Search for dark matter from the LHC @13TeV

Dissecting the LHC results
LPNHE, Paris, 20-21 April 2017

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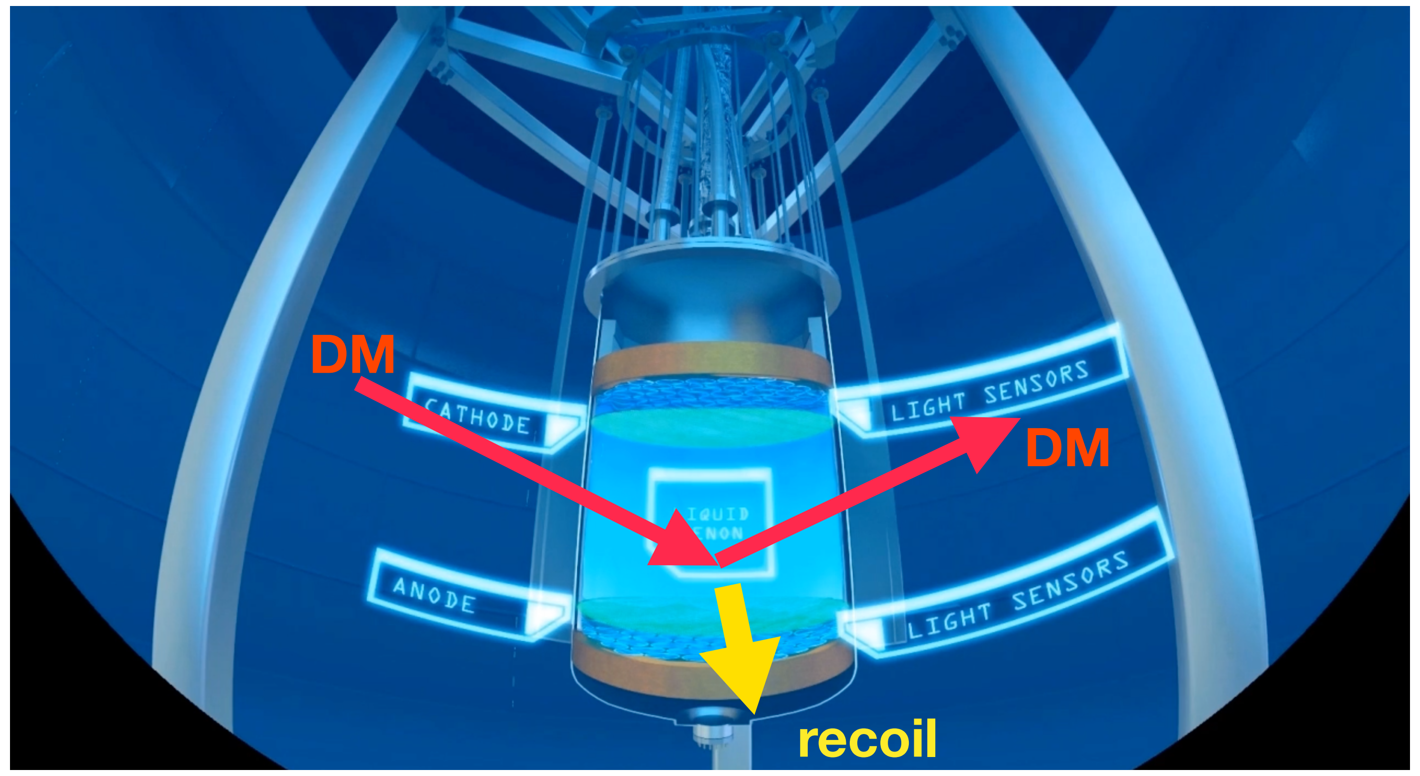
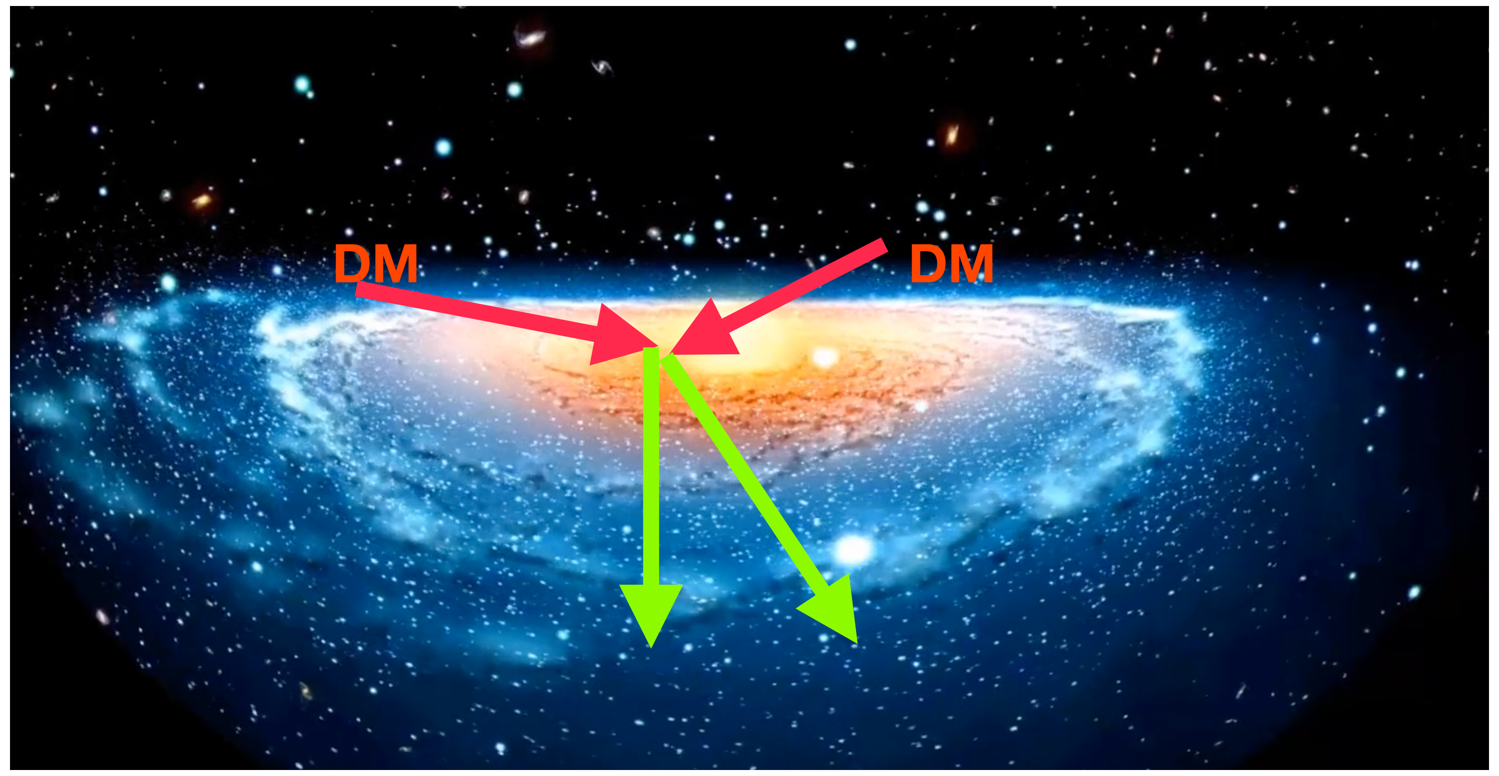
LPNHE, Institut Lagrange de Paris
on behalf of ATLAS and CMS Collaborations

Motivation and Detection of Dark Matter

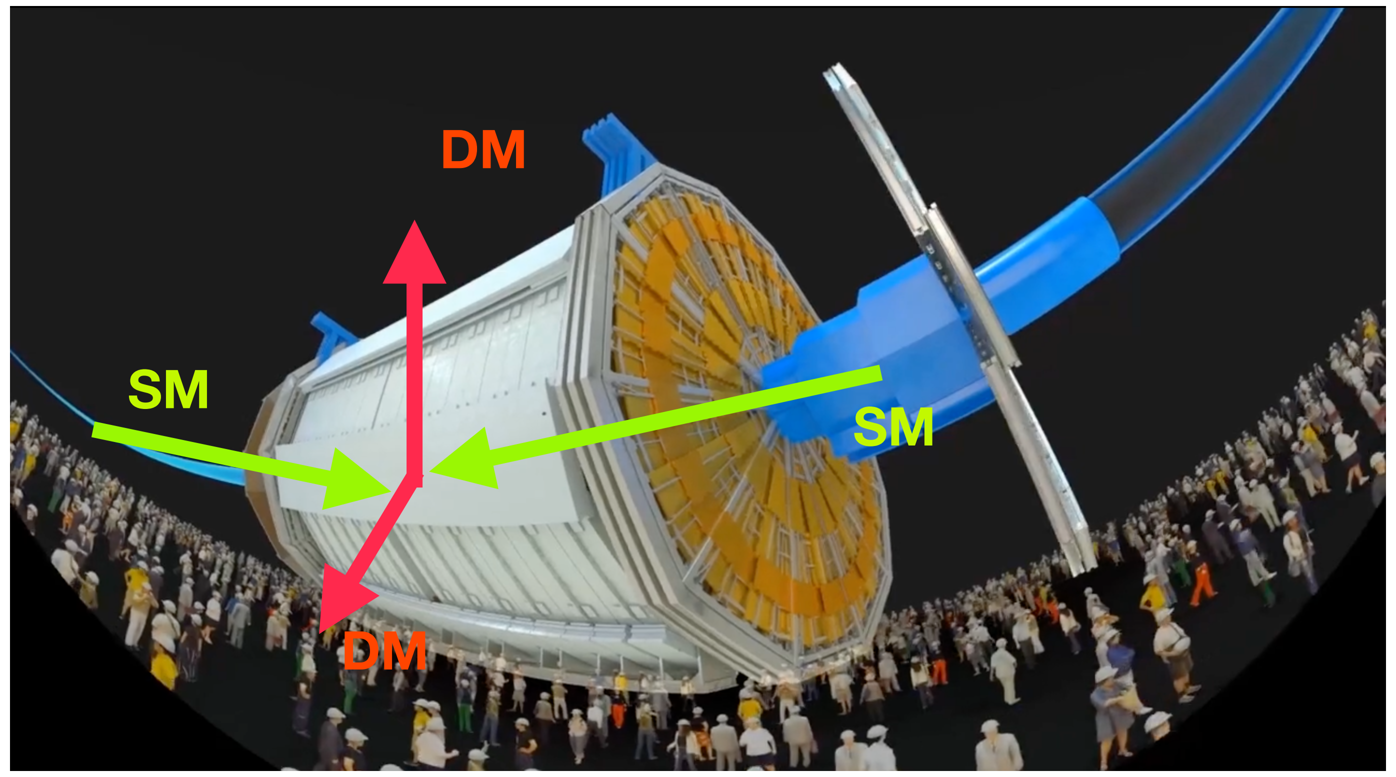
Direct Method



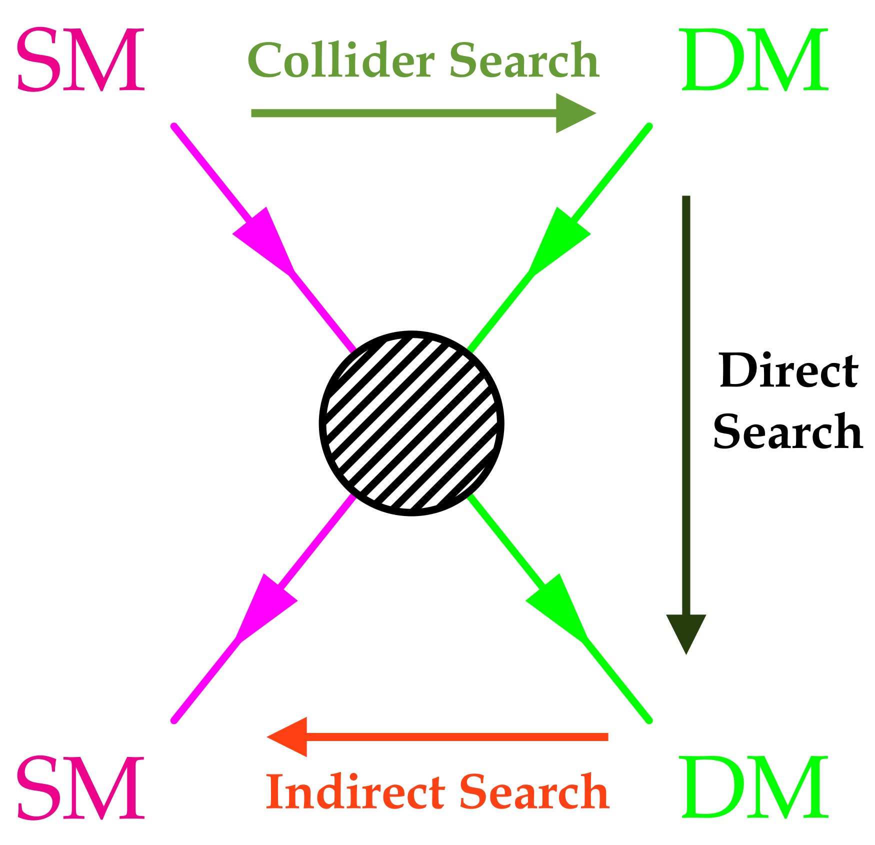
Indirect Method



Collider Method

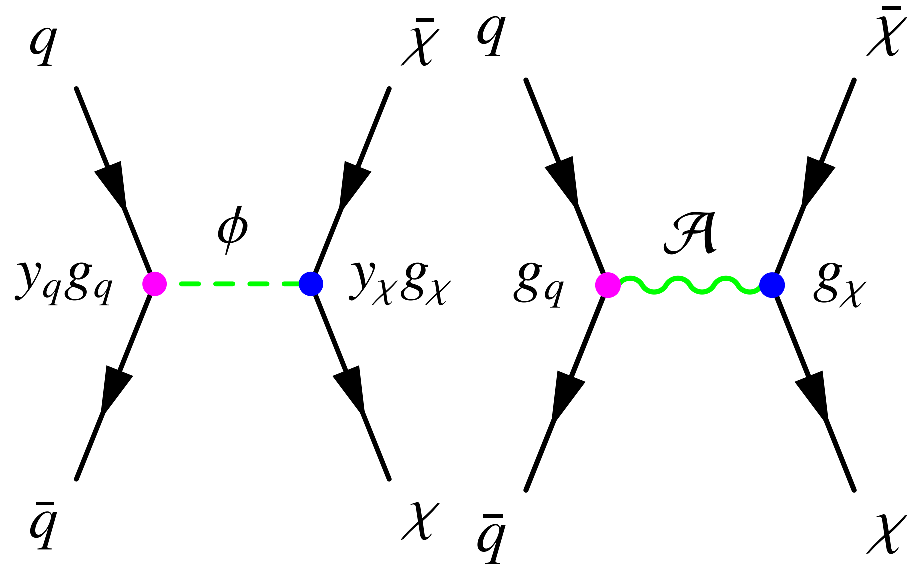


- Dark Matter (DM) has been one of the main unsolved problems in physics
  - Much evidence from astrophysical measurements, but no evidence yet for non-gravitational interactions between DM and SM particles
- Three detection ways:
  - Direct method ($\chi q \rightarrow \chi q$): DM-nucleon elastic scattering, a recoil with E~50 keV
  - Indirect method ($\chi\chi \rightarrow qq$): DM pair-annihilation, decay to various observable particles: tt, bb, WW, ZZ, γγ, ……
  - Collider method ($qq \rightarrow \chi\chi$): main topic of this talk



“History” of DM searches at the LHC

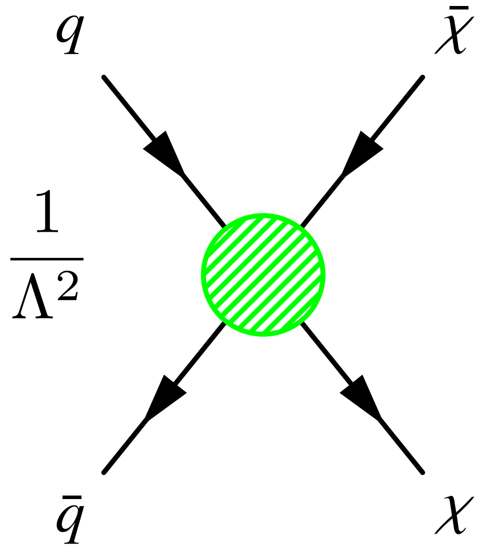
Run2



$$\frac{g_\chi g_q}{Q_{tr}^2 - M^2} = -\frac{g_\chi g_q}{M^2}\left(1 + \frac{Q_{tr}^2}{M^2} + O\left(\frac{Q_{tr}^4}{M^4}\right)\right) \sim -\frac{1}{\Lambda^2}$$

$Q_{tr} << M$

Run1



vector mediator

$$-\sum_q g_q \mathcal{A}_\mu \bar{q}\gamma^\mu(\gamma^5)q - g_\chi \mathcal{A}_\mu \bar{\chi}\gamma^\mu(\gamma^5)\chi$$

scalar mediator

$$-\sum_q g_q y_q \phi \bar{q}(\gamma^5)q - g_\chi y_\chi \phi \bar{\chi}(\gamma^5)\chi$$

TABLE I. Operators coupling WIMPs to SM particles. The operator names beginning with D, C, R apply to WIMPS that are Dirac fermions, complex scalars or real scalars, respectively.

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

PRD 82, 116010 (2010)

PRD 85, 056011 (2012)

- Two different approaches:
  - **Effective field theory (EFT)**: several nonrenormalizable operators without the UV physics specified
    - largely model-independent
    - but cannot be reliable when parton energies in the events are comparable to the effective mass scale
    - don’t account the constraints on the UV physics generating these operators (e.g. contains from recent dijet/dilepton searches)
  - **Simplified models**: UV particles are kept as degrees of freedom, but more model-dependent

DM searches at the LHC (Mono-X) @13TeV

arXiv.org > hep-ex > arXiv:1507.00966

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High Energy Physics – Experiment

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

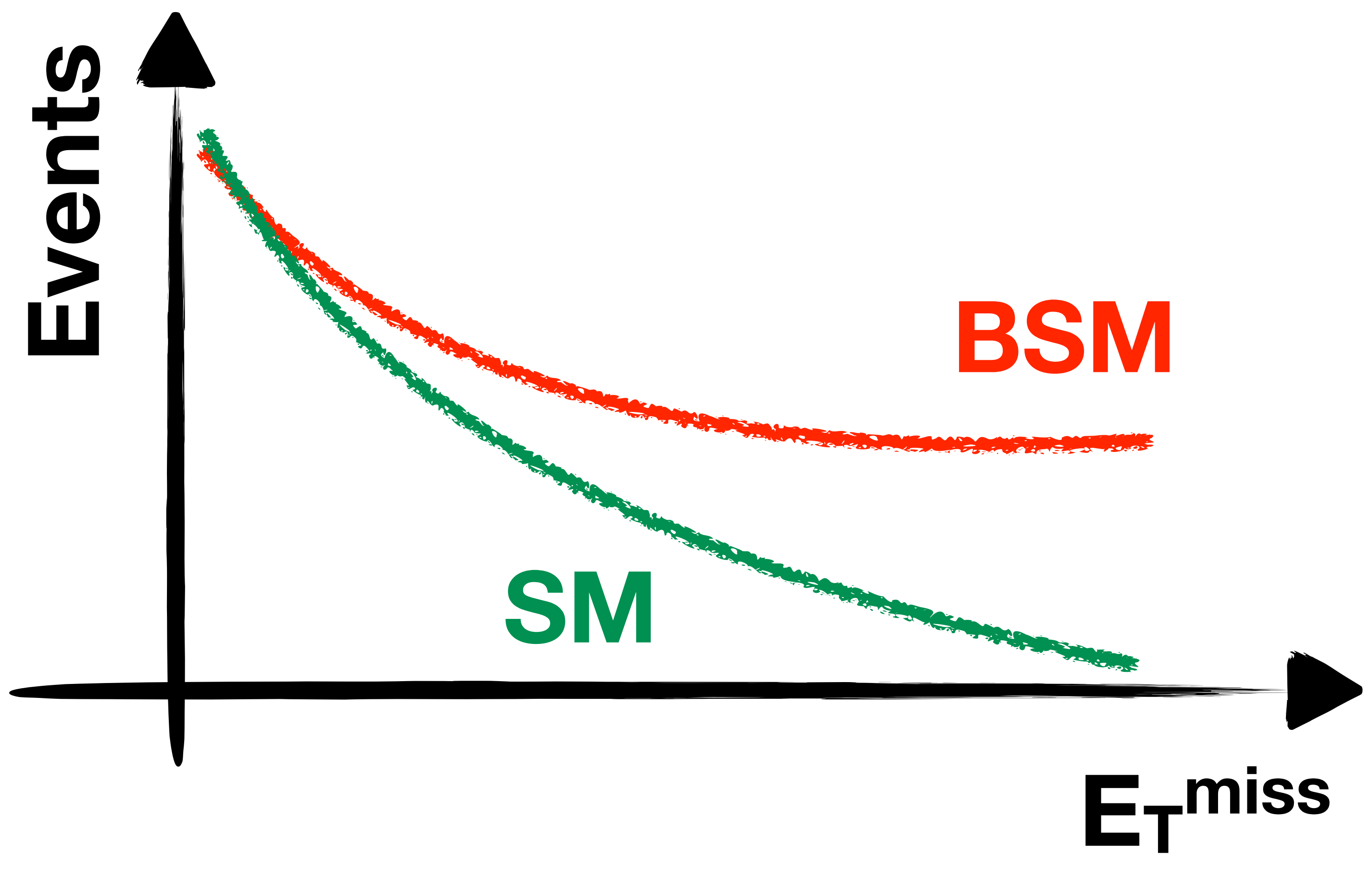
Daniel Abercrombie, Nural Akchurin, Ece Akilli, Juan Alcaraz Maestre, Brandon Allen, Barbara Alvarez Gonzalez, Jeremy Andrea, Alexandre Arbey, Georges Azuelos, Patrizia Azzi, Mihailo Backović, Yang Bai, Swagato Banerjee, James Beacham, Alexander Belyaev, Antonio Boveia, Amelia Jean Brennan, Oliver Buchmueller, 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 ... Kerstin Hoepfner, Siew Yan Hoh, Dylan George Hsu, Shih-Chieh Hsu, Yutaro Iiyama, Valerio Ippolito, Thomas Jacques, ... Kahlhoefer, Alexis Kalogeropoulos, Laser Seymour Kaplan, Lashkar Kashif, Valentin V. Khoze, Raman Khurana ... Kovalskyi, Suchita Kulkarni, Shuichi Kunori, Viktor Kutzner, Hyun Min Lee, Sung-Won Lee, Seng ... Romain Madar, Sarah Malik, Fabio Maltoni, Mario Martinez Perez, Olivier Mattelaer, Kentarou ... Megy, Enrico Morgante, Stephen Mrenna, Siddharth M. Narayanan, Andy Nelson, Sérgi... ...scilla Pani, Michele Papucci, Manfred Paulini, Christoph Paus, Jacopo Pazzini, Björn Penn... ...ina, Massimiliano Procura, Shamona F. Qazi, Davide Racco, Emanuele Re, Antonio Riotto, The... ...avid Salek, Arturo Sanchez Pineda, Subir Sarkar, Alexander Schmidt, Steven Randolph Schramm ... Livia Soffi, Norraphat Srimanobhas, Kevin Sung, Tim M. P. Tait, Timothee Theveneaux-Pelzer, ... Sonaina Undleeb, Alessandro Vichi, Fuquan Wang, Lian-Tao Wang, Ren-Jie Wang, Nikola Wha... ...Sau Lan Wu, Hongtao Yang, Yong Yang, Shin-Shan Yu, Bryan Zaldivar, Marco Zanetti, Zhiqing ... (collapse list)

A big effort between LHC experimentalists and theorists!

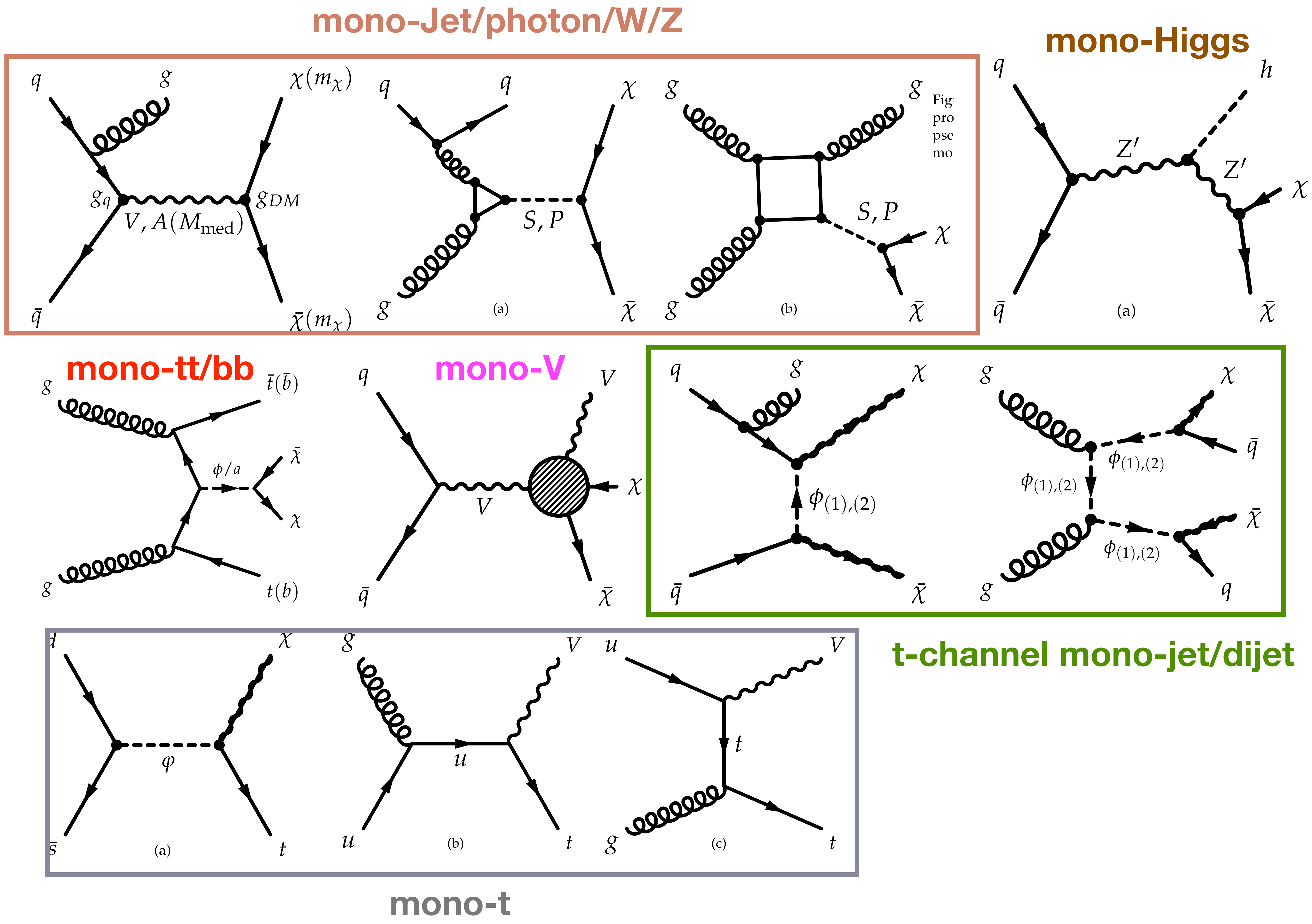
This document is the final report of the ATLAS-CMS Dark Matter Forum, a forum organized by the ATLAS and CMS collaborations with the participation of experts on theories of Dark Matter, to select a minimal basis set of dark matter simplified models that should support the design of the early LHC Run-2 searches. A prioritized, compact set of benchmark models is proposed, accompanied by studies of the parameter space of these models and a repository of generator implementations. This report also addresses how to apply the Effective Field Theory formalism for collider searches and present the results of such interpretations.

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

- **Mono-X:** a final state of MET + Jet(s), photon, W, Z, Higgs, top/b quark
- X can be emitted either directly from ISR through SM gauge interactions or from a BSM vertex coupling



DM searches at the LHC (Mono-X) @13TeV



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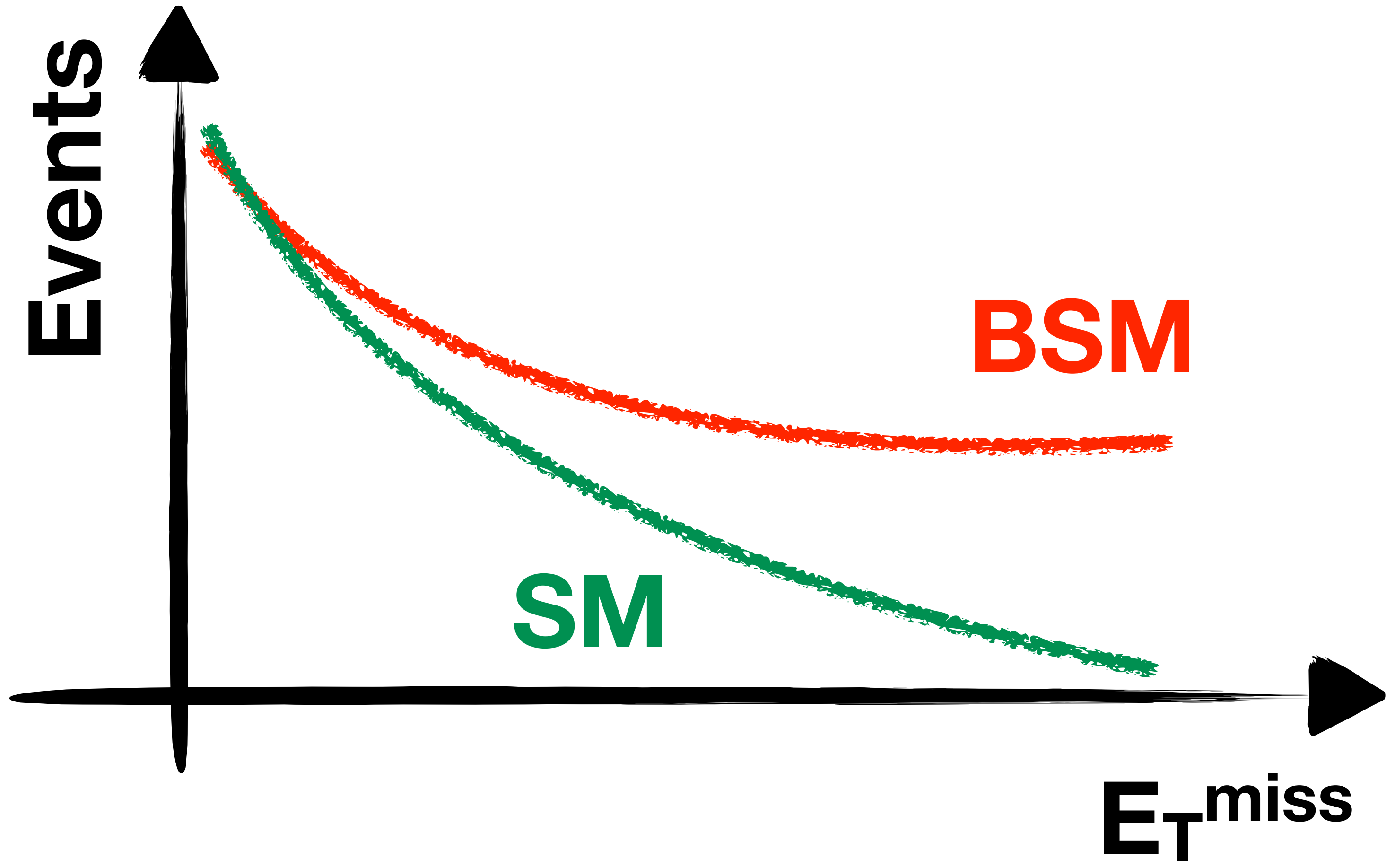
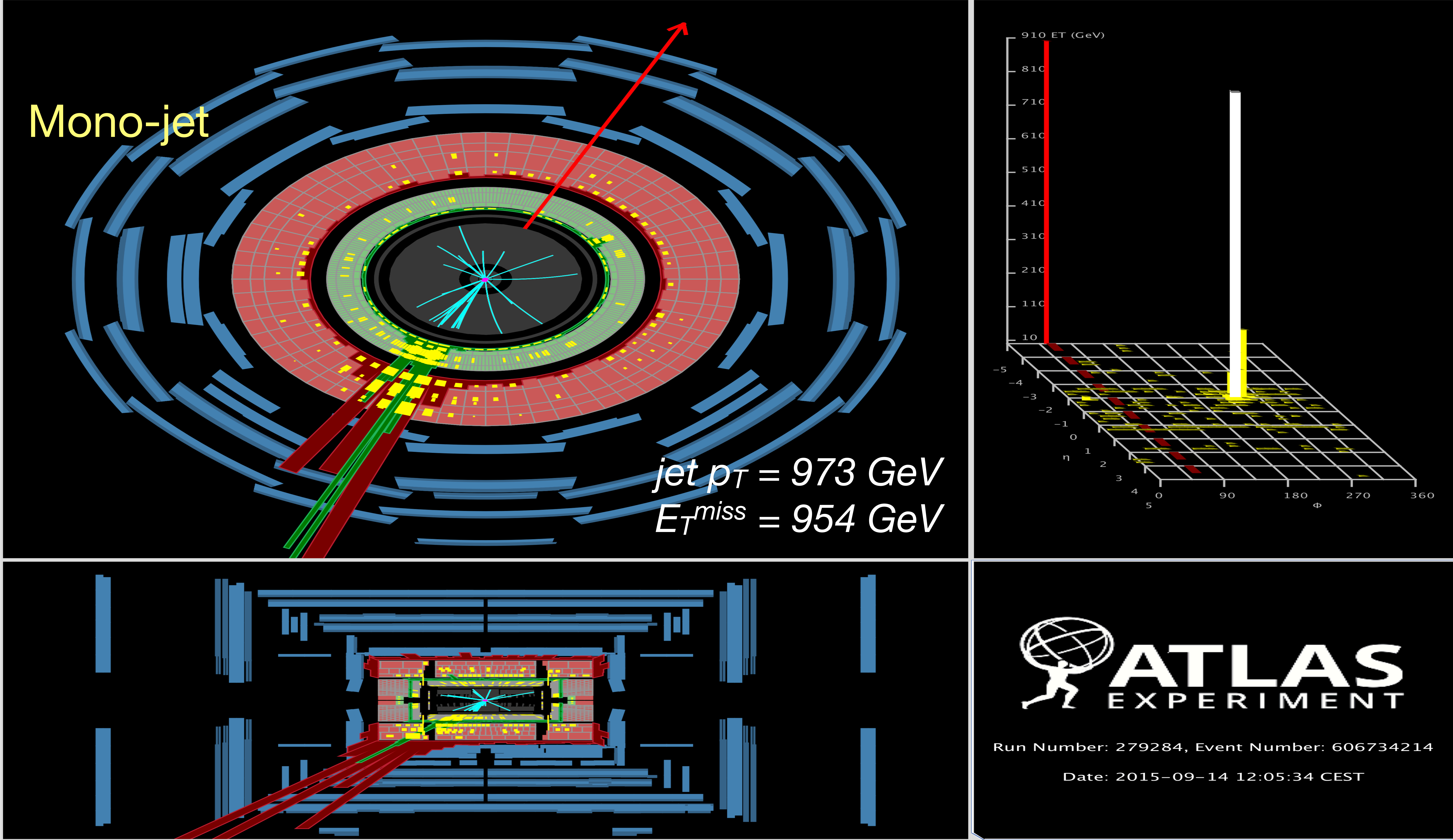
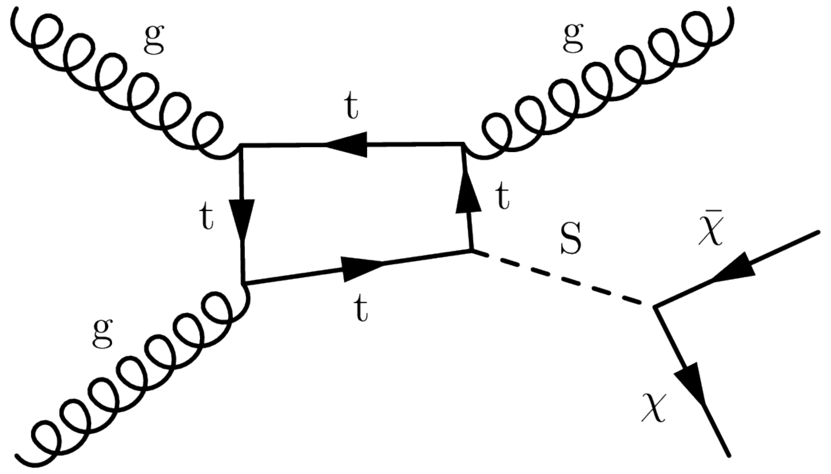
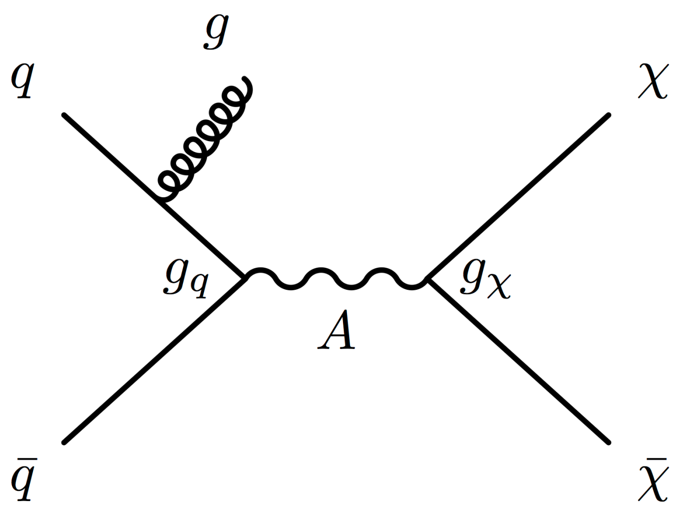


Channels		ATLAS EXPERIMENT	CMS
Mono-jet		EXOT-2015-03	CMS-EXO-16-037
Mono-V	Mono-W/Z(jj)	EXOT-2015-08	CMS-EXO-16-037
	Mono-W($\ell\nu$)		
	Mono-Z($\ell\ell$)	ATLAS-CONF-2016-056	CMS-PAS-EXO-16-038
	Mono-γ	EXOT-2016-32	CMS-PAS-EXO-16-039
Mono-Higgs	Mono-H($\gamma\gamma$)	ATLAS-CONF-2017-024	CMS-EXO-16-012
	Mono-H(bb)	ATLAS-CONF-2017-028	
	Mono-H($\rightarrow ZZ^* \rightarrow 4\ell$)	ATLAS-CONF-2015-059	
Mono-HF	Mono-t (had)		CMS-PAS-EXO-16-040
	Mono-tt (had)	ATLAS-CONF-2016-077	CMS-PAS-EXO-16-005
	Mono-tt (semi-lep)	ATLAS-CONF-2016-050	
	Mono-tt (lep)	ATLAS-CONF-2016-076	CMS-PAS-EXO-16-028
	Mono-b		CMS-PAS-B2G-15-007
	Mono-bb	ATLAS-CONF-2016-086	
Reinterpretation	Invisible Higgs Search	ATLAS-CONF-2016-056	HIG-16-016
	Di-jet Search	EXOT-2016-21, Summary Page	CMS-PAS-EXO-16-056, CMS DP-2016/057
	Z'($\ell\ell$) Search	ATLAS-CONF-2017-027	EXO-15-005


Mono-jet
jet p_T = 973 GeV
E_T^{miss} = 954 GeV
910 ET (GeV)
η
Φ
ATLAS
EXPERIMENT
Run Number: 279284, Event Number: 606734214
Date: 2015-09-14 12:05:34 CEST

Mono-jet

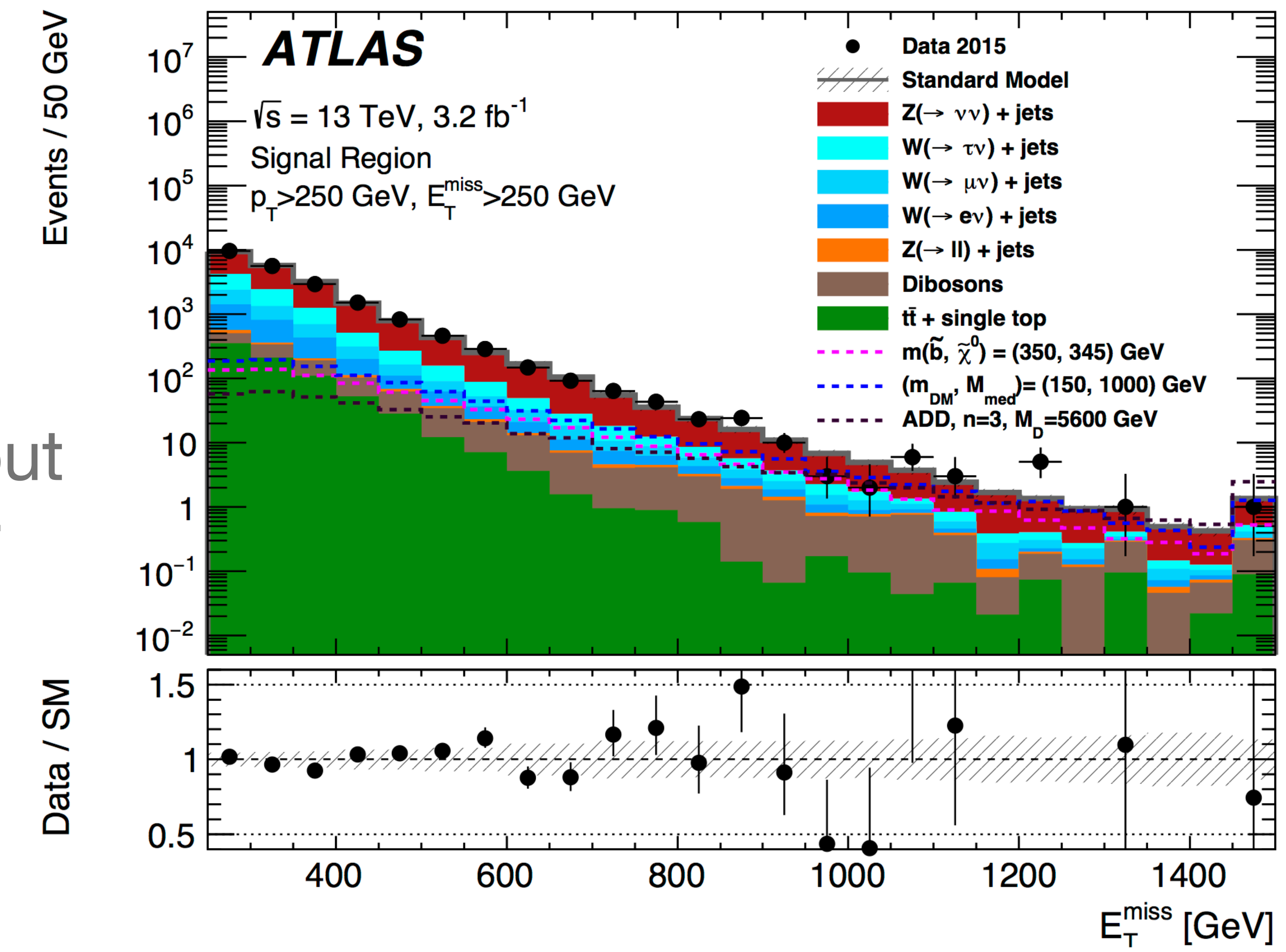


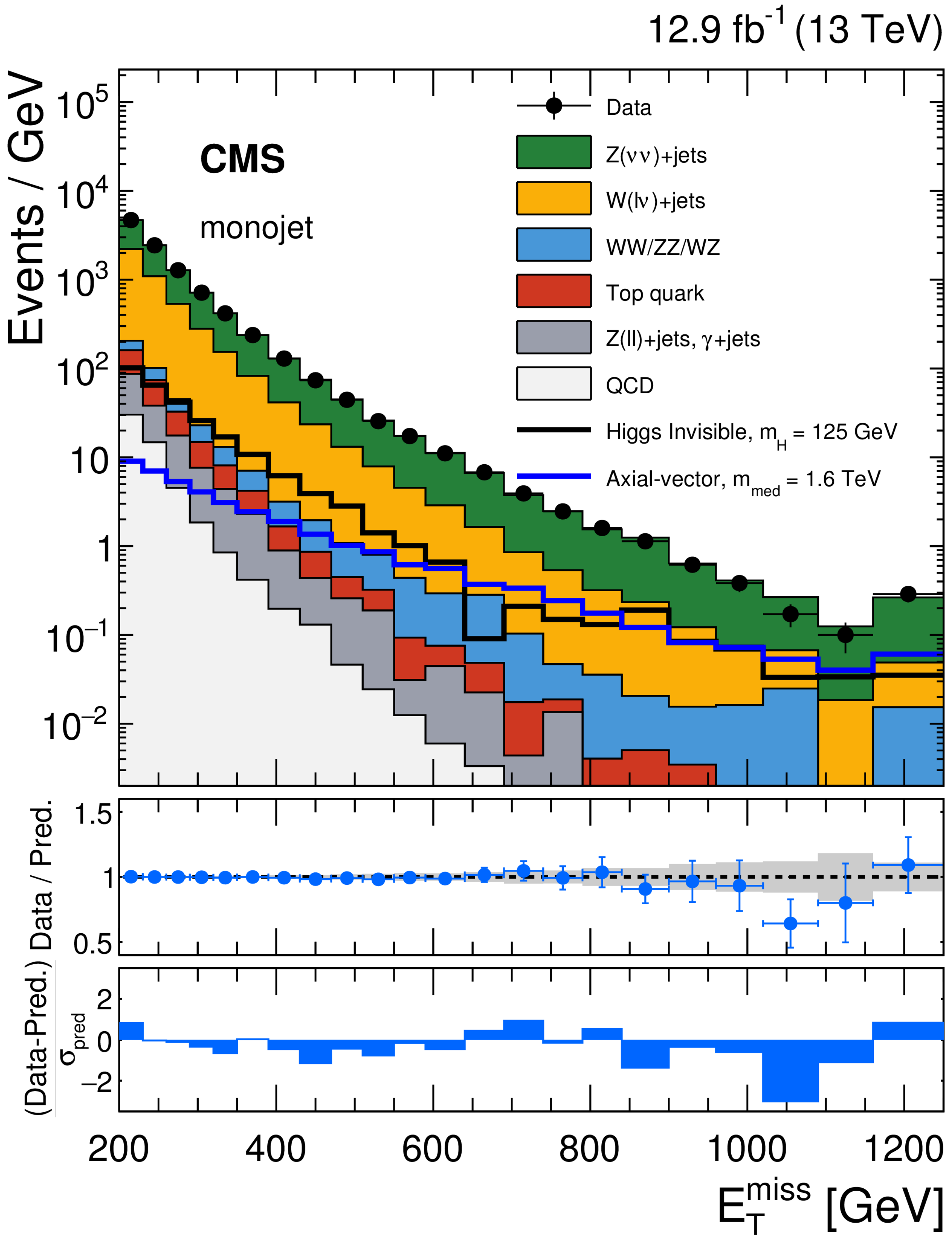


EXOT-2015-03
CMS-EXO-16-037

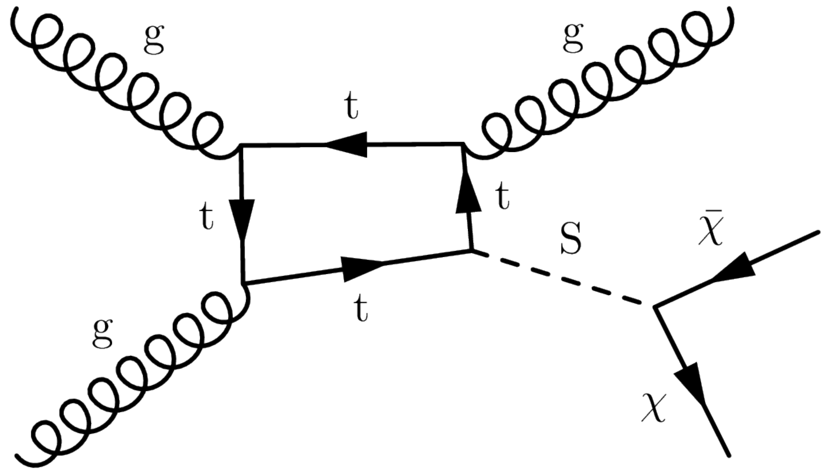
- A most sensitive search channel for DM at the LHC, signature with an ISR jet recoiling off a large MET
- Event selection:
  - a well-identified leading jet p_T >100 (250) GeV, E_T^{miss} > 200 (250) GeV for CMS (ATLAS)
  - lepton-veto, up to three extra low-pT jets
  - well-separated between leading energetic jet and E_T^{miss}

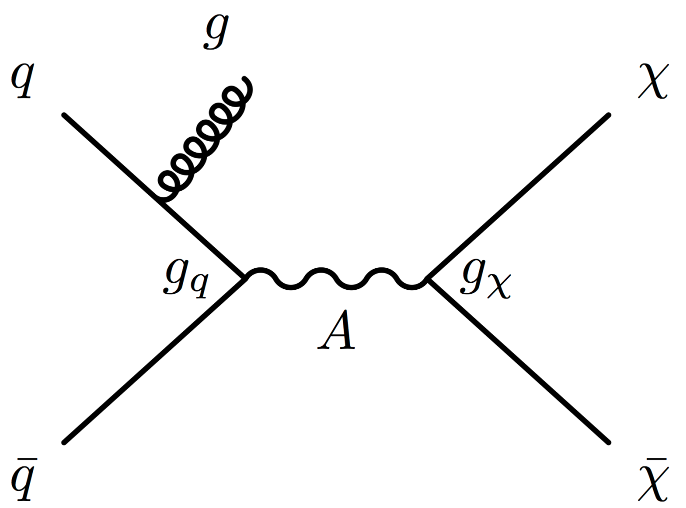
- Main backgrounds:
  - Z(νν) + jets: 60%, dominant and irreducible
  - W(ℓν) + jets: 30%, reduced with lepton veto, but leptons could be out of acceptance or from the detector inefficiency
  - Others(DY, Top, VV) are MC estimated





