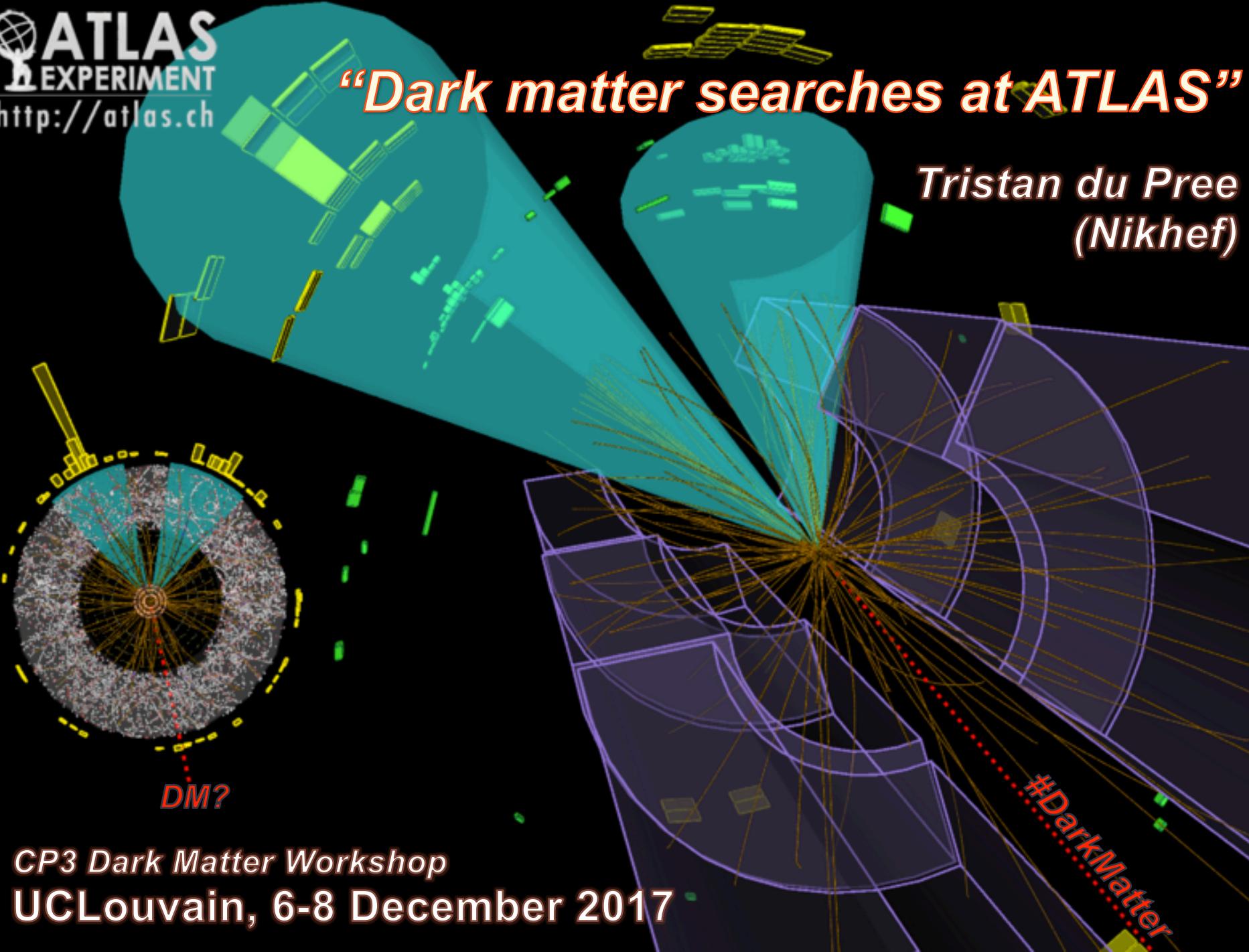


“Dark matter searches at ATLAS”

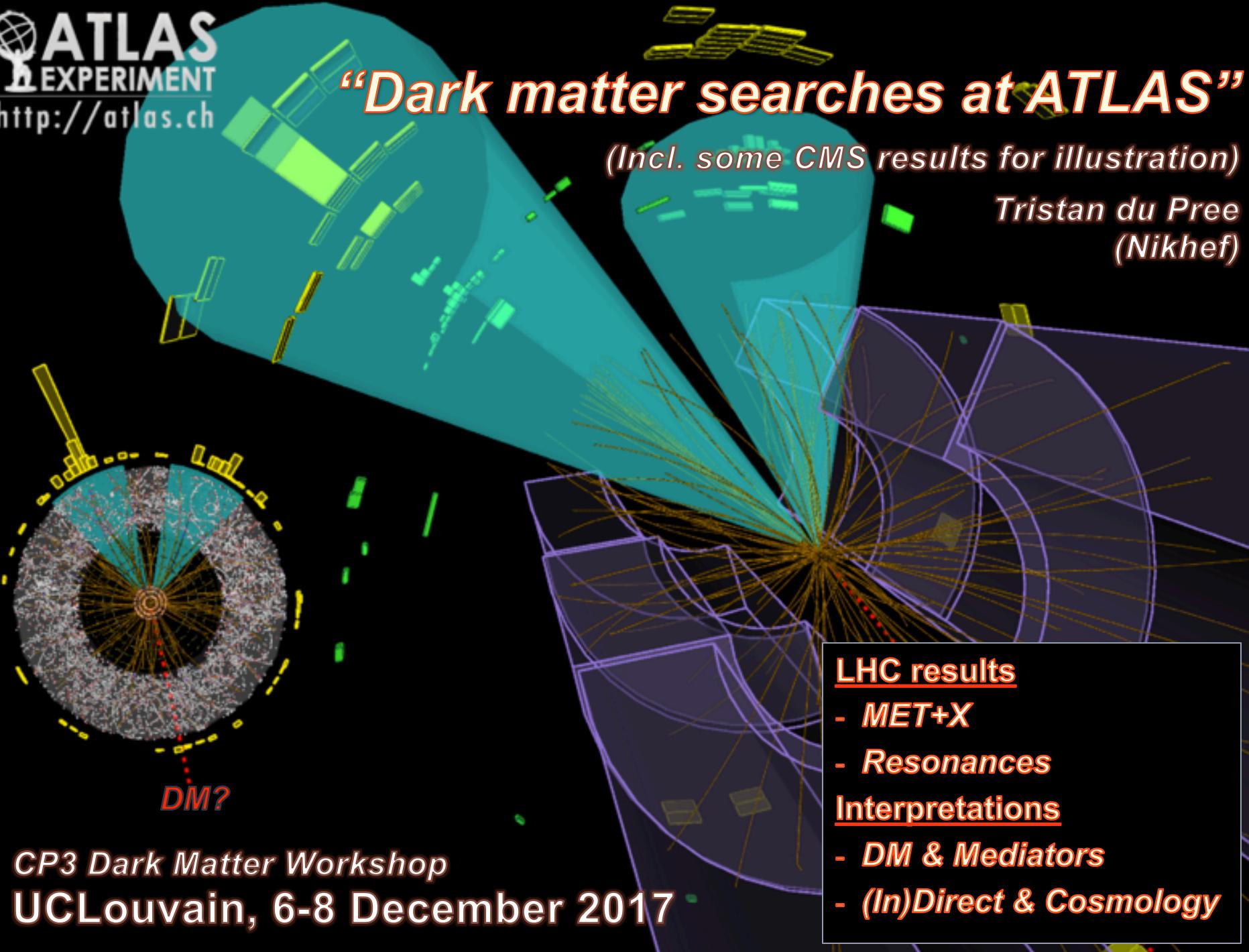
Tristan du Pree
(Nikhef)

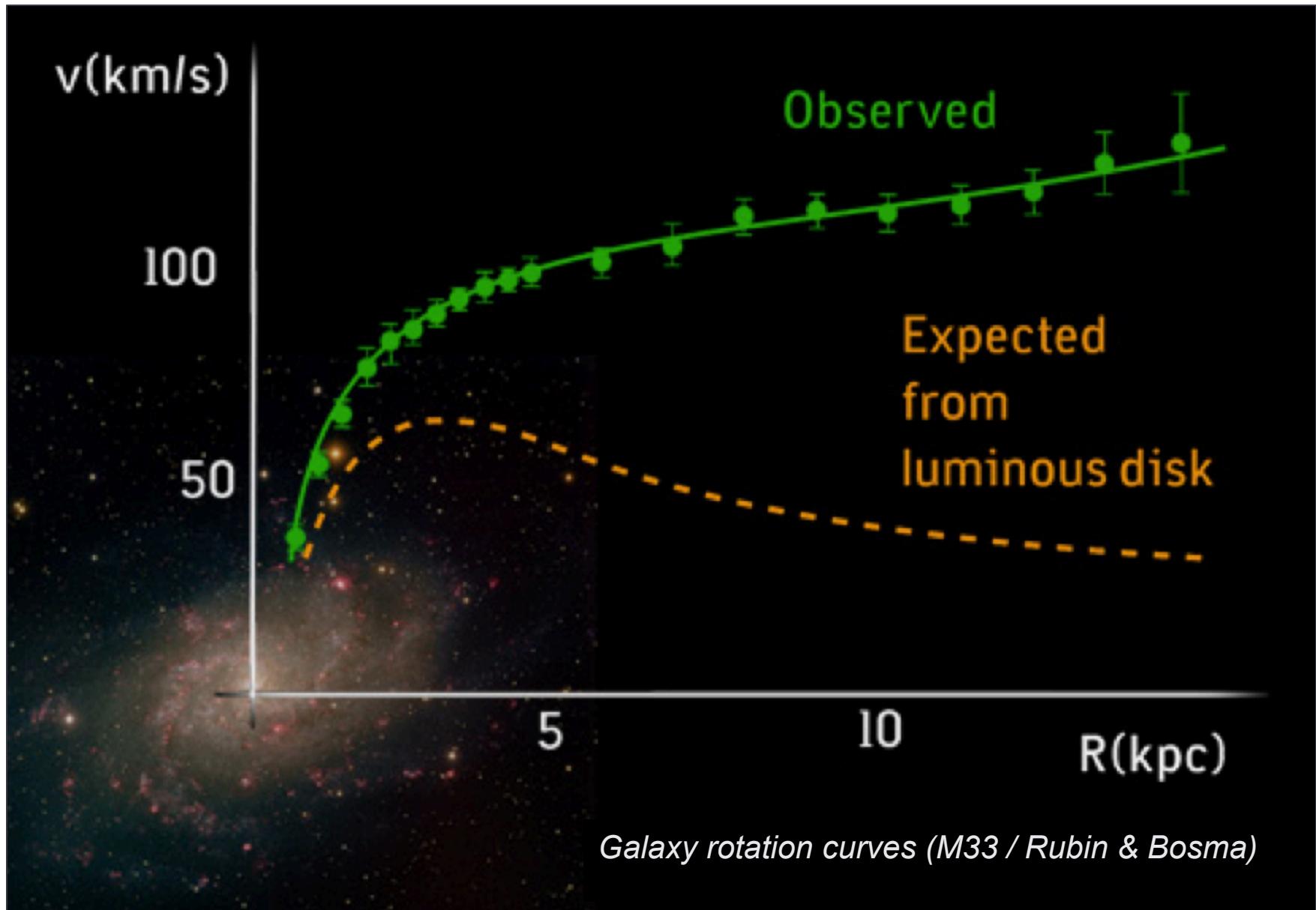


“Dark matter searches at ATLAS”

(Incl. some CMS results for illustration)

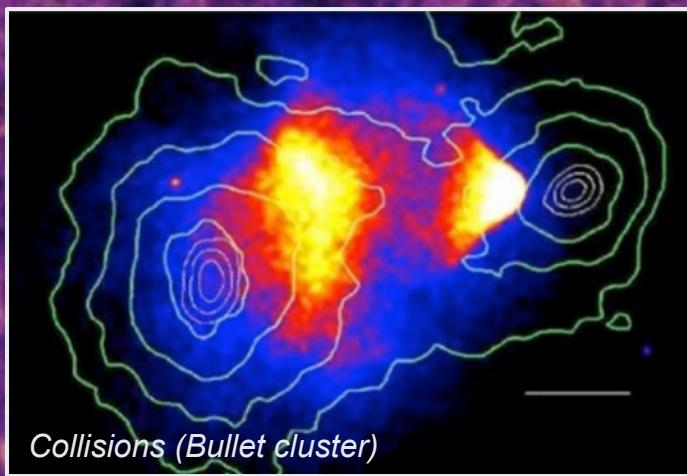
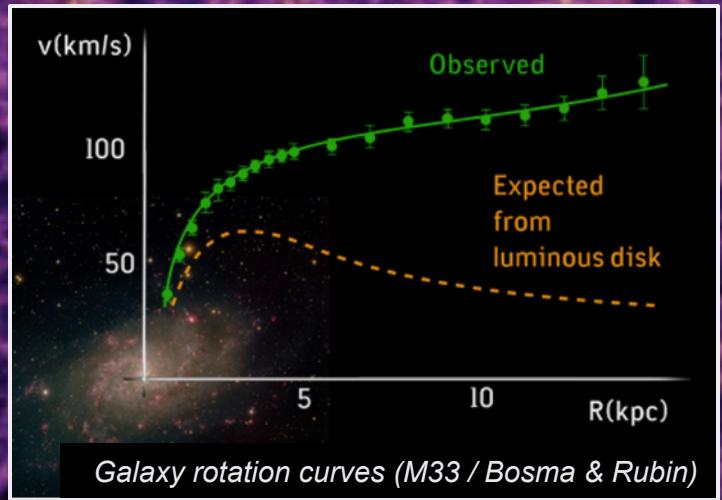
Tristan du Pree
(Nikhef)





*The rotation curves **alone** can be described by dark matter or modified gravity*

Large-scale structures (Millennium)



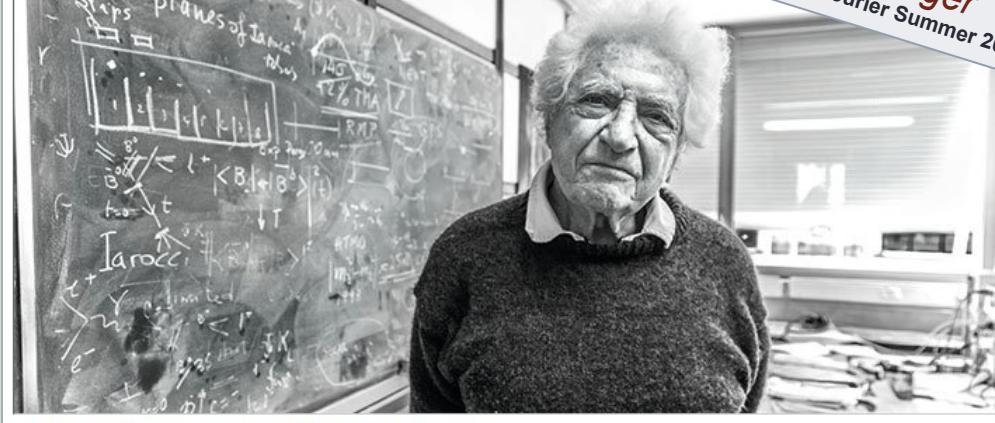
Experiment & Theory

Electron-Positron (LEP) collider. The results of this and the other LEP experiments, he says, "dominated CERN physics, perhaps the world's, for a dozen or more years, with crucial precise measurements that confirmed the Standard Model of the unified electroweak and strong interactions".

These days, Jack still comes to CERN with the same curiosity for the field that he always had. He says he is "trying to learn astrophysics, in spite of my mental deficiencies", and thinks that the most interesting question today is dark matter. "You have a Standard Model which does not predict everything and it does not predict dark matter, but you can conceive of mechanisms for making dark matter in the Standard Model," he says. "You don't know if you really understand it, but you can imagine it. And I am not the only one who doesn't know."



From the sky, like Dark Energy, DM, baryogenesis and neutrino ...
the picture repeatedly suggested by the data in the last 20 years is simple and clear: take the SM, extended to include Majorana neutrinos, which can explain the smallness of active neutrino masses by the see-saw mechanism and baryogenesis through leptogenesis, plus some form of DM, as valid up to some very high energy. Indeed at present in particle physics the most crucial experimental problem is the nature of DM. In this case a vast variety of possible solutions exist from WIMPS to axions or to keV sterile neutrinos or.... Clearly



Jack Steinberger photographed in his office at CERN in 2016.

G. Altarelli
arXiv:1407.2122



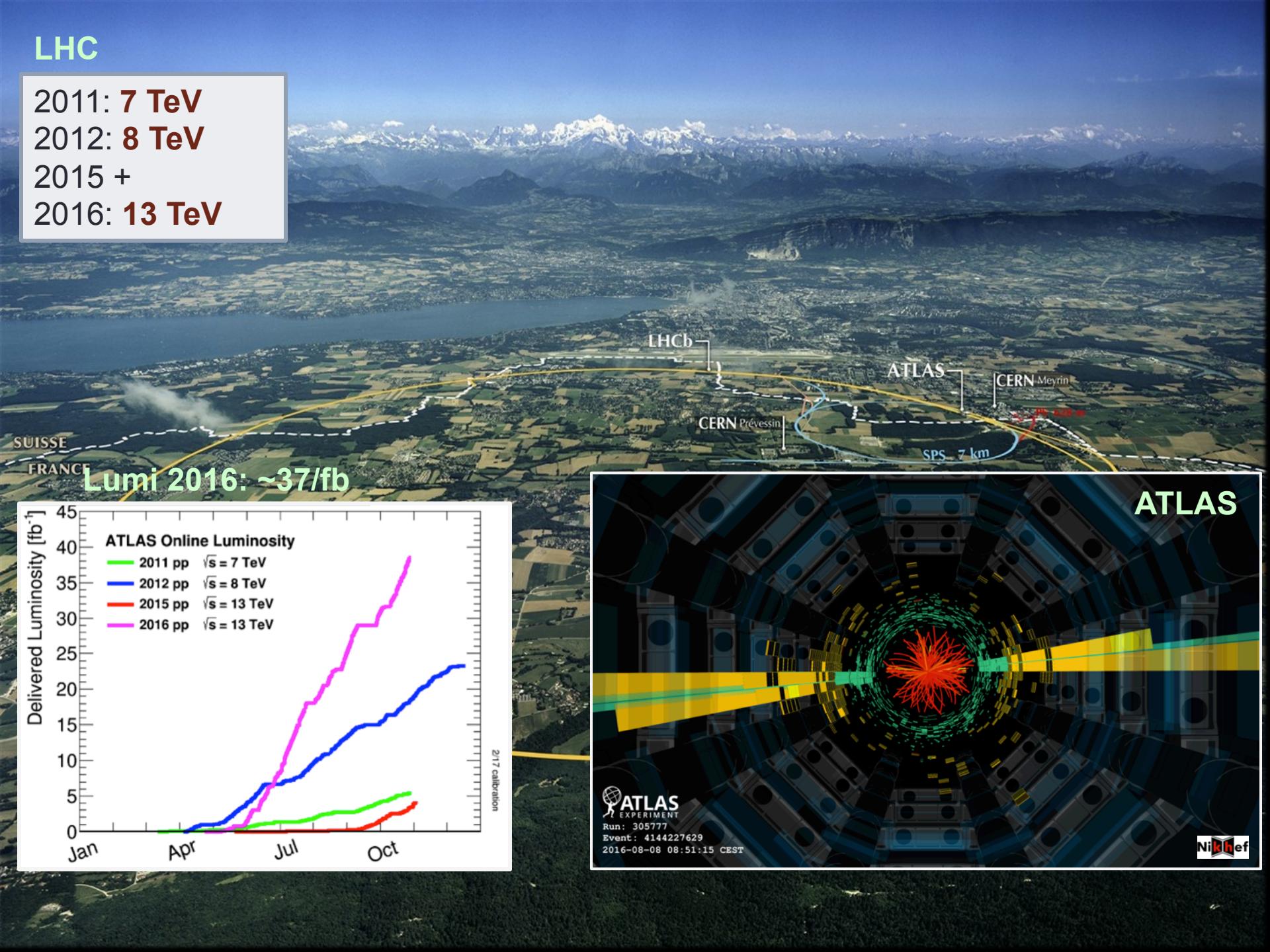
LHC

2011: 7 TeV

2012: 8 TeV

2015 +

2016: 13 TeV

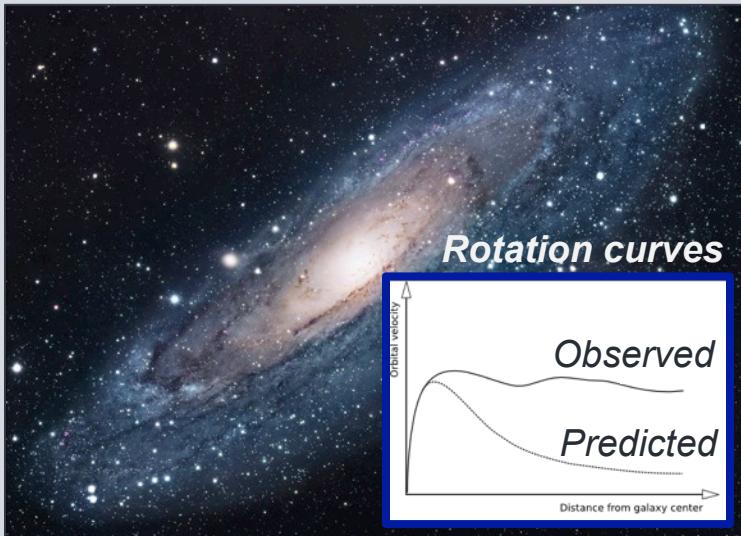




Dark Matter

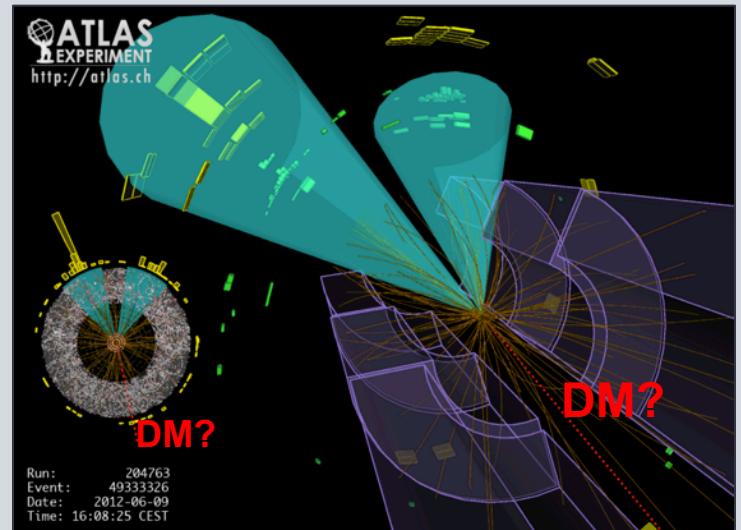
Astronomy

- Observation in Space
 - Gravitational evidence
 - Galaxy rotation curves

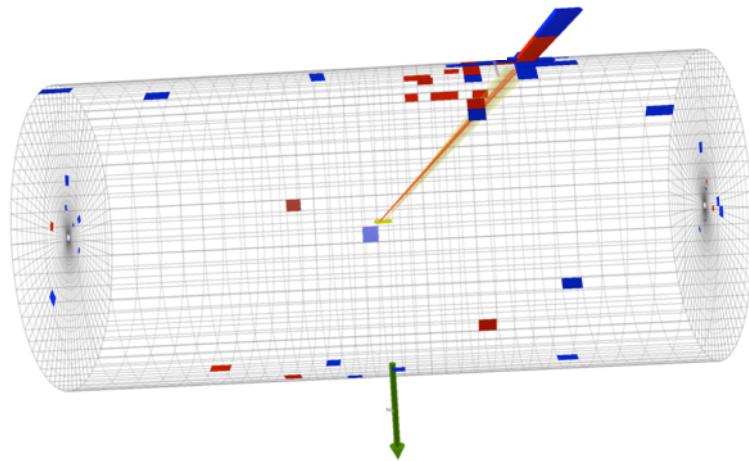
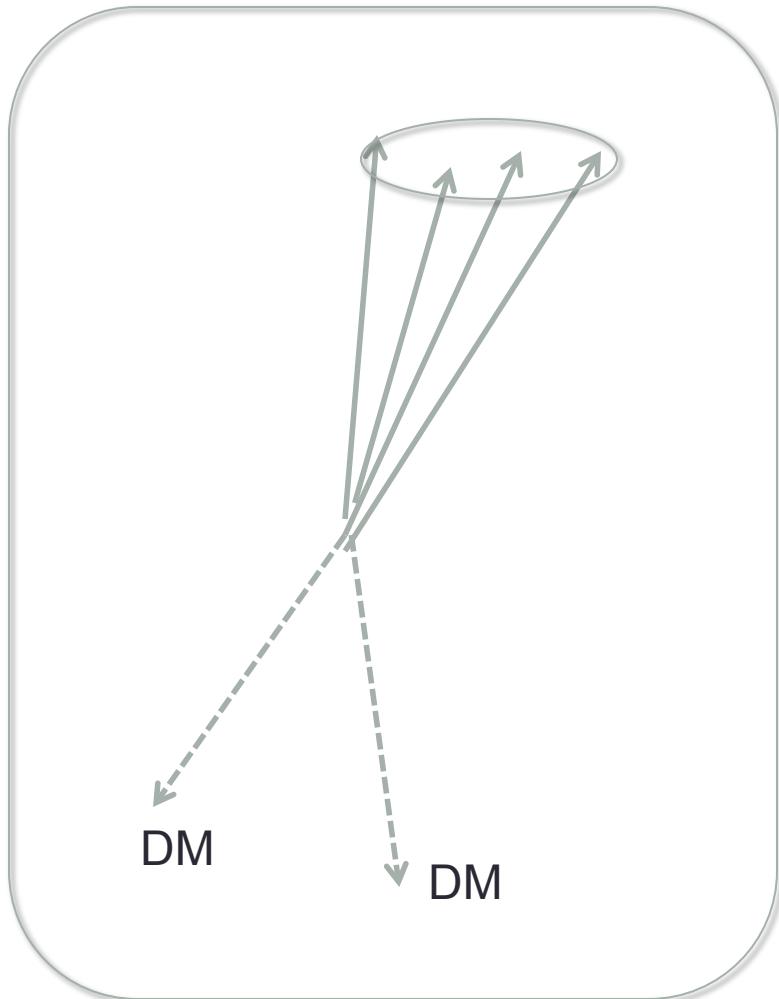


