FAYET FEST

Dark Matter searches at the LHC

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PHYSICS REPORTS

A Review Section of Physics Letters



R-PARITY-VIOLATING SUPERSYMMETRY

R. BARBIER, C. BÉRAT, M. BESANÇON, M. CHEMTOB, A. DEANDREA, E. DUDAS, P. FAYET, S. LAVIGNAC, G. MOREAU, E. PEREZ, Y. SIROIS

Volume 420, Nos. 1–6, November 2005
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1. **Phenomenology of the Production, Decay, and Detection of New Hadronic States Associated with Supersymmetry**
(1273) Glennys R. Farrar, Pierre Fayet (Caltech). Apr 1978. 5 pp.
Published in **Phys.Lett. 76B (1978) 575-579**
CALT-68-648
DOI: 10.1016/0370-2693(78)90858-4
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
KEK scanned document
Detailed record - Cited by 1273 records 1000+

2. **Supersymmetry**
(1110) Pierre Fayet, S. Ferrara (Ecole Normale Superieure). Jun 1976. 208 pp.
Published in **Phys.Rept. 32 (1977) 249-334**
LPTENS-76-11
DOI: 10.1016/0370-1573(77)90066-7
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 1110 records 1000+

3. **Spontaneously Broken Supersymmetric Theories of Weak, Electromagnetic and Strong Interactions**
(1064) Pierre Fayet (Ecole Polytechnique). Sep 1977. 6 pp.
Published in **Phys.Lett. 69B (1977) 489**
LPTENS 77/11
DOI: 10.1016/0370-2693(77)90852-8
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 1064 records 1000+

4. **Supergauge Invariant Extension of the Higgs Mechanism and a Model for the electron and Its Neutrino**
(864) Pierre Fayet (Ecole Normale Superieure). Nov 1974. 21 pp.
Published in **Nucl.Phys. B90 (1975) 104-124**
PTENS-74-7
DOI: 10.1016/0550-3213(75)90636-7
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record - Cited by 864 records 500+

5. **R-parity violating supersymmetry**
(828) R. Barbier (Lyon, IPN) *et al.*. Jun 2004. 261 pp.
Published in **Phys.Rept. 420 (2005) 1-202**
DOI: 10.1016/j.physrep.2005.08.006
e-Print: **hep-ph/0406039** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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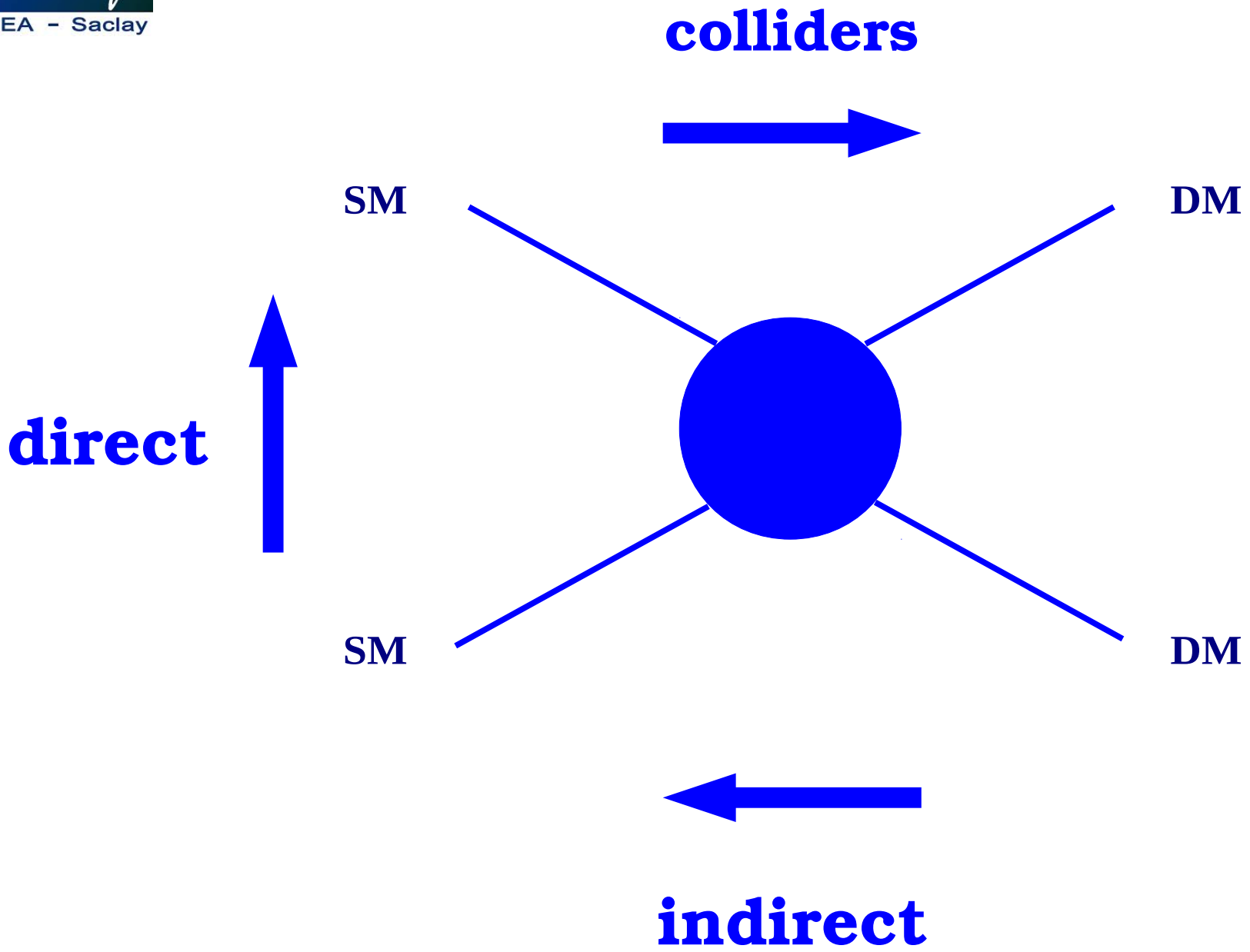
ORTS



YMMETRY

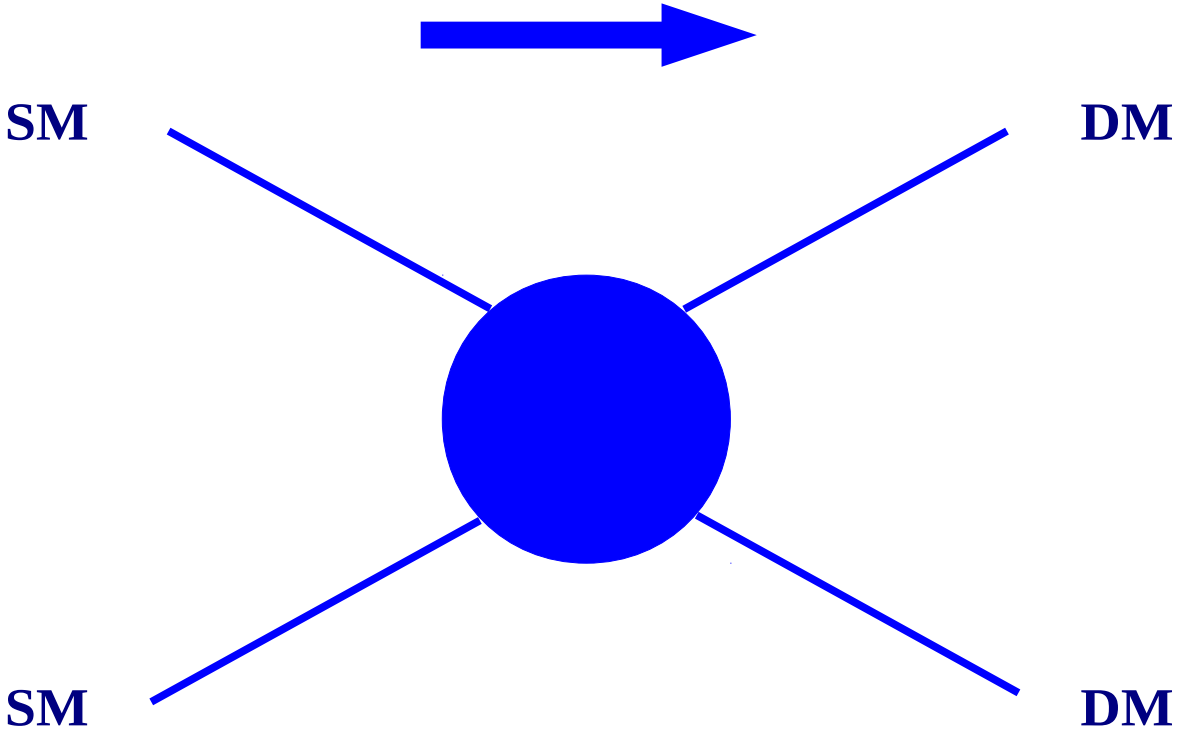
R. BARBIER, C. BÉRAT, M. BESANÇON, M. CHEMTOB, A. DEANDREA, E. DUDAS, P. FAYET, S. LAVIGNAC, G. MOREAU, E. PEREZ, Y. SIROIS

Dark Matter searches



DM at colliders

colliders



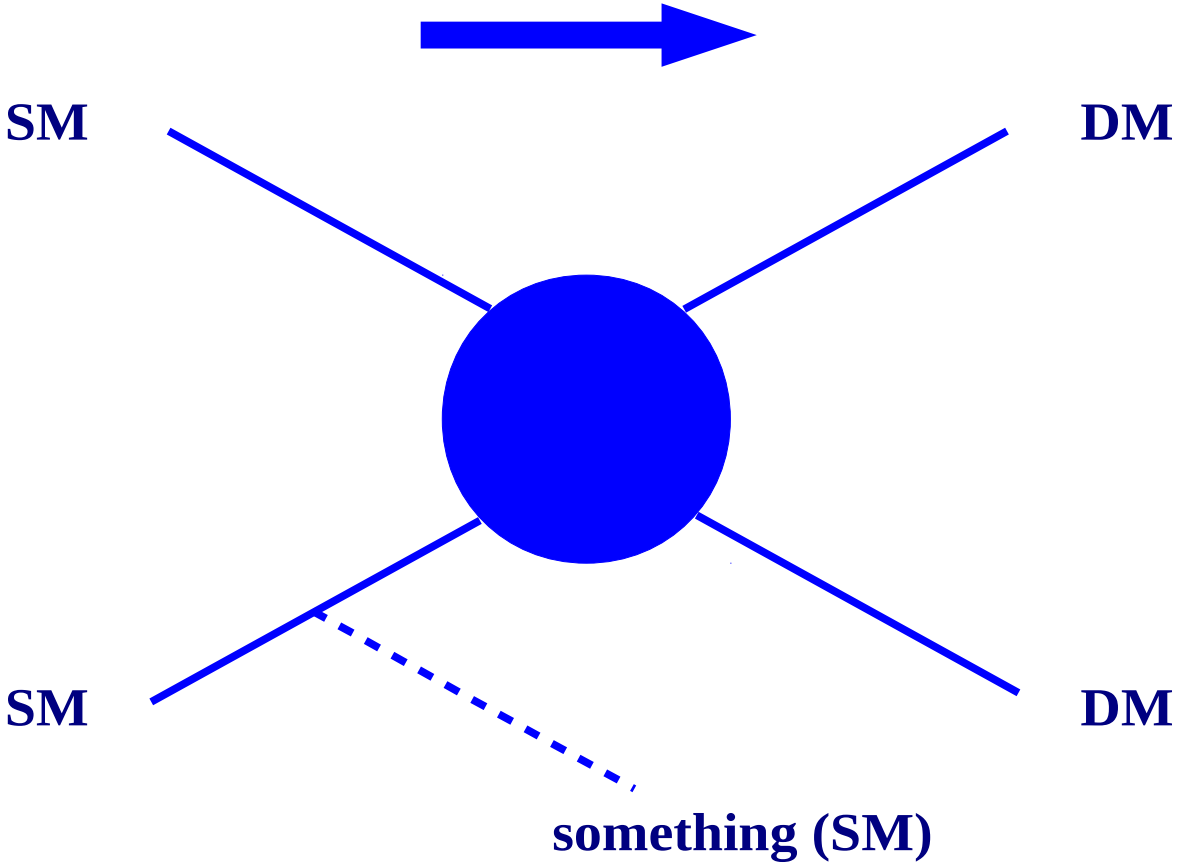
nothing to see that way

DM particles escape detector without interacting

source of missing energy in the event signature

DM at colliders

colliders



Missing Transverse Energy + mono something searches

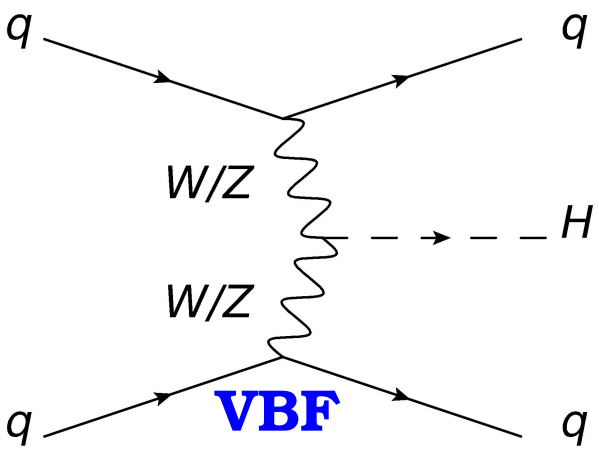
→ MET + X searches

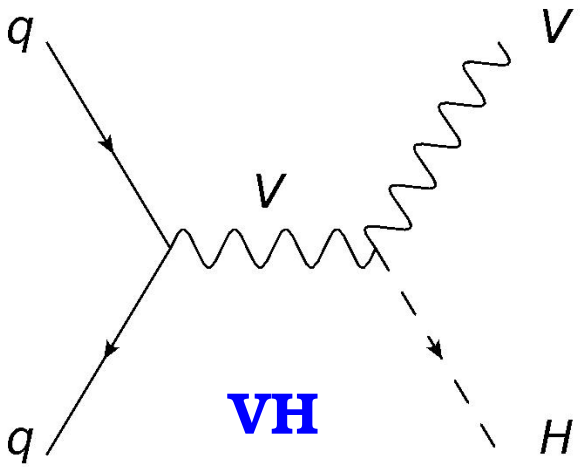
X = something = jet , γ , Z , W , H , b , t , $t\bar{t}$