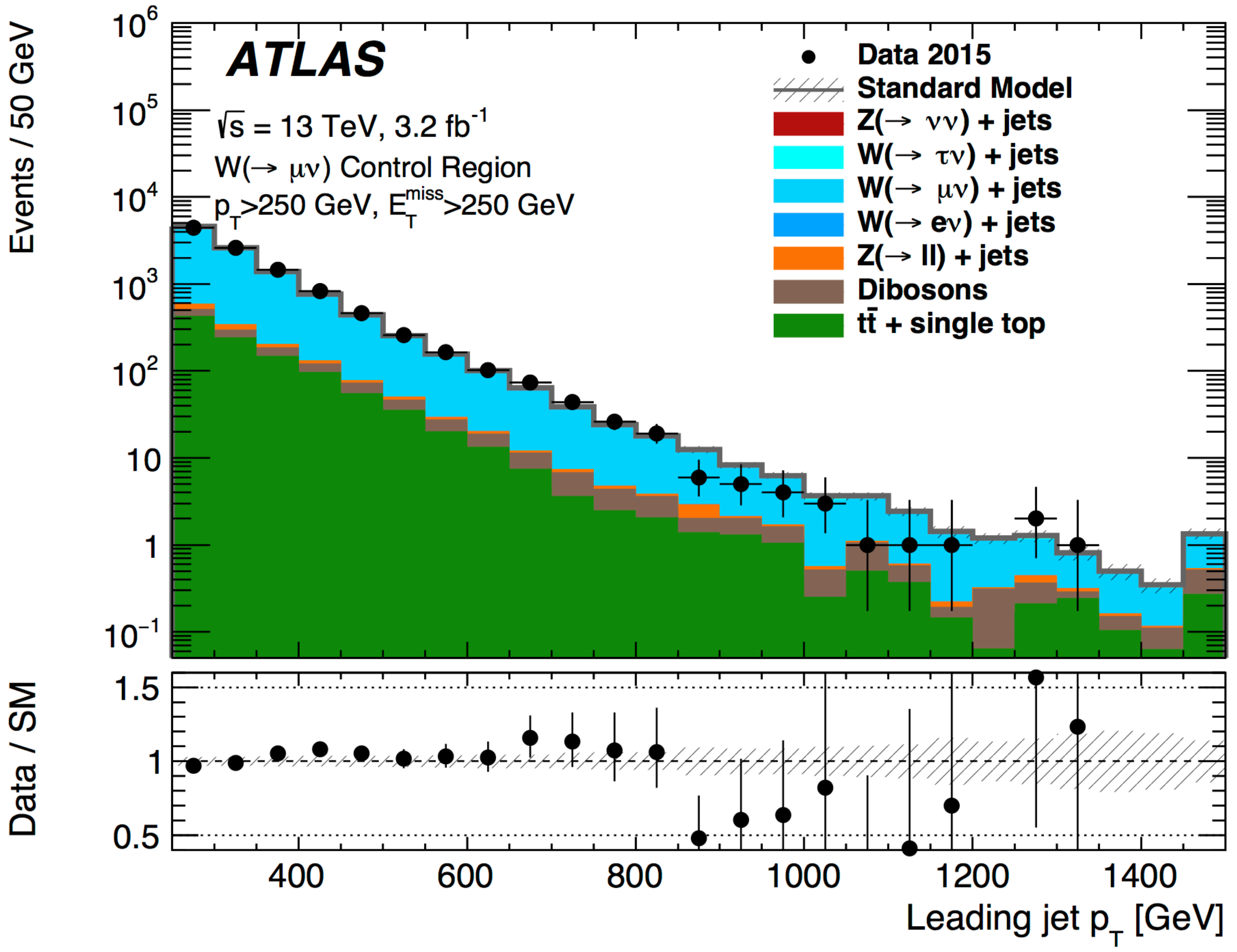
Mono-jet

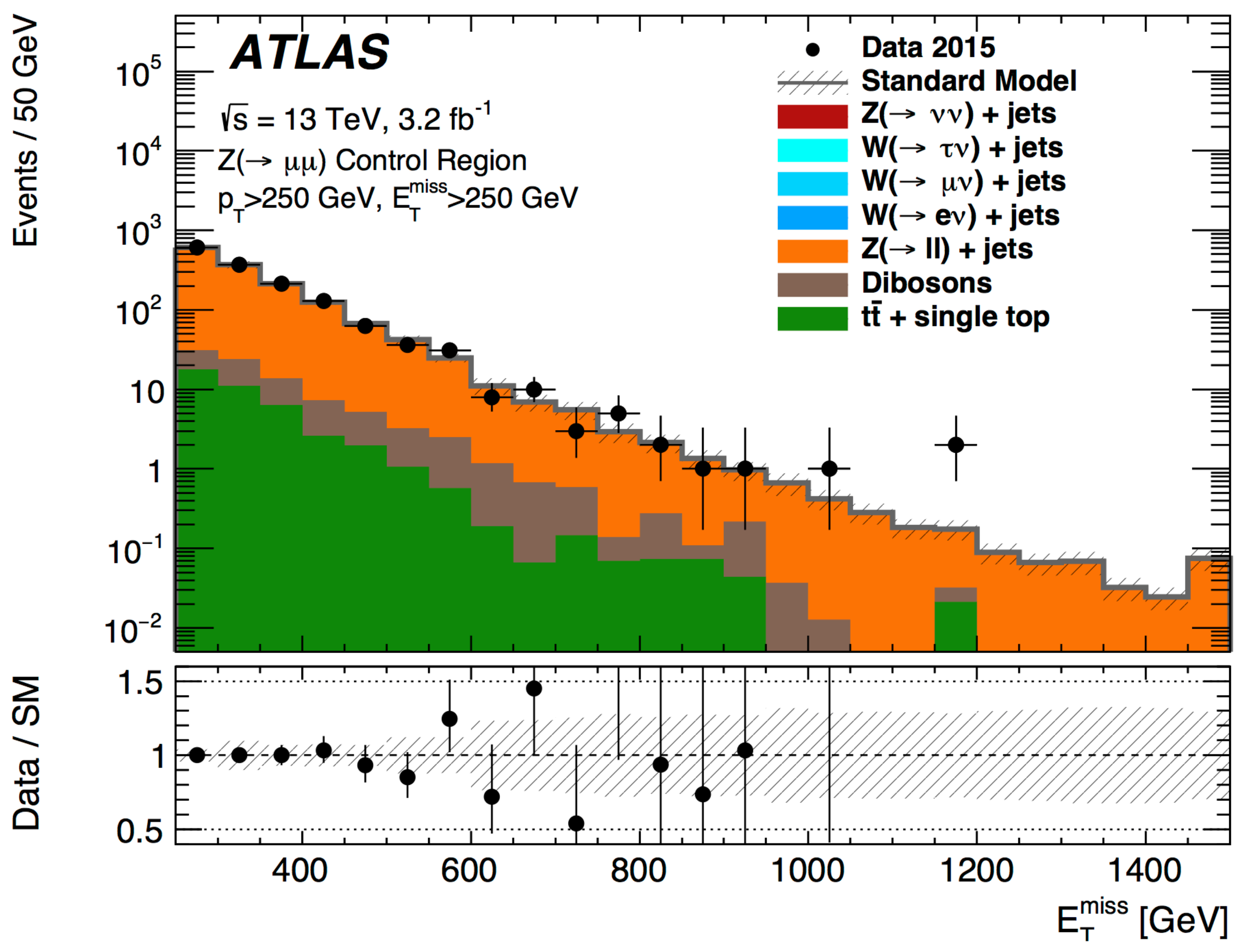


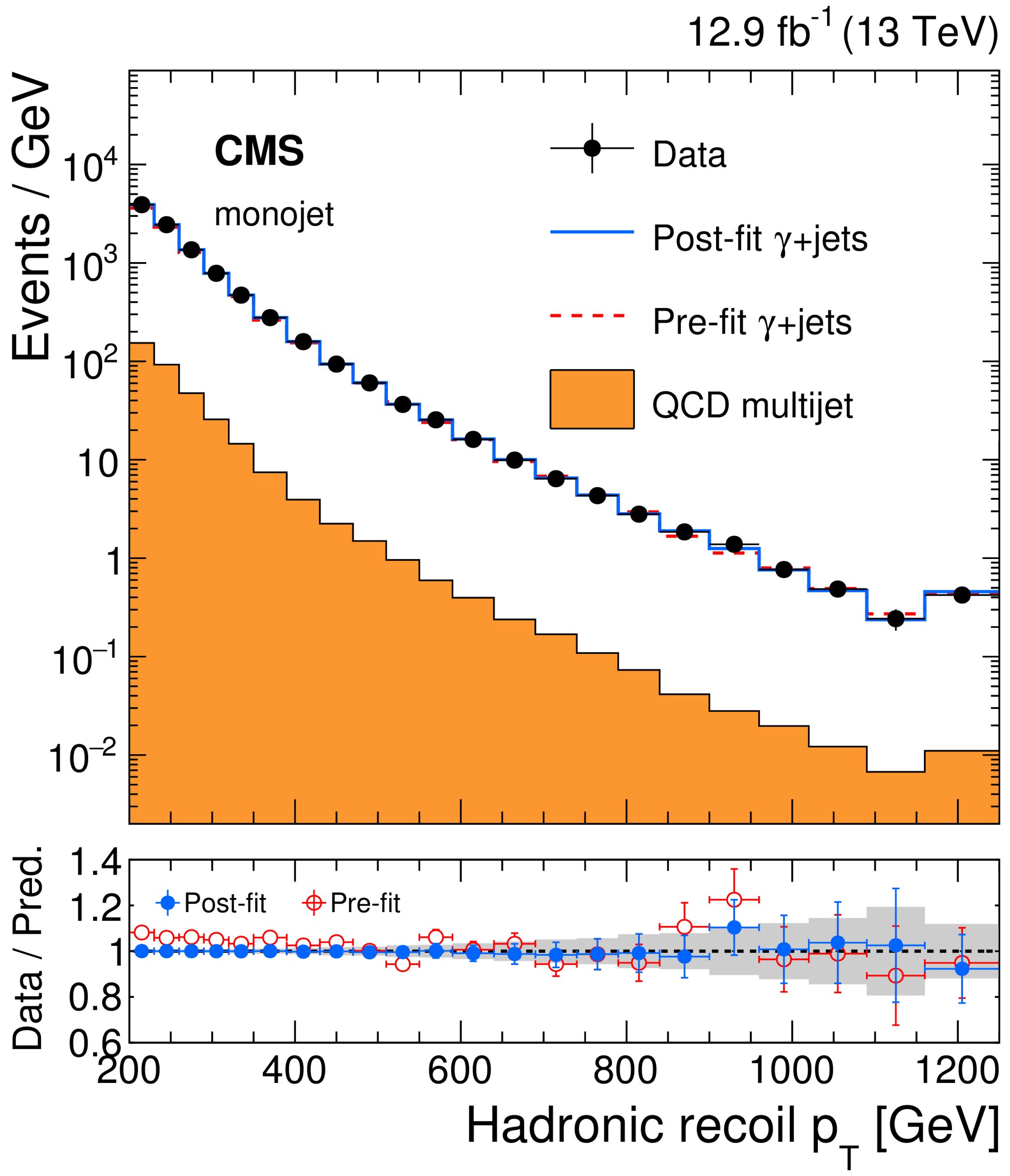


EXOT-2015-03
CMS-EXO-16-037

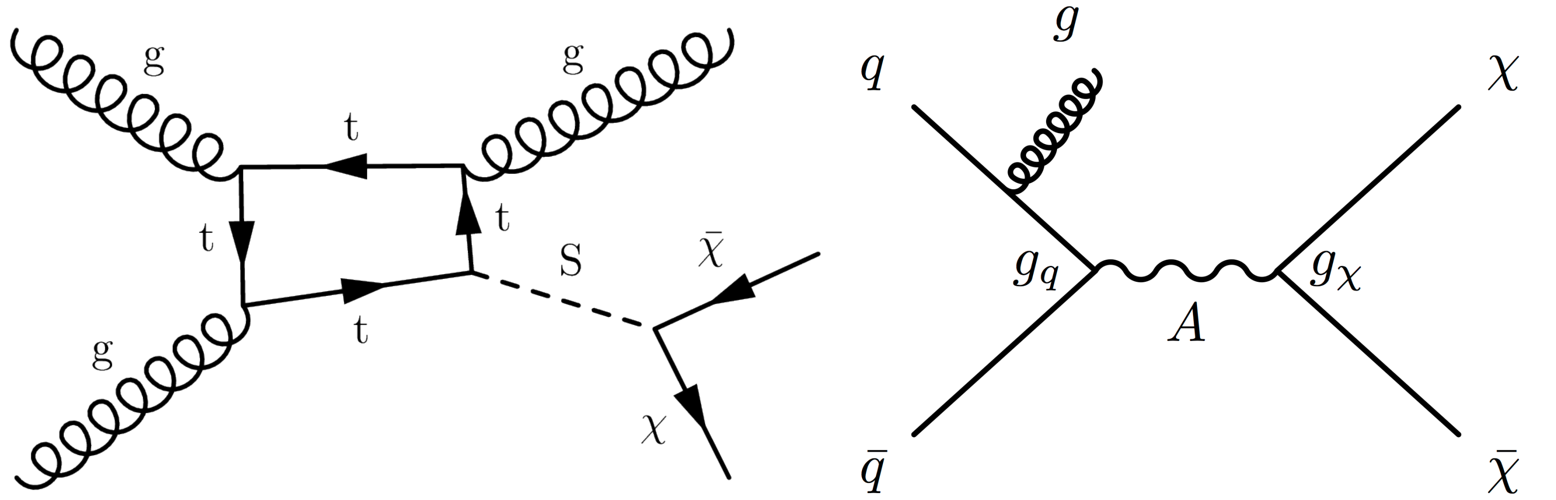
- To constrain two main backgrounds: Z(νν) + jets and W(ℓν) + jets, global simultaneous likelihood fits to CRs are used:
  - ATLAS: W(μν)+jets, W(eν)+jets, and Z/γ*(μμ)+jets
  - E_T^{miss} tail can be contaminated due to detector energy resolution, jet energy mis-measurements, pileup energy fluctuations, and instrumental noise
  - CMS: W(e/μν) + jets, Z/γ*(ee/μμ) + jets, and γ + jets (large statistics, similar jet multiplicity, underlying event, and pileup conditions as the DY process for the region of interest at high p_T region)





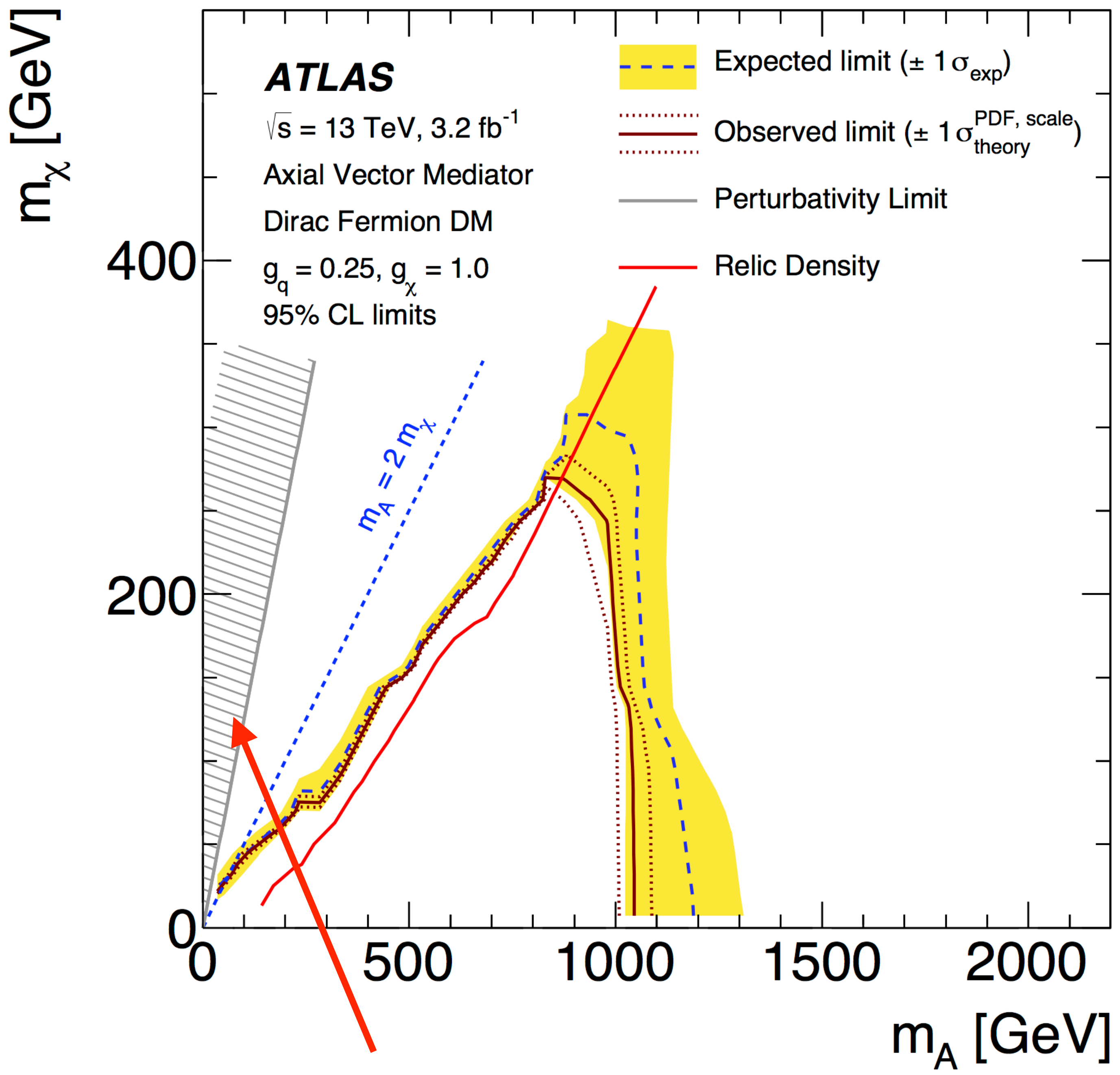


Mono-jet

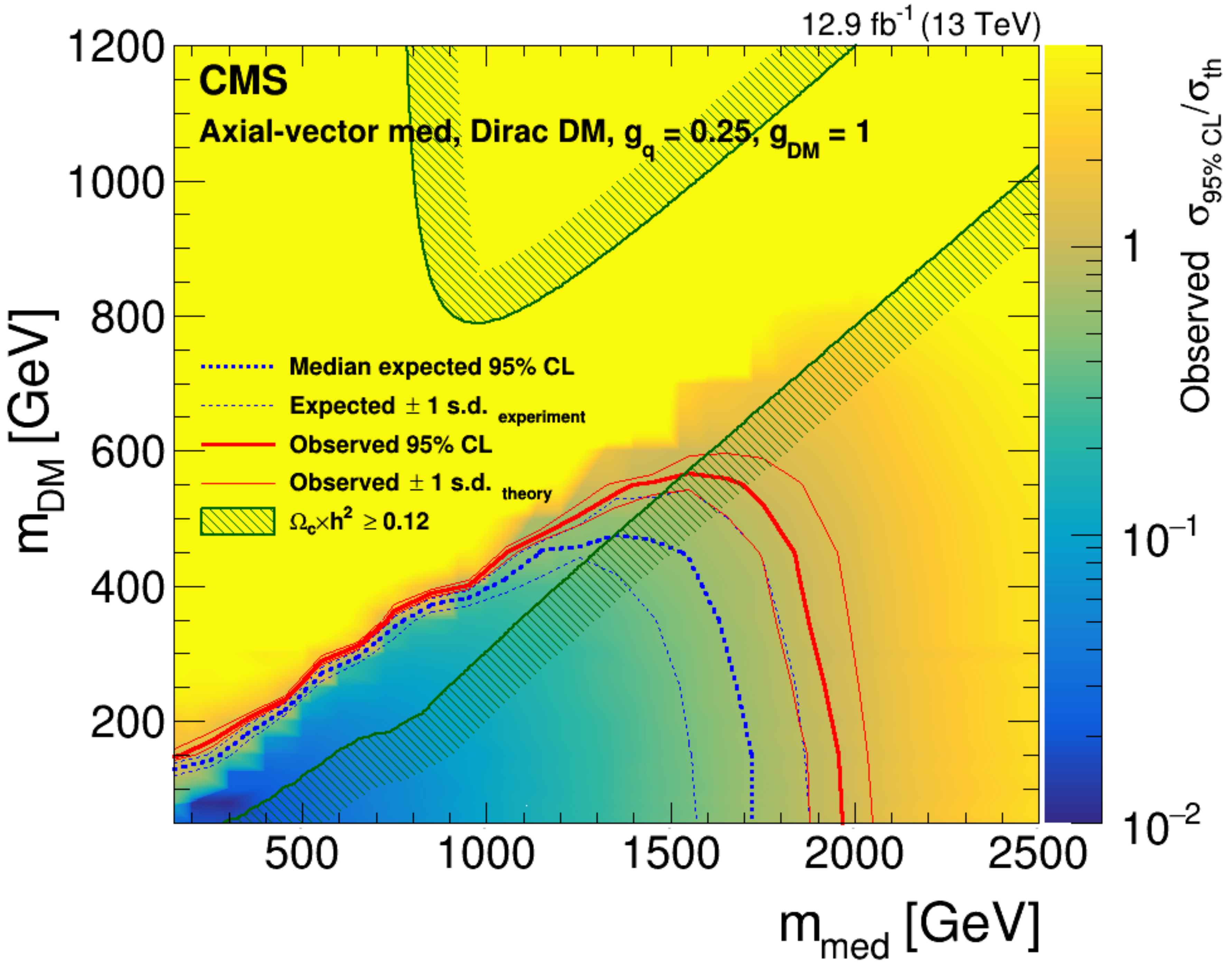


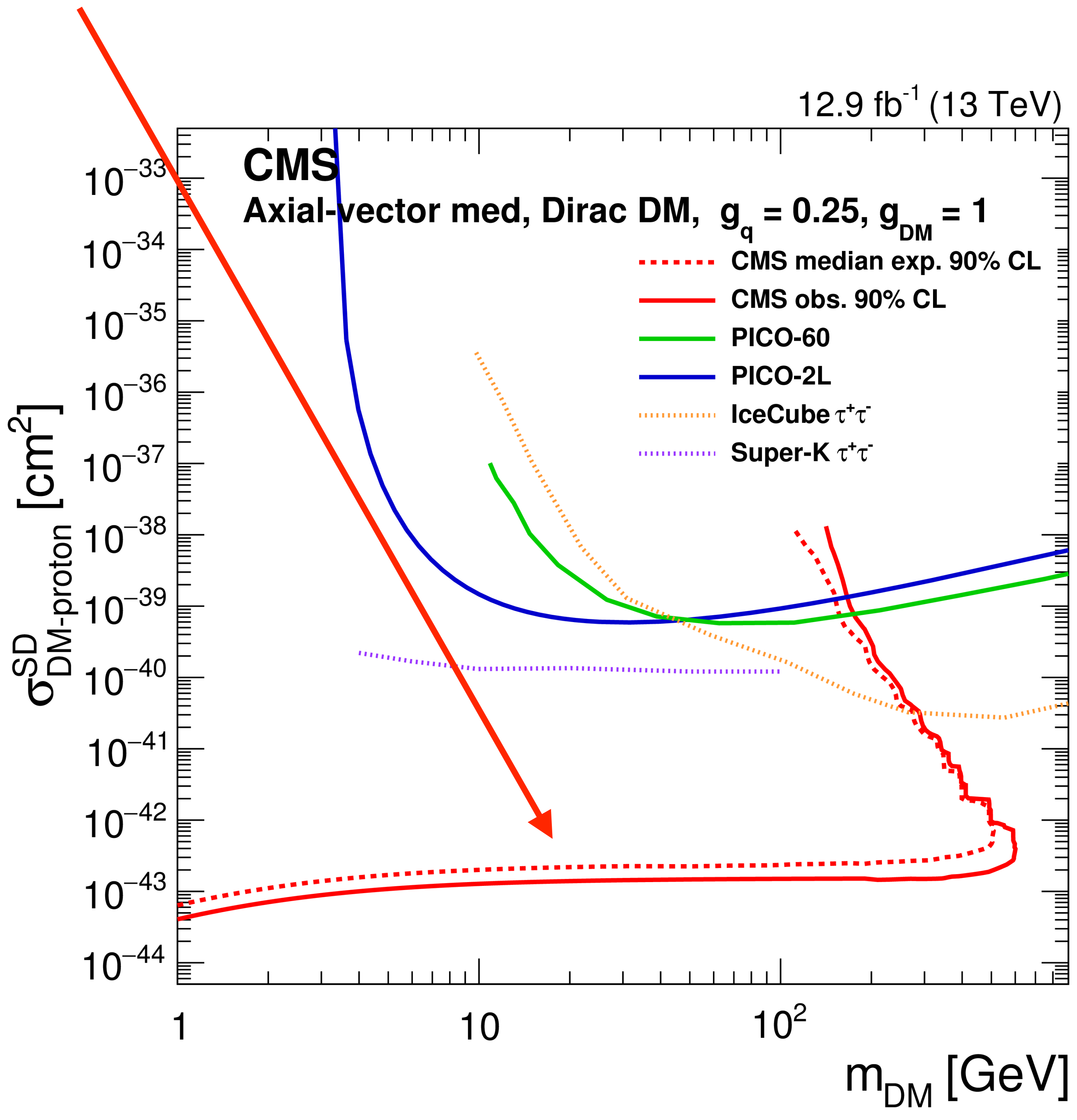
EXOT-2015-03
CMS-EXO-16-037

- No significant excess is observed
- Interpretation in terms of simplified models with (axial) vector and (pseudo) scalar mediators
    - Exclusion: vector mediator mass < 1 TeV @90%CL (ATLAS, 3.2fb^{-1}), < 2 TeV (CMS, 12.9 fb^{-1})
- Limits on spin-dependent DM-nuclei cross-section is more sensitive w.r.t. direct searches



perturbative unitarity violation
for axial vector coupling





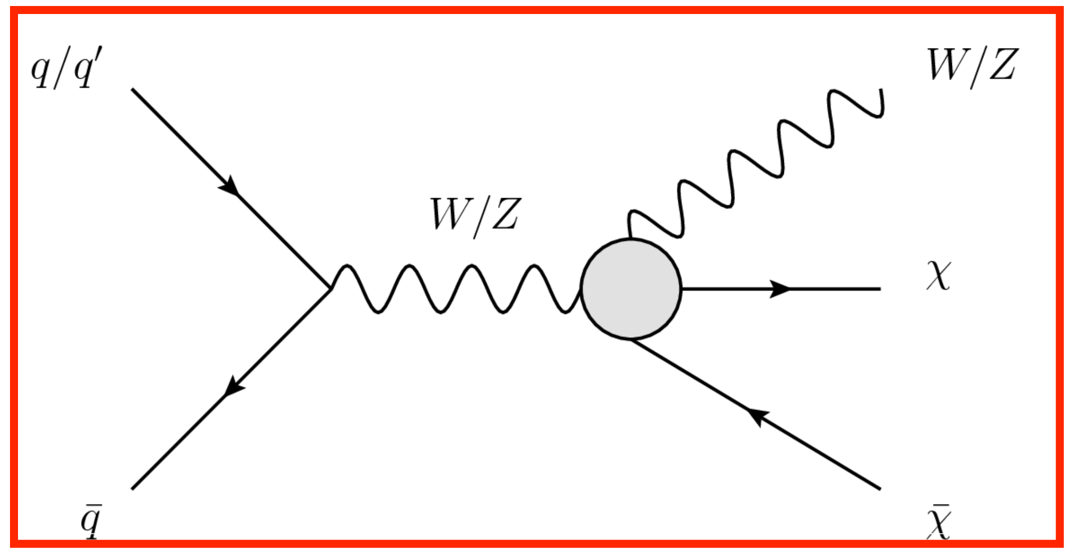

Mono-V(jj)
ATLAS
EXPERIMENT
Run Number: 280950, Event Number: 1526222948
Date: 2015-10-04 04:31:01 CEST

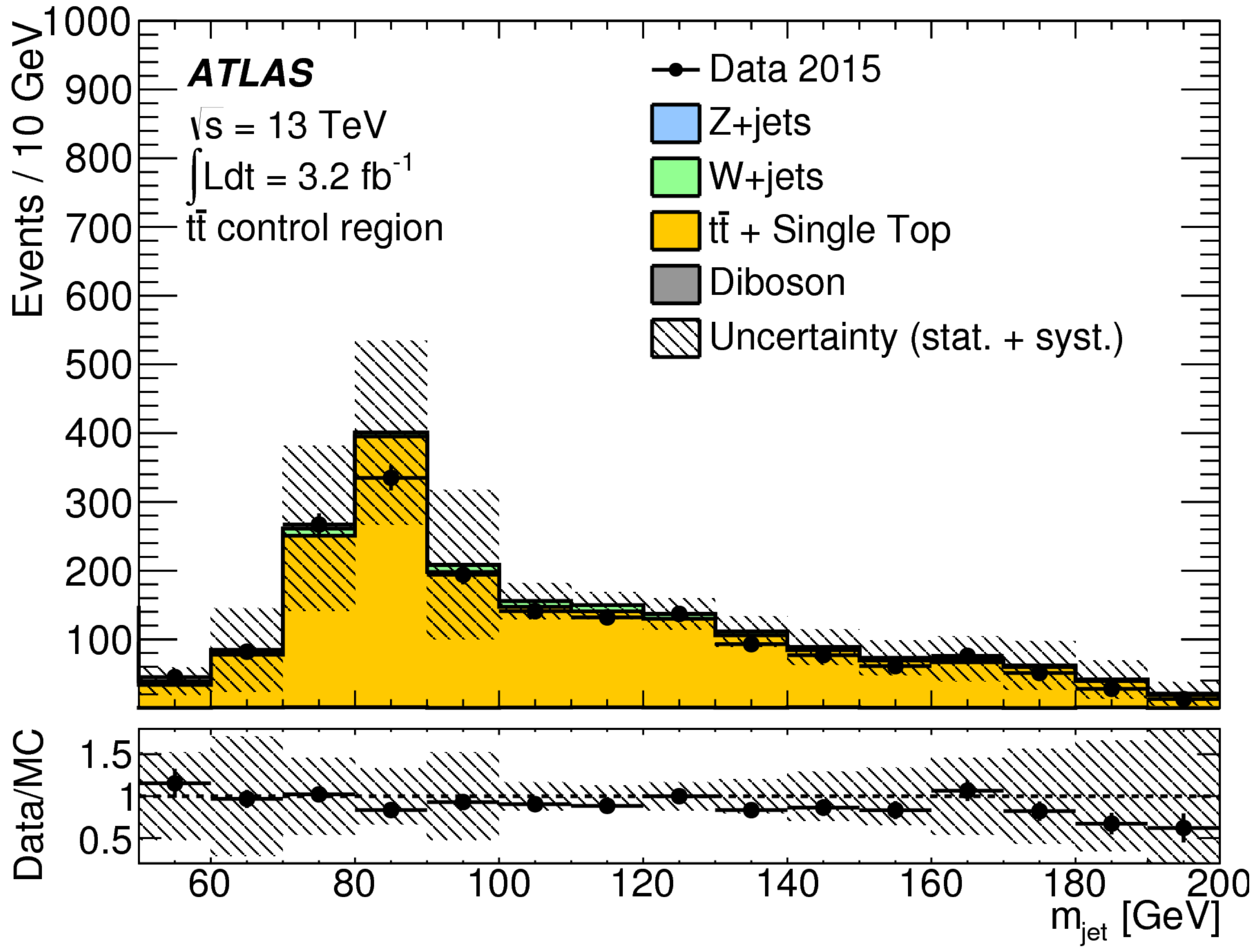
Mono-V(jj)

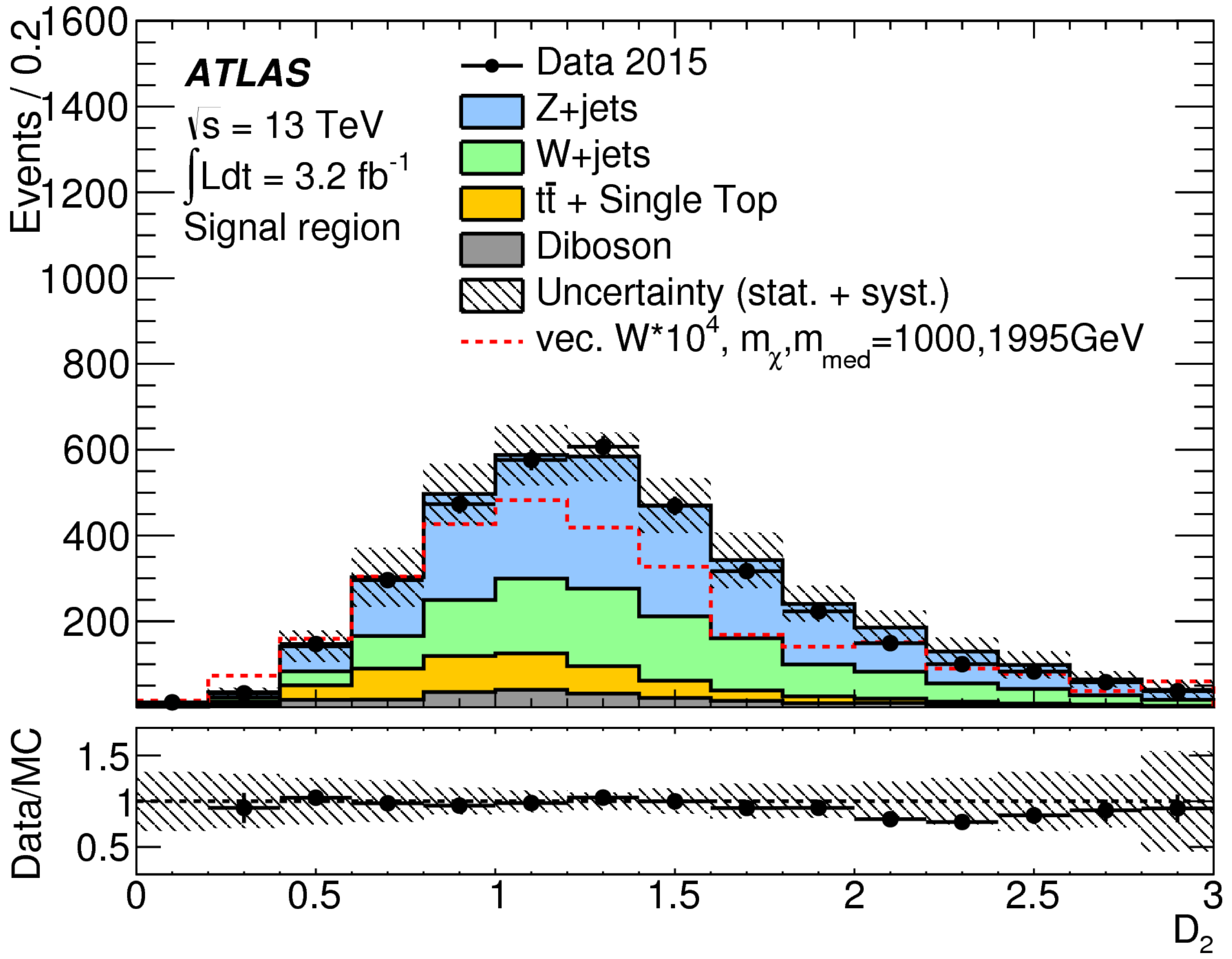
EXOT-2015-08
CMS-EXO-16-037

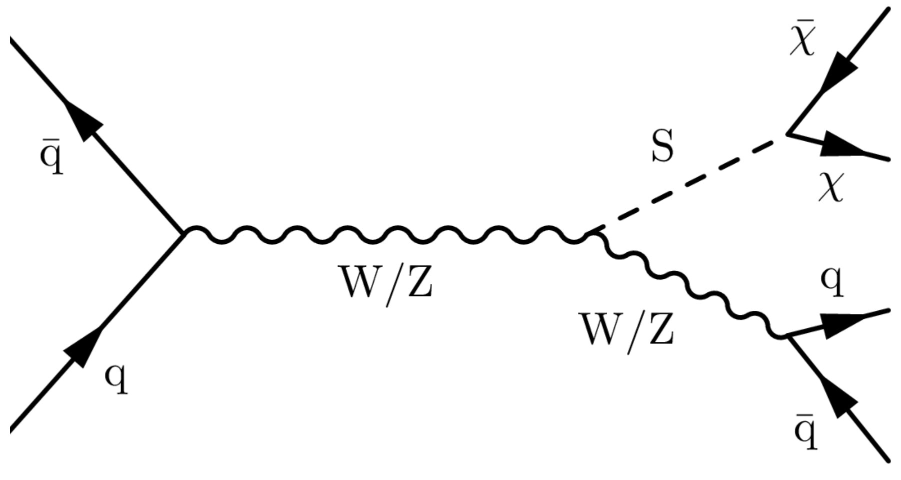
- Signature: a boosted W/Z boson with hadronic decay recoiling against a large MET
  - a large-R jet with R=**0.8**(1.0) and pT > **250** (200) GeV for **CMS**(ATLAS)
  - Jet mass compatible with W/Z boson
  - Jet substructure (subjetness) to discriminate W/Z from QCD

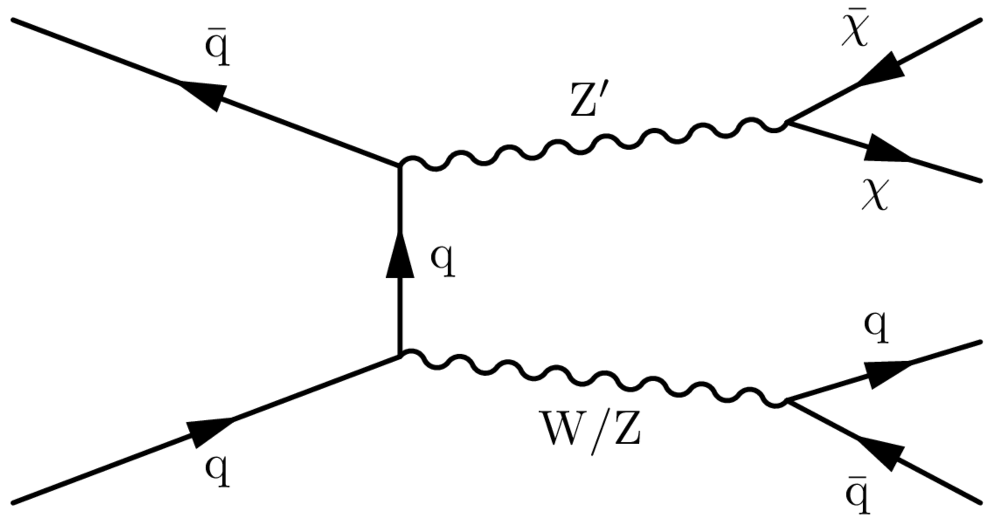
$$\frac{1}{\Lambda^3}\bar{\chi}\chi\left(c_1 B_{\mu\nu}B^{\mu\nu} + c_2 F^i_{\mu\nu}F^{i,\mu\nu}\right)$$





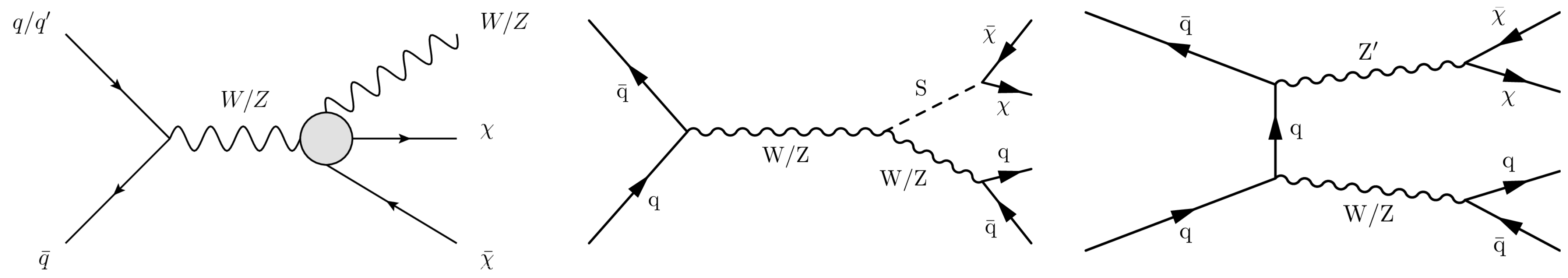






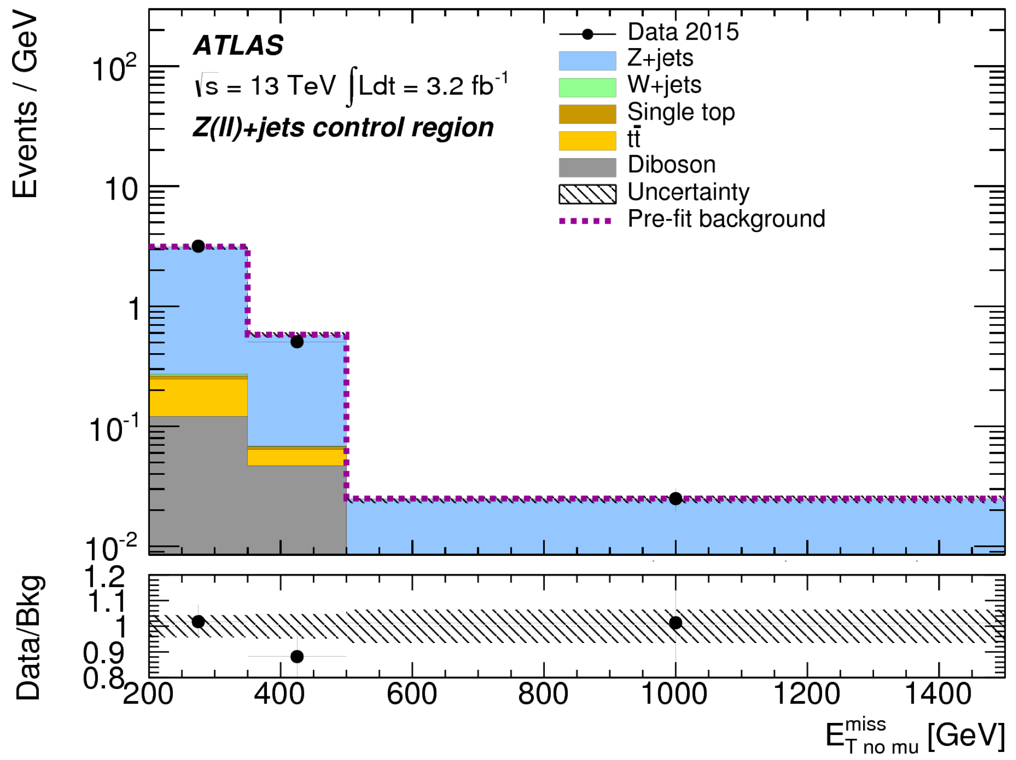
- Three type of benchmark models are considered:
  - Two simplified model with vector or scalar mediator in s-channel (same with mono-jet)
  - A dimension-7 operator: VVχχ (EFT model of DM directly coupling to gauge bosons)

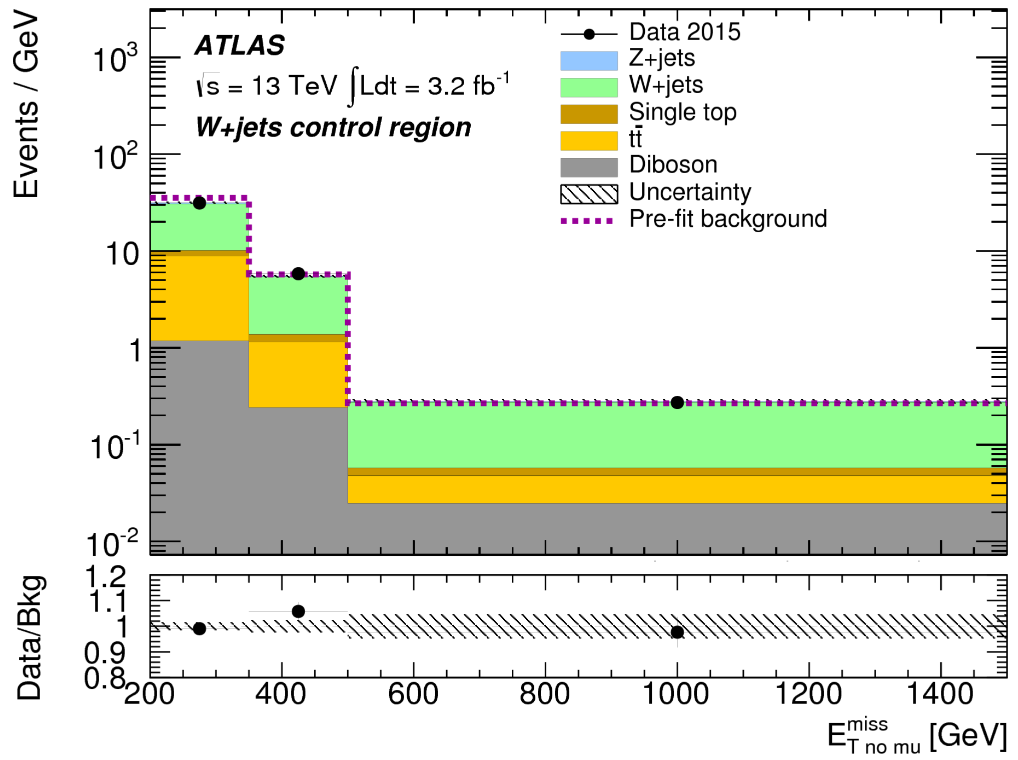
Mono-V(jj)

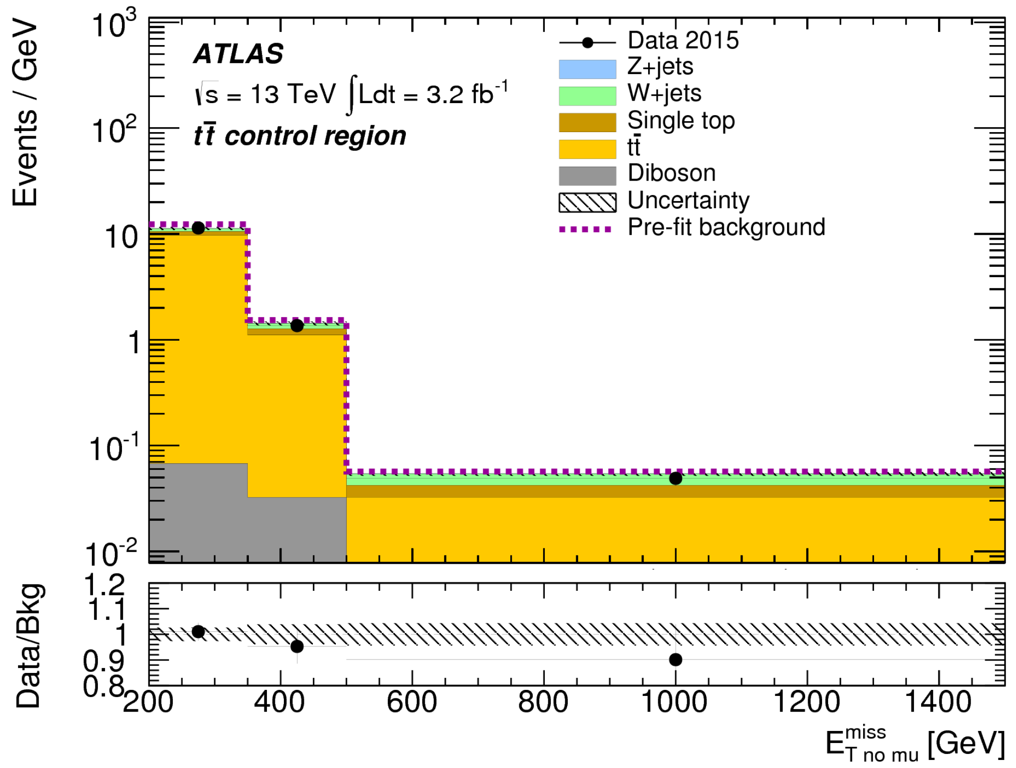


EXOT-2015-08
CMS-EXO-16-037

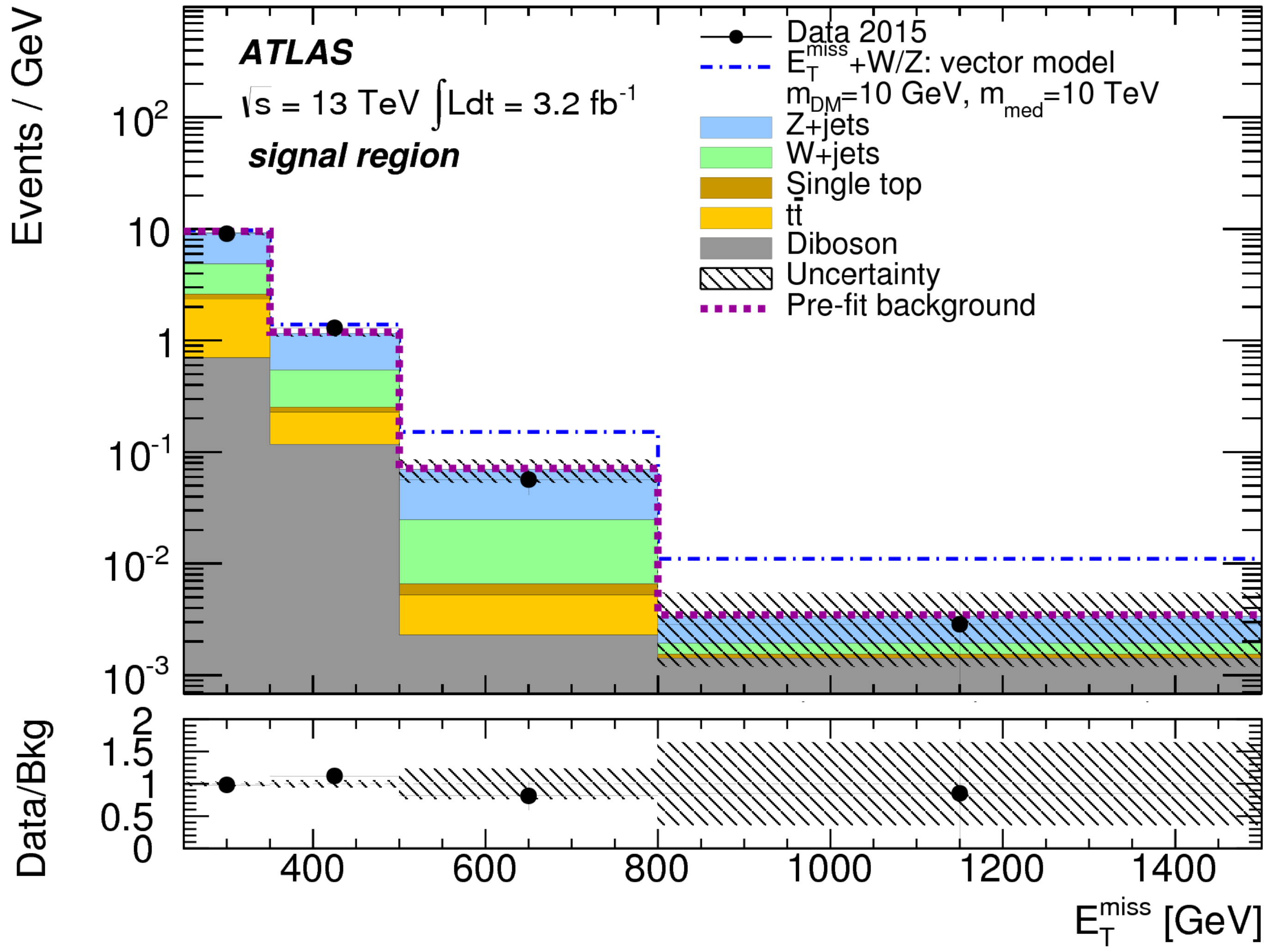
- Similar with Mono-jet, main backgrounds: Z(νν) + jets and W(ℓν) + jets and ttbar are constrained from global simultaneous likelihood fits to CRs
  - ATLAS: W(μν)+jets, W(eν)+jets, and Z/γ∗(μμ)+jets
  - CMS: W(e/μν) + jets, Z/γ∗(ee/μμ) + jets, and γ + jets

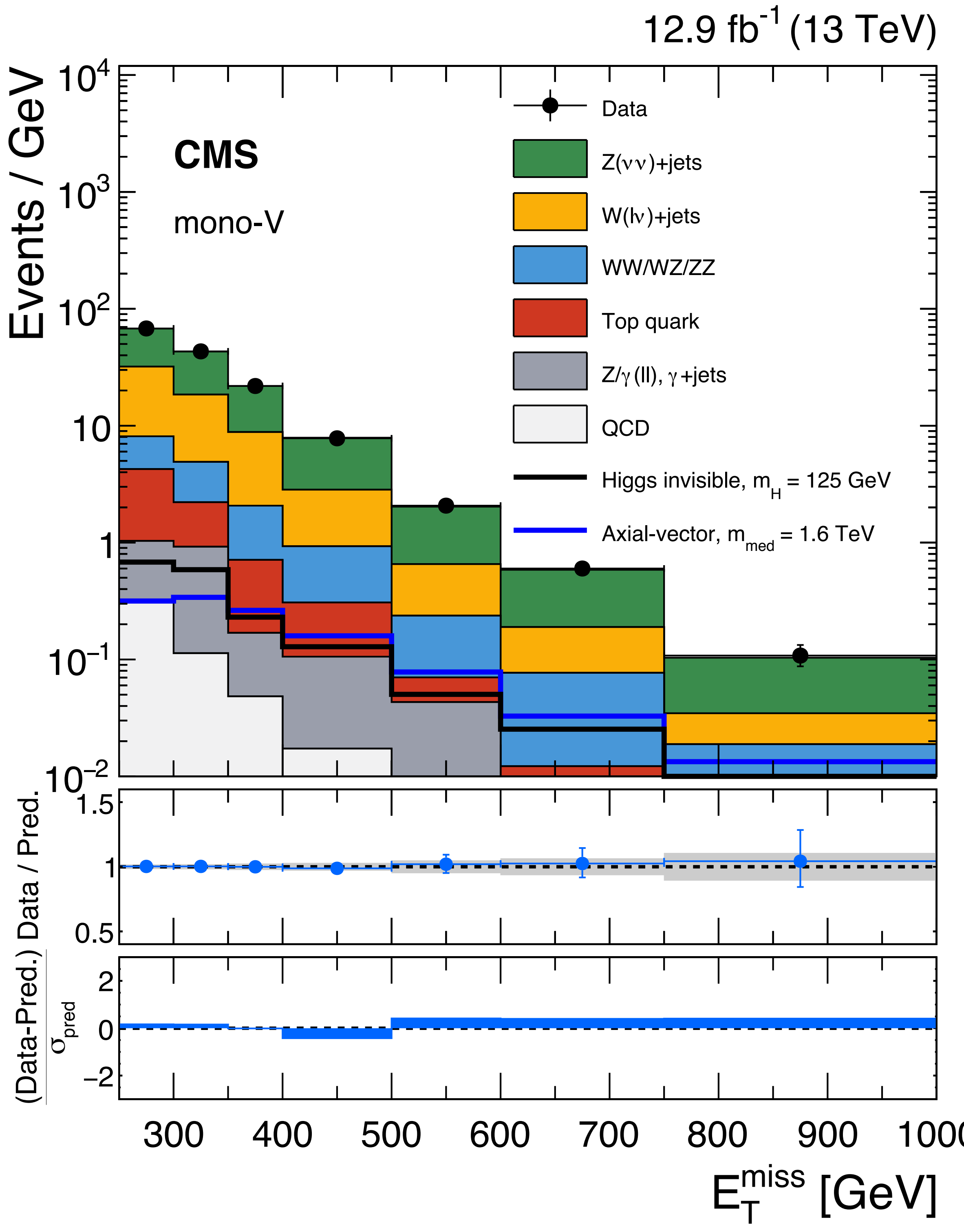




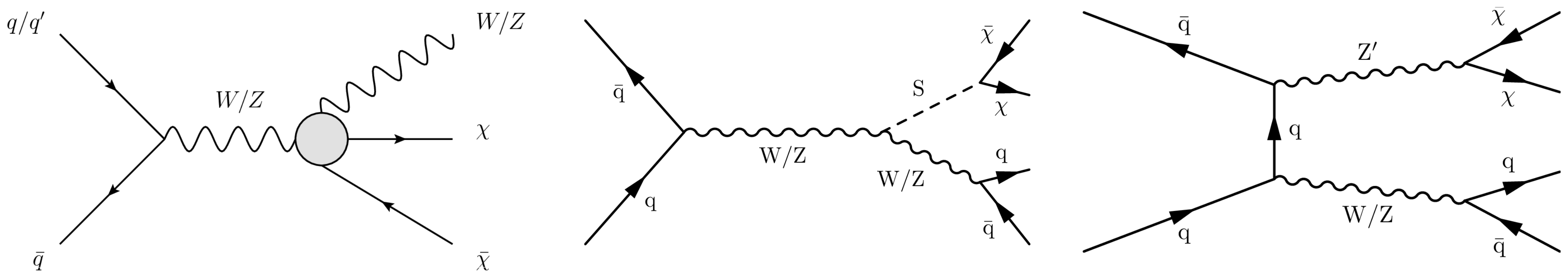


Process	Normalization Factor
Z+jets	1.01 ± 0.16
W+jets	0.90 ± 0.16
$t\bar{t}$	0.91 ± 0.18



