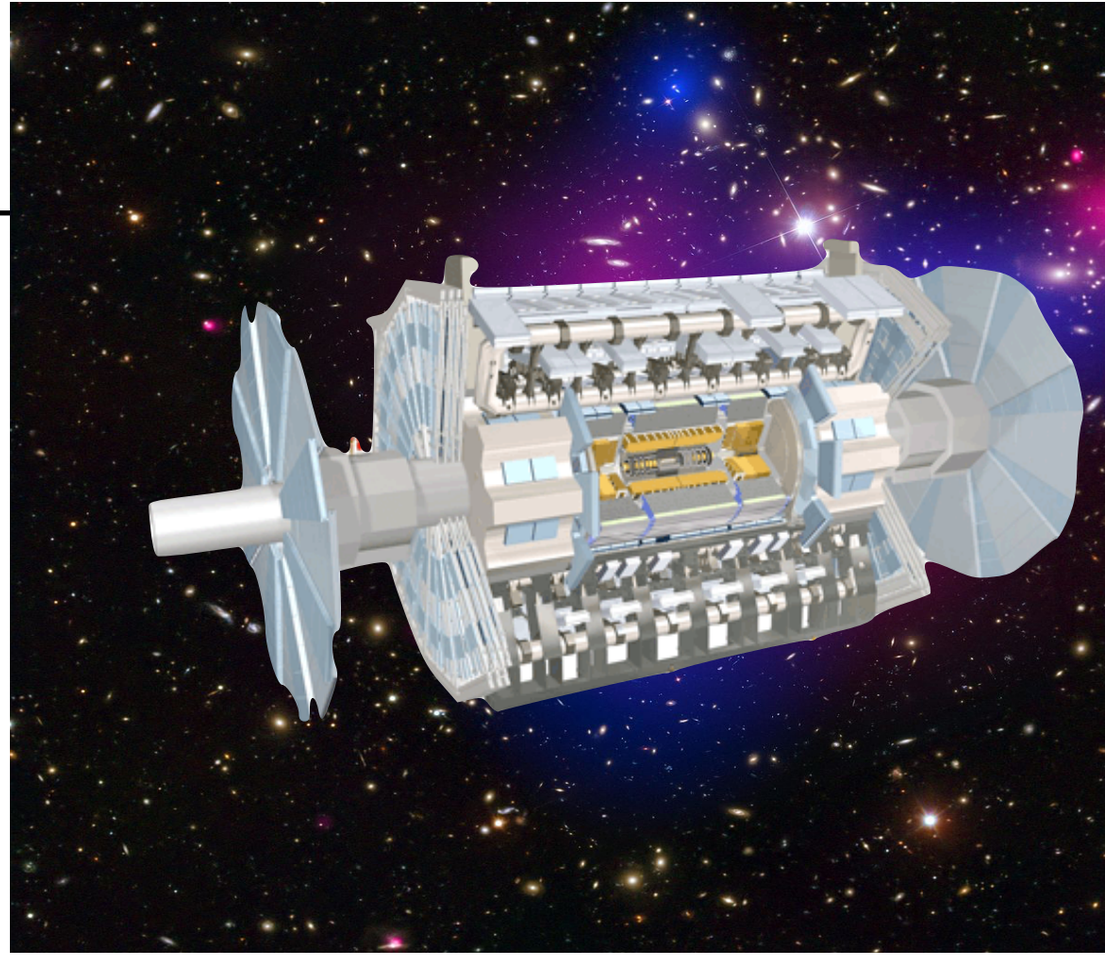
Dark Matter searches with the ATLAS detector

Edoardo Farina
University of Pavia and INFN

on behalf of the ATLAS Collaboration

ICNFP Conference, 2019

Dark matter at LHC



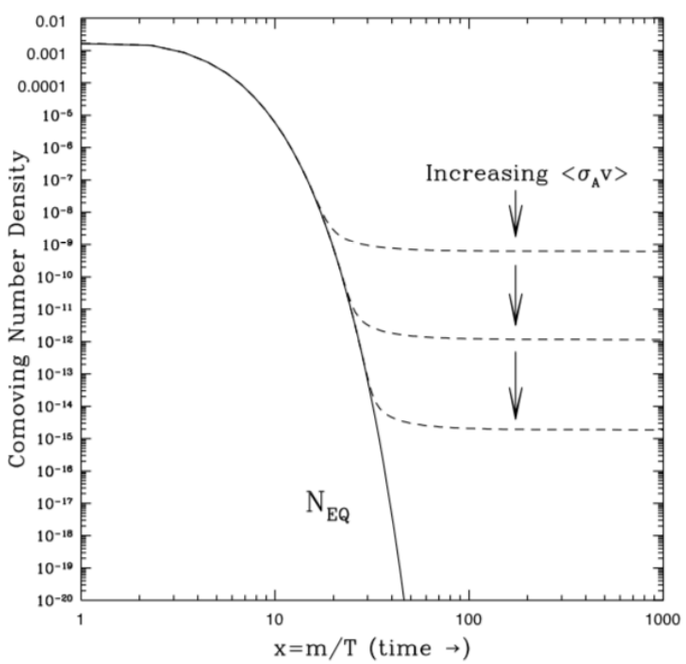
What we know about dark matter:

- Strong evidence of its existence
- It interacts via gravitational force
- DM is electrically neutral

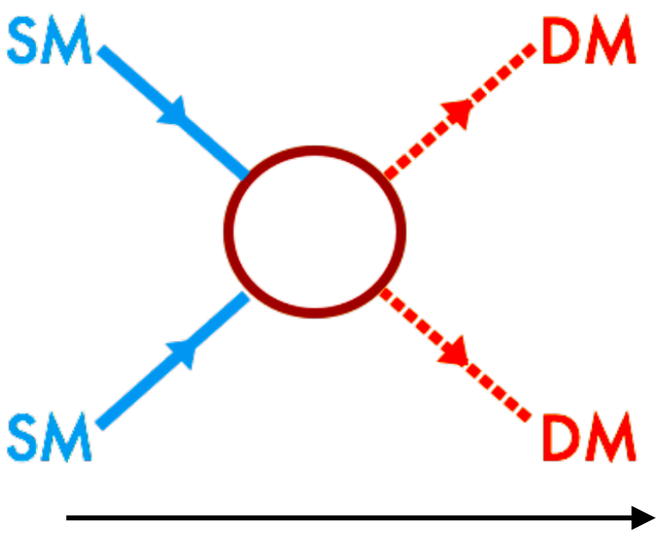
What can LHC tell us about Dark Matter?

- Stable WIMP DM and SM are in thermal equilibrium
- When annihilation rate drops below expansion rate, DM falls out of equilibrium (freeze-out)
- If relic density is considered, a WIMP having mass order of 100 GeV and typical electroweak cross section is obtained

A "remarkable" coincidence..



$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



Collider

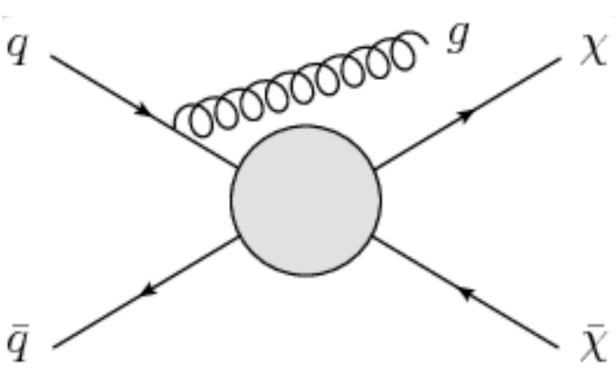
https://arxiv.org/pdf/hep-ph/9710467.pdf

Unveiling dark matter at colliders

Run I paradigm:

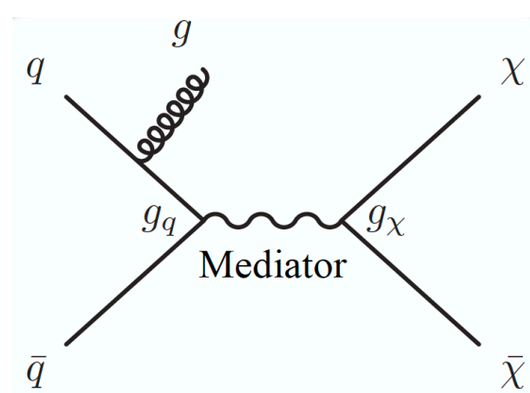
EFT

Valid when momentum transfer lower than mediator mass



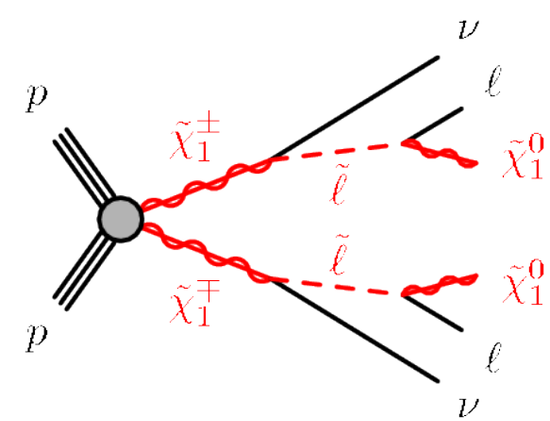
Run II paradigm:

- In general not-UV-complete models
- Good benchmark for searches
- comparison with DD
- One-mediator simplified models
- V/AV mediators
- Scalar/Pseudo scalar spin 0 mediators
- ...



DM interpretation of complete model

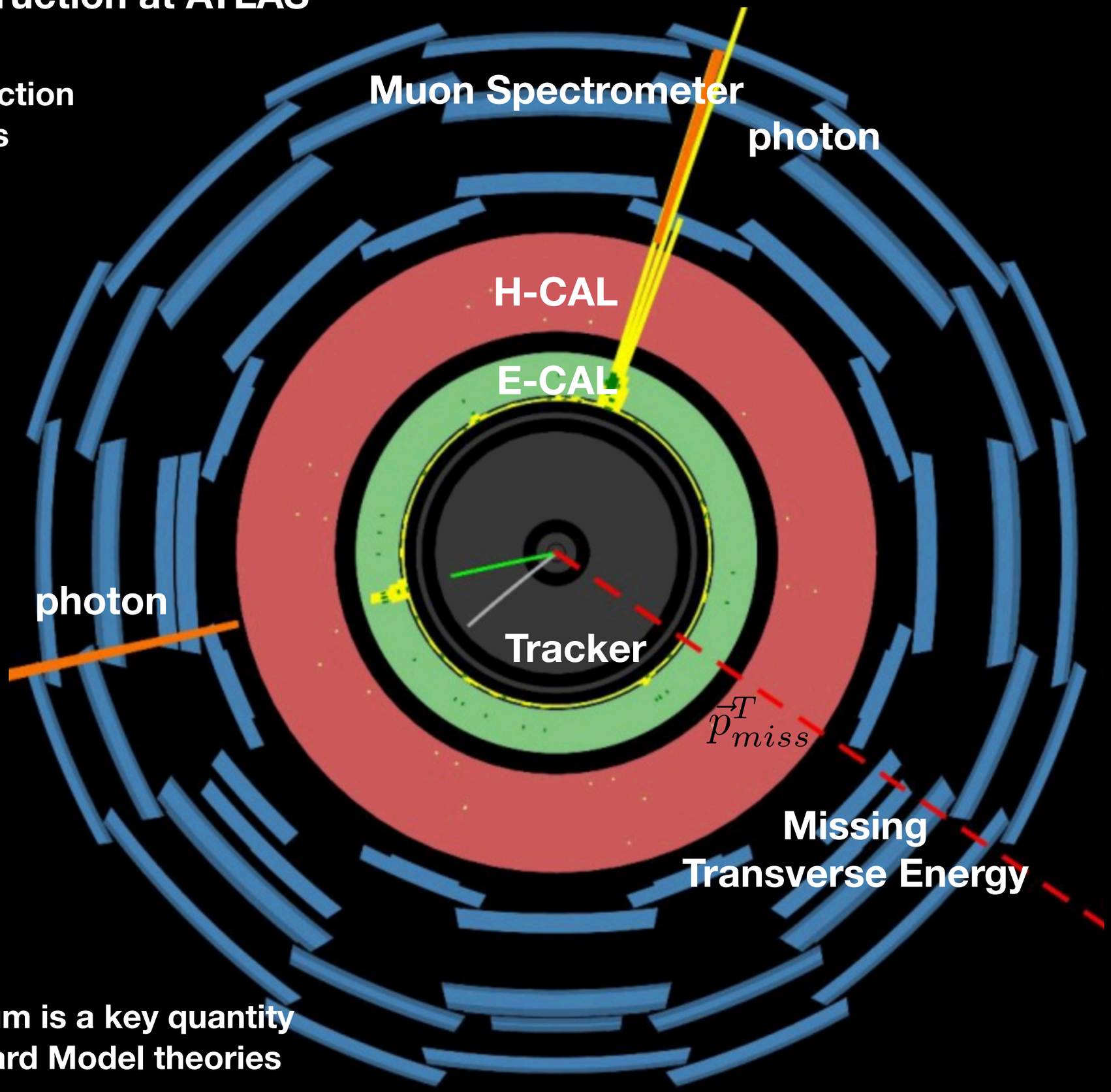
SUSY R-Parity conserved models: sparticles cannot decay only into SM particles

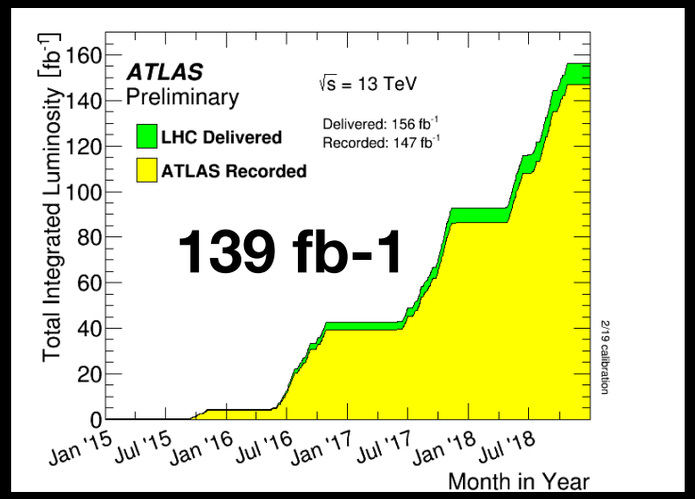


completeness

Physics objects reconstruction at ATLAS

Candidate event of Zγγ production
with Z decaying into neutrinos



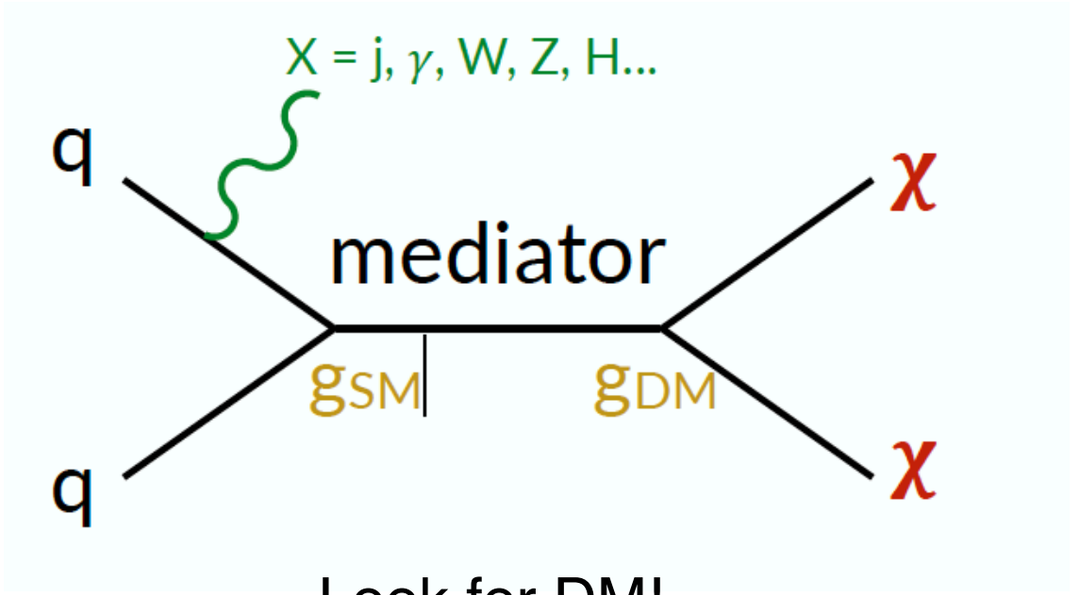


Missing transverse momentum is a key quantity
to investigate Beyond Standard Model theories

WIMP would result in MET

ATLAS simplified mediator searches

X + MET



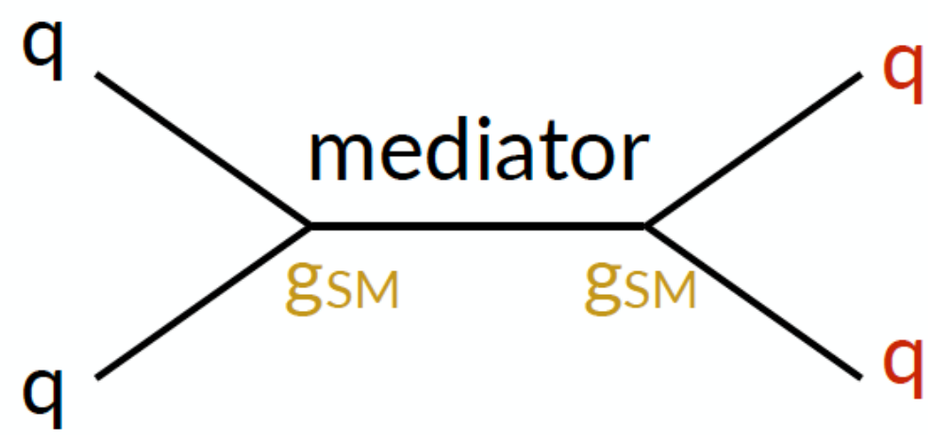
Look for DM!

jet + MET JHEP 01 (2018) 126
γ + MET Eur. Phys. J. C 77 (2017) 393
H(bb) + MET ATLAS-CONF-2018—039
V + MET JHEP 10 (2018) 180
t + MET JHEP 05 (2019) 41
H(γγ) + MET Phys. Rev. Lett. D 96 (2017)

HF + MET Eur. Phys. J. C 78 (2018) 18
tt + MET JHEP 06 (2018) 108
4 top + MET JHEP 09 (2017) 088
H->inv Phys. Rev. Lett. 122 (2019)
tt + MET (same sign) JHEP 12 (2018) 039

Most of the X+MET signatures have been covered by ATLAS (and CMS)

DI+X



Visible (resonant) signature

Di-jet ATLAS-CONF-2019-007
Angular dijet resonances PRD 96 (2017) 052004
Di-jet @ ISR Phys. Lett. B 795 (2019) 56
Di-jet @ trigger level Phys. Rev. Lett. 121 081801
Di-b-jet Phys. Rev. D 98 (2018) 032016
Di-top Eur. Phys. J. C 78 (2018) 565
Di-lepton Phys. Rev. B 796 (2019)
Boosted dijet + ISR Phys. Lett. B 788 (2019) 316
Boosted di-b-jet+ISR ATLAS-CONF-2018-052
1L tt resonances EPJC 78 (2018) 565
Hadronic tt resonances Phys. Rev. D 99 (2019) 092004

ATLAS simplified mediator searches

All 2015+2016 (36 fb-1) results have been collected and interpreted in a summary paper according to different mediator based simplified models:

Vector/Axial Vector
Vector Baryonic-number-charged
Vector Flavour-changing
Scalar/Pseudo Scalar
Scalar Colour-charged
2 Higgs doublets model + vector and pseudoscalar mediator
JHEP 05 (2019) 142

jet + MET JHEP 01 (2018) 126
γ + MET Eur. Phys. J. C 77 (2017) 393
H(bb) + MET ATLAS-CONF-2018—039
V + MET JHEP 10 (2018) 180
t + MET JHEP 05 (2019) 41
H(γγ) + MET Phys. Rev. Lett. D 96 (2017)

HF + MET Eur. Phys. J. C 78 (2018) 18
tt + MET JHEP 06 (2018) 108
4 top + MET JHEP 09 (2017) 088
H->inv Phys. Rev. Lett. 122 (201
tt + MET (same sign) JHEP 12 (2018) 039

New Results!

