

FCC vs The Cosmos

Outline

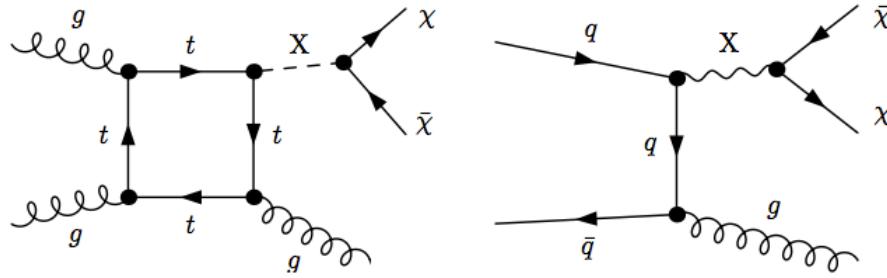
- **DM at 14+100 TeV**
<http://arxiv.org/abs/1509.02904>
- **Relic constraints**
<https://cds.cern.ch/record/2046121>
- **FCC vs Relic**

*FCC-hh BSM meeting
5 October 2015 – CERN*

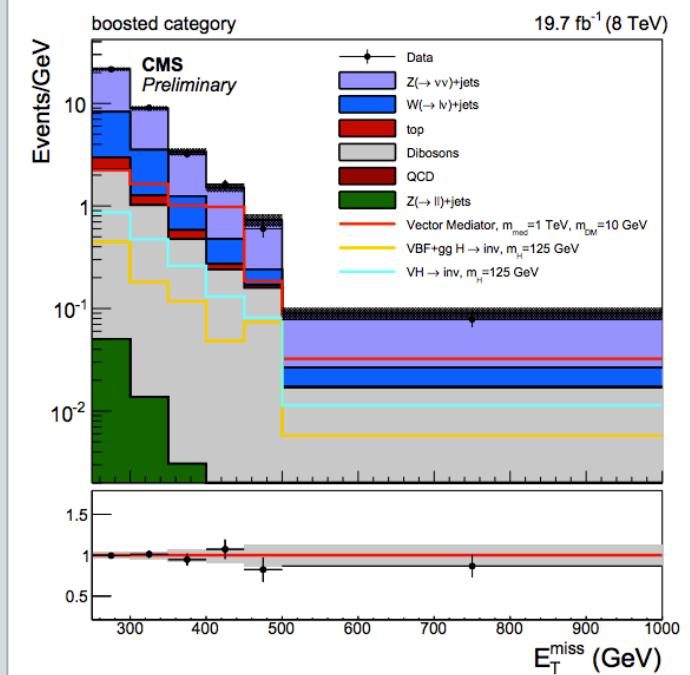
DM @ LHC

- DM simplified mediator models [e.g. LHC Dark Matter Forum - arXiv:1507.00966]
 - Vector & Axial & Scalar & Pseudoscalar

$$\begin{aligned}\mathcal{L}_{\text{scalar}} &\supset -\frac{1}{2}m_{\text{MED}}^2 S^2 - g_{\text{DM}} S \bar{\chi}\chi - \sum_q g_{SM}^q S \bar{q}q - m_{\text{DM}} \bar{\chi}\chi, \\ \mathcal{L}_{\text{pseudo-scalar}} &\supset -\frac{1}{2}m_{\text{MED}}^2 P^2 - ig_{\text{DM}} P \bar{\chi}\gamma^5\chi - \sum_q ig_{SM}^q P \bar{q}\gamma^5 q - m_{\text{DM}} \bar{\chi}\chi, \\ \mathcal{L}_{\text{vector}} &\supset \frac{1}{2}m_{\text{MED}}^2 Z'_\mu Z'^\mu - g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu\chi - \sum_q g_{SM}^q Z'_\mu \bar{q}\gamma^\mu q - m_{\text{DM}} \bar{\chi}\chi, \\ \mathcal{L}_{\text{axial}} &\supset \frac{1}{2}m_{\text{MED}}^2 Z''_\mu Z''^\mu - g_{\text{DM}} Z''_\mu \bar{\chi}\gamma^\mu\gamma^5\chi - \sum_q g_{SM}^q Z''_\mu \bar{q}\gamma^\mu\gamma^5 q - m_{\text{DM}} \bar{\chi}\chi.\end{aligned}$$



CMS-PAS-HIG-15-001
See also LPCC seminar: <https://indico.cern.ch/event/388149/>



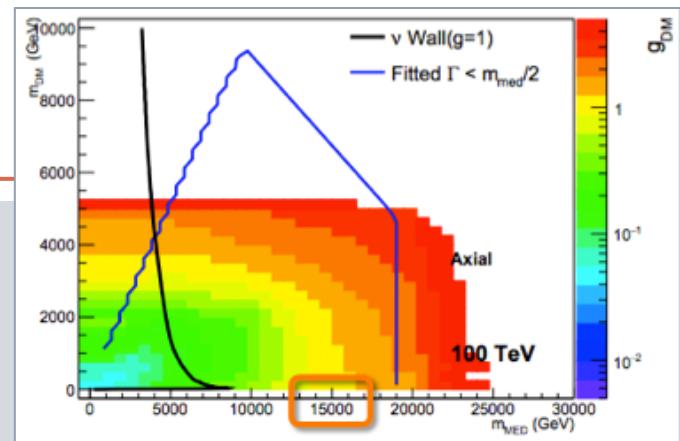
- Main discriminating observable in mono-jet final state: MET

8 → 14 & 100

LHC-8TeV projections for
LHC-14TeV and FCC-100TeV

From <http://arxiv.org/abs/1509.02904>

P.Harris (CERN), V.V.Khoze (Durham), M.Spannowsky (Durham), C.Williams (Buffalo)



8 → 14 & 100 TeV

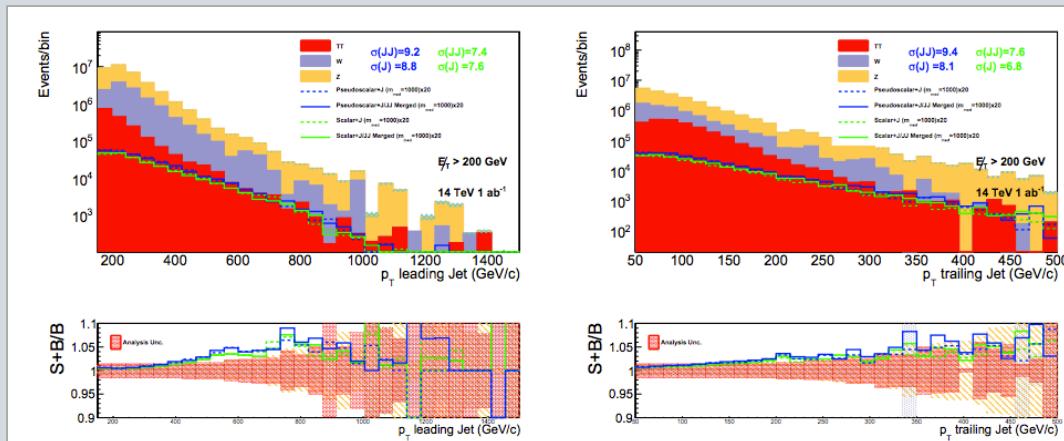
Settings for projection studies

1. Detector: CMS-like

- Extend lepton acceptance up to $|\eta| < 5.5$ [at 100 TeV]

2. Generator: Modeling of extra jets

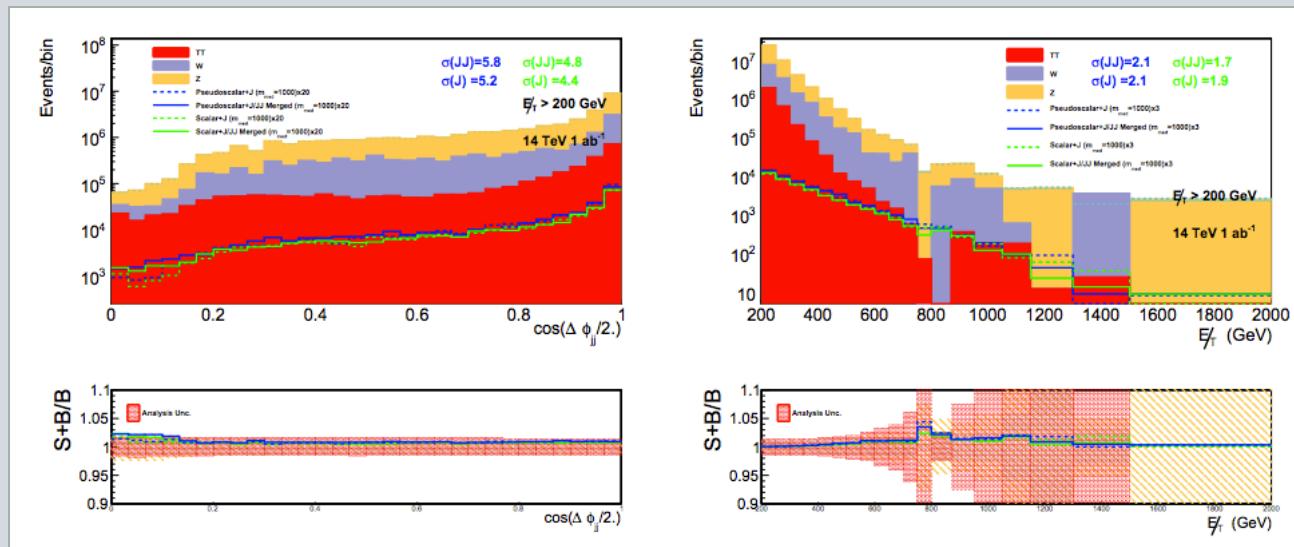
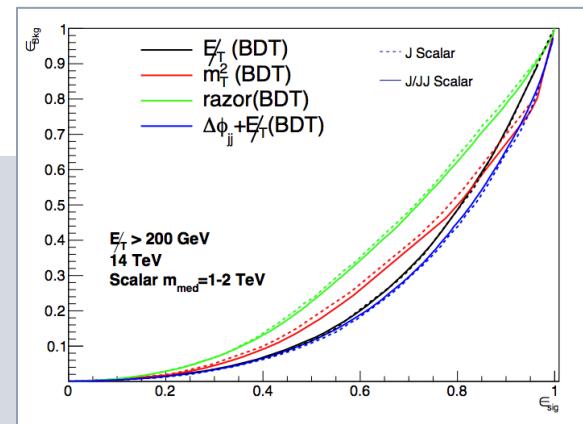
- PDFs, matching scales, W/Z/H radiation, higher order...
 - Full details in <http://arxiv.org/abs/1509.02904>



3. Benchmark luminosity: 1 ab^{-1} [to ease comparison]
4. Analysis strategy [see next page]

Analysis strategy

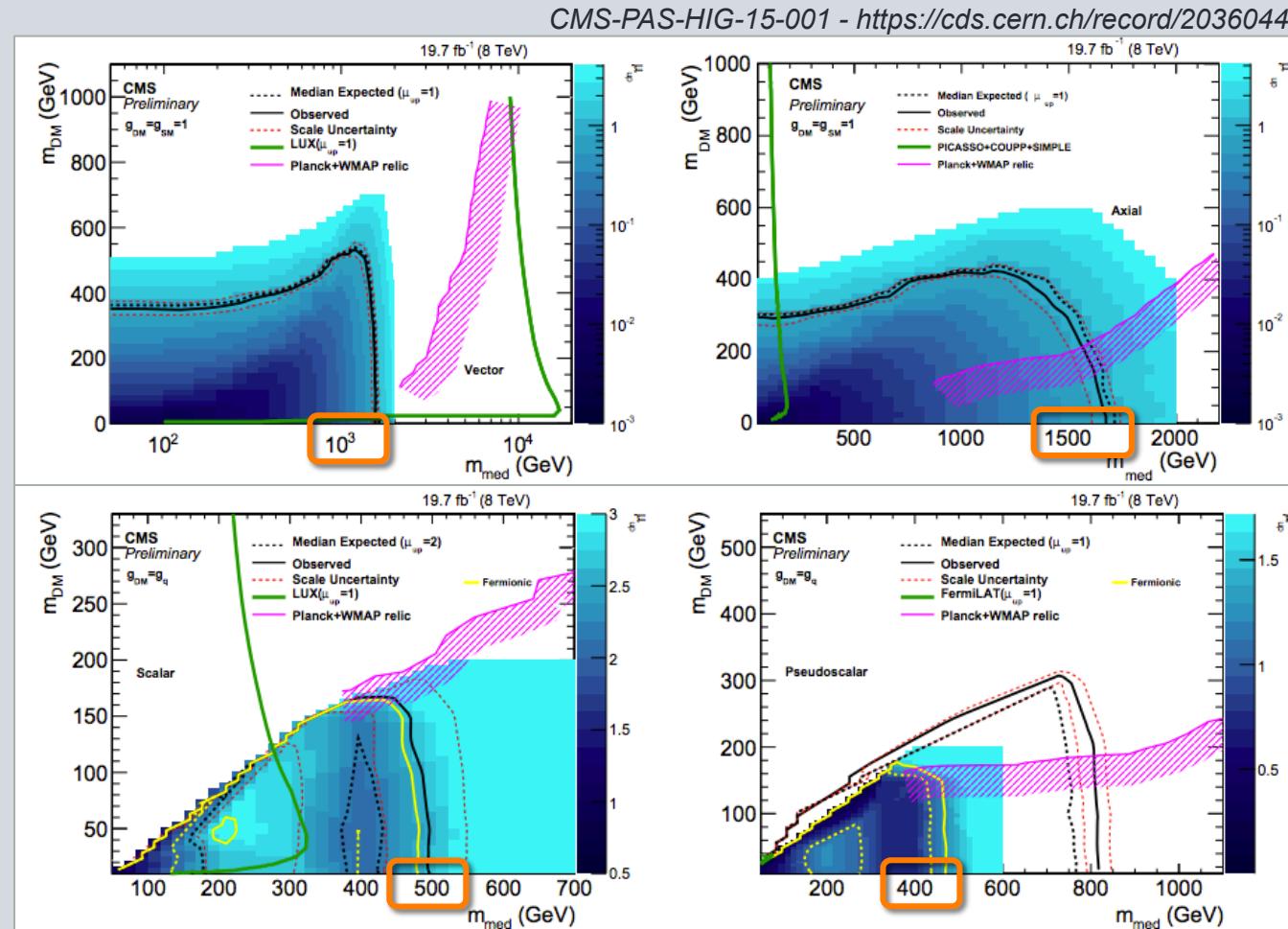
- Shape analysis à la CMS PAS HIG-15-001
 - Dominant backgrounds: **Z(vv)+jet** and **W(lv)+jets**
 - Control regions: **di- μ** : Z($\mu\mu$)+jets and **single- μ** : W(lv)+jets



- Most discriminating observables: **MET & $\cos\Delta\Phi_{jj}$**
 - Fit MET in bins of $\cos\Delta\Phi_{jj}$

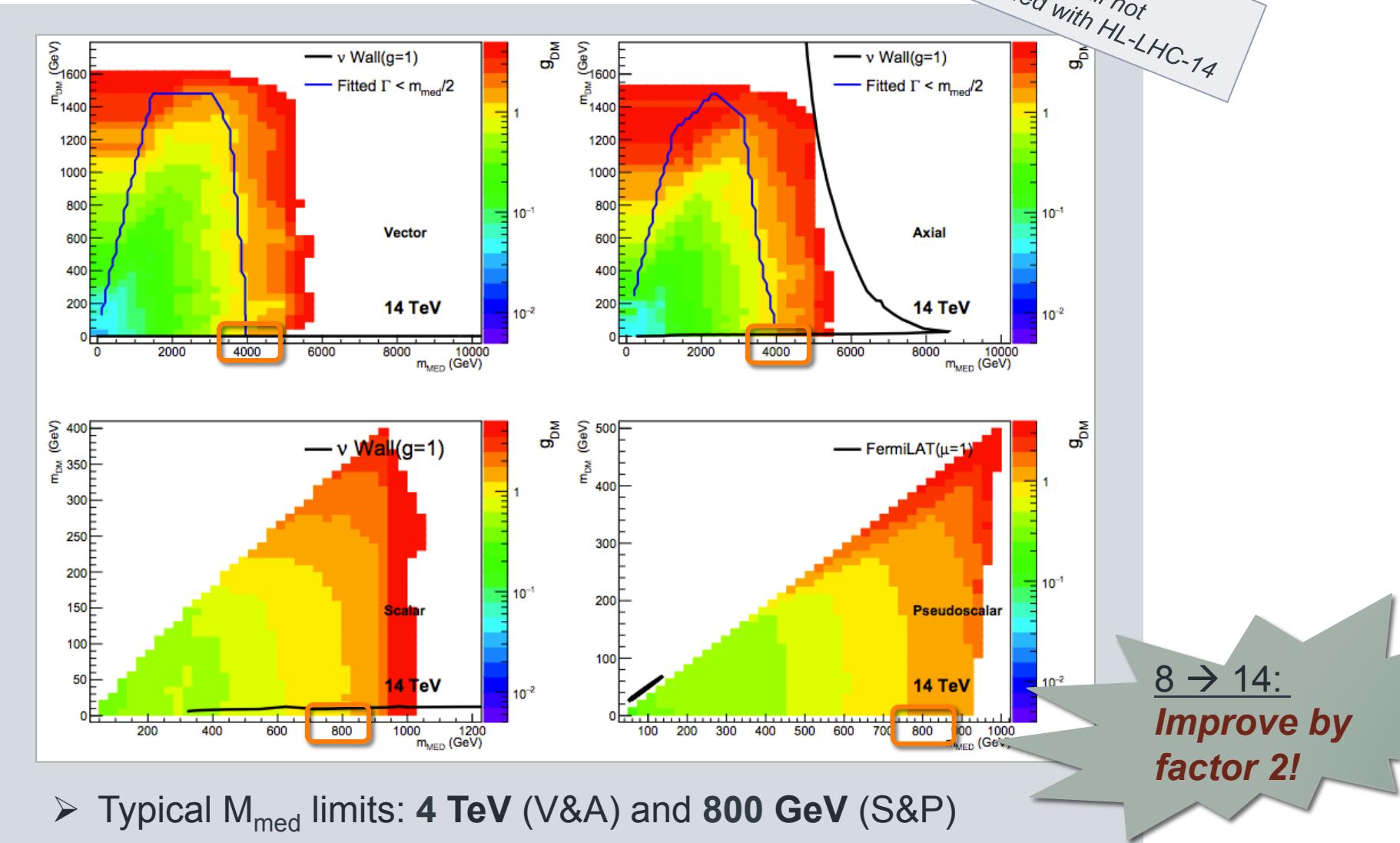
8 TeV results

CMS Run-2 vs DD
Complementary for A&S&P



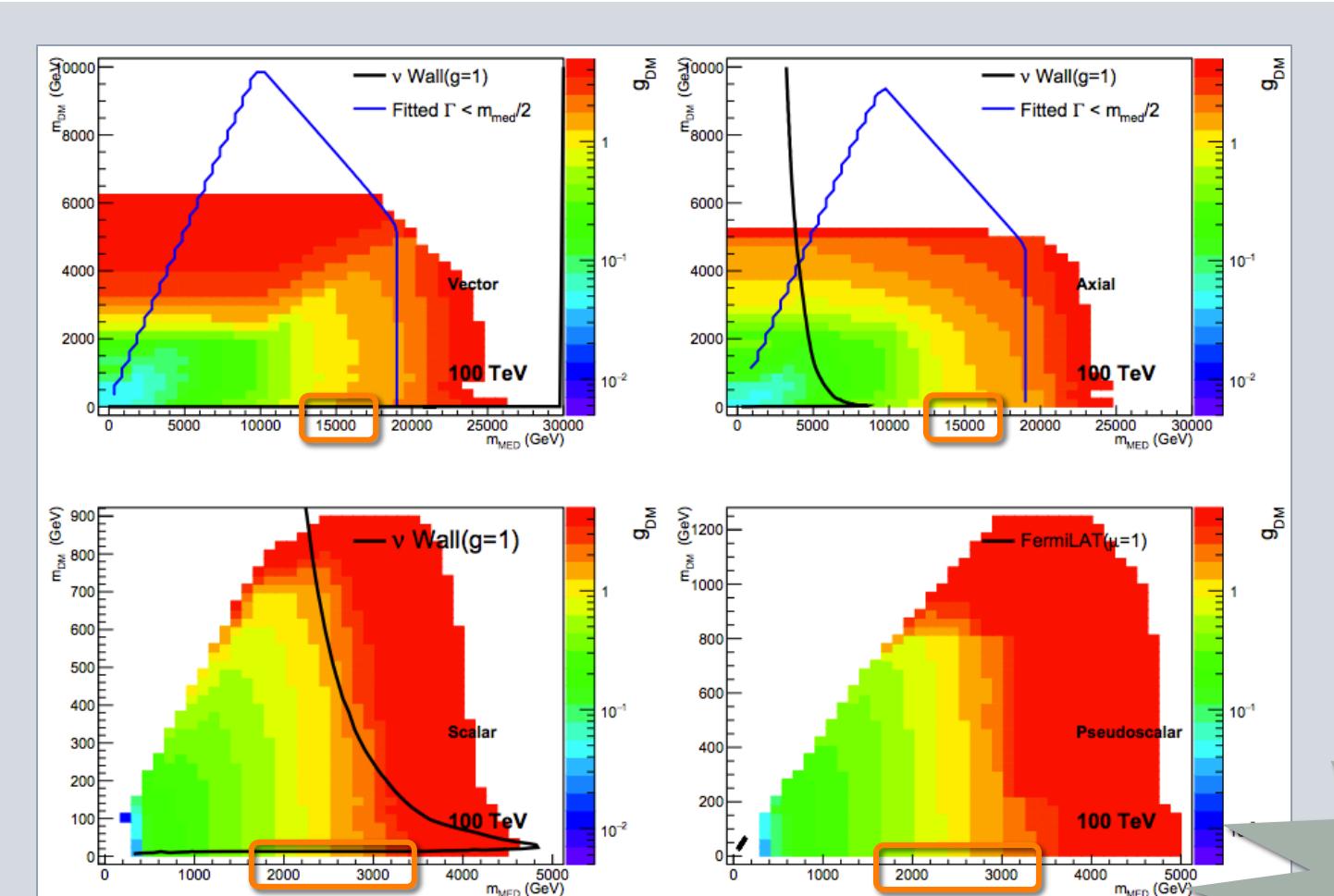
- Typical M_{med} limits: 2 TeV (V&A) and 500 GeV (S&P)

14 TeV projection



100 TeV projection

S&A&P
complementary to DD!

