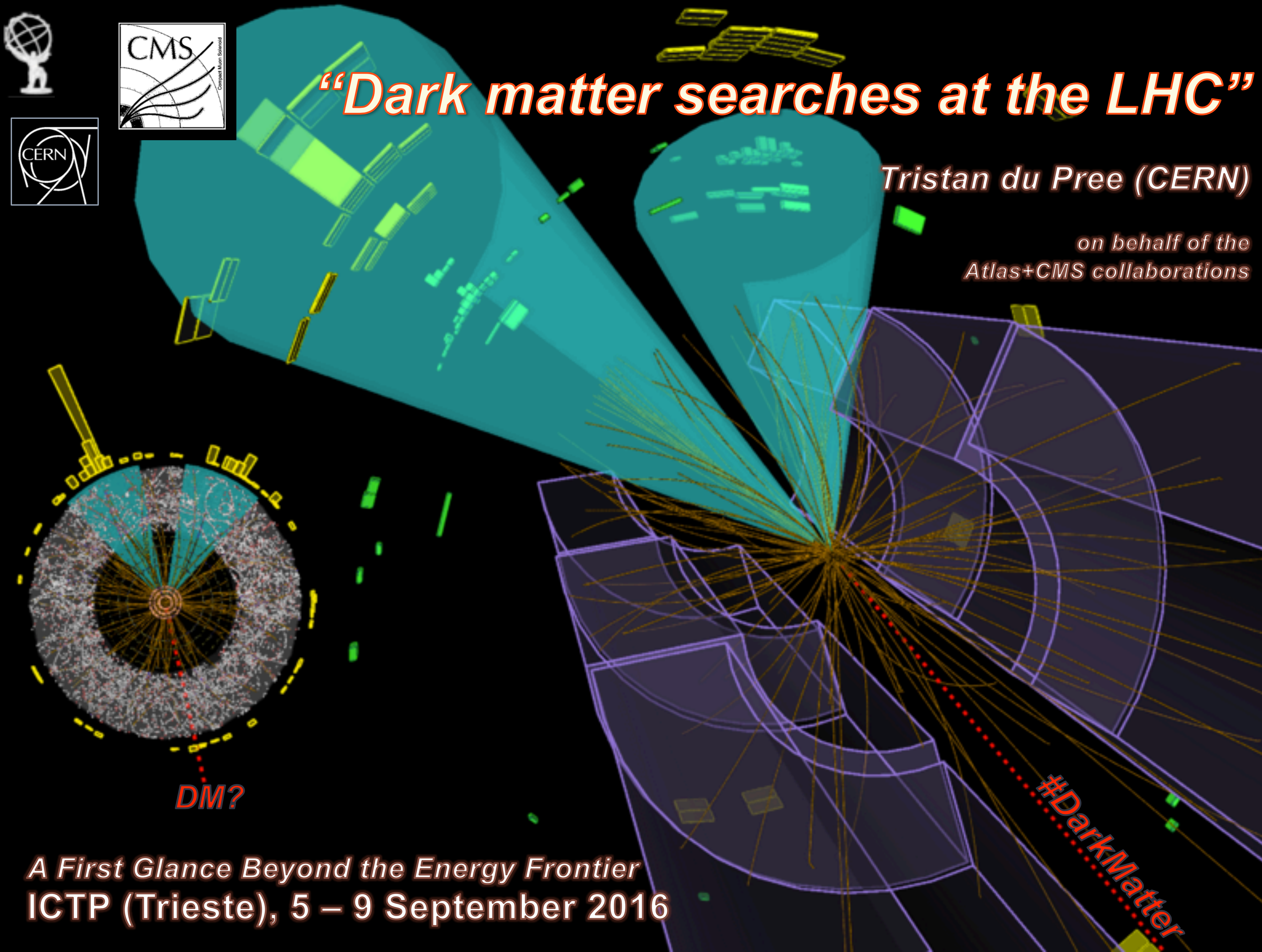
"Dark matter searches at the LHC"

Tristan du Pree (CERN)

on behalf of the
Atlas+CMS collaborations



A First Glance Beyond the Energy Frontier

ICTP (Trieste), 5 – 9 September 2016

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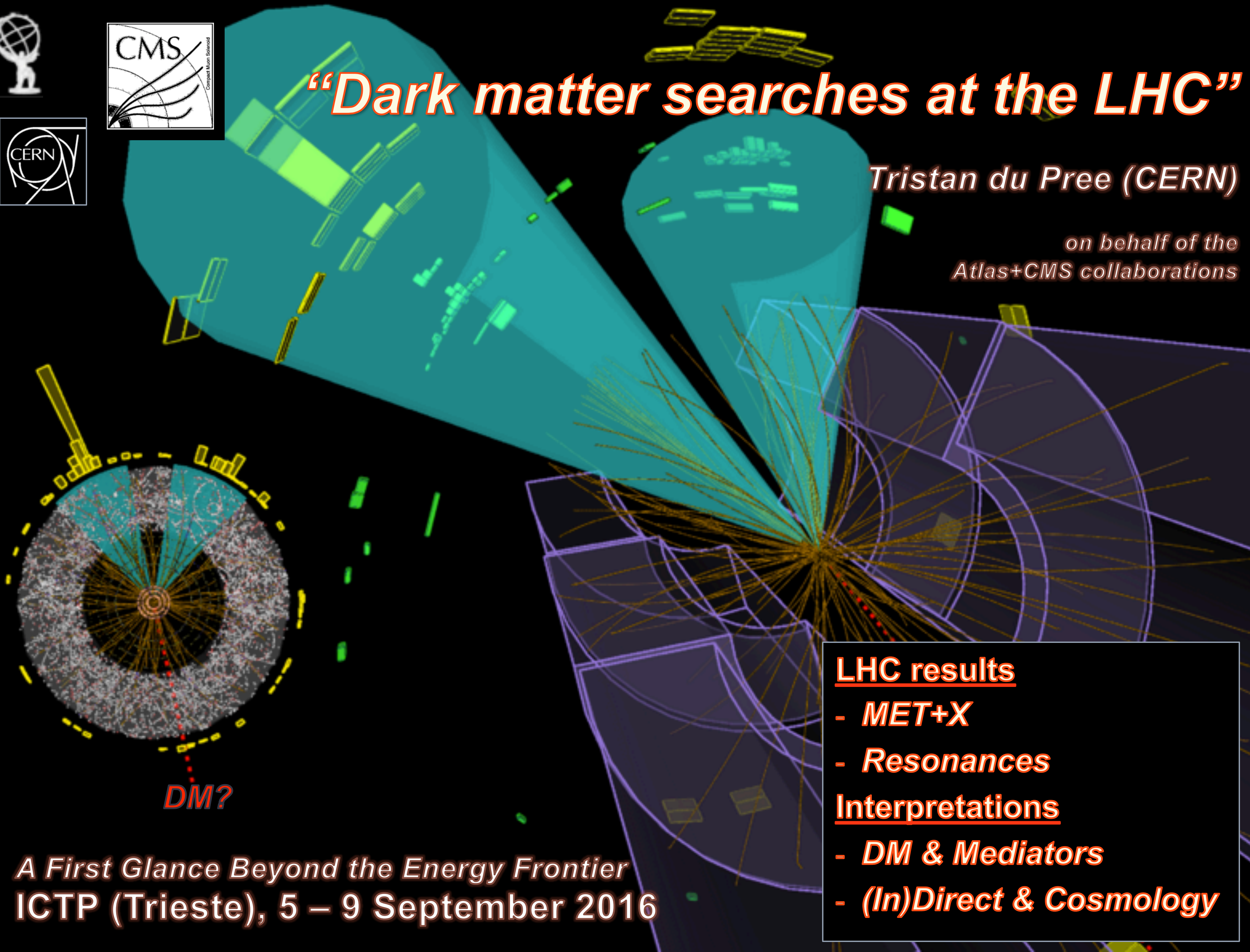
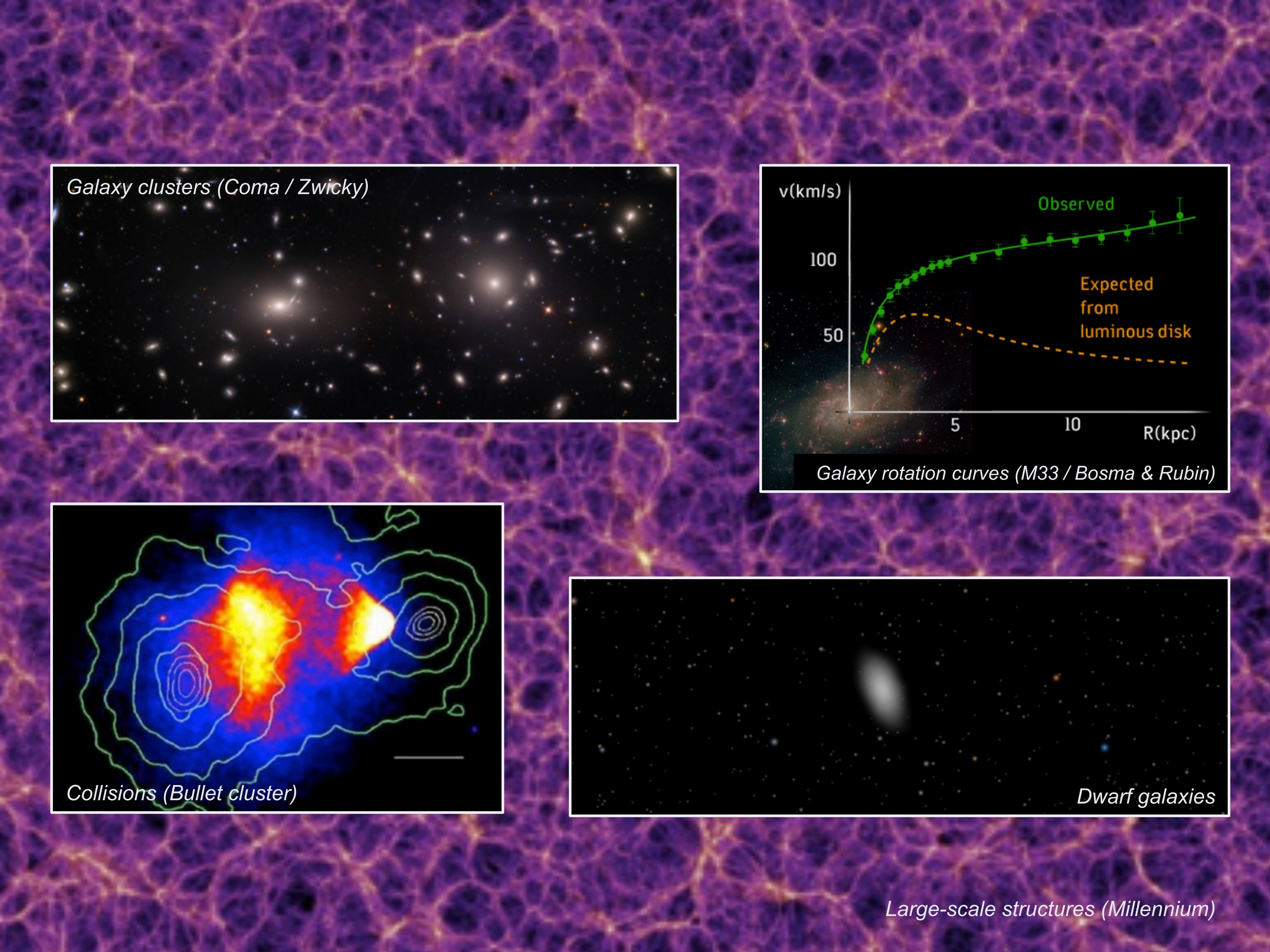


LHC results
- *MET+X*
- *Resonances*

Interpretations
- *DM & Mediators*
- *(In)Direct & Cosmology*

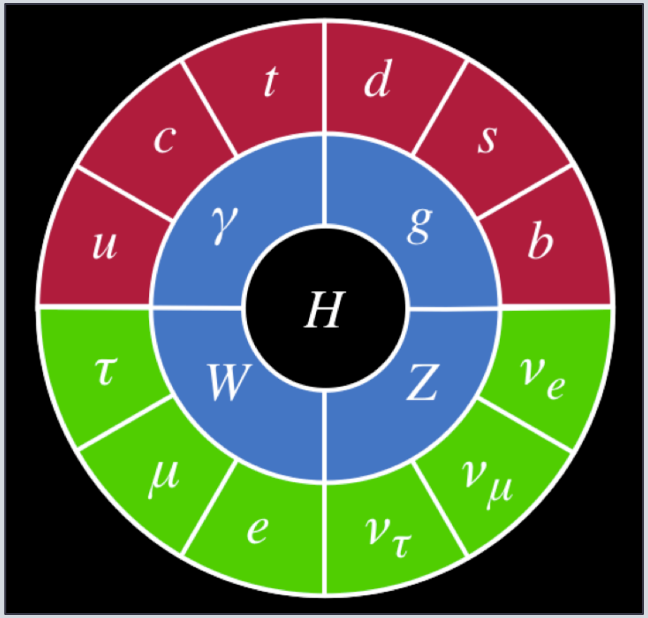
A First Glance Beyond the Energy Frontier
ICTP (Trieste), 5 – 9 September 2016

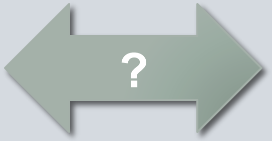


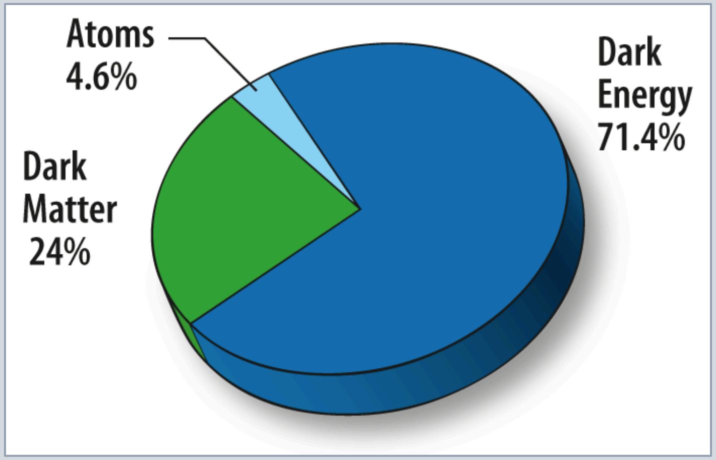
Galaxy clusters (Coma / Zwicky)
v(km/s)
Observed
100
Expected
from
luminous disk
50
5
10
R(kpc)
Galaxy rotation curves (M33 / Bosma & Rubin)
Collisions (Bullet cluster)
Dwarf galaxies
Large-scale structures (Millennium)

BSM

After LHC Run-1







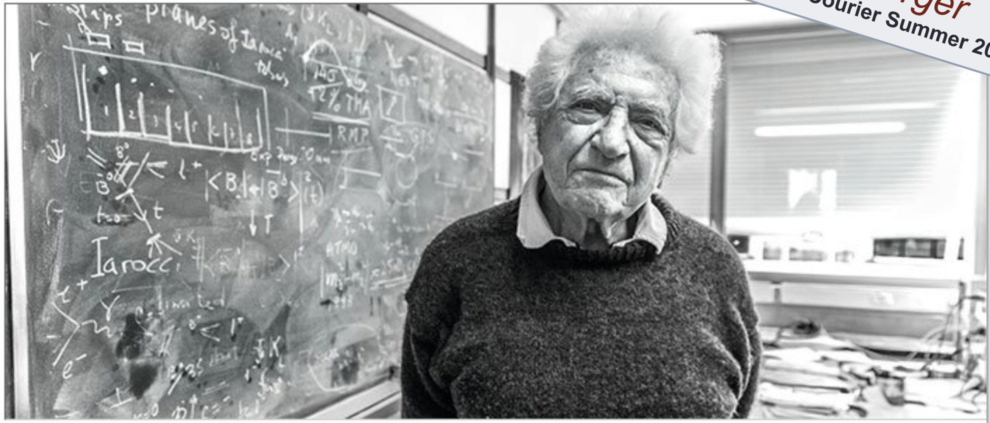
- **DM appears at various astrophysical scales**
  - But particle nature unclear - **we don't know what it is!**
  - Search with **Direct Detection** + **Indirect Detection** + **LHC**!

Experiment & theory

J.Steinberger
CERN Courier Summer 2016

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."



Jack Steinberger photographed in his office at CERN in 2016.

G.Altarelli
arXiv:1407.2122

from the sky, like Dark Energy, DM, baryogenesis and neutrino m... the picture repeatedly suggested by the data in the last 20 years is sim... 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

I.

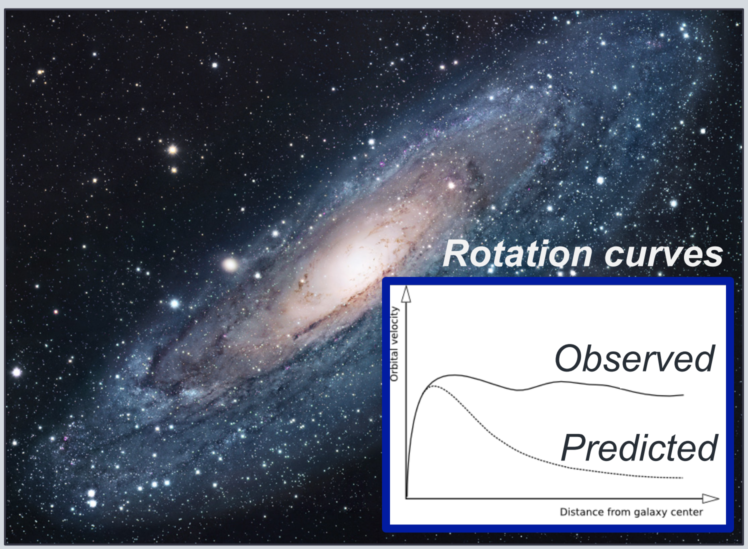
Run-1 mono-jet

one detailed example

Dark Matter

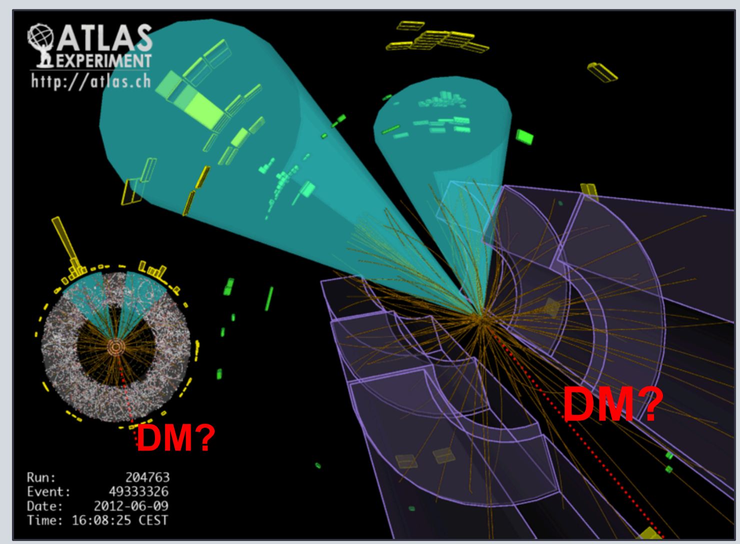
Astronomy

- **Observation in Space**
  - **Gravitational** evidence
  - Galaxy rotation curves



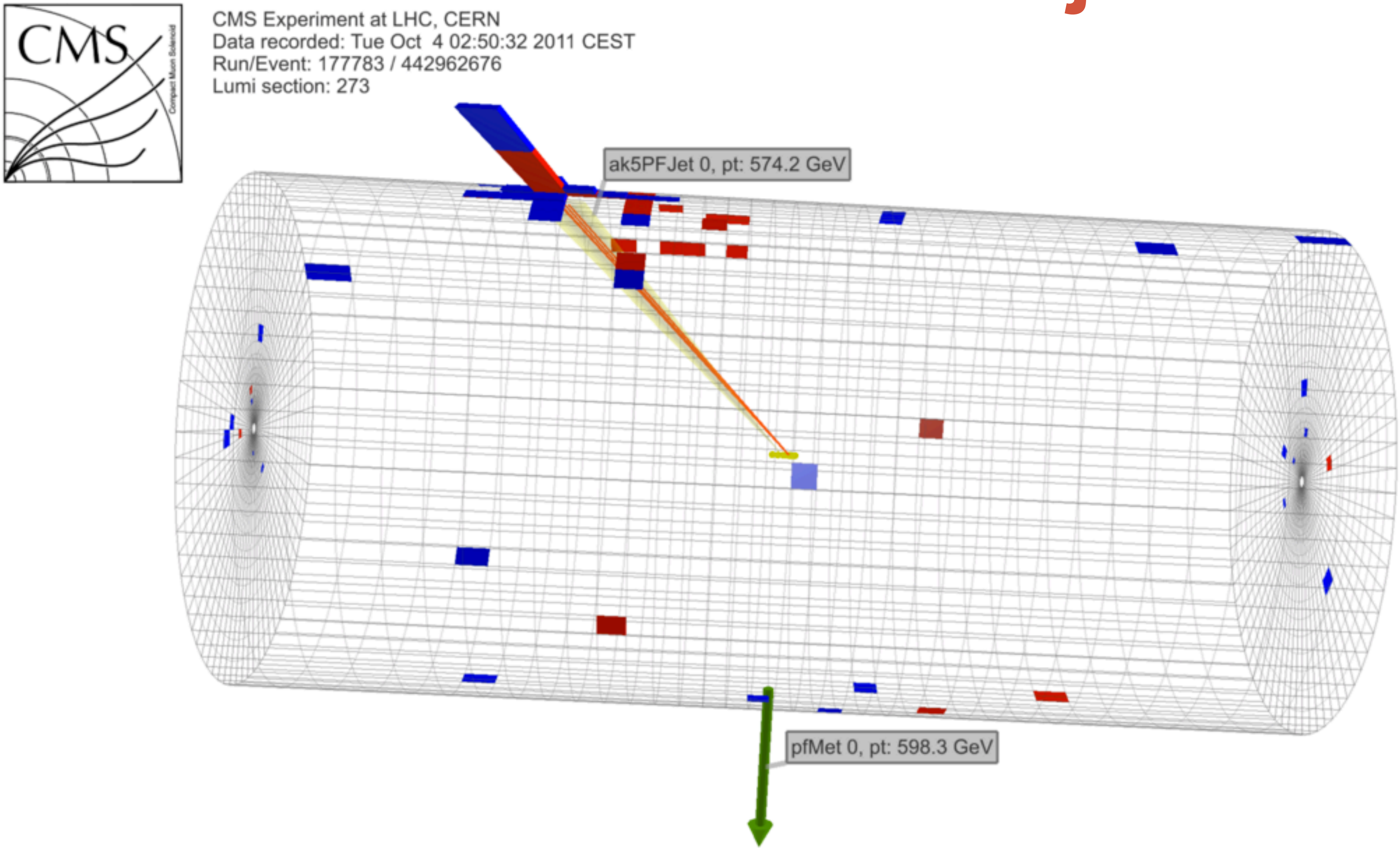
LHC @ 13 TeV

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

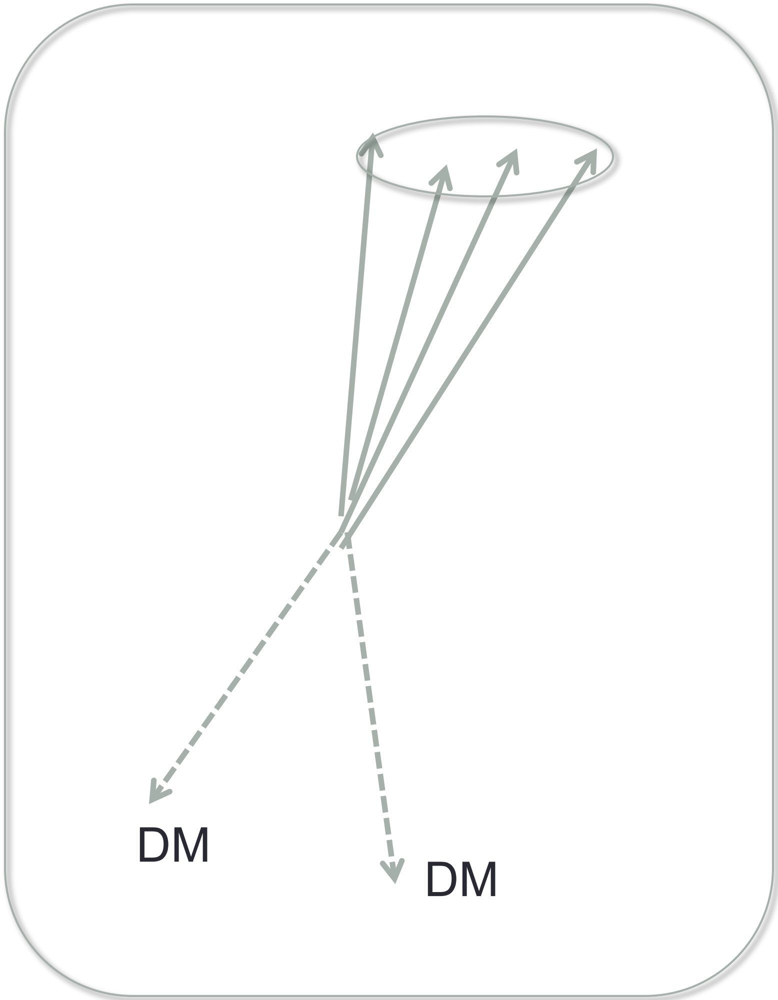


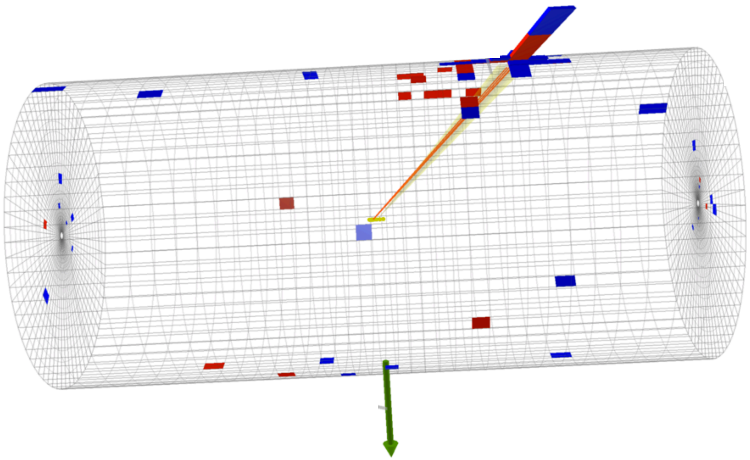
LHC SUSY searches: ***C.Rogan*** *[yesterday]*

