Dark Matter searches at the LHC

Lorentz center
Workshop @Oort

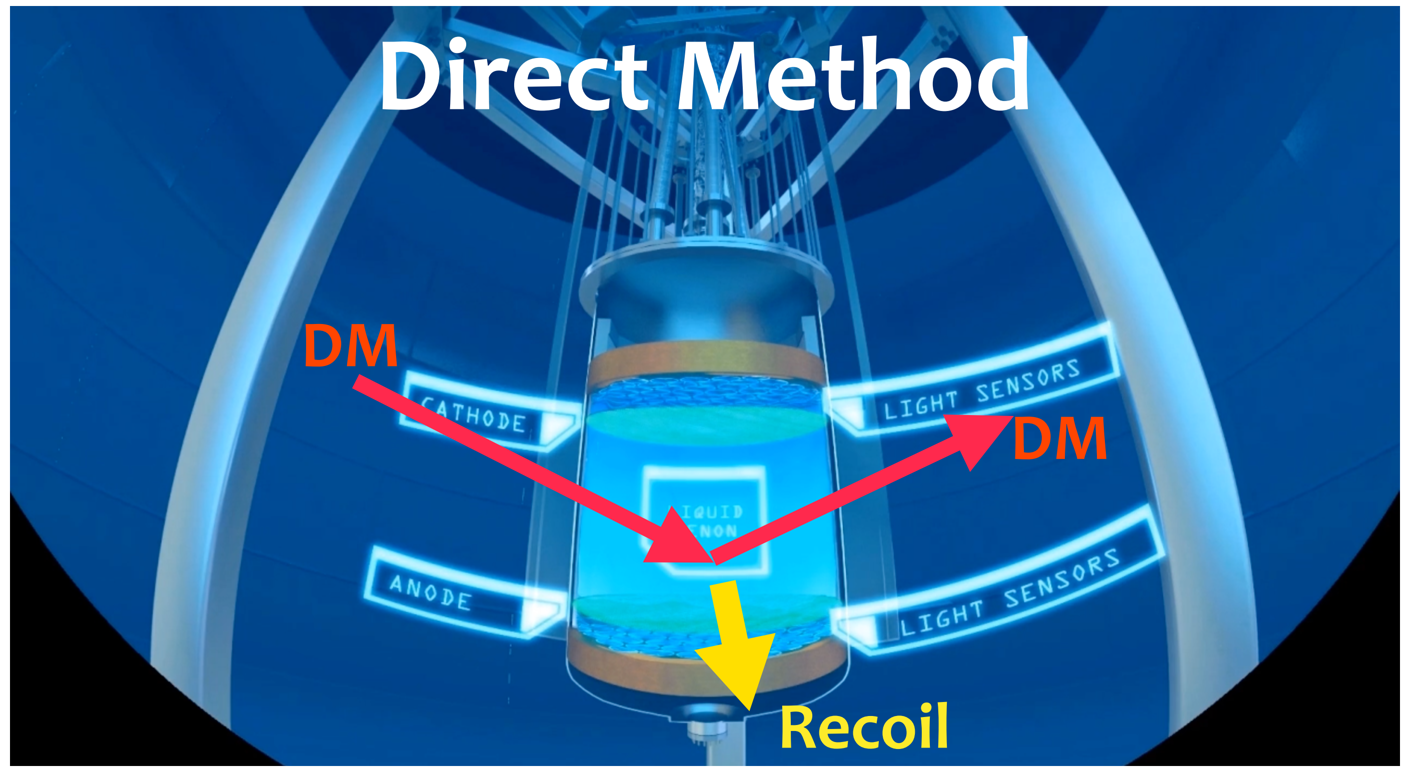
Accelerating the Search for Dark Matter with Machine Learning

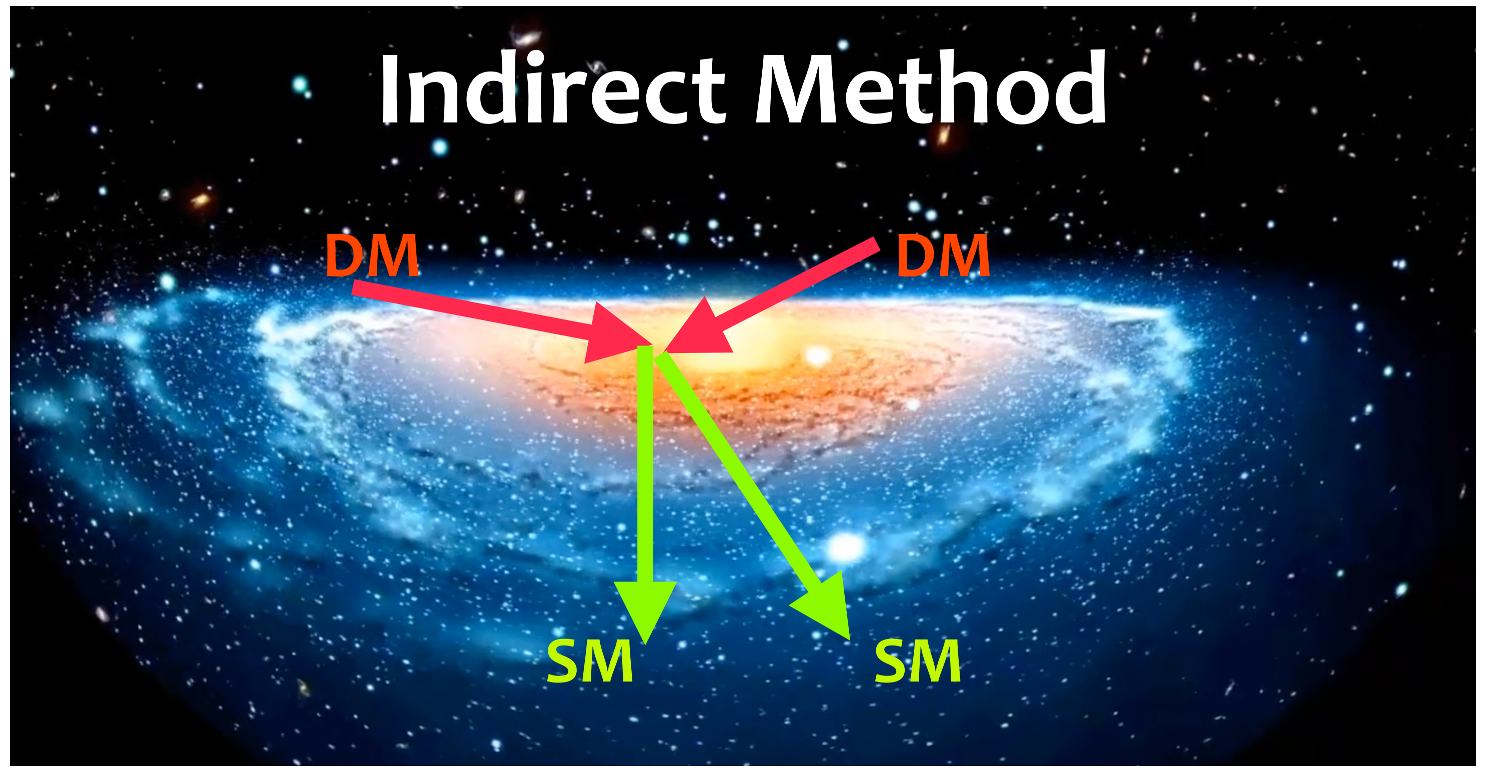
15 - 19 January 2018, Leiden, the Netherlands

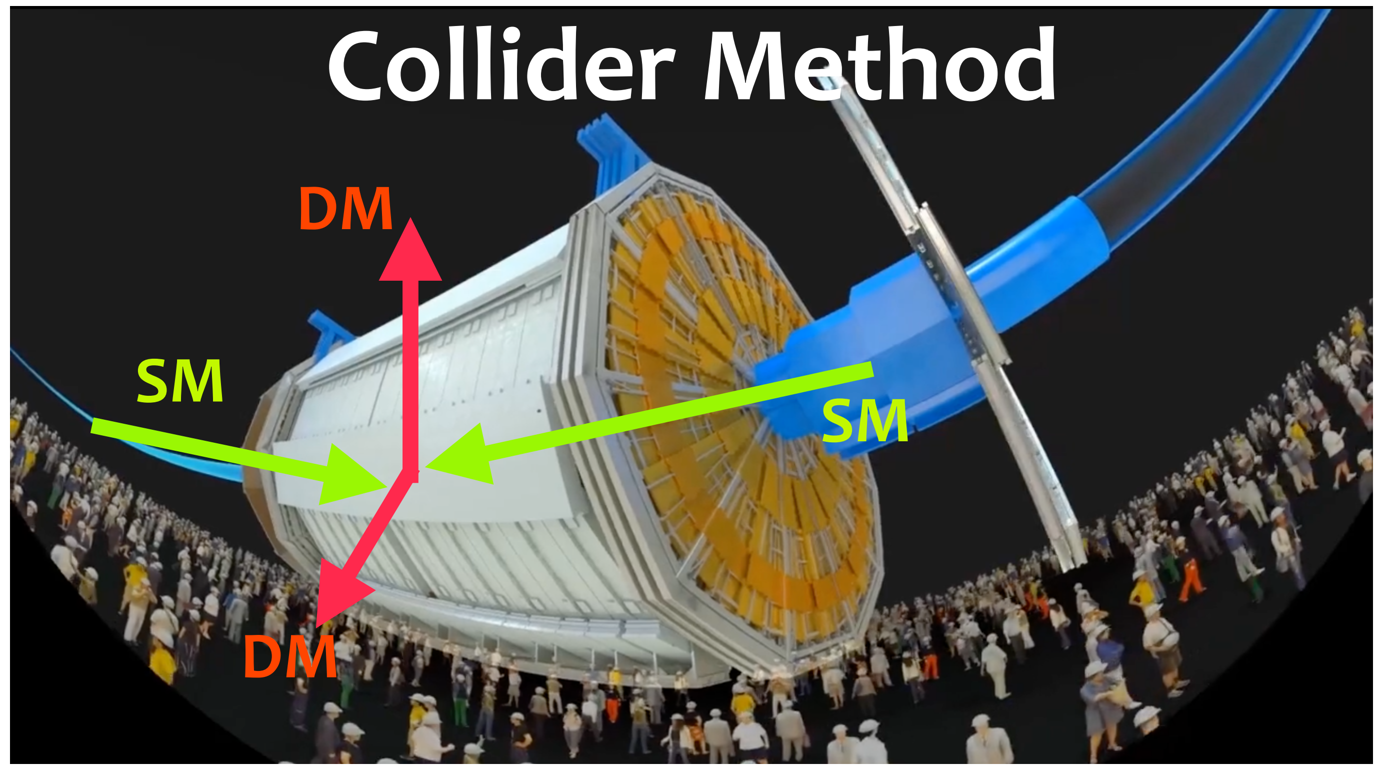
Ren-Jie Wang
LPNHE-Paris/CNRS-IN2P3
On behalf of the ATLAS&CMS Collaborations

Detections of Dark Matter

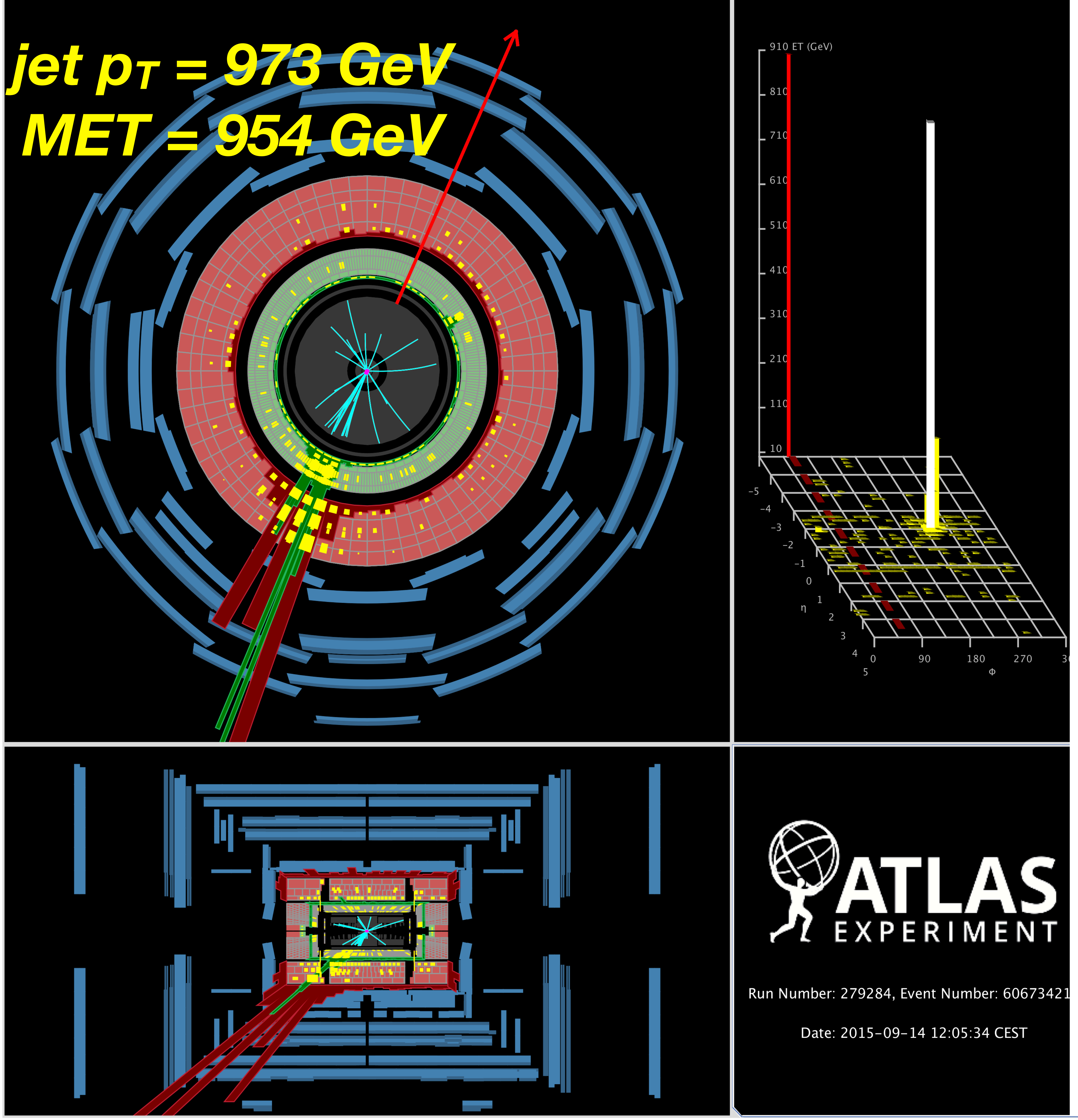
- ***Identifying DM is one of the most important questions in physics now***
- DM is likely a new as yet undetected particle
- Three detection ways:

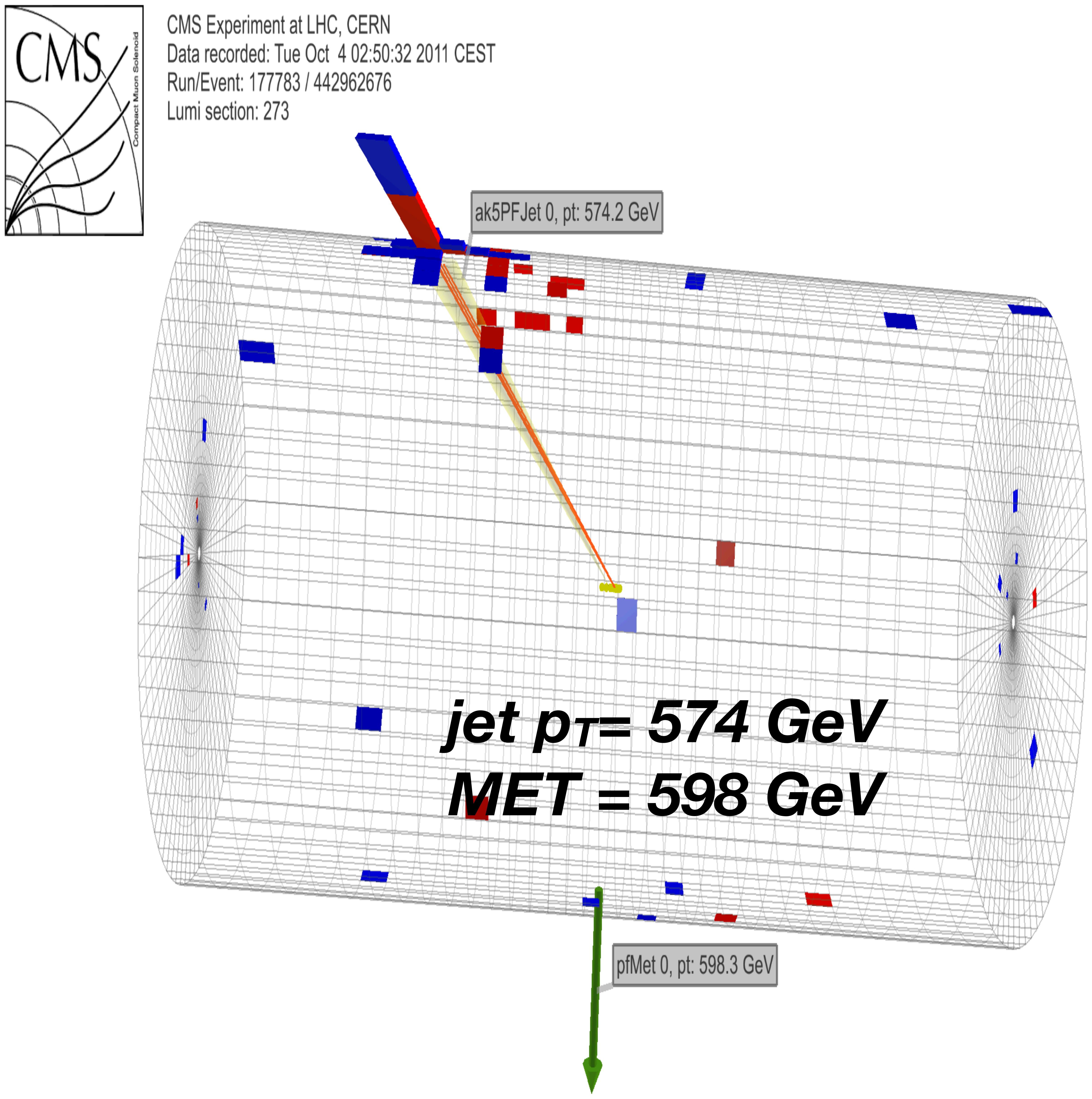






- **Direct method (χq→χq):** DM-nucleon elastic scattering, with a keV recoil
- **Indirect method (χχ→qq):** DM pair-annihilation, decay to various observable particles: tt, bb, WW, ZZ, γγ, … …
- **Collider method (qq → χχ):** DM production at collider, model dependent





Are DM new weekly interacting massive particles (WIMPs)?