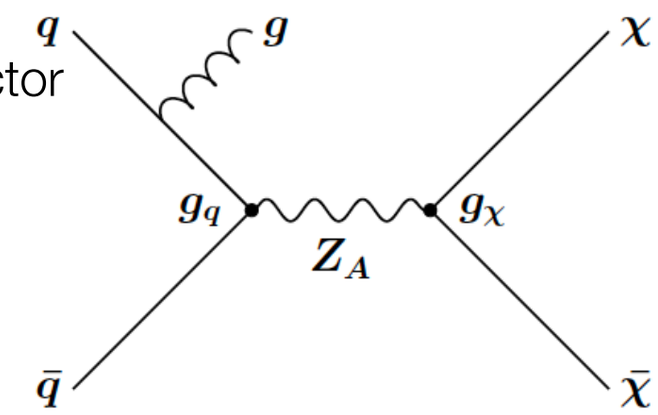
Di-jet ATLAS-CONF-2019-007
Angular dijet resonances PRD 96 (2017) 052004
Di-jet @ ISR Phys. Lett. B 795 (2019) 56
Di-jet @ trigger level Phys. Rev. Lett. 121 081801
Di-b-jet Phys. Rev. D 98 (2018) 032016
Di-top Eur. Phys. J. C 78 (2018) 565
Di-lepton Phys. Rev. B 796 (2019)
Boosted jet + ISR Phys. Lett. B 788 (2019) 316
Boosted di-b-jet+ISR ATLAS-CONF-2018-052
1L tt resonances EPJC 78 (2018) 565
Hadronic tt resonances Phys. Rev. D 99 (2019) 092004

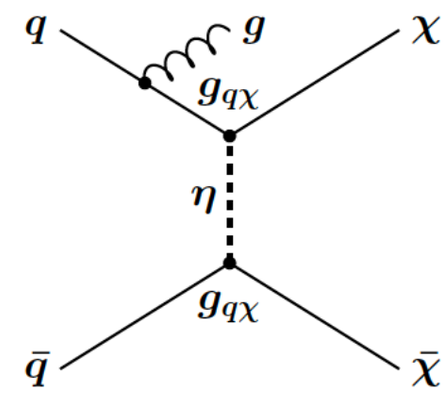
Most of the X+MET combinations have been covered by ATLAS (and CMS)

jet + MET analysis

Simplified models:

- s-channel exchange of spin-1 mediator with axial-vector (vector) couplings
- t-channel scalar coloured mediator, spin 0
- Sensitive to many other BSM scenarios



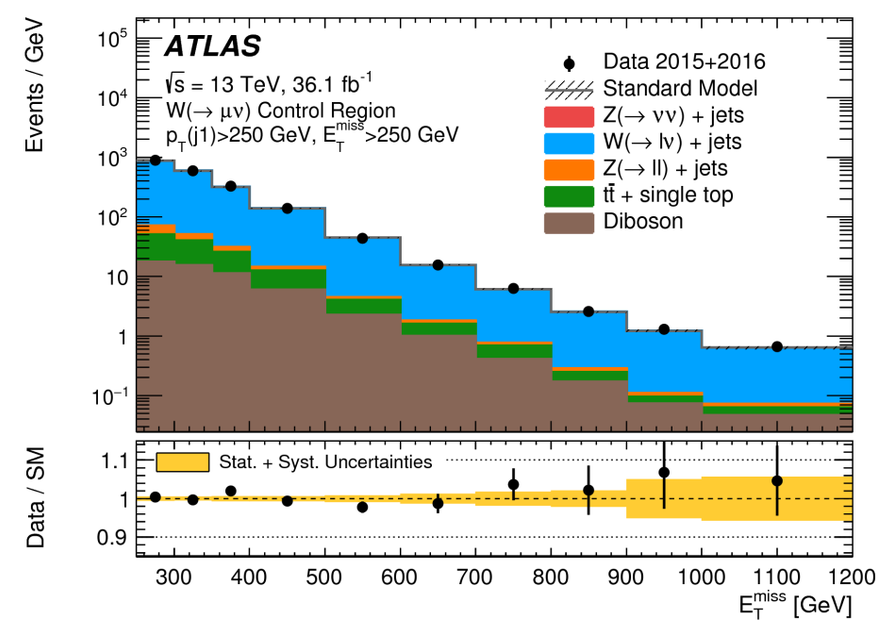


Target:
Jet with high transverse momentum, large MET due to Dark Matter unseen particle. Moderate jet activity.

Background estimates:

Z(vv)+jets background constrained using simultaneous fit to ETmiss distribution in W(→ℓ**ν**)/ Z(→ℓℓ) + jets control regions

W/Z+jets MC predictions (NLO SHERPA) reweighted to account for higher order corrections



jet + MET analysis

Simplified model:

- s-channel exchange of spin-1 mediator with axial-vector (vect
- t-cha
- Sens

Jet
ME

Bac

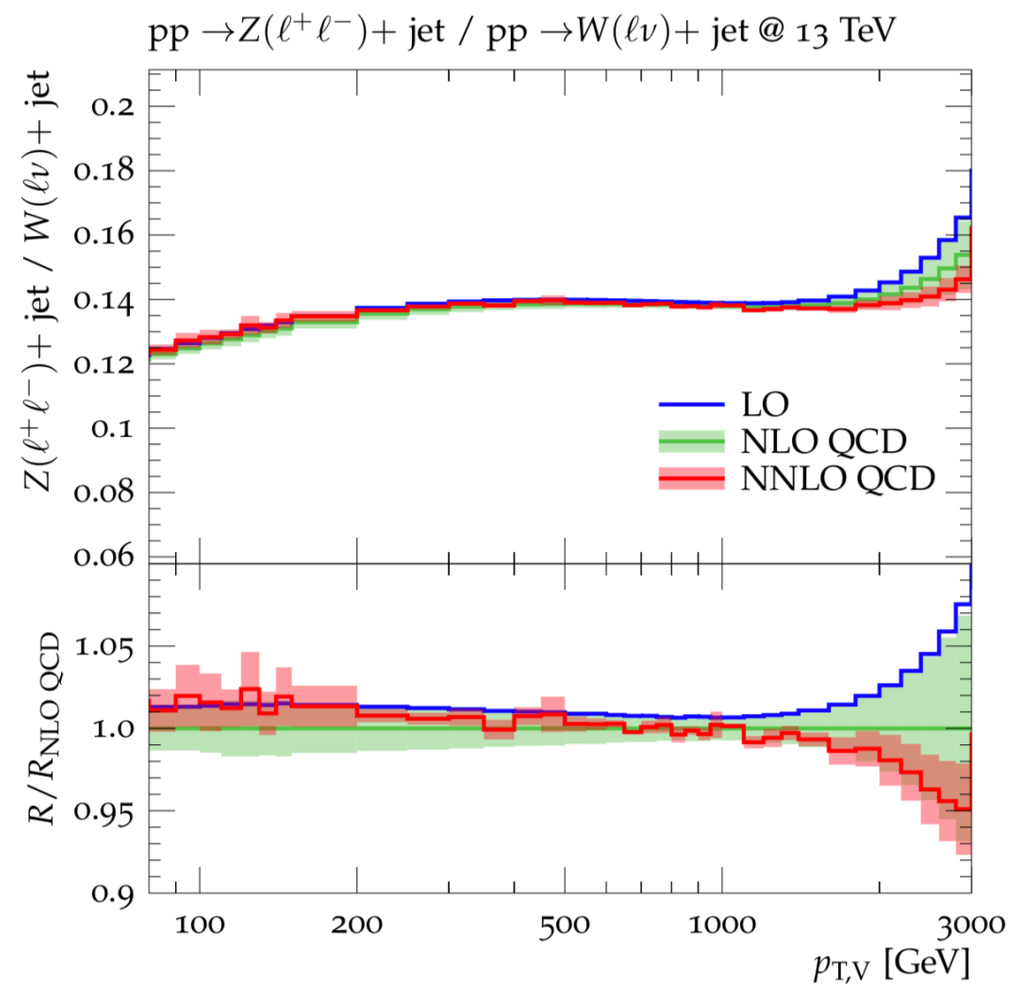
Z(
si
Z(

W
to

Constrain Z(vv)+jets by estimating W+jets

Calculate **Z+jets vs W+jets** difference at:

NNLO(αS)+NNLL(αS)
NLO(αEW)

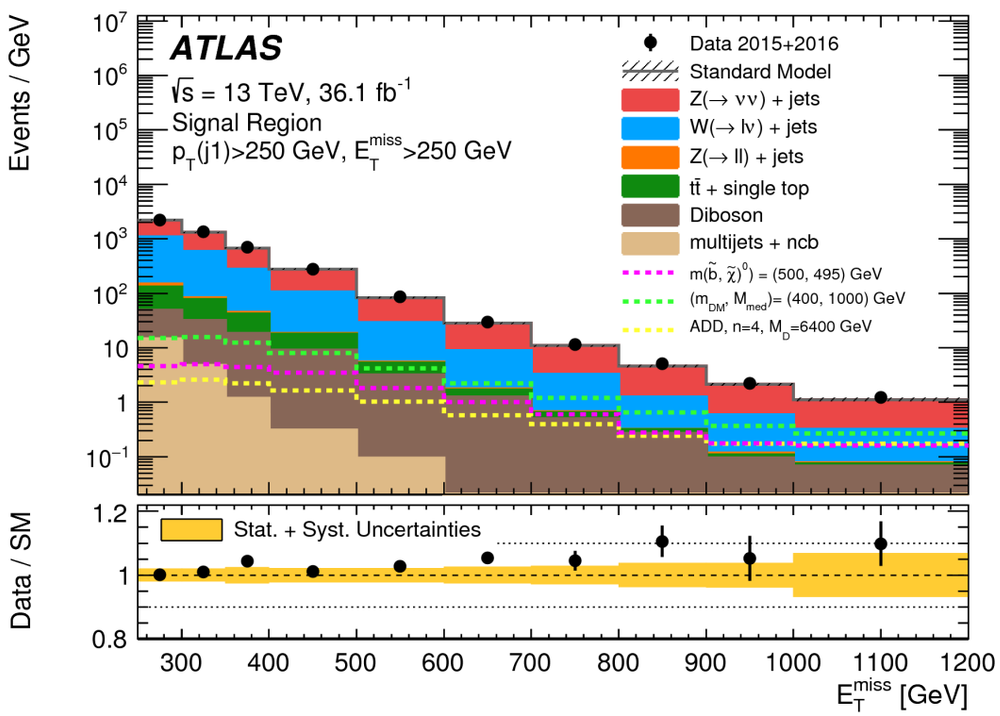


EPJC 77 (2017) 829

jet + MET analysis

Reached high precision in the background prediction uncertainty:

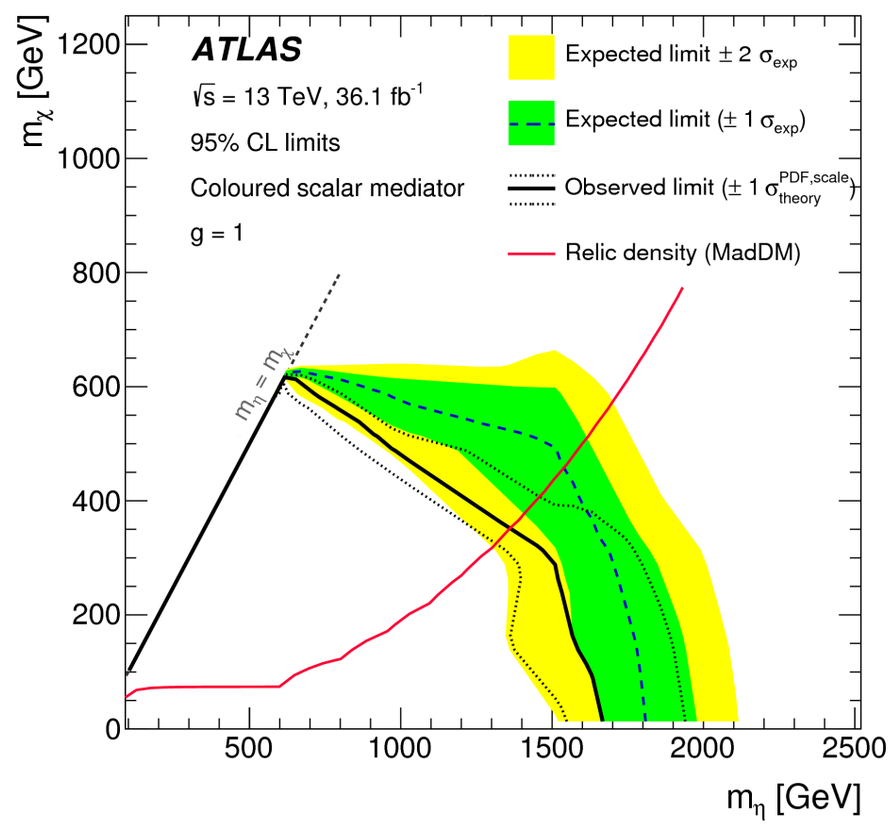
- 2% at 'low' MET
- 7% in the TeV regime



10 signal regions in bins of ET miss

t-channel results

Mediator masses up to about 1.67 TeV are excluded at 95%CL for light dark-matter particles.



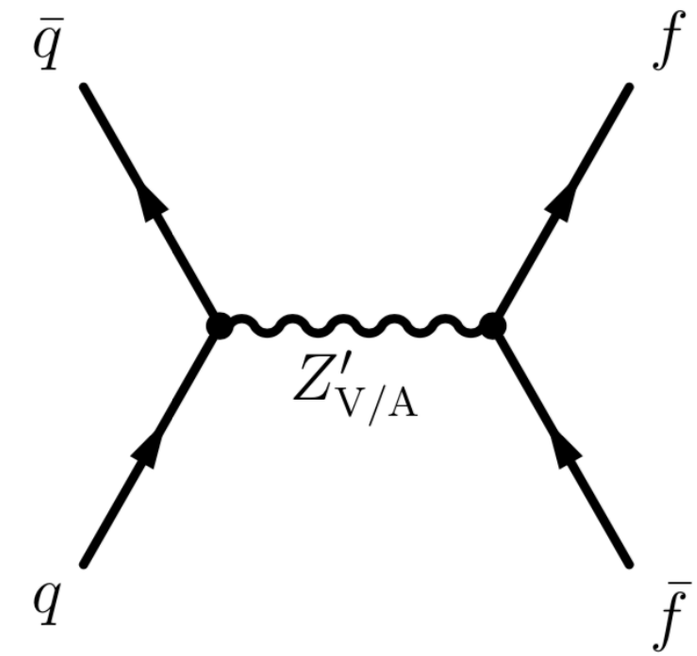
Dilepton analysis

Phys. Rev. B 796 (2019)

Simplified model:

- Spin-1 vector boson (Z', Z'$_{SSM}$)
- Sensitive to many BSM scenarios

Very **clean signature**, fully reconstructed and excellent detection efficiency

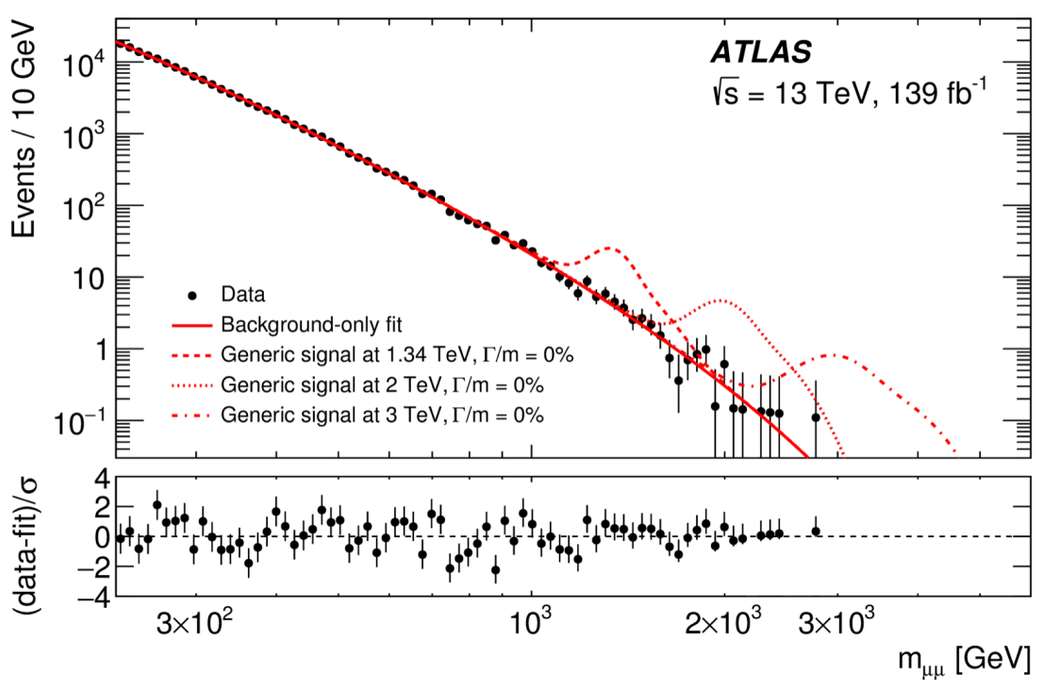


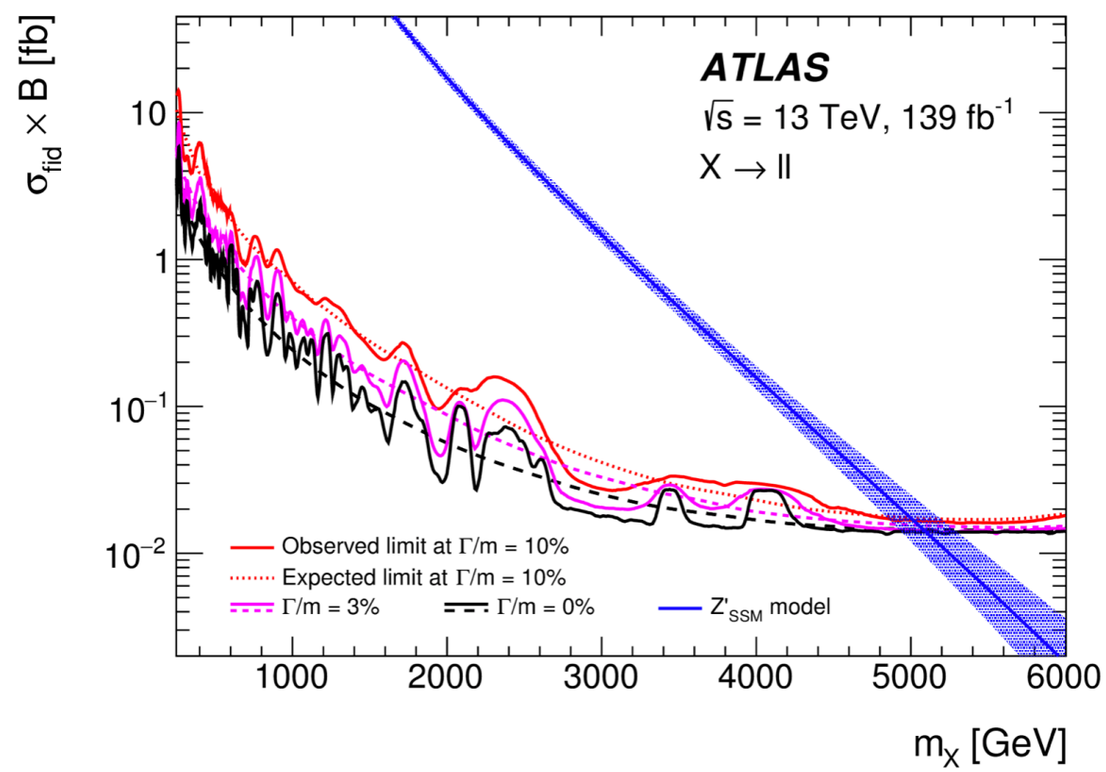
Search strategy:

Require ***ee*** or ***μμ*** pairs with $m_{\ell\ell}$>225 GeV to avoid Z boson peak region.