LHC @ 13 TeV

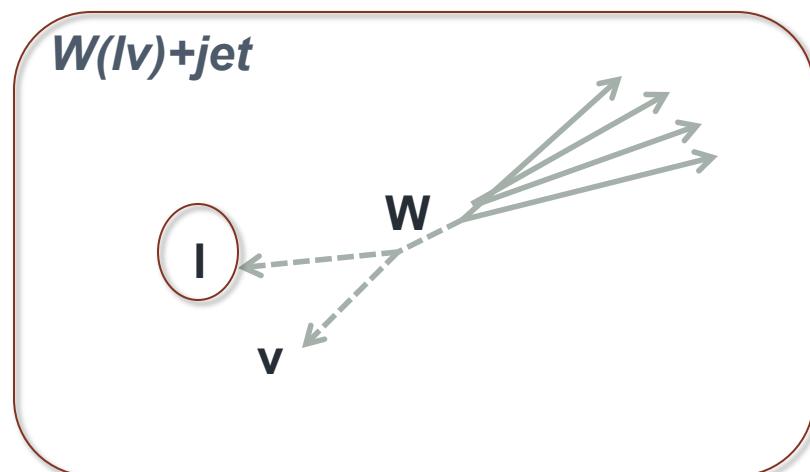
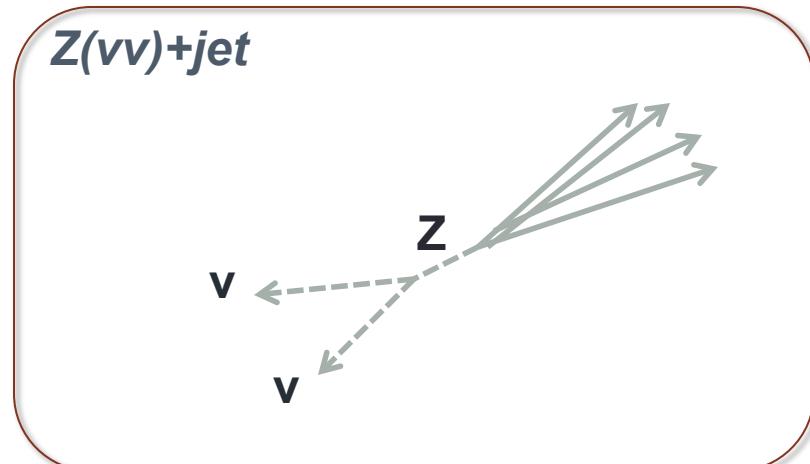
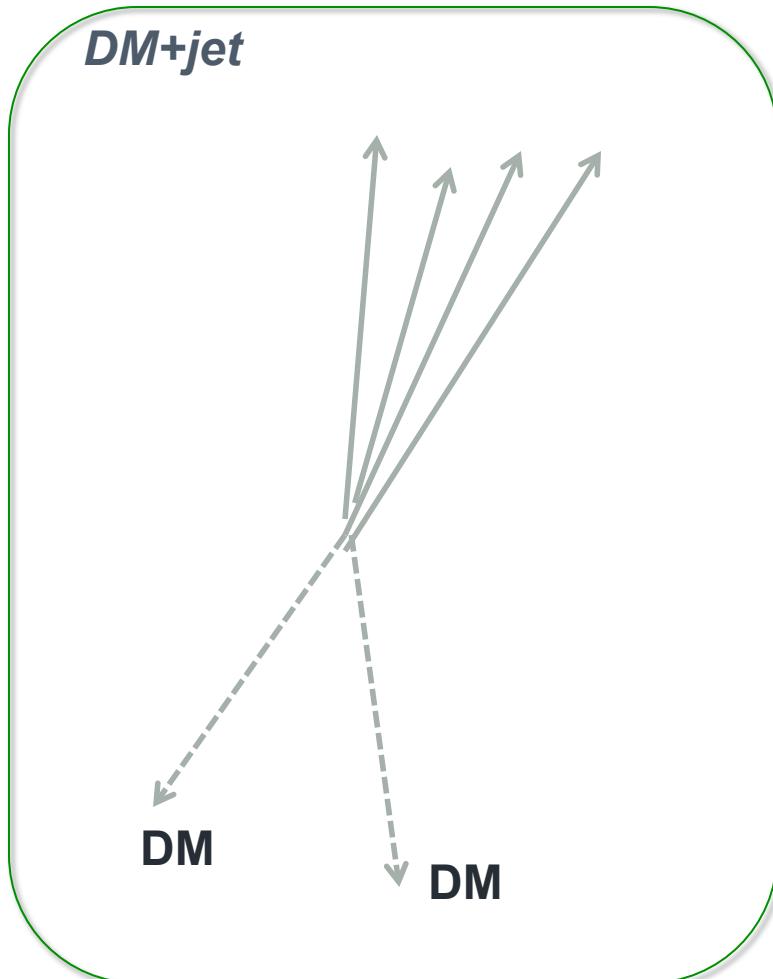
- Production at Collider
 - No interaction with detector
 - Search for energy imbalance



Monojet signal



Main backgrounds: V+jets



Selection

Event topology

- $\Delta\Phi(j_1, \text{MET}) > 2.0$
- $\Delta\Phi(j_1, j_2) < 2.0$
 - If #jets=2
 - For ISR based

- Raw
- Pass standard MET/noise
- Plus recoil corrections
(more details later)

- Default jets: **AK5 PF jets**
- $|\eta| < 2.5$ & $p_T > 30$
- Require PFJetID loose & PUJetID loose

*“if you want to see **nothing**,
you have to reconstruct **everything**”*

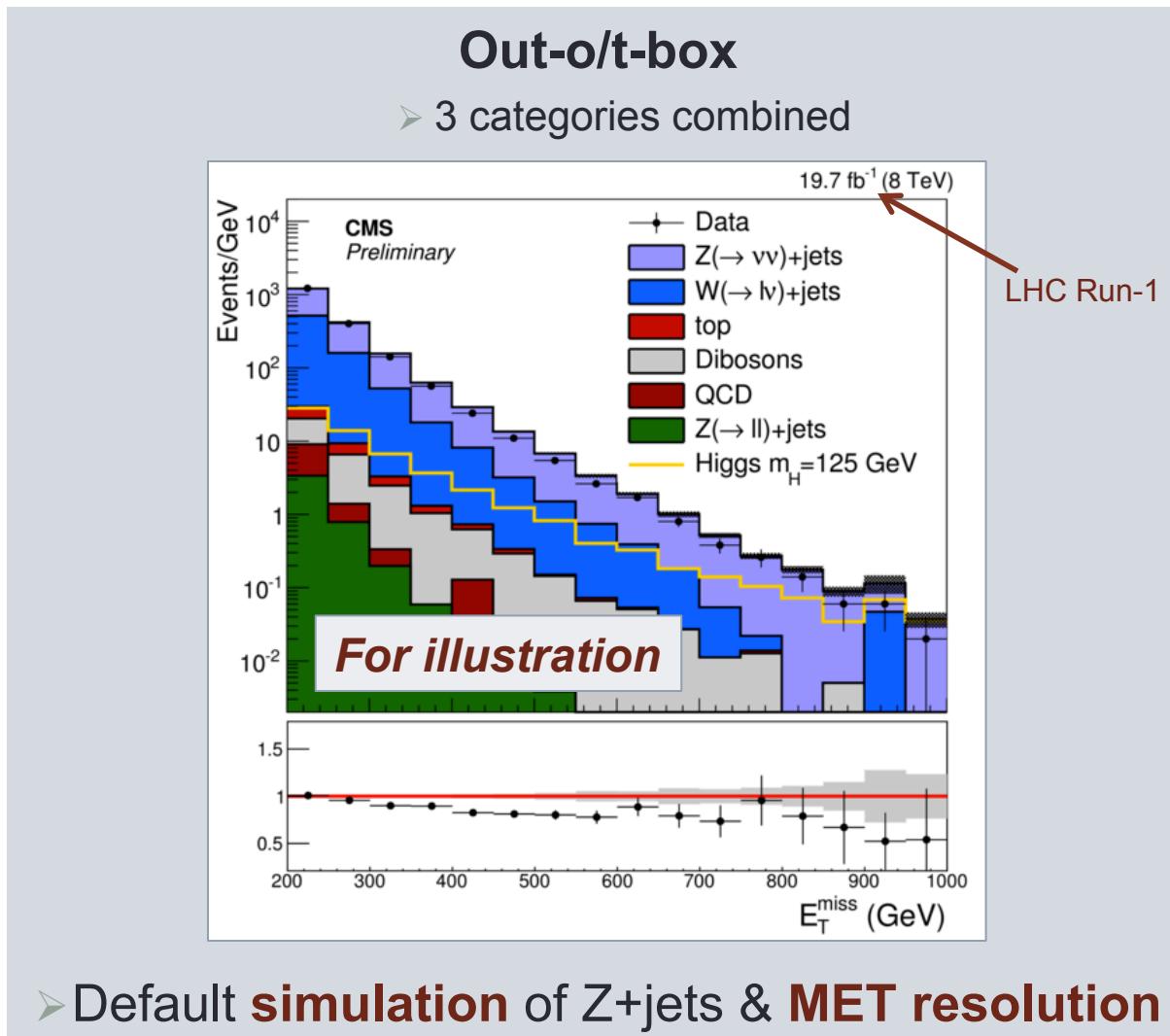
CR ($\mu+\gamma$)

- μ : $|\eta| < 2.1$ & $p_T > 10$
& POGTightID
- γ : $|\eta| < 2.5$ & $p_T > 160$
& EGammalD medium

Vetoes ($j+\mu+\gamma+e+\tau$)

- **#jets** > 2
- μ : $\eta < 2.4$ & $p_T > 10$ GeV & Global+Tracker
- γ : $\eta < 3.0$ & $p_T > 10$ GeV & EGammalD medium
- e : $\eta < 2.5$ & $p_T > 10$ GeV & EGammalD veto
- τ : $\eta < 2.5$ & $p_T > 15$ GeV & HPSPFTauID loose

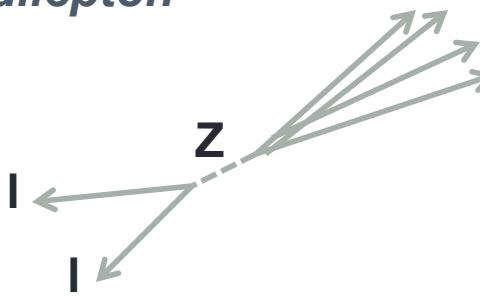
Data vs sim



Control V+jets

- Main challenges**
- **Reconstruction**
 - MET
 - **Theory**
 - NLO
 - **Control statistics**
 - $Z(\mu\mu):Z(vv) = 1:6$

dilepton

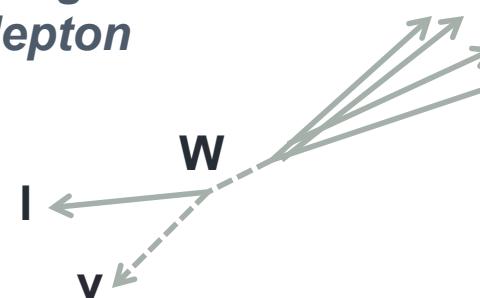


$Z(l\bar{l}) + \text{jets}$

→ Recoil

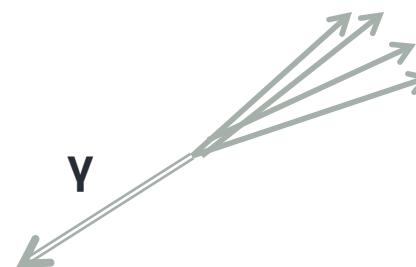
But $\mu\mu/vv = 1/6$

single lepton



$W(l\nu) + \text{jets}$

photon



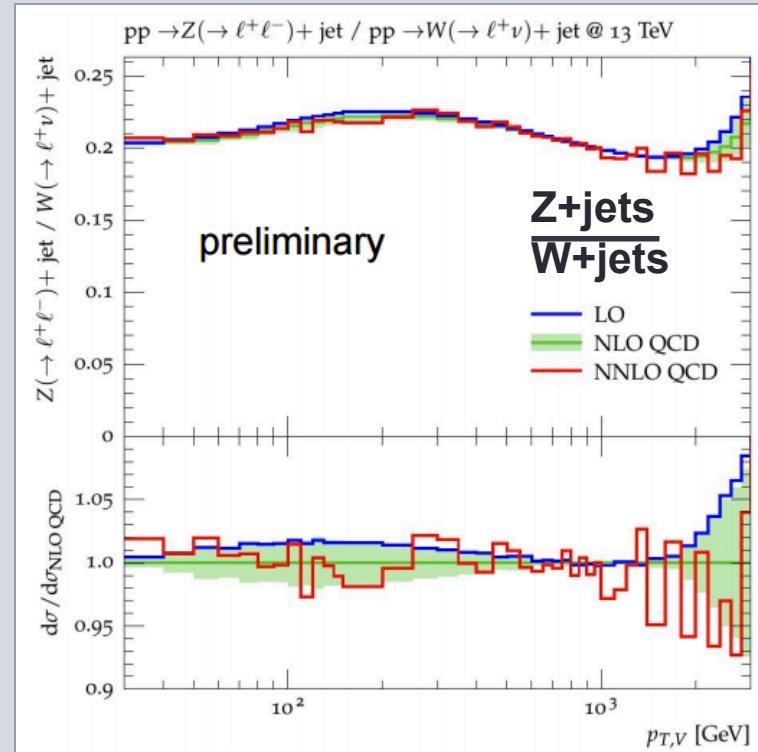
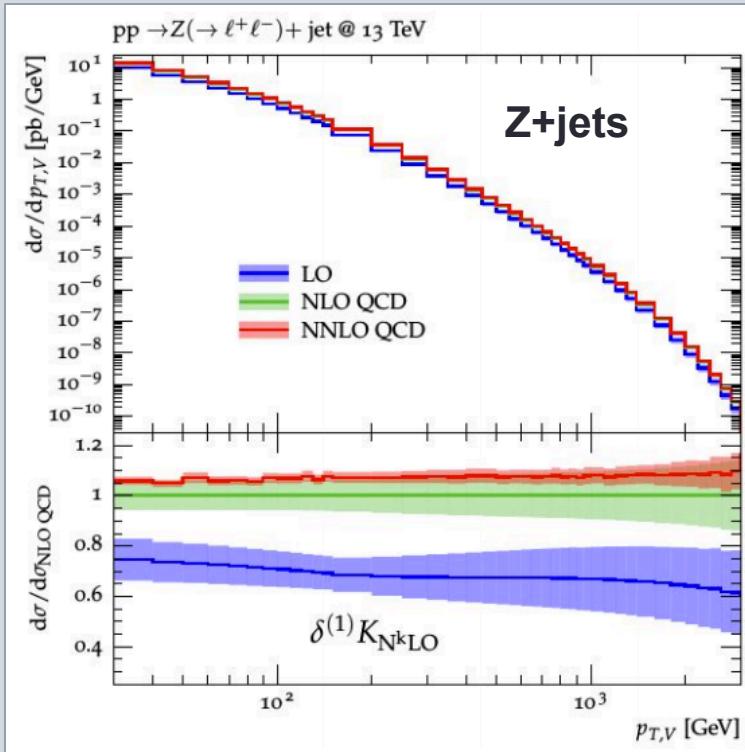
$\gamma + \text{jets}$ (CMS)

→ Z/γ

V+jets

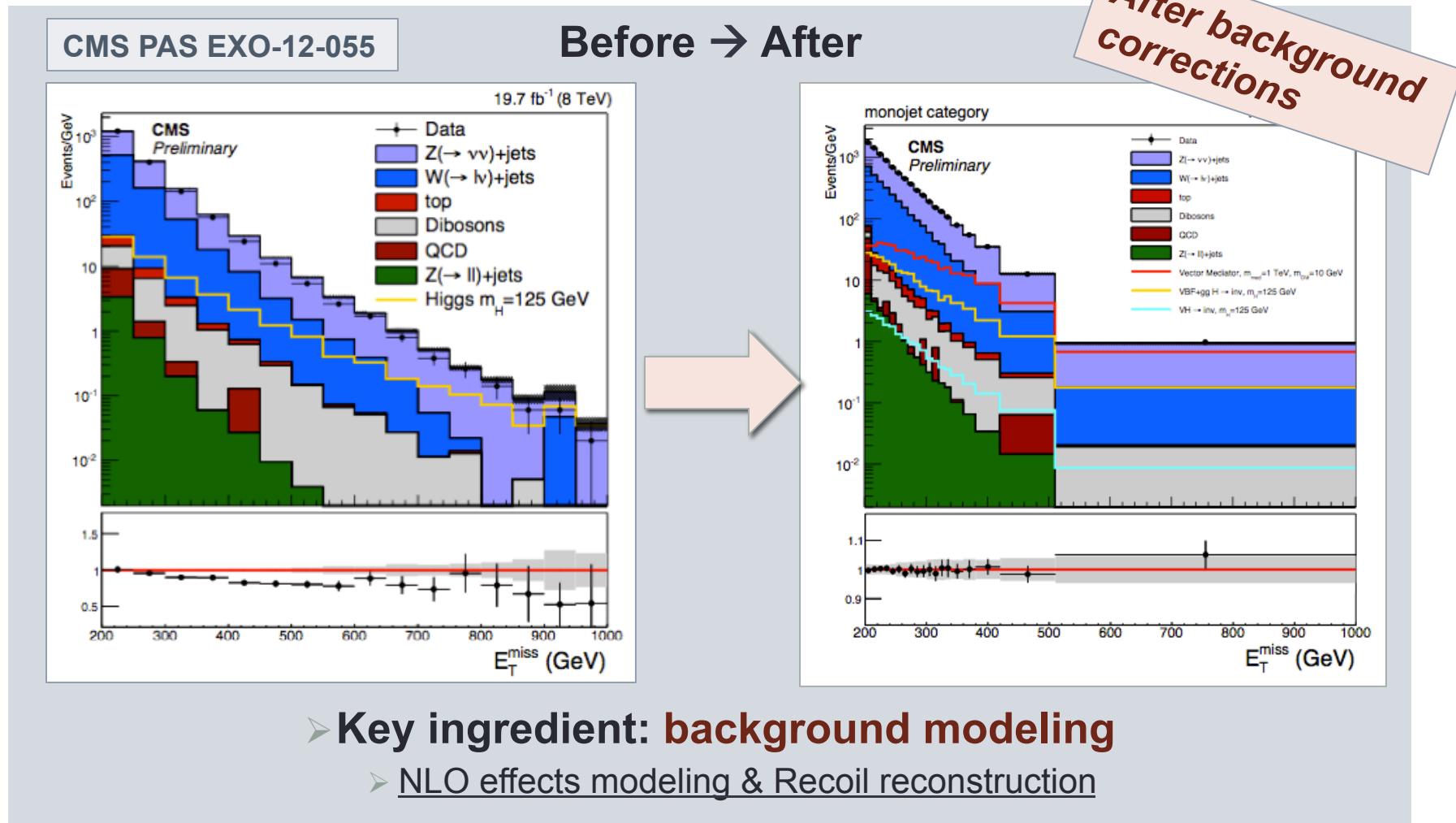
S.Pozzorini et al
<https://indico.cern.ch/event/570151/timetable/#20170505>

- **SM@LHC** (A'dam, April 2017)



