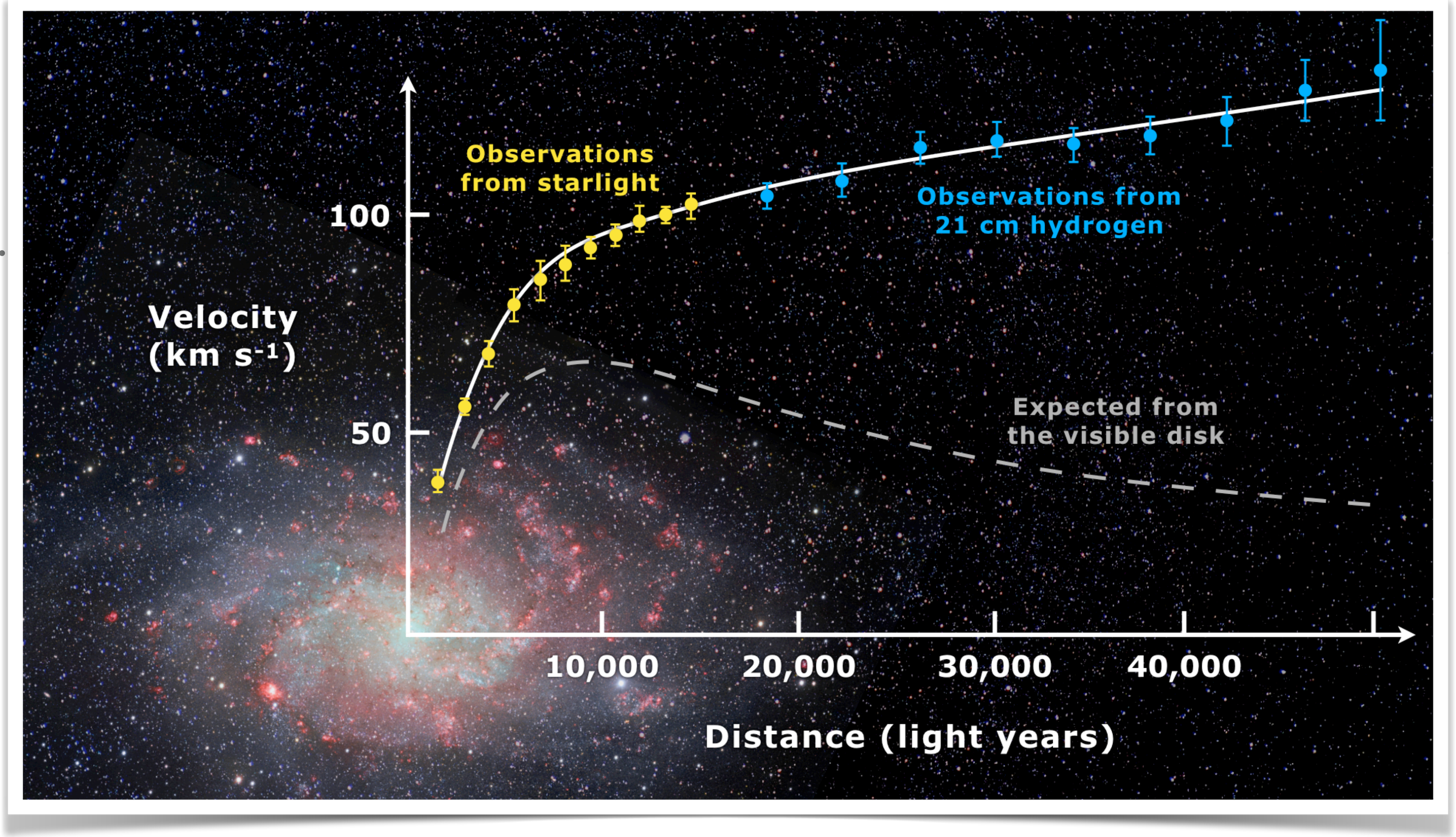
Dark Matter Searches at the LHC

Vulcano 2024 Workshop 31st, May 2024

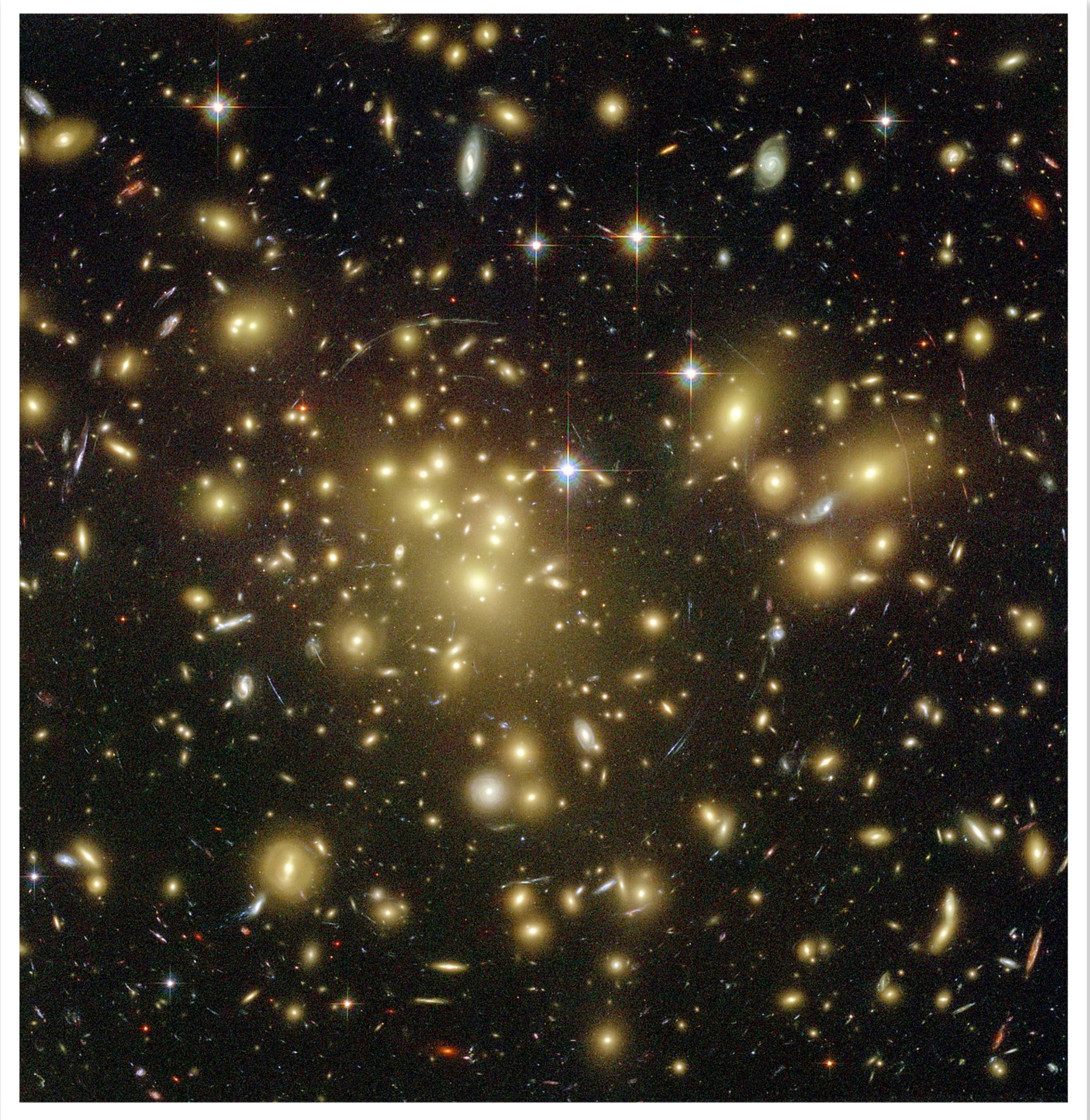
Claudia Seitz on behalf of ATLAS and CMS

Dark Matter

- Compelling evidence from astrophysical observations for existence of non-luminous, gravitationally interacting matter

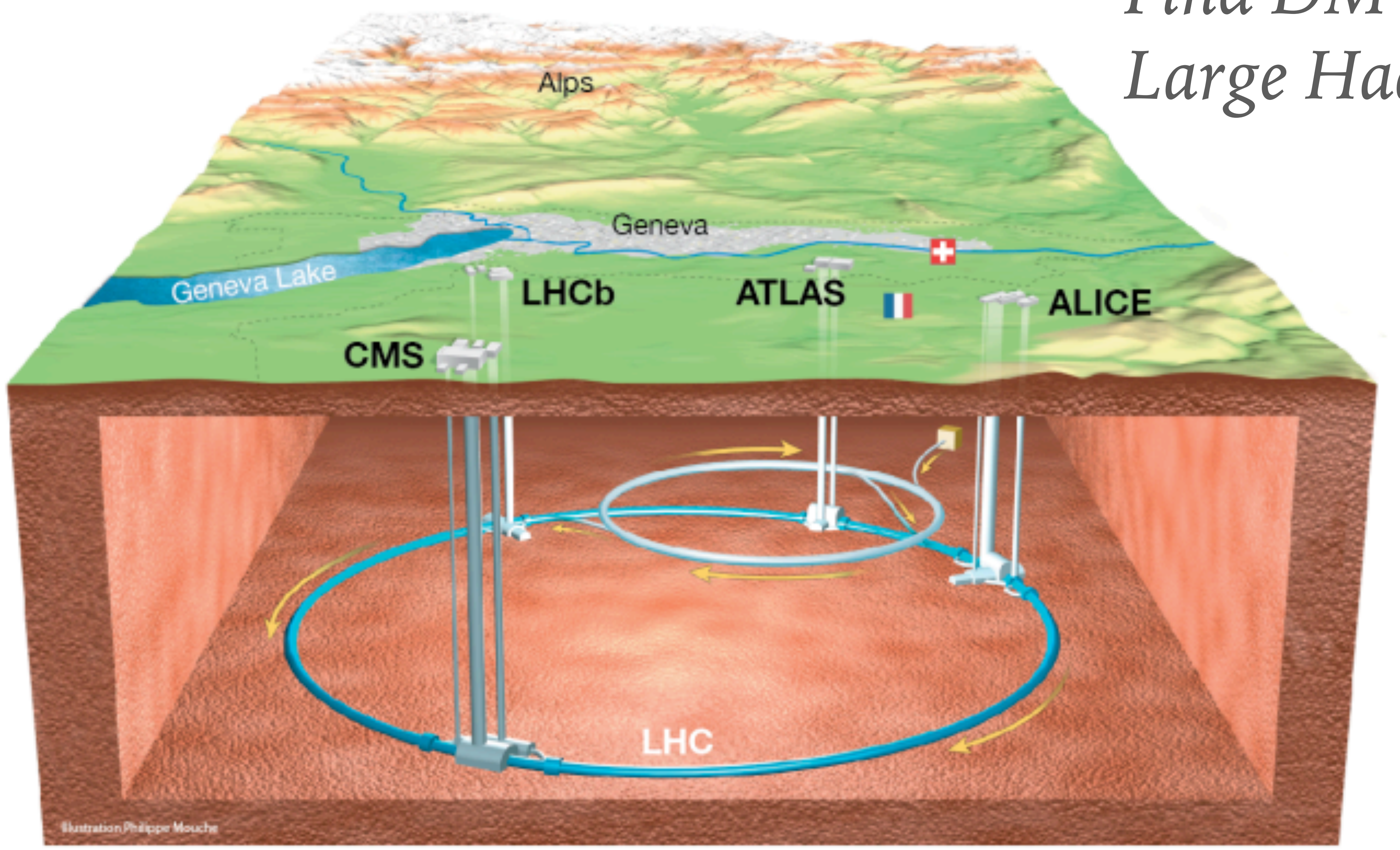


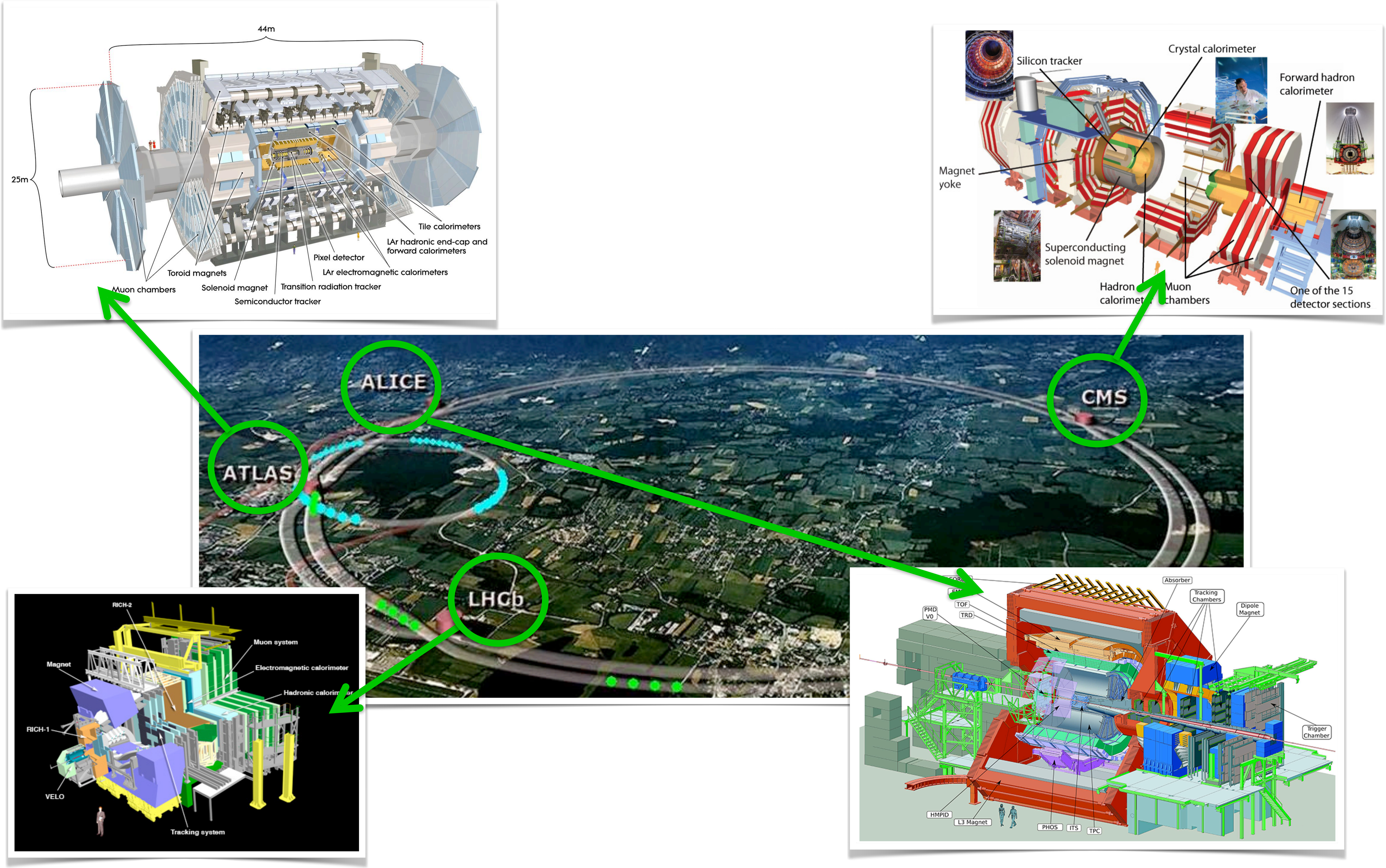
Rotational curves of galaxies



Strong gravitational lensing as observed by the [Hubble Space Telescope](#) in [Abell 1689](#)

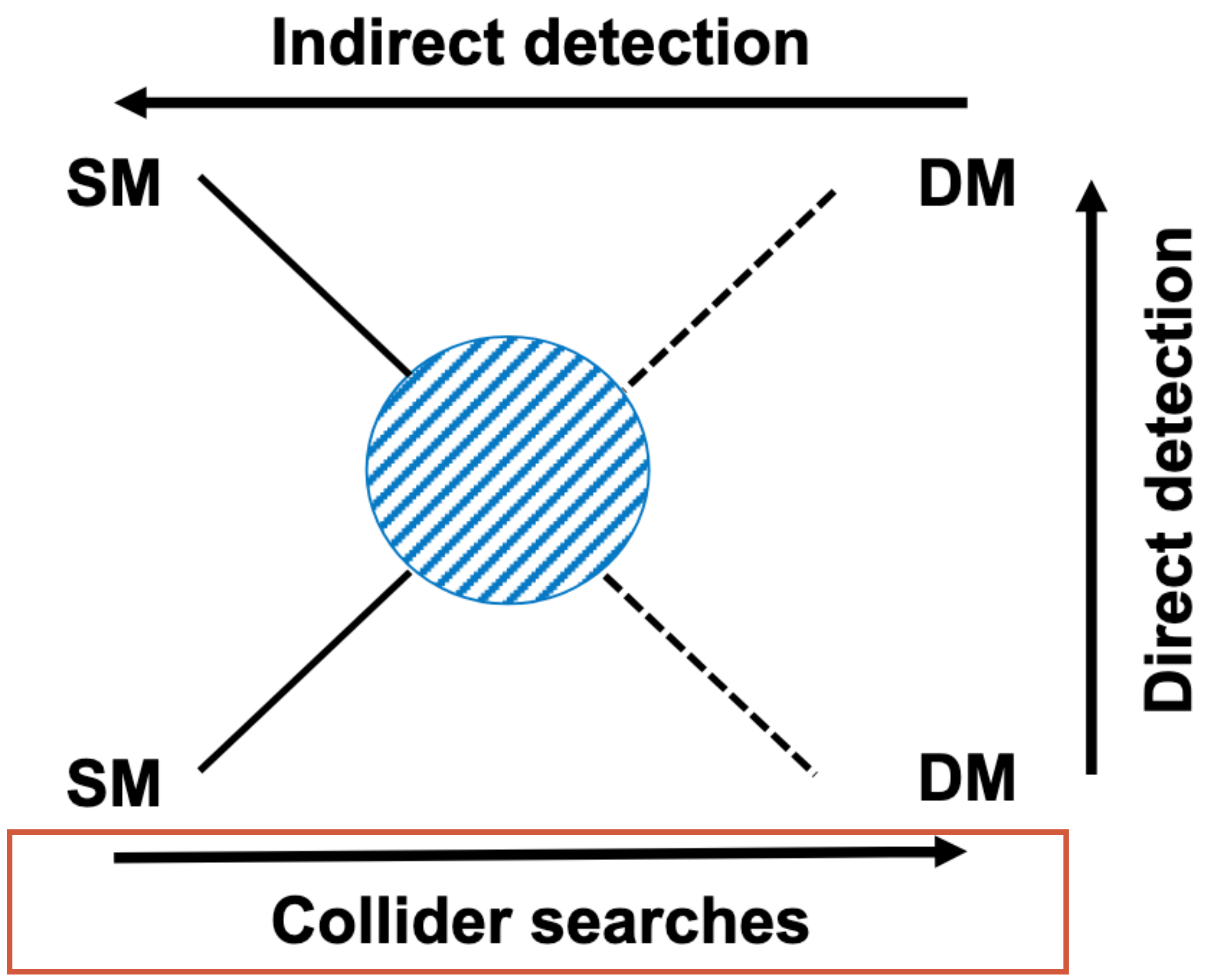
Find DM at the Large Hadron Collider?




44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker
Silicon tracker
Crystal calorimeter
Forward hadron calorimeter
Magnet yoke
Superconducting solenoid magnet
Hadron calorimeter
Muon chambers
One of the 15 detector sections
ALICE
ATLAS
CMS
LHCb
RICH-2
Muon system
Magnet
Electromagnetic calorimeter
Hadronic calorimeter
RICH-1
VELO
Tracking system
Absorber
Tracking Chambers
Dipole Magnet
PMD
V0
TOF
TRD
Trigger Chamber
HMPID
L3 Magnet
PHOS
ITS
TPC

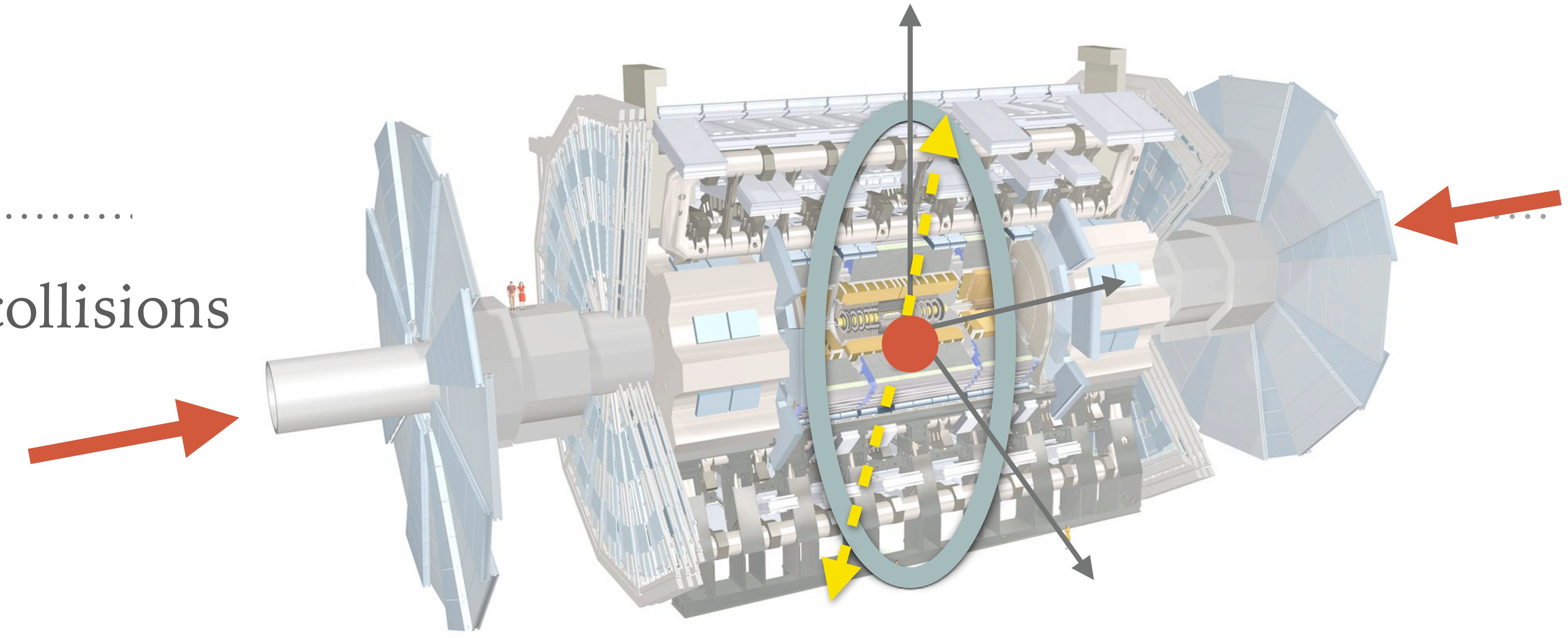
Dark Matter searches at colliders

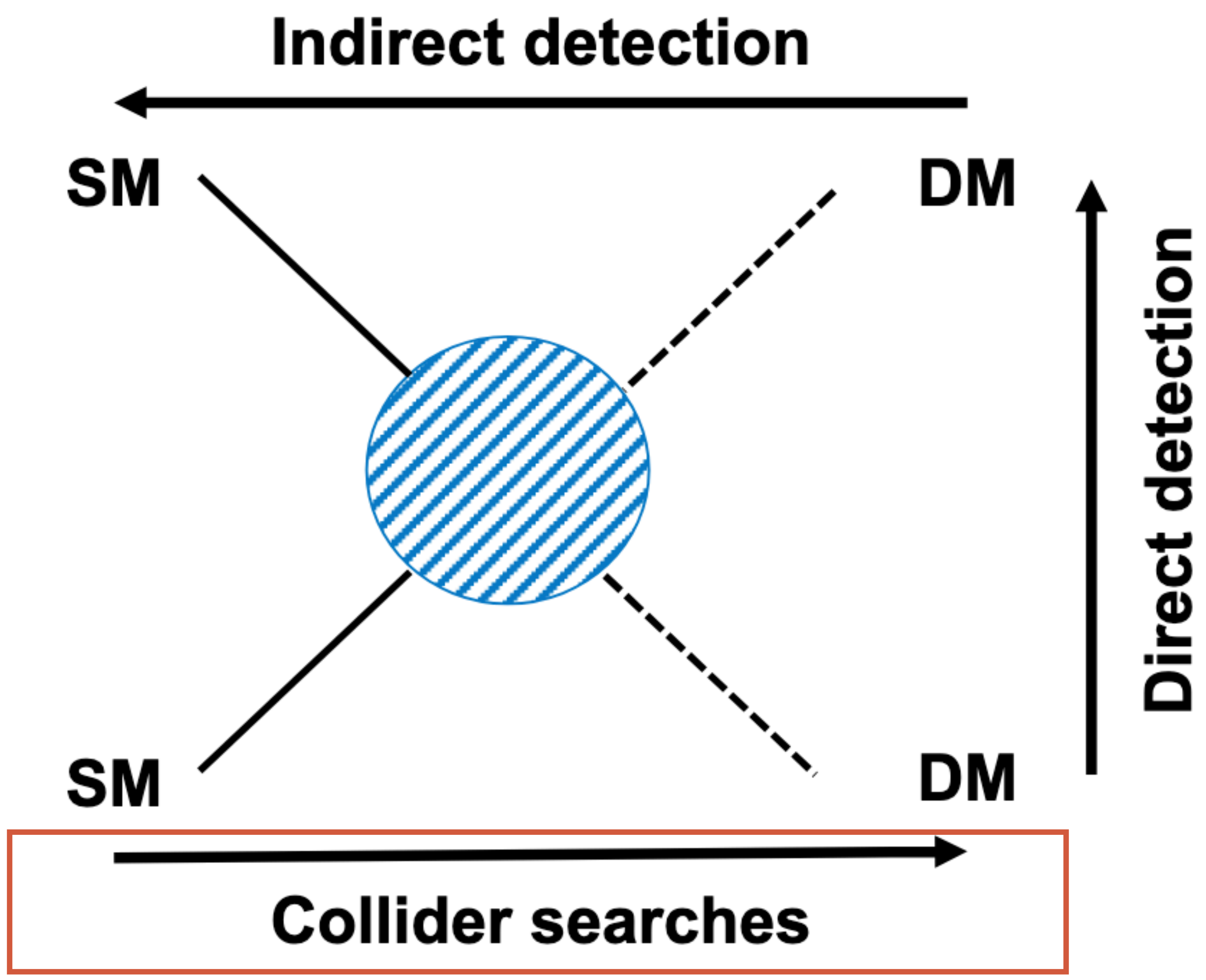
- Assumption: DM can be produced in **proton-proton** collisions
  - DM does not interact with the detector

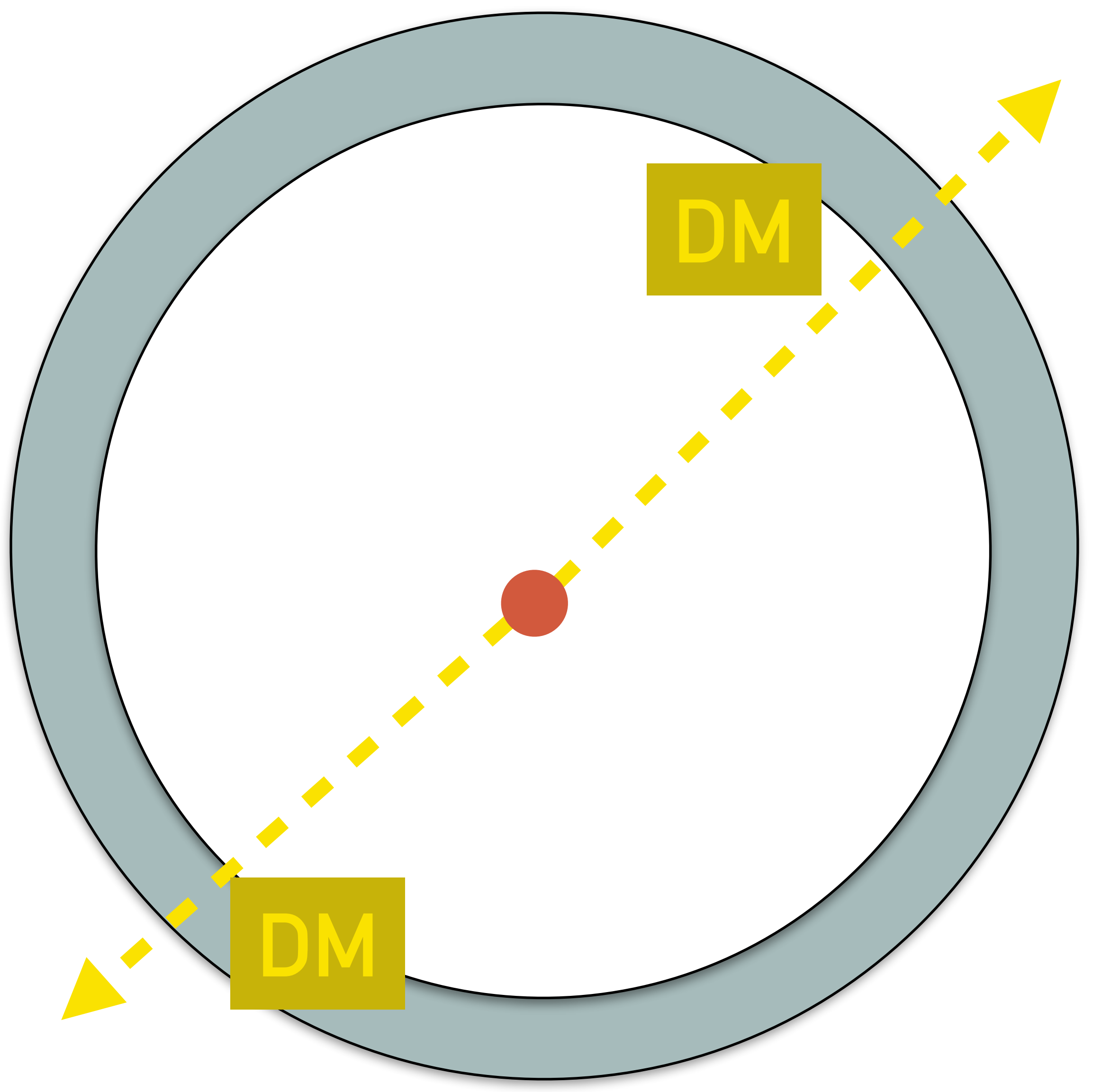


Dark Matter searches at colliders

- Assumption: DM can be produced in **proton-proton** collisions
  - DM does not interact with the detector

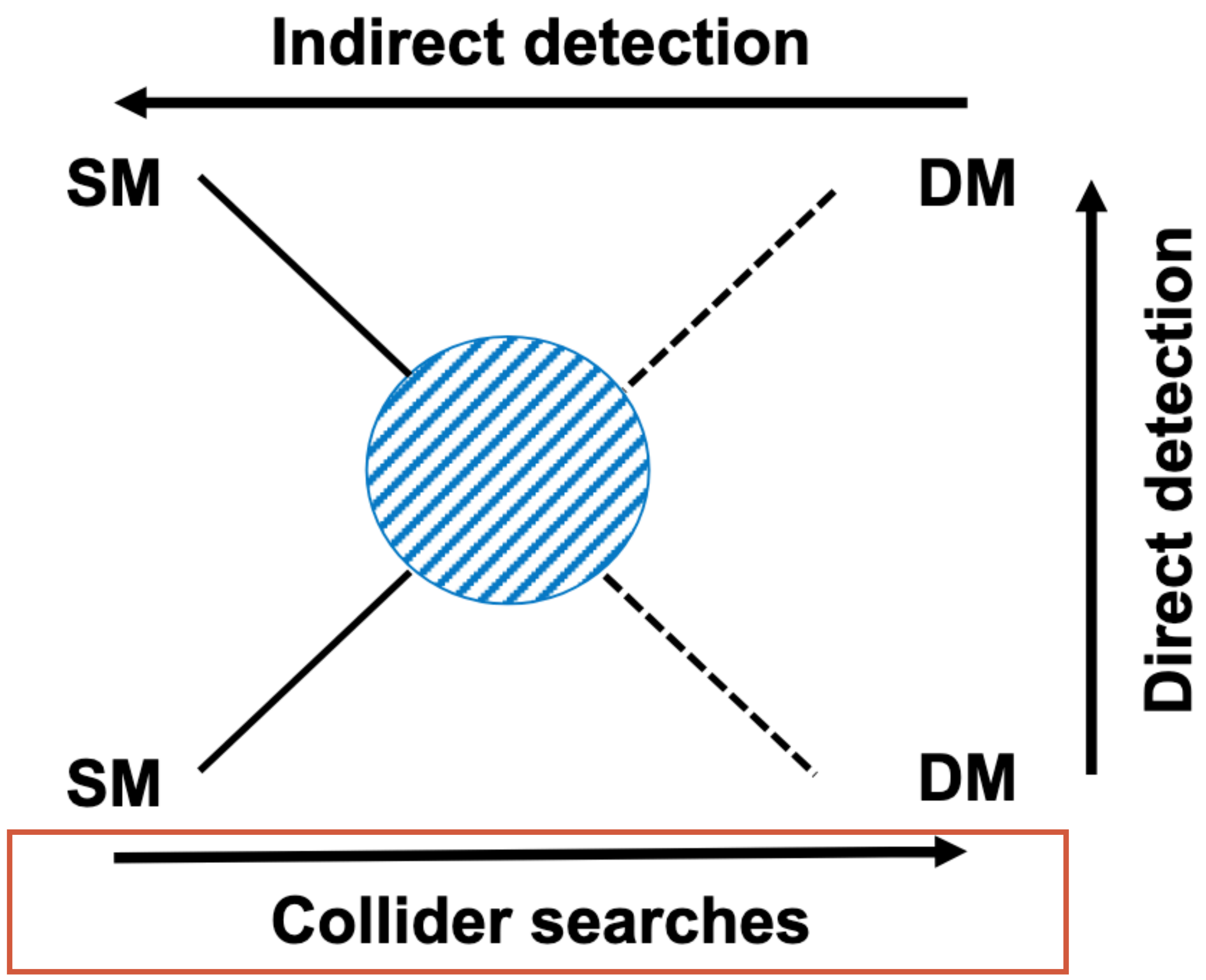


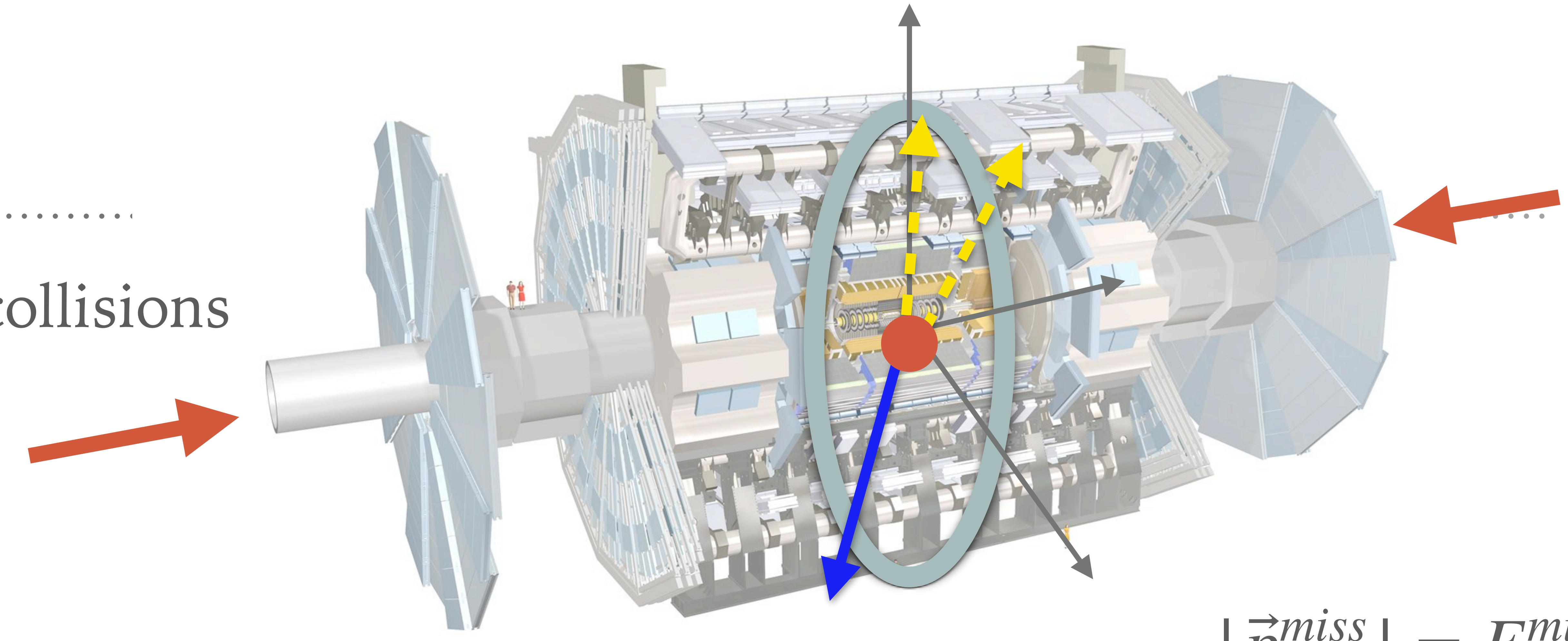




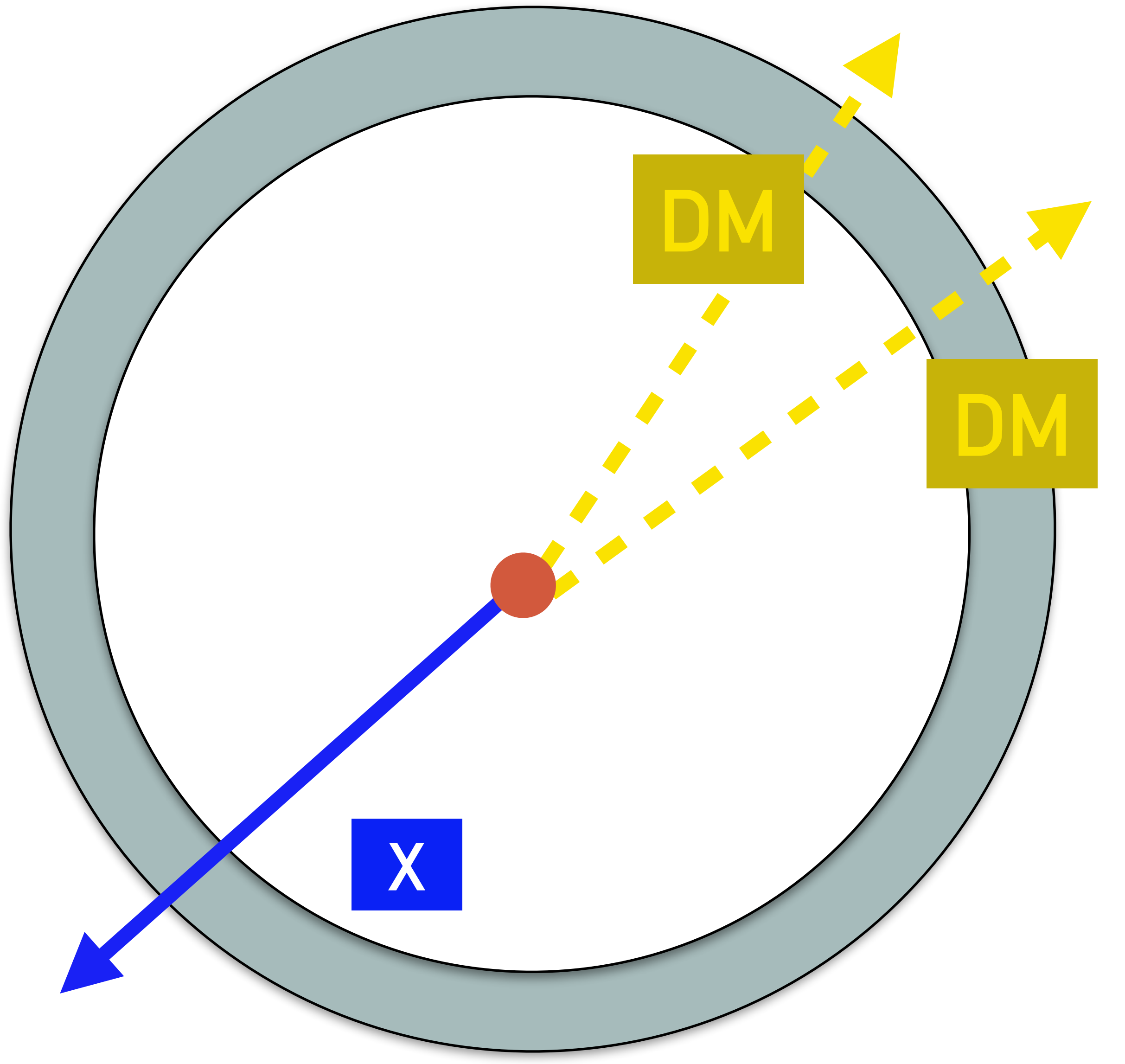
Dark Matter searches at colliders

- Assumption: DM can be produced in **proton-proton** collisions
  - DM does not interact with the detector





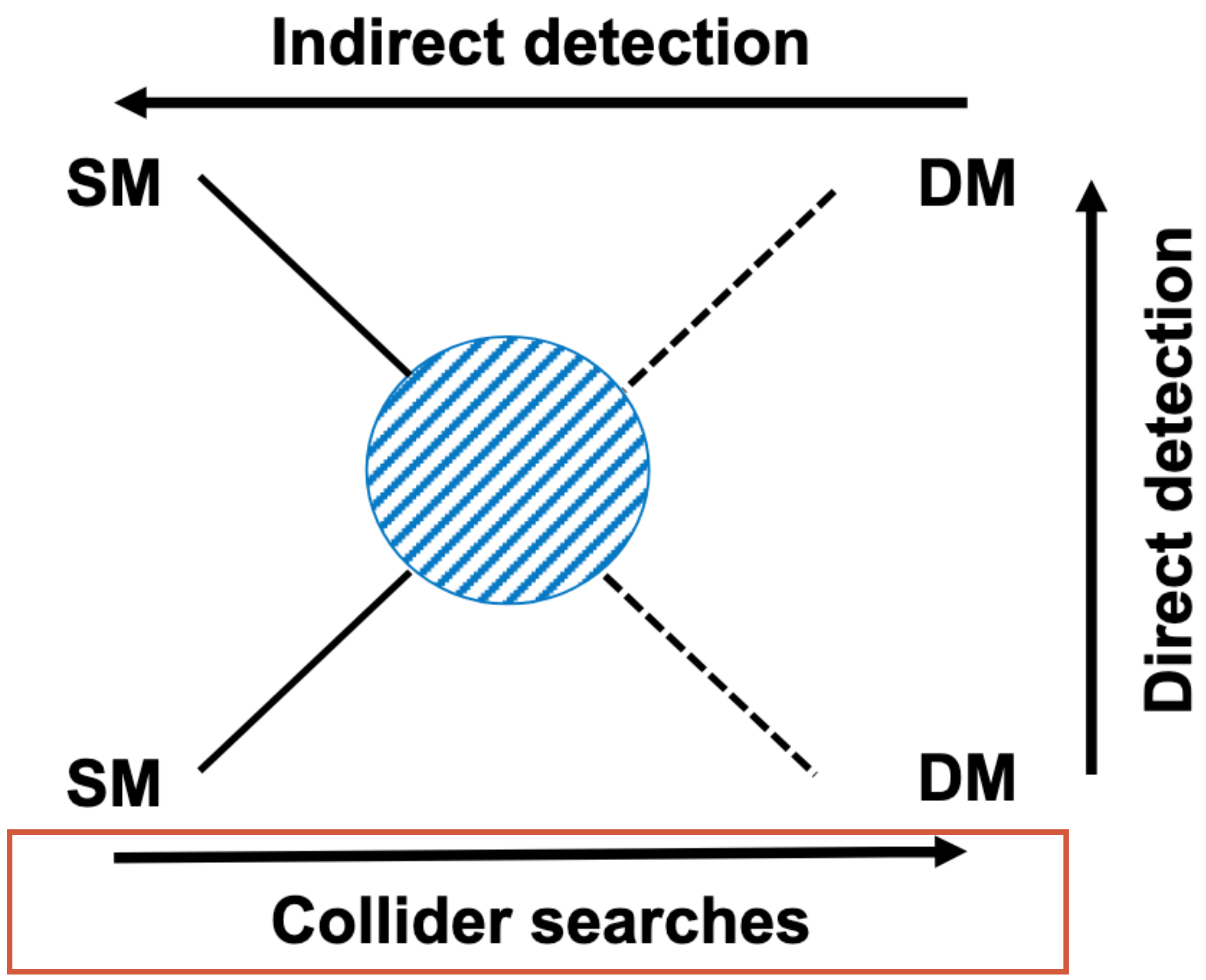
$$|\vec{p}_T^{miss}| = E_T^{miss}$$

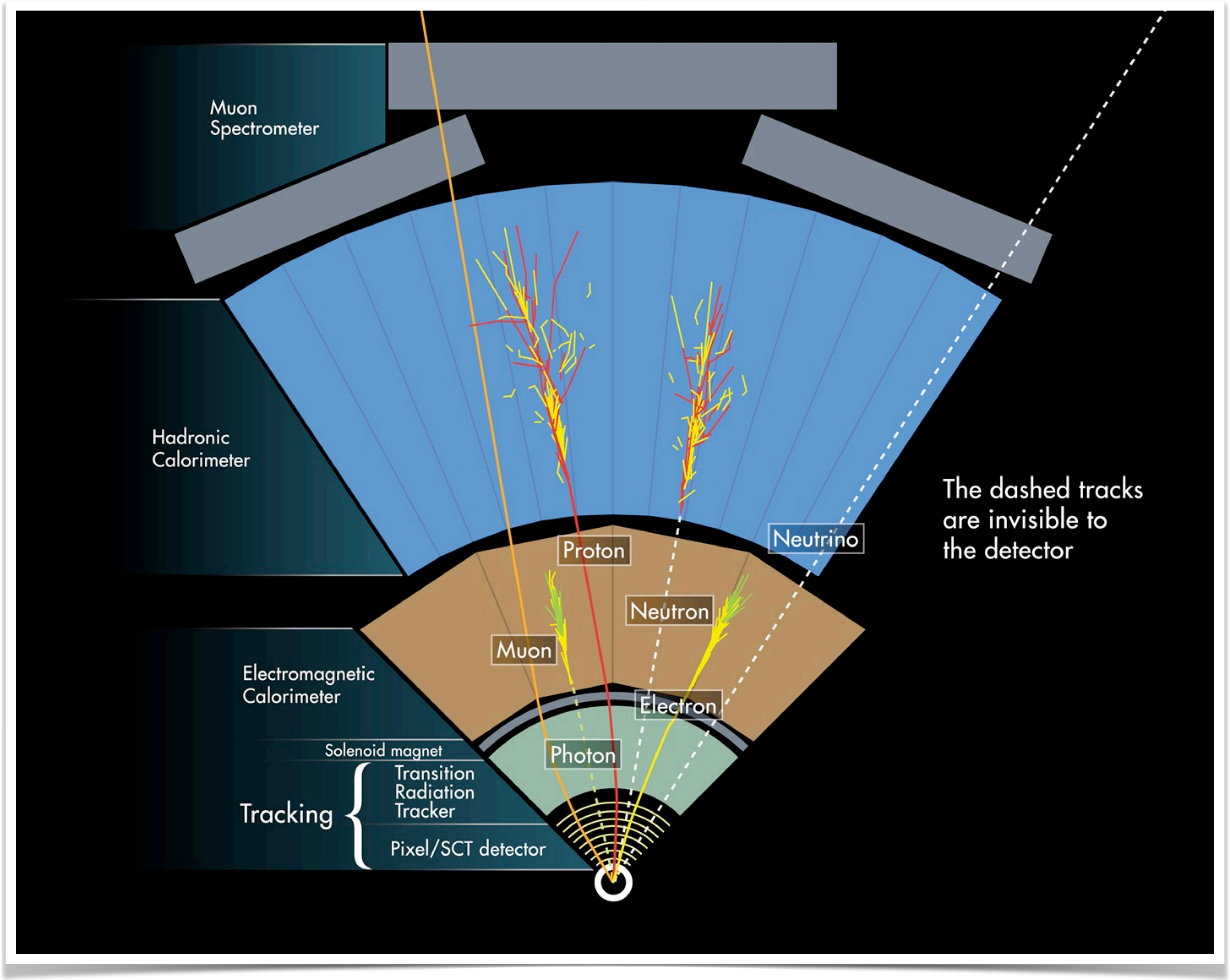


- Presence of DM can be inferred due to a **momentum imbalance in transverse plane** when produced in association with particles "X"

Dark Matter searches at colliders

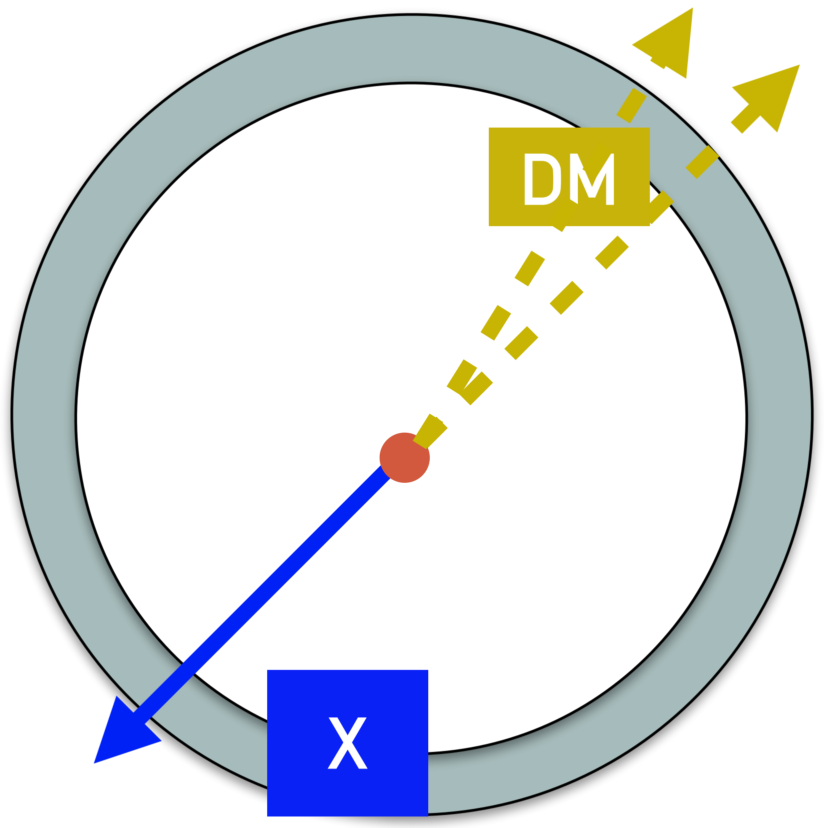
- Assumption: DM can be produced in **proton-proton** collisions
  - DM does not interact with the detector

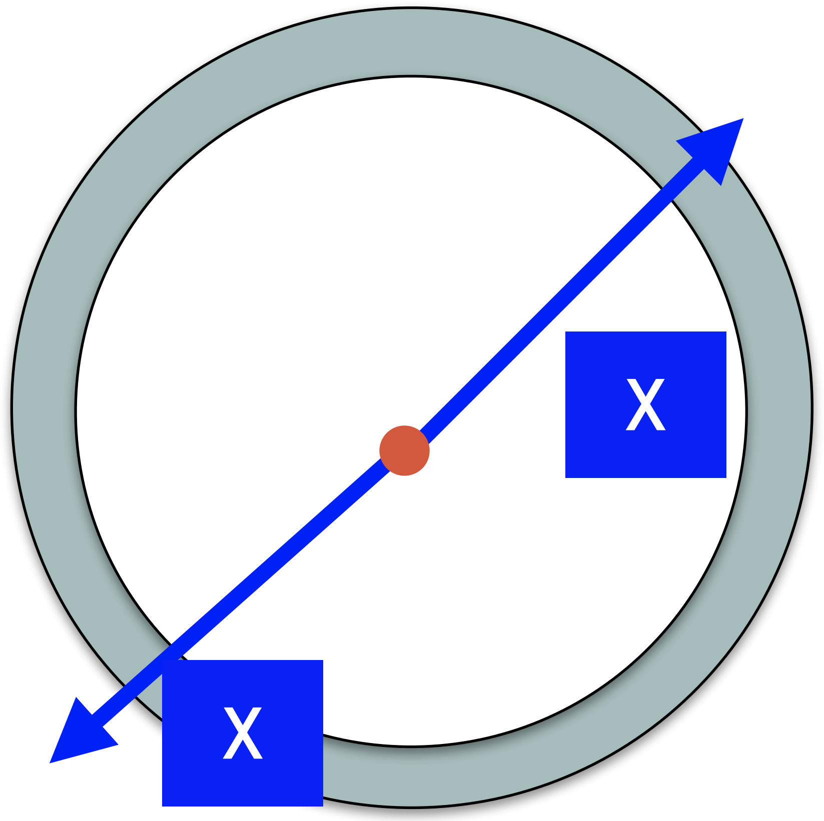




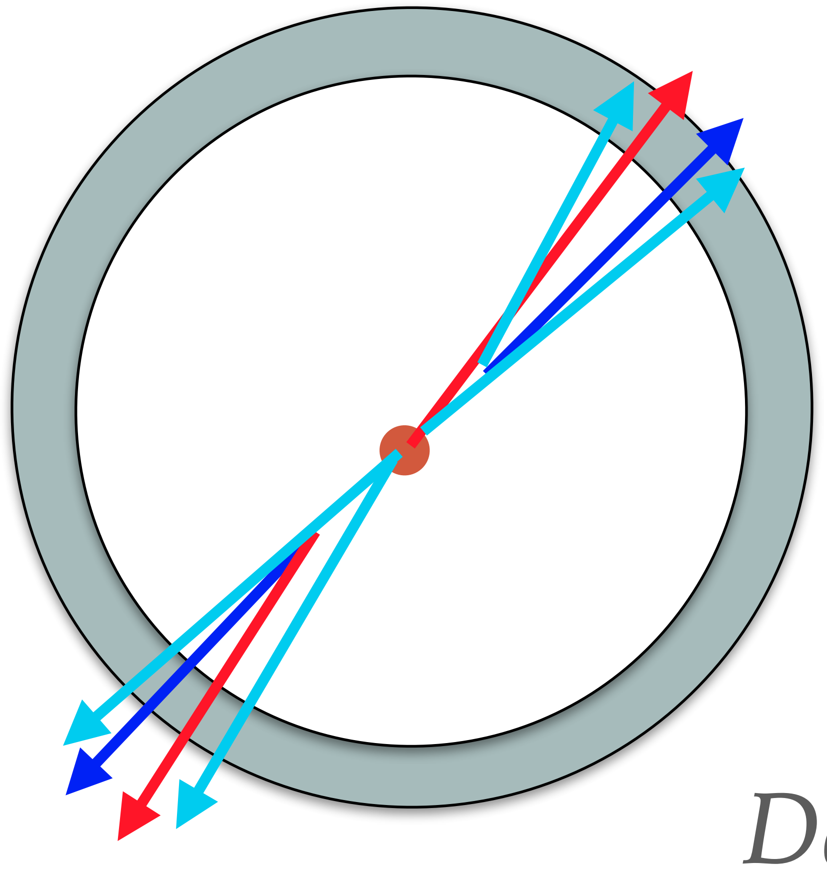
How are we trying to find DM at the LHC?