Benchmark models fo LHC Run-2 DM searches

arXiv.org > hep-ex > arXiv:1507.00966

Search or Article I
(Help | Advanced sear

High Energy Physics – Experiment

Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

Daniel Abercrombie, Nural Akchurin, Ece Akilli, Juan Alcaraz Maestre, Brandon Allen, Barbara Alvarez Gonzalez, Jeremy Andrea, Alexandre Arbey, Georges Azuelos, Patrizia Azzi, Mihailo Backović, Yang Bai, Swagato Banerjee, James Beacham, Alexander Belyaev, Antonio Boveia, Amelia Jean Brennan, Oliver Buchmueller, Matthew R. Buckley, Giorgio Busoni, Michael Buttignol, Giacomo Cacciapaglia, Regina Caputo, Linda Carpenter, Nuno Filipe Castro, Guillelmo Gomez Ceballos, Yangyang Cheng, John Paul Chou, Arely Cortes Gonzalez, Chris Cowden, Francesco D'Eramo, Annapaola De Cosa, Michele De Gruttola, Albert De Roeck, Andrea De Simone, Aldo Deandrea, Zeynep Demiragli, Anthony DiFranzo, Caterina Doglioni, Tristan du Pree, Robin Erbacher, Johannes Erdmann, Cora Fischer, Henning Flaecher, Patrick J. Fox, Benjamin Fuks, Marie-Helene Genest, Bhawna Gomber, Andreas Goudelis, Johanna Gramling, John Gunion, Kristian Hahn, Ulrich Haisch, Roni Harnik, Philip C. … Kerstin Hoepfner, Siew Yan Hoh, Dylan George Hsu, Shih-Chieh Hsu, Yutaro Iiyama, Valerio Ippolito, Thomas Jacques, Xiangyang … Kahlhoefer, Alexis Kalogeropoulos, Laser Seymour Kaplan, Lashkar Kashif, Valentin V. Khoze, Raman Khurana, Khristian … Kovalskyi, Suchita Kulkarni, Shuichi Kunori, Viktor Kutzner, Hyun Min Lee, Sung-Won Lee, Seng Pei Liew, Tongya… Madar, Sarah Malik, Fabio Maltoni, Mario Martinez Perez, Olivier Mattelaer, Kentarou Mawatari, Christop… Morgante, Stephen Mrenna, Siddharth M. Narayanan, Andy Nelson, Sérgio F. Novaes, Klaas Ole P… Manfred Paulini, Christoph Paus, Jacopo Pazzini, Björn Penning, Michael E. Peskin, Debo… Davide Racco, Emanuele Re, Antonio Riotto, Thomas G. Rizzo, Rainer Roehrig, … …xander Schmidt, Steven Randolph Schramm, William Shepherd, Gurpreet Singh … …M. P. Tait, Timothee Theveneaux-Pelzer, Marc Thomas, Mia Tosi, Daniele Trocino, … …-Tao Wang, Ren-Jie Wang, Nikola Whallon, Steven Worm, Mengqing Wu, Sau Lan W… …aldivar, Marco Zanetti, Zhiqing Zhang, Alberto Zucchetta (collapse list)

(Submitted on 3 Jul 2015)

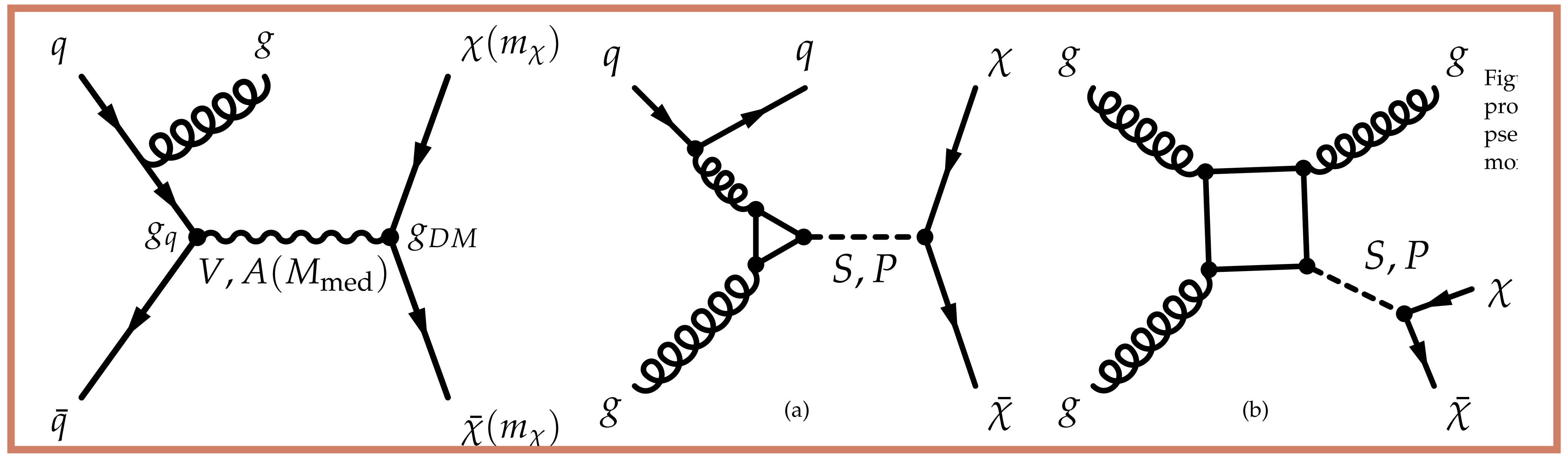
This document is the final … …zed by the ATLAS and CMS collaborations with the participation of experts on theorie… …simplified models that should support the design of the early LHC Run-2 searches. A… …accompanied by studies of the parameter space of these models and a repository of generator i… …apply the Effective Field Theory formalism for collider searches and present the results of such interpr…

Subjects: **High E…** …(hep-ex); High Energy Physics – Phenomenology (hep-ph)

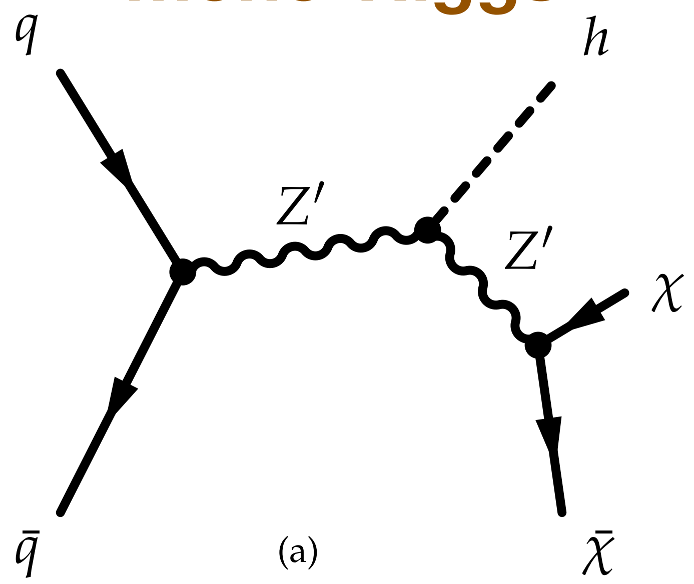
A big effort is made between LHC experimentalists and theorists!

Benchmark models fo LHC Run-2 DM searches

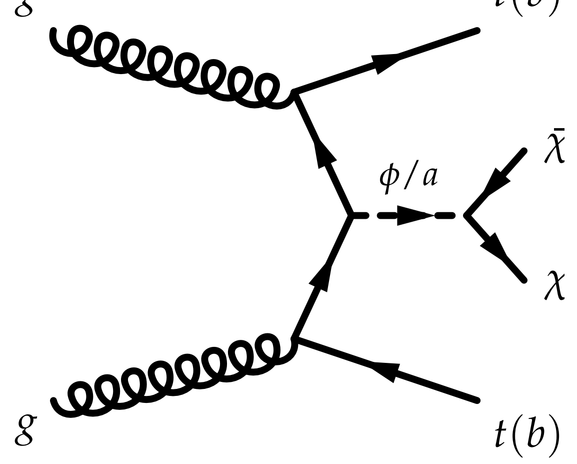
mono-Jet/photon/W/Z



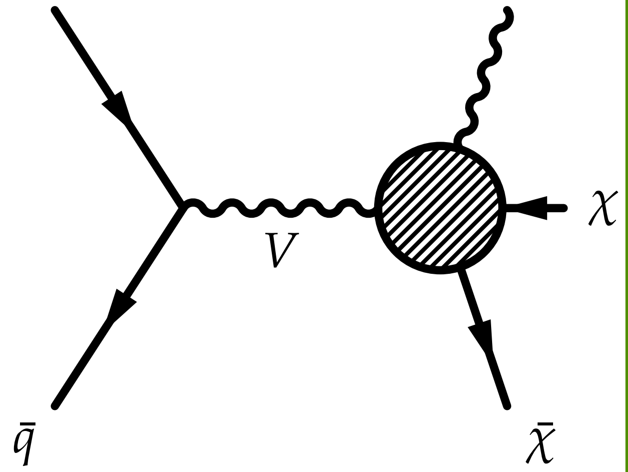
mono-Higgs

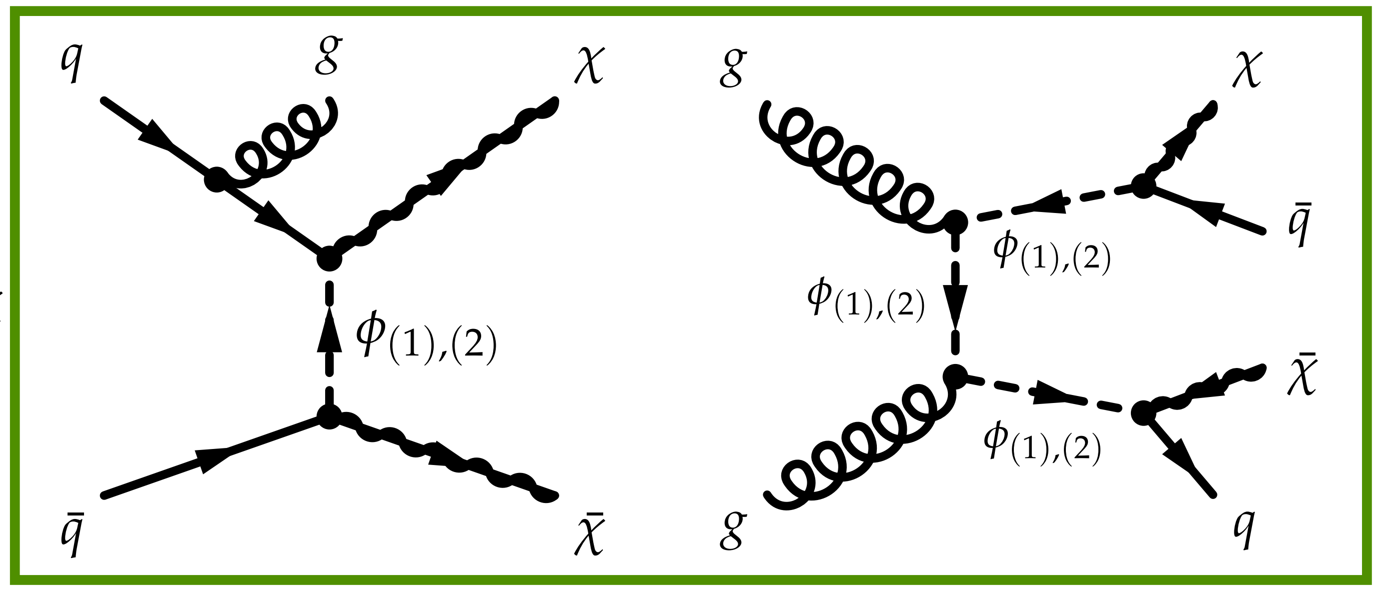


mono-tt/bb

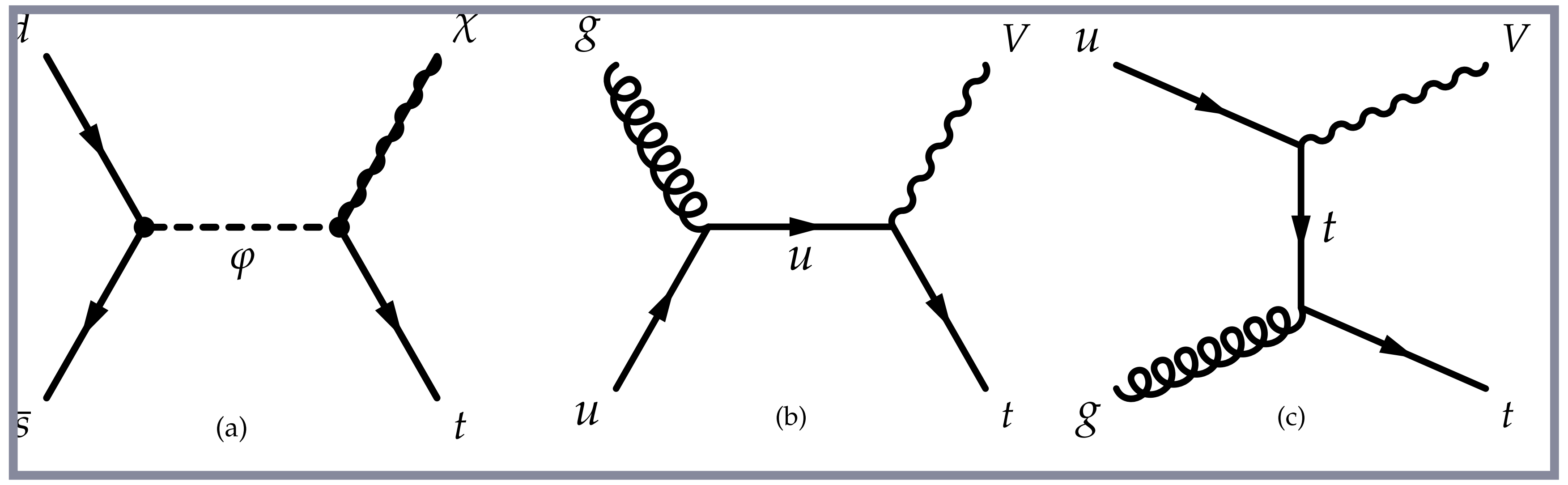


mono-V





t-channel mono-jet/dijet

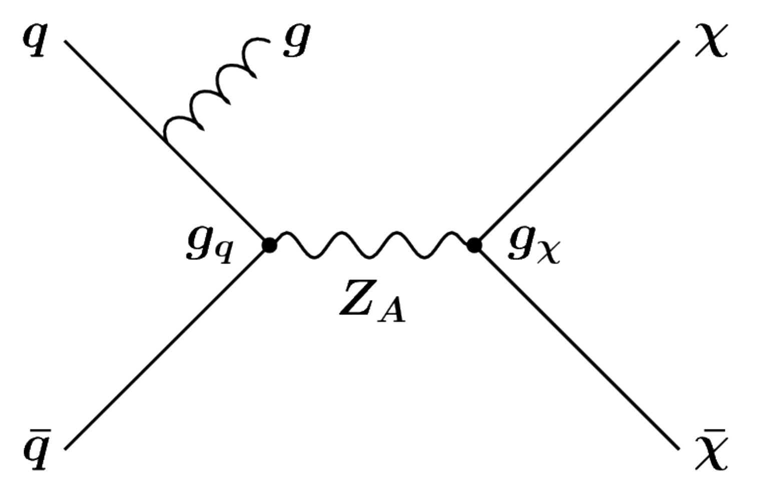


mono-t

- ***Mono-jets*: the most powerful in general**
- ***Mono-photons*: First used for DM searches**
- **Mono-W: Distinguish DM couplings to u- and d- type of quarks**
- **Mono-Z: clean signature**
- **Mono-Tops/Bs: Couplings to tops/b-quarks**
- **Mono-Higgs: Higgs-portals**

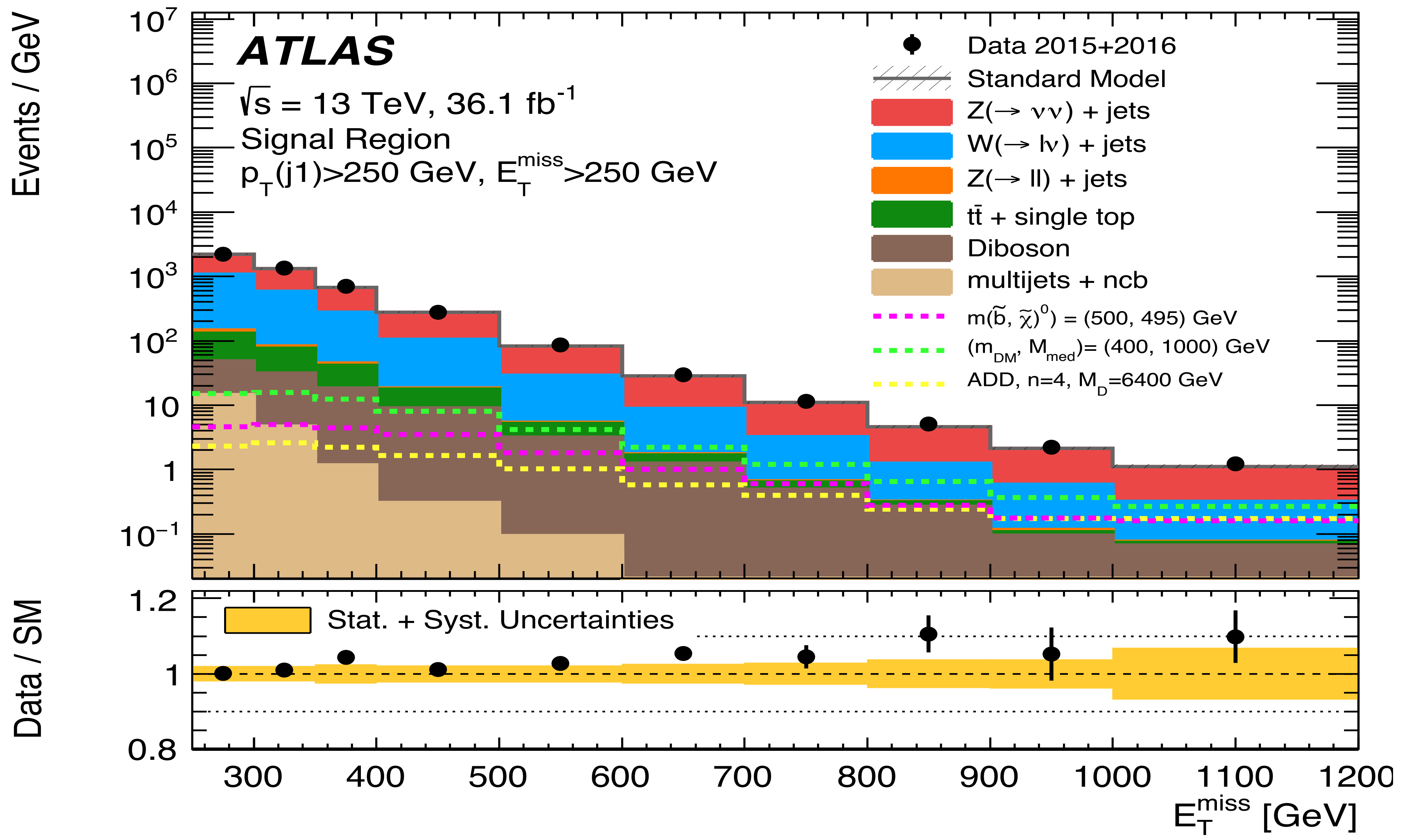
X can be emitted either directly from ISR through SM gauge interactions or from a BSM vertex coupling

