DARK MATTER SEARCHES AT ATLAS AND CMS: RUN 1 RESULTS AND RUN 2 POTENTIAL

Caterina Doglioni, University of Geneva

On behalf of the ATLAS and CMS Collaborations

16/03/2015 – 50th Rencontres de Moriond (EW)

Dark Matter at the LHC past and near future searches

1. The heart of the (dark) matter: WIMPs

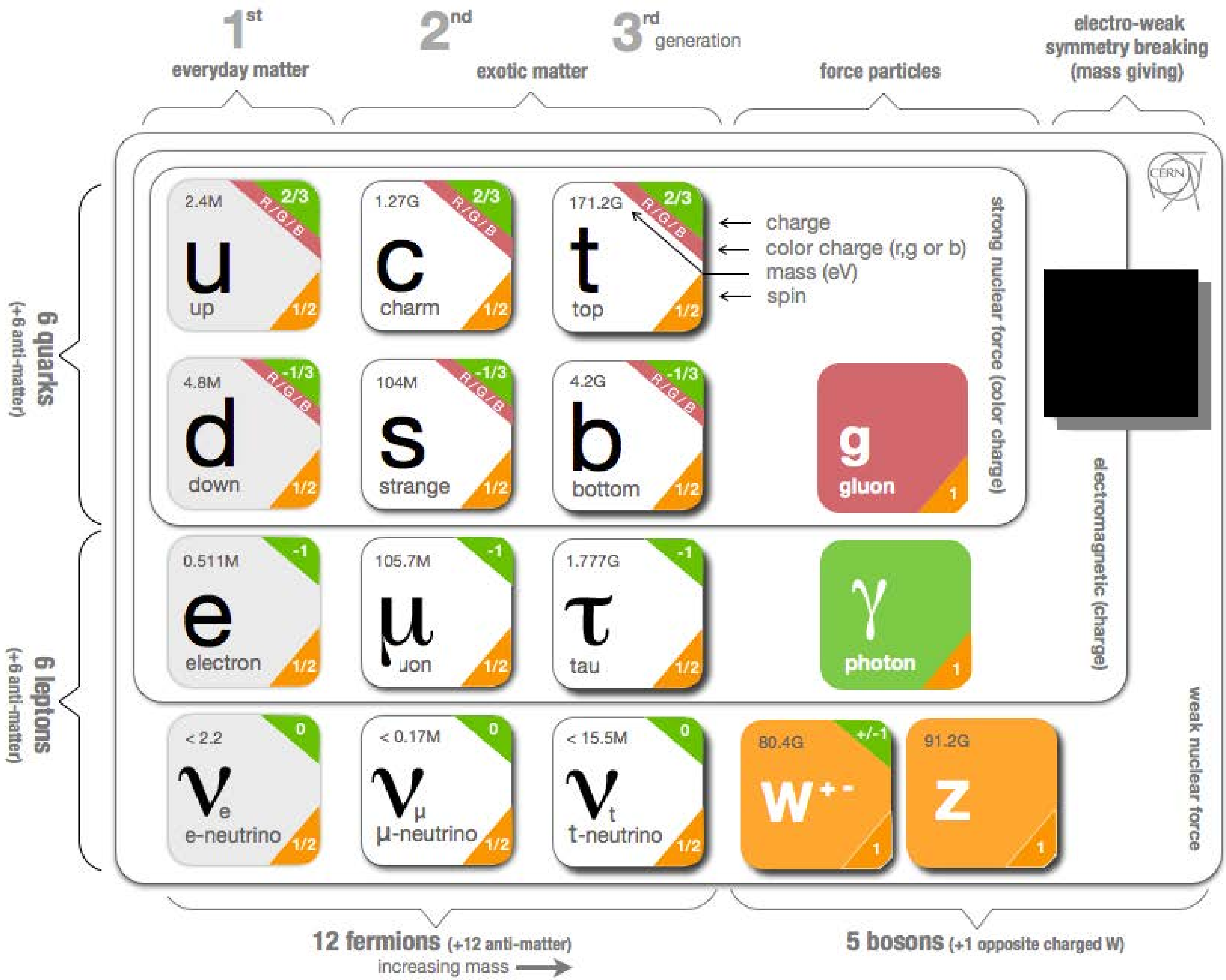
2. MET+X searches and Effective Field Theories:
(jet+MET, W+MET, heavy flavors+MET)

3. The case for simplified models and specific examples
(photon+MET, Z+MET,t+MET, Higgs→MET)

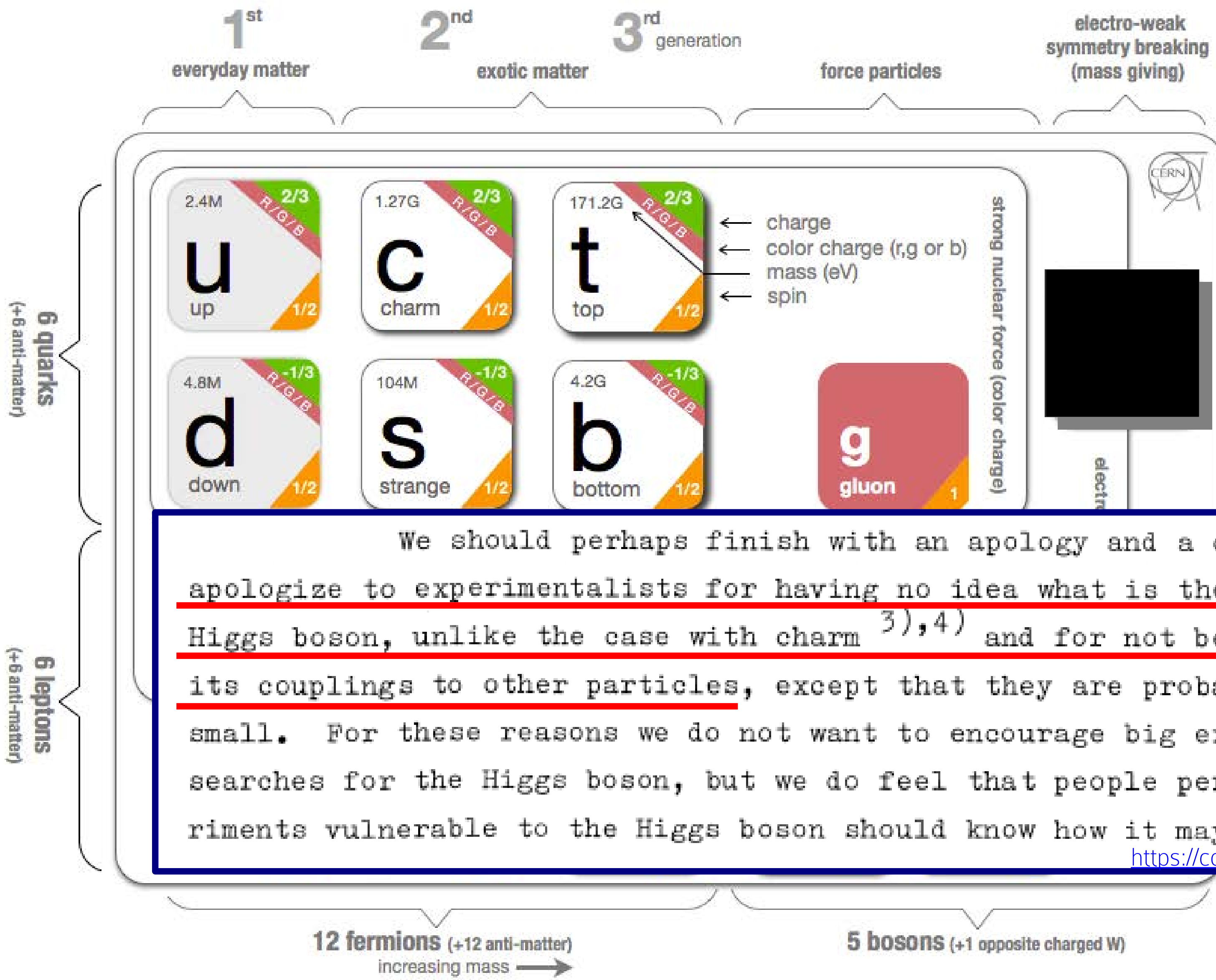
More CMS and ATLAS results:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP

THE HEART OF THE MATTER, PRE-LHC



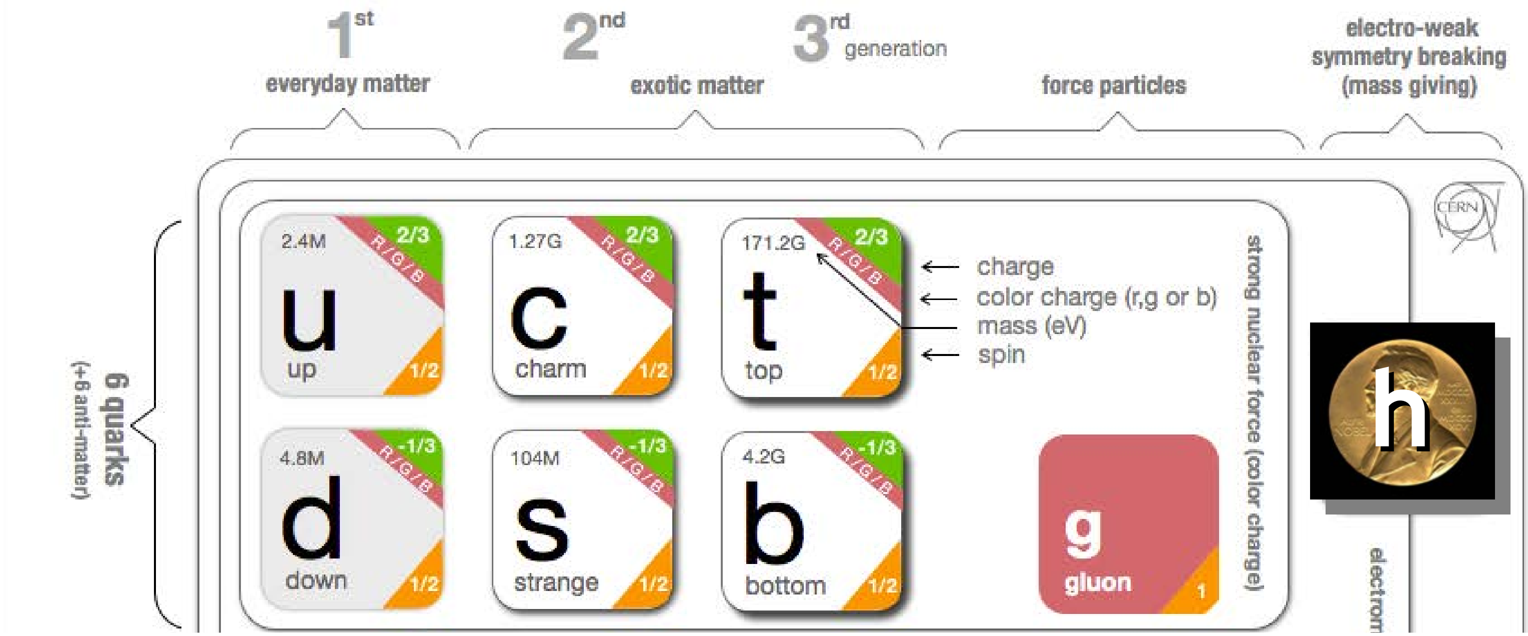
THE HEART OF THE MATTER, PRE-LHC

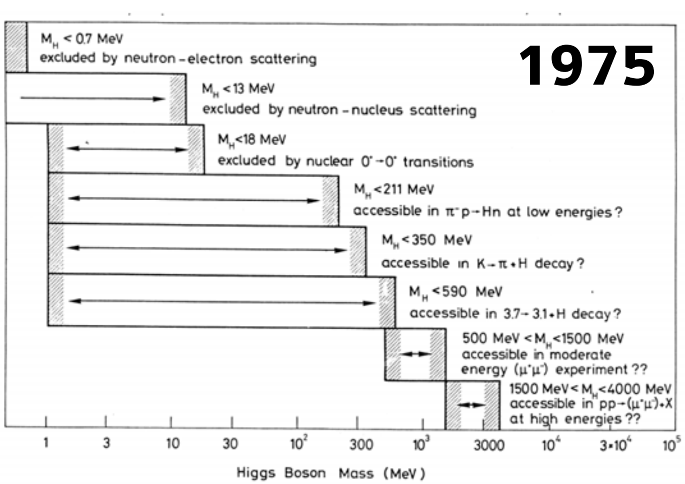


> We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm 3),4) and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