Monojet event

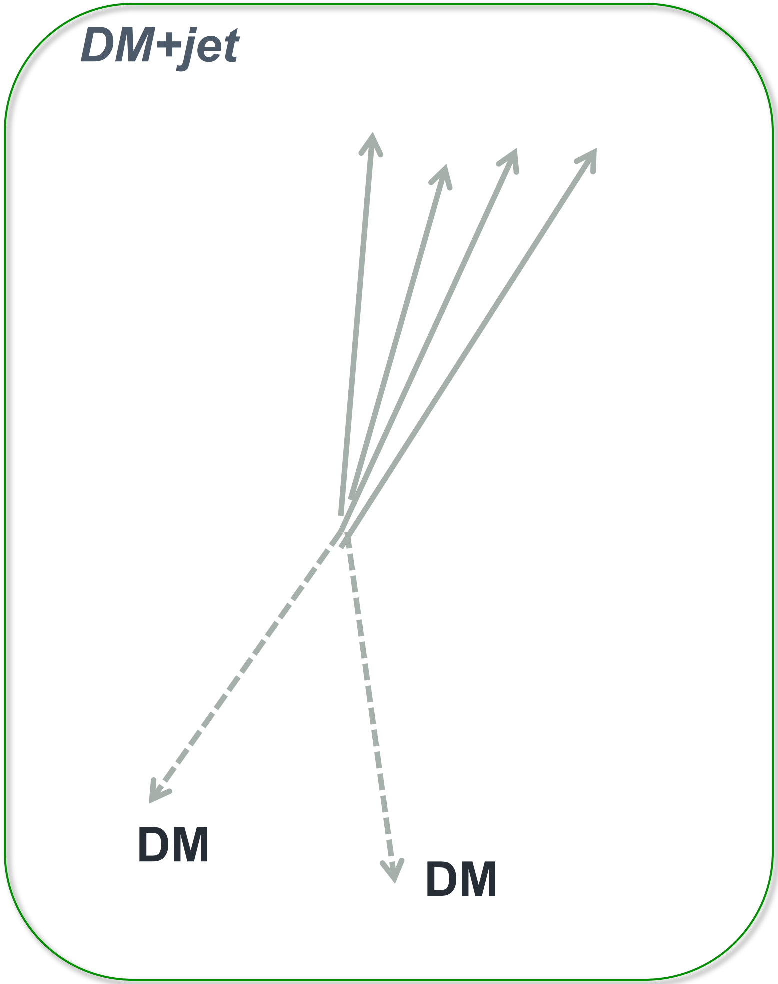


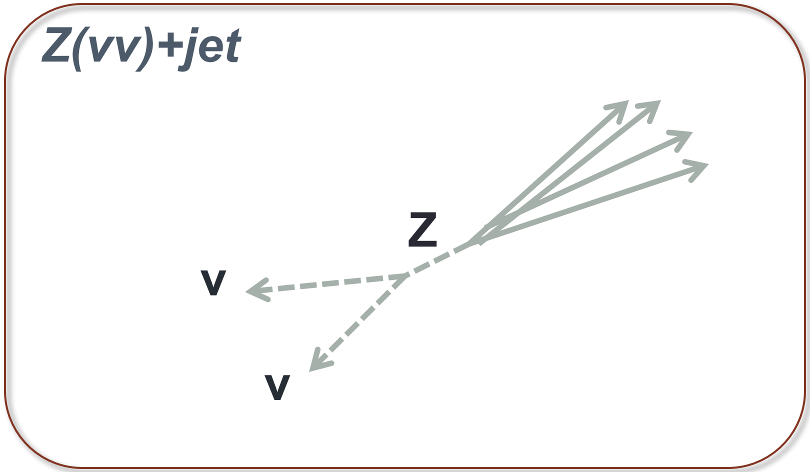
Monojet signal

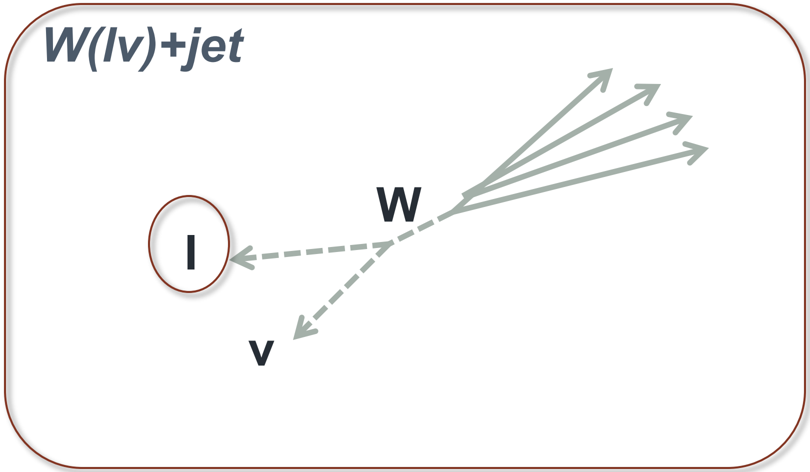




Main backgrounds: V+jets







Selection

CMS PAS EXO-12-055

MET

- 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

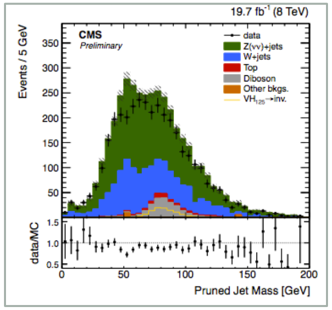
MET+JET

Event topology

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

Event categorization

1. **Monojet**
2. **Boosted V**
3. **Resolved V**



EVENT

CR (*μ+γ*)

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

Vetoes (*j+μ+γ+e+τ*)

- ***#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

CONTROL

Selection

Event topology

- **ΔΦ(j_1,MET)** > 2.0
- **ΔΦ(j_1,j_2)** < 2.0
  - If **#jets=2**
  - For **ISR** [bec

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

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

- Default jets: **AK5** PF jets
- |η| < 2.5 & p_T >30
- Require PFJetId loose & PUJetID loose

CR (*μ+γ*)

- *μ*: |η|<2.1 & p_T > 10 & POGTightID
- *γ*: |η|<2.5 & p_T > 160 & EGammaID medium

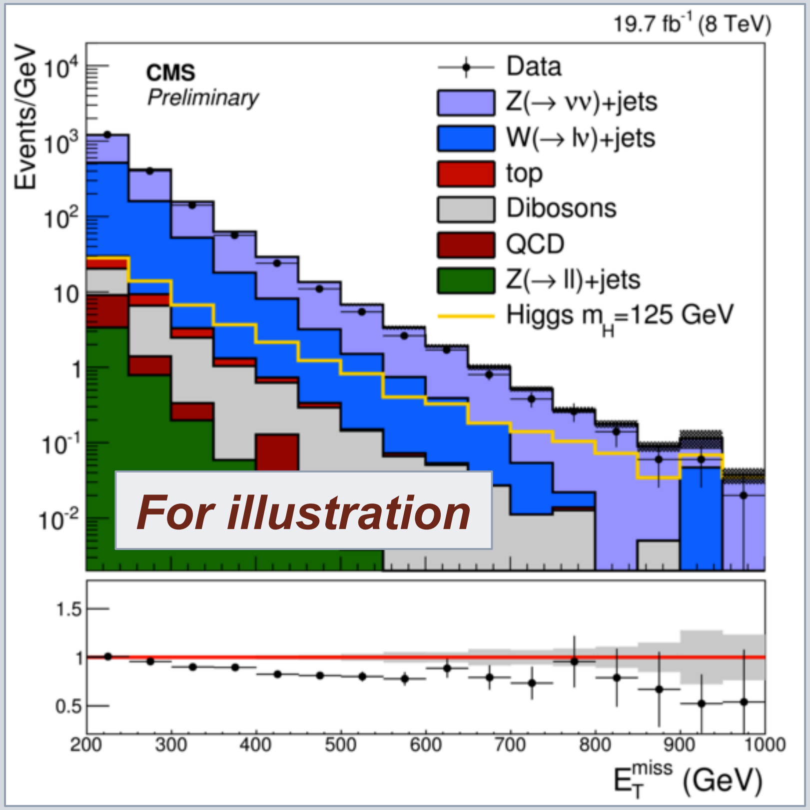
Vetoes (*j+μ+γ+e+τ*)

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

Data vs sim

Out-o/t-box

- 3 categories combined



- Default **simulation** of Z+jets & **MET resolution**

Strategy

Main challenges

- **Reconstruction**
  - MET
- **Theory**
  - NLO
- **Control statistics**
  - Z(μμ):Z(νν) = 1:6

Other exp. eff. corr

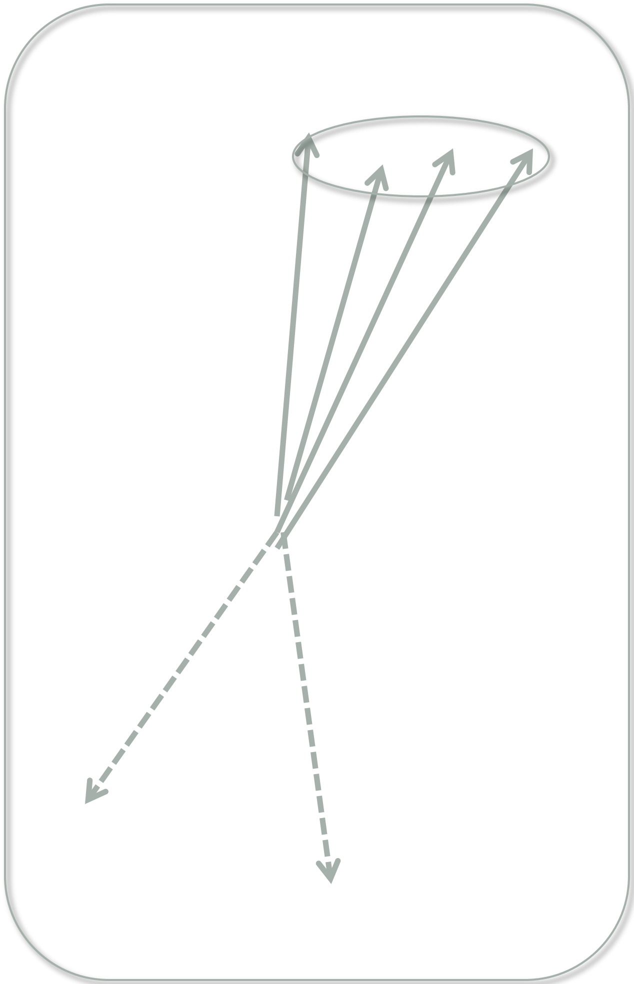
- **Trigger**
- **Vetoes**
  - Electron & Muon
  - Tau *[largest veto unc]*

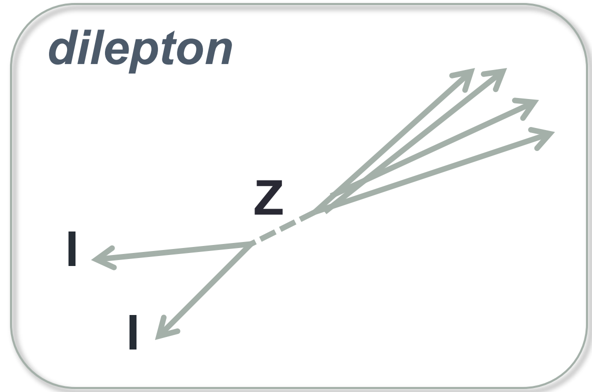
Solution

- **V+jets CRs: 1-μ + 2-μ + γ**
  - W+jets + Z+jets and γ+jets
- **Fake MET = recoil**
  - Sum over visible leptons
    - Use as a proxy for MET

CMS MET reconstruction performance: *http://arxiv.org/abs/1502.05207*
First recoil corrections in CMS MET paper: *http://arxiv.org/abs/1012.2466*

SR vs CR

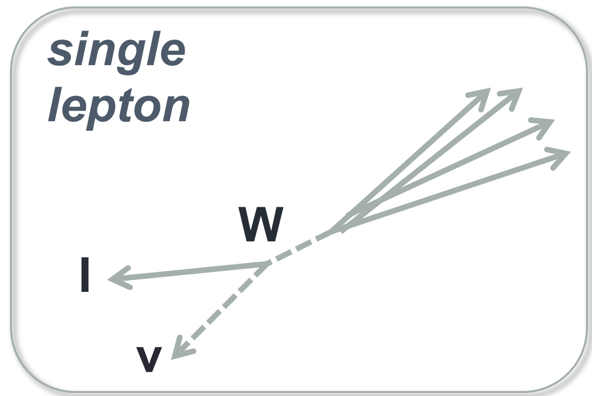




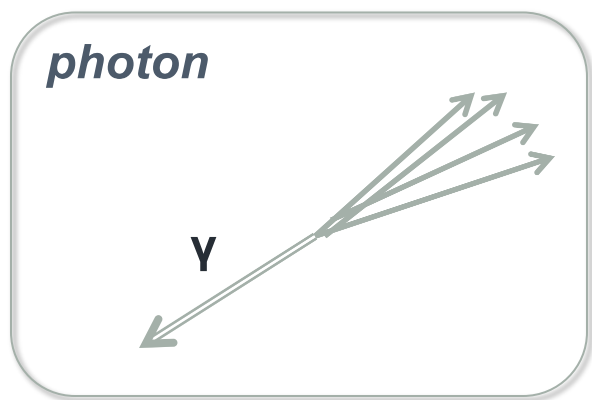
Z(μμ)+jets

➔Recoil

But μμ/vv = 1/6



W(uv)+jets



γ+jets

➔ Z/γ

V+jets fit

- **Control regions** with correction factor **R**

$$N_i^{Z_{\mu\mu}|\gamma} = \frac{\mu_i^{Z\to\nu\nu}}{R_i^{Z|\gamma}} \qquad N_i^{W} = \frac{\mu_i^{W\to l\nu}}{R_i^{W}}$$

- **Simultaneous fit** in SR and CR – *[yield μ]*
  - **BR & eff** per **bin/category**
    - *[theo/exp nuisances (ϑ,φ)]*
- **Differential** *[NLO k-factor for p_T(V)]*

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

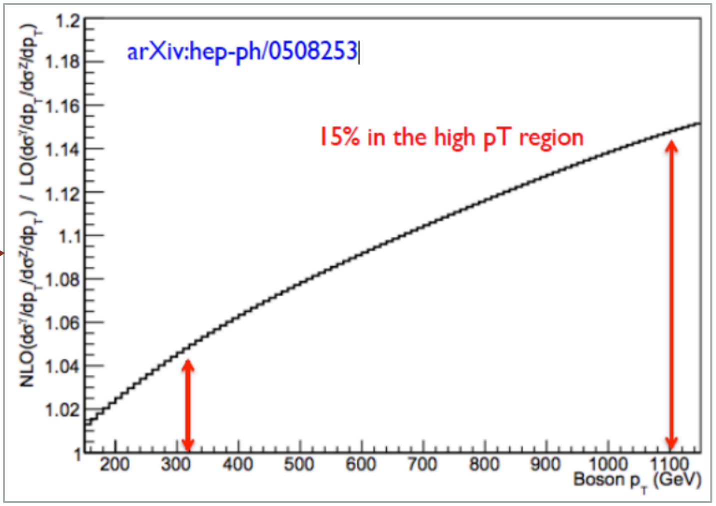
V+jets fit

- **Control regions,** correction factor **R**

$$N_i^{Z_{\mu\mu}|\gamma} = \frac{\mu_i^{Z\to\nu\nu}}{R_i^{Z|\gamma}} \qquad N_i^{W} = \frac{\mu_i^{W\to l\nu}}{R_i^{W}}$$

- **Simultaneous fit** in SR and CR
  - **BR & eff** per **bin/category**
    - *[yield μ, theo/exp nuisances (ϑ,ϕ)]*
- **Differential** *[NLO k-factor for* $p_T(V)$*]*

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



1. **Z+jets QCD** NLO
   - Using **aMC@NLO**
2. **EWK** NLO correction
   - Using ratio **Z+jet/γ+jet**

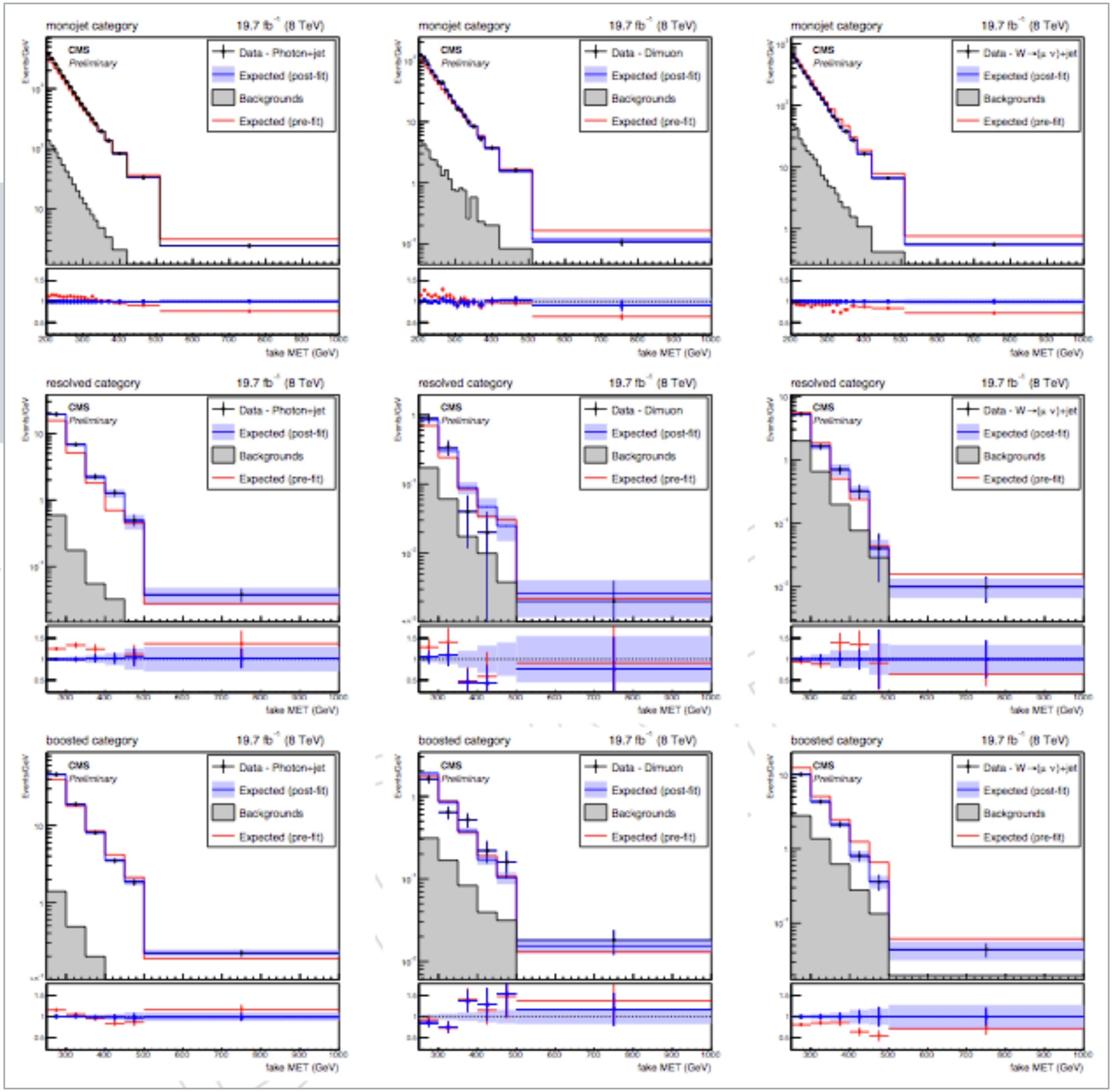
- Uncertainty:
  - **EWK dominant at high MET**

Control regions

- **Recoil after fits**
  - All final states
- **In agreement**

photon / dimu / single mu

boosted / resolved / monojet

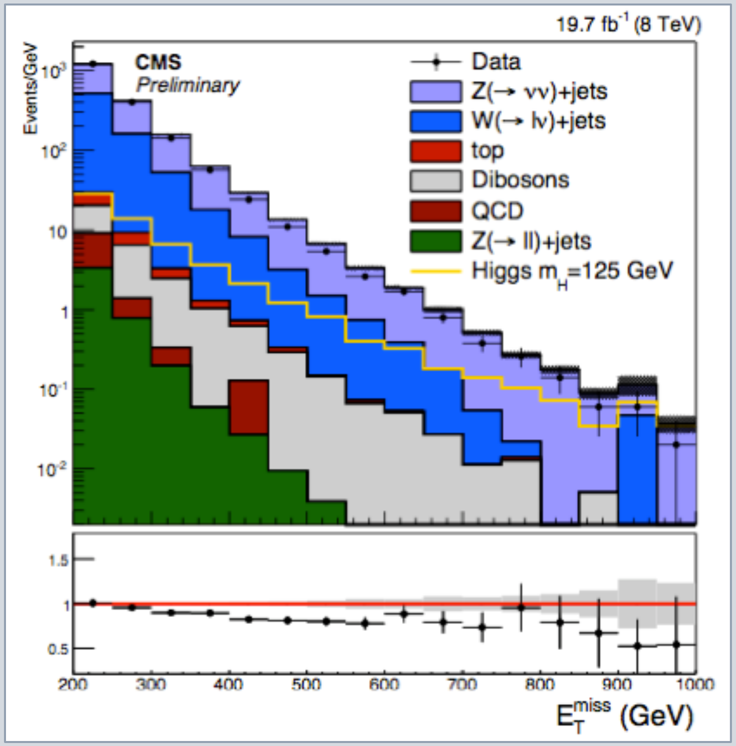


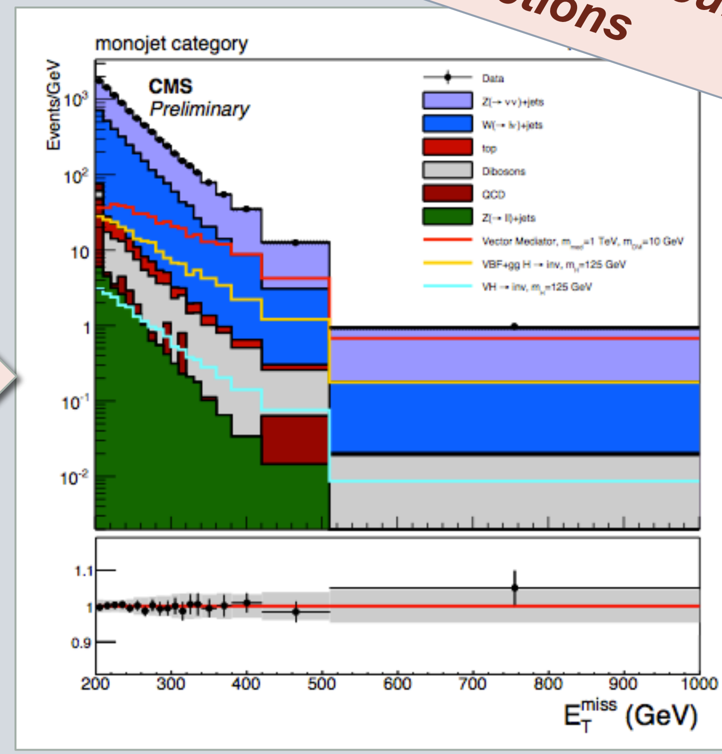
Backgrounds

CMS PAS EXO-12-055

Before → After

After background corrections





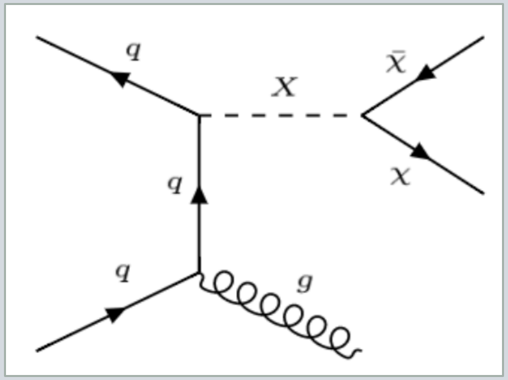
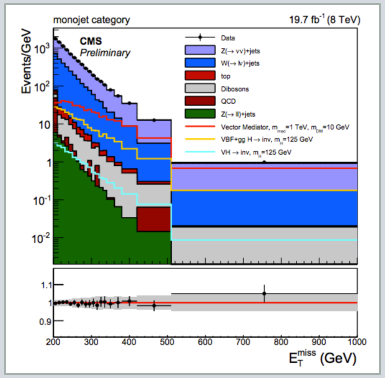
- **Key ingredient: background modeling**
  - NLO effects modeling & Recoil reconstruction