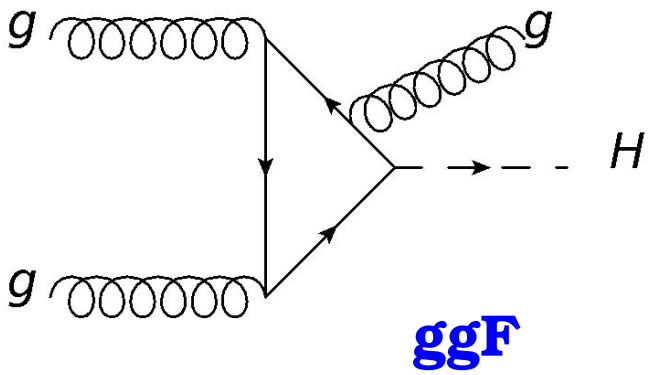
DM at colliders

Higgs boson seen as a portal to the dark sector

- Higgs produced in association with SM particles







Higgs boson decays into a pair of DM particles → invisible Higgs decay
(if kinematically allowed)

- constraints on invisible width of the Higgs from combination
of precision measurement of the production and decay rates
+ constraints from the above invisible Higgs decay searches

DM at colliders

outline

effective and simplified approach

MET + X searches (examples)

invisible Higgs boson

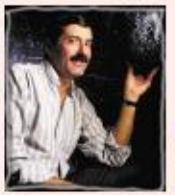
summary

DM at LHC

Signature	ATLAS	CMS
MET + jets	PRD94 (2016) 032005	PAS EXO-16-037
MET + photon	EXOT-2015-05	PAS EXO-16-039
MET + Z(ll)	ATLAS-CONF-2016-056	PAS EXO-16-010 PAS EXO-16-038
MET + W/Z (qq)	EXOT-2015-08	PAS EXO-16-037
MET + Higgs	EXOT-2015-13 ATLAS-CONF-2016-087 ATLAS-CONF-2015-059	PAS EXO-16-011 PAS EXO-16-012
MET + ttbar	ATLAS-CONF-2016-077 ATLAS-CONF-2016-050 ATLAS-CONF-2016-076	PAS EXO-16-005
MET + top		PAS EXO-16-040
MET + b-jet	ATLAS-CONF-2016-086	PAS B2G-15-007
dijets	ATLAS-CONF-2016-030 ATLAS-CONF-2016-69 ATLAS-CONF-2016-070	PAS EXO-16-030 PAS EXO-16-032
Invisible Higgs	JHEP 1511 (2015)206	arXiv:1610.09218


jungle of DM theories

Theories of Dark Matter



MSSM

R-parity violating

NMSSM

Supersymmetry

WIMPless DM

Hidden Sector DM

Self-Interacting DM

Techni-baryons

mSUGRA

pMSSM

Gravitino DM

Q-balls

R-parity Conserving

Dirac DM

Dark Photon

Asymmetric DM

Light Force Carriers

Extra Dimensions

Dynamical DM

Warm DM

Sterile Neutrinos

Solitonic DM

Quark Nuggets

UED DM

6d

5d

Warped Extra Dimensions

RS DM

T-odd DM

Axion DM

Little Higgs

QCD Axions

Axion-like Particles

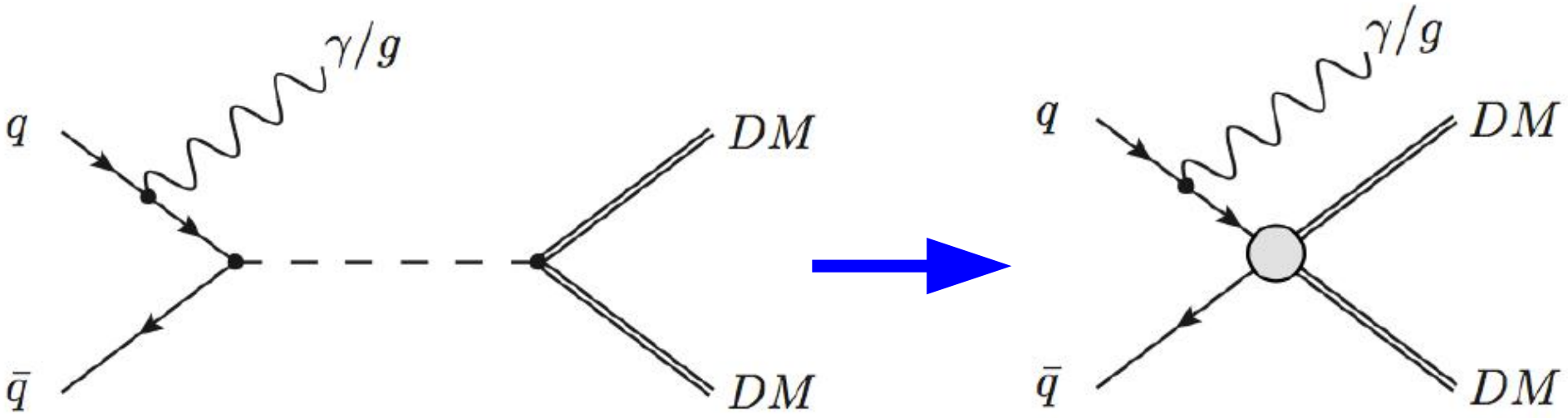
Littlest Higgs

T Tait


effective and simplified models

DM at colliders

effective approach very often used



at energies much smaller than the heavy mediator mass M it can be integrated out resulting into non renormalizable operators for DM interactions with partons

lowest-dimensional effective operator has dimension 6

for example for scalar mediator of mass M and couplings g_χ and g_q

$$O_S = \frac{1}{\Lambda^2}(\bar{\chi}\chi)(\bar{q}q) \qquad \text{with} \quad \frac{1}{\Lambda^2} = \frac{g_\chi g_q}{M^2}$$

DM at colliders
effective operators

Assuming DM particle is a SM singlet a light Majorana particle interacting through higher dim. op.

$$L^{\text{dim 6}}_{\text{int,qq}} = G_\chi \left[\bar{\chi}\Gamma^\chi \chi \right] \times \left[\bar{q}\Gamma^q q \right] \quad \text{and} \quad L^{\text{dim 7}}_{\text{int,GG}} = G_\chi \left[\bar{\chi}\Gamma^\chi \chi \right] \times \left(\text{GG or G}\tilde{G} \right)$$

where G is the gluon field strength and $\tilde{G}^{\mu\nu} = \epsilon^{\mu\nu\rho\sigma} G_{\rho\sigma} / 2$

Name	Type	G_χ	Γ^χ	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	–
M8	GG	$i\alpha_s/8M_*^3$	γ_5	–
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	–
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$	γ_5	–

assume only one M operator dominating at a time

Goodman, Ibe, Rajamaran, Shepherd, Tait, Yu, PLB 695 (2011) 185

DM at colliders

effective operators

operator names with D, C, R apply
to DM particles that are respectively

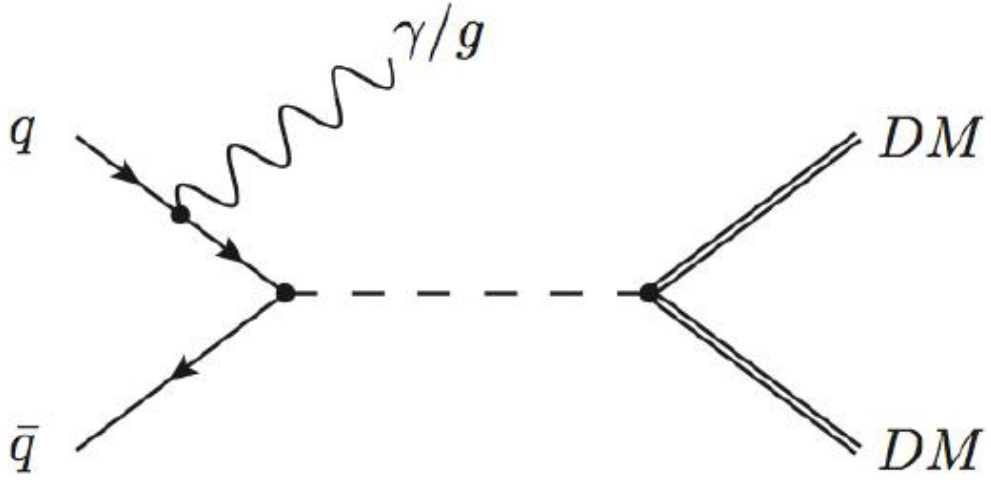
- Dirac fermions
- complex scalars
- real scalars

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

Goodman, Ibe, Rajamaran, Shepherd, Tait, Yu, PRD 82 (2010) 116010

DM at colliders

use simplified models

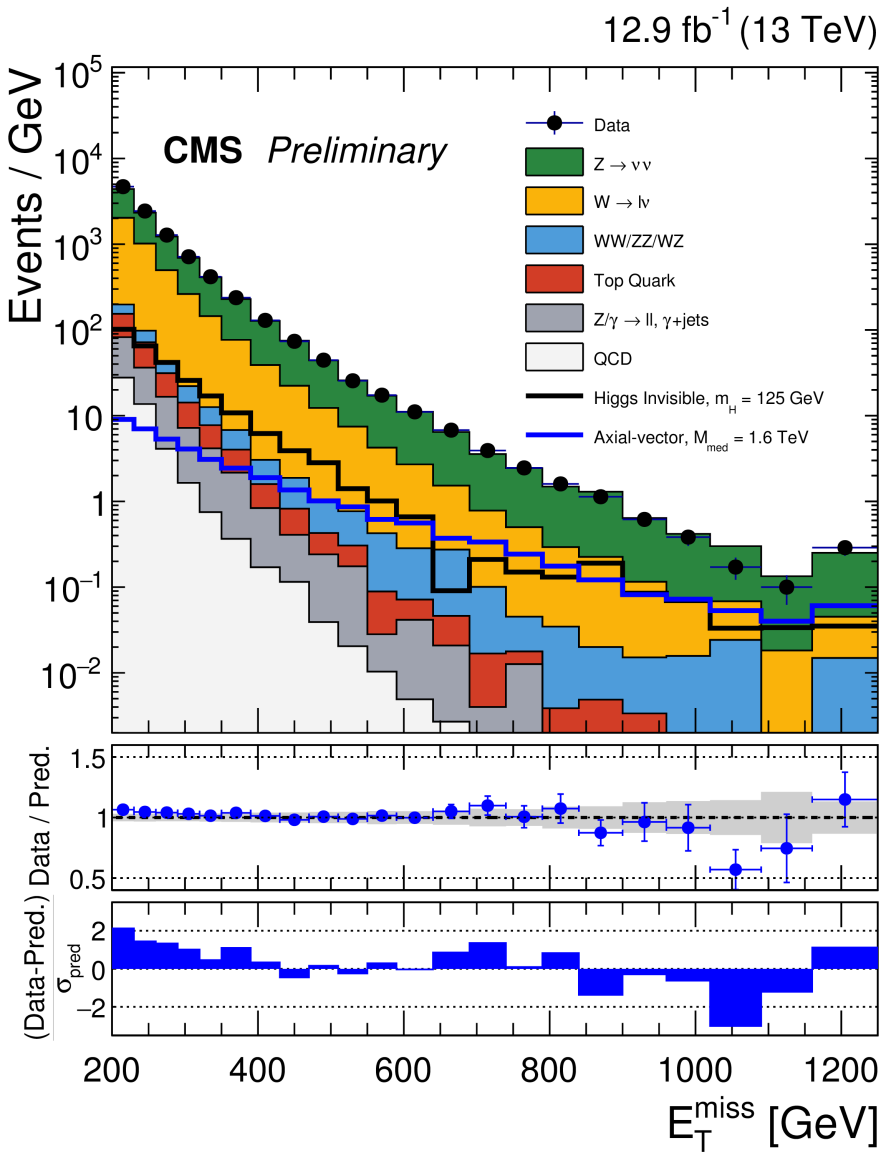


only SM + DM sector (including mediator particle) with 4 parameters

- DM mass
- mediator mass
- coupling of mediator to SM particles
- coupling of mediator to DM particle

Malik et al. arXiv:1409.4075 Abdallah et al. arXiv:1409.2893

MET + X searches at the LHC
Experimental challenges



- dominant background in most DM searches

$Z(\nu\nu) + X$ and $W(l\nu) + X$
(charged lepton is lost in W case)

- estimate dominant backgrounds from data

low MET : use visible $Z(ll) + X$
and $W(l\nu) + X$

dominant systematic: lepton reconstruction efficiency

high MET : use $\gamma + X$
and theoretically predicted ratio
of processes

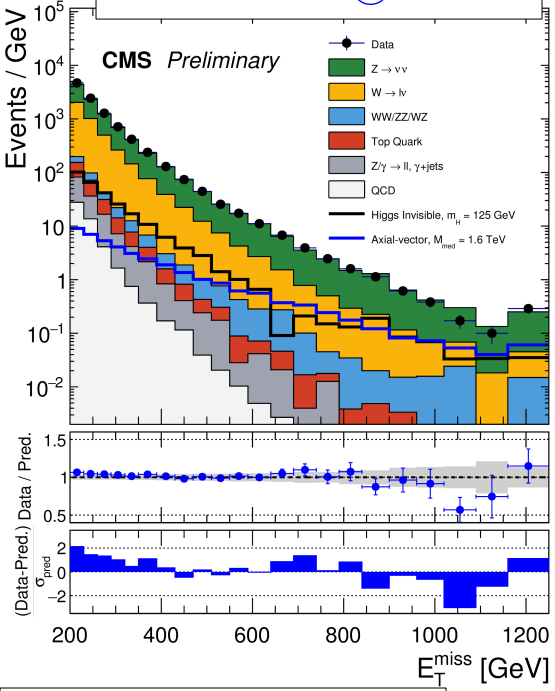
dominant systematic: NLO EWK effects

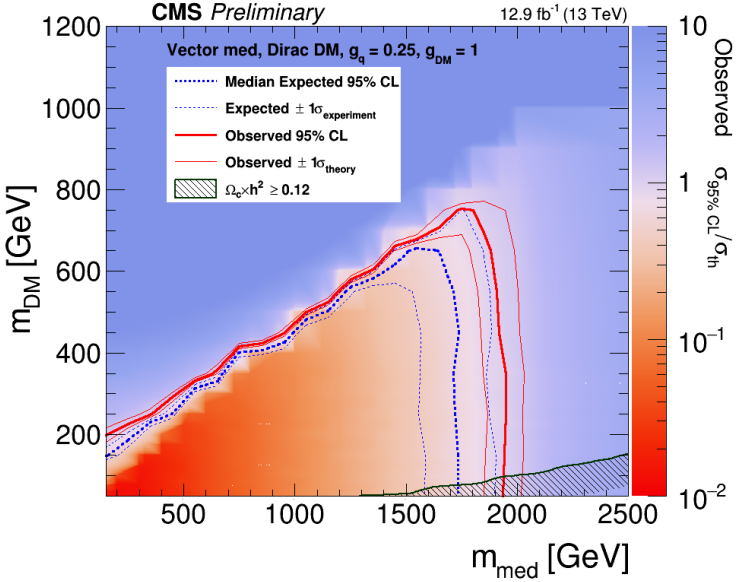
MET + jet(s)

