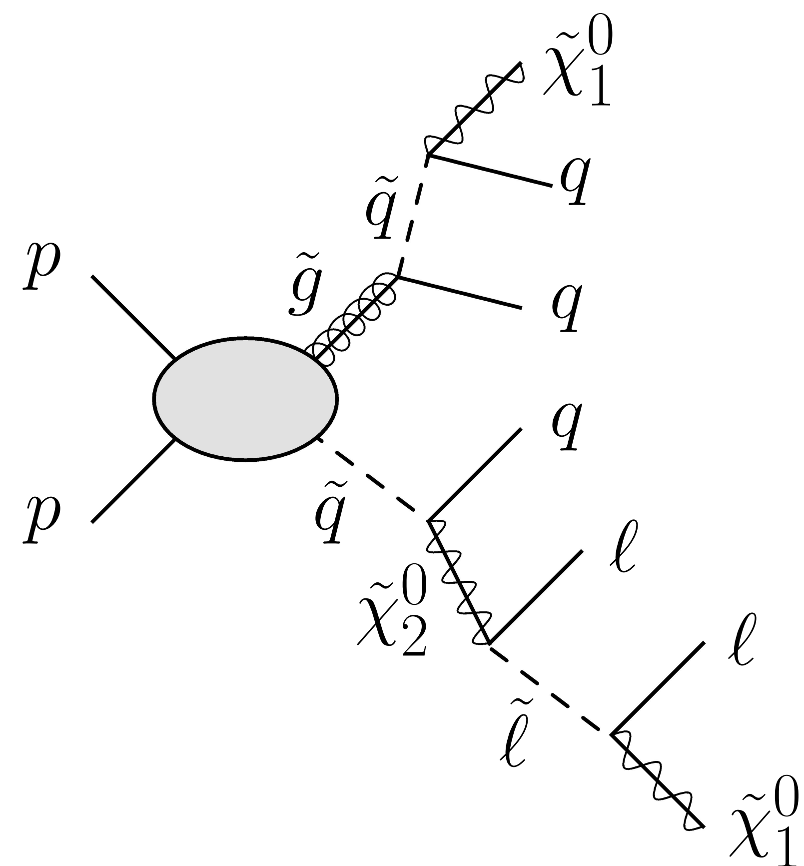
$$M_{T2}^2 \equiv \min_{\not{\mathbf{p}}_1 + \not{\mathbf{p}}_2 = \not{\mathbf{p}}_T} \left[\max \left\{ m_T^2(\mathbf{p}_{Tl^-}, \not{\mathbf{p}}_1), m_T^2(\mathbf{p}_{Tl^+}, \not{\mathbf{p}}_2) \right\} \right]$$

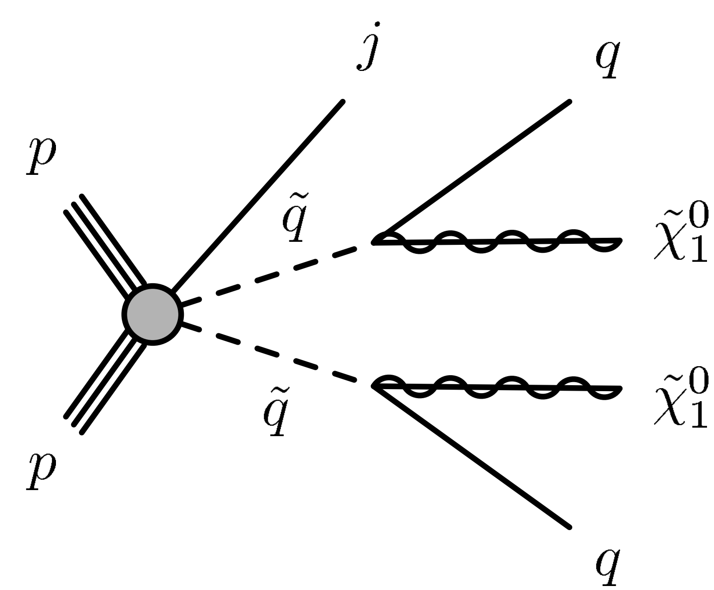


hep-ph/9906349
1502.04358

Supersymmetry





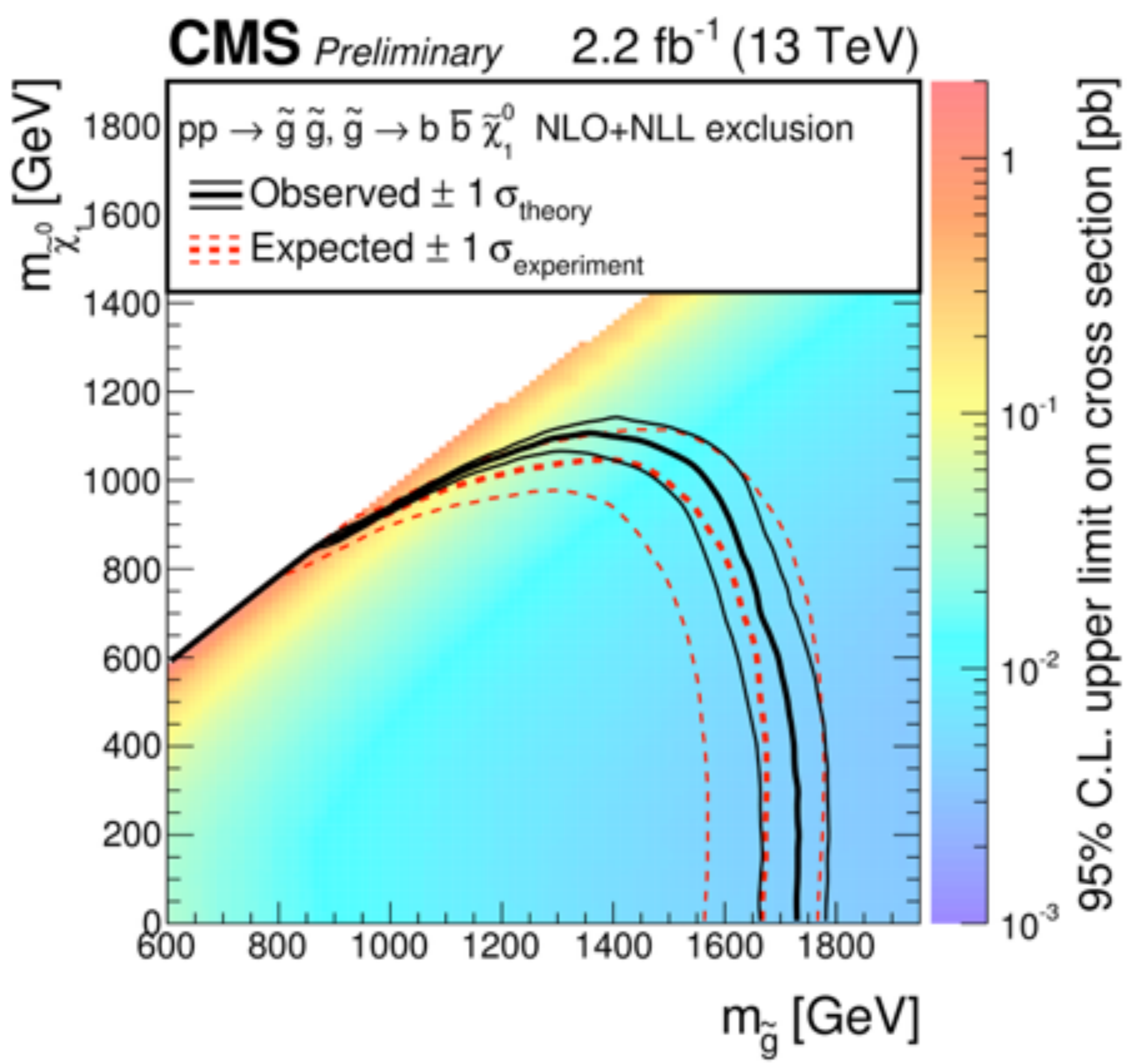


- SUSY searches usually involve 2 or more visible final state particles and missing transverse momentum (due to LSP dark matter).
- Compressed spectra may lead to monojet final states (soft jets due to small mass splitting).

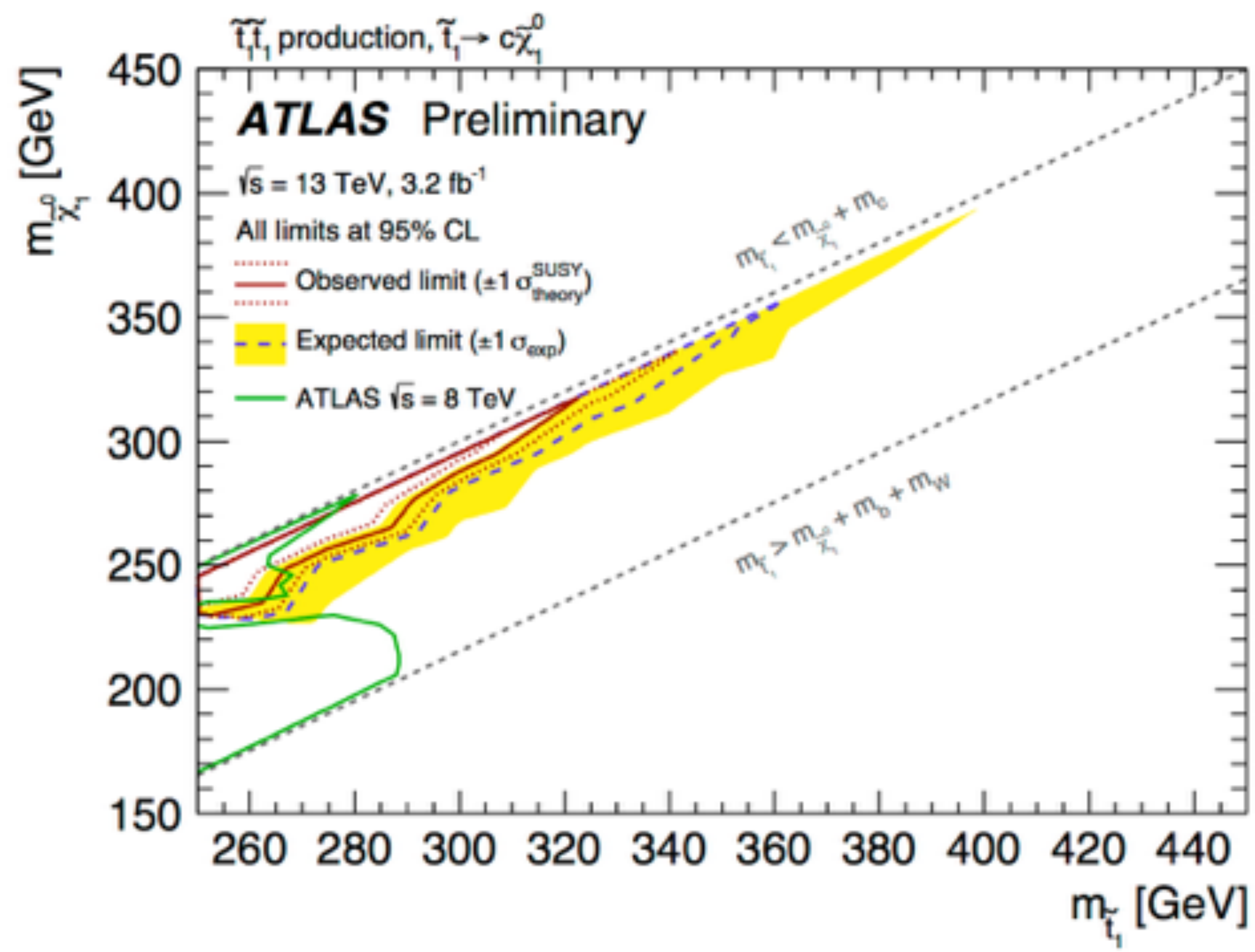
➡ complementarity between mono-X and SUSY

Examples from Run-2

- CMS inclusive 0L, MT2
  bottom squark NLSP
  [1603.04053]

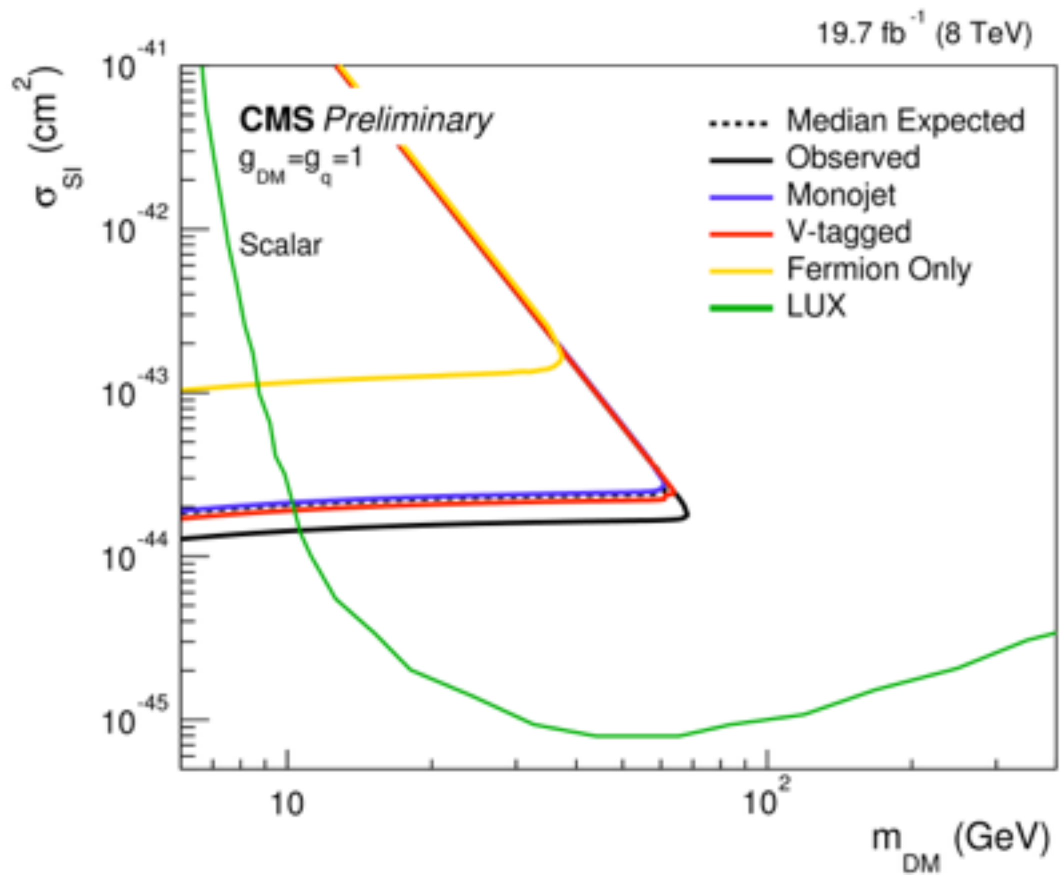


- ATLAS monojet
  top squark NLSP
  [EXOT-2015-03]