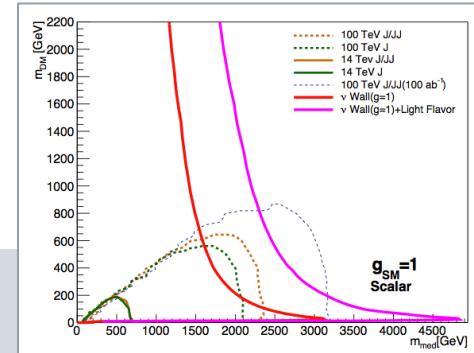


14 → 100:
*Improve by
factor 3-5*

- Typical M_{med} limits: 15 TeV (V&A) and 2500 GeV (S&P)

8 → 14 → 100 TeV

- Comparisons of M_{med} limits (for $g_{\text{DM}}=1$)



	8 TeV [0.02 / ab]	14 TeV [1 / ab]	100 TeV [1 / ab]
V & A	2 TeV	4 TeV	15 TeV
S & P	500 GeV	800 GeV	2500 GeV

➤ Improvements 8→14→100

- Center-of-mass collision energy**
- Luminosity** (and a bit **analysis techniques**: mono-jet → multi-jet)

➤ 14→100: improve limit on M_{med} by factor **3-5**

- **100 TeV**: Complementarity wrt **DD**, especially for **S&A&P**

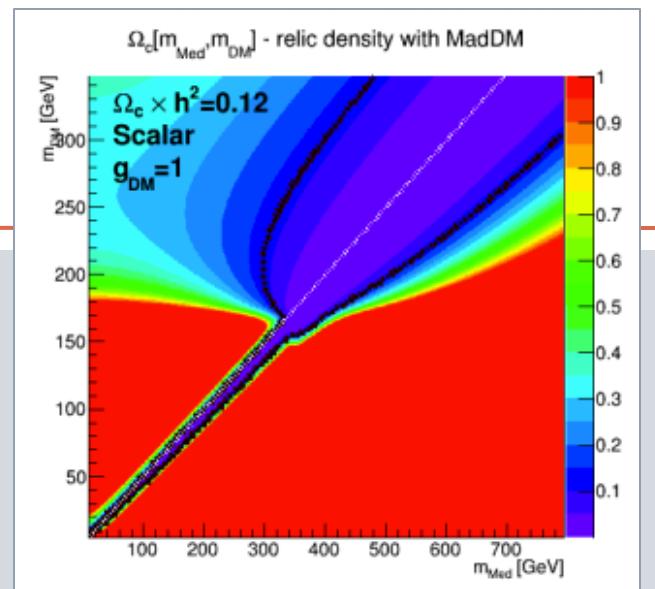
➤ ... and how about constraints from **relic observations**?

RELIC DM

Relic constraints for simplified mediator models

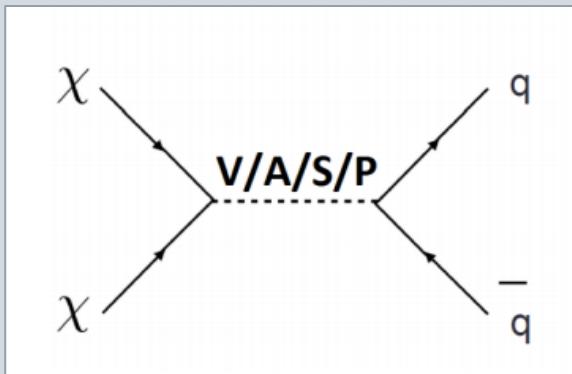
From <https://cds.cern.ch/record/2046121>

C.Roskas (CERN summer student) & TdP (CERN)



Motivation

- Observed relic DM constrains annihilation
- Planck: $\Omega_{\text{DM}} \times h^2 = 0.11$



- Test LHC simplified mediator models
 - Complementary constraints to same models
 - Upper limits on masses → can be used for FCC design
- Use MadDM (see next page)

Why MadDM?



Perhaps the only set of tools able to integrate dark matter phenomenology with collider physics is **CalcHEP** [1] and **micrOMEGAs** [2], while other popular collider tools such as **MadGraph** [3] and **Sherpa** [4] lack this ability. In addition, model specific dark matter tools such as **DarkSusy** [5] allow for detailed calculations of galactic dark matter relic signals in the framework of super-symmetric models but without the ability to easily integrate into collider tools.

MadDM aims to bridge the gap between collider oriented event generators and dark matter physics tools. We chose to build **MadDM** on the existing **MadGraph 5** infrastructure for two reasons. First, **MadGraph** is widely used among the experimental collaborations in searches for Beyond the Standard Model (BSM) physics and we wish to provide them with the ability to easily incorporate relic density constraints into searches for models which support a dark matter candidate. Second, the Python implementation of the **MadGraph 5** code allows for a fairly straightforward development of **MadGraph** add-ons without sacrificing functionality.

➤ Cosmological interpretation of our LHC Dark Matter models!



MadDM

Functionality

- **Dark matter calculations for MadGraph models**
 - Determines Dark Matter candidate for user-specified model ($\Gamma_{\text{DM}}=0$)
 - Generates relevant DM annihilation diagrams (e.g. $XX \rightarrow \text{Med} \rightarrow \text{SM}$)
 - Solves DM density evolution equation (**standard cosmology**)
 - Output: resulting relic dark matter density ($\Omega_{\text{DM}} * h^2$)
- **Using any MG model, provides corresponding relic density**
 - **Left:** equation. **Right:** 2 \rightarrow 2 dark matter annihilation diagrams
 - Rule of thumb: $\Omega \approx 1/\sigma$. [More about this later]

$\langle \sigma_{\text{eff}} | v | \rangle$ is the effective thermally averaged annihilation cross section

$$\begin{aligned}\langle \sigma_{\text{eff}} v \rangle &\equiv \sum_{i,j=1}^N \langle \sigma(\chi_i \chi_j \rightarrow SM) v \rangle \frac{n_{\chi_i}^{\text{EQ}} n_{\chi_j}^{\text{EQ}}}{(n_{\chi}^{\text{EQ}})^2}, \\ \langle \sigma_{\chi \bar{\chi} \rightarrow X \bar{X}} | v | \rangle &= \frac{2 T m_{\chi}^2}{(2\pi)^4 n_{\text{eq}}^2 (1 + \delta_{\chi \bar{\chi}})} \int_0^1 d\beta \frac{\beta}{(1 - \beta^2)^2} \\ &\times \sqrt{\frac{\lambda(s, m_{\chi}^2, m_{\chi}^2)}{s}} K_1\left(\frac{\sqrt{s}}{T}\right) W_{ij}(s),\end{aligned}$$

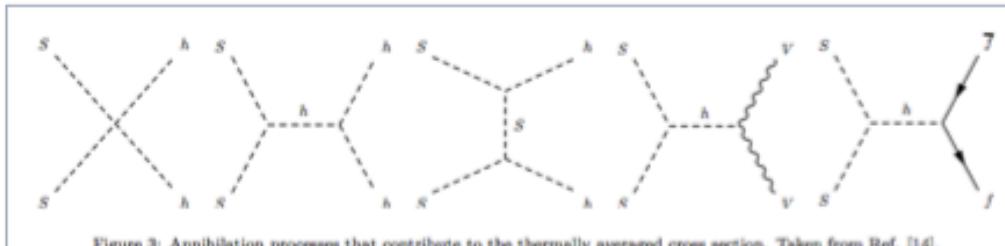
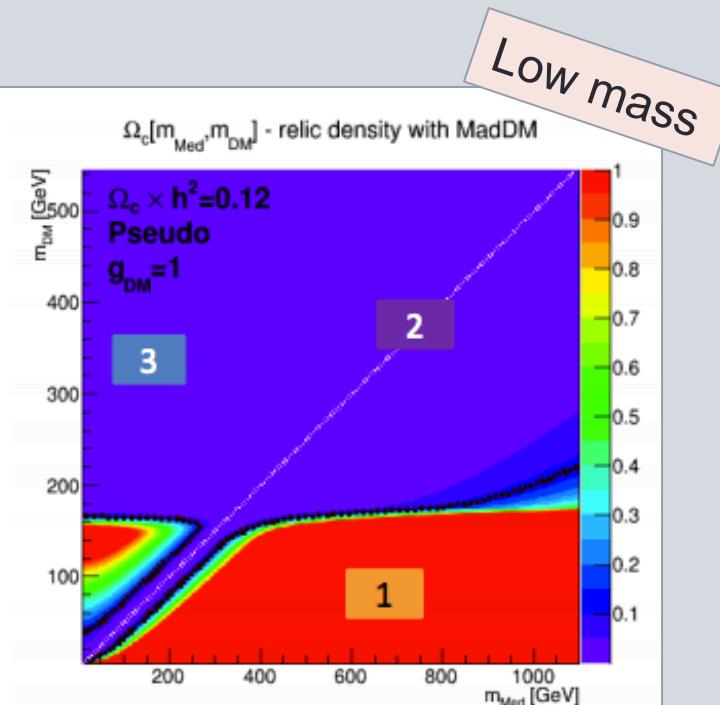


Figure 3: Annihilation processes that contribute to the thermally averaged cross section. Taken from Ref. [14].

Example

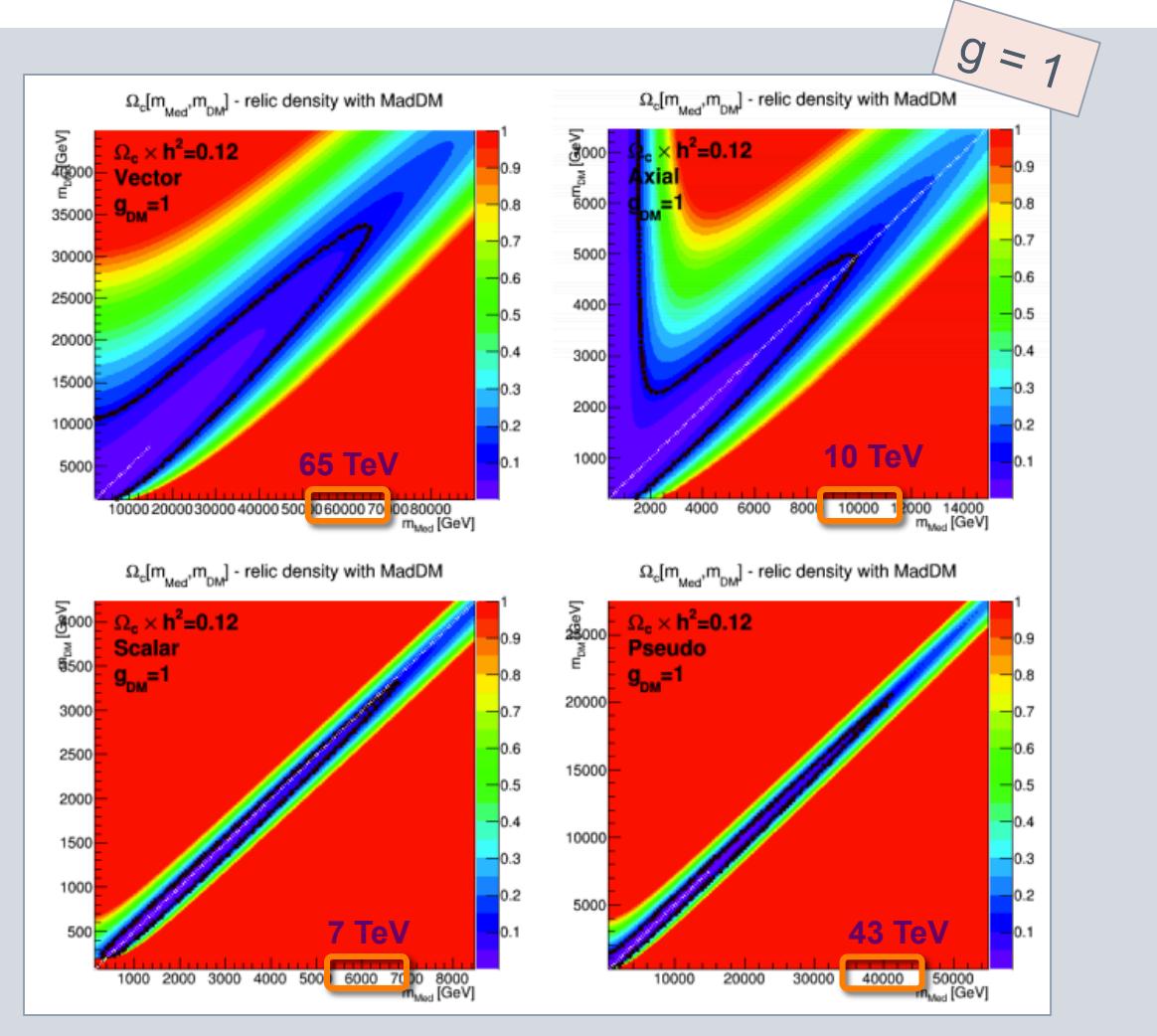
- Explanation of relic constraints

- [1] $m_\chi < m_t \rightarrow$ tight constraints
 - Suppression of the annihilation Process $\chi\chi \rightarrow Med \rightarrow SM$
- [2] $m_\Phi \sim 2 \cdot m_\chi \rightarrow$ weaker constraints
 - On-shell $\chi\chi \rightarrow Med$
- [3] $2 \cdot m_\chi > m_\Phi \rightarrow$ weaker constraints
 - Less suppressed annihilation $\chi\chi \rightarrow Med \rightarrow SM$



Relic constraints

Diagonal at high mass:
dominated by on-shell annihilation

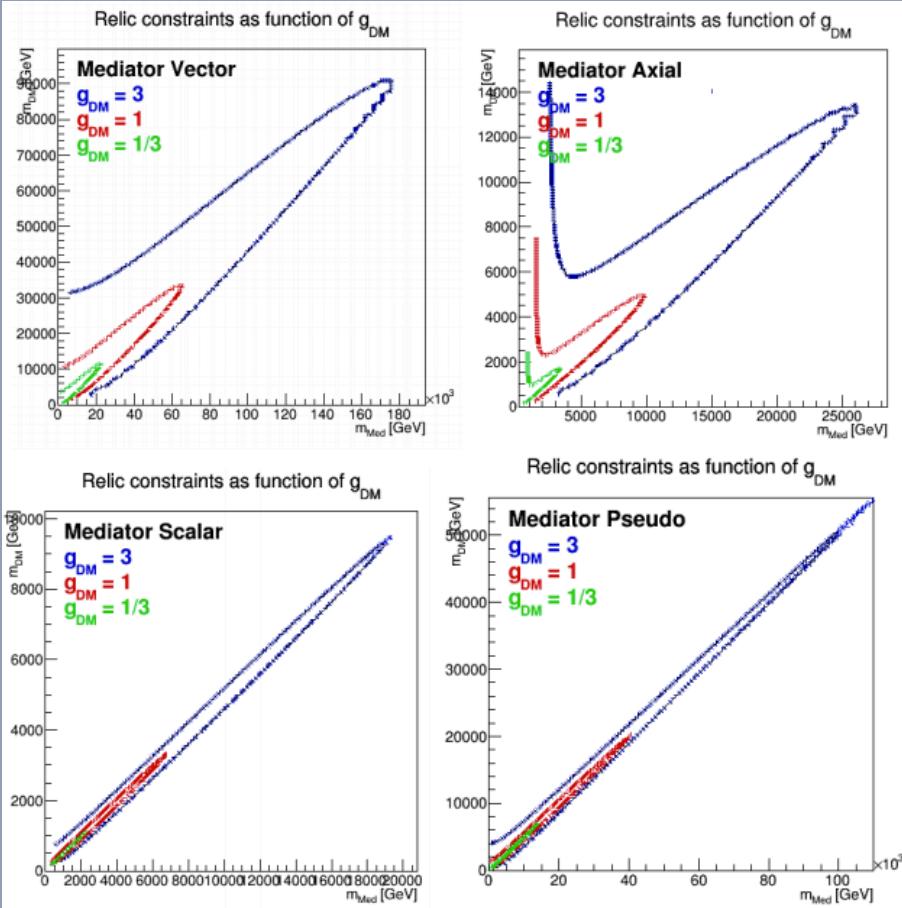


Maximally allowed masses for these mediator models by relic constraints

→ Use as guidance for FCC design

- M_{med} limits: **7 TeV (S) – 65 TeV (V)**

Relic vs coupling



Model	Coupling	$m_\Phi (\text{TeV})$	$m_\chi (\text{TeV})$
Vector	$g_{\text{DM}} = \frac{1}{3}$	24	12
	$g_{\text{DM}} = 1$	66	34
	$g_{\text{DM}} = 3$	180	94
Axial Vector	$g_{\text{DM}} = \frac{1}{3}$	3.6	1.8
	$g_{\text{DM}} = 1$	10	5
	$g_{\text{DM}} = 3$	27	14
Scalar	$g_{\text{DM}} = \frac{1}{3}$	2.0	1.0
	$g_{\text{DM}} = 1$	6.8	3.3
	$g_{\text{DM}} = 3$	19.5	9.5
Pseudo Scalar	$g_{\text{DM}} = \frac{1}{3}$	14.5	7.3
	$g_{\text{DM}} = 1$	43	21.5
	$g_{\text{DM}} = 3$	126	63

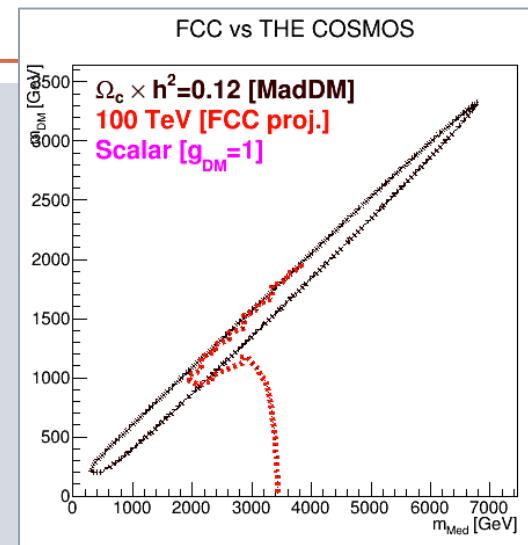
➤ Limits scale **proportional** to size of **coupling!**

RELIC VS FCC

Comparison for various couplings

- **Relic constraint**
<https://cds.cern.ch/record/2046121>
- **FCC projection**
<http://arxiv.org/abs/1509.02904>

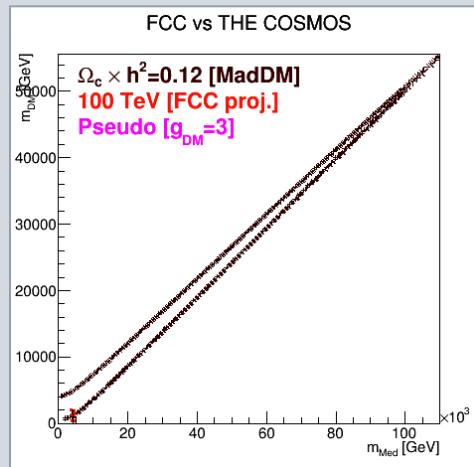
Combine these two! Work in progress (preliminary!)