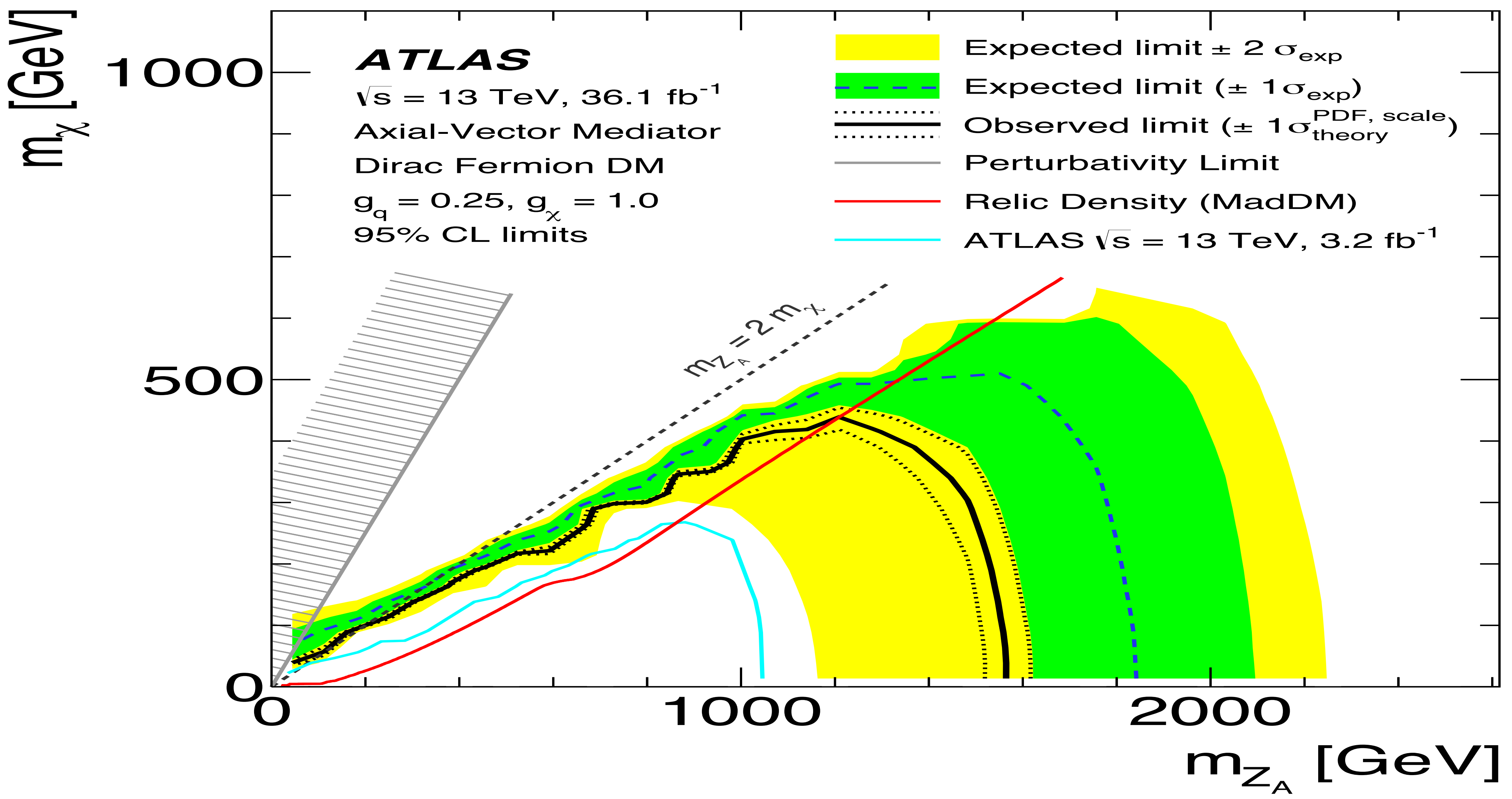
Dark Matter — Jet+X



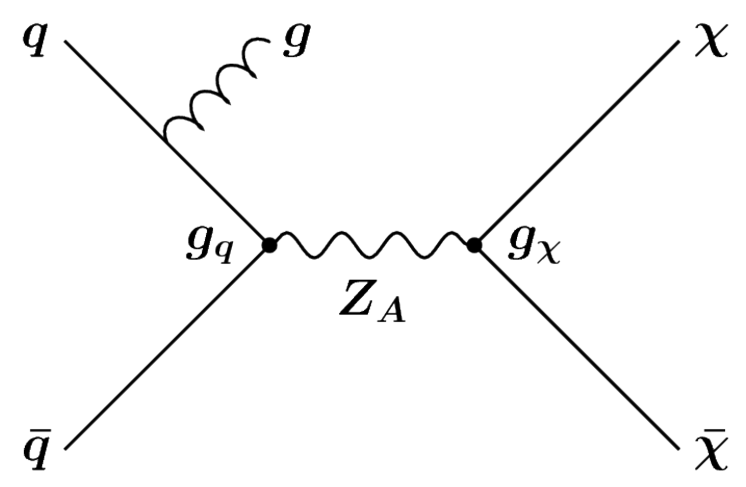
arXiv:1711.03301

- Signature: ***an ISR jet recoiling off a large MET***
- Event selection: ***a well-identified leading jet pT >250 GeV, MET > 250 GeV; well-separated between leading energetic jet and MET***; lepton-veto; up to 3 more jets with p_T>30 GeV
- Main backgrounds: ***Z(νν) + jets, W(ℓν) + jets (data-driven)***
  - re-weighted to perturbative calculations at NLO@QCD + nNNLO@EW (*arXiv:1705.04664*)
  - ***simultaneous fits*** to control regions (CRs): W(μν) +jets, W(eν)+jets, and Z/γ∗(μμ)+jets
- Dominant systematics: W/Z + jets modeling; jet energy scale and lepton efficiency
- ***No excess is found !***

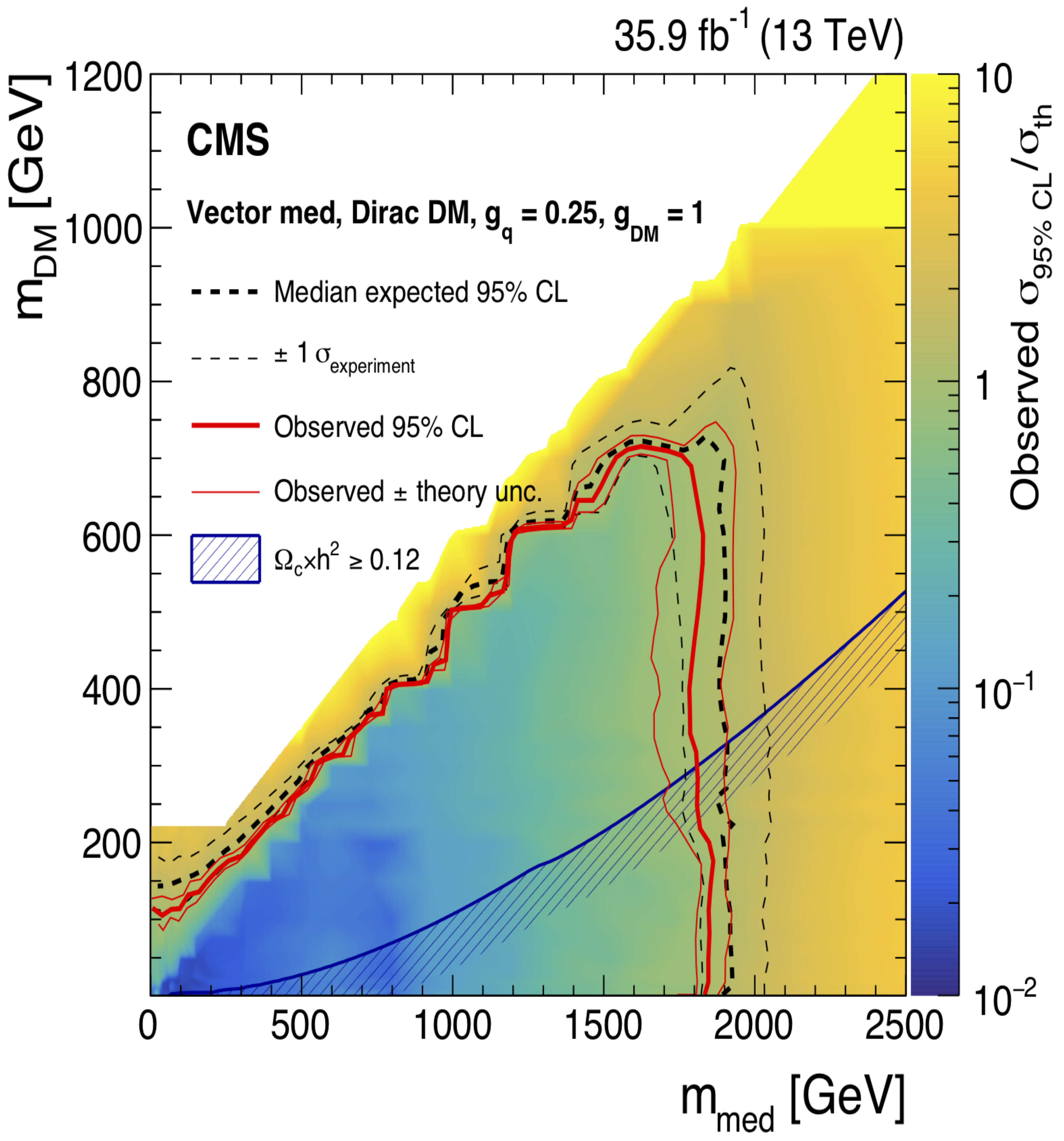


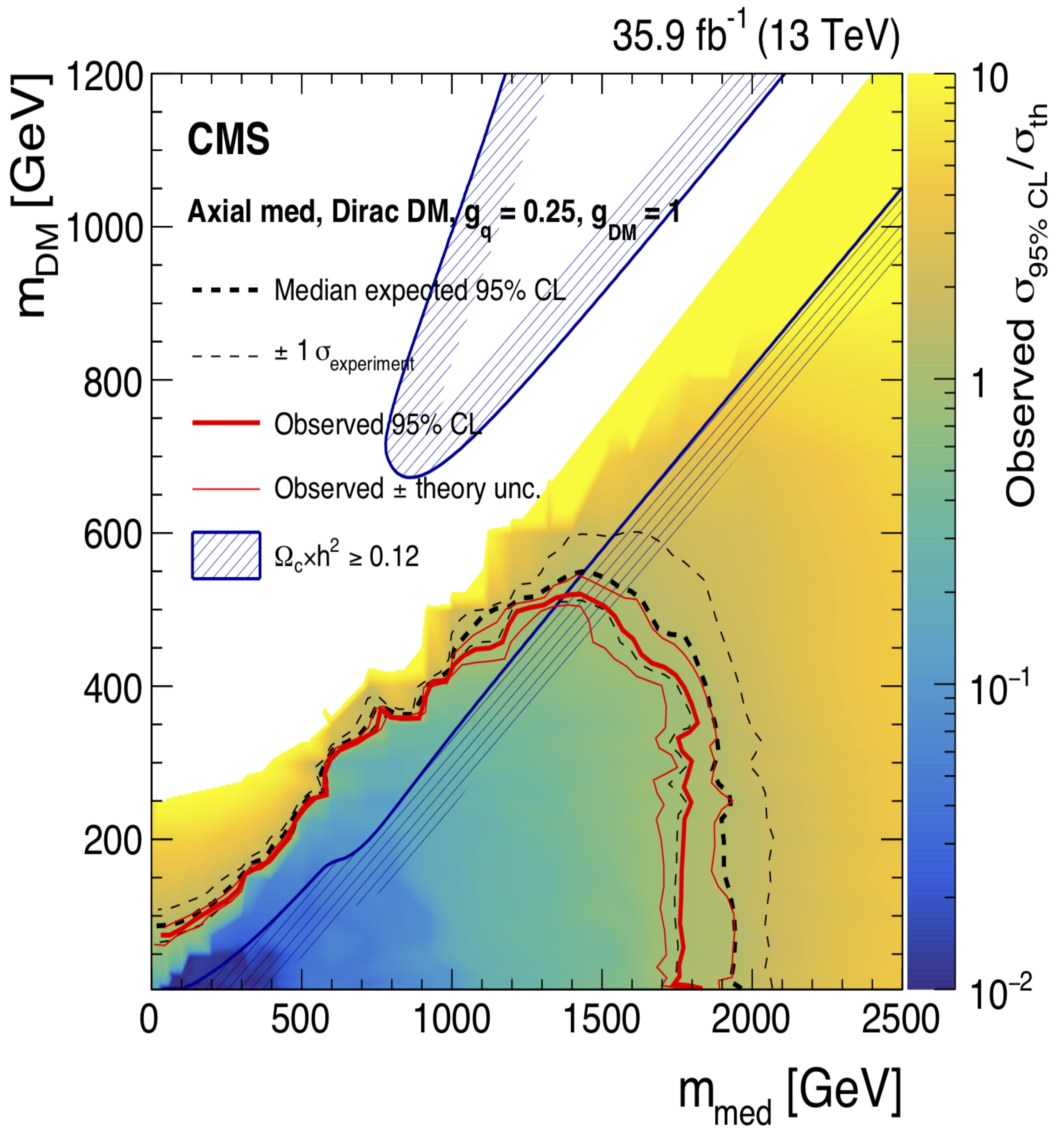


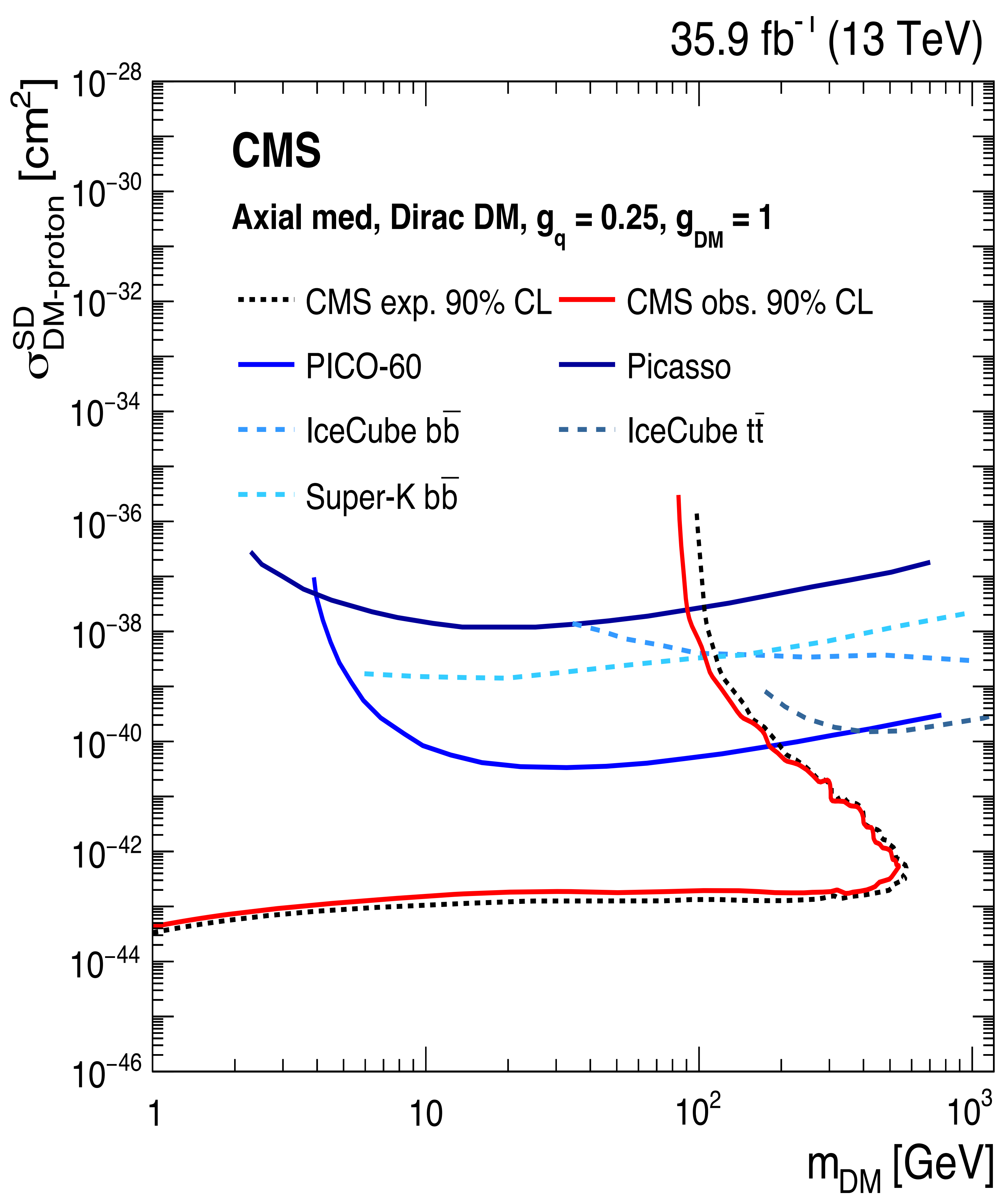
Dark Matter — Jet+X



arXiv:1712.02345



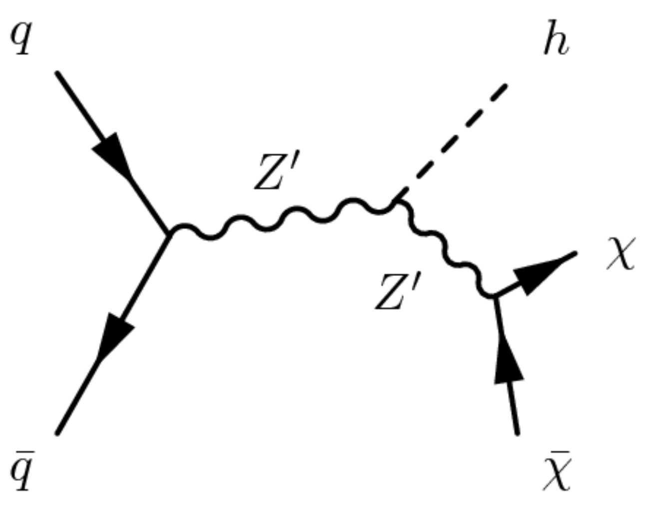


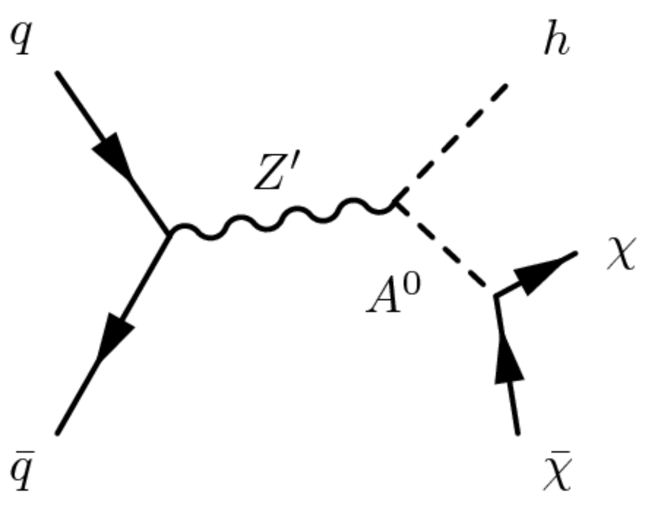


Exclude Vector (Axial-vector) mediator masses up to 1.8 TeV for DM masses up to 700(500) GeV