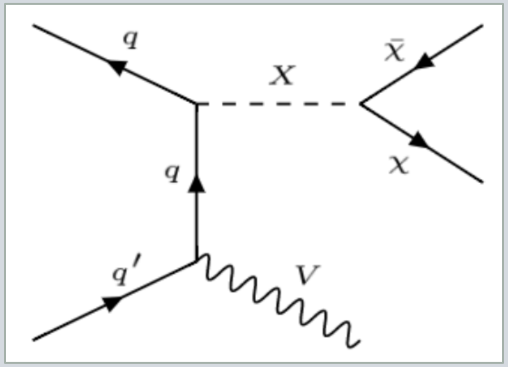
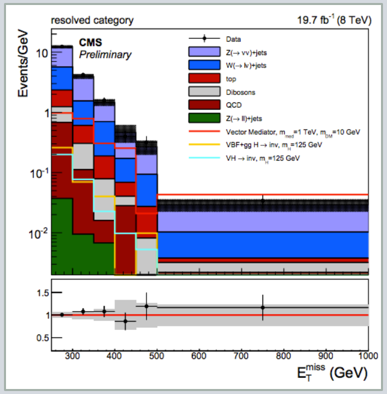
See also LPCC seminar: https://indico.cern.ch/event/388149/

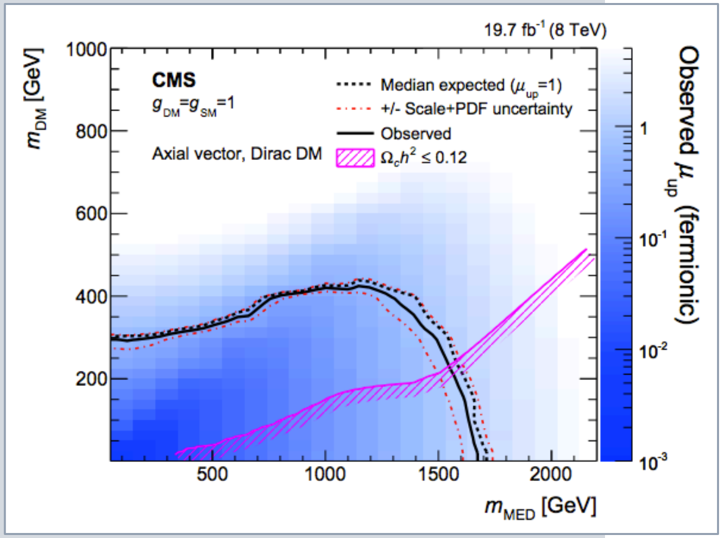
Run-1 combined interpretation

- **Mono-jet + mono-V_{had}**

CMS PAS EXO-12-055
arXiv/1607.05764

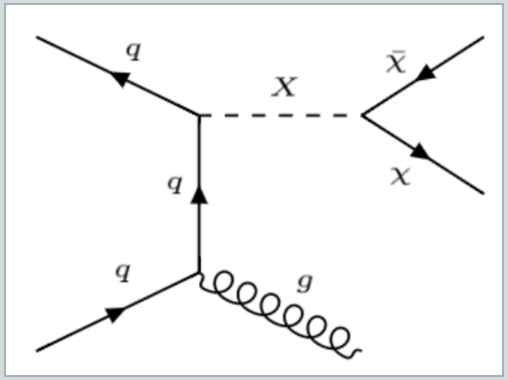


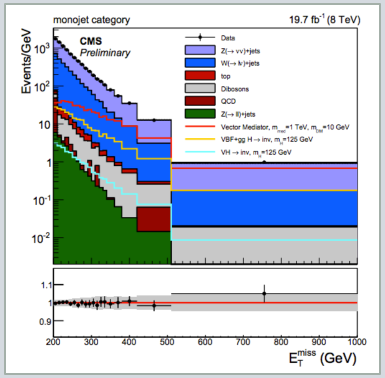
- **Constrain S&P&V&A mediators, M_Φ vs M_χ**

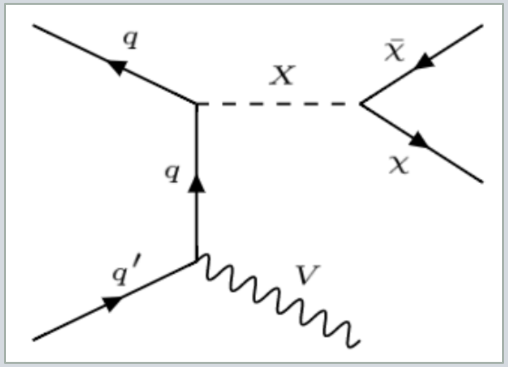
Run-1 combined interpretation

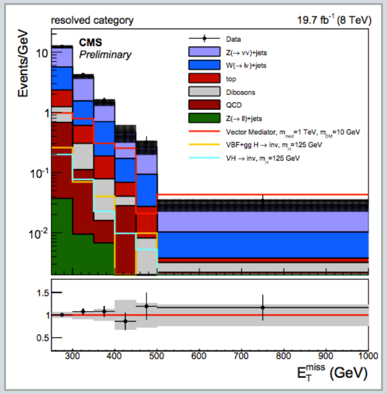
- **Mono-jet + mono-V_{had}**

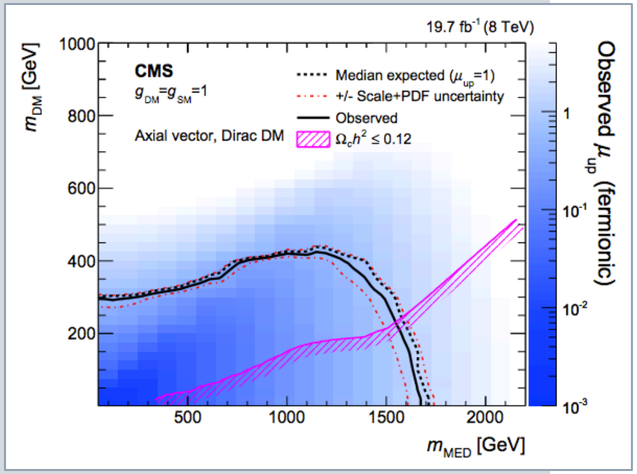
CMS PAS EXO-12-055
arXiv/1607.05764











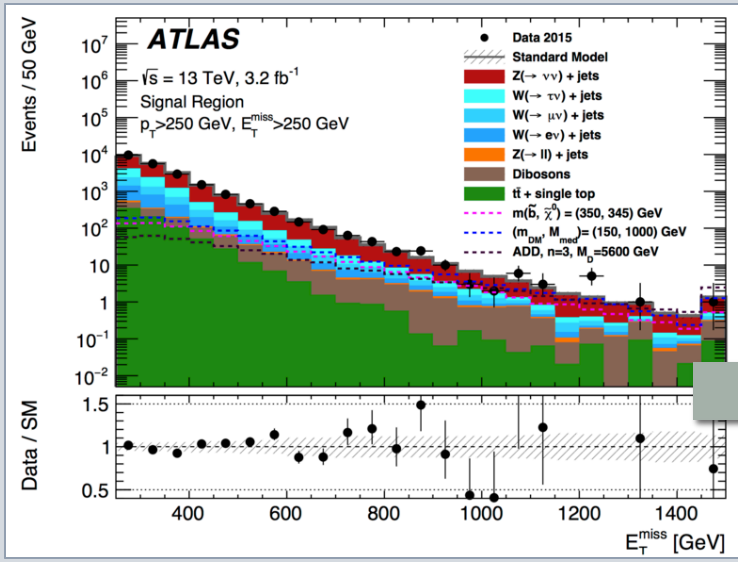
- **Selection:** No overlap
- **Combination:** Correlations

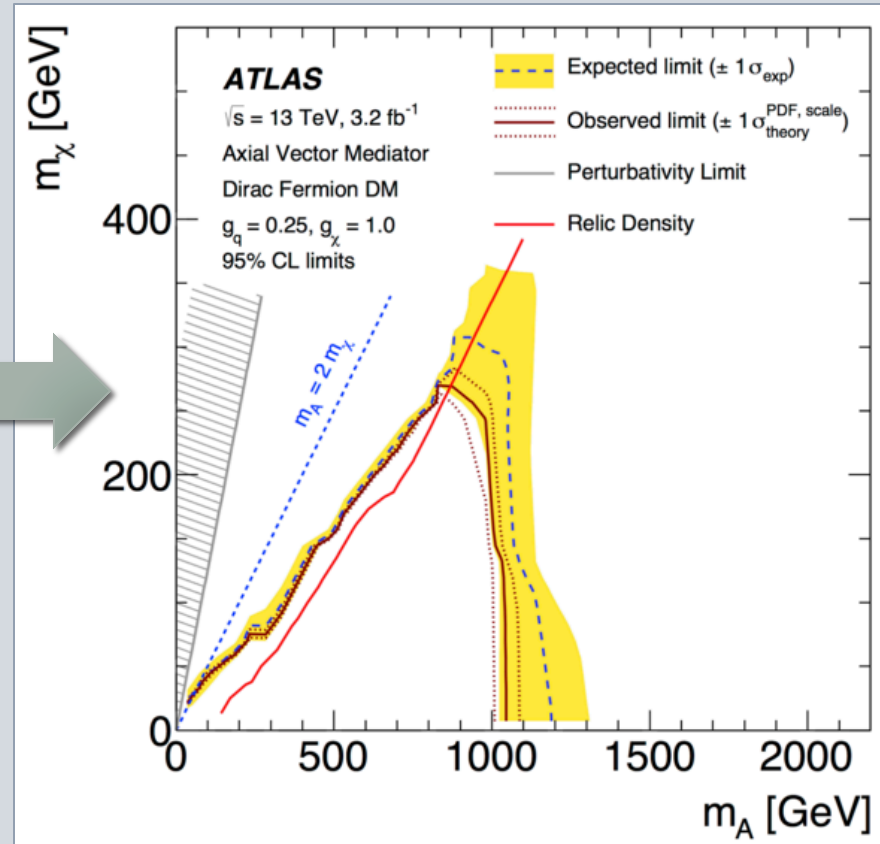
- **Challenges: trigger, MET/recoil, boosted reconstruction, NLO**

Run-2 mono-jet

ATLAS EXOT-2015-03
PRD94(2016)032005

- **Atlas 2015 dataset**





➢ **Mono-jet exclusion**
with **3.2/fb** at **13 TeV**
up to **M_{Med} ~ 1 TeV**

II.

V&A mediators

interpretation

#DMatLHC

Benchmarks

Atlas/CMS Dark Matter Forum
Simplified models
arXiv/1507.00966

LHC DM WG
Recommendations
arXiv/1603.04156

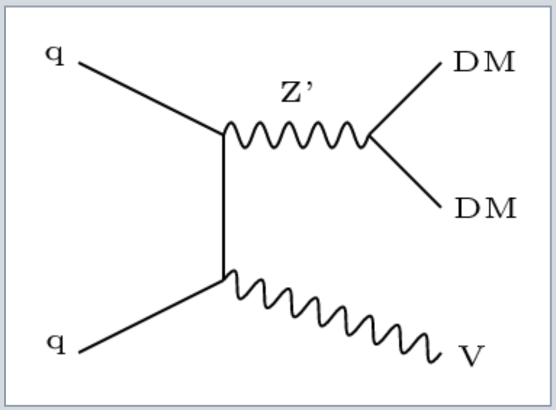
Vector	Axial
$g_{\mathrm{DM}} Z'_\mu \bar{\chi}\gamma^\mu\chi$	$g_{\mathrm{DM}} Z''_\mu \bar{\chi}\gamma^\mu\gamma^5\chi$
EWK style coupling	EWK style coupling
Scalar	**Pseudoscalar**
$g_{\mathrm{DM}} S\, \bar{\chi}\chi$	$g_{\mathrm{DM}} P\, \bar{\chi}\gamma^5\chi$
Yukawa style coupling (Mass based coupling)	Yukawa style coupling (Mass based coupling)

- *More signatures than mono-jet*

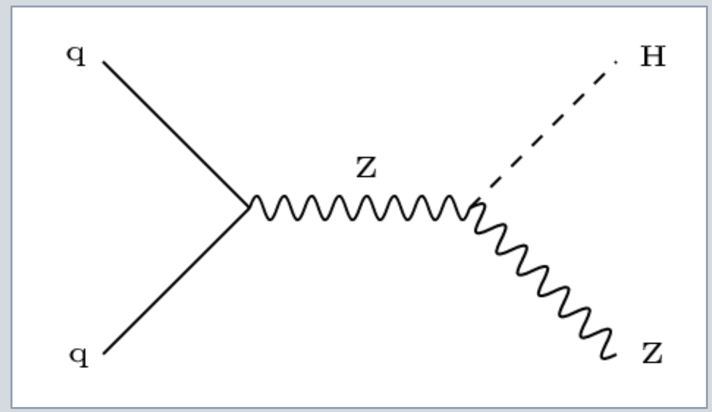
Mono-V models

Benchmark models with (enhanced) MET+V production

Vector & Axial

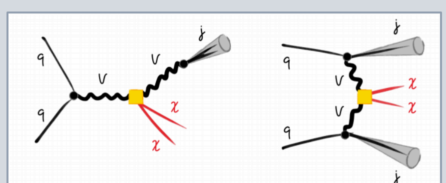


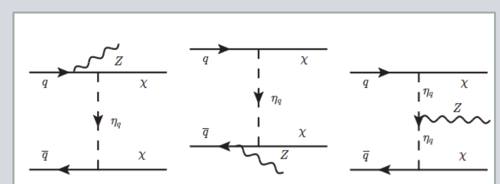
Scalar



Alternative models

- *EWK Dim-7*
- *And t-channel*

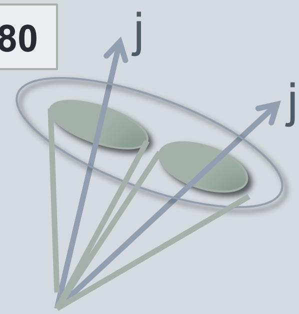


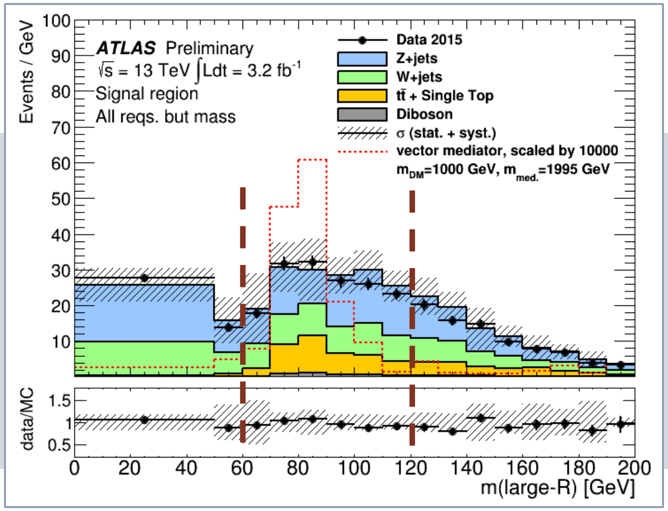


Mono-V challenges

Mono-V(qq) **ATLAS-CONF-2015-080**

- Boosted reconstruction
- **Main syst:**
  large-R jets



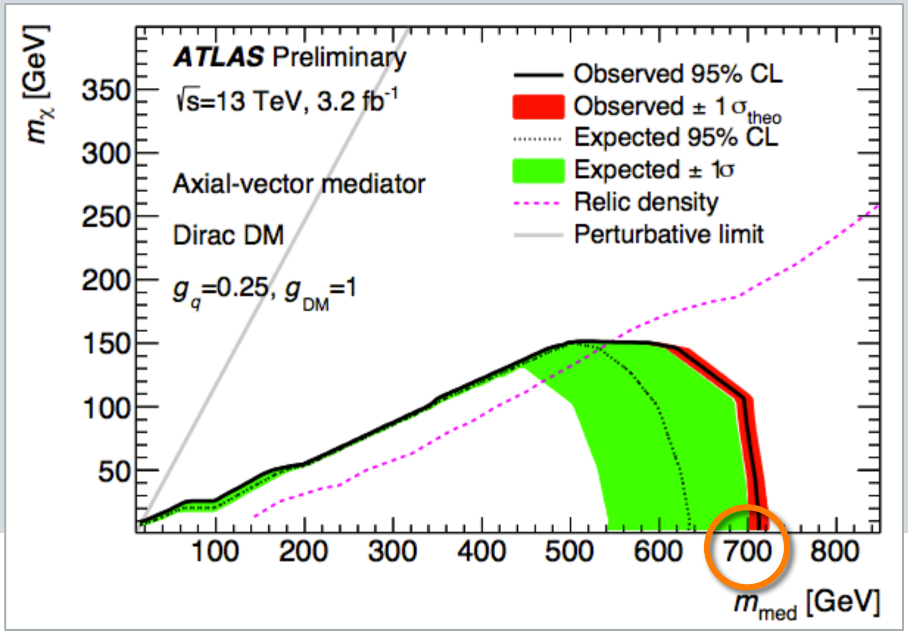


Mono-Z(ll) **arXiv:1404.0051**

- Very clean
- **Low BR**

Mono-γ **ATLAS-EXOT-2015-05**

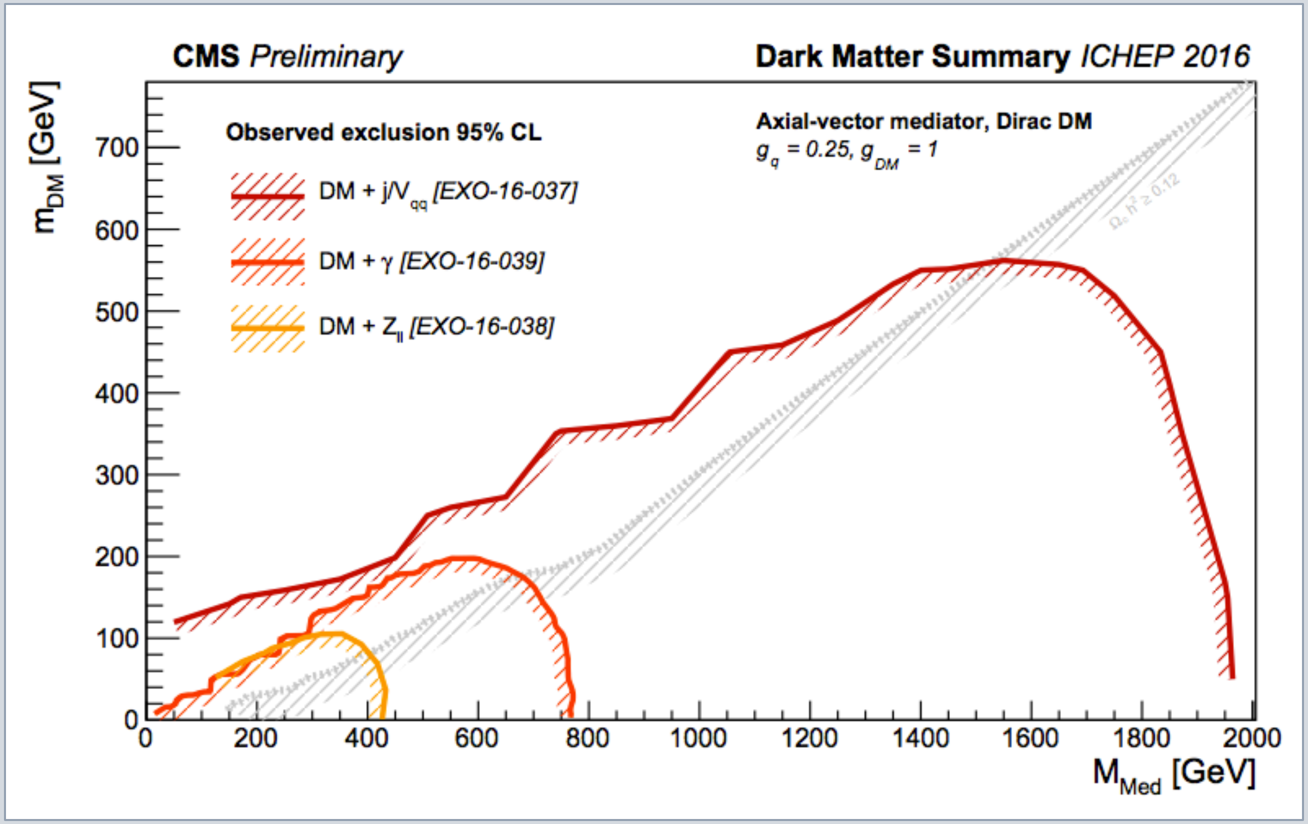
- **Challenge: fake rate**
- Constrain M_{Med} ~ 700 GeV



V&A Summary

https://cds.cern.ch/record/2208044

- MET+Z / MET+γ / MET+jet

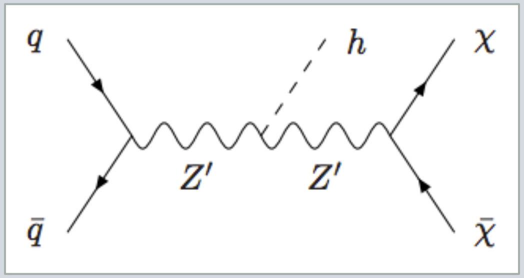


➢ Mono-jet most stringent - all channels contribute to interpretation

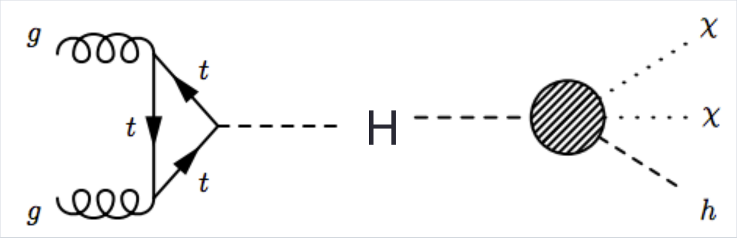
Mono-H models

Models

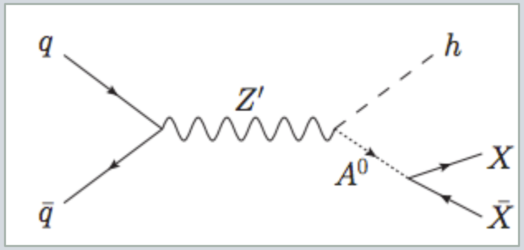
1. Simplified Z’



2. Heavy scalar



3. 2HDM (incl. Z’)



