

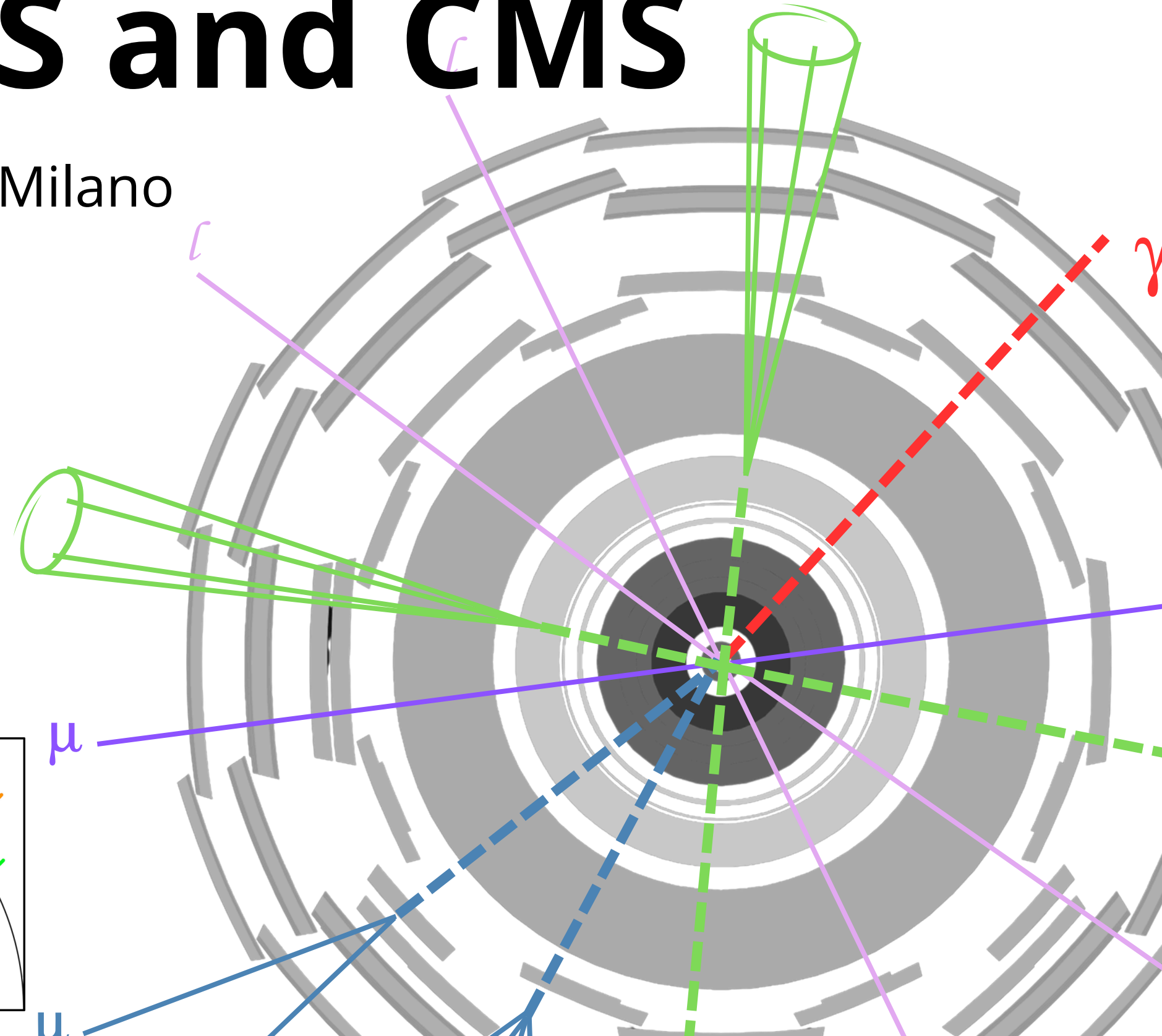
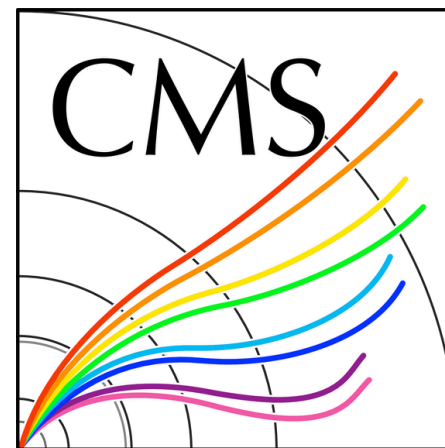
Overview of dark sector searches in ATLAS and CMS

Giulia Maineri, Università degli Studi e INFN Milano
for ATLAS & CMS Italia

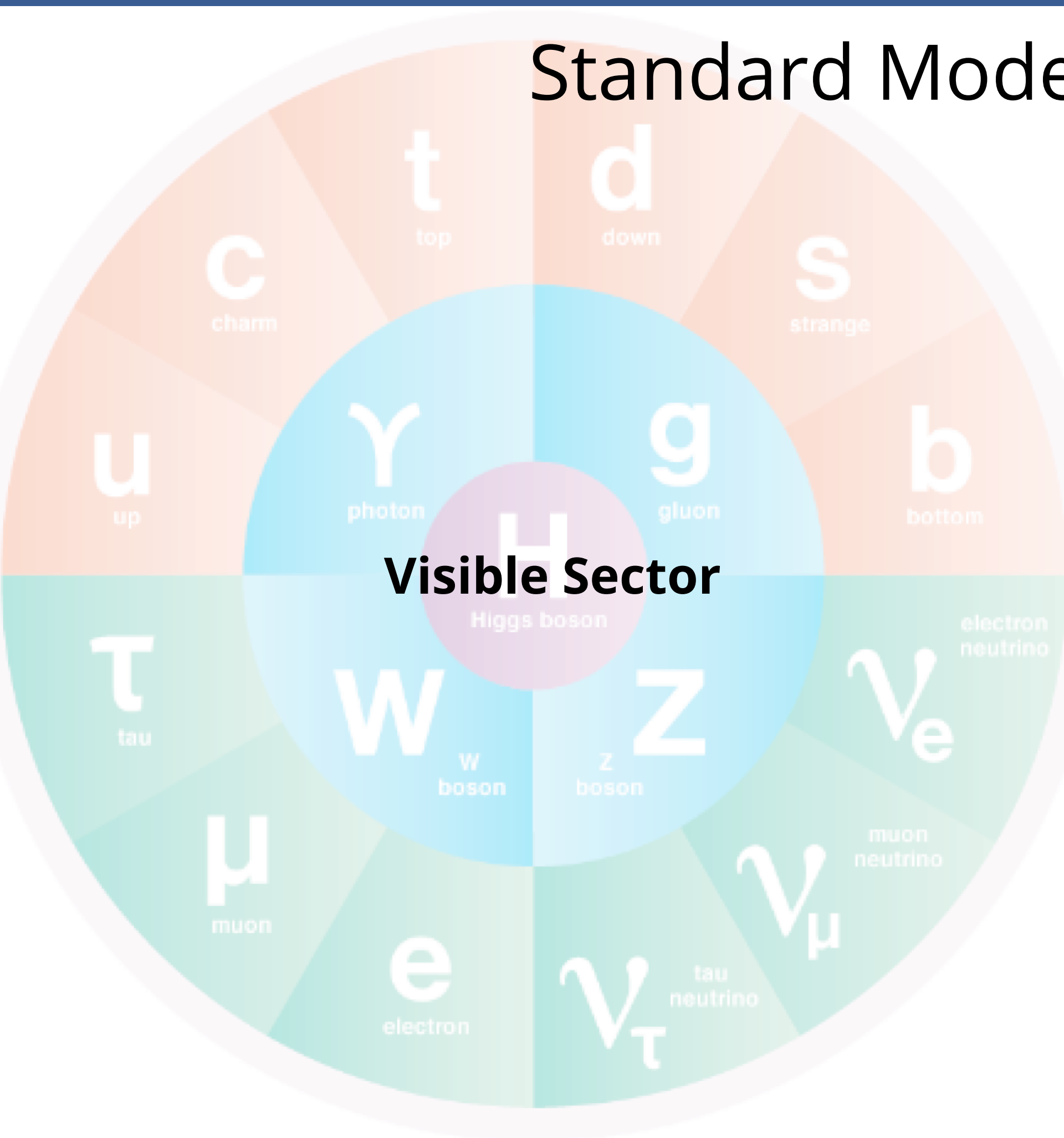


WIFAI 2025

11-14 novembre 2025, Bari



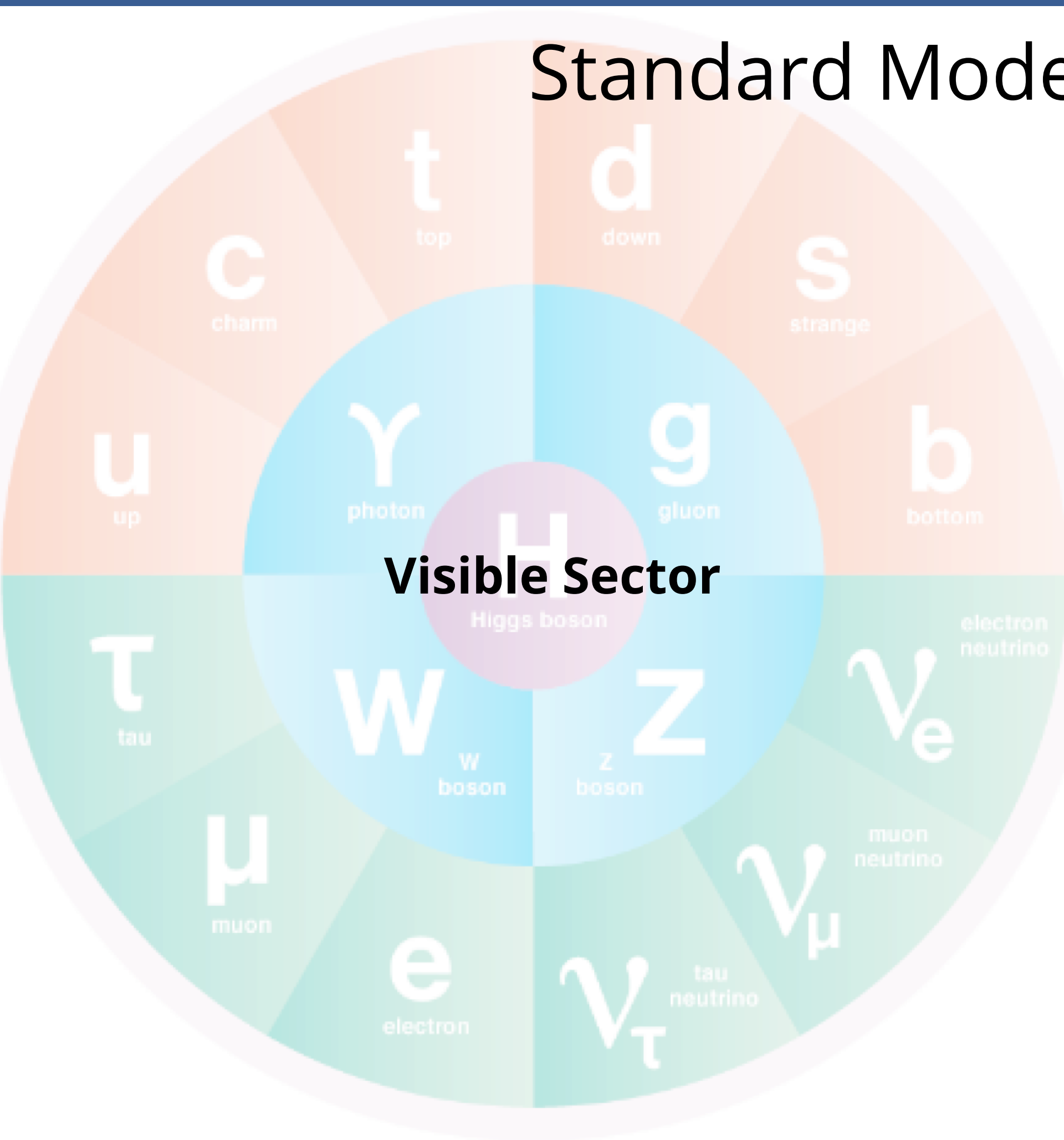
Standard Model is not enough



Dark Matter

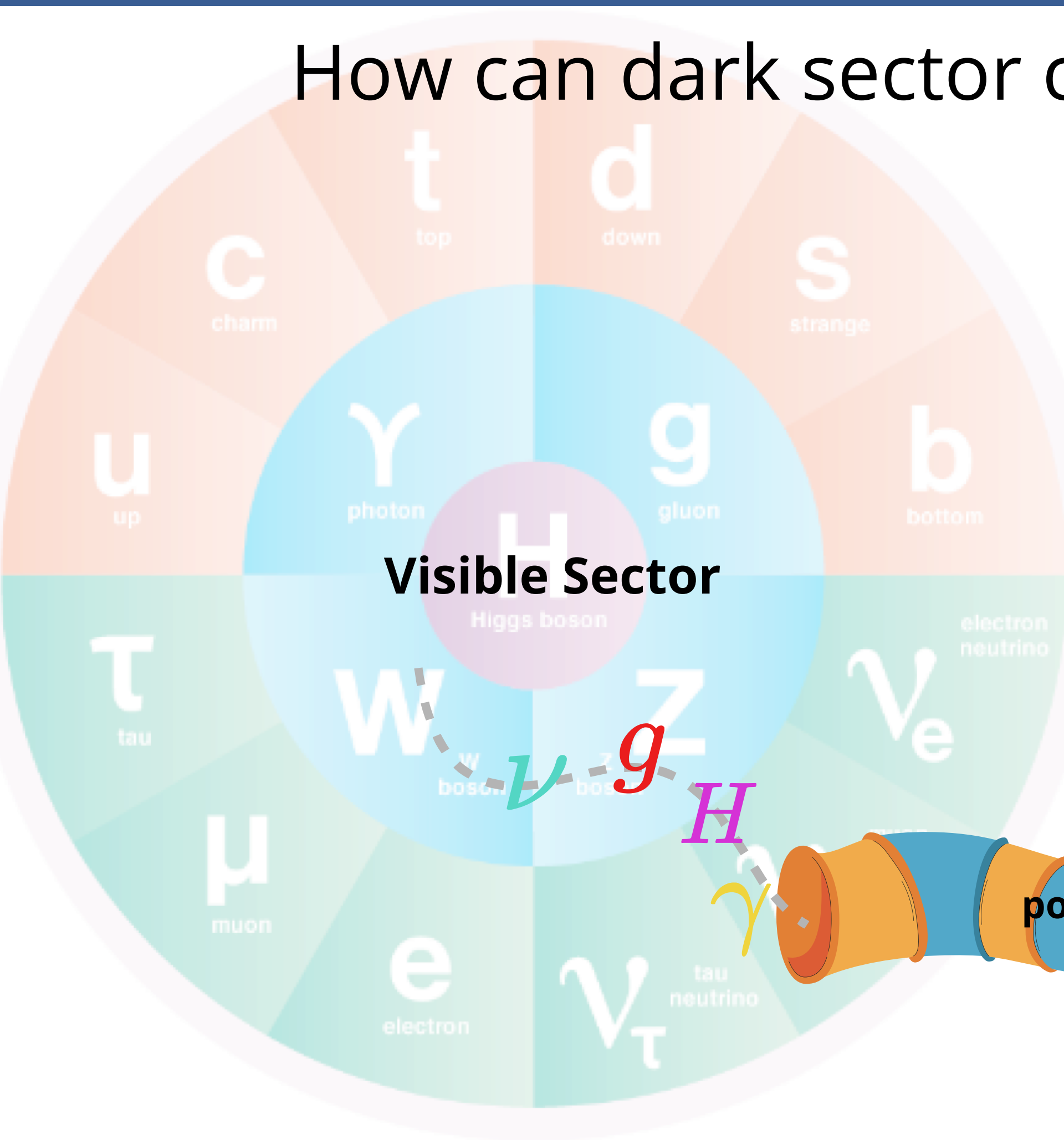
Dark Energy

Standard Model is not enough



Dark Sector

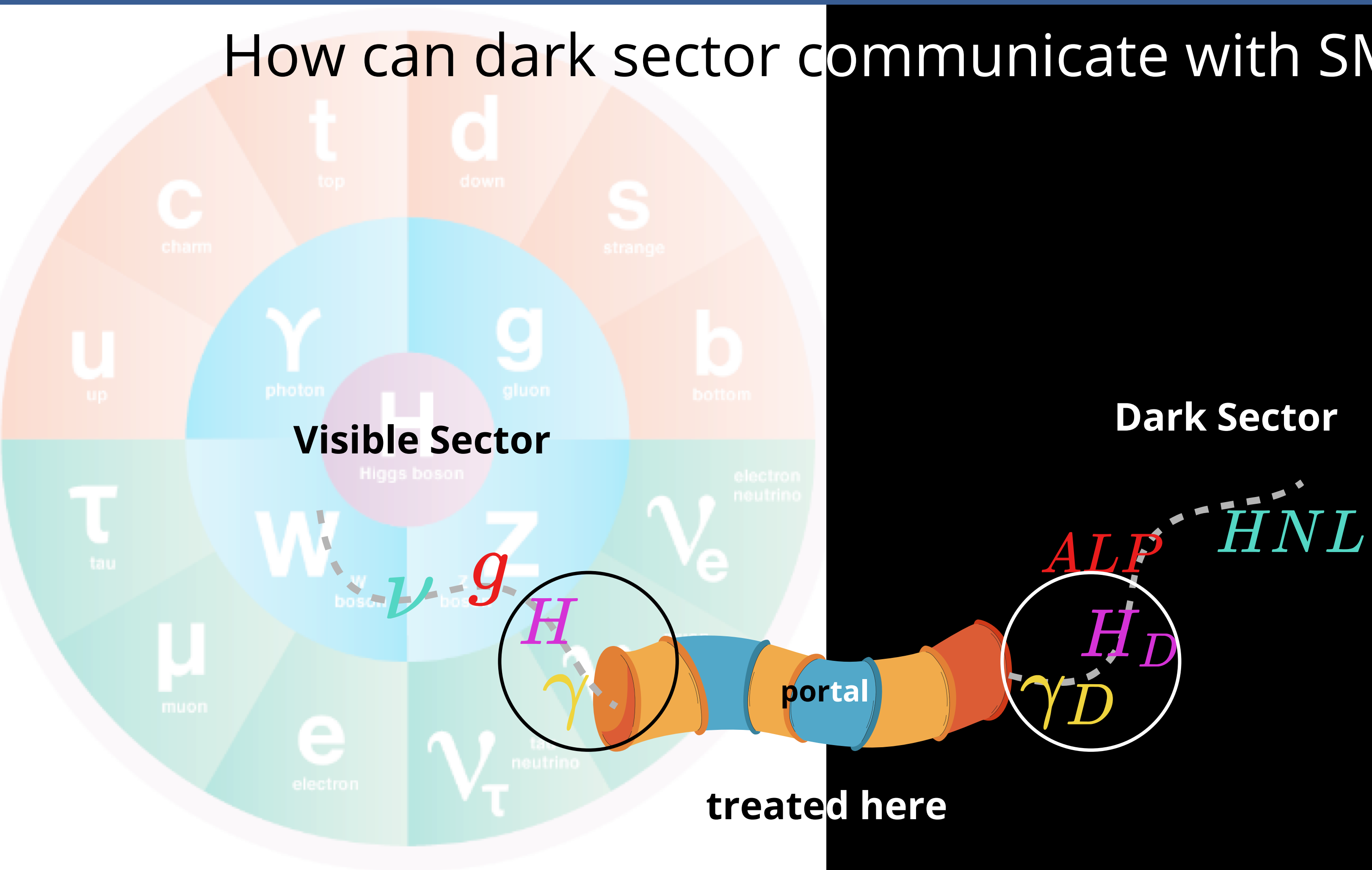
How can dark sector communicate with SM?



Dark Sector



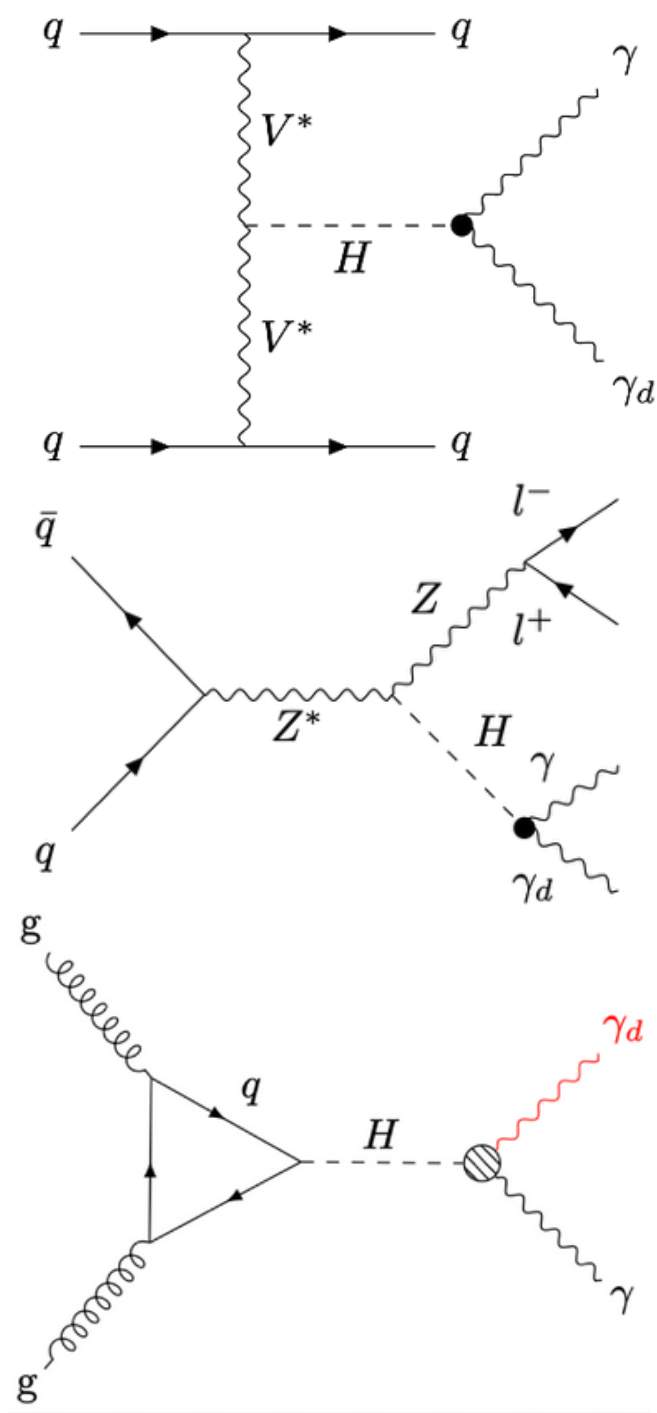
How can dark sector communicate with SM?



Dark photons

Dark photon models

Massless dark photon



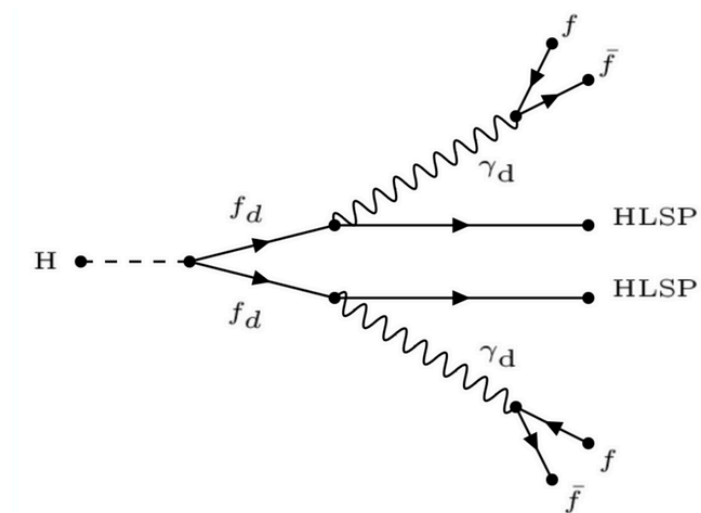
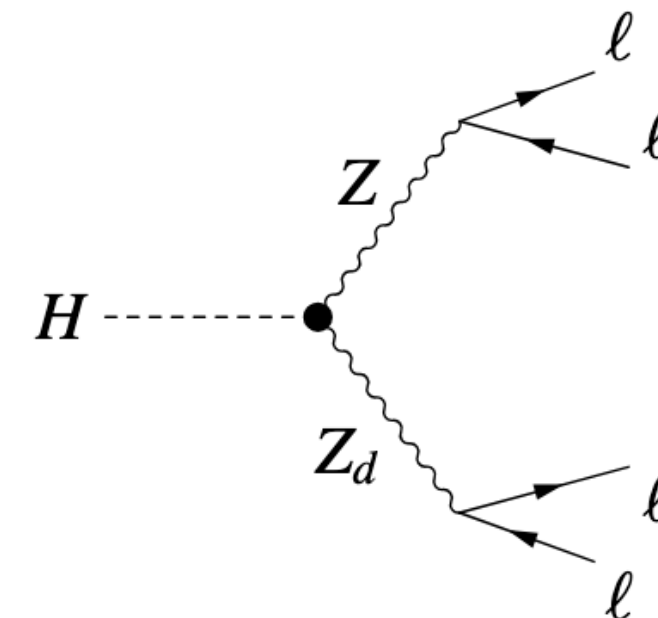
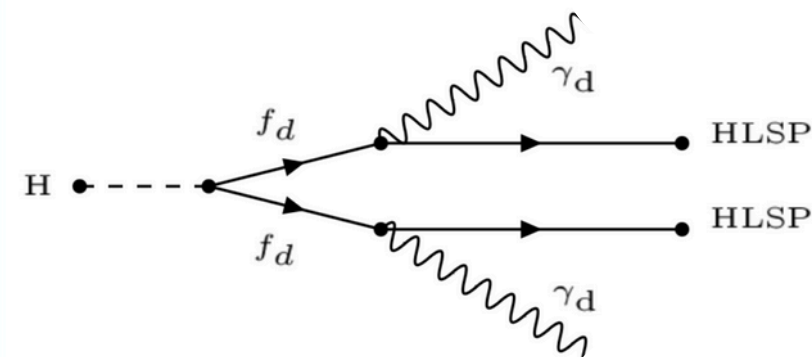
Massive dark photon

stable

decaying

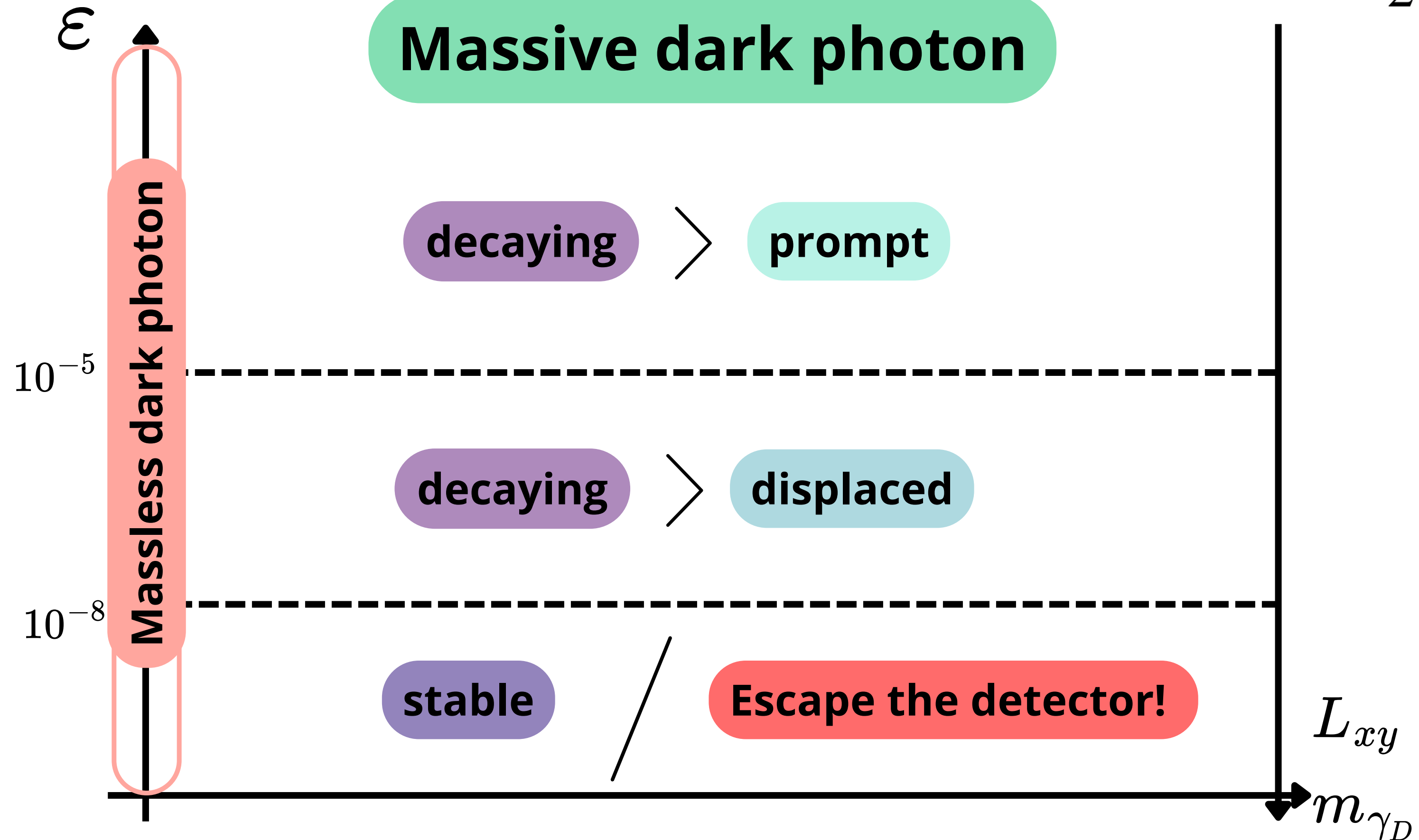
prompt

displaced

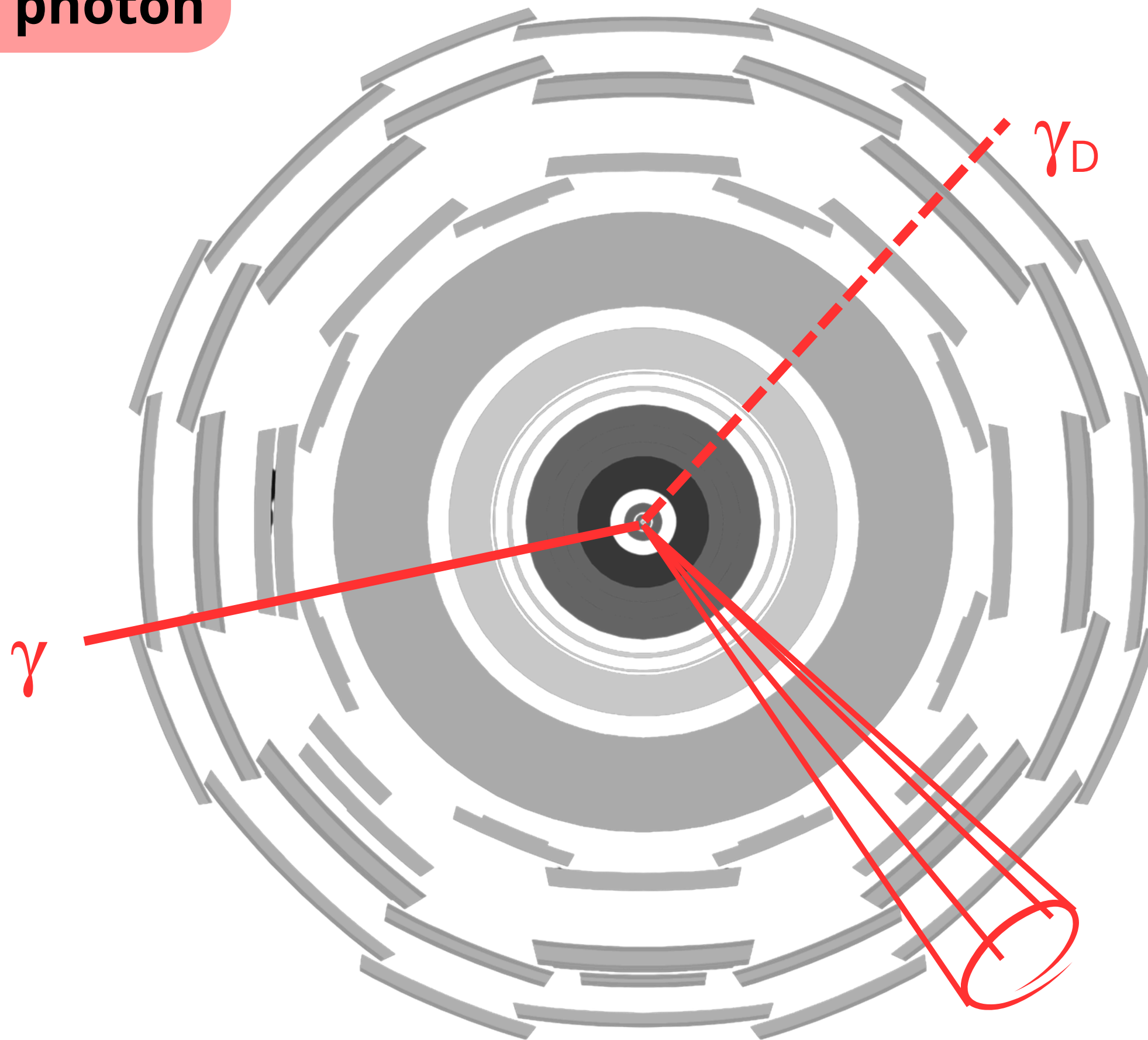


Exploring the parameter space

$$\mathcal{L} \ni \frac{\varepsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

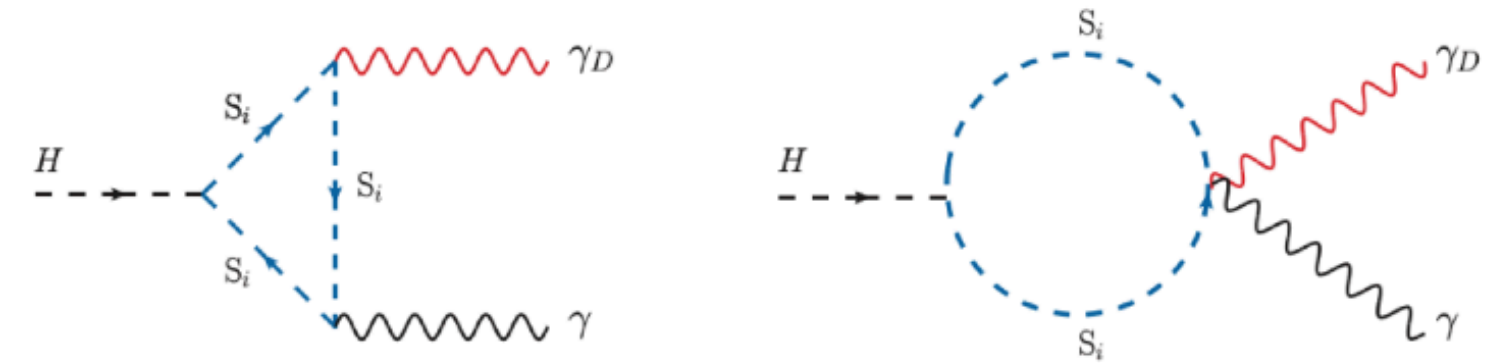


Massless dark photon

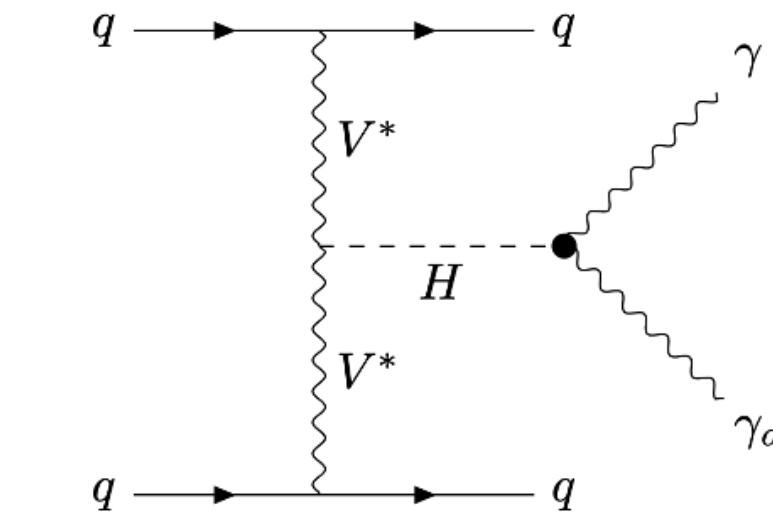
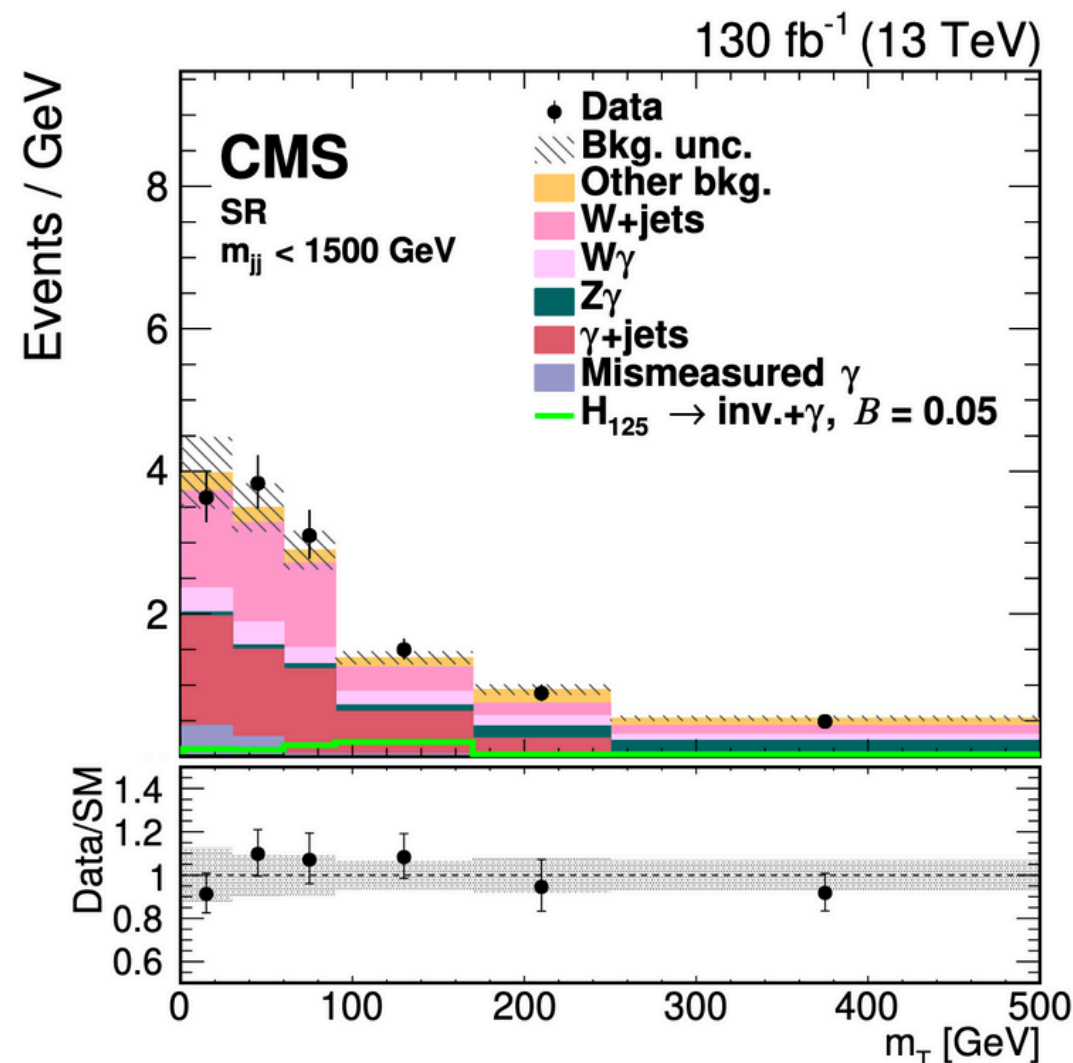


Massless dark photon

- Research channel $H \rightarrow \gamma\gamma_D$
- Vectorial portal + loops of messenger fields
- Final state $\gamma + E_T^{miss}$
- Run 2 explored VBF and ZH channels



VBF channel

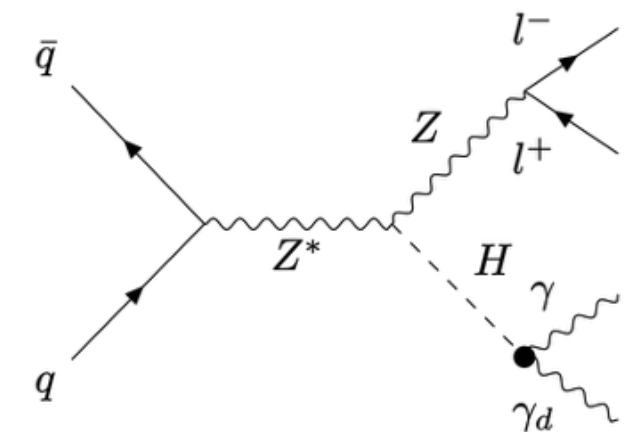
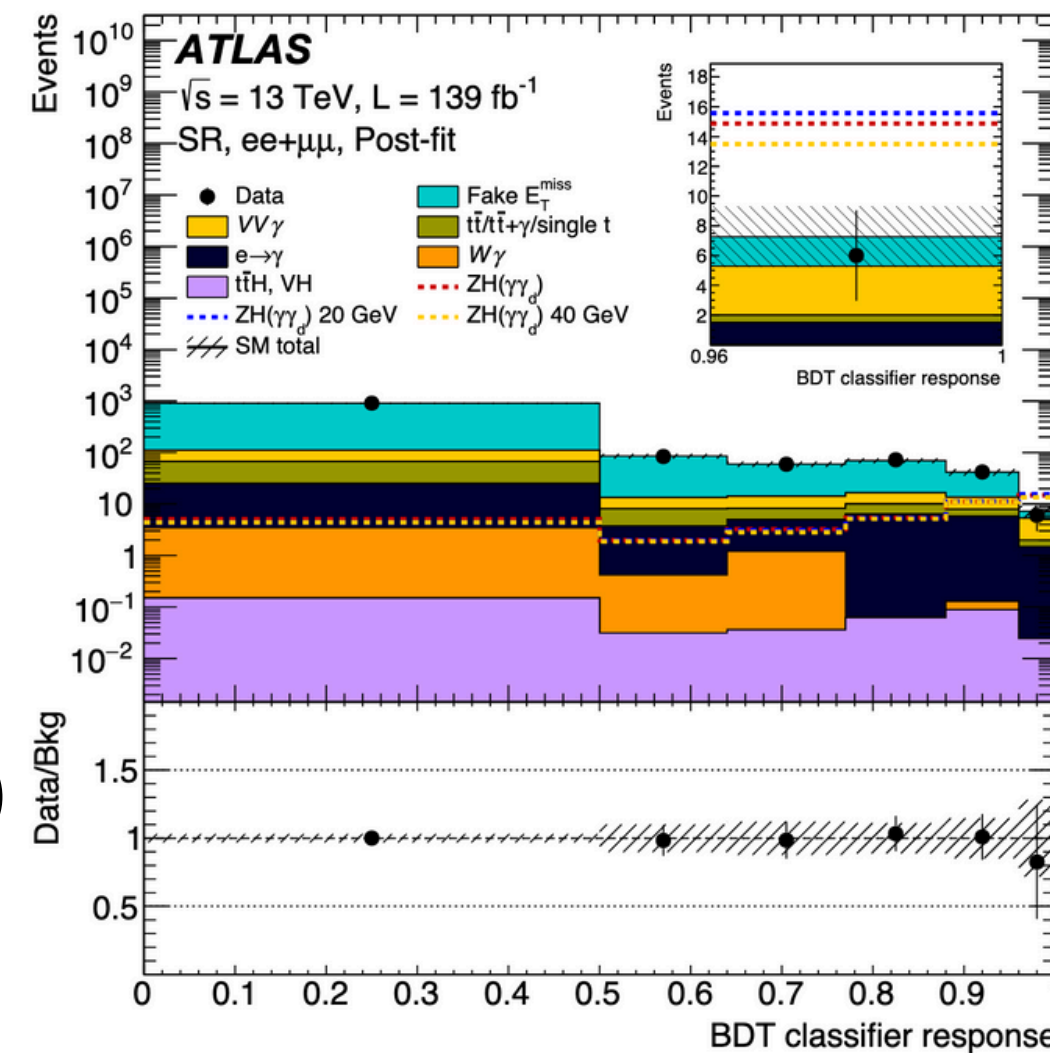


Upper obs(exp) limit
on $BR(H \rightarrow \gamma\gamma_D)$:

- **CMS**: 3.5%(2.8%)
- **ATLAS**: 1.8%(1.7%)

[JHEP03\(2021\)011](#)
[Eur. Phys. J. C 82 \(2022\) 105](#)

ZH channel



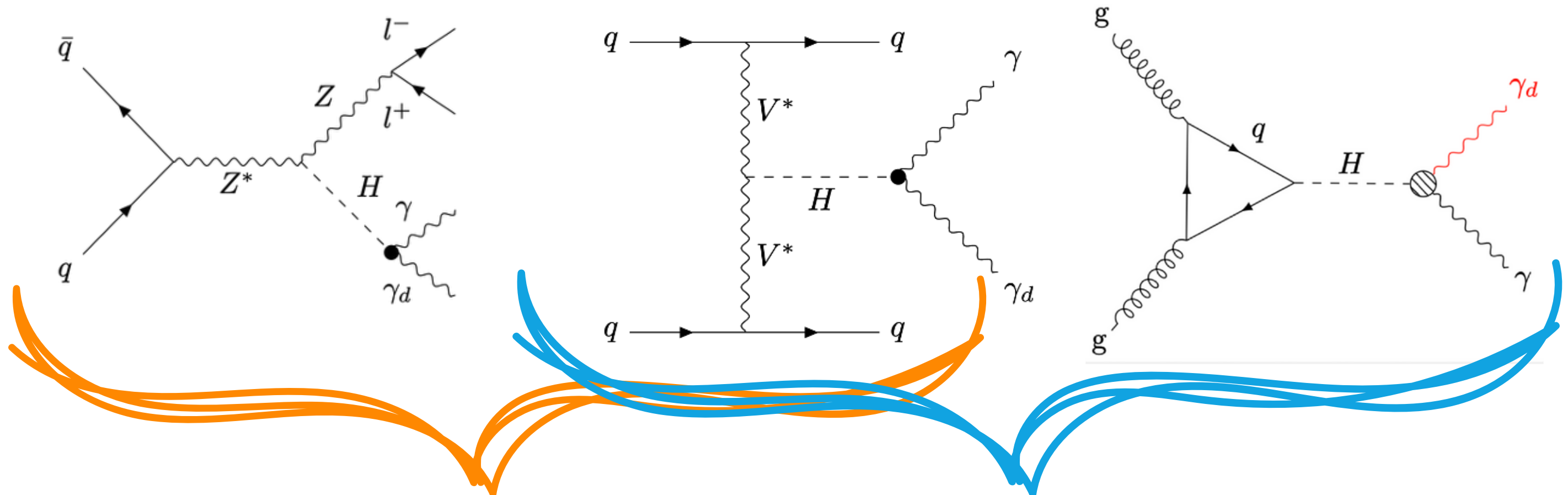
Upper obs(exp) limit
on $BR(H \rightarrow \gamma\gamma_D)$:

- **CMS**: 4.6%(3.6%)
- **ATLAS**: 2.3%(2.8%)

[JHEP10\(2019\)139](#)
[JHEP 07 \(2023\) 133](#)

Massless dark photon

NEW! combination



recast of
mono- γ analysis

SM Higgs combination: ZH and VBF

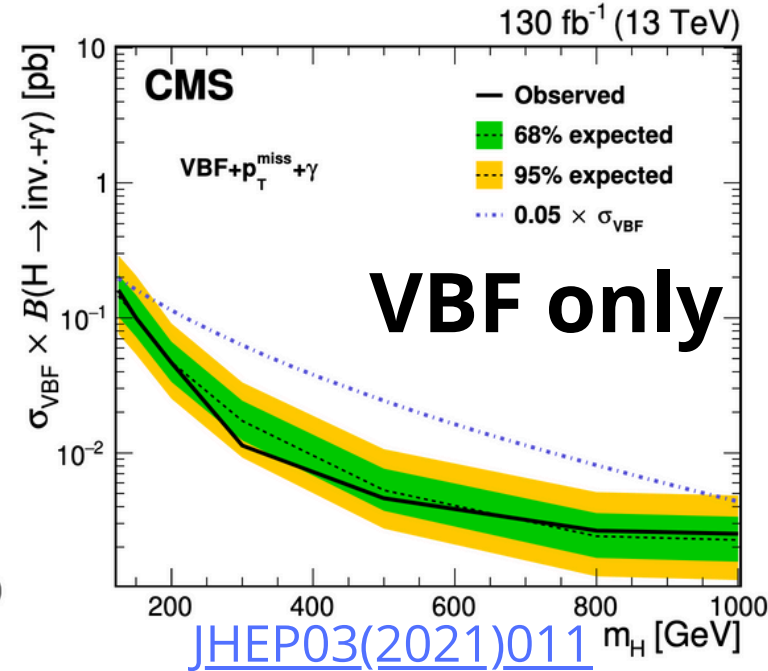
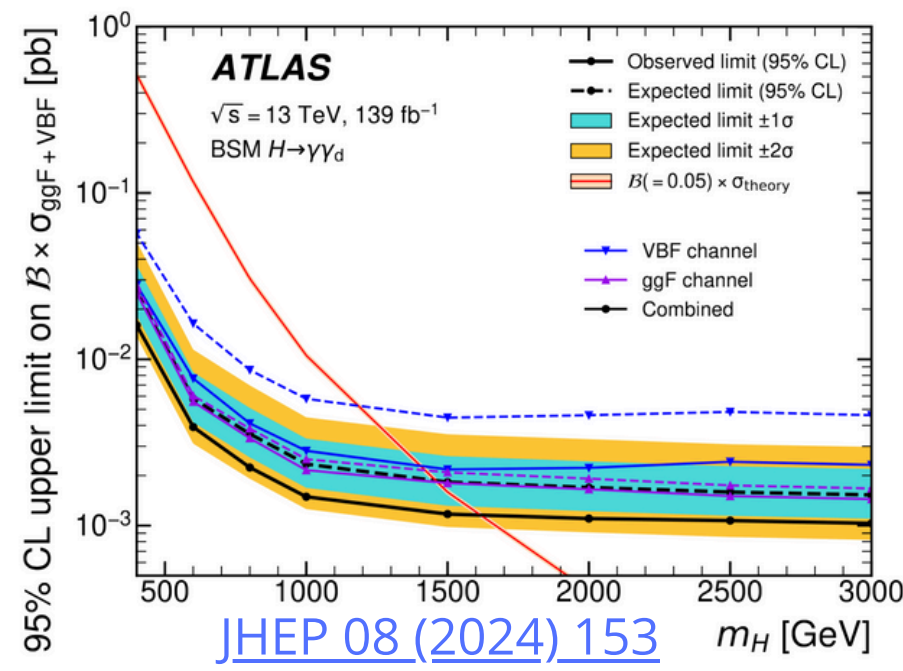
Upper obs(exp) limit on $BR(H_{SM} \rightarrow \gamma\gamma_D)$:

CMS: 2.9%(2.1%)
[JHEP03\(2021\)011](#)

ATLAS: 1.3%(1.5%)
[JHEP 08 \(2024\) 153](#)

BSM Higgs: VBF and **ggF**

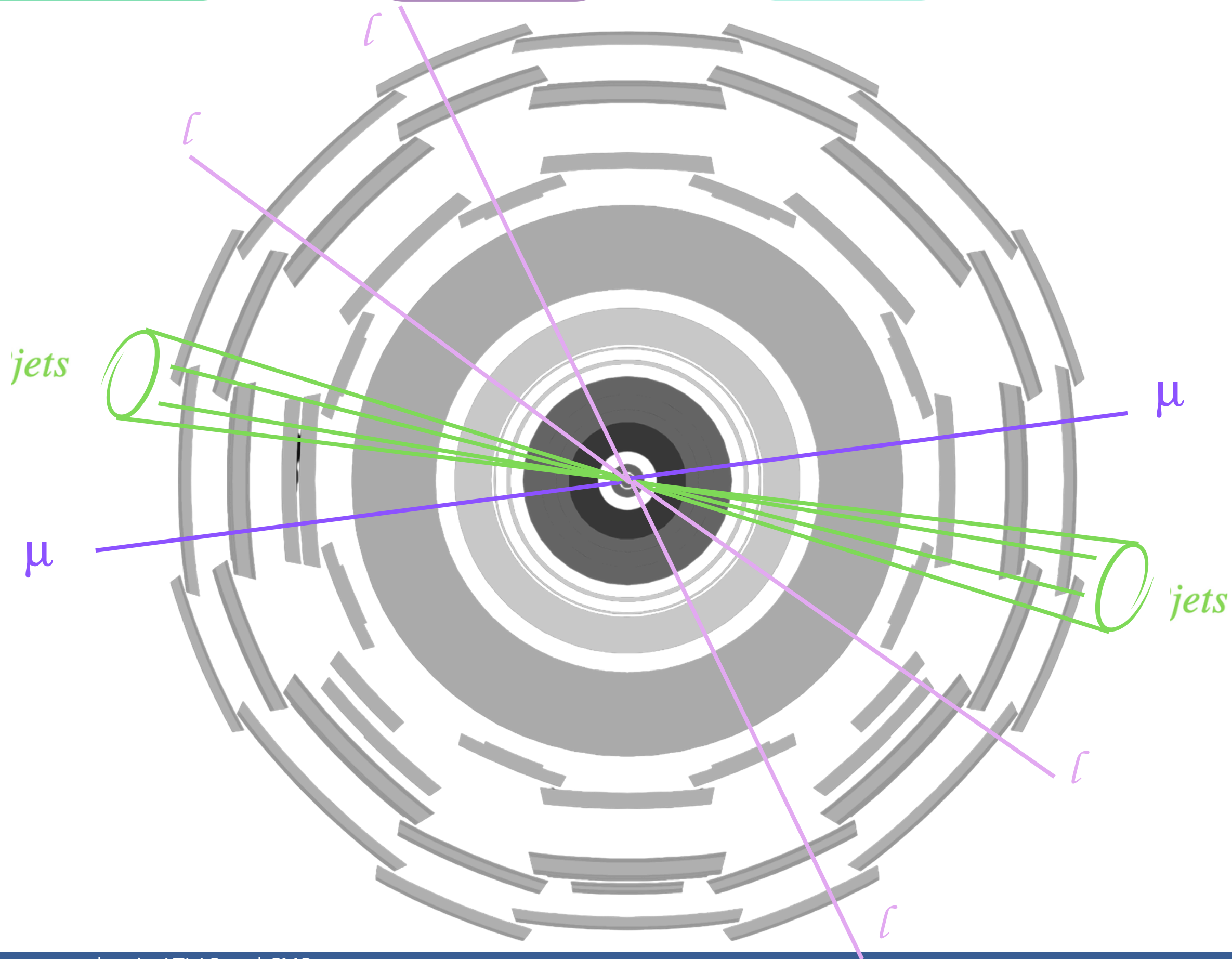
Upper obs(exp) limit on $\sigma \times BR(H_{BSM} \rightarrow \gamma\gamma_D)$:



Massive dark photon

decaying

prompt



TL/scouting analysis

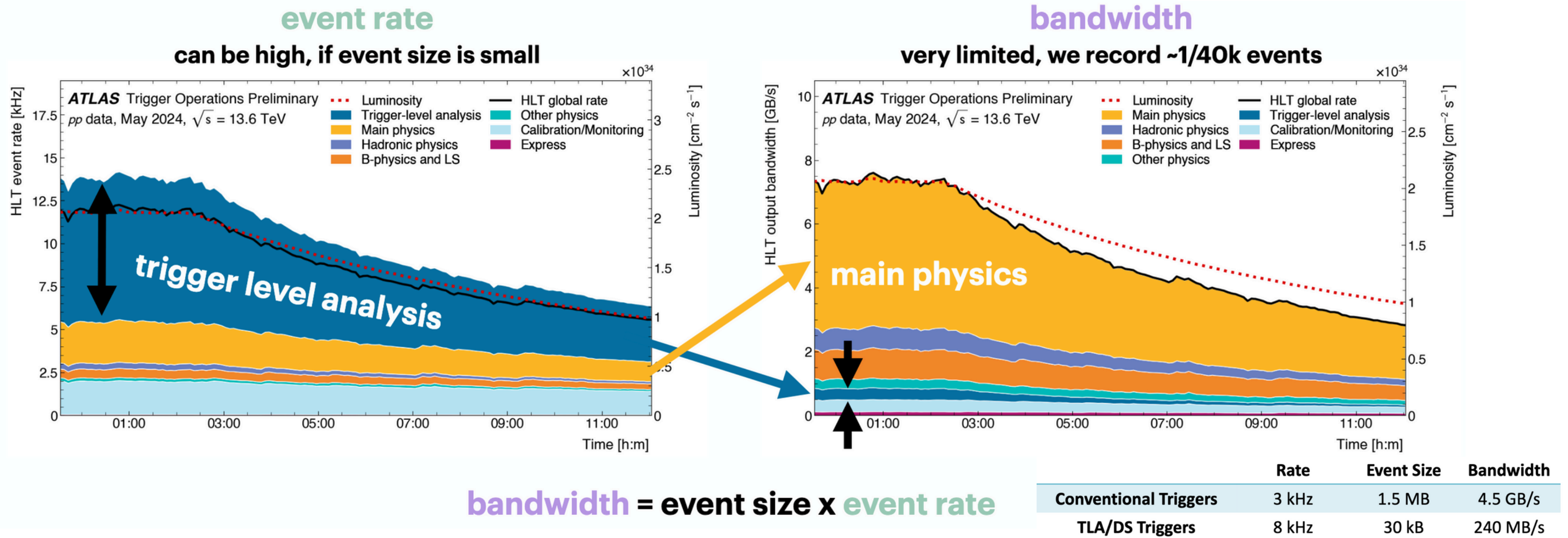
HLT processes ~92 kHz events but only 3kHz events can be saved fully

Loss of physics in low-momentum

Lower event size and gain statistic!

Size of TLA event
(relative to full event)

Size of full event



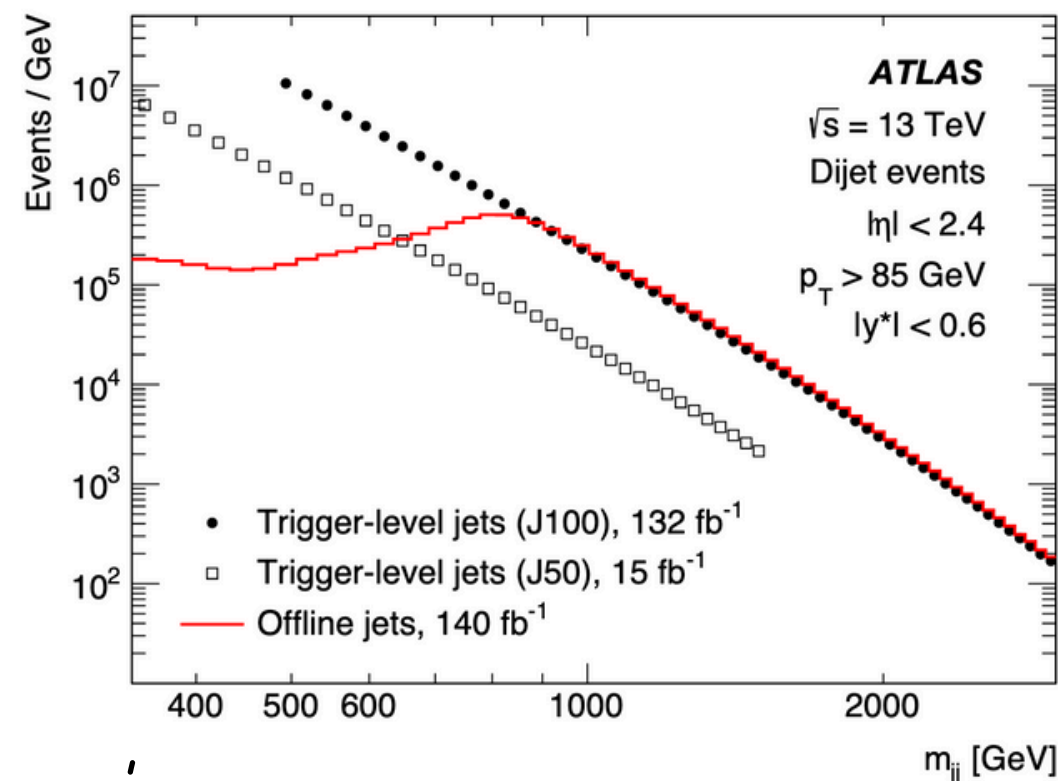
TLA analysis at the **ATLAS** detector



Submitted to: [Phys. Rev. D](#)

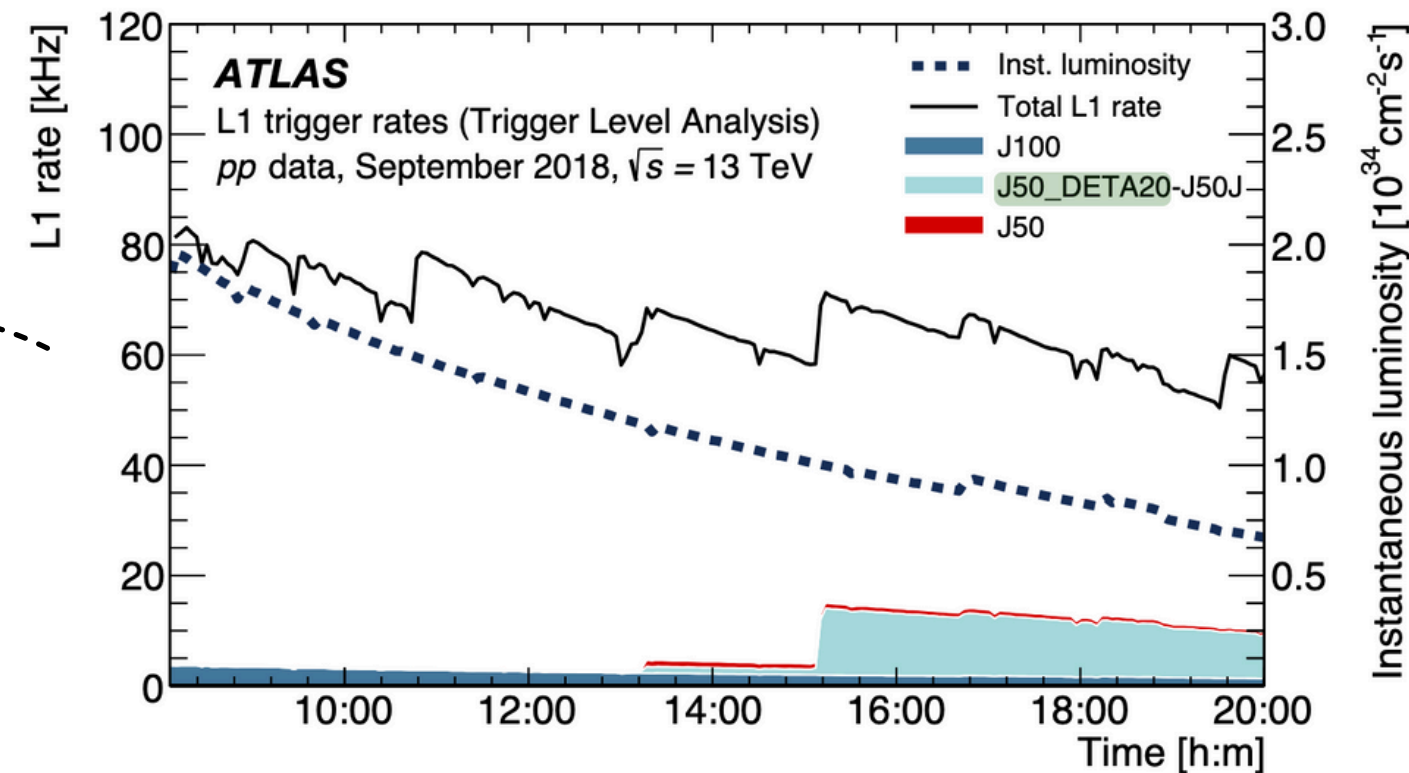
Dijet resonances

- Leptophobic axial-vector Z'
- $m_{jj} \in [375 - 1800]$ GeV

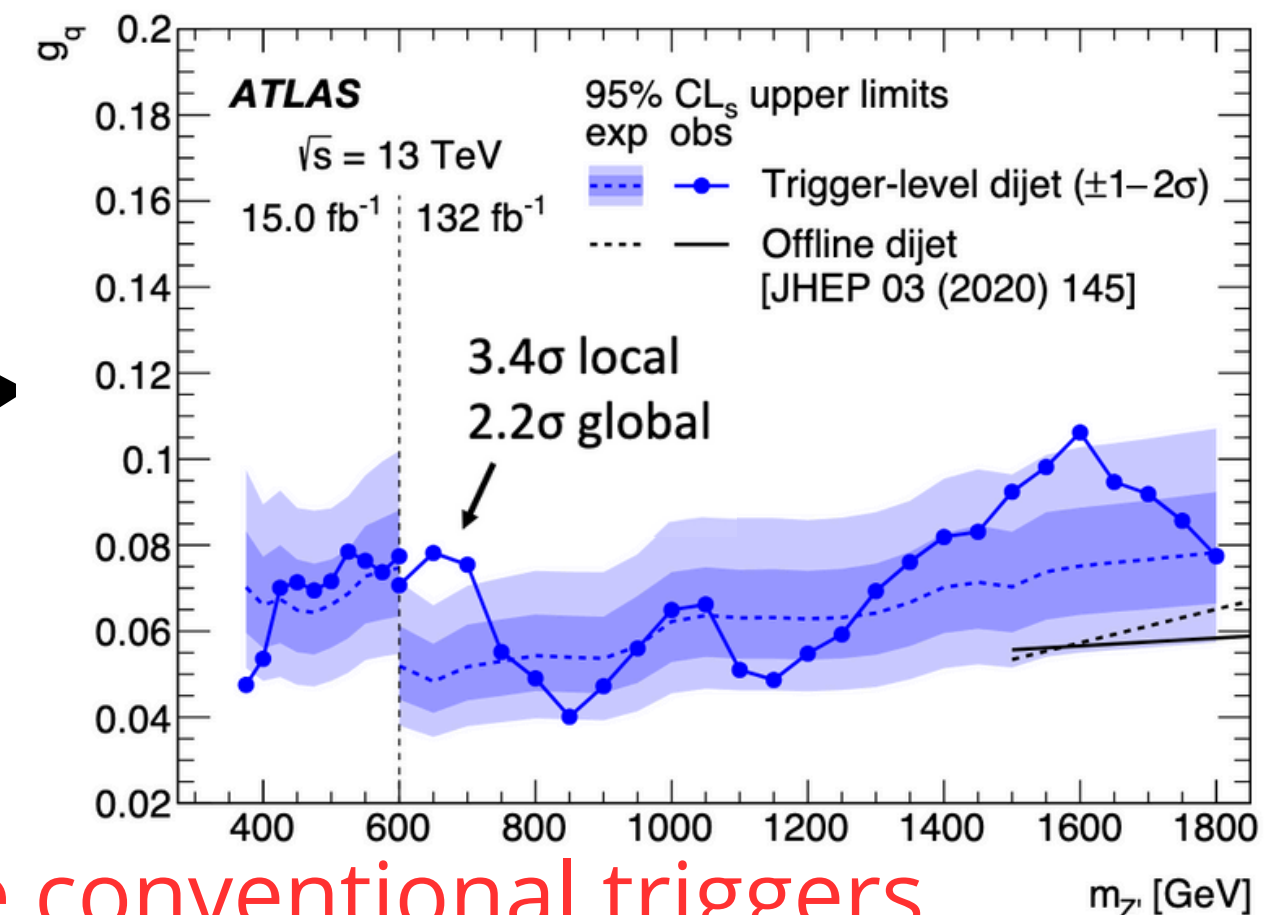


enlarged
statistic at
low masses!

upper limit on Z' -coupling
to quarks for low Z' masses



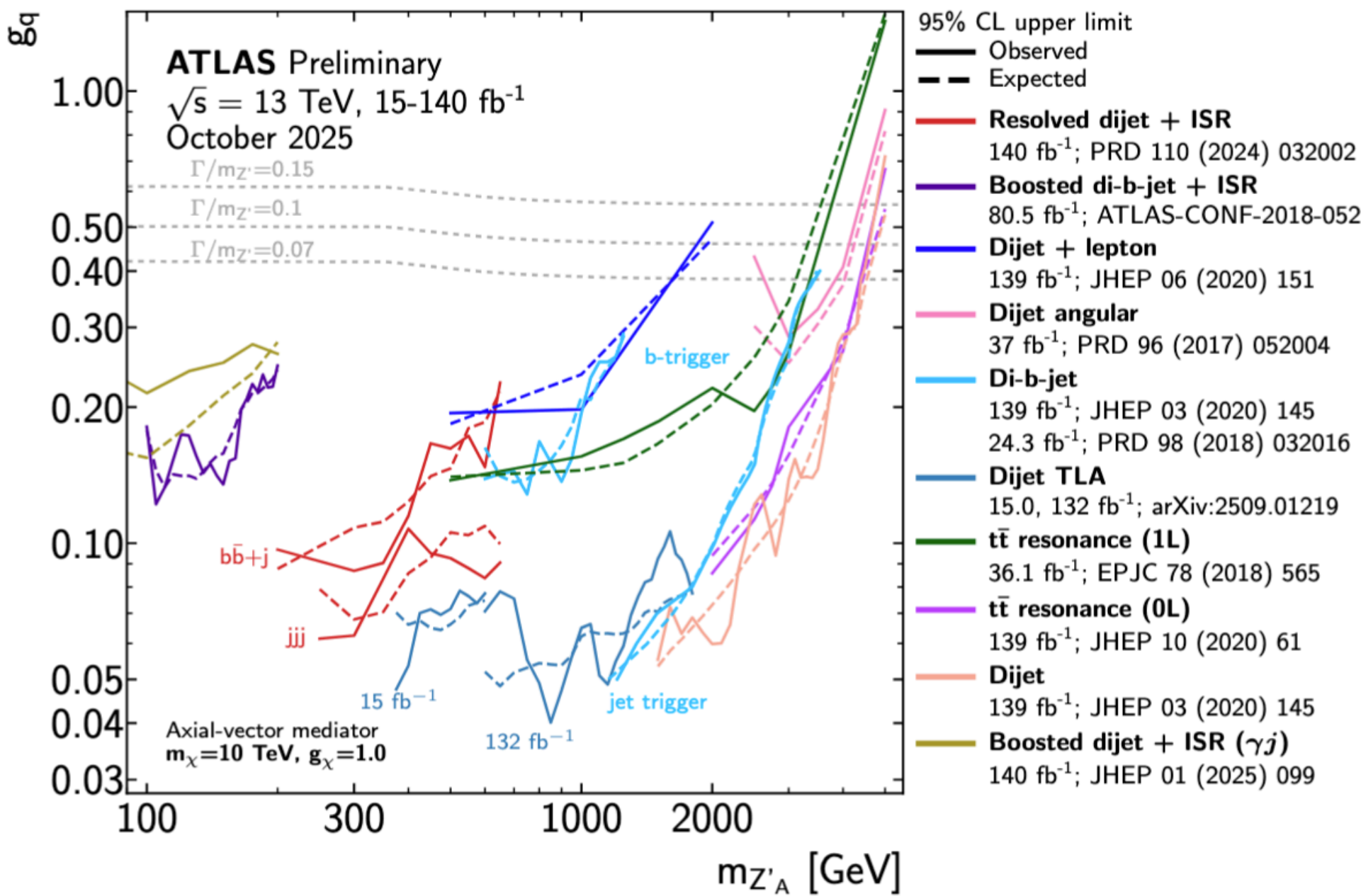
exploit L1
information



1500 GeV was the lower limit by the conventional triggers.

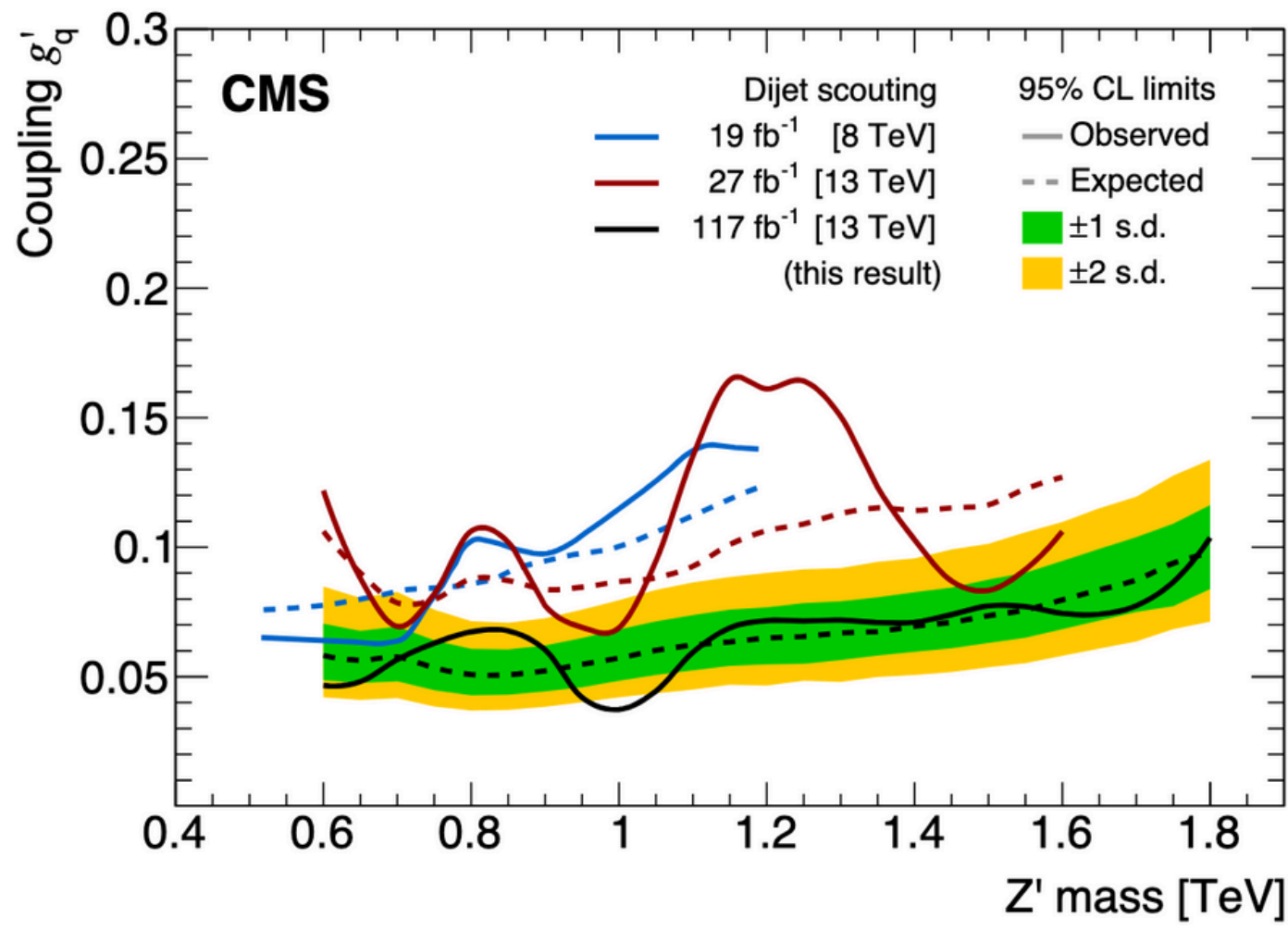
TLA analysis at the **ATLAS** and **CMS** detector

Summary plot of the coupling between SM quarks and an axial-vector mediator to the dark sector as a function of its mass



[ATL-PHYS-PUB-2025-041](#)

Recent result also at CMS for dijet resonance search using data scouting



[CMS-EXO-23-004](#)

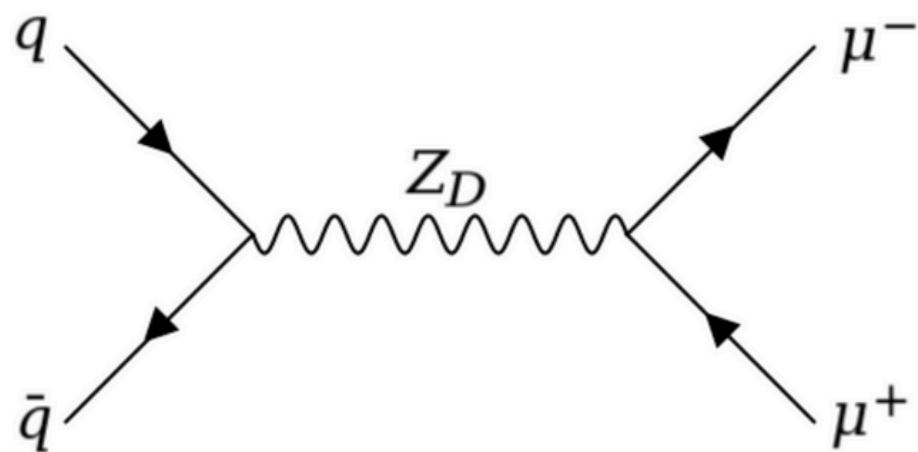
Massive dark photon

decaying

prompt

Hypercharge (vectorial) portal $Z_D \rightarrow \mu\mu$ at CMS

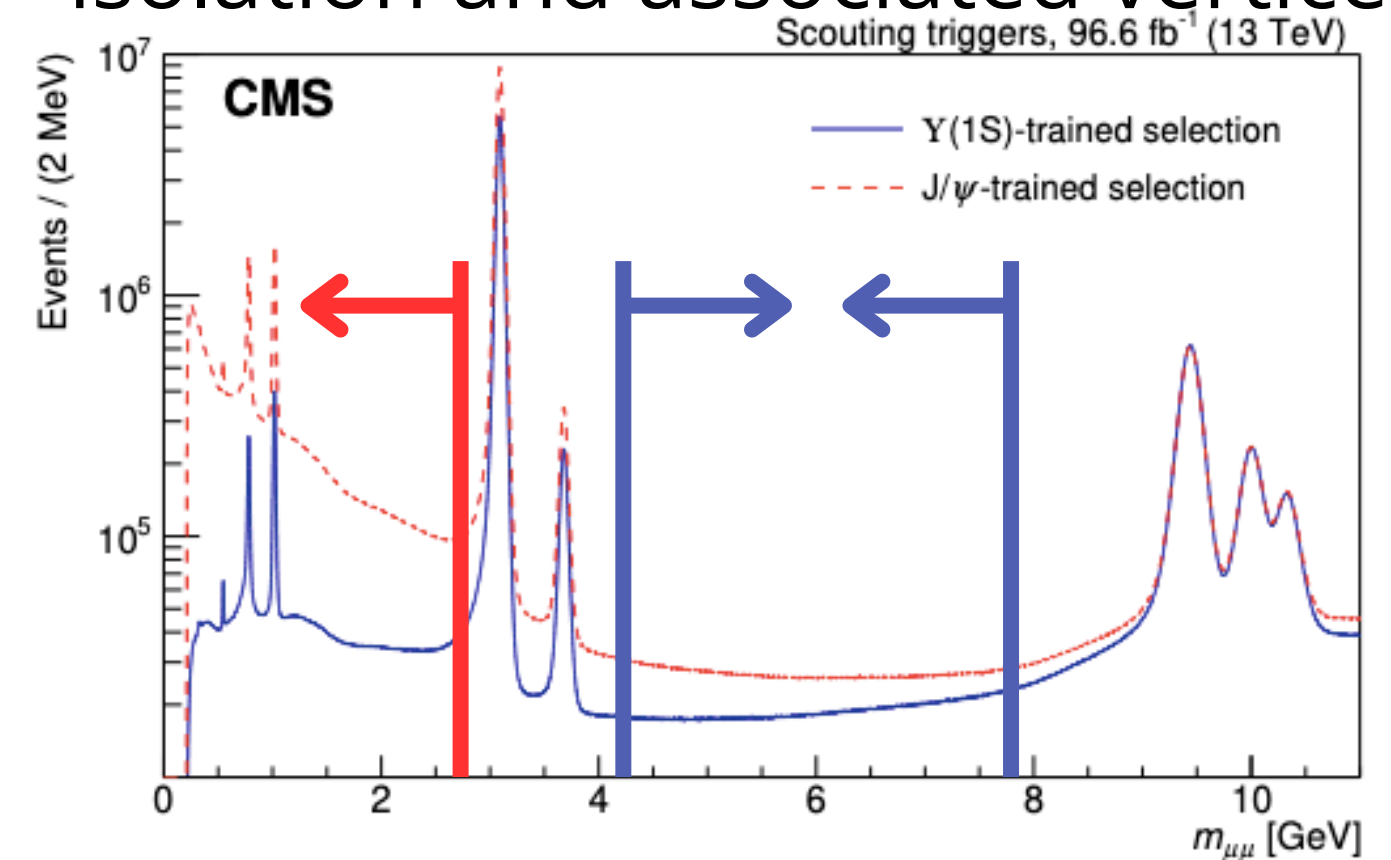
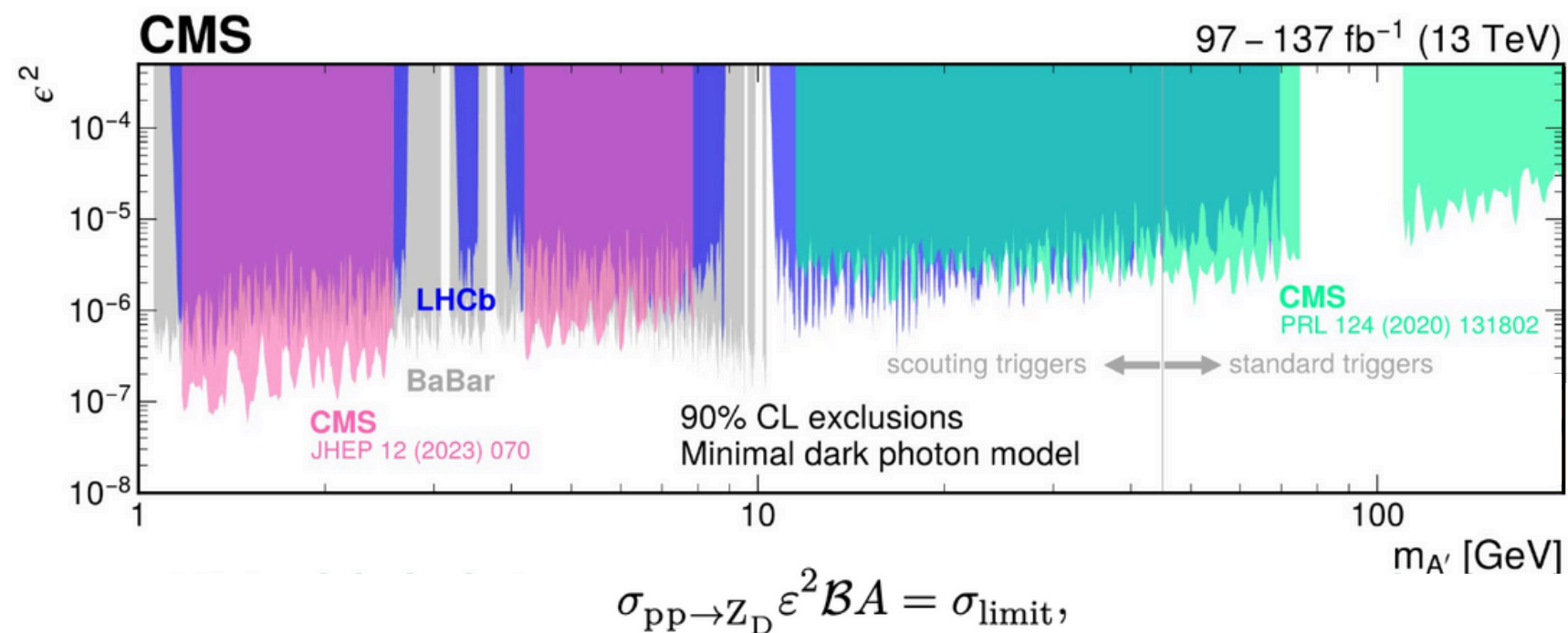
[JHEP12\(2023\)070](#)



- High rate “scouting” trigger
- $m_{\gamma_D} \in [1.1, 2.6] \text{ GeV} \cup [4.2, 7.9] \text{ GeV}$

limits on low masses!

BDT-based muon identification
using quality of tracks, relative
isolation and associated vertices



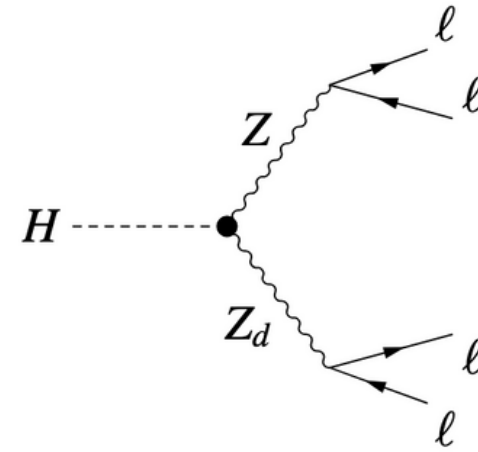
Massive dark photon

decaying

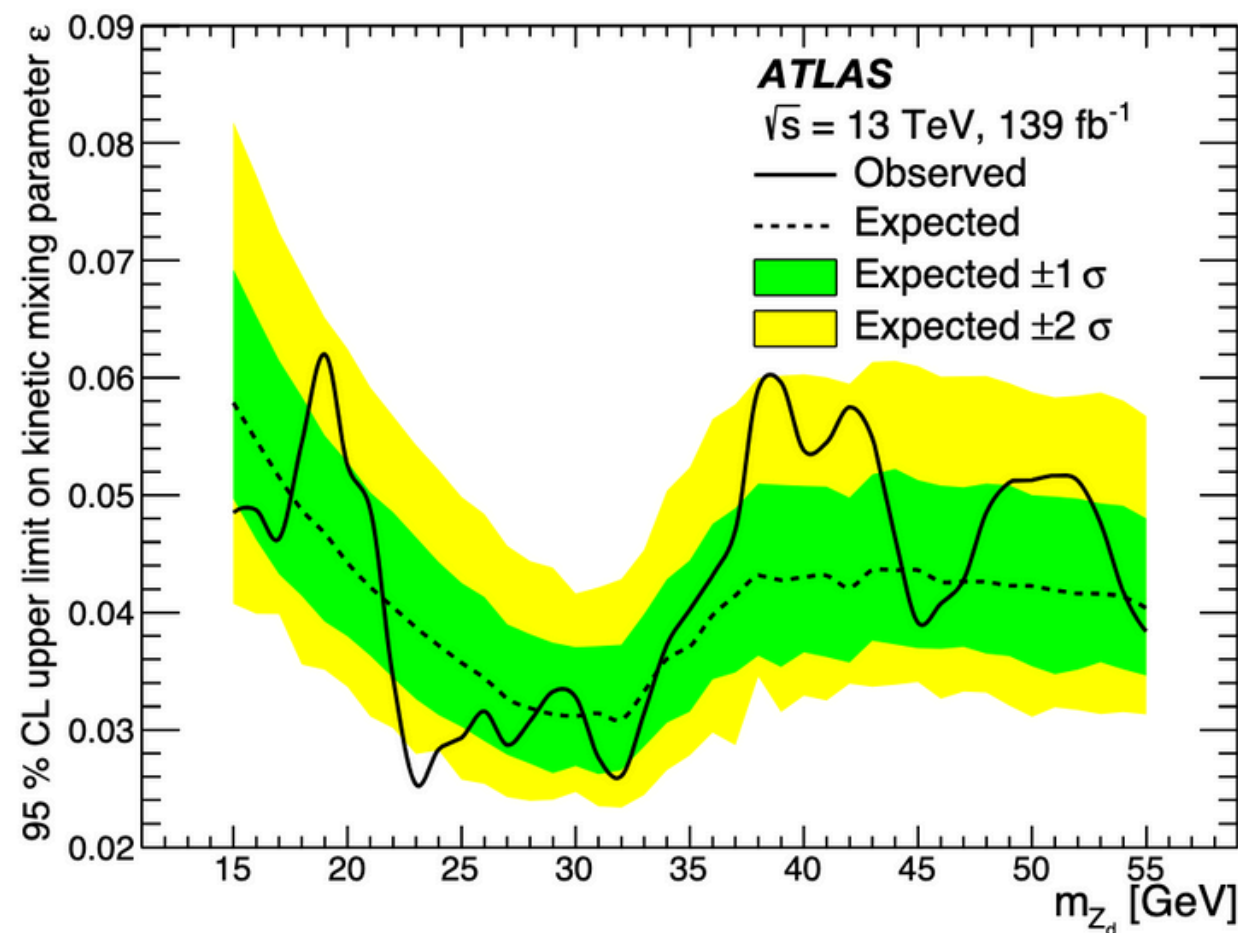
prompt

JHEP 03 (2022) 041 at ATLAS

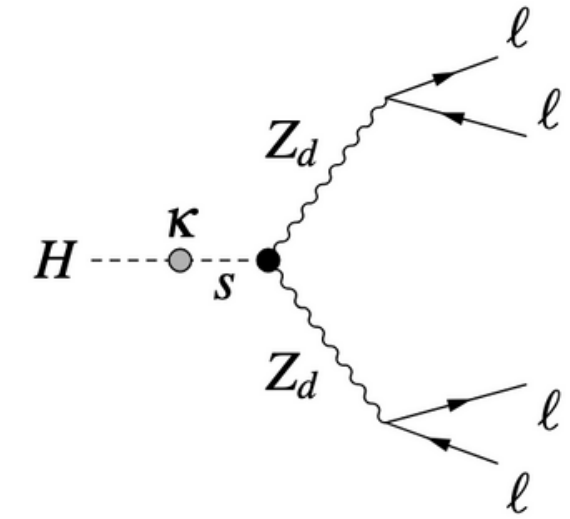
$$H \rightarrow ZZ_D \rightarrow 4l$$



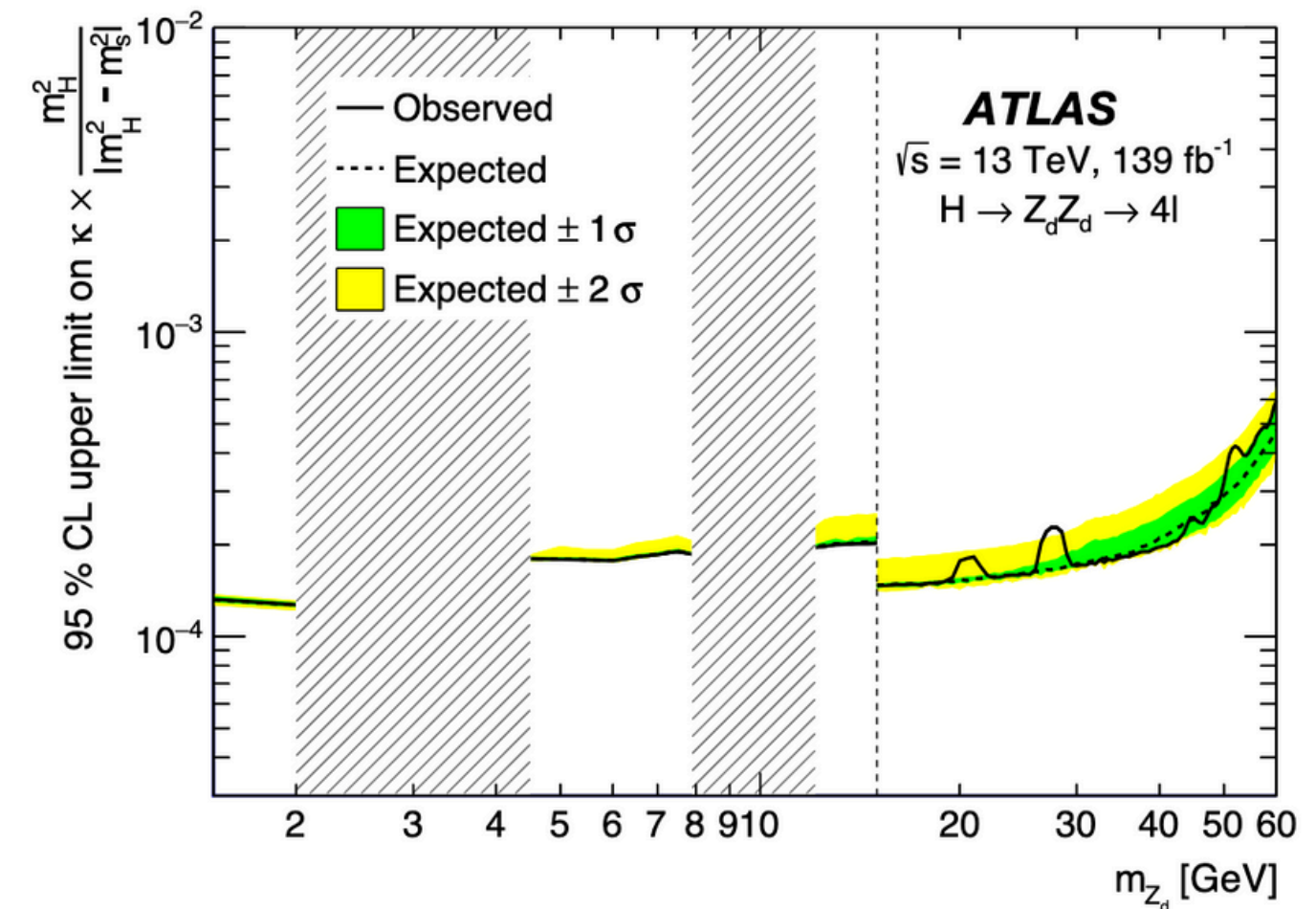
- Vectorial portal limits coupling epsilon
- $m_{\gamma_D} \in [15 - 55]$ GeV



$$H \rightarrow Z_D Z_D \rightarrow 4l$$



- Scalar portal limits coupling k
- $m_{\gamma_D} \in [1 - 60]$ GeV



Massive dark photon

decaying

prompt

Dark photon mass assumed to be much smaller than the hard scattering process energy-scale

