



Dark Matter searches at **ATLAS**

BNL Seminar

Brookhaven, 02.05.2019

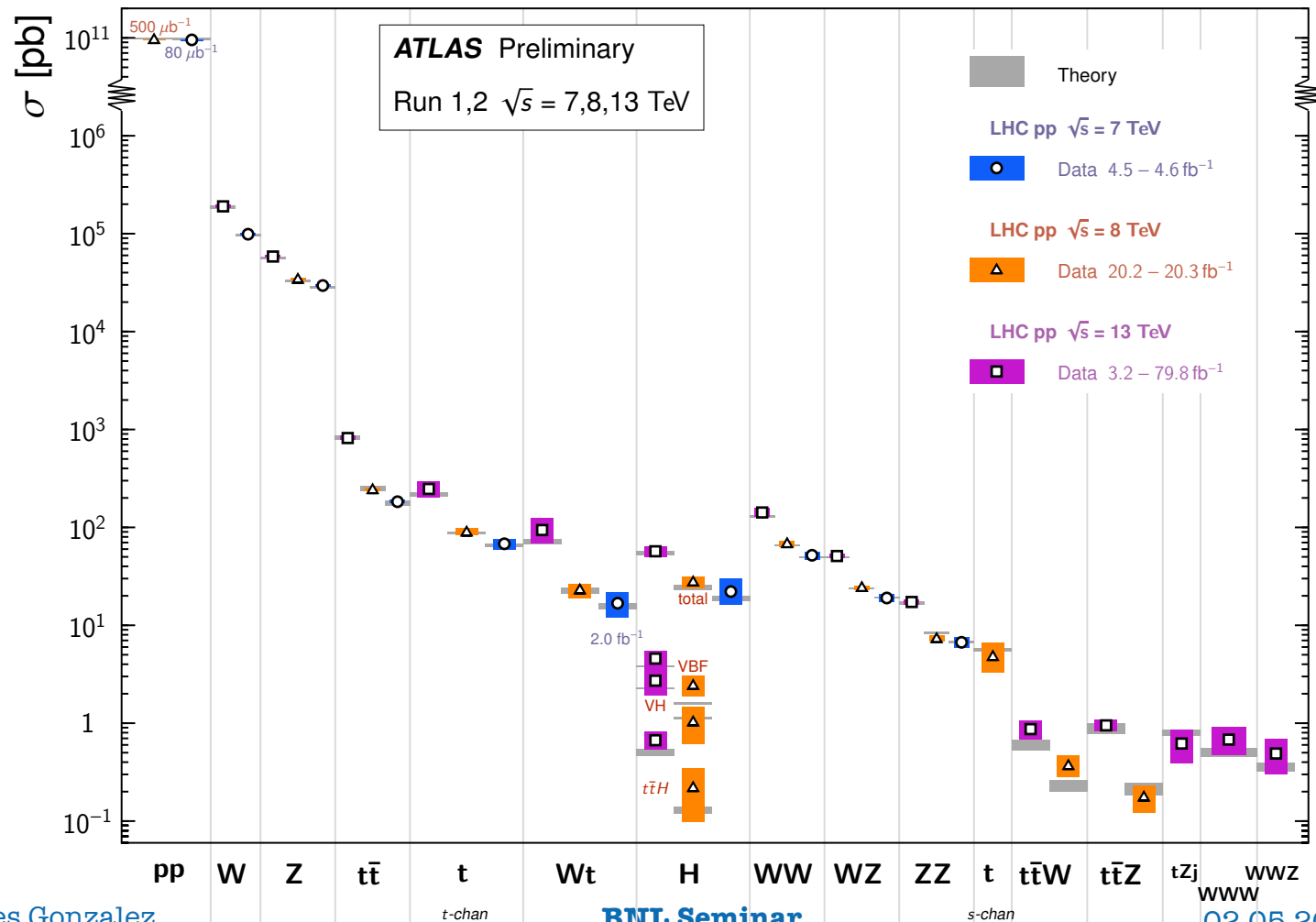
Arely Cortes-Gonzalez
CERN

Standard Model

Very **successful** theory.

- **Precise measurements in great agreement with predictions.**

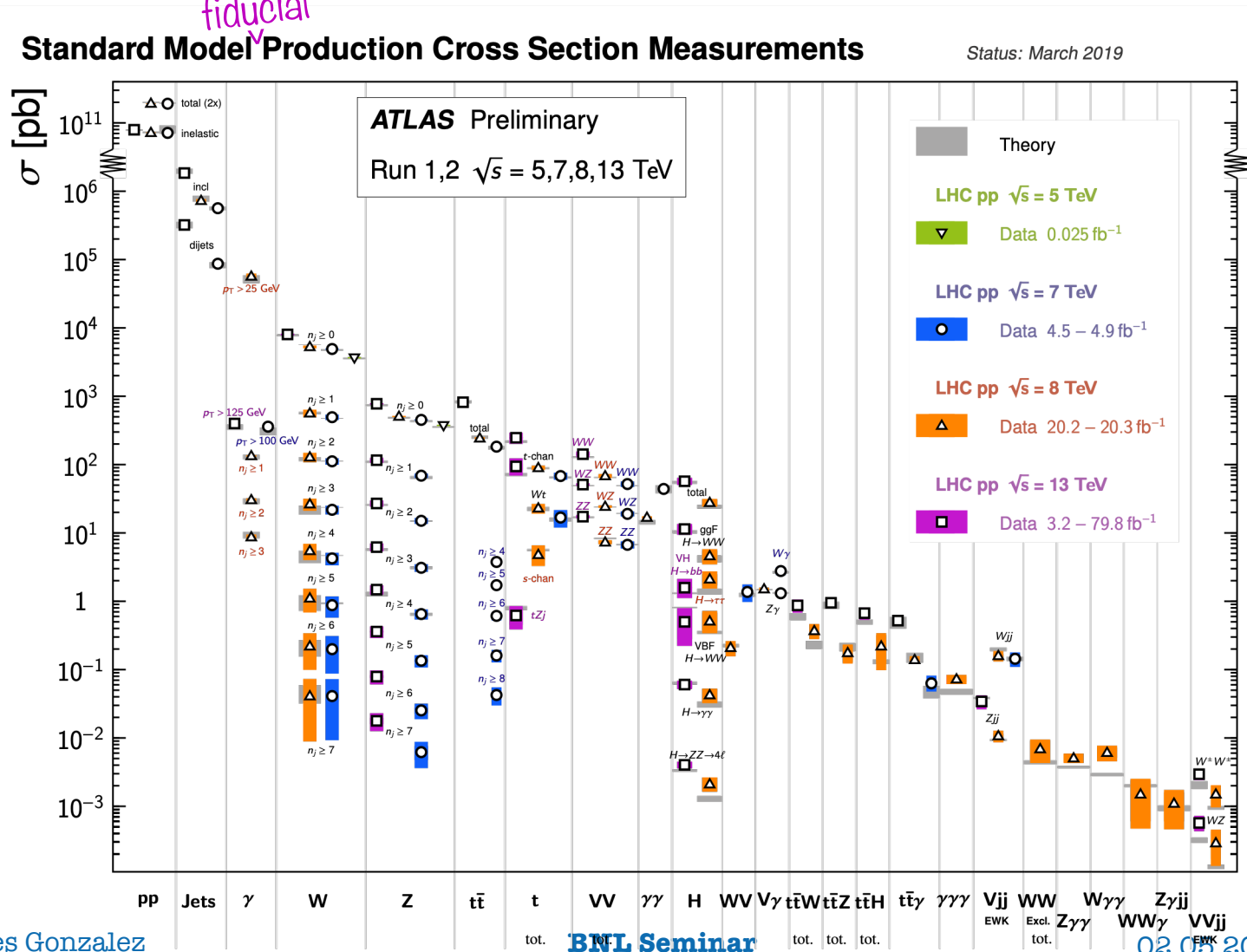
Standard Model Total Production Cross Section Measurements *Status: March 2019*



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Standard Model

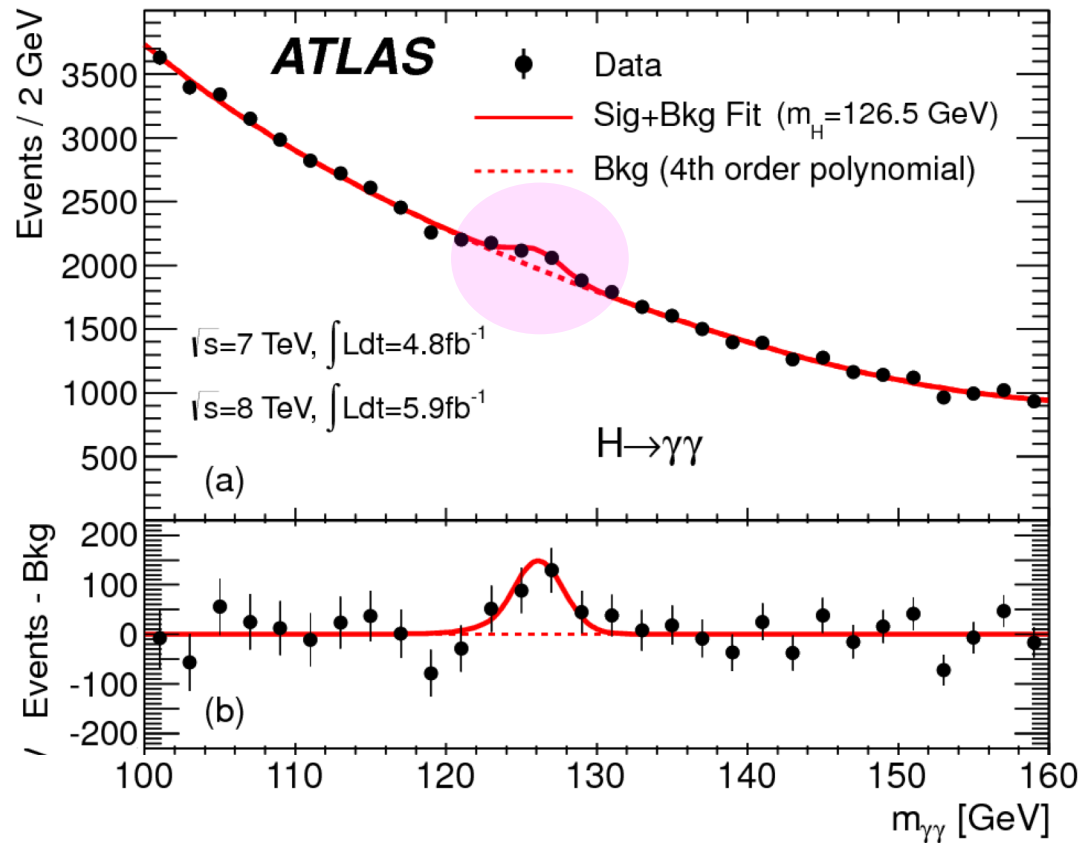
Phys. Lett. B 716 (2012) 1-29

The **Higgs discovery** further validated the SM
(*self-consistent theory*).

Run I **legacy**: Higgs discovery
The discovery of a new particle
also opened a new channel for
searches.

Still left with many open
questions....

e.g. High-levels of **fine tuning**
needed to avoid divergences in
Higgs mass corrections.



beyond Standard Model?

SM is a self-consistent theory, with predictions in agreement with measurements, but...

- **Hierarchy** problem (of mass scales).
- Large discrepancy between weak force and gravity: $m_{EW}/m_{Plank} \sim 10^{-16}$.
- **Fine tuning** needed to avoid divergences in Higgs mass corrections.
- No **Dark matter** candidate.
- Baryon **asymmetry**.
- **Neutrino** masses.

beyond Standard Model?

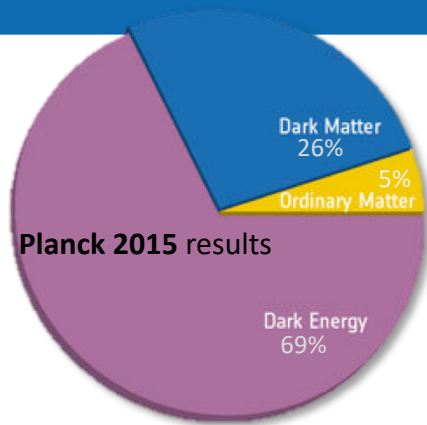
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How to solve these?

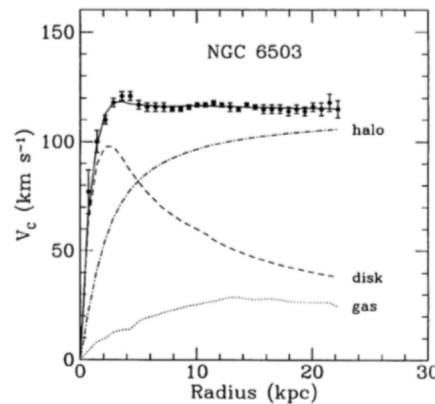
- **SUSY.**
- **Extra Dimensions.**
- **Compositeness.**
- **Sequential Standard Model.**
- **Hidden Sectors.**
- **Top partners,**
- **... New TeV scale interactions/particles!**

Observational evidence for dark matter



Presence of a **dark matter** component in the universe inferred from the observation of its gravitational interactions.

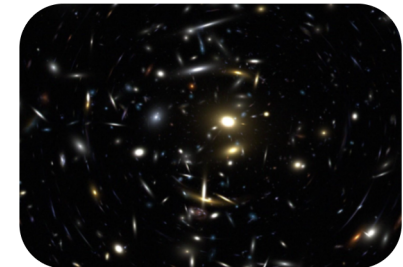
- **Cosmic Microwave Background**



- **Rotation of stars** around the center of the galaxies is not consistent with the amount of mass *observed*.



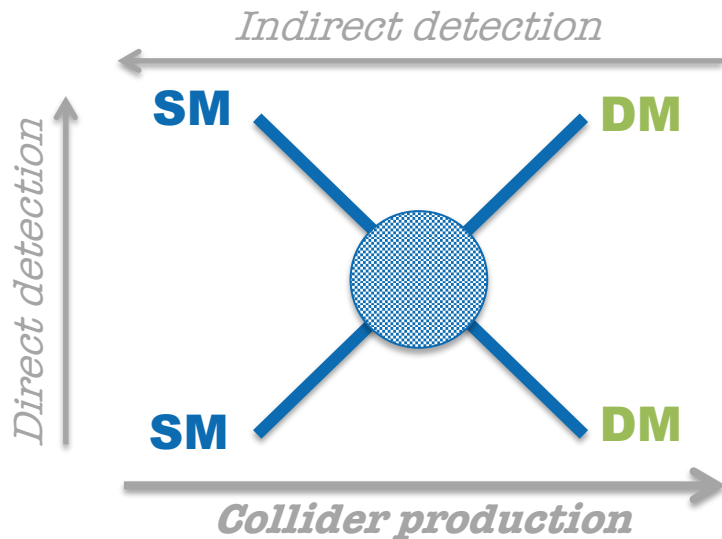
- **Collisions of cluster of galaxies.**
The *bullet cluster*.



- Interacts gravitationally.
- Cosmologically stable.
- Electrically neutral.

*Experimental evidence motivates a DM sector composed dominantly of weakly interacting massive particles: **WIMPs** (reproduces the measured relic density).*

Searches for dark matter

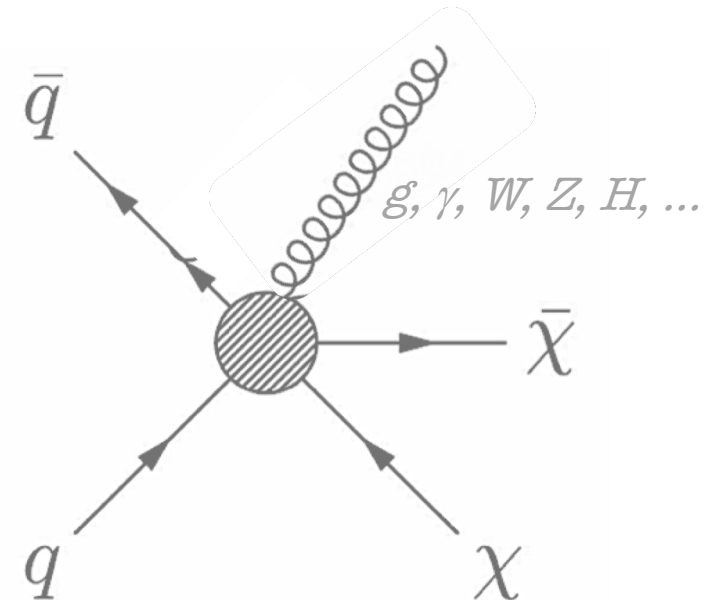


In colliders like the LHC, WIMPs can be e.g. be produced in pairs.

In general, we require some theoretical framework to define the **production** mechanism.

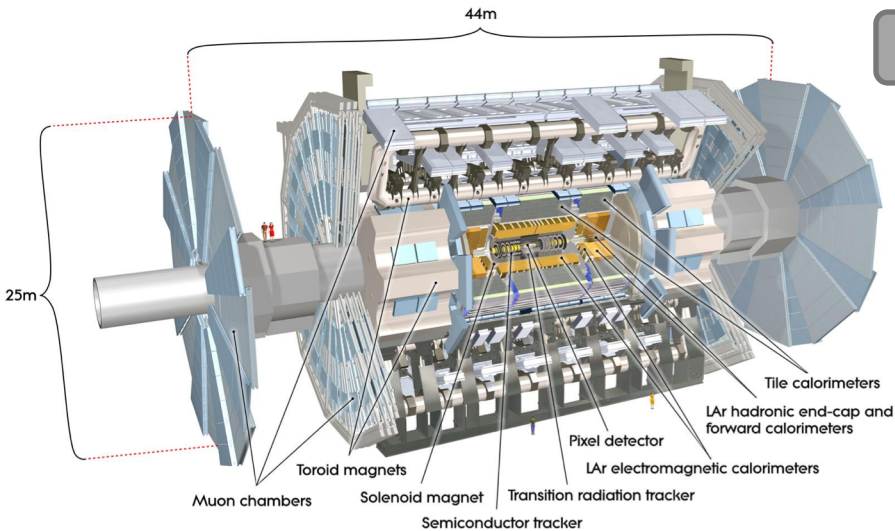
WIMPs do not interact with the detector, thus they leave a signature of **missing transverse energy** ($\mathbf{E}_T^{\text{miss}}$).

To be able to select the event, we look for visible particles produced in association with the DM particles.

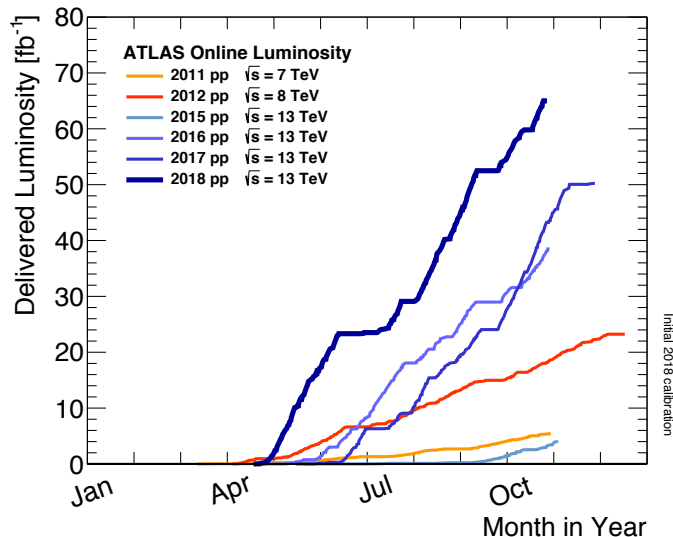
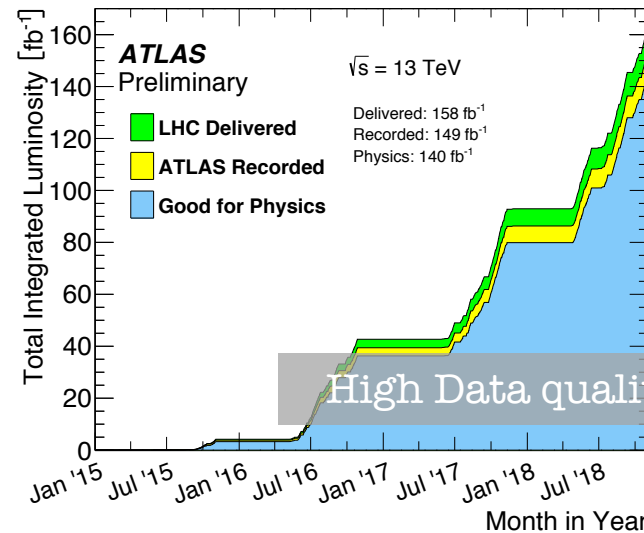


ATLAS detector data

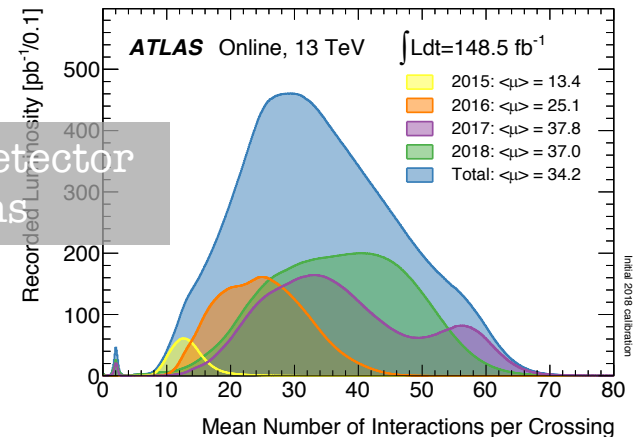
Excellent **performance by the LHC** and high **data taking efficiency** by detectors in the 13 TeV pp collisions period (Run 2, 2015-2018).



~150 fb⁻¹ @ 13 TeV recorded in 2015-2018

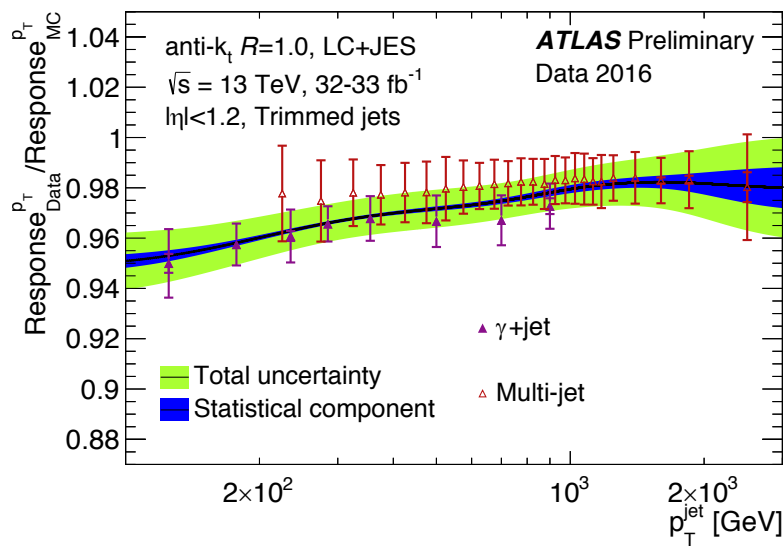
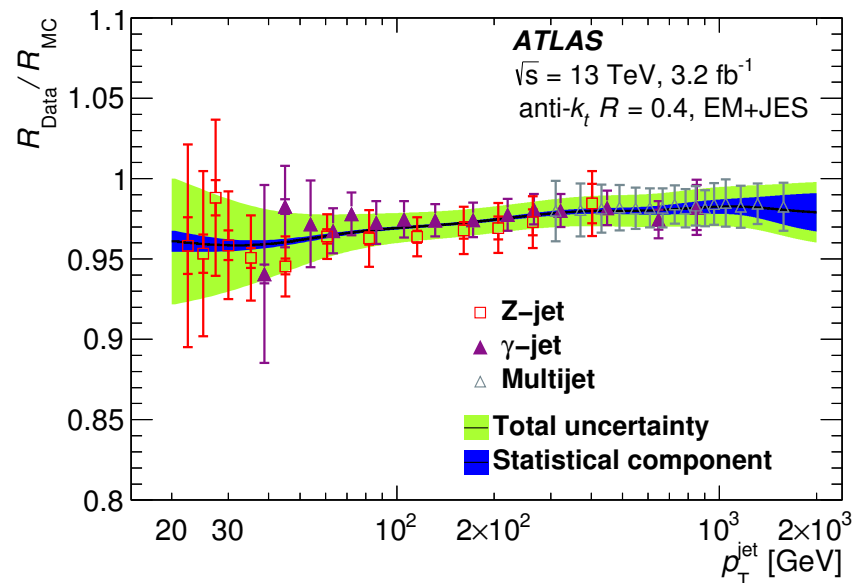
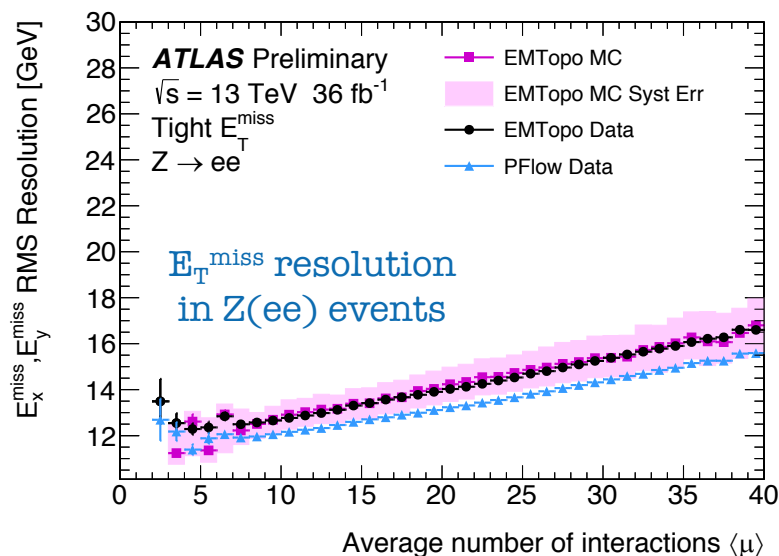


Challenging detector conditions

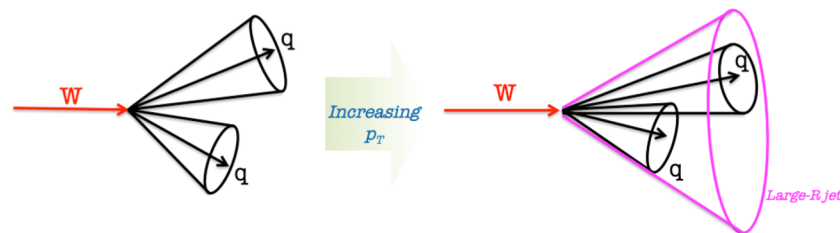


ATLAS detector data

These analyses rely in a good measurement of **missing transverse momenta**, and understanding of jet calibration up to multi-TeV scale.



Large-R jets

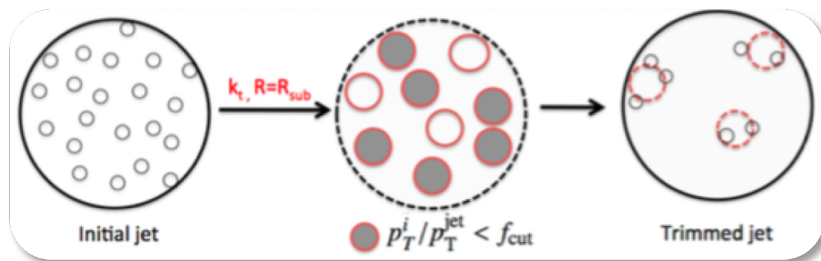


For further discrimination against backgrounds, analyses also use boson-tagging techniques.

ATLAS detector data



Energy depositions in calorimeter used to form topological clusters:
reconstruct **large R-jets**: **Anti- k_t , $R=1.0$ jets**.



Re-cluster with $R_{\text{sub}} = 0.2$.
Remove sub-jets with $f_{\text{cut}} < 0.05$.

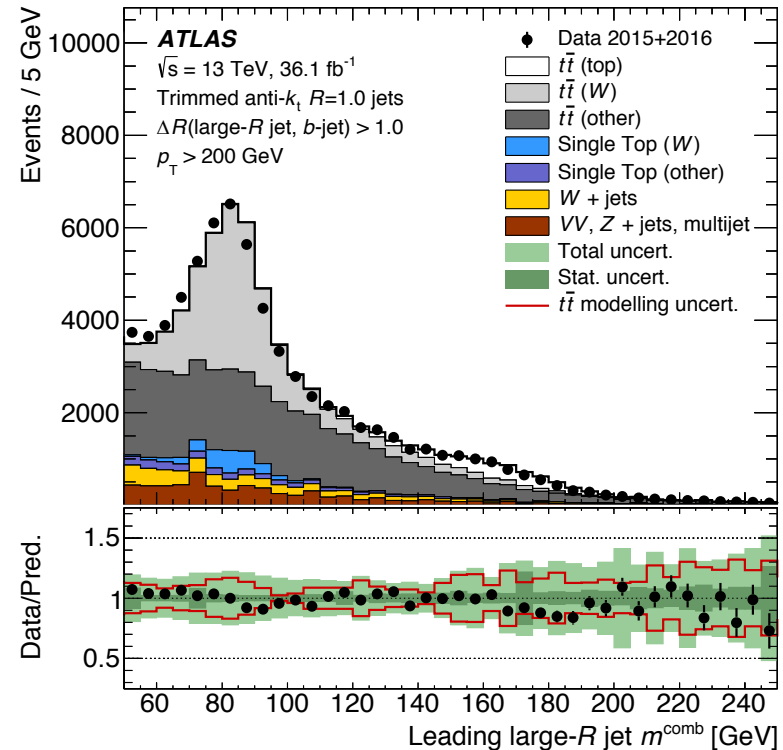
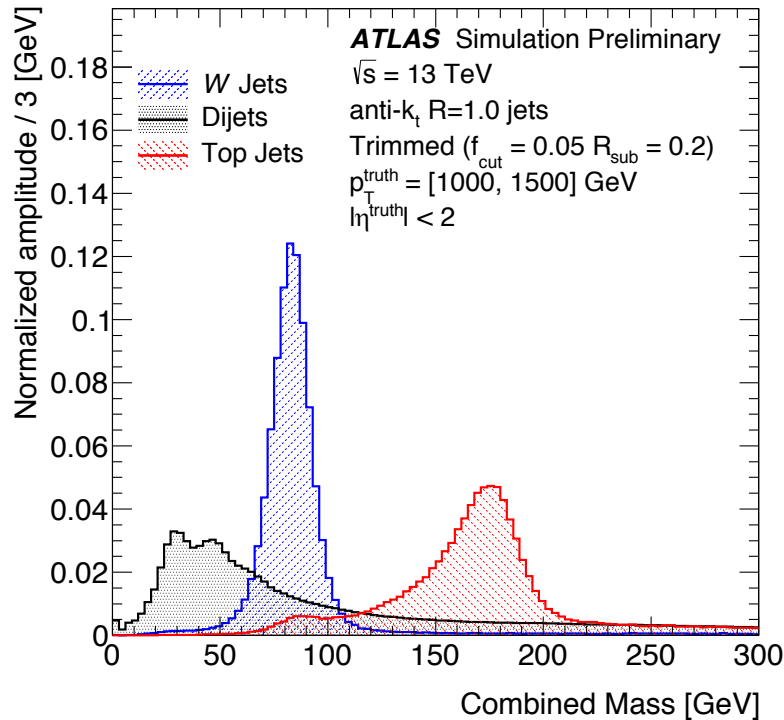
Trimming

Remove softer components
(mainly from UE and pileup).

Improved *mass resolution*.

Discriminating against background: boson tagging.

Use differences in the jet characteristics between signal and background jets.

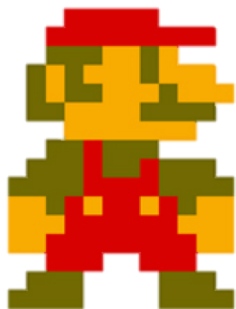


Optimized **large-R jet mass** computed using combination of calorimeter and tracking information

***Jet mass** is consistent with m_W or m_{top} .*

Mass windows for e.g. W/Z bosons are p_T -dependent.

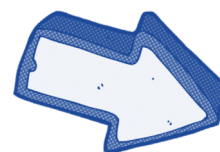
Theoretical Framework



Effective Field Theories



Simplified models



Less simplified models

Effective field theories (EFT) of DM interaction with WIMPs. Effective Lagrangian approach with parameters: M^* and m_{DM} .

Theory only valid if M^* is much larger than the energy scale present in reaction (potential issue at LHC).

Natural solution to EFT validity. Simplified models considers the production of a mediator particle.

E.g. for a s-channel mediator we can have:
 $m_{\text{med}}, m_{\text{DM}}, g_{\text{DM}}, g_q, g_l$

UV complete models, typically not restricted by Higgs measurements.

A much larger parameter space affecting the kinematics, cross sections, couplings, etc.
Much richer phenomenology!

Model generality



Theoretical Framework

Simplified Model: Spin-1 mediator

Vector or axial-vector mediator

- $E_T^{\text{miss}} + \text{jet}$
- $E_T^{\text{miss}} + \gamma$
- $E_T^{\text{miss}} + Z(\ell\ell)$
- $E_T^{\text{miss}} + V(\text{had})$
- Di-jet (low/high mass)
- Di-b-jet (low/high mass)
- Di-tops
- Di-leptons

arXiv: 1903.01400

Vector-baryon charged mediator

- $E_T^{\text{miss}} + H(bb)$
- $E_T^{\text{miss}} + H(\gamma\gamma)$
- $E_T^{\text{miss}} + H(\tau\tau)$

arXiv: 1903.01400

JHEP 09 (2018) 046

Simplified Model: Spin 0-mediator

Scalar/Pseudoscalar mediator

- $E_T^{\text{miss}} + \text{jet}$
- $E_T^{\text{miss}} + bb$
- $E_T^{\text{miss}} + tt$

ATLAS-CONF-2018-051

Scalar colour charged mediator

- $E_T^{\text{miss}} + \text{jet}$
- $E_T^{\text{miss}} + b$

ATLAS-CONF-2018-051

Higgs Portal

ATLAS h(inv) combination: ATLAS-CONF-2018-054

CMS h(inv) combination: JHEP02 (2017) 135

Extended Higgs sector DM models

2HDM+a

NEW

- $E_T^{\text{miss}} + H(bb)$
- $E_T^{\text{miss}} + H(\gamma\gamma)$
- $E_T^{\text{miss}} + Z(\ell\ell)$
- $E_T^{\text{miss}} + V(\text{had})$
- $E_T^{\text{miss}} + bb/tt$
- 4 tops
- h(inv)

CMS-PAS-EXO-16-050

arXiv: 1903.01400

2HDM+Z'_V

- $E_T^{\text{miss}} + H(bb)$
- $E_T^{\text{miss}} + H(\gamma\gamma)$
- $E_T^{\text{miss}} + H(\tau\tau)$

ATLAS-CONF-2018-039

arXiv: 1807.02826
PRD 96 (2017) 112004

JHEP 09 (2018) 046

Supersymmetry

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults>

Long-lived particles sector

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults>

Other models?!

