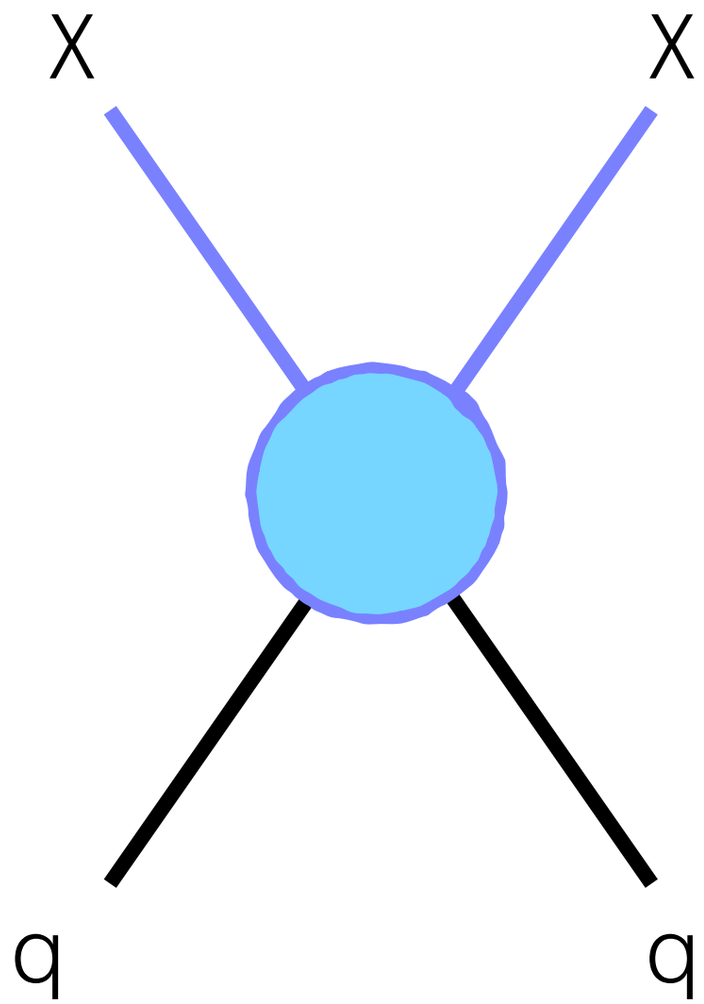
Dark matter searches at ATLAS and CMS

Kate Pachal
Duke University

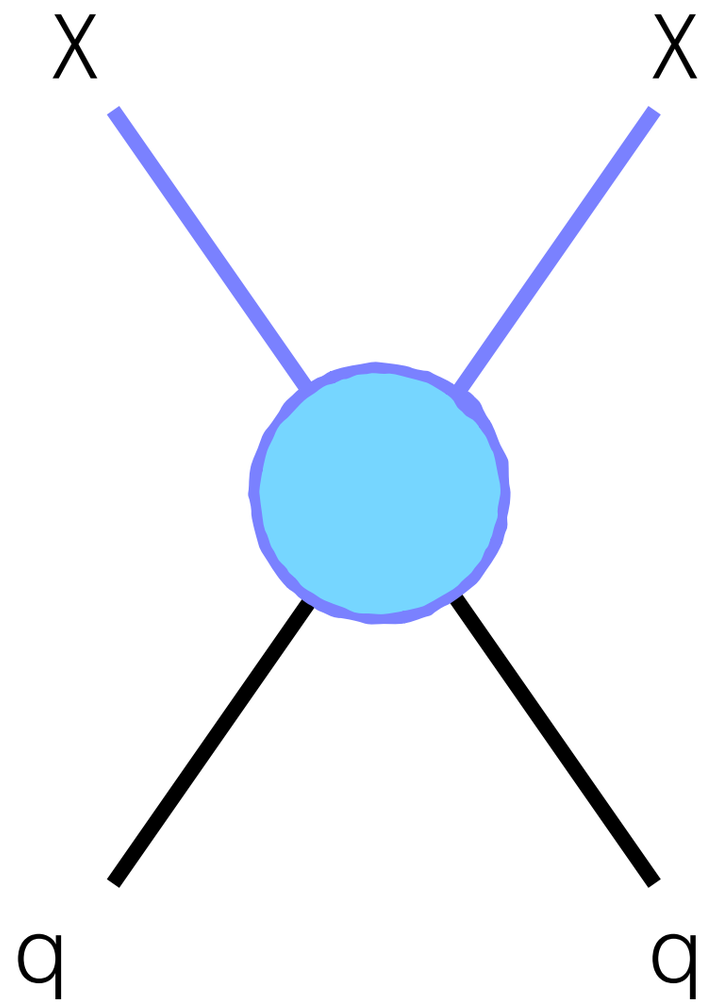
Dark matter at colliders



Dark matter at colliders

Indirect detection

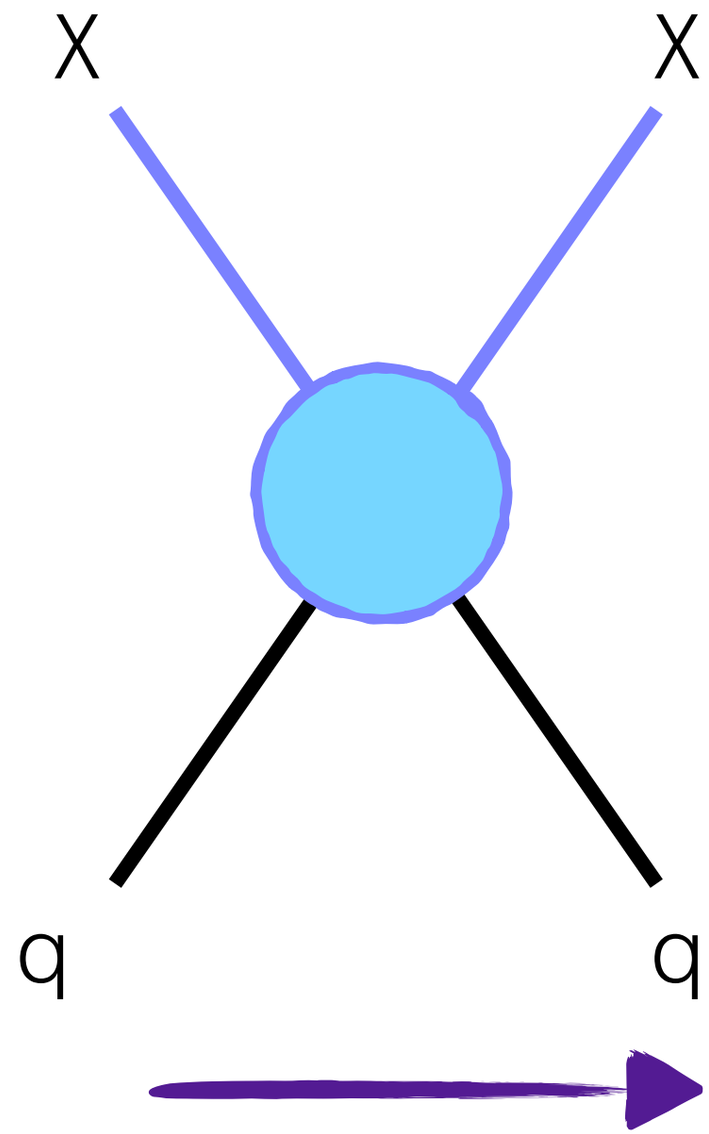
IceCube, Super-K, …



Dark matter at colliders

Indirect detection

IceCube, Super-K, …

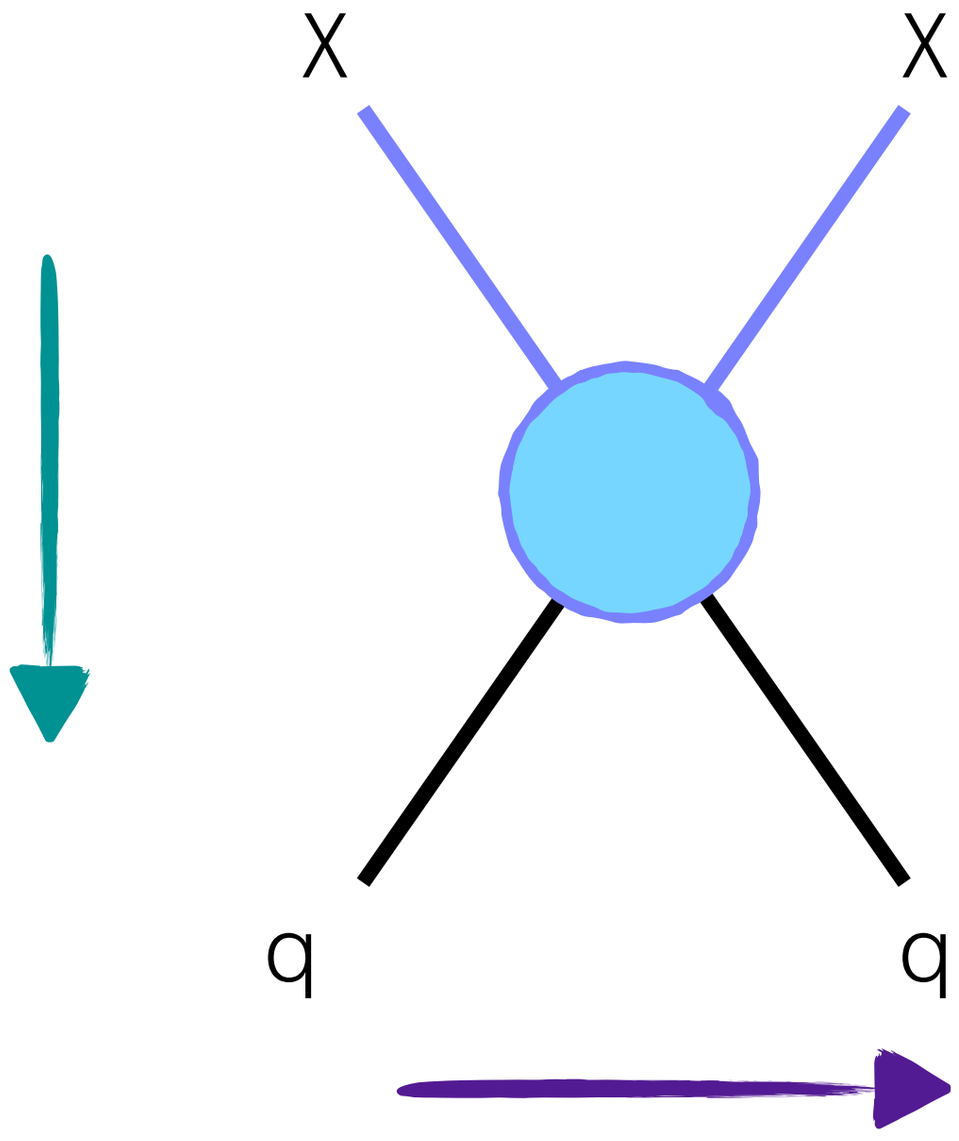


Direct detection: LUX, XENON, …

Dark matter at colliders

Indirect detection

IceCube, Super-K, …

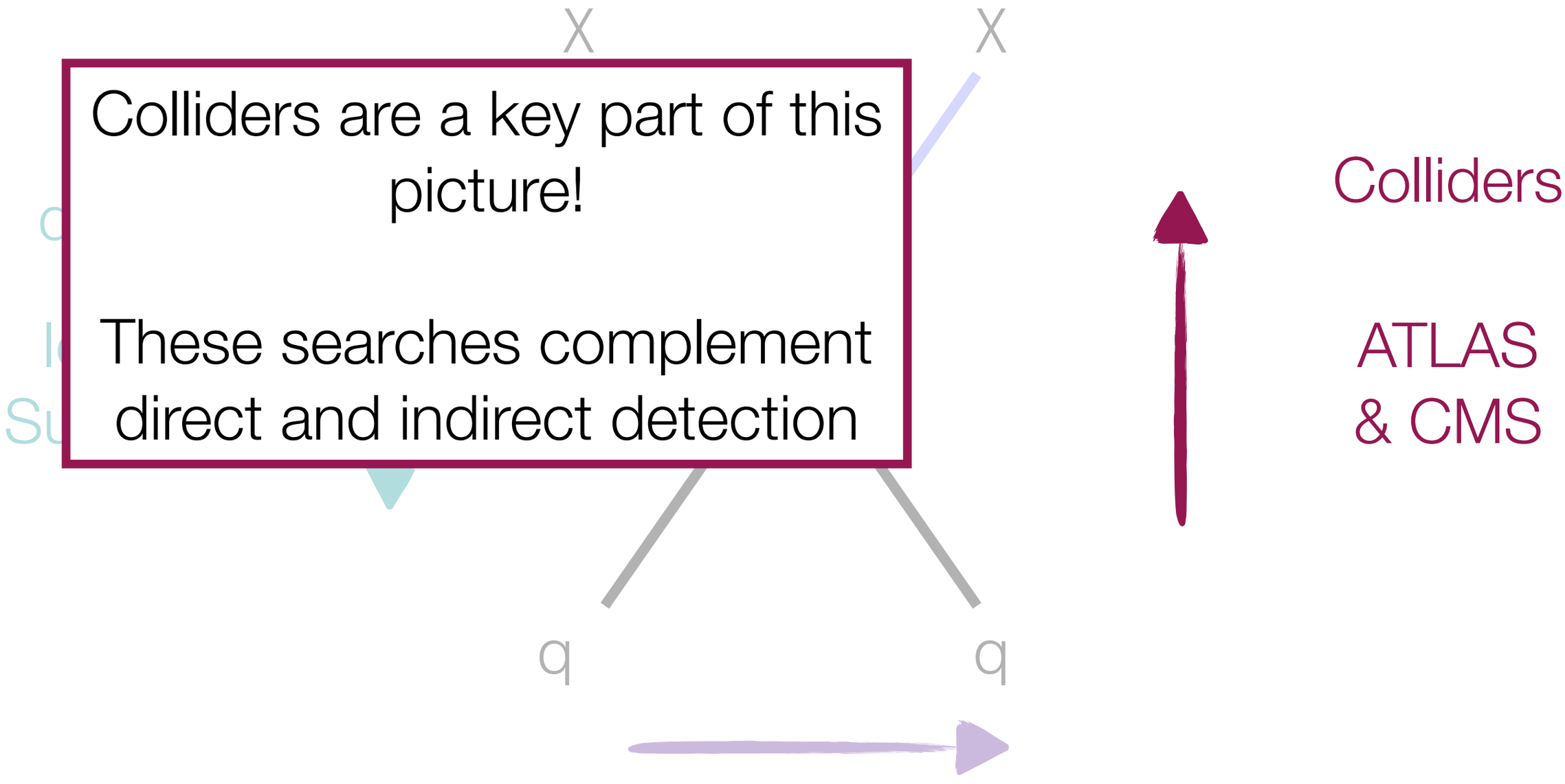


Colliders

ATLAS & CMS

Direct detection: LUX, XENON, …

Dark matter at colliders



Dark matter at colliders

Colliders are a key part of this picture!

These searches complement direct and indirect detection

Colliders

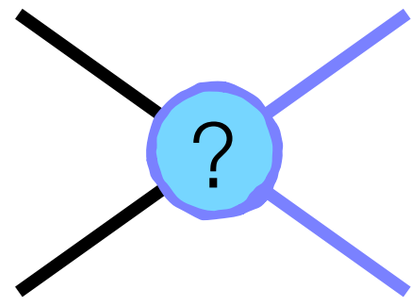
ATLAS & CMS

Today, we discuss DM searches at ATLAS and CMS

Direct detection: LUX, XENON, …

What could dark matter *really* look like at the LHC?

- Depends on assumptions!



  - At low energies, you don't really need a clearer picture. **Effective field theory** treats this as a 4-point interaction

    - EFTs are valid when the **momentum transfer is small** compared to fundamental processes - e.g. direct and indirect detection experiments

  - At the LHC, not valid: high energies require a **more complete picture**

- What should it be? **Many different models** available, with different levels of completeness/simplification and different dominant signatures

- In this talk, we'll discuss DM in a few different models, **highlighting analyses** that best constrain each

Less complete

Dipole Interactions

Dark Matter Effective Field Theories

Contact Interactions

"Sketches of models"

Dark Photon

Z′ boson

Simplified Dark Matter Models

Higgs Portal

"Squarks"

More complete

Minimal Supersymmetric Standard Model

Complete Dark Matter Models

Universal Extra Dimensions

Little Higgs

Less complete

Dipole Interactions

Dark Matter Effective Field Theories

Contact Interactions

"Sketches of models"

Dark Photon

Z′ boson

Simplified Dark Matter Models

Higgs Portal

"Squarks"

More complete

Minimal Supersymmetric Standard Model

Complete Dark Matter Models

Universal Extra Dimensions

Little Higgs

No longer done at LHC

Less complete

Dipole Interactions

Dark Matter Effective Field Theories

Contact Interactions

"Sketches of models"

Dark Photon

Z′ boson

Simplified Dark Matter Models

Higgs Portal

"Squarks"

More complete

Minimal Supersymmetric Standard Model

Complete Dark Matter Models

Universal Extra Dimensions

Little Higgs

No longer done at LHC

We'll discuss several of these!

Less complete

Dipole Interactions

Dark Matter Effective Field Theories

Contact Interactions

No longer done at LHC

"Sketches of models"

Dark Photon

Z′ boson

Simplified Dark Matter Models

Higgs Portal

"Squarks"

We'll discuss several of these!

More complete

Minimal Supersymmetric Standard Model

Complete Dark Matter Models

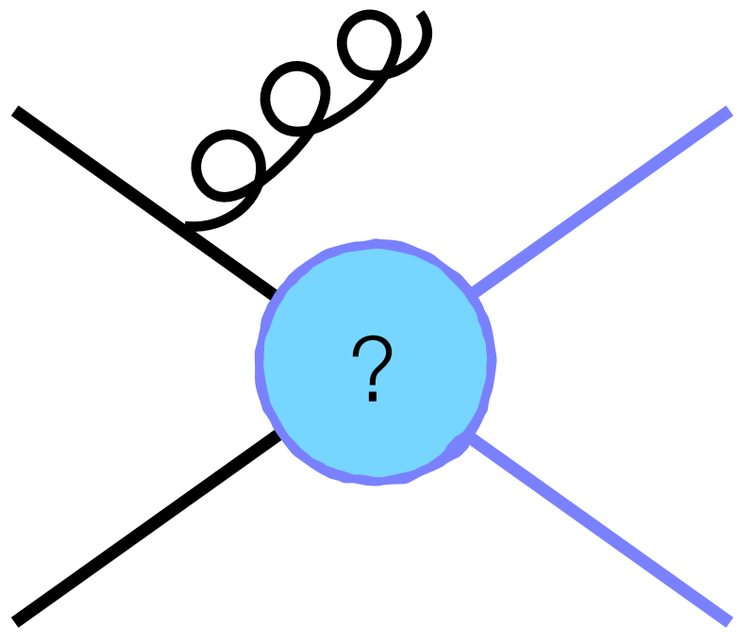
Universal Extra Dimensions

Little Higgs

Beyond today's scope

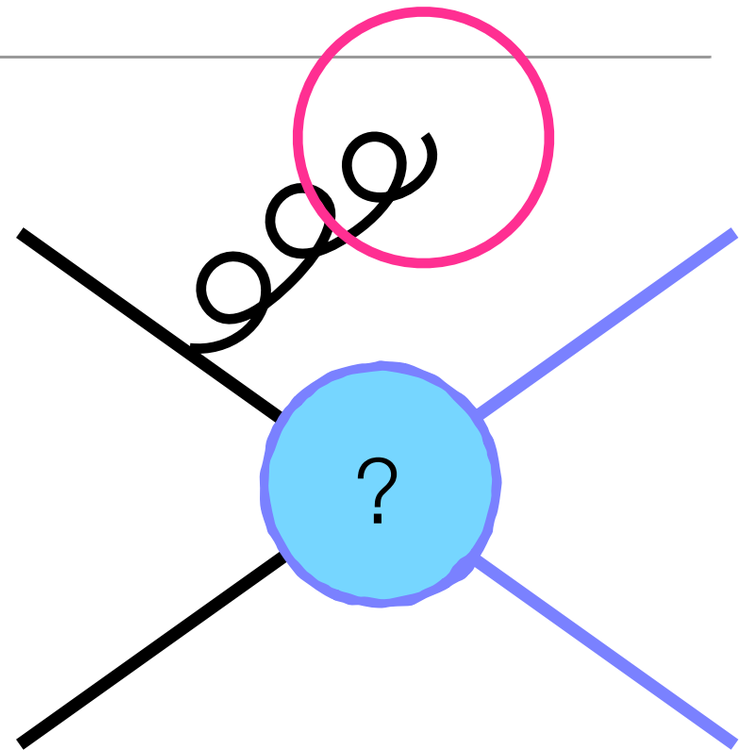
Mono-X signatures

- Key final state is M_{ET} plus a visible object



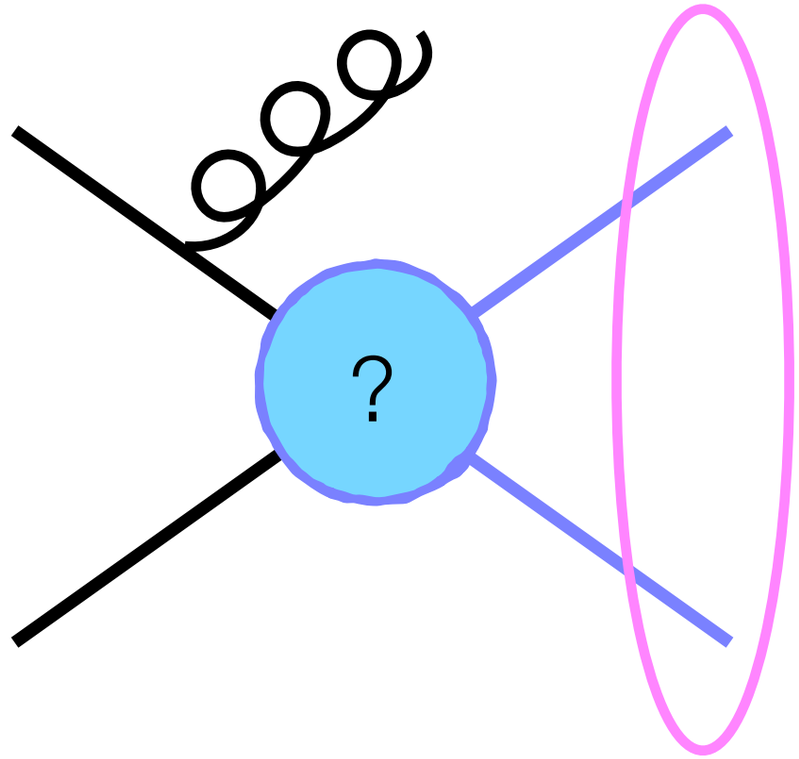
Mono-X signatures

- Key final state is M_{ET} plus a visible object
  - **Visible object** (eg. jet) gives momentum to measure and trigger on



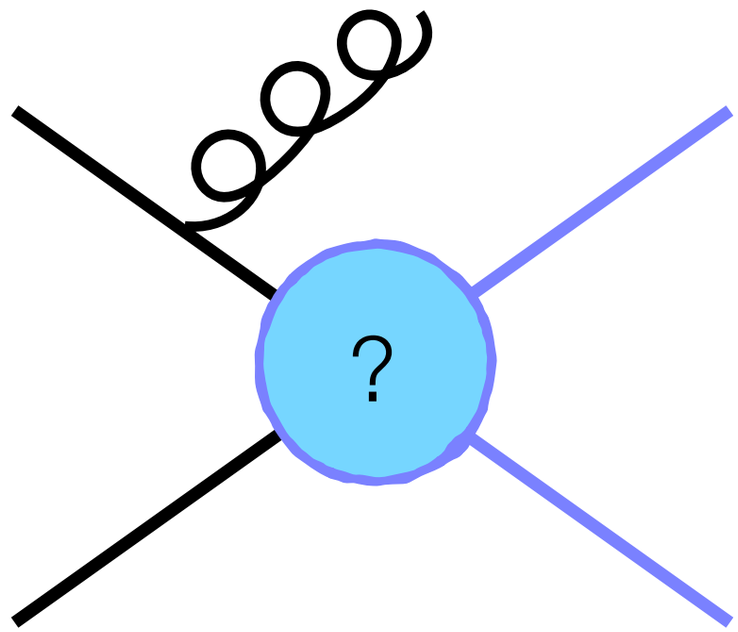
Mono-X signatures

- Key final state is M_{ET} plus a visible object
  - **Visible object** (eg. jet) gives momentum to measure and trigger on
  - Missing energy, M_{ET}, is **observed momentum imbalance** due to invisible particles



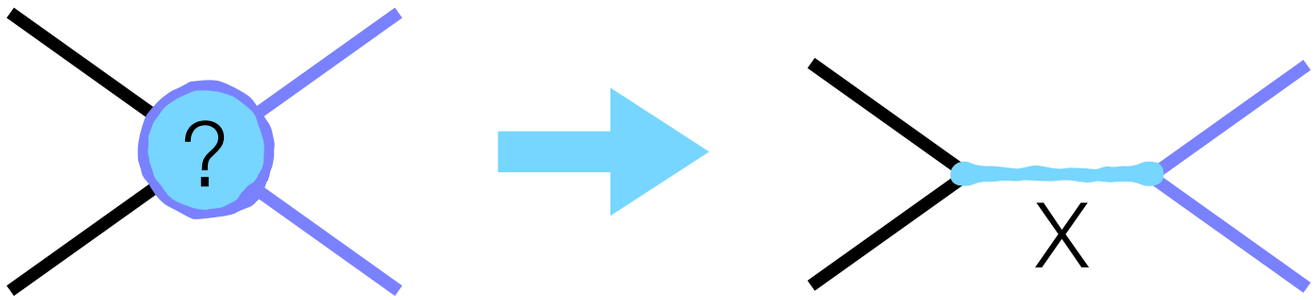
Mono-X signatures

- Key final state is M_{ET} plus a visible object
  - **Visible object** (eg. jet) gives momentum to measure and trigger on
  - Missing energy, M_{ET}, is **observed momentum imbalance** due to invisible particles



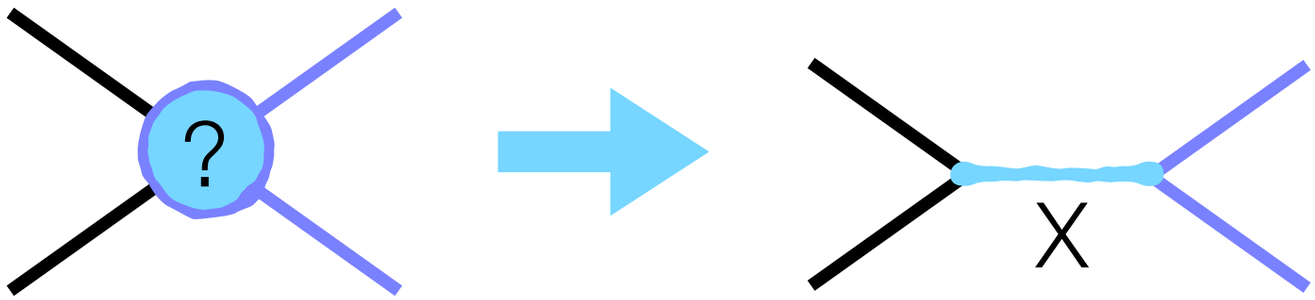
- Very **model-independent!**
  - No matter what DM-SM interaction, you can get this signature
  - Once we assume a model, though, other signatures are powerful too
- Today we will go **beyond the mono-jet signature** to showcase recent ATLAS and CMS results in the areas of their unique strengths

S-channel Z’ model and the mediator search



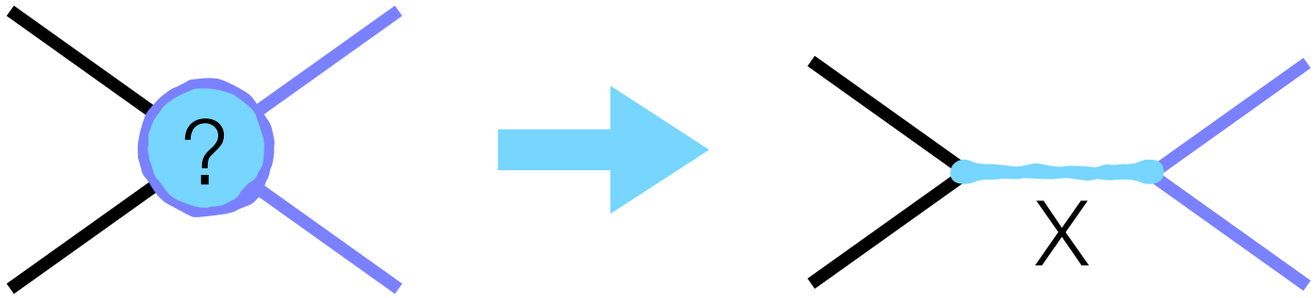
- Consider simplified S-channel model: one massive mediator, one dark matter particle, two allowed vertices

S-channel Z’ model and the mediator search



- Consider simplified S-channel model: one massive mediator, one dark matter particle, two allowed vertices
- X can be vector, axial-vector, scalar, or pseudoscalar
- Let’s pick **vector/axial-vector** Z’ for its higher cross sections

S-channel Z’ model and the mediator search

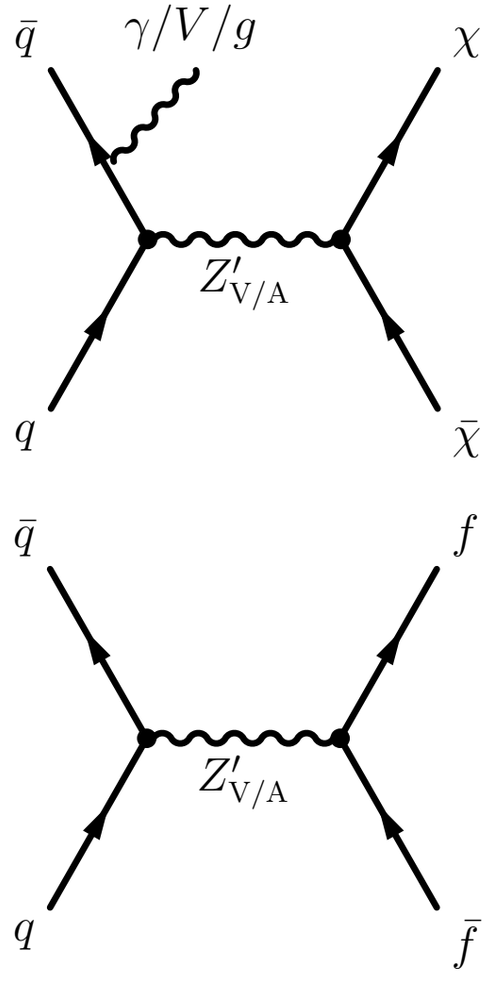


- Consider simplified S-channel model: one massive mediator, one dark matter particle, two allowed vertices

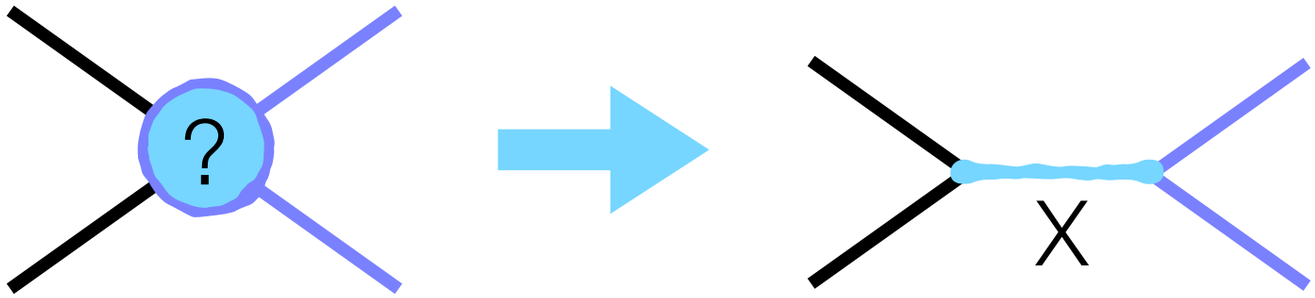
- X can be vector, axial-vector, scalar, or pseudoscalar

- Let’s pick **vector/axial-vector** Z’ for its higher cross sections

Two key signatures:

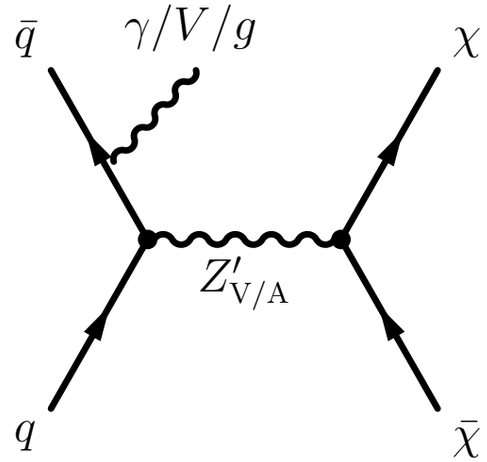


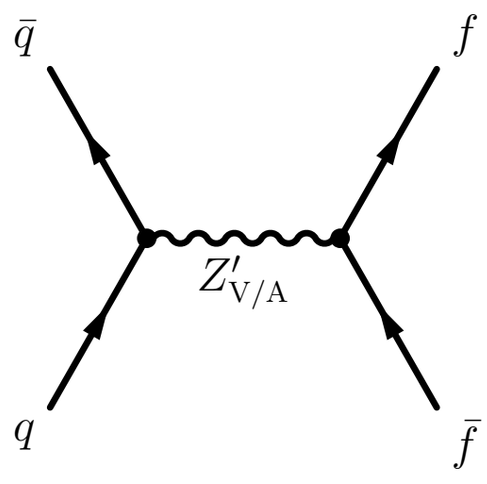
S-channel Z’ model and the mediator search



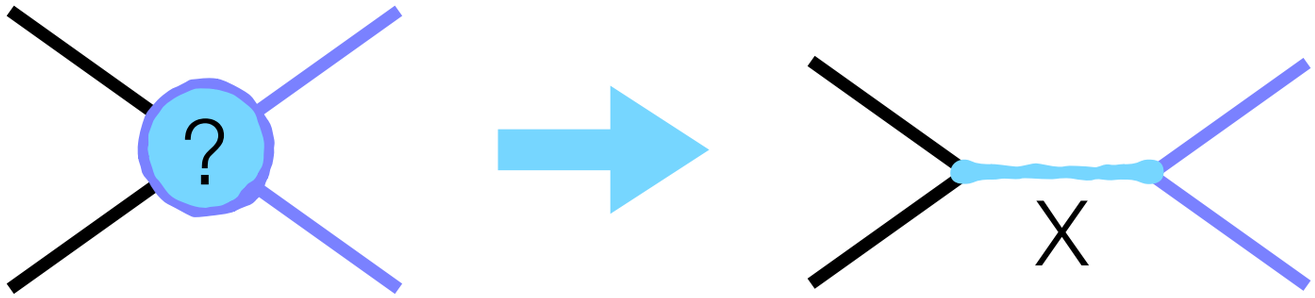
- Consider simplified S-channel model: one massive mediator, one dark matter particle, two allowed vertices
  - X can be vector, axial-vector, scalar, or pseudoscalar
  - Let’s pick **vector/axial-vector** Z’ for its higher cross sections
- **Mono-X** is important here, of course!
- BUT we also gain a **visible channel**: we have coupling to qq at minimum, and possibly more fermions too

Two key signatures:



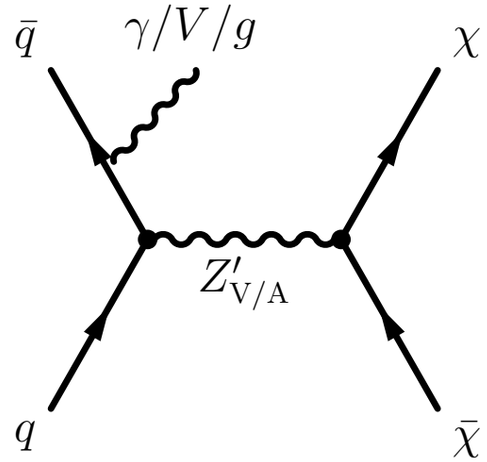


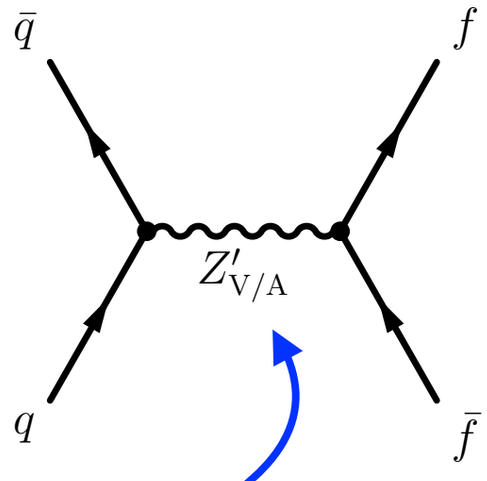
S-channel Z’ model and the mediator search