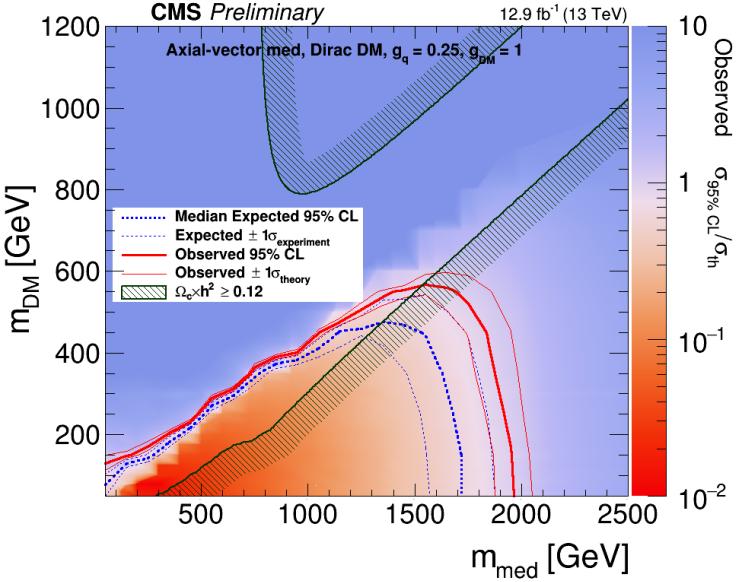
CEA – Saclay

ENS

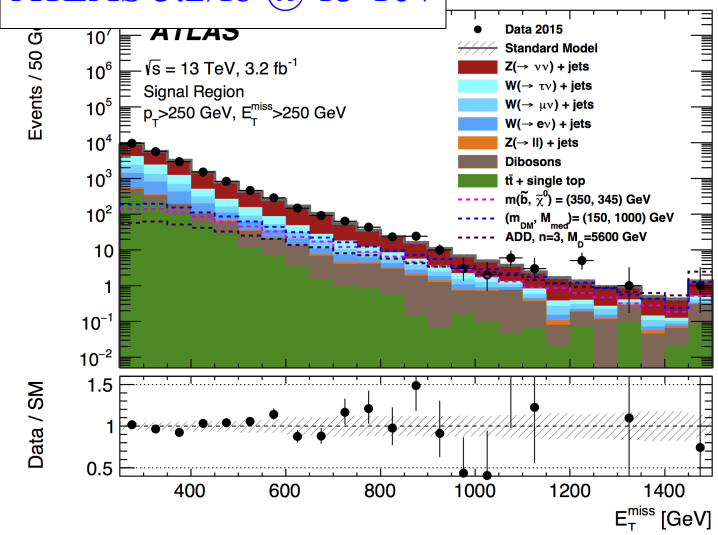
CMS 12.9/fb @ 13 TeV

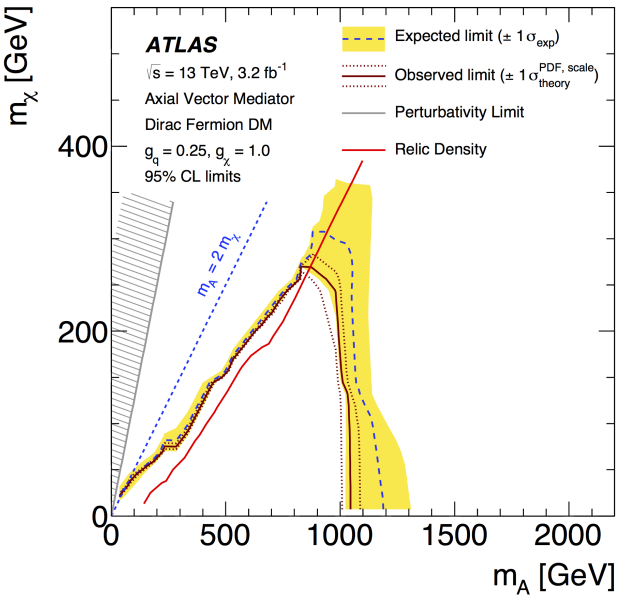


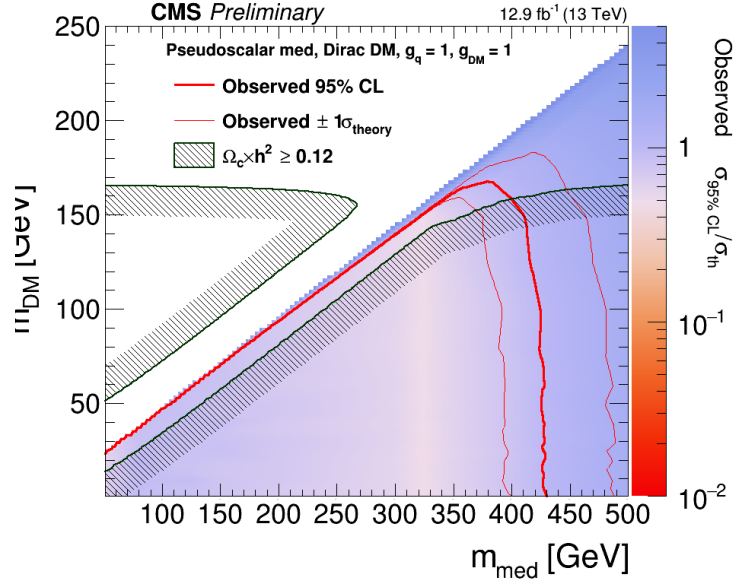




ATLAS 3.2/fb @ 13 TeV





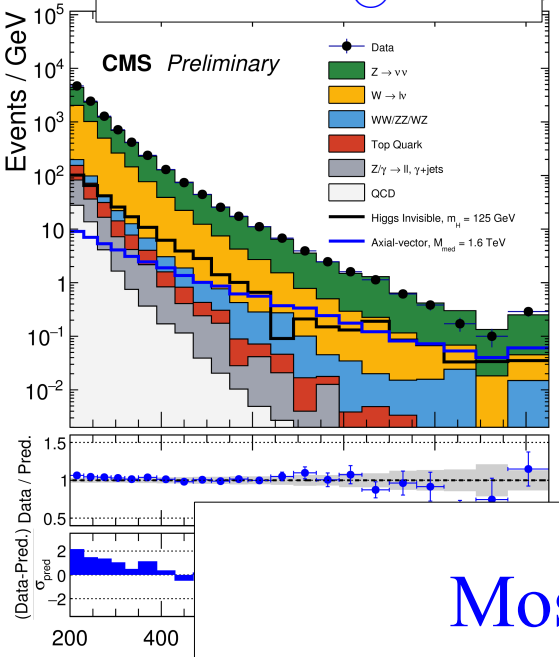


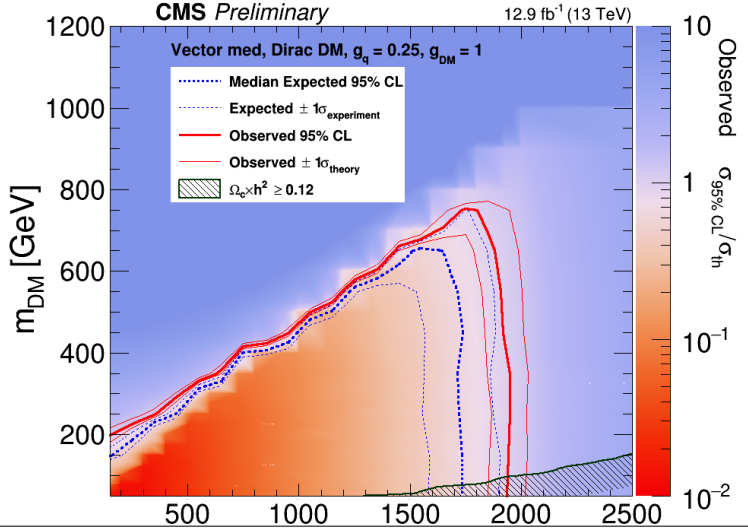
MET + jet(s)