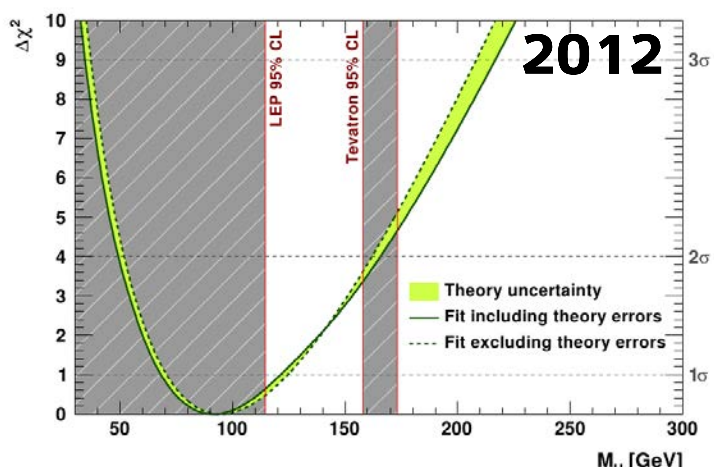
https://cds.cern.ch/record/874049

THE HEART OF THE MATTER, POST LHC RUN-1

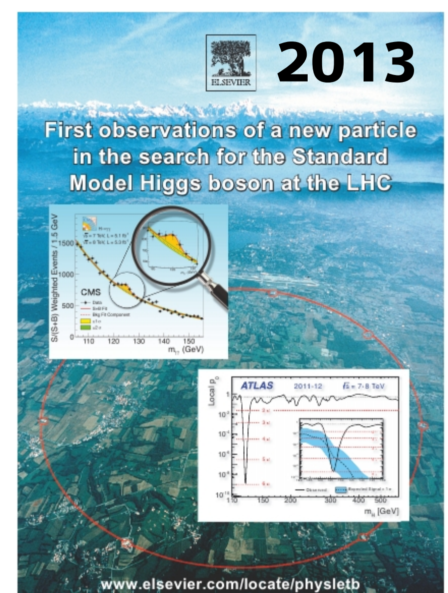




https://cds.cern.ch/record/874049



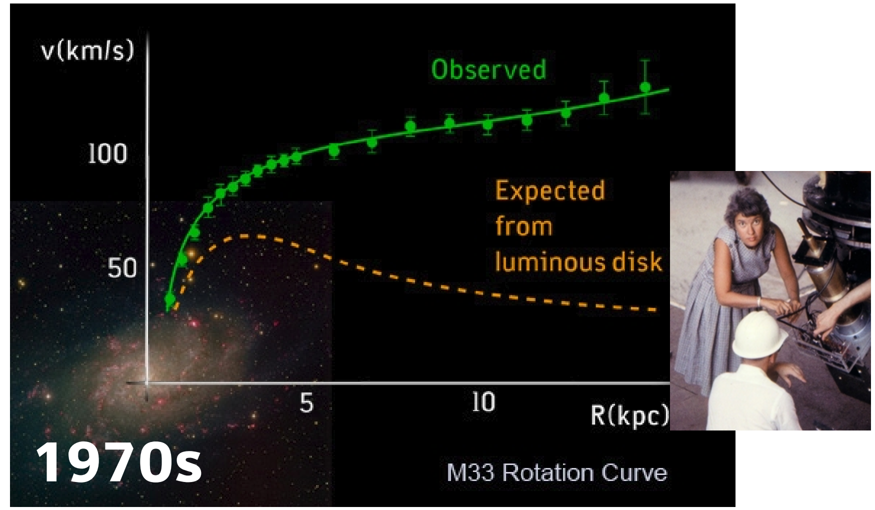
EPJC 72 (2012) 2003

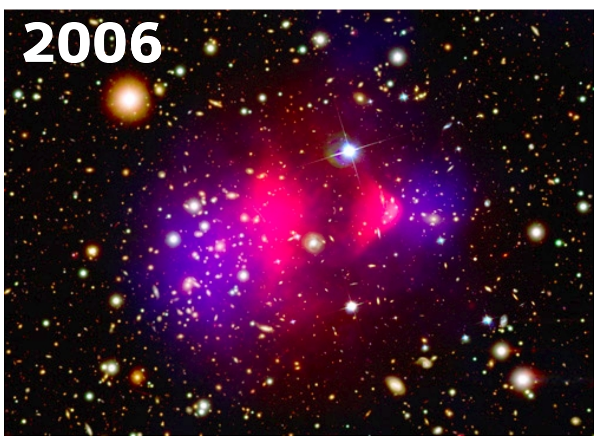


AN EMPIRICAL PROBLEM OF THE SM: DARK MATTER

F. Zwicky – Coma cluster: mass vs light output

V. Rubin – Velocity of gas near Andromeda galaxy

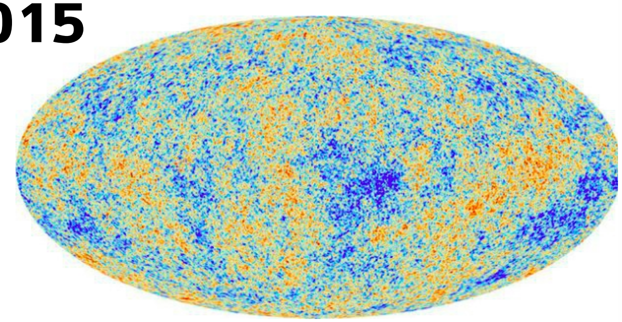


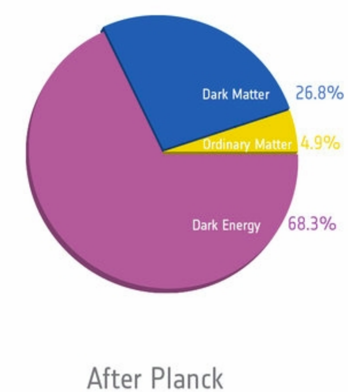


Chandra/Hubble (NASA) – Visible mass of bullet cluster
vs dark mass inferred from gravitational lensing

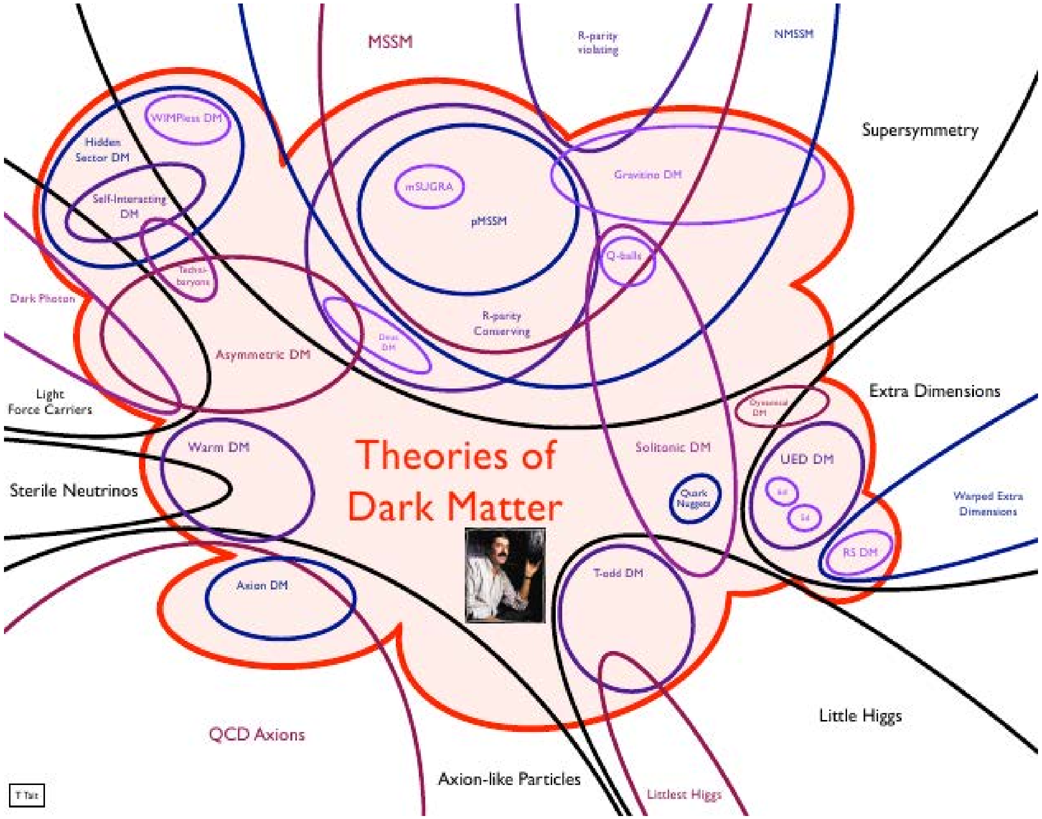
Planck – Dark matter vs standard matter composition
using CMB (temperature) fluctuations

2013
2015

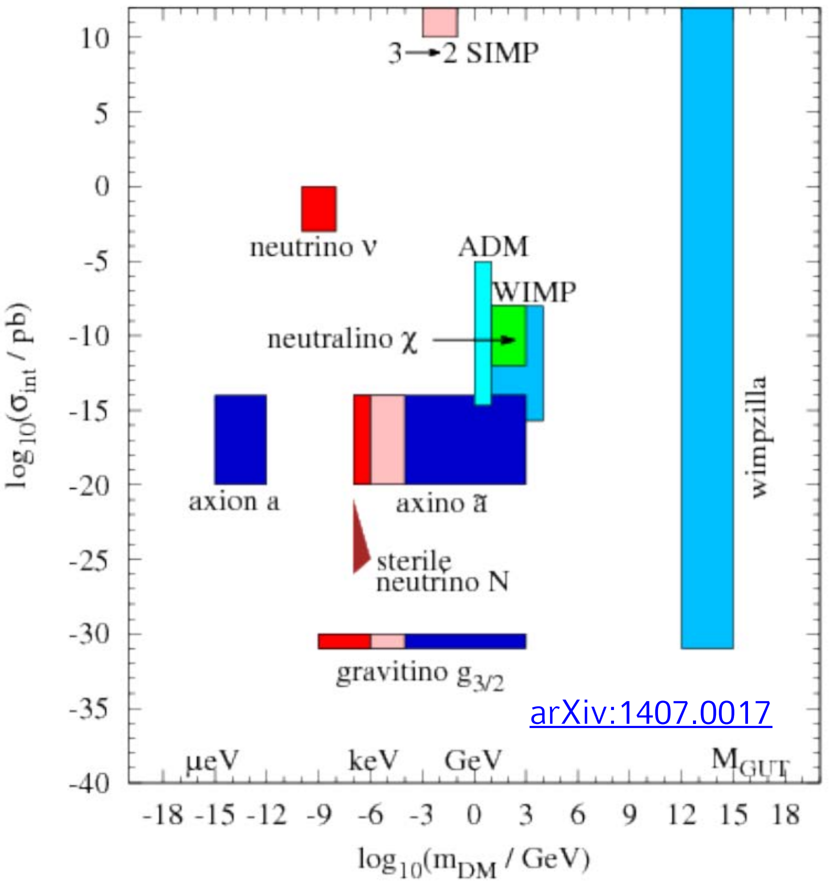




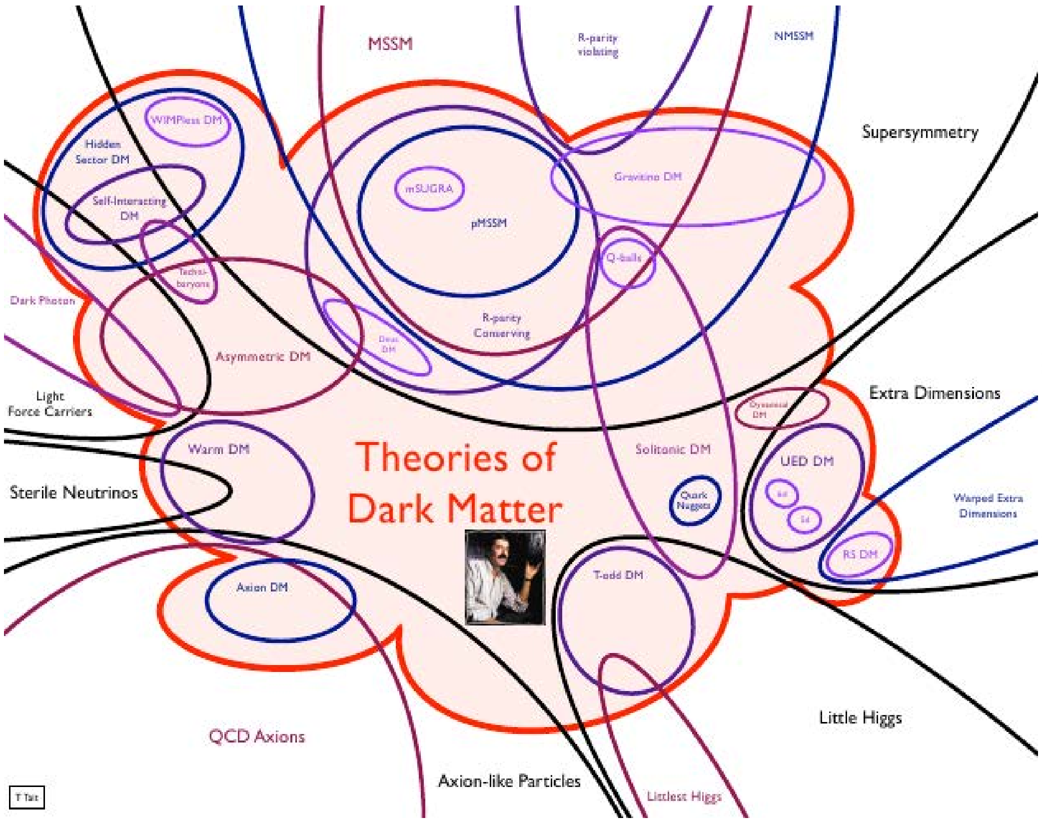
THEORIES OF DARK MATTER



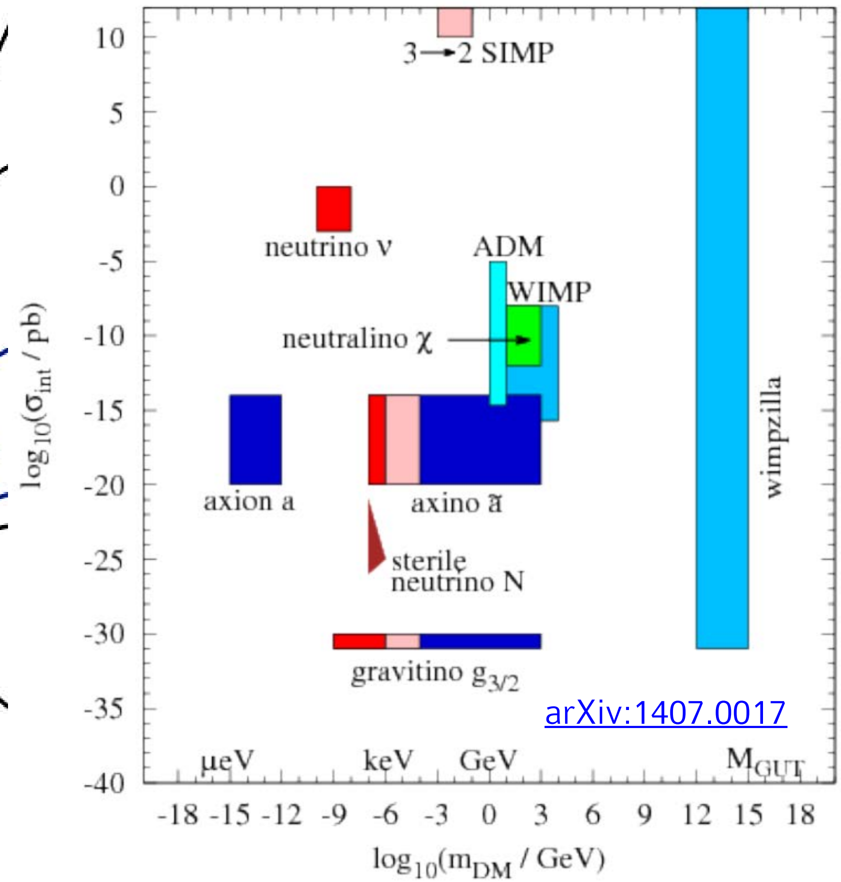
[Tim Tait, DM@LHC 2013]