Look for excess in the $\mathbf{m_{\ell\ell}}$ distribution

$$f_{\ell\ell}(m_{\ell\ell}) = f_{\mathrm{BW},Z}(m_{\ell\ell}) \cdot (1 - x^c)^b \cdot x^{\sum_{i=0}^{3} p_i \log(x)^i},$$





Dilepton analysis

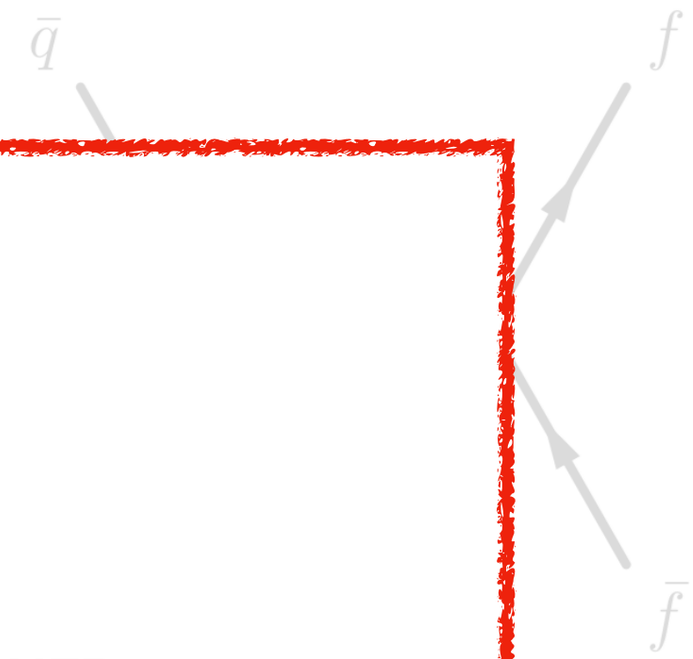
Phys. Rev. B 796 (2019)

Simplified model:

- Spin-1 vector boson (Z', Z'$_{SSM}$)
- Se

Very **clean signature**, fully reconstructed and

Requi
boson
Look



More insight in Deshan's presentation at ICNFP:

Searches for new phenomena in dilepton final states using the ATLAS detector

3×10^2 10^3 2×10^3 3×10^3

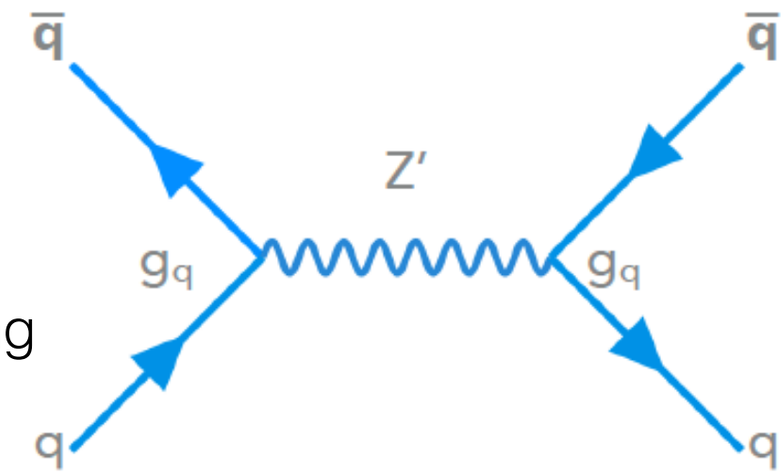
$m_{\mu\mu}$ [GeV]

m_X [GeV]

Two jets analysis

ATLAS-CONF-NOTE-2019-007

High-mass dijet search looking for Z' (dark matter mediator), W', W*, quantum black holes, excited quarks

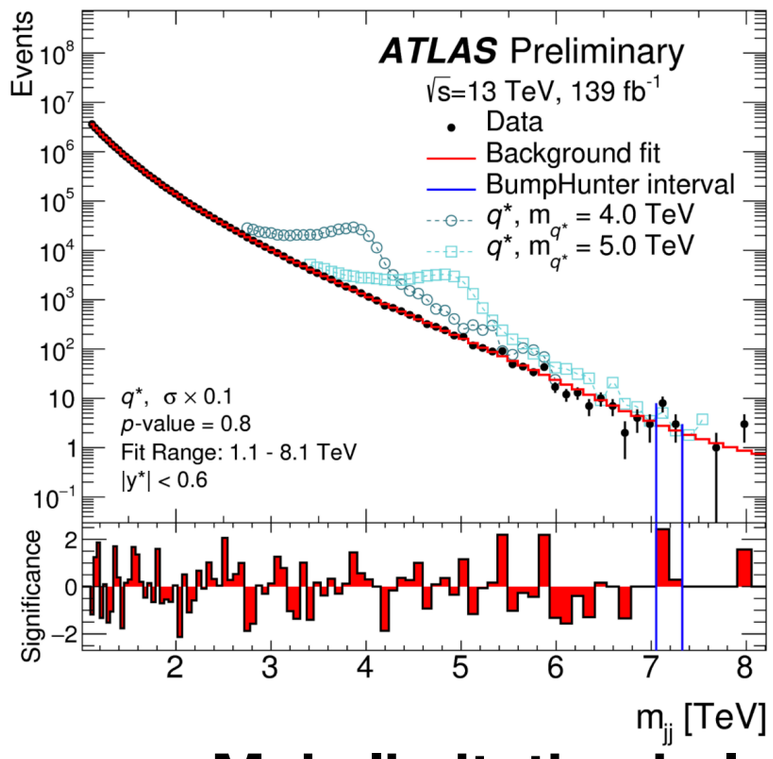


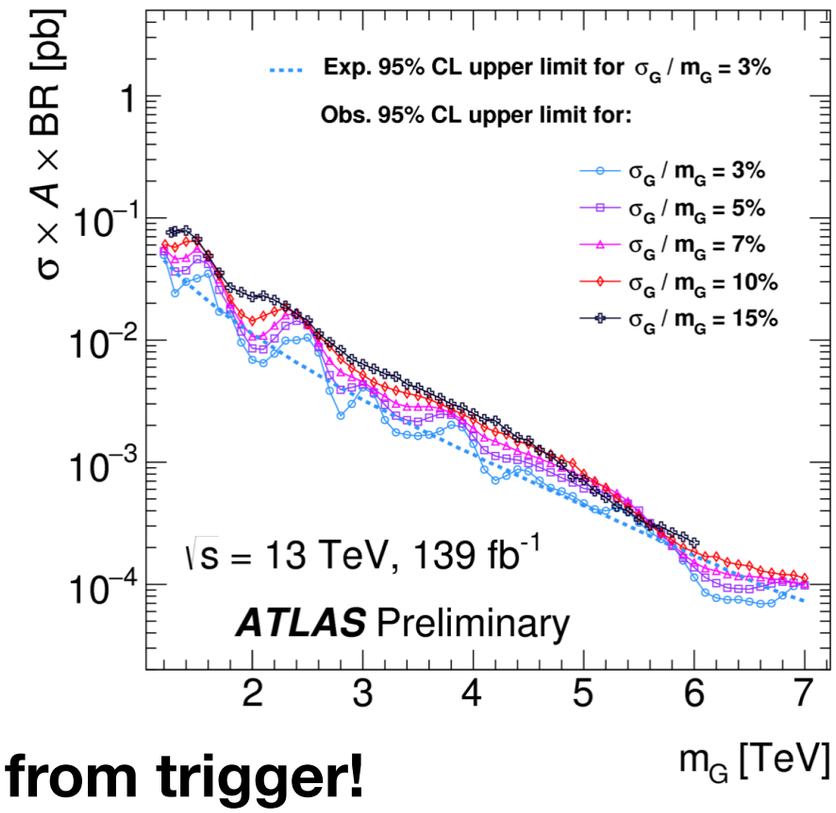
Selection based on **jet pt and rapidity** difference (leading jet > 420 GeV, subleading > 150 GeV) with y*<0.6

Search approaches:

$$f(x) = p_1 (1-x)^{p_2} x^{p_3 + p_4 \ln x + p_5 (\ln x)^2}$$

- Bump hunt in the falling standard model invariant mass spectrum

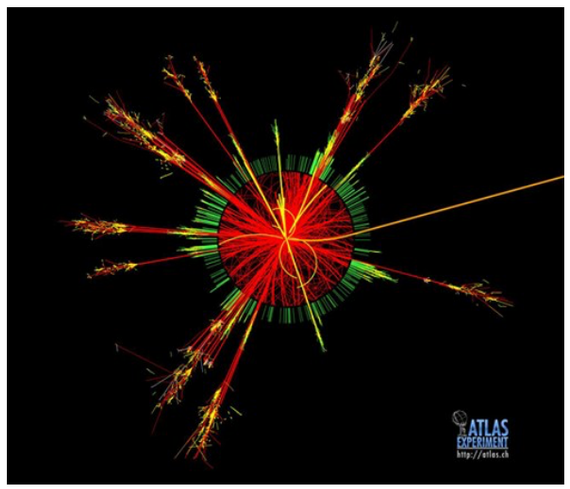




Main limitation below 1 TeV arises from trigger!

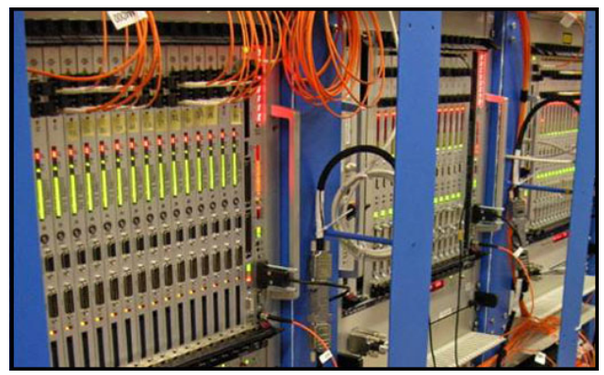
Trigger level Two jets analysis

40 MHz



L1

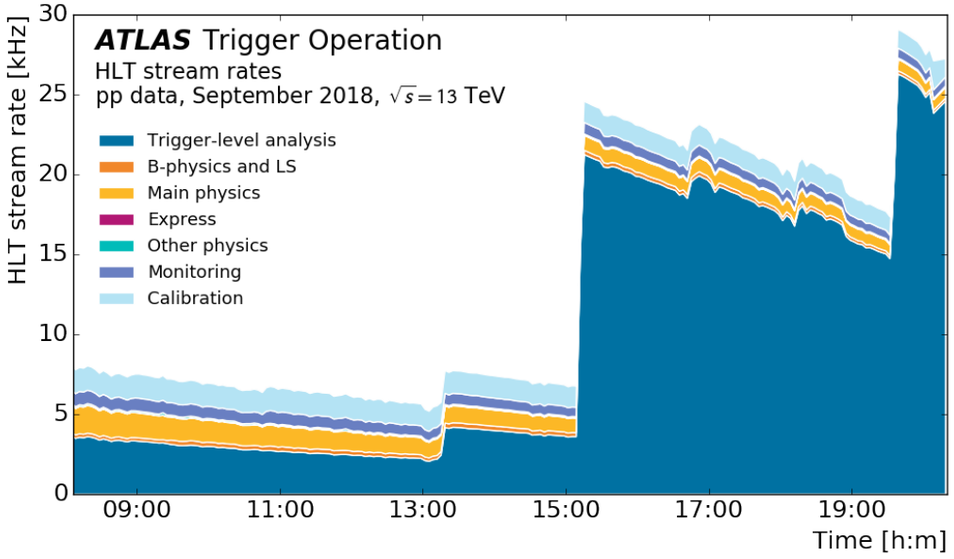
100 kHz

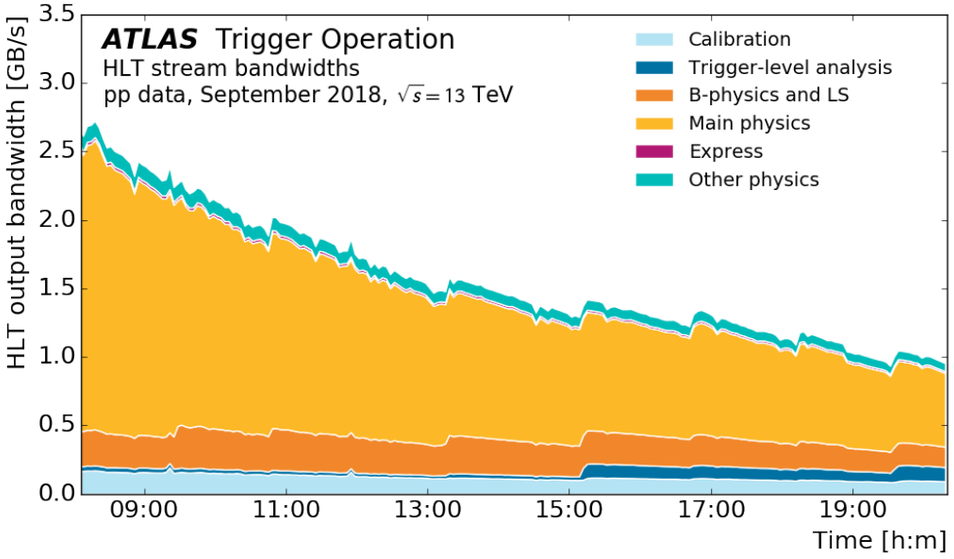


High Level Trigger

1 kHz

Use only partially reconstructed events to increase rate (TLA)



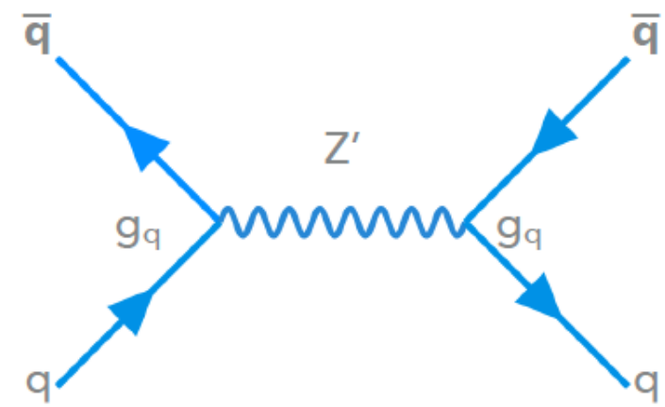


Atlas public trigger page

Trigger level Two jets analysis

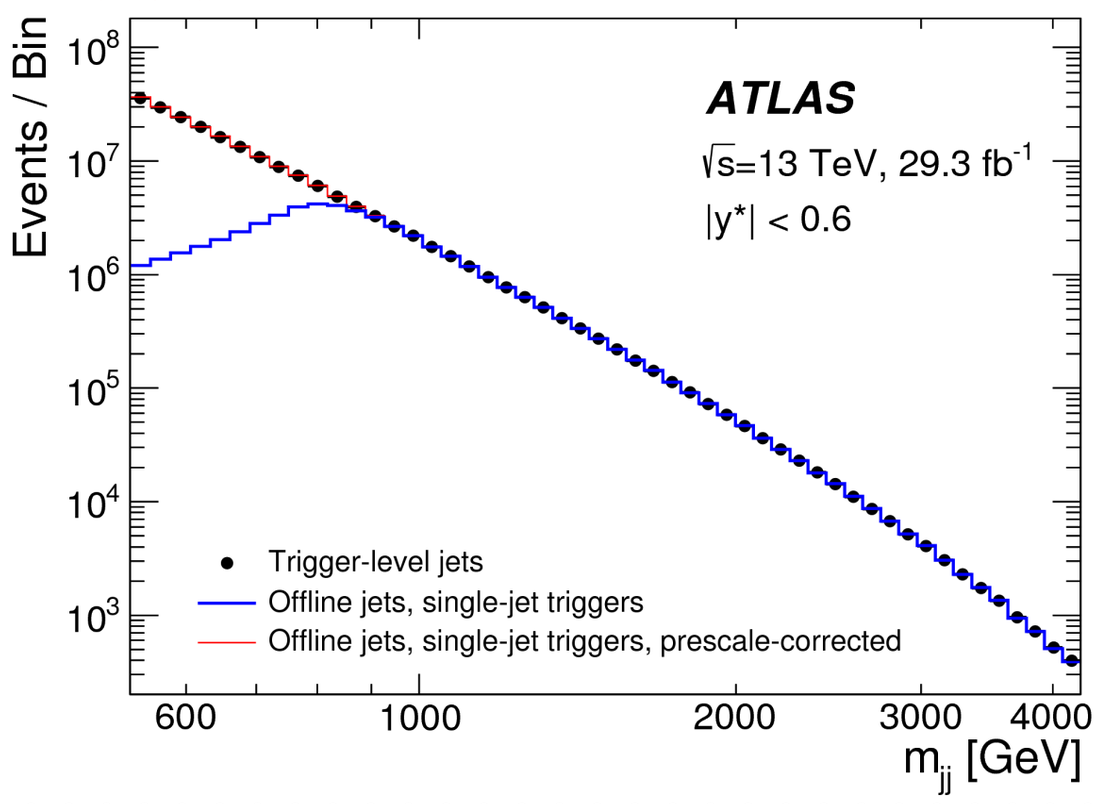
Phys. Rev. Lett. 121 (2018) 081801

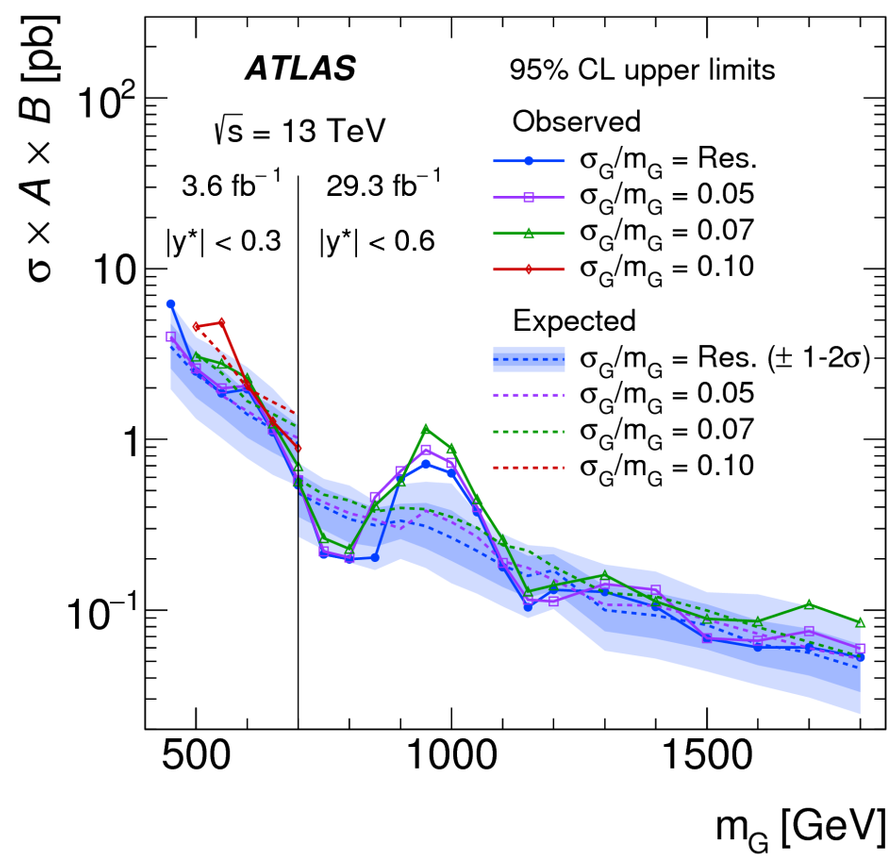
Use trigger level objects in a reduced event format (0.5%) allows to take data at much higher rates



- Require at least 2 jets with **jet pt** > 185 (220) GeV
- Look for excess in the $\mathbf{m_{jj}}$ distribution
- Sensitive in the mass region between 450 and 1800 GeV

Challenge: Calibrate HLT jets!