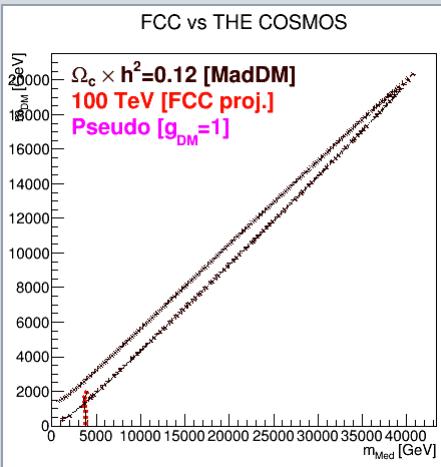
P&S

Preliminary

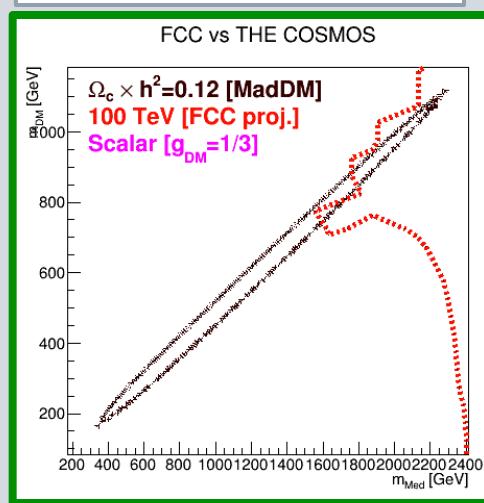
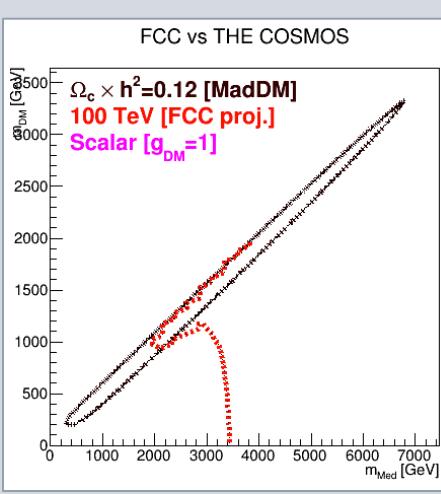
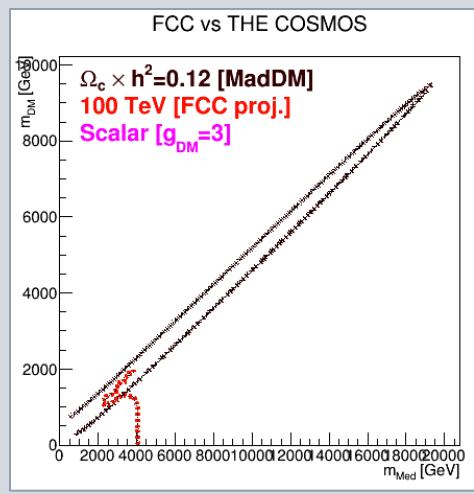
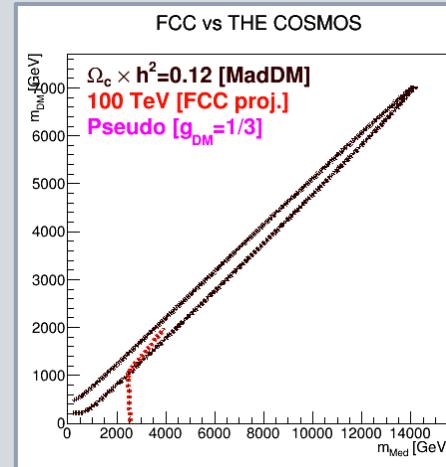
$g = 3$



$g = 1$



$g = 1/3$

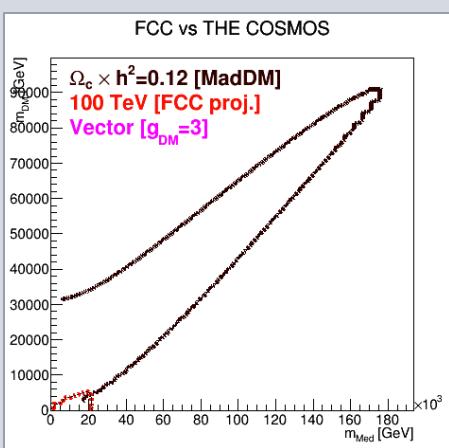


- FCC relatively best for **Pseudoscalar** mediator and **small couplings**

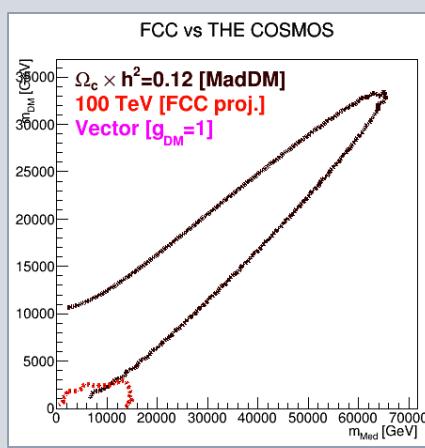
V&A

Preliminary

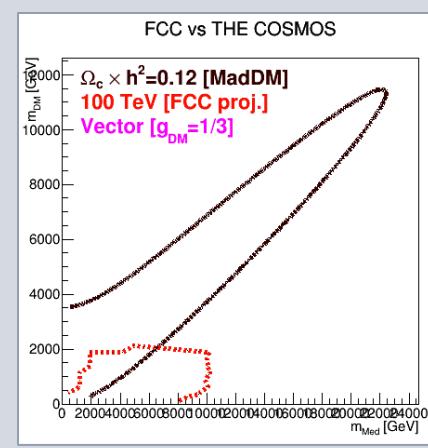
$g=3$



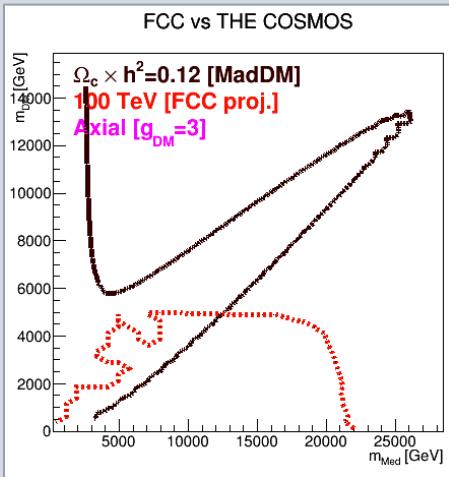
$g=1$



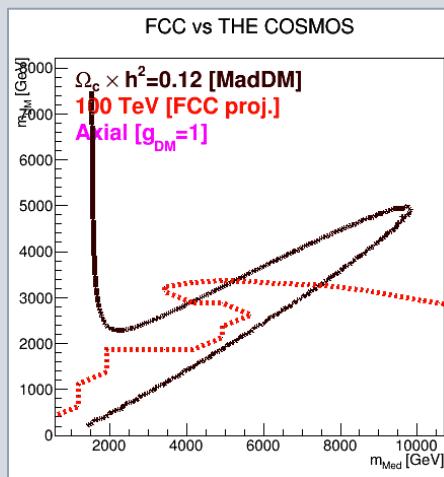
$g=1/3$



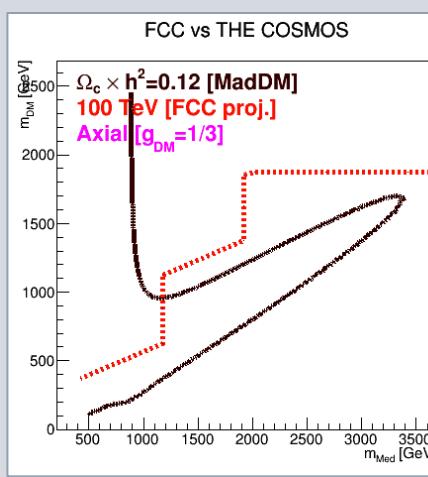
FCC vs THE COSMOS



FCC vs THE COSMOS



FCC vs THE COSMOS



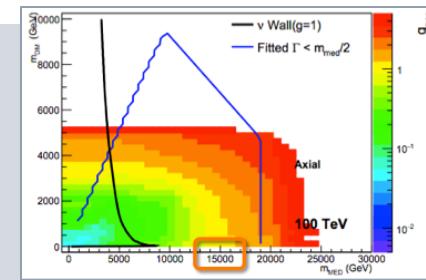
➤ FCC relatively best for **Axial-vector** mediator and **small couplings**

Conclusions

DM constraint comparisons: LHC&FCC vs DD&relic

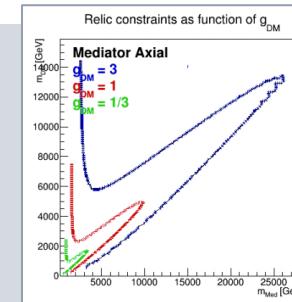
- **DM FCC projections**

- Modeling of extra jets important
- Complementary to DD for Axial & Pseudo
- Sensitivity **scales with collision energy**



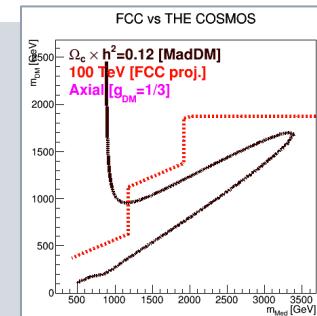
- **Relic DM**

- Complementary info to Collider & DD
- At high mass dominated by on-shell annihilation
- Cosmological constraint **scales with coupling**



- **Relic vs FCC**

- Compared constraints collider vs relic
- FCC especially powerful for **Pseudo&Axial**, in particular for smaller couplings



Towards a no-lose theorem for DM?

- Outlook: compare various constraints
 - Relic constraints
 - Direct Detection
 - Theory bounds (width)
- And using LHC simplified models...
- ...we might have a no-lose theorem for DM at FCC

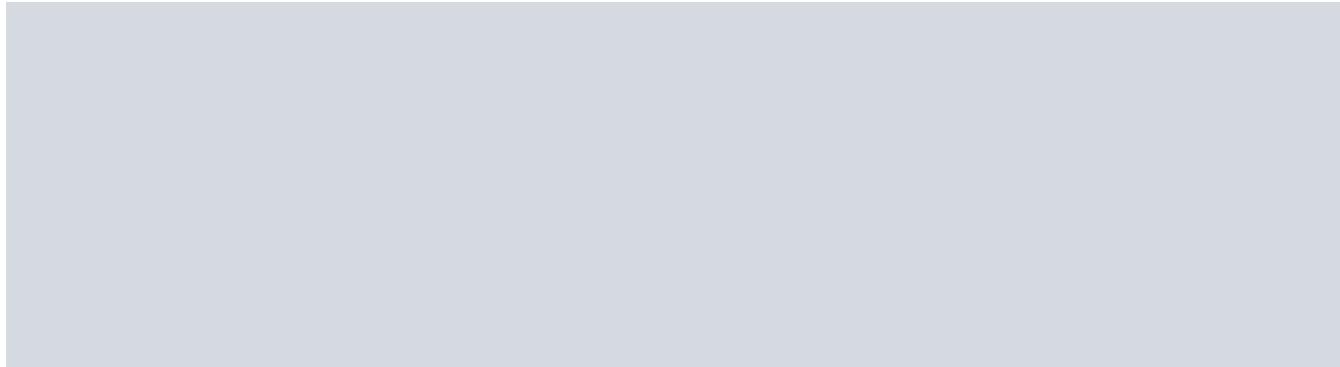
1. Vector: excluded by LHC+DD+Relic
2. Axial: mostly excluded with FCC
3. Scalar: almost covered with FCC
4. Pseudo: most challenging



**Thank you for
your attention!**



BACKUP



100 TeV modeling

- 100 TeV modeling

Firstly, there is the obvious issue regarding tuning and PDF fits, which have been undertaken at much lower energy than those accessible at FCC's. Of particular importance are the extraction of the gluon PDF's, which will dominate the initial state configurations. Secondly, there is the accuracy of the perturbative component of the simulations. This is particularly worrisome. At FCC energies emission of additional radiation will result in copious jet-production around the Electroweak scale. This will require delicate handling with respect to matching and merging of parton shower and matrix element emissions. Since matching prescriptions typically require scales which separate emissions into the two categories, one can easily imagine existing tools for LHC physics are not optimal for future FCC predictions. An additional concern relates to the simulation of Electroweak bosons, at 100 TeV, the mass of the W , Z and H bosons become small scales, and Sudakov logarithms associated with their emission from partons becomes relevant. The resolution of these issues will take many years of research and improvements to existing tools. However given the likely timescale of construction, and the rapid improvement in theoretical tools, none of the above issues should be

Shape

- Shape based

The signal extraction is performed with a full shape analysis in which the shape for the dominant backgrounds are taken from control regions. For the $Z \rightarrow \nu\bar{\nu}$ background, the $Z \rightarrow \mu^+\mu^-$ control region is used as a background. For the $W \rightarrow \ell\nu$, top and diboson backgrounds, we use the single lepton control region. For each of these control regions the full statistical uncertainty on the shape is propagated per bin on each of the backgrounds with an additional one percent uncertainty uncorrelated per bin to account for additional modelling uncertainties. For all but the tail bins of the shape uncertainties on the \cancel{E}_T spectrum are roughly 1% with the dominant uncertainty resulting from the additional one percent modelling uncertainty. Finally, the signal is profiled using the standard limit extraction (CL_s) [58, 59]. Additional nuisances are placed on the background normalization for lepton efficiencies and luminosity. These are constrained to very small values due to the large dataset in the signal region and do not affect the limit sensitivity.

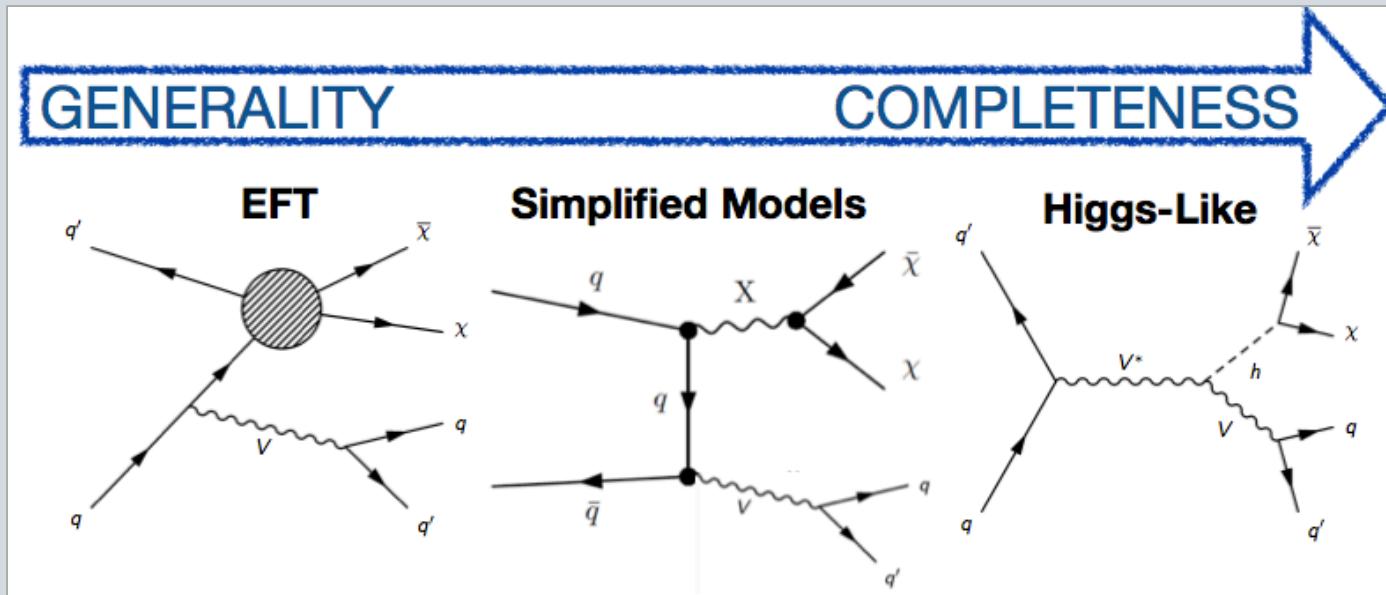
Shapes

B. Kinematic distributions for signal and background

In light of using multi-leg Monte Carlos and recent developments in shape based analysis for Dark Matter projections [55], the analysis selection was re-optimized from a previous cut and count analysis by considering a shape based analysis in both single and pairwise combinations of variables that take into account both the leading and trailing jets. To find sensitive variables to separate signal from backgrounds we focused on \cancel{E}_T , m_T^2 , the razor variables, the scalar sum of all jets above 30 GeV (h_T), and the angle between the two leading jets $\Delta\phi_{jj}$ [55–57]. Figure 2, shows the performance of these variables when compared with an amalgam of signal Monte Carlos. For these signal models, a dark matter mass of 50 GeV is taken (ensuring on-shell decays for both). The range of samples consist of those with different mediator masses ranging from 1 TeV to 2 TeV in 100 GeV intervals. The samples are combined by cross-section weights. We recall that the 1 jet Monte Carlo is generated with full on and off shell width effects, whereas the 1-jet/2-jet merged sample is generated explicitly on-shell. When considering the single variable performance, we find \cancel{E}_T is the most discriminating variable. As a result, combining these variables into pairwise combinations using a boosted decision tree we find that the most sensitive combination is \cancel{E}_T and $\Delta\phi_{jj}$ between the two leading jets. This can be readily seen in the left plot in Fig. 2 where the $\Delta\phi_{jj} + \cancel{E}_T$ combination is shown as the solid line in blue. In the lower-left quadrant of the plot the reconstruction efficiency of the signal ϵ_{sig} significantly exceeds that of the background, for example for $\epsilon_{\text{sig}} \simeq 0.5$ we have $\epsilon_{\text{bkg}} \simeq 0.1$ on the blue contour in Fig. 2. A comparison with higher dimensional sets of variables in the right panel shows even further improvement, particularly when the second jet merged MC is used. However, for this further optimization to manifest itself in the analysis requires precise knowledge of the kinematic discrimination of \cancel{E}_T in the far tails of the distribution. Additionally we note that the larger differences between the one-jet and two-jet signal MC, can be indicative of greater sensitivity to theoretical modeling. Thus, we do not extend these studies beyond their current projections. Our final extractions are then performed by fitting the \cancel{E}_T distribution in two bins of $\Delta\phi_{jj}$ ($\Delta\phi_{jj} < 1.1$ and $\Delta\phi_{jj} > 1.1$). The binning is optimized such that the full spectrum is covered with MC samples. Additionally a selection of $\min(\Delta\phi_{\cancel{E}_T, j_i}) \geq 0.5$, where i runs over all jets is applied to minimize the impact of QCD multi-jet events where one or several of the jets are miss-measured. As a result of this selection being applied, this background is neglected throughout the course of these studies. Further improvements could be obtained by using finer bins for the tails of the distribution⁴.

EFT vs Mediator

- **Goal:** probe broad range of DM models
 - Combining categories: **mono-jet + mono-V (boosted+resolved)**



- As discussed by **Atlas/CMS Dark Matter Forum**

DMF report

- Out since last week

arXiv.org > hep-ex > arXiv:1507.00966

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 Andriamonje, 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, Guillermo Gomez Ceballos, Yangyang Cheng, Jiaxin Chen, 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, et al. (94 additional authors not shown)

(Submitted on 3 Jul 2015)

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.