[arXiv:1407.0017]



[Tim Tait, DM@LHC 2013]



[arXiv:1407.0017]

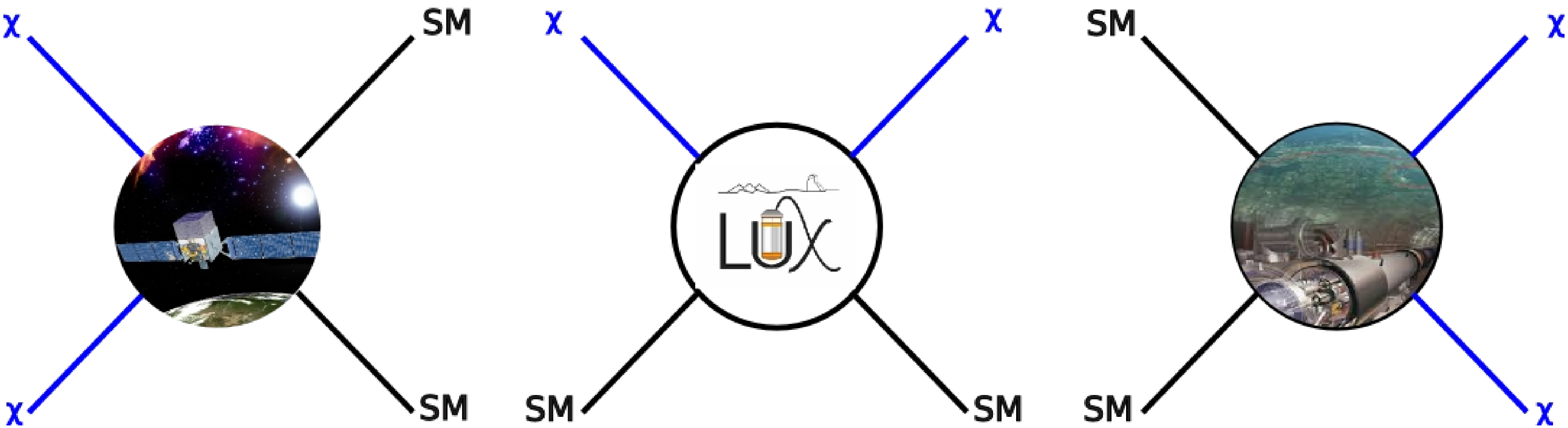
This talk: mostly focus on "model-independent" searches, but **still WIMPs**
(see SUSY talk for more specific neutralino DM, EXO talk for further dark particles)

PREJUDICE: WIMP DARK MATTER

(Our) **preferred DM candidate**
matches cosmological observations (e.g. thermal relic density):
dark, stable, cold, weakly interacting with SM particles,
mass of up to a few TeV → a **WIMP**

Good News! Complementary Dark Matter experiments

Indirect detection | Direct detection | Colliders

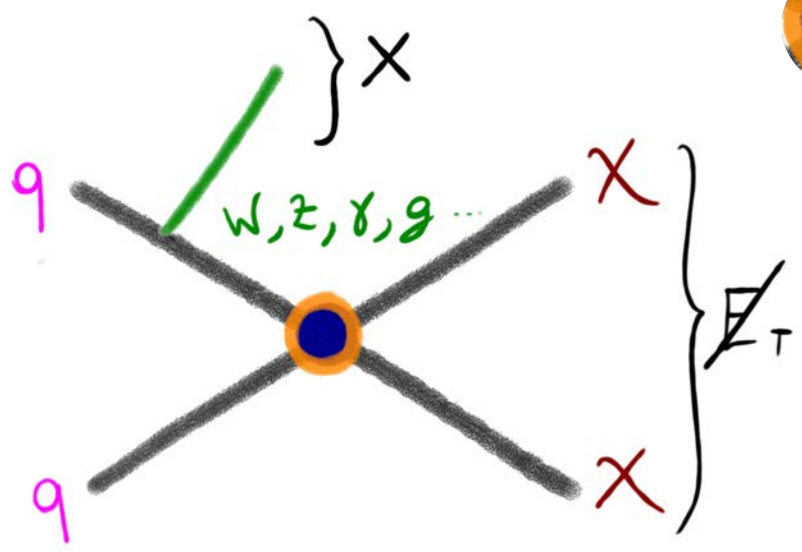


COLLIDER EXPERIMENTS: ATLAS AND CMS

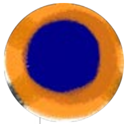
- ATLAS and CMS → **physics with jets, leptons, photons**
  - General-purpose experiments, covering ~ full solid angle
  - Excellent tracking, calorimetry, muon spectrometer

Invisible DM particles escape detection:

LHC experiment strategy: tag events using **recoiling** object(s), measure **missing transverse momentum (Missing E_T)**



arxiv:1008.1783


= **EFT Operators** representing types of DM-SM interactions with DM particles

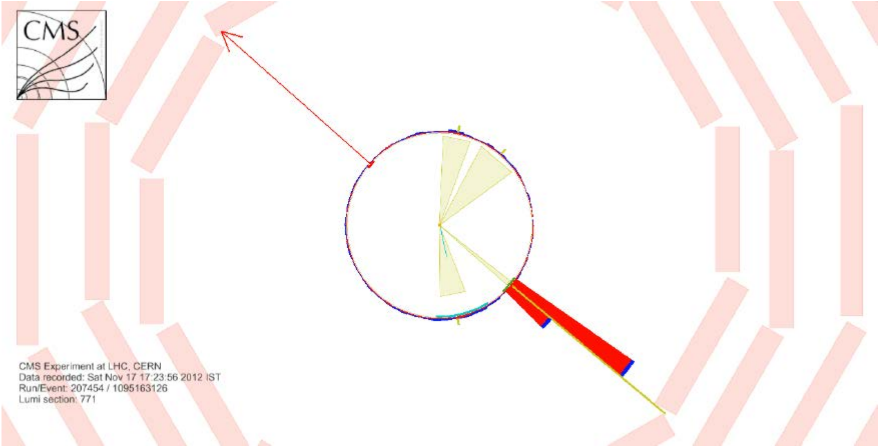
Advantages:
Limited number of degrees of freedom: scale of interaction (M* or Λ), DM mass

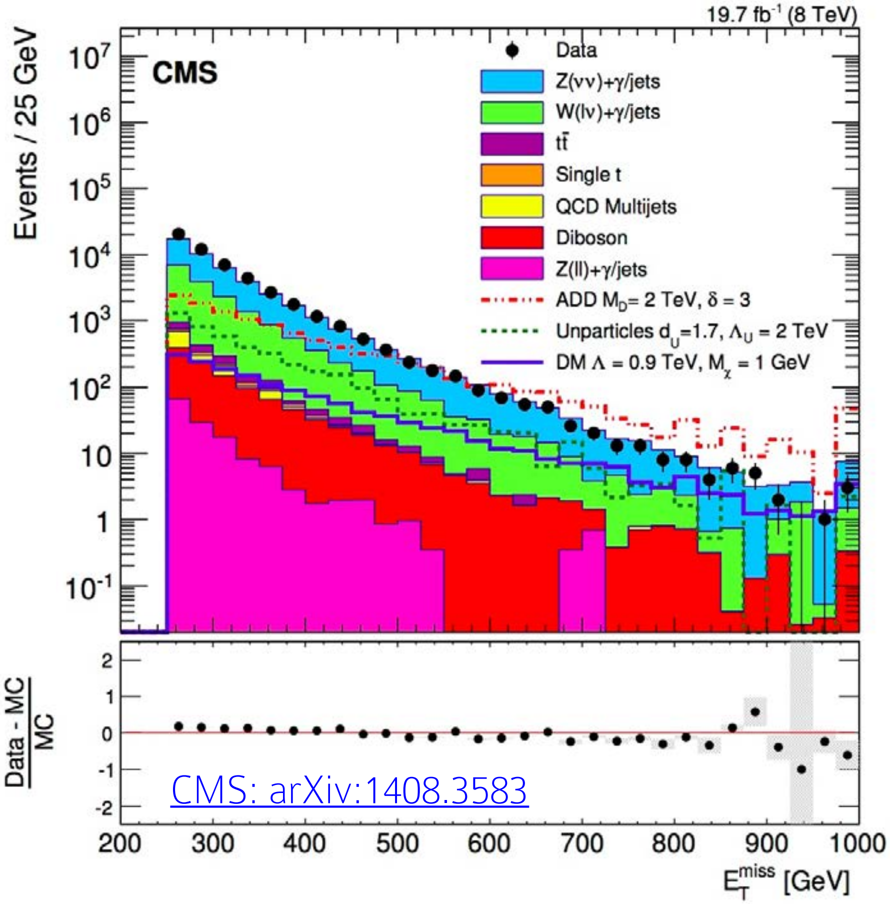
Disadvantages:
Only applicable at **low momentum transfer**

Invisible DM particles **escape detection:**

LHC experiment strategy: tag events using **recoiling** object(s), measure **missing transverse momentum (Missing E_T)**

CMS: arXiv:1410.8812





CMS: arXiv:1408.3583

Dark Matter signature:

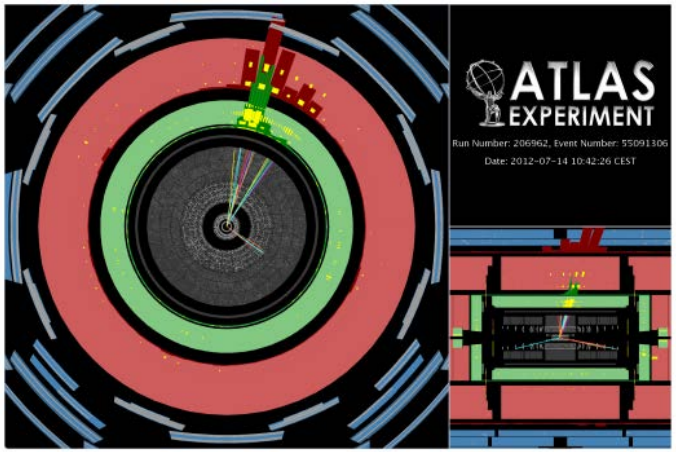
excess in **tails of E_T distribution**

(searches also sensitive to other models)

JET+MET SEARCHES

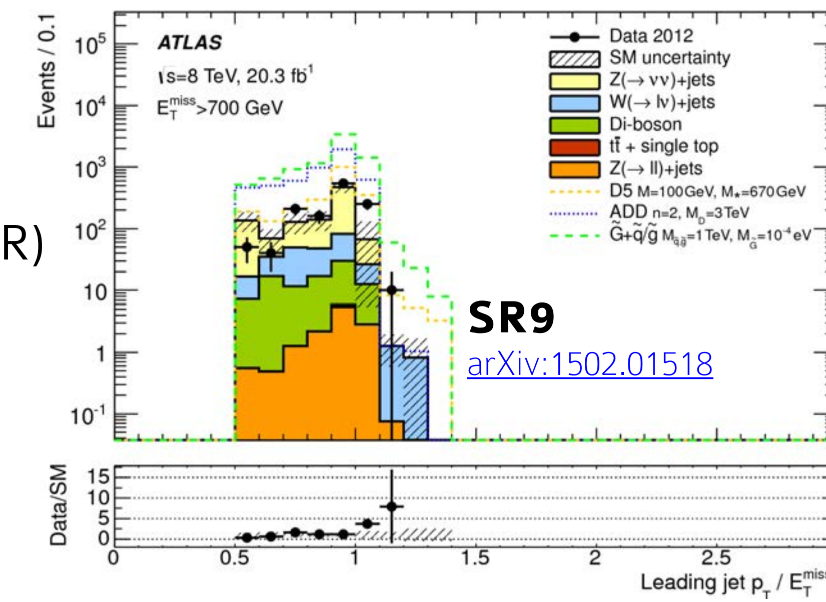
ATLAS: arXiv:1502.01518
CMS: arXiv:1408.3583

Jet+MET: look for excess of events with high pT jet(s), high missing transverse momentum



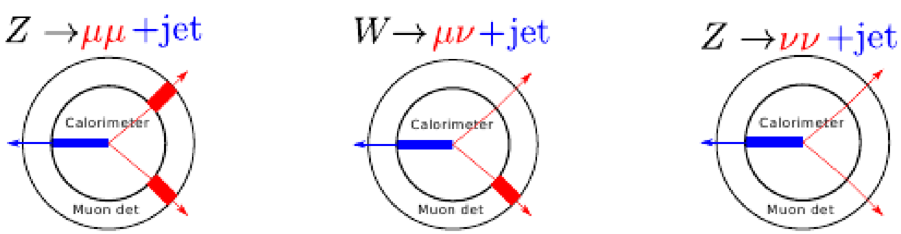
Signal regions (SR):
Cut and count analysis, varying jet pT and MET thresholds

Dominant background uncertainties:
W/Z backgrounds (theory, CR stat.)
Object reconstruction (jet/MET)
e.g. SR9: pT > 700 GeV, MET > 700 GeV: total background uncertainties: 14%