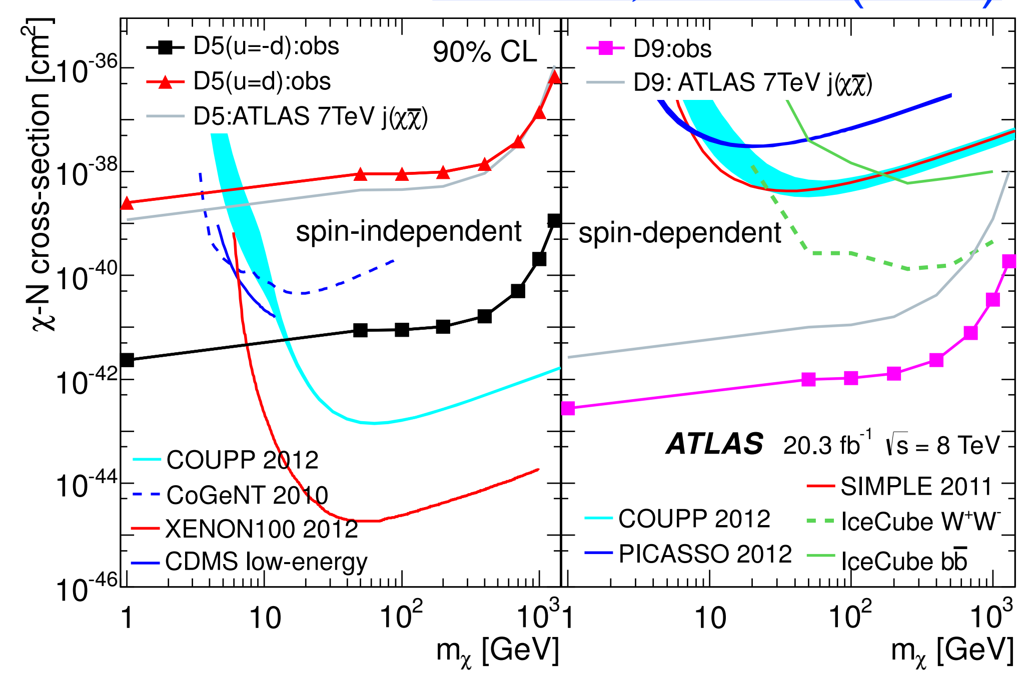


Mono-W/Z(qq)

- jet final states
  - Mono-W/Z(qq) signal may also pass the monojet selection.
  - CMS accounts for this by performing a combined search for new physics in the V/jet + MET final states.
    EXO-12-055

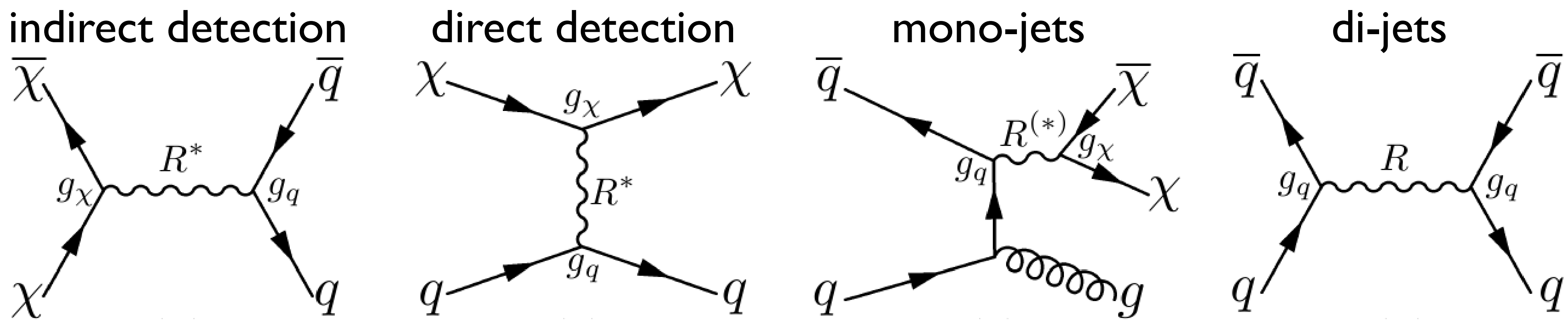


- gauge invariance
  - Constructive interference (u = -d) leads to enhanced LHC sensitivity. PRL 112, 041802 (2014)

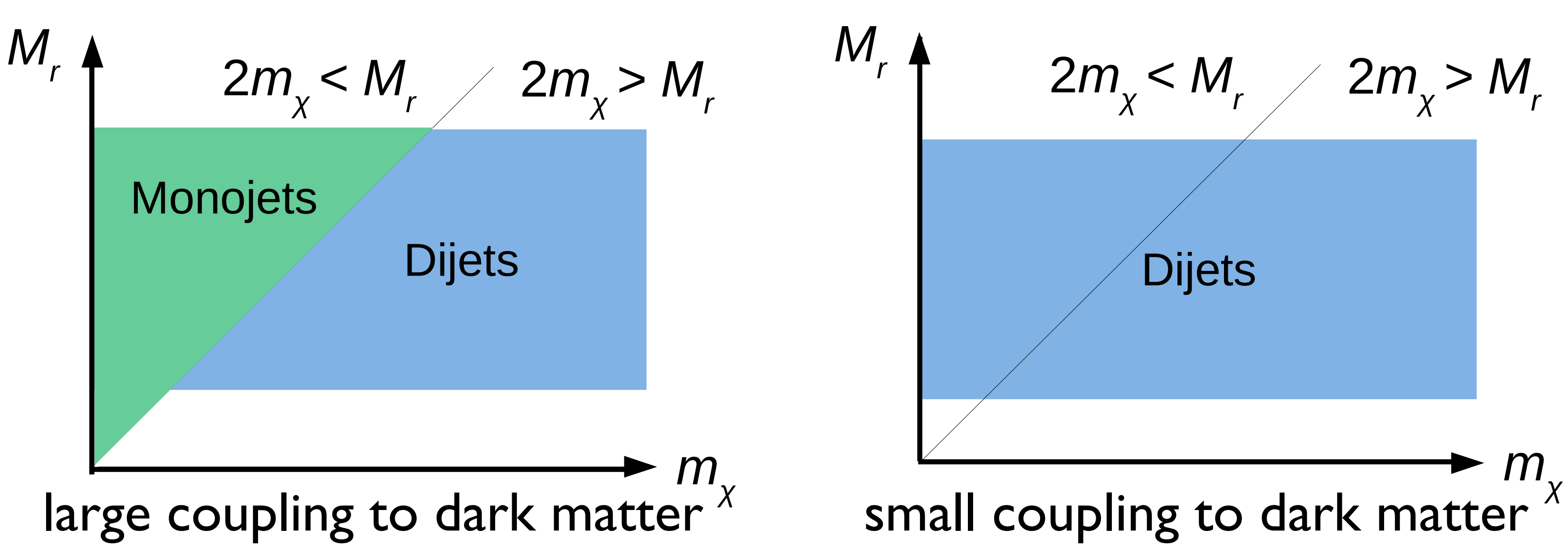


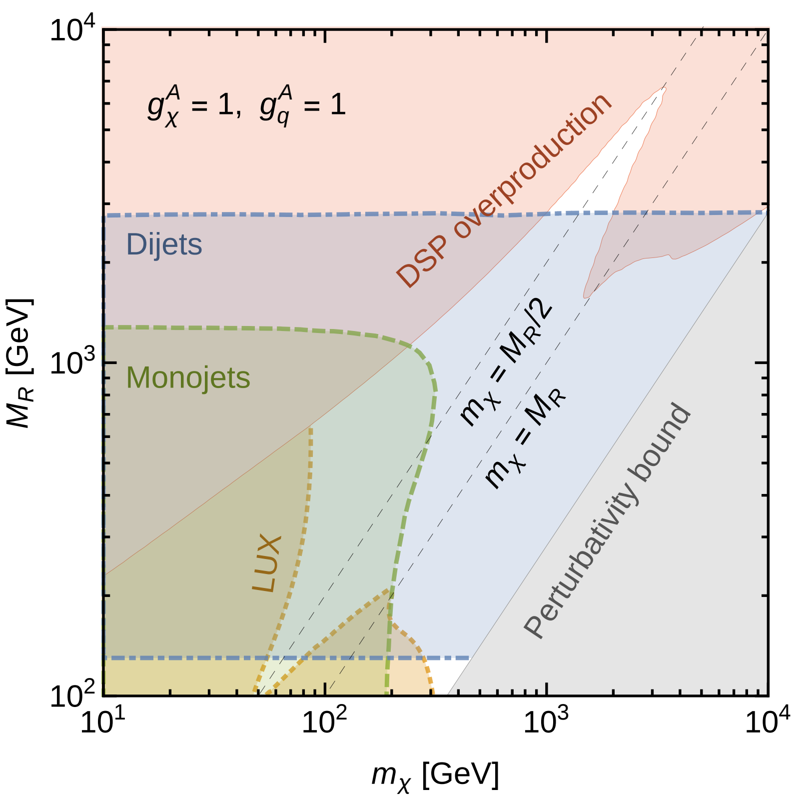
  - However, such extreme interference violates gauge invariance.
    1503.07874

Searching for new mediators



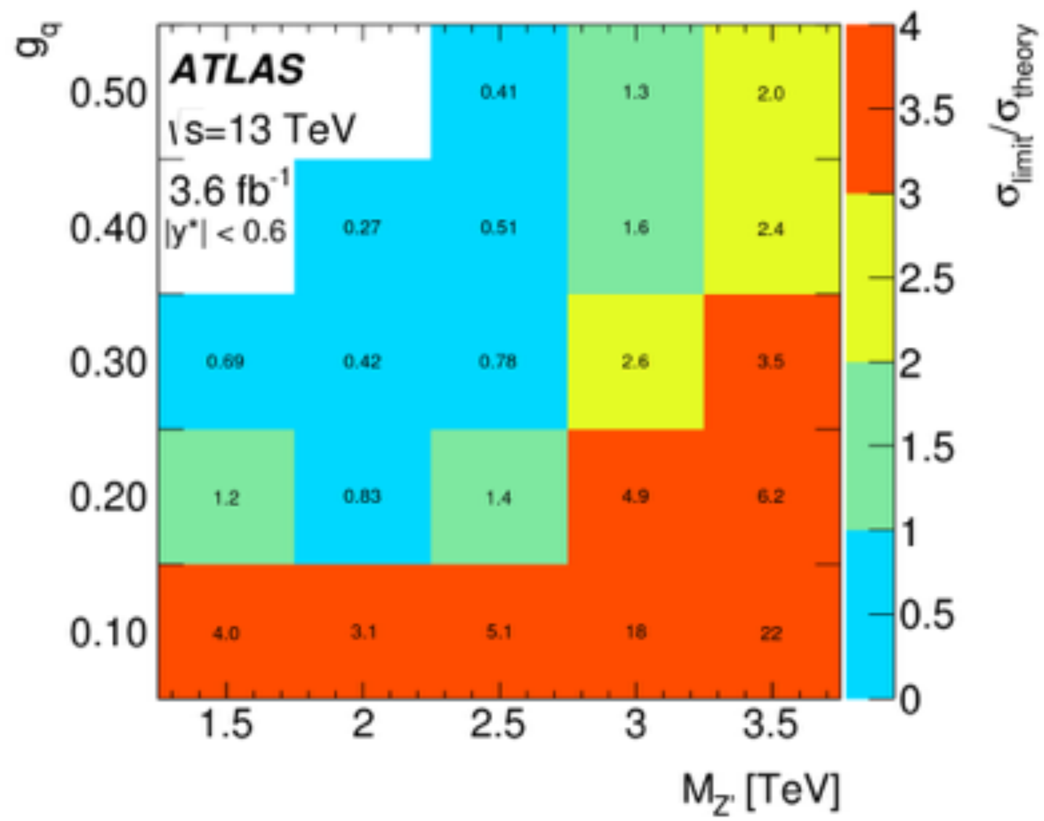
- s-channel simplified models: 4 free parameters: m_χ, M_R, g_q, g_χ
- Simplified models allow for a richer phenomenology and more complex interpretations → complementarity among various search channels at the LHC, e.g. mono-jets and di-jets 1503.05916