- Models & interpretation in EXO-12-055 already consistent with the report!
 - <http://arxiv.org/abs/1507.00966>

Mediator Lagrangians

Vector

$$g_{\text{DM}} Z'_\mu \bar{\chi} \gamma^\mu \chi$$

EWK style coupling
(equal to all leptons)

Axial

$$g_{\text{DM}} Z''_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$$

EWK style coupling
(equal to all leptons)

Scalar

$$g_{\text{DM}} S \bar{\chi} \chi$$

Yukawa style coupling
(Mass based coupling)

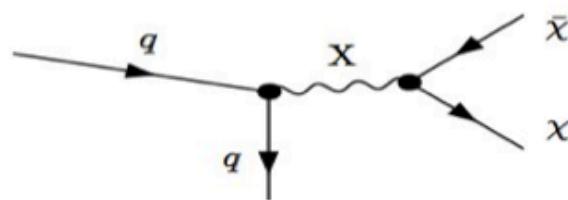
Pseudoscalar

$$g_{\text{DM}} P \bar{\chi} \gamma^5 \chi$$

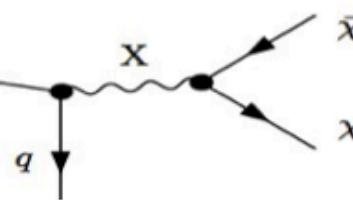
Yukawa style coupling
(Mass based coupling)

Direct Detection

Vector

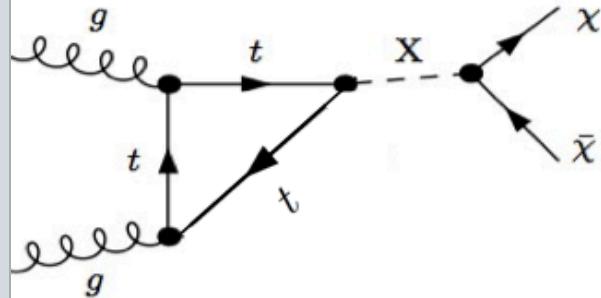


Axial

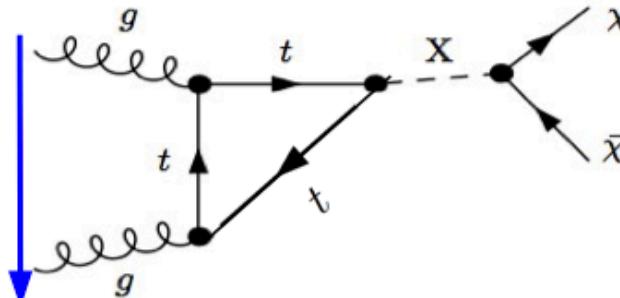


spin-dependent

Scalar



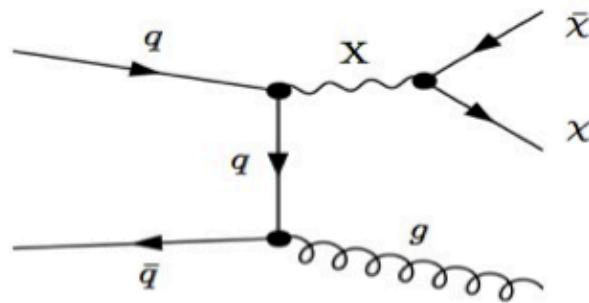
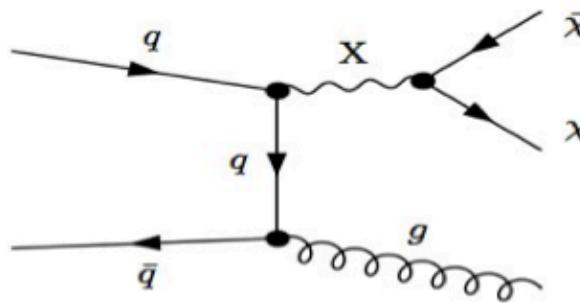
Pseudoscalar



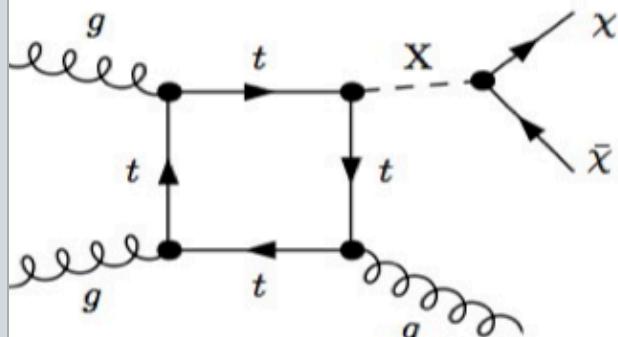
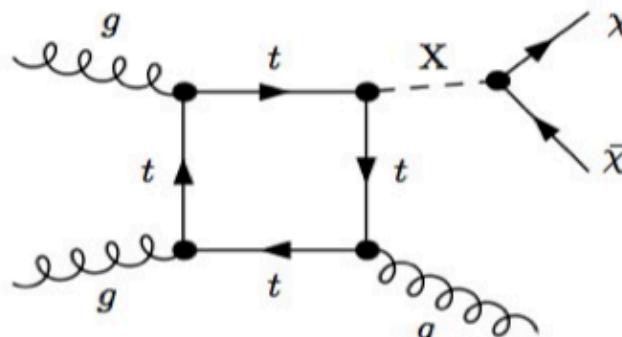
spin-dependent

LHC – Mono-jet

MCFM

Vector**Axial**

MCFM

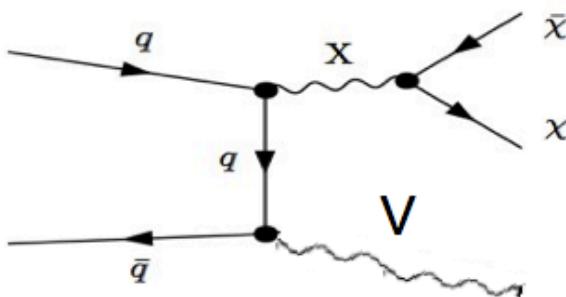
Scalar**Pseudoscalar**

Used for ‘fermionic’ interpretation

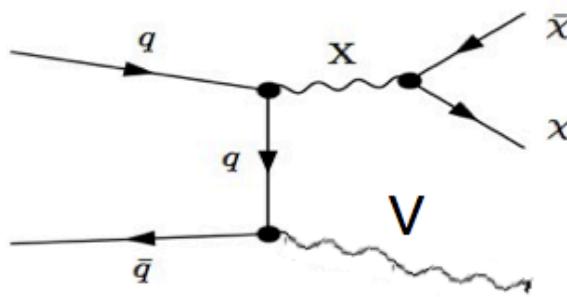
LHC – Mono-V

MadGraph

Vector



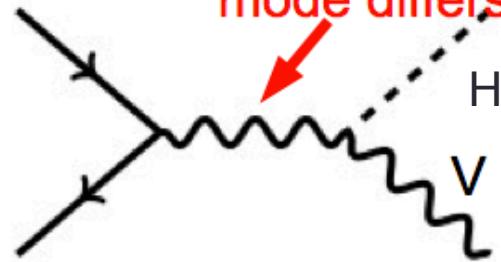
Axial



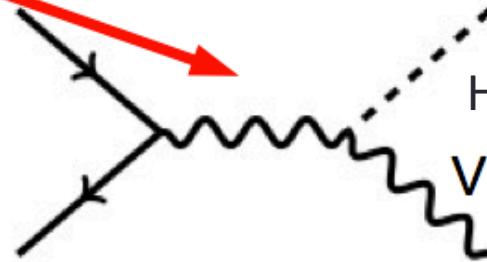
JHUGen

Scalar

Dominant production mode differs

Dominant from V -strahlung

Pseudoscalar

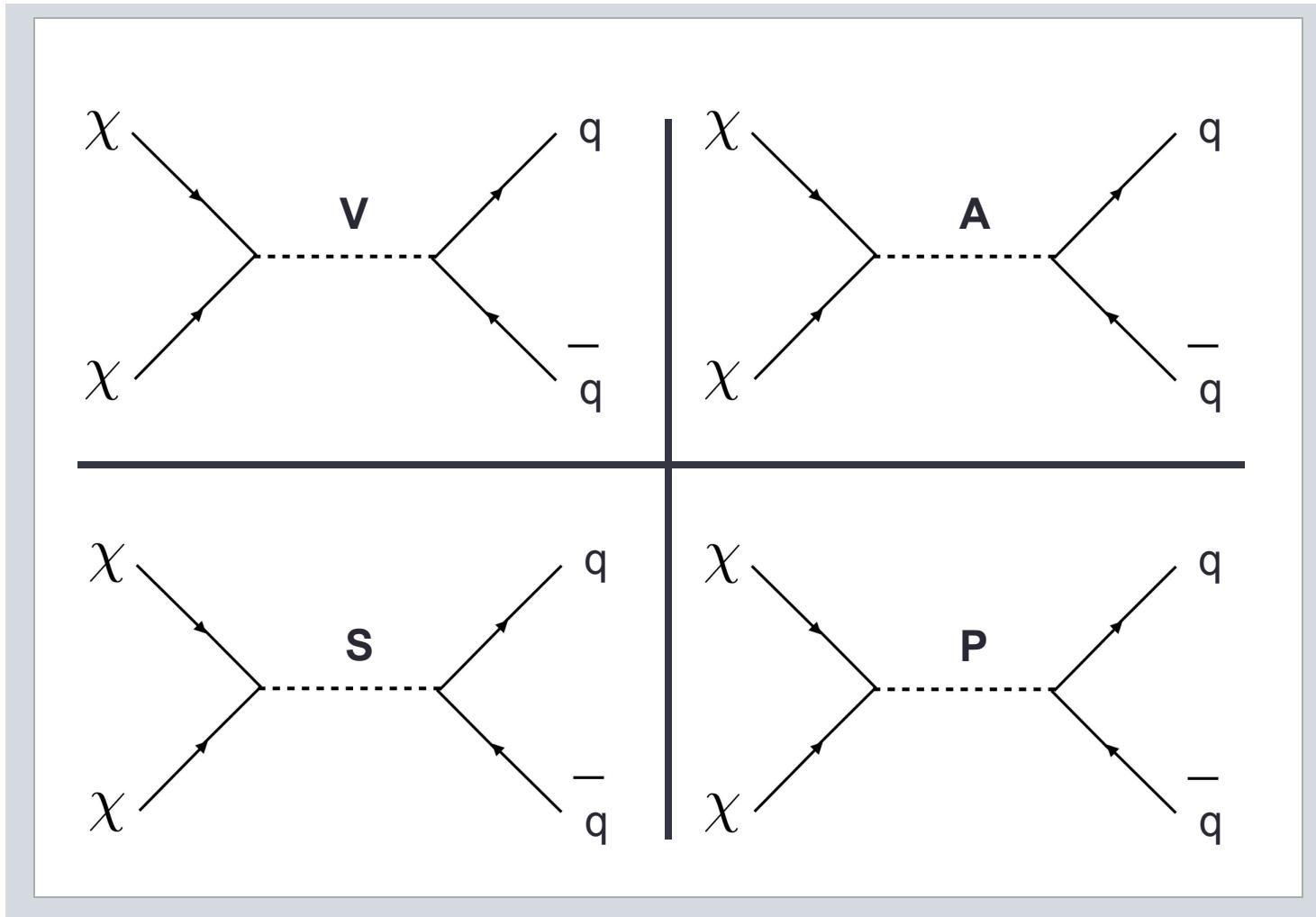
Enhanced boson p_T

Same diagram as *monojet*
Modified ξ enhances *mono-W*

Relic - Annihilation



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



ANALYSIS SETUP

Signal signature:

- MET+jet

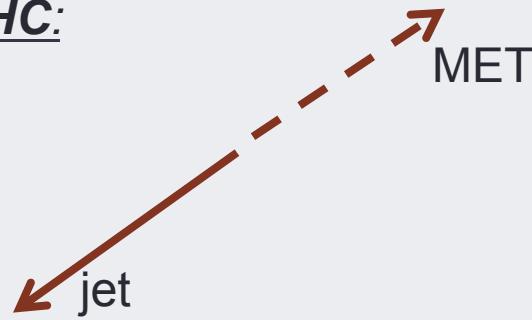
Main backgrounds:

- Z($\nu\nu$)+jet
- W($\ell\nu$)+jet

Control samples:

- Z($\mu\mu$)+jet [double-mu]
- W($\ell\nu$)+jet [single-mu]
- γ +jet [photon]

LHC:



Objects & selection

*"if you want to see **nothing**,
you have to reconstruct
everything"*

MET (final discriminating observable)

- Raw **PFMet > 200** GeV
- Pass standard MET/noise **filters**
- Plus **recoil corrections** (more details later)

Jets

- Large jets: **CA8 CHS PF Jets**
 - **Substructure - boosted V**
- Default jets: **AK5 PF jets**
- $|\eta| < 2.5$ & $p_T > 30$
- Require PFJetID loose & PUJetID loose

Event topology

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

CR ($\mu+\gamma$)

- **μ :** $|\eta| < 2.1$ & $p_T > 10$
& POGTightID
- **γ :** $|\eta| < 2.5$ & $p_T > 160$
& EGammaID 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 & EGammaID medium
- **e:** $\eta < 2.5$ & $p_T > 10$ GeV & EGammaID veto
- **τ :** $\eta < 2.5$ & $p_T > 15$ GeV & HPSPFTauID loose

CATEGORIZATION

Selection strategy

- Boosted $V \rightarrow J$
- Resolved $V \rightarrow jj$

Further improve sensitivity

Strategy

Categorization [mutual exclusive]

1. Boosted V cat

- **PFMET** > 250 GeV
- **CA8 CHS Jet** p_T > 200 GeV
- **CA8 CHS Jet** passes Boosted V-tag

2. Resolved V cat

- **Not category 1**
- PFMET > 250 GeV
- **2 AK5 Jets** – passing resolved V-tag
- **$60 < M_{jj} < 110$ GeV**
- **Veto b-jets** (top)

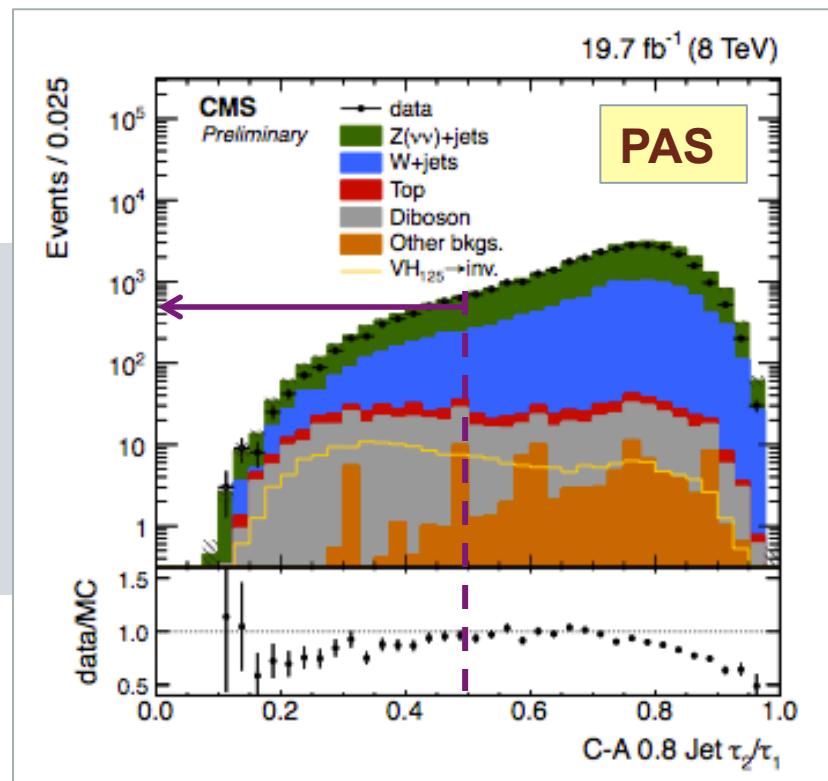
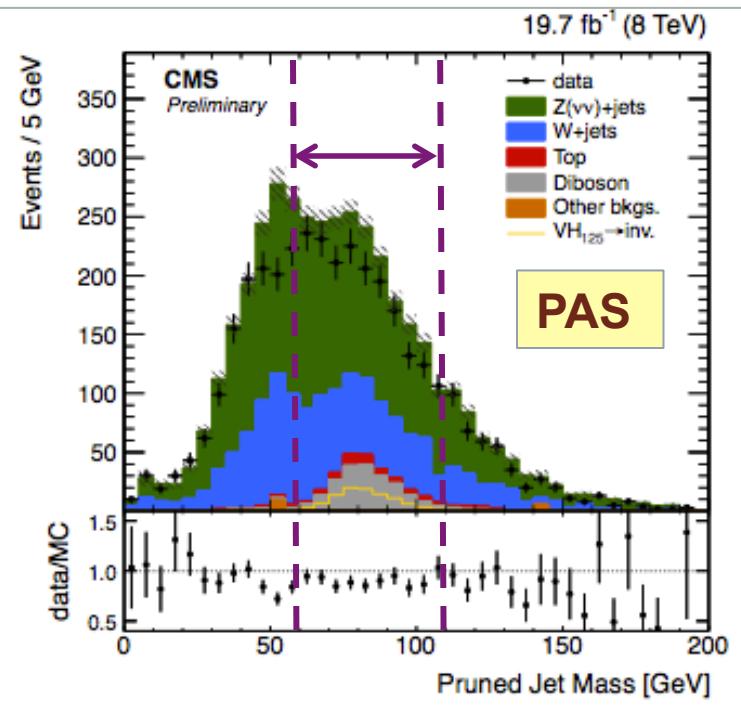
3. Monojet category

- **Not category 1 & 2**
- **AK5 Jet** p_T > 150 GeV



“Boosted”

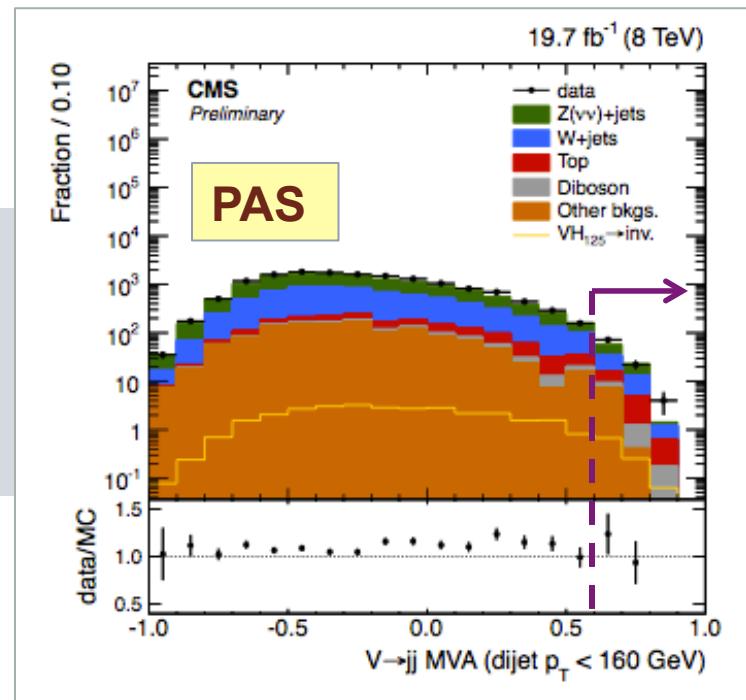
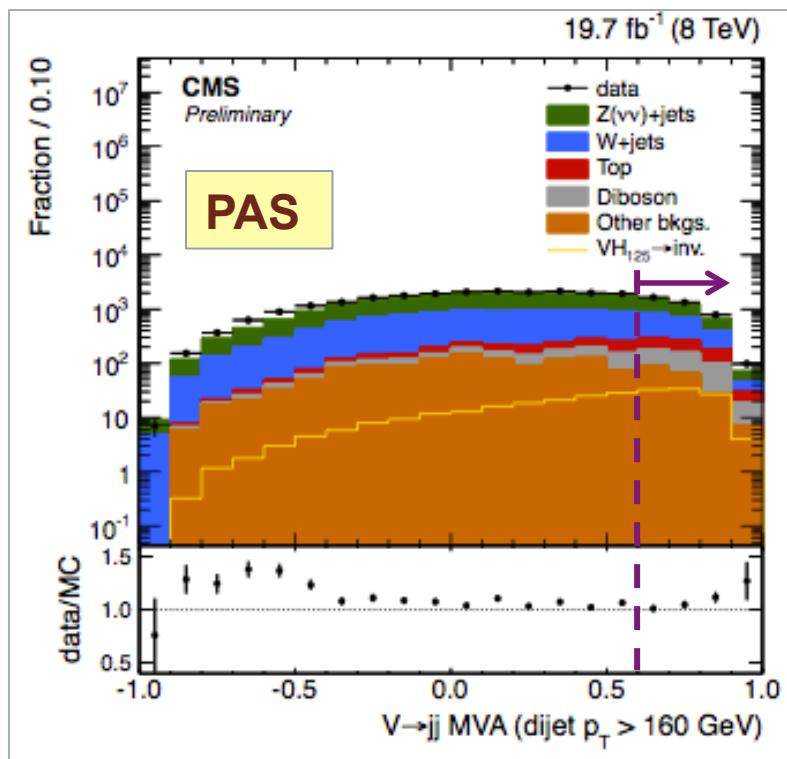
- $V \rightarrow J$ ‘fatjet’ tagger
 - Cut-based
 - Based on CMS standard
 - Efficiency uncertainties
 - Follow JetMet recommendations