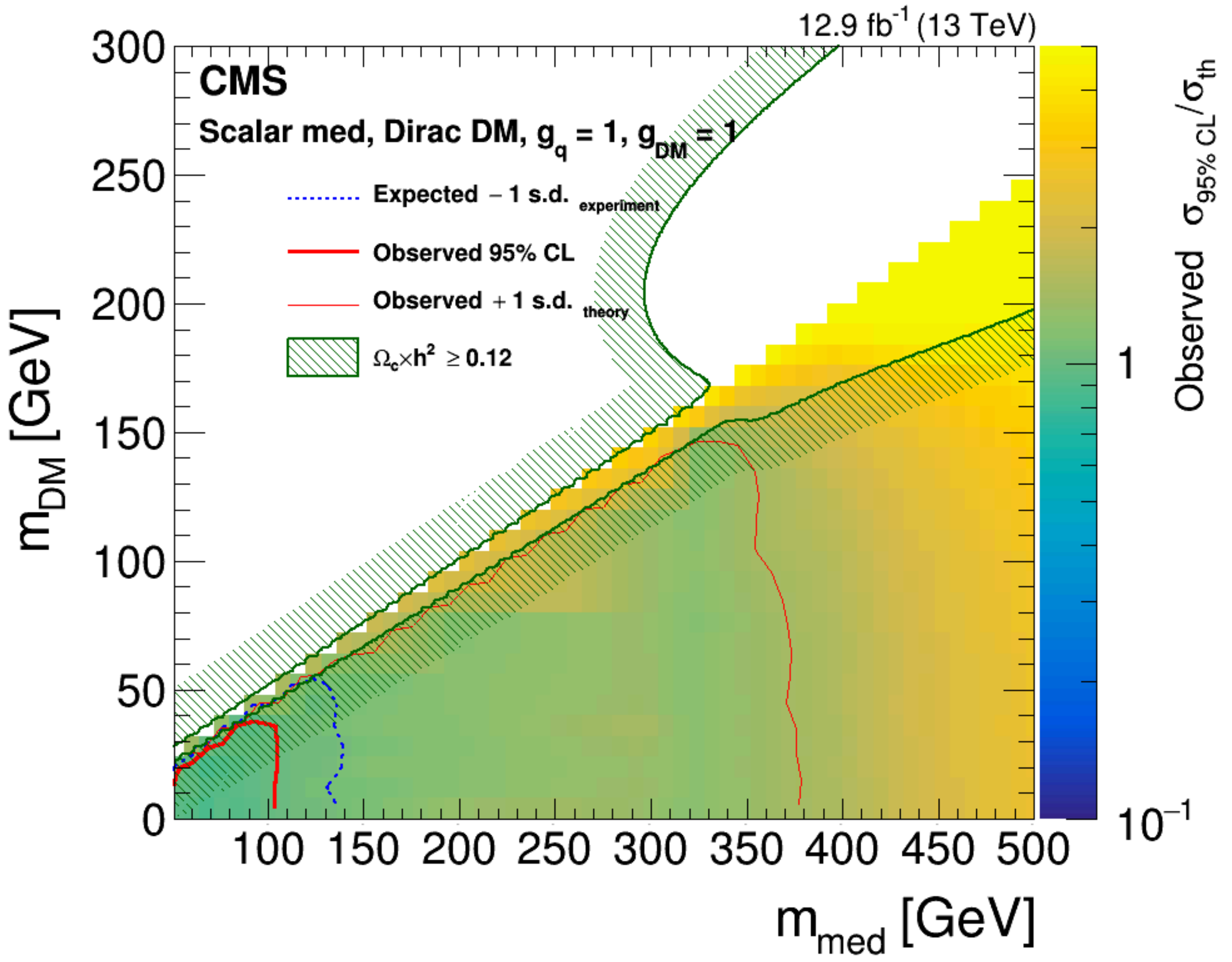


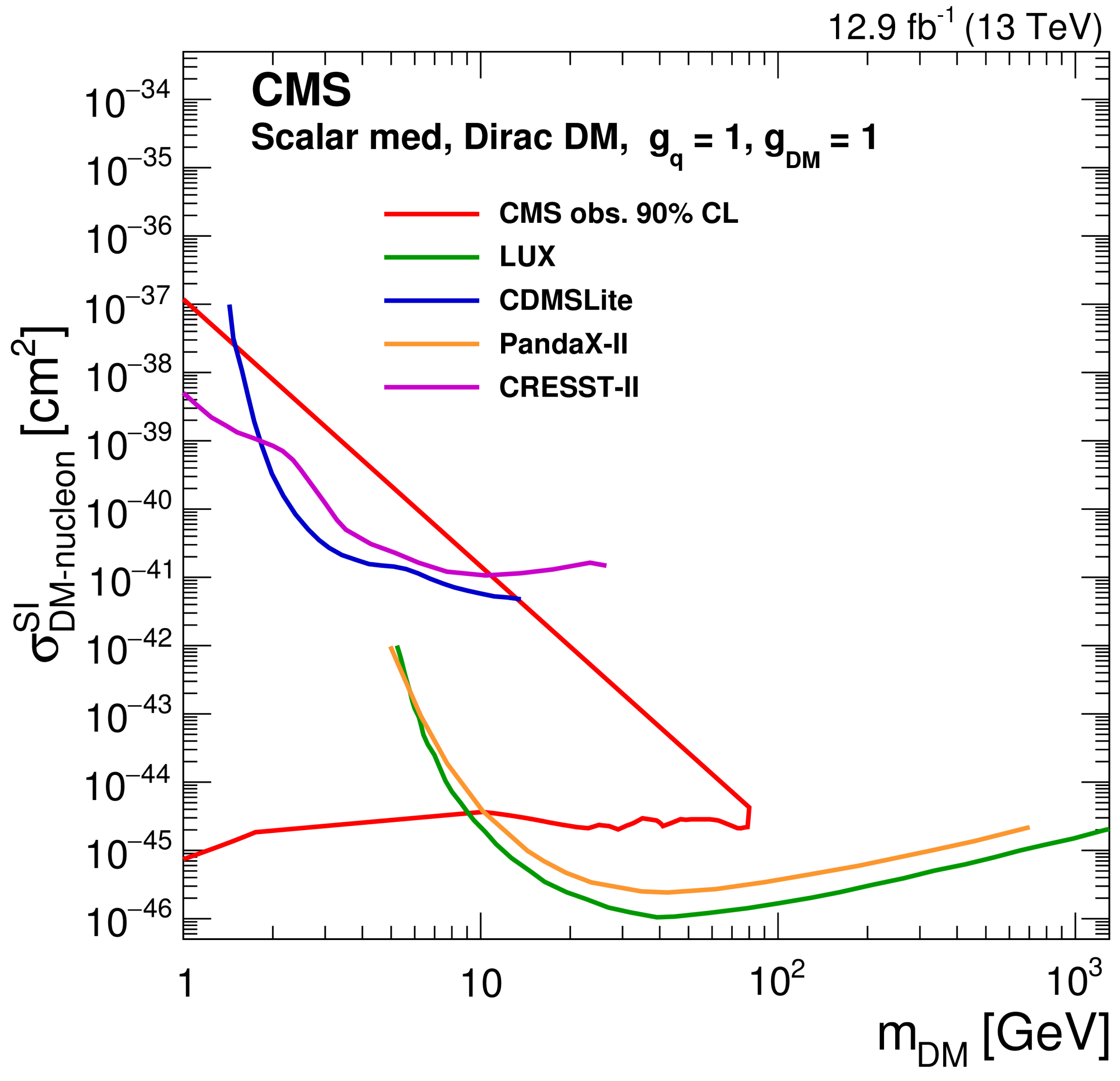
Mono-V(jj)

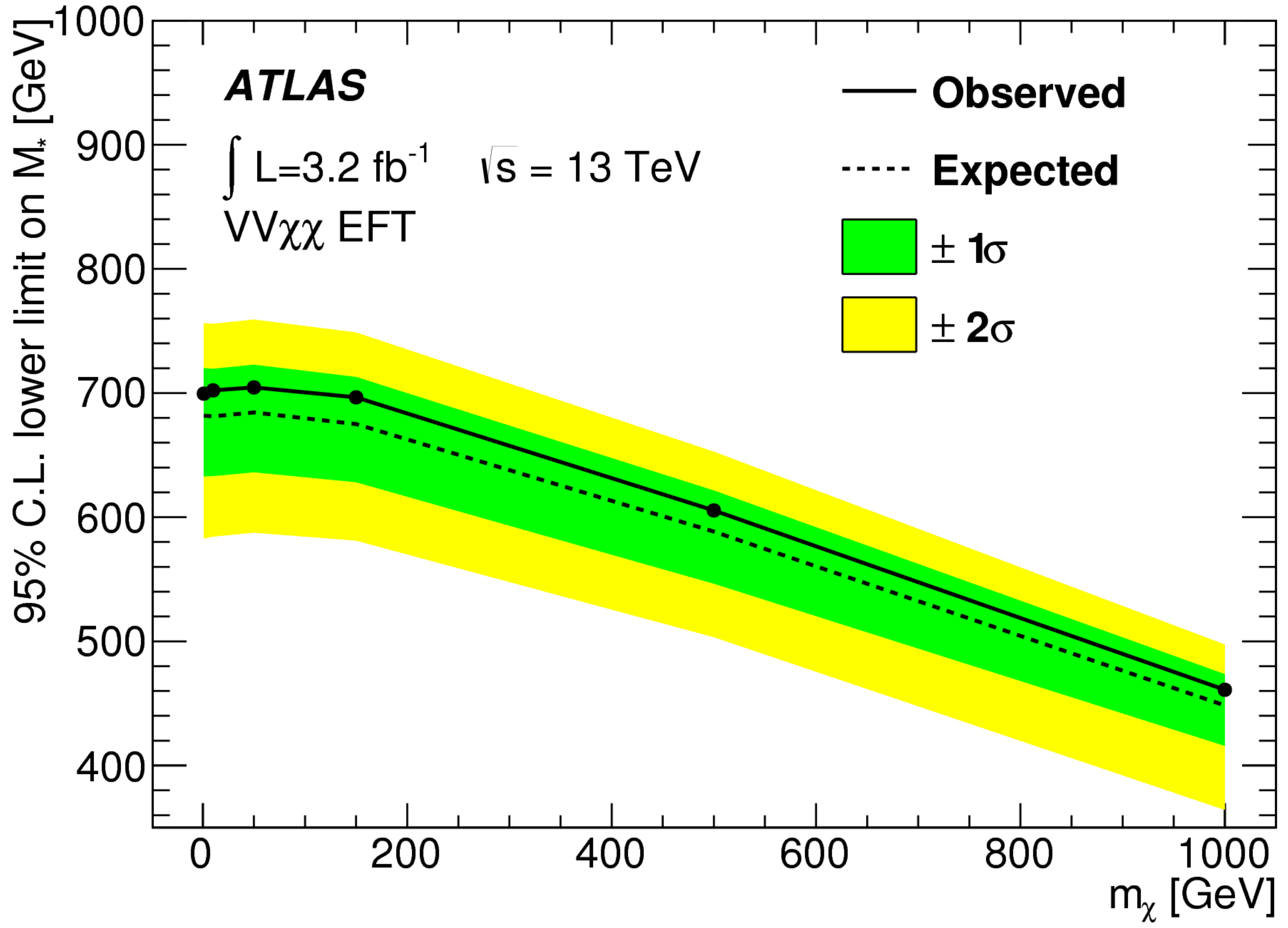


EXOT-2015-08
CMS-EXO-16-037

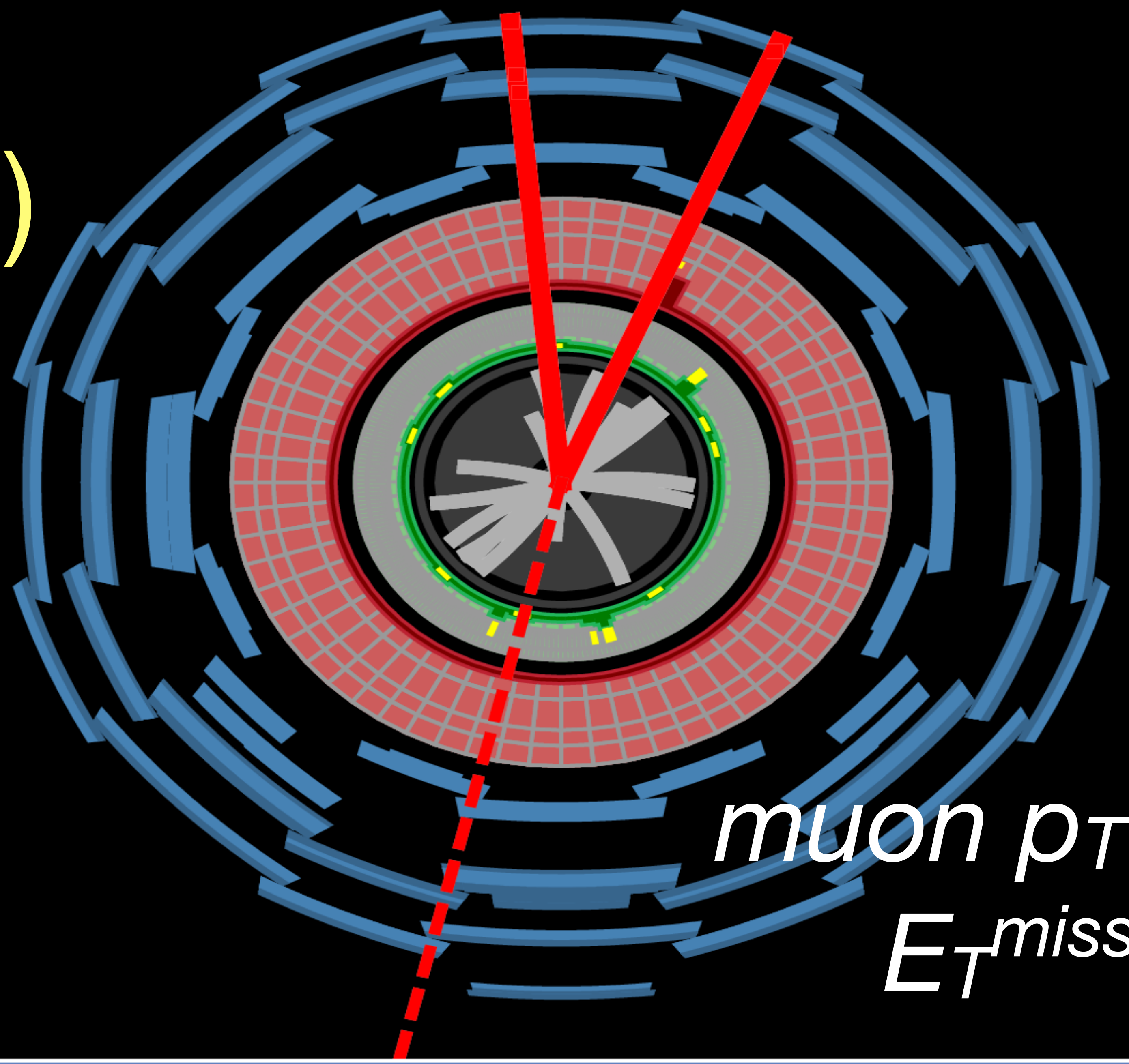
- Good agreement with SM predictions, no significant excess is observed
  - 2D Interpretation in terms of simplified models with (axial) vector and (pseudo) scalar mediators, exclude Mmed < 100 GeV for DM mass at 1GeV at 95%CL (12.9 fb-1)
  - 1D upper limits on cutoff scales for dimension-7 operator: VVχχ, cutoff scale < 700 GeV is excluded at 95%CL (3.2 fb-1) for DM mass at 1GeV
- Limits on both spin-dependent and spin-independent DM-nuclei cross-section, more sensitive w.r.t. direct searches at low DM mass region (<10 GeV)







Mono-Z($\ell^+\ell^-$)



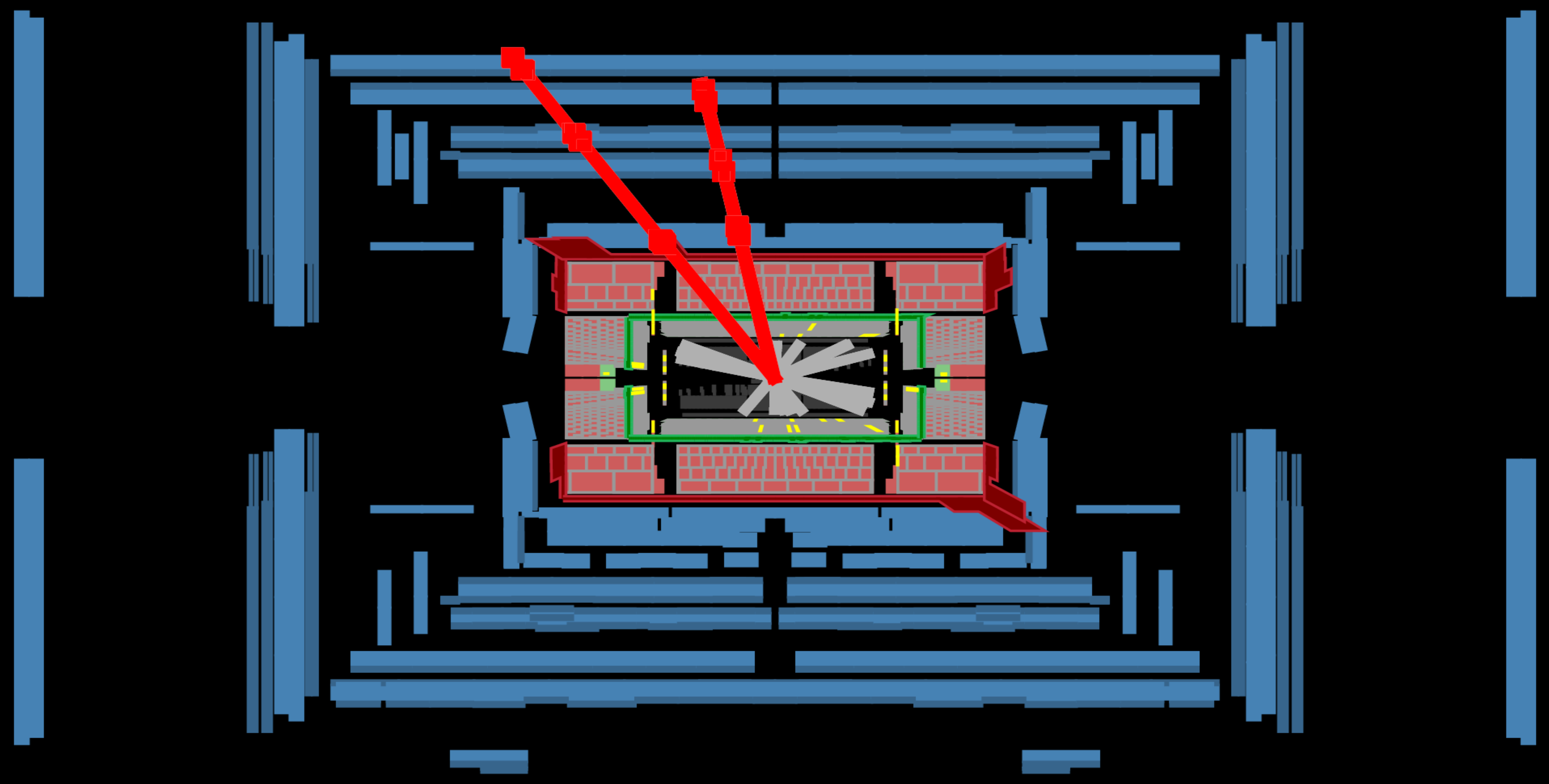
muon p_T = 115, 90 GeV

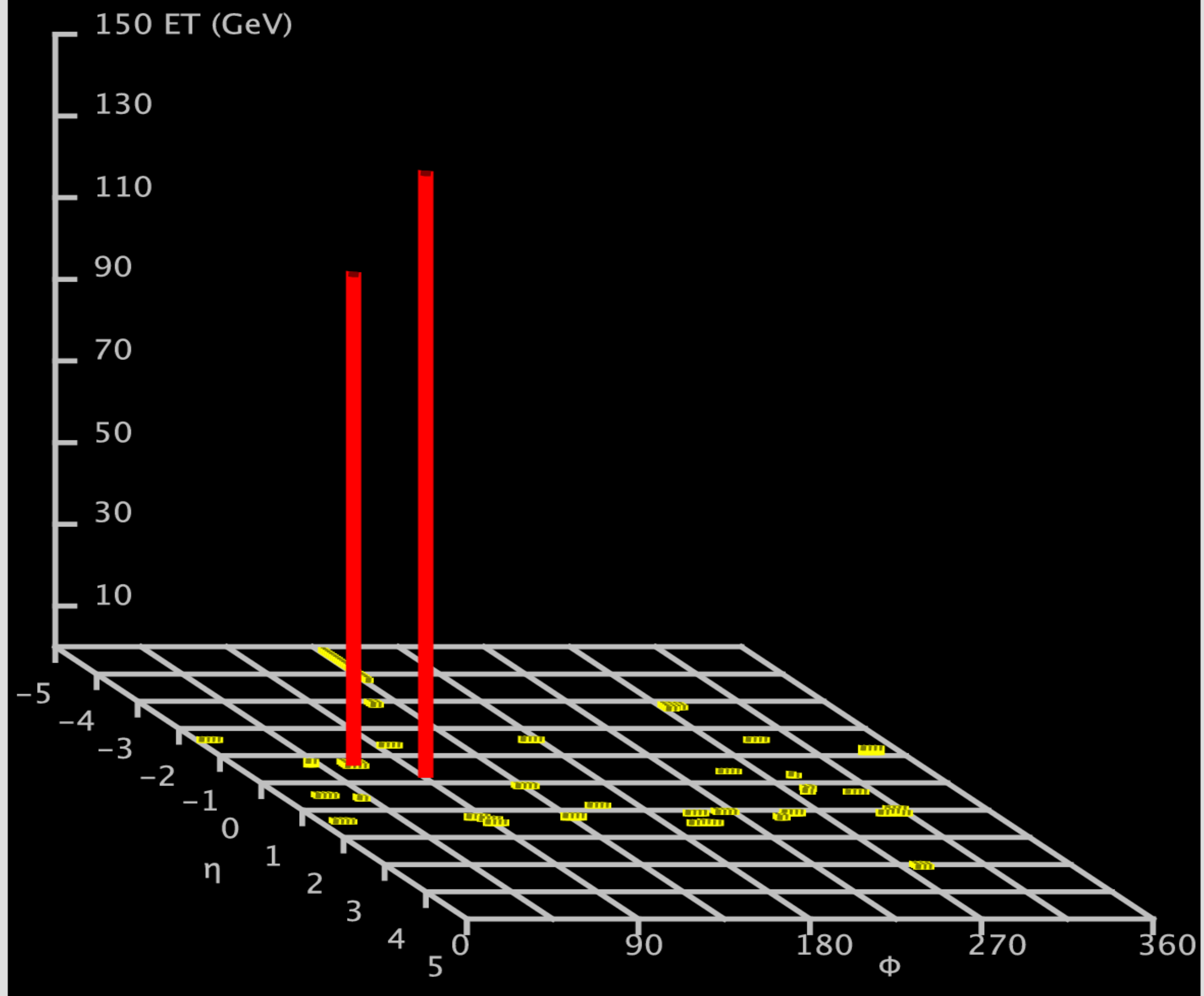
E_T^{miss} = 254 GeV

ATLAS EXPERIMENT

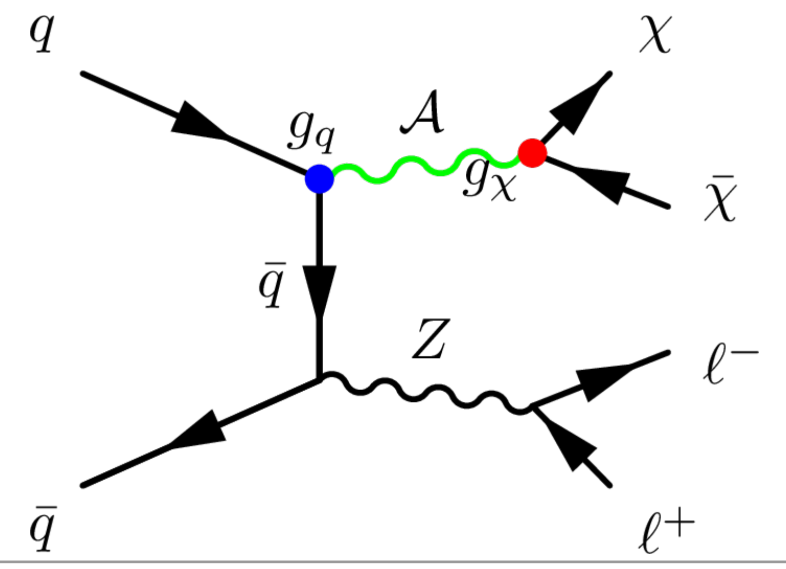
Run Number: 302137, Event Number: 1157671228

Date: 2016-06-16 01:03:36 CEST



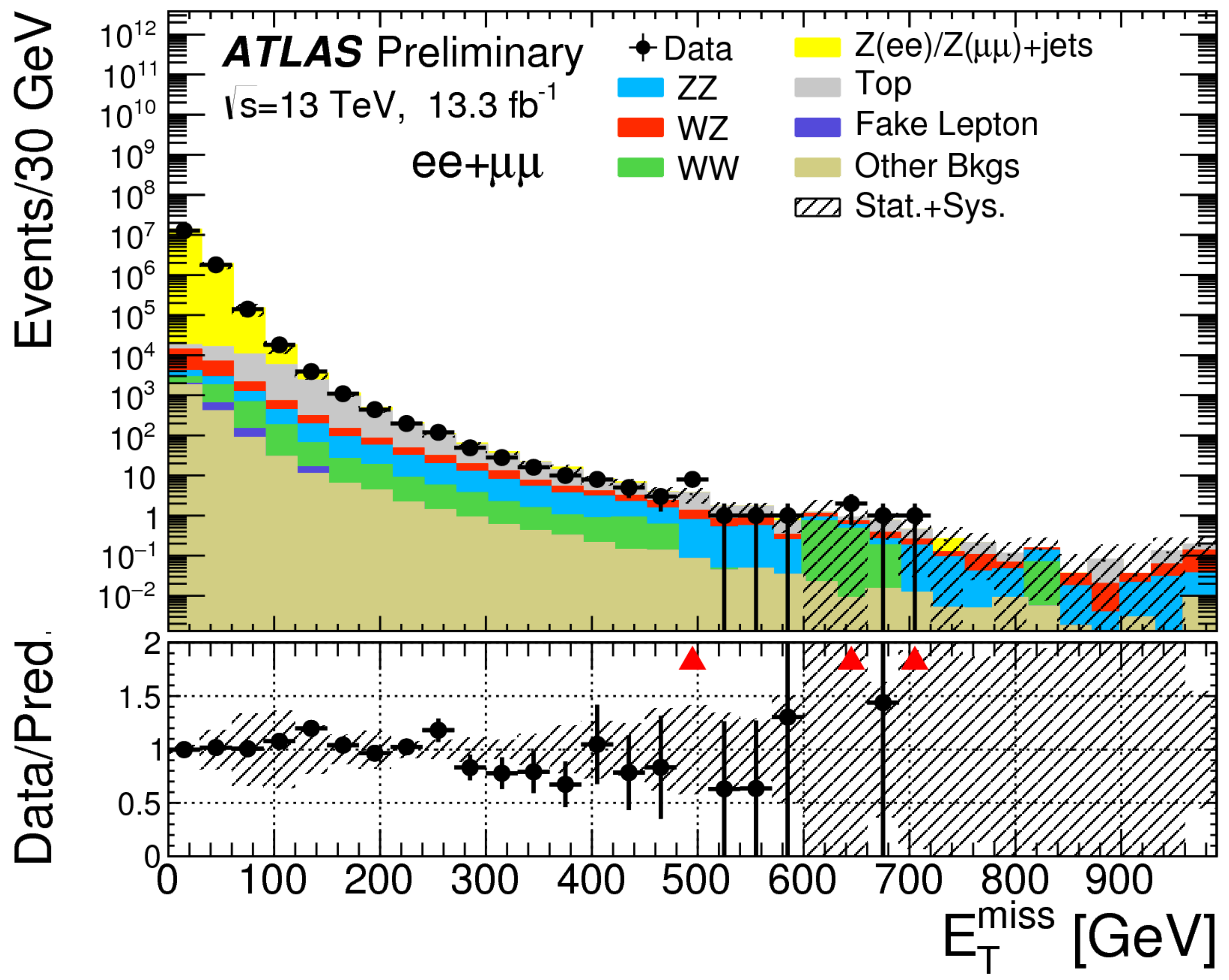


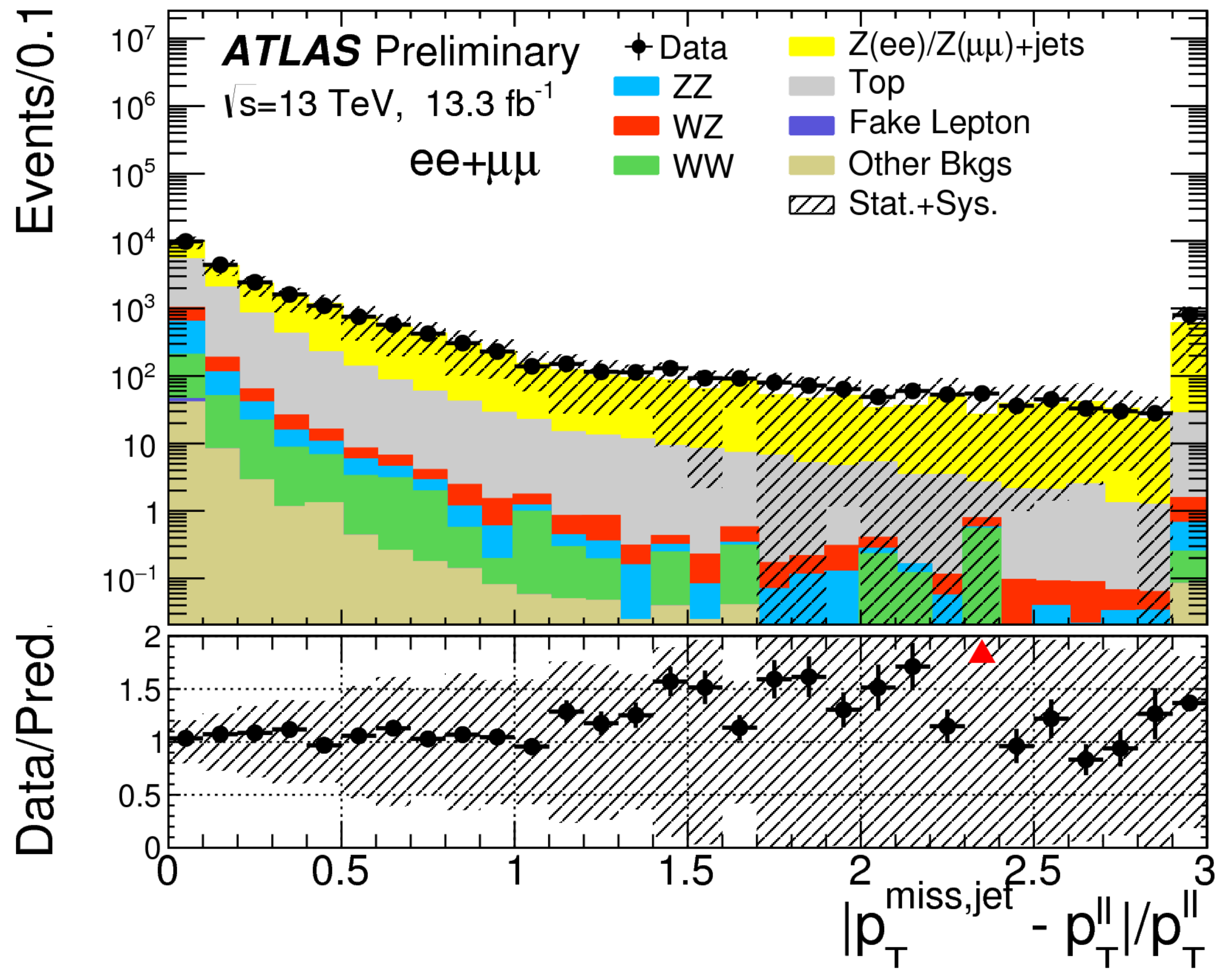
Mono-Z($\ell^+\ell^-$)



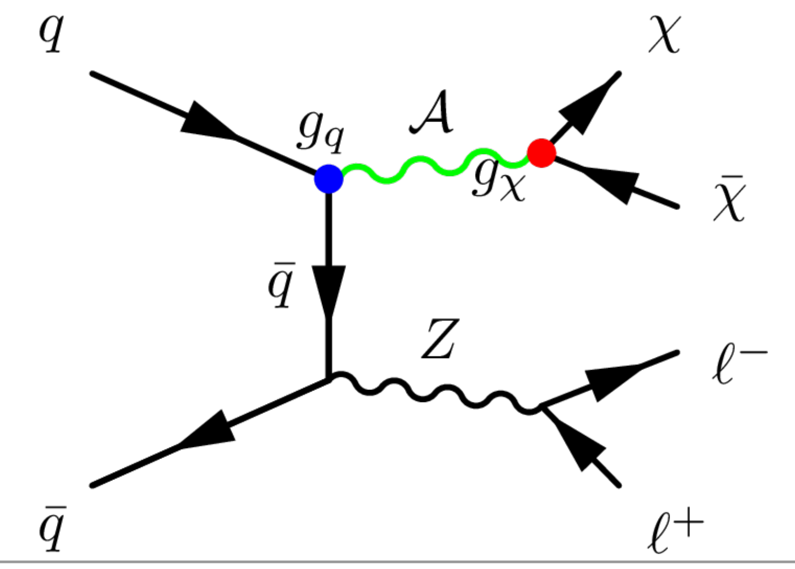
ATLAS-CONF-2016-056
CMS-PAS-EXO-16-038

- Signature: a Z($\ell^+\ell^-$) boson with a large MET
- Event selection in ATLAS **(CMS)**:
  - Mass: -15 GeV < m($\ell^+\ell^-$) - m_Z < 15 **(10)** GeV
  - Two leading leptons with pT>30,20 **(25/20,20)** GeV
  - 3rd lepton veto
  - MET>90 **(100)** GeV
  - $\Delta\phi(p_T^{\ell\ell}$, MET) > 2.7 **(2.8)** rad, $\Delta\phi$(MET, jets) > 0.7**(0.5)** rad
  - Bjet veto **(and 0 or 1 jets, tau-jet veto)**
  - ||MET + jet pT| - $p_T^{\ell\ell}|/p_T^{\ell\ell}$ < 0.2, **(|MET - $p_T^{\ell\ell}|/p_T^{\ell\ell}$ < 0.4)**
  - $\Delta R(\ell^+\ell^-)$ < 1.8, $p_T^{\ell\ell}$/mT < 0.9 **($p_T^{\ell\ell}$ > 60 GeV)**
- Models: vector mediator benchmark models are considered: vector/axial-vector couplings



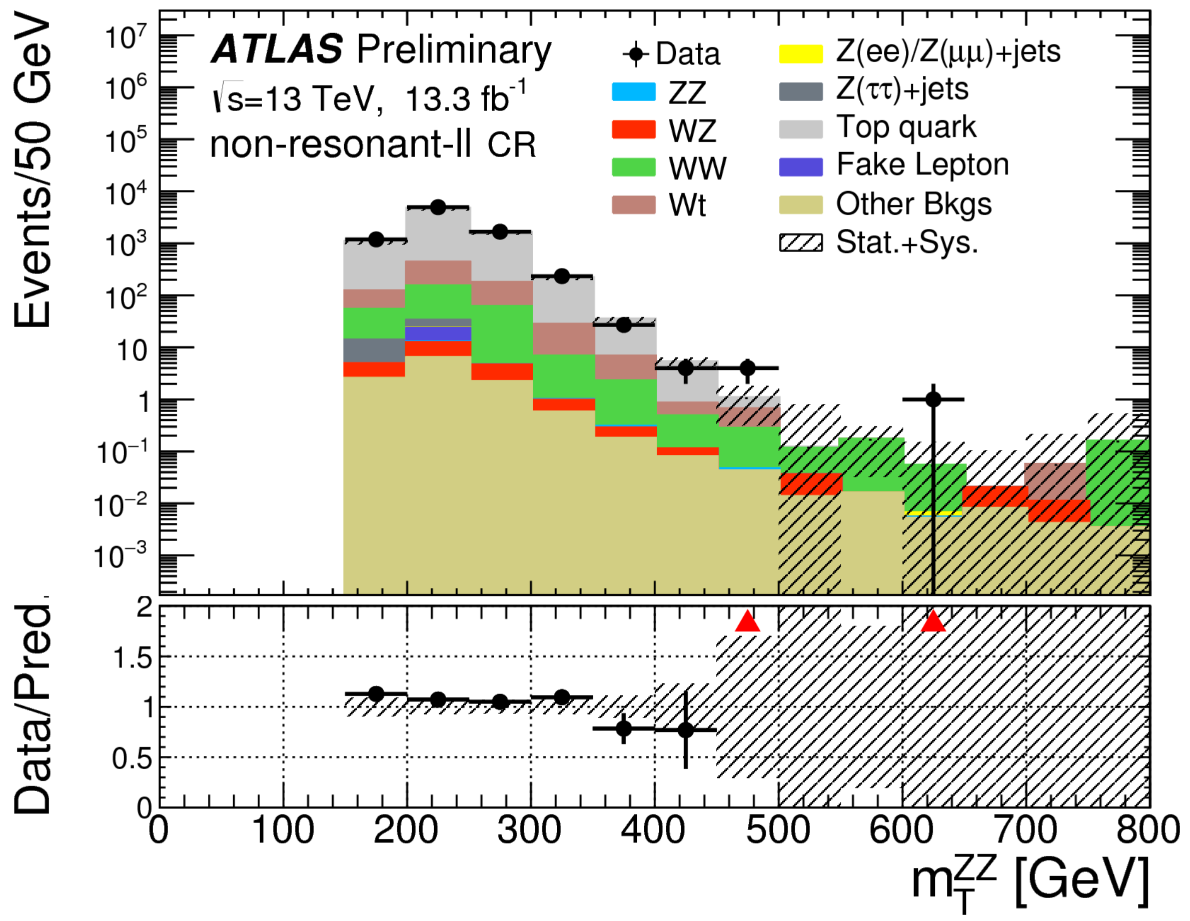


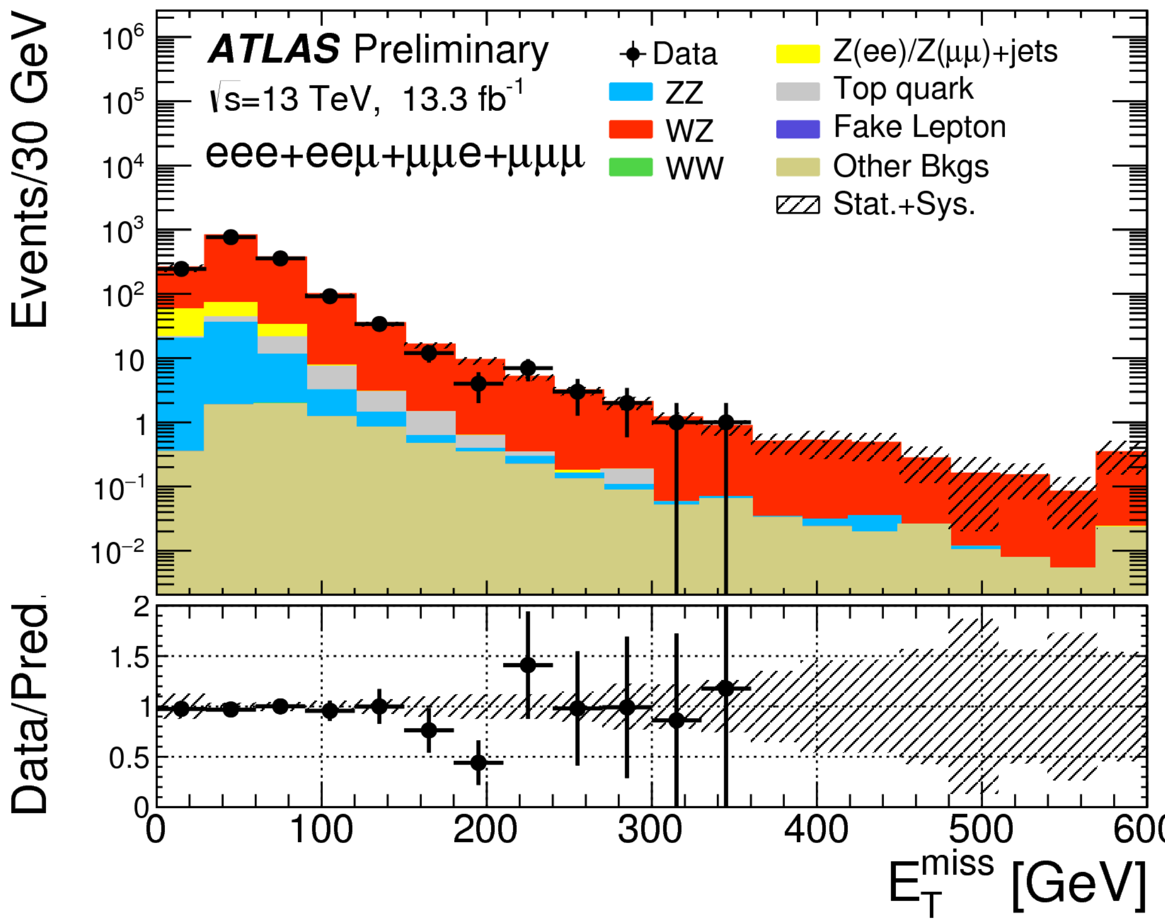
Mono-Z($\ell^+\ell^-$)

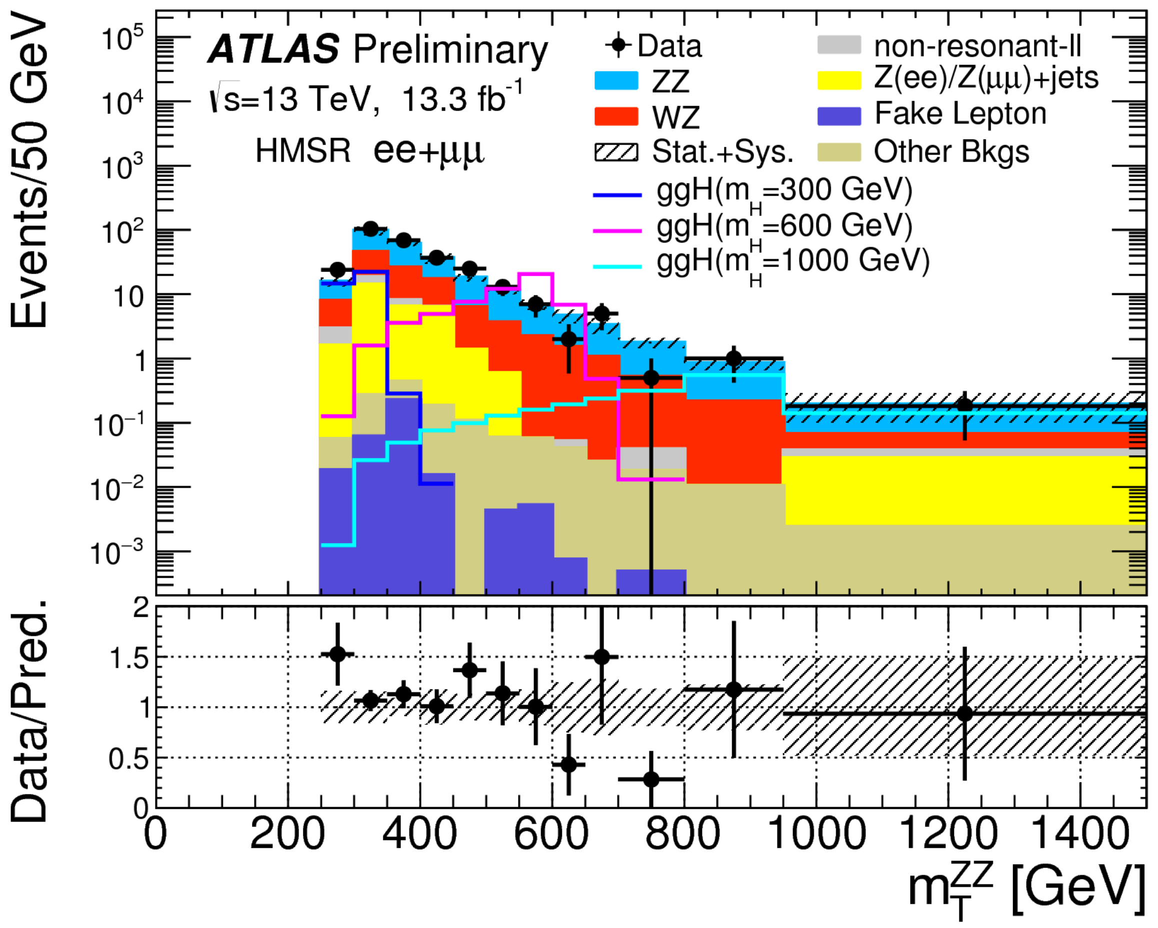


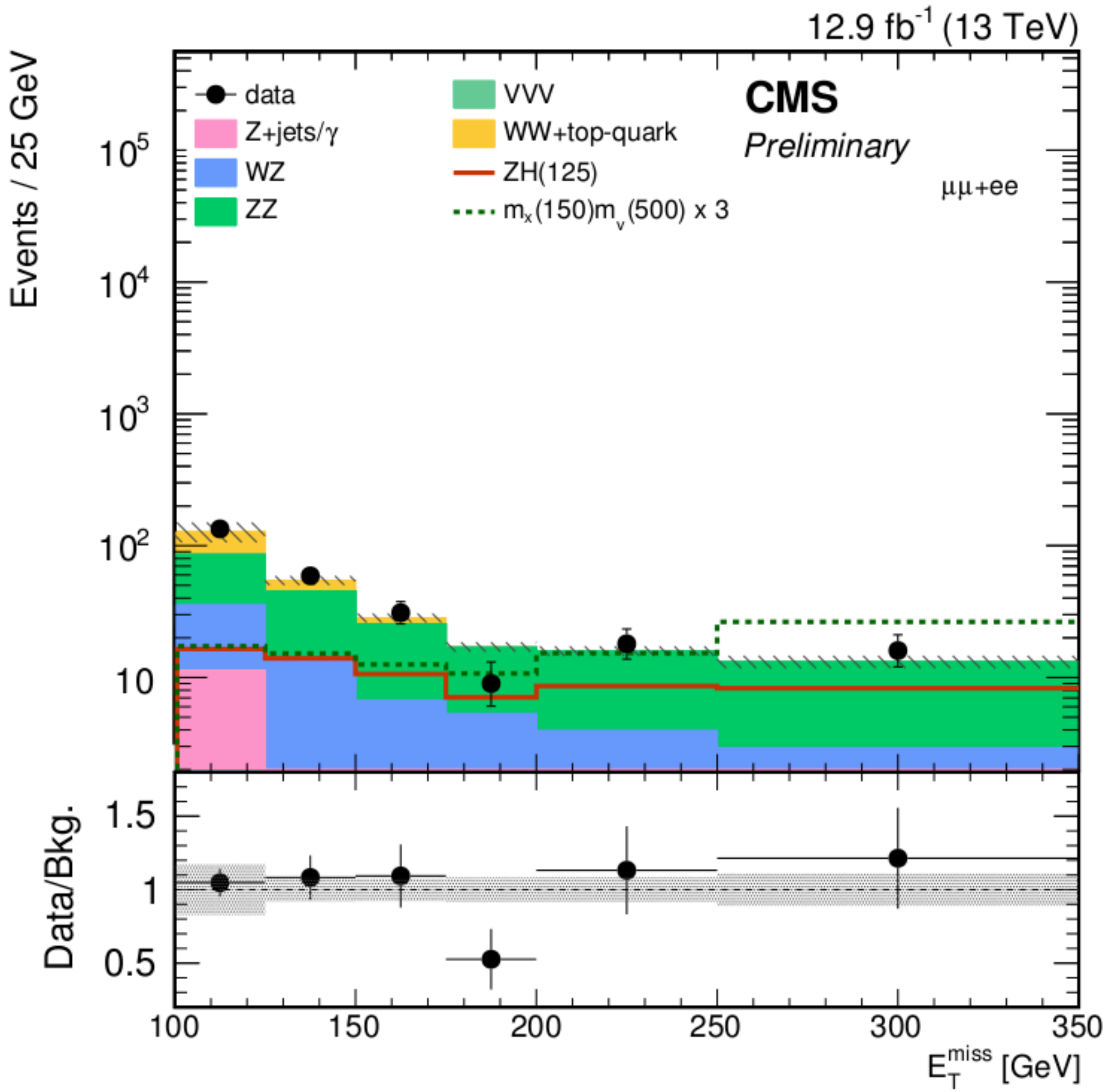
ATLAS-CONF-2016-056
CMS-PAS-EXO-16-038

- Backgrounds:
  - Z/γ*+jets: fake MET from instrumental effects (data-driven from 1D/2D sideband)
  - WW, Top, Z→ τ+τ-: non-resonant in m($\ell\ell$) at Z mass region (MC/data-driven using the eμ events)
  - WZ →3ℓν: similar to ZZ when one lepton is not detected (MC/data-driven from 3-lepton control)
  - ZZ→2ℓ2ν: irreducible, dominant (after selection), estimated from MC simulation
  - W+jets/QCD: fake leptons from jets (small background) (data-driven, fake rate measurement)

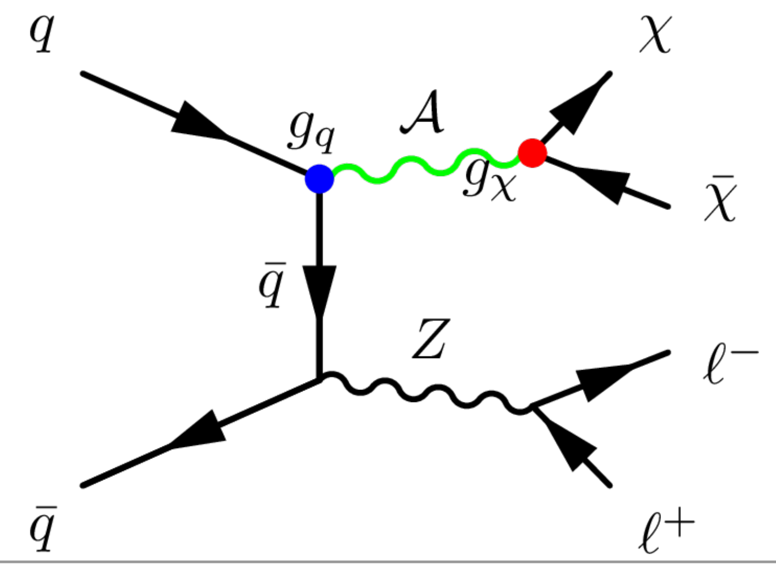






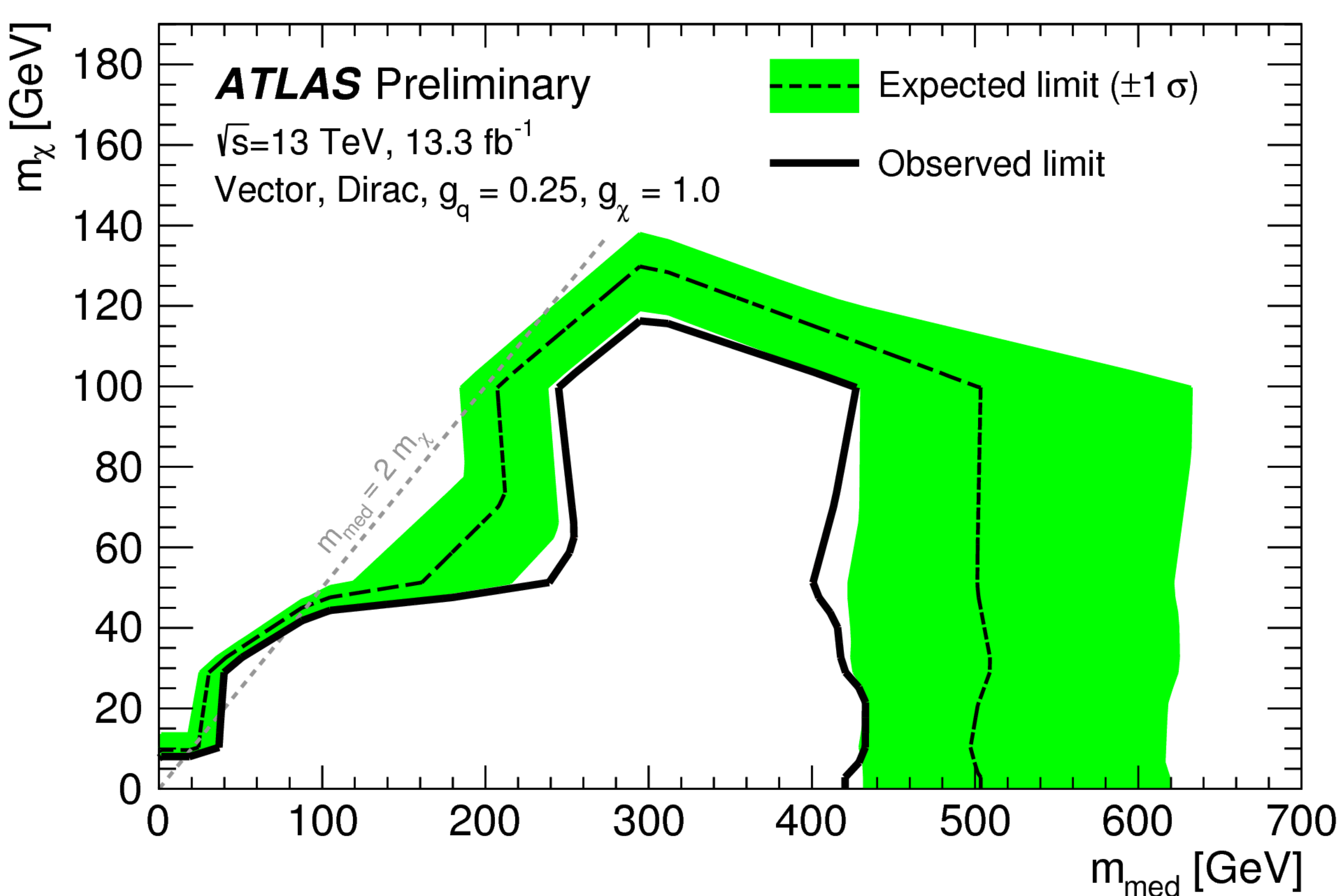


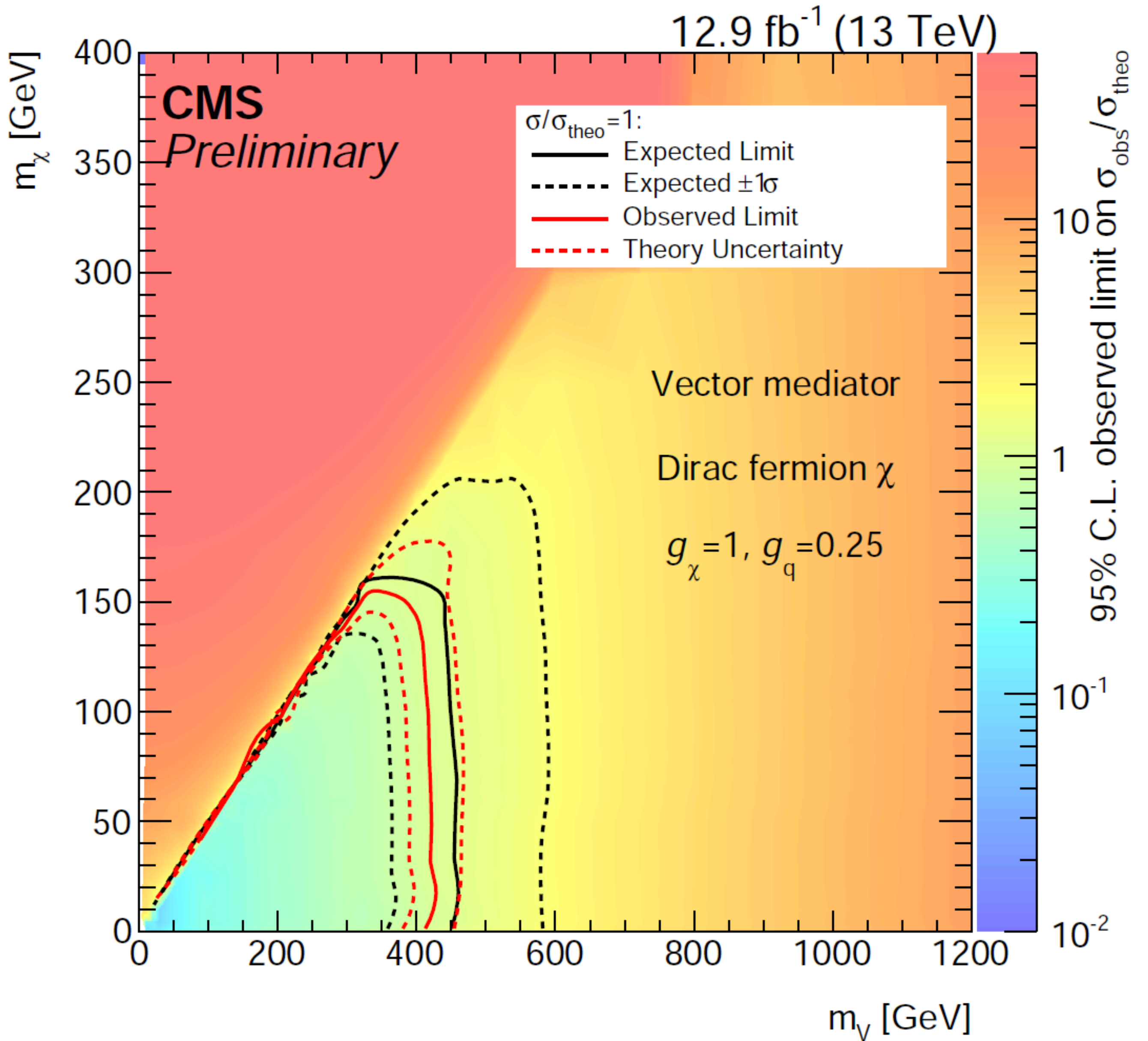
Mono-Z($\ell^+\ell^-$)