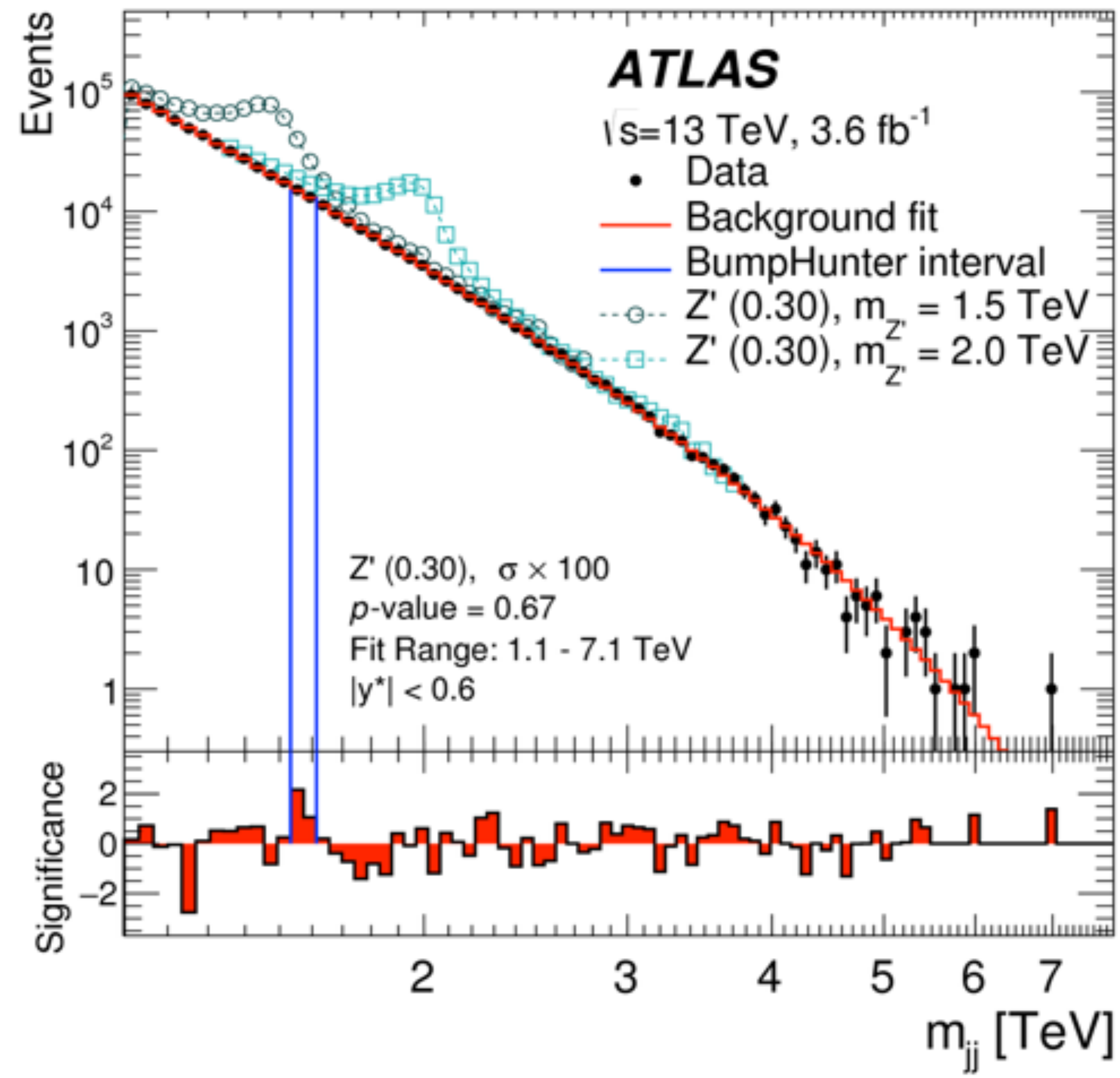




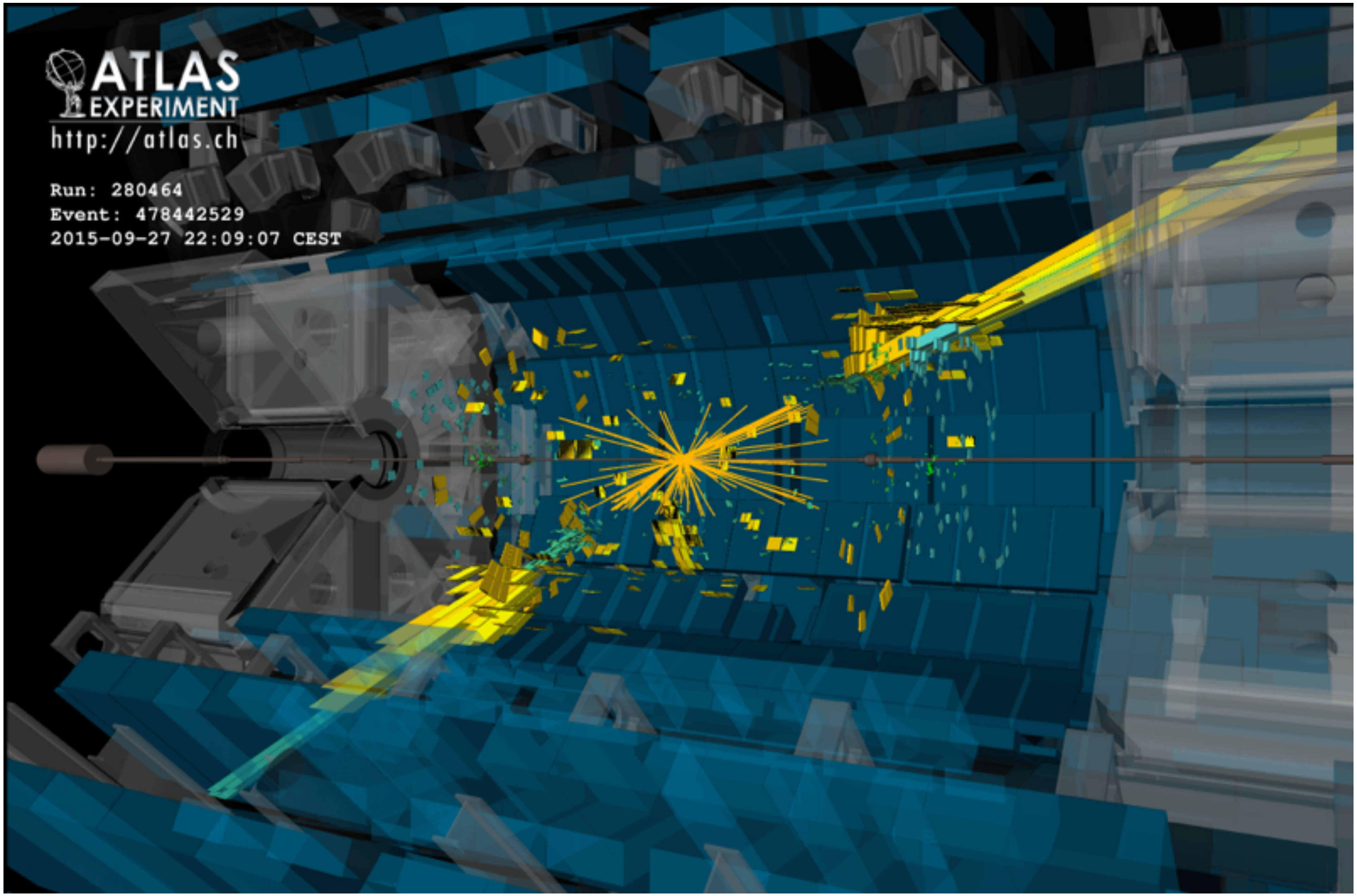
Dijet resonances

- Selection:
  - $p_T > 440$ GeV
  - $|y^*| = \frac{1}{2}|y_1 - y_2| < 0.6$
- Background obtained from a fit
  $p1\,(1-x)^{p2}\,x^{p3 + p4 \ln x}$
- BumpHunter most discrepant interval



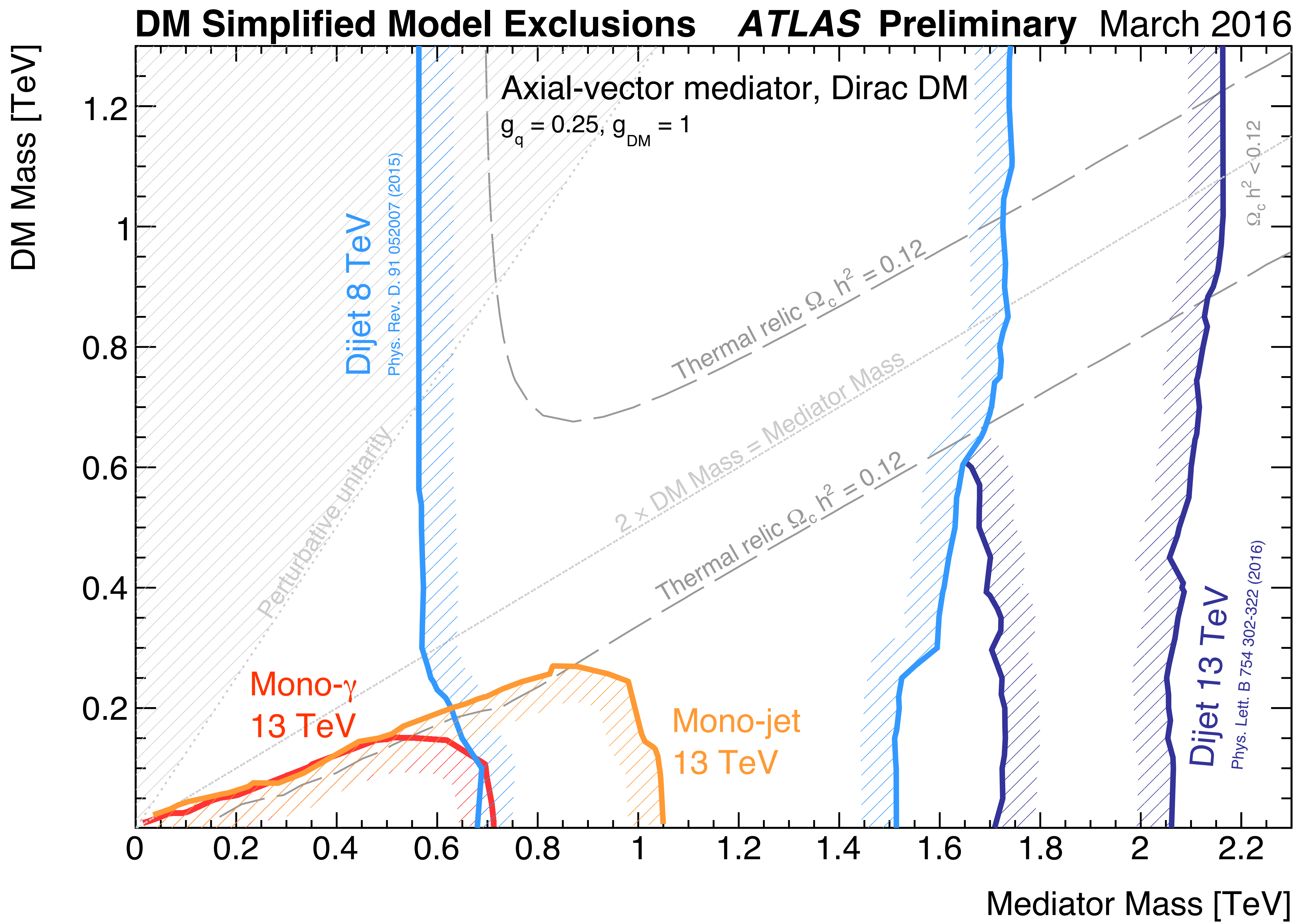


Dijet event



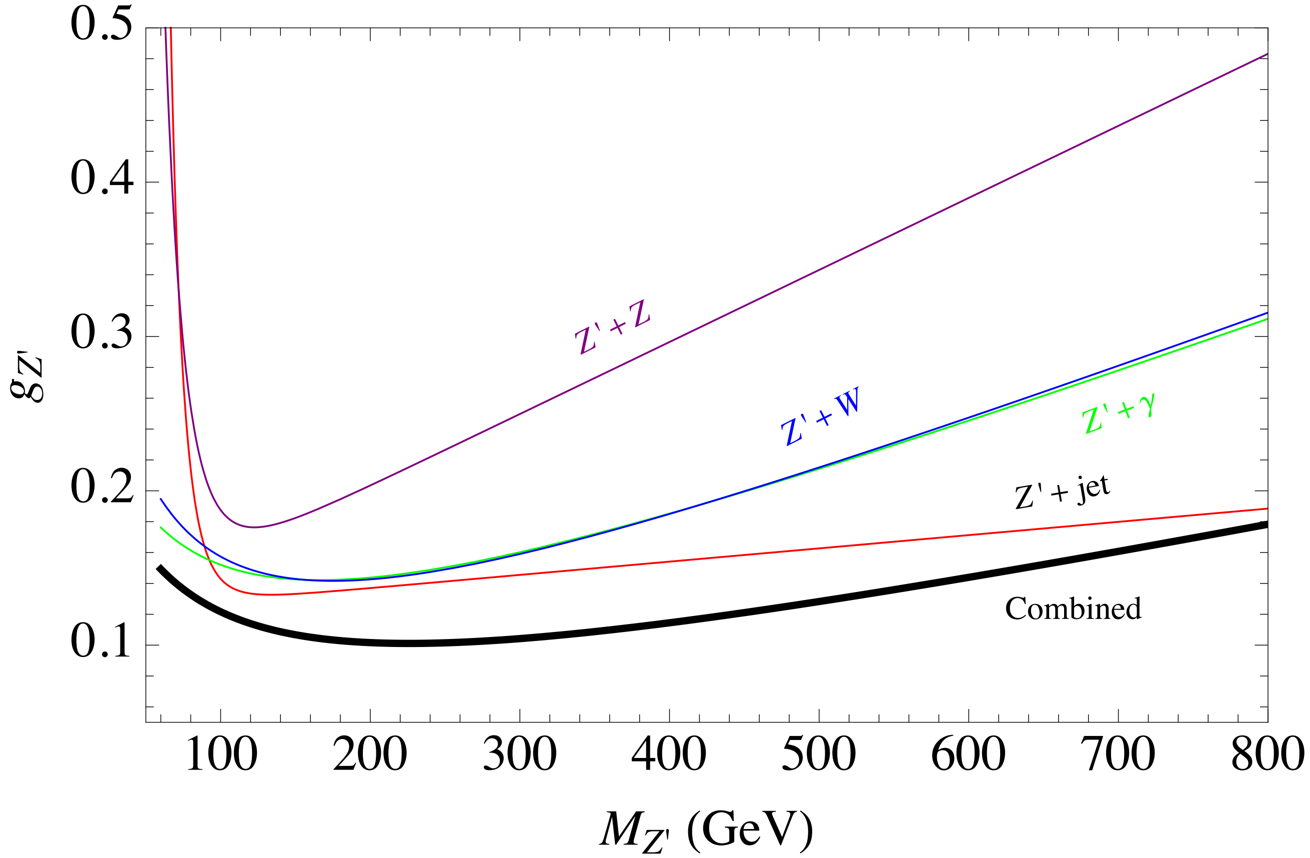
two central high-pT jets with invariant mass of 7.9 TeV observed in the ATLAS 13 TeV data

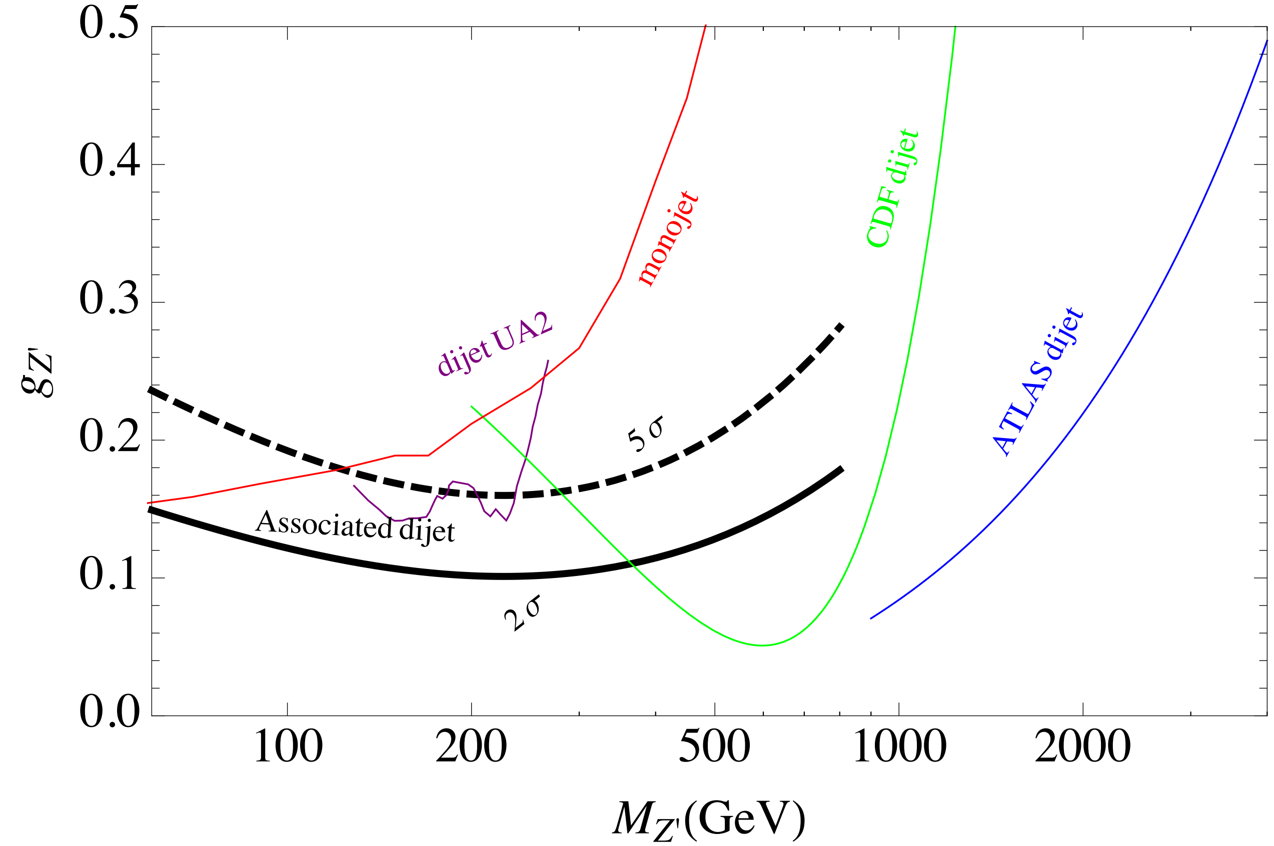
Summary plot



Associated dijet production

- For large couplings, the usual searches for narrow resonances no longer apply.
- The multijet background limits the LHC searches for Z’ below 1 TeV.
- Searching for associated dijet production may increase the sensitivity to lower masses.