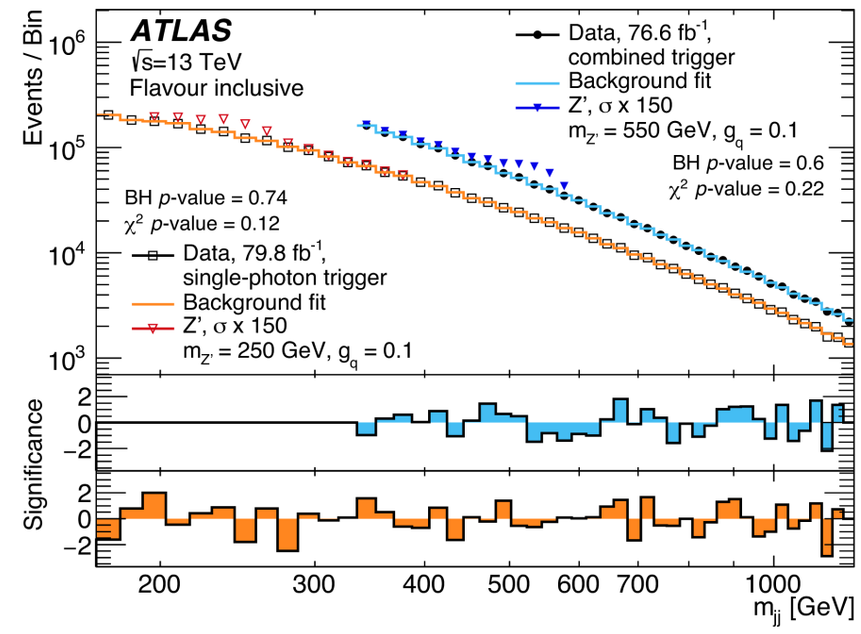
Exploring lower mass range - ISR

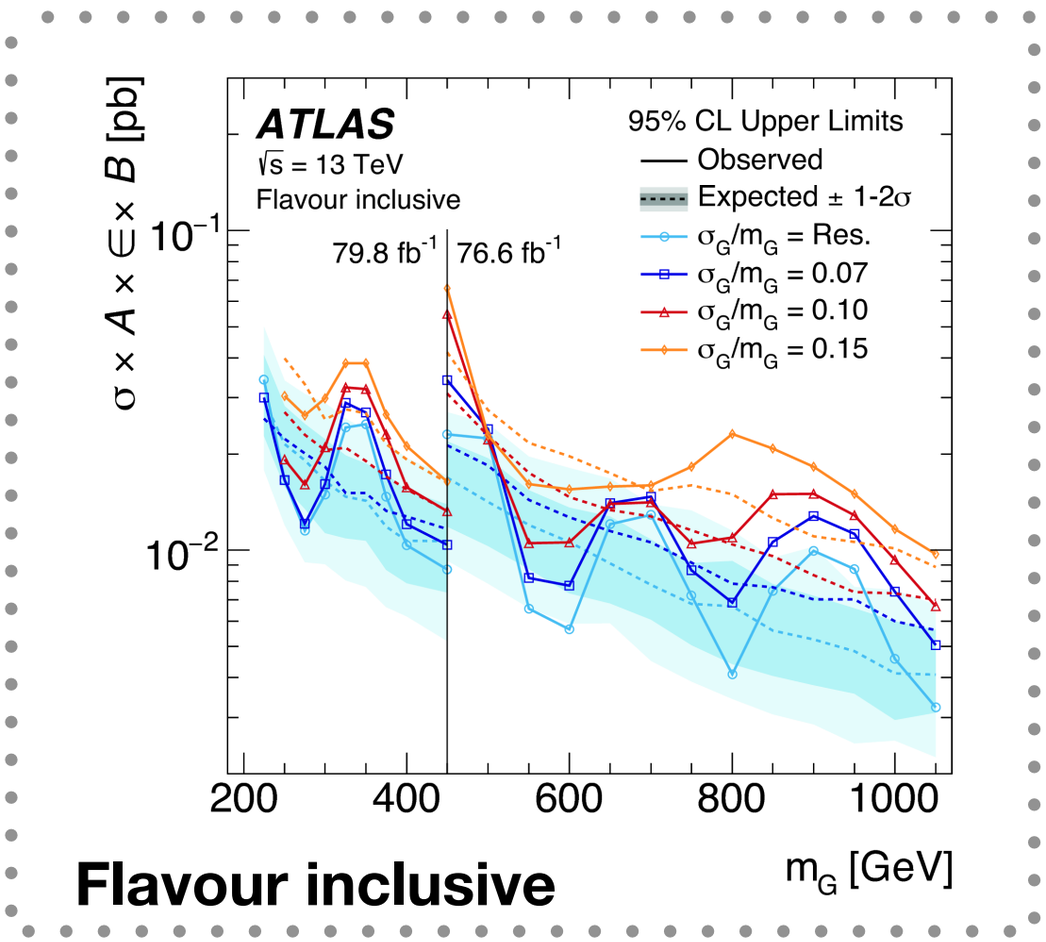
Phys. Lett. B 795 (2019) 56

Requires **additional photon** radiated off one colliding parton

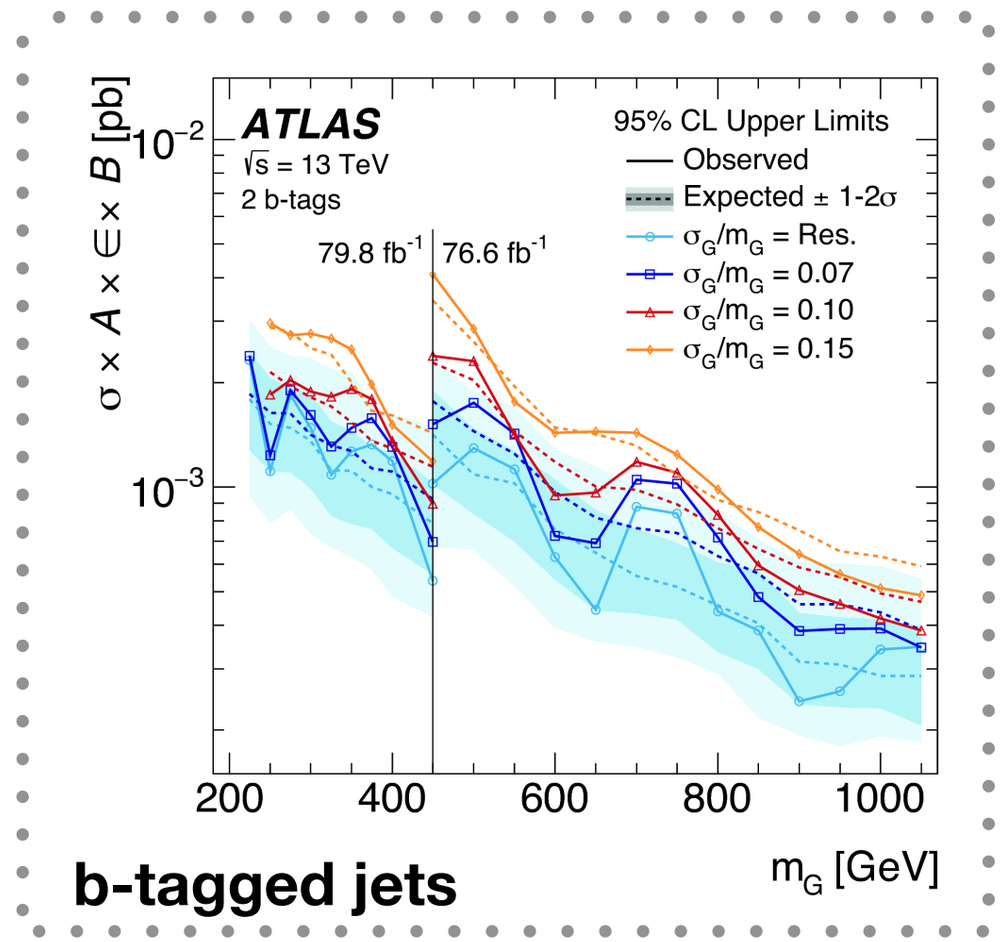
Combined trigger requires
E^{γ}_{T}>95 GeV and jet pt > 25 GeV

Single photon trig requires
E^{γ}_{T} > 150 GeV





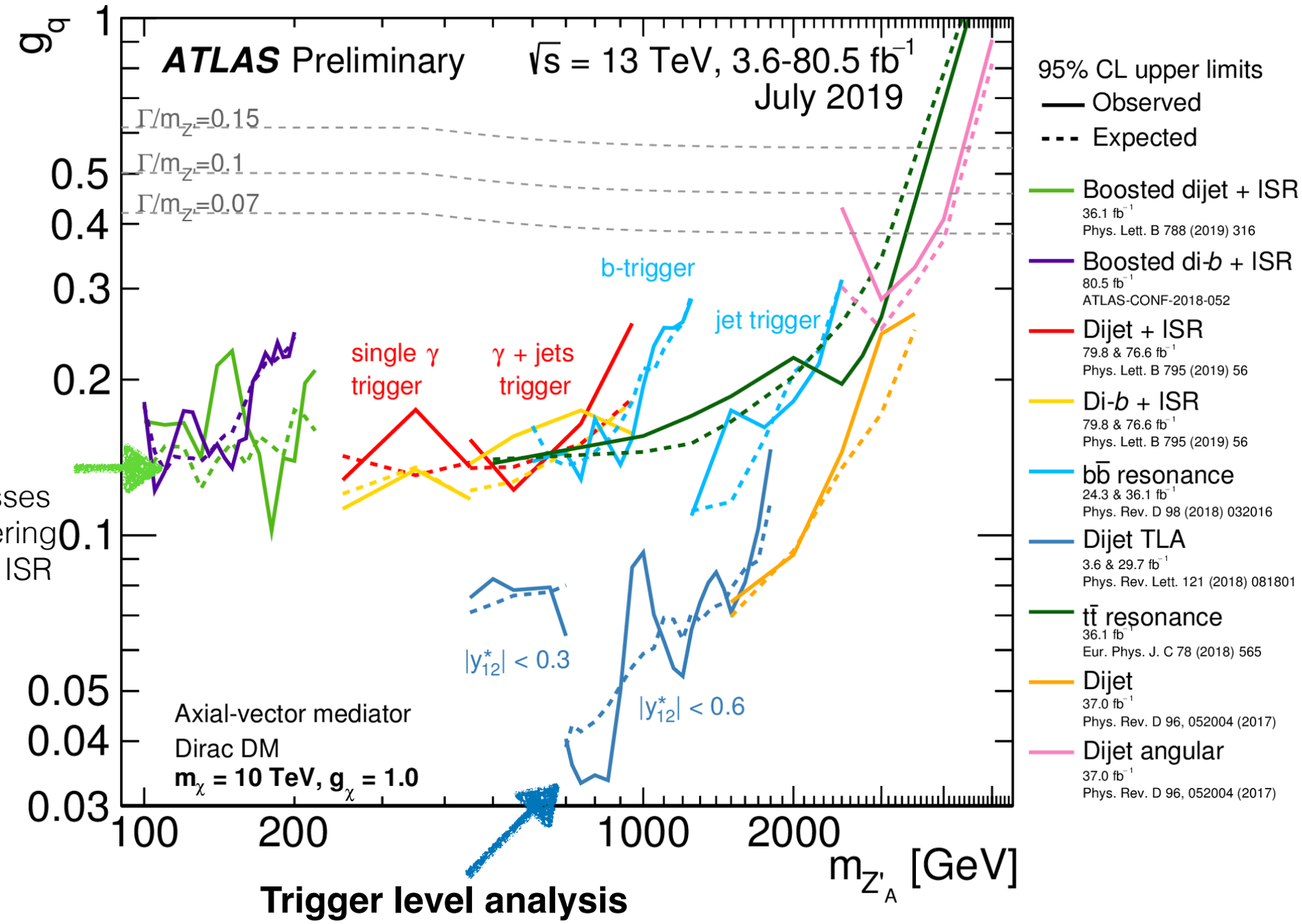
Flavour inclusive



b-tagged jets

Resonant searches summary

JHEP 05 (2019) 142



Dijet + ISR
Sensitivity at low masses enhanced by considering boosted jets/jets and ISR

Trigger level analysis
Partially stored events to increase bandwidth

Great complementarily among resonant searches from 100 GeV to 2.5 TeV
Constraints on the width of the resonance affect the exclusion limits

Resonant searches summary

JHEP 05 (2019) 142

More details in Trine's presentation at ICNFP:

Searches for resonances in hadronic final states with the ATLAS detector

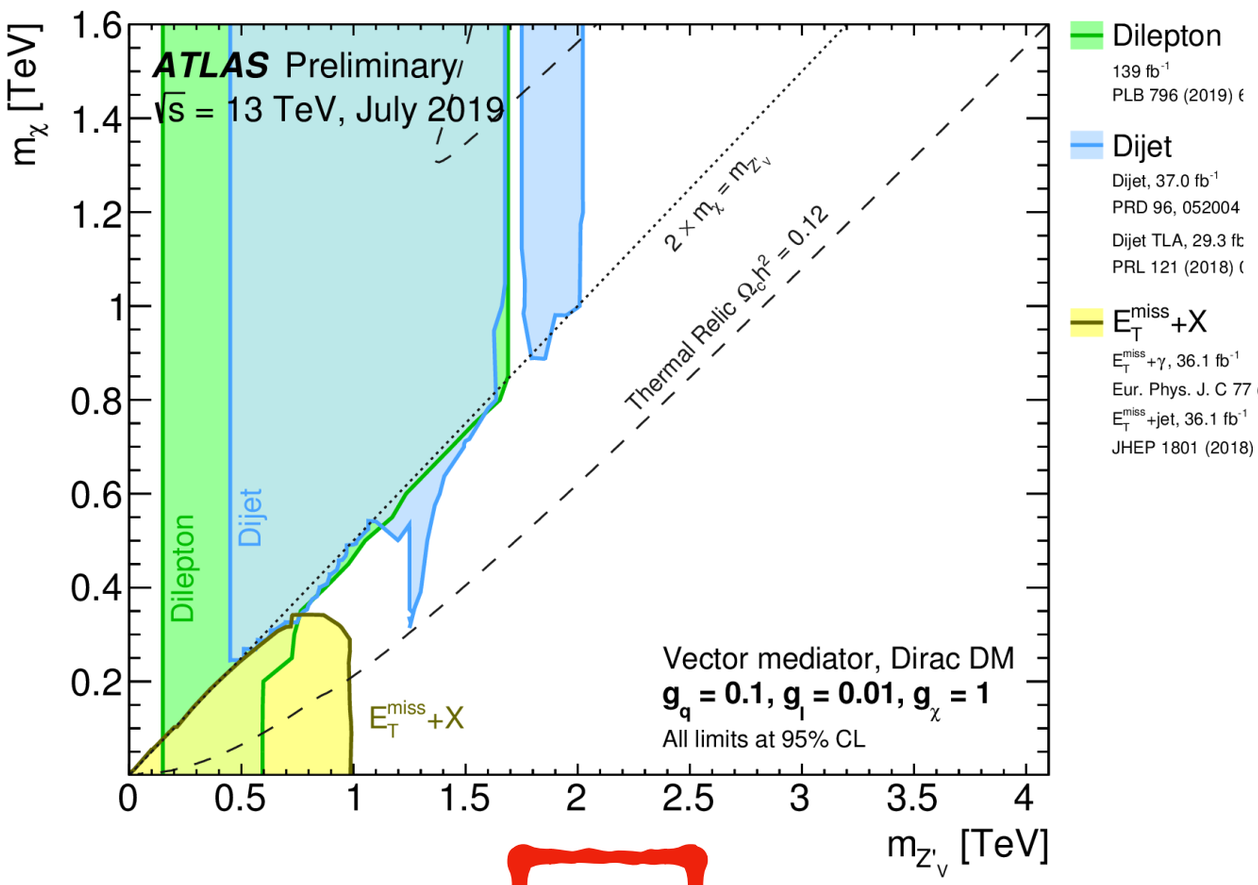
Great complementarily among resonant searches from 100 GeV to 2.5 TeV
Constraints on the width of the resonance affect the exclusion limits

Vector/Axial Vector mediator results

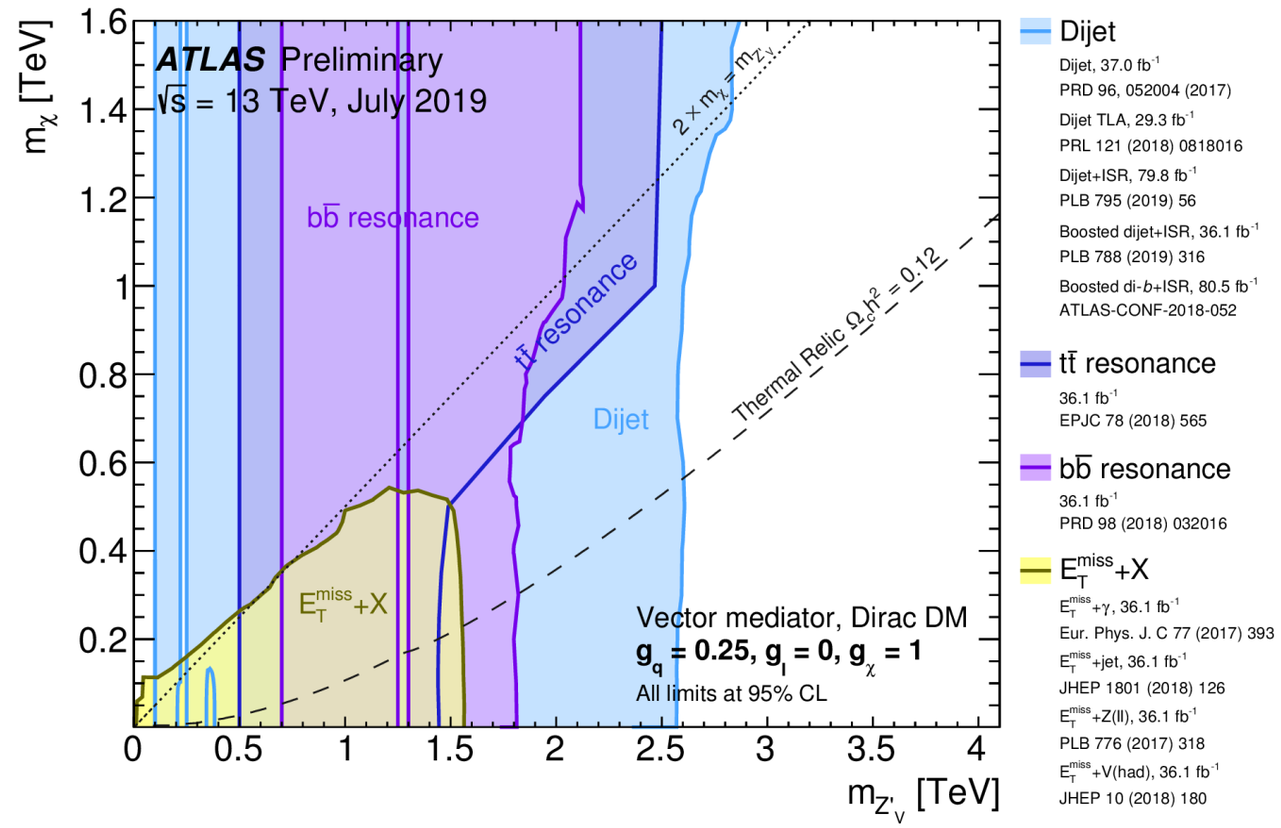
JHEP 05 (2019) 142

Resonant searches dominate the exclusion plots due to relatively high coupling to quarks