➤ Precision: **NLO uncertainties** vs **NNLO predictions**

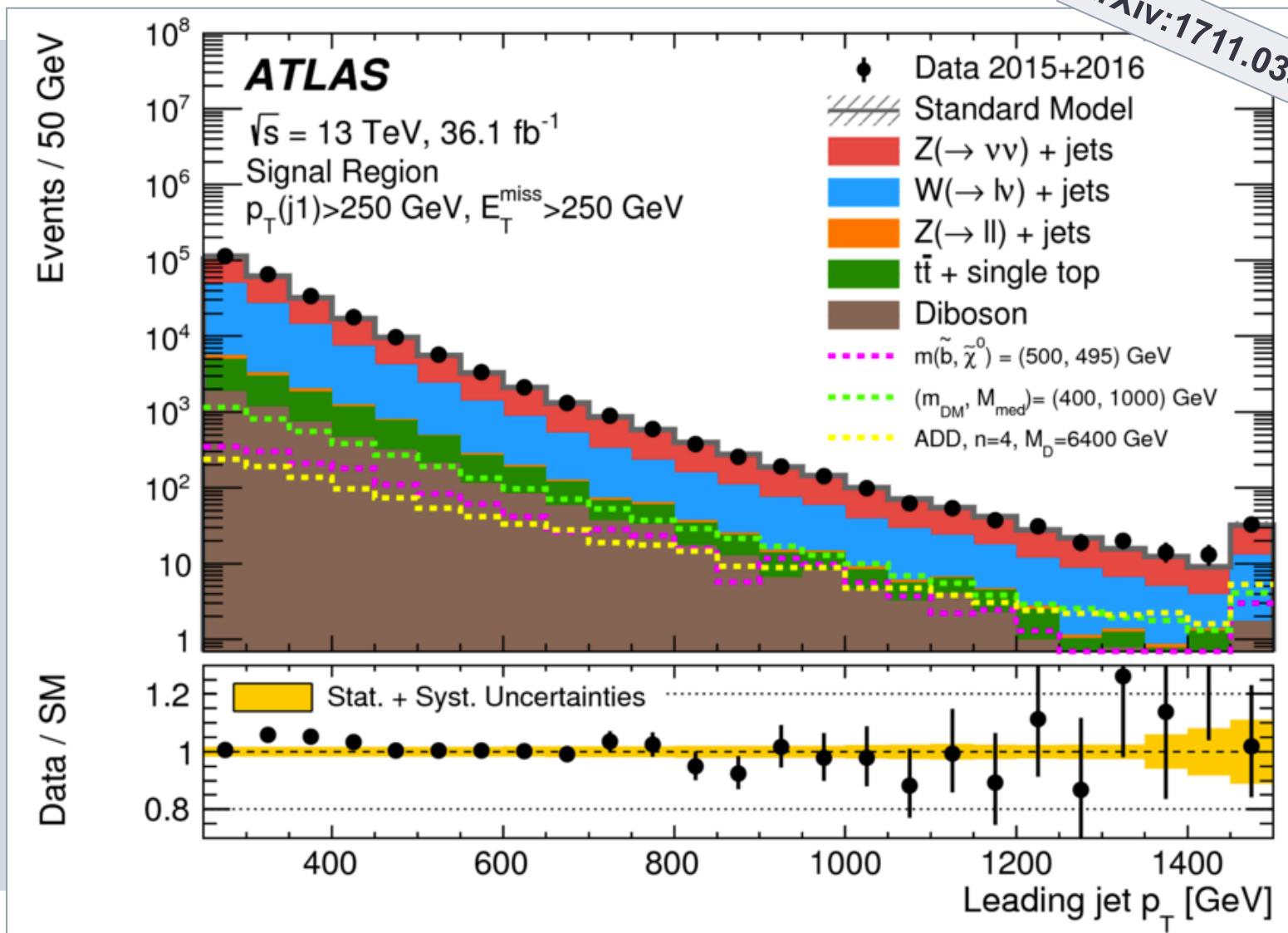
Backgrounds



ATLAS

LHC Run-2

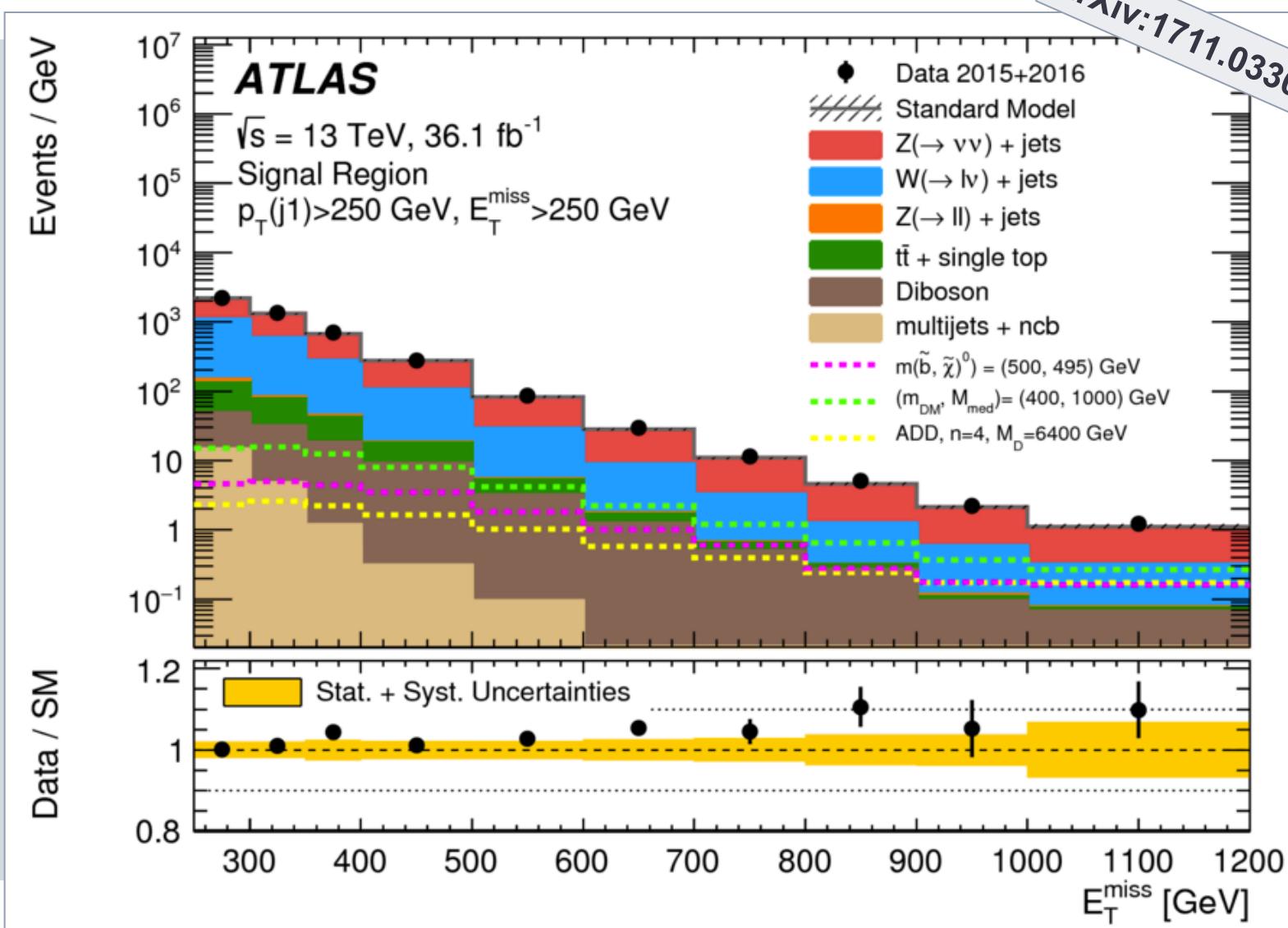
arXiv:1711.03301



ATLAS

LHC Run-2

arXiv:1711.03301



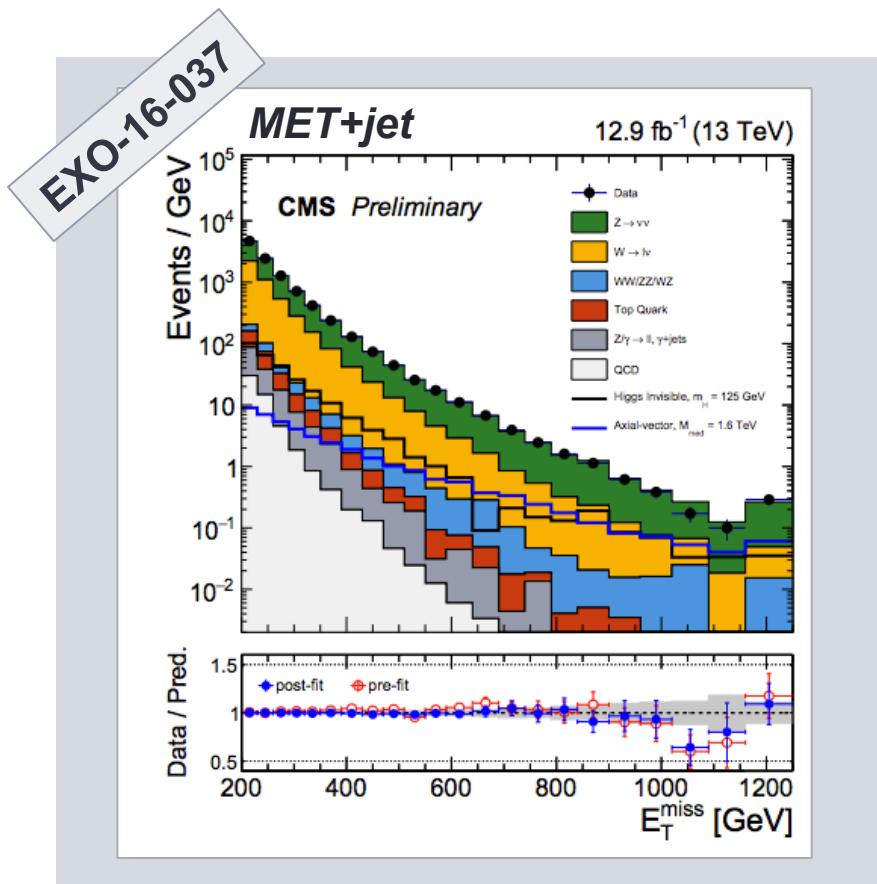


Interpretations

#DMatLHC

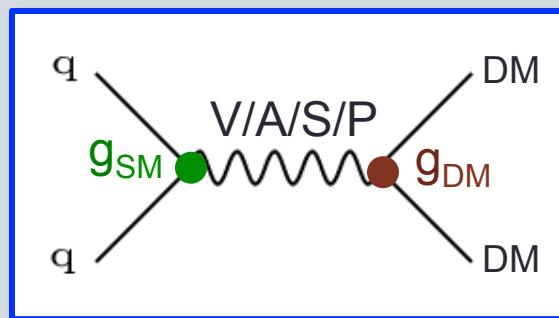
MET+X

Reconstruction



Interpretation

- **Model: DM-SM mediator**
 - **Axial / Vector** ($X = j/V/Z/\gamma$)
 - **Pseudo / Scalar** ($X = j/V/Z/bb/tt$)



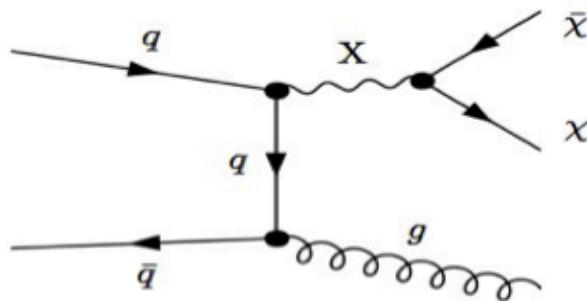
- **LHC DM WG**
 - [arXiv:1507.00966](#) / [arXiv:1603.04156](#)
 - **New:** [arXiv:1703.05703](#)

LHC – Mono-jet

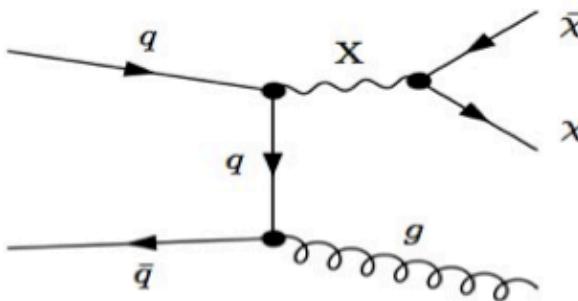
Atlas/CMS
Dark Matter Forum
Simplified models
[arXiv/1507.00966](https://arxiv.org/abs/1507.00966)

LHC DM WG
Recommendations
[arXiv/1603.04156](https://arxiv.org/abs/1603.04156)

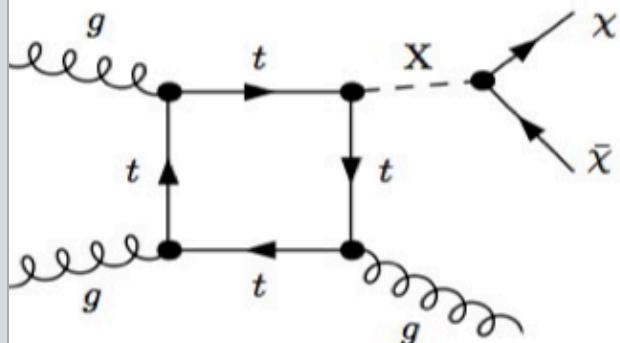
Vector



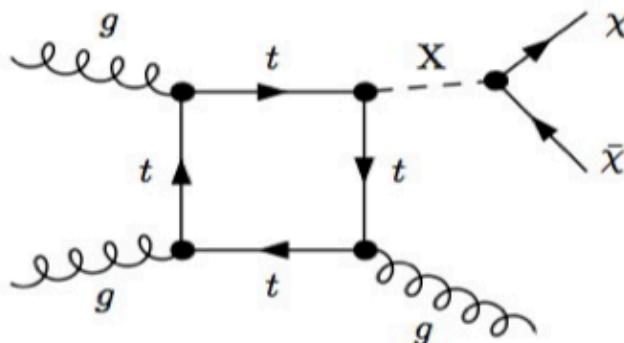
Axial



Scalar



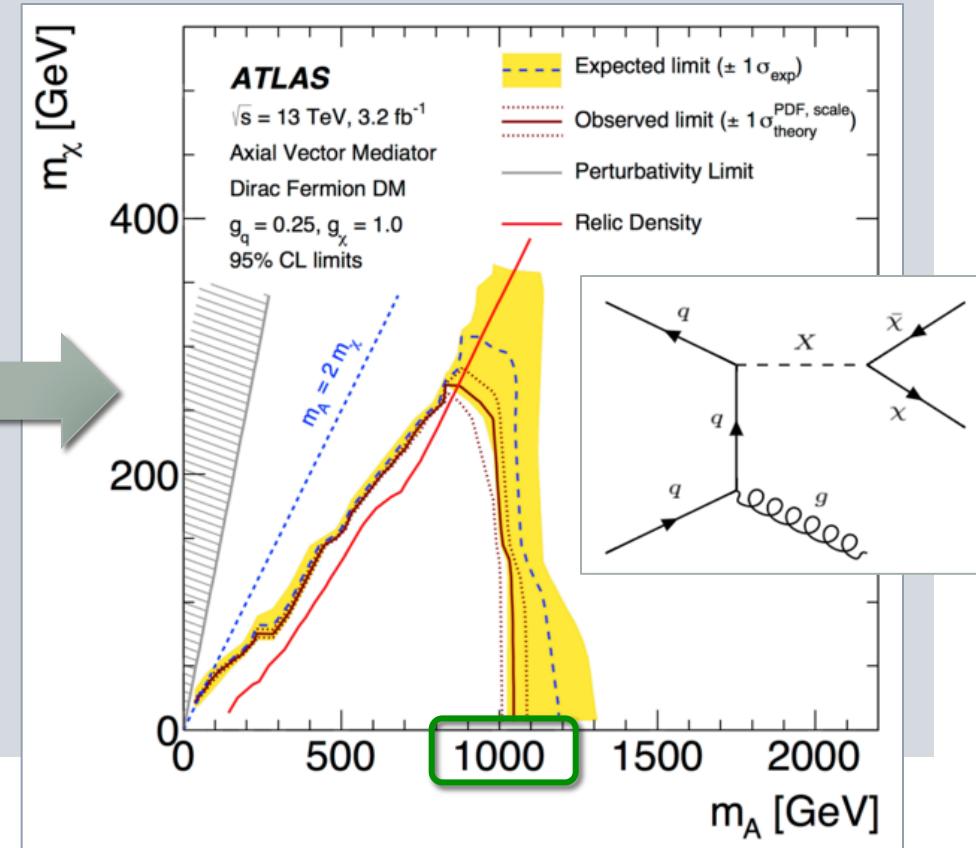
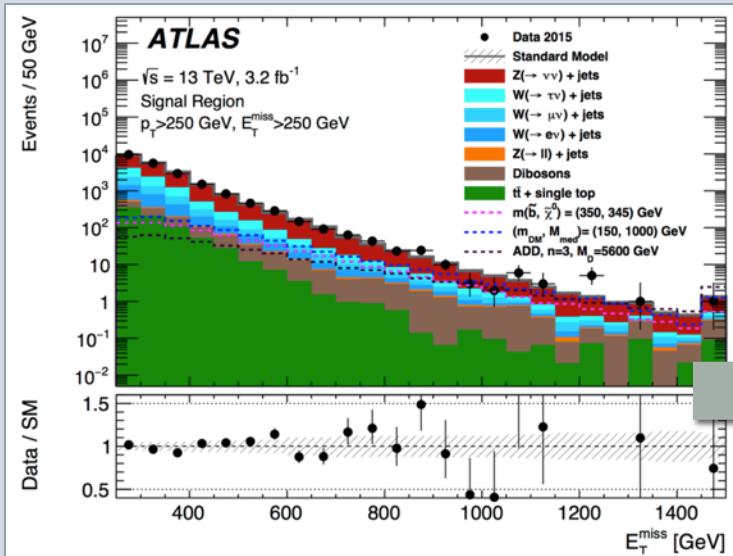
Pseudoscalar



DM+jet

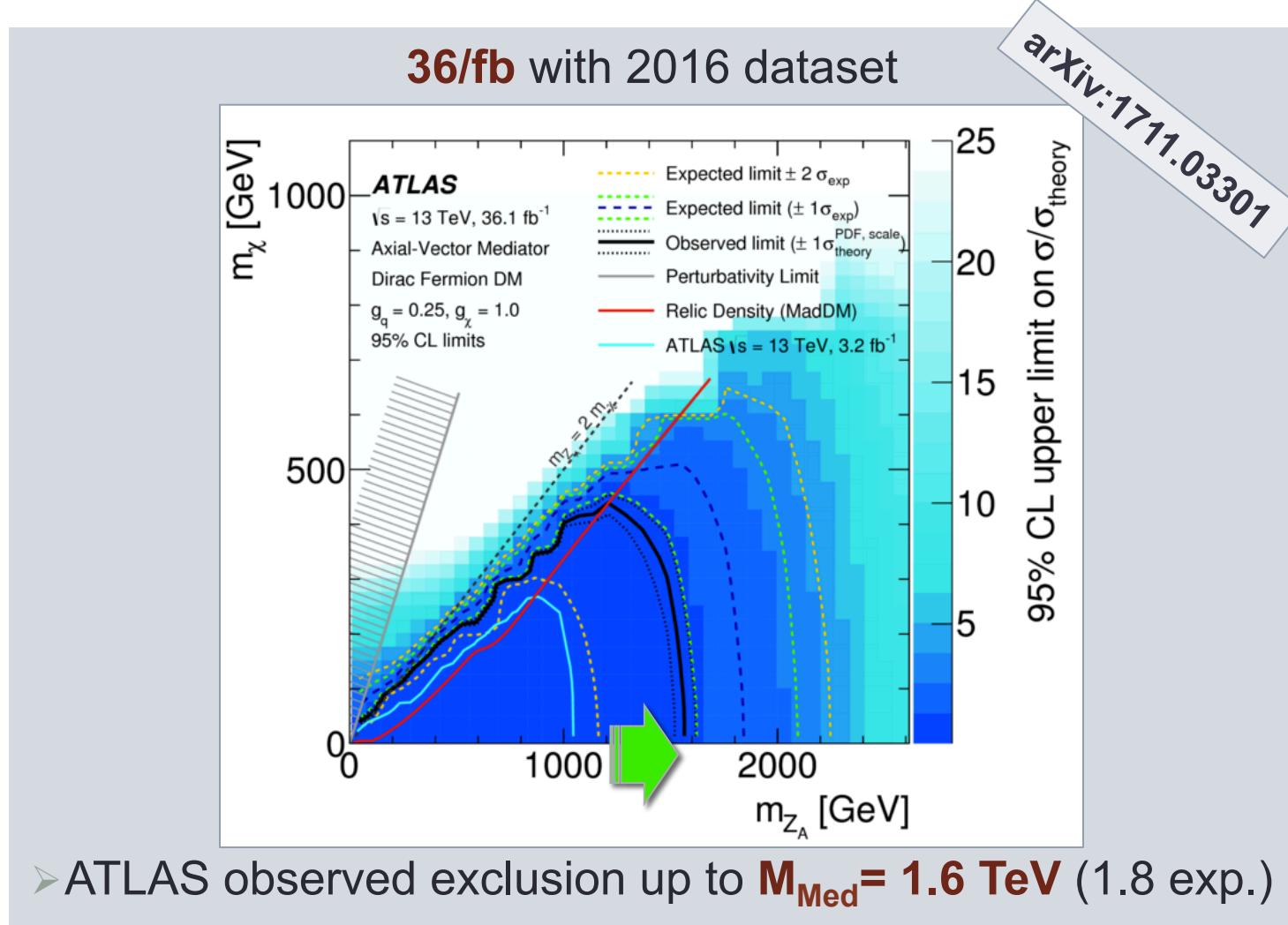
ATLAS EXOT-2015-03
PRD94(2016)032005

- **Atlas 2015 dataset (3.2/fb at 13 TeV)**



➤ **Mono-jet exclusion**
 up to $M_{\text{Med}} \sim 1 \text{ TeV}$

Interpretation





Comparison



Collider production

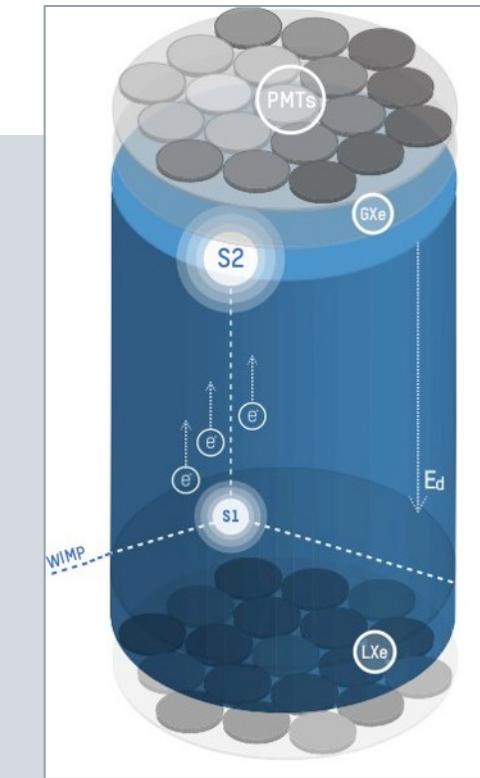
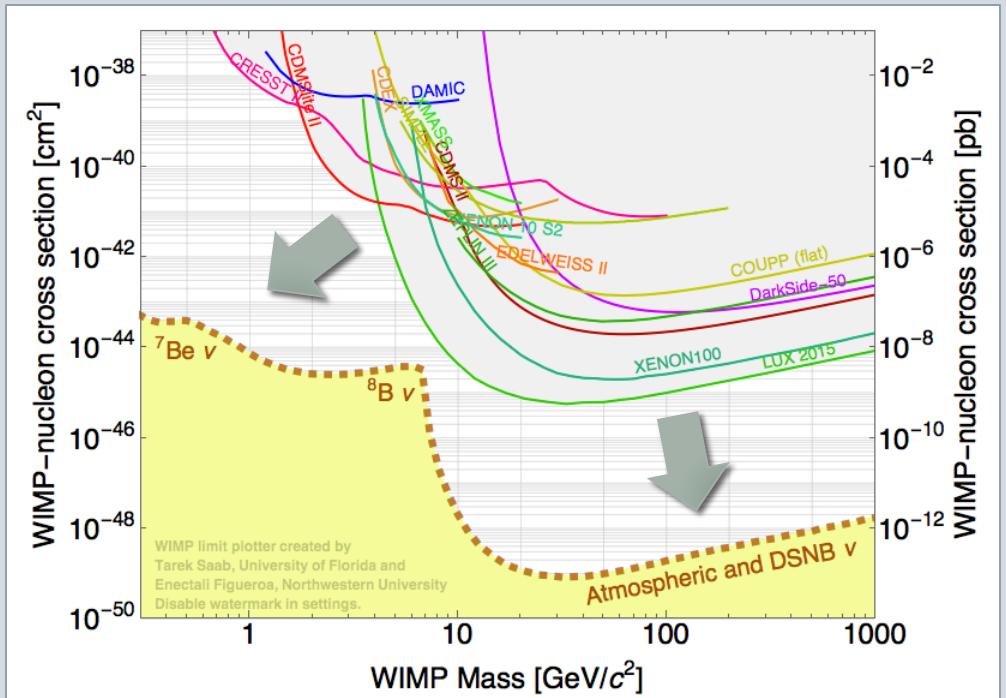


Direct Detection



DD

Direct detection summary:

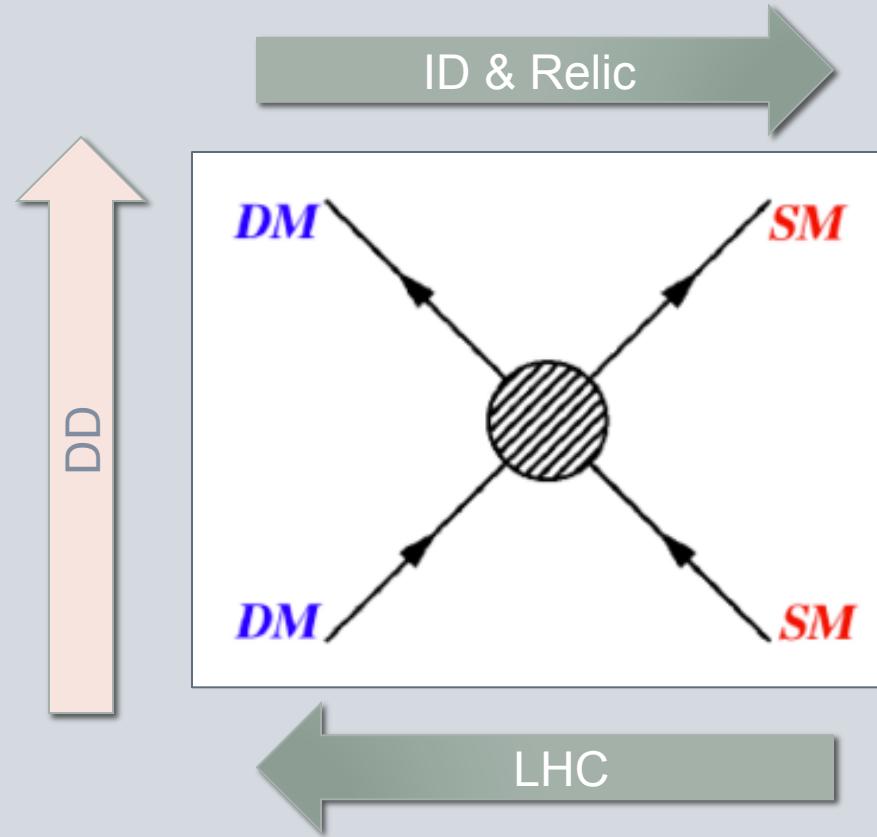


- **High mass:** recent improvements by LUX & PandaX
- **Intermediate mass:** close to neutrino floor
- **Low-mass DM:** still largely unexcluded