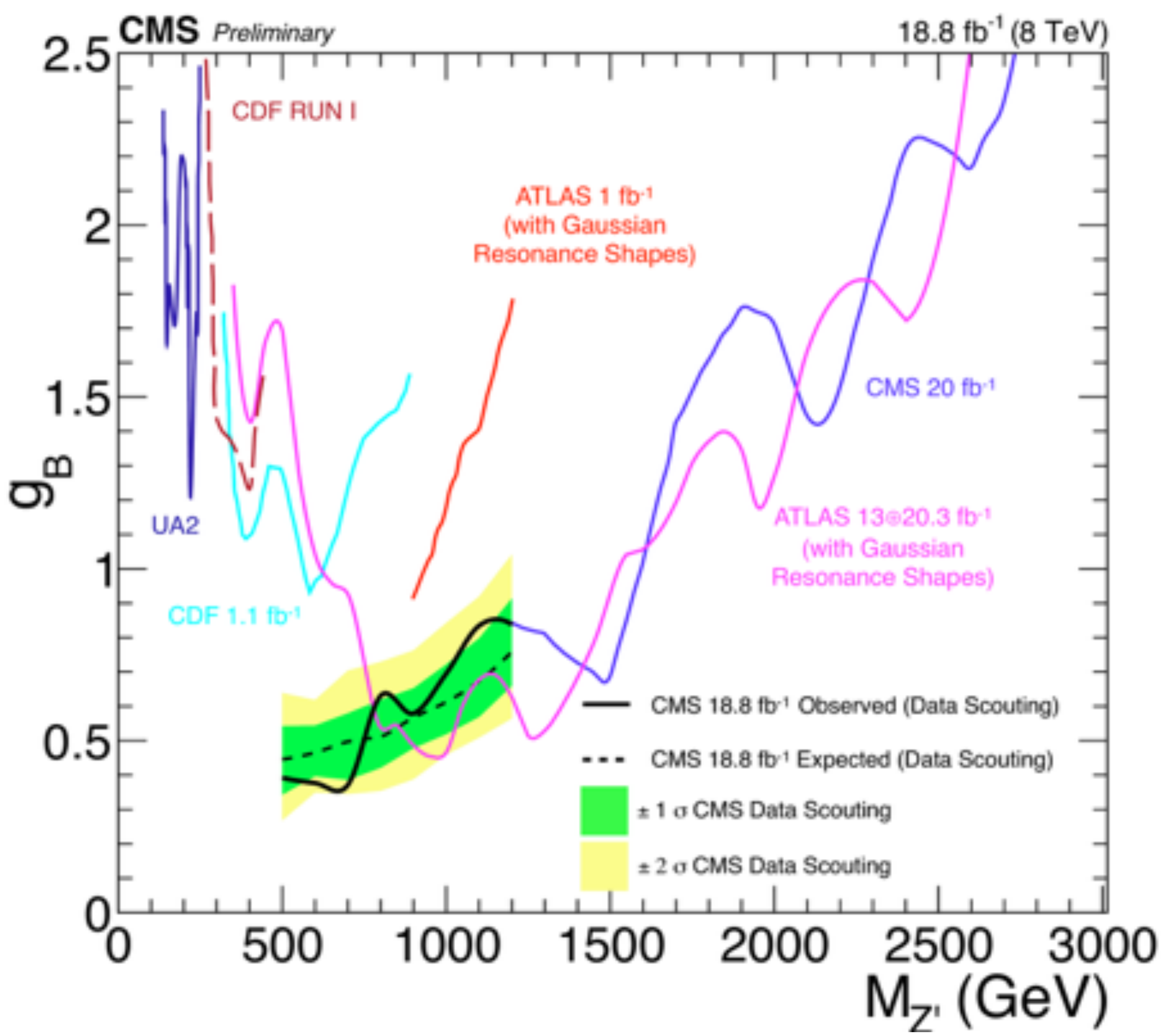


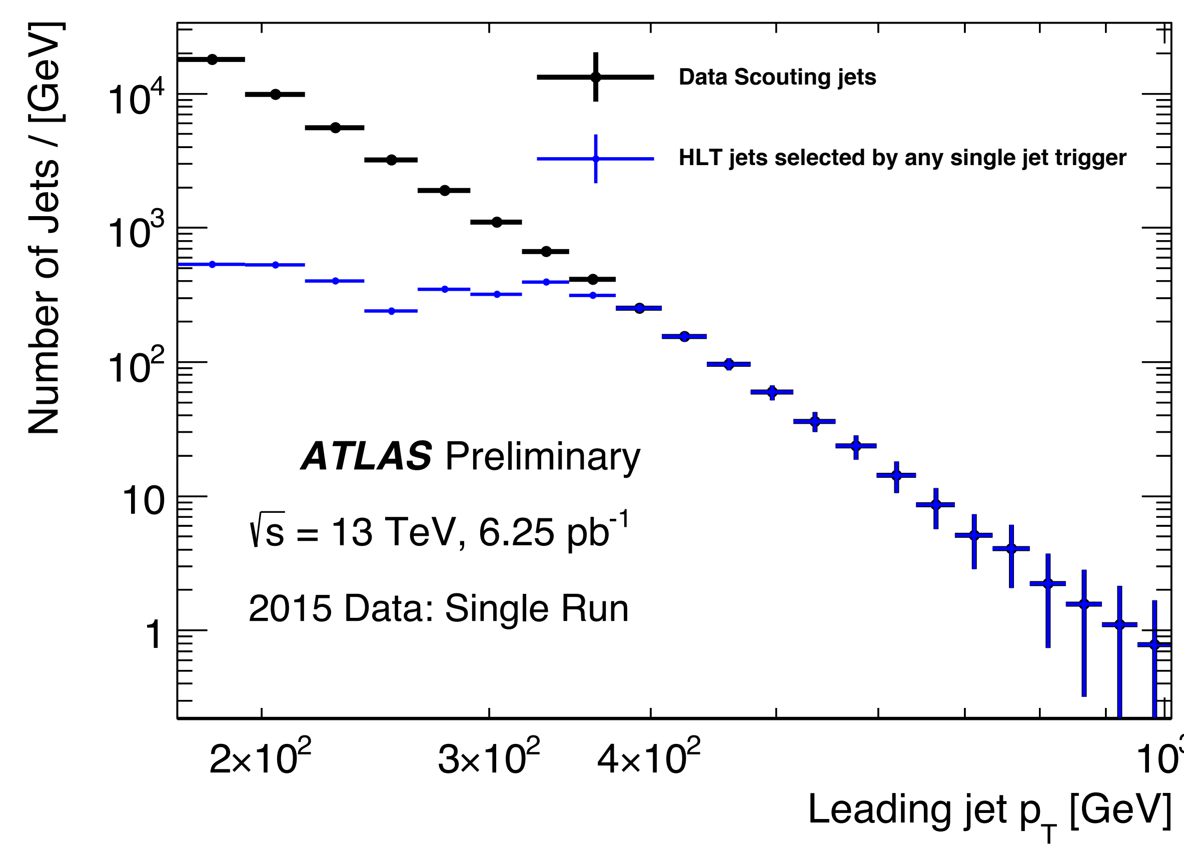


Trigger-level analysis

- The dijet rate is too high to record at low masses
  → online data scouting (trigger level analysis)

EXO-14-005

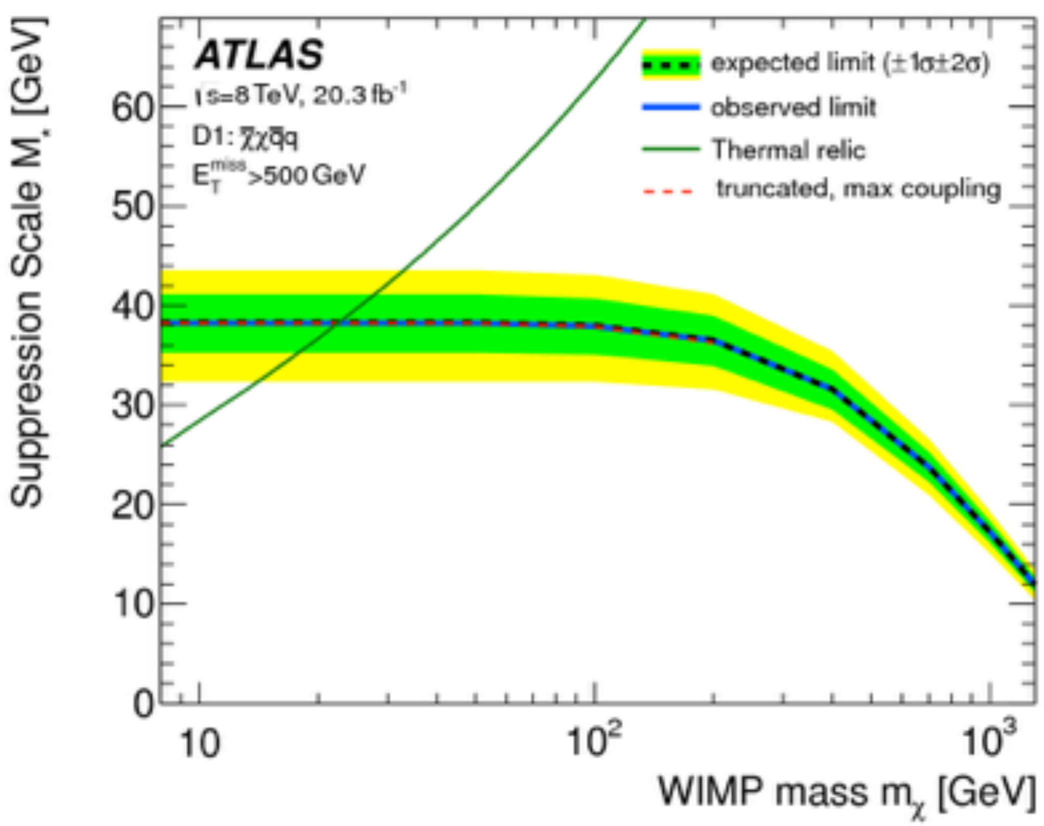




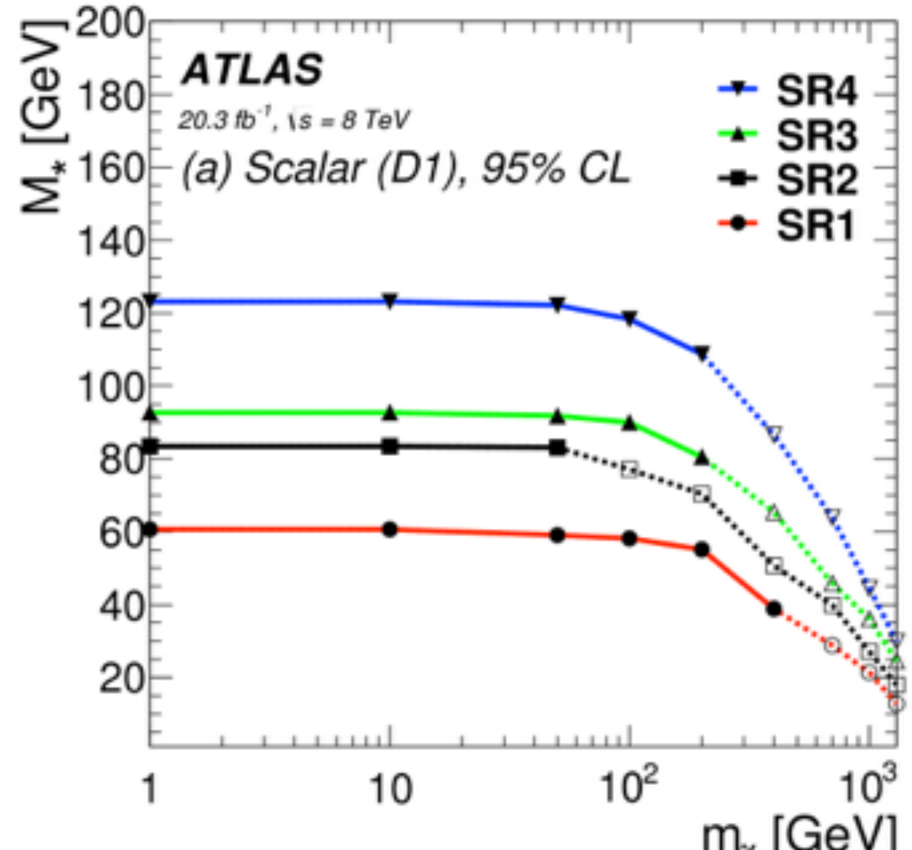
DM + heavy flavour

- search for DM in association with top or bottom quarks
- Many theoretically motivated scenarios (e.g. 2HDM, pMSSM) privilege the coupling of spin-0 mediators to down generation quarks.
- Monojet is suppressed for Yukawa-like couplings.

EXOT-2013-13



EXOT-2014-01



Reinterpretation

- It would be good if every analysis provided sufficient information in electronic format to reinterpret the results in the context of different models:
  - signal region definitions, cutflow, cross section, acceptance, efficiency, experimental uncertainties
  - likelihood from each signal region, correlations among signal regions
- Les Houches accord 1203.2489 (also appendix B in the DM Forum report 1507.00966)

- Are ATLAS and CMS giving sufficient information for reinterpretation?

- Examples worth following:
  - ATLAS 13 TeV monojet search EXOT-2015-03
    - simplified shape fit is used to in order to enhance sensitivity to various models
    - yields from exclusive signal regions are given for reinterpretation
  - CMS 8 TeV direct top squark search in the single lepton final state SUS-13-011
    - code to calculate observables is given at the analysis webpage
  - CMS 8 TeV SUSY search with boosted W bosons and b jets SUS-14-007
    - gives detailed likelihood description

BSM Higgs searches

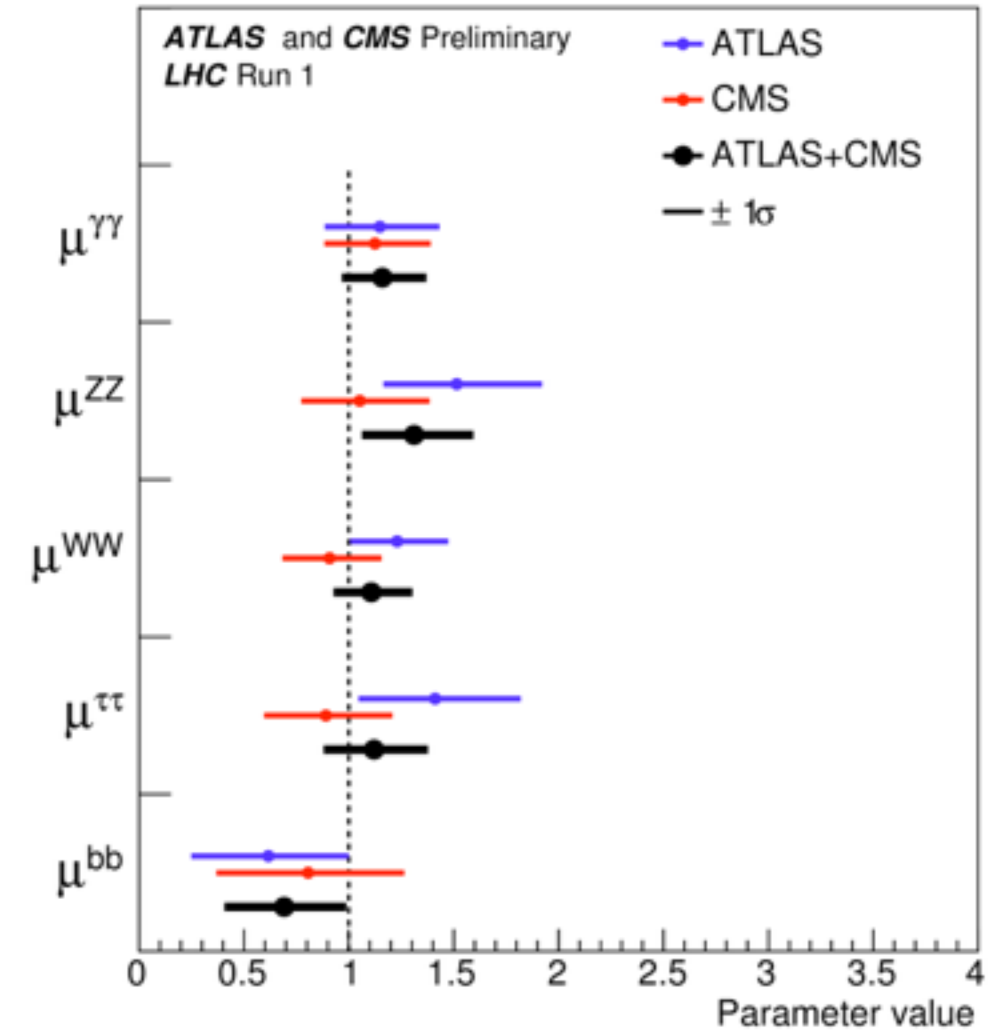
- 2HDM
  - simplest possible extension of the Standard Model
- 2HDM and nMSSM
  - two Higgs doublets and an additional complex singlet
- hMSSM
  - simple parameterisation of the CP-conserving MSSM Higgs sector using m_H = 125 GeV