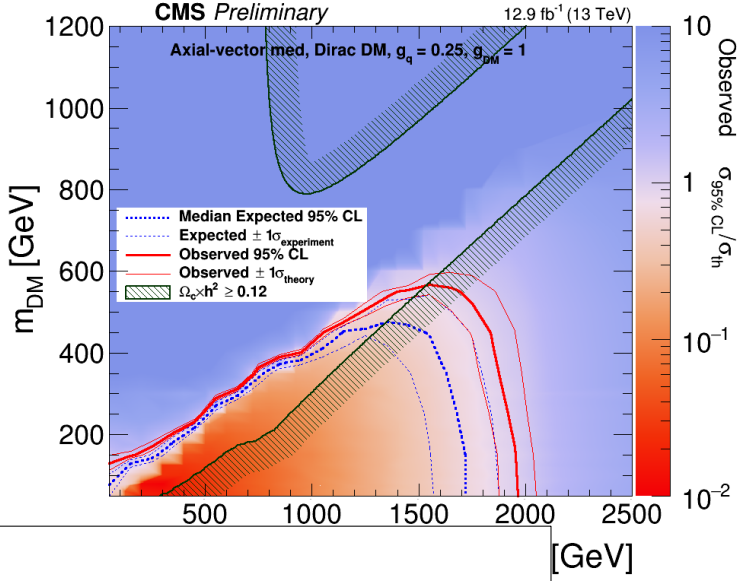
CEA – Saclay

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CMS 12.9/fb @ 13 TeV

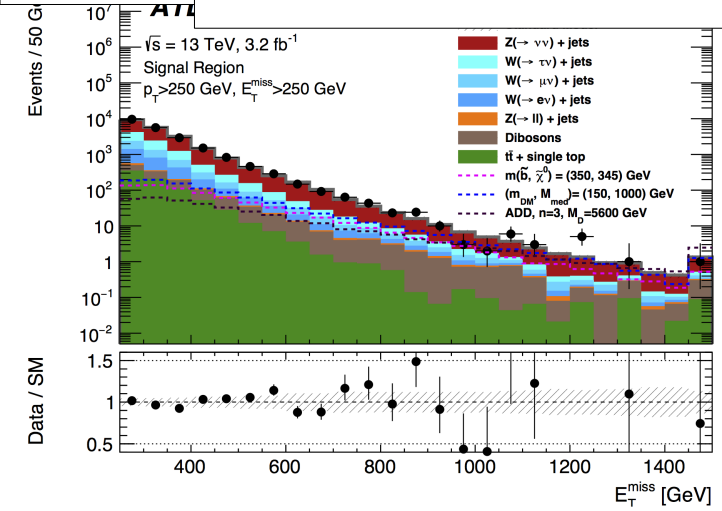


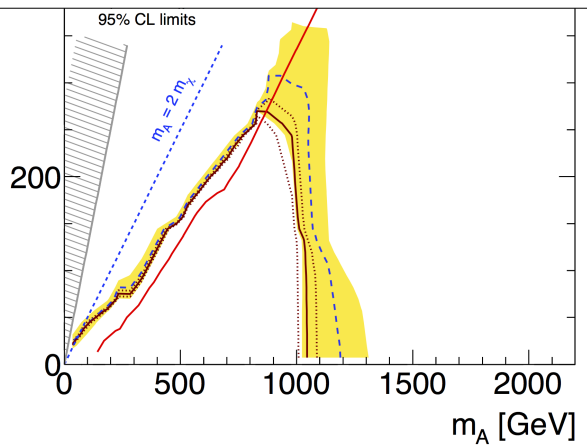


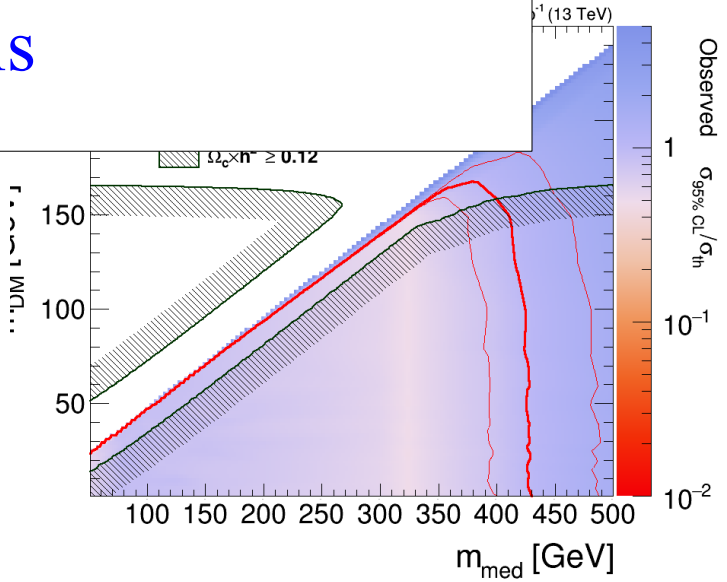


Most sensitive channel for DM searches
in a large class of models

ATLAS 3.2





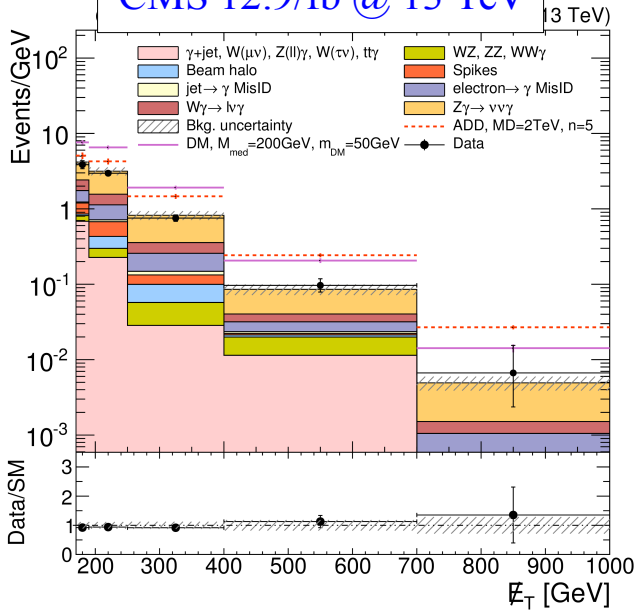


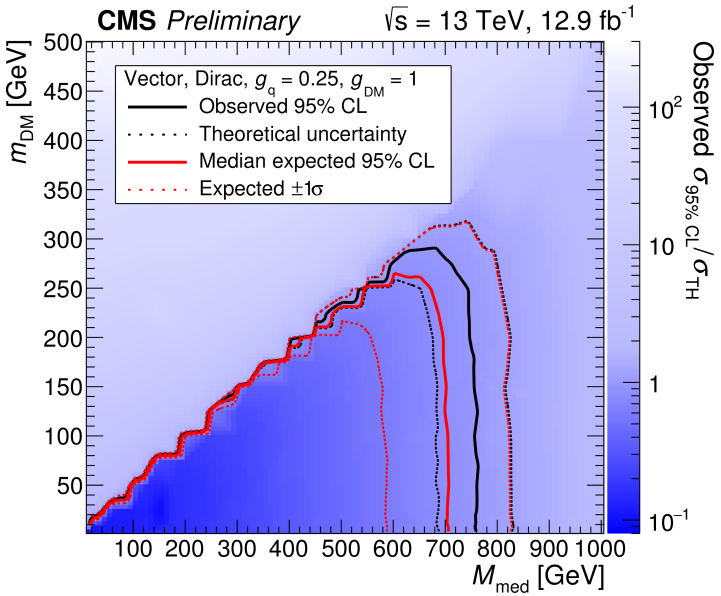
MET + photon

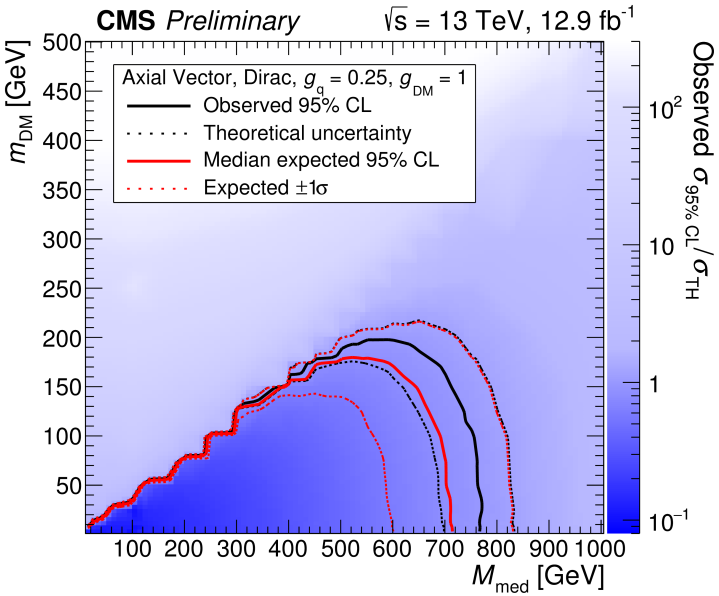
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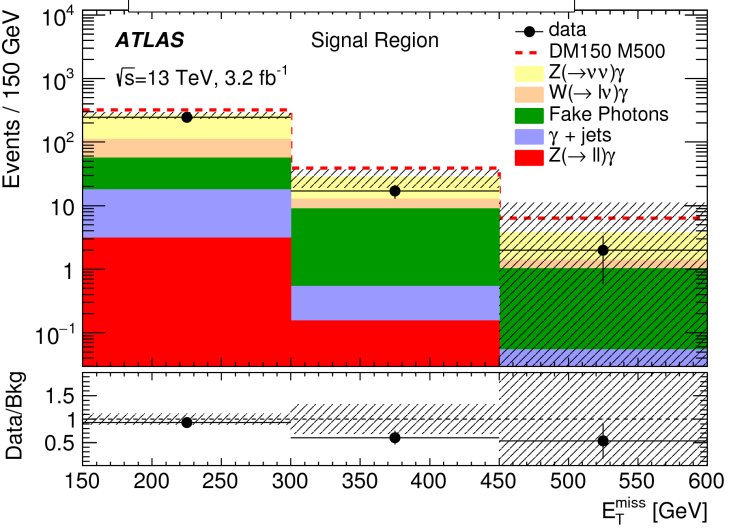
CMS 12.9/fb @ 13 TeV

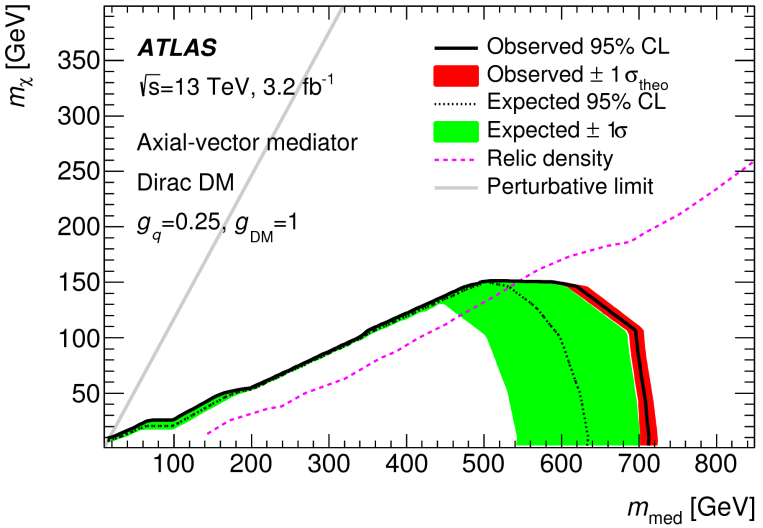






ATLAS 3.2/fb @ 13 TeV





- clean signature

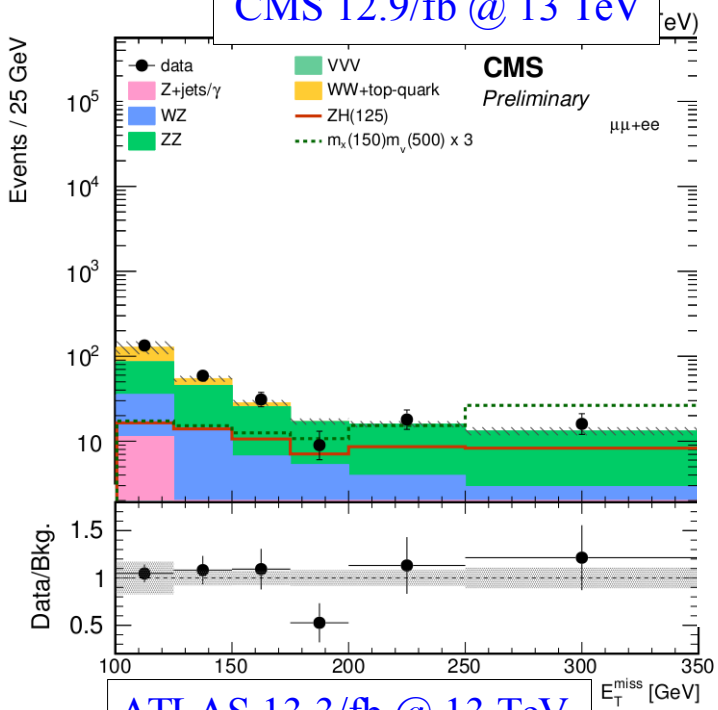
- fake photons can be an issue at higher luminosity

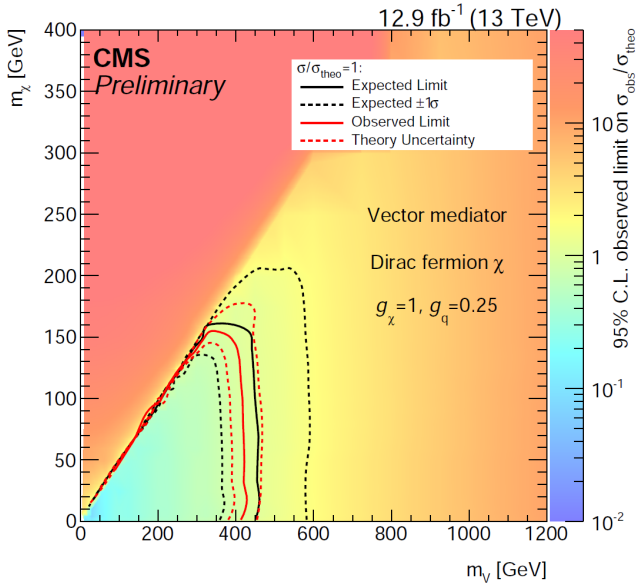
MET + Z(ll)

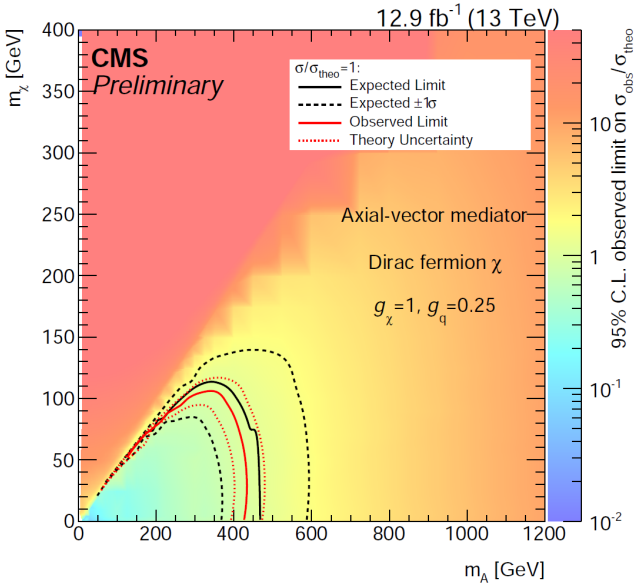
CEA – Saclay

ENS

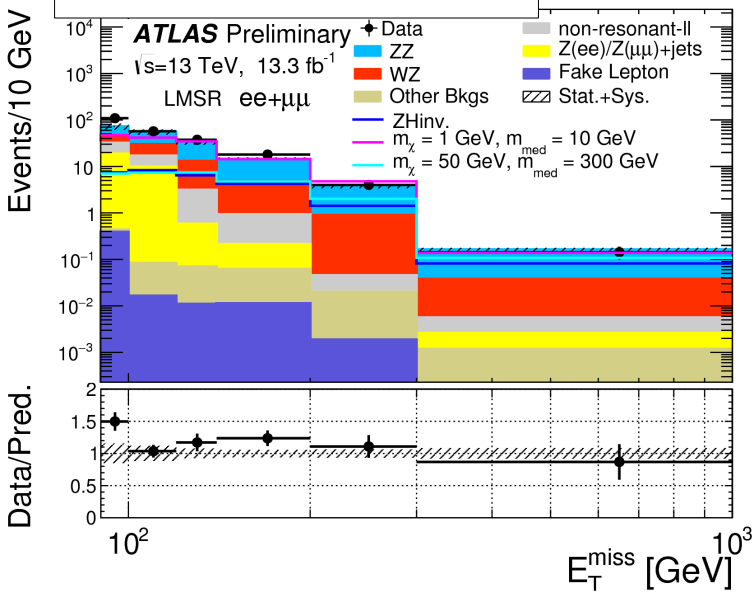
CMS 12.9/fb @ 13 TeV

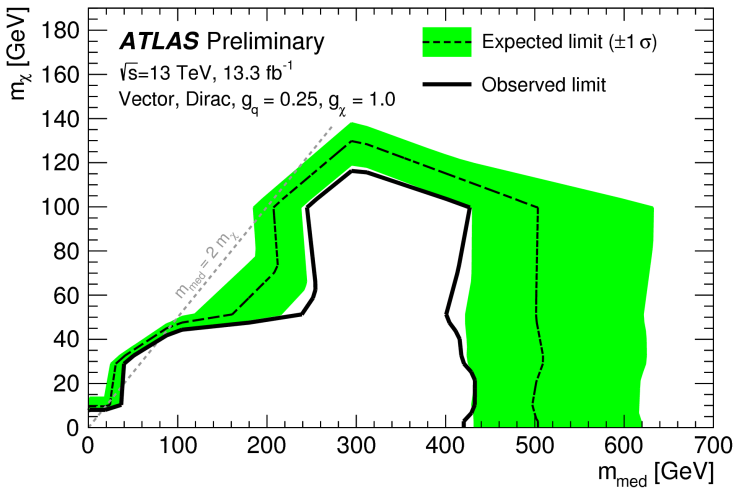






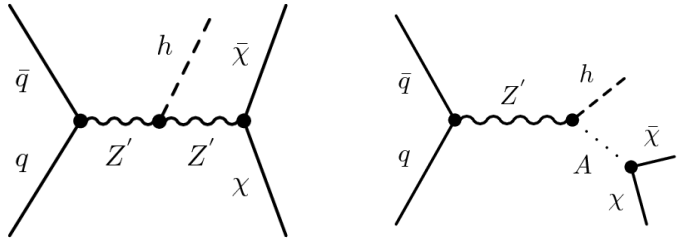
ATLAS 13.3/fb @ 13 TeV



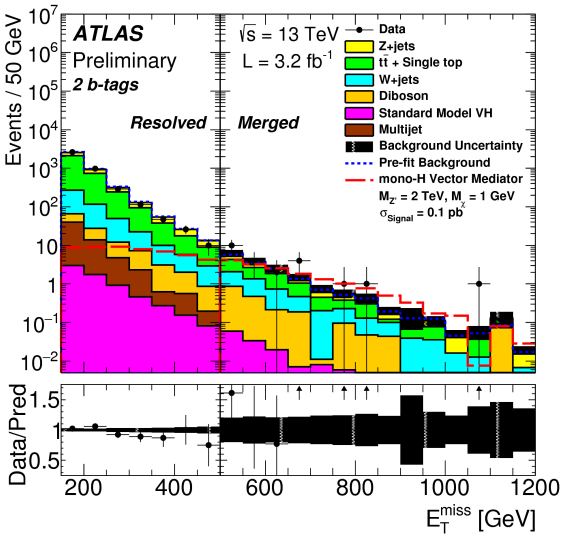


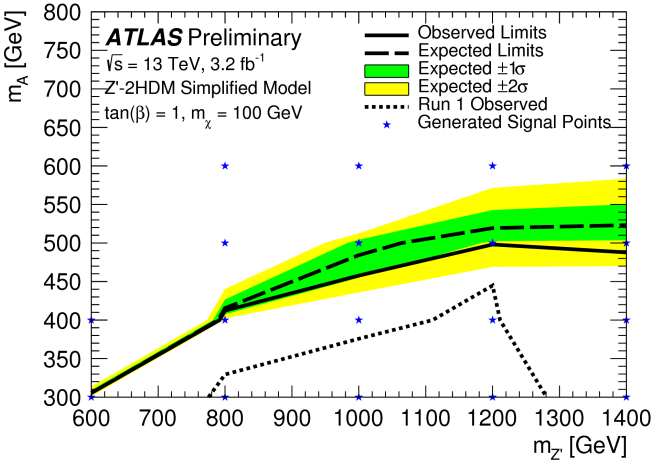
MET + Higgs(bb)