PandaX
arXiv/1608.07400
LUX
arXiv/1608.07648

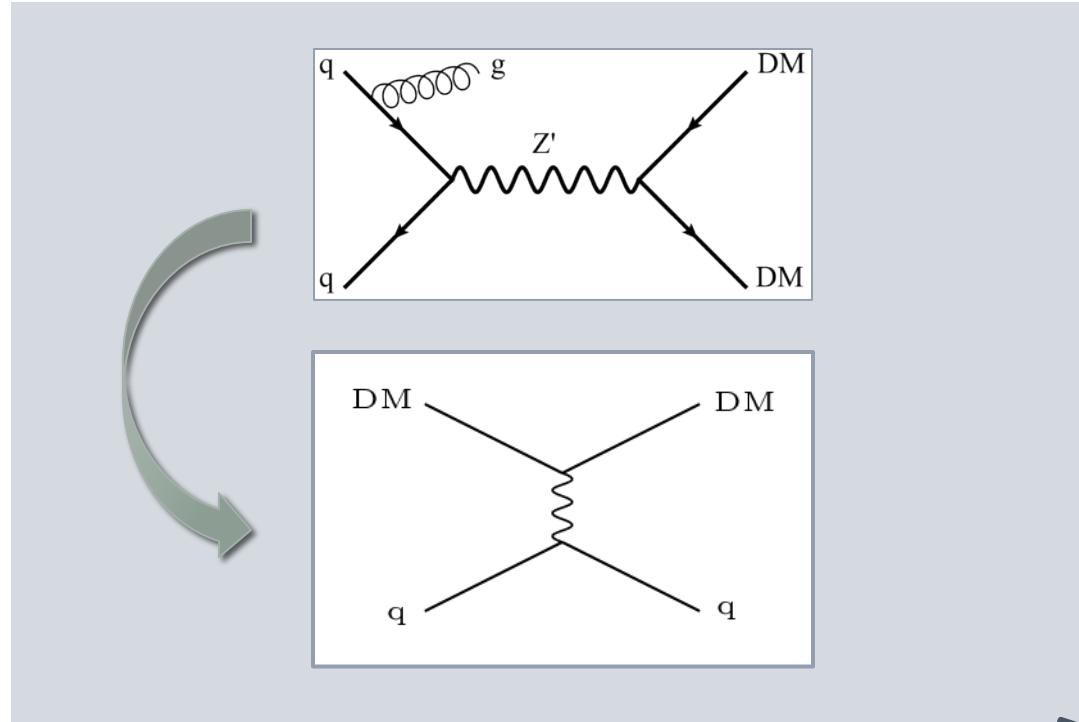
LHC vs DD vs ID&Relic

Test the same coupling in different ways:



➤ Which SM-DM interaction? **LHC DMF benchmarks!**

DD interpretation



90% CL $(M, m) \rightarrow (m, \sigma)$

➤ **V (SI)**

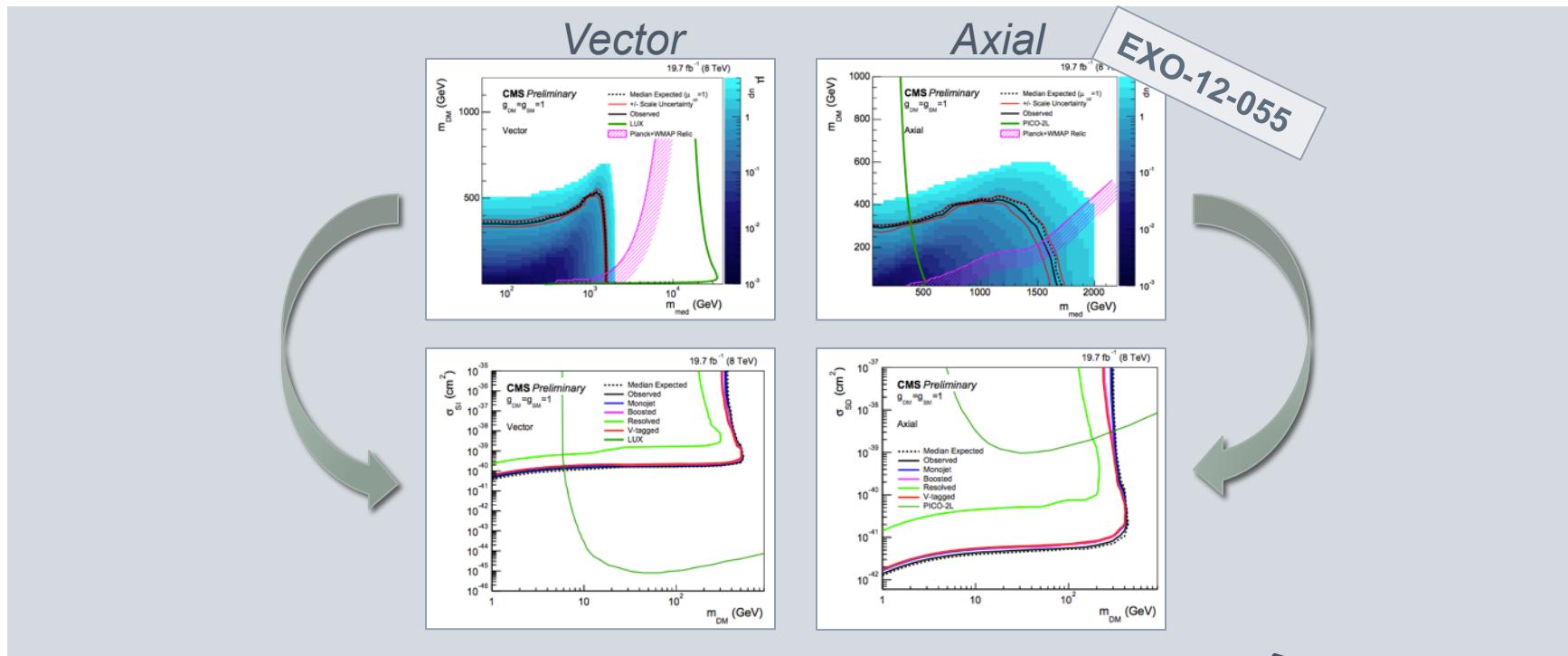
$$\sigma_{\text{SI}} \simeq 6.9 \times 10^{-41} \text{ cm}^2 \cdot \left(\frac{g_q g_{\text{DM}}}{0.25}\right)^2 \left(\frac{1 \text{ TeV}}{M_{\text{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1 \text{ GeV}}\right)^2. \quad (4.3)$$

➤ **AV (SD)**

$$\sigma^{\text{SD}} \simeq 2.4 \times 10^{-42} \text{ cm}^2 \cdot \left(\frac{g_q g_{\text{DM}}}{0.25}\right)^2 \left(\frac{1 \text{ TeV}}{M_{\text{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1 \text{ GeV}}\right)^2. \quad (4.10)$$

LHC DM WG ($g_q = 0.25$, $g_{\text{DM}} = 1$)
<https://arxiv.org/abs/1603.04156>

DD interpretation



90% CL (M, m) \rightarrow (m, σ)

➤ V (SI)

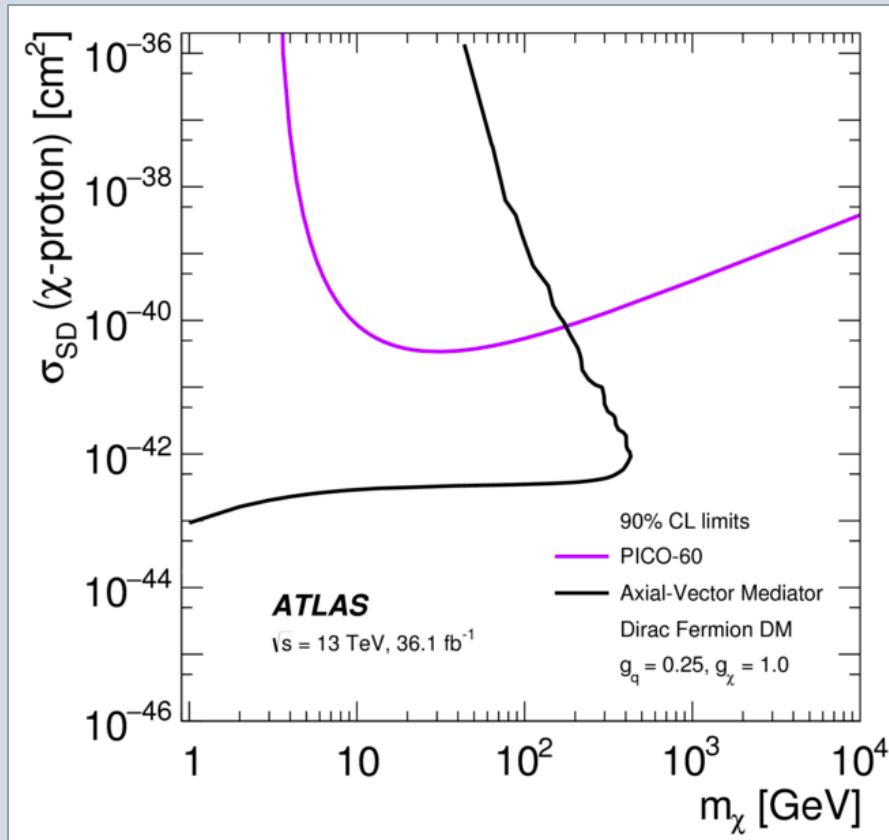
$$\sigma_{\text{SI}} \simeq 6.9 \times 10^{-41} \text{ cm}^2 \cdot \left(\frac{g_q g_{\text{DM}}}{0.25} \right)^2 \left(\frac{1 \text{ TeV}}{M_{\text{med}}} \right)^4 \left(\frac{\mu_{n\chi}}{1 \text{ GeV}} \right)^2. \quad (4.3)$$

➤ AV (SD)

$$\sigma^{\text{SD}} \simeq 2.4 \times 10^{-42} \text{ cm}^2 \cdot \left(\frac{g_q g_{\text{DM}}}{0.25} \right)^2 \left(\frac{1 \text{ TeV}}{M_{\text{med}}} \right)^4 \left(\frac{\mu_{n\chi}}{1 \text{ GeV}} \right)^2. \quad (4.10)$$

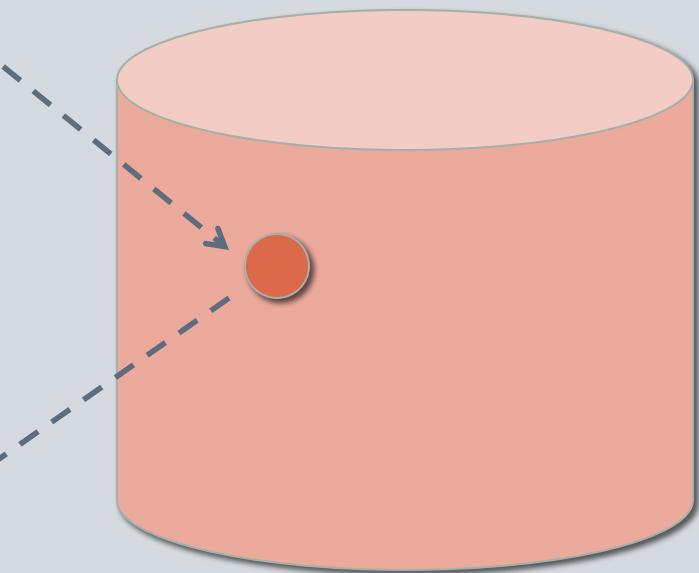
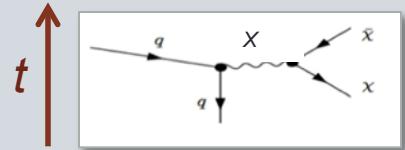
LHC DM WG ($g_q=0.25, g_{\text{DM}}=1$)
<https://arxiv.org/abs/1603.04156>

ATLAS vs DD

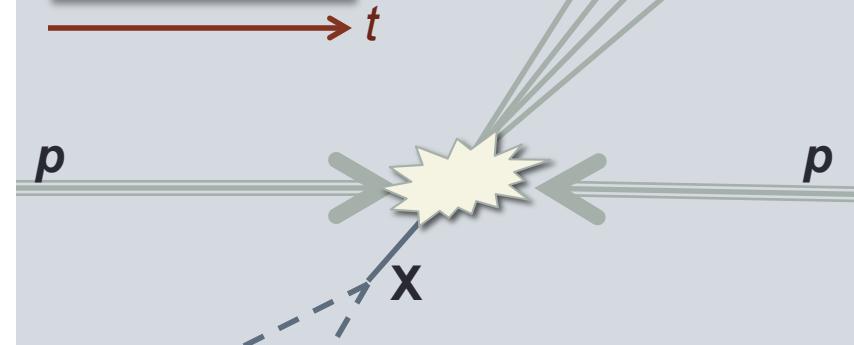
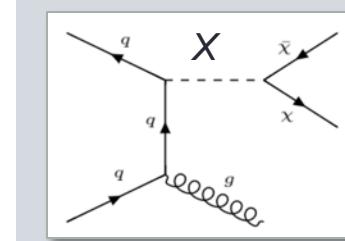


➤ LHC particularly competitive for **low m_{DM}**

DD vs LHC



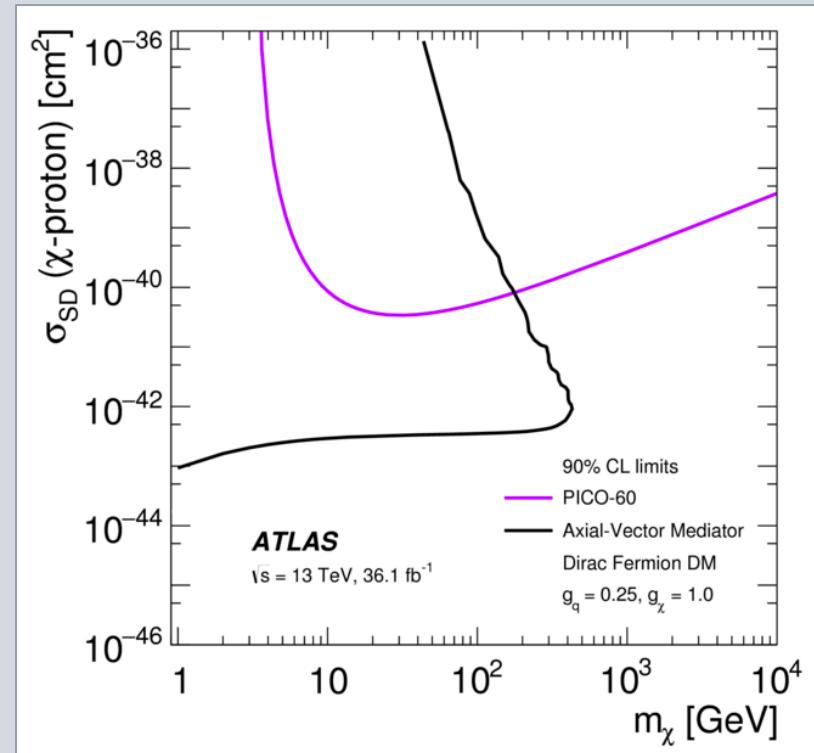
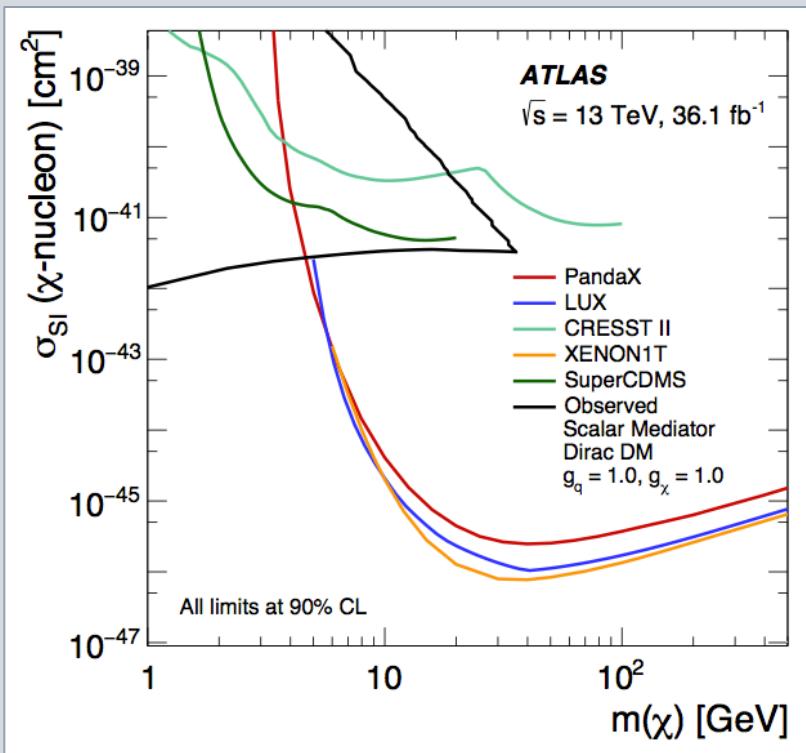
➤ DD challenging for low M_{DM}



➤ LHC indifferent to M_{DM} !

➤ LHC best for low-mass Dark Matter!

ATLAS vs DD



➤ LHC particularly competitive for **low m_{DM}** and **SD**



H→invisible ?

H \rightarrow inv

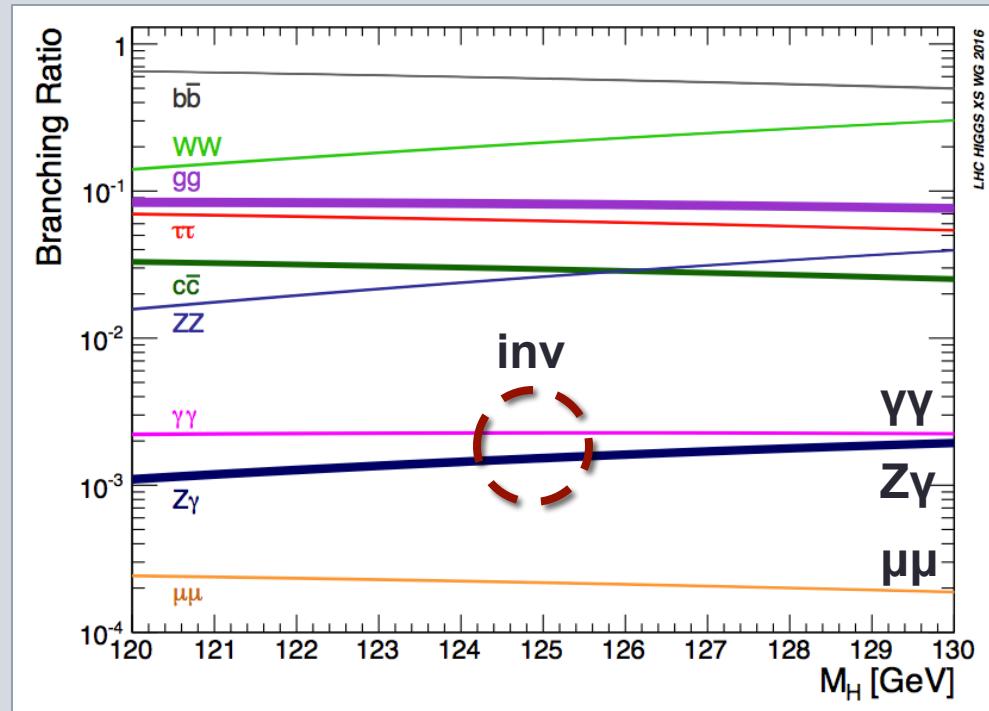
1. Higgs boson ‘gives mass’
2. Dark Matter is massive



➤ Higgs coupling to DM?

SM H \rightarrow inv

- H \rightarrow Z(vv)Z(vv) rare in SM: BR_{inv} \sim 0.1%

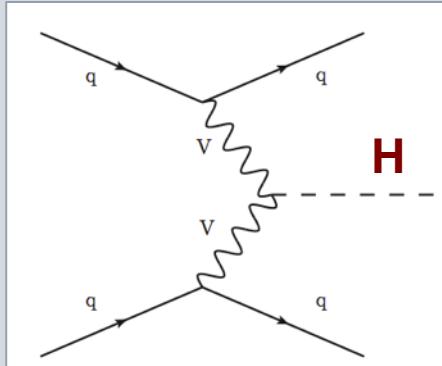
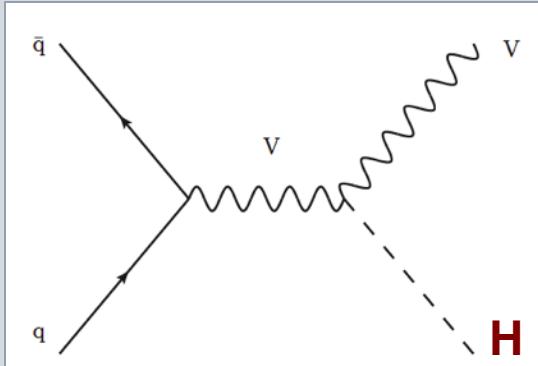
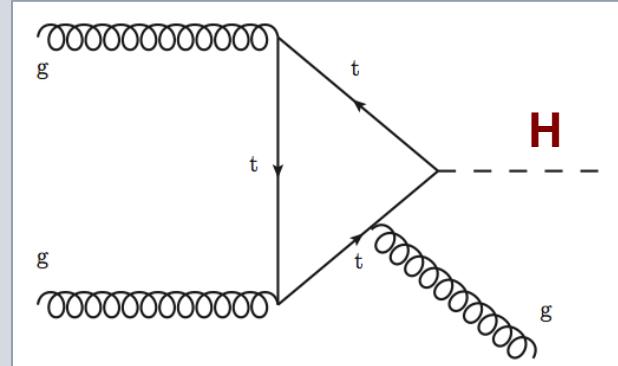