Large Lorentz boost

Highly collimated decay products (Lepton Jets) :

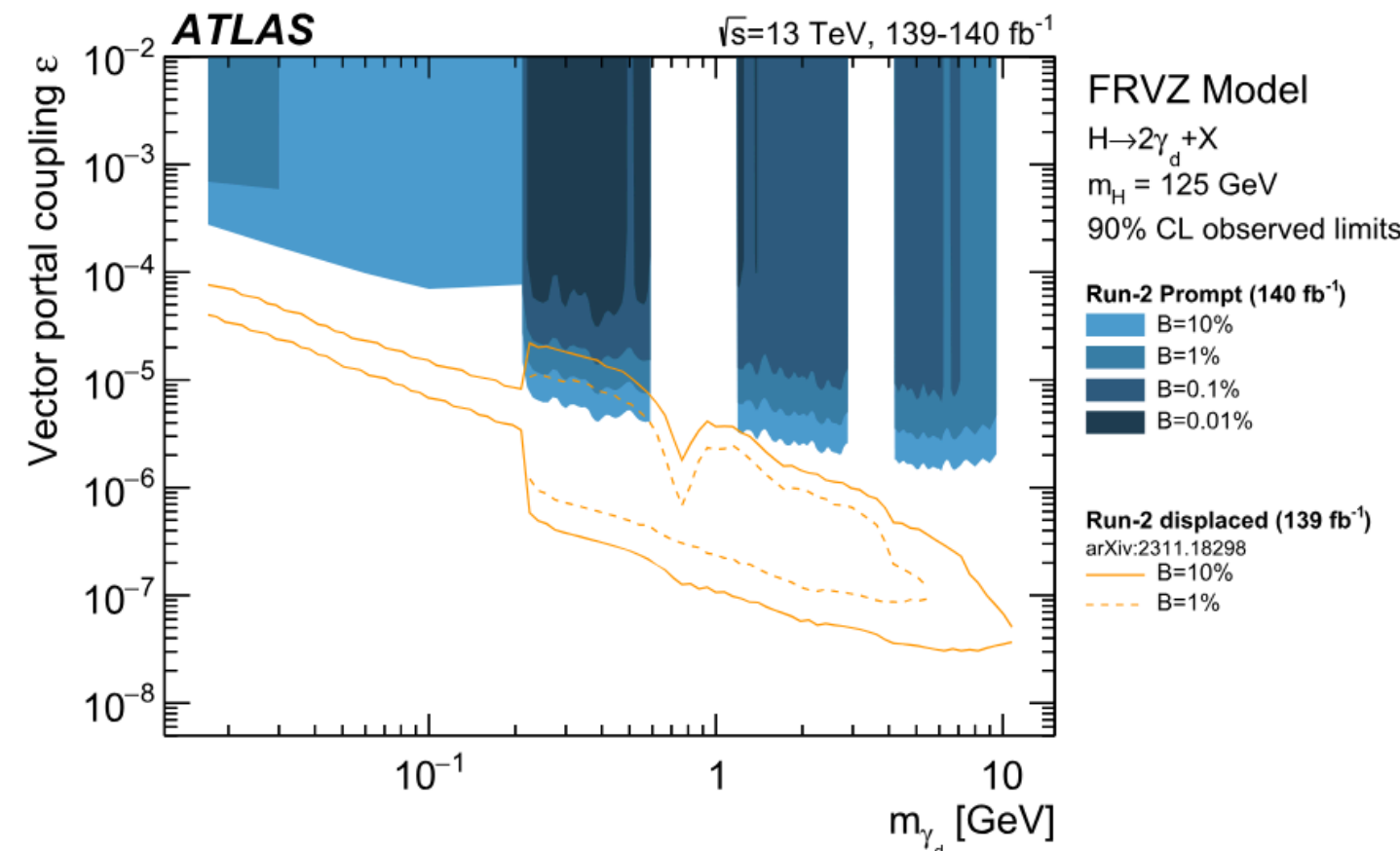
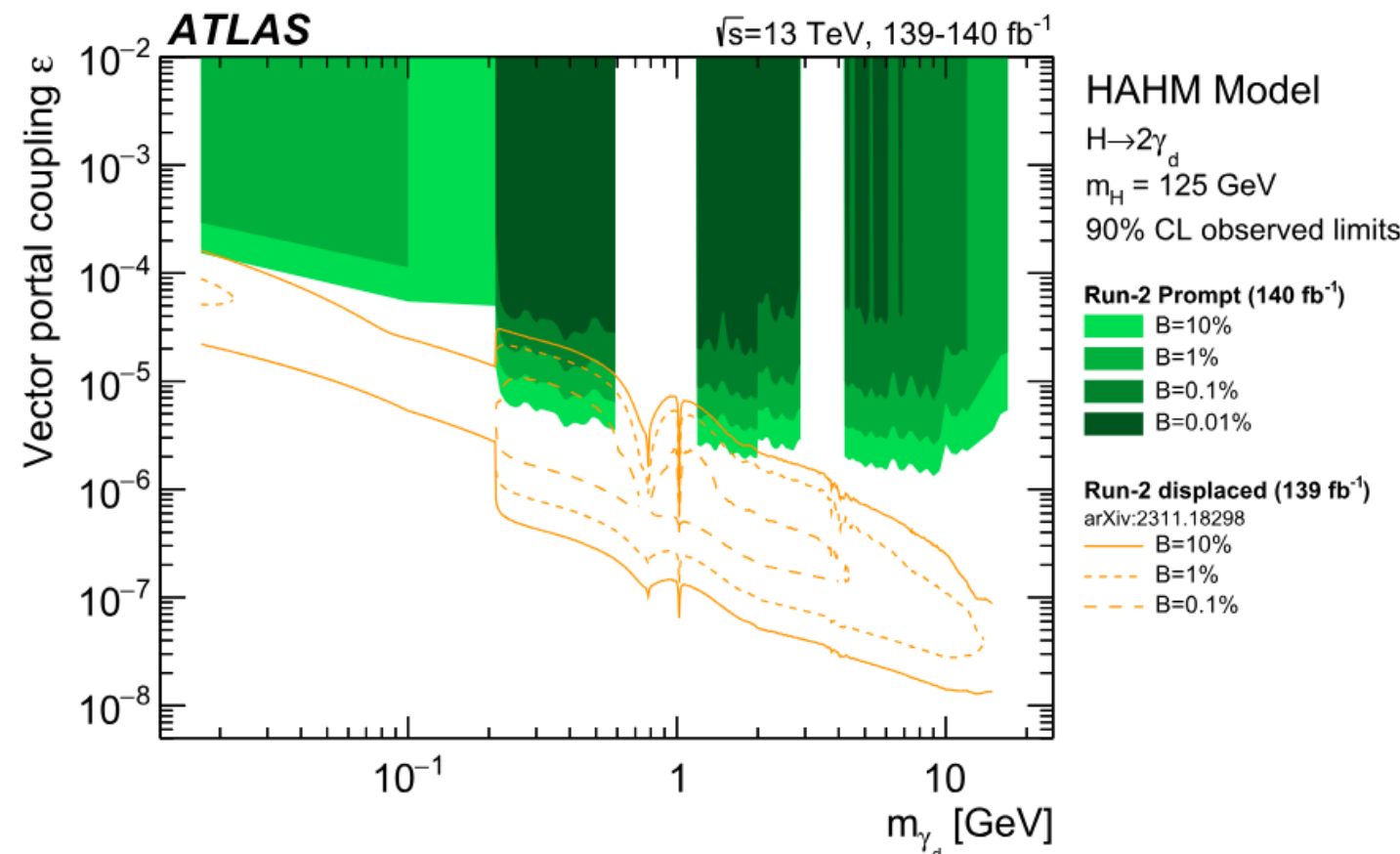
○ Muonic LJets

○ Electronic LJets

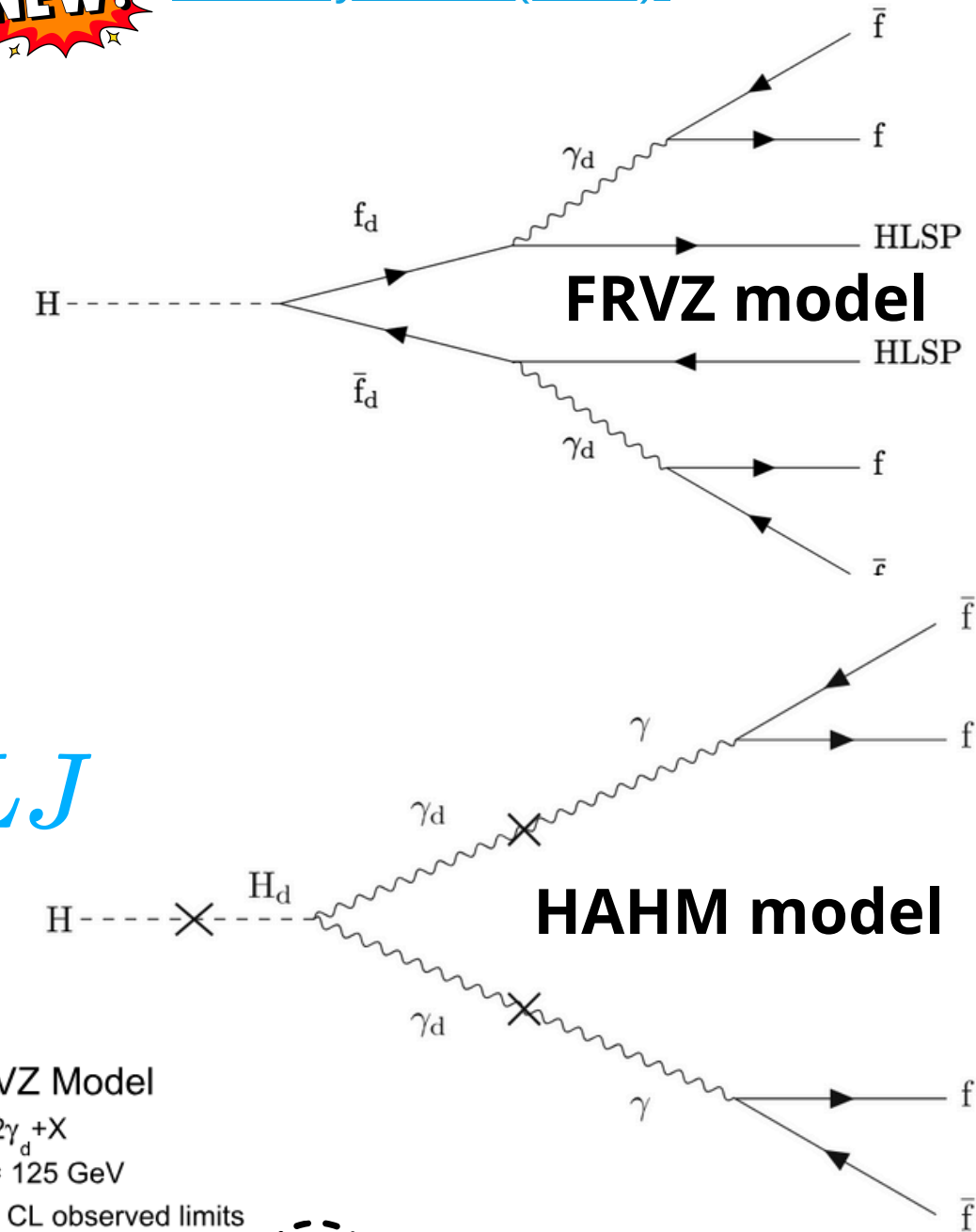
3 channels:

$2eLJ, 2\mu LJ, 1\mu LJ + 1eLJ$

+ p_T^{miss} from Hidden Lightest Stable Particles



[Eur. Phys. J. C \(2025\)](#) at **ATLAS**

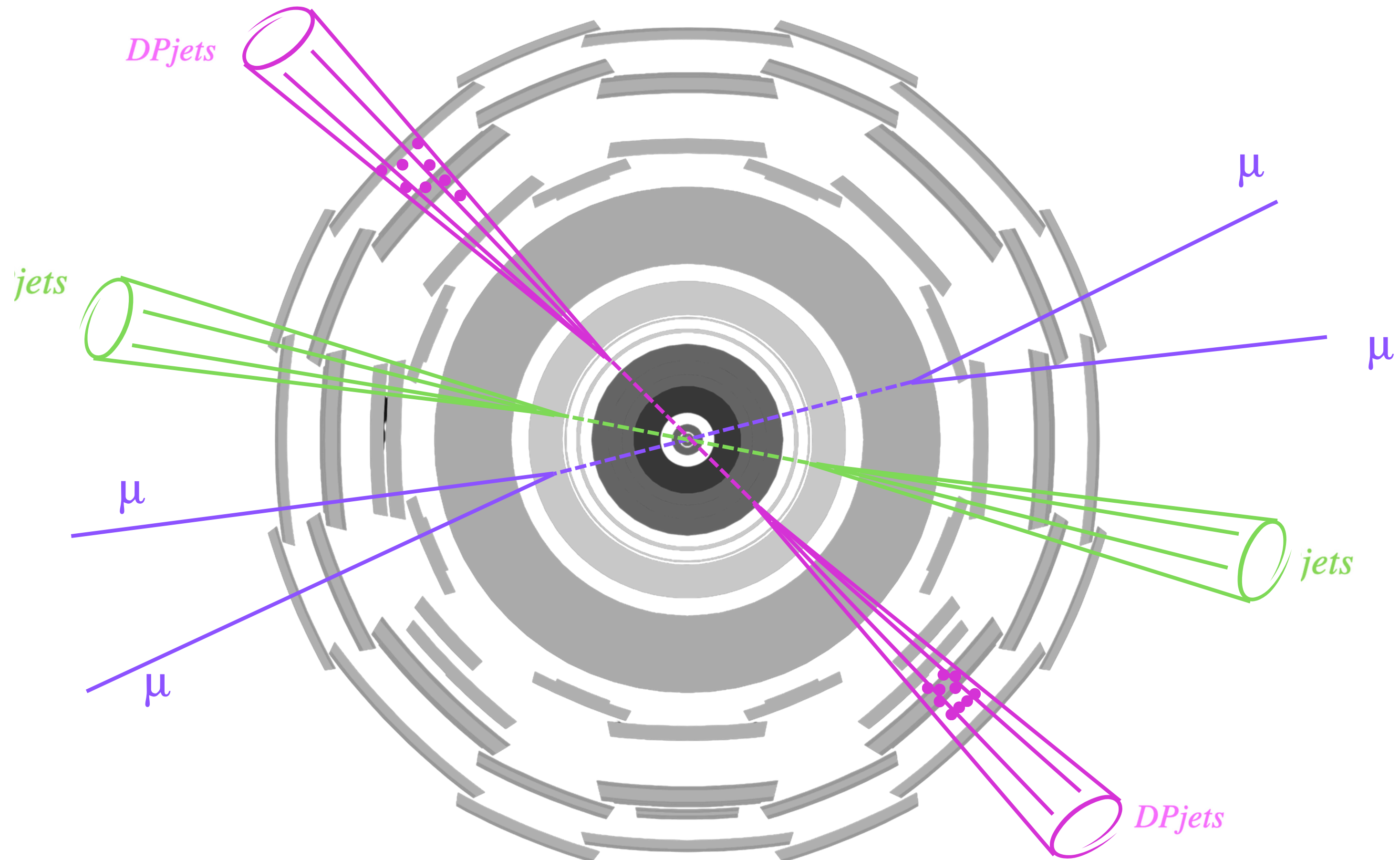


Limits on masses
down to 10 MeV

Massive dark photon

decaying

displaced



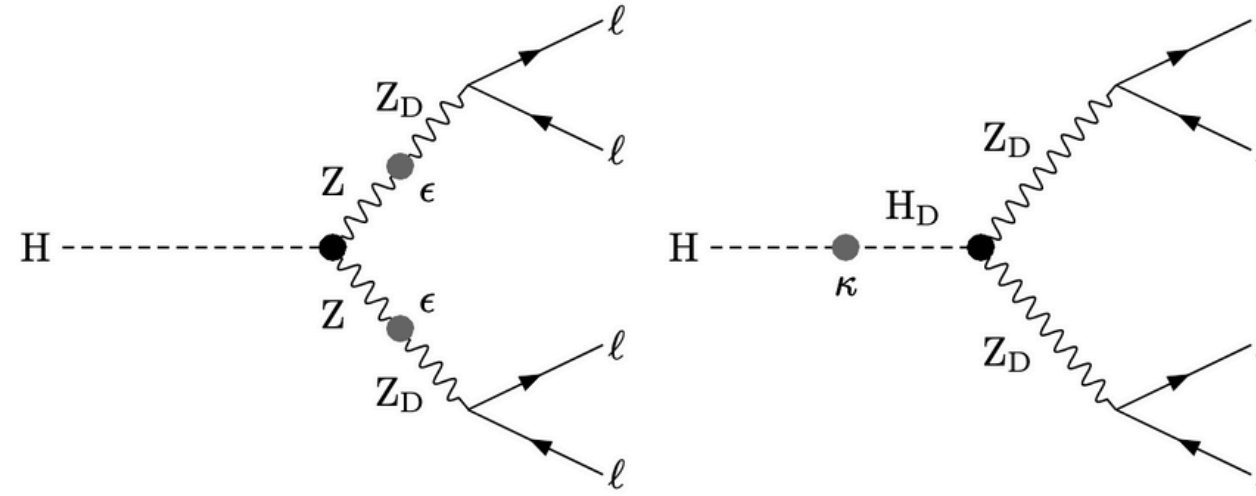
Massive dark photon

decaying

displaced

High rate “scouting” trigger

$$H \rightarrow Z_D Z_D \rightarrow 4l$$



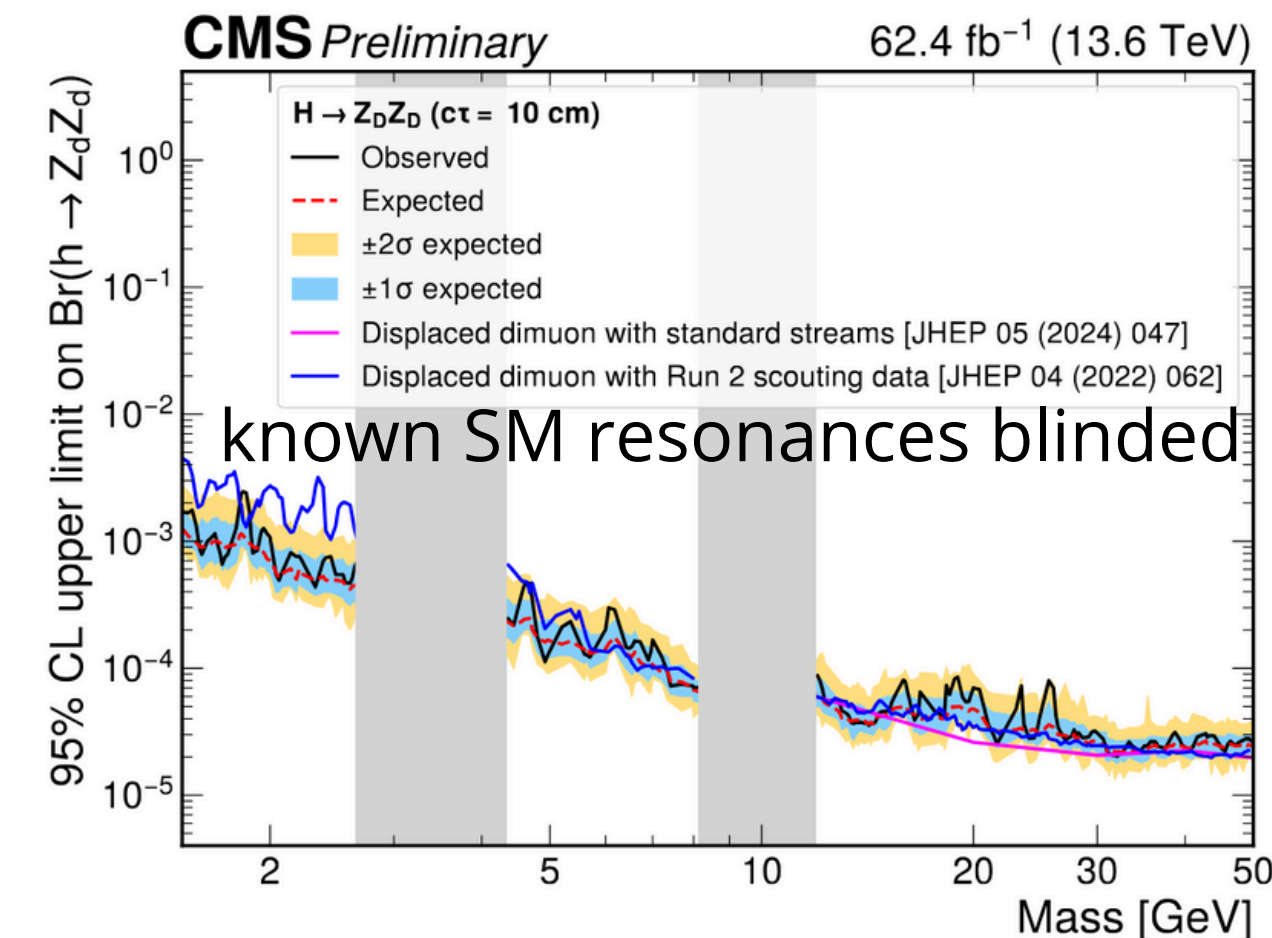
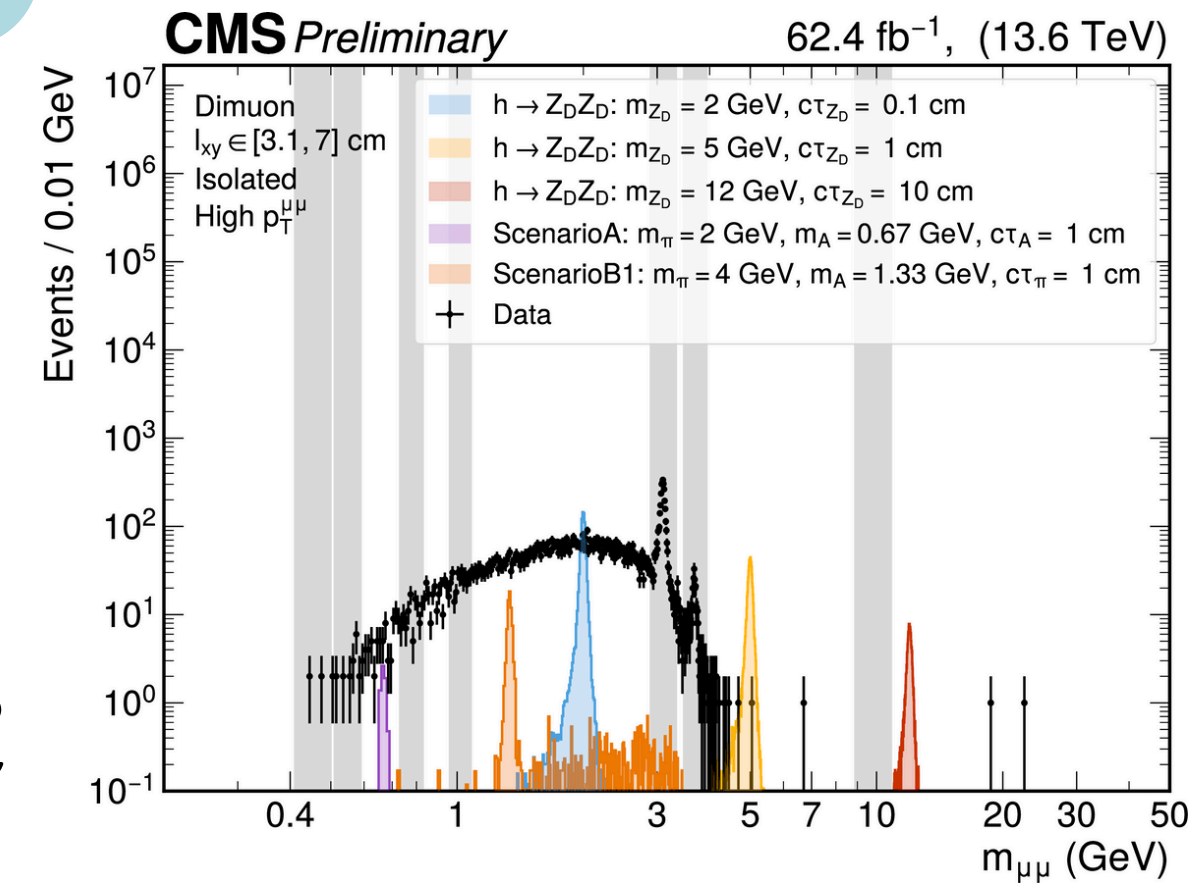
- HAHM model
- At least 2 OS L1 muons with requirements on $p_T, \eta, \Delta R$ and associated to secondary vertex
- From Run2 to Run3 muon scouting trigger updated:

Pixel hit requirements removed: Transverse displacements of muons >11 cm now accessible

More detailed information on the hits of muon tracks stored: Improves the background rejection



EXO-24-016 at CMS



Massive dark photon

decaying

displaced

other models

NEW! Events with displaced jets in the Muon Spectrometer

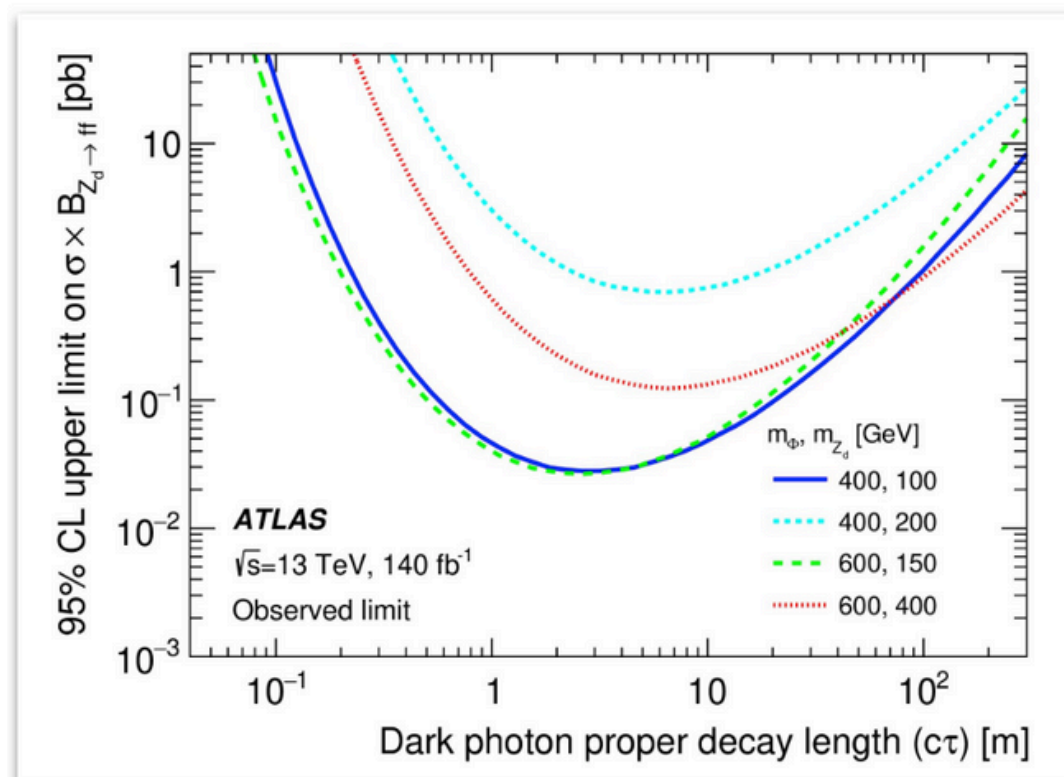
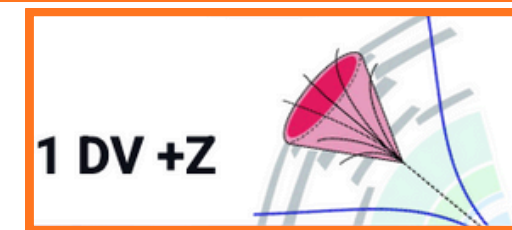
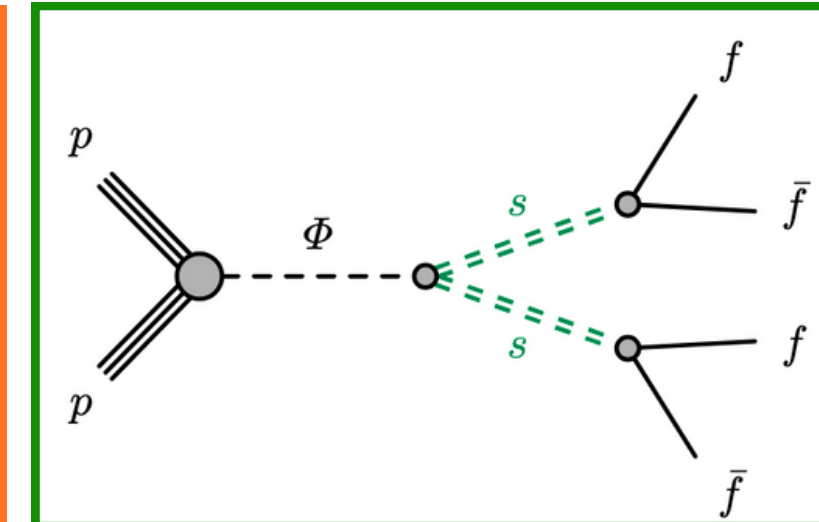
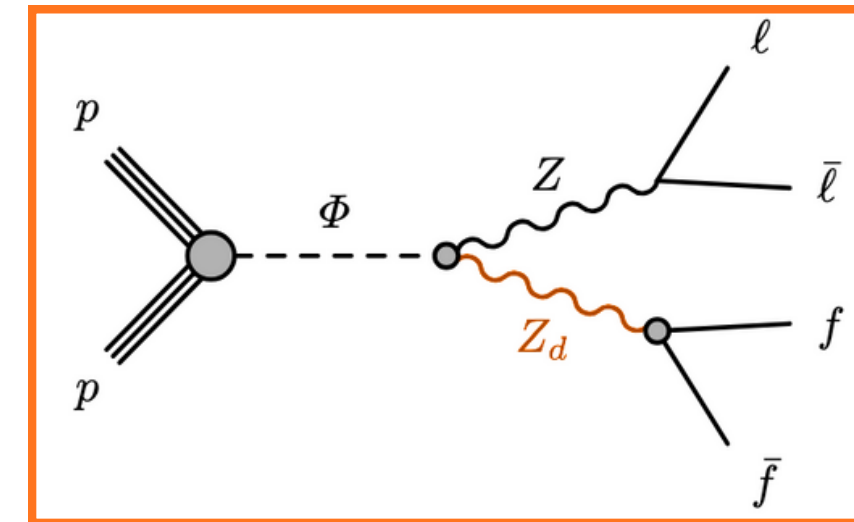
at **ATLAS**

[Submitted to: Phys. Rev. D.](#)

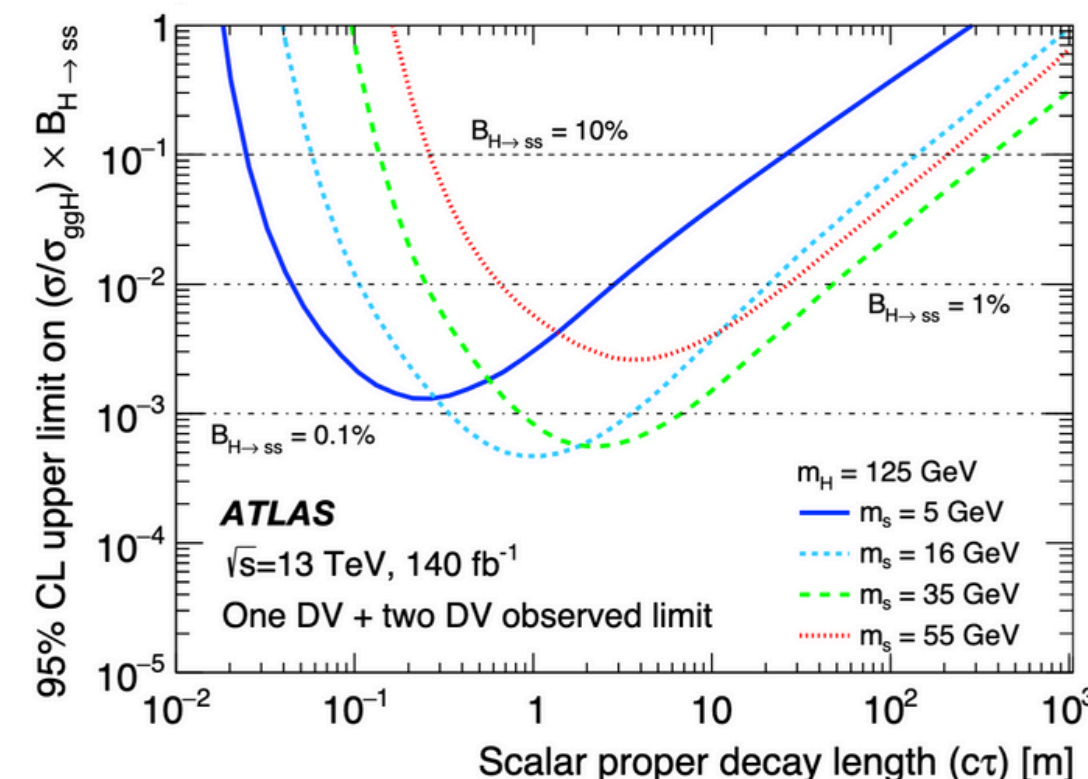
- Several signal models, among which:

- dark photon + Z
- scalar portal

- Signature: 1 Displaced Vertex in MS (+ prompt Z)
- 2 NN trained with different inputs used for ABCD



Results for dark photon model



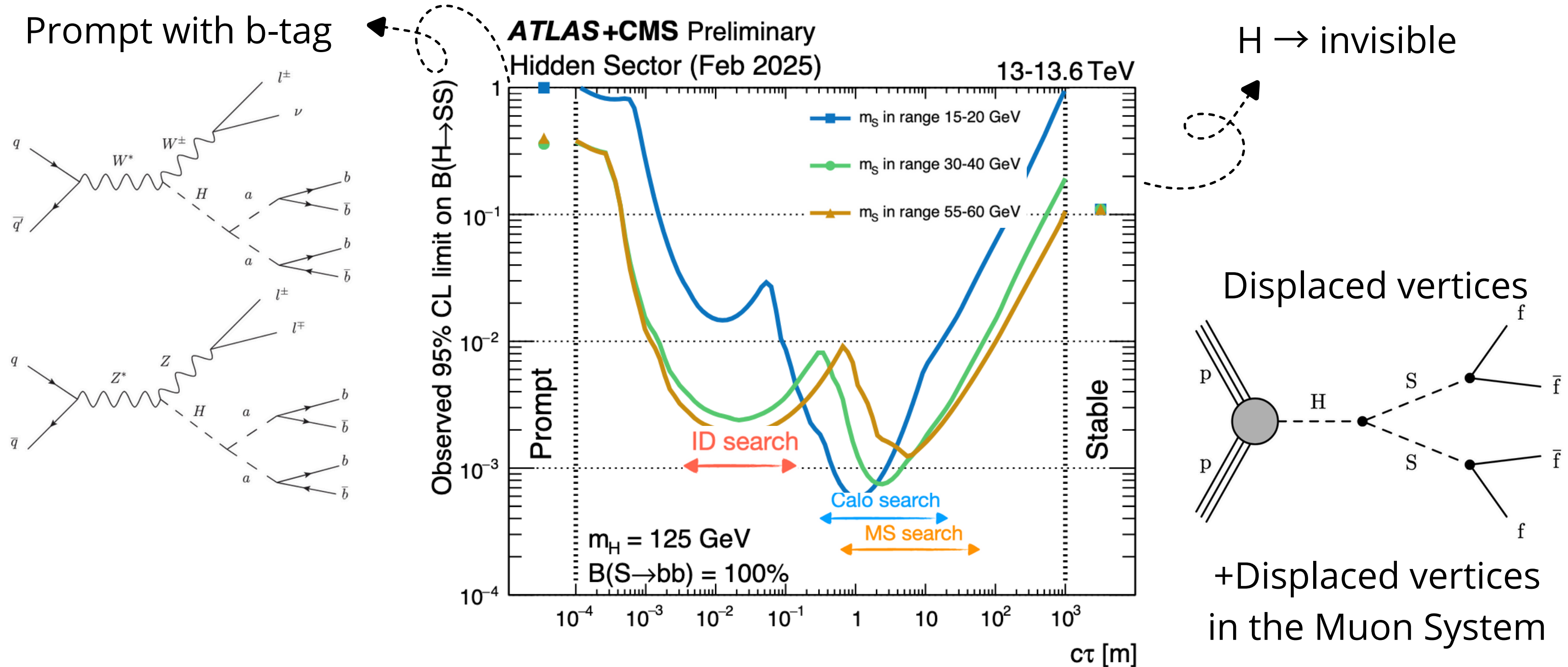
Results for Higgs to scalars model

Higgs to scalar particles



LHC best: **ATLAS** + **CMS** [ATL-COM-PHYS-2025-002](#)

Summary plot for Higgs boson mediated hidden sector involving Long Lived Particles

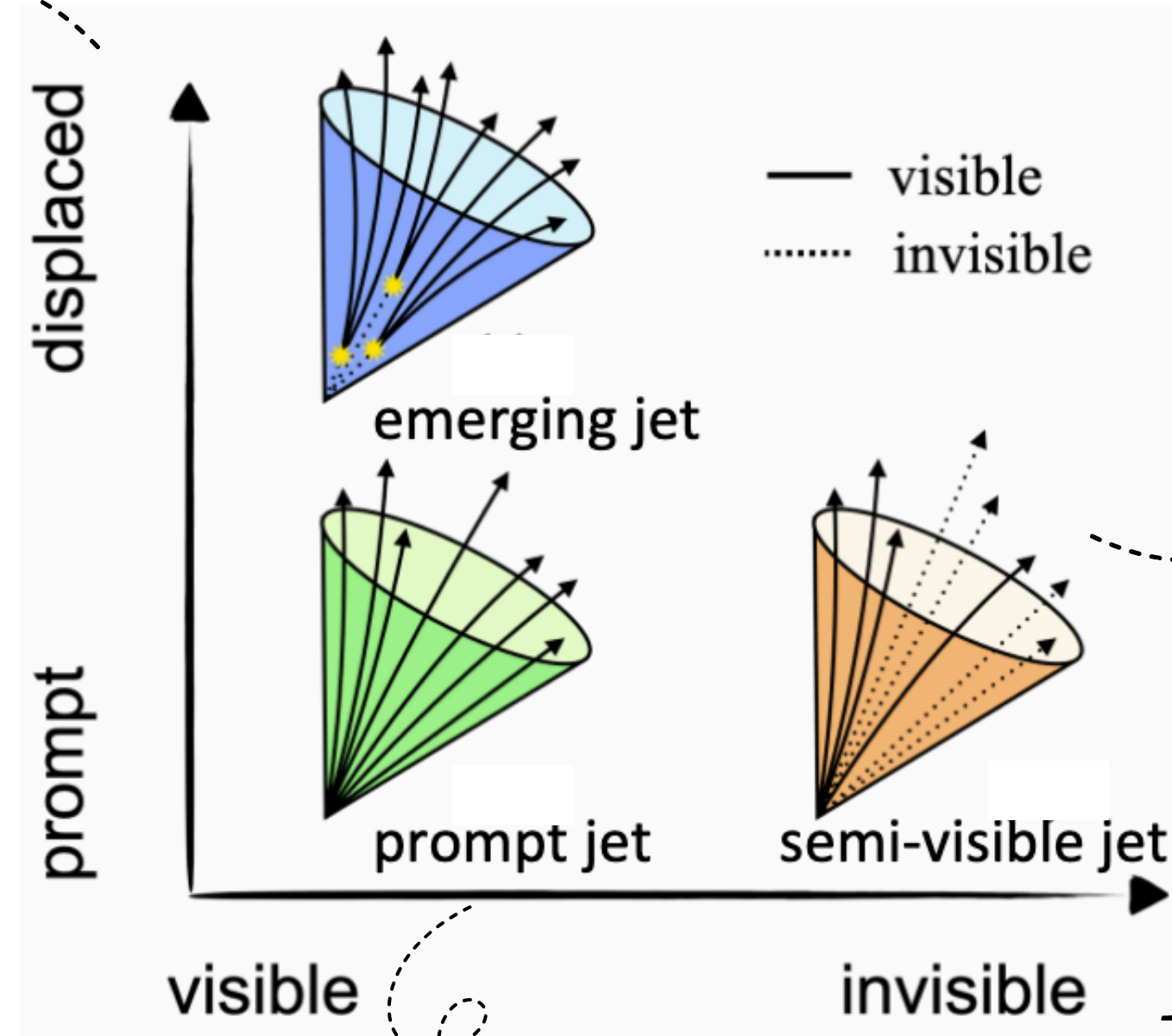
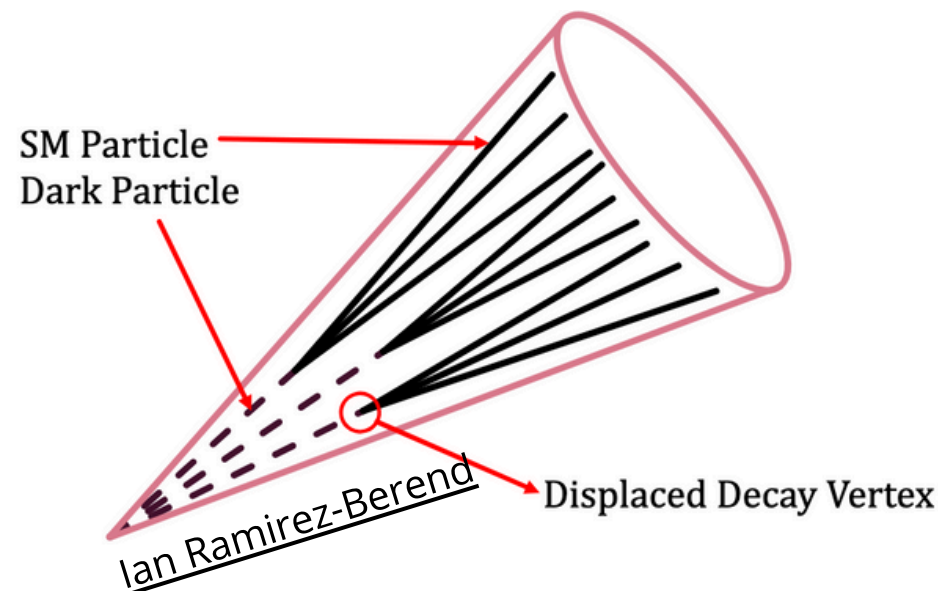


Dark jets

A variety of signatures

Emerging jets

dark quarks hadronize into LL dark hadrons decaying to SM
signature: charged tracks appearing at displaced vertices ✨