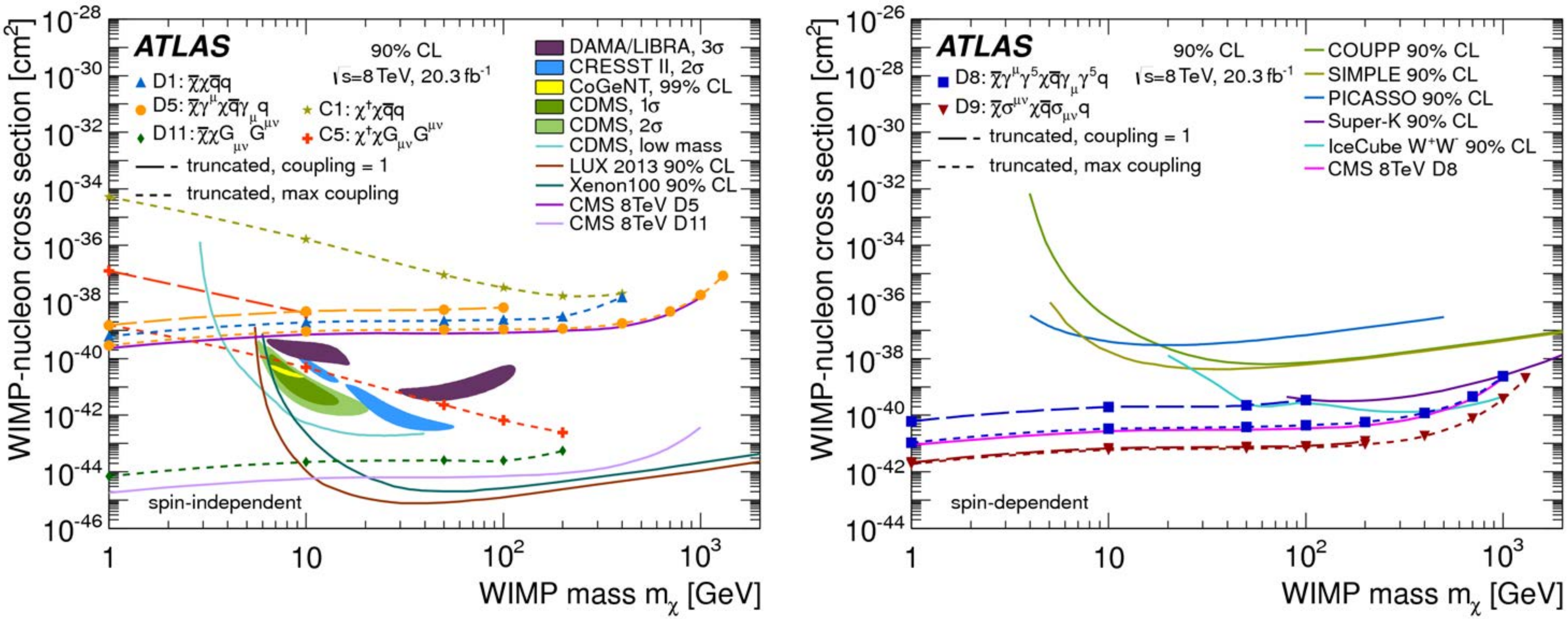


SR9
arXiv:1502.01518

Background estimation (main: Zνν+jets):
use transfer factors from W/Z control regions (CR)



Graphics by S. Schramm



Model-dependent comparison

Needs **agreement** on benchmarks and assumptions

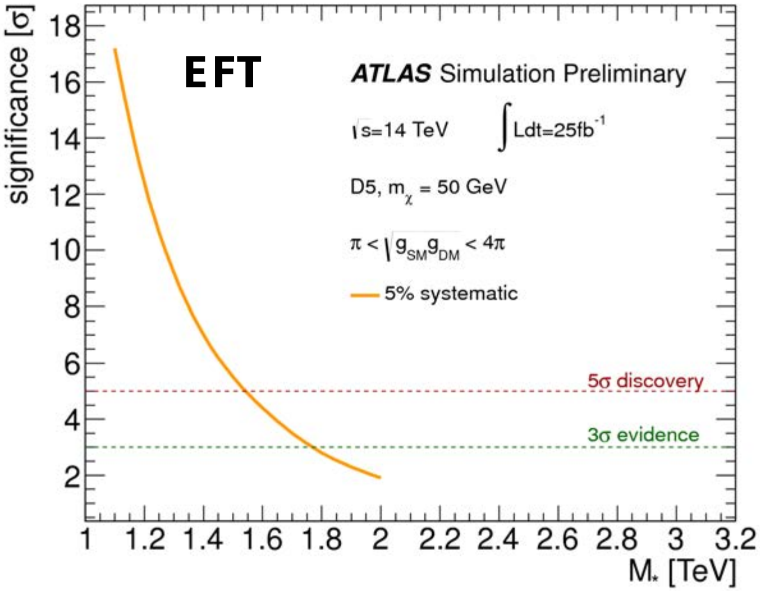
→ e.g. **truncation** procedure to ensure **EFT validity**

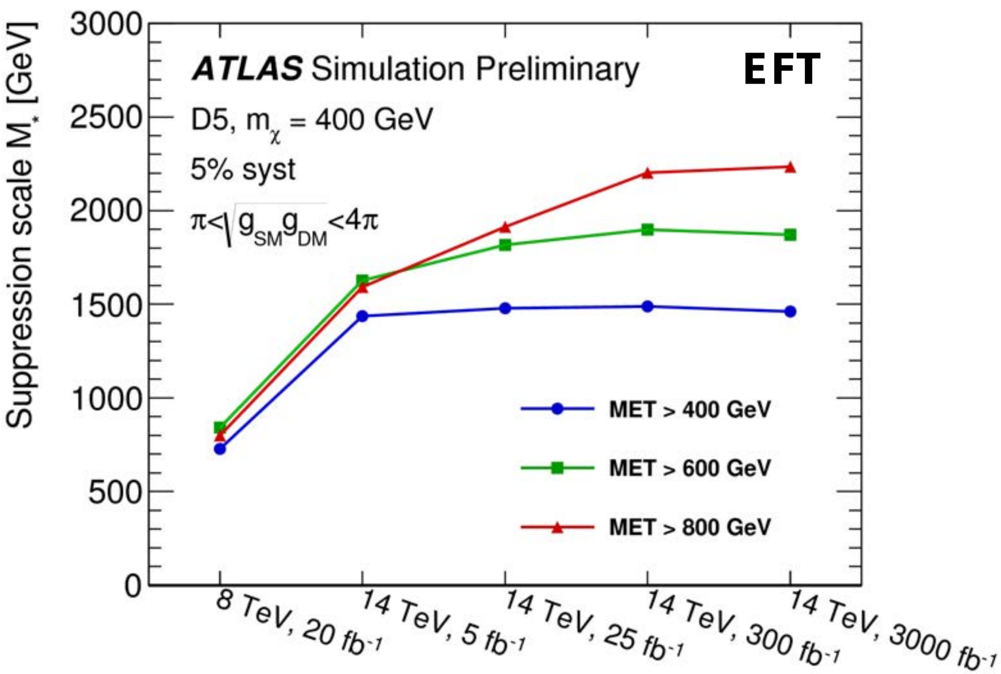
Complementarity of direct/indirect detection and colliders:

outlines strengths of each of the experiments

Adopting similar **search strategy** as **8 TeV**
Generator-level backgrounds **+ smearing** for pile-up and detector conditions

	$\sqrt{s}$ [TeV]	μ	L [fb^{-1}]
	8	20	20
Phase 0 upgrade (2014-2015)	14	60	25
Phase 1 upgrade (2018)	14	60	300
Phase 2 upgrade (2022)	14	140	3000

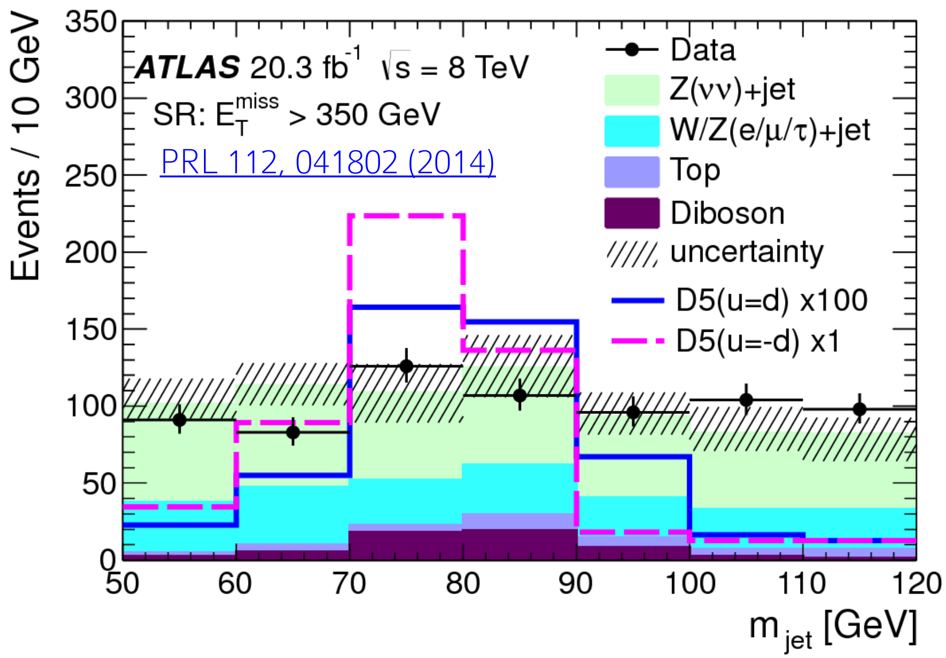




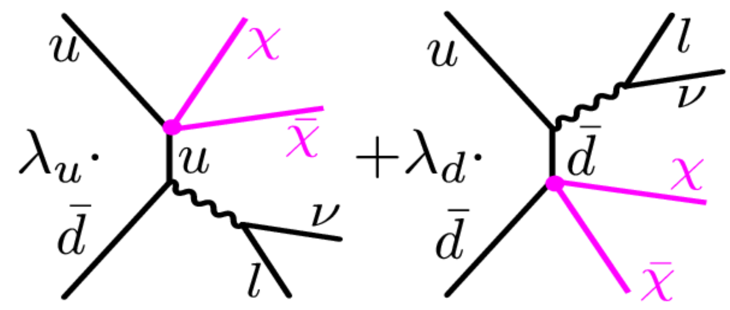
Surpassing previous limits within **1st year of data taking**

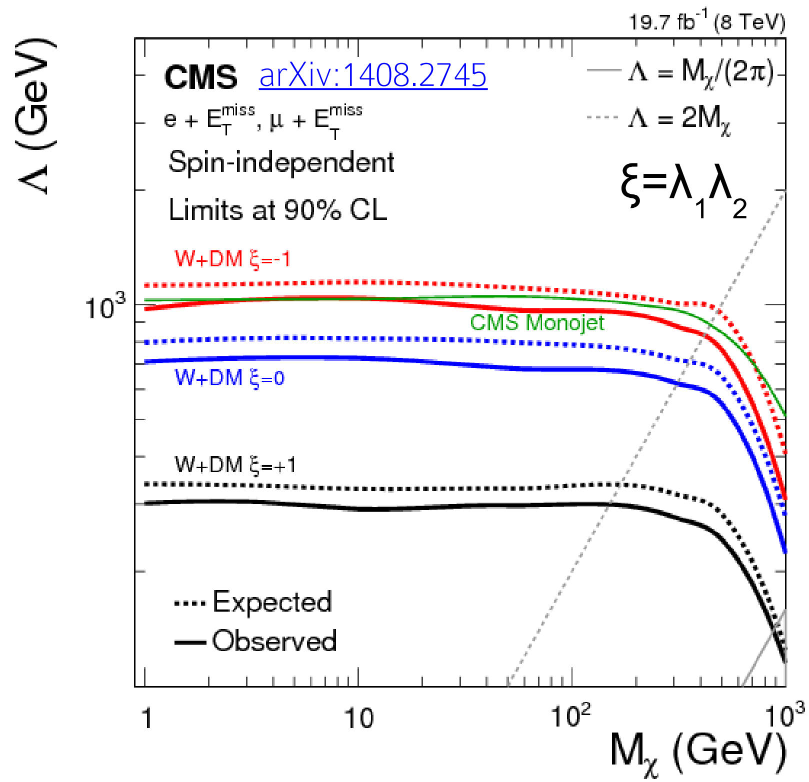
MET+W/Z/γ: look for excess of events with high pT boson (decay products), high missing transverse momentum

W/Z → jj: use of single fat jet mass for W/Z tagging



Advantage for W: interference





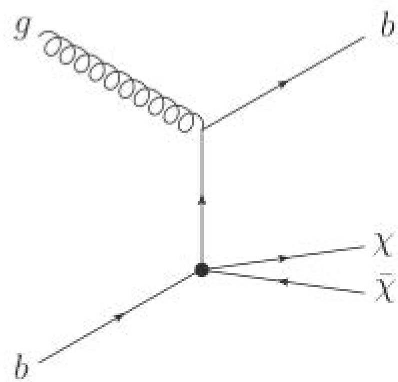
ATLAS:
W/Z → jj: PRL 112, 041802 (2014)
Z → ll: PRD 90, 012004 (2014)
W → lν: JHEP 09 (2014) 037
photon: PRD 91, 012008 (2015)

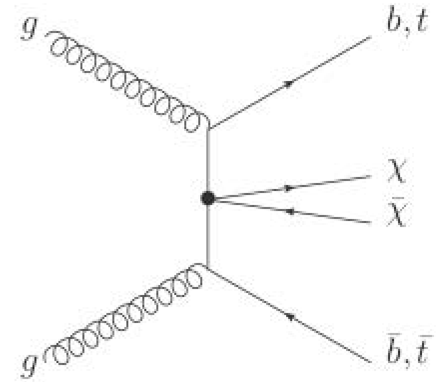
CMS:
W → lnu: arXiv:1408.2745
photon: arXiv:1410.8812

DM with heavy flavors:

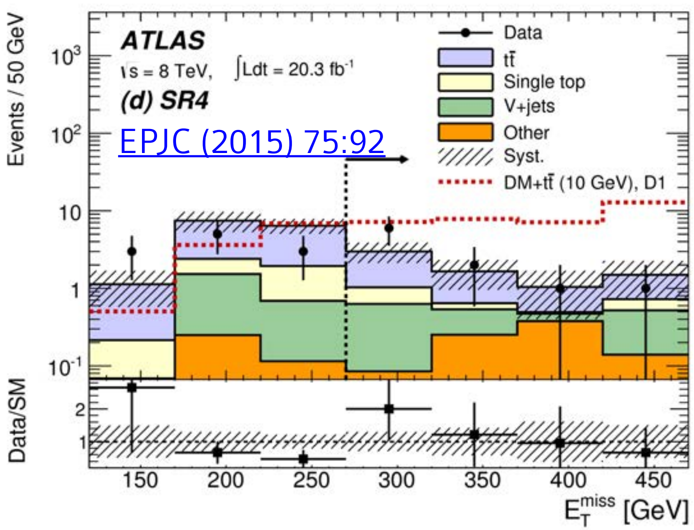
favoured for some EFT operators

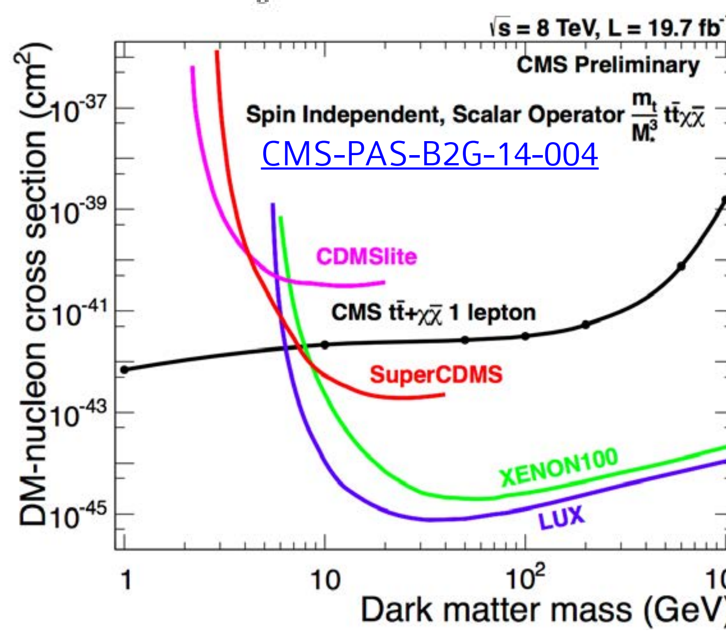
$$\mathcal{O} = \sum_q \frac{m_q}{M_*^3} \bar{q} q \bar{\chi} \chi,$$





