Searches for Dark Matter plus Heavy Flavor Production at the LHC

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(on behalf of the ATLAS and CMS Collaborations)

DM@LHC Workshop, 3rd – 5th April 2017

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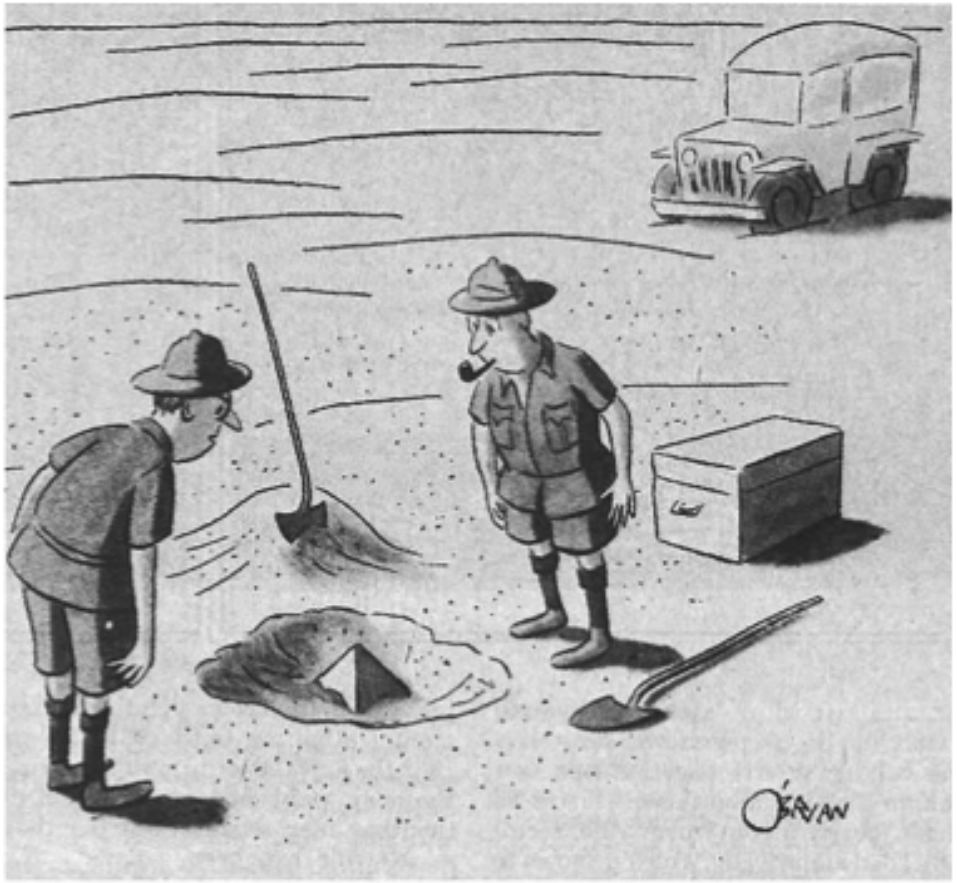
Outline

- **LHC and ATLAS/CMS**
- **Theory Framework**
- **DM+HF results**
- **Final notes**



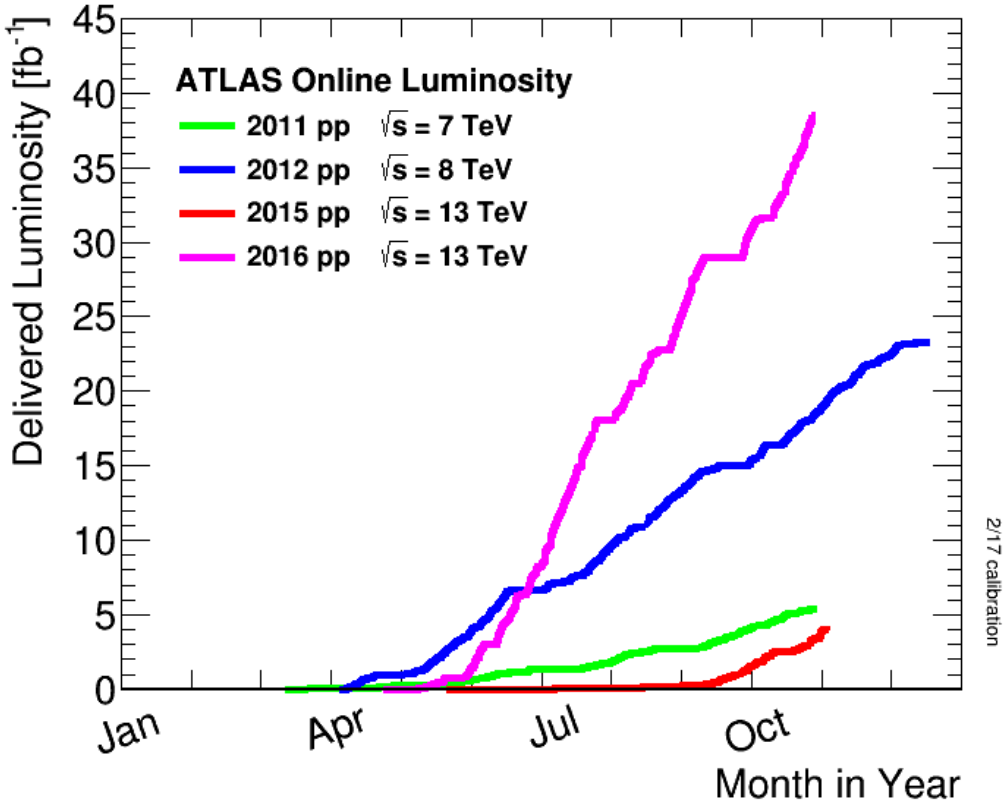
"This could be the discovery of the century. Depending, of course, on how far down it goes."

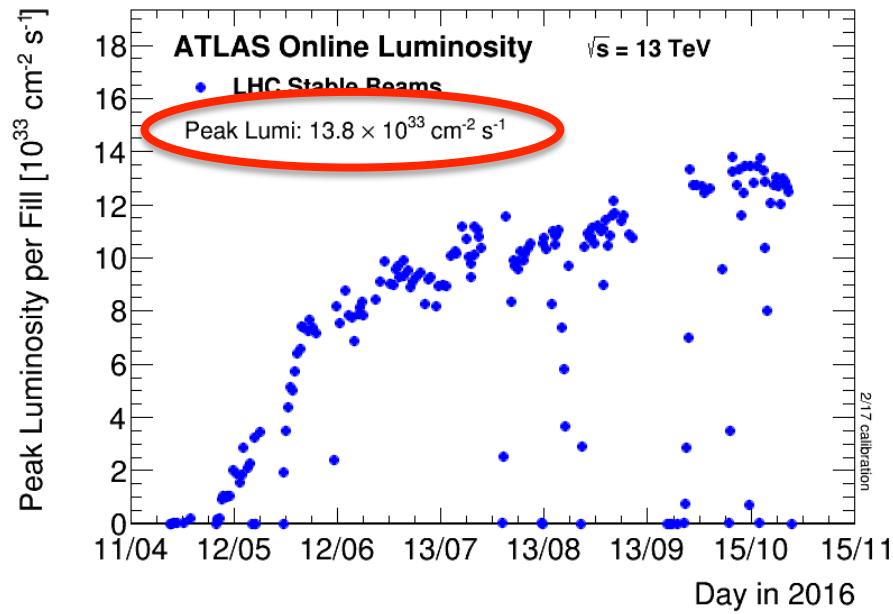
This talk is focused on dedicated DM searches inspired by simplified models with light mediators

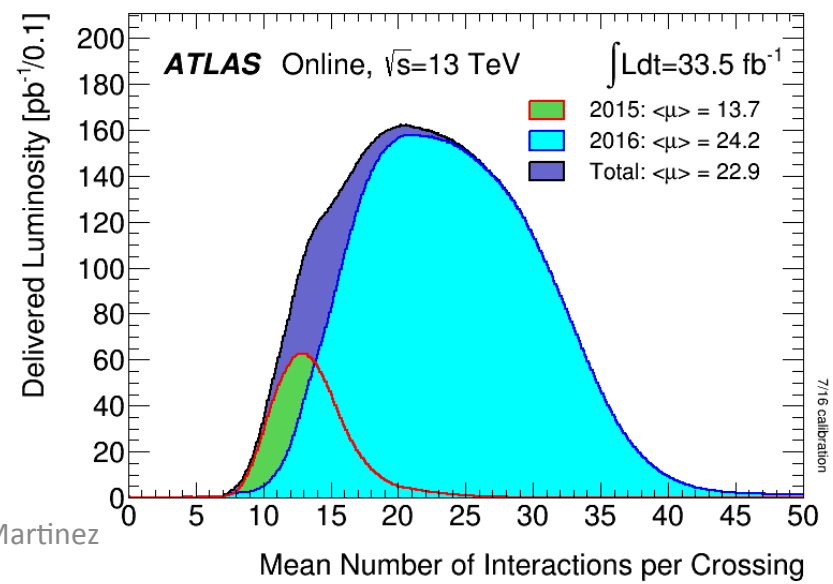
→ Searches for SUSY 3rd generation squarks and mono-H (→ bb) covered by separate talks

LHC Performance (2010-2016)

Spectacular LHC performance (rapid increase of data samples)

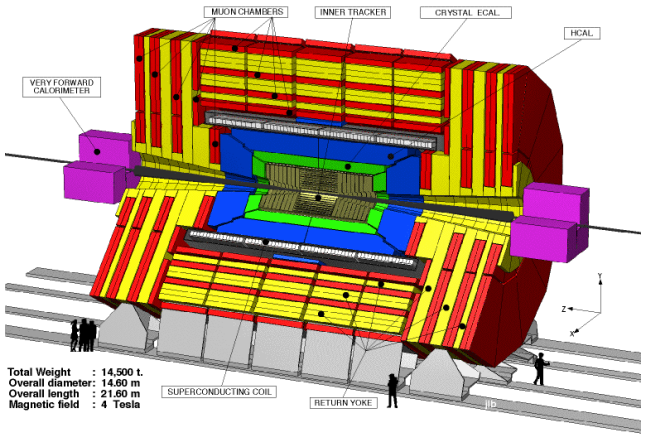


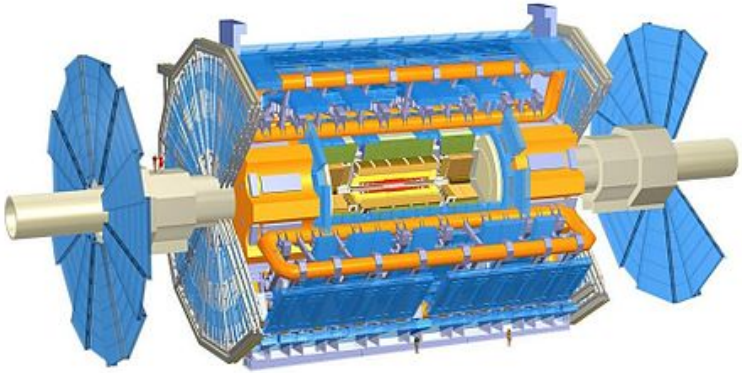


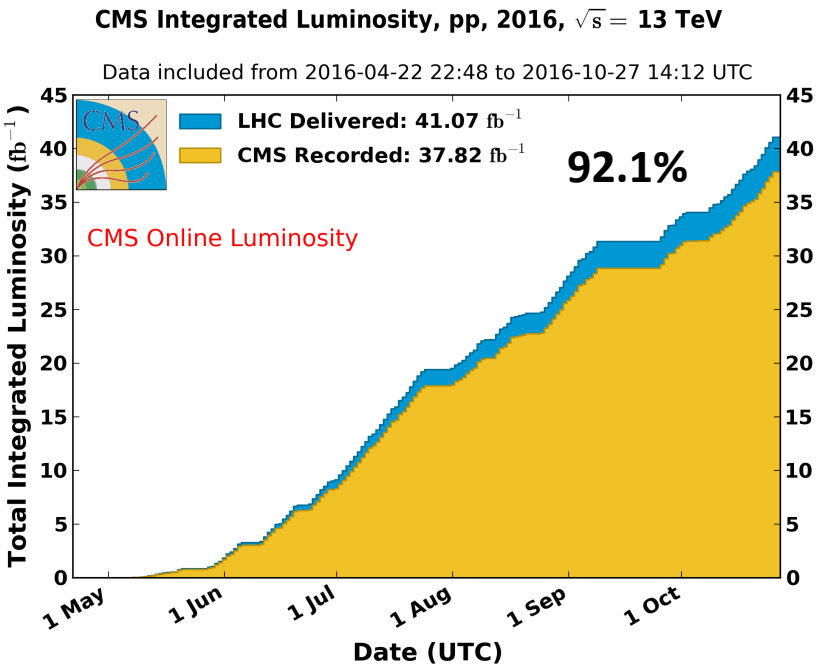


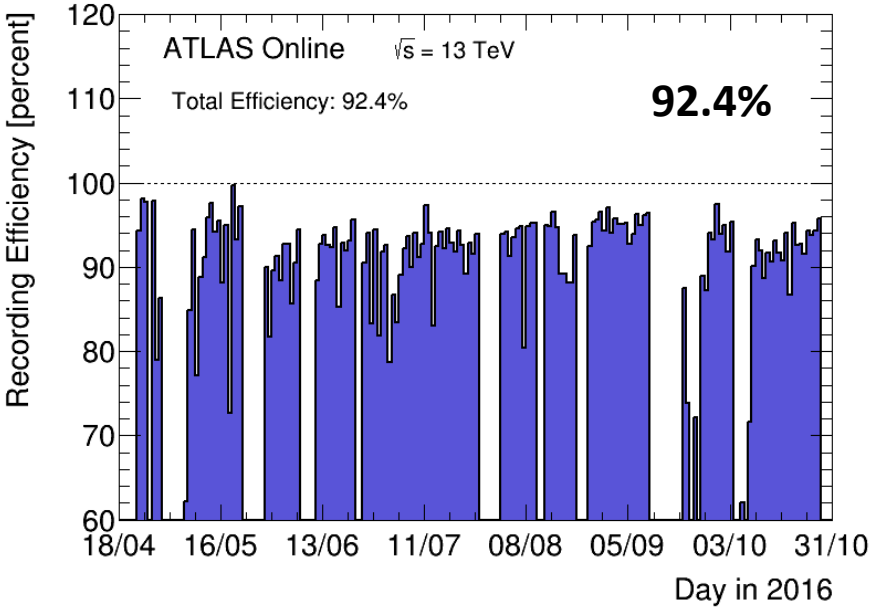
LHC performed beyond expectations in 2016 leading to a data samples of about 40 fb-1 (..at the costs of increased pile-up levels)

ATLAS/CMS Performance









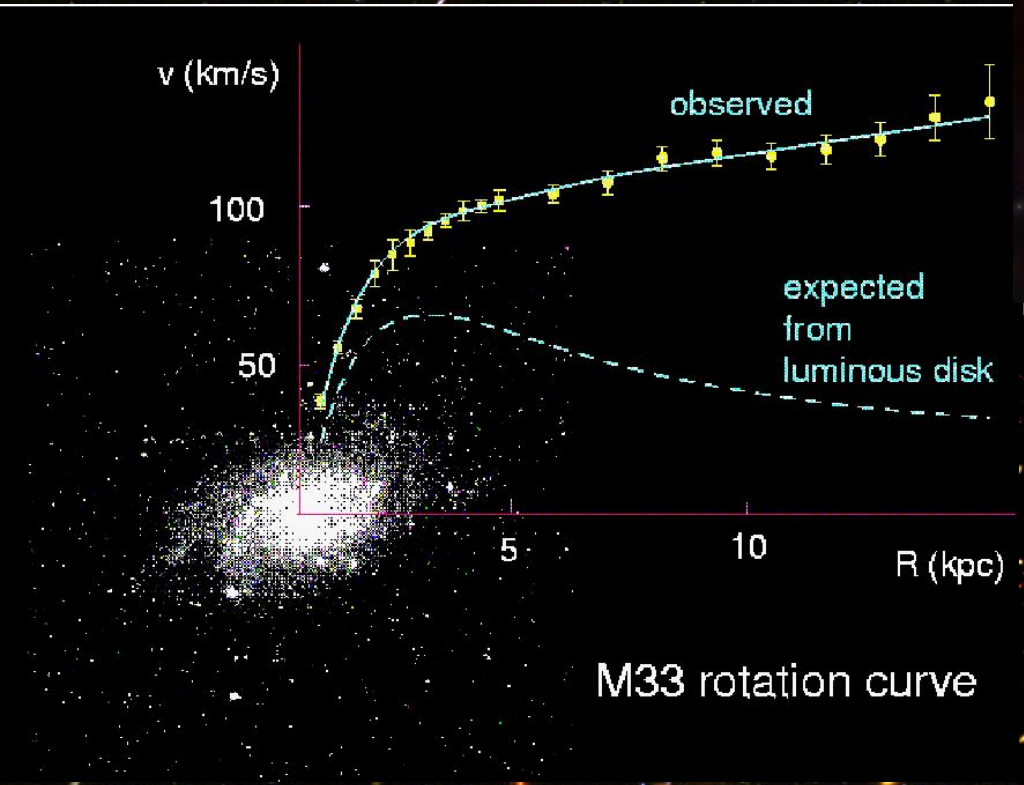
The experiments collected high-quality data with efficiencies above 92%

At the moment both experiments are still furiously analyzing the data

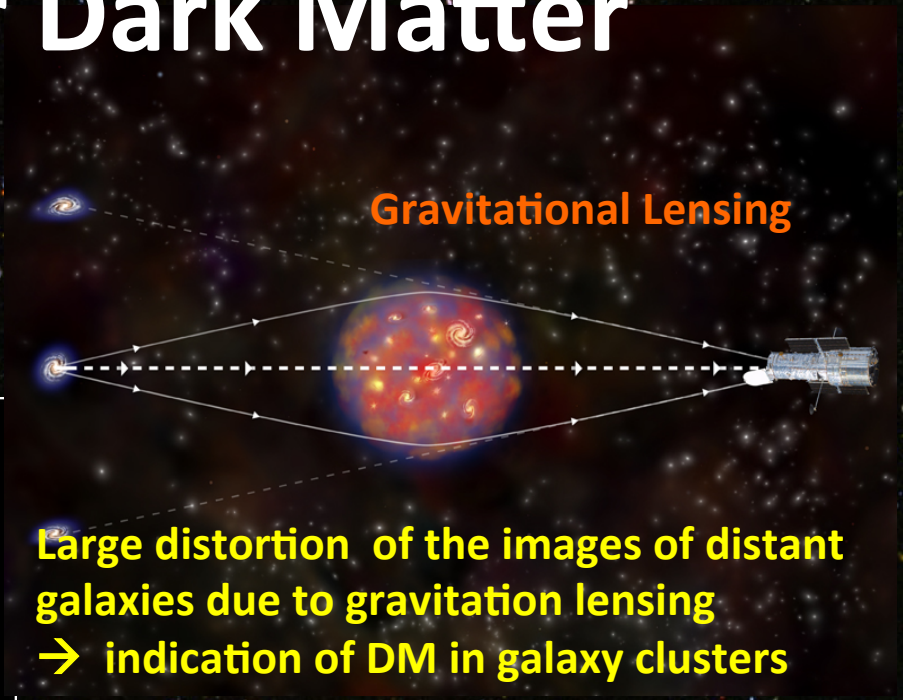
Evidence for Dark Matter

The rotation of the stars around the center of the galaxies is not consistent with the amount of mass observed $(L/M \text{ ratio})_{SUN}$.