MET+X analyses sensitive up to 1.5 TeV, on shell



	V1	V2	A1	A2
g_q	0.25	0.1	0.25	0.1
g_ℓ	0	0.01	0	0.1
g_χ	1	1	1	1



	V1	V2	A1	A2
g_q	0.25	0.1	0.25	0.1
g_ℓ	0	0.01	0	0.1
g_χ	1	1	1	1

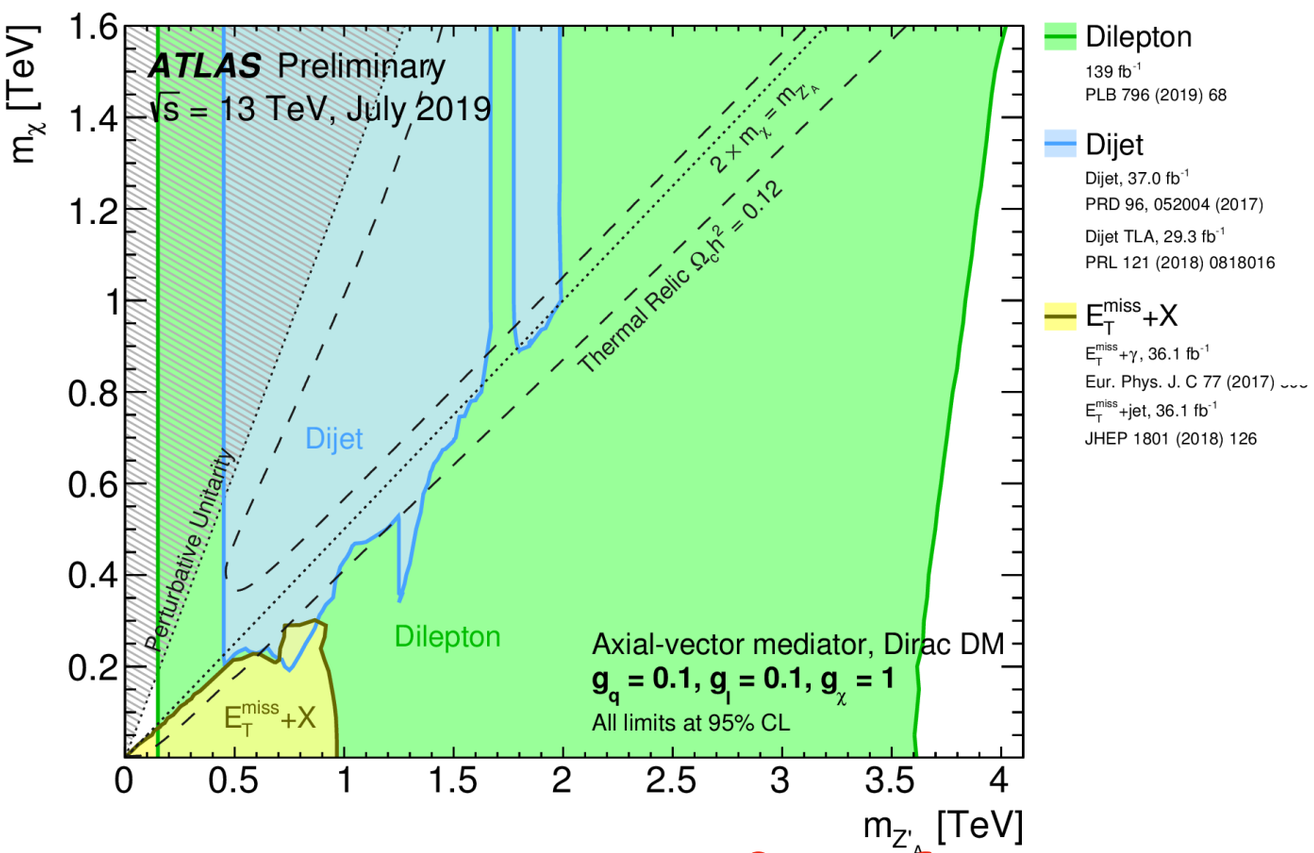
Resonant searches exclude from 150 GeV to 3.5 TeV, complemented at low mass by MET+X

Vector/Axial Vector mediator results

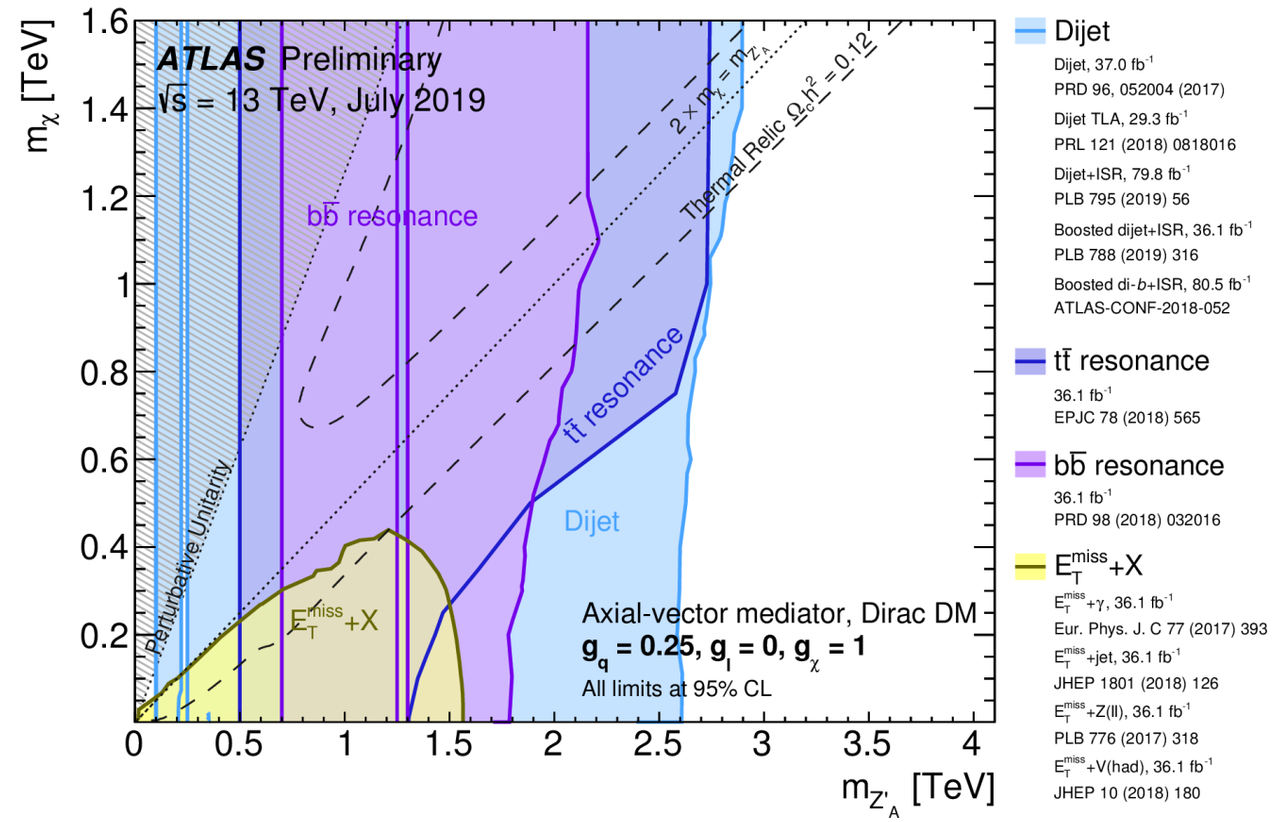
JHEP 05 (2019) 142

Resonant searches dominate the exclusion plots due to relatively high coupling to quarks

MET+X analyses sensitive up to 1.5 TeV, on shell



	V1	V2	A1	A2
g_q	0.25	0.1	0.25	0.1
g_ℓ	0	0.01	0	0.1
g_χ	1	1	1	1

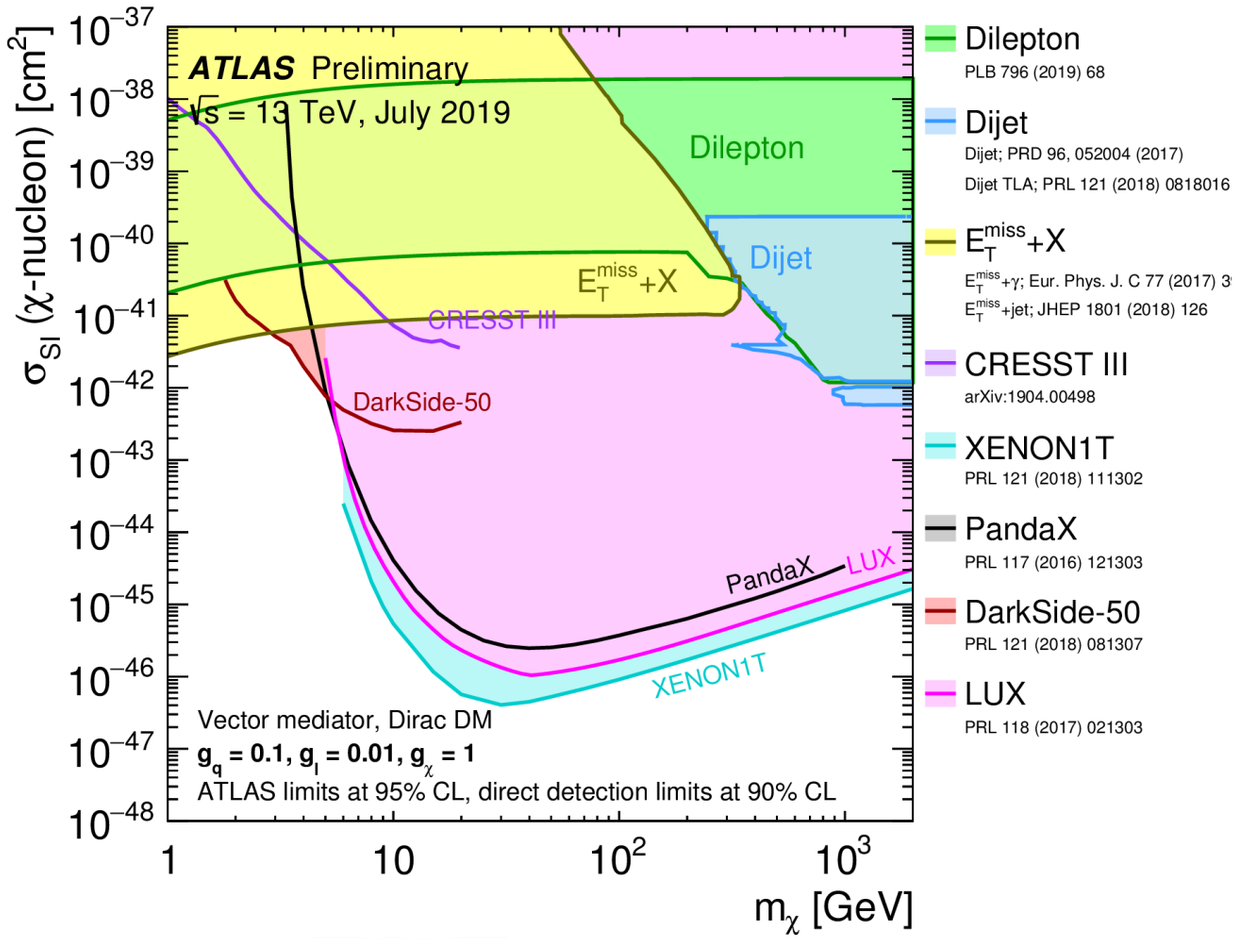


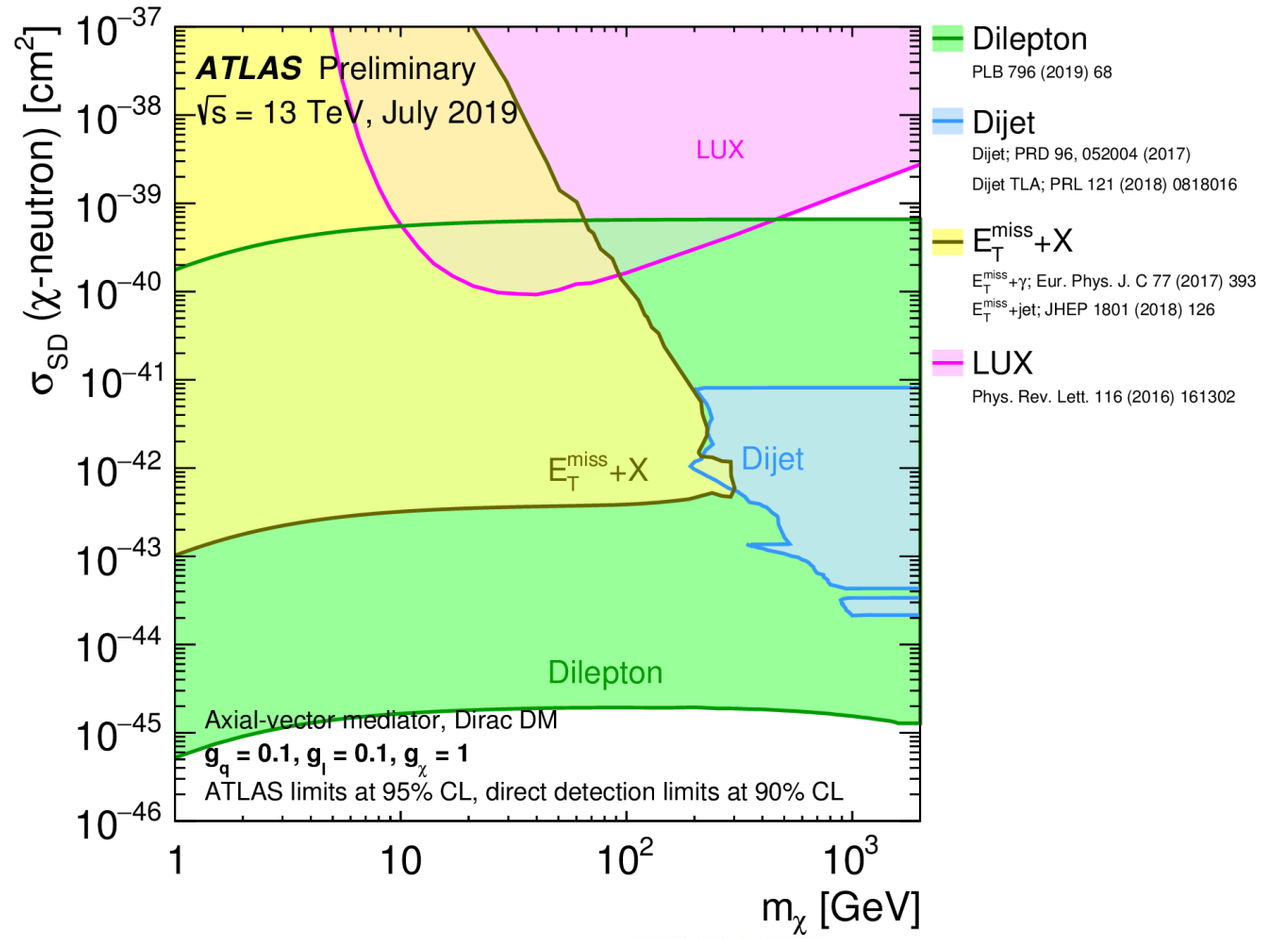
	V1	V2	A1	A2
g_q	0.25	0.1	0.25	0.1
g_ℓ	0	0.01	0	0.1
g_χ	1	1	1	1

Resonant searches exclude from 150 GeV to 3.5 TeV, complemented at low mass by MET+X

Vector/Axial Vector mediator results

JHEP 05 (2019) 142





	V1	V2	A1	A2
g_q	0.25	0.1	0.25	0.1
g_ℓ	0	0.01	0	0.1
g_χ	1	1	1	1

	V1	V2	A1	A2
g_q	0.25	0.1	0.25	0.1
g_ℓ	0	0.01	0	0.1
g_χ	1	1	1	1

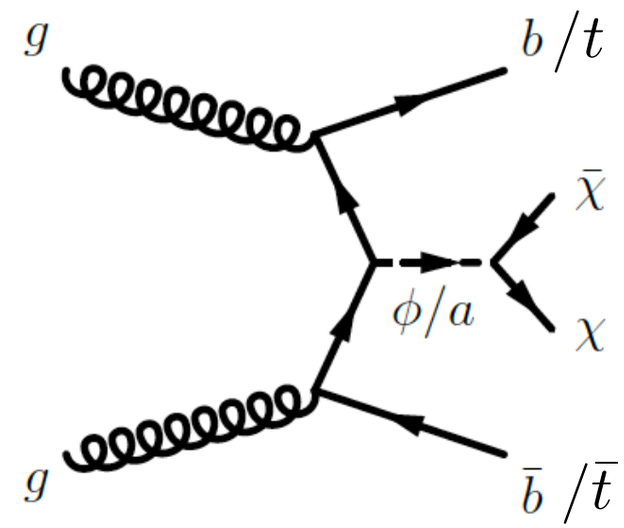
ATLAS limits are converted into spin dependent/independent χ-nucleon cross sections. Limits are at 95% CL, in the limit of validity of the model parameters

Scalar and pseudo scalar mediators

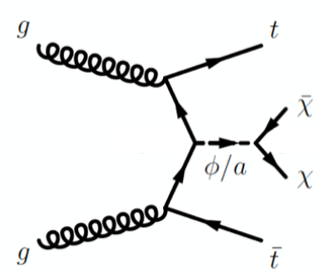
Eur. Phys. J. C 78 (2018) 18
JHEP 06 (2018) 108

Mediator particle couples to both **SM** and **DM** sectors:
-) spin 0 scalar or pseudoscalar color neutral

Yukawa-like couplings between DM and SM sectors, enhanced cross section for tops and bottoms



2 Leptons final state:



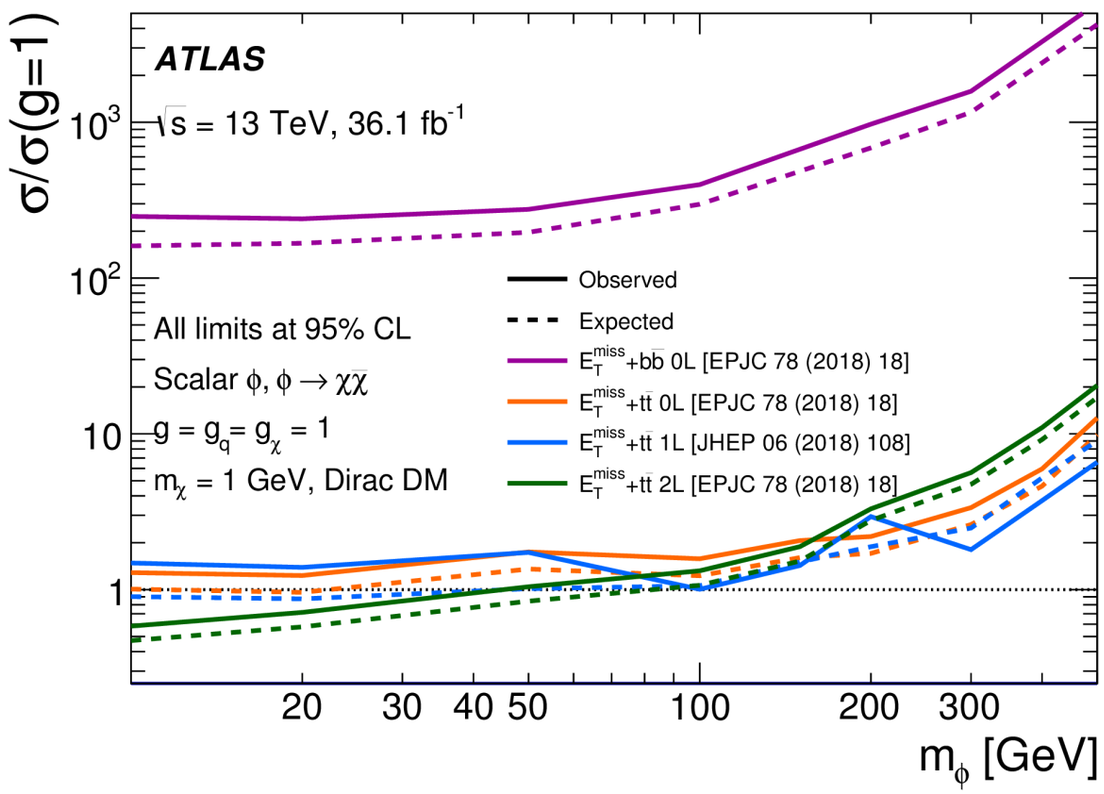
Analysis strategy: 1 SR
Major backgrounds: fake and non prompt leptons,
top pairs, ttZ (vv)
Main discr. variables: stranverse invariant mass (m_{T2}) and $E_{\mathrm{T}}^{\mathrm{miss}}$