- Consider simplified S-channel model: one massive mediator, one dark matter particle, two allowed vertices
  - X can be vector, axial-vector, scalar, or pseudoscalar
  - Let’s pick **vector/axial-vector** Z’ for its higher cross sections
- **Mono-X** is important here, of course!
- BUT we also gain a **visible channel**: we have coupling to qq at minimum, and possibly more fermions too

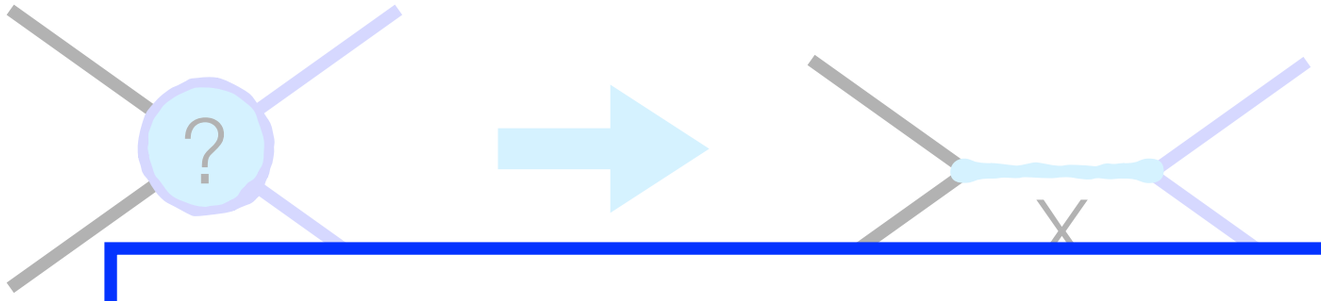
Two key signatures:





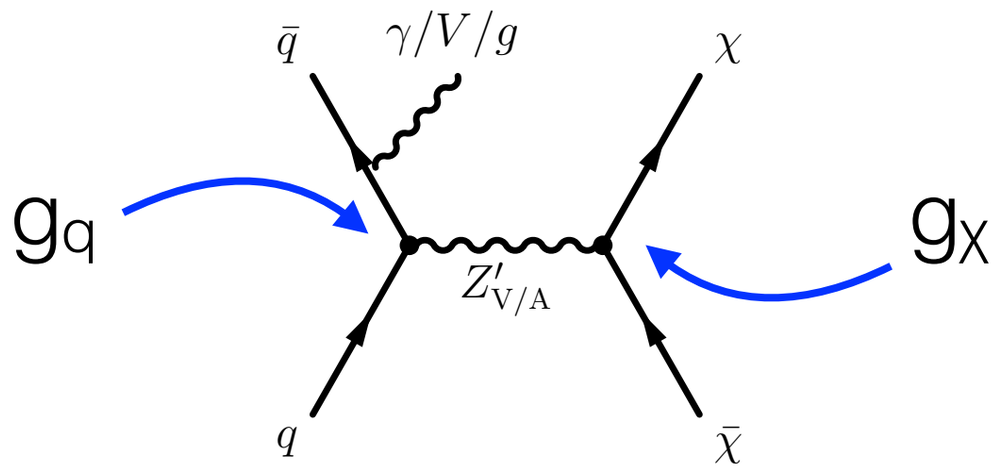
Resonance

S-channel Z’ model and the mediator search



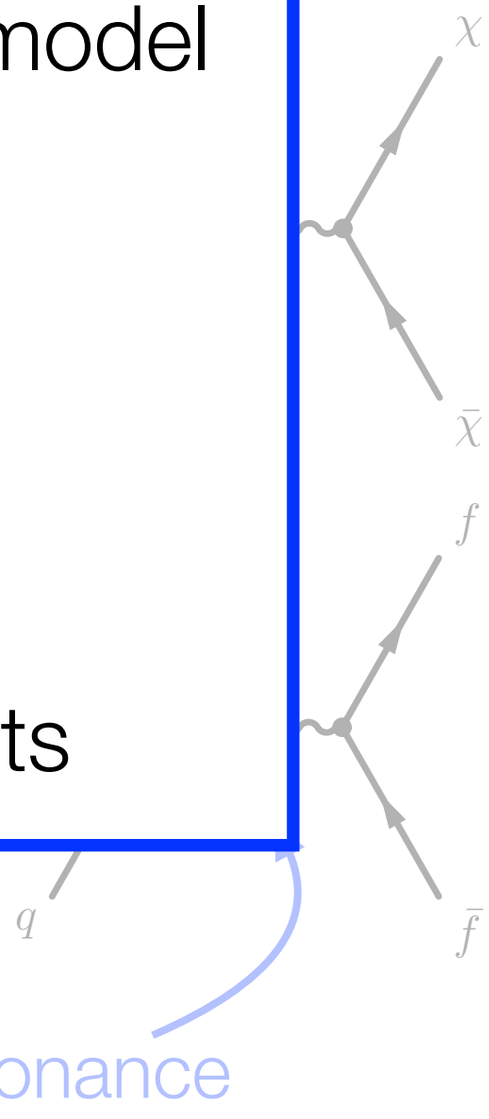
Two key signatures:

Note: only two new couplings in this model



Values selected strongly affect limits

- Conside
  mediator
  - X can
  - Let’s
    sectio
- **Mono-X**
- BUT we also gain a **visible channel**: we have coupling to qq at minimum, and possibly more fermions too

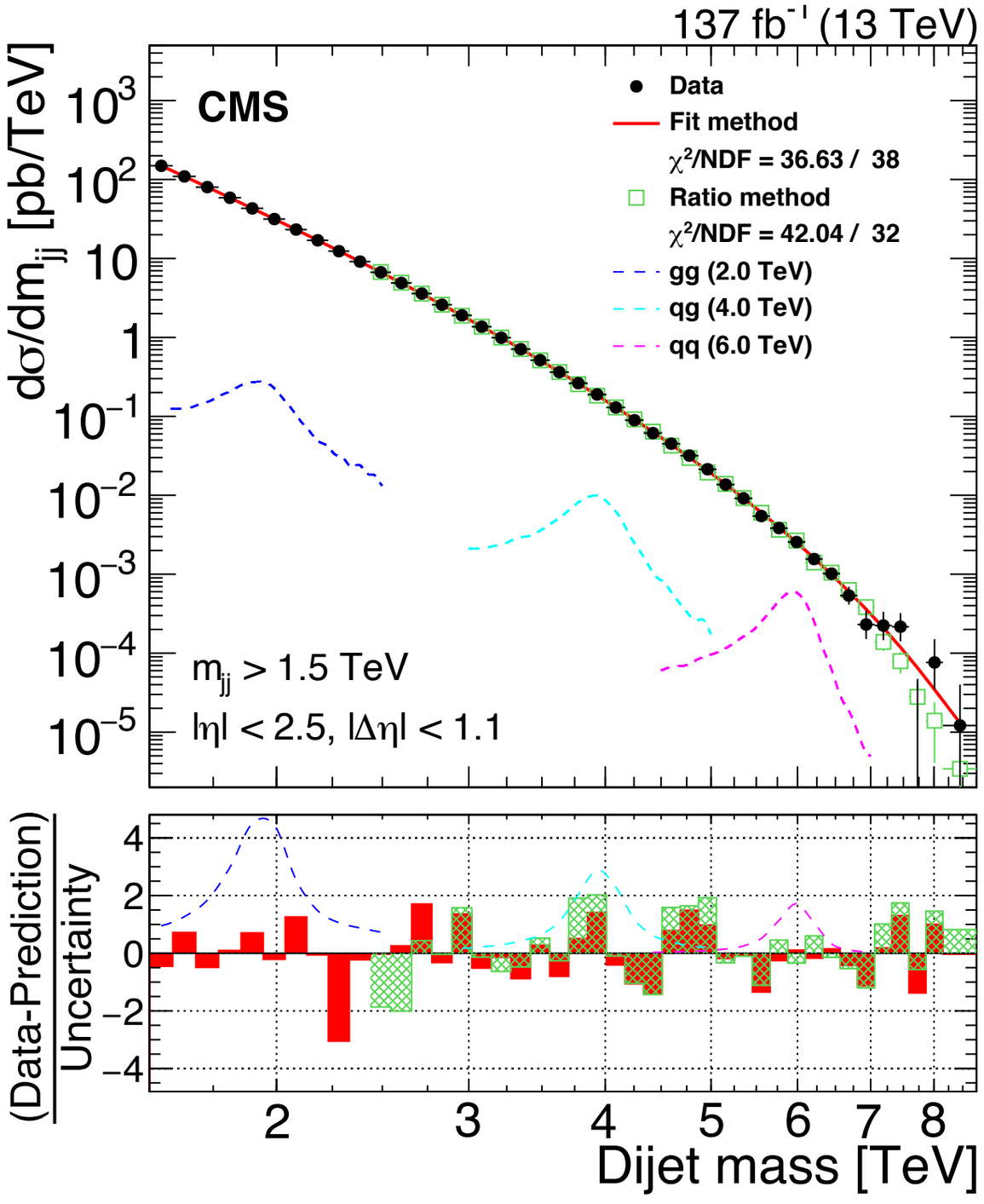


ATLAS EXOT-2019-03

CMS EXO-19-012

Dijet resonances

- Simplest mediator search: if qq→Z' produces the mediator, it can decay back to quarks
- QCD jet invariant mass spectrum will fall smoothly, while signals will appear as peaks



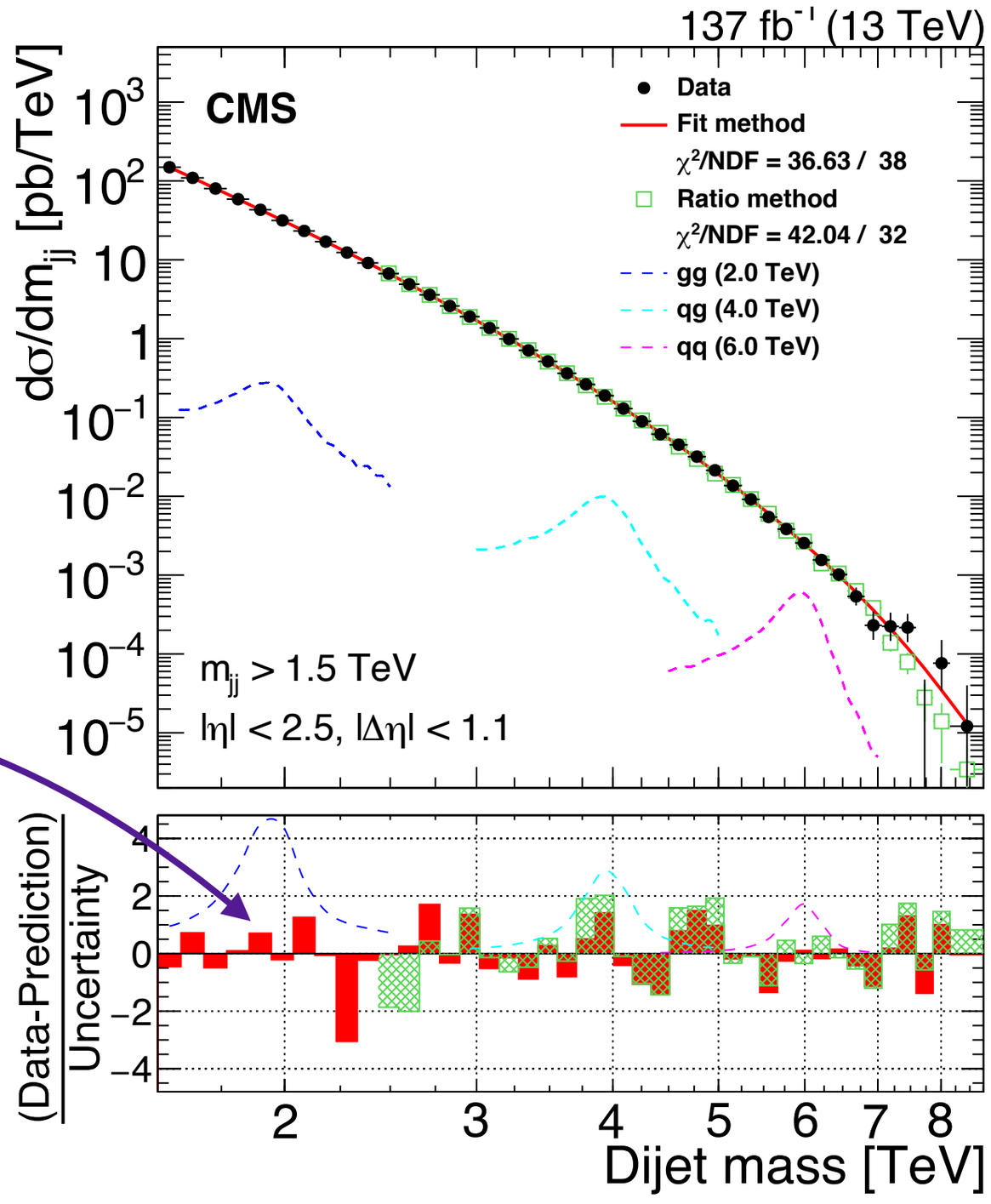
ATLAS EXOT-2019-03

CMS EXO-19-012

Dijet resonances

- Simplest mediator search: if qq→Z' produces the mediator, it can decay back to quarks
- QCD jet invariant mass spectrum will fall smoothly, while signals will appear as peaks

Standard approach uses fitted functional form to parameterise backgrounds



ATLAS EXOT-2019-03

CMS EXO-19-012

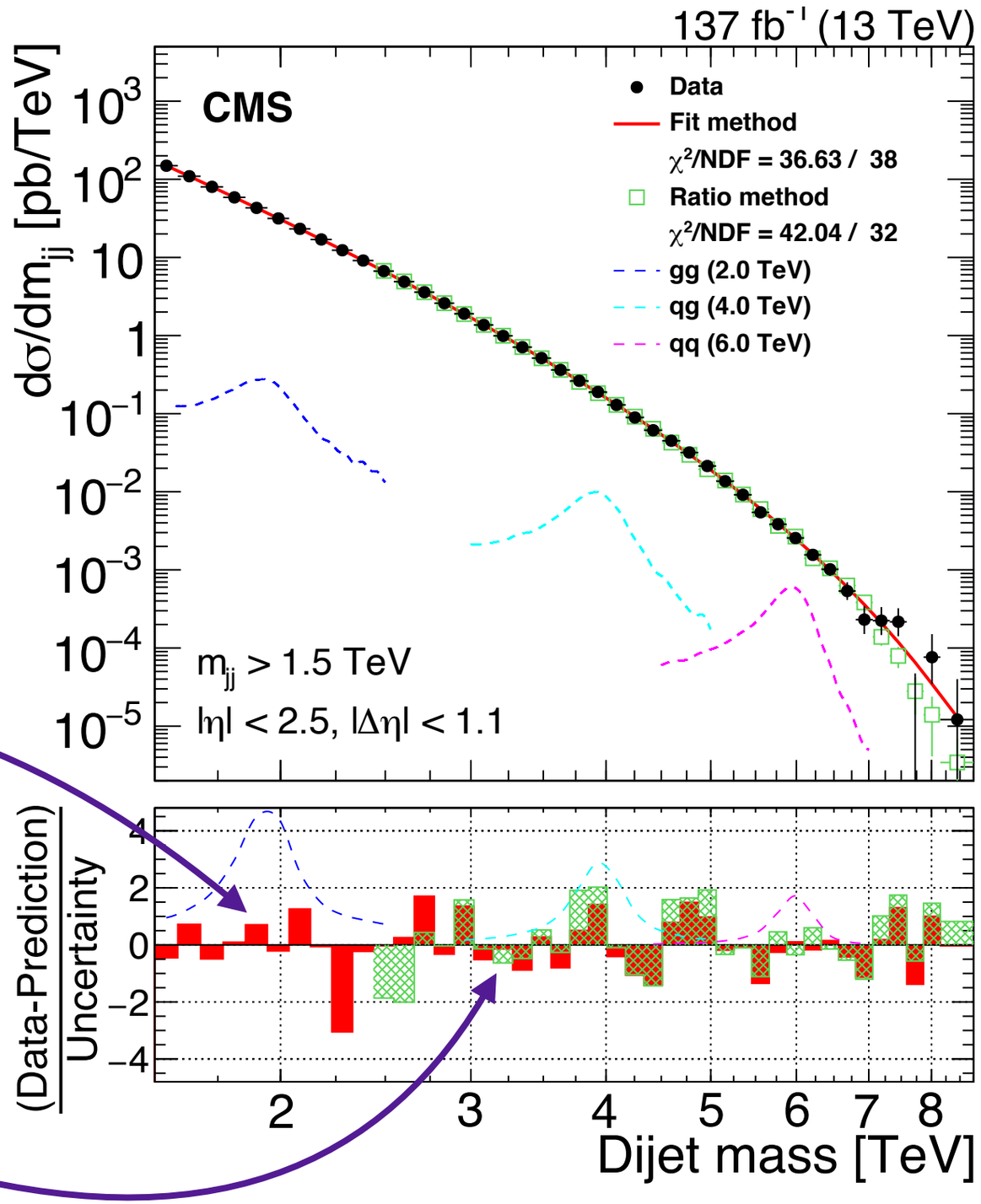
Dijet resonances

- Simplest mediator search: if qq→Z' produces the mediator, it can decay back to quarks
- QCD jet invariant mass spectrum will fall smoothly, while signals will appear as peaks

Standard approach uses fitted functional form to parameterise backgrounds

New method scales data at high dijet Δη to predict central Δη

Good agreement between methods



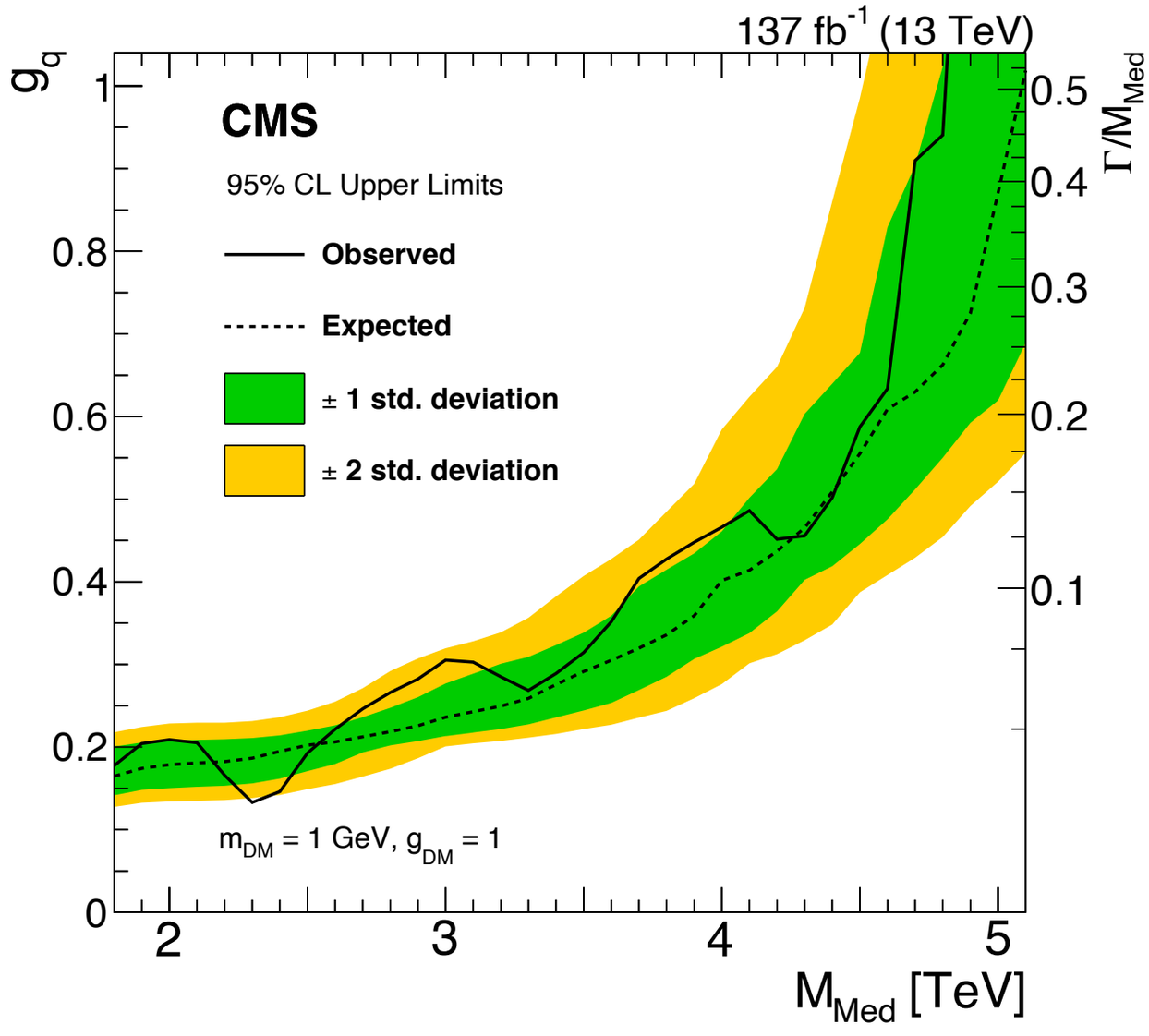
ATLAS EXOT-2019-03

CMS EXO-19-012

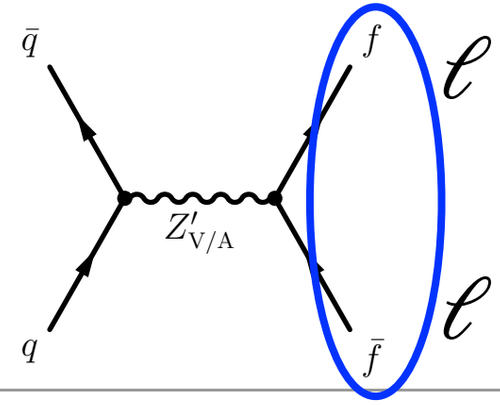
Dijet resonances

- Simplest mediator search: if qq→Z' produces the mediator, it can decay back to quarks
- QCD jet invariant mass spectrum will fall smoothly, while signals will appear as peaks

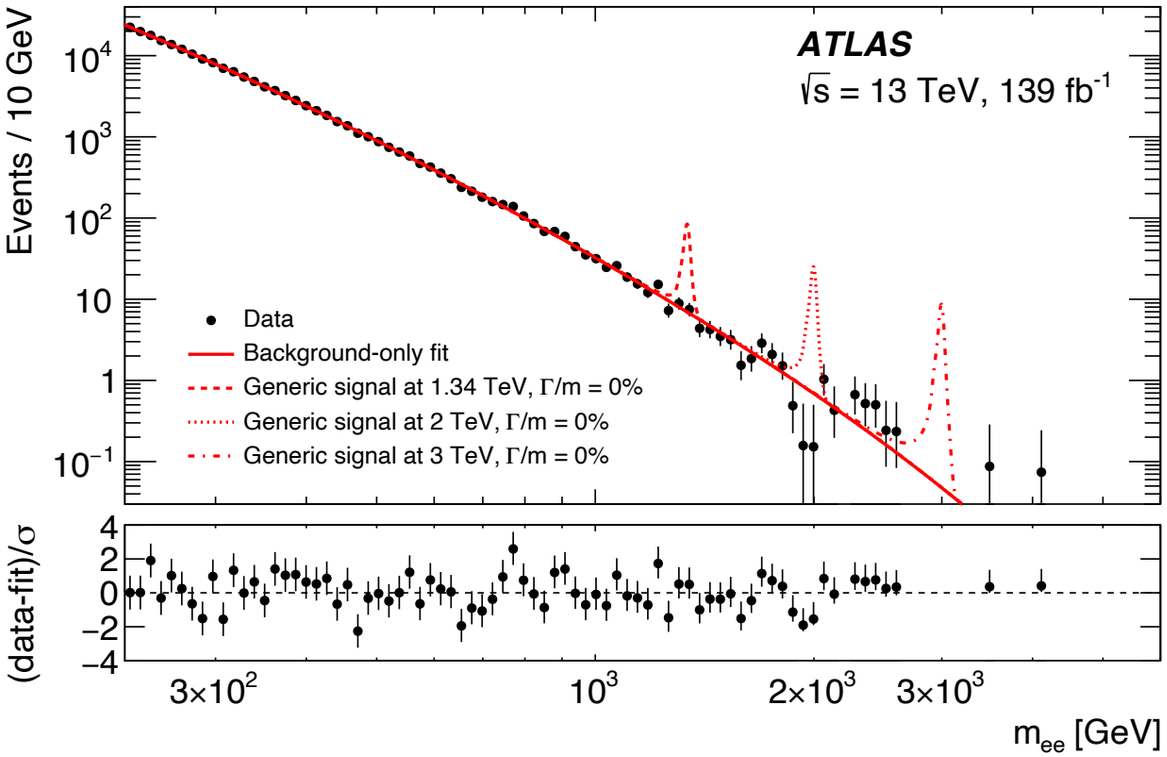
Ratio-based estimate much more stable when peaks are wide: limits extend to width-to-mass ratio of 50%!

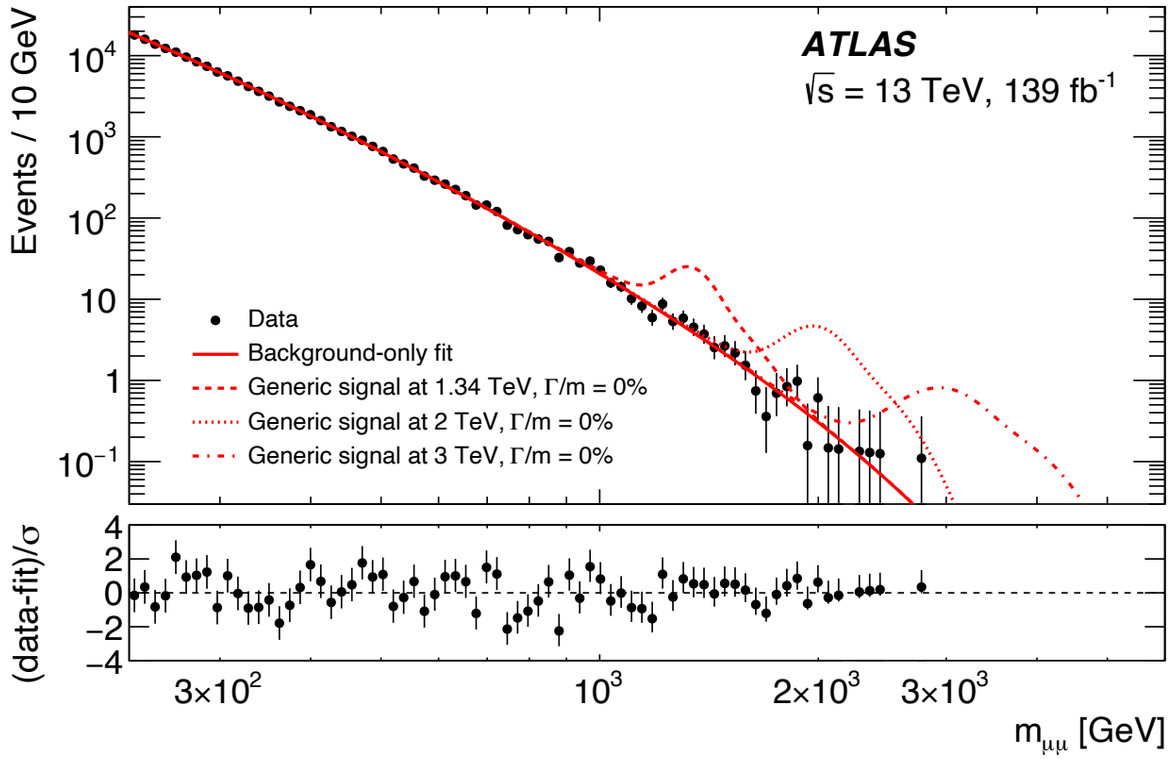


Leptophilic Z’ mediators



If mediator can **couple to leptons**, get a clean, powerful decay channel with lower background than for dijets

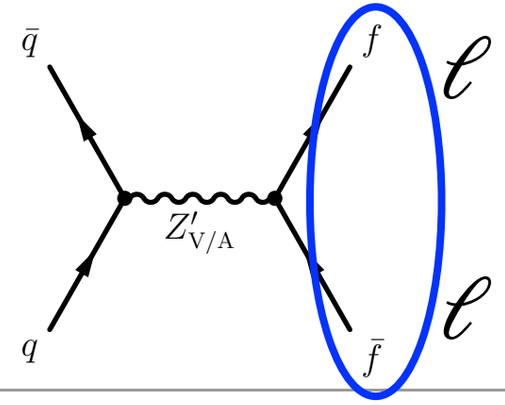




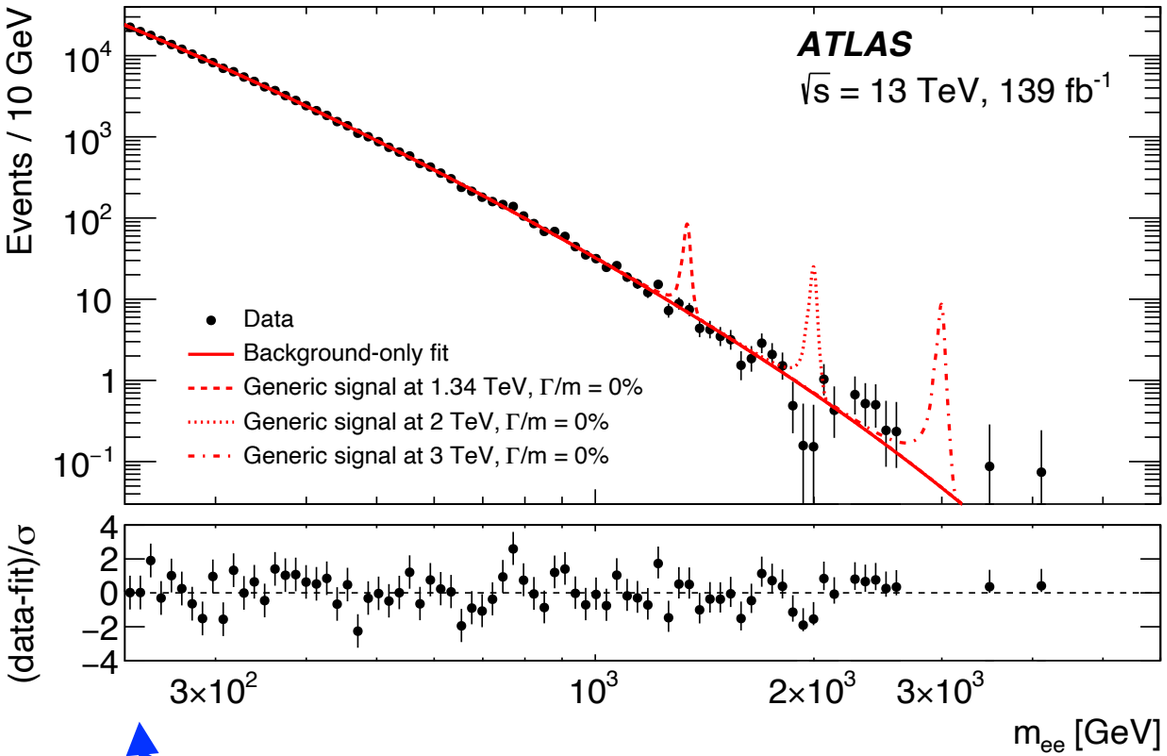
ATLAS EXOT-2018-08

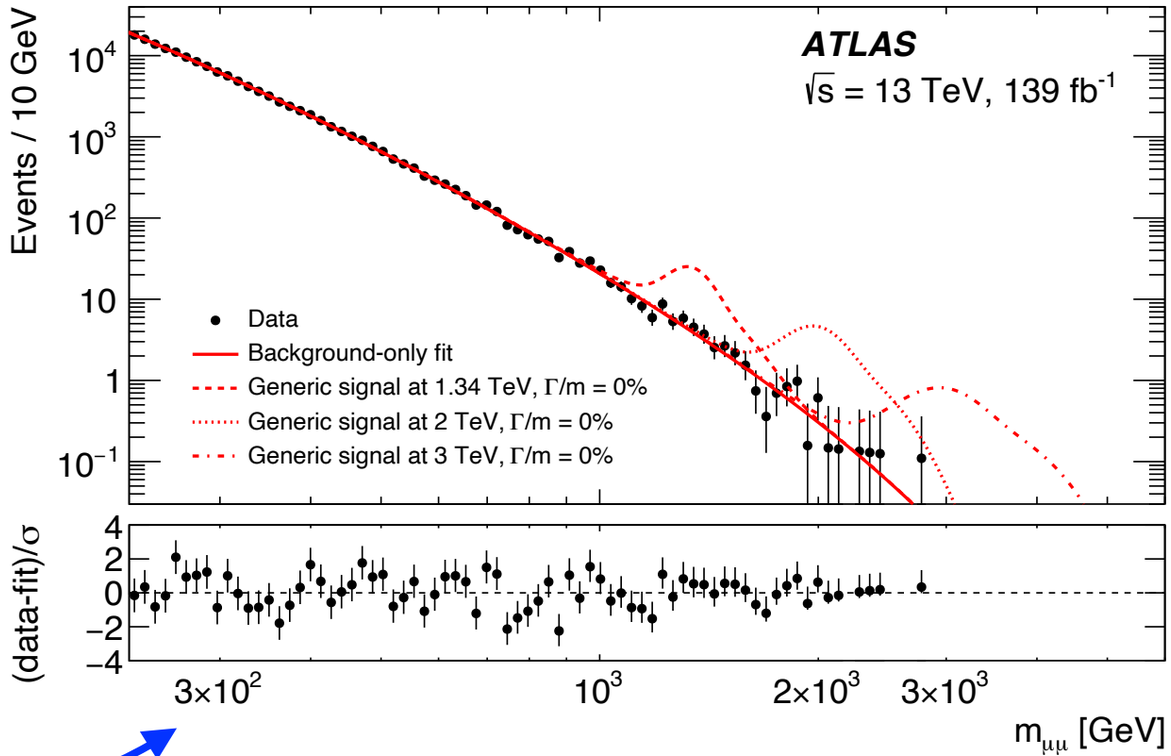
CMS PAS ATLAS EXO-19-019

Leptophilic Z' mediators



If mediator can **couple to leptons**, get a clean, powerful decay channel with lower background than for dijets

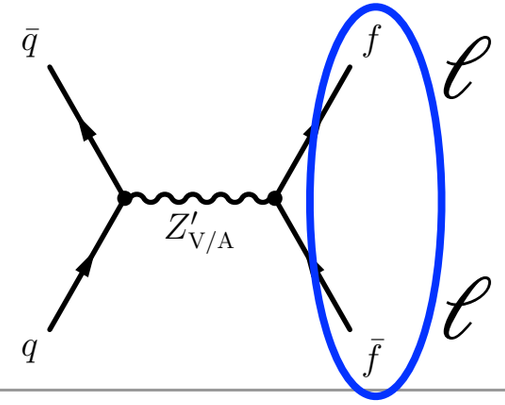




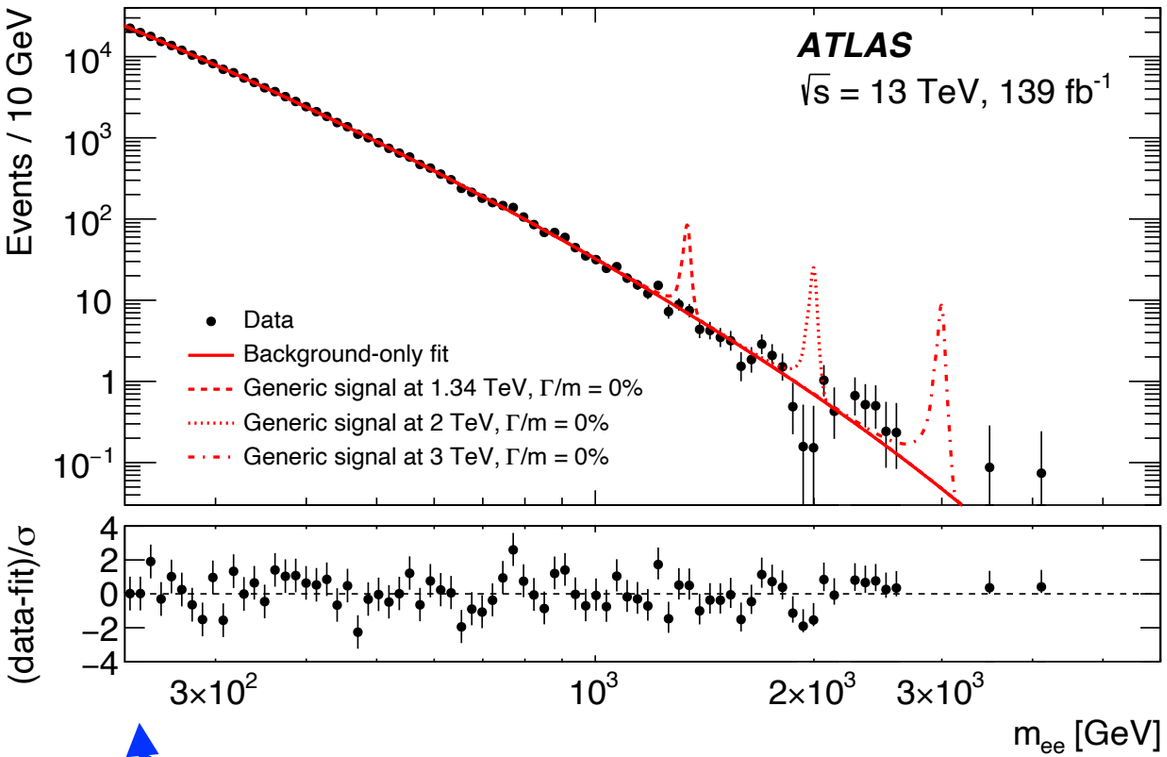
Lepton triggers have lower thresholds, so lower masses available