- high mass Higgs search
  - diphoton excess
    - 750 GeV with 3.6 local significance by ATLAS ATLAS-CONF-2016-018
    - 760 GeV with 2.6 local significance by CMS EXO-16-018

- invisibly decaying Higgs bosons

Indirect searches

[ATLAS-CONF-2015-044; CMS-PAS-HIG-15-002]

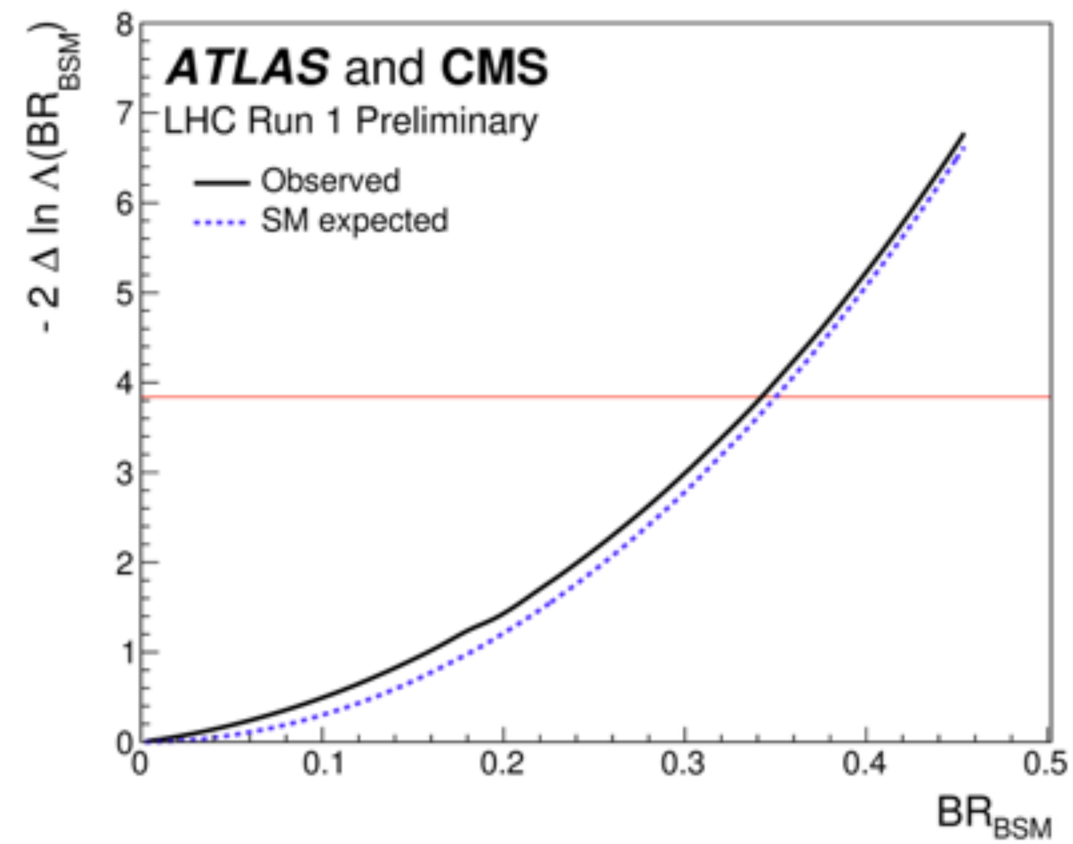


- ATLAS and CMS provide impressive measurements of the Higgs boson (e.g. mass measured within 0.2%)

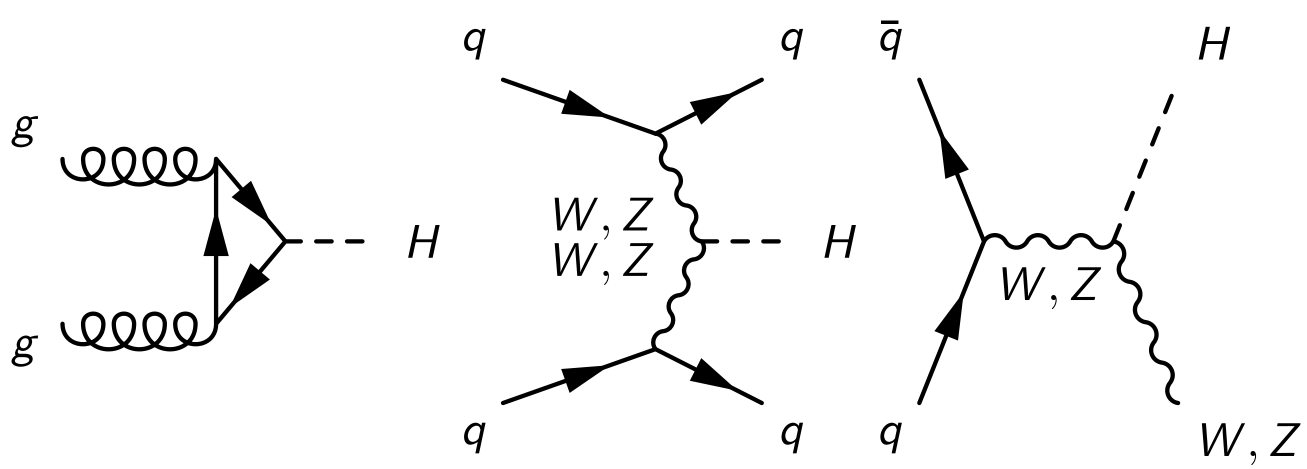
- A lot of parameters are still relatively unconstrained (e.g. the indirect limit on the width is ~4 Γ_{SM})

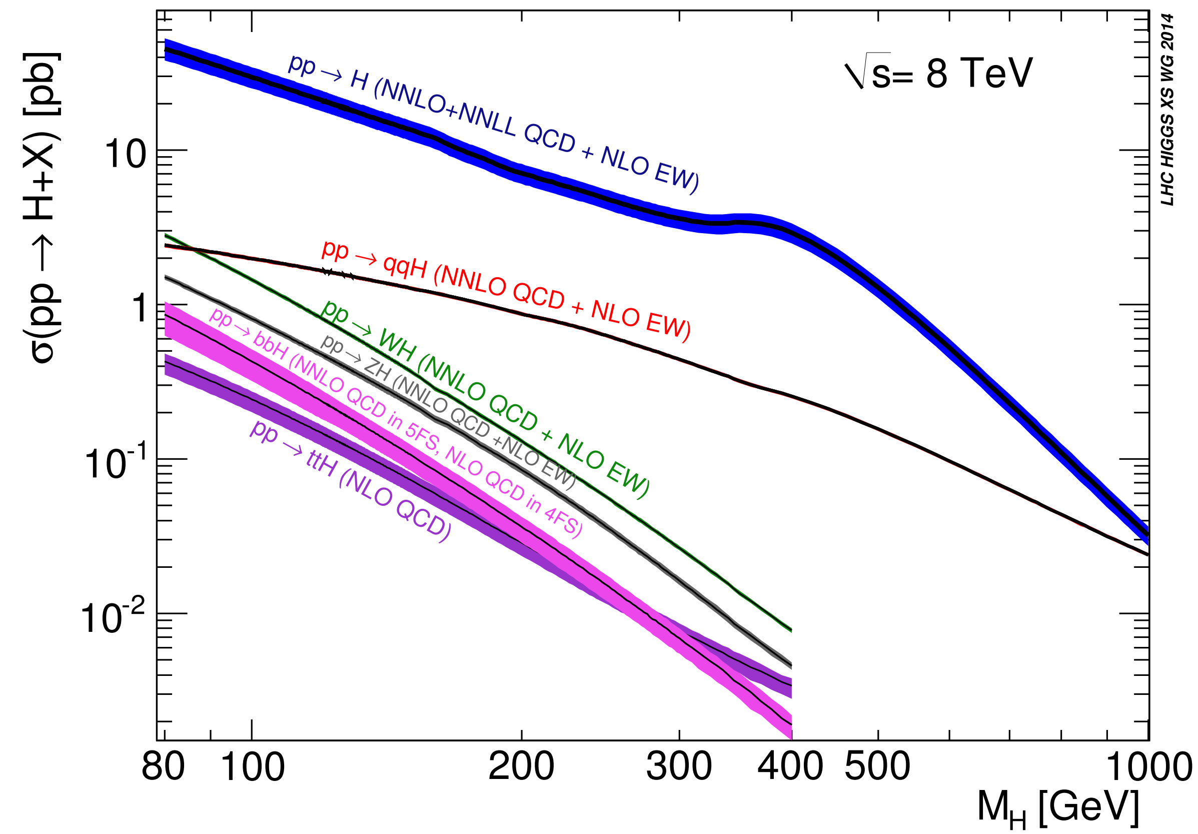
➡ room for Higgs boson couplings to DM

- ATLAS+CMS combination gives indirect observed (expected) limit on BR_{BSM} of 0.34 (0.35).



Direct searches

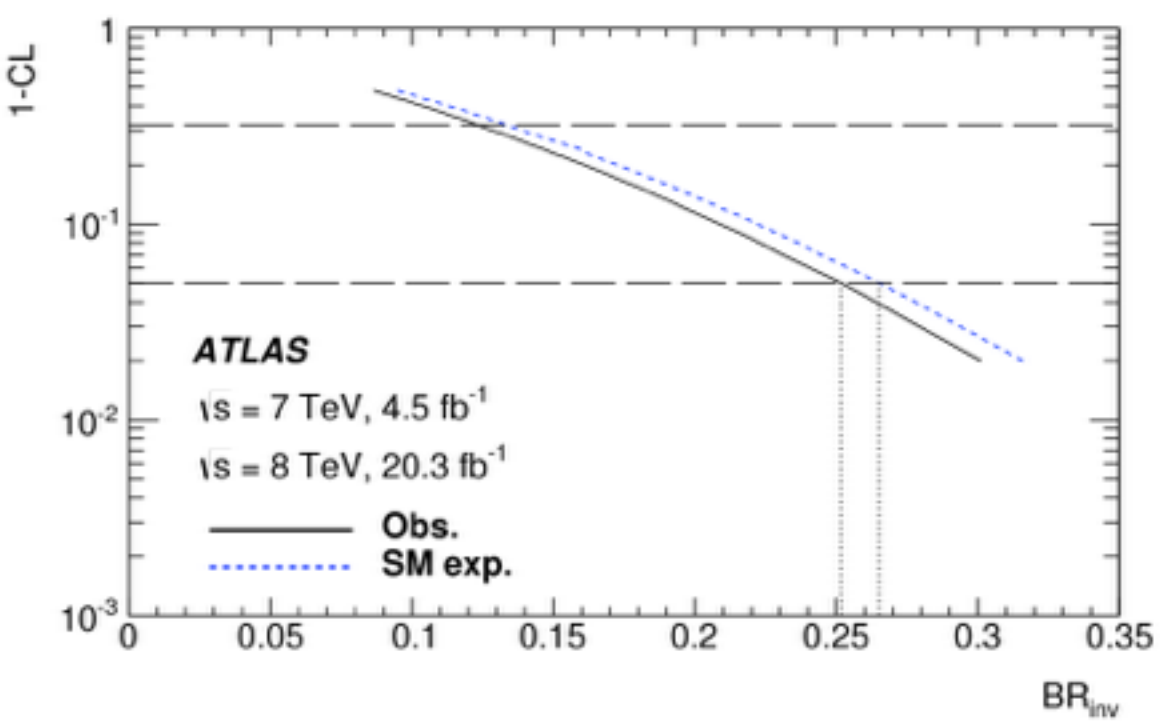




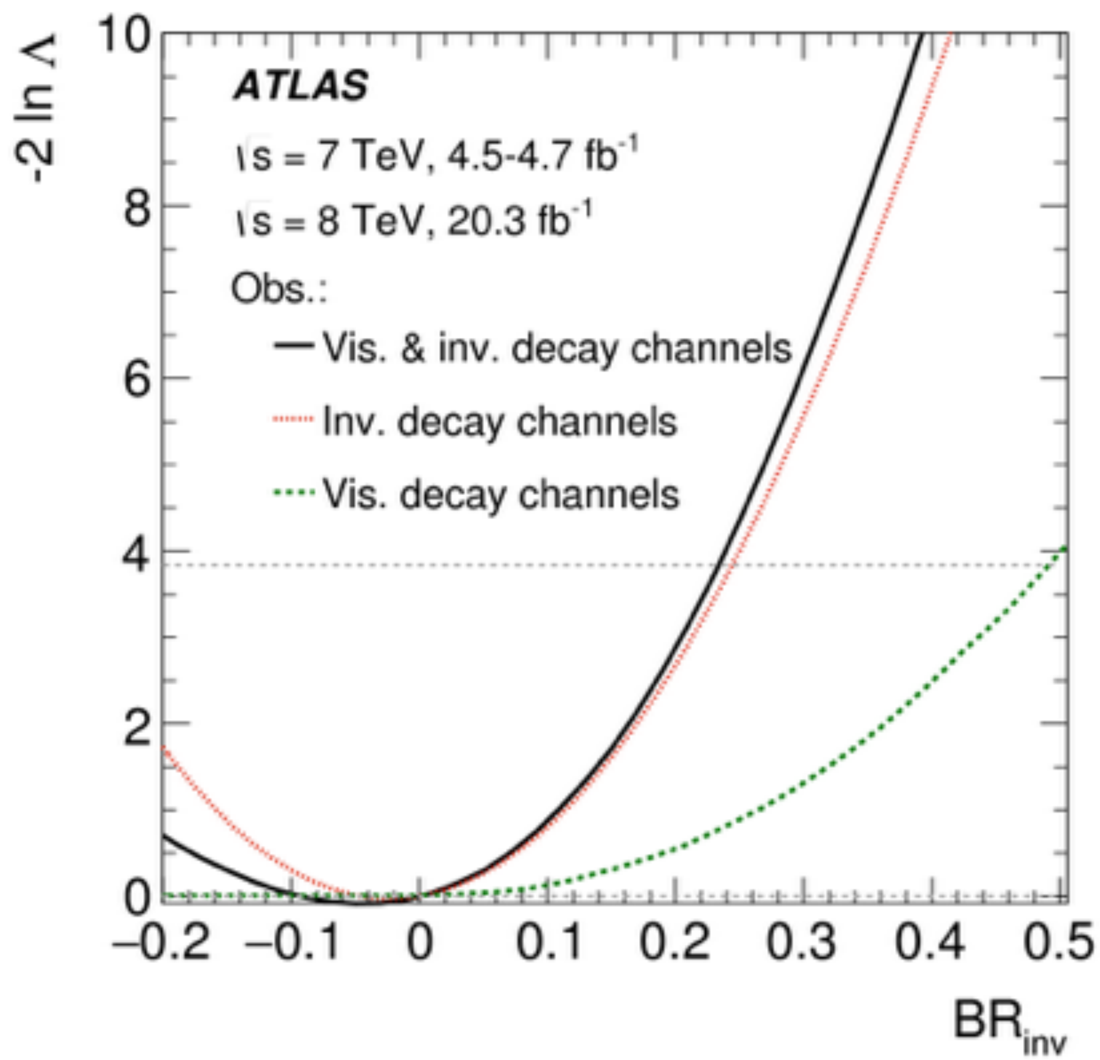
- Dedicated searches for invisibly decaying Higgs bosons are performed for the following Higgs production mechanisms:
  - gluon fusion: needs ISR, high signal (and background) rate
  - vector boson fusion: second highest rate and district topology, most sensitivity
  - associated production: clean final states, low rate

