Searches for Dark Matter with the ATLAS and CMS Experiments at the LHC

EDSU-Tools 2024 — 5th World Summit

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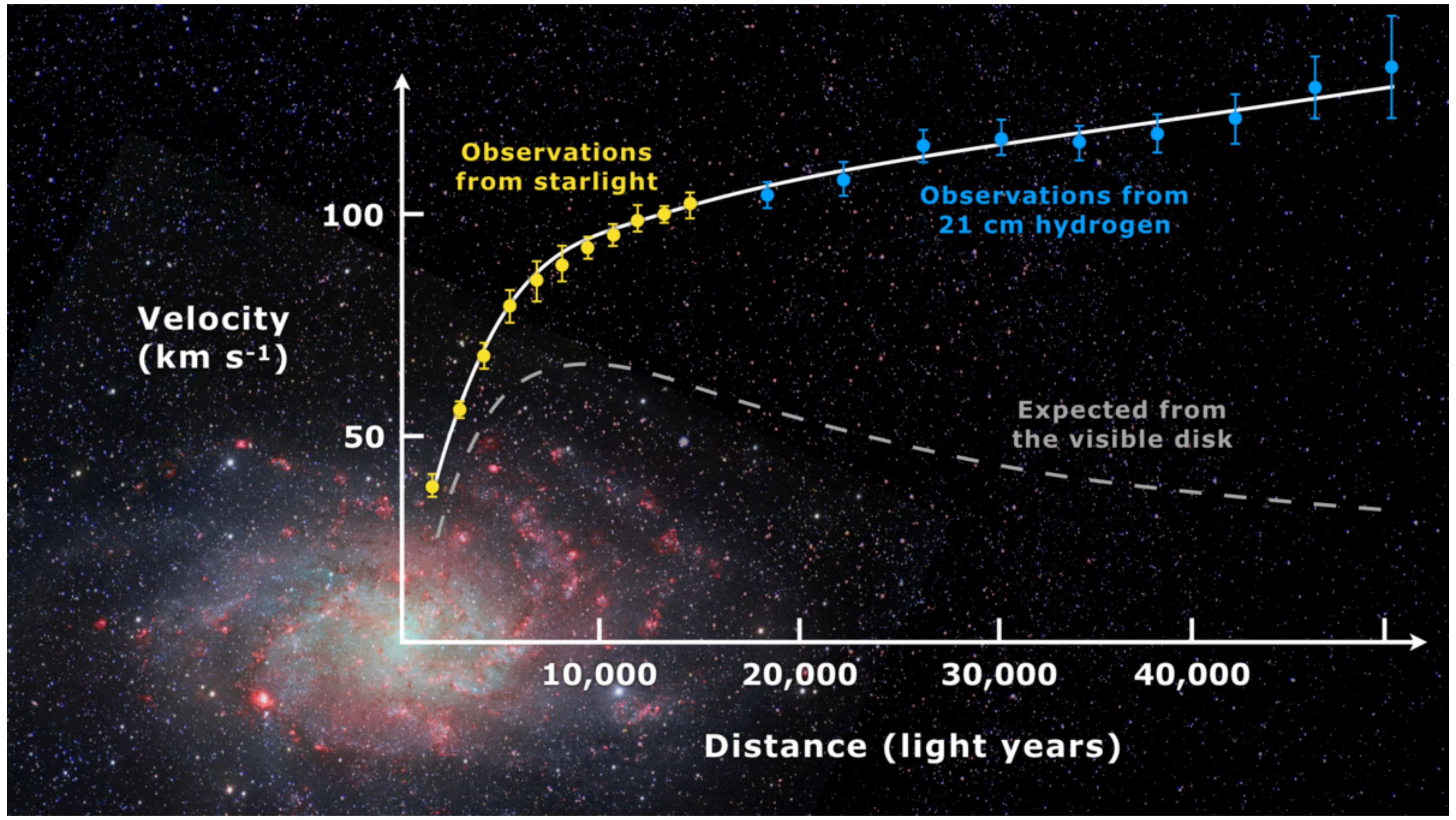
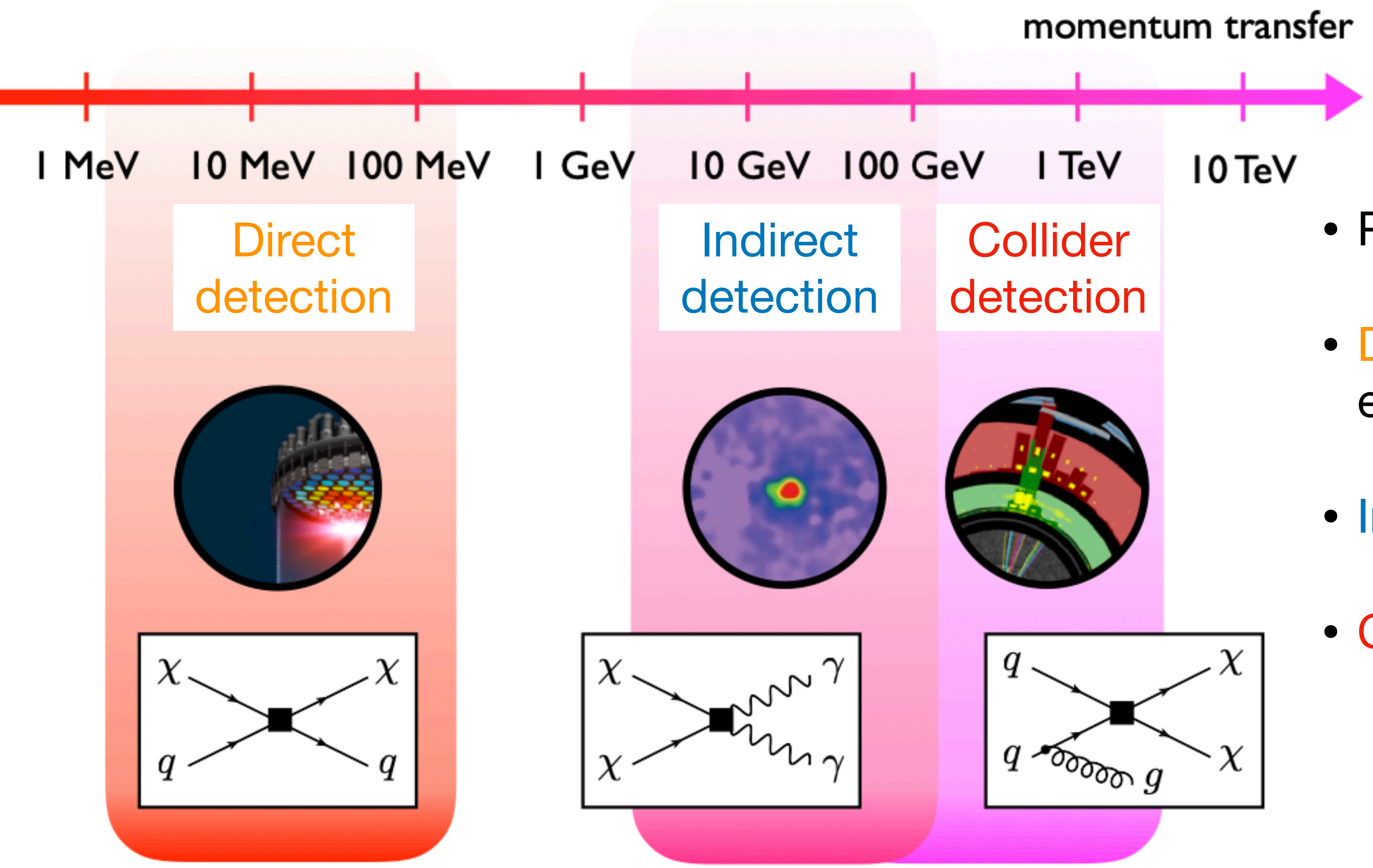
on behalf of ATLAS and CMS collaborations

Noirmoutier, 04/06/2024

Dark Matter

- Dark Matter existence supported by plethora of astrophysical measurements.
  - NOT sufficiently explained by Standard Model, making DM nature a central question in particle physics.
  - ***DM candidate***: a strong consideration in many beyond-the-SM models.



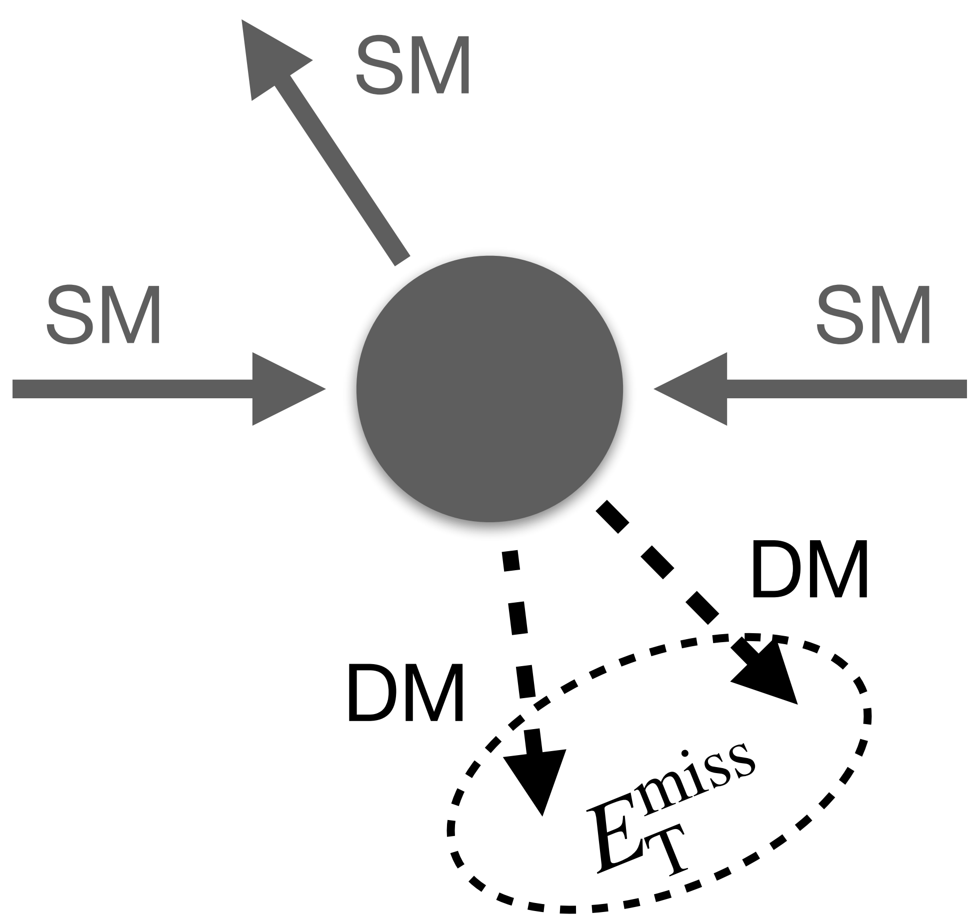


arXiv:1810.09420

- Probes of DM underway in several areas.
- Direct searches for elastic scattering between DM and nuclei or electrons.
- Indirect searches for products of DM annihilation or decay.
- Collider searches for production of DM from collisions of SM particles
  - complementarity to other detections at GeV-TeV scale.
  - provide access to particles mediating interactions between DM and SM sector.

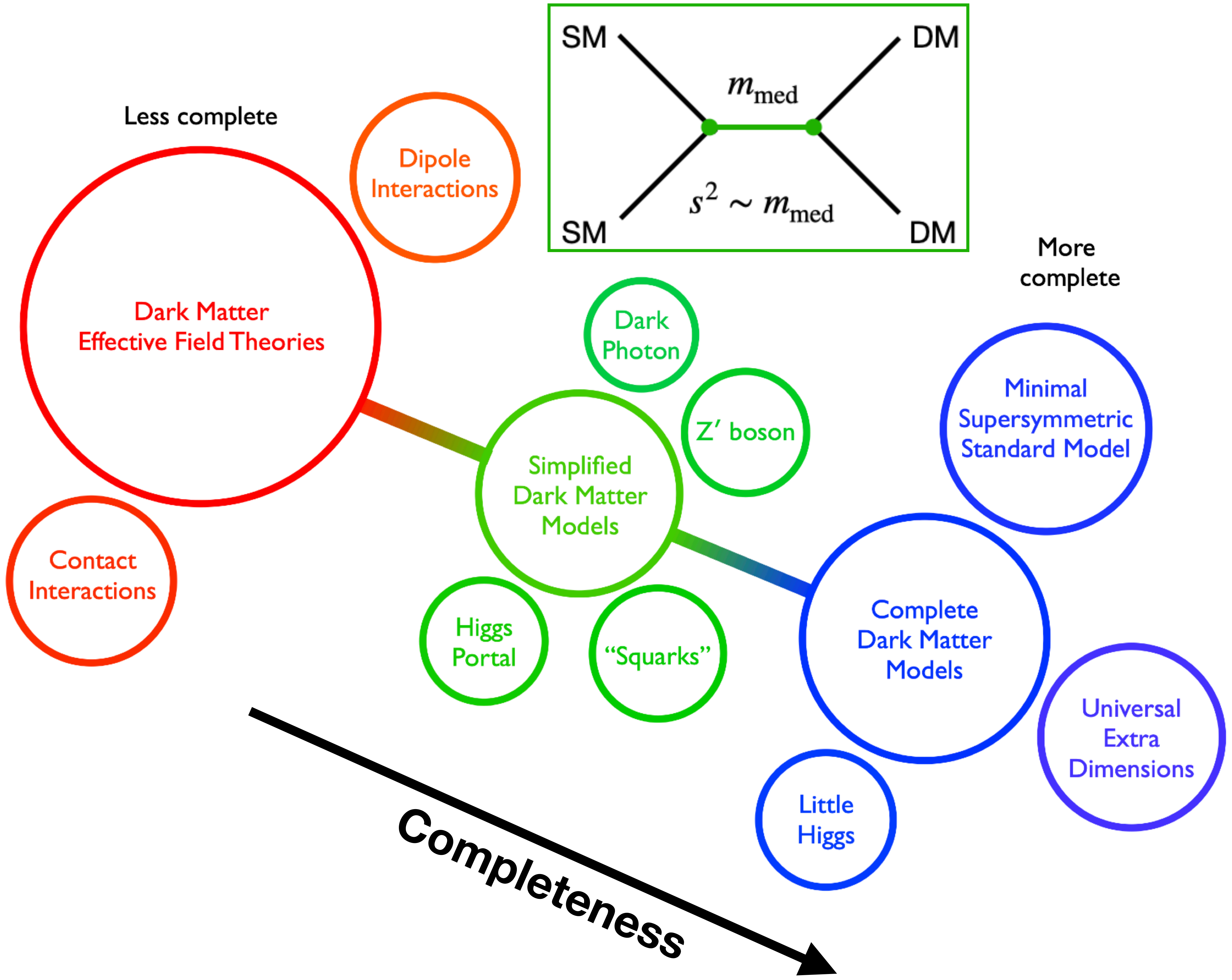
Dark Matter probes at the LHC (ATLAS and CMS)

- ATLAS and CMS sensitive to wide variety of potential DM candidates.
- Most of DM searches at the LHC focus on ***Weakly Interacting Massive Particles*** (***WIMPs)***.
    - usually in ***simplified models*** where DM couples to SM via mediator.
    - more complete (hence more complicated) models e.g *2HDM(+a)* also considered.
    - detected in signatures with large **Missing Transverse Momentum** recoiling against SM particles.



- Also search for ***(Hidden) Dark Sector*** such as Dark Photon, Dark Higgs, Dark QCD, and so on.

DM benchmark models at LHC



arXiv:1506.03116v3

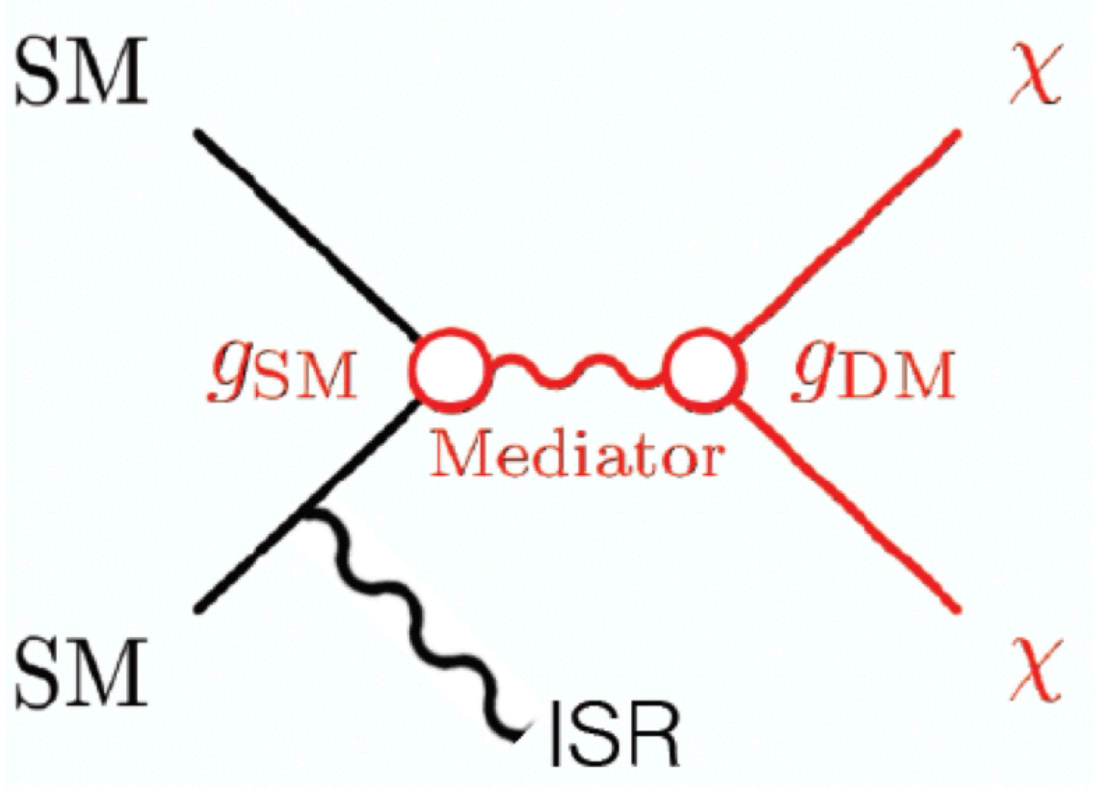
In this talk, I am trying my best to give you an overview of most recent, interesting DM searches at ATLAS and CMS!!!

Simplified Models

- Simplified s-channel models most commonly used for LHC Run-2 DM searches:
    - a fermionic DM χ;
    - a mediator: **vector / axial-vector / scalar / pseudo-scalar**.

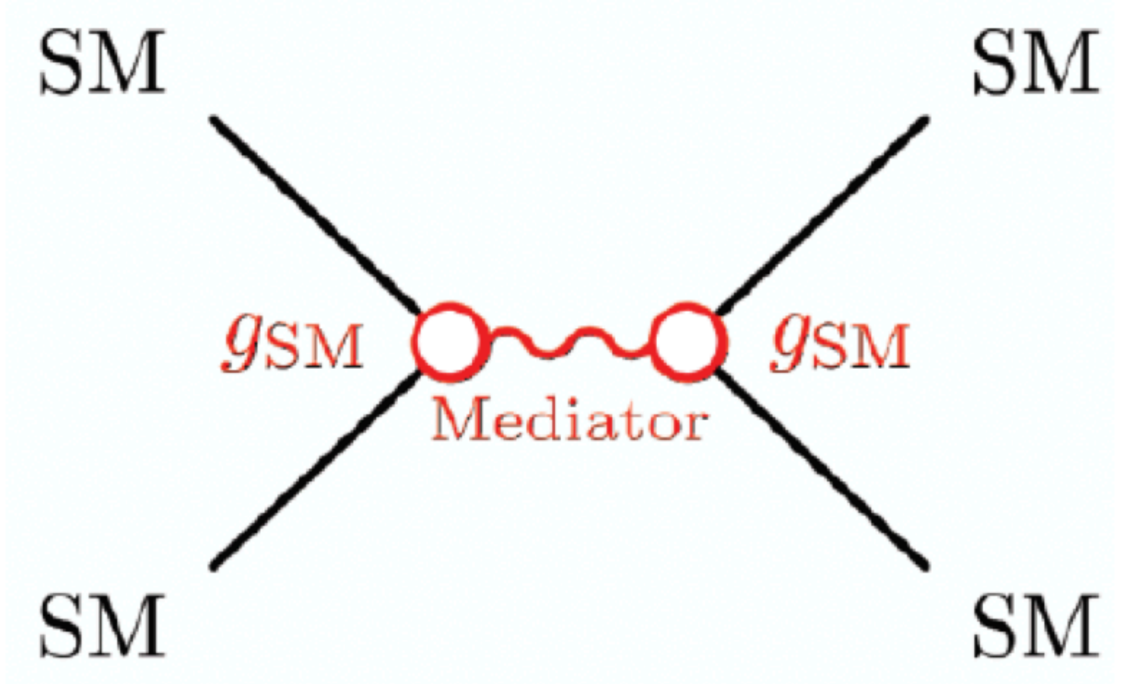
- **Minimal set of free parameters: DM and mediator masses, DM and SM couplings.**

- Two complementary key signatures:



$E_{\mathrm{T}}^{\mathrm{miss}} + X$ (**mono-X**)

invisible mediator decays, detected using Initial State Radiation or associated visible production (usually jet / photon / V).



Resonance

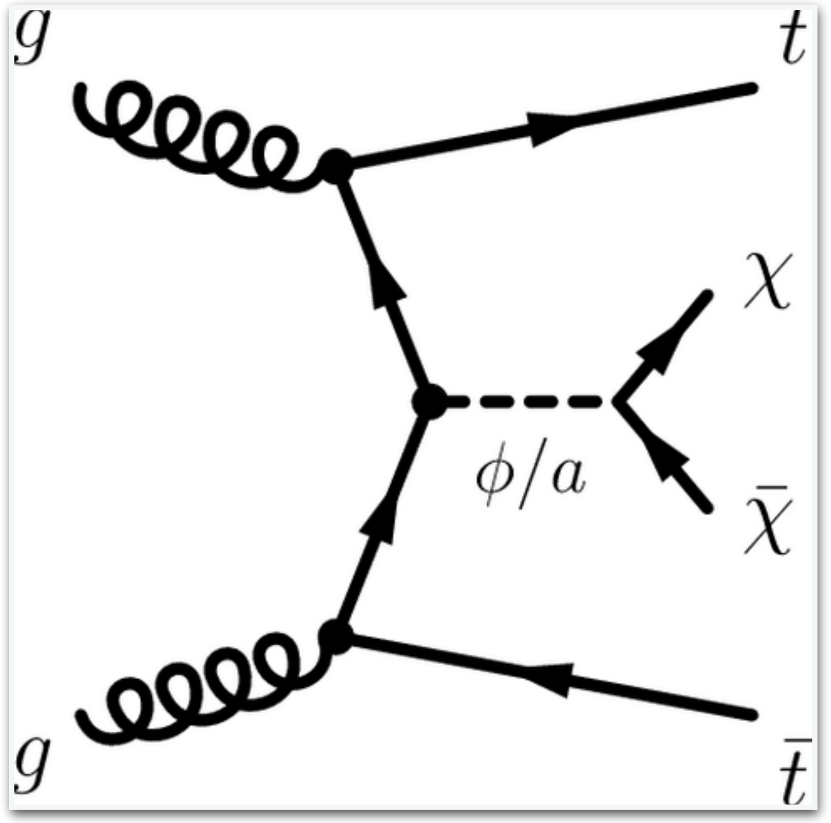
visible mediator decays, allowing for reconstruction from decay products.

Simplified Models

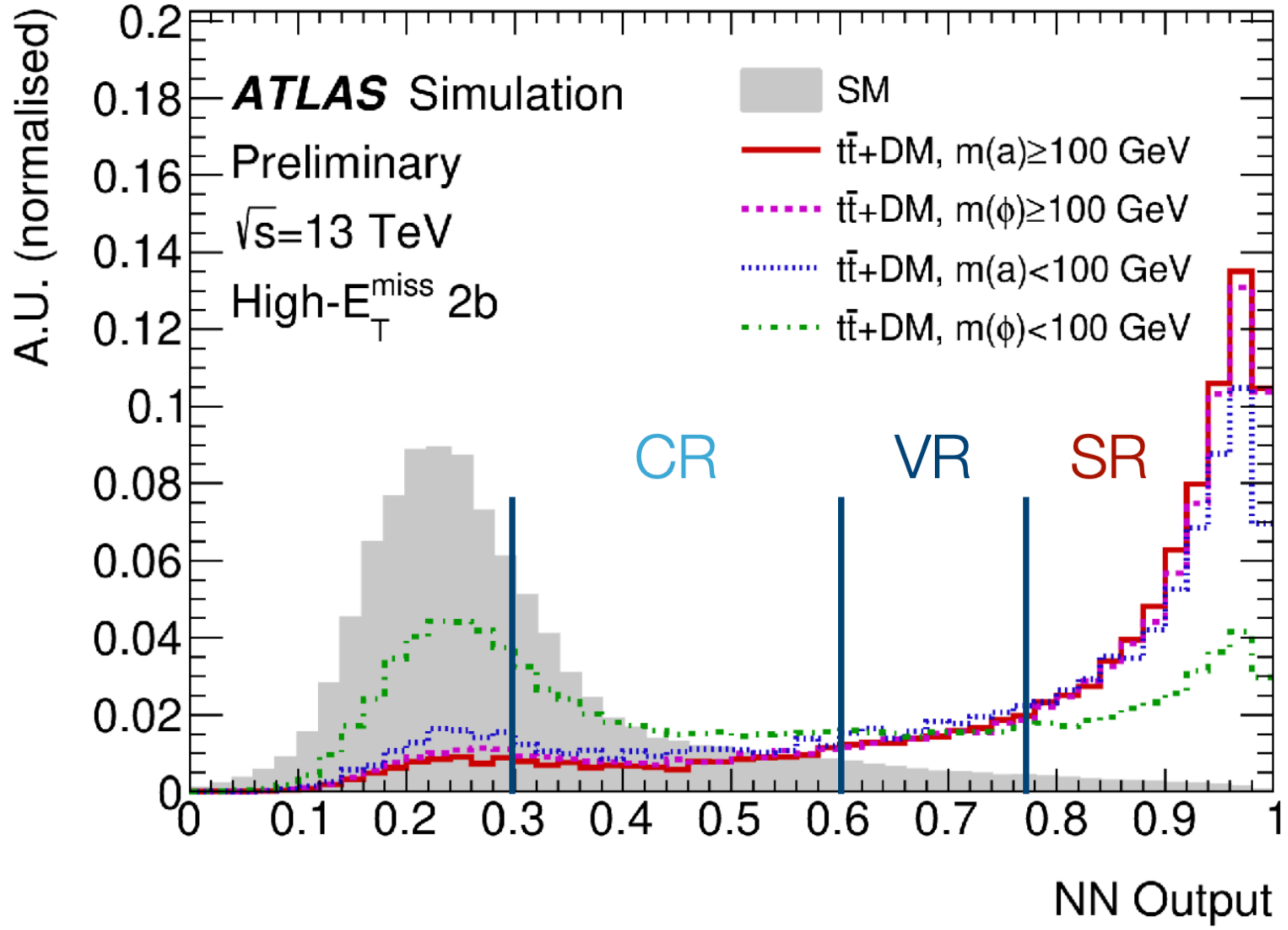
- **Recent results highlighted in this talk**:
  - ATLAS $\mathrm{DM} + t\bar{t}$ search **JHEP03 (2024) 139**
  - CMS $\mathrm{DM} + t\bar{t}$ and $\mathrm{DM} + t$ search **CMS-PAS-EXO-22-014**
  - ATLAS resolved dijet + ISR search **arXiv:2403.08547**
  - ATLAS Higgs Invisible Decays **PLB 842 (2023) 137963**

- **NOT in today talk but interesting to consider**:
  - Summary of DM searches in s-channel model (***backup***) **ATLAS arXiv:2404.15930** **CMS DM summary**
  - CMS Higgs invisible decays (***backup***) **EPJC 83 (2023) 933**
  - ATLAS $\mathrm{DM} + t$ search (including both vector and scalar mediators) **arXiv:2402.16561**

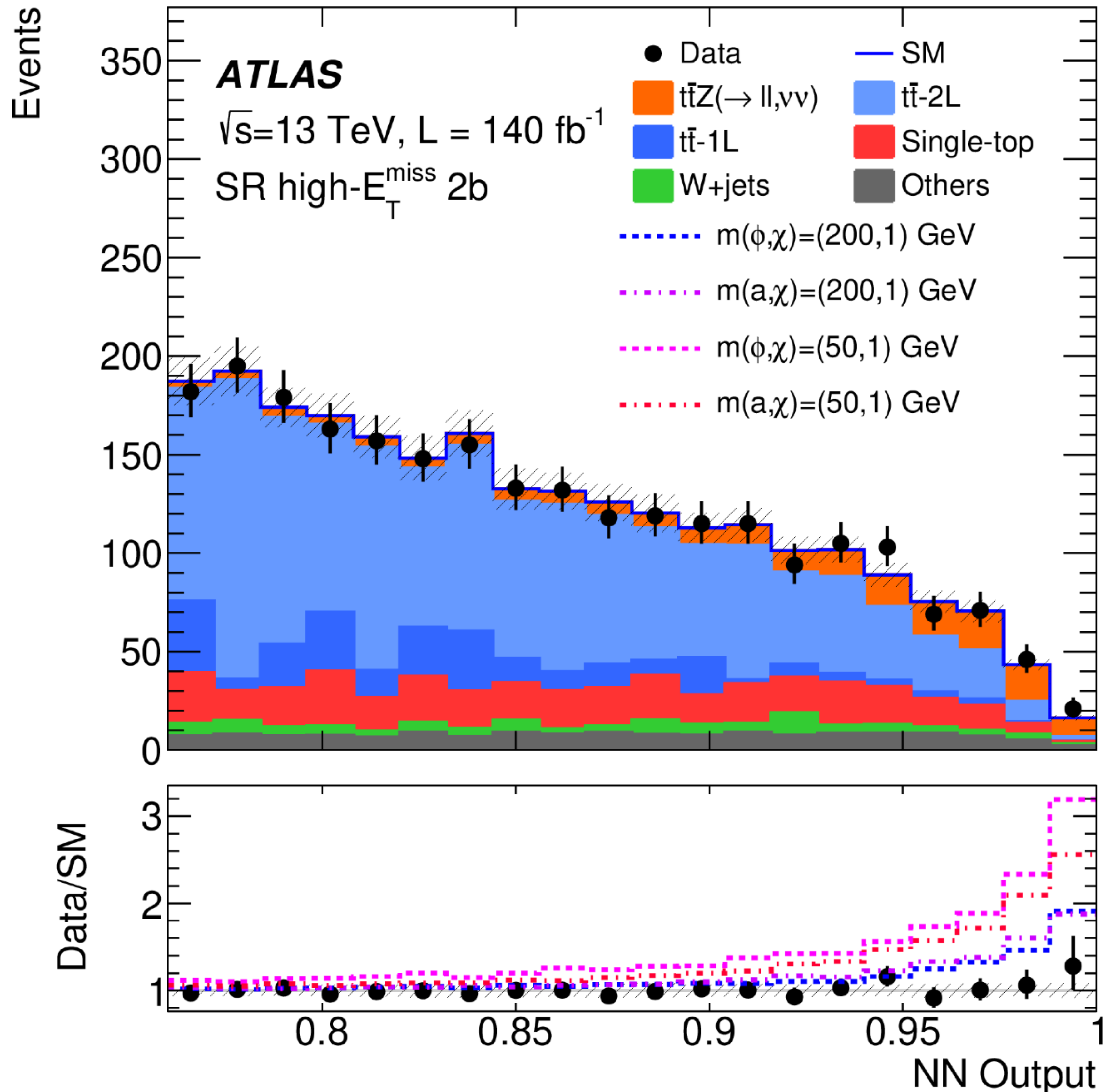
ATLAS $\mathrm{DM} + t\bar{t}$ search JHEP03 (2024) 139



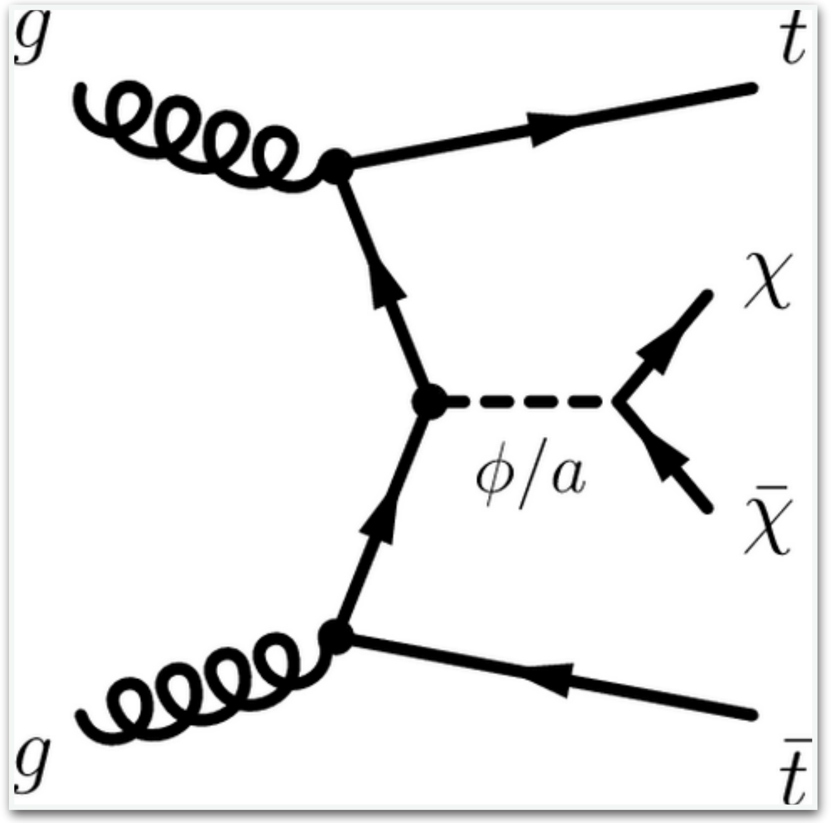
- Production of **DM from s-channel (pseudo-)scalar mediator decay** in association with **two top quarks in 1-lepton channel.**
- **8 event categories** according to number of large-R jets and b-tagged jets as well as presence of top-tagged large-R jet.
  - to target top quark decays at different p_{T} and maximize signal acceptance.
- ***Two Neural Networks*** exploited for resolved top tagging and signal event separation to achieve higher sensitivity.