- **Subjettiness**
 - Measure of 2-prongness
 - $\tau_2/\tau_1 < 0.5$
- **Pruned jet mass**
 - Cleaned of PU/UE
 - $M_{WZ} = [60, 110] \text{ GeV}$

“Resolved”

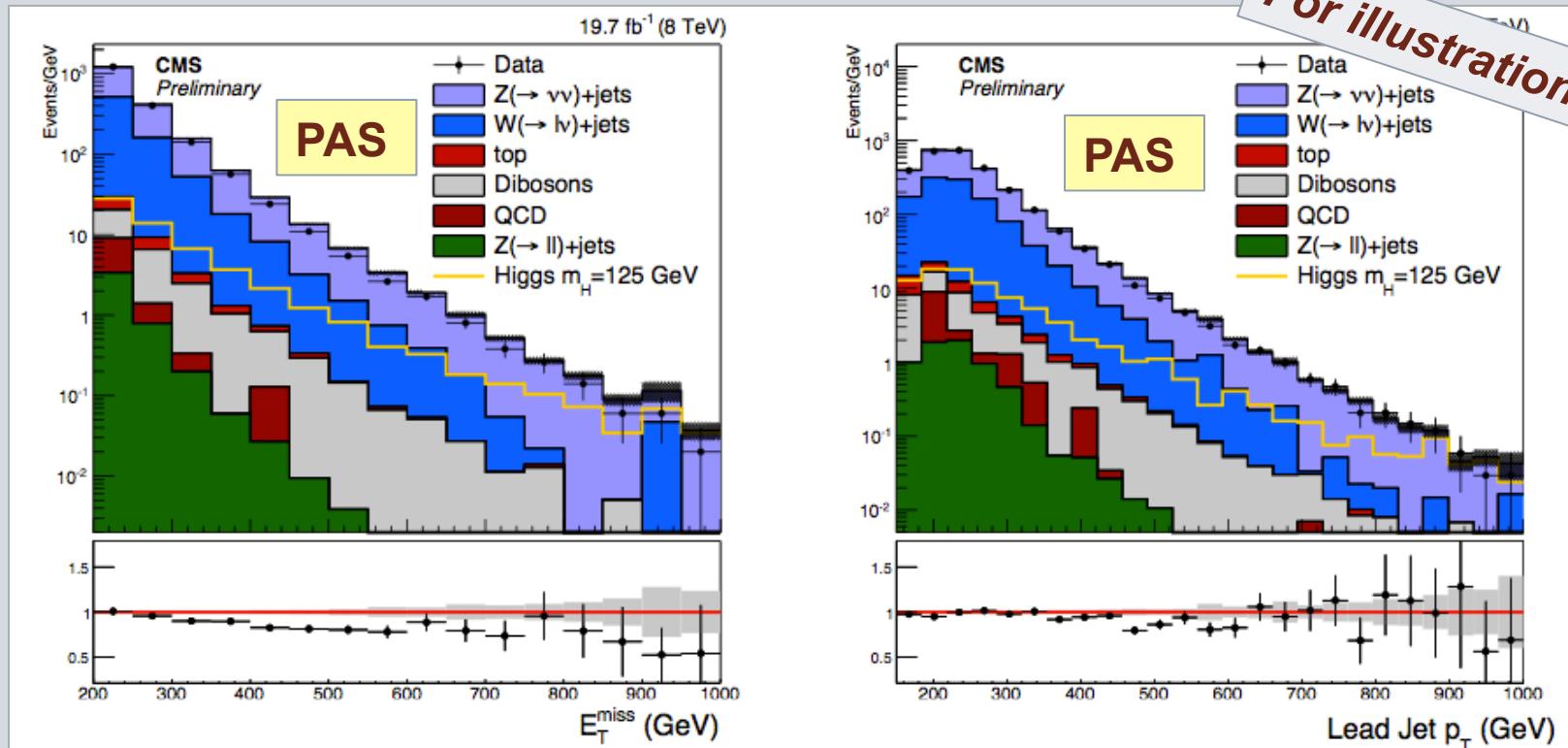
- **V \rightarrow jj tagger : BDT**
 - Based on JME-14-002
 - High and low p_T
 - **MVA > 0.6**



- **Quark/gluon discriminator**
 - Likelihood - jet shower shape
- **Jet color pull**
 - Pull vector (jet axis, color flow)
- **Modified mass drop**
 - $\text{Max}(m_{j1}, m_{j2})/m_{jj} \times \Delta R$
 - Small for dijet from massive object
- **p_T(jj)/M(jj)**

Data/sim

- Out-of-t-box
 - 3 categories combined



- Default simulation of Z+jets & MET resolution

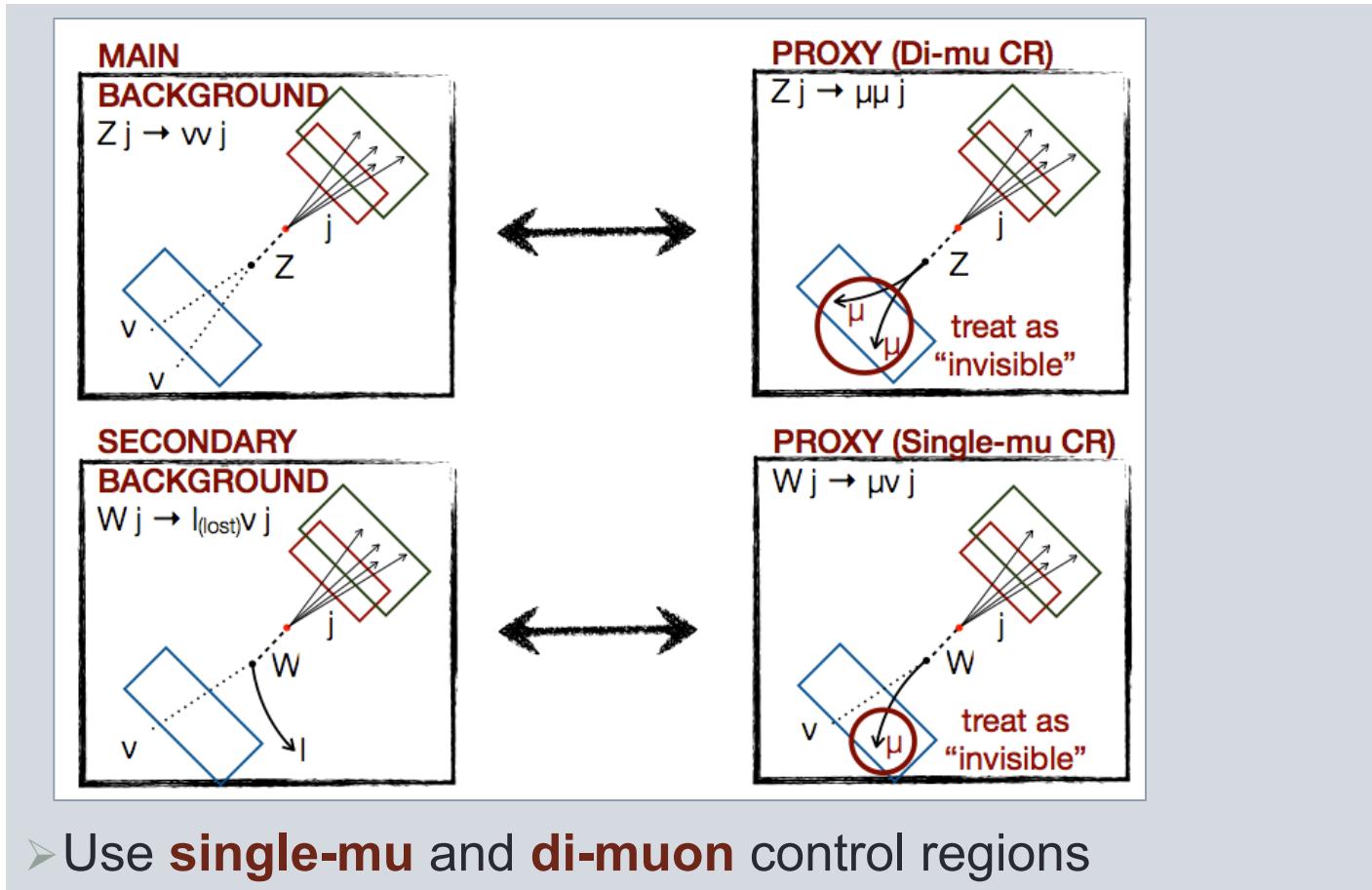
BACKGROUNDS

Reconstruction & MET modeling

Theory

Fit

Backgrounds: V+jets



➤ Use **single-mu** and **di-muon** control regions

➤ Control MET: 'fake MET' = '|Recoil|'

➤ Sum over visible leptons

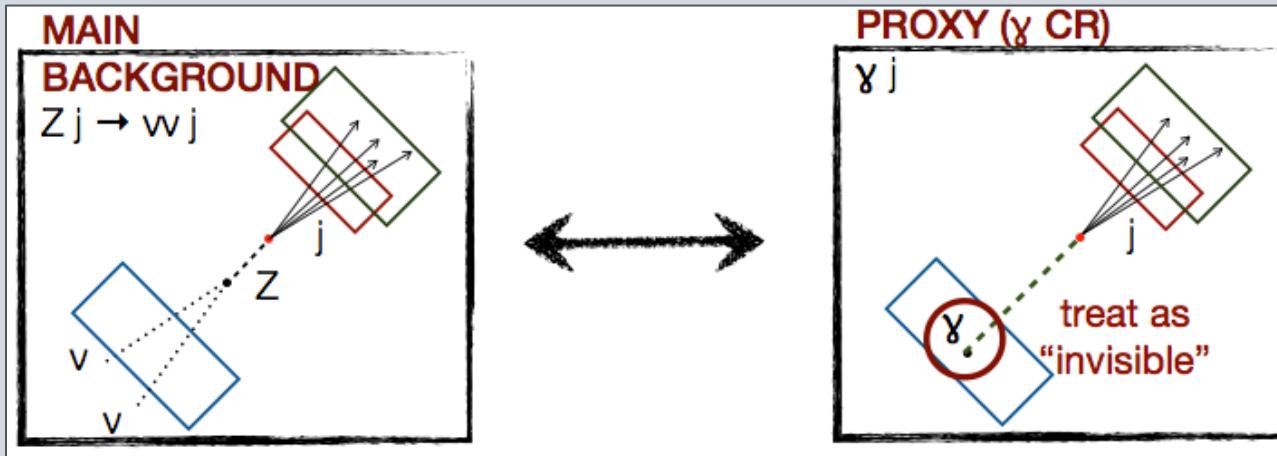
$$\text{RECOIL } \vec{U} = -\text{MET} - \sum_i \vec{p}_T(\ell_i)$$

$\gamma + \text{jet}$

$$Z(\nu\nu) : Z(\mu\mu) = 6$$

Challenges:

1. Reconstruction: ME_T
 2. Prediction: Theory
 3. Statistics: $Z(\mu\mu) + \text{jet} \rightarrow$ exploit $\gamma + \text{jet}$ in photon CR!
- } all $V + \text{jet}$



- Use ratio $Z + \text{jet}/\gamma + \text{jet}$!
- Z & γ similar at $\text{large } p_T(V) \sim \text{MET}$

➤ Main effort & novelty & improvement of the analysis

Experimental corrections

Experimental efficiency correction

- Muons
- Photons
- Taus
 - Largest veto uncertainty

Recoil corrections

- Detector effects
- Use events with no **real MET**

$$\text{RECOIL } \vec{U} = -\text{MET} - \left(\sum_i \vec{p}_T(\ell_i) \right)$$

- Low p_T : $Z(\mu\mu) + \text{jets}$
- High p_T : $\gamma + \text{jets}$



- Recoil results on next page

V+jets fit

- Control regions with correction factor **R**

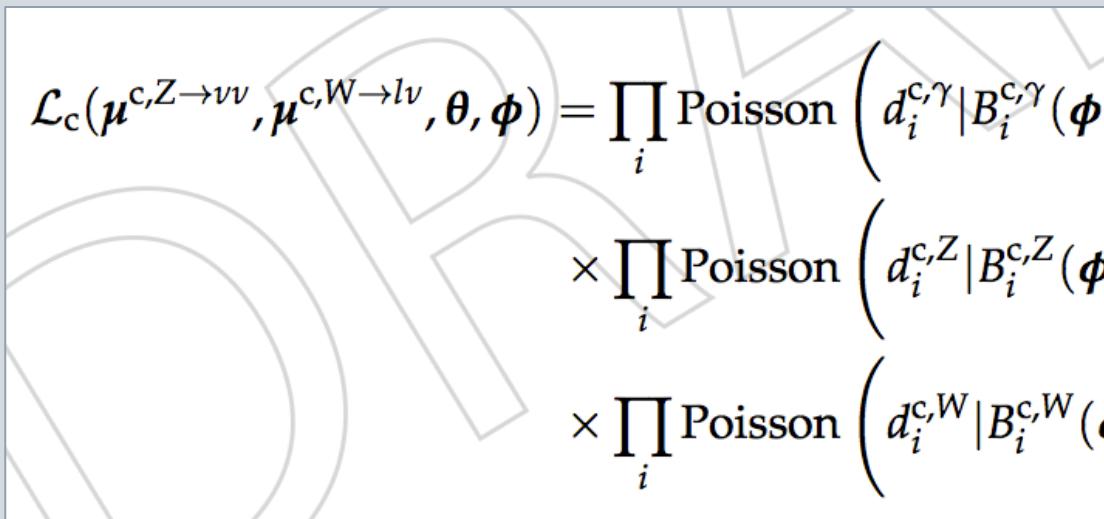
$$N_i^{Z_{\mu\mu}|\gamma} = \frac{\mu_i^{Z \rightarrow \nu\nu}}{R_i^{Z|\gamma}}$$

$$N_i^W = \frac{\mu_i^{W \rightarrow l\nu}}{R_i^W}$$

- **Main backgrounds:** W(lν)+jets and Z(νν)+jets
- **R** – corrects for differences in **efficiency & BR**
- **R_i** – for different **MET bins** and different **categories**
- **Differential** – include **NLO k-factor for p_T(V)**

Background

- **Simultaneous fit**



$$\begin{aligned} \mathcal{L}_c(\mu^{c,Z \rightarrow \nu\nu}, \mu^{c,W \rightarrow l\nu}, \theta, \phi) = & \prod_i \text{Poisson} \left(d_i^{c,\gamma} | B_i^{c,\gamma}(\phi) + \frac{\mu_i^{c,Z \rightarrow \nu\nu}}{R_i^{c,\gamma}(\theta)} \right) \\ & \times \prod_i \text{Poisson} \left(d_i^{c,Z} | B_i^{c,Z}(\phi) + \frac{\mu_i^{c,Z \rightarrow \nu\nu}}{R_i^{c,Z}(\theta)} \right) \\ & \times \prod_i \text{Poisson} \left(d_i^{c,W} | B_i^{c,W}(\phi) + \frac{\mu_i^{c,W \rightarrow l\nu}}{R_i^{c,W}(\theta)} \right) \end{aligned}$$

- **Modeling of V+jets in signal and control regions**

➤ Include (exp/theo) uncertainties as nuisances (δ, ϕ)

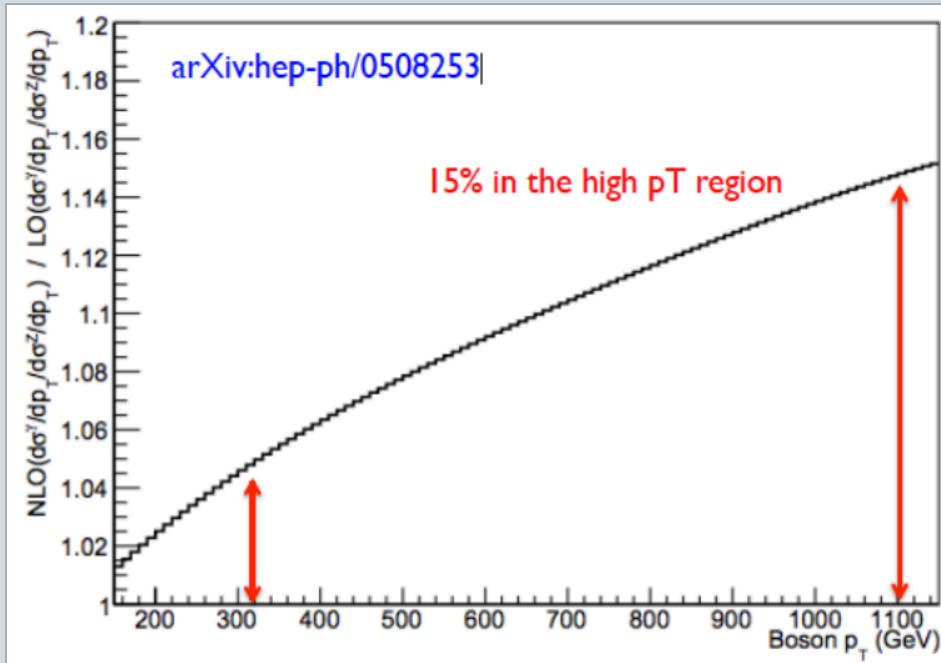
- E.g. **renormalization, factorization, PDF, EWK, ...**
- **Theory component** in R^Y [see next page]

➤ Parameterize expected yield in signal region as μ

- **Result: improve modeling → see next page**

Theory corrections

- QCD NLO included by using **aMC@NLO**
- EWK correction below
 - Ratio: **NLO Z+jet/ γ +jet** correction



- Uncertainty: EWK dominant at high MET

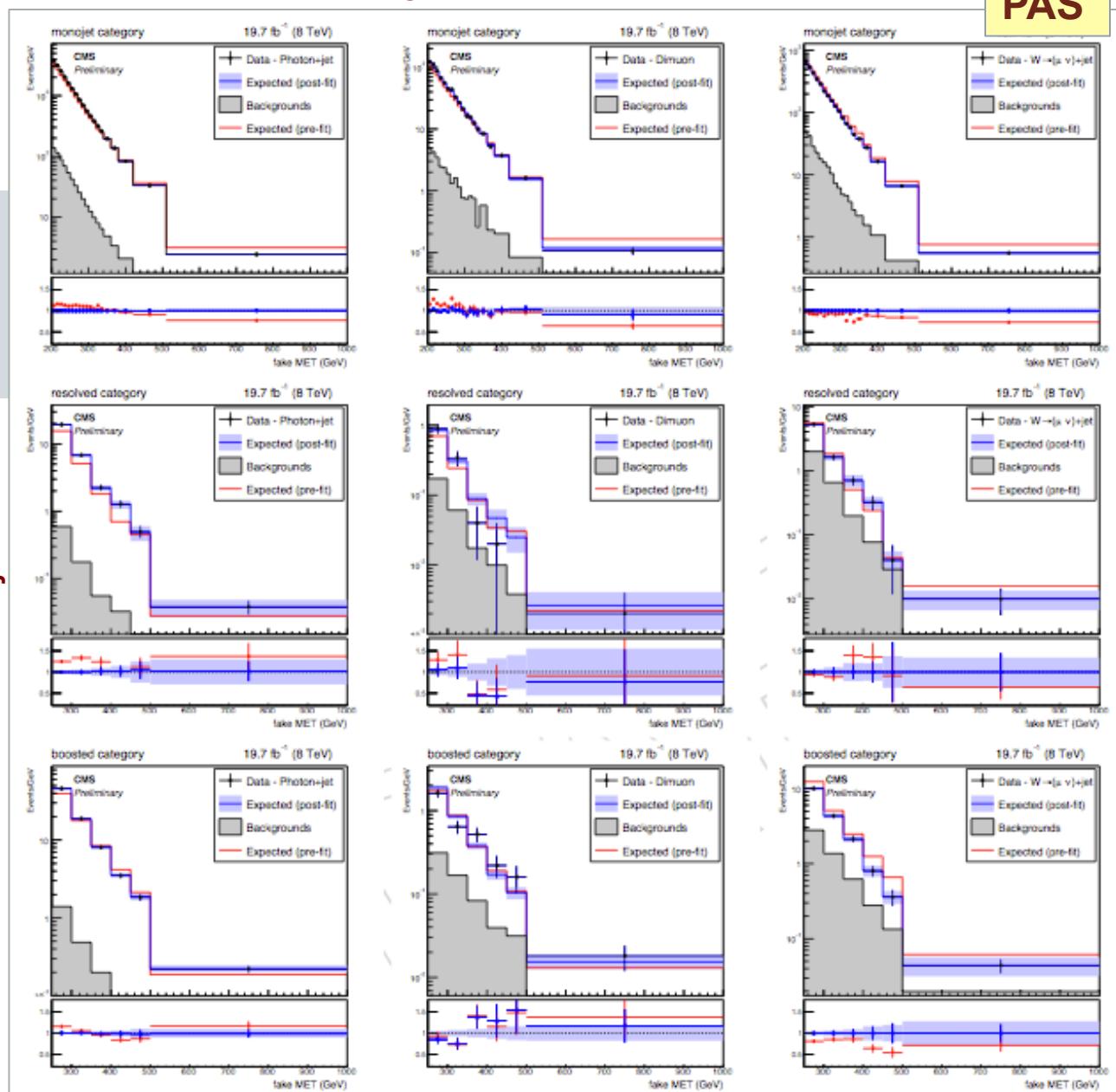
Control regions

- After fits
 - In agreement
 - All final states

boosted / resolved / monojet

photon / dimu / single mu

PAS



RESULTS

Yields & systematics

Constraints on simplified models

Interpretation & comparison

Systematics

- Summary
 - Control region fits crucial

Table 1: Systematic uncertainties and their effect on the expectation for the SM backgrounds.