Spherical dark matter halo



Gravitational Lensing



Large distortion of the images of distant galaxies due to gravitation lensing
→ indication of DM in galaxy clusters

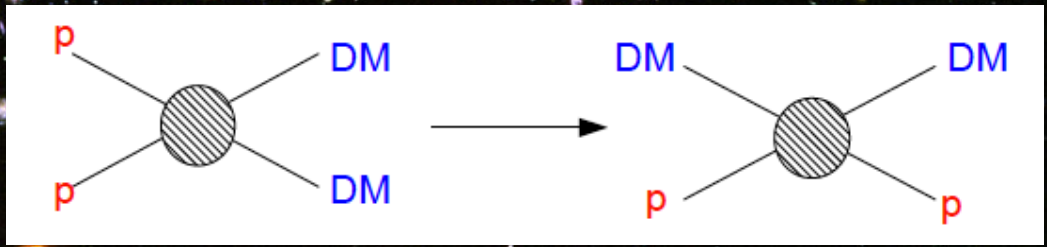
Collisions of clusters of galaxies

Considered the ultimate demonstration of the presence of Dark Matter since this does not involve Newton's Law

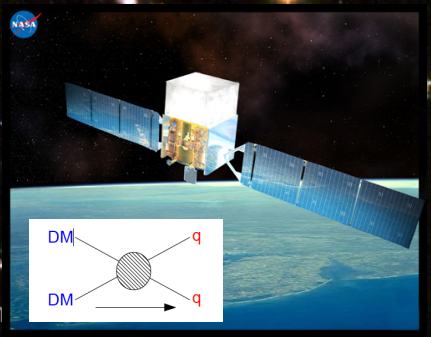
Introductory notes (II)

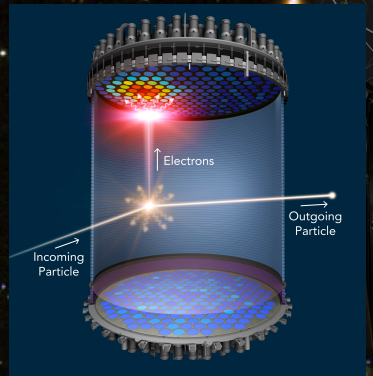
If Dark Matter turns to be WIMP like (weakly interacting) there is a chance to produce it directly at colliders (Golden channel → Mono-jet final state)

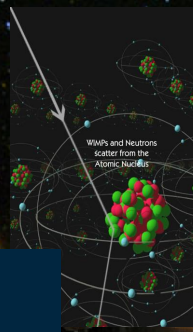
This makes the LHC complementary to direct-detection dedicated experiments underground



Some of the models explored at the LHC are also inspired by the Higgs boson and /or indirect searches at satellites → heavy flavors involved

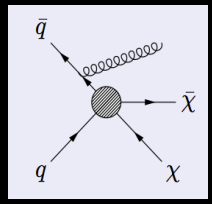




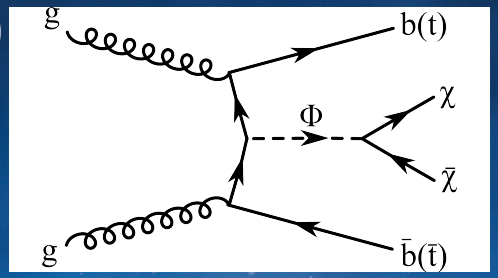


Benchmark Models

In Run II the ATLAS and CMS experiments moved away from the use of EFT inspired models with questionable validity at high-Q^2



A set of well-defined simplified diagrams with heavy mediators is now considered motivated by a number of different considerations (DM Forum: arXiv:1507.00966)



- Simple extensions of SM symmetries
- Minimal Flavor Violation
- Assuming Yukawa couplings → favor 3rd generation
- Some models inspired by satellite "hints"

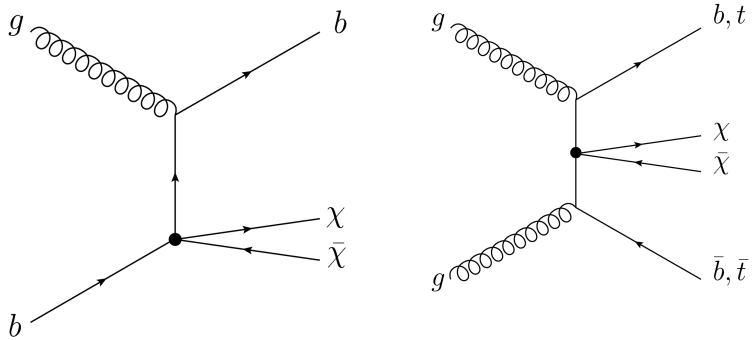
In some cases a clear overlap with SUSY-inspired simplified models for direct production of 3rd generation squarks

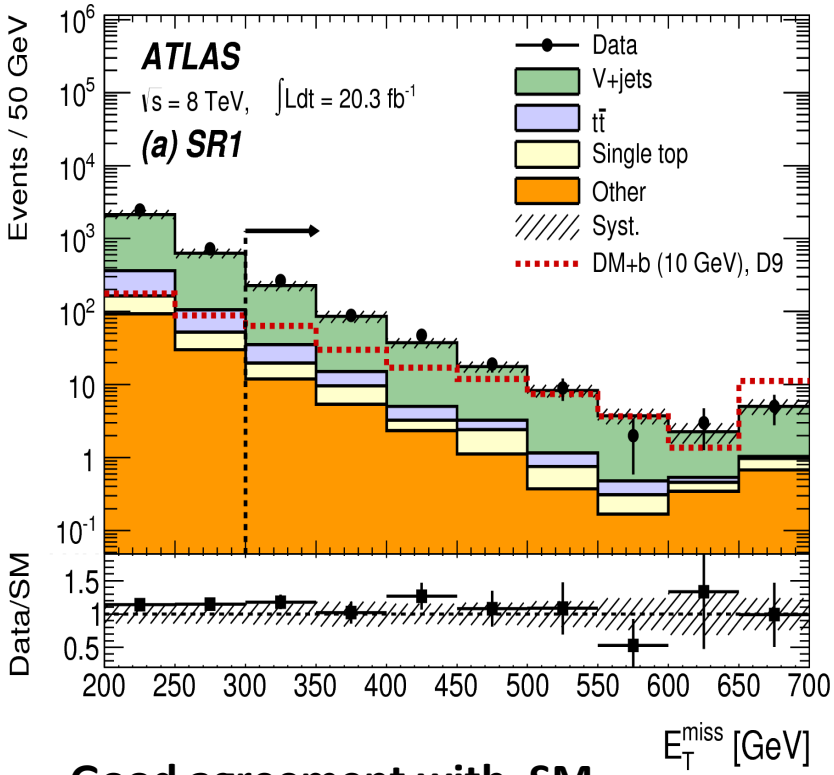
This talk focused on DM+HF

Eur. Phys. J. C (2015) 75:92

DM+b/bb

$\sqrt{s}$=8 TeV, 20.3 fb^{-1}





Good agreement with SM

Mono-b targeted event selection criteria

E_T^{miss} > 300 GeV
p_T (j1) > 100 GeV
$N_{jet}(p_T$ > 30 GeV) < 2
At least one b-tagged jet
$\Delta\phi$ (E_T^{miss}, jets) > 1.0
Lepton vetoes

Other signal regions target DM+bb (not discussed yet in this slide)

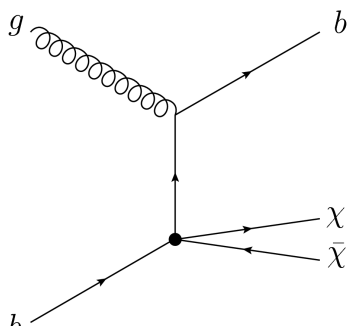
Z(→ νν)+jets and W(→lν)+jets backgrounds constrained in Z+jets, γ+jets and W+jets control regions (tt-bar from MC validated in control regions)

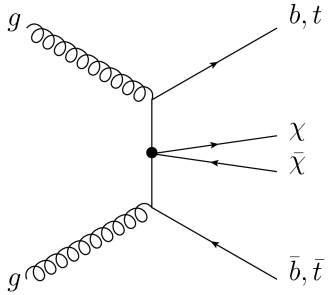
Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

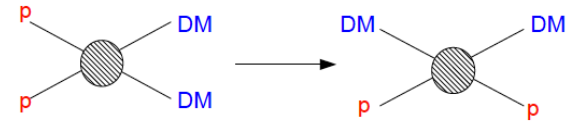
Eur. Phys. J. C (2015) 75:92

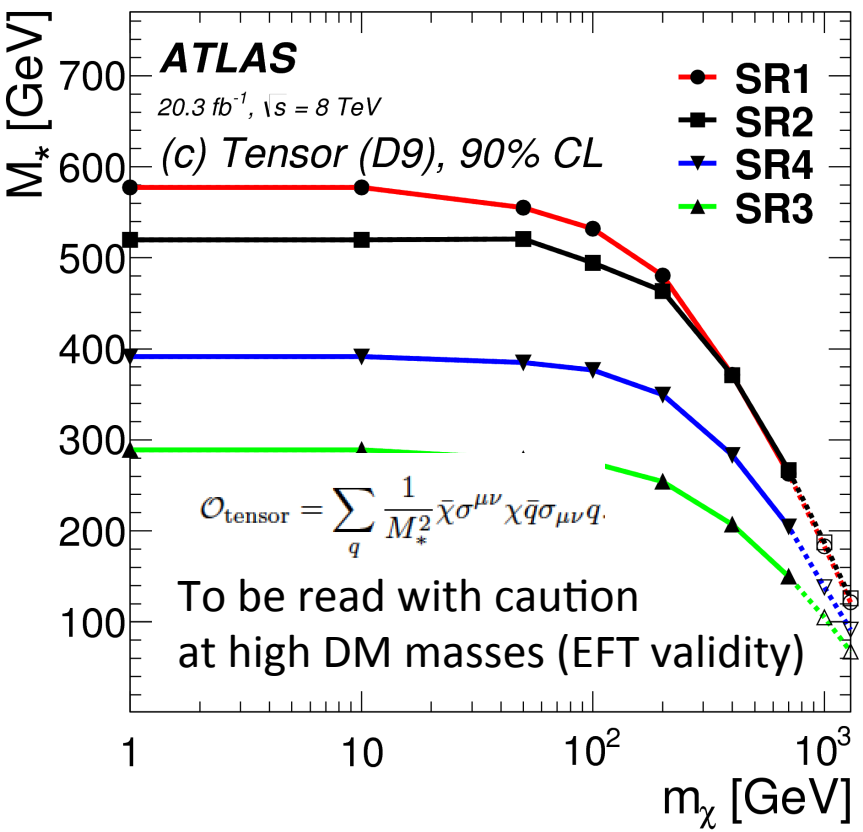
DM+b

√s=8 TeV, 20.3 fb^{-1}

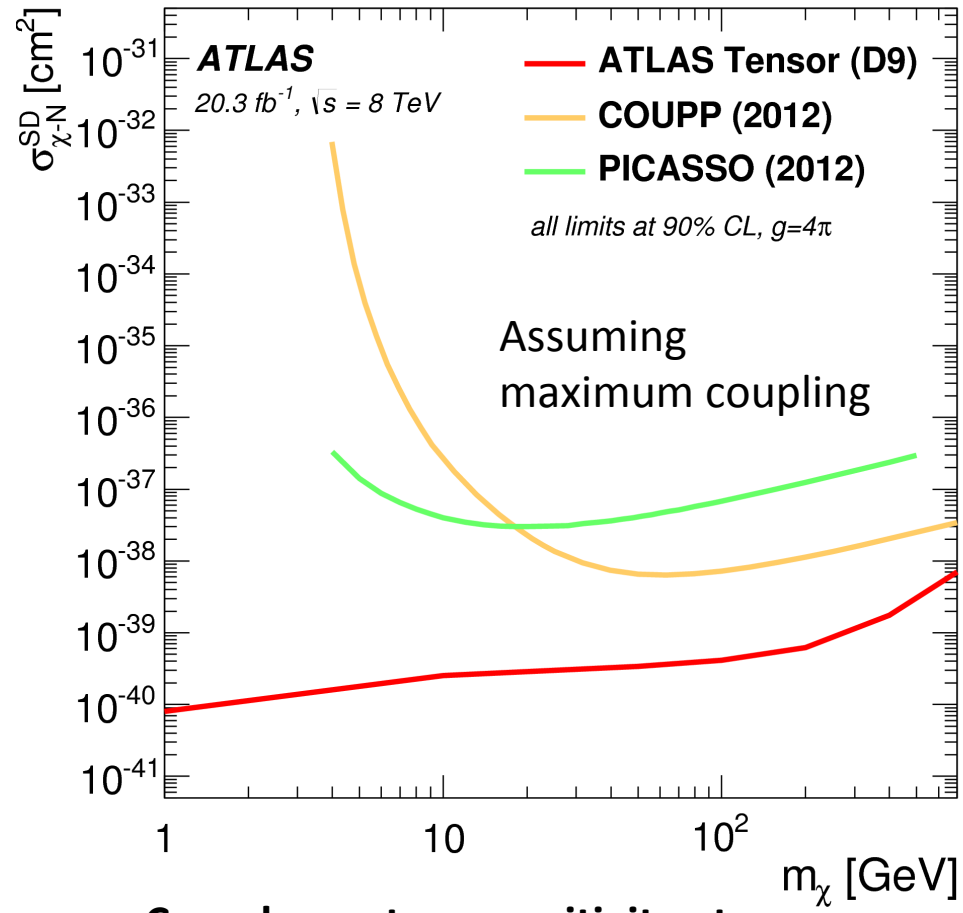








$$\mathcal{O}_{\text{tensor}} = \sum_q \frac{1}{M_*^2} \bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q.$$



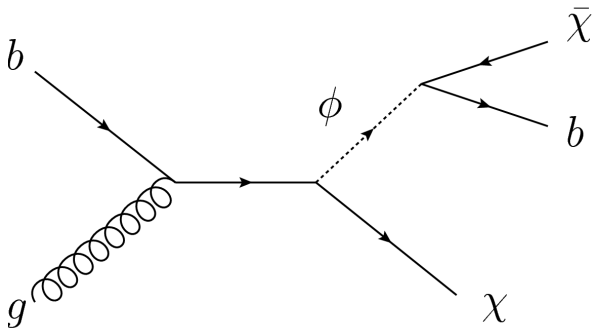
Complementary sensitivity at very low DM masses

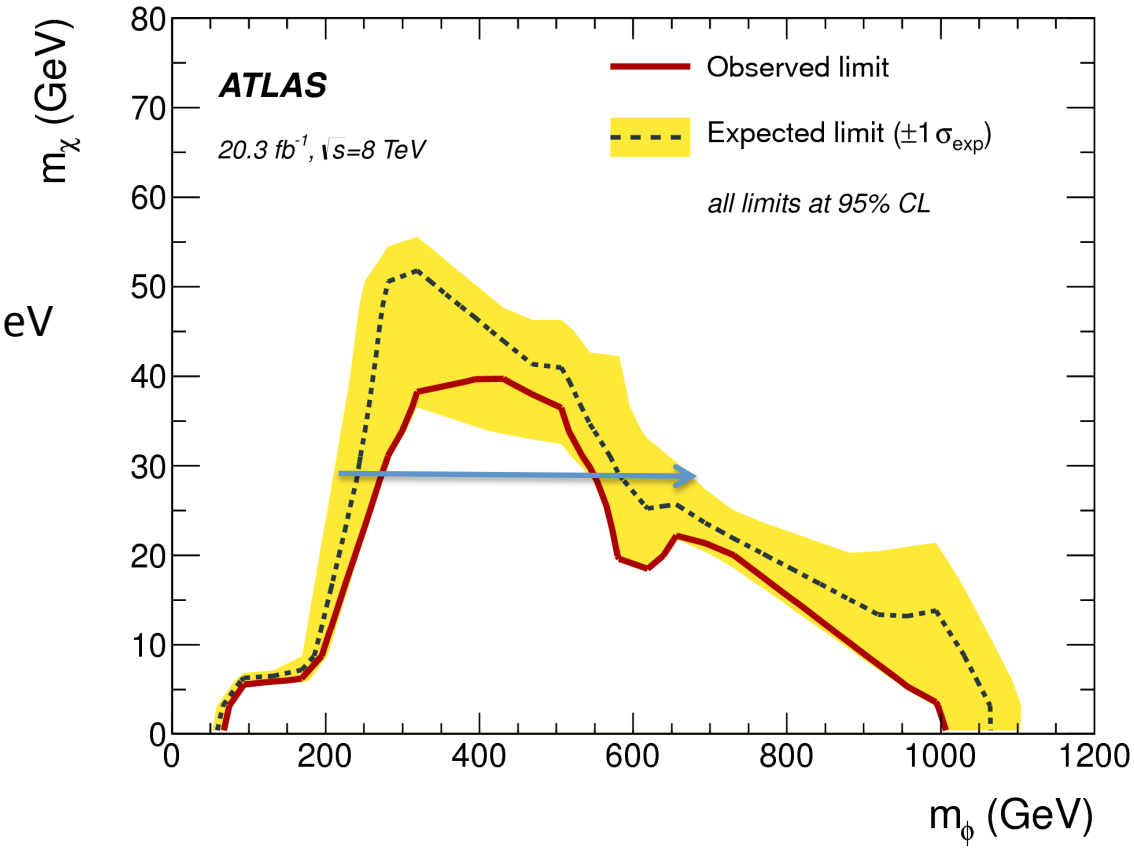
Eur. Phys. J. C (2015) 75:92

√s=8 TeV, 20.3 fb^{-1}

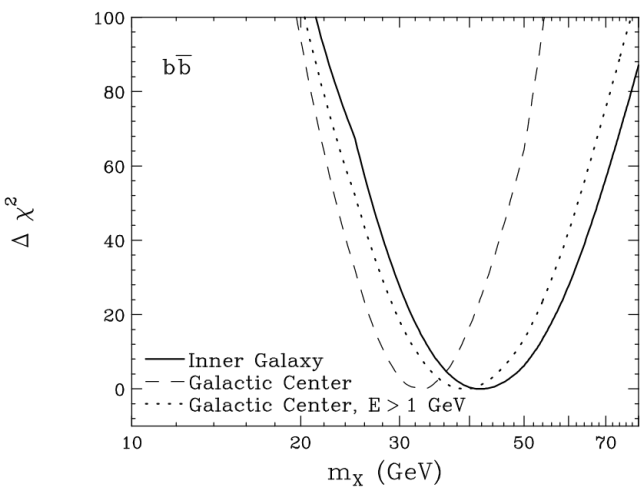
DM+b

Bottom Flavored DM model
(motivated to accommodate Fermi-LAT hints)
P. Agrawal et al., Phys. Rev. D 90, 063512 (2014)





Analysis of Fermi-LAT data
points to DM mass point of ~35 GeV



Taken from: T. Daylan et al.,
Physics of the Dark Universe Volume 12, P1, 2016

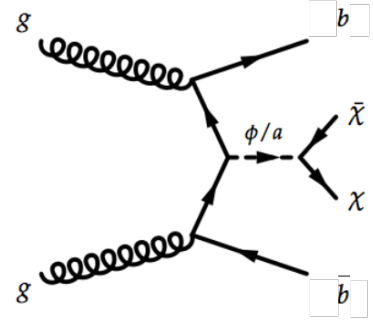
For a DM mass of 35 GeV, mediator masses in the range 300 – 500 GeV are excluded at 95% CL

ATLAS-CONF-2016-086

DM+bb

$\sqrt{s}$=13 TeV, 13.3 fb^{-1}

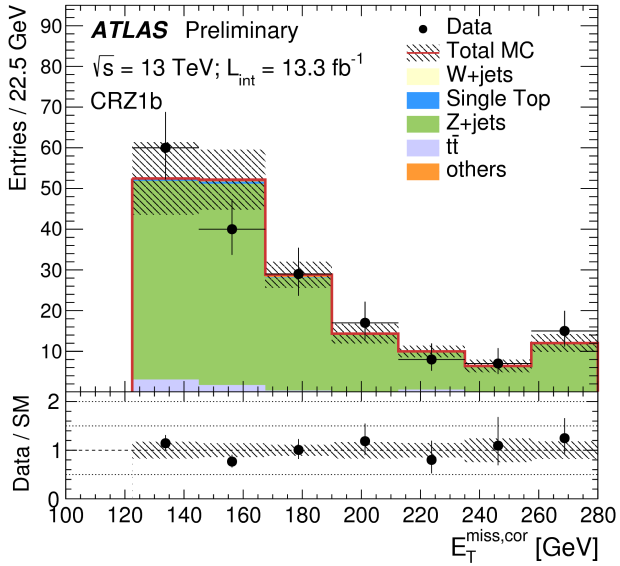
Parameters:
Mediator and DM masses
(minimal mediator width)
couplings: $g_q, g_{DM} = g = 1$