No significant deviations from SM

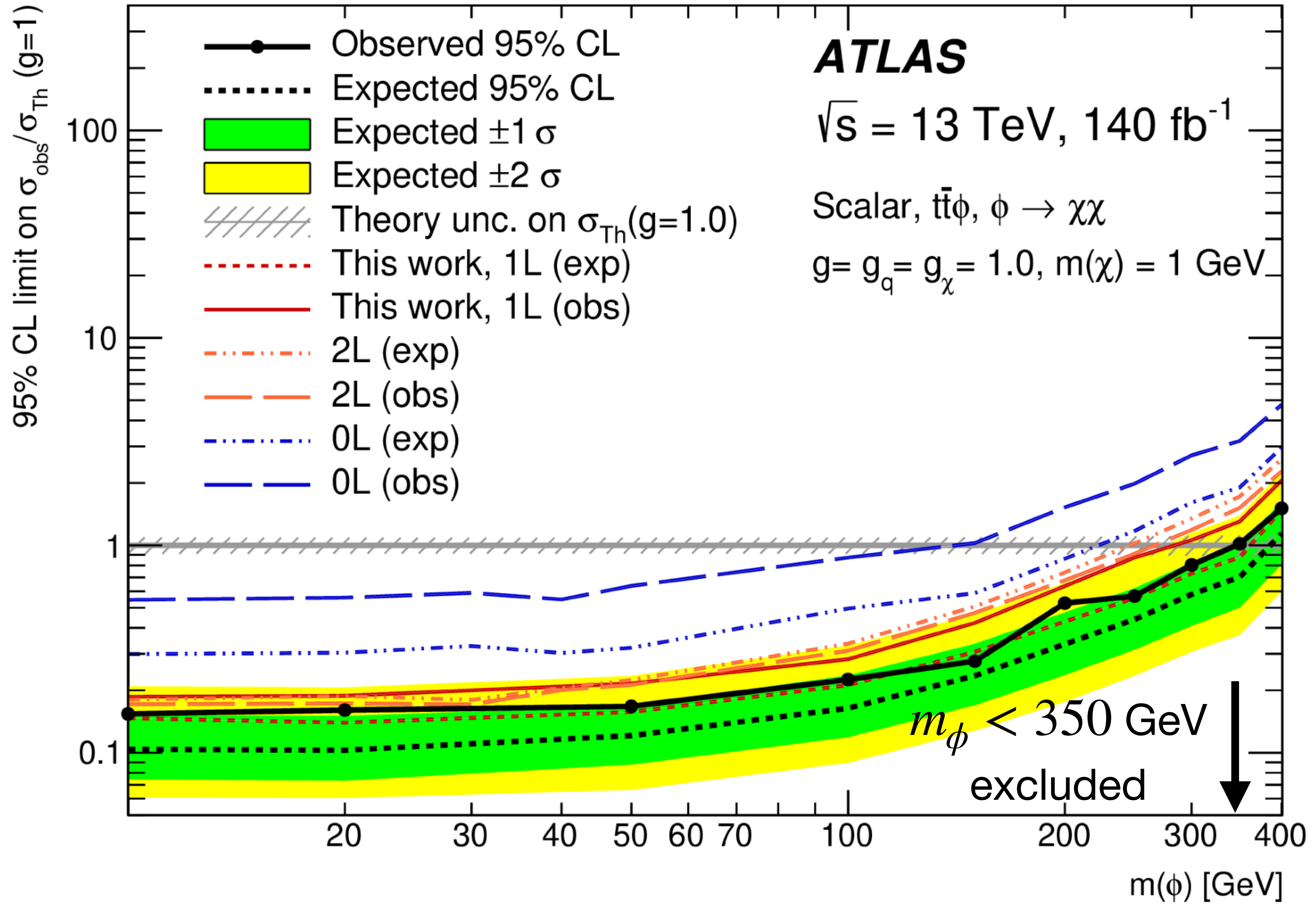


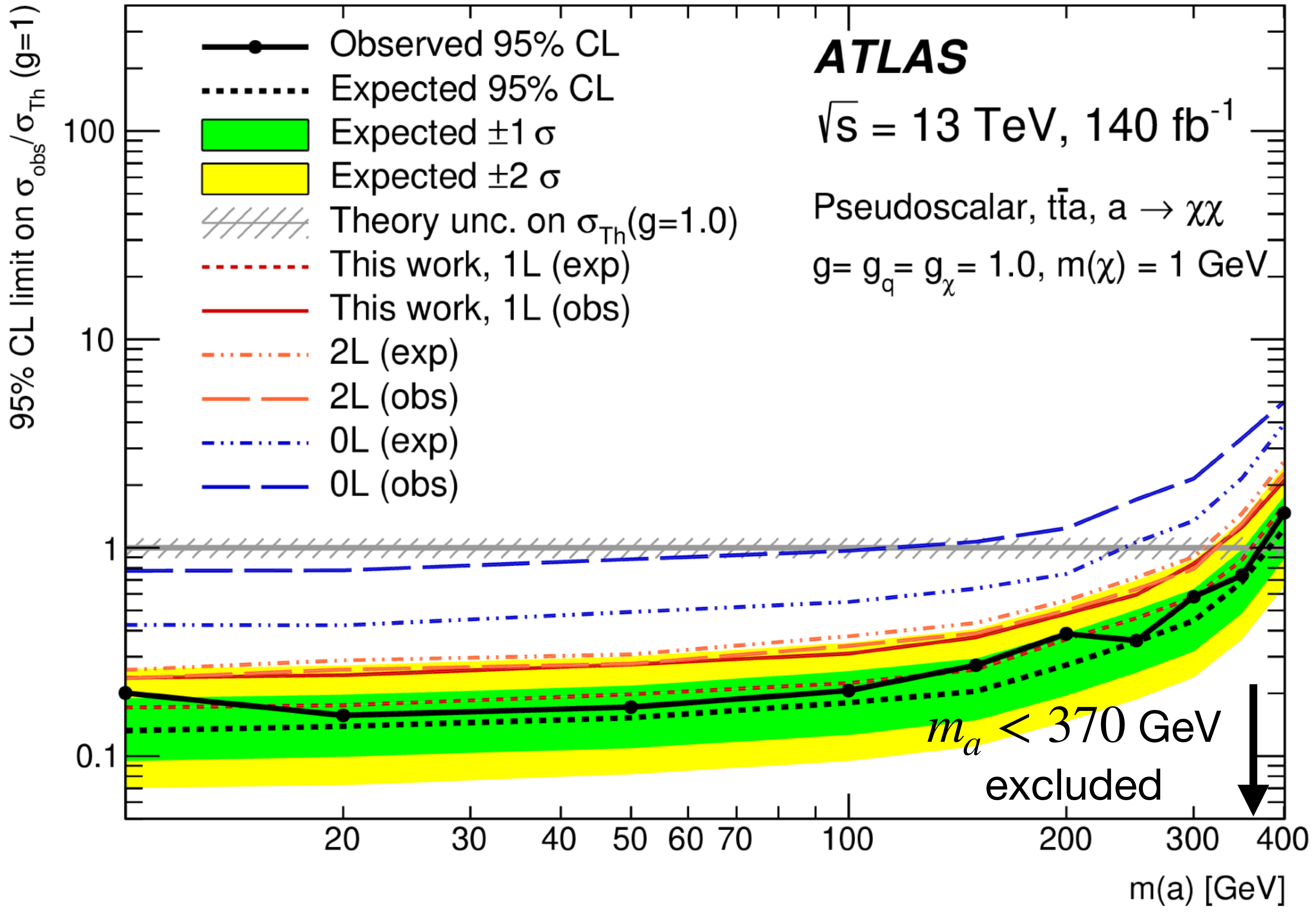
ATLAS $\mathrm{DM} + t\bar{t}$ search [JHEP03 (2024) 139]



- Production of **DM from s-channel (pseudo-)scalar mediator decay** in association with **two top quarks in 1-lepton channel.**

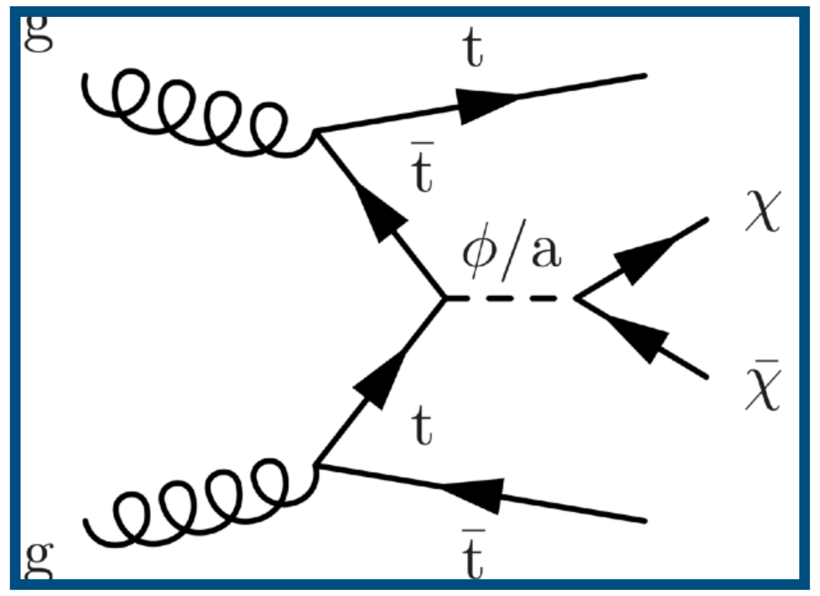
95% CL limits set by combination with 0- and 2-lepton channels



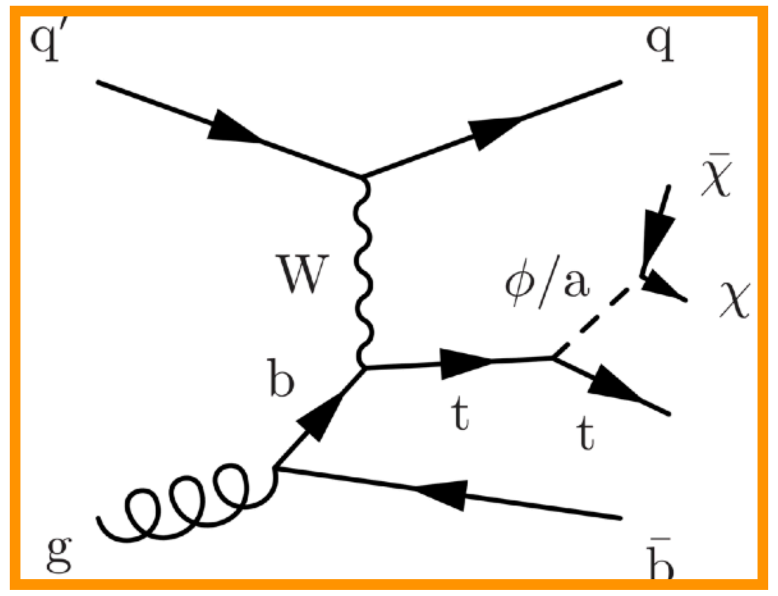


CMS $\mathrm{DM} + t\bar{t}$ and $\mathrm{DM} + t$ search [CMS-PAS-EXO-22-014]

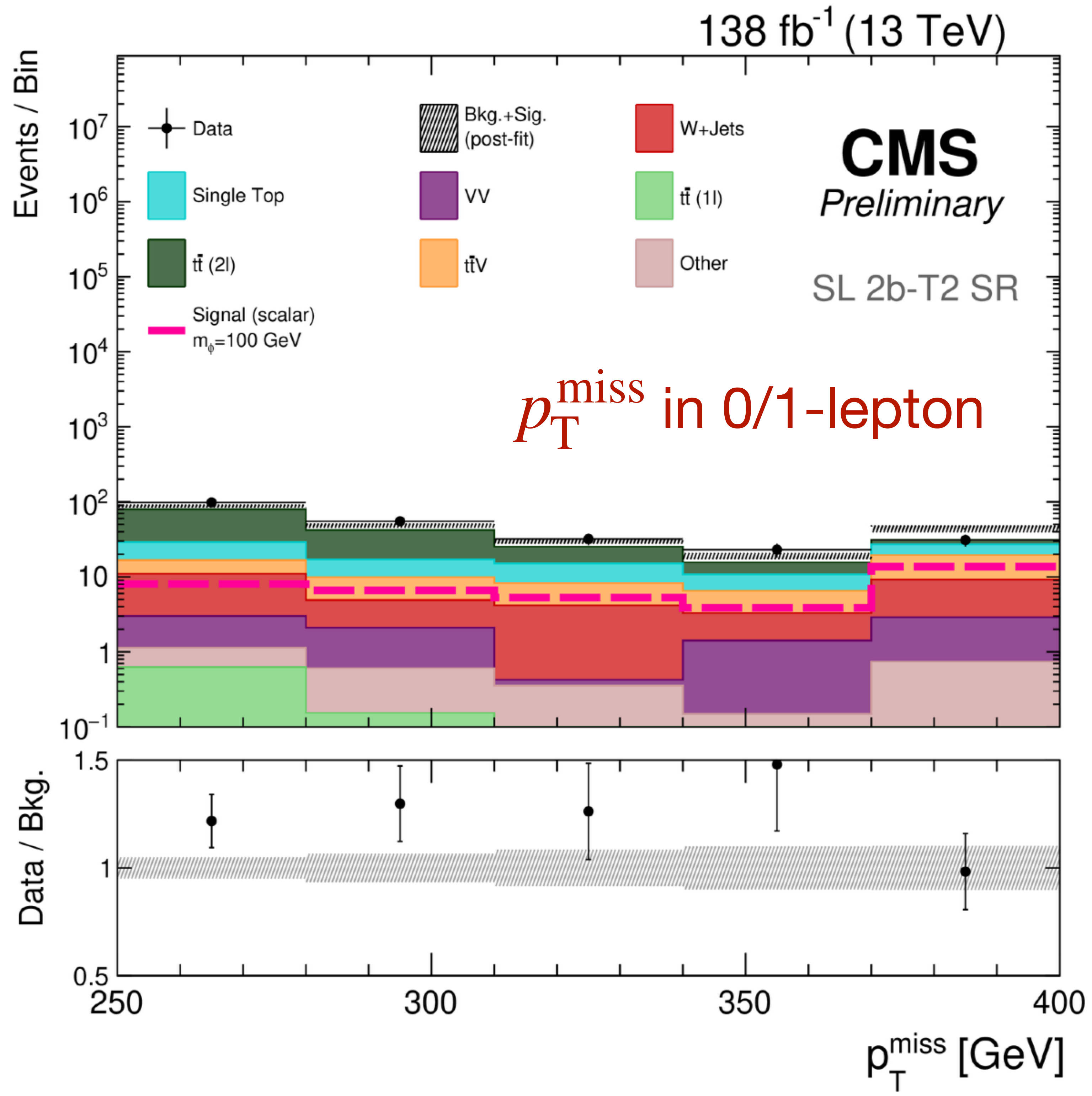
- Production of **DM from s-channel (pseudo-)scalar mediator decay** in association with **single-top** or **top-quark pair**.
- 3 separate channels: **0, 1 and 2 leptons** in final state
  - further classified into orthogonal regions based on b-tagged jet and forward jet multiplicities.
- NN employed to improve signal-background discrimination in 2-lepton channel.



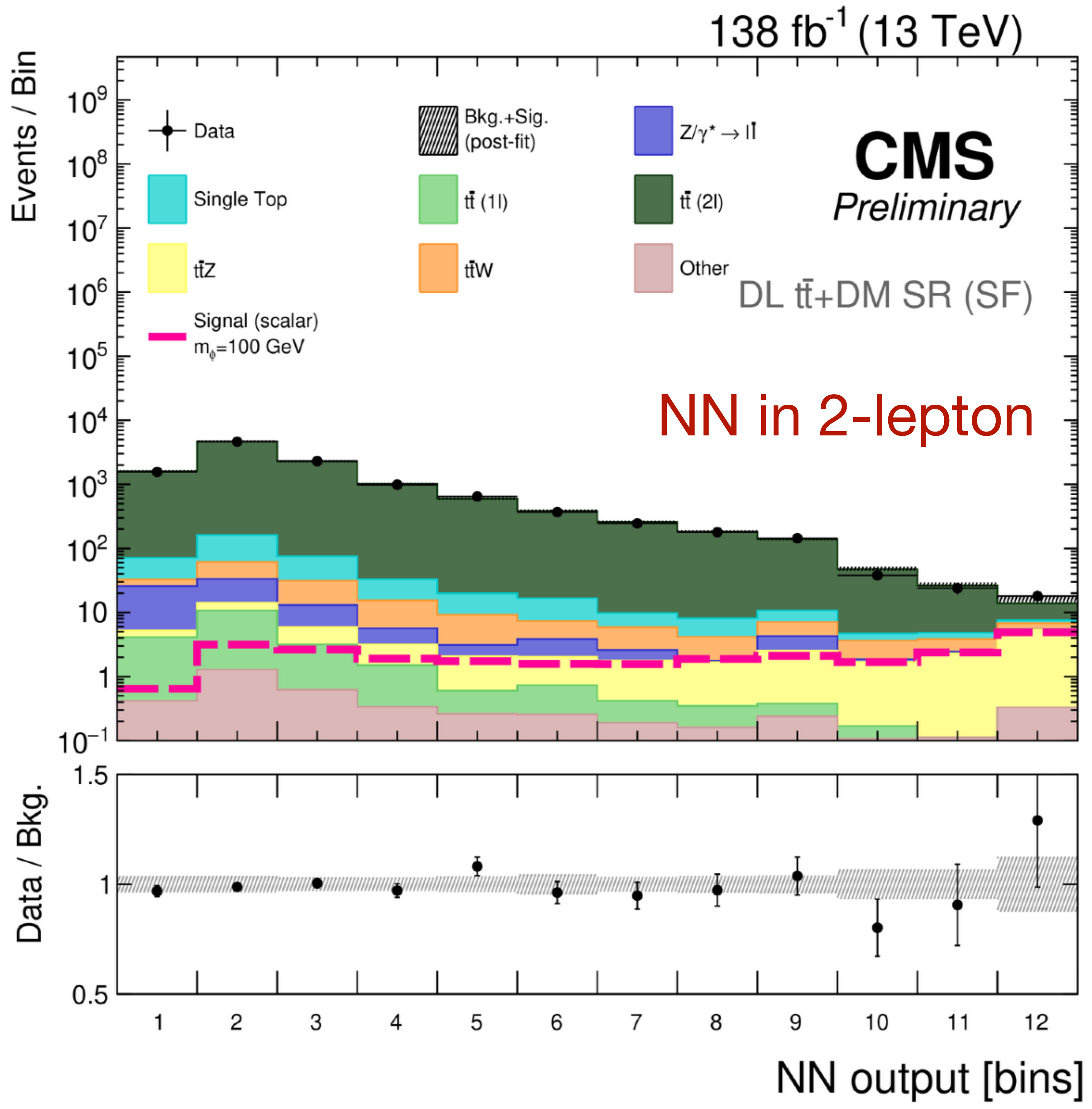
$\mathrm{DM} + t\bar{t}$



$\mathrm{DM} + t$

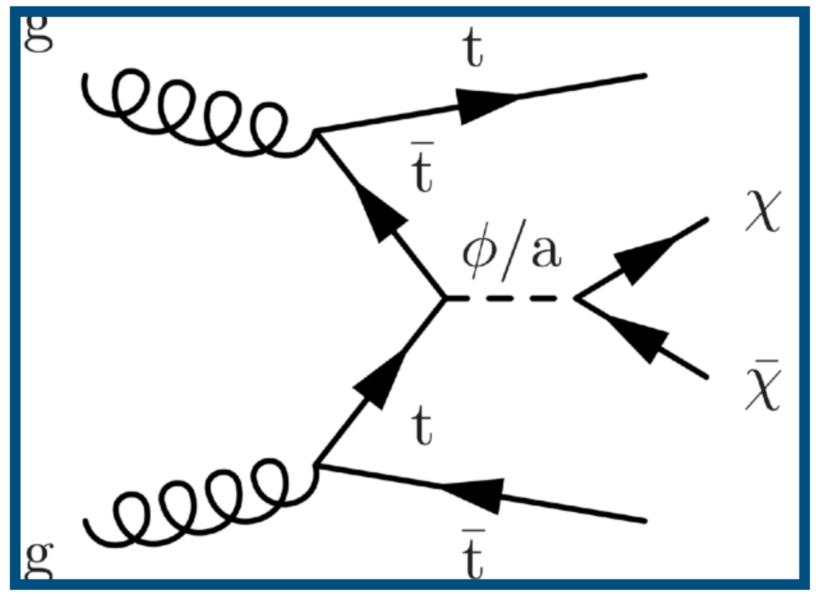


No significant deviations from SM

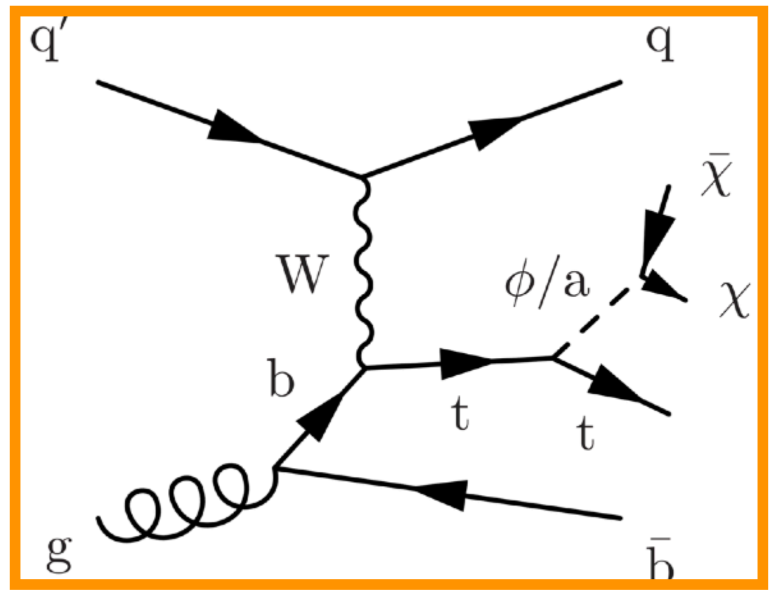


CMS $\mathrm{DM} + t\bar{t}$ and $\mathrm{DM} + t$ search CMS-PAS-EXO-22-014

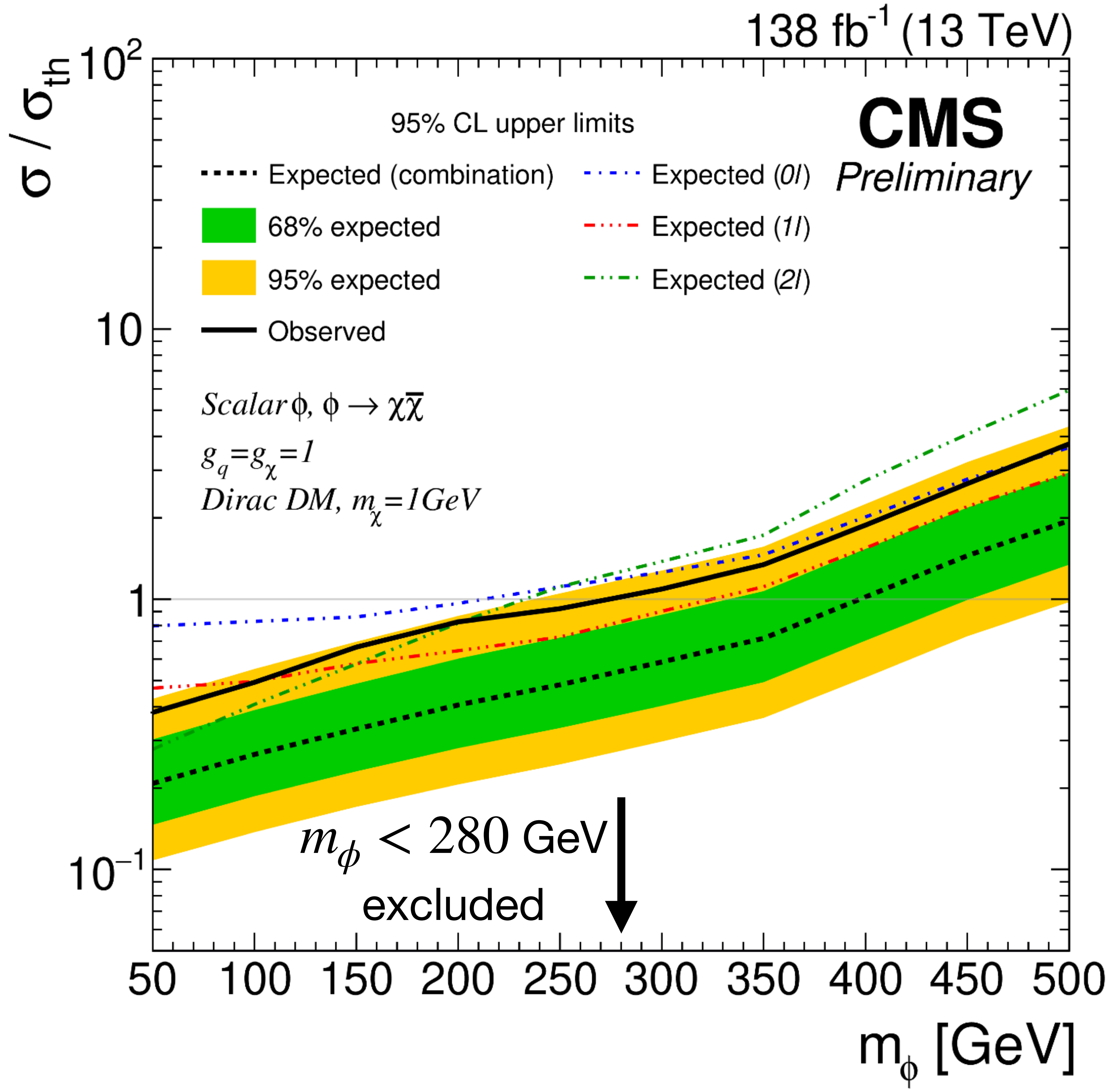
- Production of **DM from s-channel (pseudo-)scalar mediator decay** in association with **single-top** or **top-quark pair**.
- **95% CL limits derived from combination of 3 channels for sum of both** $\mathrm{DM} + t\bar{t}$ **and** $\mathrm{DM} + t$ **signals**

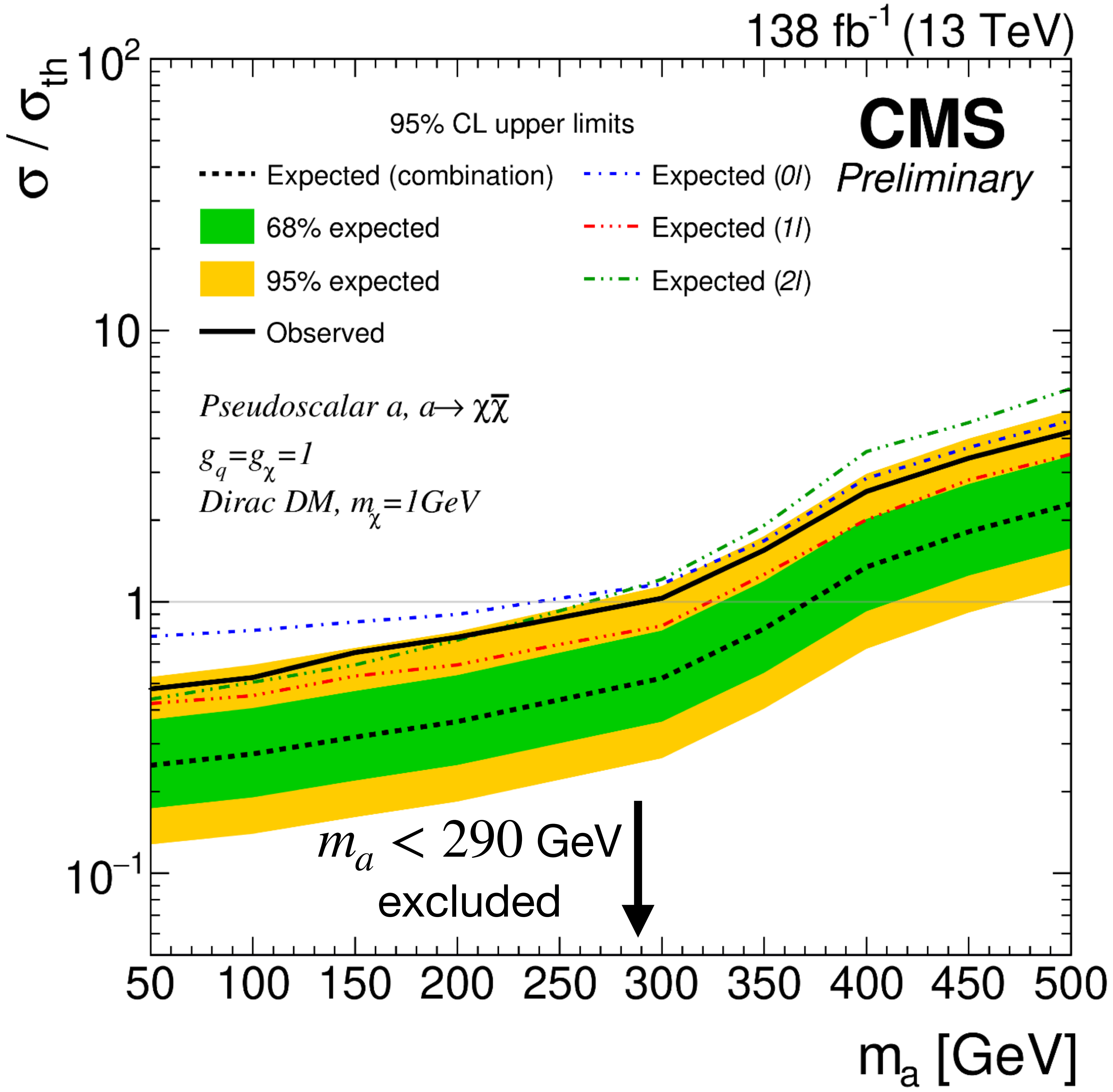


$\mathrm{DM} + t\bar{t}$

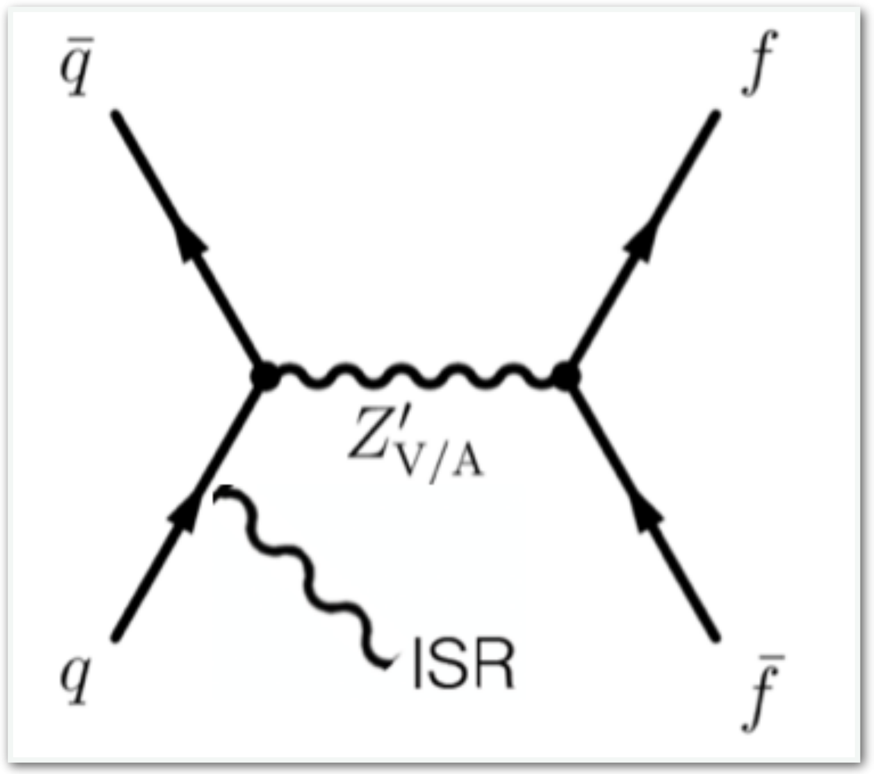


$\mathrm{DM} + t$

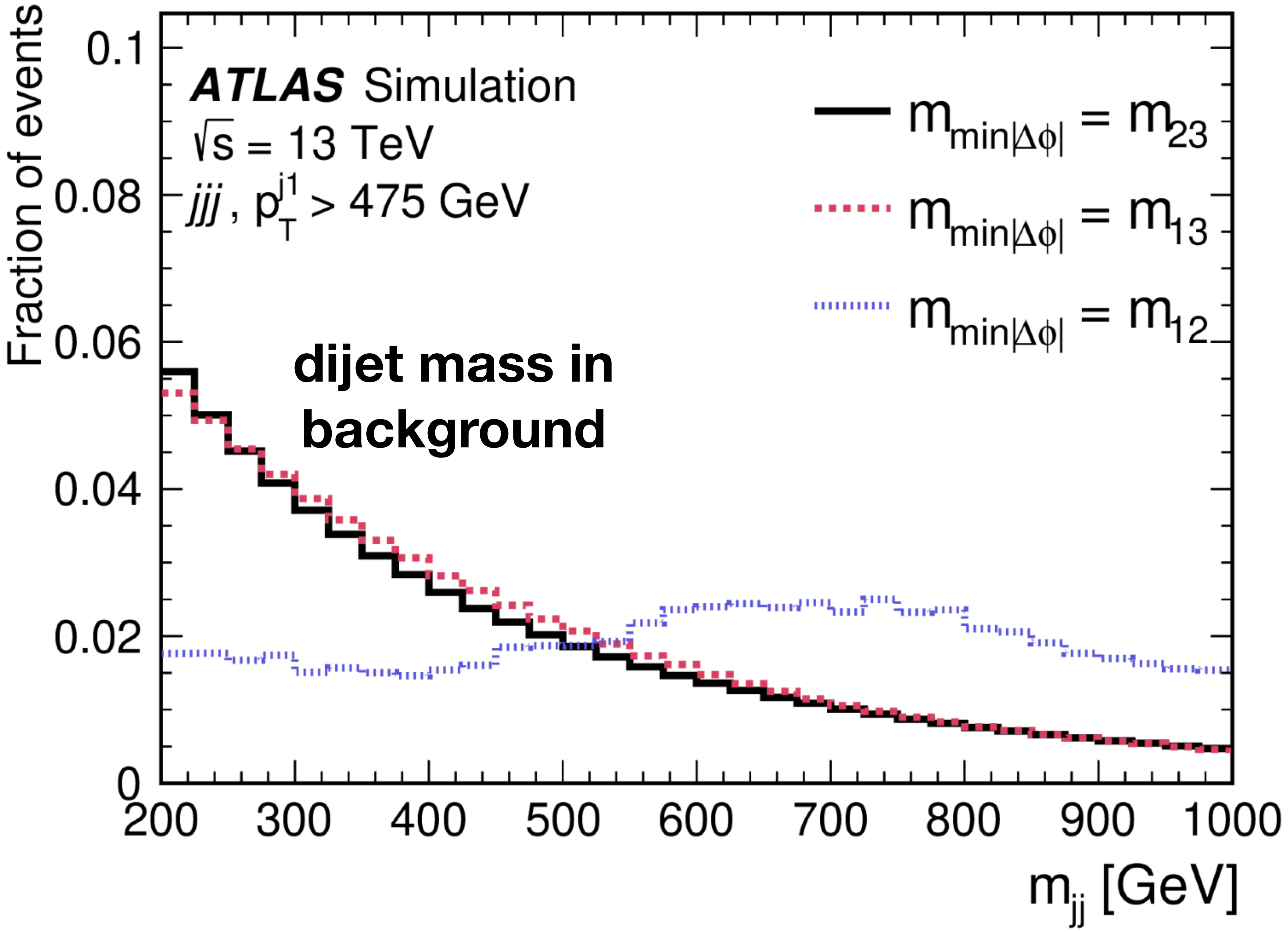




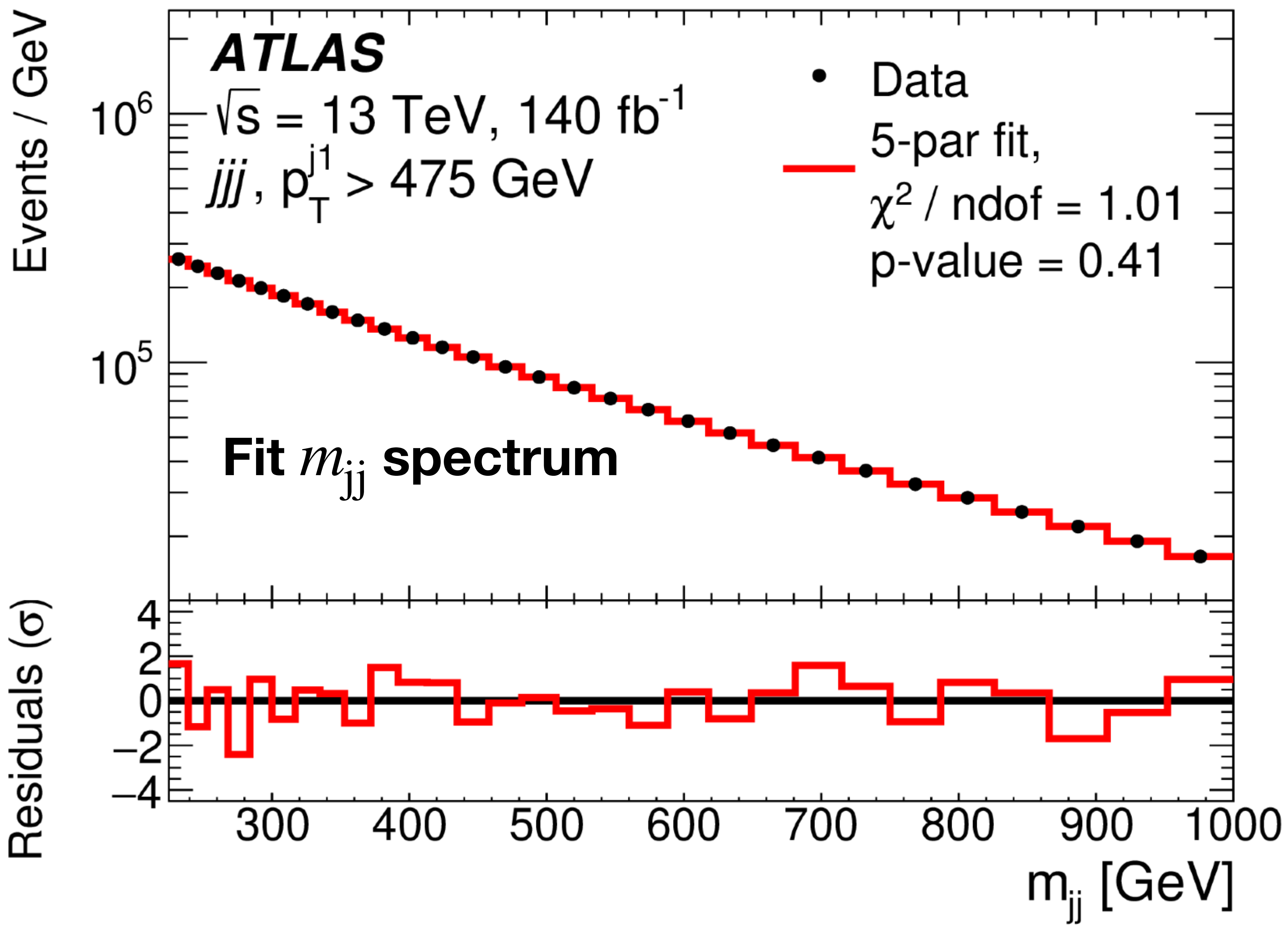
ATLAS resolved dijet + ISR search arXiv:2403.08547



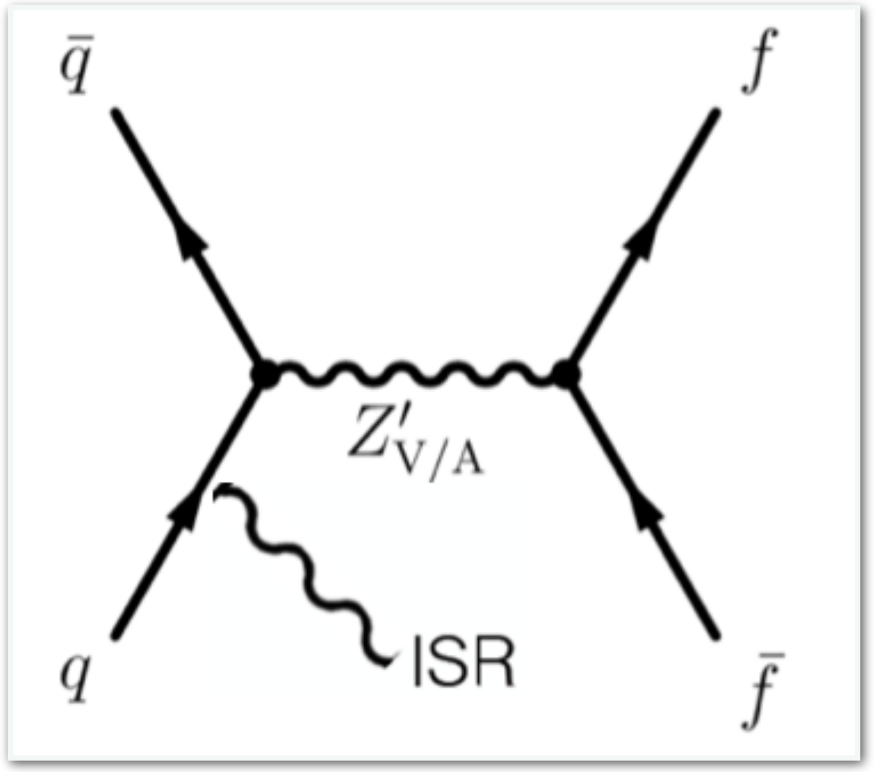
- Production of **spin-1 mediator decaying into 2 jets** recoiling against a **jet or photon from ISR**.
    - Using ISR jet or photon for trigger to overcome trigger bandwidth limitation, thus give access to low-mass dijet resonances.
- **4 event categories** including inclusive or b-tagged resolved jets: γjj, γbb, jjj, and jbb.
- For jjj and jbb channels, **non-trivial combinatorics** applied to select jet pair from mediator decay.
    - ensuring a smoothly falling m_{jj} spectrum in background.