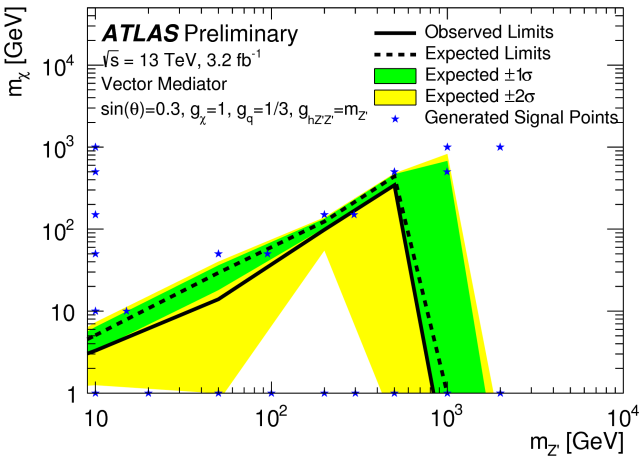
- ISR-like production (Yukawa suppressed)
- H → bb (highest Xsection)



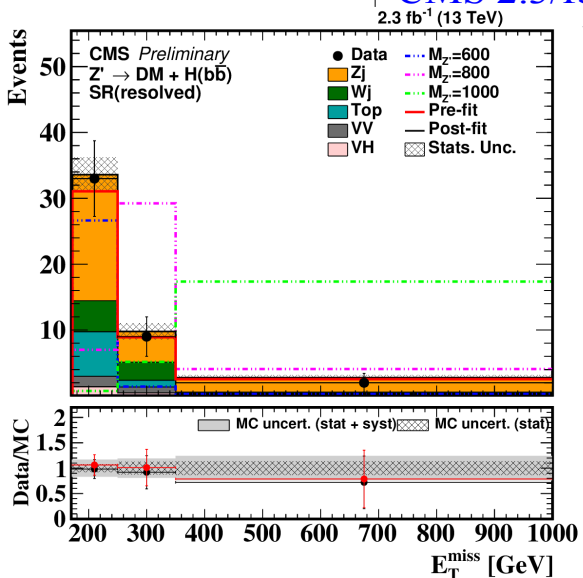
ATLAS 3.2/fb @ 13 TeV

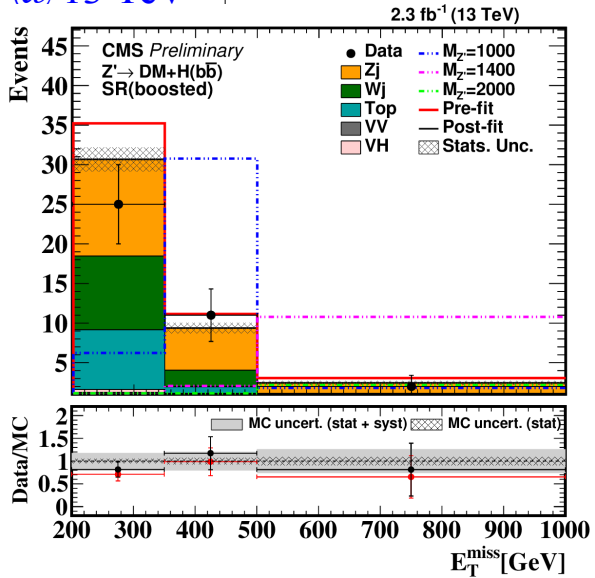


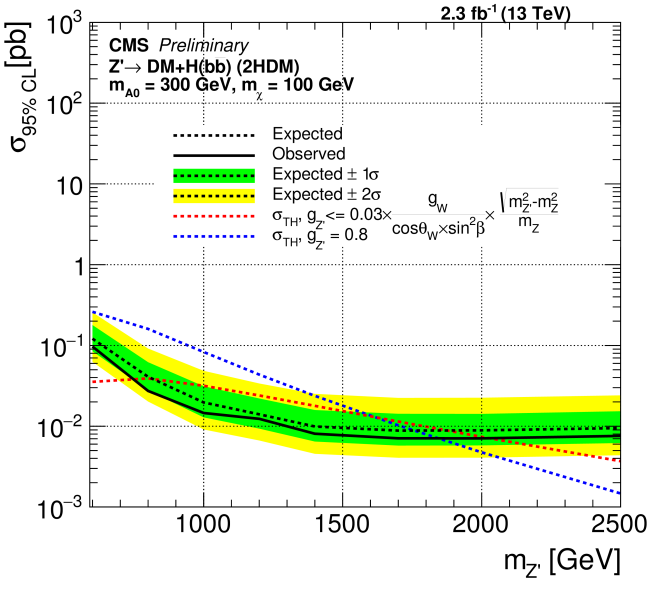




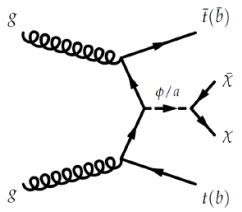
CMS 2.3/fb @ 13 TeV







CEA – Saclay

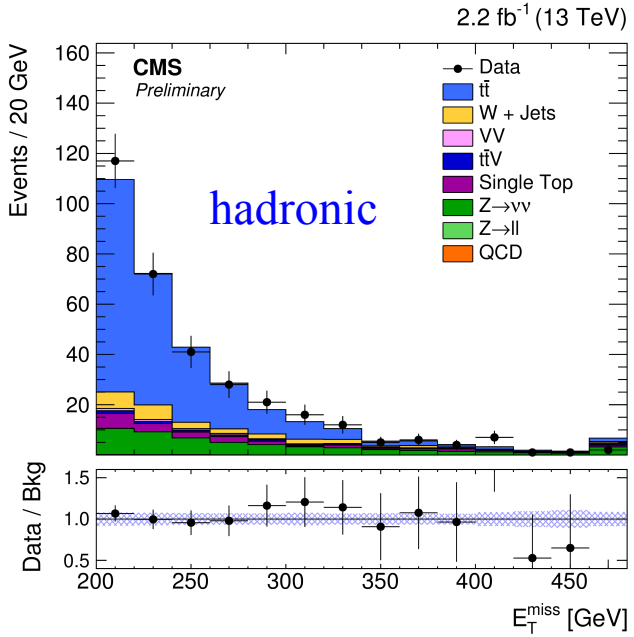


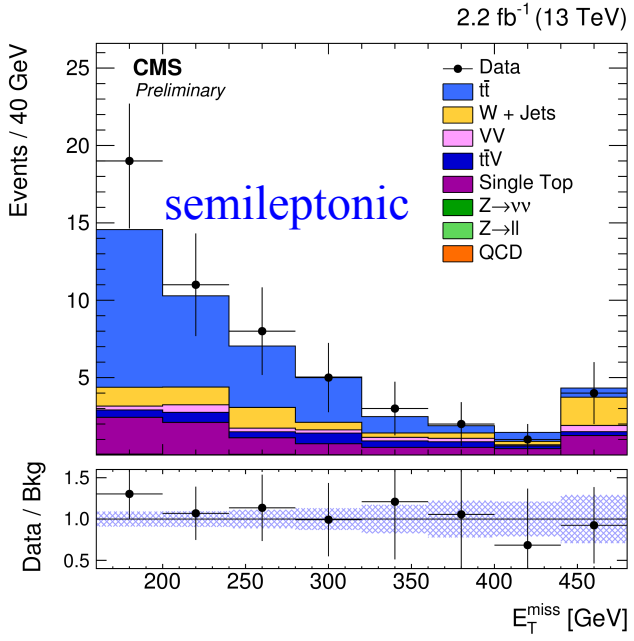
MET + ttbar

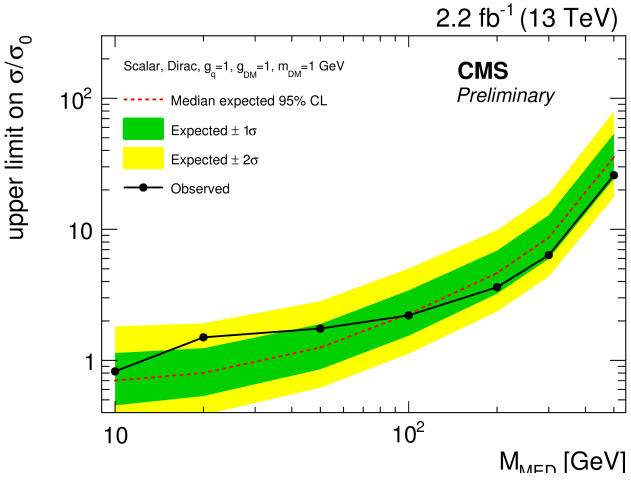
scalar

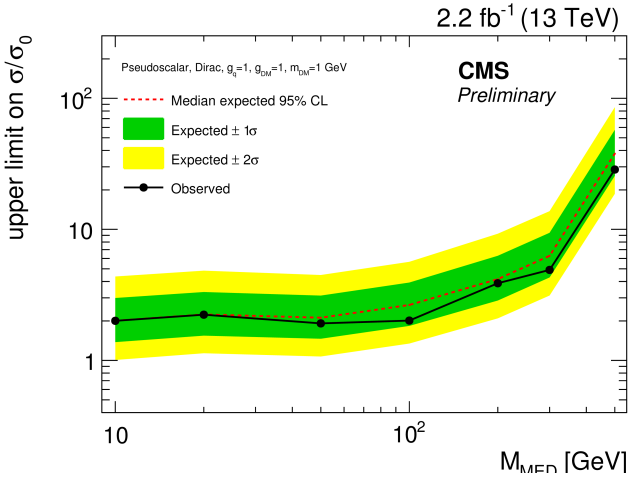
pseudo-scalar

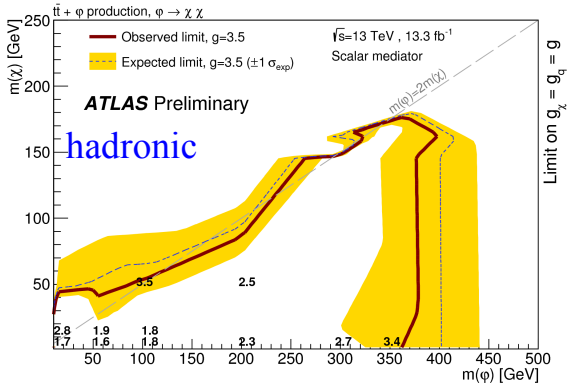
ENS

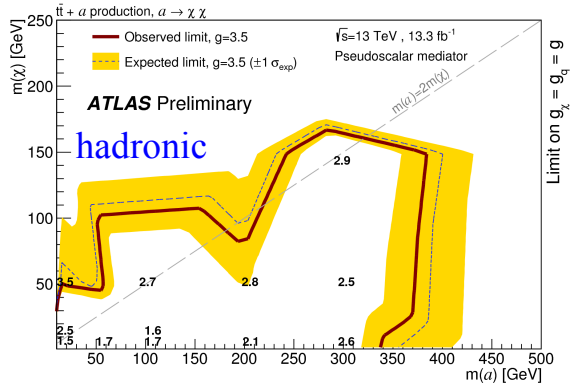


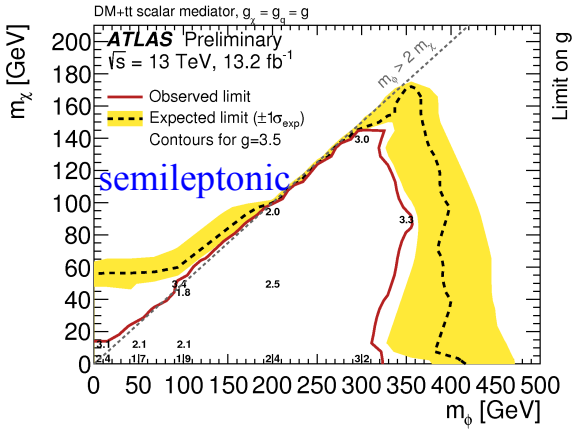


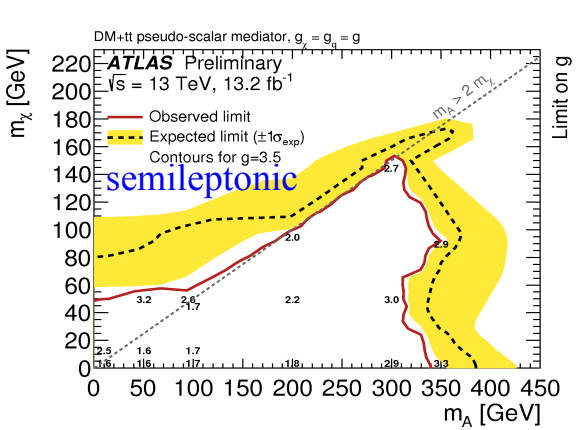




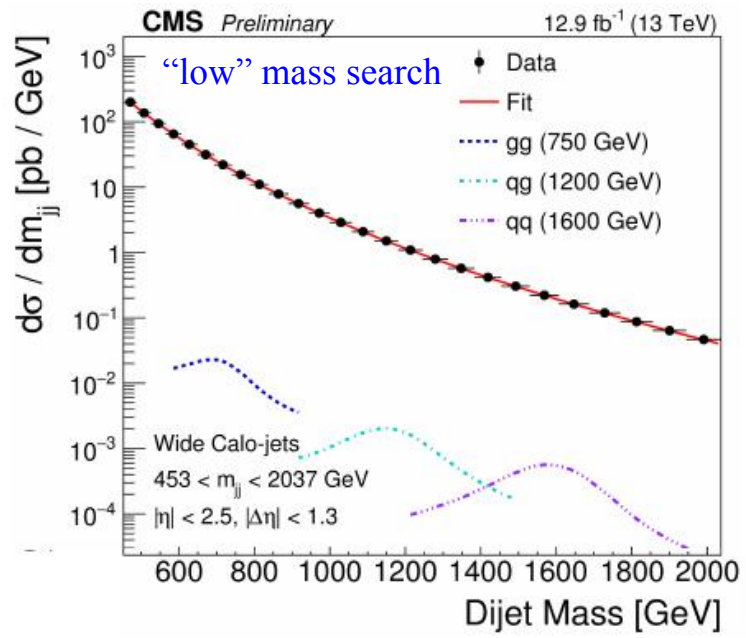