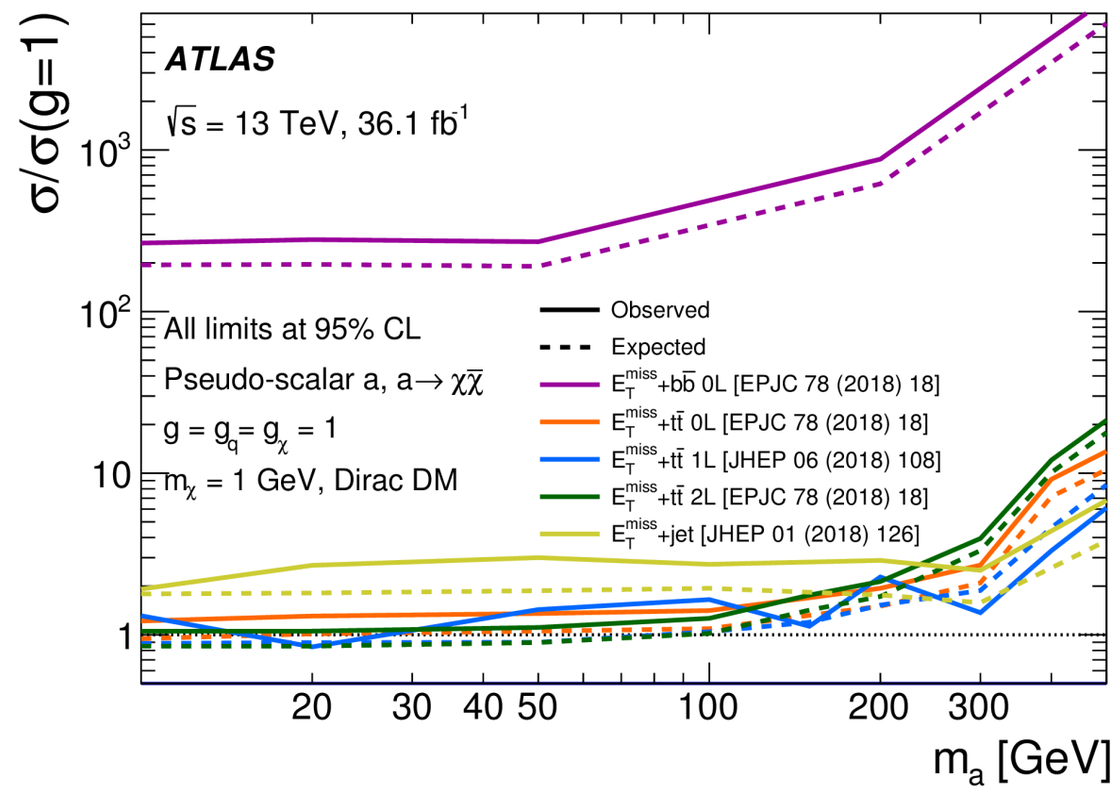
0 Leptons final state:

Analysis strategy: 2 SRs
Major backgrounds: Z+jets, top pairs, ttZ (vv)
Main discr. variables:
Large *R* jet masses, transverse invariant masses and $E_{\mathrm{T}}^{\mathrm{miss}}$

Scalar/Pseudo scalar mediator results

Eur. Phys. J. C 78 (2018) 18





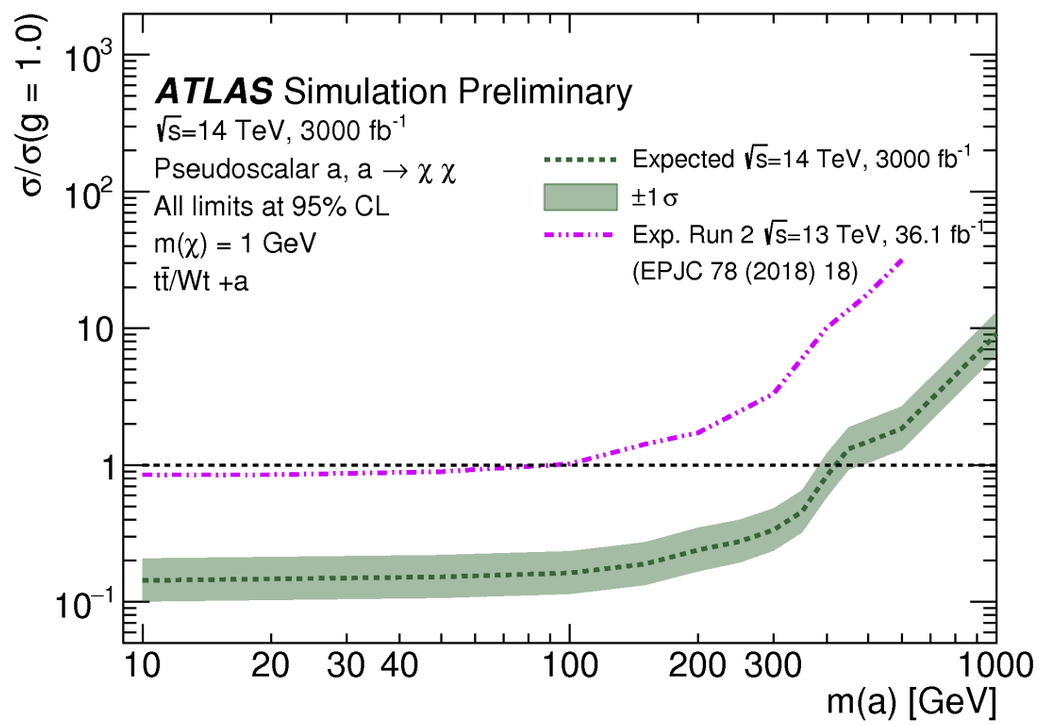
Scalar/pseudo scalar limits provided by MET+tt/bb analyses.

Fully leptonic channel excludes mediator mass up to 45 GeV in the scalar case, while mediator in the range 15-25 GeV are excluded in the pseudo scalar one. Results do not depend on the DM mass, as long as the DM is on-shell

Scalar/Pseudo scalar mediator results

Estimated sensitivity with 3000 fb-1 at 14 TeV

ATL-PHYS-PUB-2018-036



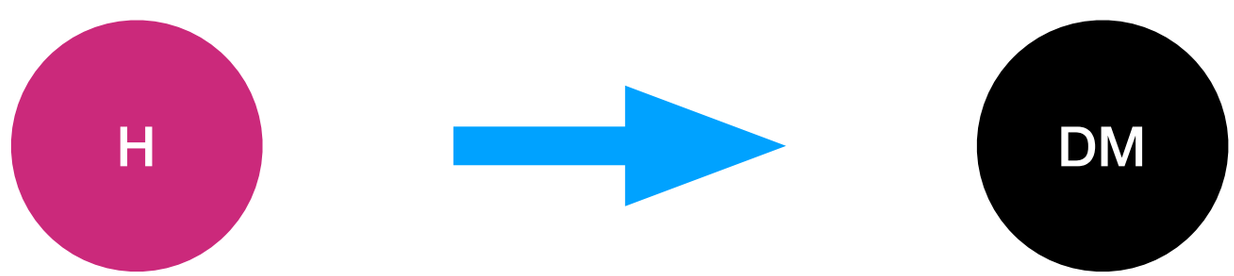
In comparison to results obtained with 36 fb−1 in Run 2, the exclusion potential at the HL–LHC is found to improve **by a factor of ~3–8.7**

Results do not depend on the DM mass, as long as the DM is on-shell

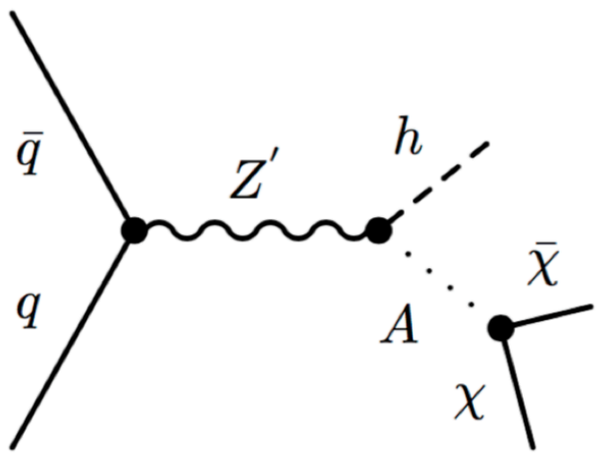
Higgs boson as a probe

Mediator coupling to Higgs, SM and Dark Sector

Yukawa coupling to Dark Sector



2HDM+Z', towards less simple models



Extension of type-II 2HDM

Z' decays to a Higgs boson h and pseudoscalar **A** of a 2HDM (**A->χχ**)

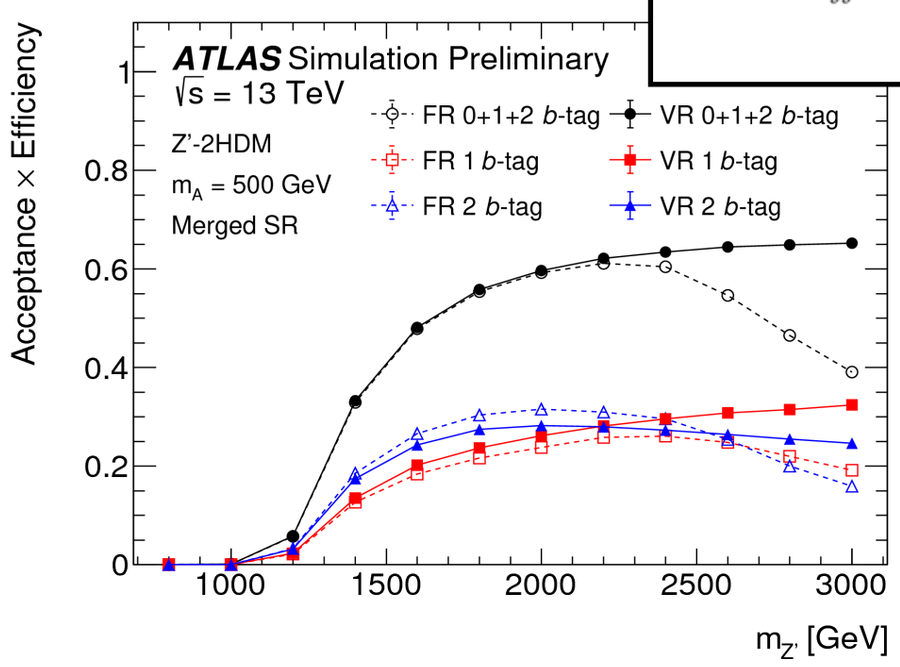
A couples to both SM and DM sectors

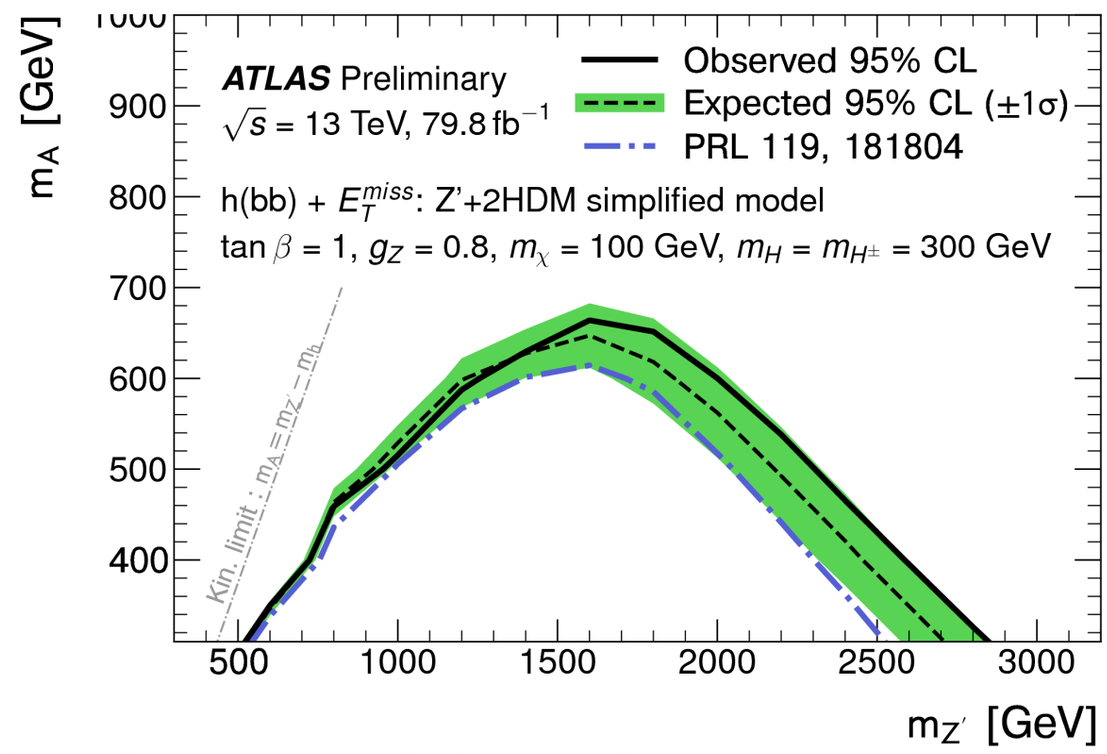
5 free parameters: **m(Z'), tanβ, m(χ), m(H±)**

H-> bb signature:

- Targeting final state with jet activity and missing transverse energy.
- Use of variable radius jet to improve efficiency for boosted Higgs.
- Fit of **m_{jj}** distribution

$$R \rightarrow R_{eff}(p_T) = \frac{\rho}{p_T}$$



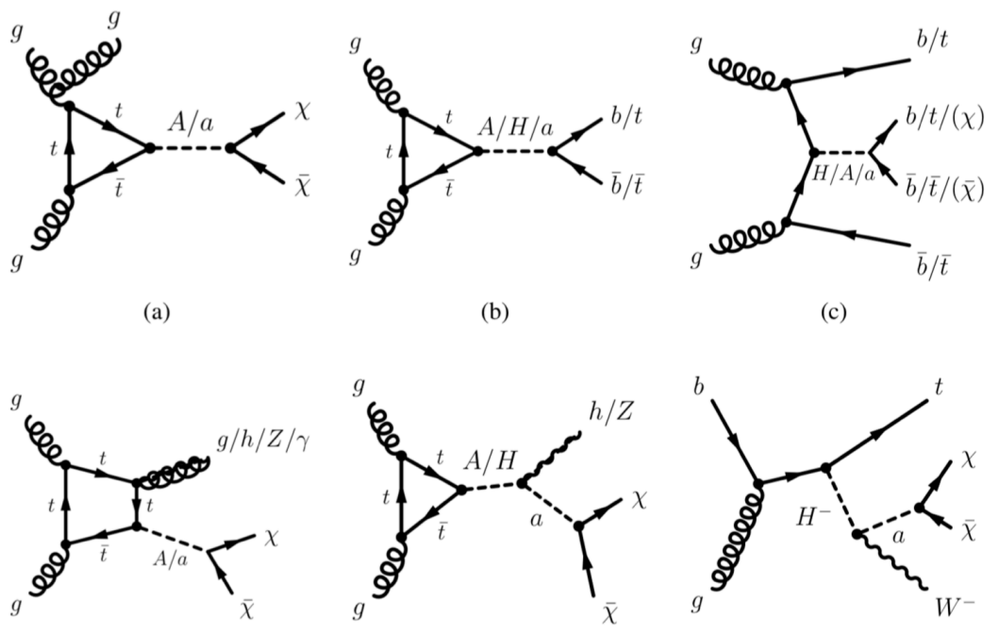


low Z' masses excluded by H->γγ

ATL-CONF-2018-051

2HDM+a, towards less simple models

JHEP 05 (2019) 142



Particle content:
- CP even: h, H
- CP odd: A, a
- Charged: $H^{\pm}$
- Dirac DM: χ

Extension of type-II 2HDM

Pseudoscalar mediator *a* couples DM to SM and mixes with heavy pseudoscalar A of 2HDM.

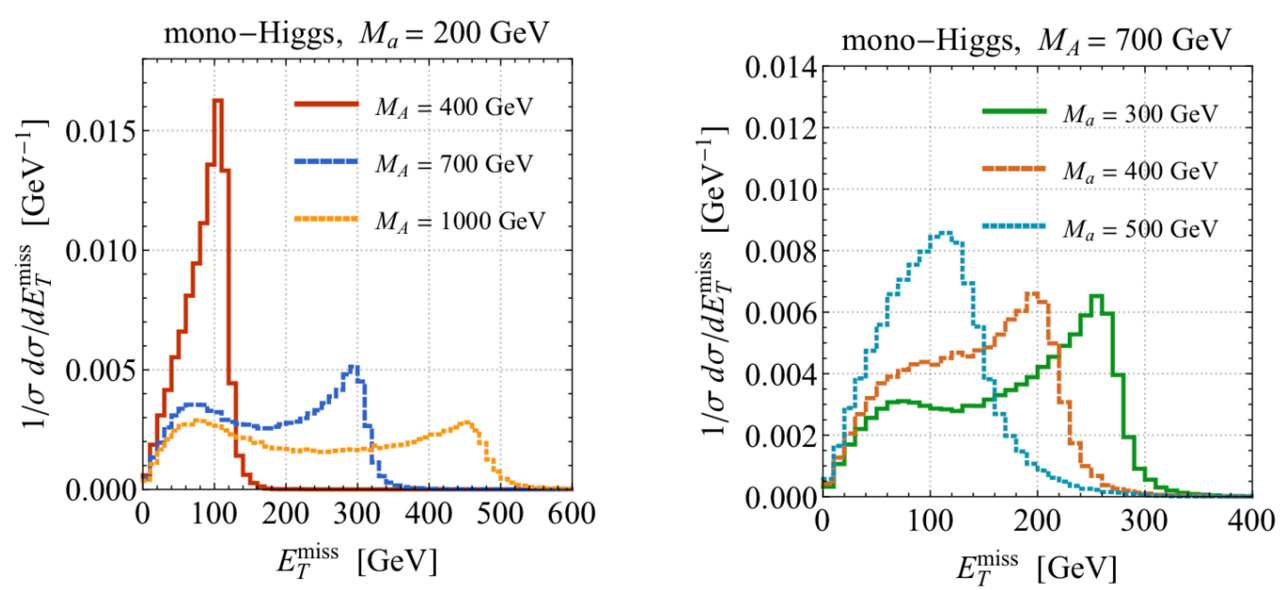
14 parameters, most of them constraint by precision Higgs boson measurements:

mA : mass of pseudo scalar A
ma: mass of mediator a
sinθ: mixing angle between a and A
tanß: ratio of VEVs of the two Higgs doublets