No significant excess of BSM events



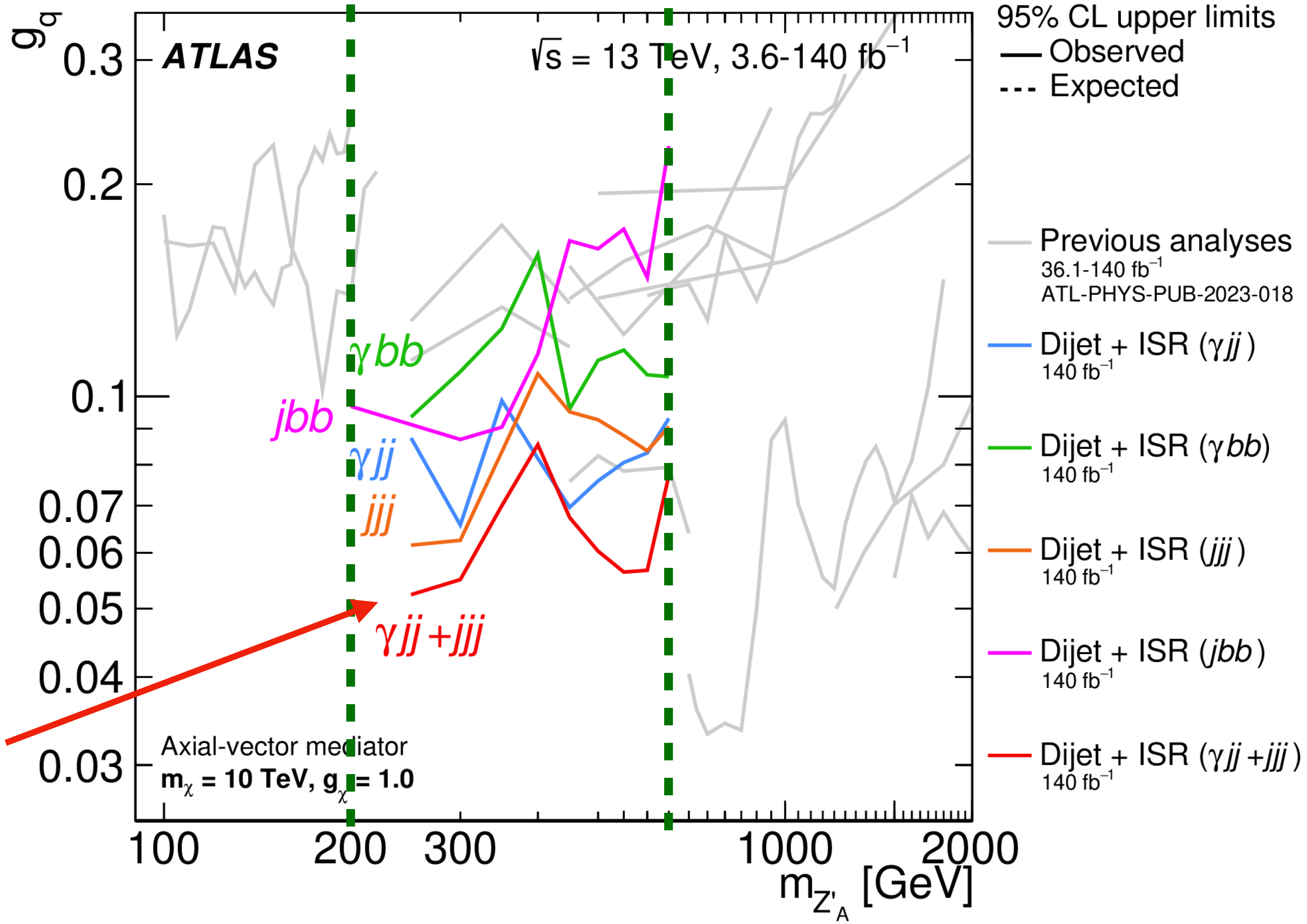
ATLAS resolved dijet + ISR search arXiv:2403.08547



- Production of **spin-1 mediator decaying into 2 jets** recoiling against a **jet or photon from ISR**.

this search set upper limits for mediator masses 200 - 650 GeV, complementary to previous analyses.

Combination of γjj and jjj improves limits on mediator-quark coupling



ATLAS Higgs Invisible Decays

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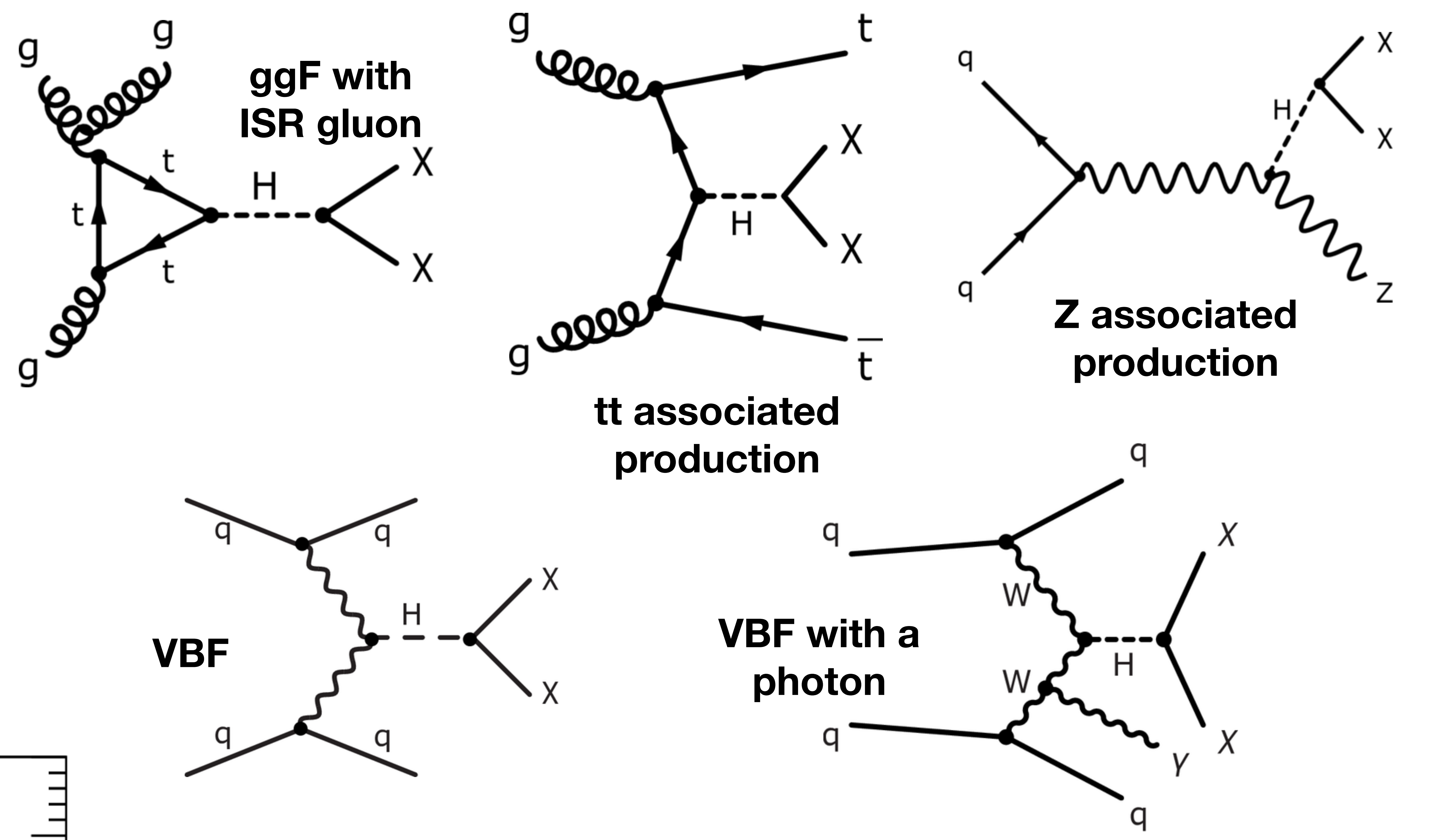
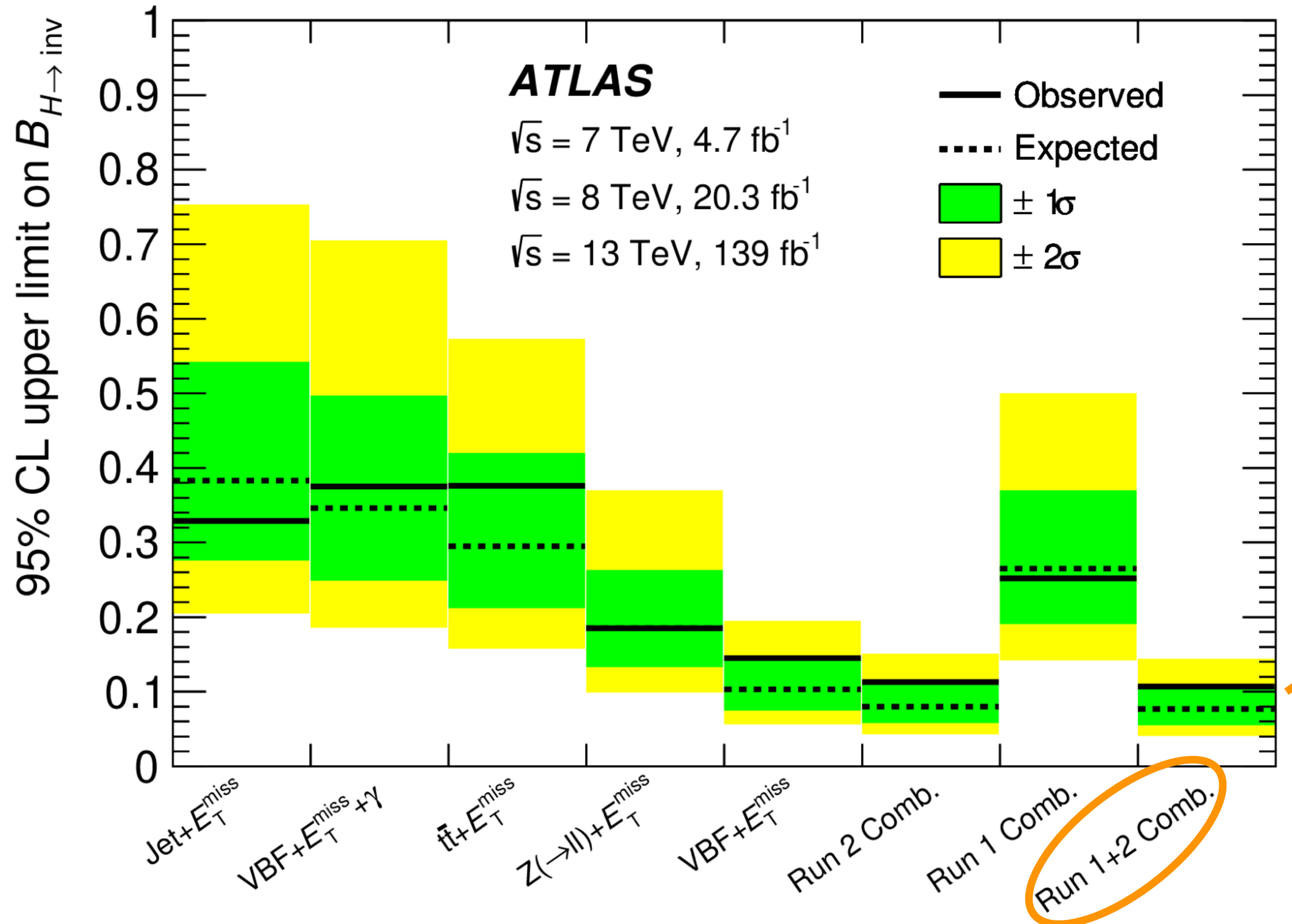


- SM Higgs boson ($m_H = 125$ GeV) can act as a portal between DM and SM via Yukawa-type couplings.
  - possible Higgs decay into a pair of invisible DM, resulting in a larger $\mathrm{BR}(H \to \mathrm{inv})$ wrt SM prediction (0.12%).
  - can be searched with $E_{\mathrm{T}}^{\mathrm{miss}} + X$ signatures in different Higgs production modes.



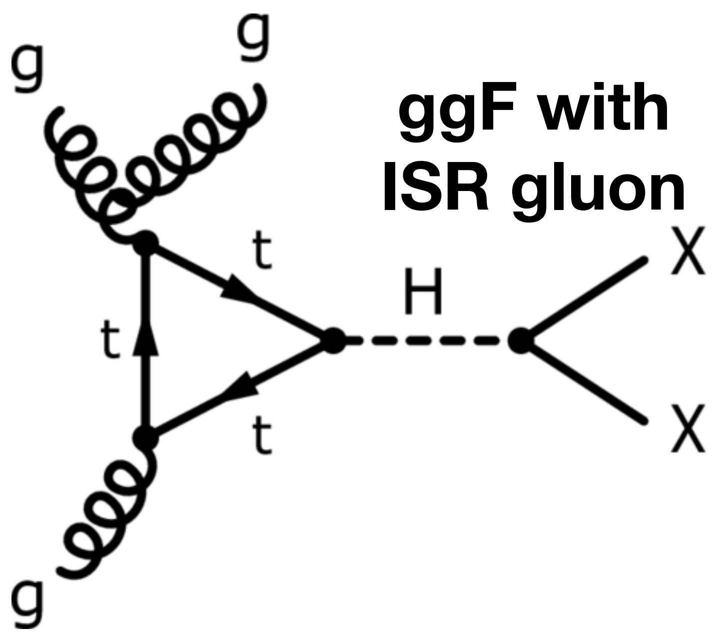
Stat. Combination of Run-1 and Run-2 results set **observed (expected)** limit on $\mathrm{BR}(H \to \mathrm{inv})$: **10.7% (7.7%)**

Most stringent limit at the LHC so far!

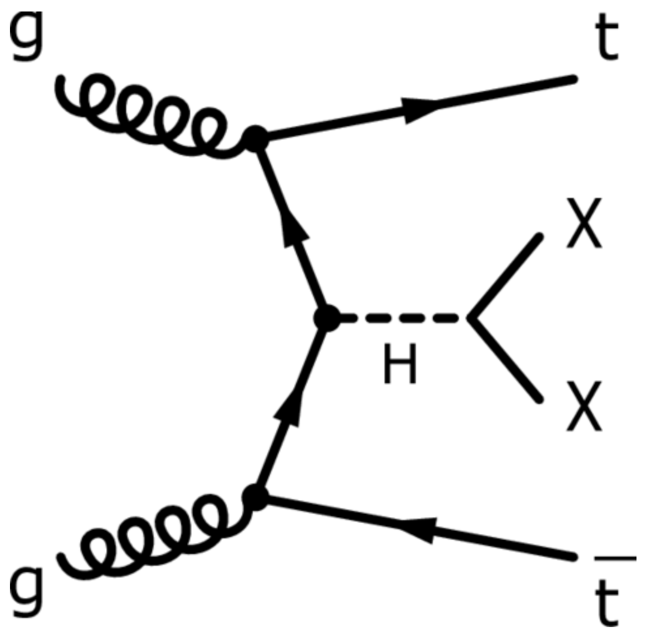
ATLAS Higgs Invisible Decays

[PLB 842 (2023) 137963](https://doi.org/10.1016/j.physletb.2023.137963)

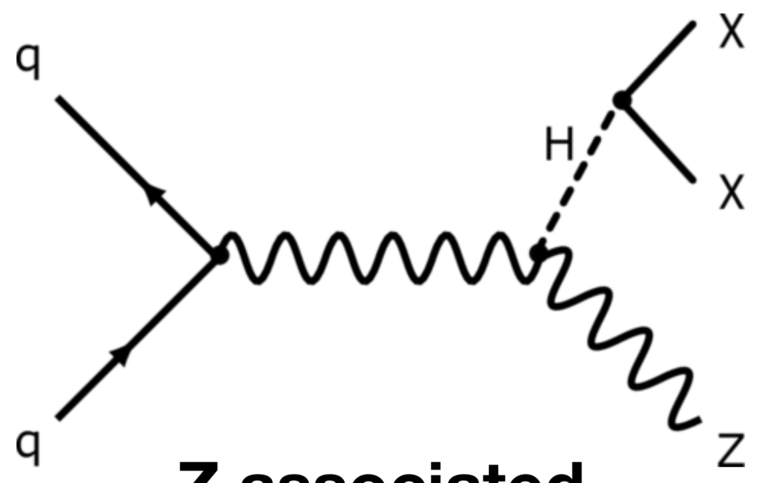
- SM Higgs boson ($m_H = 125$ GeV) can act as a portal between DM and SM via Yukawa-type couplings.



ggF with ISR gluon

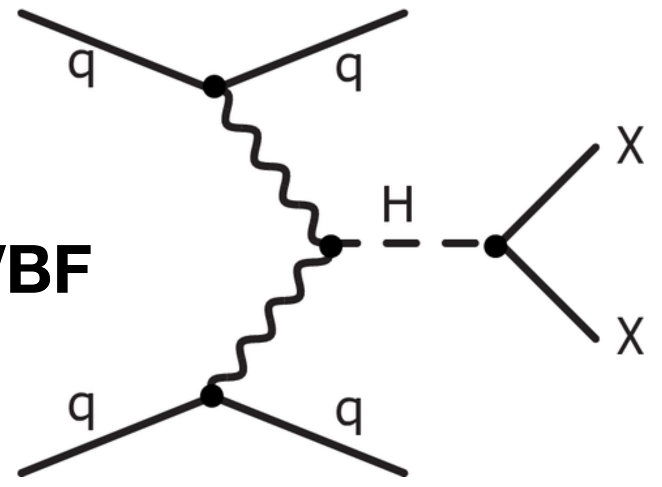


tt associated production

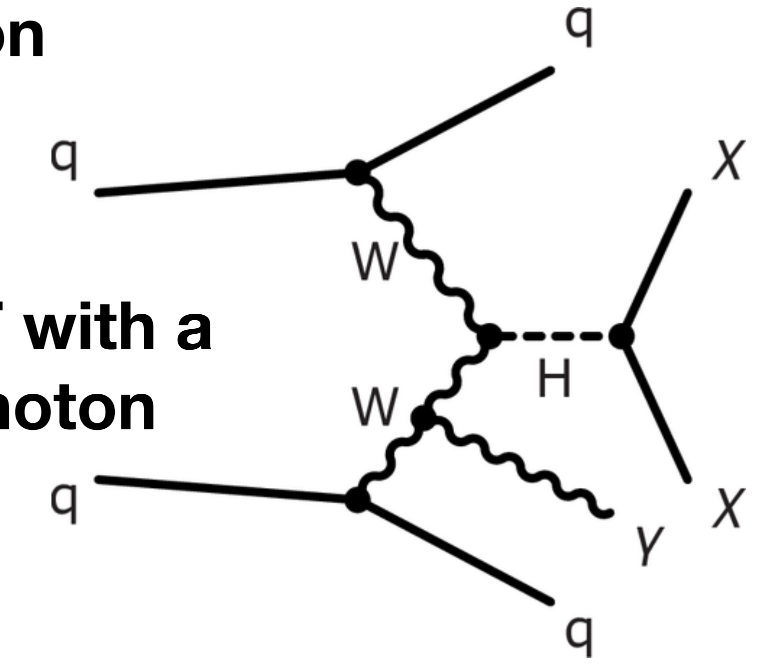


Z associated production

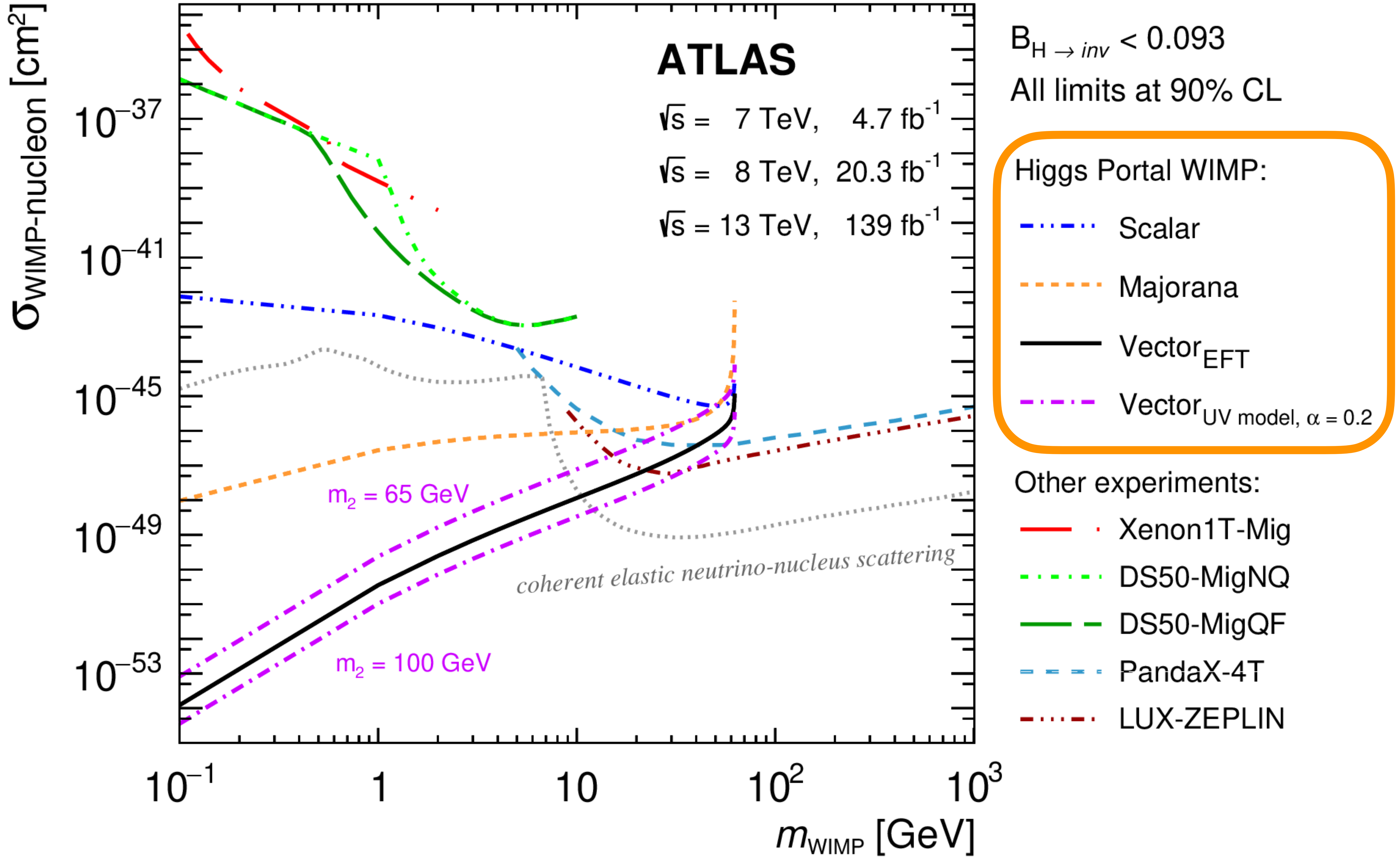
VBF



VBF with a photon



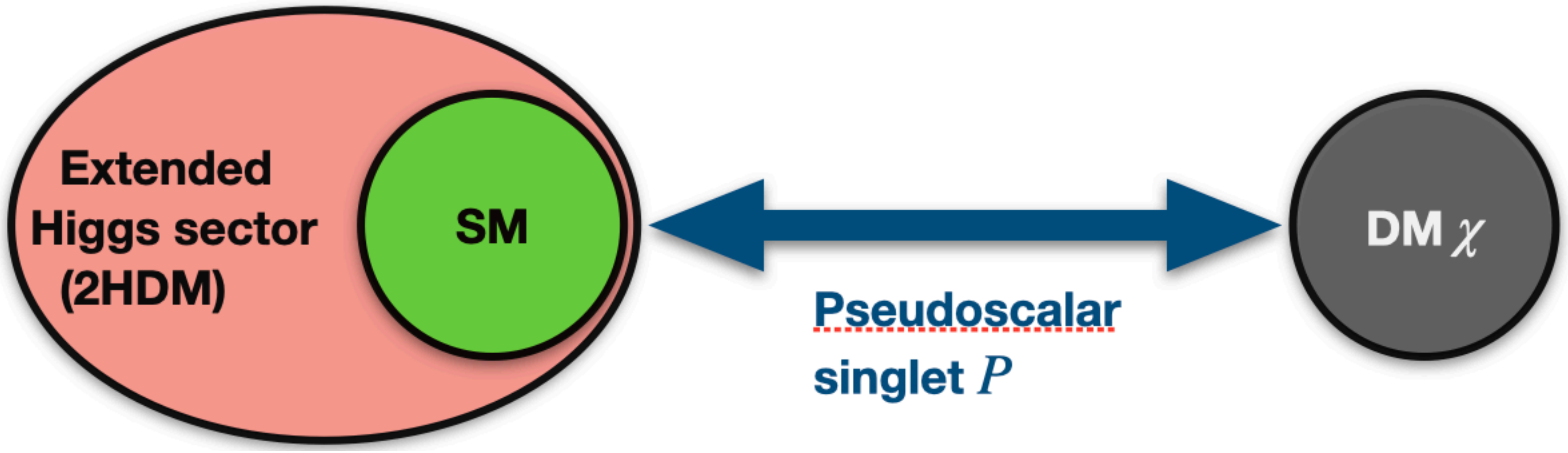
comparison with DD experiments



translated to upper limits on WIMP-nucleon scattering cross-section for Higgs portal models

Complementarity between LHC DM searches and DD experiments.

Two-Higgs-Doublet-Model + pseudo-scalar mediator (2HDM+a) [LHC Dark Matter Working Group](#) [JHEP05 (2017) 138](#)



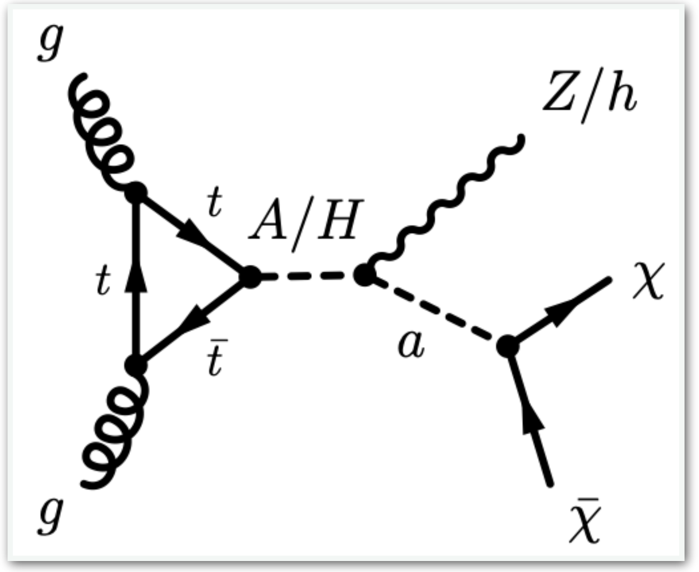
- Scalars: h, H,
- Pseudoscalar: A,
- Charged Higgs: H±

\+ Pseudoscalar: a + Dirac DM χ

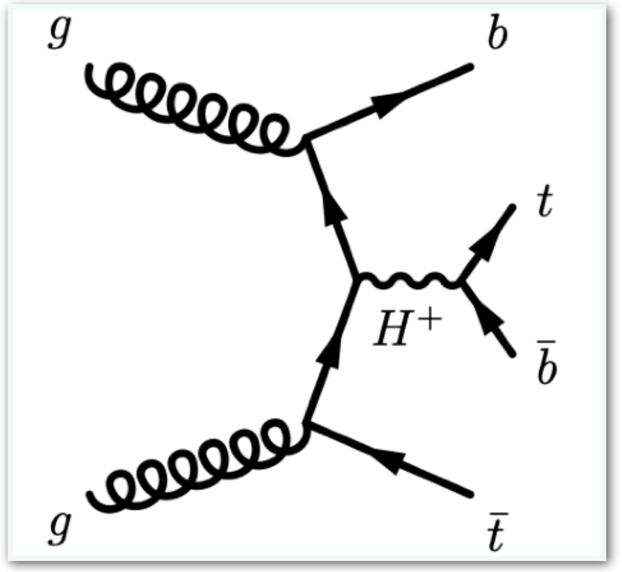
- Minimal, UV-complete extension of pseudo-scalar simplified models.
- Fully defined by 14 parameters but reduced to **5 unconstrained parameters.**

$m_A = m_H = m_{H^\pm}$	**masses of additional heavy Higgs**
m_a	**mass of pseudo-scalar mediator**
m_χ	**DM mass**
$\sin\theta$	**mixing angle between the pseudo-scalars**
$\tan\beta$	**ratio of 2 Higgs doublet VEVs**

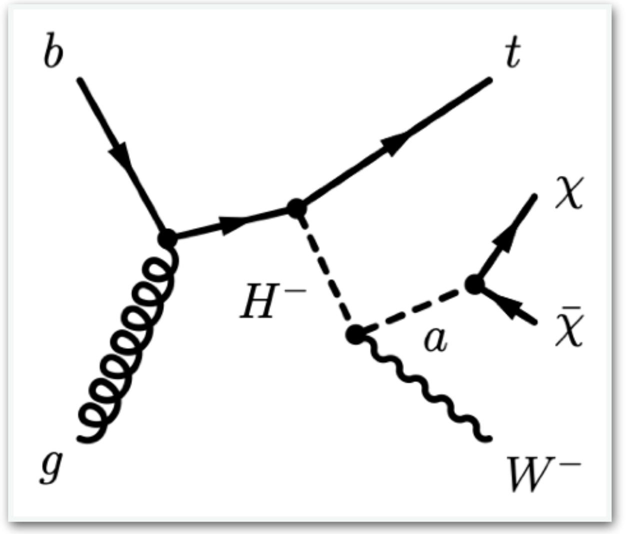
- 2HDM+a is complicated **BUT more theoretically complete,** predicting broader range of collider signatures wrt common simplified models.