$E_T^{miss} + X$





Resonance searches

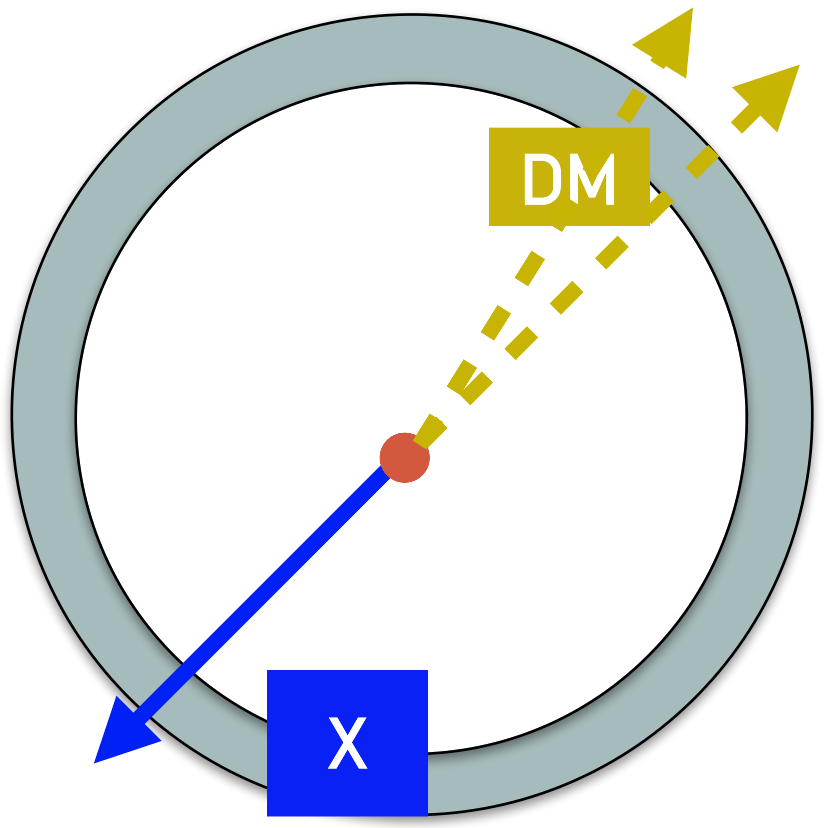


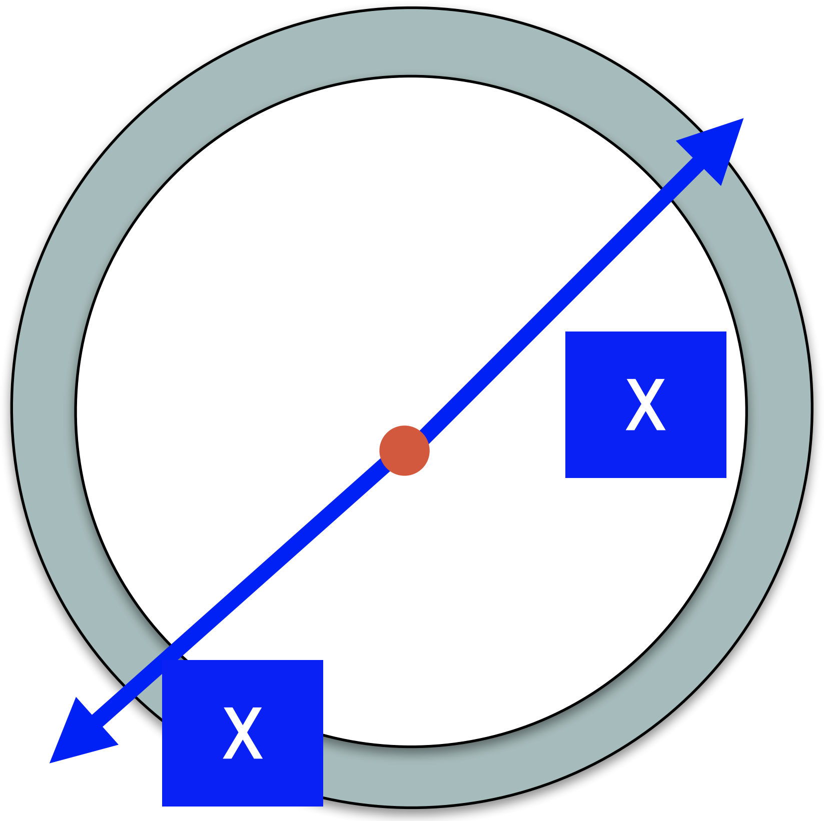
Dark QCD: emerging jets

- Several ways of approaching this issue
  - **Signature driven**
    - Conventional: known SM particles w/o E_T^{miss}
    - Unconventional: Dark QCD, semi visible or emerging jets, ….
  - **Model driven**
    - start from a specific theory prediction
      $\Rightarrow$ design and optimize for a specific model
- **All these strategies are followed at the LHC**

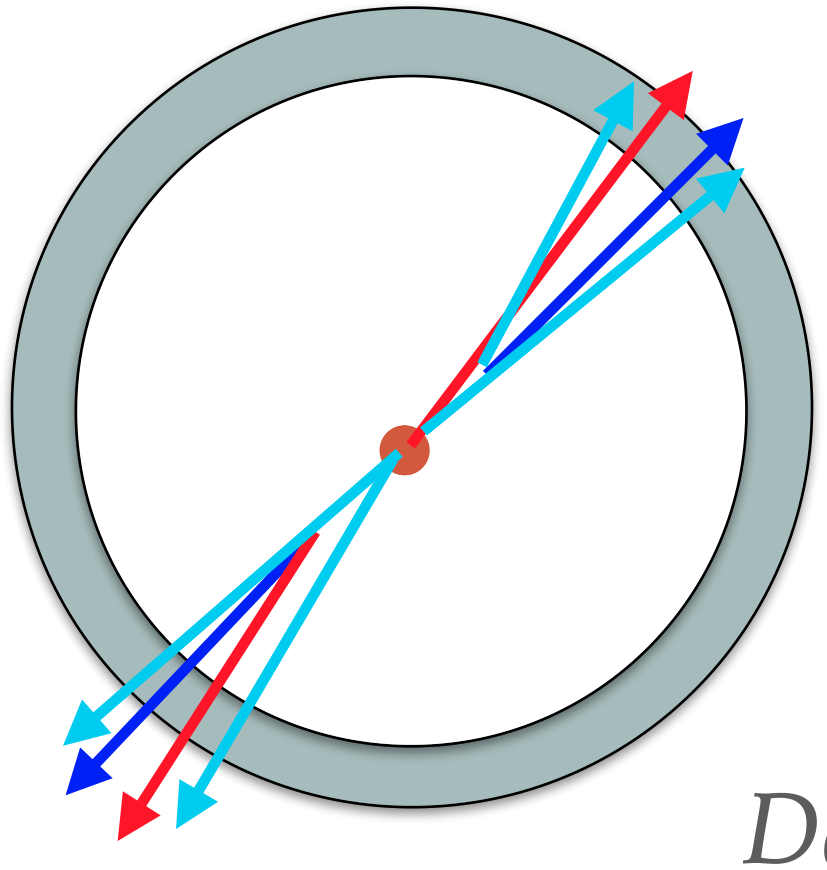
How are we trying to find DM at the LHC?

$E_T^{miss} + X$





Resonance searches



Dark QCD: emerging jets

- Several ways of approaching this issue
  - **Signature driven**
    - Conventional: known SM particles w/o E_T^{miss}
    - Unconventional: Dark QCD, semi visible or emerging jets, ….
  - **Model driven**
    - start from a specific theory prediction
      ⇒ design and optimize for a specific model

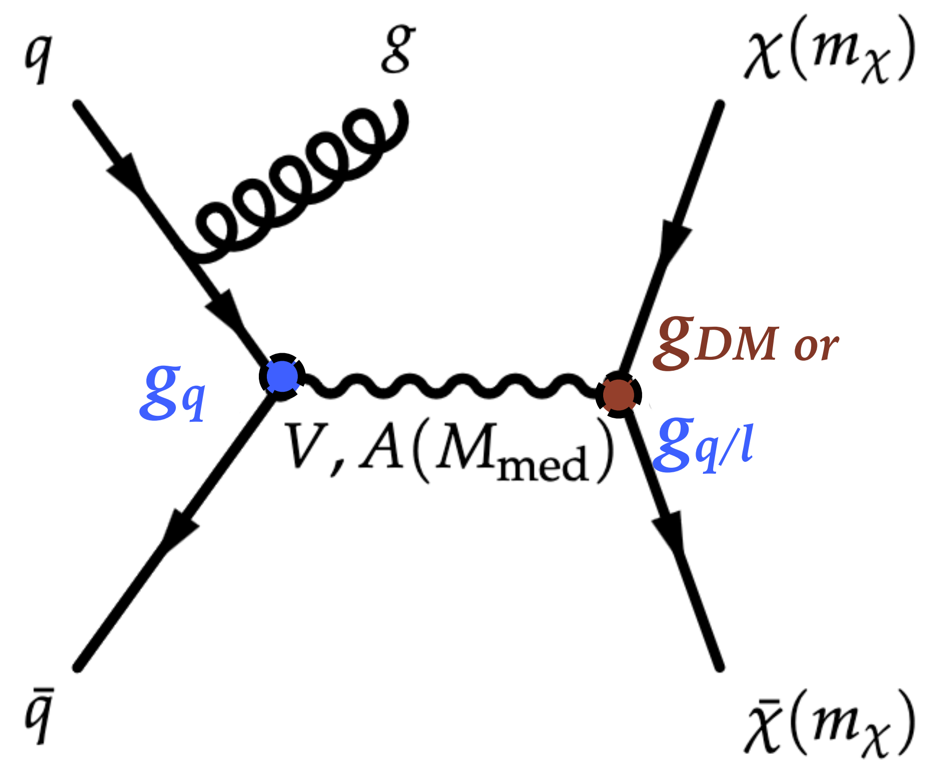
- **All these strategies are followed at the LHC**

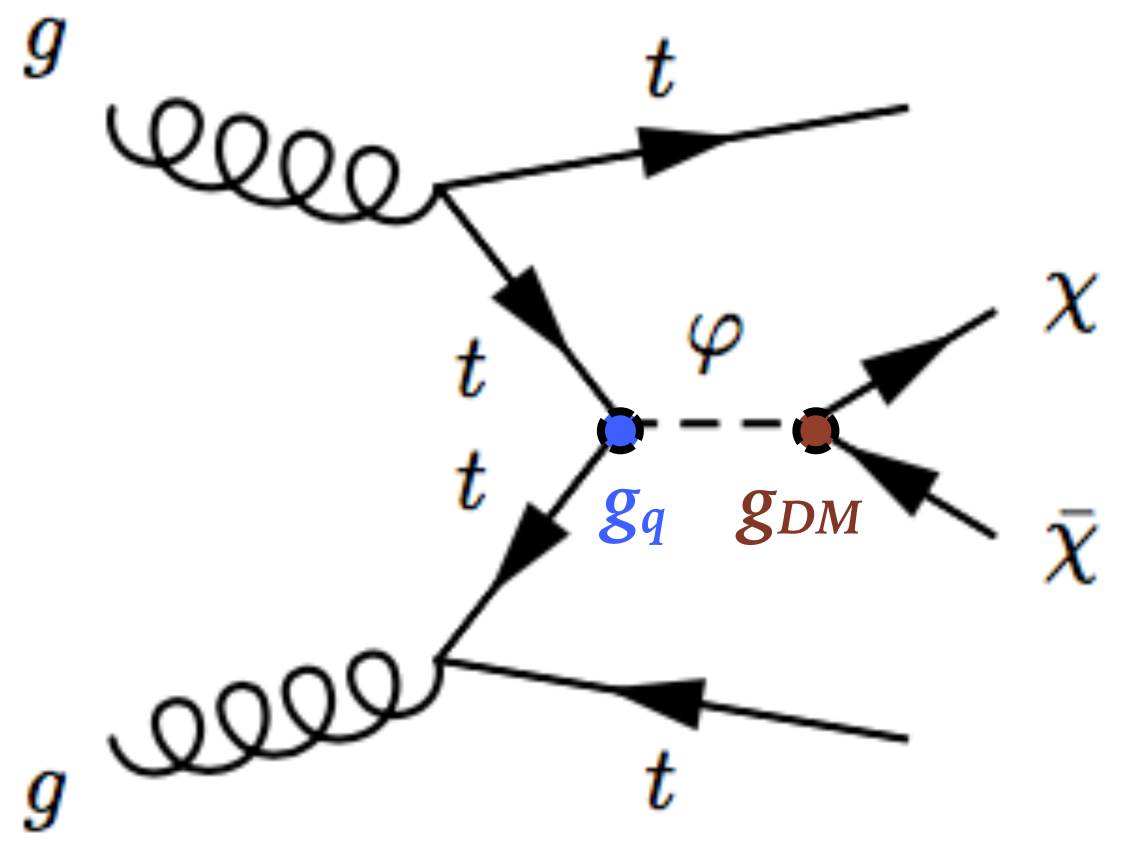
New summary reports:

ATLAS: arxiv:2403.09292 and CMS: arxiv:2405.13778

Signature driven: Simplified dark matter models

- WIMP model for DM production at colliders
- **Production of new mediator**
  - Mediator decays into two Dirac fermion dark matter particles χ, which escape detection



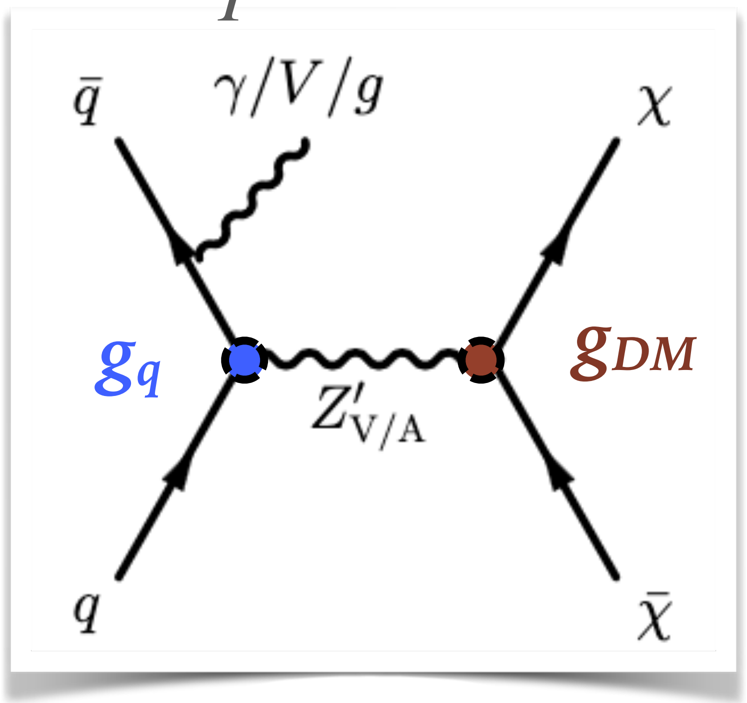


  - Small set of parameters:
    - Type of mediator: **vector, axial-vector, scalar or pseudo scalar**
    - Masses: $\mathbf{m_{med}}$, $\mathbf{m_\chi}$
    - Couplings: **$g_{q/l}$ (SM (quarks/leptons) and mediator)**, **g_χ (mediator and DM)**

arxiv:2405.13778
Phys. Rev. D 103 (2021) 112006
JHEP 05 (2020) 033

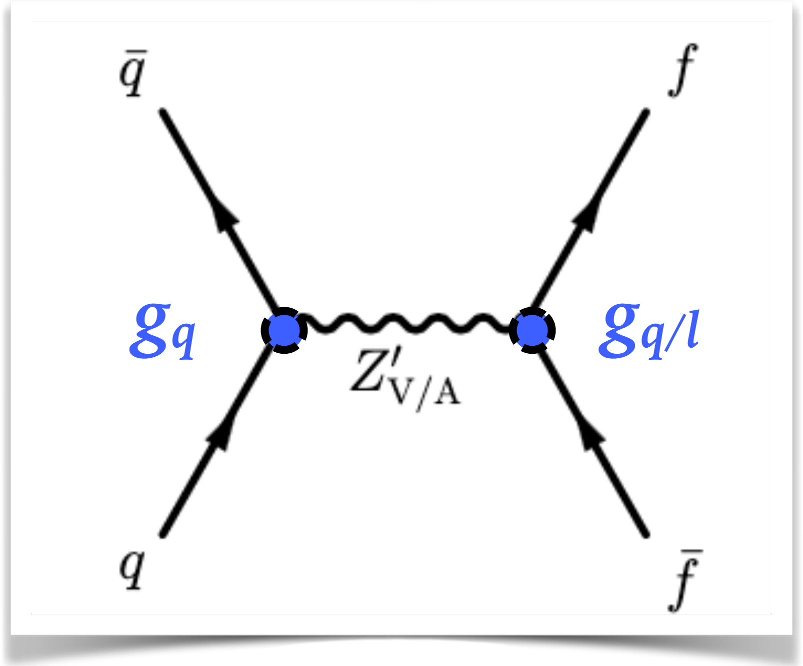
Vector and Axial-Vector

$E_T^{miss} + X$

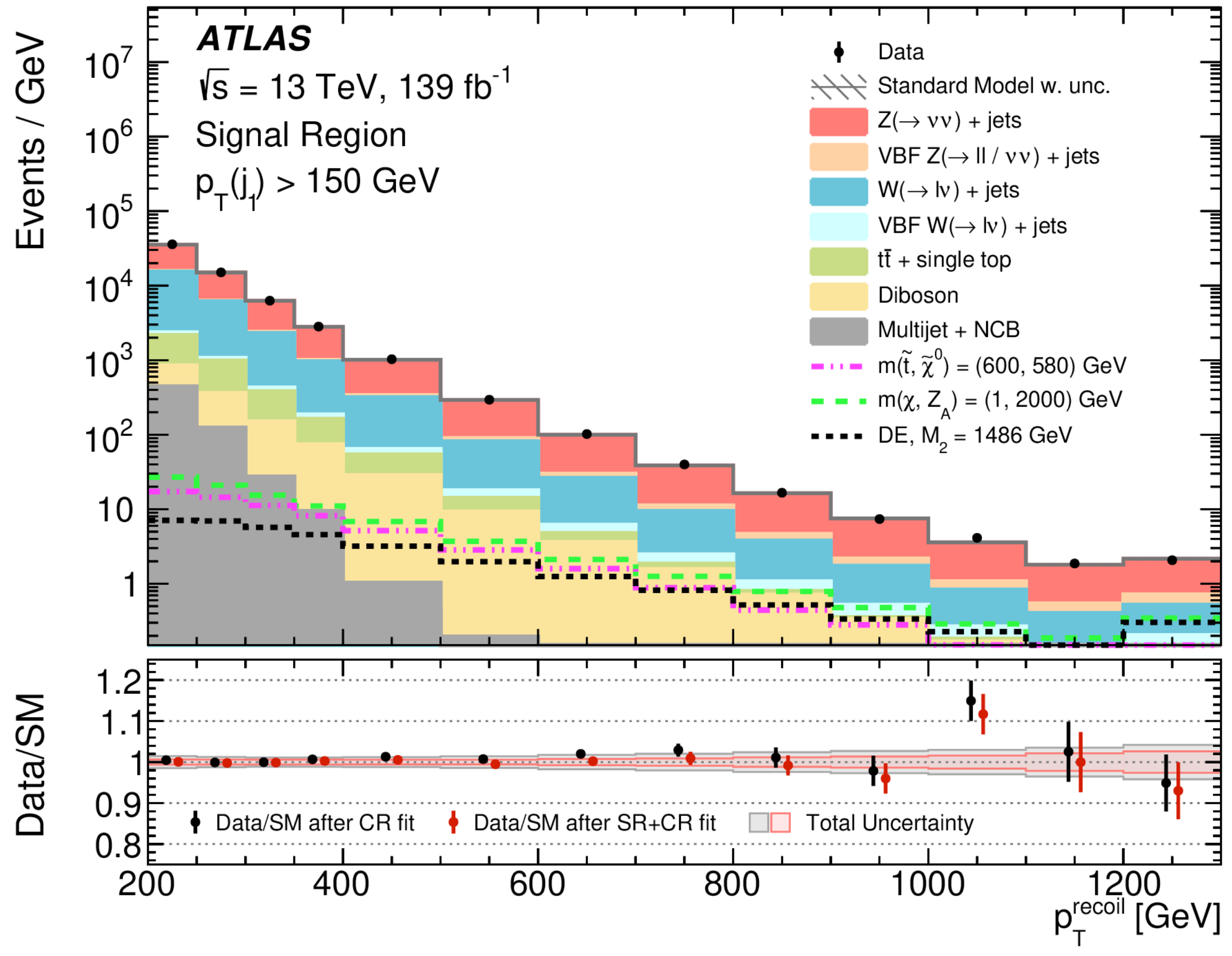


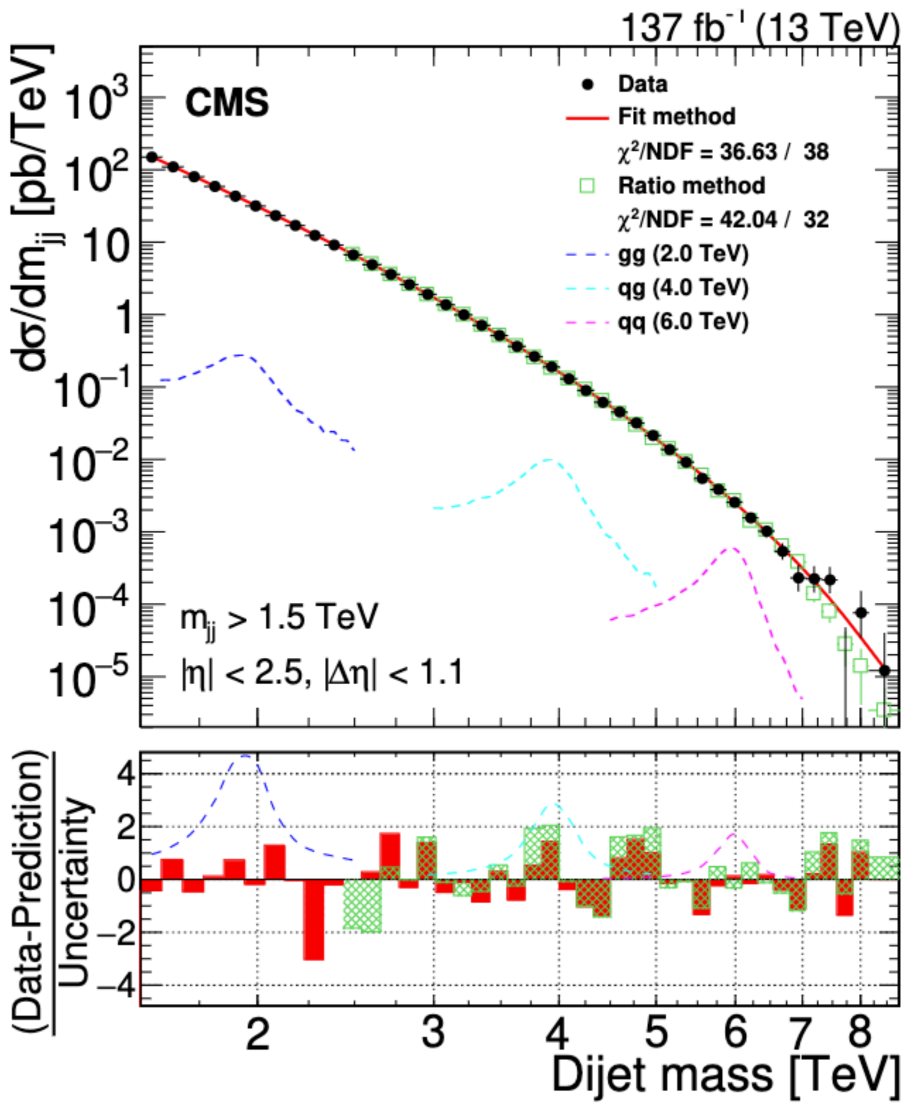
Signature: initial state radiation (jet, photon, W, Z) + E_T^{miss}

Visible resonance



Signature: di-jet, di-photon, di-lepton resonances

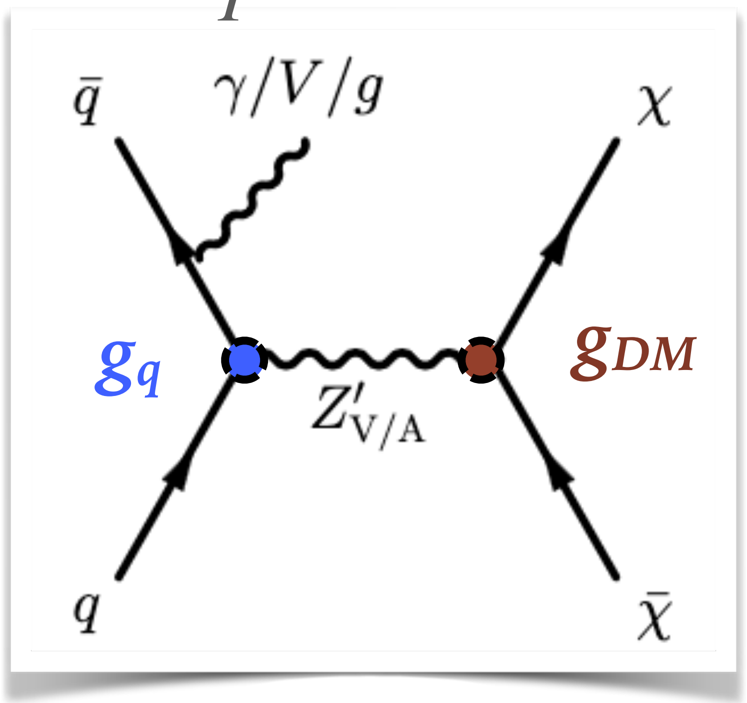




arxiv:2405.13778
Phys. Rev. D 103 (2021) 112006
JHEP 05 (2020) 033

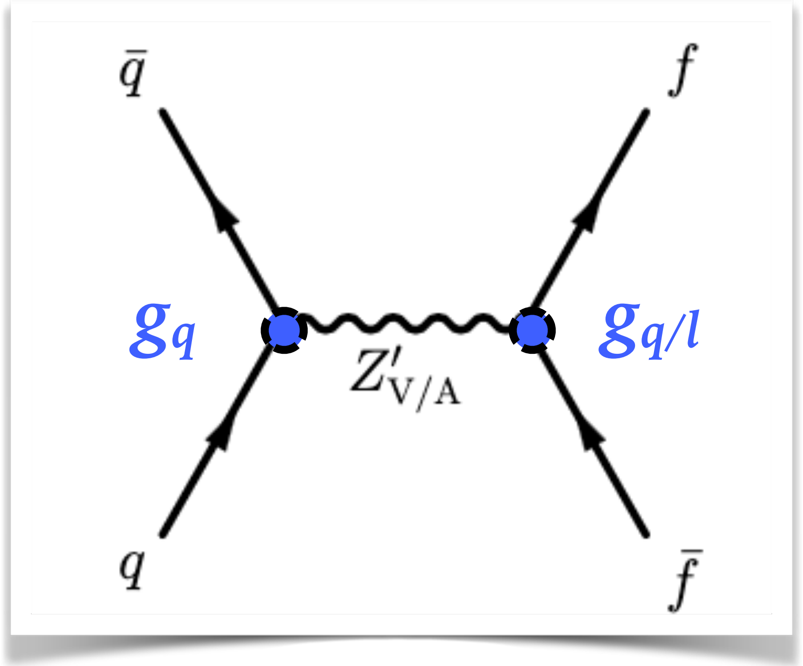
Vector and Axial-Vector

$E_T^{miss} + X$

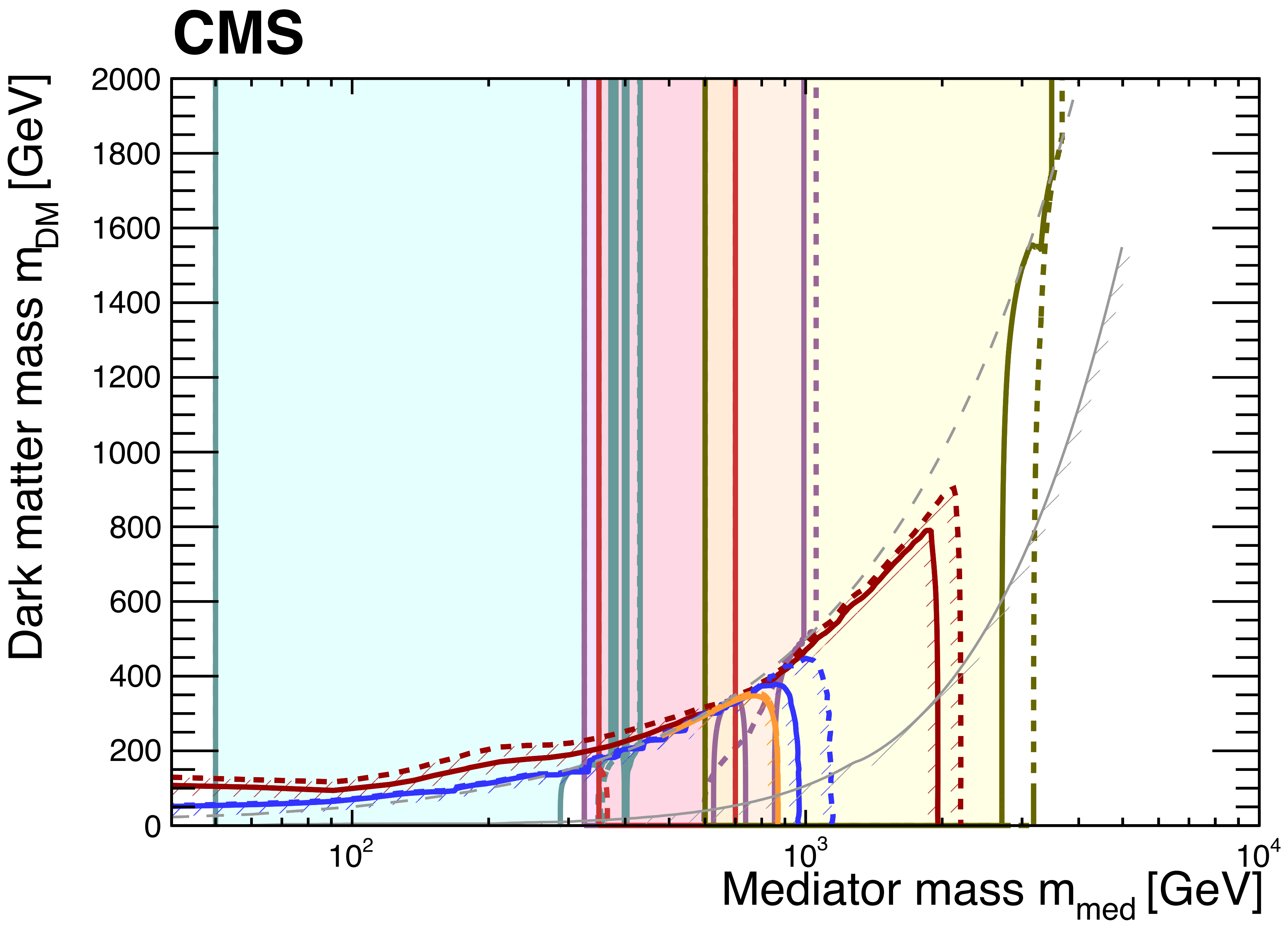


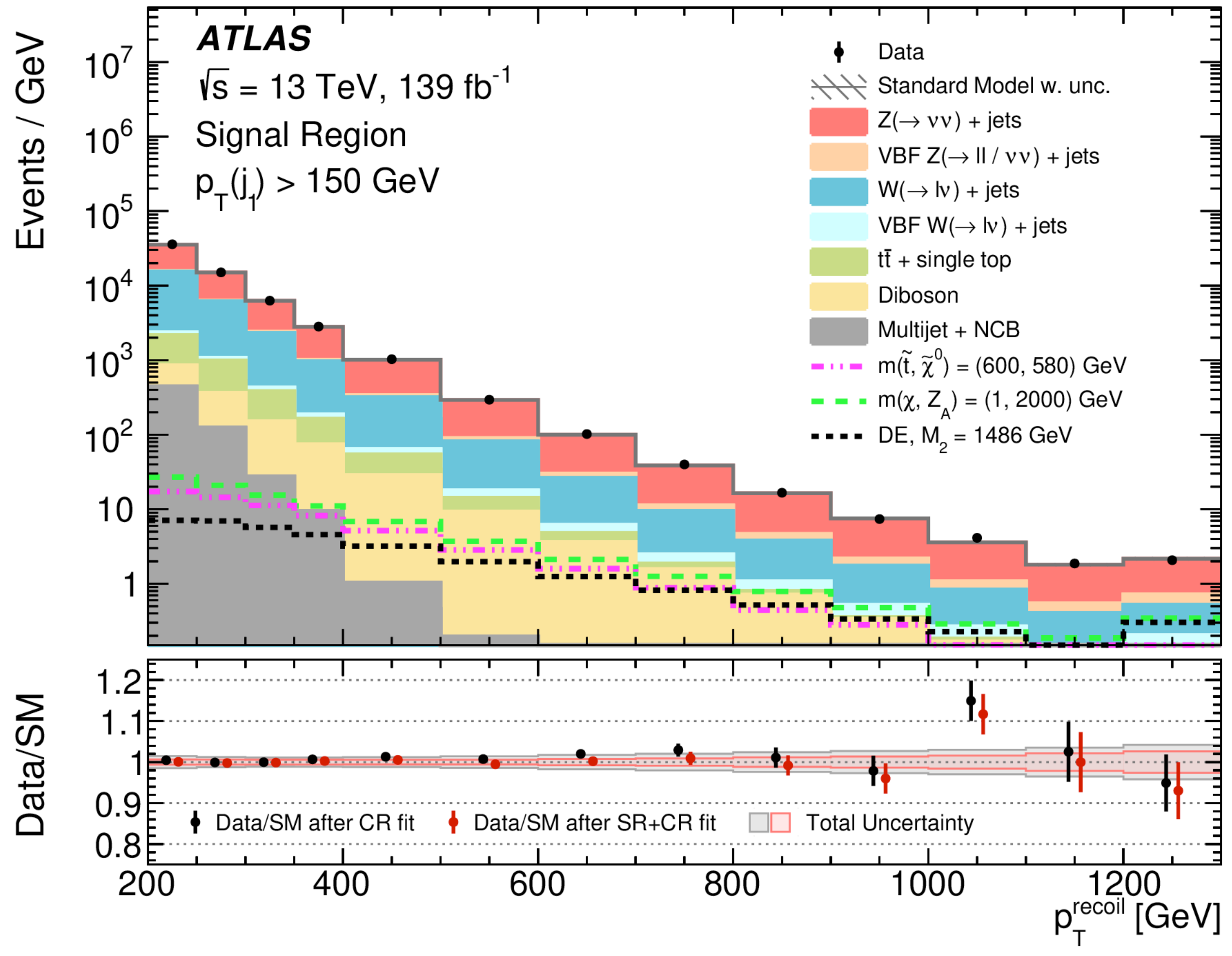
Signature: initial state radiation (jet, photon, W, Z) + E_T^{miss}

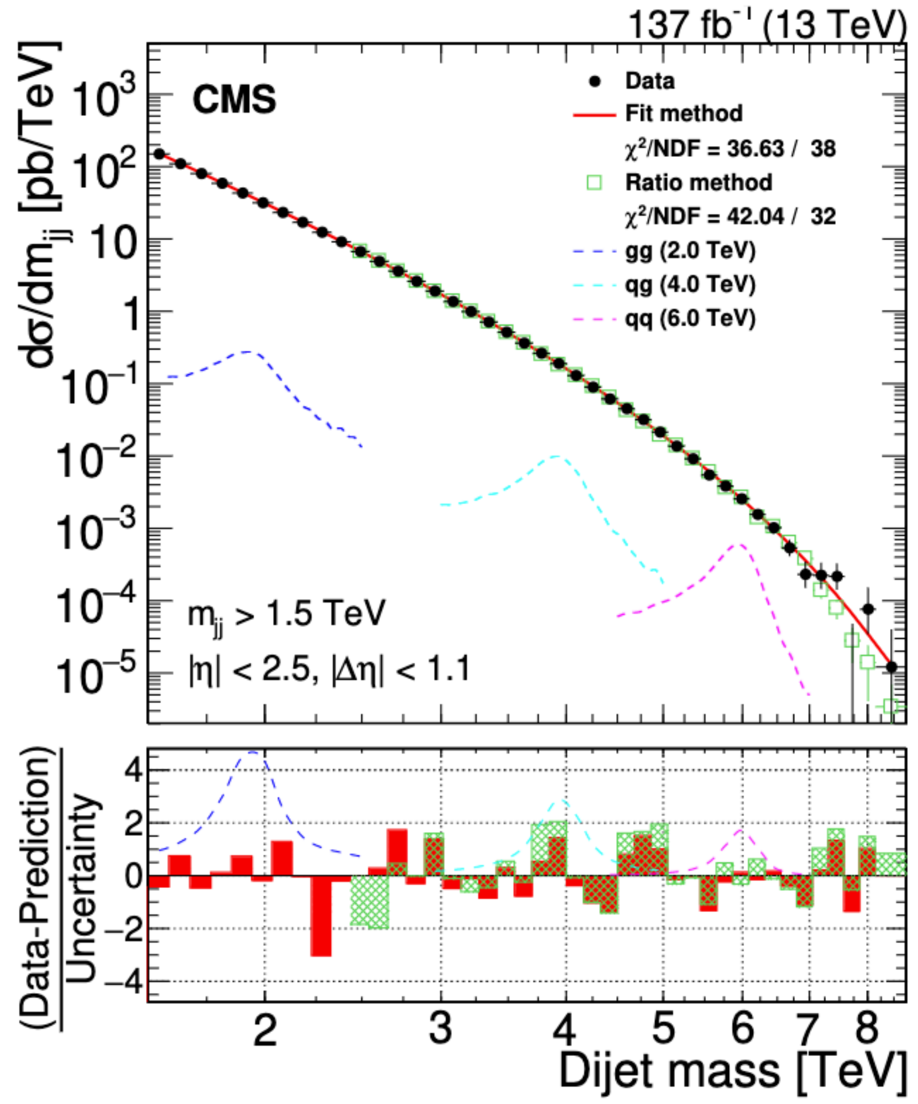
Visible resonance



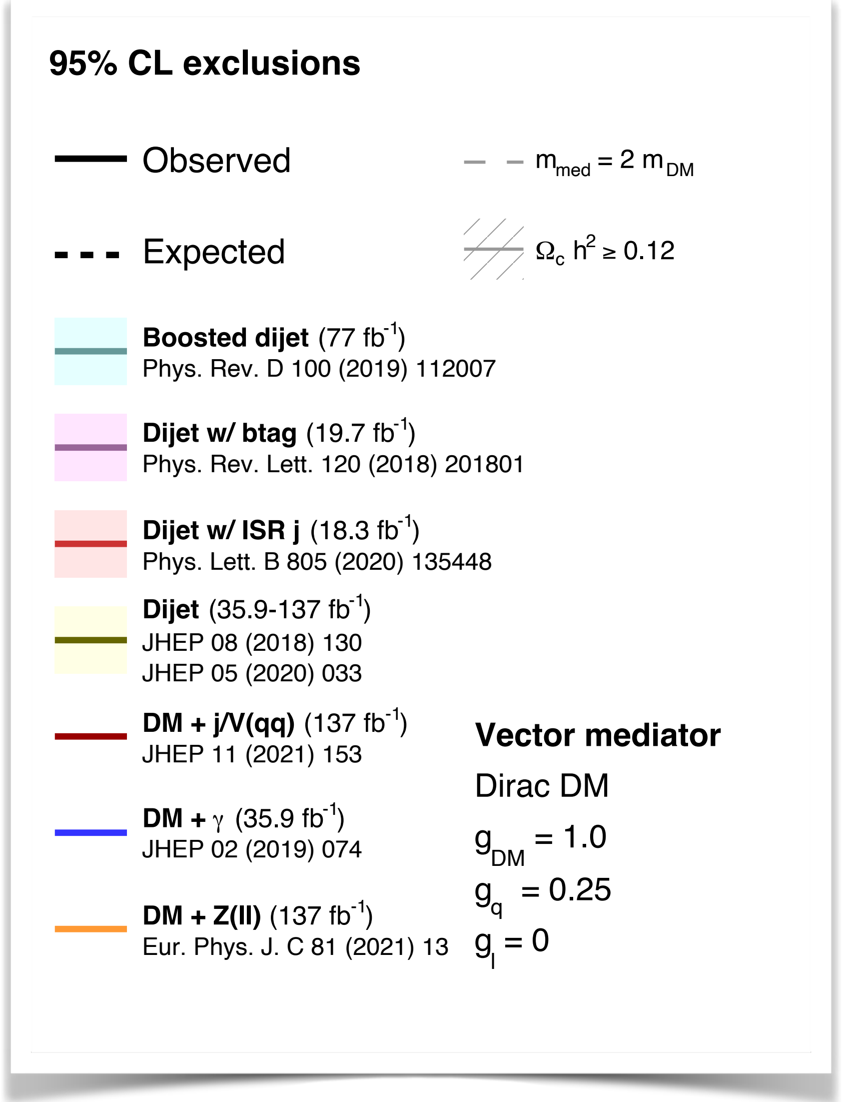
Signature: di-jet, di-photon, di-lepton resonances