Different signal regions,
backgrounds normalized from control regions





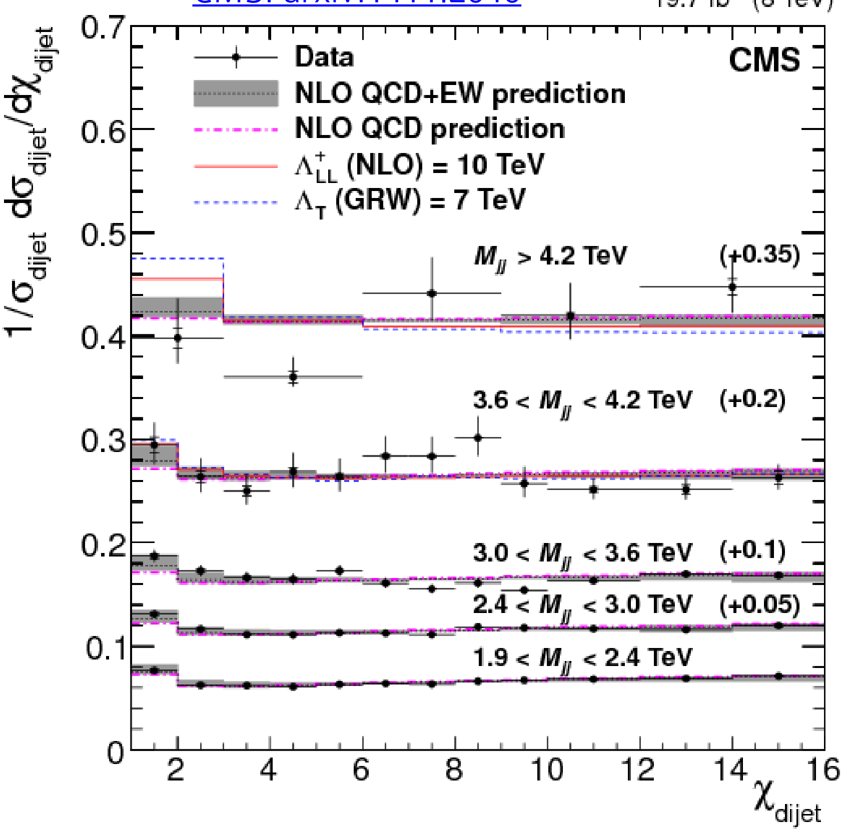
More details on CMS ttbar+MET searches
Deborah Pinna's YSF talk

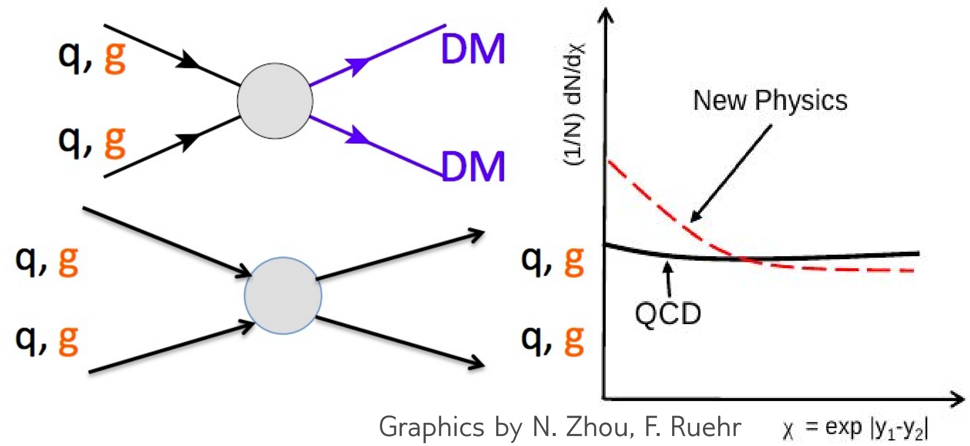
ATLAS: ttbar->all-hadronic: EPJC (2015) 75:92
single lepton stop search: JHEP 11 (2014) 118

CMS: ttbar->semileptonic: CMS-PAS-B2G-14-004
ttbar->dilepton: CMS-PAS-B2G-13-004

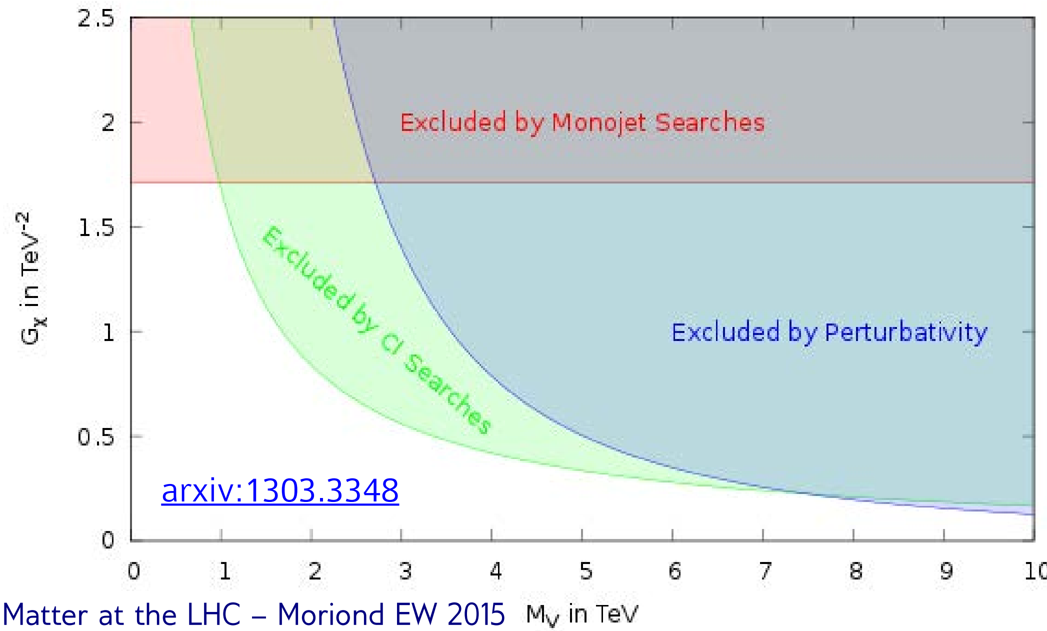
Dijet angular distributions
probe contact interactions

CMS: arxiv:1411.2646



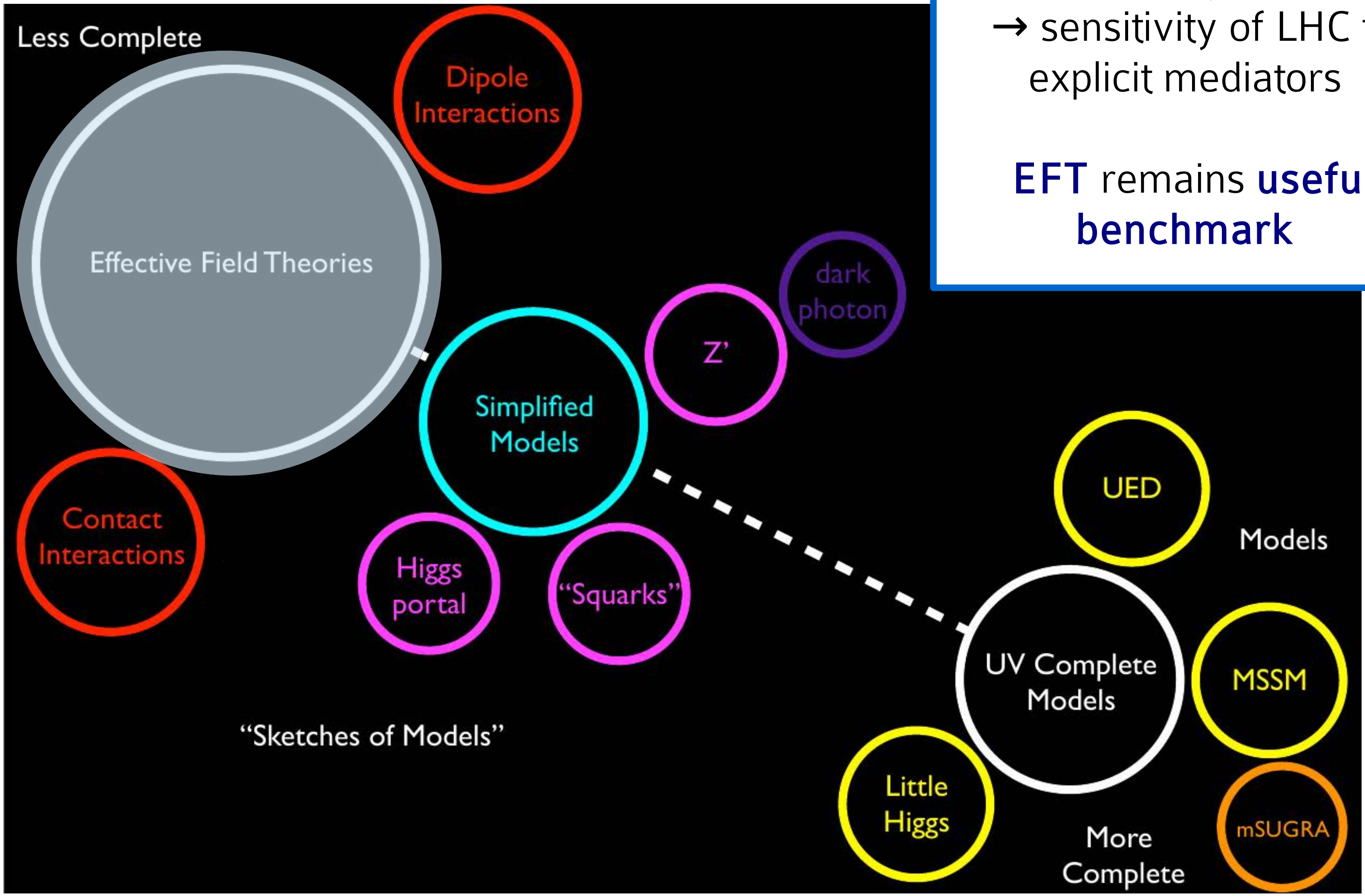


→ can **reinterpret** constraints in **EFT framework for DM**



RUN-1/RUN-2: MOVING TO SIMPLIFIED MODELS

Tim Tait, DM@LHC 2013

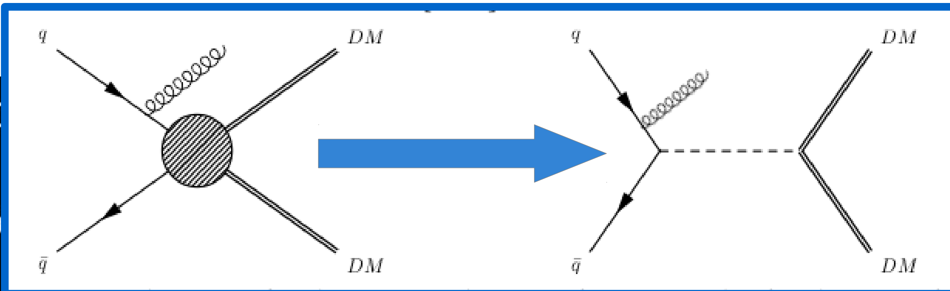


EFT validity issues:
→ sensitivity of LHC to explicit mediators

EFT remains **useful benchmark**

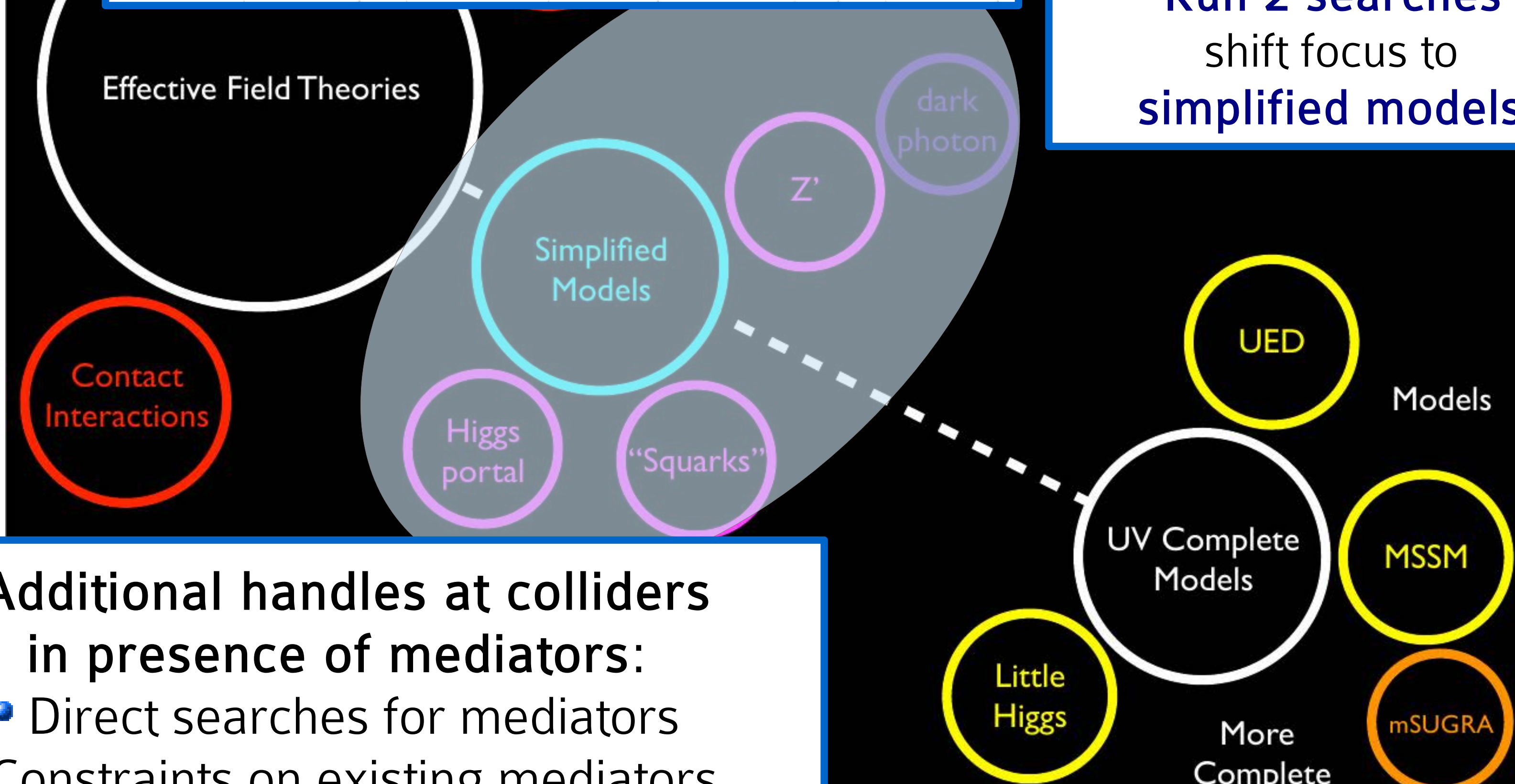
RUN-1/RUN-2: MOVING TO SIMPLIFIED MODELS