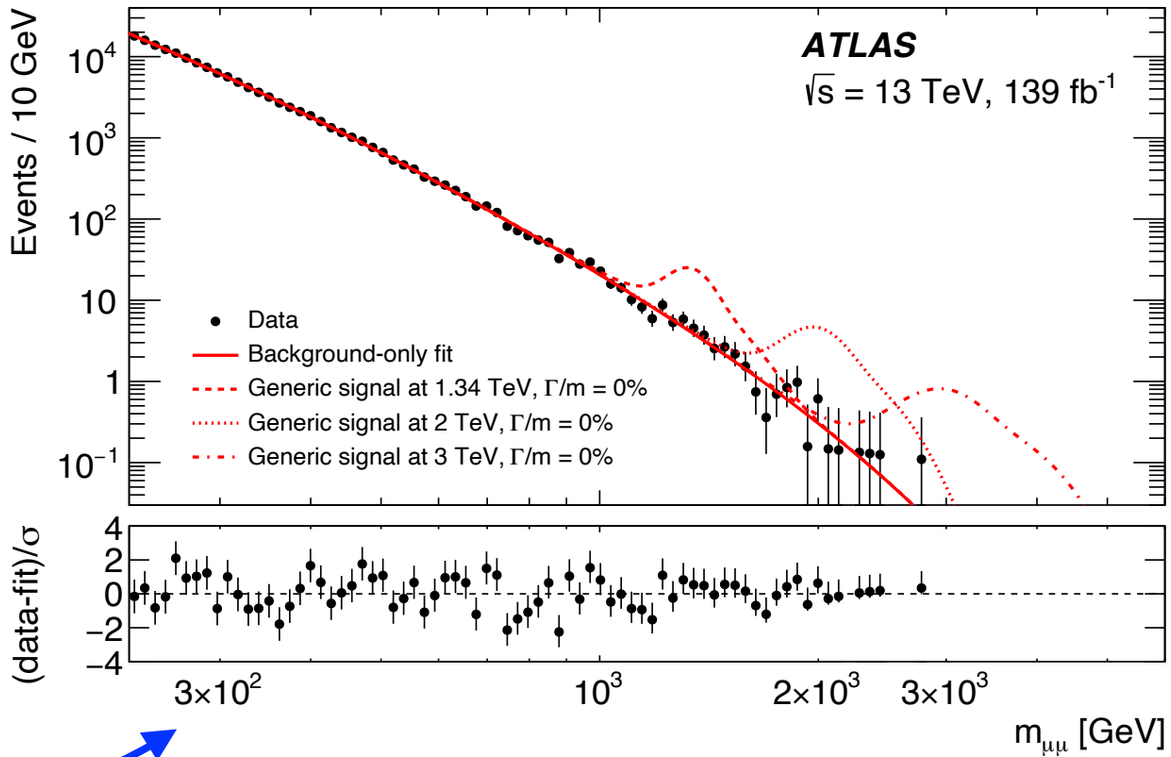
CMS PAS ATLAS EXO-19-019 | ATLAS EXOT-2018-08

Leptophilic Z' mediators



If mediator can **couple to leptons**, get a clean, powerful decay channel with lower background than for dijets





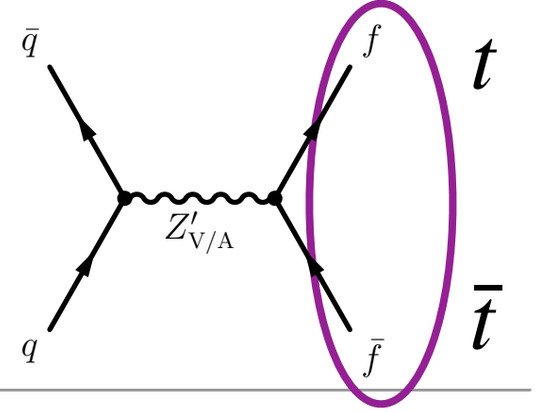
Lepton triggers have lower thresholds, so lower masses available

Resolution better in ee channel: track resolution degrades with p_T while calorimeter resolution improves

CMS PAS ATLAS EXO-19-019

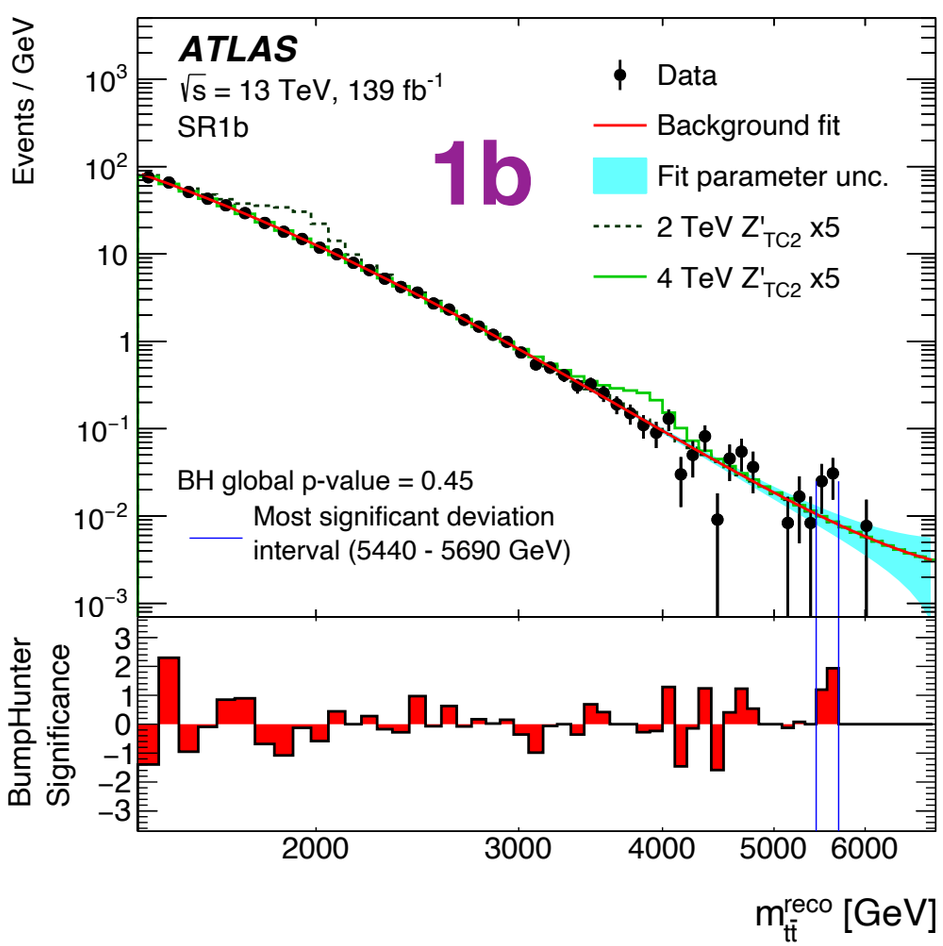
ATLAS EXOT-2018-08

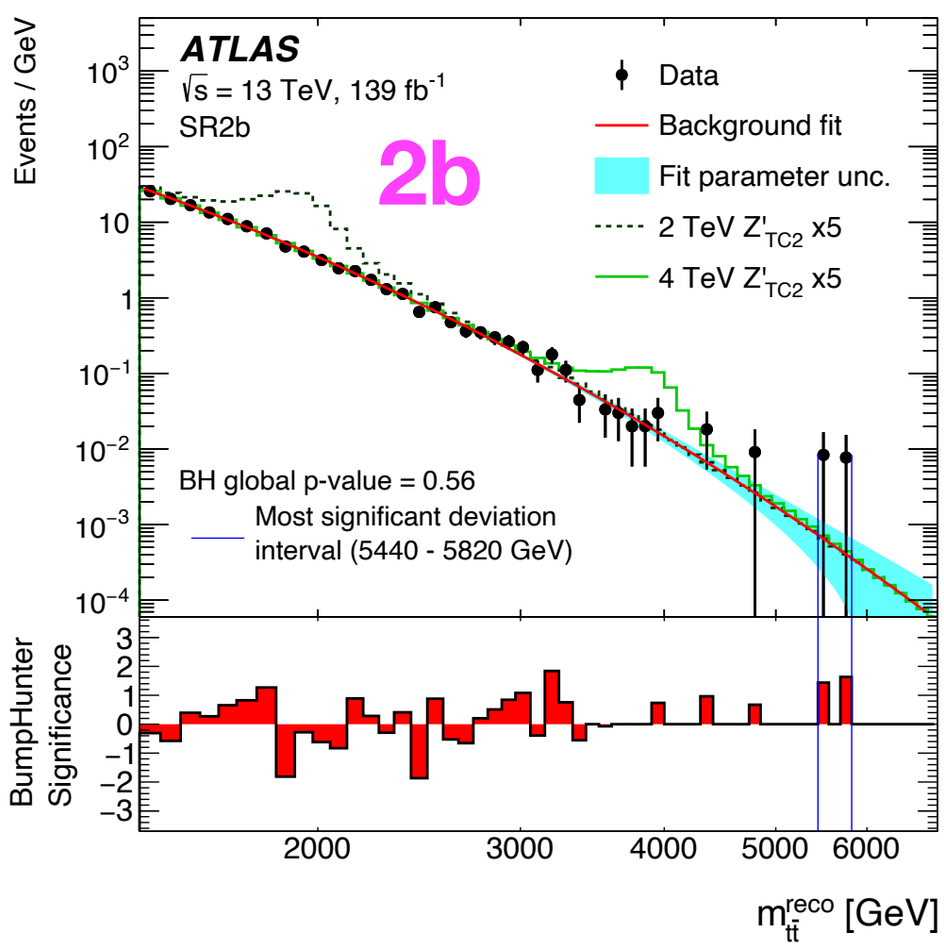
Top quark resonances



- Hadronically decaying tops reconstructed as large-radius jets. Identify them using substructure information and high jet mass

- Constituent tracks identify b-hadron decays inside large-R jets. 2 signal regions (**1b** and **2b**) ensure good total signal efficiency

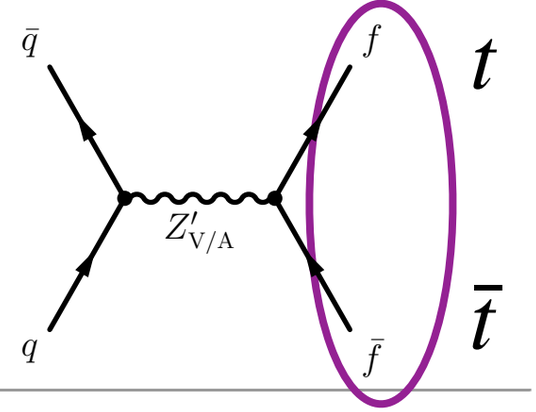




Smooth fit to invariant mass spectrum of top-tagged jets

ATLAS EXOT-2018-48

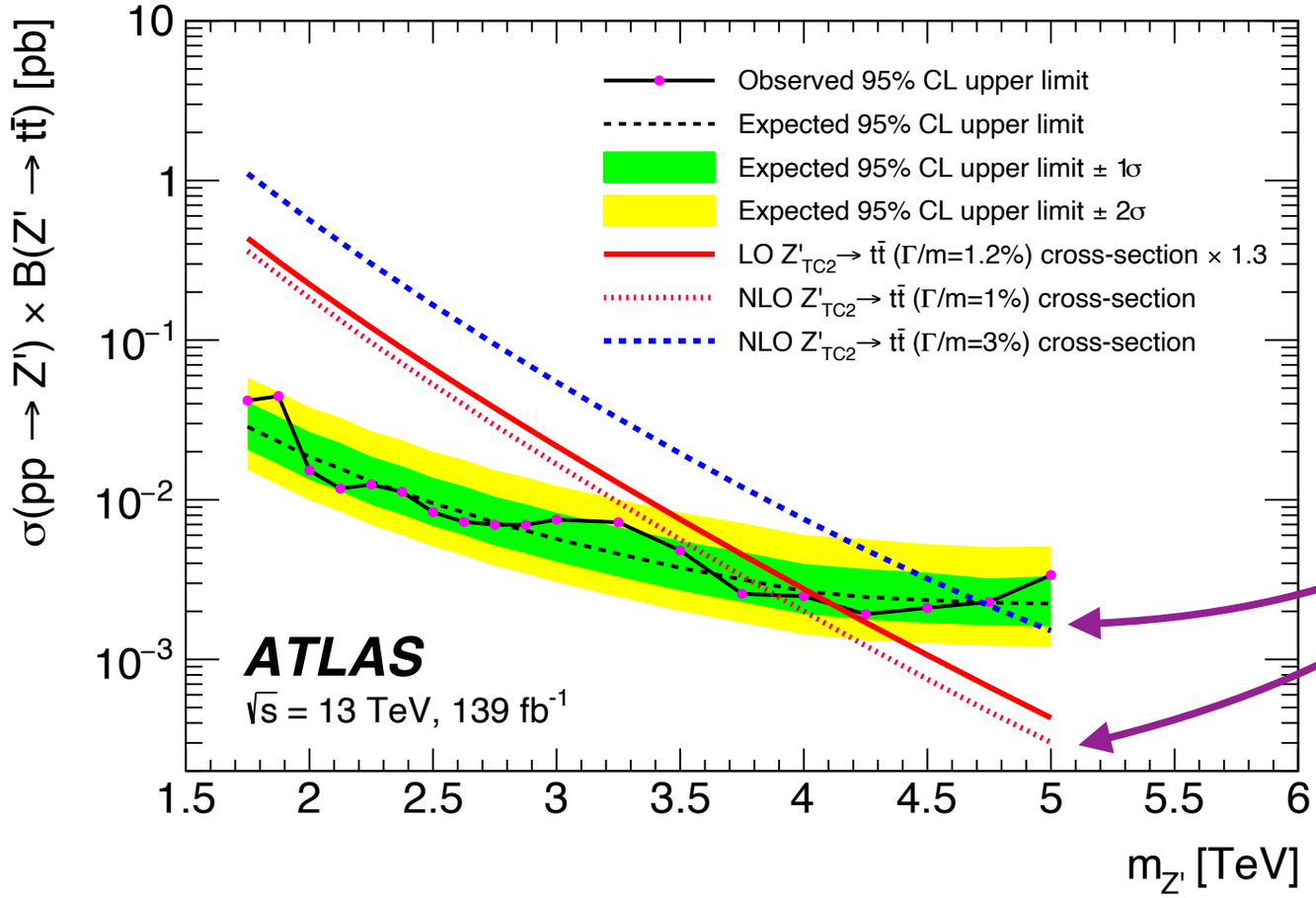
Top quark resonances



- Hadronically decaying tops reconstructed as large-radius jets. Identify them using substructure information and high jet mass

- Constituent tracks identify b-hadron decays inside large-R jets. 2 signal regions (**1b** and **2b**) ensure good total signal efficiency

Statistical combination of SR 1b and SR 2b



Effect of resonance width

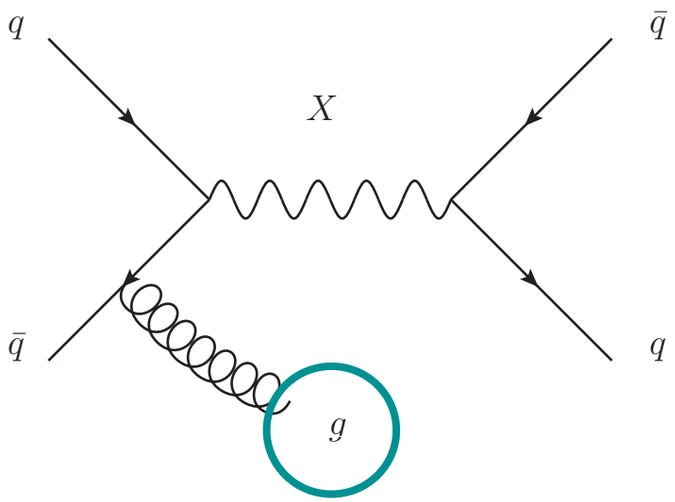
Low-mass mediator searches

- Challenging to search for low mass mediators because decay products don't have **enough momentum** to pass triggers
- Two main methods to overcome this: triggering on an **associated object** or performing analysis at the **"trigger level"**

Low-mass mediator searches

- Challenging to search for low mass mediators because decay products don't have **enough momentum** to pass triggers
- Two main methods to overcome this: triggering on an **associated object** or performing analysis at the **"trigger level"**

Triggering on ISR



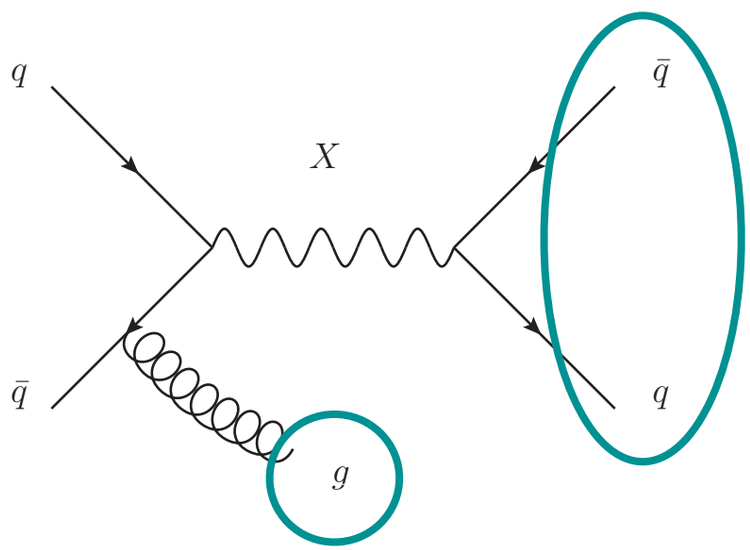
Hard radiation produces jet passing trigger

CMS EXO-18-012

Low-mass mediator searches

- Challenging to search for low mass mediators because decay products don't have **enough momentum** to pass triggers
- Two main methods to overcome this: triggering on an **associated object** or performing analysis at the **"trigger level"**

Triggering on ISR



Hard radiation produces jet passing trigger

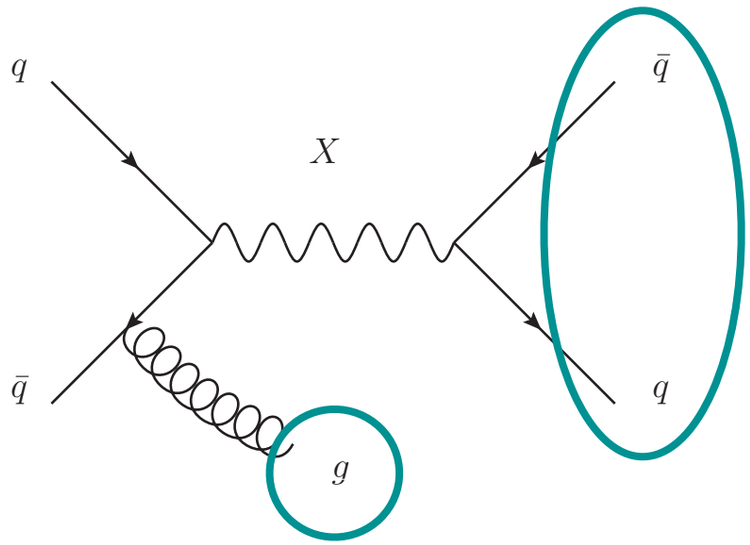
Decay products of boosted Z' are collimated into one large radius jet

CMS EXO-18-012

Low-mass mediator searches

- Challenging to search for low mass mediators because decay products don't have **enough momentum** to pass triggers
- Two main methods to overcome this: triggering on an **associated object** or performing analysis at the **"trigger level"**

Triggering on ISR



Hard radiation produces jet passing trigger

Decay products of boosted Z' are collimated into one large radius jet

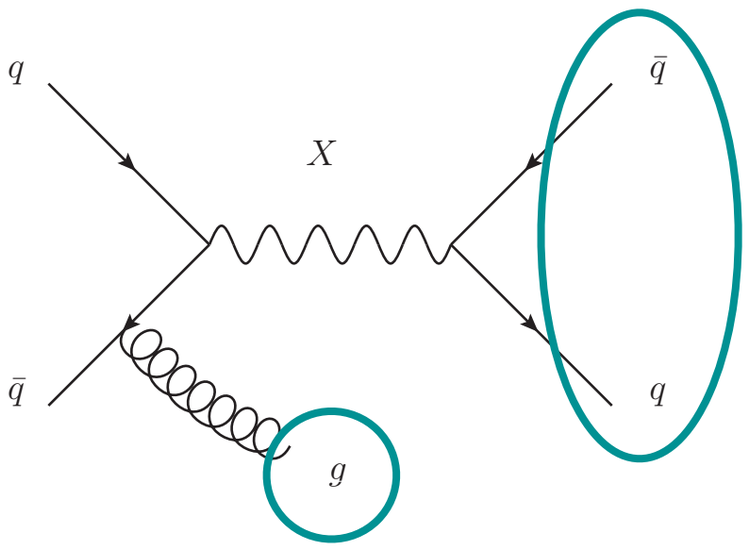
Use *substructure* variables to reject QCD; select two-prong-like topology

CMS EXO-18-012

Low-mass mediator searches

- Challenging to search for low mass mediators because decay products don't have **enough momentum** to pass triggers
- Two main methods to overcome this: triggering on an **associated object** or performing analysis at the **"trigger level"**

Triggering on ISR

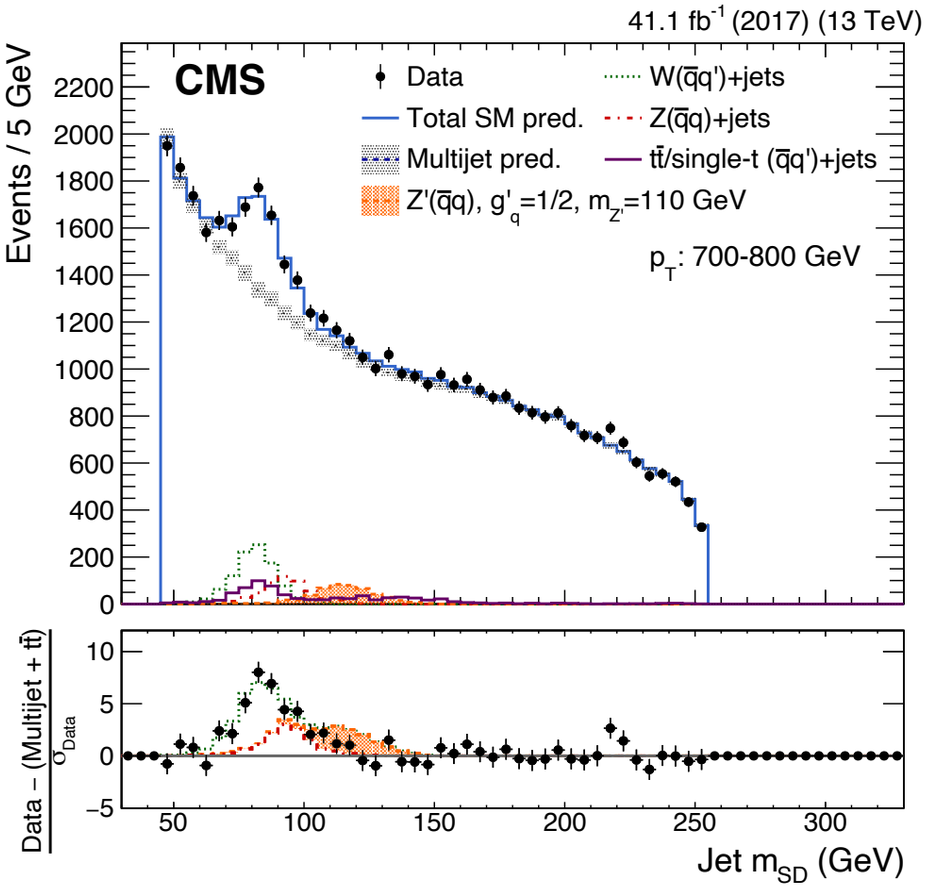


Hard radiation produces jet passing trigger

Decay products of boosted Z' are collimated into one large radius jet

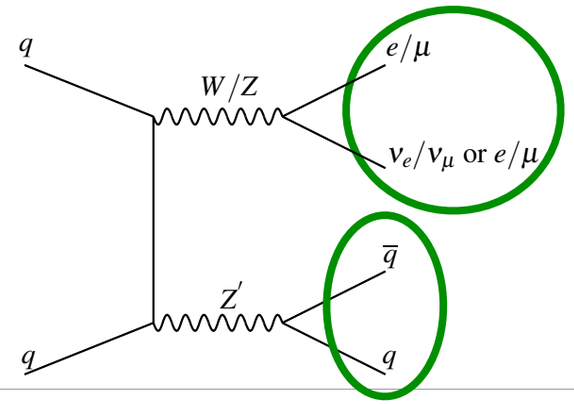
Use *substructure* variables to reject QCD; select two-prong-like topology

Estimate background with events failing large-R jet selections

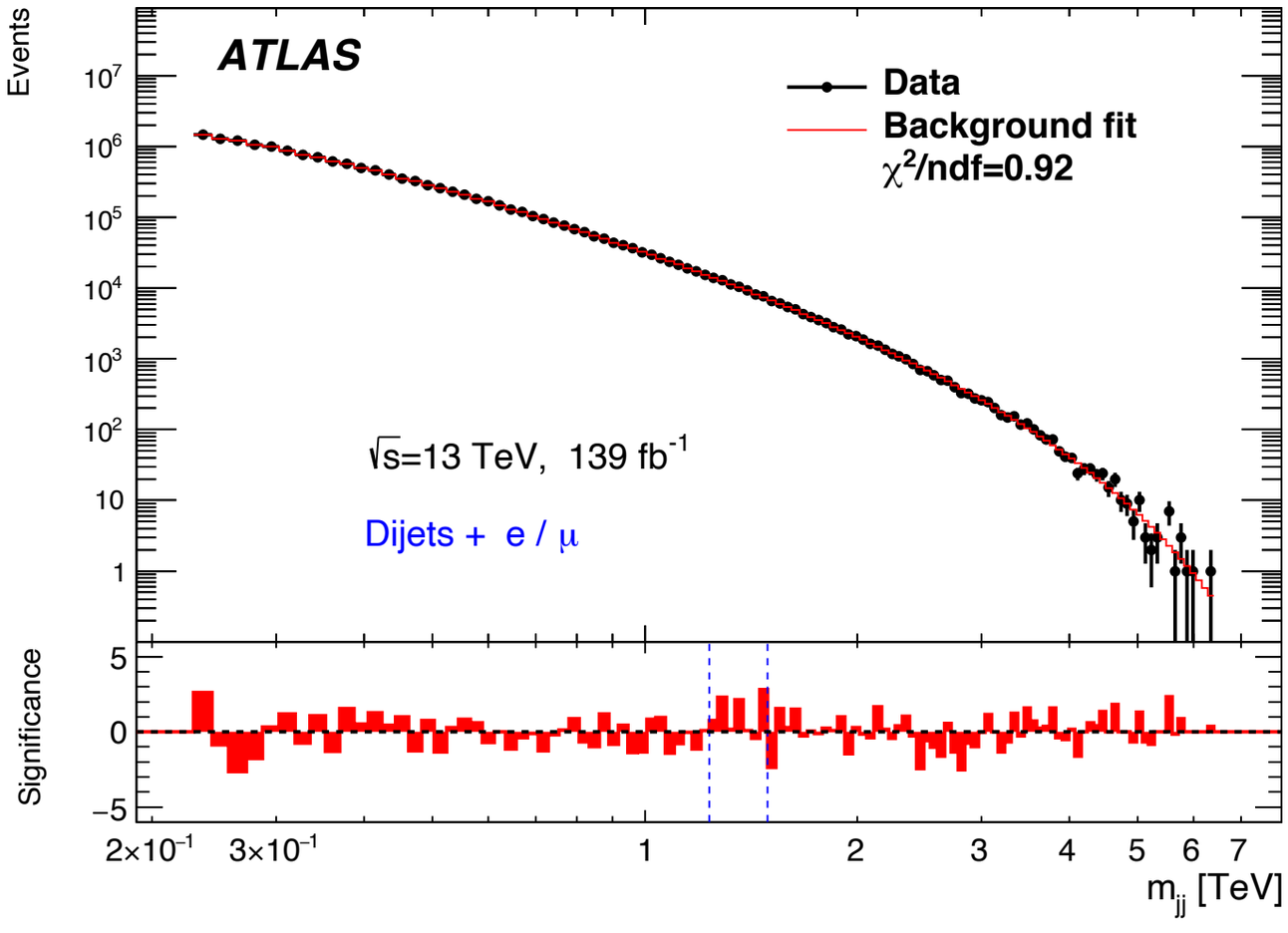


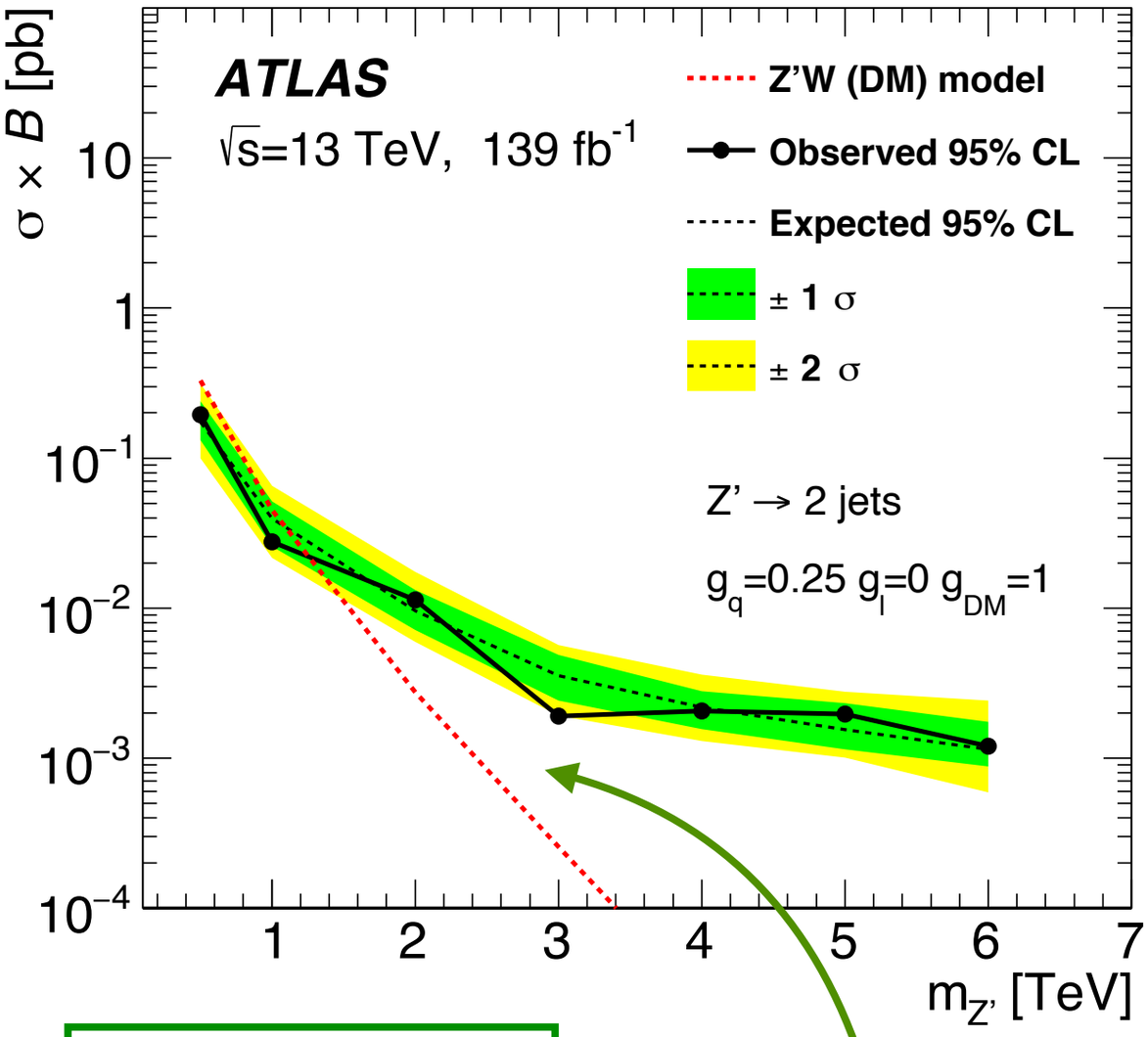
CMS EXO-18-012

Initial state radiation of a W or Z



- Large mass range simultaneously accessible by considering W/Z radiation and **triggering on a lepton**
- Fit dijet invariant mass spectrum with functional form





Fit to combined e/μ channels

ATLAS EXOT-2018-32

Lower probability of radiating W/Z → lower limit

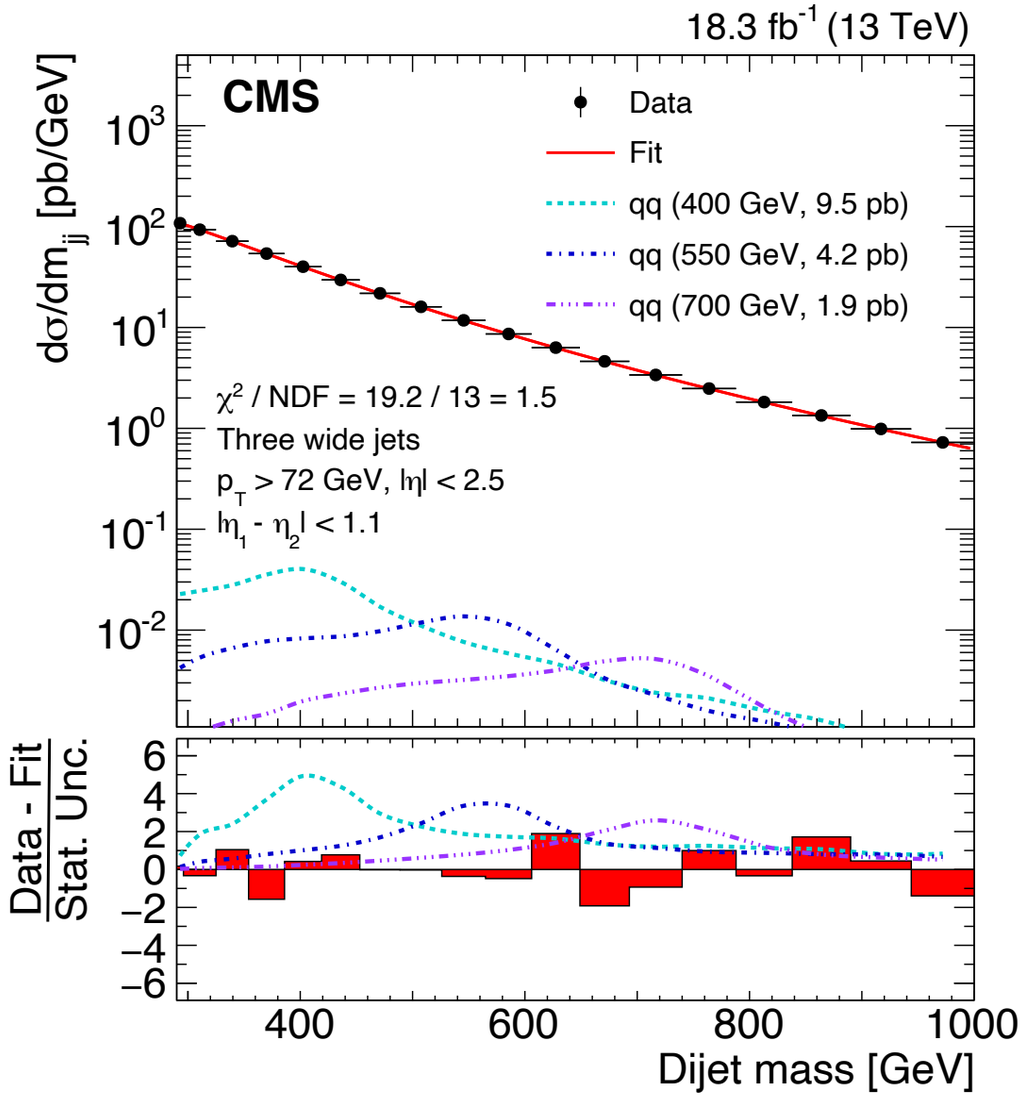
ATLAS EXOT-2016-20

Light mediators at the trigger level

Trigger level strategy: instead of saving a lot of data for a small number of events, save very minimal data for a large number of events.