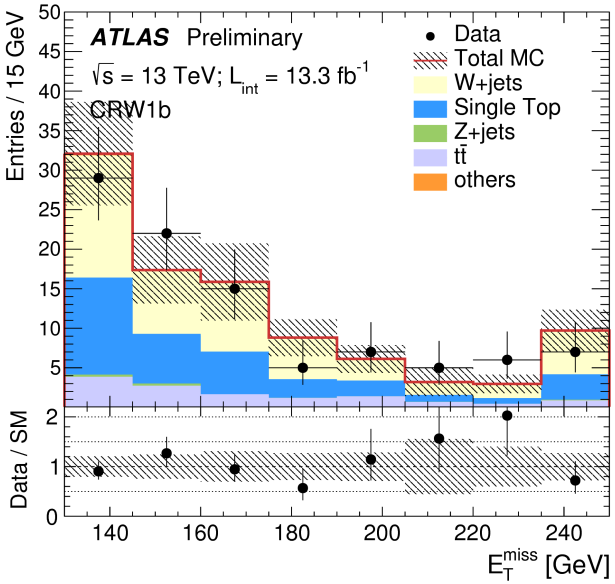


The analysis is optimized for a spin-0 mediator
Final state characterized by

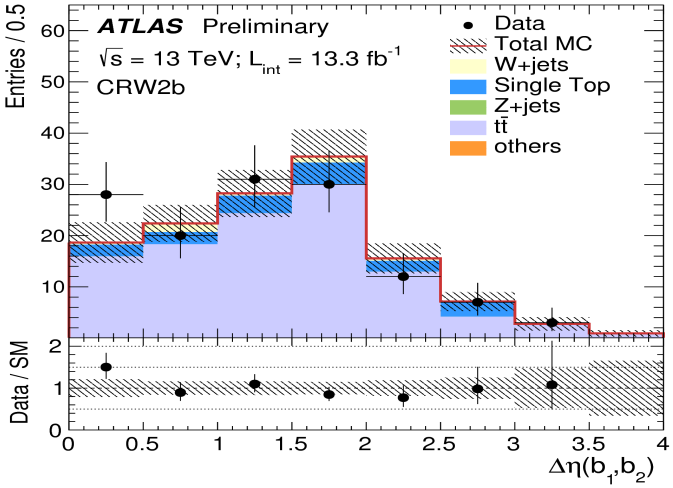
- Two b-jets, no more than 3-jets,
- Large missing transverse energy
- No leptons
- Azimuthal E_T^{miss}-Jet separation against QCD

As expected SM backgrounds driven by
Z(→νν)+bb, W(→lν)+bb and top quark production





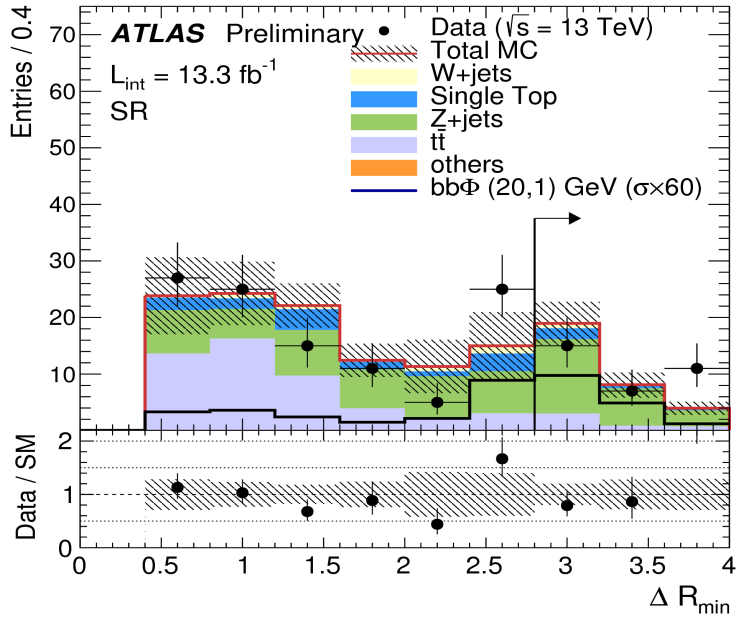
Normalization of main background processes are constrained in dedicated control regions in data

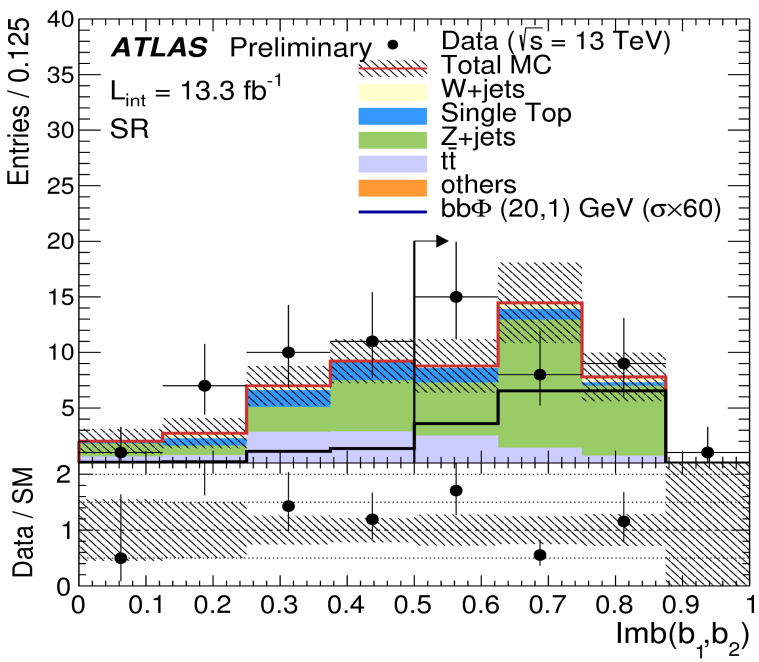


ATLAS-CONF-2016-086

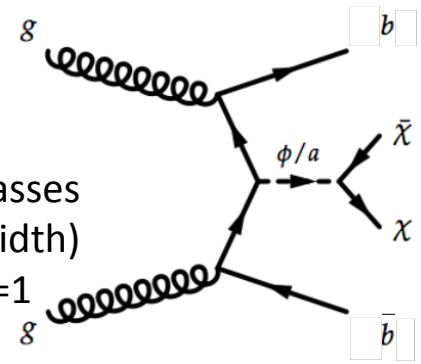
DM+bb

√s=13 TeV, 13.3 fb^{-1}





Parameters:
Mediator and DM masses
(minimal mediator width)
couplings: g_q,g_{DM} = g=1



The analysis is optimized for relatively light mediators (with mass < 300 GeV) and very light DM masses (1 GeV)

Discriminants based on different final state topologies between irreducible Z+bb and DM+bb from differences in spin and mass.

Signal with well separated jets and b-jets and reduced p_T-imbalance between them

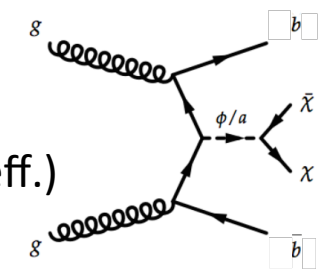
$$\Delta R_{min} = \min\left(\Delta R_{ij}\right) > 2.8 \qquad Imb(b_1, b_2) = \frac{p_T(b_1) - p_T(b_2)}{p_T(b_1) + p_T(b_2)} > 0.5$$

Good agreement with SM expectations

ATLAS-CONF-2016-086

DM+bb

$\sqrt{s}$=13 TeV, 13.3 fb^{-1}



Good agreement with SM. Analysis still dominated by statistics…
(uncertainties mainly coming from jet energy scale and b-tagging eff.)

	SR
Observed	33
Total background	31.0 ± 6.2
W+jets	1.2 ± 0.8
Z+jets	22.6 ± 5.7
$t\bar{t}$	4.7 ± 1.4
single top	2.6 ± 1.1
others	-
pre-fit W+jets	1.2 ± 0.8
pre-fit Z+jets	20.1 ± 6.0
pre-fit $t\bar{t}$	5.8 ± 1.5
pre-fit single top	2.7 ± 1.1
pre-fit others	-

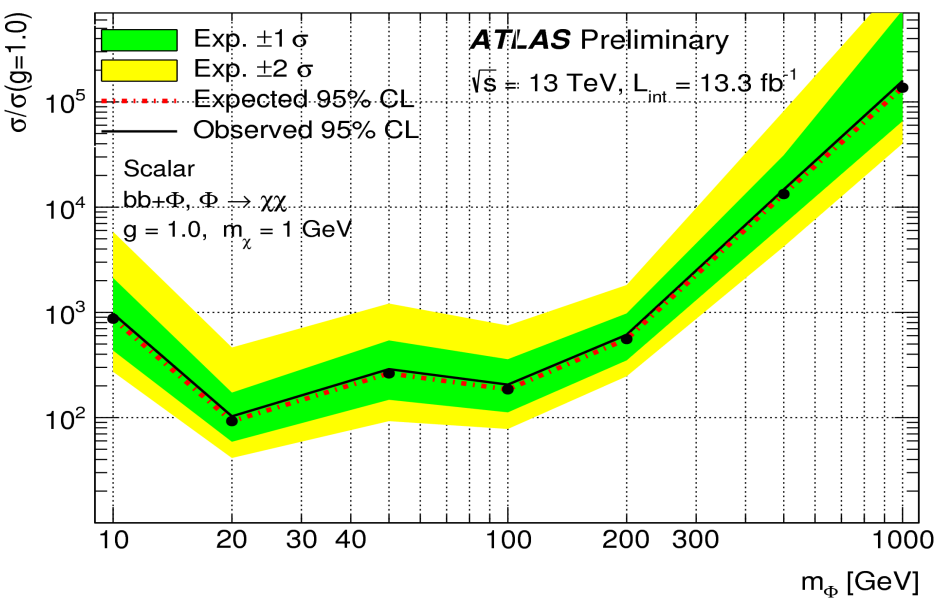
Observed: 33 events
SM prediction: 31.0 +- 6.2

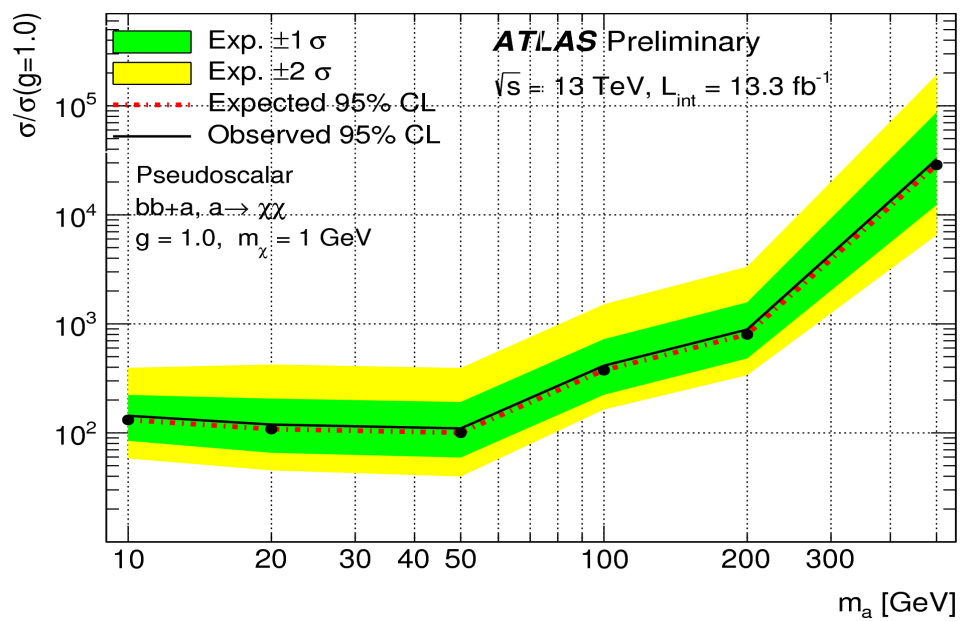
Model-independent 95% CL limits on visible cross section: 1.38 fb

Cross section limits vs mediator mass (DM of 1 GeV and g=1)

$m_{\Phi(a)}$ [GeV]	σ_{UL} [pb] Scalar	Pseudoscalar
10	6366	897
20	510	574
50	569	213
100	110	222
200	52	76
500	29	48
1000	9.3	-

95%CL upper limits w.r.t σ_{signal} @ g=1

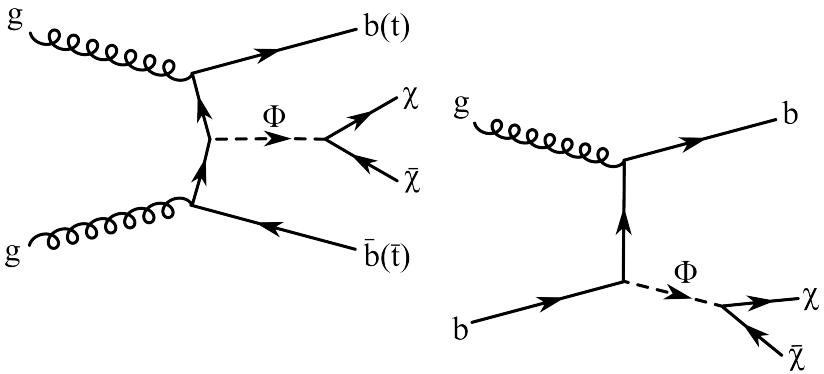


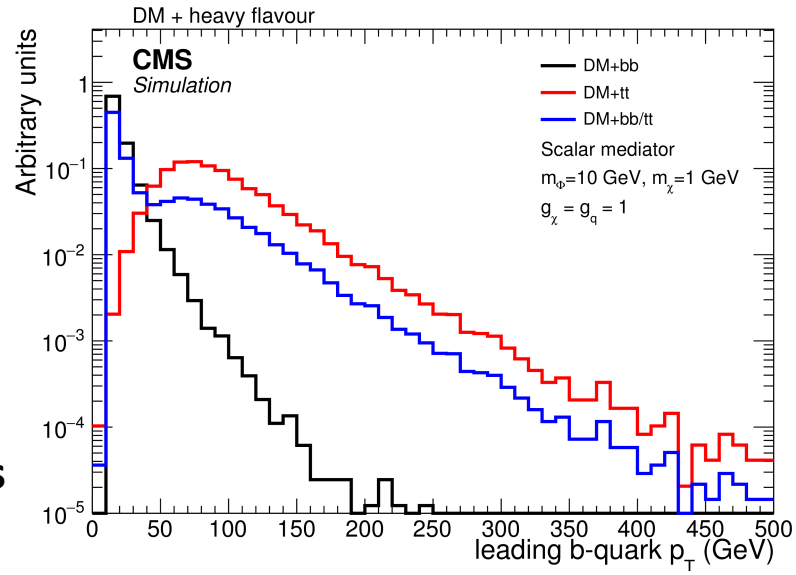


CMS-PAS-B2G-15-007

DM+b/bb

√s=13 TeV, 2.17 fb^{-1}



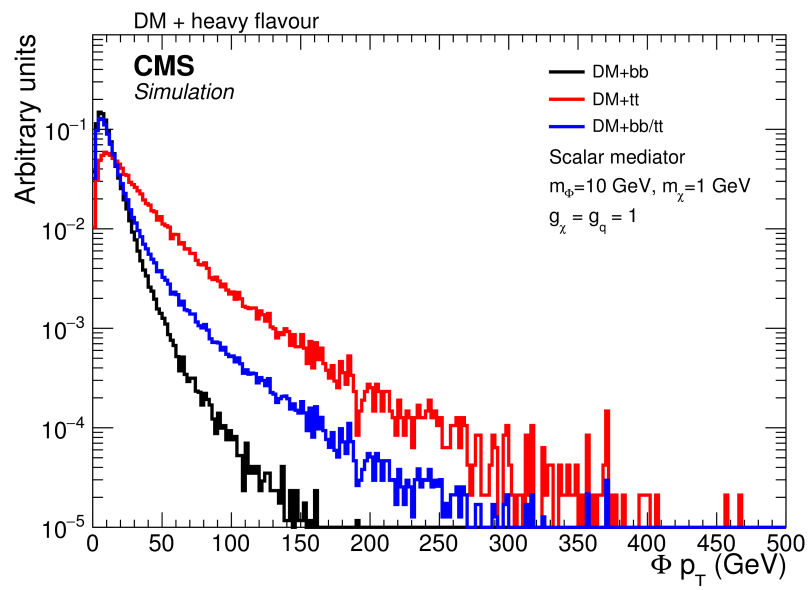


Analysis targets both DM+bb and DM+tt
Analysis strategy with two signal regions with exclusive 1- and 2-b-jets

Veto on leptons and > 1 additional jet
Imposed azimuthal E_T^{miss}-Jet separation

Signal final state characterized by large missing transverse momentum energetic b-jets (enhanced for DM+tt)

As expected SM backgrounds driven by Z(→νν)+bb, W(→lν)+bb and top quark production



CMS-PAS-B2G-15-007

DM+b/bb

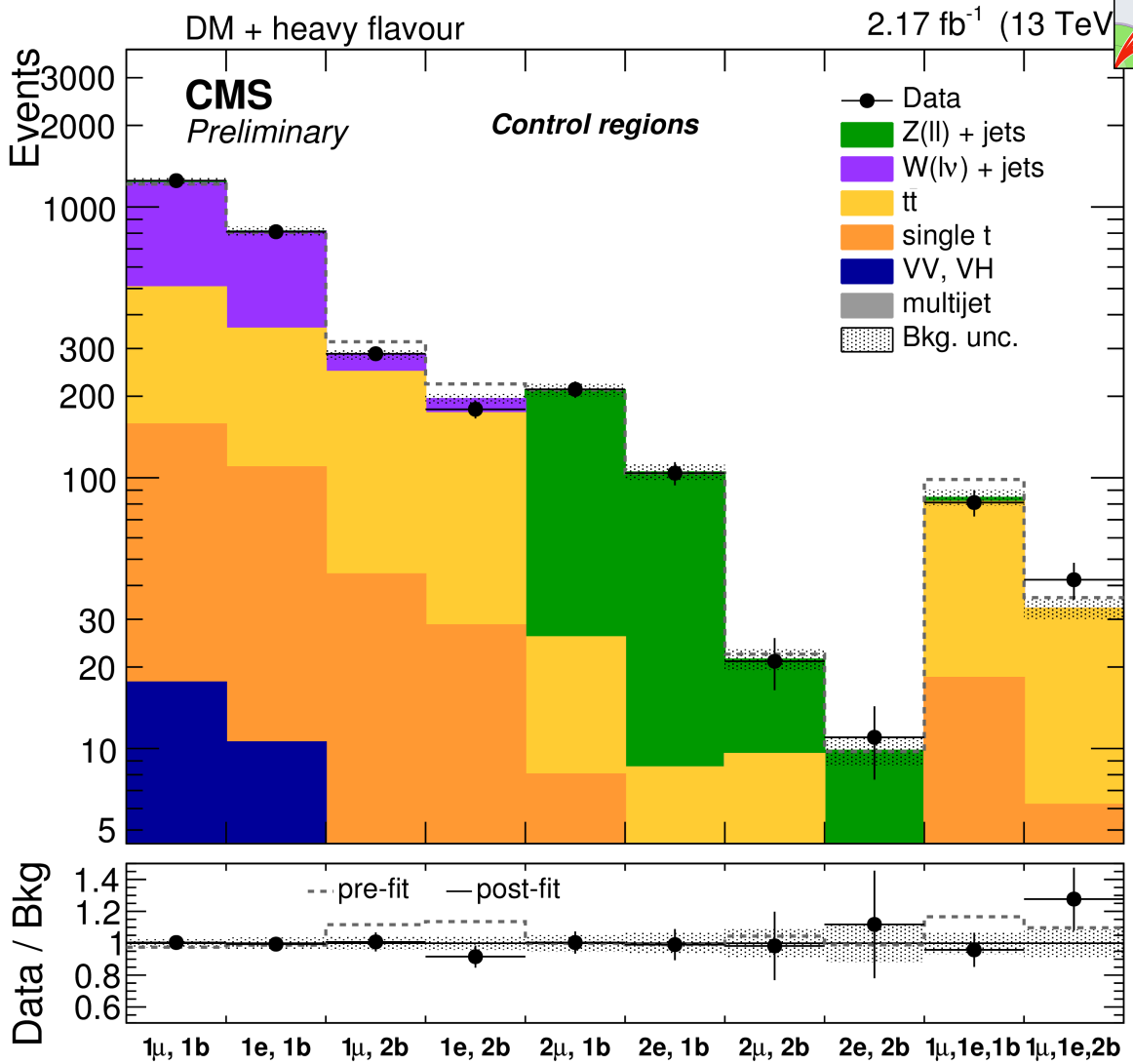
√s=13 TeV, 2.17 fb^{-1}

Normalization of dominant background Processes are constrained in dedicated control regions in data using a simultaneous fit to data and MC predictions