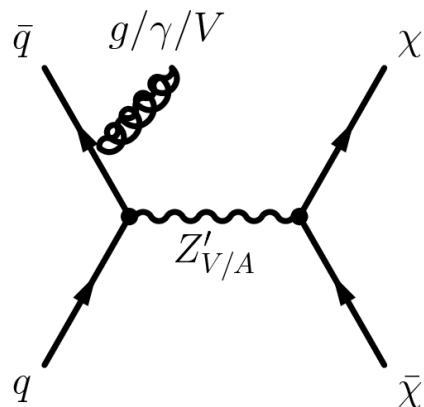
Theoretical Framework

Short description	Acronym	Symbol	J^P	Charge	Signatures
Vector/axial-vector mediator	V/AV	Z'_V/Z'_A	$1^\mp$	-	jet/ γ / $W/Z + E_T^{\text{miss}}$, difermion resonance
Vector baryon-number-charged mediator	VBC	Z'_B	1^-	baryon-number	$h + E_T^{\text{miss}}$
Vector flavour-changing mediator	VFC	Z'_{VFC}	1^-	flavour	$t\bar{t}, t + E_T^{\text{miss}}$
Scalar/pseudo-scalar mediator	S/PS	ϕ/a	$0^\pm$	-	jet + E_T^{miss} , $t\bar{t}/b\bar{b} + E_T^{\text{miss}}$
Scalar colour-charged mediator	$\text{SCC}_{q/b/t}$	$\eta_{q/b/t}$	0^+	colour, 2/3 electric-charge	jet + E_T^{miss} , $b + E_T^{\text{miss}}$, $t + E_T^{\text{miss}}$
Two-Higgs-doublet plus vector mediator	2HDM + Z'_V	Z'_V	1^-	-	$h + E_T^{\text{miss}}$
Two-Higgs-doublet plus pseudo-scalar mediator	2HDM + a	a	0^-	-	$W/Z/h + E_T^{\text{miss}}$, $t\bar{t}/b\bar{b} + E_T^{\text{miss}}$, $h(\text{inv}), t\bar{t}t\bar{t}$

See [arXiv:1903.01400](#) for further details and references.

Simplified Models

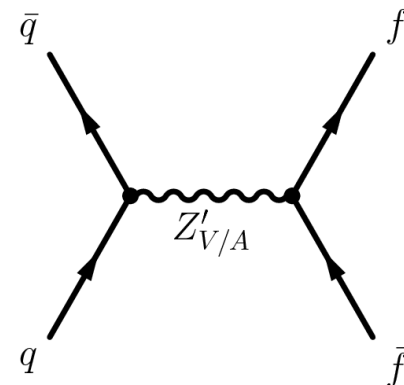
Spin 1: V/AV



s-channel mediator Z' : mediates interaction between SM and DM.

Most sensitive $X+E_T^{\text{miss}}$ channel:
jet+ E_T^{miss} , “jet” has α_s couplings to initial state quarks.

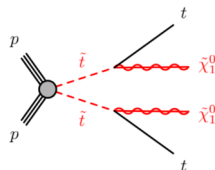
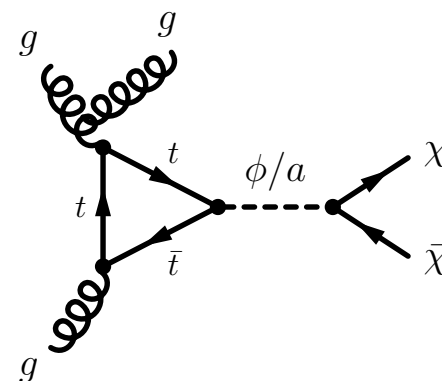
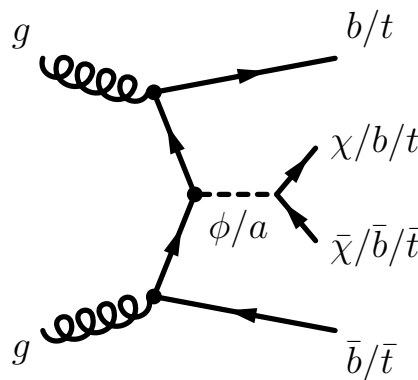
Vector/Axial-vector mediator,
Parameters: m_{DM} , $m_{Z'}$, g_{DM} , g_q , g_l .
Channels: jet/ γ /Z/W+ E_T^{miss}



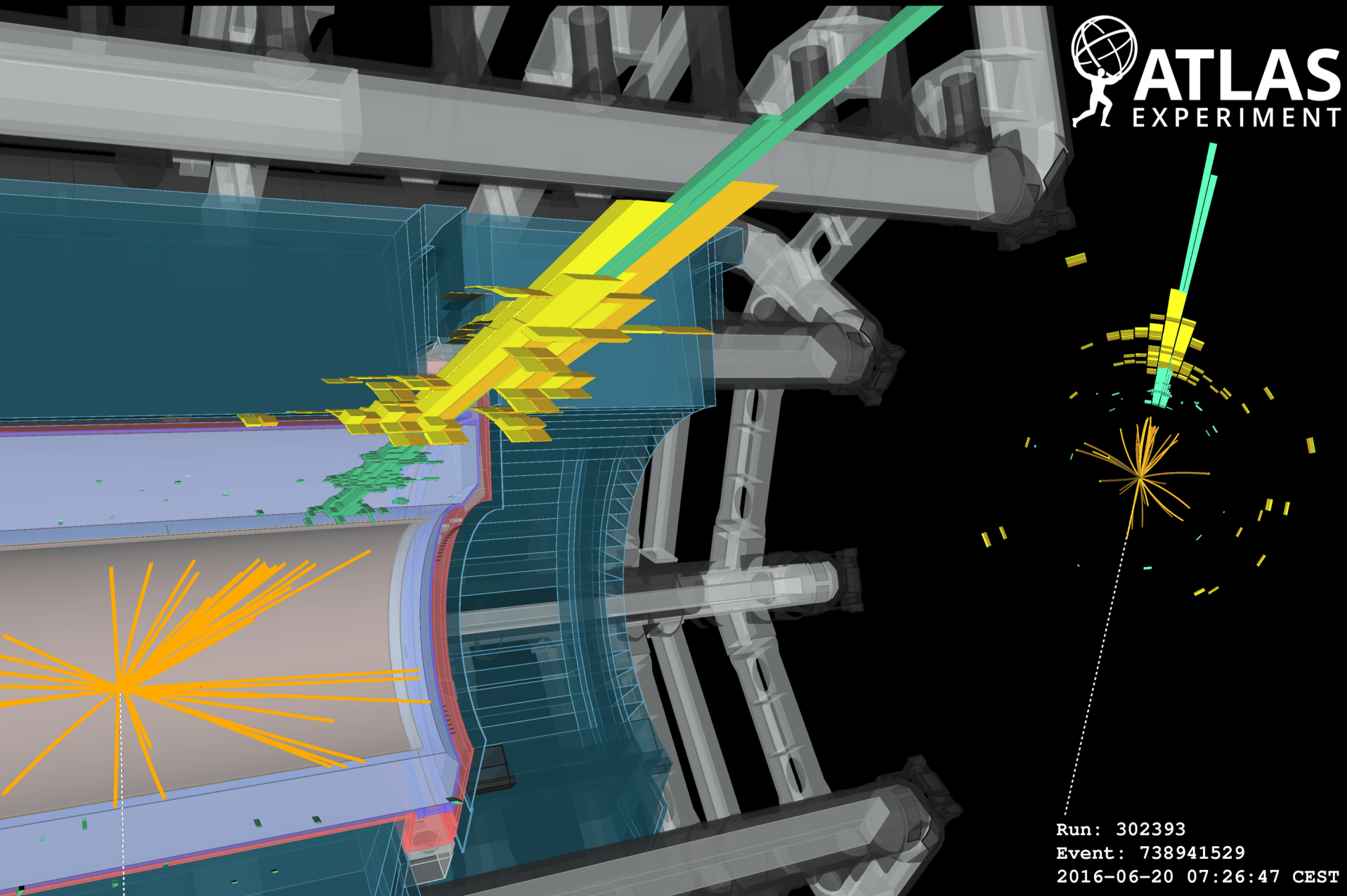
*Mediator can decay into fermions: limits from **resonance** searches!*

Spin 0: S/PS

Scalar and pseudo scalar mediators: better sensitivity from E_T^{miss} +HF searches.



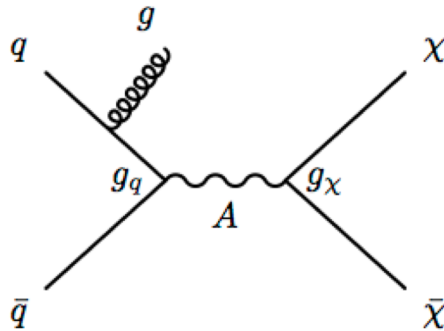
Similar topology as stop and sbottom SUSY searches.



Run: 302393
Event: 738941529
2016-06-20 07:26:47 CEST

Benchmark DM model

Axial-vector (s-channel) mediator,
 $g_{\text{DM}} = 1, g_q = 0.25$.



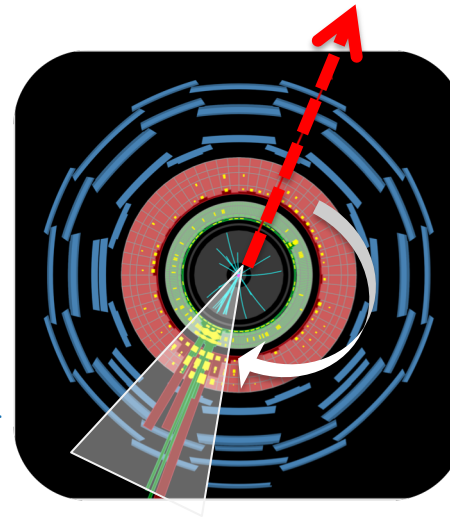
Most sensitive Mono- X channel

“jet” has α_s couplings to initial state quarks.

Selection

Signal region:
veto on muons
and electrons.

Jet $p_T > 250 \text{ GeV}$
 $|\eta| < 2.4$



$N_{\text{jets}} (p_T > 30 \text{ GeV}) \leq 4$

$\Delta\phi(E_T^{\text{miss}}, \text{jets}) > 0.4$

Strategy

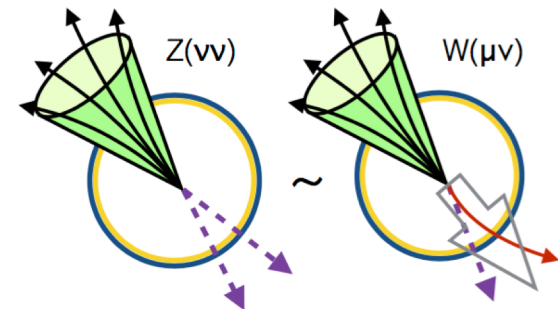
- Dominant bkg: **$Z(\nu\nu) + \text{jets}$** , followed by $W(l\nu) + \text{jets}$.
- W/Z bkg modelled at NLO QCD & EW.
 - **Sherpa NLO(LO) for 1,2(3,4) partons + theory corrections as a function of $p_T(W/Z)$.**
 - [arXiv:1705.04664]
- **$V + \text{jets}$** and **top** bkg normalized in dedicated CRs.
- DiBosons from MC. NCB and Multijets data driven.

$W/Z + \text{jets}$ background

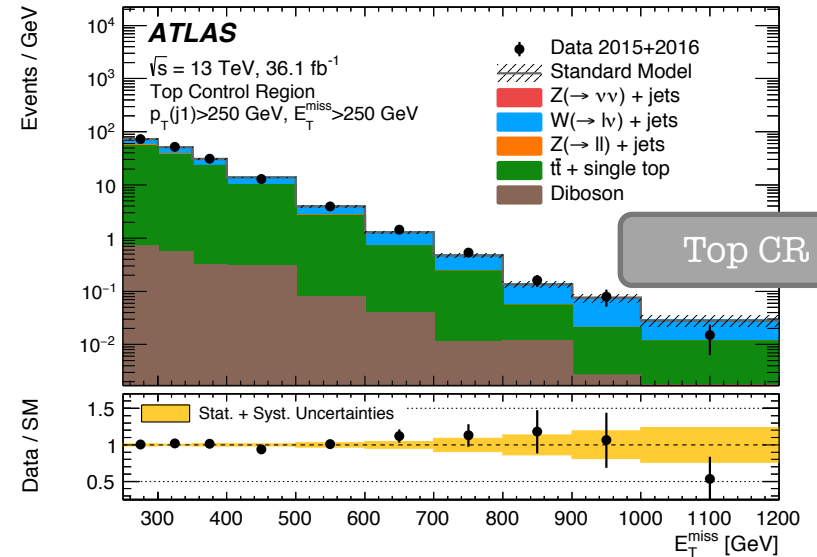
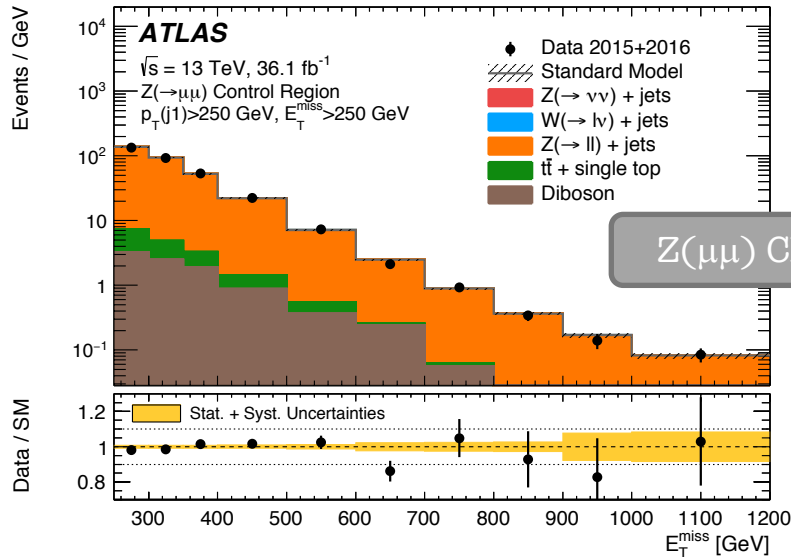
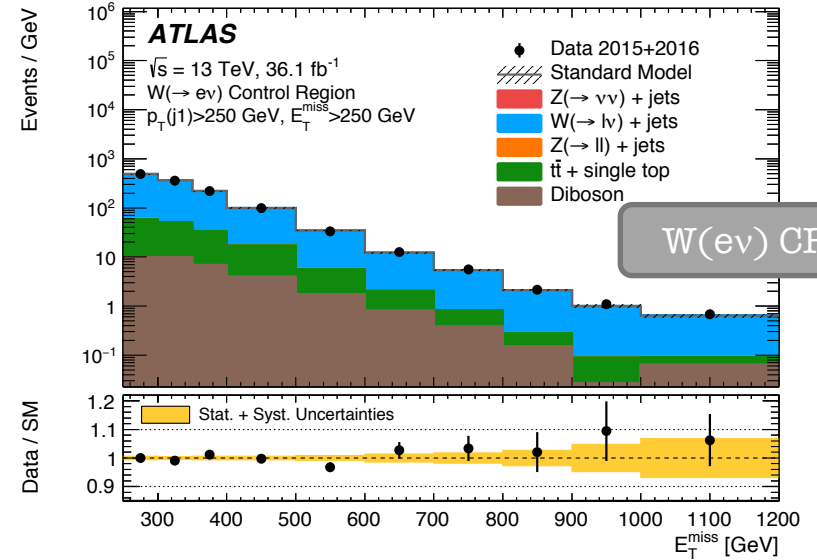
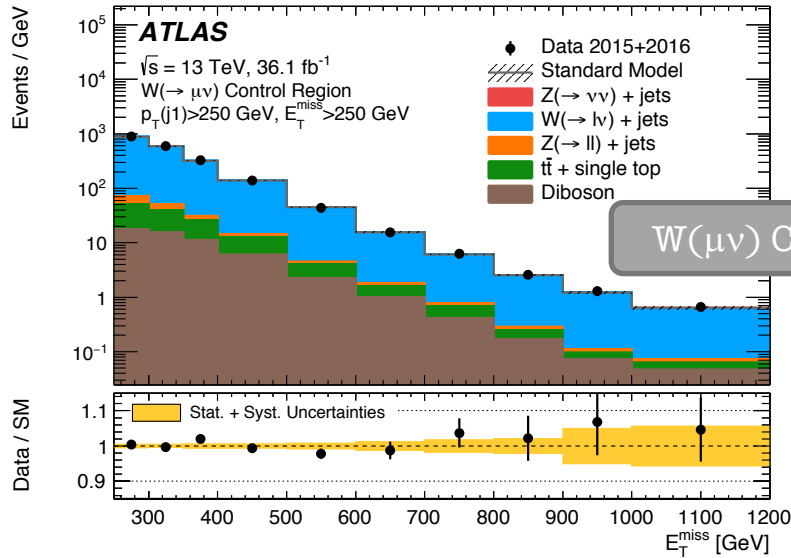
e.g. $W(\mu\nu)$ CR used to constrain $Z(\nu\nu)$.

Muons treated as invisible:

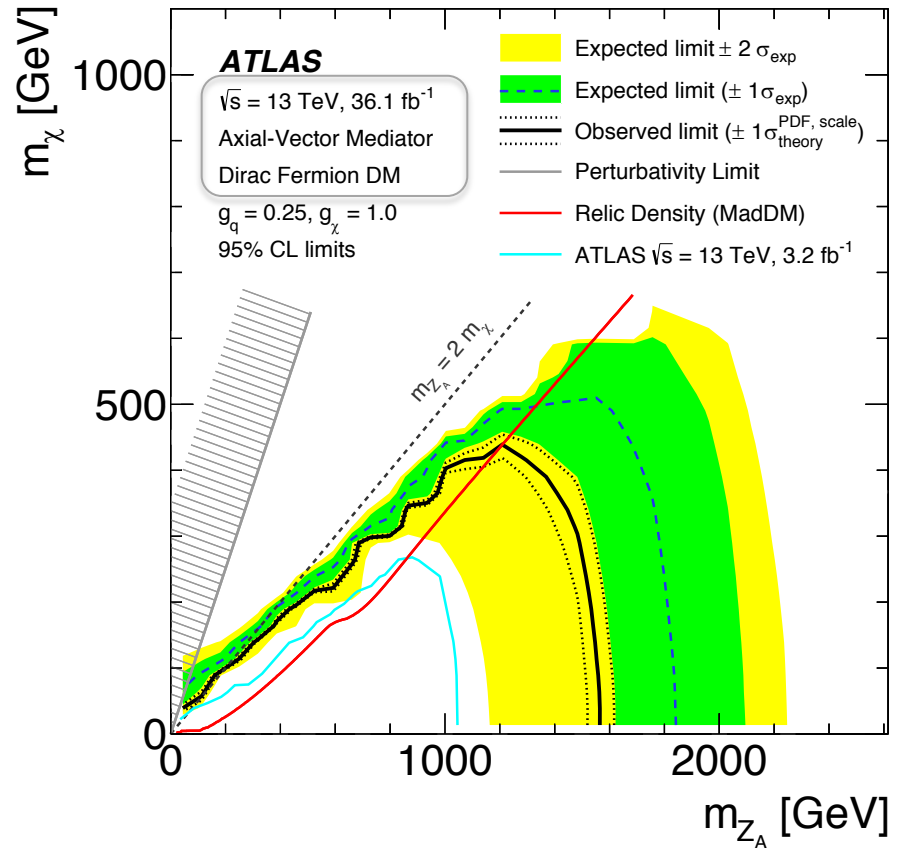
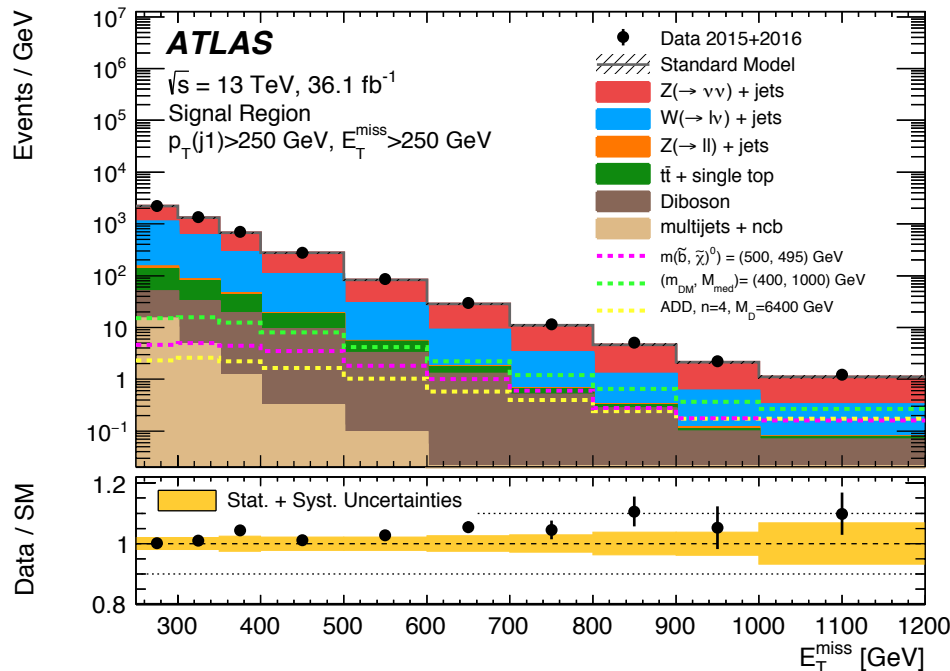
$E_T^{\text{miss}} \sim \text{boson } p_T$



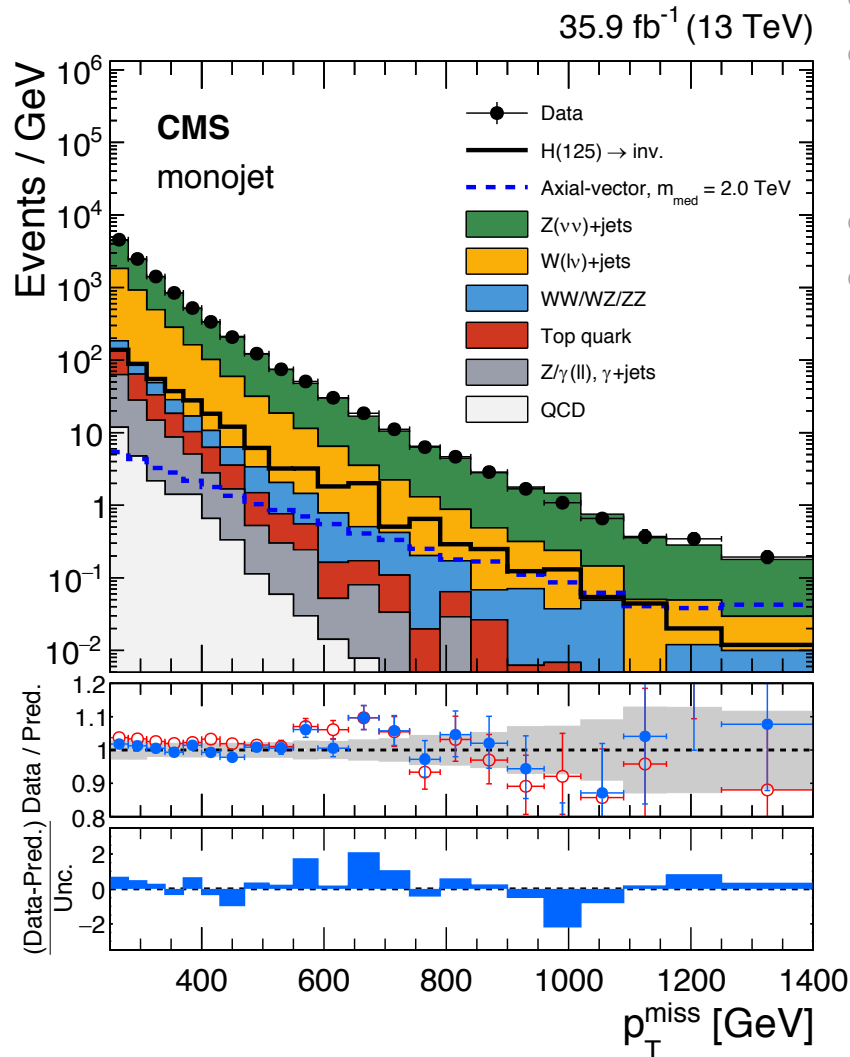
Similarly for $Z(l\bar{l})$ CRs.



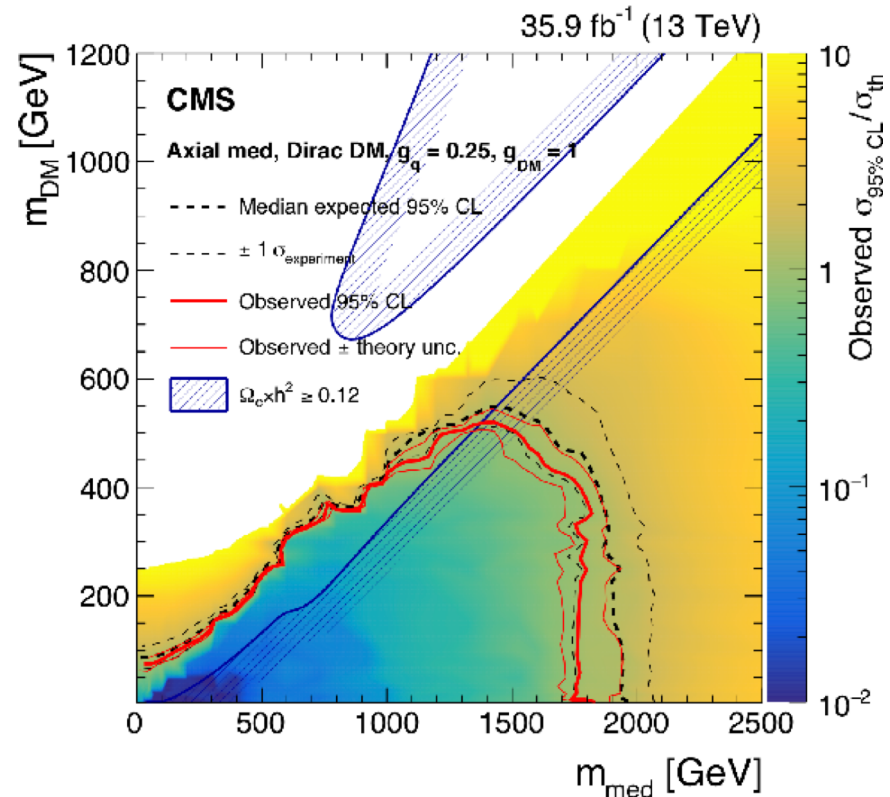
- **2-5% background uncertainty in SR.**
- *Theory uncertainty*: 0.7-1% to account for extrapolation between $W(l\nu)$ and $Z(l\ell)$ CRs and $Z(\nu\nu)$ in the SR.
- *Experimental uncertainties* mainly from jet energy scale and electron/muon efficiency.

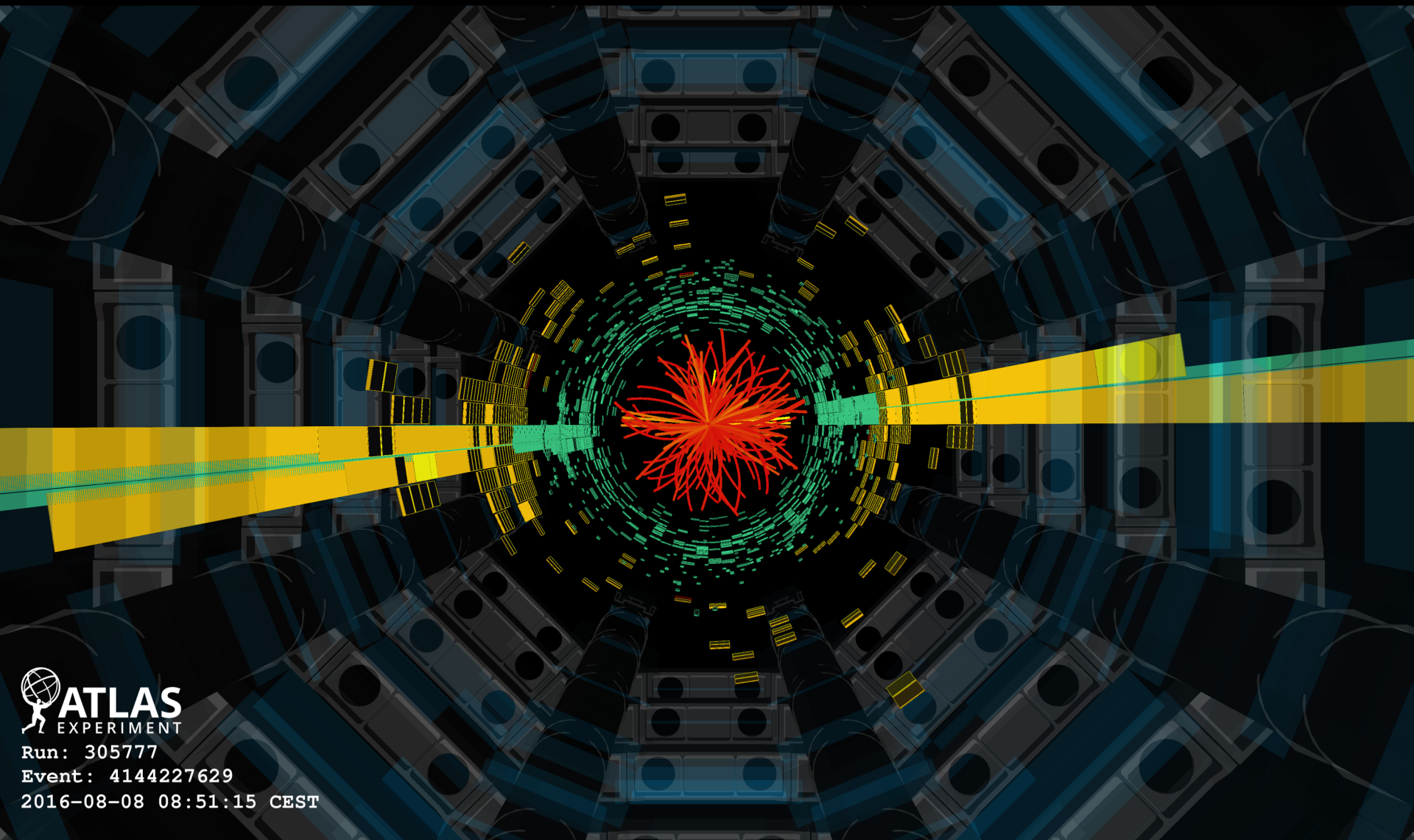


Limits on a vector model are also given.
This channel has sensitivity to several SUSY stop/sbottom compressed decay channels and LED.



- $E_T^{\text{miss}} > 250$ GeV, leading jet $p_T > 100$ GeV.
- Reject mono-V events:
 - $R=0.8$ jets, $p_T > 250$ GeV,
 - $m_{\text{jet}} \sim m_{W/Z}$, consistent with 2 prong
- It also includes γ +jets CR in the global fit.
- Normalization factors extracted for E_T^{miss} bins.





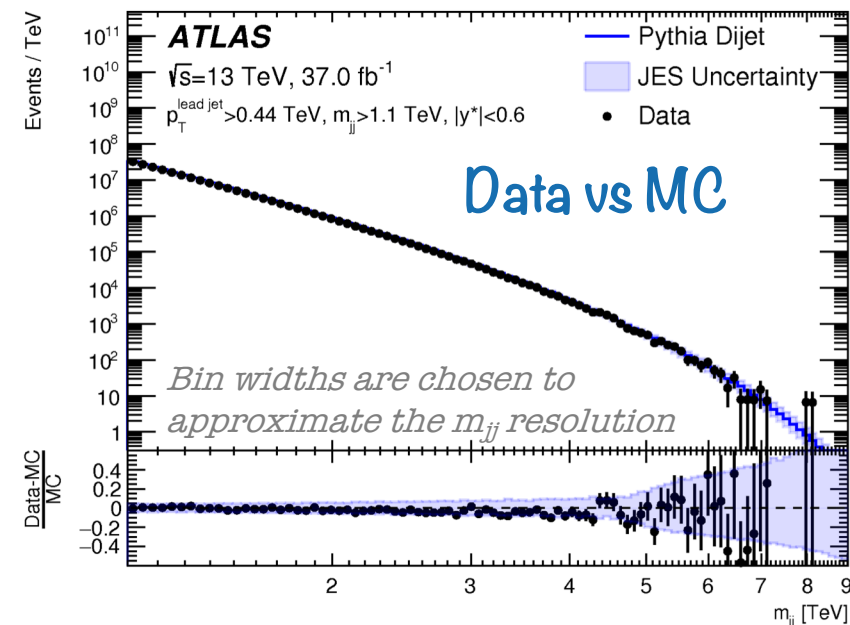
 **ATLAS**
EXPERIMENT

Run: 305777

Event: 4144227629

2016-08-08 08:51:15 CEST

Experimental searches: Dijet



Strategy: **Resonance**

$$f(z) = p_1(1 - z)^{p_2} z^{p_3} z^{p_4} \log z$$

With increasing luminosity and corresponding m_{jj} range extension, a single global fit may not necessarily work.