Axial-vector mediator -> Spin dependent DD limits

Dark Matter — Higgs ($\gamma\gamma$) + X



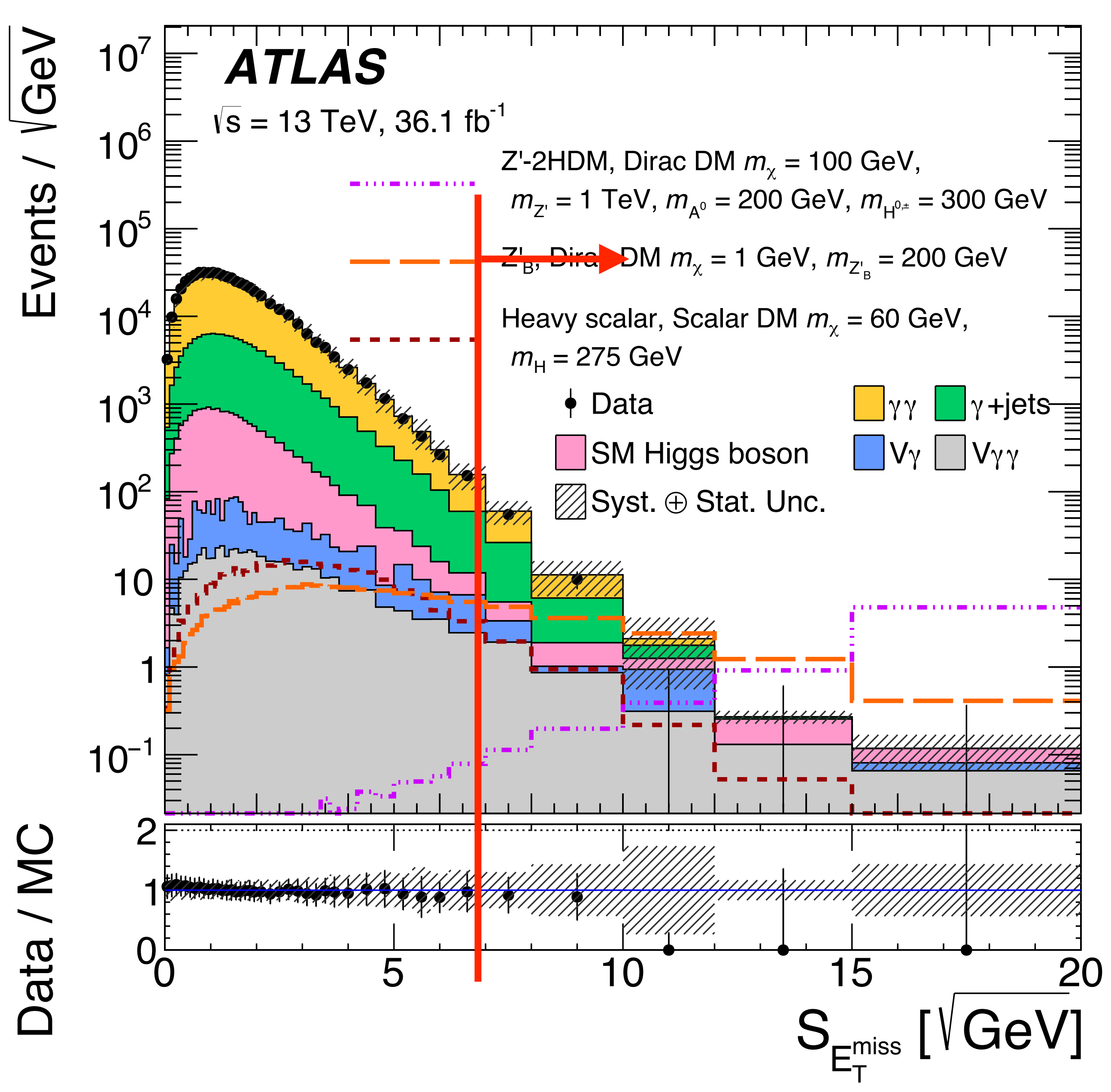


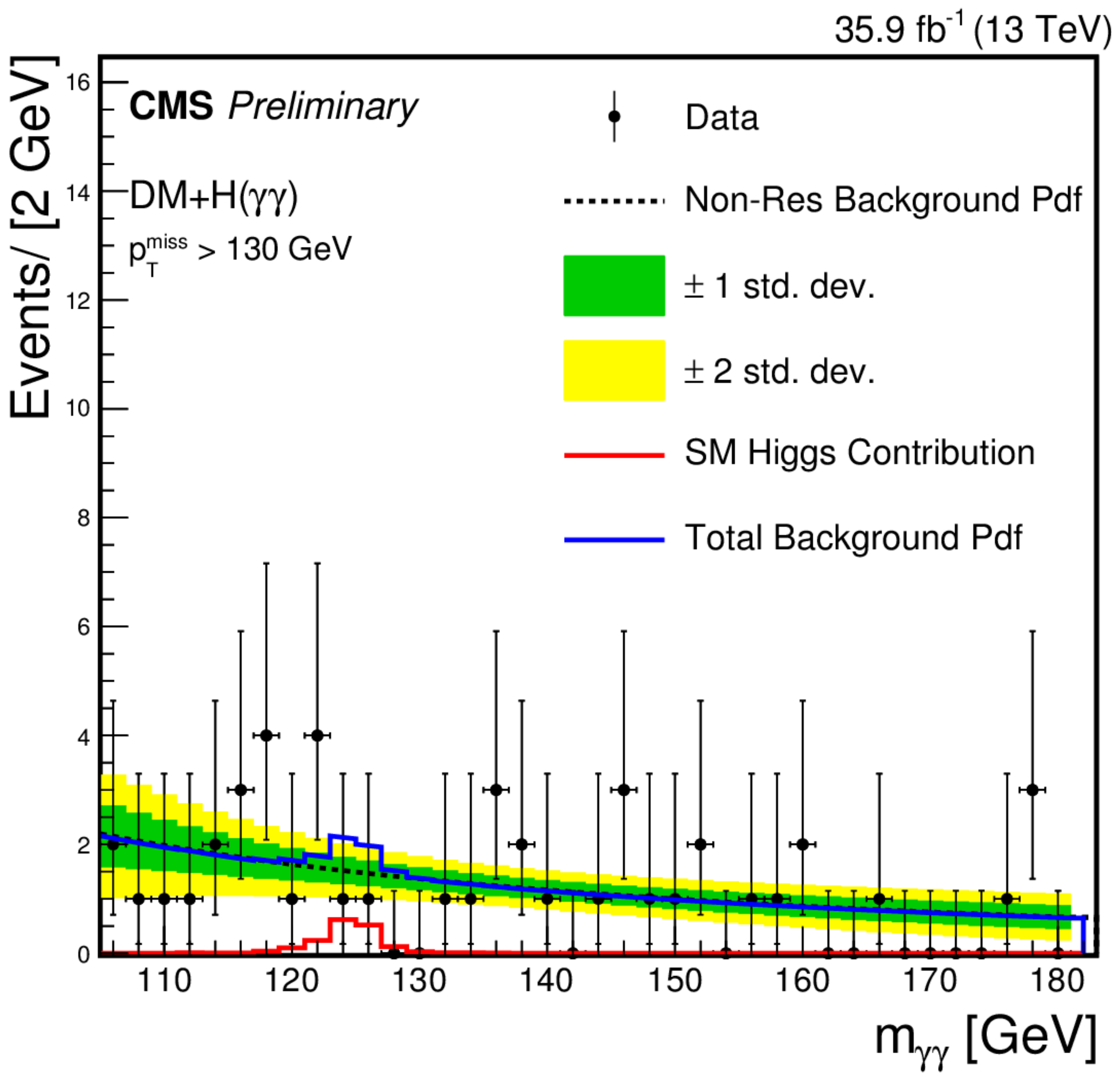
JHEP 10 (2017) 180

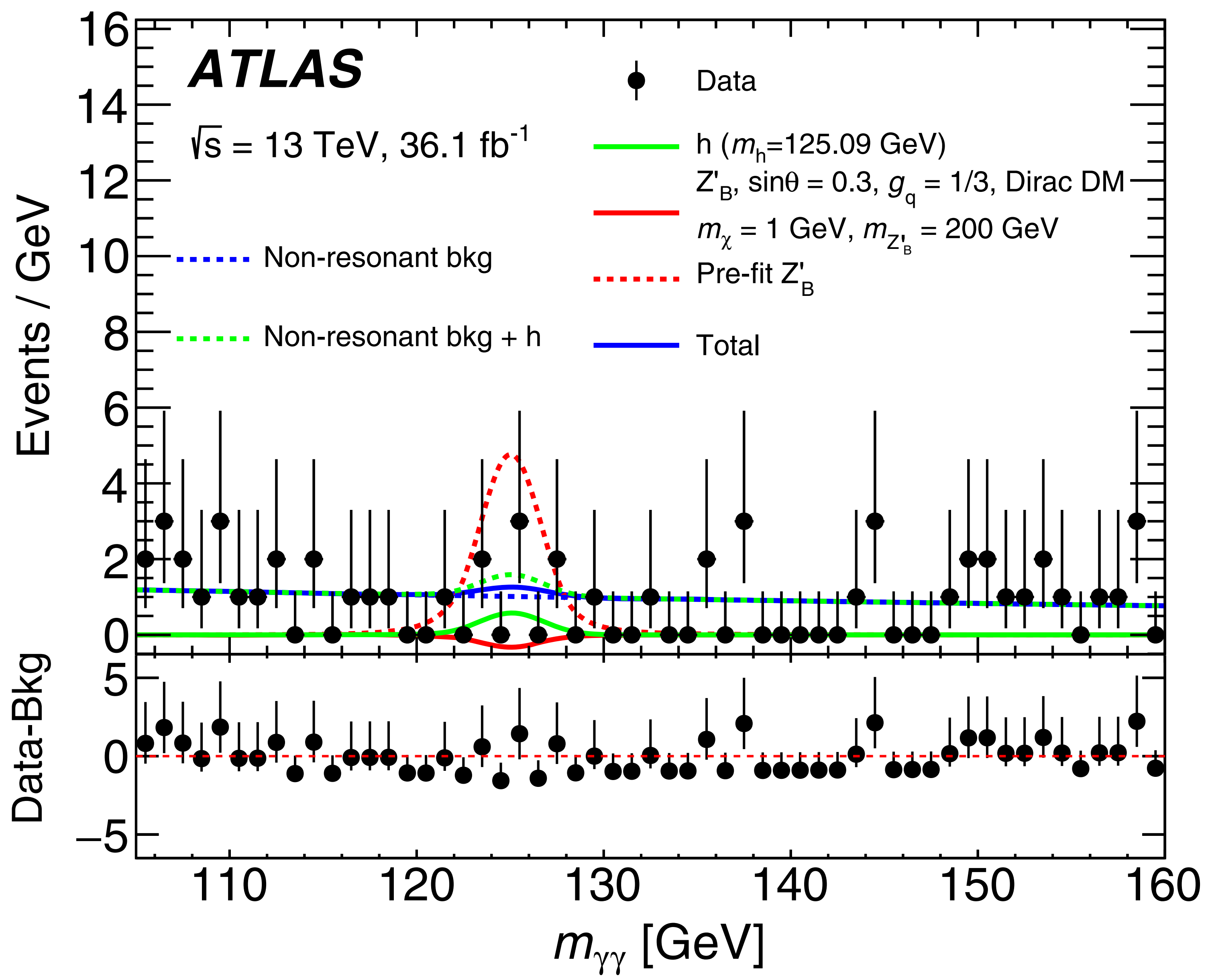
PRD 96 (2017) 112004

- Signature: two well-identified photons compatible with the 125 GeV Higgs boson plus MET
- ISR Higgs boson is Yukawa suppressed, a mono-Higgs signal can only be through BSM vertex
  - **fully data-driven** non-resonant background ($\gamma\gamma$, γ+jets), SM Higgs is MC estimated (μ_{SM} = 1)
- Main systematic uncertainties: 10% non-resonant background modeling

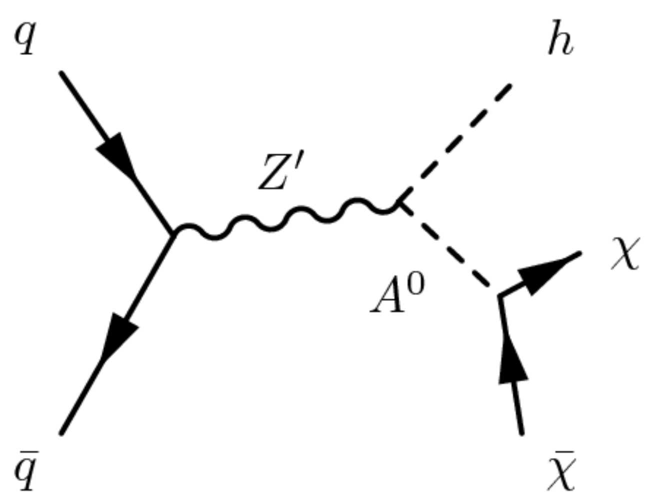
No significant BSM excess is observed!