- ➤ $E_T^{miss} + X$ searches: kinematically allowed for $m_{Med} > 2m_{DM}$
- ➤ Visible resonance searches: results less dependent on DM mass



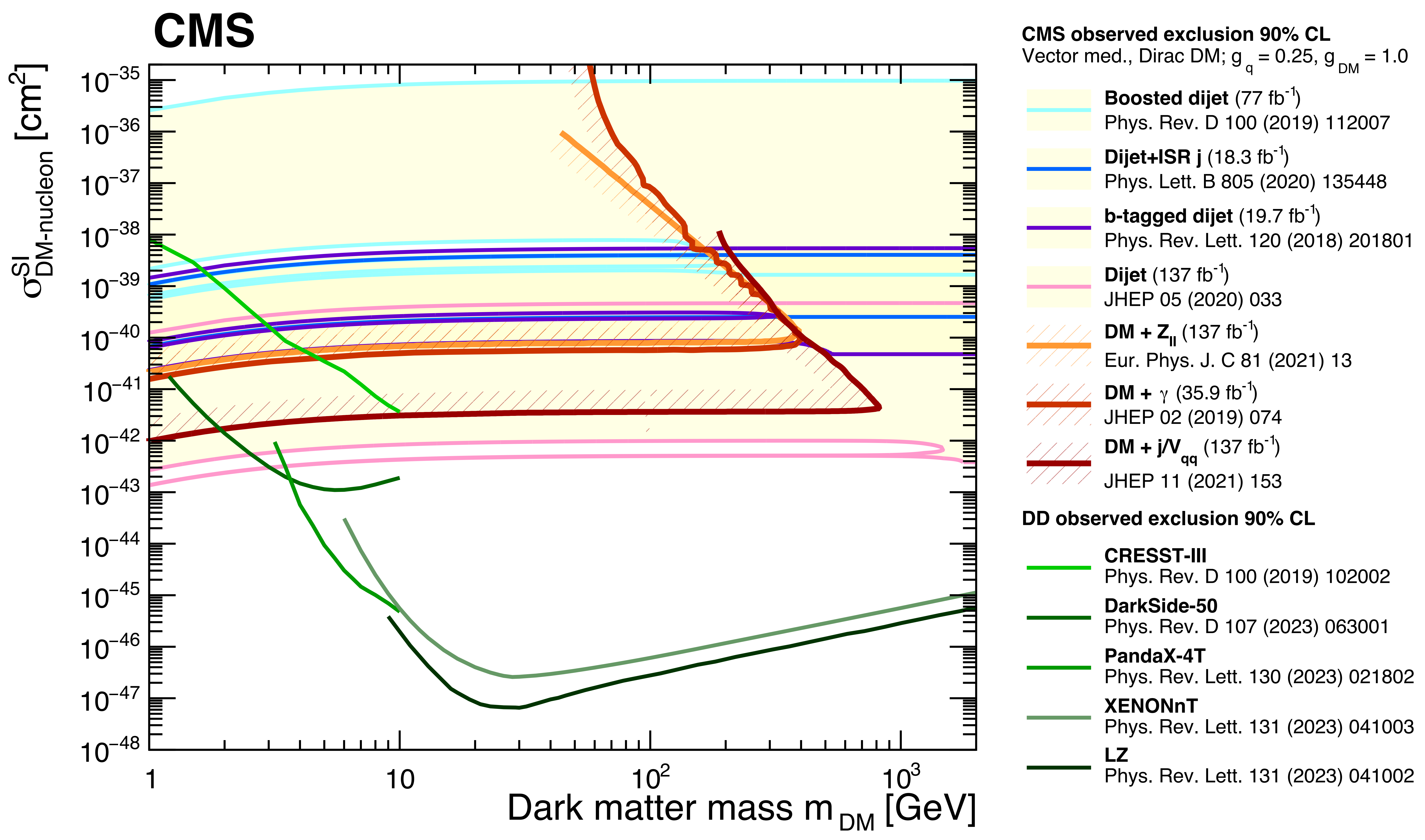
Comparing LHC results with direct detection

- *Vector mediator*
- *spin-independent (SI)*
- *DD limits enhanced by the nucleon number*

DM coupling $g_\chi = 1$

quark coupling $g_q = 0.25$

lepton coupling $g_l = 0$



Caveat: can only compare results for a specific model and set of parameters

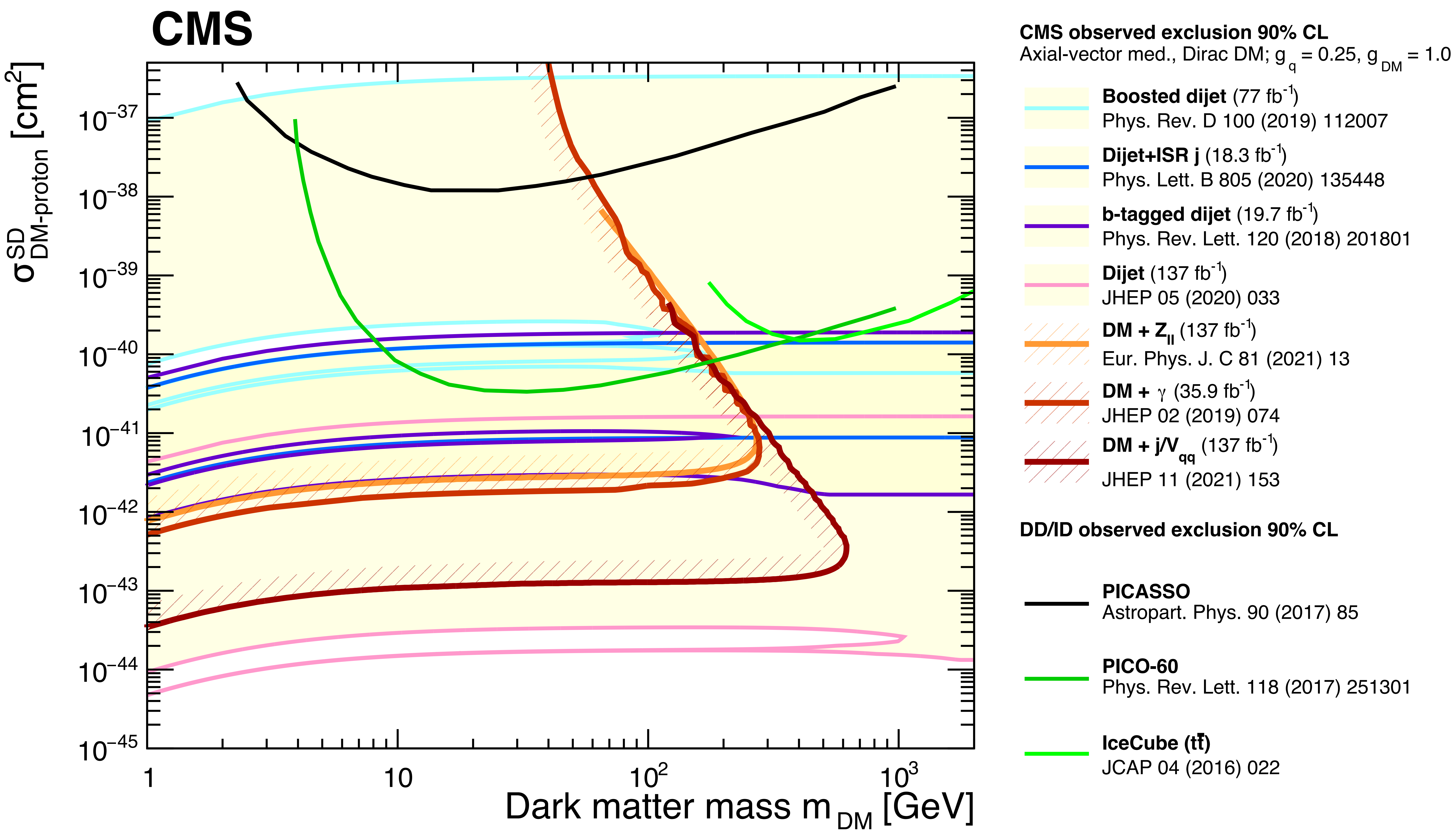
Comparing LHC results with direct detection

- *Axial-vector mediator*
- *spin-dependent (SD)*
- *no enhancement*

DM coupling $g_\chi = 1$

quark coupling $g_q = 0.25$

lepton coupling $g_l = 0$



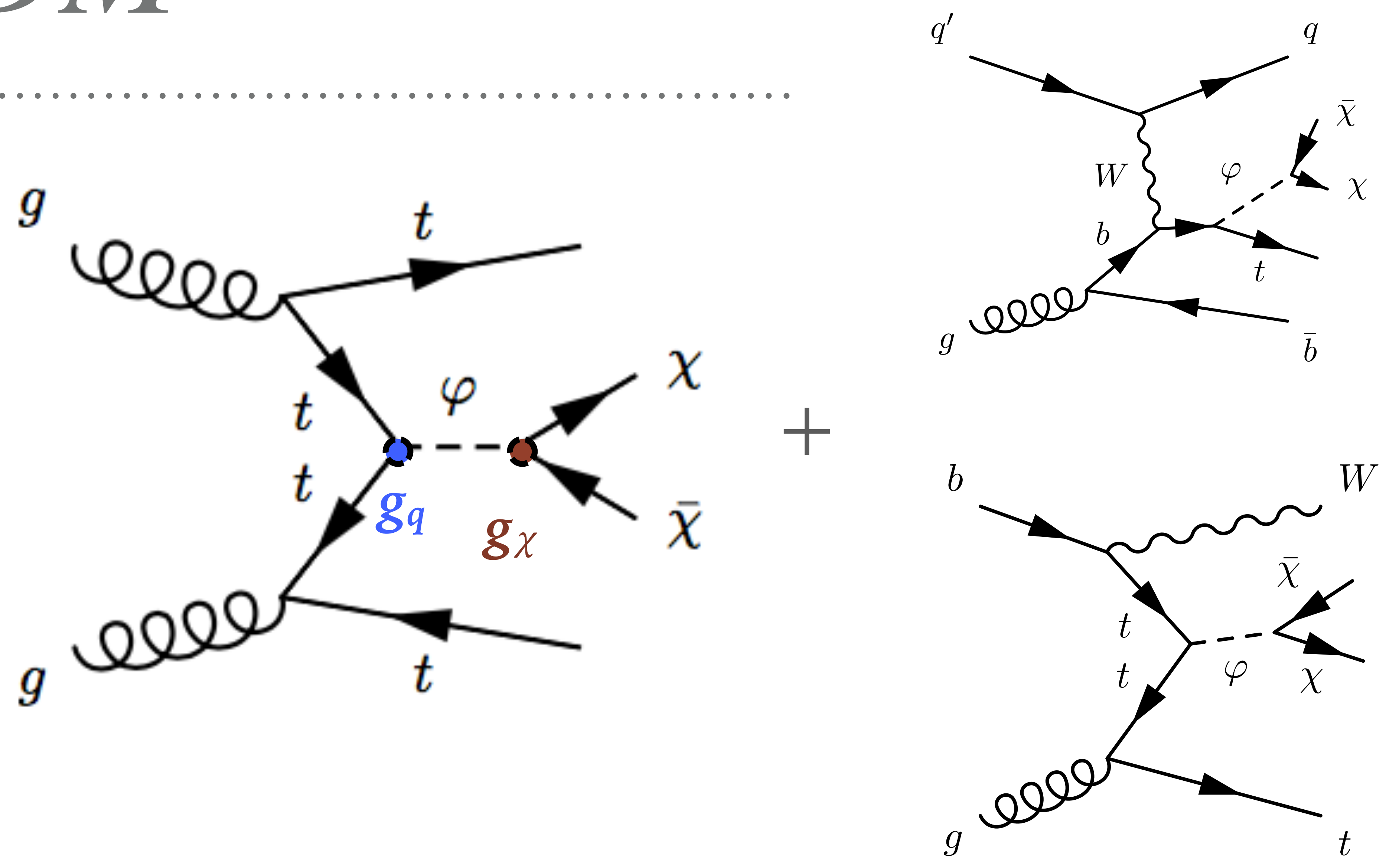
Caveat: can only compare results for a specific model and set of parameters

EXO-22-014

arxiv:2404.15930

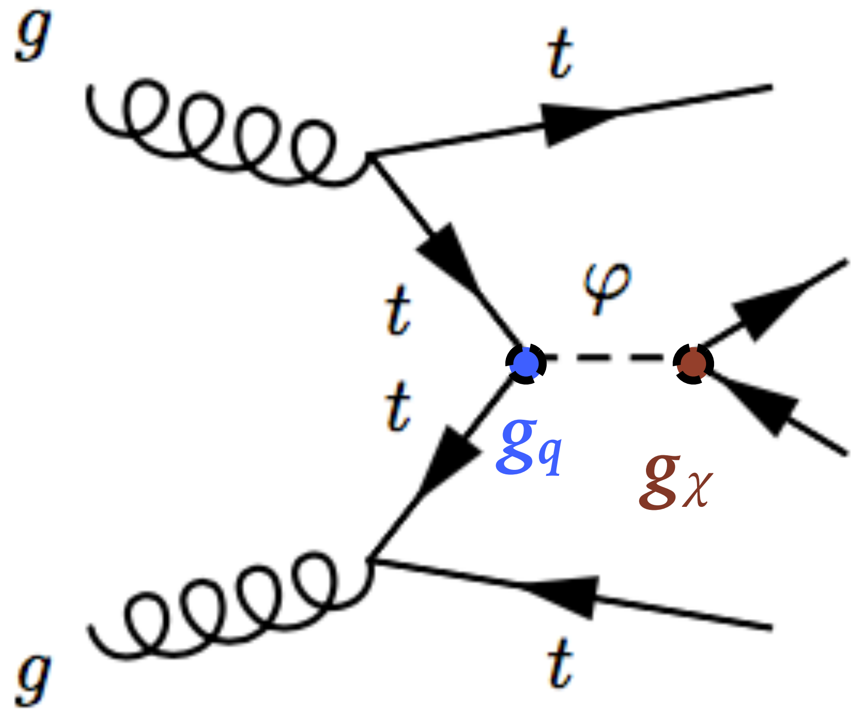
Scalar and Pseudoscalar: $(t\bar{t} + tj + tW) + DM$

- Signature: $(t\bar{t} + tj + tW) + E_T^{miss}$
- Exploit dominant top quark/W boson decay modes
  - zero, one (e/mu), and two lepton (e/mu) final states
  - number of b-jets =1 $(tj + tW)$ and =2 $(t\bar{t})$
- Exploit discriminating variable to separate signal and background
  - E_T^{miss} or neural network outputs

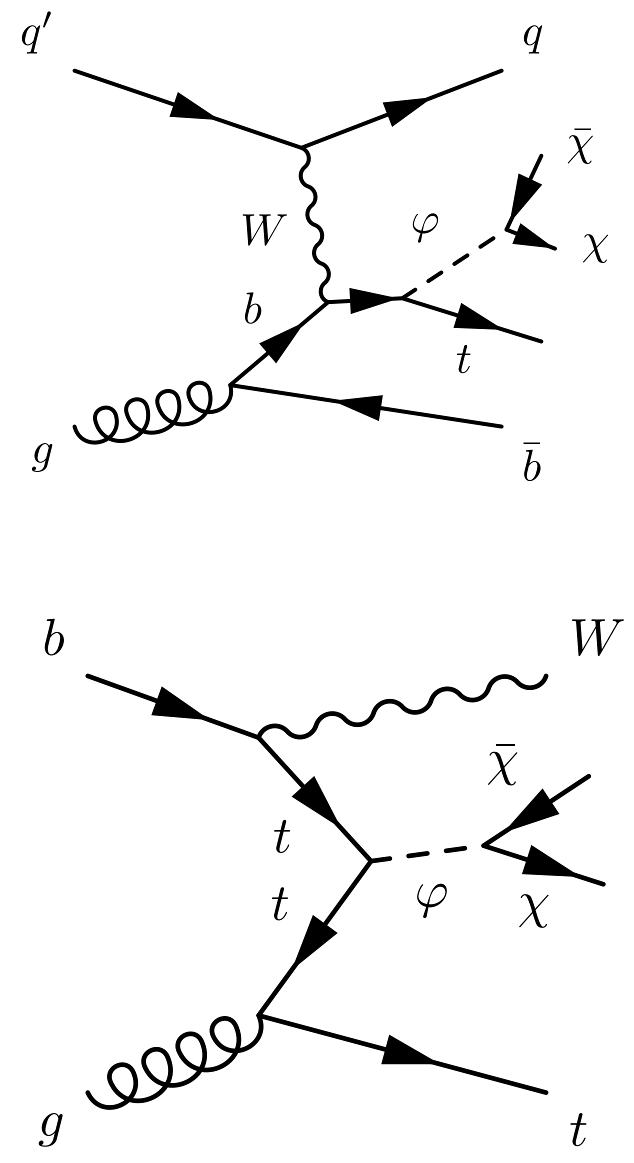


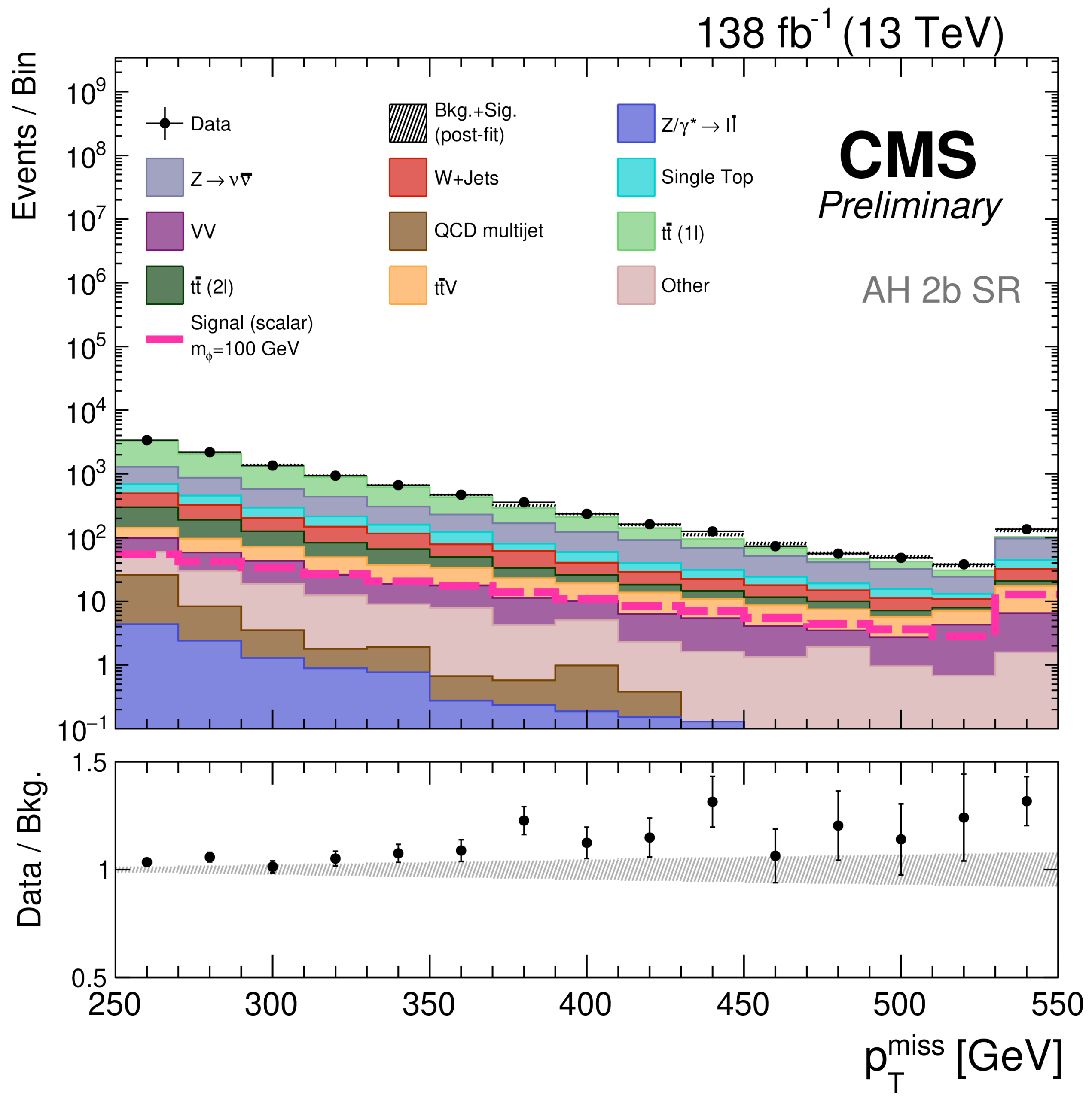
Scalar and Pseudoscalar: $(t\bar{t} + tj + tW) + DM$

- Signature: $(t\bar{t} + tj + tW) + E_T^{miss}$
- Exploit dominant top quark/W boson decay modes
  - zero, one (e/mu), and two lepton (e/mu) final states
  - number of b-jets =1 $(tj + tW)$ and =2 $(t\bar{t})$
- Exploit discriminating variable to separate signal and background
  - E_T^{miss} or neural network outputs



+



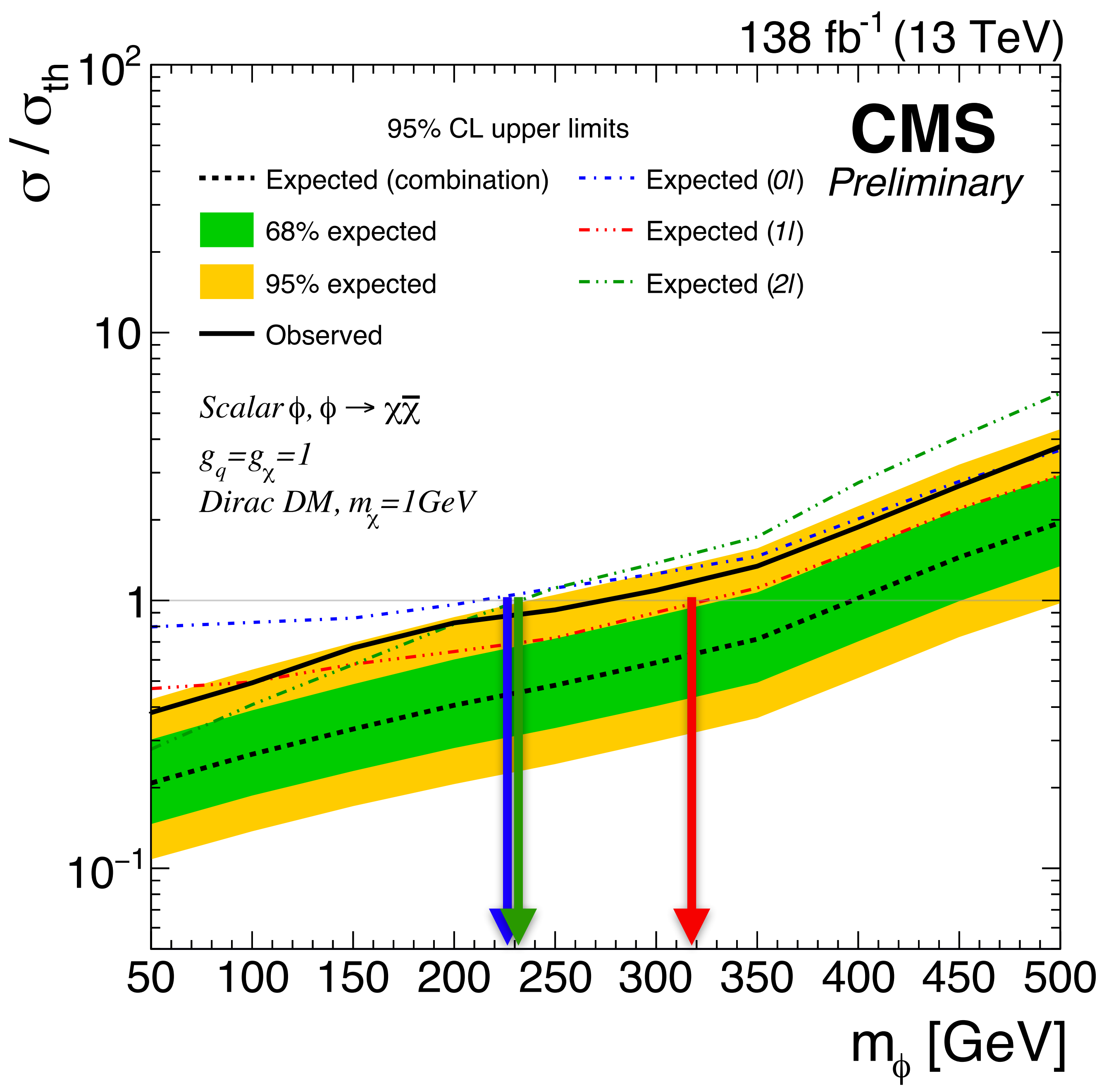


Fully hadronic signal region

- **Overall strategy**
  - Design dedicated **orthogonal signal regions** for specific signal topologies
    - Estimate **SM backgrounds** from simulation and data **control regions**
    - Extrapolate and test in Validation regions
  - **Statistically combine all SRs and CRs** for final result

Results

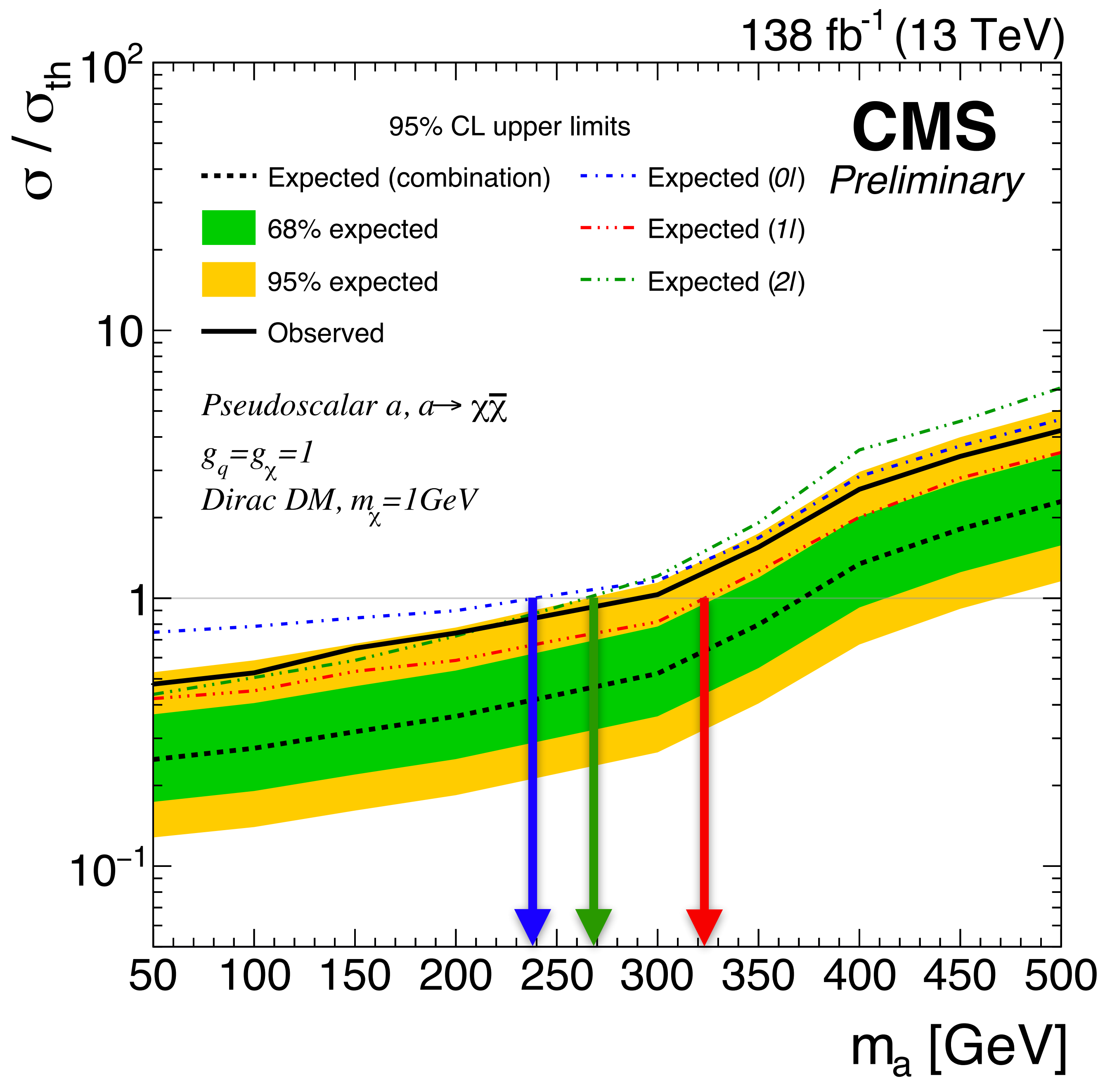
Scalar mediator



Various final states have differing sensitivity:

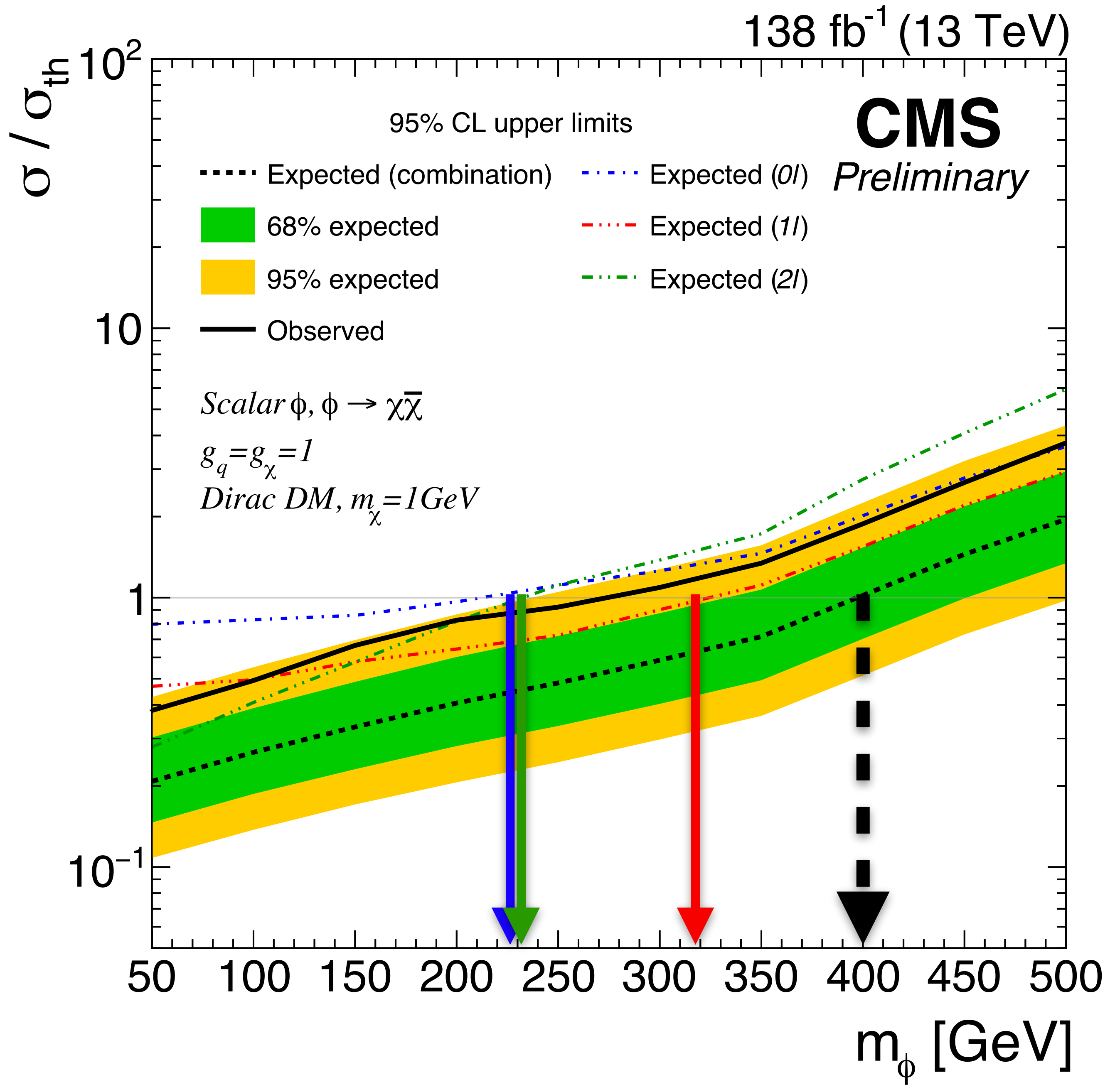
- *0 lepton*
- *1 lepton*
- *2 lepton*

Pseudoscalar mediator



Results

Scalar mediator

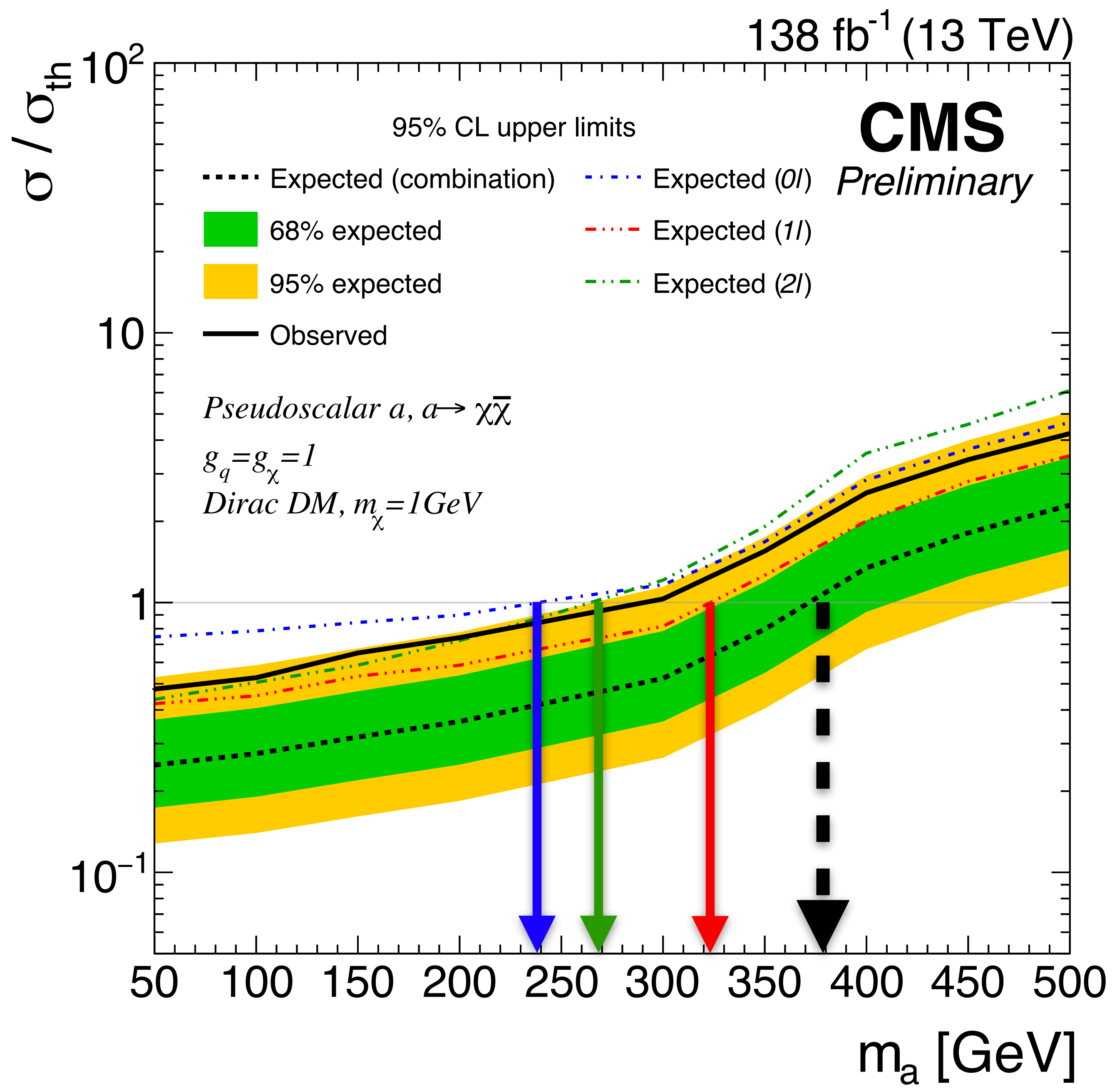


Various final states have differing sensitivity:

- *0 lepton*
- *1 lepton*
- *2 lepton*

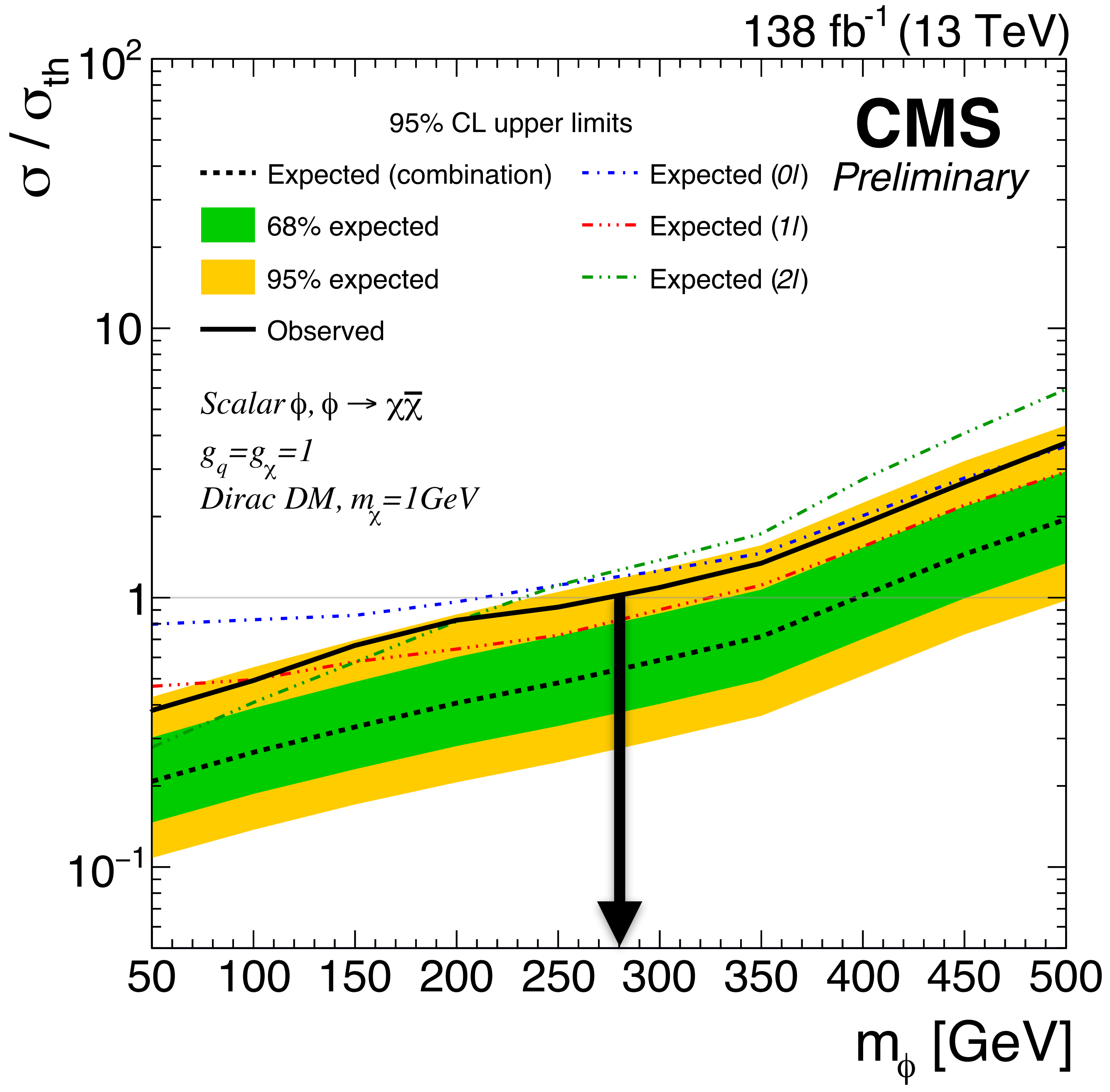
→ Combination of all three

Pseudoscalar mediator

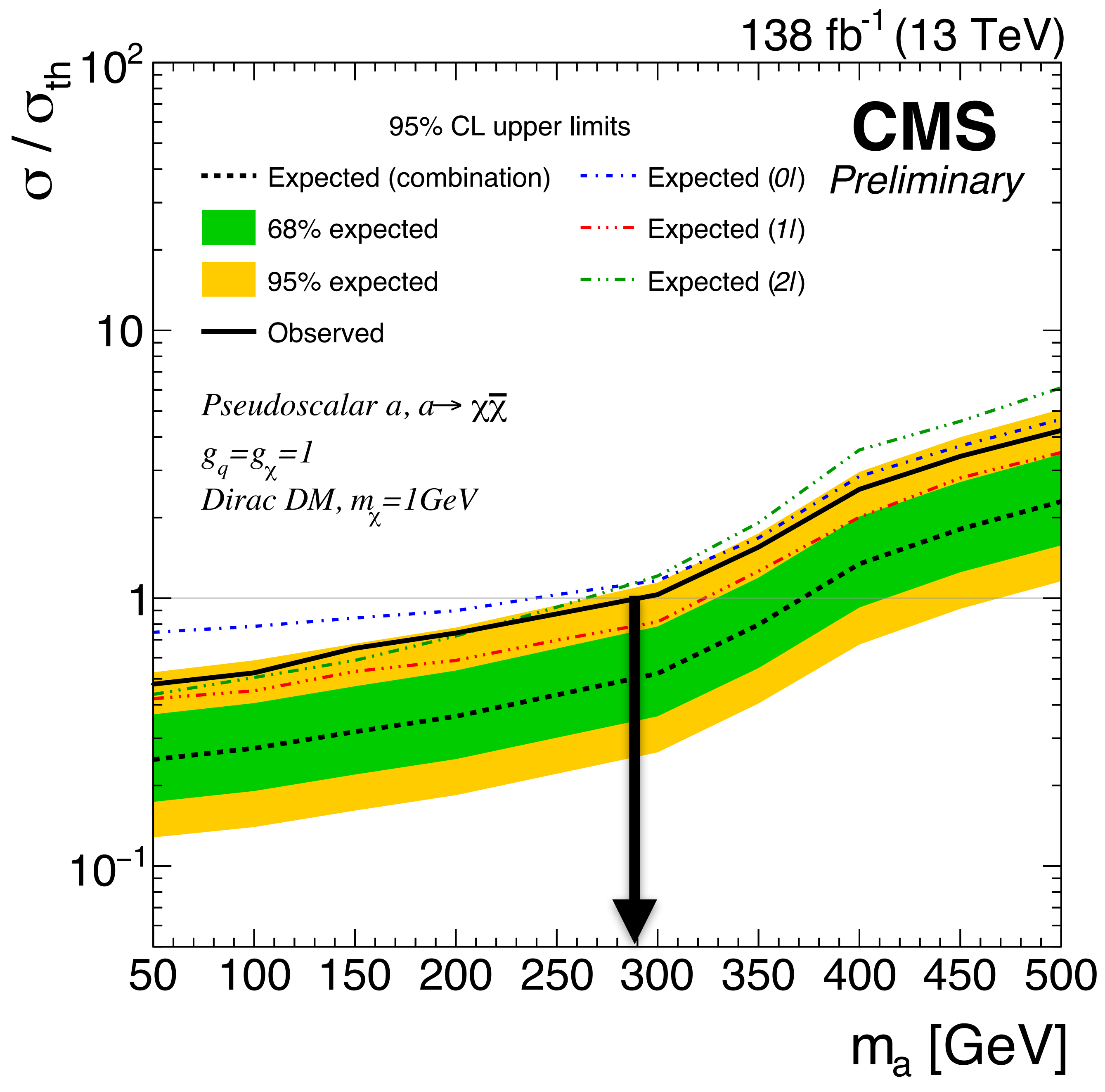


Results

Scalar mediator

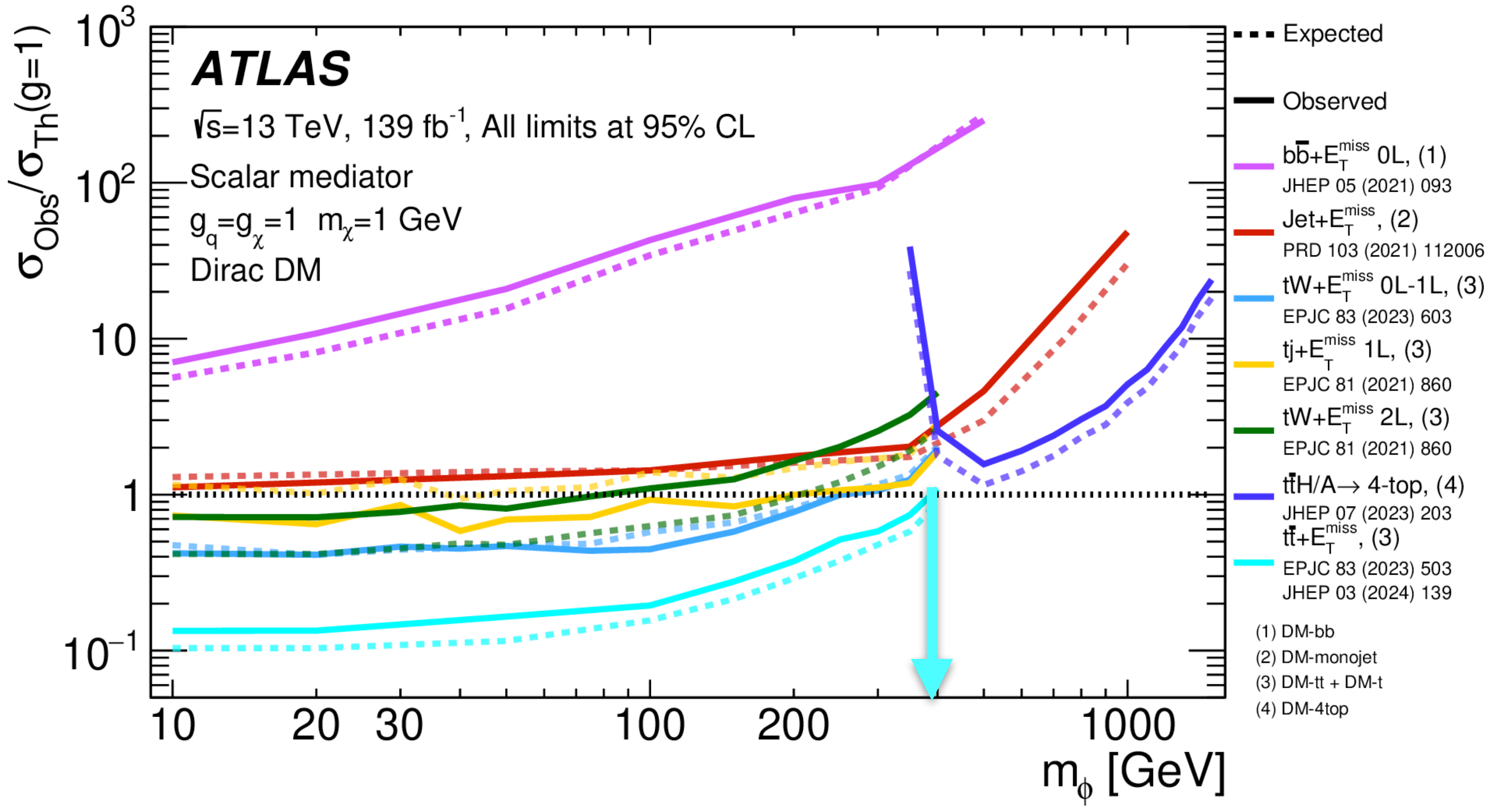


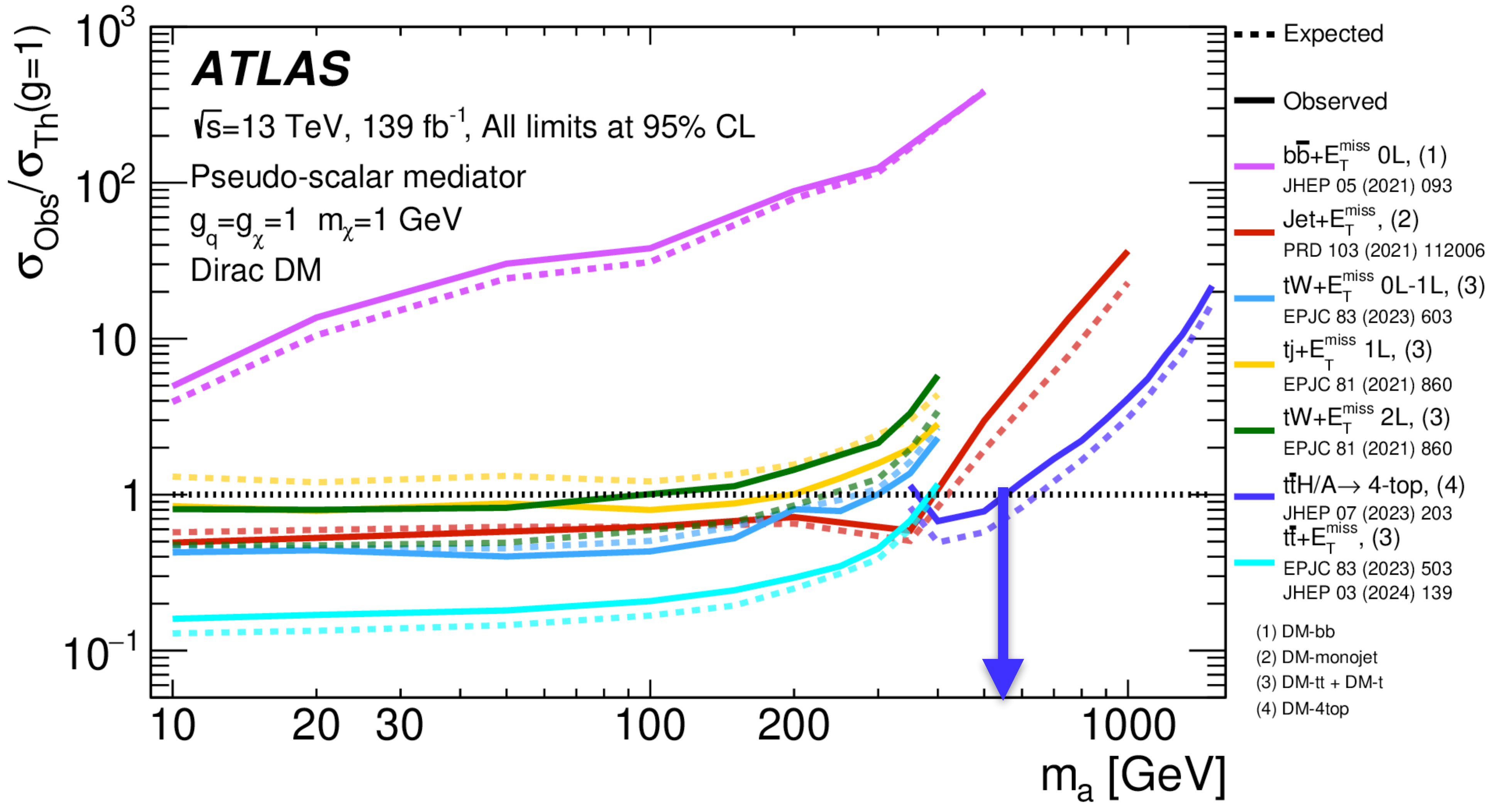
Pseudoscalar mediator



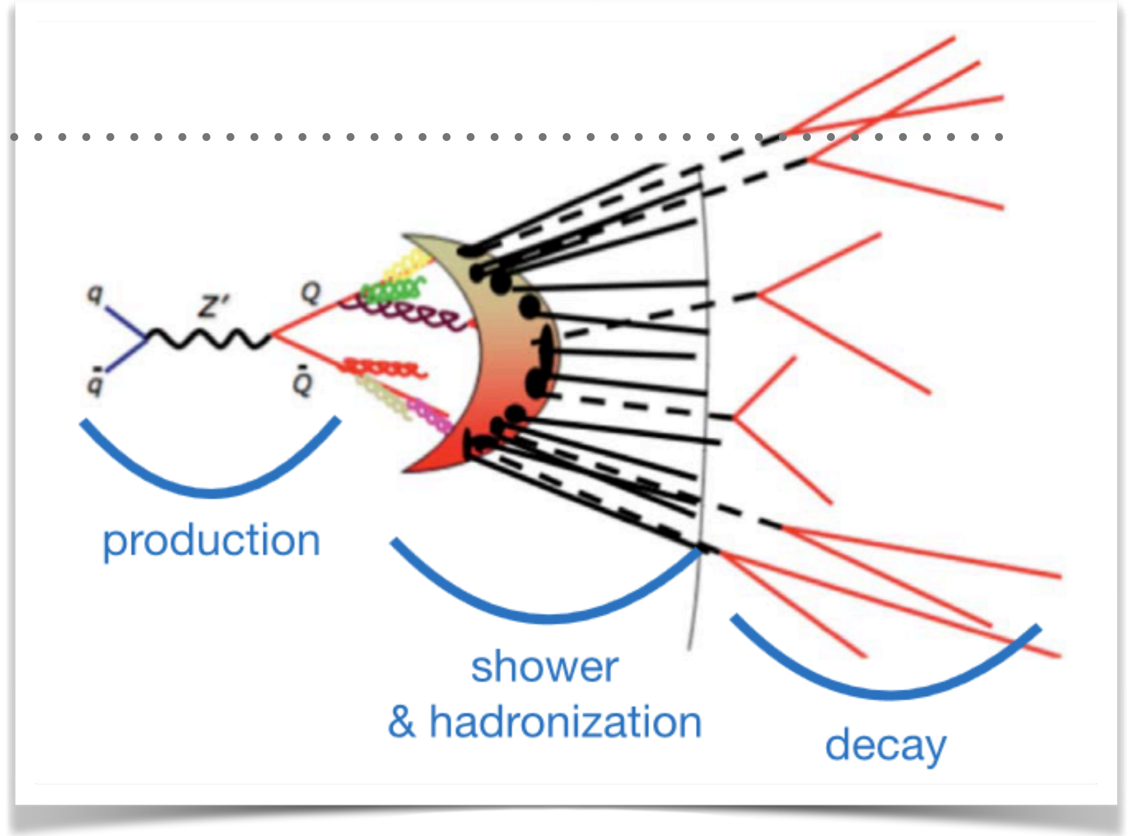
Observed exclusion limits:

from 10 GeV to 280 GeV - 500 GeV



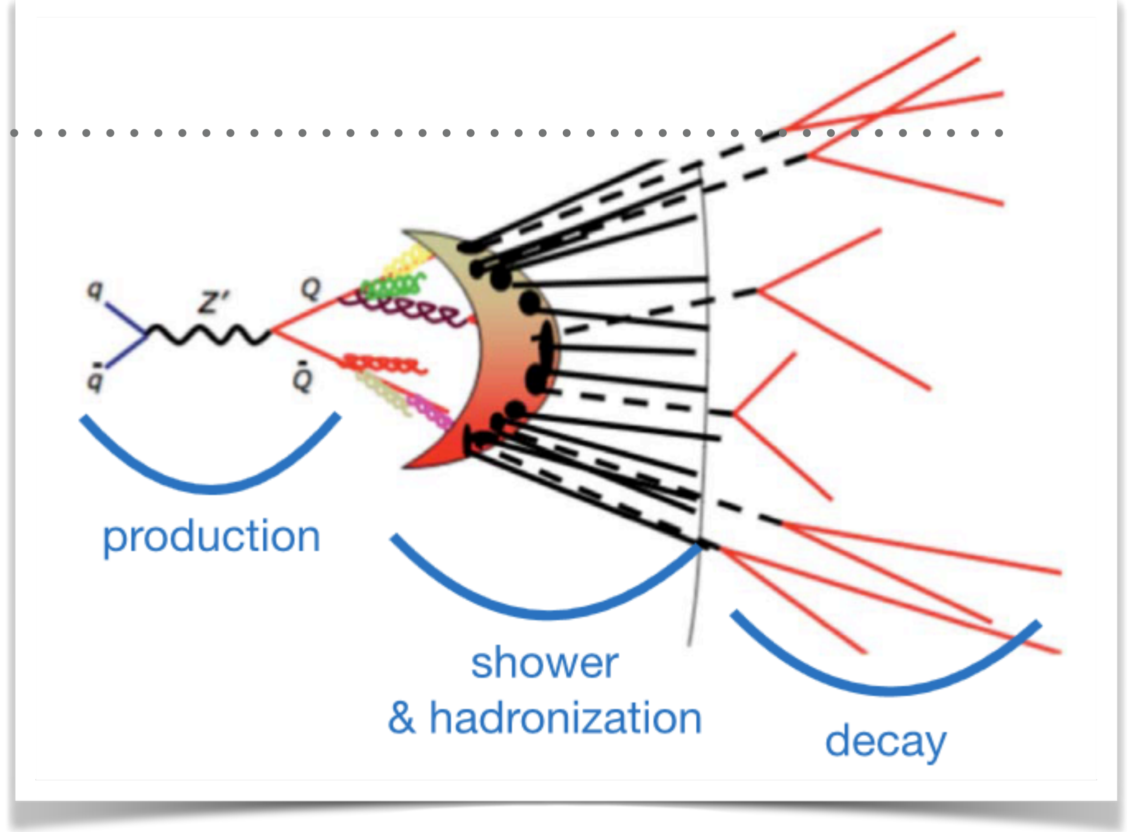


Something more unconventional?



- Idea: strongly interacting dark sector → Dark QCD
  - Production of dark quarks → leading to dark hadron shower
    = SM hadrons + stable dark hadrons (invisible DM candidate)

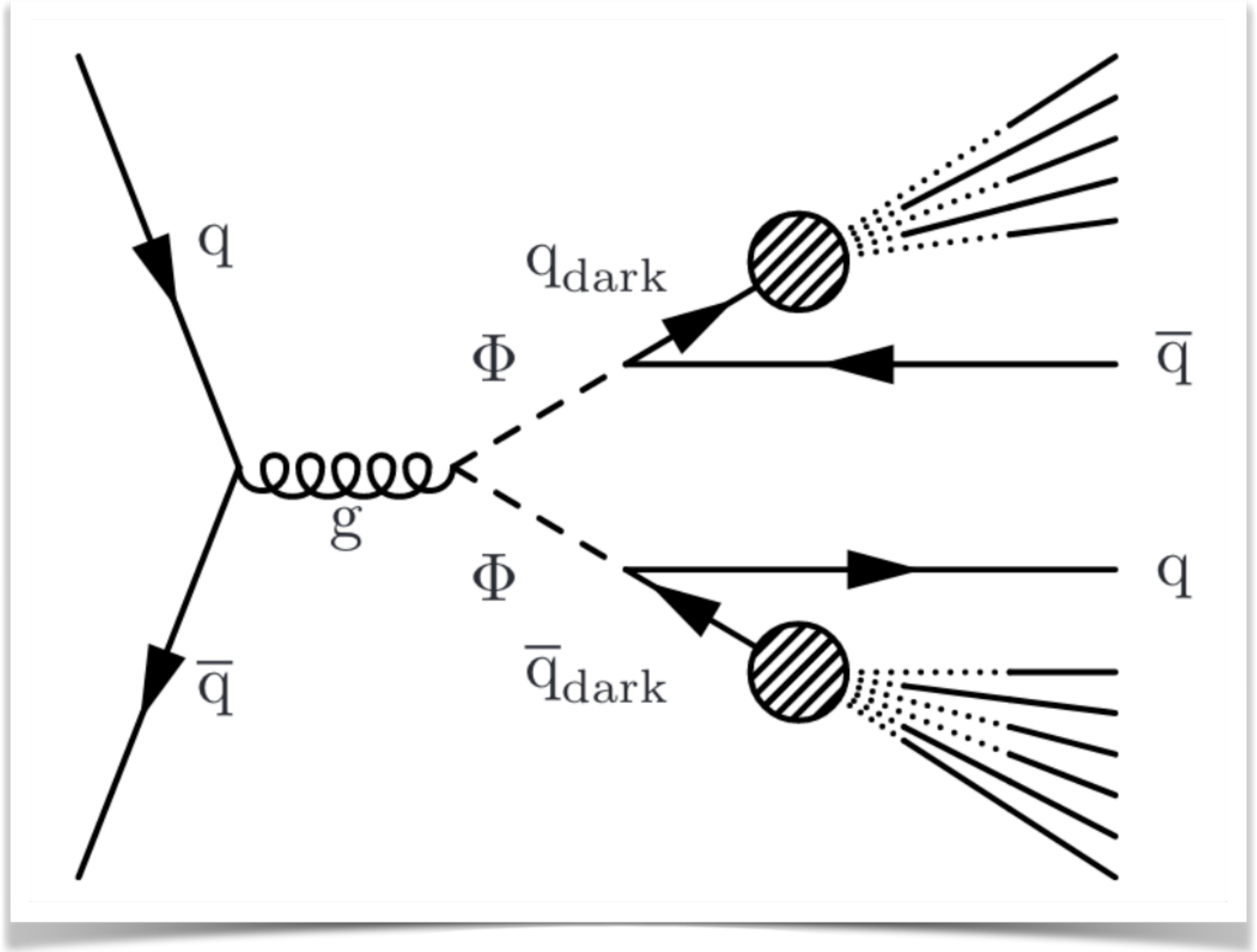
Something more unconventional?

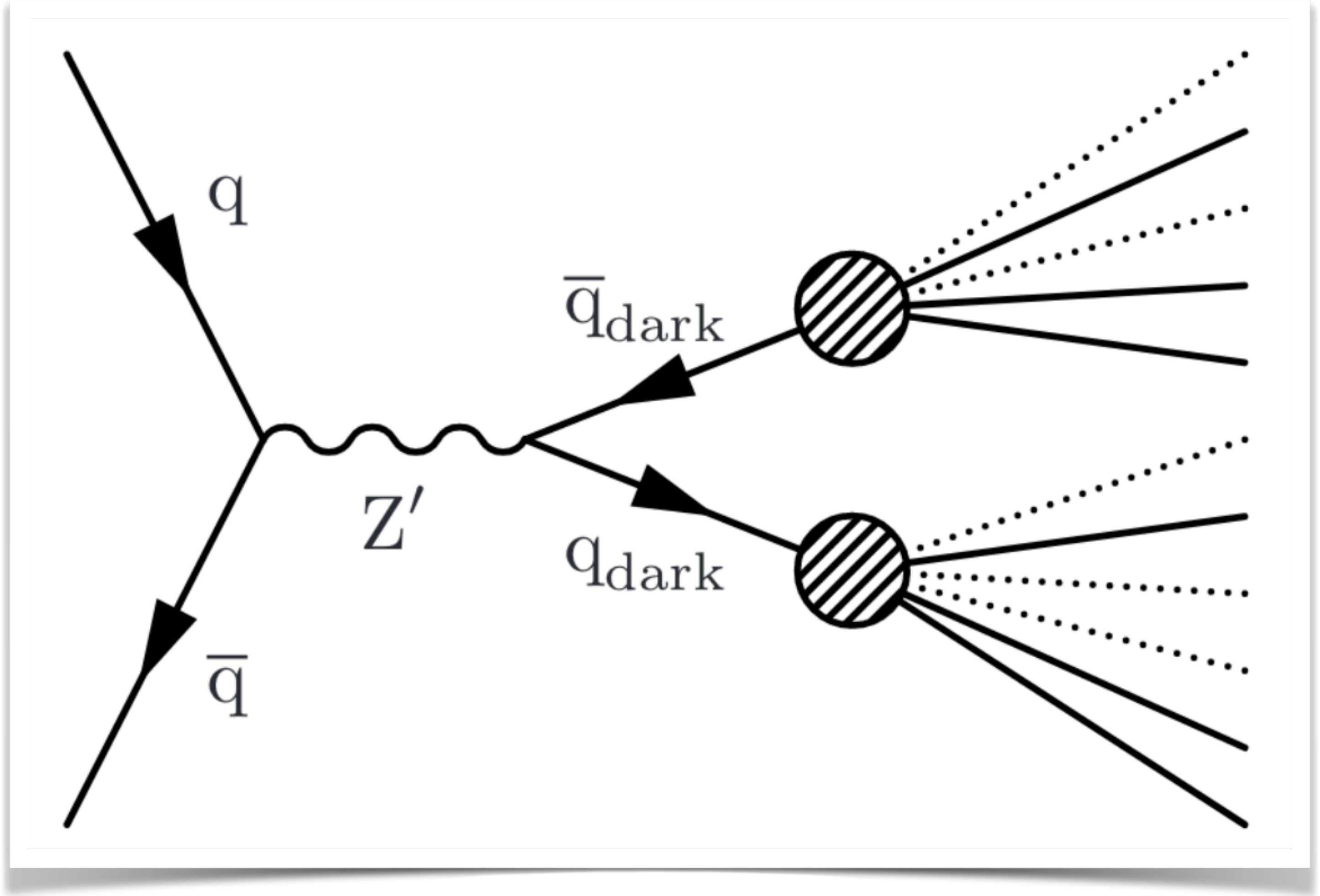


- Idea: strongly interacting dark sector → Dark QCD
  - Production of dark quarks → leading to dark hadron shower
    = SM hadrons + stable dark hadrons (invisible DM candidate)

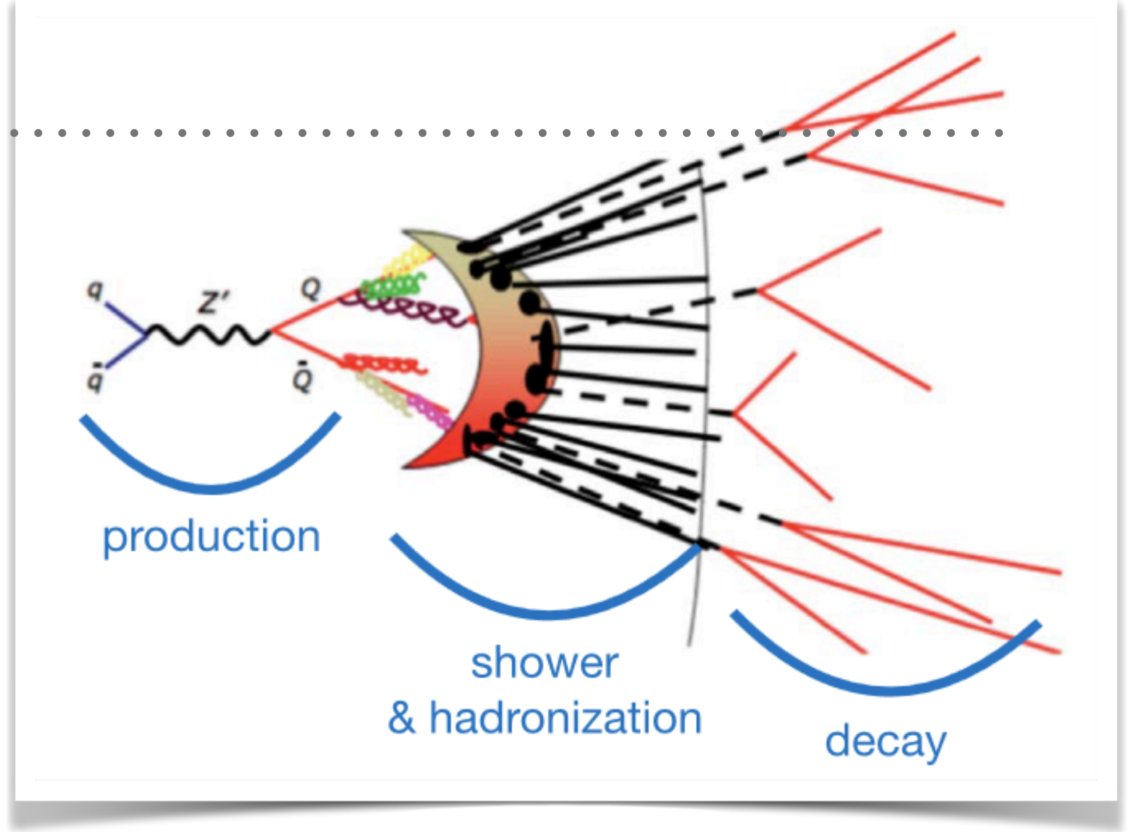
    - **Emerging jets**
      - Jets with displaced constituents characterized by $c\tau_{dark}$

    - **Semi-visible jets**
      - Jets characterized by fraction of energy carried by DM = R_{inv}



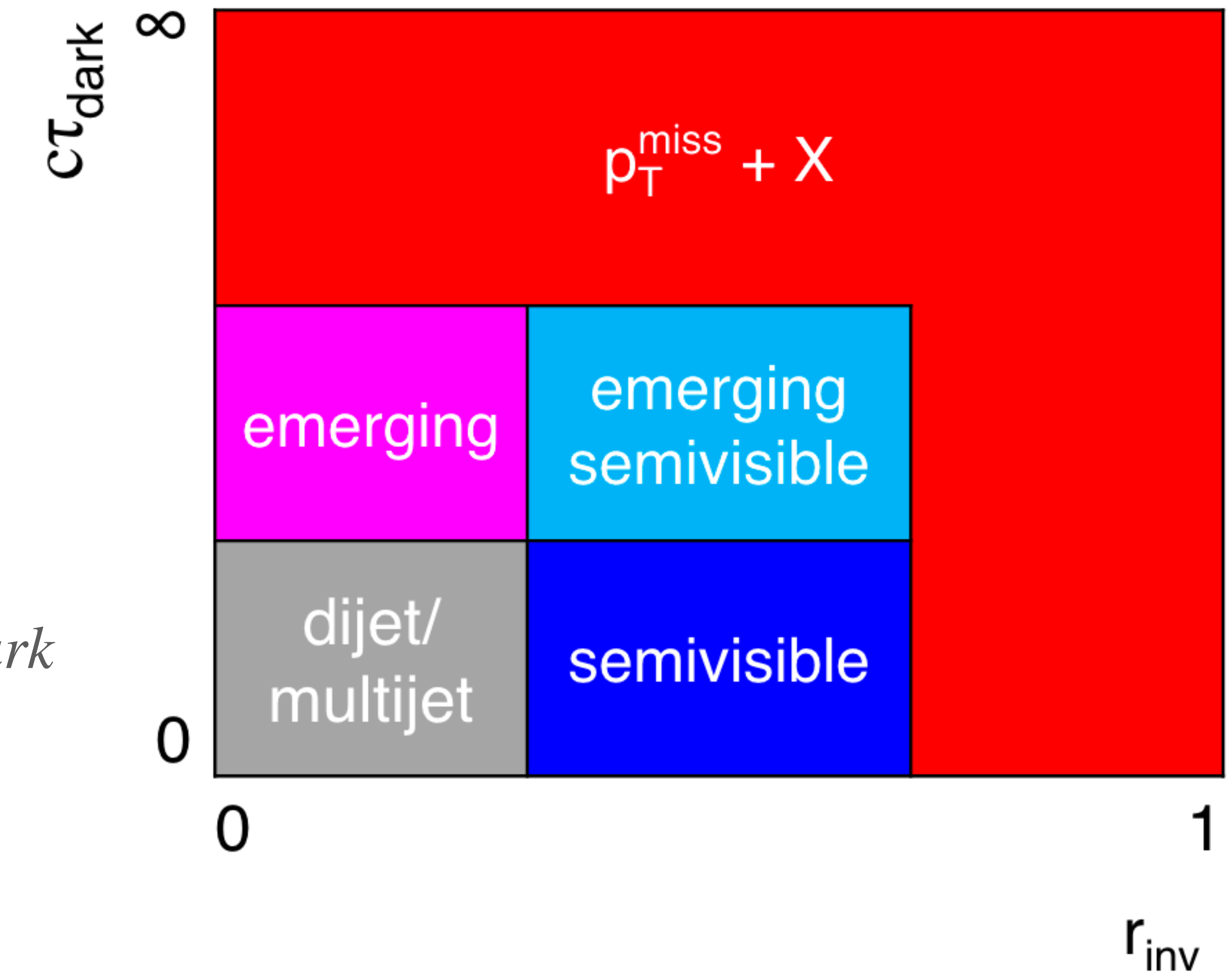


Something more unconventional?



- ➤ Idea: strongly interacting dark sector → Dark QCD
  - ➤ Production of dark quarks → leading to dark hadron shower
    = SM hadrons + stable dark hadrons (invisible DM candidate)

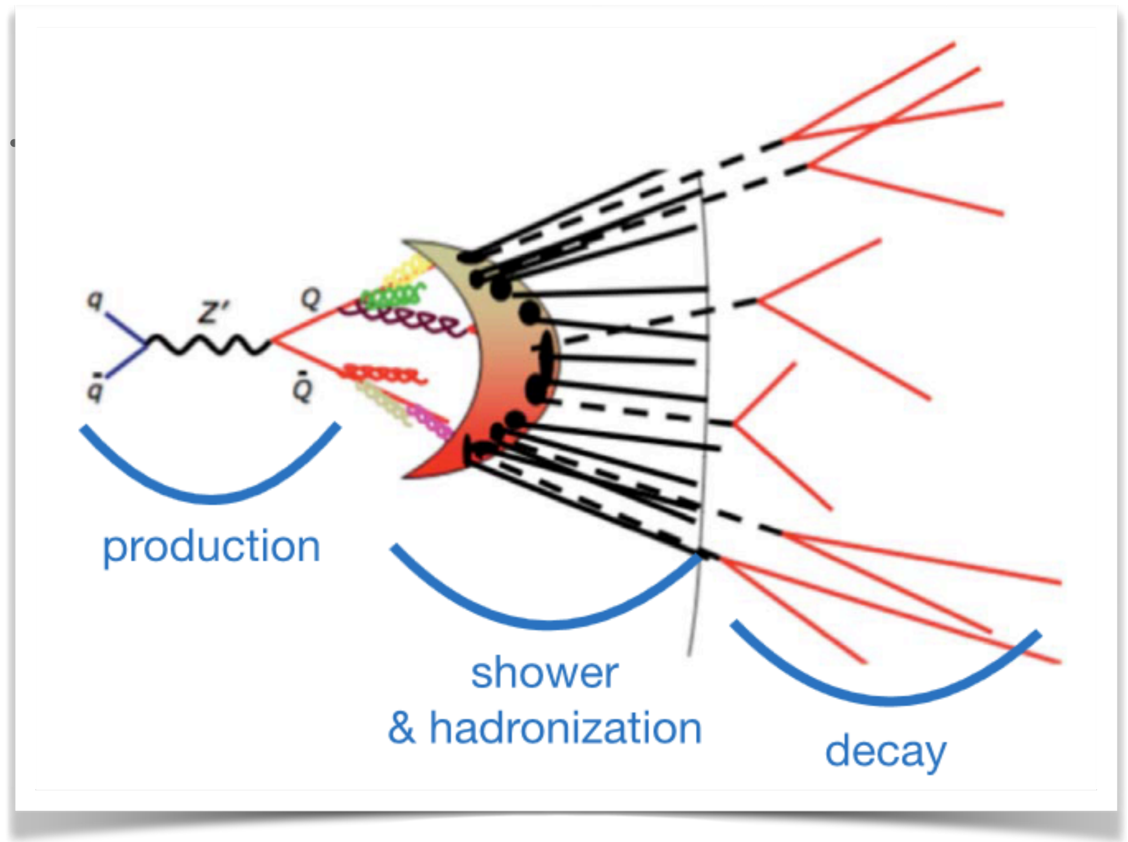
- ➤ **Emerging jets**
  - ➤ Jets with displaced constituents characterized by $c\tau_{dark}$

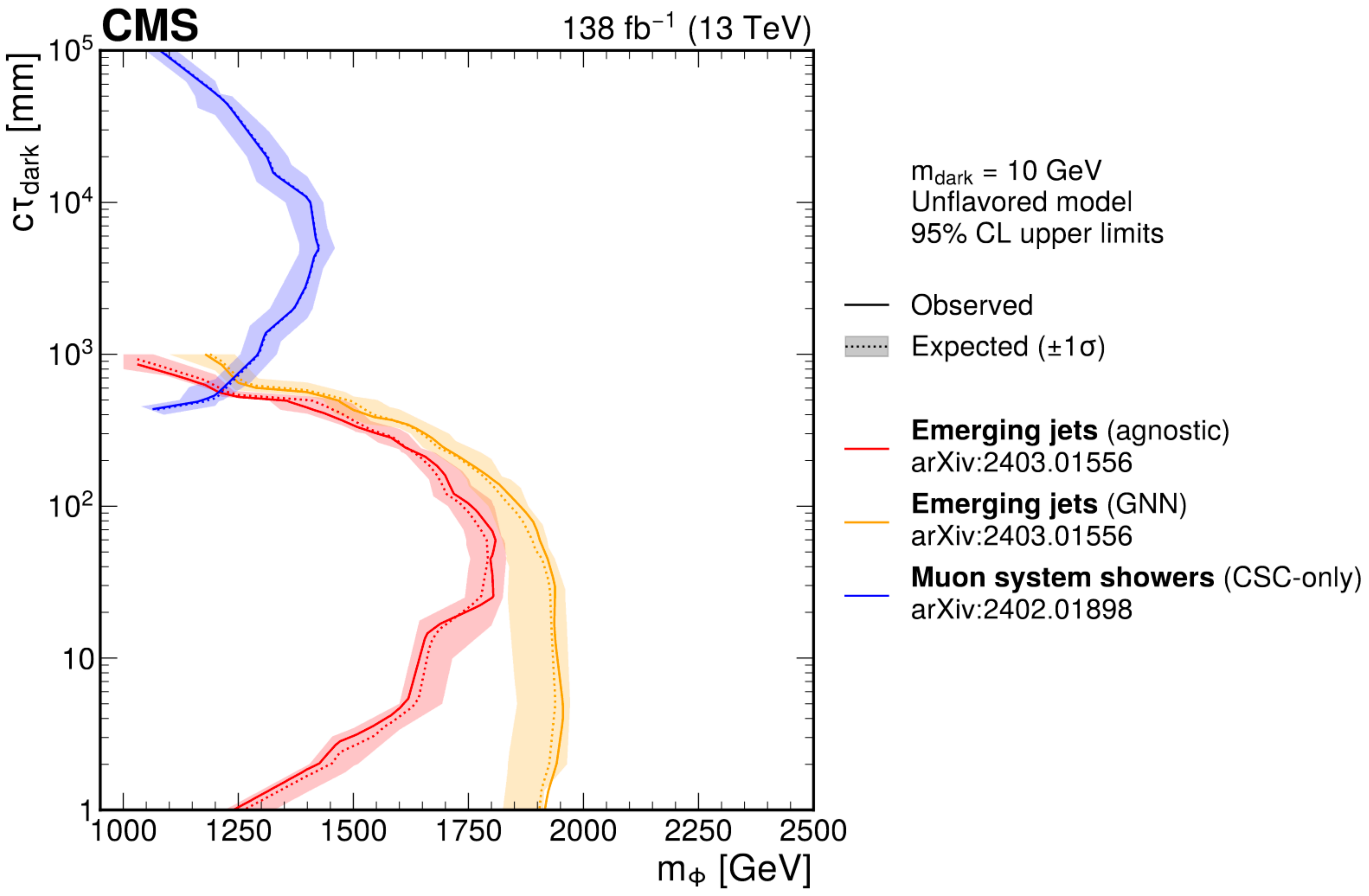


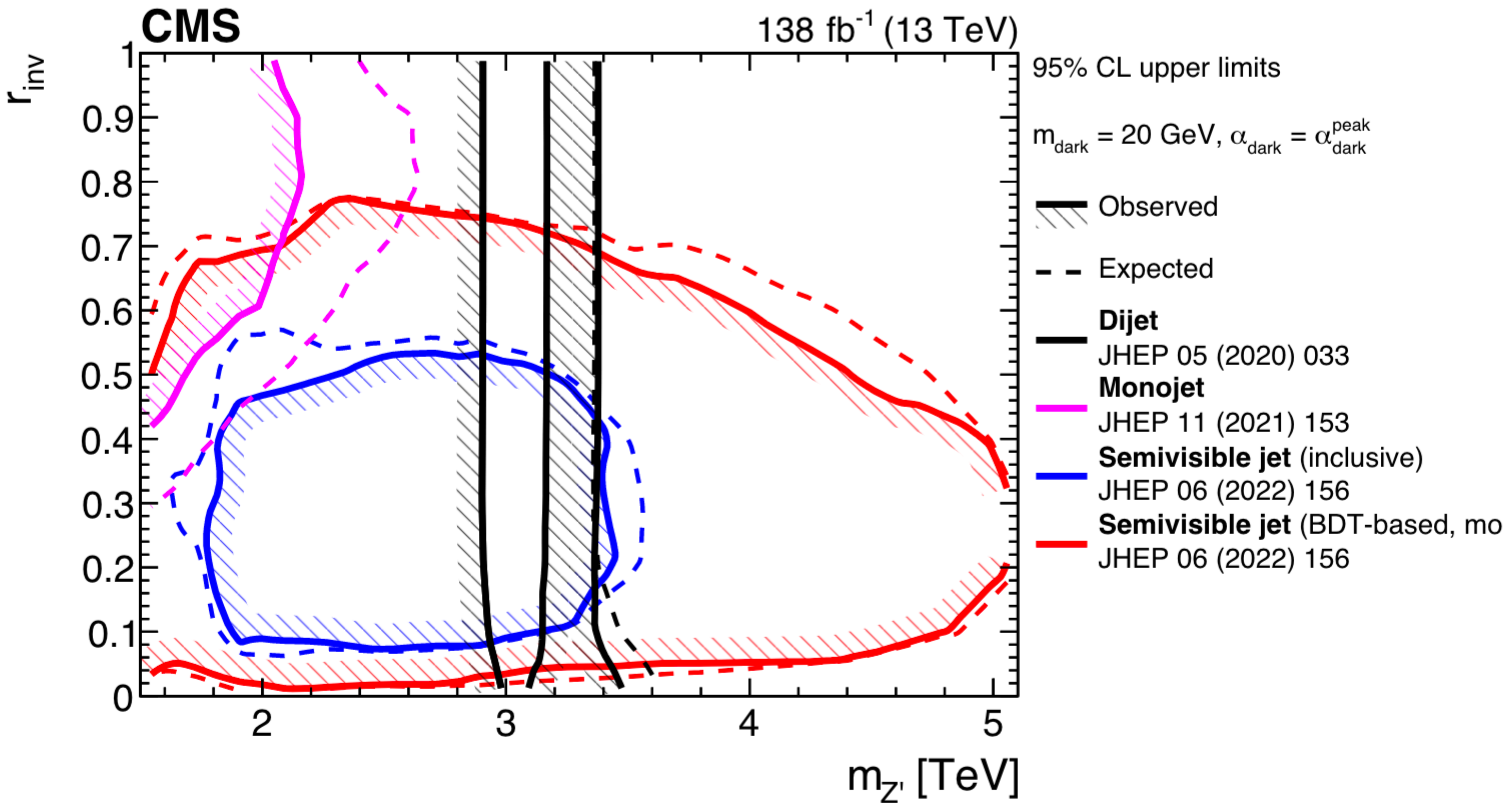
- ➤ **Semi-visible jets**
  - ➤ Jets characterized by fraction of energy carried by DM = R_{inv}

Something more unconventional?

- Idea: strongly interacting dark sector → Dark QCD
  - Production of dark quarks → leading to dark hadron shower
    = SM hadrons + stable dark hadrons (invisible DM candidate)







Model driven: 2HDM+a

➤ Type-II two Higgs doublet model + additional pseudo scalar mediator **a** that couples to DM → UV complete theory with resonant enhancement of charged heavy Higgs production

- **New particle content:**
  - CP even neutral Higgs bosons **h** and **H**
  - CP odd pseudo scalars **a** and **A**
  - two charged heavy Higgs bosons **H±**

after fixing parameters

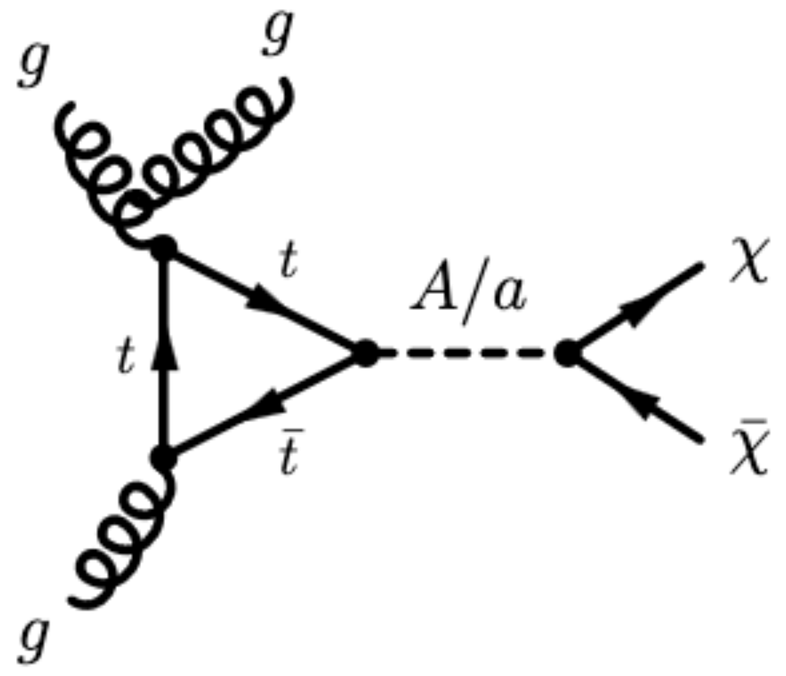
to match existing constraints

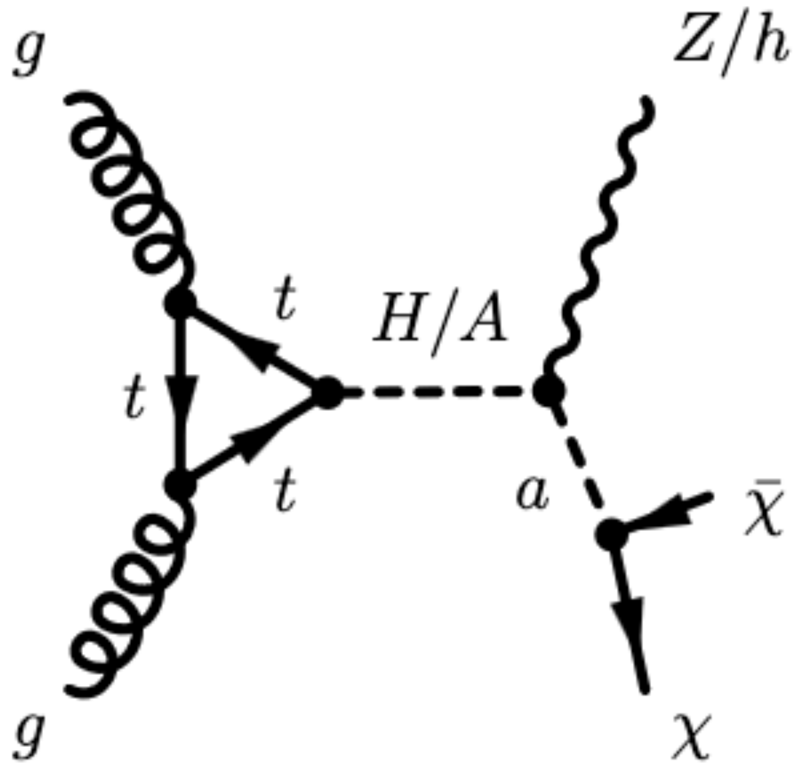
➤ **Free parameters:**
- ➤ m_a
- ➤ $M_A = M_H = M_{H\pm}$
- ➤ $\tan\beta$: ratio of the two Higgs doublet vevs
- ➤ $\sin\theta$: mixing between CP odd states **a** and **A**

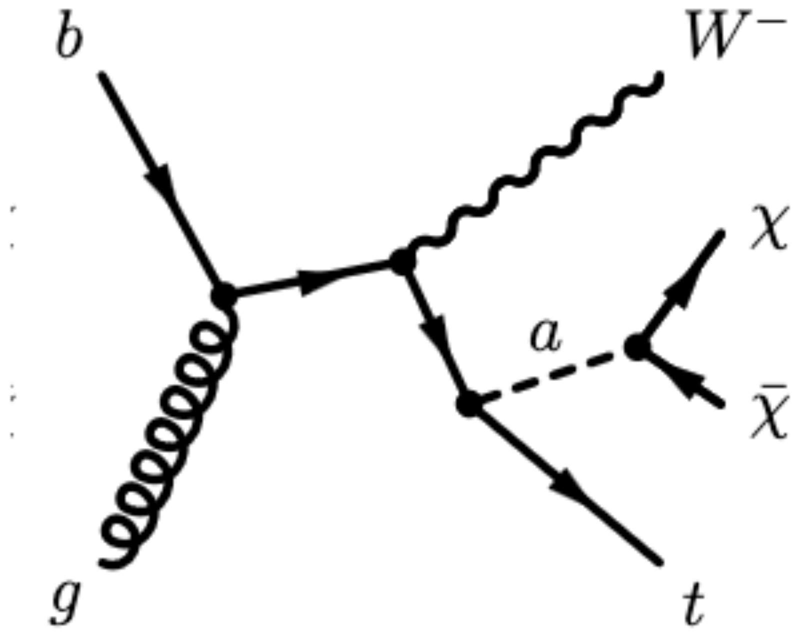
Analysis Specific Assumptions:
- m_x = 10 GeV, y_x = 1
- $\lambda_3 = \lambda_{P1} = \lambda_{P2} = 3$
- mh = 125 GeV

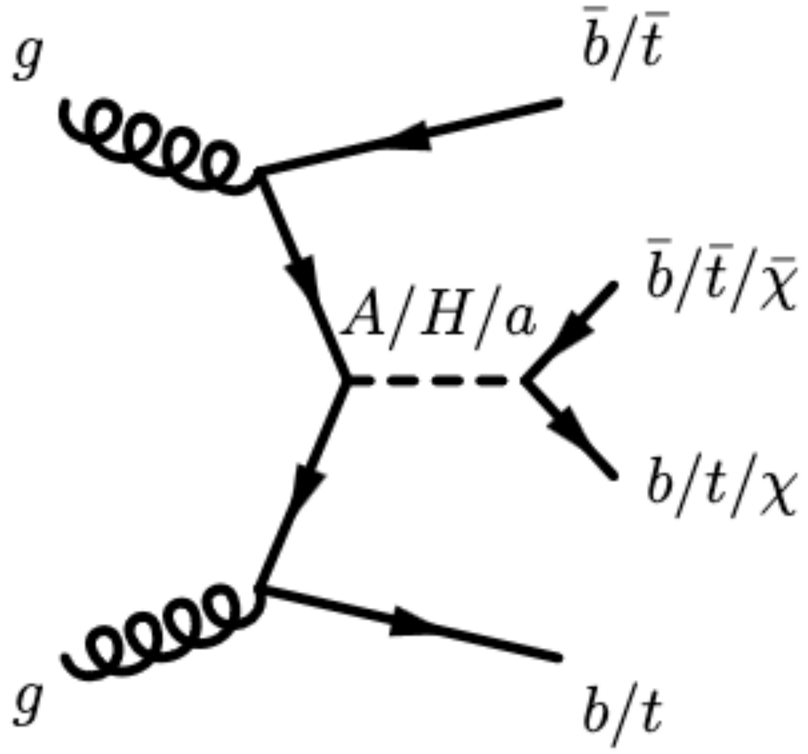
2HDM+a: what to expect?

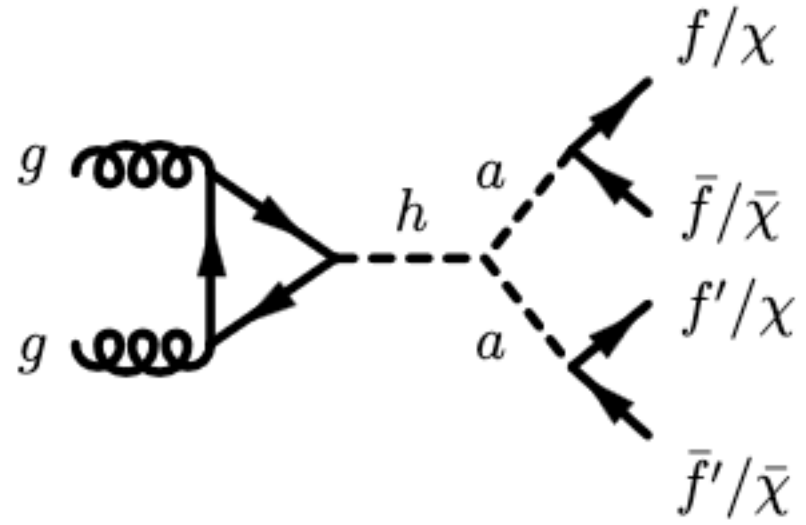
➤ Large signature space with (pretty much) everything an experimentalist could wish for

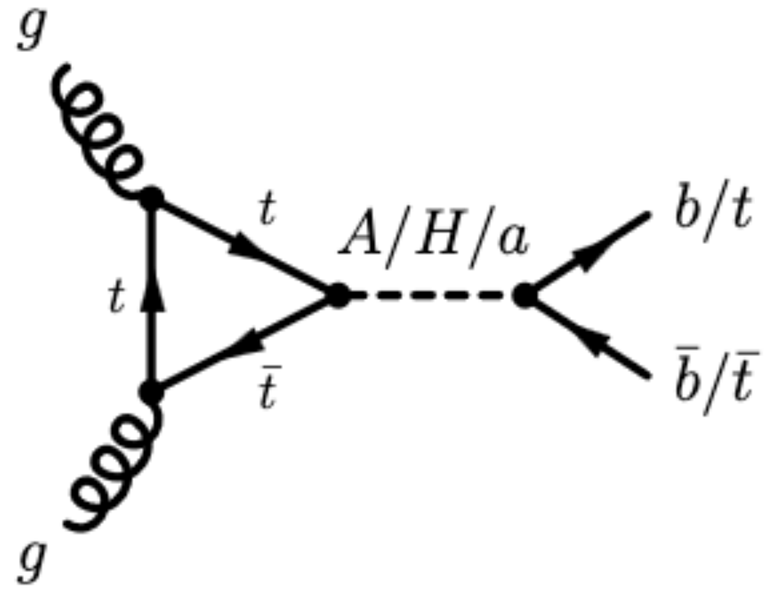


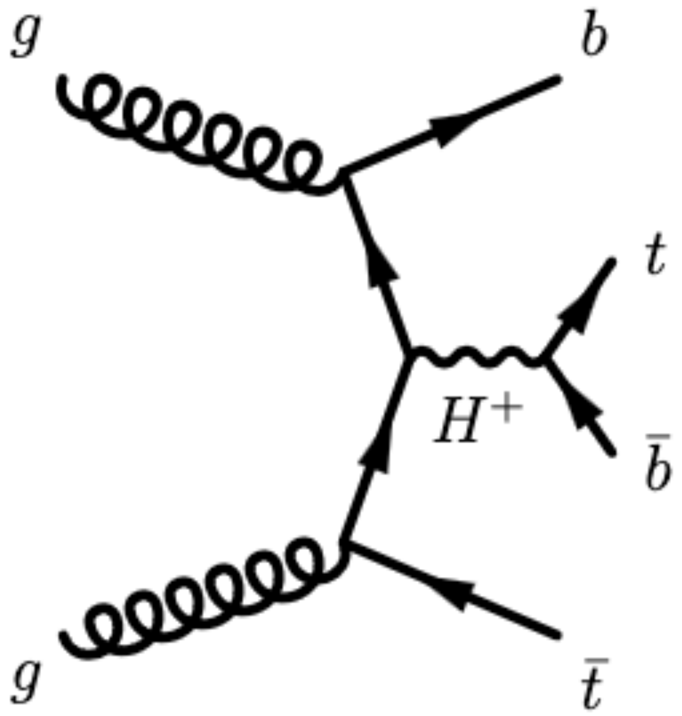








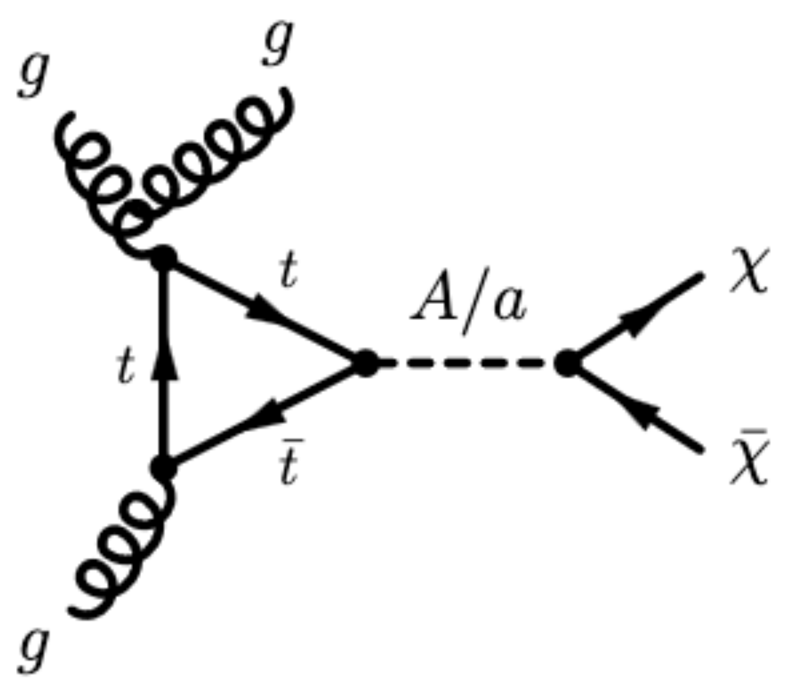




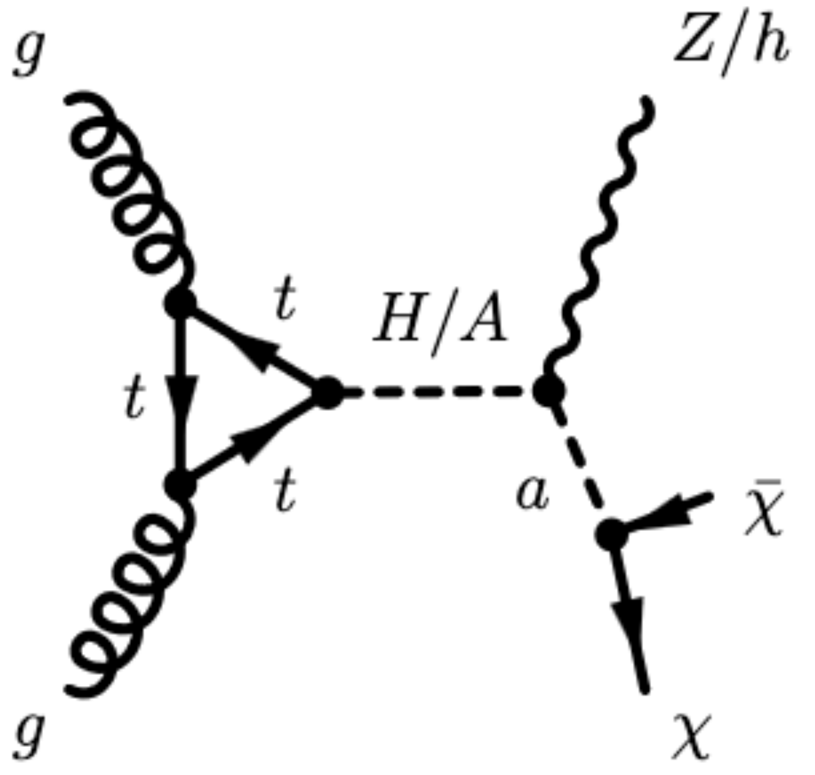
2HDM+a: what to expect?