Mono-H searches

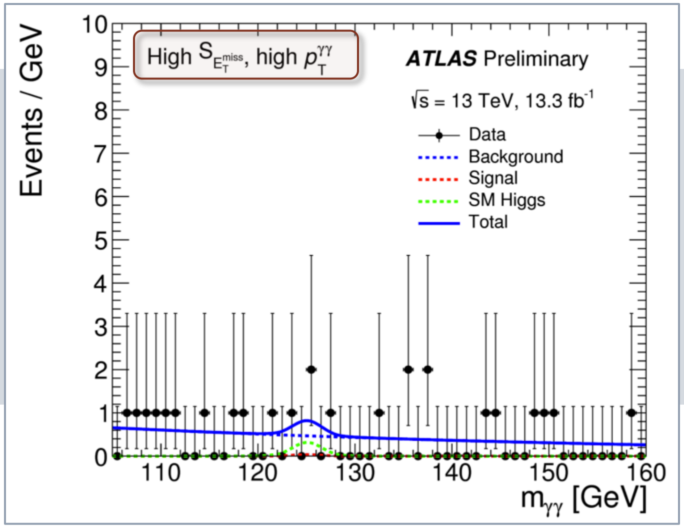
Mono-$H_{\gamma\gamma}$ @ 13 TeV

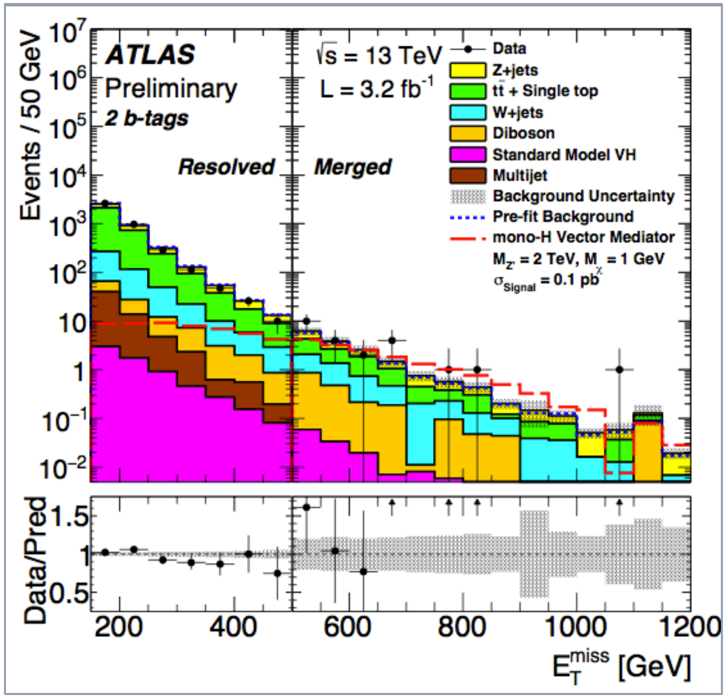
ATLAS-CONF-2016-087

4 signal regions

Interpretation: Z'

- **Challenge: statistics**





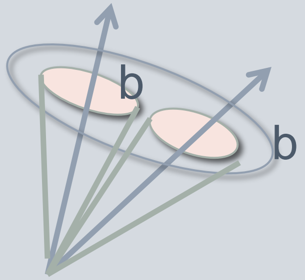
Mono-H_{bb} @ 13 TeV

ATLAS-CONF-2016-019

Boosted & resolved

Challenge: high p_T

- **Reconstruction: Boosted H→bb!**
- Limits M_{Med} ~ 0.7 TeV

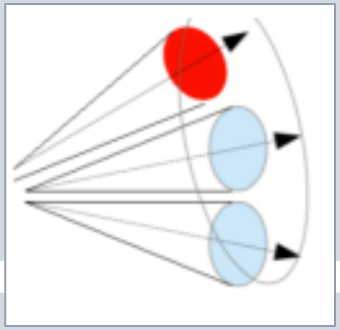


DM+t

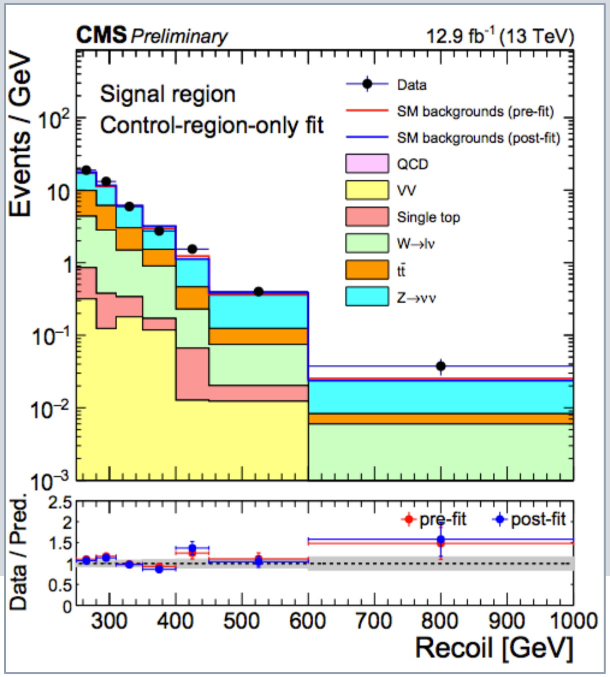
CMS PAS EXO-16-040

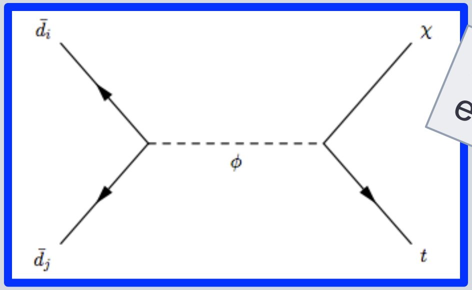
<u>'Monotop'</u>

- **One top** recoiling against MET
- **Boosted & resolved** selections: $p_T \sim 2*M_t$
- **Challenge: boosted hadronic top-tagging!**

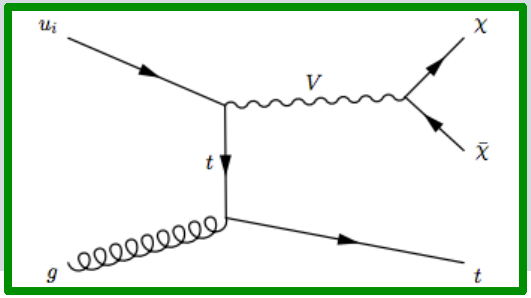


➢ **Limits on resonant & non-resonant FC models**





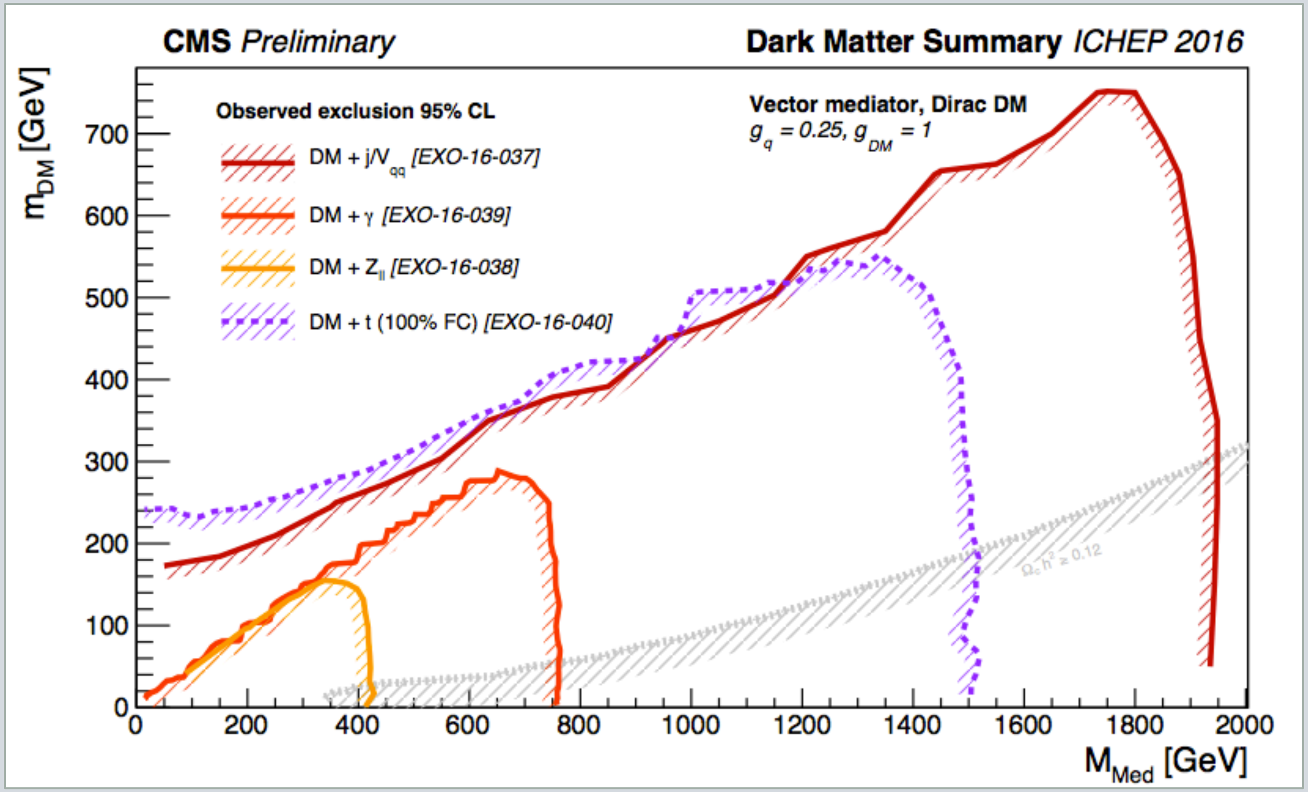
See arXiv/1407.7529
e.g. '**hylogenesis**'



V&A Summary

https://cds.cern.ch/record/2208044

- **MET+X** incl **Mono-top (100% FC)**



- Limits: $\mathbf{M_{Med}}$ **~ 2 TeV,** $\mathbf{m_{DM}}$ **~ 700 GeV** ($g_q = 0.25$, $g_{DM} = 1$)

III.

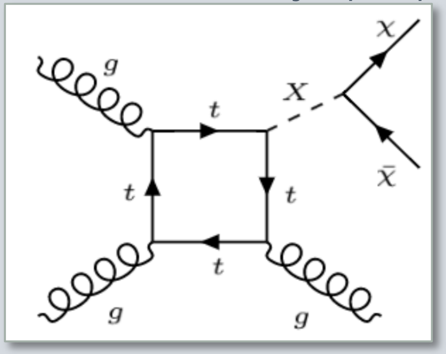
Scalar mediators
interpretation

#DMatLHC

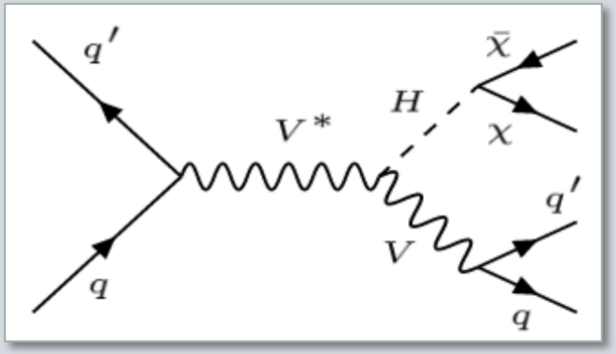
S&P in Run-2

- **Expand** Run-1 mediator interpretation strategy
  - **Mono-jet + mono-V + mono-HF + …**

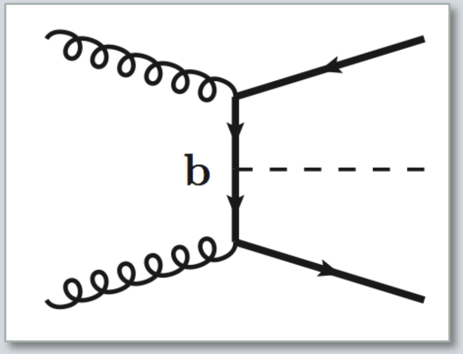
***mono-j**: top loop*



***mono-V**: Higgs strahlung*



***mono-b**: à la Z+bb*



- E.g. **Higgs** & other **(Pseudo)Scalar** mediators!
  - **Yukawa** coupling to SM HF quarks

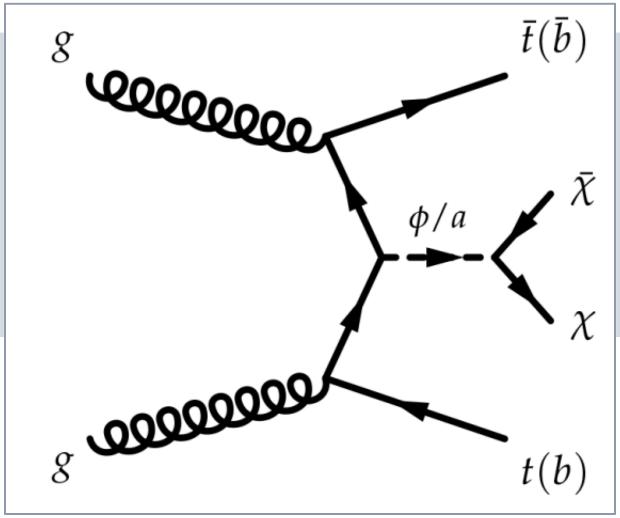
➢ **COMPLETING THE INTERPRETATION!**

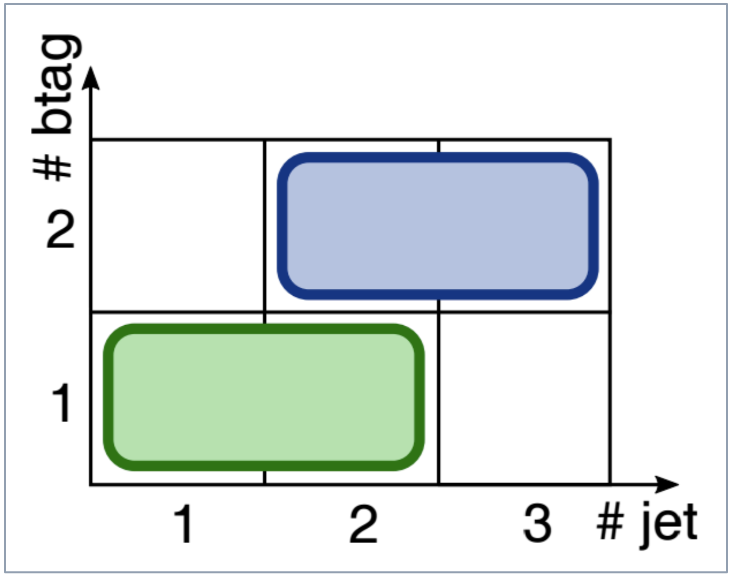
DM+bb strategy

DM+bb and DM+tt

CMS PAS B2G-15-007

- Sensitive to **scalar** & **pseudoscalar** mediators
  - ➢ Yukawa couplings!





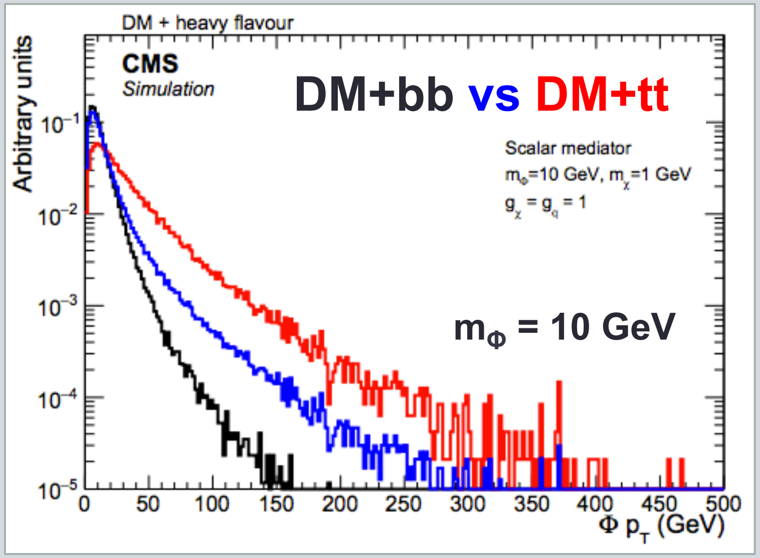
b-tagging

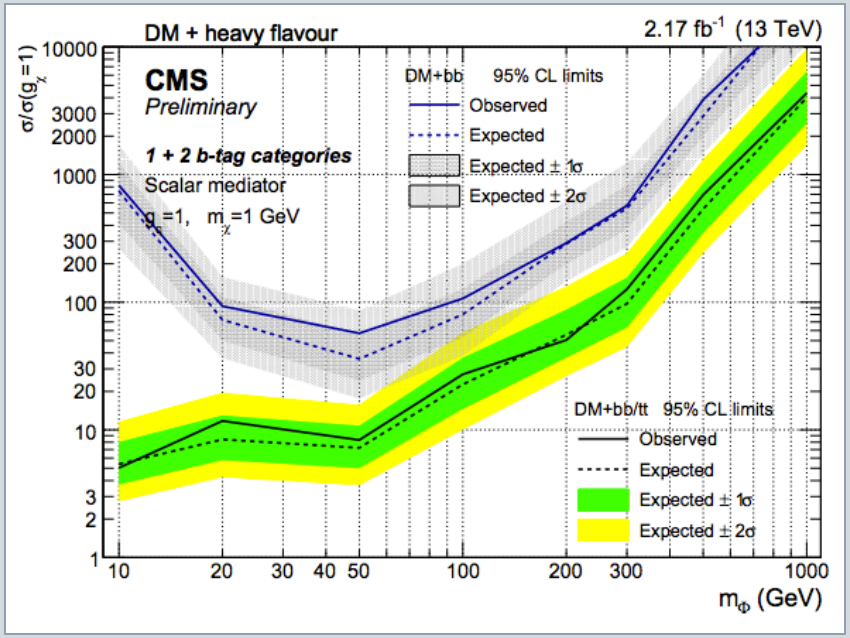
- **Categorization**
  - ➢ According to **#jets** and **#b-tags**

DM+bb sensitivity

CMS PAS B2G-15-007

Main challenge: DM+bb soft signal!





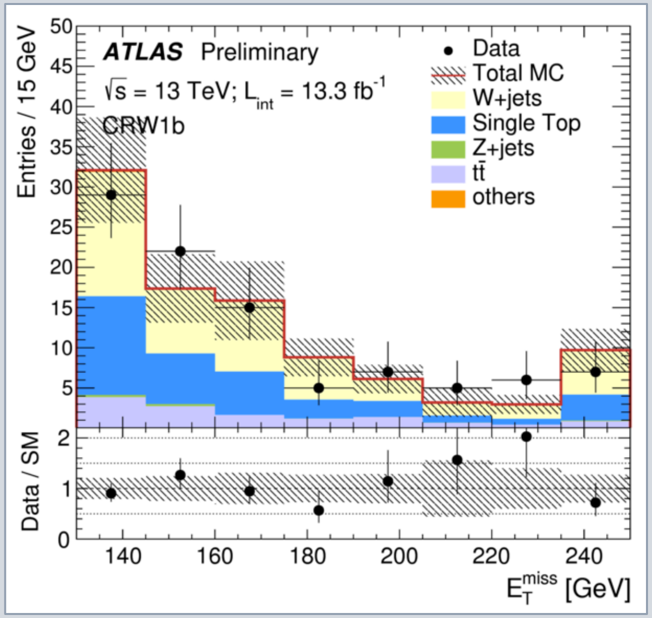
➤ **Sensitive to relatively light (pseudo)scalar mediator!**

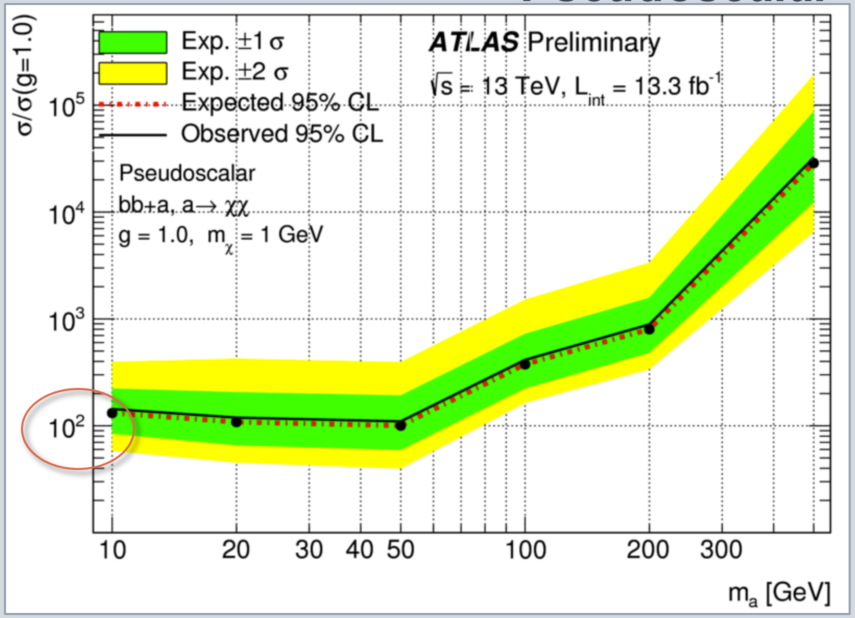
ATLAS-CONF-2016-086

DM+bb

- **New! Atlas DM+bb**

Pseudoscalar



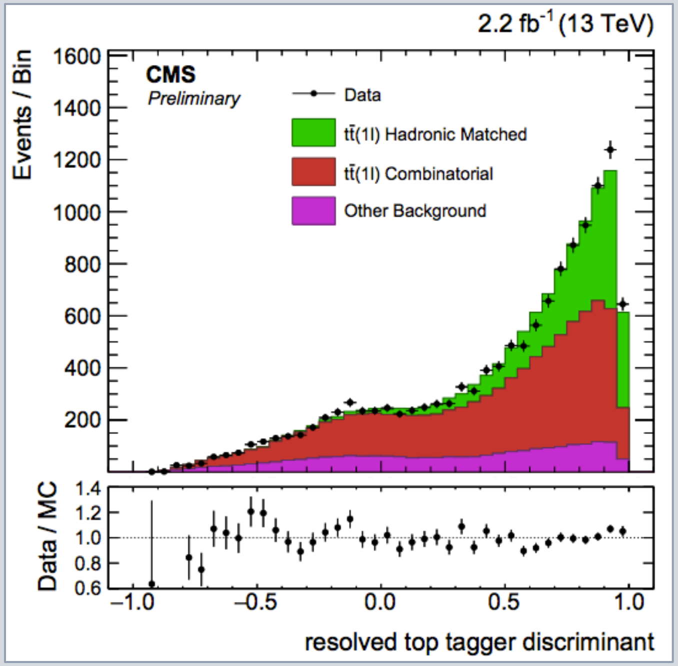


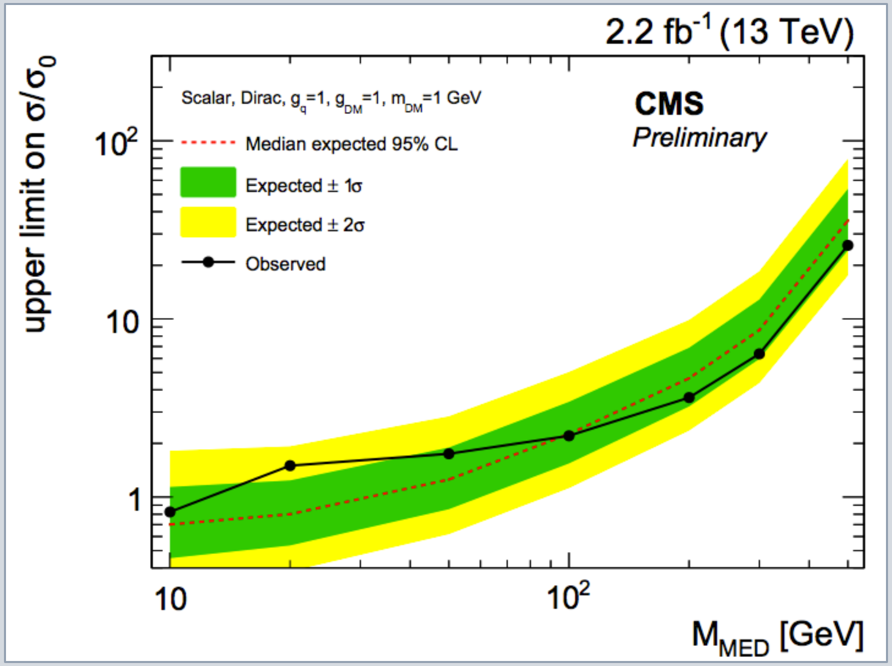
- **DM+bb signature challenging: sensitivity σ~100**

DM+tt

CMS PAS EXO-16-005

- **DM+tt**: new CMS search (hadronic & semileptonic)
  - Resolved hadronic **top tagger**
  - **Categorize** #t, #b, ΔΦ(j,MET)
- Limits on **Scalar & Pseudoscalar** mediators (**σ→1!**)