A total of 10 control regions with leptons and with same requirements as in signal regions

Other small background (e.g single-top, Diboson) taken from simulation

QCD-multijets data driven

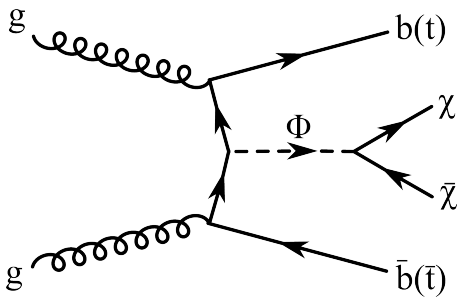


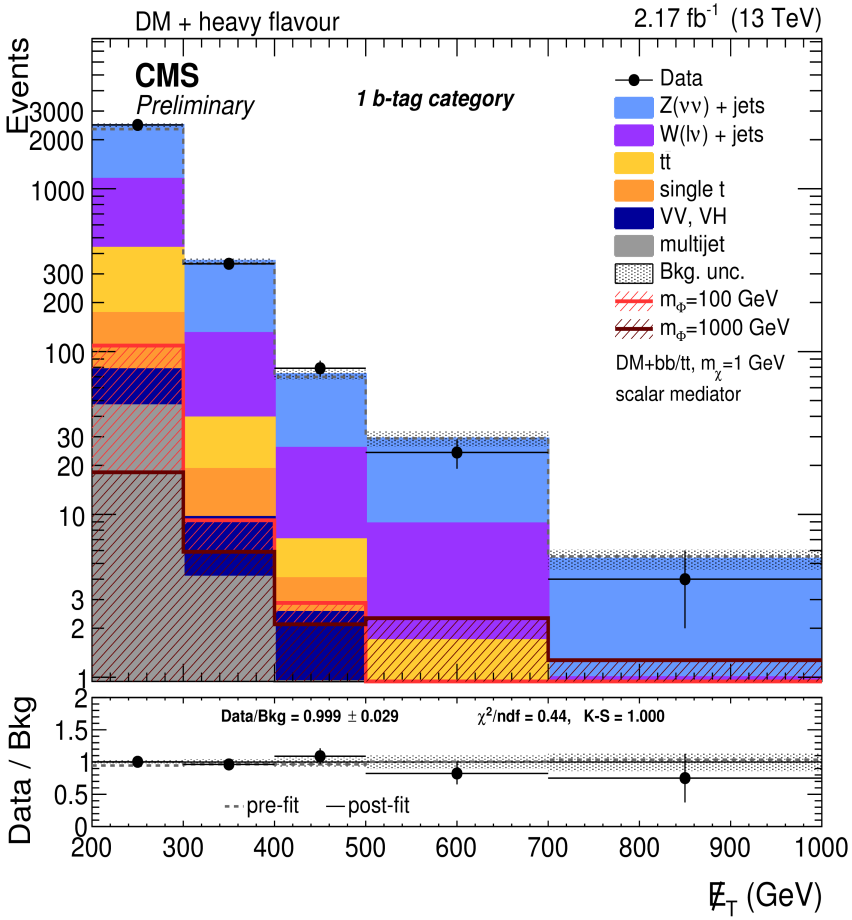
W+b W+bb Z+b Z+bb ttbar (2 leptons)

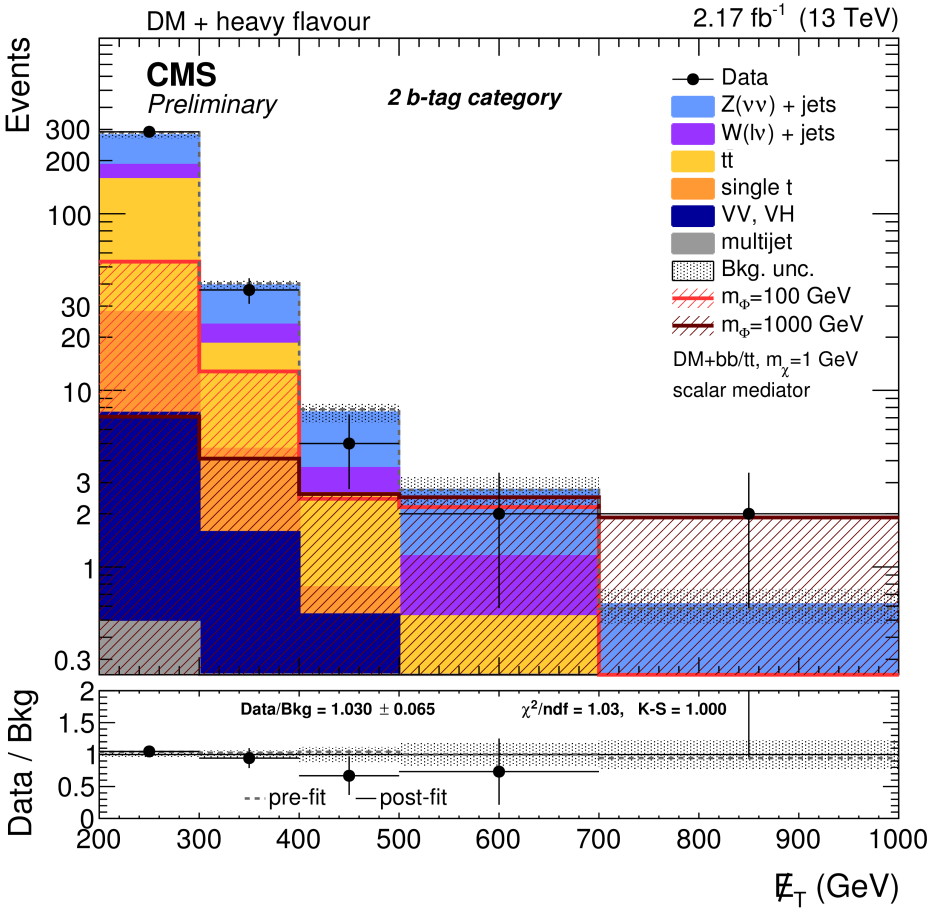
CMS-PAS-B2G-15-007

DM+b/bb

√s=13 TeV, 2.17 fb^{-1}



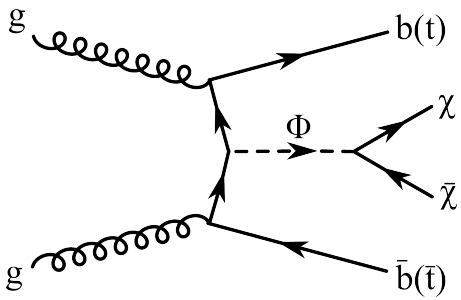




Good agreement with SM predictions

(uncertainties dominated by b-tagging efficiency and background modeling)

CMS-PAS-B2G-15-007

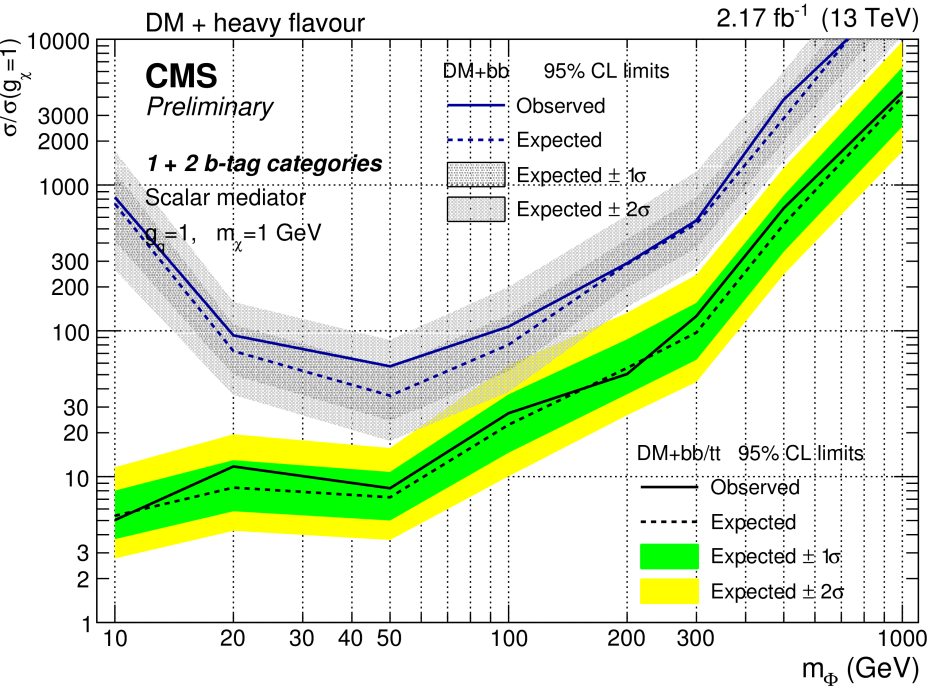


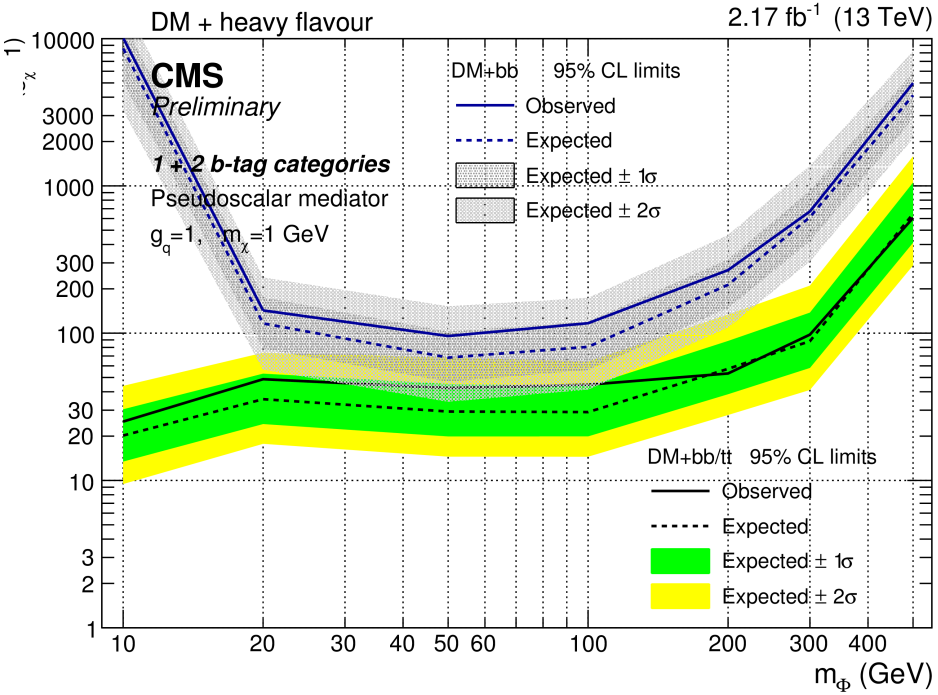
√s=13 TeV, 2.17 fb^{-1}

DM+b/bb

Combined cross section limits for DM+bb and DM+bb/tt vs mediator mass (DM of 1 GeV and g=1)

95%CL upper limits w.r.t σ_{signal} @ g=1



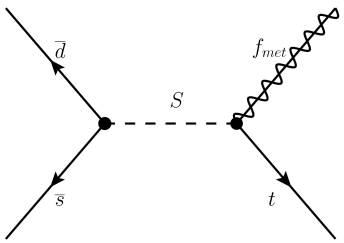


Upper limits down to (26) 5 × $\sigma/\sigma(g_\chi,g_q=1)$ are set for models with a generic pseudoscalar (scalar) mediator for low mediator and DM candidate masses.

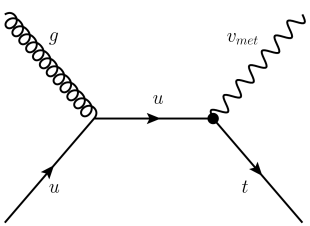
Eur. Phys. J. C75 (2015) 79

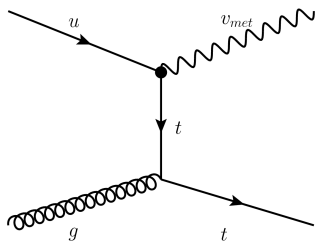
DM+t

√s=8 TeV, 20.3 fb^{-1}



Resonant channel
Spin-0 mediator → t + (invisible) fermion

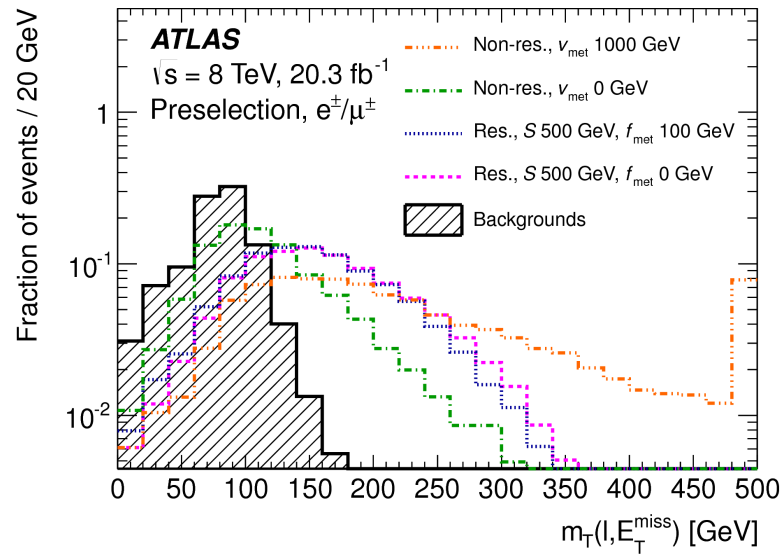


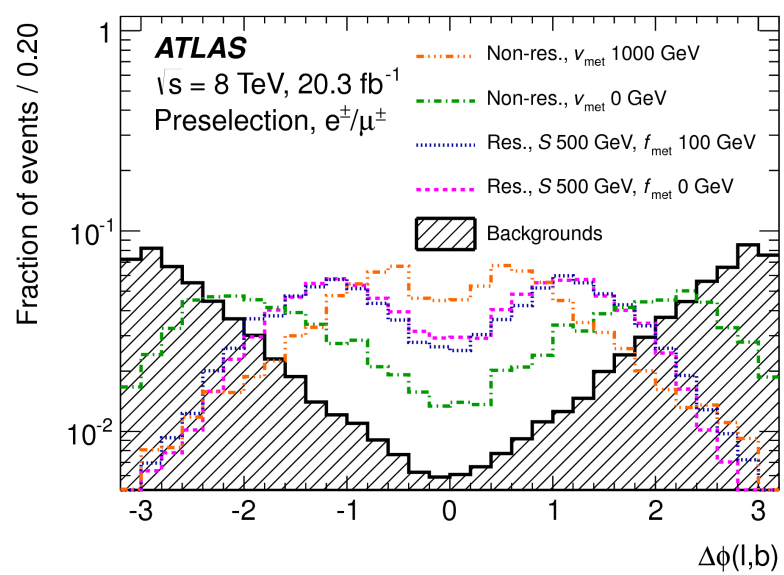


Non-resonant channel
Production of t + spin-1 (invisible) particle

No such mono-top process is available
in the SM at tree level
(t+Z (Z → νν) is GIM suppressed)
→ **Sizable event rate would indicate BSM**

Considering Top decay in lepton+jets





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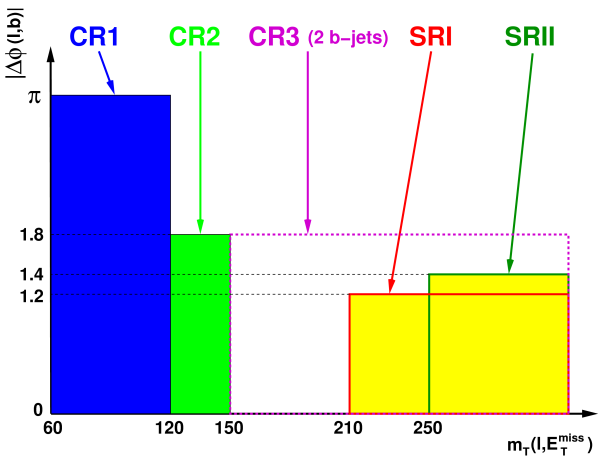
DM+t

Selection based on

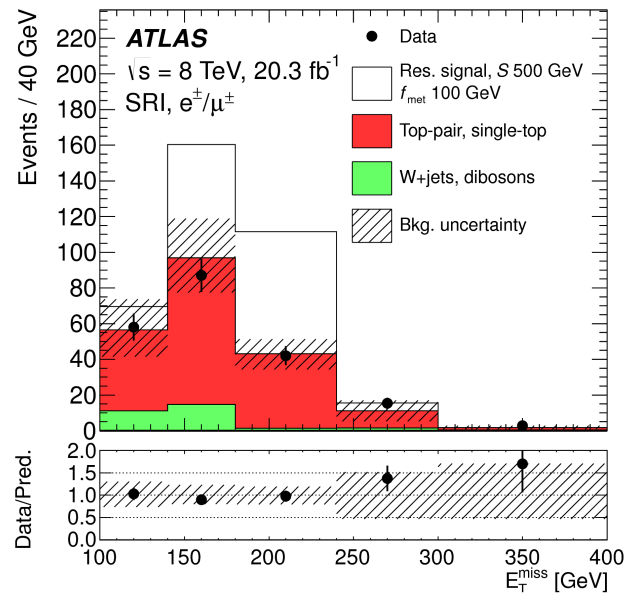
- Large missing transverse energy
- One lepton and exactly one b-tagged jet from the top semi-leptonic decay

SM background dominated by tt pairs followed by W+jets processes

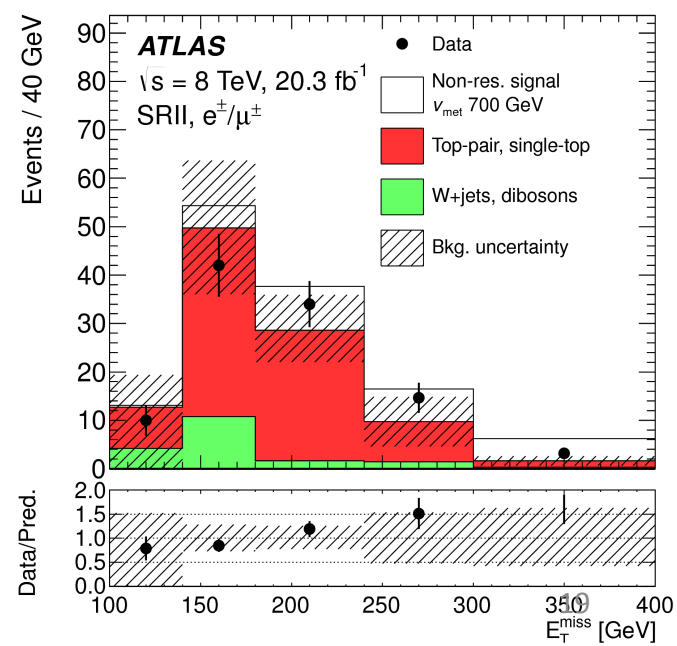
Background predictions are taken from simulation and validated in CRs



Systematic uncertainties from
Jet energy scale, b-tagging efficiency and
MC modeling + x-section uncertainties