CMS: arXiv:1408.3583



EFT validity issues:
→ sensitivity of LHC to explicit mediators

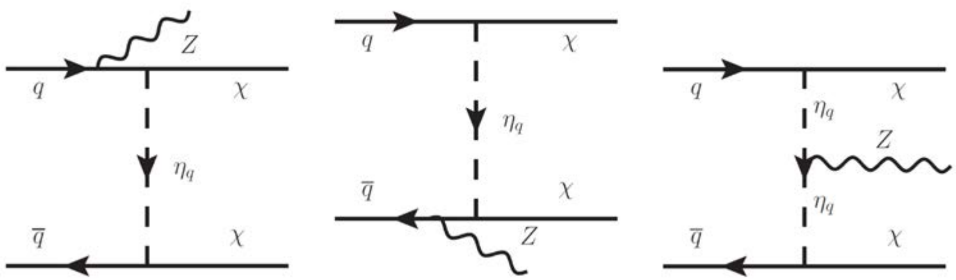
Run 2 searches shift focus to **simplified models**



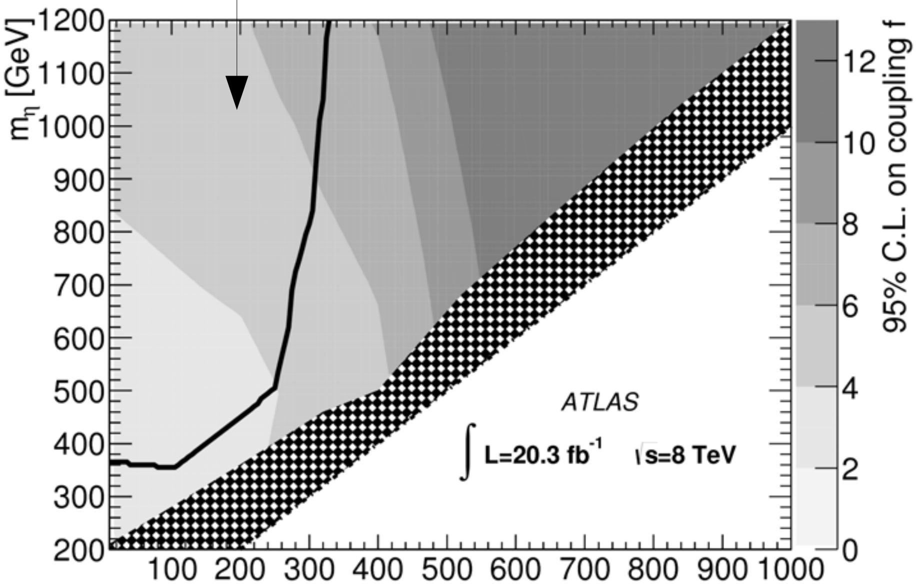
Additional handles at colliders in presence of mediators:
- Direct searches for mediators
- Constraints on existing mediators
- Additional search signatures

SELECTED SIMPLIFIED MODEL RESULTS: 8 TEV MET+X

Z → ll + MET

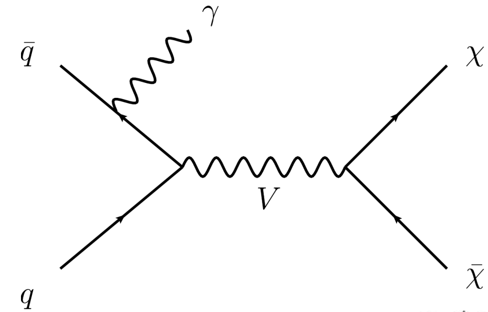


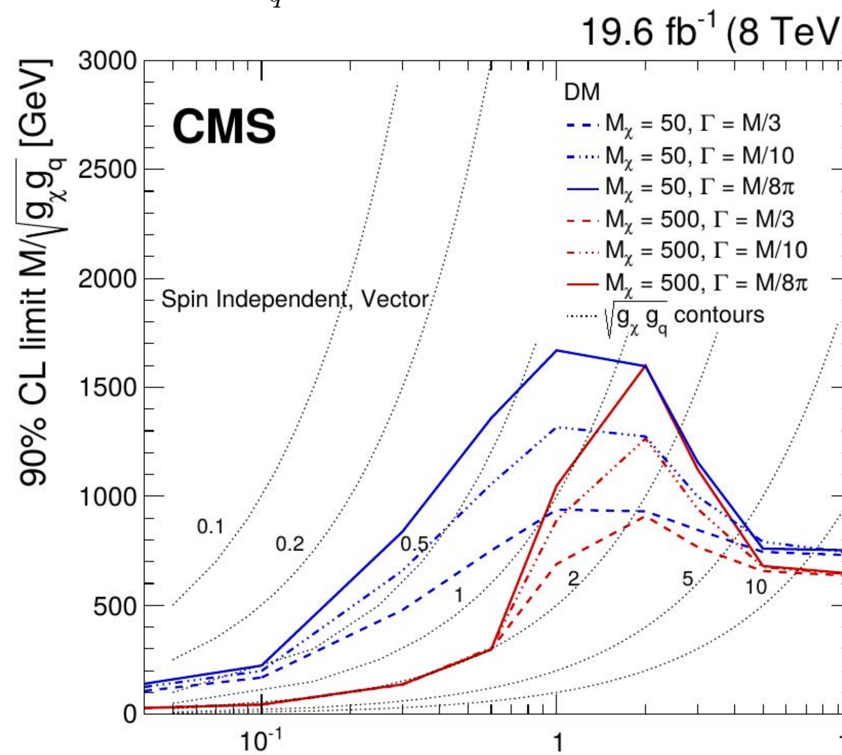
Region excluded wrt thermal relic



[ATLAS: PRD 90, 012004 (2014)](https://doi.org/10.1103/PhysRevD.90.012004)

Photon + MET



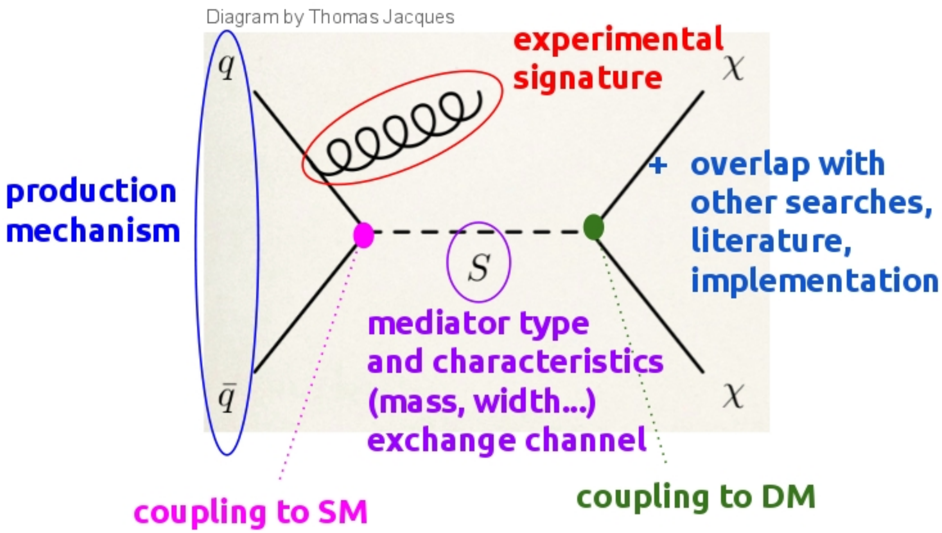


CMS: arXiv:1410.8812

ATLAS/CMS Dark Matter Forum:

experiment/theory discussion towards Run-2 DM searches

Many possibilities to be used as building blocks:



https://twiki.cern.ch/twiki/bin/view/LHCDMF/WebHome
Mailing list: lhc-dmf@cern.ch

This Forum will agree upon:

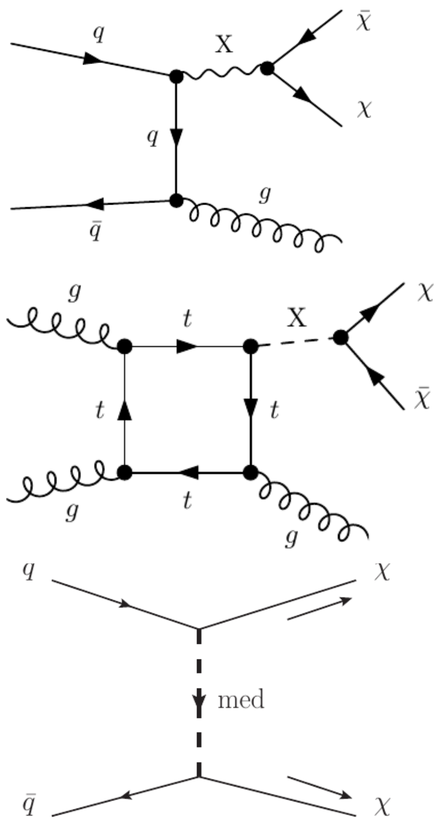
- Prioritized **set of simplified models**
- Common **model implementation and details** (e.g. matching, scales) towards MC generation of benchmarks
- **EFT validity** assessment procedure

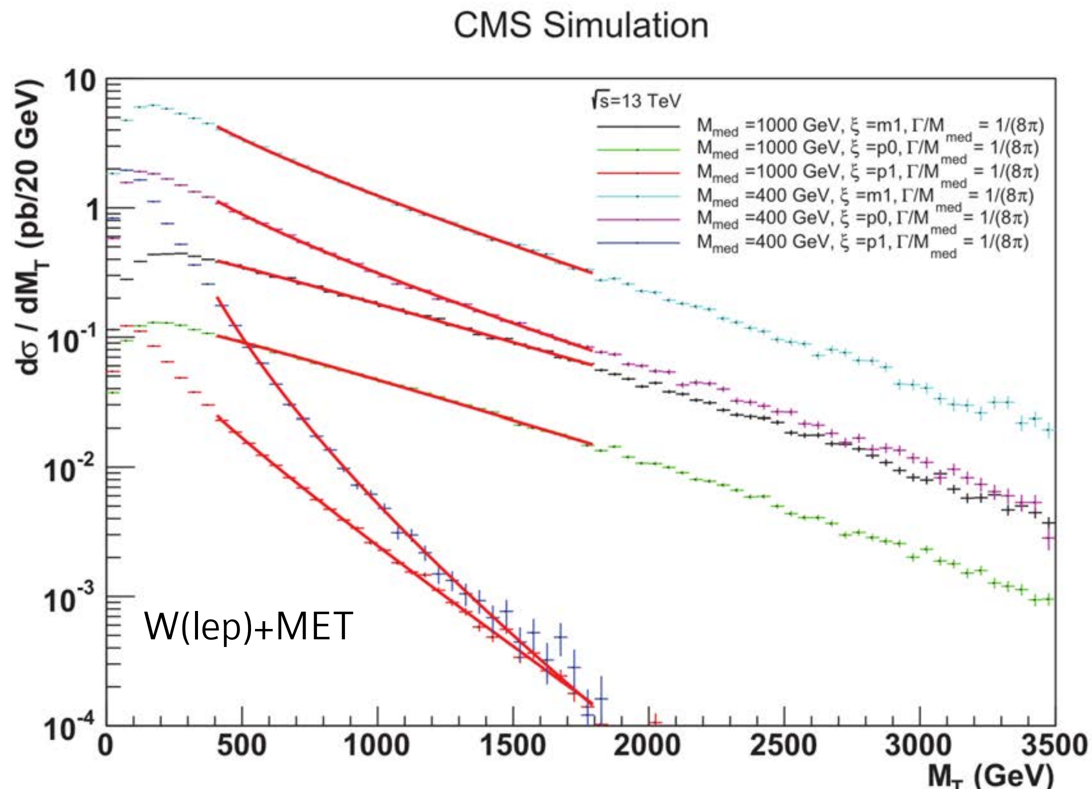
This Forum will document:

models and choices
(arXiv write-up + SVN repository)

Run-2 benchmark choices being finalized – examples:

Prioritized list of models for jet+MET search





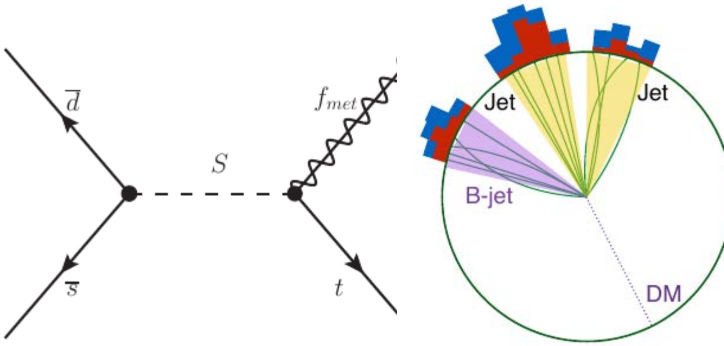
[Generator-level plot from talk at DM Forum 16/02/15]