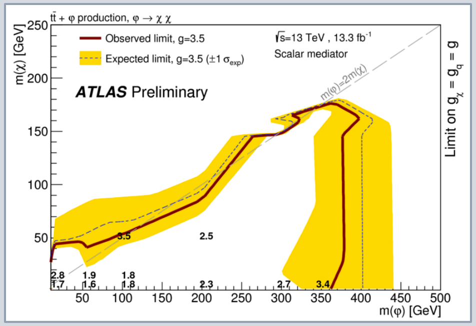


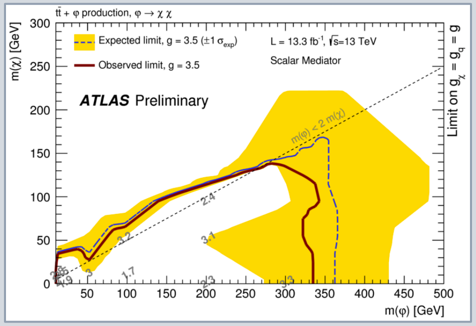
DM+tt

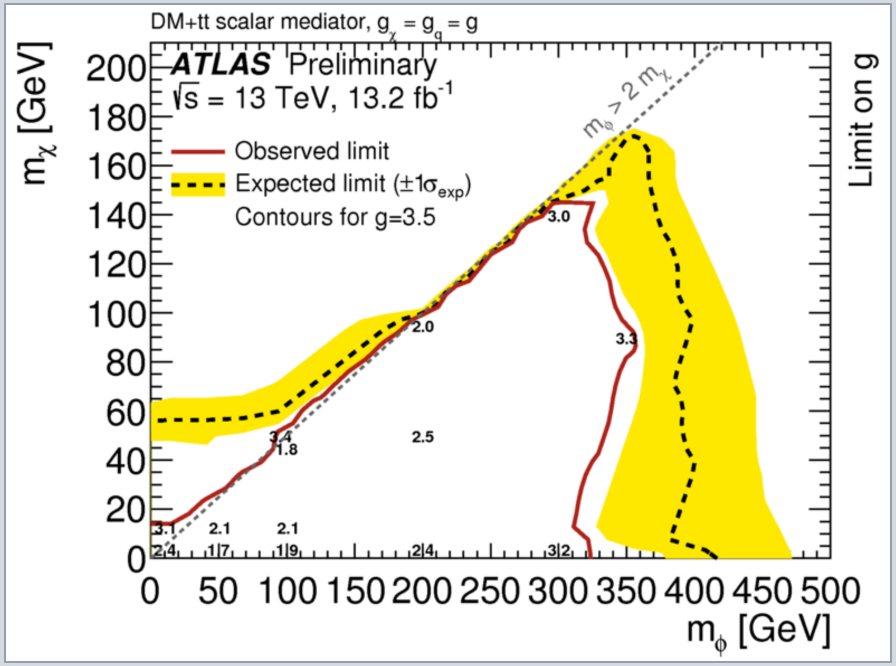
- **DM+tt**: new Atlas searches
  - ➢ Leptonic + semi-leptonic + hadronic

ATLAS CONF-2016-050
ATLAS CONF-2016-076
ATLAS CONF-2016-077

- Atlas limits on **Scalar & Pseudoscalar** mediators





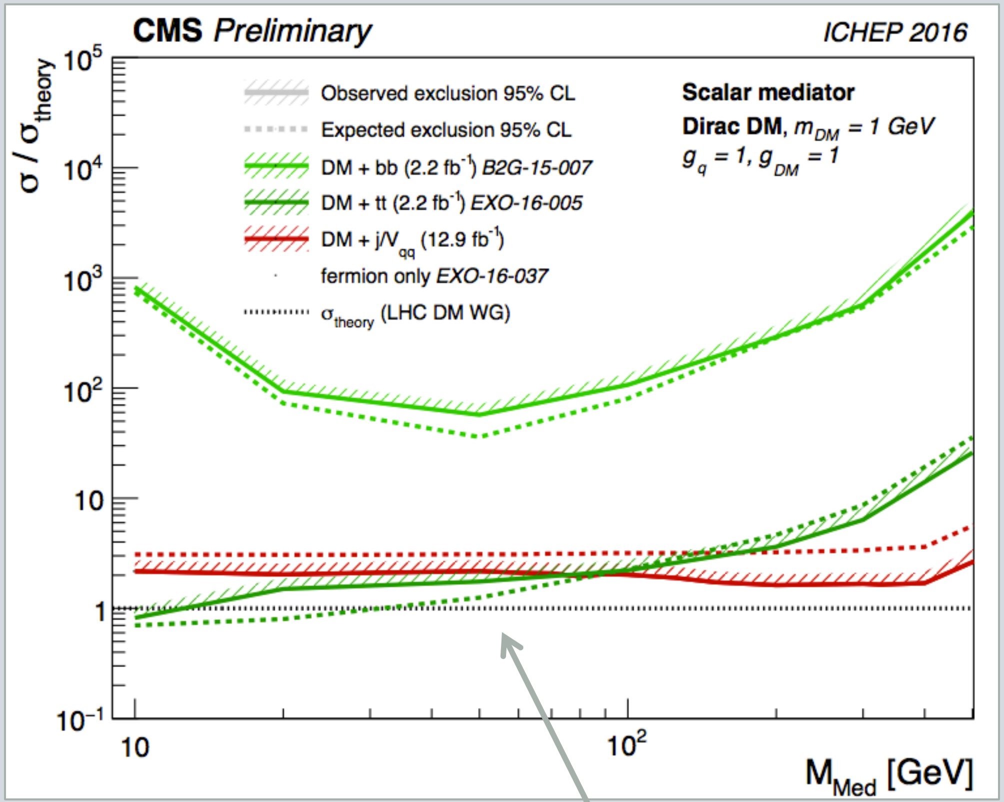


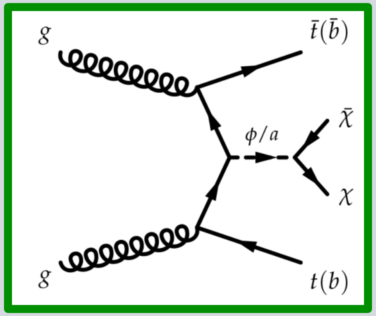
➢ *More details on stop searches by **I.Low** [yesterday]*

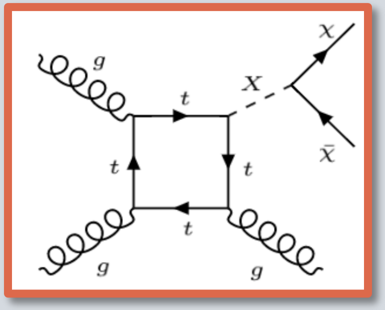
Scalar summary

https://cds.cern.ch/record/2208044

- **DM+bb** & **DM+tt** & **mono-jet** *(f-only)*







➢ ***Similar sensitivities at low M_{Med}***

H→inv

1. Higgs boson 'gives mass'
2. Dark Matter is massive

➢ Higgs coupling to DM?

H→inv

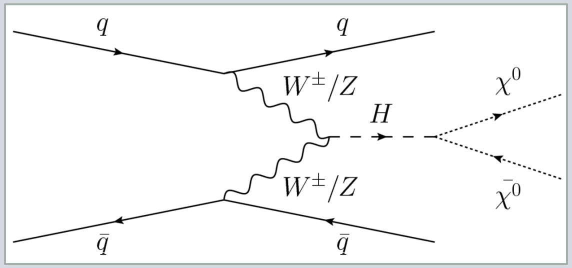
1. Higgs boson 'gives mass'
2. Dark Matter is massive

➢ Higgs coupling to DM?

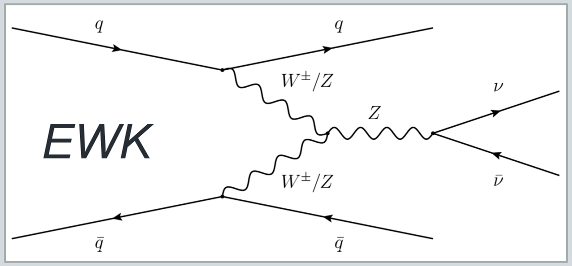
➢ Invisible Higgs decays!
  ➢ Most sensitive: VBF H_{inv}

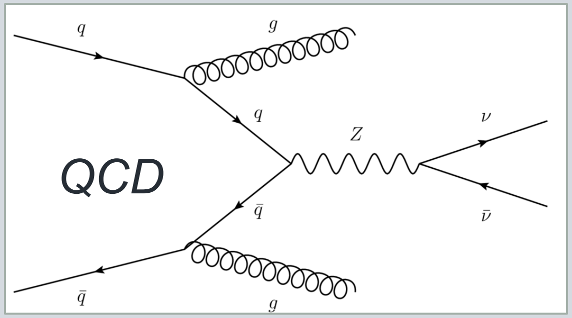
VBF

Signal VBF + H→inv



Main background: Z(νν)+jets

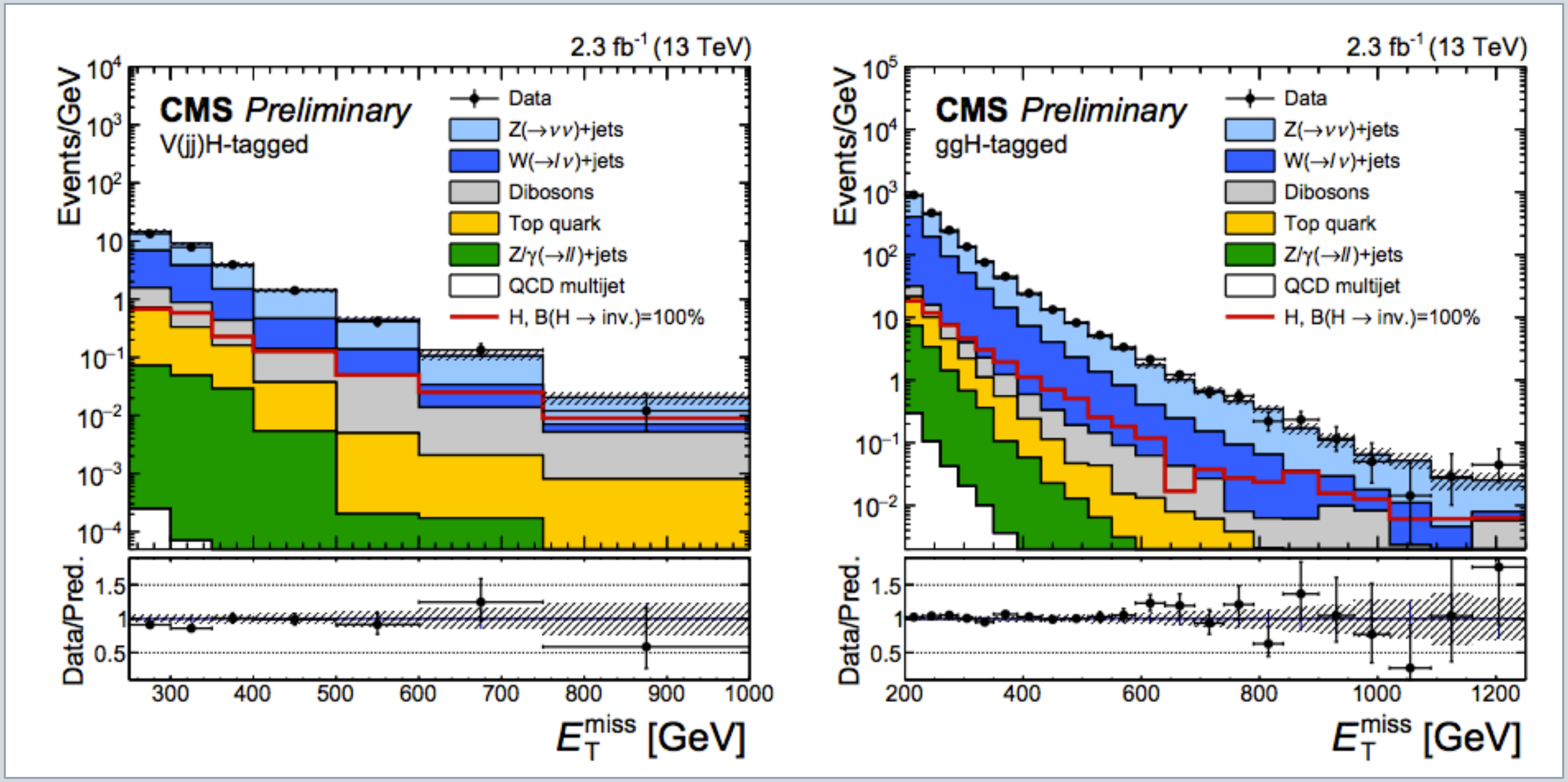




H→inv

CMS PAS HIG-16-016

- **(Left) VH**: $V_{qq}H$ & $Z_{ll}H$

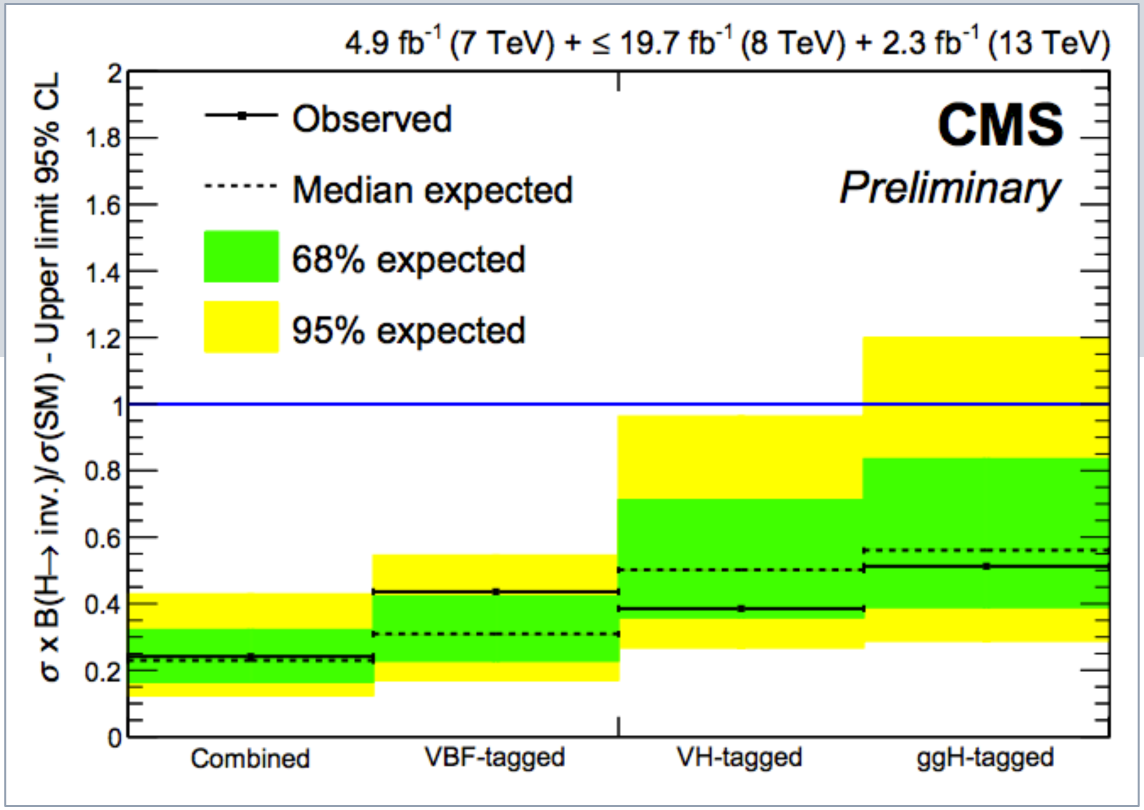


- **(Right) ggH**: mono-jet

H→inv

CMS PAS HIG-16-016

- **CMS combination**
  - **Run-1 + Run-2**
- **Production**
  - **VBF + VH + ggH**
- **New CMS result!**

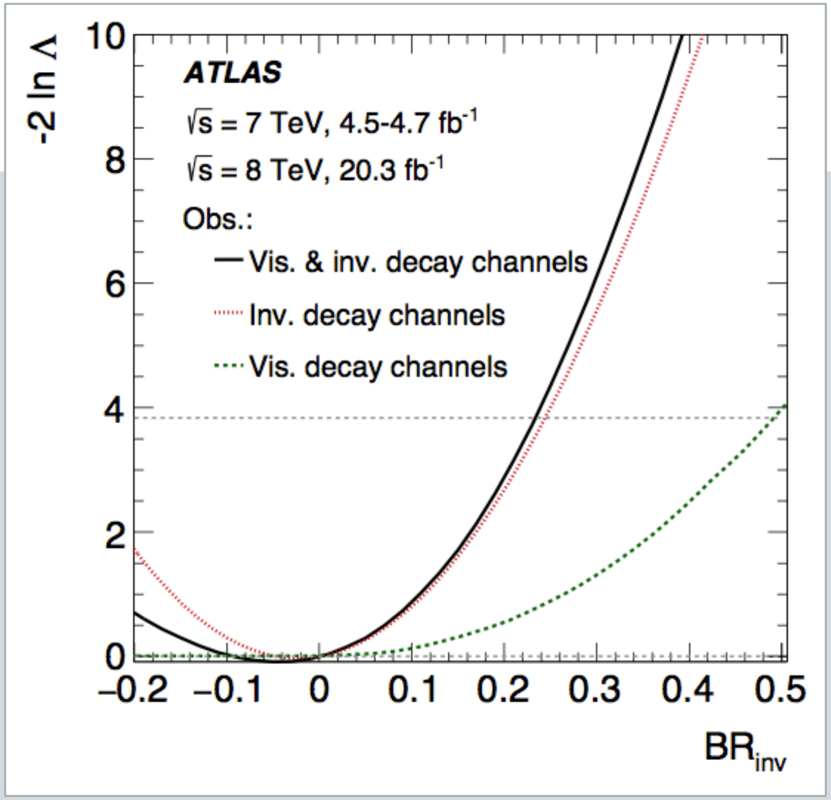


- **H_{inv} < 24% (23%)**
  - **obs(exp)**

H→inv

ATLAS run-1
combination

- **H→inv** considers constraints from **visible channels**



ATLAS arXiv/1509.00672

Decay channels	Coupling parameterisation	κ_i assumption	Upper limit on $\mathrm{BR_{inv}}$ Obs.	Exp.
Invisible decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, \mathrm{BR_{inv}}]$	$\kappa_{W,Z,g} = 1$	0.25	0.27
Visible decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, \mathrm{BR_{inv}}]$	$\kappa_{W,Z} \leq 1$	0.49	0.48
Inv. & vis. decays	$[\boldsymbol{\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, \mathrm{BR_{inv}}}]$	**None**	**0.23**	**0.24**
Inv. & vis. decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, \mathrm{BR_{inv}}]$	$\kappa_{W,Z} \leq 1$	0.23	0.23

H→inv systematics

VBF

Systematic uncertainty	Impact
Common	
W to Z ratio in QCD produced V+jets	13%
W to Z ratio in EW produced V+jets	6.3%
Jet energy scale+resolution	6.0%
QCD multijet normalisation	4.3%
PU mis-modelling	4.2%
Lepton efficiencies	2.5%
Luminosity	2.2%
Signal specific	
ggH acceptance	3.8%
QCD scale + PDF (qqH)	1.8%
QCD scale + PDF (ggH)	$< 0.2\%$
Total statistical only	$-27/+28\%$
Total uncertainty	$-33/+32\%$

Background theory

H→inv systematics

VBF

Systematic uncertainty	Impact
Common	
W to Z ratio in QCD produced V+jets	13%
W to Z ratio in EW produced V+jets	6.3%
Jet energy scale+resolution	6.0%
QCD multijet normalisation	[illegible]
PU mis-modelling	[illegible]
Lepton efficiencies	[illegible]
Luminosity	[illegible]
Signal specific	
ggH acceptance	[illegible]
QCD scale + PDF (qqH)	[illegible]
QCD scale + PDF (ggH)	[illegible]
Total statistical only	[illegible]
Total uncertainty	[illegible]

gg→H

Systematic uncertainty	Impact
Common	
Muon efficiency	24%
Electron efficiency	22%
Lepton veto efficiency	16%
b jet tag efficiency	3.2%
$W(l\nu)$+jets/$Z(\nu\nu)$+jets ratio theory	16%
γ+jets/$Z(\nu\nu)$+jets ratio theory	5.8%
Jet energy scale+resolution	10%
E_T^{miss} scale	1.8%
Luminosity	3.0%
Diboson background normalisation	2.7%
Top quark background normalisation	$<1\%$
Signal specific	
ggH p_T-spectrum	15%
QCD scale + PDF (ggH)	5.8%
Total statistical only	$-22/+25\%$
Total uncertainty	$-55/+62\%$

Background theory

Leptons (CR)

H→inv systematics

CMS PAS HIG-16-016

VBF

Systematic uncertainty	Impact
Common	
W to Z ratio in QCD produced V+jets	13%
W to Z ratio in EW produced V+jets	6.3%
Jet energy scale+resolution	6.0%
QCD multijet normalisation	4.3%
PU mis-modelling	4.2%
Lepton efficiencies	2.5%
Luminosity	2.2%
Signal specific	
ggH acceptance	2.8%

gg→H

Systematic uncertainty	Impact
Common	
Muon efficiency	24%
Electron efficiency	22%
Lepton veto efficiency	16%
b jet tag efficiency	3.2%
$W(l\nu)$+jets/$Z(\nu\nu)$+jets ratio theory	16%
γ+jets/$Z(\nu\nu)$+jets ratio theory	5.8%
Jet energy scale+resolution	10%
E_T^{miss} scale	1.8%
Luminosity	3.0%
Diboson background normalisation	2.7%
Top quark background normalisation	< 1%
Signal specific	
ggH p_T-spectrum	15%
QCD scale + PDF (ggH)	5.8%
Total statistical only	$-22/+25\%$
Total uncertainty	$-55/+62\%$

Background theory

Jets

Leptons

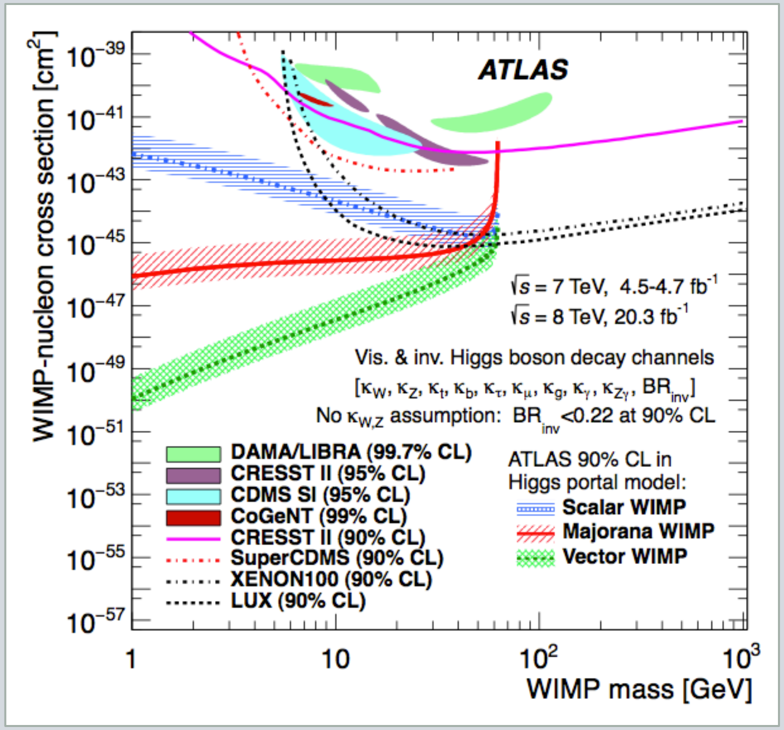
$V_{qq}H$

Systematic uncertainty	Impact
Common	
γ+jets/$Z(\nu\nu)$+jets ratio theory	32%
$W(l\nu)$+jets/$Z(\nu\nu)$+jets ratio theory	21%
Jet energy scale+resolution	12%
V-tagging efficiency	12%
Lepton veto efficiency	13%
Electron efficiency	13%
Muon efficiency	8.6%
b jet tag efficiency	5.7%
Photon efficiency	3.1%
E_T^{miss} scale	4.6%
Top quark background normalisation	6.0%
Diboson background normalisation	< 1%
Luminosity	< 1%
Signal specific	
ggH p_T-spectrum	12%
QCD scale + PDF (ggH)	3.0%
QCD scale + PDF (VH)	1.4%
Total statistical only	$-46/+50\%$
Total uncertainty	$-69/+74\%$

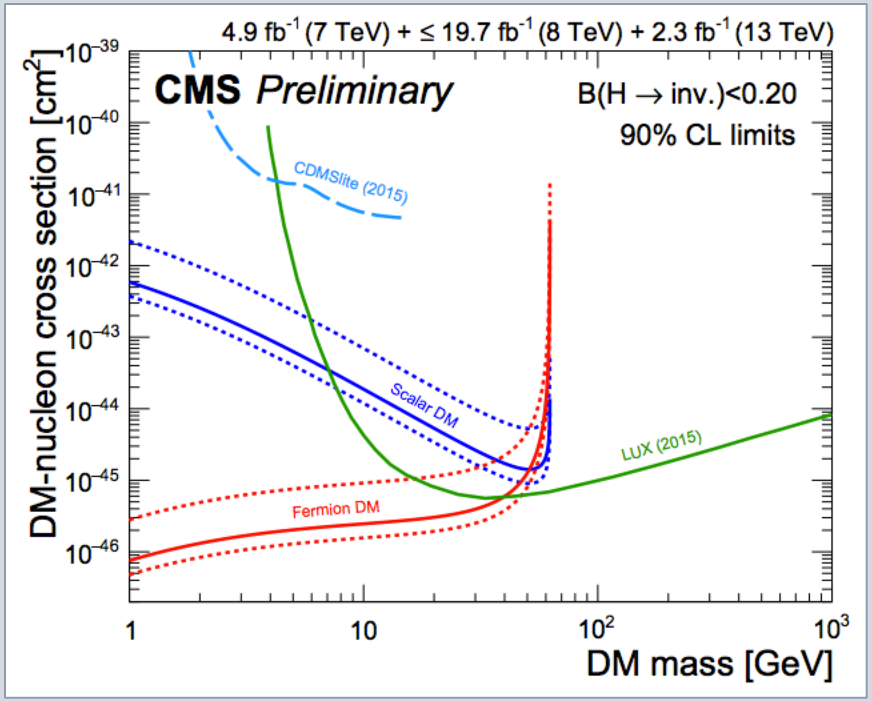
H→inv

LHC vs DD

ATLAS arXiv/1509.00672



CMS PAS HIG-16-016



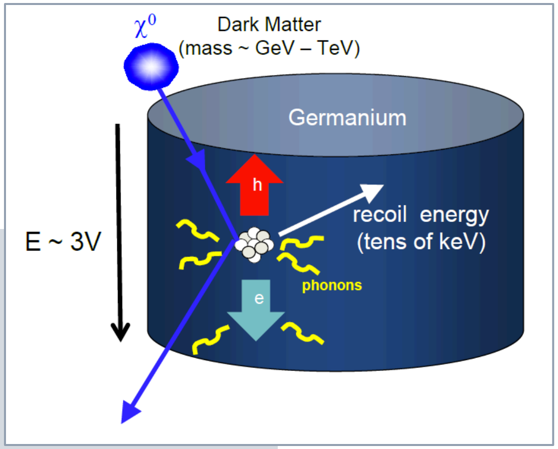
➢ LHC best for low m_{DM}

IV.