Good agreement with SM predictions



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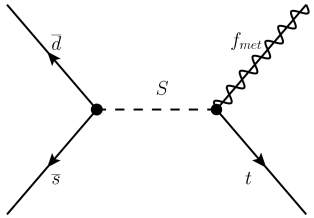
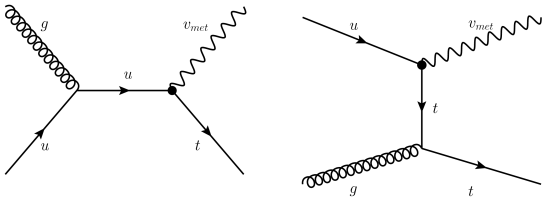
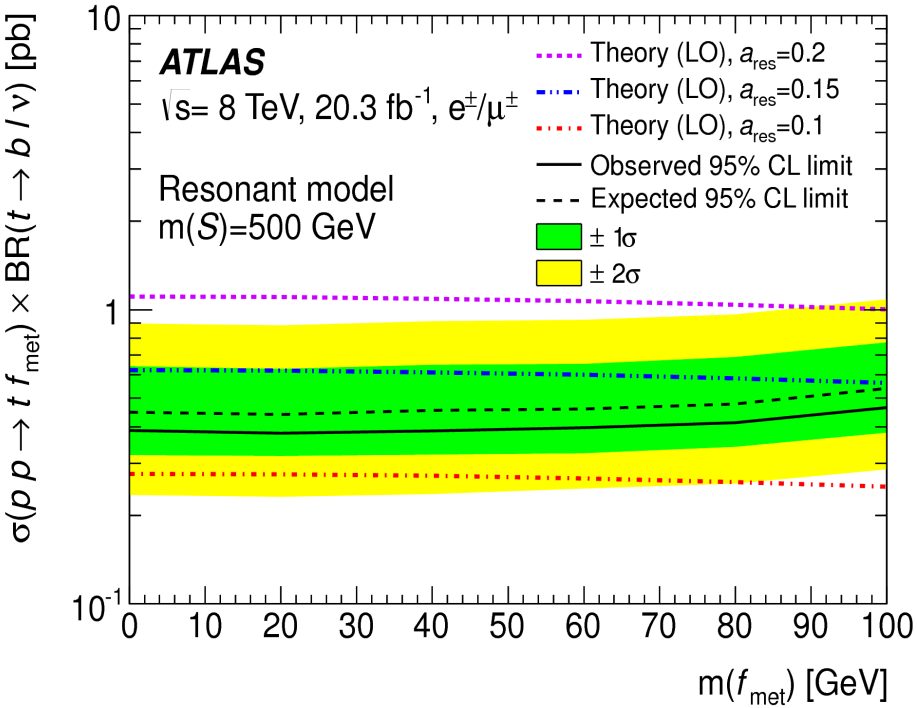
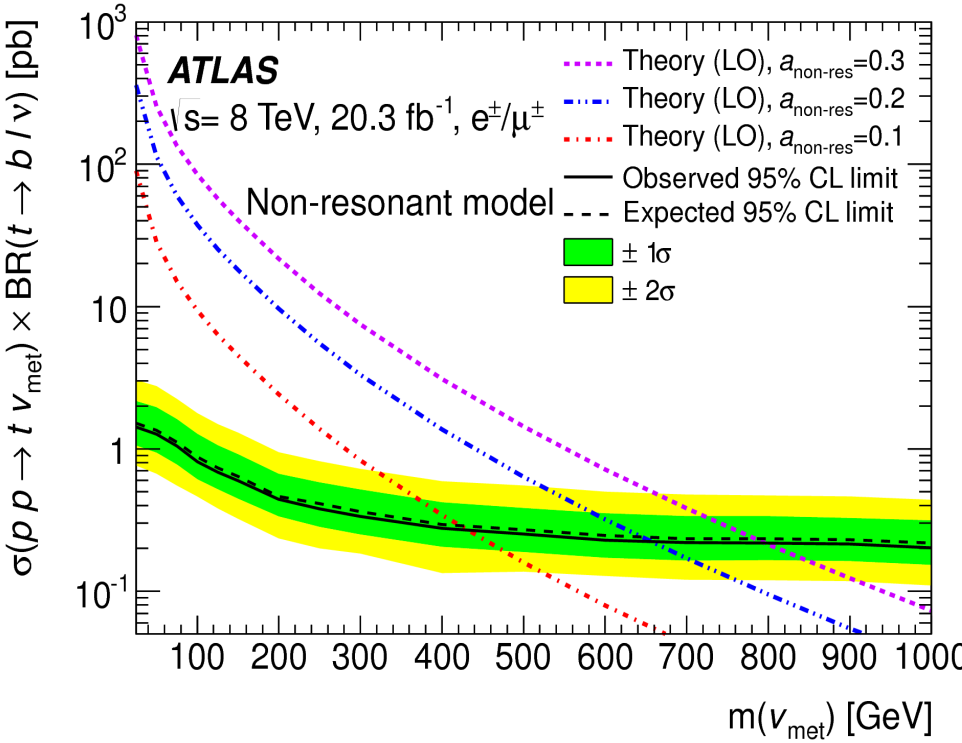
DM+t



Parameters:
Mediator mass (resonant)
Mass of invisible particles
couplings







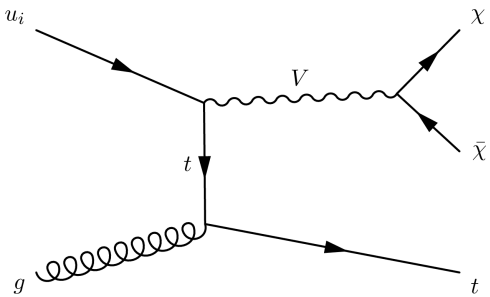
For a spin-0 mediator mass of 500 GeV Fermion masses below 100 GeV and couplings above 0.1 are excluded at 95% CL

In the non-resonant case masses below 400 – 800 GeV are excluded @ 95% CL depending on the coupling assumed

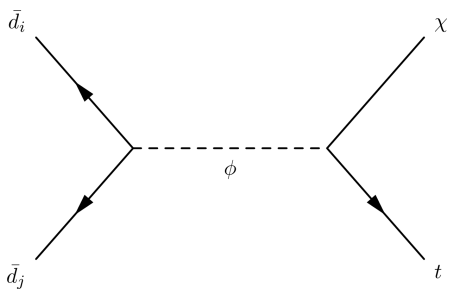
CMS-PAS-EXO-16-040

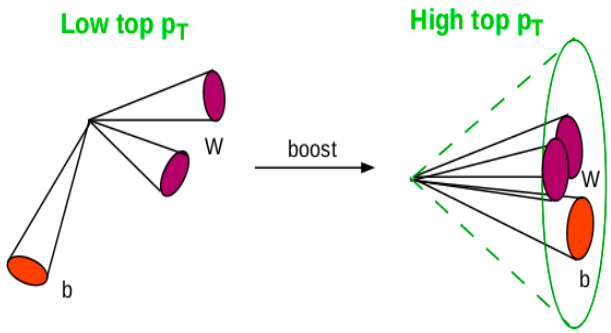
DM+t

√s=13 TeV, 12.9 fb^{-1}



Reconstruction of the hadronic top decays in boosted configurations using large-R jets (grooming applied to remove soft contributions)





Large missing transverse energy
A fat jet (R=1.5) with pT > 250 GeV
A b-jet identified inside
Jet mass in the range 110-210 GeV
N-subjettiness compatible with top decays

Veto on additional b-jets outside
Veto on isolated leptons/photons

Dominant background from tt, Z(→νν)+jets and W(→lν)+jets estimated using MC simulations constrained in dedicated control regions

Other small backgrounds
(single-top, diboson, QCD-multijets)
taken from simulation

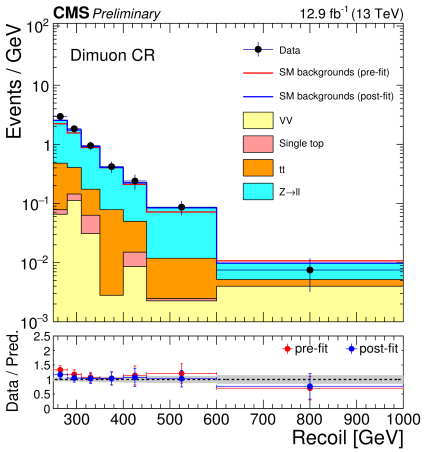
PAS EXO-16-040

DM+t

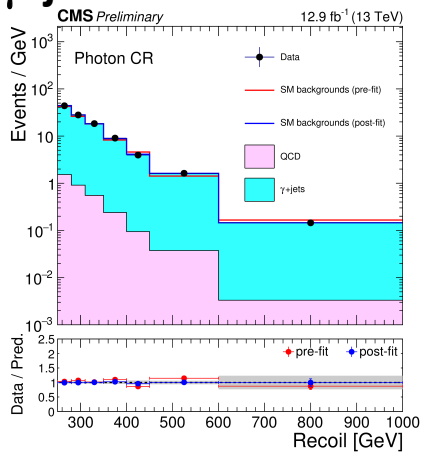
Some examples of CRs below:

Simultaneous fit **in signal+control regions** to determine SM prediction and identify potential BSM signals → **Good agreement with SM**

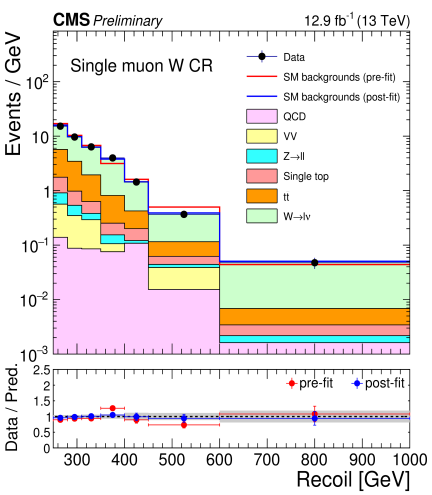
Z(→ μμ)+jets



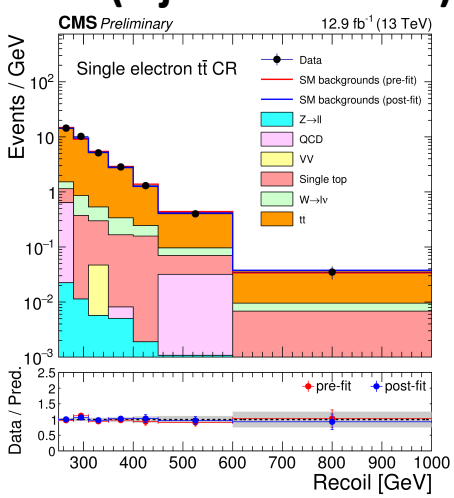
γ+jets

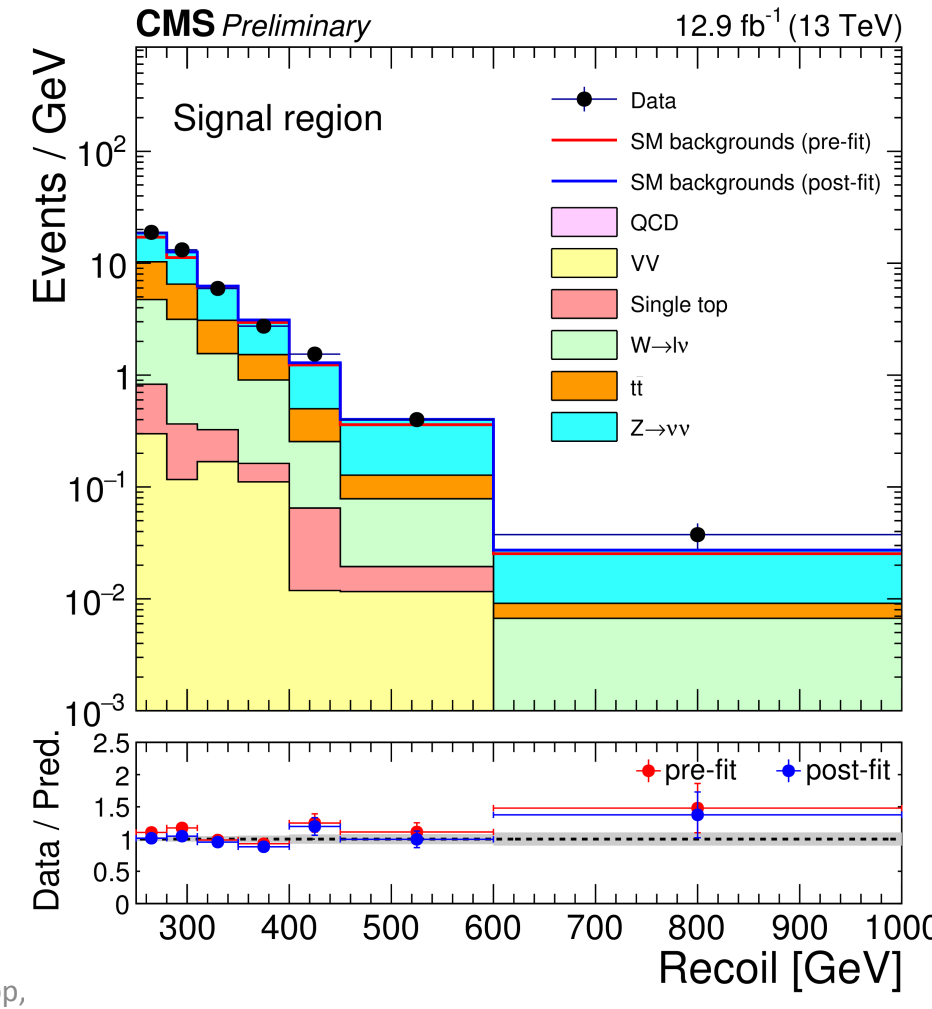


W(→ μν)+jets



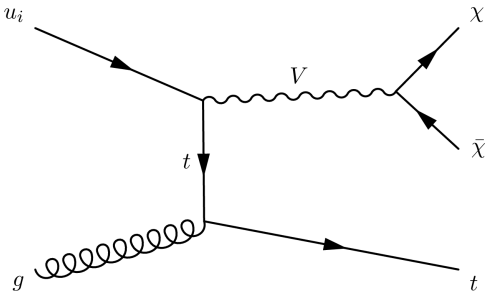
tt(l+jets e-channel)



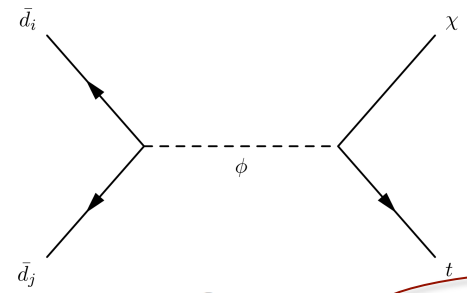


DM+t

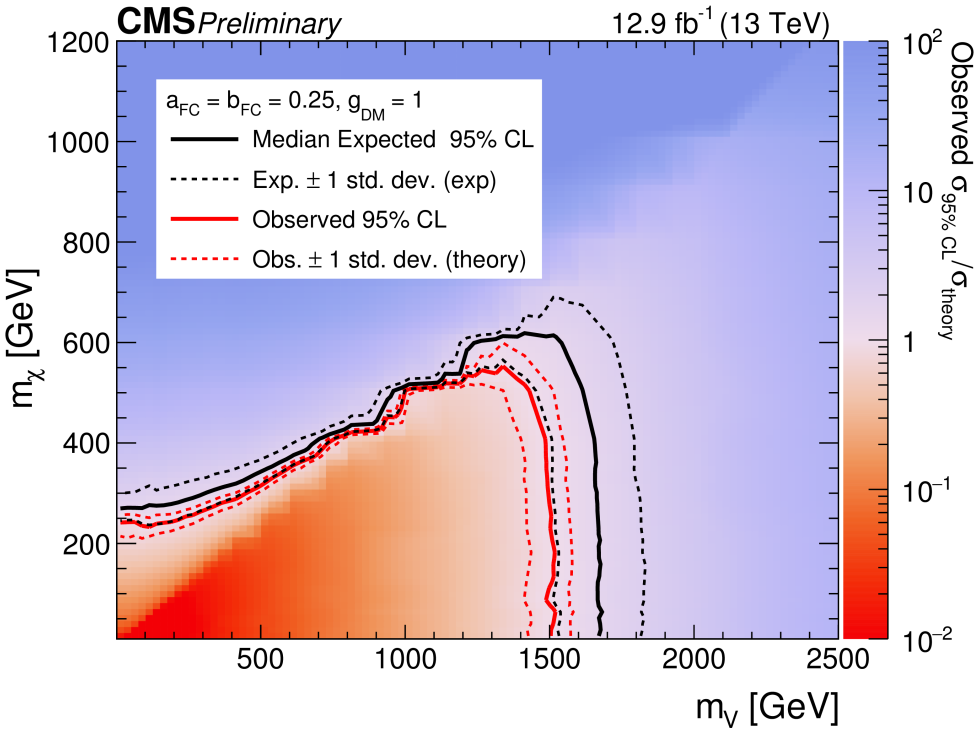
PAS EXO-16-040

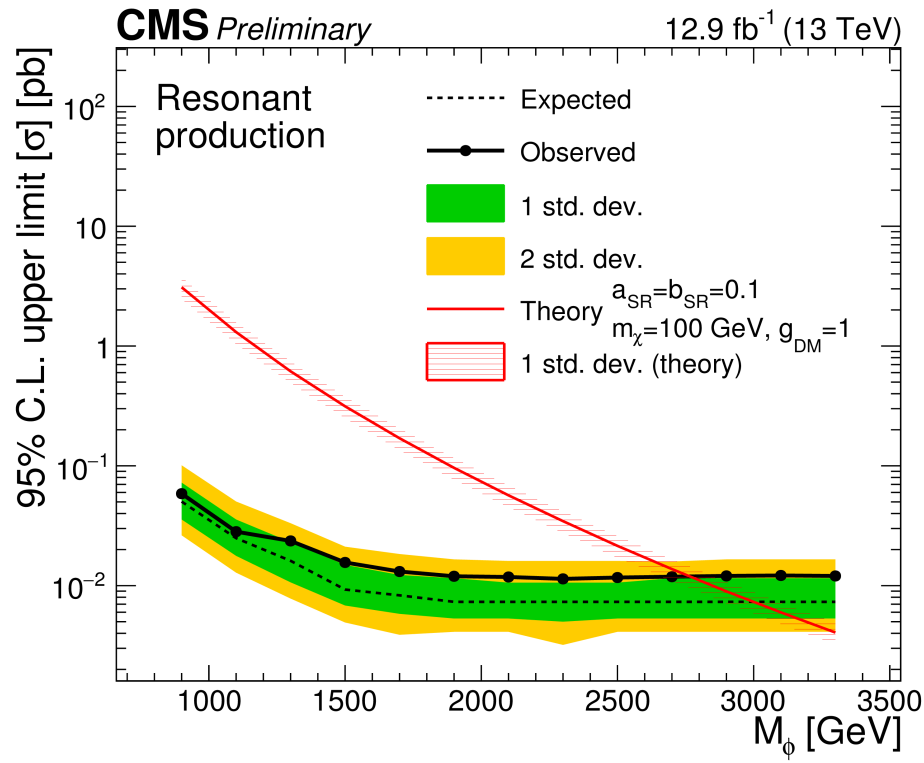


$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{kin} + V_\mu(g_{R_\chi}\bar{\chi}_R\gamma^\mu\chi_R + g_{L_\chi}\bar{\chi}_L\gamma^\mu\chi_L) + V_\mu\bar{u}_i[(a_{FC})^{ij}\gamma^\mu + (b_{FC})^{ij}\gamma^\mu\gamma^5]u_j + \text{h.c.},$$



$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{kin}(\phi_s, \chi) + (\phi\bar{d}_i^C[(a_{SR}^q)^{ij} + (b_{SR}^q)^{ij}\gamma^5]d_j + \phi\bar{t}[a_{SR}^{1/2} + b_{SR}^{1/2}\gamma^5]\chi + \text{h.c.})$$





For m_χ = 10 GeV FCNC m_V < 1.5 TeV excluded at 95% CL (for given couplings)