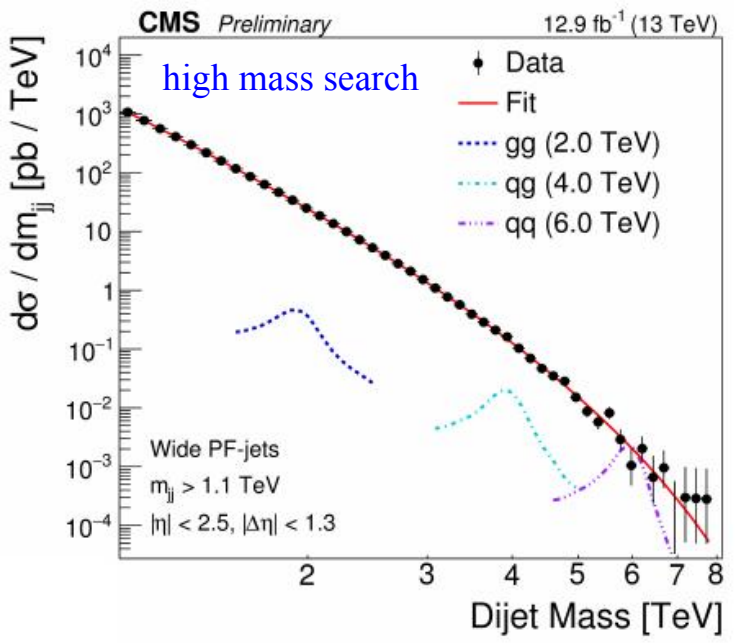


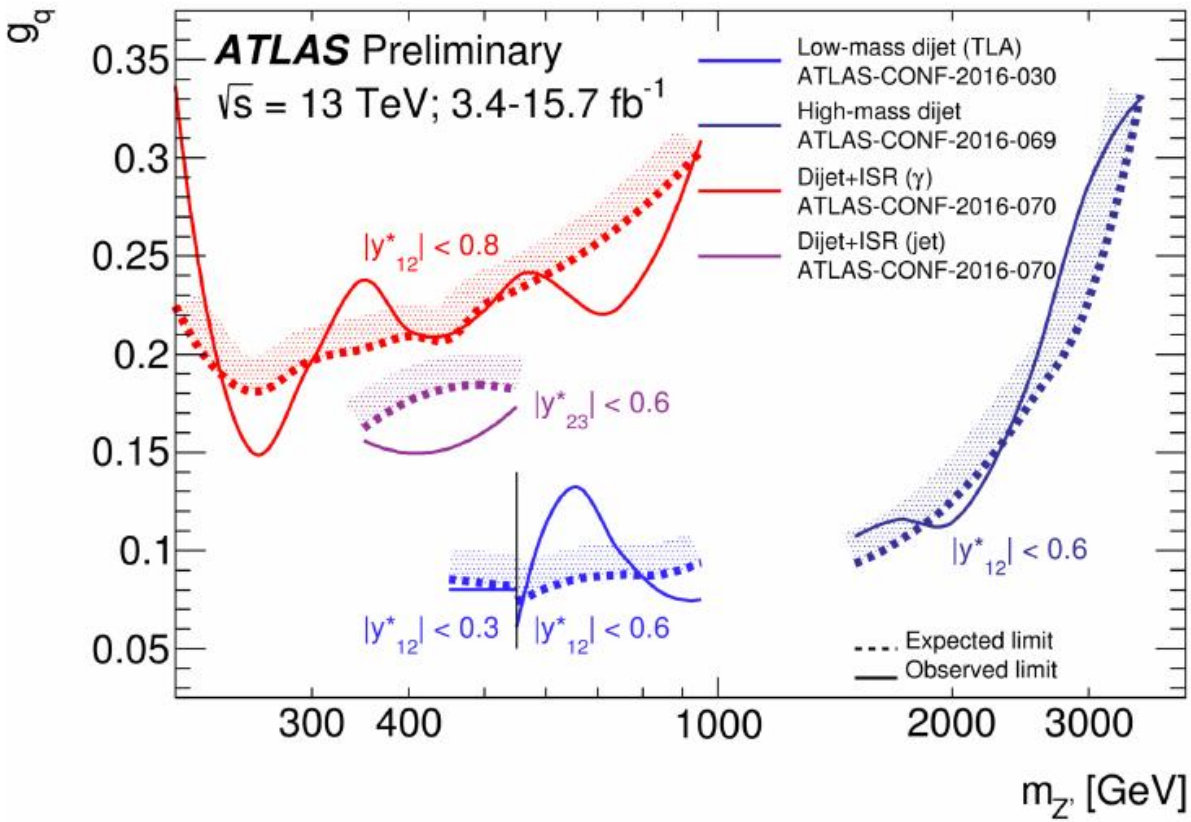




di-jet searches
searching for the mediator



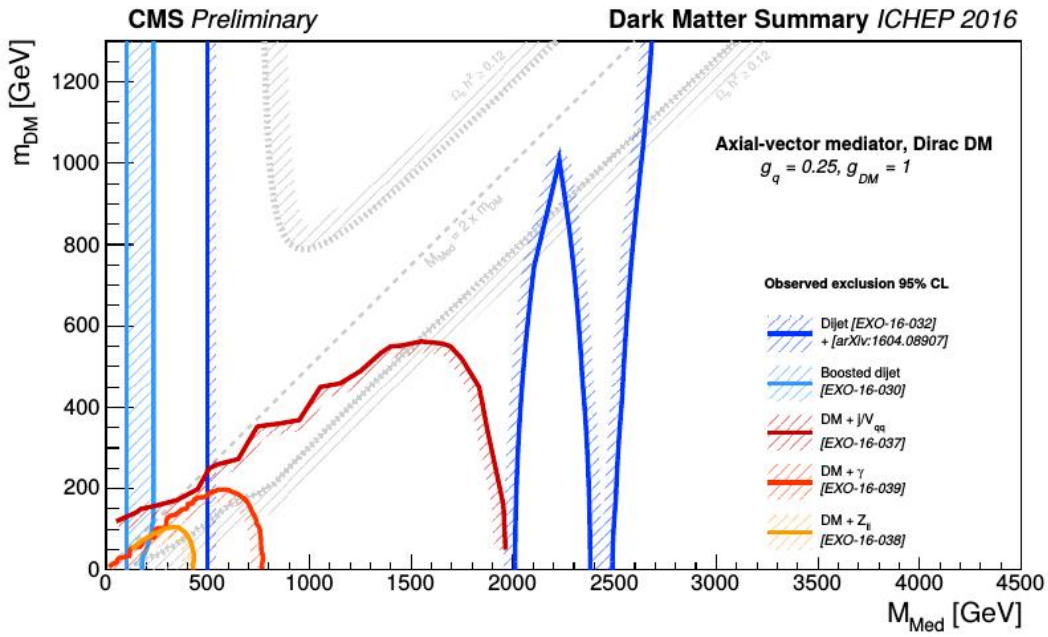


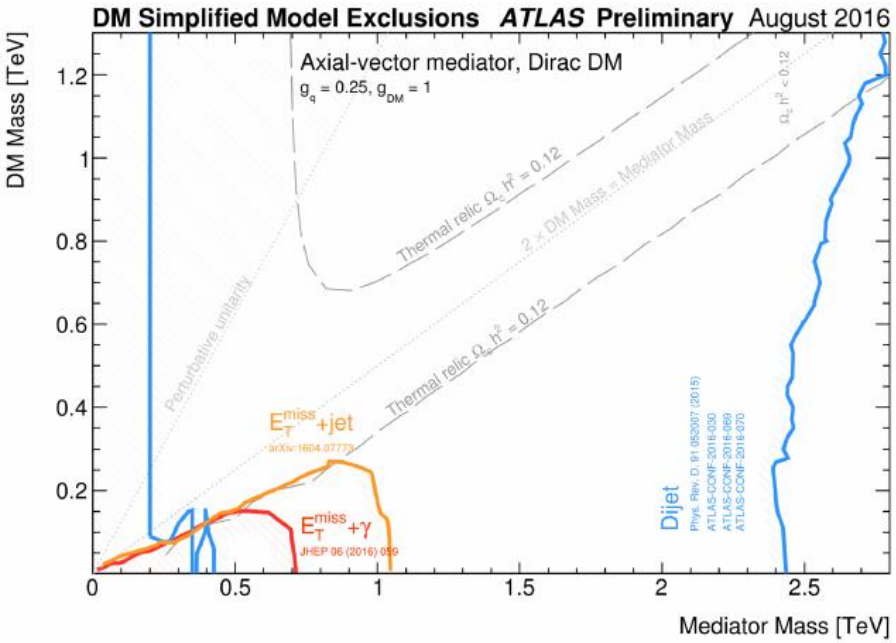


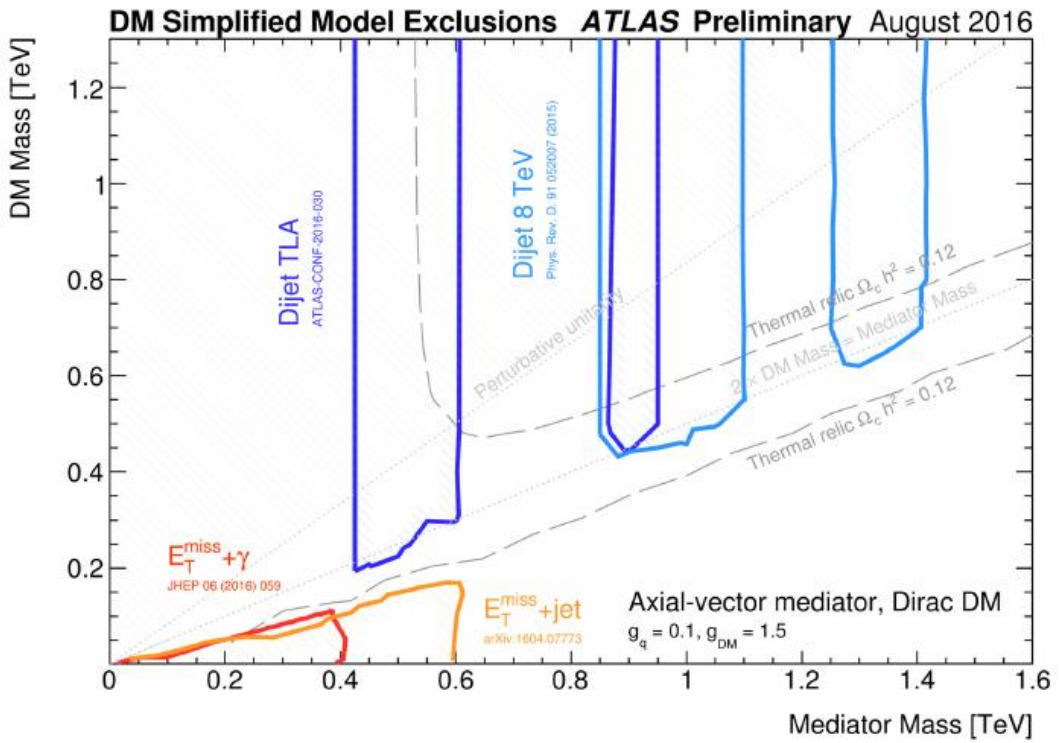
- Mediators couplings to quarks and gluon can be searched for in di-jet final state

- Strong limits are set for mediators couplings with couplings to SM as low as g_q ~ 0.1

Summary plots





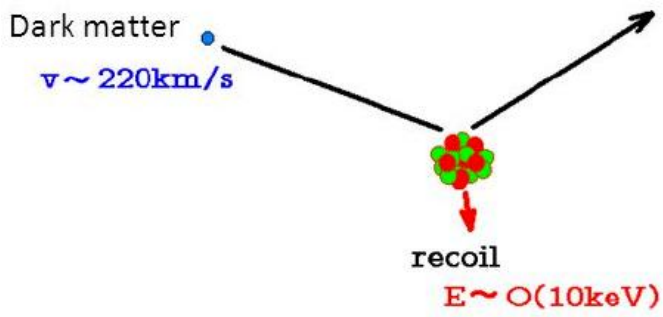


- MET + X dark matter searches can be combined with dijet mediator searches

- plots shows Simplified Model with axial-vector mediator

- for g_q = 0.25 and g_DM =1 dijet results dominate but picture is changing when couplings to SM are reduced