Selection

Events selected with lowest un-prescaled single jet trigger ($p_T > 380\text{ GeV}$).

	p_T^{leading}	$p_T^{\text{subleading}}$	$ y^* $	$ y_B $	m_{jj}
Resonance	$> 0.44\text{ TeV}$	$> 0.06\text{ TeV}$	< 0.6	-	$> 1.1\text{ TeV}$
W^*	$> 0.44\text{ TeV}$	$> 0.06\text{ TeV}$	< 1.2	-	$> 1.7\text{ TeV}$
Angular	$> 0.44\text{ TeV}$	$> 0.06\text{ TeV}$	< 1.7	< 1.1	$> 2.5\text{ TeV}$

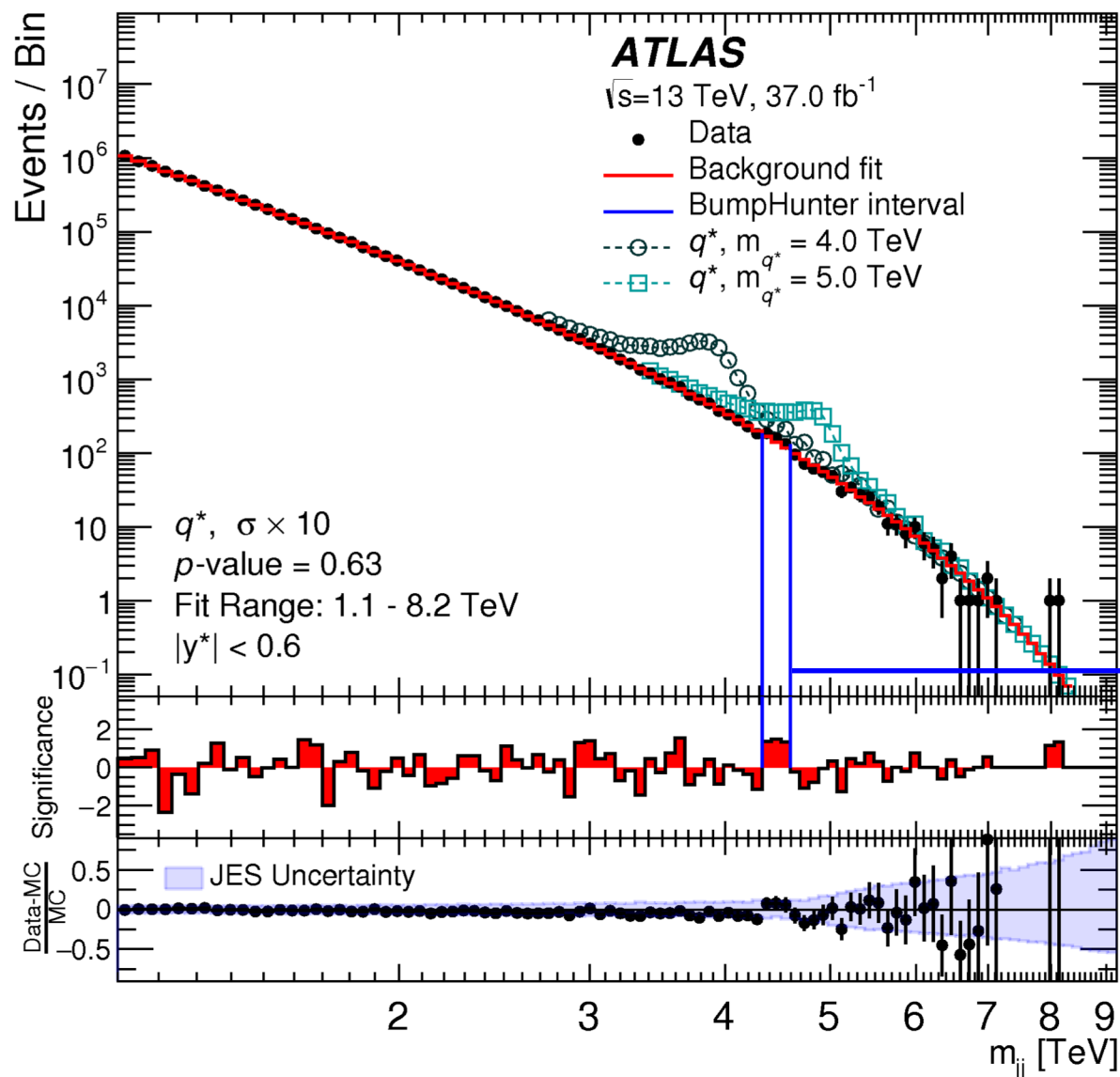
$$|y^*| = |y_1 - y_2|/2$$

Rejects forward peaking t -channel QCD processes.

Sliding Window Fit

- Perform the $f(z)$ fit in restricted (sliding) ranges (**more flexible**!).
- The limited range allows to use a 3-parameter function.
- Excellent linearity between injected and extracted signal.

Experimental searches: Dijet



Resonance Search

- **BumpHunter** algorithm compares the binned m_{jj} of data to the fitted bkg estimate.
- Global significance is computed with pseudo-experiments.

Most discrepant region:
 (global $p=0.63$) 4326–4595 GeV

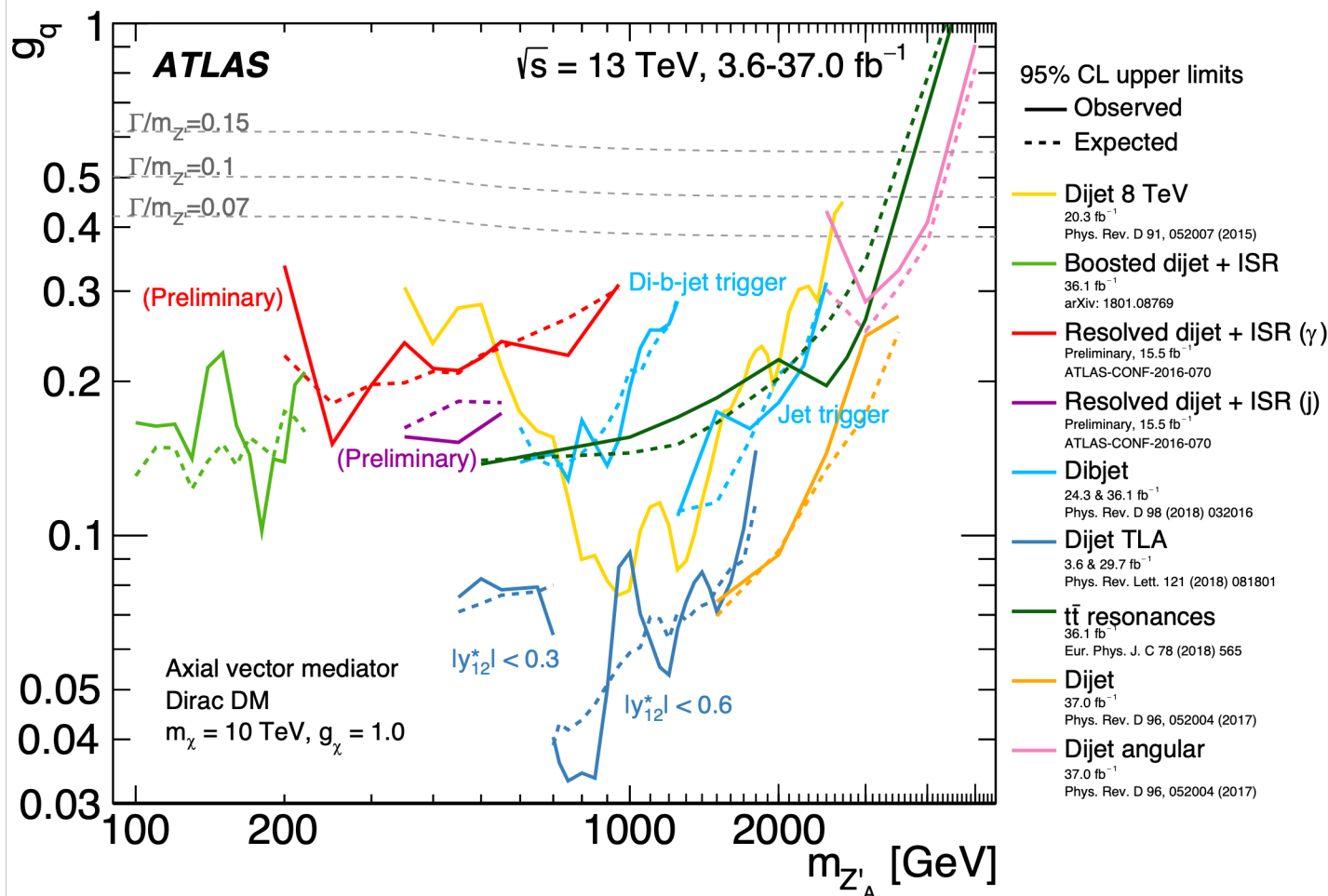
No evidence of a localized contribution from **BSM** observed.

Experimental searches: dijet

dijet resonances

New limits from di-top and di-b-jet resonance searches!

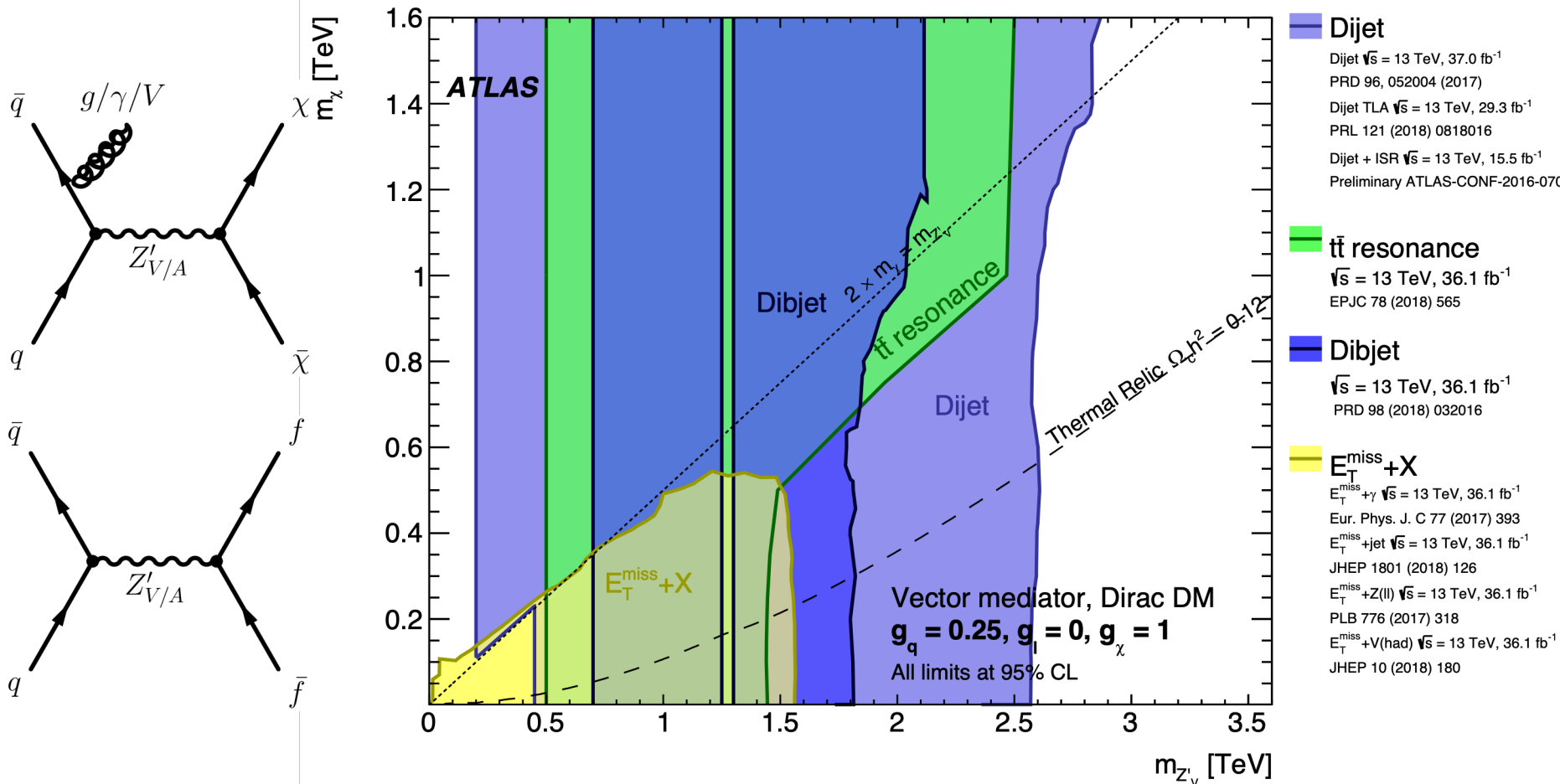
- Low m_{jj} region covered by analyses using: **trigger-level objects** or **dijet+ISR** (where the ISR object, jet or photon, is used to trigger the event). In the latter case, the dijet system can be **resolved** or **boosted**.
- Dijet angular** analysis allows to exclude signals with larger widths.



Simplified Model

$(m_{Z'}, m_{DM})$ plane

New limits from di-top and di-b-jet resonance searches!



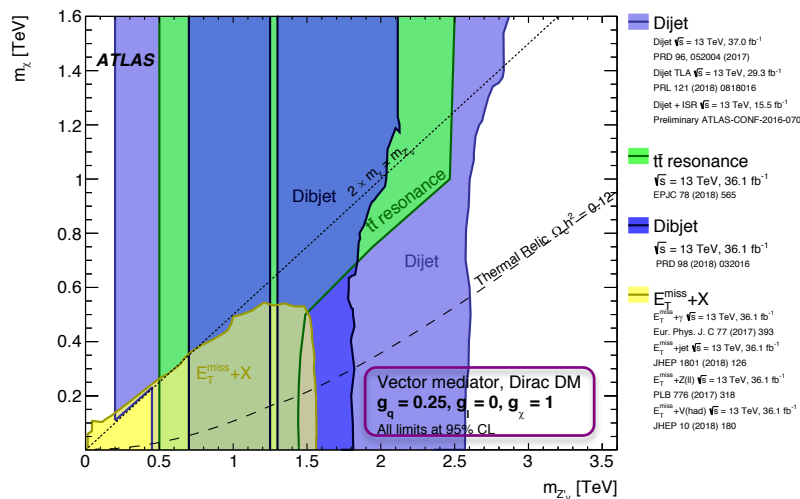
- $E_T^{\text{miss}} + \text{jet}$ provides the largest sensitivity among the searches for invisible.
- Exclusion from **dijet** resonance searches include multiple analysis techniques to cover a large mediator mass range.

Simplified Model

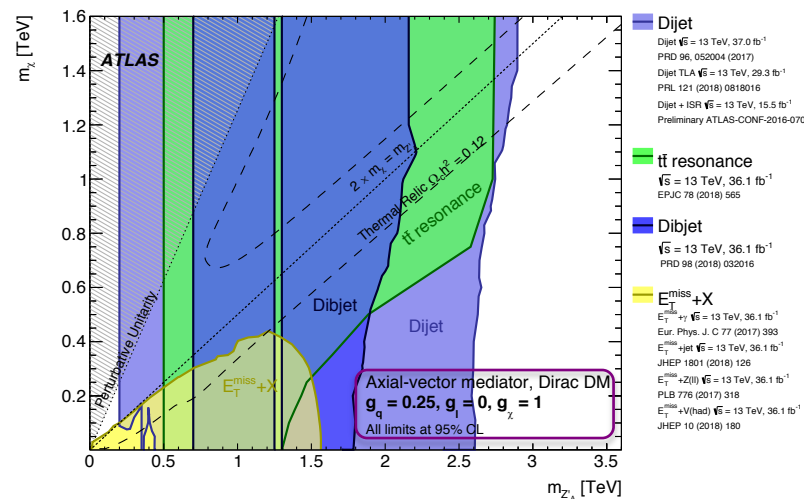
Scanning the mass-mass plane for different operators (V/AV) and different choices of couplings.

Leptophobic

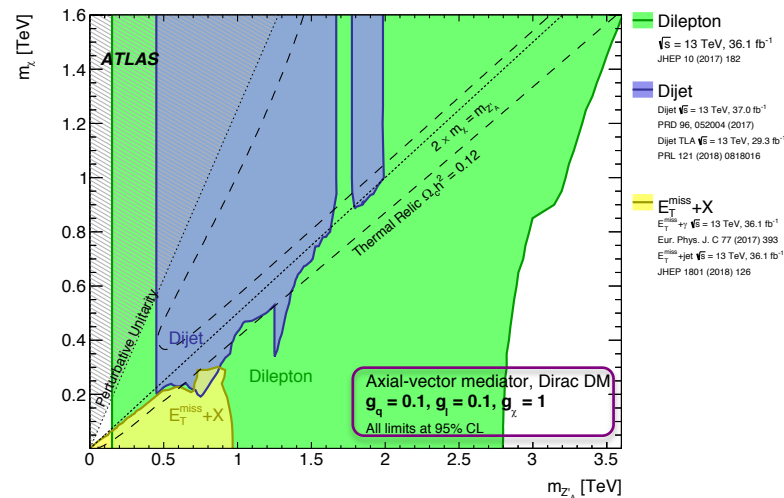
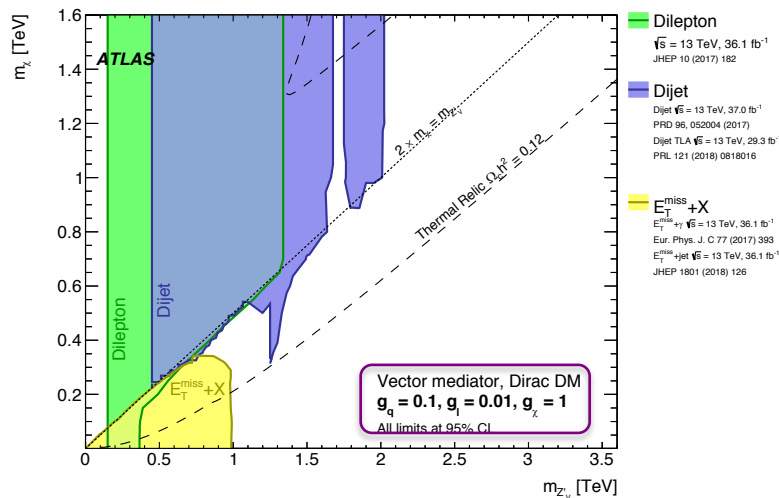
Vector



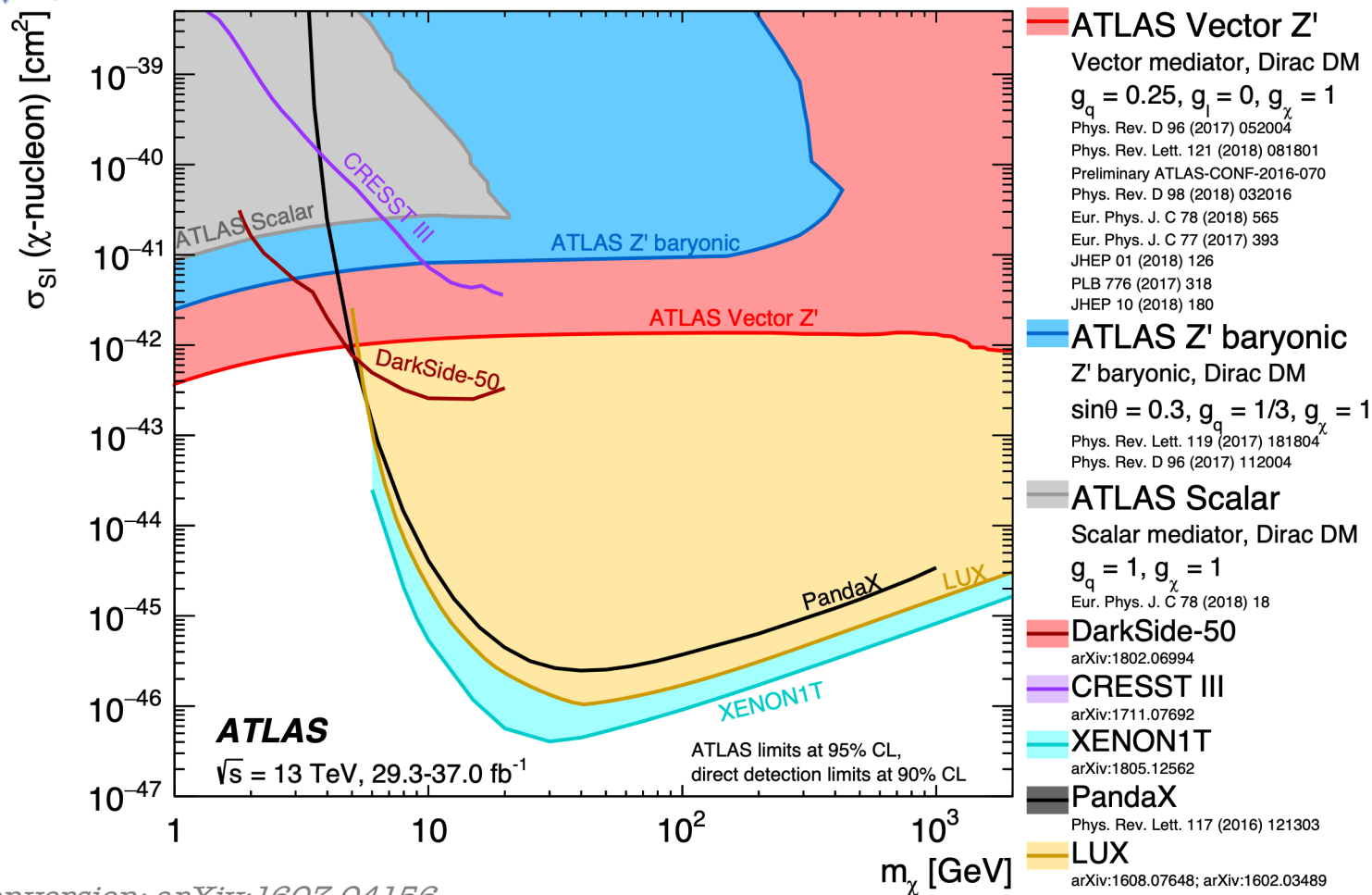
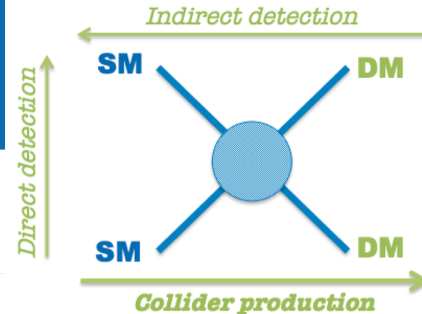
Axial-vector



Leptophilic



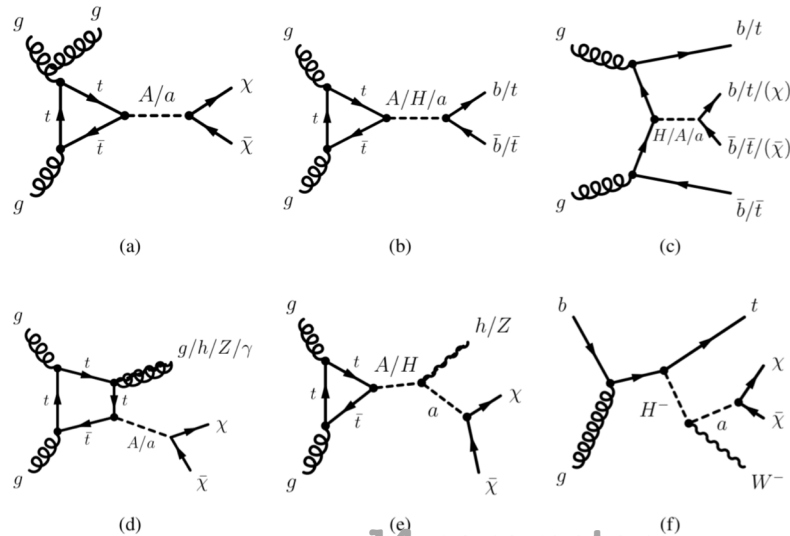
Simplified Model

model dependent
comparison

Details of conversion: arXiv:1603.04156

2HDM + a

Extension of type-II 2HDM in the alignment limit.



14 parameters

- Alignment limit: SM Higgs is the lighter of CP-even states **h**.
- $\sin(\beta - \alpha) = 1$, $m_h = 125$ GeV, $v = 246$ GeV
- Fix quartic coupling $\lambda_3 = 3$ chosen to ensure stability of Higgs potential.
 - $\lambda_3 = \lambda_{P1} = \lambda_{P2} = 3$
- $m_A = m_H = m_{H^\pm}$
- Fix DM mass and coupling (between **a** and DM).
 - $m_\chi = 10$ GeV, $y_\chi = 1$.

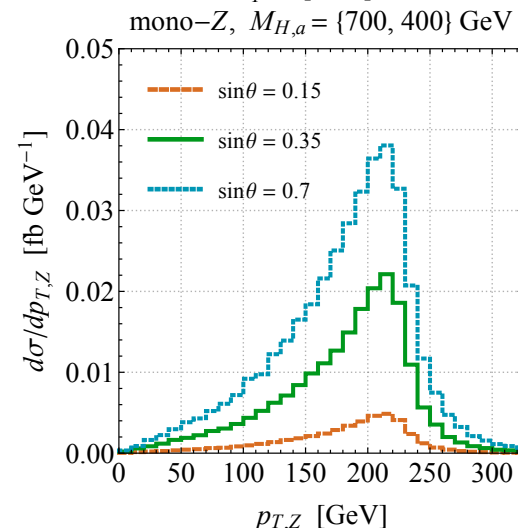
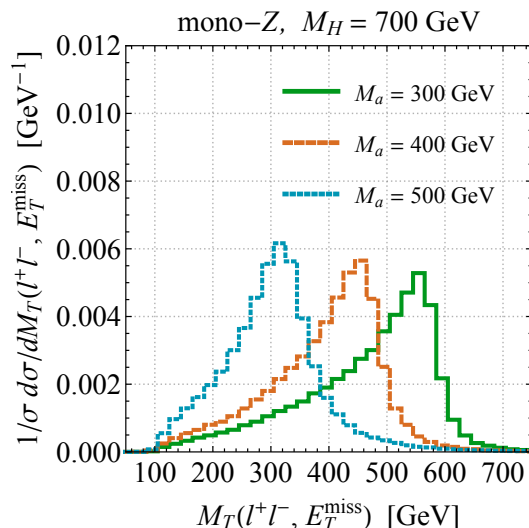
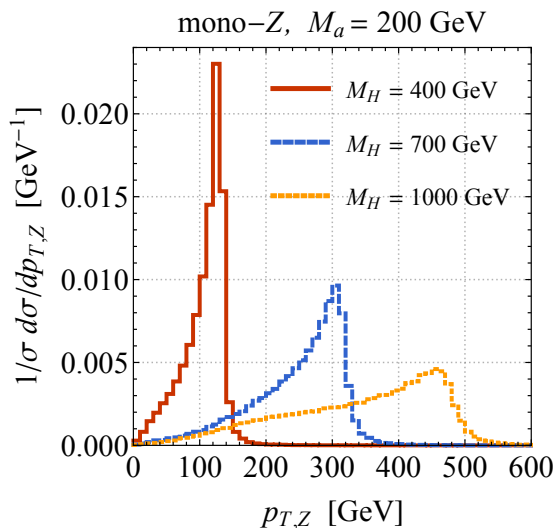
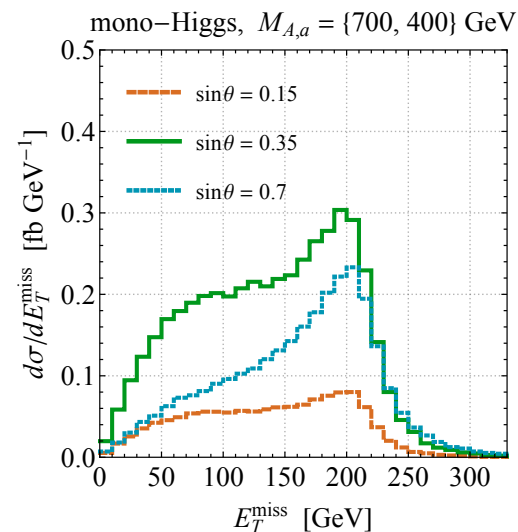
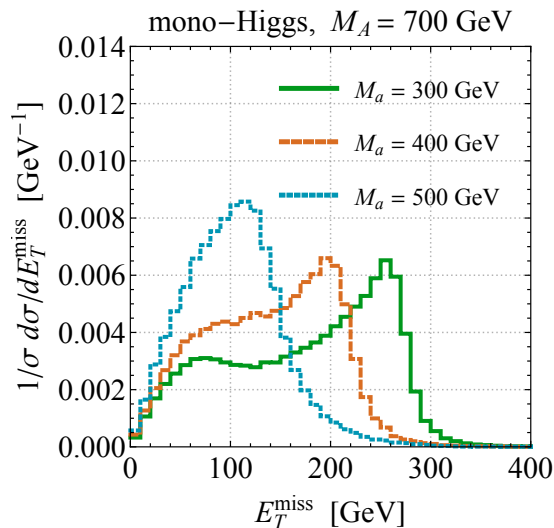
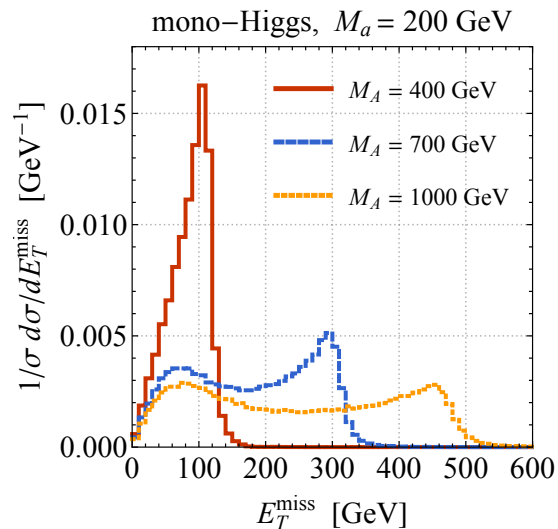
- Pseudoscalar mediator **a** couples DM to SM and mixes with heavy pseudoscalar **A** of 2HDM.
- Rich phenomenology of $E_T^{miss} + X$ signatures (complementary sensitivity).
- Additional sensitivity from resonance searches ($A/H(bb, tt)$).

free parameters

- m_A : mass of heavy pseudoscalar **A**
- m_a : mass of mediator **a**
- $\sin\theta$: mixing angle between **a** and **A**
- $\tan\beta$: ratio of VEVs of the two Higgs doublets.

2HDM + a

Interesting kinematic dependence on model parameter suggests multiple parameters scans are of interest.



Experimental searches: $E_T^{\text{miss}} + H(bb)$

$E_T^{\text{miss}} + H(bb)$

2015-2017 data!

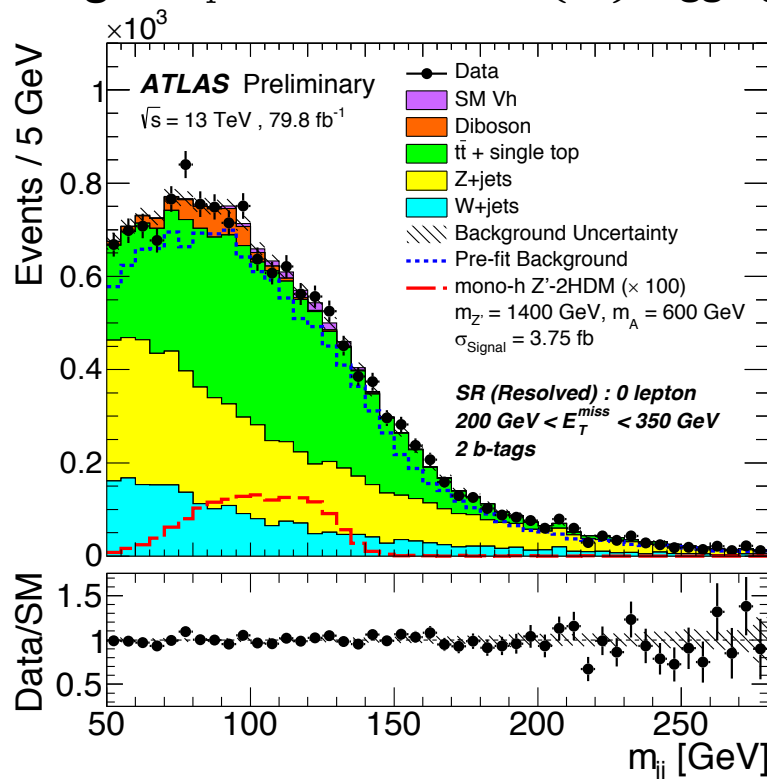
Mono-Higgs signal provides direct probe of DM-SM coupling,
 $H \rightarrow bb$ dominant decay mode.

Selection & Strategy

Resolved and **Merged** analyses defined.

Resolved: $150 < E_T^{\text{miss}} < 500$ GeV (3 bins)

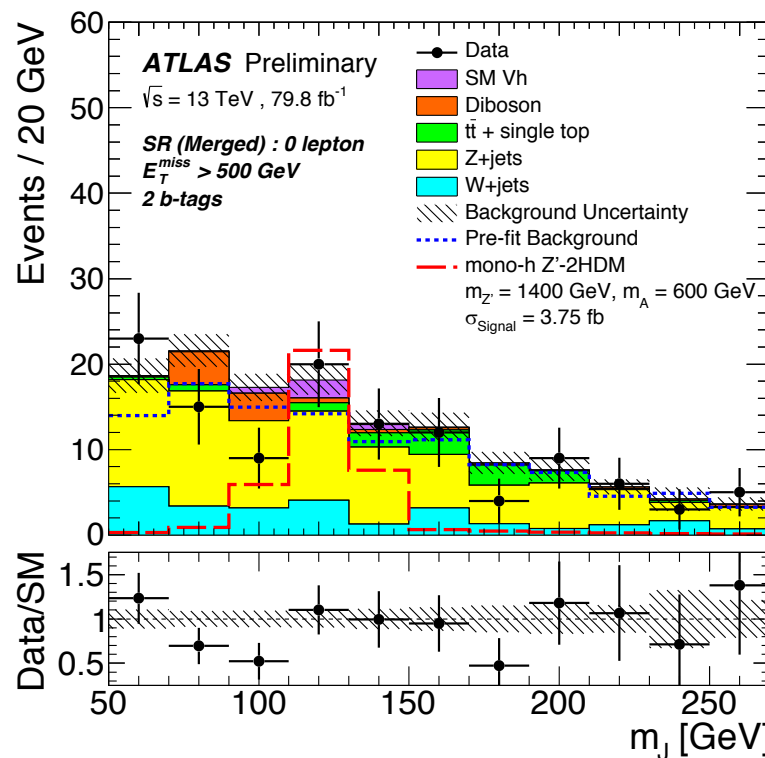
Merged: $E_T^{\text{miss}} > 500$ GeV + $h(bb)$ tagging.



Resolved region: two distinctive b-jets.

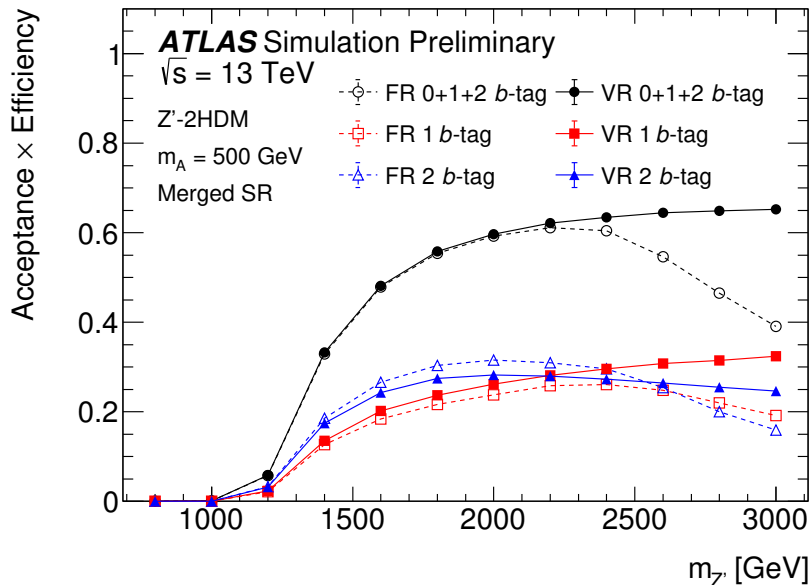
Multiple CR and SR defined by the leptons and
N(b-jets) multiplicity and E_T^{miss} regions.

Simultaneous m_{ij}/m_j shape fit in all regions.