Z'→qq

- Use H_T (scalar momentum sum) trigger and save calorimeter jet info **only**
  - Rate limited only by **level 1 trigger**
- Require three jets to get sufficiently high H_T
- Fit invariant mass of two hardest jets and search for excesses



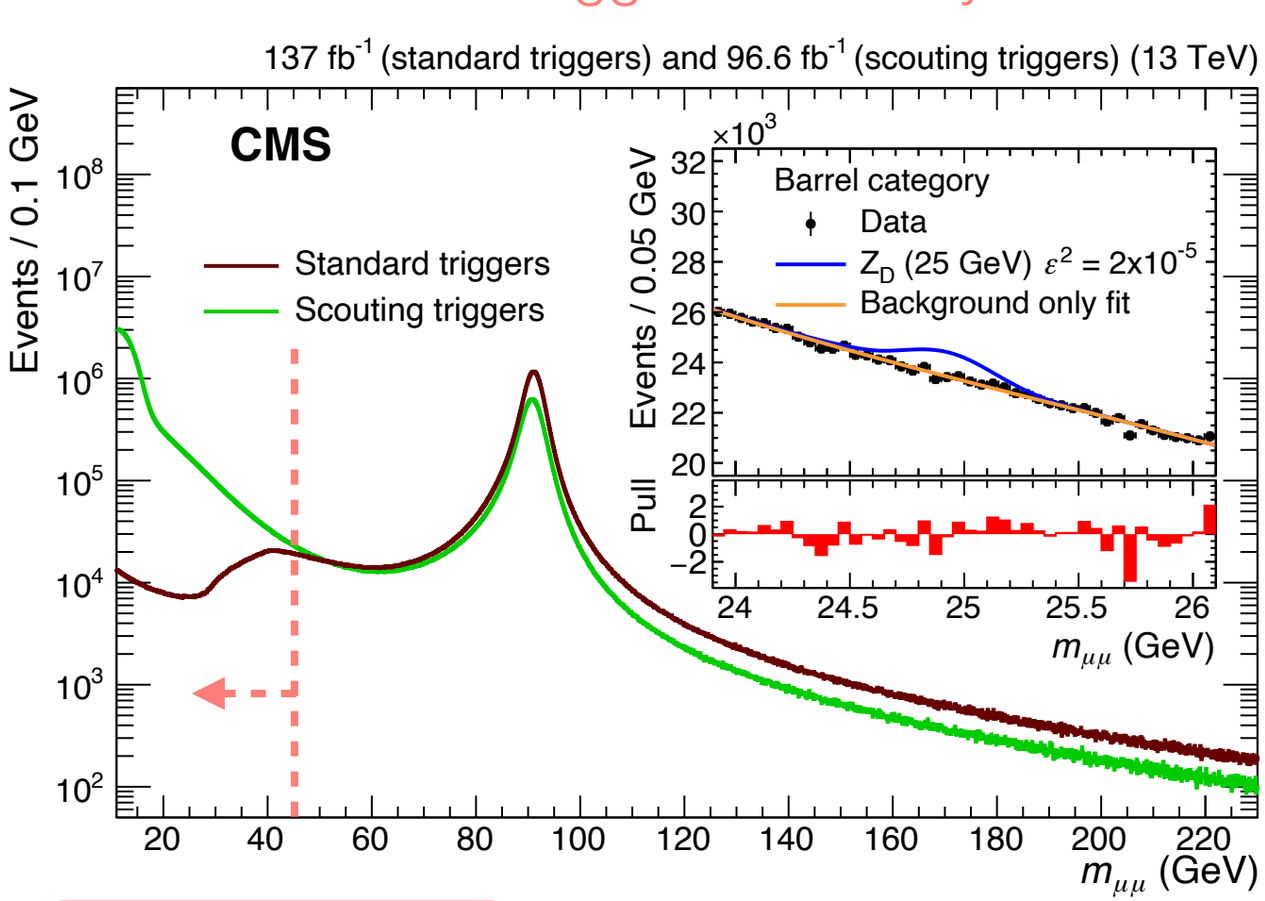
CMS EXO-19-004

Light mediators at the trigger level

Trigger level strategy: instead of saving a lot of data for a small number of events, save very minimal data for a large number of events.

$Z' \rightarrow \mu\mu$

10x - 100x gain below 45 GeV thanks to trigger level analysis

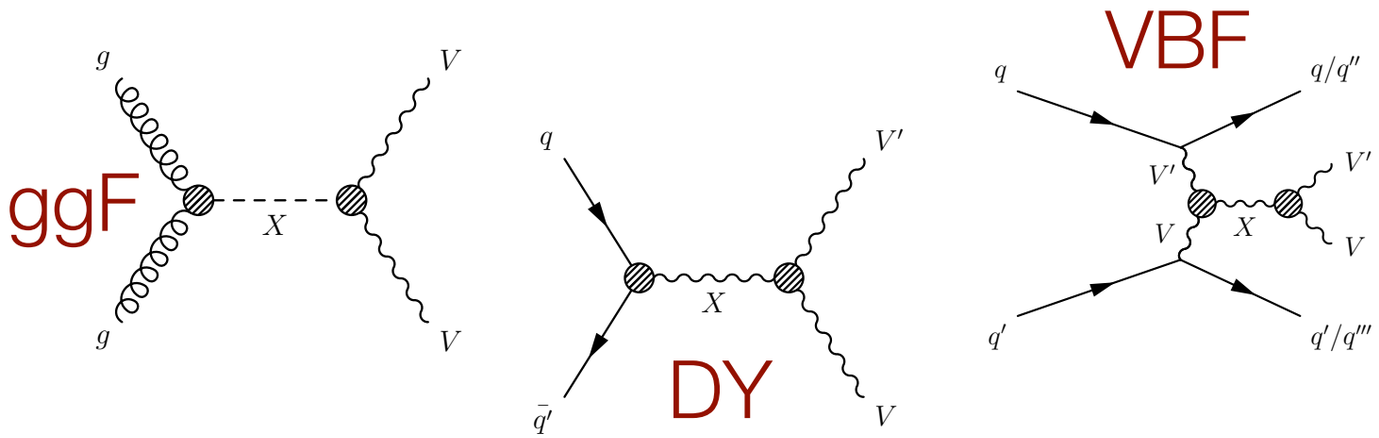


- Standard triggers access lower masses for leptons than jets
- But for very low mass resonances, still limiting
- **First ever trigger-level muons!** Save only 4-momentum, isolation, track quality information at very high rates

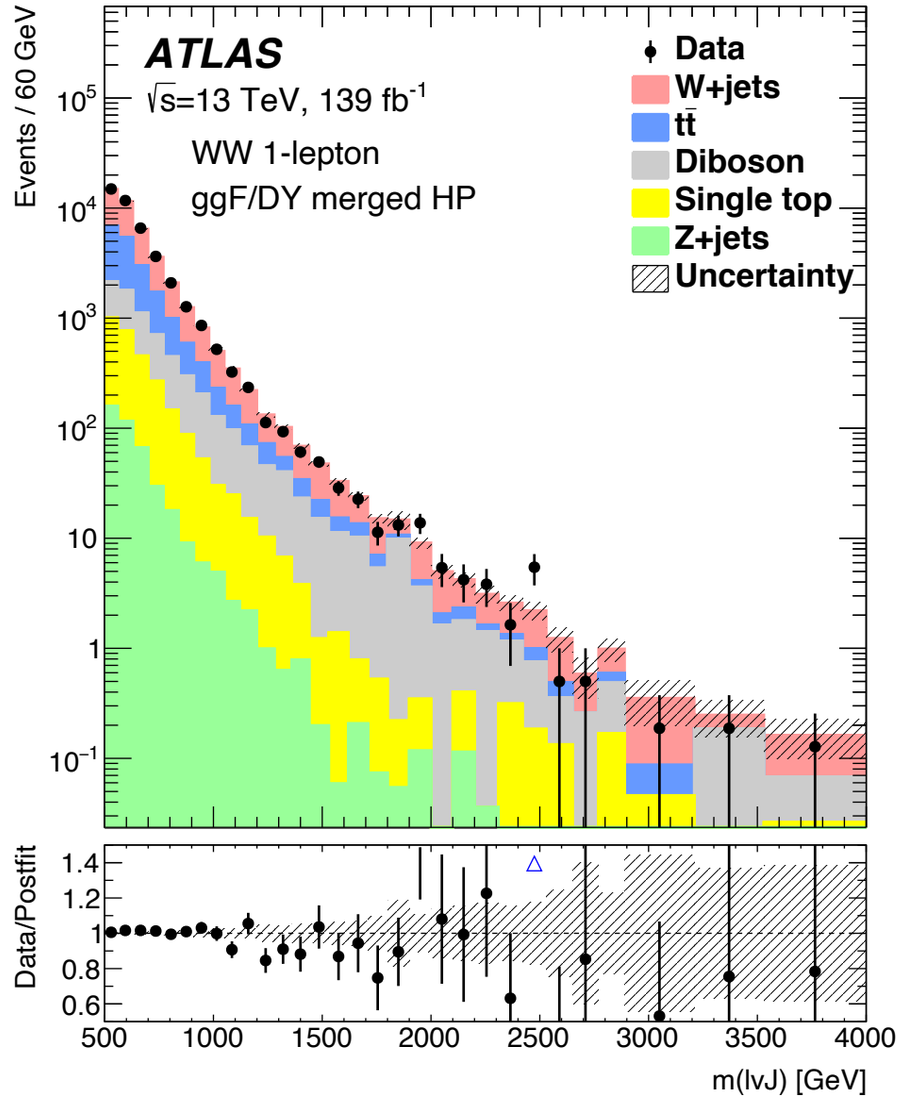
CMS EXO-19-018

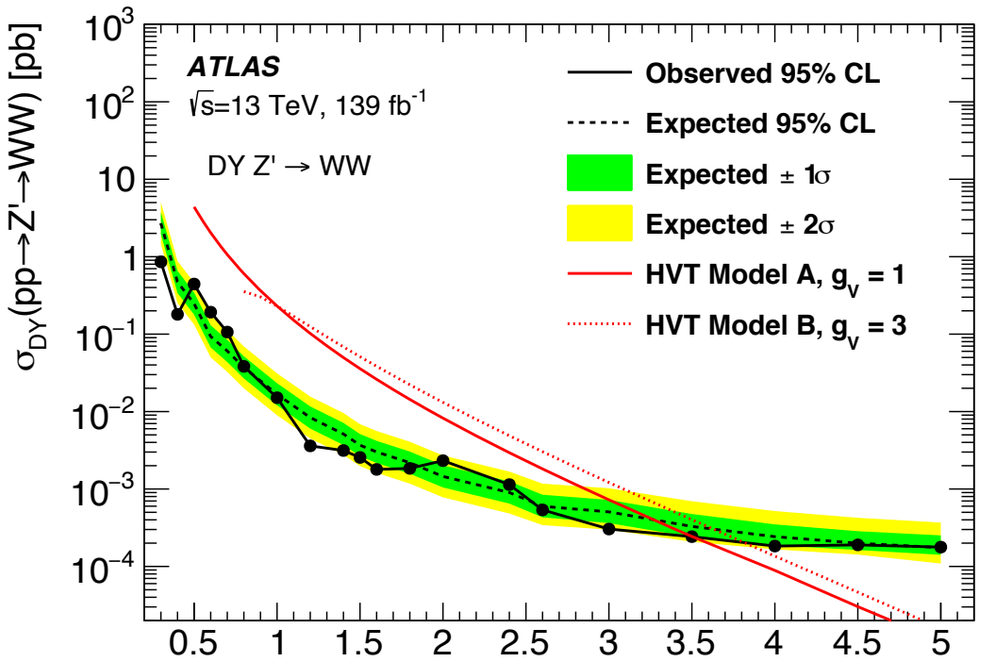
Di-boson resonances

- In some models, can allow a Z' to couple to W and Z bosons. Depending on other couplings, can produce via:



- This search is in 0, 1, 2 lepton final states
- $V \rightarrow qq$: can be high mass large-radius jet or two standard jets
- Search invariant mass or transverse mass of X for resonance peaks





ATLAS HDBS-2018-10

Invisible decays of the Higgs

- **Higgs portal DM:** new dark matter particle couples to the Standard Model **only via the Higgs**

- Assuming we understand total Higgs production cross section, **how much room** is there for BSM decays?

  - Combination of observed Higgs decays now sets upper limit on remaining branching fraction **B(h125)→BSM at ~ 30%**.

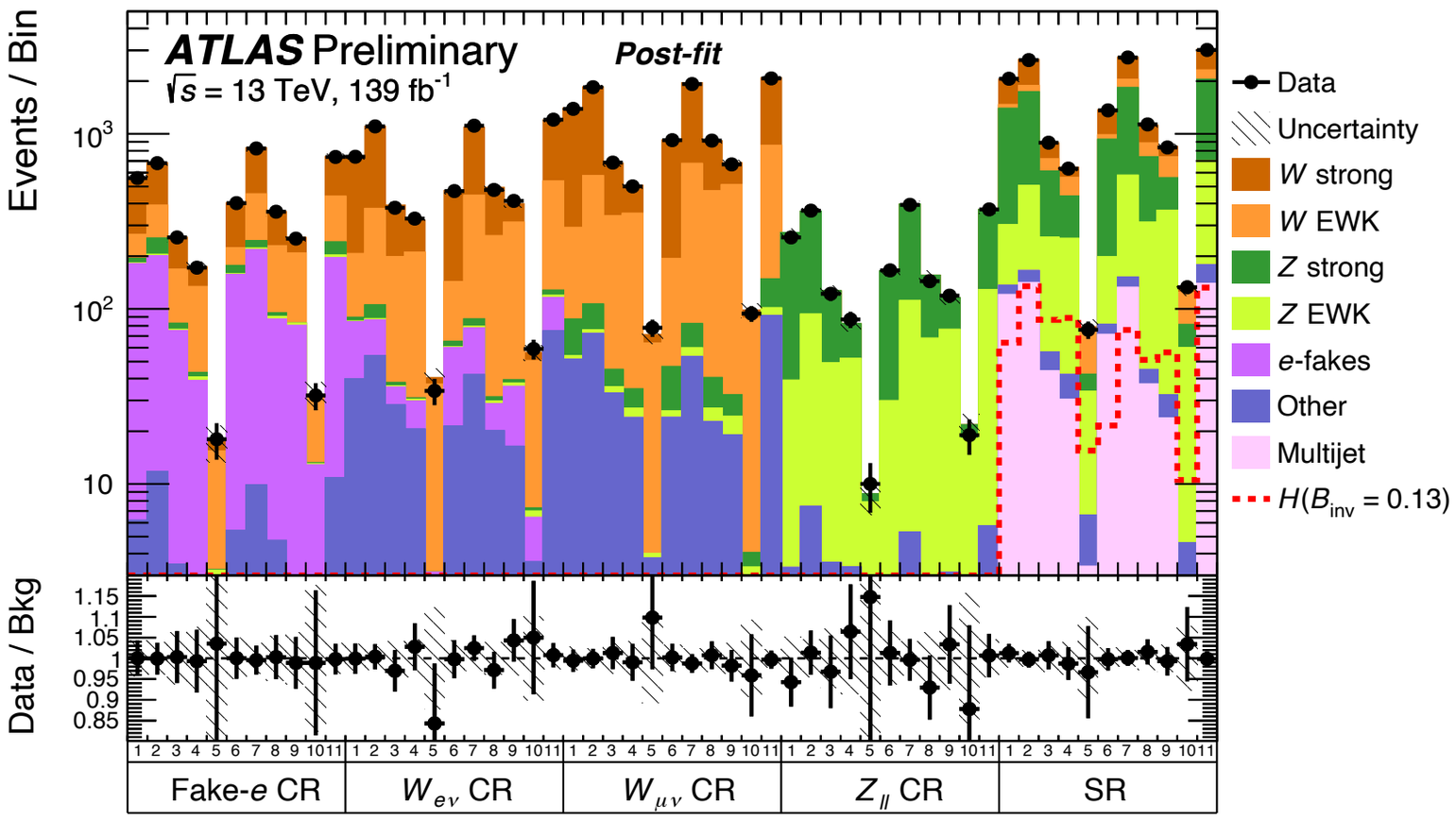
  - Could this include “invisible” decays to dark matter?

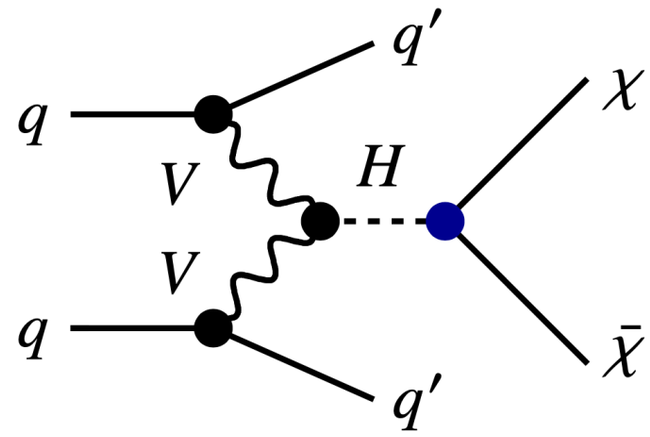
- **Very challenging searches!** Goal number is upper limit on possible H→invisible branching ratio.

  - For comparison, SM predicts H→invisible BR ~ 0.1%

VBF Higgs to dark matter

High VBF production rate for Higgs; topology with forward jets helps reject V+jets backgrounds. Other challenging backgrounds from e.g. VBF Z(vv).



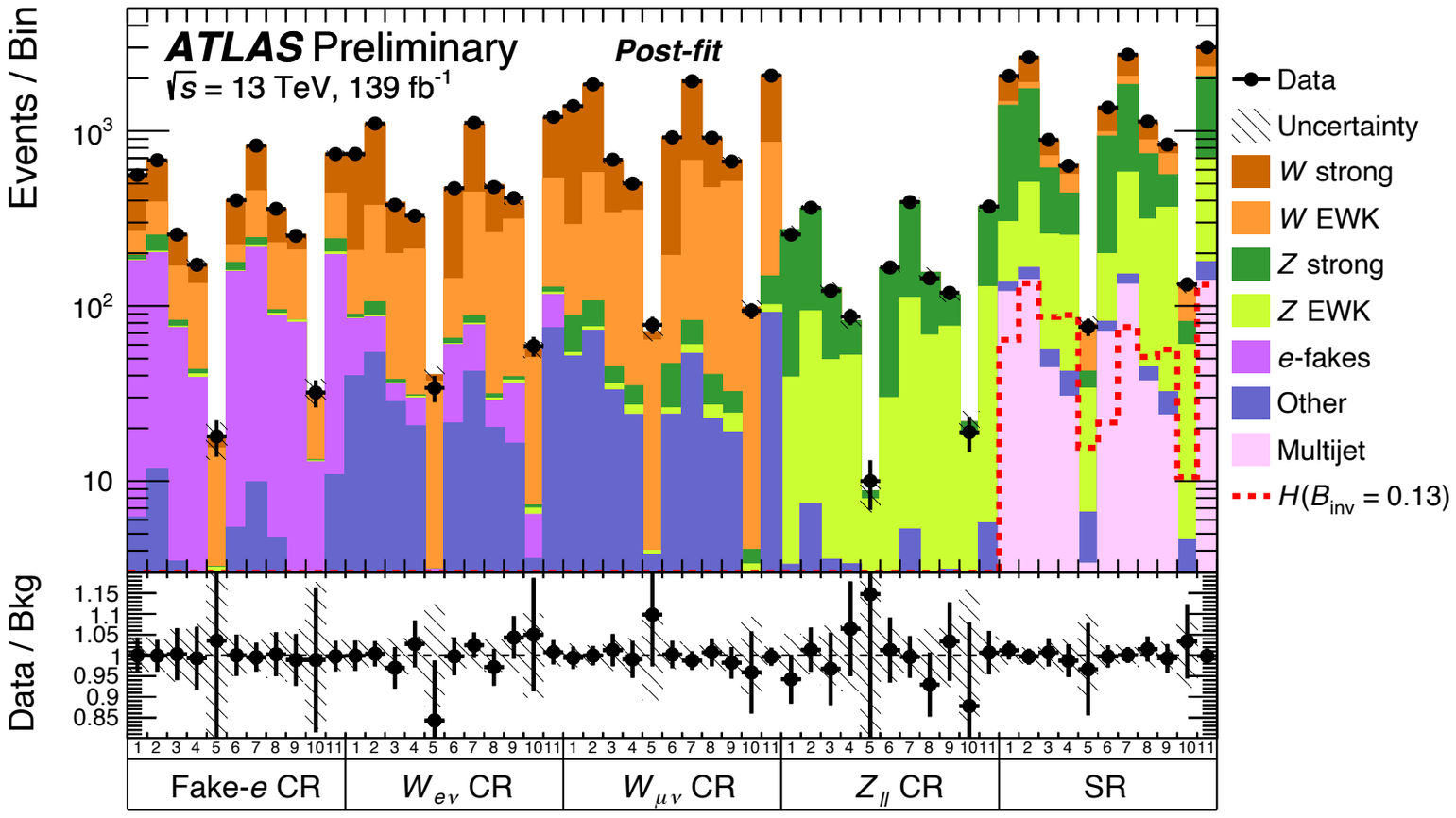


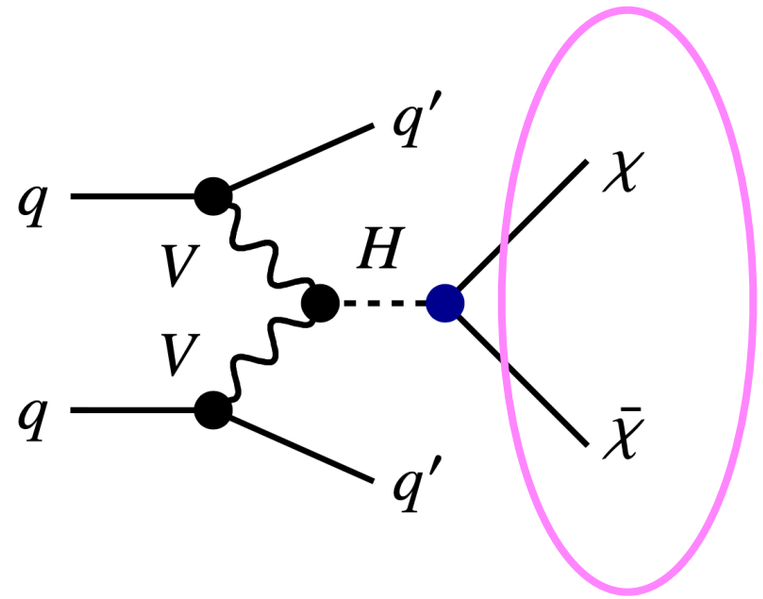
ATLAS-CONF-2020-008

Trigger on M_{ET}

VBF Higgs to dark matter

High VBF production rate for Higgs; topology with forward jets helps reject V+jets backgrounds. Other challenging backgrounds from e.g. VBF Z(vv).



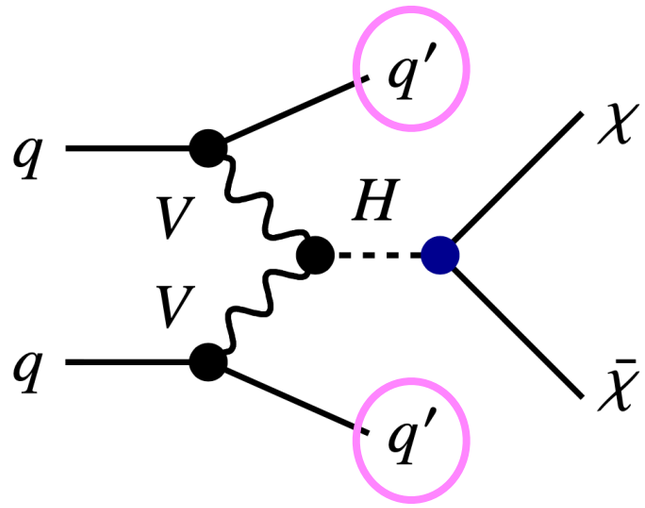


ATLAS-CONF-2020-008

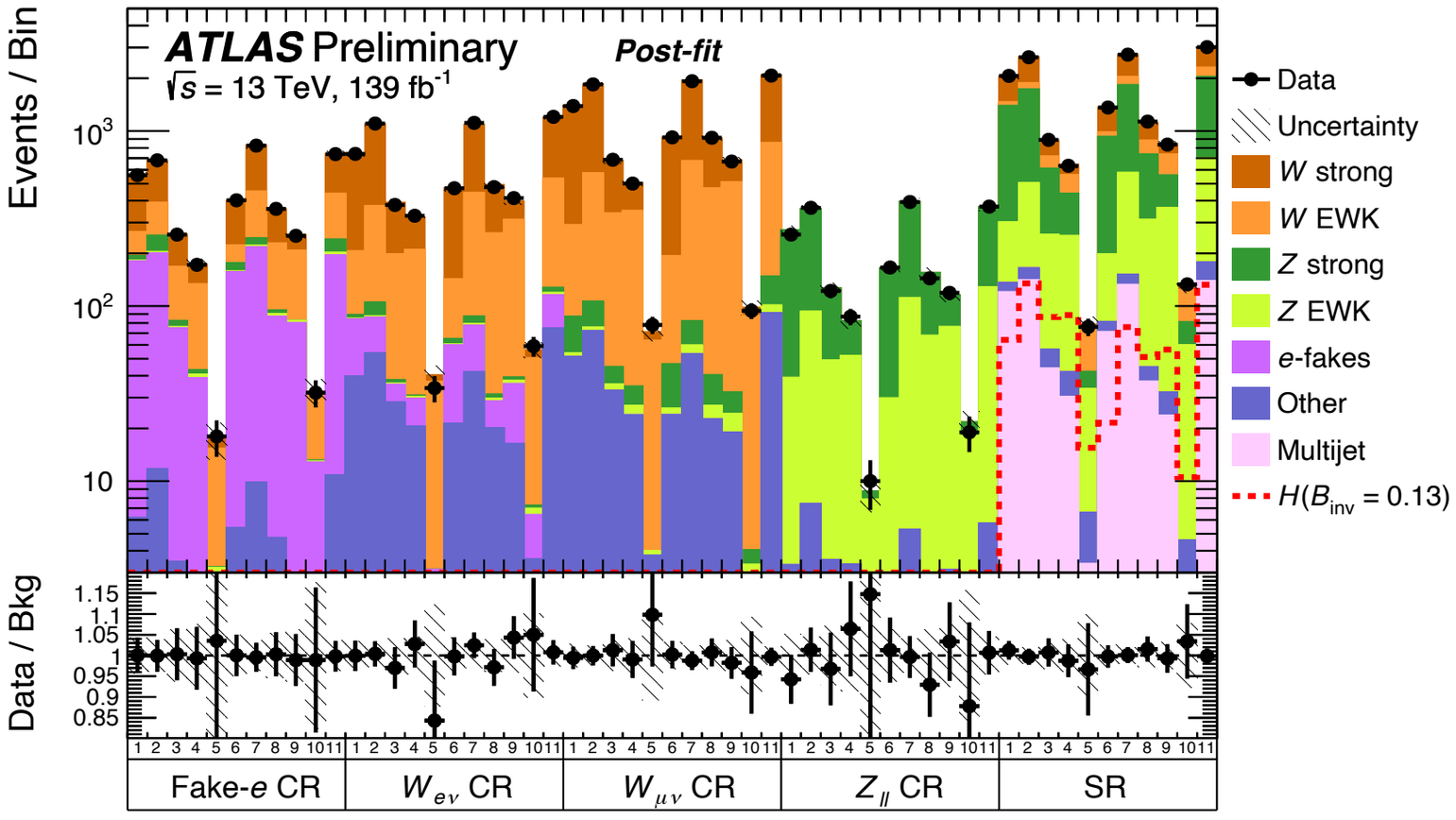
VBF Higgs to dark matter

Trigger on M_{ET}

QCD dijet back-to-back in ϕ, these jets not necessarily: require forward jets at small Δϕ



High VBF production rate for Higgs; topology with forward jets helps reject V+jets backgrounds. Other challenging backgrounds from e.g. VBF Z(vv).



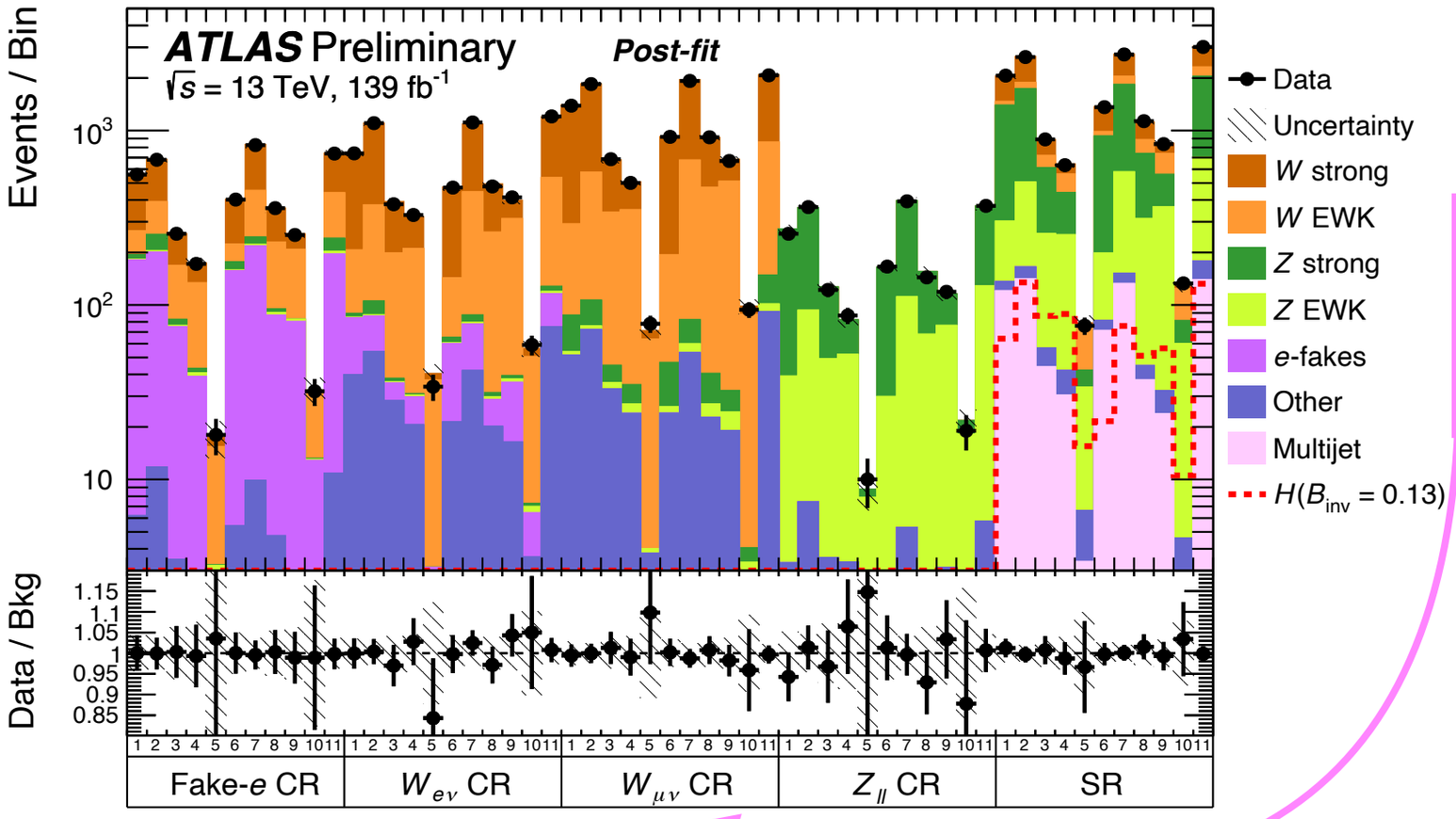
ATLAS-CONF-2020-008

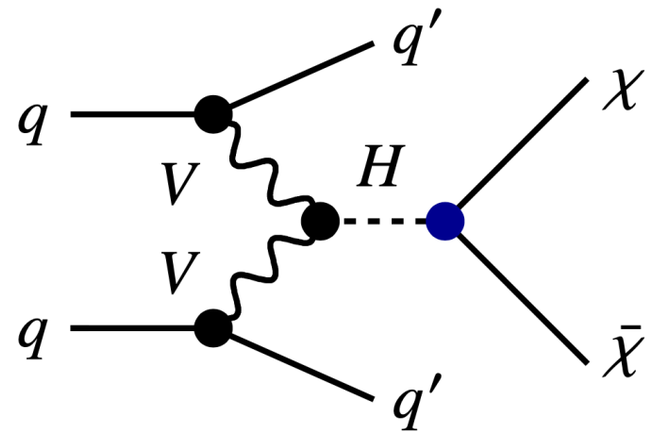
VBF Higgs to dark matter

Trigger on M_{ET}

QCD dijet back-to-back in ϕ, these jets not necessarily: require forward jets at small Δϕ

High VBF production rate for Higgs; topology with forward jets helps reject V+jets backgrounds. Other challenging backgrounds from e.g. VBF Z(vv).