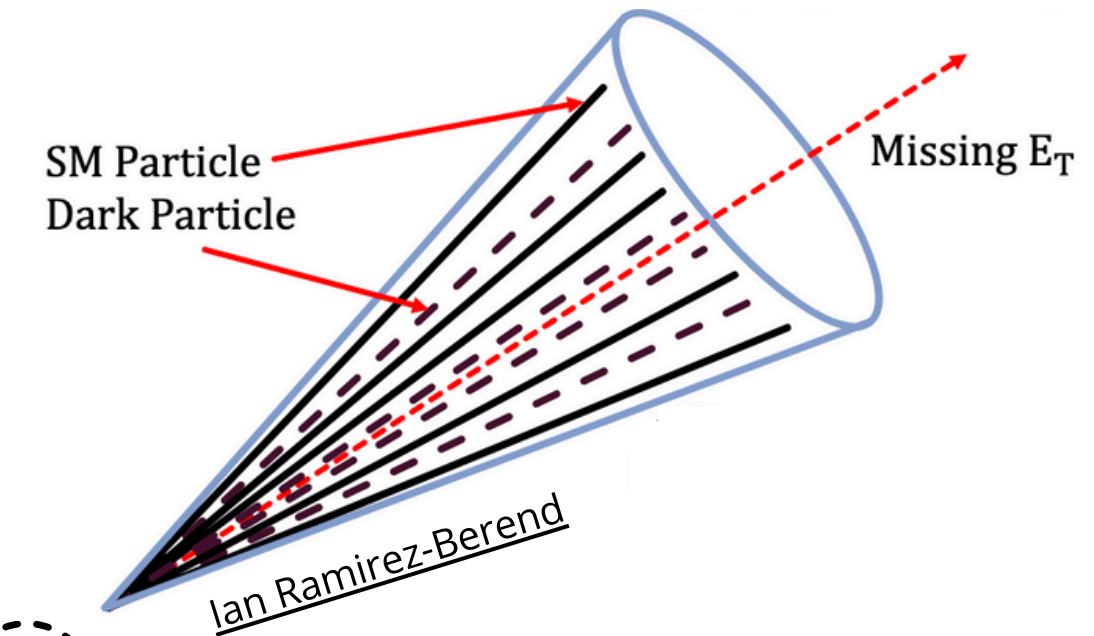
Dark jets

dark quarks hadronize into dark hadrons promptly decaying to SM

Semi Visible jets

dark quarks hadronize into dark hadrons promptly decaying to SM + stable dark hadrons 🤖

signature: p_T^{miss} along the jet axis



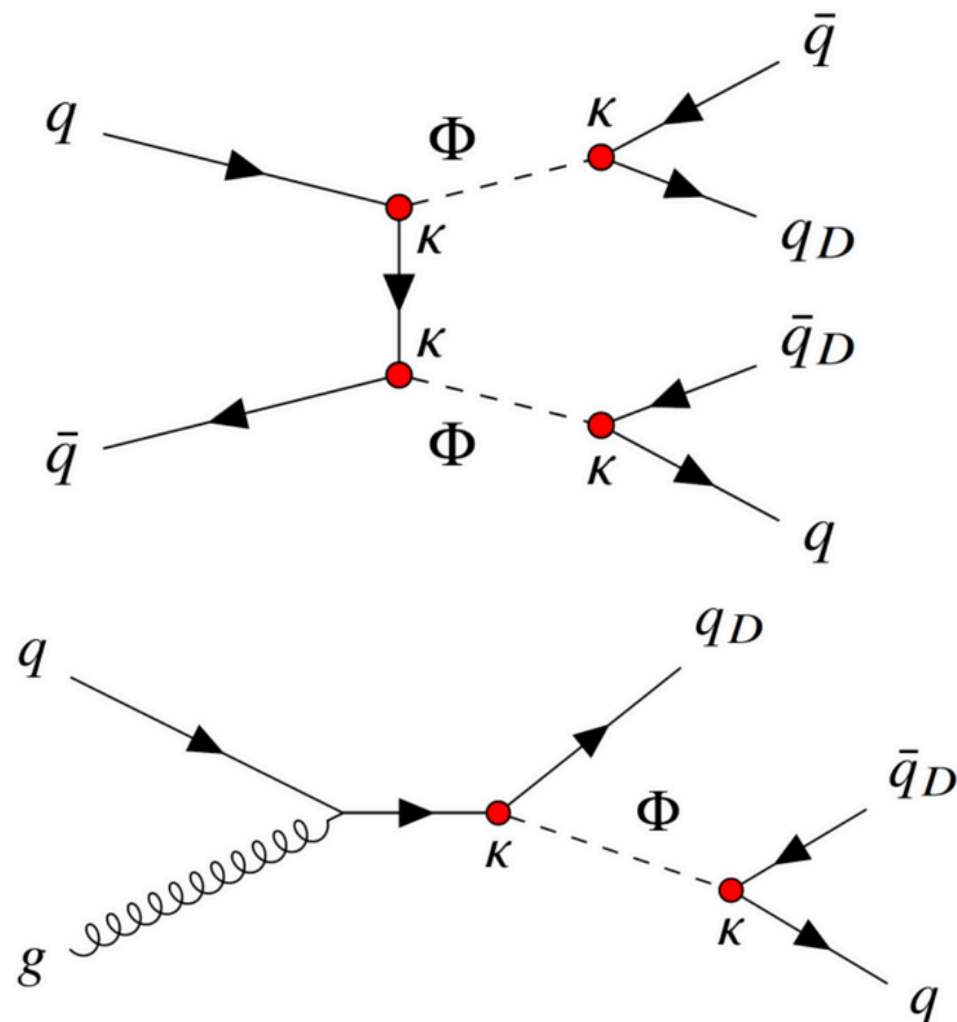
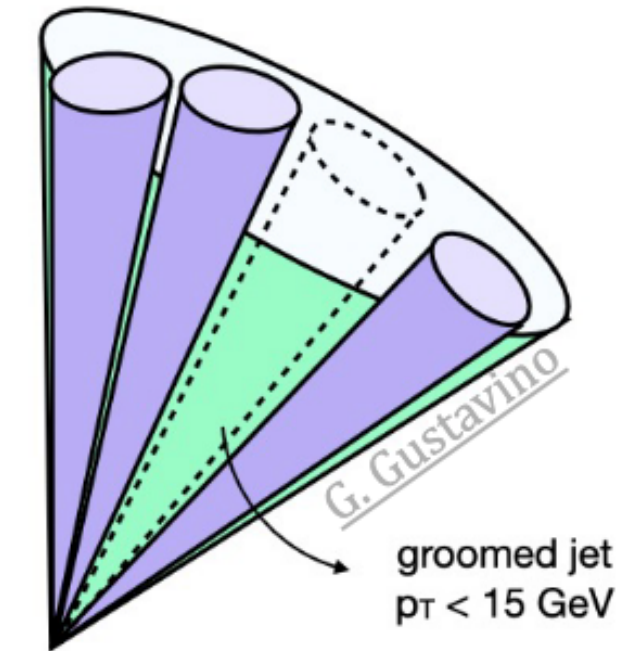
R_{inv}

R_{inv} encodes the fraction of invisible particles produced in the dark jet hadronization

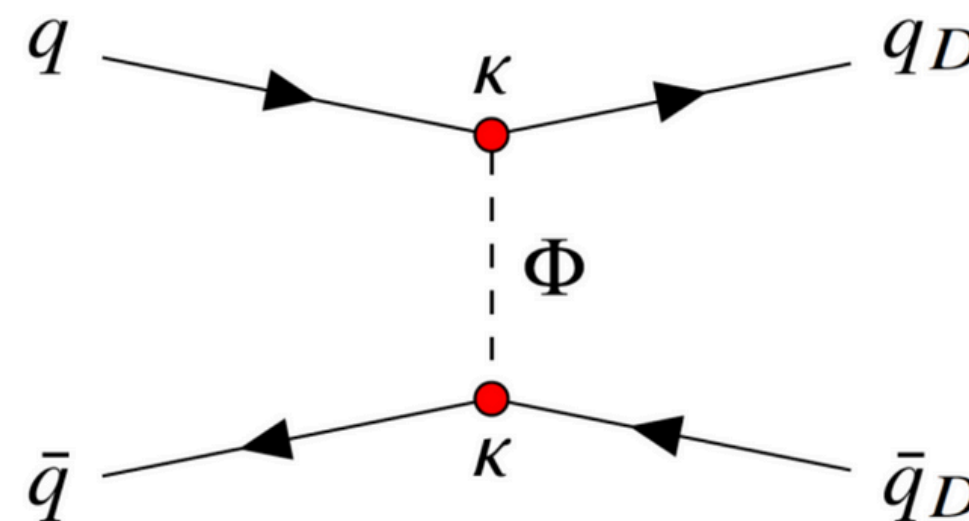
Emerging jets



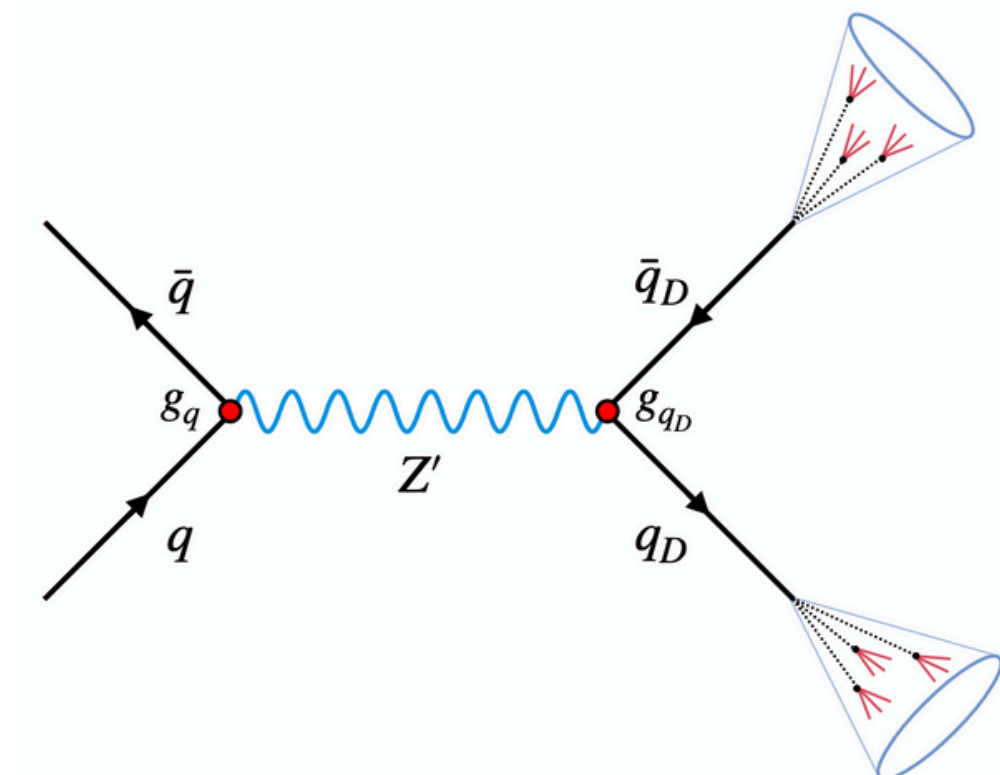
- Jets undergo a 2-stage showering process (dark sector + SM), $\Delta R = 1.0$
 - Anti-kT with $R=1.0$ for large jets
 - Anti-kT with $R=0.4$ using uncalibrated cells for small jets $\Delta R = 0.4$
 - Reclustering of small jets with $p_T > 15$ GeV in large jets
- Final state: 2 large jets and high multiplicity of secondary vertices



t-channel



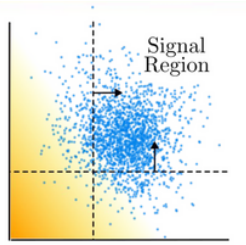
s-channel



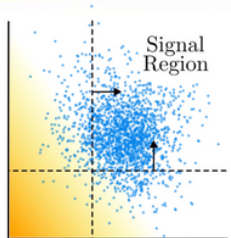
Emerging jets



- 2 strategies: cut-based and ML-based
- 2 regions: low m_{jj} (< 1 TeV) and high m_{jj} (> 1 TeV)

	 Cut-based analysis	 ML-based analysis
Trigger low m_{jj}	new dedicated trigger introduced in Run3! $N_{jet} \geq 1, p_T > 200 \text{ GeV}, \eta < 1.8, \text{PTF} < 0.08 \left(\text{PTF} = \frac{\sum_{\text{trk} \subseteq \Delta R < 1.2} p_T^{\text{trk}}}{p_T^{\text{jet}}} \right)$ Prompt Track Fraction	
Trigger high m_{jj}	$N_{jet} \geq 1, p_T > 460 \text{ GeV}$	
Bkg estimation	ABCD method	jet mistag rate method

Emerging jets

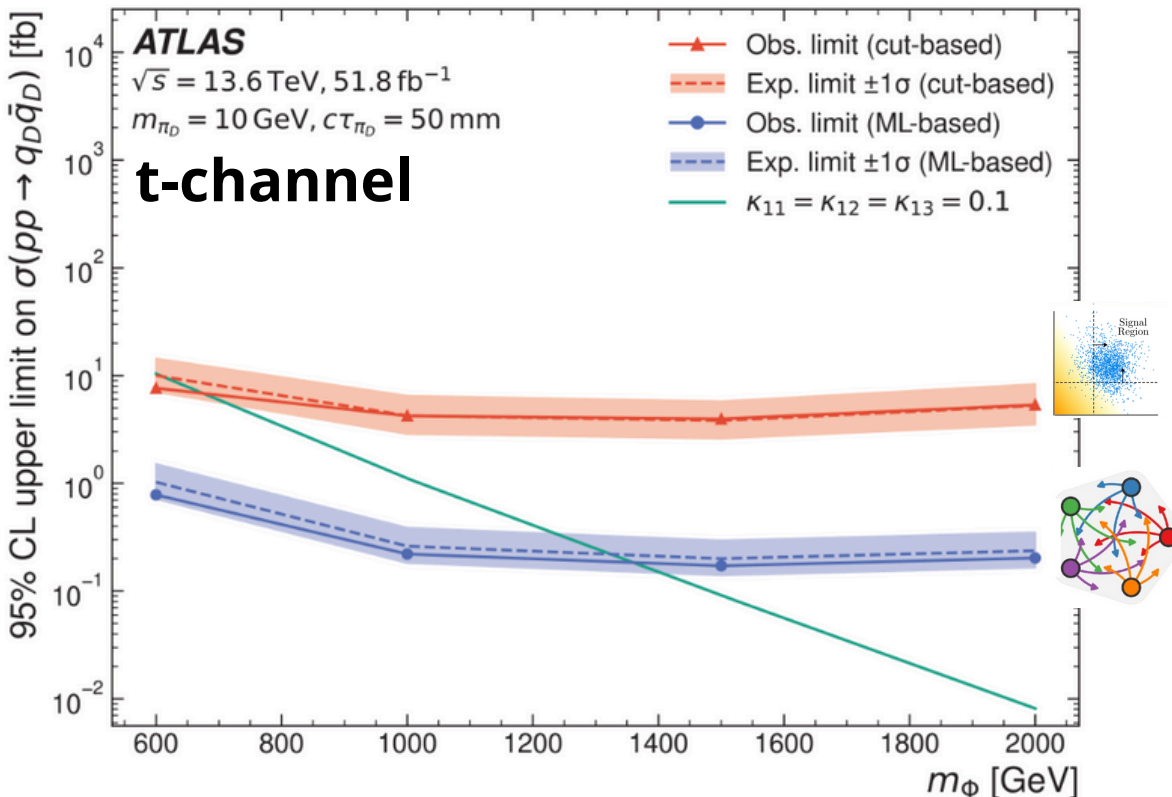
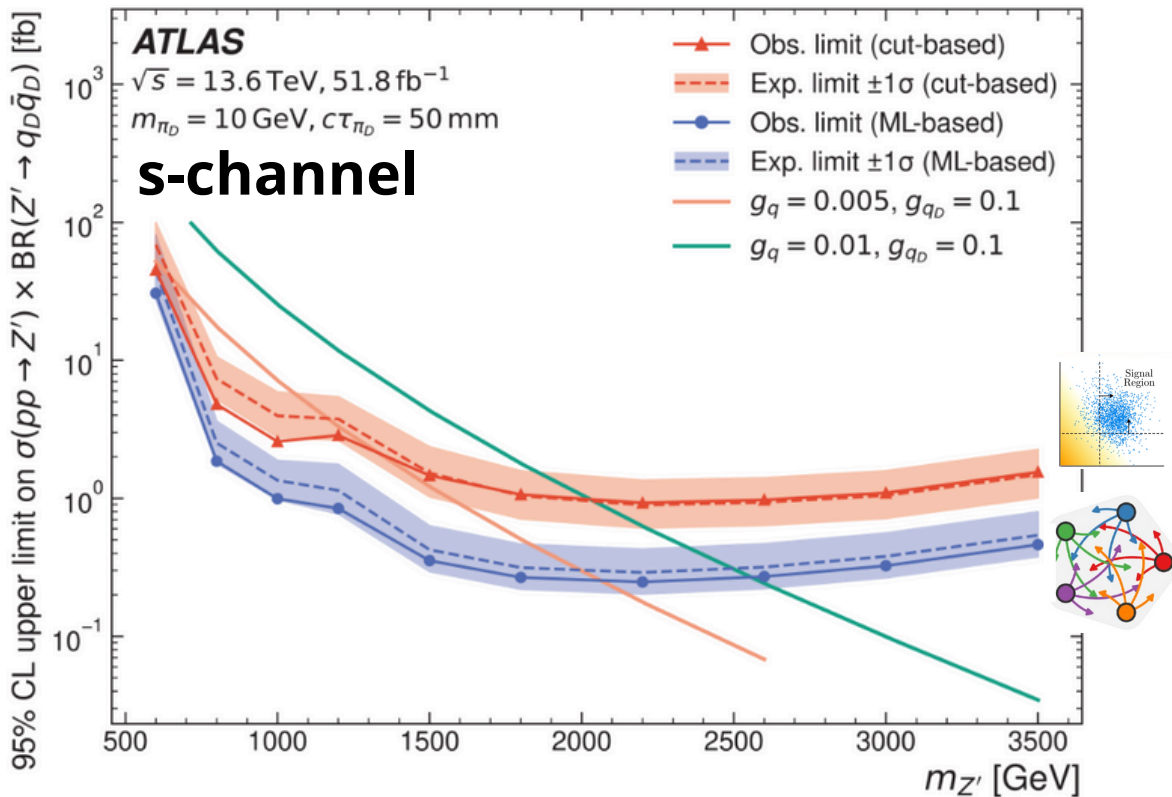


Cut-based analysis

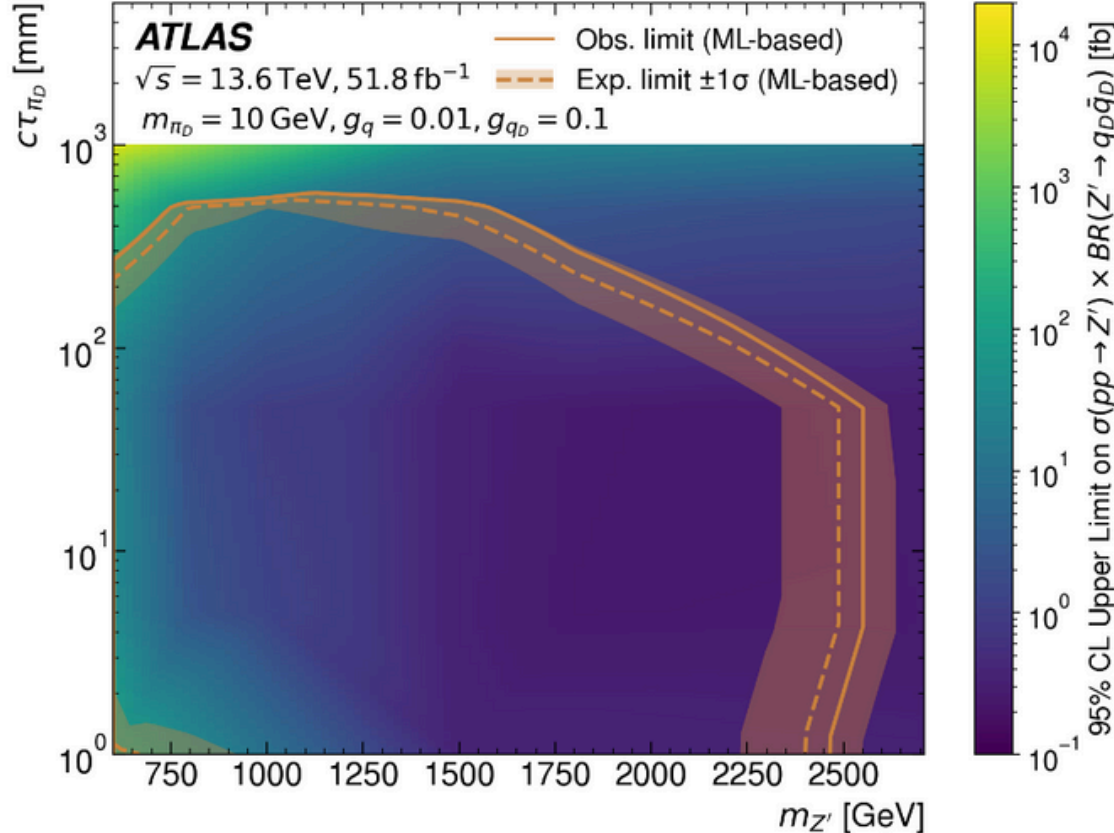
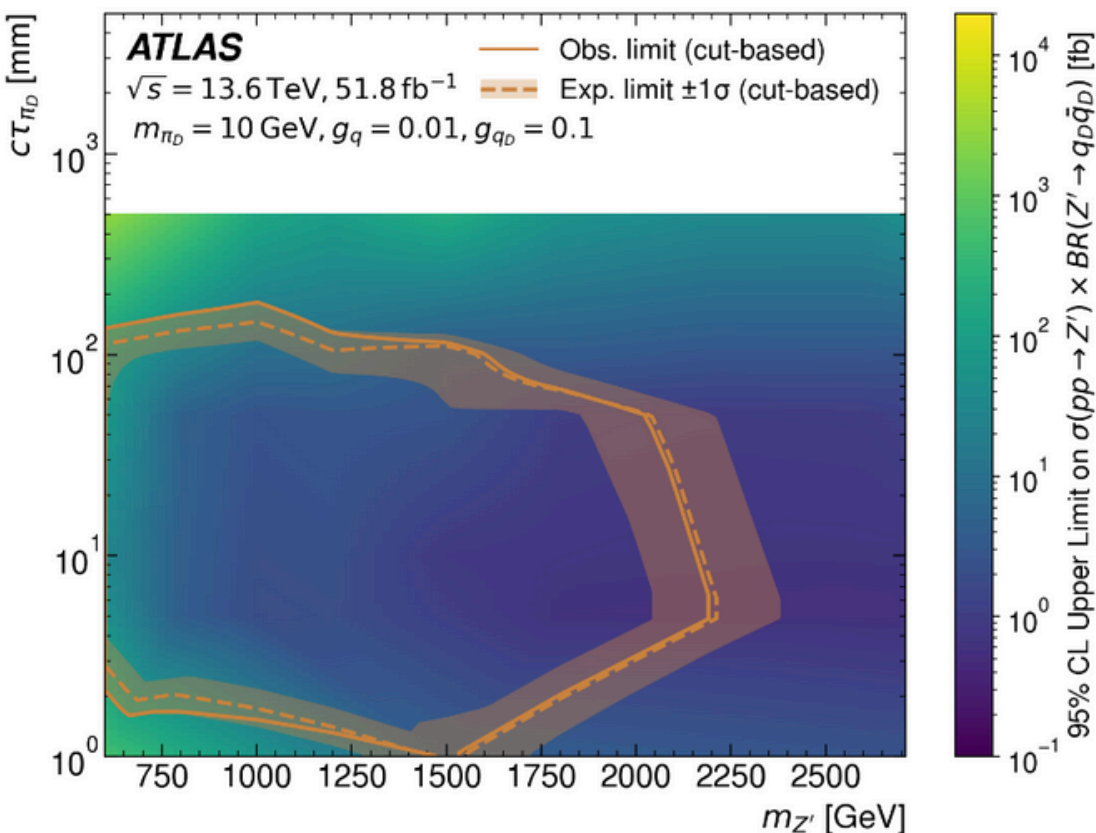


[Rep. Prog. Phys. 88 \(2025\) 097801](#) at **ATLAS**
ML-based analysis

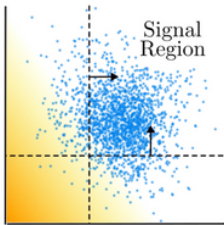
95% upper limit



Excluded
pion lifetimes
and Z' masses



Emerging jets

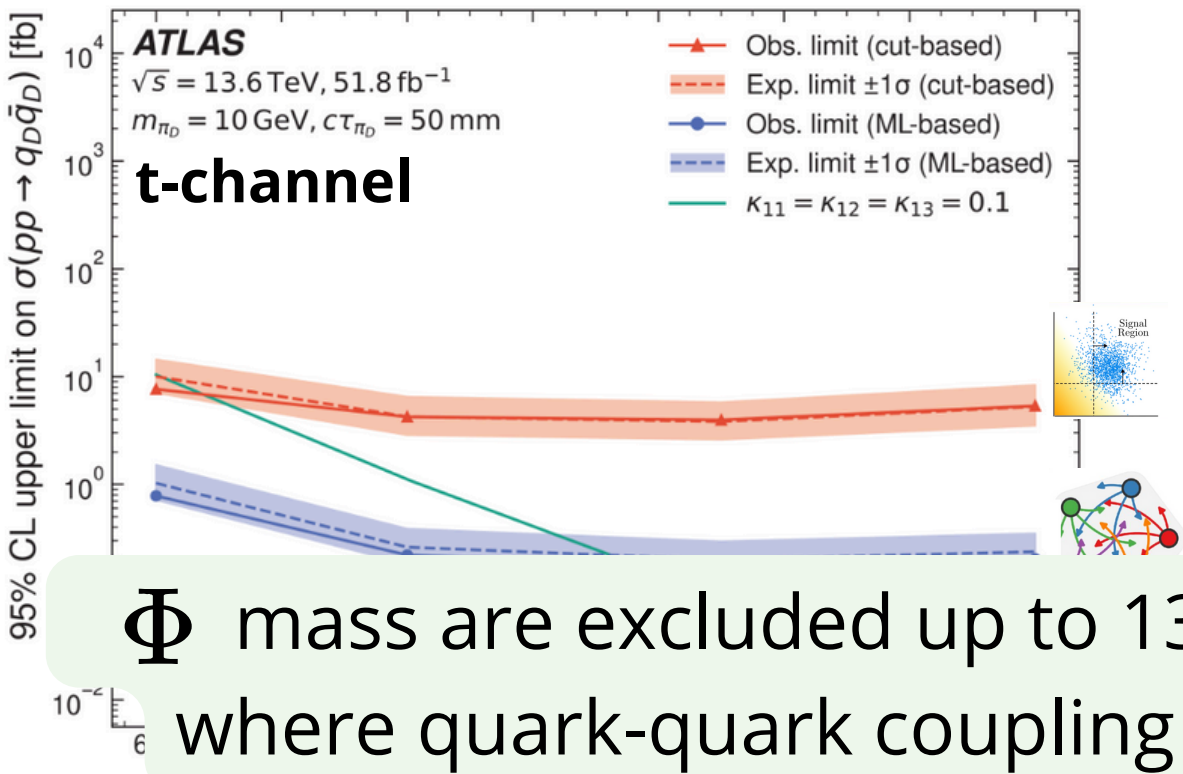
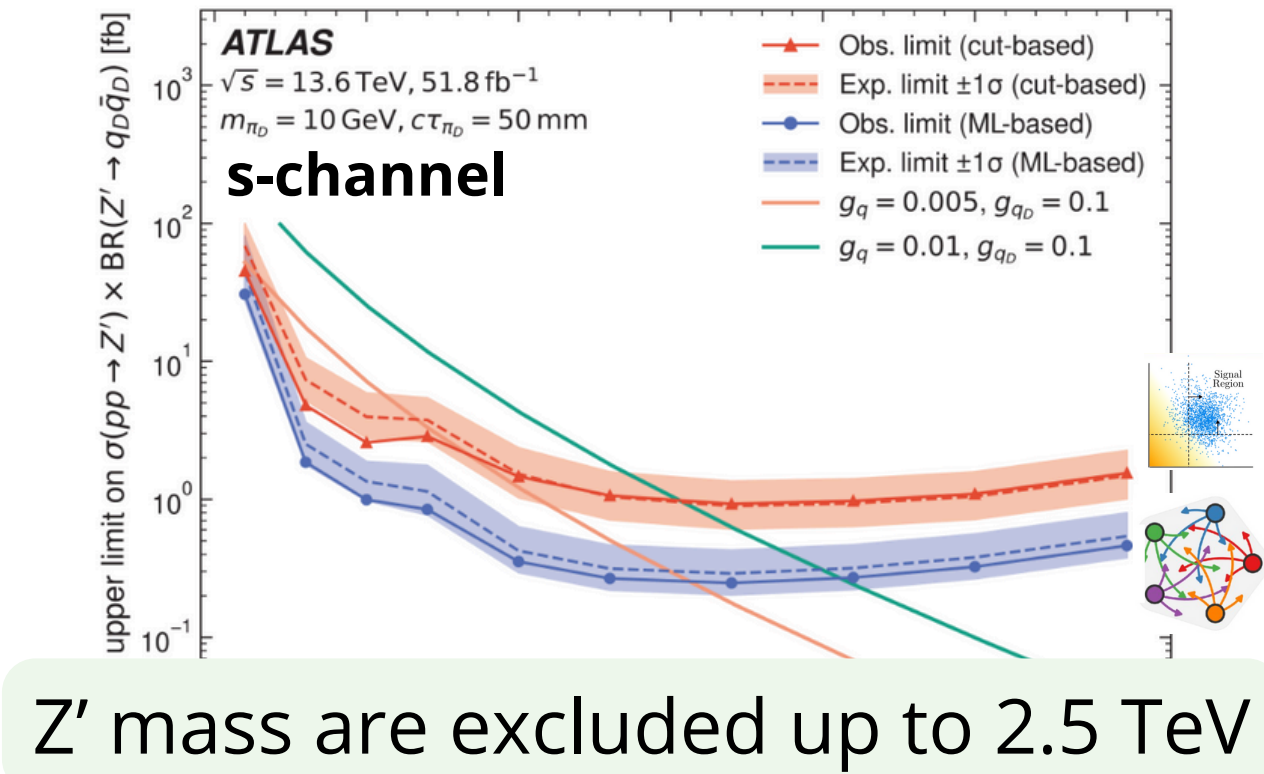


Cut-based analysis

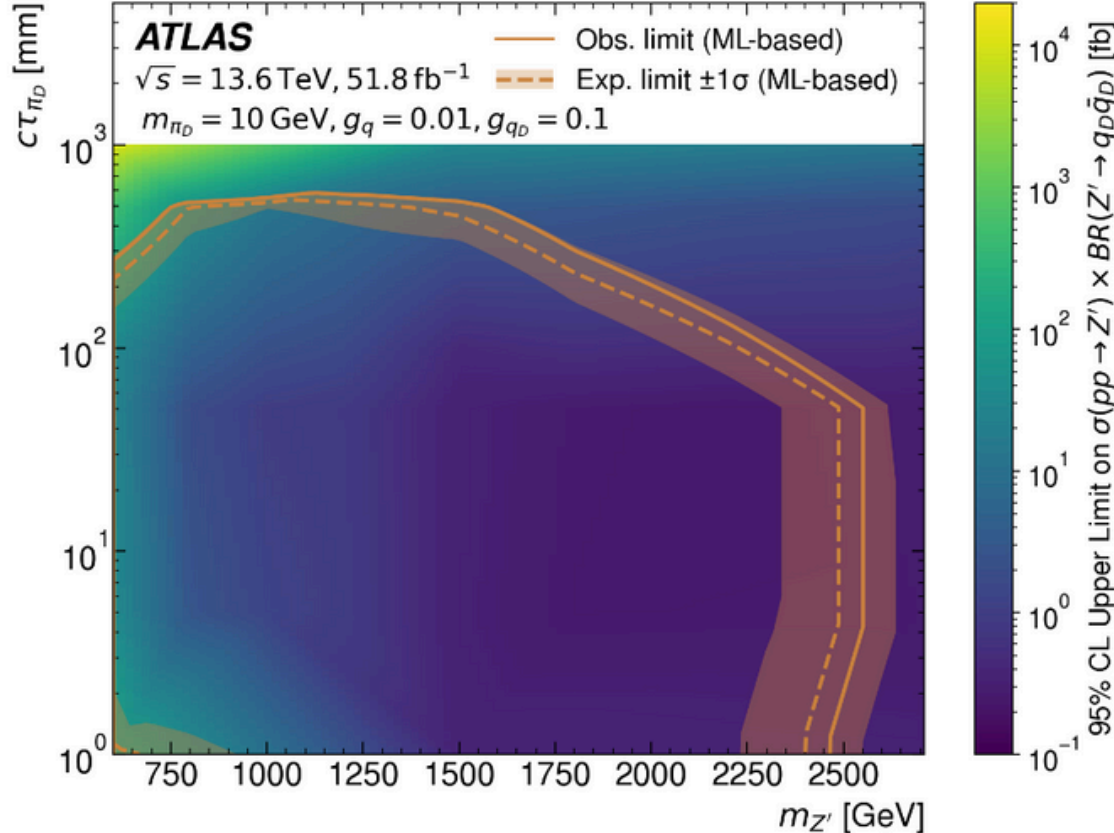
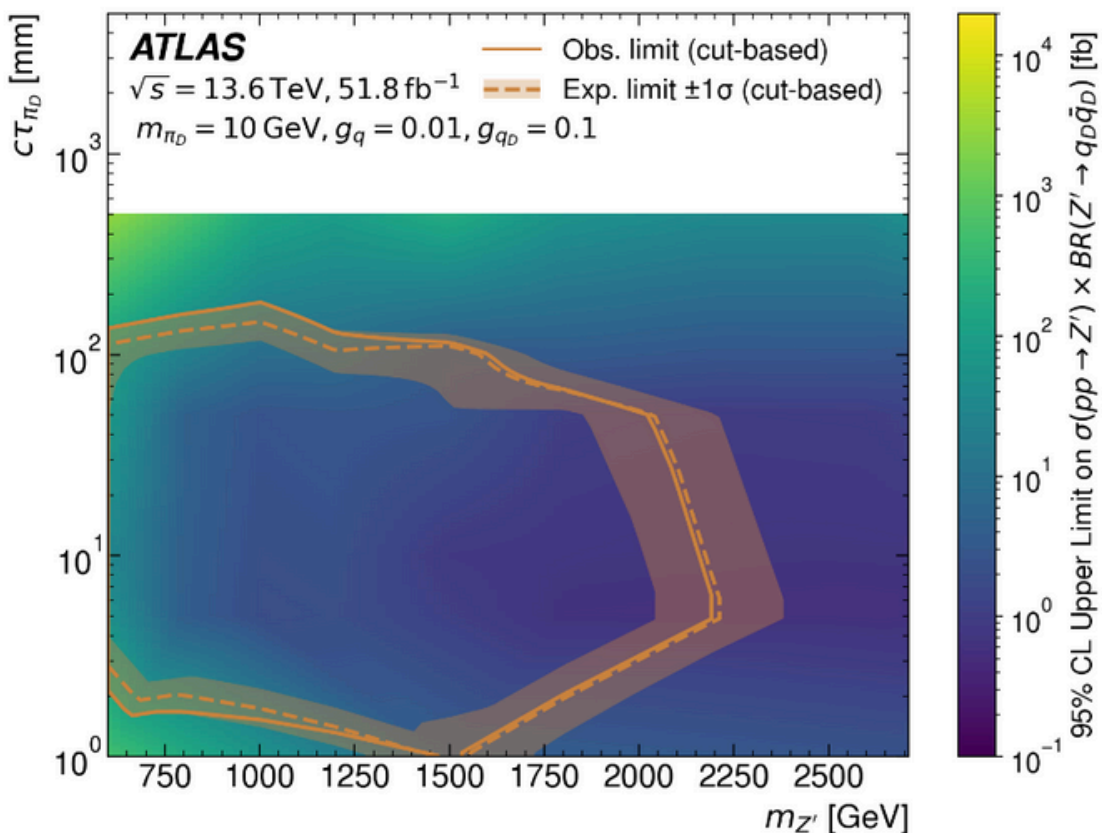


ML-based analysis

95% upper limit



Excluded pion lifetimes and Z' masses



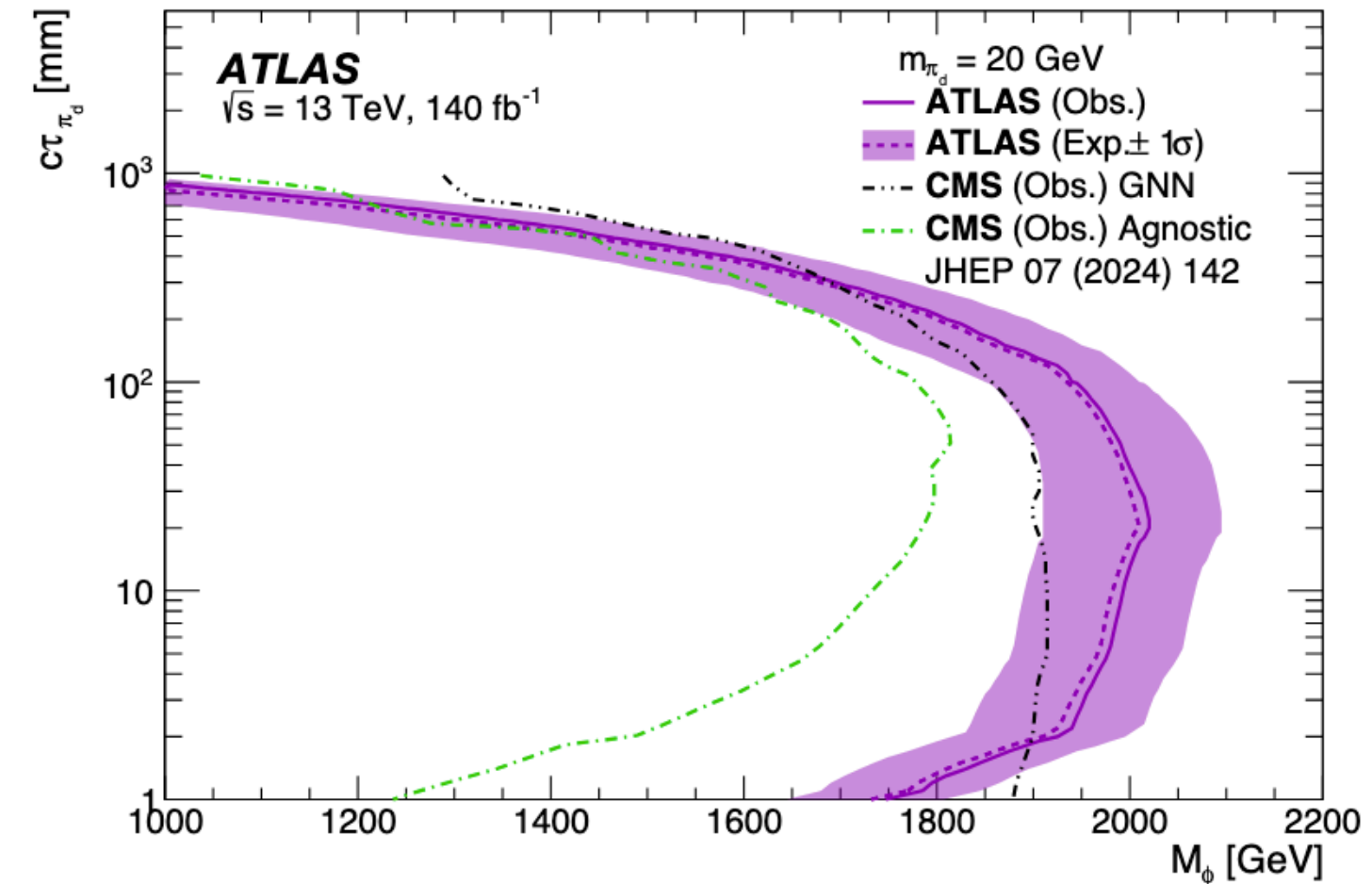
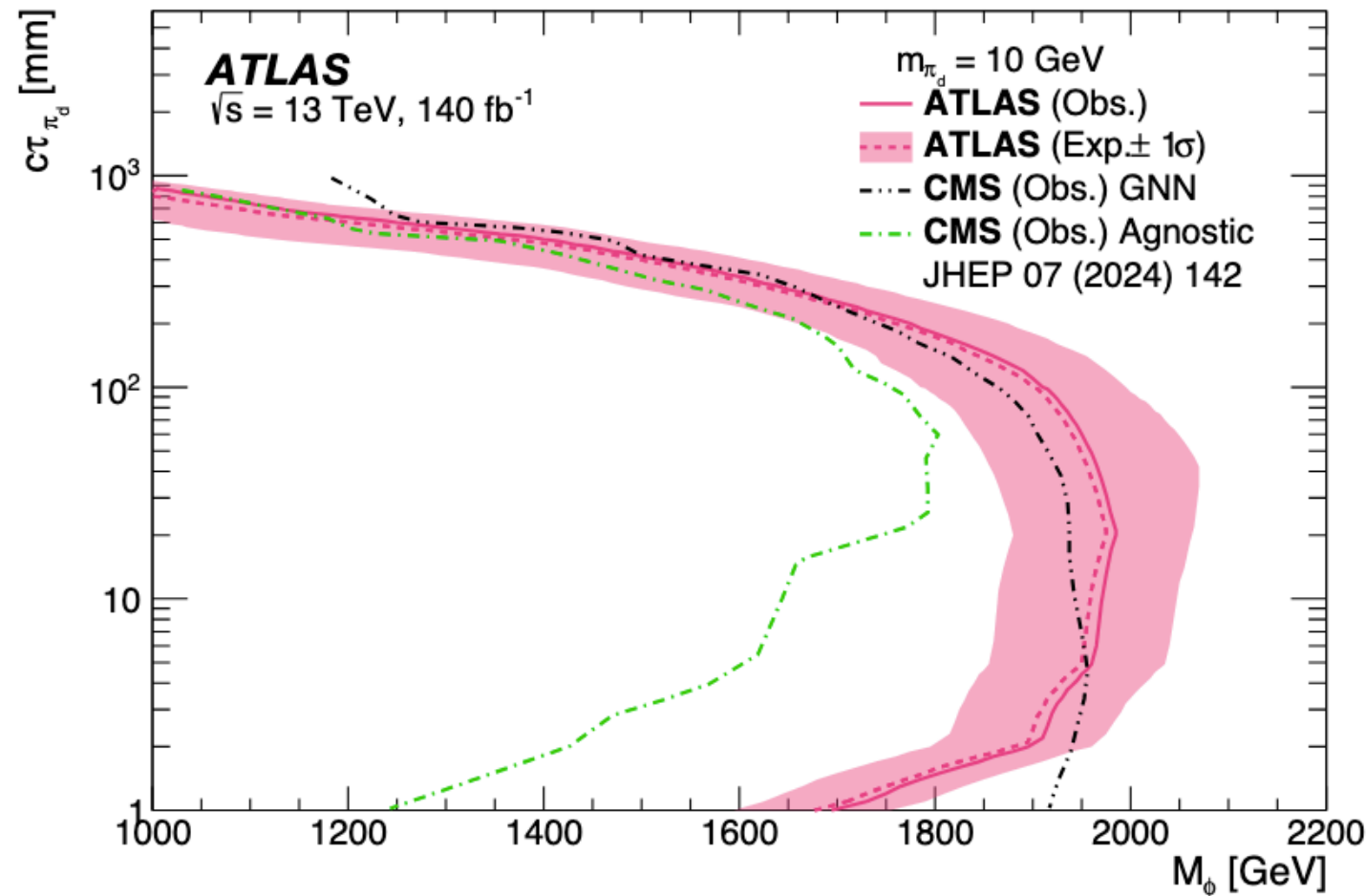
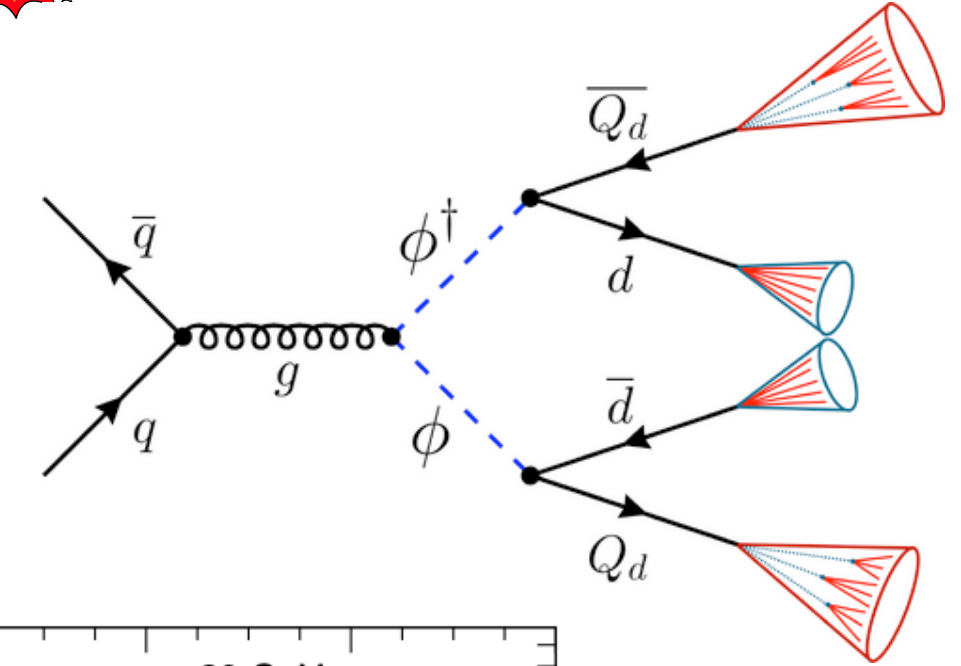
Emerging jets

- Recent result in ATLAS also using Run 2 dataset
- Signature: 2 emerging jets + 2 SM-jets
- Set limits on decay time and mediator mass



Submitted to: EPJC

at ATLAS



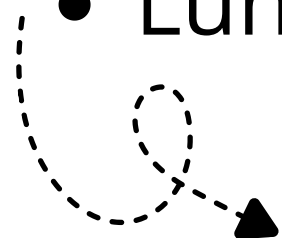
GNN-based **CMS** analysis sets stricter limits at very low and very high proper lifetimes, while **ATLAS** search is more sensitive for intermediate lifetimes (2-300 mm)