- BR_{inv} can be enhanced by various BSM processes

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG>

H \rightarrow inv processes

arXiv:1610.09218

VBF**VH****ggH**

- **VBF**

- Dedicated selection (m_{jj} , $\Delta\eta$), dominant sensitivity

- **VH**

- Both MET+Z(l ℓ) and MET+V_{had}

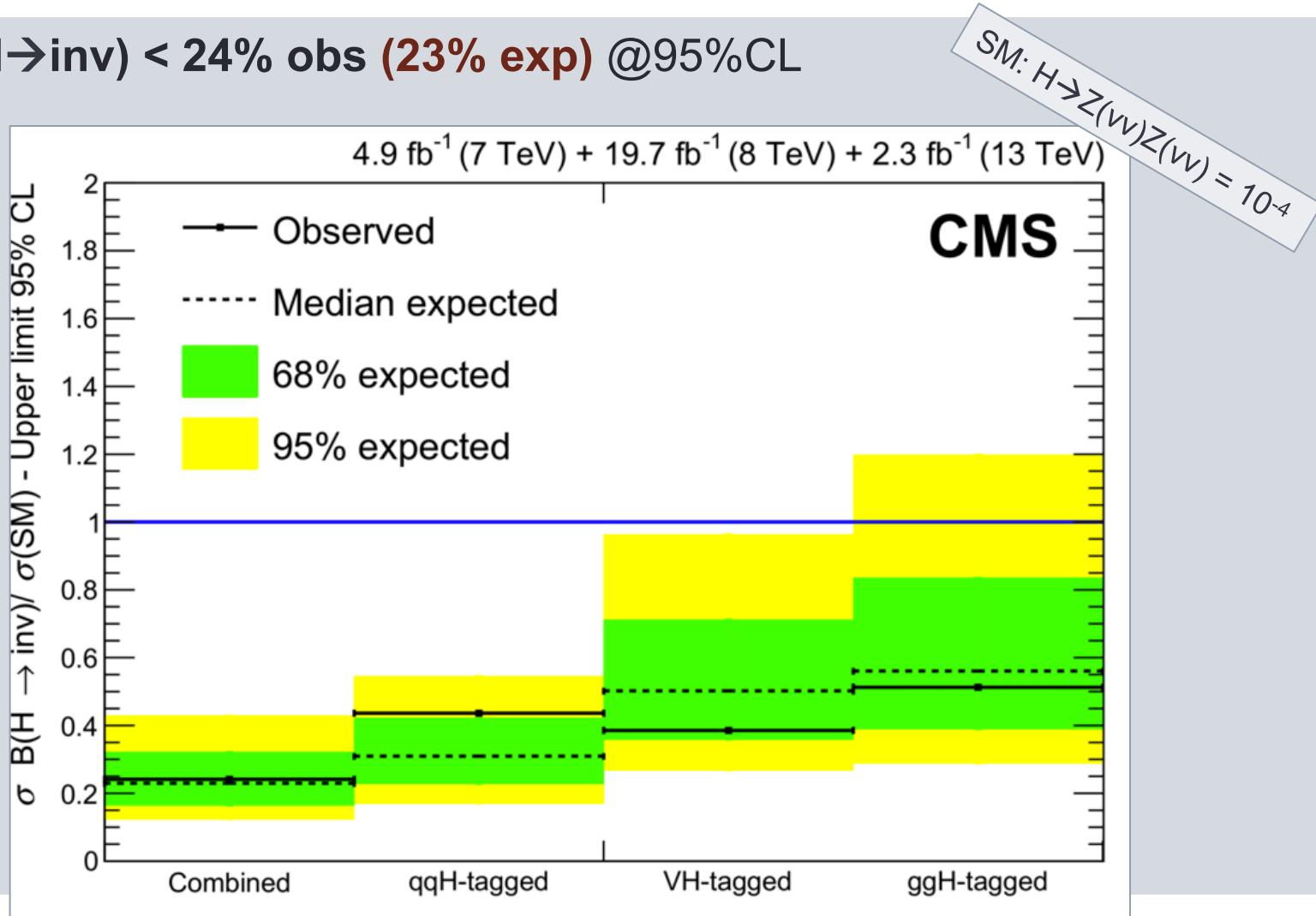
- **ggH (CMS)**

- Developments from mono-jet search

H \rightarrow inv combination

arXiv:1610.09218

- BR(H \rightarrow inv) < 24% obs (23% exp) @95%CL

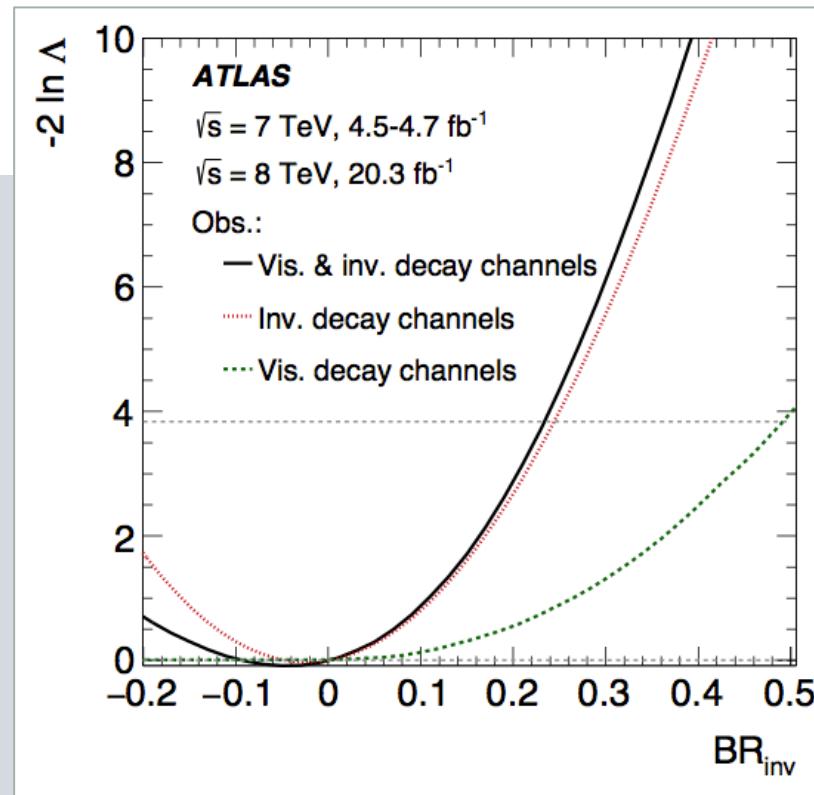


H \rightarrow inv

ATLAS run-1 combination

- H \rightarrow inv considers constraints from **visible channels**
- BR(H \rightarrow inv) < 23% obs (**24% exp**)

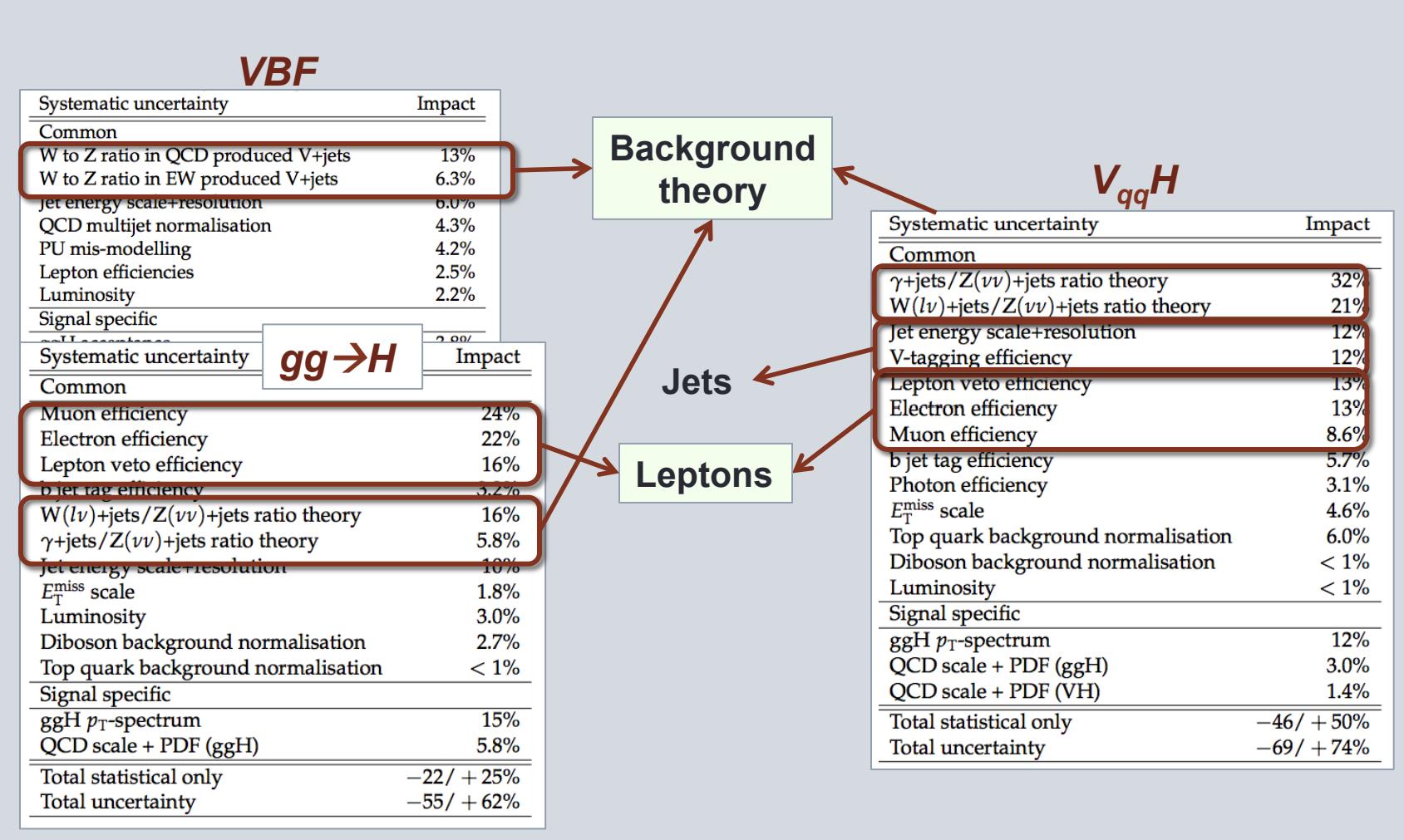
ATLAS arXiv/1509.00672



Decay channels	Coupling parameterisation	κ_i assumption	Upper limit on BR _{inv}
			Obs. Exp.
Invisible decays	$[K_W, K_Z, K_t, K_b, K_\tau, K_\mu, K_g, K_\gamma, K_{Z\gamma}, \text{BR}_{\text{inv}}]$	$K_{W,Z,g} = 1$	0.25 0.27
Visible decays	$[K_W, K_Z, K_t, K_b, K_\tau, K_\mu, K_g, K_\gamma, K_{Z\gamma}, \text{BR}_{\text{inv}}]$	$K_{W,Z} \leq 1$	0.49 0.48
Inv. & vis. decays	$[K_W, K_Z, K_t, K_b, K_\tau, K_\mu, K_g, K_\gamma, K_{Z\gamma}, \text{BR}_{\text{inv}}]$	None	0.23 0.24
Inv. & vis. decays	$[K_W, K_Z, K_t, K_b, K_\tau, K_\mu, K_g, K_\gamma, K_{Z\gamma}, \text{BR}_{\text{inv}}]$	$K_{W,Z} \leq 1$	0.23 0.23

H \rightarrow inv systematics

CMS PAS HIG-16-016



H \rightarrow inv prospects

- Assumptions
 1. 2012 performance
 2. ZH-tagged search
- H \rightarrow inv projections (CMS)
 - Run-3 (300/fb): BR < **17-28%**
 - HL-LHC (3000/fb): BR < **2-6%**

CMS-NOTE-2013-002
ATLAS-PHYS-PUB-2013-014

- Indirect constraint
 - Scan $BR_{BSM} = \Gamma_{BSM}/\Gamma_{tot}$
- Coupling modifier fit
 - Run-2 (300/fb): BR < **14-18%**
 - HL-LHC (3000/fb): BR < **7-11%**

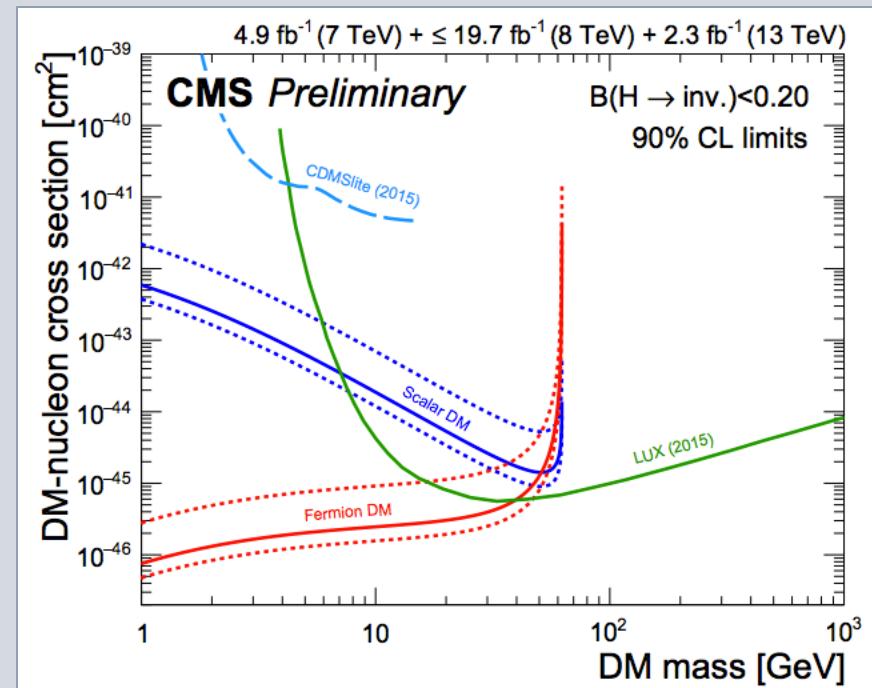
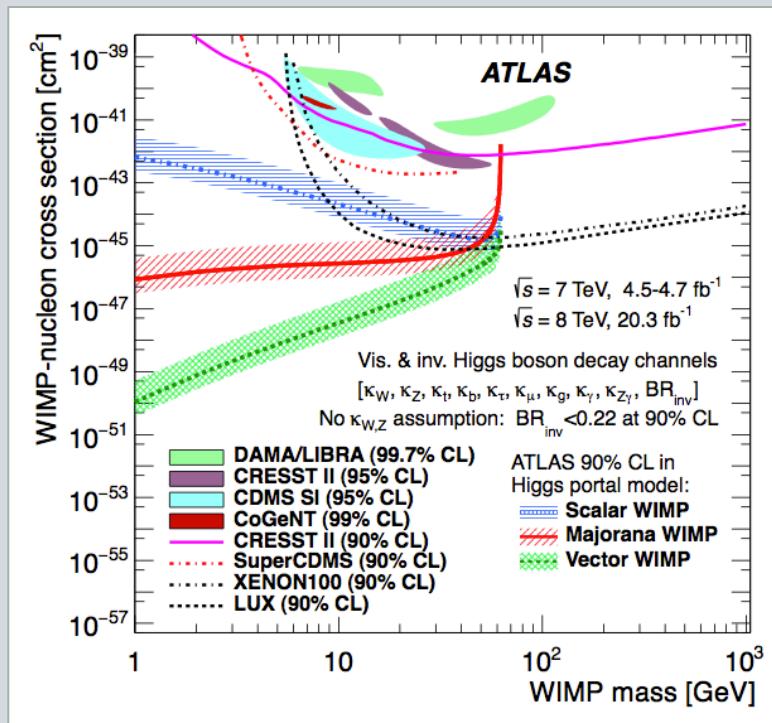
- Current sensitivity (**23%**) already in ballpark of **Run-3** projection!
 - Projection for direct H \rightarrow inv search appears on the conservative side

H \rightarrow inv

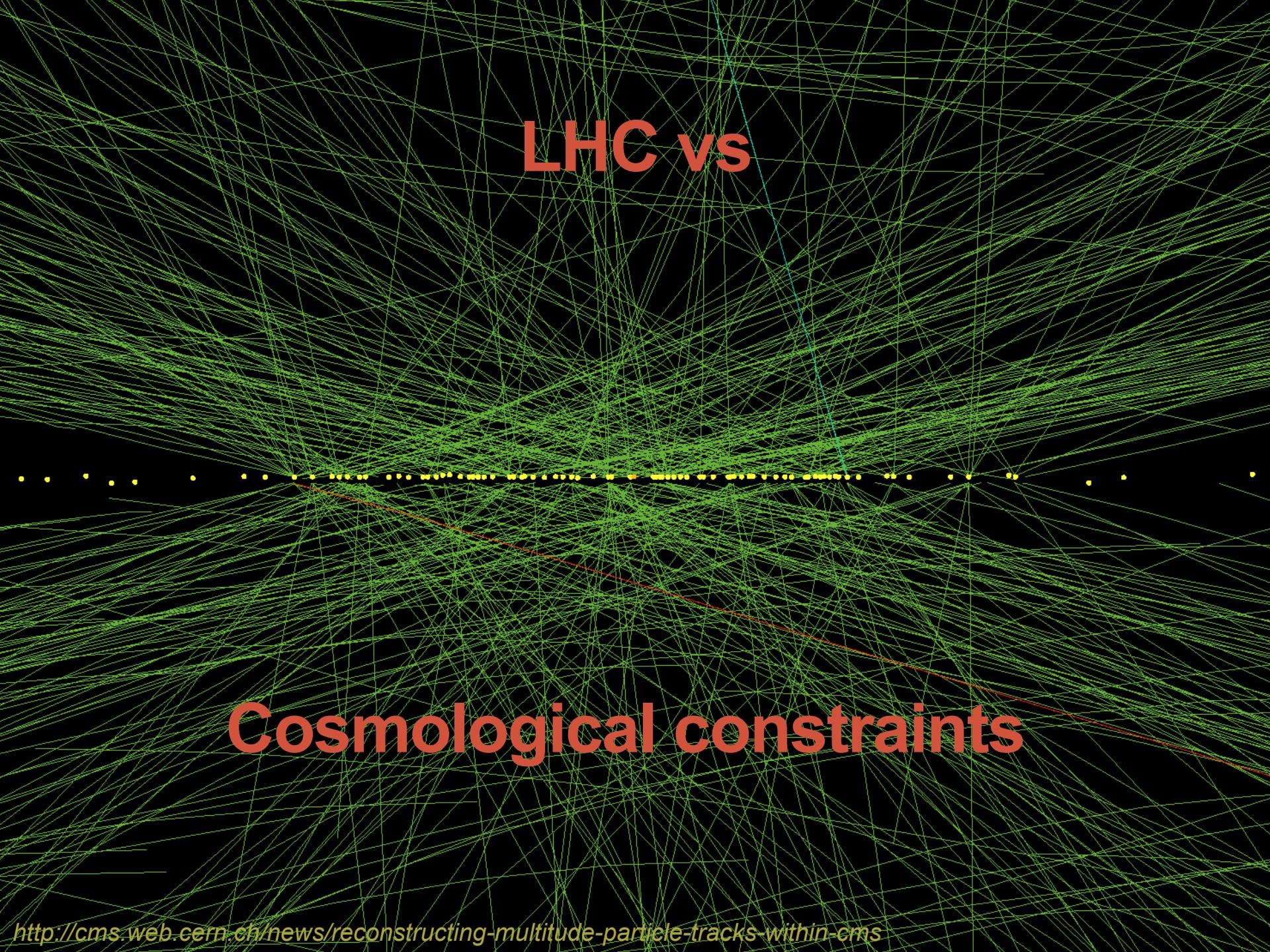
LHC vs DD

ATLAS arXiv/1509.00672

CMS PAS HIG-16-016



➤ LHC best for low m_{DM}

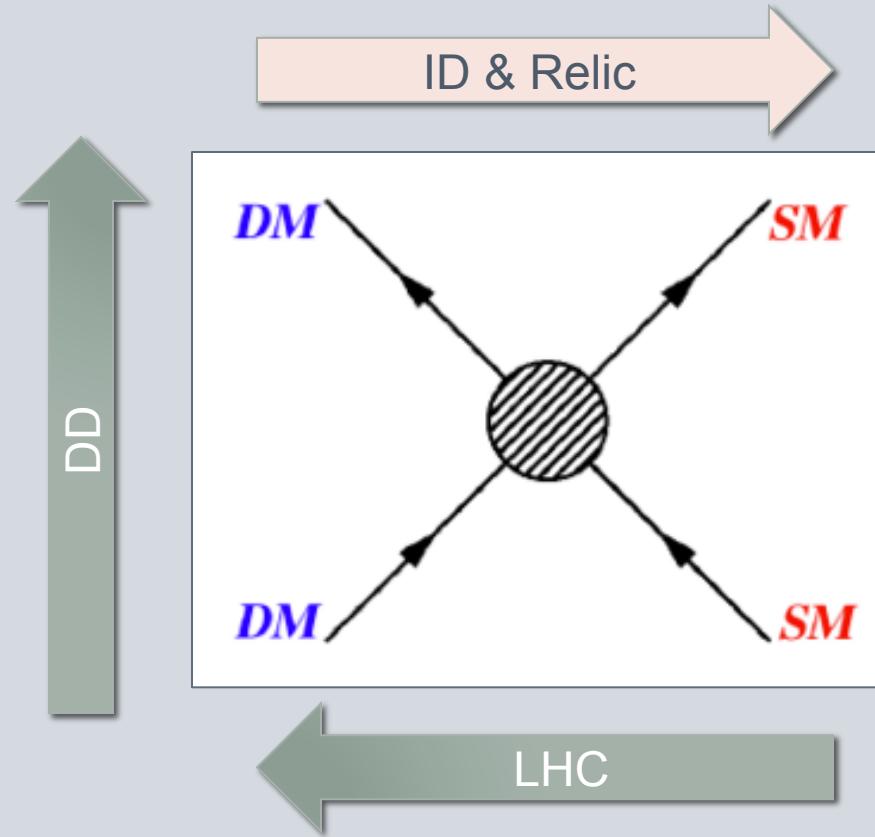


LHC vs

Cosmological constraints

LHC vs DD vs ID&Relic

Test the same coupling in different ways:

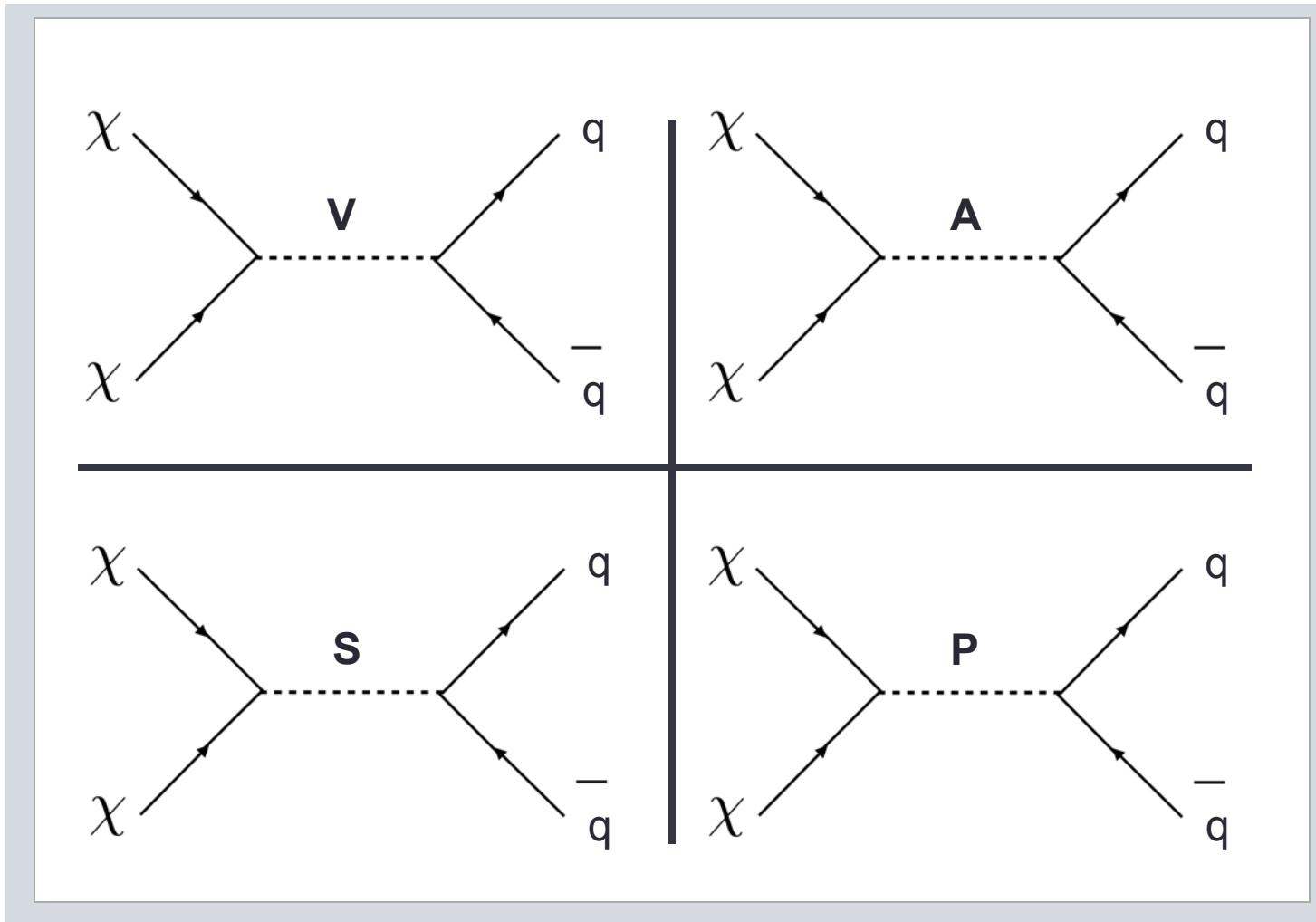


➤ Which SM-DM interaction? **LHC DMF benchmarks!**

Relic - Annihilation



<https://inspirehep.net/record/1250317>



- Additional interpretations of these models



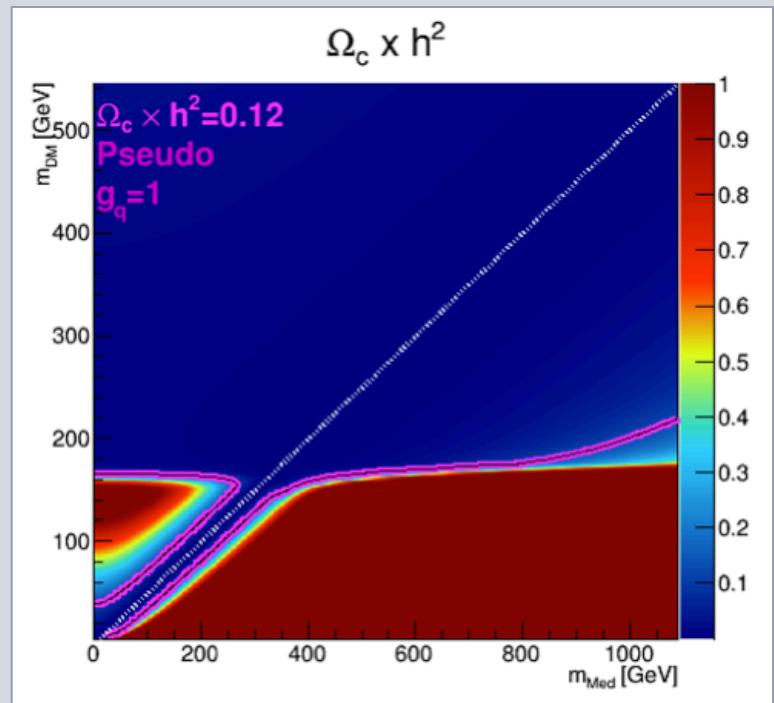
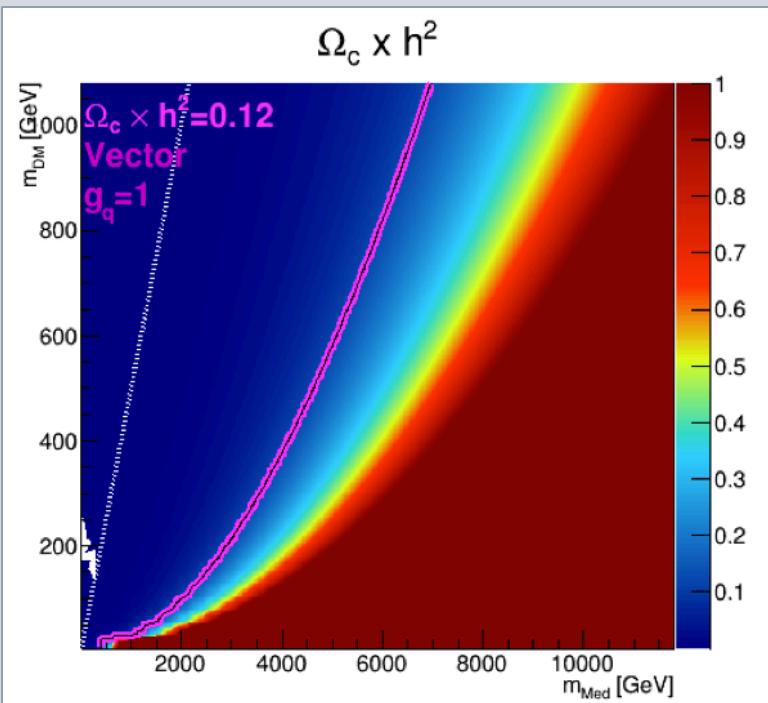
Theory & Experiment



LHC vs Relic

- **MadDM** [Vector & Pseudo]

*arXiv:1603.08525
TdP, K.Hahn, P.Harris, C.Roskas*

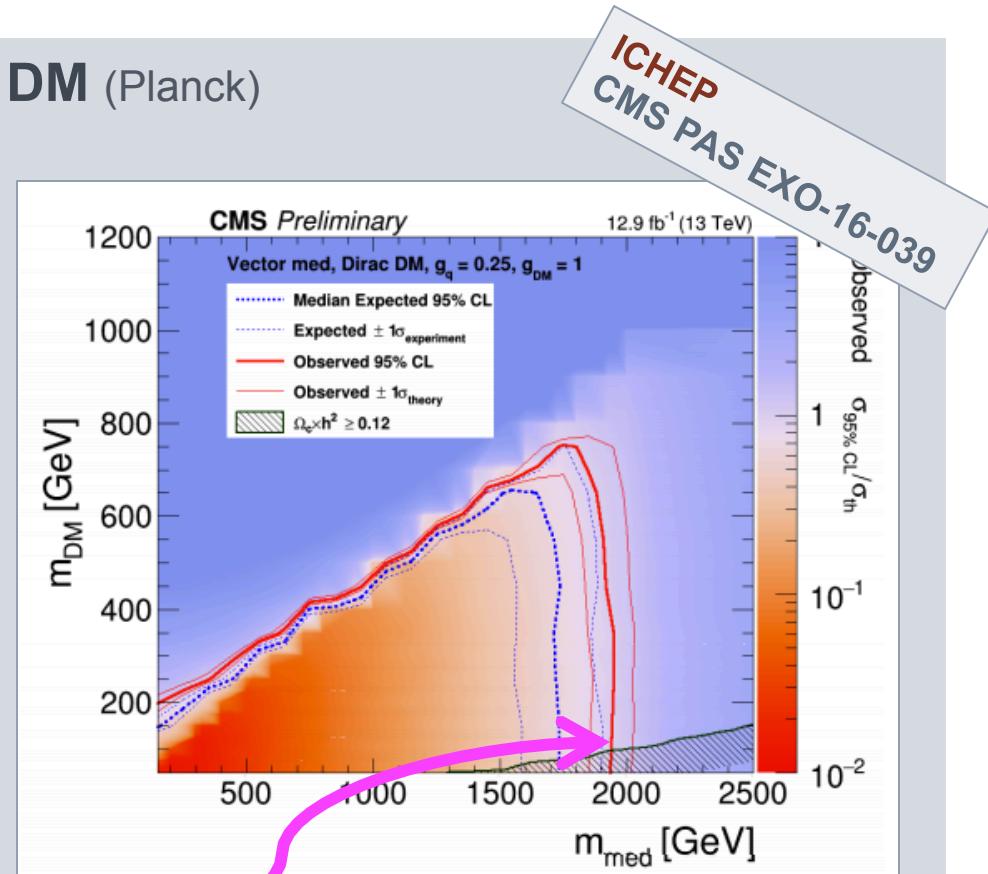
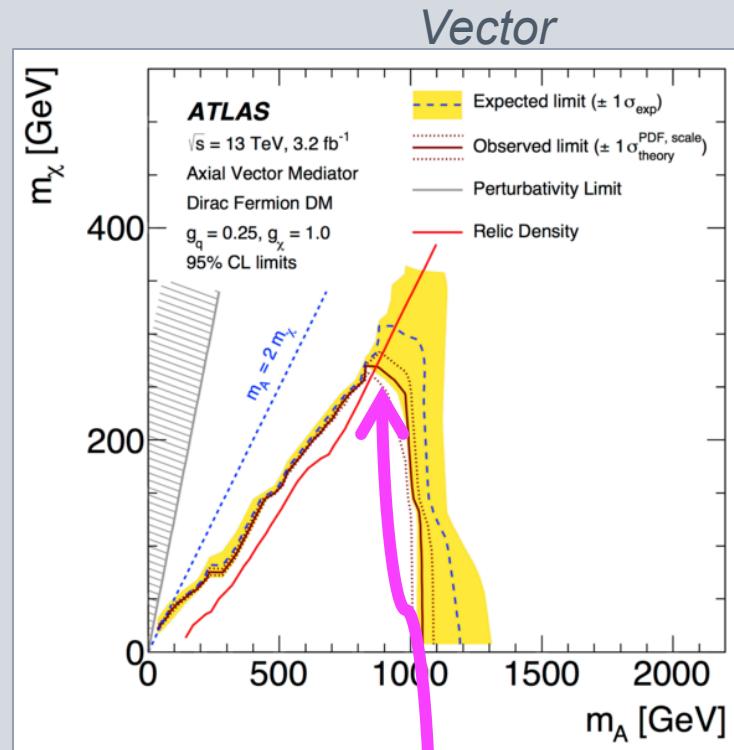


➤ Additional interpretations of LHC DM models

- Used in a.o. CMS PAS EXO-12-055, EXO-15-003, EXO-16-013
- Included in recommendations LHC DM WG ([arXiv/1603.04156](https://arxiv.org/abs/1603.04156))
- And for a future 100 TeV collider: [arXiv/1606.00947](https://arxiv.org/abs/1606.00947)

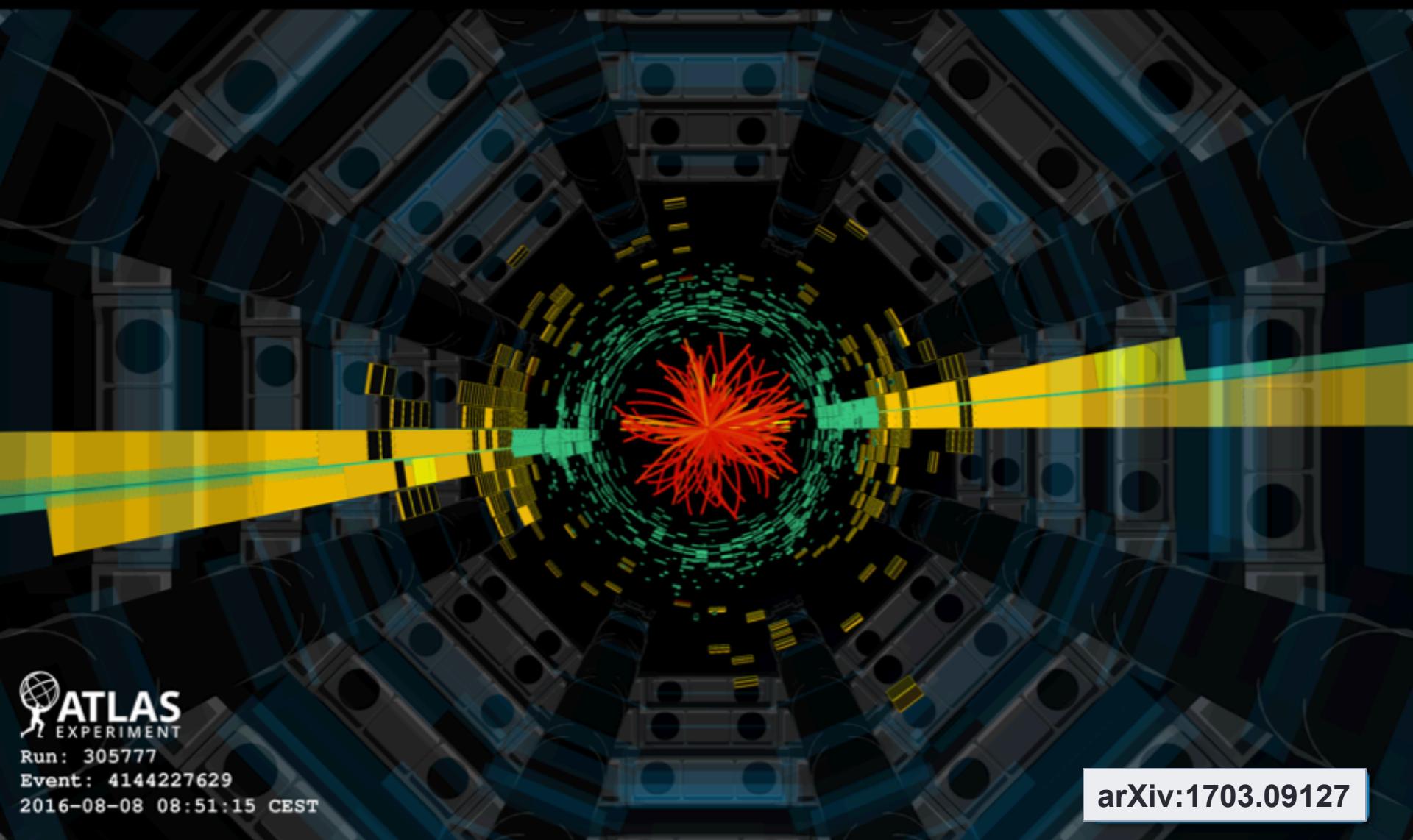
LHC vs Cosmos

- CMS / Atlas (Mono-jet+V) vs Relic DM (Planck)



➤ LHC probes **cosmologically preferred** regions

Dijet



ATLAS
EXPERIMENT

Run: 305777

Event: 4144227629

2016-08-08 08:51:15 CEST

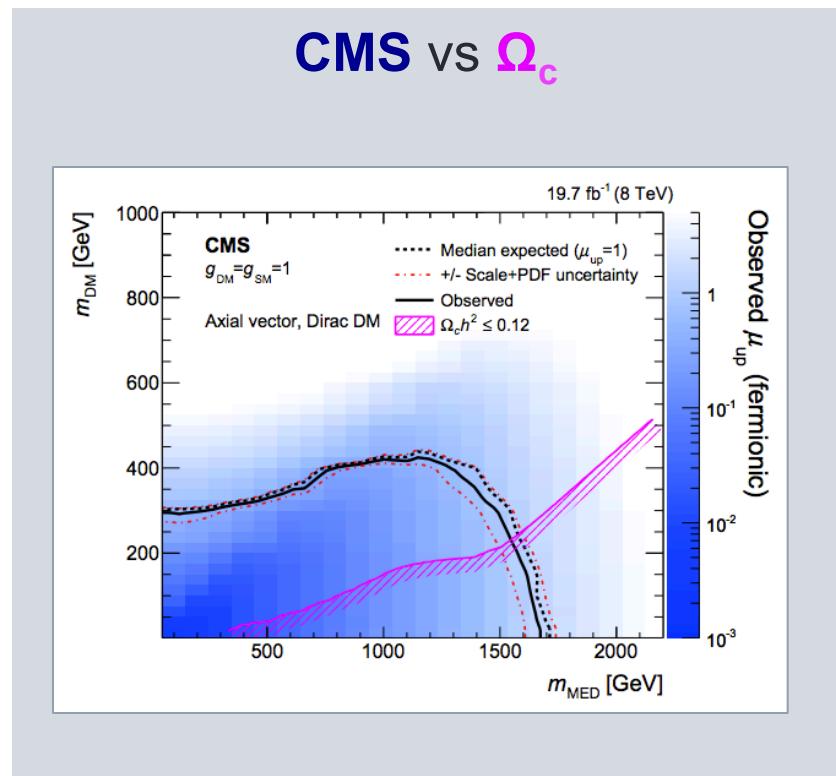
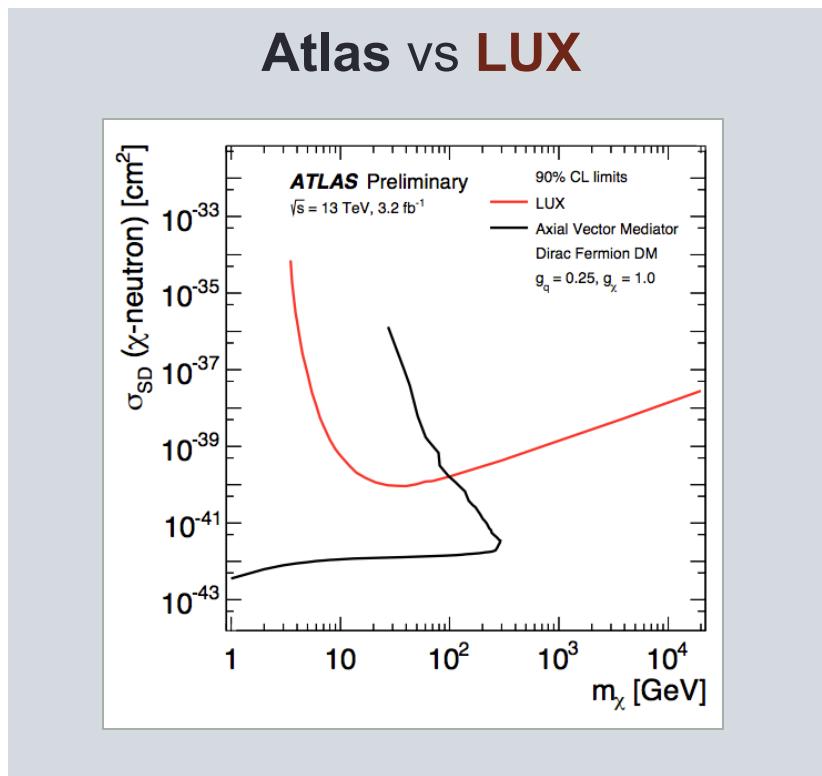
arXiv:1703.09127

Mediator searches

LHC complementarity

Atlas

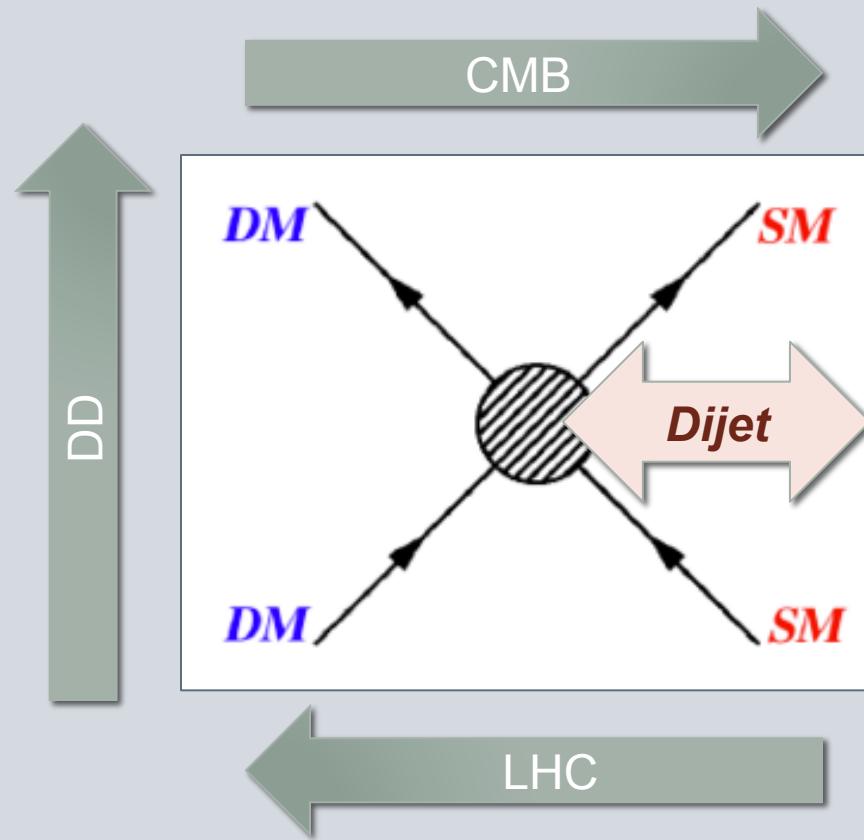
CMS



➤ But how about other mediator constraints ?

LHC vs DD vs Relic vs Dijet

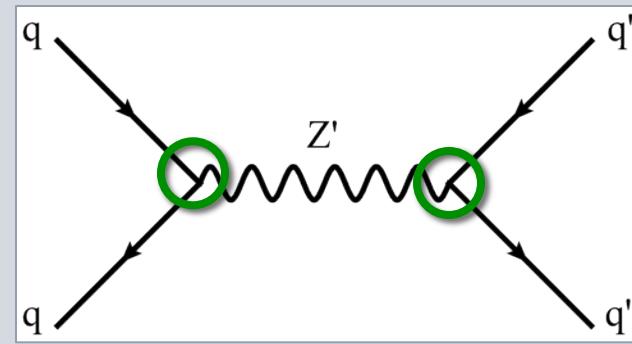
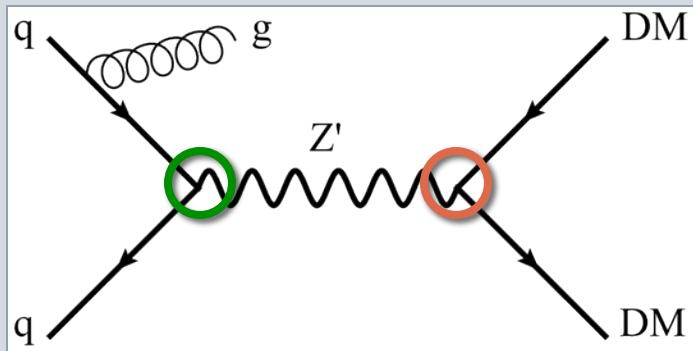
Test the same coupling in different ways:



➤ Compare LHC to other DM constraints & resonance searches

Z' vs Z'

➤ Monojet vs Dijet

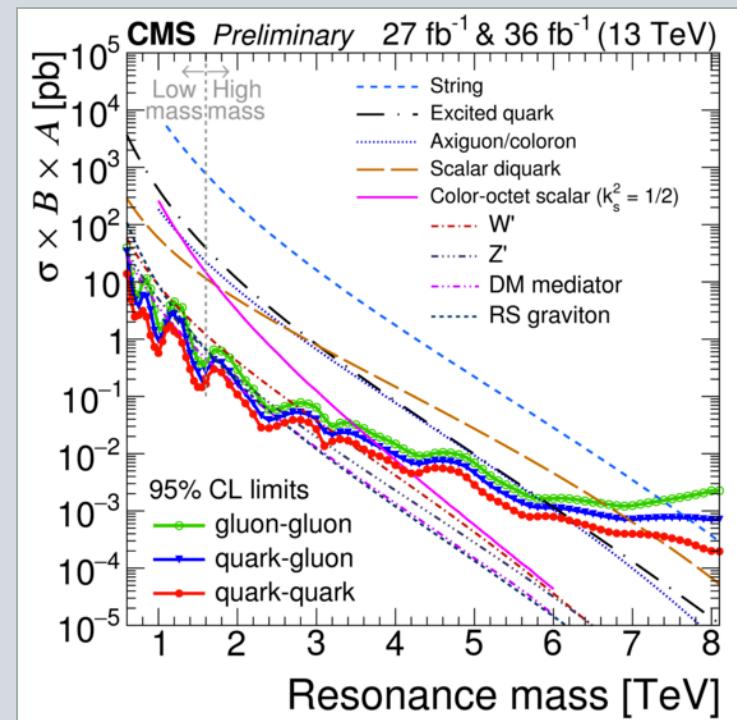
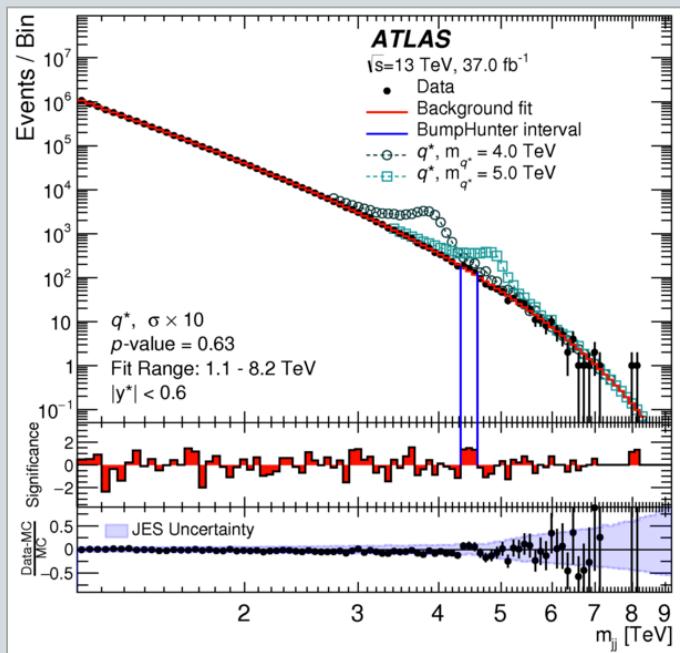
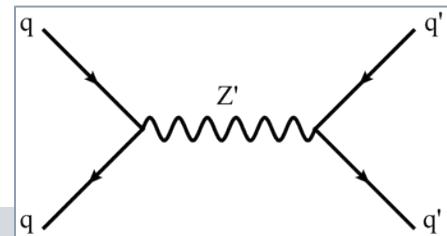


➤ Possibly same mediator!