Fitting multiple CRs constrains W and Z backgrounds

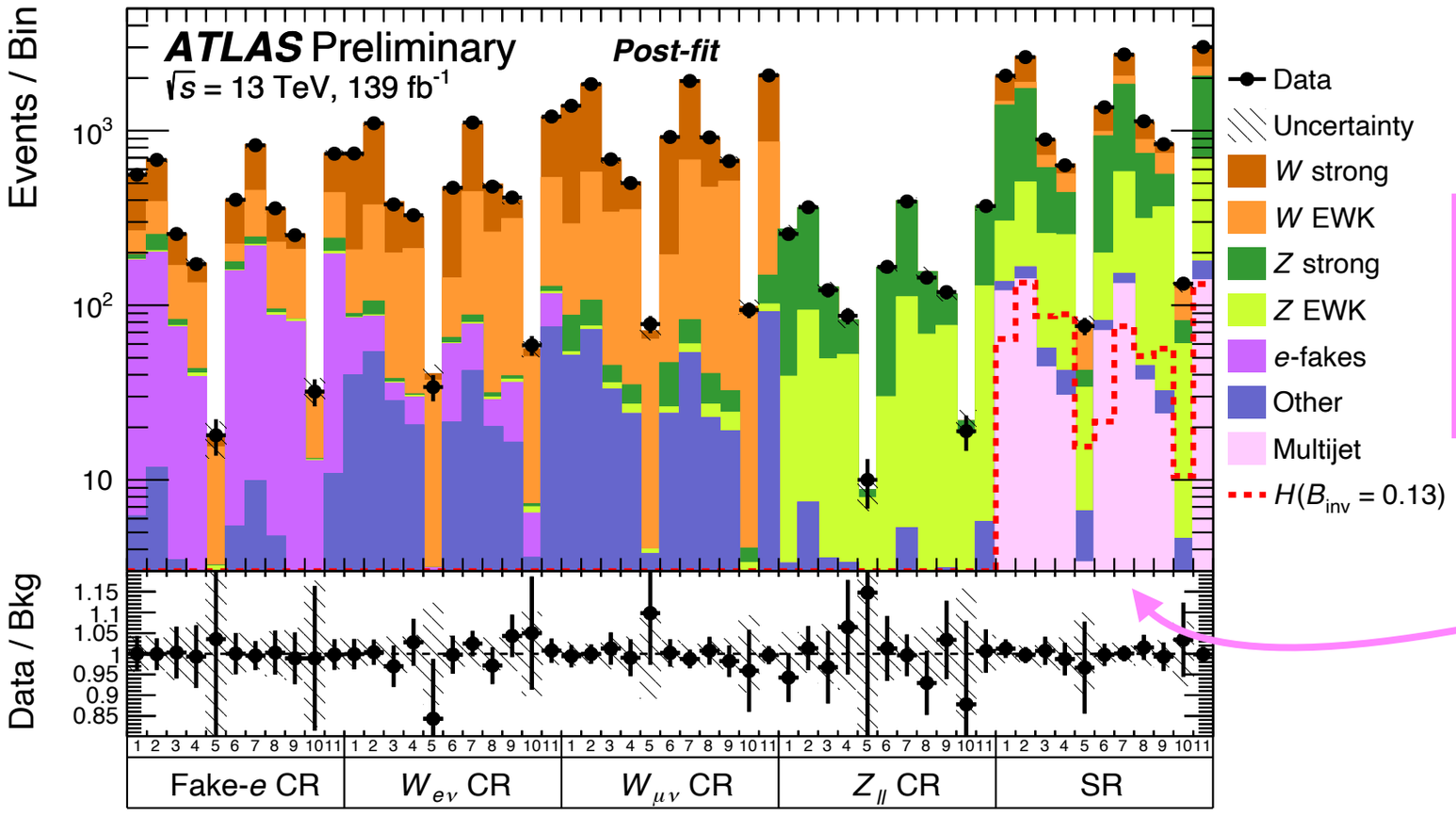
ATLAS-CONF-2020-008

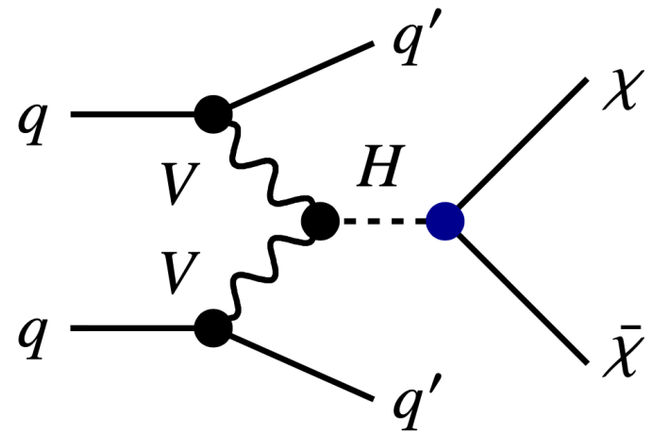
VBF Higgs to dark matter

Trigger on M_{ET}

QCD dijet back-to-back in ϕ, these jets not necessarily: require forward jets at small Δϕ

High VBF production rate for Higgs; topology with forward jets helps reject V+jets backgrounds. Other challenging backgrounds from e.g. VBF Z(vv).





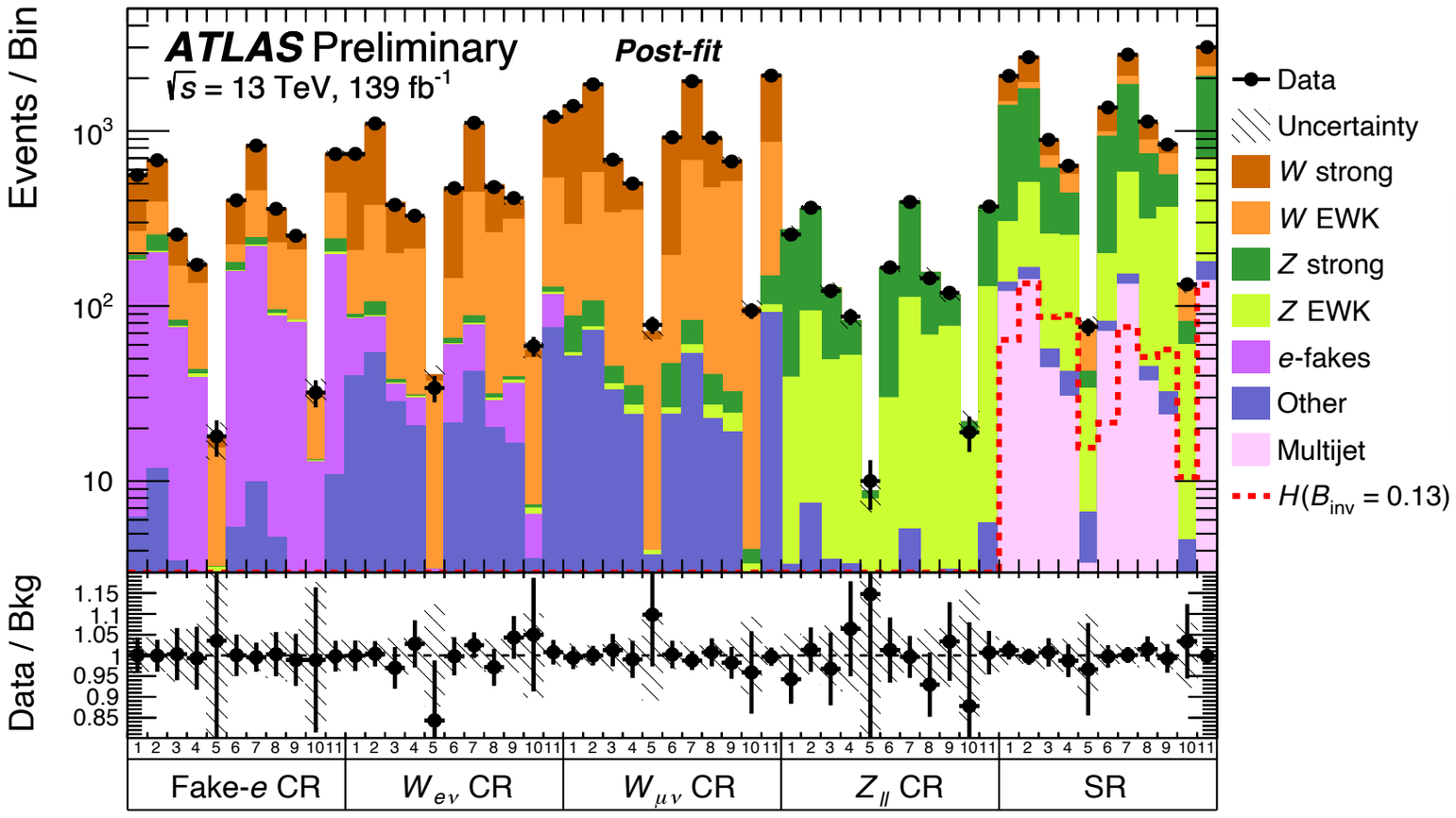
Fitting multiple CRs constrains W and Z backgrounds

Data-driven estimate of multijet bkg

ATLAS-CONF-2020-008

VBF Higgs to dark matter

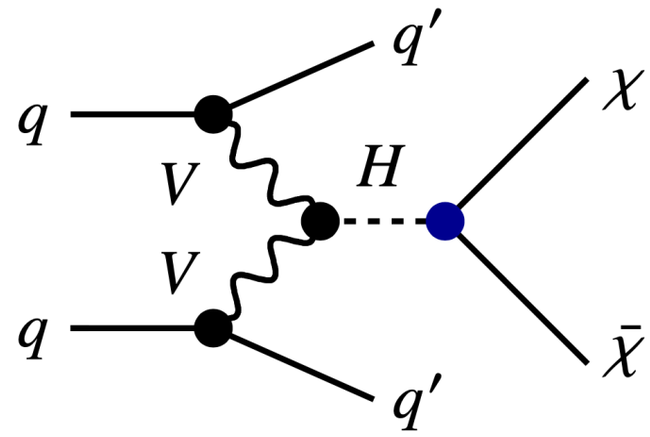
High VBF production rate for Higgs; topology with forward jets helps reject V+jets backgrounds. Other challenging backgrounds from e.g. VBF Z(vv).



[ATLAS-CONF-2020-008]

Trigger on M_{ET}

QCD dijet back-to-back in ϕ, these jets not necessarily: require forward jets at small Δϕ

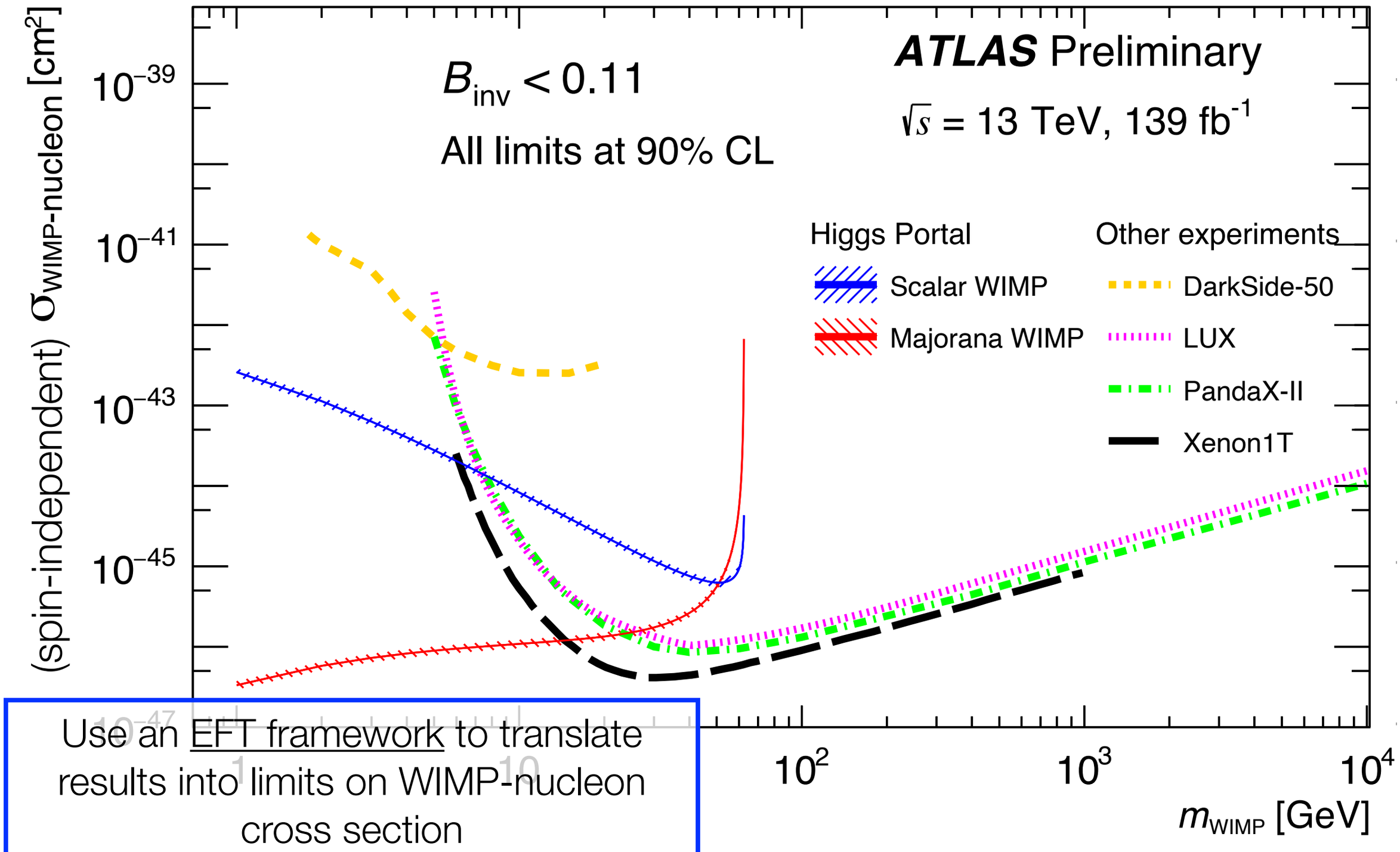


Fitting multiple CRs constrains W and Z backgrounds

Data-driven estimate of multijet bkg

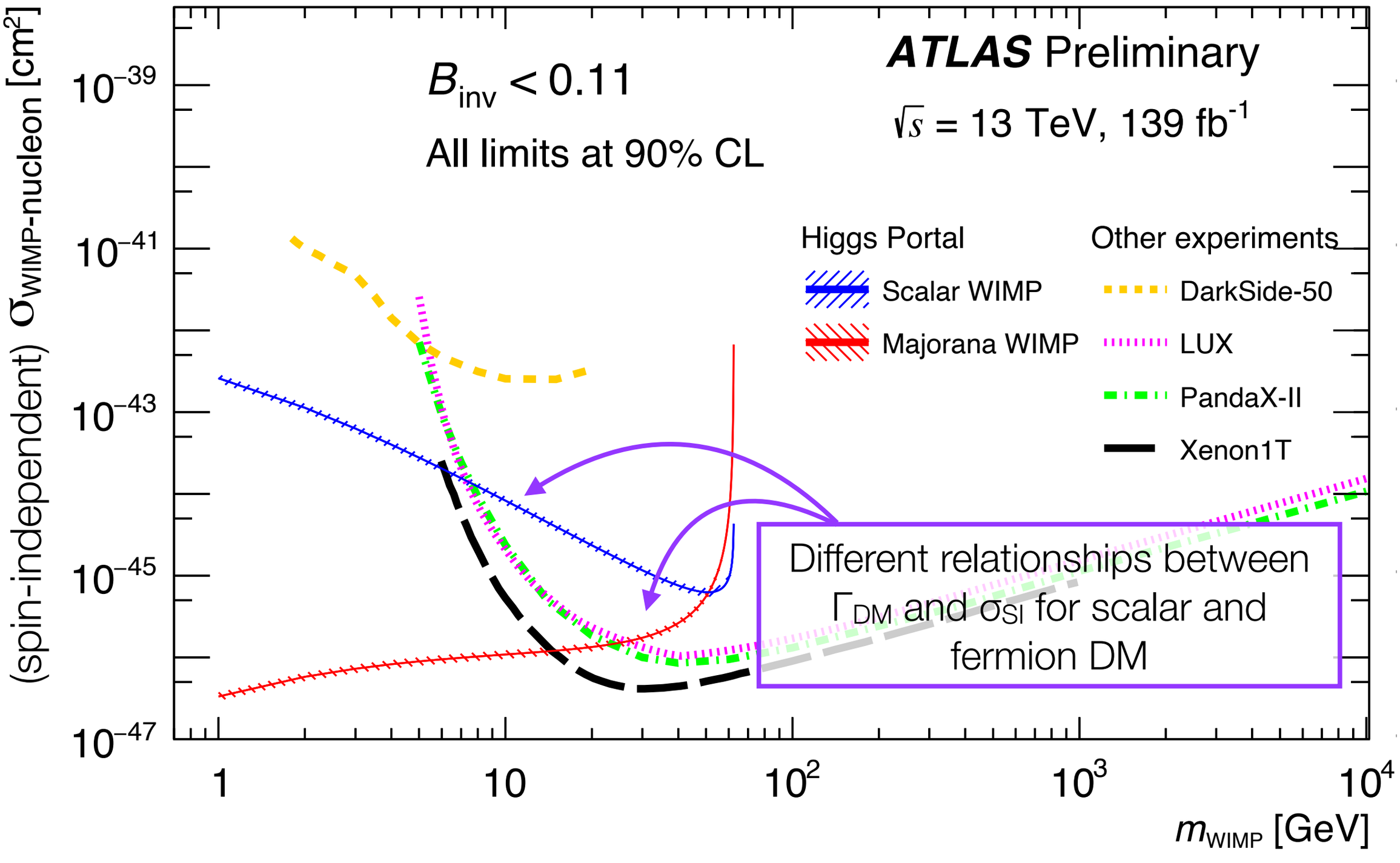
Result: upper limit on B(h125)→χχ of 13% ! (obs and exp)

Comparison to direct detection limits

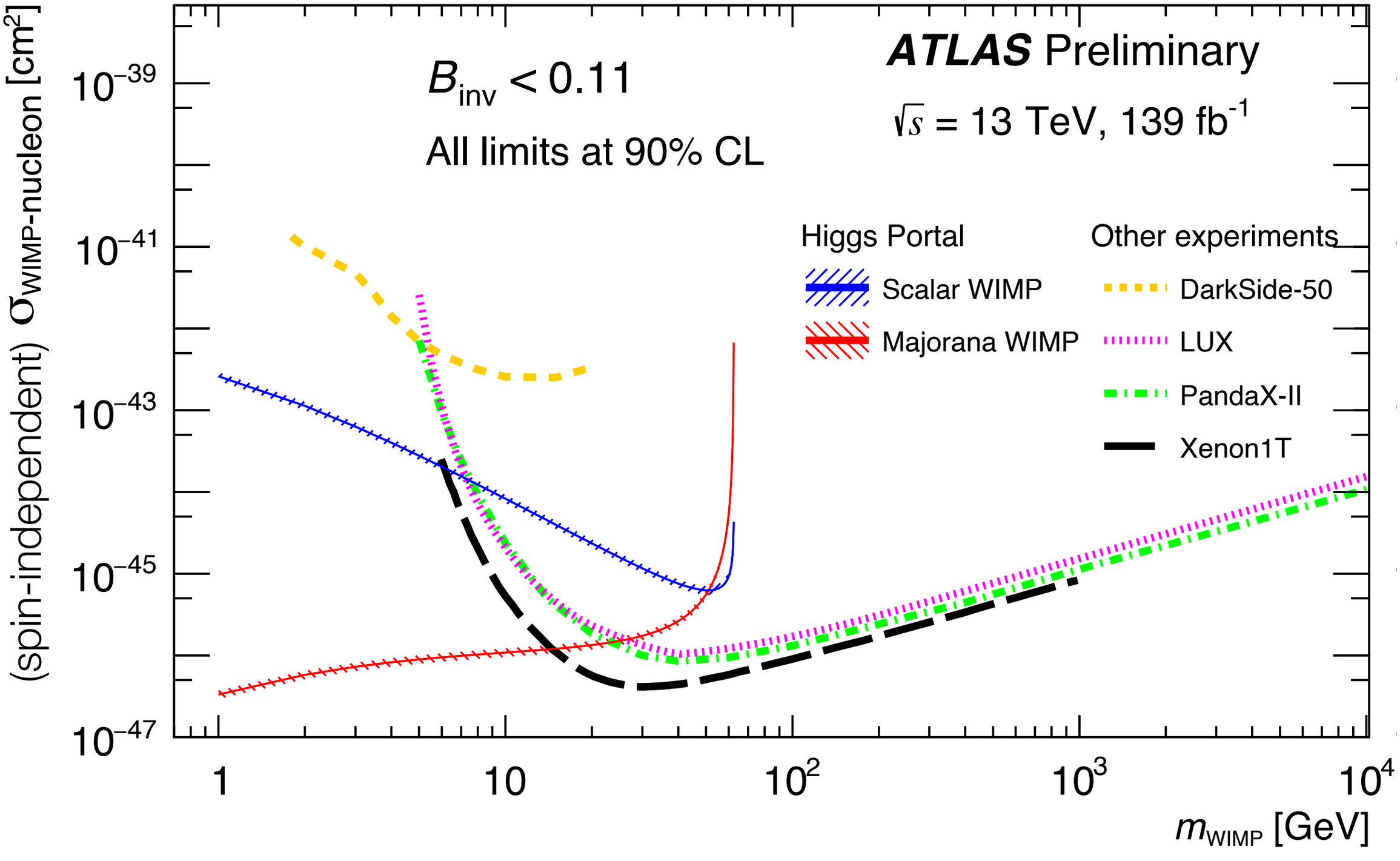


Use an EFT framework to translate results into limits on WIMP-nucleon cross section

Comparison to direct detection limits



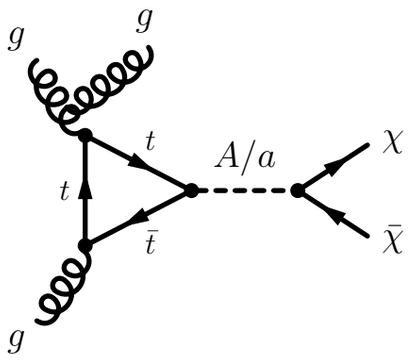
Comparison to direct detection limits

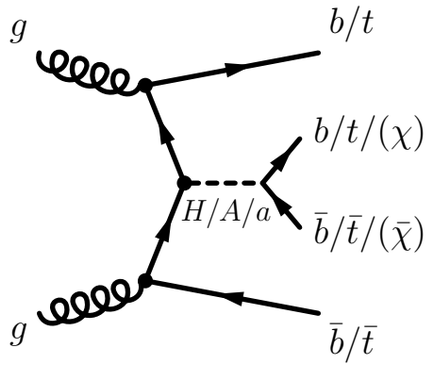


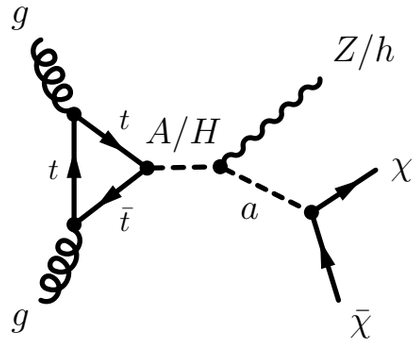
2HDMa and its dominant signatures

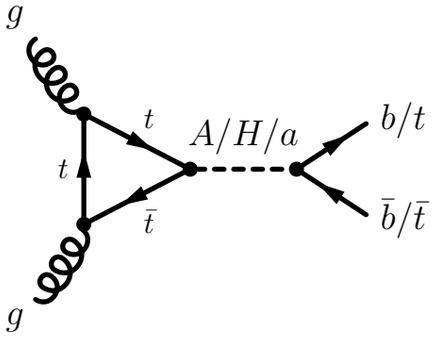
- Now instead, consider **two-Higgs doublet model** plus a pseudo-scalar

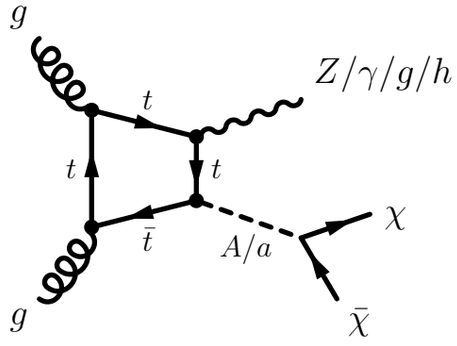
- Like Z' simplified model, we search in M_{ET}+X or look for visible mediator decays, but couplings prioritise **third generation** and signatures with **vector bosons and Higgs:**







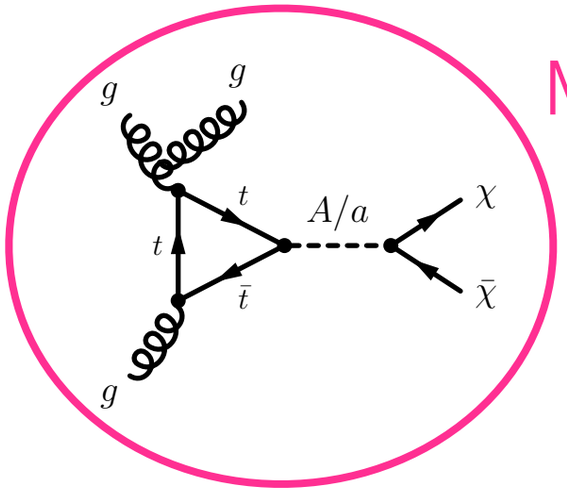


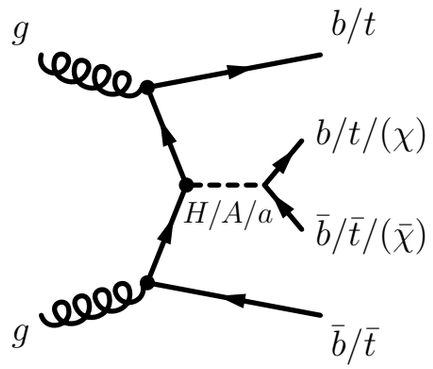


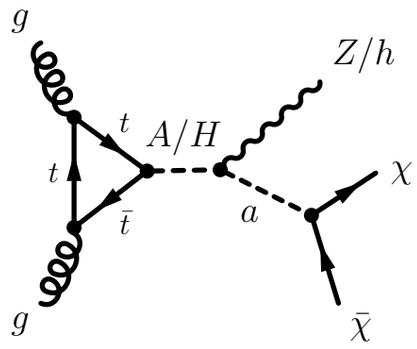
2HDMa and its dominant signatures

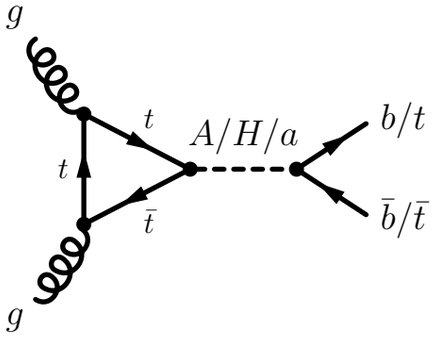
- Now instead, consider **two-Higgs doublet model** plus a pseudo-scalar
- Like Z' simplified model, we search in M_{ET}+X or look for visible mediator decays, but couplings prioritise **third generation** and signatures with **vector bosons and Higgs:**

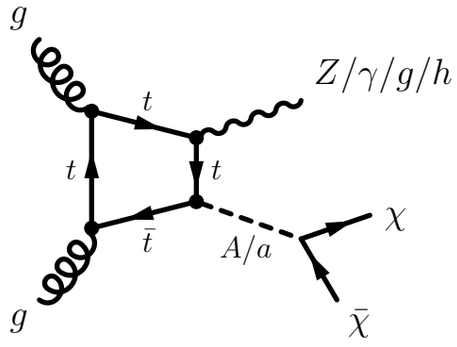
Monojet





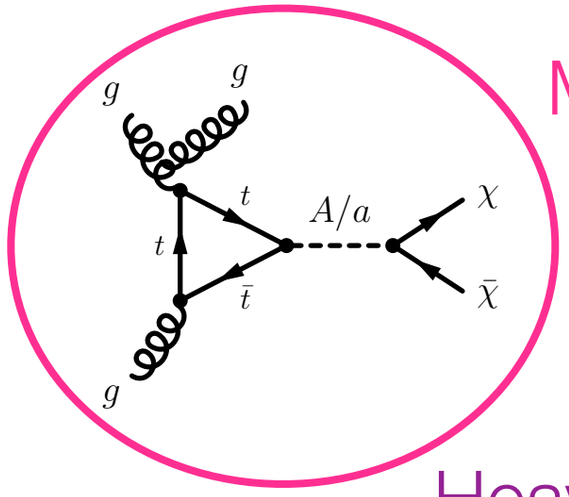




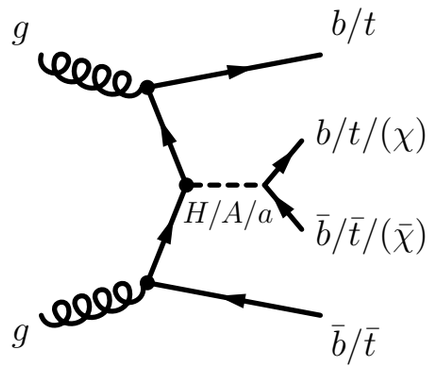


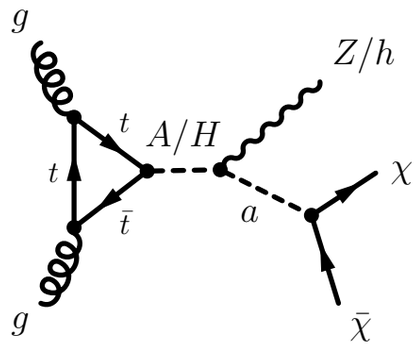
2HDMa and its dominant signatures

- Now instead, consider **two-Higgs doublet model** plus a pseudo-scalar
- Like Z' simplified model, we search in M_{ET}+X or look for visible mediator decays, but couplings prioritise **third generation** and signatures with **vector bosons and Higgs:**

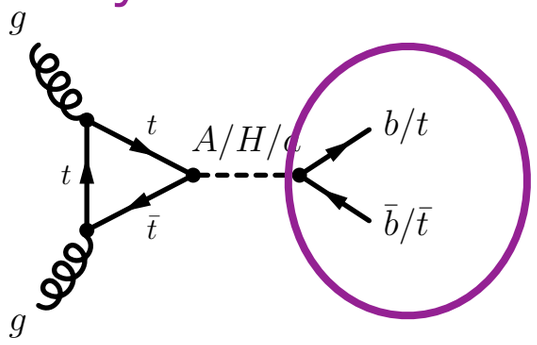


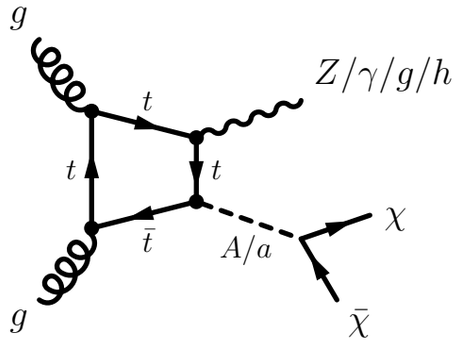
Monojet





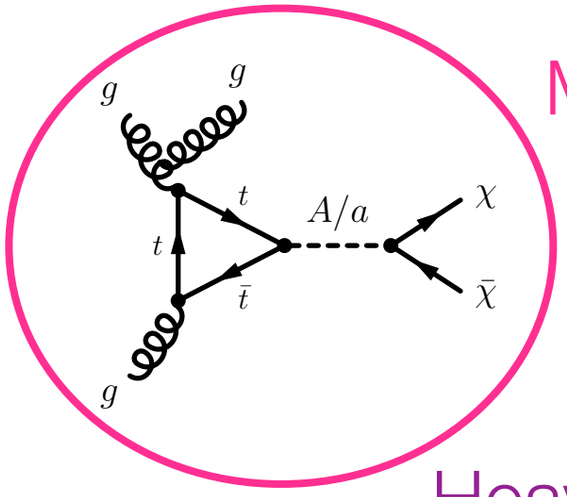
Heavy flavour resonances





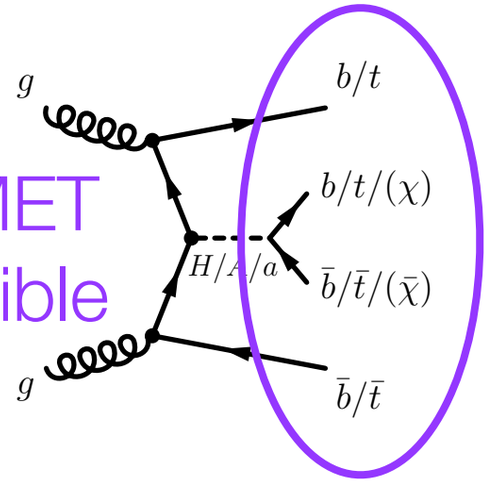
2HDMa and its dominant signatures

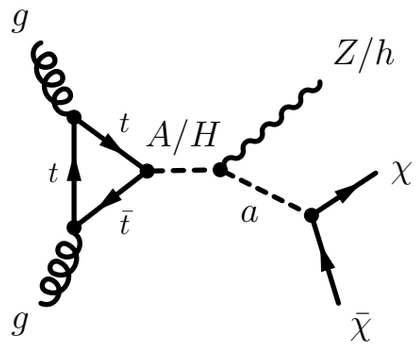
- Now instead, consider **two-Higgs doublet model** plus a pseudo-scalar
- Like Z' simplified model, we search in M_{ET}+X or look for visible mediator decays, but couplings prioritise **third generation** and signatures with **vector bosons and Higgs:**



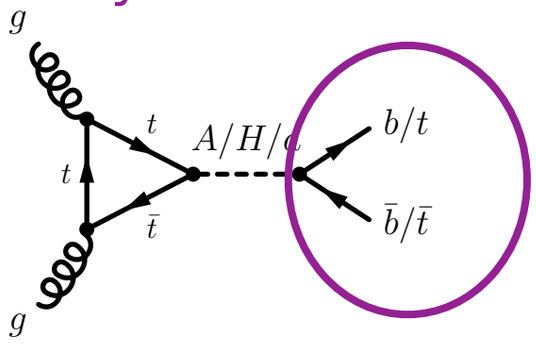
Monojet

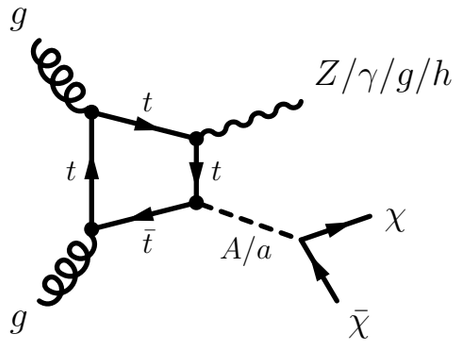
tt/bb+MET
or all visible





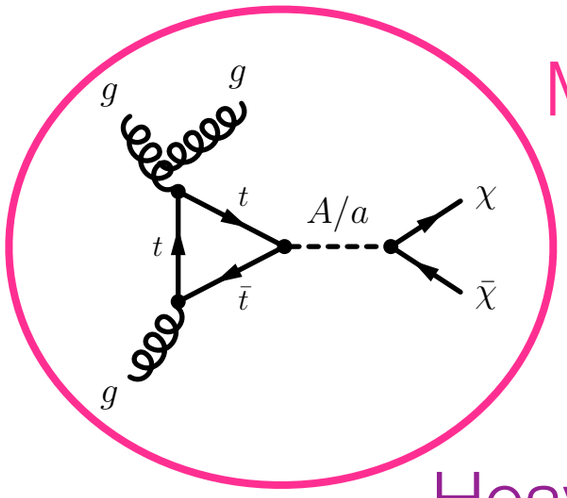
Heavy flavour resonances



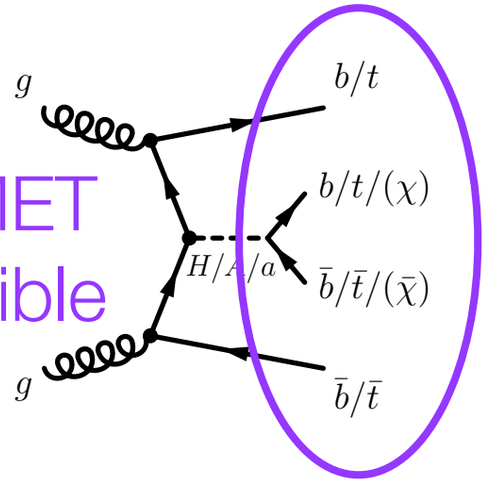


2HDMa and its dominant signatures

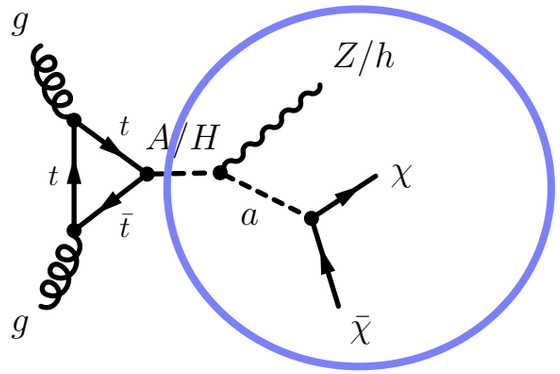
- Now instead, consider **two-Higgs doublet model** plus a pseudo-scalar
- Like Z' simplified model, we search in M_{ET}+X or look for visible mediator decays, but couplings prioritise **third generation** and signatures with **vector bosons and Higgs:**