Very rich phenomenology of signatures

Different choice of model parameters results in different kinematics

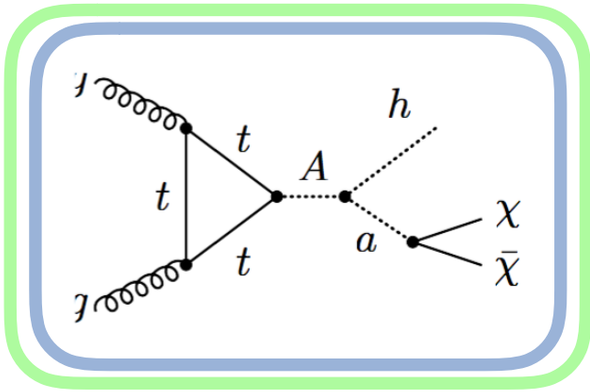
Simplified model, but UV-complete

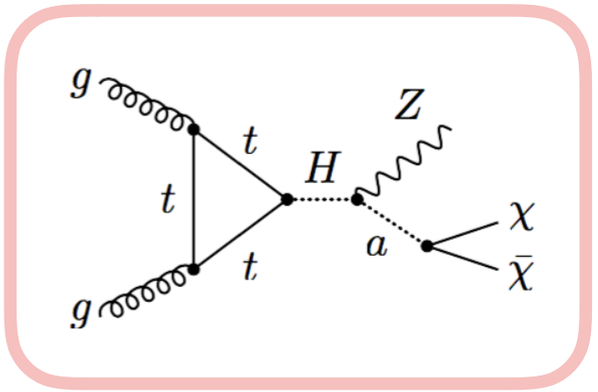


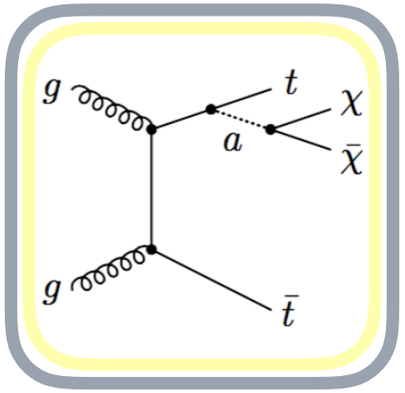
arXiv:1810.09420

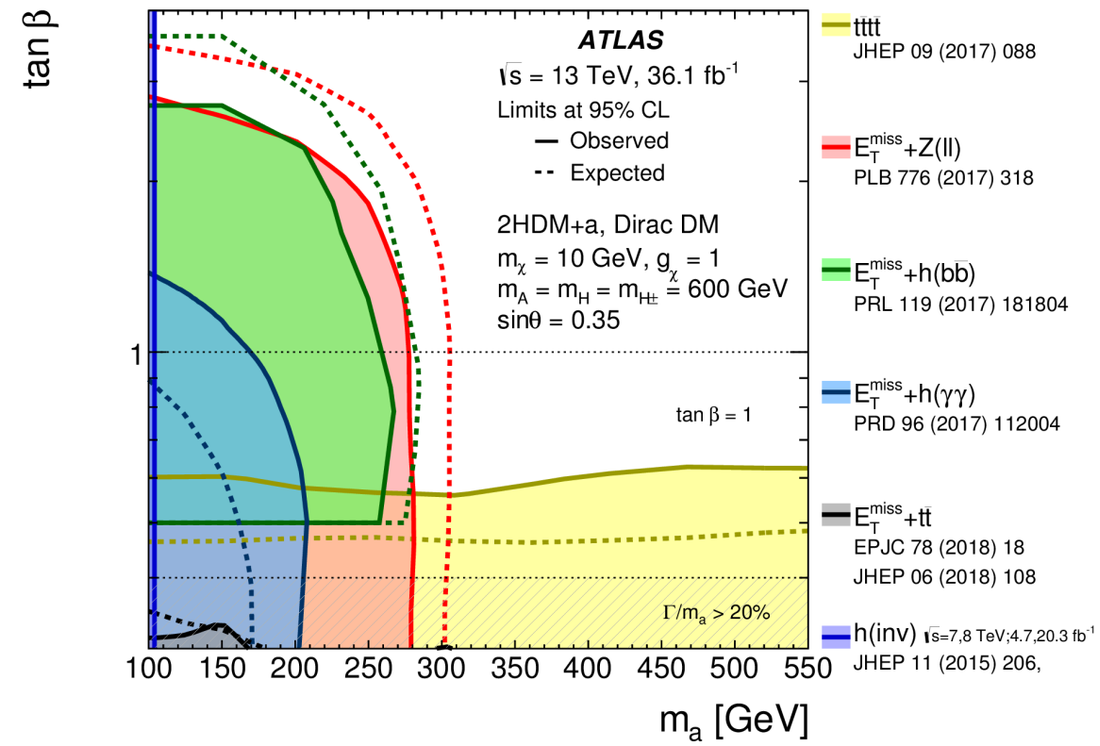
2HDM+a, towards less simple models

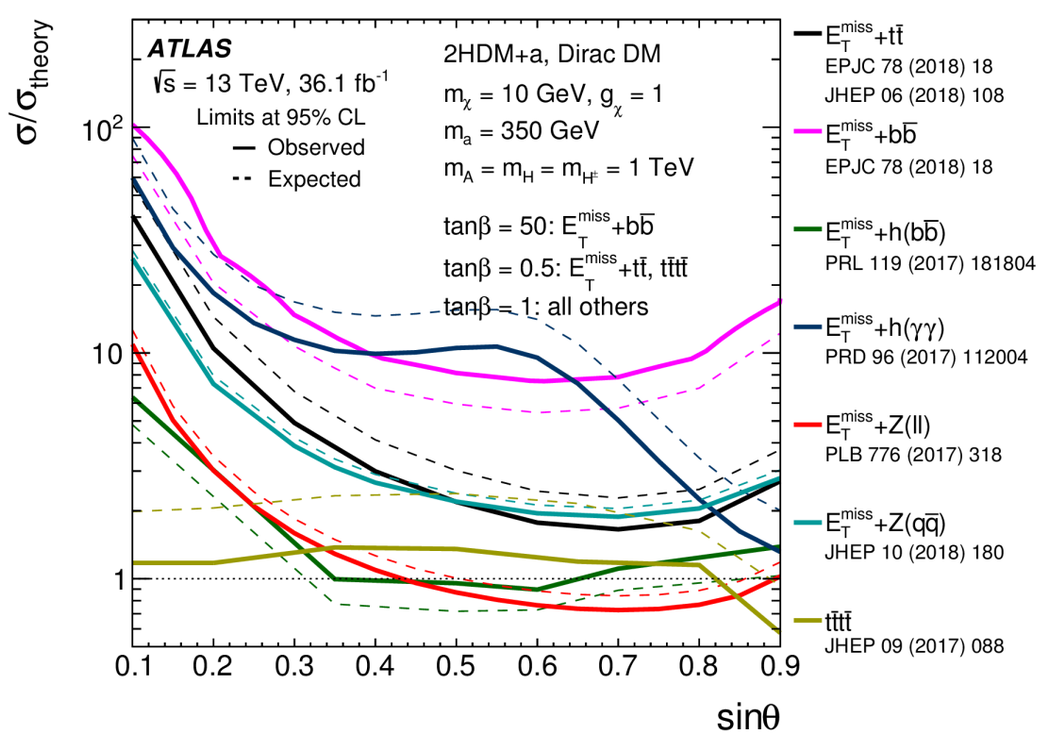
JHEP 05 (2019) 142

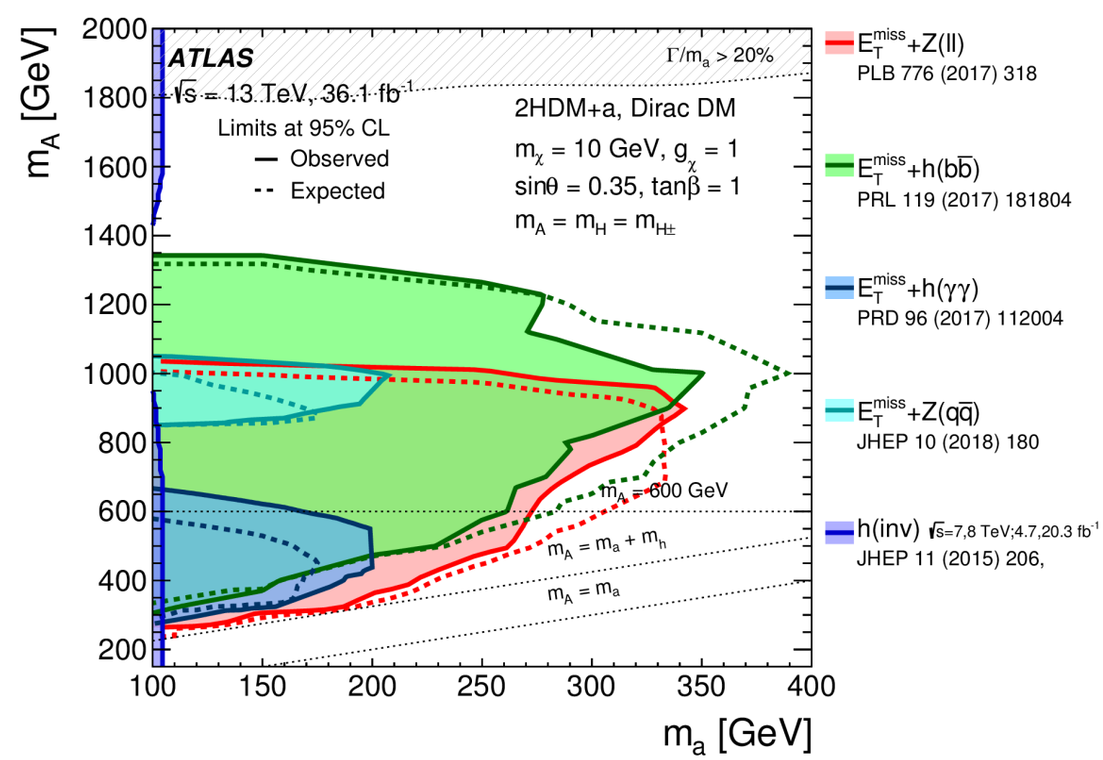






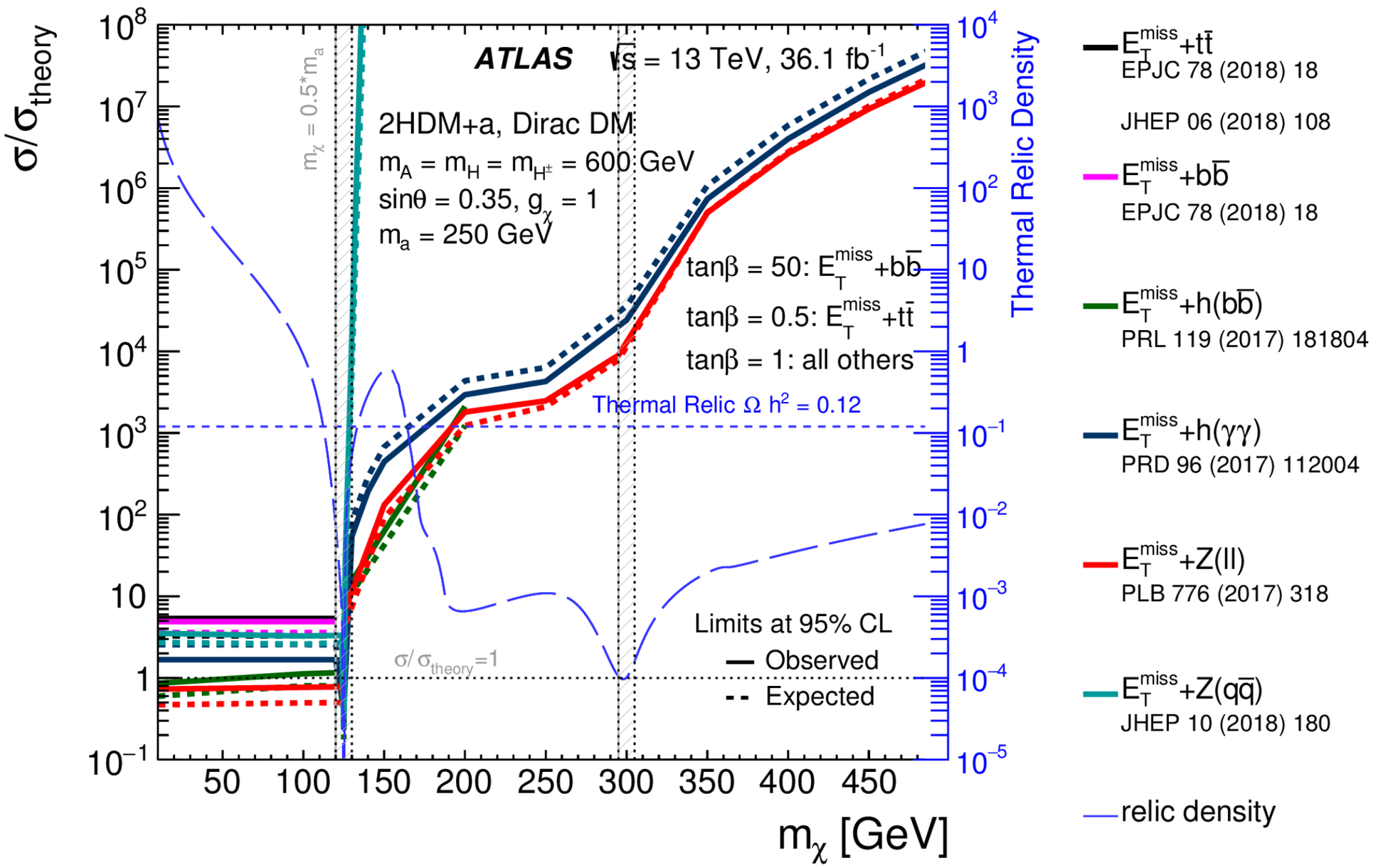






2HDM+a results

JHEP 05 (2019) 142

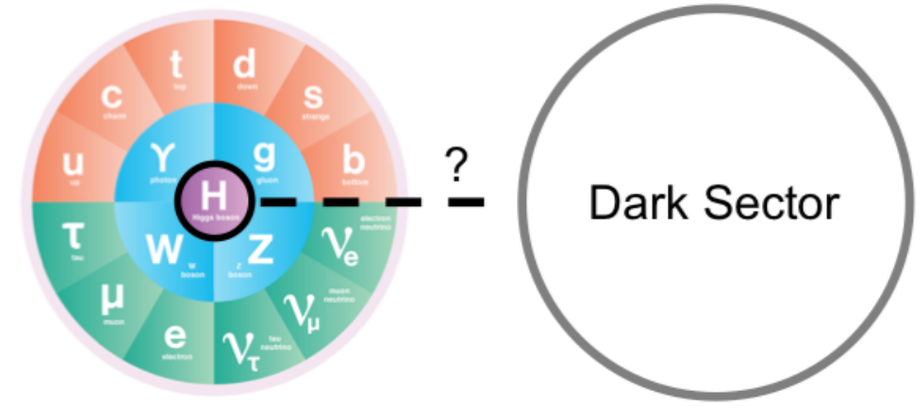


Higgs to invisible

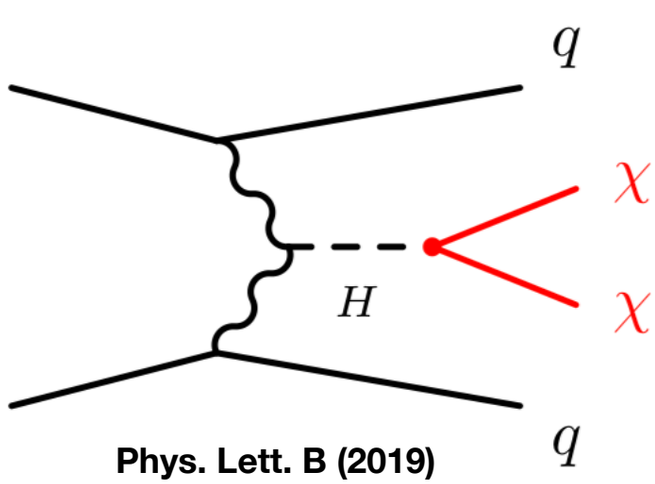
Phys. Rev. Lett. 122 (2019)

Higgs boson coupling to Dark Matter particles

SM contribution to **H -> inv** from
H -> ZZ* -> 4ν (~10^{-3})

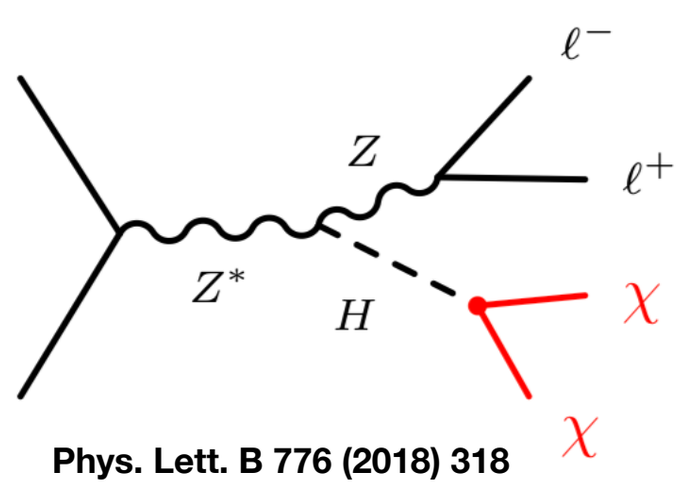


Vector-Boson-Fusion



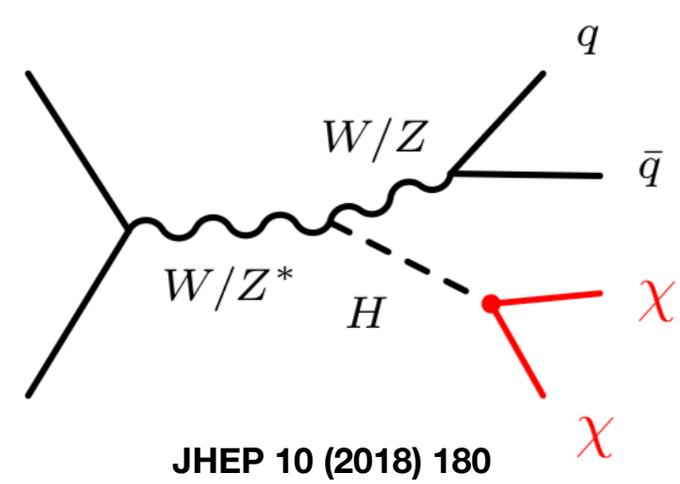
Phys. Lett. B (2019)

Z(->leptons)H



Phys. Lett. B 776 (2018) 318

V(->hadrons)H



JHEP 10 (2018) 180

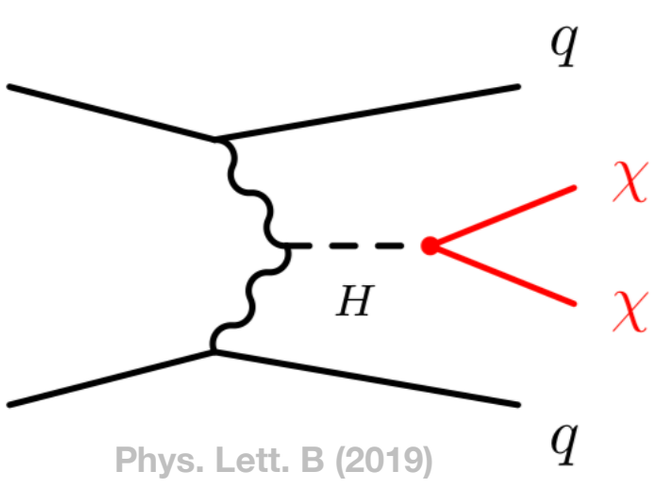
Higgs to invisible

Phys. Rev. Lett. 122 (2019)

Higgs boson coupling to Dark Matter particles

SM contribution to **H -> inv** from
H -> ZZ* -> 4ν (~10^{-3})