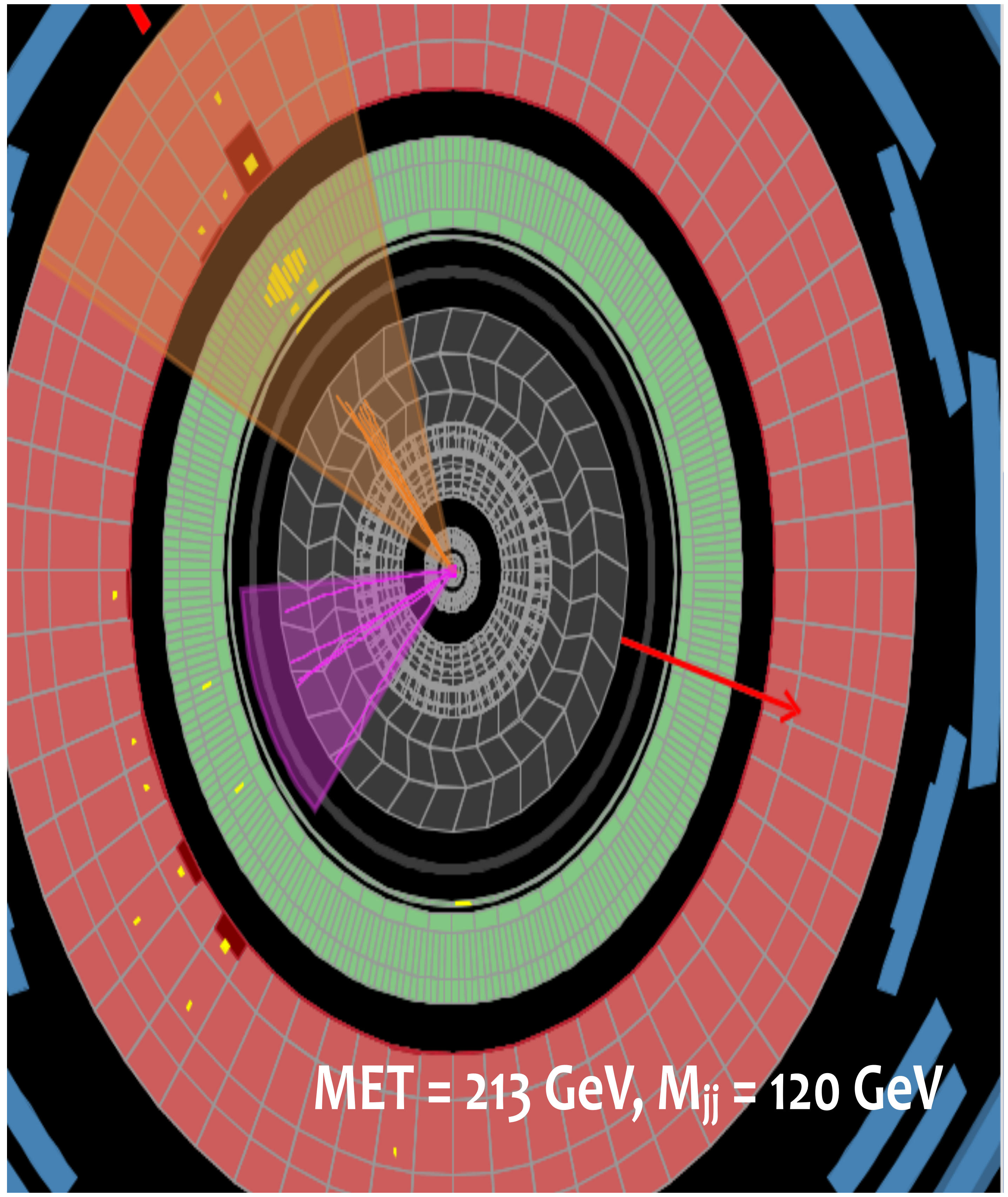




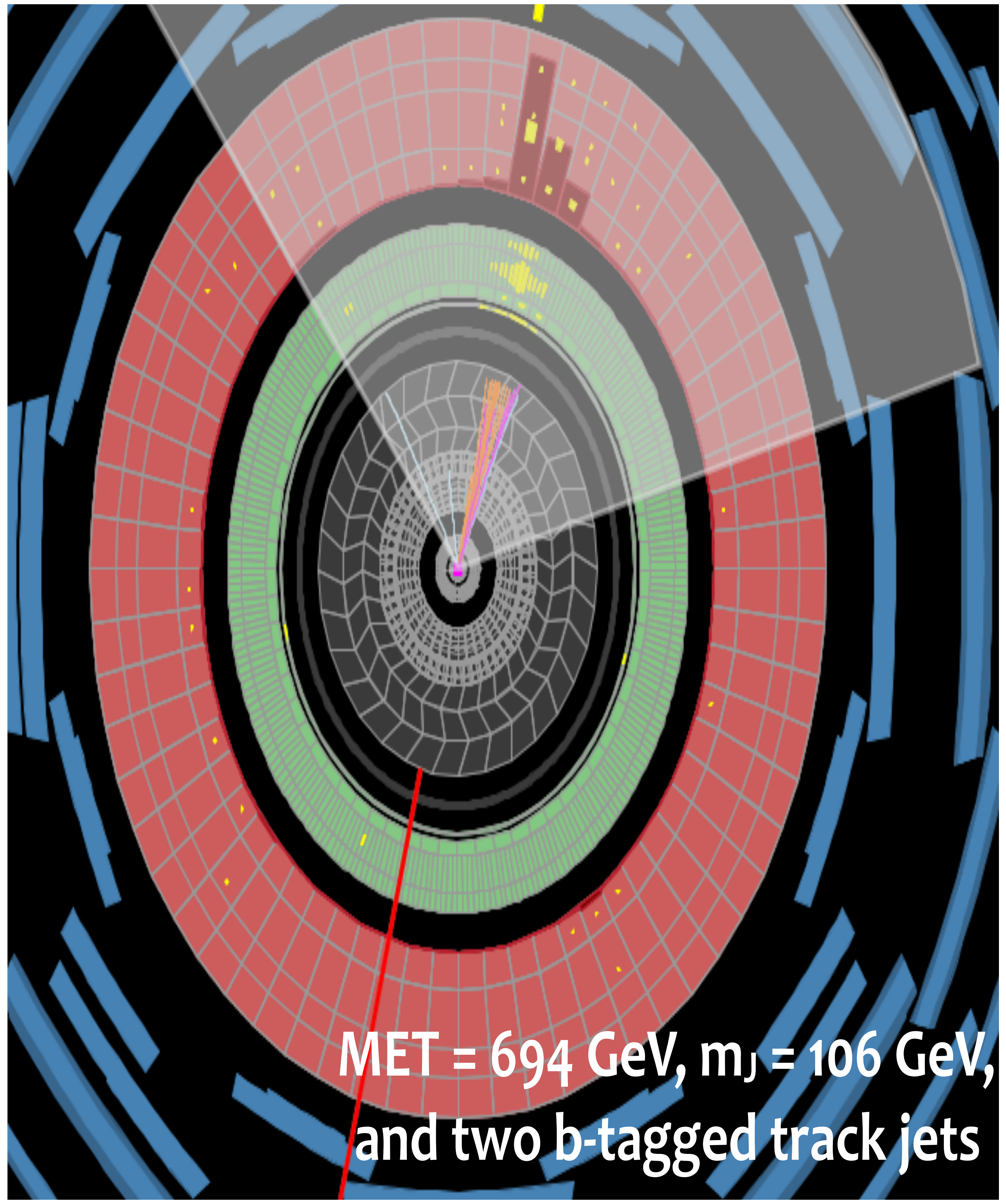
Dark Matter — Higgs (bb) + X



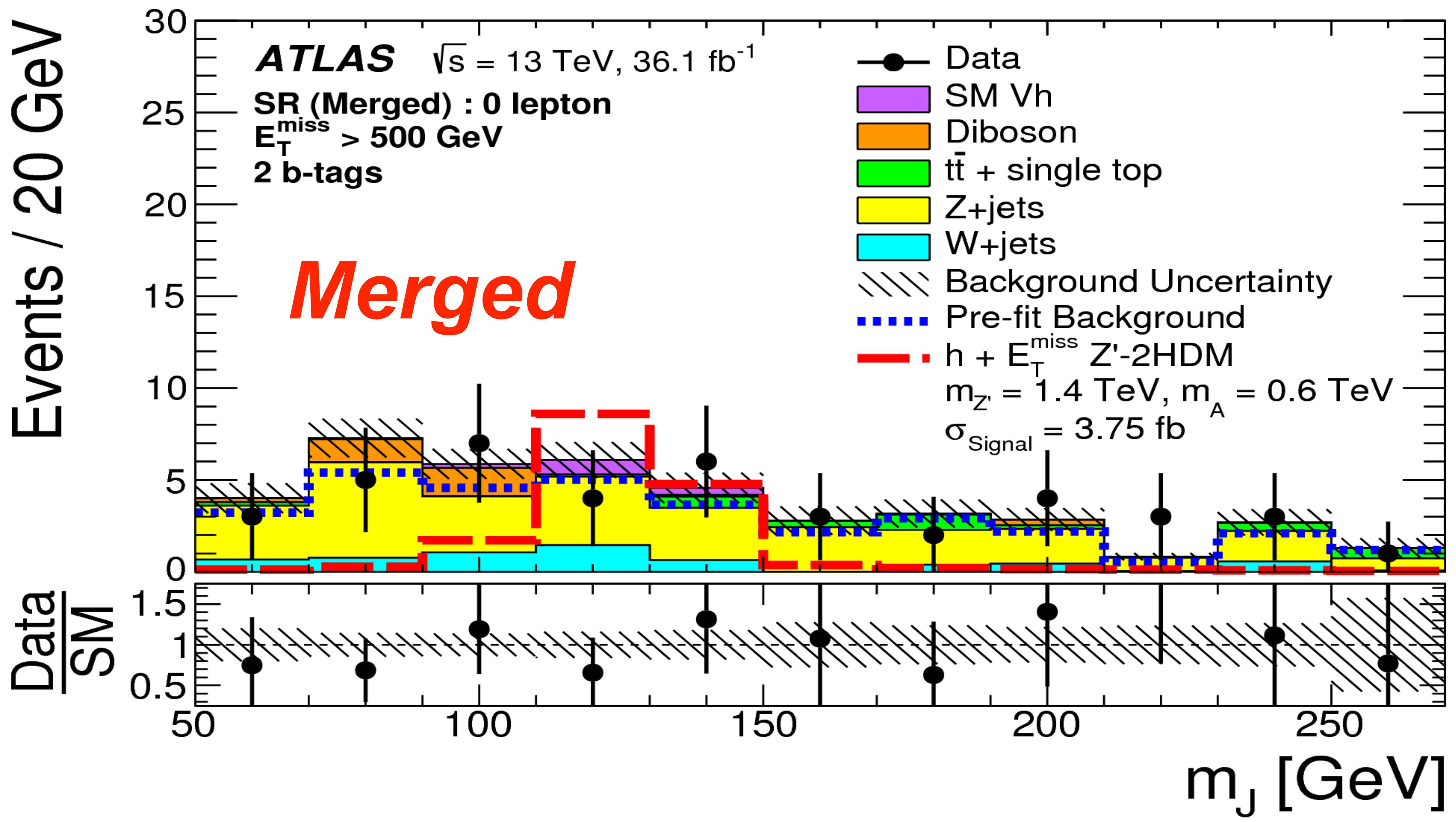
PRL 119 (2017) 181804

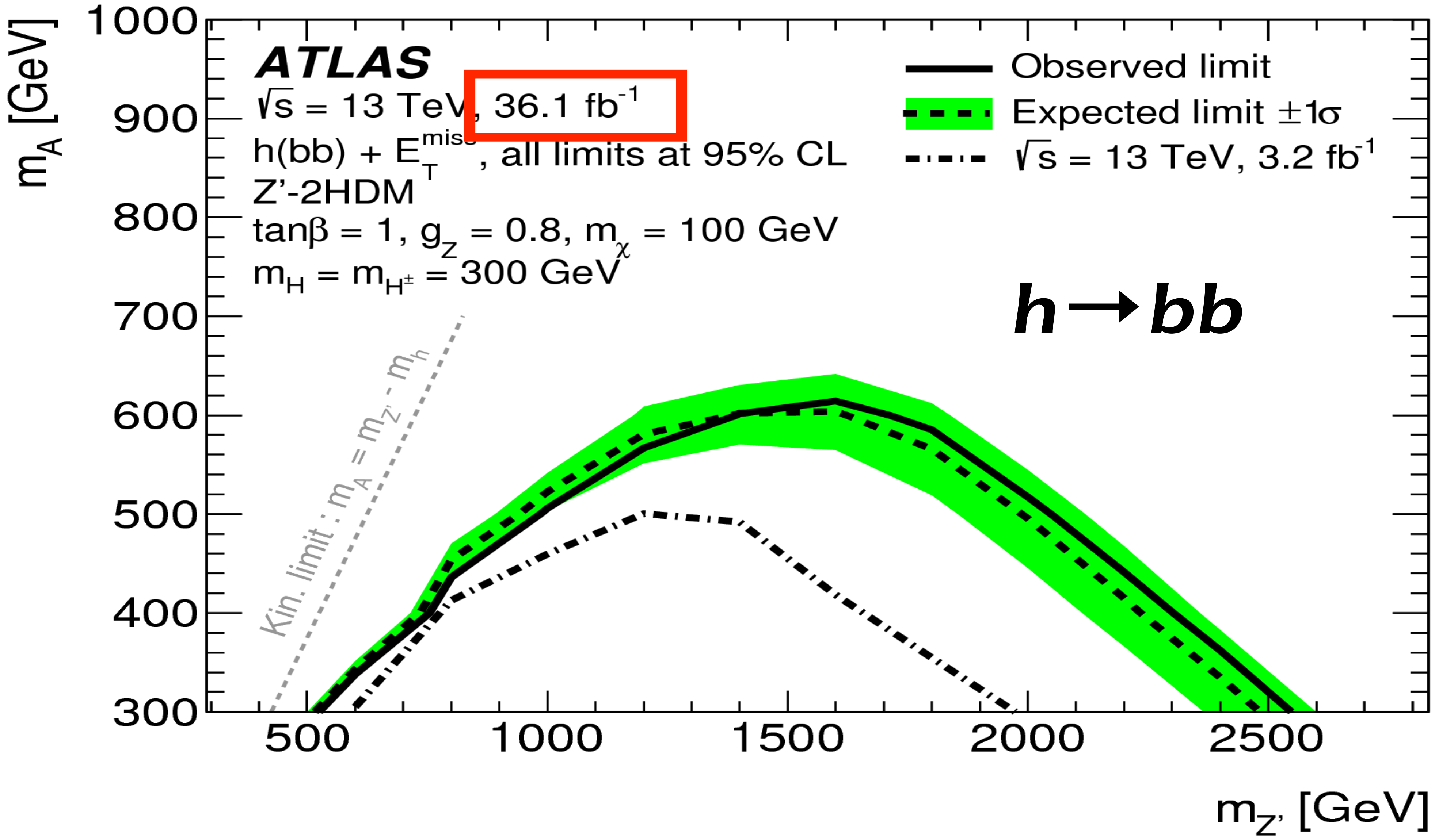


Resolved: two b-tagged track-jets + intermediate MET

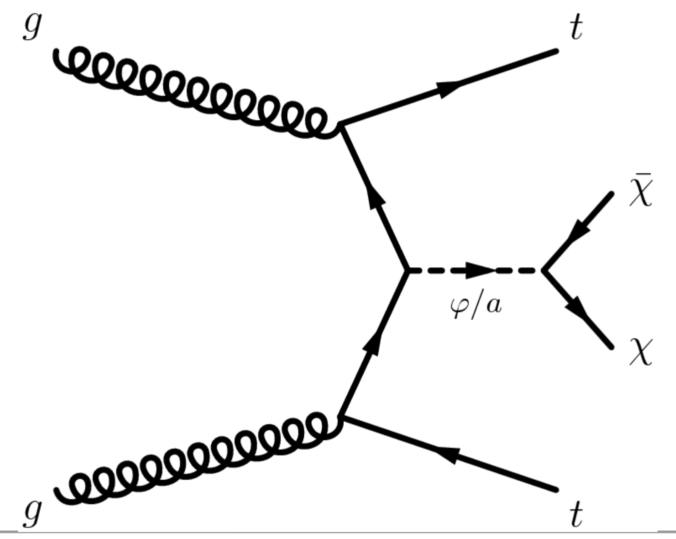


Merged: one large-R jet with two b-tagged tracks + large MET





Dark Matter — ttbar + X

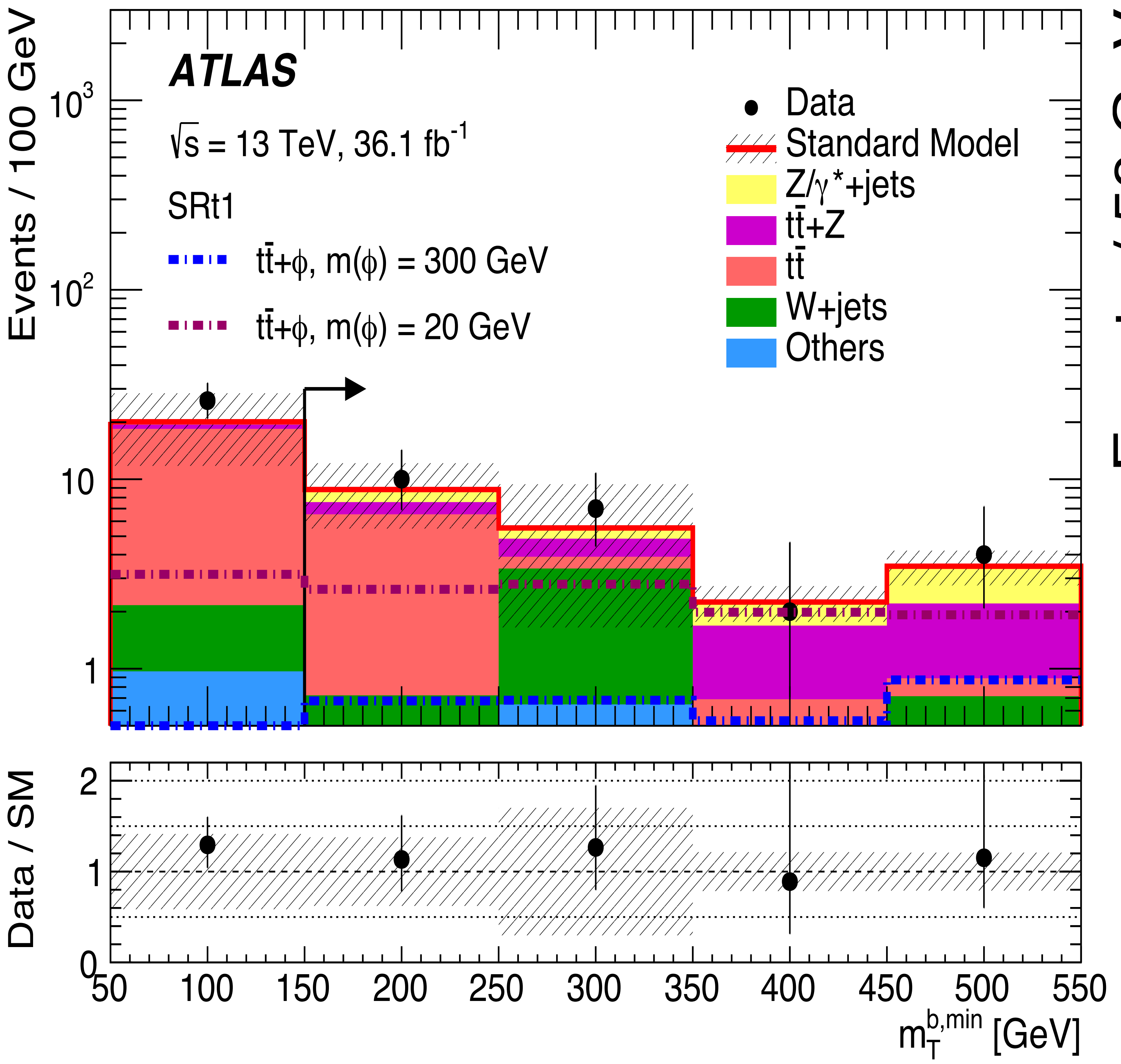


EPJC 78 (2018) 18
arXiv:1711.11520

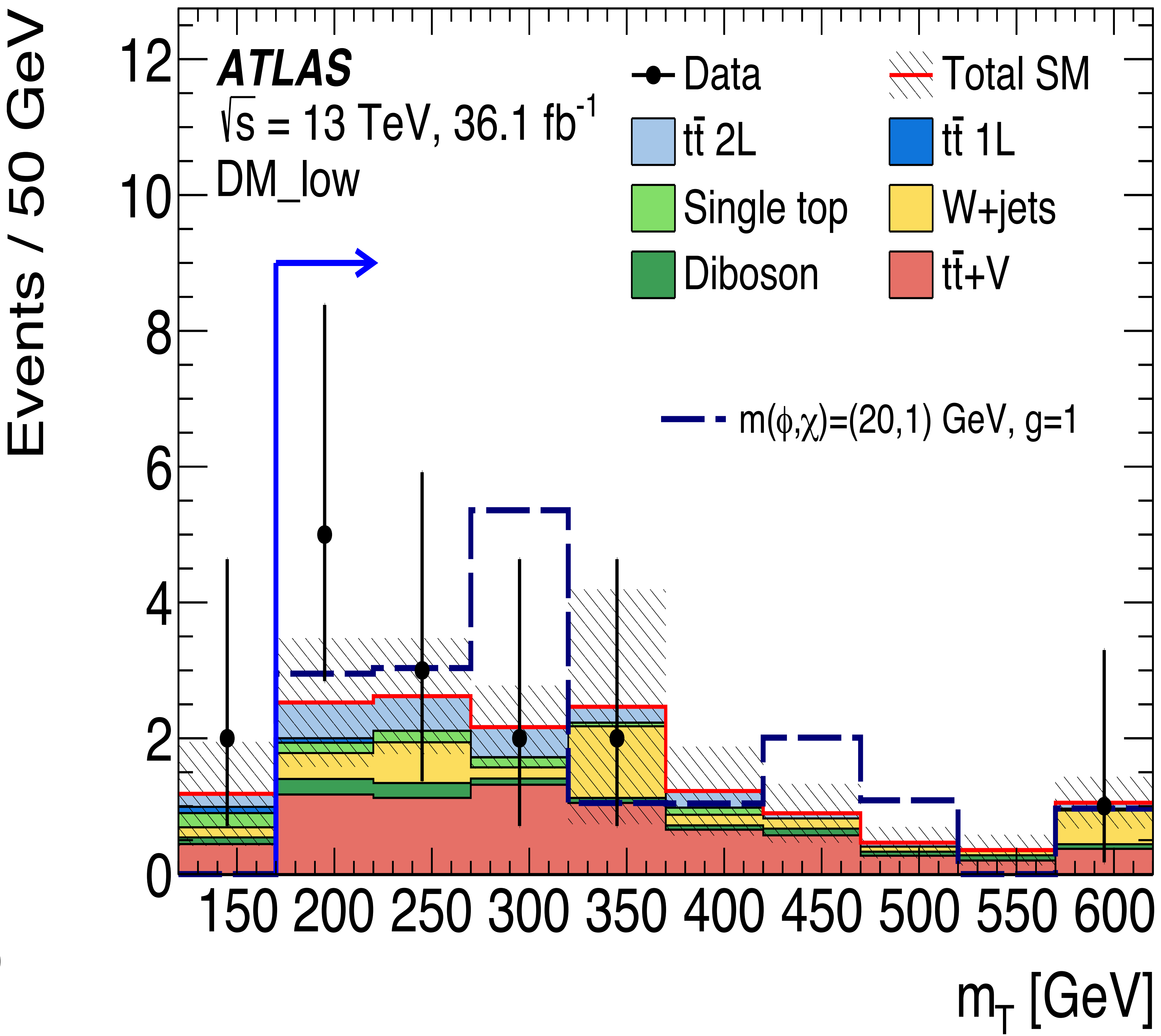
- ***Complicated final states*** (can be improved by using machine learning)
  - multiple jets (≥2/1/0 b-quarks), 0/1/2 well-identified lepton, and MET