Monojet

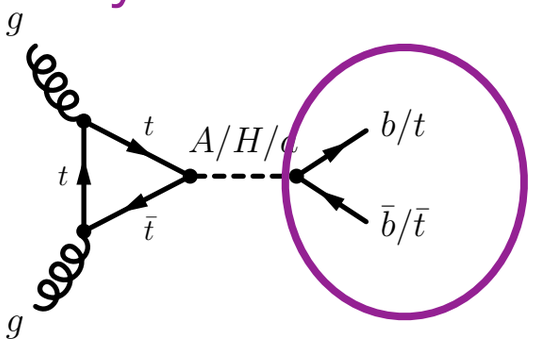


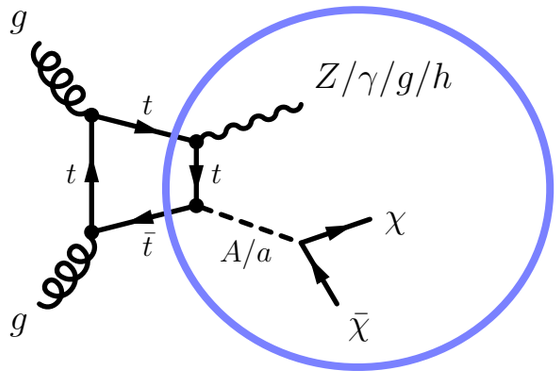
tt/bb+MET
or all visible



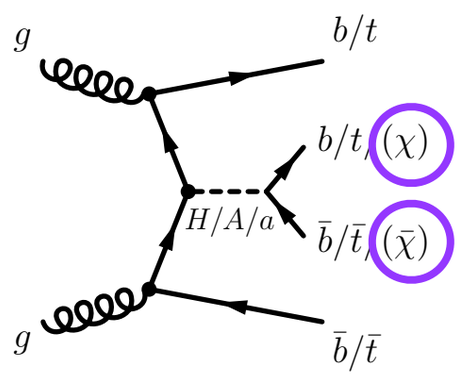
Mono-Z/h

Heavy flavour resonances

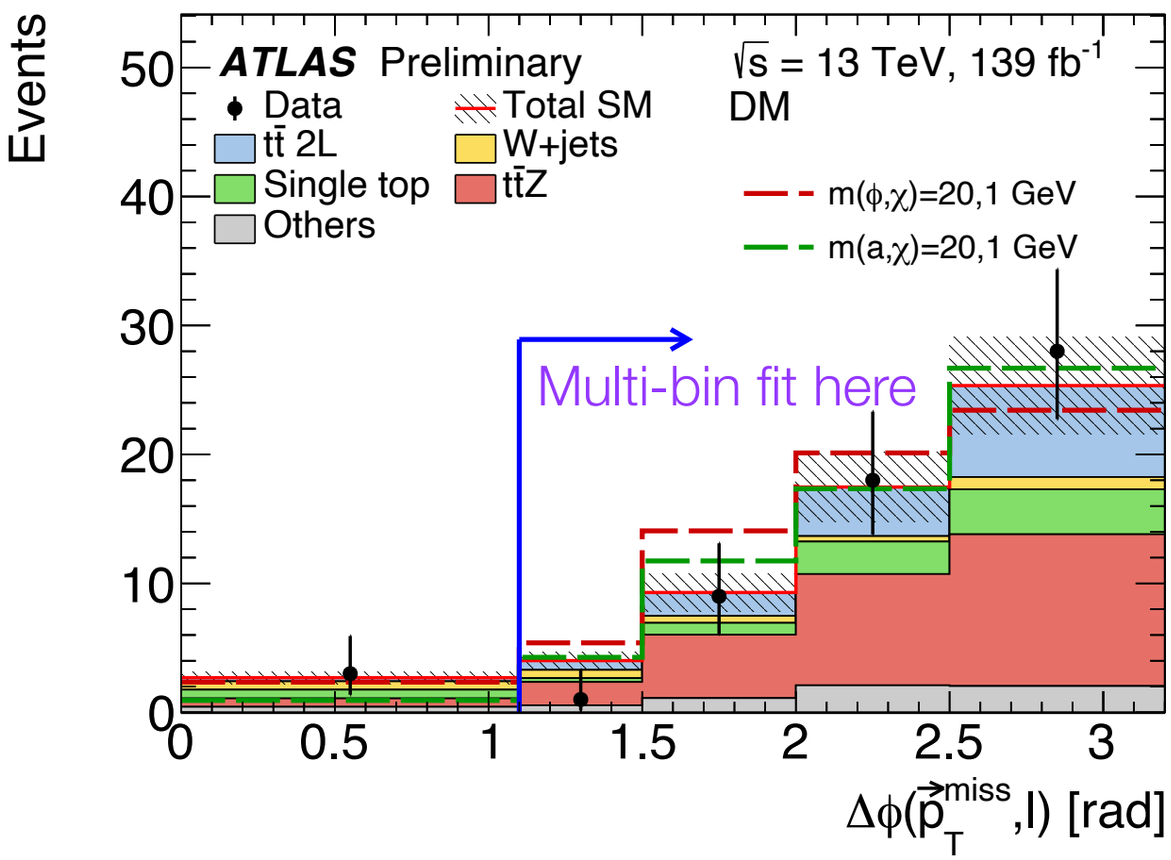


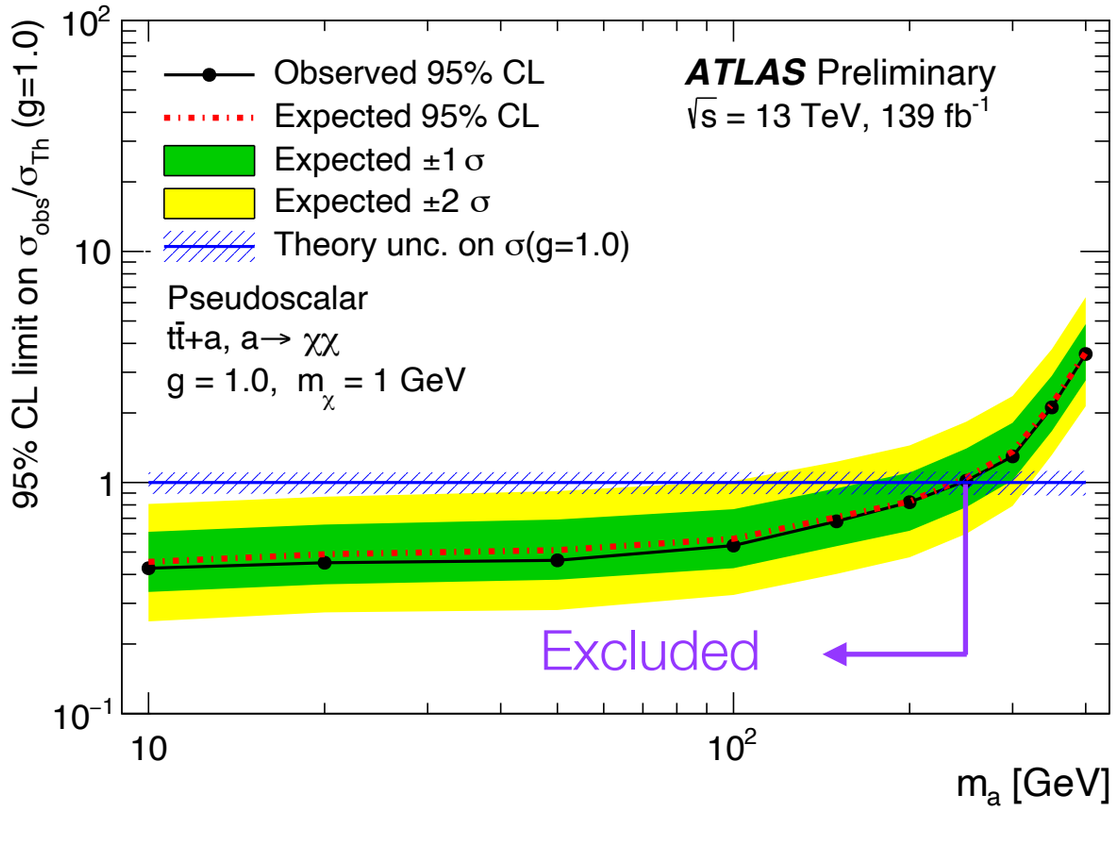


Heavy flavour + MET



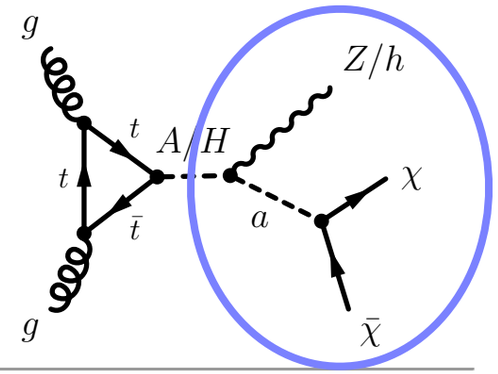
- Looking for DM in two tops and high missing momentum final state
  - Selecting one-lepton decay balances high stats with suppression of QCD; at least two b-tags keeps top-like events
- Dominant background: ttZ with Z→νν: constrain with a ttZ(ll) control region



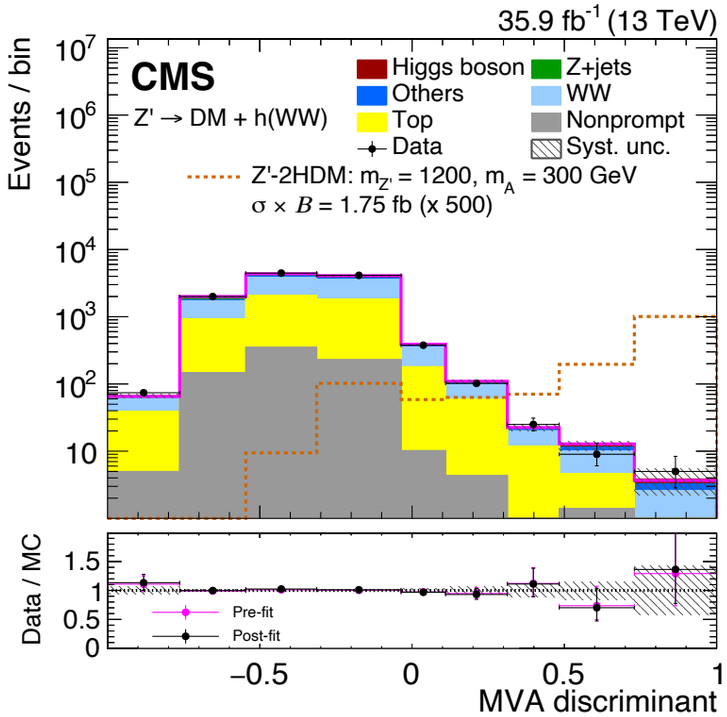


ATLAS-CONF-2020-003

Mono-V/Higgs

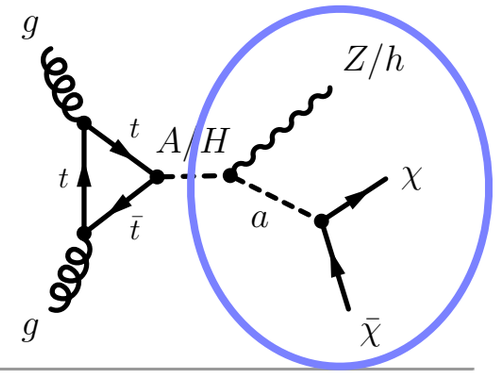


- Mono-Z/h has special sensitivity in 2HDM+X models
- CMS combination of Higgs to bb, γγ, ττ, WW, and ZZ interpretated in 2HDM+Z':



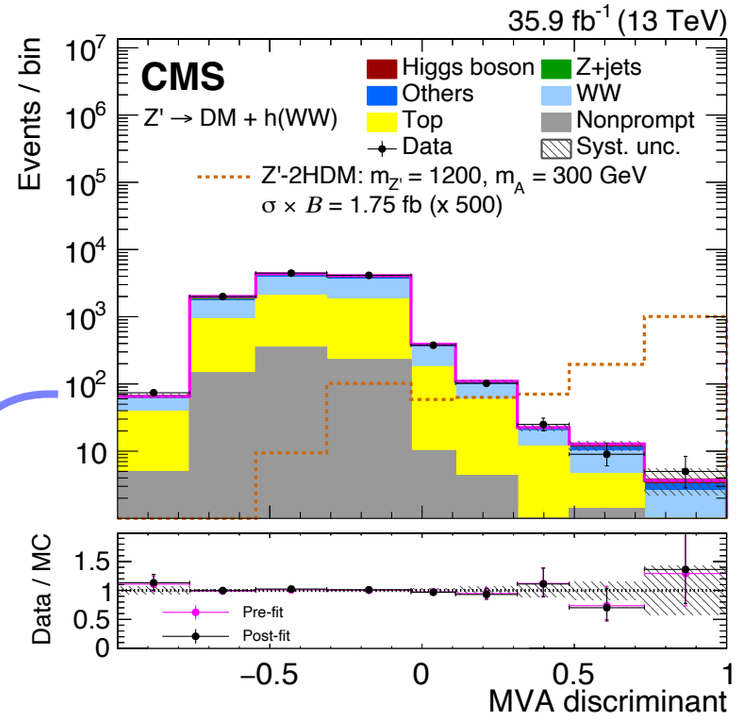
CMS EXO-18-011

Mono-V/Higgs



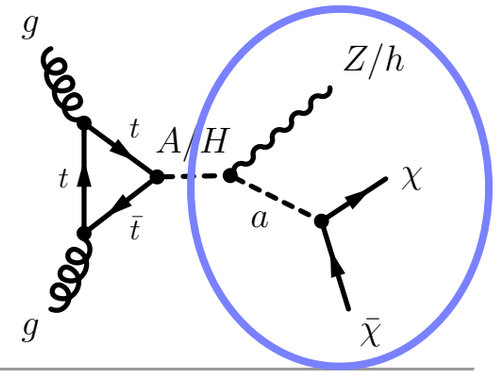
- Mono-Z/h has special sensitivity in 2HDM+X models
- CMS combination of Higgs to bb, γγ, ττ, WW, and ZZ interpretated in 2HDM+Z':

h(WW) BDT trained on momenta, transverse masses, angular variables



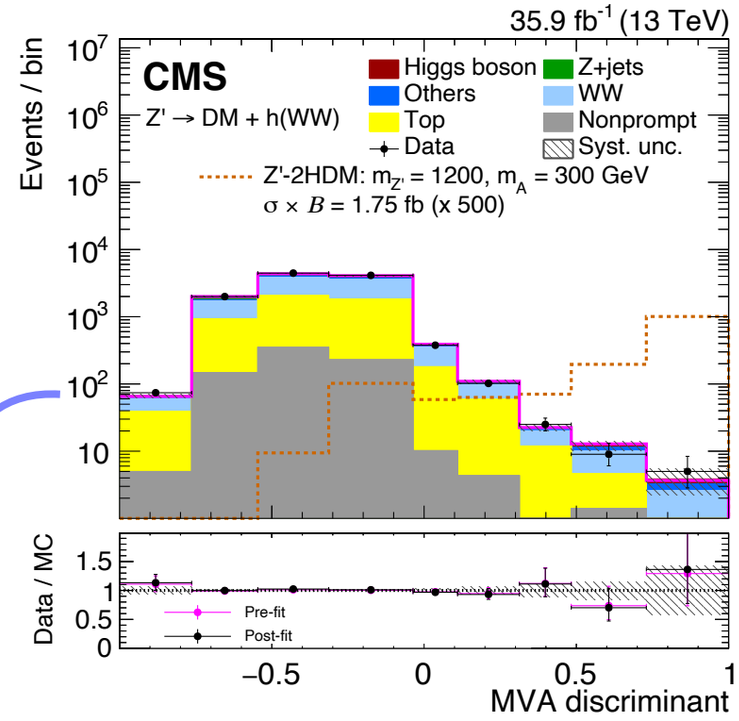
CMS EXO-18-011

Mono-V/Higgs

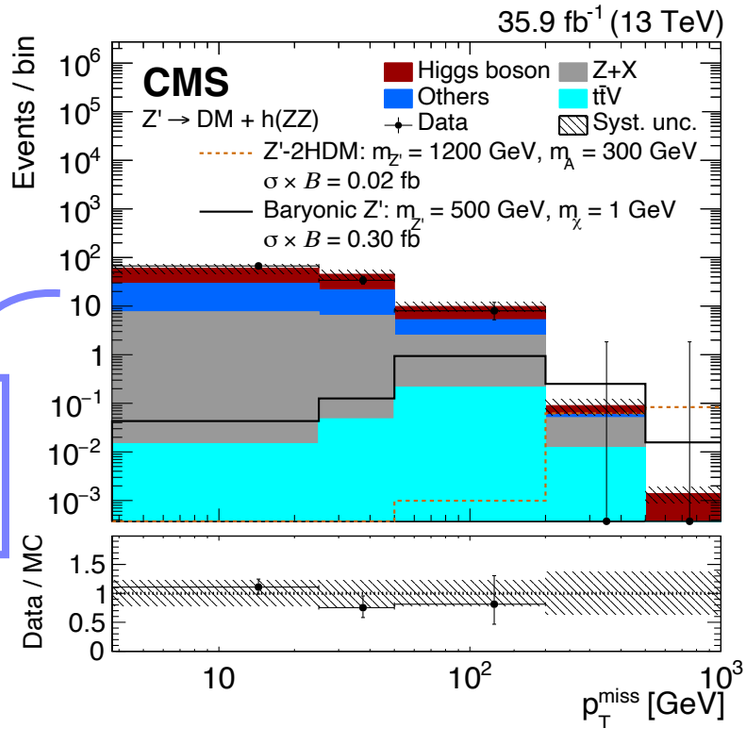


- Mono-Z/h has special sensitivity in 2HDM+X models
- CMS combination of Higgs to bb, γγ, ττ, WW, and ZZ interpretated in 2HDM+Z':

h(WW) BDT trained on momenta, transverse masses, angular variables

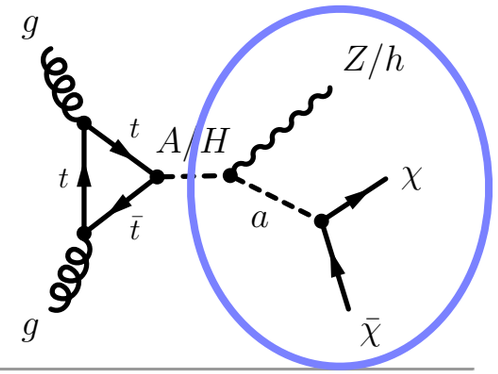


ZZ uses M_{ET} distribution

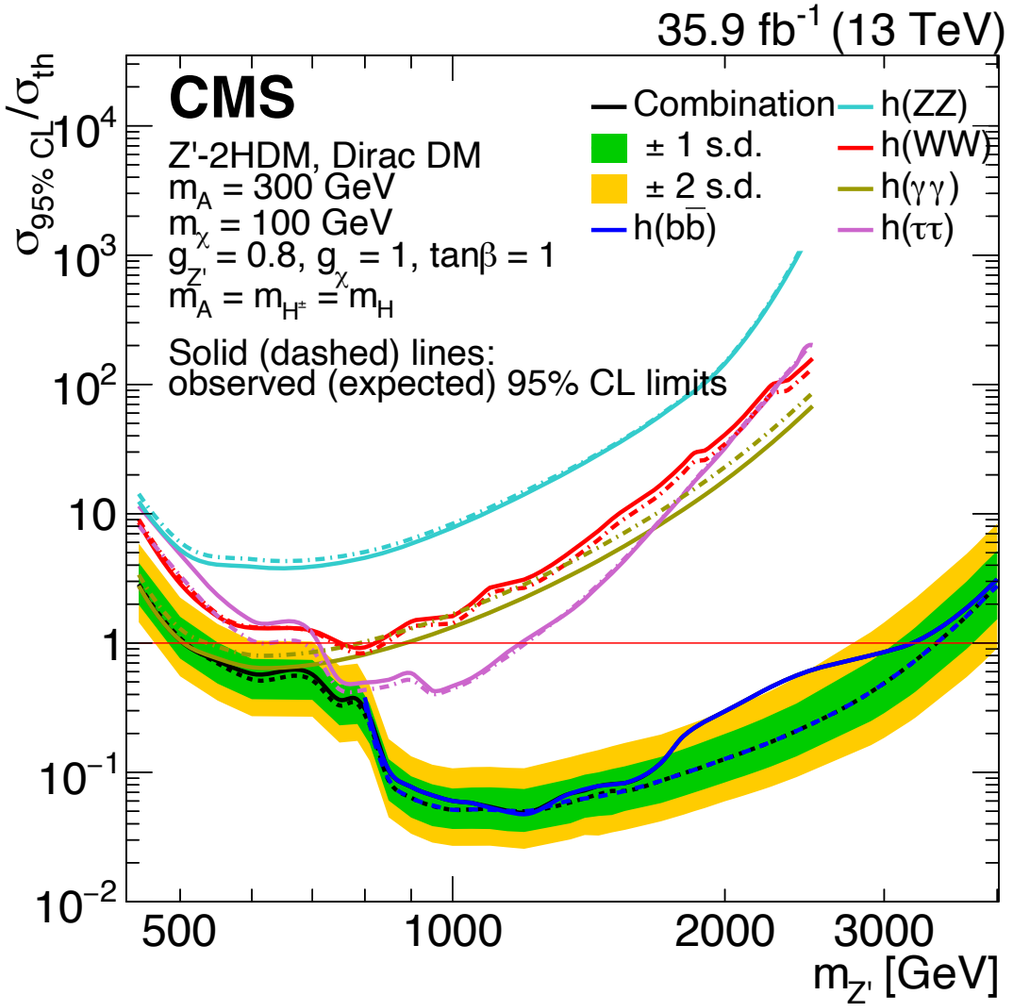


CMS EXO-18-011

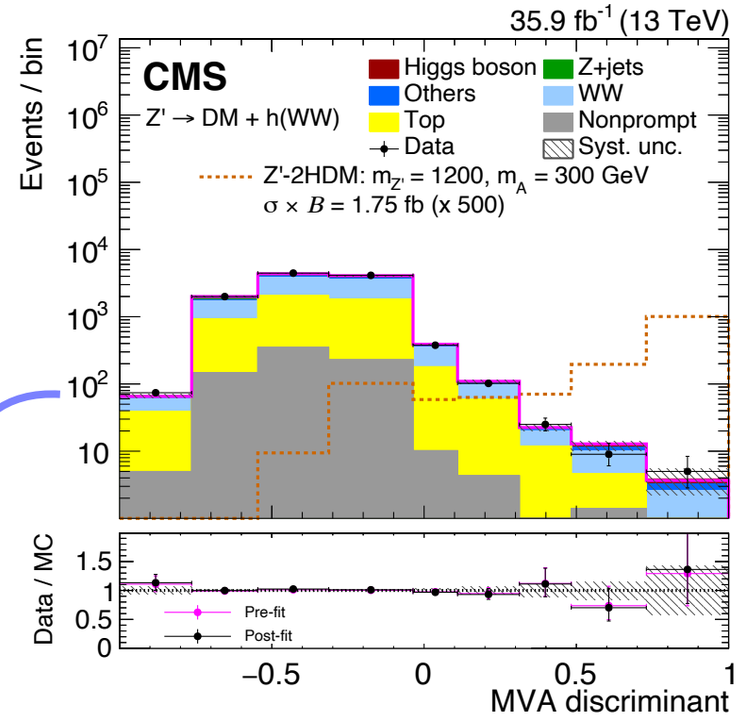
Mono-V/Higgs



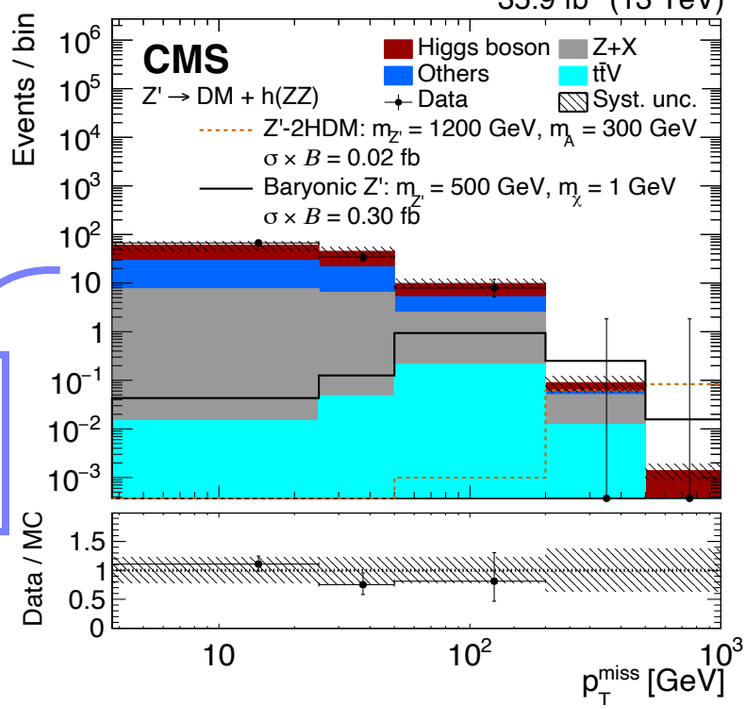
- Mono-Z/h has special sensitivity in 2HDM+X models
- CMS combination of Higgs to bb, γγ, ττ, WW, and ZZ interpretated in 2HDM+Z':



h(WW) BDT trained on momenta, transverse masses, angular variables

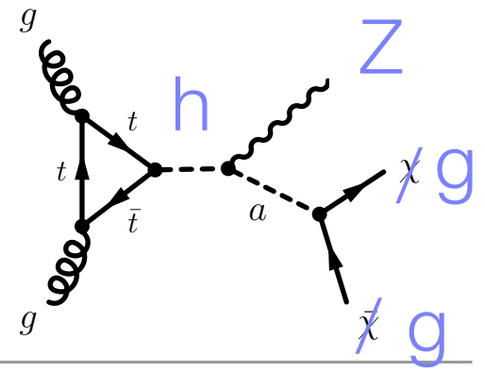


ZZ uses M_{ET} distribution



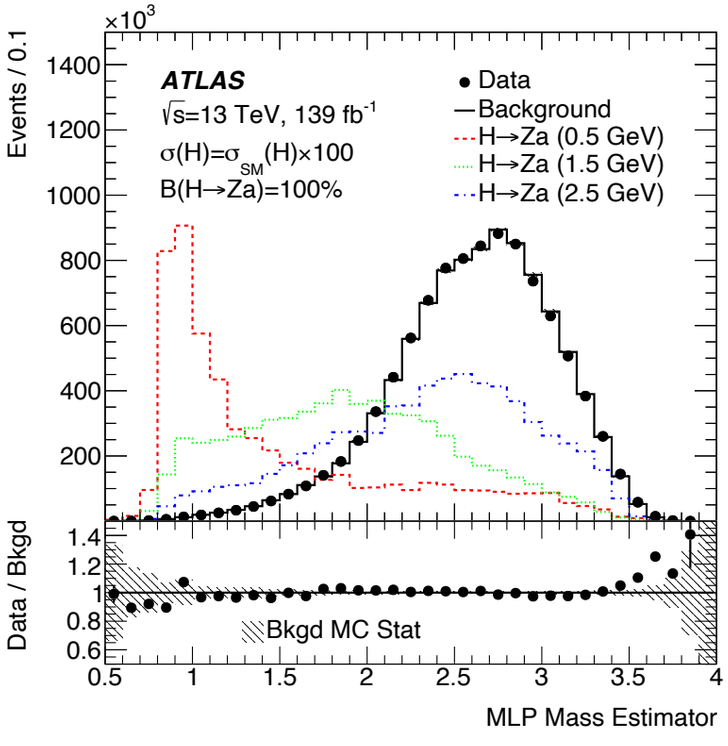
CMS EXO-18-011

Visible *a* decays



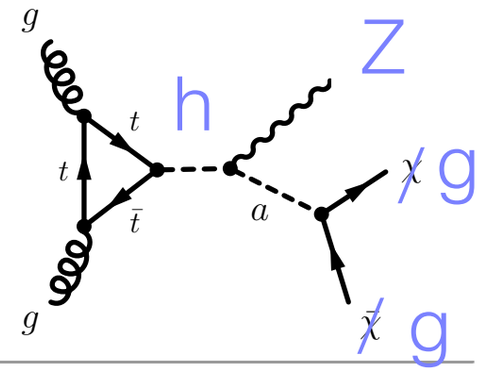
Looking for very light *a* (below 4 GeV): such high boost that it is reconstructed as one small-radius jet

Train on two-pronged nature of jet substructure to learn resonance mass



ATLAS HDBS-2018-37

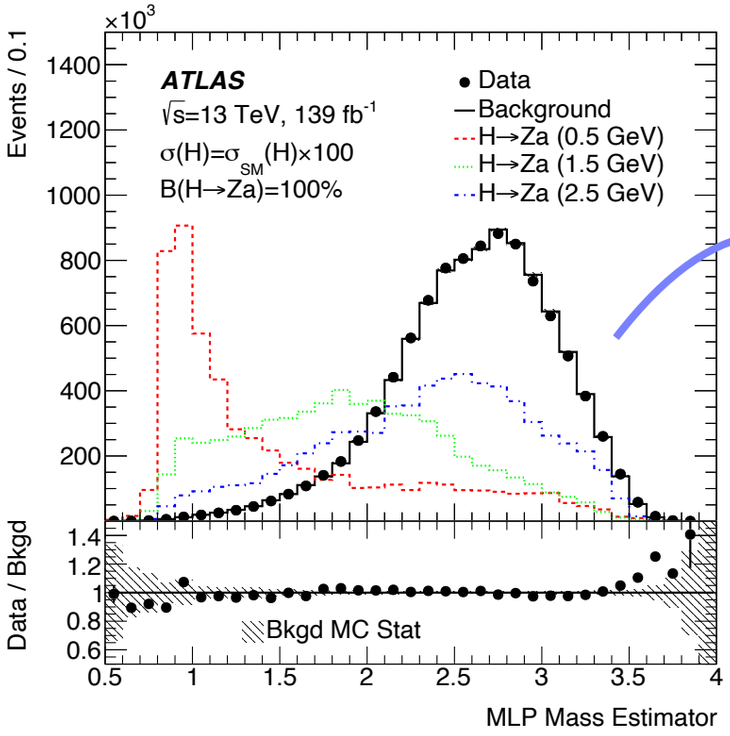
Visible *a* decays

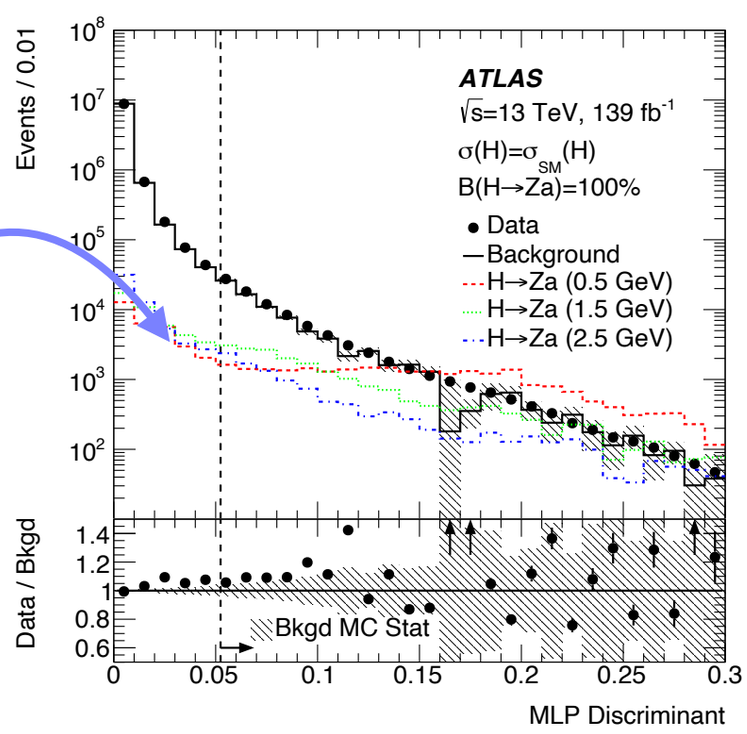


Looking for very light *a* (below 4 GeV): such high boost that it is reconstructed as one small-radius jet

Train on two-pronged nature of jet substructure to learn resonance mass

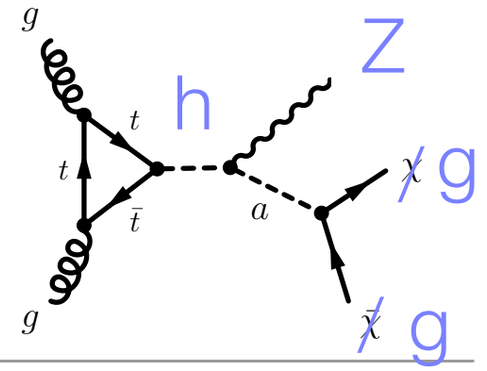
Use learned mass, substructure variables to train selection NN





ATLAS HDBS-2018-37

Visible *a* decays

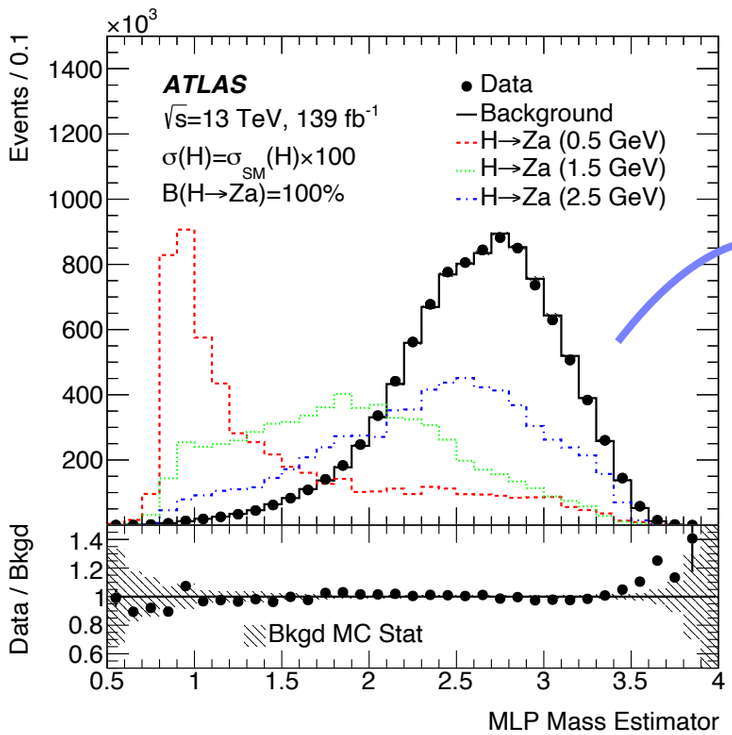


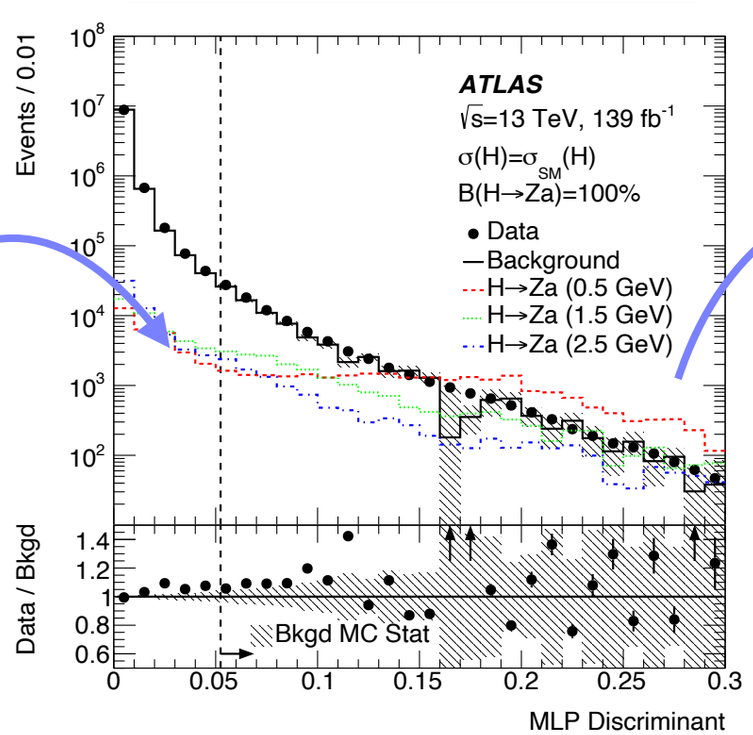
Looking for very light *a* (below 4 GeV): such high boost that it is reconstructed as one small-radius jet

