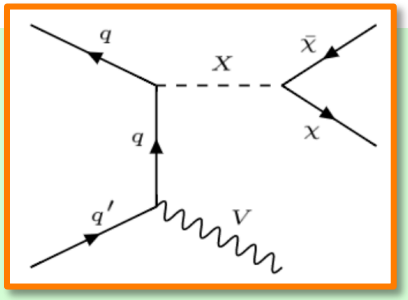
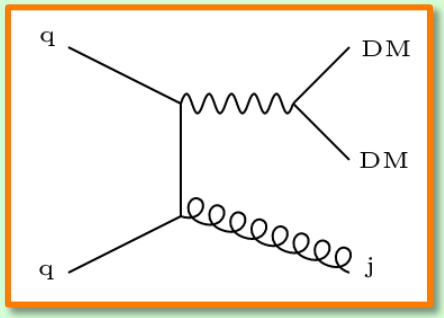
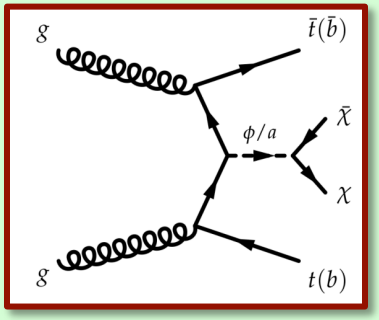
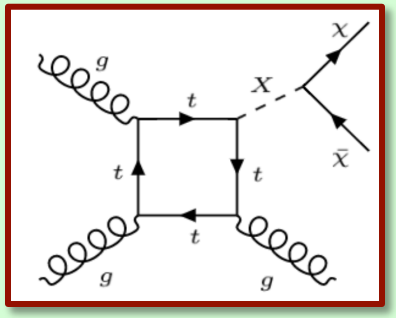
“Summaries of CMS Dark Matter searches”



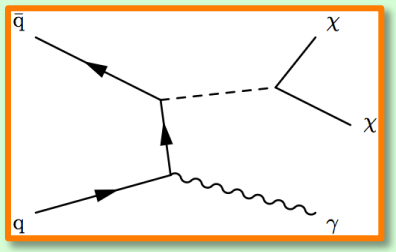




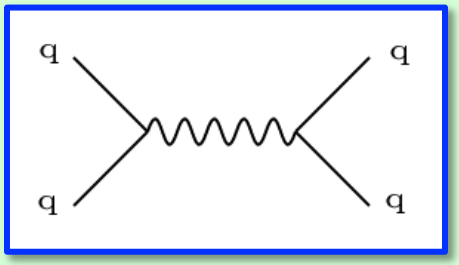
MET+X S&P



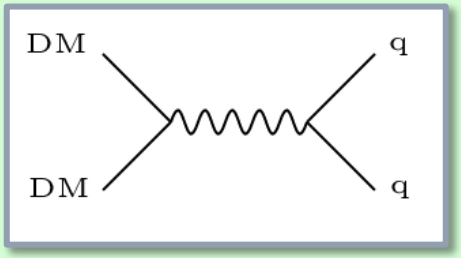
MET+X V&A



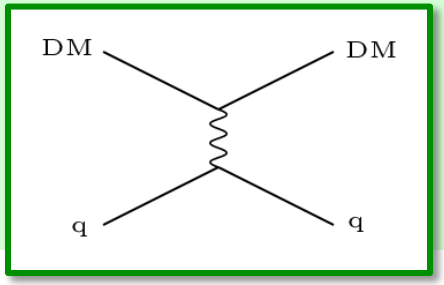
LHC dijet



CMB / ID



DD



- **S&P** *[MET+X, X = j/tt/bb]*
- **V&A** *[MET+X, X = j/V/Z/γ/t]*
- **Resonances** *[dijets]*
- **DD & ID/Ω_c**

Tristan du Pree (CERN)

on behalf of the CMS Collaboration

LHC Dark Matter Working Group

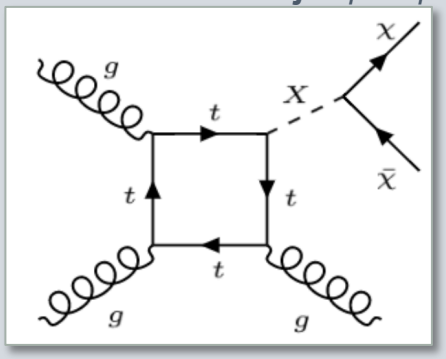
CERN, 19 – 20 September 2016

S&P in Run-2

$g_q = 1, g_{DM} = 1$

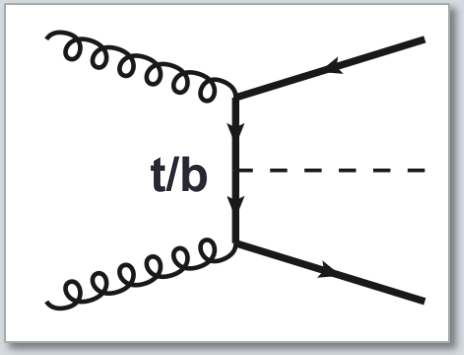
- **Expand** Run-1 **S&P** mediator interpretation strategy
  - **DM+jet(s) & DM+HF**
  - **Yukawa** coupling to SM HF quarks

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



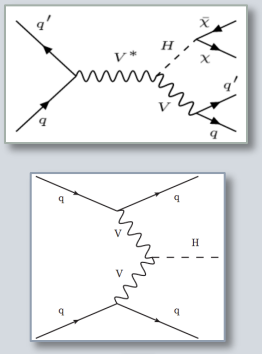
+

***DM+HF**: à la ttH*



(VBF & VH)

(+)



CMS VBF & VH searches for S&P do exist *(see backup)*

- But not yet in CMS summary *(fermion-only coupling)*

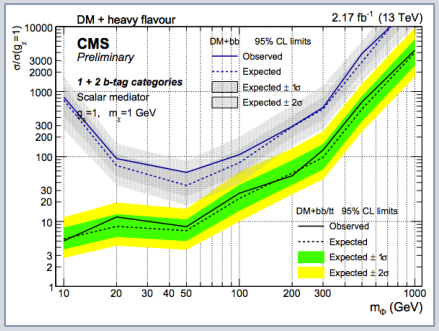
S&P summaries

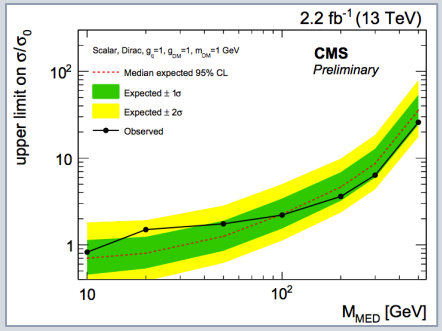
DM+bb: CMS PAS B2G-15-007

DM+tt: CMS PAS EXO-16-005

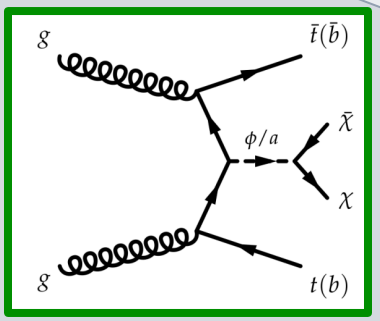
DM+j: CMS PAS EXO-16-037

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

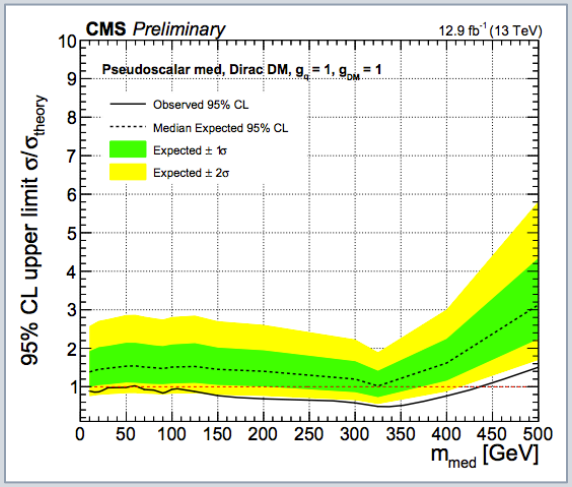


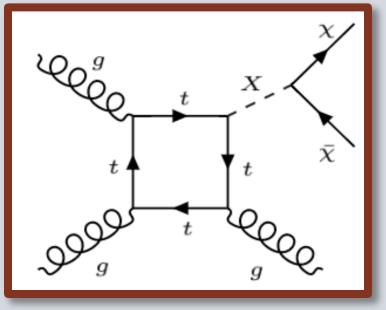


m_{DM} = 1 GeV



- **Mono-jet**
  - fermion



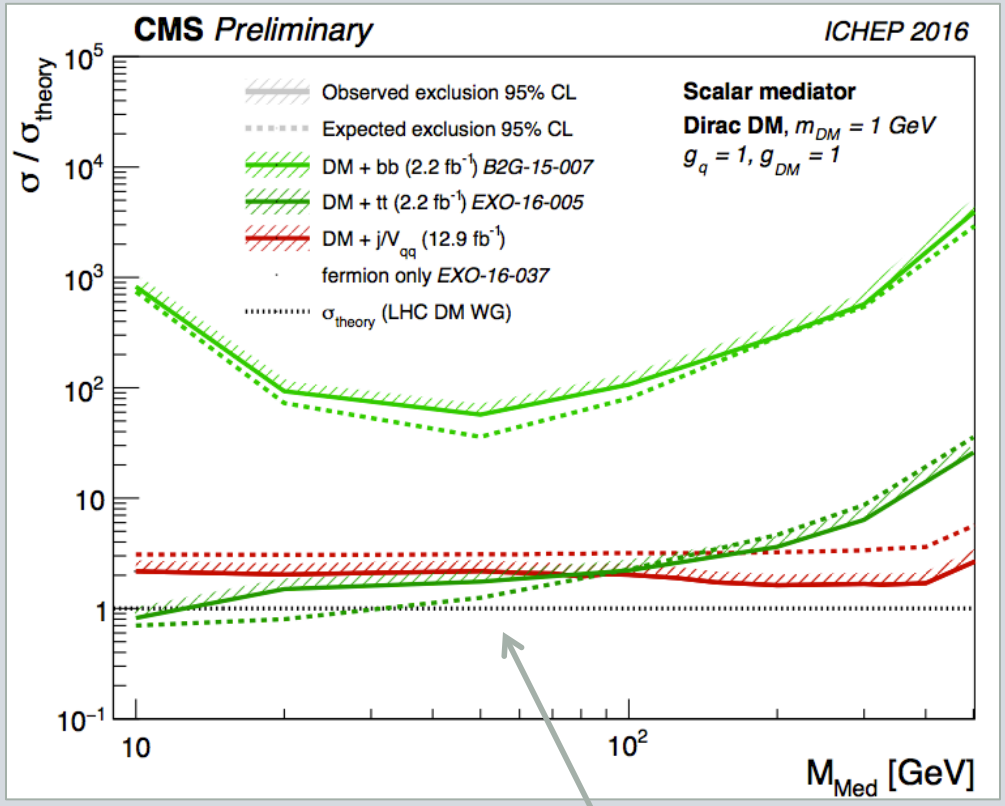


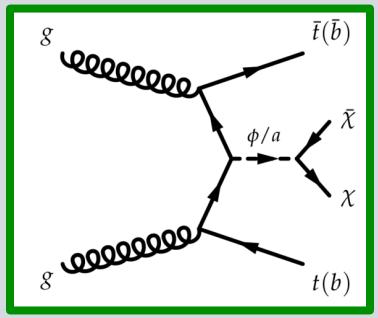
➢ *CMS S&P analyses: dedicated talks by Z.Demiragli (mono-jet) & K.Sung (DM+HF)*

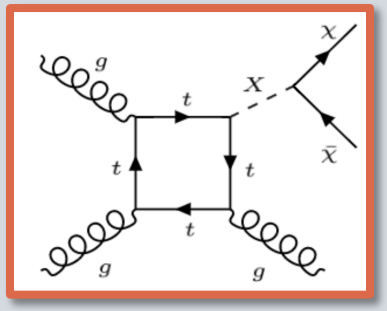
Scalar summary

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

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





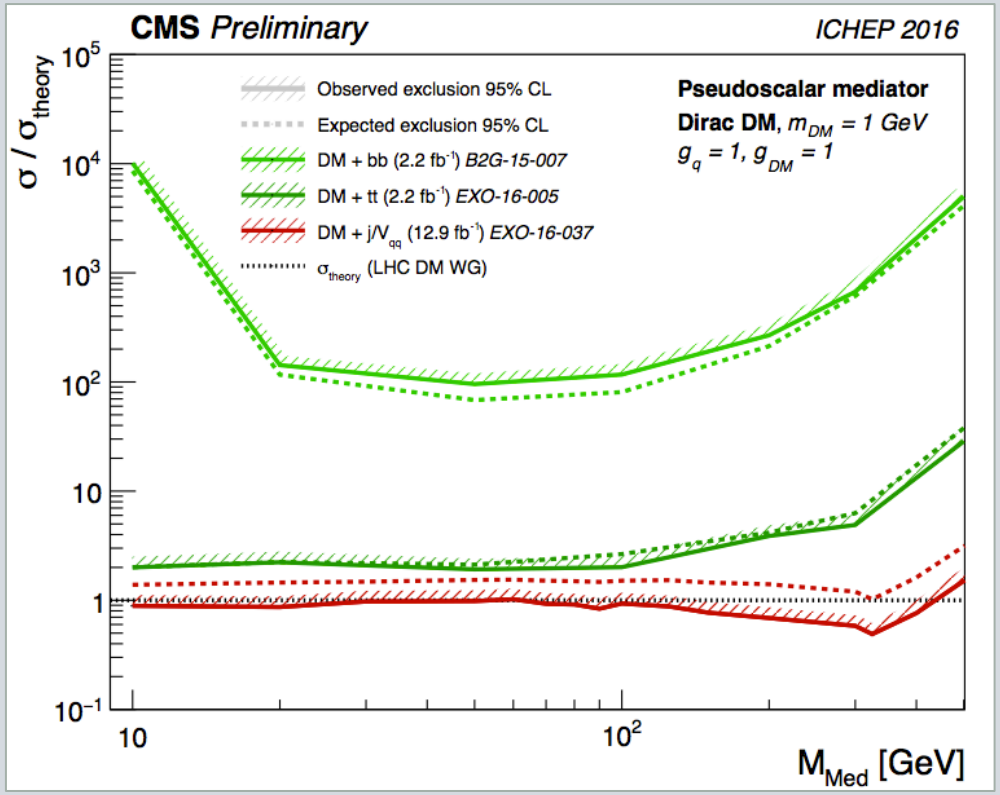


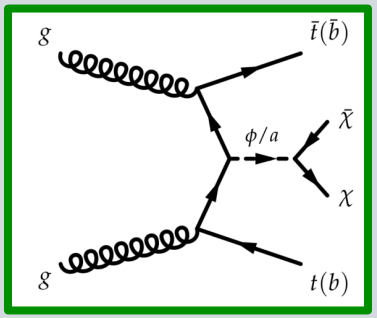
- **Low M_{Med}: sensitivities similar and approaching σ/σ_{theory} ~1**
  - *Case for combined interpretation?*

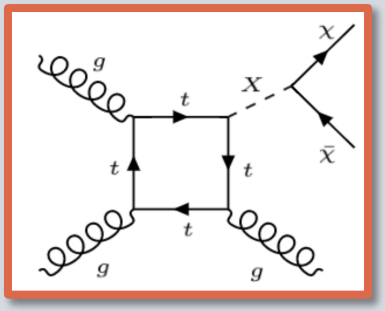
Pseudoscalar

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

- **DM+bb & DM+tt & mono-jet**



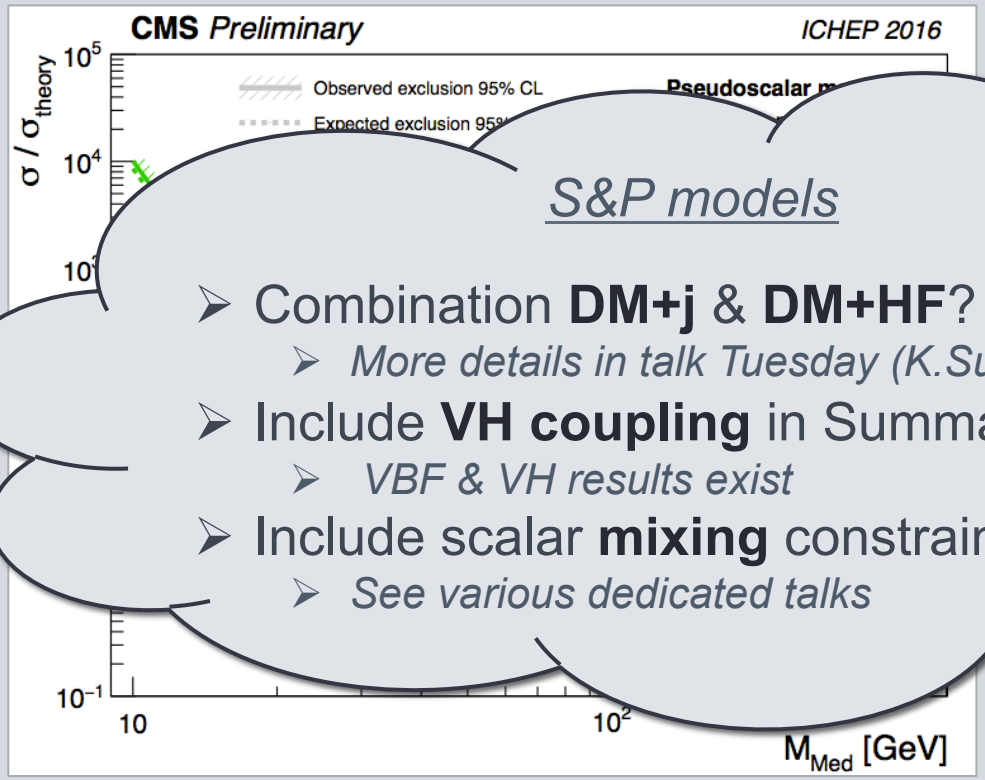




- **Low M_{Med}: sensitivities similar and close to σ/σ_{theory} ~1**
  - *Case for combined interpretation?*

S&P

- **DM+bb & DM+tt & mono-jet**



S&P models

- Combination **DM+j** & **DM+HF**?
  - *More details in talk Tuesday (K.Sung)*
- Include **VH coupling** in Summary?
  - *VBF & VH results exist*
- Include scalar **mixing** constraints?
  - *See various dedicated talks*

- **Similar sensitivities at low M_{med}!**

II.