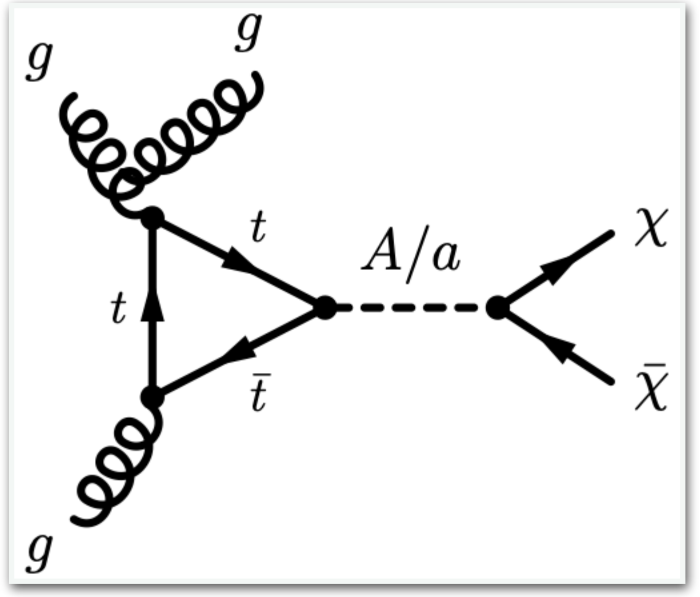
$E_T^{miss} + Z/h$



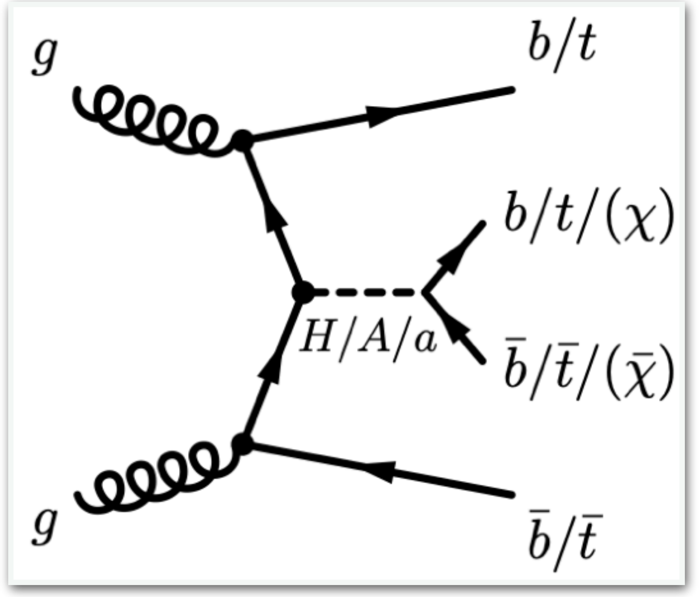
$tbH^\pm(tb)$



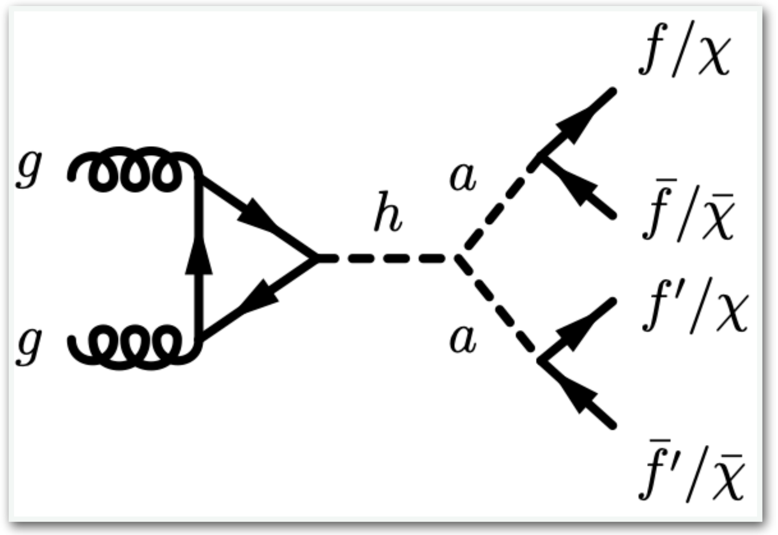
$E_T^{miss} + tW$



E_T^{miss} + jet



$t\bar{t}t\bar{t}$



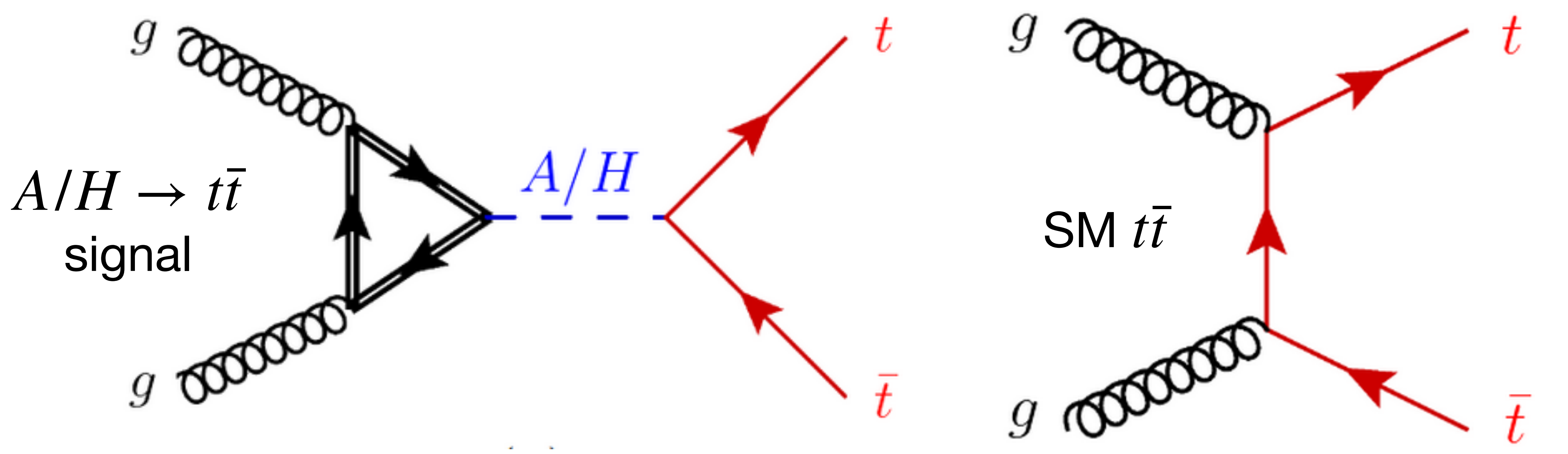
$h \to aa \to 4f$ or $h \to$ inv

Two-Higgs-Doublet-Model + pseudo-scalar mediator (2HDM+a)

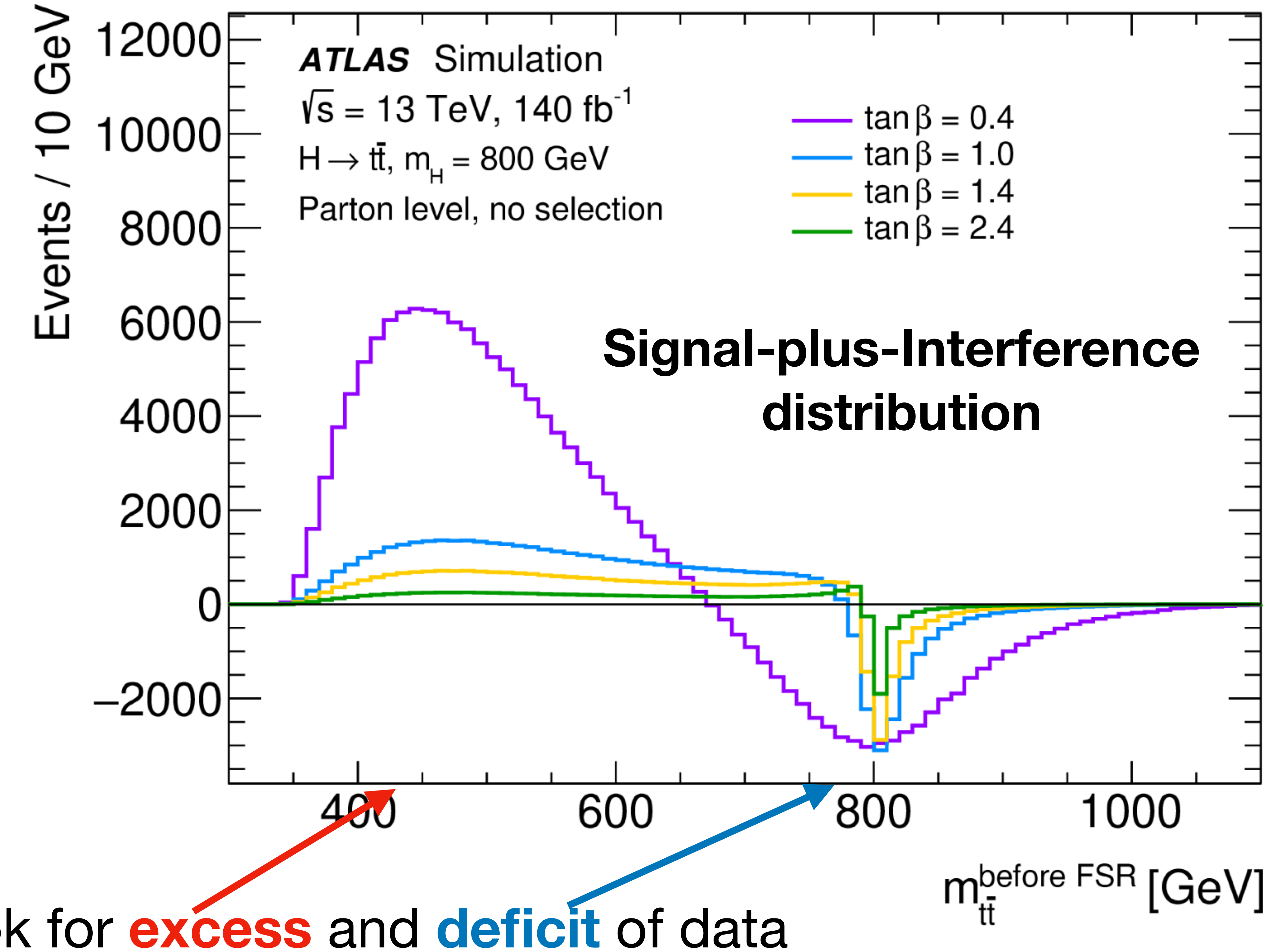
- **Recent results highlighted in this talk**:
    - ATLAS $A/H \to t\bar{t}$ search **arXiv:2404.18986**
    - CMS *nonresonant* $bb + E_{\mathrm{T}}^{\mathrm{miss}}$ search **CMS PAS SUS-23-008**

- **NOT in today talk but interesting to consider**:
    - ATLAS 2HDM+a DM combination and summary (***backup***) **arXiv:2306.00641**
    - ATLAS heavy resonance search with final states 4l + $E_{\mathrm{T}}^{\mathrm{miss}}$ (in 2HDM + scalar mediator) **arXiv:2401.04742**

ATLAS $A/H \to t\bar{t}$ search arXiv:2404.18986

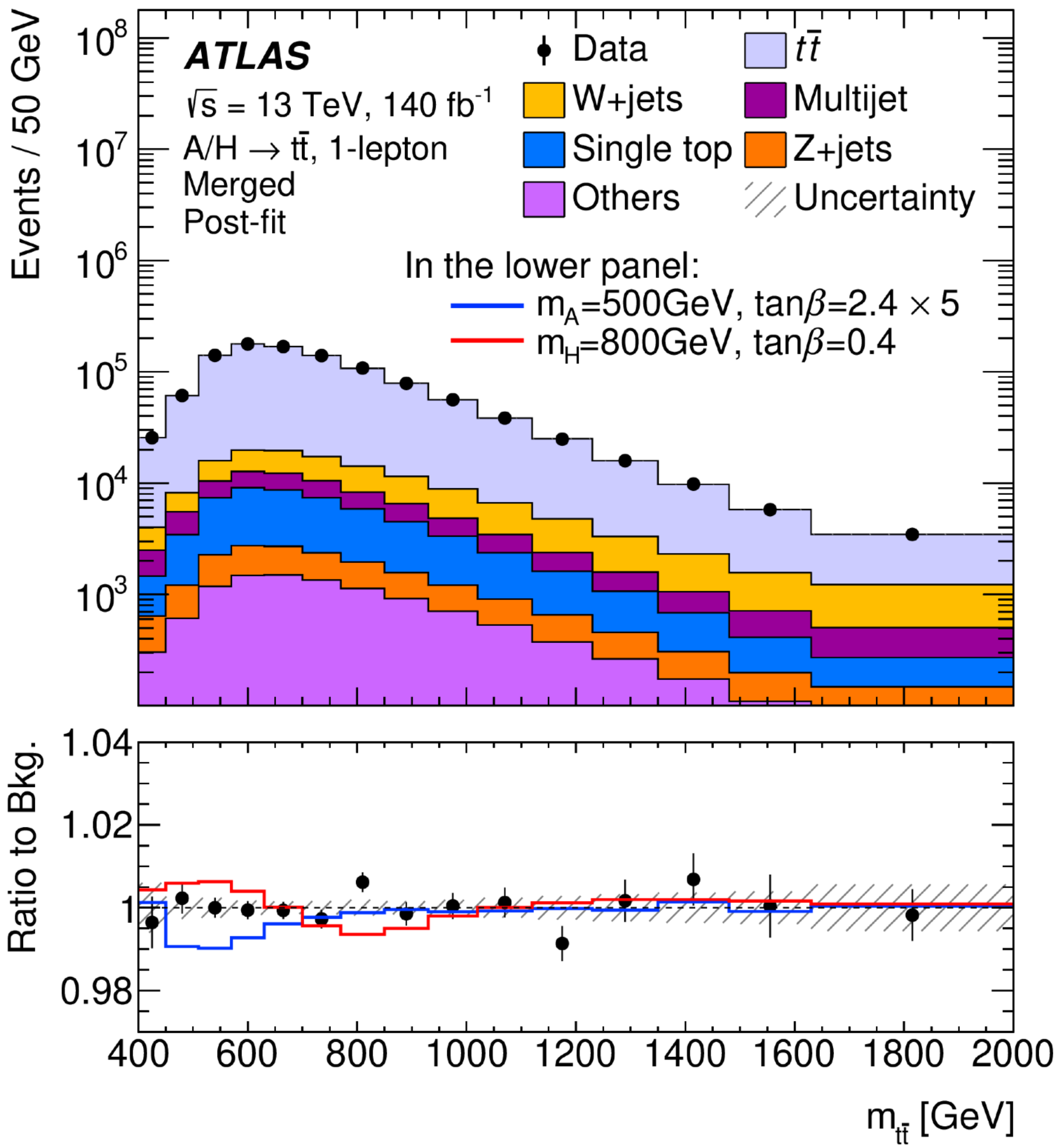


- Search for neutral, massive scalar or pseudo-scalar states of 2HDM+a decaying into a top quark pair.
  - **significant interference with SM $t\bar{t}$ production taken into account.**
- **1-lepton channel**: events split into 2 categories targeting **merged** and **resolved hadronic top quark decays.**
- **2-lepton channel**: split into ee, $\mu\mu$, and $e\mu$ with opposite-sign electric charge.



look for **excess** and **deficit** of data events compared to SM expectation.

No significant deviation from SM



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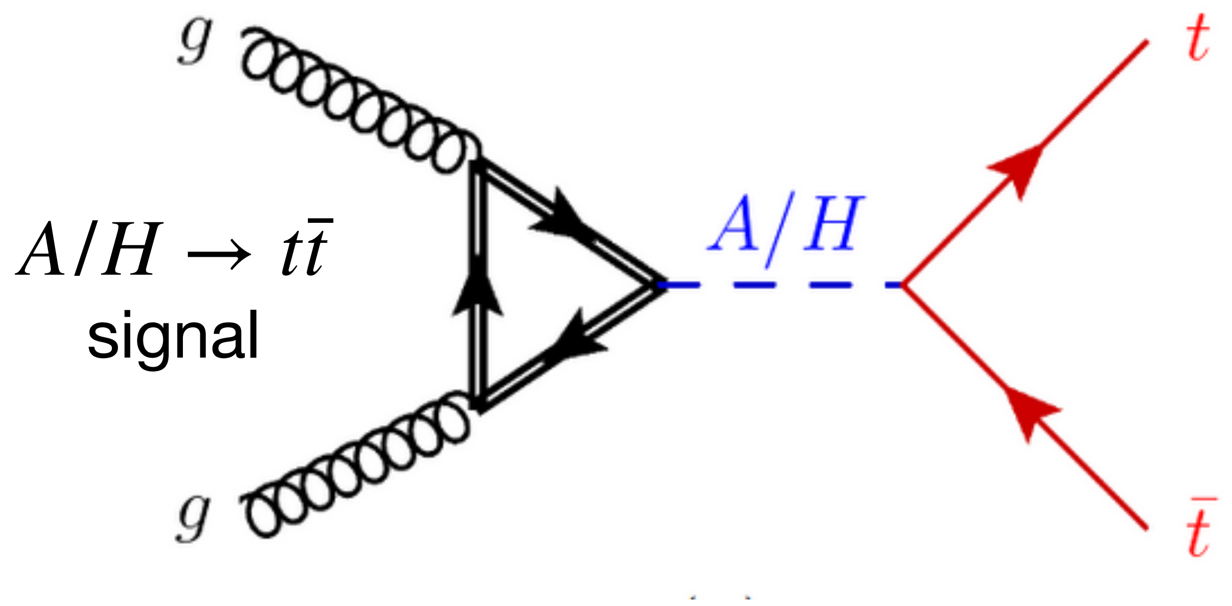
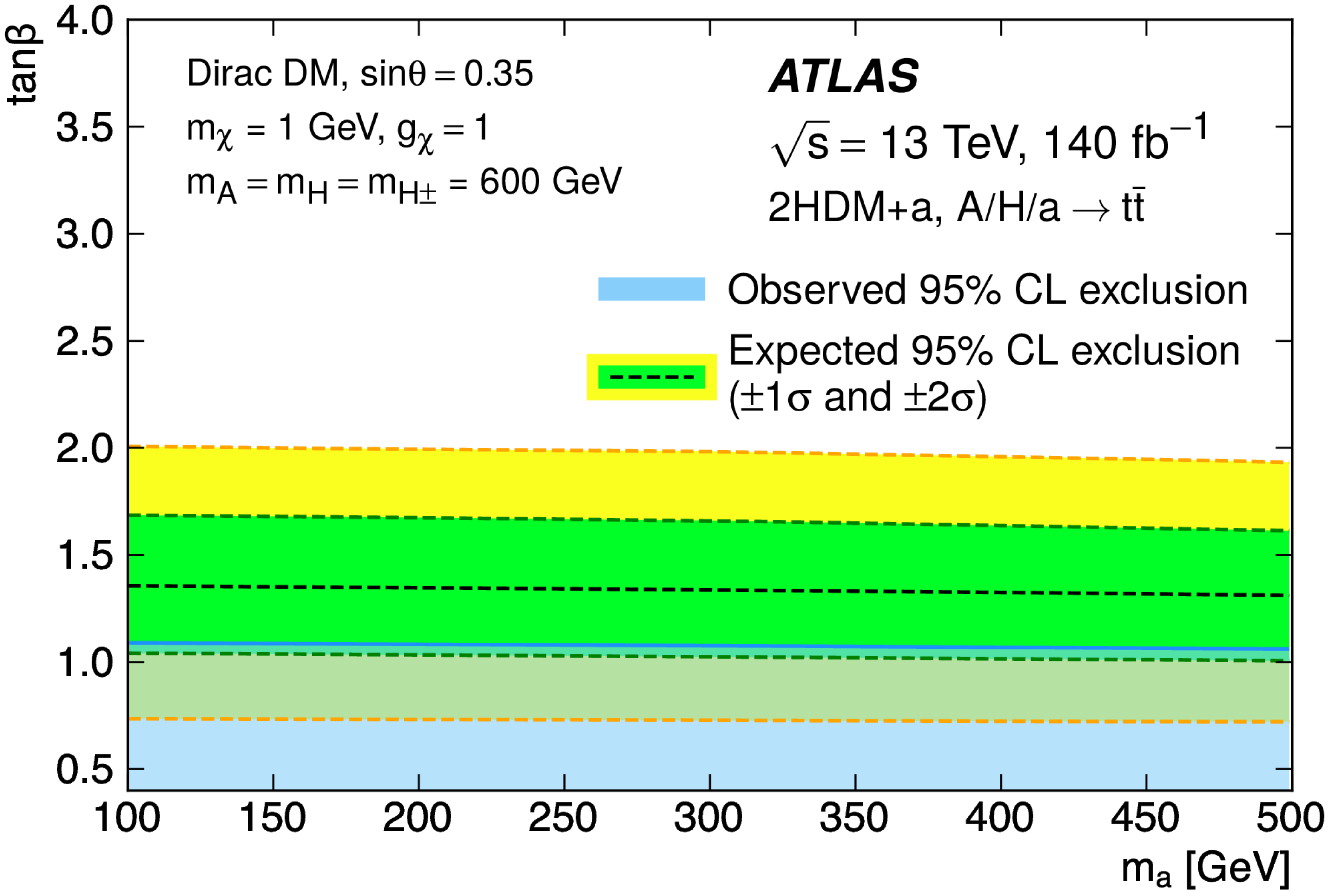
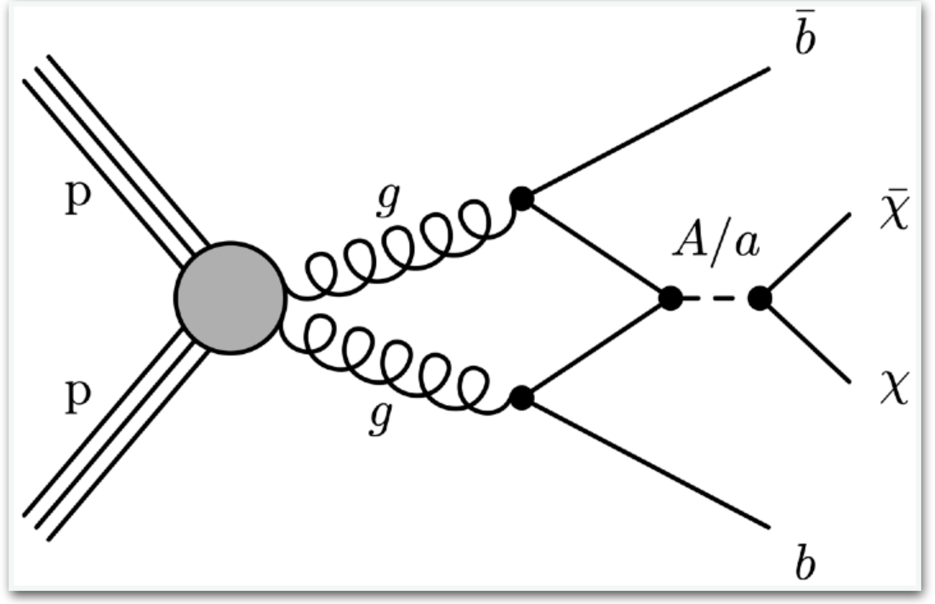


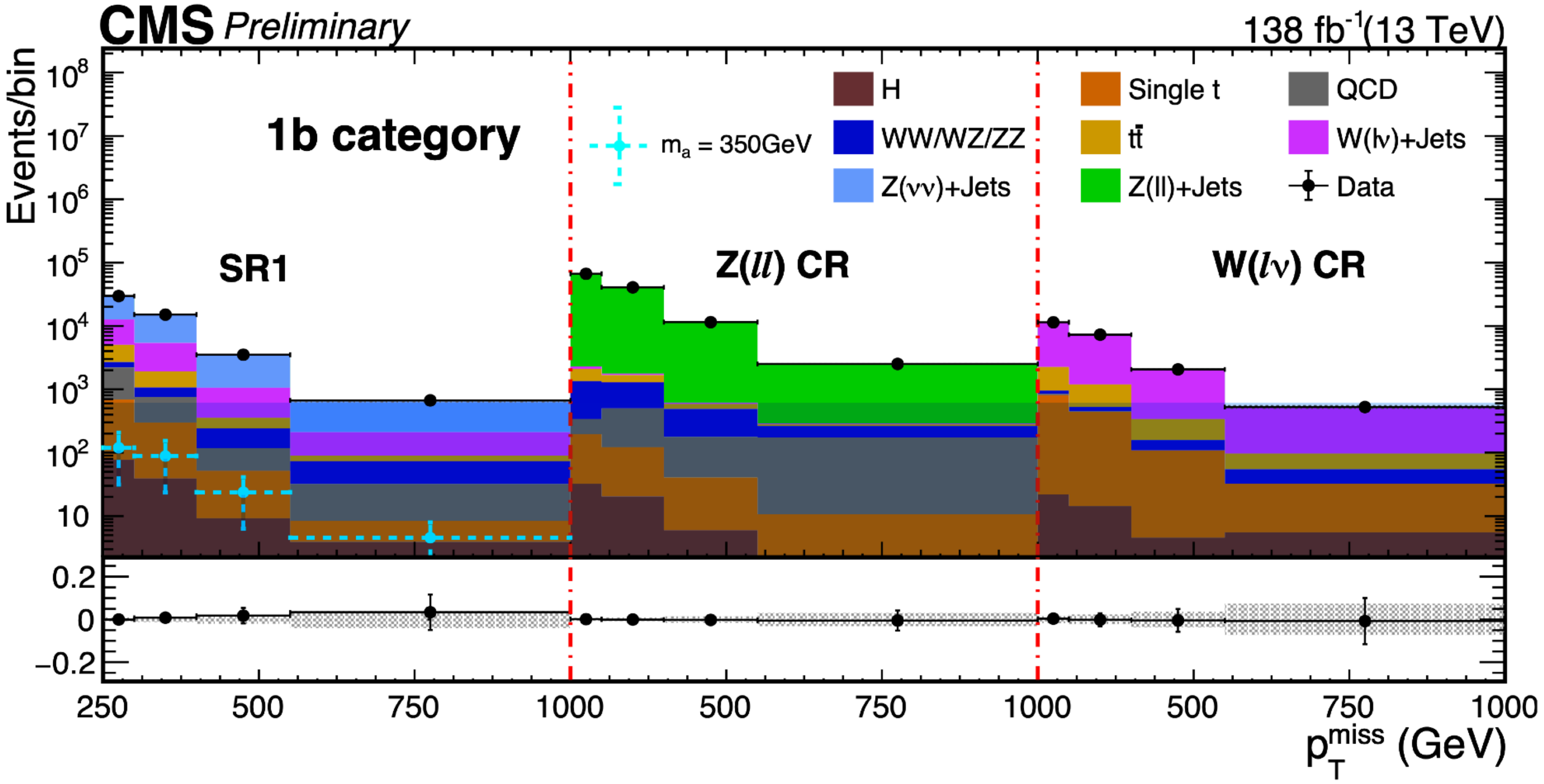


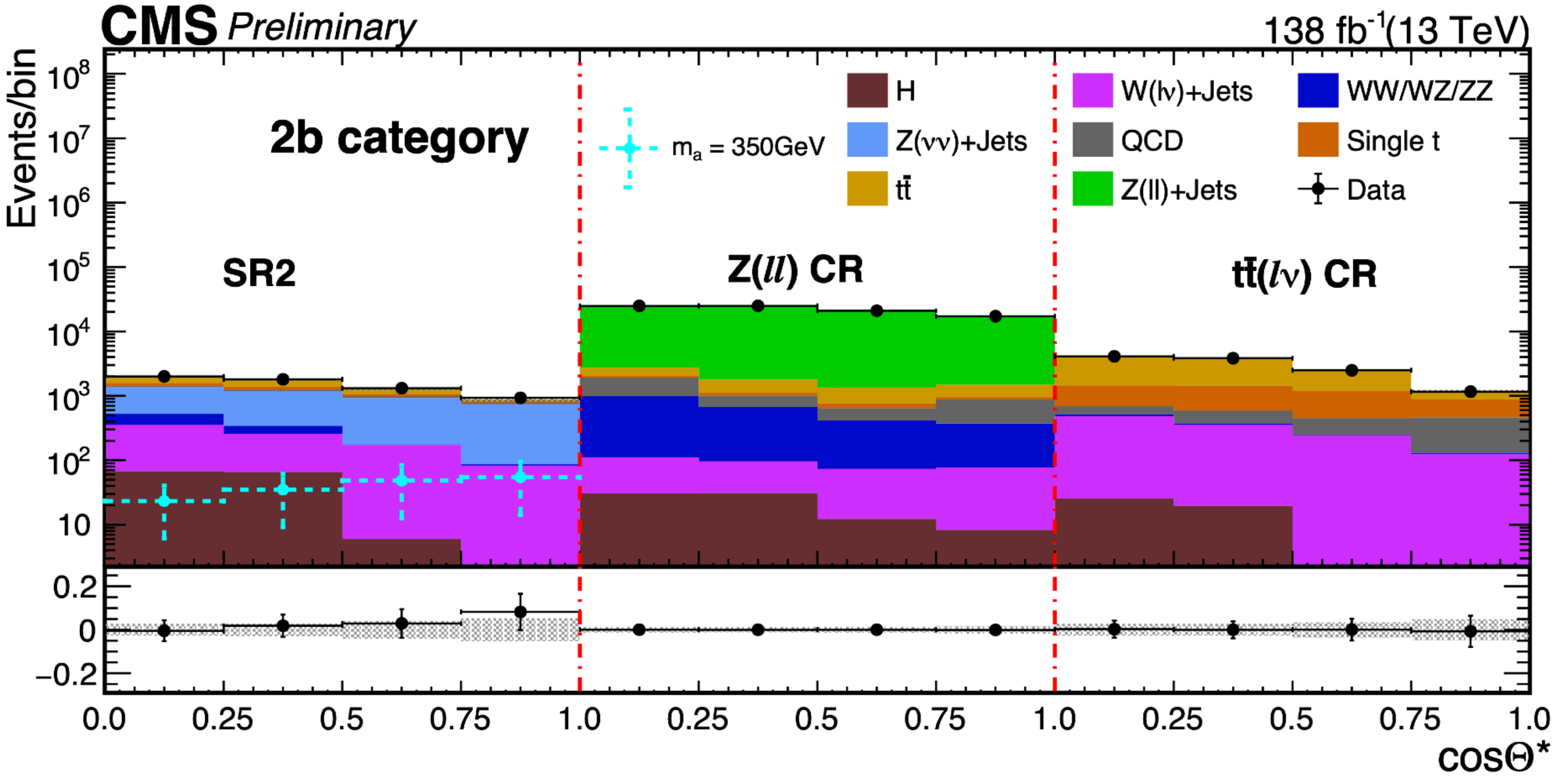
$\tan\beta \lesssim 2.0$ excluded for whole mediator mass range of [100, 500] GeV

CMS *nonresonant* $bb + E_T^{miss}$ search [CMS PAS SUS-23-008]



- The **first search at LHC** to probe DM produced in association with **2 nonresonant b-quarks** in 2HDM+a.
- Events classified into **2 categories**: **1 or 2 b-tagged jets**.
- Compare E_T^{miss} measurement between Particle-Flow and Calorimeter-only to reduce QCD multijet background.



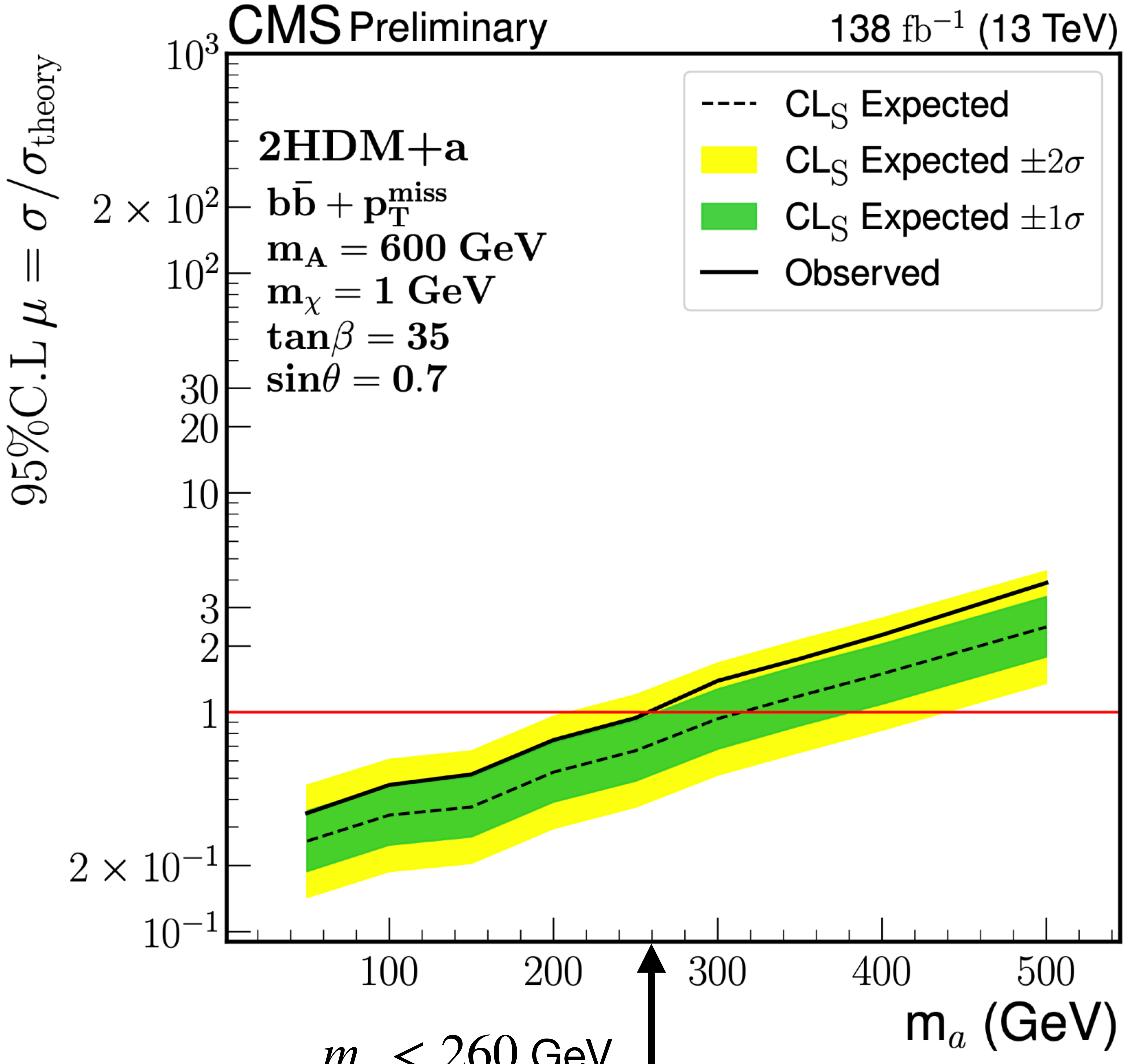


No significant deviation from SM

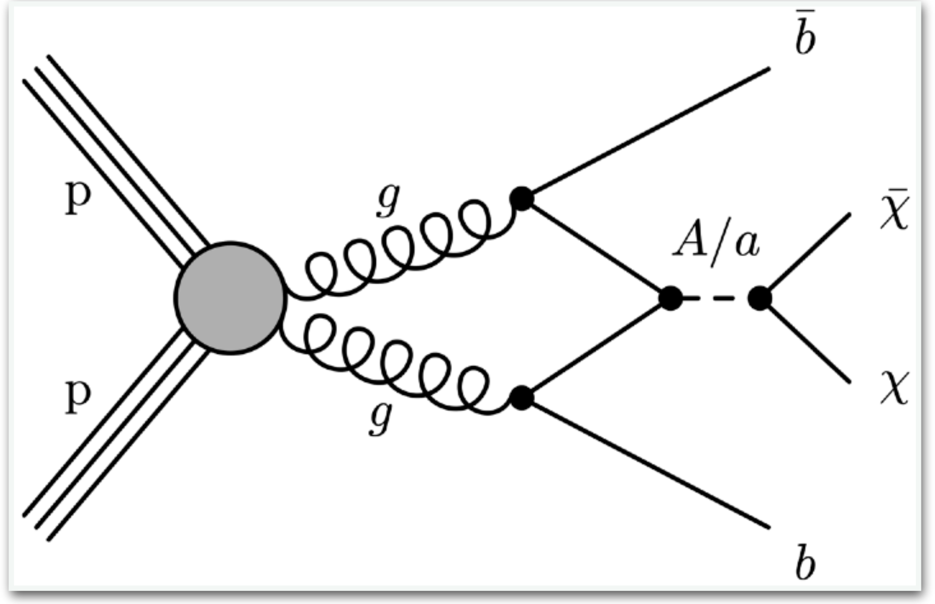
$$\cos\Theta^* = \left|\tanh\left(\frac{\eta_1 - \eta_2}{2}\right)\right|$$

CMS *nonresonant* $bb + E_T^{\text{miss}}$ search [CMS PAS SUS-23-008]

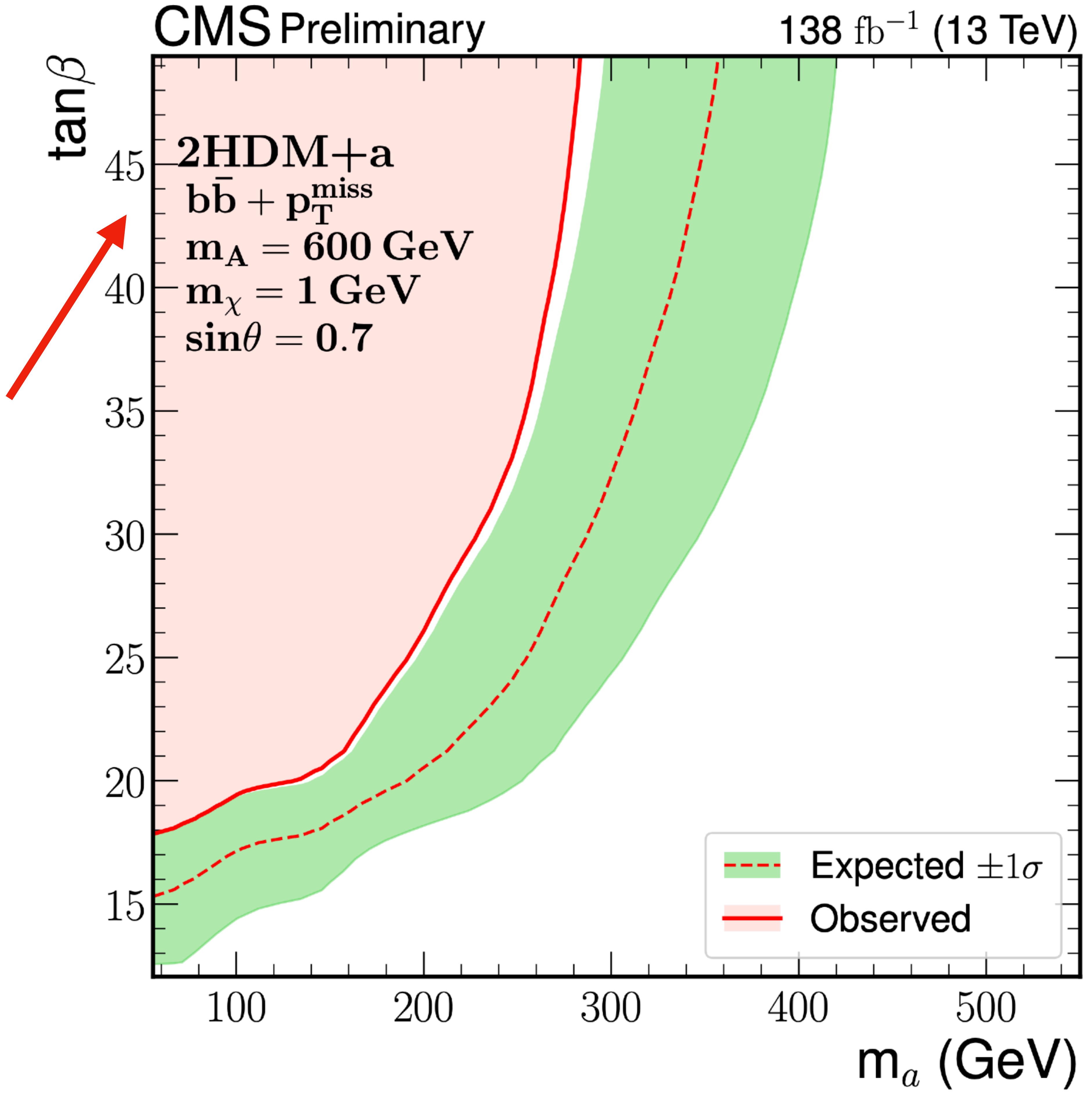
- The **first search at LHC** to probe DM produced in association with **2 nonresonant b-quarks** in 2HDM+a.