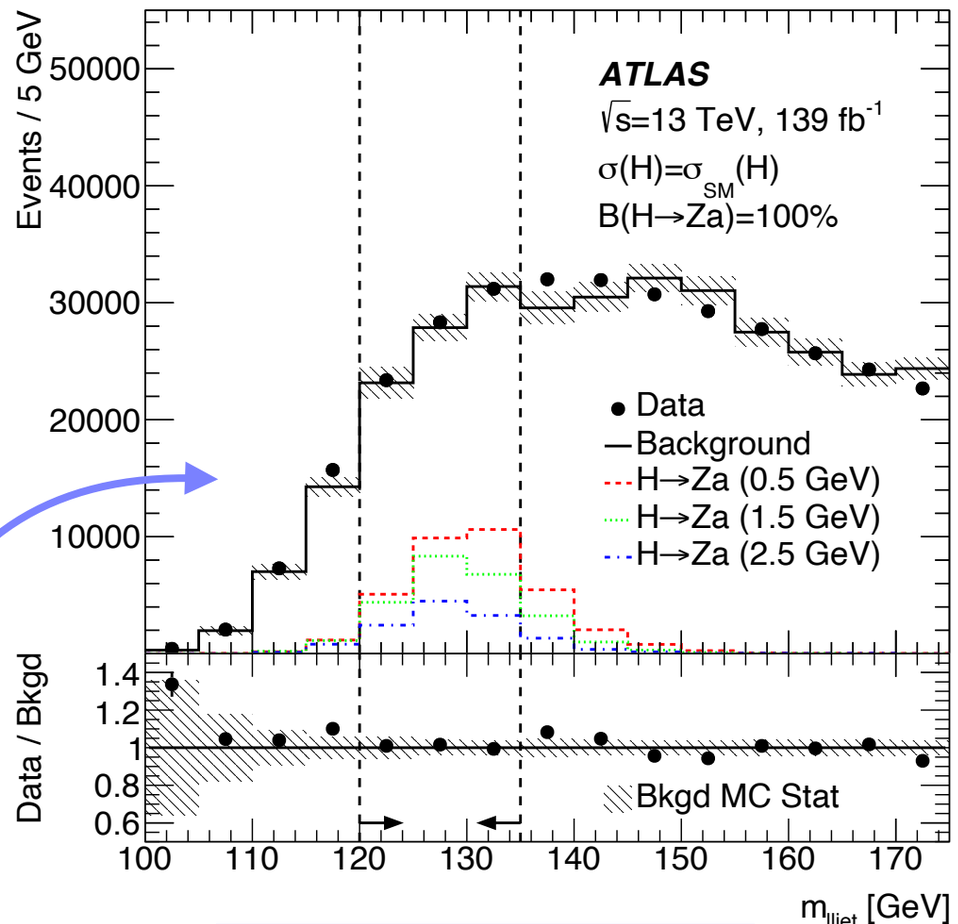
Train on two-pronged nature of jet substructure to learn resonance mass

Use learned mass, substructure variables to train selection NN

Higgs mass window defines signal region



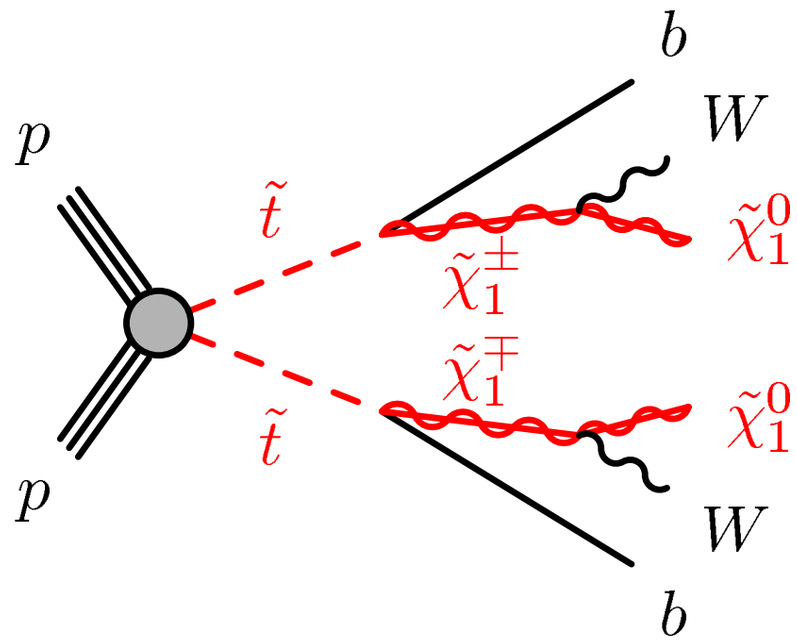




ATLAS HDBS-2018-37

SUSY as a dark matter generator

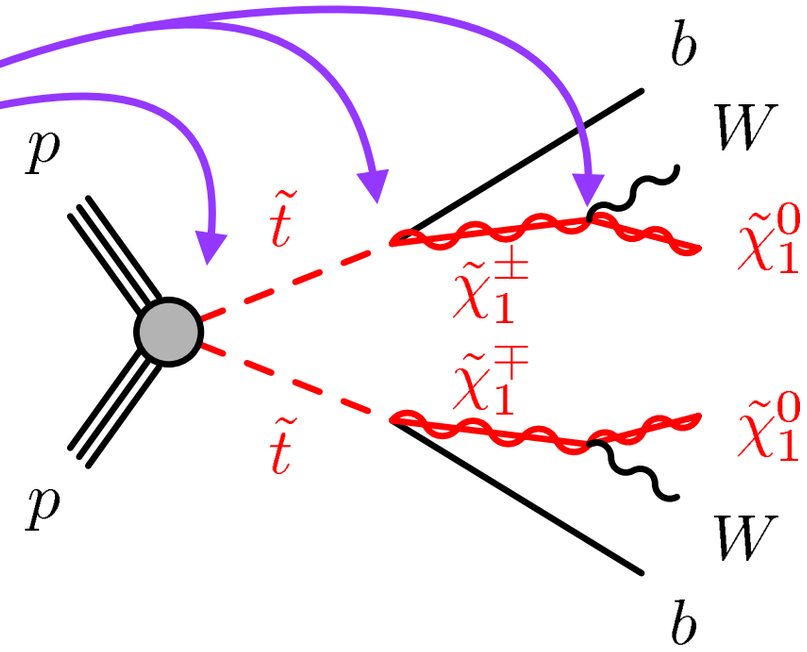
- Remember that supersymmetry can be a dark matter model too:



SUSY as a dark matter generator

- Remember that supersymmetry can be a dark matter model too:

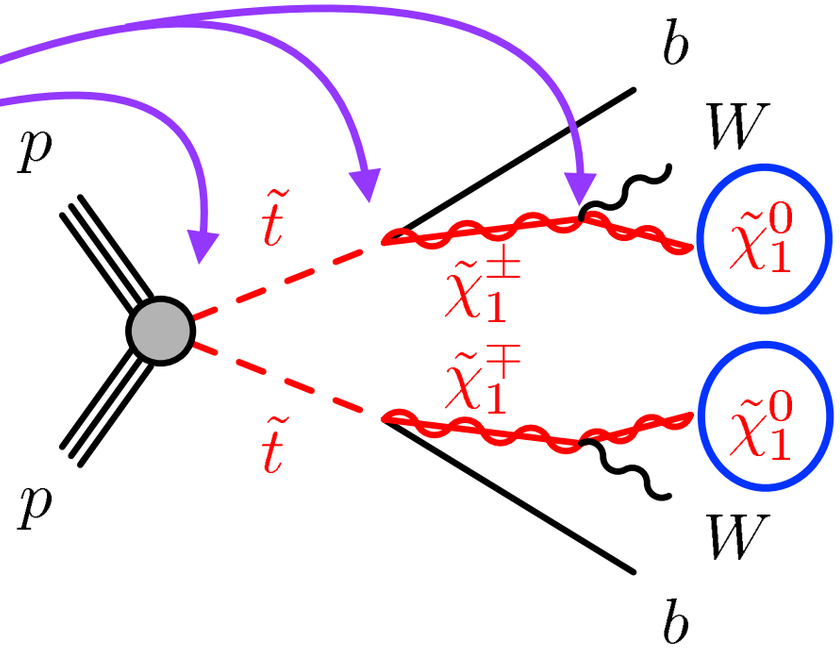
R-parity conservation requires even number of SUSY particles in each interaction



SUSY as a dark matter generator

- Remember that supersymmetry can be a dark matter model too:

R-parity conservation requires even number of SUSY particles in each interaction

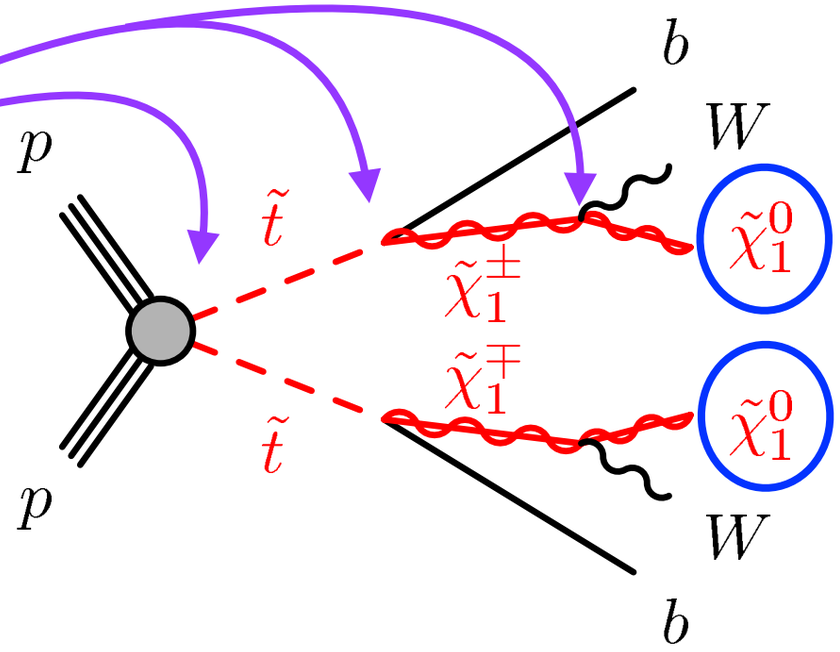


Therefore lightest SUSY particle must be stable → dark matter candidate!

SUSY as a dark matter generator

- Remember that supersymmetry can be a dark matter model too:

R-parity conservation requires even number of SUSY particles in each interaction



Therefore lightest SUSY particle must be stable → dark matter candidate!

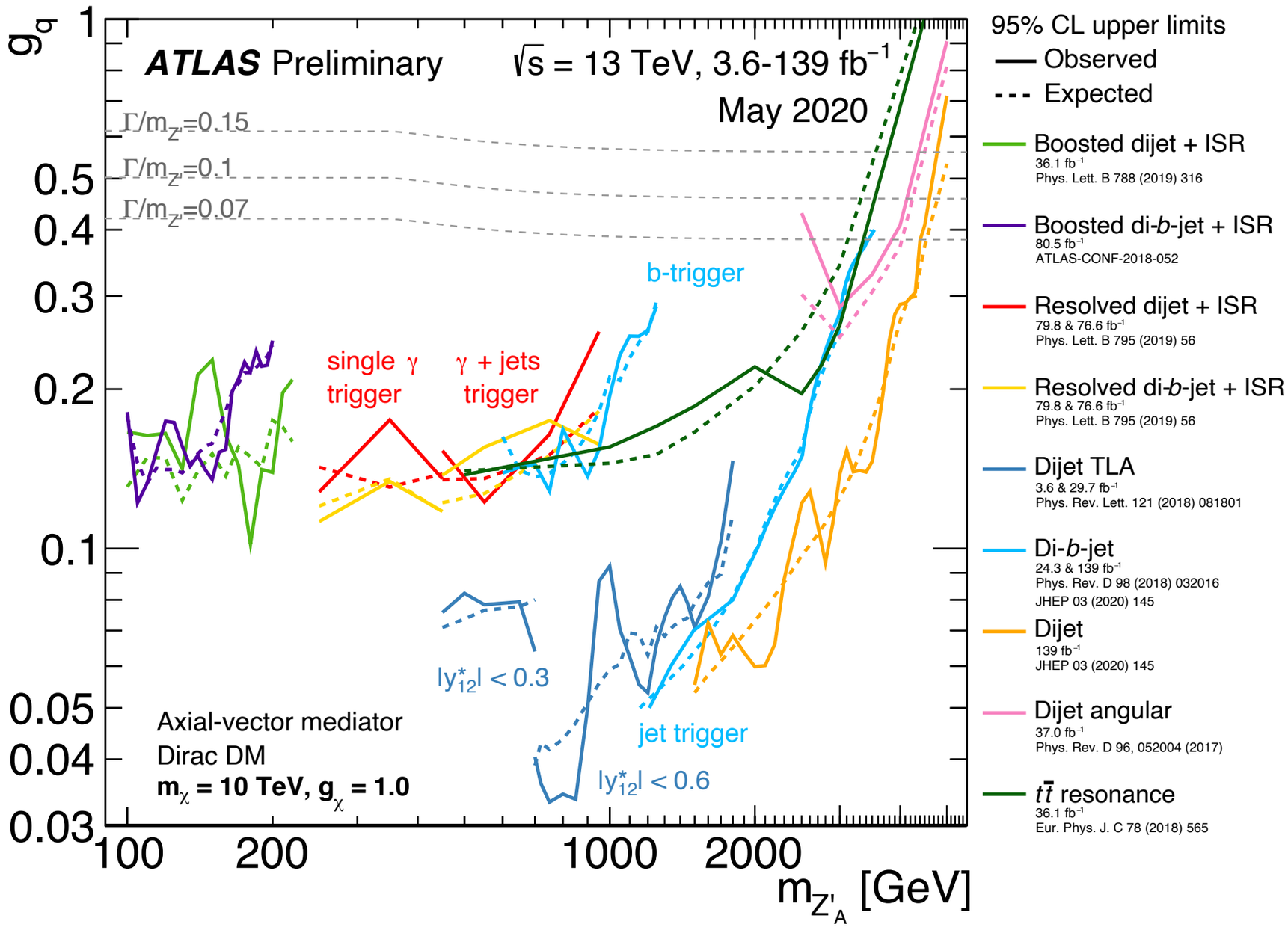
- Quality of DM candidate still depends on other assumptions
  - Lots of parameter choices give too high relic density, be careful!
- For details of our SUSY (dark matter) search program, see talk from A. Kalogeropoulos

ATLAS EXOT public plots

How are all these results related?

- Benefit of picking a few simplified models is we get a framework to put these all on the same page
- This gives context for where our search program is strongest or weakest

Example: dijet-like resonance searches

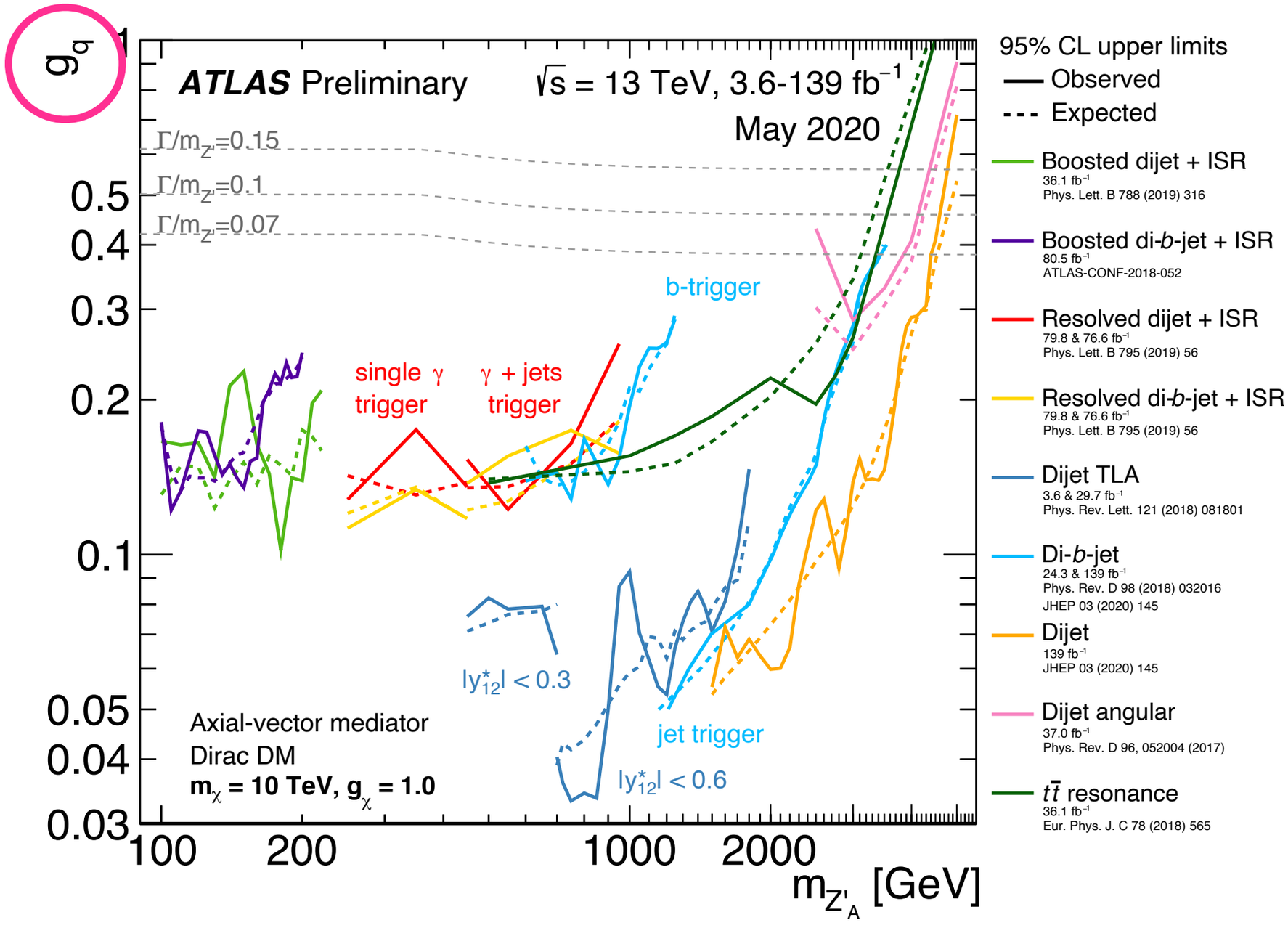


ATLAS EXOT public plots

How are all these results related?

- Benefit of picking a few simplified models is we get a framework to put these all on the same page
- This gives context for where our search program is strongest or weakest

Example: dijet-like resonance searches

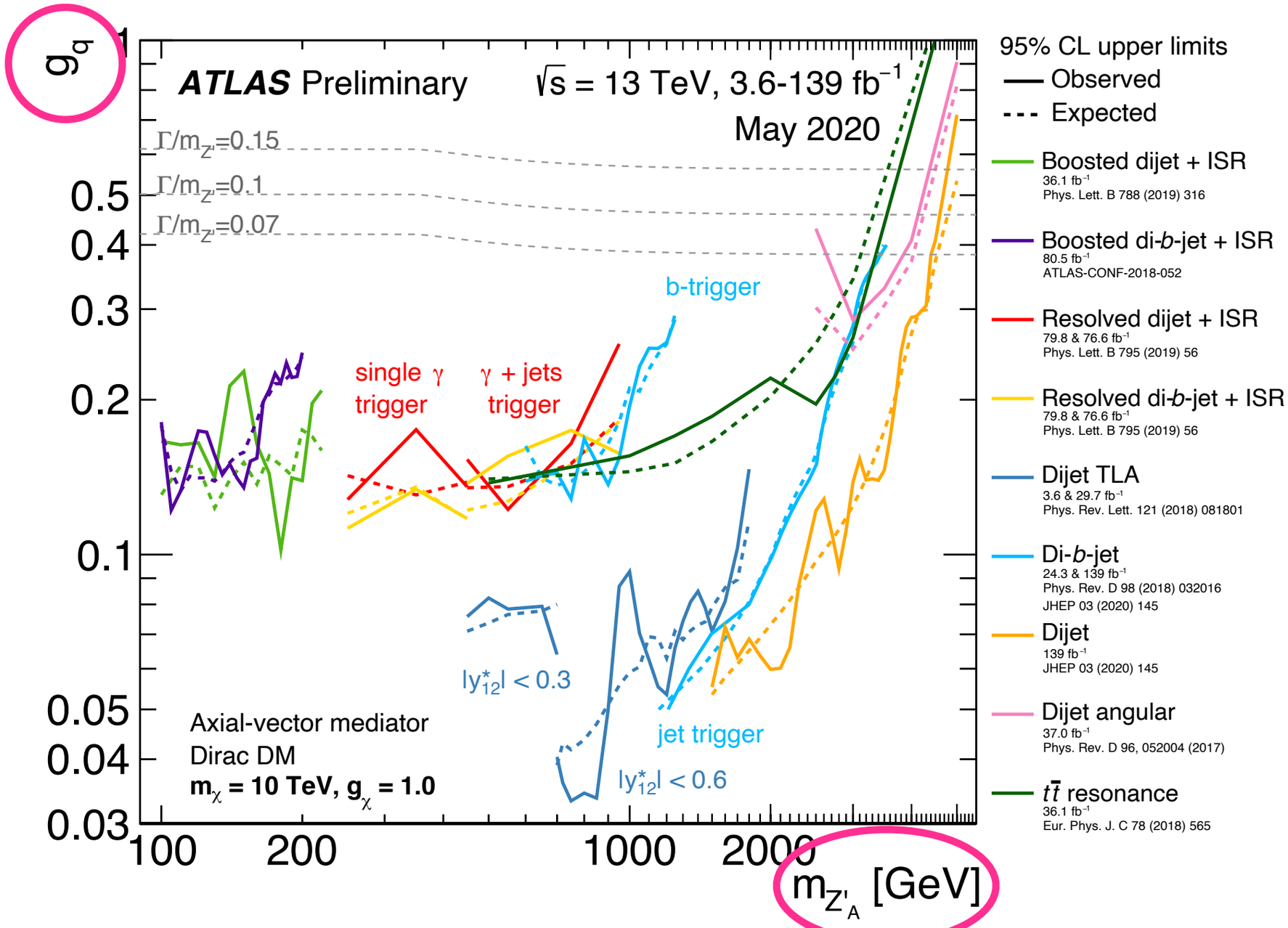


ATLAS EXOT public plots

How are all these results related?

- Benefit of picking a few simplified models is we get a framework to put these all on the same page
- This gives context for where our search program is strongest or weakest

Example: dijet-like resonance searches

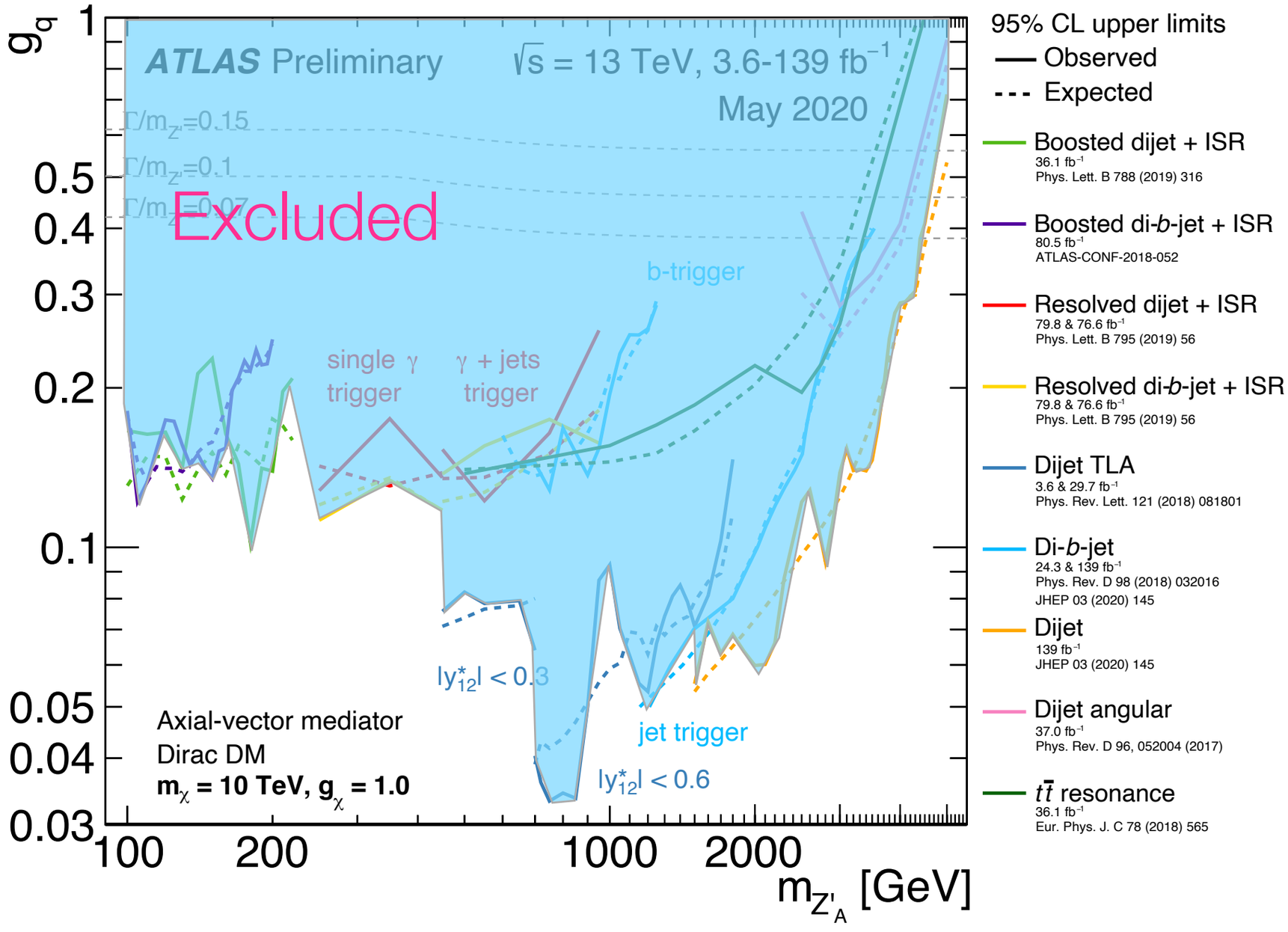


ATLAS EXOT public plots

How are all these results related?

- Benefit of picking a few simplified models is we get a framework to put these all on the same page
- This gives context for where our search program is strongest or weakest

Example: dijet-like resonance searches

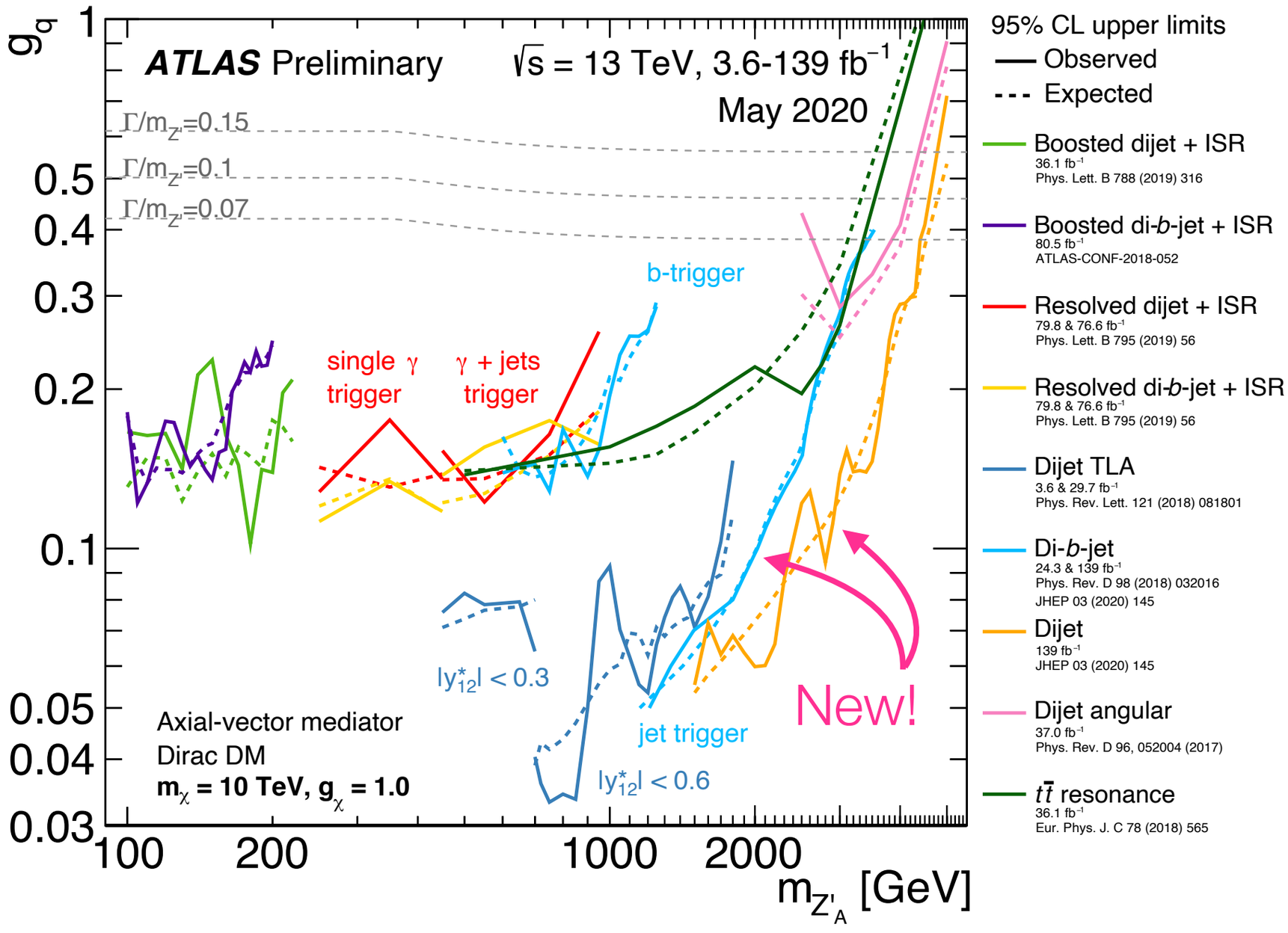


ATLAS EXOT public plots

How are all these results related?

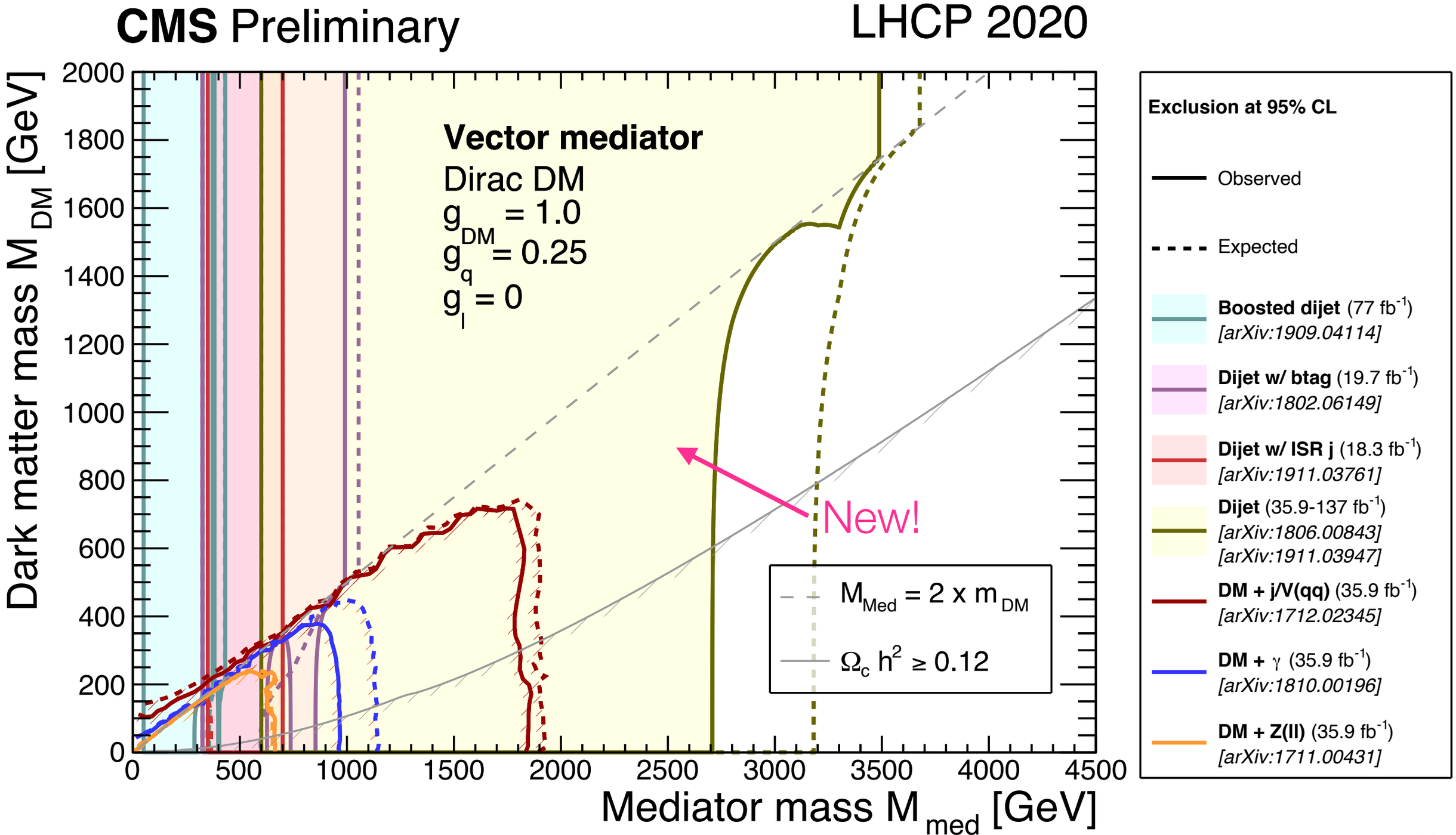
- Benefit of picking a few simplified models is we get a framework to put these all on the same page
- This gives context for where our search program is strongest or weakest