No significant excess above SM expectation is observed in all three channels

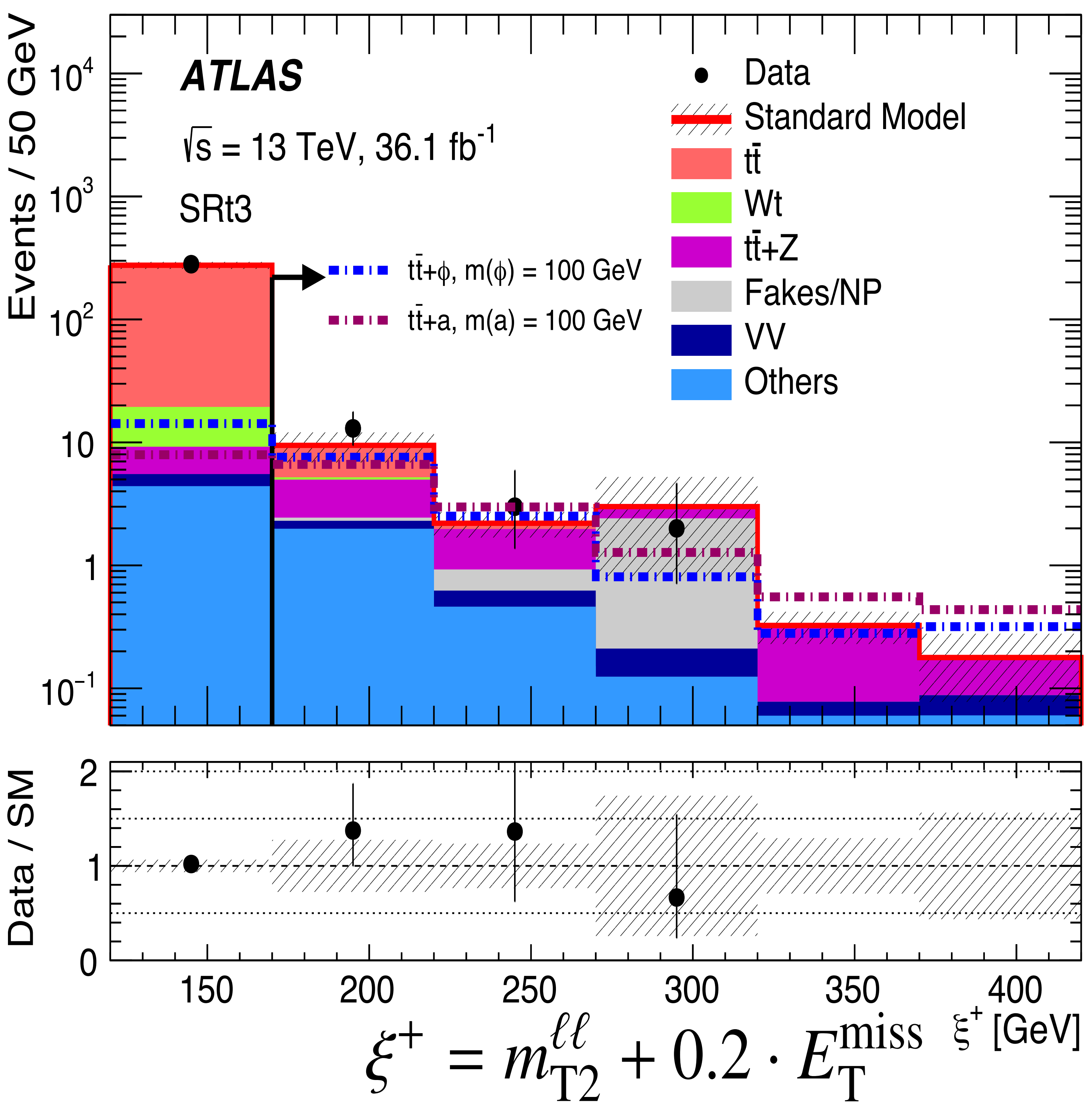
0 lepton



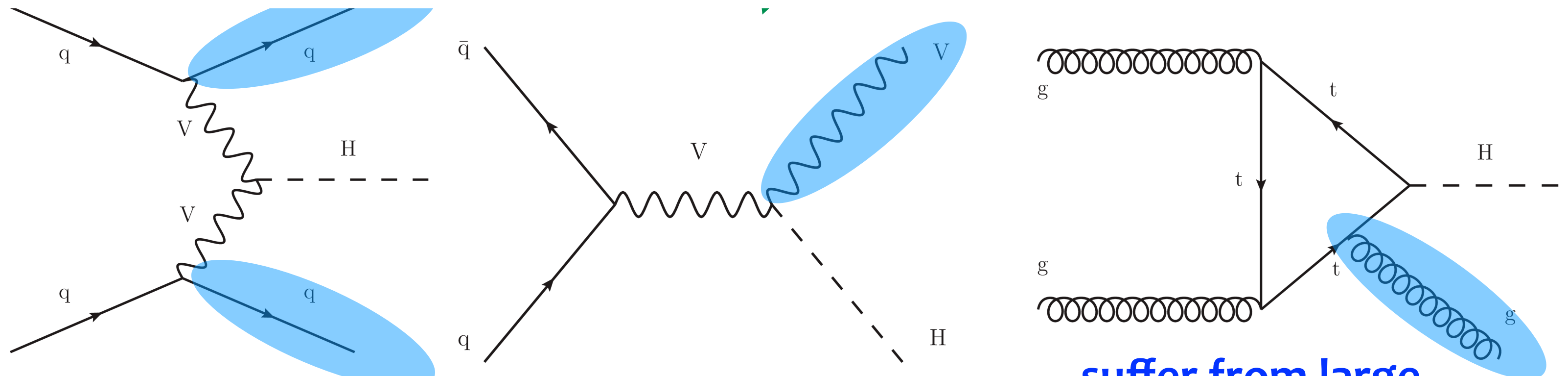
1 lepton



2 leptons



A deeper probe of the Higgs sector

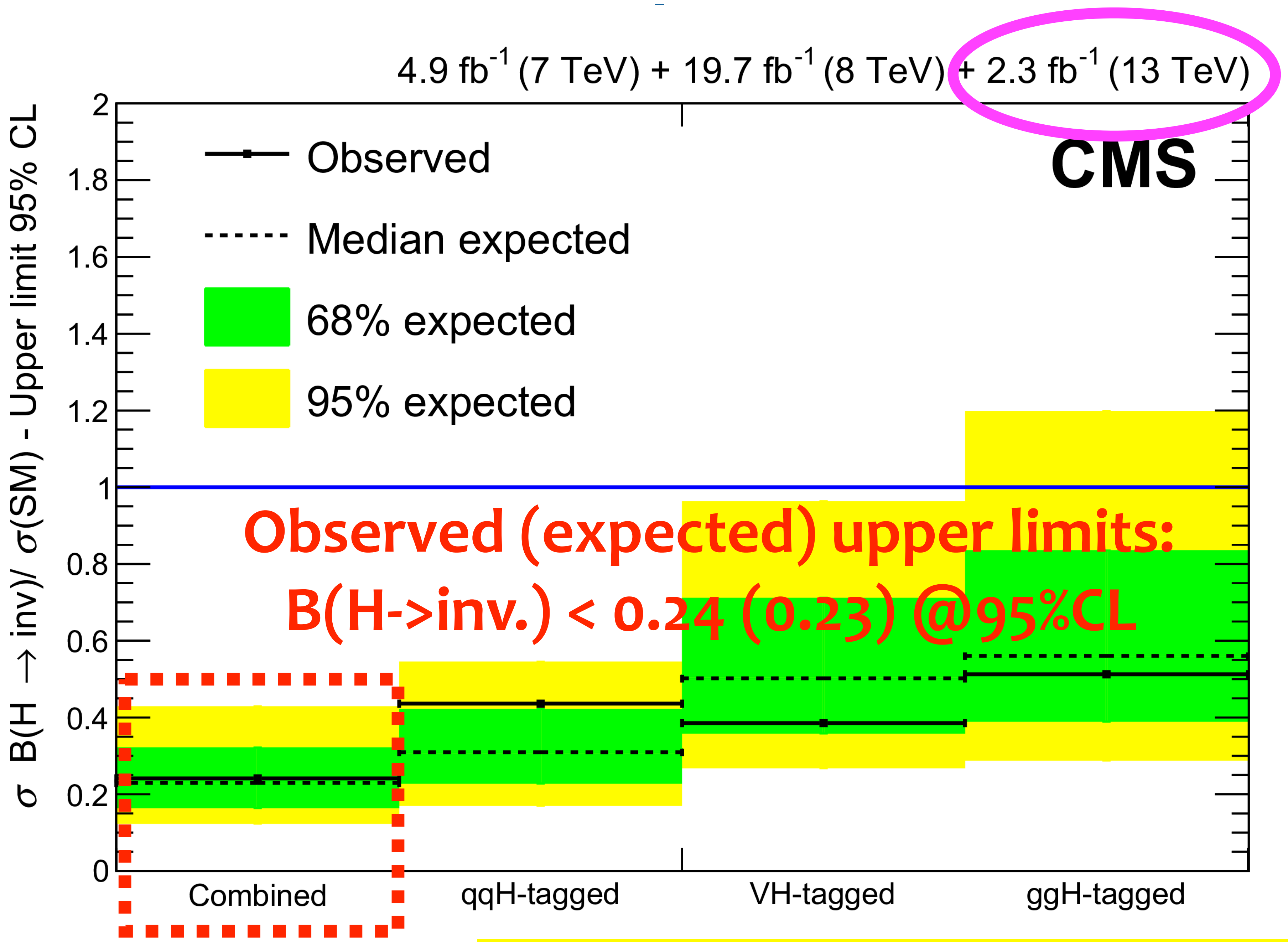


suffer from large backgrounds

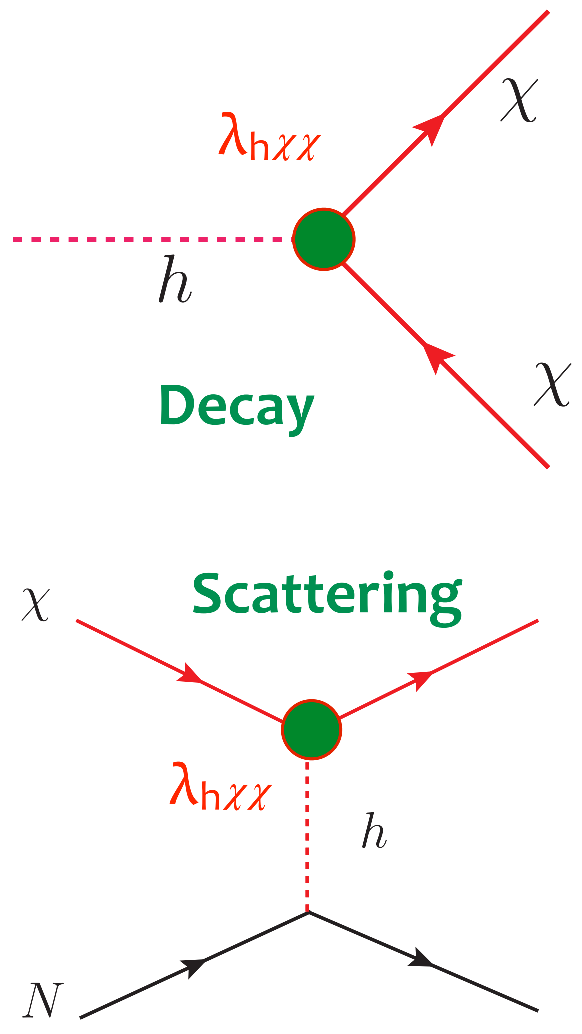
JHEP 02 (2017) 135

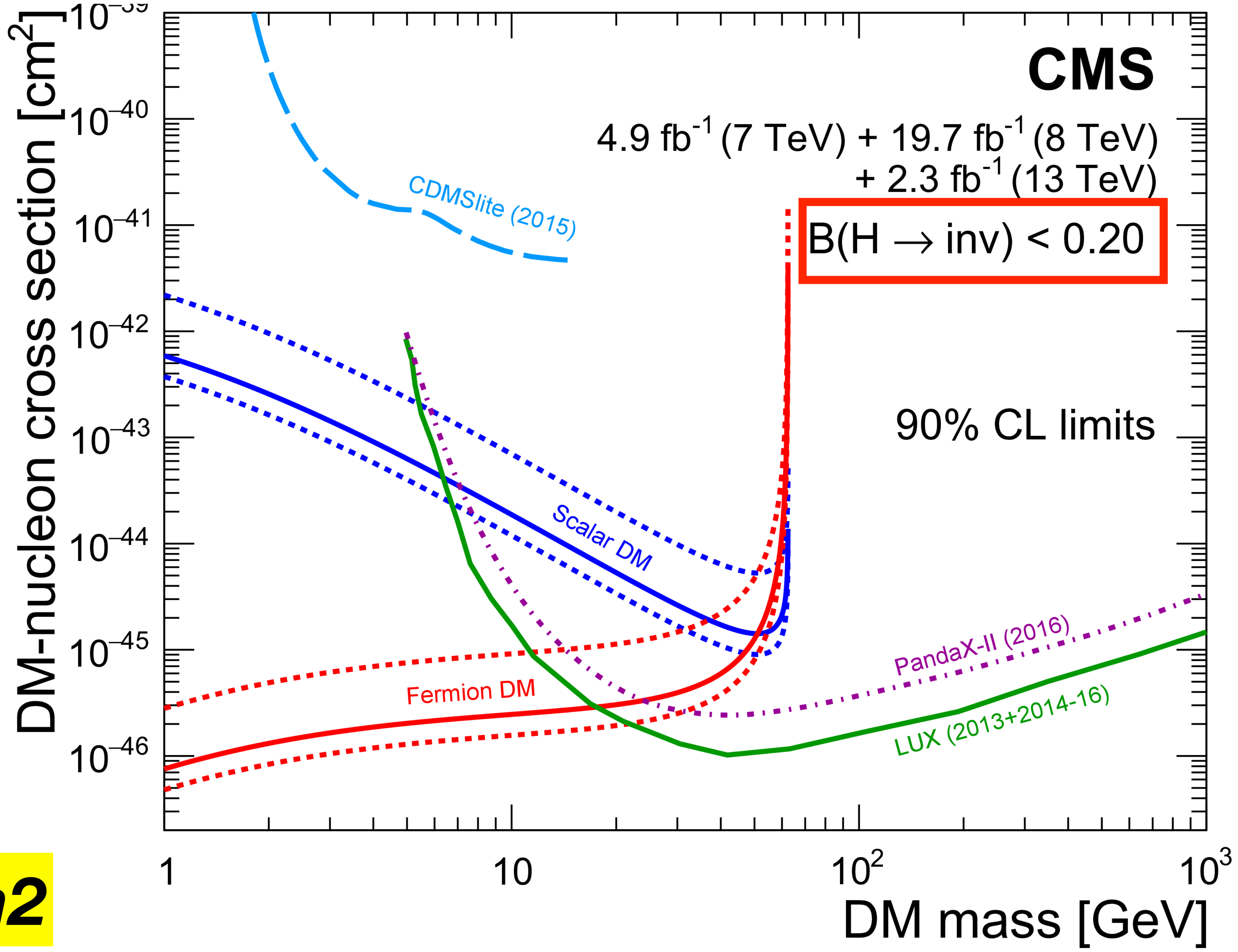
- Total width: Γ_H = 4 MeV, too small to be resolved experimentally
  - very loose bound from interference gg→ZZ
  - no way to access it indirectly (via production rates) in a precise way

- ***Invisible decay width: DM connection!***
  - the mass of the DM is less than half of the Higgs mass



Observed (expected) upper limits: B(H->inv.) < 0.24 (0.23) @95%CL



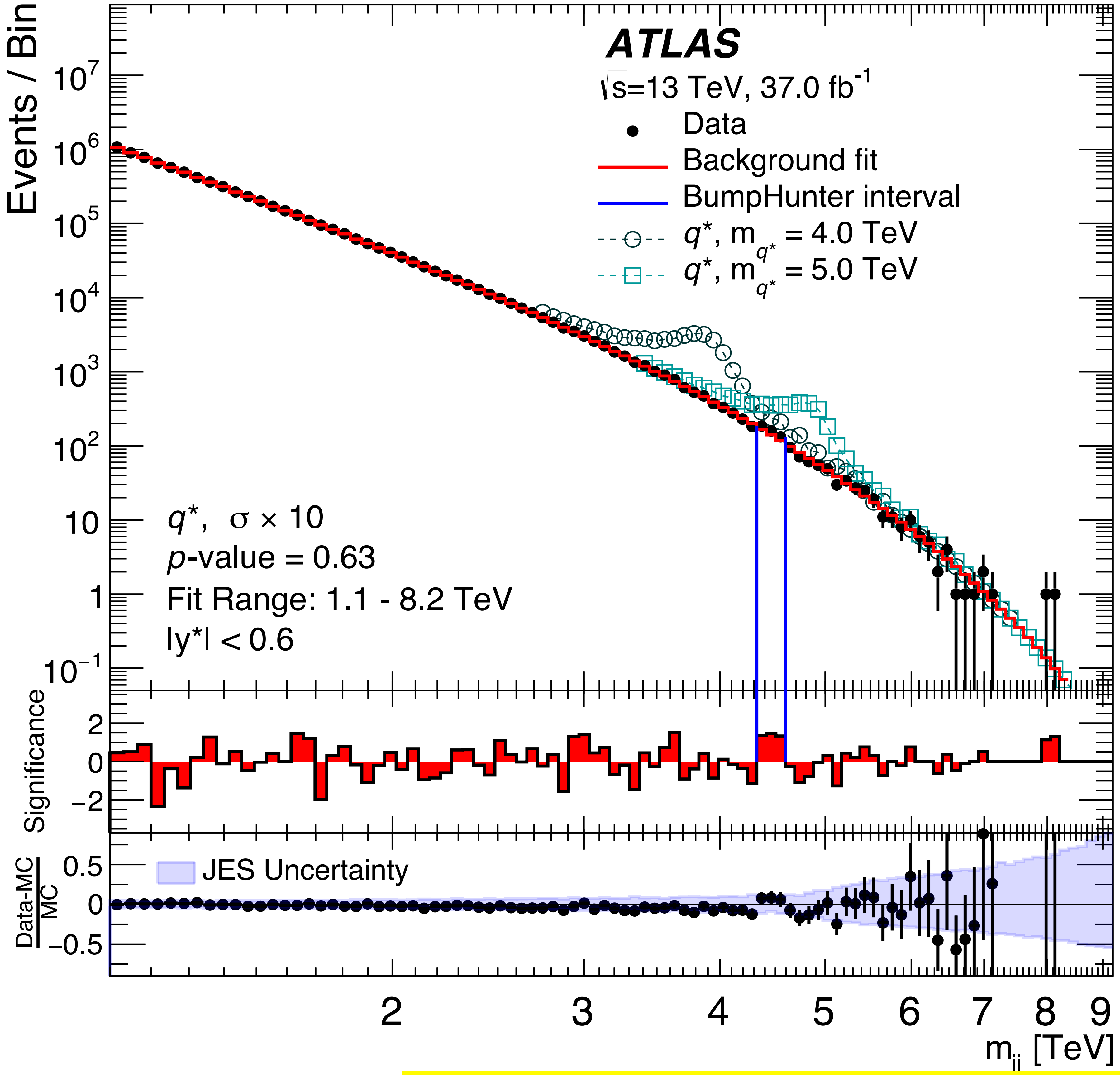


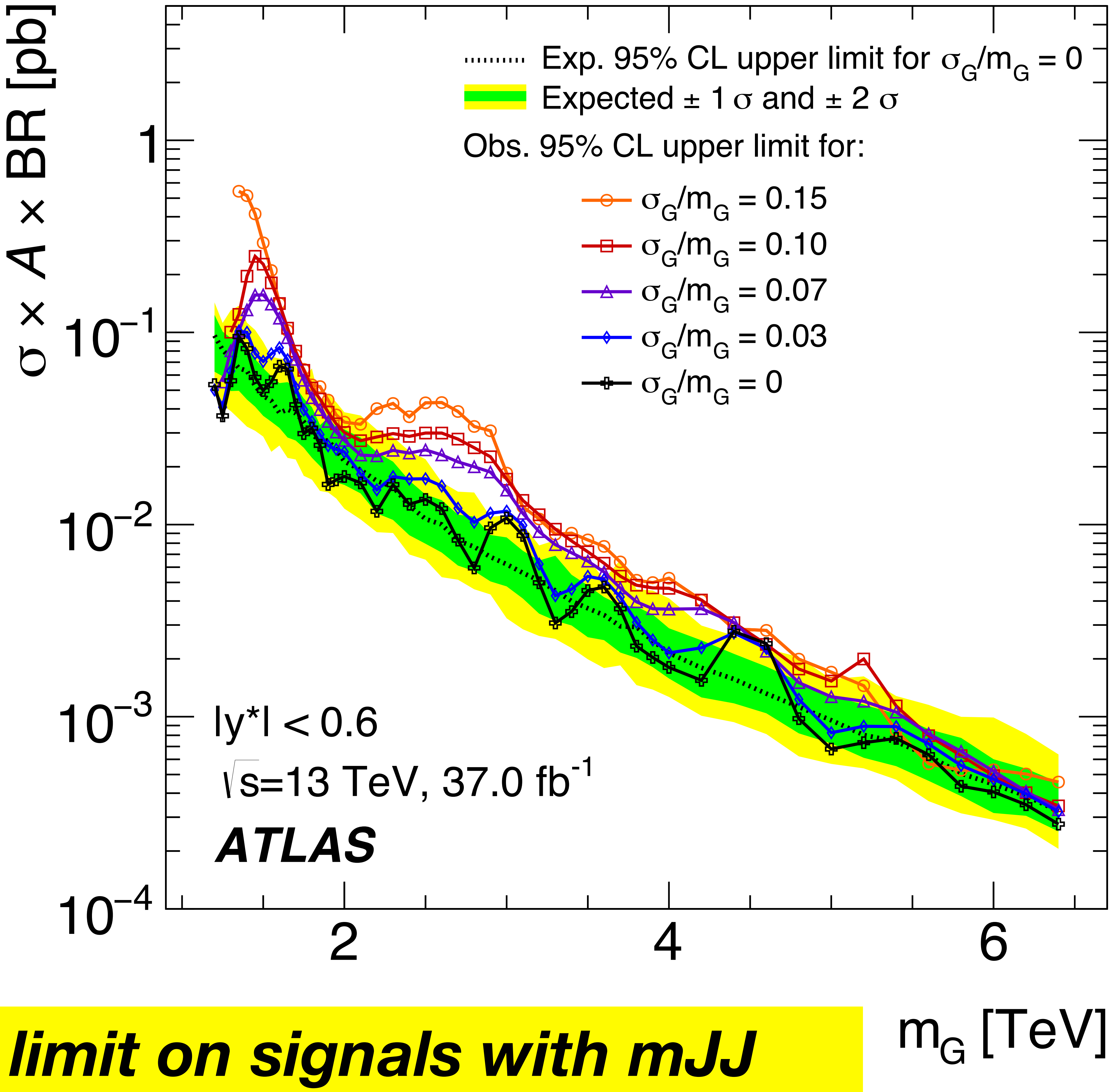
Improvement in near future: <10%@Run2

Recast from dijet resonant search

Phys. Rev. D 96, 052004

- Signature: ≥ 2 jets with p_T > 440 (60) GeV ➪ No excess is observed !

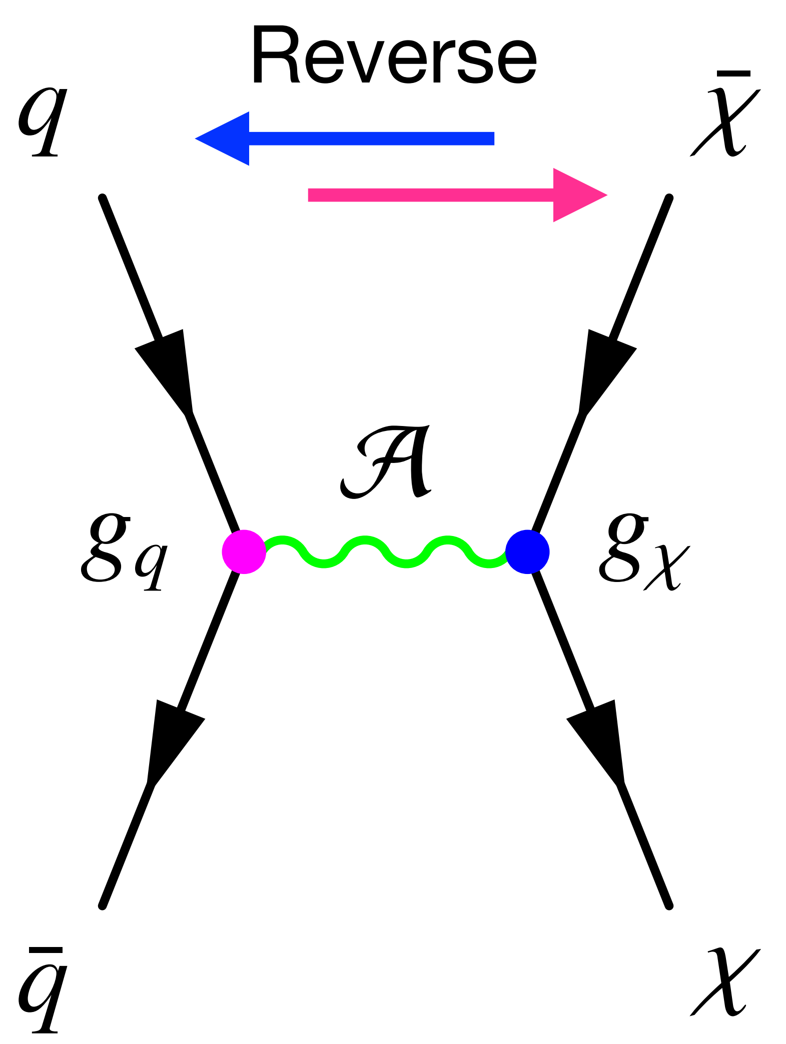


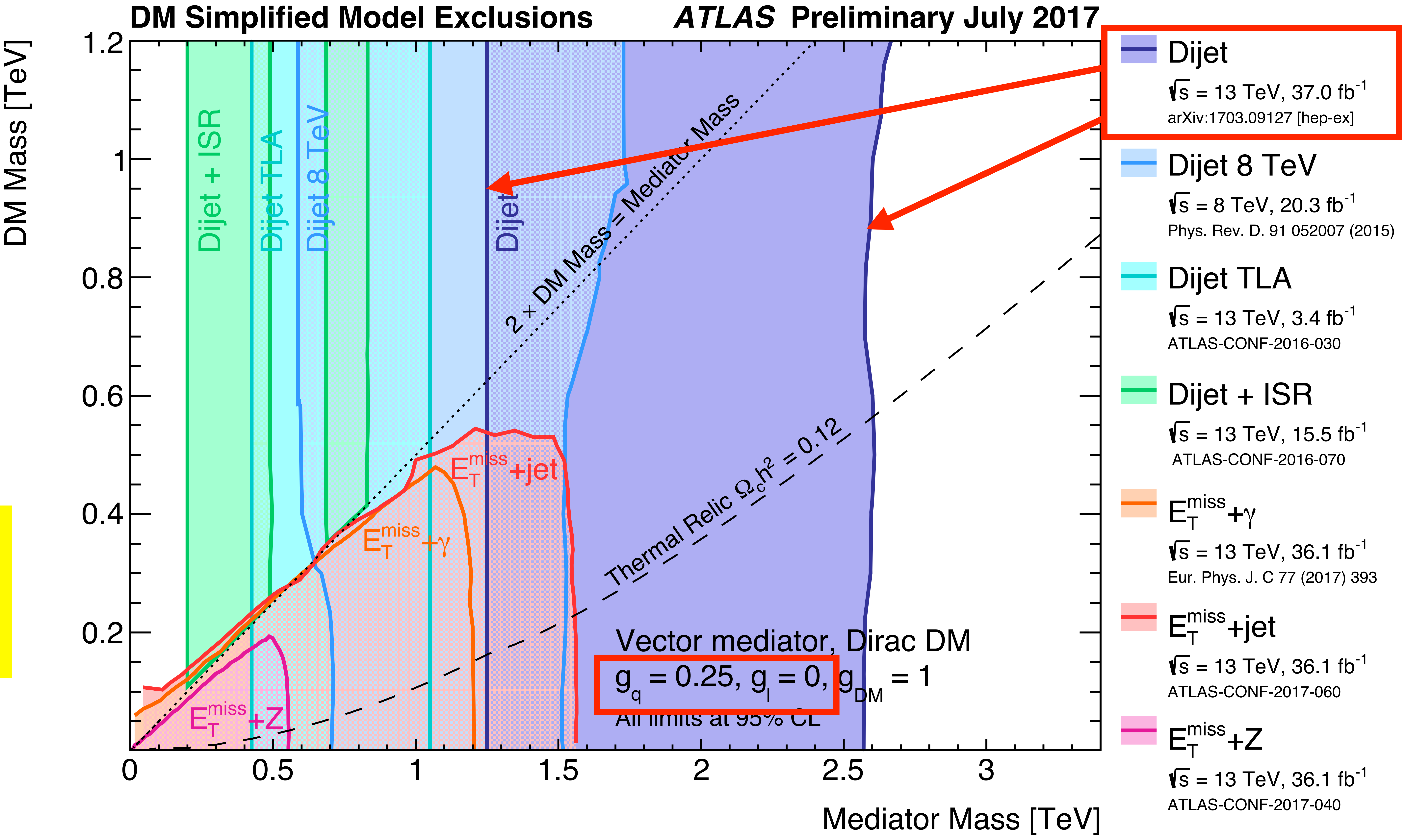


- *Expected limit for a narrow width signal*
- *Observed limits for signal with width ranges from* ***0 to 15%m_{JJ}***

model-independent limit on signals with mJJ between 1.1 - 6.5 TeV (Gaussian shape)