V&A mediators

MET+X

V&A DM+X

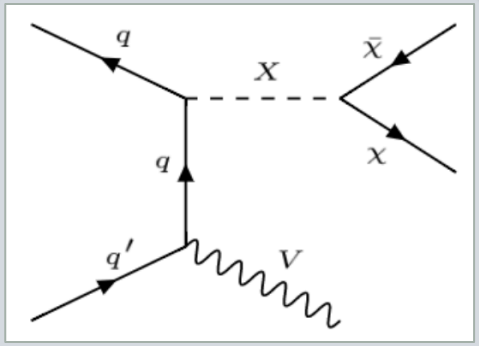
DM+Z: CMS PAS EXO-16-038

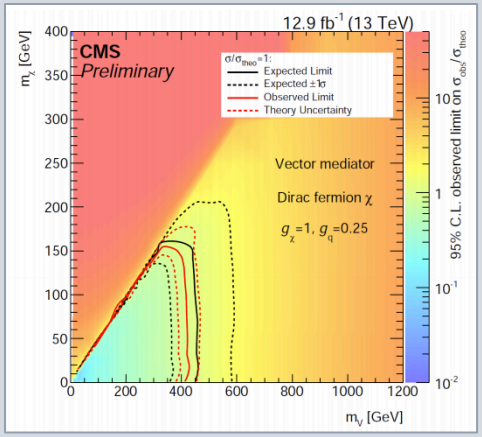
DM+γ: CMS PAS EXO-16-039

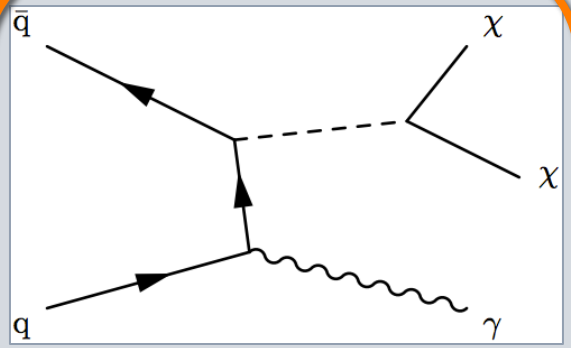
DM+j: CMS PAS EXO-16-037

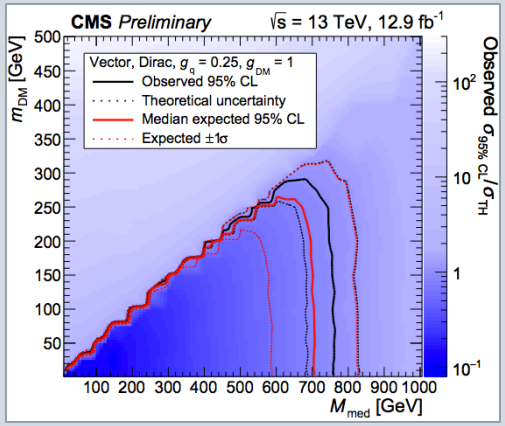
CMS DM+Z, DM+γ, DM+j

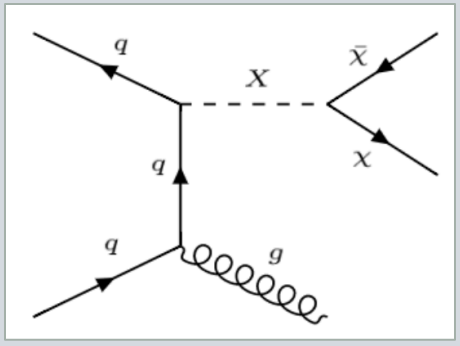
$g_q = 0.25, g_{DM} = 1$

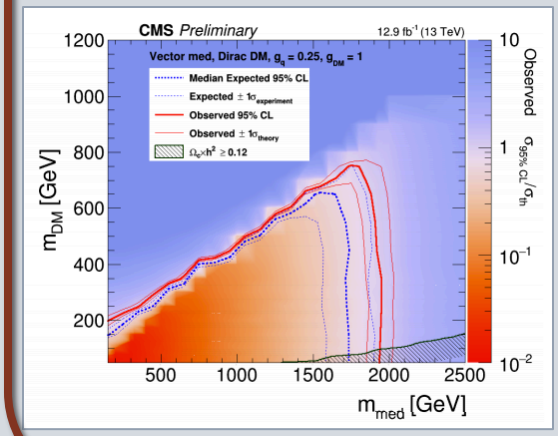








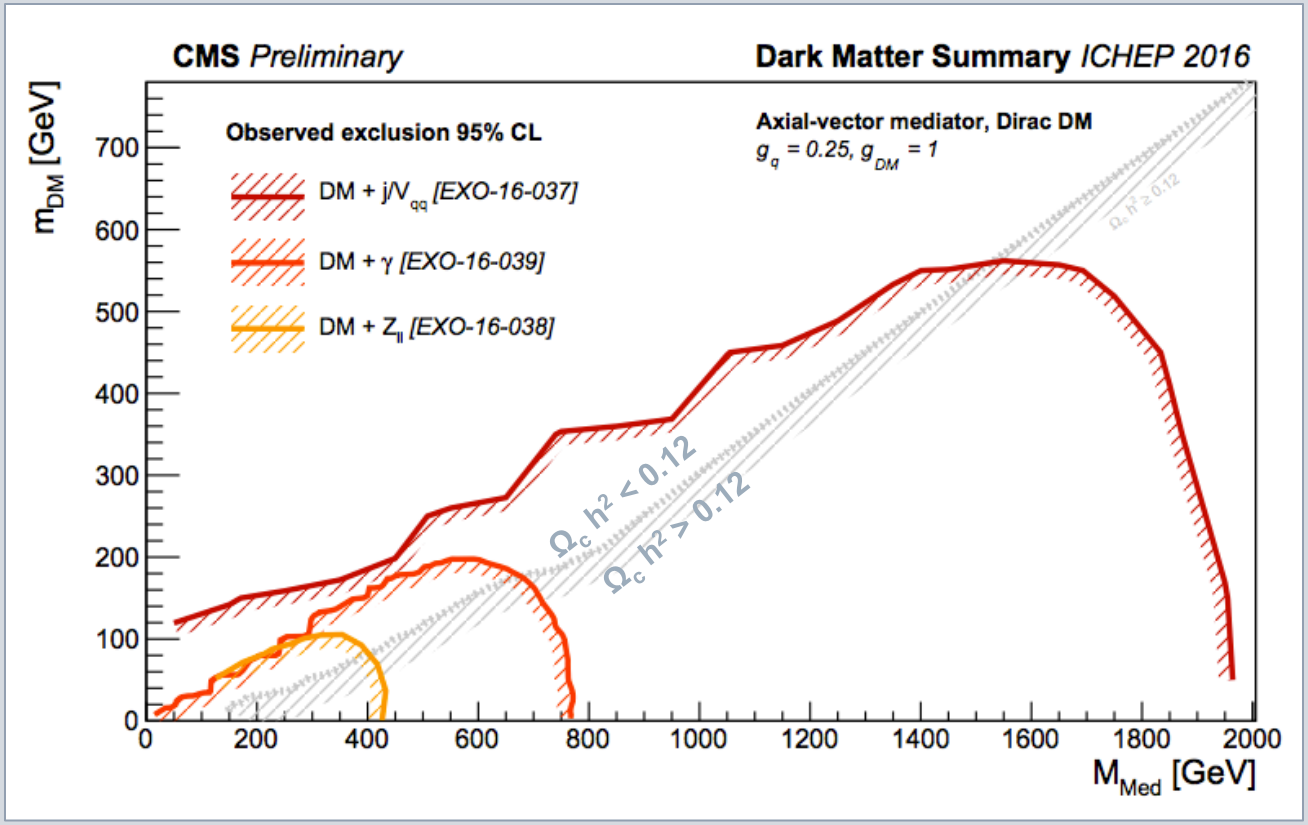




AV Summary

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

- **DM+Z / DM+γ / DM+jet**



- Limits: **M_{Med} ~ 2 TeV, m_{DM} ~ 600 GeV** *(g_q = 0.25, g_{DM} = 1)*
  - Mono-jet most stringent - all channels contribute to interpretation

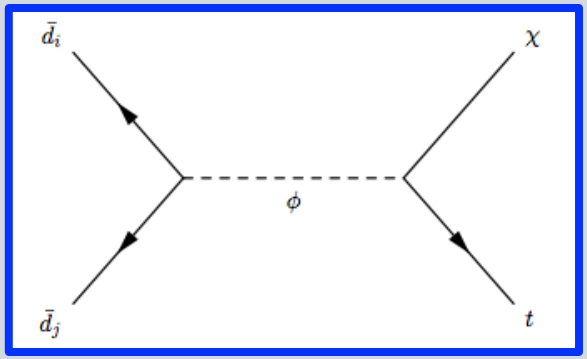
V+

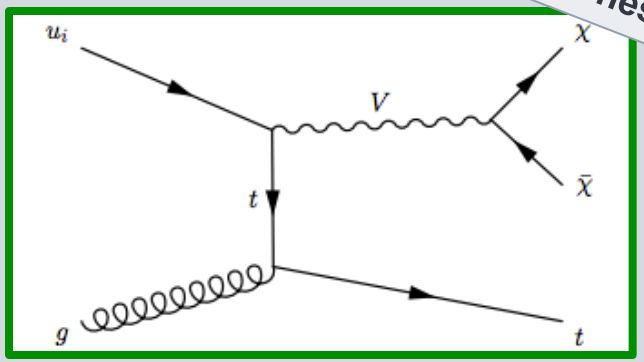
CMS PAS EXO-16-040

Mono-t: Top tagging & Flavor changing

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

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





- Additional parameter
  - **NB:** Other couplings now the same as for default V mediator model

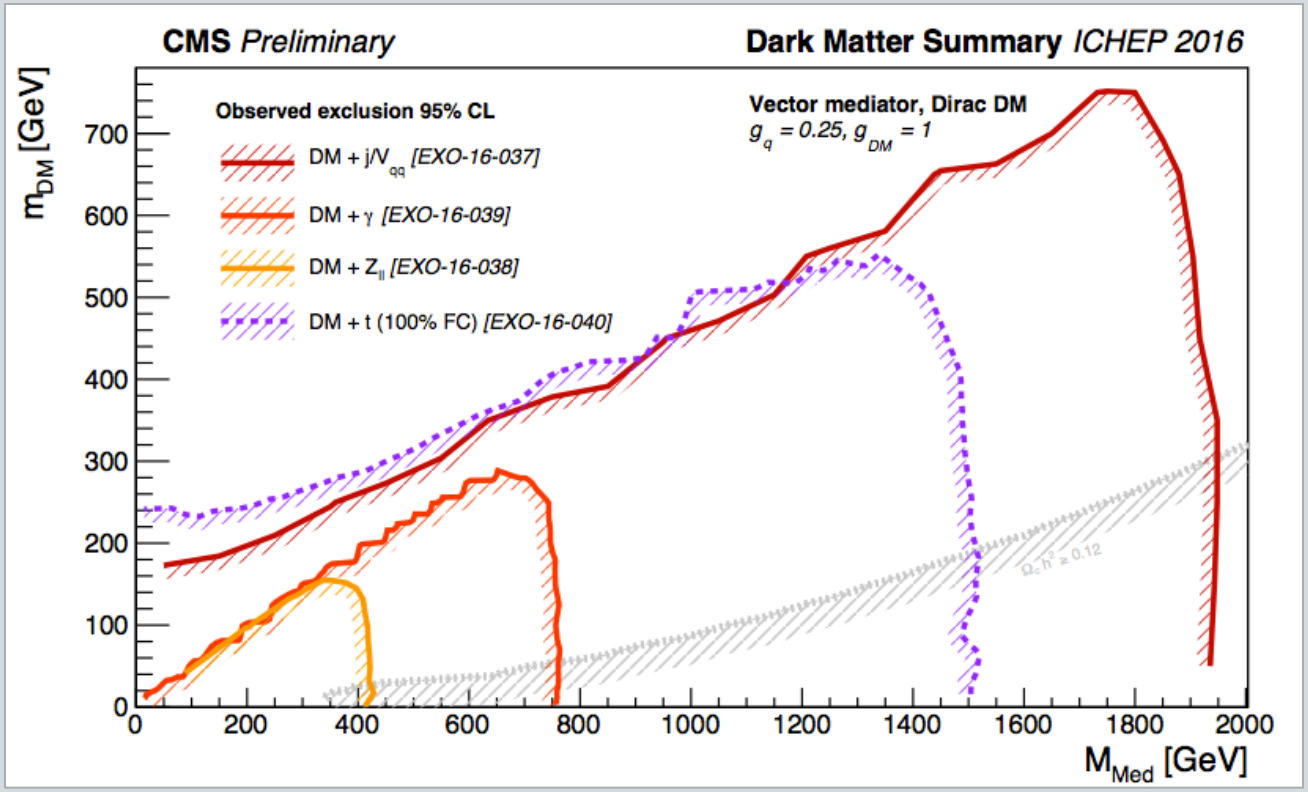
Mono-H searches: also additional parameters