Example: dijet-like resonance searches



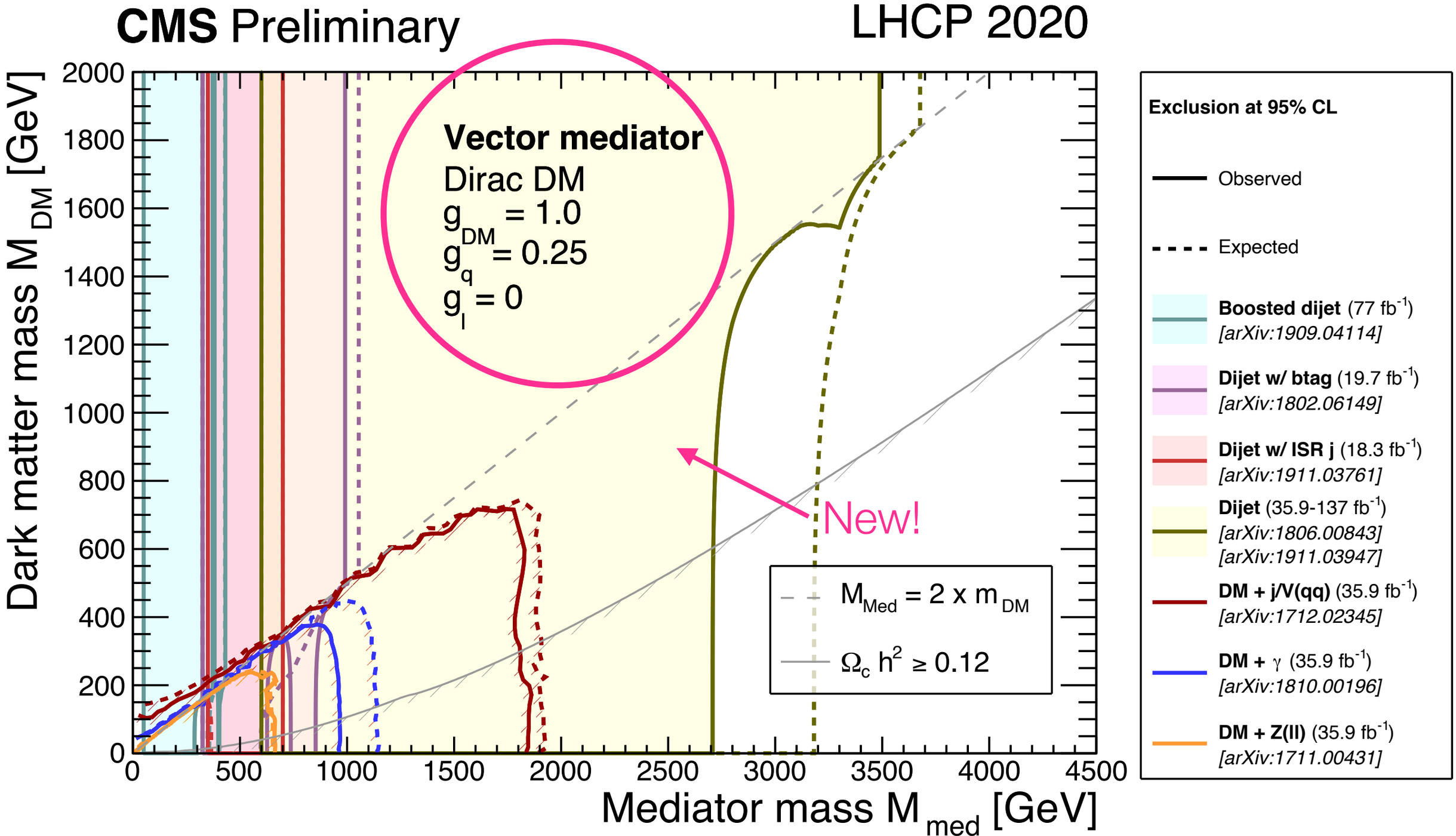
CMS EXO public plots

Z’ mediator models



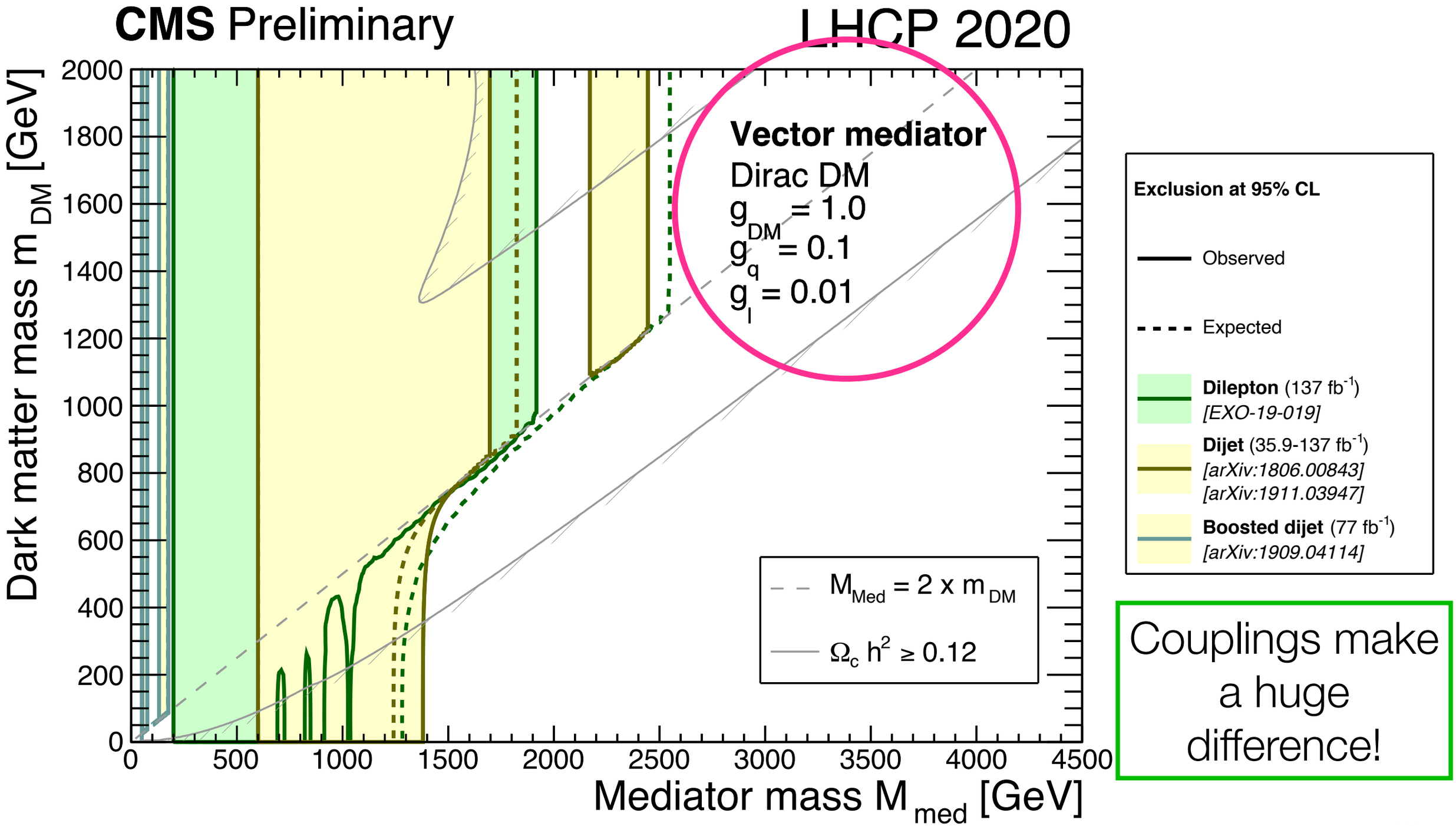
CMS EXO public plots

Z’ mediator models



CMS EXO public plots

Z’ mediator models

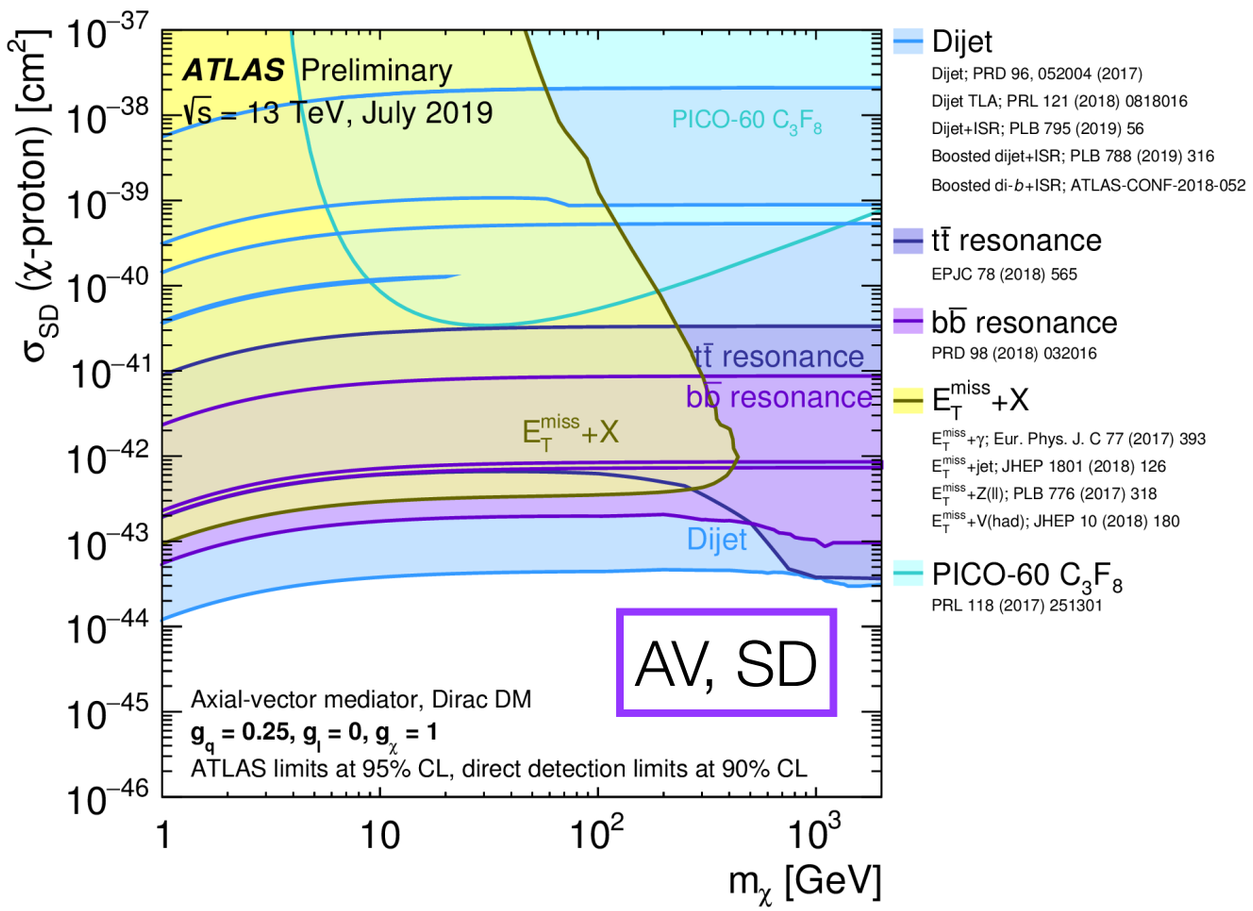


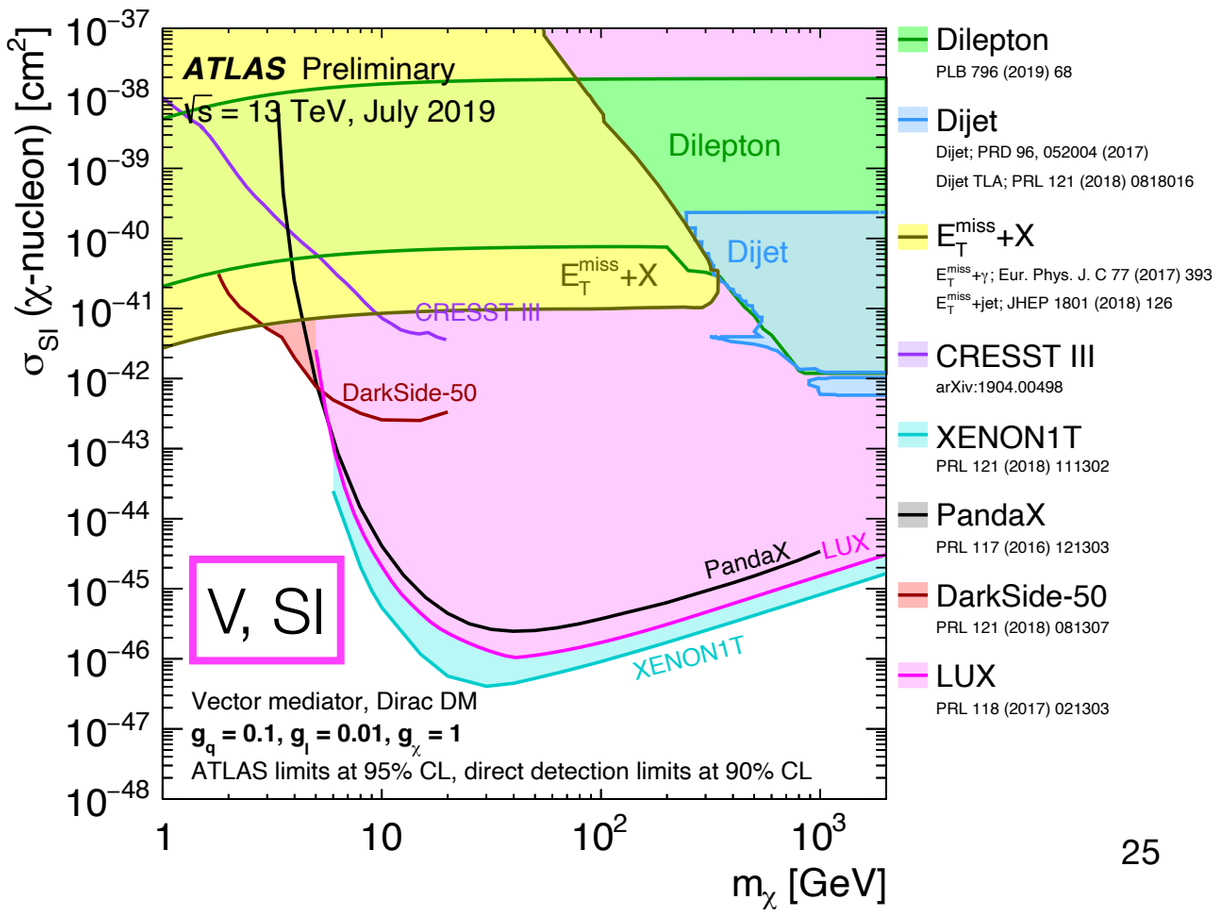
Couplings make a huge difference!

Plots: CombinedSummaryPlotsEXOTICS
How comparisons are made: arXiv:1603.04156
Great talk from Fady Bishara

With the non-collider world

- Important to contextualise collider limits alongside direct and indirect detection results
- Results are very model dependent! Here, showing comparisons to **direct detection**:
  - Axial-vector mediators have **spin-dependent** interactions, vector mediators have **spin-independent** interactions. Different sets of limits for each (also note coupling choices!):





Conclusions

- Explored the **wide range of analyses** which can constrain dark matter at the LHC, and showed the unique contributions of each
    - Higgs to invisible searches, resonance searches, and M_{ET}-based signatures are all **key contributors** to the DM search program
- More full Run 2 results are **in progress now** - stay tuned for exciting updates!
- DM possibilities are **super diverse**: broader dark sector searches, SUSY searches, and long-lived particle searches can all be handles on dark matter

For more, see these talks:

Dark matter in ATLAS, J. Burr

Dark sectors in ATLAS and CMS, M. Queitsch-Maitland

Dark matter in CMS, V. Sharma

Heavy resonances in ATLAS and CMS, O. Gonzalez

Higgs to invisible searches, D. Schaefer

EXO Experimental overview, I. Ochoa

Backup

2HDM+a details

arXiv:1810.09420
ATLAS EXOT-2017-32

- Additional Higgs doublet leads to five Higgs-like particles: SM-like (h, H), CP-odd pseudo-scalar A, two charged Higgs (H+, H-). Extend with extra DM mediator (here, a pseudo scalar a). A and a can mix; dark matter χ couples to a.
- Relevant parameters of model: Higgs particle masses (6, with 1 fixed given that m_h should be 125 GeV), dark matter mass, quartic couplings between a and scalar doublets (3), coupling between a and DM (1), EW VEV (1), ratio of VEVs of the Higgs doublets, called tan(β) (1), mixing angle of CP-even eigenstates α (1), mixing angle of CP-odd eigenstates θ (1). Total: 14.
  - Therefore much more complicated to summarise/scan!

2HDM+a details

arXiv:1810.09420
ATLAS EXOT-2017-32

- In ATLAS summary effort, chose:
  - Type II 2HDM with v and h fixed by Standard Model higgs
  - Coupling of a to scalar doublets large enough to ensure Higgs potential stability, and all equal
    - $m_A = m_H = m_{H+-}$
    - Coupling of a to $\chi = 1$
    - Thus parameters left to vary in scan are: ma, mA, mX, tan(β), sin(θ)
- Scenarios tested taken from recommendations from LHC DM WG

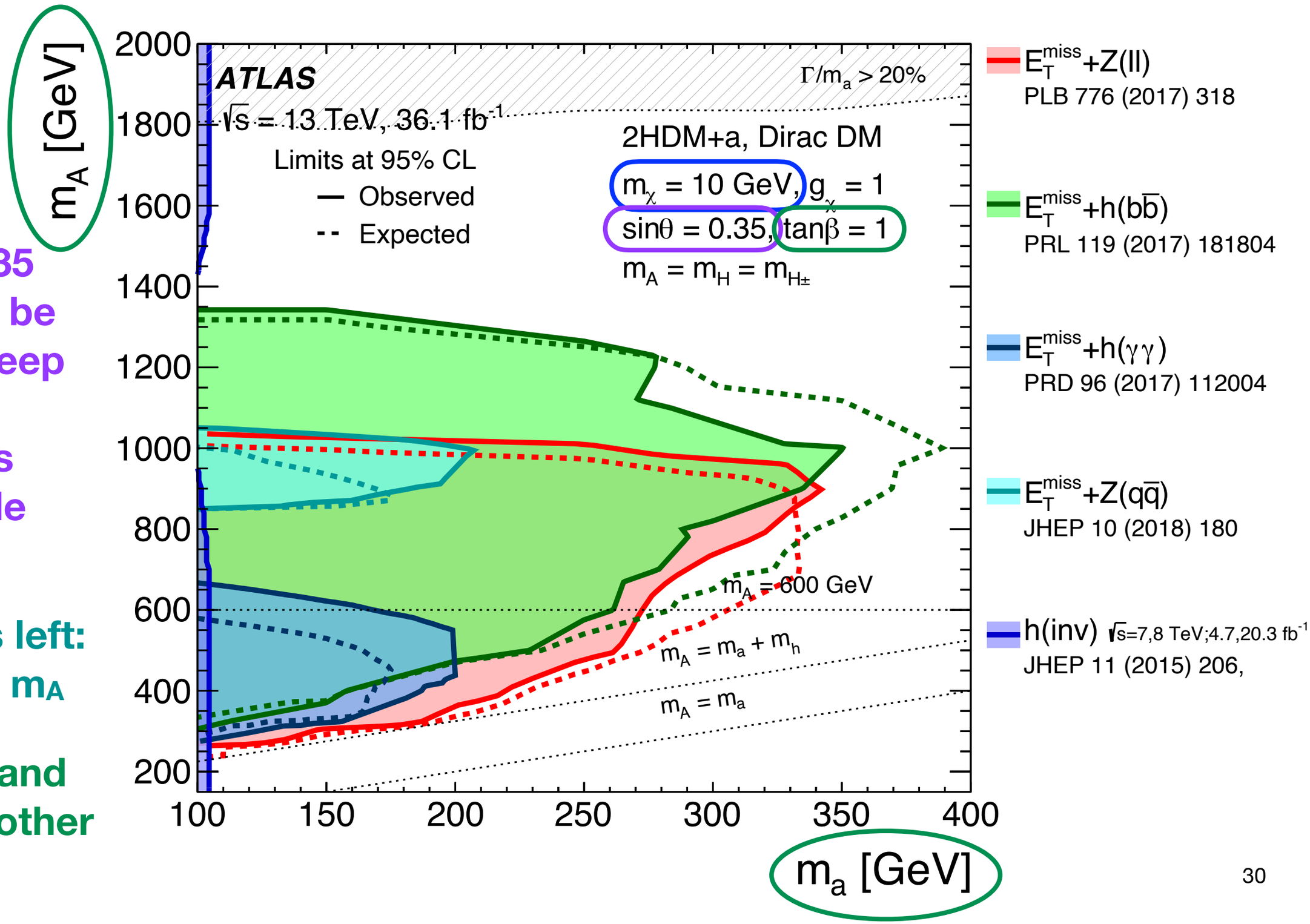
2HDM+a summary plots

Light DM

sin(θ) = 0.35 allows H to be heavy but keep quartic couplings reasonable

Three parameters left: tan(β), m_a, m_A

Fix one and scan the other two



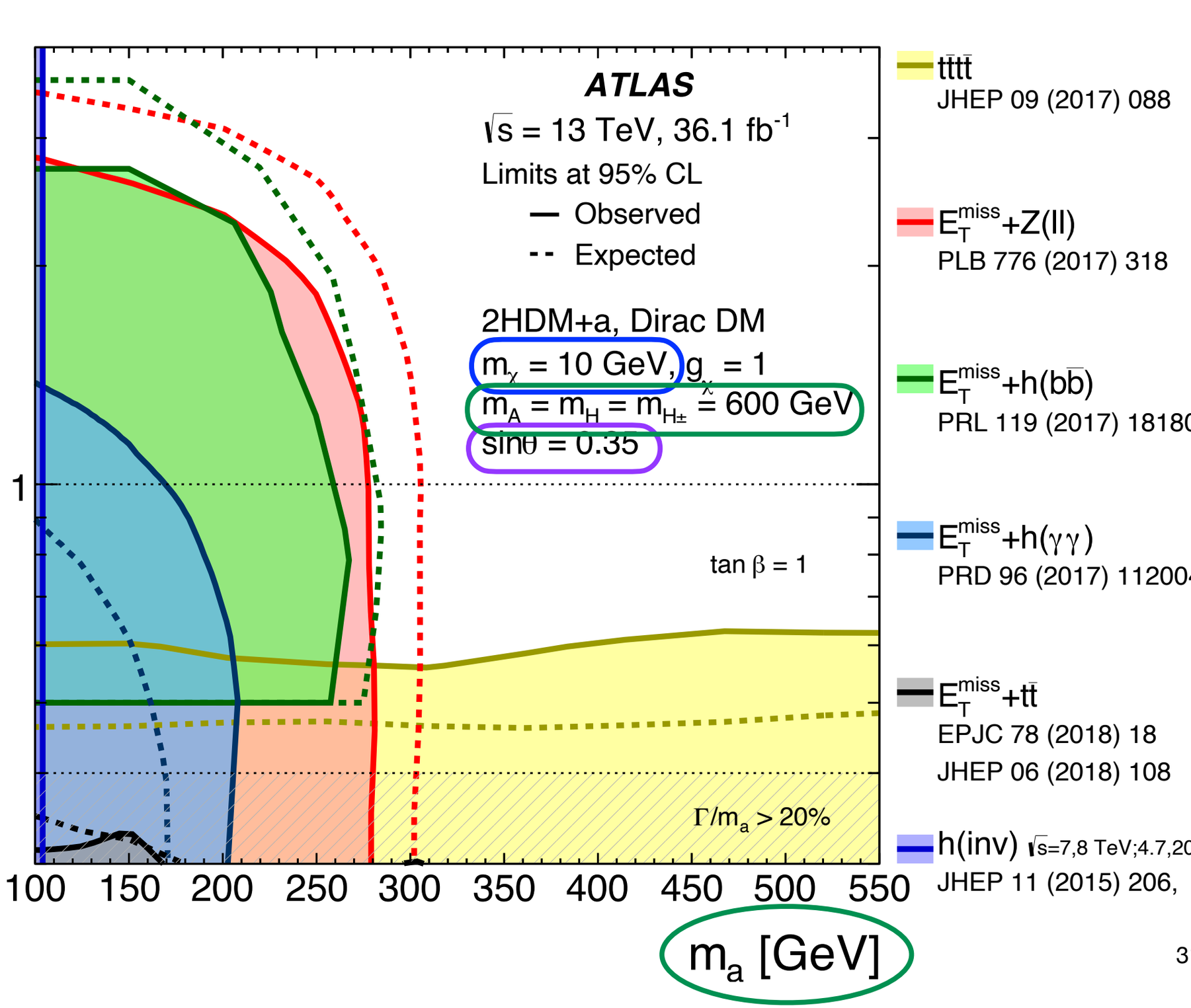
2HDM+a summary plots

Light DM

sin(θ) = 0.35 allows H to be heavy but keep quartic couplings reasonable

Three parameters left: tan(β), m_a, m_A

Fix one and scan the other two



Comparing Z’ collider limits to direct detection

- Spin-independent interactions: assume σSIproton = σSIneutron and simply set one DM-nucleon interaction cross section limit. For spin-independent interactions, need to be set separately on proton and neutron

- Calculate SI and SD cross sections for S-channel simplified models and we find:

$$\sigma_{\mathrm{SI}} = \frac{f^2(g_q) g_{\mathrm{DM}}^2 \mu_{n\chi}^2}{\pi M_{\mathrm{med}}^4}$$

Vector: $f(g_q) = 3g_q$

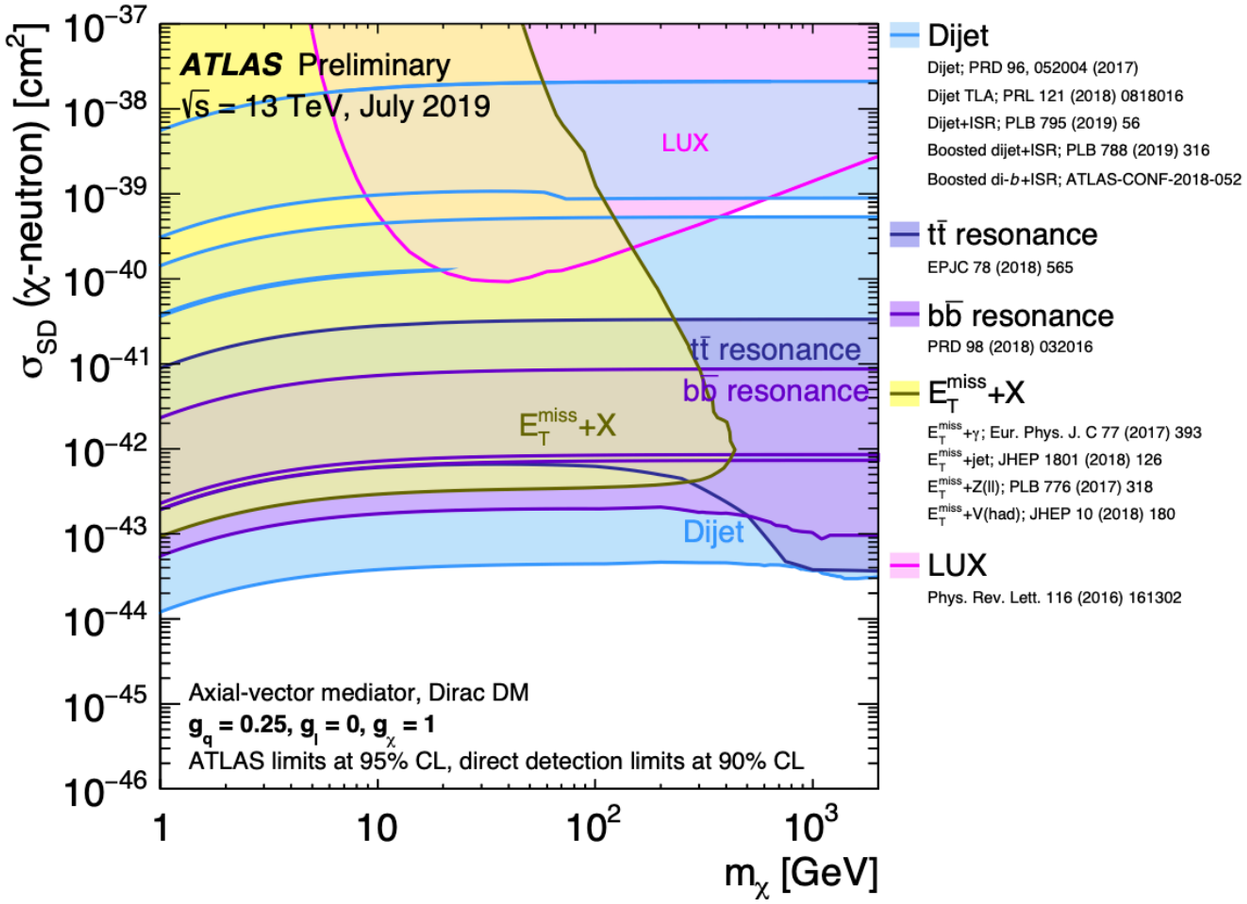
$$\sigma_{\mathrm{SD}} = \frac{3 f^2(g_q) g_{\mathrm{DM}}^2 \mu_{n\chi}^2}{\pi M_{\mathrm{med}}^4}$$

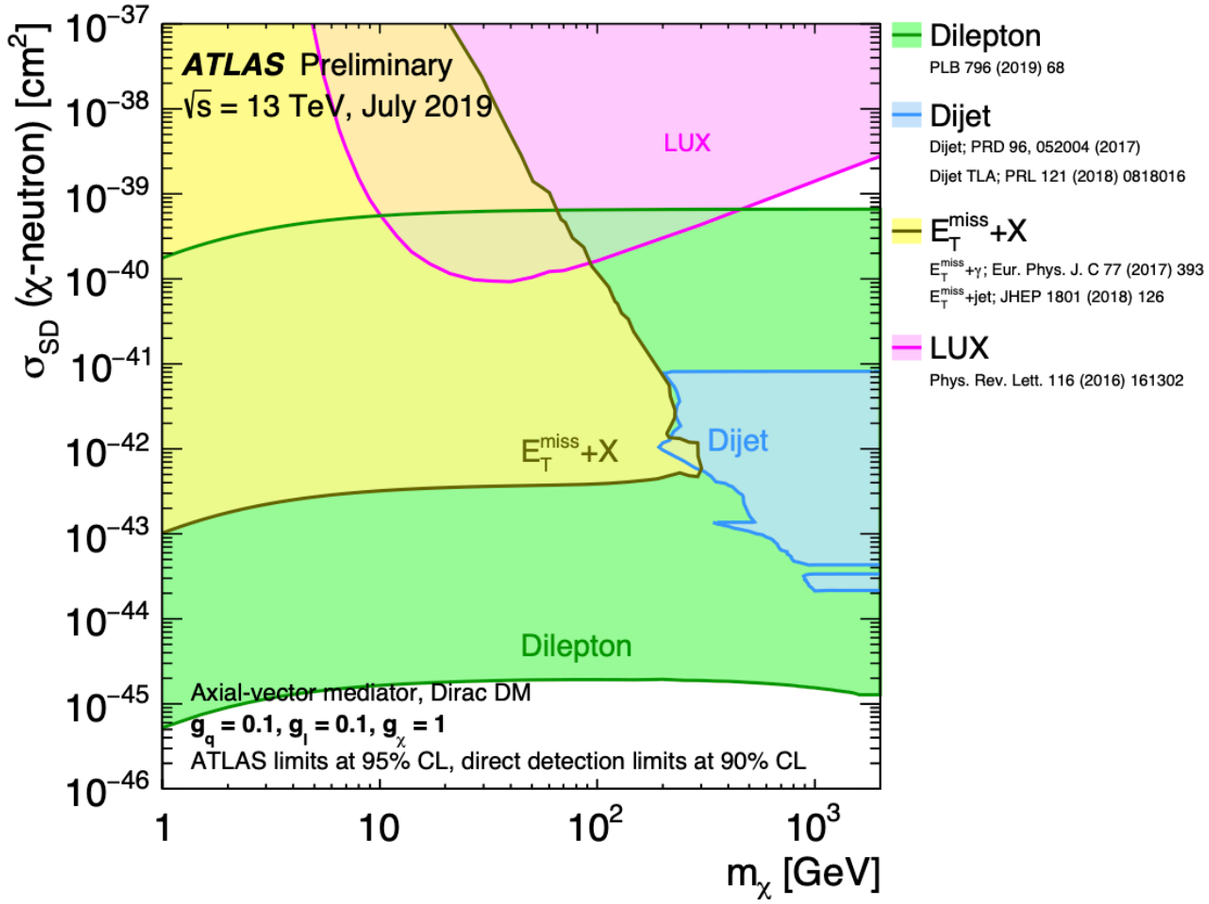
Axial-vector: $f(g_q) = 0.32 g_q$

$$\mu_{n\chi} = m_n m_{\mathrm{DM}} / (m_n + m_{\mathrm{DM}})$$

And combine information to translate from Mmed to σ

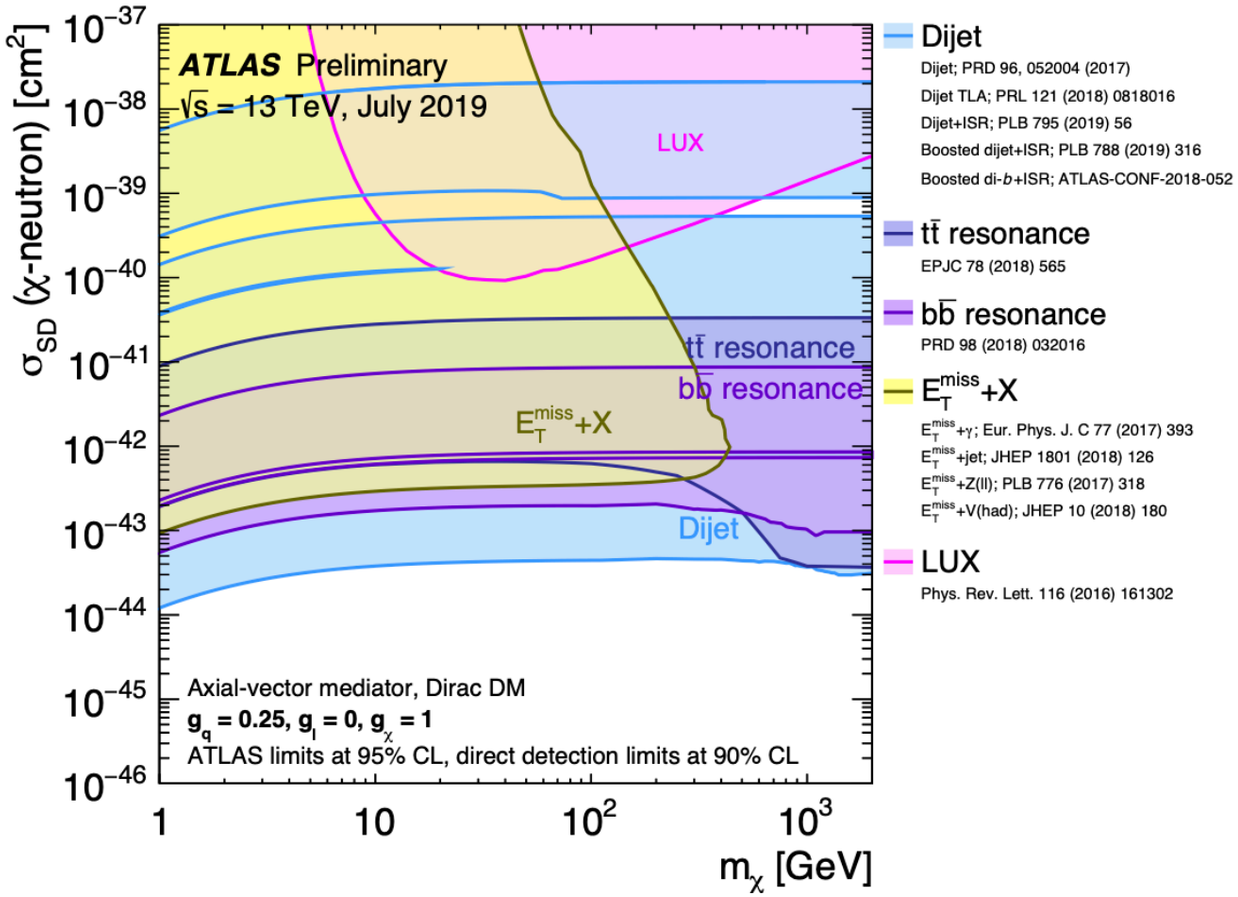
Other direct detection ATLAS plots

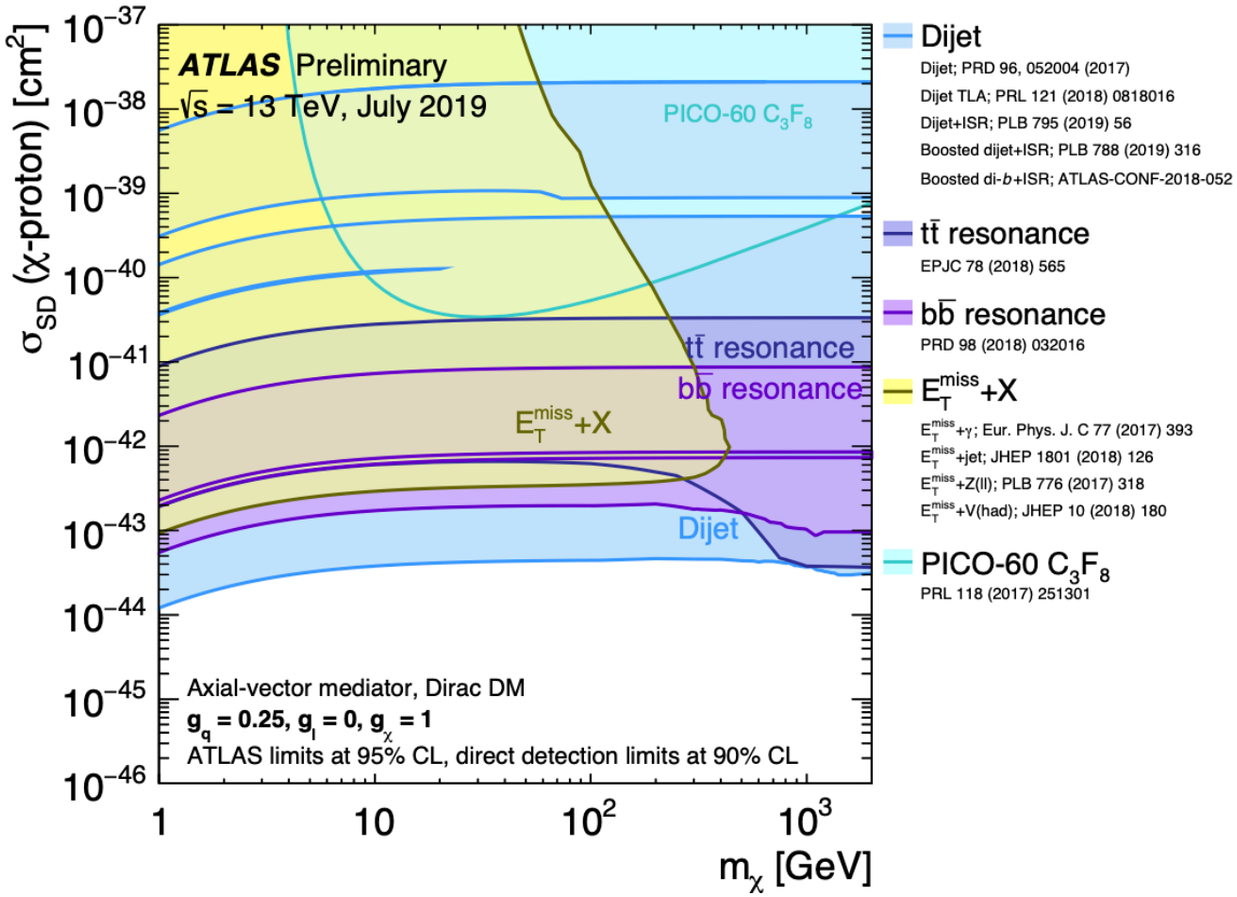




Different couplings

Other direct detection ATLAS plots





Proton versus neutron