Vector-Boson-Fusion

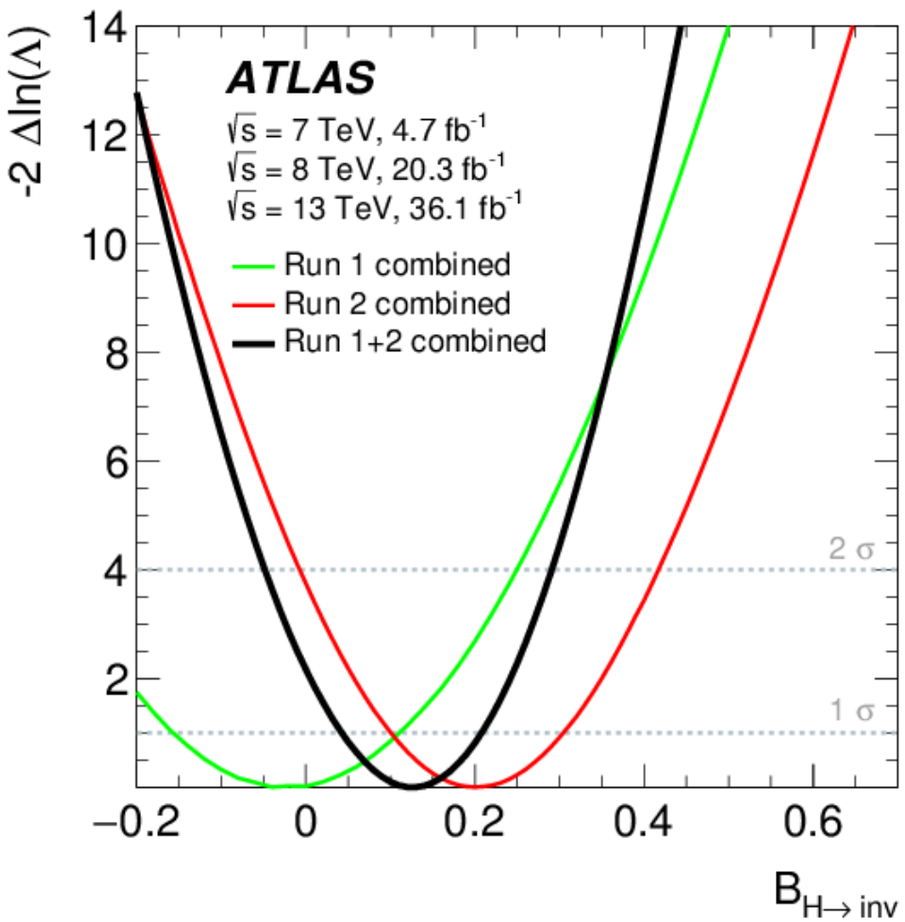


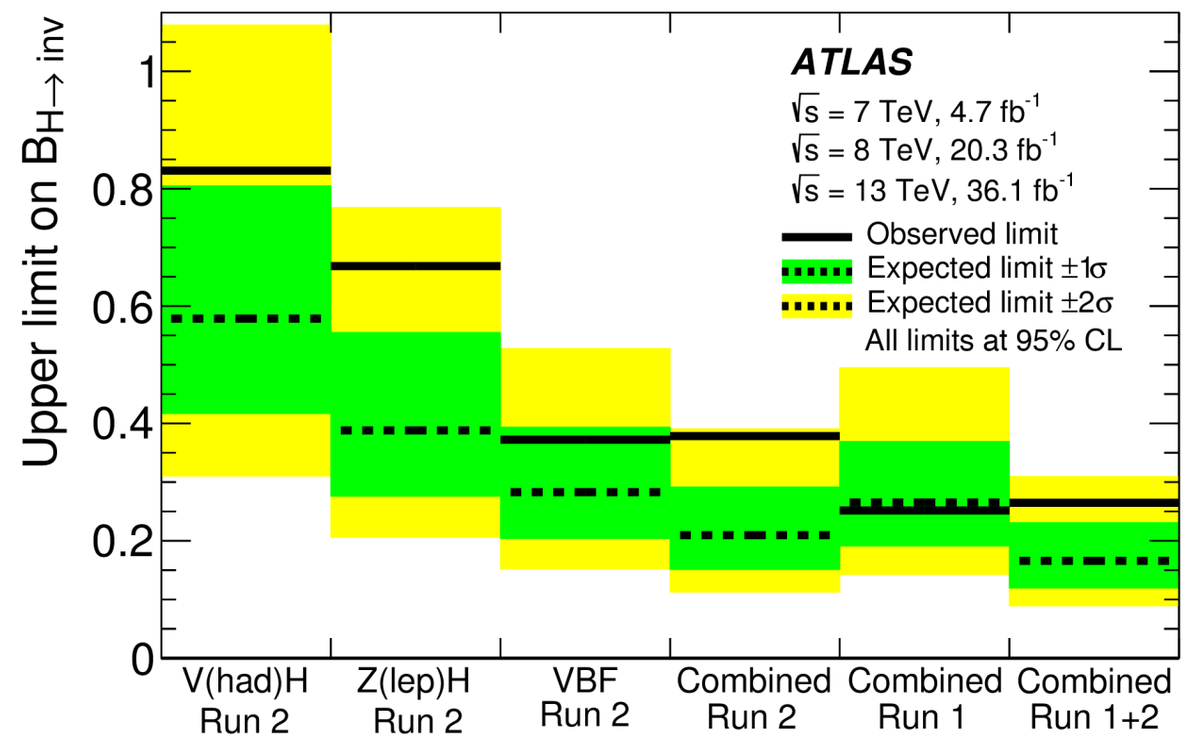
Phys. Lett. B (2019)

- Targeting a final state with 2 jets having $\mathbf{m_{jj}}$ >1TeV, no muons/electrons and missing transverse energy > 180 GeV
- Limited by MC statistics, jet energy scale and V+jets modelling

Higgs to invisible

Phys. Rev. Lett. 122 (2019)

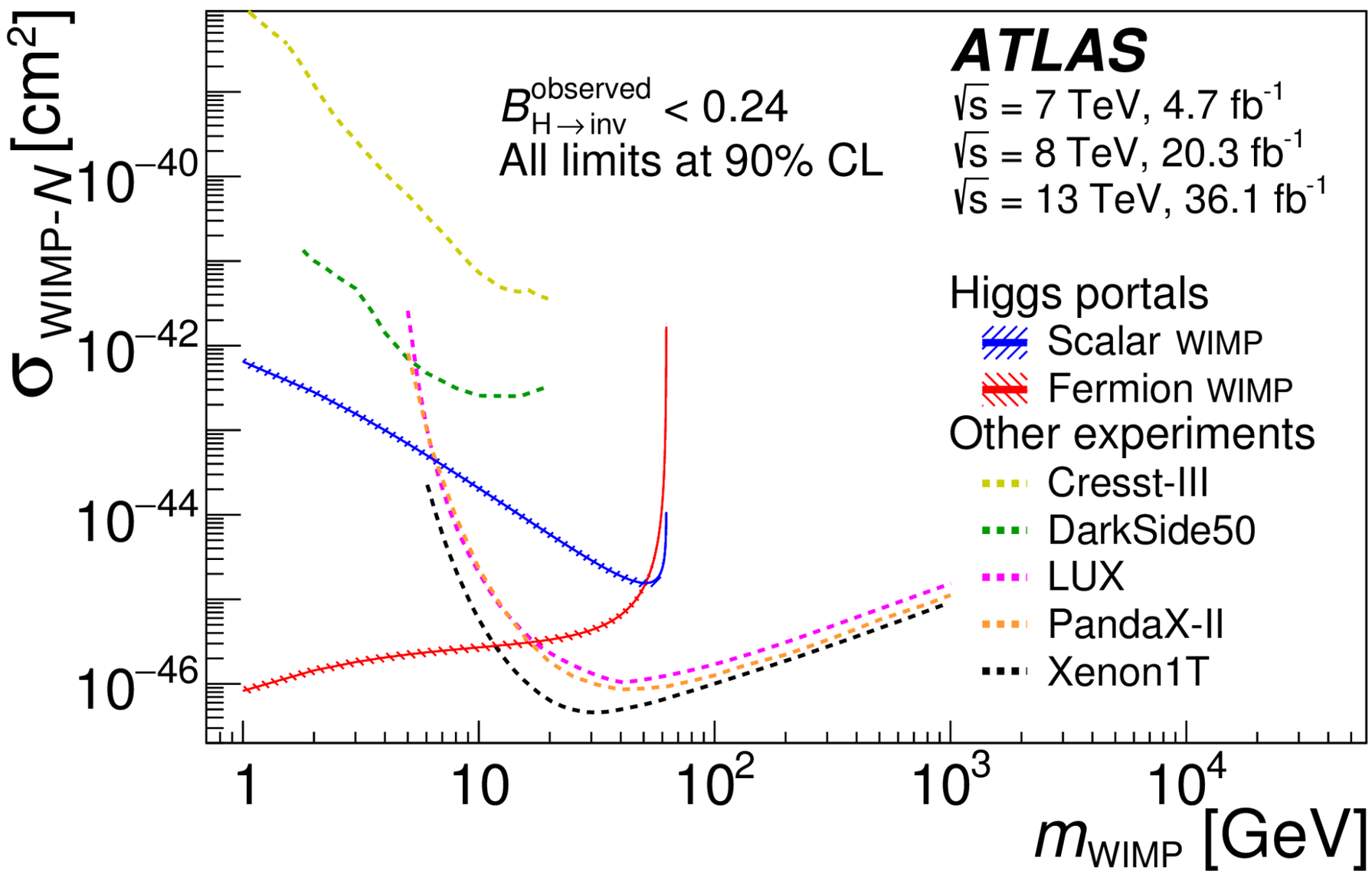




$$\mathcal{B}_{H\to\mathrm{inv}} < 0.26\ (0.17^{+0.07}_{-0.05})$$

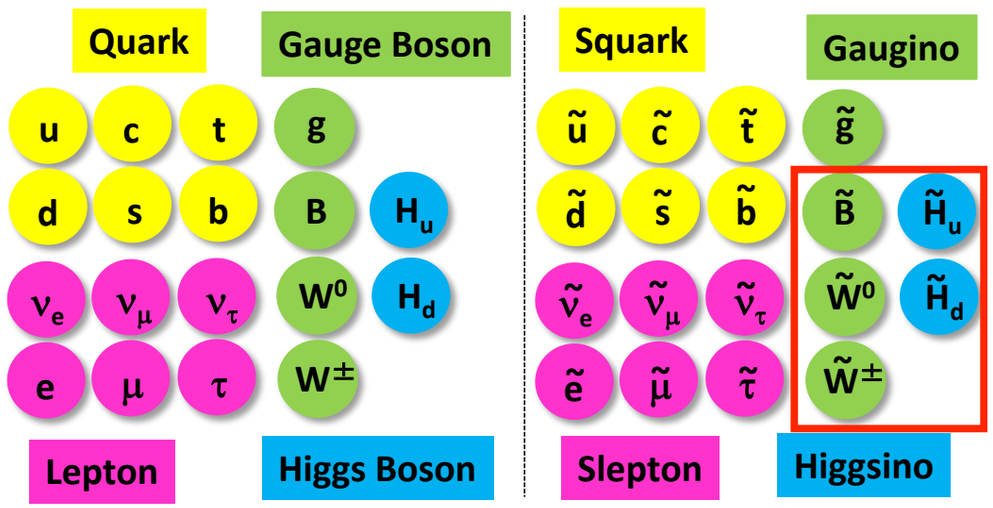
Higgs to invisible

Phys. Rev. Lett. 122 (2019)



SUSY models

Possible SM extension based on a *broken Symmetry* between bosons and fermions: each SM particle has a supersymmetric partner differing by 1/2 spin

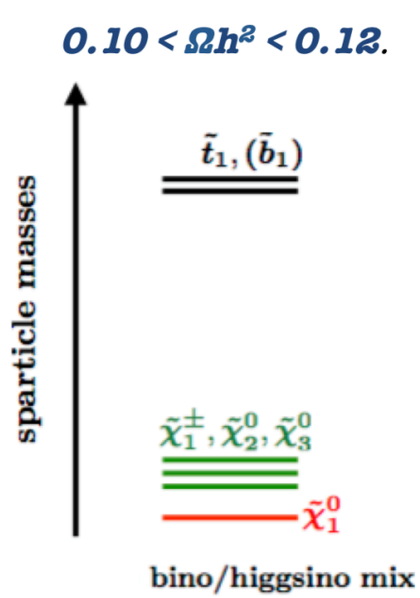


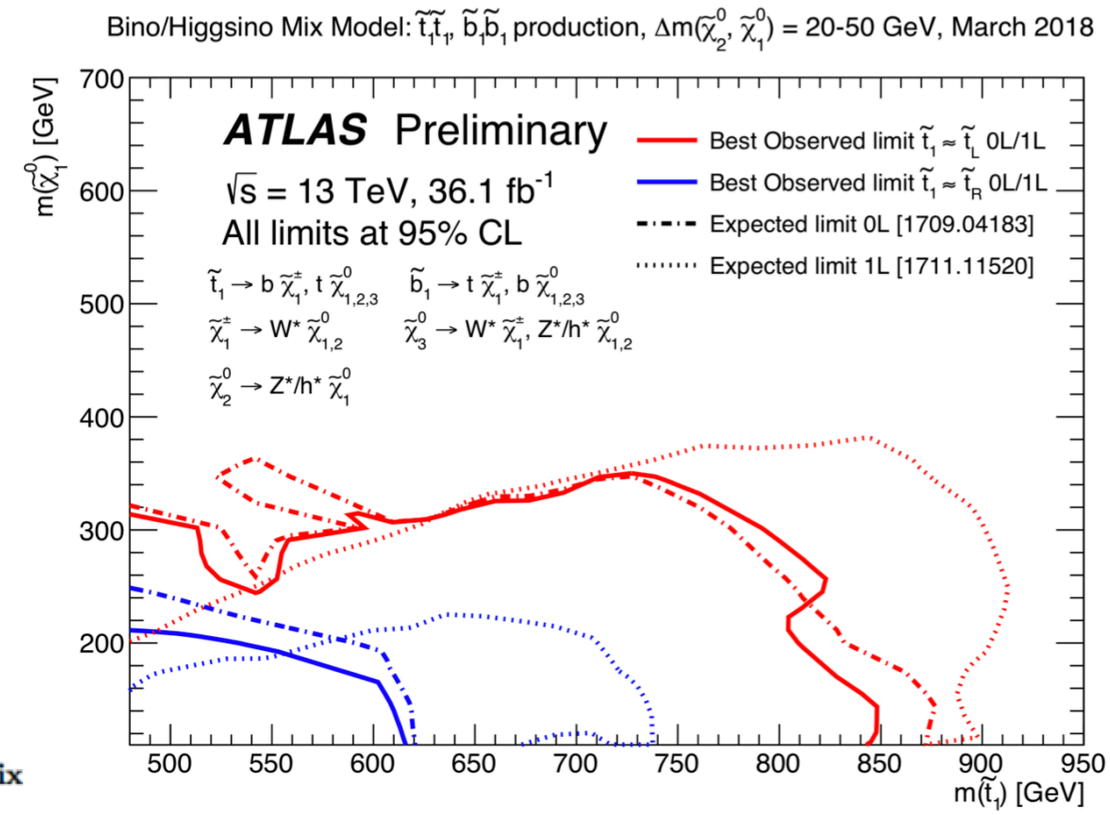
Could provide explanations to:

- Naturalness
- Gauge coupling unification
- Dark matter

SUSY models can provide relic densities consistent with measurements:

- Pure higgsino obtains relic density for masses 1TeV.
- Pure wino obtains right relic density for masses 2.5 TeV
- Bino/higgsino mix mode may satisfy the SM higgs mass and the DM relic density





SUSY models

Possible SM extension based on a *broken Symmetry* between bosons and fermions: each SM particle has a supersymmetric partner differing by 1/2 spin

Don't miss the ATLAS SUSY most recent results at ICNFP:

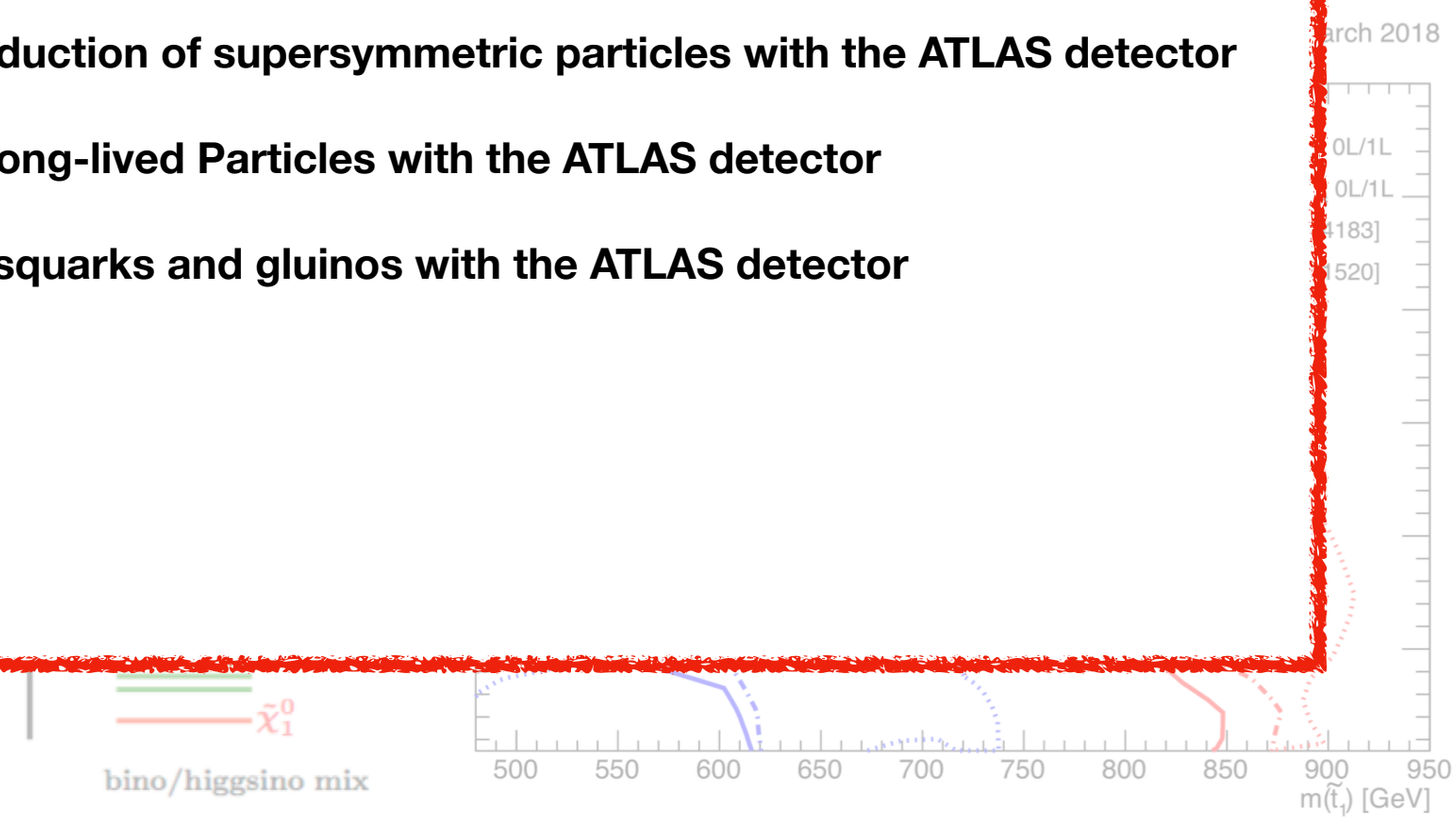
Searches for electroweak production of supersymmetric particles with the ATLAS detector

Search for Long-lived Particles with the ATLAS detector

Searches for squarks and gluinos with the ATLAS detector

SUSY
relic
wi

- Pu
  d
- Pu
  de
- Bin
  satisfy the SM higgs mass and the DM relic density



Conclusions

Dark matter searches at colliders are well motivated from the physics point of view and are becoming recently more and more popular

A common effort has been undertaken by both the ATLAS and CMS Collaborations and theoreticians

Effective field theories left the floor to Simplified Model in Run-II and we are now considering more complex models for future

Many complementary scenarios are being investigated; looking everywhere!

No excesses have been found so far