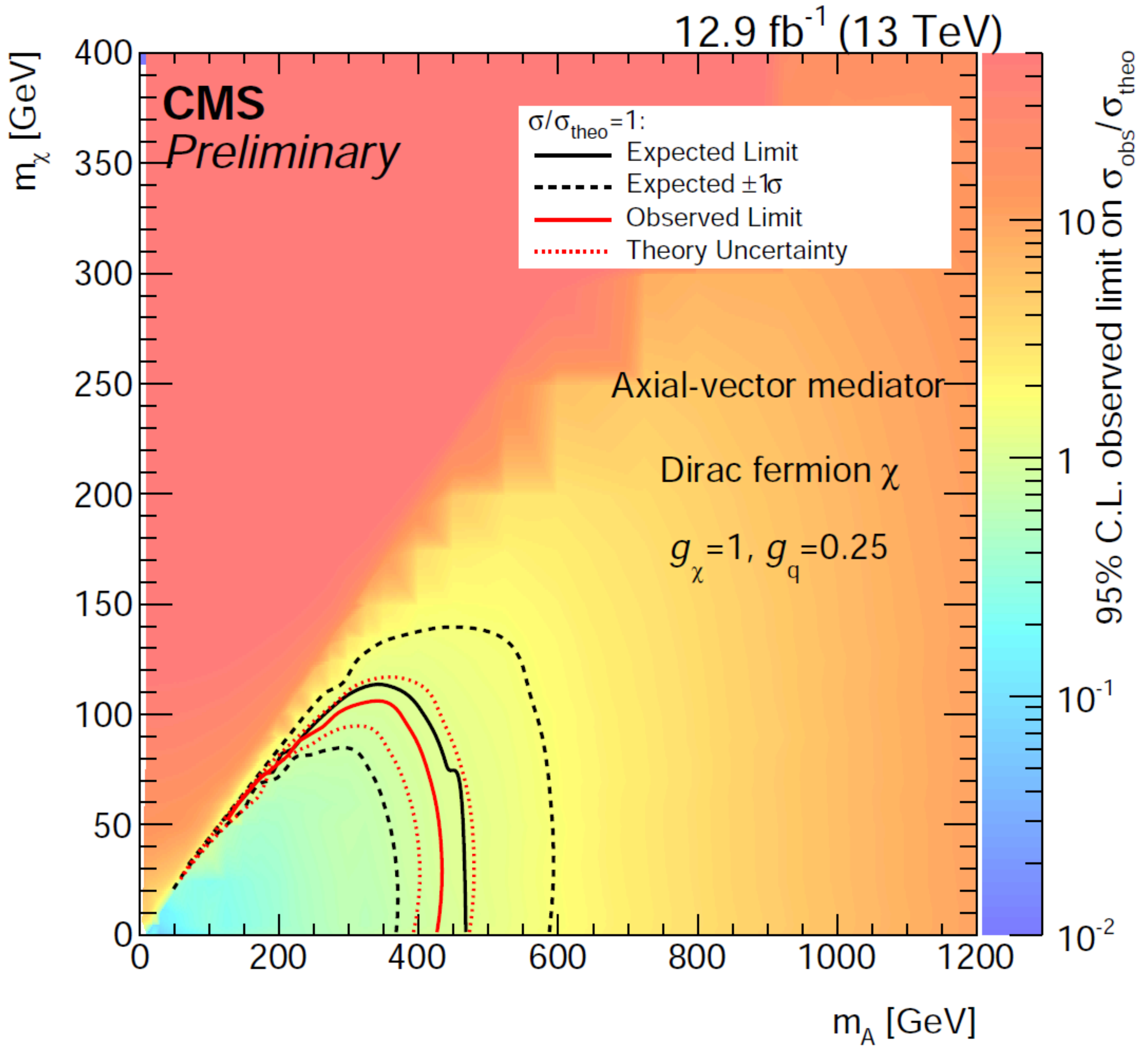


ATLAS-CONF-2016-056
CMS-PAS-EXO-16-038

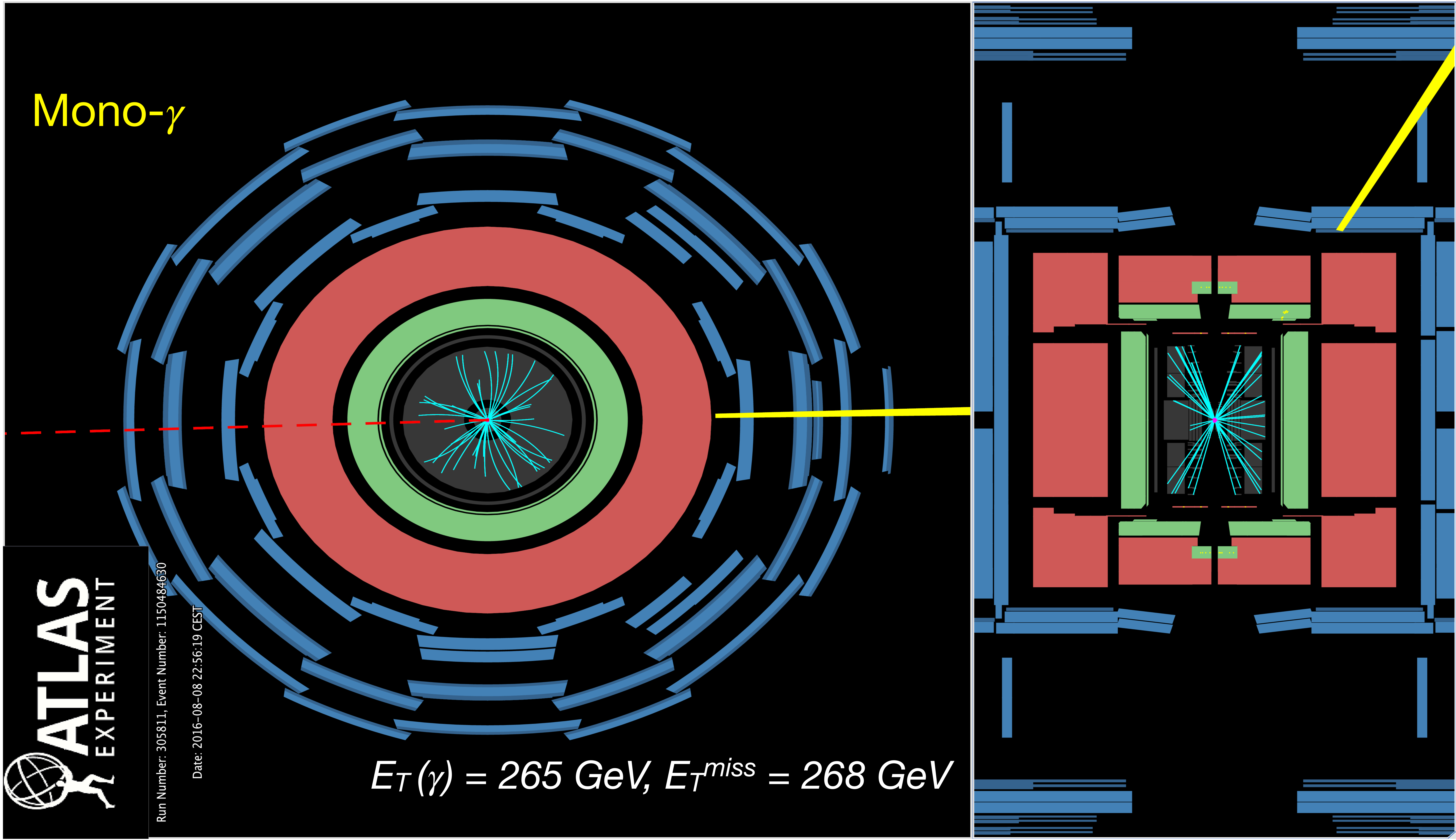
- Main systematic errors: data-driven Z+jets from 1D/2D sideband, ZZ theoretical uncertainties
- Good agreement with SM predictions, no significant excess is observed
- 2D limit interpretation in terms of simplified models with vector/axial-vector mediators
  - For DM mass = 1 GeV, vector mediator mass < 420 (450) GeV are excluded at 95% CL for vector coupling





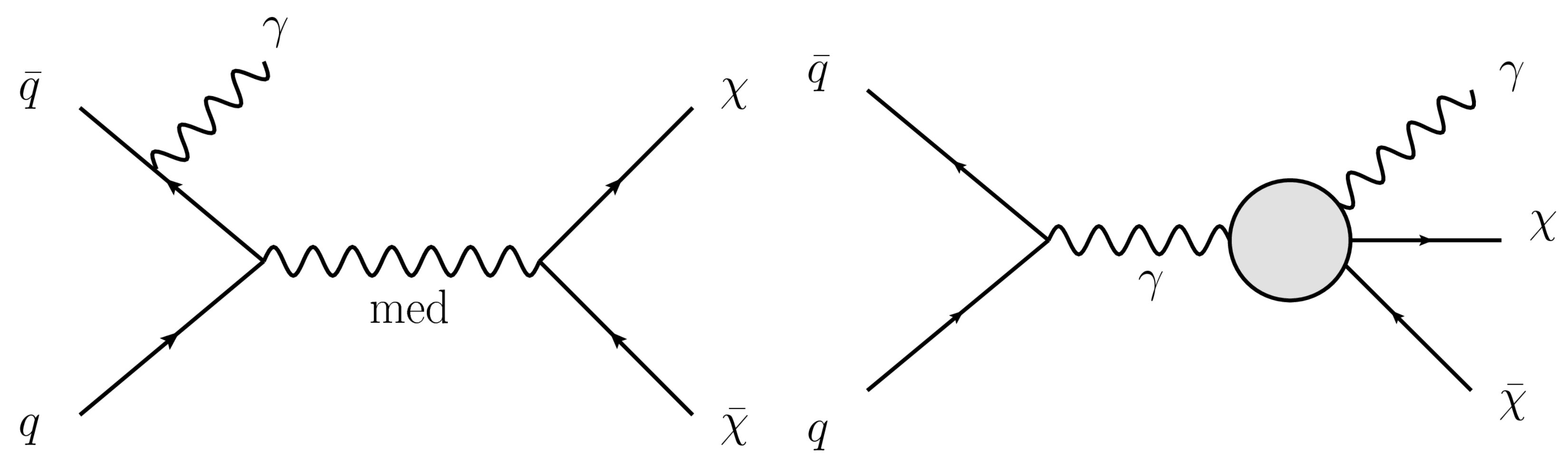


Mono-γ



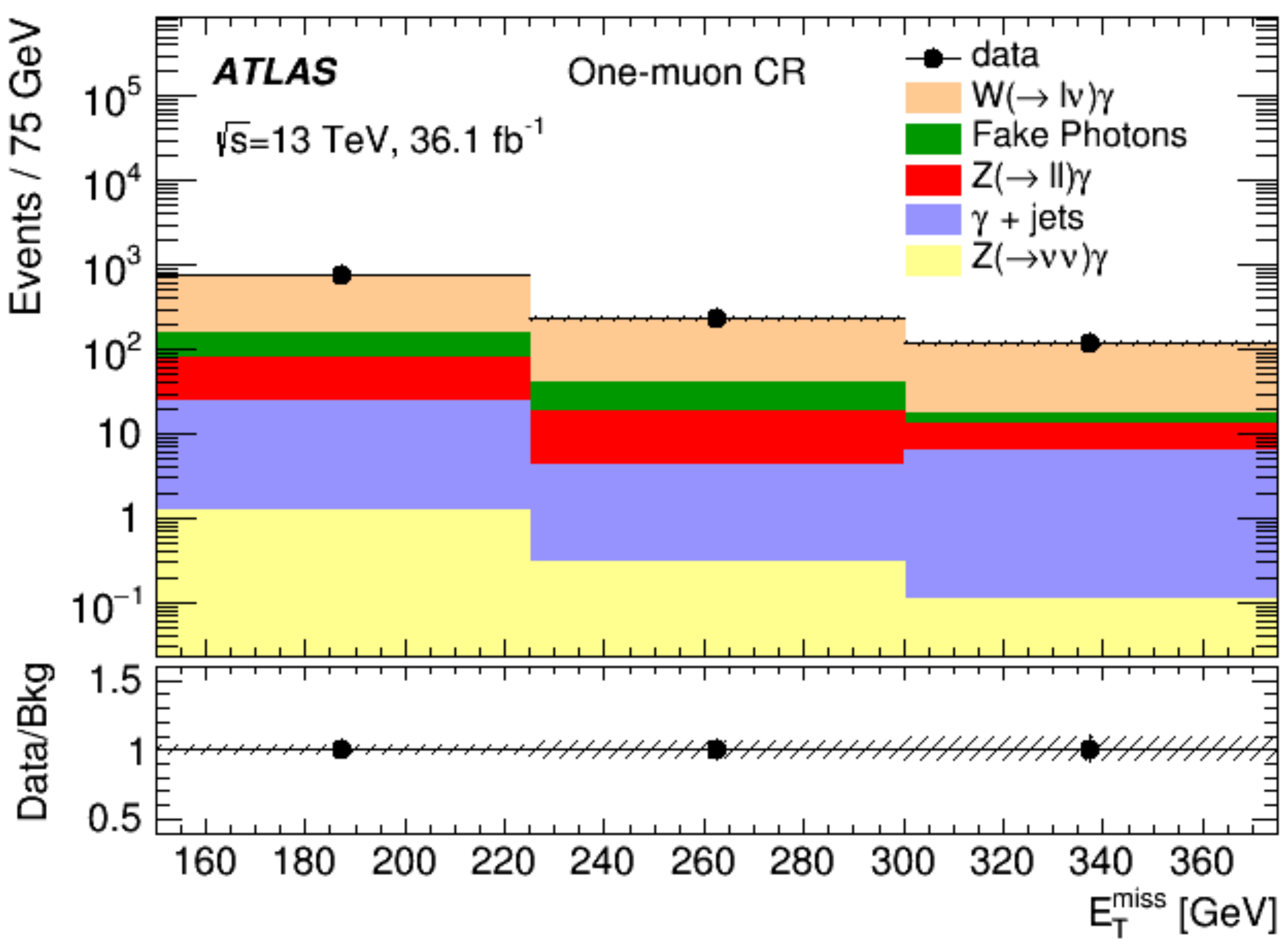
$E_T(\gamma) = 265$ GeV, $E_T^{miss} = 268$ GeV

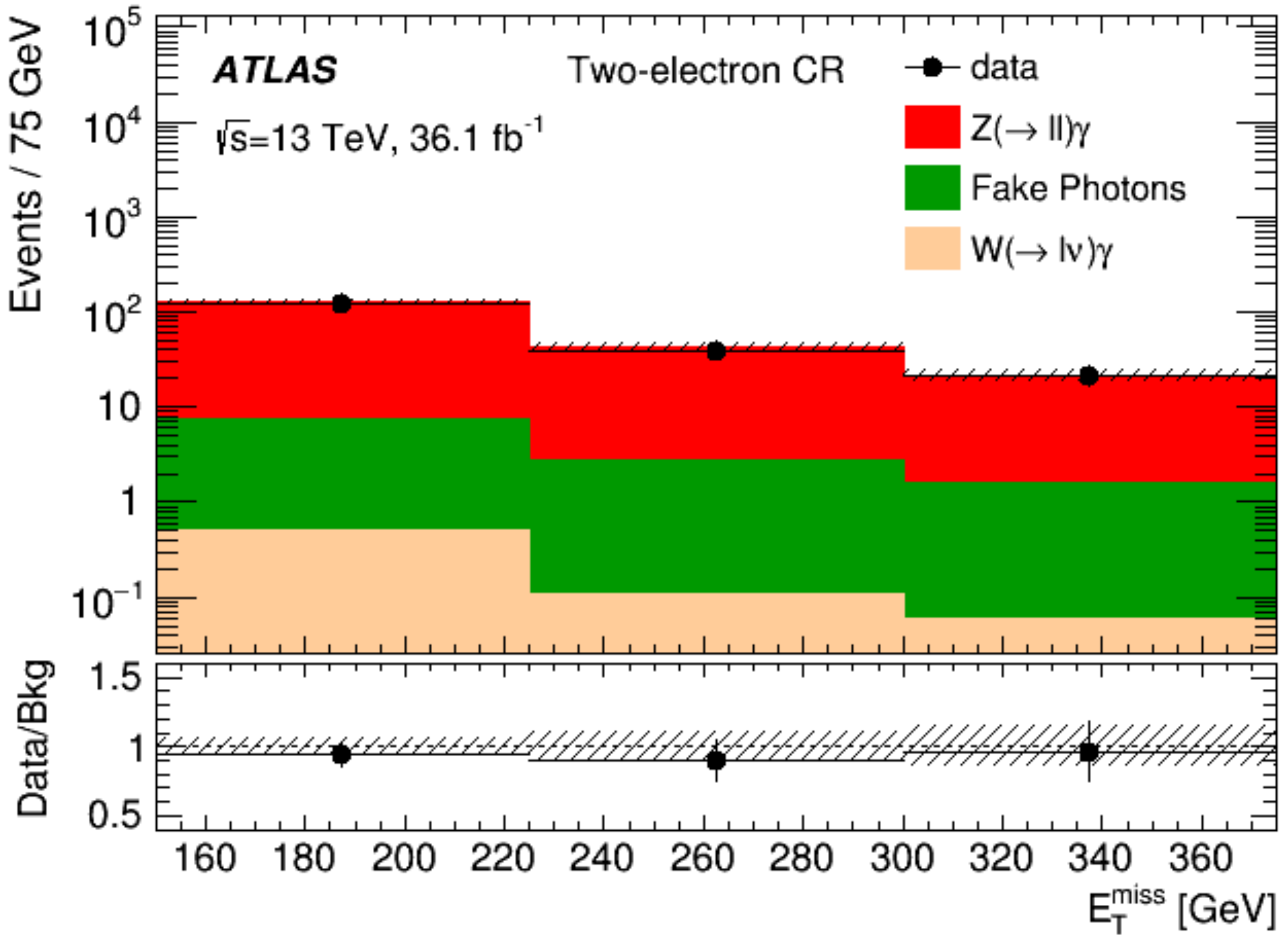
Mono-γ

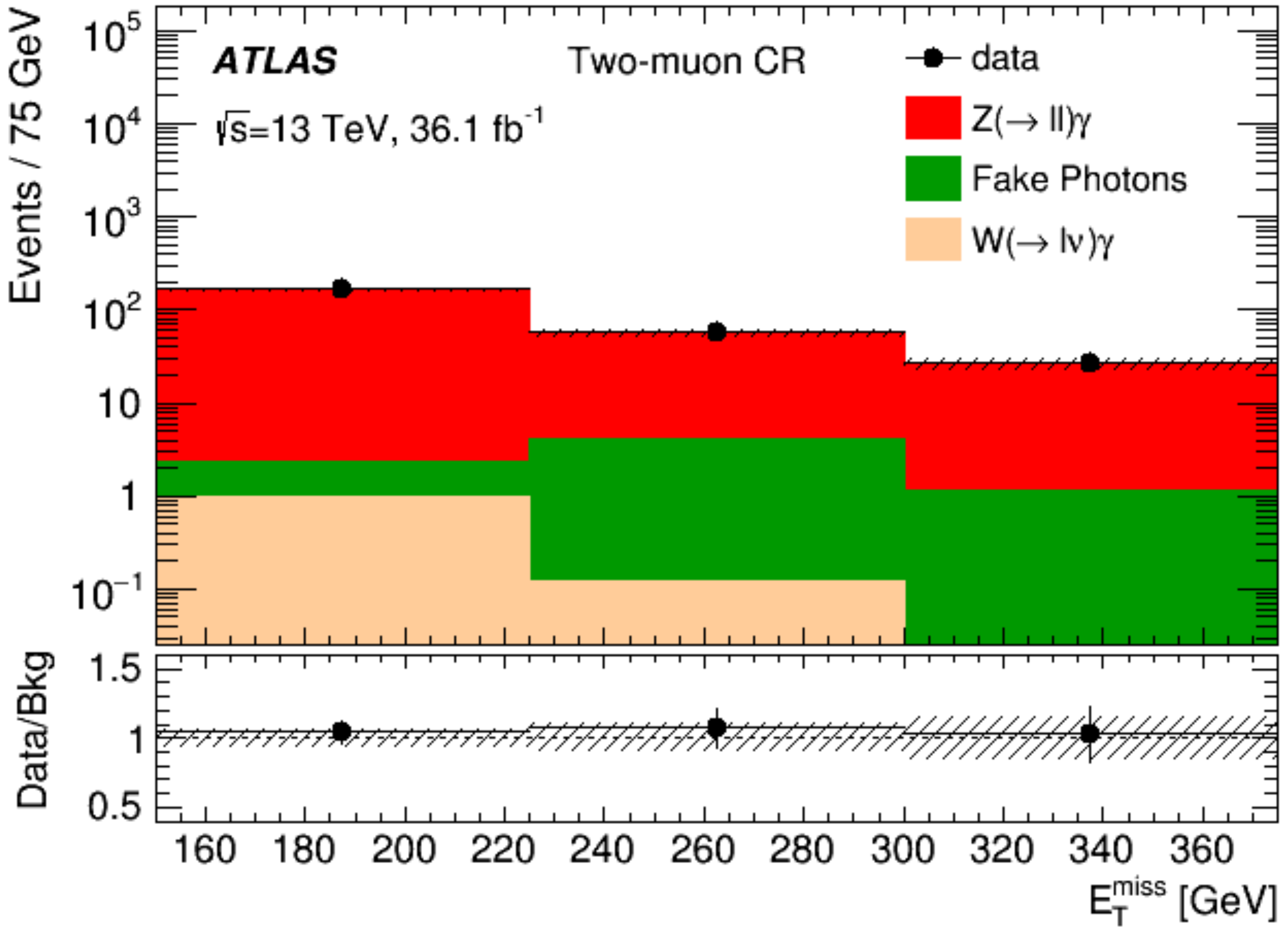


EXOT-2016-32
CMS-PAS-EXO-16-039

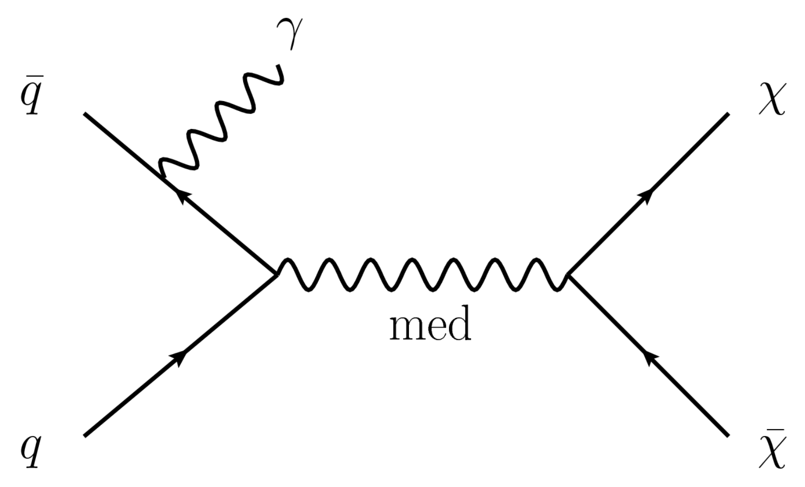
- A clean signature of high pT photon and large MET
- Event selection:
  - a well-identified photon with PT > 150 **(175)** GeV, and large MET> 150 **(170)** GeV in ATLAS **(CMS)**
  - good separation between photon and MET, jet and MET
  - lepton veto, at most one jet
- Similar with mono-W/Z(jj), three type of benchmark models are considered:
  - Two simplified model and a dimension-7 operator VVχχ

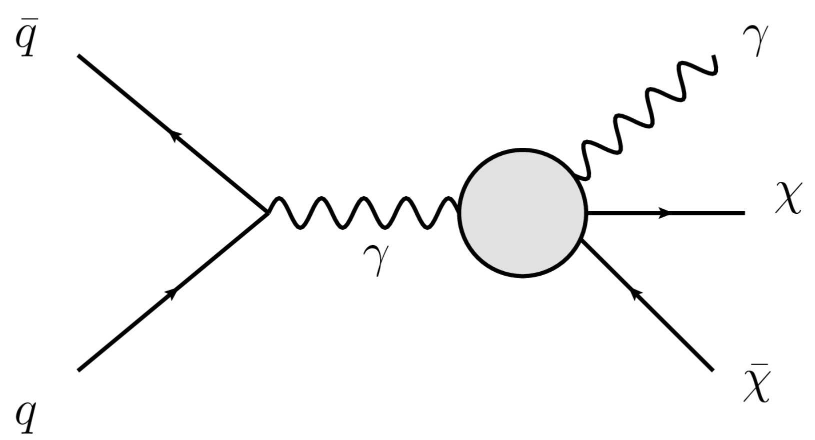






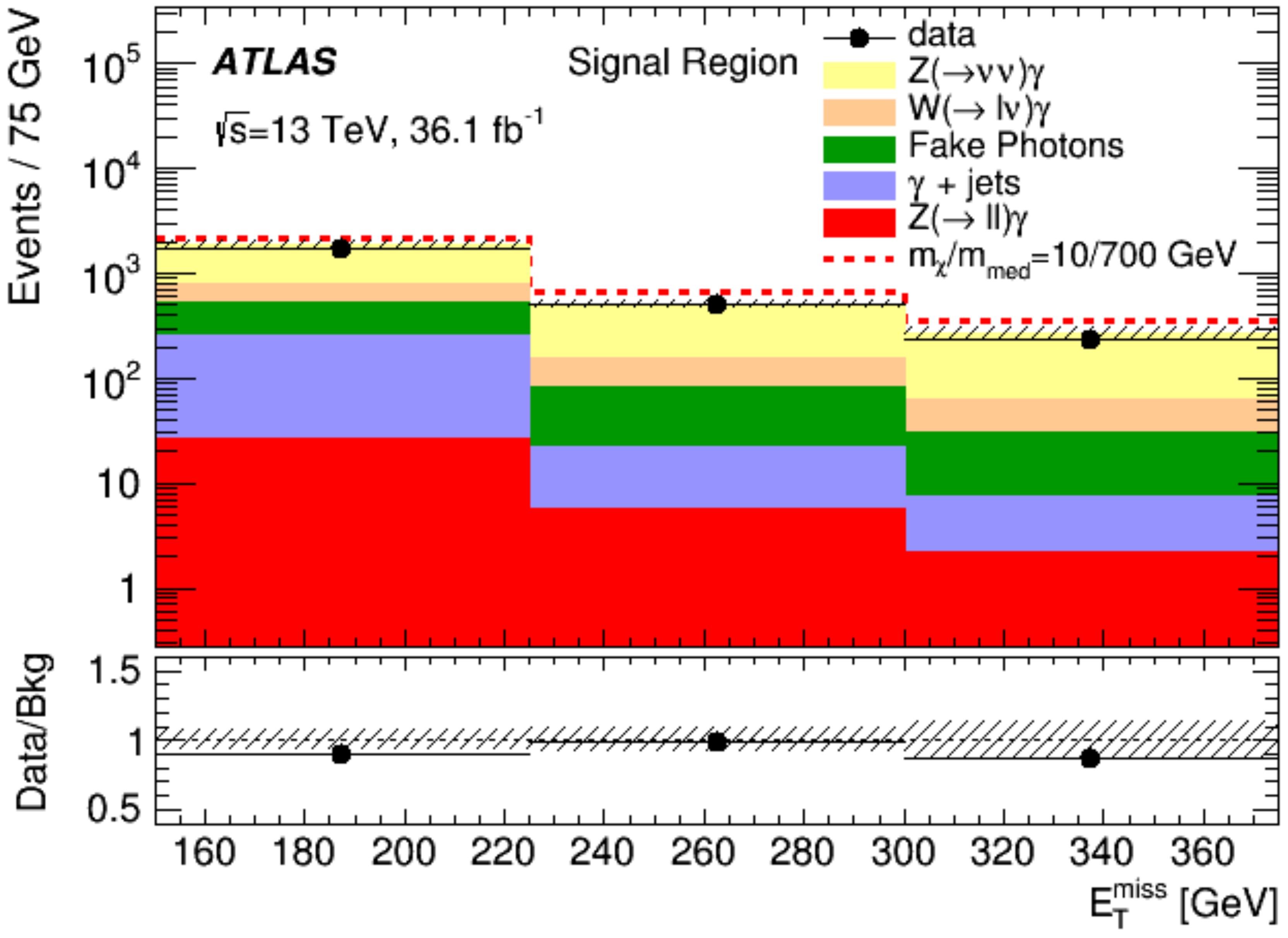
Mono-γ

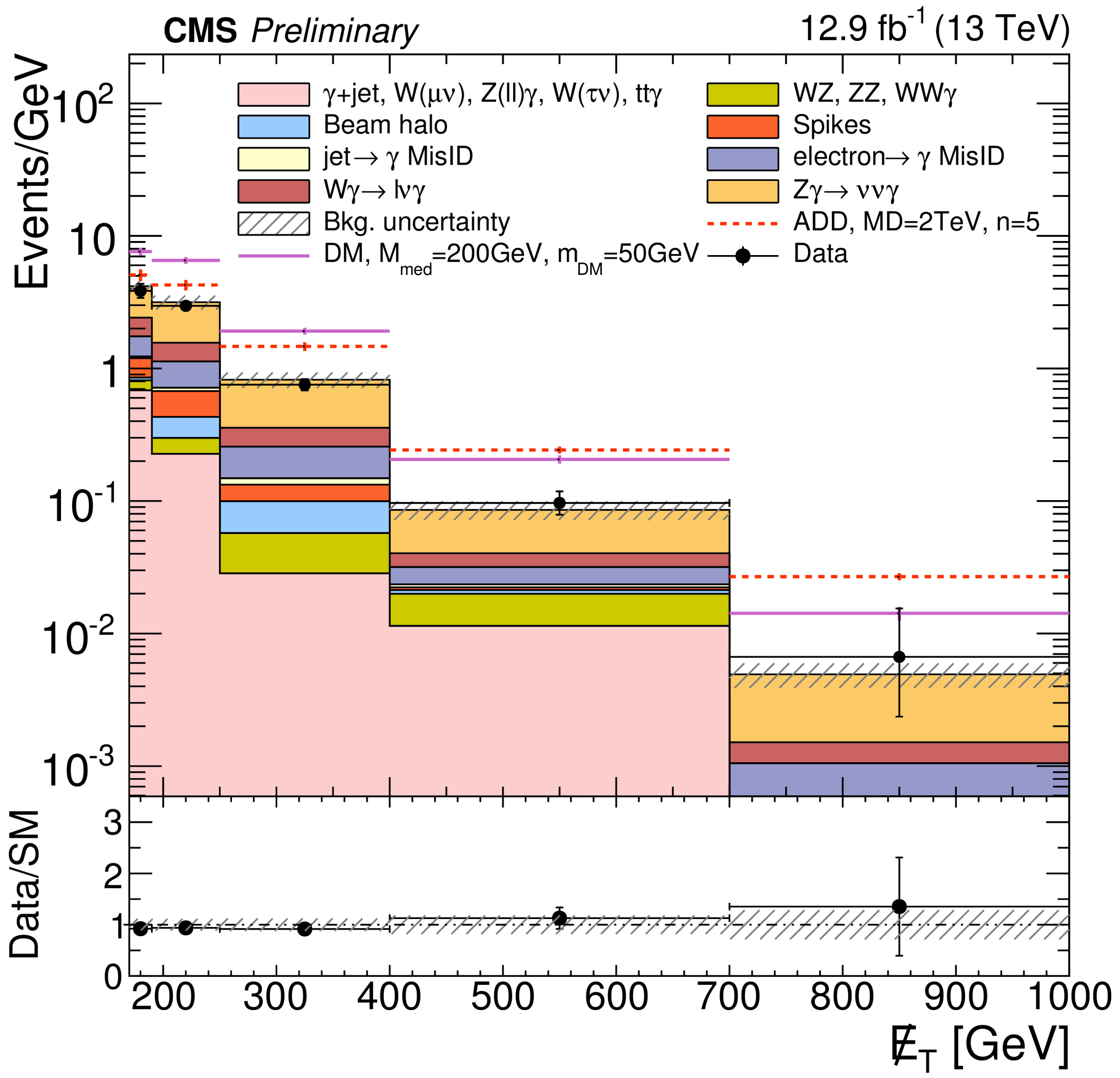


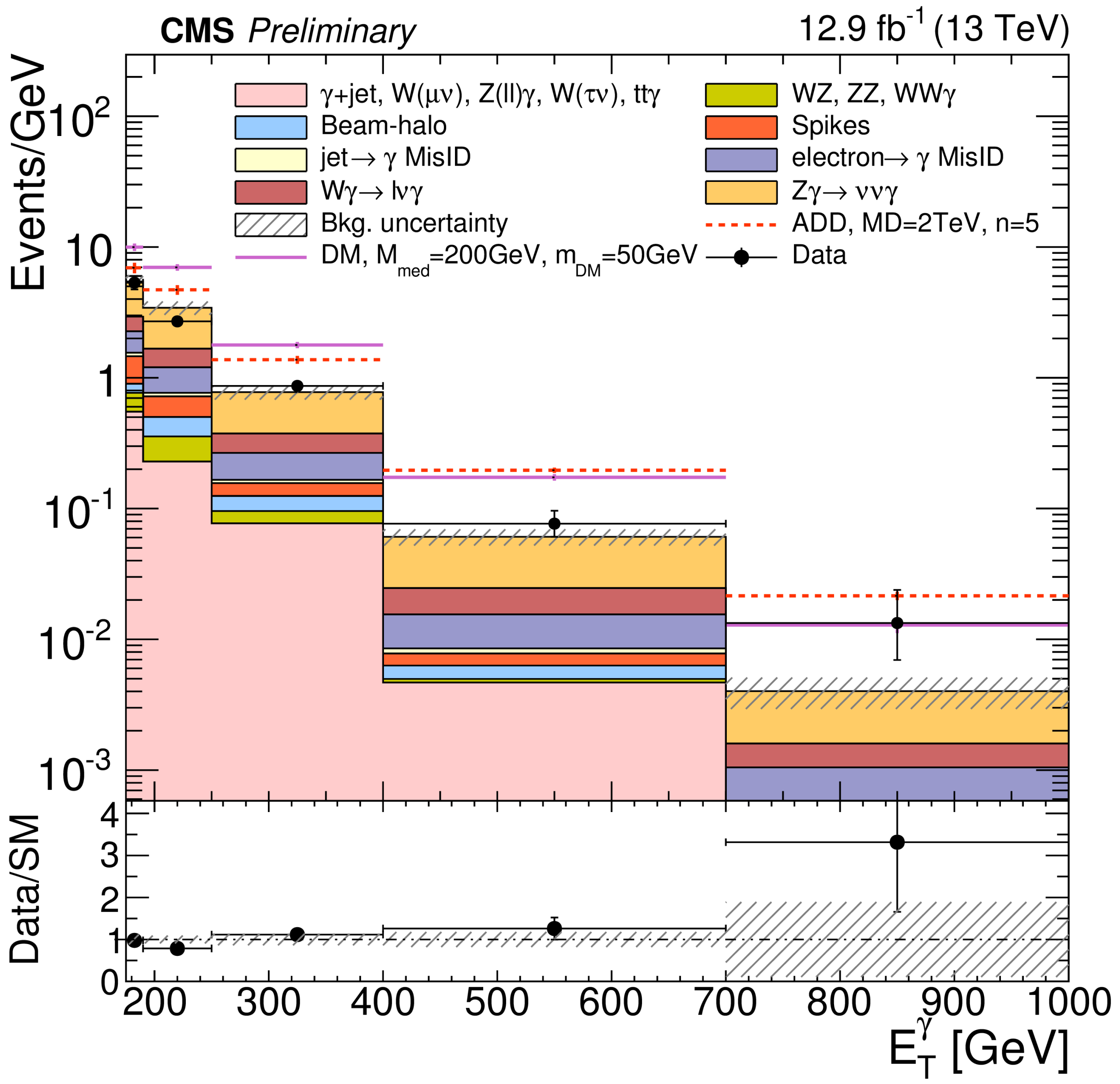


EXOT-2016-32
CMS-PAS-EXO-16-039

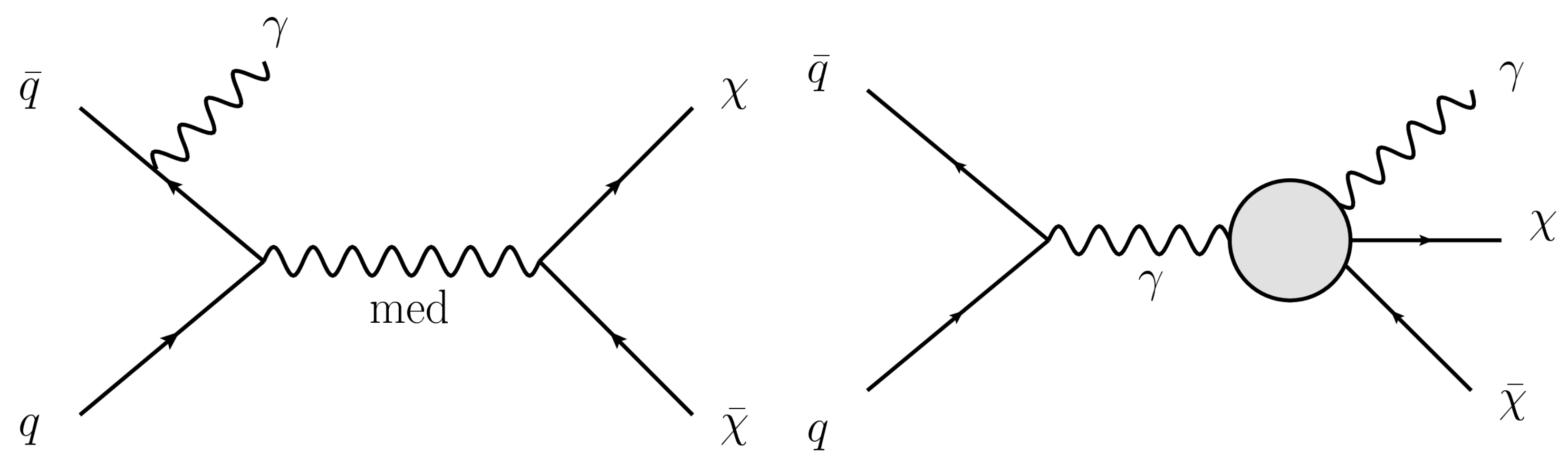
- Background contains real photon: $Z\gamma$, $W\gamma$, γjets
  - using simultaneous fitted Data/MC SF in different background-enriched CRs
- Background contains fake photon
  - fake photon from jets: ABCD with reversing/loosing ISO/ID
  - fake photon from electrons: measure P(e ->γ) in using Z peak





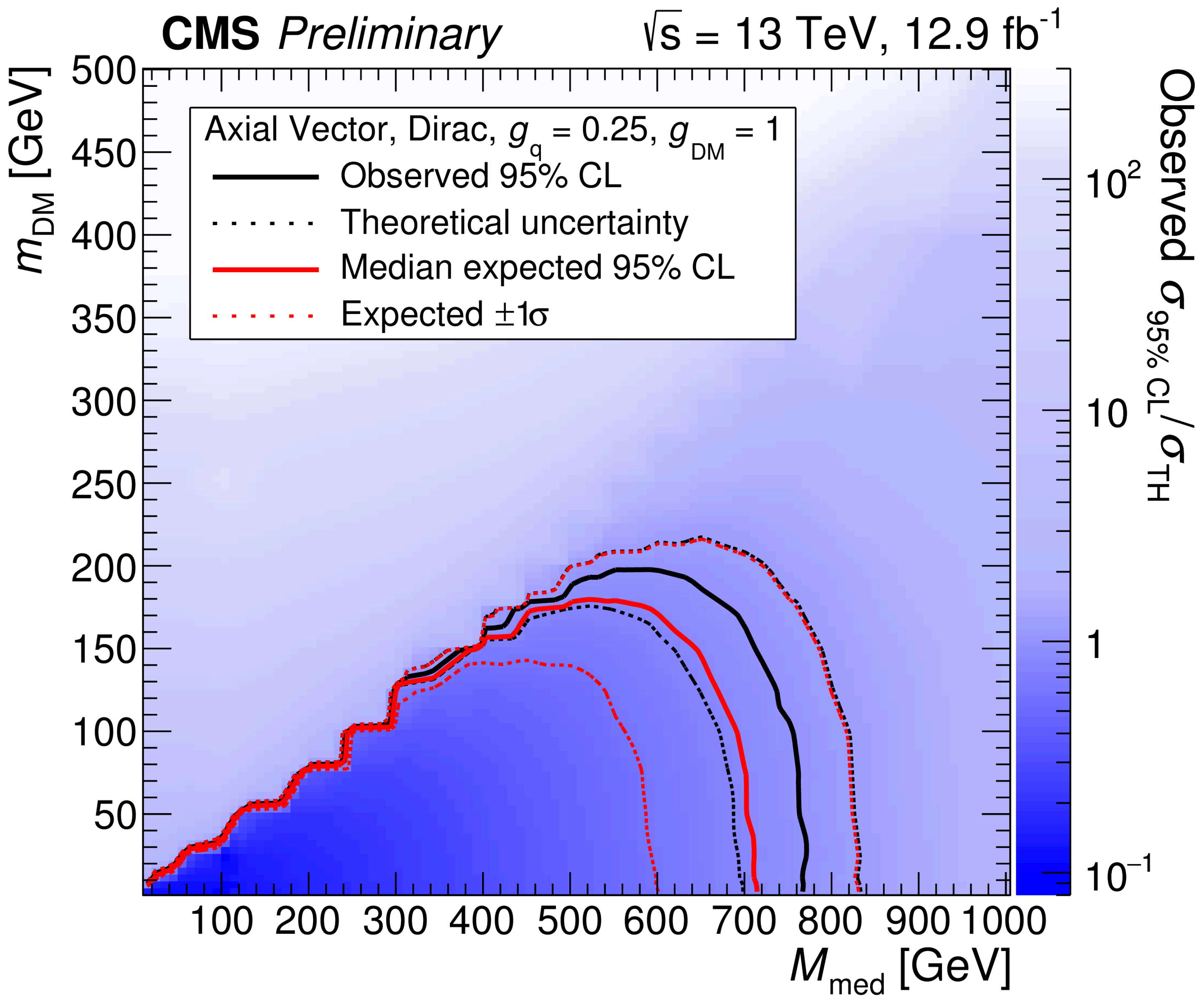


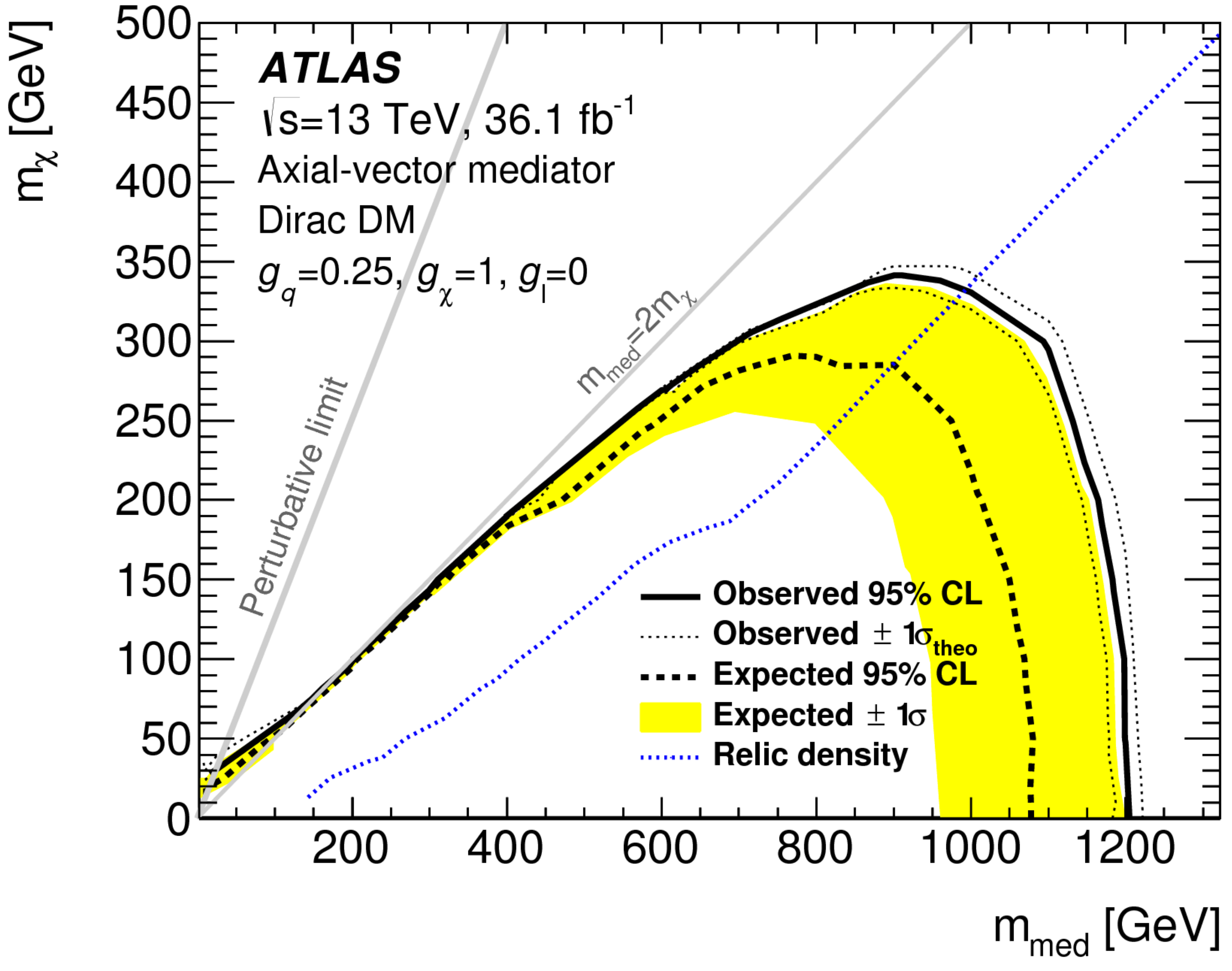
Mono-γ

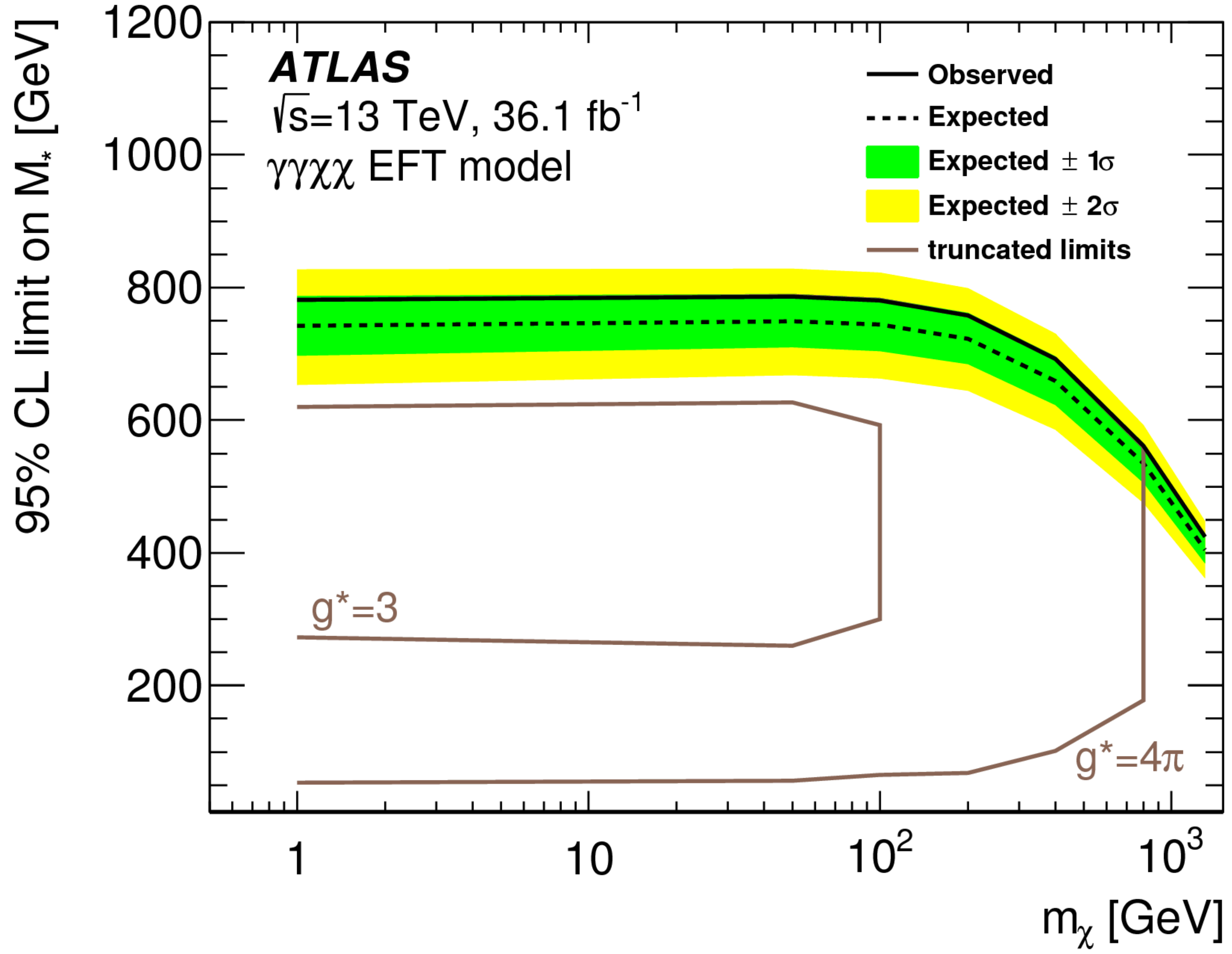


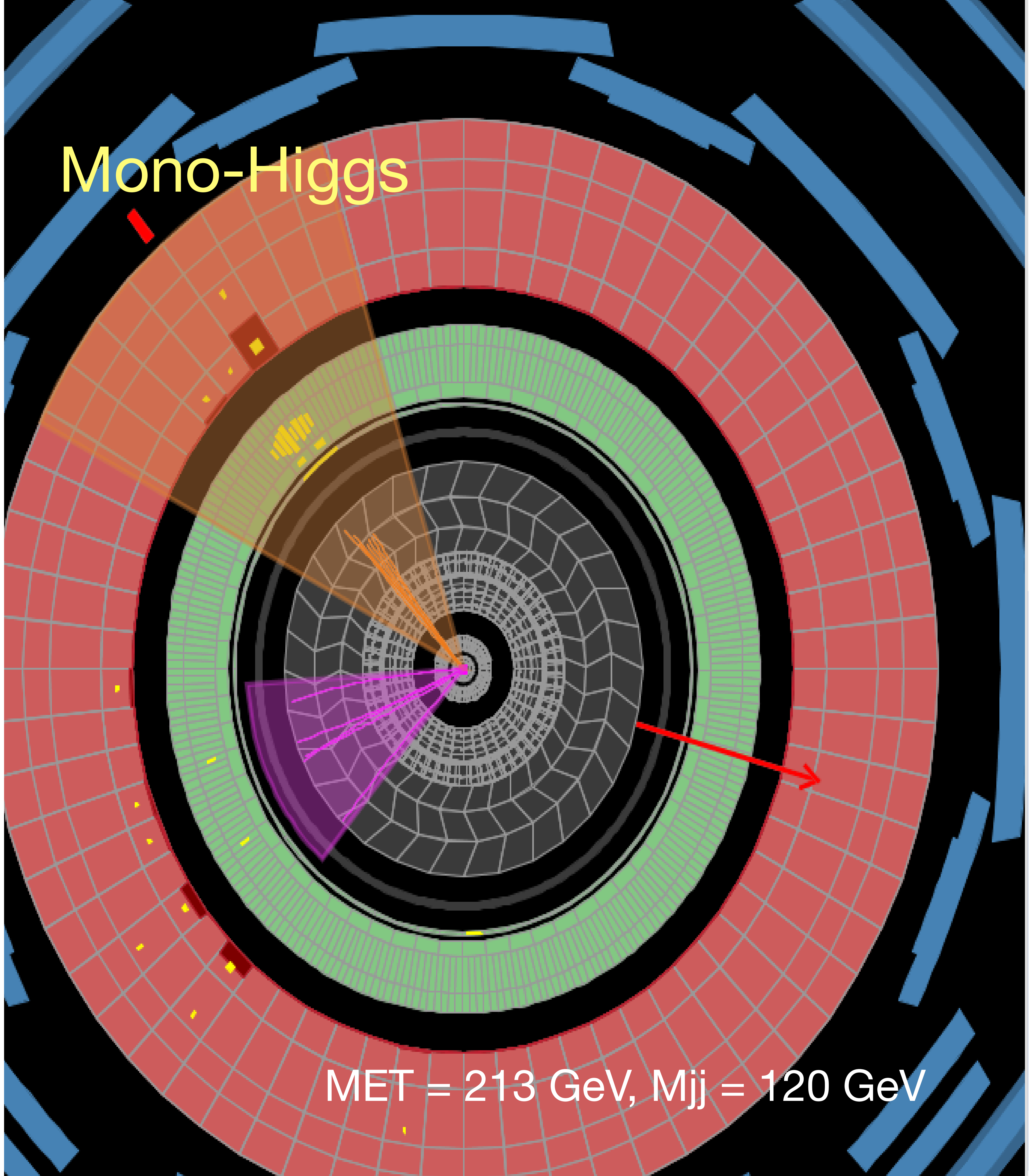
EXOT-2016-32
CMS-PAS-EXO-16-039

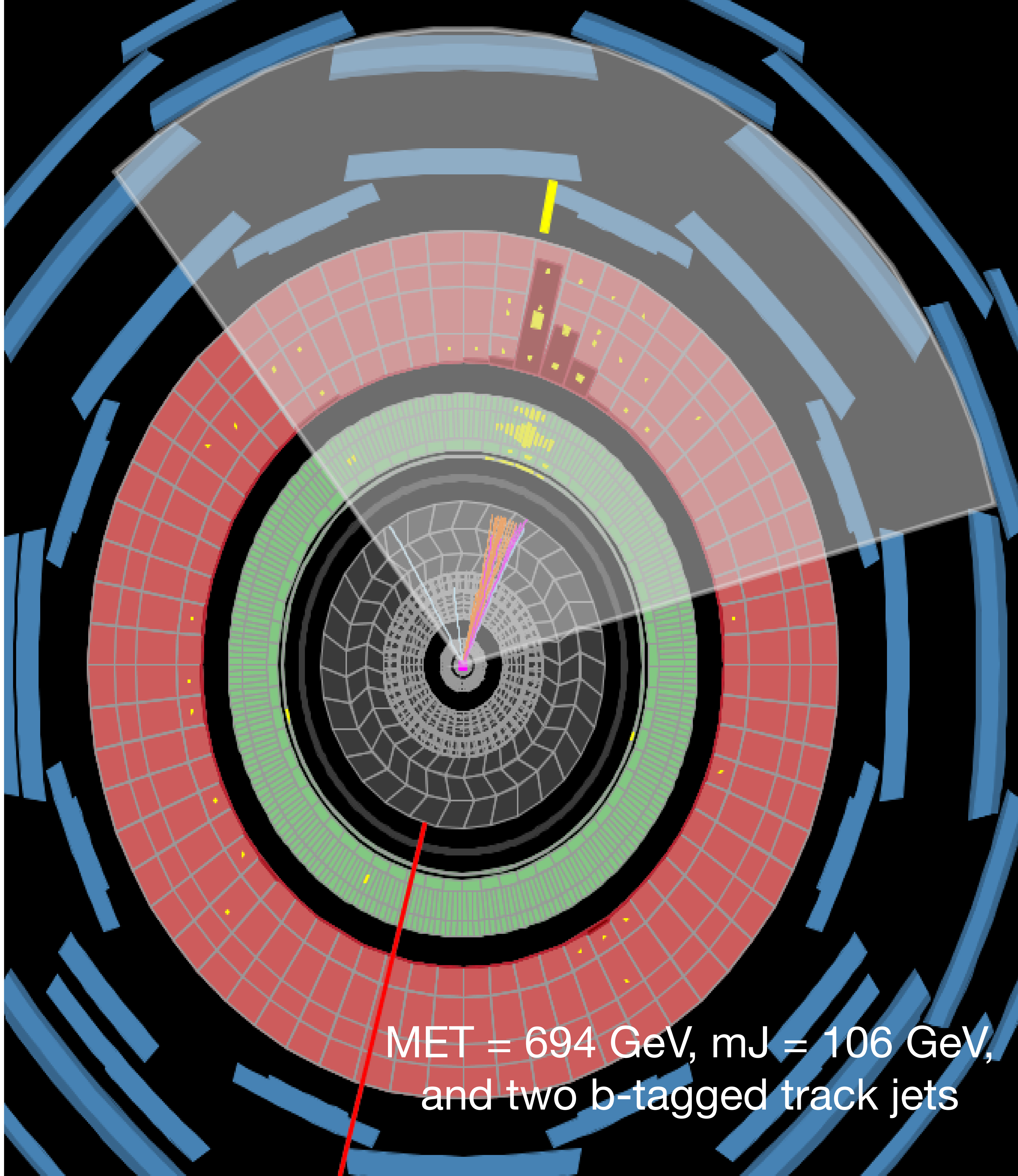
- Results is translated in terms of simplified models with (axial) vector and (pseudo) scalar mediators
  - Exclusion: vector mediator mass < 1.2 TeV @95%CL (ATLAS, 36 fb-1), < 0.75 TeV (CMS, 13 fb-1)
- Upper limits are set on cutoff scale for dimension-7 operator with a contact interaction as a function of DM mass
  - cutoff scale < 800 GeV is excluded at 95%CL (36 fb-1) for DM mass1 GeV
  - EFT invalid regions for different couplings 3, and 4pi