Semi Visible jets



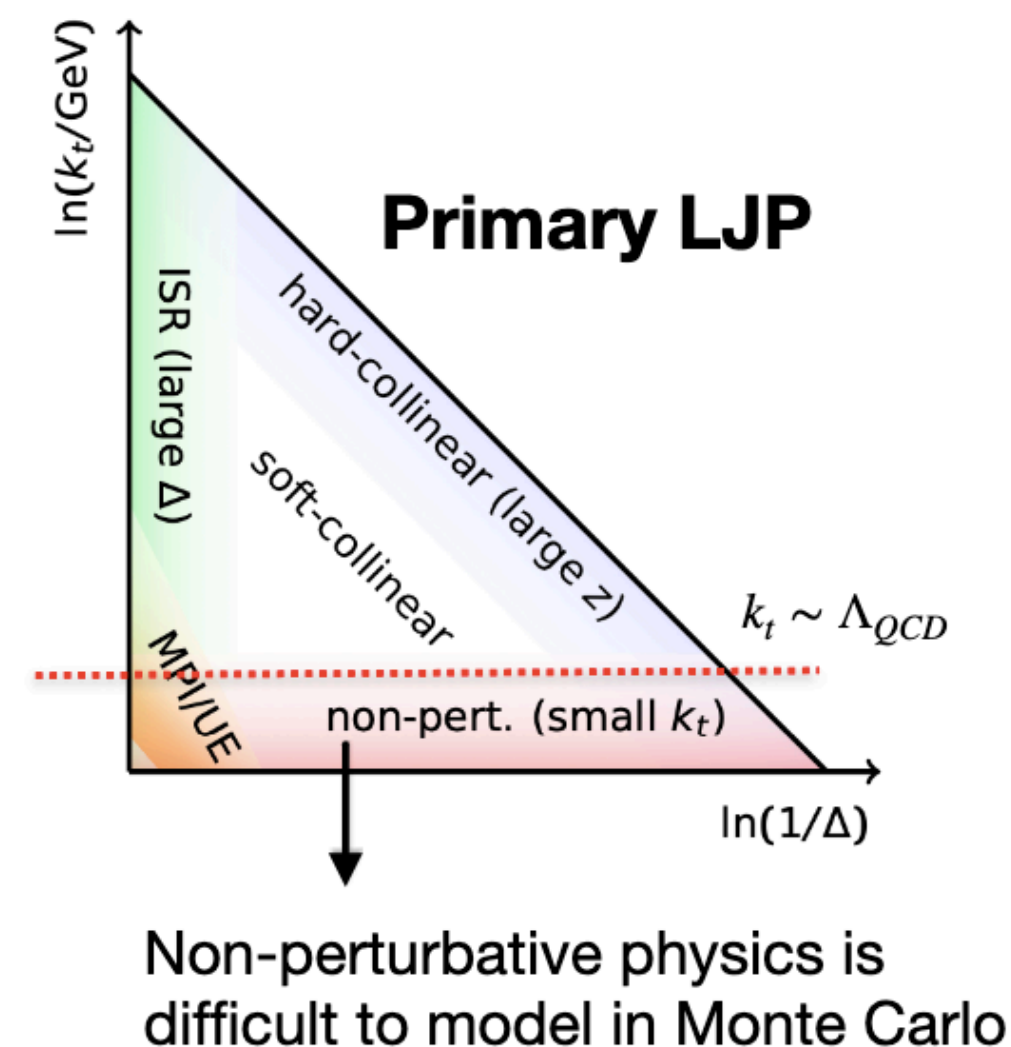
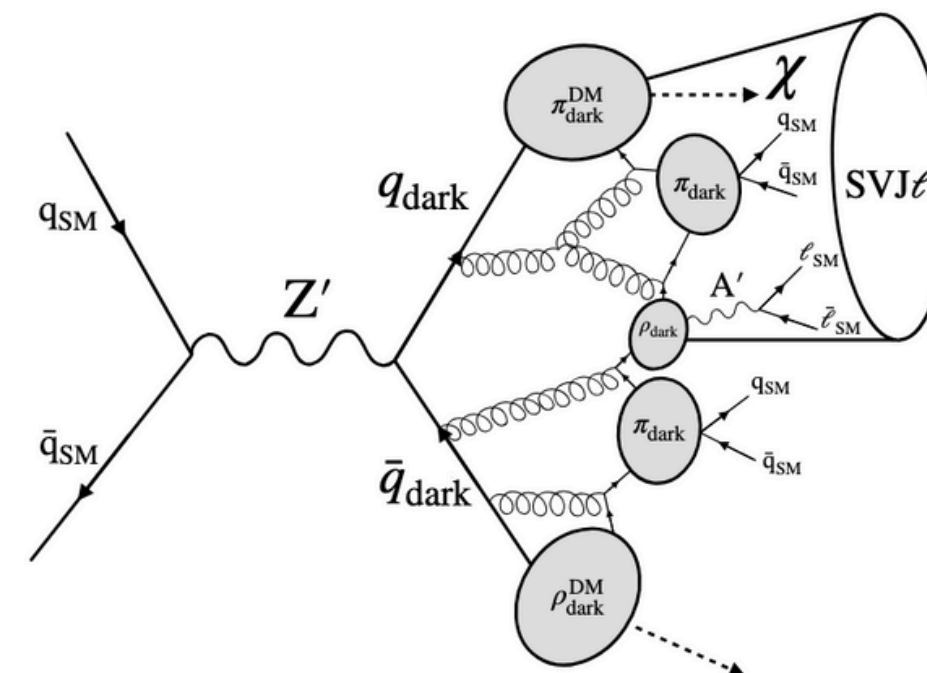
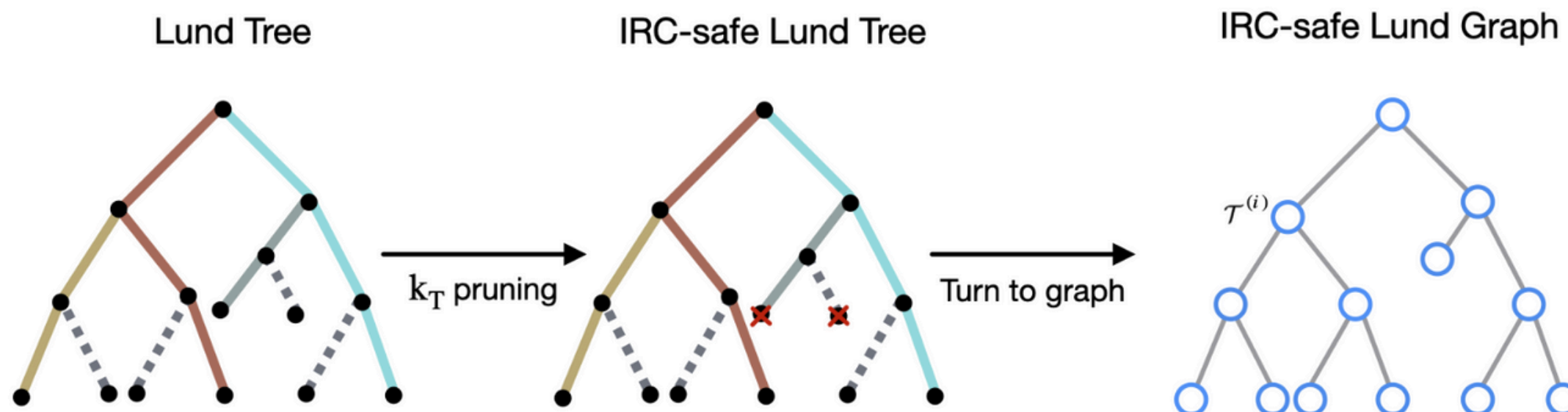
EXO-24-029 at CMS

- Lepton-enriched semivisible jets
- Events triggered by presence of hadronic activity
- LundNet as jet tagging method



- GNN aims to encode parton showering and hadronization underlying jet formation (generalization of the Lund Jet Plane)
- k_T -pruning technique used to remove low- k_T radiation and increase robustness against non-perturbative effects

➡ IRC-safe Lund graph



Semi Visible jets

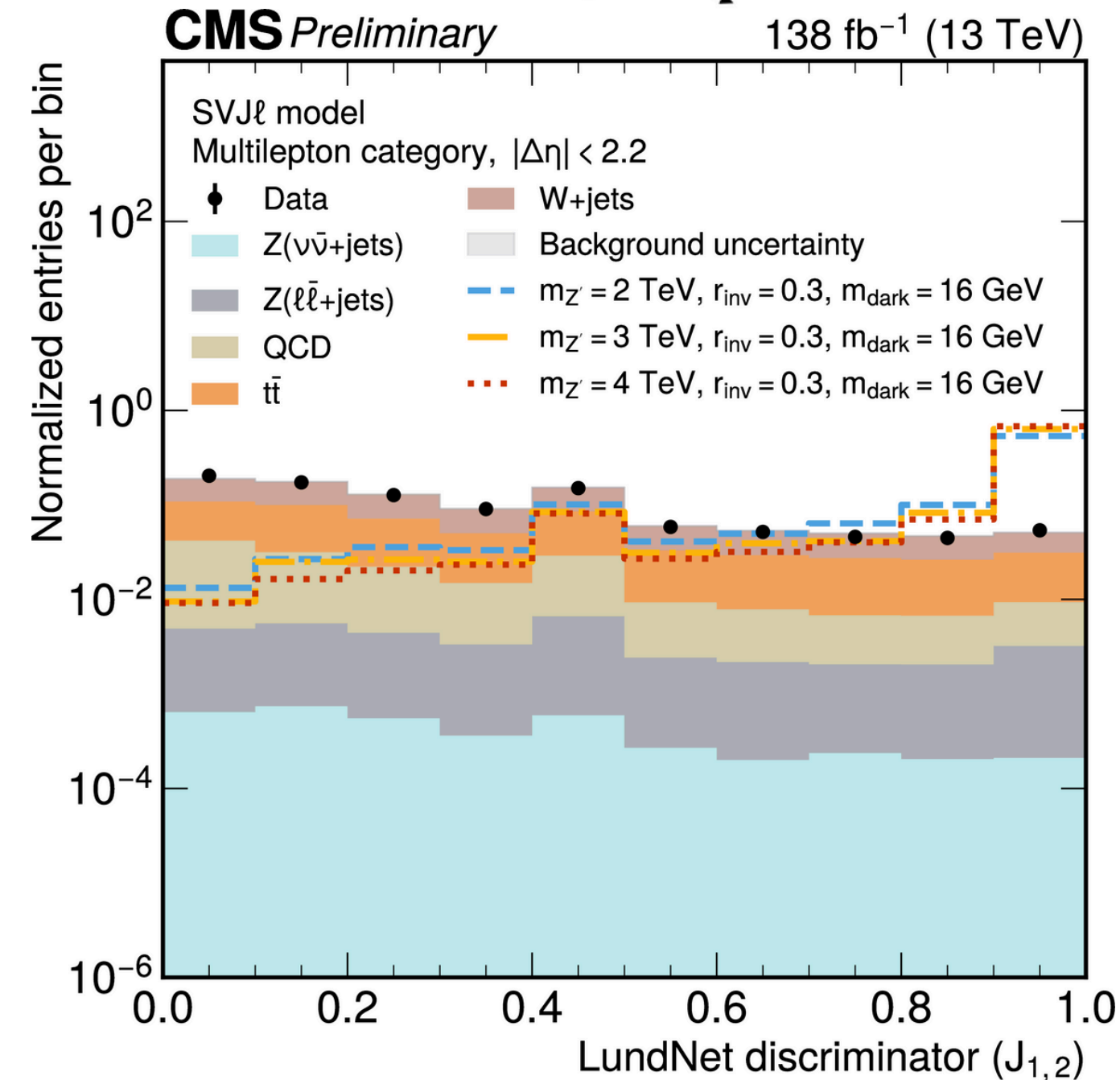
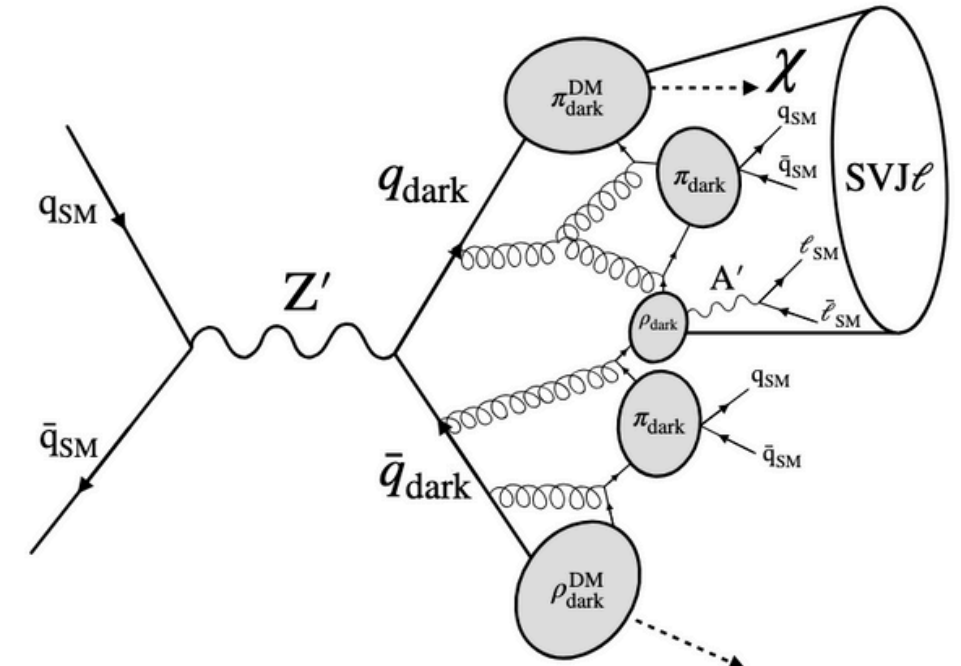
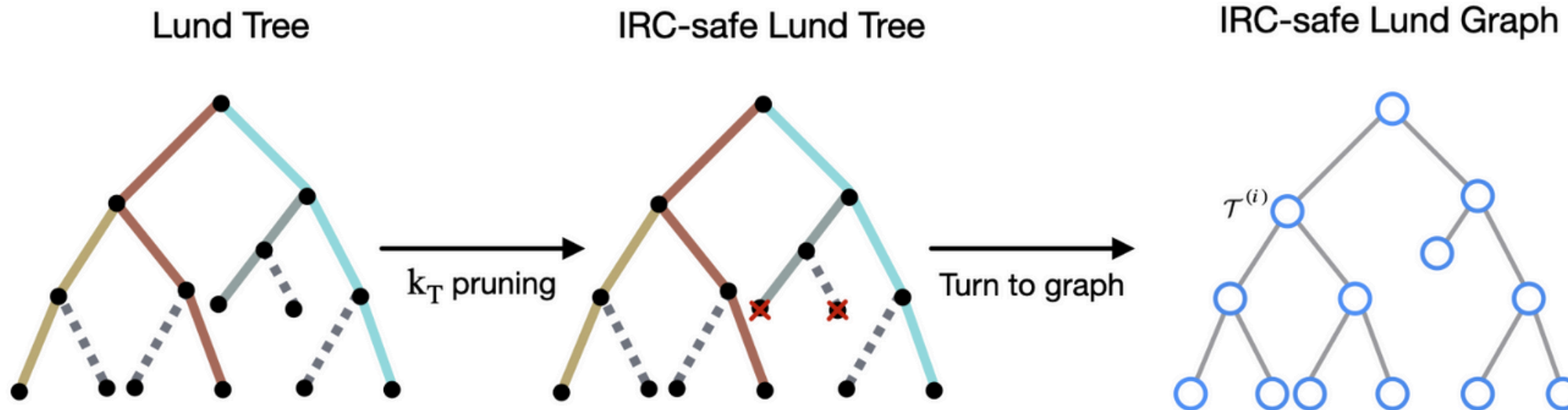


EXO-24-029 at CMS

- Lepton-enriched semivisible jets
- Events triggered by presence of hadronic activity
- LundNet as jet tagging method

- GNN aims to encode parton showering and hadronization underlying jet formation (generalization of the Lund Jet Plane)
- k_T -pruning technique used to remove low- k_T radiation and increase robustness against non-perturbative effects

→ IRC-safe Lund graph



Semi Visible jets

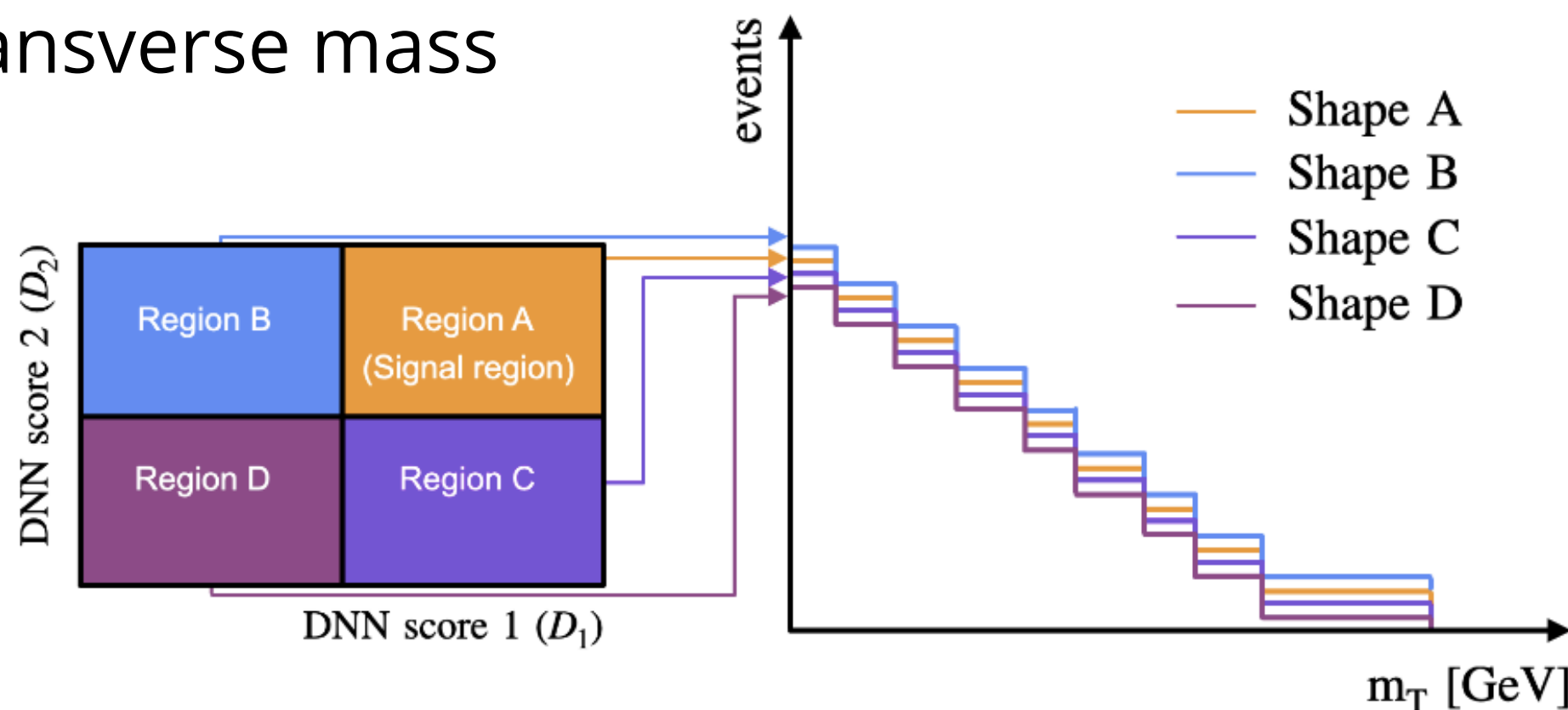


EXO-24-029 at CMS

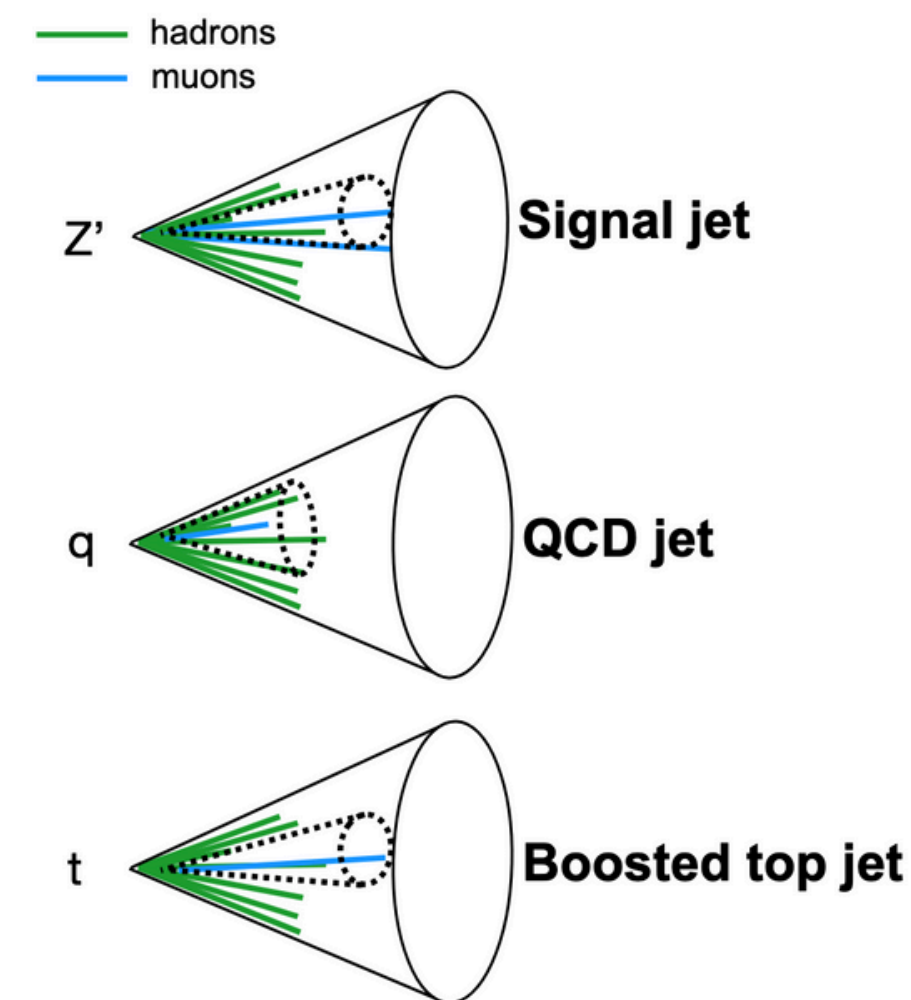
- Lepton-enriched semivisible jets
- Events triggered by presence of hadronic activity
- LundNet as jet tagging method → GNN score
- ML-based ABCD method for background estimation

DNNs optimization

- inputs: event-level features + GNN score for 2 hardest jets
- DNNs scores used for ABCD method in bins of dijet transverse mass



To distinguish background we need to look inside jets!



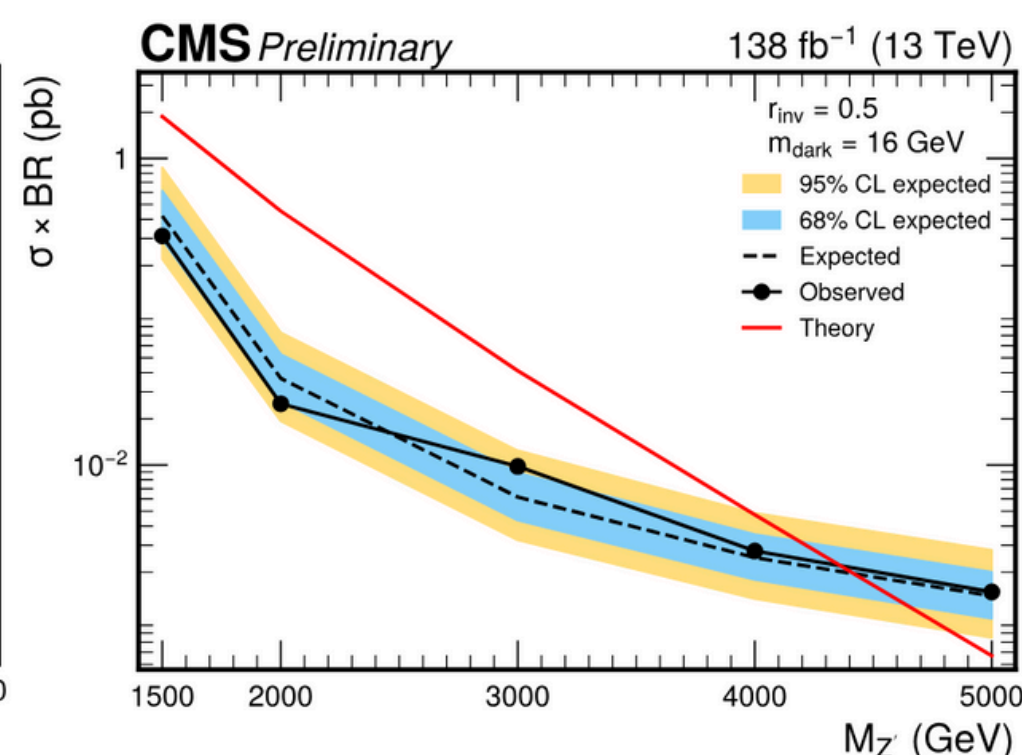
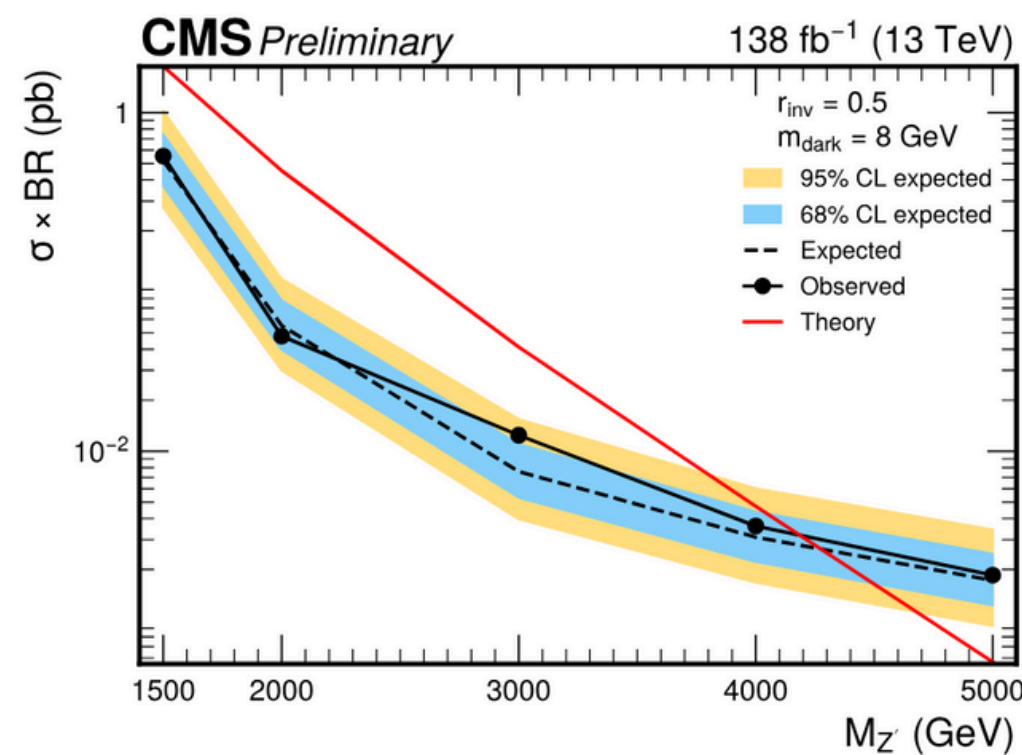
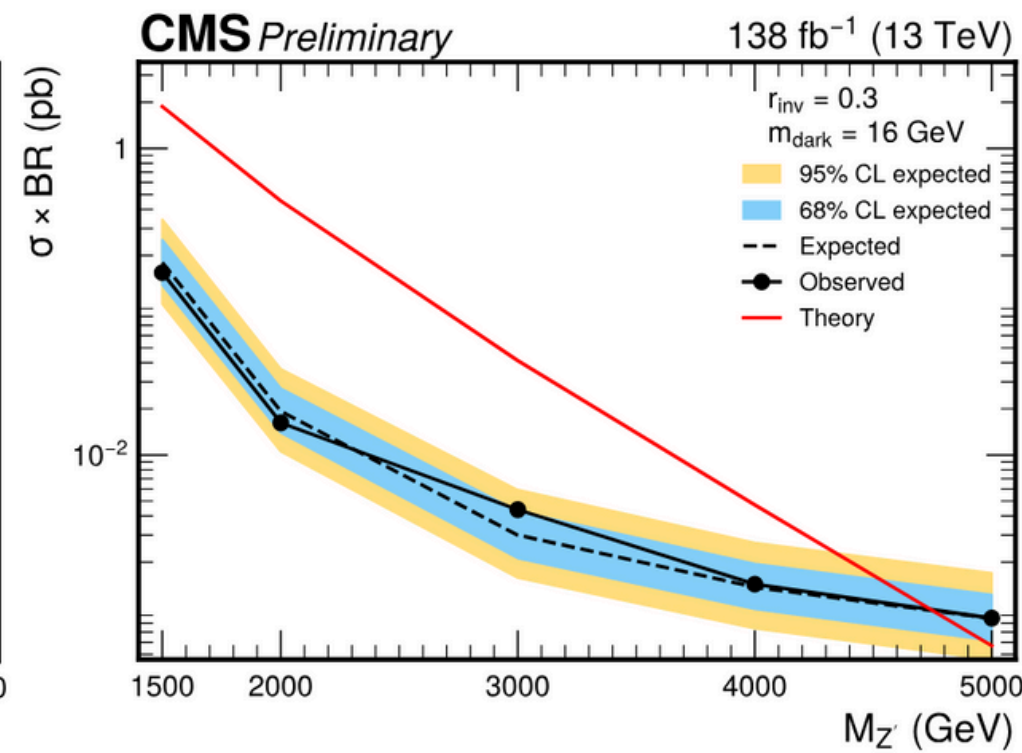
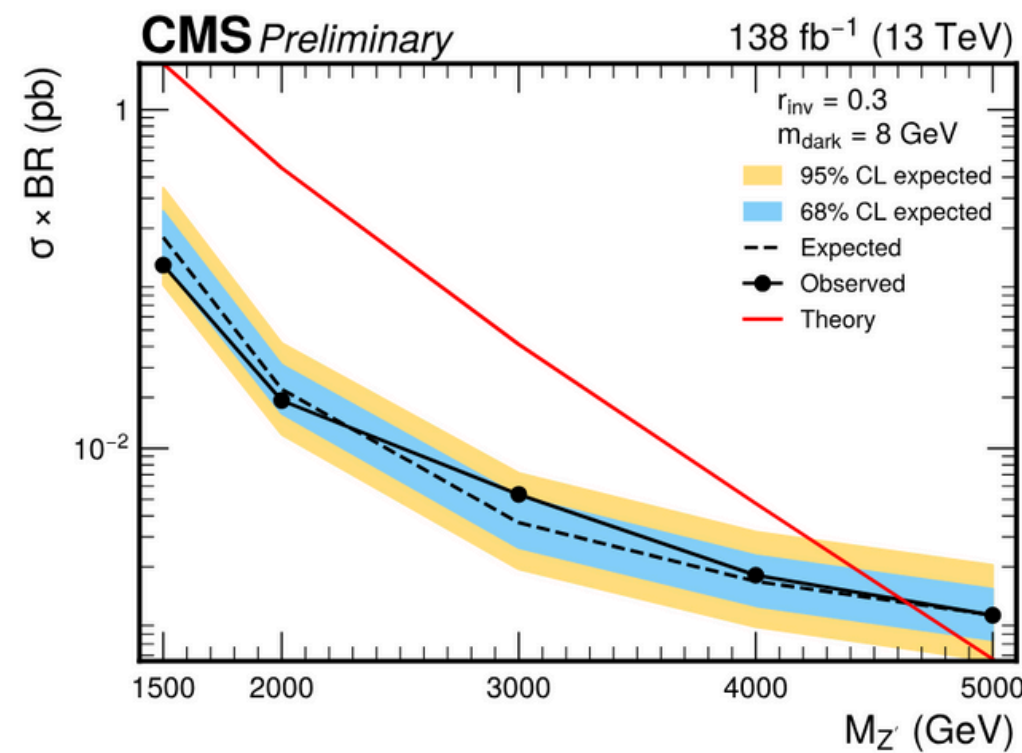
Semi Visible jets



EXO-24-029 at CMS

Exclude wide variety of signals!

m_{dark}



Analysis selection
optimised for low r_{inv}

r_{inv}

Dark Higgs

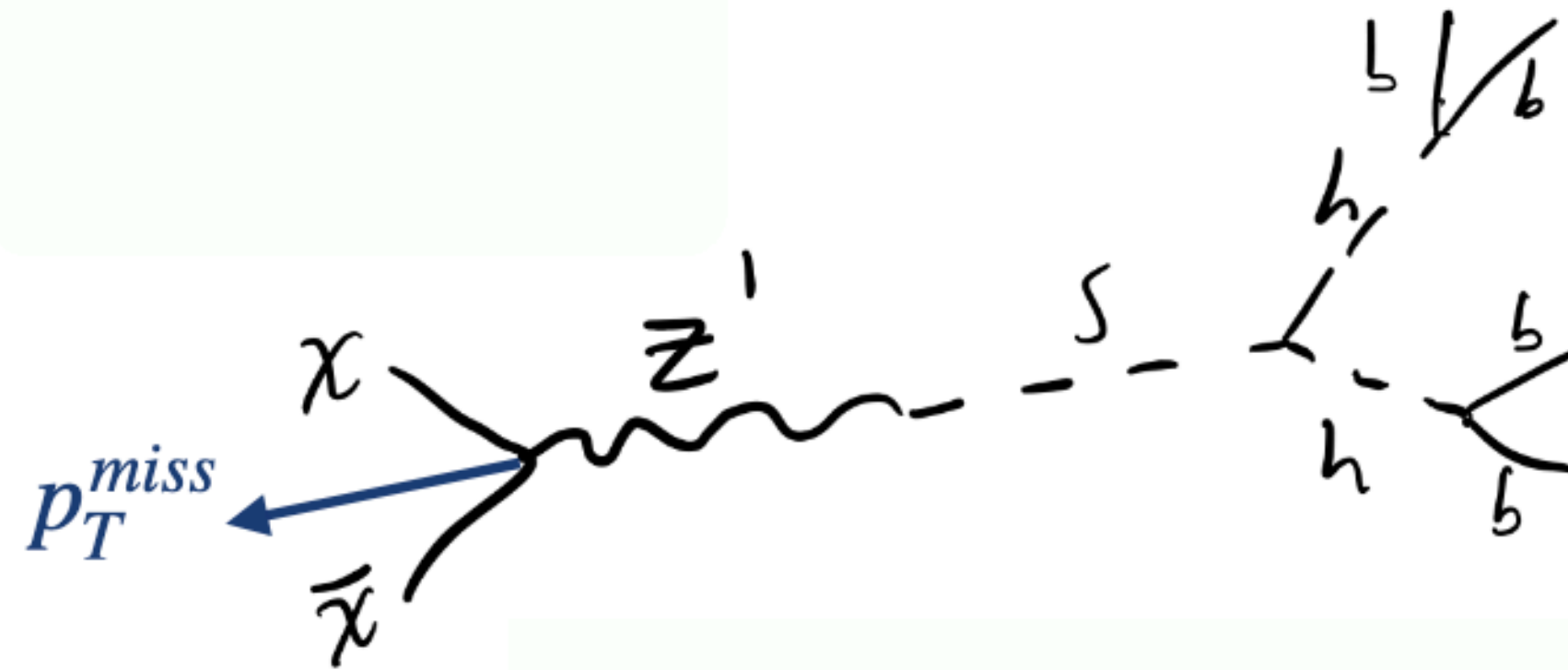
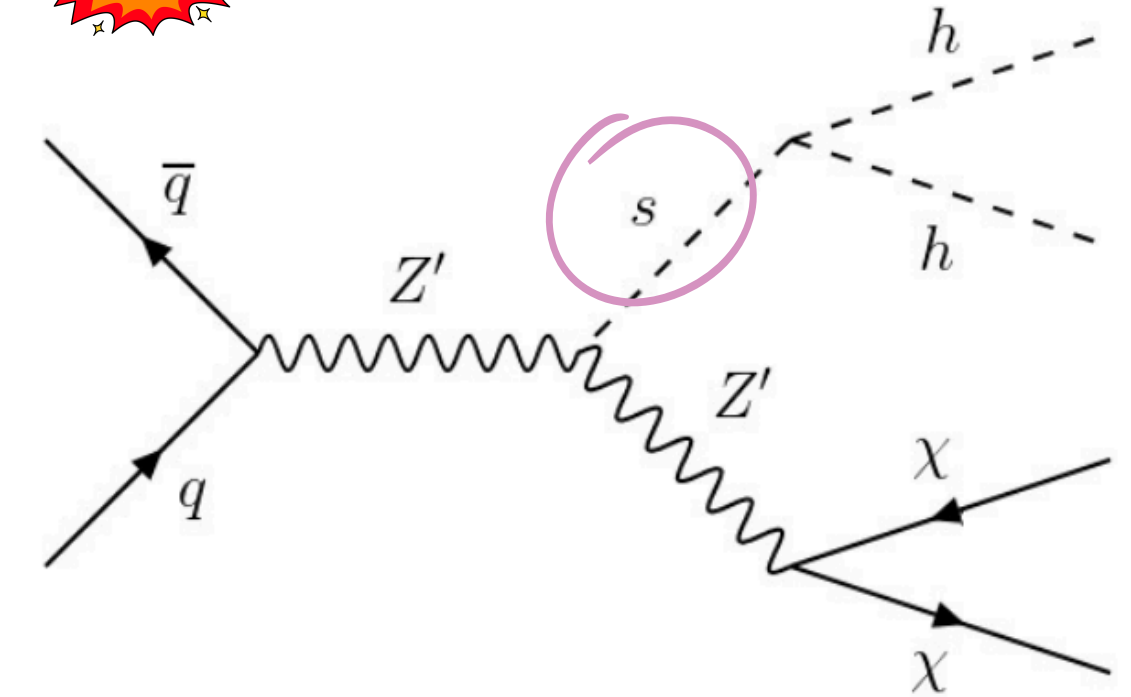
Dark Higgs

- Implementation of Dark Higgs model with an extra broken $U(1)'$ symmetry with a massive Z' mediator and fermionic DM candidates
- Final state: $\chi\chi + hh \Rightarrow E_T^{miss} + b\bar{b}b\bar{b}$
- Lepton veto + 4-7 jets (at least 3 b-tagged) required



[JHEP09\(2025\)067](#)

at **ATLAS**



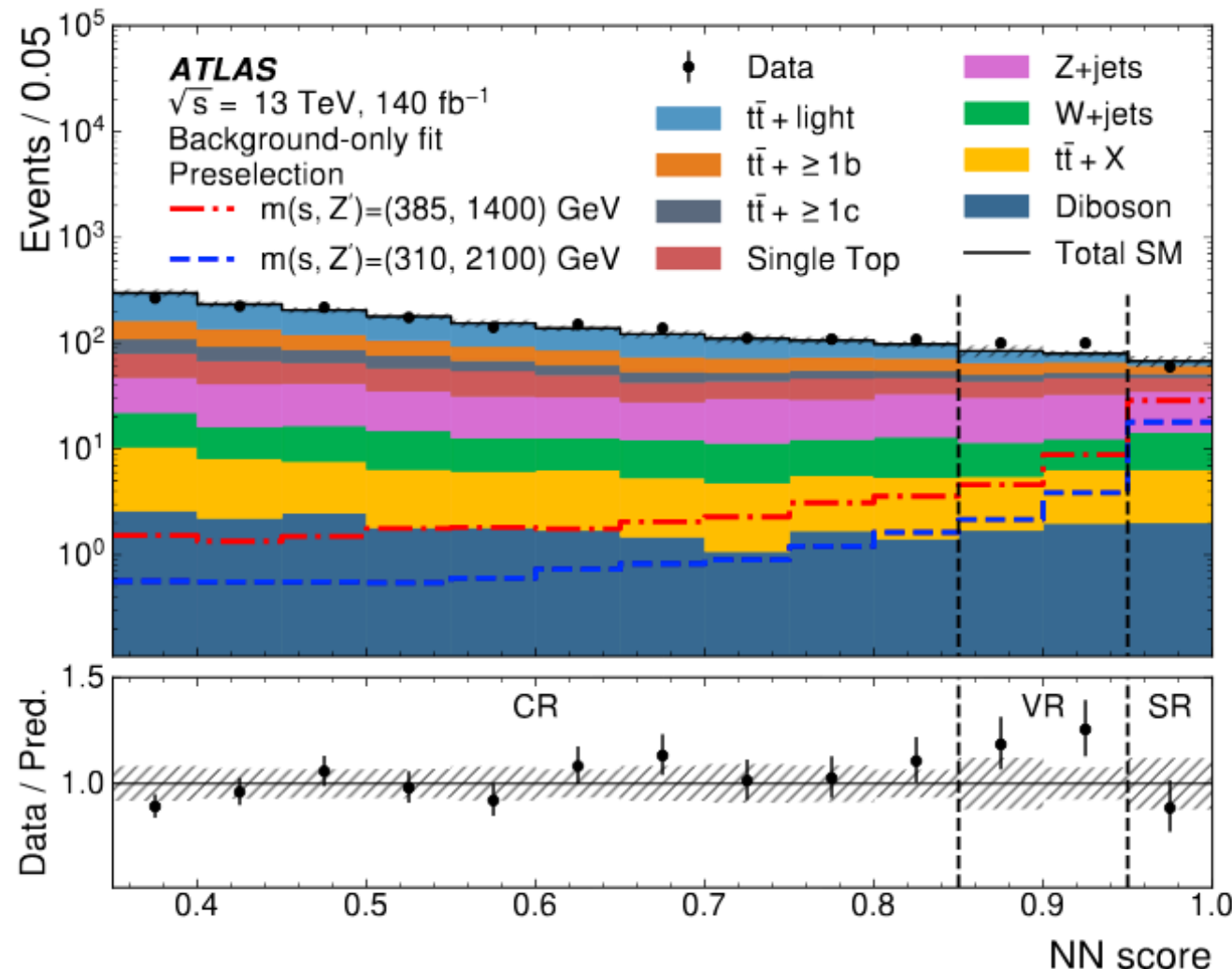
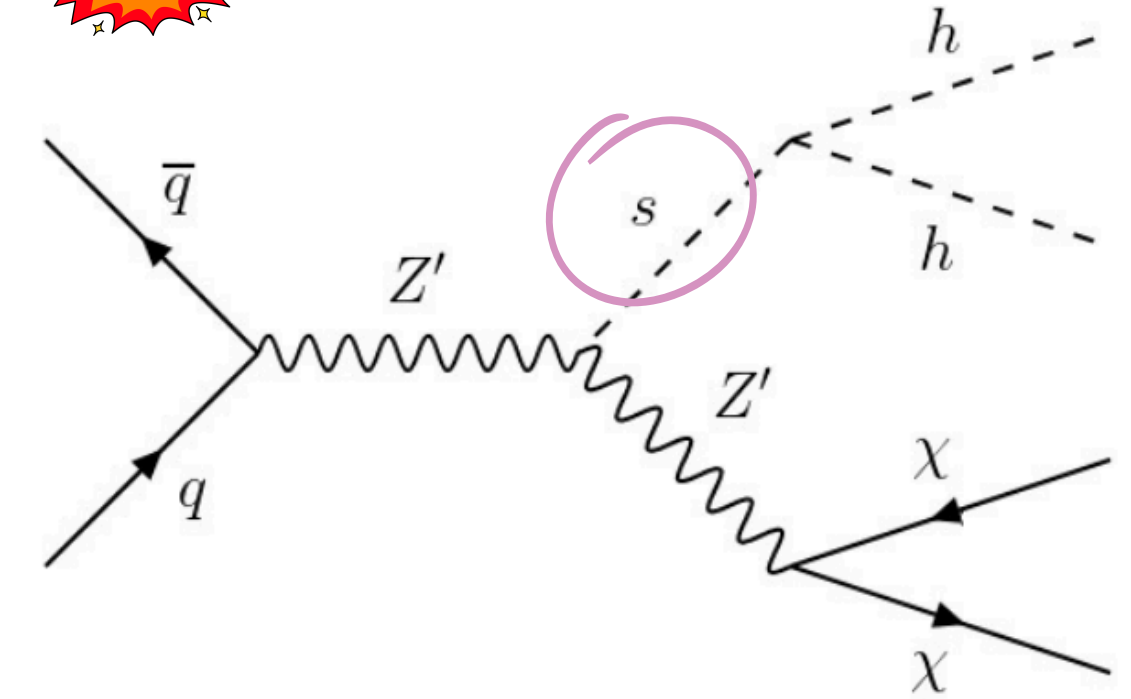
Dark Higgs

- Implementation of Dark Higgs model with an extra broken $U(1)'$ symmetry with a massive Z' mediator and fermionic DM candidates
- Final state: $\chi\chi + hh \Rightarrow E_T^{miss} + b\bar{b}b\bar{b}$
- Lepton veto + 4-7 jets (at least 3 b-tagged) required



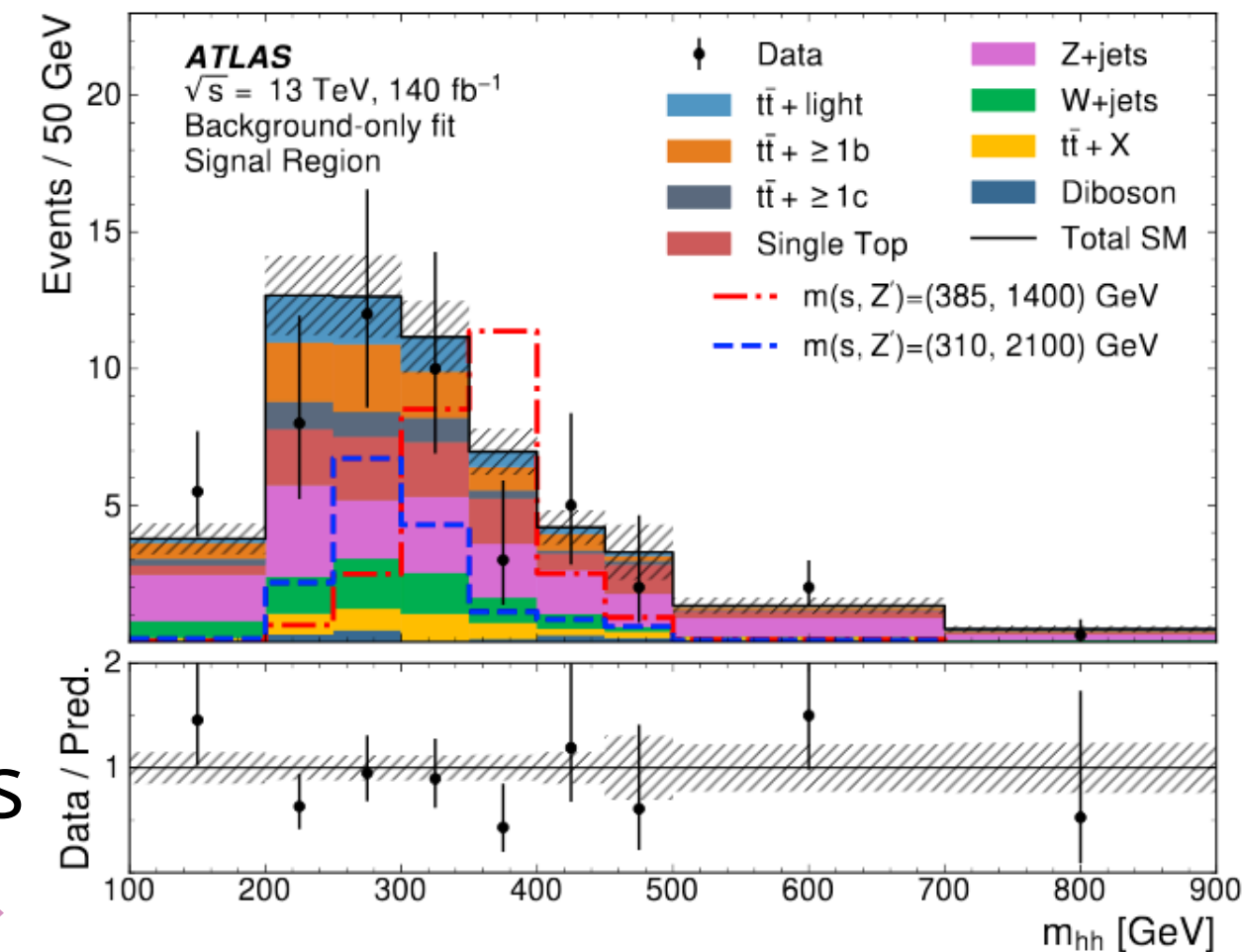
JHEP09(2025)067

at ATLAS



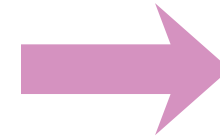
NN trained on kinematic variables and preselected events; cut on NN score increases discrimination power of the SR