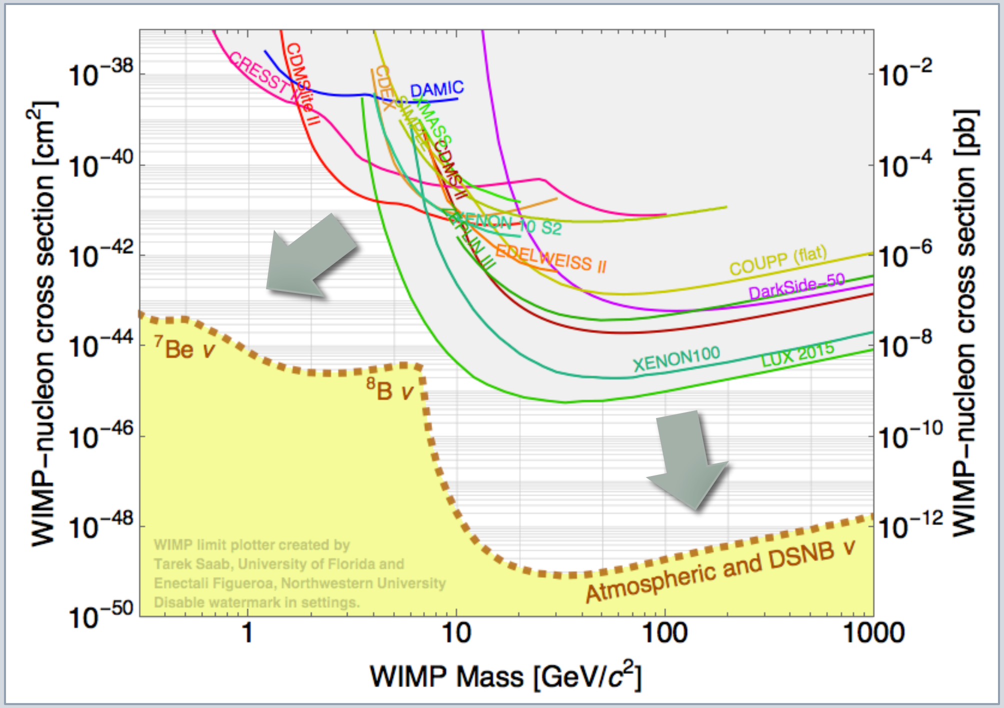
Interpretations
comparison to DD

#DMatLHC

DD



Direct detection summary:



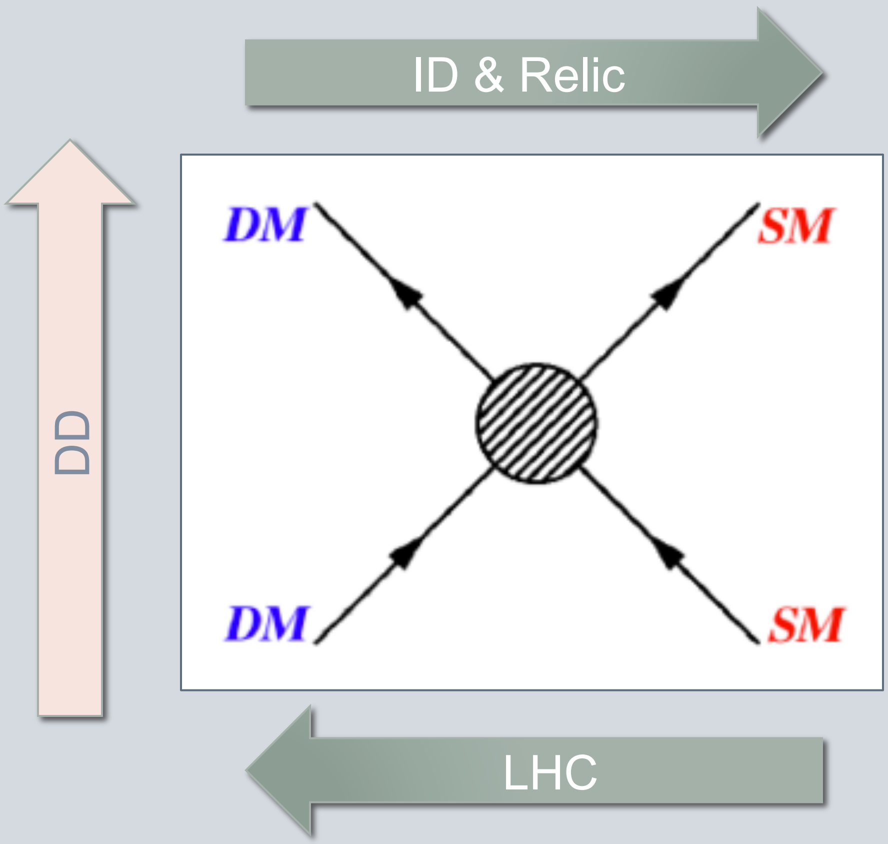
http://cdms.berkeley.edu/limitplots/mmWIMP_limit_plotter.html

PRL
PandaX published
arXiv/1608.07400
LUX submitted
arXiv/1608.07648

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

LHC vs DD vs ID&Relic

<u>Test the same coupling in different ways:</u>

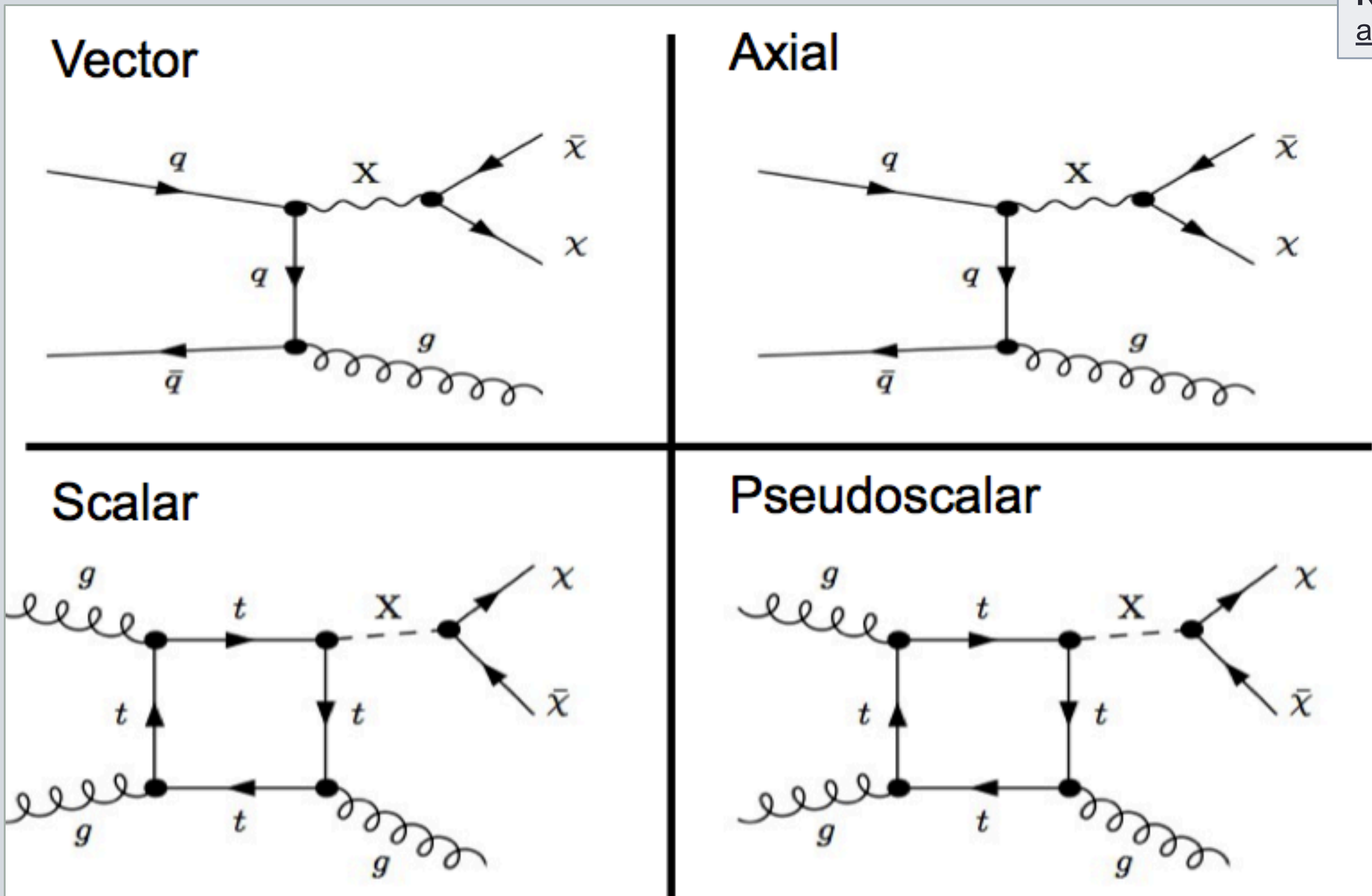


- **Which SM-DM interaction? LHC DMF benchmarks!**

LHC – Mono-jet

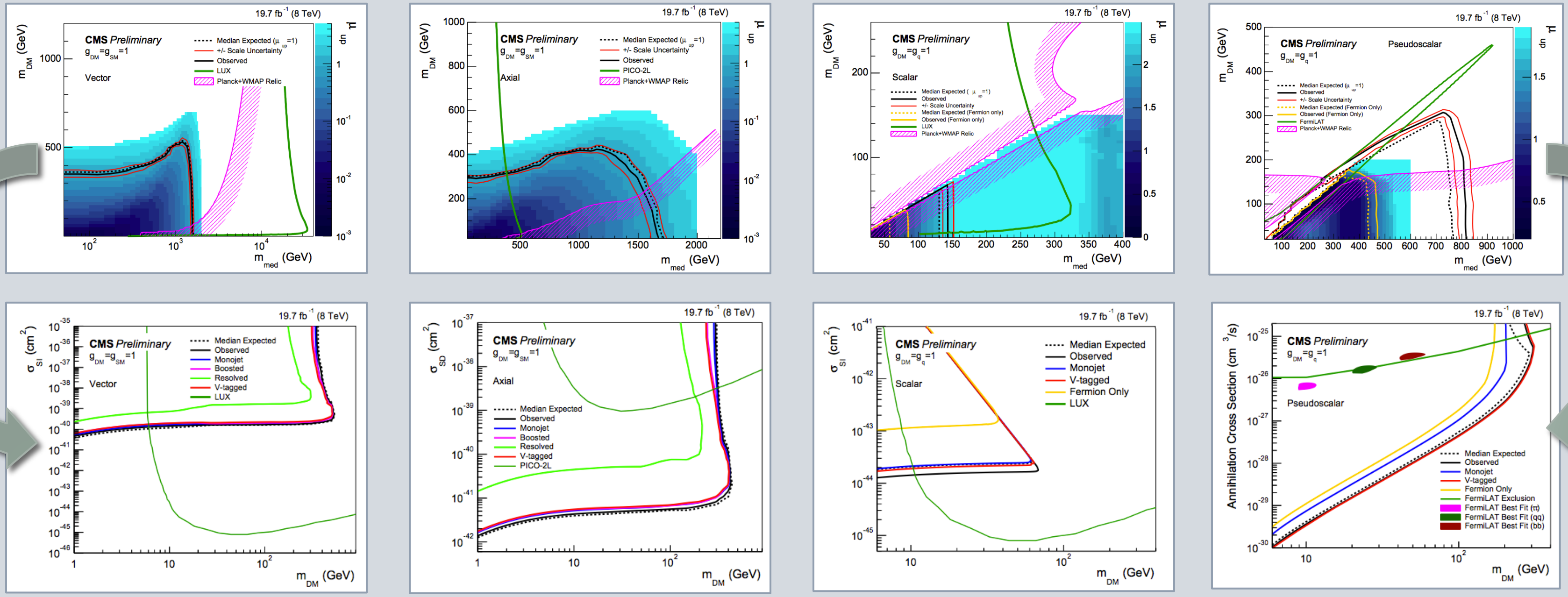
Atlas/CMS Dark Matter Forum
Simplified models
arXiv/1507.00966

LHC DM WG
Recommendations
arXiv/1603.04156



DD interpretations

Vector Axial Scalar Pseudo



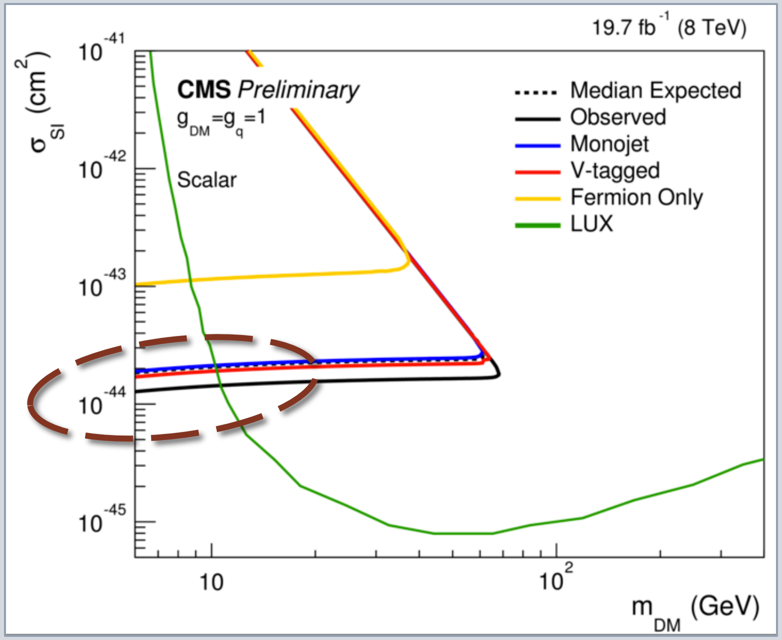
LHC complementary to **Relic** and **DD**

LHC vs DD/ID

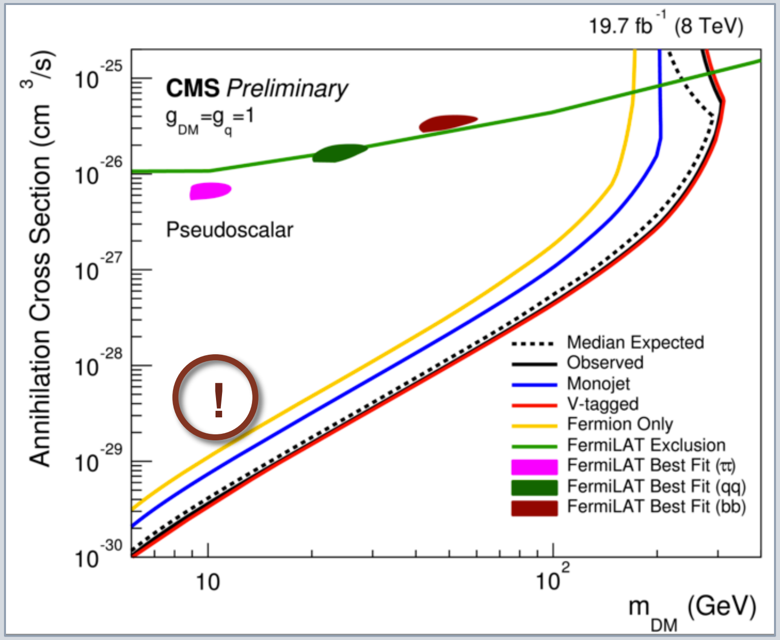
CMS PAS EXO-12-055

- **LHC** especially competitive for **Pseudoscalar!**

Scalar



Pseudo

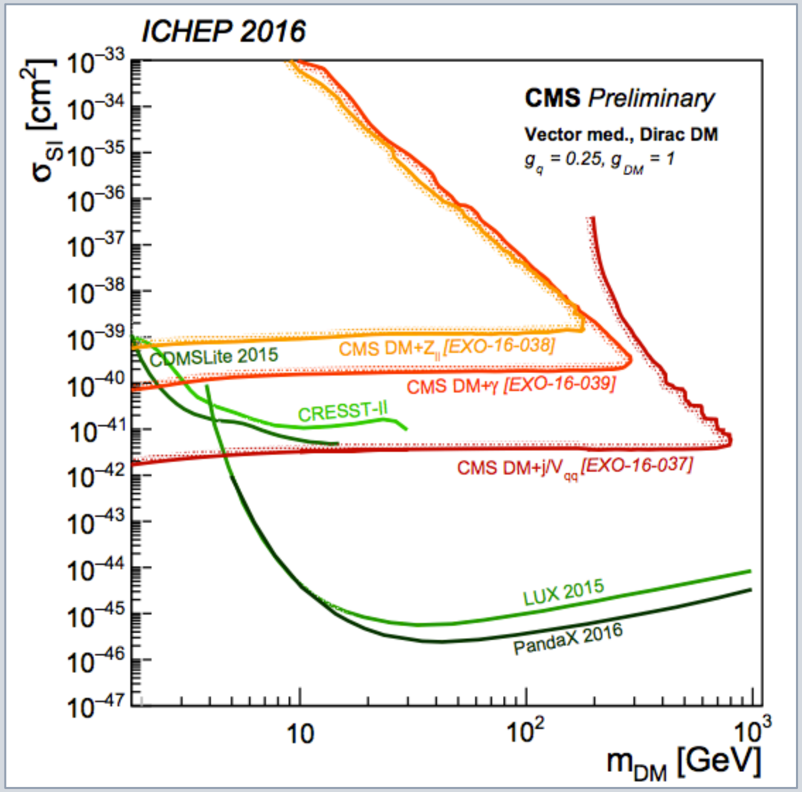


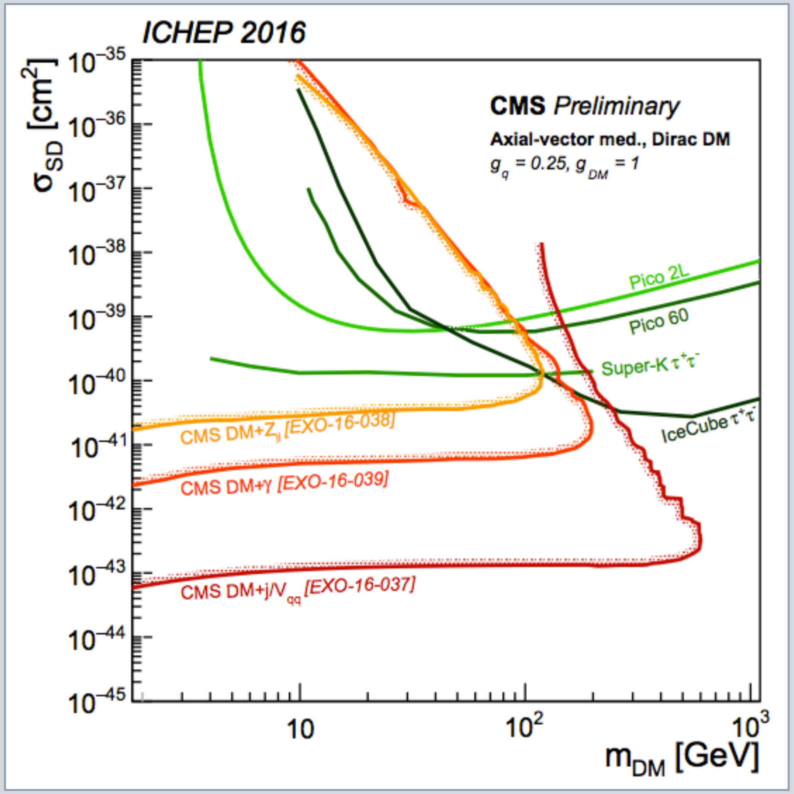
➢ and **LHC** clearly better at **low mass**!

LHC vs DD/ID

https://cds.cern.ch/record/2208044

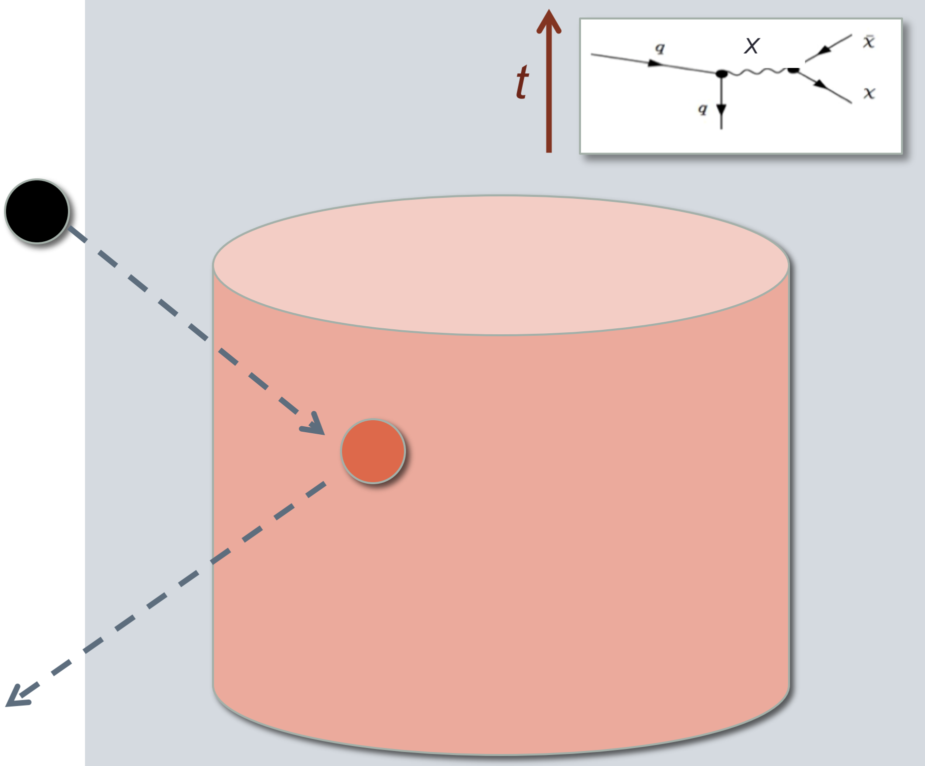
- **LHC** especially competitive for **Pseudoscalar** and **Axial**



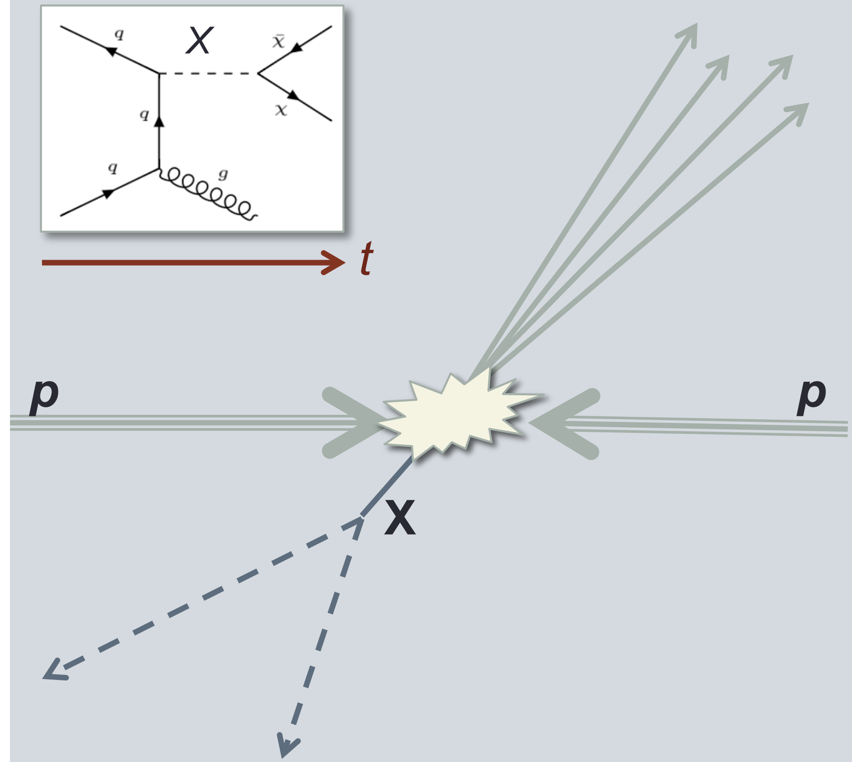


- and **LHC** clearly better at **low mass**!