- Dijet is also a **DM mediator** search!
- Use dijet search for **DM interpretation**

Dijet

- Regular dijet search: $p p \rightarrow X \rightarrow jj$

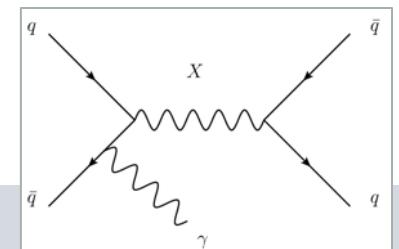


- Search for bump
 - Limits on various models, up to **~8 TeV**
 - Low mass: limited by **trigger rate**

ATLAS-EXOT-2016-021
CMS PAS EXO-16-056

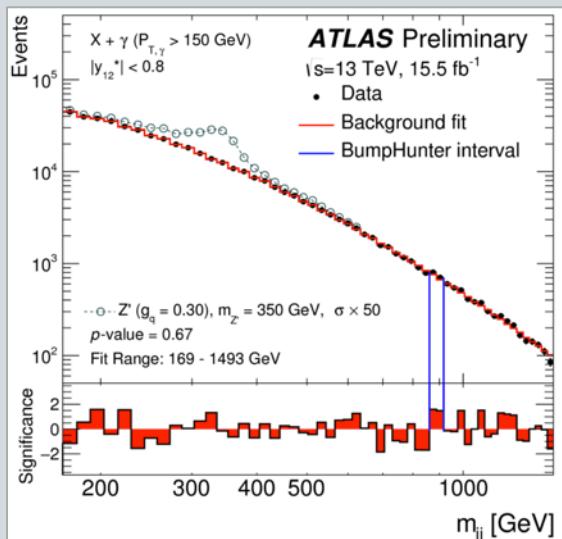
Dijets

Bypass the dijet rate problem: **TLA/Scouting & ISR**



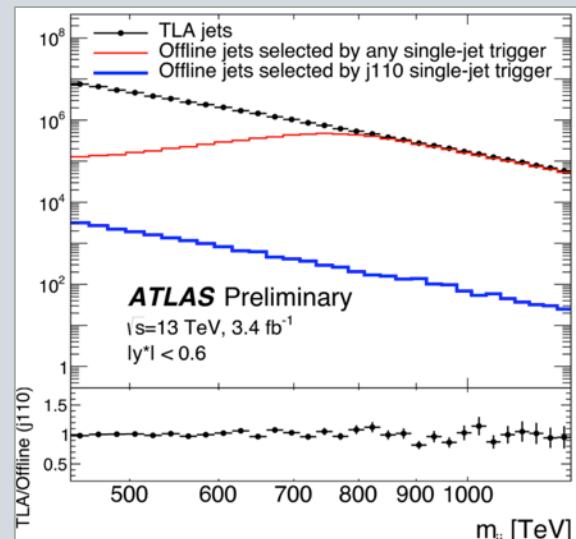
LOW MASS

Dijet+ISR
ATLAS-CONF-2016-070



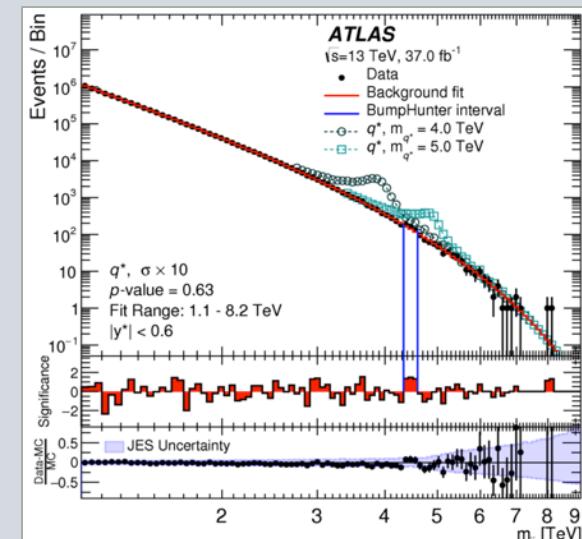
MEDIUM MASS

Dijet @ Trigger
ATLAS-CONF-2016-030



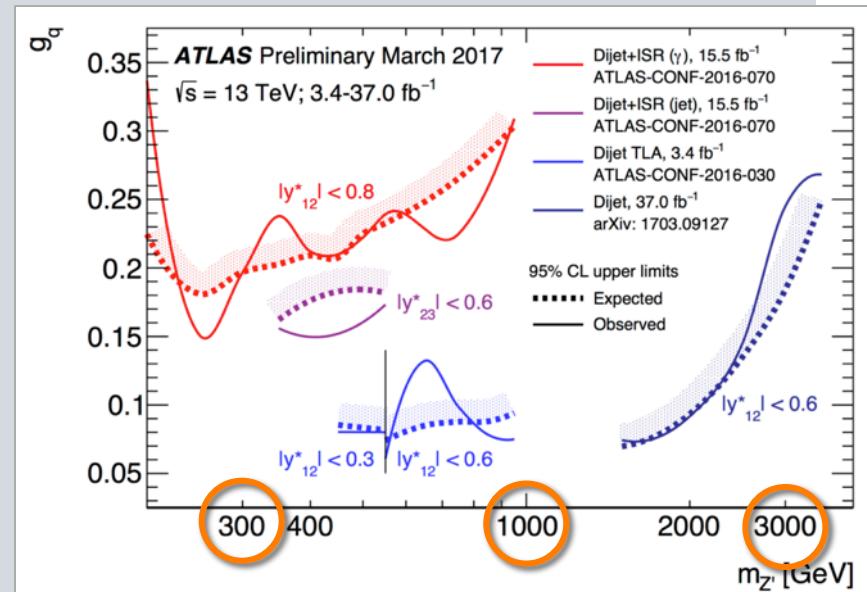
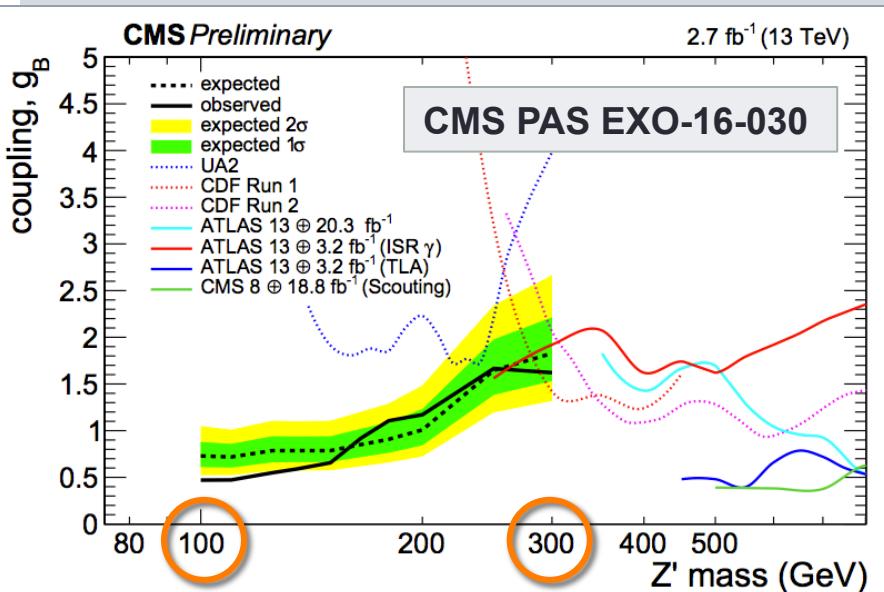
HIGH MASS

Traditional dijet
ATLAS-EXOT-2016-021



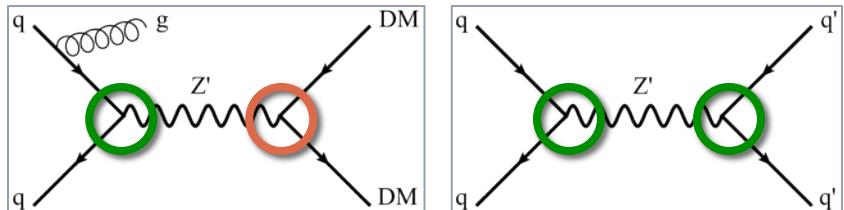
Dijets

- CMS+ATLAS summary: **Boosted, ISR- γ , ISR-j, TLA, regular**



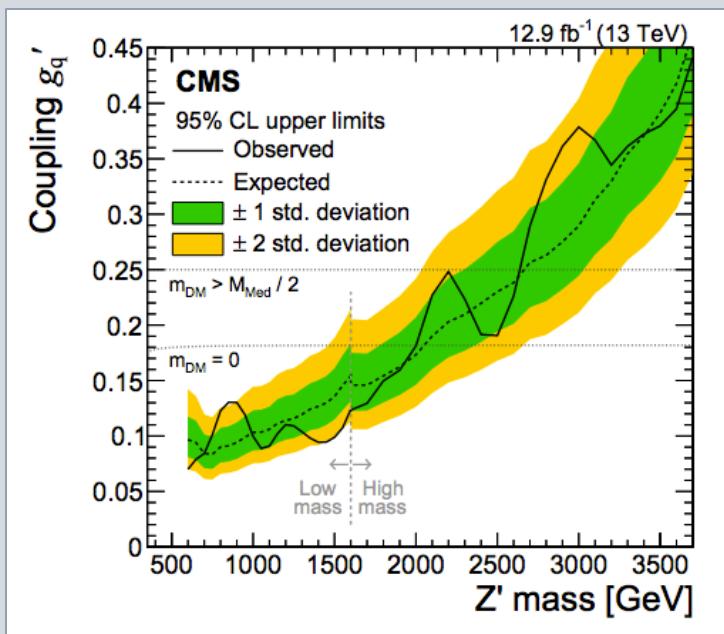
➤ Spanning range from **100 GeV** to **>3 TeV**

Reinterpretation



- Dijet DM interpretation method
 - Limits: x-sec → coupling

EXO-16-032
arXiv:1611.03568



$$\Gamma_{f\bar{f}}^V = \frac{g_f^2(m_{\text{MED}}^2 + 2m_f^2)}{12\pi m_{\text{MED}}} \sqrt{1 - \frac{4m_f^2}{m_{\text{MED}}^2}}$$

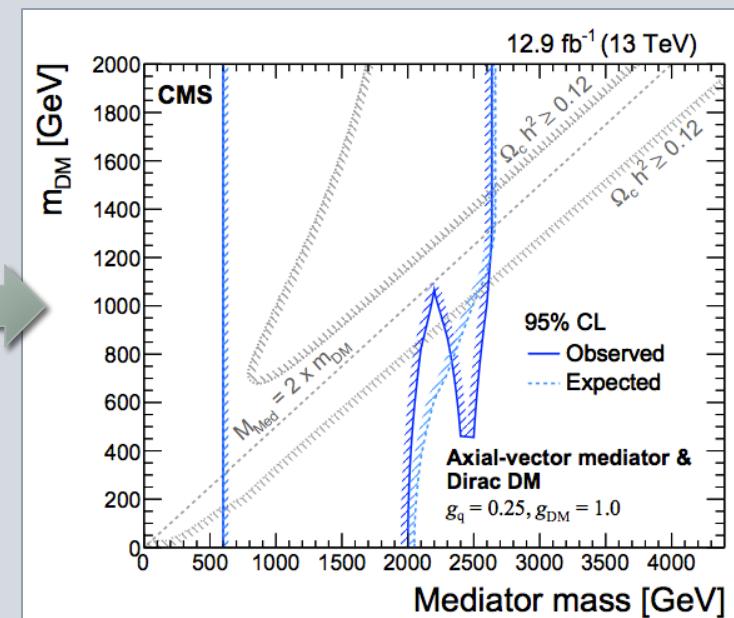
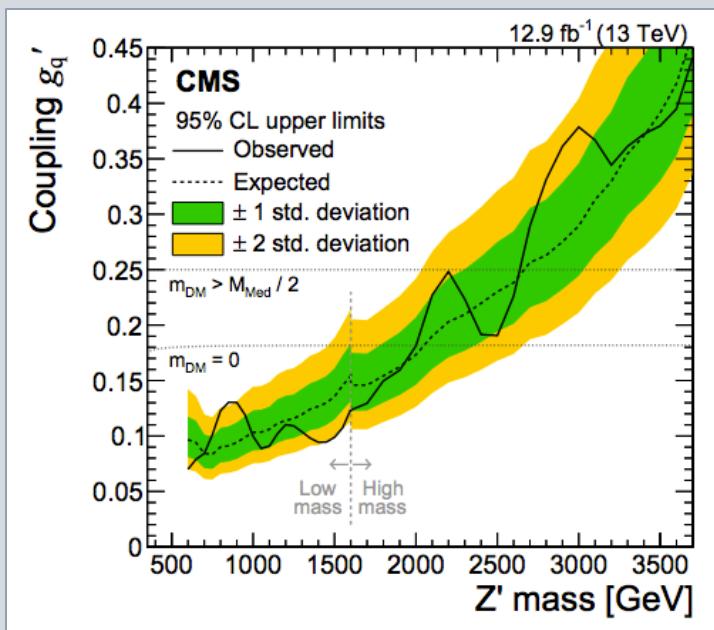
$$\Gamma_{\text{MED},\min}^{V,A} = \Gamma_{\chi\bar{\chi}}^{V,A} + \sum_{i=1}^{N_f} N_c \Gamma_{q_i\bar{q}_i}^{V,A}$$

- Compare to predicted coupling with DM
 - Include effect on Z' of SM couplings & DM width

Reinterpretation

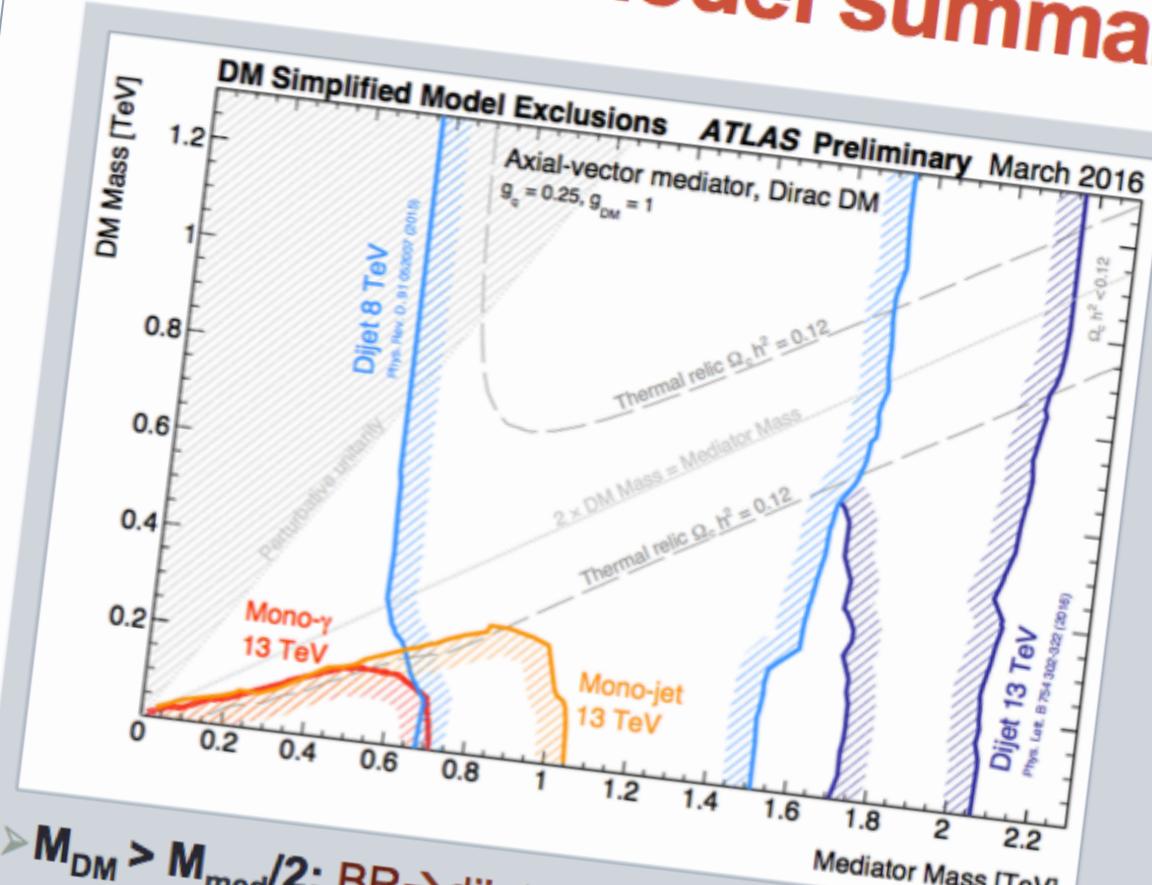
- Dijet DM interpretation
 - Limits: x-sec → coupling

EXO-16-032
arXiv:1611.03568



- Compare to predicted coupling with DM
 - Include width width for Z' coupling to SM & DM

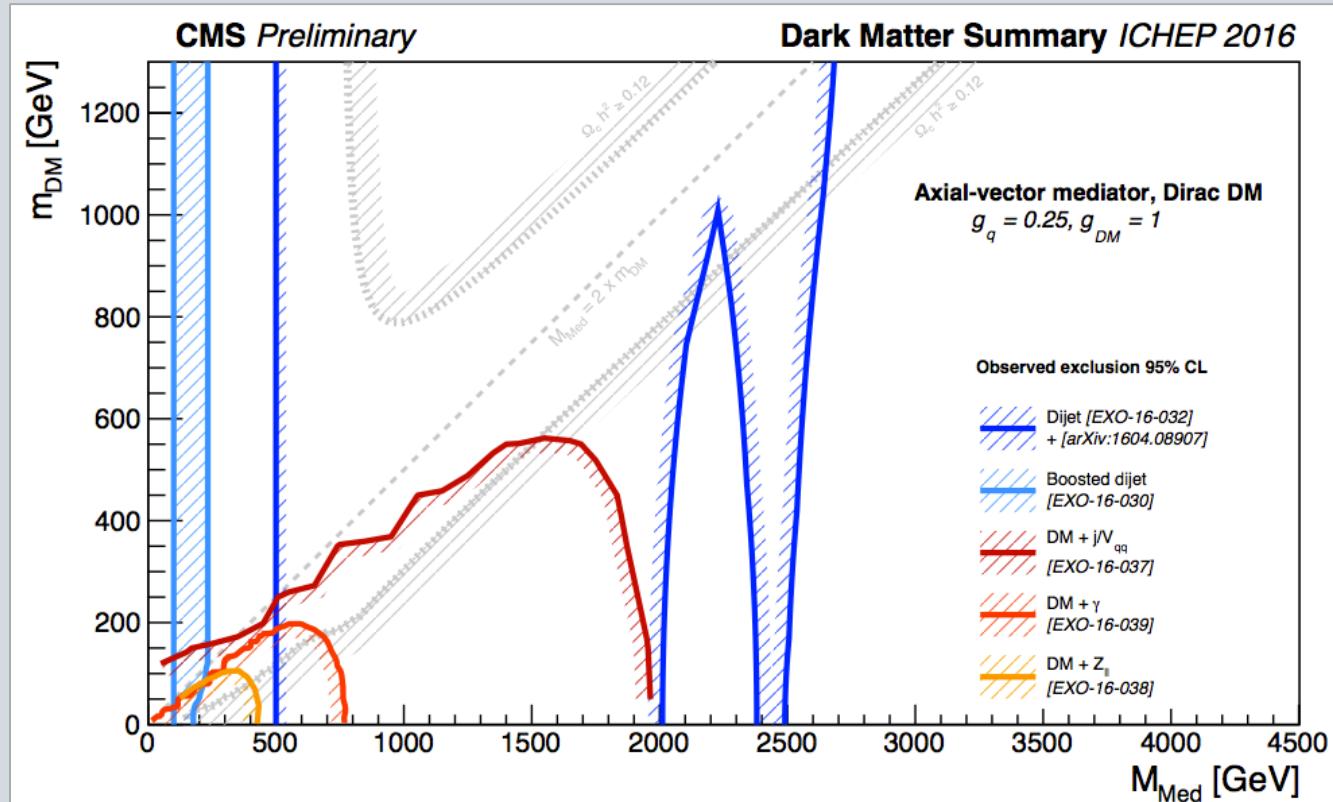
Simplified model summary



➤ $M_{DM} > M_{med}/2$: BR \rightarrow dijet dominates [limit ~constant]

(M,M)

- MET+X vs Dijet

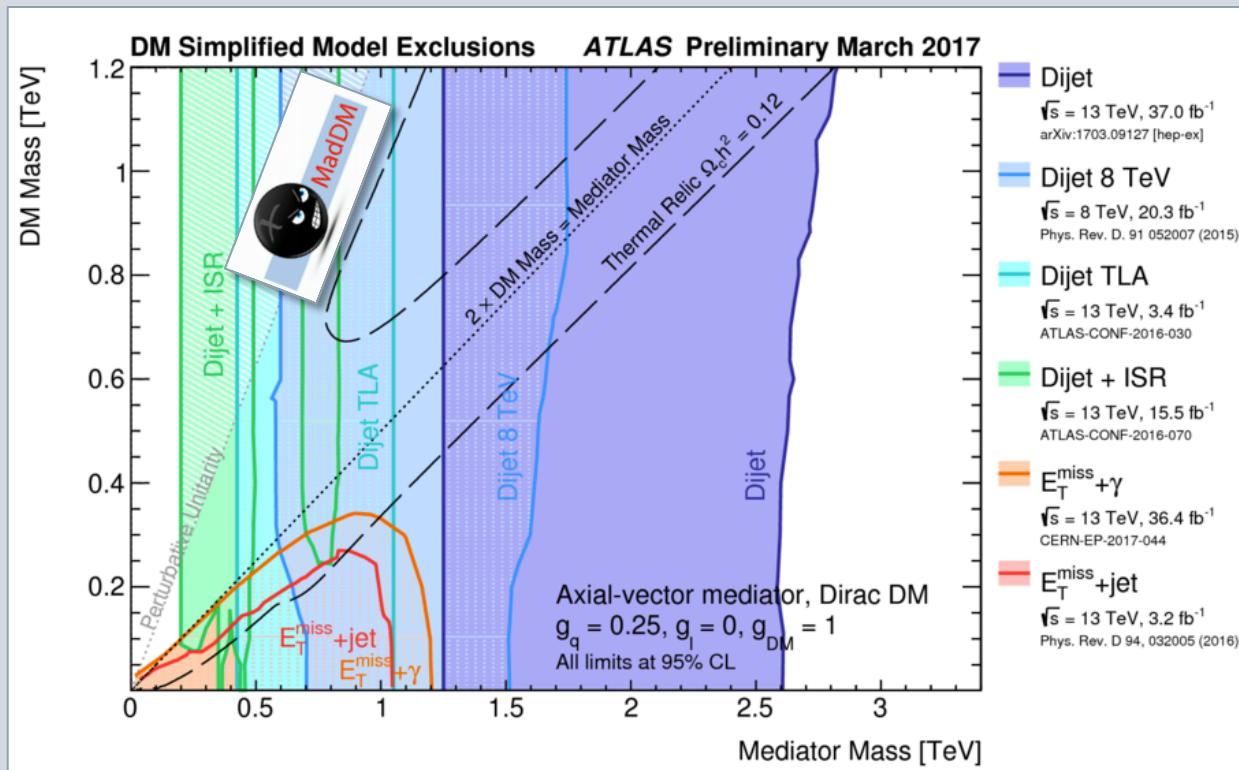


➤ Low mass and above diagonal

CERN-CMS-DP-2016-057
<https://cds.cern.ch/record/2208044>

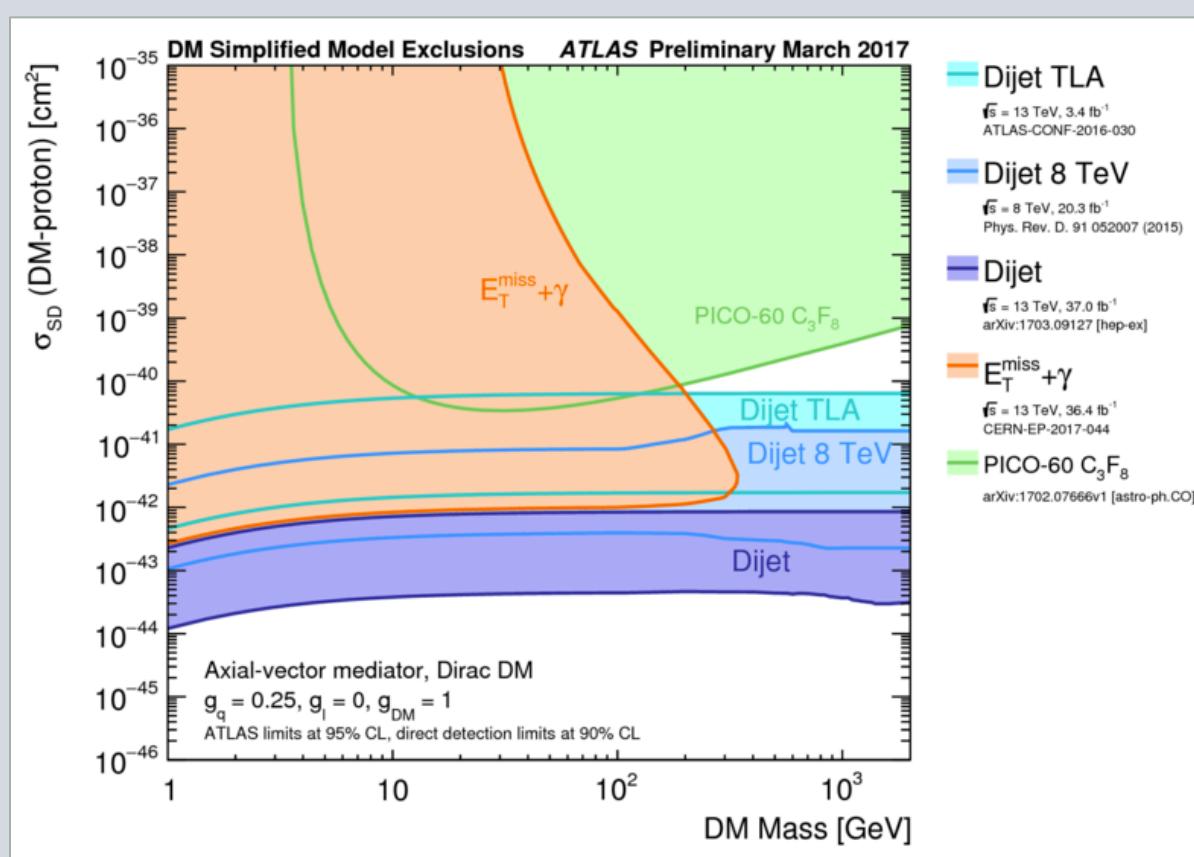
DM Mediator summary

- Detailed breakdown



- Excluding almost full space $M_{\text{Med}} < 2.5 \text{ TeV}$
 - For these couplings, alternative scenarii in backup