$m_a < 260$ GeV excluded



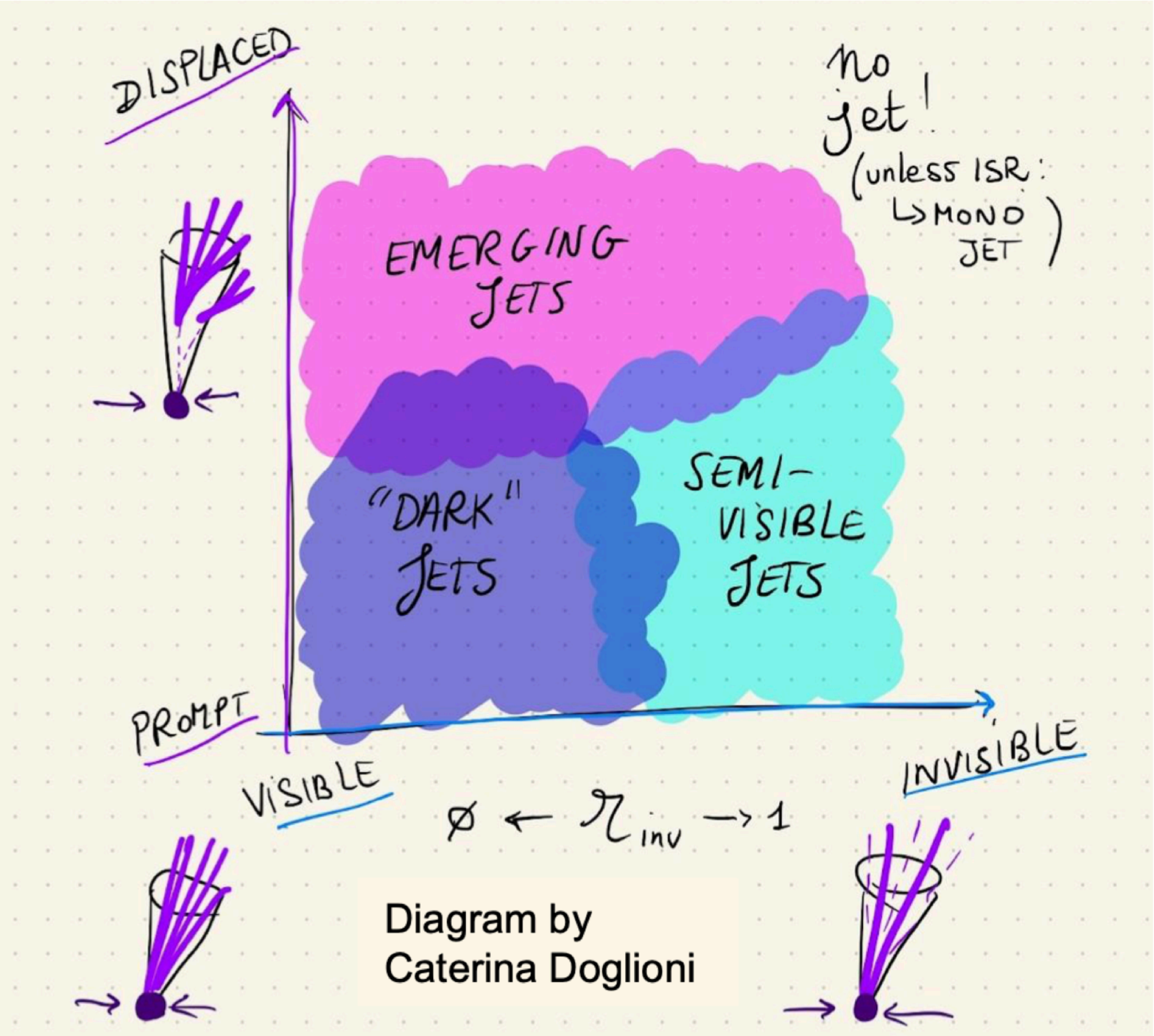
More sensitive at high-tan β region

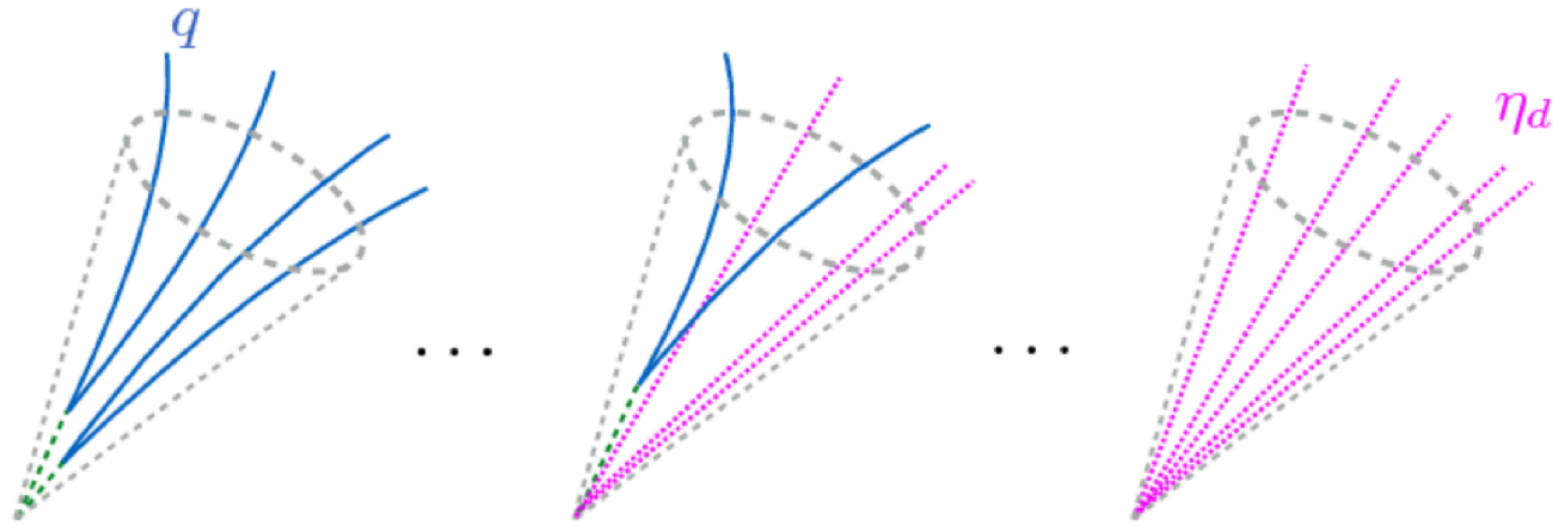


Dark Sector

- DM and mediator are ***part of in [a Hidden Dark Sector]*** which consists of particles not undergoing SM gauge interactions.
  - DS particles and mediators can be **light and long-lived**.
  - can **(very weakly) interact with SM sector** via mediators, which could be DM candidate OR provide portals encoded in a mixing term of the Lagrangian.
- Possible to have ***strongly interacting dark sectors*** with new *SU(N)*
  - *Dark quarks form bound dark hadron states*
  - Stable dark hadrons can be DM candidates.
  - Unstable dark hadrons can decay into SM quarks, others escape the detector without any interactions ⟶ dark or semi-visible jets.
- **Wide variety of unusual collider signatures to explore!**

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2)H^\dagger H$
Axion, a	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N LHN$





η_{inv} fraction of energy carried by invisible (DM) particles

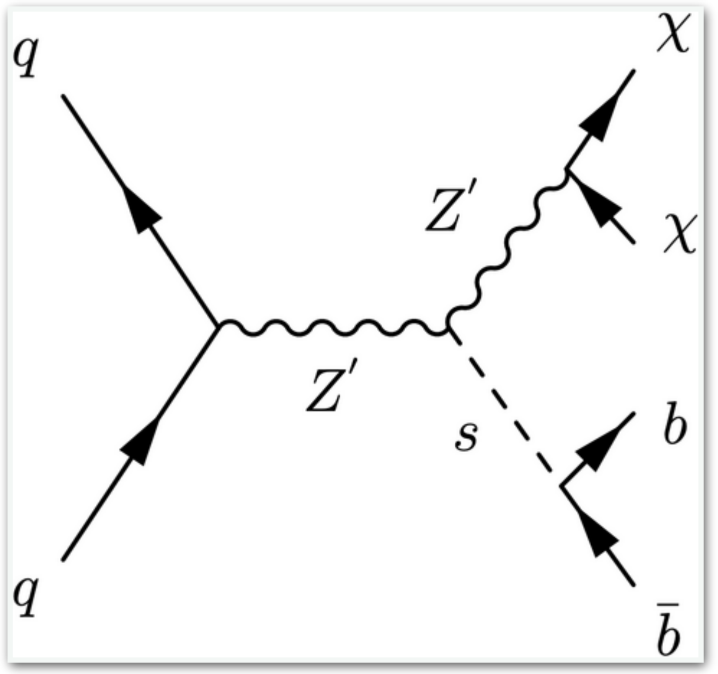
Dark Sector

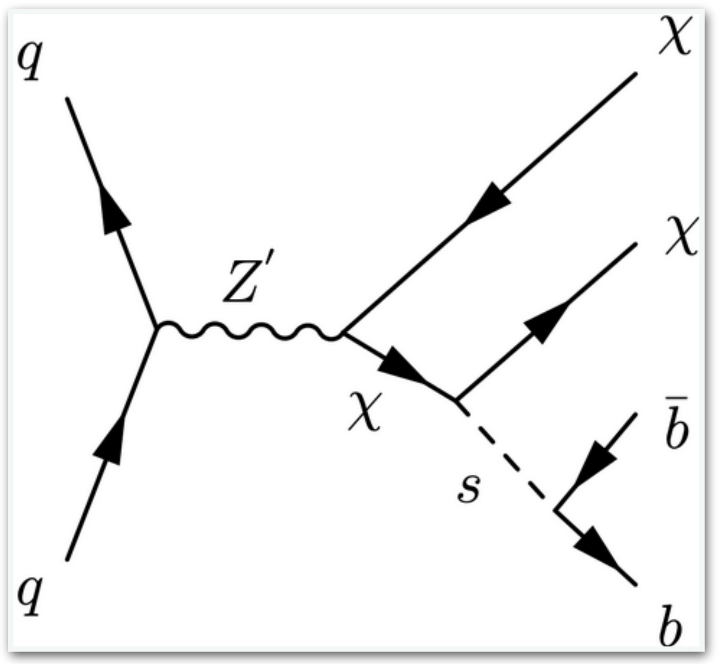
- **Recent results highlighted in this talk**:
  - ATLAS *Dark Higgs* + *Z'* search **ATLAS-CONF-2024-004**
  - CMS Inelastic Dark Matter search with Dark Photon **PhysRevLett.132.041802**
  - ATLAS $H \to \gamma\gamma_\mathrm{d}$ combination **CERN-EP-2024-152**

- **NOT in today talk but interesting to consider**:
  - ATLAS Dark Jets search **JHEP02 (2024) 128**
  - ATLAS Dark Photon search in rare *Z* decays **PhysRevLett 131 251801**
  - ATLAS *Semi-Visible Jets* search (**backup**) **PLB 848 (2024) 138324**

ATLAS *Dark Higgs + Z' search*

[ATLAS-CONF-2024-004]

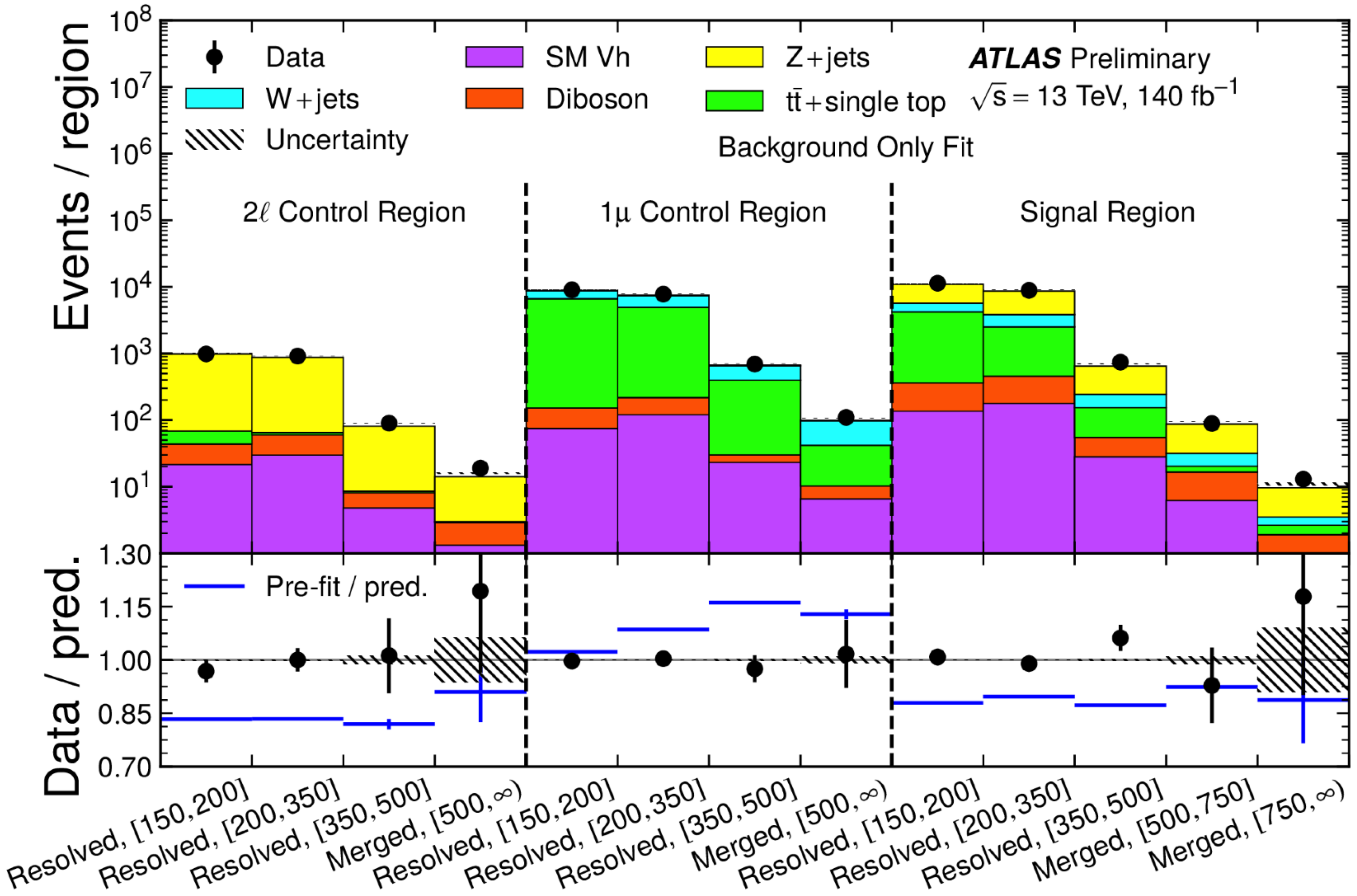




- The **first dedicated search** for DM produced via ***Z' boson*** in association with **2 resonant b-quarks** from ***Dark Higgs S*** decay with $m_{bb} < 150$ GeV.

- 2 event categories: 2 b-tagged jets (***resolved***) or 1 large-R jet with novel dedicated X→bb tagging (***merged***).
  - new tagger improves sensitivity by up to 50% w.r.t previously-used b-tagging approach.
  - events further classified into different $E_{\mathrm{T}}^{\mathrm{miss}}$ bins.

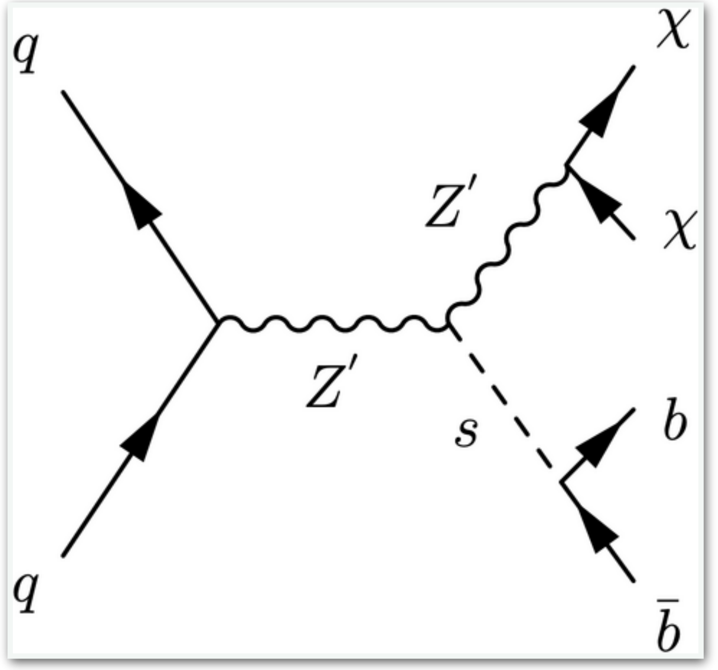
No significant deviation from SM

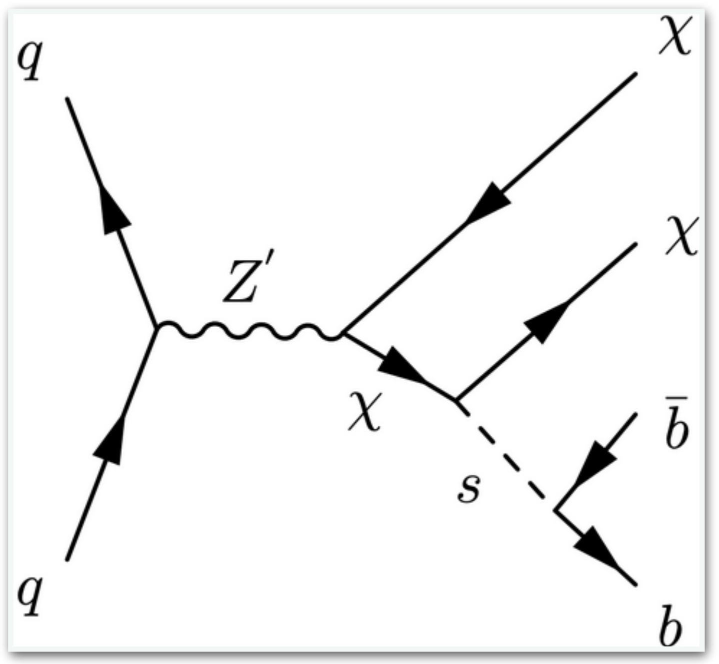


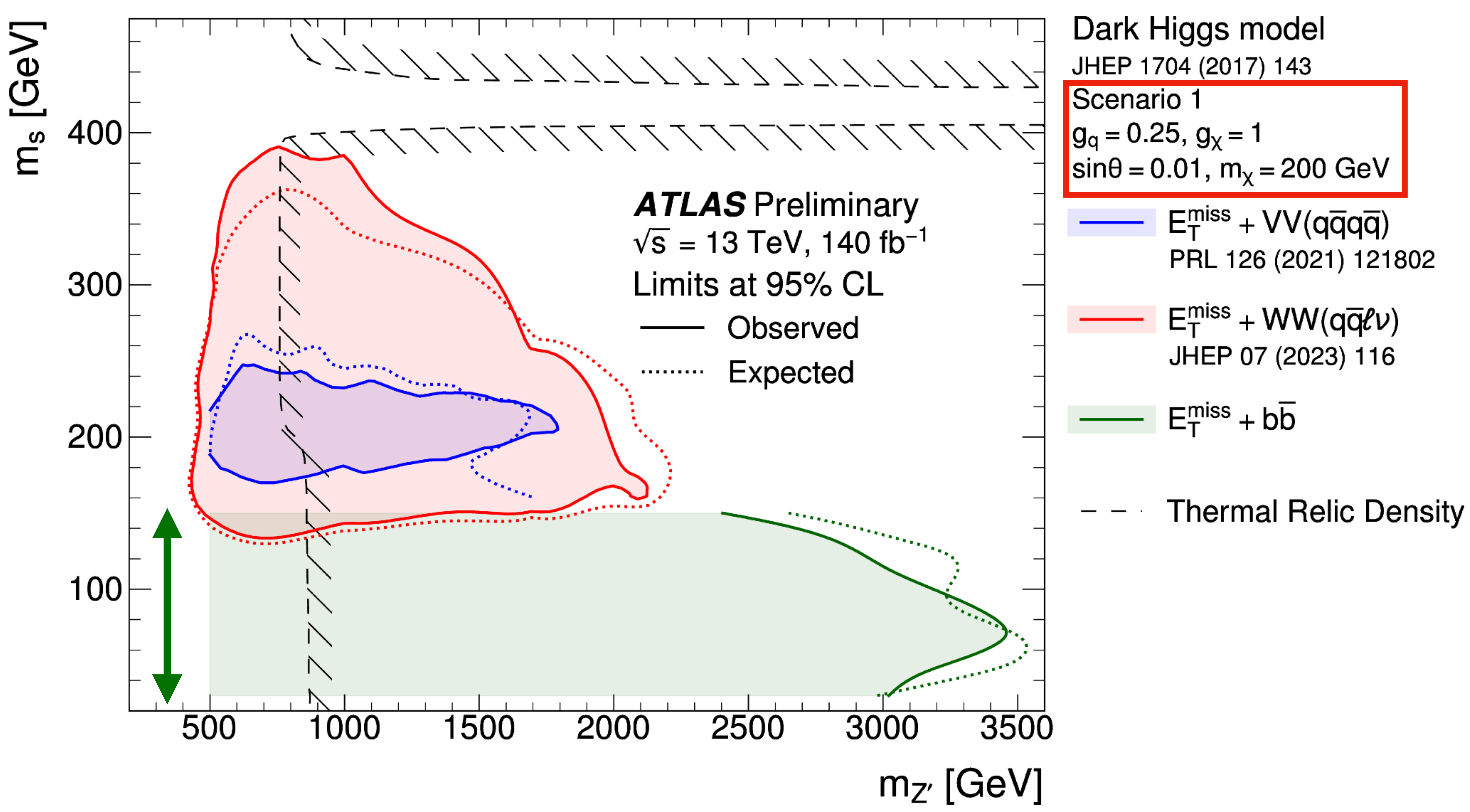
ATLAS *Dark Higgs + Z'* search

[ATLAS-CONF-2024-004]

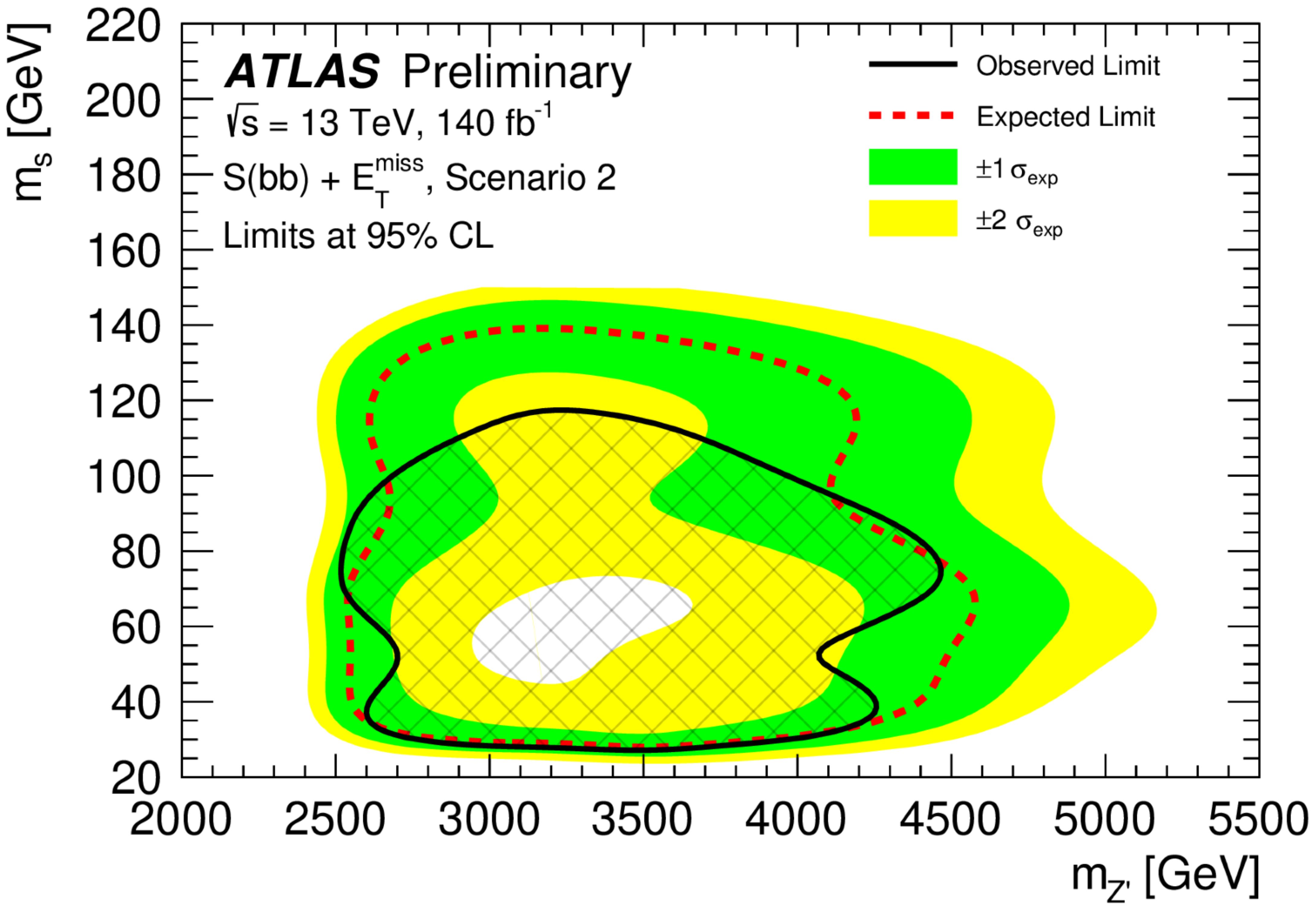
- The **first dedicated search** for DM produced via ***Z' boson*** in association with **2 resonant b-quarks** from ***Dark Higgs S*** decay with $m_{bb} < 150$ GeV.







complementary to other higher-mass Dark Higgs searches

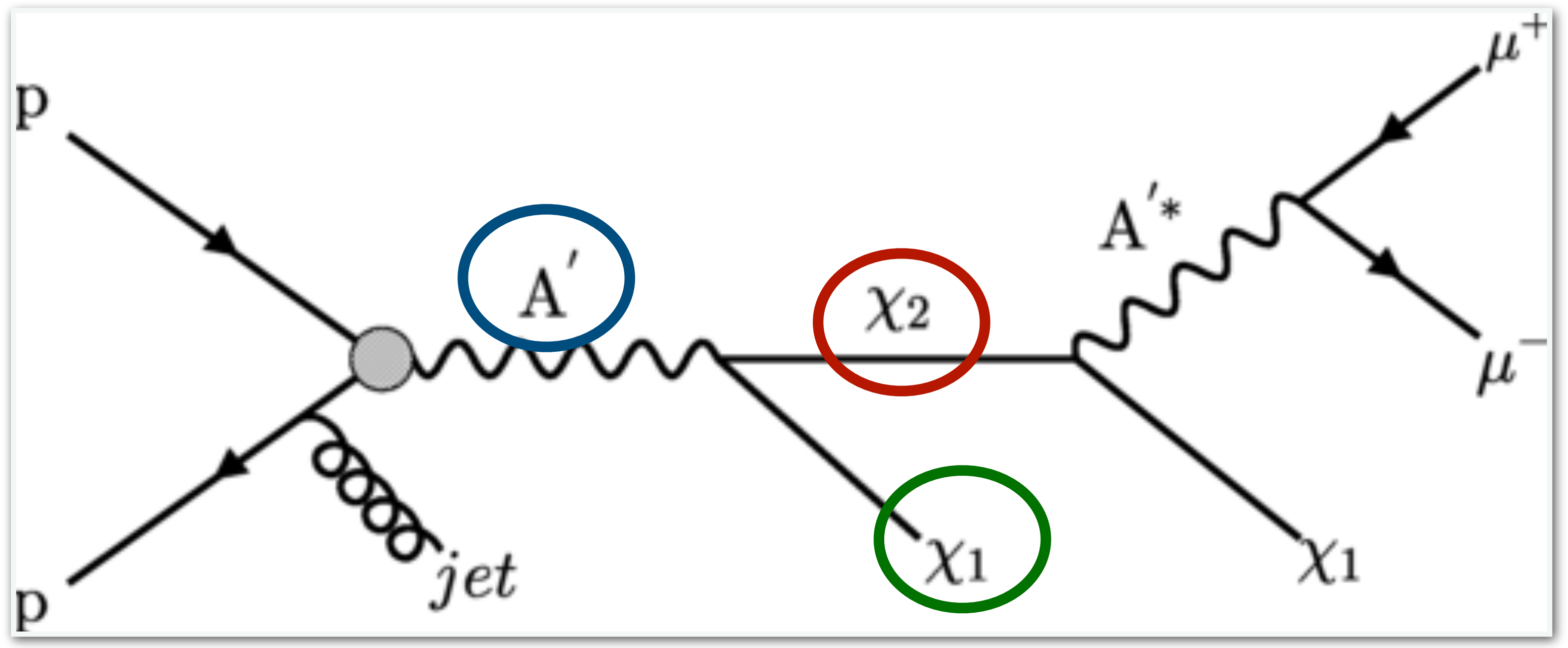


Scenario 2: g_χ varies to satisfy observed relic density, $m_\chi = 900$ GeV

CMS Inelastic Dark Matter search with Dark Photon

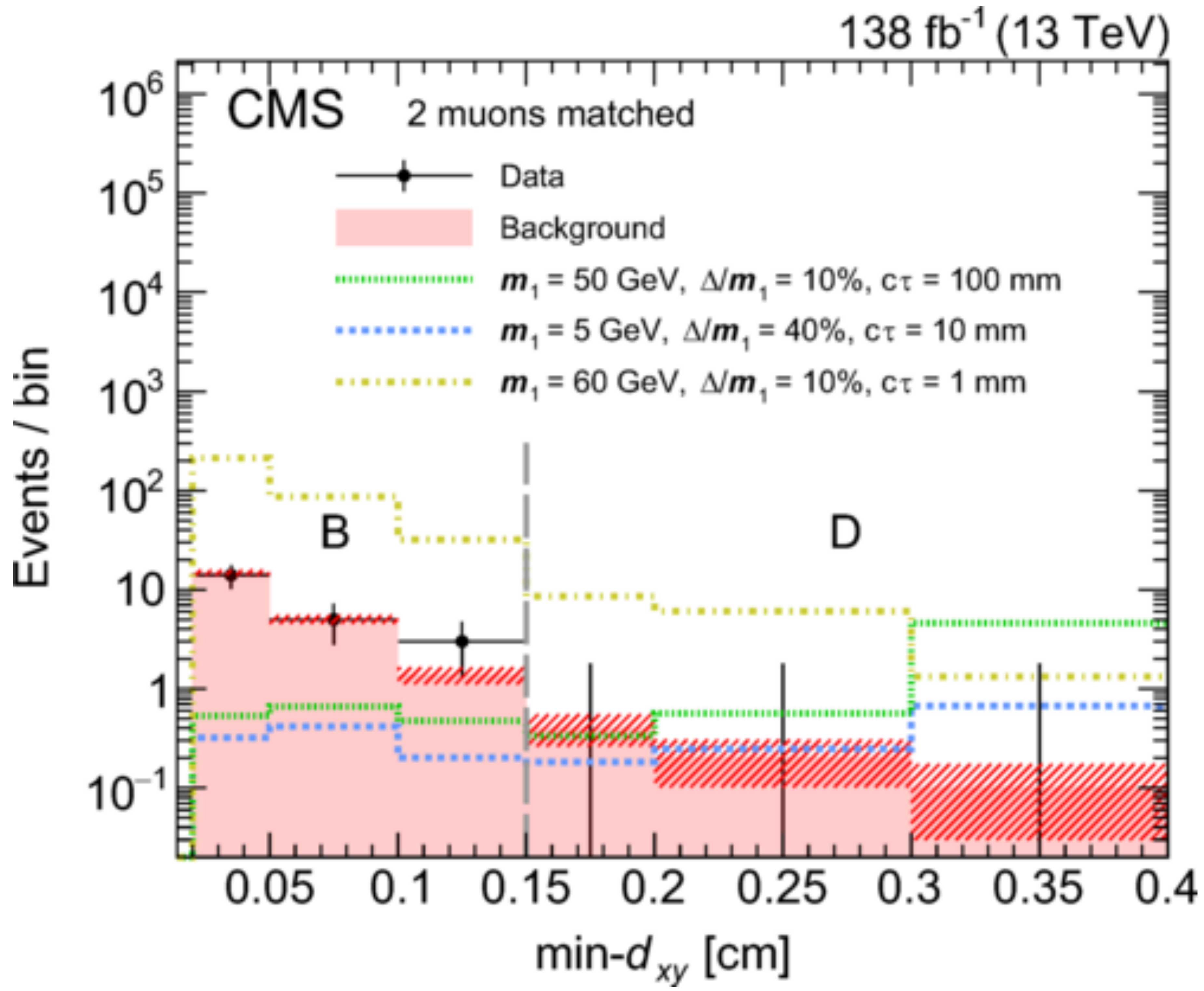
PhysRevLett.132.041802

- **First dedicated search for Inelastic DM** which could explain the ***observed thermal relic abundance*** in the universe.
- Event signature:
  - **Dark Photon A'** produced recoiling against ISR jet (for trigger).
  - A' decay promptly into 2 DM states with near mass-degeneracy: **light, stable χ_1**, and **heavy χ_2 with long lifetime**.
    - soft decay products of χ_2: pair of displaced muons.
    - large E_T^{miss} collimated with muon pair from χ_1



- Specialized **Displaced Standalone Algorithm** (DSA) applied to improve displaced muon reconstruction efficiency.
- **3 event categories** according to number of PFlow-DSA matched muons found (0 - 2).