DD vs LHC



- **DD** challenging for **low M_{DM}**



- **LHC** indifferent to **M_{DM} !**

- **LHC best for low-mass Dark Matter!**

V.

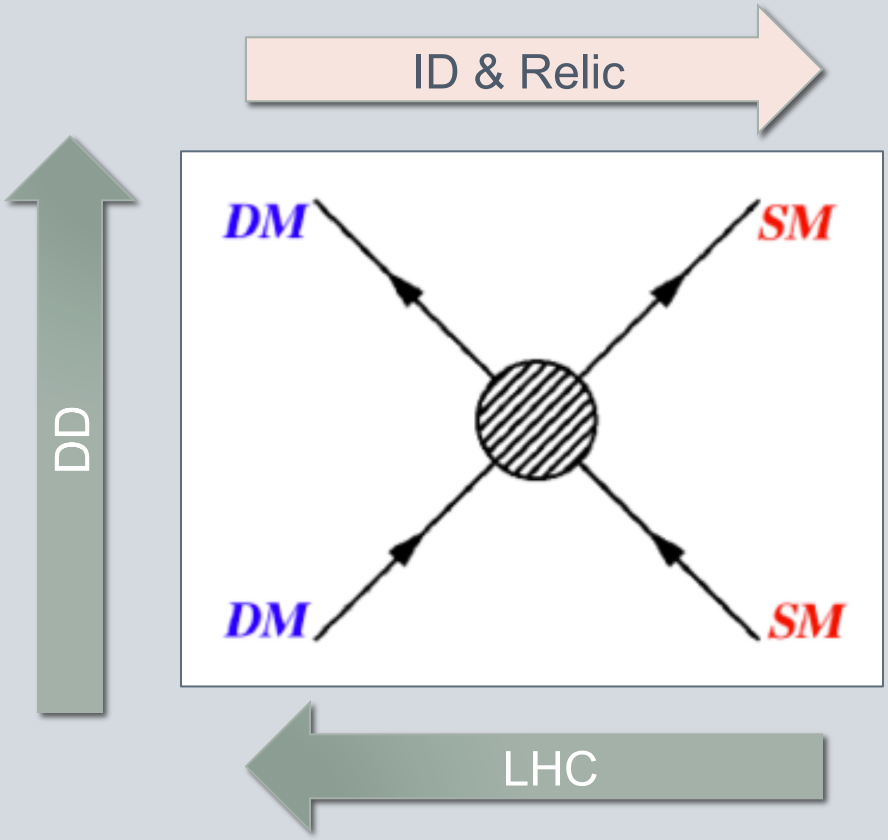
Interpretation

comparison to annihilation

#DMatLHC

LHC vs DD vs ID&Relic

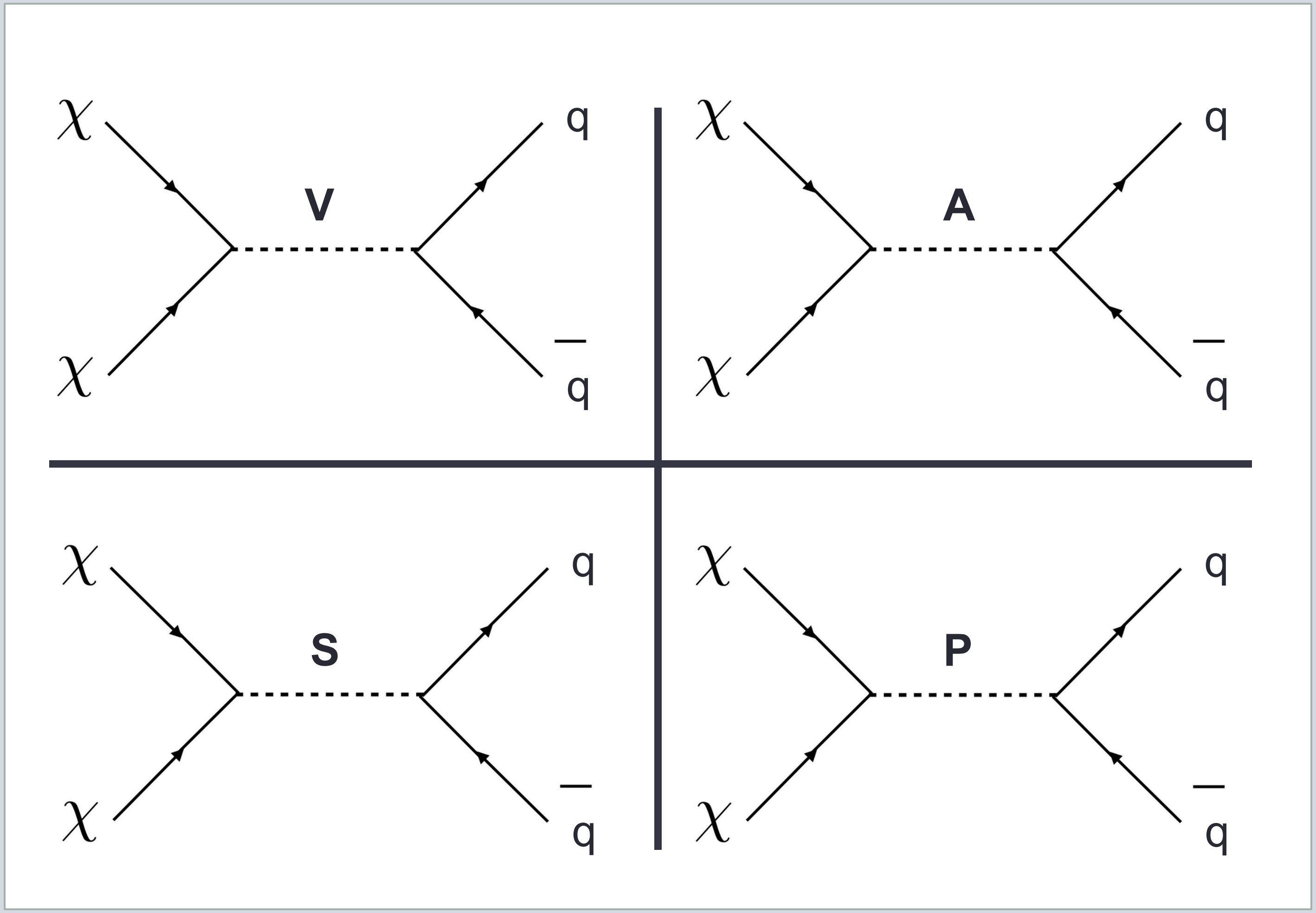
Test the same coupling in different ways:



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

Relic - Annihilation

https://inspirehep.net/record/1250317

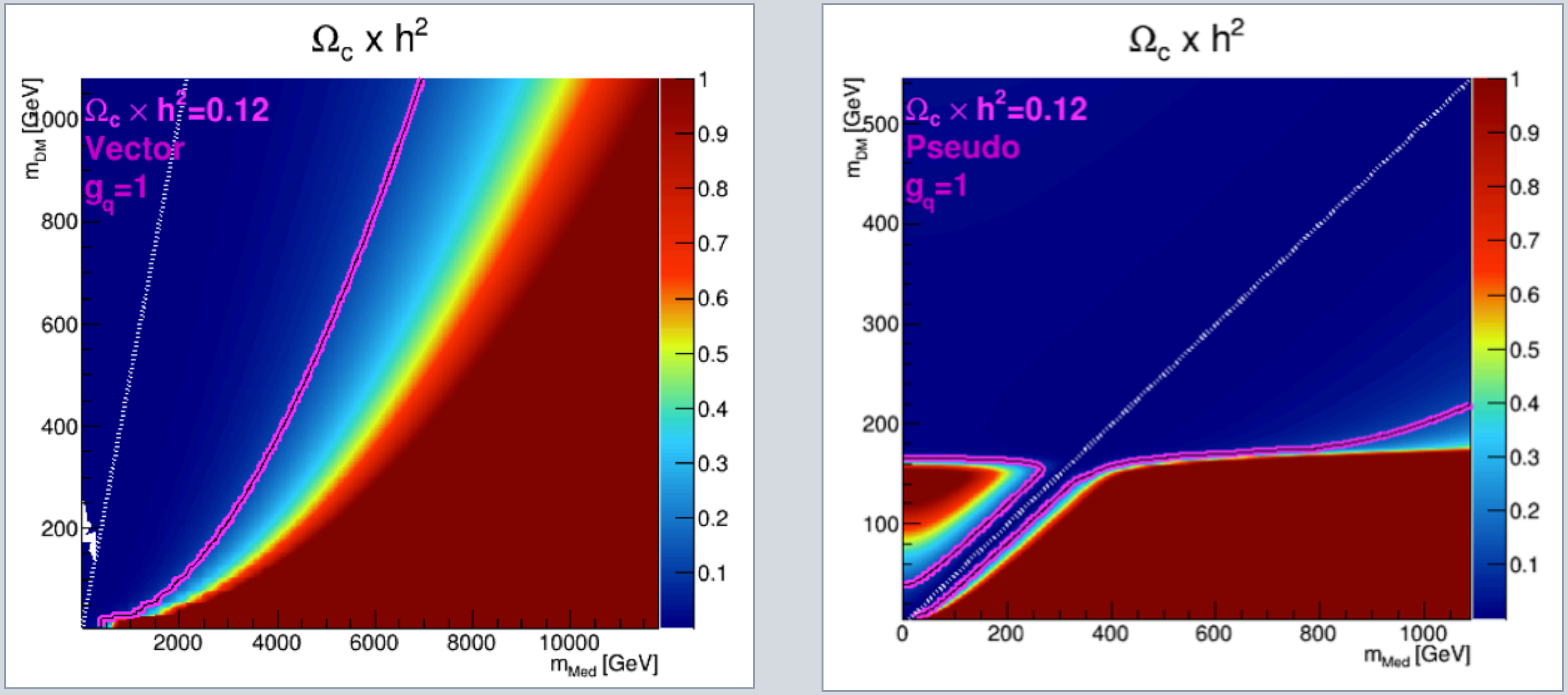


➢ Additional interpretations of these models

LHC vs Relic

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

- **MadDM** [Vector & Pseudo]



➢ Additional limits on LHC DM models

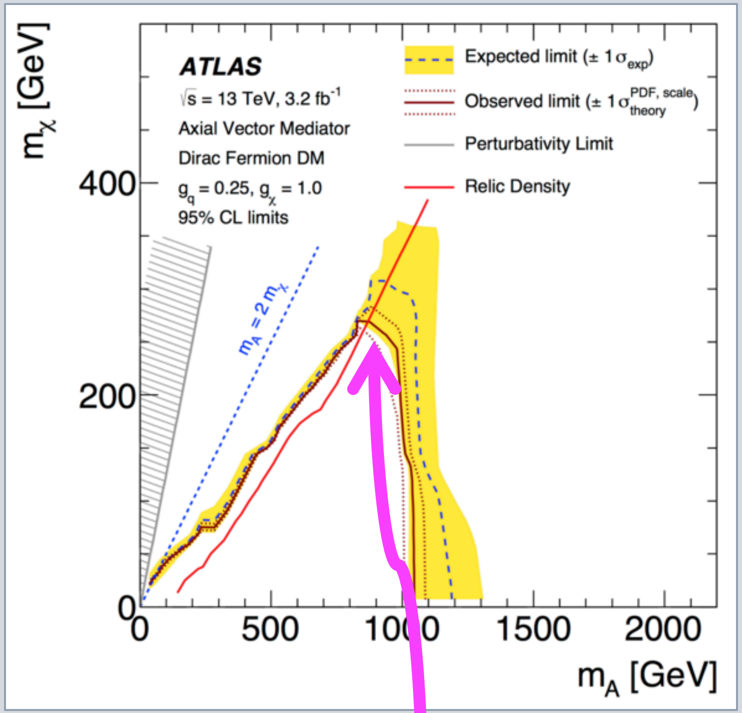
- Also in **EXO-12-055, EXO-15-003, EXO-16-013** and **LHC DM WG** (arXiv/1603.04156)

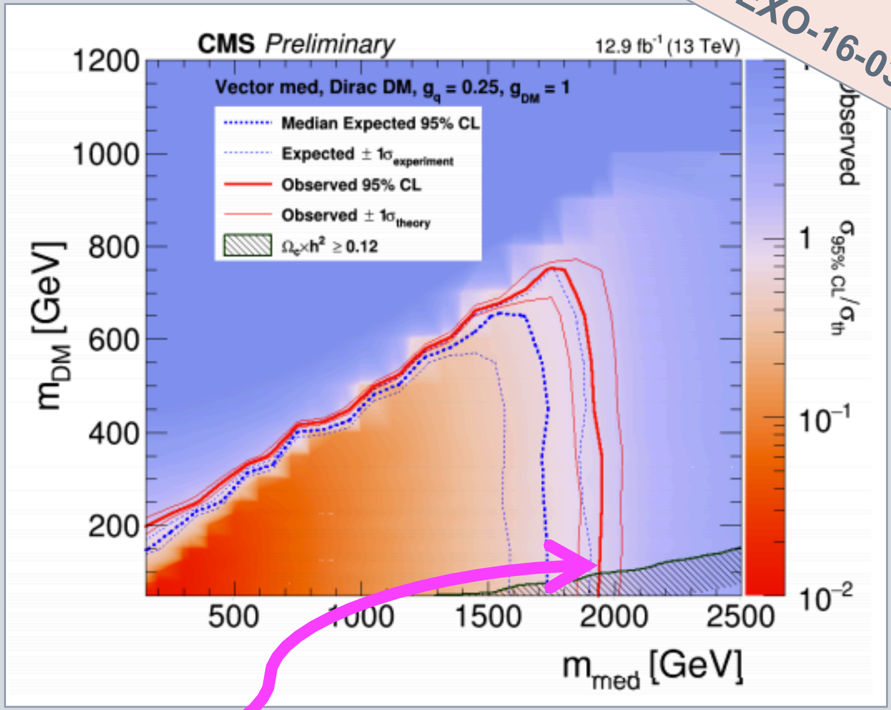
LHC vs Cosmos

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

New! (ICHEP)
CMS PAS EXO-16-039

Vector



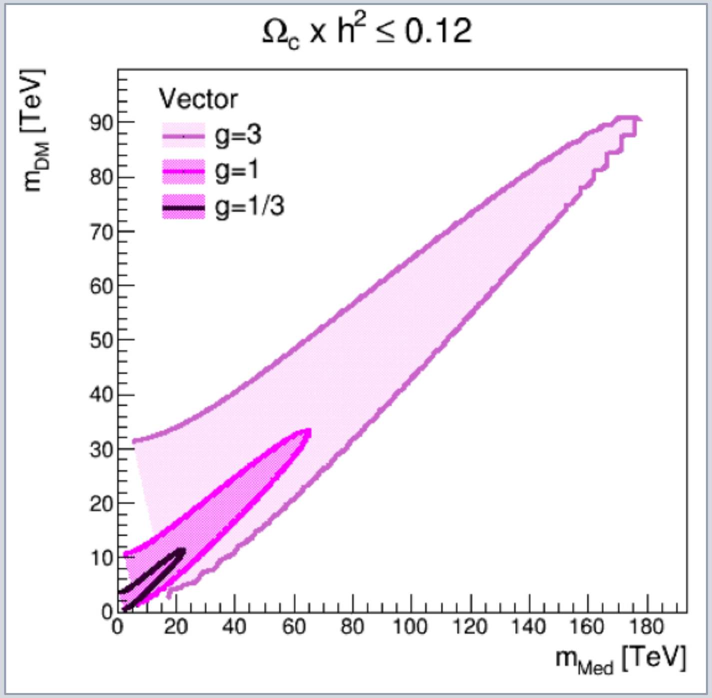


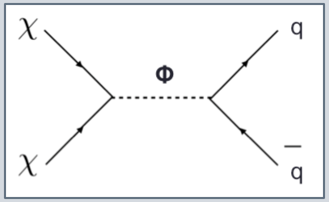
➢ **LHC probes cosmologically preferred regions**

Relic vs Coupling

arXiv:1603.08525

- **Upper bounds** [Vector]





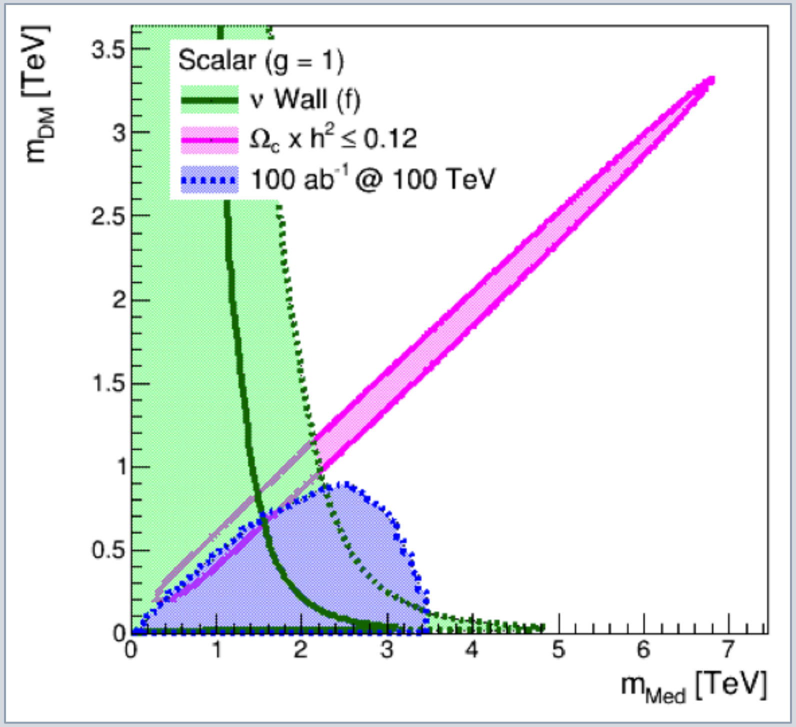
➢ **Constraints scale with coupling**
  - ➢ Allowed region extends to **O(10)-O(100) TeV**

See also FCC-hh BSM: https://indico.cern.ch/event/439927/

FCC vs DD vs Ω_c

- **Complementarity** [Scalar]

100 TeV collider
arXiv/1606.00947



- **Scalar and Axial show clear complementarity**
  - **Vector excluded – Pseudoscalar most challenging**

- *100 TeV collider studies: see also **M.Reece** [yesterday]*

VI.

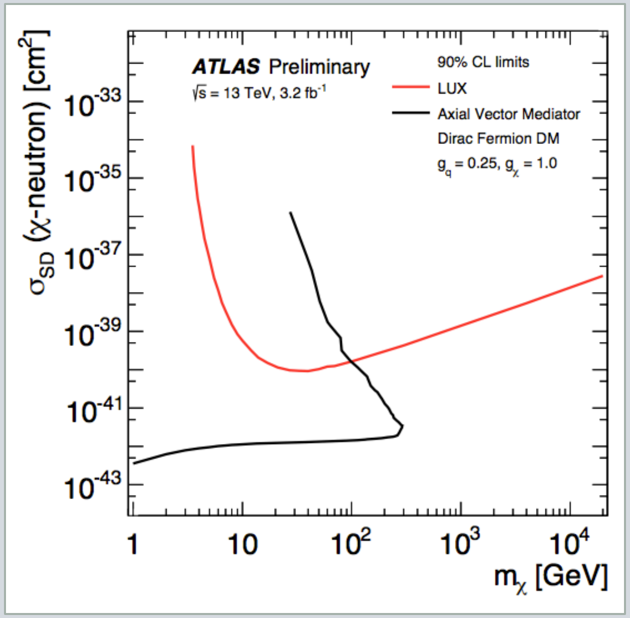
Resonances
mediator searches

#DMatLHC

LHC complementarity

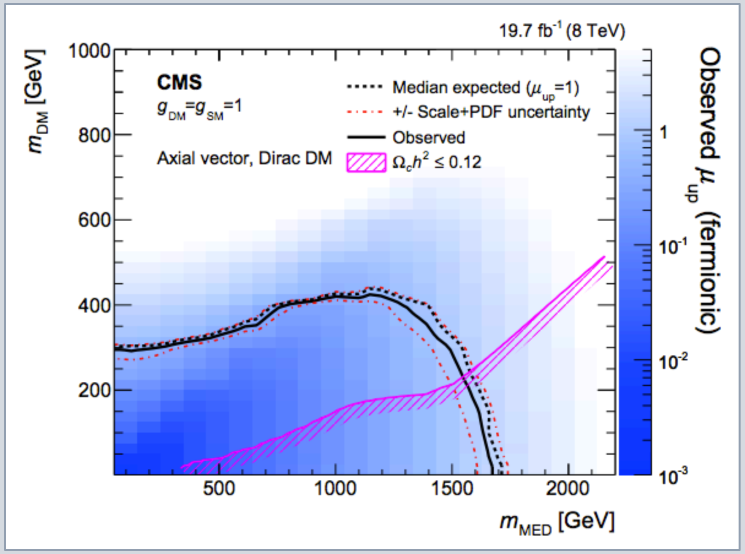
Atlas

Atlas vs **LUX**



CMS

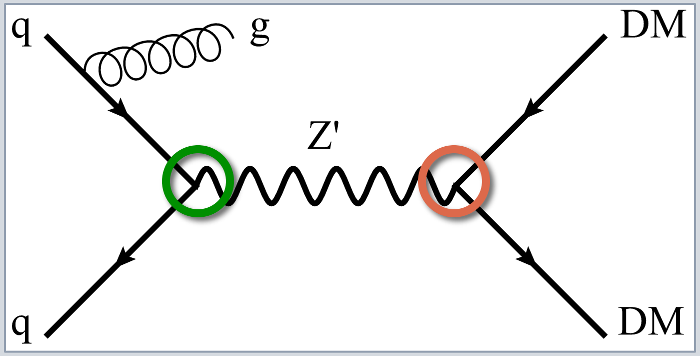
CMS vs Ω_c

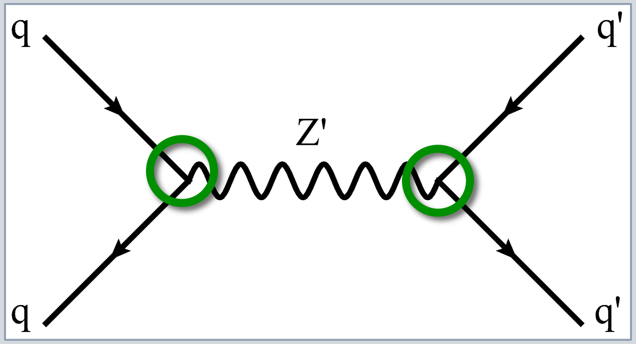


➢ **But how about other mediator constraints ?**

Z' vs Z'