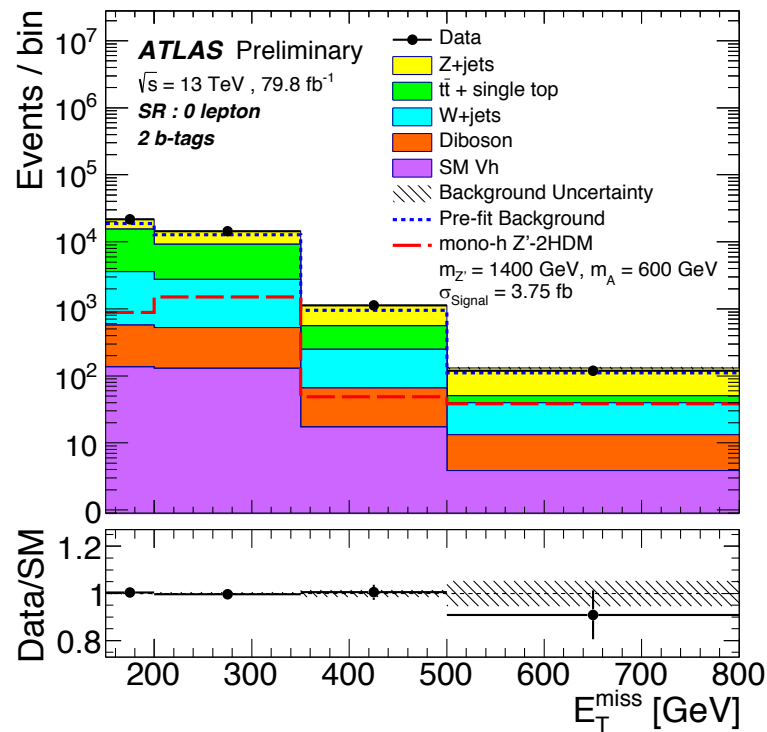
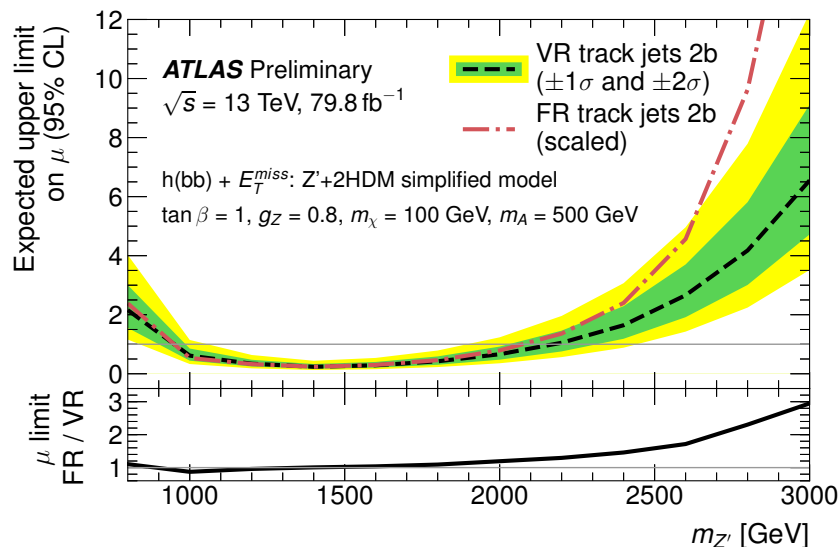


Merged region: boosted Higgs $\rightarrow$ large- R jet
with substructure selection.

Experimental searches: $E_T^{\text{miss}} + H(bb)$



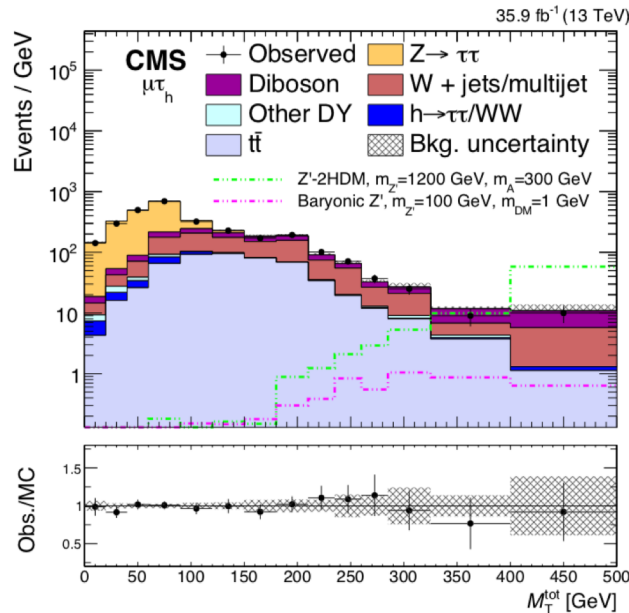
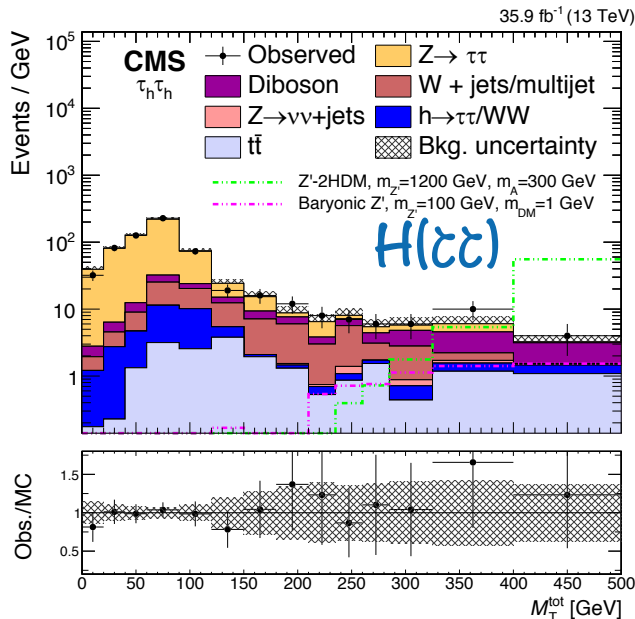
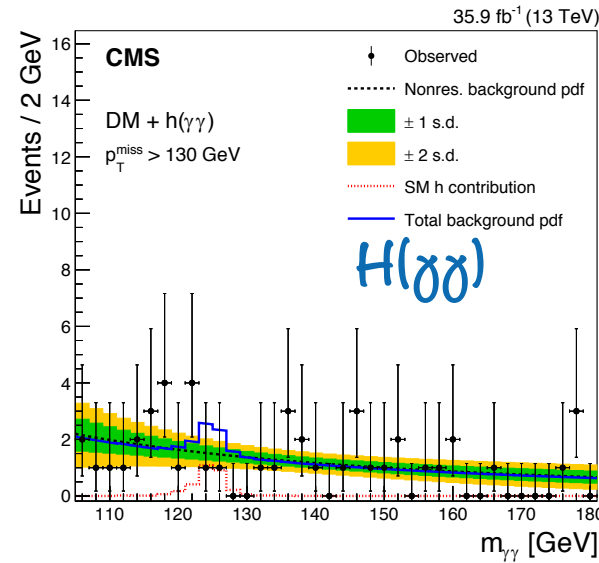
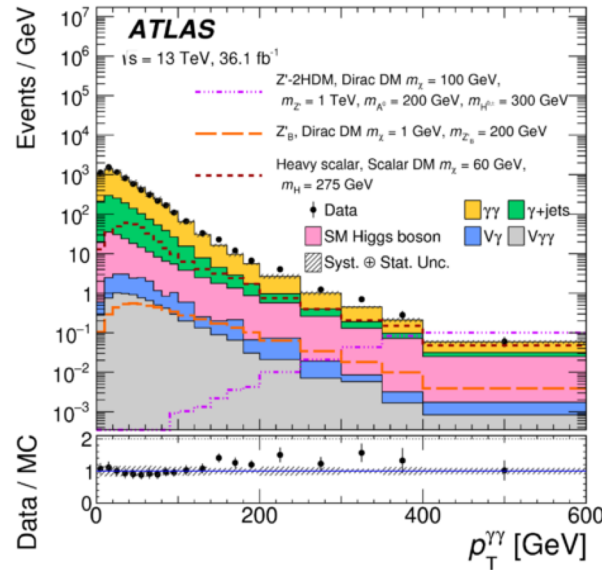
In the merged region the reconstruction of these subjects is based on a jet algorithm using tracks as inputs and a radius parameter that decreases as the subject p_T increases.



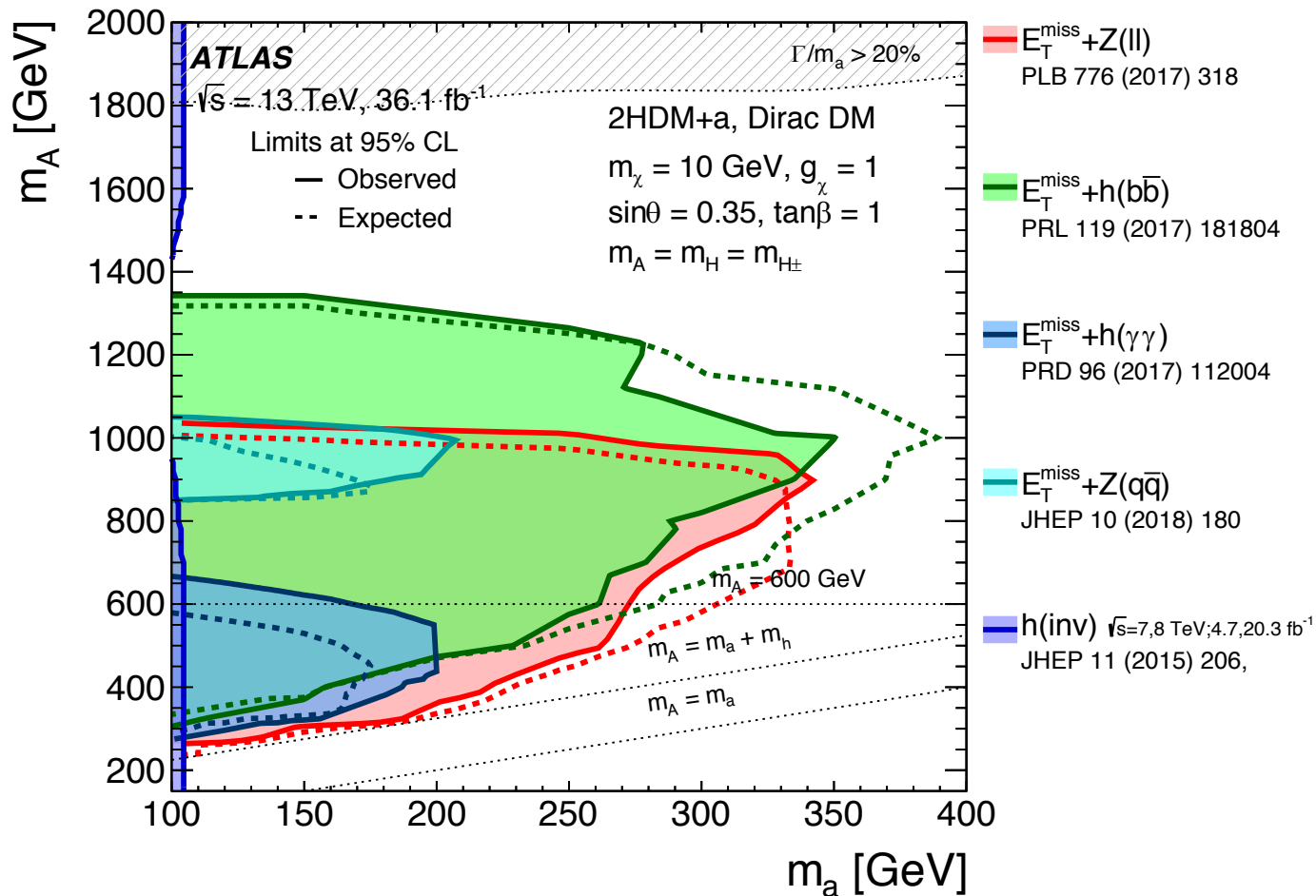
Experimental searches: $E_T^{\text{miss}} + H(\gamma\gamma, \tau\tau)$

$$E_T^{\text{miss}} + H(\gamma\gamma, \tau\tau)$$

Both CMS and ATLAS do a search for $E_T^{\text{miss}} + H(\gamma\gamma)$, by selecting a pair of photons with an invariant mass close to $m_h = 125 \text{ GeV}$. Backgrounds are extracted by fitting an analytic function to the $m_{\gamma\gamma}$ distribution.



CMS also performs a search for $E_T^{\text{miss}} + H(\tau\tau)$, and combines it with $E_T^{\text{miss}} + H(\gamma\gamma)$ results. It combines 3 final states: $e\tau_{\text{had}}$, $\mu\tau_{\text{had}}$, $\tau_{\text{had}}\tau_{\text{had}}$. Limits extracted from fit to total transverse mass distribution.

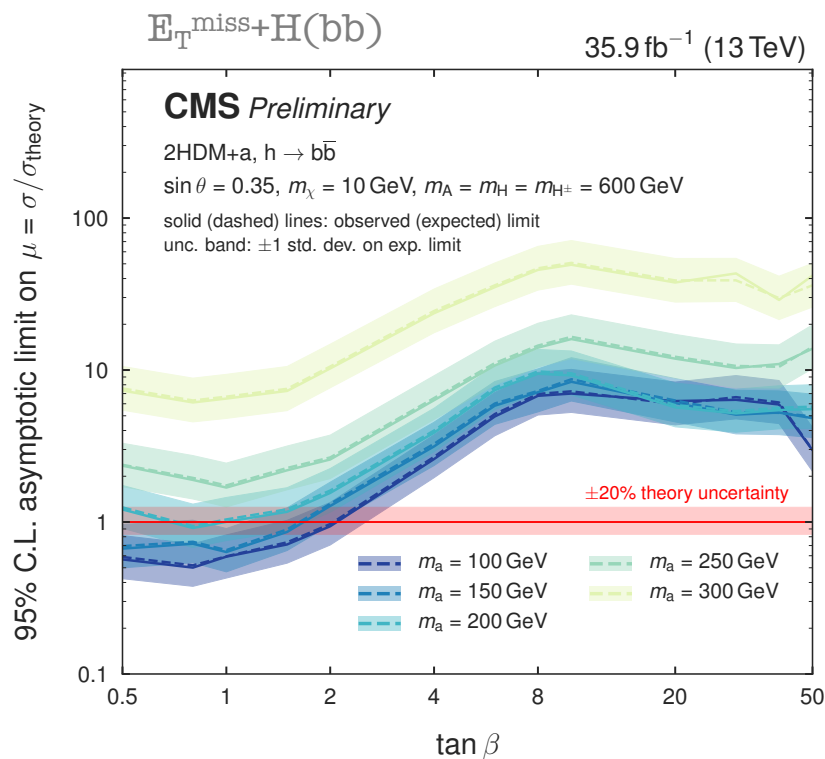


Assuming $\tan\beta=1$ and $\sin\theta=0.35$, scanning the masses of **A** and **a**.

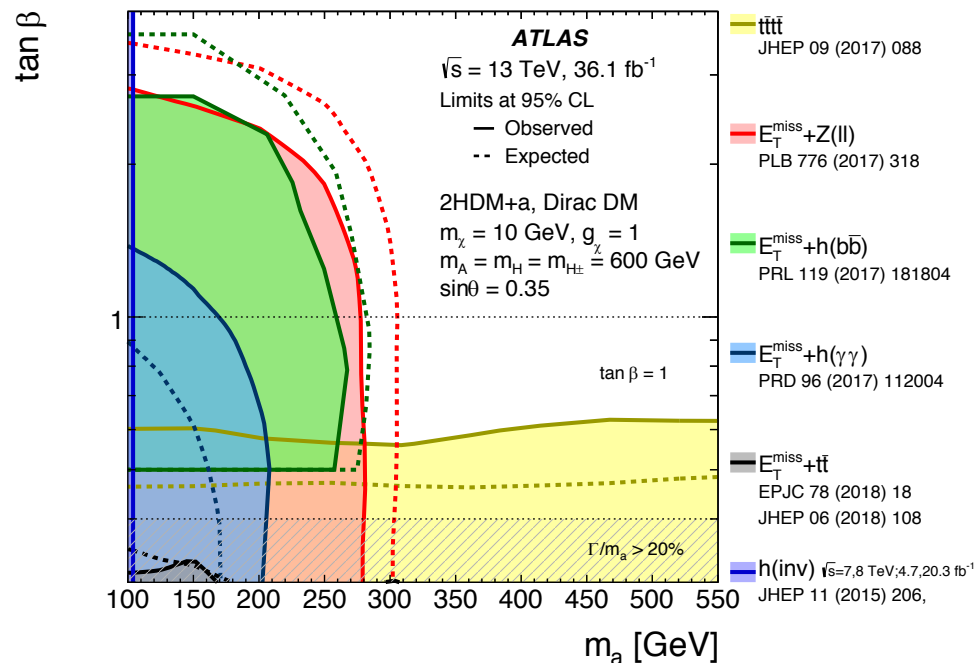
Exclusion sensitivity dominated by $E_T^{\text{miss}} + Z(\ell\ell)$ and $E_T^{\text{miss}} + H(bb)$.

$h(\text{invisible})$ BR limits used to constrain very low values of m_a , being only sensitive to the **a** boson production cross section.

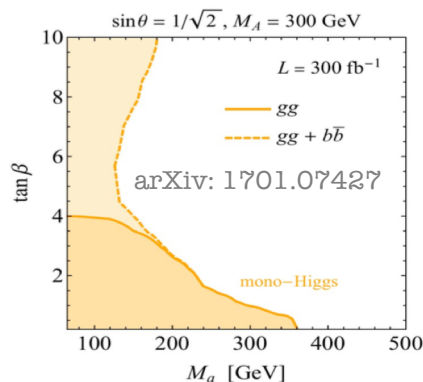
Parameter chosen to have H and Z produced resonantly, dominating exclusion at low m_a .



Using 2015+2016 data results in ATLAS.



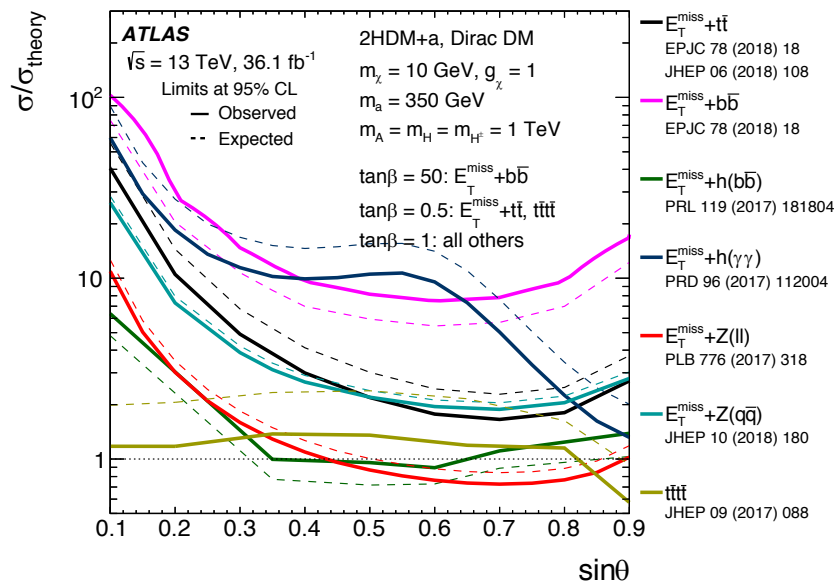
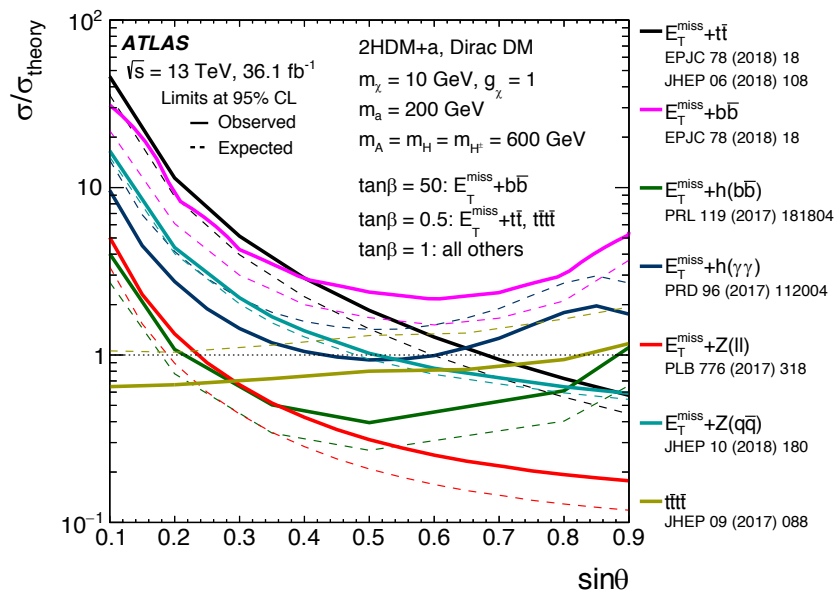
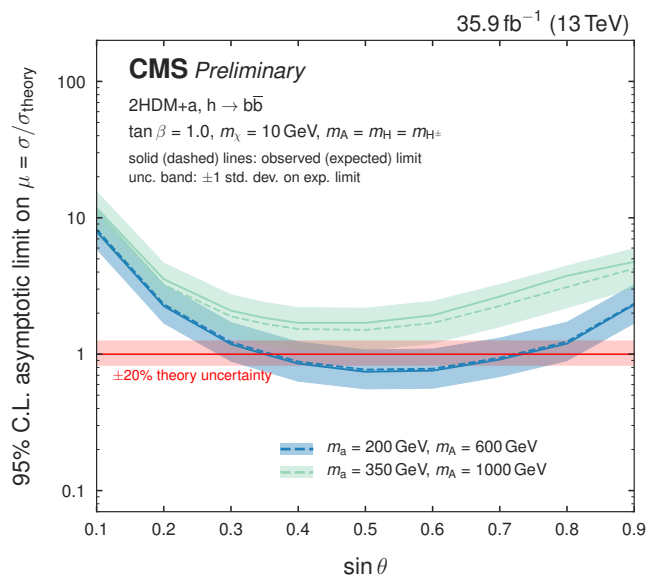
**Only gg fusion production considered in this ATLAS plot.*



Interplay between gg
fusion and bb
annihilation production
along $\tan \beta$.

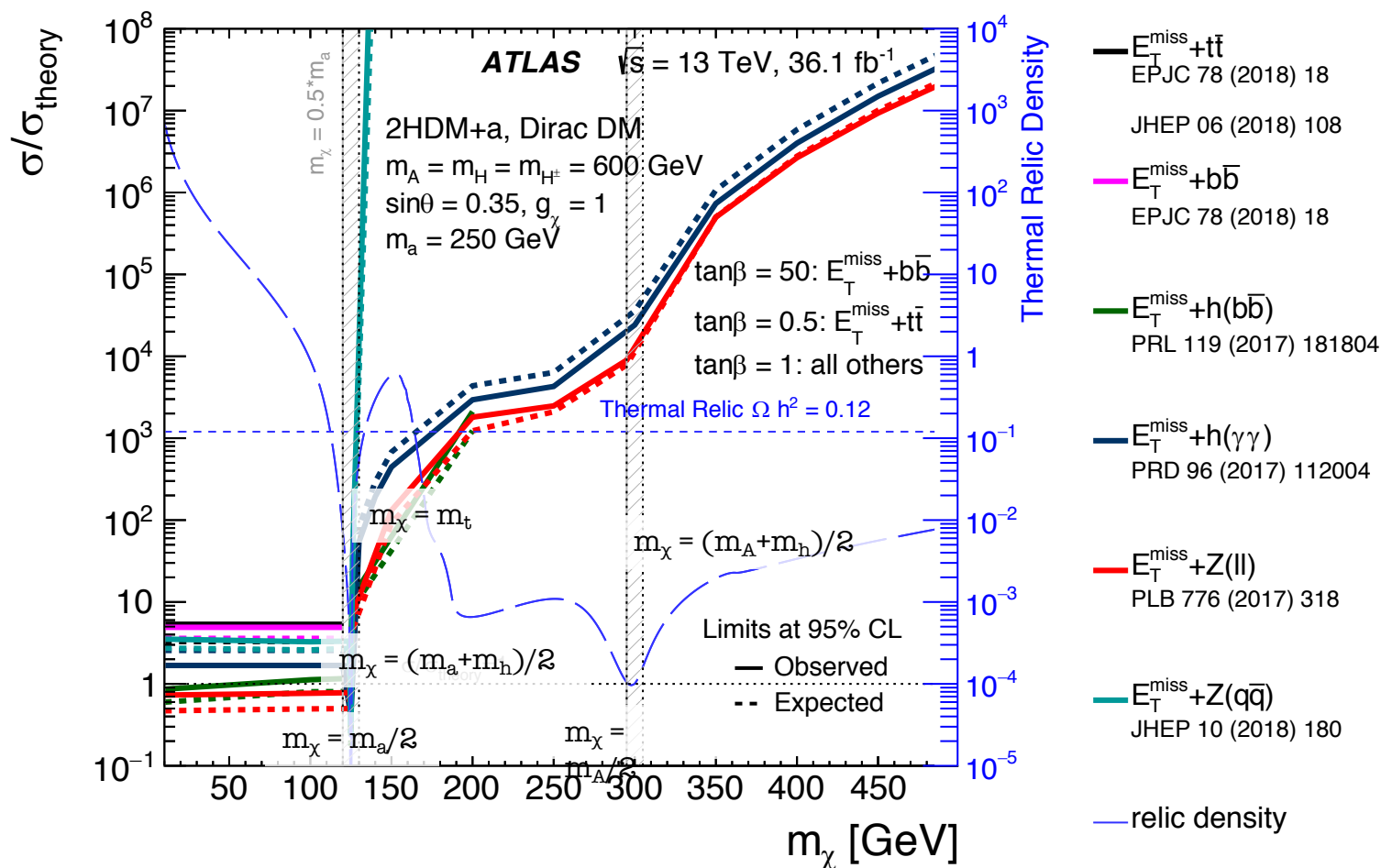
Exploring mixing angle $\sin\theta$

- The production diagrams for $E_T^{\text{miss}}+h$ have different dependence on the mixing angle (low and high m_a assumptions).
- The sensitivity of $E_T^{\text{miss}}+Z$ analyses improves as a function of $\sin\theta$.
- Other signatures presented for different $\tan\beta$ assumptions.



*Relic density predicted by **2HDM+a** has a strong dependence on m_χ*

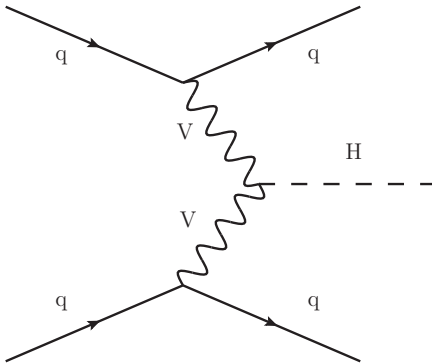
Two **a**-funnel and **A**-funnel regions at $m_\chi=125$ GeV and $m_\chi=300$ GeV, respectively (relic density depleted by the resonant enhancement of $\chi\chi \rightarrow A/a \rightarrow \text{SM}$).



Higgs to invisible

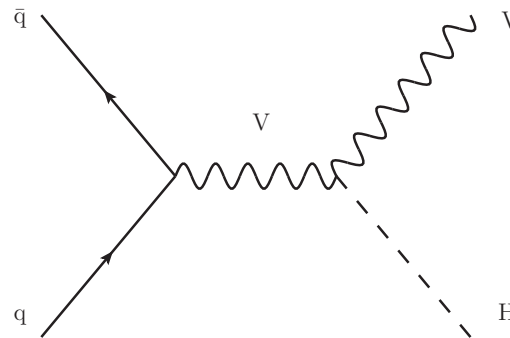
- Many beyond Standard Model theories predict Higgs boson decays to invisible final states, with the final state particles being the DM candidates.
 - Higgs portal model:** Higgs boson mediates the interaction between DM and SM.
- Current limits on branching ratios (BR) still leave room for BSM properties
→ this decay channel is an excellent search channel for new physics.
 - SM BR is $\sim 0.12\%$ (4ν).
 - It can also be used to probe deviations from SM Higgs couplings.

Production modes



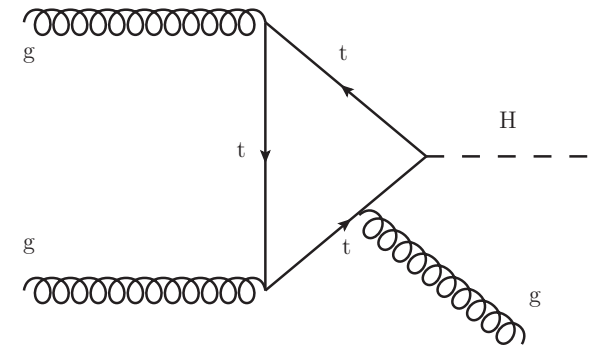
Vector Boson Fusion

$$E_T^{miss} + 2 \text{ jets}$$



Associated VH prod.

$$E_T^{miss} + Z/W (\ell\ell, qq)$$



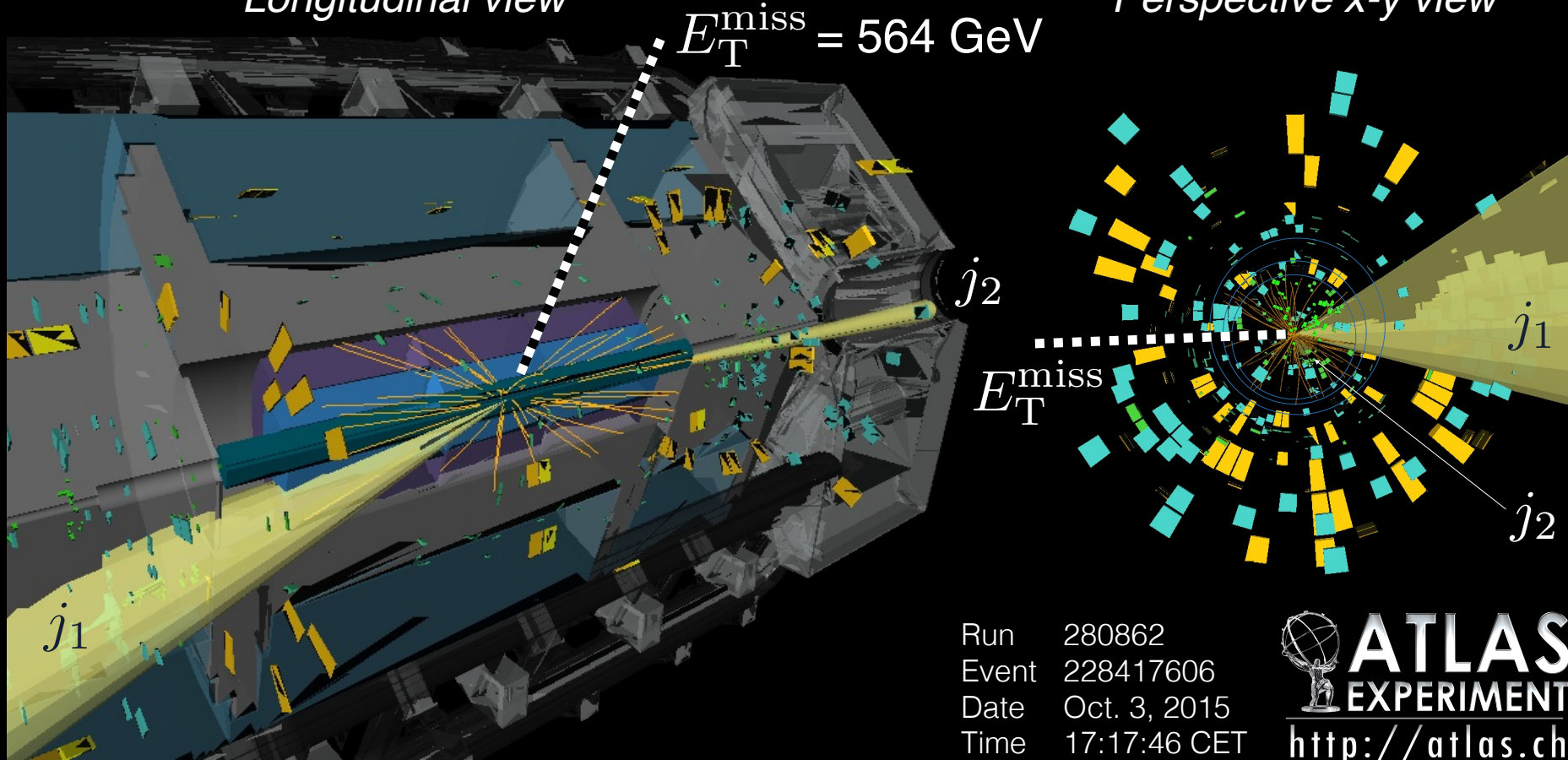
gluon-gluon fusion

$$E_T^{miss} + \text{jet}$$

Candidate in signal region of $H \rightarrow \chi\bar{\chi}$ with two VBF jets ($m_{jj} = 3.6$ TeV)

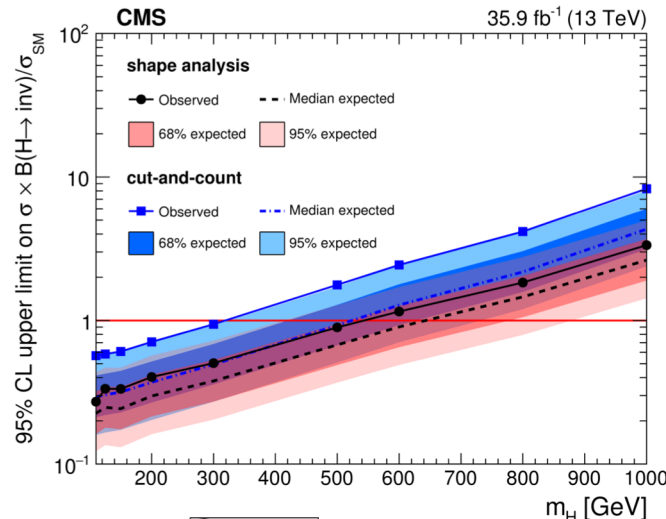
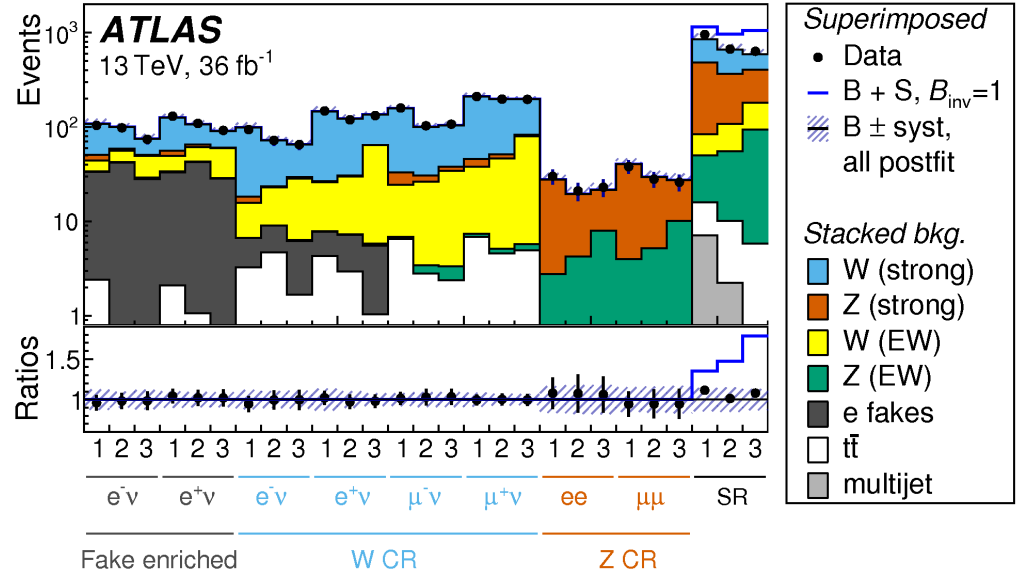
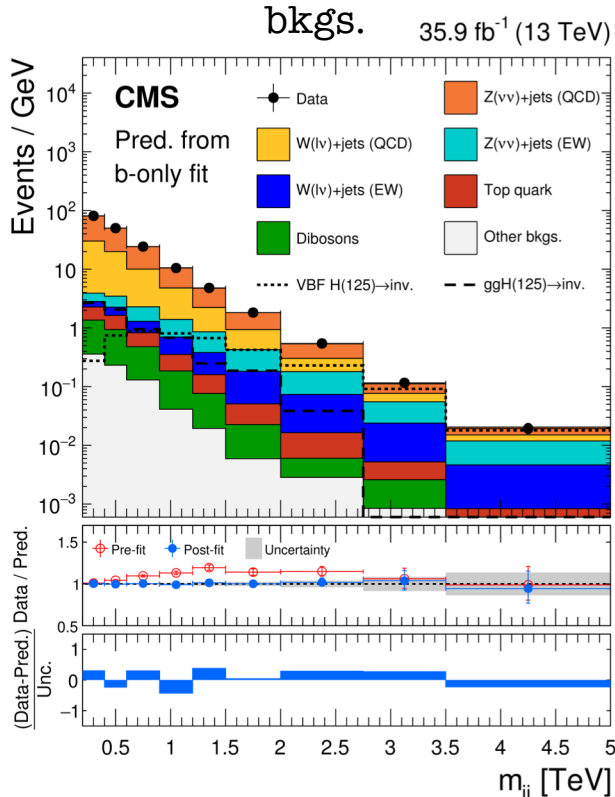
Longitudinal view

Perspective x-y view



$E_T^{\text{miss}} + \text{VBF}$

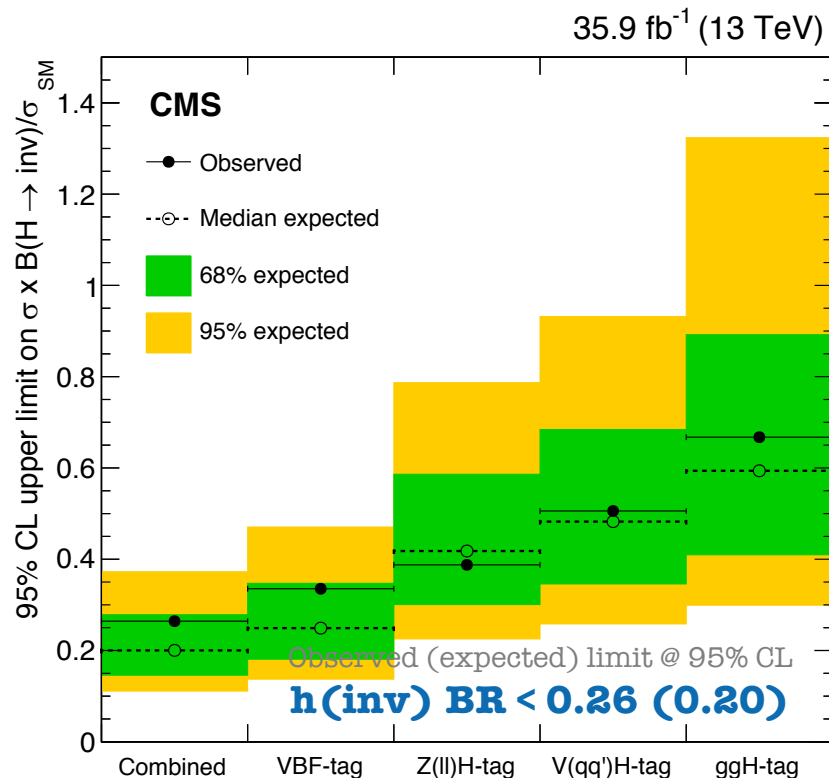
Analyses based in a combined fit of multiple control and signal regions. Control regions are defined with 1-2 leptons to constrain W/Z+jets



Both analyses employ a shape fit of the dijet mass distribution, which brings additional sensitivity to the final result.