Recast from dijet resonant search



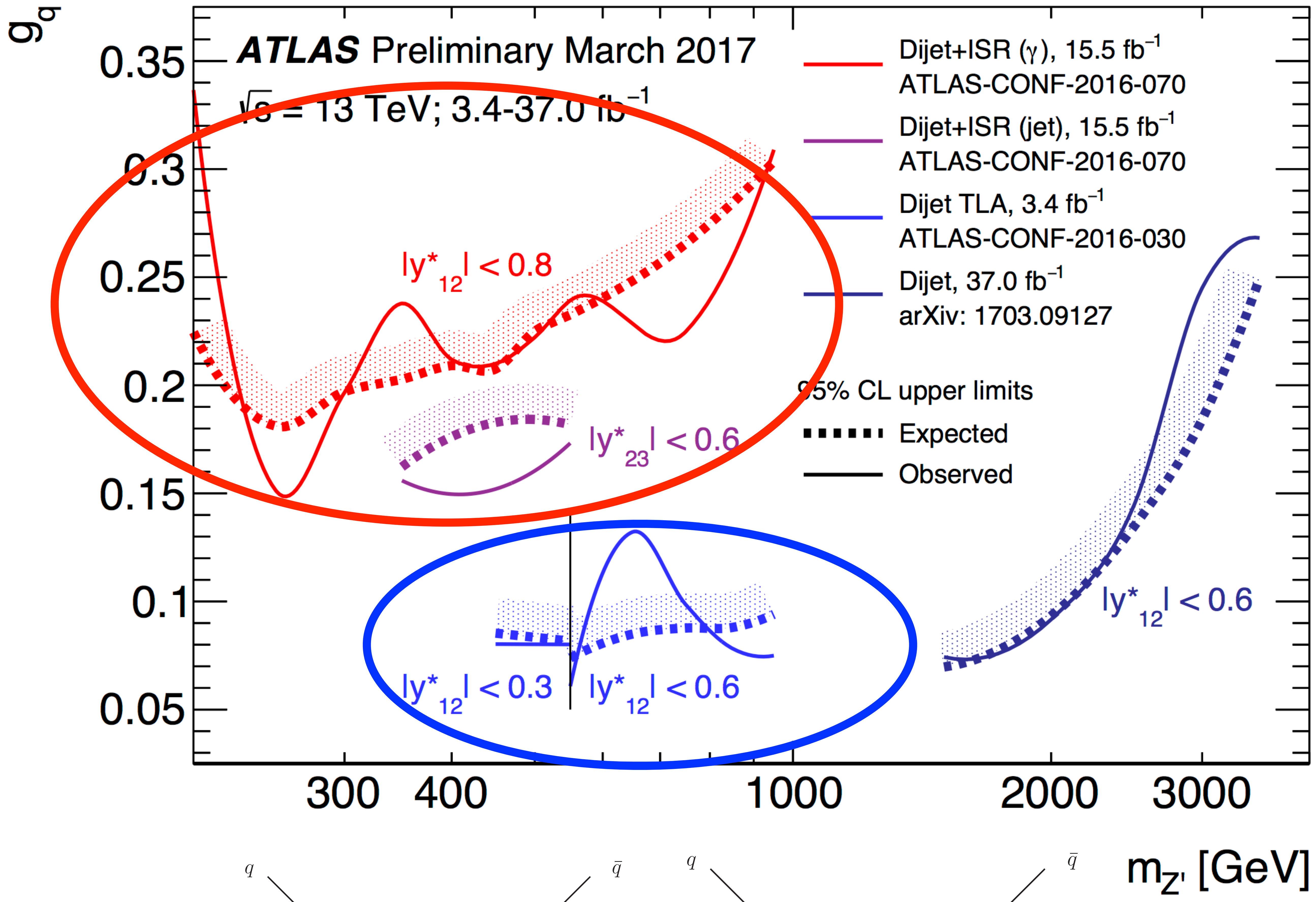


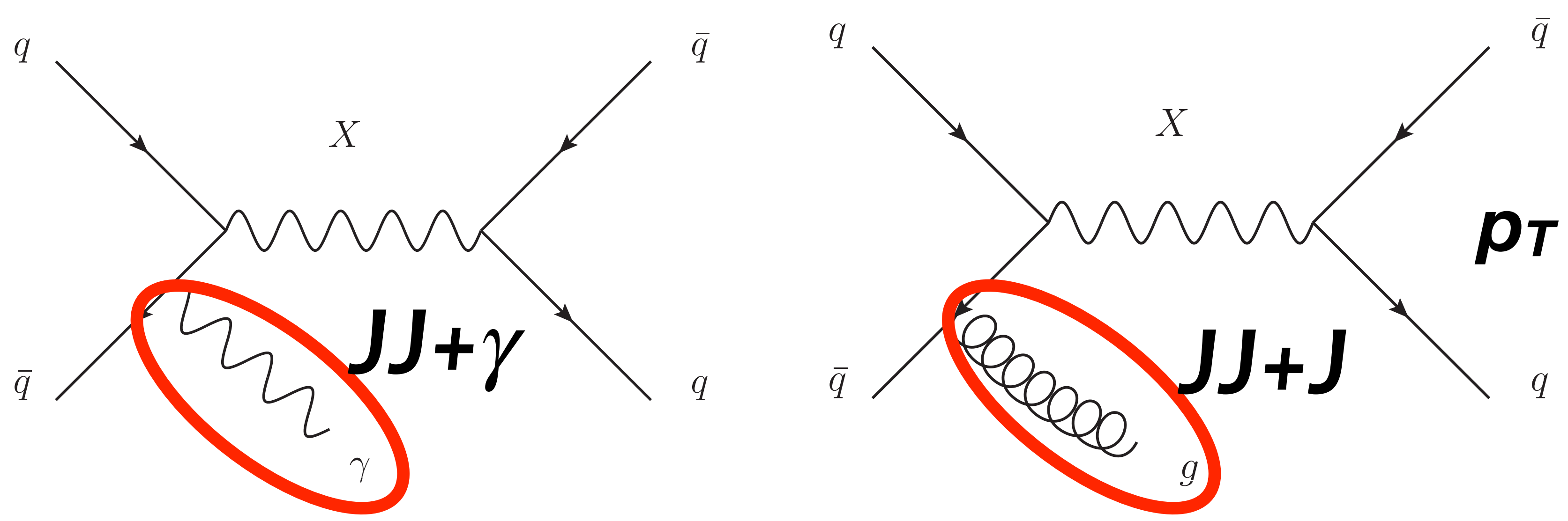
How to expand dijet analysis at low mJJ region ?

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Recast from dijet resonant search

ATLAS-CONF-2016-030
ATLAS-CONF-2016-070

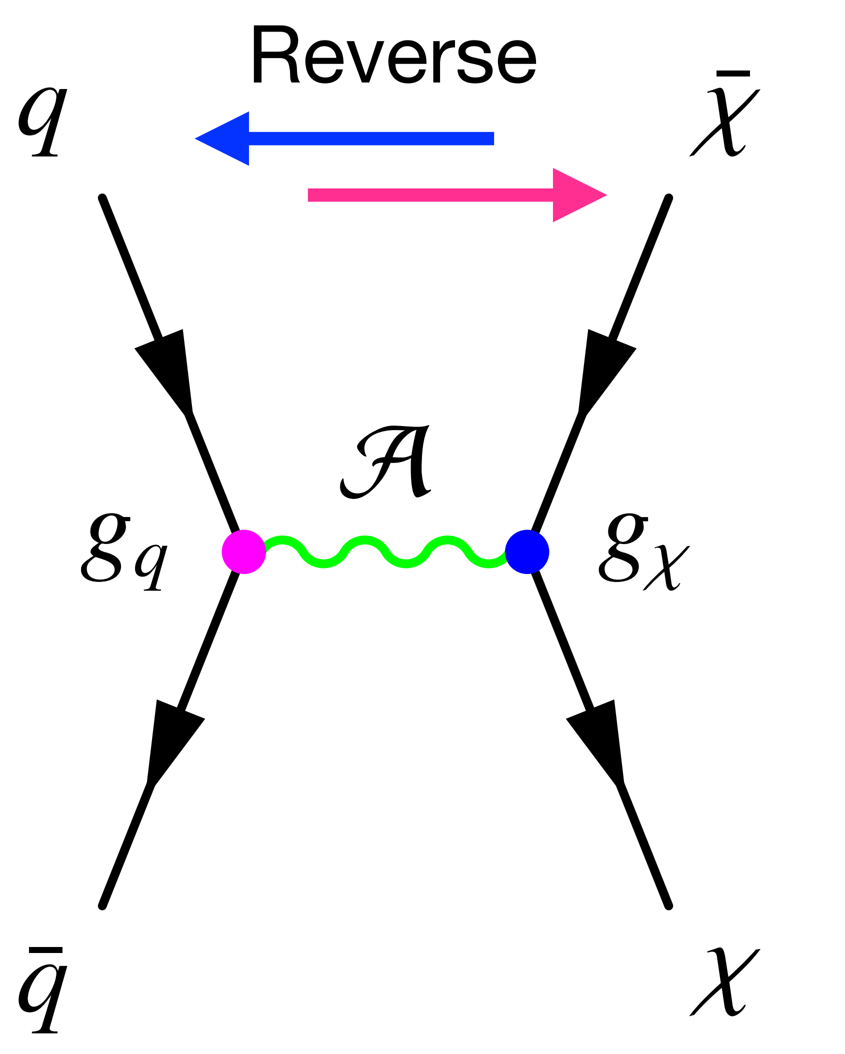


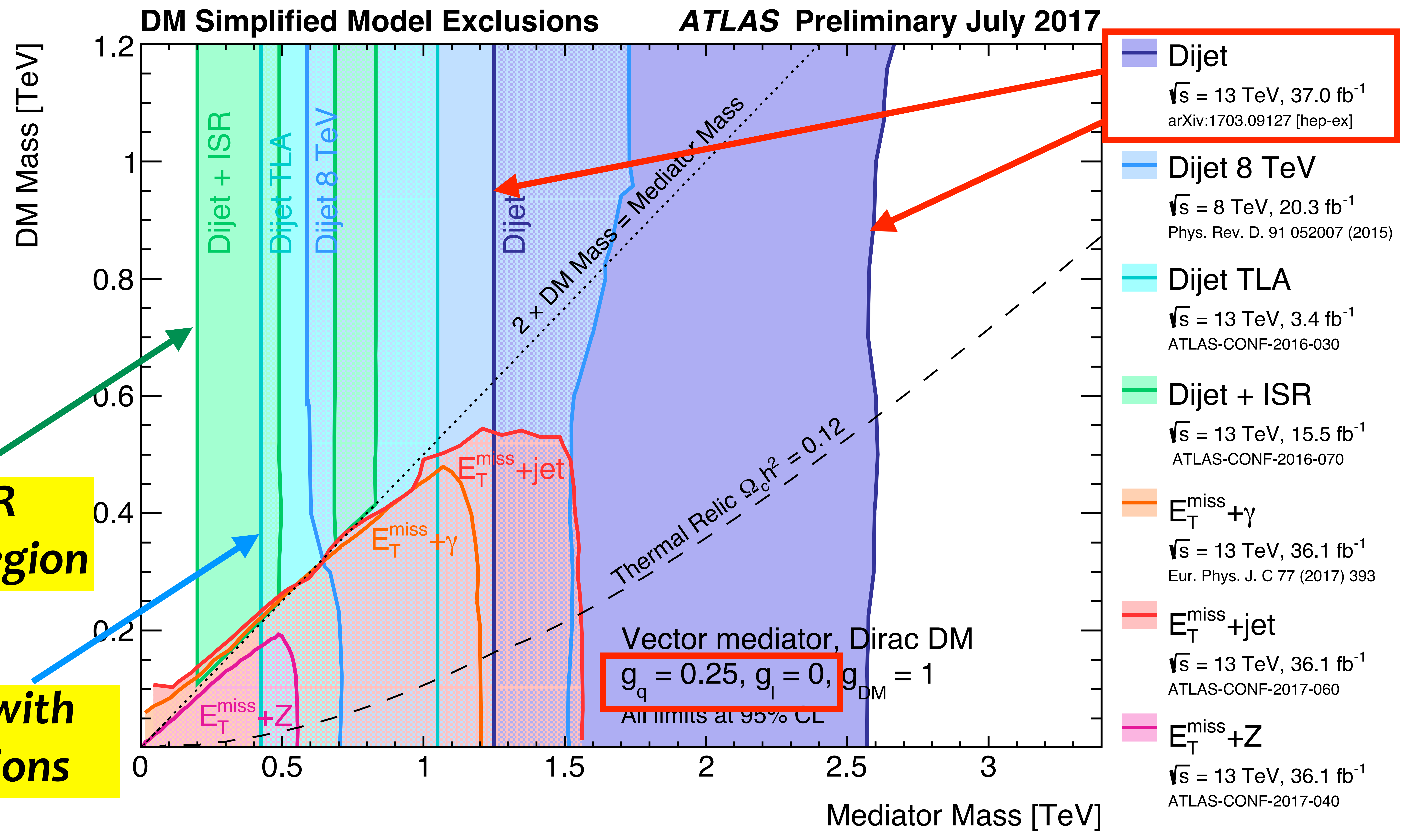


p_T of jets > 25 GeV

- In order to expand dijet analysis at low m_{JJ} region
  - *✗ fully lower the jet thresholds at the trigger level, but will exponential increase bandwidth*
  - *✓stores partial event informations (5% of full event size)*
    - dedicated jet calibration for trigger level jets
  - *✓ Trigger selection ISR objects to reach low m_{JJ} region*
    - *JJ+γ: single-photon trigger (E_T>140Gev)*
    - *JJ+J: single-jet trigger (p_T>380 GeV)*

Recast from dijet resonant search





Trigger selection on ISR objects to reach low m_{JJ} region

Trigger-Level Analysis with partial event informations

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Recast the limits from interpretation of dilepton resonant search

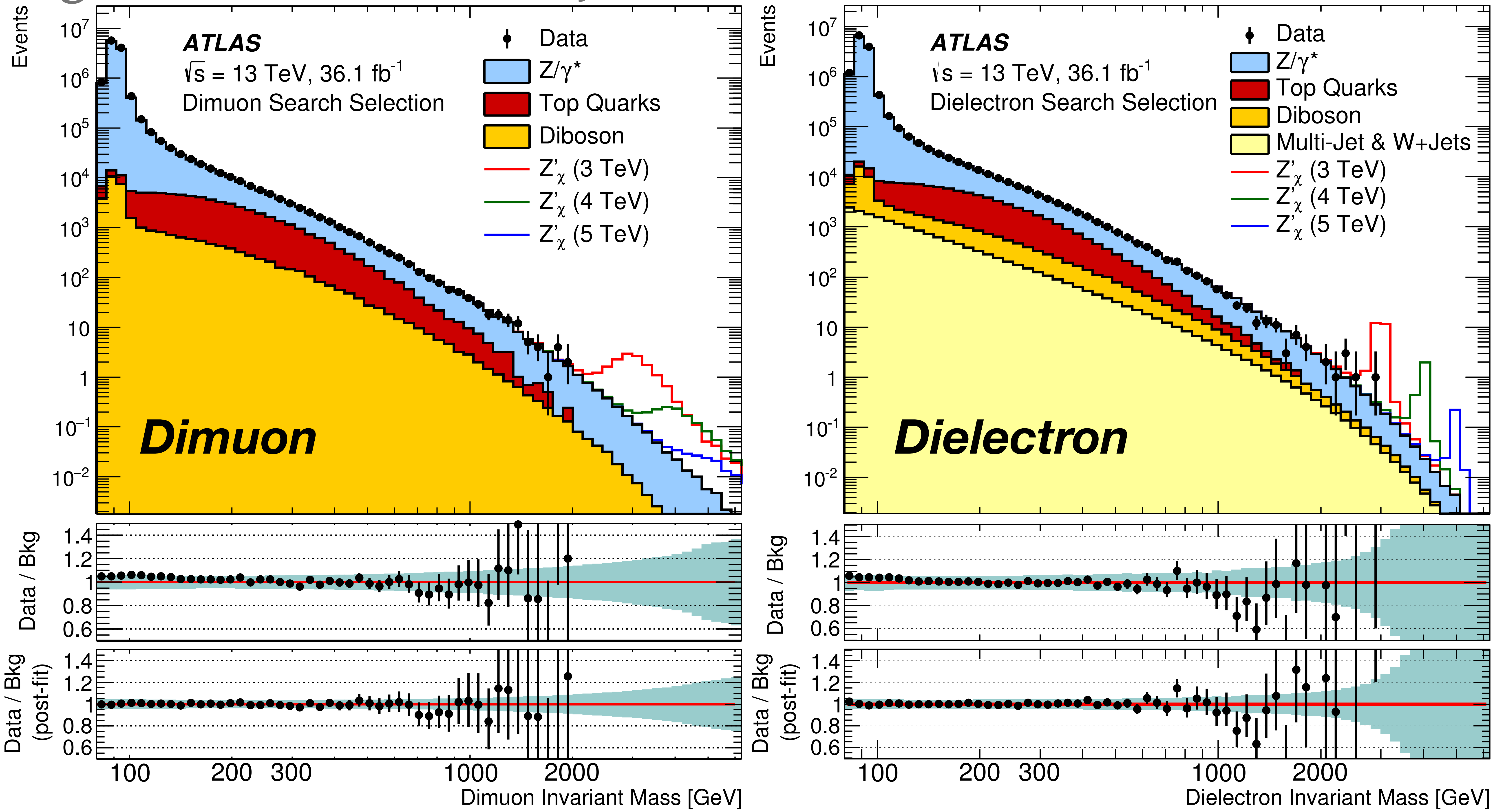
Gauge invariance implies the vector mediator couplings to leptons….