ATLAS combination

- combination of direct searches
  - VBF
  - associated production, Z→ll
  - associated production, W/Z→jj
- observed (expected) limit at 95% CL on BR_{inv} of 0.25 (0.27)

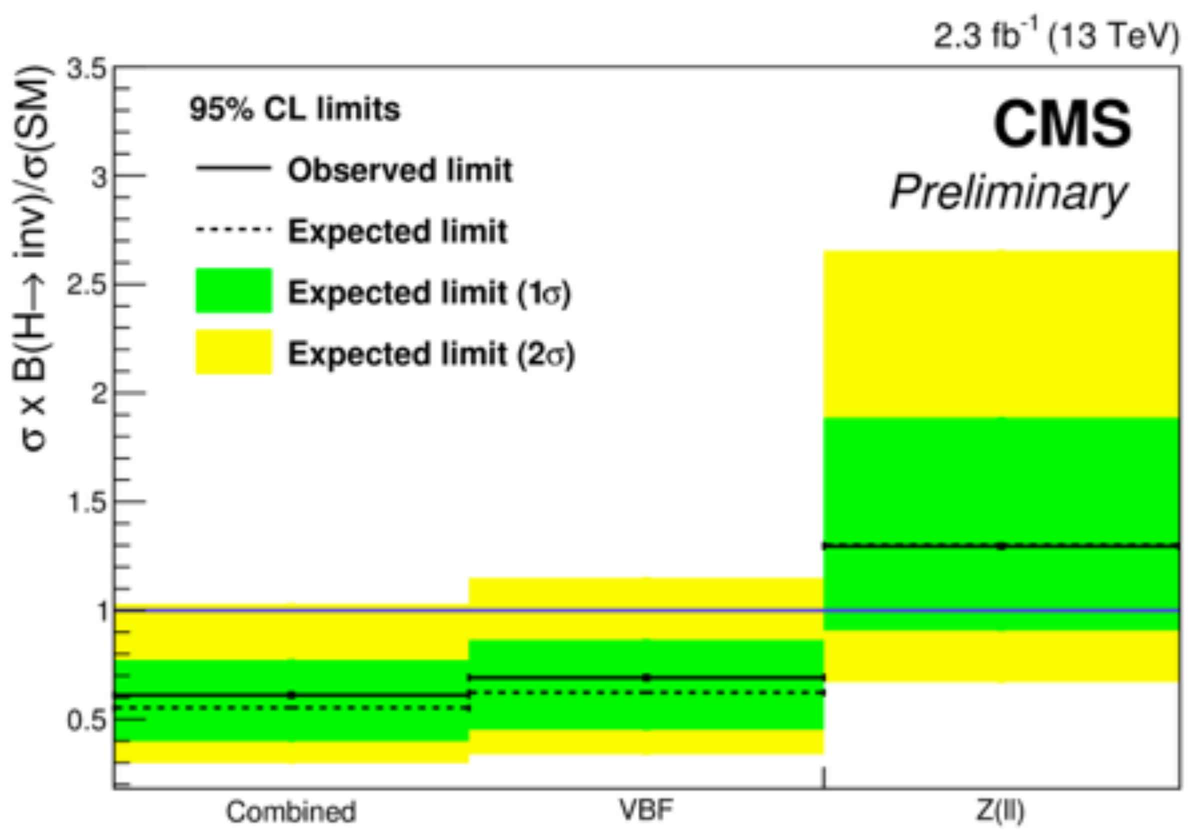


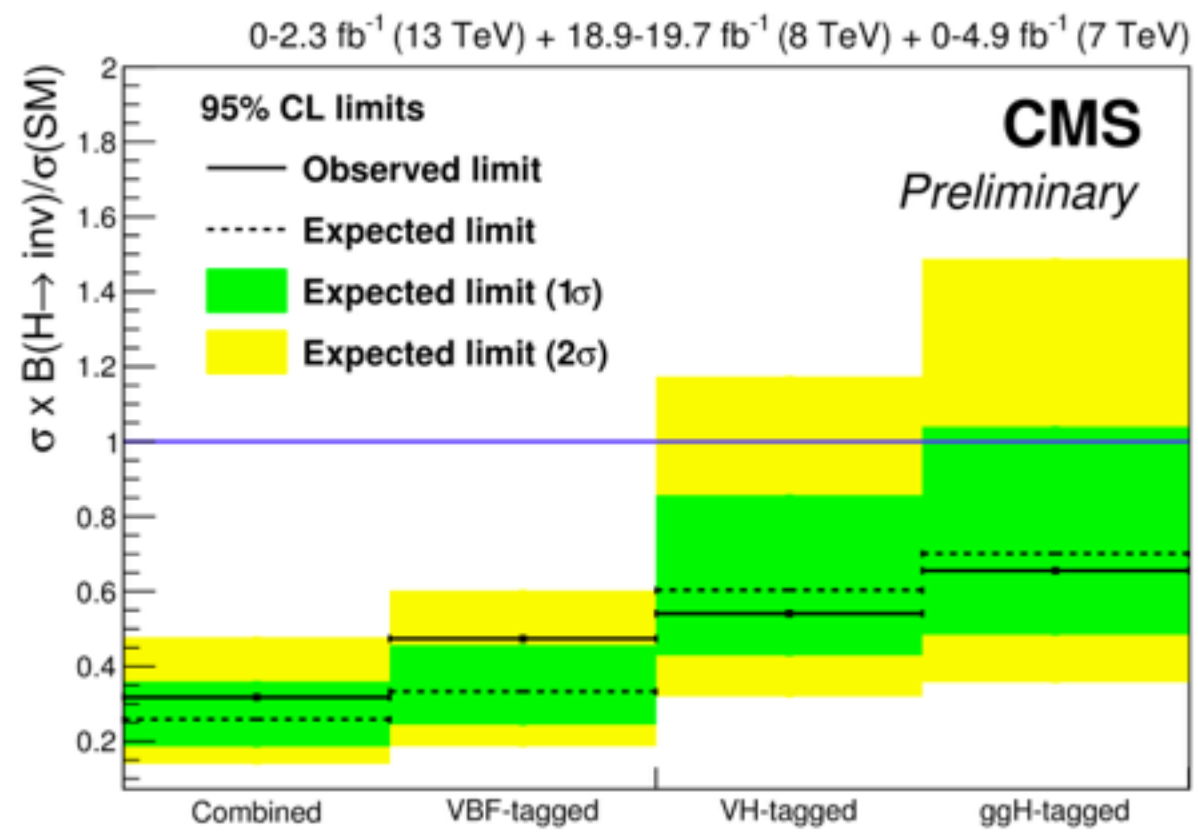
- Combining with indirect searches adds assumption on the Higgs total width.
- observed (expected) limit at 95% CL on BR_{inv} of 0.23 (0.24)



CMS combination

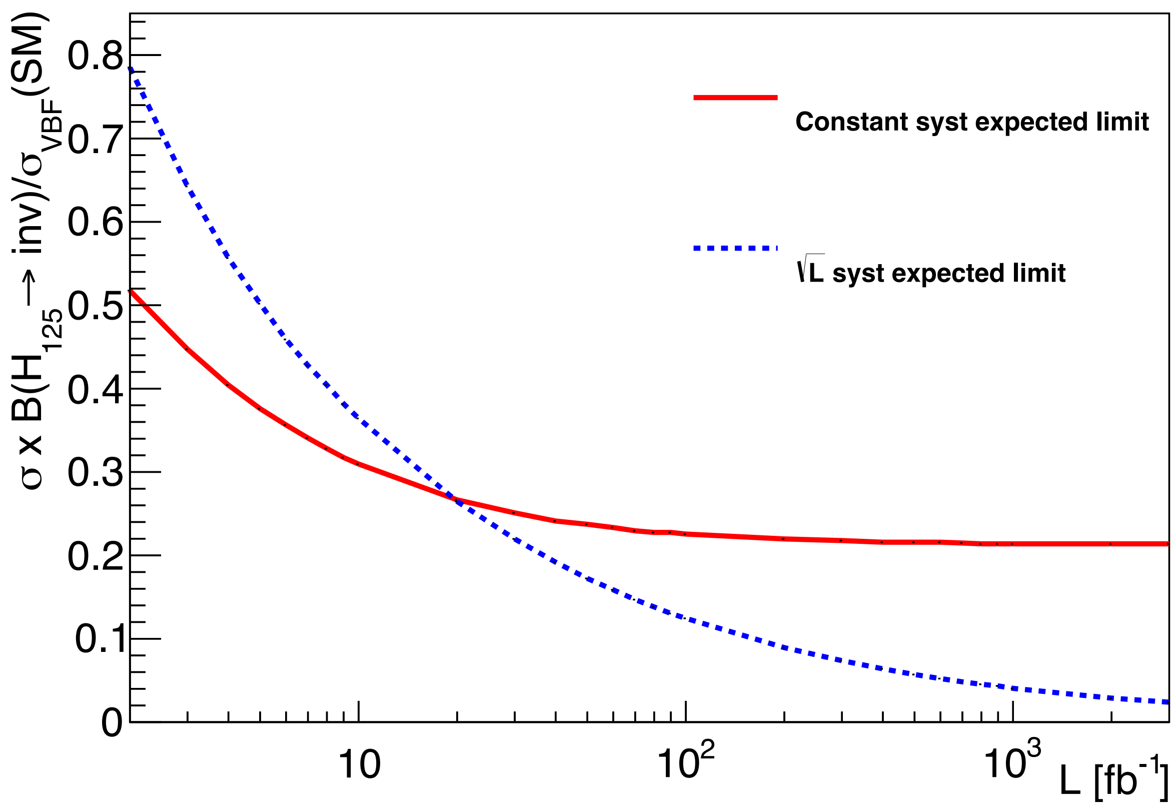
- Combination of direct searches from Run-1 and Run-2
- observed (expected) limit at 95% CL on BR_{inv} of 0.32 (0.26)





Future projections

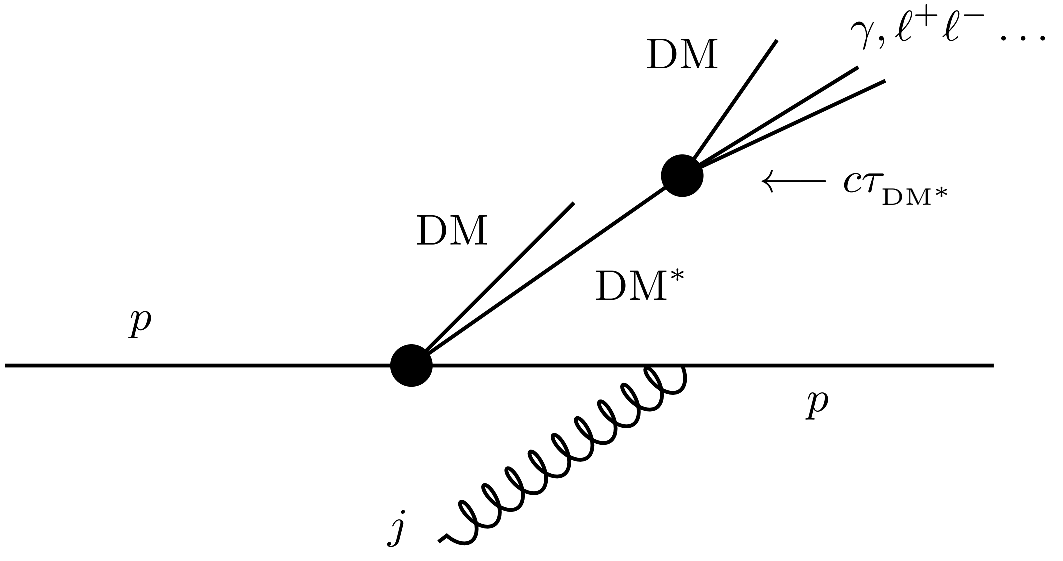
- projection of the CMS VBF analysis
- BR_{BSM} ~ 5% may be reached with the full LHC data set with the systematic uncertainty improving as $\sqrt{L}$



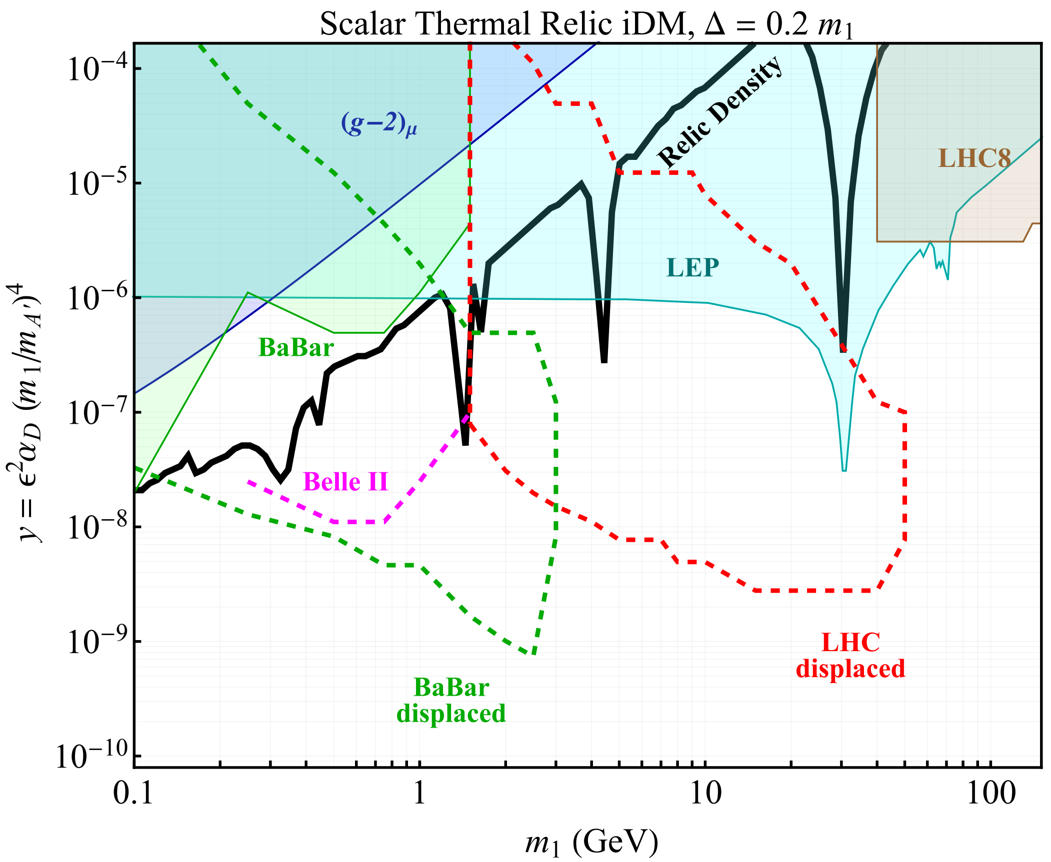
Inelastic Dark Matter

- two dark states that couple inelastically

$$pp \to X + \mathrm{DM} + \mathrm{DM}^*$$
$$\to X + \mathrm{DM} + \left(\mathrm{DM}^* \to \mathrm{DM} + Y\right) \equiv X + \not{E}_\mathrm{T} + Y$$