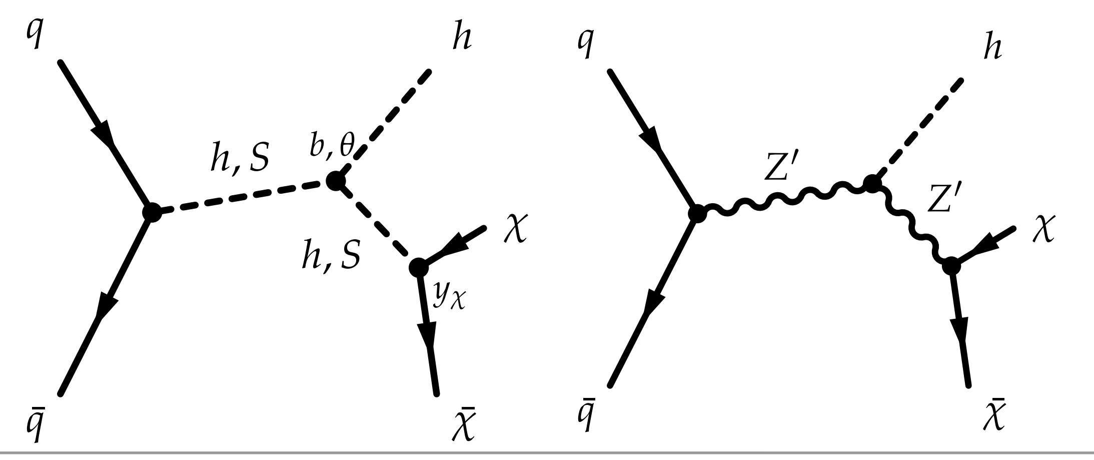




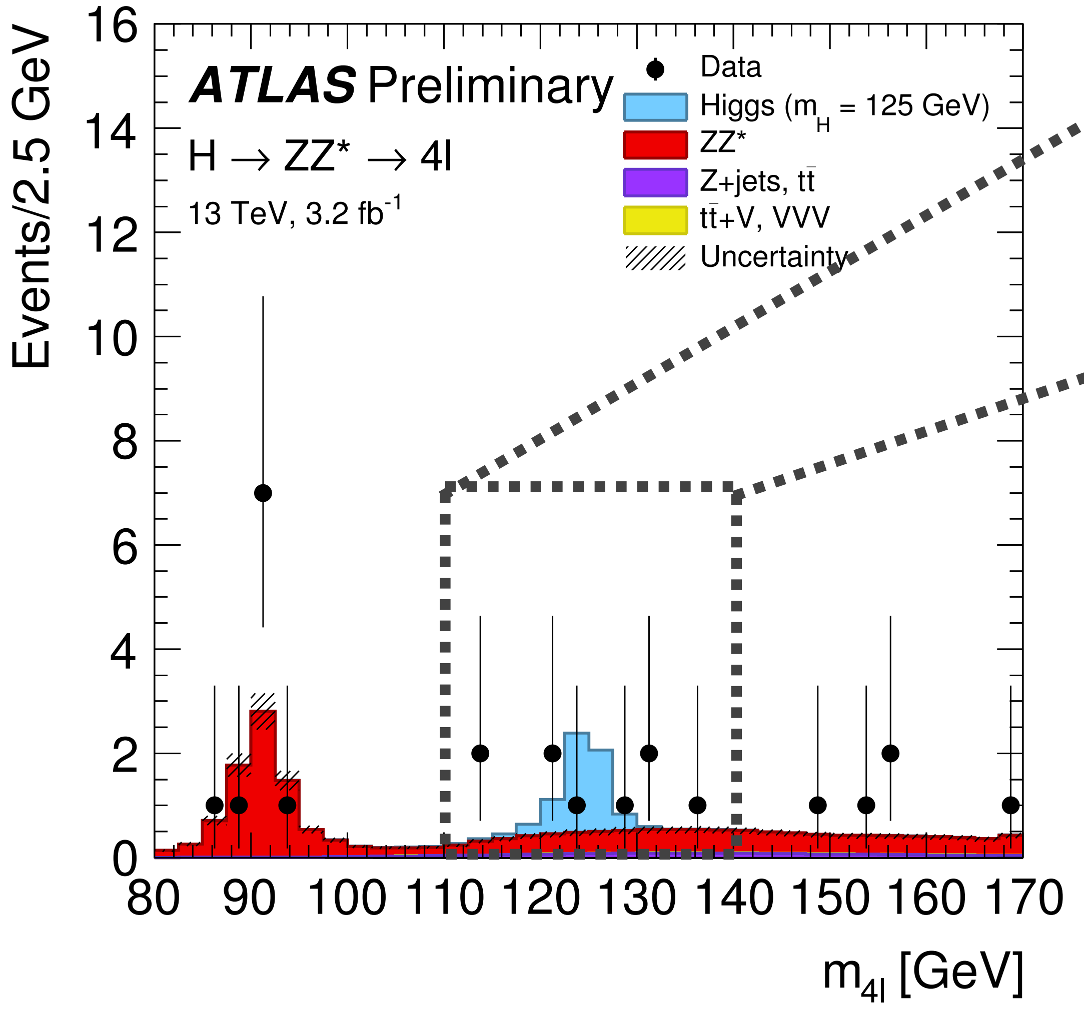

Mono-Higgs
MET = 213 GeV, Mjj = 120 GeV

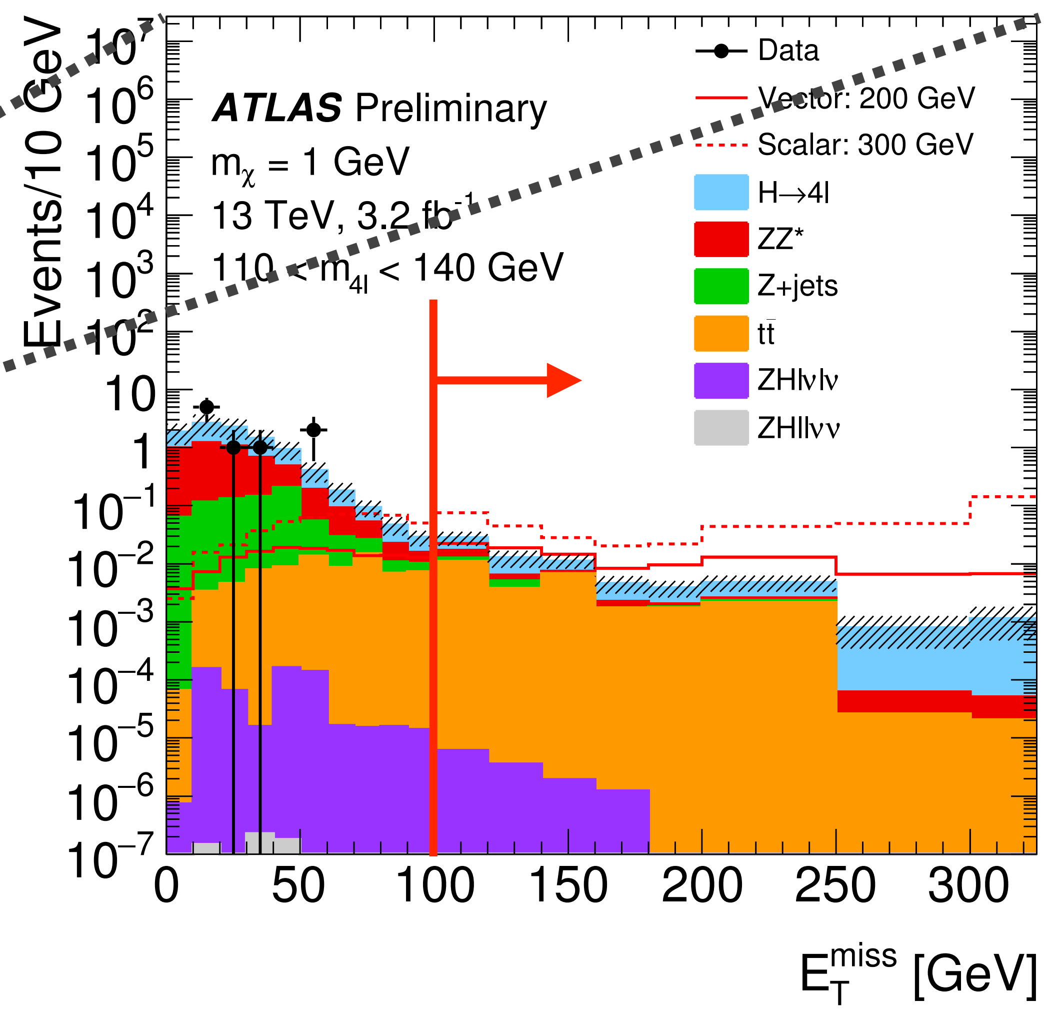

MET = 694 GeV, mJ = 106 GeV,
and two b-tagged track jets

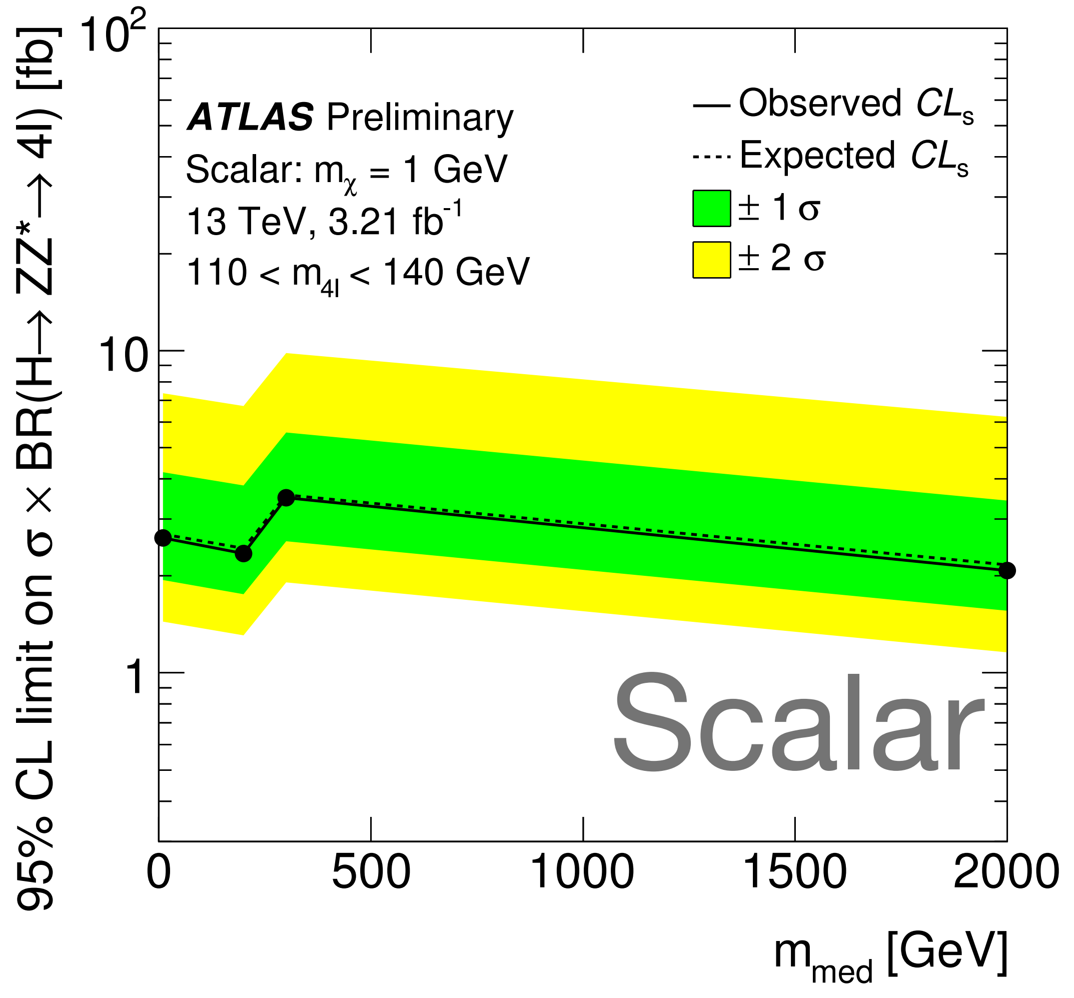
Mono-Higgs(→ZZ*→4ℓ)

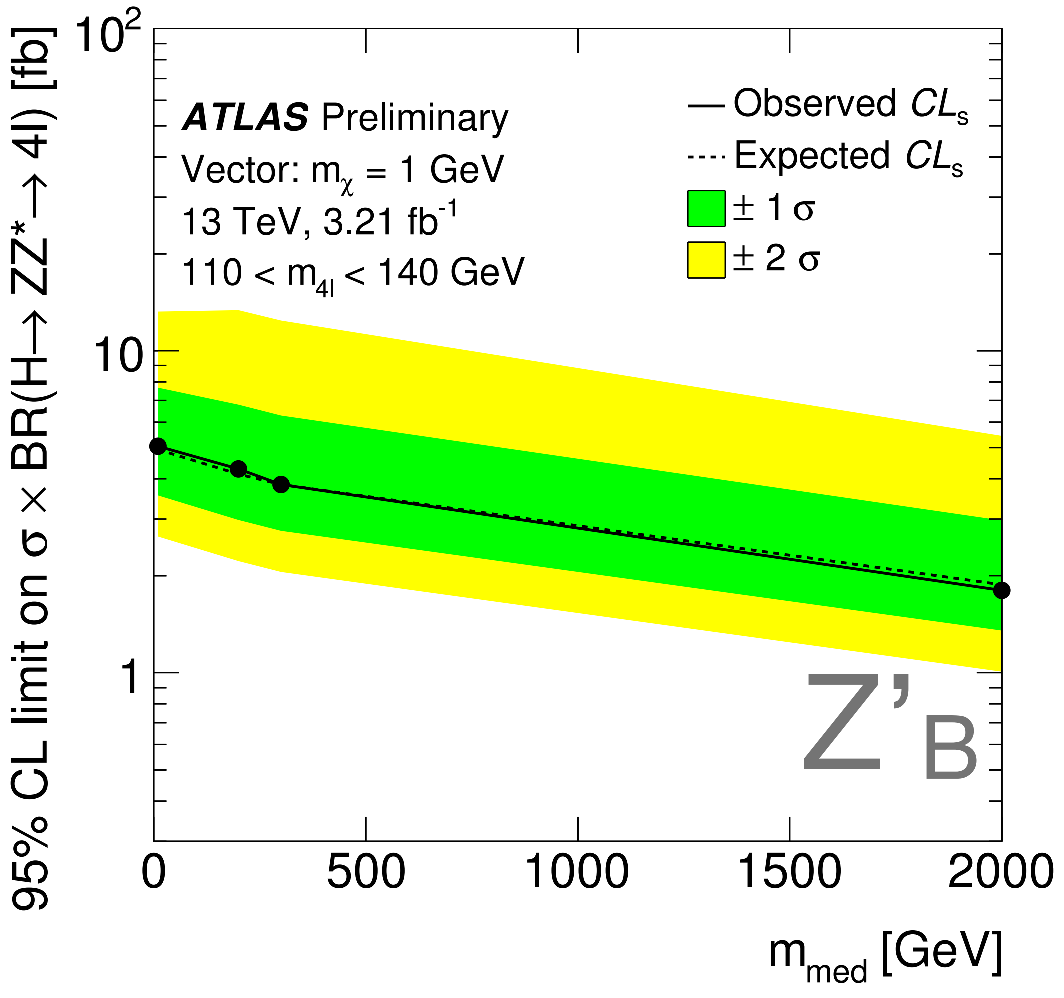


ATLAS-CONF-2015-059



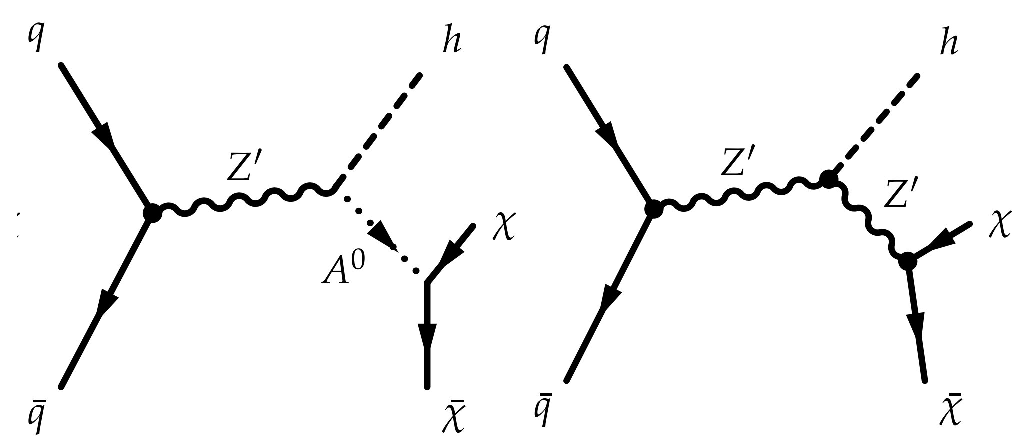






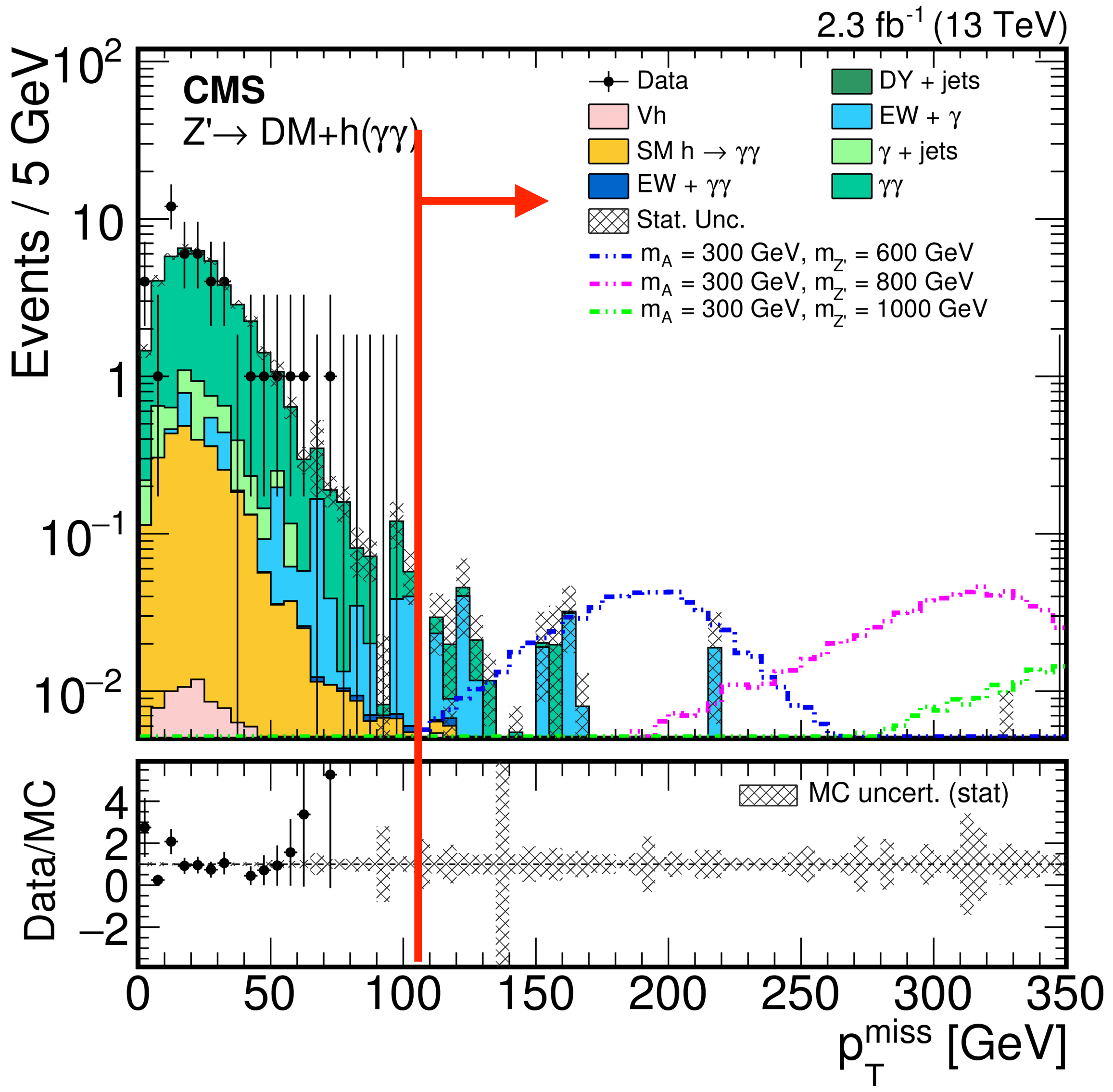
- H→ZZ*→4ℓ has low BR, but this channel is very clean
- Multi-leptons triggers (Efficiency > 99%)
- Event selection: at least four well-identified, isolated leptons, same flavor-opposite-charge lepton pair match to Z mass
- Background:
  - ZZ* (irreducible): from simulation with NNLO@QCD, NLO@EWK correction
  - ttV/VVV: from simulation
  - Z+jets, ttbar: shape and normalization data-driven
- Signal region: $m_{4\ell}$ [110,140] GeV, MET>100 GeV
- No significant BSM excess is observed! Upper limit is set on the production cross section times BR as a function of mediator mass in both Scalar and Z'B scenarios, no exclusion yet @3.2 fb^{-1}

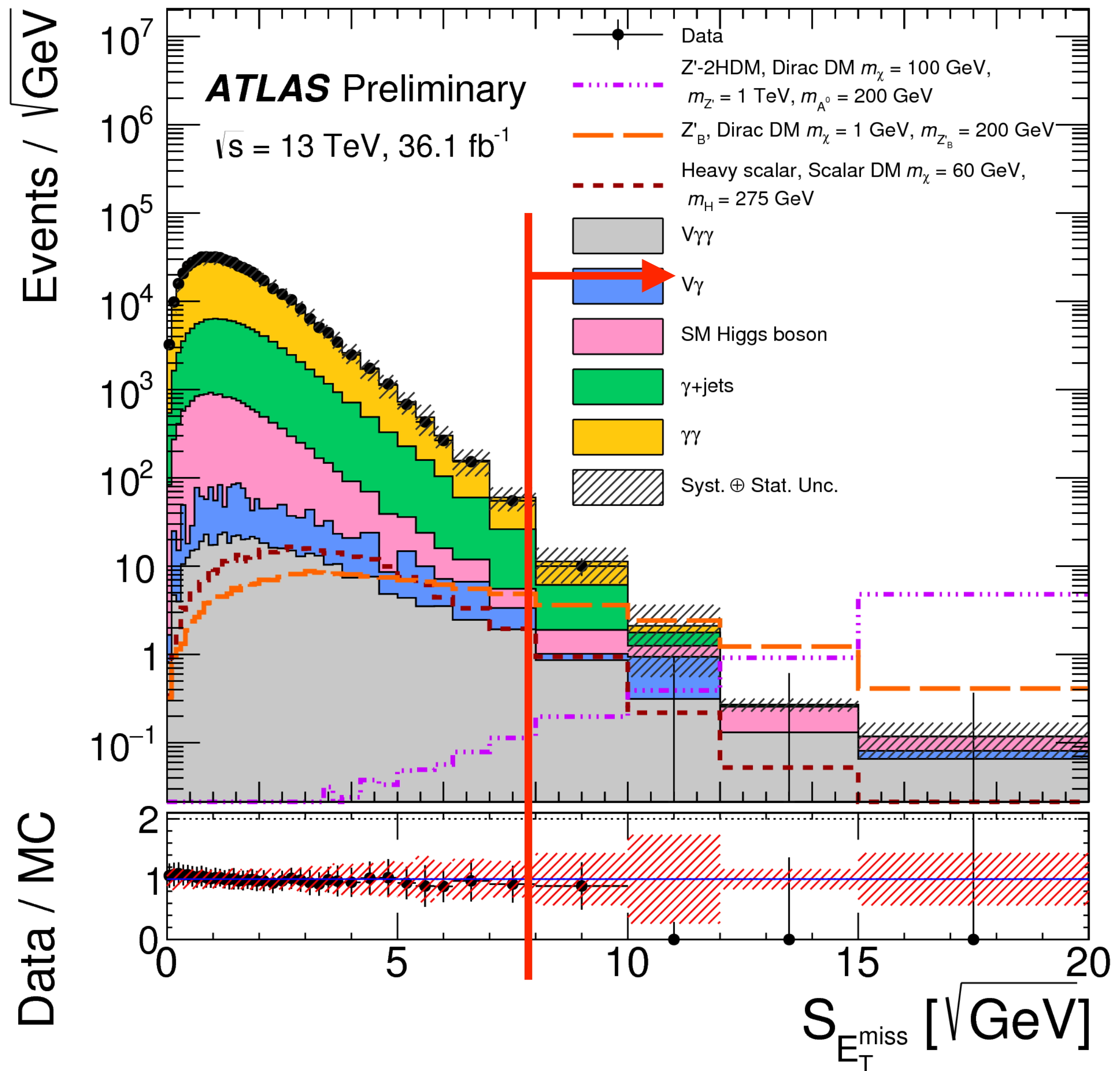
Mono-Higgs($\rightarrow\gamma\gamma$)



ATLAS-CONF-2017-024
CMS-EXO-16-012

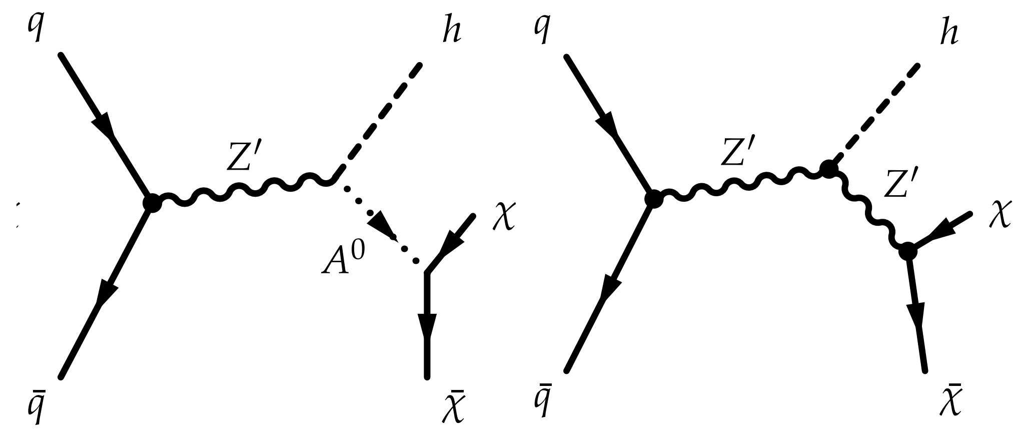
- Signature: two well-defined photons compatible with the 125 GeV Higgs boson plus MET
- MET is calculated w.r.t. the diphoton vertex including track-based soft term
- Non-resonant background
  - $\gamma\gamma$: dominant, need large MET Significance cut to reject
  - γ+jets: second dominant, similar to $\gamma\gamma$ when the jet is mis-identified as a photon
  - Vγ, V$\gamma\gamma$: visible contribution at after MET Significance / MET cut, where a lepton is misidentified a photon or not well-reconstructed (induce fake MET)
- Resonant background: SM Higgs, ZH is irreducible





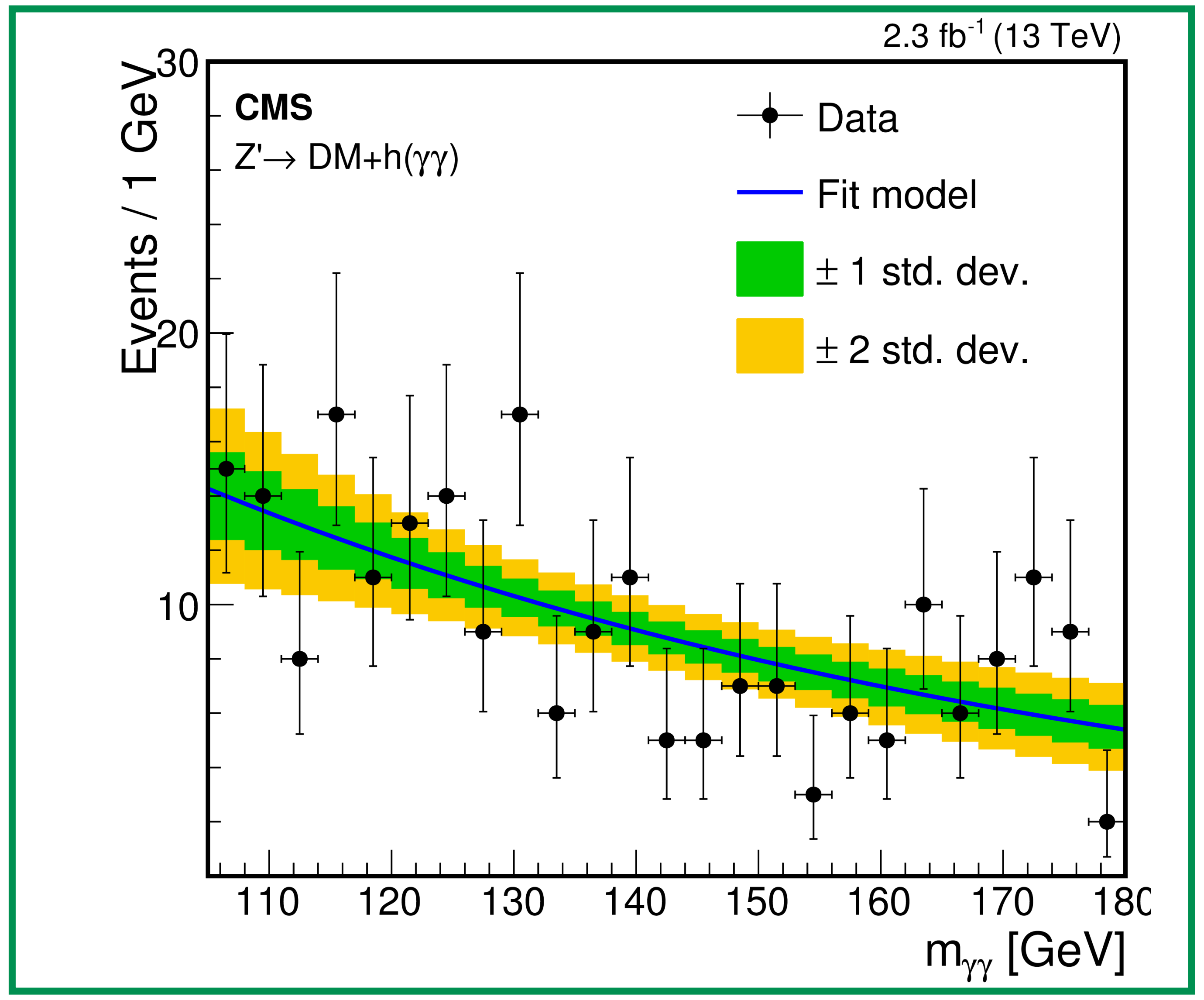
ATLAS	CMS
$p_T^{\gamma\gamma}$ >25,25 GeV	$p_T^{\gamma\gamma}$ > 30,20 GeV
$E^{\gamma 1}_T/m_{\gamma\gamma} > 0.35$ $E^{\gamma 2}_T/m_{\gamma\gamma} > 0.25$	$E^{\gamma 1}_T/m_{\gamma\gamma} > 0.5$ $E^{\gamma 2}_T/m_{\gamma\gamma} > 0.25$
$p_T^{\gamma\gamma}$ > 90 GeV, **MET significance > 7**	$P_T^{\gamma\gamma}$ > 90 GeV, **MET> 105 GeV**
$m_{\gamma\gamma}$ > 105 GeV	$m_{\gamma\gamma}$ > 95 GeV
Lepton veto	**$\lvert\Delta\phi(\gamma\gamma, p_T^{miss})\rvert > 2.1$, $\min(\lvert\Delta\phi(jet, p_T^{miss})\rvert) > 0.5$**

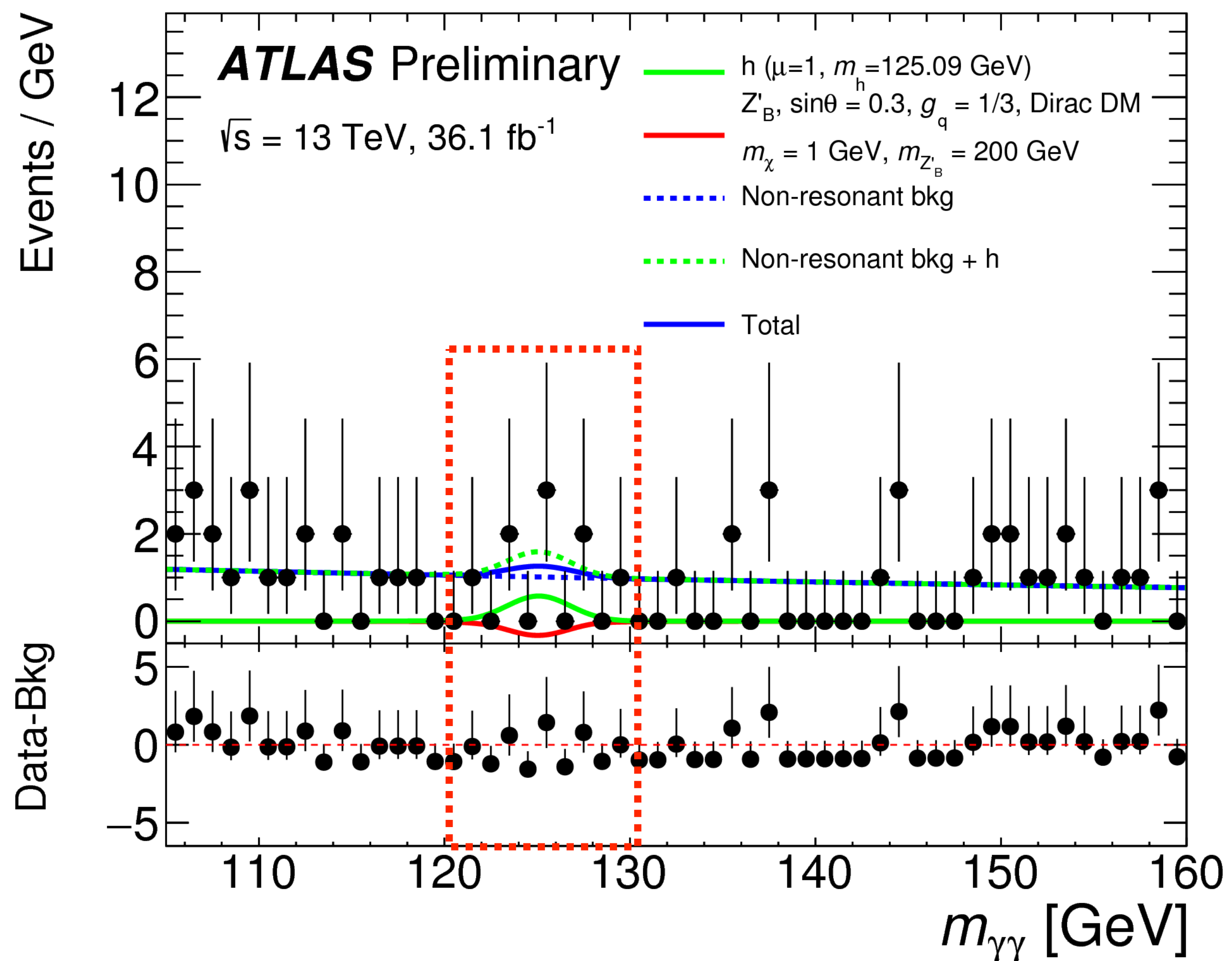
Mono-Higgs($\rightarrow\gamma\gamma$)



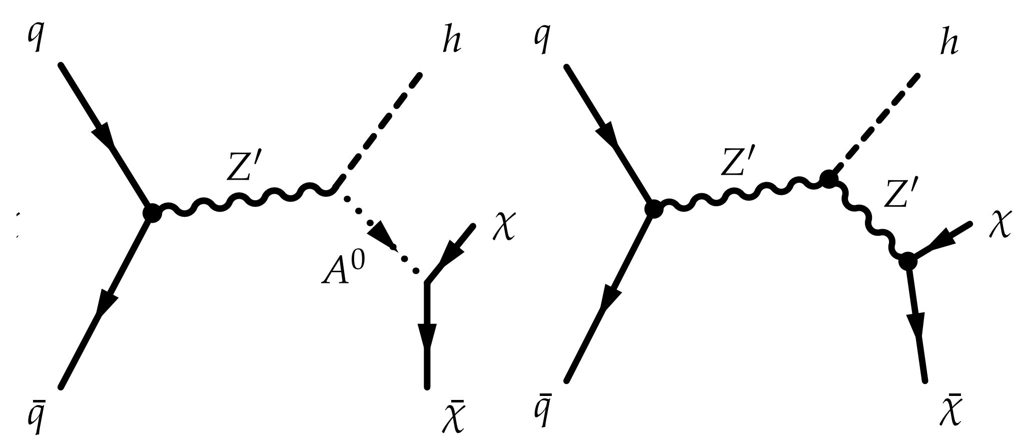
ATLAS-CONF-2017-024
CMS-EXO-16-012

- Data-driven non-resonant background ($\gamma\gamma$, γ+jets, Vγ, V$\gamma\gamma$):
  - CMS:
    - Shape of the mγγ distribution is evaluated in data with MET<105 GeV CR, normalization is obtained by using scale factor in sideband
  - ATLAS:
    - Both of the normalization and the shape are obtained from fitting to the diphoton invariant mass distribution in SR
    - The signal and backgrounds are extracted by fitting analytic functions to the $m_{\gamma\gamma}$ distribution in each category
    - Double-sided Crystal Ball function is used to model the signal and SM Higgs shapes
- No BSM excess is observed!
- Main uncertainties: statistical uncertainties 10% (20%), non-resonant background modeling 7% (20%)



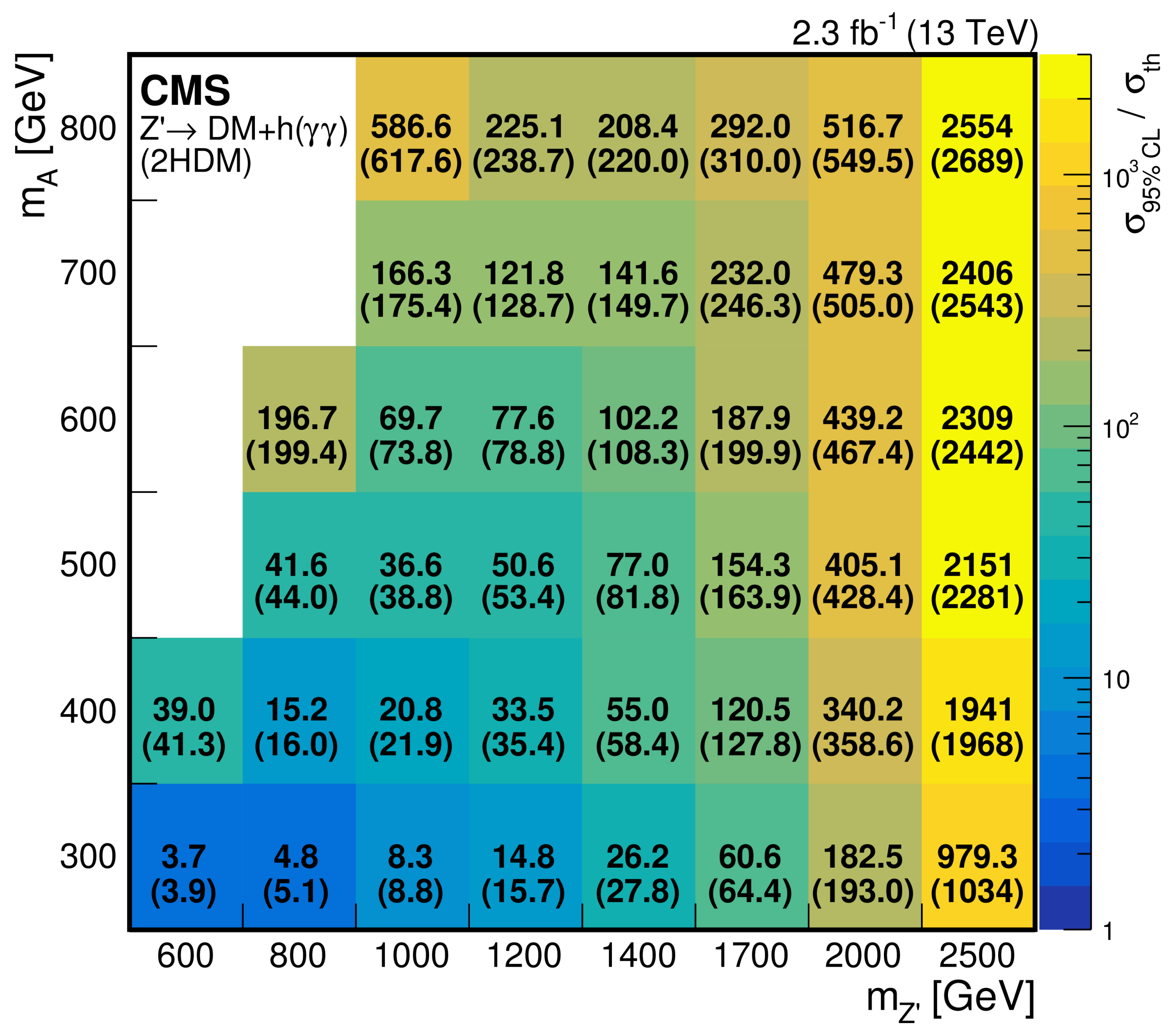


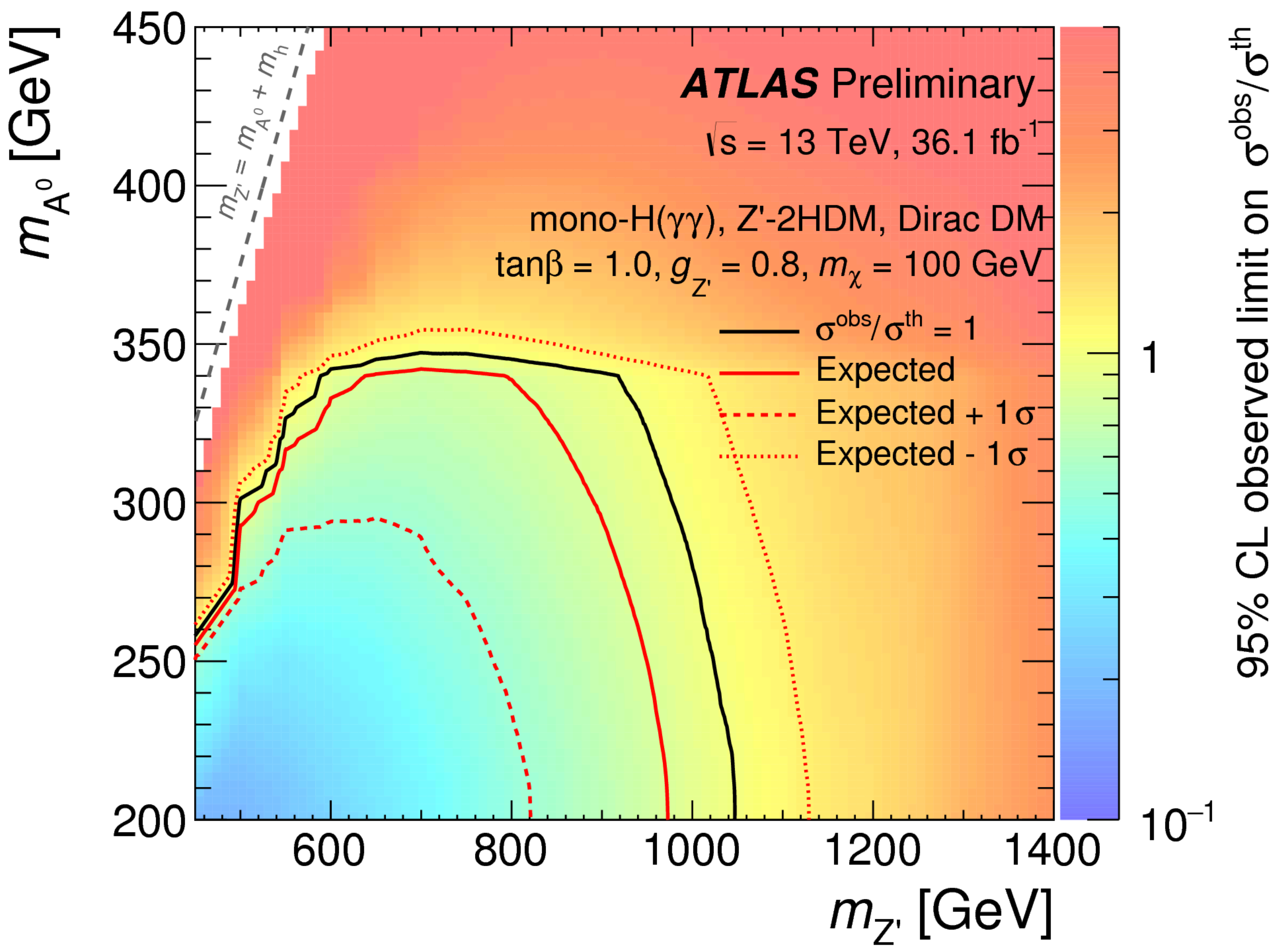
Mono-Higgs(→$\gamma\gamma$)

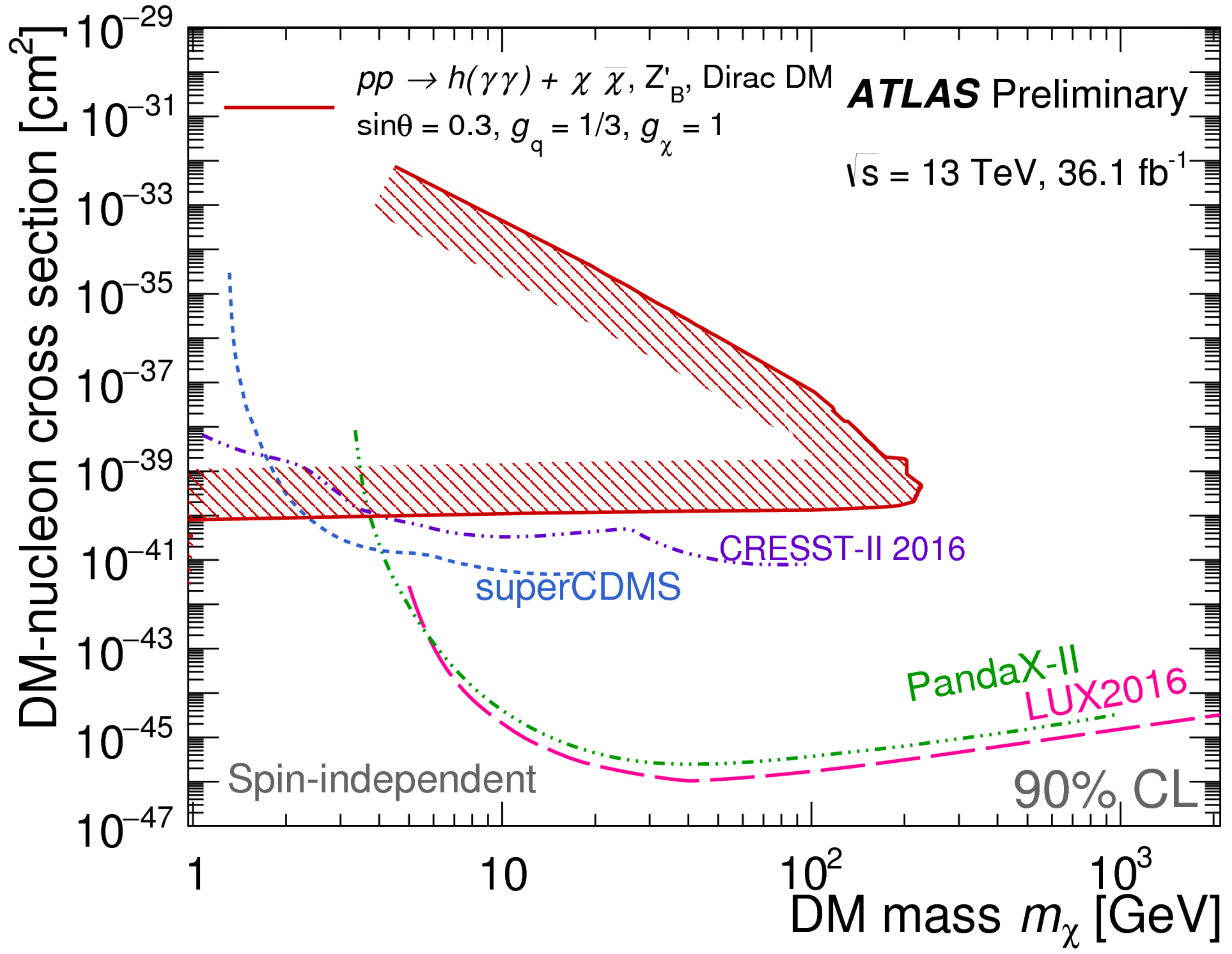


ATLAS-CONF-2017-024
CMS-EXO-16-012

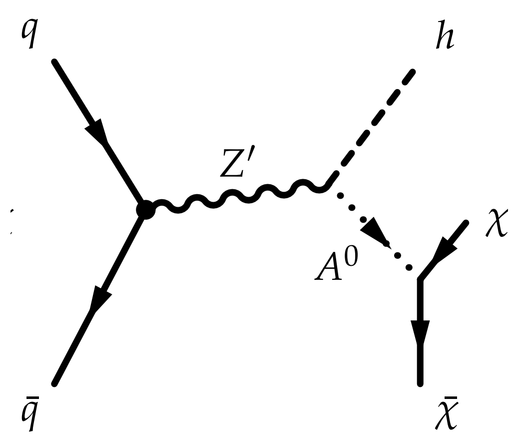
- Upper limit is set on the production cross section times BR as a function of mediator mass in both Z'B and Z'-2HDM scenarios
  - ATLAS: Upper limit on mZ'<1.04 TeV is excluded for mA=200 GeV (36.1fb^{-1})
  - CMS: no exclusion yet @2.3 fb^{-1}
- The spin independent DM-nucleon cross section in the context of the Z'B simplified model with vector couplings comparing with constraints from direct detection experiments





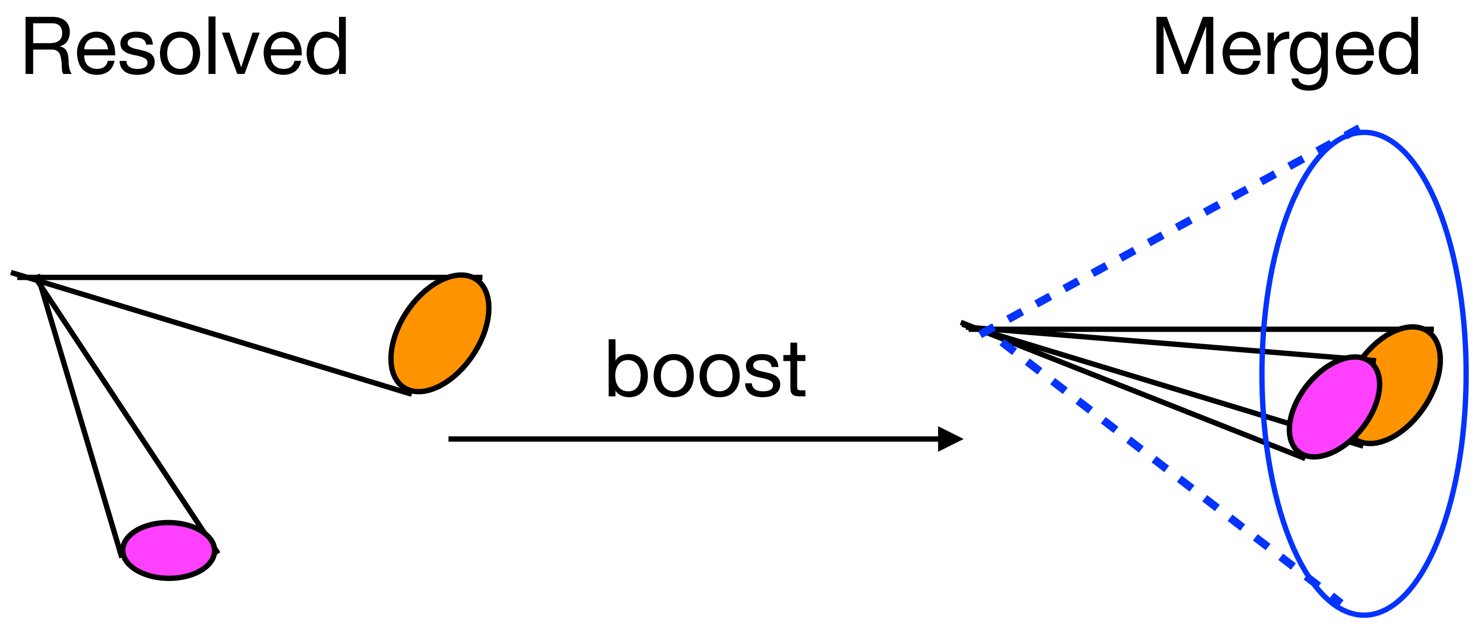


Mono-Higgs(→*bb*)