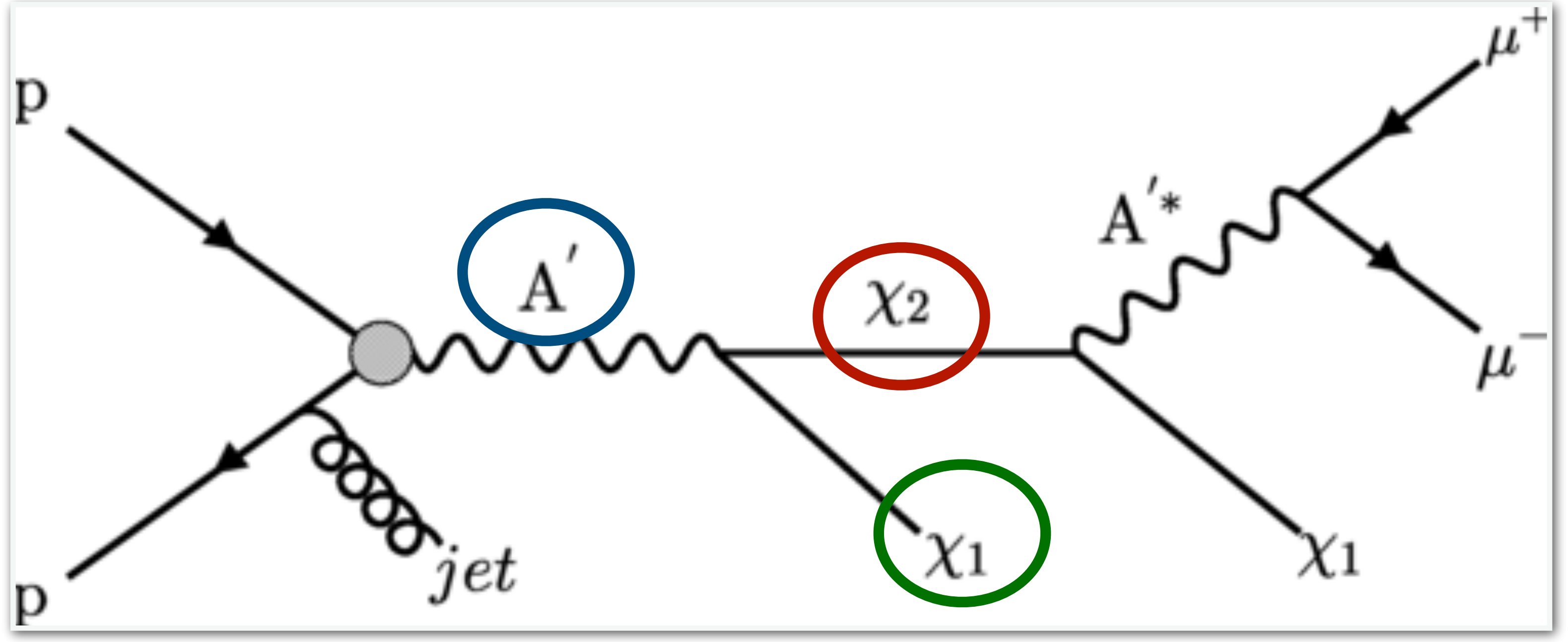
No significant deviation from SM

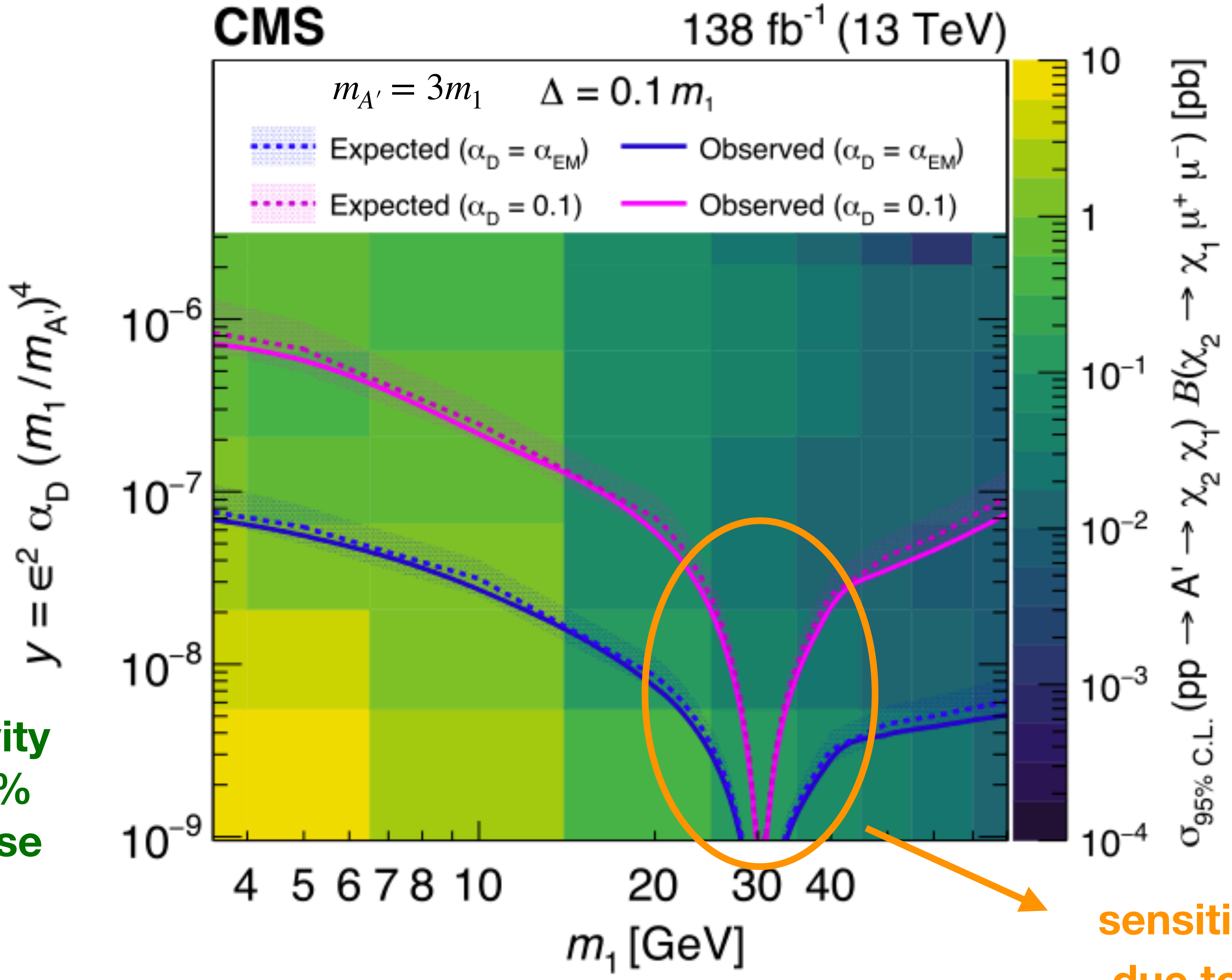


CMS Inelastic Dark Matter search with Dark Photon

PhysRevLett.132.041802

- **First dedicated search for Inelastic DM** which could explain the ***observed thermal relic abundance*** in the universe.



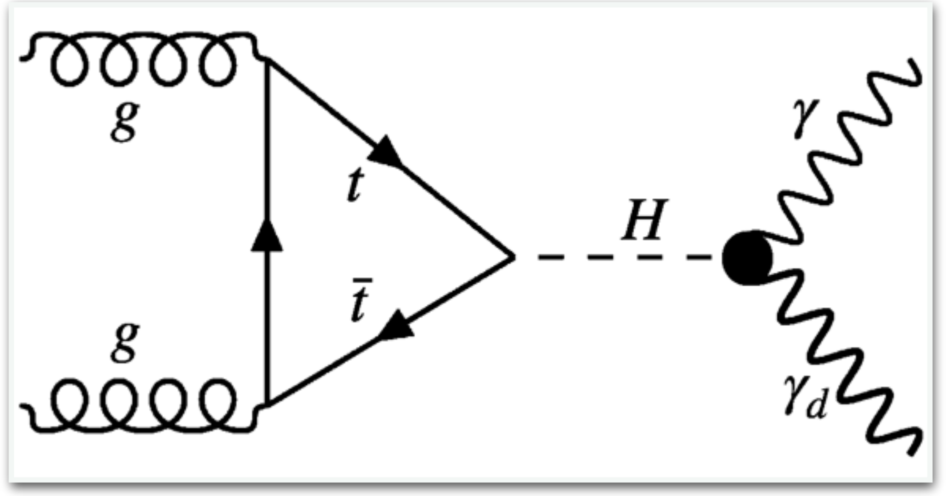


Strongest sensitivity obtained with 10% mass-splitting case

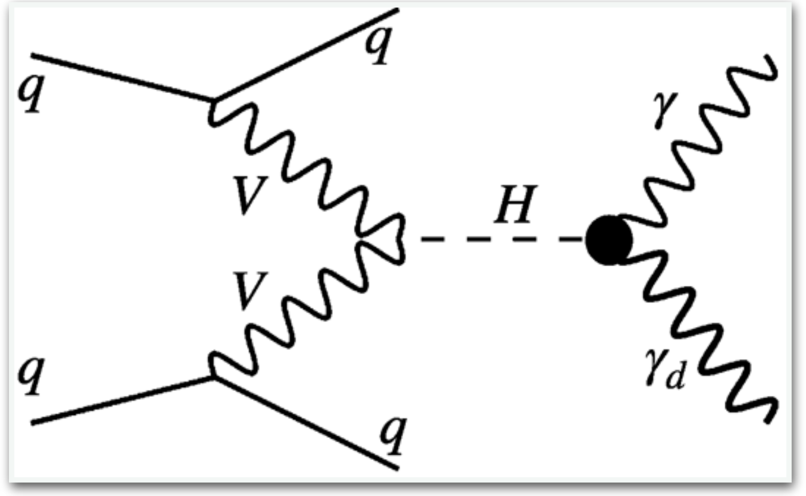
sensitivity amplified due to A'-Z mixing

ATLAS $H \to \gamma\gamma_d$ combination CERN-EP-2024-152

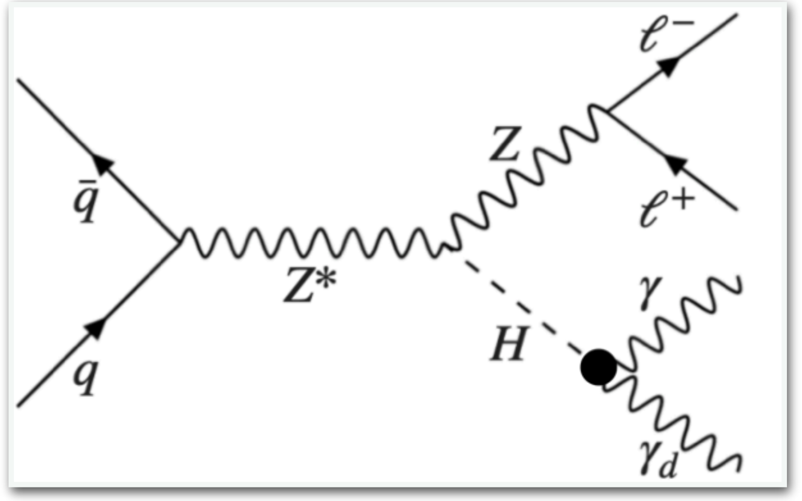
- Combination of recent Run-2 searches for **Higgs boson decays into photon and massless dark photon** in **3 final states**.



$\gamma + E_T^{miss}$
(*Mono-photon* reinterpretation)

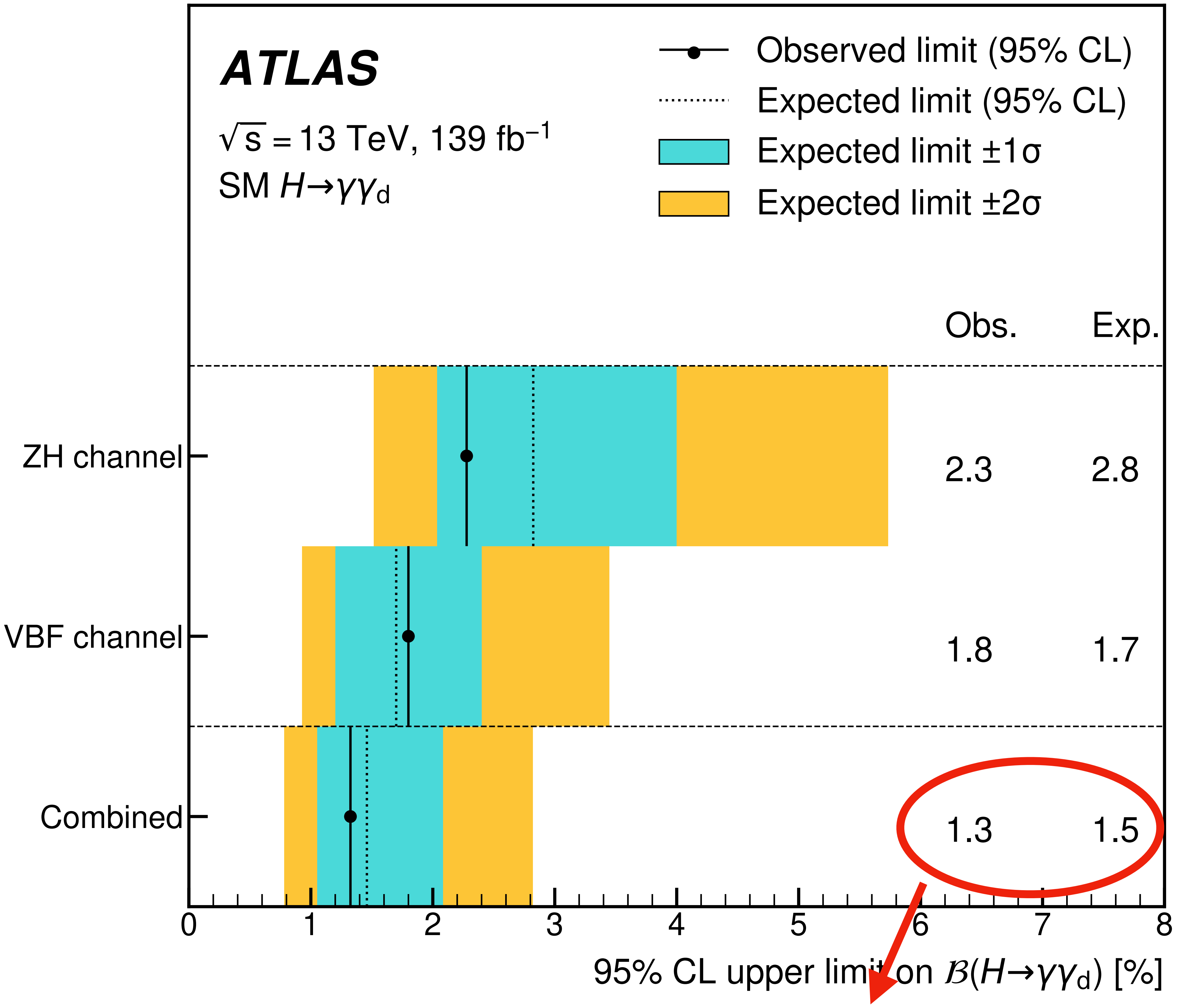


$\gamma + E_T^{miss}$ + VBF jets
(*VBF analysis*)



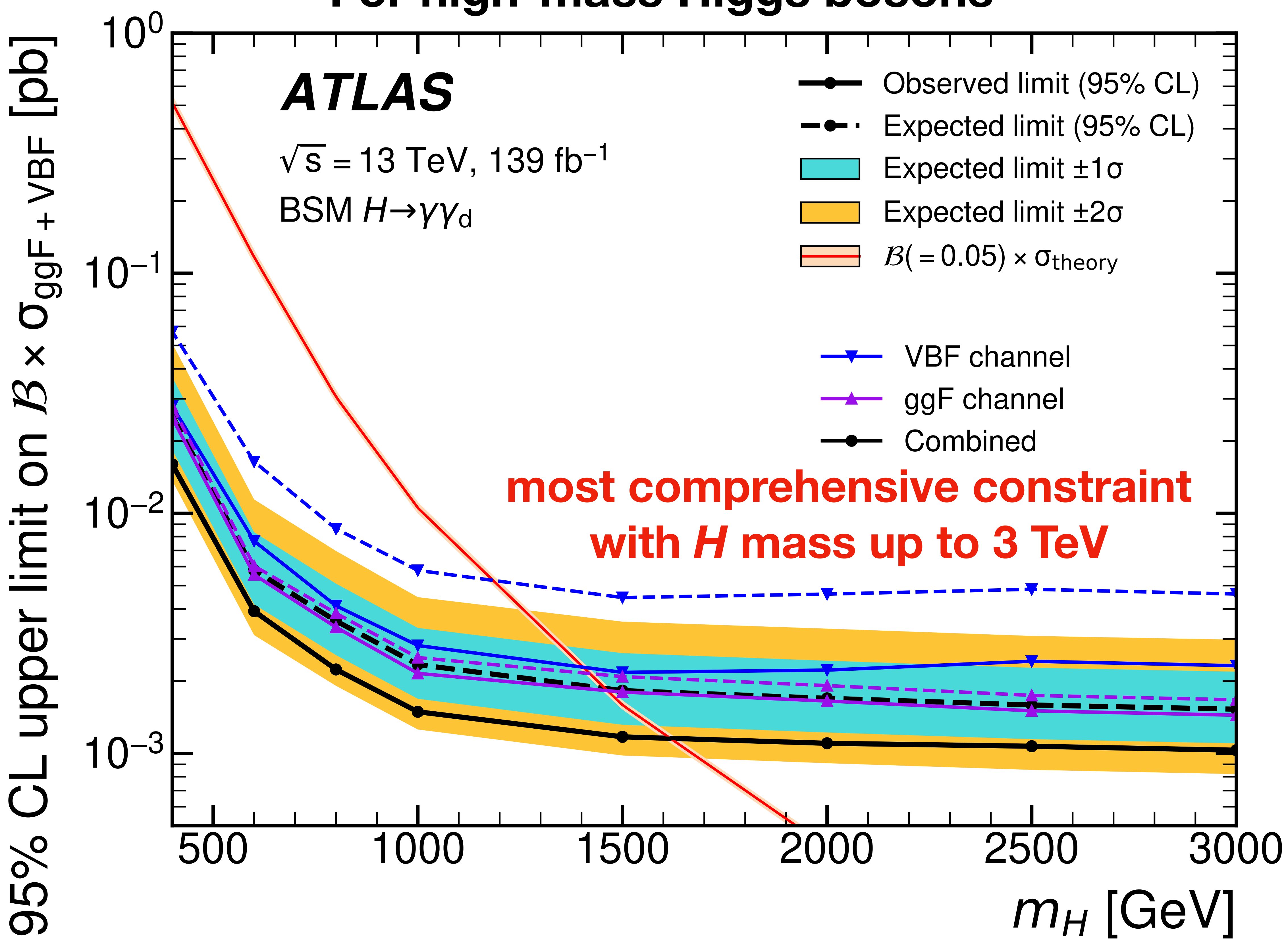
$\gamma + E_T^{miss} + Z(\to \ell\ell)$
(*ZH analysis*)

For SM Higgs boson



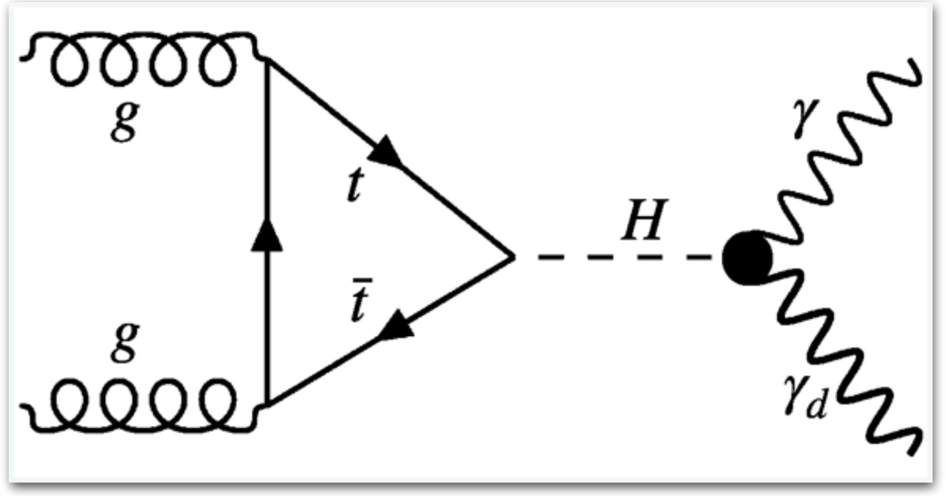
most stringent limit on BR($H_{125} \to \gamma\gamma_d$) at LHC to date

For high-mass Higgs bosons

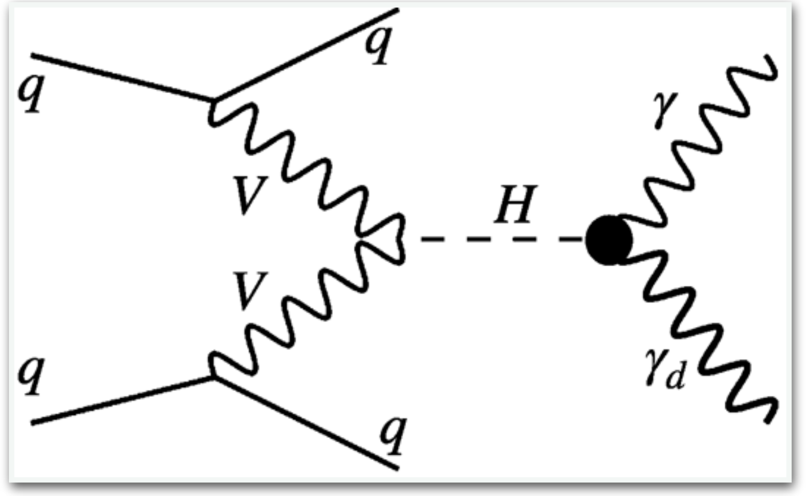


ATLAS $H \to \gamma\gamma_{\mathrm{d}}$ combination CERN-EP-2024-152

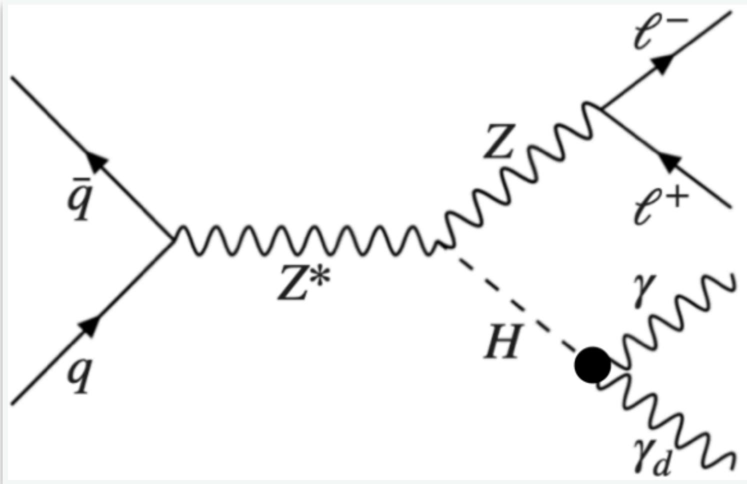
- Combination of recent Run-2 searches for **Higgs boson decays into photon and massless dark photon** in **3 final states**.



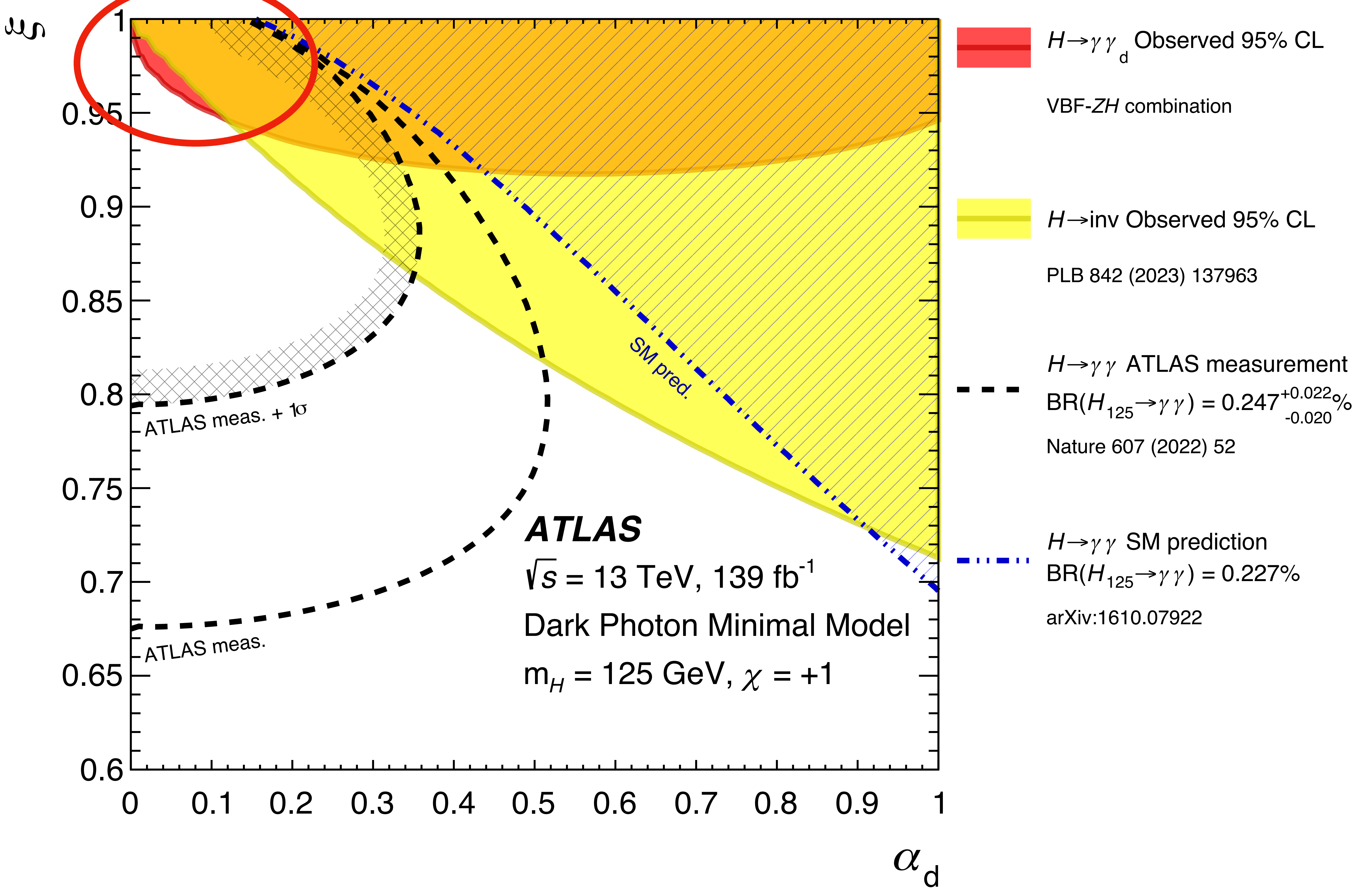
$\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$
(*Mono-photon* reinterpretation)



$\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$ + VBF jets
(*VBF analysis*)



$\gamma + E_{\mathrm{T}}^{\mathrm{miss}} + Z(\to \ell\ell)$
(*ZH analysis*)



- **For the first time**, upper limits on BRs of $H_{125} \to \gamma\gamma_{\mathrm{d}}$ and $H_{125} \to \mathrm{inv}$ also interpreted as constraints on ***Dark Photon Minimal Model*** with a messenger sector.

- $H_{125} \to \gamma\gamma_{\mathrm{d}}$ combination gives additional sensitivity in low-fine-structure-constant region where disfavoured by ATLAS BR($H_{125} \to \gamma\gamma$) measurement.

Conclusions

- Unfortunately, Dark Matter particles have NOT YET been discovered at the colliders. DM nature is still one of central questions to our understandings about the Universe.
- Wide range of DM benchmark models and experimental signatures has been probed at both ATLAS and CMS using full Run-2 data:
  - Constraints set not only on Simplified Models but also on extended Higgs models and Dark Sector.
  - Many combination efforts to improve sensitivity reach.
  - Results are complementary to Direct and Indirect experiments.
- LHC Run-2 results are still coming.
- Much more to come with Run-3 dataset including upgraded detectors and innovative methods.

STAY TUNED!

Thank you for attention

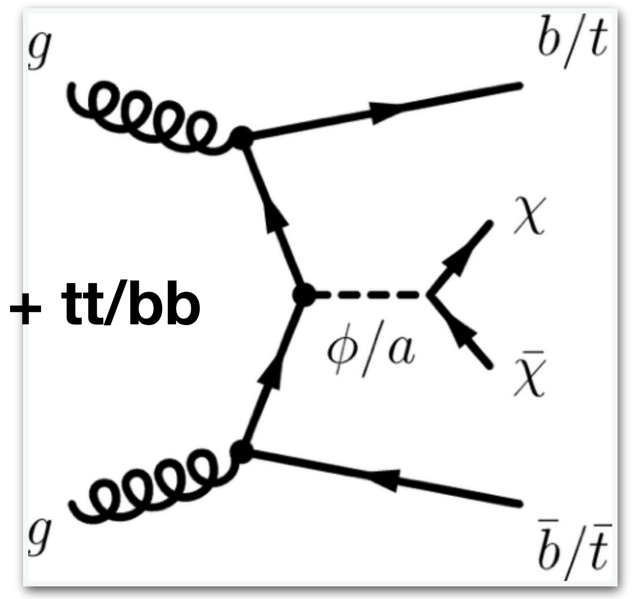
Backup

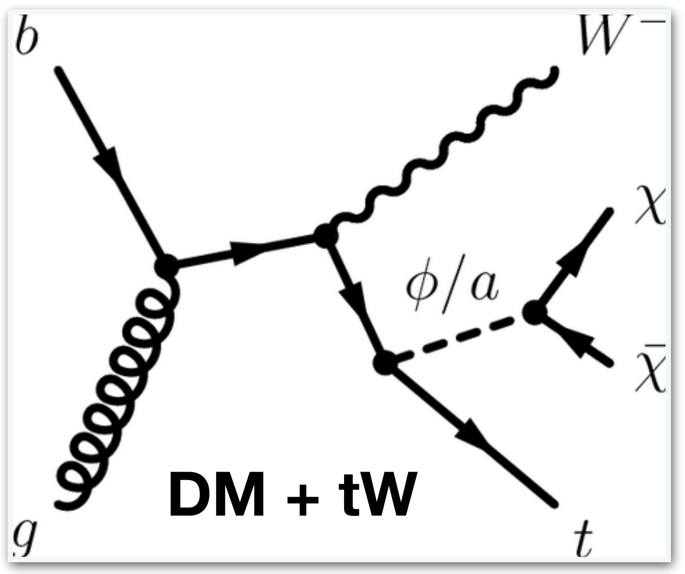
Simplified Models

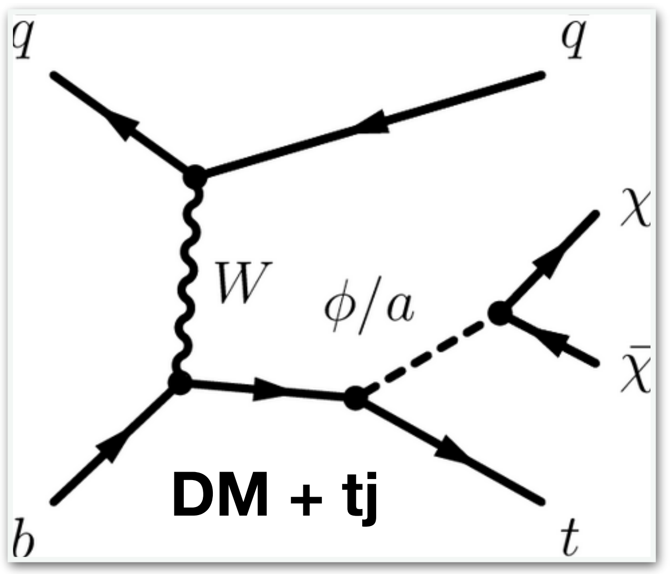
Summary: Spin-0 (pseudo-)scalar mediators

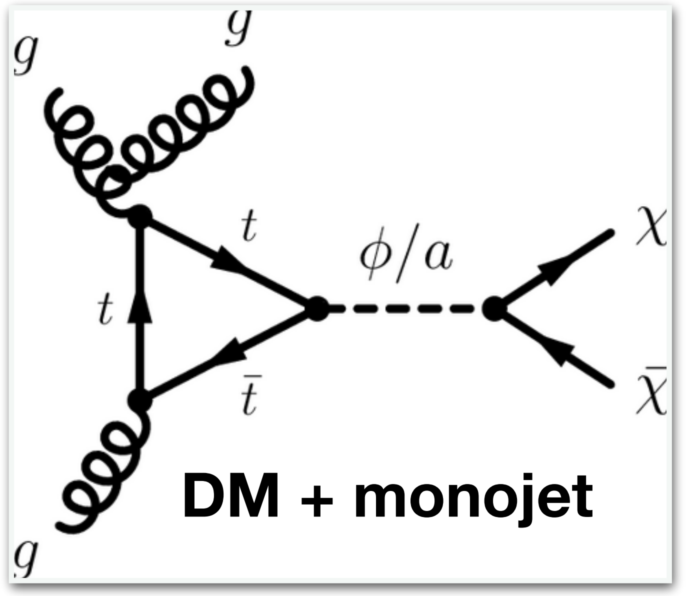
- Simplified models with scalar (ϕ) or pseudo-scalar (a) mediator
  - Yukawa-like couplings $\longrightarrow$ sensitivity dominated by searches for *heavy flavour quarks* + $E_{\mathrm{T}}^{\mathrm{miss}}$.
  - Most stringent constraints from $\mathrm{DM} + t\bar{t}$ channel.