➤ Large signature space with (pretty much) everything an experimentalist could wish for

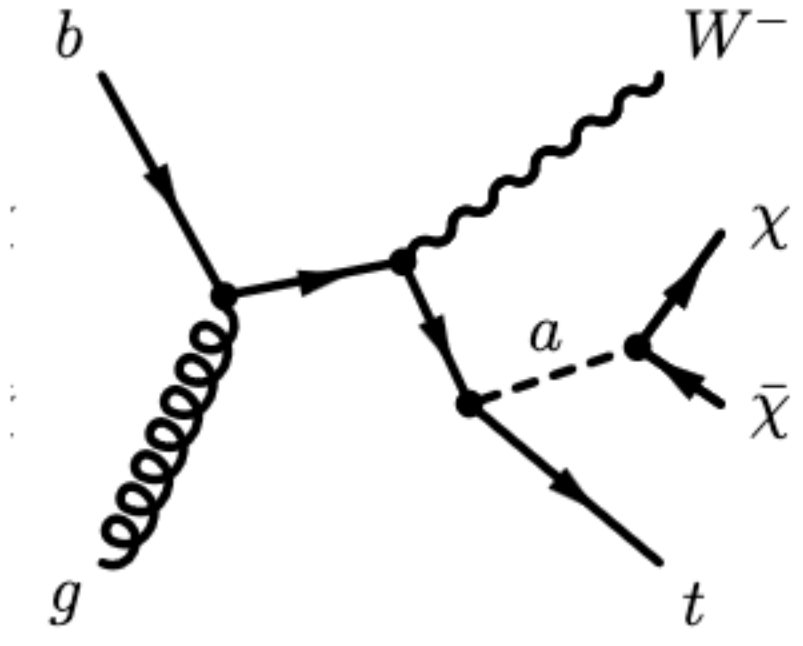
mono-jet + E_T^{miss}



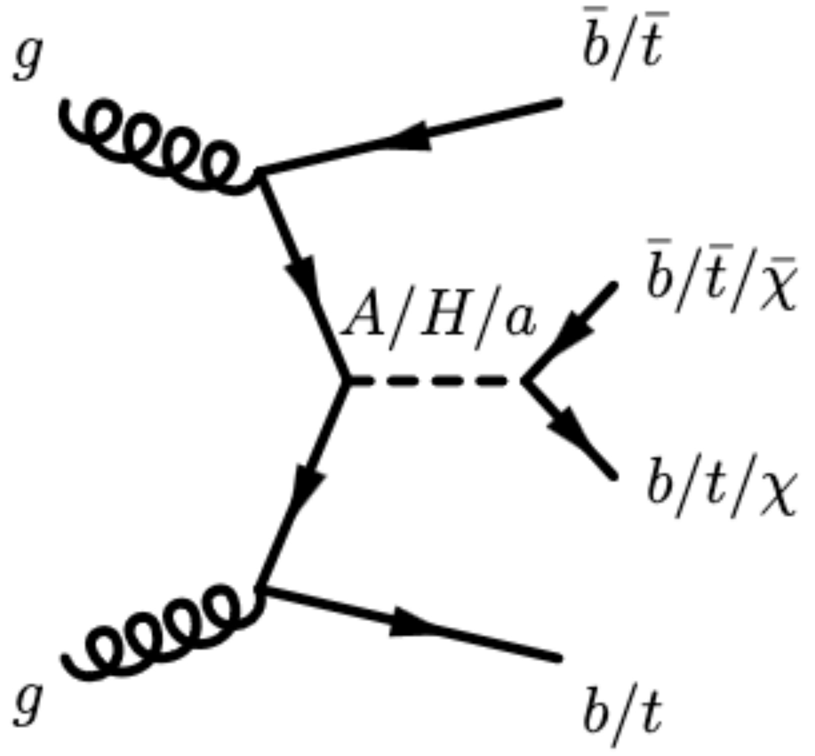
mono-H/Z/γ + E_T^{miss}

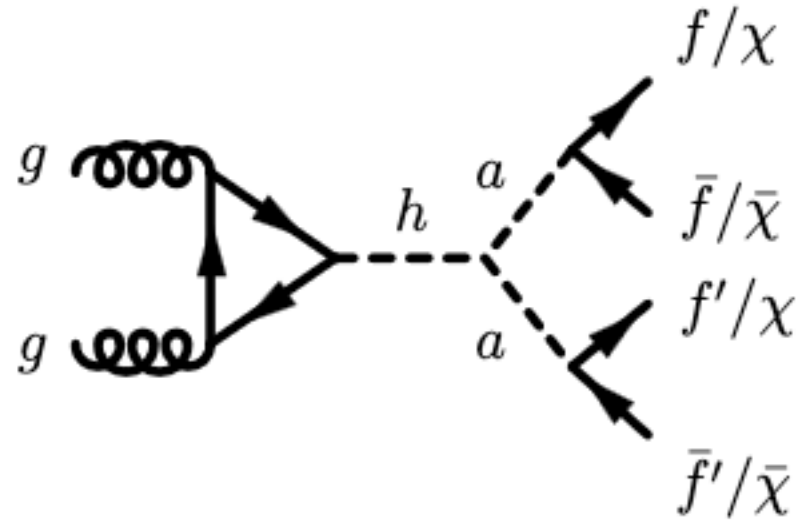


$tW + E_T^{miss}$

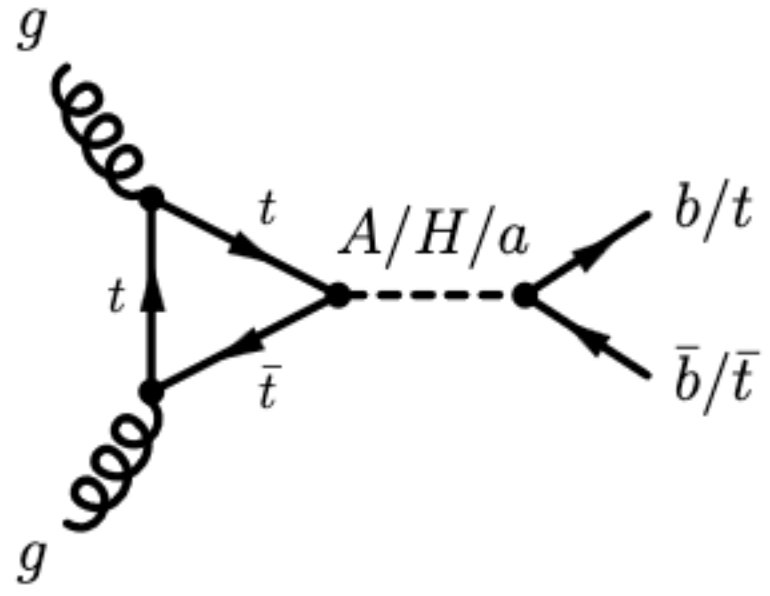


$t\bar{t}/b\bar{b} + E_T^{miss}$ (or 4 t/4b)

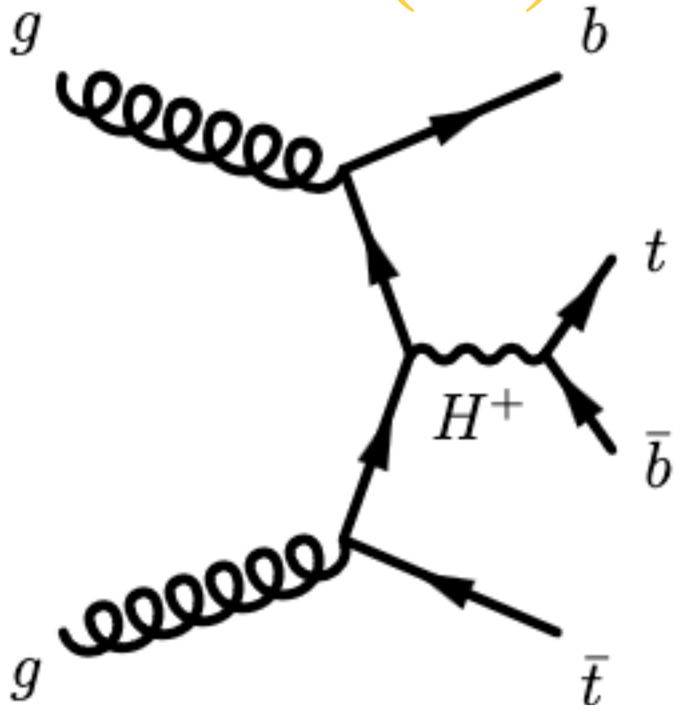




$t\bar{t}$ resonances



$tbH^+(tb)$

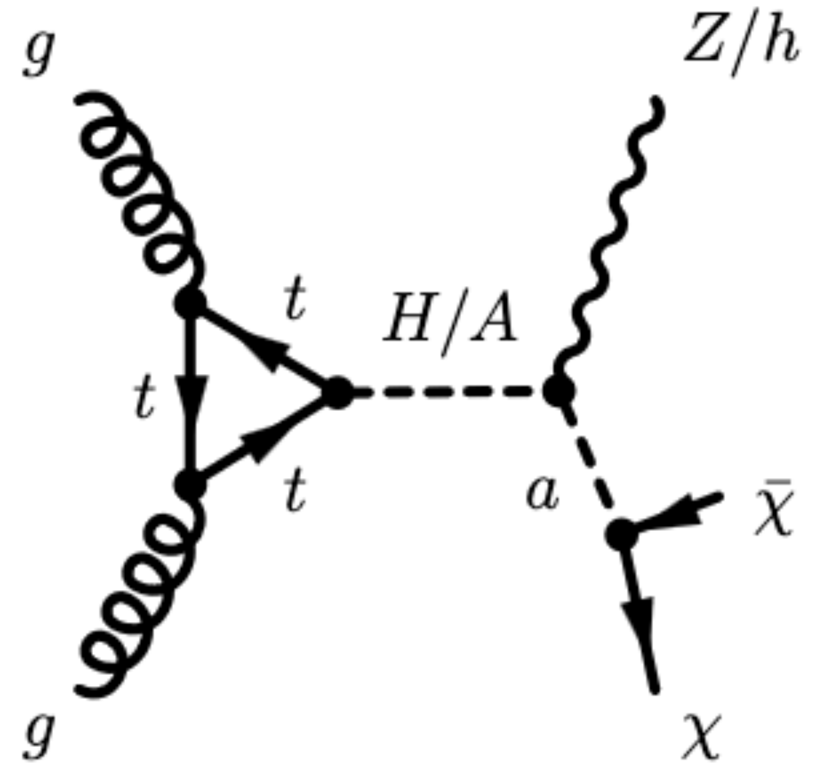


2HDM+a: what to expect?

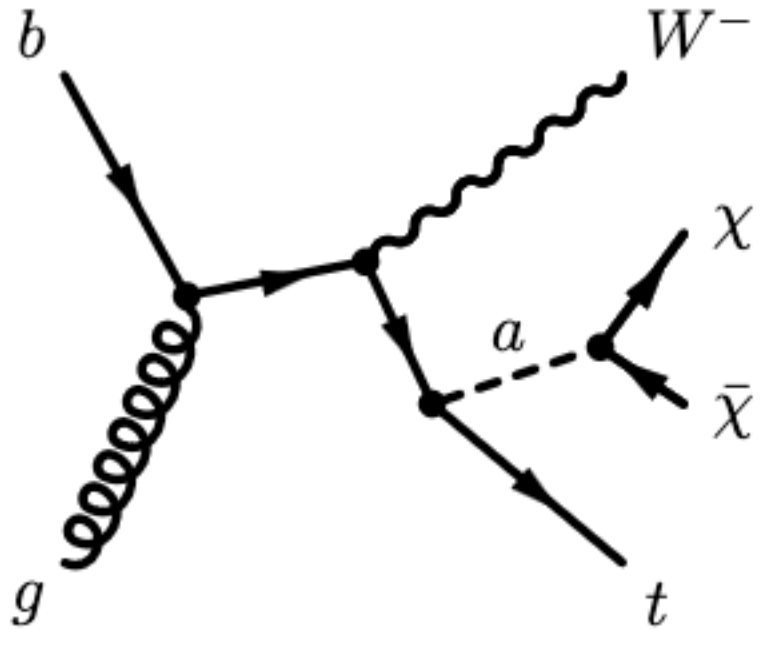
➤ Large signature space with (pretty much) everything an experimentalist could wish for

mono-jet + E_T^{miss}

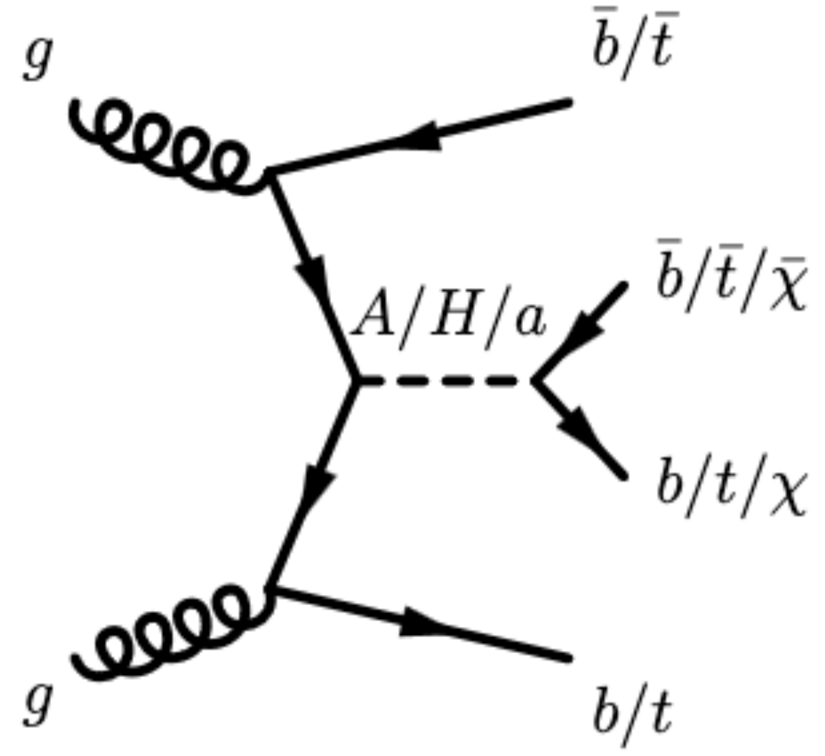
mono-H/Z/γ + E_T^{miss}



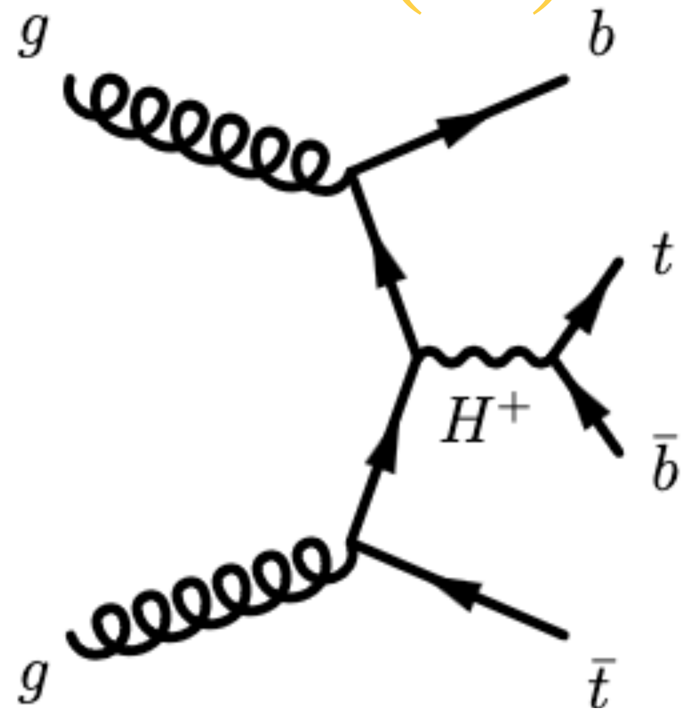
$tW + E_T^{miss}$



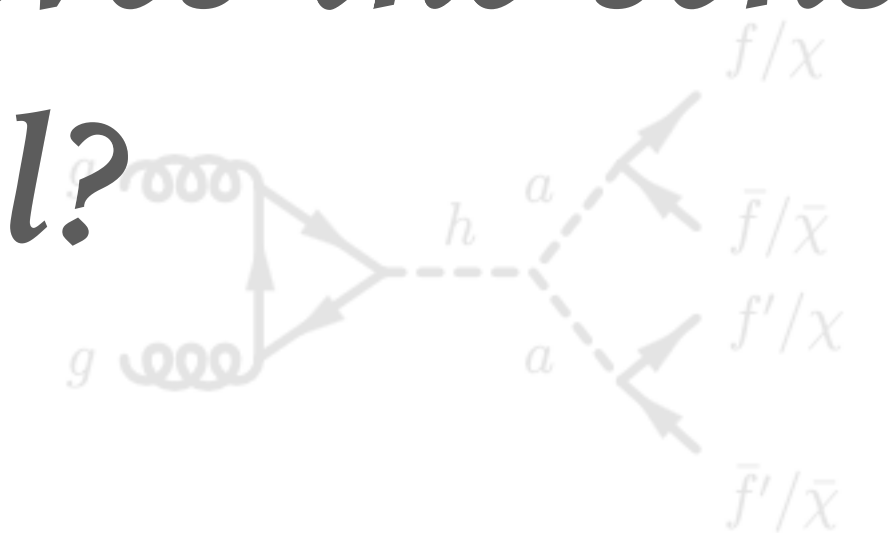
4 tops



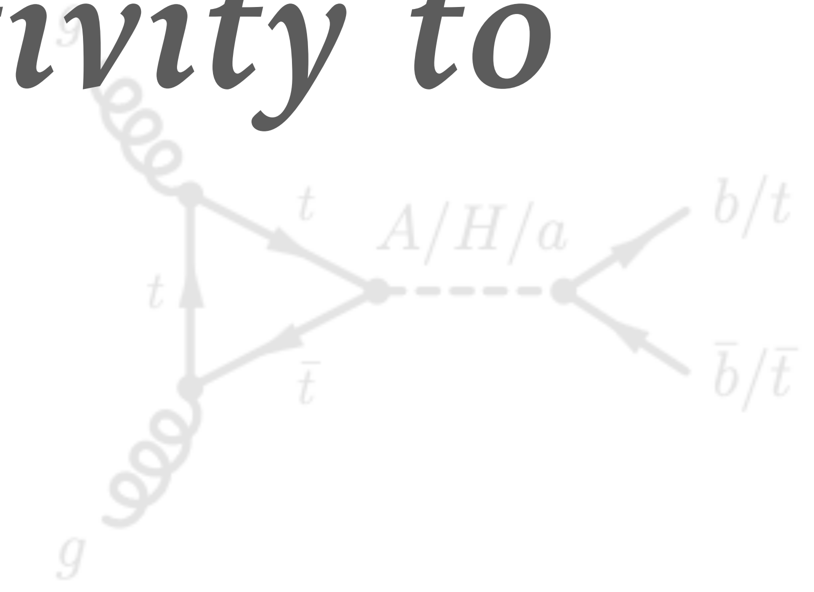
$tbH^{+}(tb)$



What drives the sensitivity to the model?

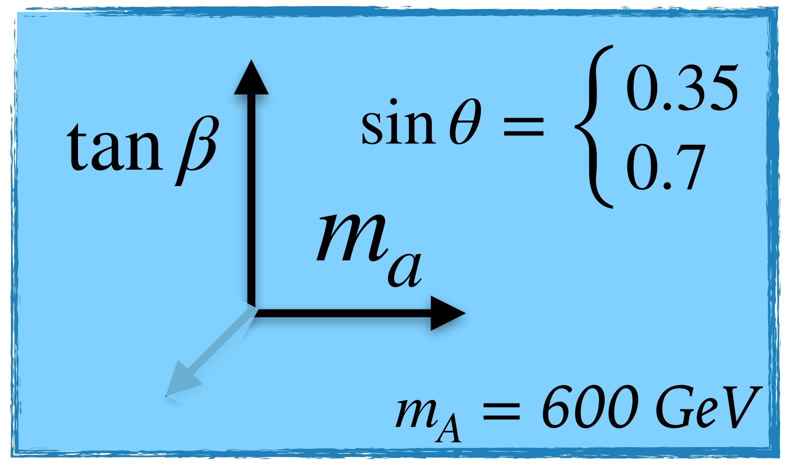


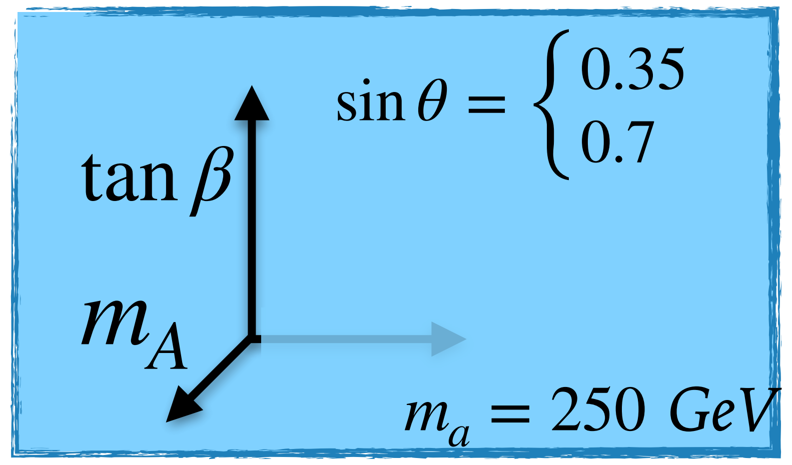
$t\bar{t}$ resonances

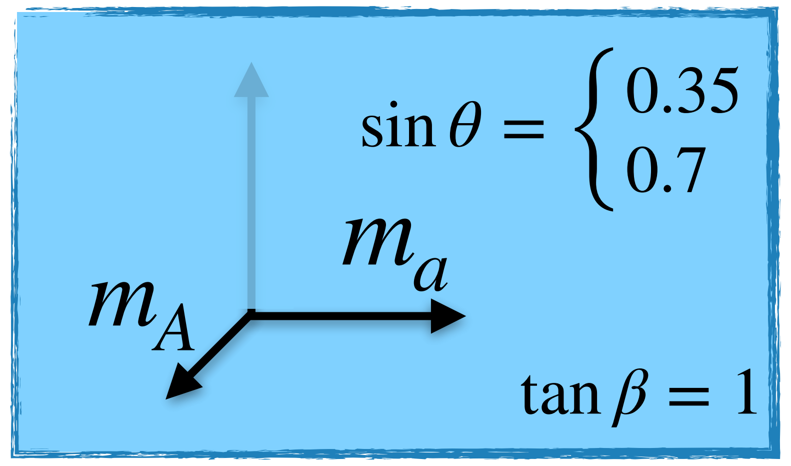


arXiv:2306.00641

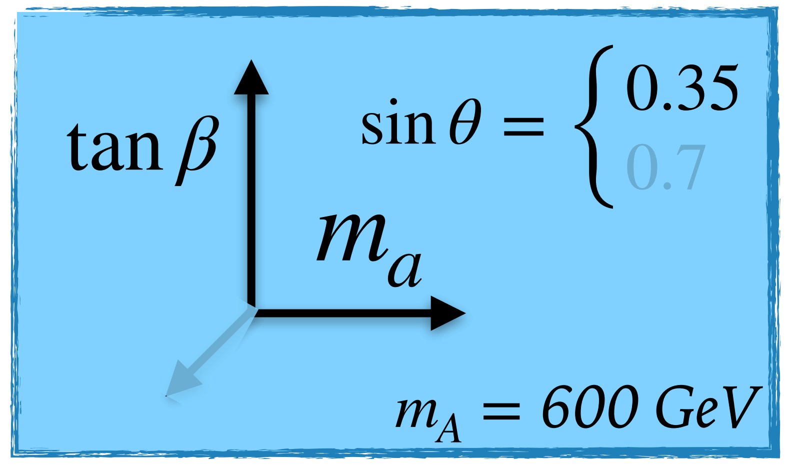
2HDM+a: parameter landscape

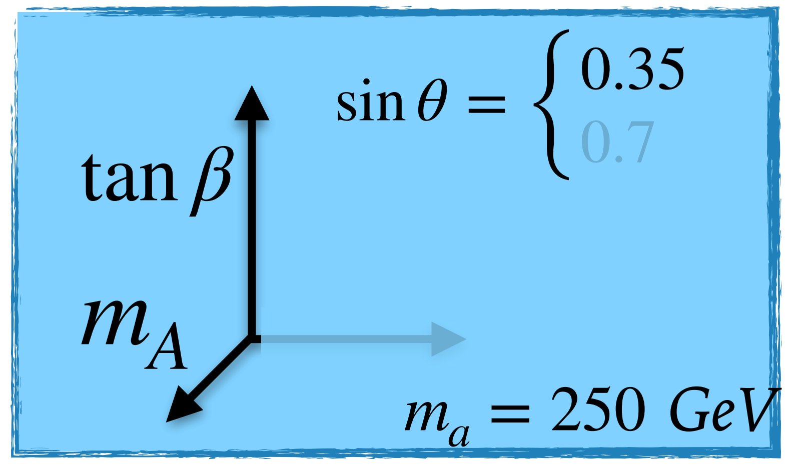


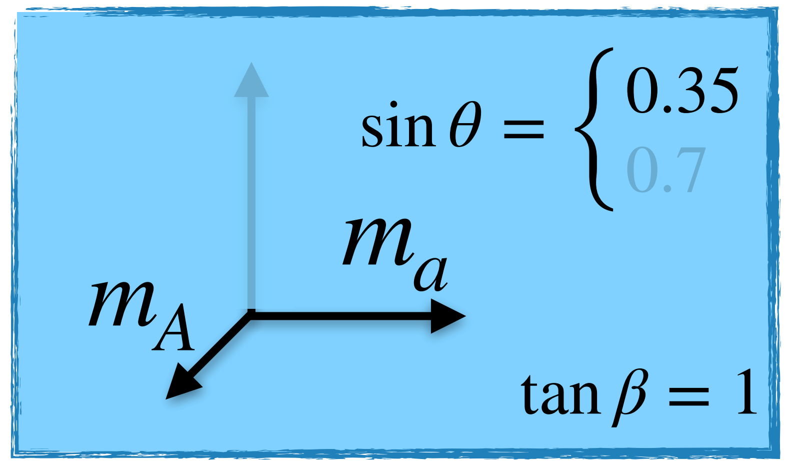


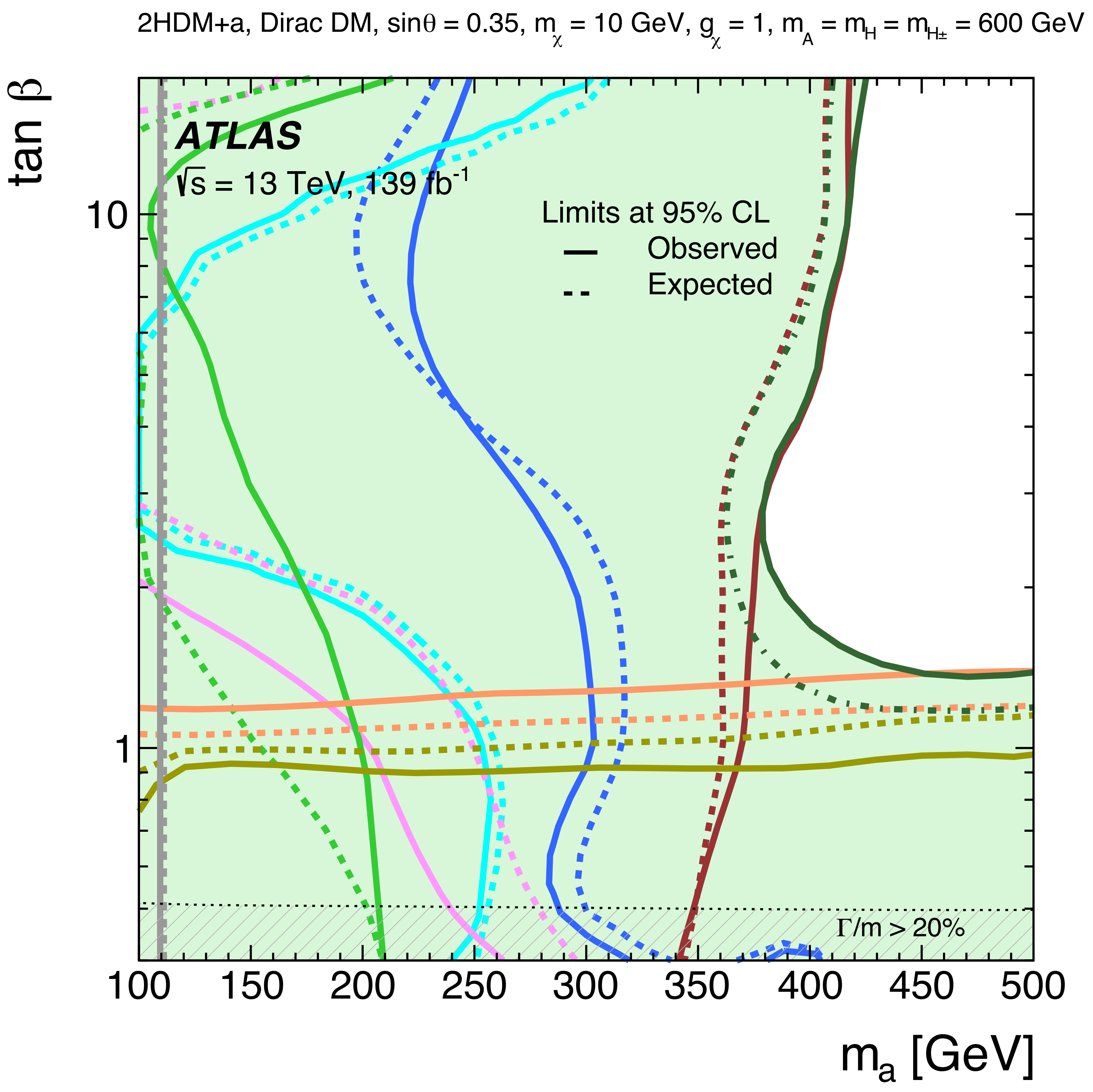


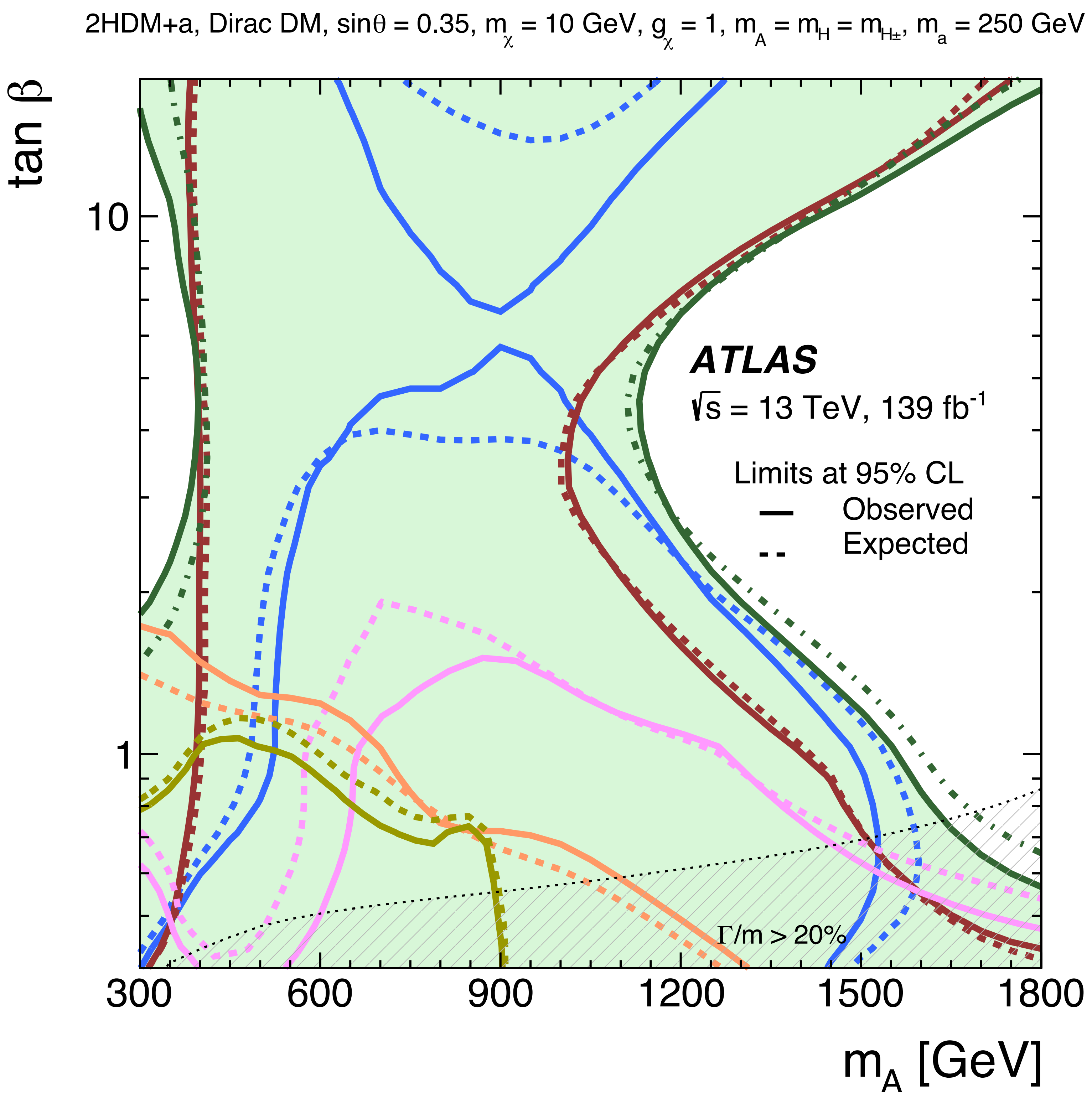
2HDM+a: parameter landscape $\sin\theta = 0.35$

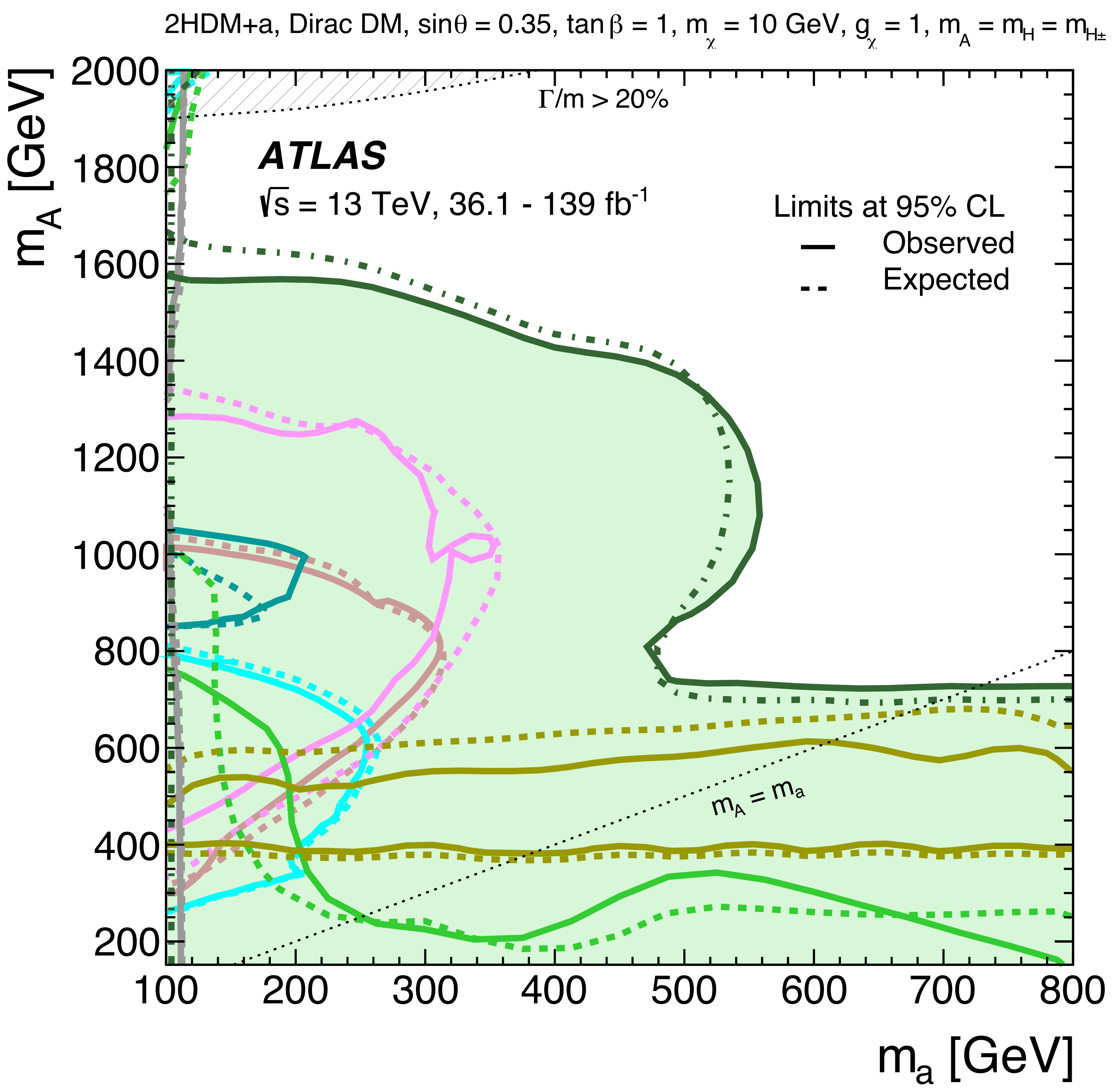








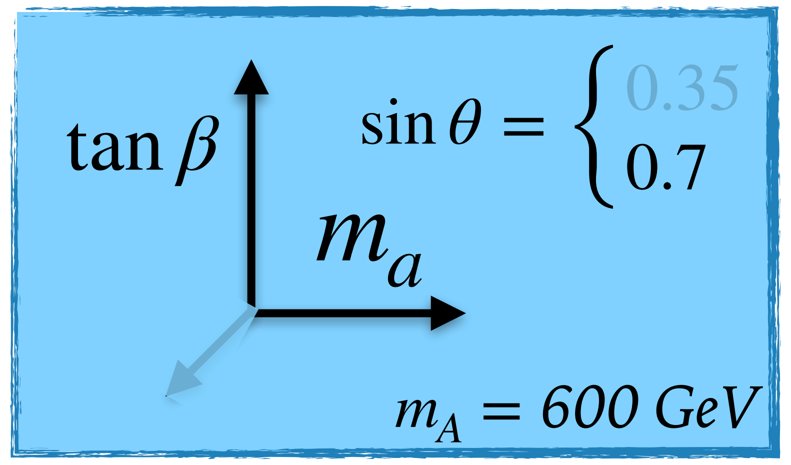


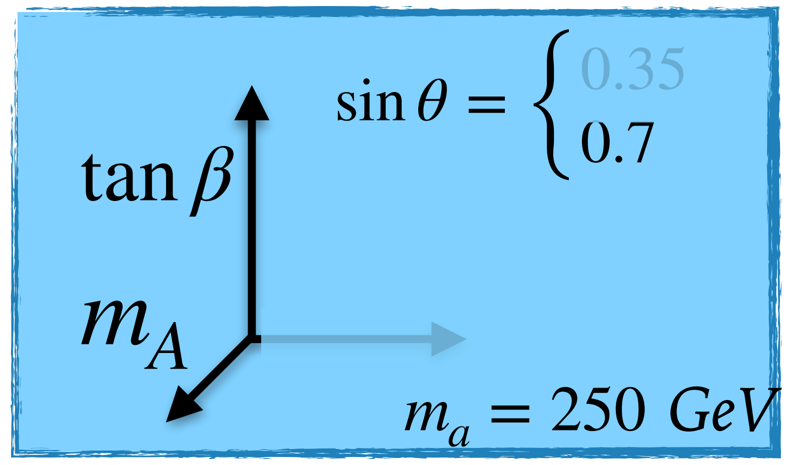


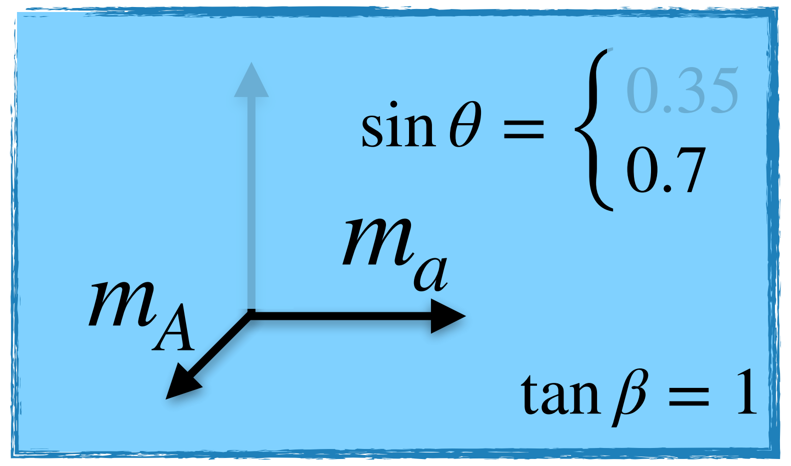
- E_T^{miss}+h($b\bar{b}$), 139 fb^{-1} — JHEP 11 (2021) 209
- E_T^{miss}+h(γγ), 139 fb^{-1} — JHEP 10 (2021) 13
- E_T^{miss}+Z(ll), 139 fb^{-1} — PLB 829 (2022) 137066
- E_T^{miss}+tW, 139 fb^{-1} — arXiv:2211.13138
- E_T^{miss}+j, 139 fb^{-1} — PRD 103 (2021) 112006
- tbH$^\pm$(tb), 139 fb^{-1} — JHEP 06 (2021) 145
- $t\bar{t}t\bar{t}$, 139 fb^{-1} — arXiv:2211.01136
- h→invisible, 139 fb^{-1} — arxiv:2301.10731
- Combination — E_T^{miss}+h($b\bar{b}$), E_T^{miss}+Z(ll), tbH$^\pm$(tb)