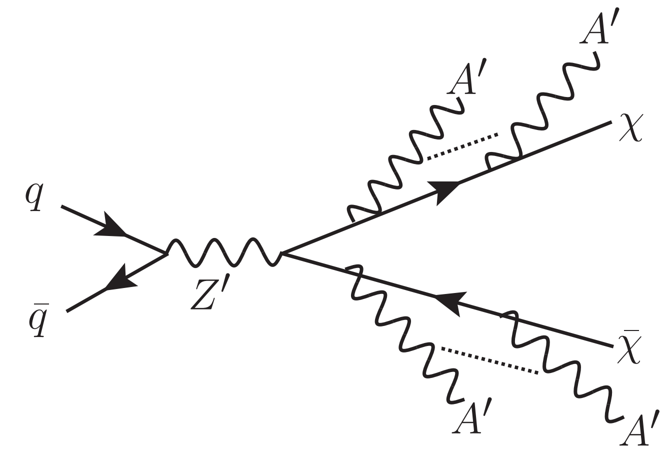
- experimental signature:
  - jet + MET + soft collimated particles
  - long-lived decays
- proposed search:
  - dark photon model
  - monojet + MET + displaced muon jet

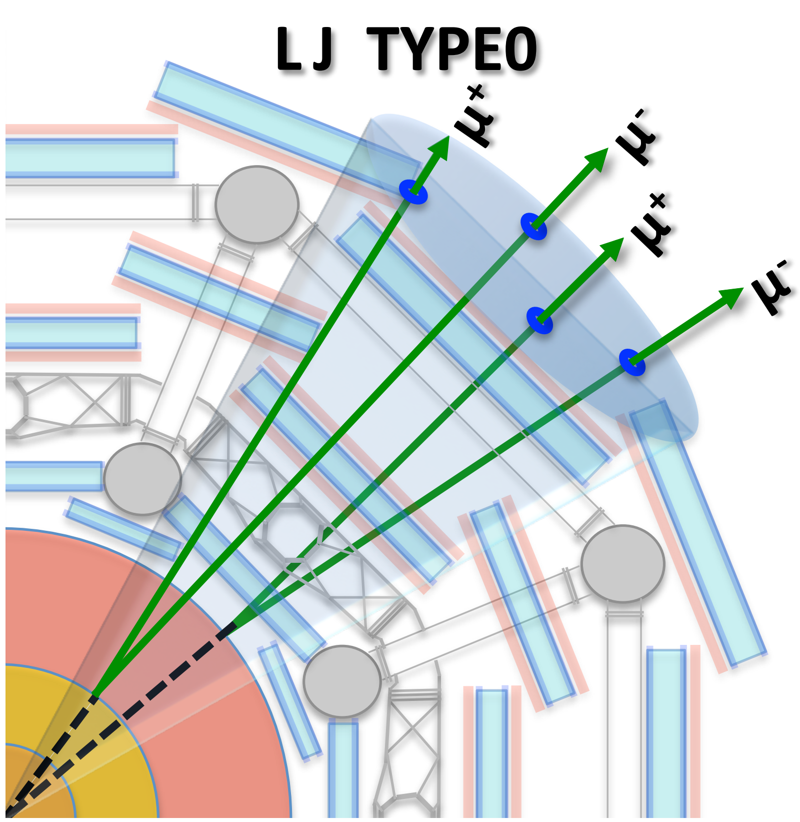


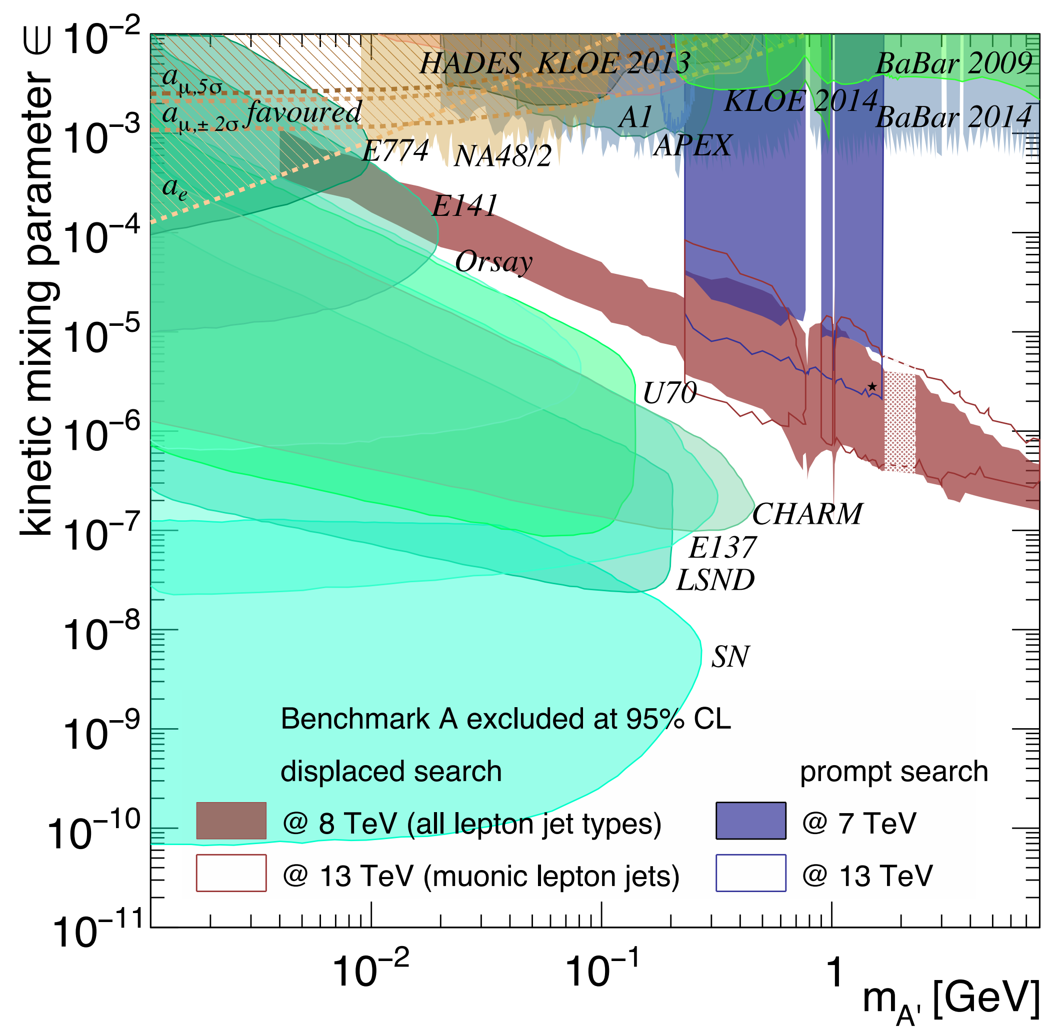
1505.07459
1409.0746

Dark radiation

- more dark radiation
- lepton jets

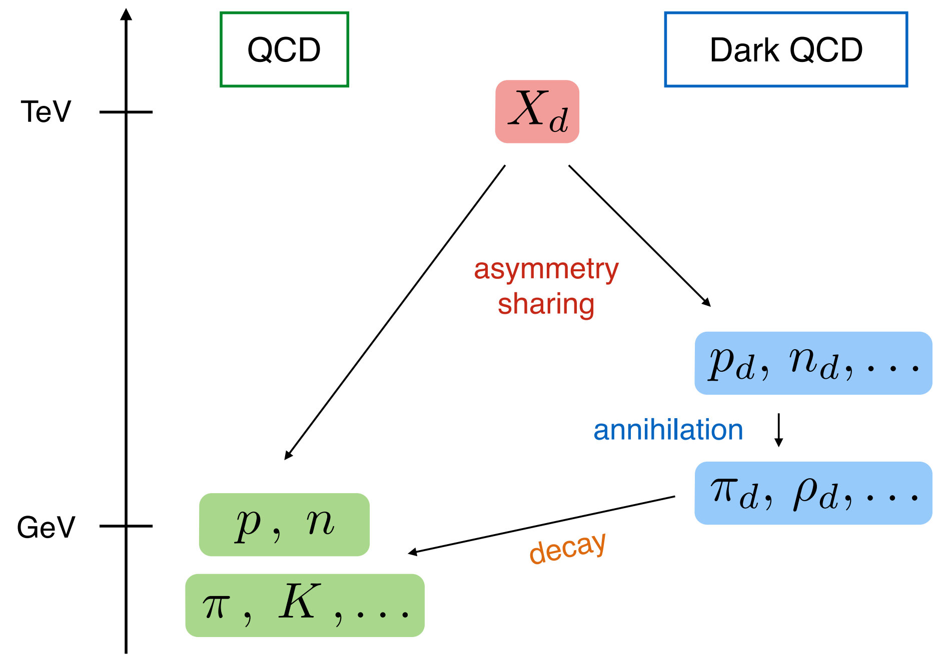






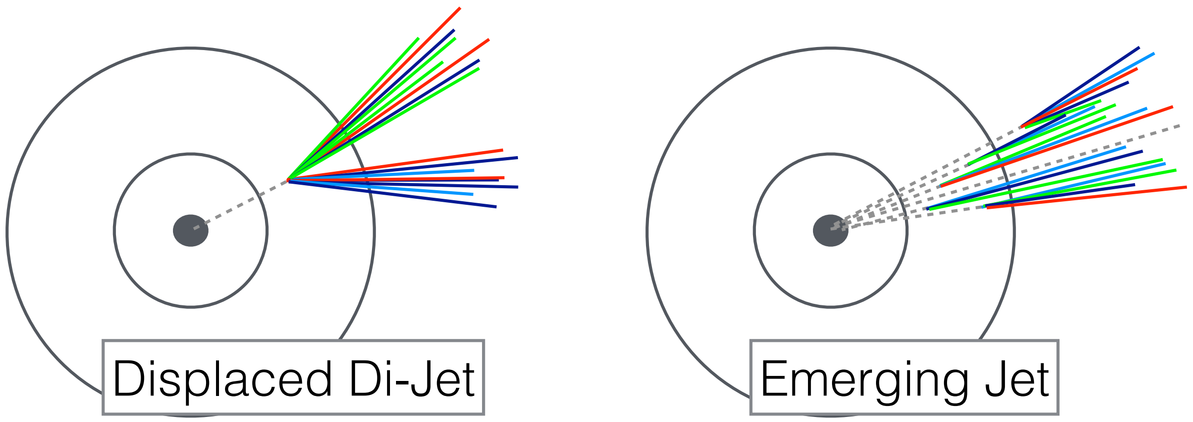
1502.05409

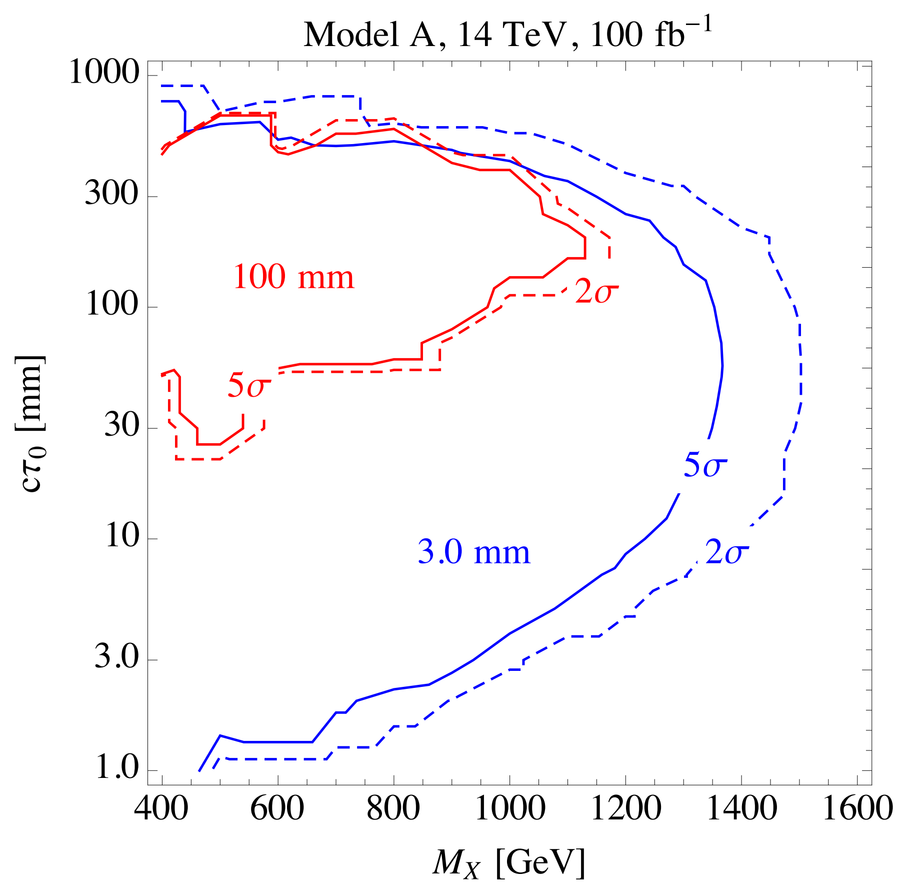
Composite dark sector



- asymmetric dark matter, dark QCD
- DM is composite dark photon
- long-lived, unstable dark pions

- experimental signature:
  - two **emerging jets** (two QCD jets)
  - different compared to displaced jet searches