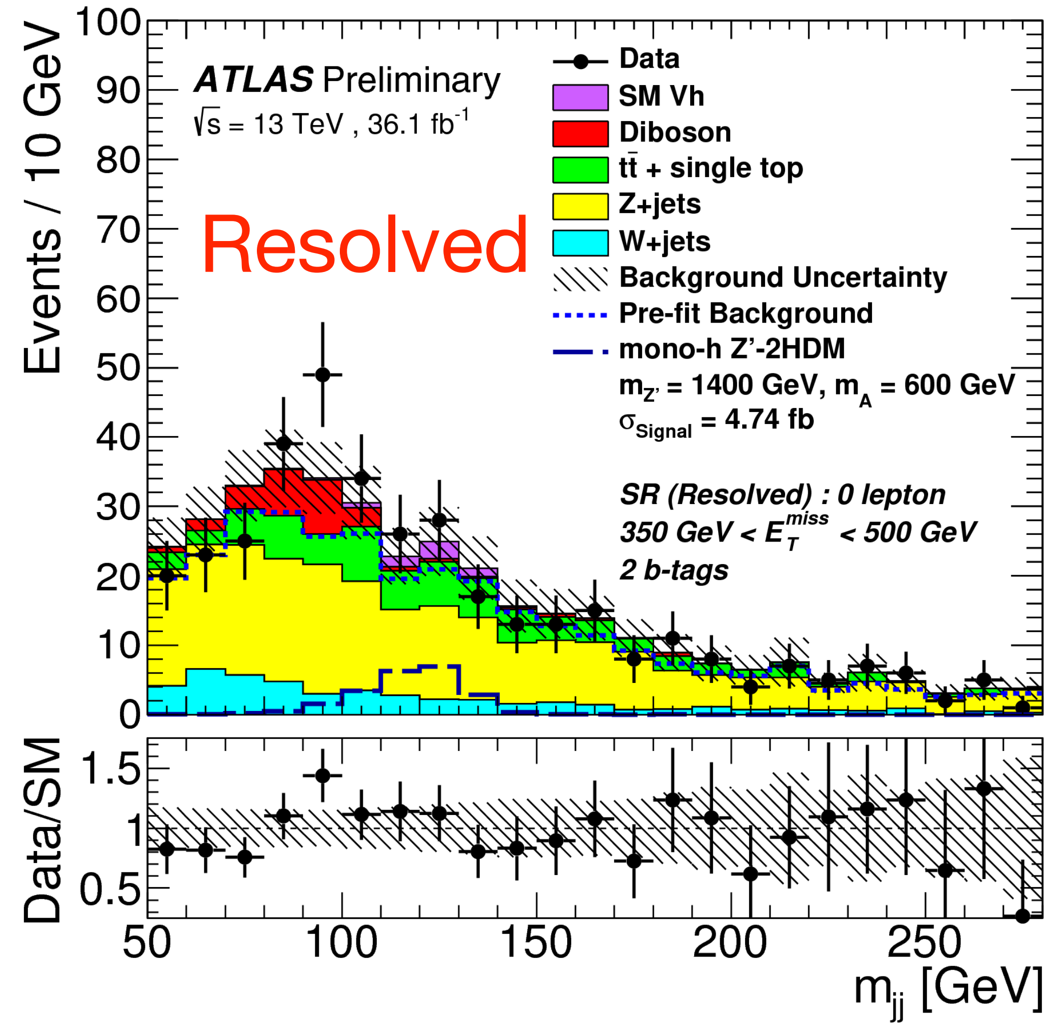


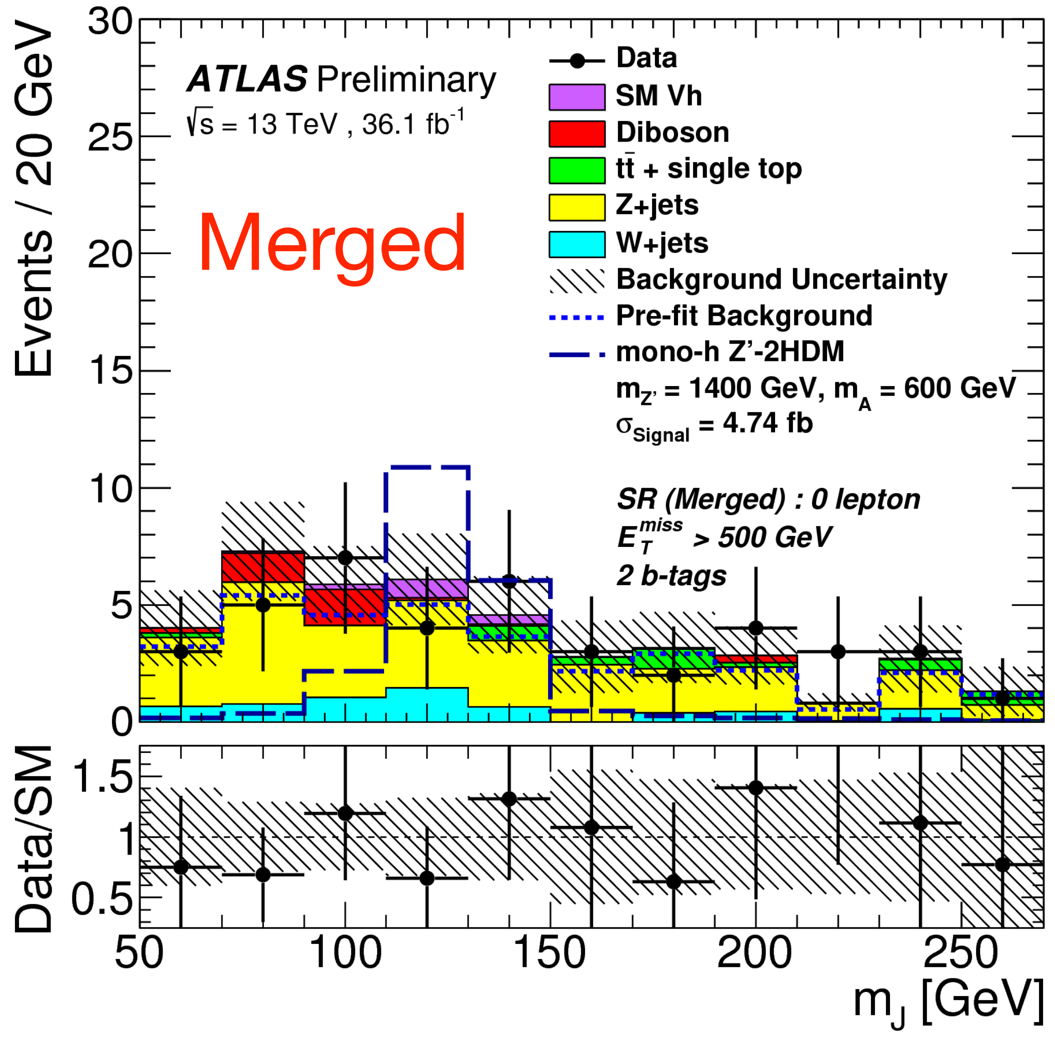
ATLAS-CONF-2017-028
CMS-EXO-16-012

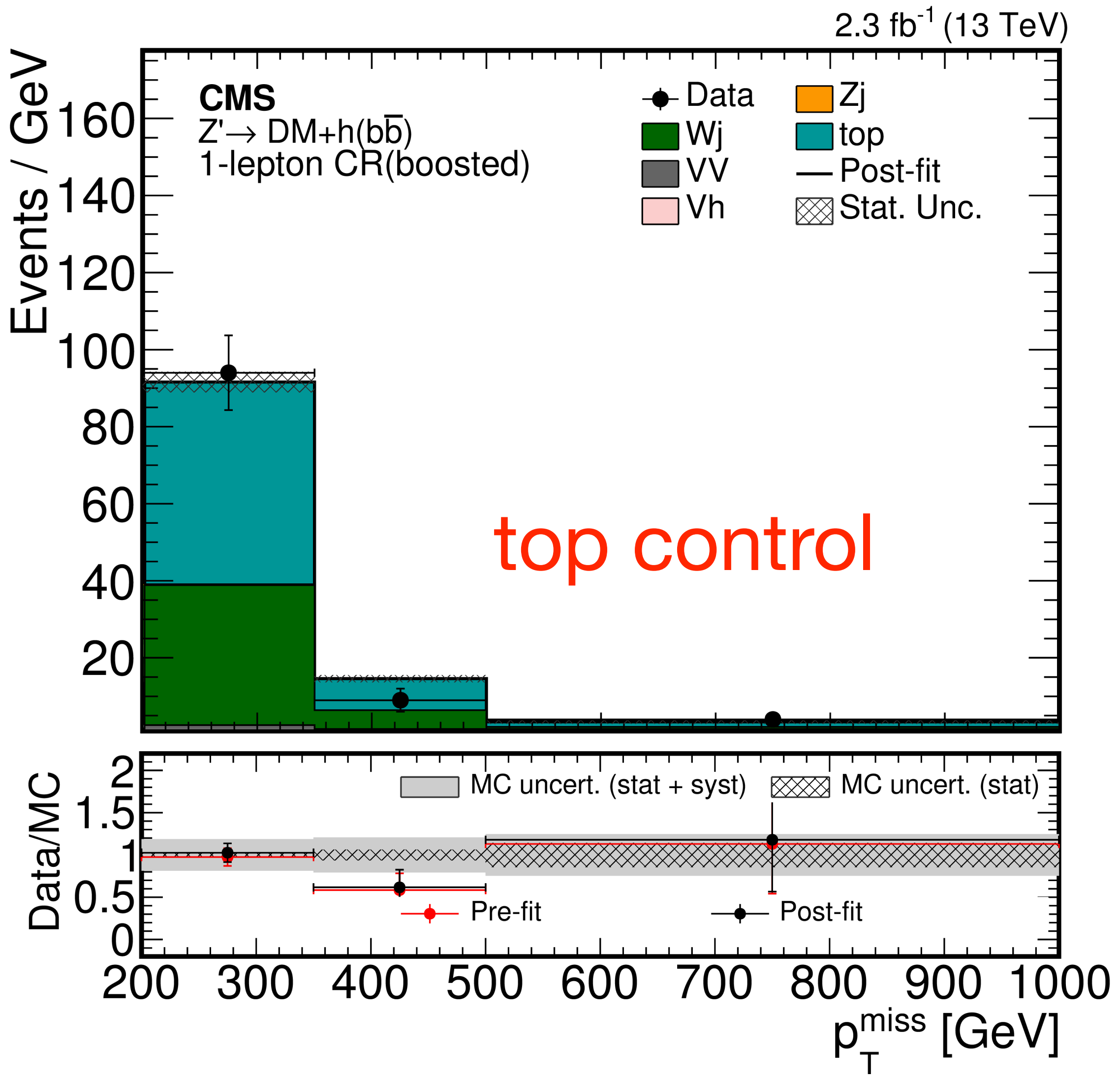
- Two signal regions based on if the Higgs is boosted or not:

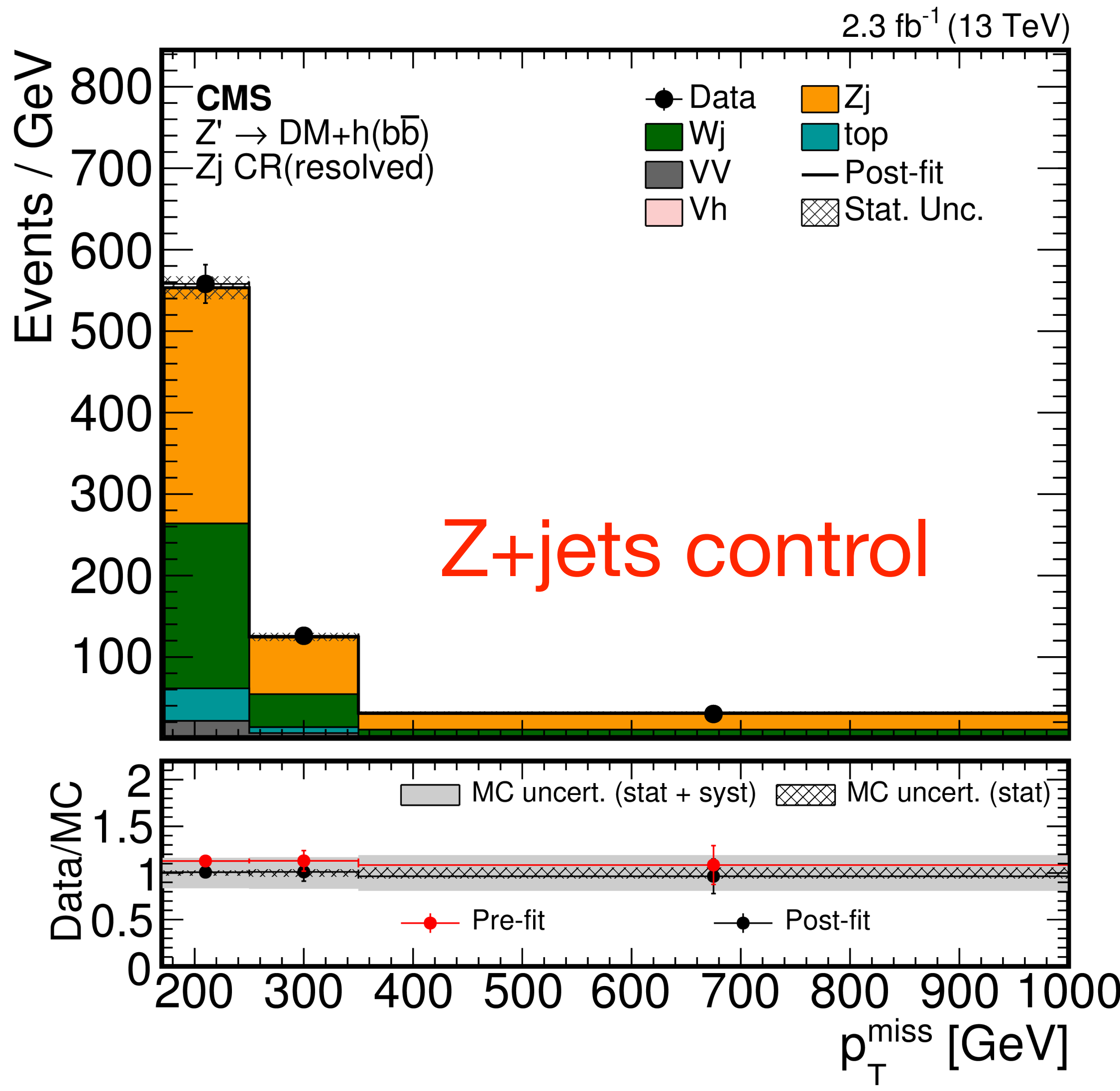


  - Resolved: two b-tagged jets + intermediate MET
  - Merged: one large-R jet with two b-tagged tracks + large MET
- Background:
  - two main backgrounds: W/Z+jets (15~65%); ttbar(45~80%)
  - control regions are defined with 1-/2-lepton events

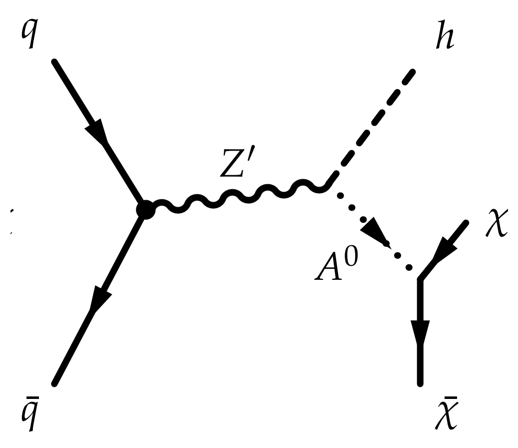






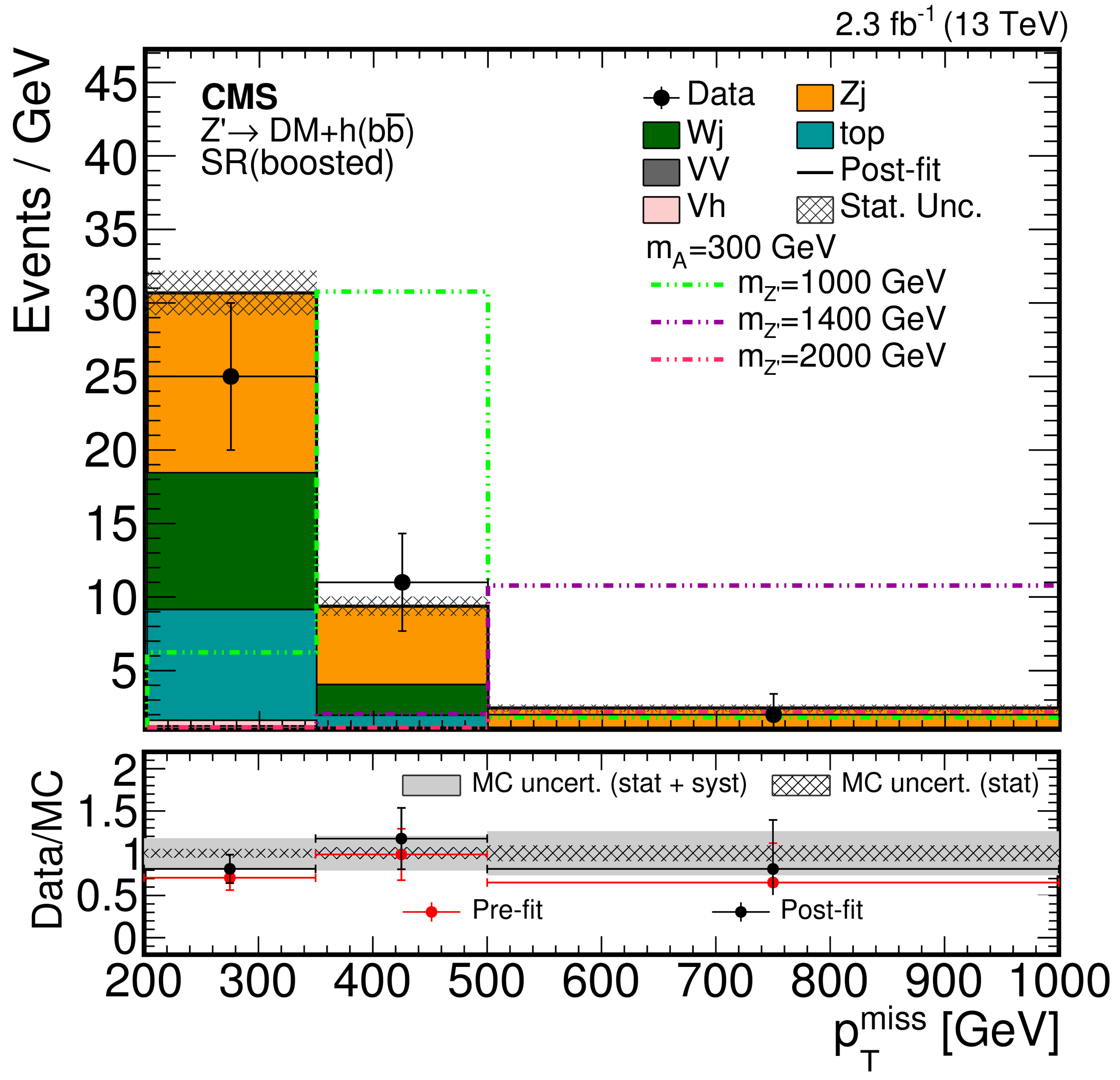


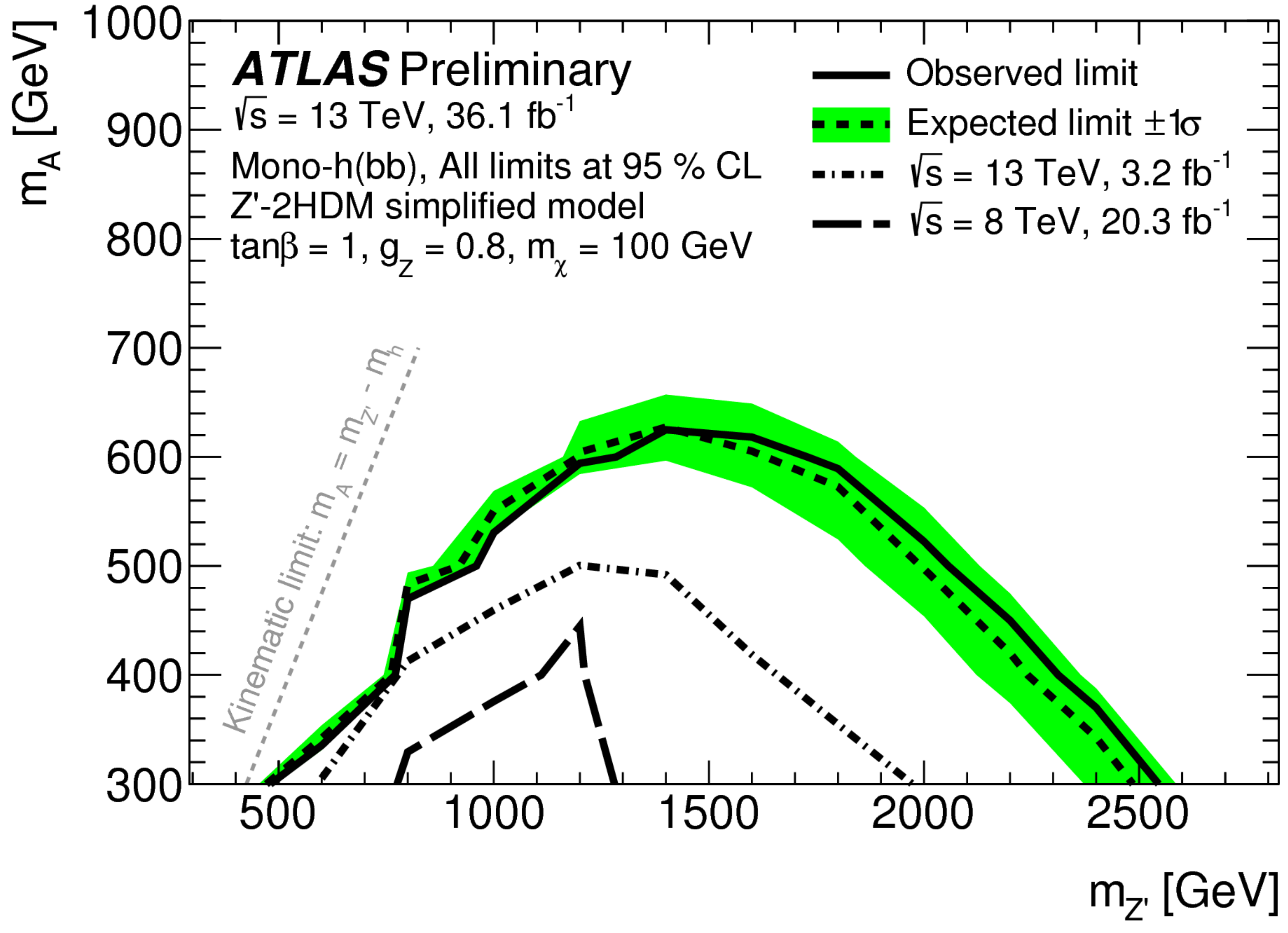
Mono-Higgs(→*bb*)

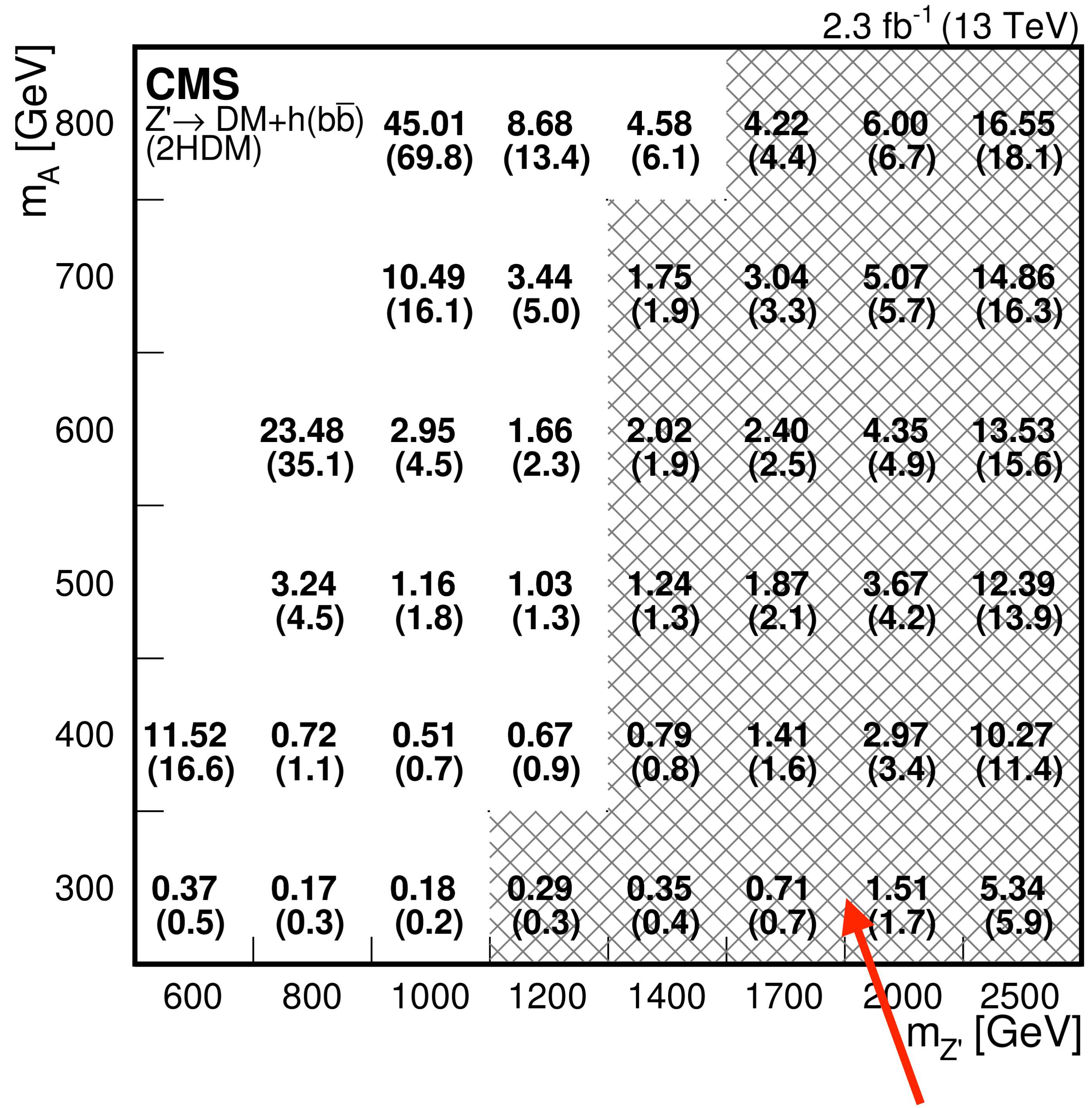


ATLAS-CONF-2017-028
CMS-EXO-16-012

- A profile likelihood fit **dijet/single-large-R-jet mass (ATLAS)** / MET (CMS) simultaneously in all SRs and CRs
- No significant BSM excess is observed
- 2D Limit contour (mDM, mZ’) is set for Z’-2HDM scenario
    - For mA = 300 GeV, the Z’-2HDM model is excluded at 95% CL for 0.5 TeV < MZ’ < 2.5 TeV (ATLAS) @ 36 fb-1, (XX TeV) < MZ’ <~1.8 TeV (CMS) @ 2.3 fb-1,





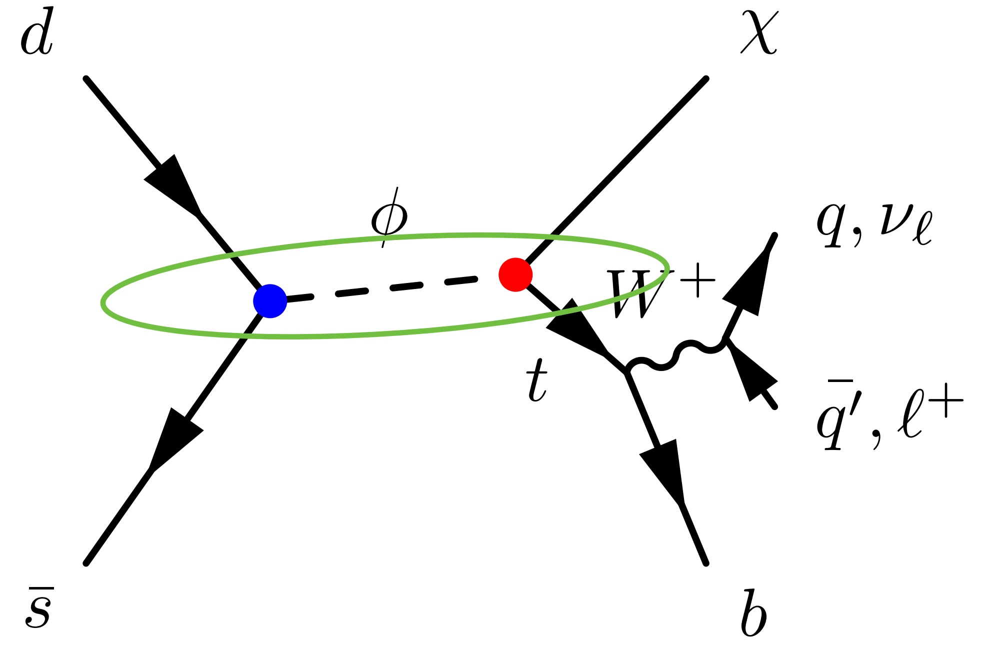


Mono-Heavy Flavor (new physics associated with DM satisfies minimal flavor violation)

Mono-t (had)

CMS-PAS-EXO-16-040

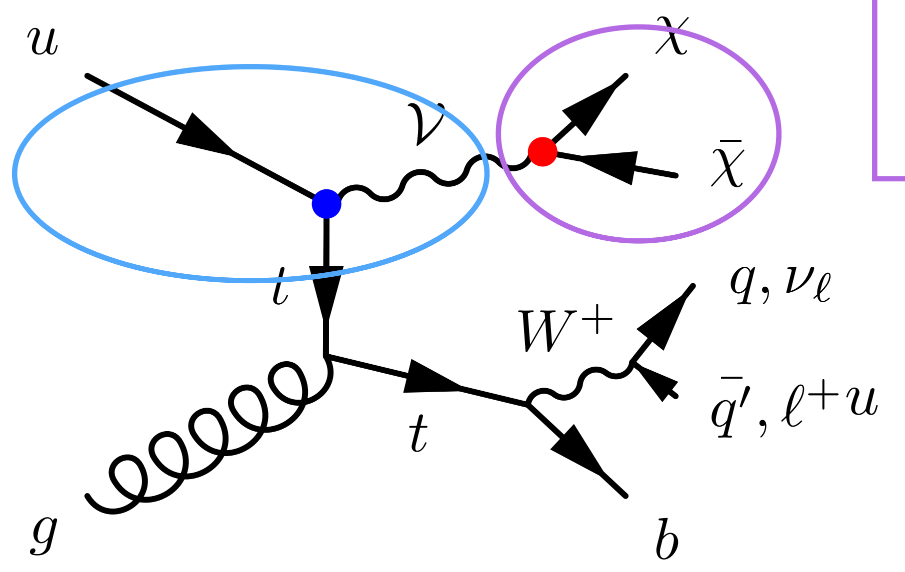
- Signature: a large MET plus a boosted top quark with **hadronic** decay
- In SM, this signature could occur as the loop-induced associate production with a Z boson decaying into a pair of neutrinos, but such FCNC process is suppressed by the GIM mechanism
- Resonant scalar mediator:
  - Majorana fermion as DM, a colored scalar (ϕ) decaying to top quark and DM

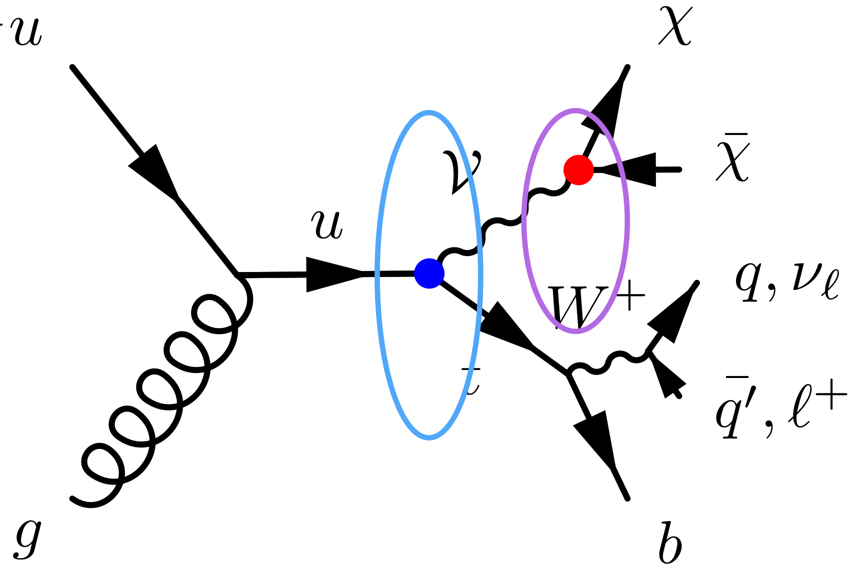


$$\mathcal{L} = \left[a V_\mu \bar{u} \gamma^\mu P_R t + \lambda \varphi \bar{d}^c P_R s + y \varphi \bar{\chi} P_R t + \text{h.c.} \, , \right]$$

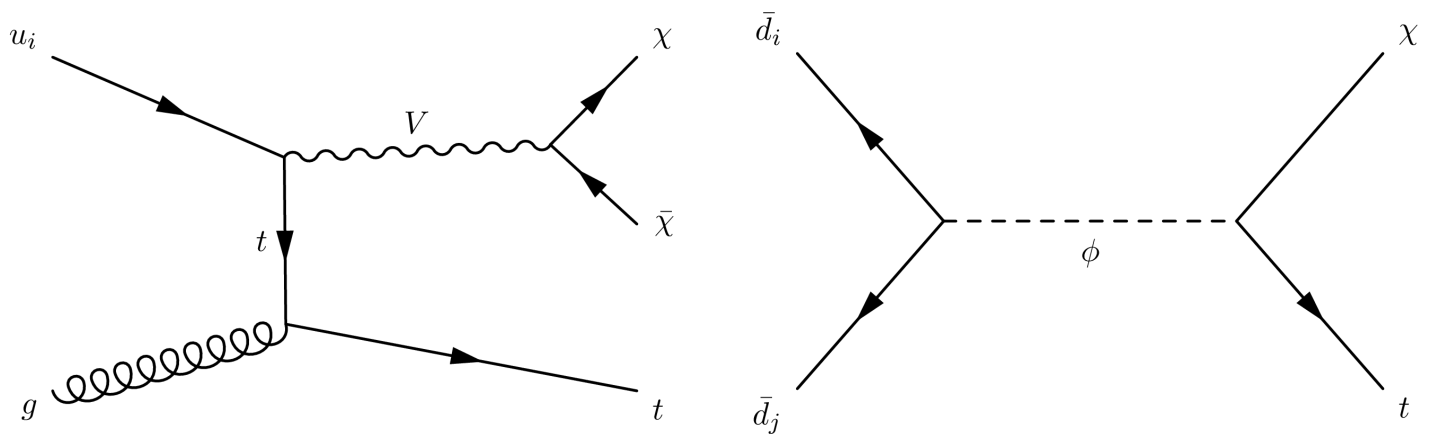
- Non-resonant vector mediator FCNC model:
  - Dirac fermion as DM, flavor-changing neutral interactions of u-t-V

$$\mathcal{L} = g_{DM} V_\mu \bar{\psi} \gamma^\mu \psi \, .$$



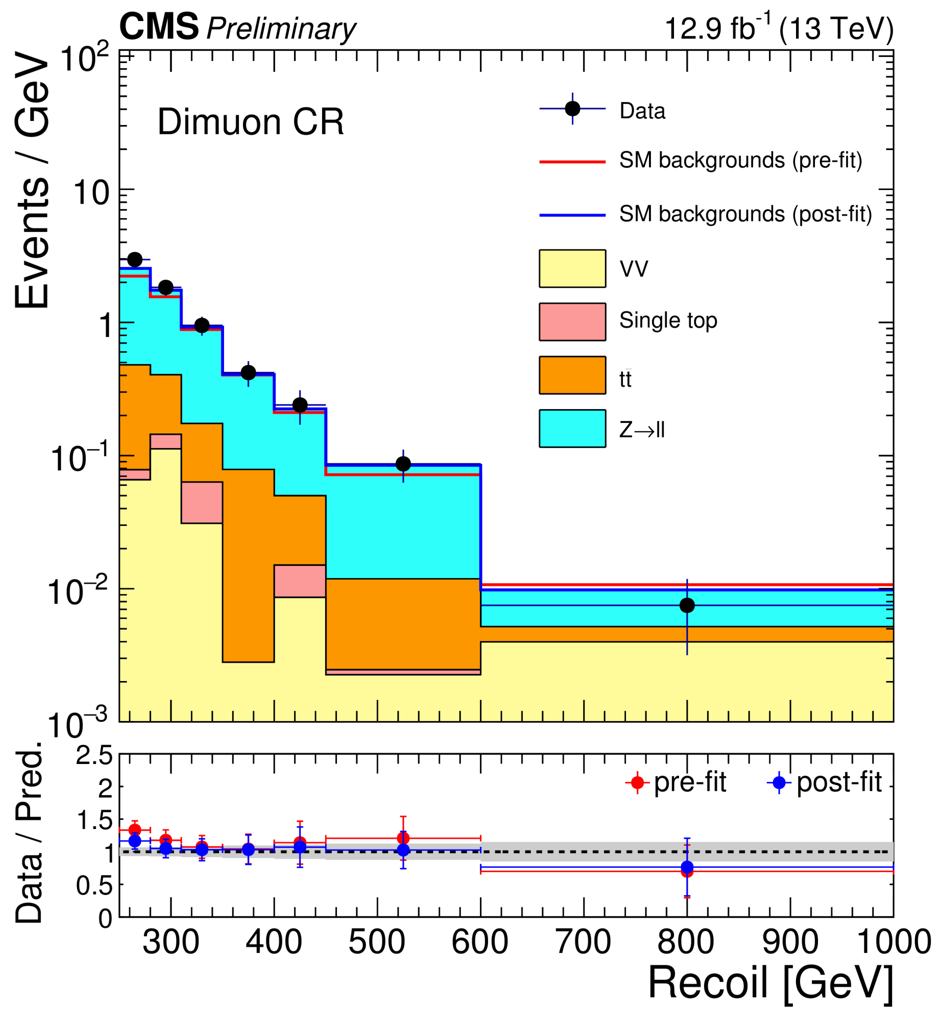


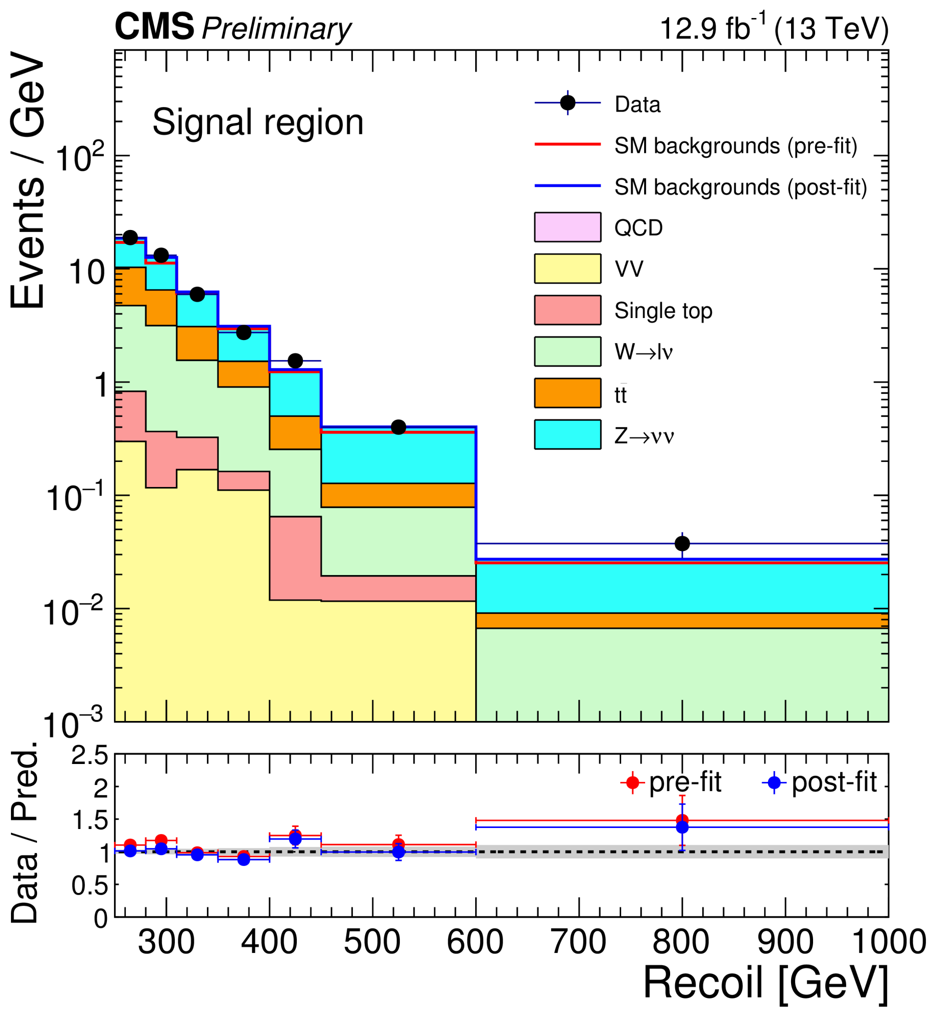
Mono-t (had)

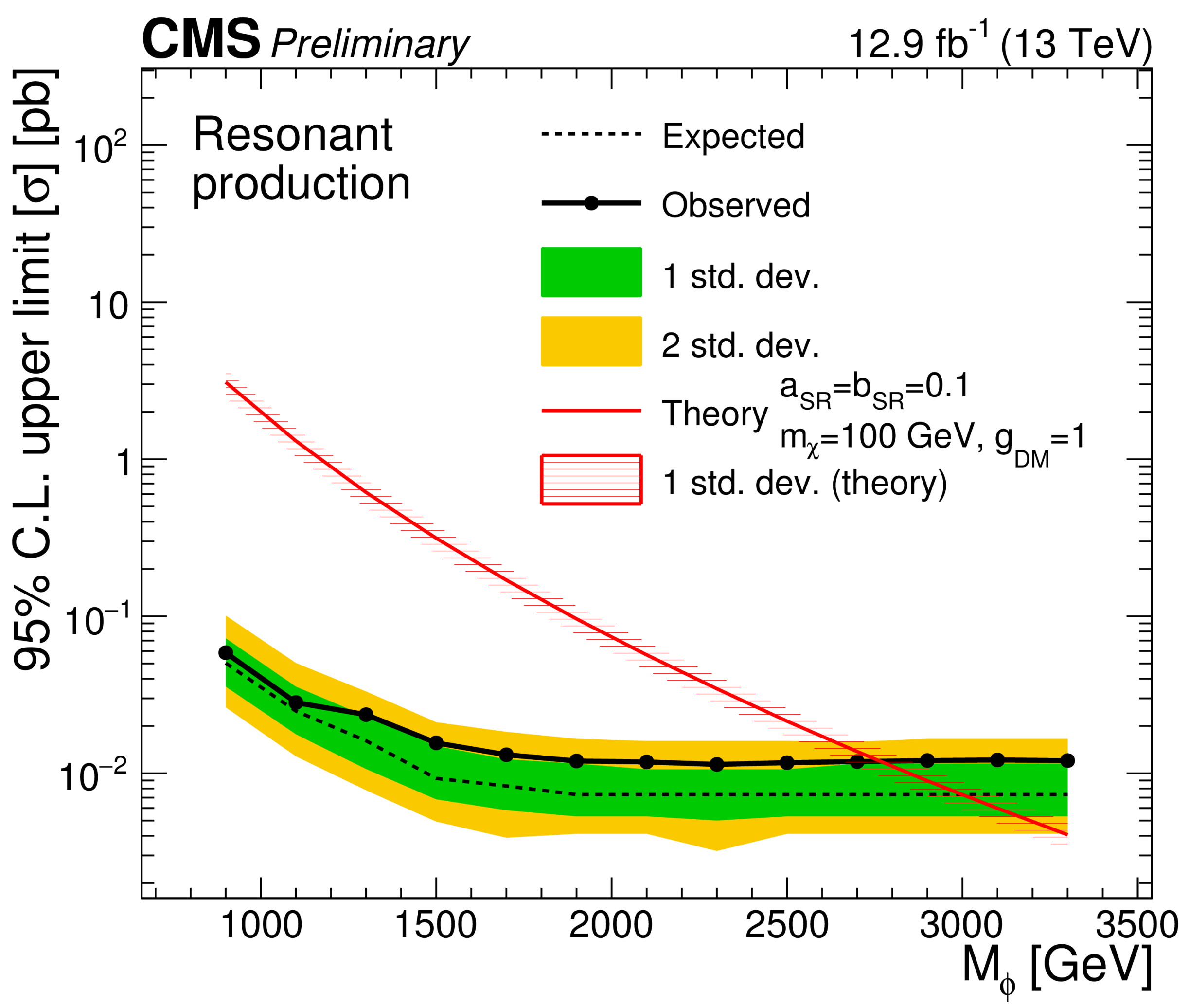


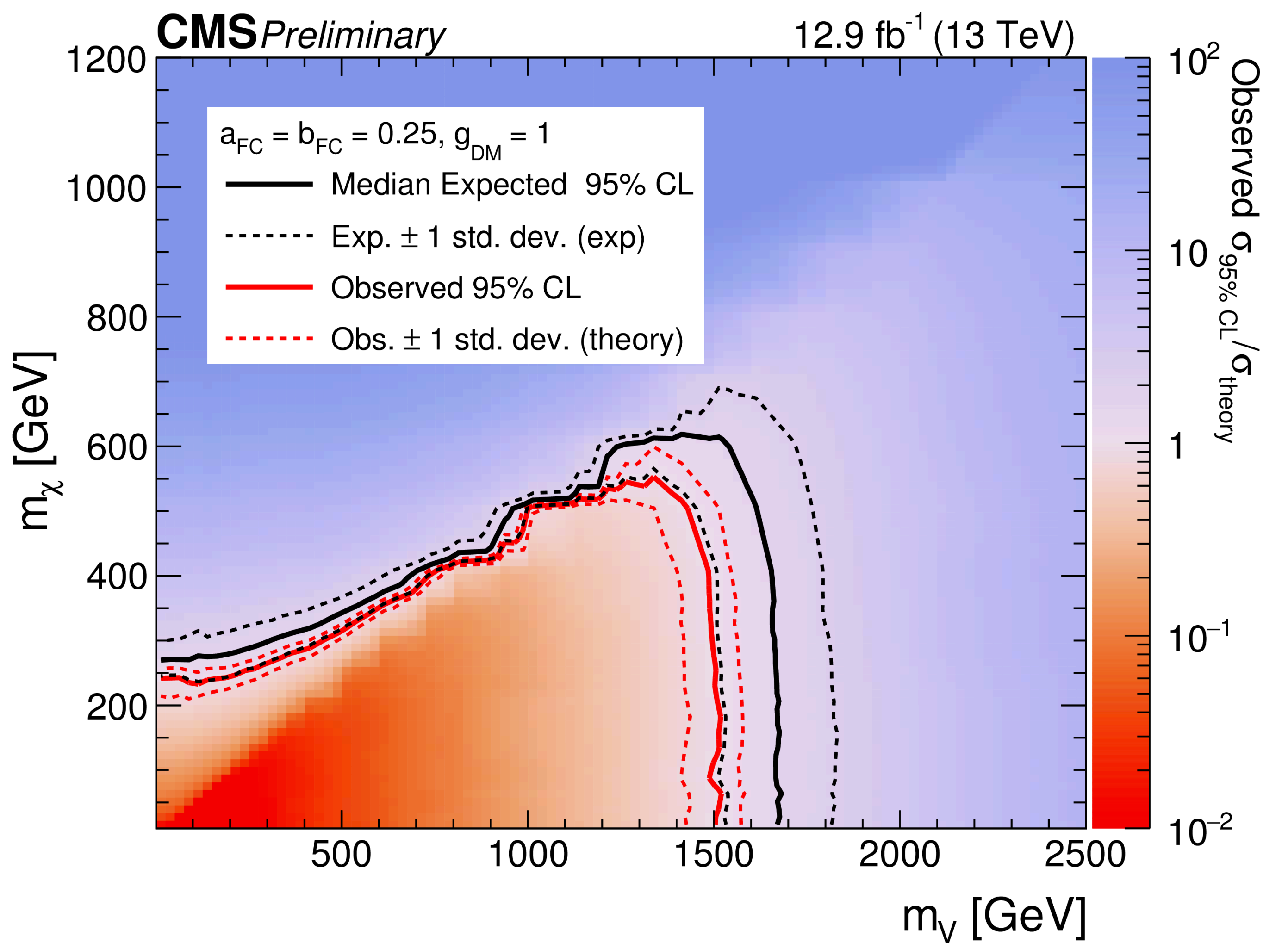
CMS-PAS-EXO-16-040

- Main background: ttbar, Z(vv) + jets , and W(lv) + jets — estimated from different CRs by a simultaneous fit
- Selection:
  - ETmiss> 250 GeV, a large-R(0.1) fat jet top-tagged with pT > 250 GeV and |η| < 2.5, matched with a b quark within the cone,
  - Veto on additional b jets, lepton, photon and tau
- Good agreement with SM predictions
- The FCNC is excluded for vector mediator 0.3 < MV < 1.5 TeV, assuming mχ = 10 GeV
- For mχ = 100 GeV, the resonant scalar model is excluded for 0.9 < Mϕ < 2.7 TeV at 95% CL

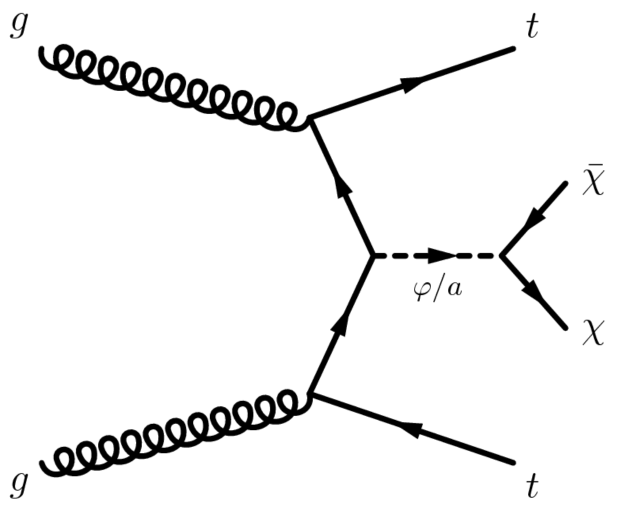








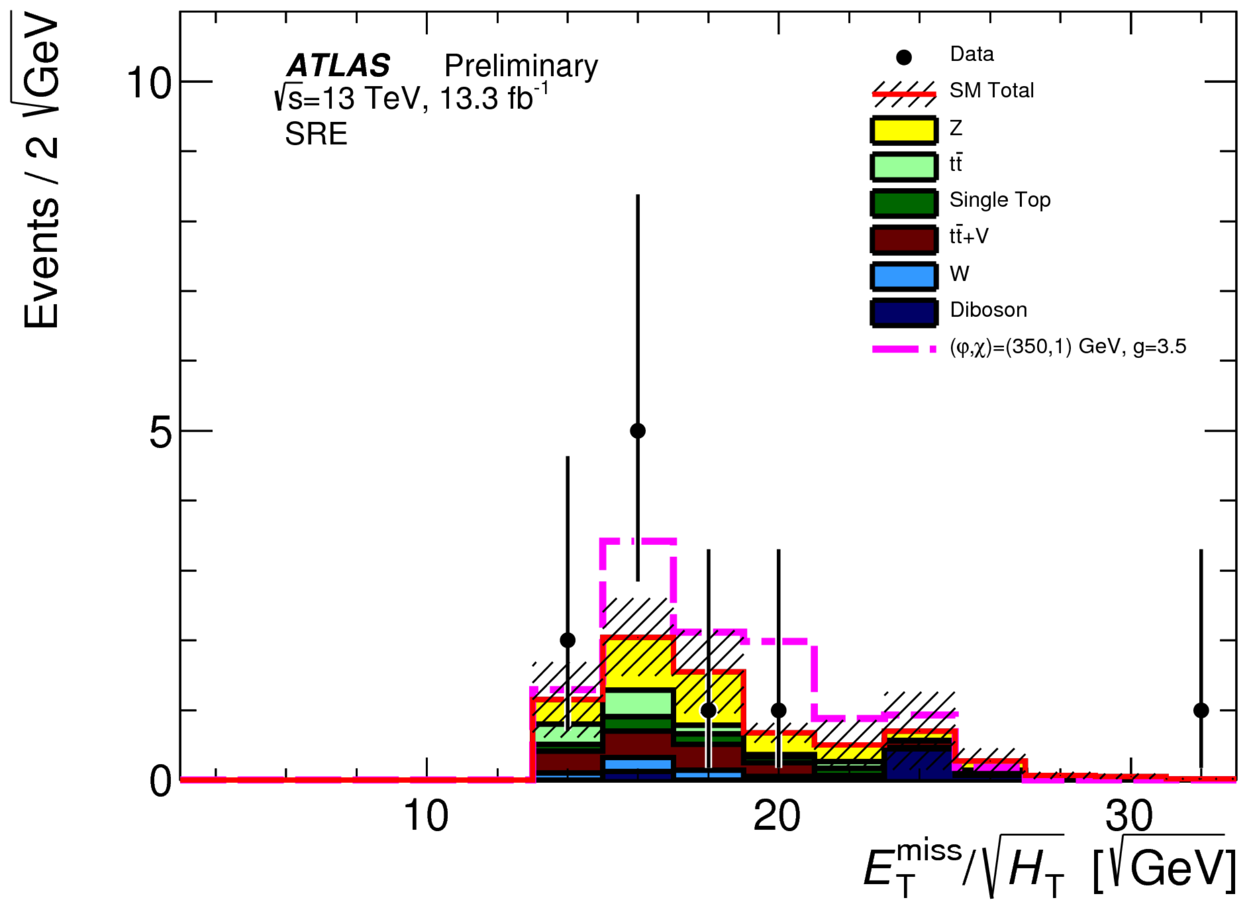
Mono-tt (0 lepton)