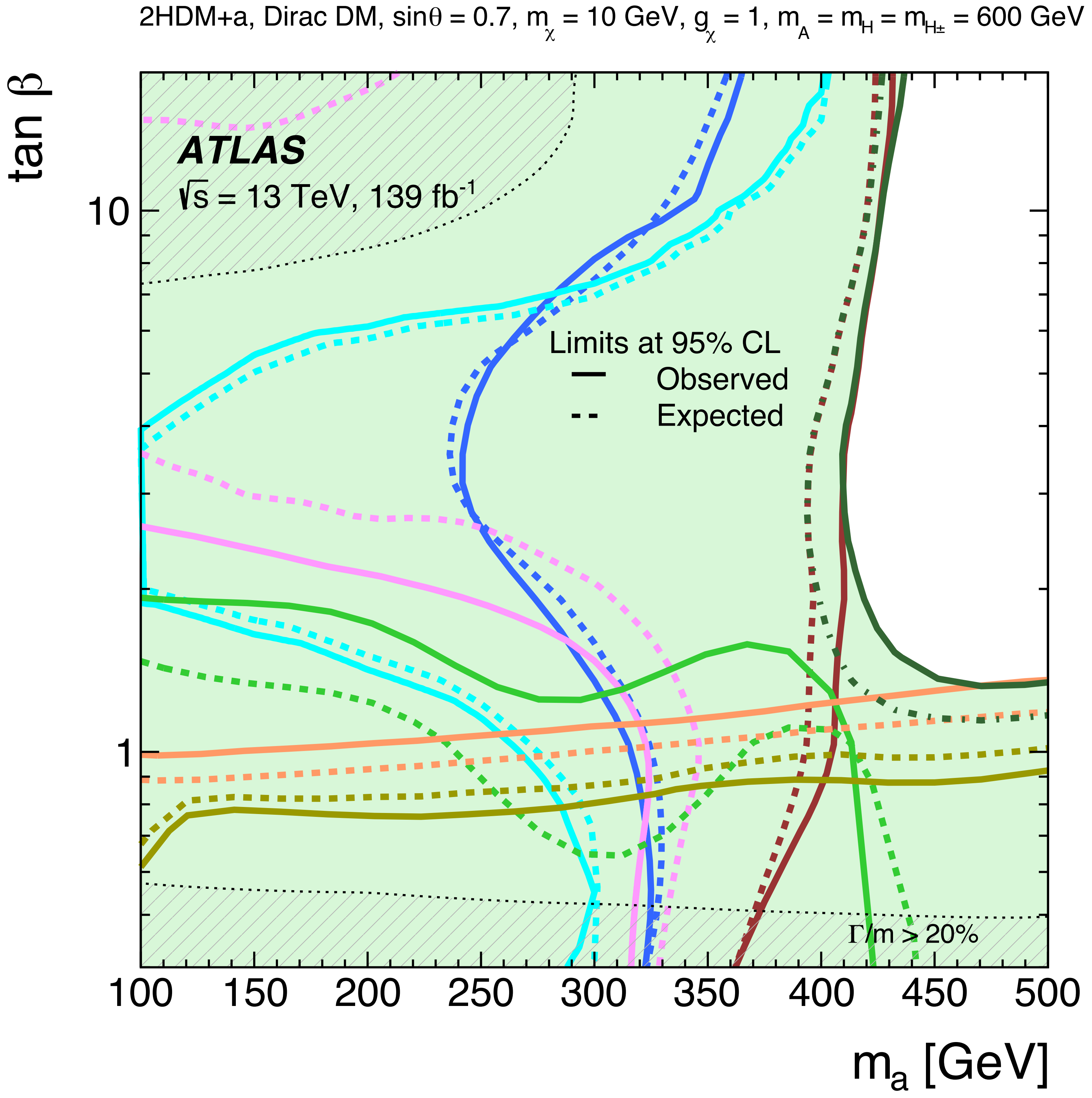
arXiv:2306.00641

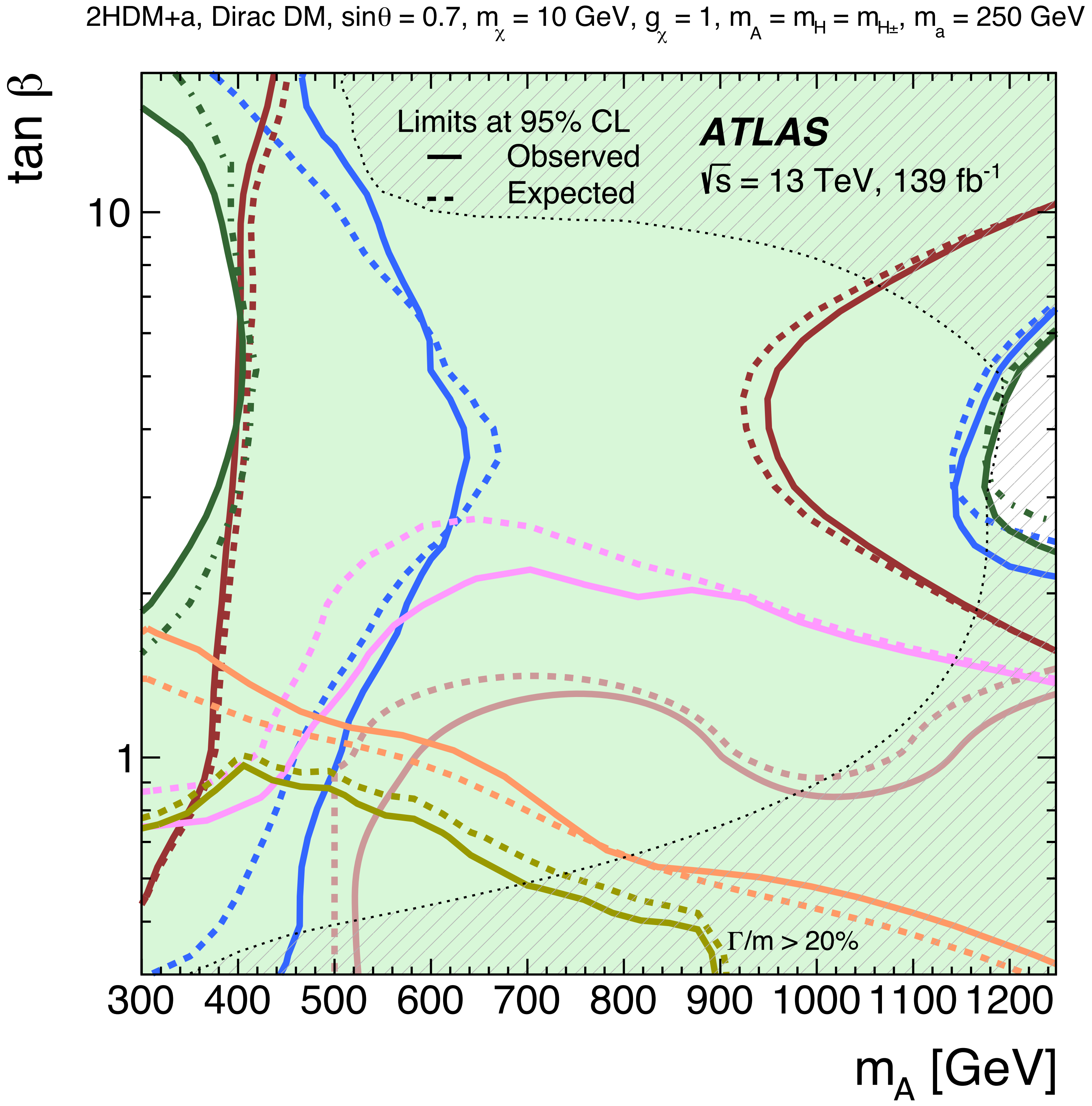
2HDM+a: parameter landscape $\sin\theta = 0.7$

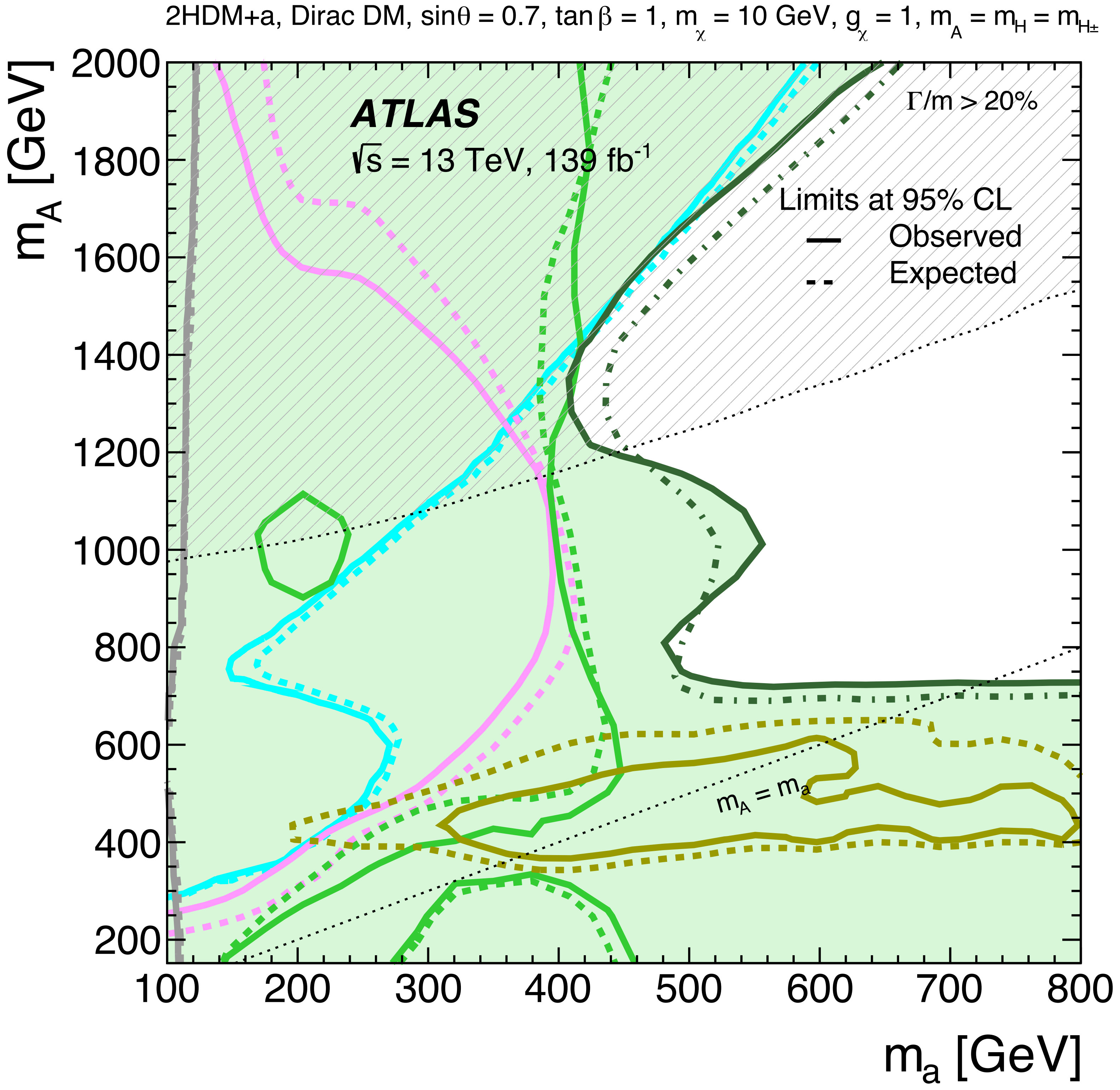










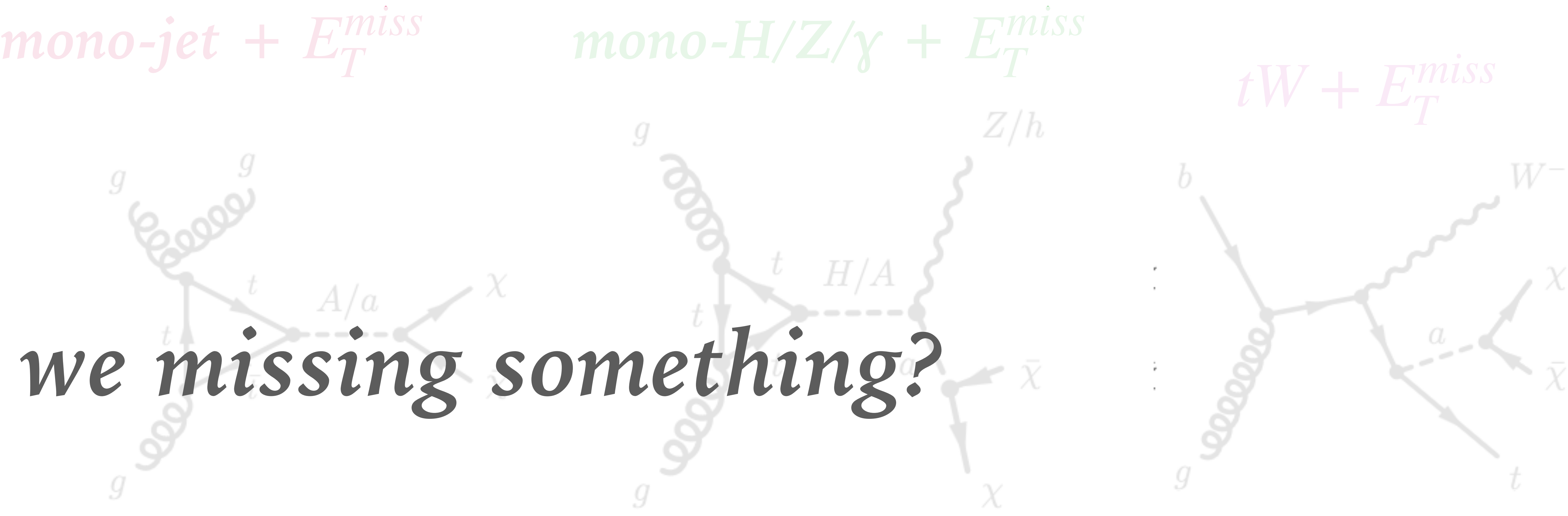


- E_T^{miss}+h($b\bar{b}$), 139 fb^{-1} — JHEP 11 (2021) 209
- E_T^{miss}+h($\gamma\gamma$), 139 fb^{-1} — JHEP 10 (2021) 13
- E_T^{miss}+Z(ll), 139 fb^{-1} — PLB 829 (2022) 137066
- E_T^{miss}+tW, 139 fb^{-1} — arXiv:2211.13138
- E_T^{miss}+j, 139 fb^{-1} — PRD 103 (2021) 112006
- tbH$^{\pm}$(tb), 139 fb^{-1} — JHEP 06 (2021) 145
- $t\bar{t}t\bar{t}$, 139 fb^{-1} — arXiv:2211.01136
- h→invisible, 139 fb^{-1} — arxiv:2301.10731
- Combination — E_T^{miss}+h($b\bar{b}$), E_T^{miss}+Z(ll), tbH$^{\pm}$(tb)

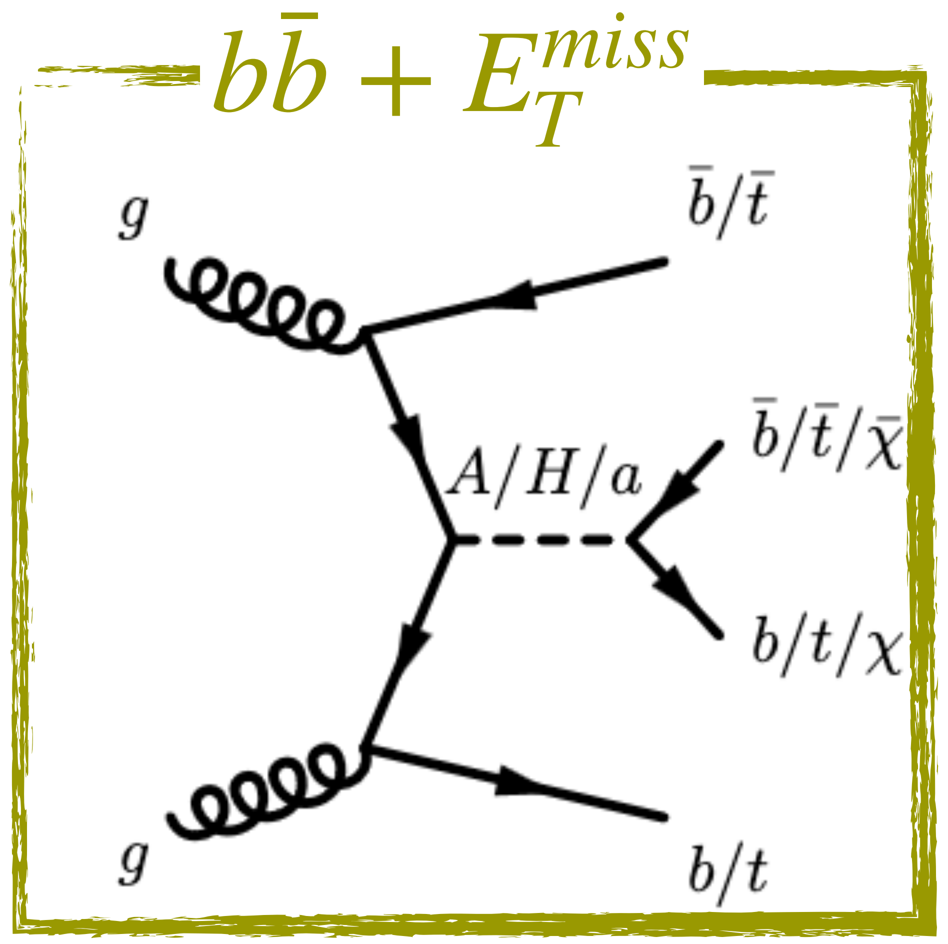
Sensitivity to different final states changes!

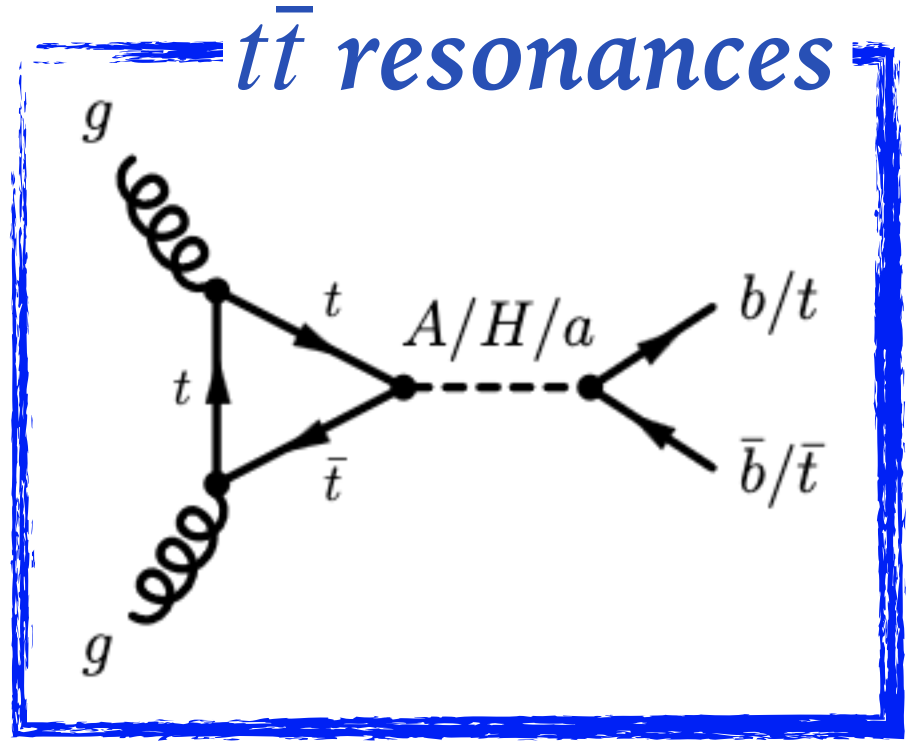
2HDM+a: what to expect?

➤ Large signature space with (pretty much) everything an experimentalist could wish for

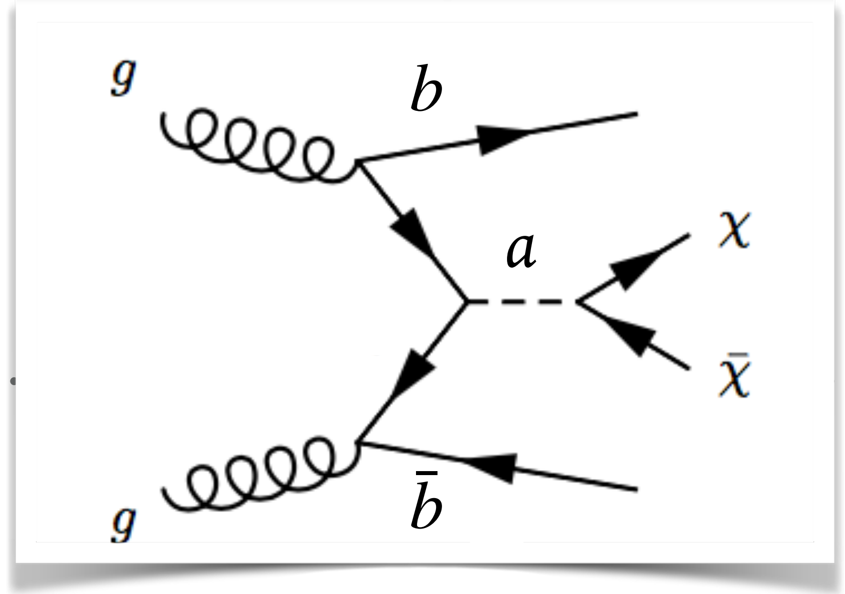


Are we missing something?



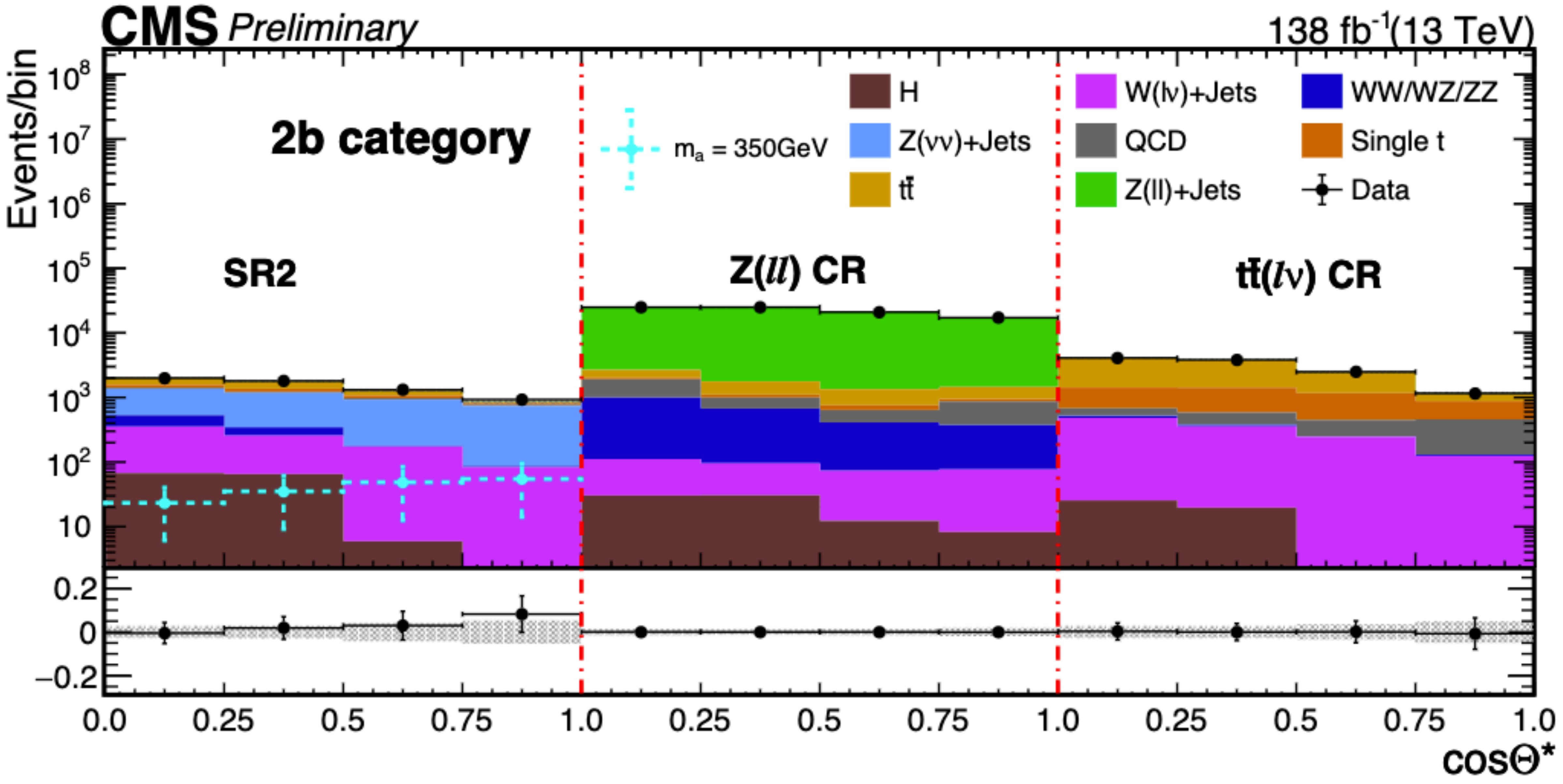


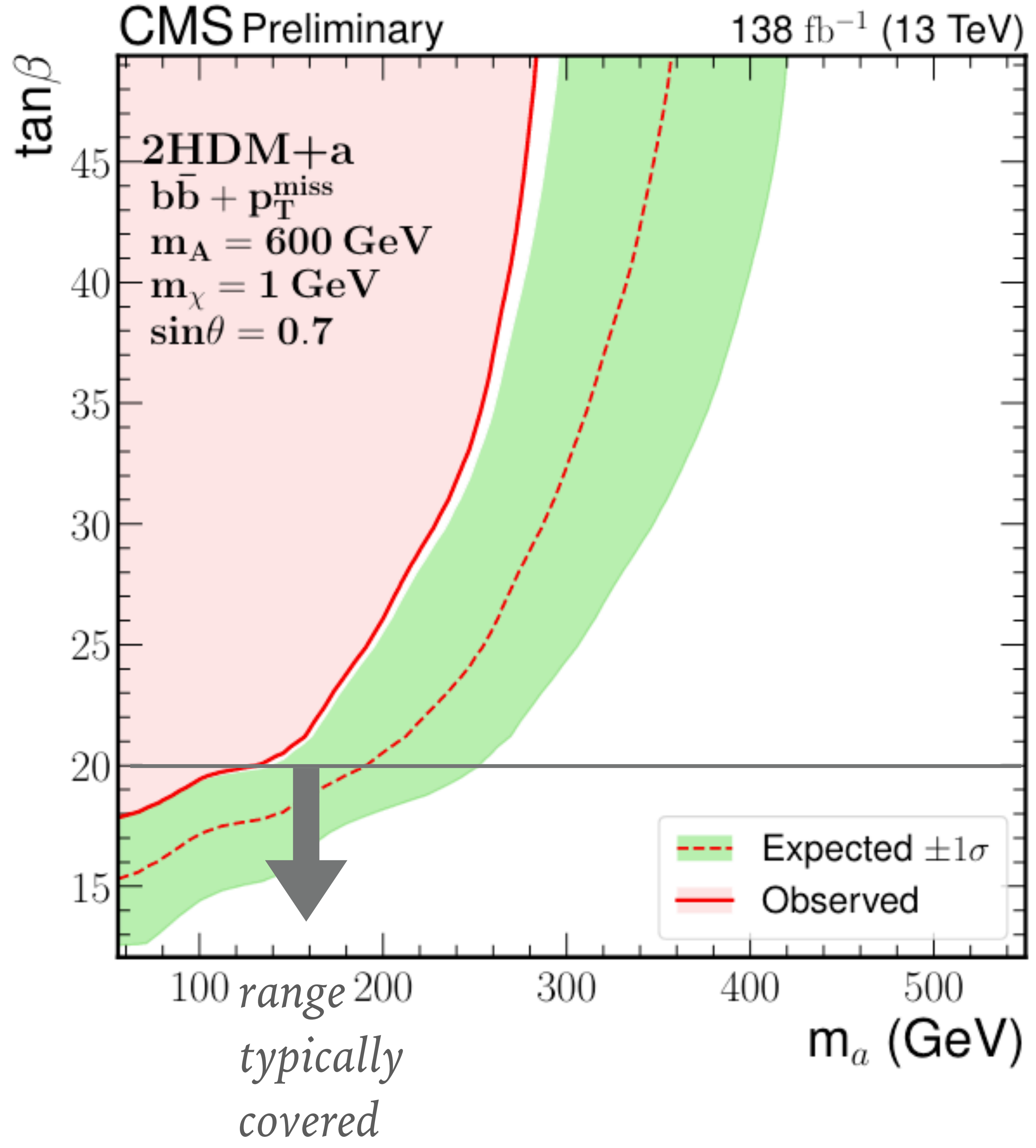
Non-resonant $b\bar{b} + E_T^{miss}$



- At high $\tan\beta$ production cross section of this process is enhanced
- Events categorized by E_T^{miss} > 200 GeV number of b-jets: 1b or 2b
  - Discriminating variables:

$$E_T^{miss} \ \text{and} \ \cos\Theta^{\star} = \left| \tanh\left(\frac{\eta_{b1} - \eta_{b2}}{2}\right) \right|$$

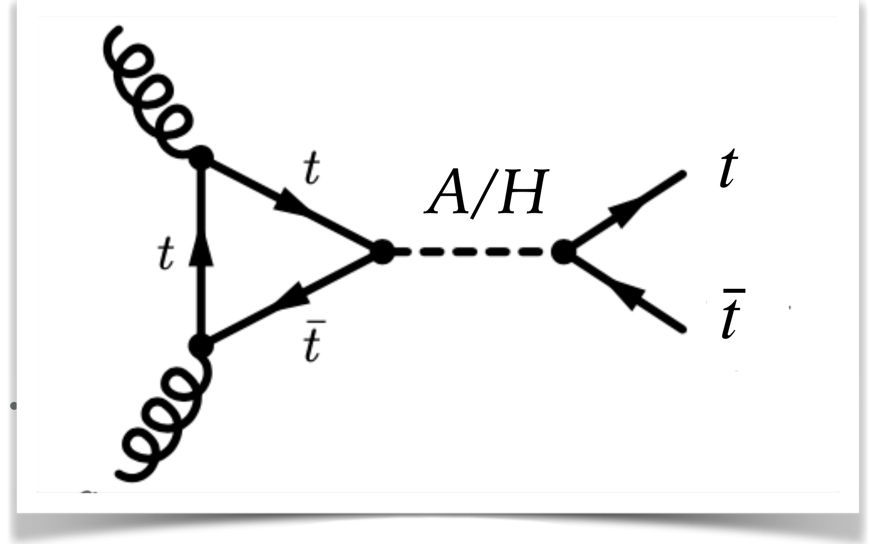




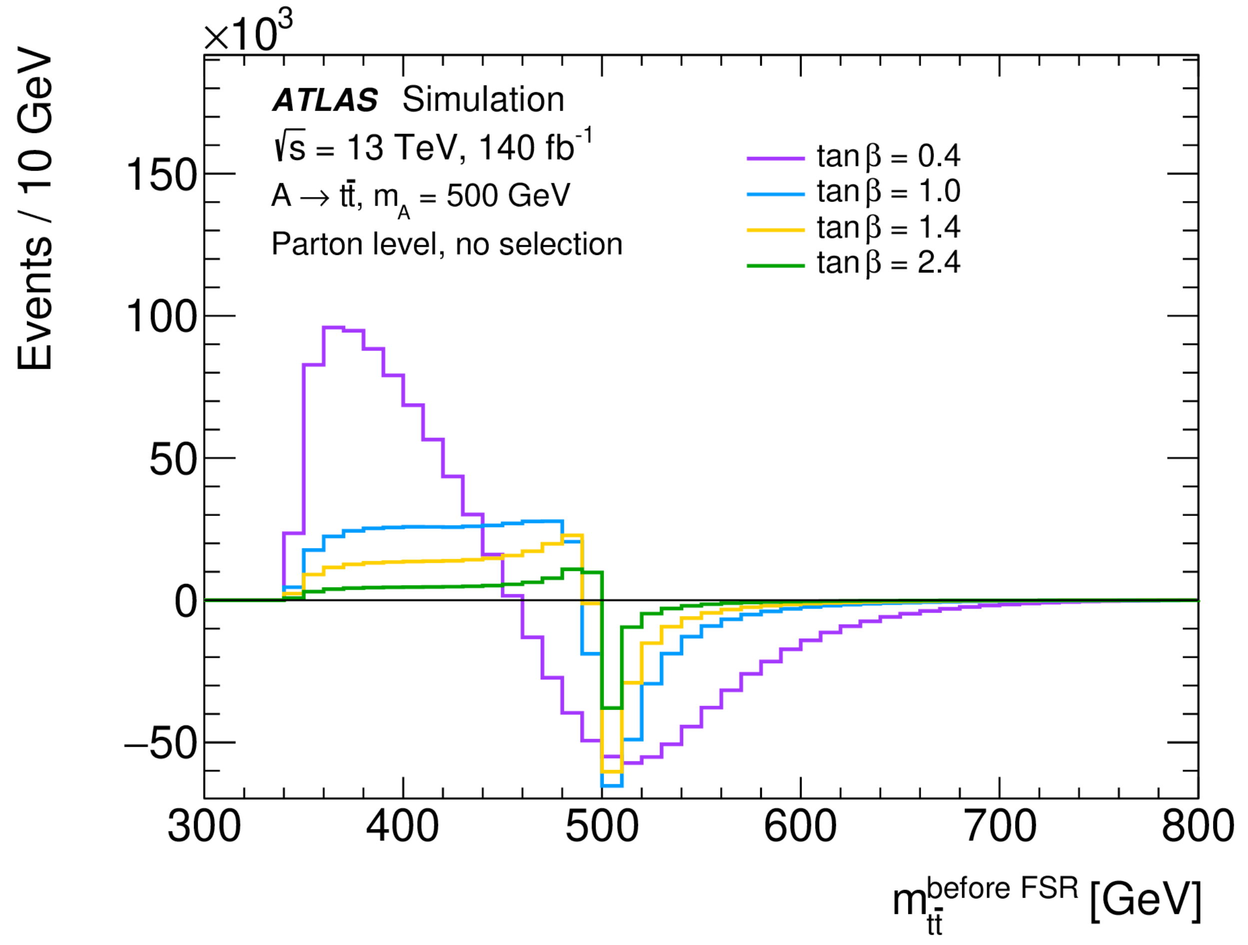
Main backgrounds estimated in control regions

arxiv:2404.18986

Resonant $t\bar{t}$ production

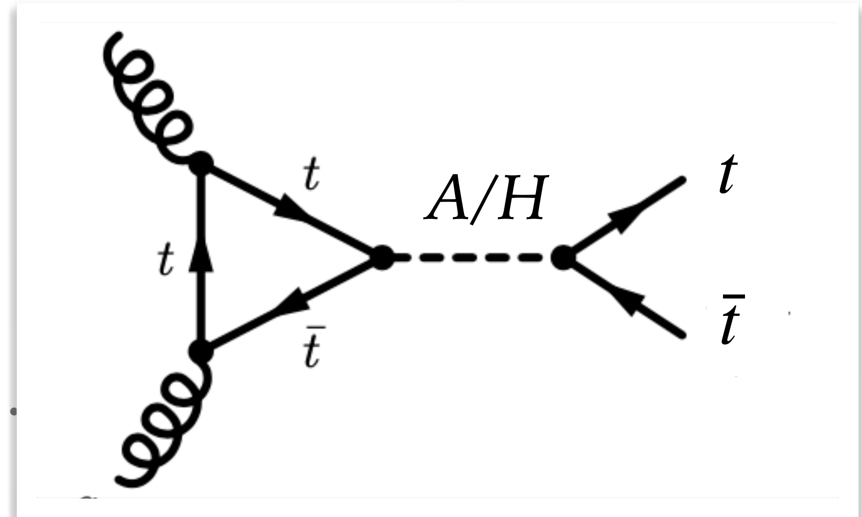


- Neutral bosons with $m_{H/A} > 2m_{t\bar{t}}$ decay pre-dominantly to $t\bar{t}$ → **resonance peak**
- Interference with the SM leads to a non-trivial di-top invariant mass distribution $m_{t\bar{t}}$
  - **Peak-dip structure** strongly model dependent
  - Needs dedicated strategy to implement the likelihood for interpretation

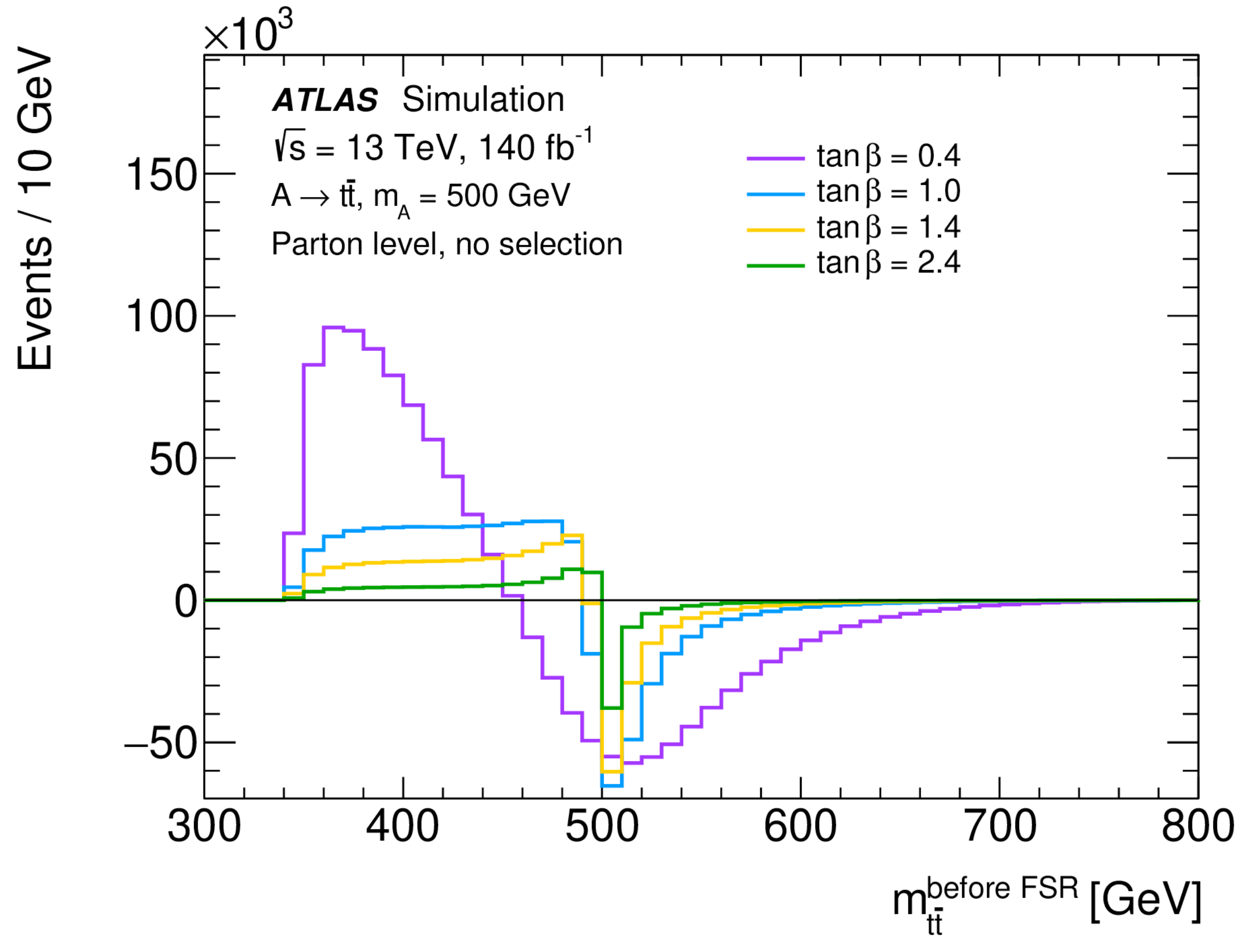


arxiv:2404.18986

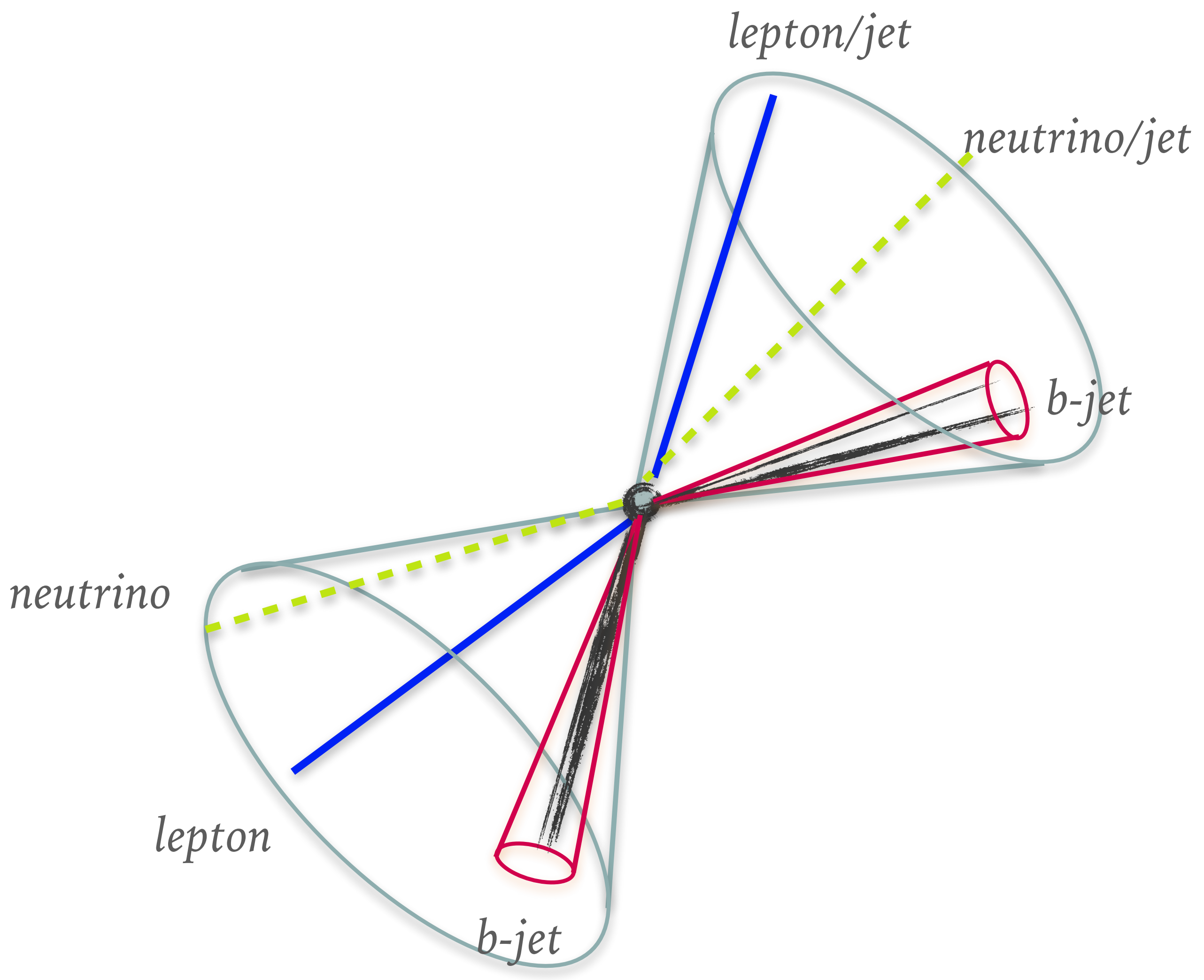
Resonant $t\bar{t}$ production

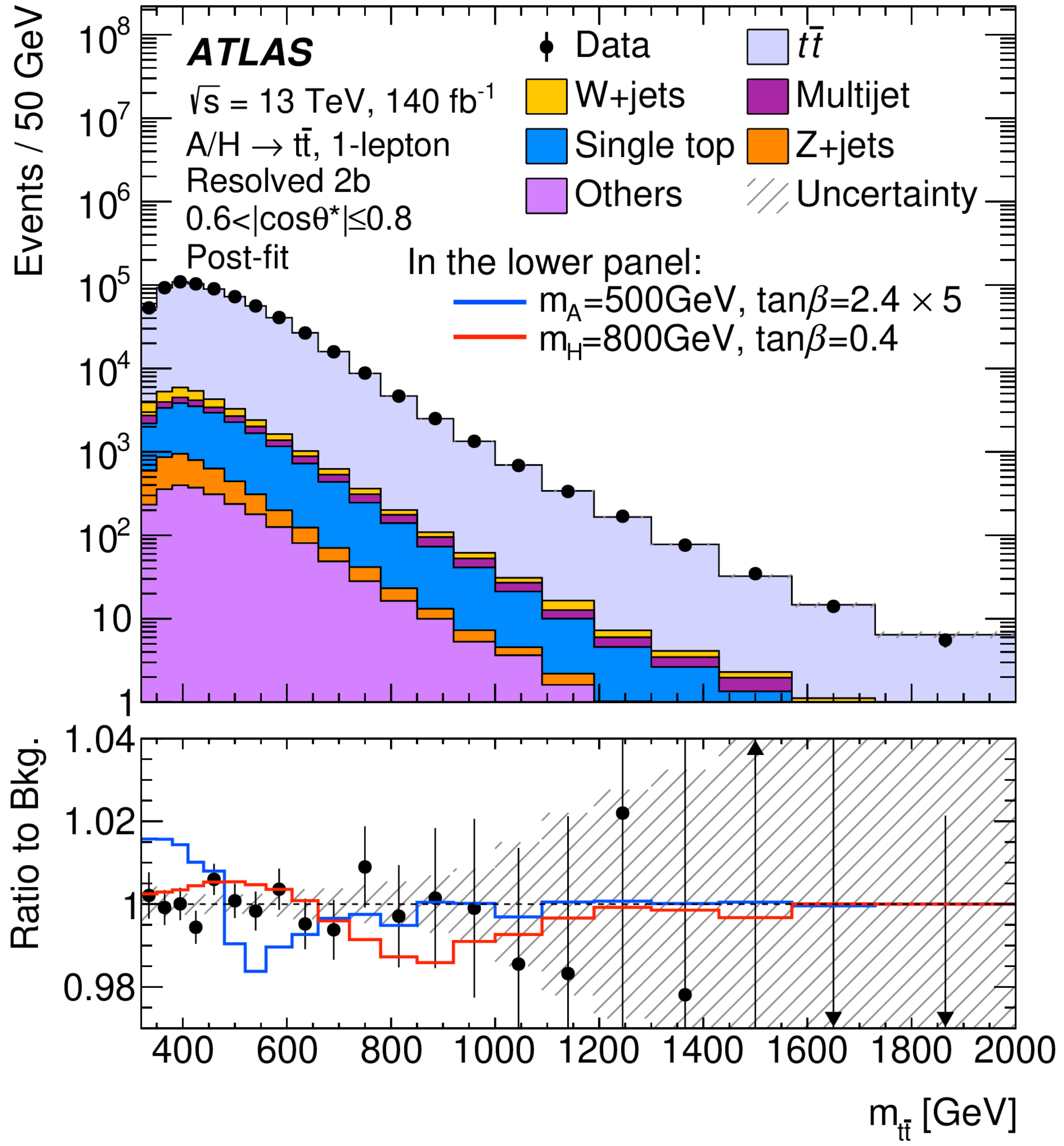


- Neutral bosons with $m_{H/A} > 2m_{t\bar{t}}$ decay pre-dominantly to $t\bar{t}$ → **resonance peak**
- Interference with the SM leads to a non-trivial di-top invariant mass distribution $m_{t\bar{t}}$
  - **Peak-dip structure** strongly model dependent
  - Needs dedicated strategy to implement the likelihood for interpretation



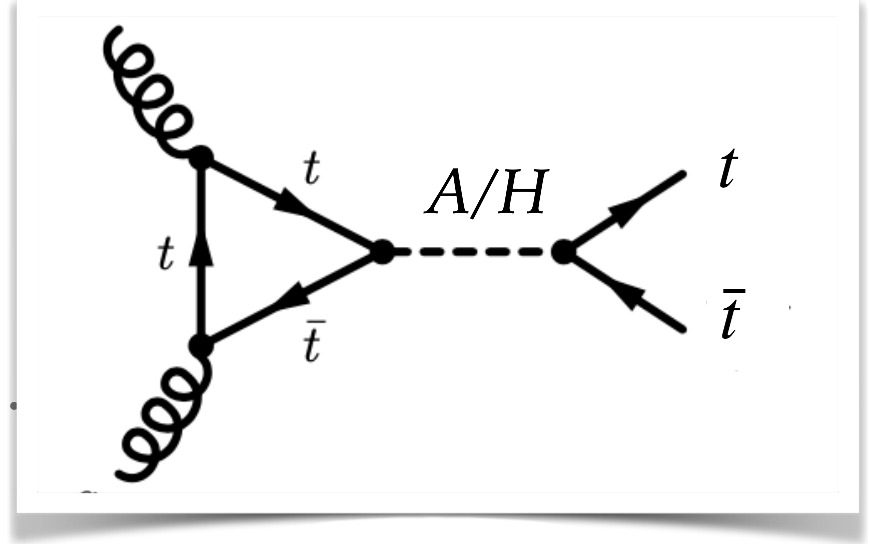
- Aim: **reconstruct proxy for $m_{t\bar{t}}$ distribution**