Higgs $\rightarrow$ invisible

The 2016 data results from VBF, VH associated production and gg fusion searches are combined.

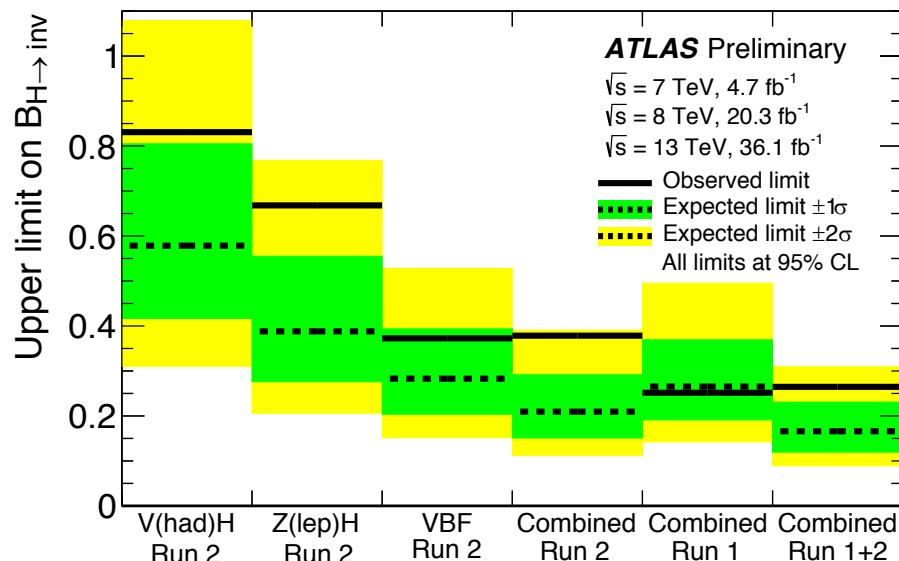


From the combined measurements of the Higgs boson couplings (2016 data),
visible+invisible combination

Observed (expected) limit @ 95% CL
 $H(\text{inv}) \text{ BR} < 0.22 \text{ (0.17)}$

New combination from ATLAS!
Run 1 + Run 2 (2015-2016) result:

Observed (expected) limit @ 95% CL
 $H(\text{inv}) \text{ BR} < 0.26 \text{ (0.17)}$

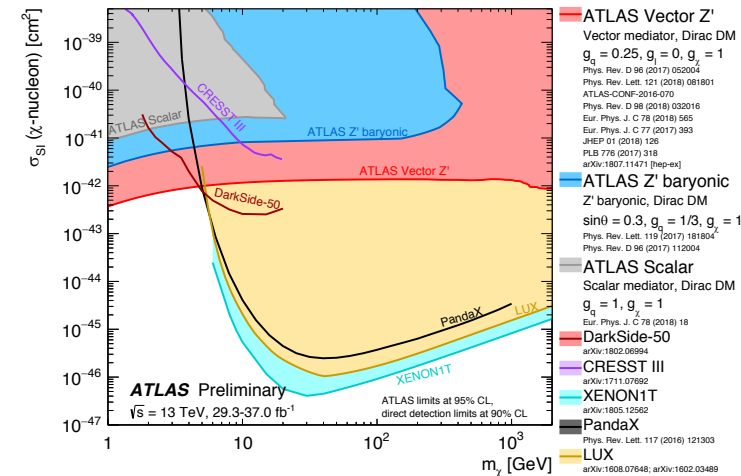
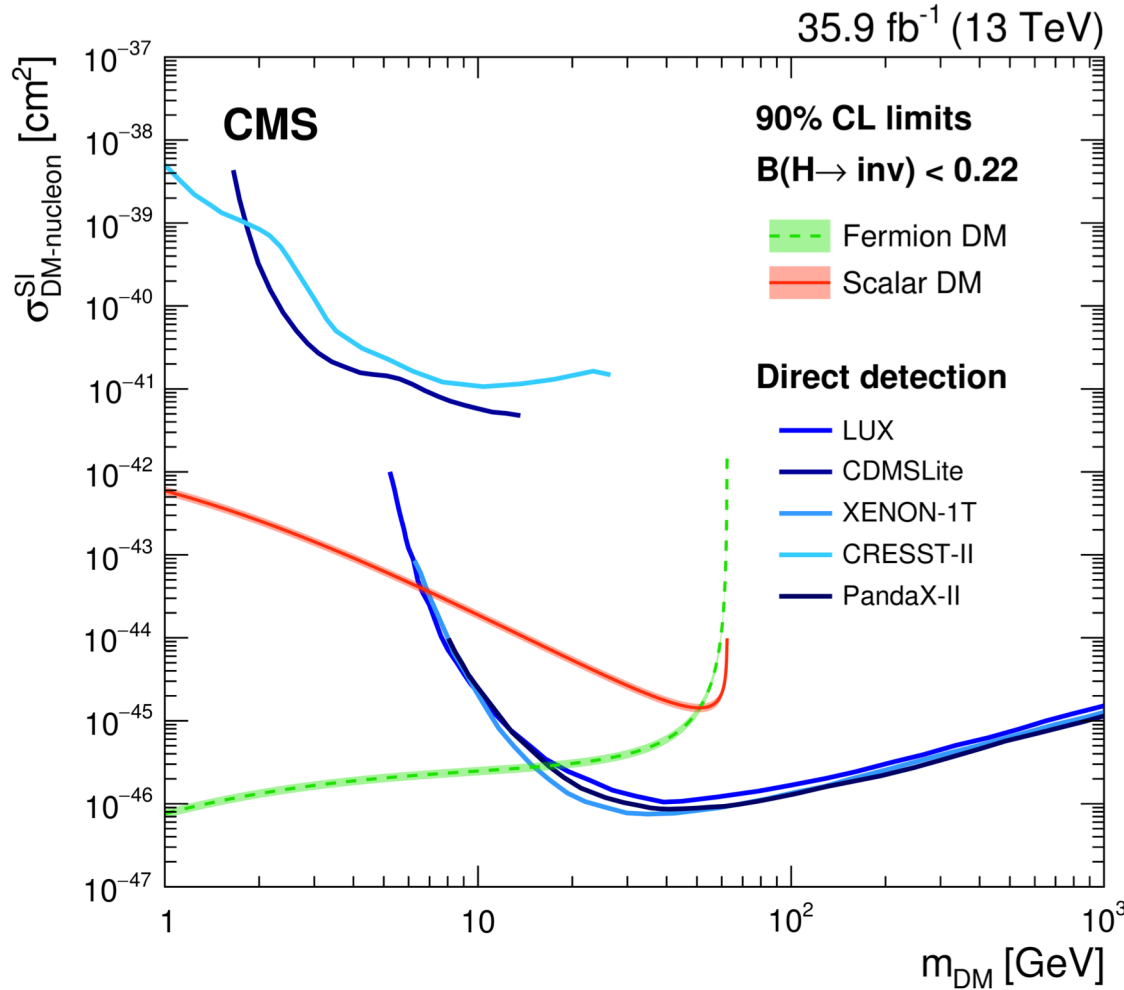


Two different combination yielding similar
(expected) sensitivity.



2016 combination

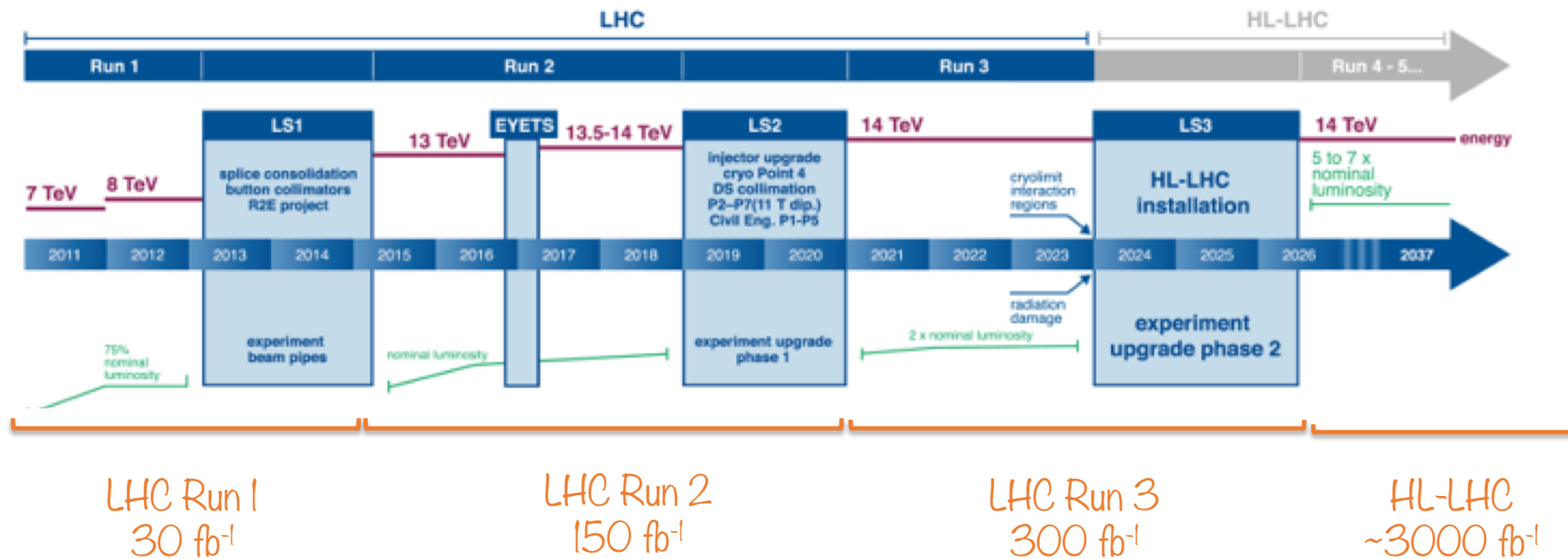
Observed limit @ **90% CL**
 $H(\text{inv}) \text{ BR} < 0.22 \text{ (obs)}$



Looking forward...

- Exciting new results from ATLAS and CMS collaborations!
 - Introduced simplified models for interpretation of Dark Matter searches at the start of Run 2.
 - Now: new generation of UV complete models being explored for the Run 2 legacy analyses.
- Many other DM models not discussed.
 - Scalar/Pseudoscalar mediator, vector baryon charged mediator, 2HDZ', ...
 - SUSY naturally includes a DM candidate. E.g. in GMSB scenarios the gravitino is often the LSP, thus a DM candidate.
 - Multiple models predicting long-lived particles signatures now being explored (more challenging reconstruction/triggering!).
- New 2HDM+a model probed with 2015+2016 data... improved sensitivity expected for full LHC run 2 dataset.
 - This model highlights complementarity between different signatures, both $E_T^{\text{miss}} + X$ and resonance searches.
 - Great prospects for future exploration of the parameters space.

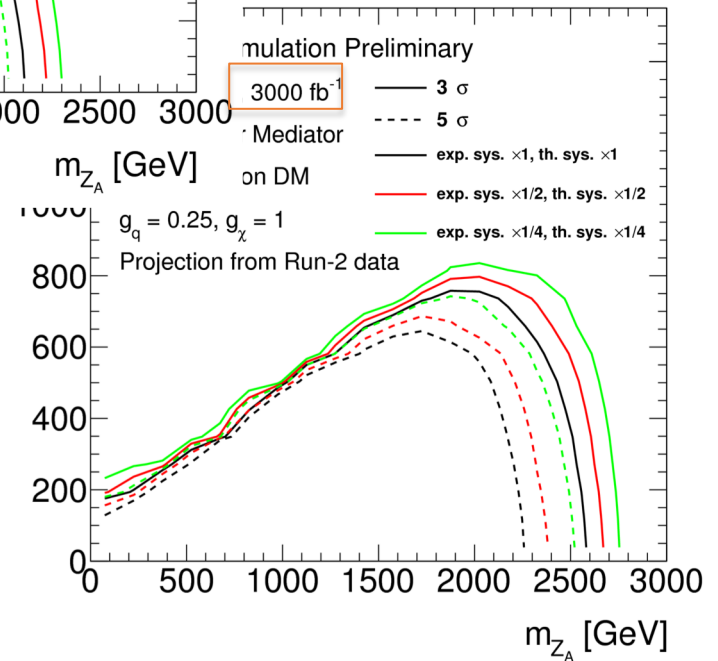
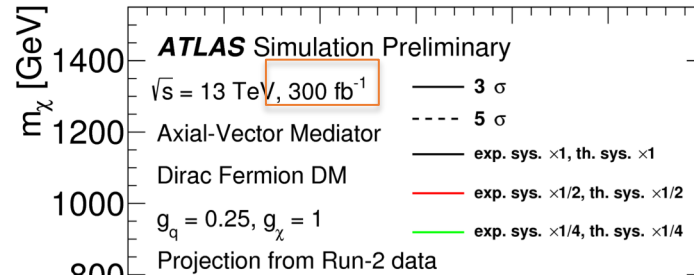
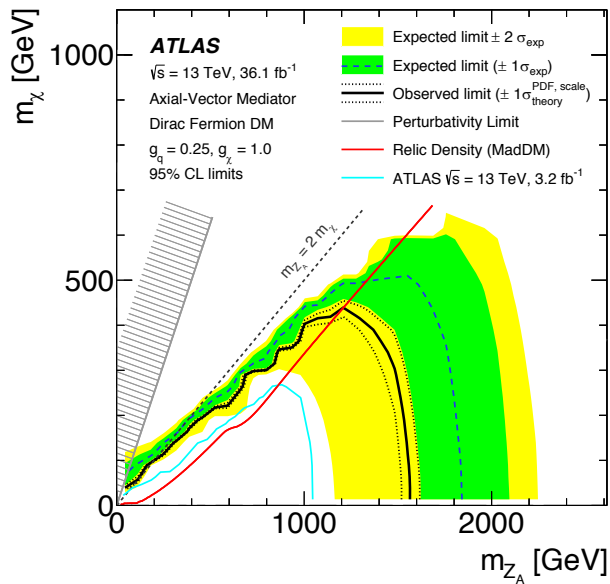
LHC legacy



Legacy discoveries/measurements?

Beyond the LHC

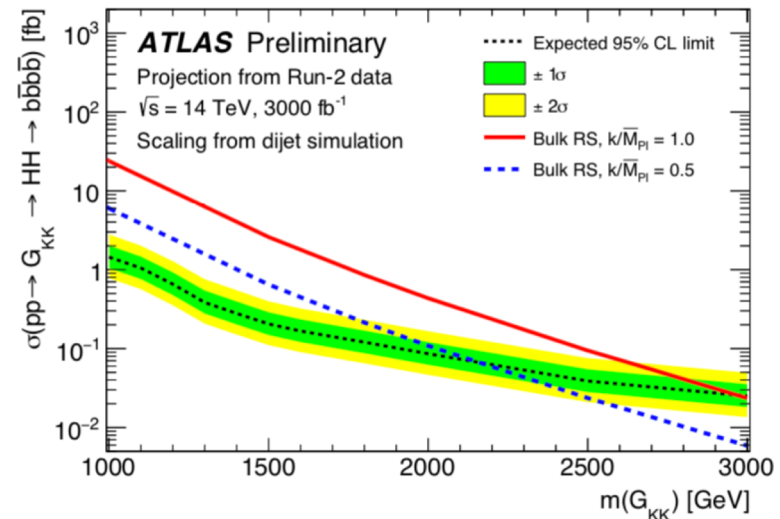
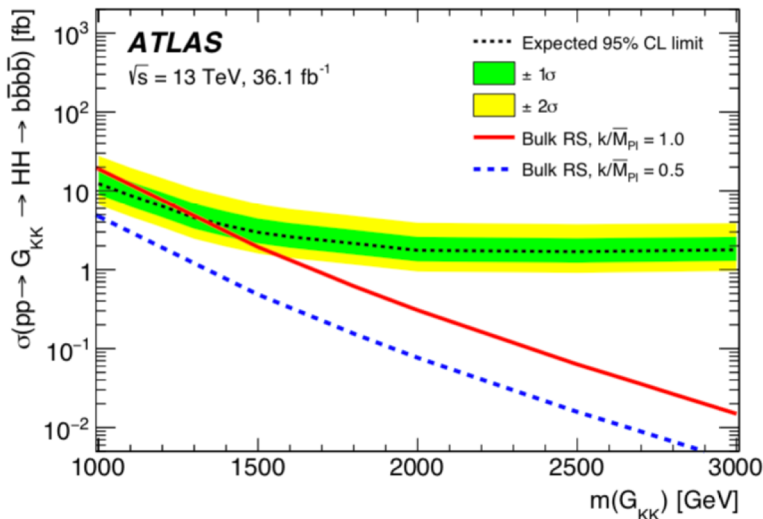
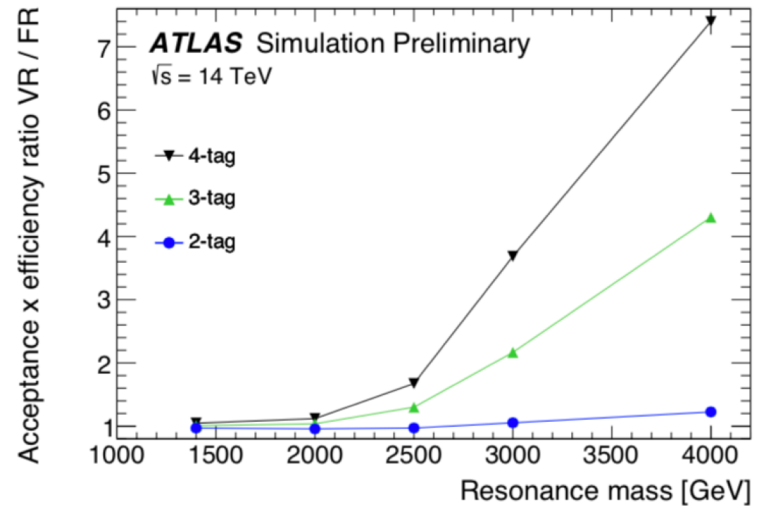
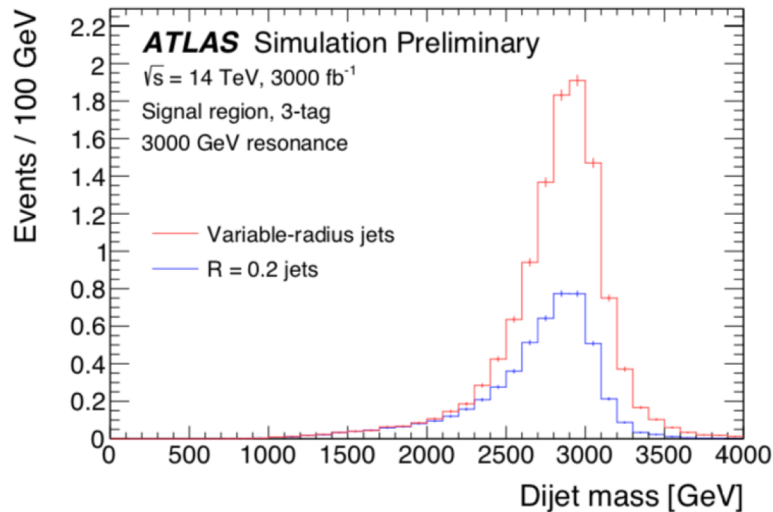
$E_{T\text{miss}} + \text{jet}$



Beyond the LHC

$HH(bbbb)$

Improvements using the variable radius jets
(as recently introduced in the $E_T^{\text{miss}} + H(bb)$ analysis).

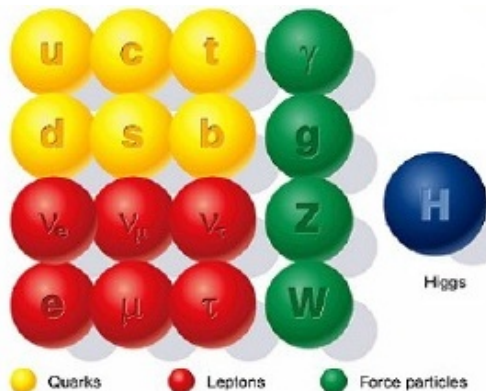




Thank you!

SUSY-inspired models

Standard Model

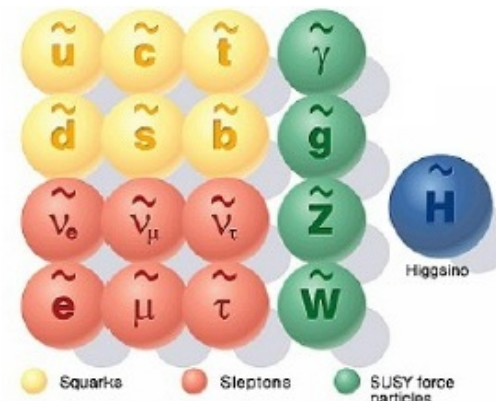


Superpartner

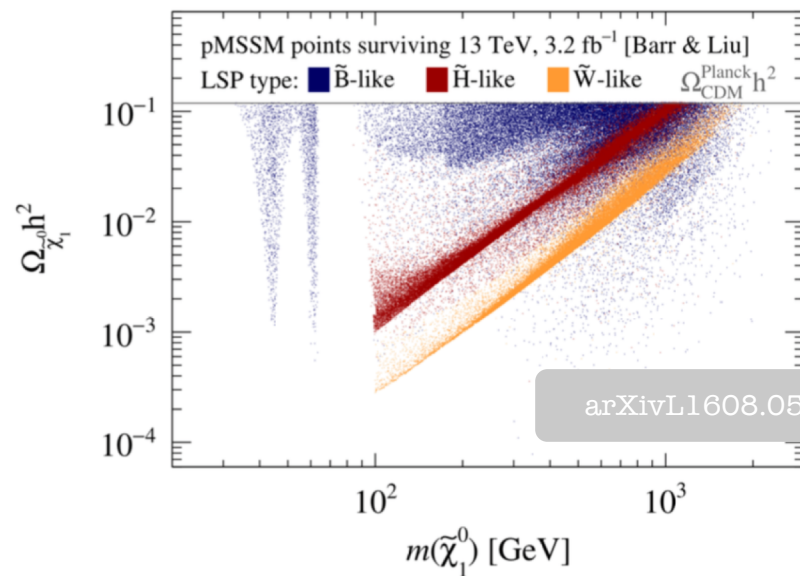
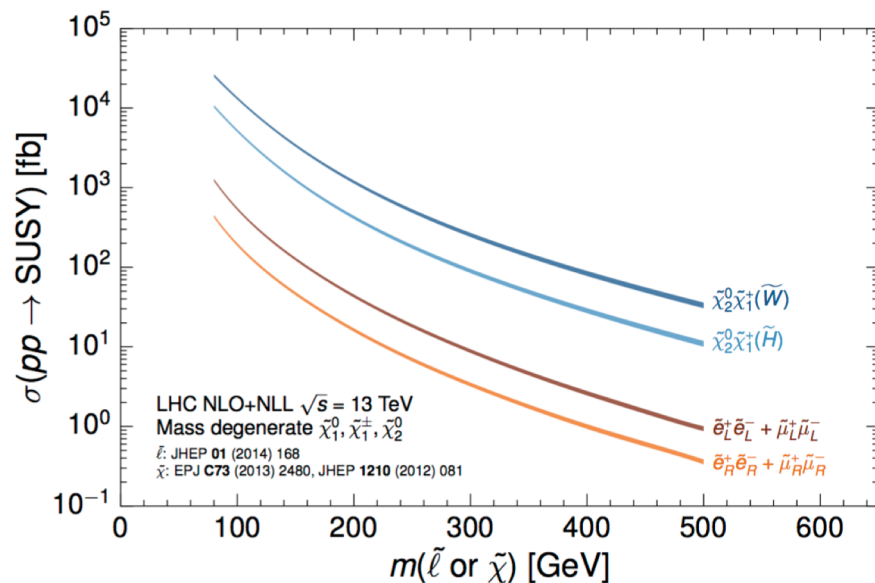
for every SM particle.

- Spin differs by one half.
- Mostly heavier than SM partners [broken symmetry].

SUSY



While SM does not have a viable DM candidate, in SUSY if R-parity is conserved, lightest SUSY particle (LSP) is stable $\rightarrow$ Good candidate for Dark Matter.



arXiv:1608.05379

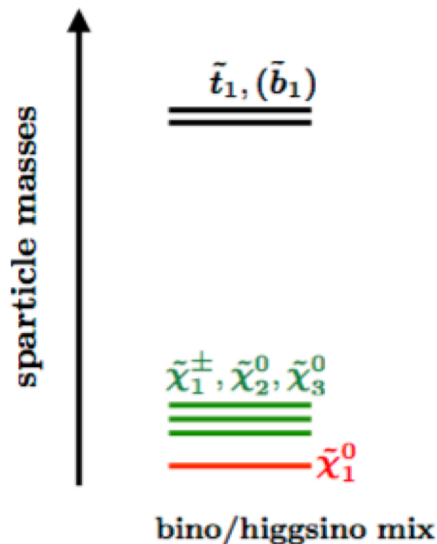
SUSY-inspired models

Electroweak sector

$\tilde{B}$ (bino), $\tilde{W}$ (wino), $\tilde{H}$ (higgsino)

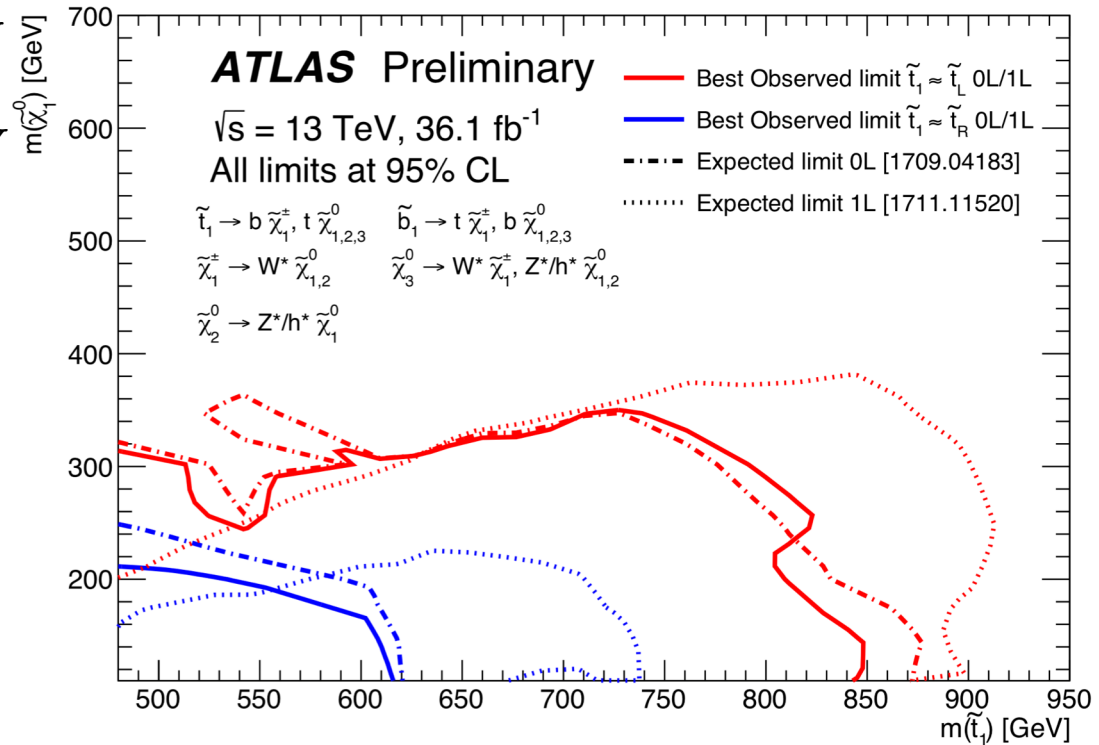
- Some models can give a relic density consistent with measurements.
- Pure higgsino obtains relic density for masses 1 TeV.
- Pure wino obtains right relic density for masses 2.5 TeV
- Bino/higgsino mix mode may satisfy the SM higgs mass and the DM relic density:*

$$0.10 < \Omega h^2 < 0.12.$$



Well-tempered neutralino SUSY model may provide a viable DM candidate, while addressing the problem of naturalness by targeting an LSP which is an admixture of bino and higgsino.

Bino/Higgsino Mix Model: $\tilde{t}_1\tilde{t}_1^*, \tilde{b}_1\tilde{b}_1^*$ production, $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 20\text{--}50$ GeV, March 2018

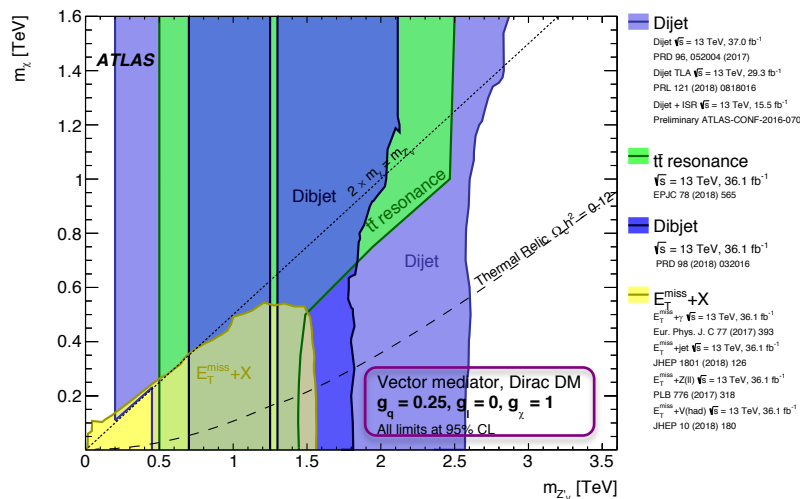


Simplified Model

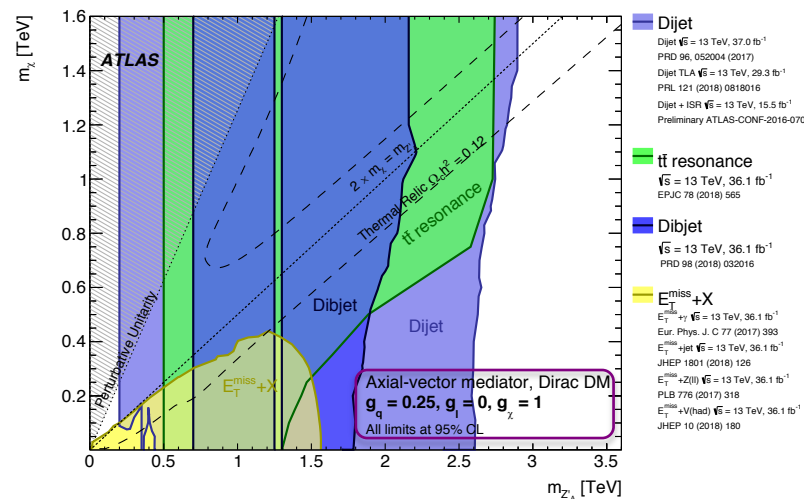
Scanning the mass-mass plane for different operators (V/AV) and different choices of couplings.