Systematic Uncertainty	Process	Boosted	Resolved	Monojet
Control region fits [†]	$Z(\nu\nu) + \text{jets}$	6-20%	7.6-44%	2.5-9.5%
	$W(l\nu) + \text{jets}$	10.5-55%	14.5-320%	3.6-17%
Tau-id efficiency	$W(l\nu) + \text{jets}$		3.6%	
V-tag efficiency [‡]	Dibosons, Top		10%,6%	
b-tag efficiency	Top		4%	
E_T^{miss} recoil	Dibosons	0.6%	2.8%	0.3%
	Top	1.1%	1.8%	1.3%
	$Z(l\bar{l}) + \text{jets}$	5.8%	9.4%	0.7%
$t\bar{t}$ norm	Top		7%	
Dibosons norm	Dibosons		10%	
QCD norm	QCD		50%	
Luminosity	All except V+jets		2.6%	

PAS

[†] The relevant components of the fit uncertainties relating to theory and muon/photon identification scale-factors in the control regions, described in Sec 5.1, are included here and correlated between event categories.

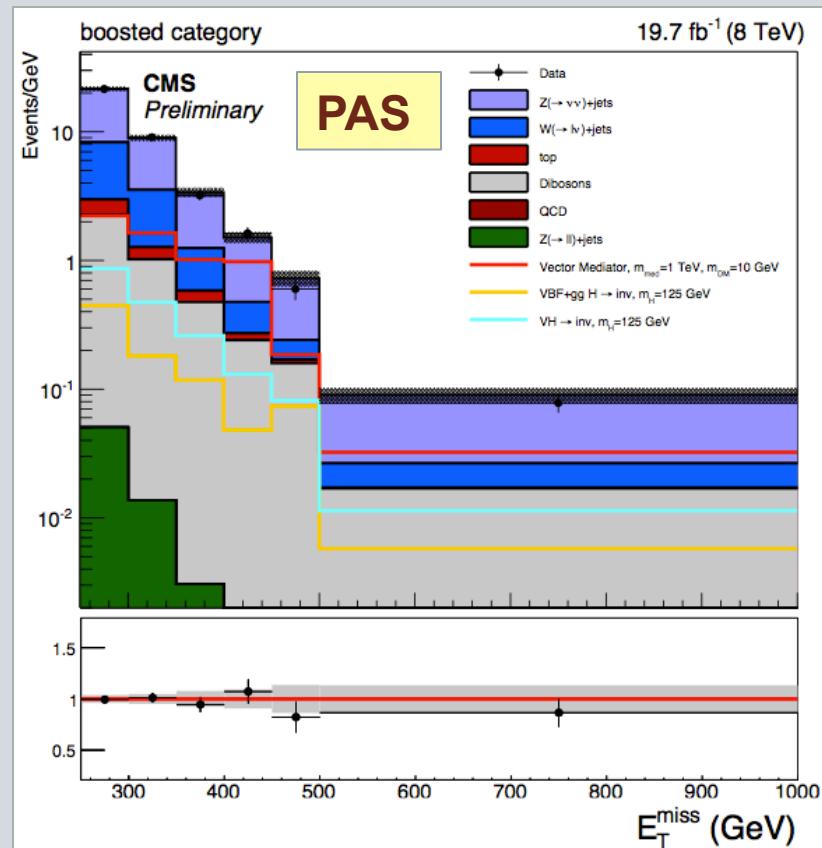
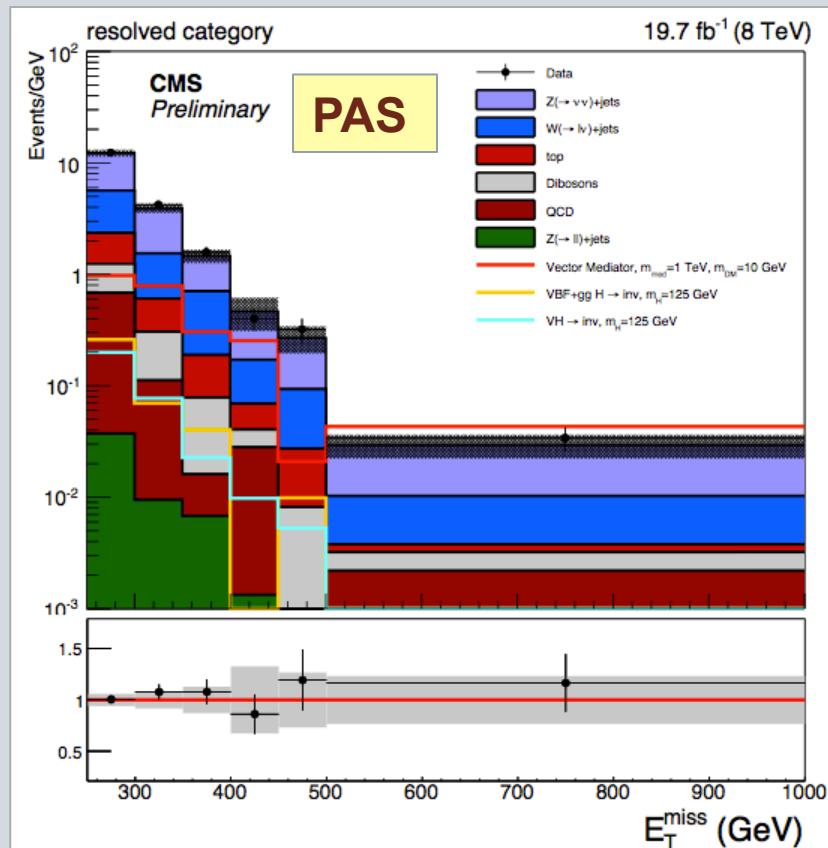
The numbers here indicate the range of the size of the uncertainties (the smallest to largest) due to these fits but should not be interpreted as the systematic which is propagated to the signal extraction

[‡] Uncertainty modeled as migration between the V-tagged (boosted and resolved) and monojet categories.

- Yields in signal region after fit agree within 1%
 - Full tables, for 3 categories, in backup & PAS

MET shape

- Resolved (left) + boosted (right)

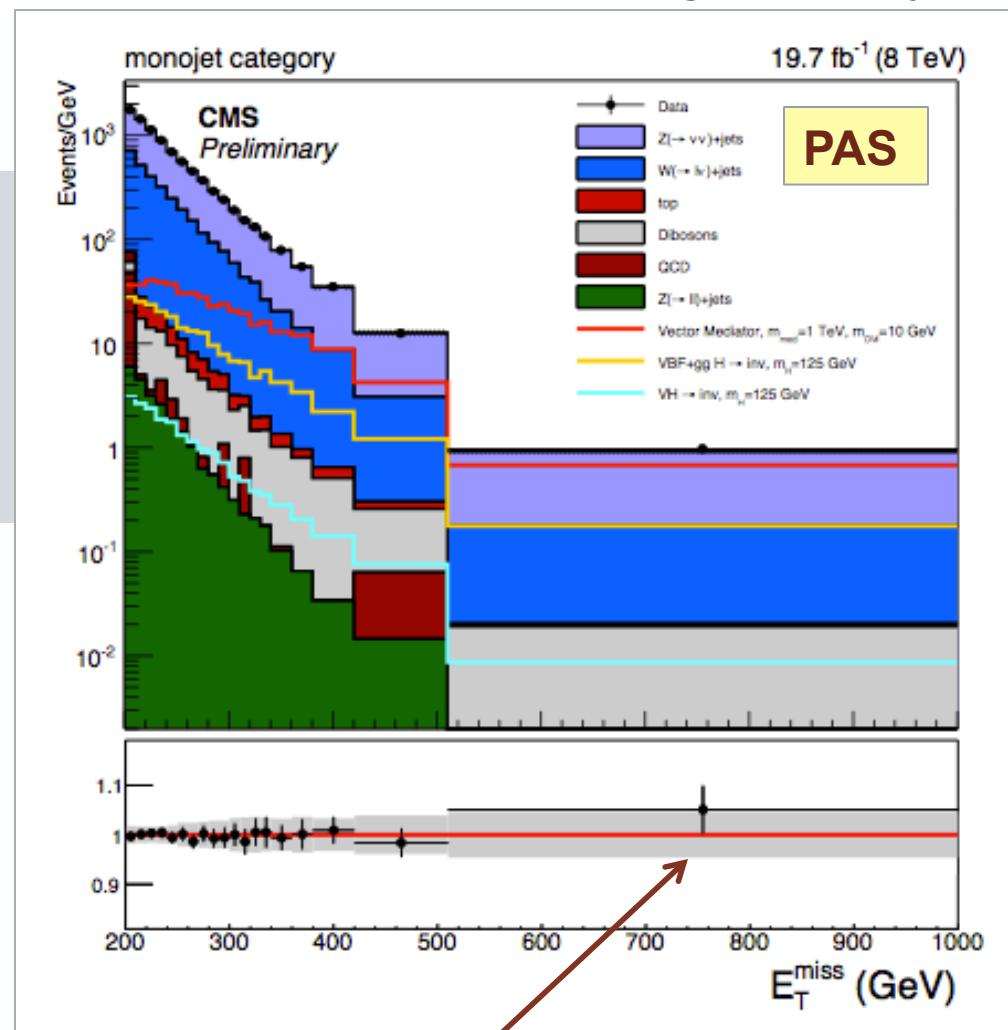


➤ Sensitive to H : **VH (light blue)** **VBF+gg (yellow)**

MET shape

- Monojet category
 - **Z'** [1TeV]
 - **VBF+ggH**
 - **VH**

background-only fit



- Largest excess: 1.9 sigma local significance
 - Highest MET bin in the monojet category

Results - reminder

Vector

$$g_{\text{DM}} Z'_\mu \bar{\chi} \gamma^\mu \chi$$

EWK style coupling
(equal to all leptons)

Axial

$$g_{\text{DM}} Z''_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$$

EWK style coupling
(equal to all leptons)

Scalar

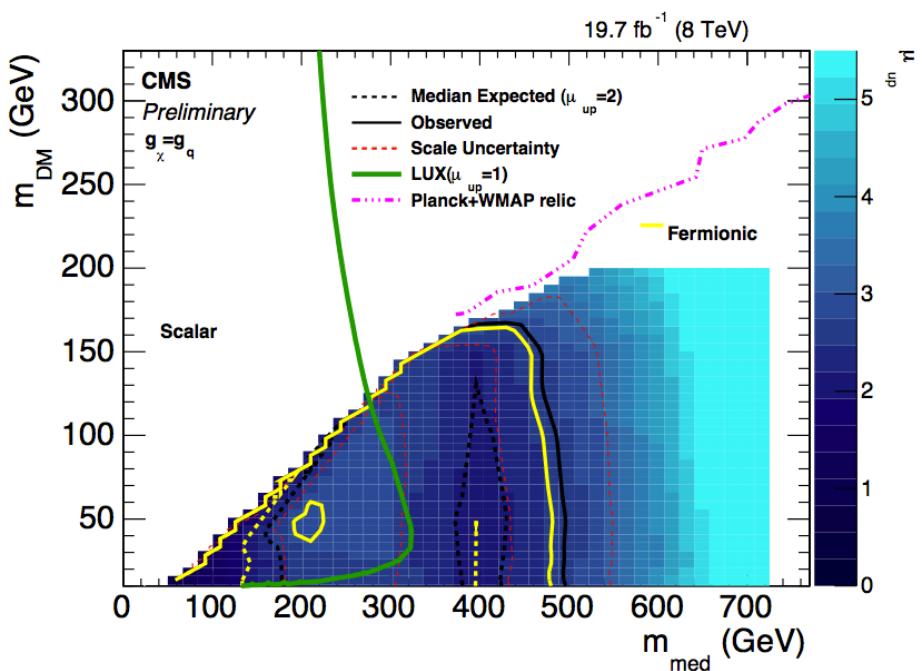
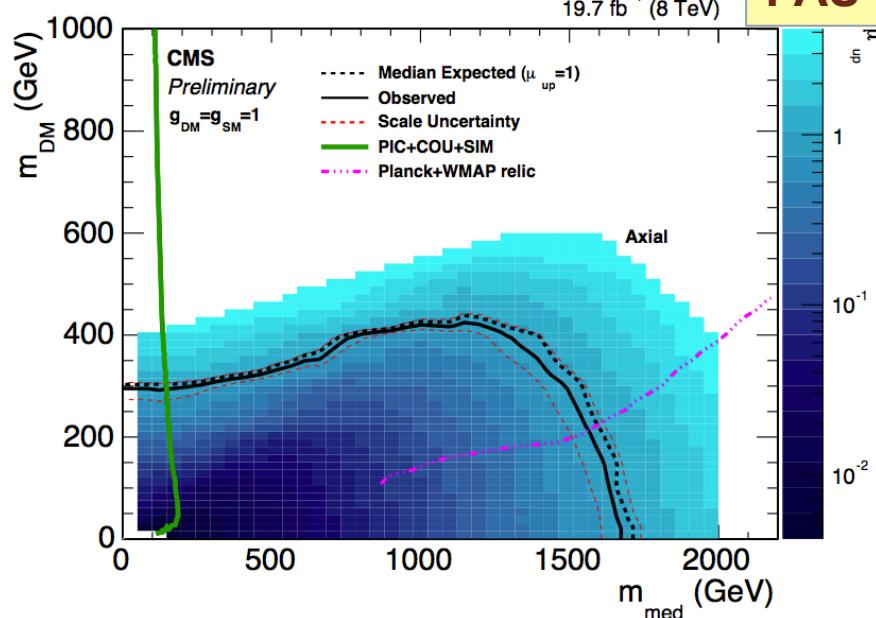
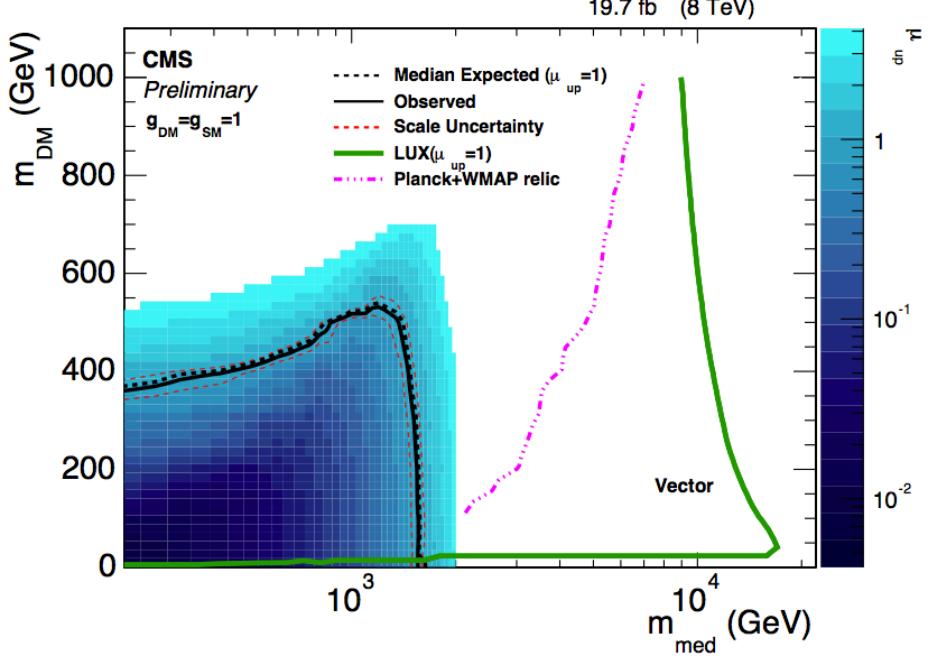
$$g_{\text{DM}} S \bar{\chi} \chi$$

Yukawa style coupling
(Mass based coupling)

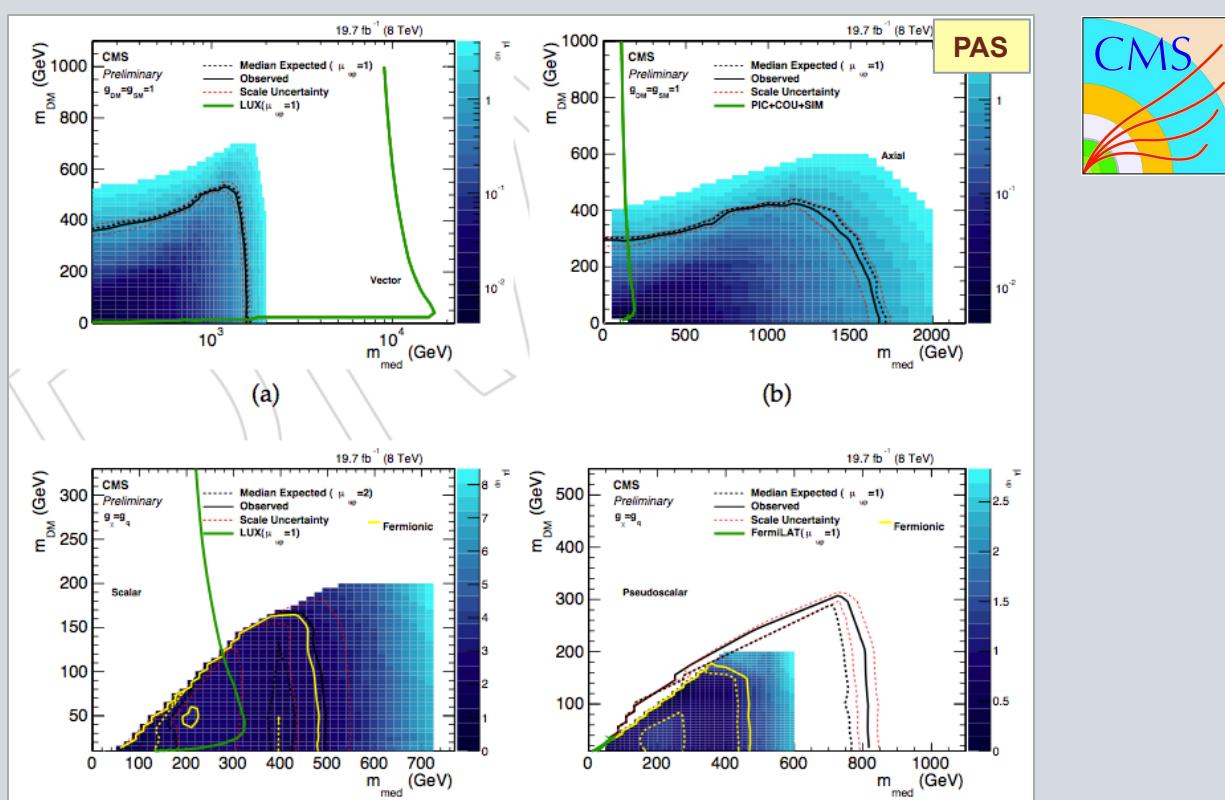
Pseudoscalar

$$g_{\text{DM}} P \bar{\chi} \gamma^5 \chi$$

Yukawa style coupling
(Mass based coupling)



Mediator constraints

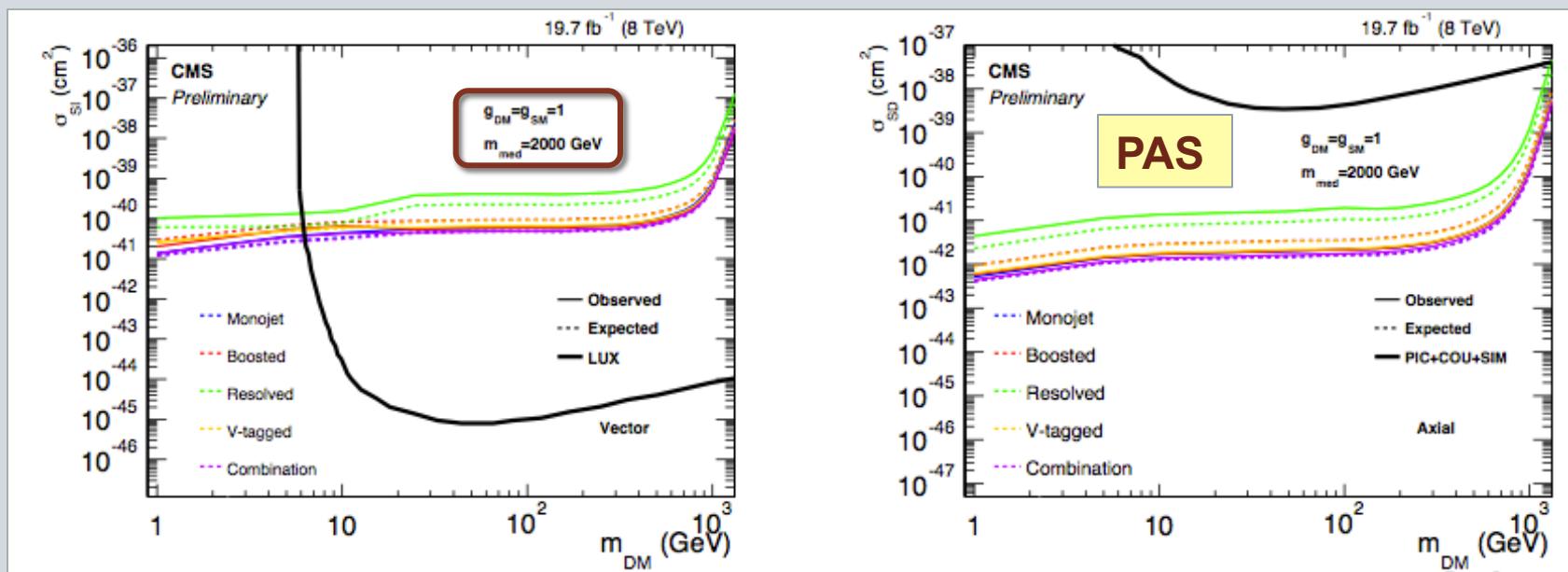


- Vector: CMS contributes at small M_{DM}
- Scalar: CMS & DD partially overlapping
- Axial&Pseudo: strongest constraints from CMS!