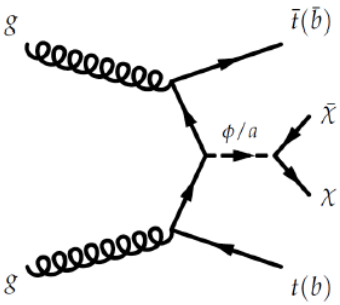
For m_χ = 100 GeV, $M\phi$ < 2.7 TeV excluded at 95% CL (for given couplings)

CMS PAS EXO-16-005

DM+tt

√s=13 TeV, 2.2 fb^{-1}

(hadronic and semileptonic)



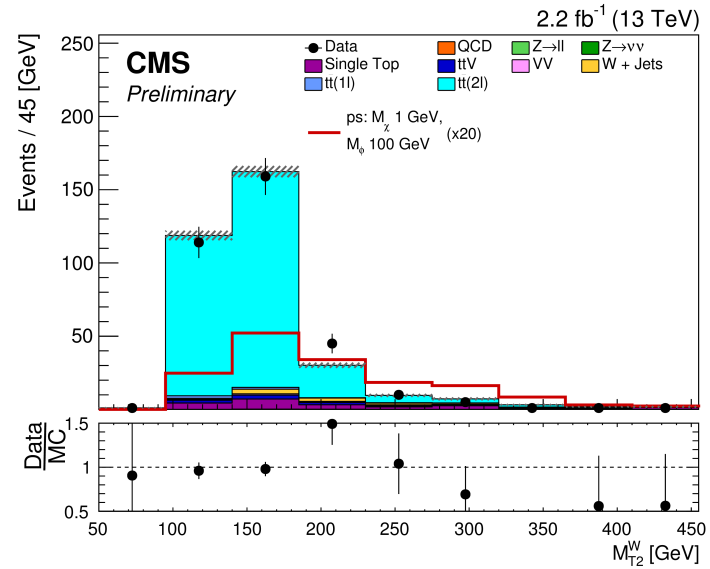
Semileptonic:

One high-pT (30 GeV) lepton, E_T^{miss} > 160 GeV

Three or more jets, at least one b-jet

m_T (lepton, E_T^{miss}) > 160 GeV, m^W_{T2} > 200 GeV

$\Delta\phi$ (E_T^{miss}, jets) > 1.2 (2 leading jets)



Hadronic:

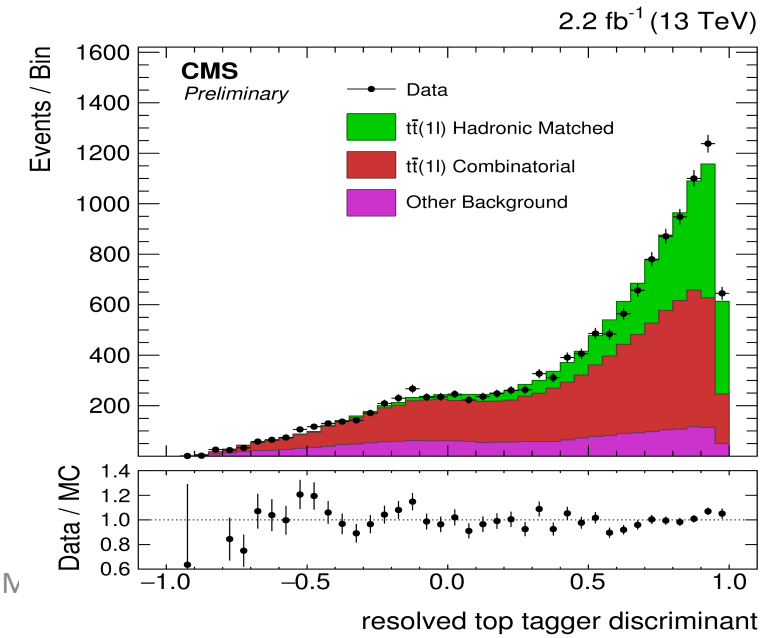
Lepton veto, E_T^{miss} > 200 GeV,

Four or more jets, at least 2-bjets

$\Delta\phi$ (E_T^{miss}, jets) > 1.0 (up to 6th jet)

→ Novel top-tagger using NN discriminants

→ Event characterization based on it

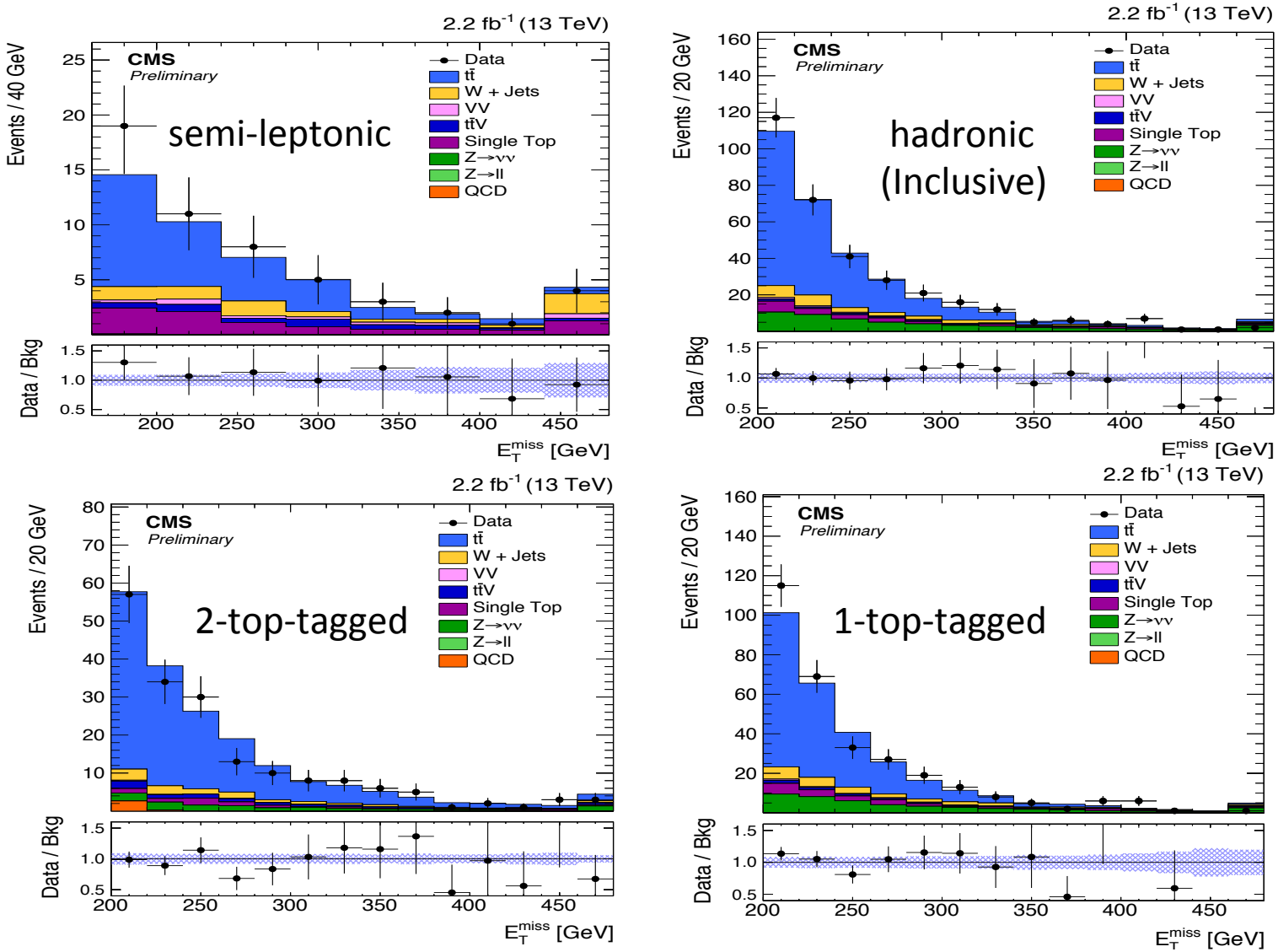


Dominant backgrounds(tt, W+jets) constrained in different control regions (as usual)

CMS PAS EXO-16-005

DM+tt

√s=13 TeV, 2.2 fb^{-1}

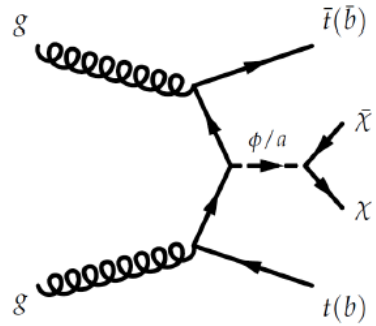


A binned maximum likelihood fit is performed simultaneously to the E_T^{miss} distributions →making full use of the shape → good agreement with SM

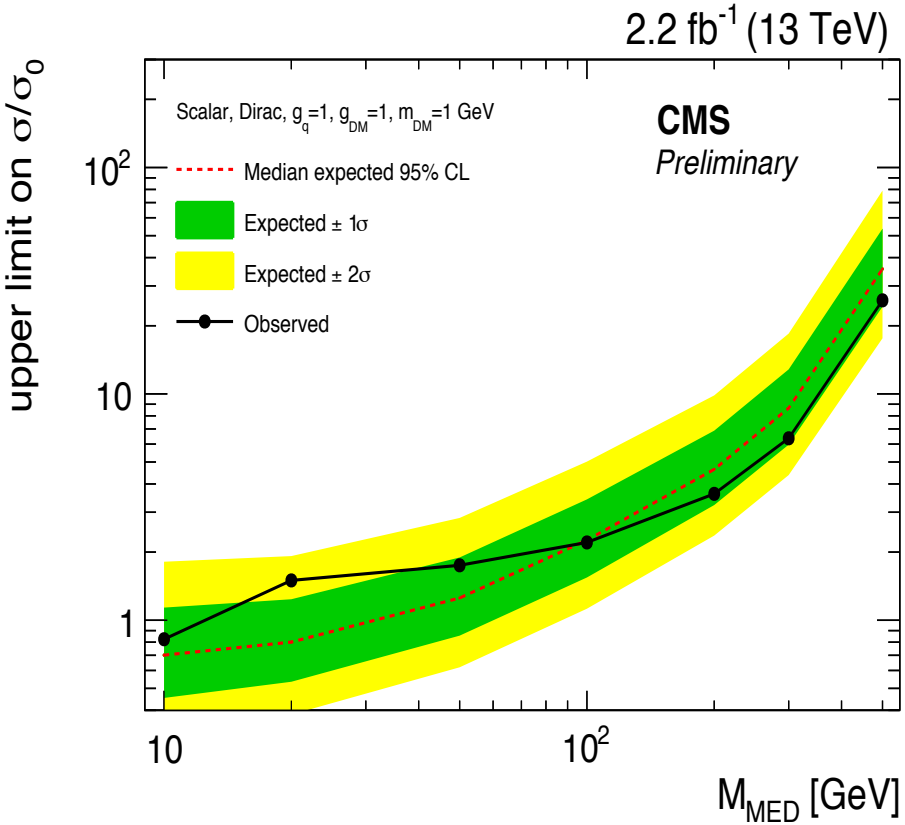
CMS PAS EXO-16-005

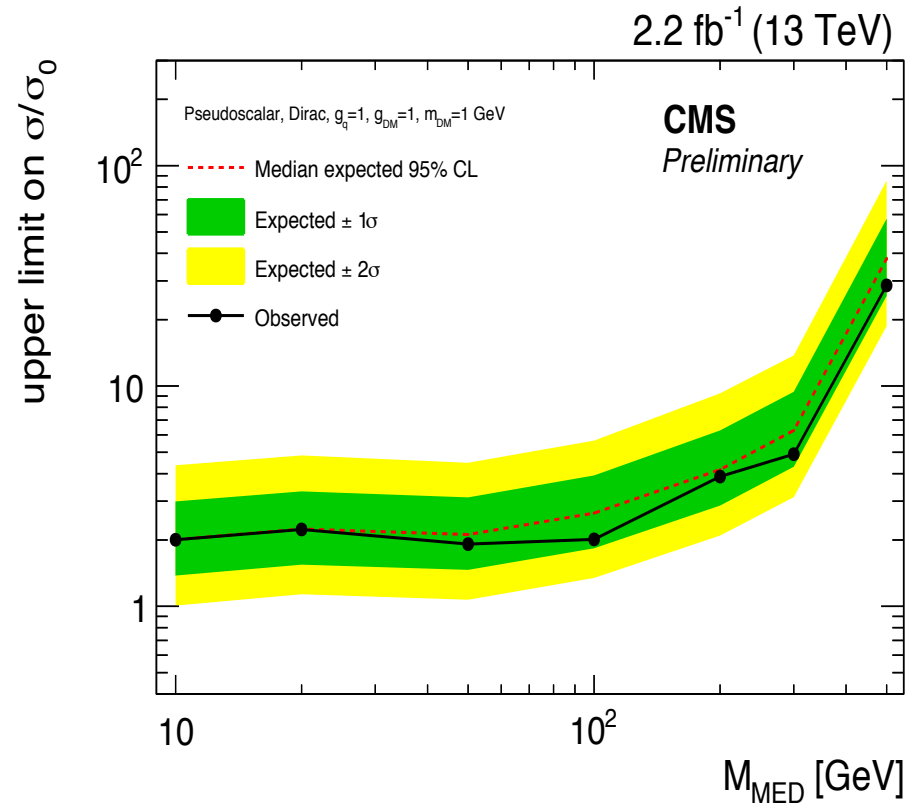
√s=13 TeV, 2.2 fb^{-1}

DM+tt



m_{DM} = 1 GeV, couplings = 1





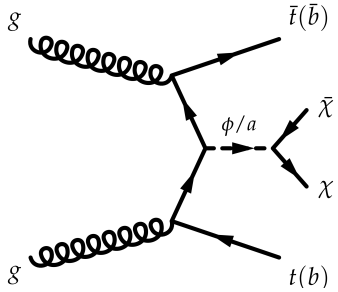
Upper limits on the DM production cross section as a function of the DM-particle mass m_{DM} and mediator mass m_{MED} → 95% confidence level (CL) are placed on the ratio to theory cross section → sensitivity for exclusion for scalar @ low m_{MED} masses.

CMS-PAS-EXO-16-028

√s=13 TeV, 2.2 fb^{-1}

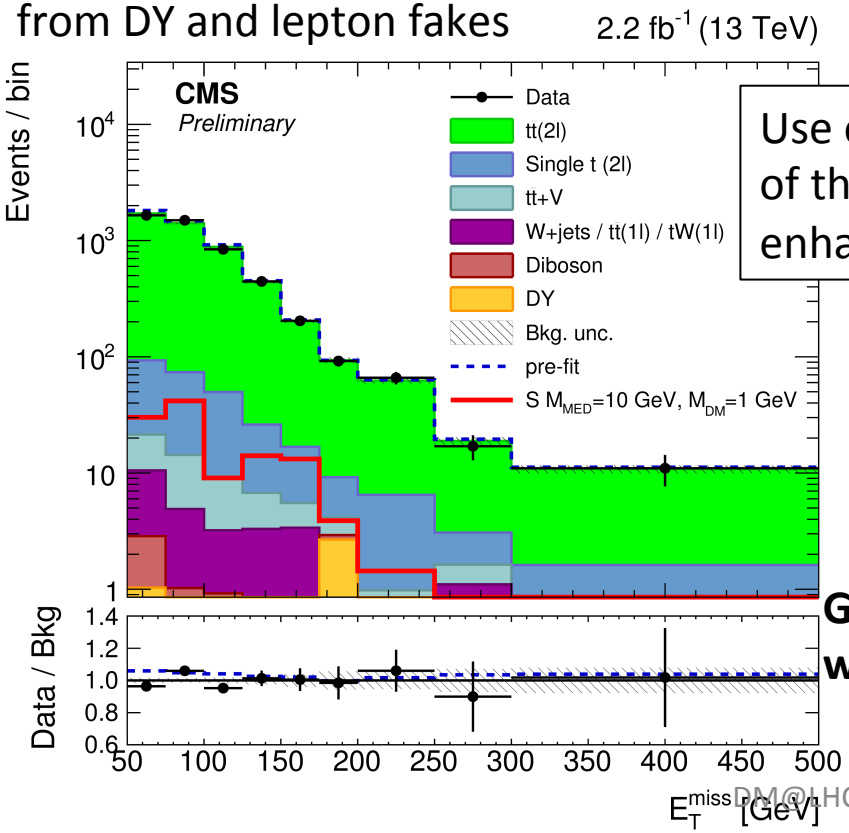
DM+tt

(dilepton channel)



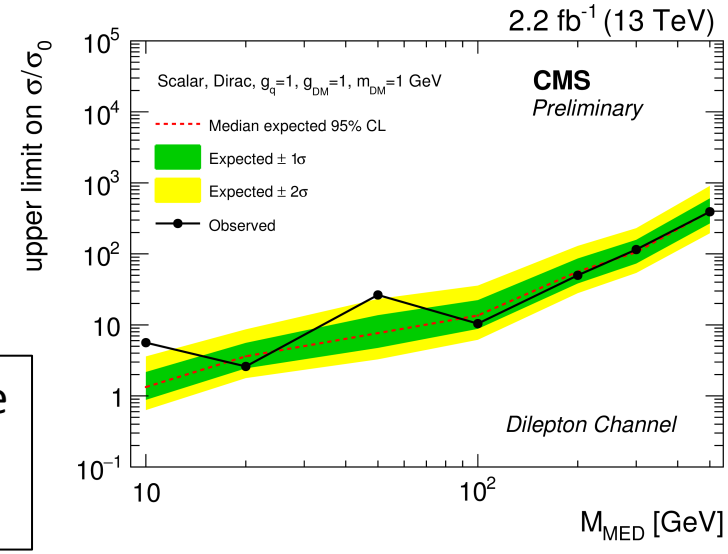
Considering dilepton channels (ee,μμ,eμ)
→ Moderate E_T^{miss}, at least one b-jet, multiple jets
→ Dominated by top production

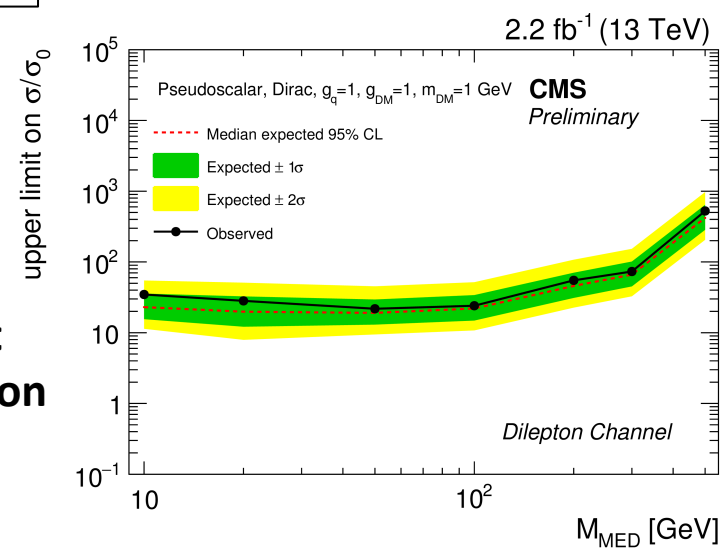
Most backgrounds from simulation
Data driven background estimations
from DY and lepton fakes