- *Discussed in more detail in dedicated presentation (S.-S.Yu)*

V&A Summary

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

- **MET+X** & **Mono-top**

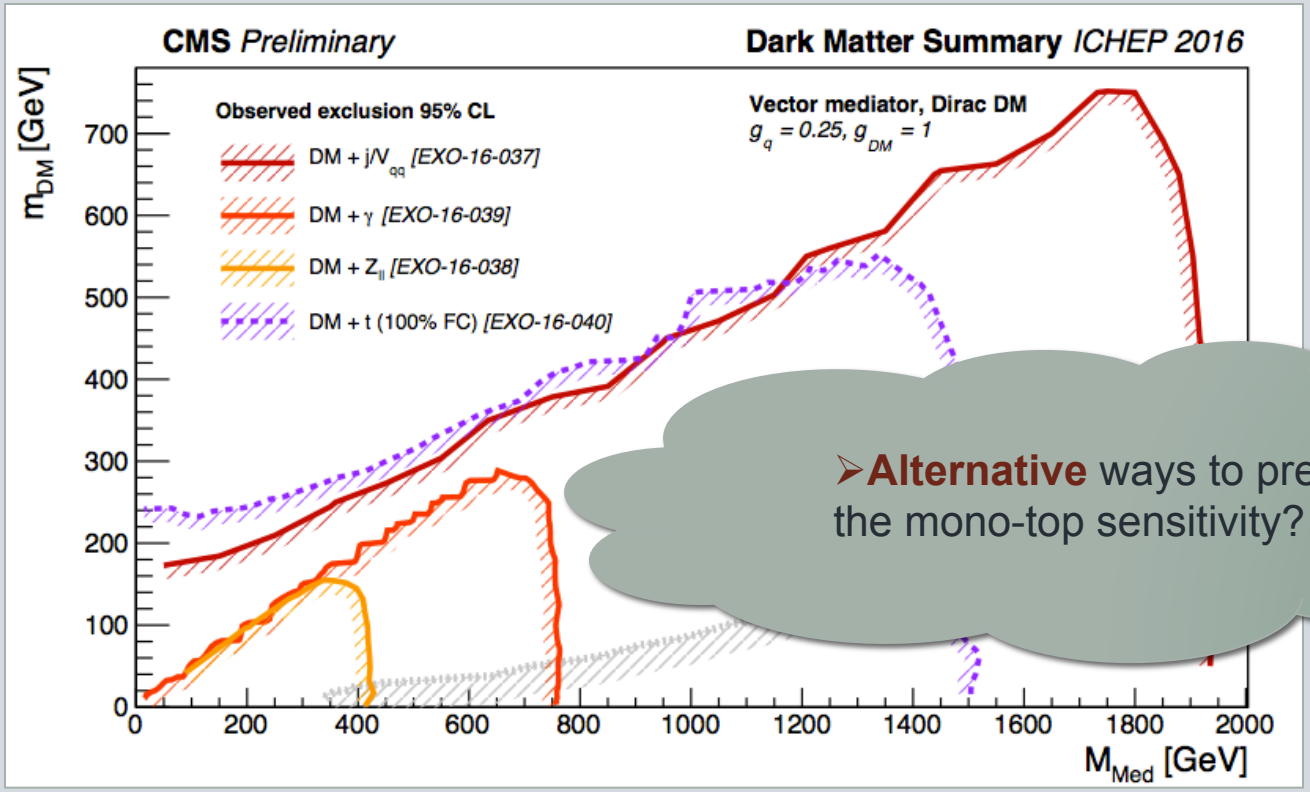


- This plot: **FC = 100%**

V&A Summary

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

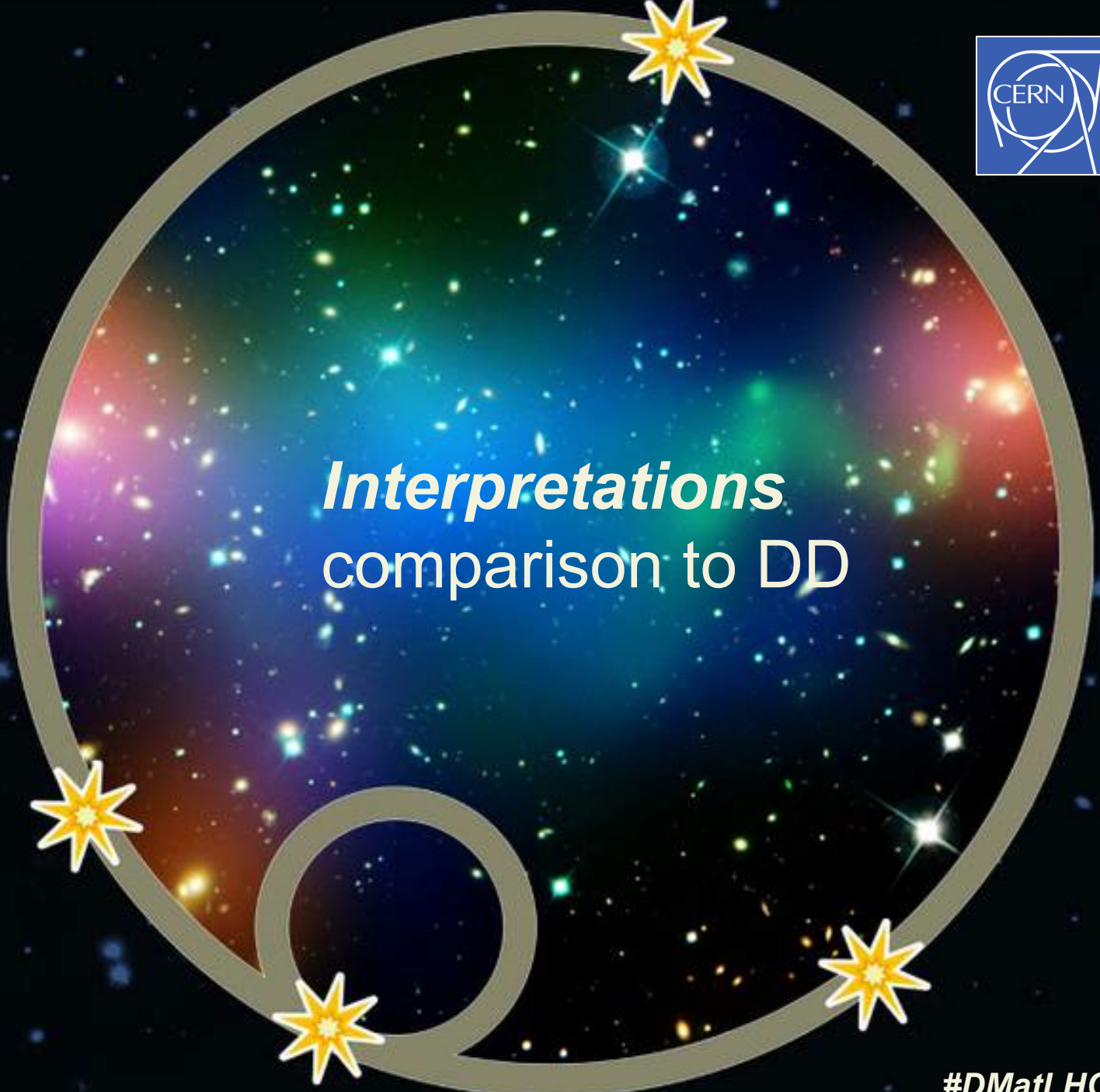
- **MET+X** & **Mono-top**



➢**Alternative** ways to present the mono-top sensitivity?

- **This plot: FC = 100%**

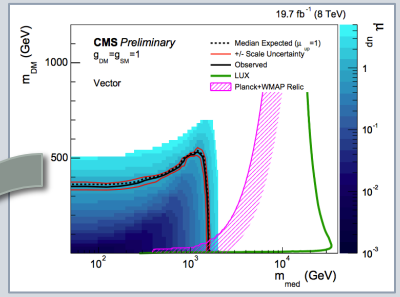
III.

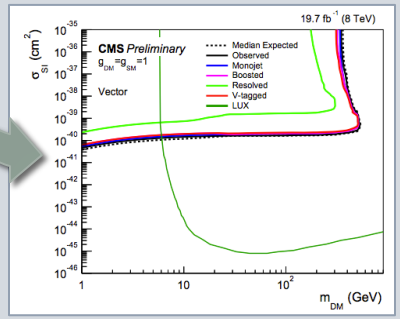


Interpretations
comparison to DD

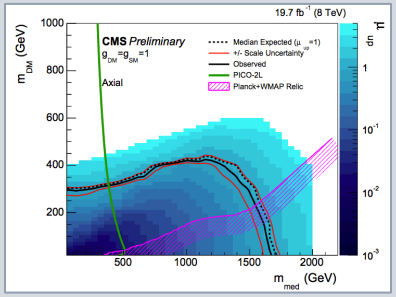
DD interpretation method

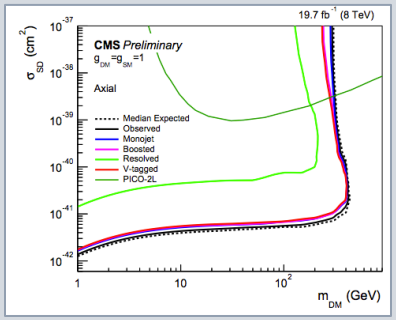
Vector



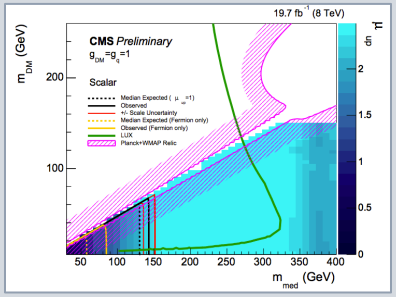


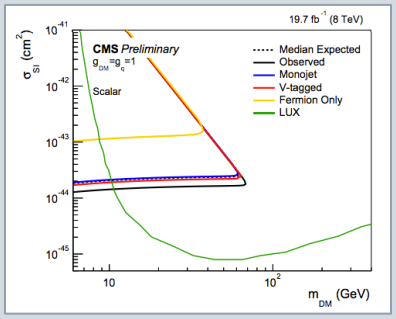
Axial



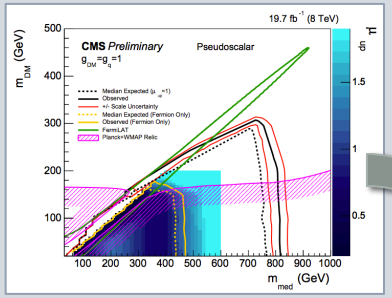


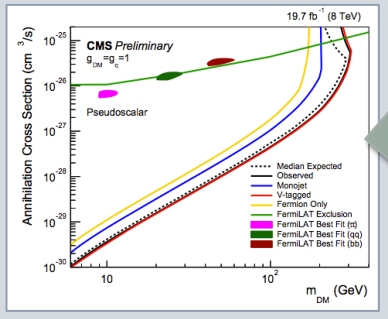
Scalar





Pseudo





90% CL (M,m) → (m,σ)

- **V (SI)**

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

- **AV (SD)**

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

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

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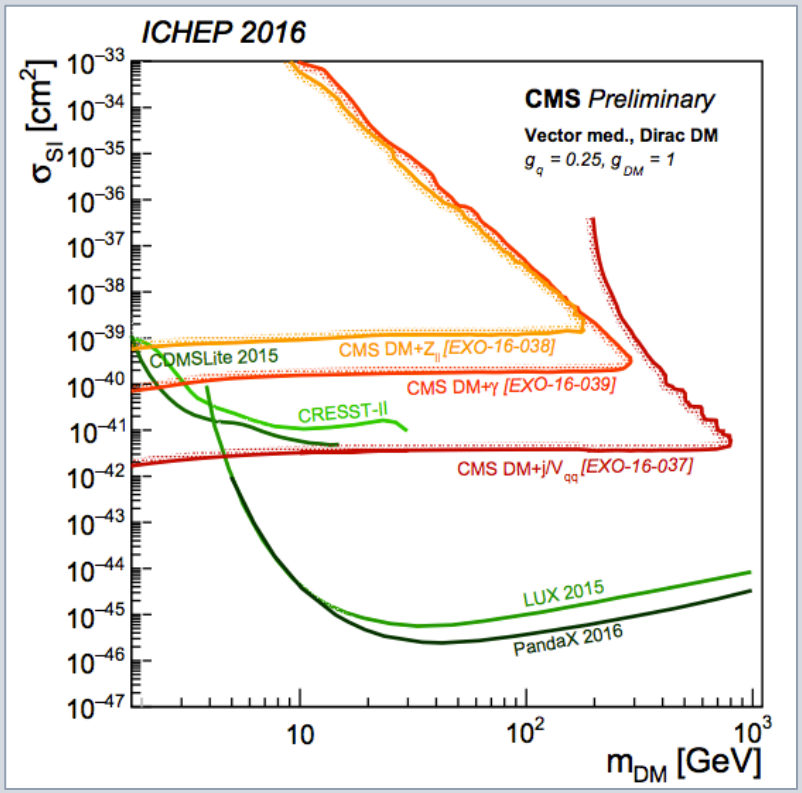
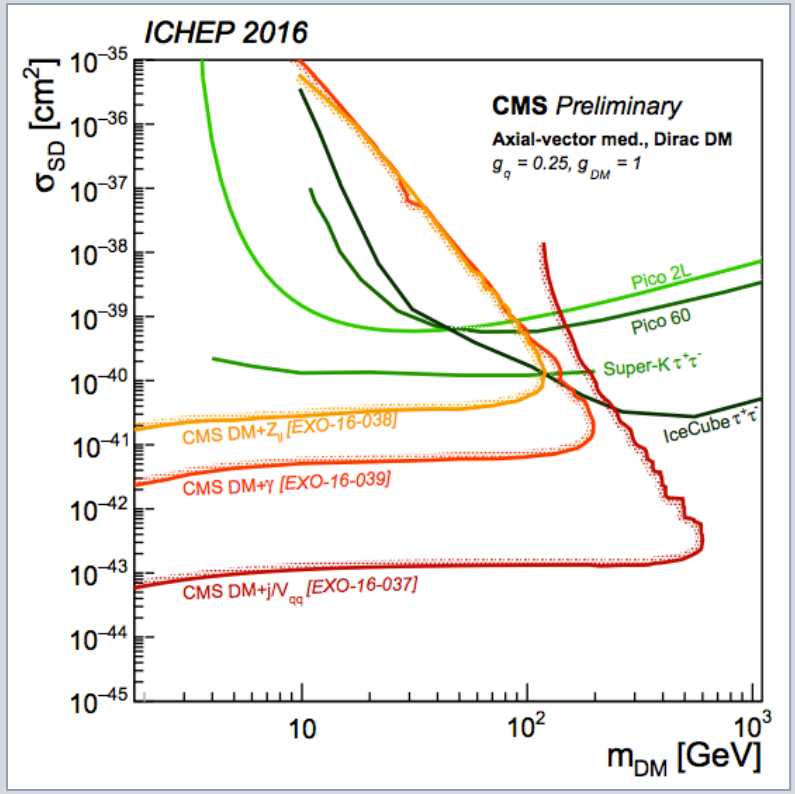
https://cds.cern.ch/record/2208044

LHC vs DD/ID

LHC especially competitive for **SD** *(Pseudoscalar & Axial)*





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

- *Request from DD community to show Cresst/CDMSlite limits down to m_{DM}~0.5 GeV*

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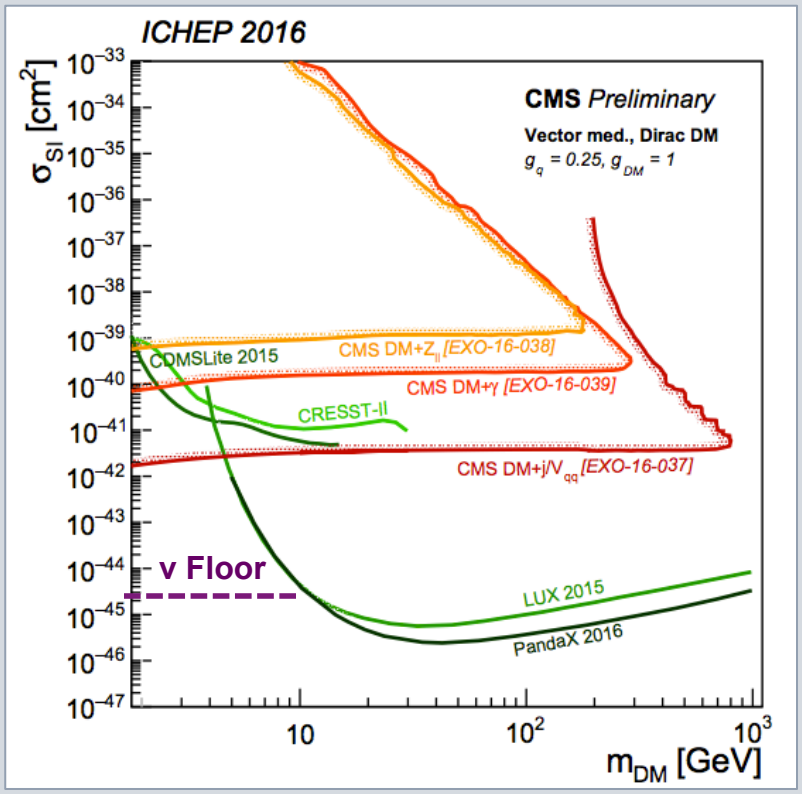
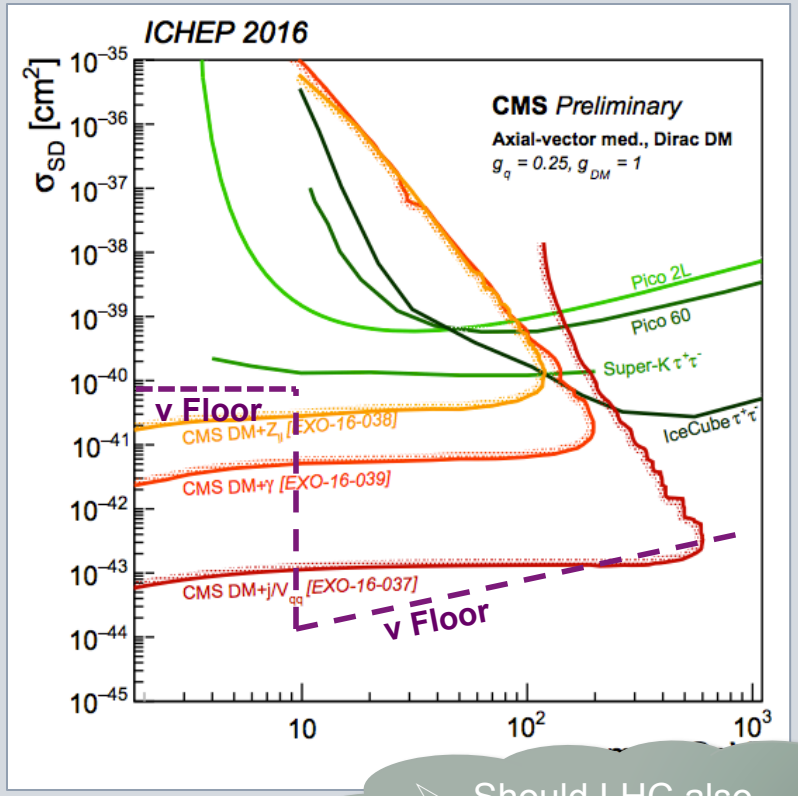
https://cds.cern.ch/record/2208044

v Floor

LHC especially competitive for **SD** & **low mass**





➢ Already below **v floor** for **Spin Dependent!**

➢ Should LHC also show v floor?