(σ, M_{DM}) constraints

- Vector (left) & Axial (right)
 - $M_\Phi = 2 \text{ TeV}$

V/A: $M_\Phi = 2 \text{ TeV}$

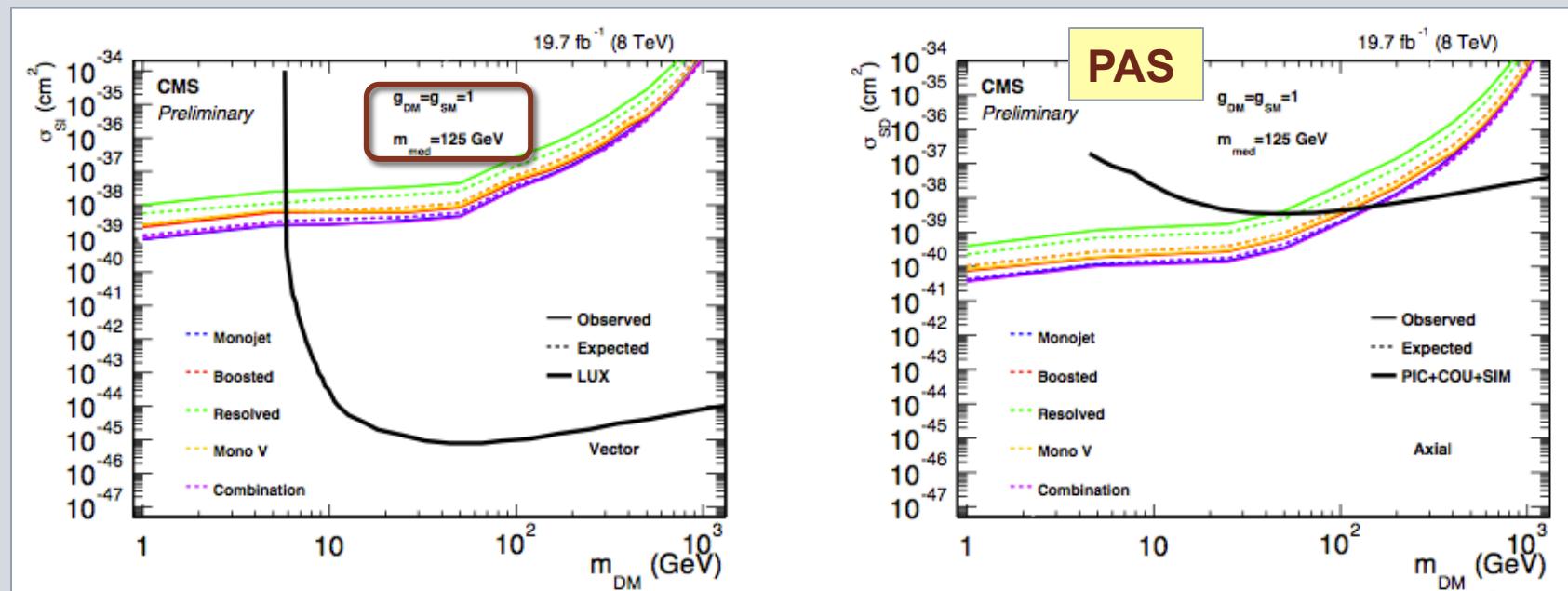


- Modified couplings in backup [$\xi=0,-1$]
- **CMS contributes significantly at small DM mass!**
 - Axial also at higher DM masses

(σ, M_{DM}) constraints

- Vector (left) & Axial (right)
 - $M_\Phi = 125 \text{ GeV}$

V/A: $M_\Phi = 125 \text{ GeV}$



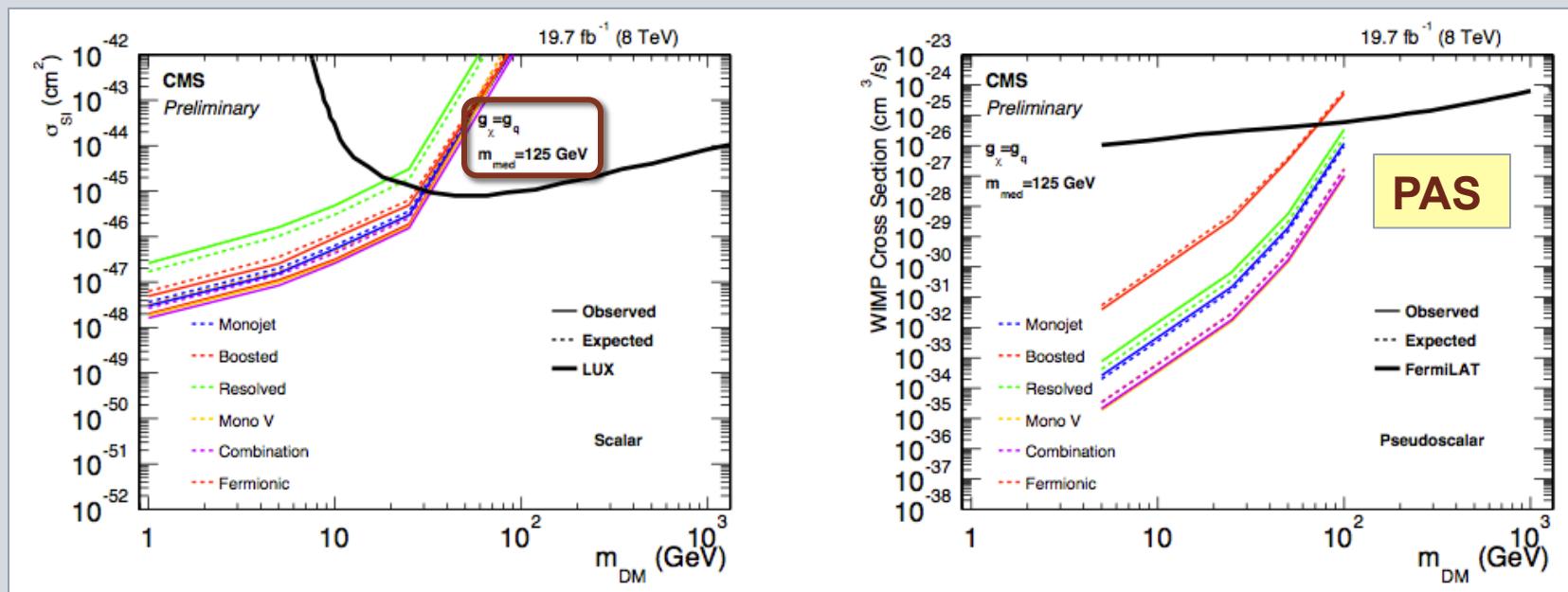
- Modified couplings in backup [$\xi=0, -1$]
- CMS contributes significantly at small DM mass
 - Axial also at higher DM masses

Φ^{125} constraint

➤ Scalar (left) and pseudoscalar (right)

- For $M_\Phi = 125$ GeV

S/P: $M_\Phi = 125$ GeV



➤ S&P: comparison to Direct Detection

➤ Significant complementarity CMS – in particular at small M_{DM}

H \rightarrow DM

“What if the H boson
is the SM-DM mediator?”

- H \rightarrow inv interpretation

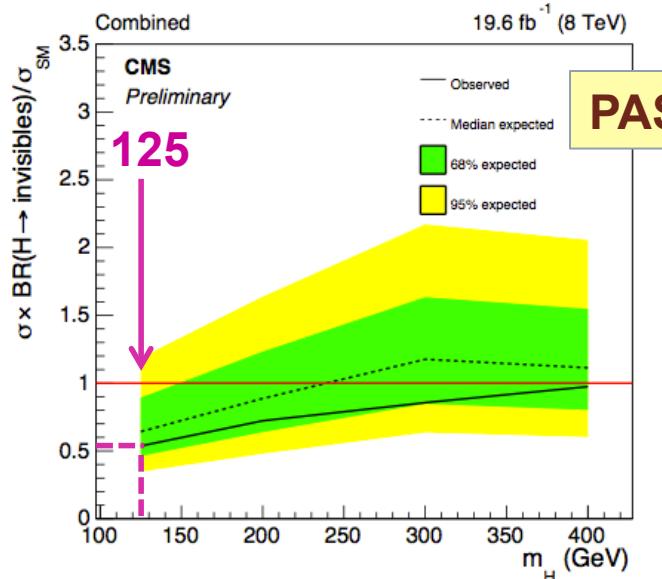
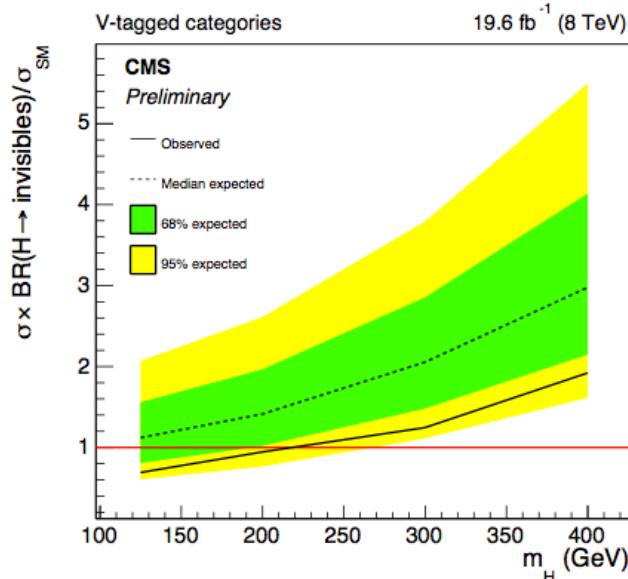


Figure 8: Expected (dashed) and observed (solid) upper limits on μ at the 95% CL as a function of the Higgs boson mass when combining the two V-tagged categories (left) and combining all three categories (right).

➤ Limit @ 125 GeV: $\sigma \times BR(H \rightarrow \text{inv}) / \sigma_{\text{SM-H}} < 0.53$ (0.62)

Comparisons of $H \rightarrow \text{inv}$

Older references:

- Z(l \bar{l})H [HIG-13-018]
- Z(bb)H [HIG-13-028]
- VBF [HIG-13-013]

Complementary constraints on $H \rightarrow \text{inv}$

- **Combination** [HIG-13-030]
 - Published: arXiv/1404.1344
 - Z(l \bar{l} +bb)H(inv): $\text{BR}_{H \rightarrow \text{inv}} < 81\% (83\%)$
 - VBF: $\text{BR}_{H \rightarrow \text{inv}} < 65\% (49\%)$
- **New VBF $H \rightarrow \text{inv}$** [CMS PAS HIG-14-038]: $\text{BR}_{H \rightarrow \text{inv}} < 57\% (40\%)$
- **Indirect constraints** [CMS PAS HIG-13-005]: $\text{BR}_{H \rightarrow \text{inv}} < 52\% (56\%)$
 - Fitting for Γ_{BSM}



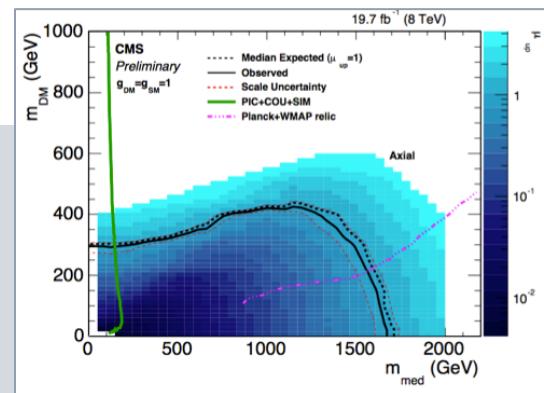
Combination of VBF+Z(l \bar{l} +bb)H:
 $\text{BR}_{H \rightarrow \text{inv}} < 58\% (44\%)$

Monojet [CMS PAS EXO-12-055]

- **Mono-V/j** : $\text{BR}_{H \rightarrow \text{inv}} < 53\% (62\%)$
 1. **Include V \rightarrow hadronic final state**
 2. **MET shape**
 3. **Use γ +jet**
 - More details on analysis improvements in backup

Conclusions

- New CMS DM results
 - Include MET+V: (boosted) **V-tagging**
 - Include simplified **mediator** models
- Improved background modeling
 - Several control regions - exploit large statistics **y+jet** final state
- No significant difference observed
 - **1.9 sigma** excess in most sensitive bin
- Interpretation
 - Comparison: **DD** vs **Relic** vs **LHC**
 - CMS is **complimentary**
 - H-boson interpretation **$\text{BR}(H \rightarrow \text{inv}) < 53\%$**

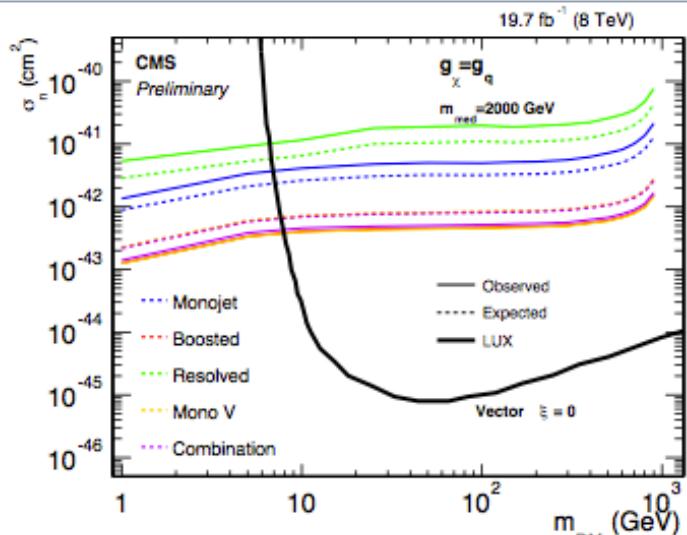


Backup

- **More results**
 - $\chi_i = 0, -1$
- **Signal fit**
- **Sensitivity breakdown**
 - Wrt previous monojet
- **H \rightarrow inv**
 - New combination
- **MadDM**
 - Motivation & explanation
- **Recoil method**
- **NLO**
 - Z+jet/ γ +jet
- **Samples/selection/yields**
- **More motivation**

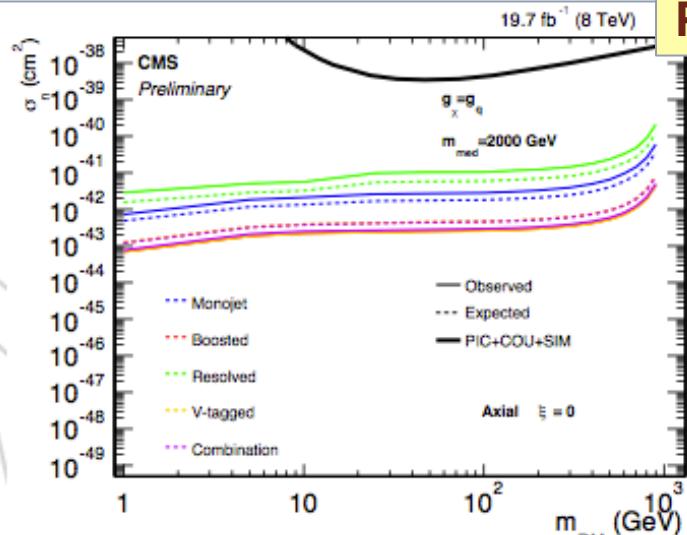
**Xi =
0,-1**

PAS

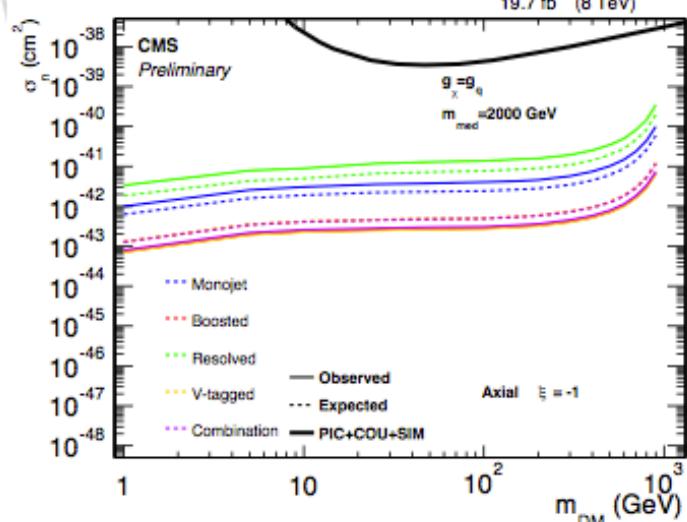
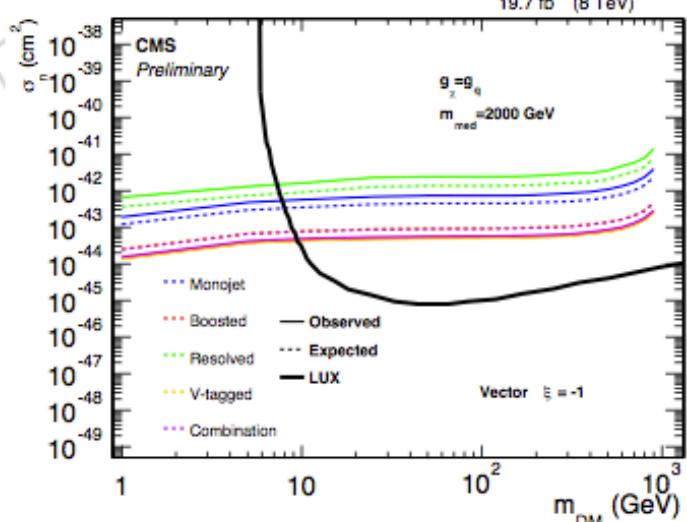


(c)

$M_{Z'} = 2 \text{ TeV}$



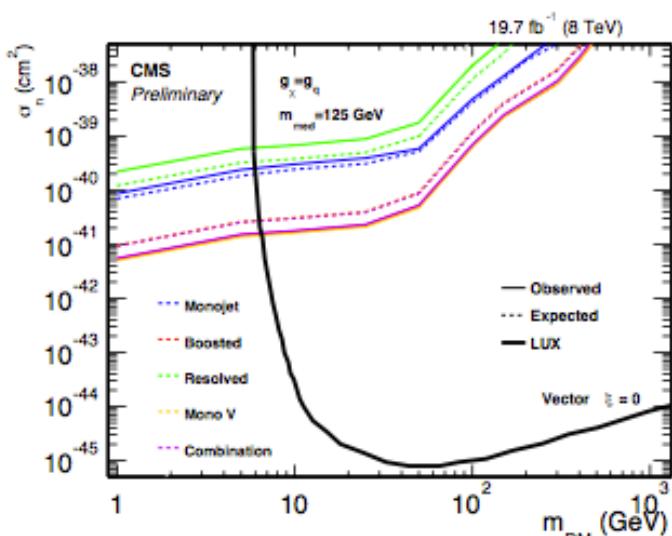
(d)