Use of the full shape of the E_T^{miss} to enhance sensitivity

Good agreement with SM prediction



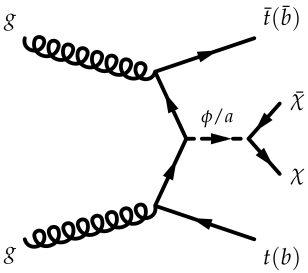


CMS-PAS-EXO-16-028

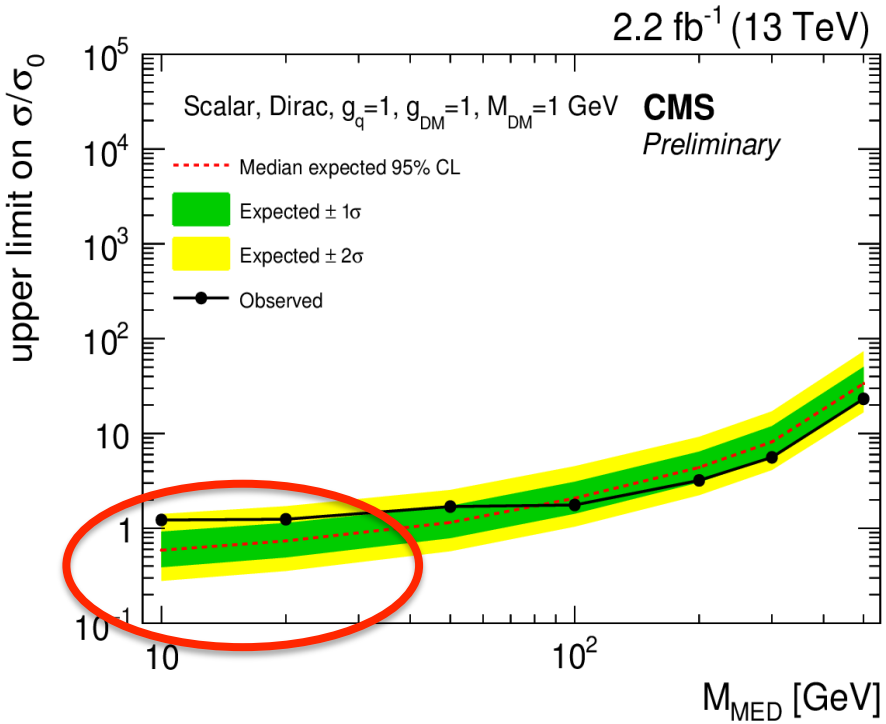
√s=13 TeV, 2.2 fb^{-1}

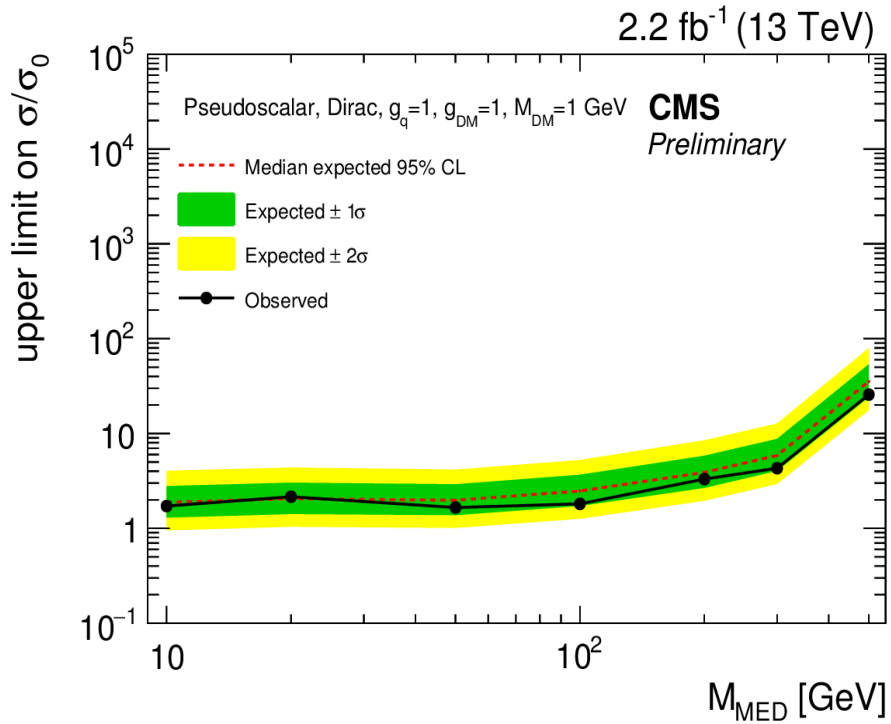
DM+tt

(all channels)



CMS combination of hadronic, semi-leptonic and dilepton channels





The combination analysis obtains an expected exclusion of scalar mediators with masses up to 39 GeV at 95% CL, with the assumption of Dirac DM particles with M_{DM}=1 GeV and g_q=g_{DM}=1

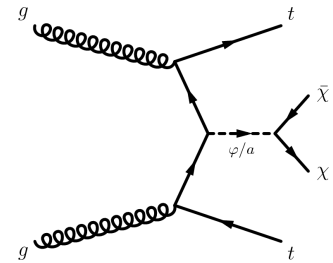
In the case of pseudoscalar mediator the expected sensitivity at the edge of that needed for exclusion

ATLAS-CONF-2016-077

√s=13 TeV, 13.3 fb^{-1}

DM+tt

(hadronic channel)



Large E_T^{miss} and E_T^{miss} significance
At least four jets, and 2 b-jets, lepton veto

Reconstruction of two large jets R=1.2
with masses above 140 and 60 GeV

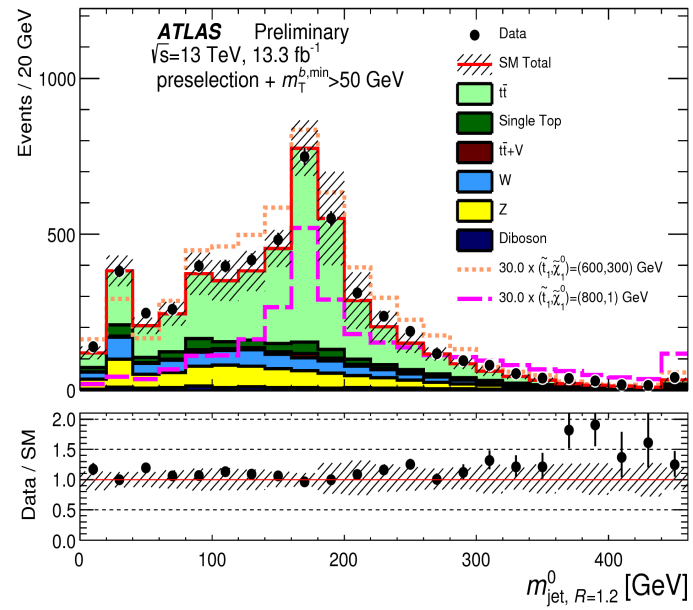
Some topological requirements optimized
for a DM signal with M_{MED} = 350 GeV and M_{DM} = 1 GeV

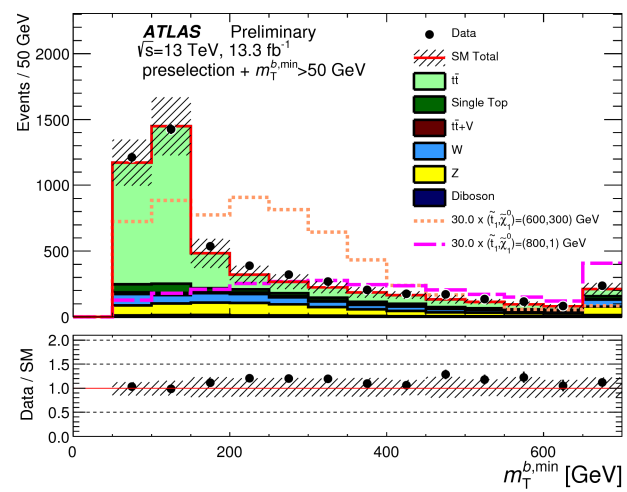
$\Delta R(bb) > 1.5$, $M_T^{b,min} > 200$ GeV

$$m_T^{b,min} = \sqrt{2\, p_T^b\, E_T^{miss} \left[1 - \cos\Delta\phi\left(\mathbf{p}_T^b, \mathbf{p}_T^{miss}\right)\right]}$$

→ Dominated by top production (tt & Z(→ νν)+jets)

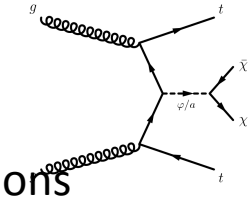
Background normalizations constrained in
dedicated control regions.

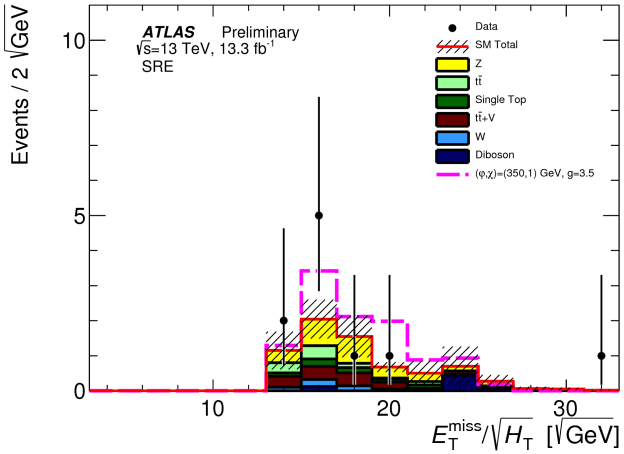




ATLAS-CONF-2016-077

DM+tt

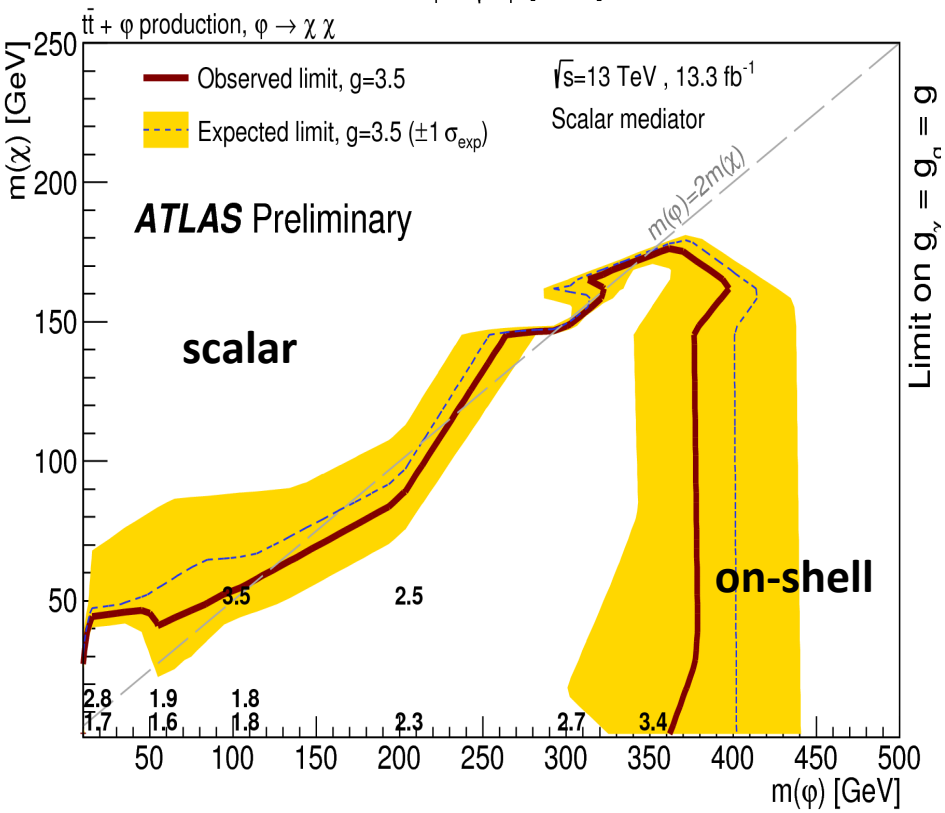


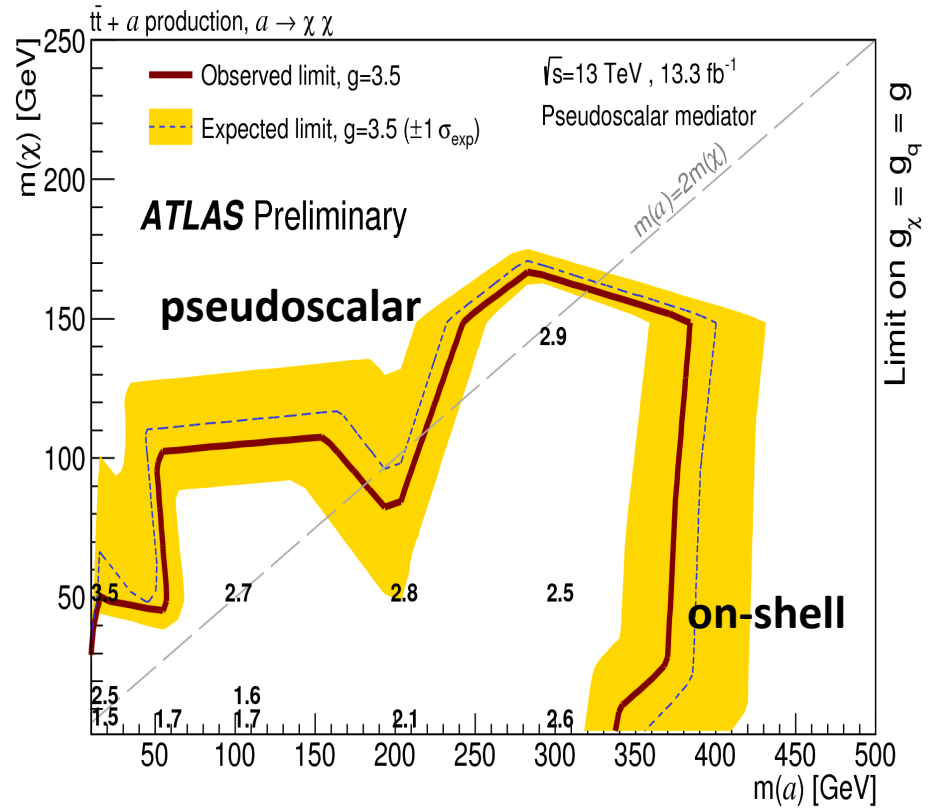


Good agreement with SM predictions

95% CL limits on visible cross section of 0.72 fb

Limits on DM models assuming g= 3.5
For on-shell scalar/pseudoscalar mediators masses in the range 300 – 350 GeV excluded



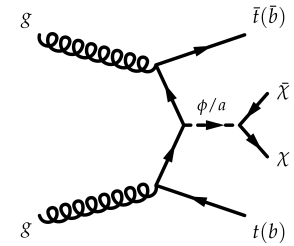


ATLAS-CONF-2016-050

√s=13 TeV, 13.3 fb^{-1}

DM+tt

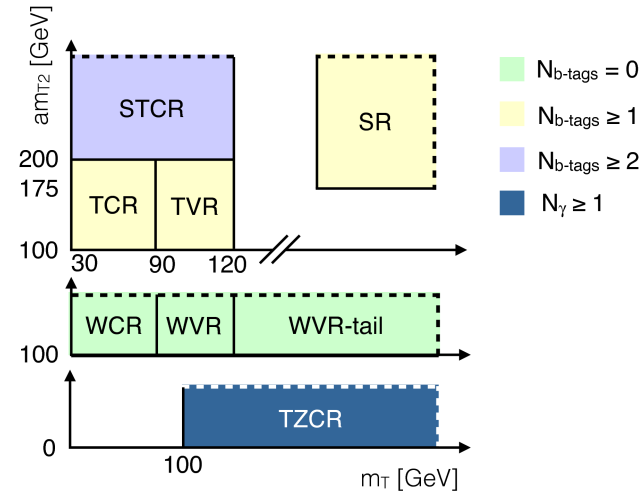
(semileptonic channel)



Large E_T^{miss} and E_T^{miss} significance
At least one lepton
At least four jets, and 1 b-jets
Azimuthal separations: jets, E_T^{miss}, lepton

Some topological requirements based on variants of m_{T2} (arXiv:hep-ph/9906349)

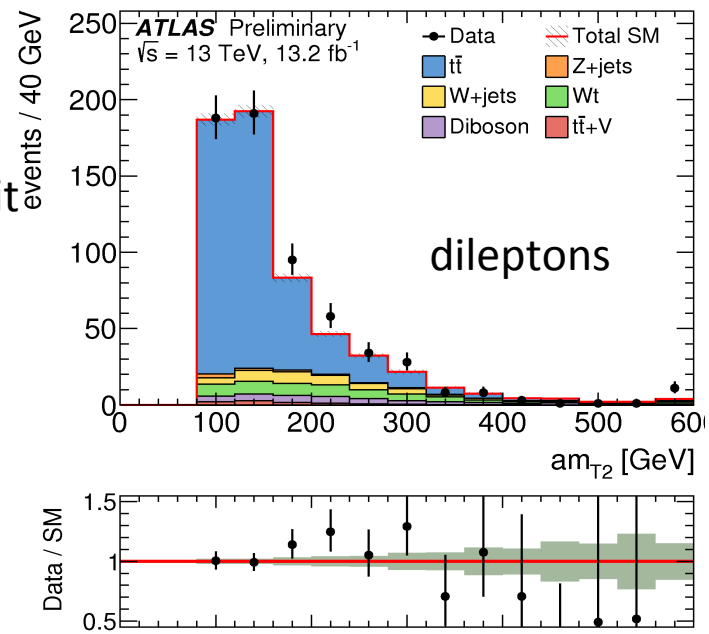
$$m_{T2}(\mathbf{p}_{T,1}, \mathbf{p}_{T,2}, \mathbf{q}_T) = \min_{\mathbf{q}_{T,1}+\mathbf{q}_{T,2}=\mathbf{q}_T} \{\max[\, m_T(\mathbf{p}_{T,1}, \mathbf{q}_{T,1}), m_T(\mathbf{p}_{T,2}, \mathbf{q}_{T,2})\,]\}$$

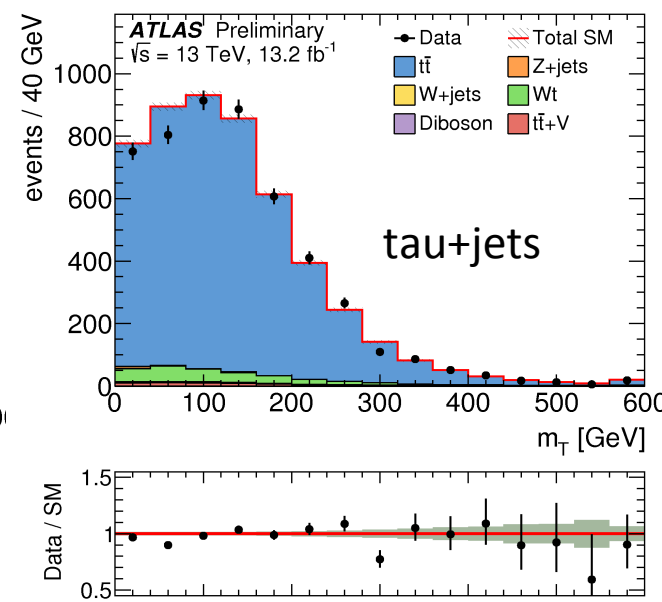


Background dominated by top processes.