Leptophobic

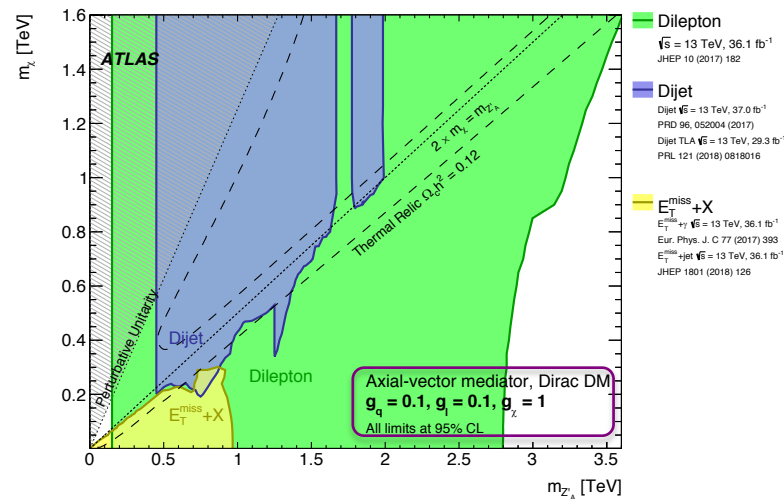
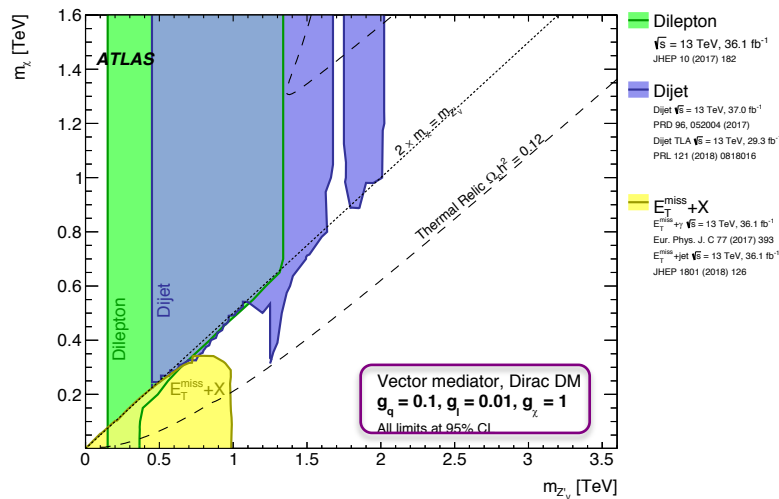
Vector



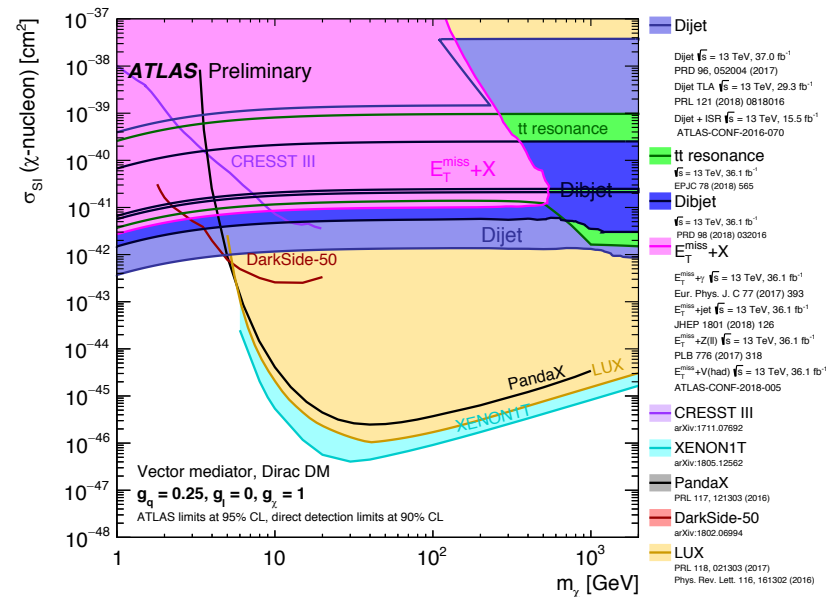
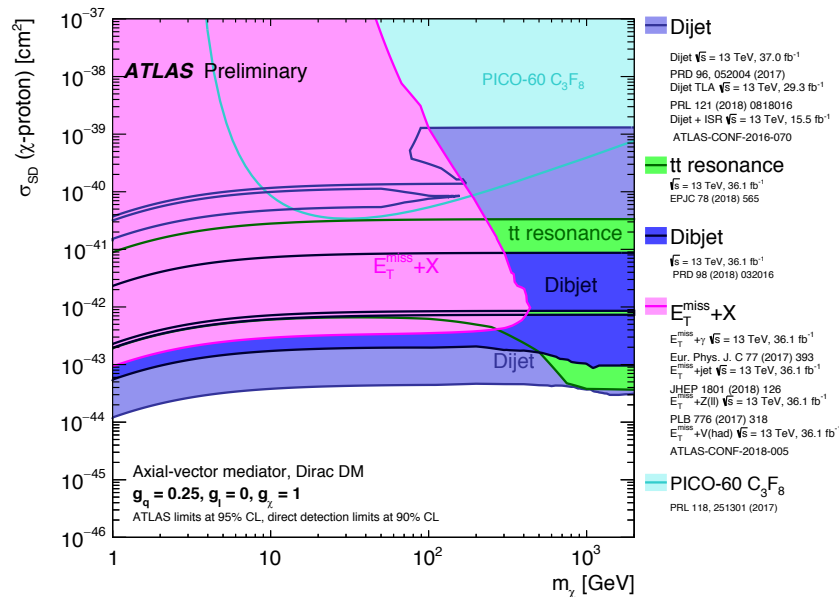
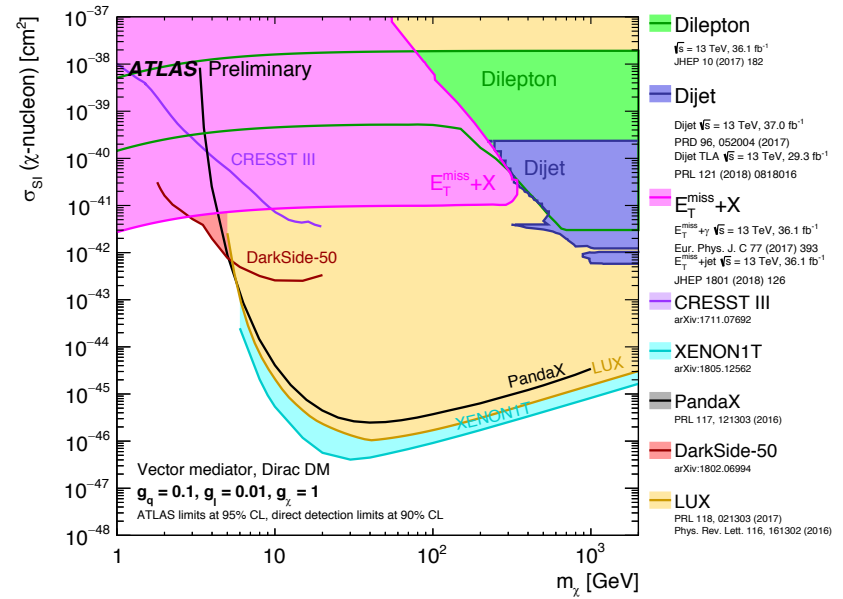
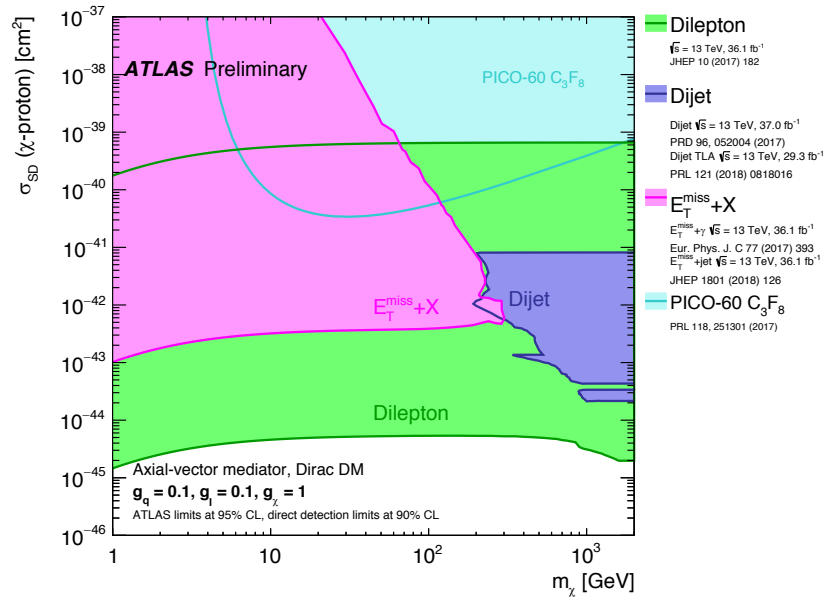
Axial-vector



Leptophilic

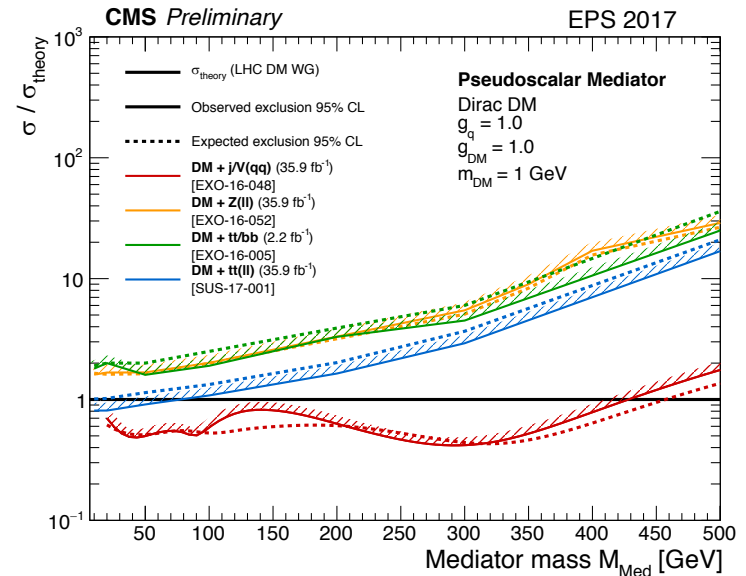
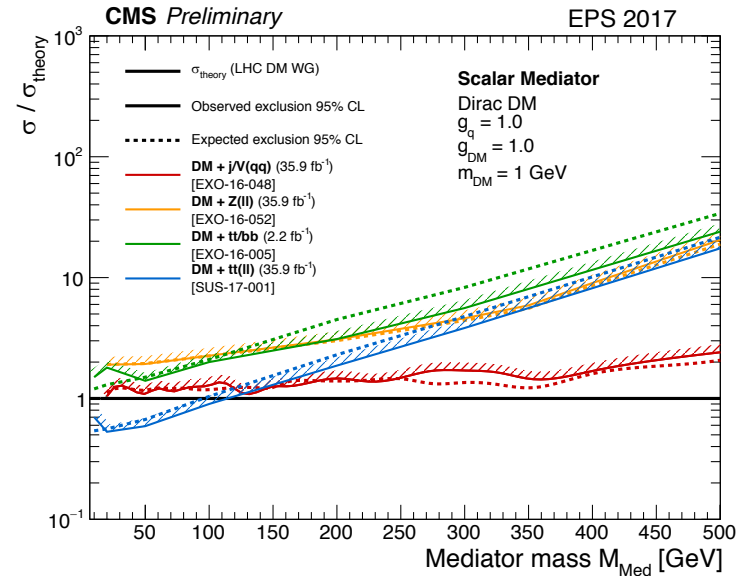
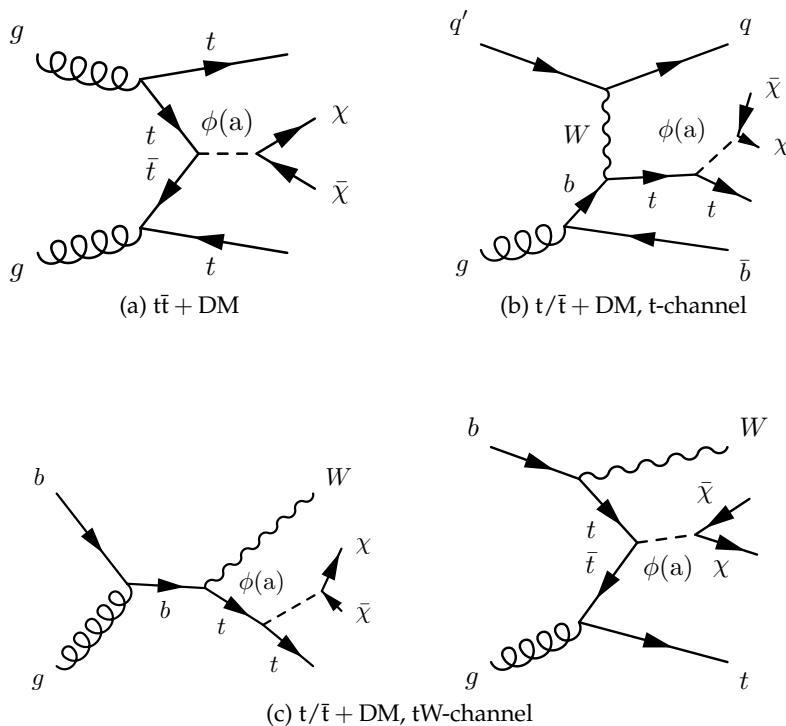


Simplified Model



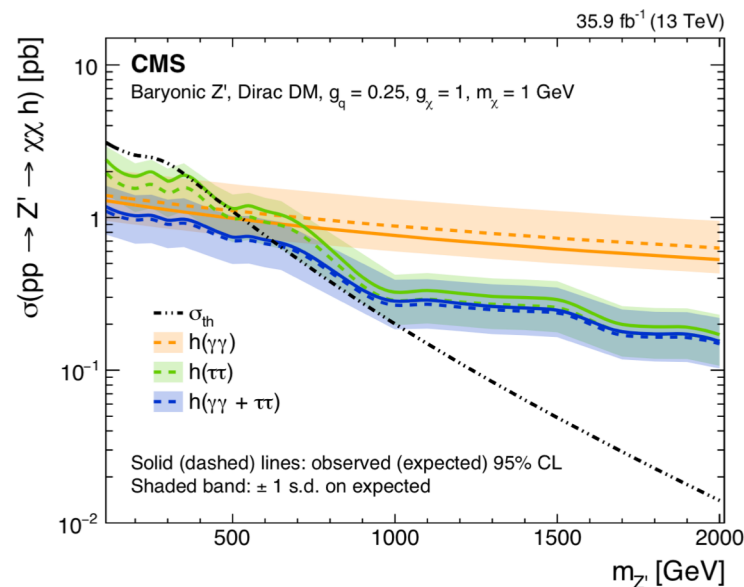
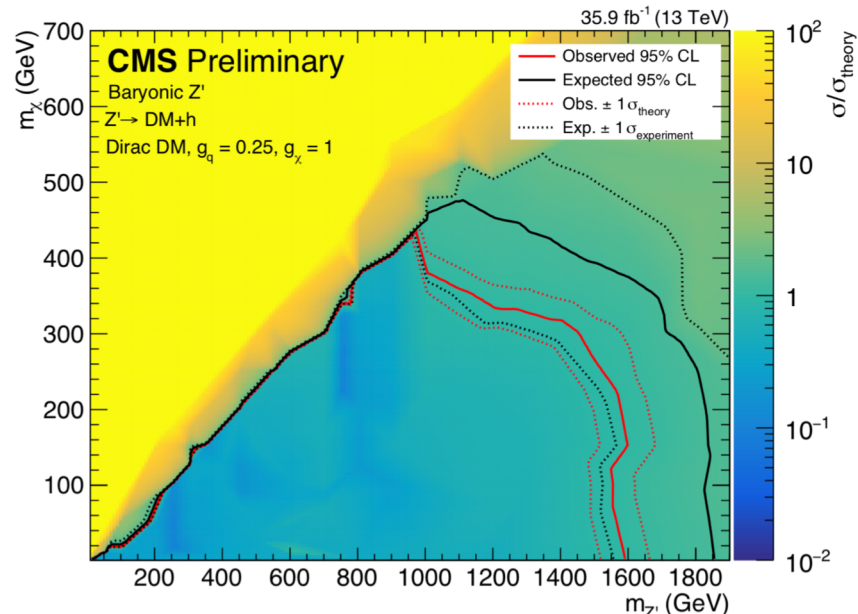
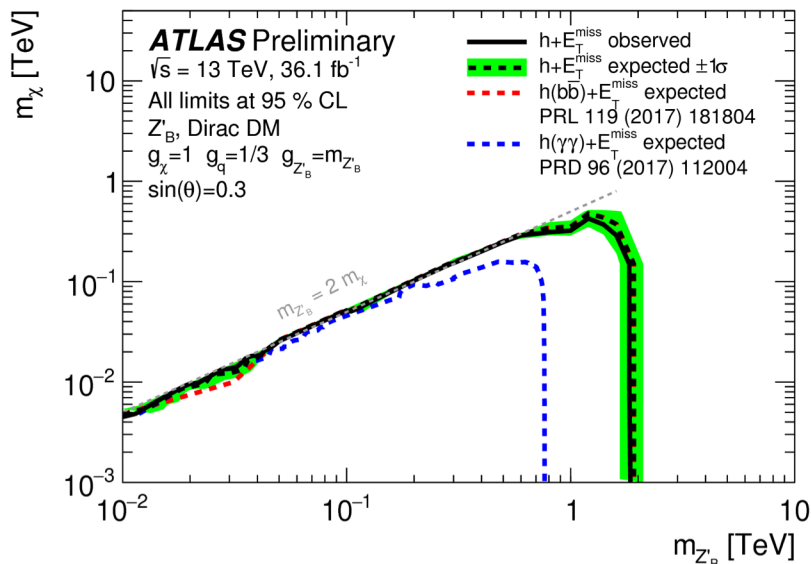
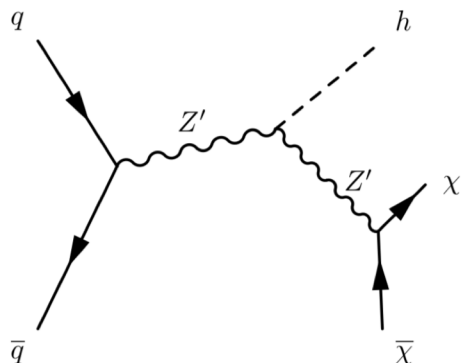
(Pseudo)scalar

Scalar and pseudo scalar mediators:
better sensitivity from $E_T^{\text{miss}} + \text{HF}$
searches.



Baryonic Z'

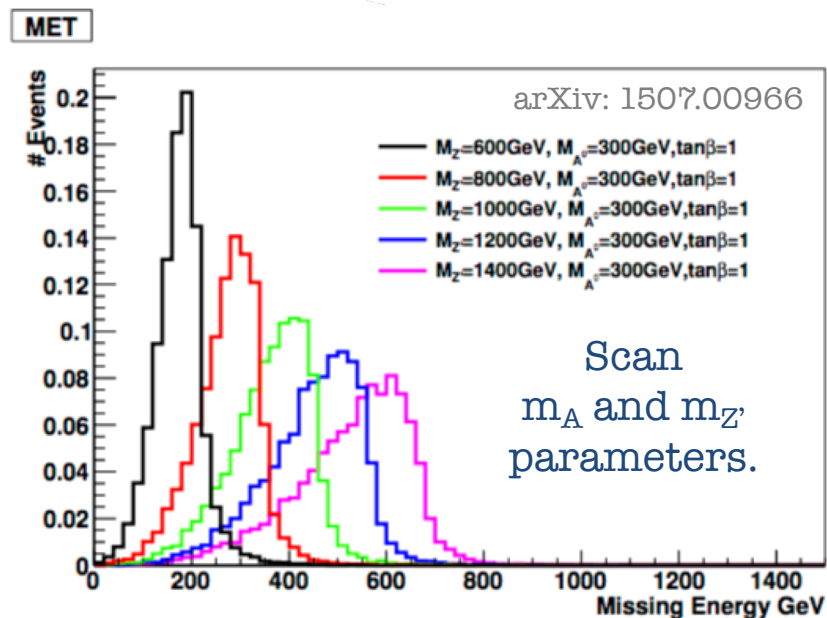
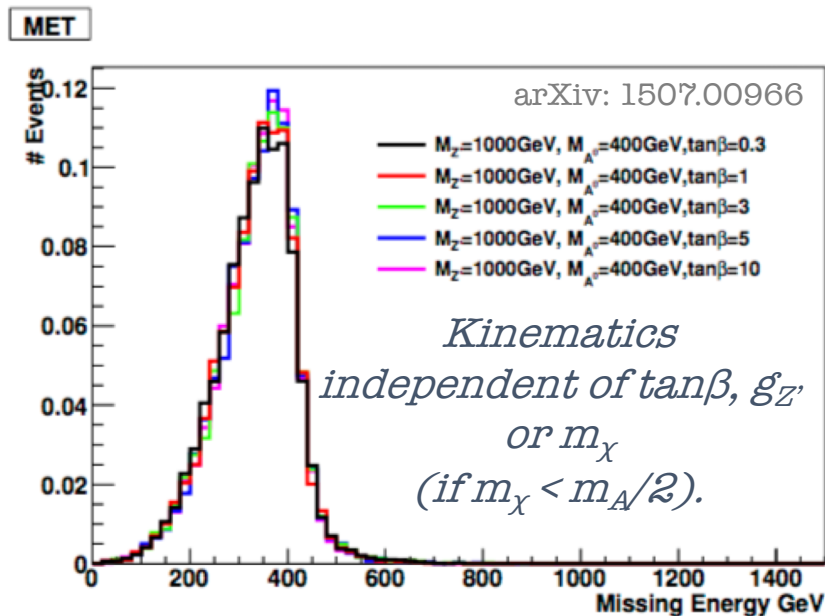
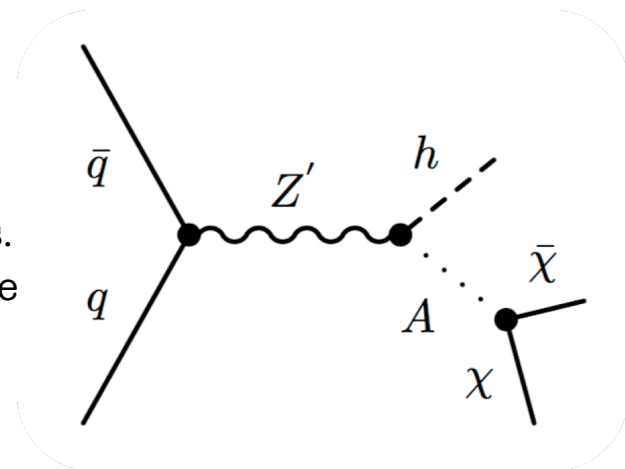
The **baryonic gauge boson Z'_B** arises from a new $U(1)_B$ baryon symmetry. Requires to introduce baryonic Higgs (additional $g_{hZ',Z'}$ coupling). There is mixing between the h_B and SM Higgs boson.



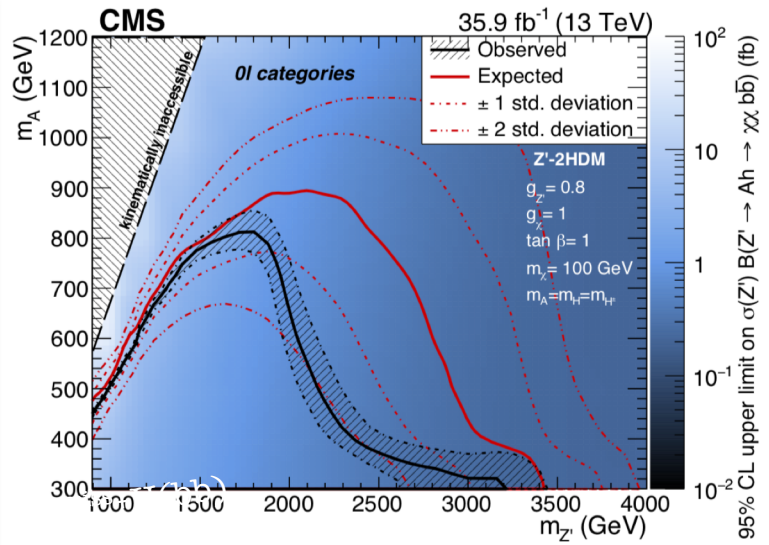
2HDM + Z'

Extension of type-II 2HDM in the alignment limit.

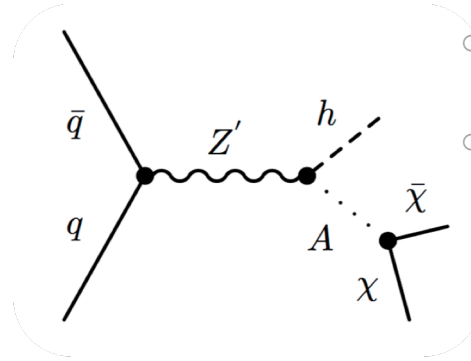
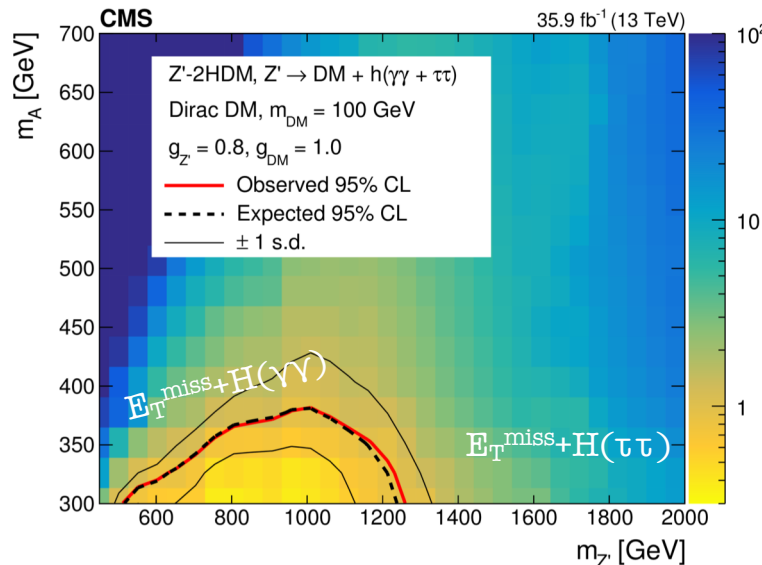
- Z' decays to a Higgs boson **h** and pseudoscalar **A** of a 2HDM ($A \rightarrow \chi\chi$).
- Assumes 2HDM for DM coupling.
 - **A** couples to DM and complies with EW precision measurements.
- Parameters: gauge coupling $g_{Z'} = 0.8$, ratio of up- and down-type vacuum expectation values, $\tan\beta = 1$, $m_\chi = 100$ GeV.
- Charged Higgs bosons: $m_{H^\pm} = 300$ GeV (CMS: $m_{H^\pm} = m_A$).



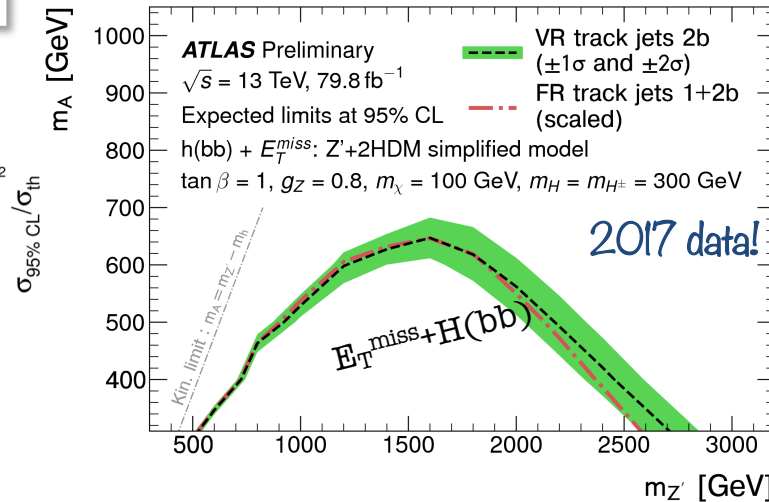
2HDM + Z'



*Best limits from CMS
heavy resonance search.*



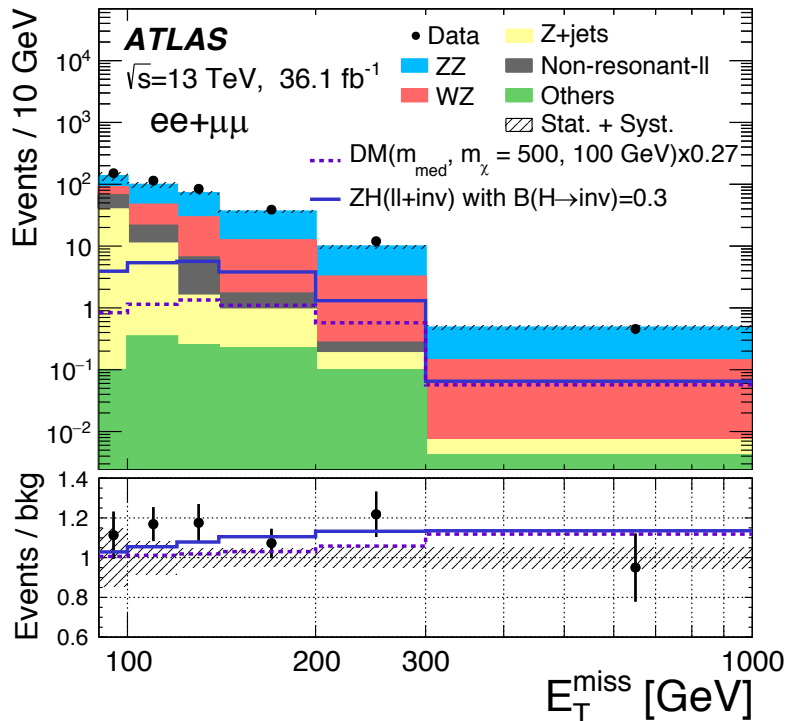
- Extension of type-II 2HDM in the alignment limit.
- Z' decays to a Higgs boson **h** and pseudoscalar **A** of a 2HDM. Assumes 2HDM for DM coupling ($A \rightarrow \chi\chi$).



ATLAS
 $E_T^{\text{miss}} + H(b\bar{b})$
analysis
improved by the
use of **variable-
radius jets**
(compared to
fixed-radius jets
used previously).

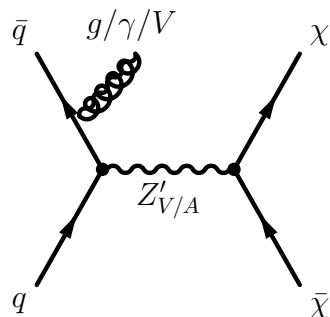
- $E_T^{\text{miss}} + H(\gamma\gamma)$ has better sensitivity at low $m_{Z'}$.
- CMS also includes results from $E_T^{\text{miss}} + H(\tau\tau)$ covering the $\sim$ medium mediator mass region.

Experimental searches: $E_T^{\text{miss}} + Z(\text{ll})$



Main uncertainty from ZZ modeling.

$E_T^{\text{miss}} + W/Z (\text{jj})$
search also
performed:
JHEP10 (2018)180



Selection & Strategy

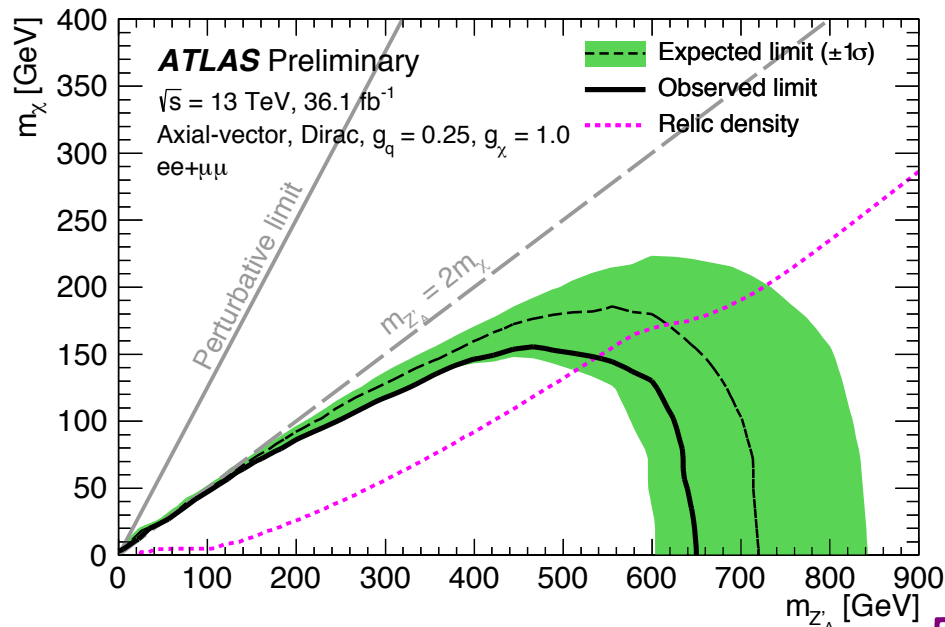
$$E_T^{\text{miss}} > 90 \text{ GeV}, E_T^{\text{miss}}/H_T > 0.6,$$

$$\Delta\phi(Z, E_T^{\text{miss}}) > 2.7,$$

2 leptons ee/ $\mu\mu$ (small ΔR_{ll} , near m_Z).