- **Monojet** vs **Dijet**





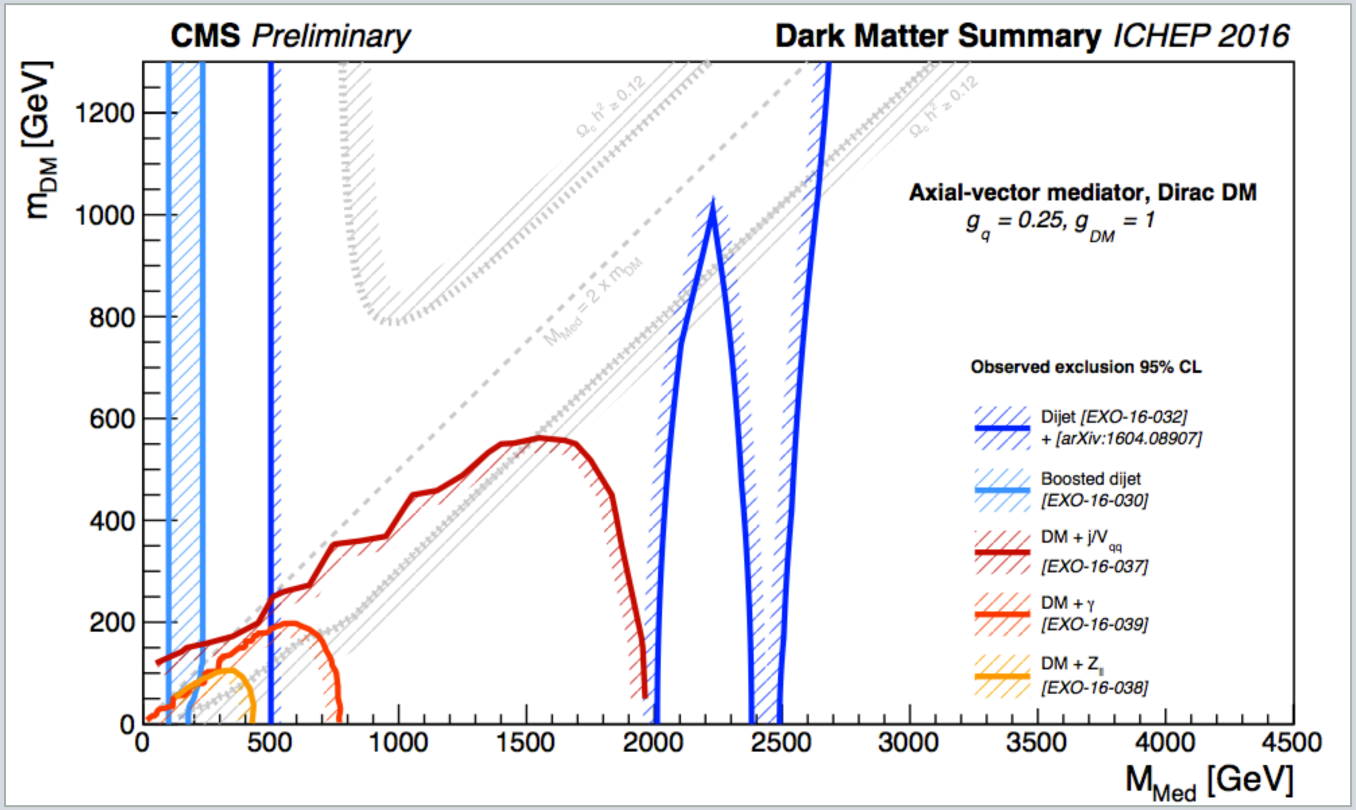
- **Possibly same mediator!**
  - Dijet is also a **DM mediator** search!
  - Use dijet search for **DM interpretation**

- *More details on dijet analyses by* ***F.Dias*** *&* ***J.Bendavid*** *[tomorrow]*

CMS dijet

https://cds.cern.ch/record/2208044

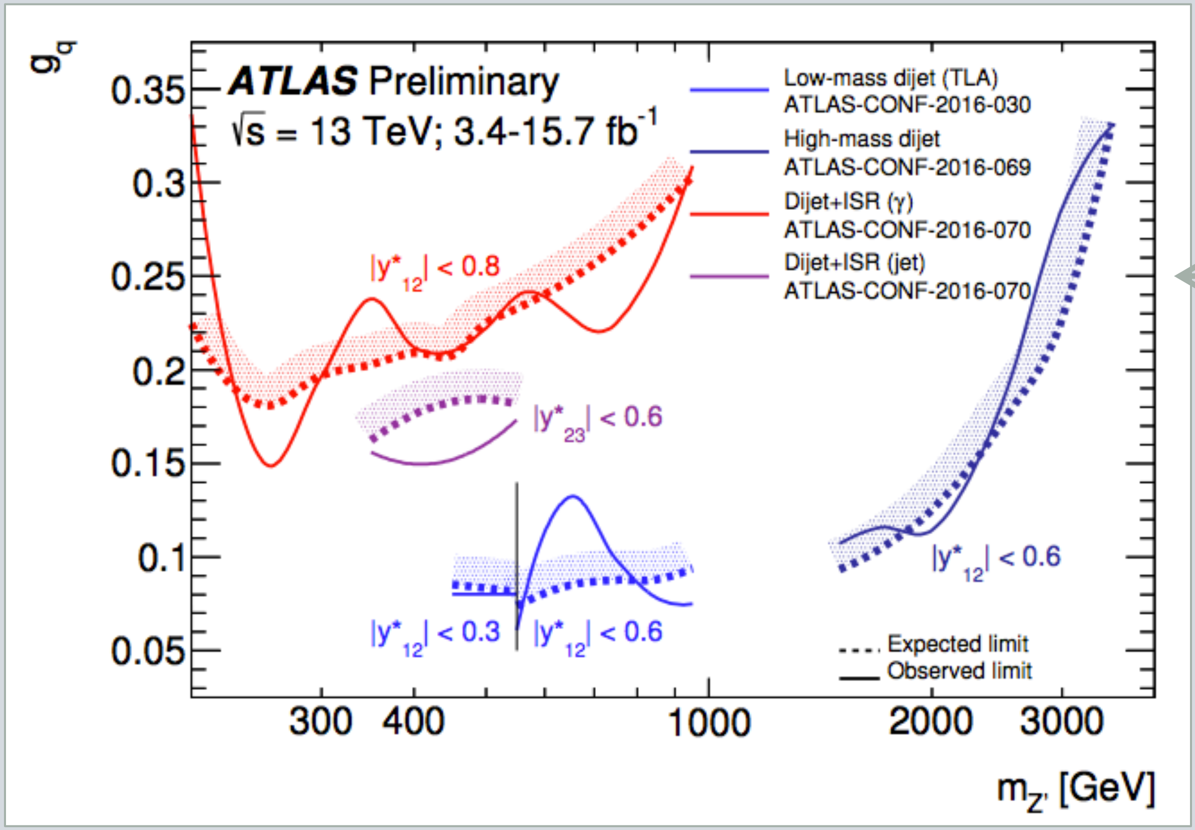
- **MET+X** vs **Dijet**



- High mass till **~2.5 TeV**, low-mass boosted down to **0.1 TeV**

Atlas dijet

- **Coupling vs mass**



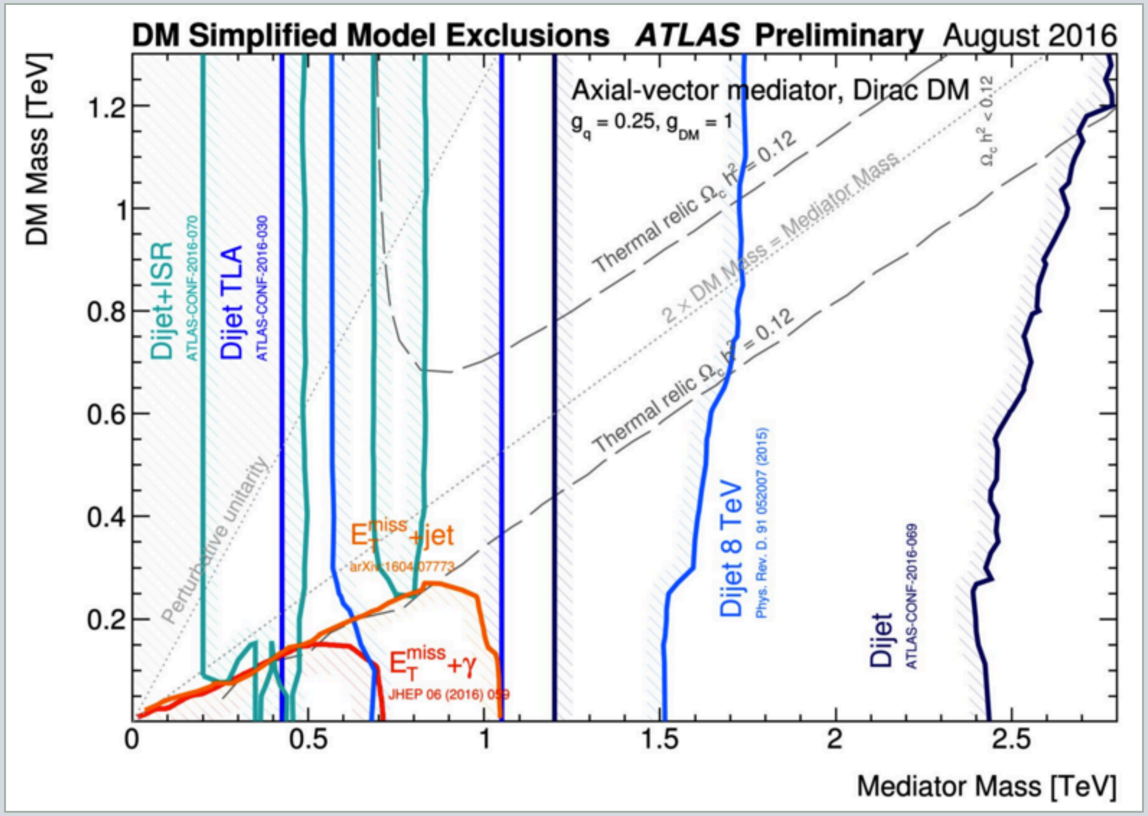
$g_q = 0.25$

➢ Dijet+ISR-γ, dijet+ISR-j, TLA ('scouting'), High mass (13TeV)

*Atlas dijet+ISR reaches **higher masses**, scouting down to **lower masses***

Atlas dijet

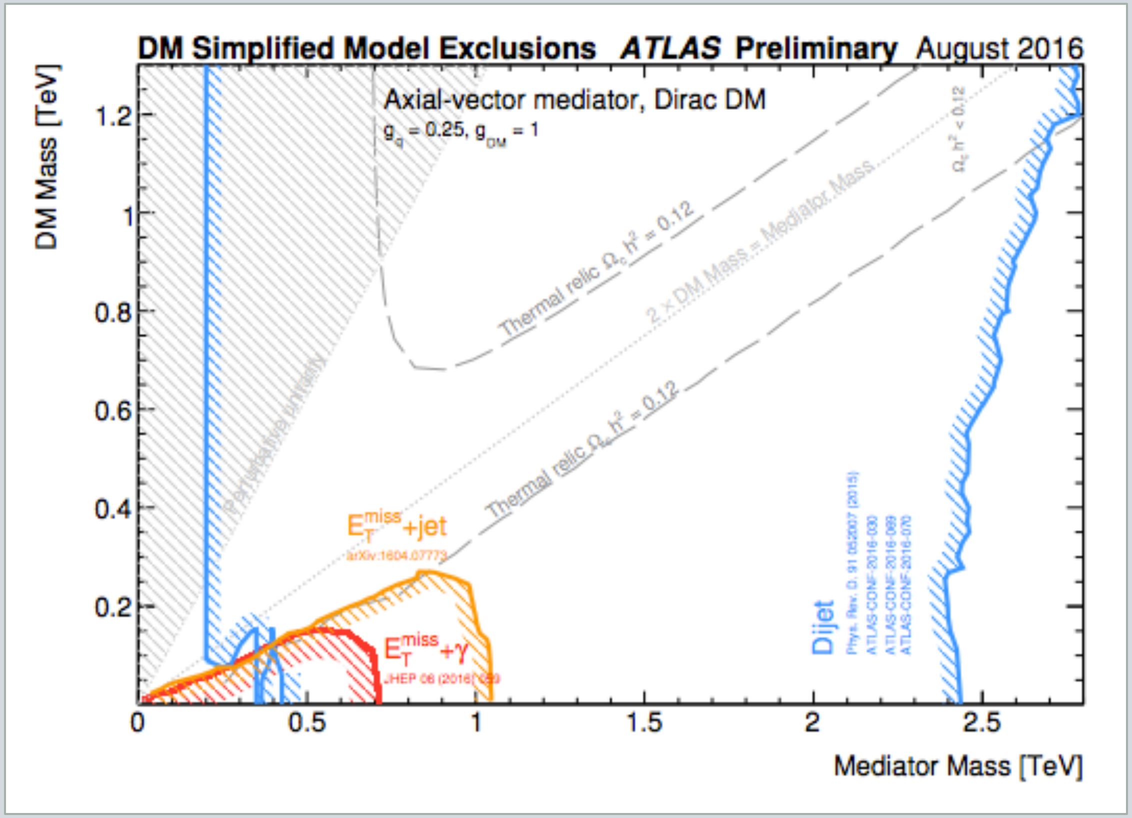
- **Detailed breakdown**



➢ Dijet from low to high mass: dijet+ISR, **TLA**, 8 TeV, **13 TeV**

Atlas mediator constraints

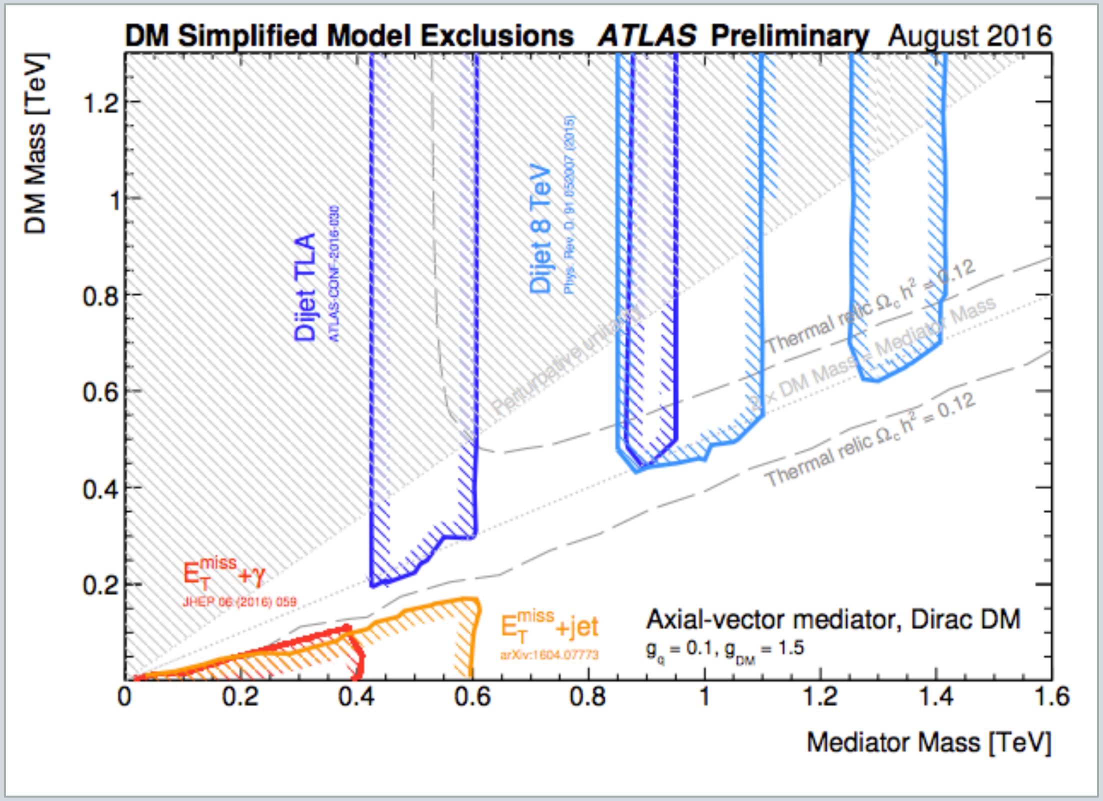
- **Detailed breakdown**



➢ Excluding almost full space **M_{Med} < 2.5 TeV** *(for these couplings)*

Alternative scenarii

- **Modified coupling** *(g_q = 0.1, g_{DM} = 1.5)*



➢ **Dijet plays less dominant role**

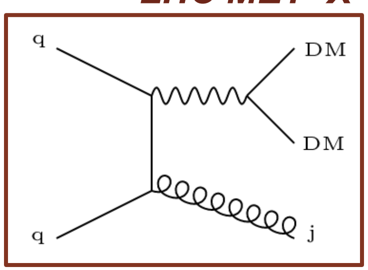
➢ Expected for small g_q & very large g_q

Conclusions

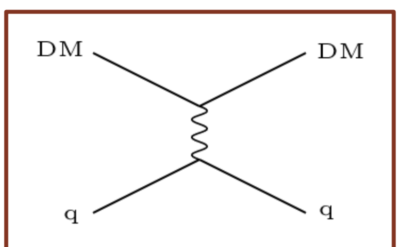
- **Broad range of LHC searches for Dark Matter**
  - MET+X: **X = j / γ / V / Z / t(t) / b(b) / H**
- **LHC experiments also sensitive to Mediator**
  - Benchmark mediators: V & A & S & P
    - ➢ Atlas & CMS can probe **low m_{DM}**
    - ➢ Constrain **M_{Med} ~ 2.5 TeV** and **BR(H→inv) < 24%**
- **Collider searches complementary**
  - (In)direct detection, Cosmology
    - ➢ Interplay with LHC **resonance searches**

➢ **This will be an exciting decade for Dark Matter!**

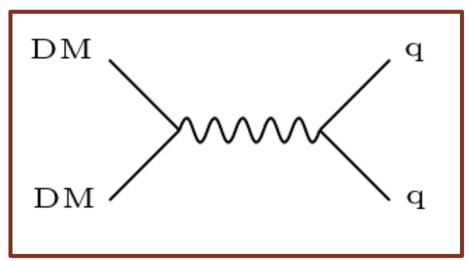
LHC MET+X



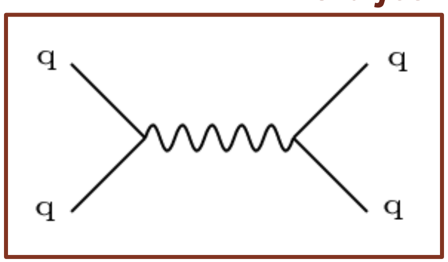
DD / ID



CMB



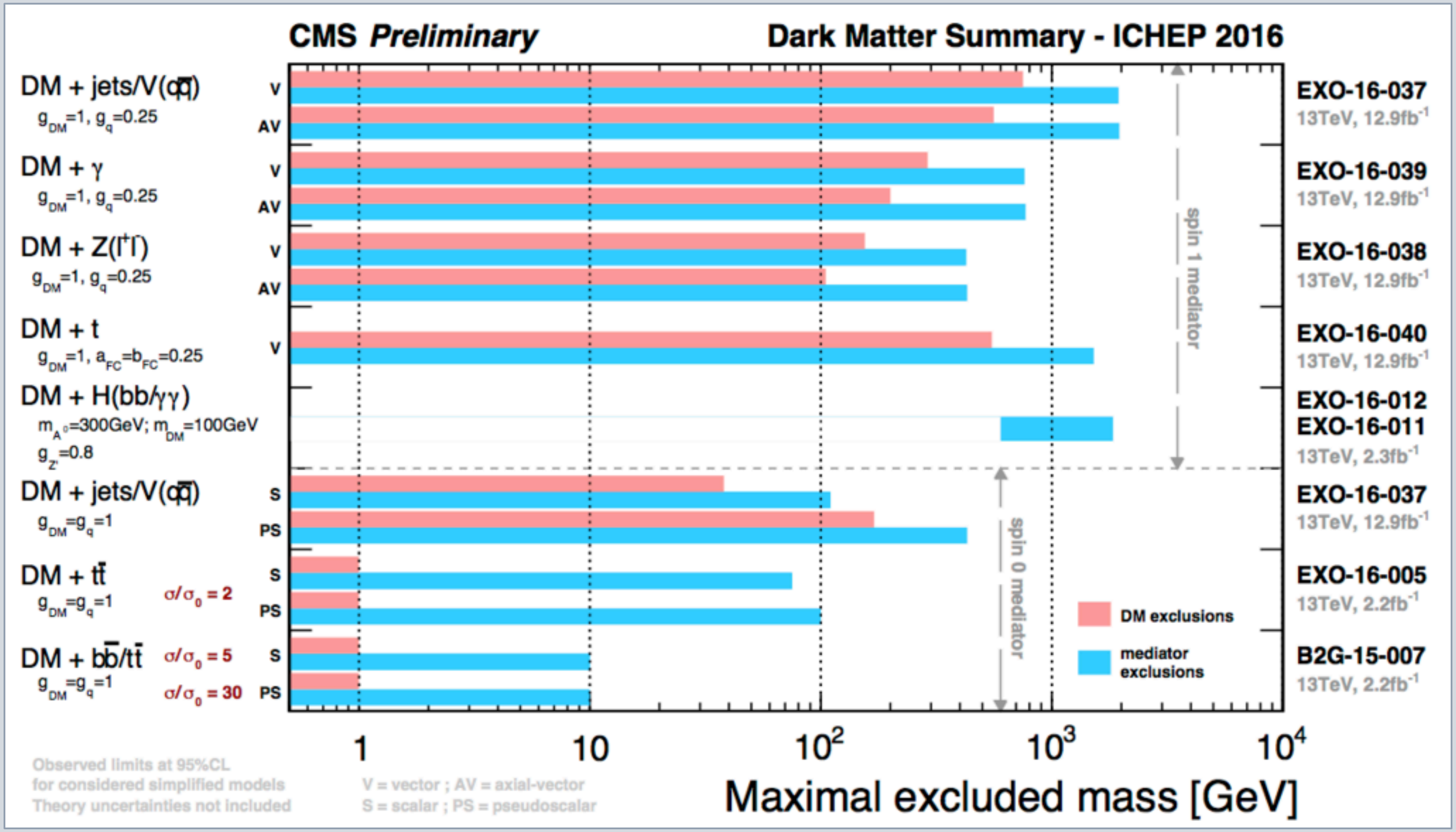
LHC dijet



Thank you for your attention!

@Tristan_duPree

CMS Bar chart



Analysis summary table

Analysis	Dataset	Public link		
Production search:				
E_T^{miss}+jet	2015	Paper:	EXOT-2015-03	
$E_T^{miss}+\gamma$	2015	Paper:	EXOT-2015-05	
E_T^{miss}+Z($\rightarrow \ell\ell$)	2015+2016	Note:	ATLAS-CONF-2016-056	new!
E_T^{miss}+W/Z($\rightarrow qq$)	2015	Paper:	EXOT-2015-08	new!
E_T^{miss}+H($\rightarrow bb$)	2015	Note:	ATLAS-CONF-2016-019	
E_T^{miss}+H($\rightarrow \gamma\gamma$)	2015+2016	Note:	ATLAS-CONF-2016-087	new!
E_T^{miss}+H($\rightarrow \ell\ell\ell\ell$)	2015	Note:	ATLAS-CONF-2015-059	
E_T^{miss}+b-jets	2015+2016	Note:	ATLAS-CONF-2016-086	new!
$E_T^{miss}+t\bar{t}$ (0ℓ)	2015+2016	Note:	ATLAS-CONF-2016-077	new!
$E_T^{miss}+t\bar{t}$ (1ℓ)	2015+2016	Note:	ATLAS-CONF-2016-050	new!
$E_T^{miss}+t\bar{t}$ (2ℓ)	2015+2016	Note:	ATLAS-CONF-2016-076	new!
Mediator search:				
Dijet	2015+2016	Note:	ATLAS-CONF-2016-069	new!
Trigger-level dijet	2015	Note:	ATLAS-CONF-2016-030	
Dijet+ISR	2015+2016	Note:	ATLAS-CONF-2016-070	new!
Summary plots:				
Mediator searches	2015+2016	Plot:	Summary plot page	new!
Search combination	2015+2016	Plot:	Summary plot page	new!

CMS 13 TeV Searches For Dark Matter

	X	Dataset	CMS Documentation
Focus of this talk	jet or V (hadronic)	2016, 12.9 fb	EXO-16-037
	photon	2016, 12.9 fb	EXO-16-039
	Z (ll)	2015, 2.3 fb	EXO-16-010
	Z (ll)	2016, 12.9 fb	EXO-16-038
	Higgs (bb)	2015, 2.3 fb	EXO-16-012
	Higgs (γγ)	2015, 2.3 fb	EXO-16-011
	tt (semilep+had)	2015, 2.2 fb	EXO-16-005
	t (hadronic)	2016, 12.9 fb	EXO-16-040
Previous Results	jet or V (hadronic)	2015, 2.3 fb	EXO-16-013
	photon	2015, 2.3 fb	EXO-16-014
	bb and tt	2015, 2.2 fb	B2G-15-007
	t (hadronic)	2015, 2.3 fb	EXO-16-017