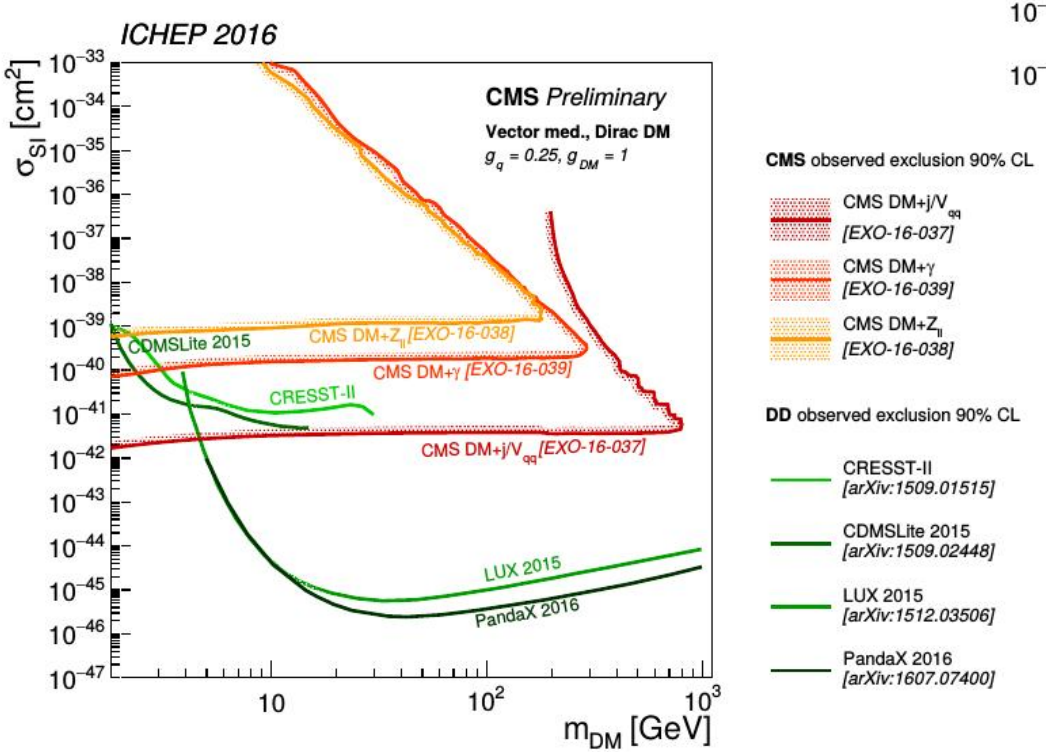
Comparison with DD and ID searches

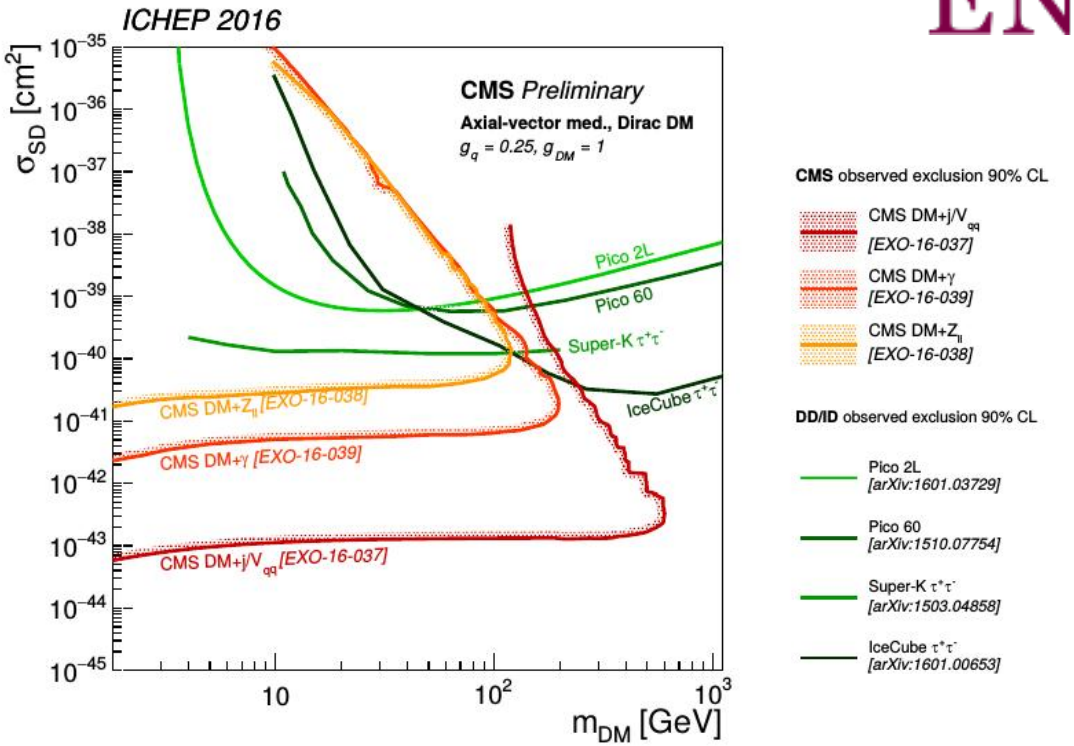


$$\mathrm{L} = \sum_{\mathrm{N}=\mathrm{p},\,\mathrm{n}} f_N\, \bar{\chi}^o \chi^o \bar{\mathrm{N}}\mathrm{N} + a_N\, \bar{\chi}^o \sigma \chi^o \bar{\mathrm{N}} \sigma\, \mathrm{N}$$

Spin-independent (SI) interaction

Spin-dependent (SD) interaction



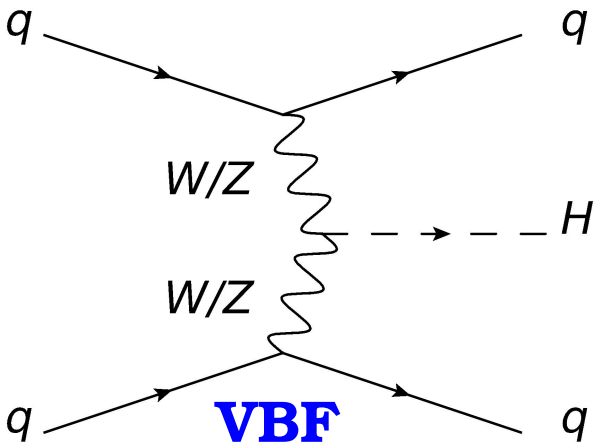


- Simplified Models allow for comparison with Direct and Indirect Detection searches

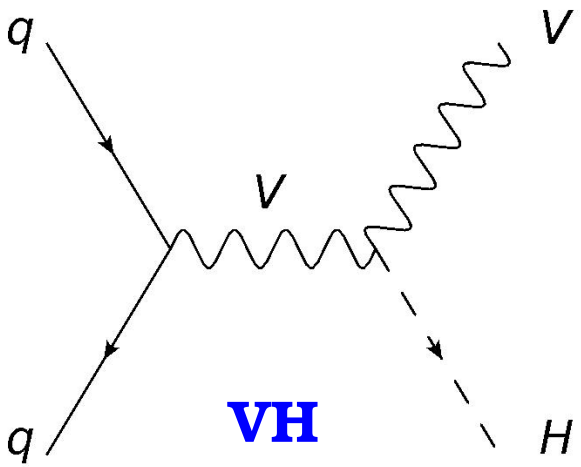
- Relic density not used in the constraints

- Results strongly depend on the choice of SM and DM couplings

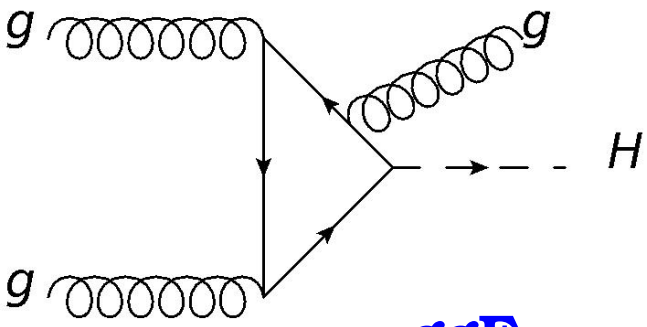
Invisible Higgs boson



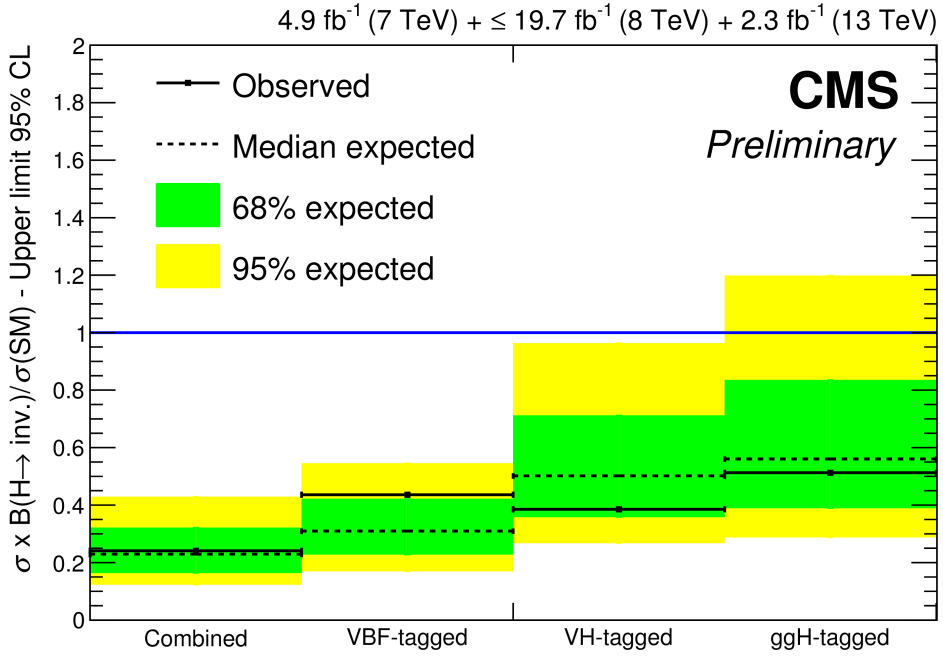
VBF

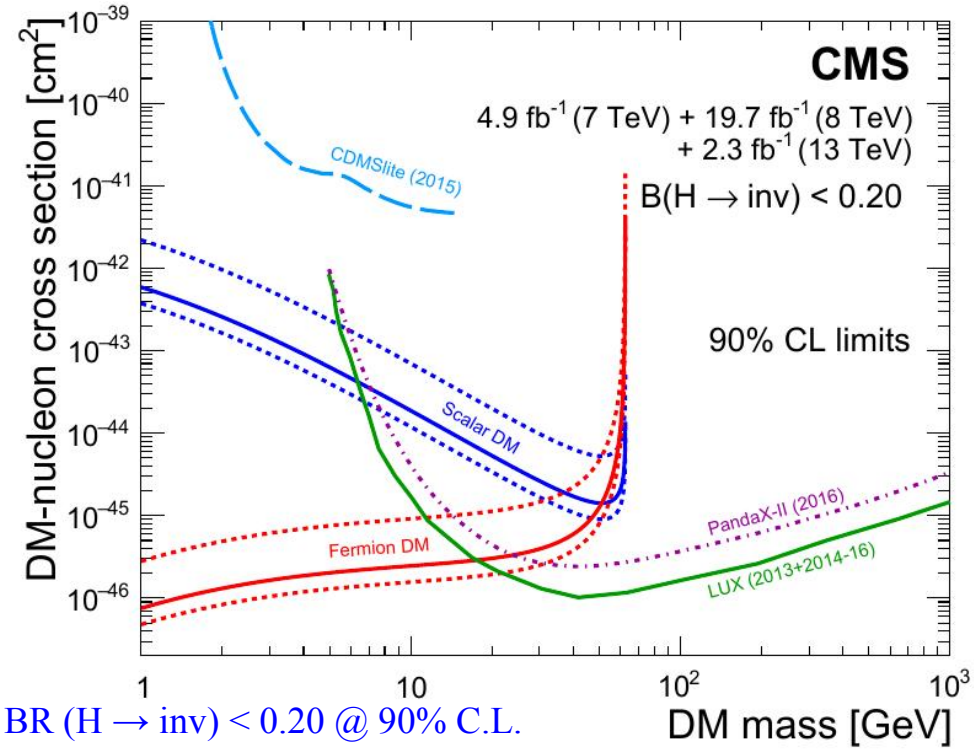


VH



ggF





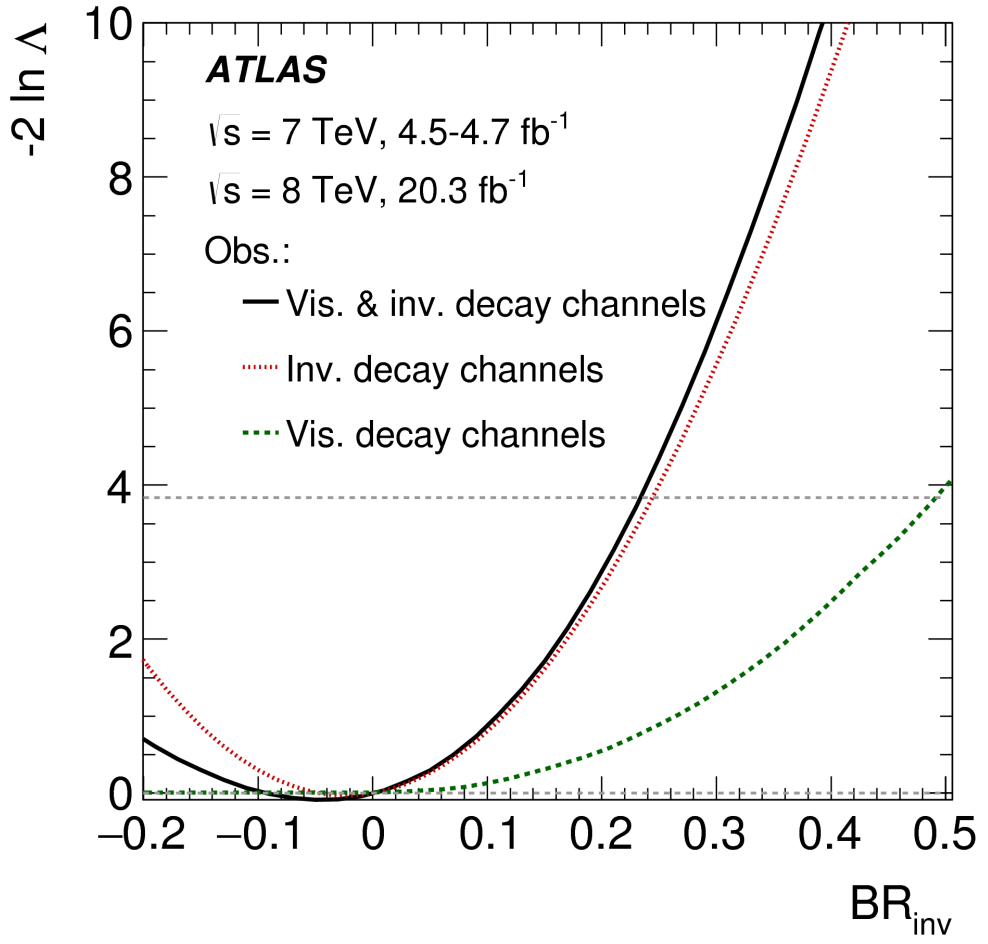
BR (H → inv) < 0.24 (0.23 expected) @ 95% C.L. and BR (H → inv) < 0.20 @ 90% C.L.