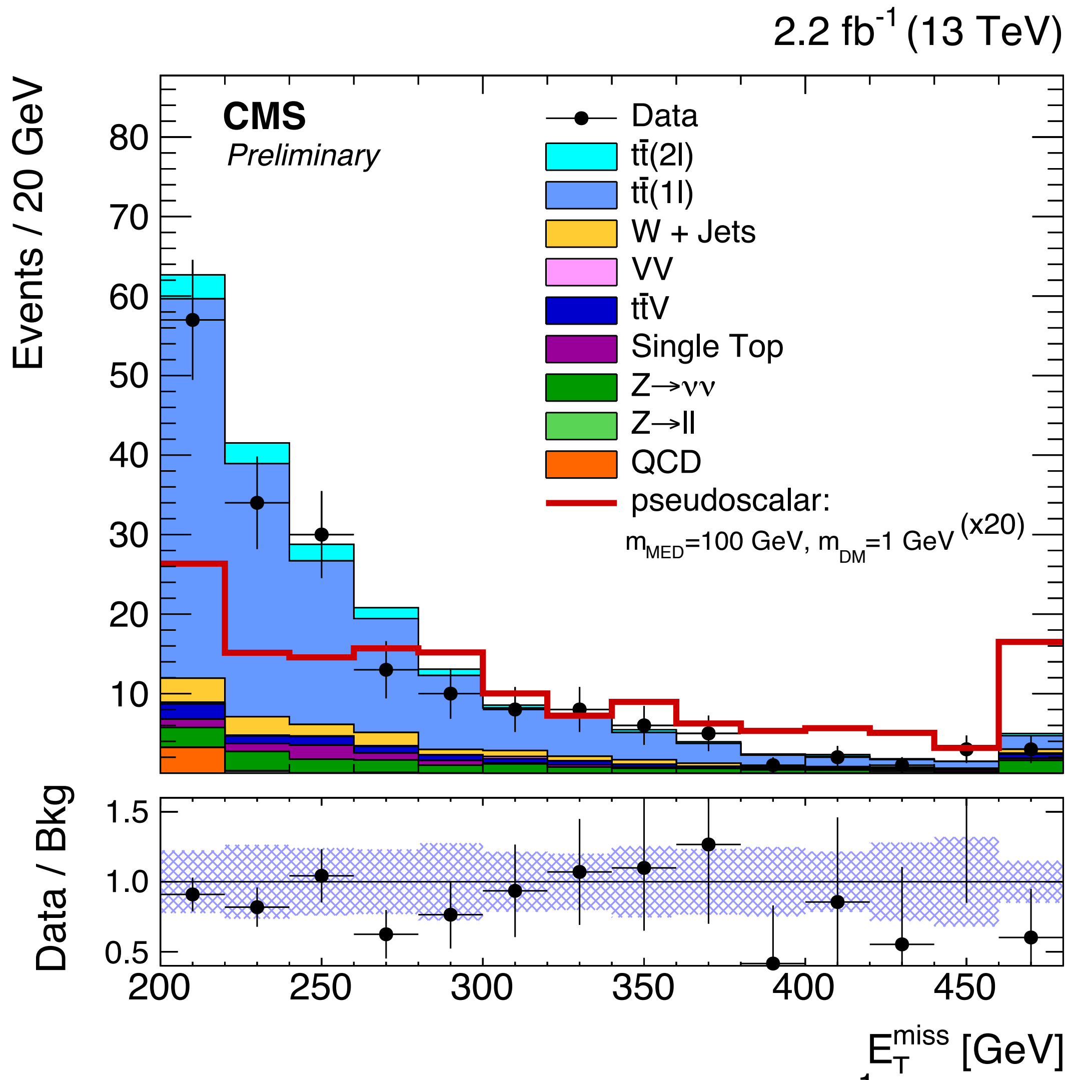


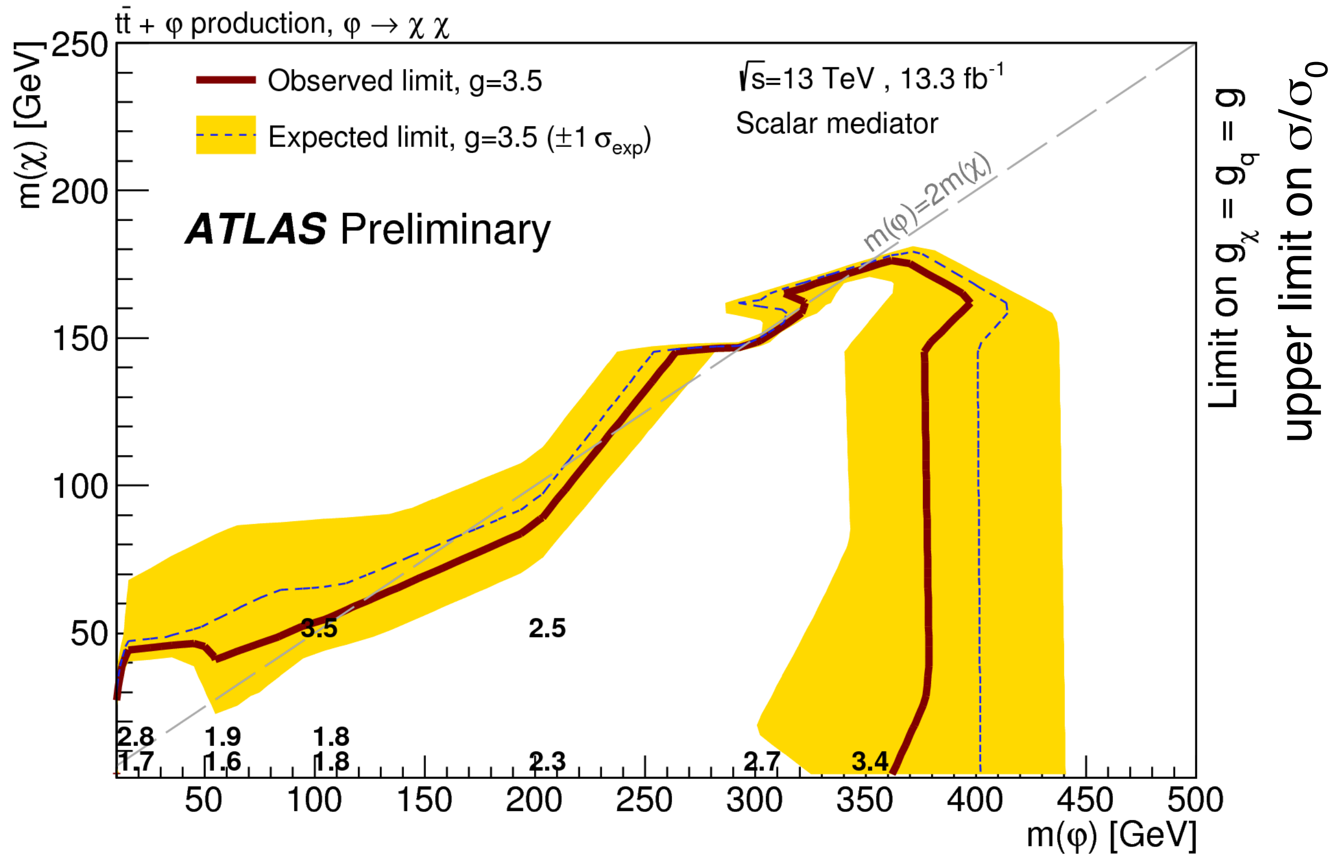
ATLAS-CONF-2016-077
CMS-PAS-EXO-16-005

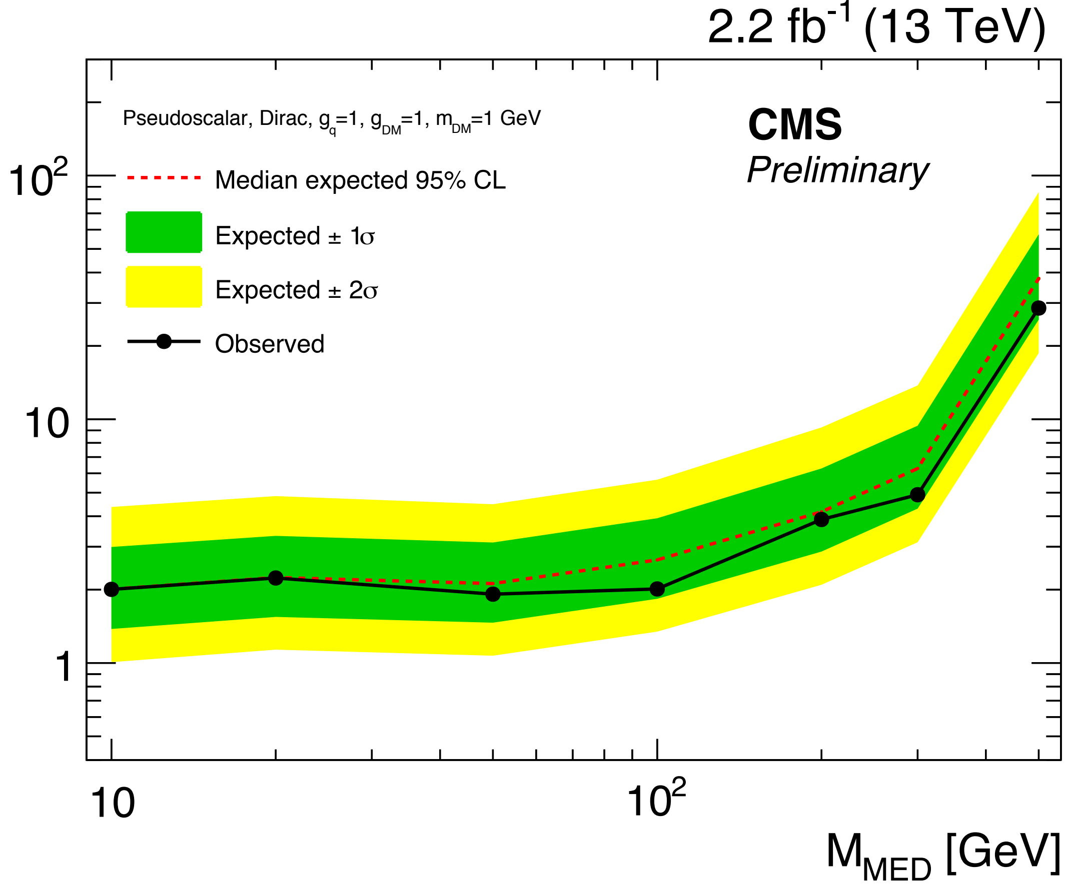
- Signature of multiple jets (2 b-quarks), no leptons, and significant MET
- backgrounds are constrained in different CRs

ATLAS	CMS
MET>300 GeV	MET>200GeV
Δφ (jet, MET) > 0.4 (up to 2 jets)	Δφ(jet , Emiss) > 1 (up to 6 jets)
trkMET> 30 GeV Δφ (trkMET , MET) < π/3,	**lepton veto**
m(top-jet)>140, 60 GeV, ΔR(b,b) > 1.5	**<= 2 top tagged jets**
mT(b,MET)> 200 GeV MET significance > 14	



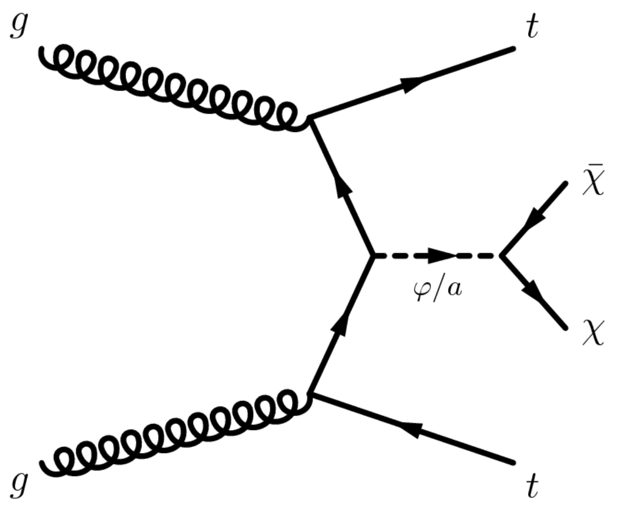






- Good agreement with SM predictions
- ATLAS: Observed limits on g= 3.5, for mχ = 10 GeV, the scalar model is excluded for Mϕ < 350 GeV @95% CL

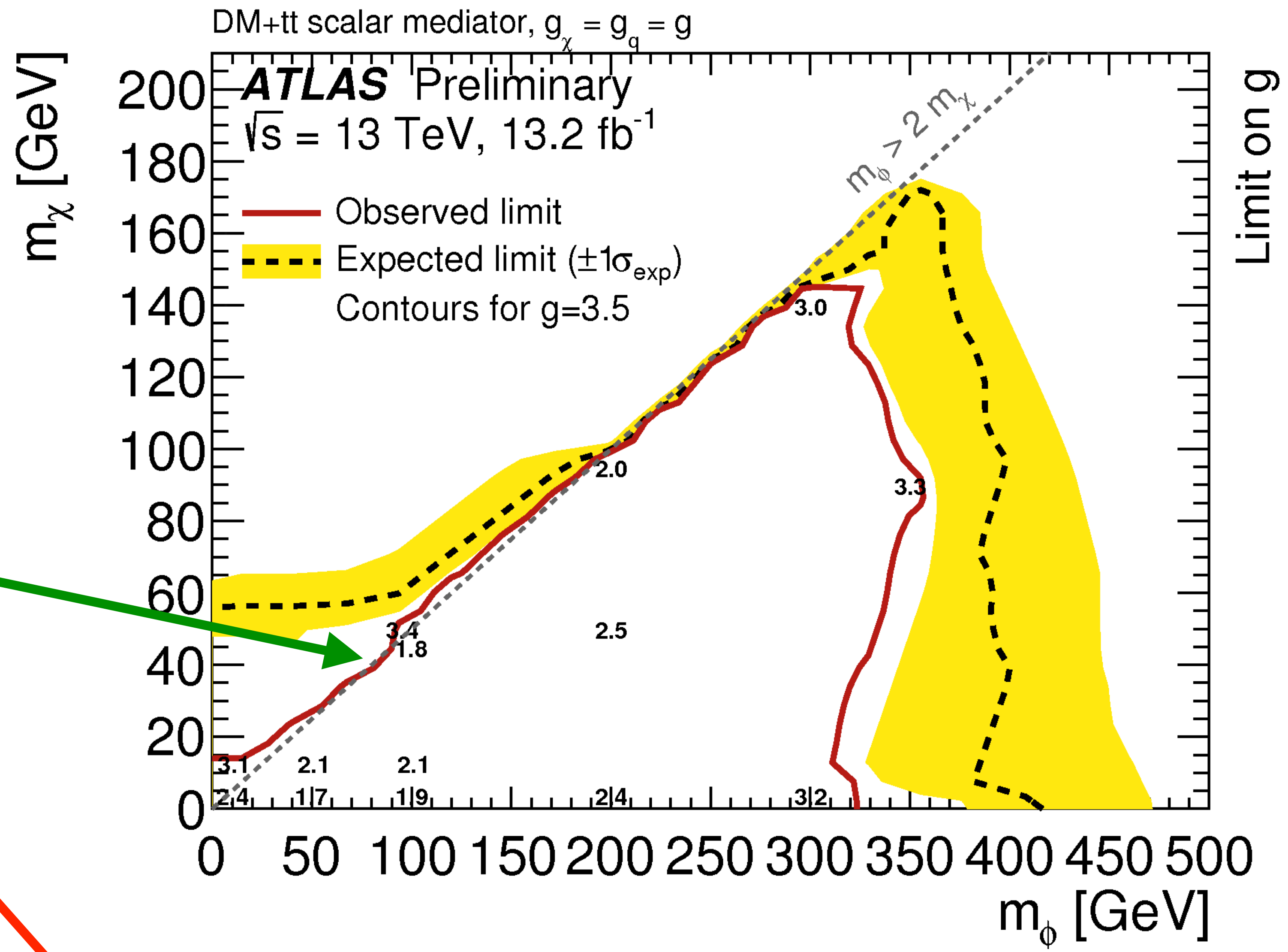
Mono-tt (1 lepton)



ATLAS-CONF-2016-050
CMS-PAS-EXO-16-005

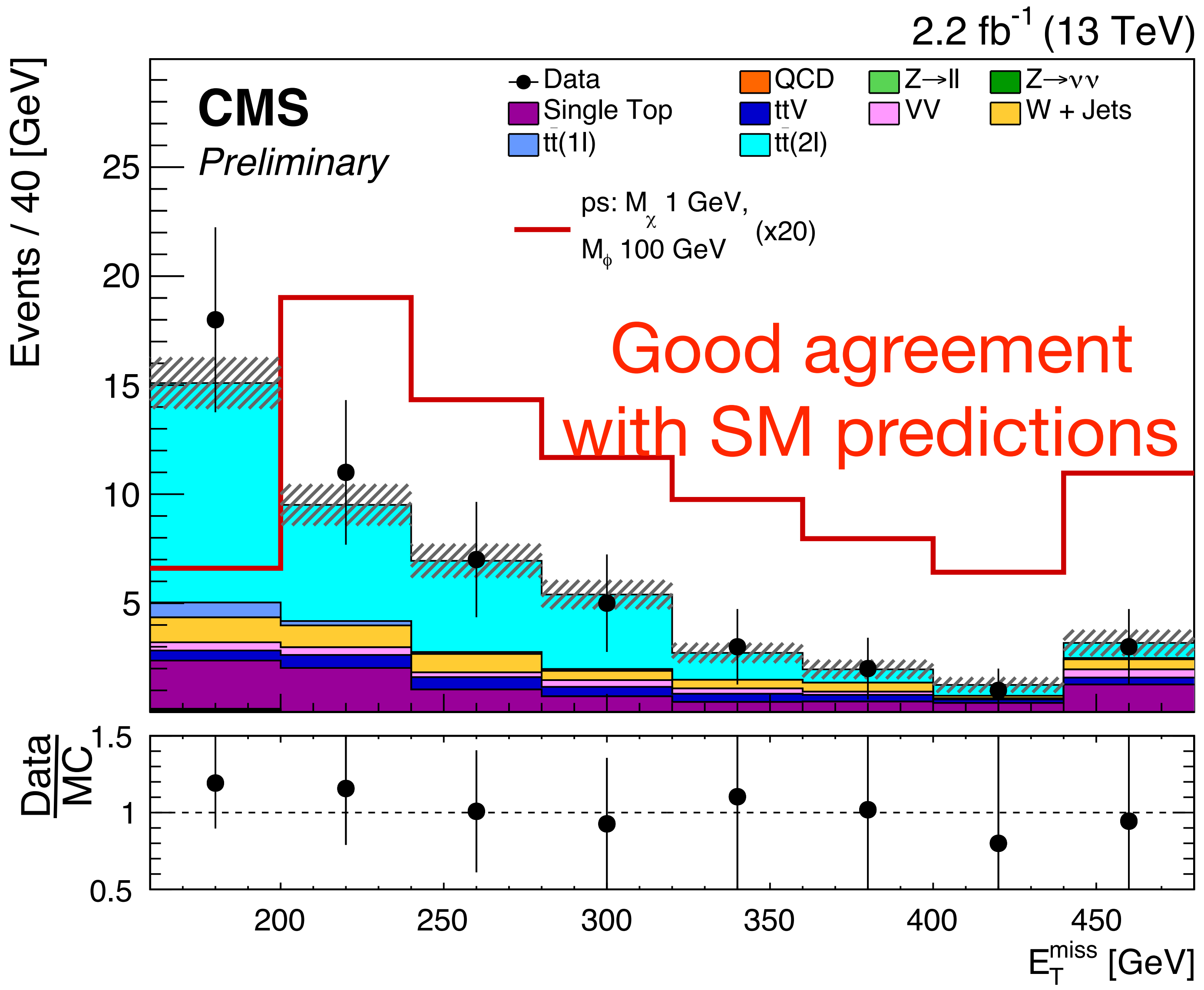
- Signature of multiple jets (1 b-quarks), a well-identified lepton, and MET
- CMS: lepton with pT > 30 GeV, ETmiss > 160 GeV, >= 3jets, at least 1 bjet, mT> 160 GeV, m^{W}_{T2} > 200 GeV, Δφ (ETmiss, jets) > 1.2 (up to 2 jets)
- ATLAS

Variable	DM_low	DM_high
Number of (jets, *b*-tags)	(≥ 4, ≥ 1)	(≥ 4, ≥ 1)
Jet p_T > [GeV]	(60 60 40 25)	(50 50 50 25)
E_T^{miss} [GeV]	> 300	> 330
$H_{T,sig}^{miss}$	> 14	> 9.5
m_T [GeV]	> 120	> 220
am_{T2} [GeV]	> 140	> 170
$\min(\Delta\phi(\vec{p}_T^{miss}, jet_i))(i \in \{1-4\})$	> 1.4	> 0.8
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	> 0.8	–

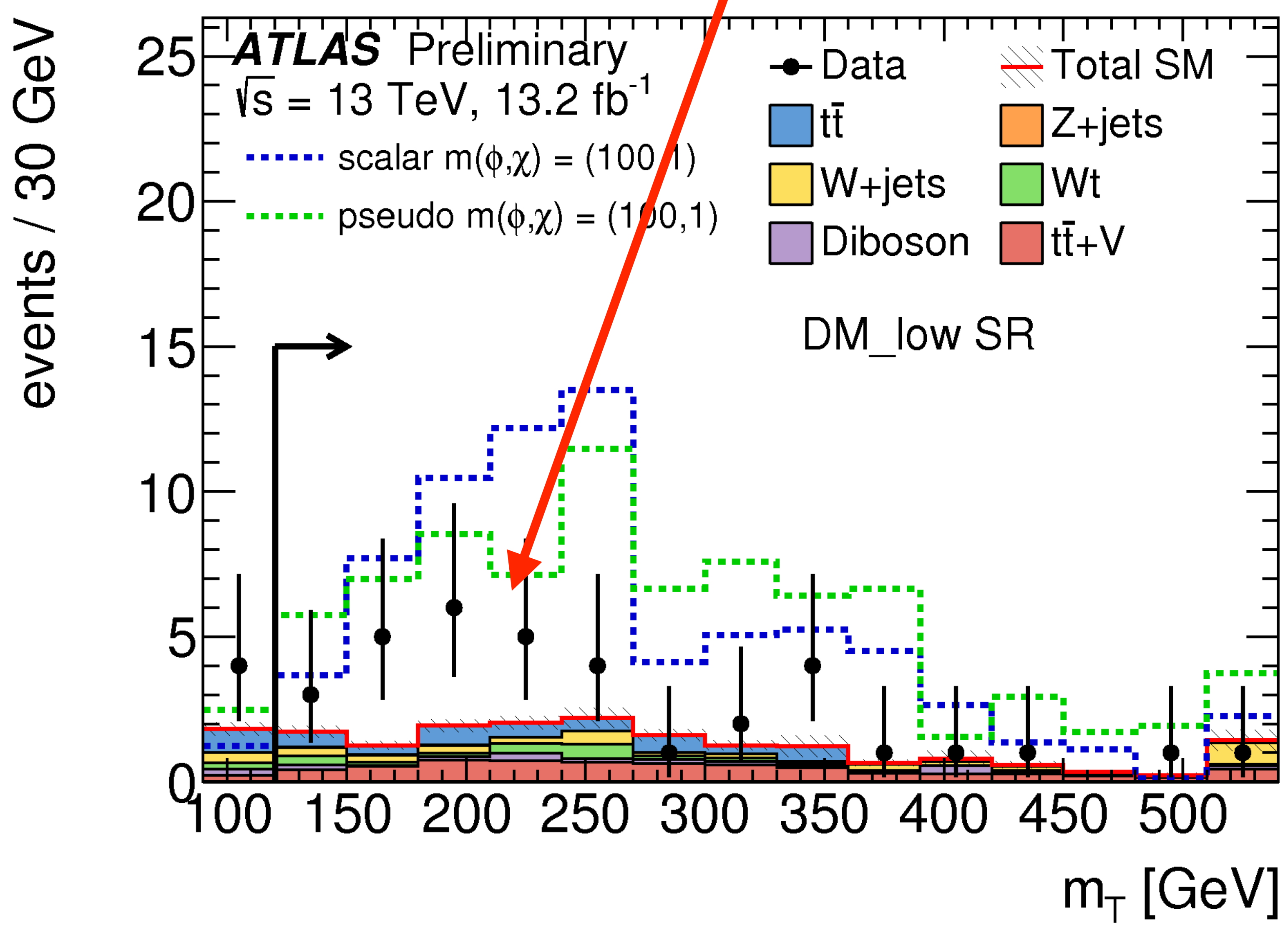


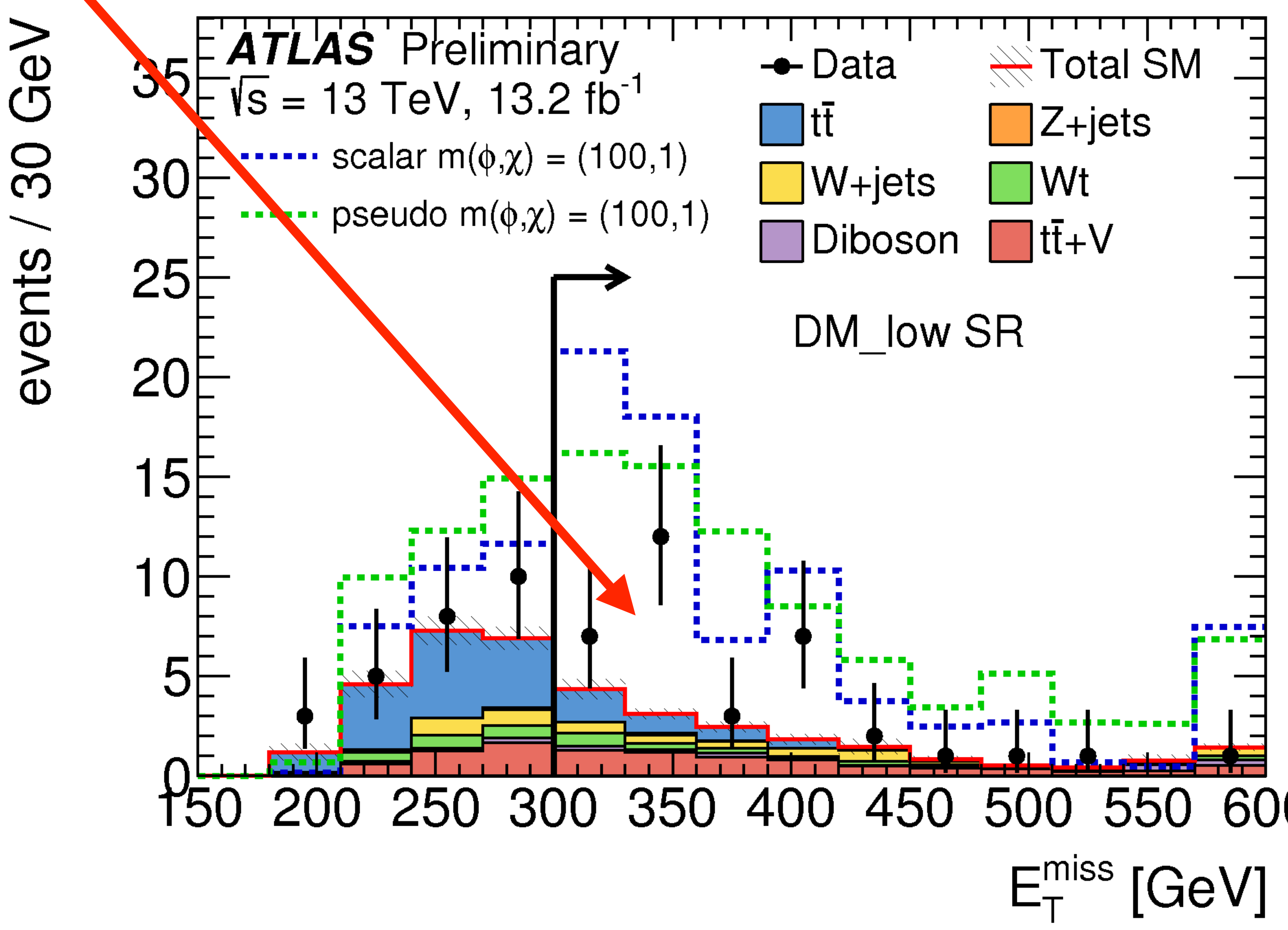
Limits on g= 3.5

Local significance of 3.3σ in one of the SRs (need more data)

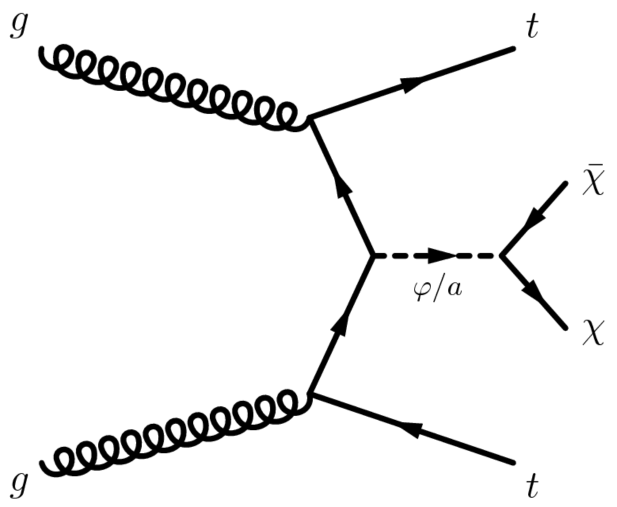


Good agreement with SM predictions



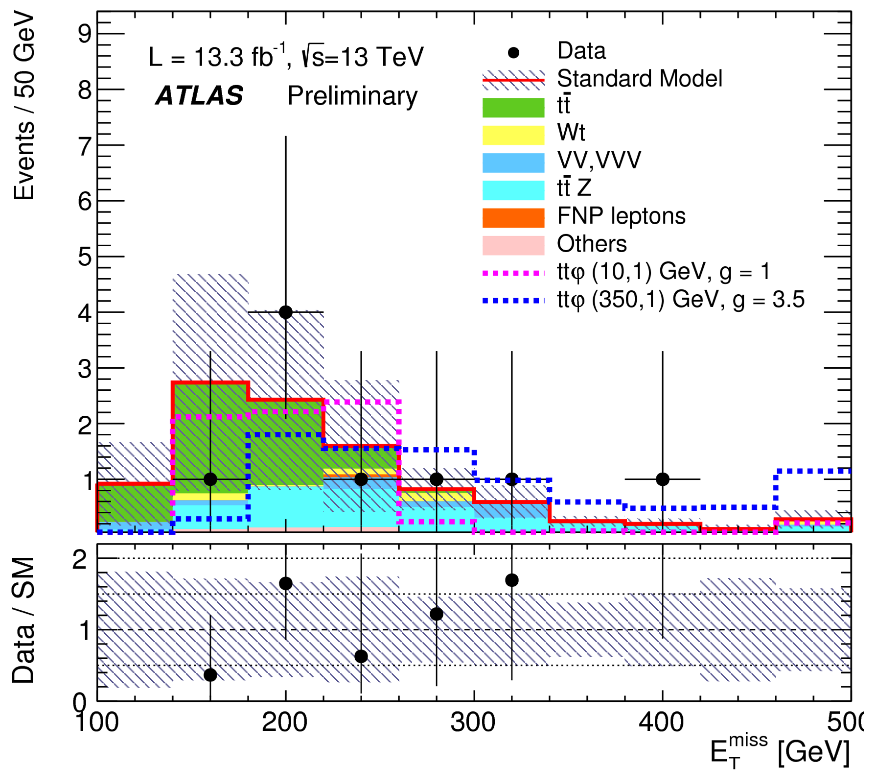


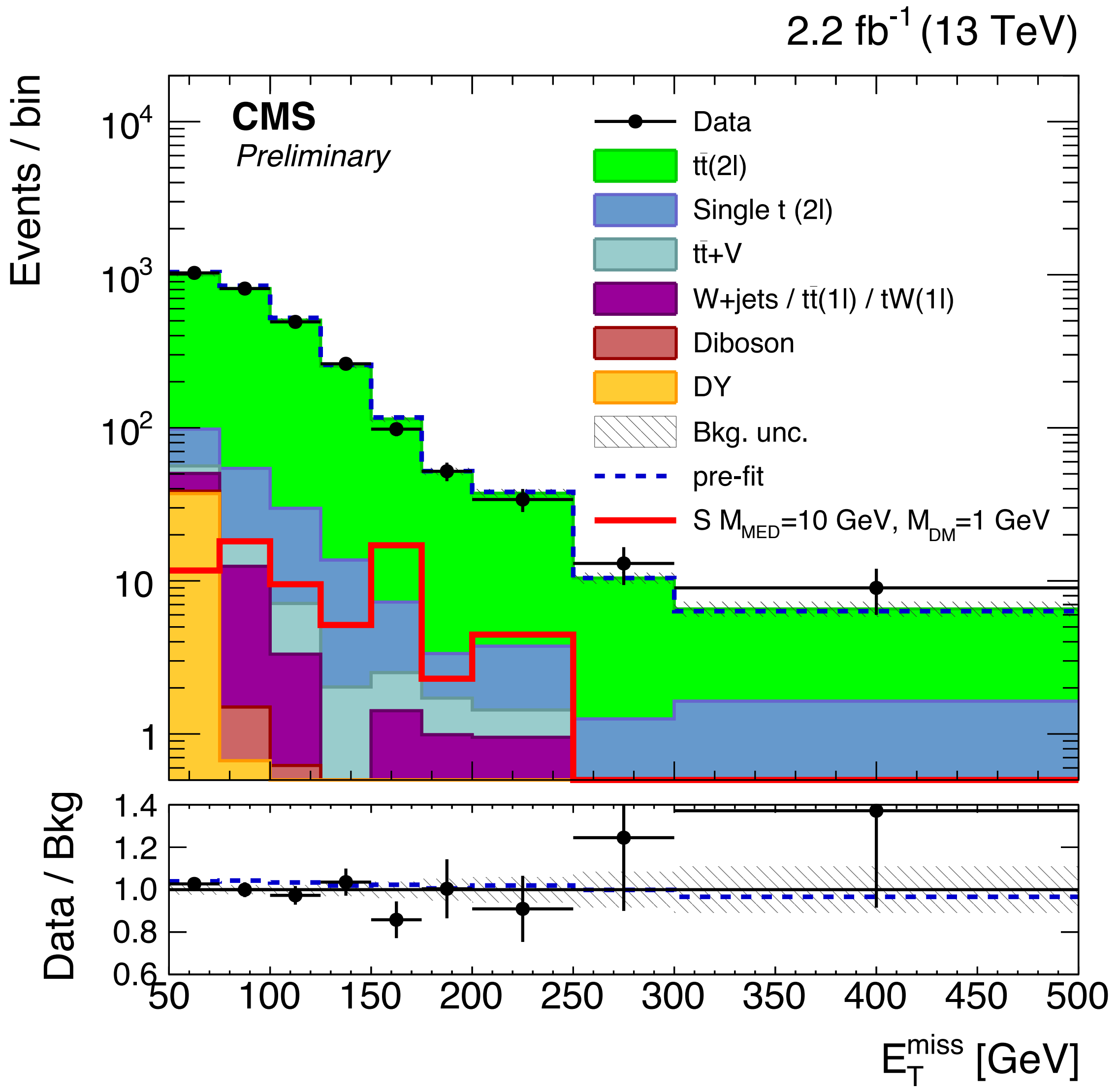
Mono-tt (2 leptons)

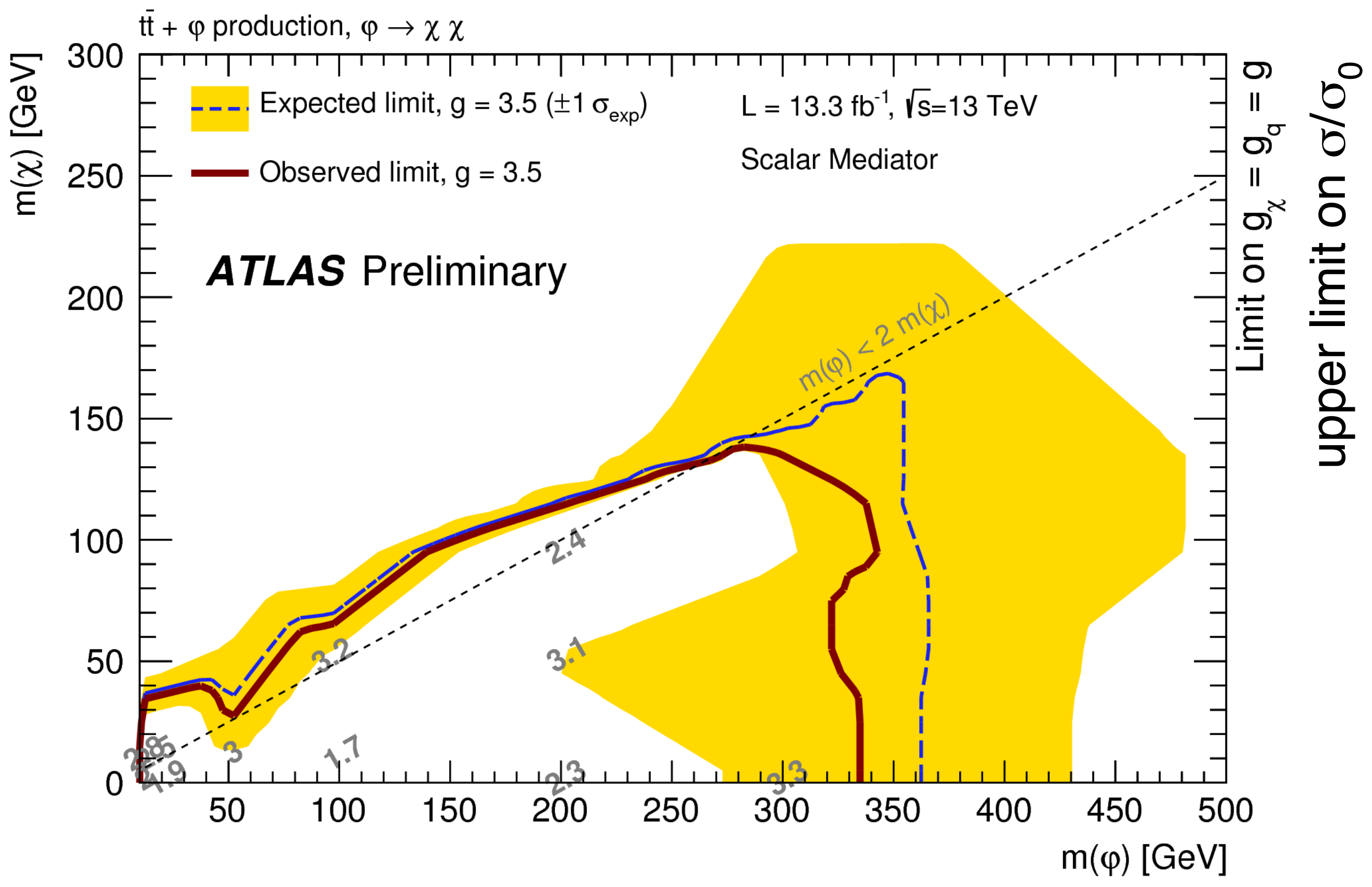


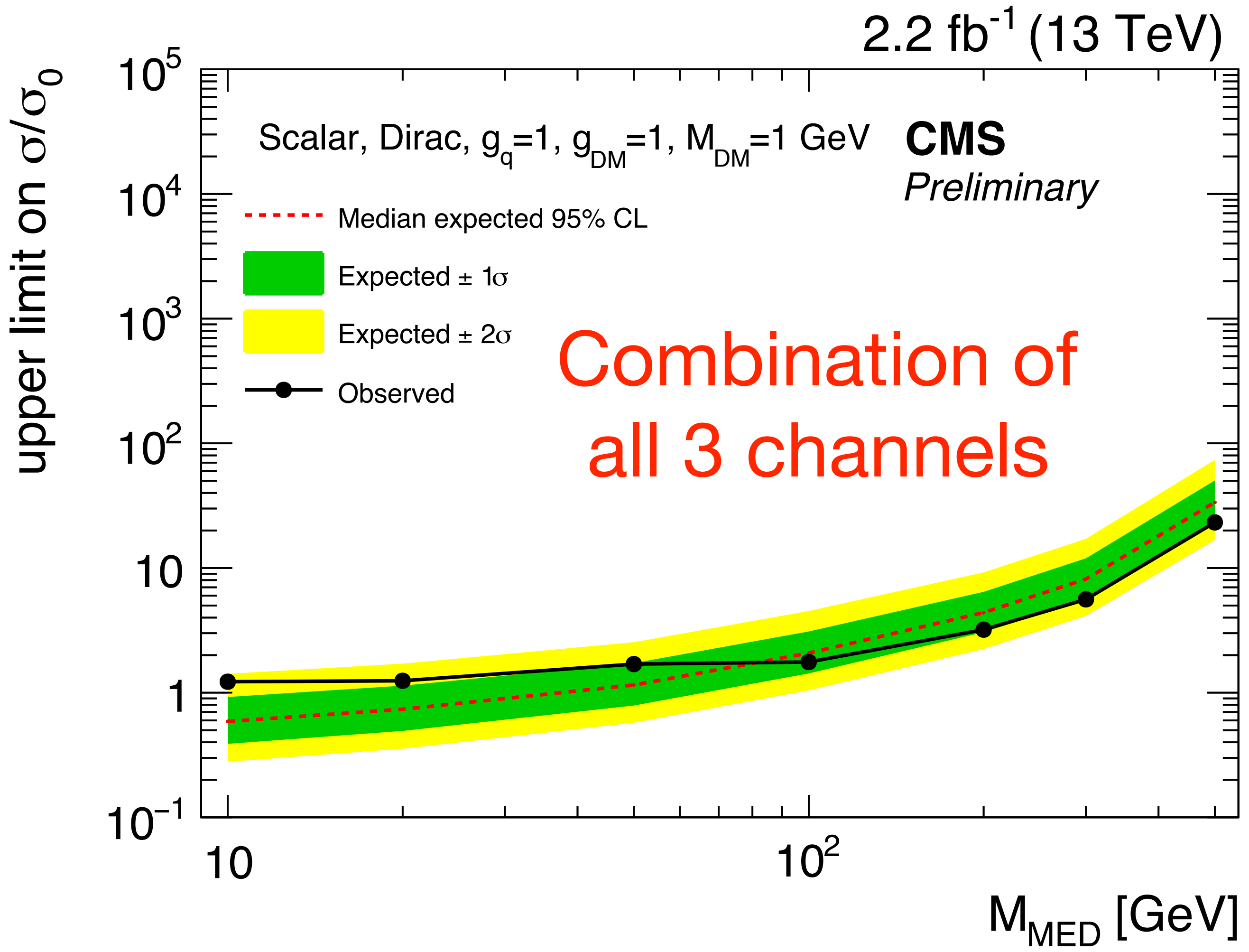
ATLAS-CONF-2016-076
CMS-PAS-EXO-16-028

- Signature of either two electrons, two muons or an electron and a muon with moderate ETmiss
- Backgrounds: mainly from top production, normalization constrained in CRS
- No significant excess above SM expectation is observed in the EmissT distributions
- ATLAS: Observed limits on g= 3.5, for mχ = 1 GeV, the scalar model is excluded for Mϕ < 340 GeV @95% CL
- CMS: only an expected exclusion of scalar mediators with masses up to 39 GeV at 95% CL

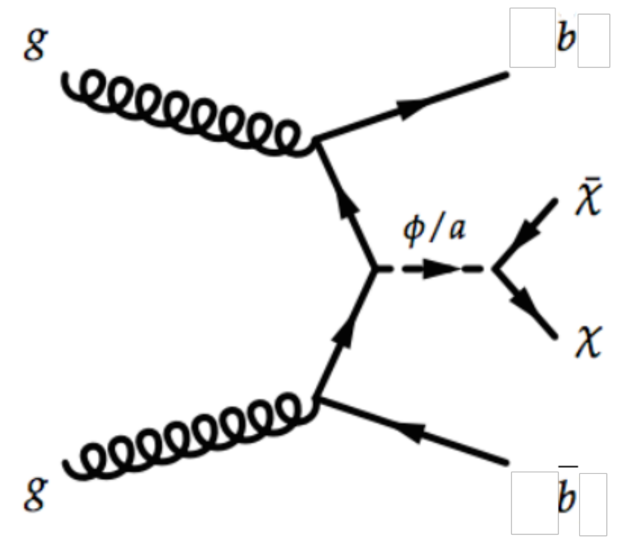


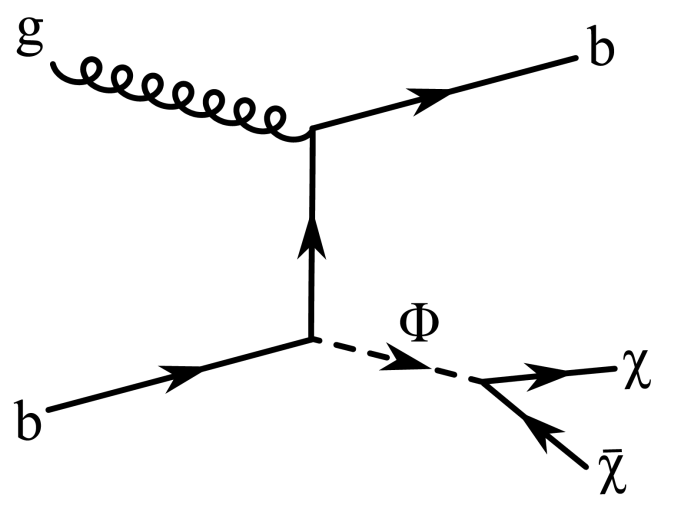






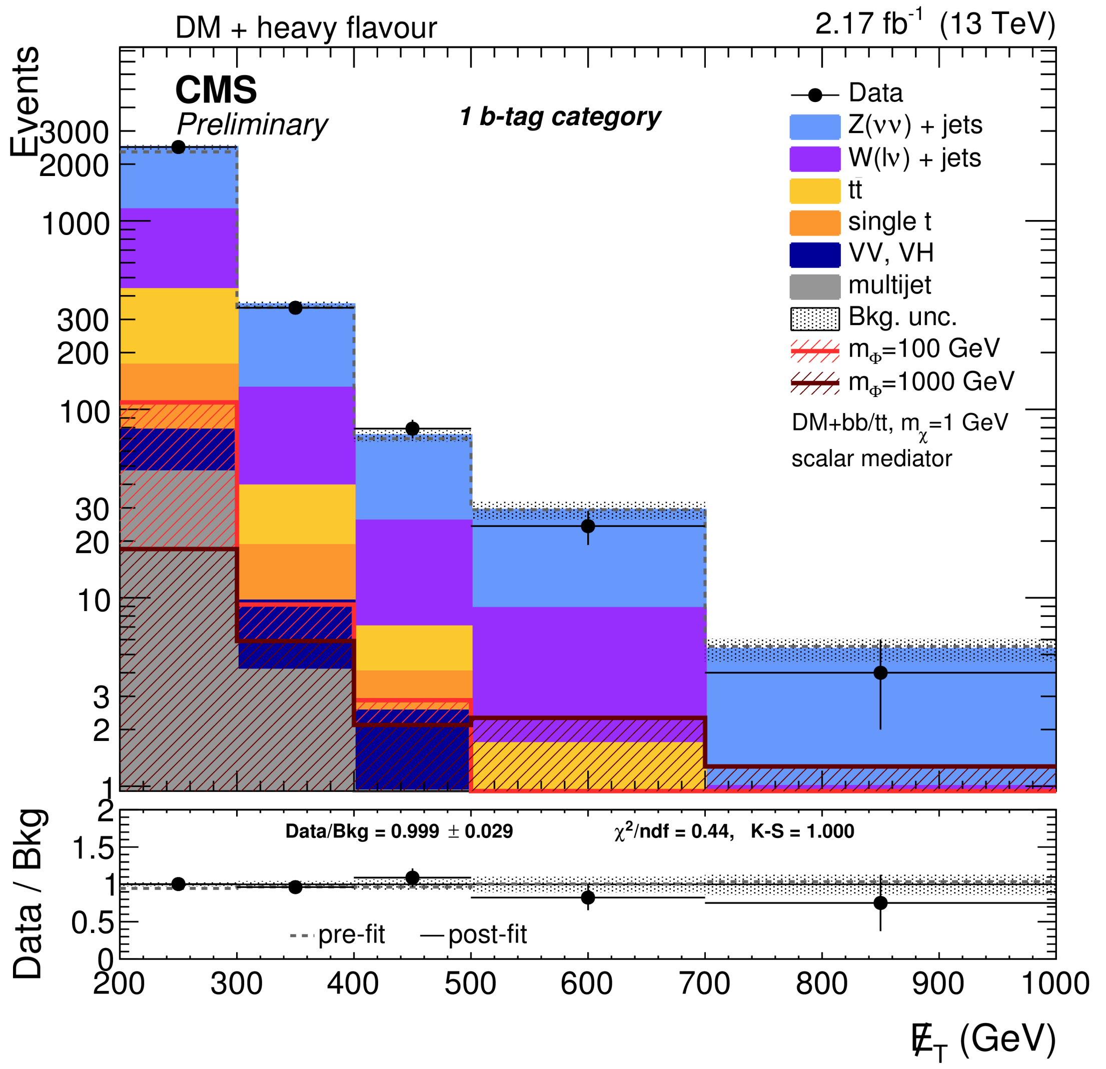
Mono-b/bb

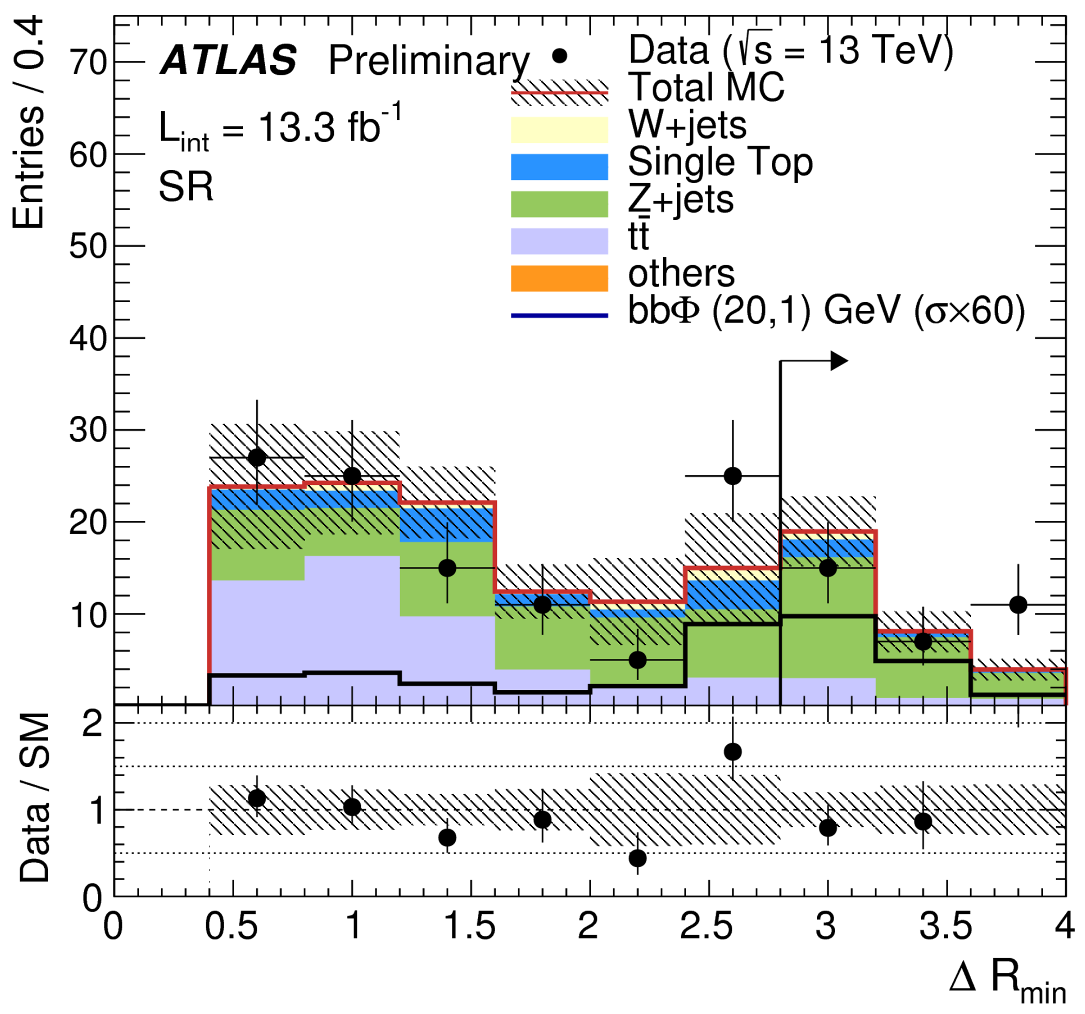


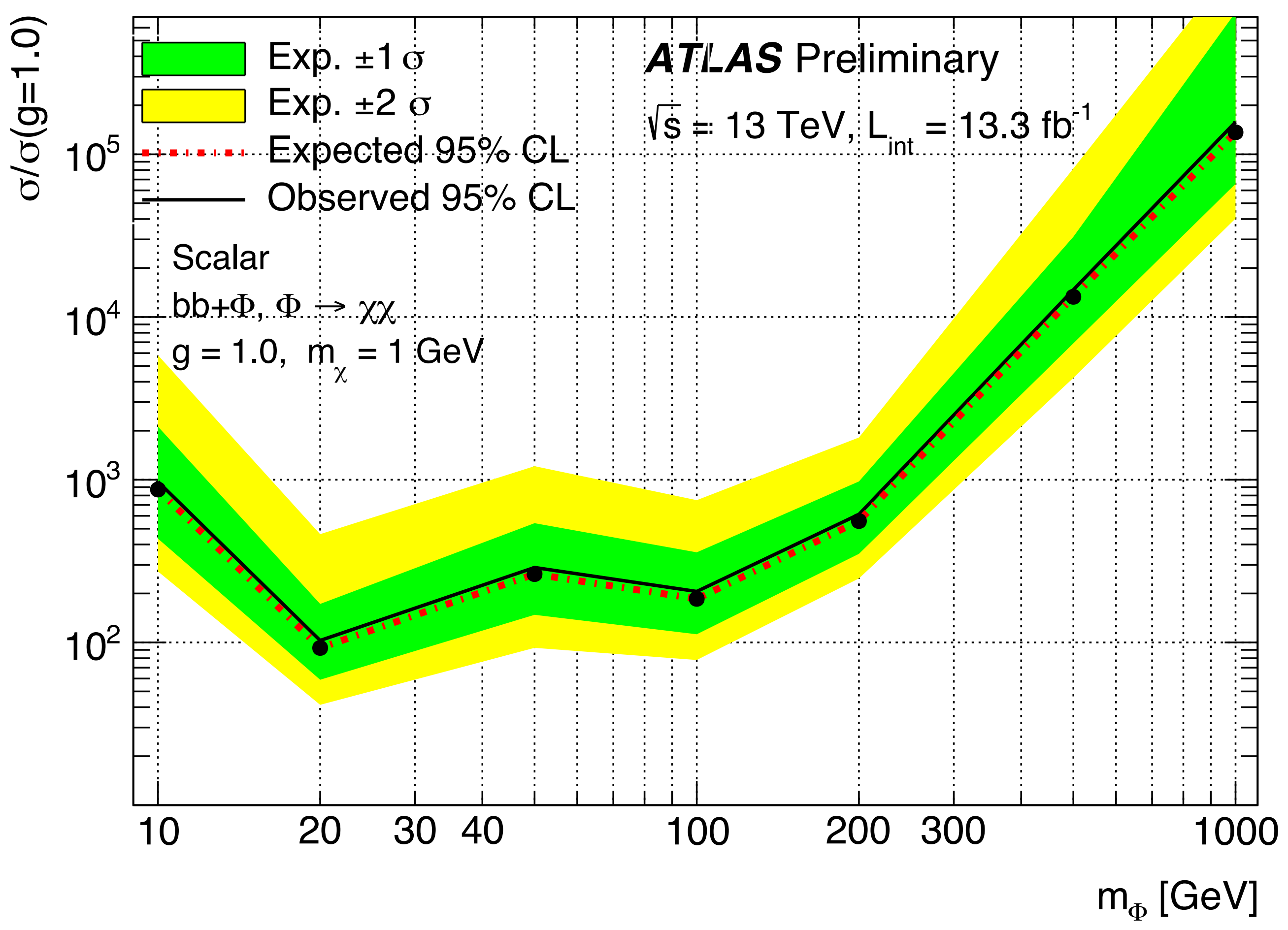


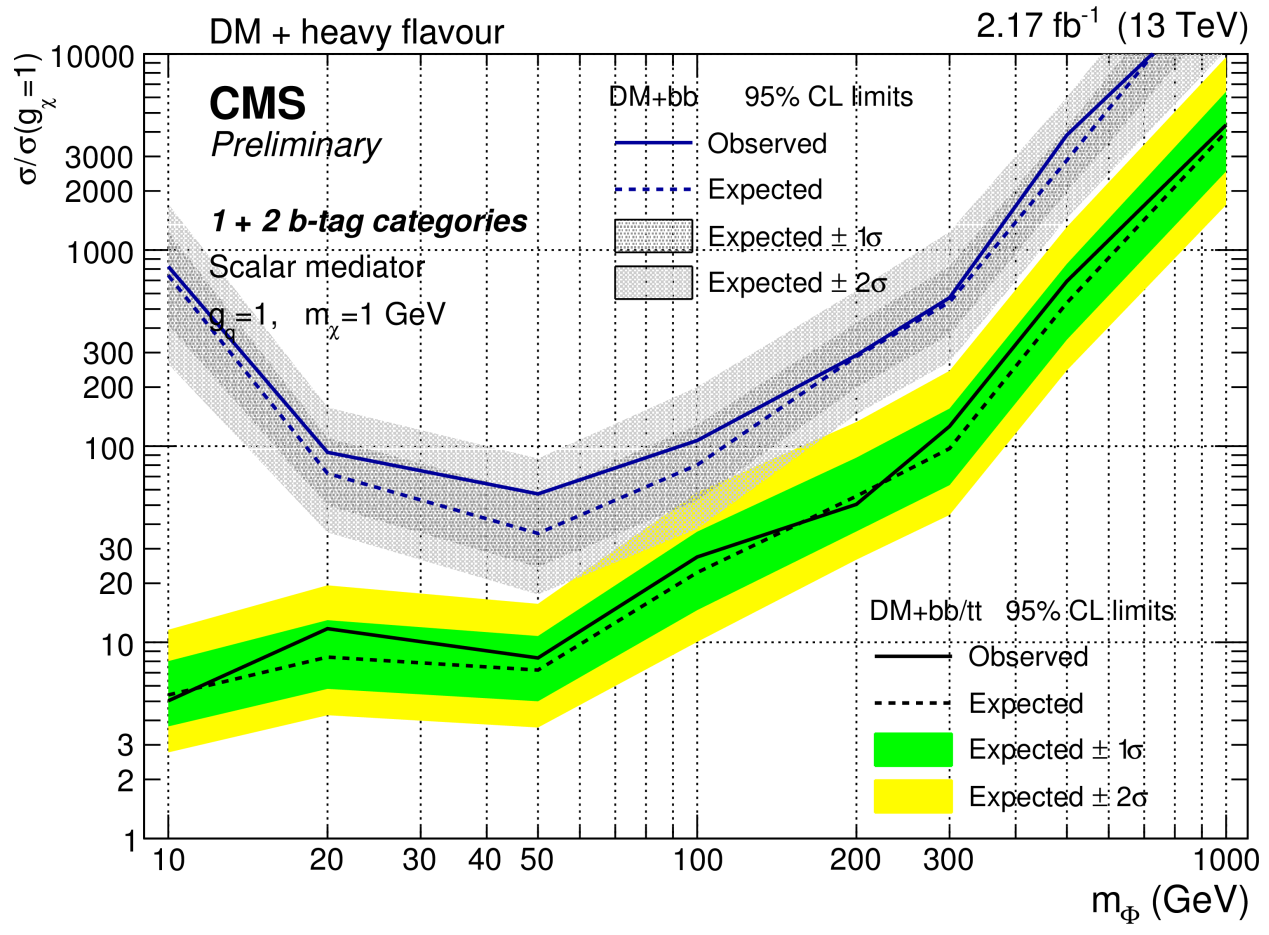
ATLAS-CONF-2016-086
CMS-PAS-B2G-15-007

- Signature of 1/2 bjet, no leptons, and significant MET
- Mains backgrounds: Z/W+jets, ttbar, single-top (constrained in different CRs in data)
- No significant excess above SM expectation is observed in the EmissT distributions
- CMS combines mono-bb and mono-tt with 1 or 2 btag categories
    - no exclusion yet for both ATLAS and CMS @13.3/2.2 fb^{-1}