SI curve based on http://cdms.berkeley.edu/limitplots/mm/WIMP_limit_plotter.html

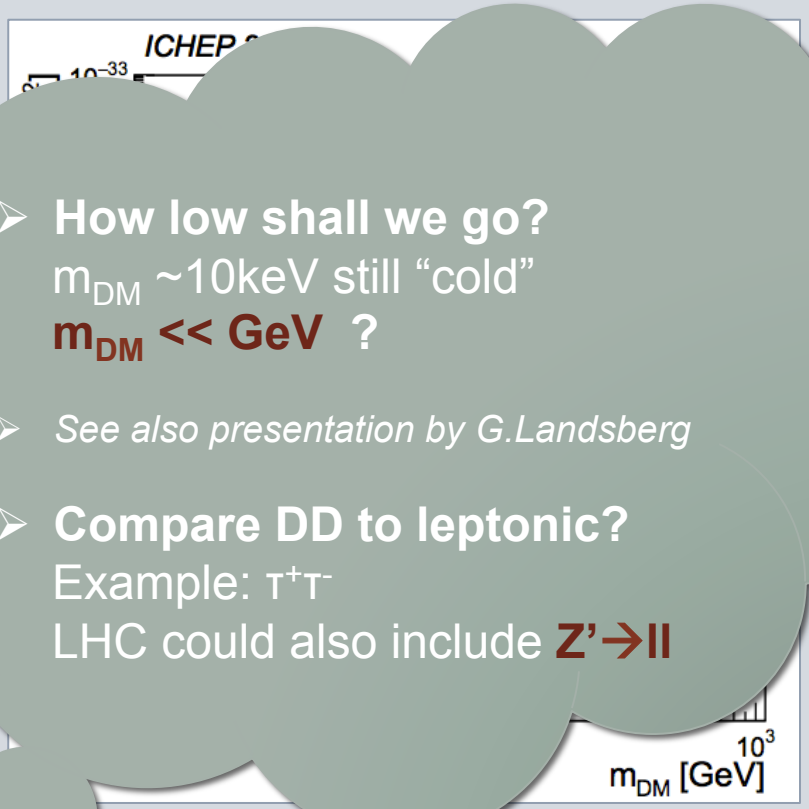
SD curve based on arxiv/1506.08309

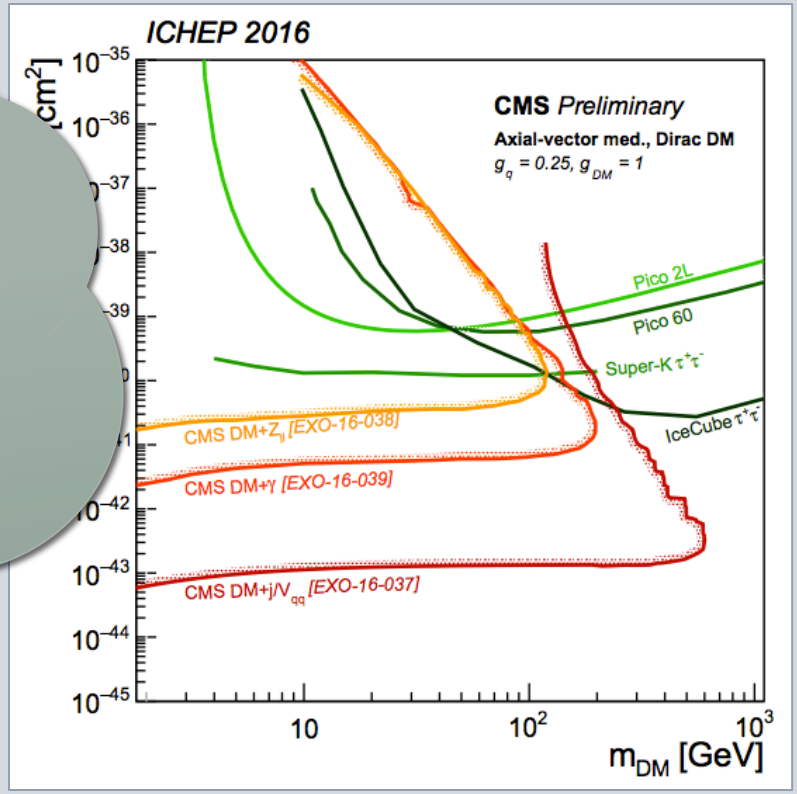
CERN-CMS-DP-2016-057
https://cds.cern.ch/record/2208044

LHC vs DD/ID

LHC especially competitive for **SD** (**Pseudoscalar** & **Axial**)

- **How low shall we go?**
  m_{DM} ~10keV still "cold"
  m_{DM} << GeV ?
- *See also presentation by G.Landsberg*
- **Compare DD to leptonic?**
  Example: $\tau^+\tau^-$
  LHC could also include **Z'→ll**

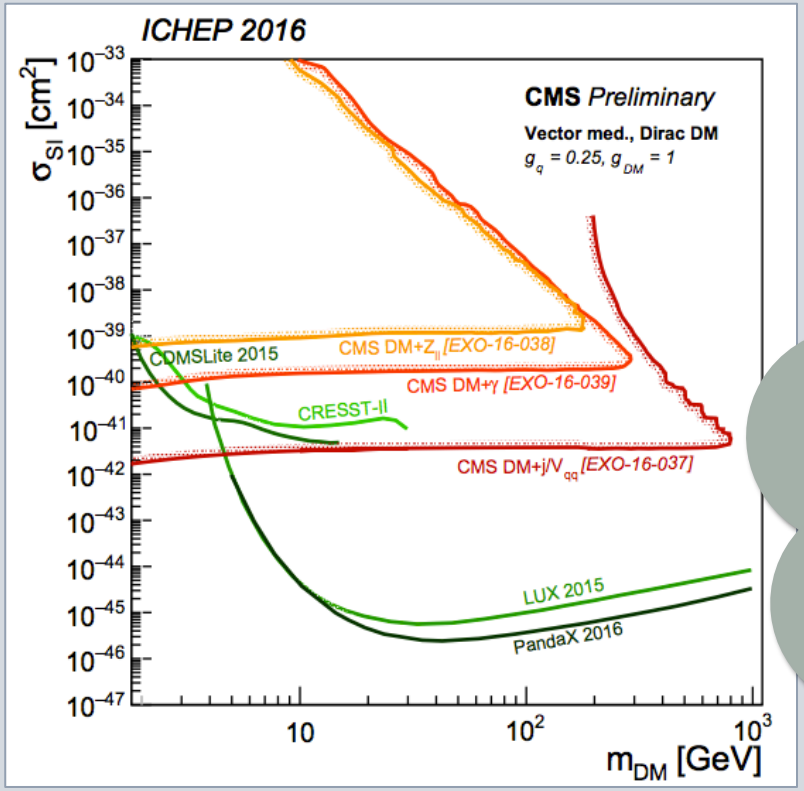




and **LHC** clearly better at **low mass**!

LHC vs DD/ID

LHC competitive for **SD** and **low m_{DM}**!



PandaX PRL arXiv/1607.07400v3

elastic WIMP-nucleon cross sections with a [illegible] cluded value of 2.5×10^{-46} cm^2 at a WIMP mass [illegible] 40 GeV/c^2, the world best reported limit so far. The result is complementary to the searches performed at the LHC, which have produced various WIMP-nucleon cross section limit in the range from 10^{-40} to 10^{-50} (c.f. Refs. [23] and [24]), dependent on the dark matter production models. The PandaX-II experiment continues to take physics data to explore the previously unattainable WIMP parameter space.

Comparison to DD

- **DD experiments often don't show LHC**
  Some progress recently…
  LHC cited in PRL & sometimes shown at TeVPA
  … but not yet standard

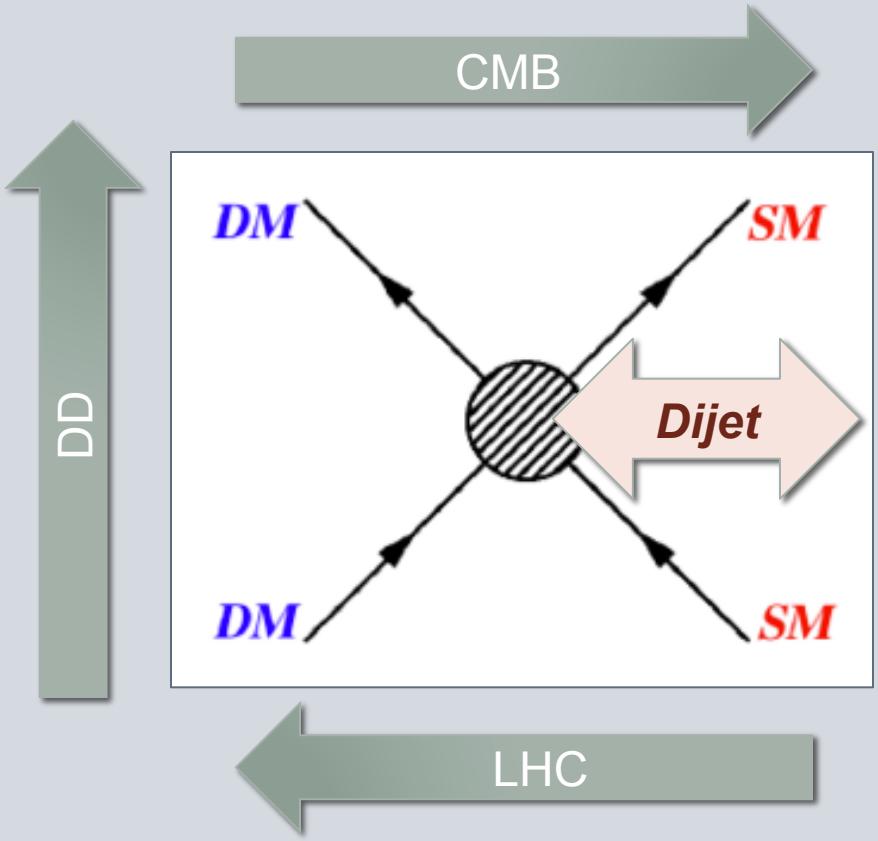
IV.

Resonances
mediator searches

#DMatLHC

LHC vs DD vs Relic vs Dijet

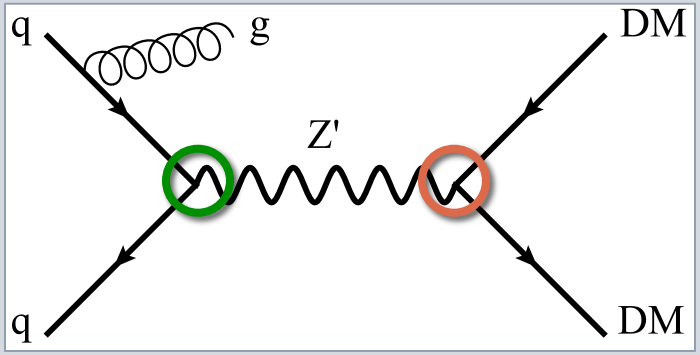
Test the same coupling in different ways:

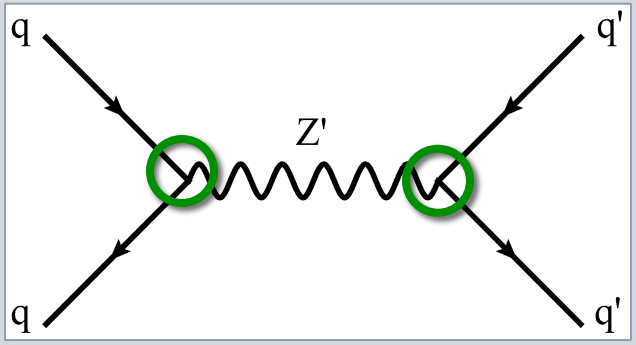


- Compare LHC to other DM constraints & resonance searches

Z' vs Z'

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





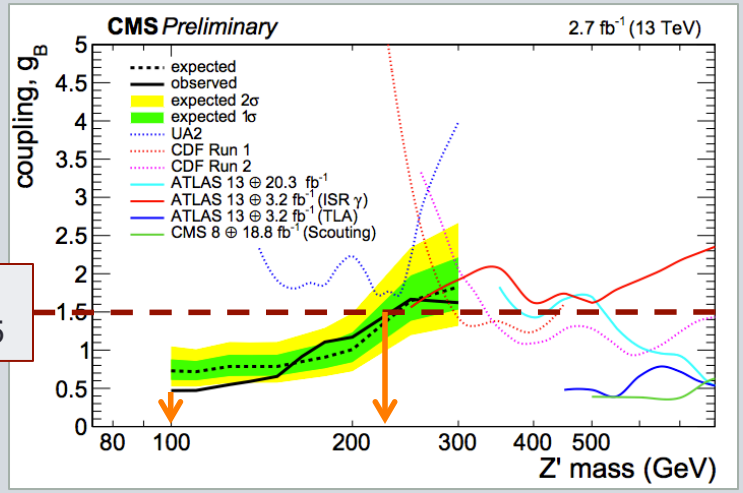
- **Possibly same mediator!**
  - Dijet is also a **DM mediator** search!
  - Use dijet search for **DM interpretation**

CMS dijets

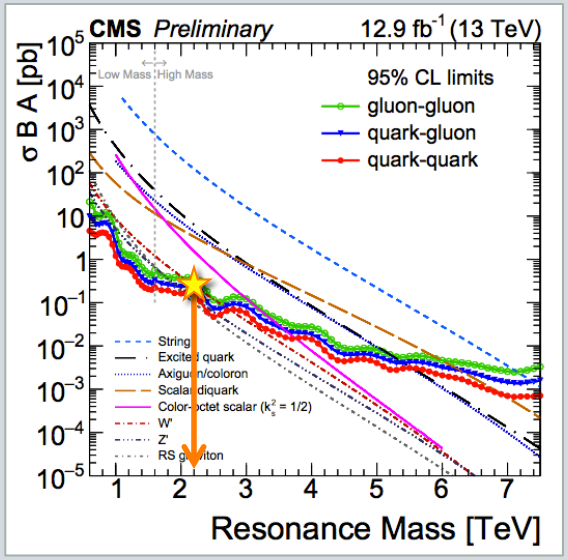
Boosted dijet: **CMS PAS EXO-16-030**

Dijet: **CMS PAS EXO-16-032**

- **Low-mass & high-mass searches**



$g_B = 1.5$
$g_q = 0.25$



- **Reinterpret as search for DM mediator**
  - *More details in presentation by A.Boveia & C.Doglioni*