Mono-jet vs Dijet vs DD



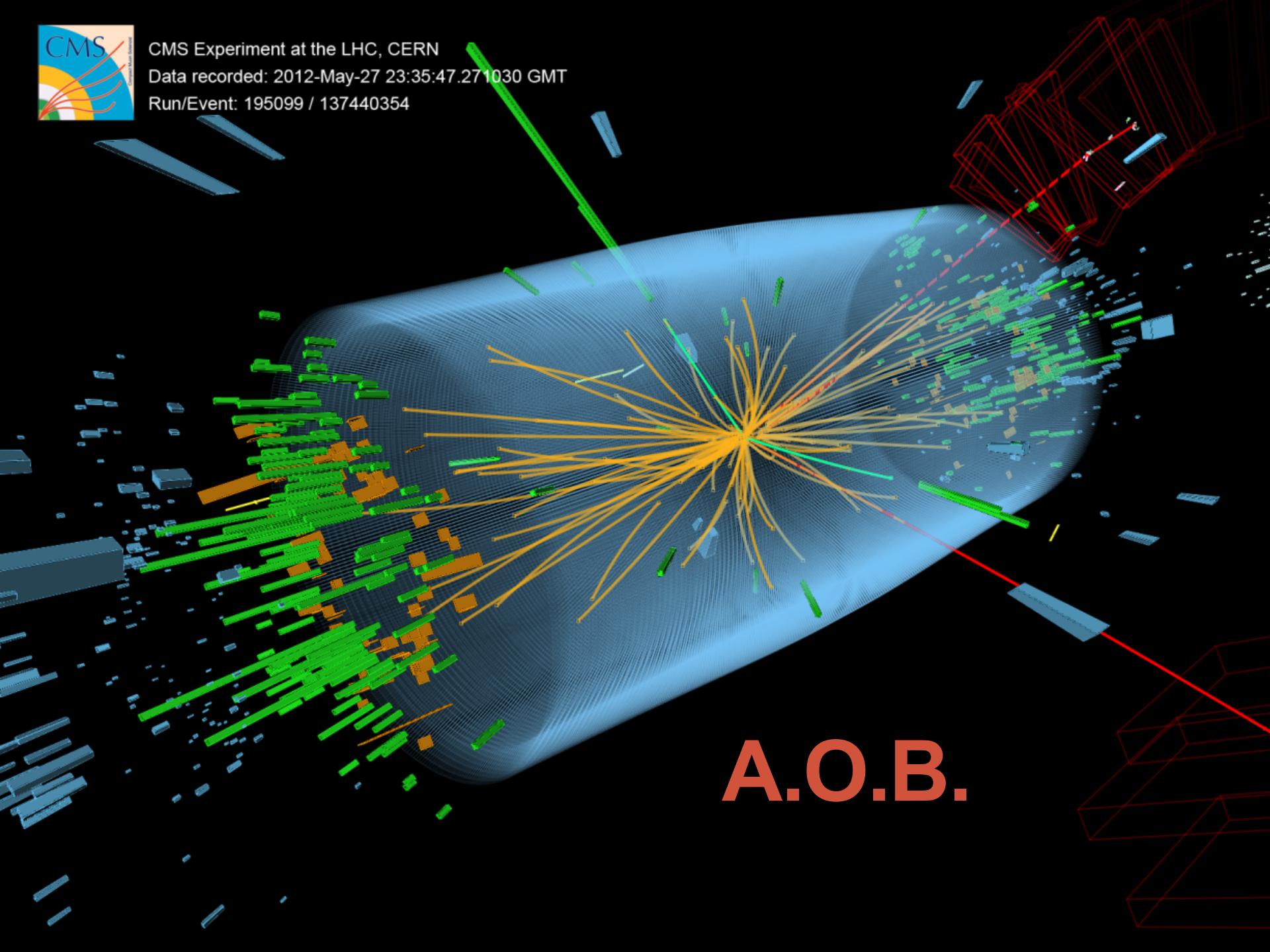
➤ LHC powerful for low m_{DM} and Spin-Dependent
 (MET+X and resonances)



CMS Experiment at the LHC, CERN

Data recorded: 2012-May-27 23:35:47.271030 GMT

Run/Event: 195099 / 137440354

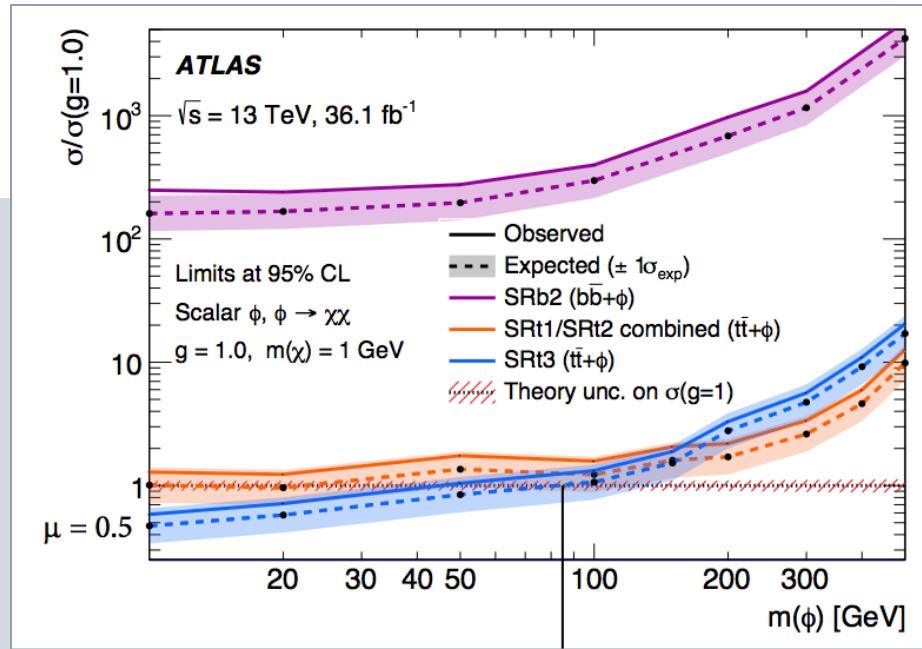
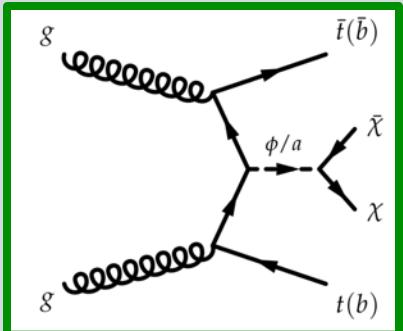


A.O.B.

AOB

- **DM+HF**
 - DM+bb
 - DM+tt

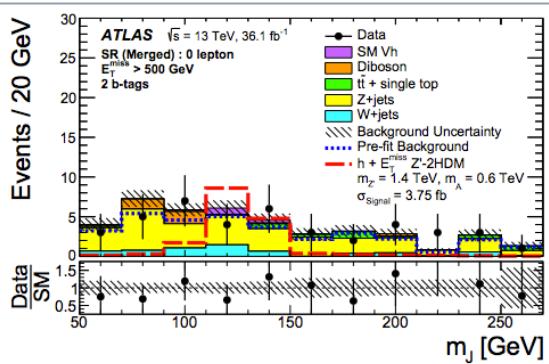
arxiv:
1711.11520



➤ (Pseudo)Scalar Mediator

- **Mono-H**

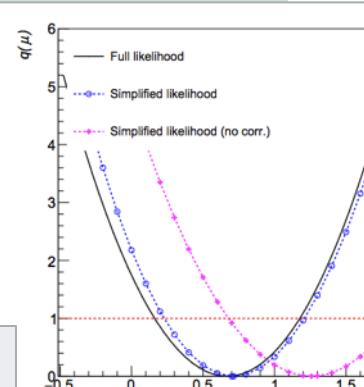
arxiv:
1707.01302



- Less simple models, e.g. Z'-2HDM
- Experimentally interesting final states

• Reinterpretations

- Dedicated Forum at CERN
- S.Kraml et al



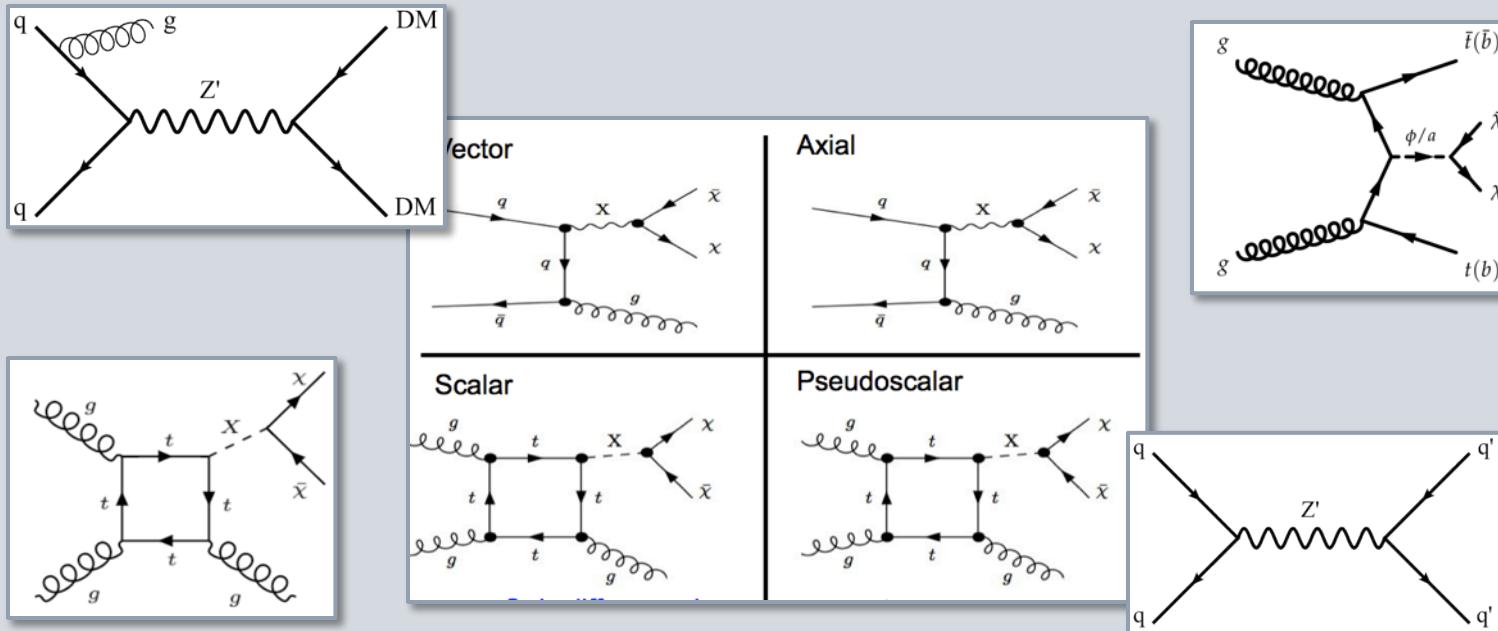
CMS-NOTE-2017-001

My thoughts

*Just some
questions & opinions
for discussion*

1) Models

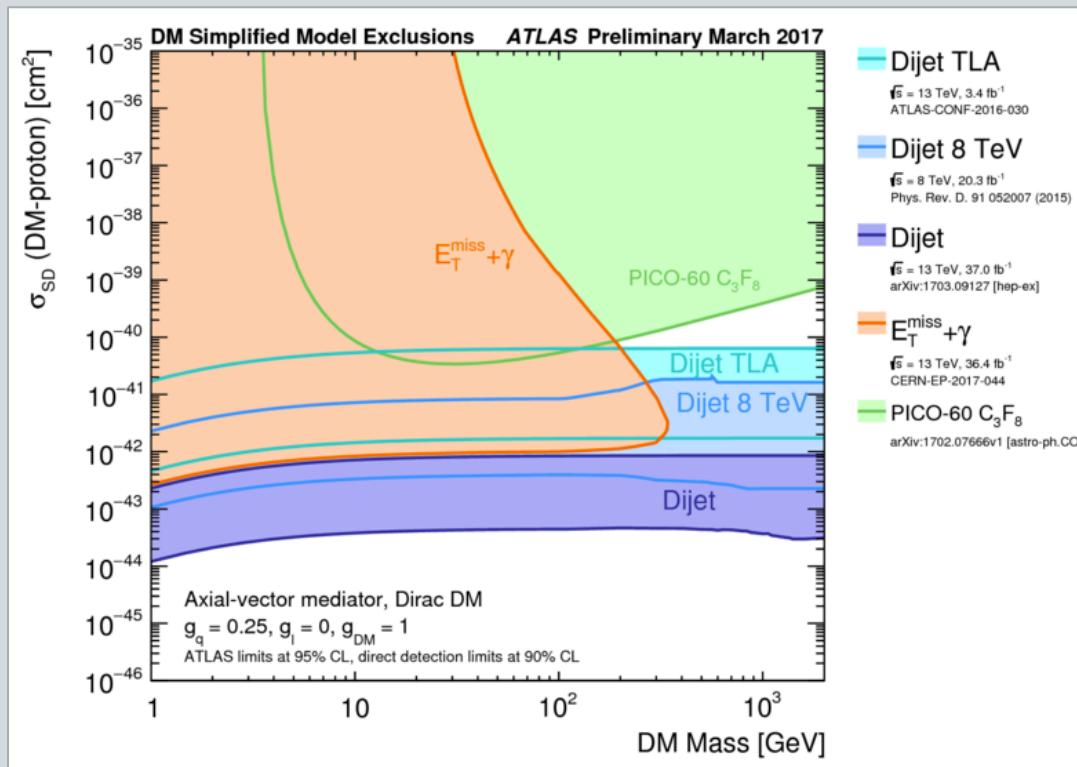
The LHC DM WG models are great
 Consistent comparisons & huge variety of final states



➤ How useful are further model developments?

2) DD

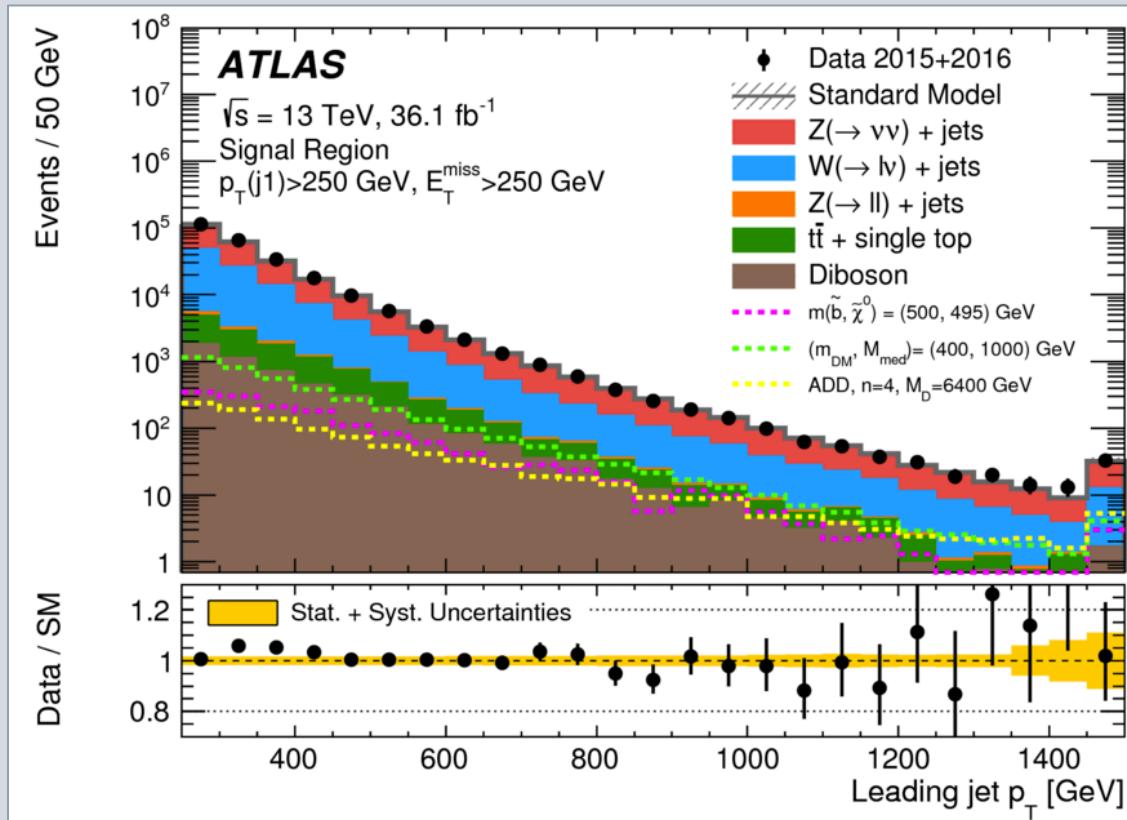
Our DD plots are awesome



➤ Could we make a version with LHC fixed to Ω_{DM} ?

3) Backgrounds

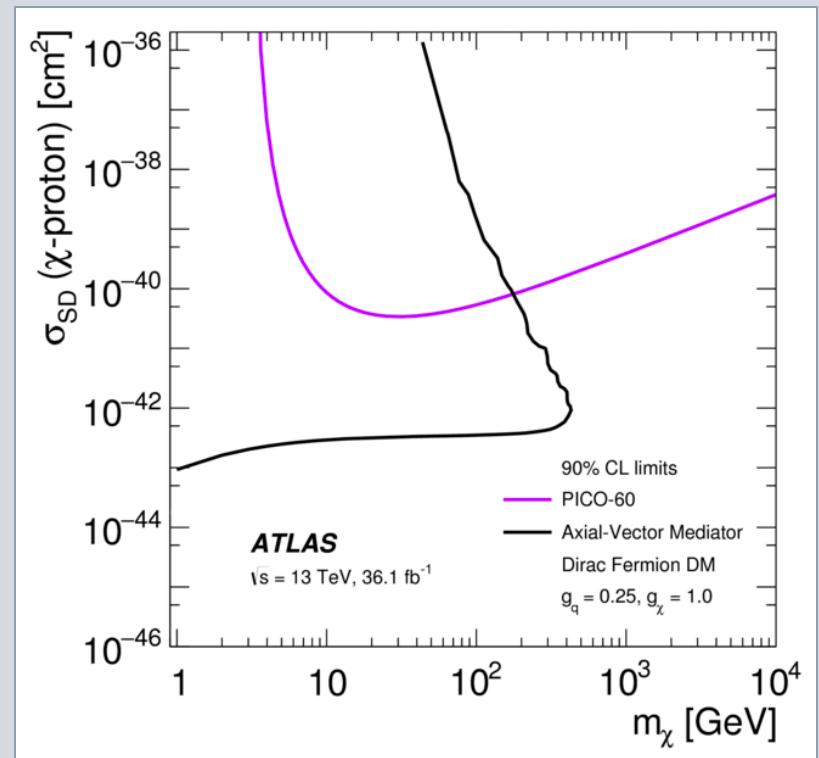
Fantastic description of V+jets



➤ Background precision crucial for progress

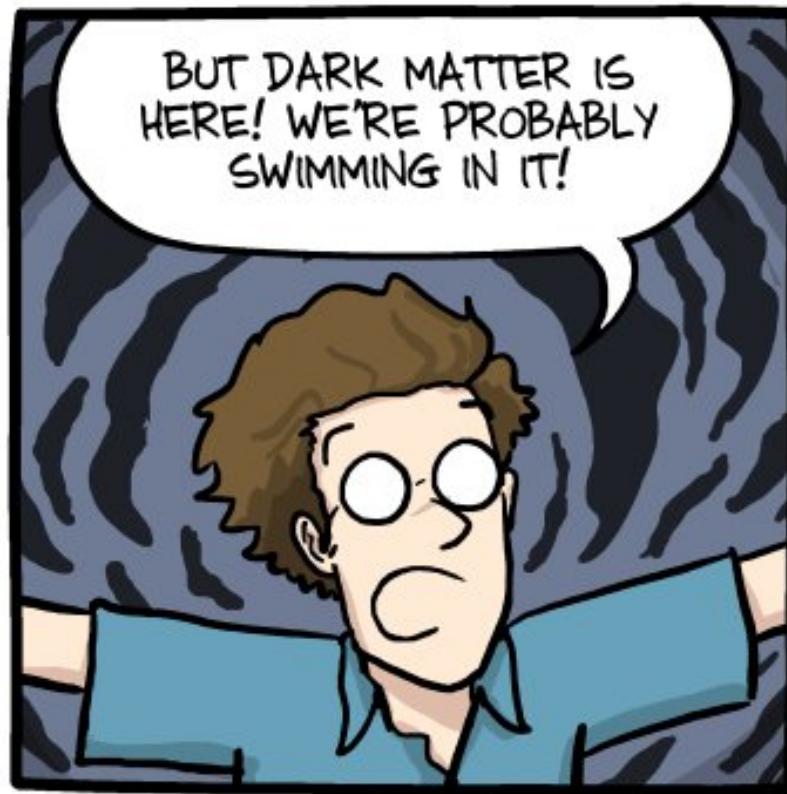
Conclusions

- **LHC powerful DM tool**
 - MET+jet and other mono-X
- **Complementary to DD**
 - Low mass, spin-dependent
- **Resonance interpretations**
 - Visible part of SM-DM interactions
- **Recent & upcoming updates**
 - LHC: mono-jet, dijet, MET+HF, etc
 - DD: Xenon1T
- **Expanding LHC program**
 - Low-mass, long-lived, boosted



➢ **Constraints are model-dependent, need to search everywhere!**

To be continued...



PhD Comic ('We have no idea')
SMBC: <http://www.smbc-comics.com/comic/phd>