Fit in invariant mass shows no excess



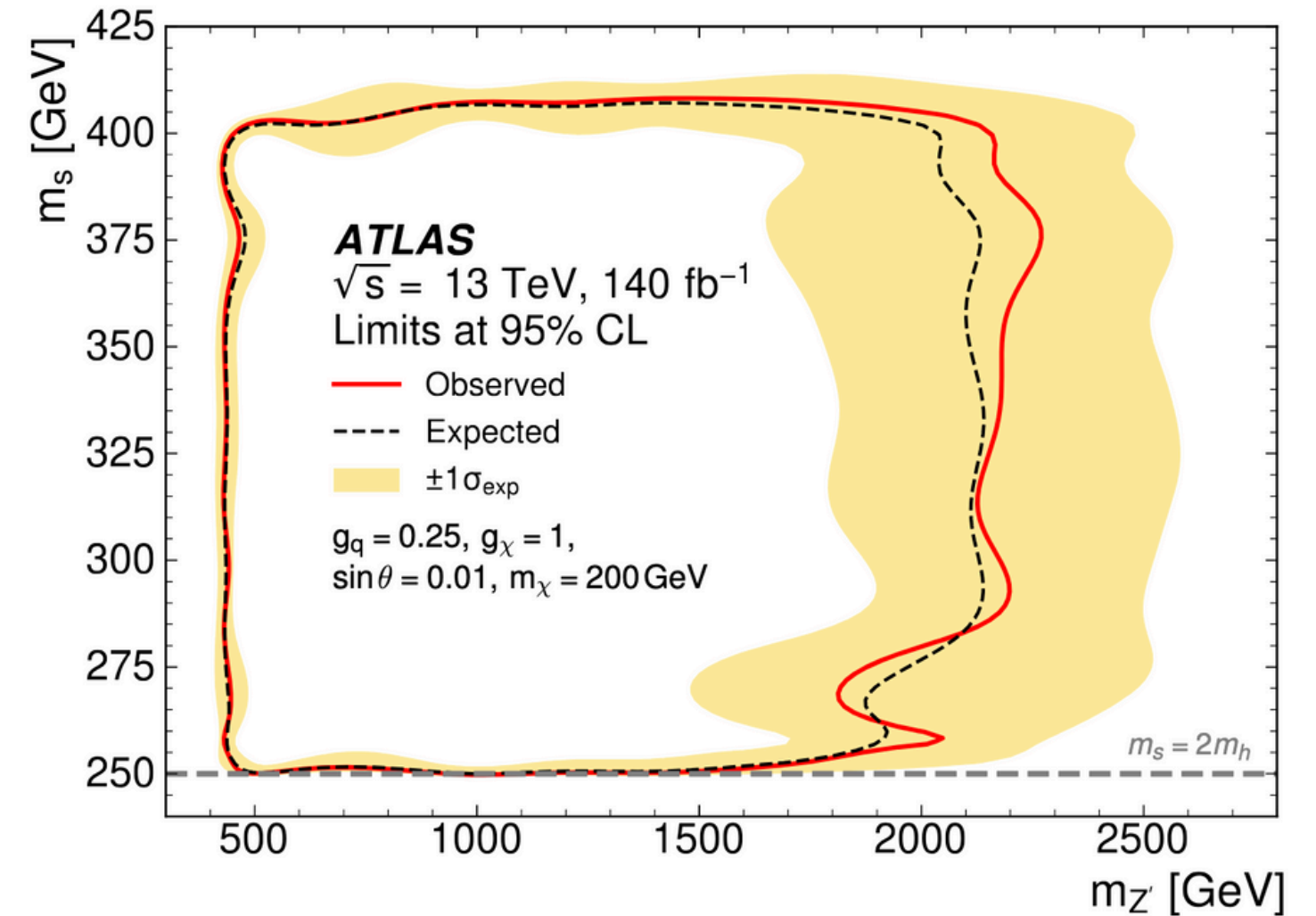
Dark Higgs

exclusion limits set in the
 $(m_{Z'}, m_s)$ plane

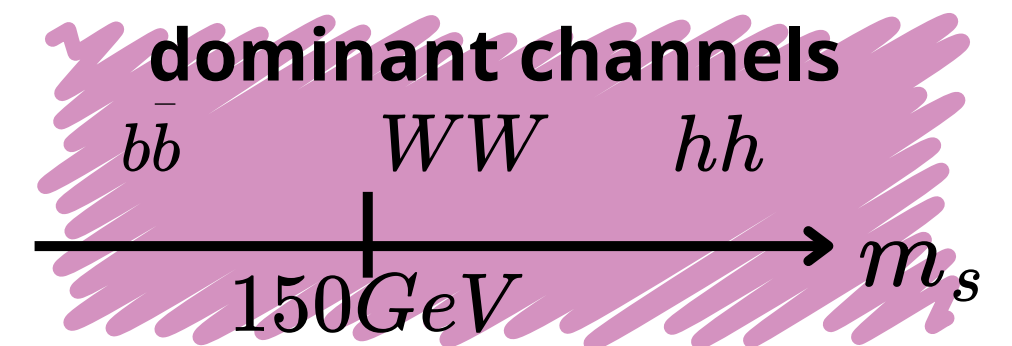
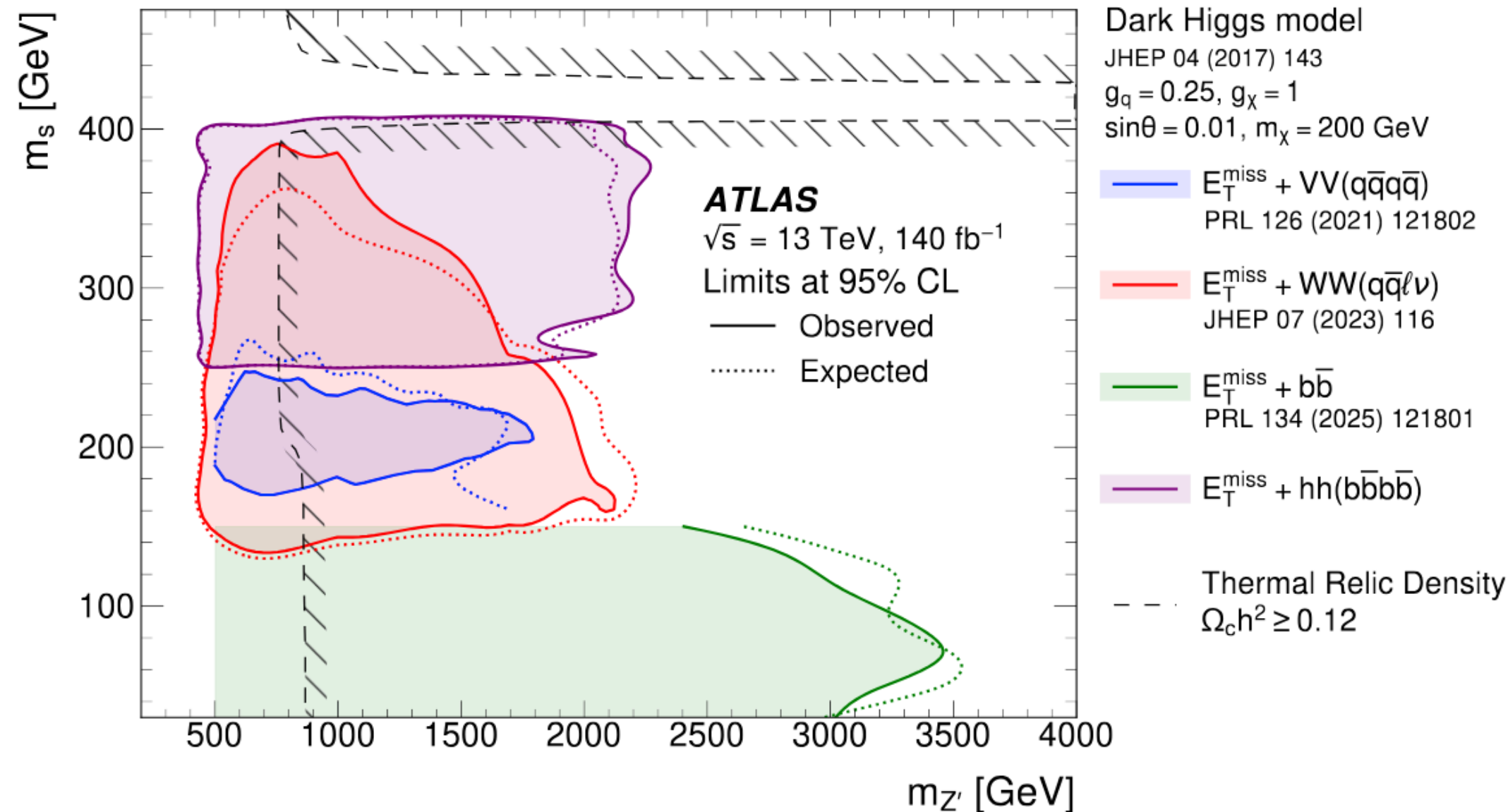
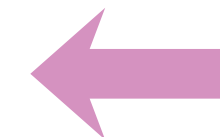


[JHEP09\(2025\)067](#)

at **ATLAS**



Summary plot of limits set by
 ATLAS dark Higgs searches



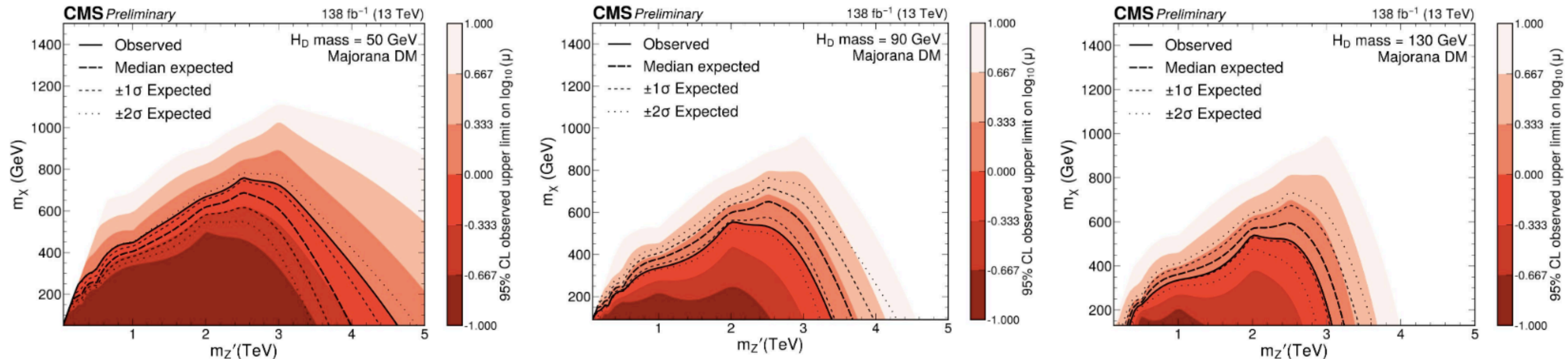
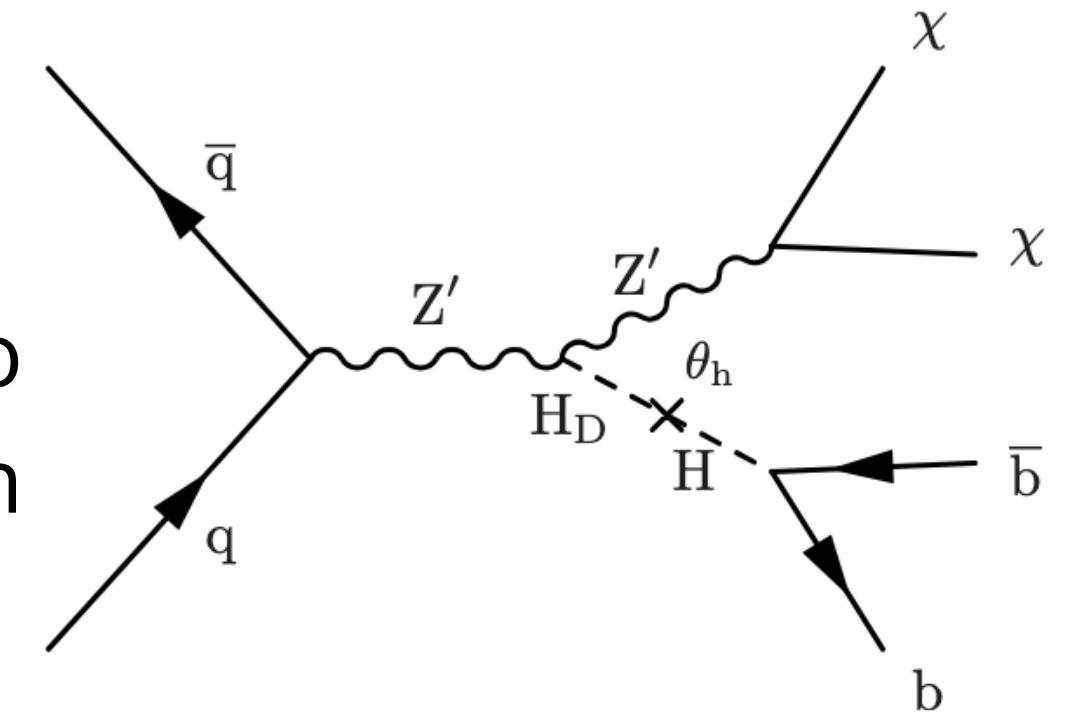
Dark Higgs



SUS-23-013

at CMS

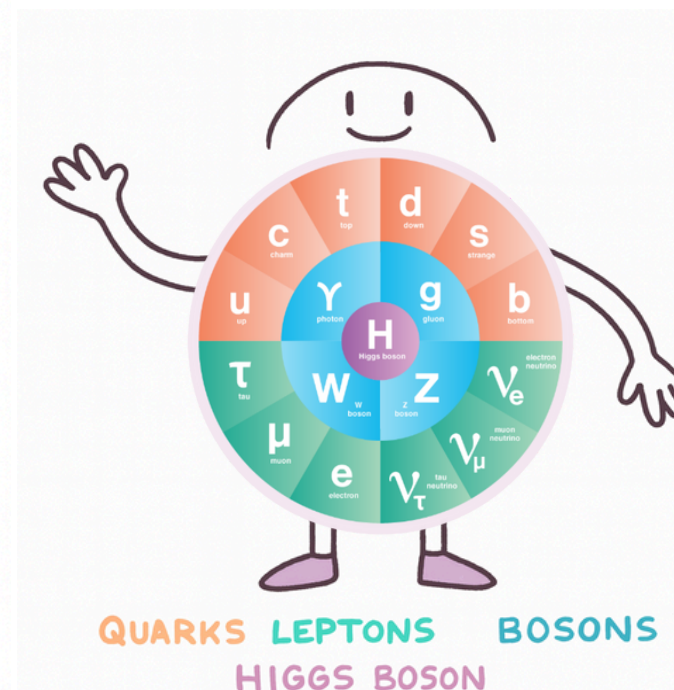
- Final state: $\chi\chi + h \Rightarrow E_T^{miss} + b\bar{b}$
- Fit invariant mass in bins of U (hadronic recoil $\vec{p}_T^{miss} + \vec{p}_T^l$)
- AK15 jet processed with Soft-Drop (SD) algorithm, to prune away soft, wide-angle radiation not associated with the hard scattering process that formed the jet



Conclusions

- Wide variety of dark sector **signatures** are being explored at the LHC, covering different regions of the phase space and involving different models
- Different **analysis strategy** adopted to maximize sensitivity across the kinematic spectrum
- **Machine Learning** techniques extensively used, opening new opportunities to probe unconventional new-physics scenarios

The search for new physics (must) go on!



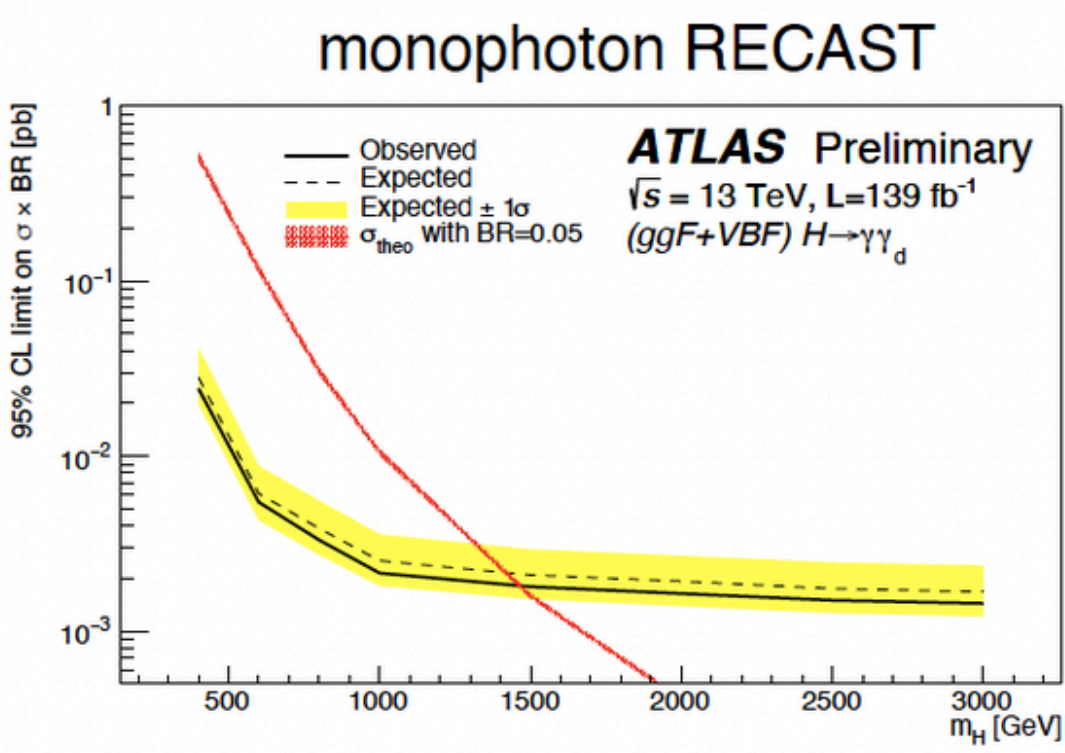
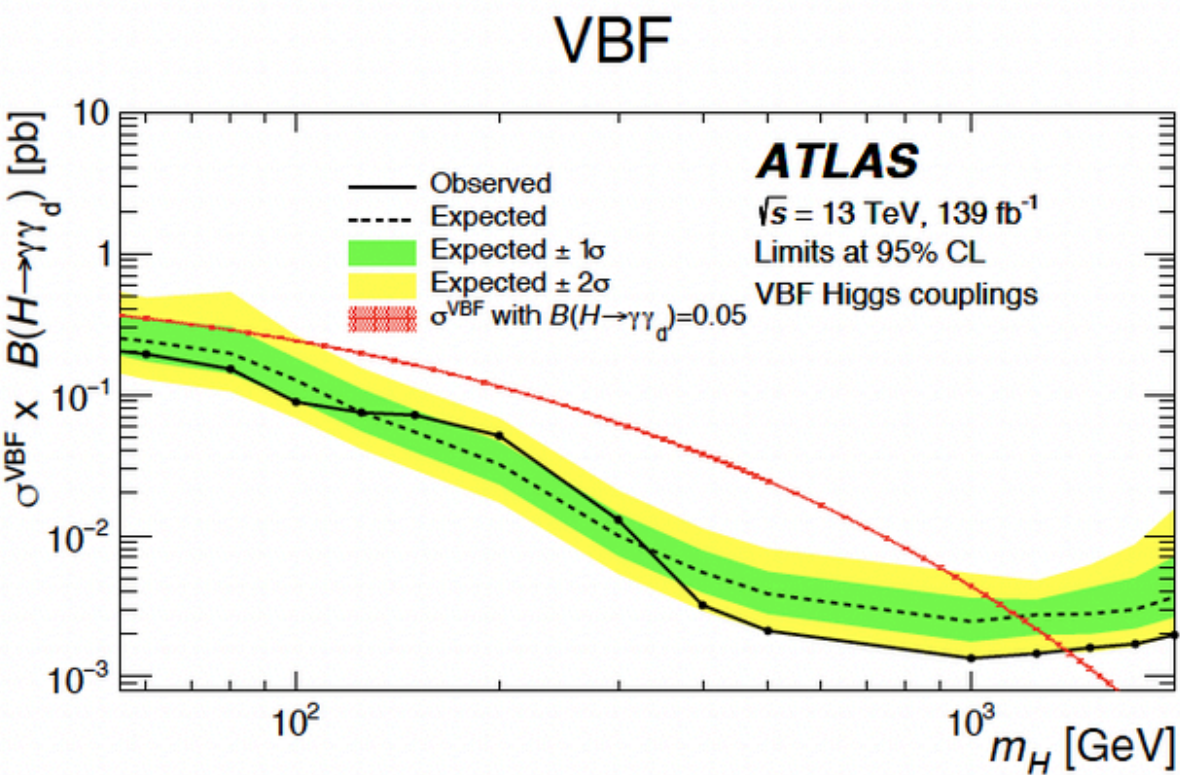
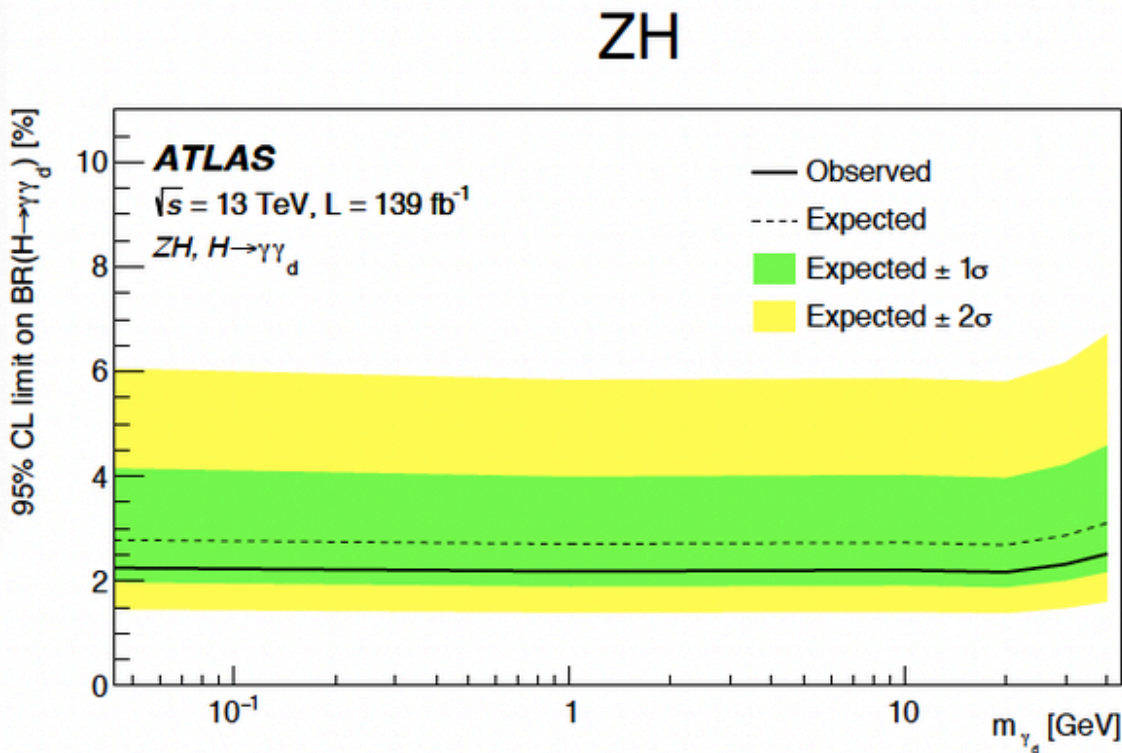
Thank you for
the attention

Backup

Massless dark photon



combination

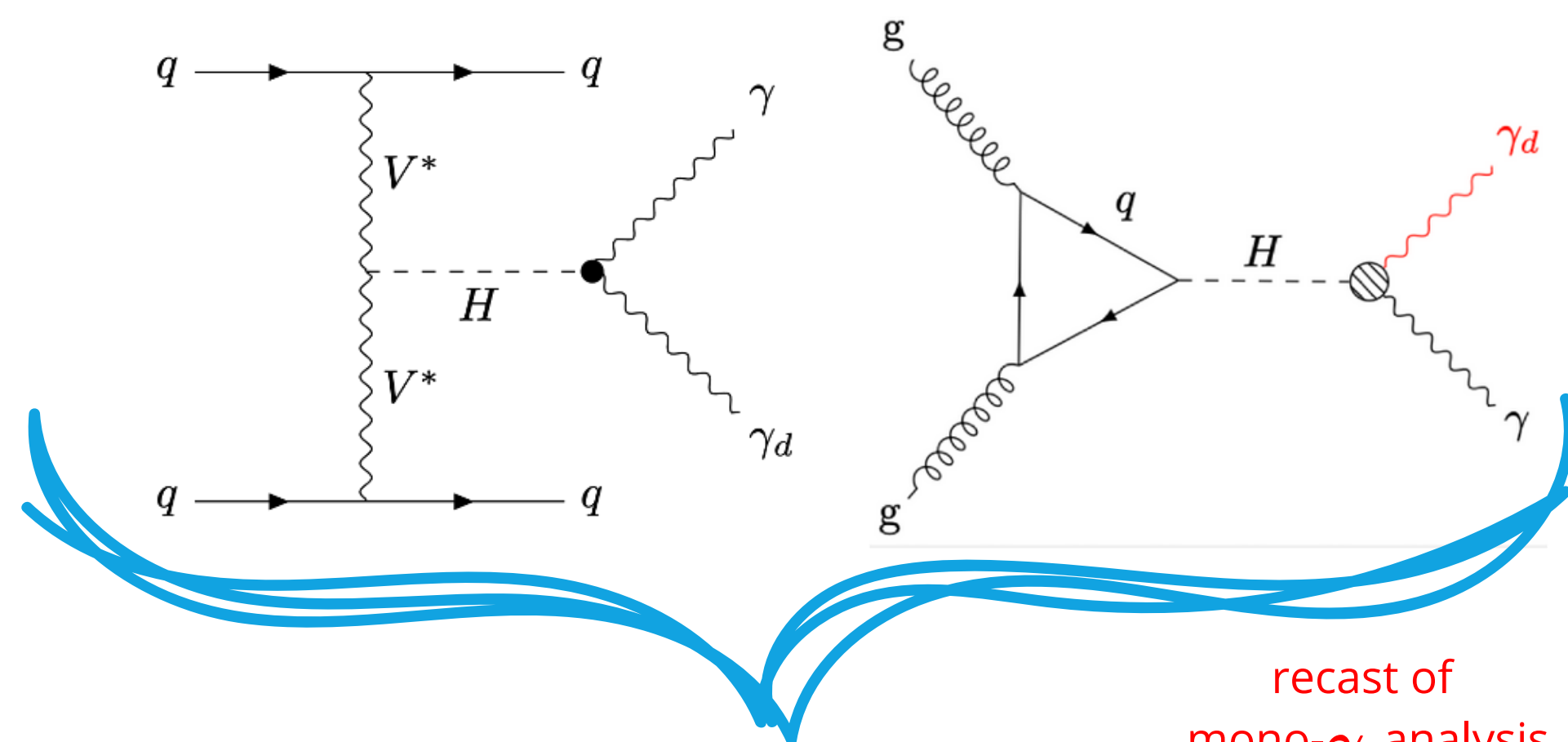


• Most straightforward and worthy scenarios for the statistical combination, based on 3 input analyses.

Input analysis	Signals	m_H	m_{γ_d}	Combination scenarios
ZH	SM (ZH) $H \rightarrow \gamma\gamma_d$	125 GeV	[0, 40] GeV	ZH + VBF for SM Higgs, massless γ_d , targeting BR(H125 $\rightarrow \gamma\gamma_d$)
VBF	SM (ggF + VBF) $H \rightarrow \gamma\gamma_d$	125 GeV	Massless γ_d	
	BSM (VBF) $H \rightarrow \gamma\gamma_d$	[60, 2000] GeV	Massless γ_d	Monoph- + VBF for Heavy Higgs, massless γ_d , targeting $\sigma(\text{ggF} + \text{VBF}) \times \text{BR}(H \rightarrow \gamma\gamma_d)$
Monophoton	BSM (ggF + VBF) $H \rightarrow \gamma\gamma_d$	[400, 3000] GeV	Massless γ_d	

Massless dark photon

NEW! combination



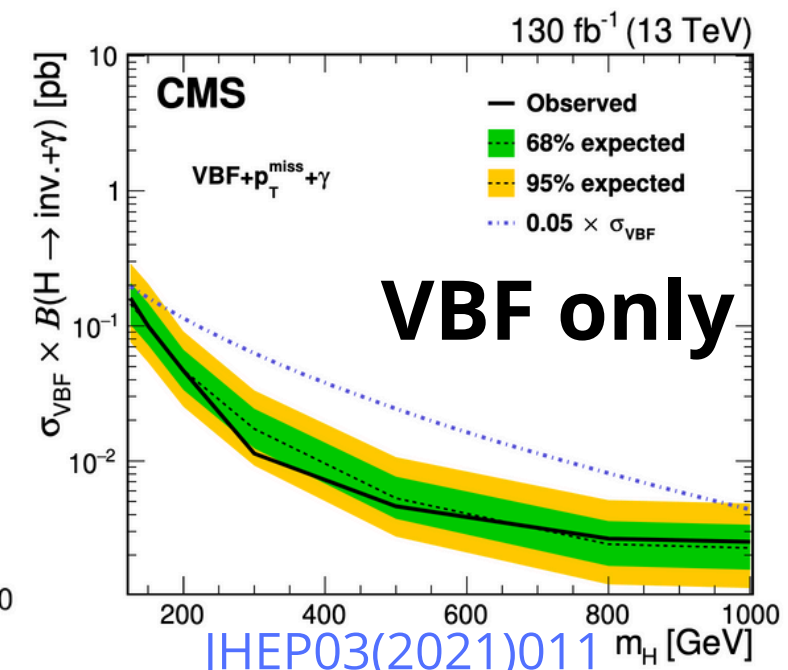
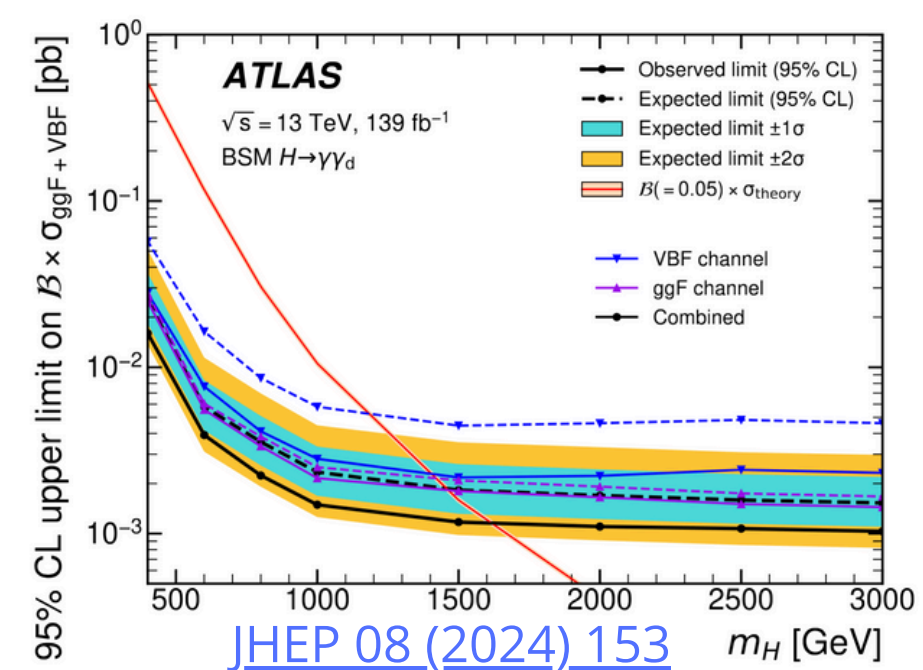
recast of
mono- γ analysis

BSM Higgs: VBF and ggF

Upper obs(exp) limit on $\sigma \times BR(H_{BSM} \rightarrow \gamma\gamma_D)$:

Observed limits

16 fb (26 fb) for $m_H = 400$ GeV
to 1.0 fb (1.5 fb) for $m_H = 3$ TeV.



Observed limits

≈ 160 fb for $m_H = 125$ GeV to
 ≈ 2 fb for $m_H = 1$ TeV

TLA analysis at the **ATLAS** detector

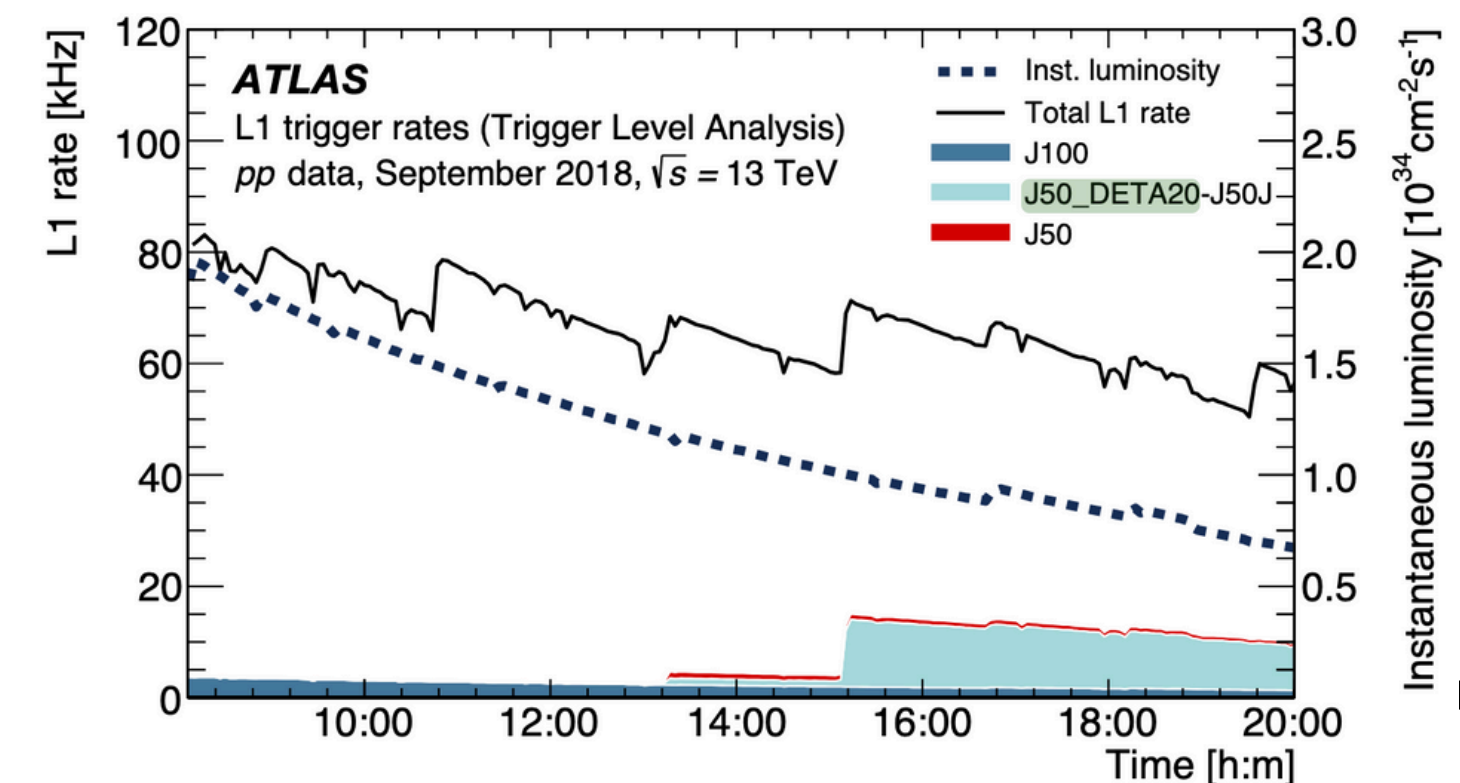


[Submitted to: Phys. Rev. D](#)

L1 records jets from **eta x phi = 0.2 x 0.2** cells. Only jets with **|eta| < 3.1** and pT requirement enter the TLA stream.

- From 2016–2018, **pT > 100 GeV (J100)** (lowest single-jet L1 trigger)
- In 2017, added a prescaled trigger with **pT > 50 GeV** at the end of the fill (allowed by declining instantaneous luminosity)
- In 2018, added luminosity-dependent combination of triggers:
 - **single-jet L1 pT > 50 GeV (J50)**
 - two L1 jets satisfying $pT > 50$ GeV for the leading jet, $pT > 15$ GeV for the sub-leading + delta rapidity < 1

Used in the analysis: **J100** and **J50**



TLA analysis at the **ATLAS** detector



[Submitted to: Phys. Rev. D](#)

Event selection

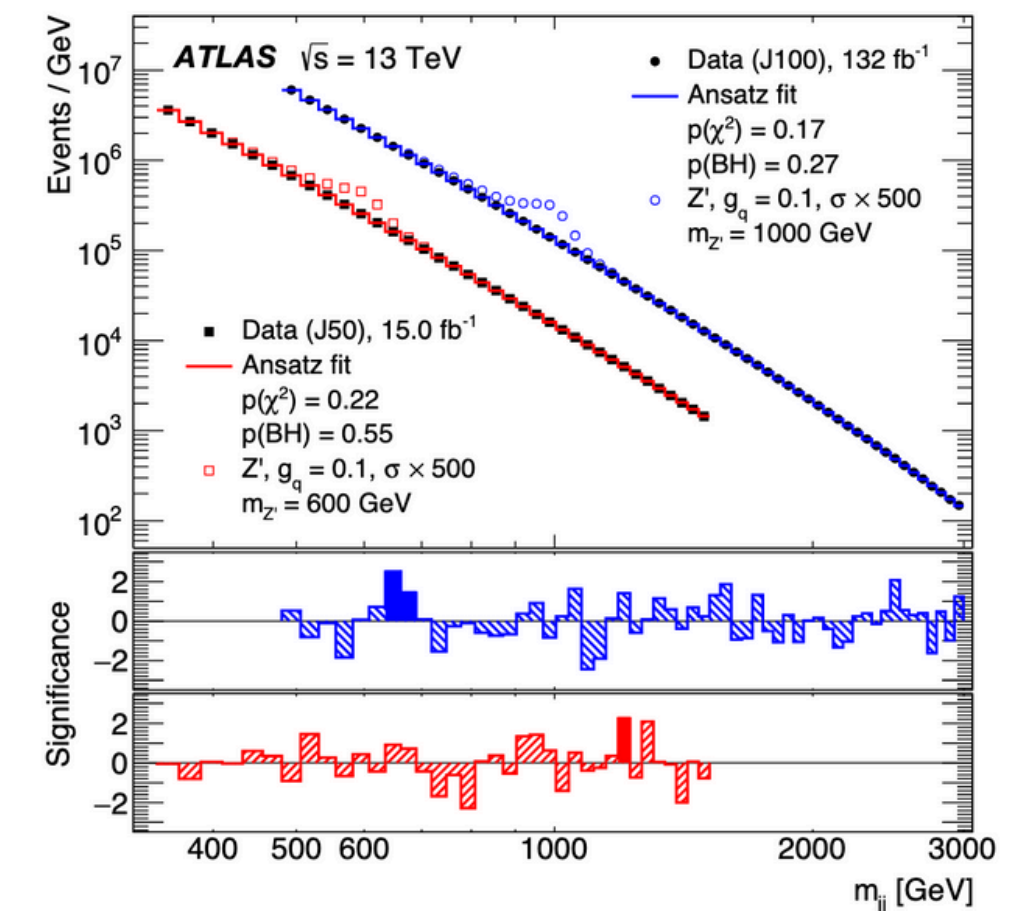
- ≥ 1 jet with $p_T > 85$ GeV and $|\eta| < 2.4$
- 2 highest p_T jets with $|y| < 0.6$

2 Signal Regions:

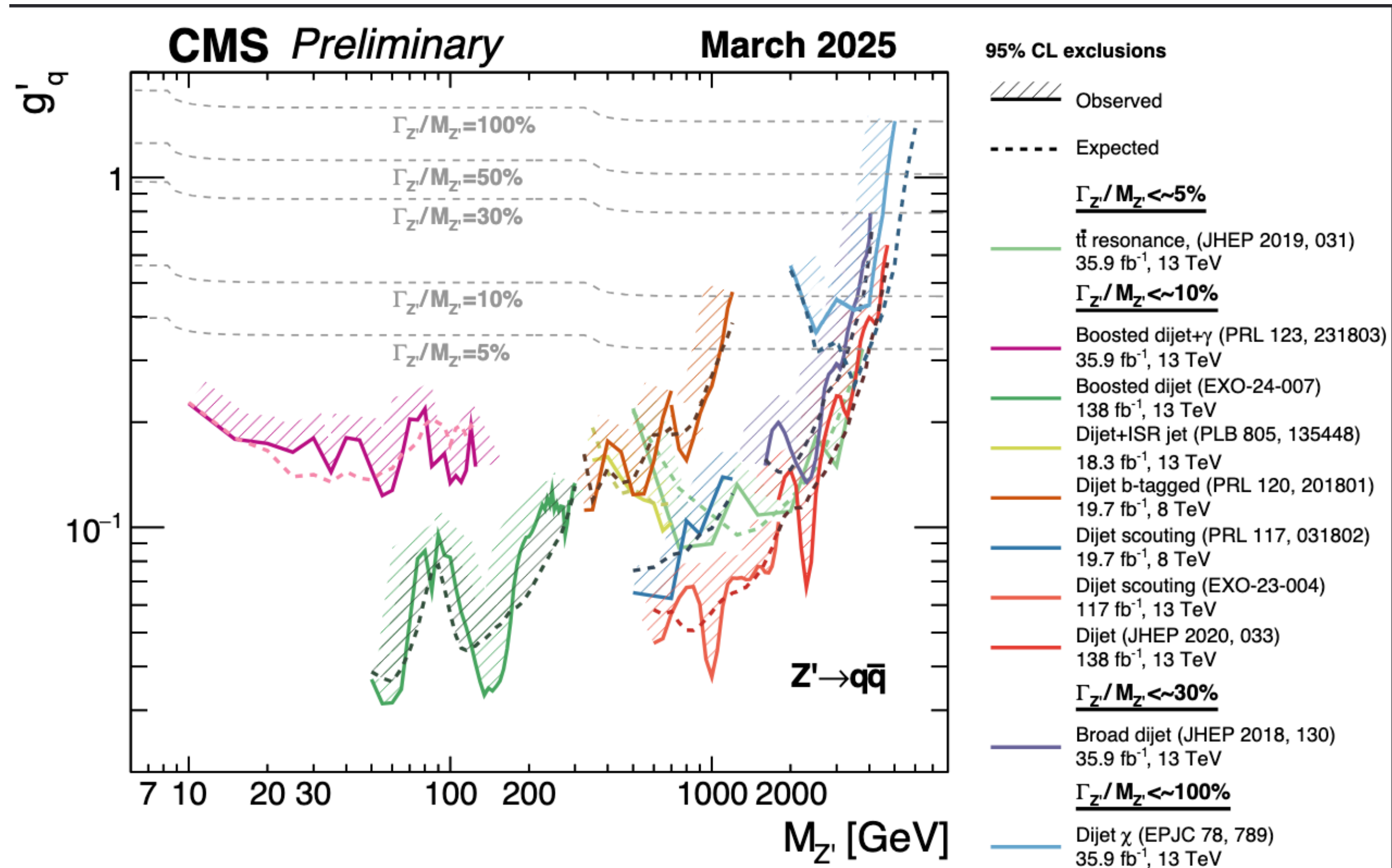
- J100 trigger: $m_{JJ} > 481$ GeV
- J50 trigger: $m_{JJ} > 344$ GeV

Background estimation with a polynomial (ansatz) fit:

- choose fitting function: polynomial + jet systematics shape (optimal for dijets)
- fit data in each SR $\rightarrow$ good agreement with bkg-only ansatz
- BumpHunter algorithm used to further assess localised excesses



TLA analysis at the **ATLAS** and **CMS** detector [SummaryPlotsEXO13TeV](#)



Massive dark photon



decaying

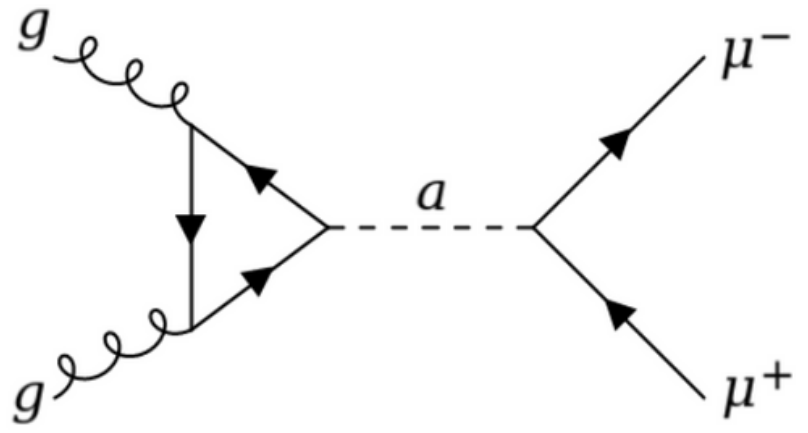


prompt

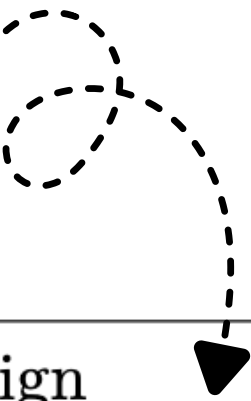
$Z_D \rightarrow \mu\mu$ at CMS

[JHEP12\(2023\)070](#)

Results also interpreted for a **2HDM+S model**

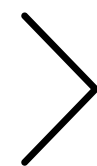


For such a model, the gluon fusion is the dominant channel and the muons pT is expected to be higher: dedicated Signal Region



Preselection	$L_{xy} < 0.2 \text{ cm}, \eta^\mu < 1.9, \text{ Opposite sign}$			
Signal selection	Inclusive		high- p_T	
Mass	$m_{\mu\mu} < 4 \text{ GeV}$	$m_{\mu\mu} > 4 \text{ GeV}$	$m_{\mu\mu} < 4 \text{ GeV}$	$m_{\mu\mu} > 4 \text{ GeV}$
p_T^μ	$> 4 \text{ GeV}$		$> 5 \text{ GeV}$	
Muon	J/ ψ ID	Y ID	J/ ψ ID	J/ ψ ID
Vertex	$L_{xy}/\sigma_{L_{xy}} < 3.5$	$L_{xy} < 0.015 \text{ cm}$	$L_{xy}/\sigma_{L_{xy}} < 3.5$	$L_{xy}/\sigma_{L_{xy}} < 3.5$
$p_T^{\mu\mu}$	—	—	$> 35 \text{ GeV}$	$> 20 \text{ GeV}$

Massive dark photon



decaying



prompt

$Z_D \rightarrow \mu\mu$ at CMS

[JHEP12\(2023\)070](#)

Identification criteria based on MVA: one algorithm for each invariant mass range. For $m_{\mu\mu} < 2.6$ GeV is trained using a partial J/ψ sample, $m_{\mu\mu} > 4.2$ GeV is trained using an $Y(1S)$ sample. Inputs are:

- information on the quality of the muon tracks: # of hits in the pixel detector, # of contributing layers in the strip tracker, and χ^2 of the muon track fit.
- the relative isolation of the muon: scalar p_T sum of reconstructed tracks in a cone of $\Delta R = 0.3$ around the muon
- the vertex that the muons are associated with: χ^2 of the common vertex fit and L_{xy}

➡ higher efficiency while still keeping the misidentification rate low

Experimental systematic uncertainties

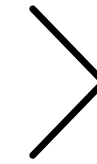
Mayor contribution form background normalization

Effect	$m_{\mu\mu} < 2.6$ GeV	$m_{\mu\mu} > 4.2$ GeV
Integrated luminosity	2.3–2.5%	
Mass resolution	20%	
Signal shape	1.3–2.7%	1.4–1.7%
Trigger efficiency	1–16%	
Muon ID efficiency	4–9%	12–20%
Vertex selection	—	3%
Efficiency application	8%	4%
D^0 meson normalization	20–25%	—

Massive dark photon



decaying



prompt

[JHEP 03\(2022\)041](#)

at **ATLAS**

3 searches in the same analysis

- High-mass (HM): $H \rightarrow XX \rightarrow 4\ell$ ($15 \text{ GeV} < m_X < 60 \text{ GeV}$).
- Low-mass (LM): $H \rightarrow XX \rightarrow 4\mu$ ($1 \text{ GeV} < m_X < 15 \text{ GeV}$).
- Single Z boson (ZX): $H \rightarrow ZX \rightarrow 4\ell$ ($15 \text{ GeV} < m_X < 55 \text{ GeV}$).