CMS dijets

Boosted dijet: **CMS PAS EXO-16-030**

Dijet: **CMS PAS EXO-16-032**

- **Low-mass & high mass searches**
  - **Reinterpret as search for DM mediator**

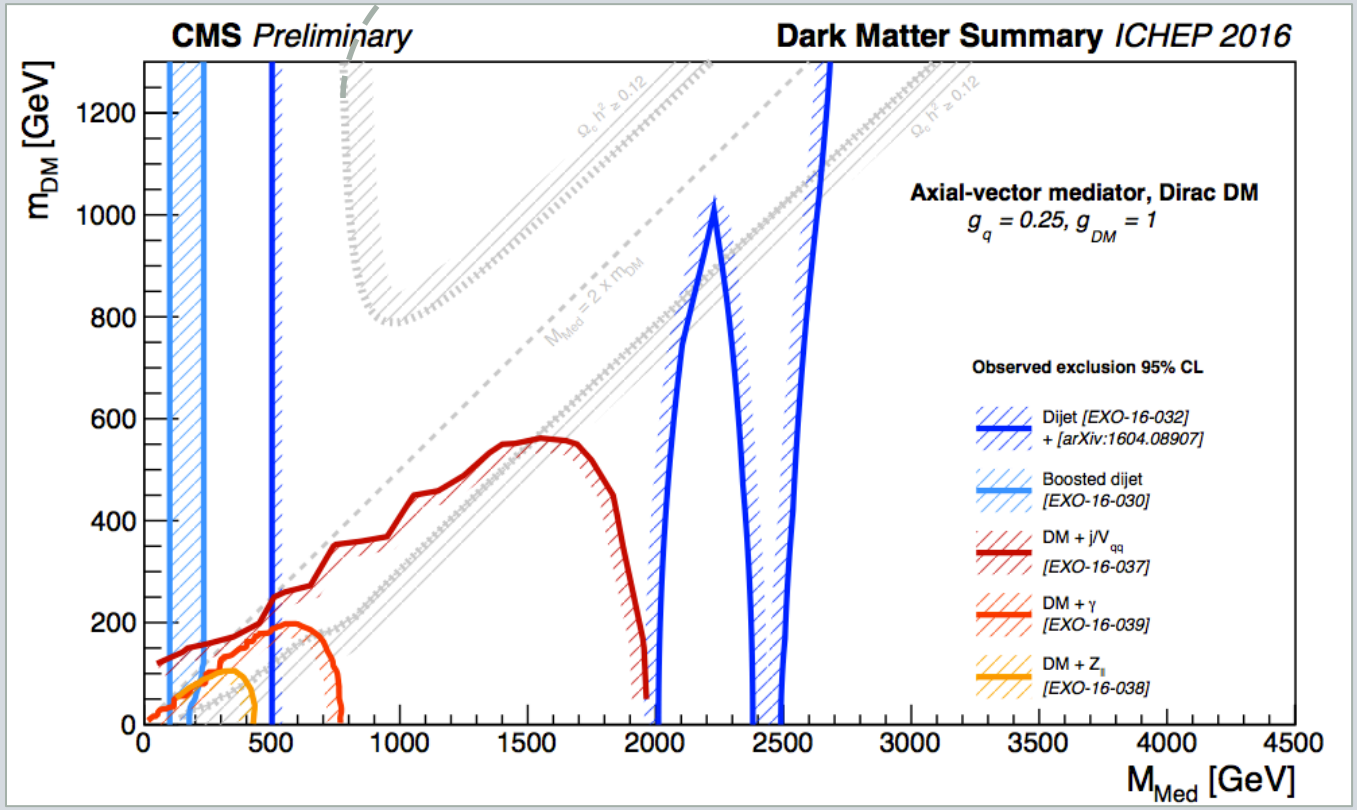
Procedure: Coupling to top

1. **Current** reinterpretation procedure (plots in this talk)
   - Consider top coupling in production (**width**)
   - Also include BR(Z'→tt) in **decay**
2. **Proposed future** reinterpretation procedure (conservative)
   - Consider top coupling in production (**width**)
   - Ignore BR(Z'→tt) decays
     - Effectively reduce BR by 1/6 → **5/6xBR**

(M,M)

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

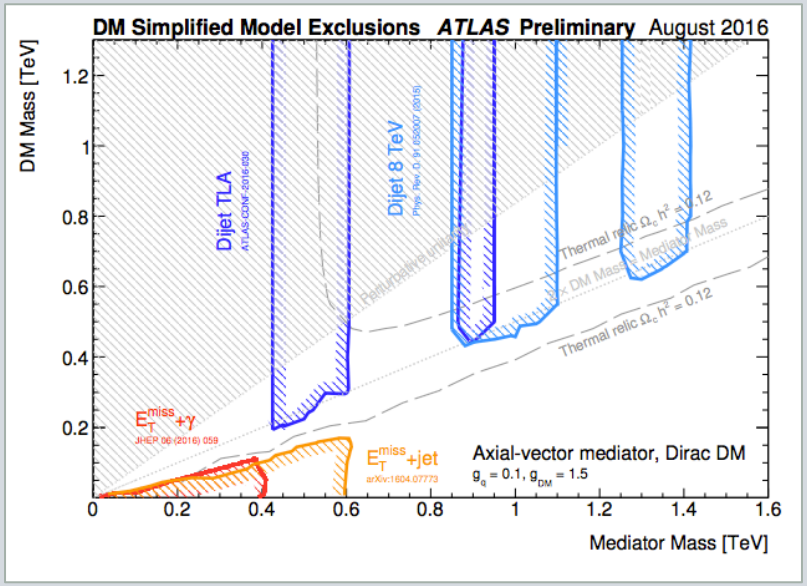
- **MET+X** vs **Dijet** → *MadDM curves being followed up*



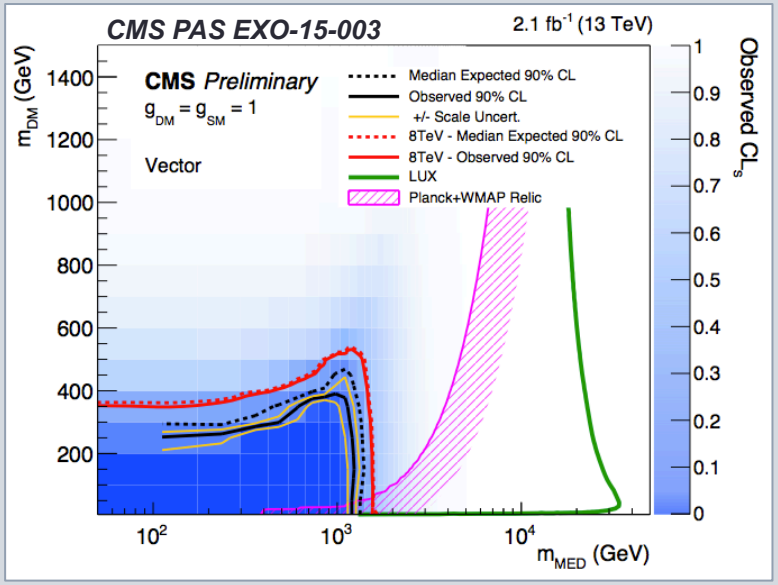
- High mass till **~2.5 TeV**, low-mass boosted down to **0.1 TeV**
  - *This plot: (g_q = 0.25, g_{DM} = 1.0)*

Alternative scenarii

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



- **CMS modified coupling**
  (g_q = 1.0, g_{DM} = 1.0)

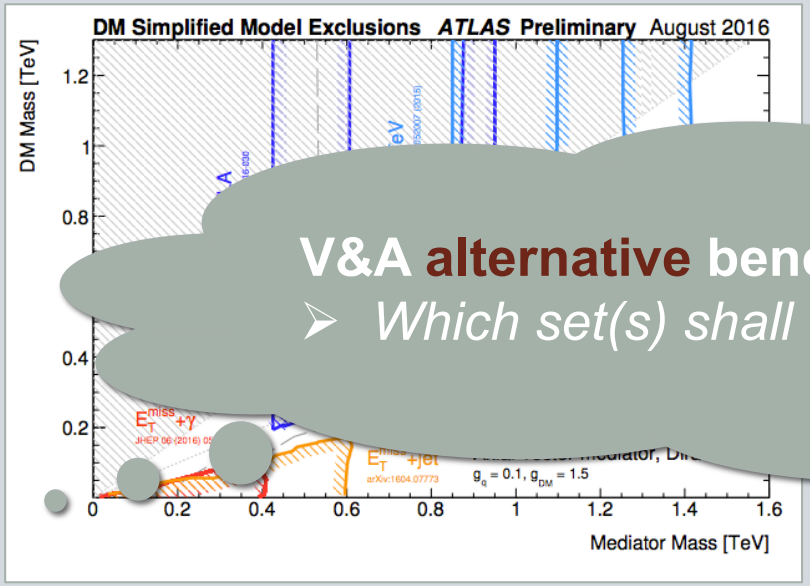


Both cases: dijet plays less dominant role

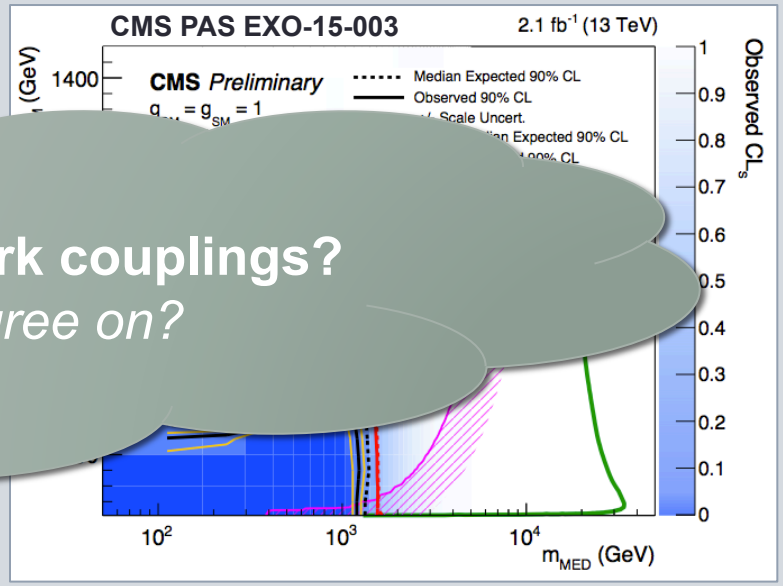
- Small ratio g_q/g_{DM} ➔ mono-jet preferential w.r.t. dijet
- Large product g_q*g_{DM} ➔ too wide peak for regular dijet analysis

Alternative scenarii

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



- **CMS modified coupling**
  (g_q = 1.0, g_{DM} = 1.0)



V&A alternative benchmark couplings?

➢ *Which set(s) shall we agree on?*

Both cases: dijet plays less dominant role

➢ **Small ratio g_q/gDM ➔ mono-jet preferential w.r.t. dijet**

➢ **Large product g_{SM}*g_{DM} ➔ too wide peak for regular dijet analysis**

For discussion

Main

Proposal for discussion

- **Dijet reinterpretation**
  - **Top**:
    Include top contribution in width, but reduce BR by 5/6 in decay
- **Couplings (Z')**
  - **Alternative couplings:**
    We would like to agree on a few alternative benchmarks

Also

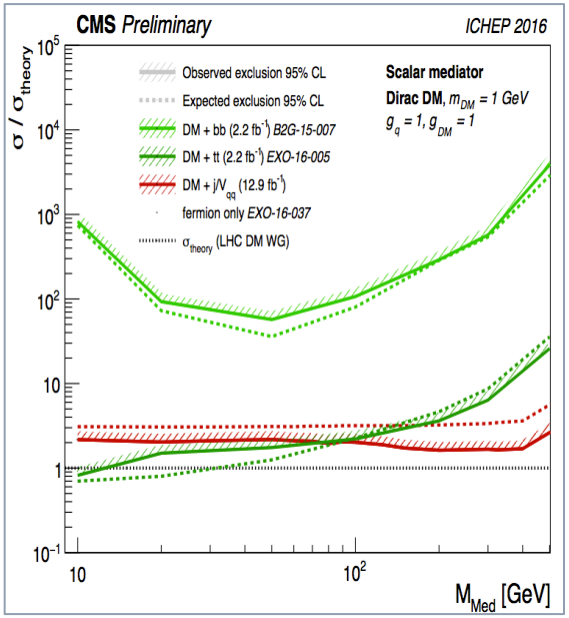
- **DD**: How low should/can we go in m_{DM}?
- **Mediator** reinterpretations: include **Z'→ll** and **Z'→tt**?
  - *See dedicated presentation by B.Zaldivar & F.Kahlhoefer & S.Vogl*
- **Combination** (S&P): DM+jet(s) & DM+tt
- **Model considerations:** V&A (perturbativity) S&P (mixing)
  - *See various dedicated presentations, today+tomorrow*

Conclusions

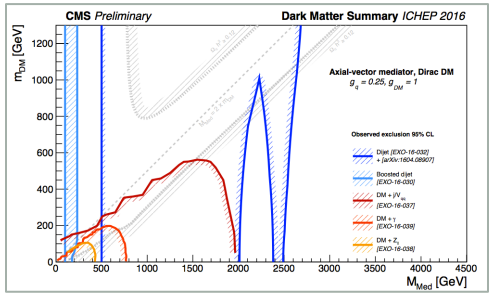
- **CMS various DM summary plots at ICHEP**
  - **V&A** (M,m) + **SI&SD** (m,σ) + **S&P** (M,σ) + **barplot**
- **Useful to compare sensitivities**
  - **MET+X** & **DD** & **CMB** & **Dijet**
- **Preparing for next versions**

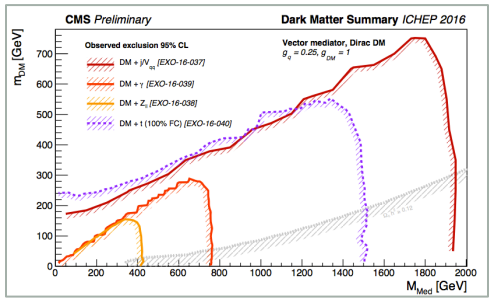
CERN-CMS-DP-2016-057
https://cds.cern.ch/record/2208044