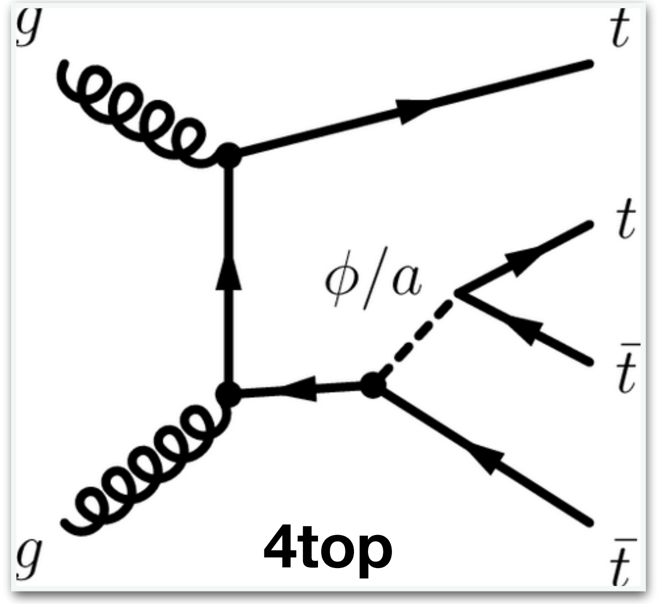
DM + tt/bb



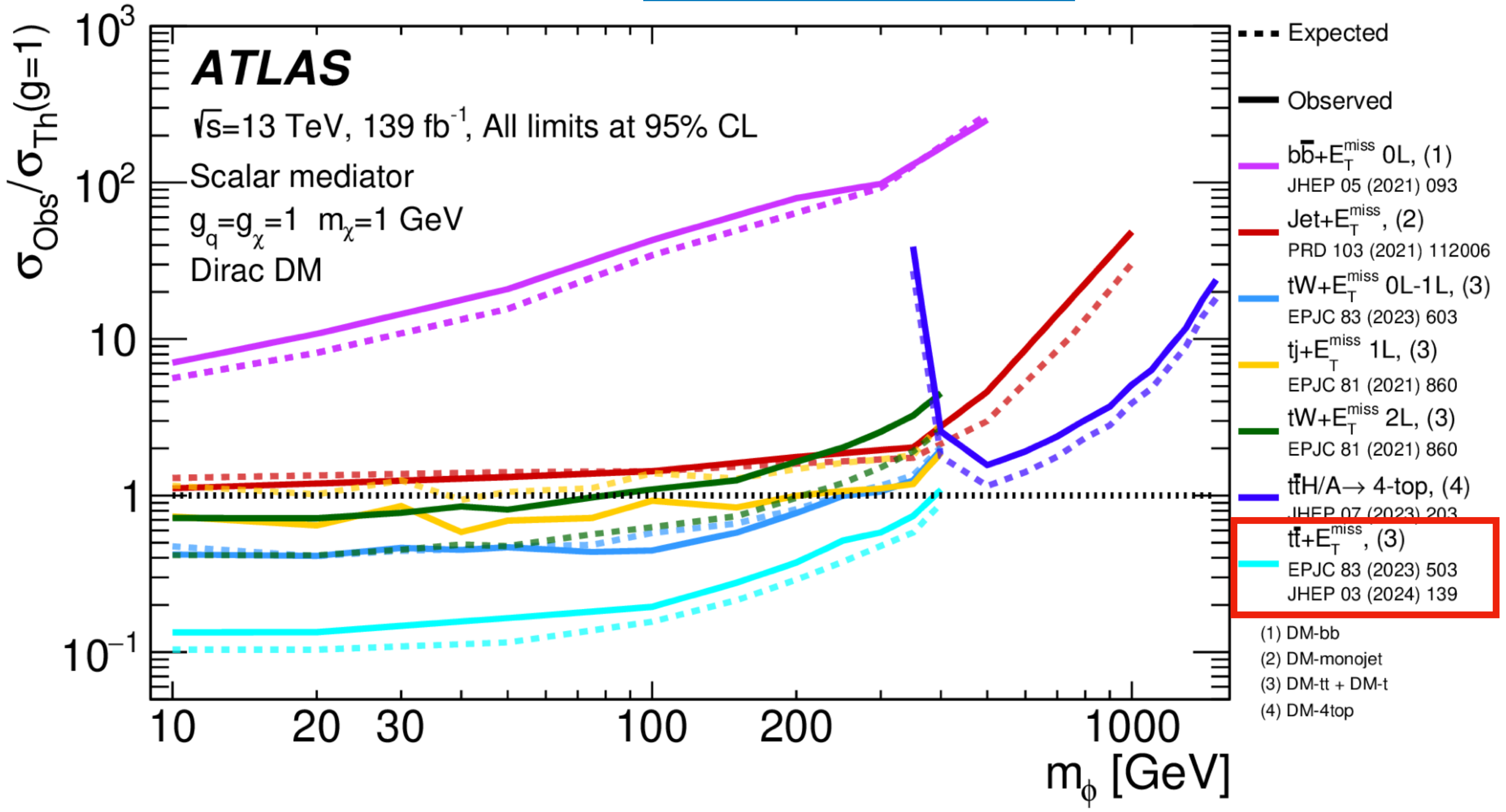




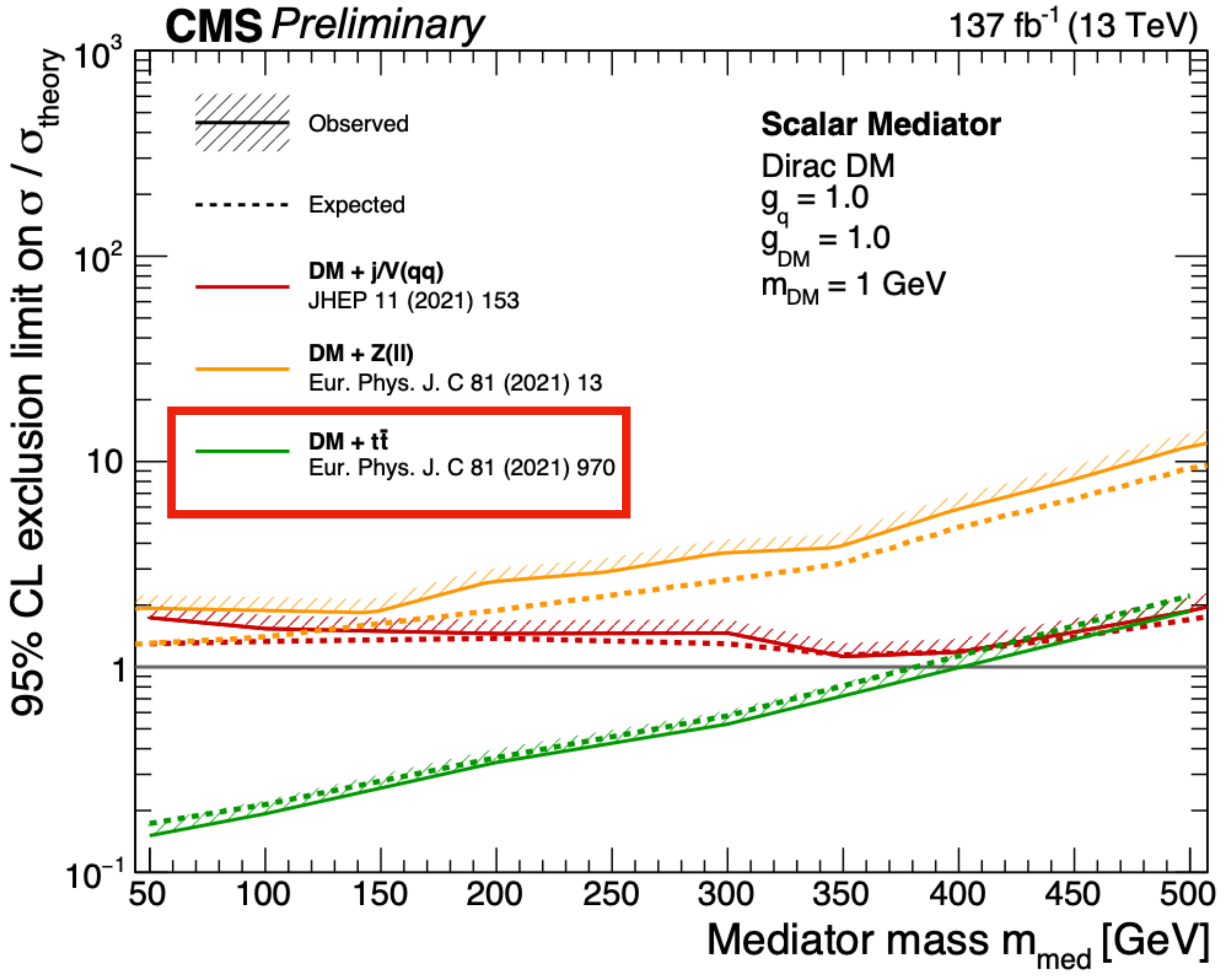




ATLAS arXiv:2404.15930



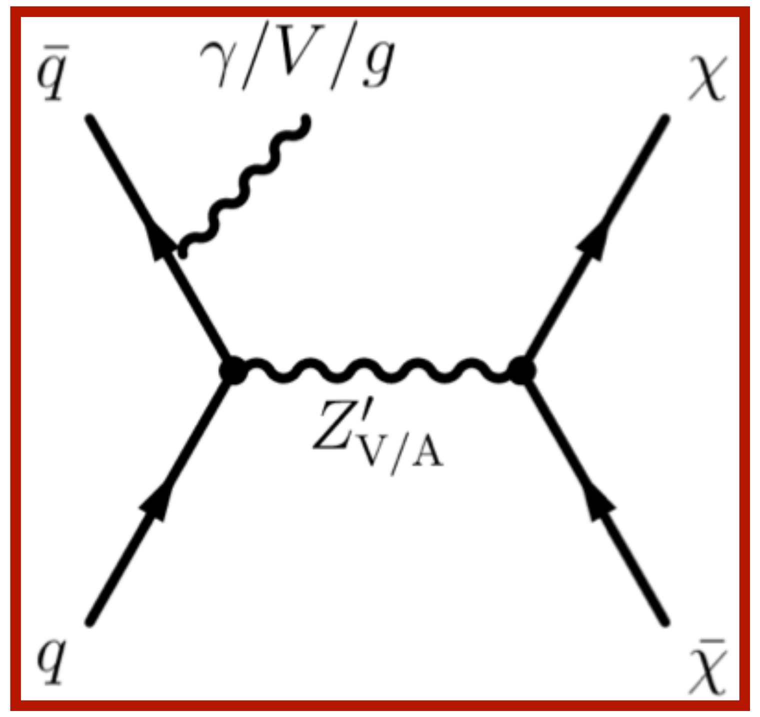
CMS DM summary



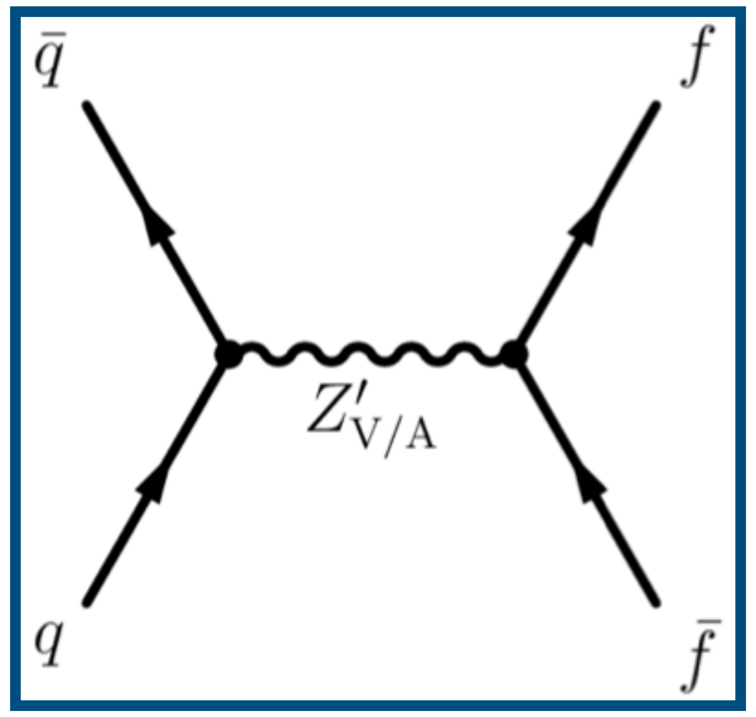
Simplified Models

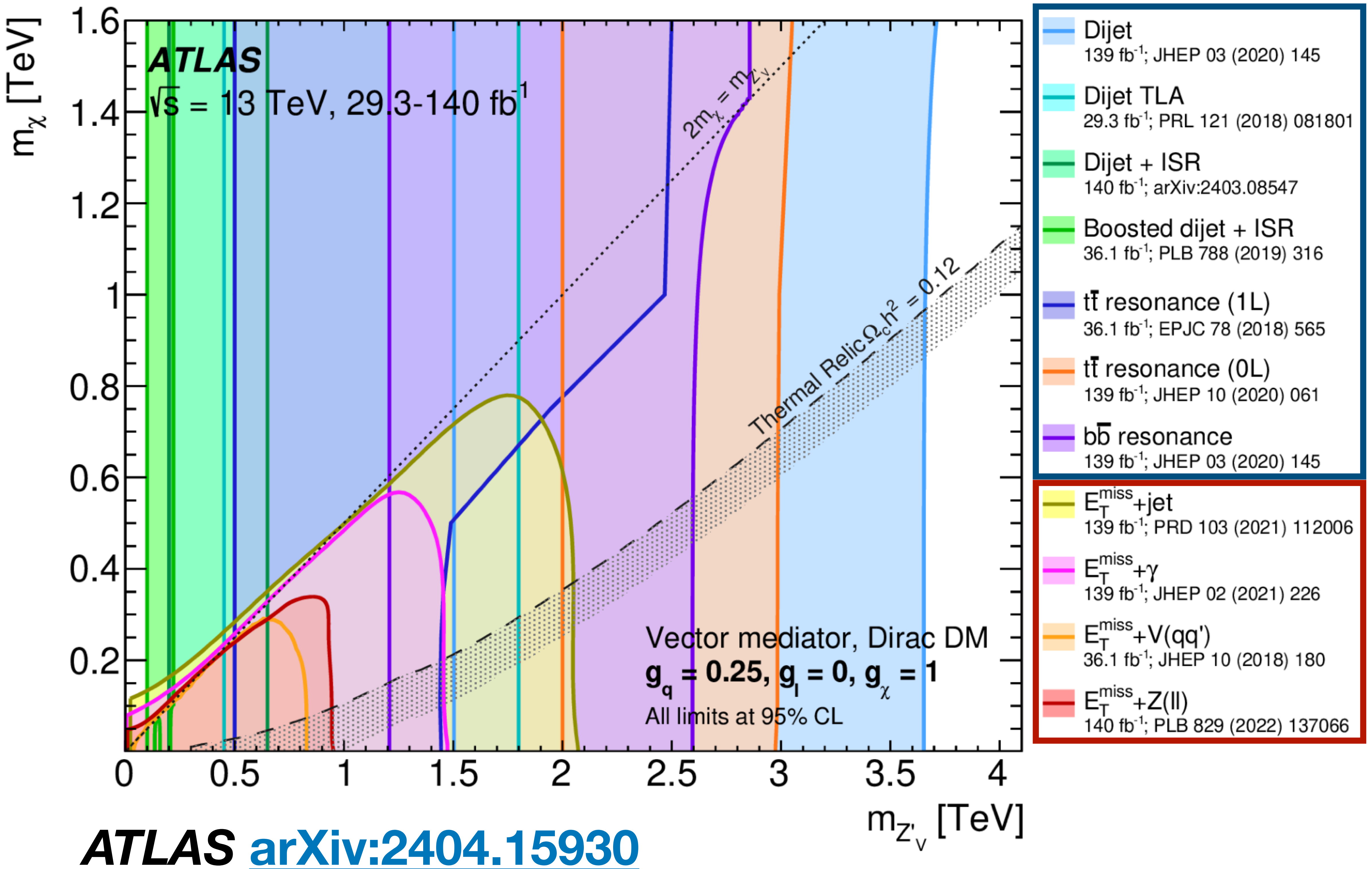
Summary: Spin-1 (axial-)vector mediators

- Large fraction of m_χ - $m_{\rm med}$ plane has been excluded by searches using simplified models with vector or axial-vector mediator during Run-2.
  - **Mono-X** searches: mono-jet is the most sensitive channel.
  - **Resonance** searches: minimal dependency on DM mass at high mediator masses.

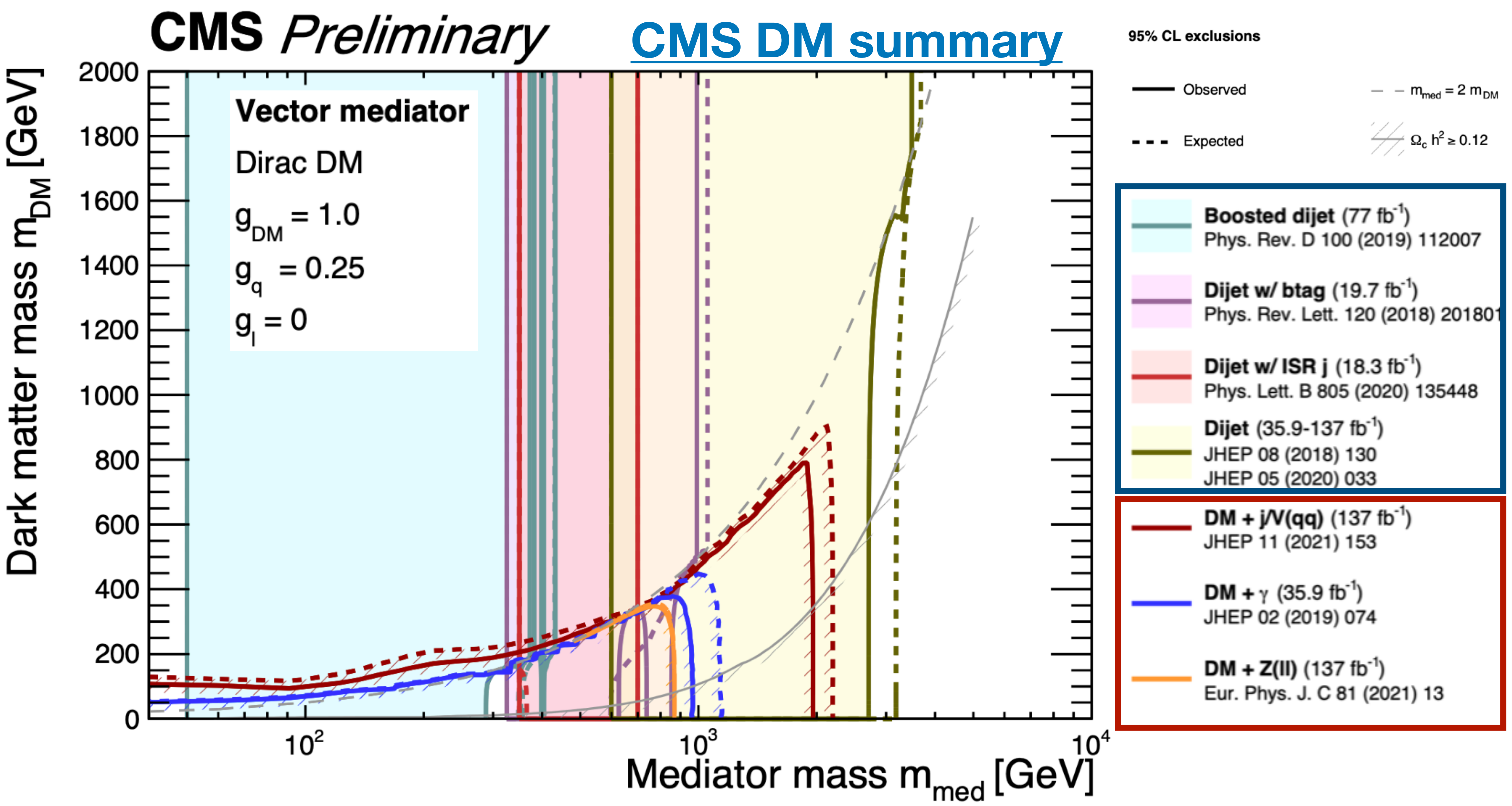


only if
$2m_\chi \lesssim m_{\rm med}$



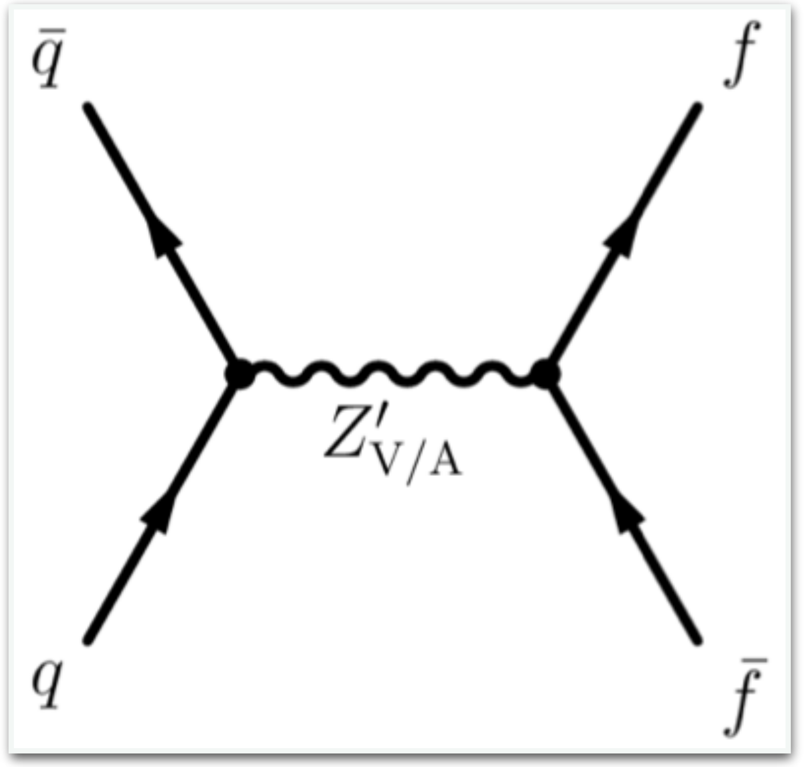


ATLAS [arXiv:2404.15930]

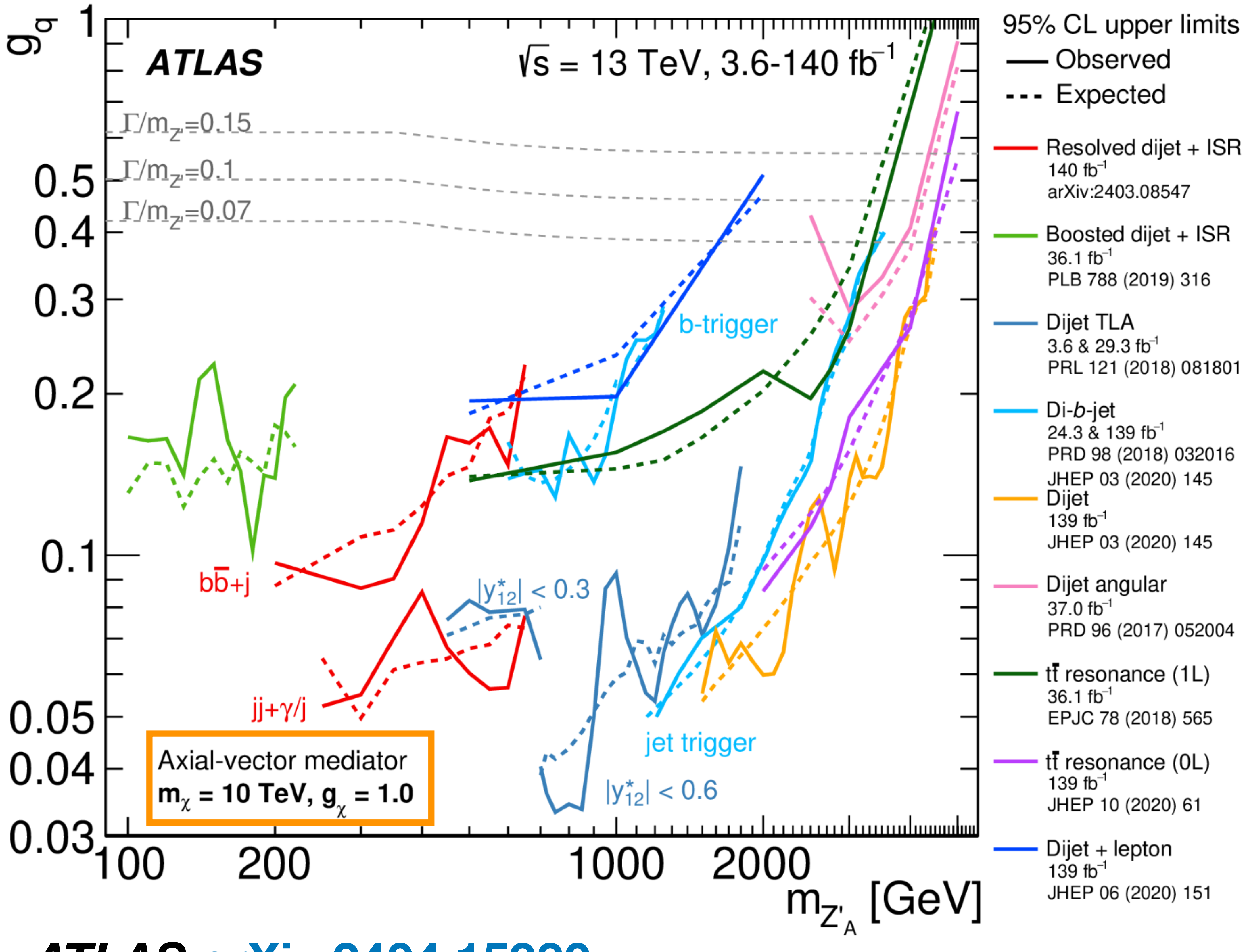


Simplified Models

Summary: Spin-1 (axial-)vector mediators

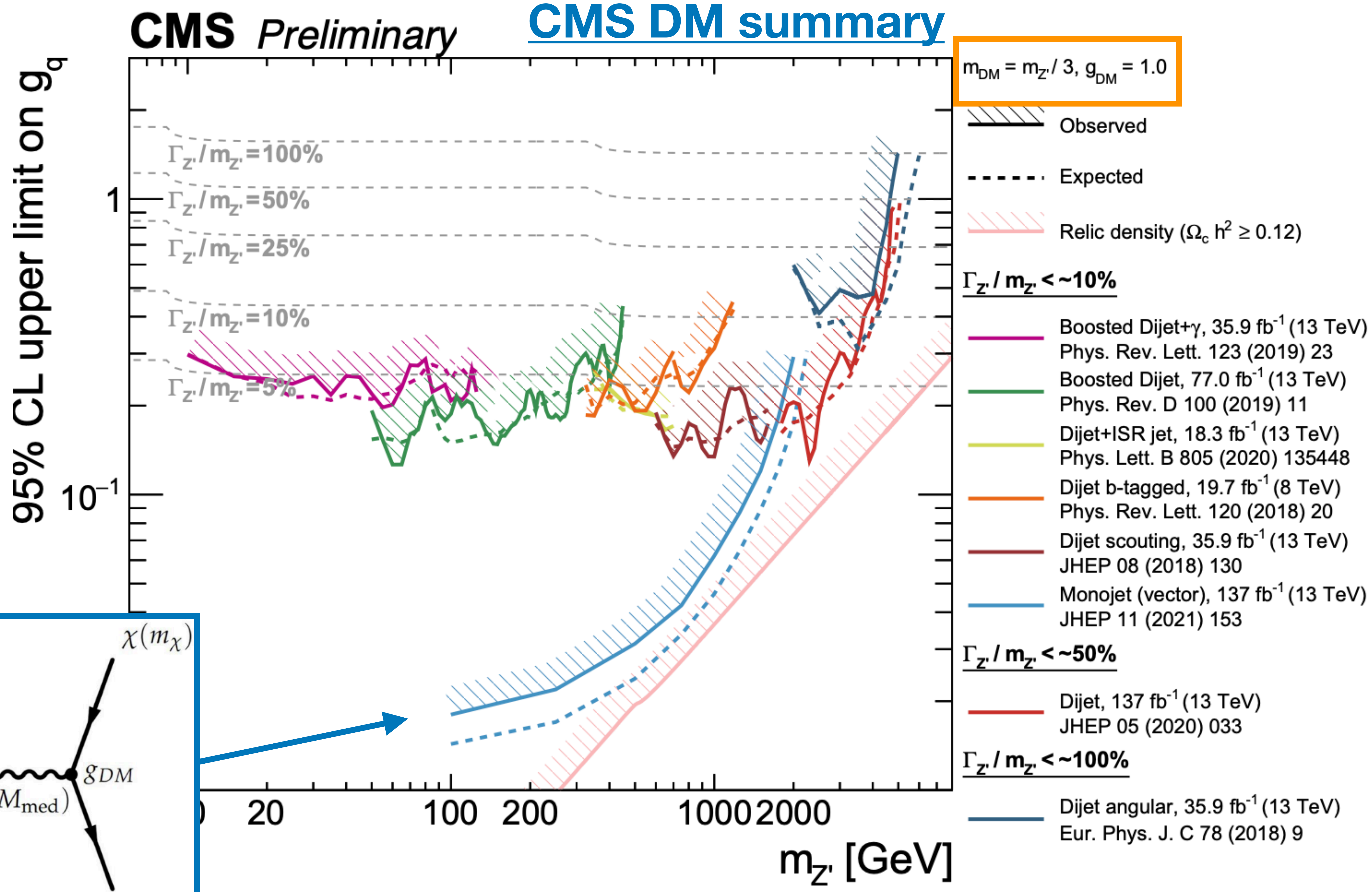


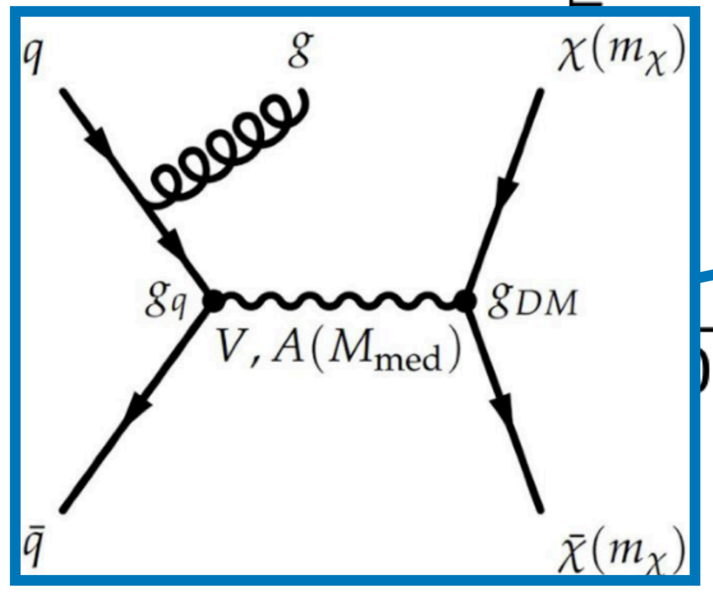
- Resonance searches exploited to set 95% CL limits on spin-1 axial-vector mediator's coupling to quarks as a function of mediator mass.