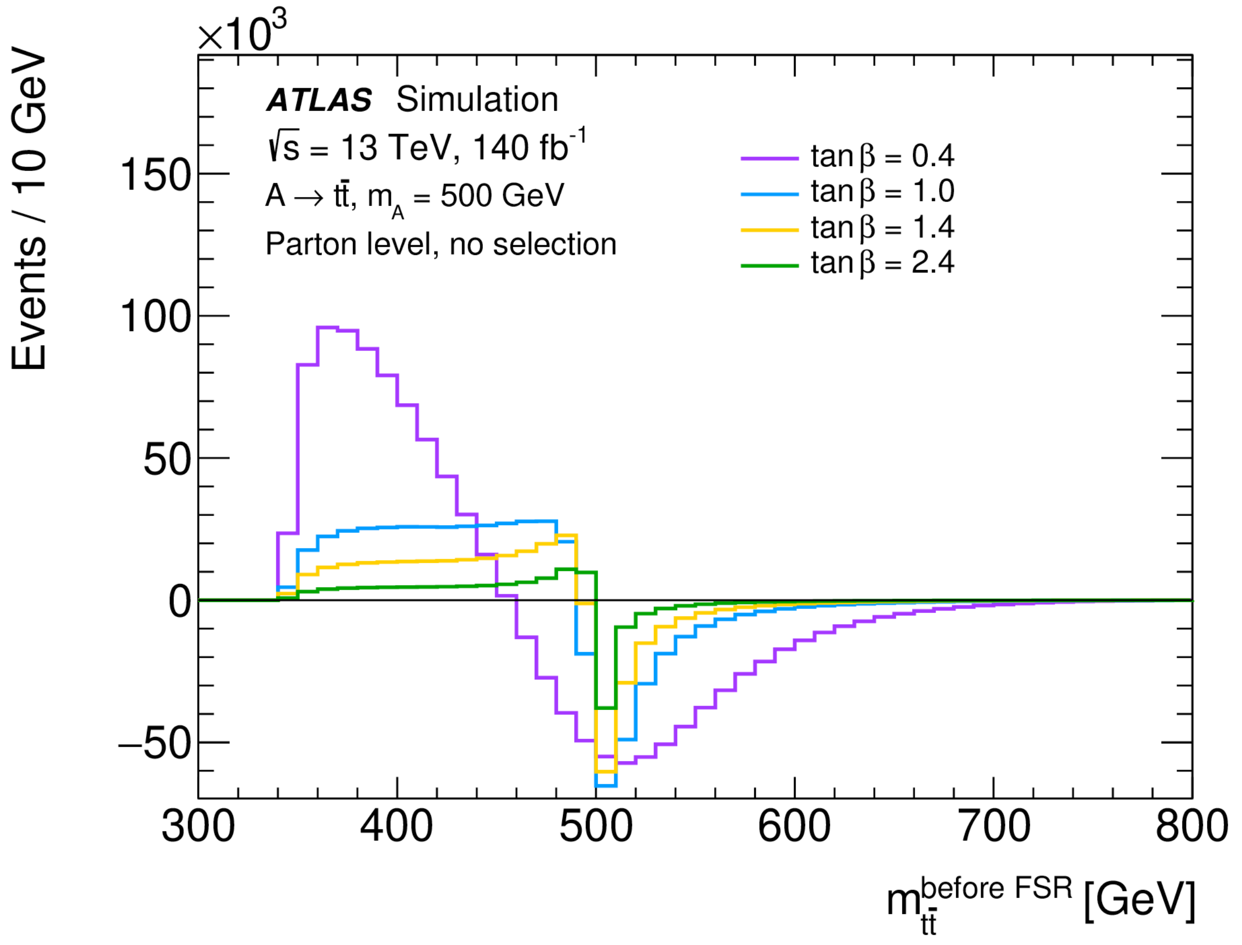


arxiv:2404.18986

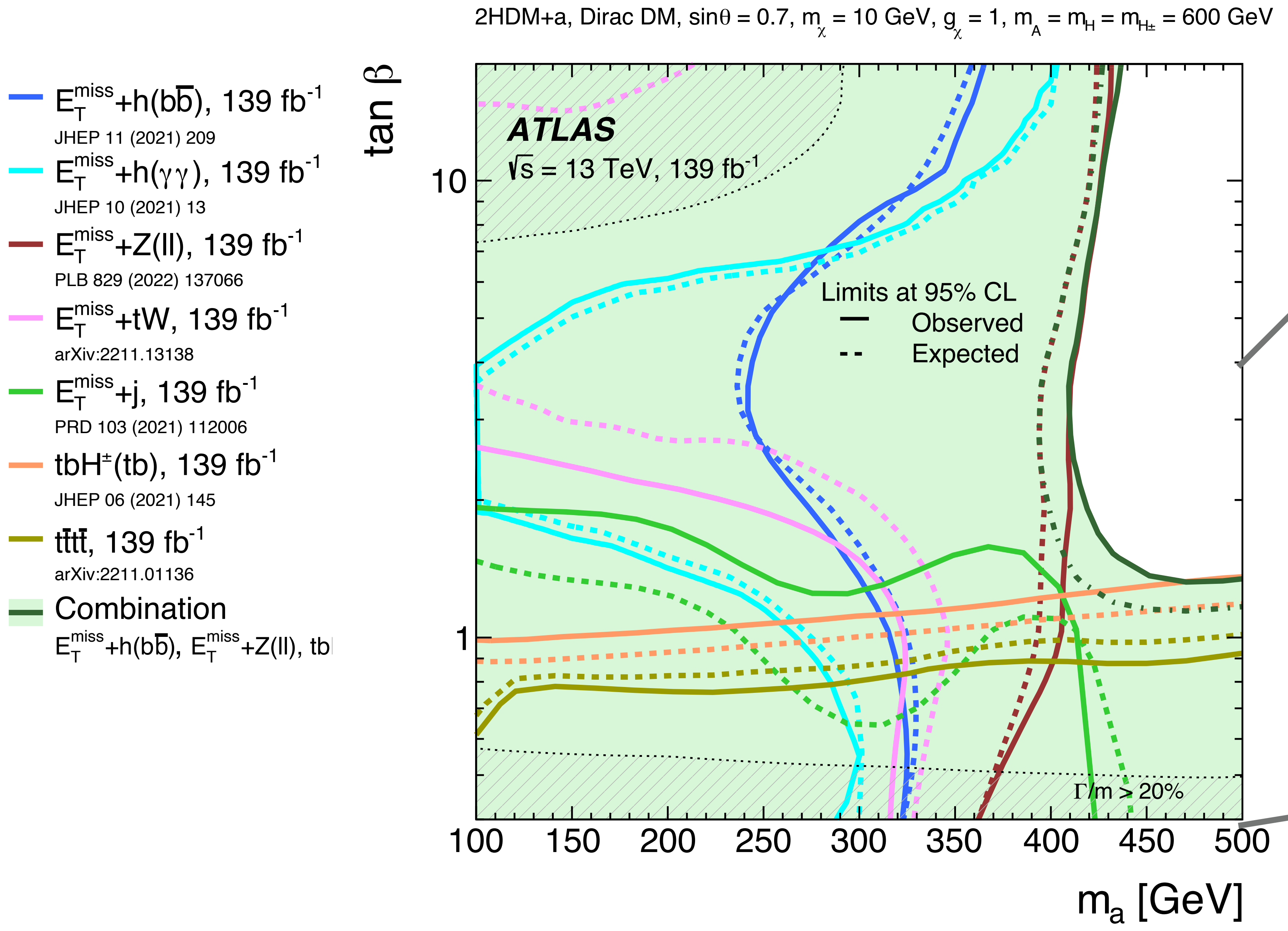
Resonant $t\bar{t}$ production

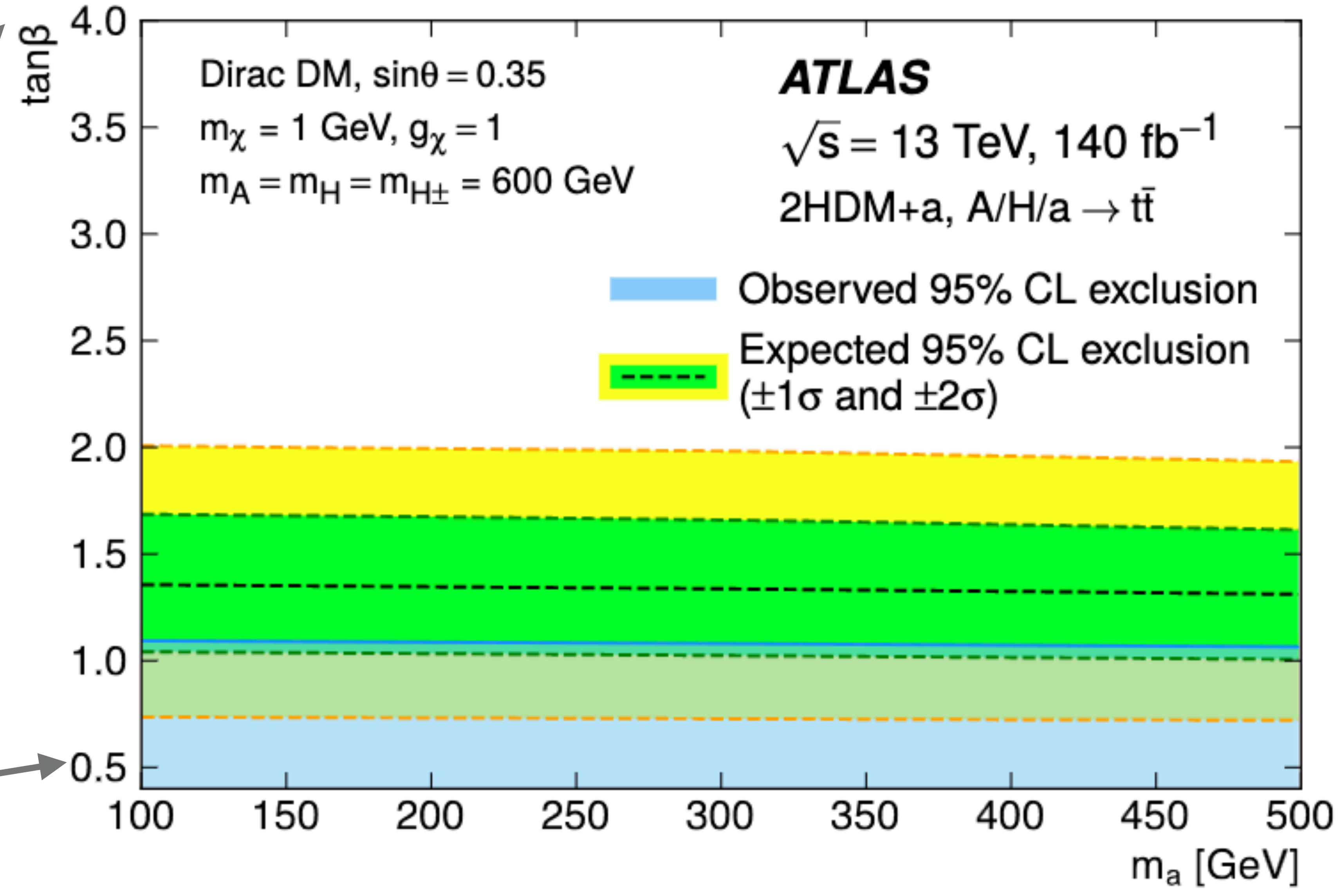


- Neutral bosons with $m_{H/A} > 2m_{t\bar{t}}$ decay pre-dominantly to $t\bar{t}$ → **resonance peak**
- Interference with the SM leads to a non-trivial di-top invariant mass distribution $m_{t\bar{t}}$
  - **Peak-dip structure** strongly model dependent
  - Needs dedicated strategy to implement the likelihood for interpretation



- Aim: **reconstruct proxy for $m_{t\bar{t}}$ distribution**





Result competitive with tbH(tb) limits

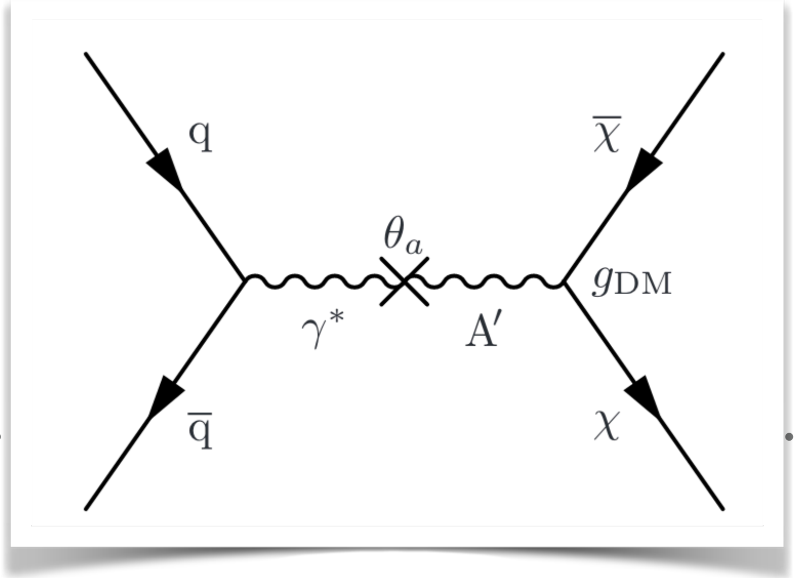
Summary and Outlook

- Large number of results finalized using the full Run 2 LHC dataset
  - Exploration of vast variety of final states
  - Extensive studies of various models and interpretations
    - Relative importance of the various processes can change quickly when model parameters change → always check assumptions
    - Colliders offer a unique opportunity in addition to DD and ID DM searches

- Much more to come with the data taking years ahead
  - More luminosity, upgraded detectors, new analysis techniques, improvements in the theory modeling, ….

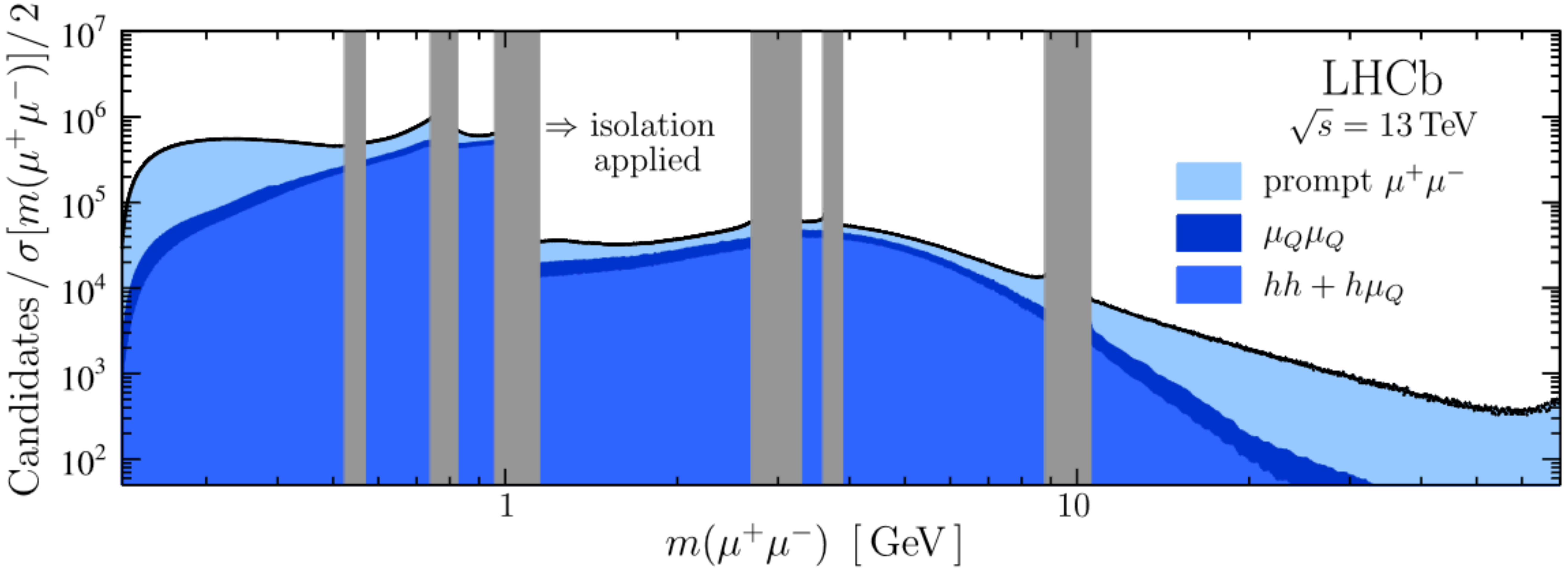
BACKUP

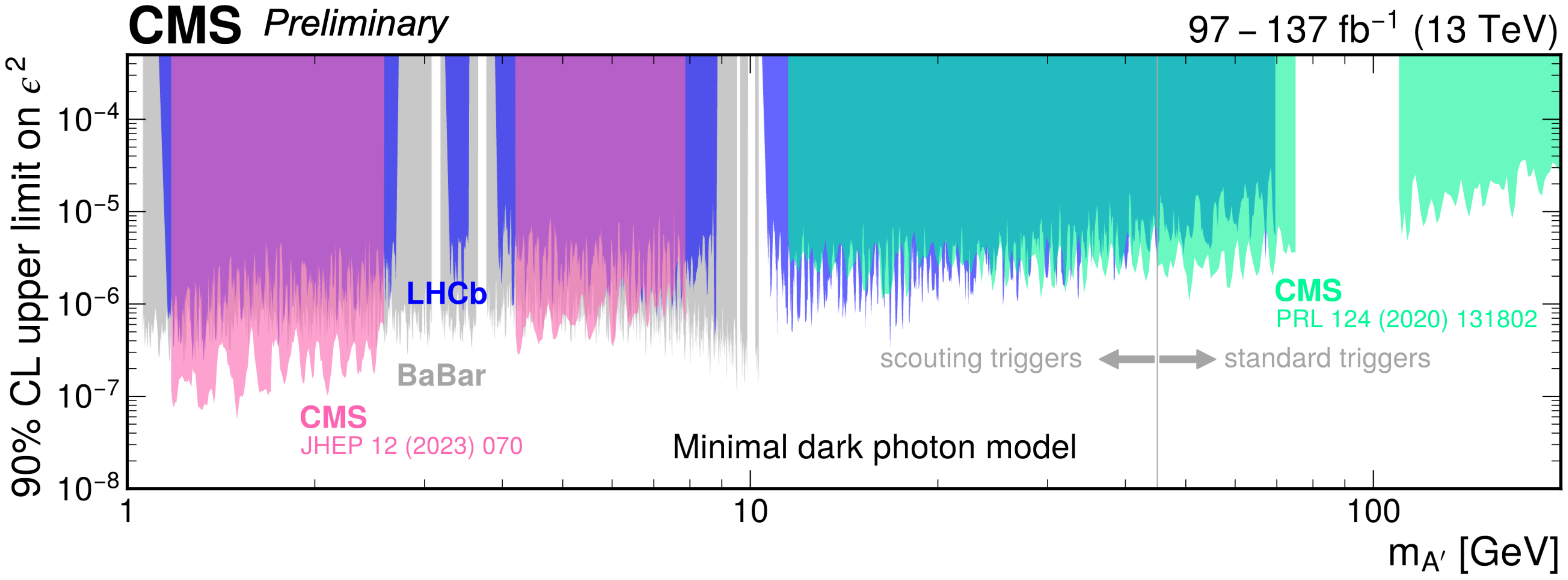
Dark Photons



- SM photon couples to dark photon A’
  - Search in di-muon mass spectrum

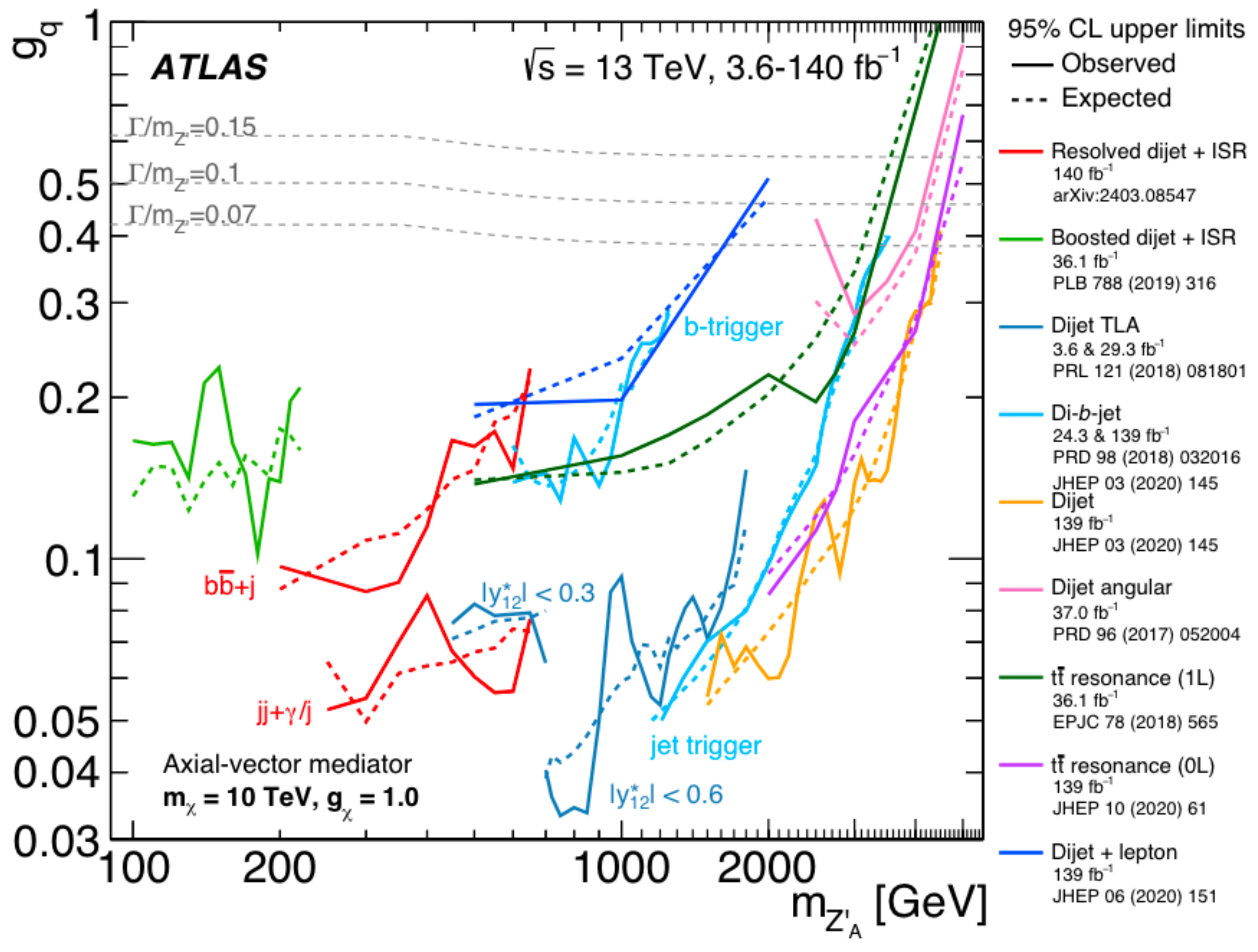
PhysRevLett.124.041801

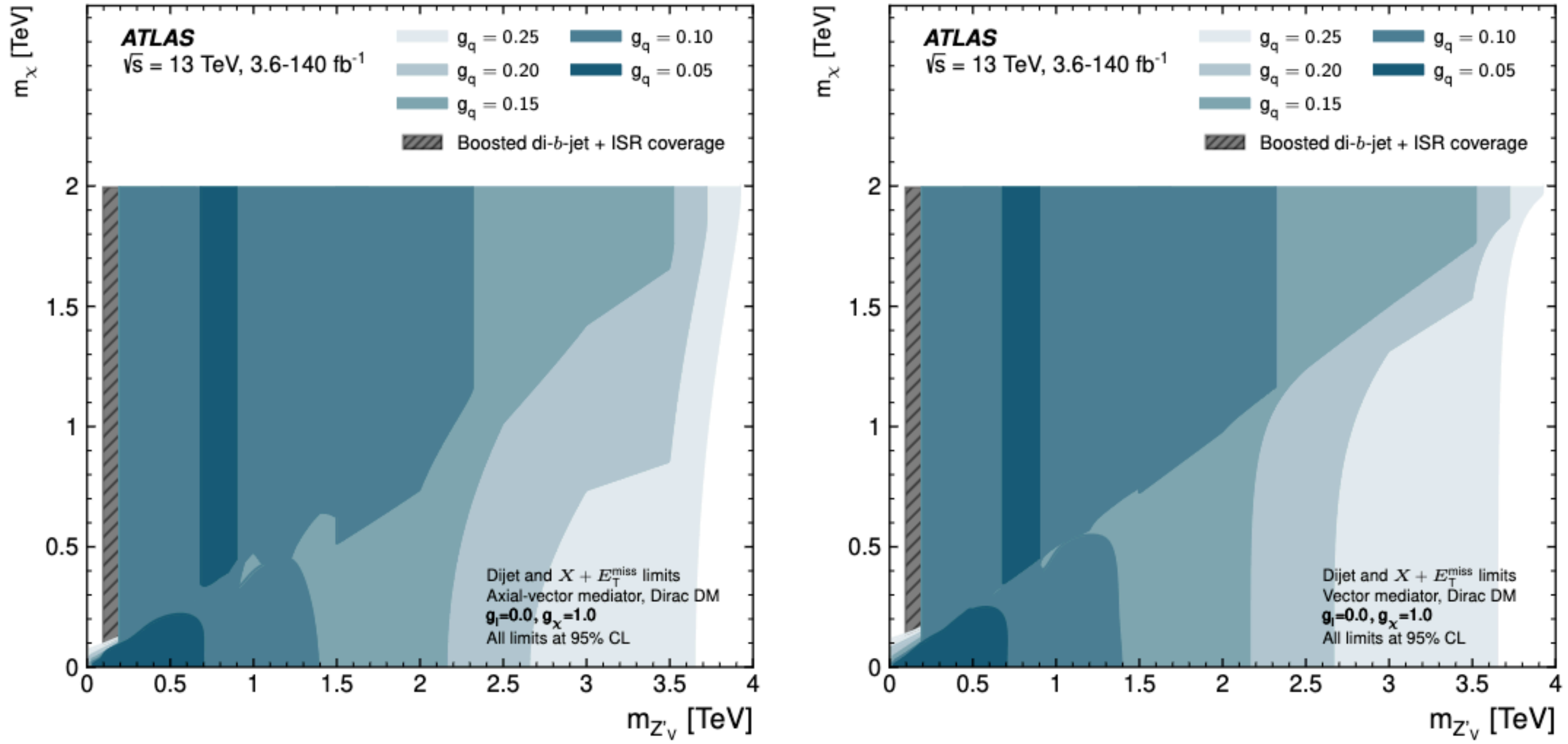




Vector/Axial-vector

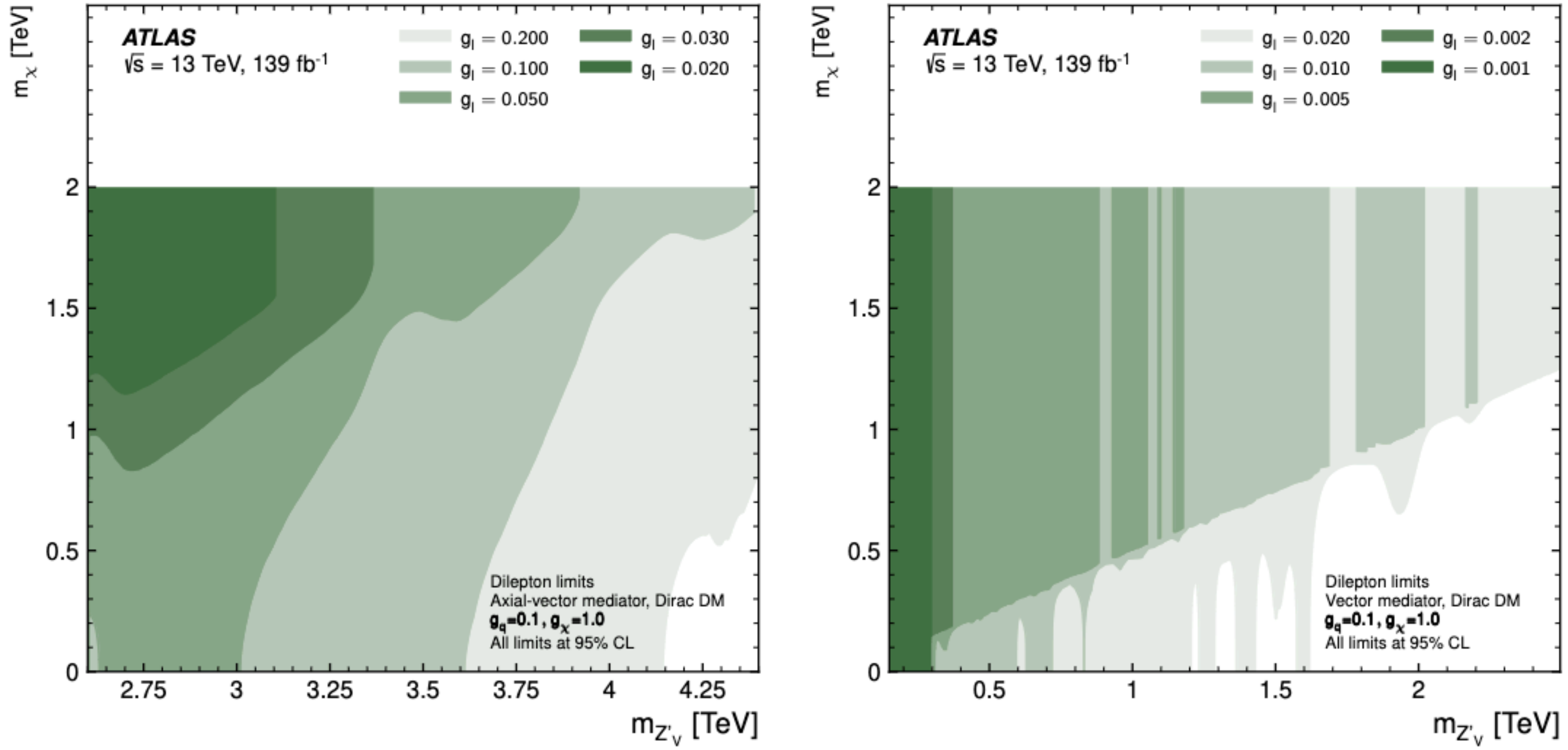
Dependence of coverage on the different coupling scenarios



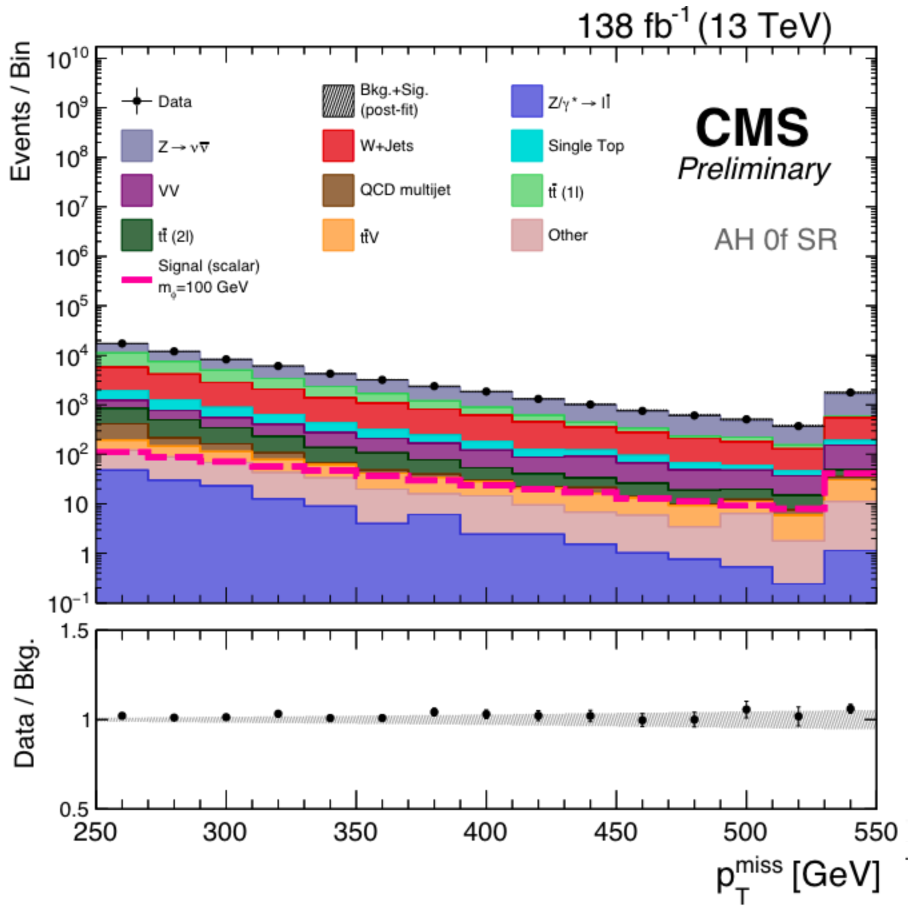


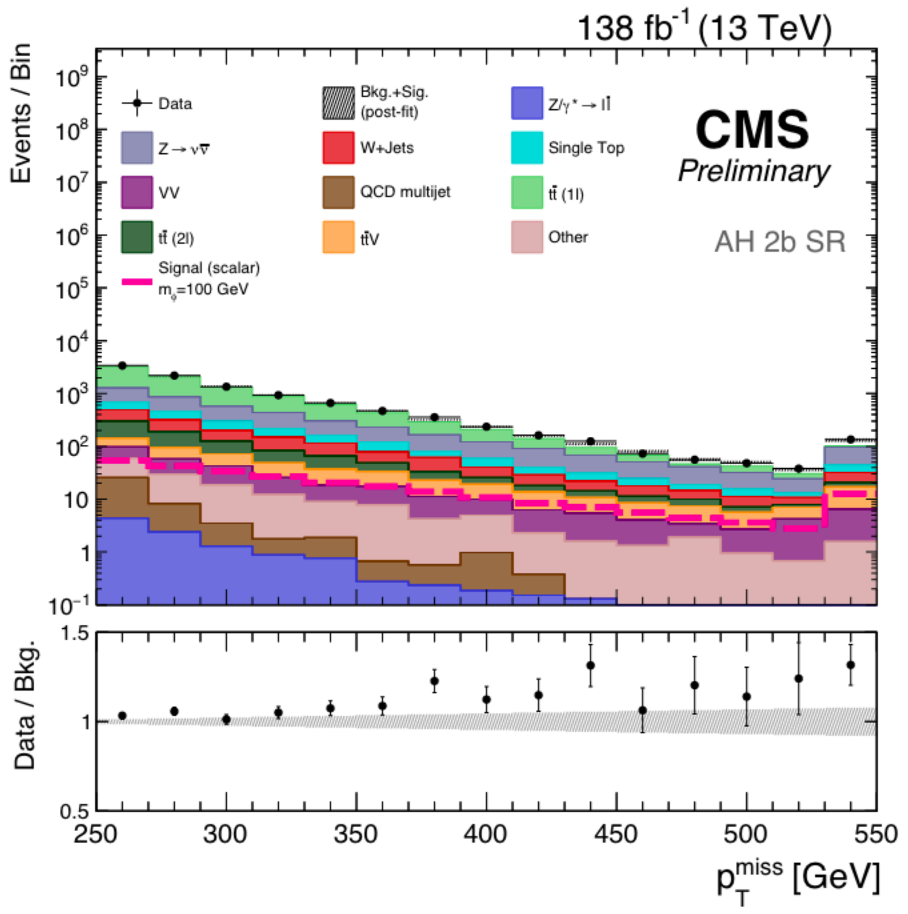
(a)

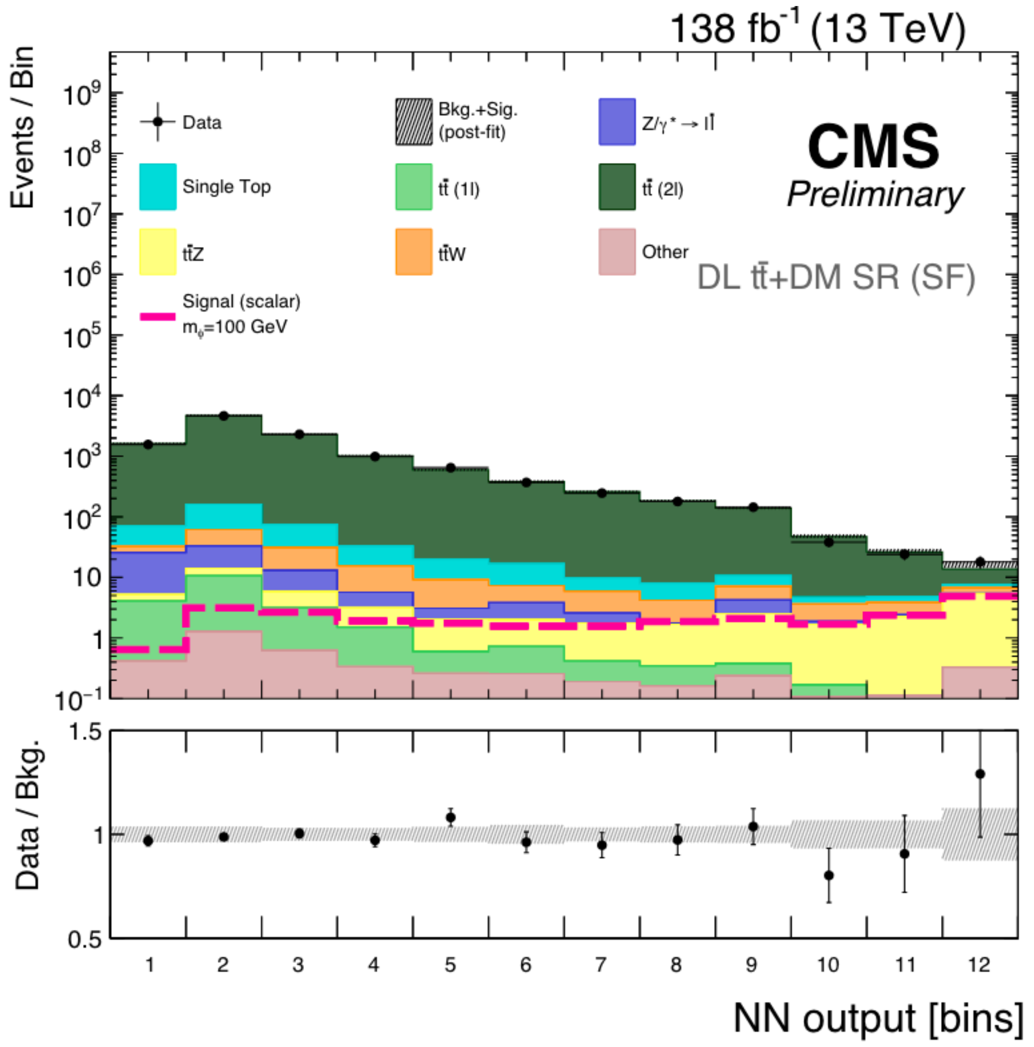
(b)



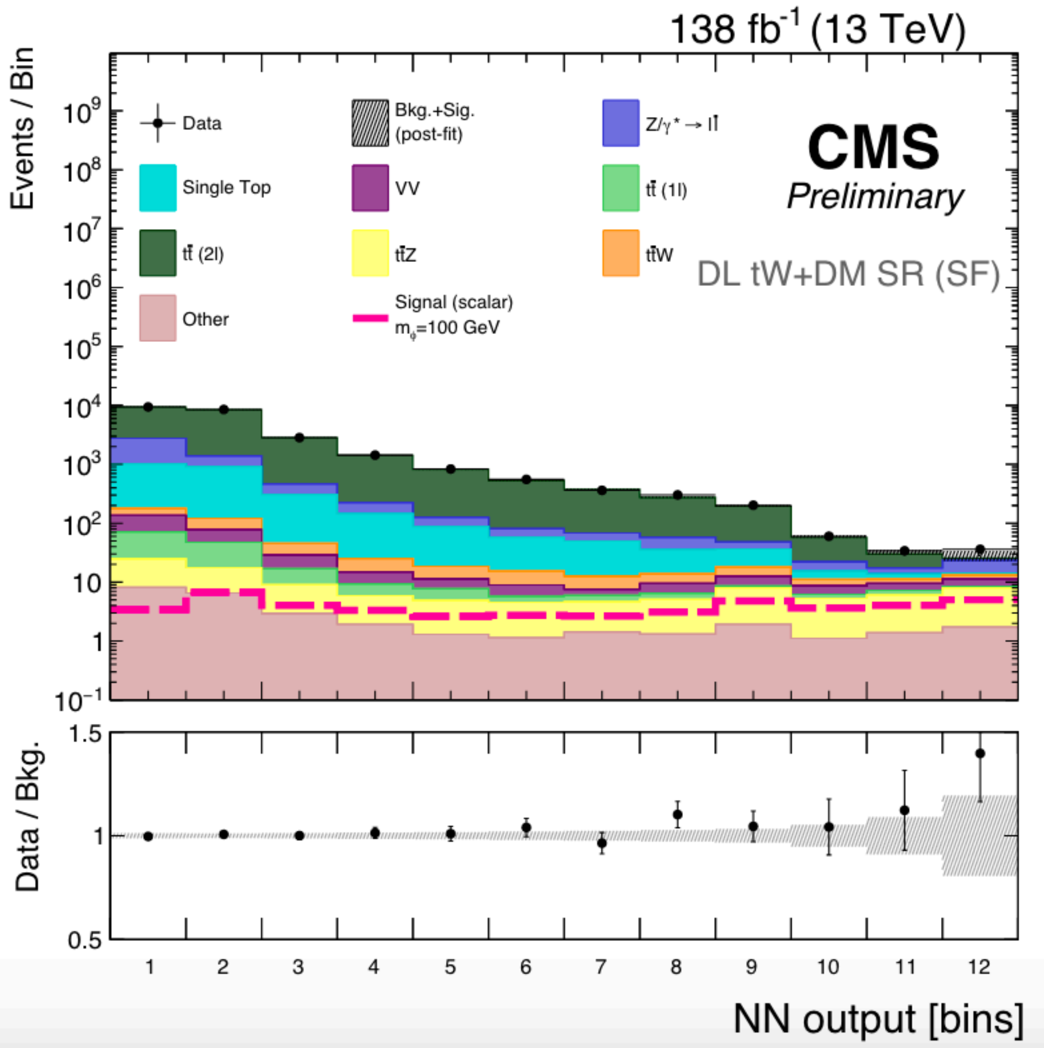
CMS:DMtt







	All-hadronic SRs			Single-lepton SRs			Dilepton SRs	
	0l, 1 b-tag, 0 FJ	0l,1 b-tag, 1 FJ	0l, 2 b-tag	1l, 1 b-tag, 0 FJ	1l, 1 b-tag, 1FJ	1l, 2 b-tag	2l, 1 b-tag	2l, 2 b-tag
n_{lep}		$= 0$			$= 1$		$= 2$	
n_{jet}		≥ 3			≥ 2		≥ 1	
n_{b}	$=1$	$=1$	≥ 2	$= 1$	$=1$	≥ 2	$= 1$	≥ 2
Forward jets	$=0$	≥ 1	—	$= 0$	≥ 1	—	—	—
$p_{\mathrm{T}}(\mathrm{j}_1)/H_{\mathrm{T}}$	—		<0.5		—		—	
$p_{\mathrm{T}}^{\mathrm{miss}}$		>250 GeV			>250 GeV		—	
m_{T}		—			>140 GeV		—	
$m_{\mathrm{T2}}^{\mathrm{W}}$		—			>180 GeV		—	
$\min\Delta\phi(\mathrm{j}_{1,2}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$		>0.8 rad.			>0.8 rad.		—	
$m_{\mathrm{T}}^{\mathrm{b}}$		>140 GeV			>140 GeV		—	
m_{ll}		—			—		>20 GeV	
$\lvert m_{\mathrm{ll}} - m_{\mathrm{Z}}\rvert$		—			—		> 15 GeV (ee and $\mu\mu$)	
$m_{\mathrm{T2}}^{\mathrm{ll}}$		—			—		>80 GeV	
Pass $\mathrm{t\bar{t}}$ reco		—			—		—	yes



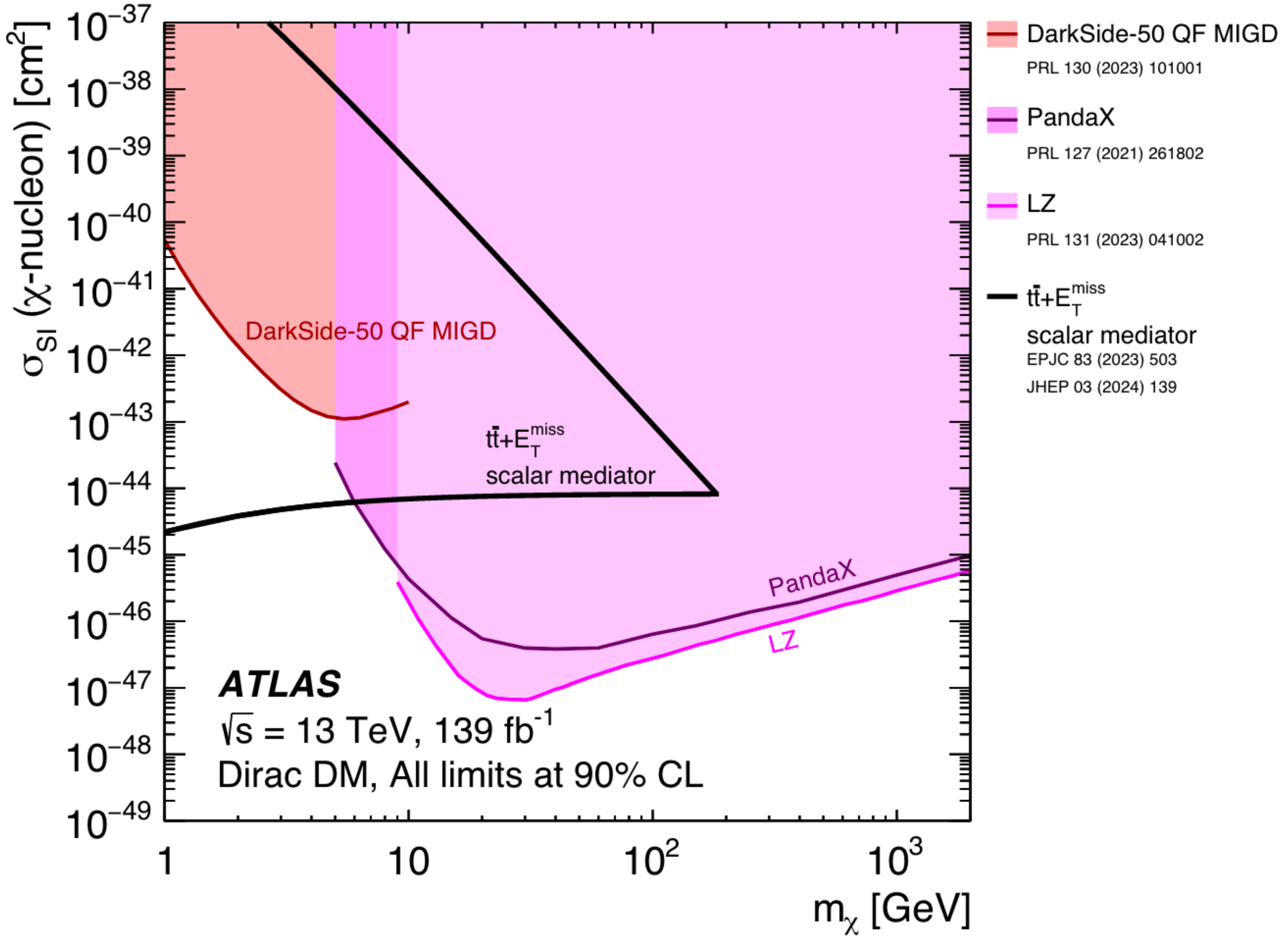
Neural Network in DL region trained on:

- 1b: opening angle between the two leptons and the two-lepton system and MET, …

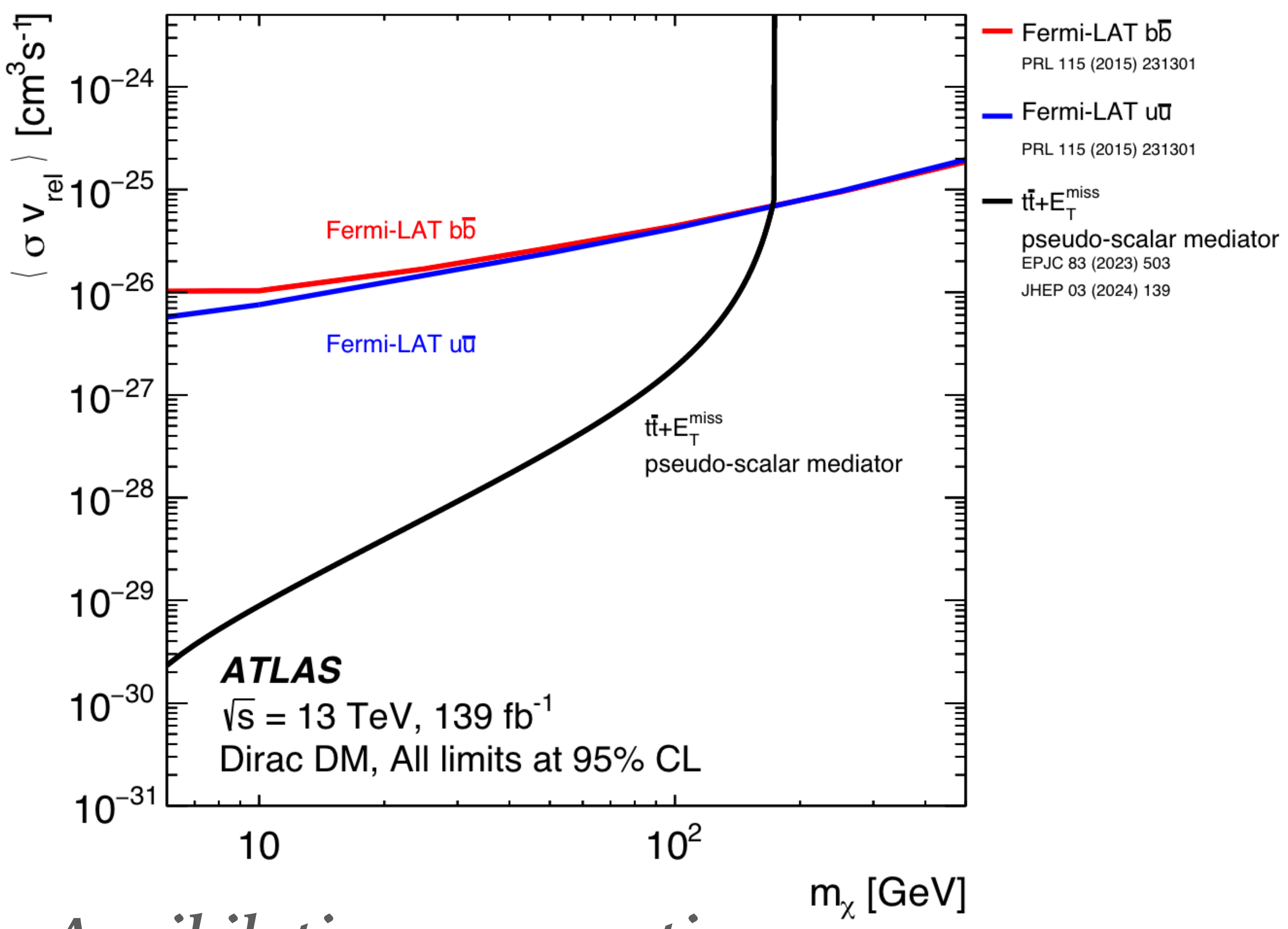
- 2b: variables related to reconstruction of the ttbar system