Study of choice of benchmark points for searches with W/Z/gamma

http://arxiv.org/abs/1411.0535
http://arxiv.org/abs/1409.2893

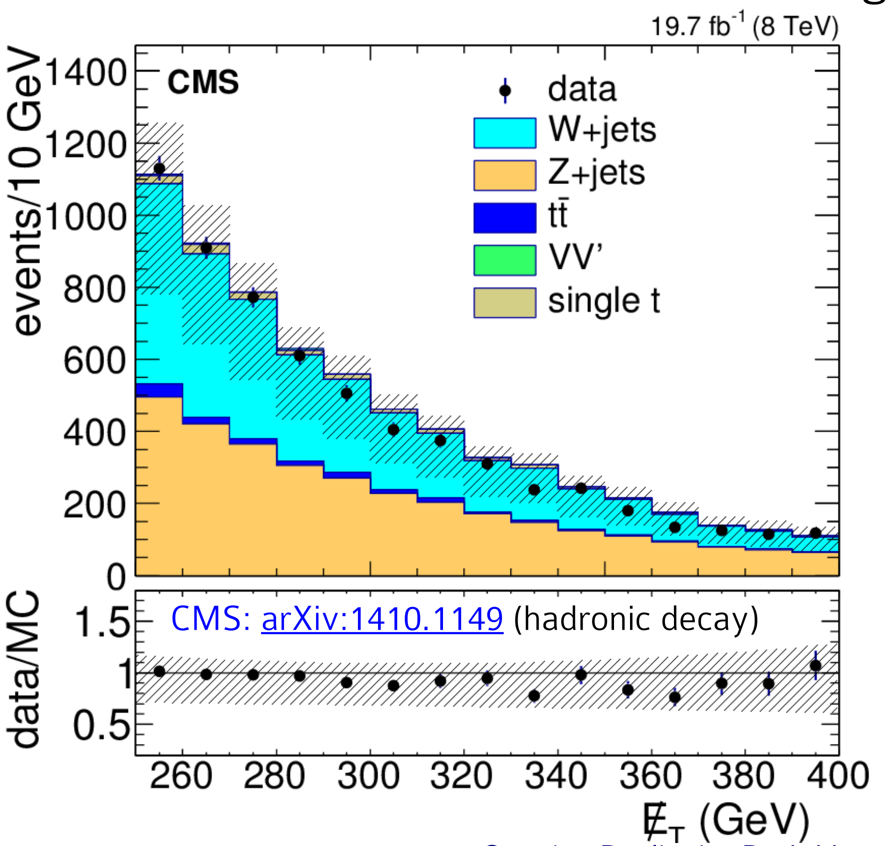
Many BSM models predict single top+MET
→ group main characteristics
in simplified models (resonant/non resonant)

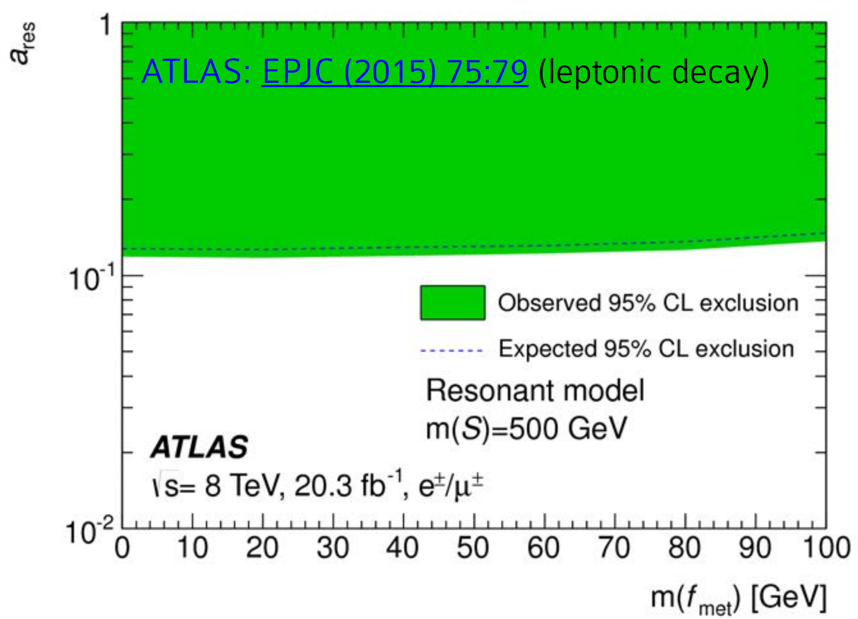
Example: resonant model, all-had



Graphics by D. Berry

Background estimation (main: V+jets):
use transfer factors from data control regions

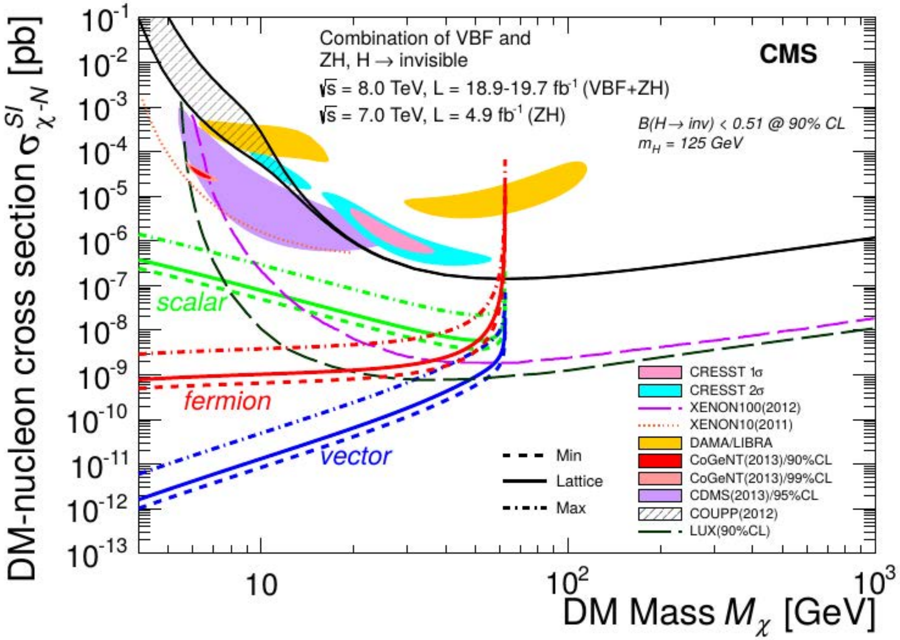




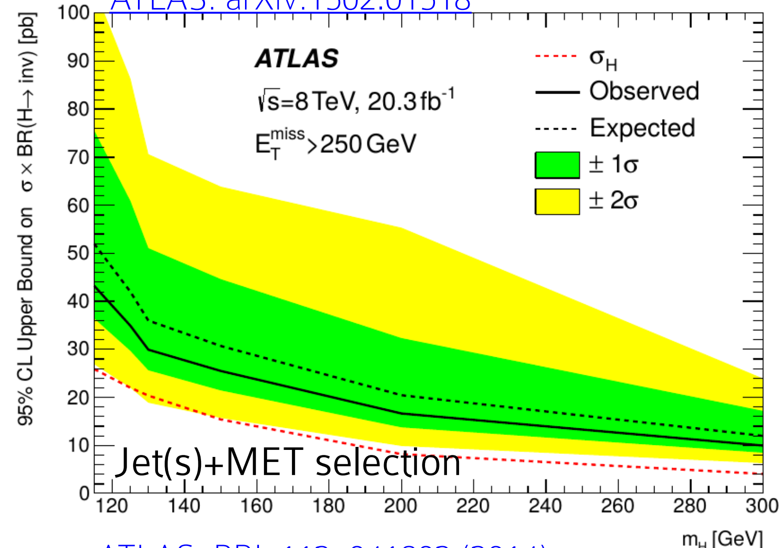
Higgs boson could **mediate DM/SM interactions**
→ search for enhancements of **invisible decays**

More details on exotic Higgs decays in Paolo Meridiani's talk

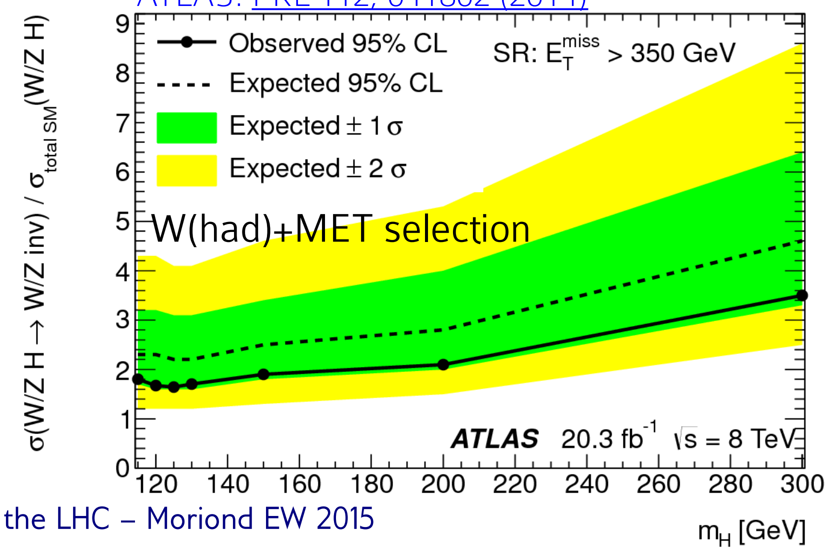
CMS: EPJC 74 (2014) 2980



ATLAS: arXiv:1502.01518



ATLAS: PRL 112, 041802 (2014)



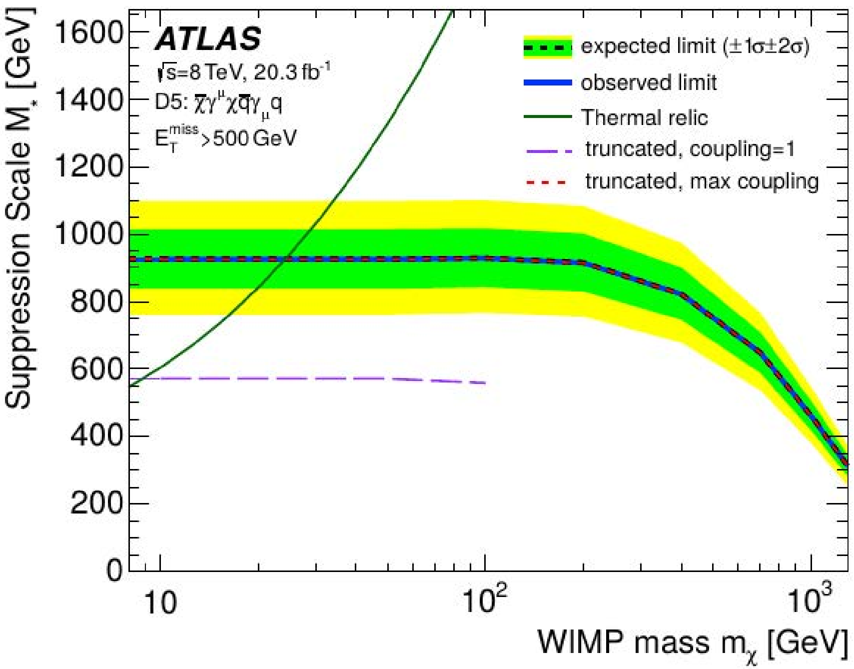
Higgs boson discovered, **Dark Matter** still at large
→ looking for DM particle candidates at the LHC

Preparing the ground for Run-2 searches:
LHC results **complementary** to other **Dark Matter experiments**

> We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the DM particles unlike the case with the Higgs and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do ~~not~~ want to encourage big experimental searches for DM particles , but we do feel that people performing experiments vulnerable to DM particles should know how they may turn up.

BACKUP SLIDES

Name	Initial state	Type	Operator
C1	qq	scalar	$\frac{m_q}{M_\star^2}\chi^\dagger\chi\bar{q}q$
C5	gg	scalar	$\frac{1}{4M_\star^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$



Limit on **suppression scale of EFT** M*

EFT validity addressed explicitly

Previous papers: only accounting for kinematic constraints and theory perturbativity
This paper: more explicit constraint
(stronger for some operators)

$$Q^2_{\rm tr} < \Lambda^2$$

(coupling/operator-dependent statement)

Under discussion in literature and ATLAS/CMS DM Forum

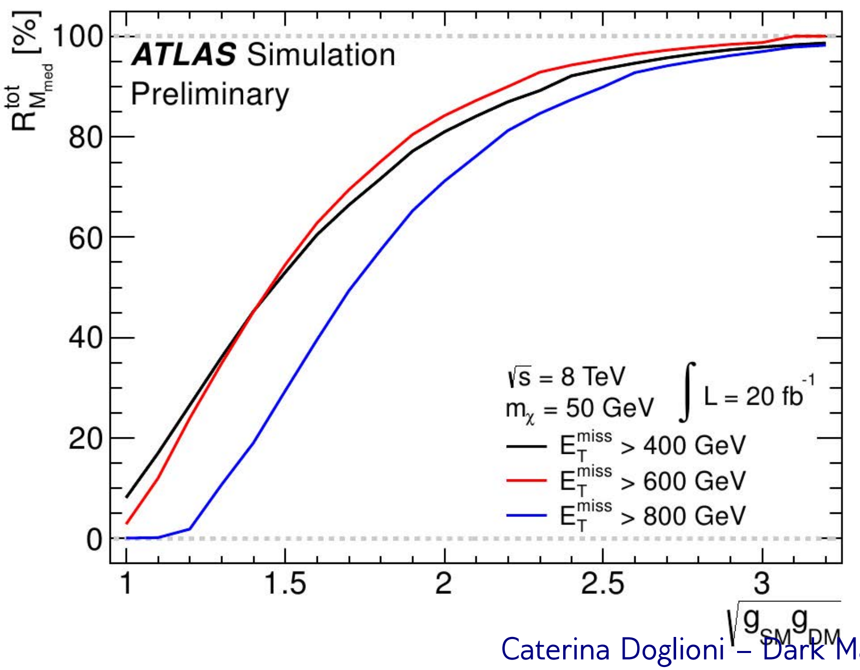
MONO-JET PROSPECTS AND EFT VALIDITY ATL-PHYS-PUB-2014-007

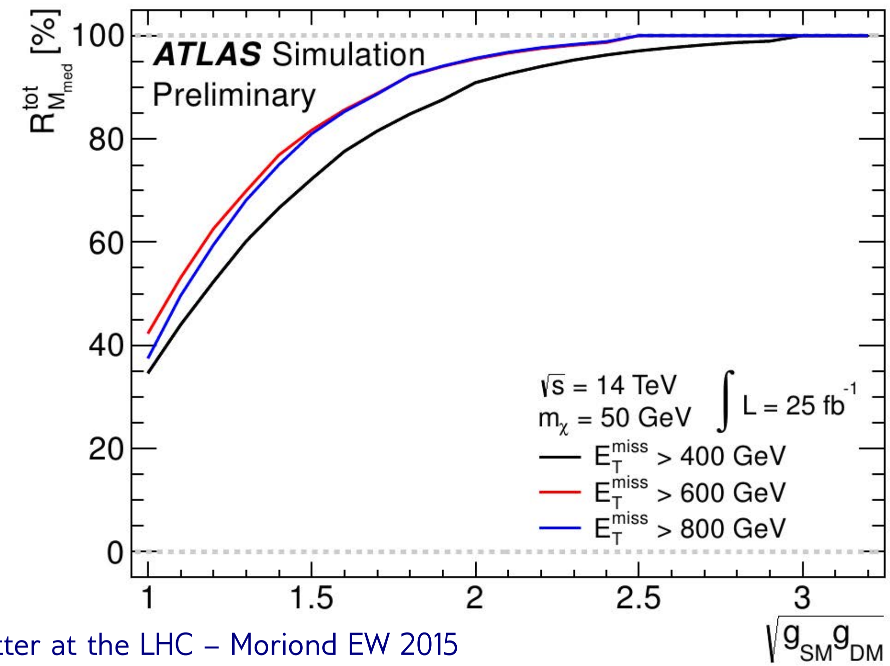
Early DM searches: what do we gain/lose from CoM increase?