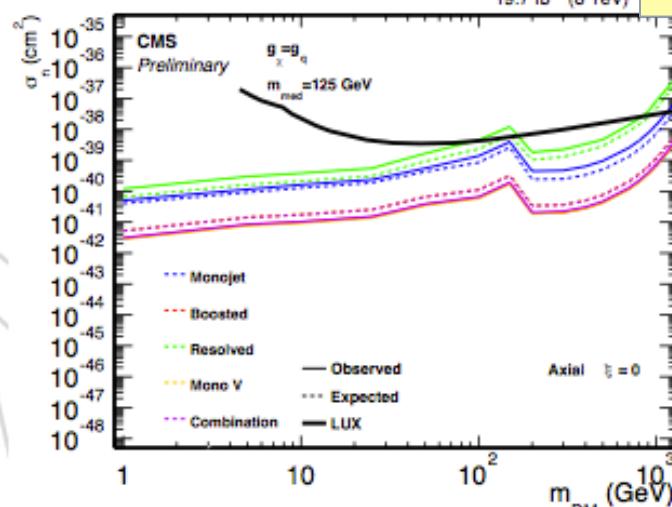
Mono-W enhanced → Monojet no longer dominant

**X_i =
0,-1**

PAS

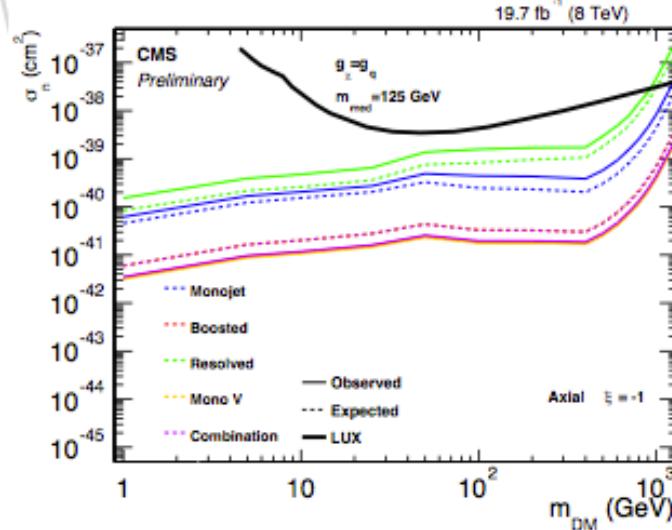
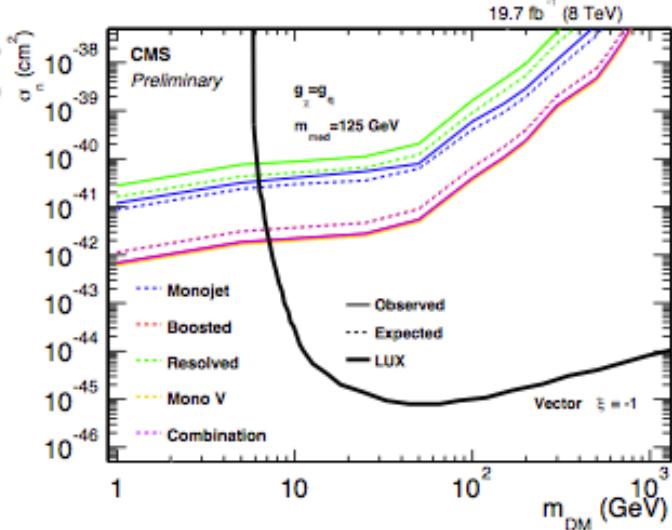


(c)



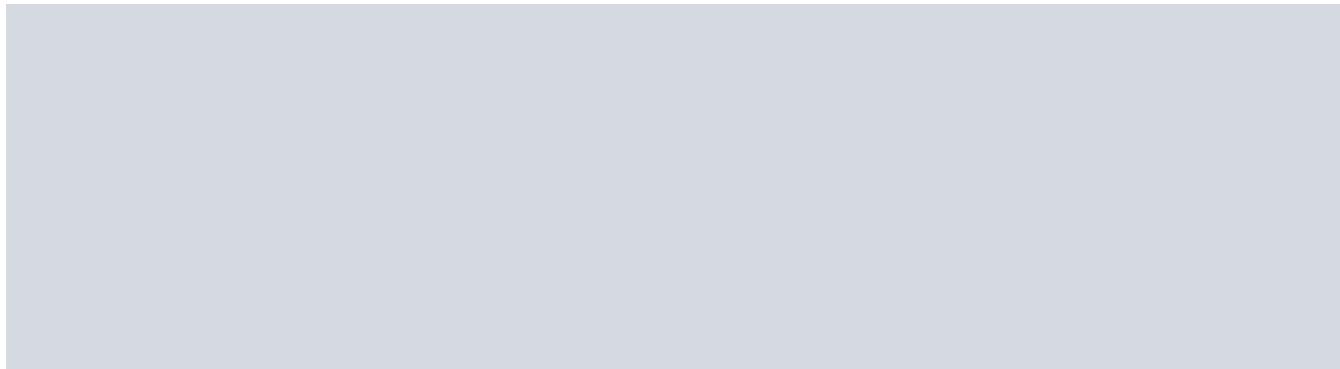
$M_{Z'} = 125 \text{ GeV}$

(d)



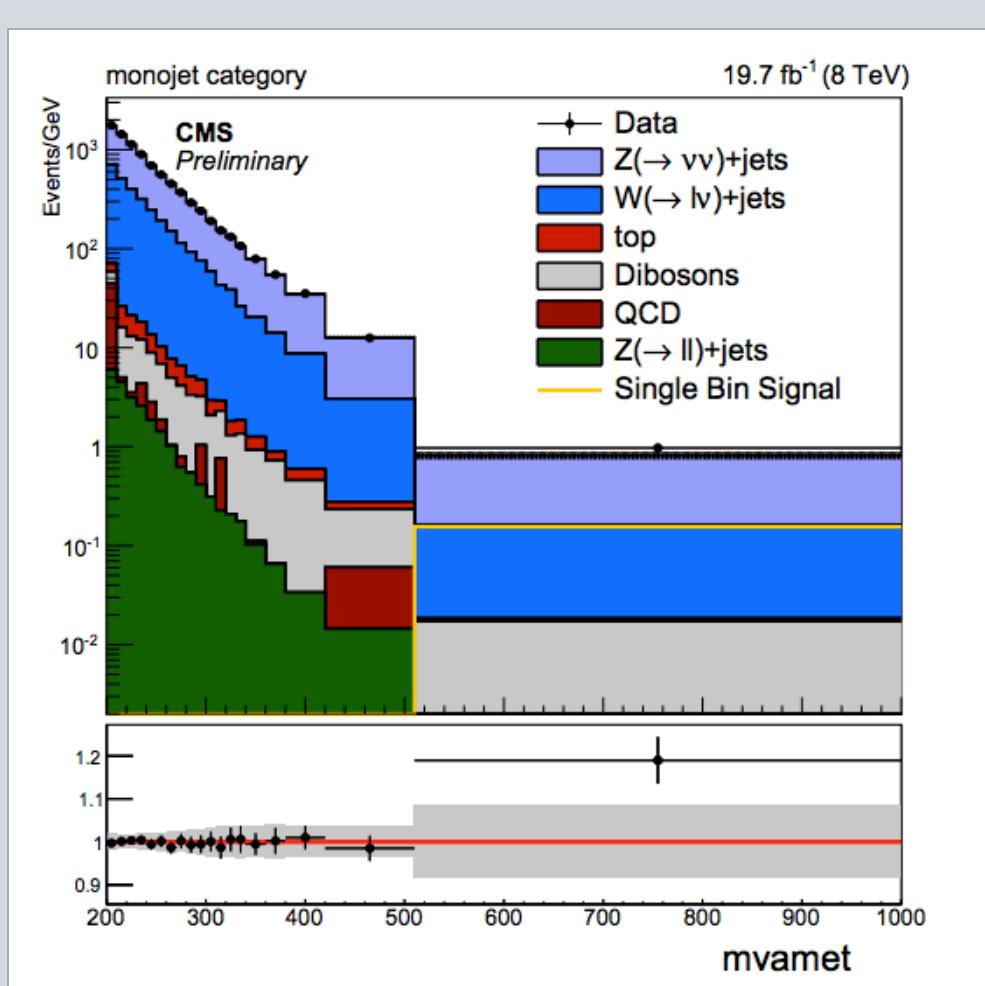
Mono-W enhanced → Monojet no longer dominant

SIGNAL FIT



Signal fit

- Signal fit
 - One bin



SENSITIVITY

Sensitivity comparison wrt old monojet

Selection & yields

Full breakdown

Comparing Old Analysis with New

- Consider monojet $MET > 500$ GeV for New:
 - Data : 535 Bkg : 473 ± 43 (prefit)
- Consider $MET > 500$ GeV for Old:
 - Data : 934 Bkg : 1040 ± 100
- Yields differ by factor of 2(+10% better unc.)
- Differences
 - Using pfMET raw in place of pfMET type 1
 - $METRaw @ 500 = MET\ type1 @ 540$ GeV
 - $Z \rightarrow \nu\nu$ goes from 690 to 486 switching $METs$
 - The tau veto is much stronger in the new monojet
 - This reduces the W+jets background
 - Absolute uncertainty is smaller than old analysis

Comparing Realistic Scenario²

Old $MET > 550$ GeV

E_T^{miss} (GeV) \rightarrow	>550
$Z(\nu\nu)+\text{jets}$	362 ± 64
$W+\text{jets}$	123 ± 13
$t\bar{t}$	2.8 ± 1.4
$Z(\ell\ell)+\text{jets}$	1.0 ± 0.5
Single t	—
QCD multijets	0.5 ± 0.3
Diboson	20 ± 10
Total SM	509 ± 66
Data	519

New $MET > 500$ GeV & boost veto

Expected Yields	Monojet ($E_T^{\text{miss}} > 500$ GeV)
$Z(\rightarrow \nu\nu)+\text{jets}$	381.8 ± 41.0
$W(\rightarrow l\nu)+\text{jets}$	81.1 ± 12.5
Dibosons	9.2 ± 0.9
top	0.9 ± 0.1
$Z(\rightarrow ll)+\text{jets}$	0.3 ± 0.001
QCD	0.0 ± 0.0
Total Backgrounds	473.0 ± 42.9
Data	535

$\gamma+\text{jets}$

T veto

- Correcting for MET (> 550 for old > 500 for new)
 - Observe yields in close agreement
 - $W+\text{jets}$ is lower by 50% (due to T veto)
 - $Z+\text{jets}$ has a 50% lower uncertainty (due to $\gamma+\text{jets}$)
- Final result gives pre-fit unc. that is 50% lower
 - Note signal yield is about 10% higher due to MET

How does the result change

- Low Mass (125 GeV Scalar):
 - $5.1(\text{Old}+MET>500) \rightarrow 4.5(\text{New}+\gamma+\text{jets}) \rightarrow 2.4(+\text{shape}) \rightarrow 0.8(+\text{VH})$
- Medium Mass (925 GeV Scalar) $\times 10^3$:
 - $10.8(\text{Old}+MET>500) \rightarrow 6.5(\text{New}+\gamma+\text{jets}) \rightarrow 3.6(+\text{shape}) \rightarrow 3.4(+\text{VH})$
- High Mass(1925 GeV Vector):
 - $8.6(\text{Old}+MET>500) \rightarrow 3.8(\text{New}+\gamma+\text{jets}) \rightarrow 2.1(+\text{shape}) \rightarrow 2.1(+\text{VH})$
- Rules of thumb :
 - New analysis and $\gamma+\text{jets}$ bring factor of 1.2-2
 - Largest improvement comes in the tail
 - Shape brings factor of 1.8 across the board
 - VH brings a factor of 1-2 improvement
 - Gains come at the low mass region

MADDM

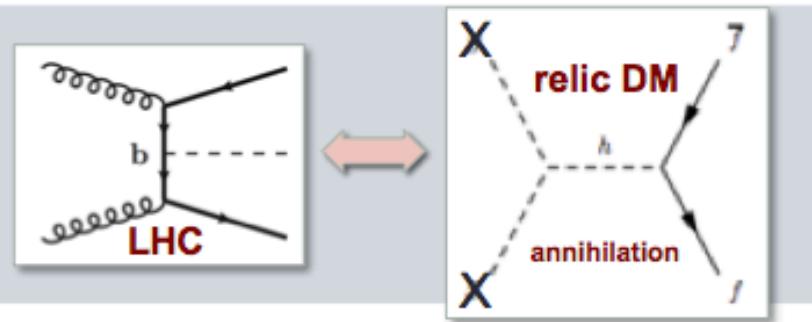
Motivation

Functionality

Explanation

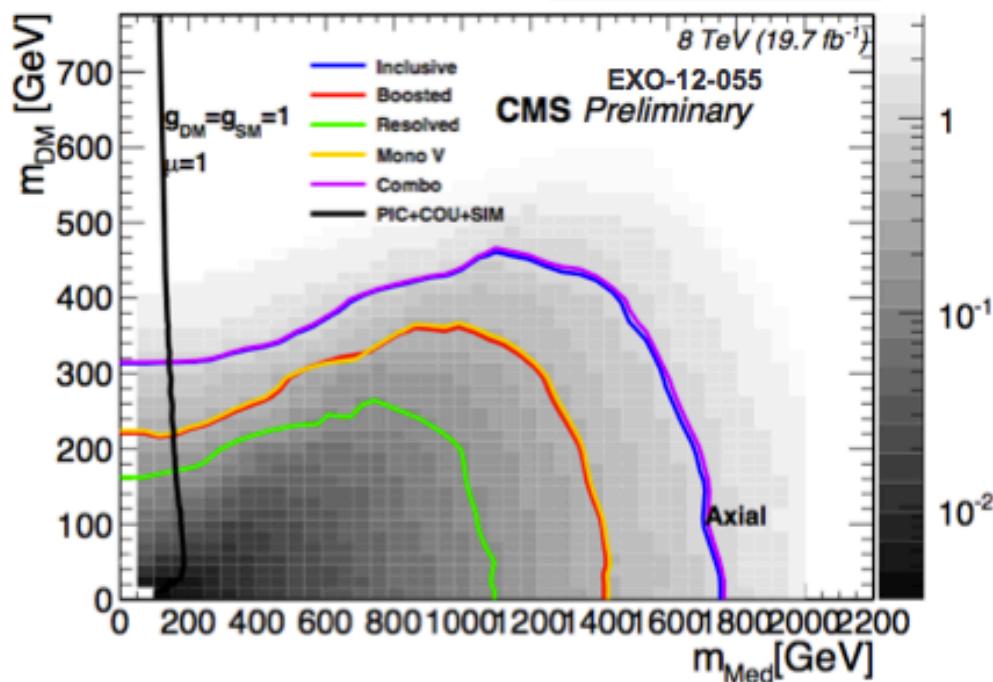
Motivation

- **Cosmological interpretations**
 - S&P&V&A mediators
 - MadGraphs models
 - Using MadDM



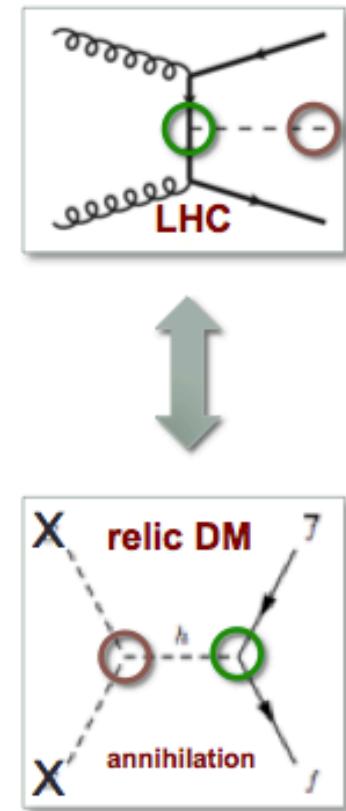
- **MadDM**
 - Relic density for LHC models
 - Annihilation $XX \rightarrow \text{Med} \rightarrow \text{SM}$
 - Ω_{DM} complementary to CMS

- **Today:** add this constraint to our CMS searches!
 - **Planck+WMAP:**
 $\Omega^* h^2 \sim 0.11$



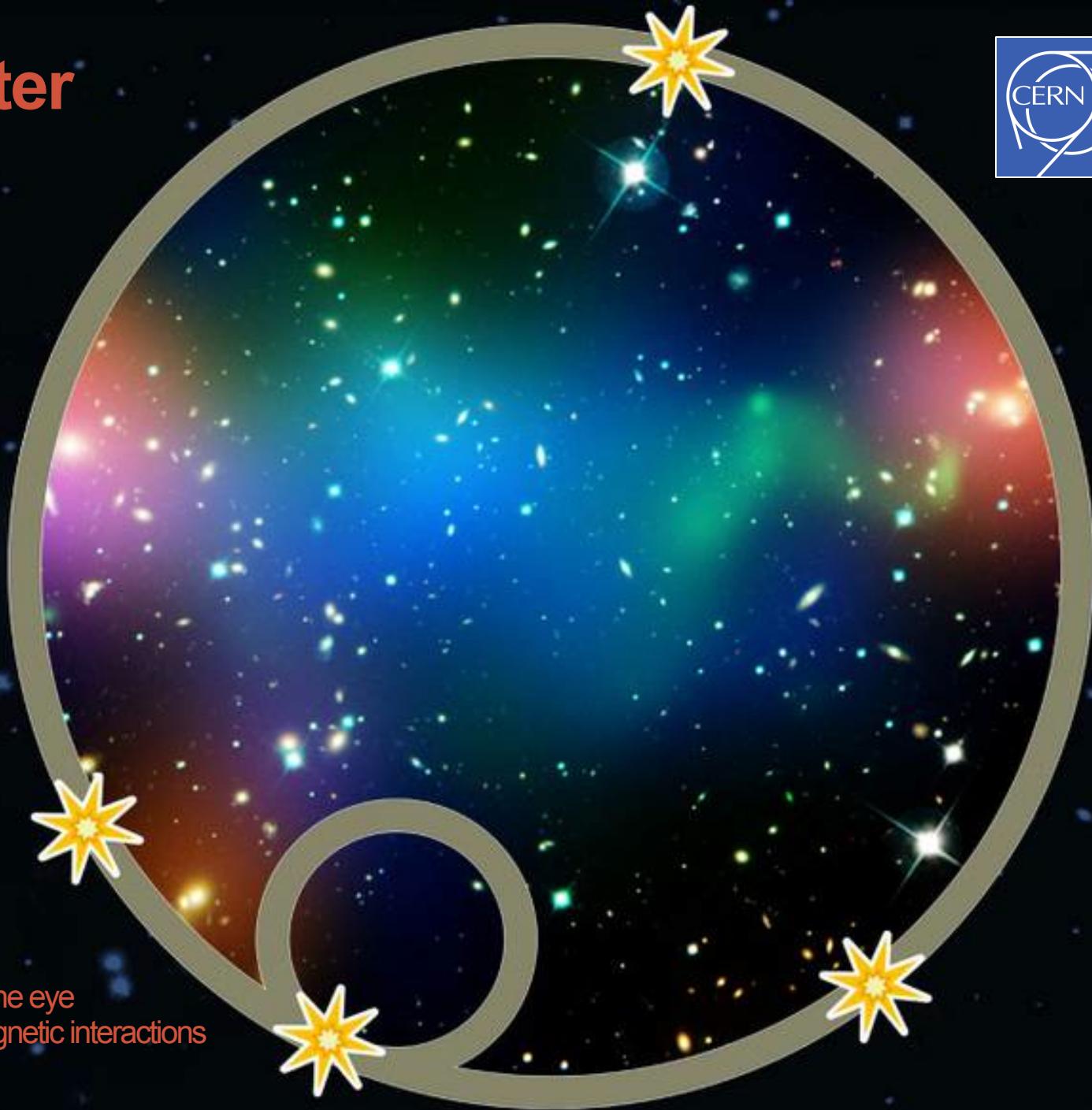
Our interpretation

- Quite complementary between LHC & cosmos
 - For all models. In particular **Pseudo&Axial**
- Heuristic argument:
 1. Large couplings
 - **Good LHC sensitivity**
 - Large annihilation, so small relic DM
→ **Loose cosmological constraints!**
 2. Small couplings
 - **Poor LHC sensitivity**
 - Small annihilation, so large relic DM
→ **Tight cosmological constraints!**
- **Same vertices!**



- So, some complementarity is expected!
 - Details are model dependent, for which now **we have the tools!**

Dark Matter



- Astro: invisible for the eye
- LHC: no electromagnetic interactions