Comparison of scalar/pseudo-scalar results with direct/indirect detection

limited sensitivity from DD experiments

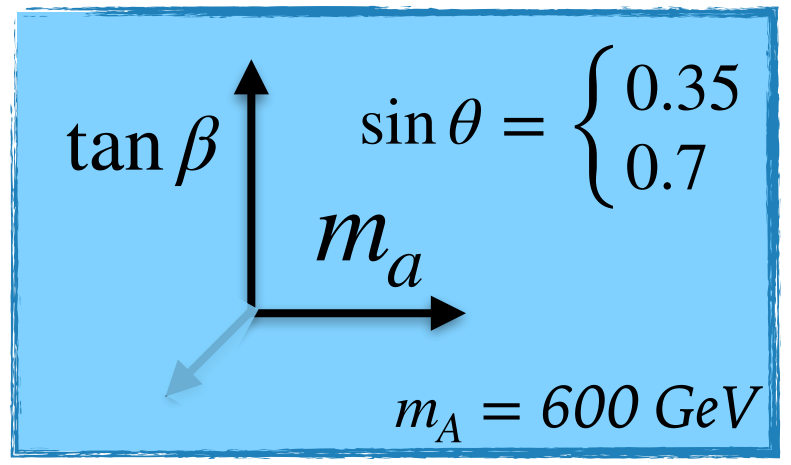


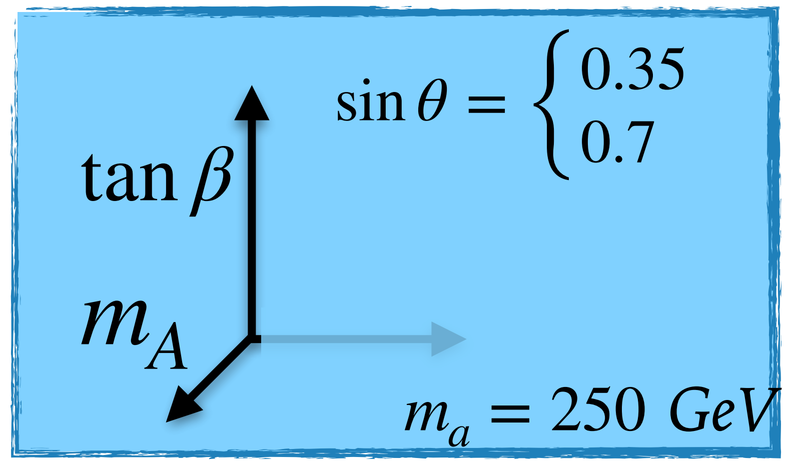
***Spin-independent** cross section for **DM-nucleon** interaction*
*for a **scalar mediator** in the tt+MET final state*

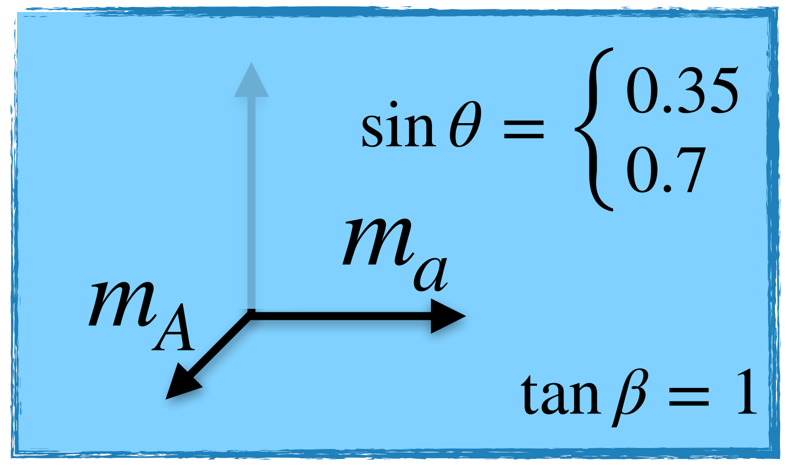


Annihilation cross section
(cross-section x relative velocity vrel, averaged over the DM velocity distribution
*for a **pseudo-scalar mediator***

2HDM+a: parameter landscape





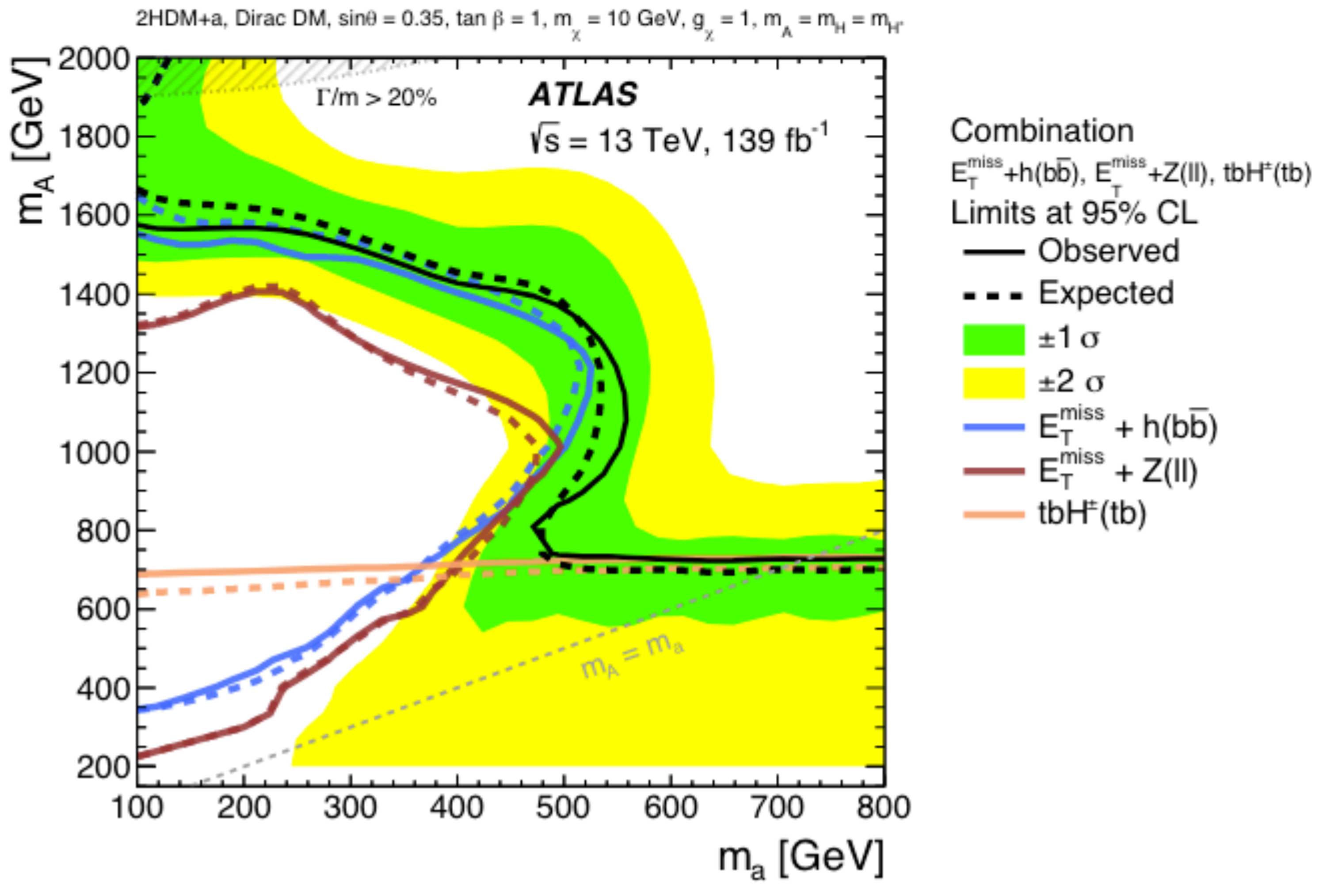


- low tan $\beta \rightarrow$ preferred coupling of **A/a** to up-type quarks
- high tan $\beta \rightarrow$ preferred coupling of **A/a** to down-type quarks and leptons

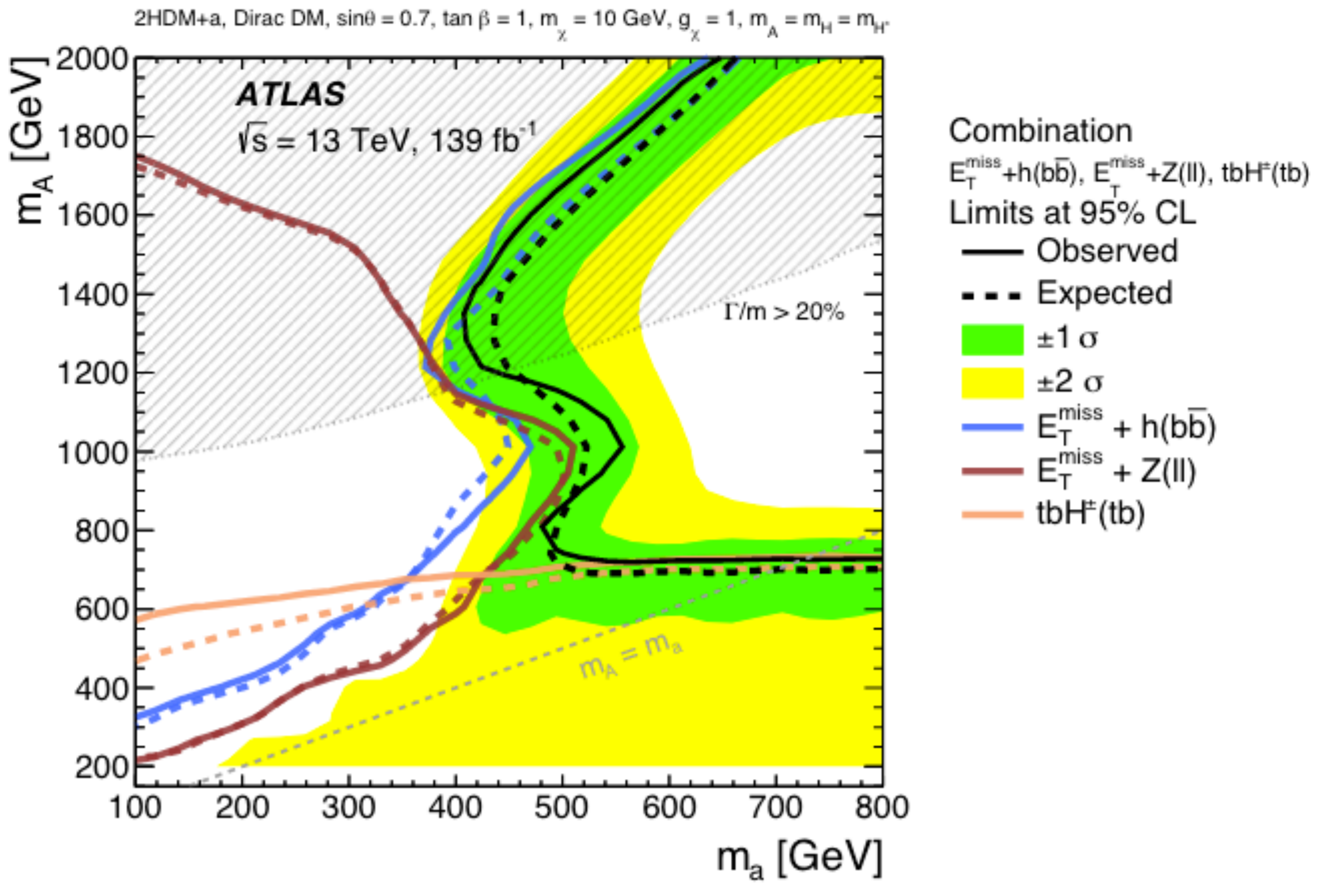
- $m_A = 600$ GeV
  $\rightarrow$ decays of **A** into $t\bar{t}$ kinematically **possible**
- $m_a = 250$ GeV
  $\rightarrow$ decays of the **a** into $t\bar{t}$ kinematically **forbidden**

- Highlight dependence on pseudo-scalar **mass hierarchy**
- $\sin\theta$ chosen for low and almost maximal mixing between **a** and **A**

2HDM+a: landscape: main contributors



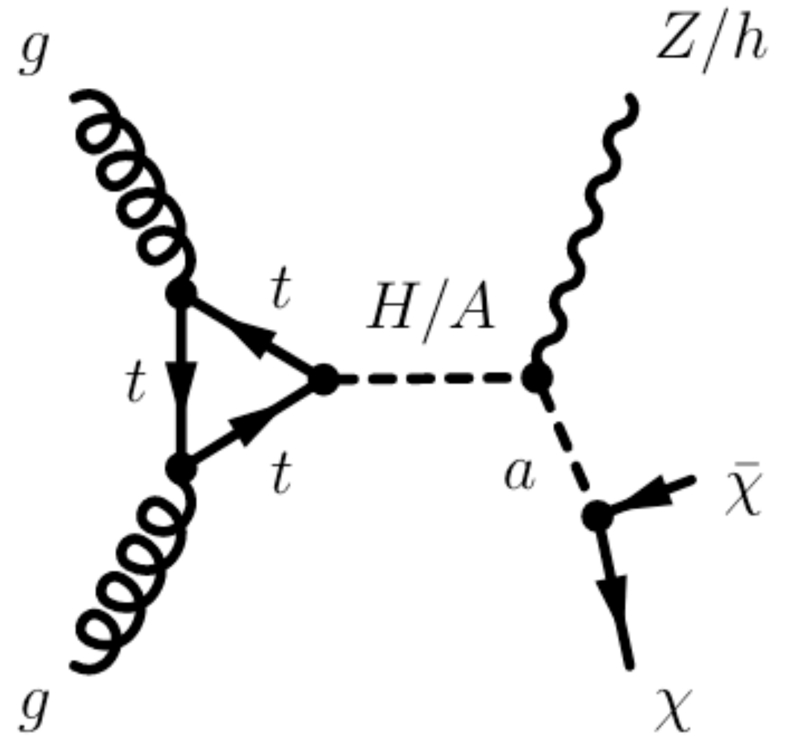
(a)

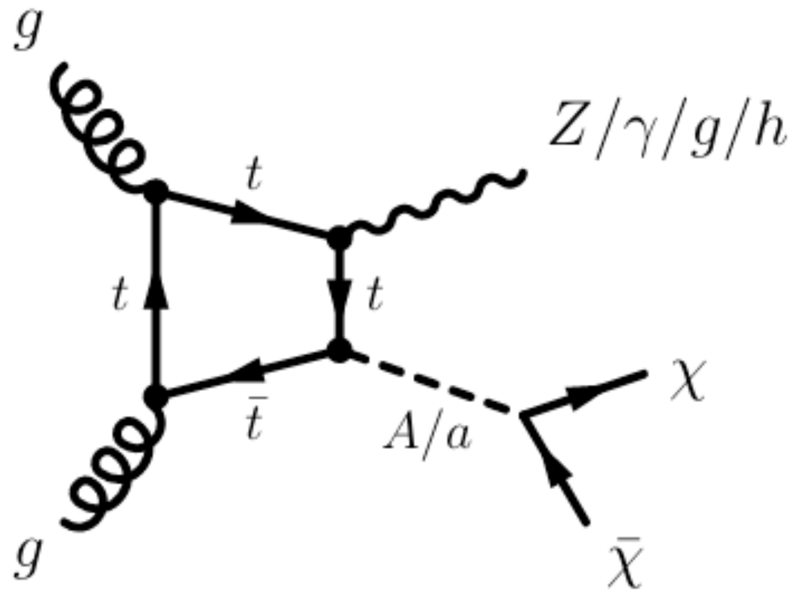


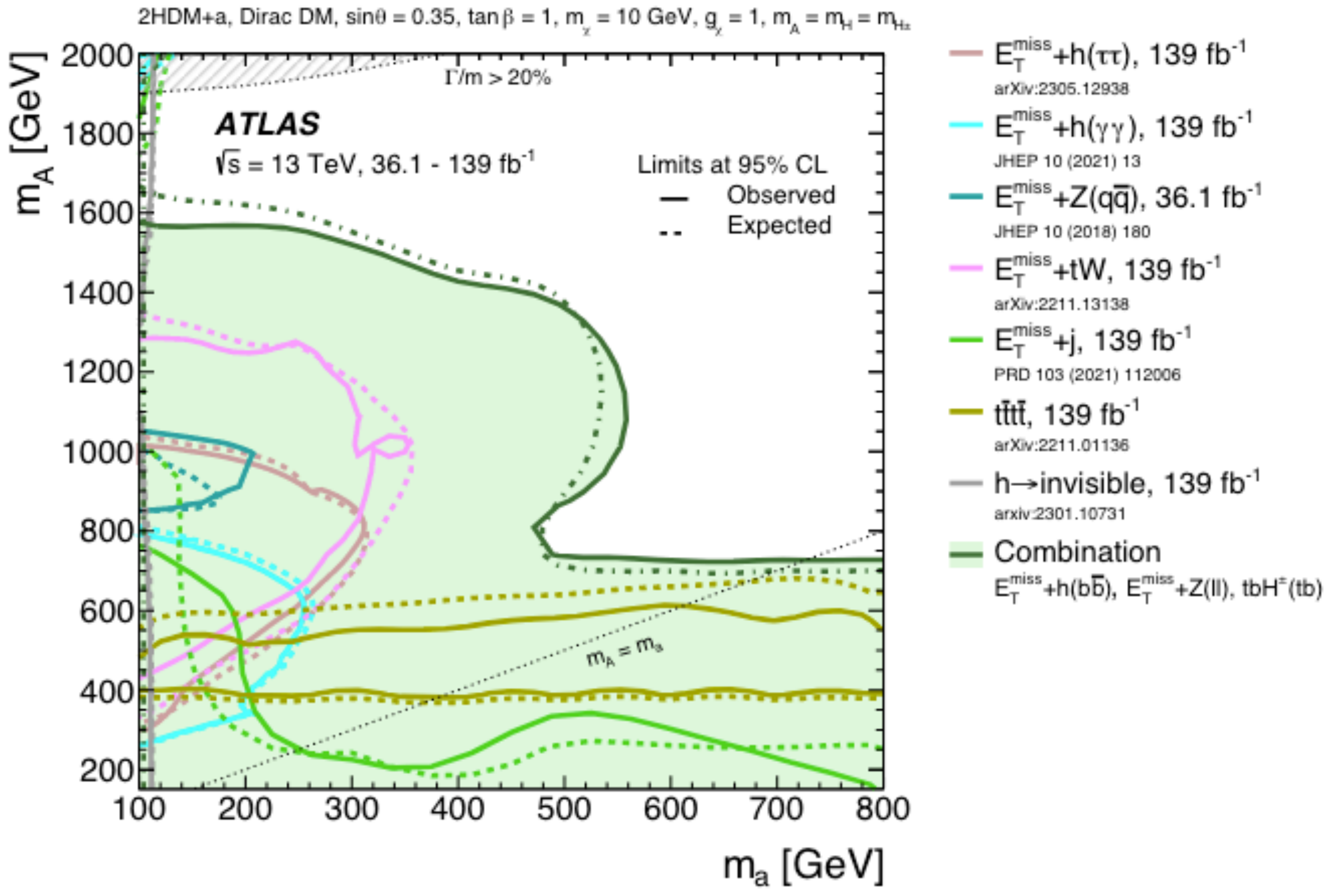
(b)

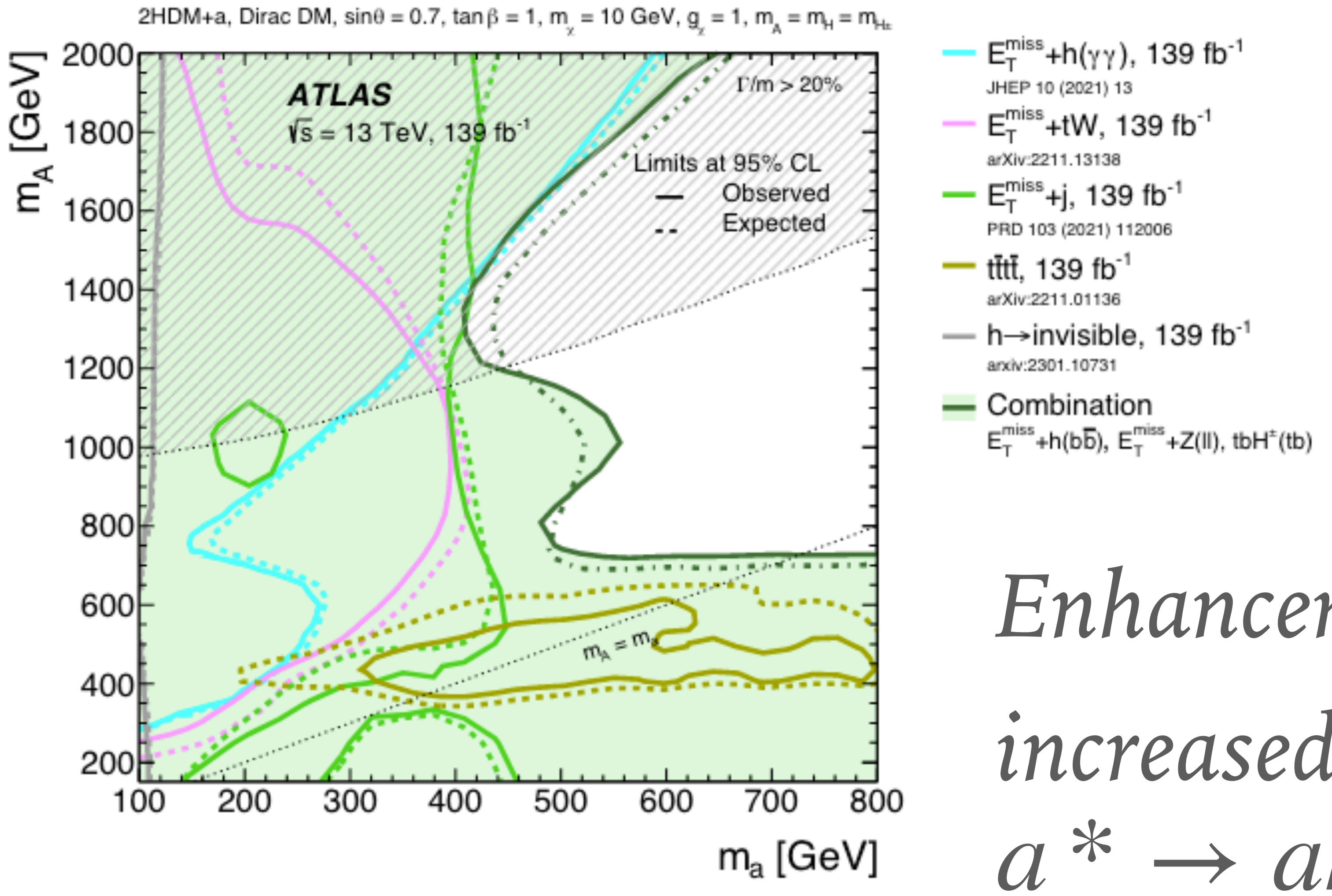
resonant

non-resonant production







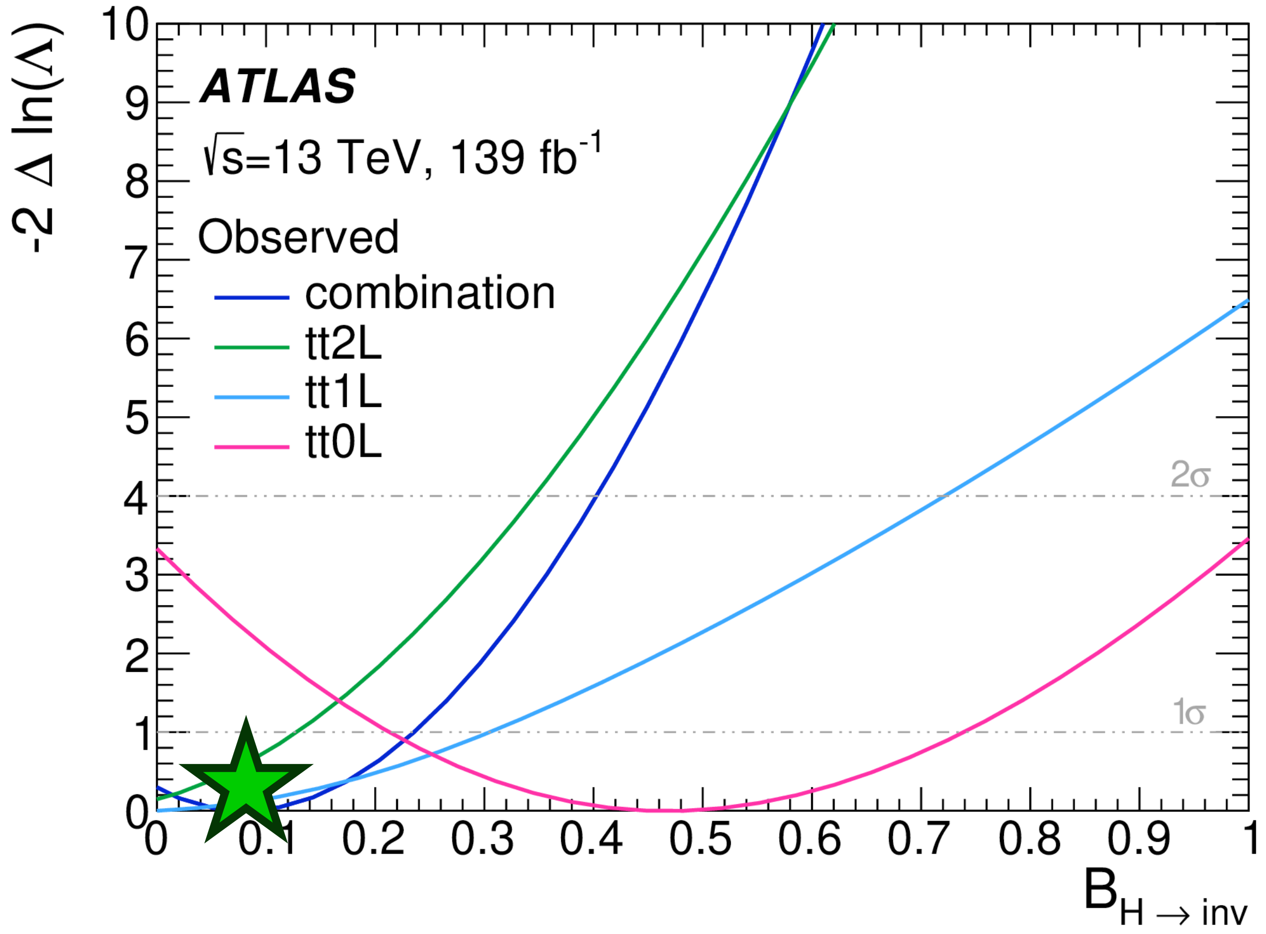


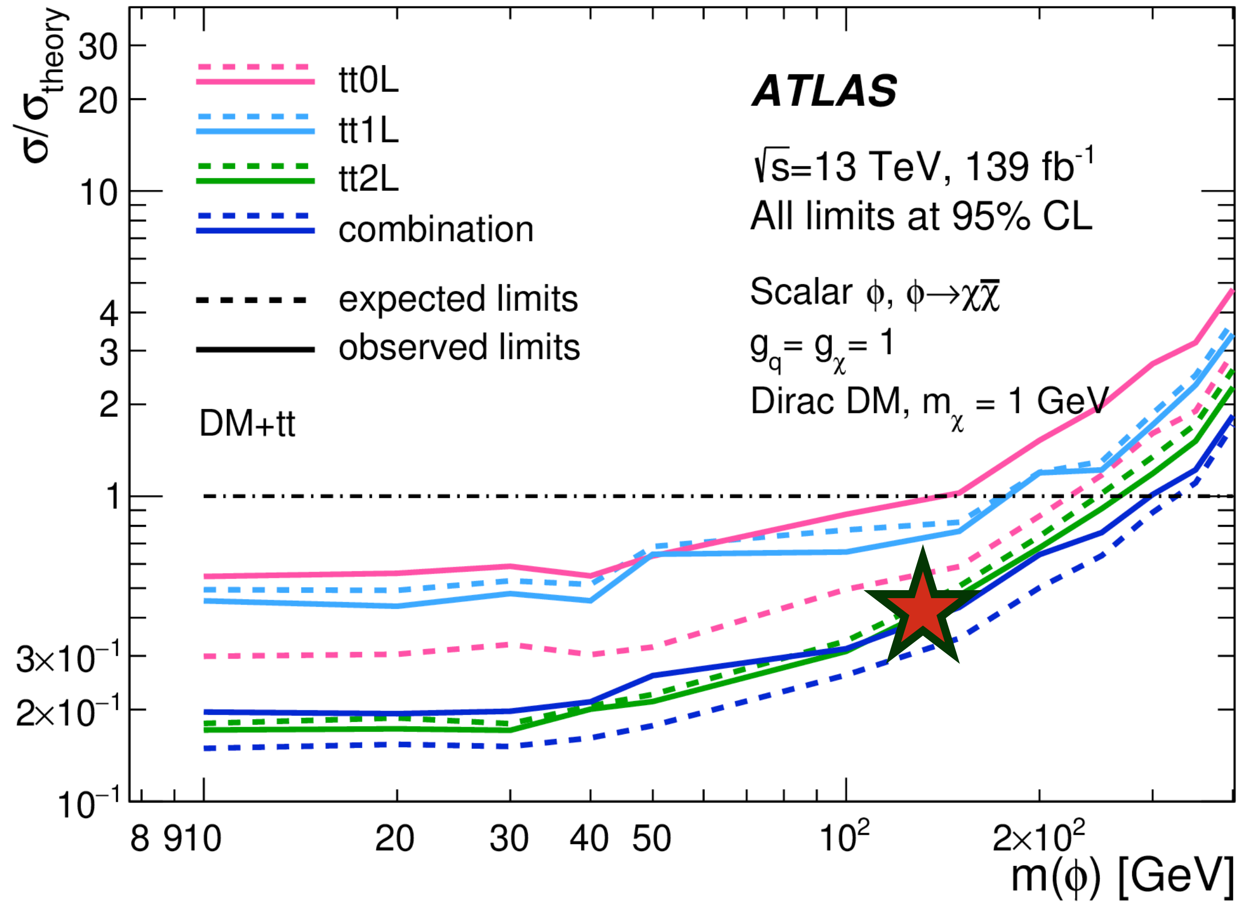
Enhancement at high m_A due to increased cross section of non-resonant $a^* \to ah$ without resonant A production

Eur. Phys. J. C 83 (2023) 503
Phys. Lett. B 842 (2023) 137963

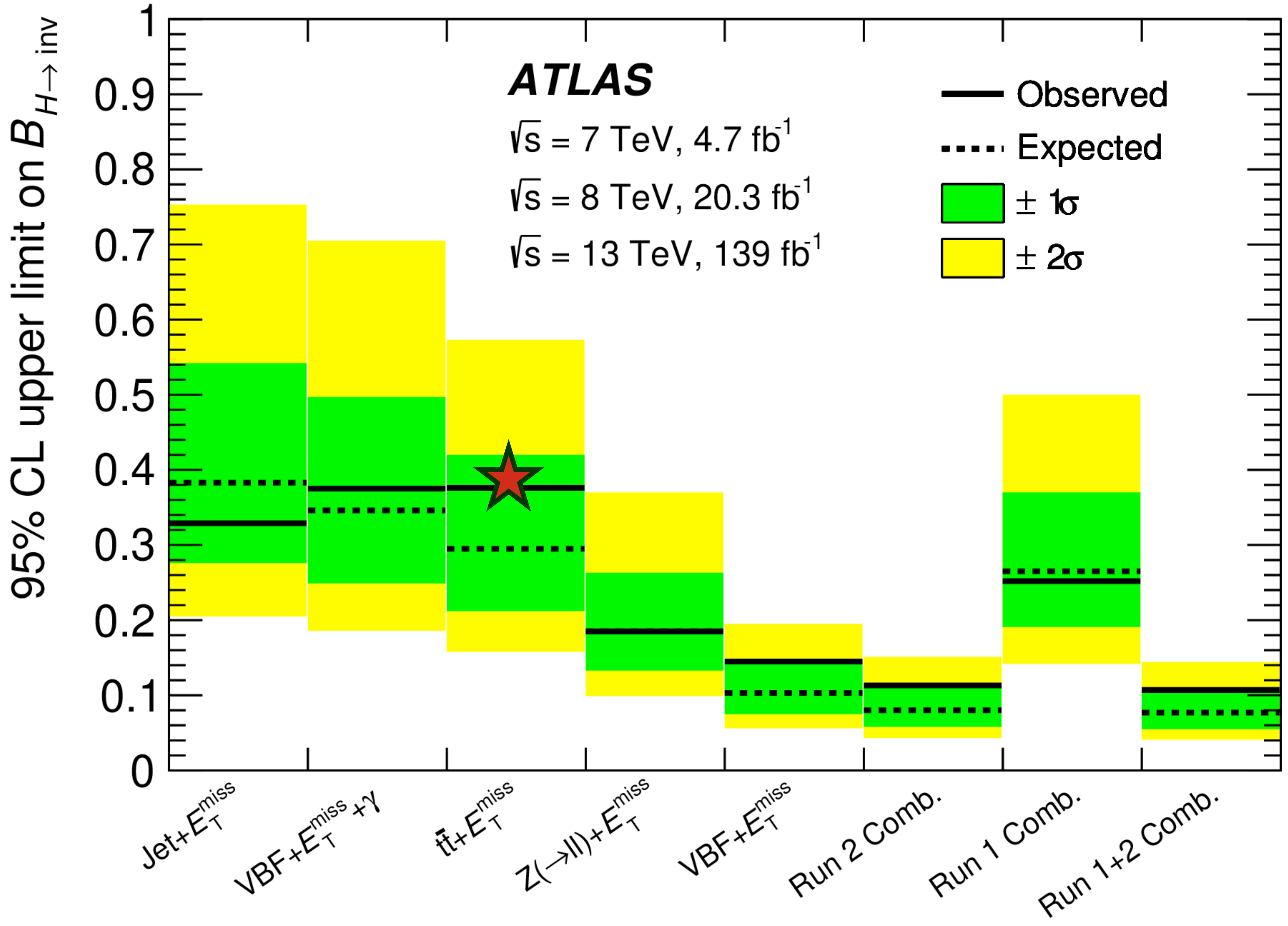
Can we say something about invisible Higgs decays?

- $t\bar{t} + E_T^{miss}$ searches for scalar mediators can also be used to place limits on h → invisible branching ratios





Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed upper limit	Expected upper limit
$t\bar{t}H$ comb.	$0.08^{+0.15}_{-0.15}$	0.38	$0.30^{+0.13}_{-0.09}$

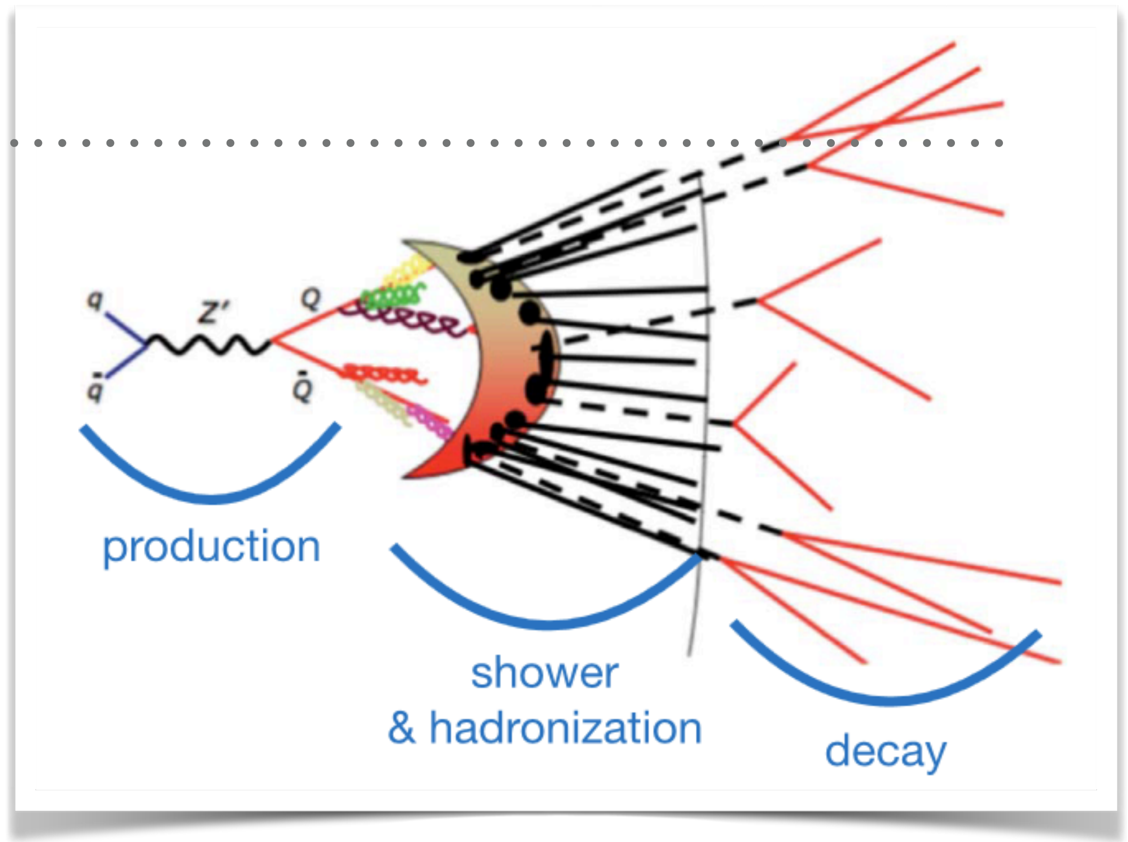


Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed 95% U.L.	Expected 95% U.L.
Jet + E_T^{miss}	$-0.09^{+0.19}_{-0.20}$	0.329	$0.383^{+0.157}_{-0.107}$
VBF + E_T^{miss} + γ	$0.04^{+0.17}_{-0.15}$	0.375	$0.346^{+0.151}_{-0.097}$
$t\bar{t}$ + E_T^{miss}	0.08 ± 0.15	0.376	$0.295^{+0.125}_{-0.083}$
$Z(\to \ell\ell) + E_T^{miss}$	0.00 ± 0.09	0.185	$0.185^{+0.078}_{-0.052}$
VBF + E_T^{miss}	0.05 ± 0.05	0.145	$0.103^{+0.041}_{-0.028}$
Run 2 Comb.	0.04 ± 0.04	0.113	$0.080^{+0.031}_{-0.022}$
Run 1 Comb.	$-0.02^{+0.14}_{-0.13}$	0.252	$0.265^{+0.105}_{-0.074}$
Run 1+2 Comb.	0.04 ± 0.04	0.107	$0.077^{+0.030}_{-0.022}$

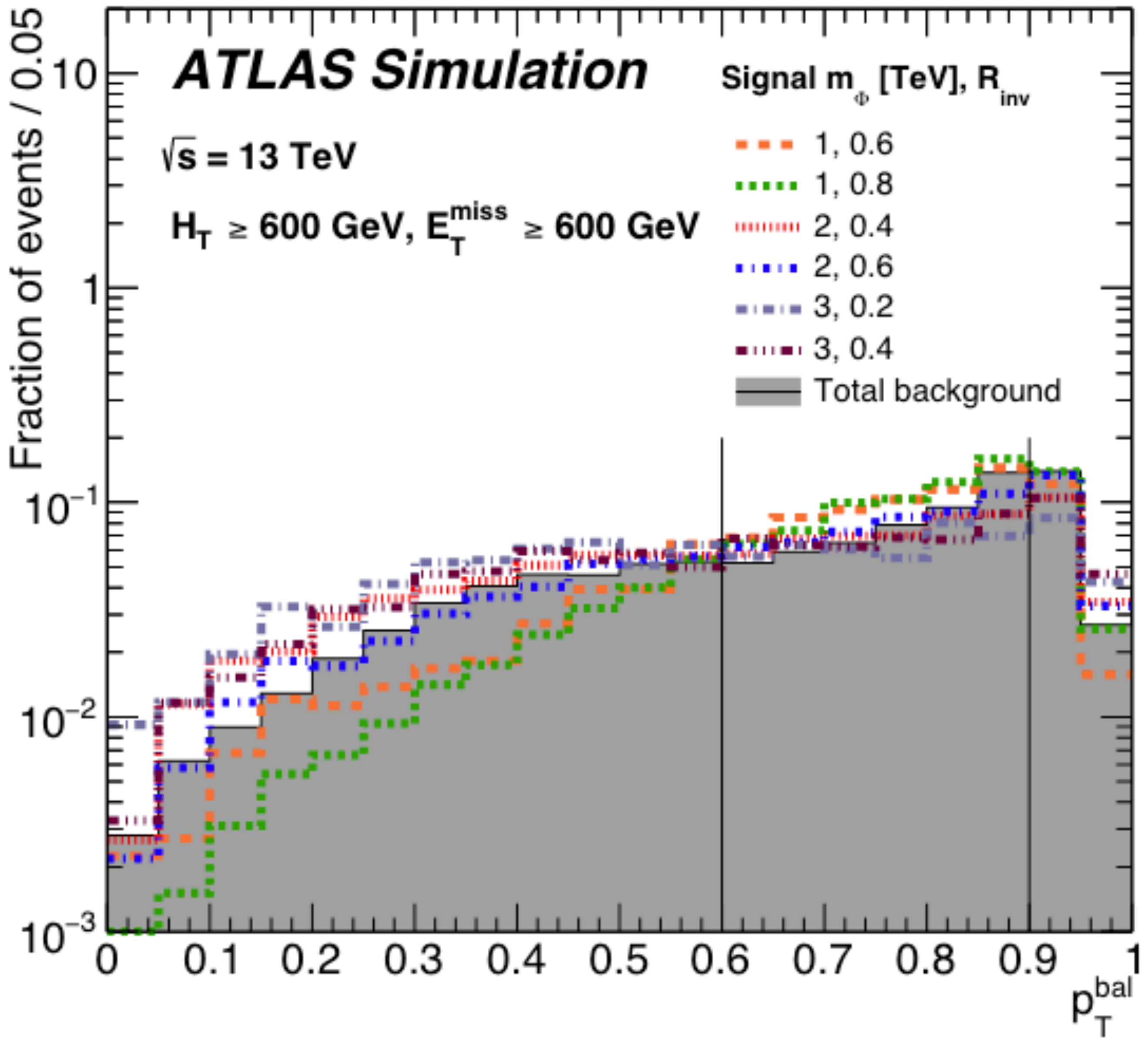
Standard model predicts:
$BR(h \to ZZ \to \nu\nu) \approx 0.1\,\%$
Current experimental limit 10.7% (7.7% expected)

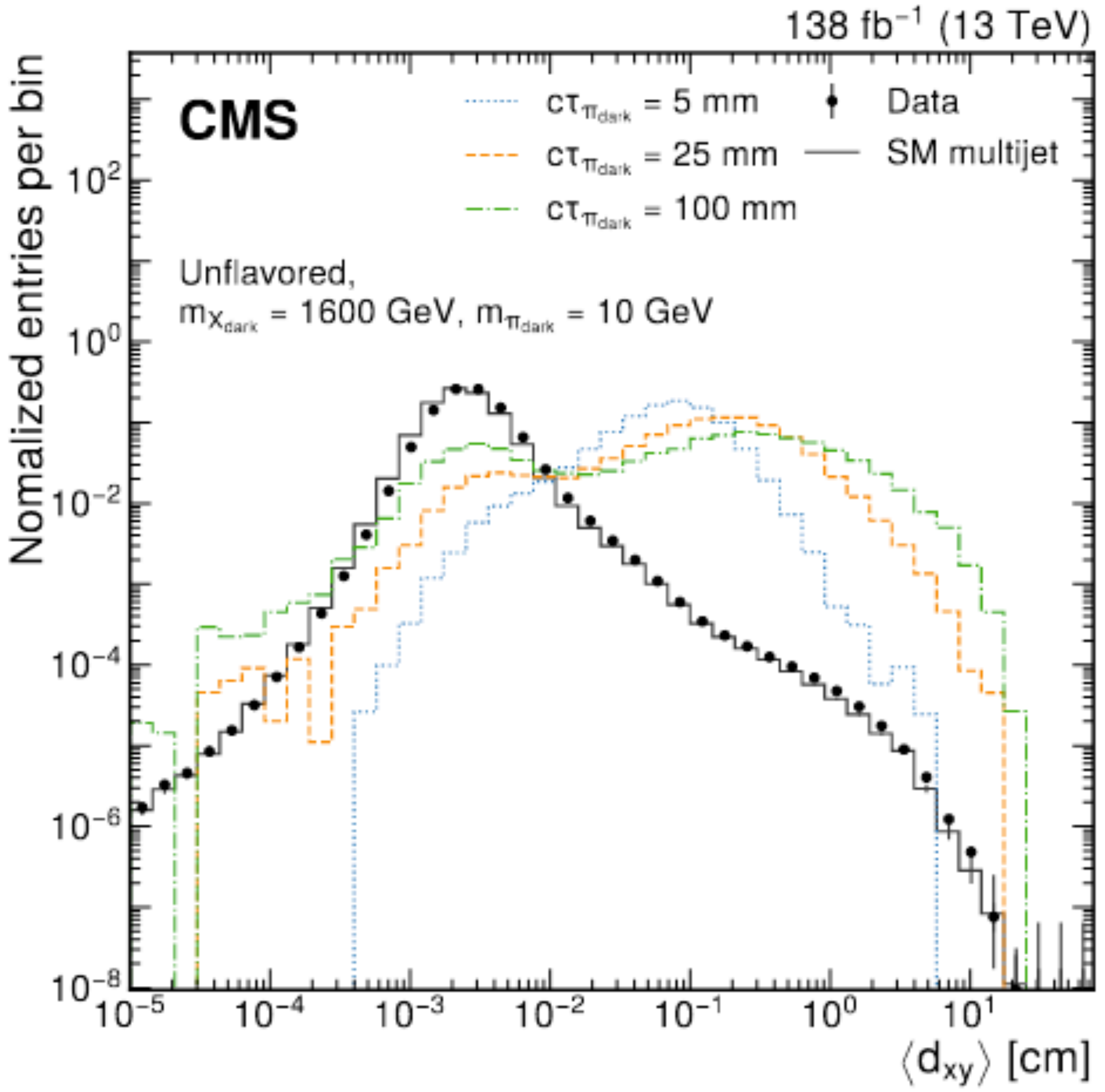
CMS-EXO-22-015 arxiv:2403.09292
J. Phys. G: Nucl. Part. Phys. 47 090501 (2020)
Phys. Lett. B 848 (2024) 138324

Something more unconventional?



- Idea: strongly interacting dark sector → Dark QCD
  - Production of dark quarks → leading to dark hadron shower = SM hadrons + stable dark hadrons (invisible DM candidate)
    - Semi-visible jets
    - Emerging jets





large fraction of the tracks within jets emerge from displaced vertices

$$p_T^{bal} = \frac{|\vec{p_T}(j_1) + \vec{p_T}(j_2)|}{|\vec{p_T}(j_1)| + |\vec{p_T}(j_2)|}$$

j_1 = jet closest, j_2 = jet farthest in azimuth from $\vec{p_T}^{miss}$ direction

Searches need dedicated algorithms to identify these objects!