Background strategy:

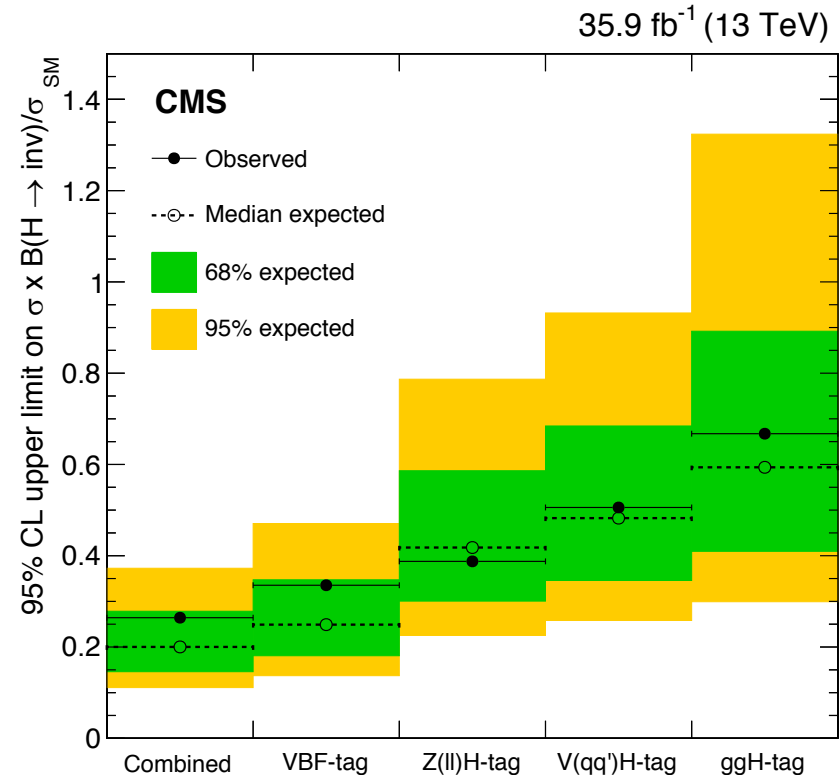
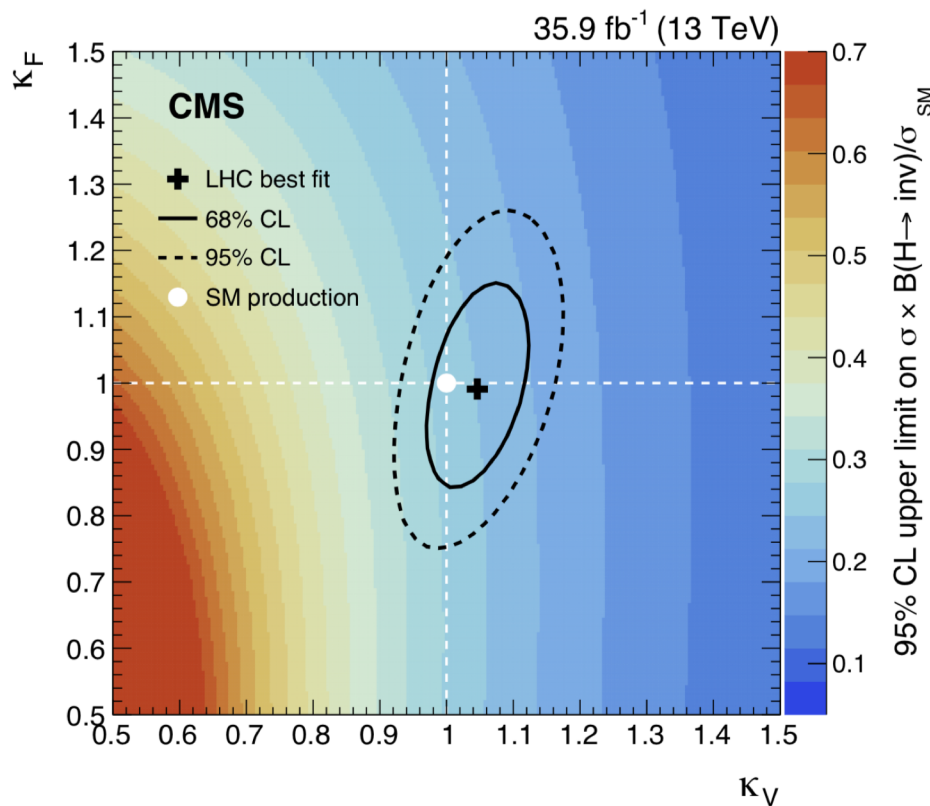
- **ZZ (llvv)** estimated from MC (irreducible).
- **WZ**: normalized in 3 leptons CR.
- **WW/top**: normalized in $e\mu$ CR.
- **Z+jets** (fake E_T^{miss}): “ABCD” method.



Higgs $\rightarrow$ invisible

The 2016 data results from VBF and VH associated production searches are combined.

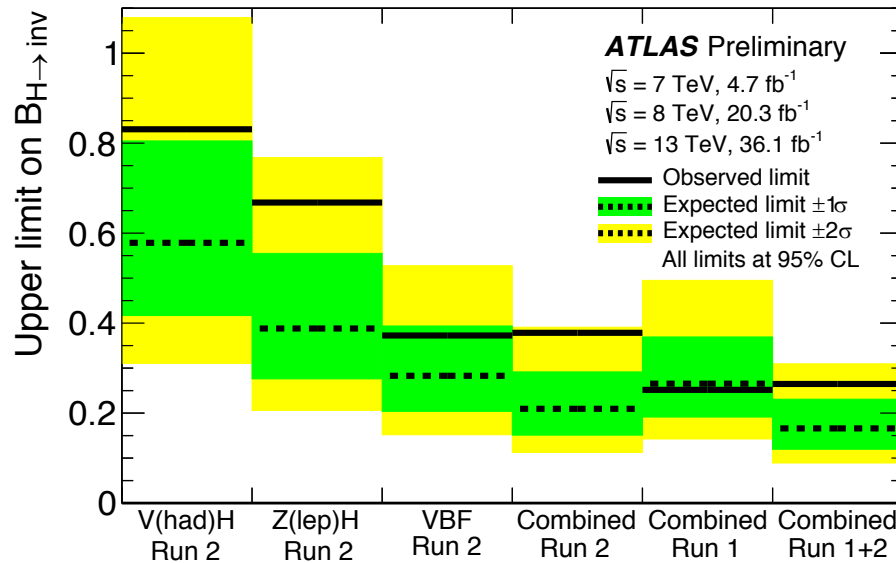
Observed (expected) limit @ 95% CL
H(inv) BR < 0.26 (0.20)



From the combined measurements of the Higgs boson couplings (2016 data),
visible+invisible combination

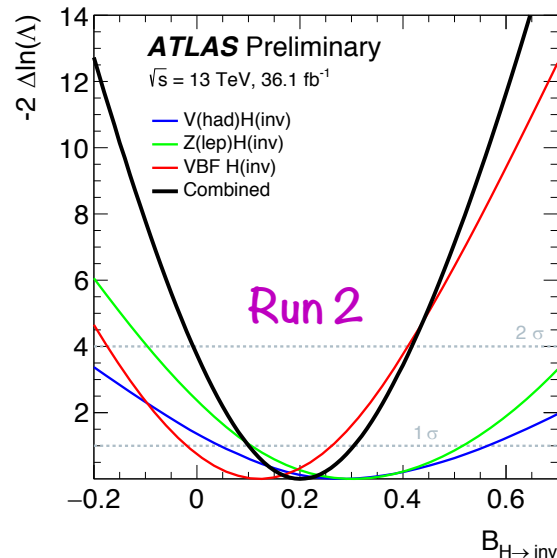
Observed (expected) limit @ 95% CL
H(inv) BR < 0.22 (0.17)

Higgs $\rightarrow$ invisible



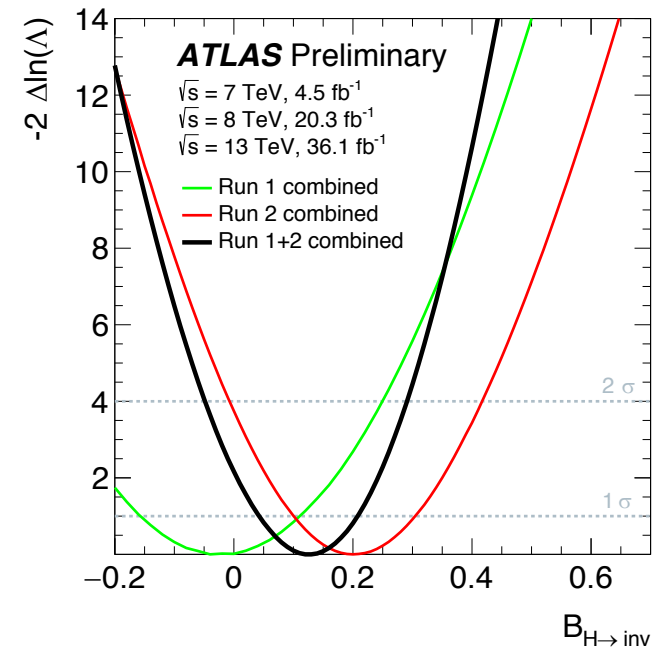
Brand new combination from ATLAS!
 Run 1 + Run 2 (2015-2016) result:

Observed (expected) limit @ 95% CL
 $H(\text{inv}) \text{ BR} < 0.26 (0.17)$



Run 2 combination
 includes results from
 VBF+H(inv), Z(ll)H(inv)
 and V(had)H(inv)

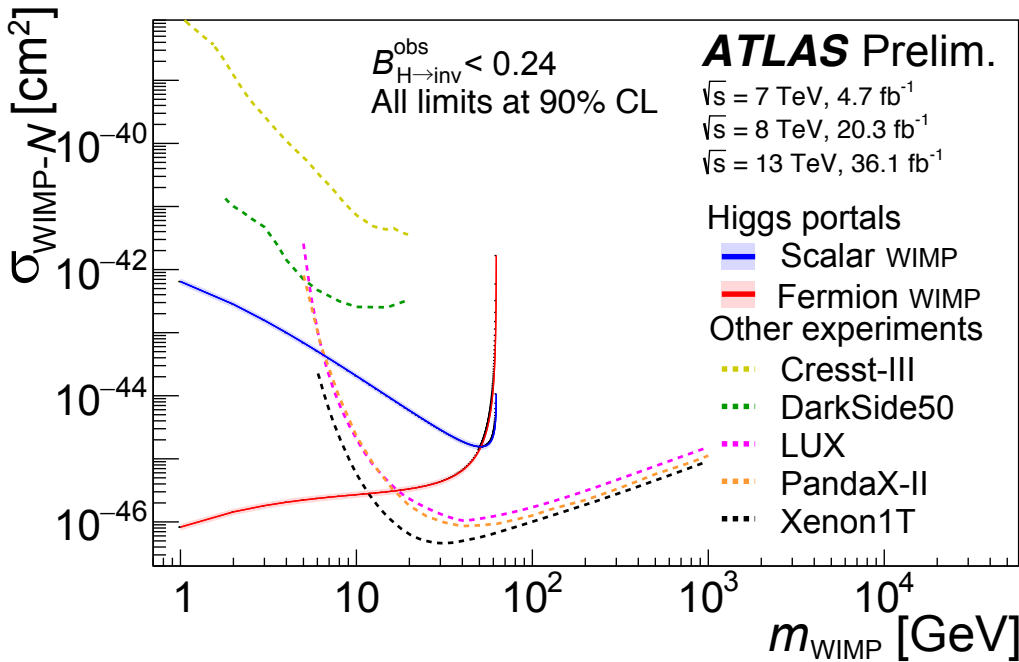
Observed (expected) limit @ 95% CL
 $H(\text{inv}) \text{ BR} < 0.38 (0.21)$



Higgs Portal



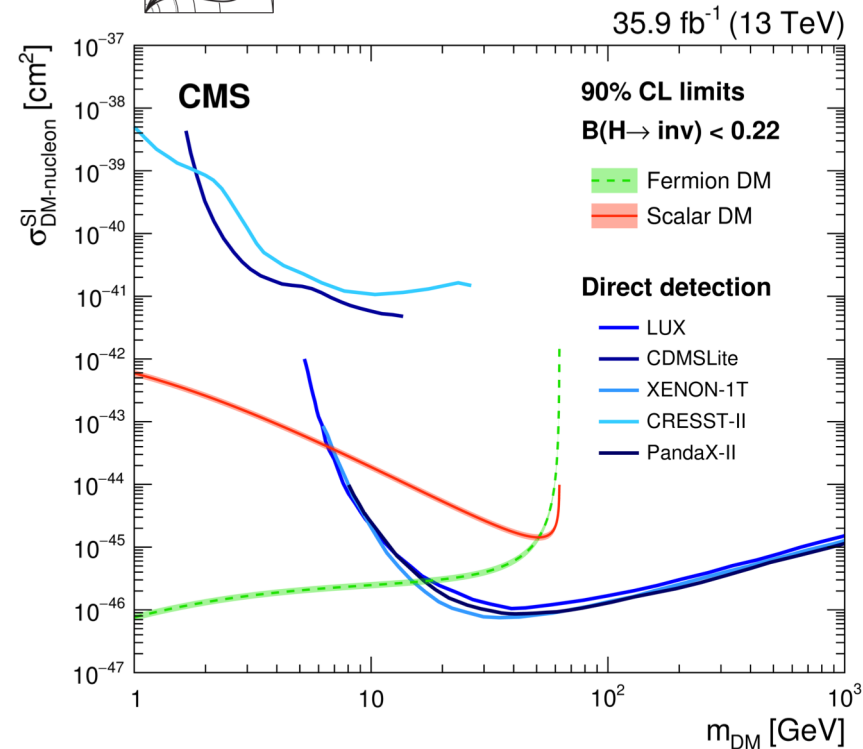
Run 1 + Run 2
combination



Observed limit @ 90% CL
 $H(\text{inv}) \text{ BR} < 0.24 \text{ (obs)}$



2016 combination



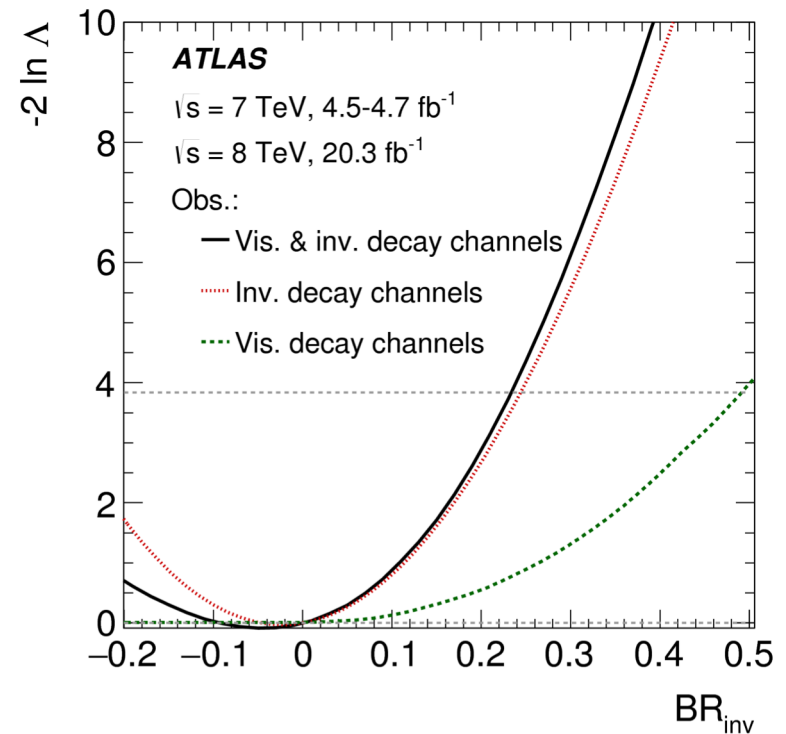
Observed limit @ 90% CL
 $H(\text{inv}) \text{ BR} < 0.22 \text{ (obs)}$

Higgs $\rightarrow$ invisible

Direct searches for invisible Higgs boson decays in VBF and VH associate production modes are statistically combined.

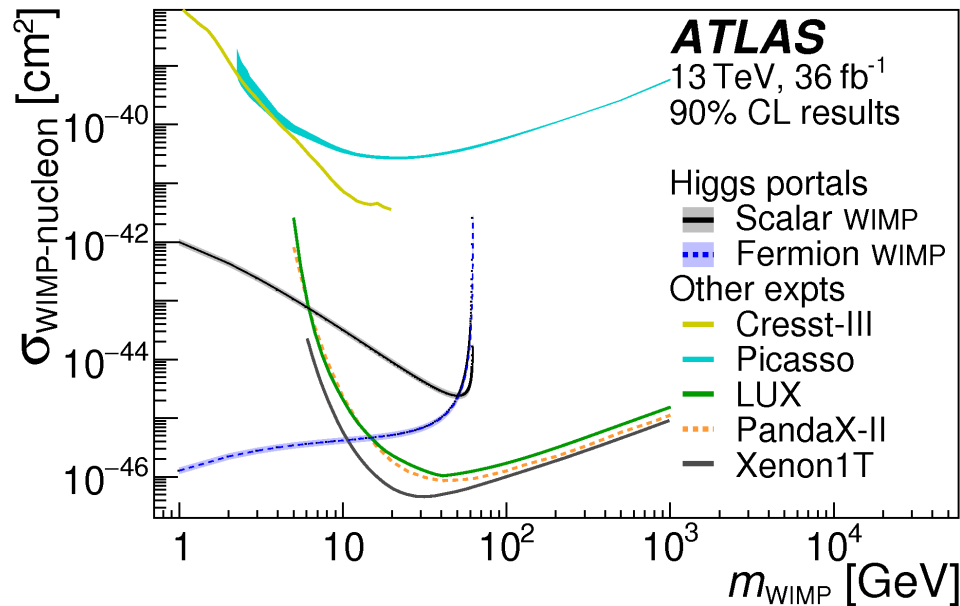
Upper BR limit: 0.25 (0.27).

The use of measured visible decay rates improves the upper limit to **0.23 (24)**.



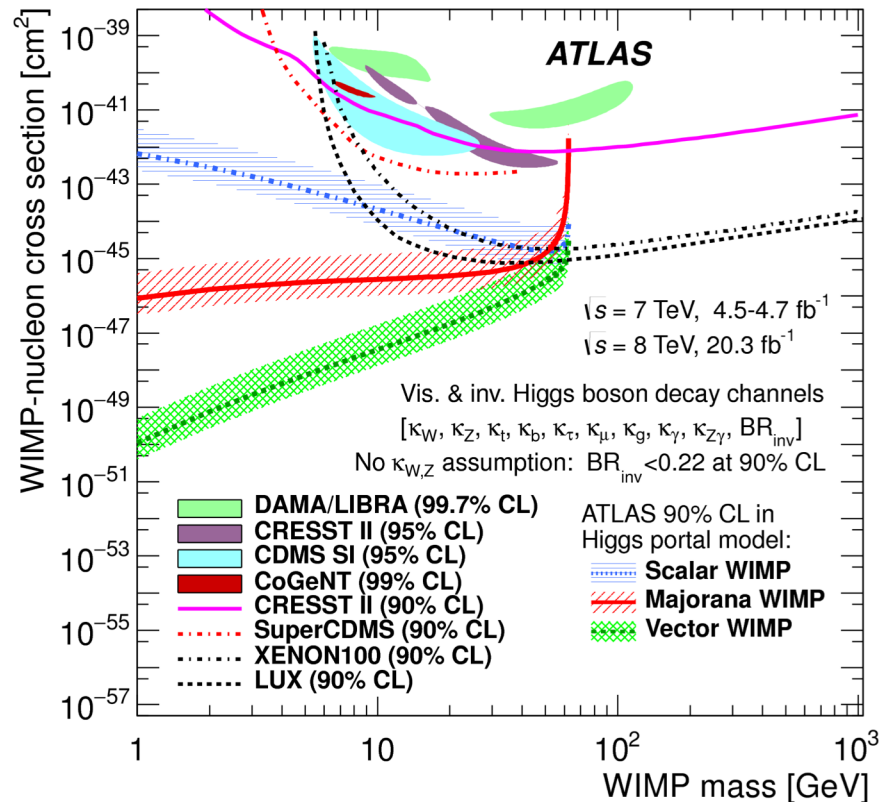
Higgs Portal

VBF + E_T^{miss}

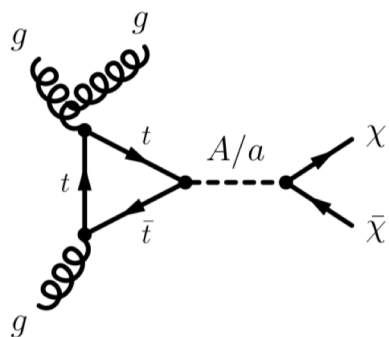


Observed limit @ 90% CL
 $h(\text{inv}) \text{ BR: } 0.32$

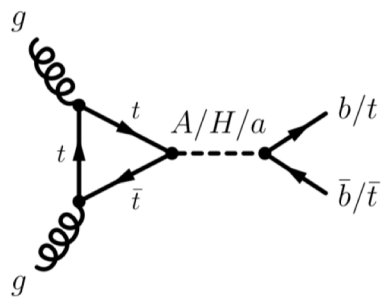
Run 1 combination



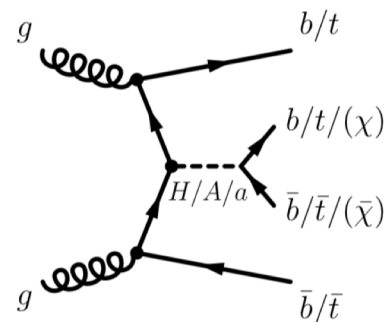
Observed limit @ 90% CL
 $h(\text{inv}) \text{ BR: } 0.22$



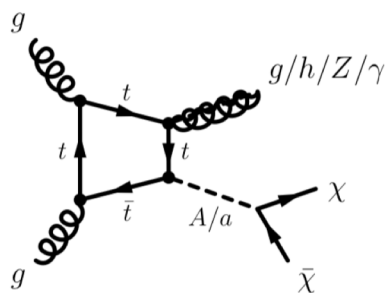
(a)



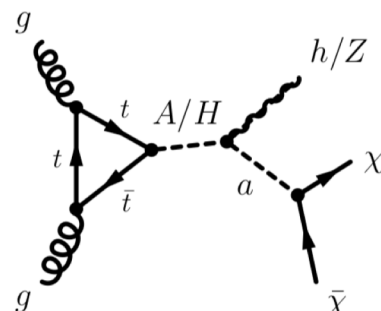
(b)



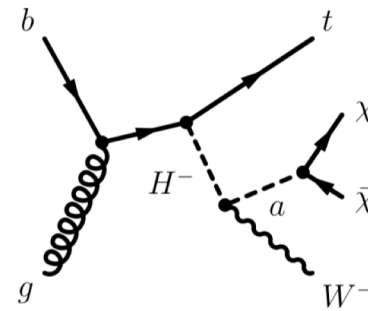
(c)



(d)



(e)



(f)

- Production cross-section for the lightest pseudo scalar, a , is dominated by loop-induced gluon fusion, associated production with HF quarks or Higgs/Z-boson.
- Higgs/Z-bosons can be produced in resonant decay of the heavier bosons into the lightest pseudo-scalar.
- A can then decay into a pair of DM or SM particles (dominantly top quarks if kinematically allowed).

All analyses follow the parameter values and limit interpretations as recommended by the LHC-DM WG (aka DM forum).

Simplified Models

Describe the model by a small numbers of free parameters:

- m_{med} (mediator mass),
- m_{DM} (WIMP mass),
- g_{DM}, g_q (couplings).

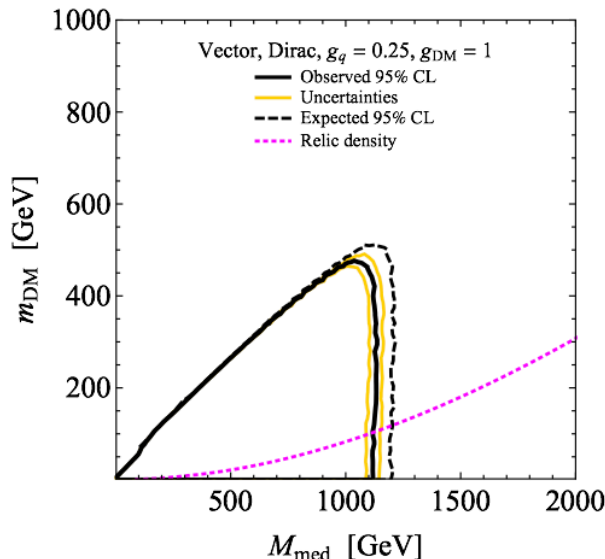
Assuming DM is a Dirac fermion (stable).
Consider different types of mediators (minimal decay width).

Vector mediator: $g_{\text{DM}} = 1$ and $g_q = 0.25$.

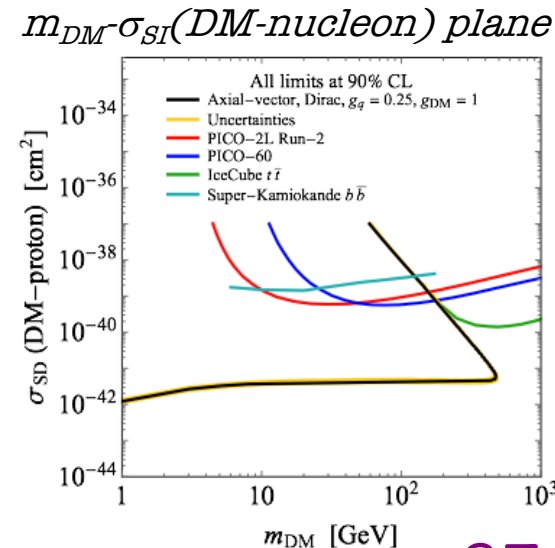
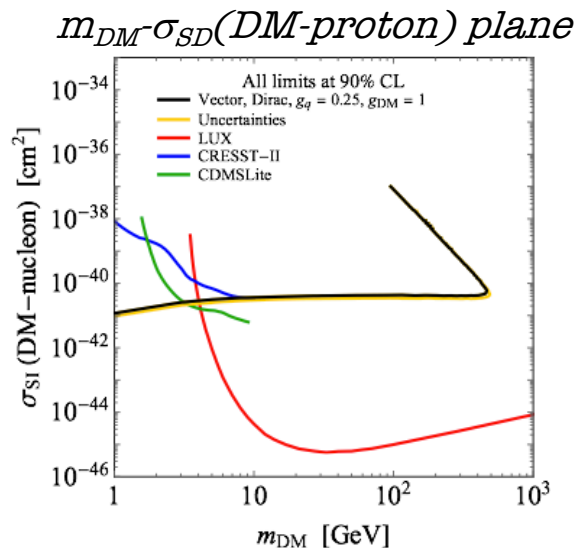
Axial-vector mediator: $g_{\text{DM}} = 1$ and $g_q = 0.25$.

Scalar mediator: $g_q = 1$ and $g_{\text{DM}} = 1$.

Pseudo-scalar mediator: $g_q = 1$ and $g_{\text{DM}} = 1$.

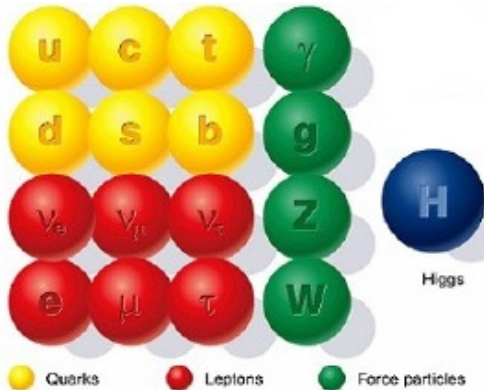


Presenting exclusion limits in the $m_{\text{DM}}-m_{\text{med}}$ plane...



SUSY-inspired models

Standard Model

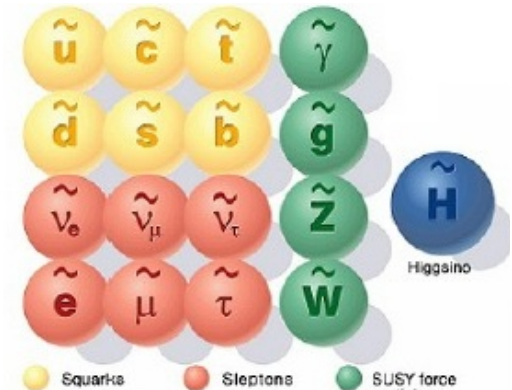


Superpartner

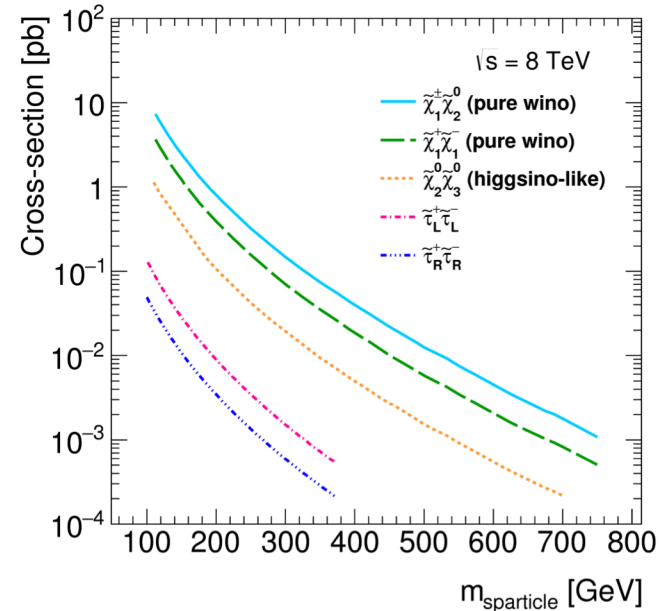
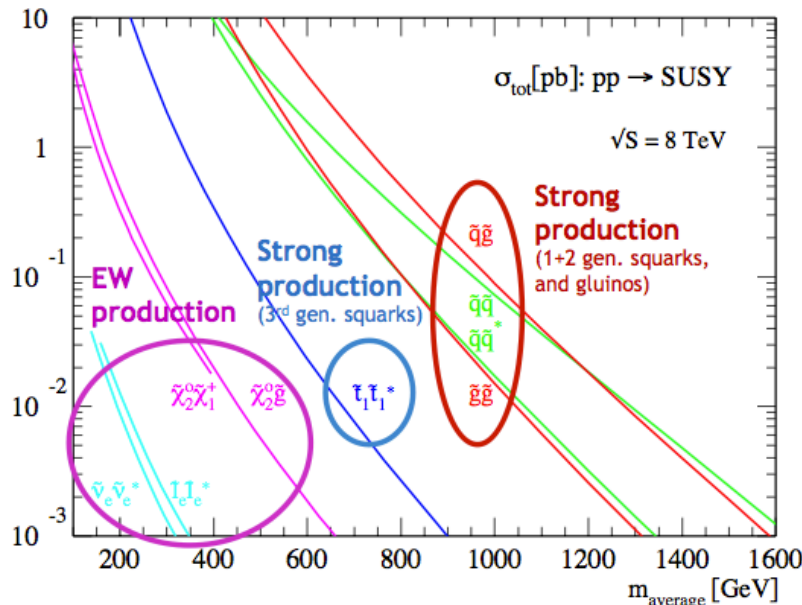
for every SM particle.

- Spin differs by one half.
- Mostly heavier than SM partners [broken symmetry].

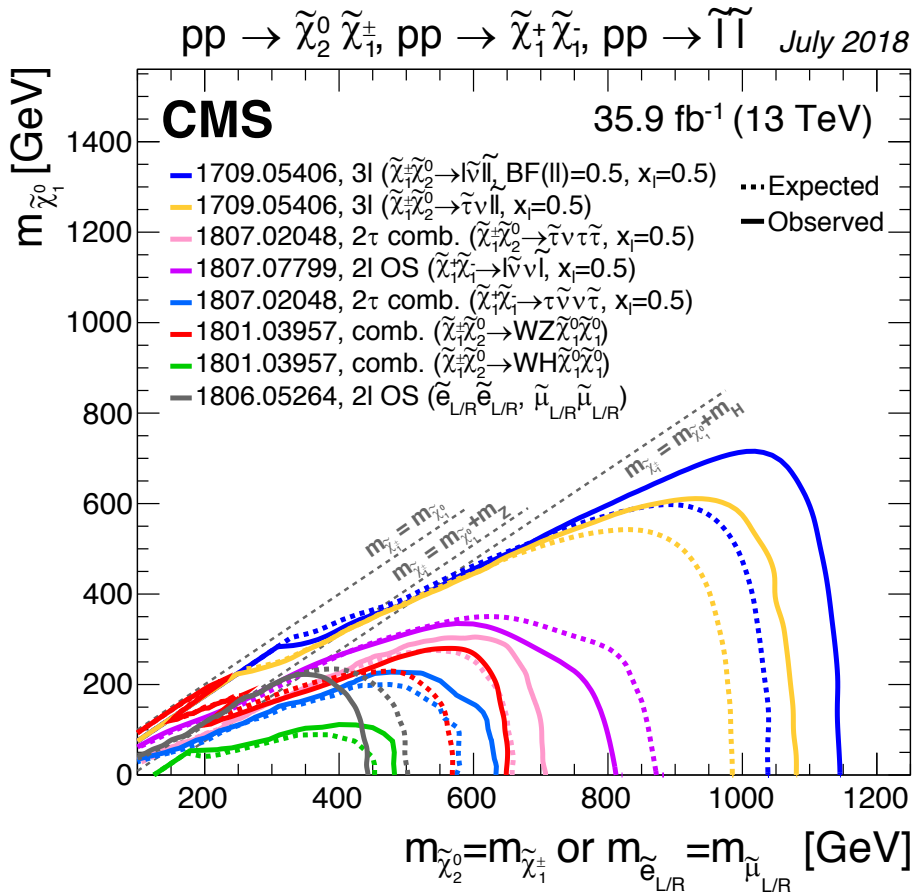
SUSY



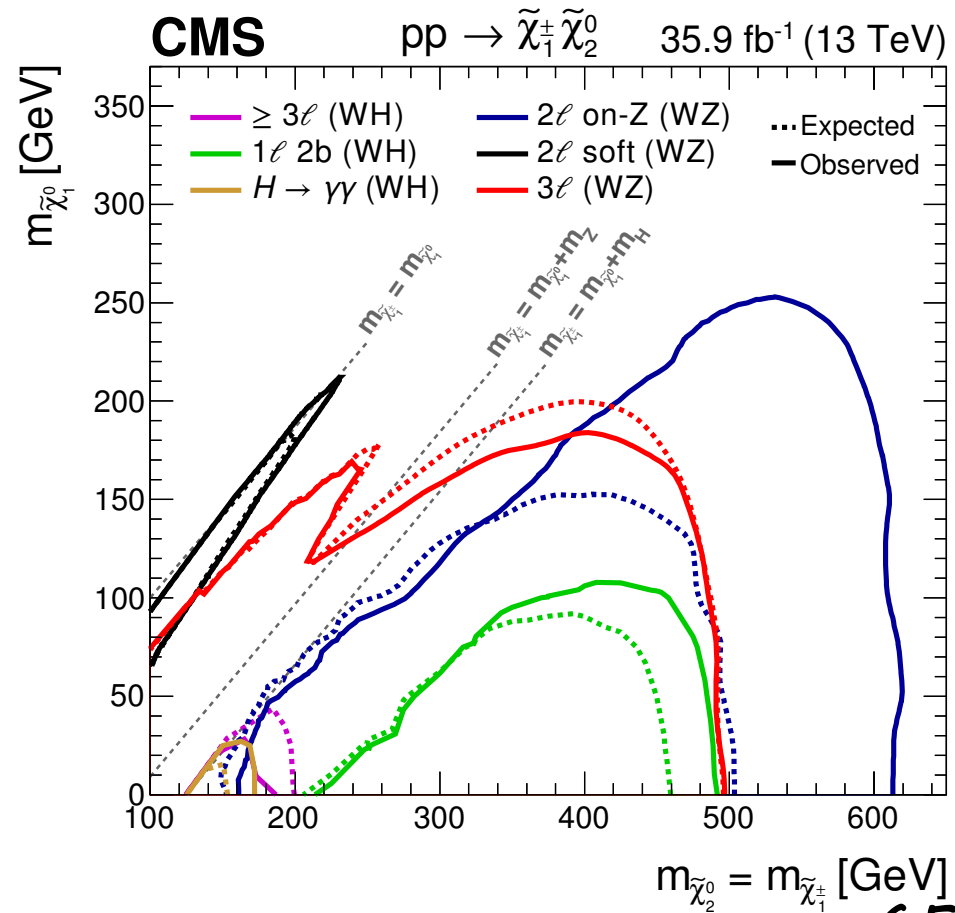
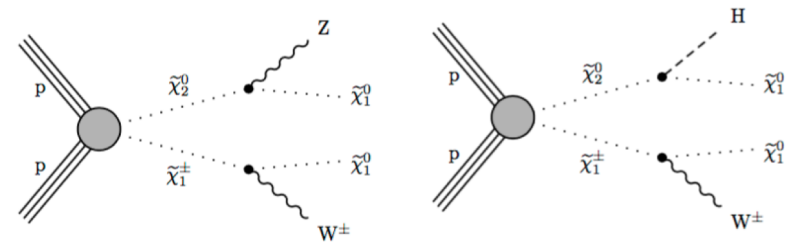
While SM does not have a viable DM candidate, in SUSY if R-parity is conserved, lightest SUSY particle (LSP) is stable $\rightarrow$ Good candidate for Dark Matter.