- Signature: a pair of electron/muon ($p_T > 30$ GeV)
  - Fully reconstructed, high signal-selection efficiency, small & well-understood backgrounds

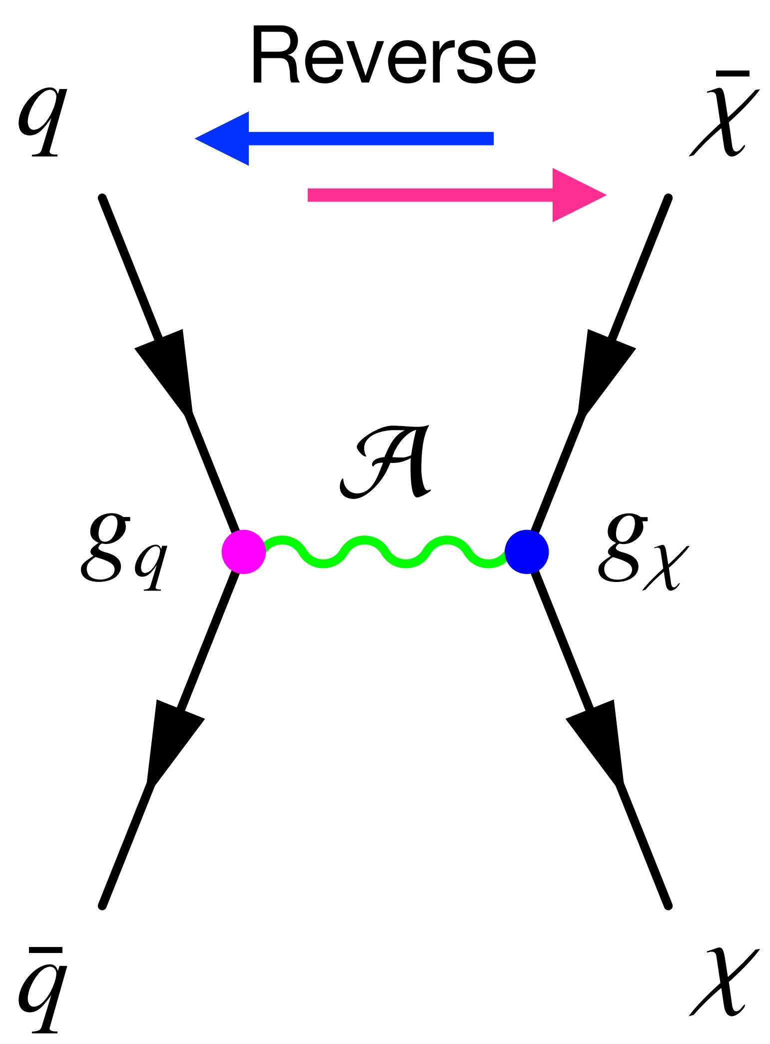
Dominant background: DY

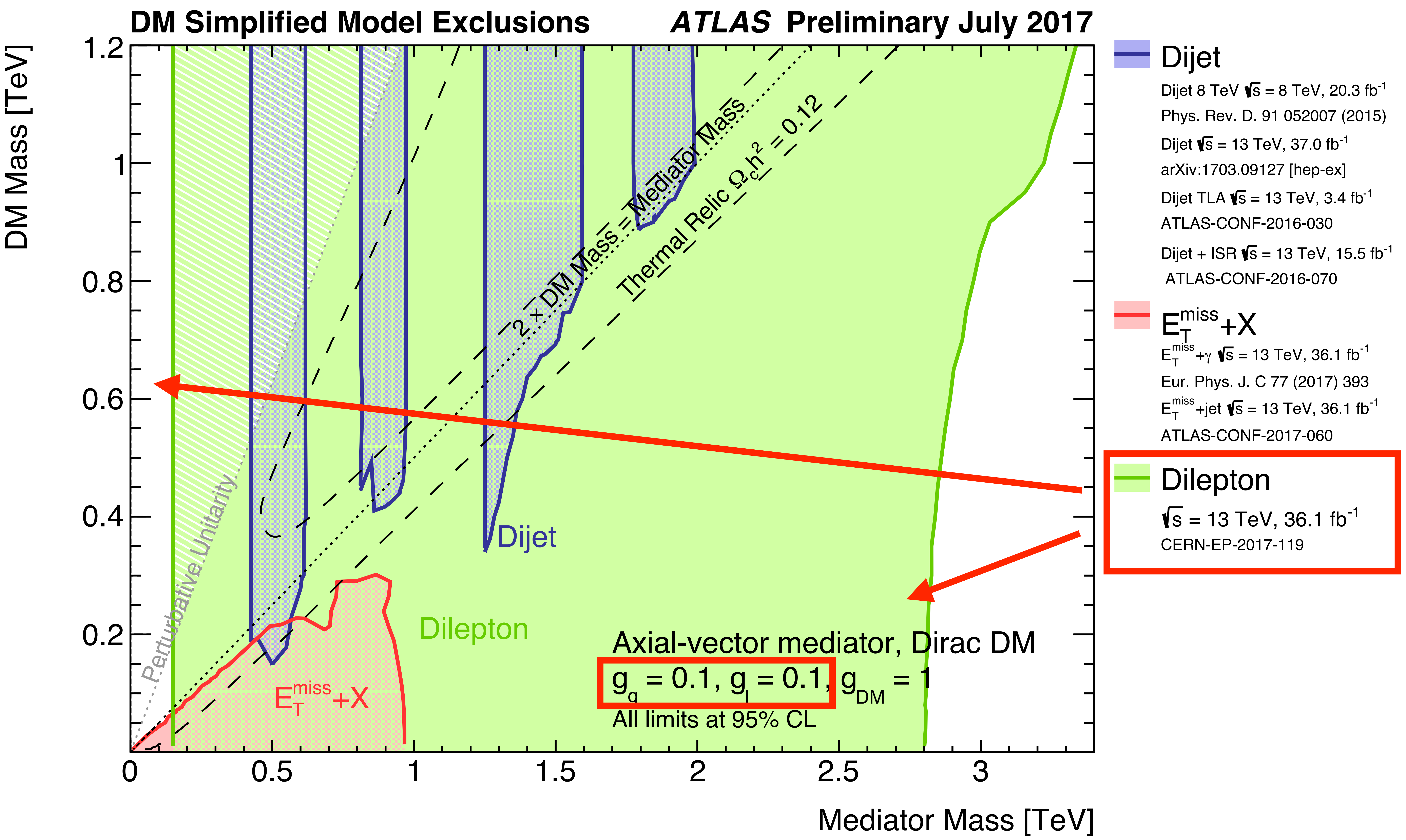
Systematic uncertainties: DY PDF variations, muon reconstruction efficiency (high p_T), electron isolation efficiency (inherent in calorimeter-based)

➪ No excess is observed !



Recast the limits from interpretation of dilepton resonant search

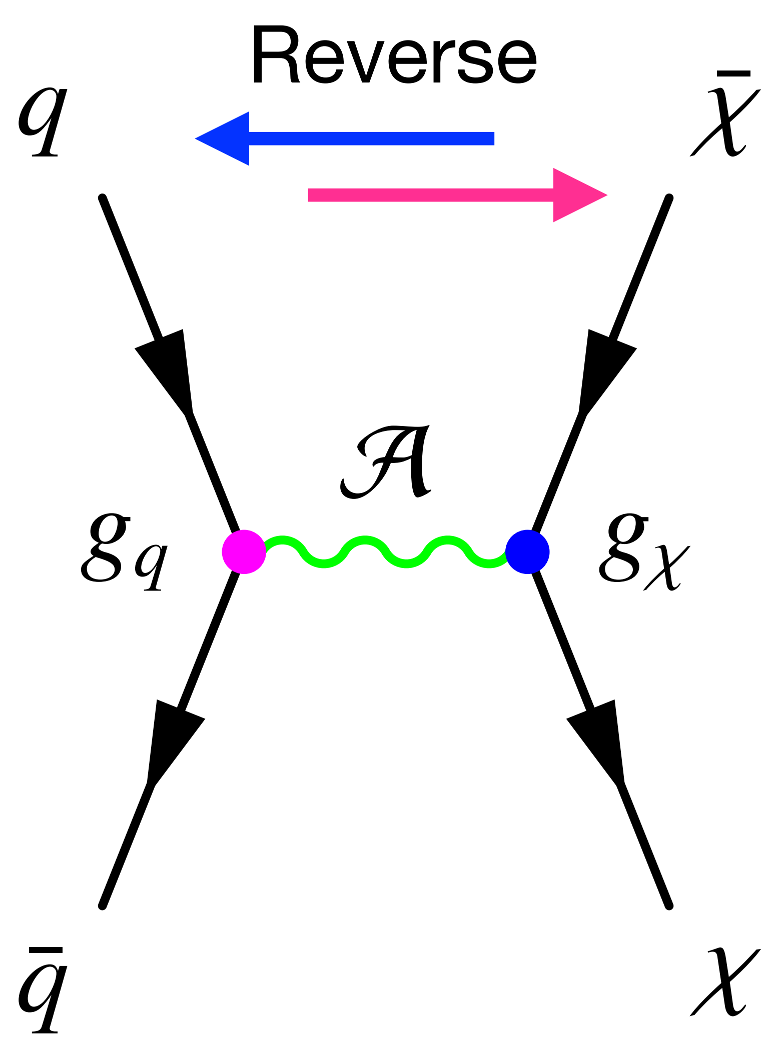




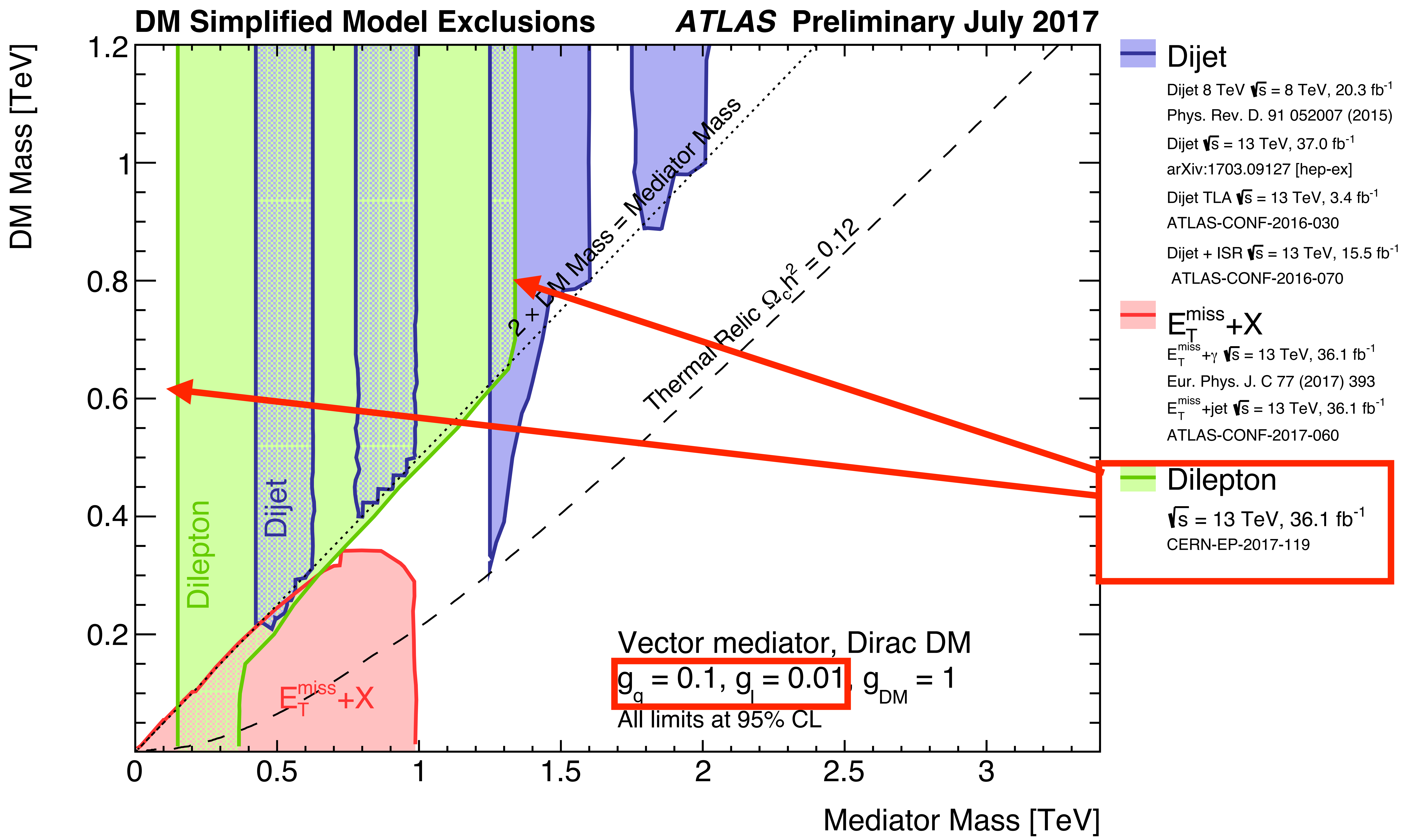
Gauge invariance implies the vector mediator couplings to leptons….

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Recast the limits from interpretation of dilepton resonant search



Gauge invariance implies the vector mediator couplings to leptons….

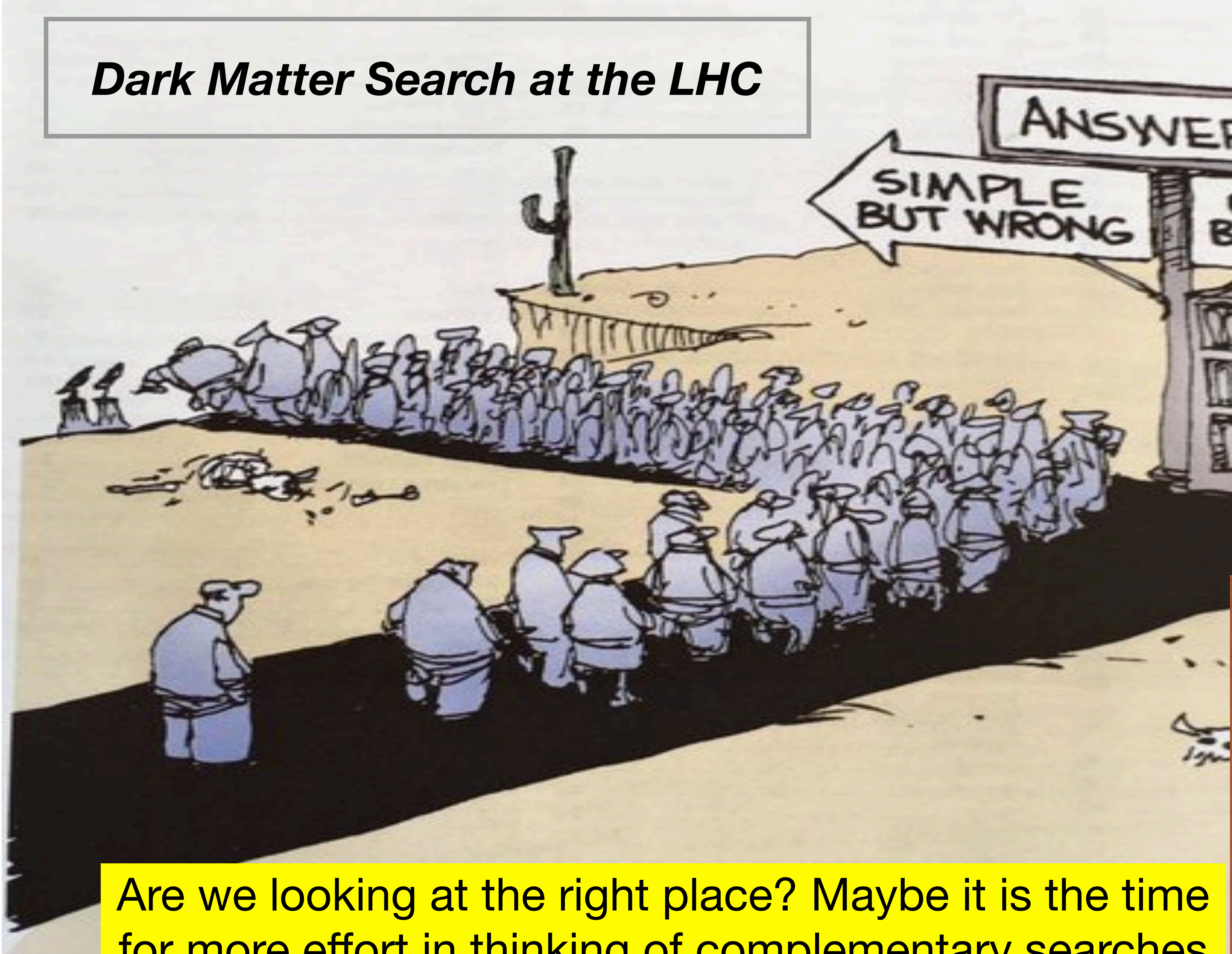


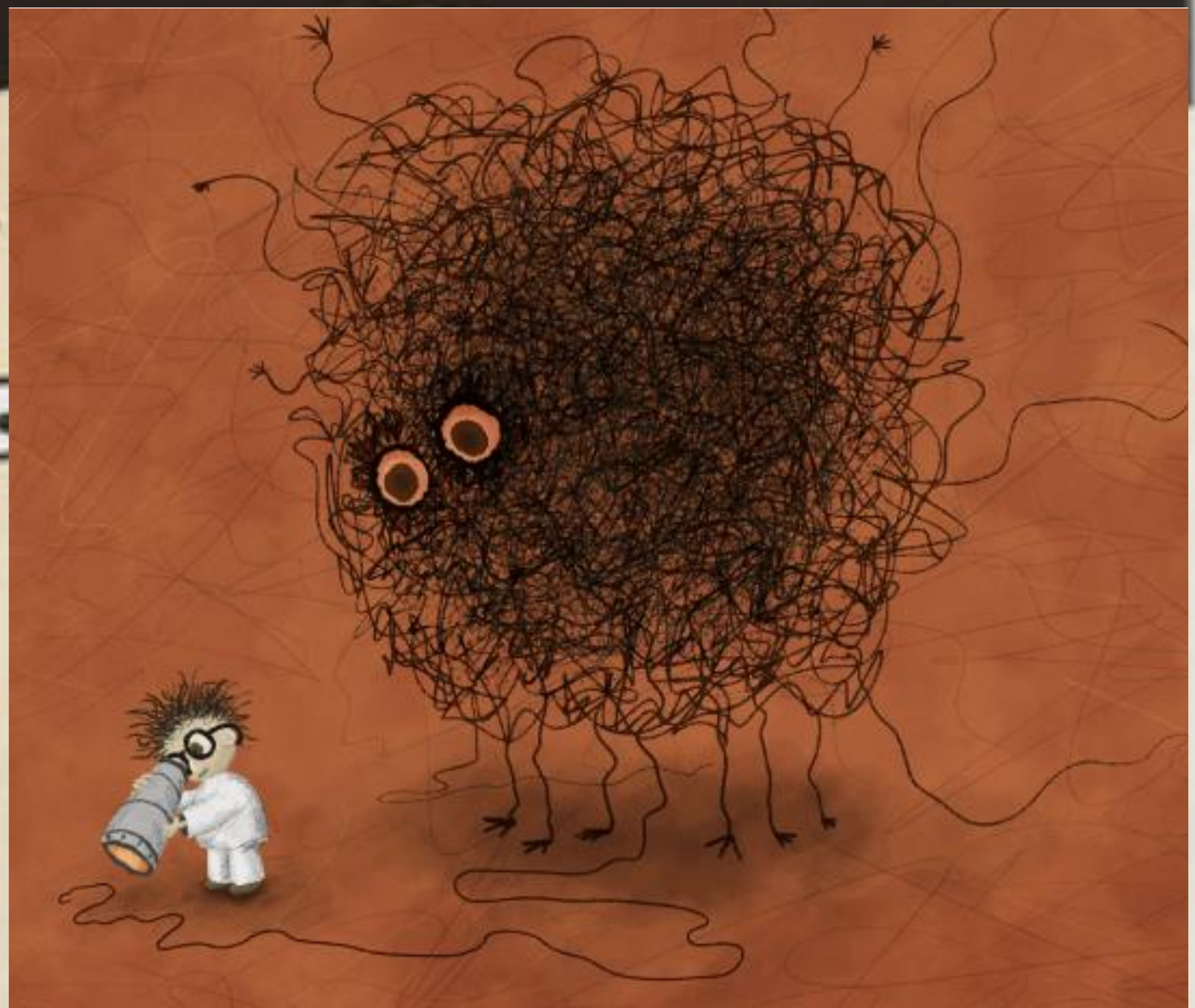
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Summary & Outlook

- Latest ATLAS (& CMS) Run II DM searches are presented
  - **No sign for DM at the LHC yet in the first 13 TeV data…**
- From EFT-based theory to more complete models ***didn't*** help to accelerate the search of DM at the LHC
- move to more **model independent analyses** where possible
- **Machine learning technique** is not fully applied in DM searches **(only in obj. reco.)**
- Could help a lot for complicated signatures, but ***need more details***:
  - Signal kinematics change much with N(>3) free parameters
  - More accurate background method from data:
    - Single data-to-MC scale-factor to simulation event
    - Event-by-event weights on data (e.g. matrix method for fake leptons)
    - Parameterization from side-band (dijet, diphoton)
    - Simultaneous fitting of Signal regions and Background regions

Dark Matter Search at the LHC





Are we looking at the right place? Maybe it is the time for more effort in thinking of complementary searches

Thanks a lot for your attention!