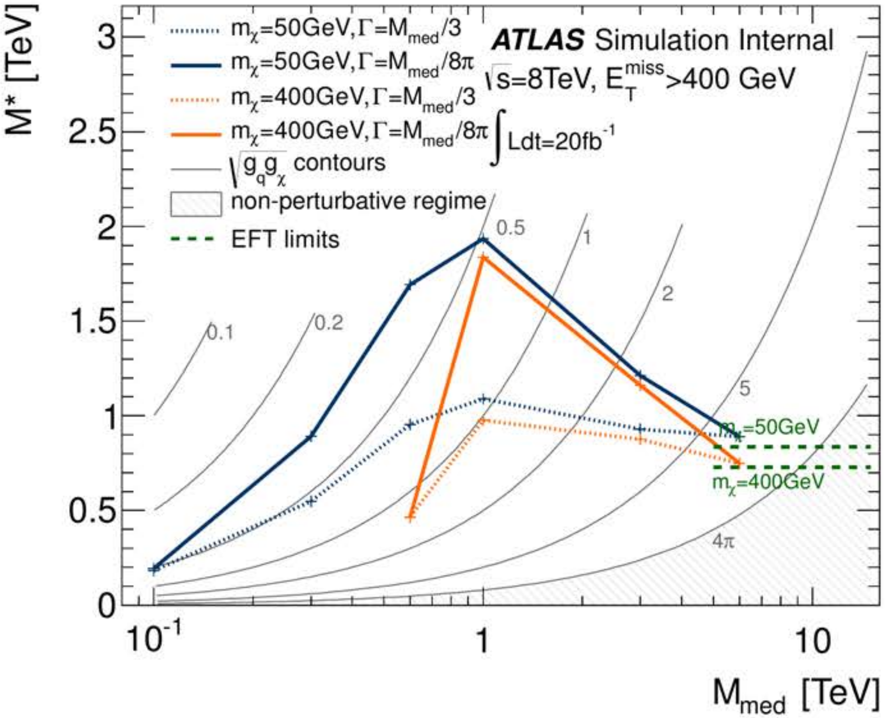
- Current monojet analysis: systematically limited at low MET, statistically limited at high MET → How high can we reach in $M*$ at 14 TeV?
- Will we have problems with the EFT validity at a higher CoM energy?

Somehow counterintuitive results! **Competing effects**: $Q_{tr} < \sqrt{g_{SM} g_{DM}} M^*$

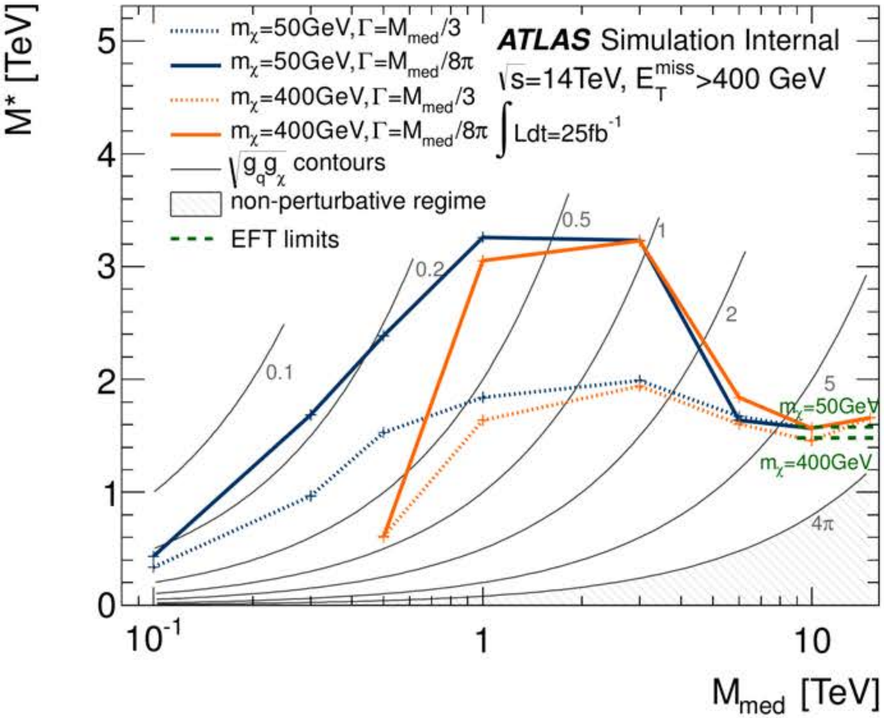
- Higher MET → higher Q_{tr} (weak correlation: MET smeared by detector)
- Increase of reach in M* → higher limits to start with → increased validity





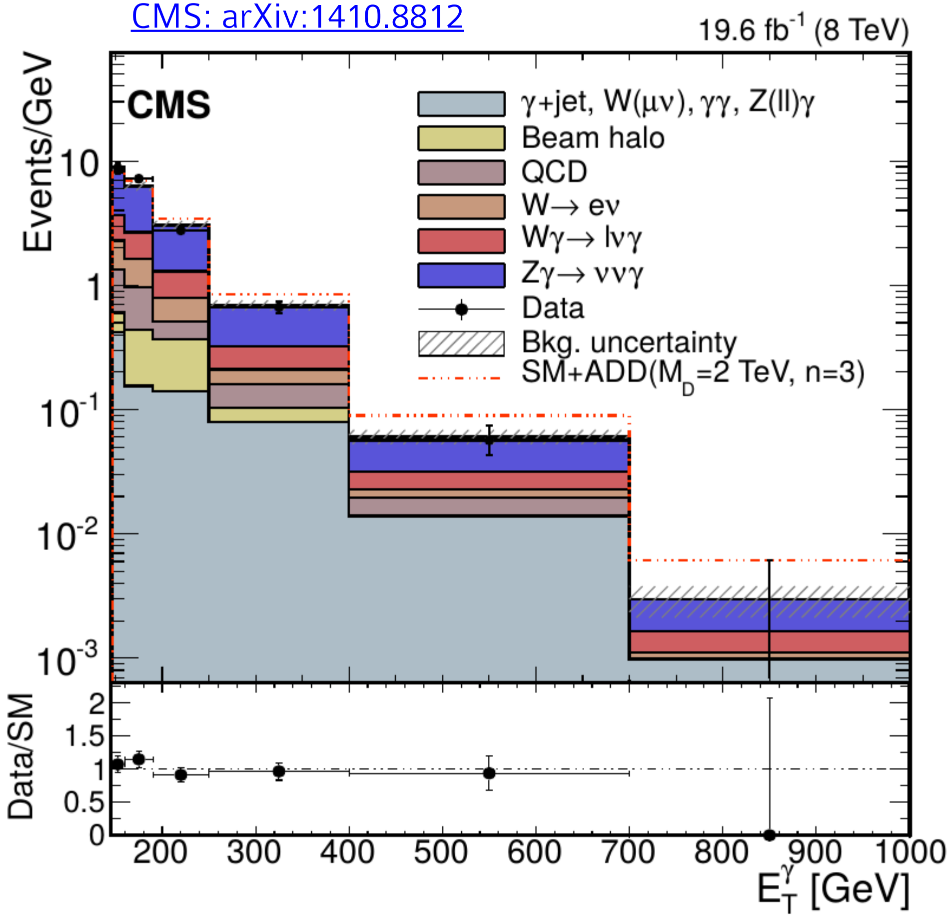


ATLAS Simulation Internal
$\sqrt{s}$=8TeV, E_T^{miss}>400 GeV
$\int Ldt=20fb^{-1}$
m_χ=50GeV,$\Gamma=M_{med}/3$
m_χ=50GeV,$\Gamma=M_{med}/8\pi$
m_χ=400GeV,$\Gamma=M_{med}/3$
m_χ=400GeV,$\Gamma=M_{med}/8\pi$
$\sqrt{g_q g_\chi}$ contours
non-perturbative regime
EFT limits
m_χ=50GeV
m_χ=400GeV
M* [TeV]
M_{med} [TeV]

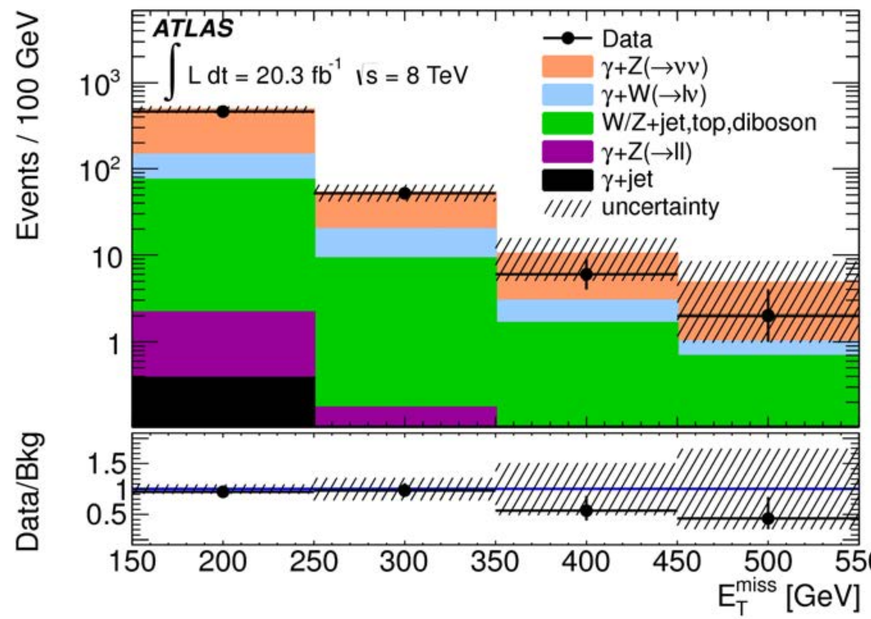


ATLAS Simulation Internal
$\sqrt{s}$=14TeV, E_T^{miss}>400 GeV
$\int Ldt=25fb^{-1}$
m_χ=50GeV,$\Gamma=M_{med}/3$
m_χ=50GeV,$\Gamma=M_{med}/8\pi$
m_χ=400GeV,$\Gamma=M_{med}/3$
m_χ=400GeV,$\Gamma=M_{med}/8\pi$
$\sqrt{g_q g_\chi}$ contours
non-perturbative regime
EFT limits
m_χ=50GeV
m_χ=400GeV
M* [TeV]
M_{med} [TeV]

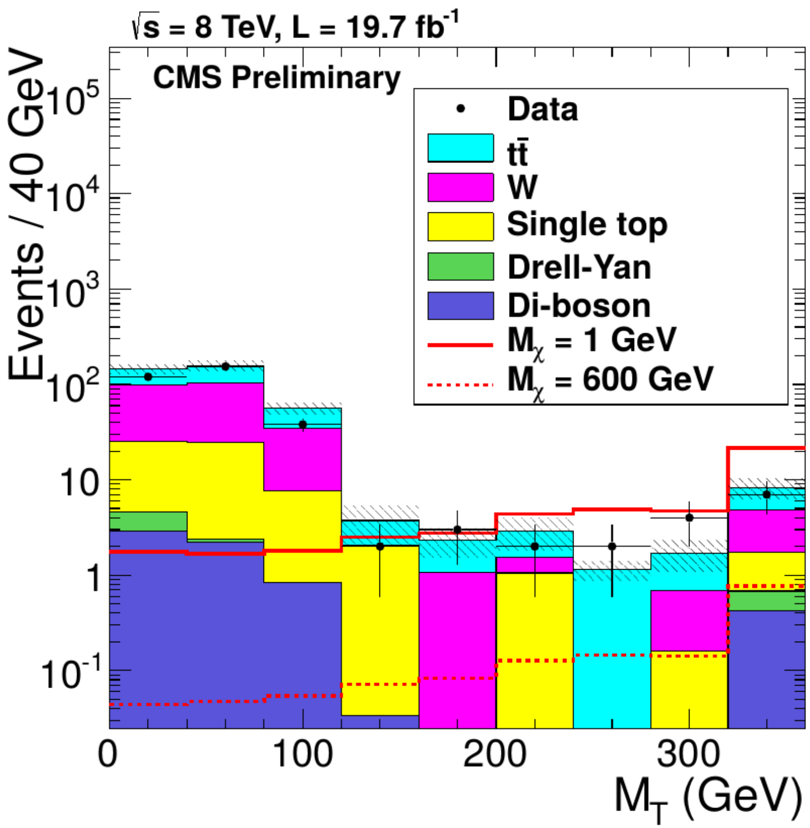
[CMS: arXiv:1410.8812]



[ATLAS: arXiv:1410.8812]



Semileptonic channel
CMS-PAS-B2G-14-004



$$M_{\mathrm{T}} \equiv \sqrt{2E_{\mathrm{T}}^{\mathrm{miss}} p_T^l (1 - cos(\Delta\phi))}$$

Dilepton channel
CMS-PAS-B2G-13-004