The analysis sets limits on:

- fiducial cross-section
- total cross-section
- branching ratio of the H decay

Limits on cross-section

$$N_{obs} = \mathcal{L} \epsilon \alpha \sigma_{tot}$$

- acceptance is model-dependent as depend on the kinematics of the BSM process and it is computed as the fraction of events in a channel that fall into a fiducial region, that is constructed cutting on generator-level variables
- efficiency is model-independent as depends mainly on detector effects and is calculated as fraction of events passing the fiducial selection that also pass the full event selection

Massive dark photon

decaying

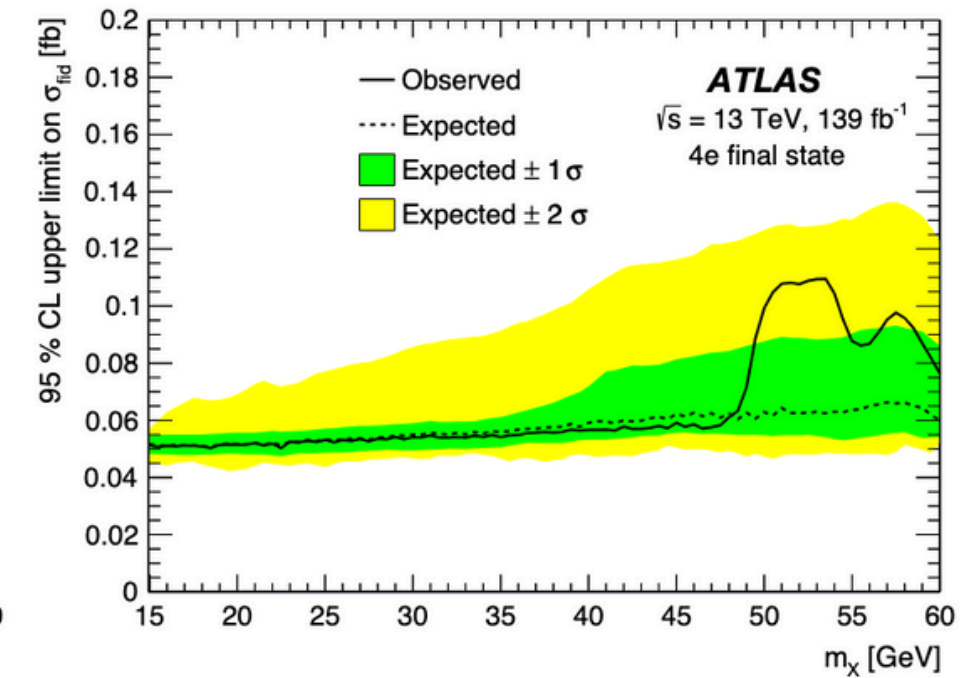
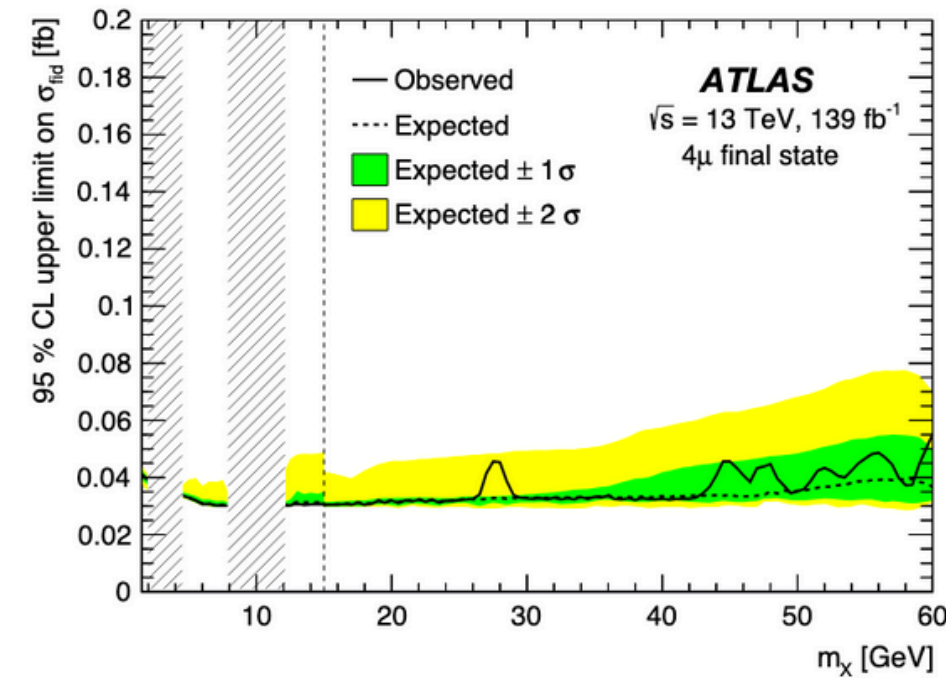
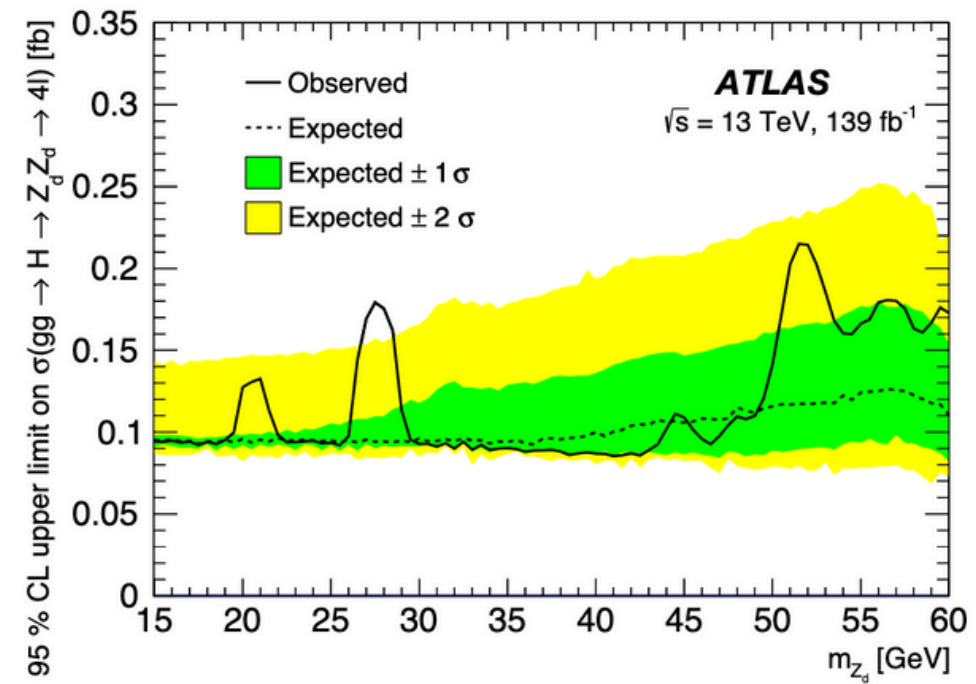
prompt

JHEP 03 (2022) 041 at ATLAS

$$H \rightarrow Z_D Z_D \rightarrow 4l$$

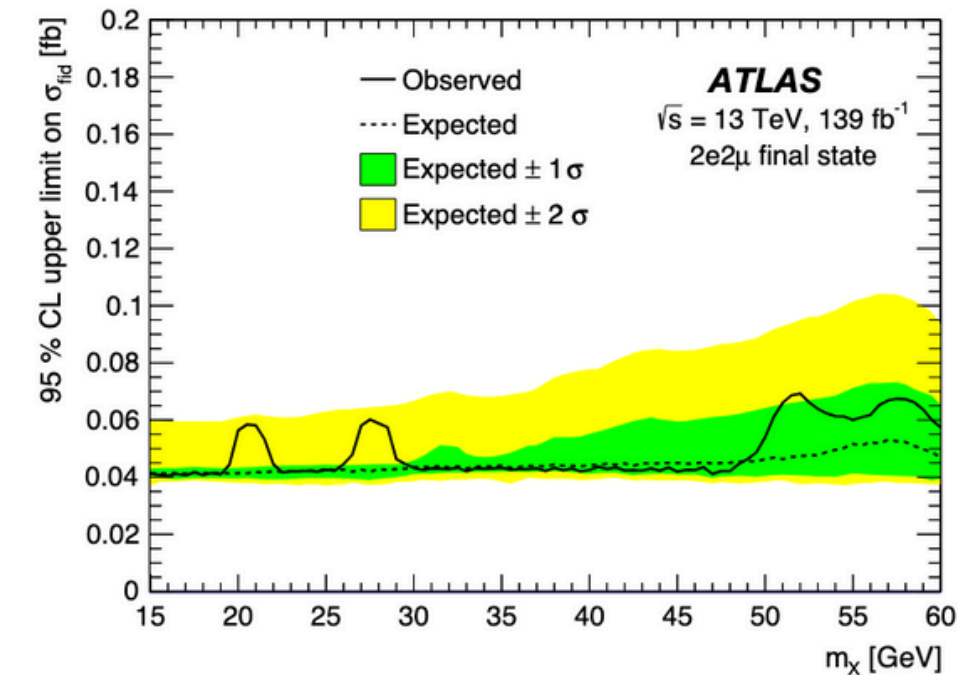
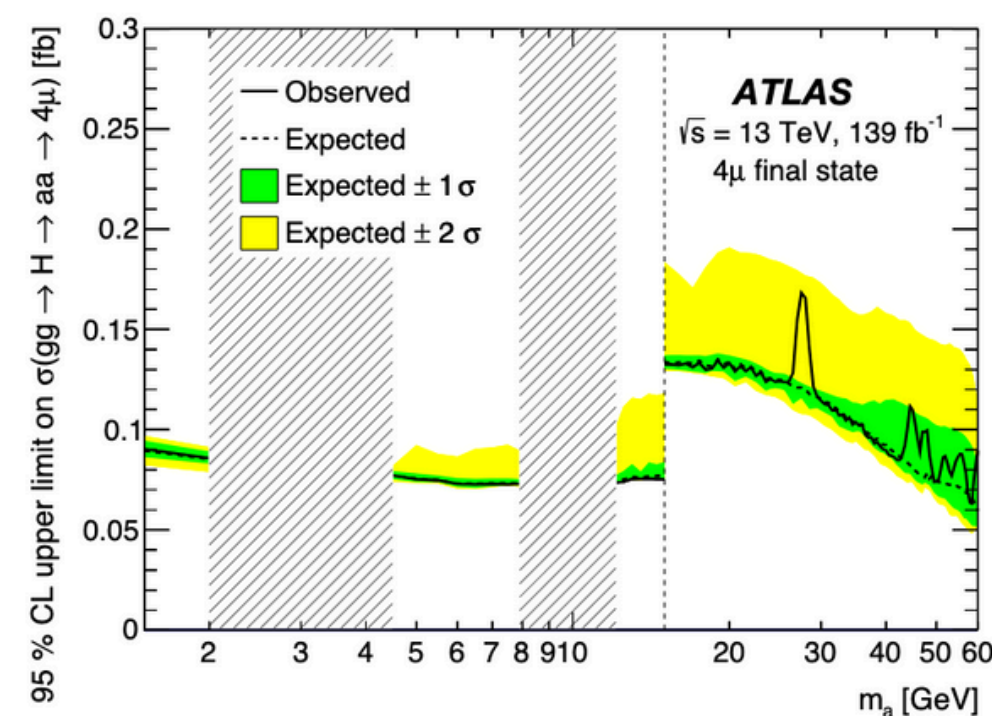
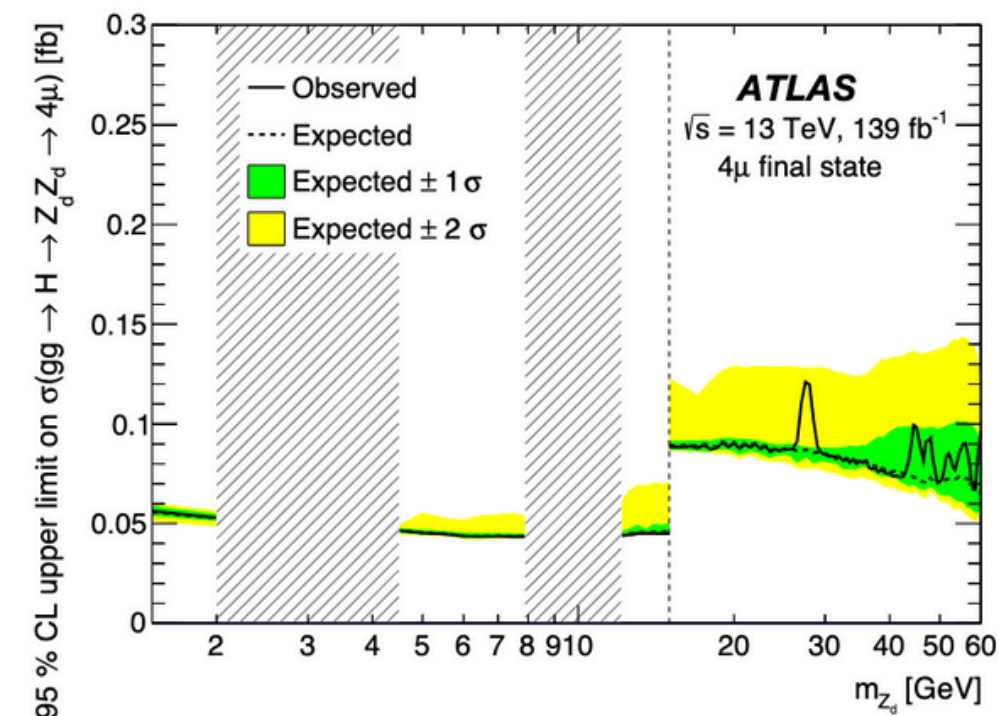
Limits on total cross-section: model-dependent

Limits on fiducial cross-section: model-independent



(a)

(b)



Massive dark photon

decaying

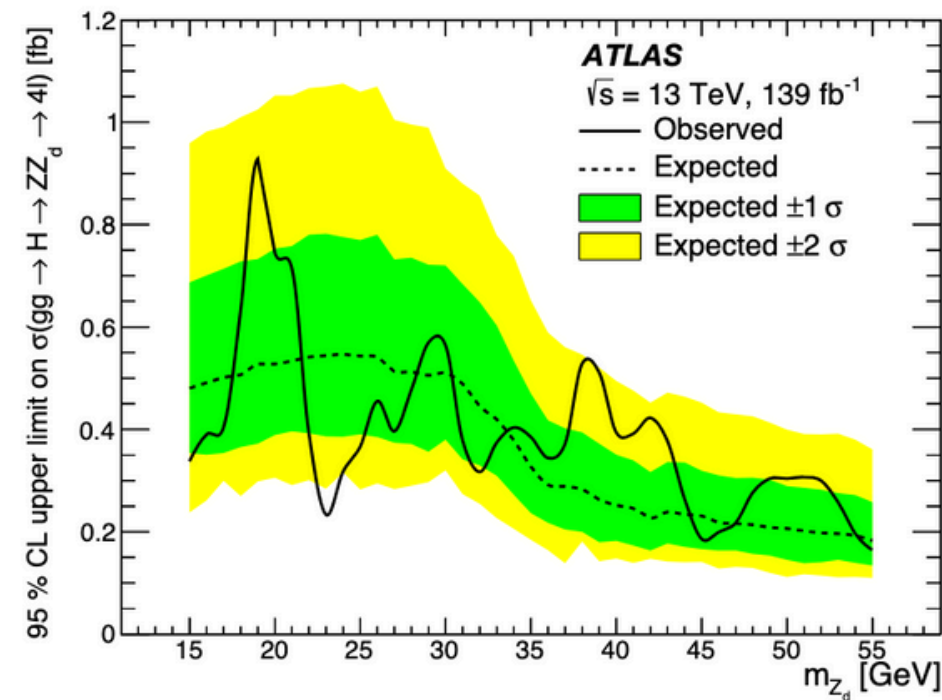
prompt

[JHEP 03 \(2022\) 041](#) at **ATLAS**

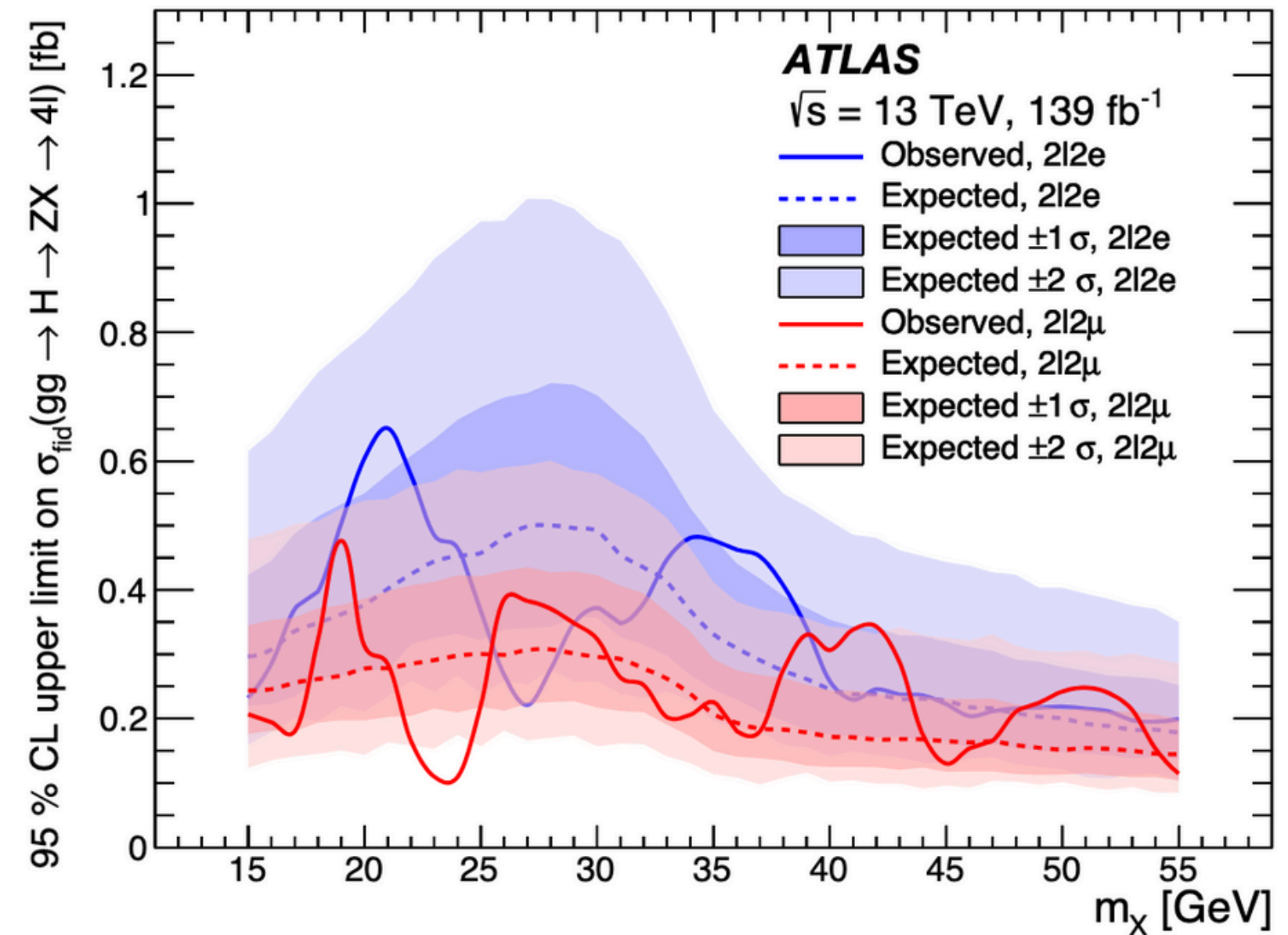
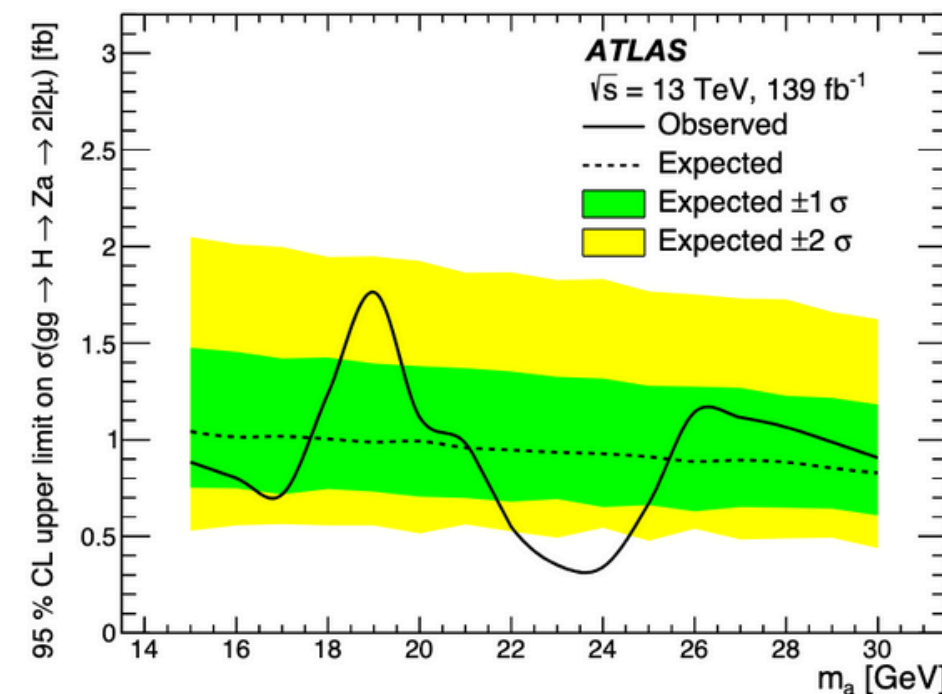
$$H \rightarrow ZZ_D \rightarrow 4l$$

Limits on total cross-section: model-dependent

Limits on fiducial cross-section: model-independent



(a)



Massive dark photon

decaying

prompt

JHEP 03 (2022) 041

at ATLAS

Limits on branching ratio

$$H \rightarrow Z_D Z_D \rightarrow 4l$$

$$\mathcal{B}(H \rightarrow XX \rightarrow 4\ell) = \frac{\sigma_{H \rightarrow XX \rightarrow 4\ell}}{\sigma_H},$$

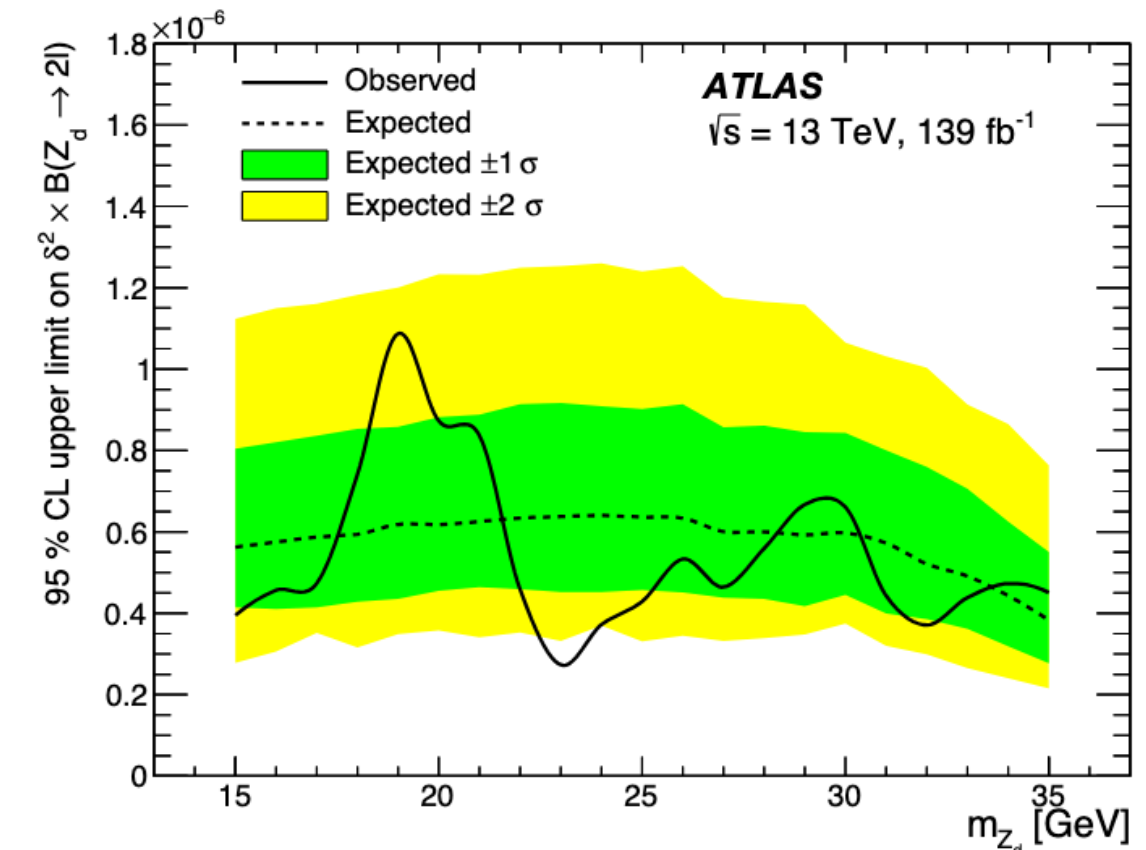
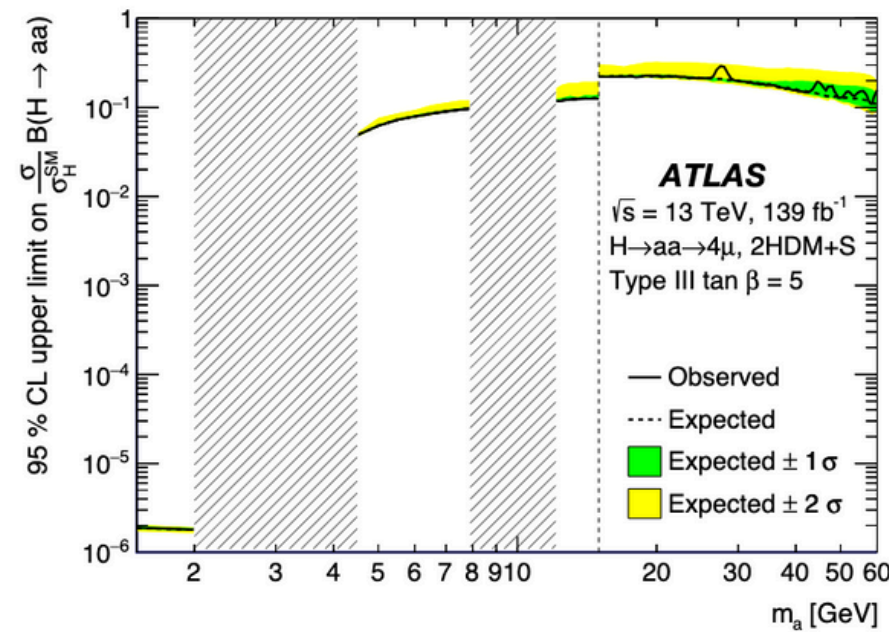
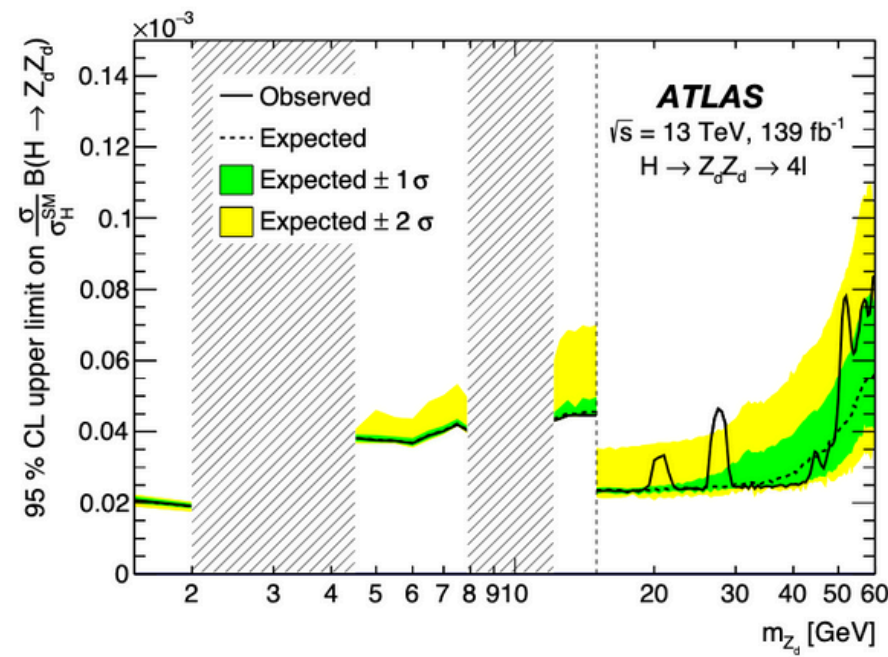
$$\mathcal{B}(H \rightarrow XX) = \frac{\mathcal{B}(H \rightarrow XX \rightarrow 4\ell)}{\sum_{\ell_1=e,\mu} \sum_{\ell_2=e,\mu} [\mathcal{B}(X \rightarrow 2\ell_1) \mathcal{B}(X \rightarrow 2\ell_2)]},$$

$$H \rightarrow ZZ_D \rightarrow 4l$$

$$R_B = \frac{\text{BR}(H \rightarrow ZZ_d \rightarrow 4\ell)}{\text{BR}(H \rightarrow 4\ell)}$$

$$\frac{R_B}{(1 - R_B)} \simeq \delta^2 \times \text{BR}(Z_d \rightarrow 2\ell) \times$$

$$\frac{\text{BR}(Z^* \rightarrow 2\ell)}{\text{BR}(H \rightarrow ZZ^* \rightarrow 4\ell)} \times \frac{f(m_{Z_d})}{\Gamma_{\text{SM}}}$$



Massive dark photon

decaying

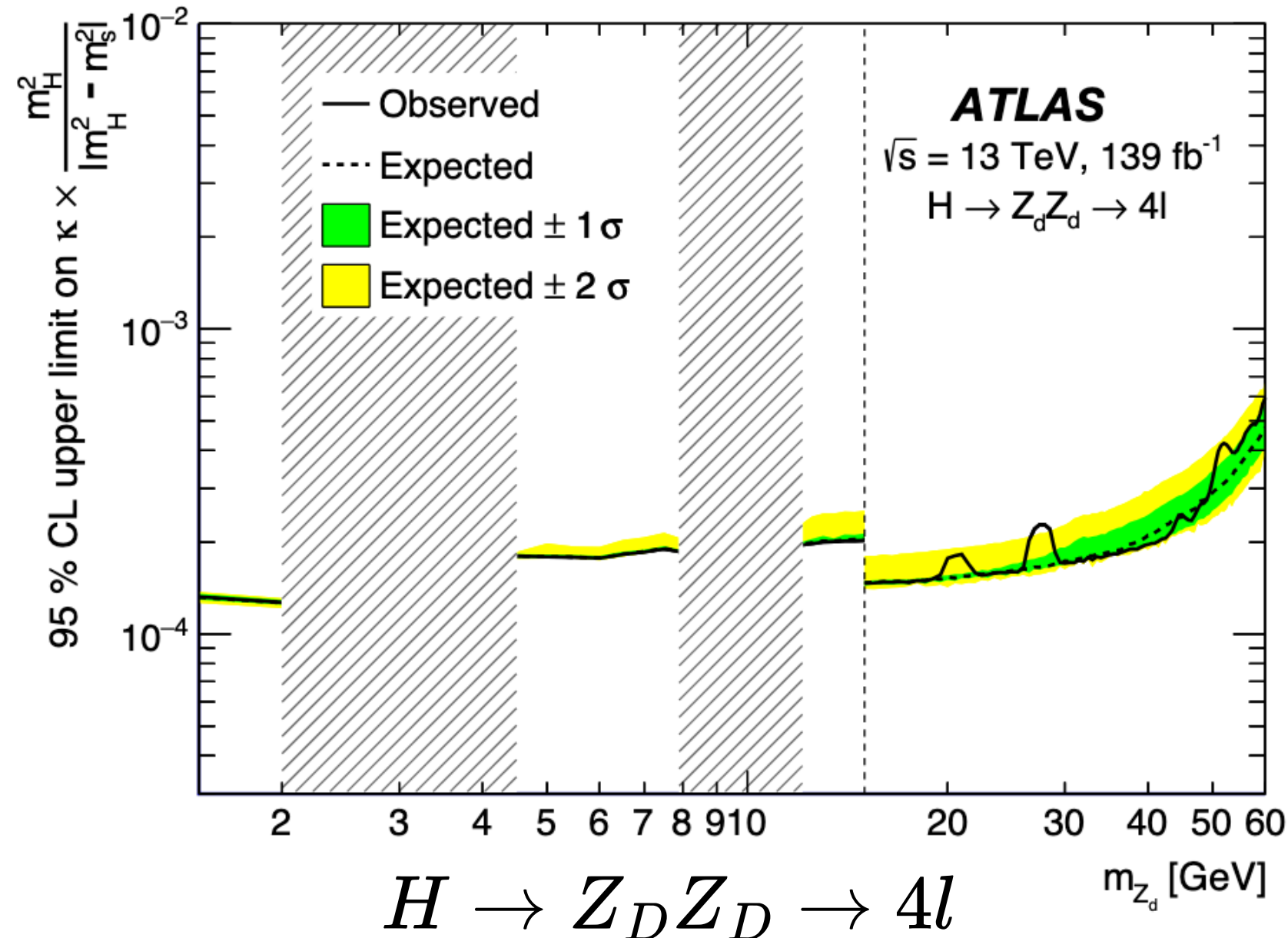
prompt

JHEP 03 (2022) 041 at ATLAS

Limits on Higgs mixing parameter

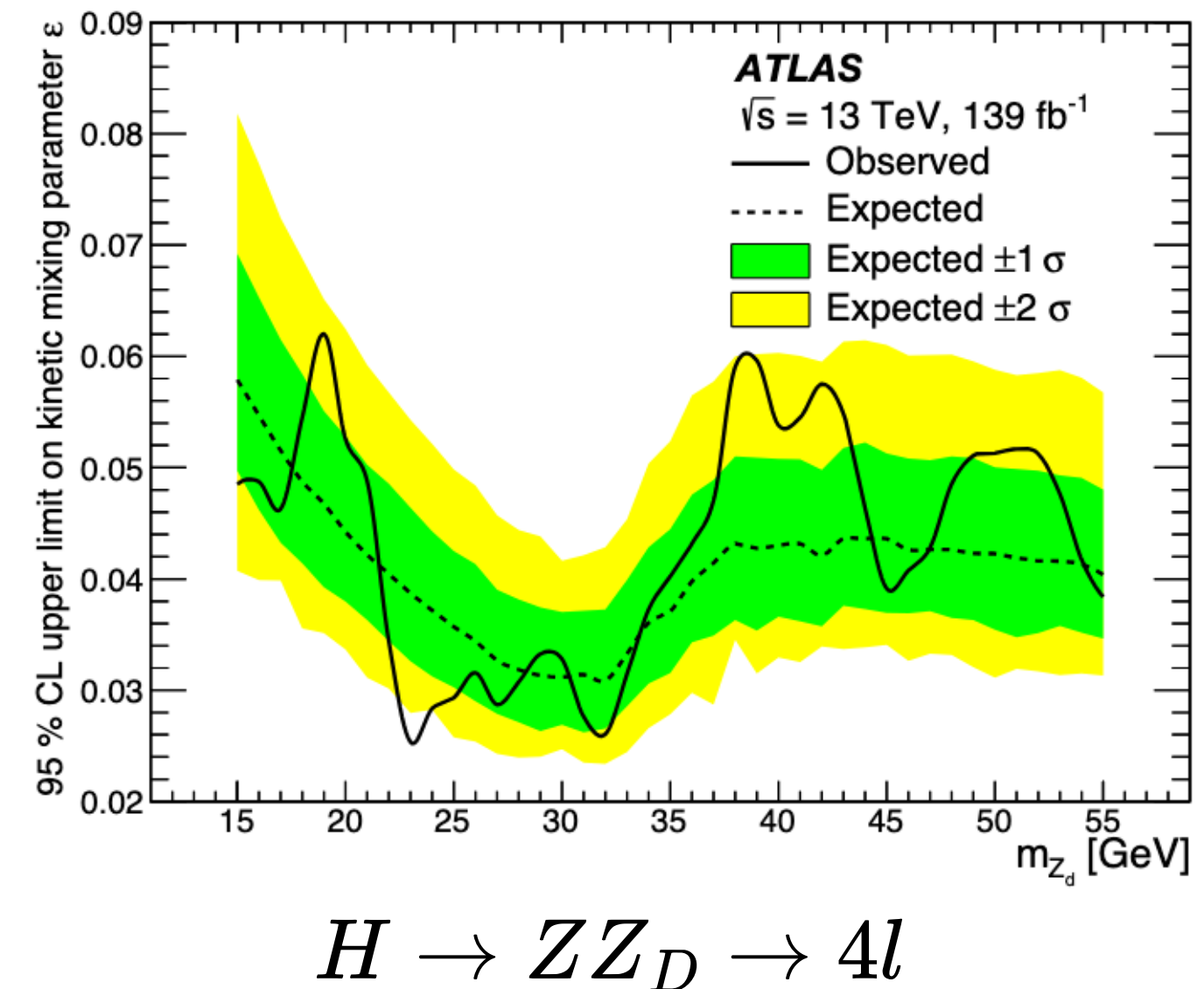
Using κ' allows to mix dependencies on S mass and κ in one only parameter

$$\kappa' = \kappa \frac{m_H^2}{|m_H^2 - m_S^2|}, \quad \kappa'^2 = \frac{\Gamma_{\text{SM}}}{f(m_{Z_d})} \frac{\mathcal{B}(H \rightarrow Z_d Z_d)}{1 - \mathcal{B}(H \rightarrow Z_d Z_d)}$$



Limits on kinetic mixing parameter

Comes from limits on the BR as $\text{BR}(Z_D \rightarrow ll)$ is proportional to epsilon squared



Massive dark photon

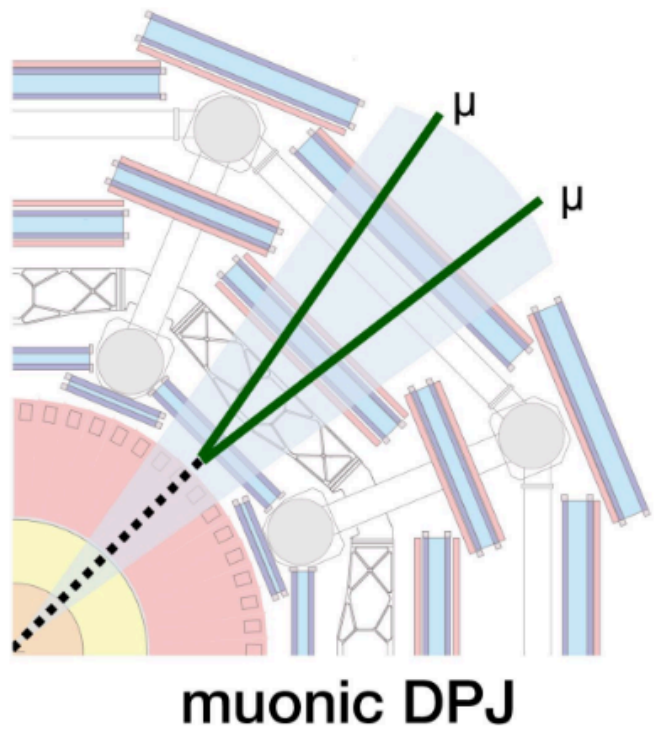
decaying

prompt

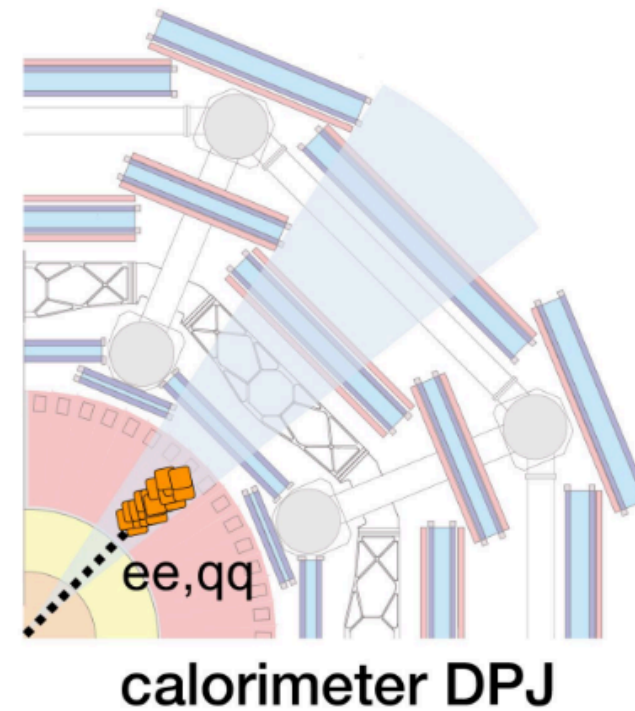


[Eur. Phys. J. C \(2025\)](#) at **ATLAS**

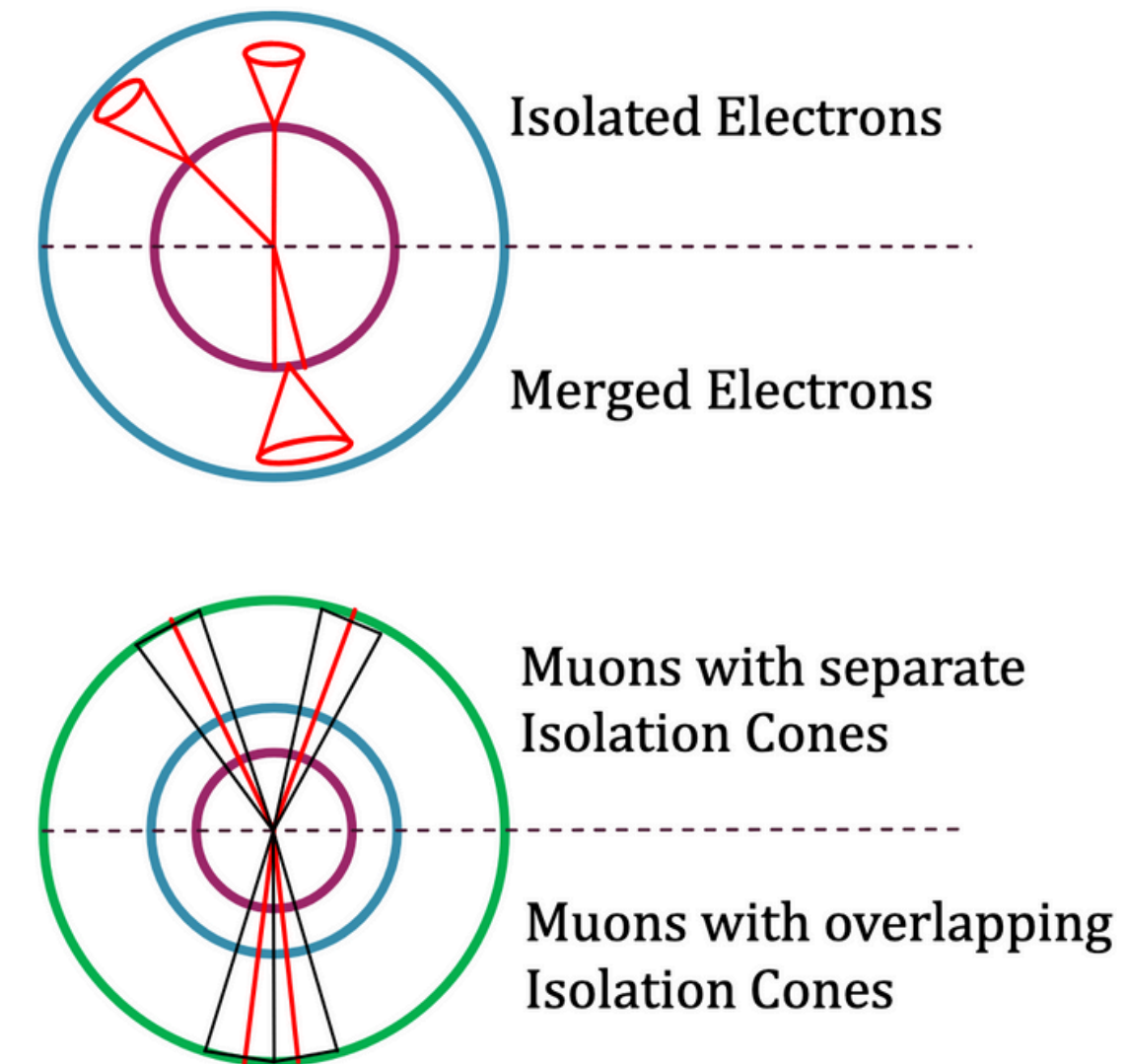
How does a Lepton Jets look like?