Scalar & Pseudoscalar

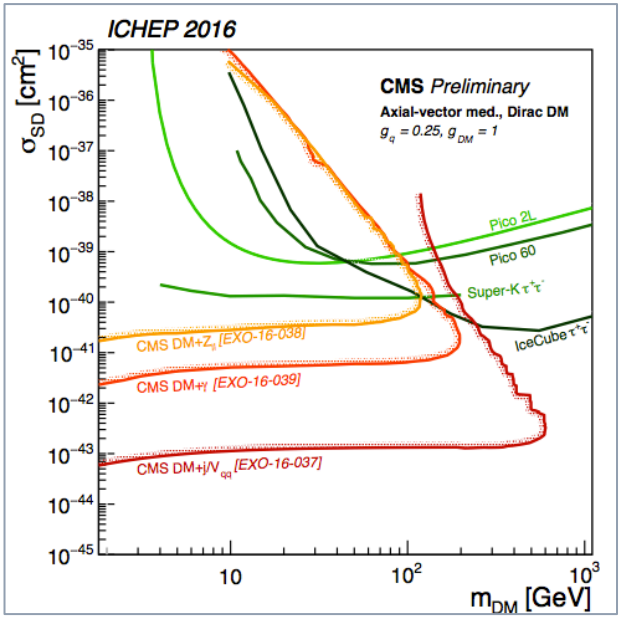


V&A (M,M) incl. dijet





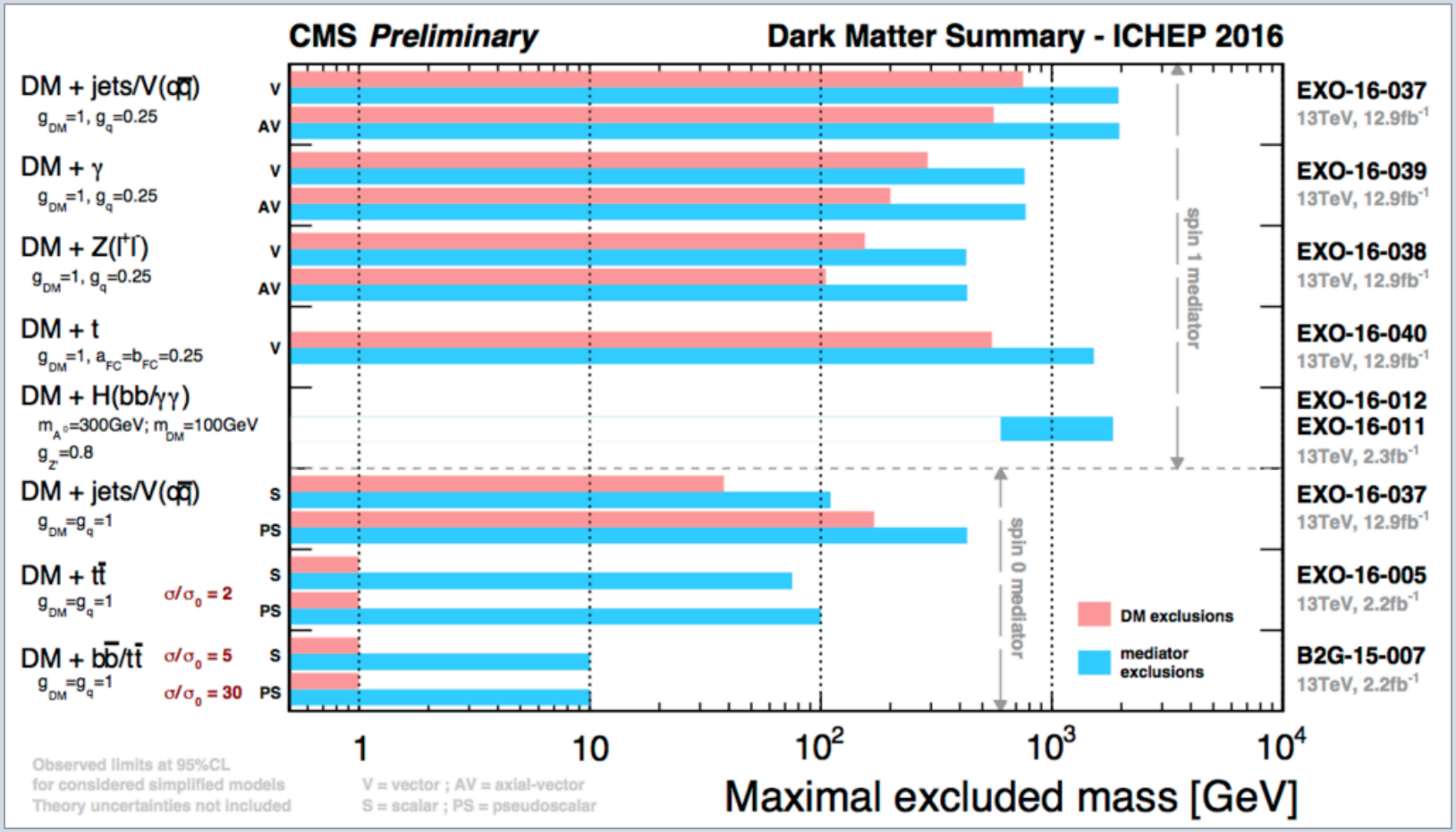
DD: SI&SD



Thank you for your attention!

#DMatLHC

1-D bar chart


CMS Preliminary
Dark Matter Summary - ICHEP 2016
DM + jets/V(qq̄)
g_DM=1, g_q=0.25
V
AV
DM + γ
g_DM=1, g_q=0.25
V
AV
DM + Z(l⁺l⁻)
g_DM=1, g_q=0.25
V
AV
DM + t
g_DM=1, a_FC=b_FC=0.25
V
DM + H(bb/γγ)
m_A0=300GeV; m_DM=100GeV
g_Z'=0.8
DM + jets/V(qq̄)
g_DM=g_q=1
S
PS
DM + tt̄
g_DM=g_q=1
σ/σ0 = 2
S
PS
DM + bb̄/tt̄
g_DM=g_q=1
σ/σ0 = 5
σ/σ0 = 30
S
PS
spin 1 mediator
spin 0 mediator
DM exclusions
mediator exclusions
EXO-16-037
13TeV, 12.9fb-1
EXO-16-039
13TeV, 12.9fb-1
EXO-16-038
13TeV, 12.9fb-1
EXO-16-040
13TeV, 12.9fb-1
EXO-16-012
EXO-16-011
13TeV, 2.3fb-1
EXO-16-037
13TeV, 12.9fb-1
EXO-16-005
13TeV, 2.2fb-1
B2G-15-007
13TeV, 2.2fb-1
1
10
10²
10³
10⁴
Maximal excluded mass [GeV]
Observed limits at 95%CL
for considered simplified models
Theory uncertainties not included
V = vector ; AV = axial-vector
S = scalar ; PS = pseudoscalar

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

Focus of this talk

X	Dataset	CMS Documentation
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

Benchmarks

Atlas/CMS Dark Matter Forum
Simplified models
arXiv/1507.00966

LHC DM WG Recommendations
arXiv/1603.04156

Vector

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

EWK style coupling

Axial

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

EWK style coupling

Run-2 V&A
$g_{SM} = 0.25$, $g_{DM} = 1$

Scalar

$$g_{\mathrm{DM}} S \, \bar{\chi} \chi$$

Yukawa style coupling
(Mass based coupling)

Pseudoscalar

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

Yukawa style coupling
(Mass based coupling)

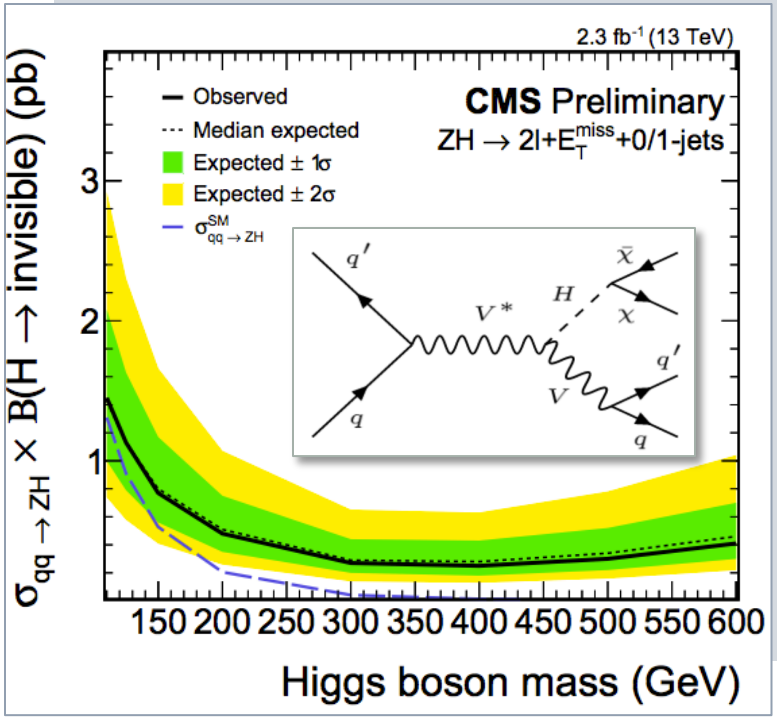
Run-2 S&P
$g_{SM} = 1$, $g_{DM} = 1$

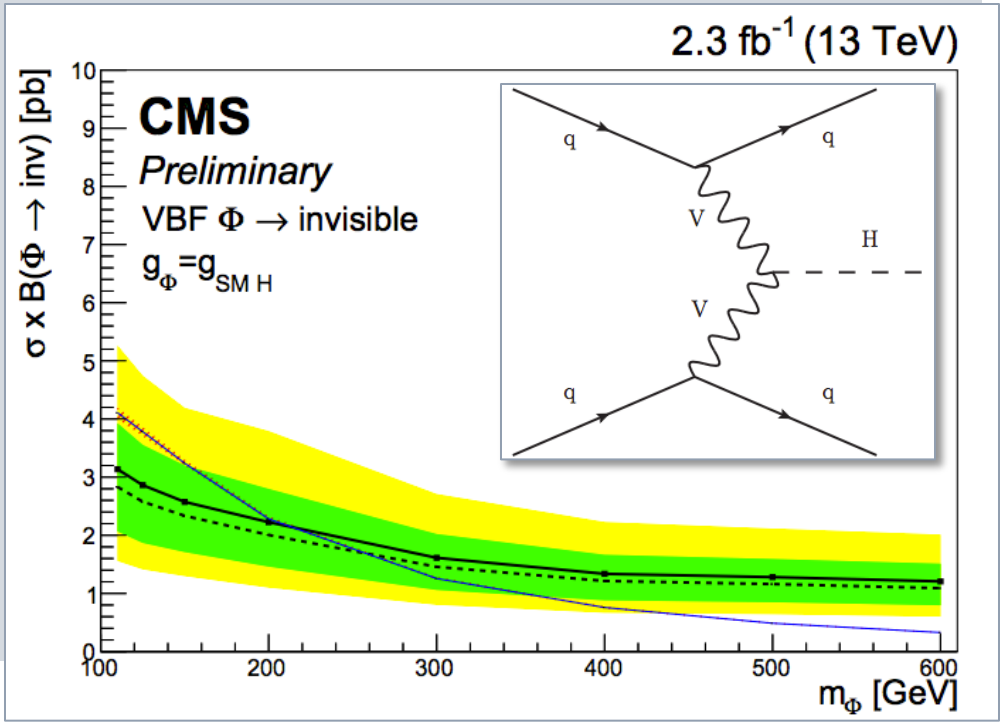
- *Various signatures for V&AS&P interpretations*

S&P in Run-2

ZH: CMS PAS HIG-16-008
VBF: CMS PAS HIG-16-009

- **Expand** Run-1 **S&P** mediator interpretation strategy
  - **DM+jet(s) + DM+HF**
    - **Yukawa** coupling to SM HF quarks
  - VH coupling: **VBF & VH**

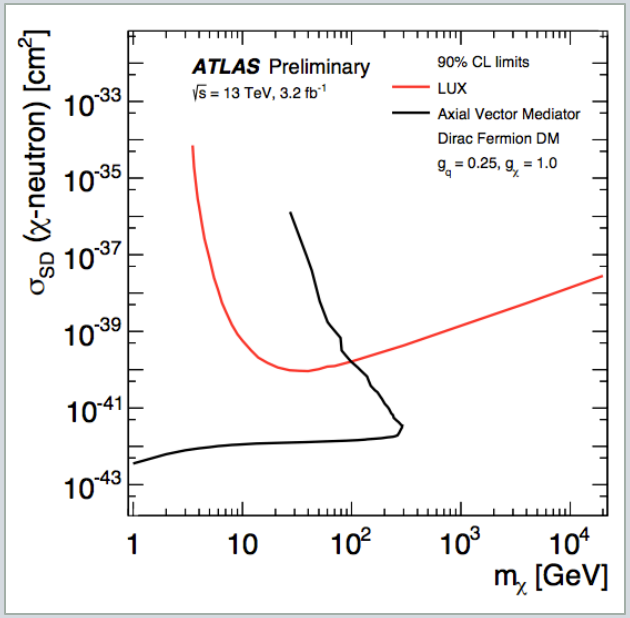




Complementarity

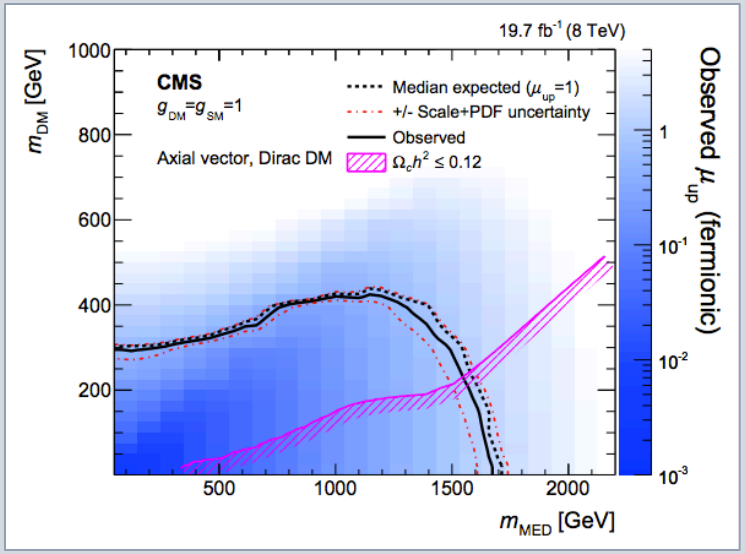
DD

LHC vs DD



CMB

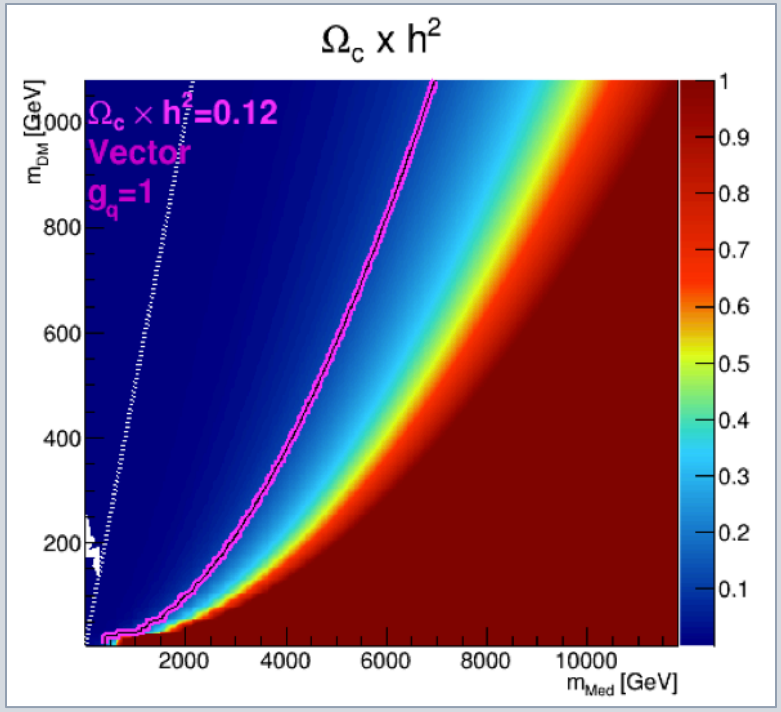
LHC vs Ω_c

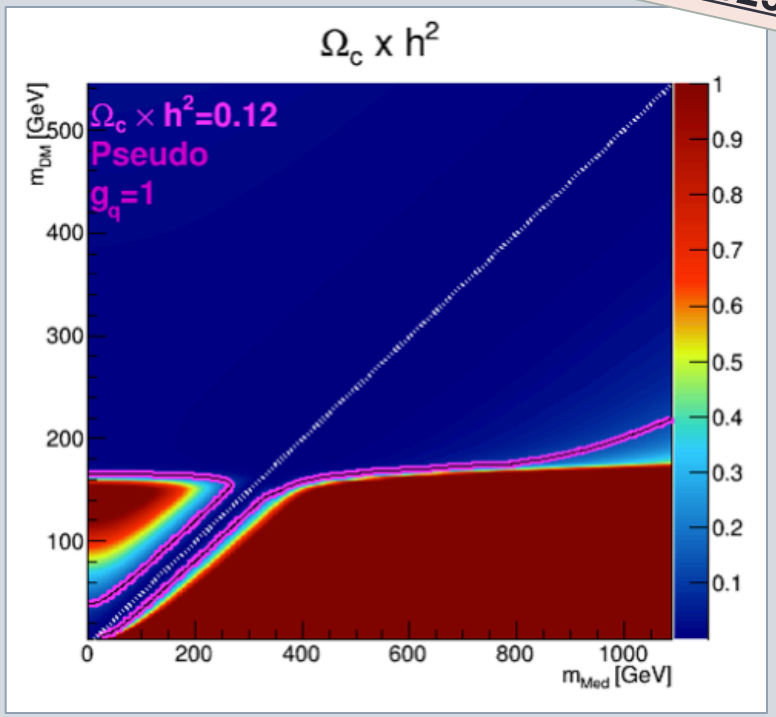


LHC vs Relic

- **MadDM** [Vector & Pseudo]

arXiv:1603.08525





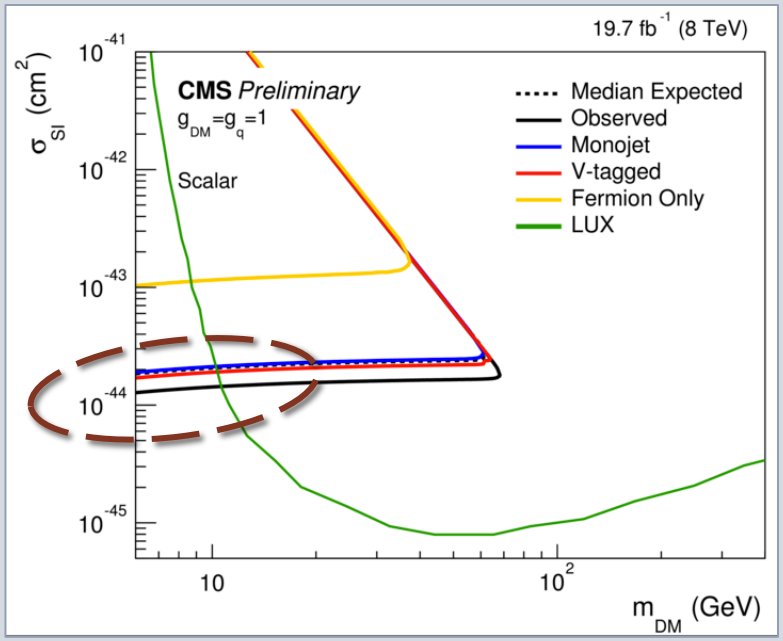
- **Additional limits on LHC DM models**
  - Also in **EXO-12-055, EXO-15-003, EXO-16-013** and **LHC DM WG** (arXiv/1603.04156)