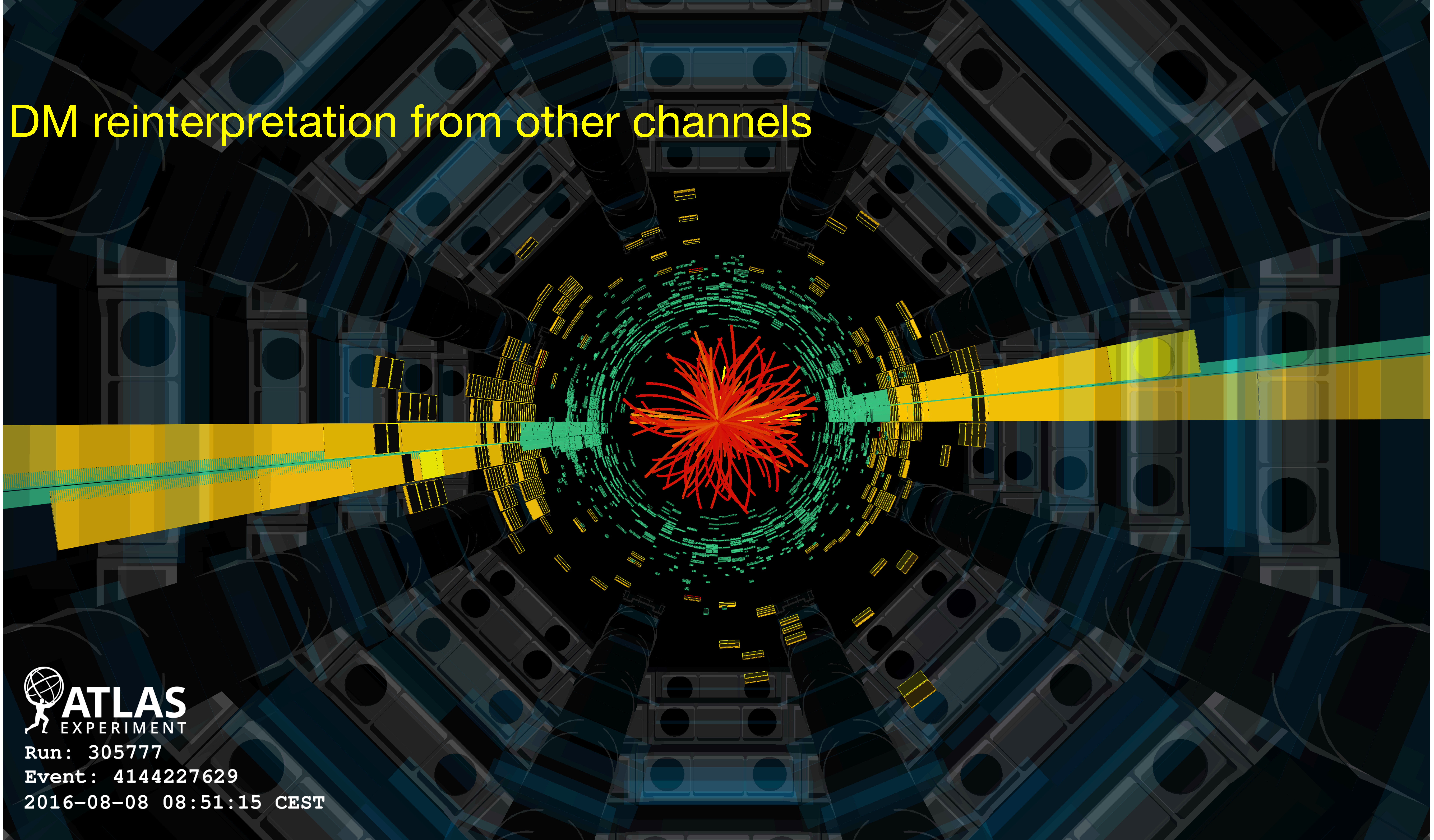






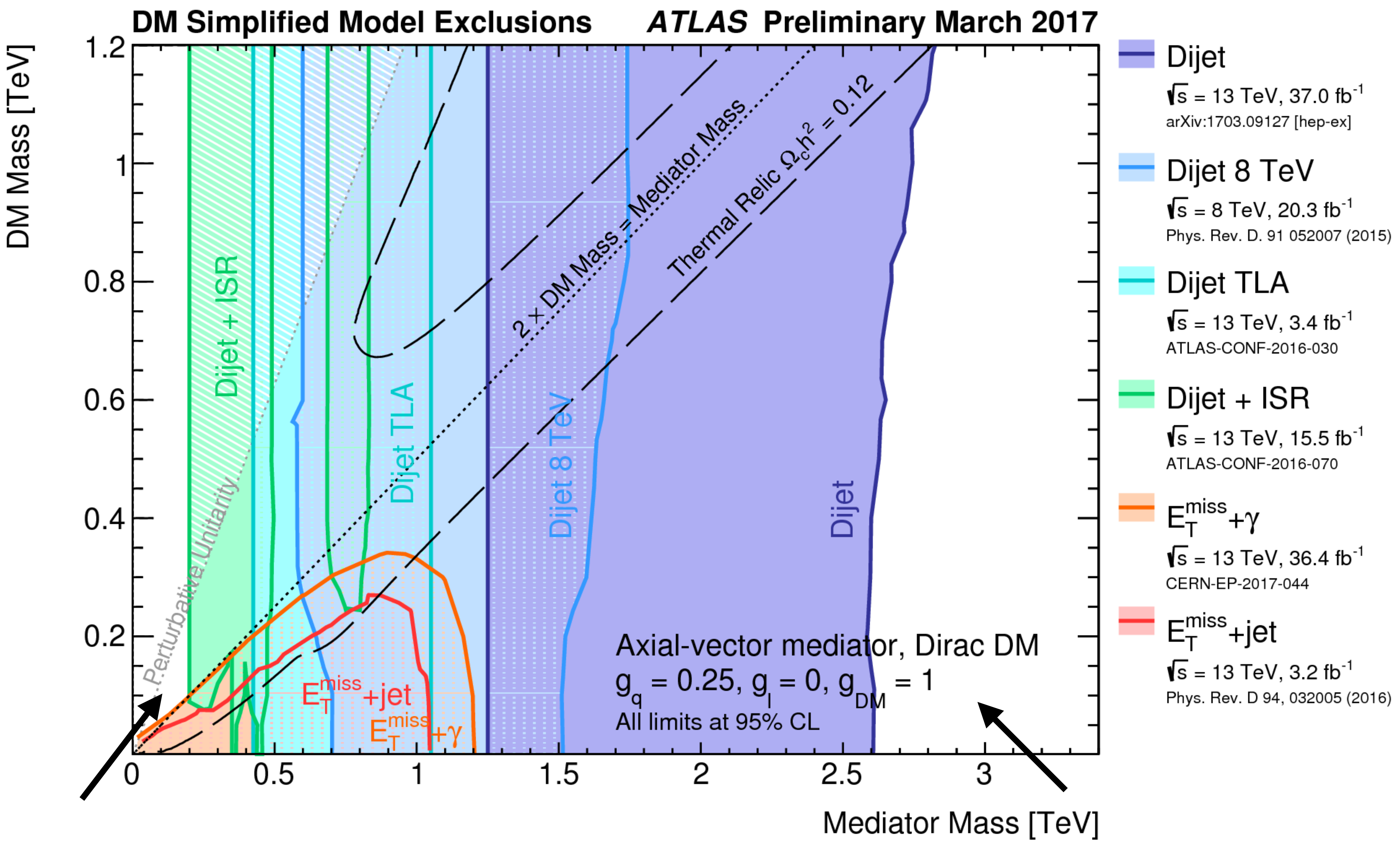


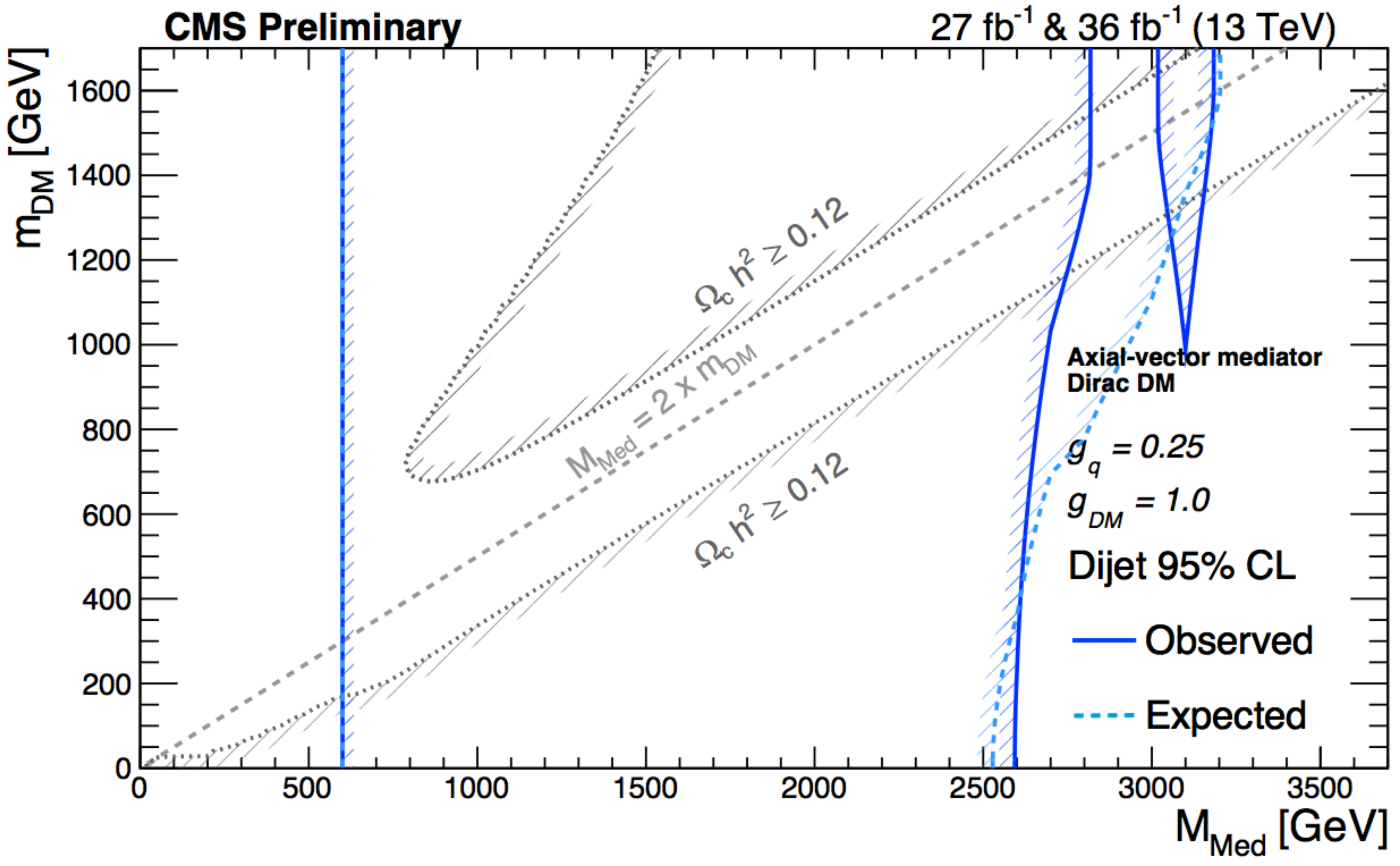
DM reinterpretation from other channels



Recast the limits from interpretation of dijet resonant search

- Vector mediator model with axial axial vector coupling
  - couplings: gq=0.25, gl=0, gDM=1





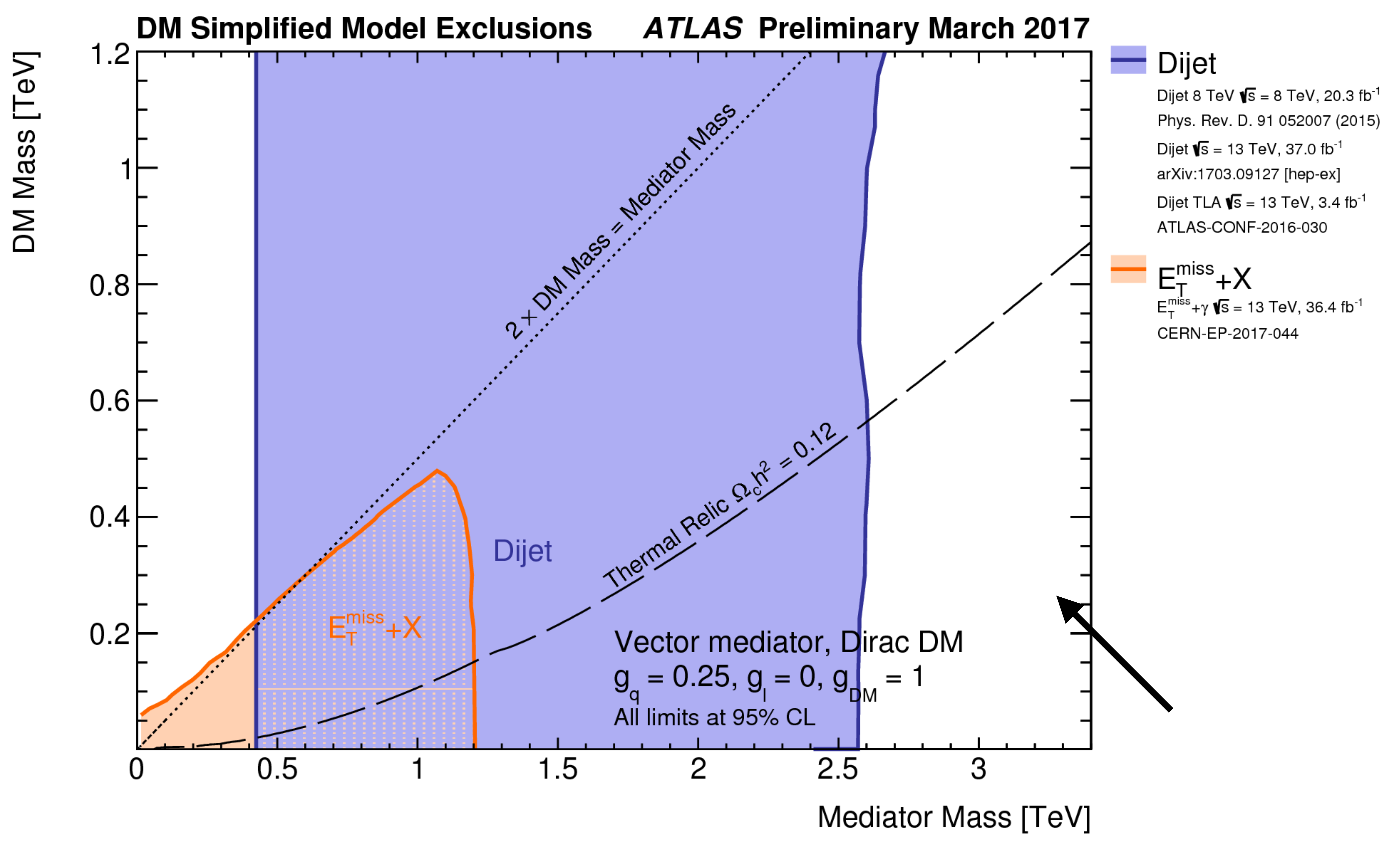
27fb-1 comes form trigger level reconstruction

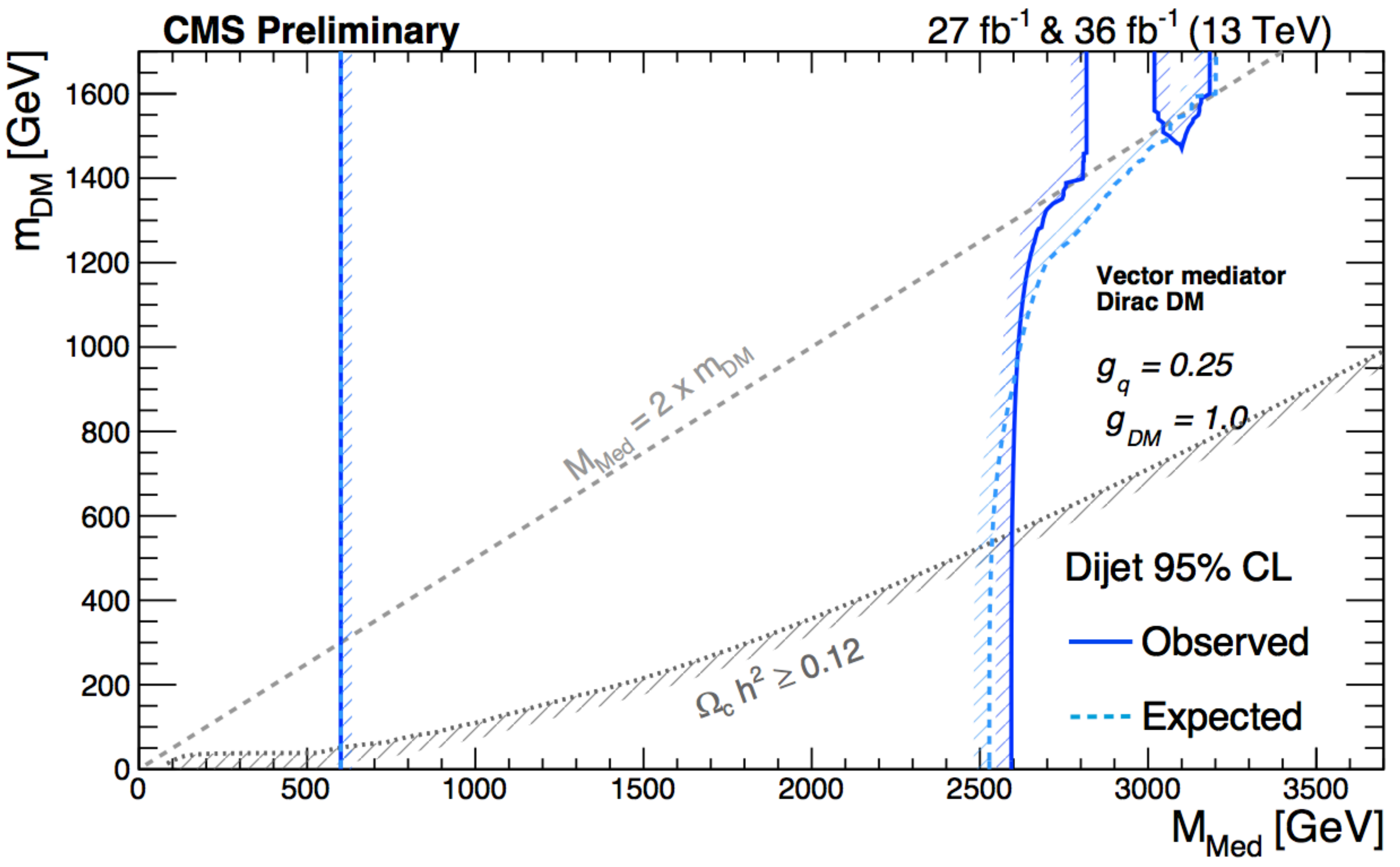
R.-J. Wang | LPNHE, Institut Lagrange de Paris

Friday, April 21, 2017

Recast the limits from interpretation of dijet resonant search

- Vector mediator model with axial vector coupling
  - couplings: gq=0.25, gl=0, gDM=1

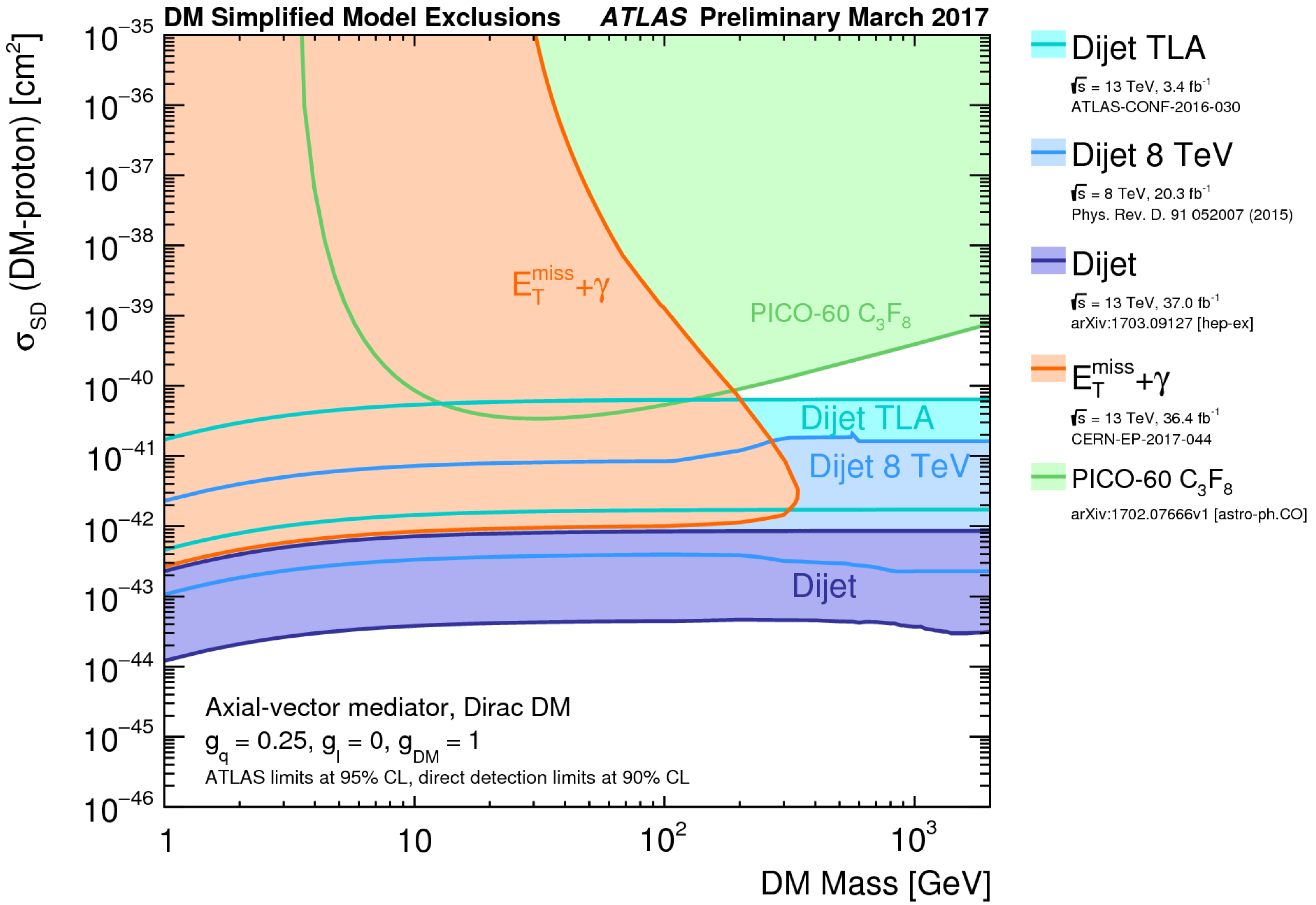


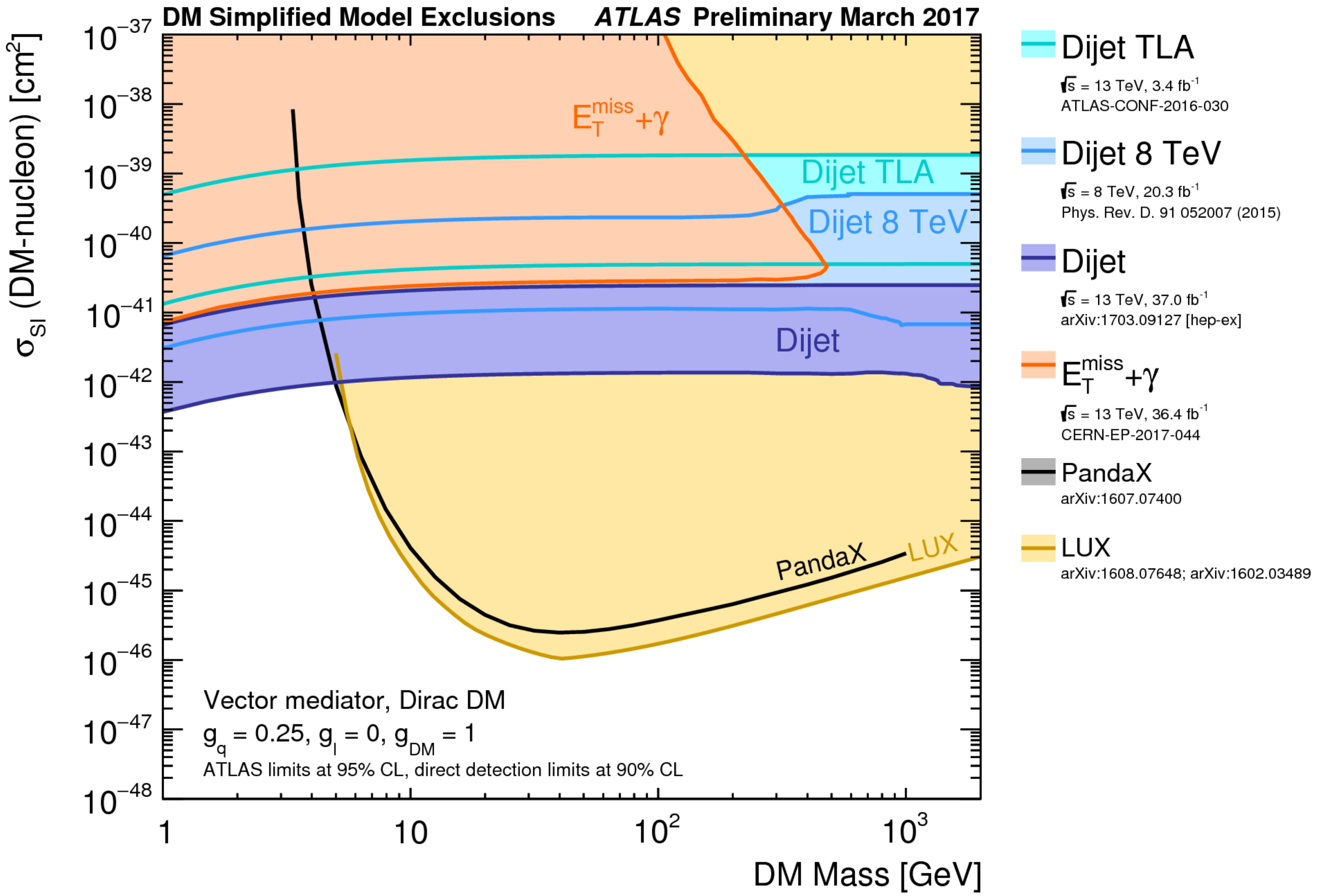


27fb-1 comes form trigger level reconstruction

Recast the limits from interpretation of dijet resonant search

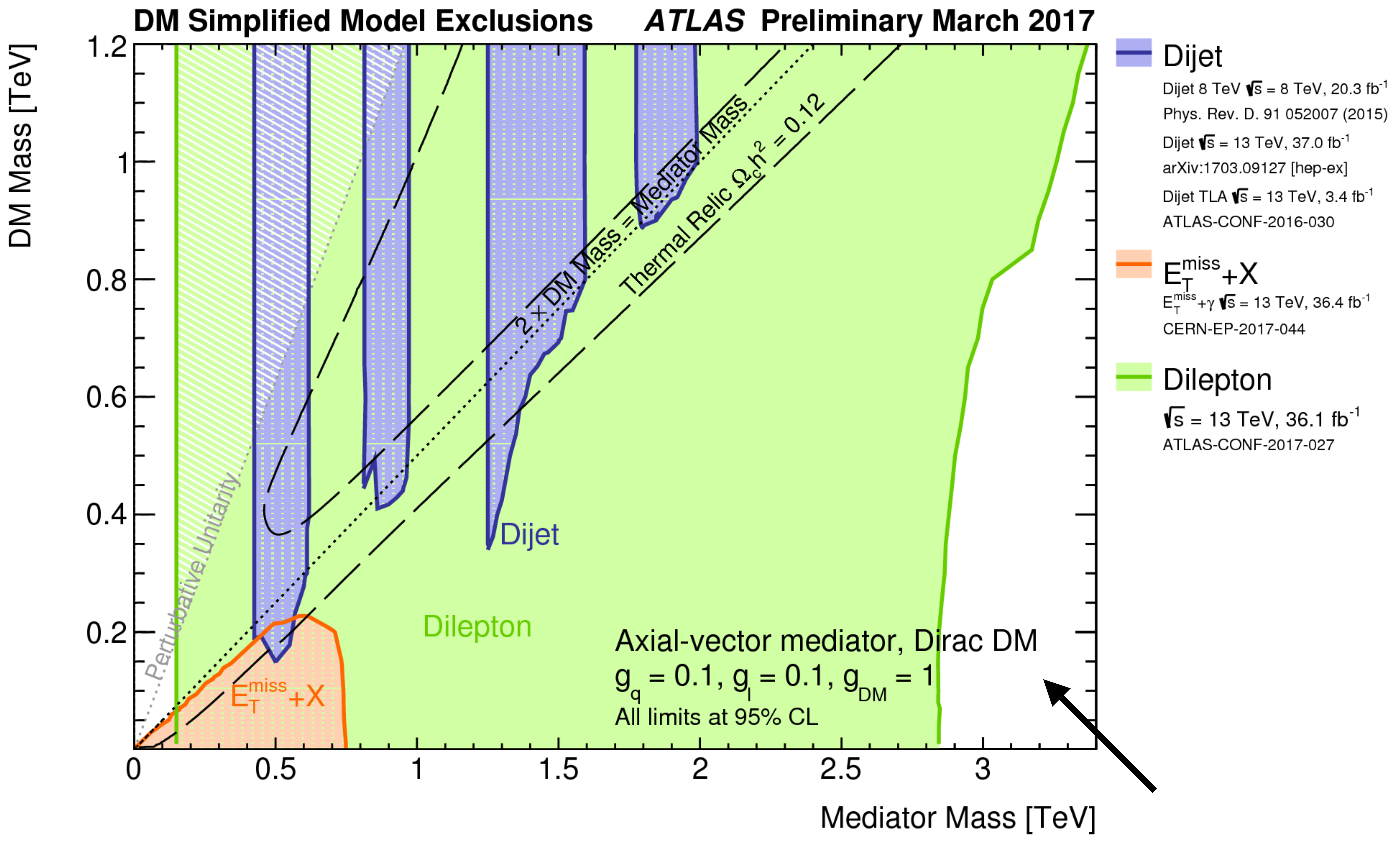
- axial-vector/pesudo-scalar coupling -> Spin dependent
- vector/scalar coupling -> Spin independent

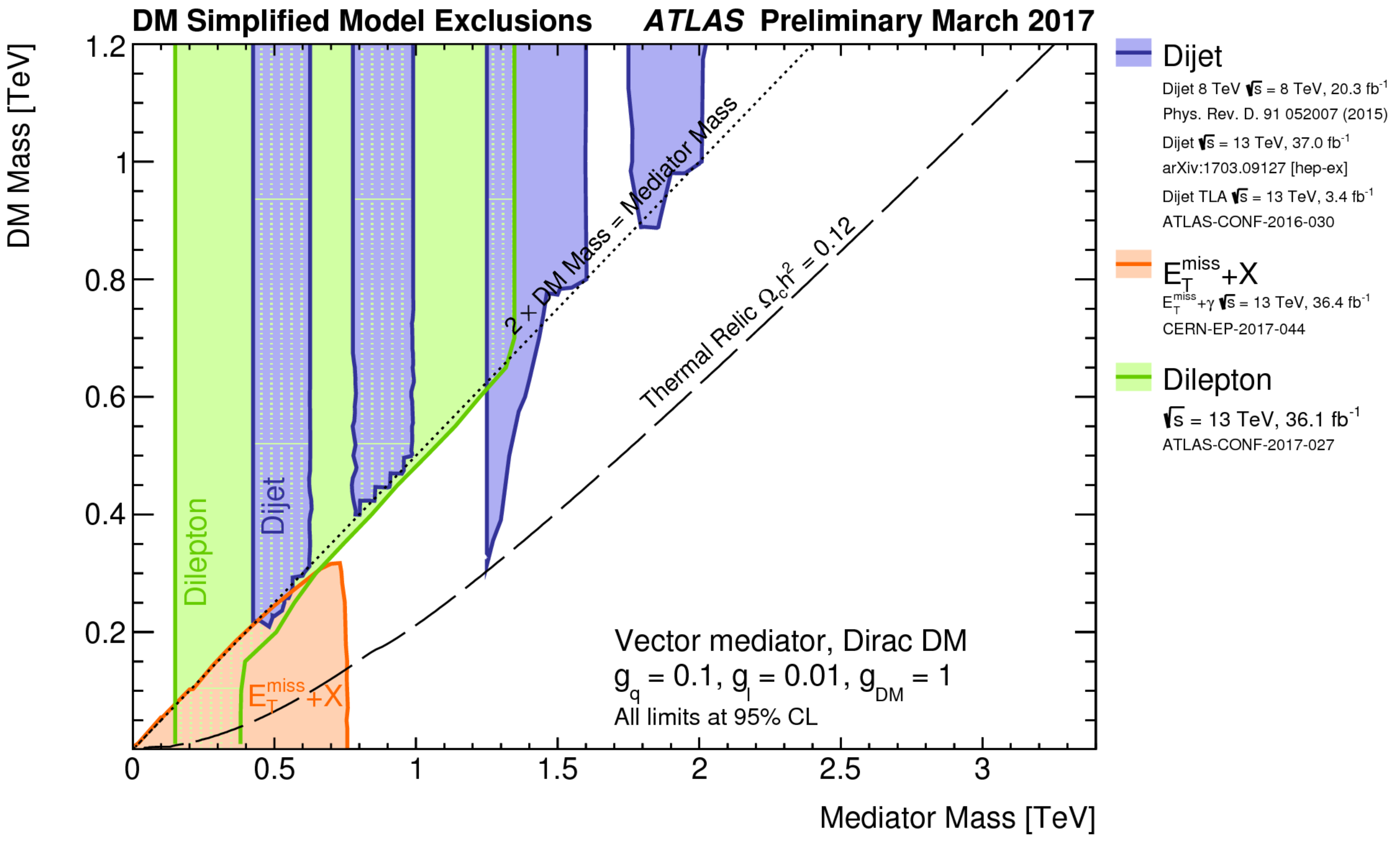




Recast the limits from interpretation of dilepton resonant search

- The leptonic branching ratio allows dilepton searches to impose powerful constraints for a wide range of mediator masses,
    - couplings: gq=0.1, gl=0.1, gDM=1

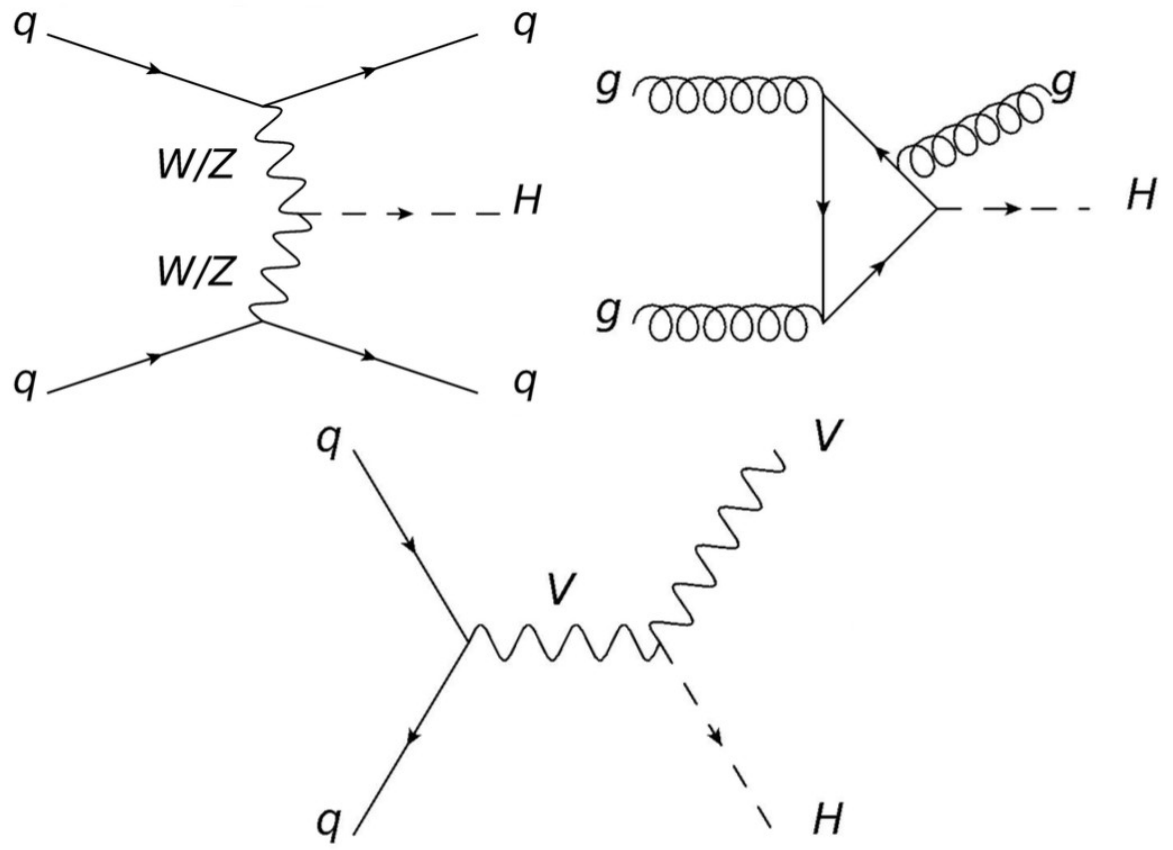


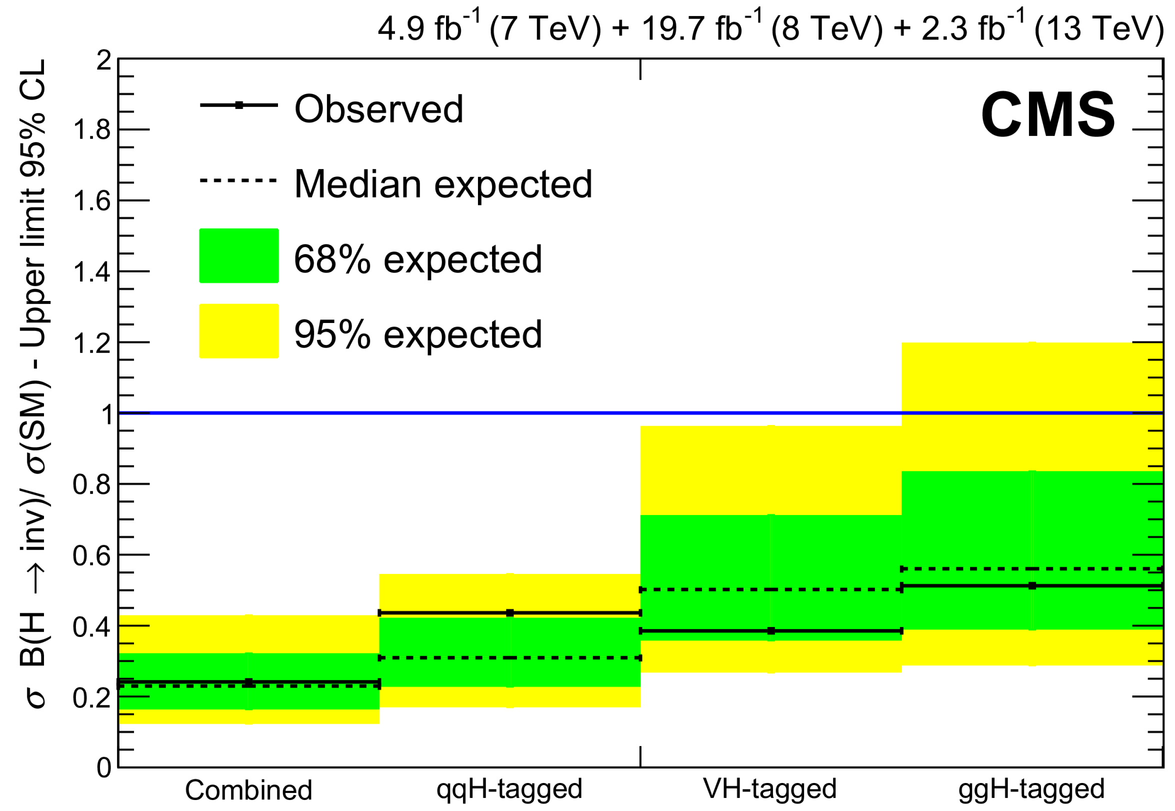


Recast the limits from interpretation of invisible Higgs search

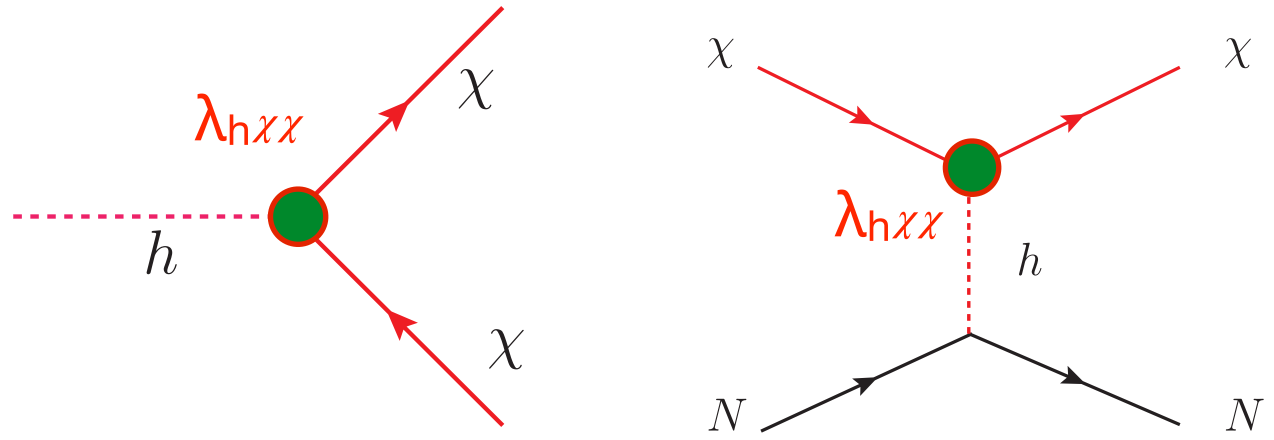
HIG-16-016
ATLAS-CONF-2016-056

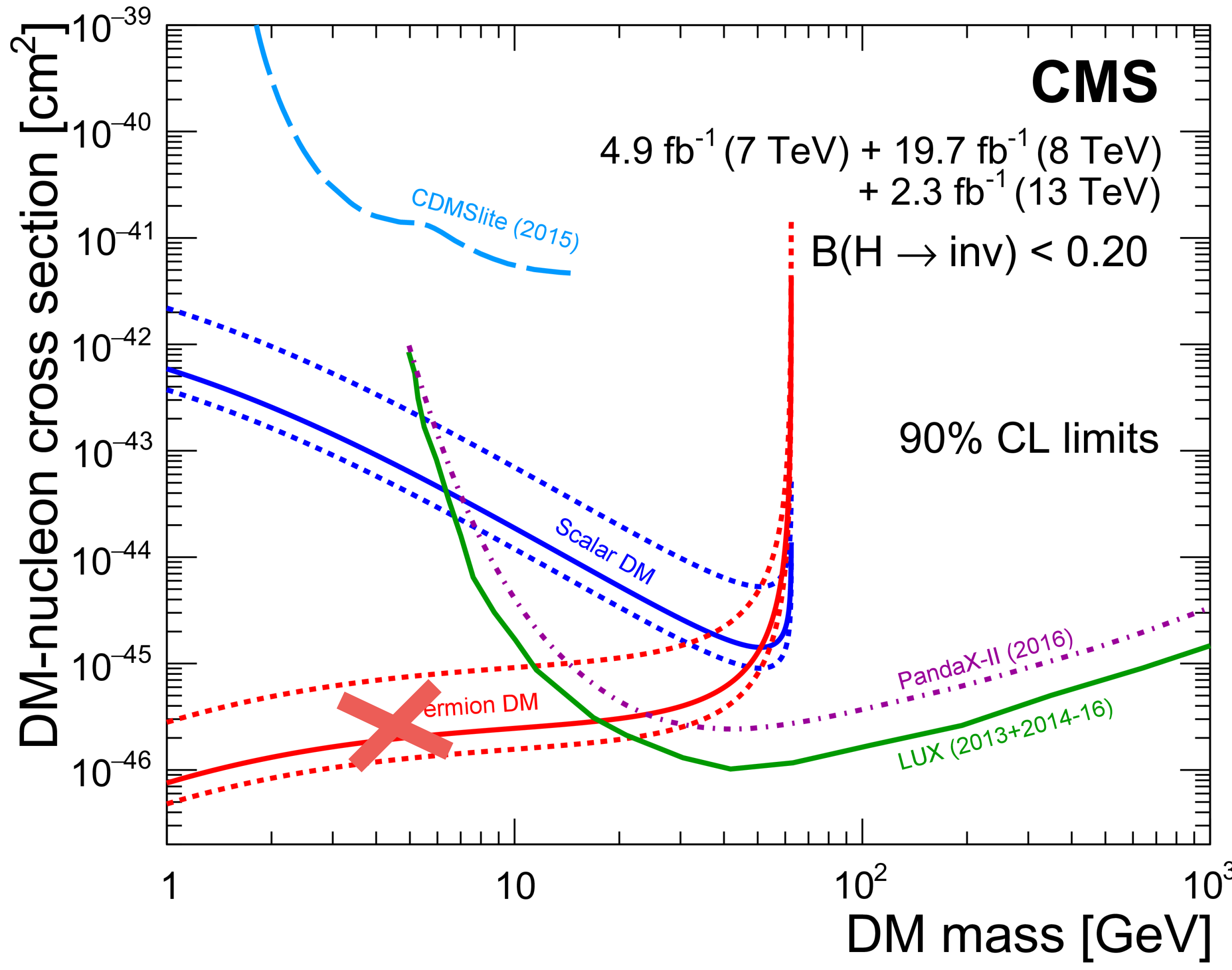
- Higgs portal DM model: a Higgs boson in the only mediator between DM and SM sectors
  - a different idea of searching for DM particles
  - strategy: assume Higgs produced with SM cross section, but having 100% BF to DM particle (Binv)

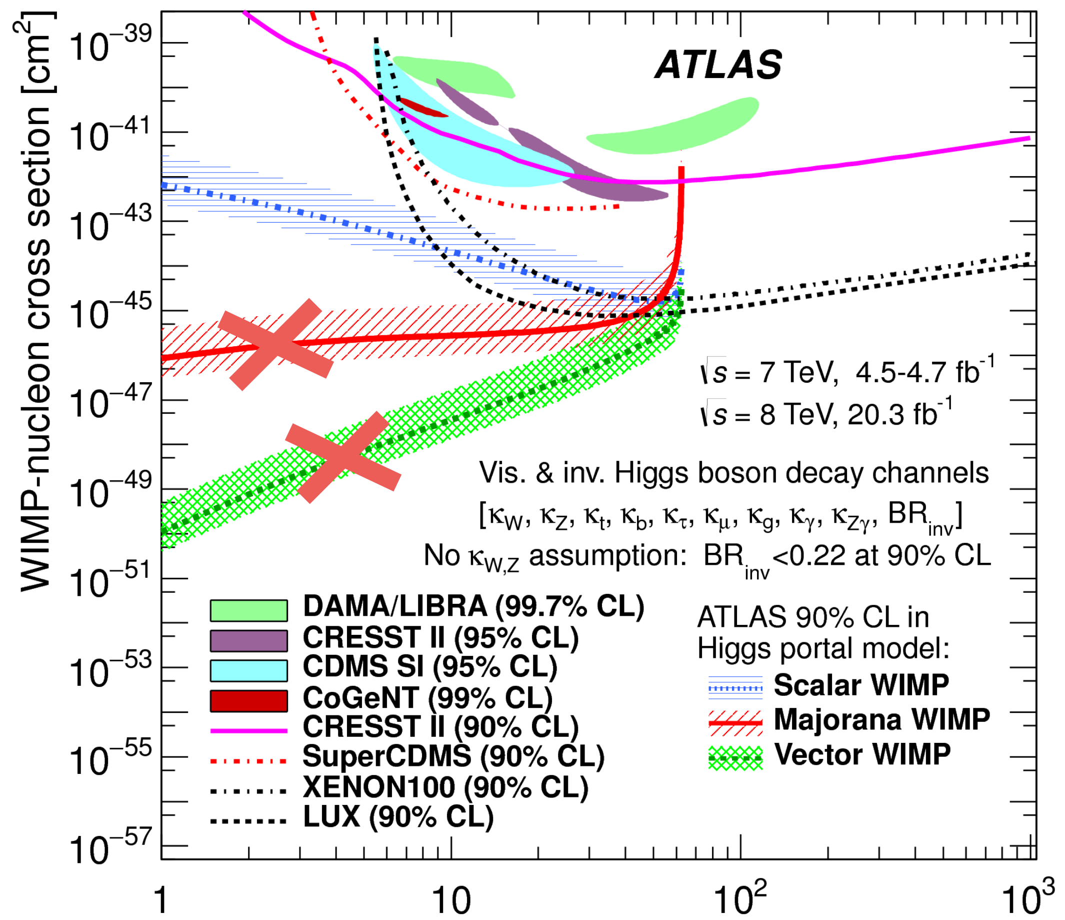




- The limit on the invisible branching fraction of Higgs can be interpreted as bounds of coupling strength $\lambda_{h\chi\chi}$







PRD 90, 055014, 2014

- Spin-1 and 1/2 Higgs-portal DM model are not renormalizable, should be more careful when doing reinterpretation

Conclusions

- Dark Matter searches from ATLAS & CMS at 13 TeV are summarized
  - Common model/interpretation has been made between ATLAS and CMS
  - Most of the signatures with 13TeV results are updated (up to 37 fb^{-1})

- Consistent with Direct and Indirect searches, no DM candidate has been seen at the LHC yet!

- Simplified models are becoming the main focus at 13TeV, but we need to think a little more …
  - Gauge invariance implies the vector mediator couplings to leptons, but already stringent constraints from electroweak precision measurements …
  - The complementary of dijet/dilepton resonant research has added a big exclusion region for simplified model already, there is no big room left…
  - Are there experimental signatures that ATLAS and CMS are not covering …
  - New ideas, future DM models, and reinterpretations...

- ***“We're out of kindergarten, but only in about third grade.” —Vera Rubin (1928-2016)***