Invisible Higgs boson

combining several production and visible decay channels including :

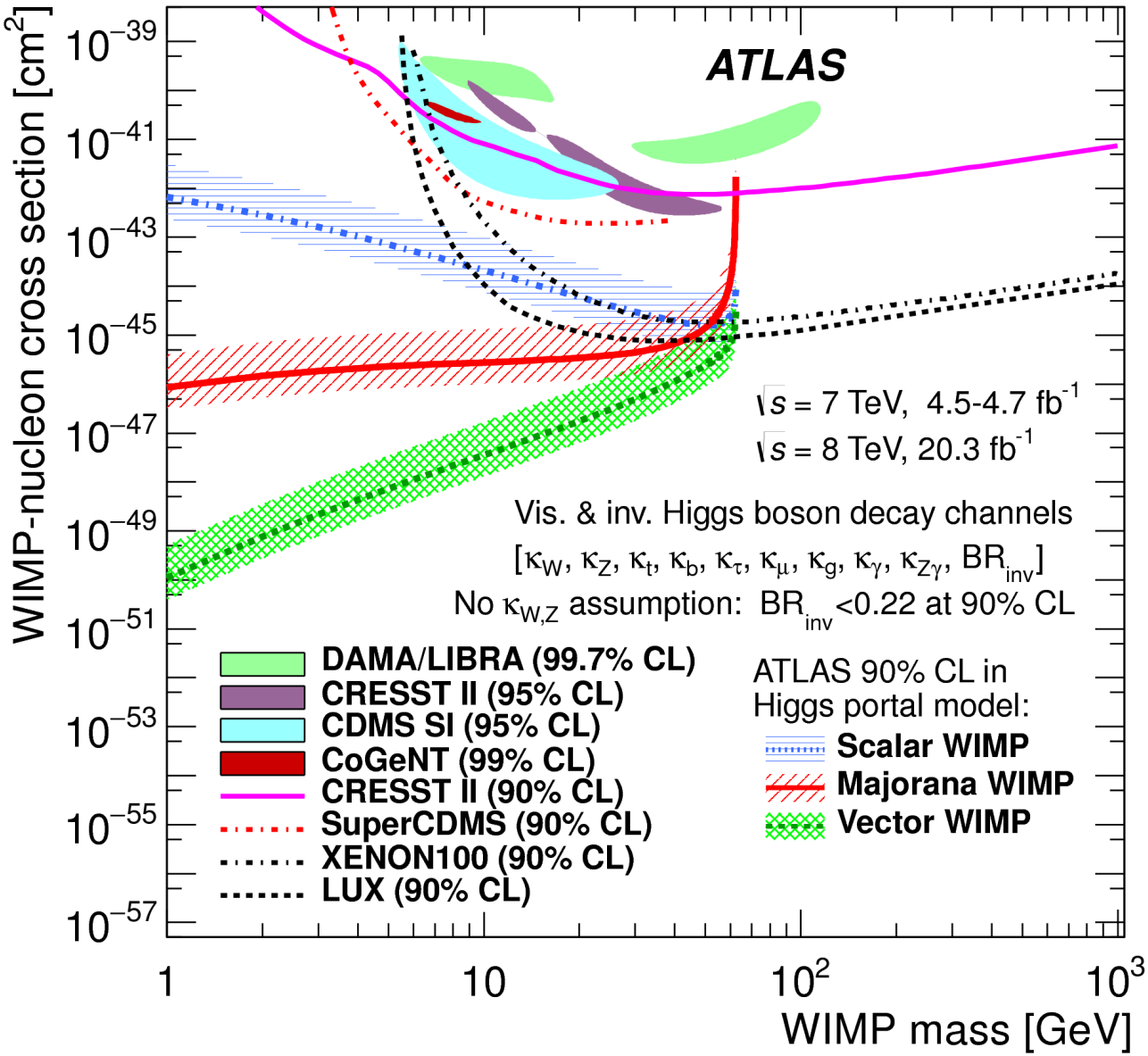
$\gamma\gamma$, WW , ZZ , $Z\gamma$, $b\bar{b}$, $\tau\tau$, $\mu\mu$

with constraints on BR(H → inv) from direct VBF and Z(ll)H searches (combined)



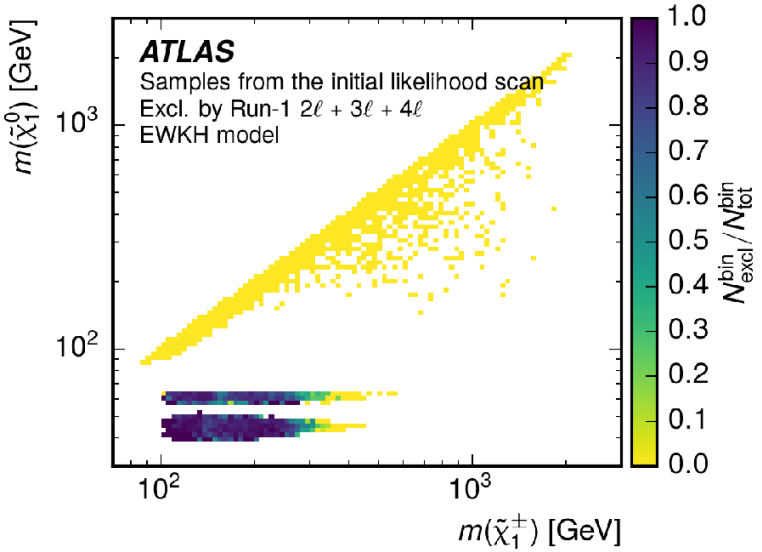
$BR_{inv} < 0.23\ (0.24\ exp.)$ at 95 % CL

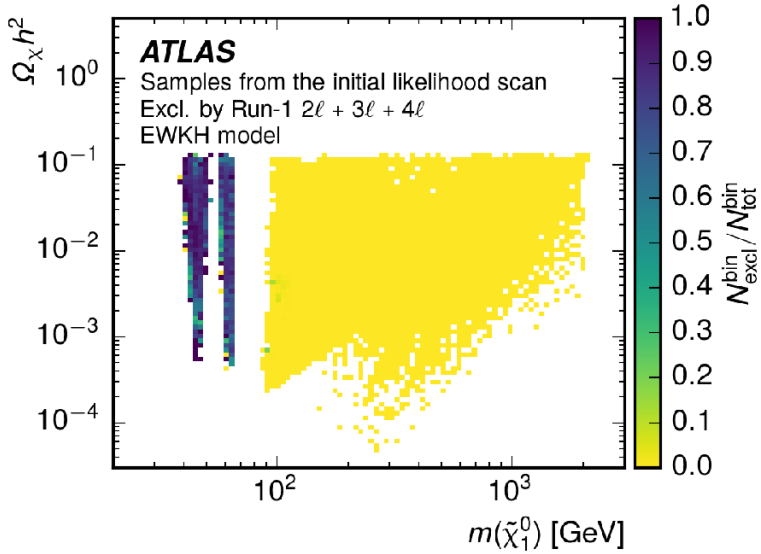
Invisible Higgs boson

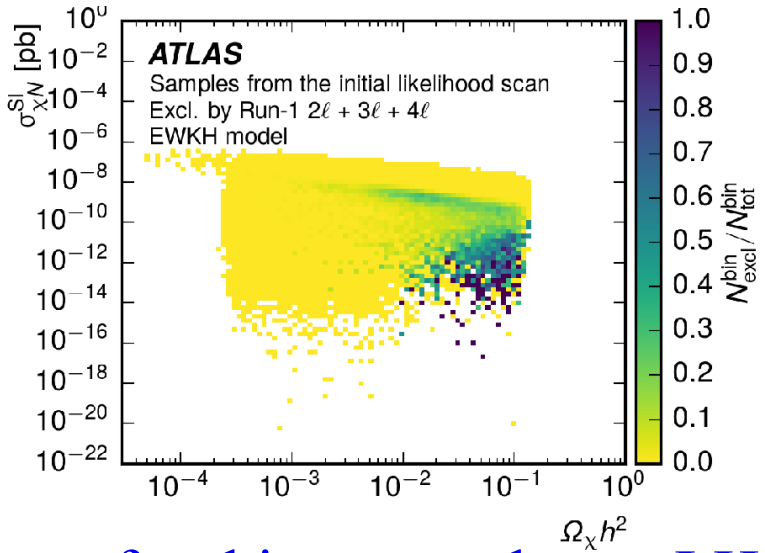


back to SUSY

…. with conserved R-parity !







DM interpretations of ewkinos searches at LHC Run 1 (8 TeV)

JHEP 09 (2016)175

will be done for Run 2 (13 TeV) data

SUMMARY

searches for Dark Matter at colliders

- **MET + X events searches, dijet events searches**
- **H precision measurements and invisible H**
- **simplified model used (+ interpretation in specific models)**
- **complementarity with direct and indirect searches**

No discovery yet → ongoing effort at LHC (full 2016 dataset + 2017 + 2018)

planning for the future

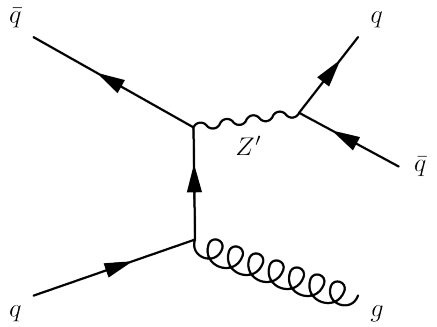
- **HL-LHC, LC, FCC … and lower energy machines(present)**

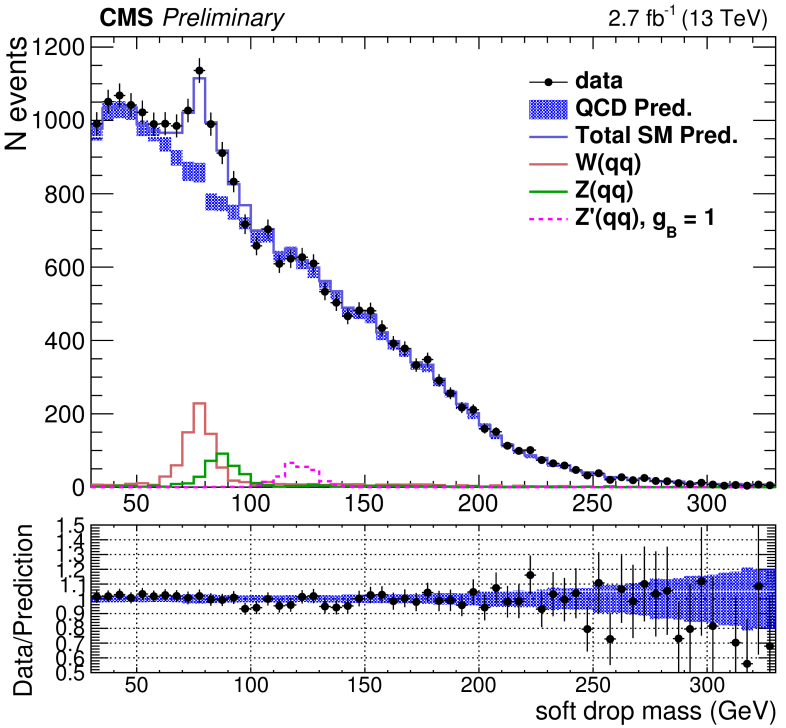
room for new ideas

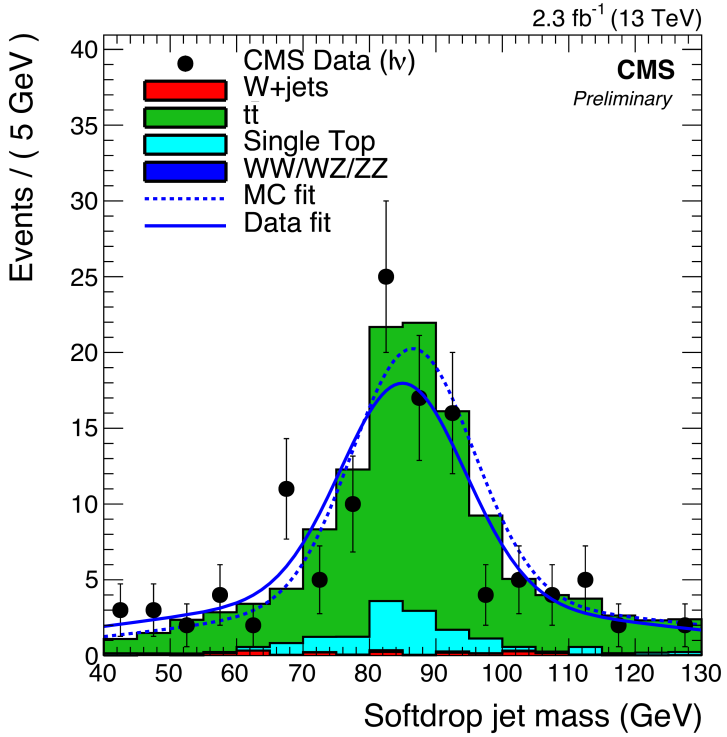

THANK YOU PIERRE !

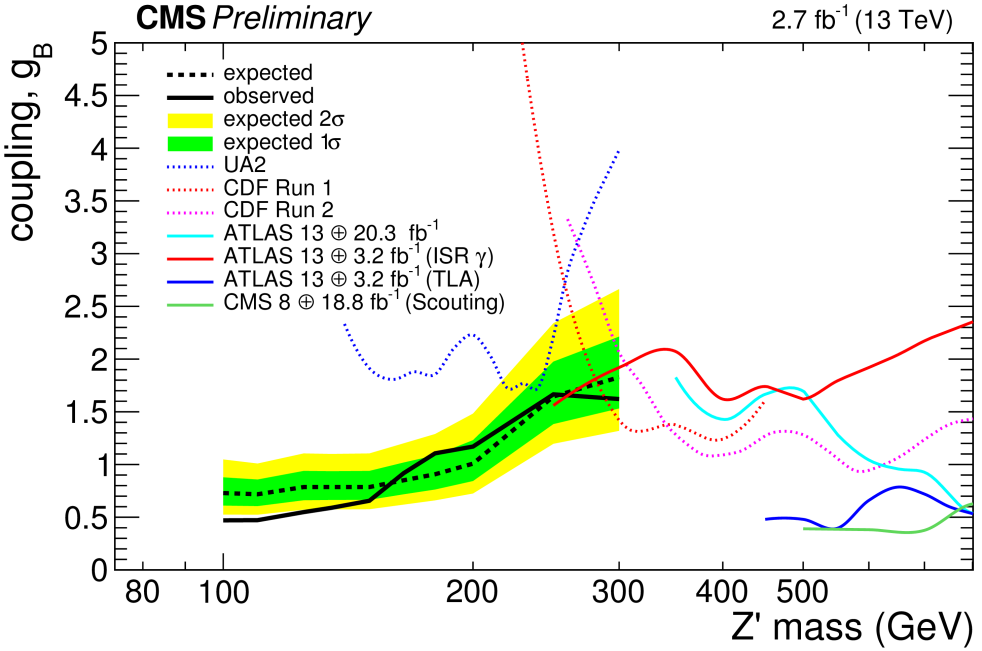
BACKUP

searching for light mediator









merged W jet in semileptonic ttbar control region

Invisible Higgs boson

translated into DM-higgs coupling constraints

$$\Gamma^{\text{inv}}(H \to SS) = \lambda_{\text{hSS}}^2 \frac{v^2 \beta_S}{128 \pi m_h}$$

$$\Gamma^{\text{inv}}(H \to f f) = \frac{\lambda_{\text{hff}}^2}{\Lambda^2} \frac{v^2 \beta_f^3 m_h}{64 \pi}$$

$$\beta_\chi = \sqrt{1 - 4 \frac{m_\chi^2}{m_h^2}}$$

$$\Gamma^{\text{inv}}(H \to V V) = \lambda_{\text{hVV}}^2 \frac{v^2 \beta_V m_h^3}{512 \pi m_V^4} \left(1 - 4 \frac{m_V^2}{m_h^2} + 12 \frac{m_V^4}{m_h^4} \right)$$

and reparameterized in terms of $\sigma_{\chi - N}$ via Higgs boson exchange

back to SUSY with conserved R-parity