LHC vs DD/ID

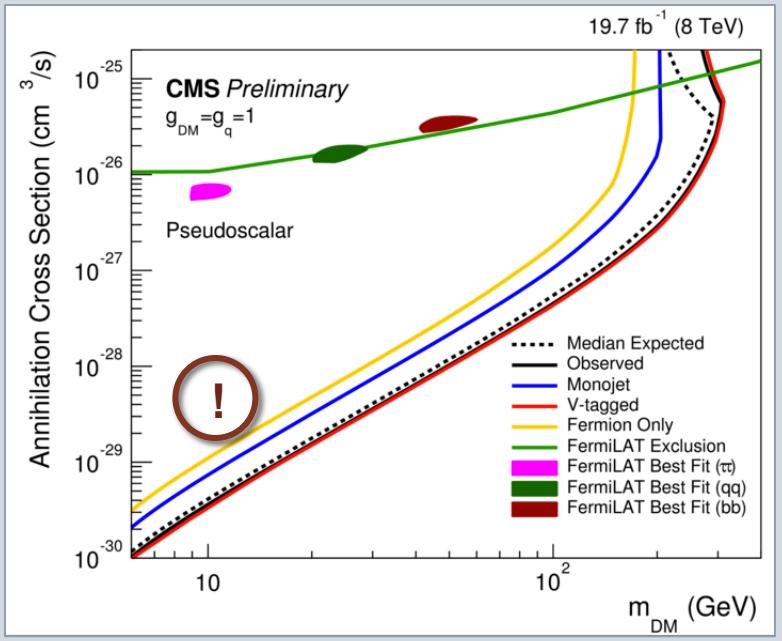
CMS PAS EXO-12-055

- **LHC** especially competitive for **SD!**

Scalar



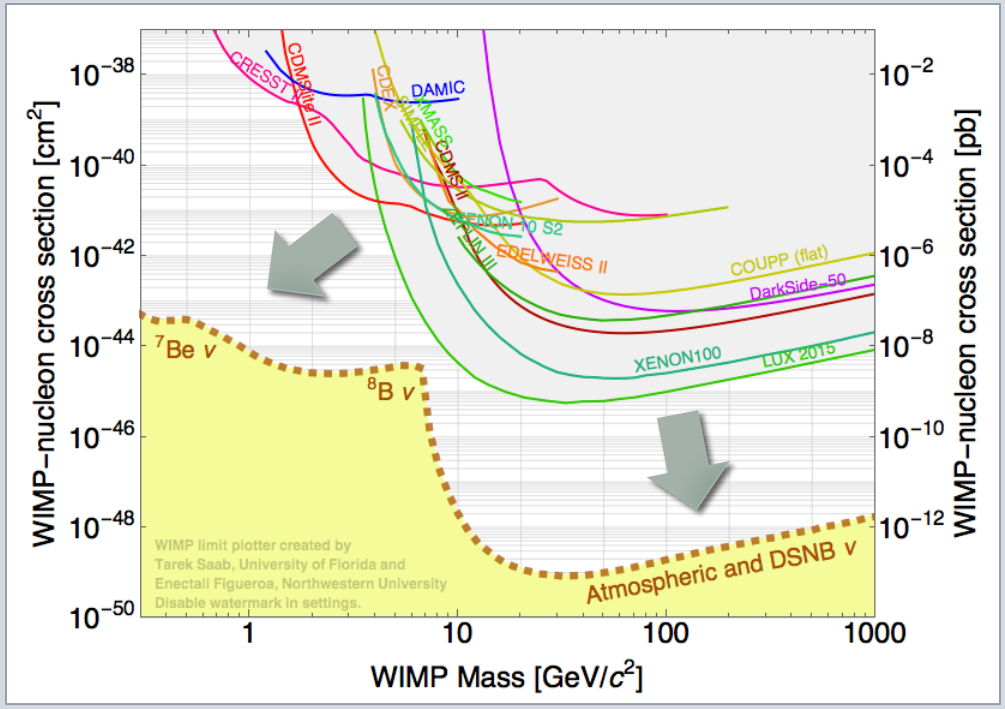
Pseudo



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

DD

Direct detection SI summary:



http://cdms.berkeley.edu/limitplots/mm/WIMP_limit_plotter.html

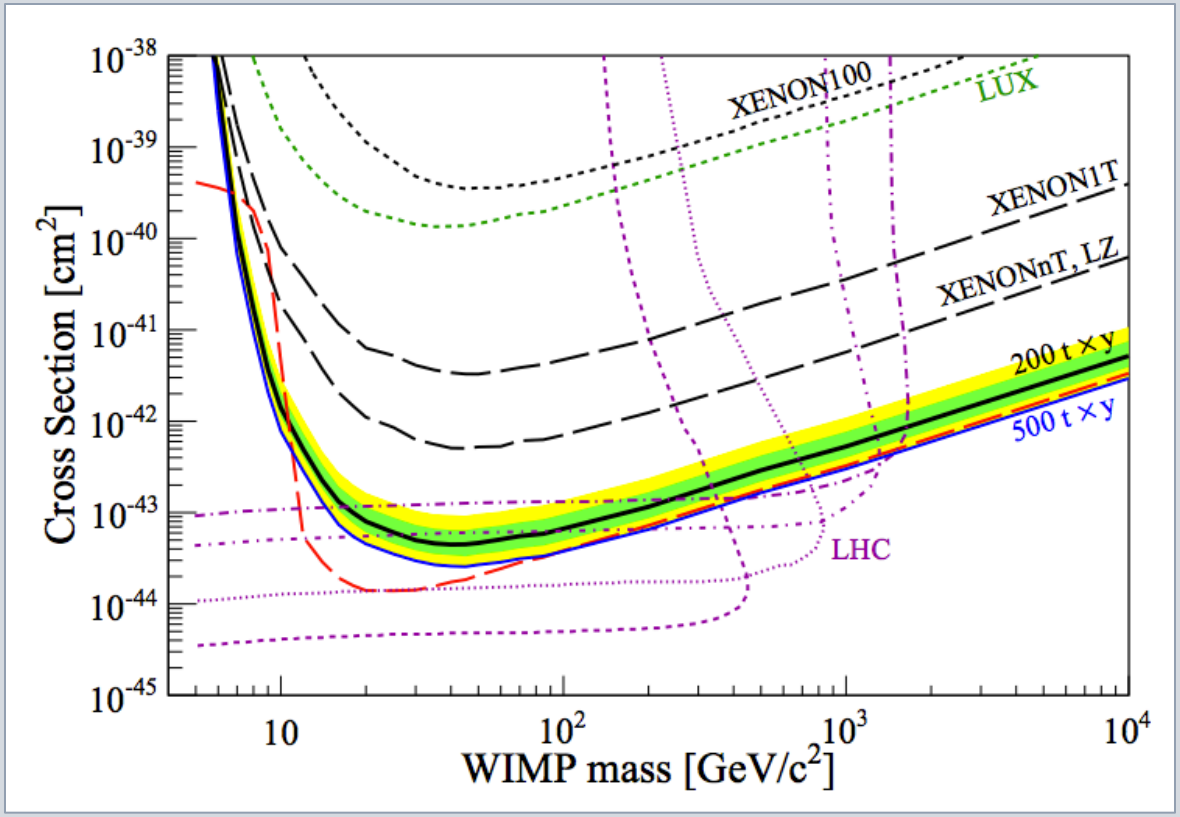
PRL
PandaX published
arXiv/1608.07400
LUX submitted
arXiv/1608.07648