SUSY-inspired models



Production of pairs of the lightest chargino and the second-lightest neutralino, of chargino pairs, and of slepton pairs.



July 2018

ATLAS Preliminary

$\sqrt{s}=13$ TeV, 36.1 fb $^{-1}$

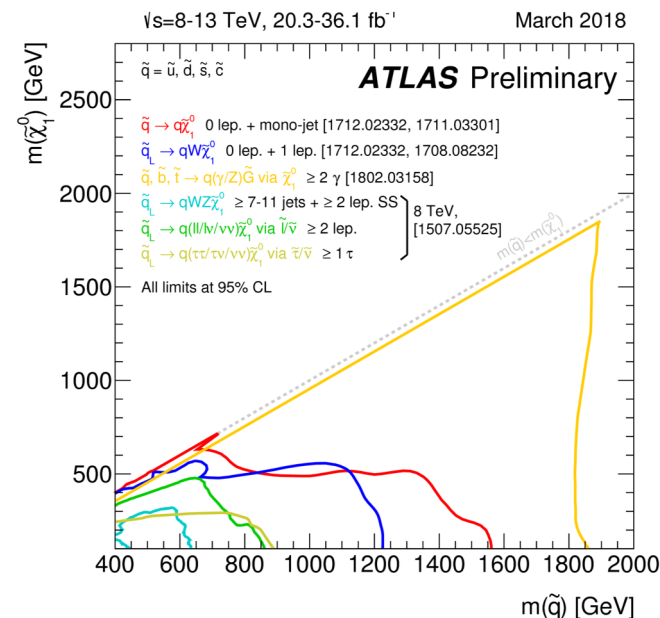
$B(\tilde{\chi}_1^0 \rightarrow h\tilde{G})$ [%]

$pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^\pm \tilde{\chi}_1^0, \tilde{\chi}_1^\pm \tilde{\chi}_2^0, \tilde{\chi}_1^0 \tilde{\chi}_2^0$ (Higgsino)
 $\tilde{\chi}_1^0 \rightarrow h\tilde{G}$ or $Z\tilde{G}$

--- Expected limits
 — Observed limits
 All limits at 95% CL

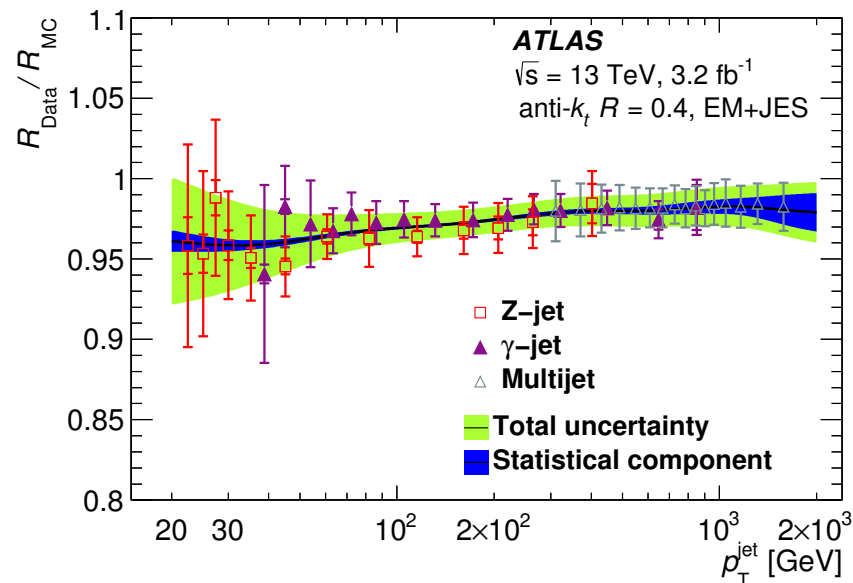
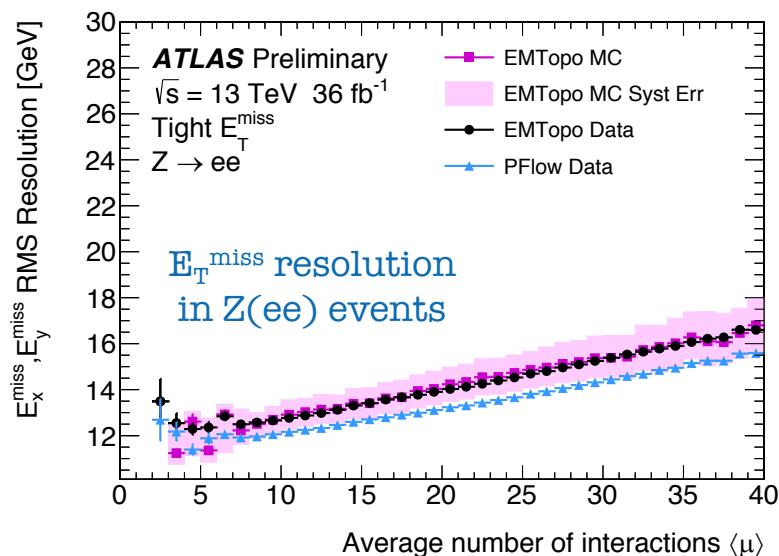
4b, arXiv:1806.04030
 4L, arXiv:1804.03602

$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0, \tilde{\chi}_2^0)$ [GeV]



ATLAS detector data

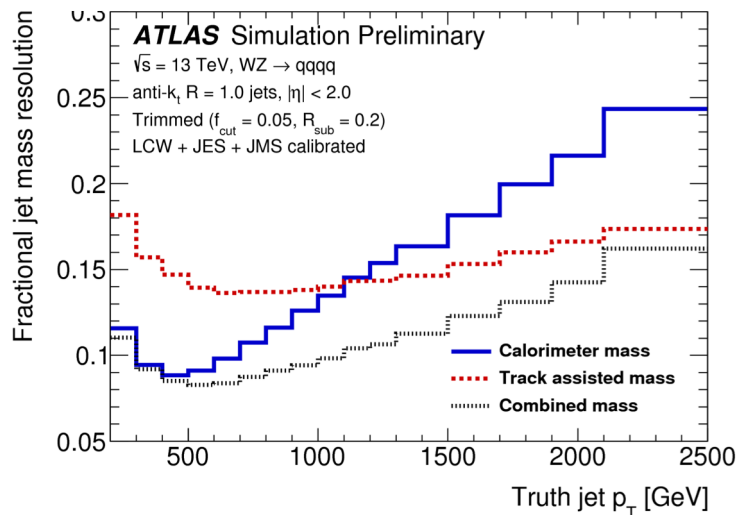
These analyses rely in a good measurement of **missing transverse momenta**, and understanding of jet calibration up to multi-TeV scale.



Large-R jets

Optimizes **large-R jet mass** computed using combination of calorimeter and tracking information

$$m_J \equiv w_{\text{calo}} \times m_J^{\text{calo}} + w_{\text{track}} \times \left(m_J^{\text{track}} \frac{p_T^{\text{calo}}}{p_T^{\text{track}}} \right)$$



$Z(\nu\nu)/Z(l\bar{l})$ ratio

Measure the ratio: $\sigma(E_T^{\text{miss}} + \text{jets})/\sigma(Z \rightarrow l\bar{l} + \text{jets})$
versus various kinematic variables

VBF + E_T^{miss}

vs. $E_T^{\text{miss}}, m_{jj}, \Delta\phi_{jj}$

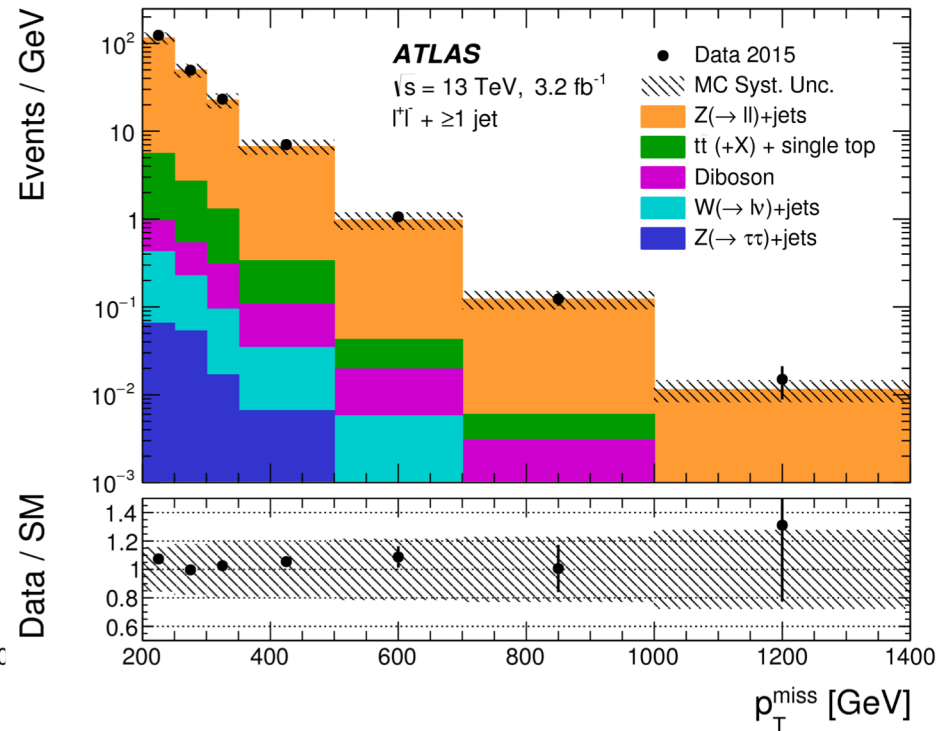
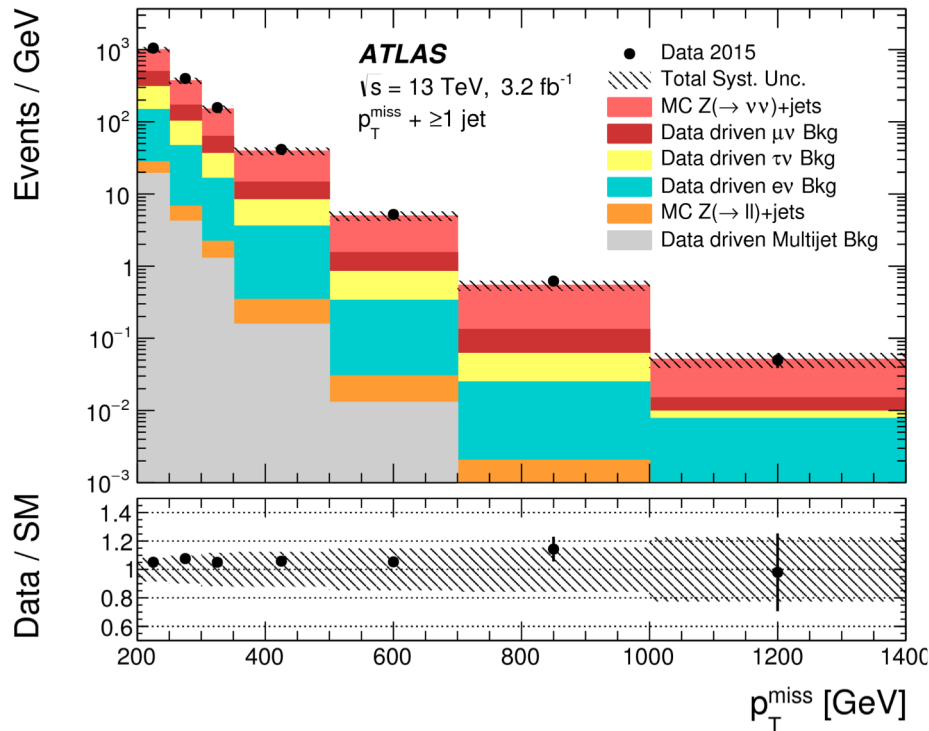
≥ 1 jet + E_T^{miss}

vs. E_T^{miss}

$Z(\nu\nu)$ +jets numerator: W-bkgs estimated in $W(\rightarrow e\nu, \mu\nu)$ CRs. MC used to extrapolate into SR: out-of-acceptance leptons and in-acceptance-leptons.

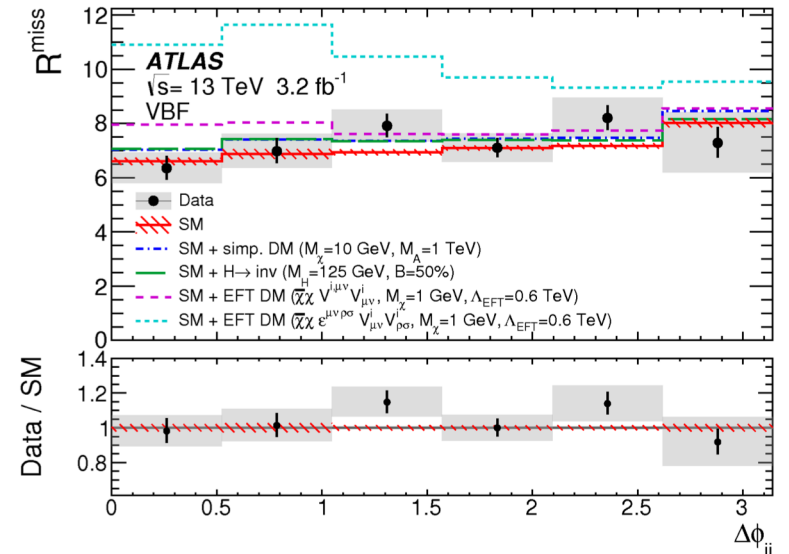
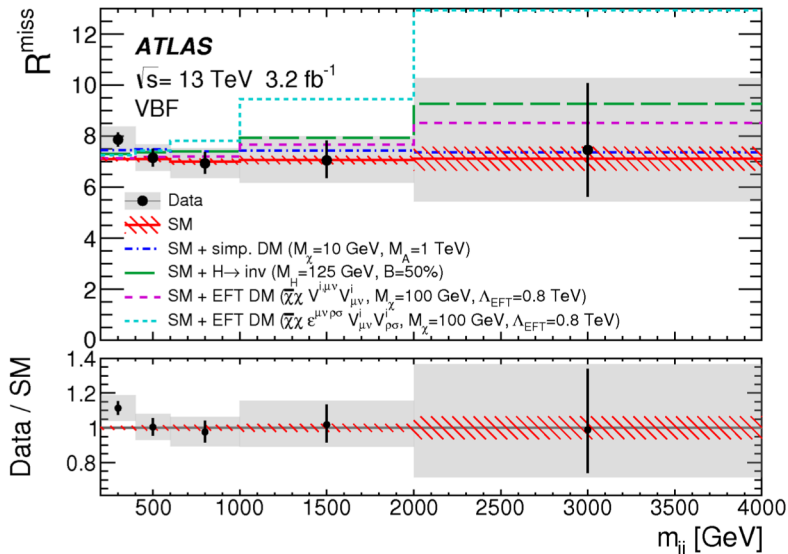
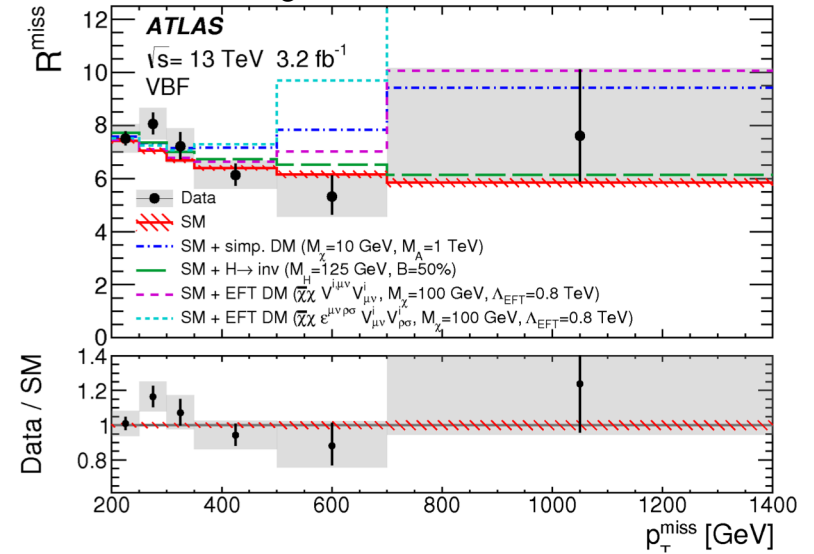
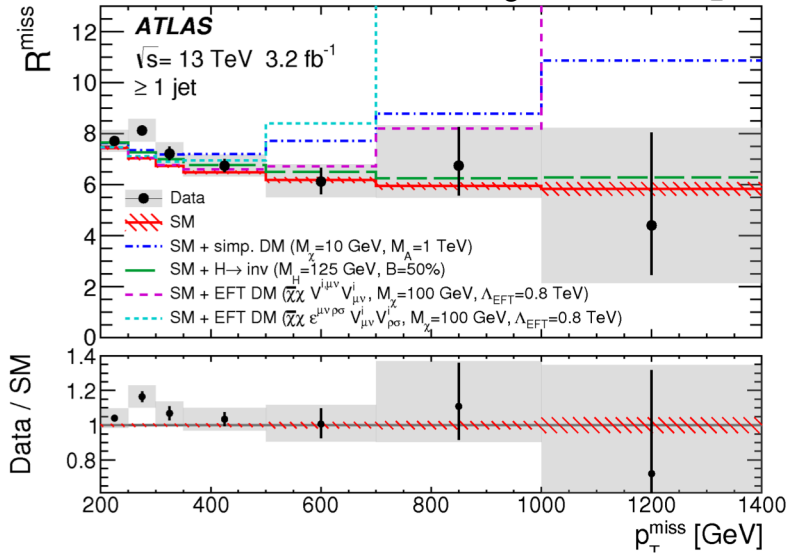
$Z(l\bar{l})$ +jets denominator: other bkg from MC.

Since SM $E_T^{\text{miss}} + \text{jets}$ is $Z(\nu\nu) + \text{jets} \rightarrow$ *Many uncertainties cancelled out in the ratio.*



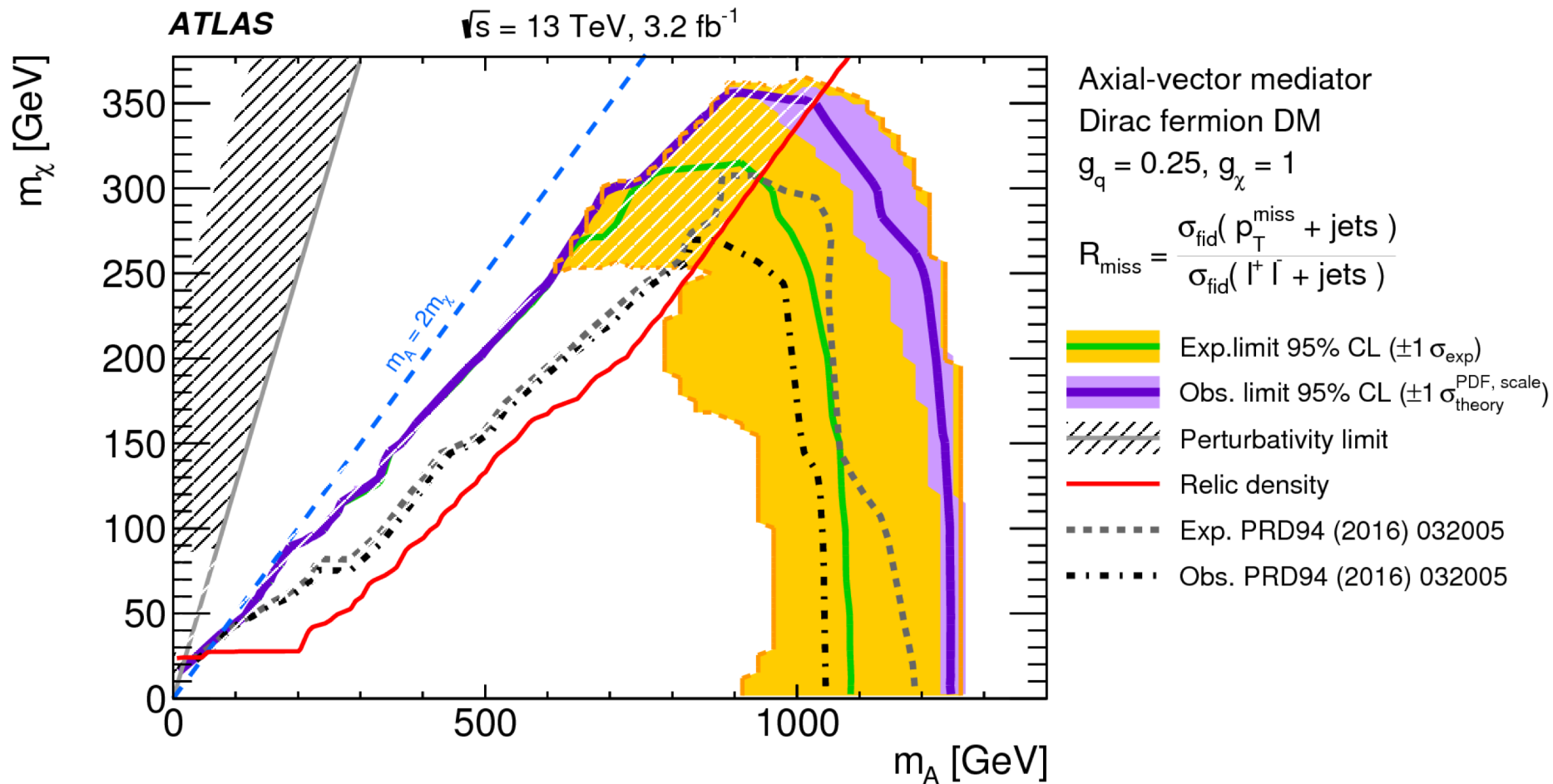
$Z(\nu\nu)/Z(\ell\ell)$ ratio

The ratio is corrected for detector effects (“unfolded”),
so can be easily reinterpreted in terms of any BSM models.

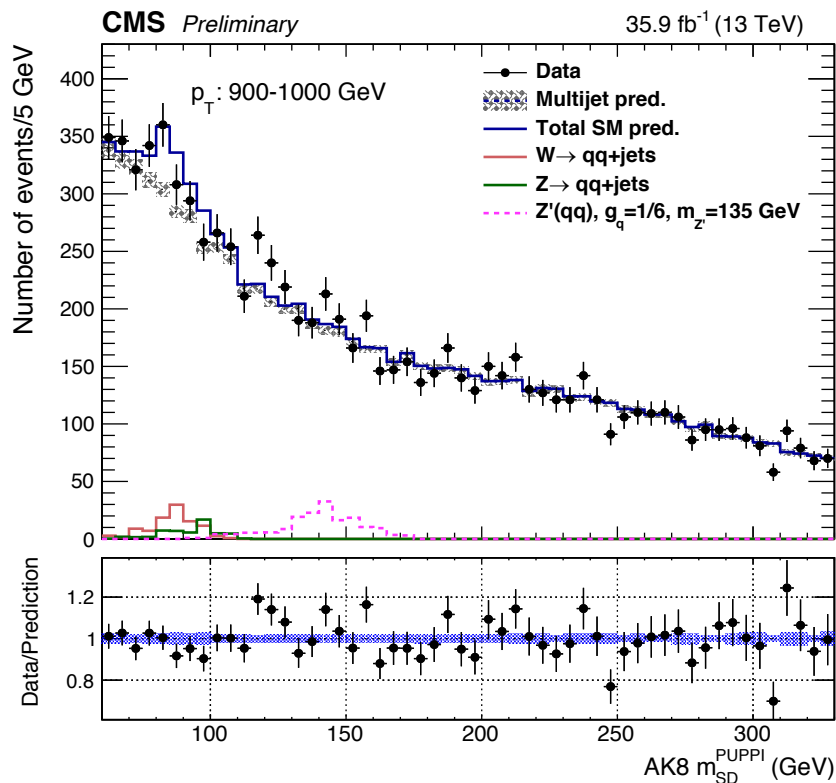


$Z(\nu\nu)/Z(\ell\ell)$ ratio

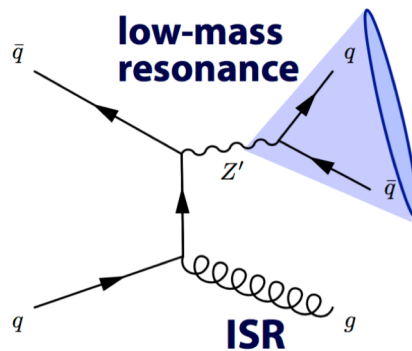
The ratio is corrected for detector effects (“unfolded”),
so can be easily reinterpreted in terms of any BSM models.



Experimental searches: Dijet (low mass)

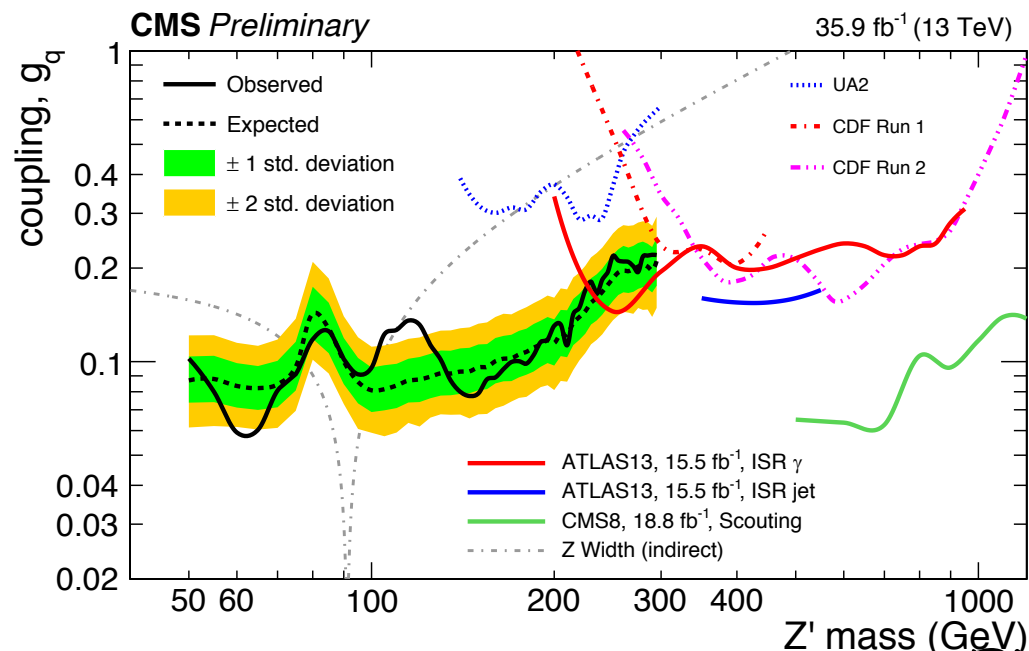


Different techniques allow us to cover **low Z' masses**:
 Di-jet + ISR (jet, photon), boosted di-jet + ISR, trigger-level analysis ('data scouting').



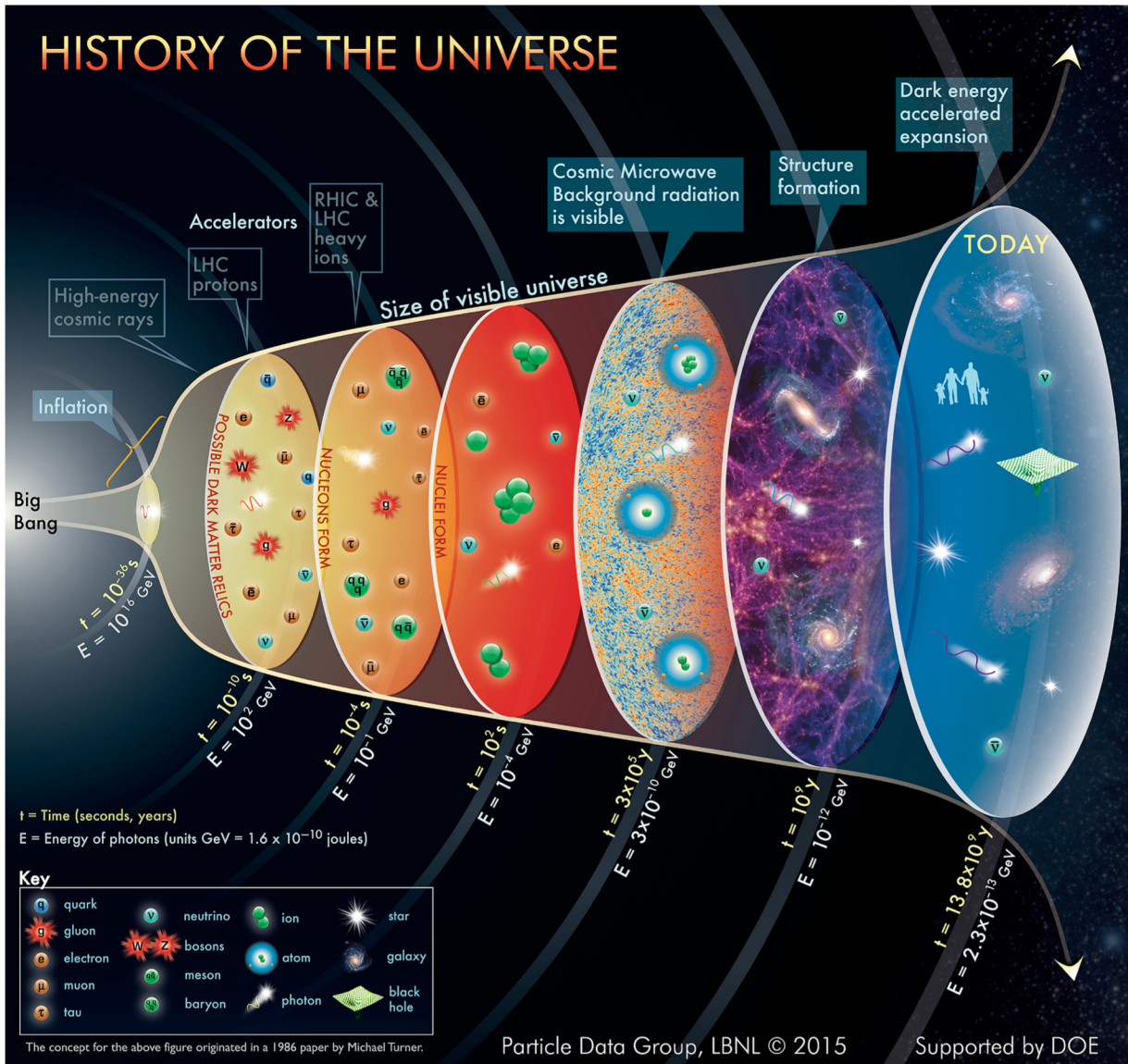
Search for low-mass new particle using **ISR boost**

Reconstruct boosted $Z' \rightarrow qq$ with a large-R jet



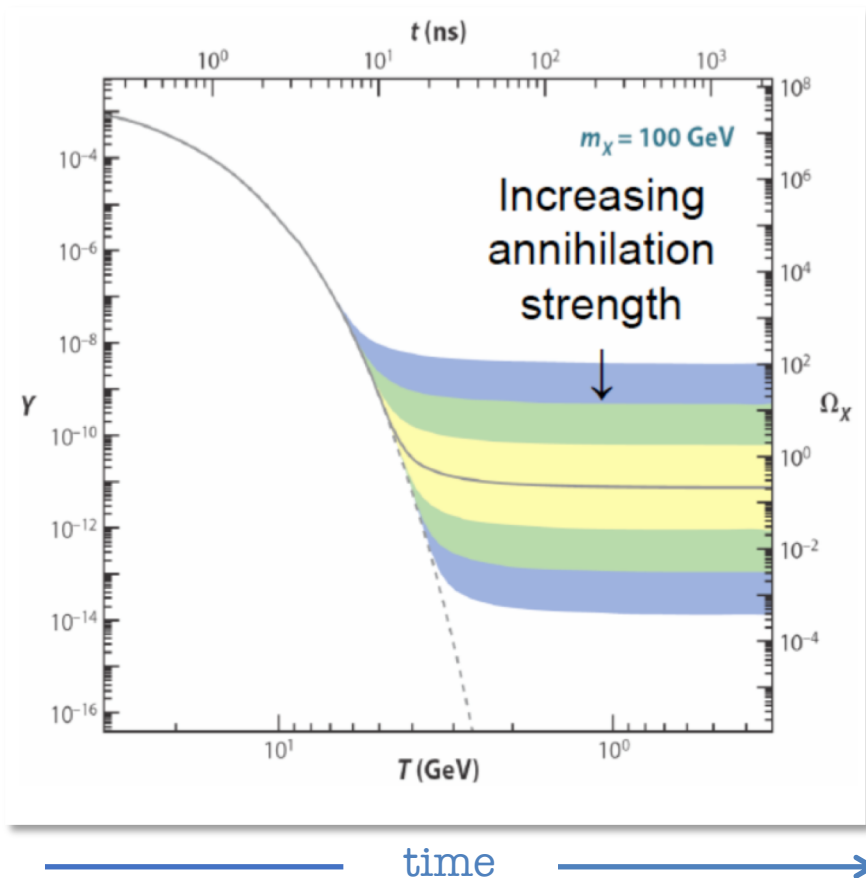
History of the Universe

Universe expansion



- SM and DM particles are initially in thermal equilibrium.
- As the universe expands and start cooling, different types of particles start freezing (*thermally freeze out*).
 - Temperatures go down, universe cools.
 - Density lowers.
- **“Freeze out”** happens when particles can no longer interact (annihilate).

WIMP miracle



- In the early universe WIMPs annihilate, keeping thermal equilibrium.
- The universe expands and cools off. The DM production drops rapidly. The amount of WIMPs *freezes out*.
 - Abundance of DM remains constant (**relic density**).
- Weakly interacting particles (masses at weak scale) can reproduce the correct DM relic abundance.