Constrained in control regions via simultaneous fit

Different control regions and validation regions defined in the plane of topological variables and different N b-jets





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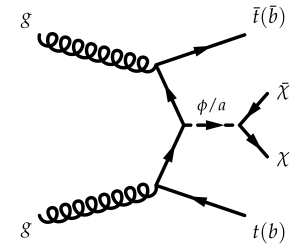
√s=13 TeV, 13.3 fb^{-1}

DM+tt

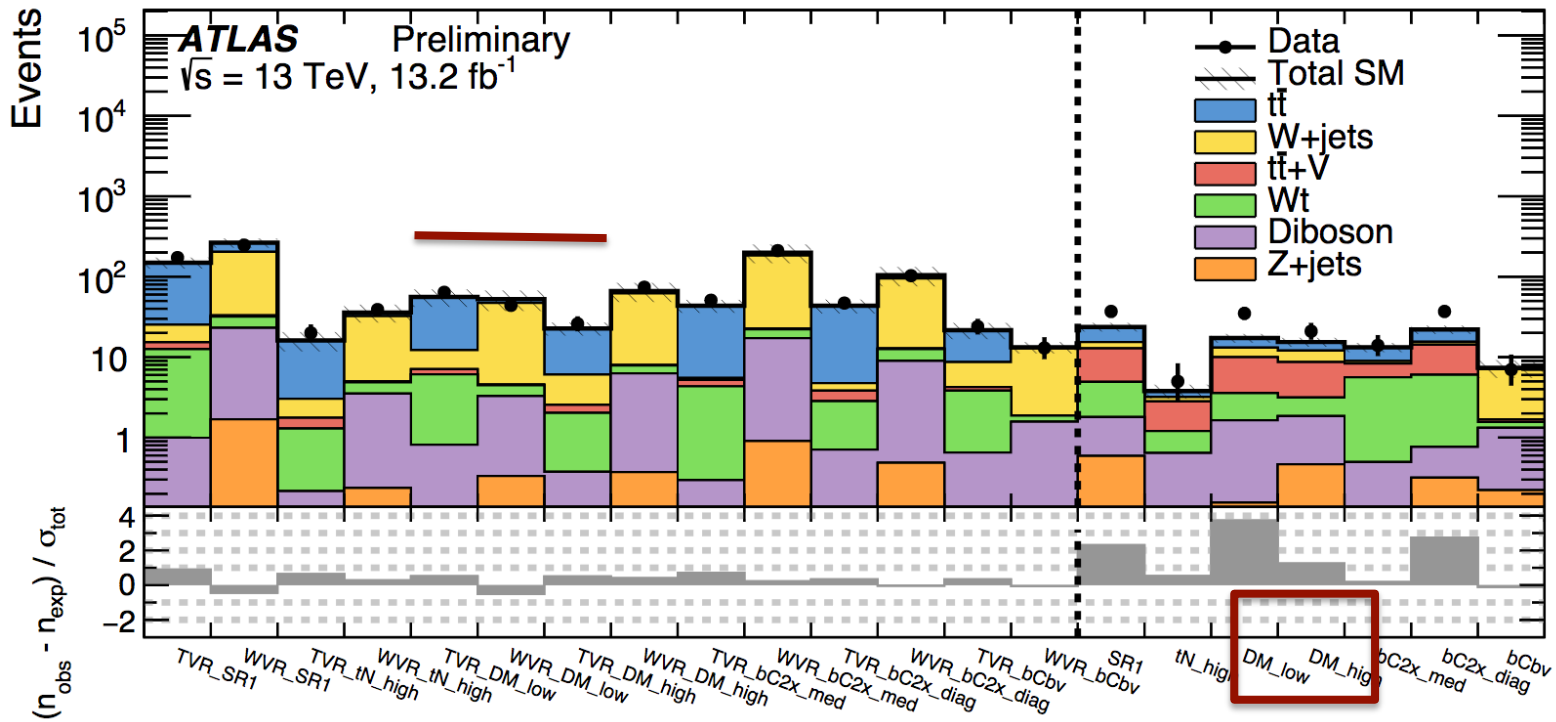
(semileptonic channel)



Variable	DM_low	DM_high
Number of (jets, b-tags)	($\geq 4, \geq 1$)	($\geq 4, \geq 1$)
Jet $p_T >$ [GeV]	(60 60 40 25)	(50 50 50 25)
E_T^{miss} [GeV]	> 300	> 330
$H_{T,sig}^{miss}$	> 14	> 9.5
m_T [GeV]	> 120	> 220
am_{T2} [GeV]	> 140	> 170
$\min(\Delta\phi(\vec{p}_T^{miss}, jet_i))(i \in \{1-4\})$	> 1.4	> 0.8
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	> 0.8	–

An about 3.3σ excess (local significance) in one of the signal regions

Nothing seen in Validation Regions



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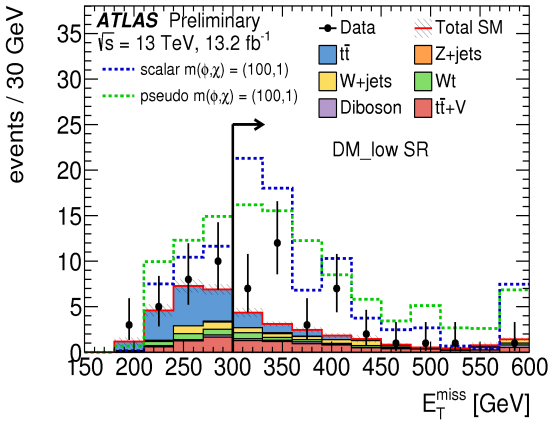
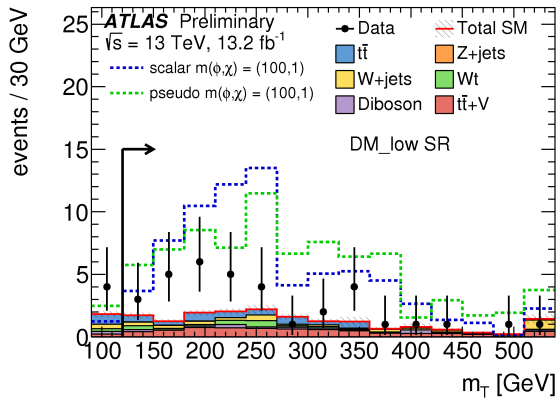
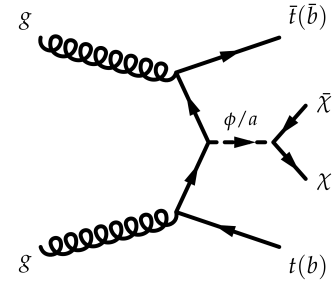
DM+tt

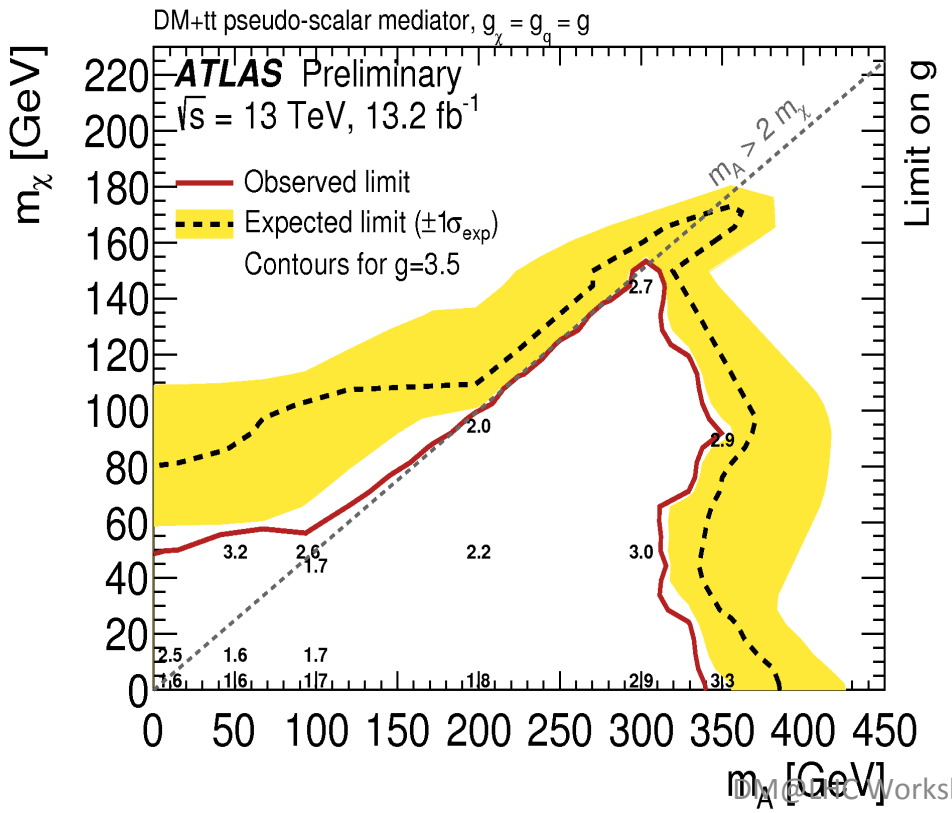


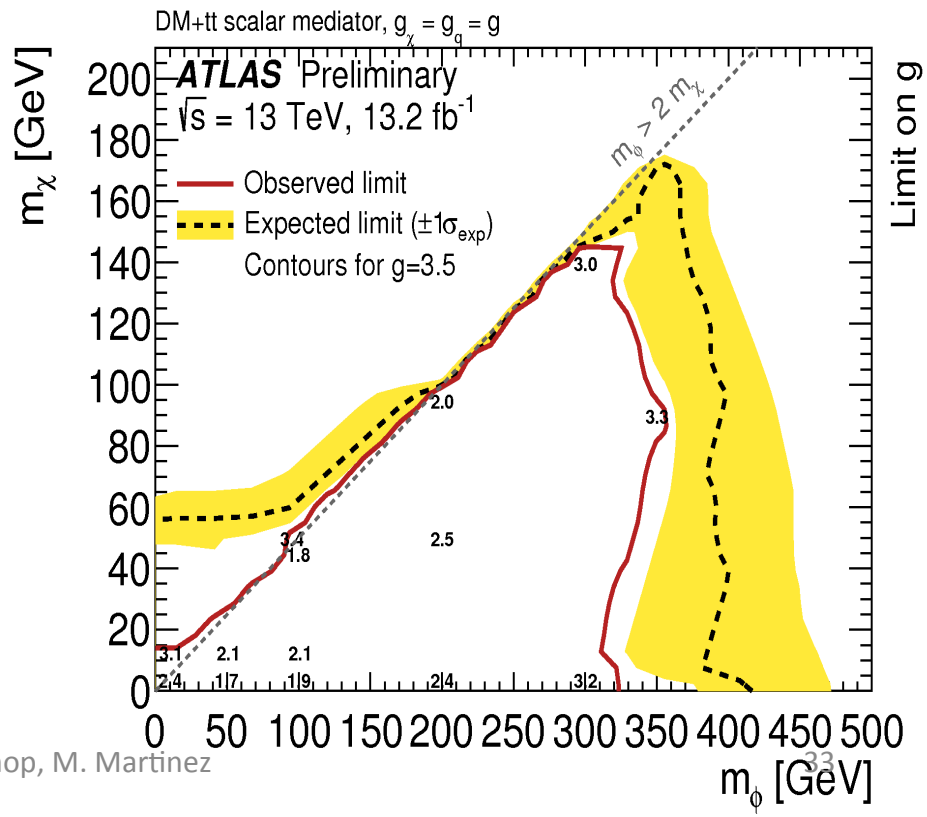




An about 3.3σ excess (local significance) in one of the signal regions

(needs more data…)





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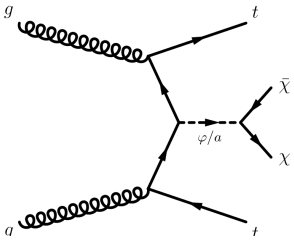
√s=13 TeV, 13.3 fb^{-1}

DM+tt

(dilepton channel)



Considering dilepton channels (ee,μμ,eμ)

→ Moderate E_T^{miss}, at least one b-jet, multiple jets

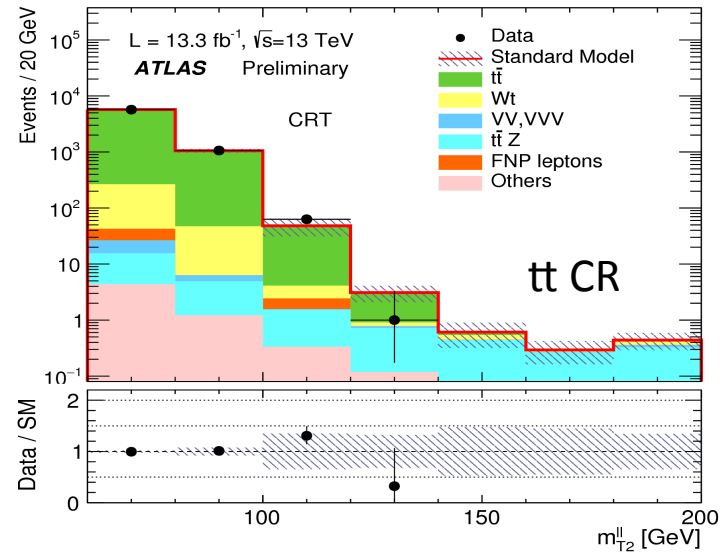
→ Topological cuts to enhance signal

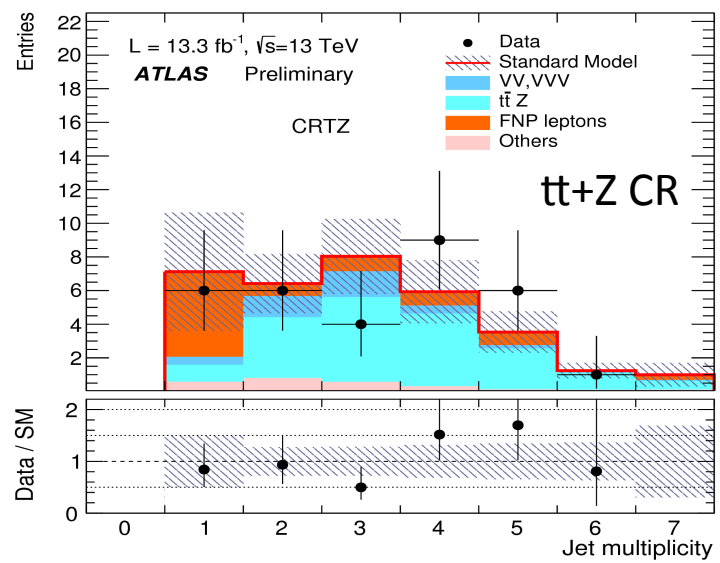
Variable	DM-SRL	DM-SRH
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV] (SF only)	>20	>20
b-jet multiplicity	> 0	> 0
$\Delta\phi_{\text{boost}}$	< 1.0	< 1.0
m_{T2}^{ll} [GeV]	>120	>120
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 180	> 260

$$m_{\text{T2}}(\mathbf{p}_{\text{T},1}, \mathbf{p}_{\text{T},2}, \mathbf{q}_{\text{T}}) = \min_{\mathbf{q}_{\text{T},1}+\mathbf{q}_{\text{T},2}=\mathbf{q}_{\text{T}}} \{\max[\, m_{\text{T}}(\mathbf{p}_{\text{T},1}, \mathbf{q}_{\text{T},1}), m_{\text{T}}(\mathbf{p}_{\text{T},2}, \mathbf{q}_{\text{T},2})\,]\}$$

→ Dominated by top production (tt & tt+Z)

Background normalizations constrained in dedicated control regions.

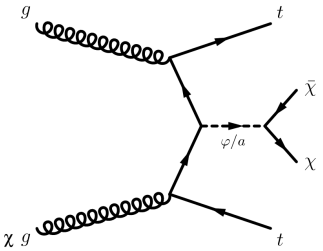


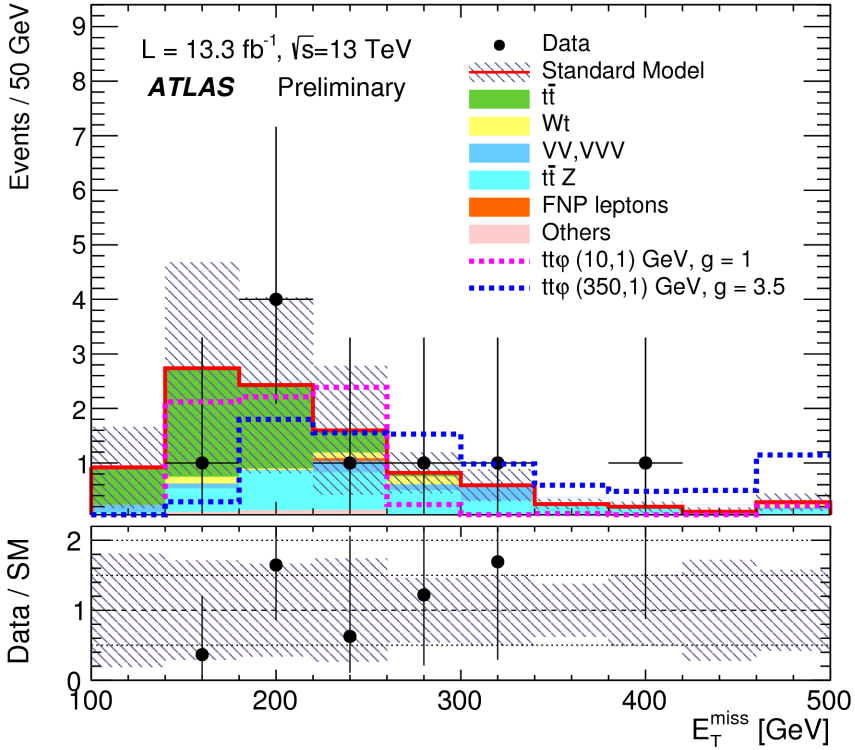


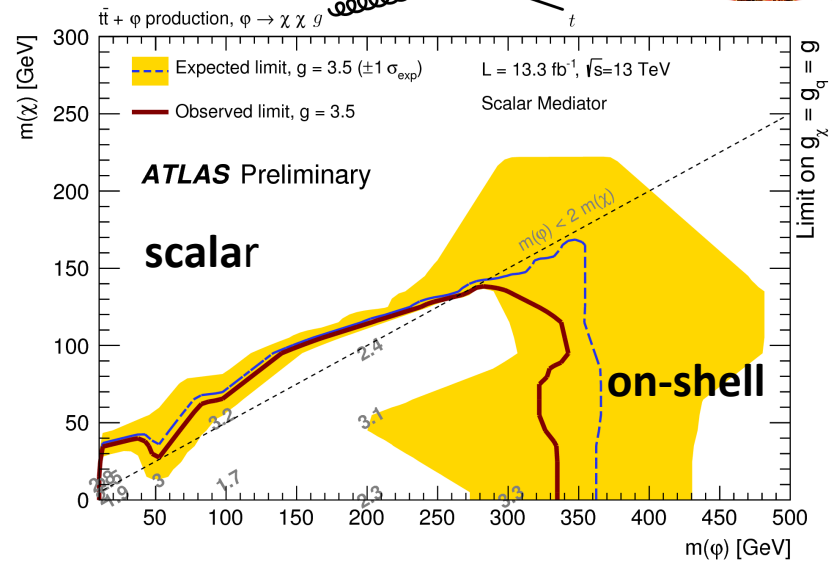
ATLAS-CONF-2016-076

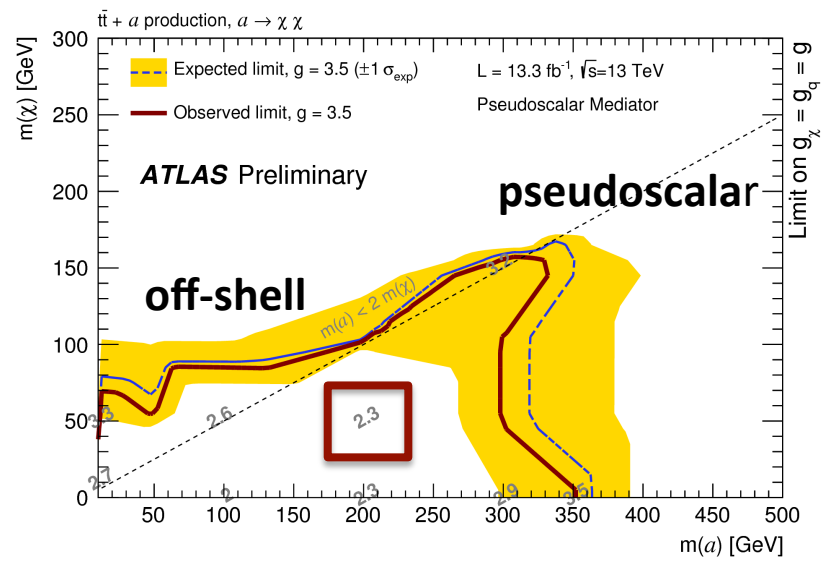
DM+tt

(dilepton channel)









Good agreement with SM predictions

95% CL limits on visible cross section in the range **0.65 fb – 0.43 fb**

Limits on DM models assuming g= 3.5

(95% limits on g in the Figures)

Final notes

- The nature of the Dark Matter remains one of the biggest questions on particle physics and its potential discovery is a pillar of the ATLAS and CMS physics programs
- The search for Dark Matter in association with heavy flavors at the LHC is well motivated and still statistically limited
- Exclusion limits on DM strongly depend on model assumptions
- The LHC is about to resume pp collisions in few months and promises to deliver lots of data in the following years
- Stay tuned!

CMS DP -2016/057

In Summary (CMS @ ICHEP2016)