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

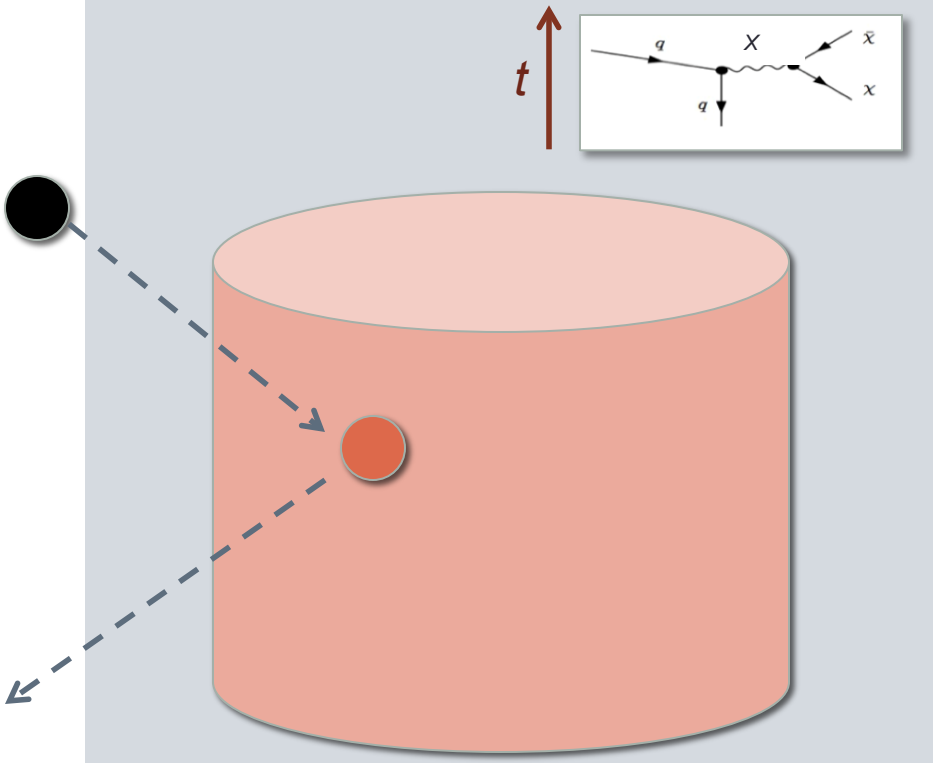
SD

Darwin reach
http://iopscience.iop.org/article/10.1088/1475-7516/2015/10/016/pdf

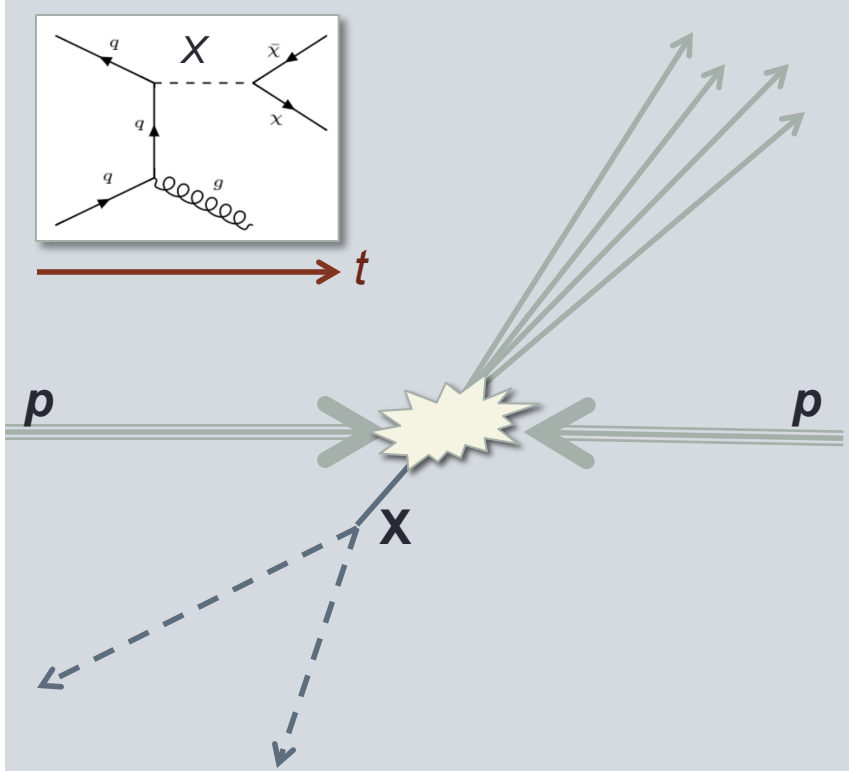
- ν Floor



DD vs LHC



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

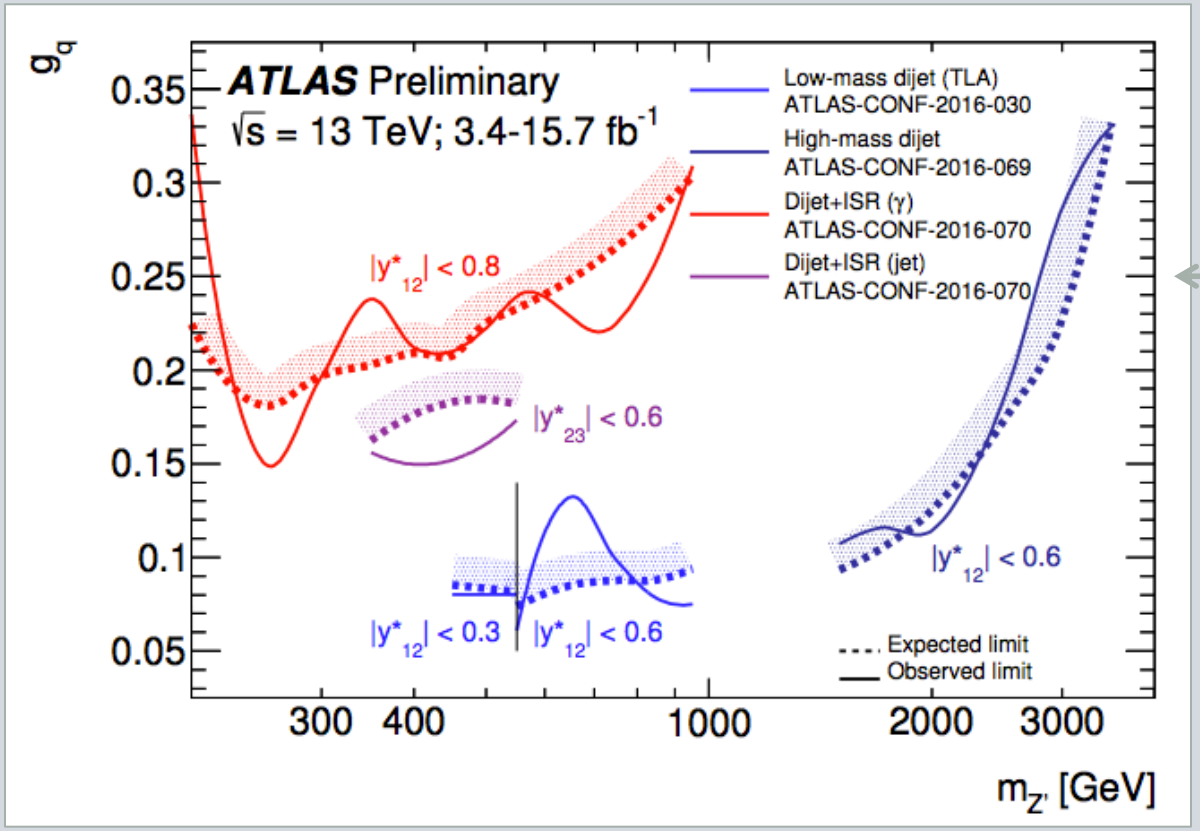


➢ **LHC** indifferent to **M_{DM} !**

➢ **LHC best for low-mass Dark Matter! (and SD)**

Atlas dijet

- **Coupling vs mass**



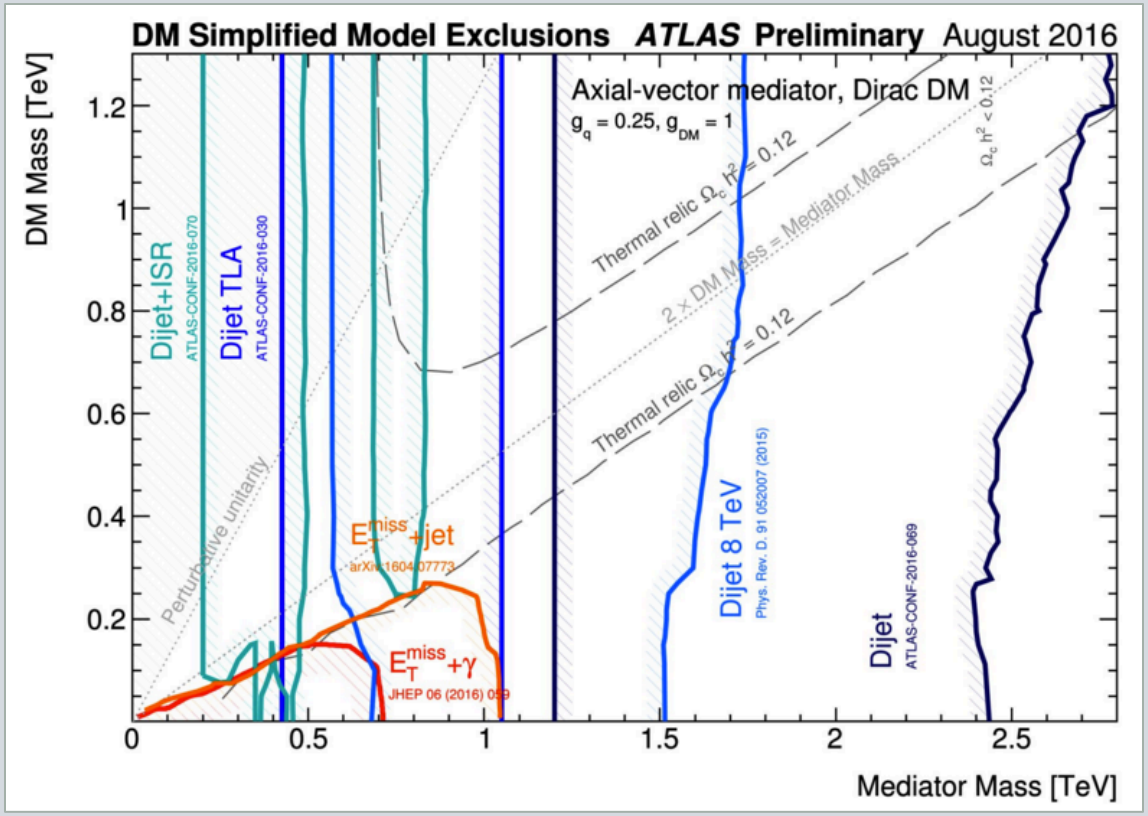
$g_q = 0.25$

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

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

Atlas dijet

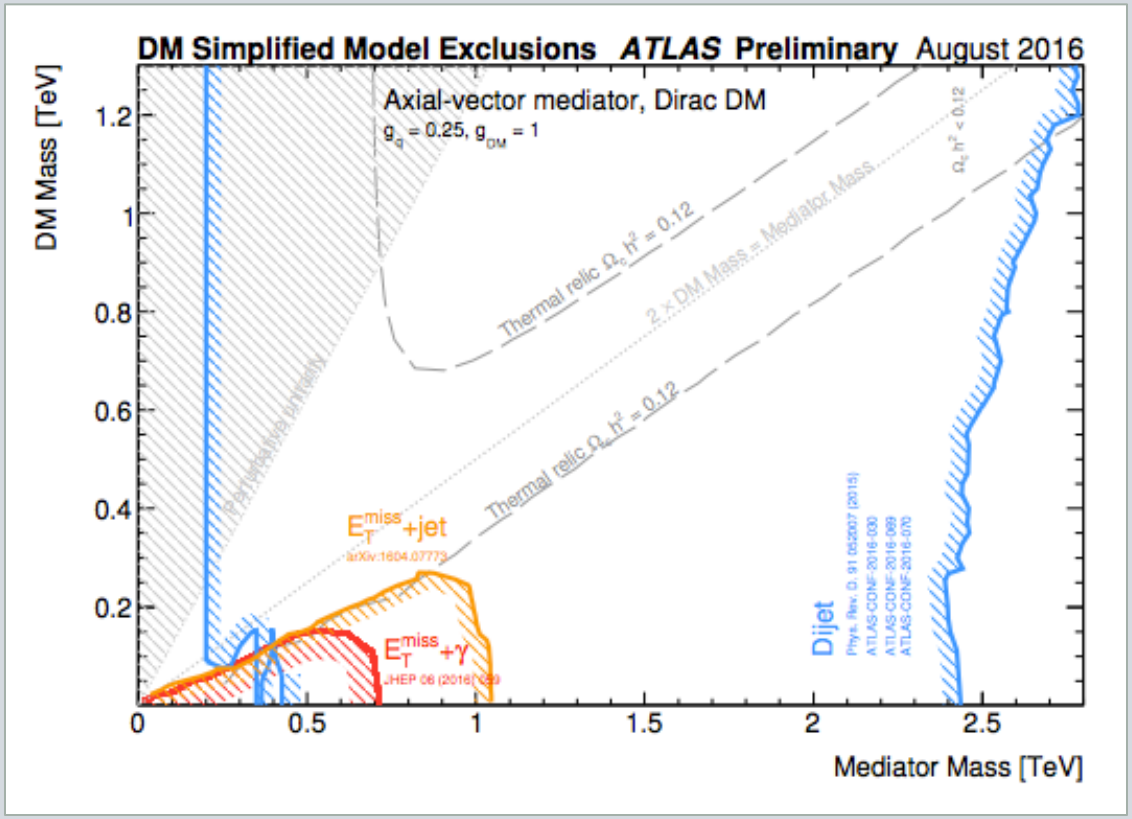
- **Detailed breakdown**



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

Atlas

- **Mediator constraints**

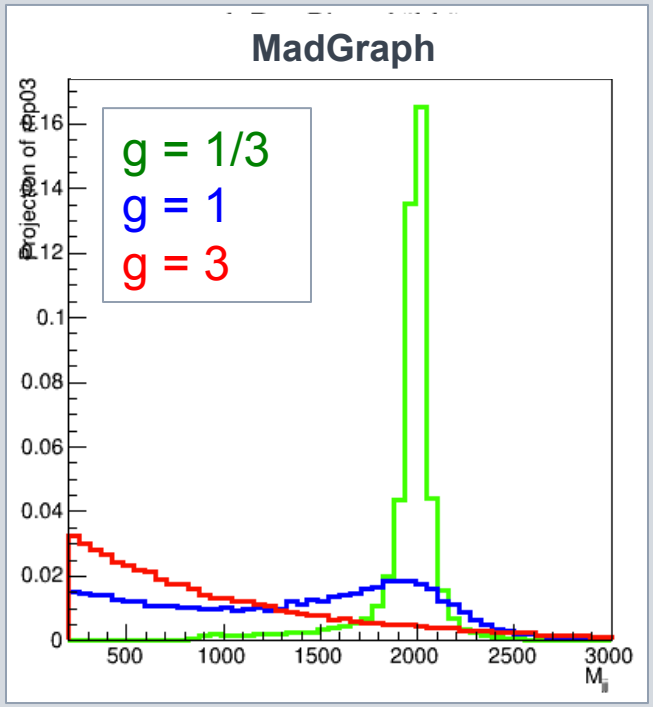


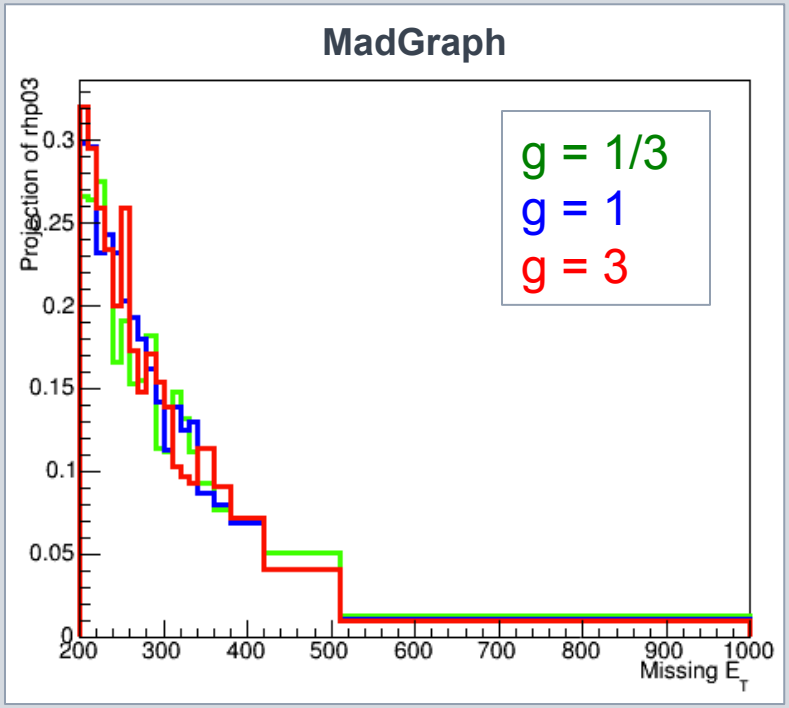
➢ Excluding almost full space $\mathbf{M_{Med} < 2.5\ TeV}$ *(for these couplings)*

Z' vs Z'

- **M_{jj}** and **MET** versus **g**

norm. to 1



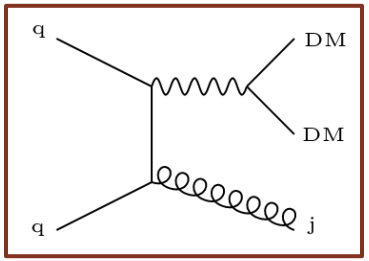


- **Small couplings**: sharp Z'→jj peak
- **Large couplings**: large Z'(DM)+j cross section

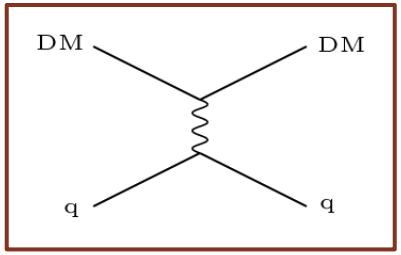
LHC MET+X

- **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**

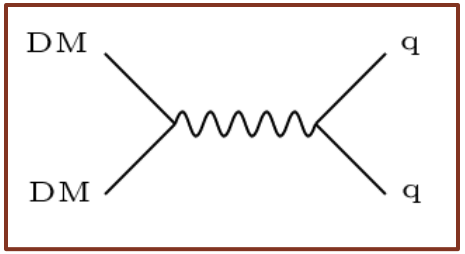
LHC MET+X



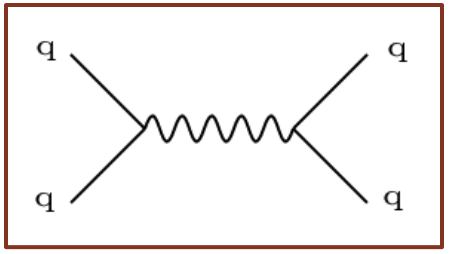
DD / ID



CMB



LHC dijet



DM @ ICHEP

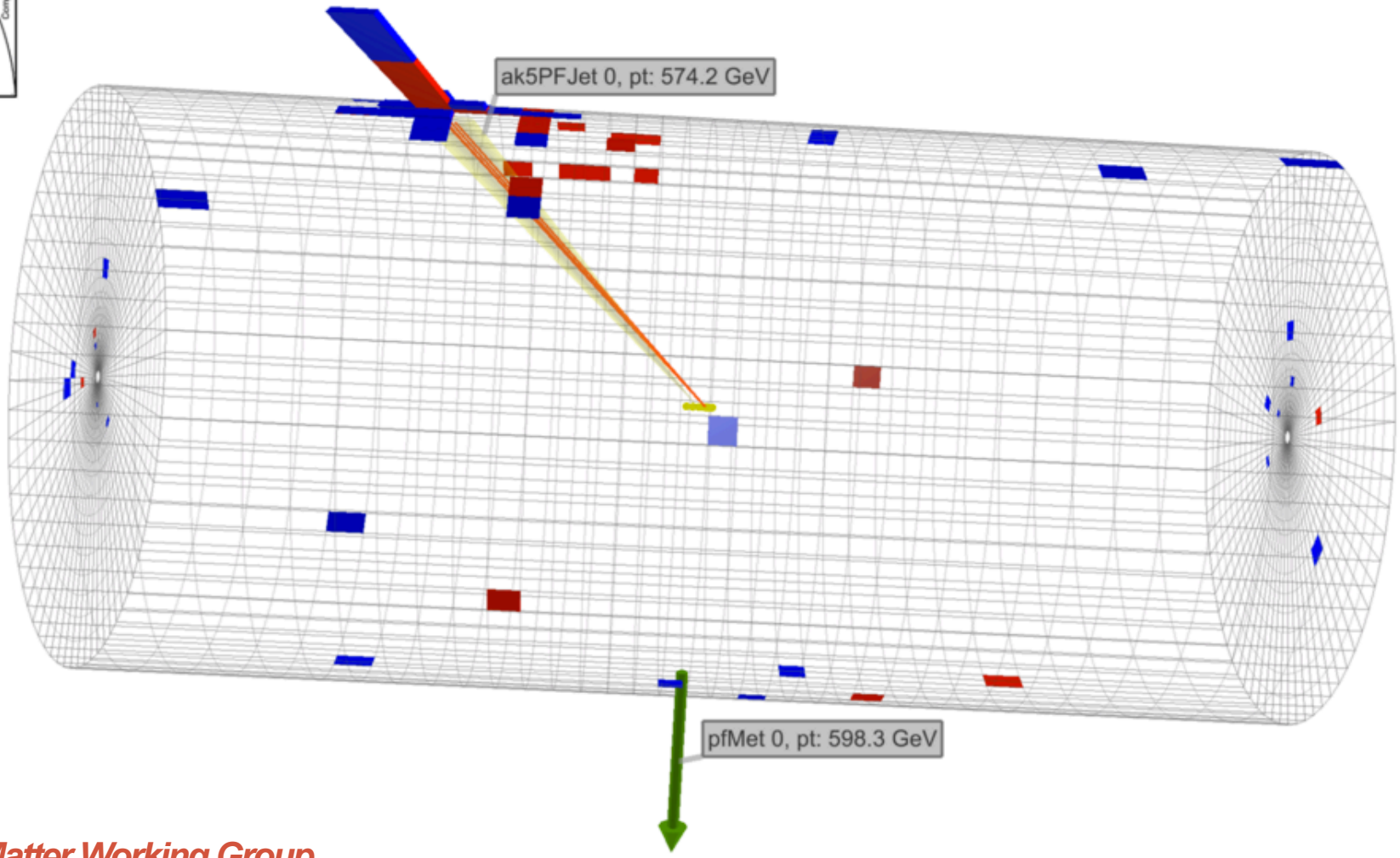
- **CMS DM Summaries at ICHEP:**
  - **CMS DM Searches**
    - http://indico.cern.ch/event/432527/contributions/2207061/
  - **LHC EXO Summary** *(plen.)*
    - http://indico.cern.ch/event/432527/contributions/2223634/
  - **LHC Highlights** *(plen.+webcast)*
    - http://indico.cern.ch/event/432527/contributions/2269781/

- Summary DPS: https://cds.cern.ch/record/2208044

“Summaries of CMS Dark Matter searches”

CMS Experiment at LHC, CERN
Data recorded: Tue Oct 4 02:50:32 2011 CEST
Run/Event: 177783 / 442962676
Lumi section: 273

Tristan du Pree (CERN)
on behalf of the CMS Collaboration



LHC Dark Matter Working Group
CERN, 19-20 September 2016

#DarkMatter?