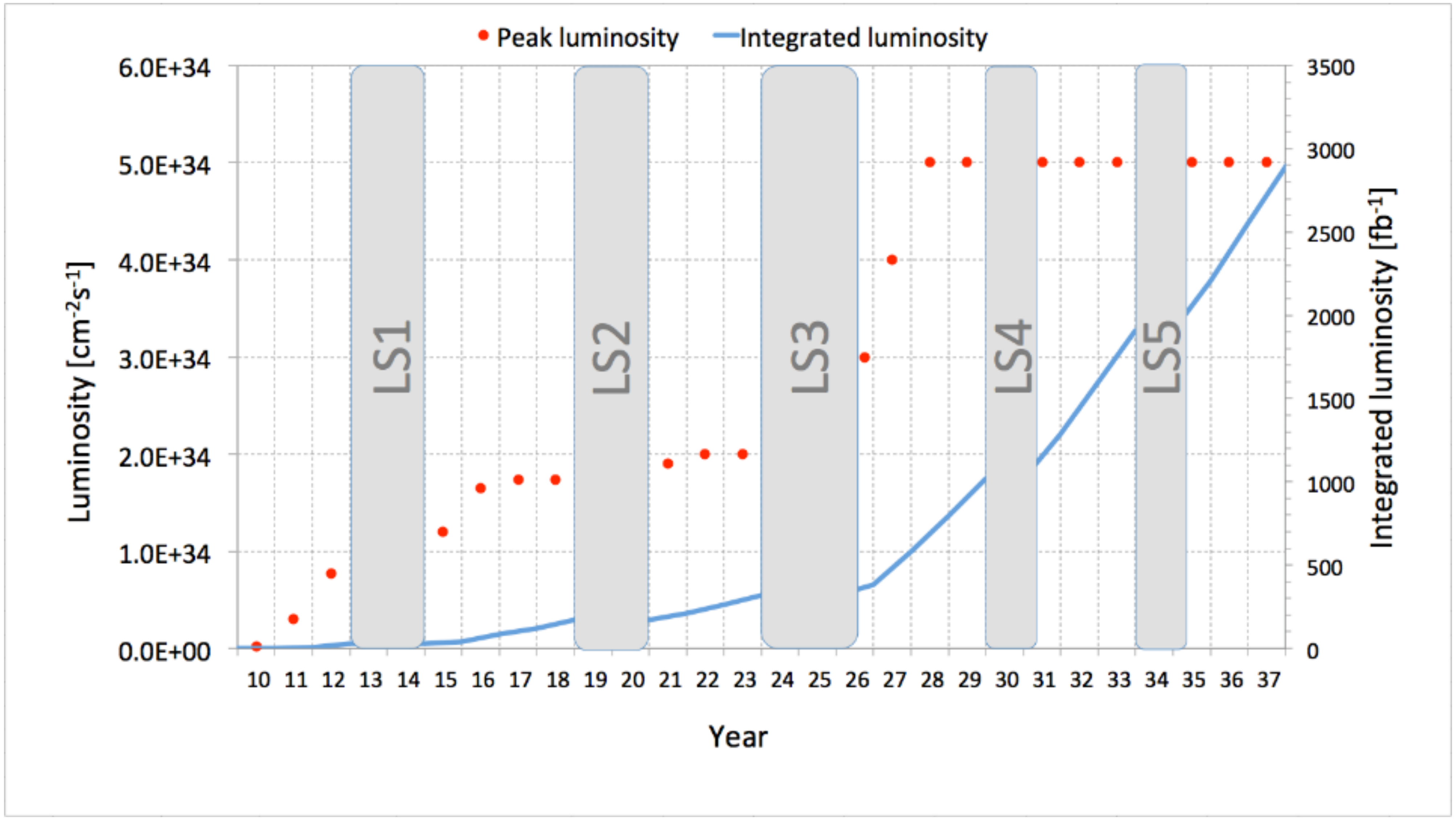
Summary

- Rich DM search programme has developed in ATLAS and CMS during Run-1.
  - mono-X
  - SUSY
  - BSM Higgs
  - long-lived particles

- Common set of benchmark models is used by ATLAS and CMS.
- Are these models well motivated? (e.g. gauge invariance implies Z' couplings to leptons → stringent constraints from electroweak precision measurements)
- Are there experimental signatures that ATLAS and CMS are not covering?
- future models and reinterpretations…

Summary

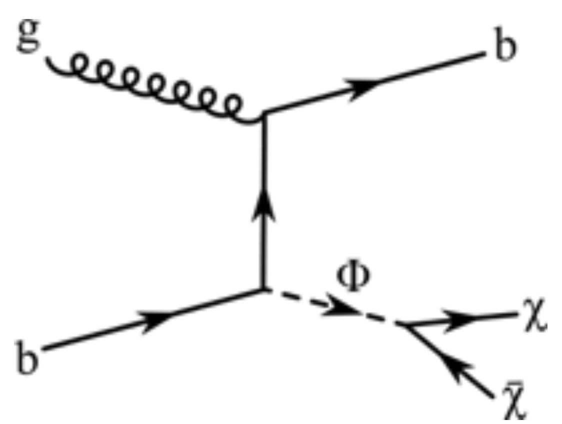
- This is only a beginning…

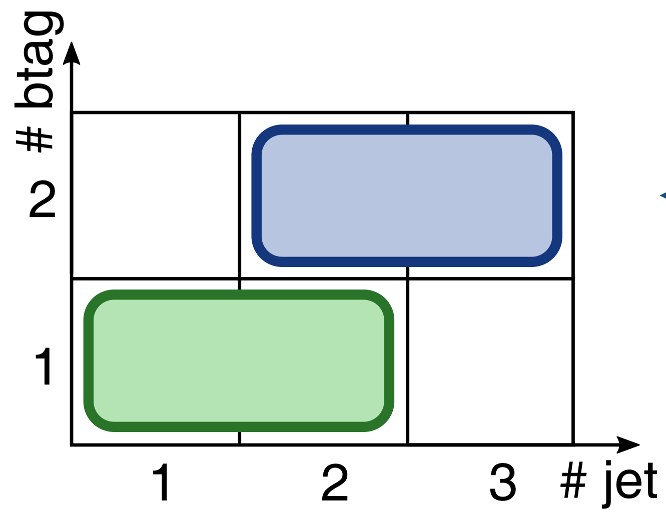


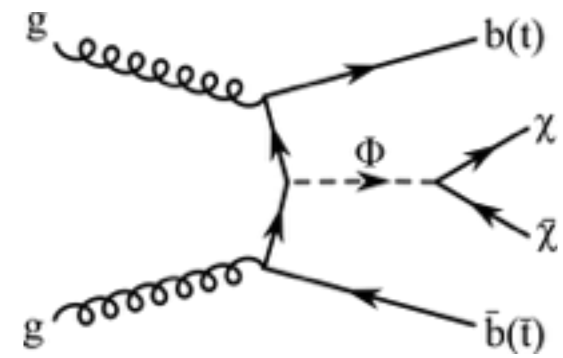
- … **Stay tuned for new results!**

extra material

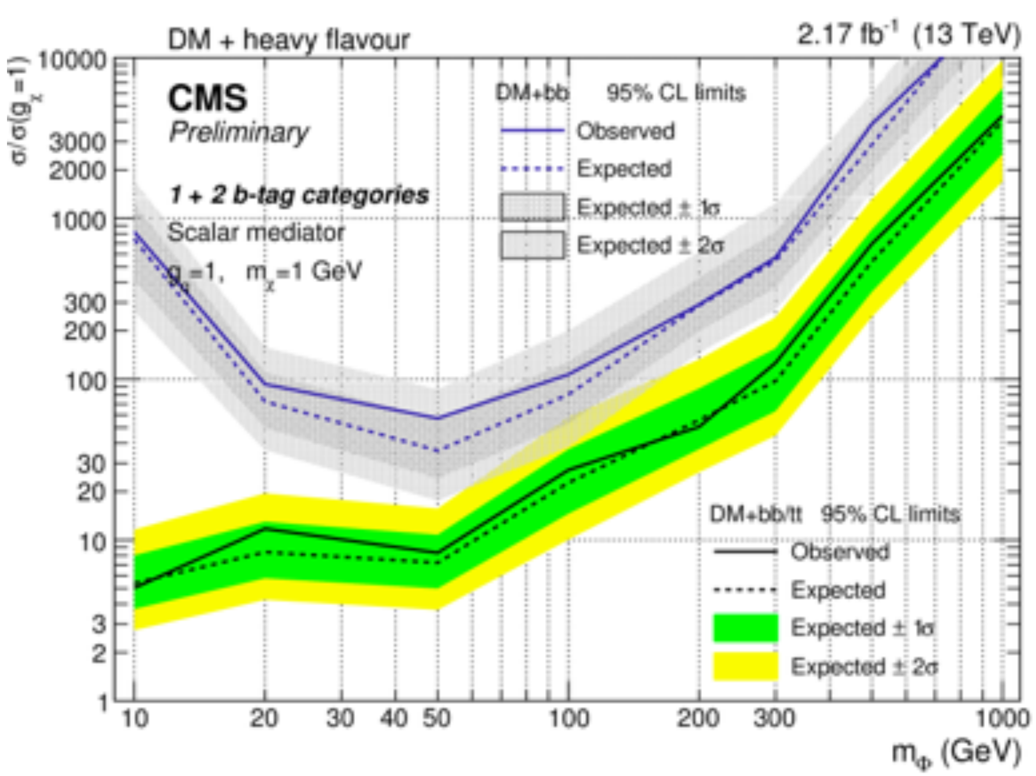
DM + bottom quarks

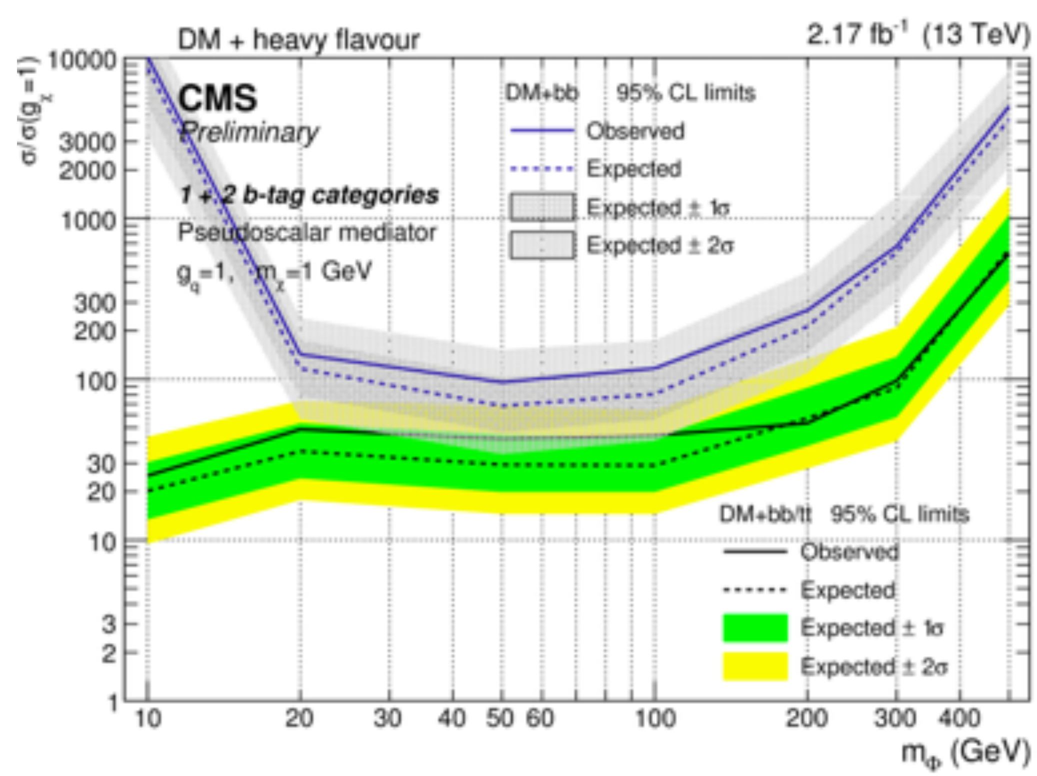




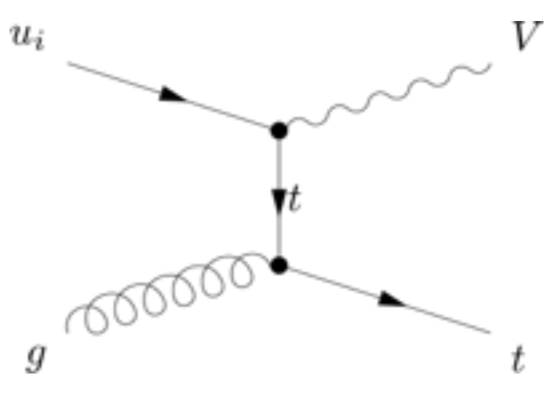


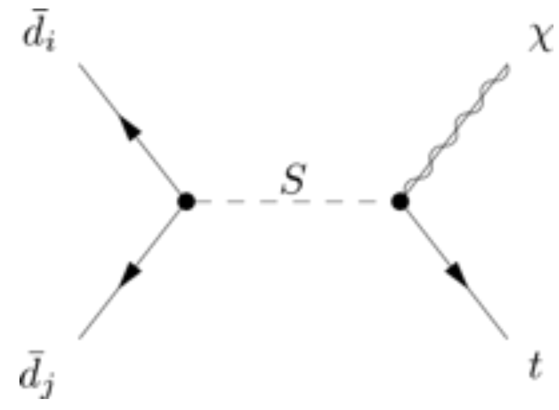
- single b-tag and double b-tag region
- interpreted in terms of scalar and pseudo-scalar mediators

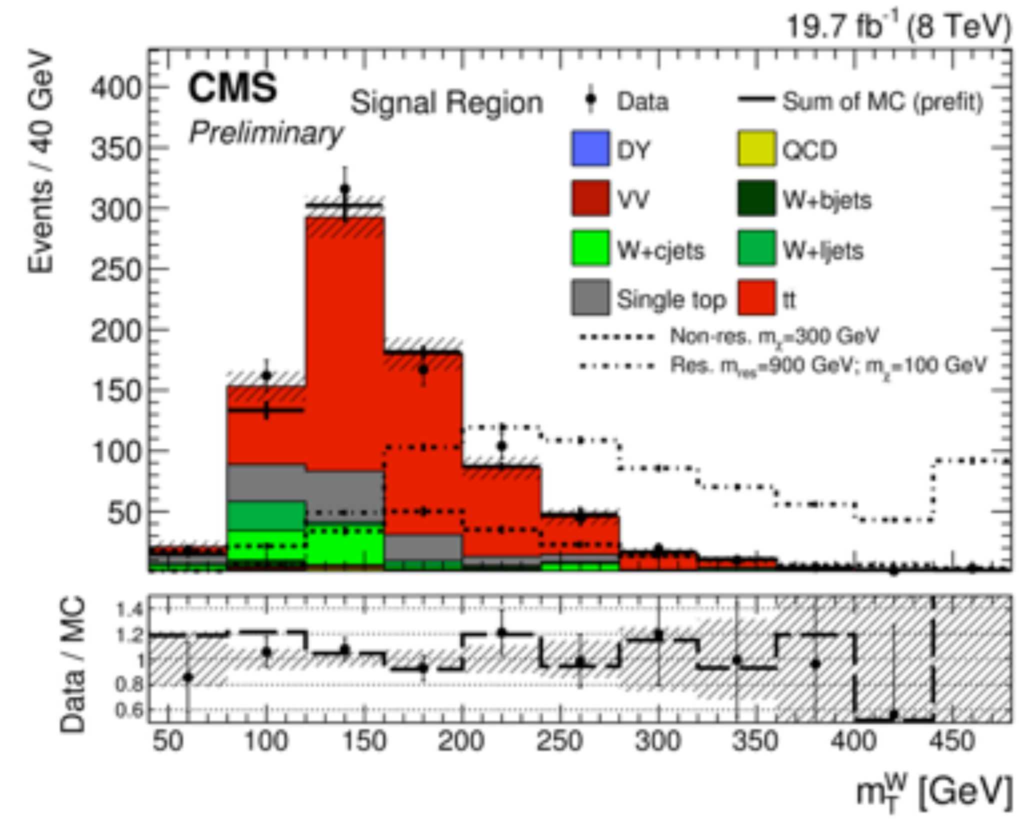




Mono-top







- FCNC interaction with an invisible vector/scalar DM particle
- resonant production through coloured mediator to invisible exotic state