ATLAS **arXiv:2404.15930**

CMS DM summary





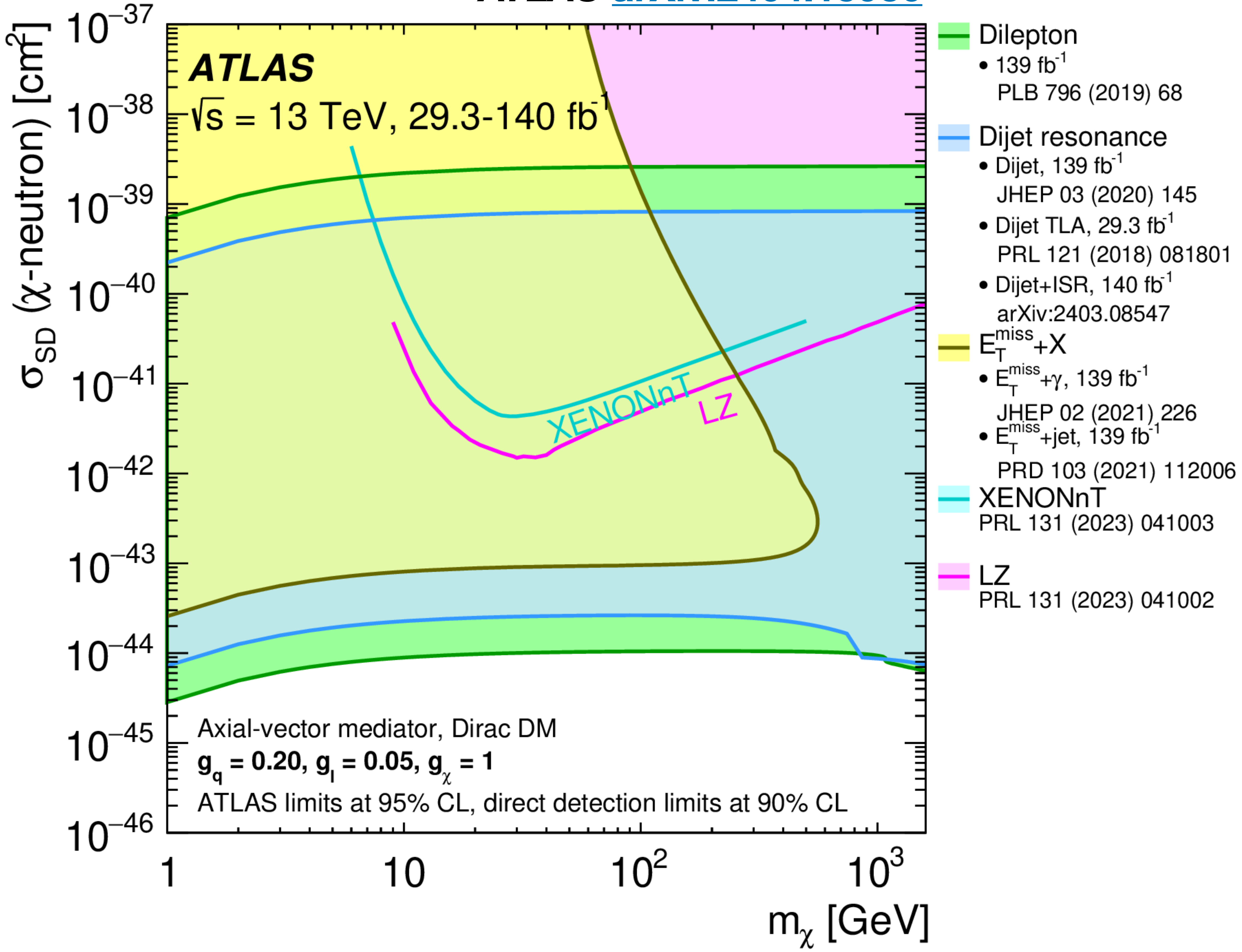
significant constraint from
CMS mono-jet search

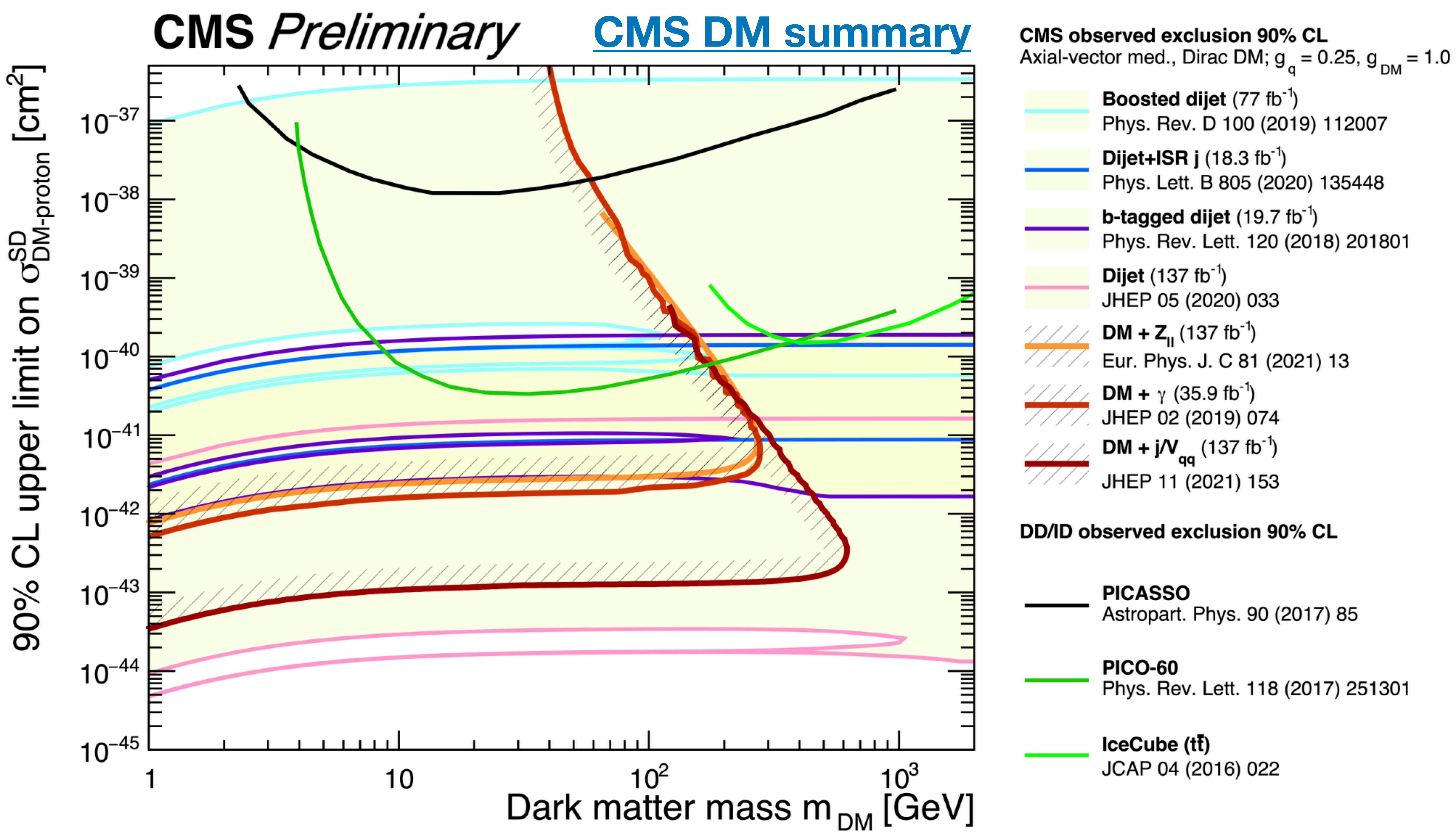
Simplified Models

Comparison with (In)direct Searches

- Results translated into limits on DM-nucleon elastic scattering cross-section, enabling comparisons with Direct or Indirect Detection experiments.
  - **LHC searches provide complementarity to DD/DI experiments with assumptions on model parameters.**

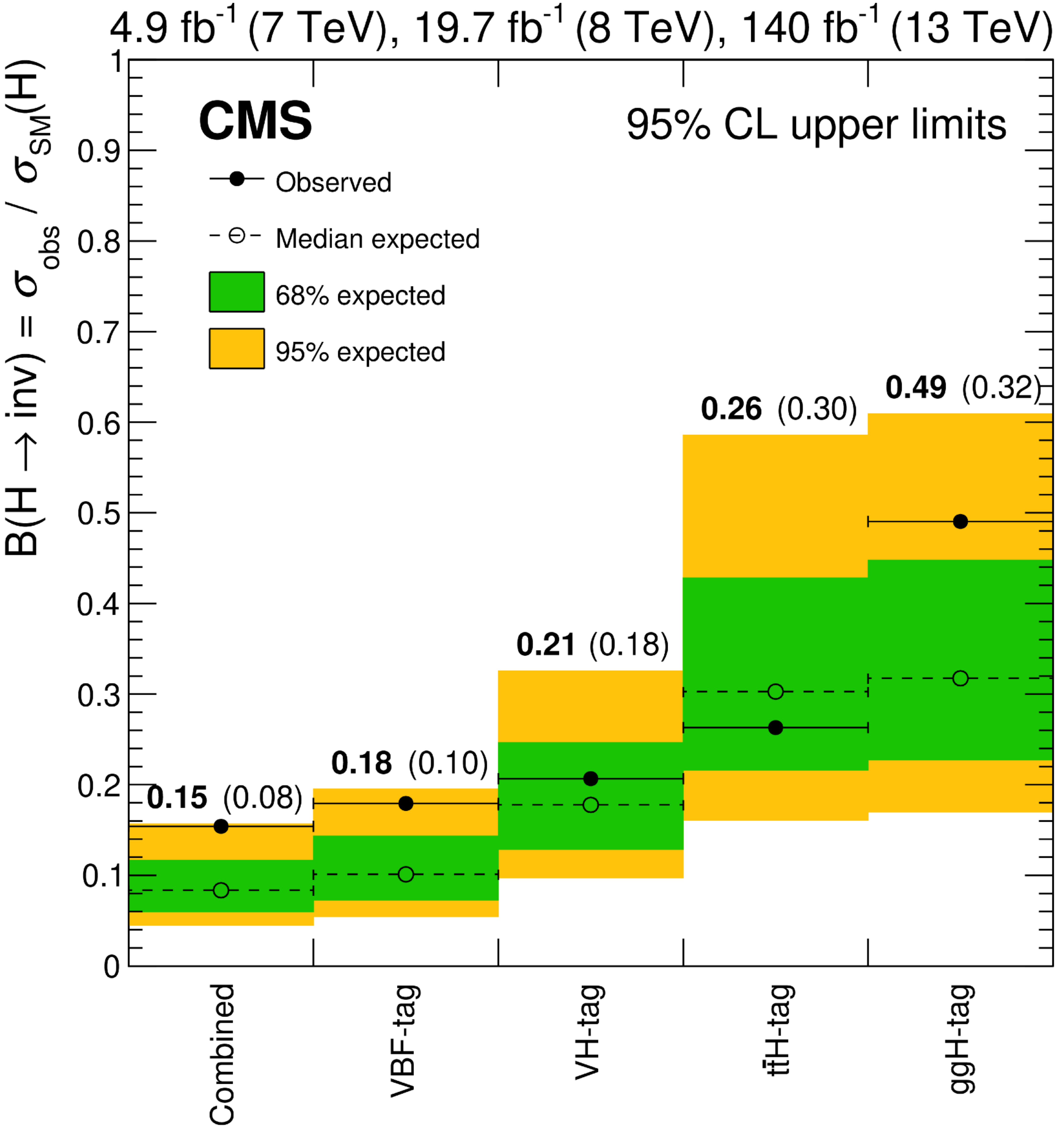
***ATLAS* arXiv:2404.15930**

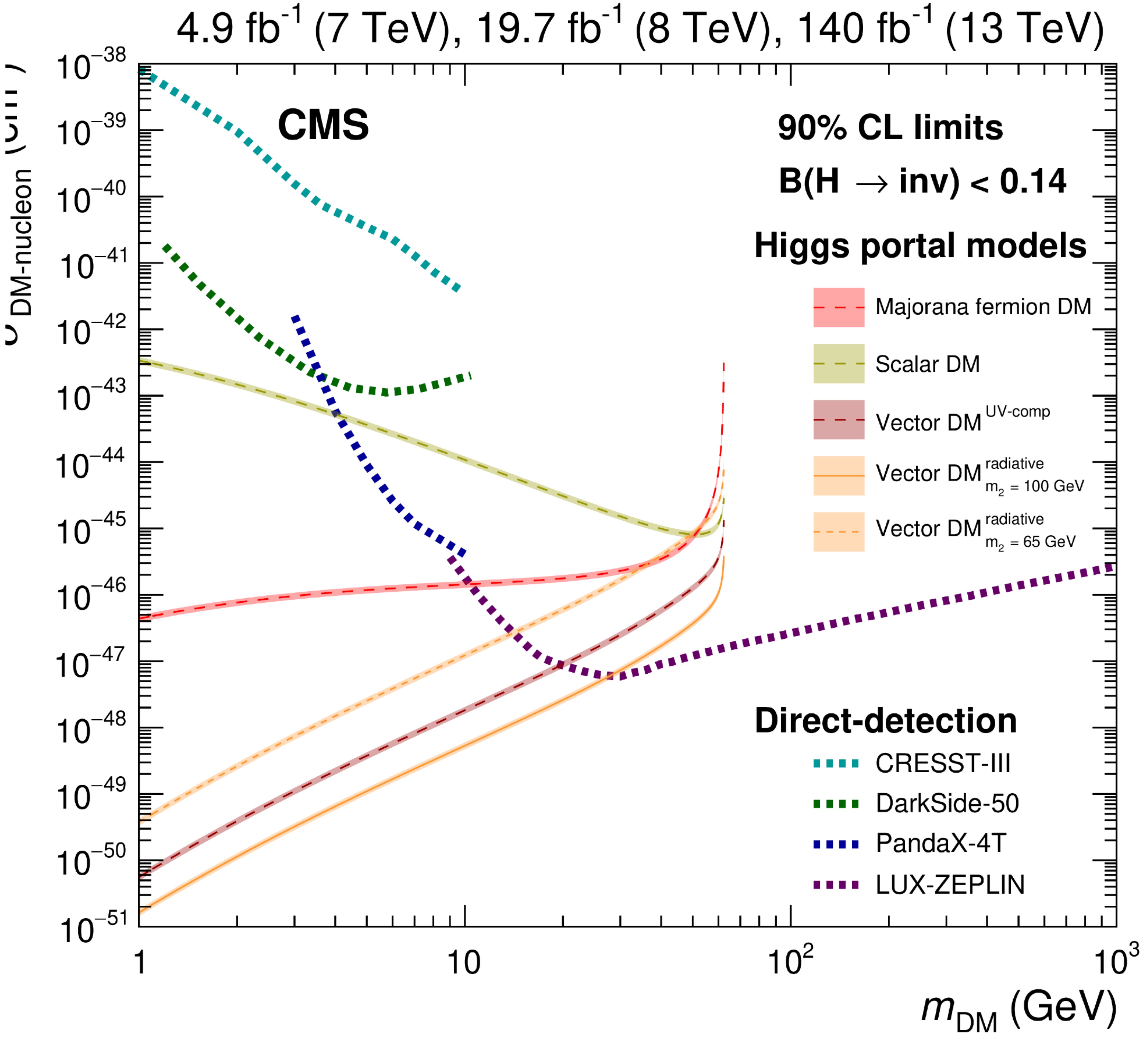




CMS Higgs Invisible Decays

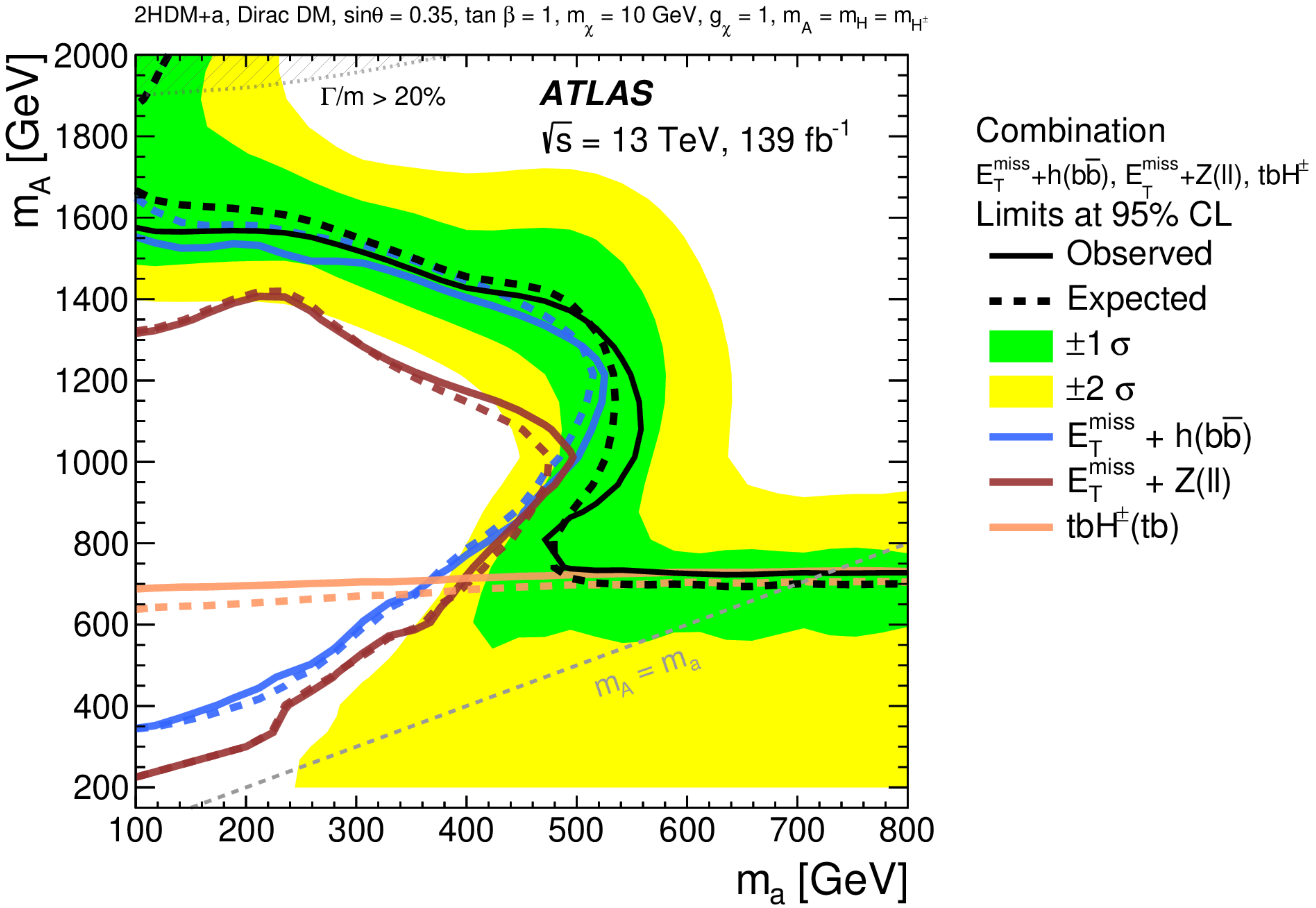
EPJC 83 (2023) 933

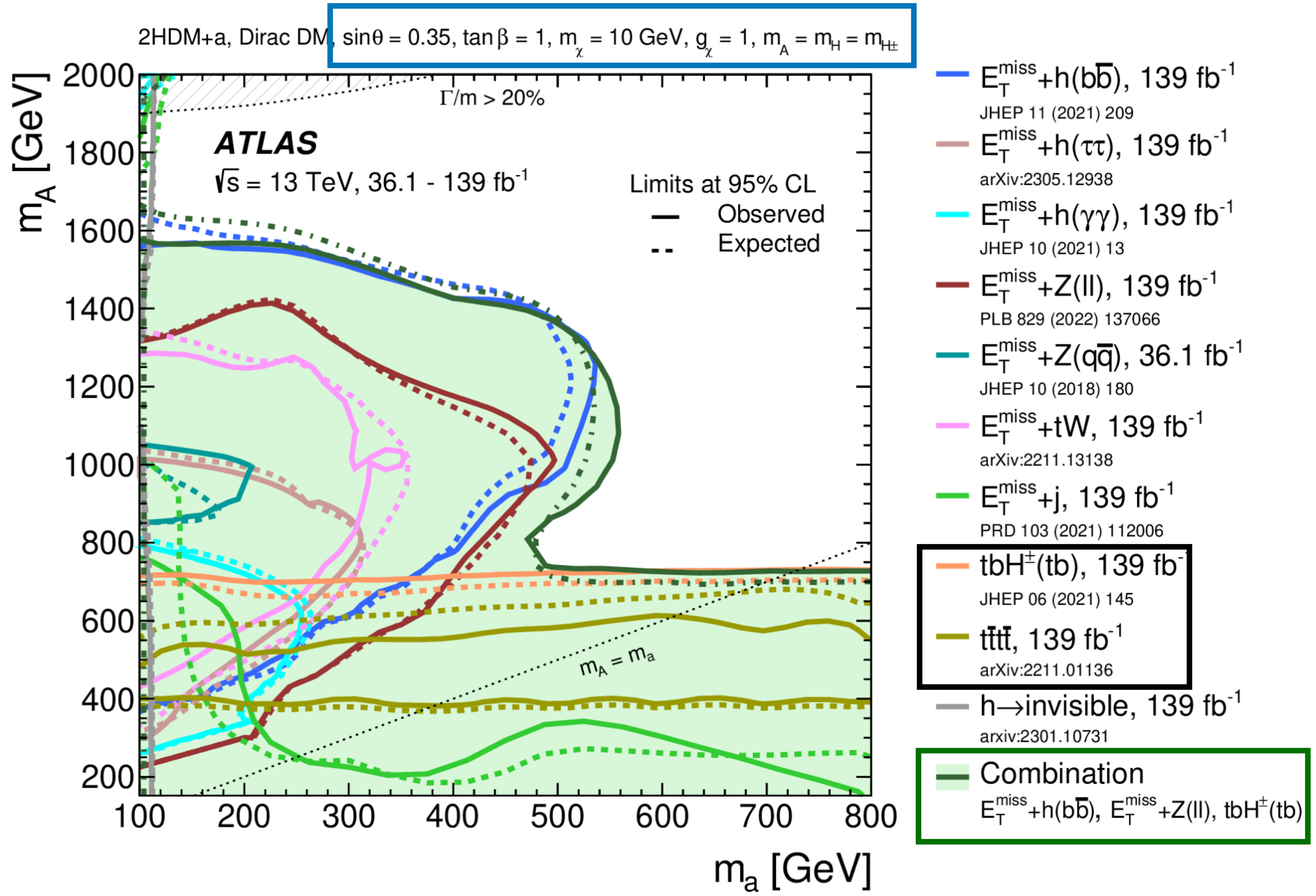




ATLAS 2HDM+a DM combination and summary [arXiv:2306.00641]

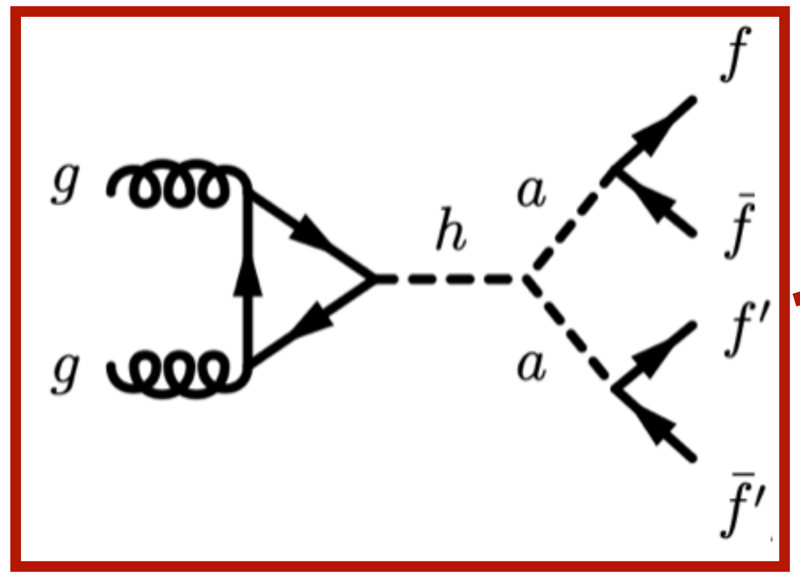
- **mono-h(bb)**, **mono-Z(ll)** and **tbH(tb)**: most sensitive channels and cover complementary regions of 2HDM+a parameter space
  - **Stat. combination** of 3 channels to maximize the exclusion power.

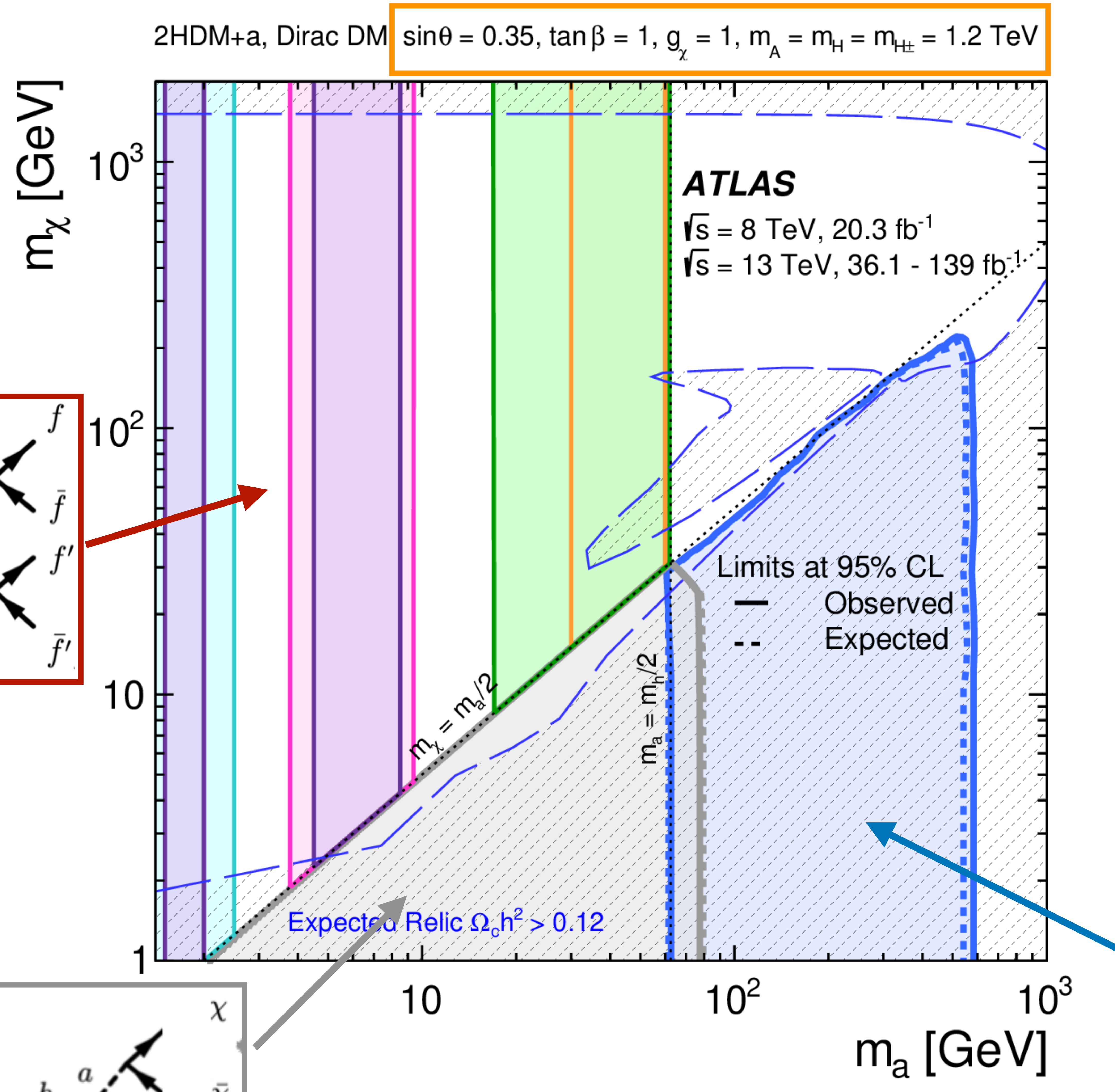




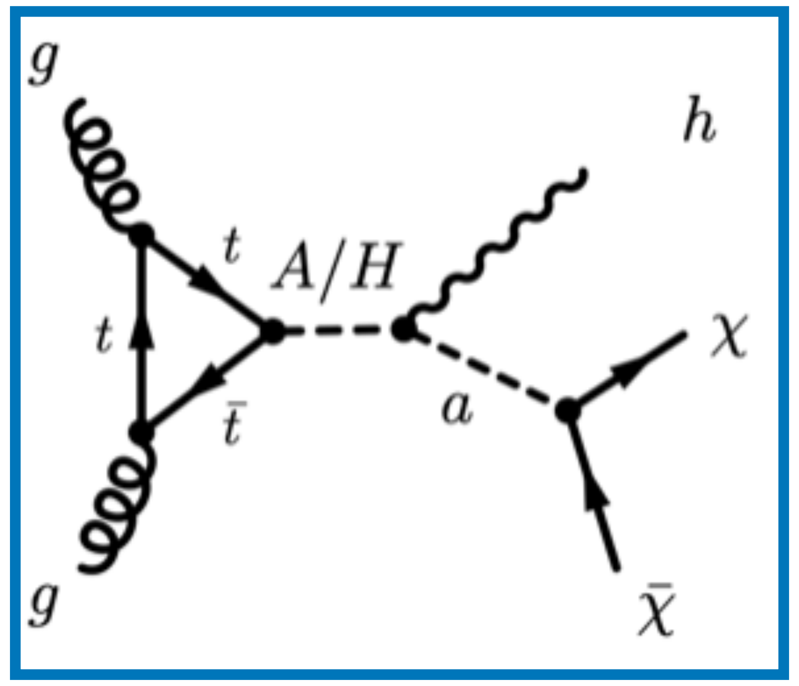
- Constraints on 2HDM+a from wide range of ATLAS DM searches derived for 6 benchmark scenarios.
  - **Searches not targeting DM give complementary constraints to DM searches.**
  - **Sensitivity driven by combination**

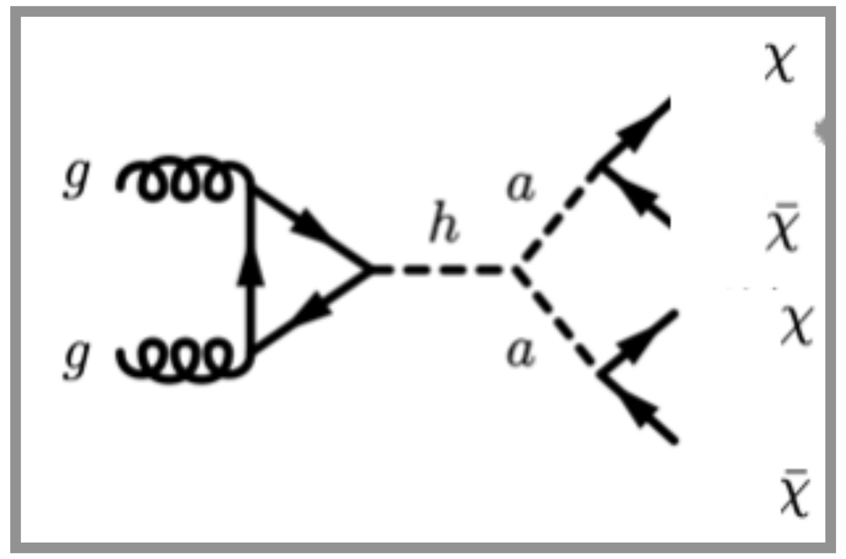
ATLAS 2HDM+a DM combination and summary arXiv:2306.00641





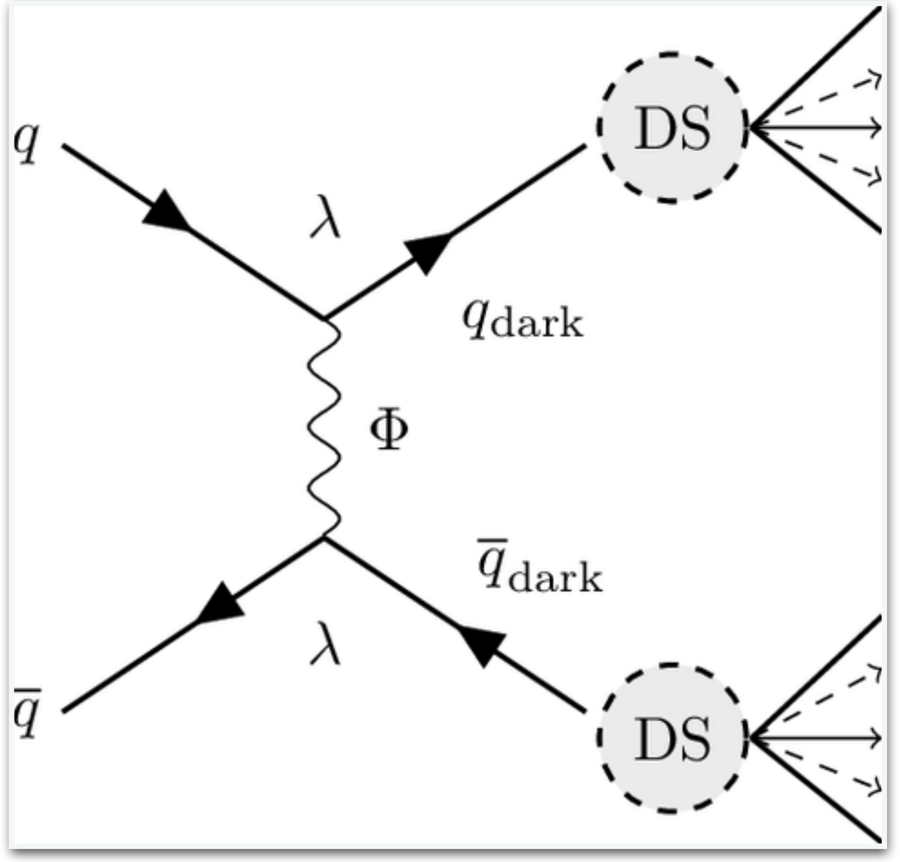
results used to constrain part of previously unprobed region where $a \nrightarrow \chi\chi$ for the 1st time





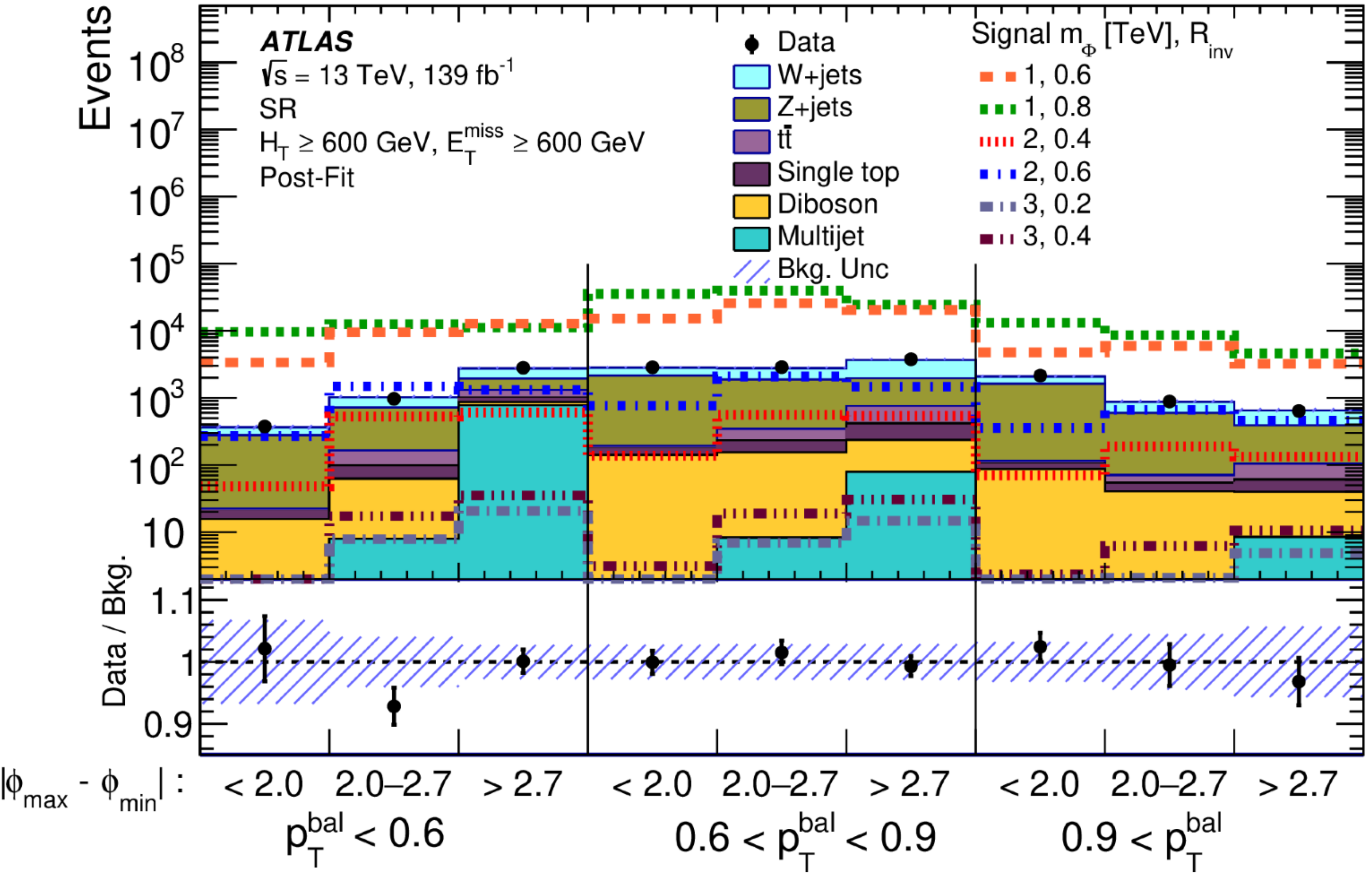
ATLAS *Semi-Visible Jets* search

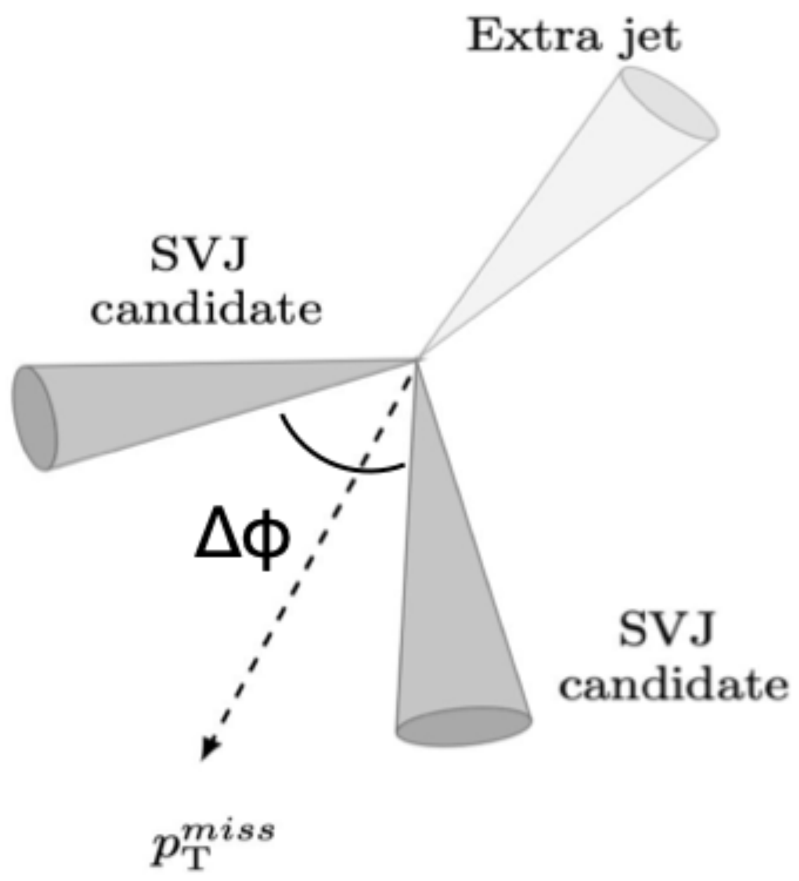
PLB 848 (2024) 138324



- Search for non-resonant SVJs in dark quark pair production via t-channel mediator Φ exchange.
  - Coupling λ is unknown.
- Stable dark hadrons in dark shower can significantly contribute to event's $p_{\rm T}^{\rm miss}$
  - requiring events to have **at least 2 jets with one align within $p_{\rm T}^{\rm miss}$ direction**.
- **9 categories** corresponding to orthogonal balance-$p_{\rm T}$ and $|\Delta\phi|$ ranges.

No significant deviation from SM





$$p_{\rm T}^{\rm bal} = \frac{|\vec{p}_{\rm T}(j_1) + \vec{p}_{\rm T}(j_2)|}{|\vec{p}_{\rm T}(j_1)| + |\vec{p}_{\rm T}(j_2)|}$$