μ DPJ
 $\gamma_d \rightarrow \mu^+ \mu^-$
Decays outside ID acceptance
Pair of close-by MS tracks with no matching jets/tracks in the ID



$calo$ DPJ
 $\gamma_d \rightarrow e^+ e^- / qq$
Targeting decays in HCAL
Low EM fraction jets with no matching MS tracks



Reconstruction:

- Cambridge-Aachen clustering with $R=0.4$
- jets with a different-flavour lepton are discarded
- sum of the charges of the LJ components = 0
- muon LJs: at least 2 muons. electron LJs: at least 1 electron + at least 2 associated ID tracks

Massive dark photon

decaying

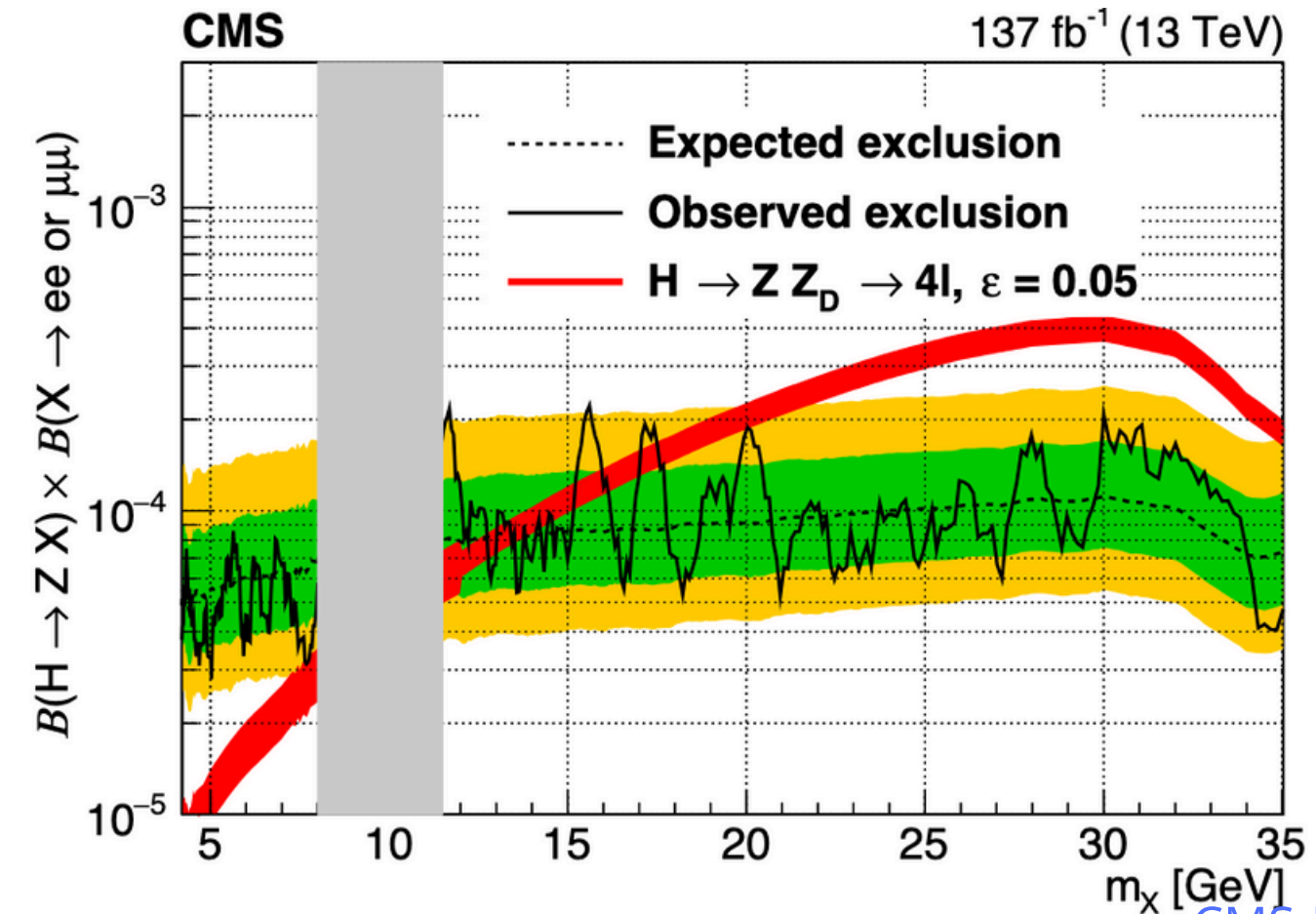
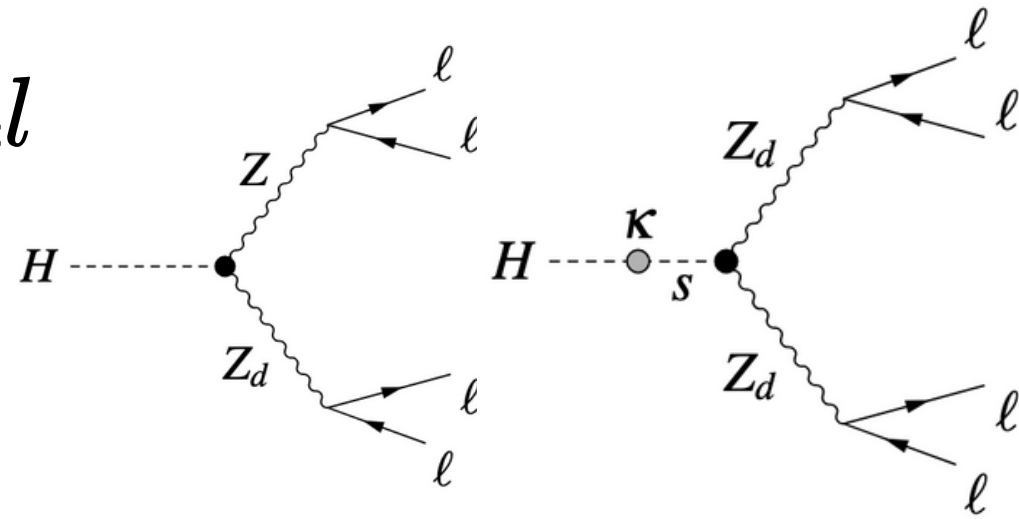
prompt

$$H \rightarrow Z_D Z_D \rightarrow 4l$$

$$H \rightarrow Z Z_D \rightarrow 4l$$

at CMS

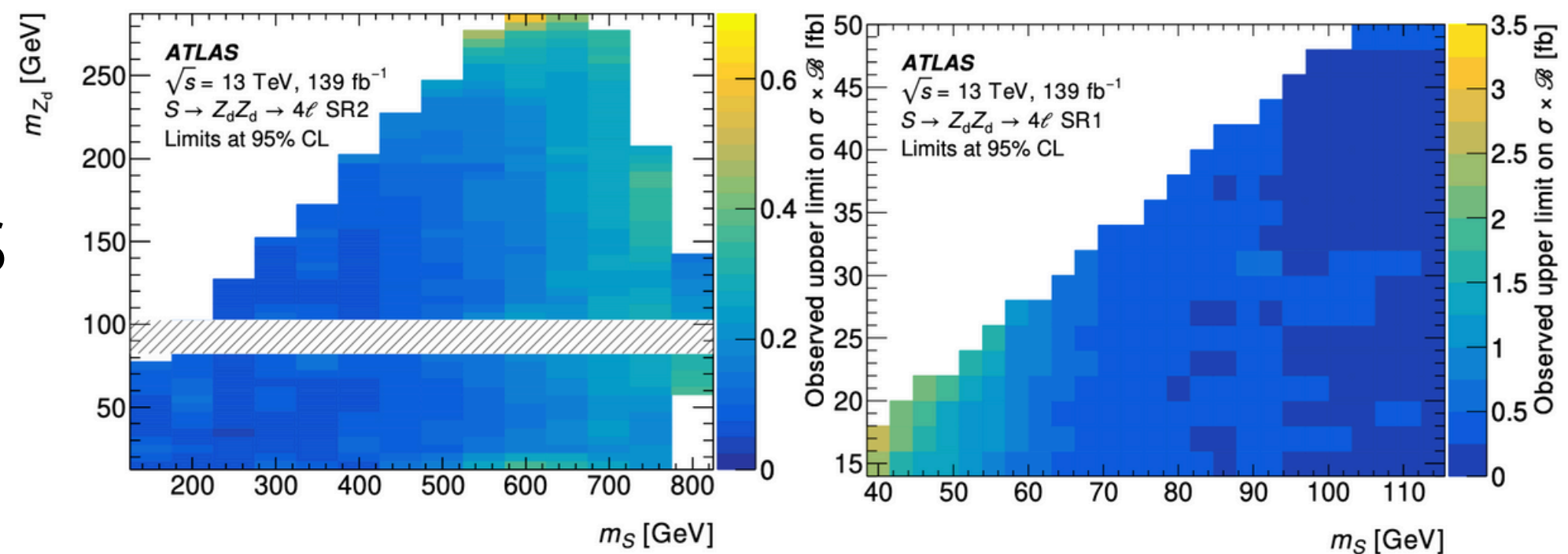
- Vectorial (ZZ_D) or scalar ($Z_D Z_D$) portal
- $m_{\gamma_D} \in [4 - 62] \text{ GeV}$



[CMS-HIG-19-007](#)

NEW! $S \rightarrow Z_D Z_D \rightarrow 4l$ at ATLAS

- Scalar portal with a new scalar boson S
- Limits on 2 parameters: m_{γ_D}, m_S
- 2 SR targeting low/high m_{ll}



[Phys. Lett. B 865 \(2025\) 139472](#)

Massive dark photon

decaying

displaced

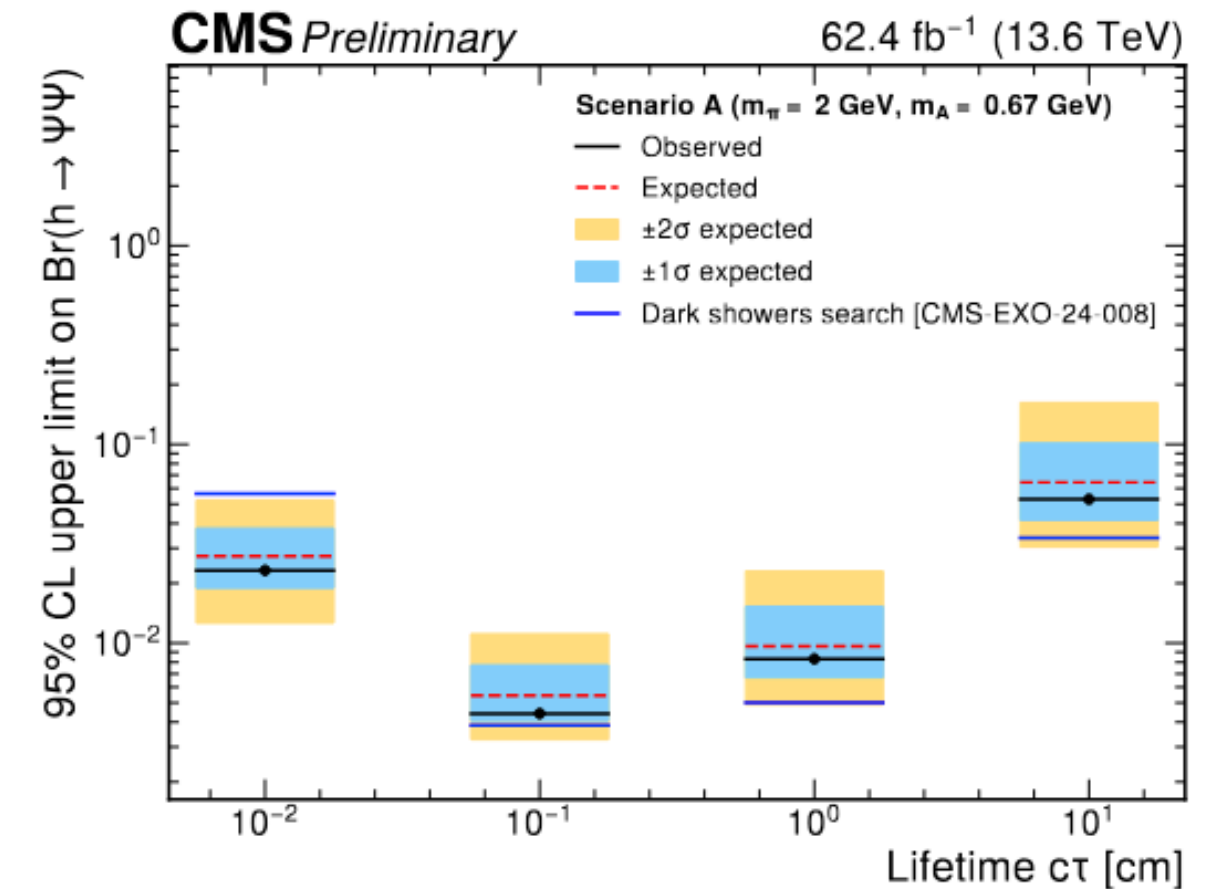
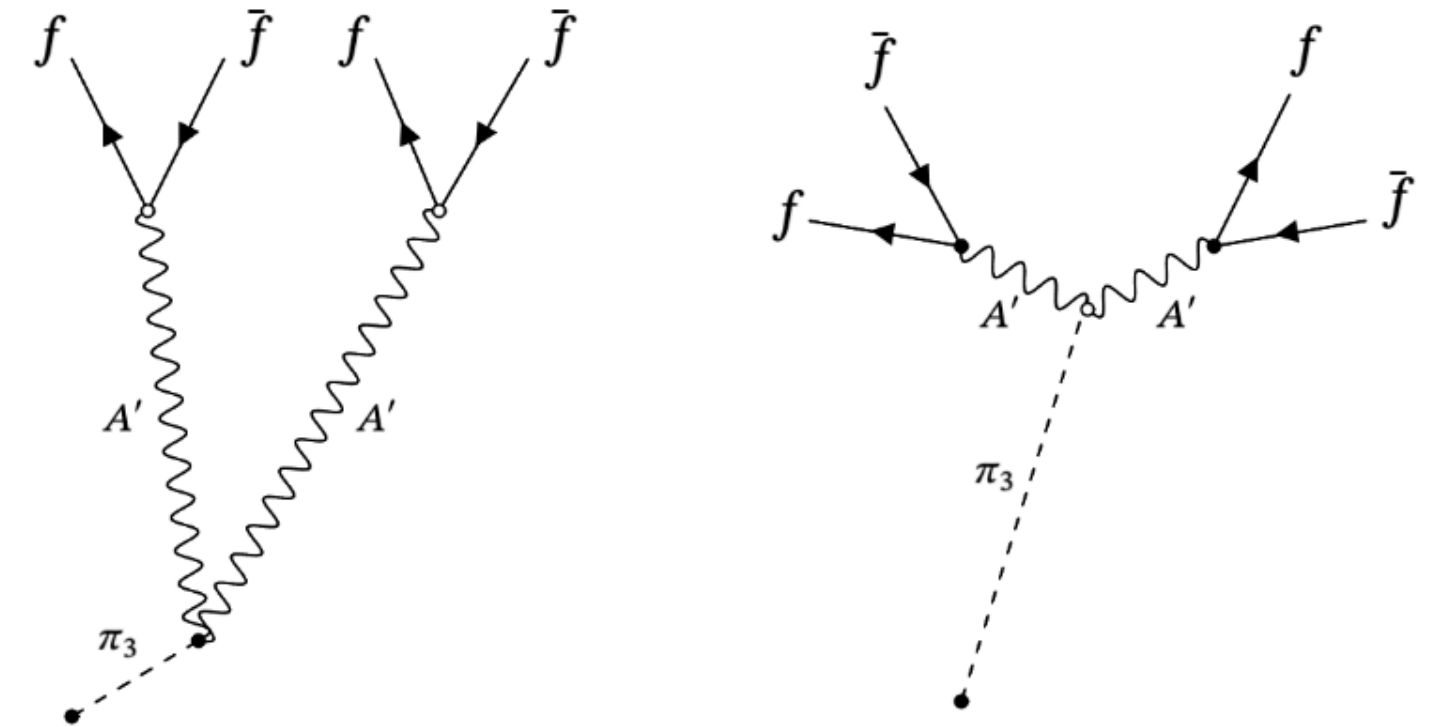


EXO-24-016 at **CMS**

High rate “scouting” trigger $H \rightarrow Z_D Z_D \rightarrow 4l$

Interpretation done also for a “dark shower” scenario, where a pseudo-boson π_3 of the dark gauge group decays into dark photons

- scenario A: long-lived dark photon (2DV)
- scenario B: π_3 is long-lived (1 DV)



Massive dark photon

decaying

displaced

other models

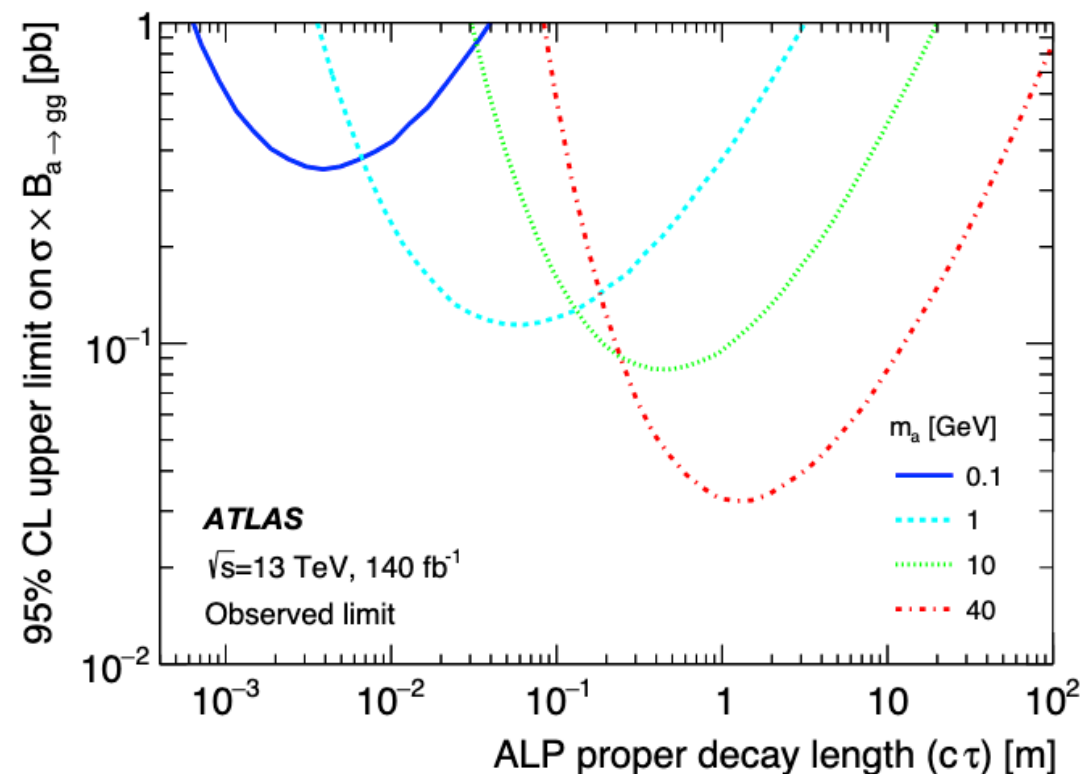
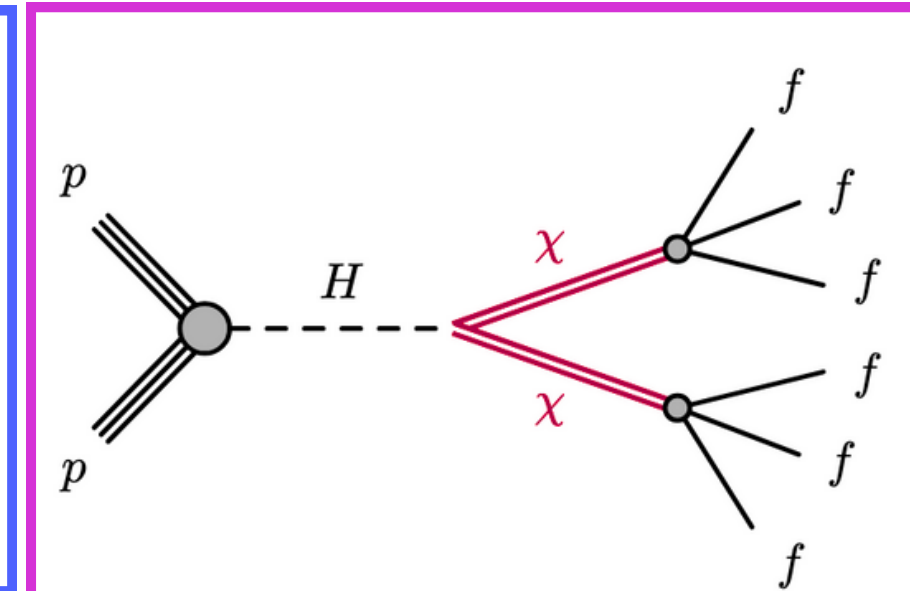
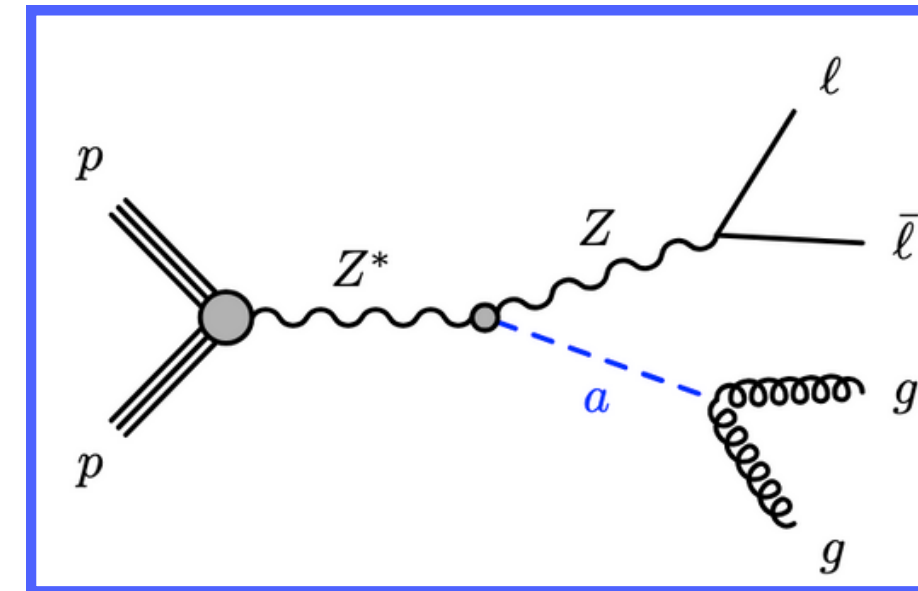
NEW! Events with displaced jets in the Muon Spectrometer

at **ATLAS**

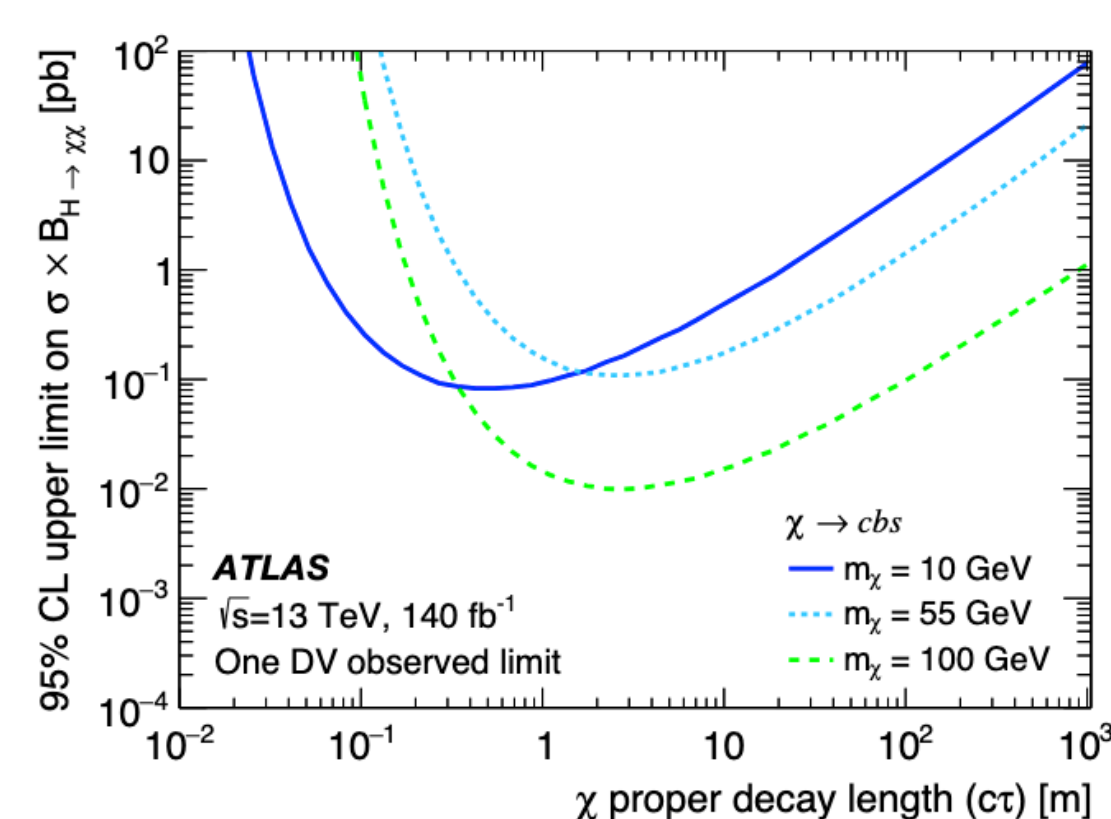
[Submitted to: Phys. Rev. D.](#)

• Several signal models, among which:

- Z+ALP
- baryogenesis

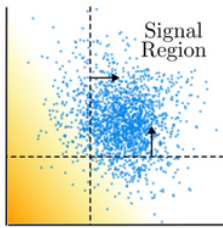


Results for
Z+ALP model



Results for
baryogenesis
model

Emerging jets



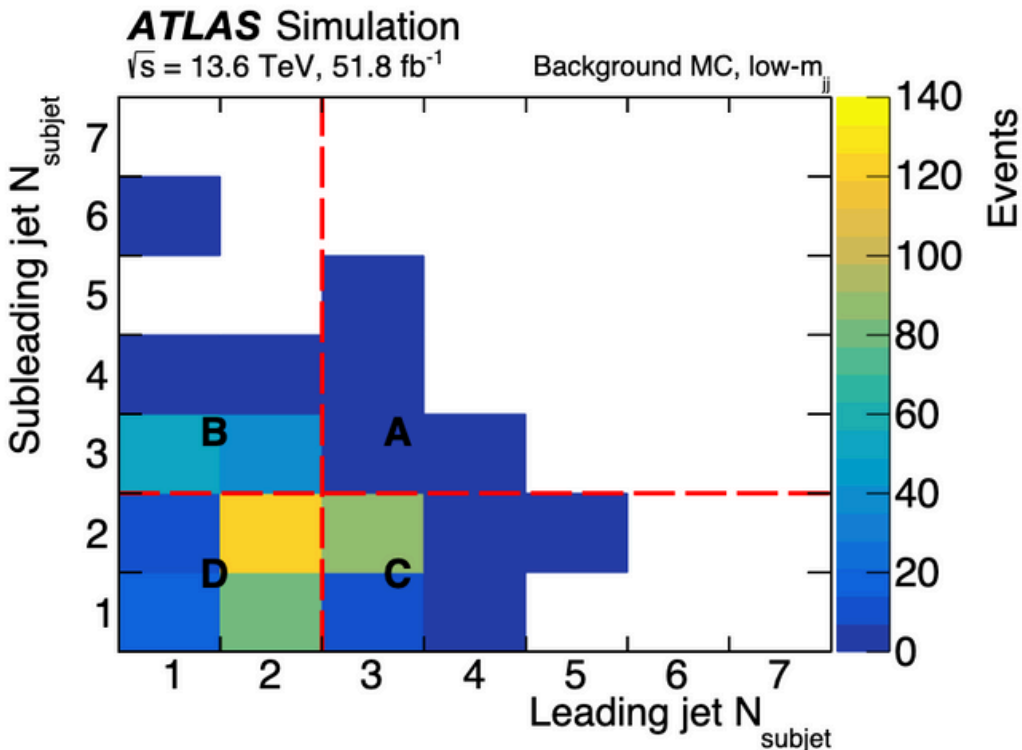
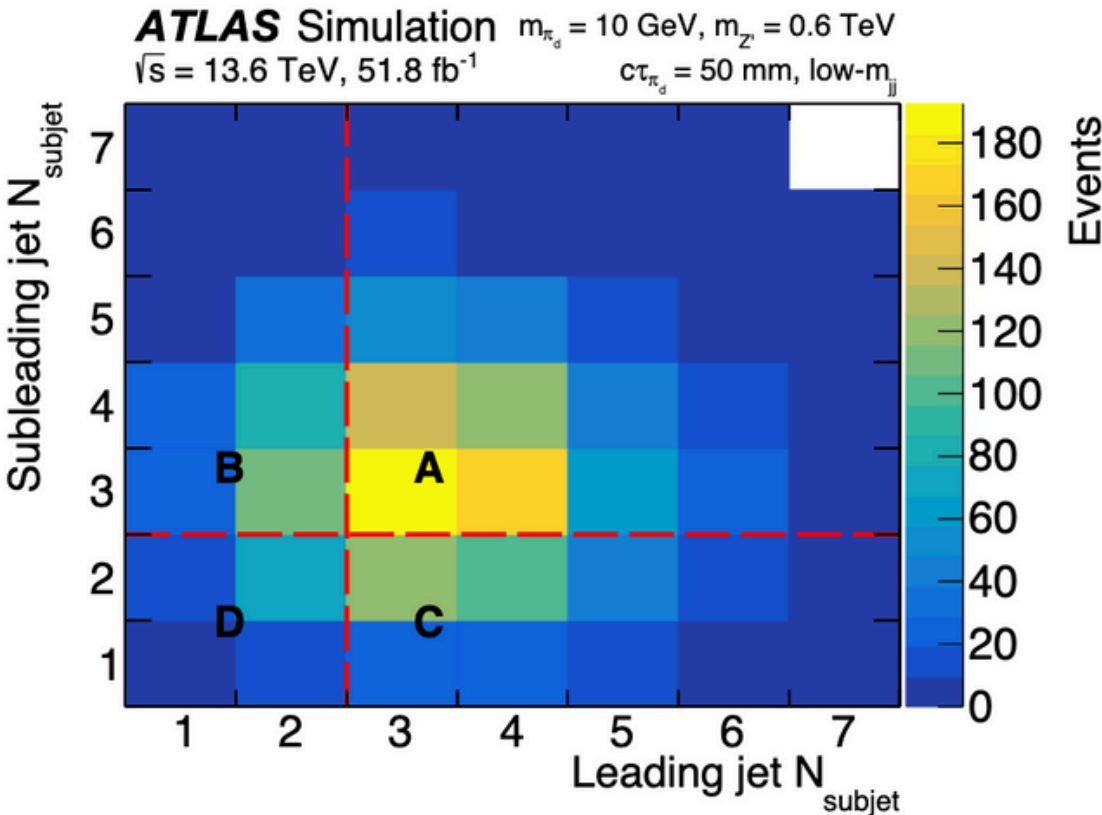
Cut-based analysis



Signal

Background

low m_{jj}

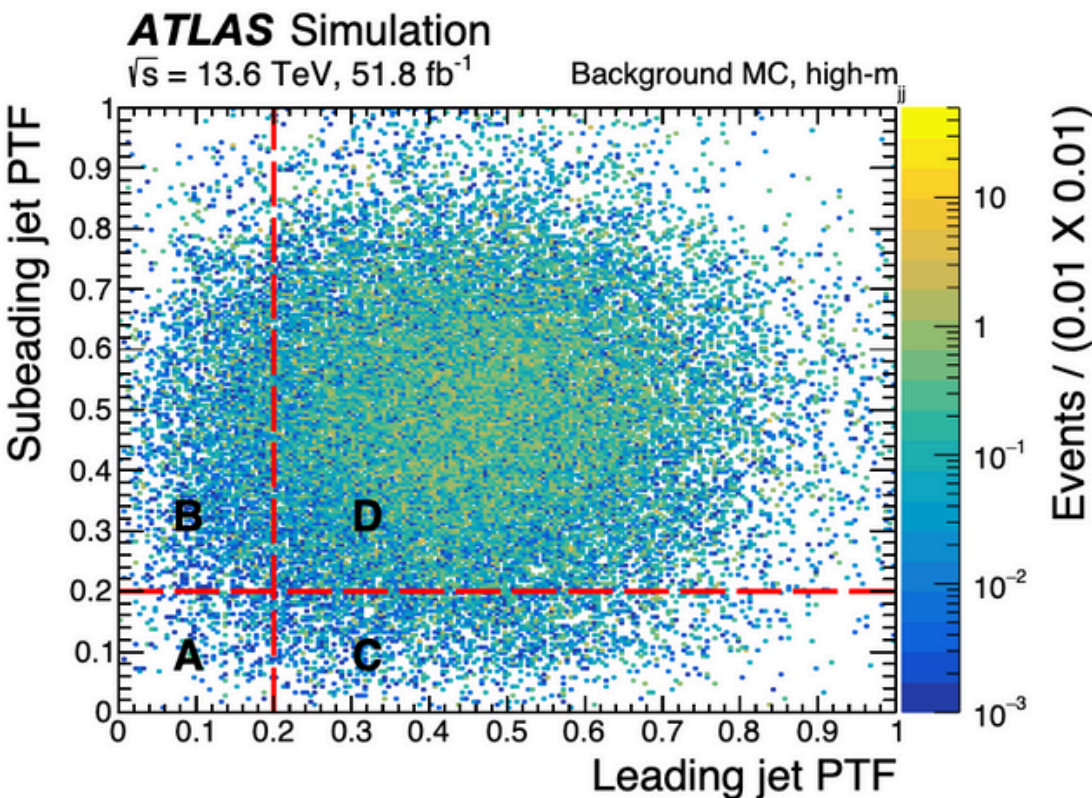
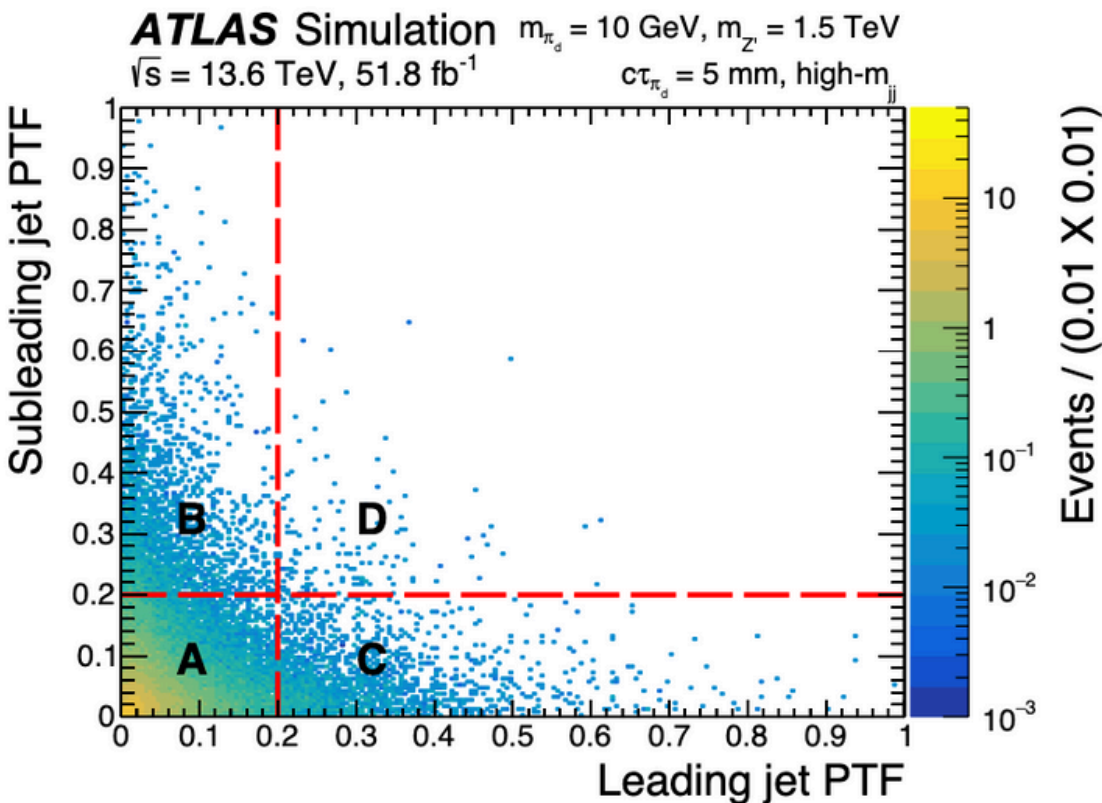


ABCD method

$$N_A = \frac{N_B \times N_C}{N_D}$$

where A is the Signal Region

high m_{jj}



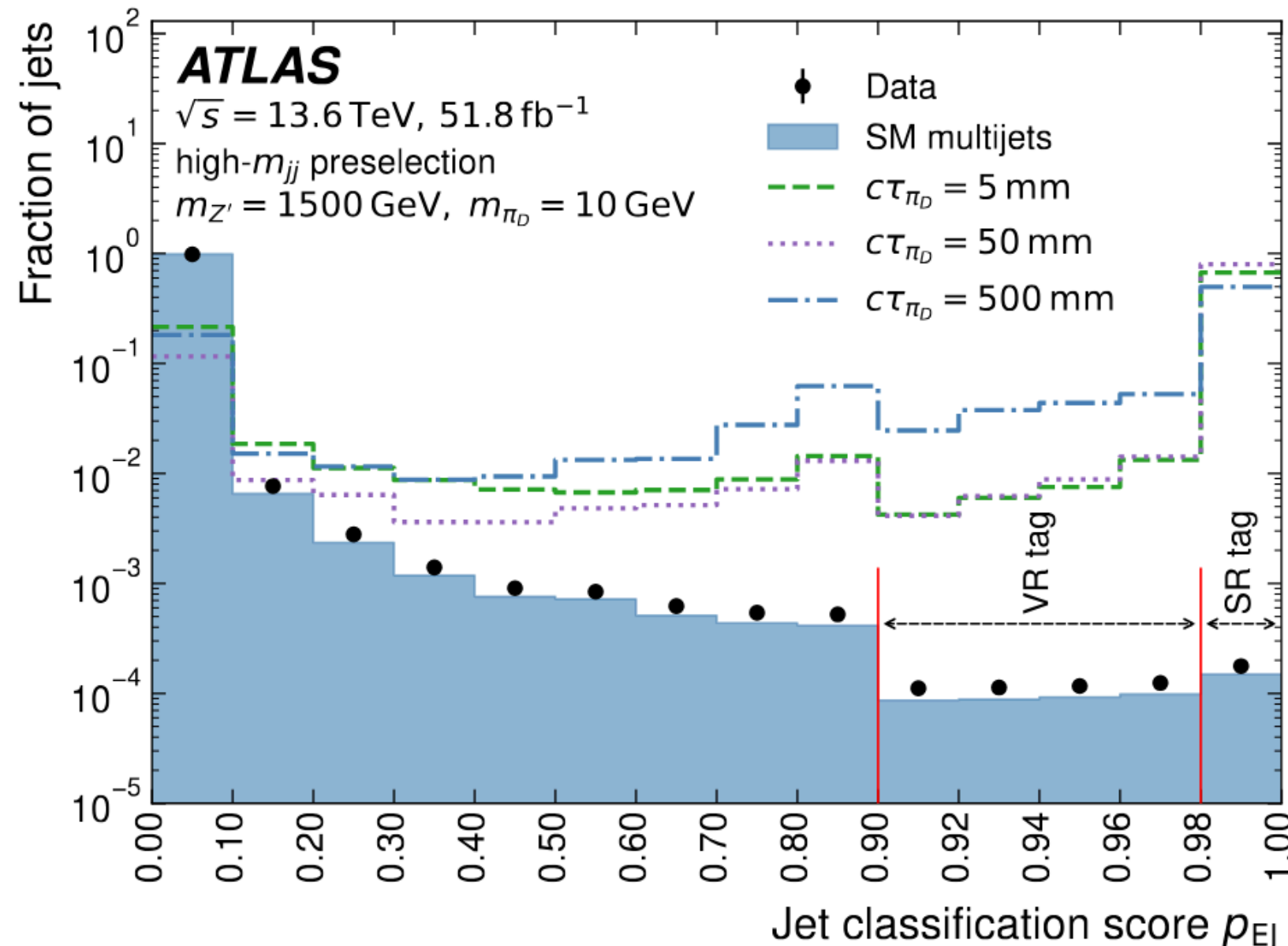
Emerging jets



ML-based analysis

GNN performing 3 tasks at the same time:

- prompt or emerging jets
- prompt, displaced, pileup, or fake tracks
- if 2 tracks originate from the same vertex



[Rep. Prog. Phys. 88 \(2025\) 097801](#) at **ATLAS**

jet mistag rate method

1. Compute mistag rate (probability for a bkg jet to be misclassified as signal) in a $n_{tag} < 2$ CR in bins of pT, PTF
2. Compute per-event weights (probabilities):

$$P(1 \text{ tag} | \text{event}) = \sum_{i=1}^{n_{\text{jet}}} P(\text{tag} | j_i) \times \prod_{k \neq i} (1 - P(\text{tag} | j_k))$$

$$P(0 \text{ tag} | \text{event}) = \prod_{i=1}^{n_{\text{jet}}} (1 - P(\text{tag} | j_i))$$

$$P(\geq 2 \text{ tag} | \text{event}) = 1 - P(1 \text{ tag} | \text{event}) - P(0 \text{ tag} | \text{event})$$

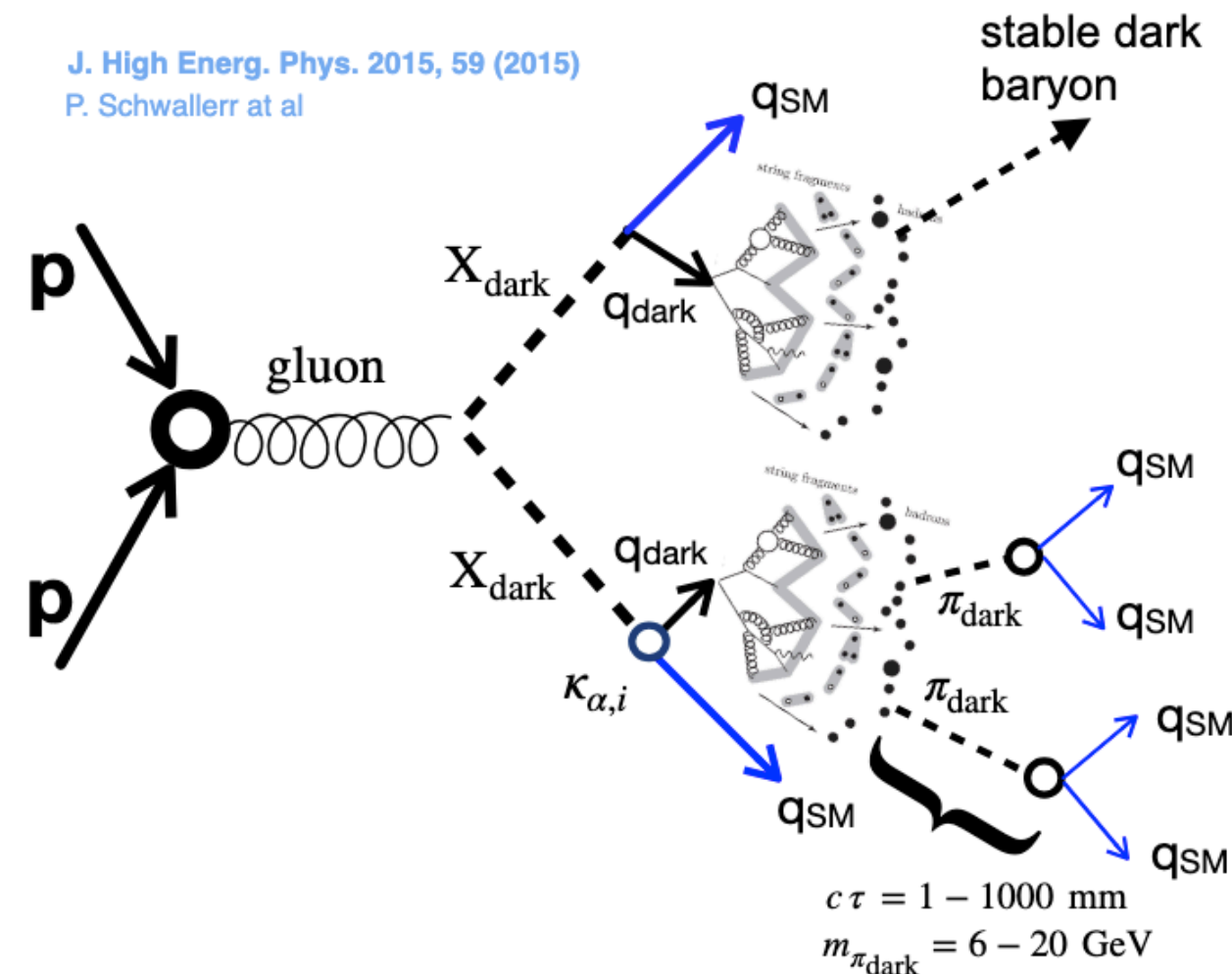
3. Obtain number of events in ≥ 2 region as sum-of-weights of per-event weight

2 scenarios considered:

- **unflavored**: only coupling of dark quarks to SM d-quarks is not negligible
- **flavored-aligned**: coupling of dark quarks to all SM d-type quarks is not negligible

Search performed with 2 different strategies:

- **model agnostic**: using track displacement and # of displaced tracks
- **GNN-based**: ParticleNet-like informed with track displacement

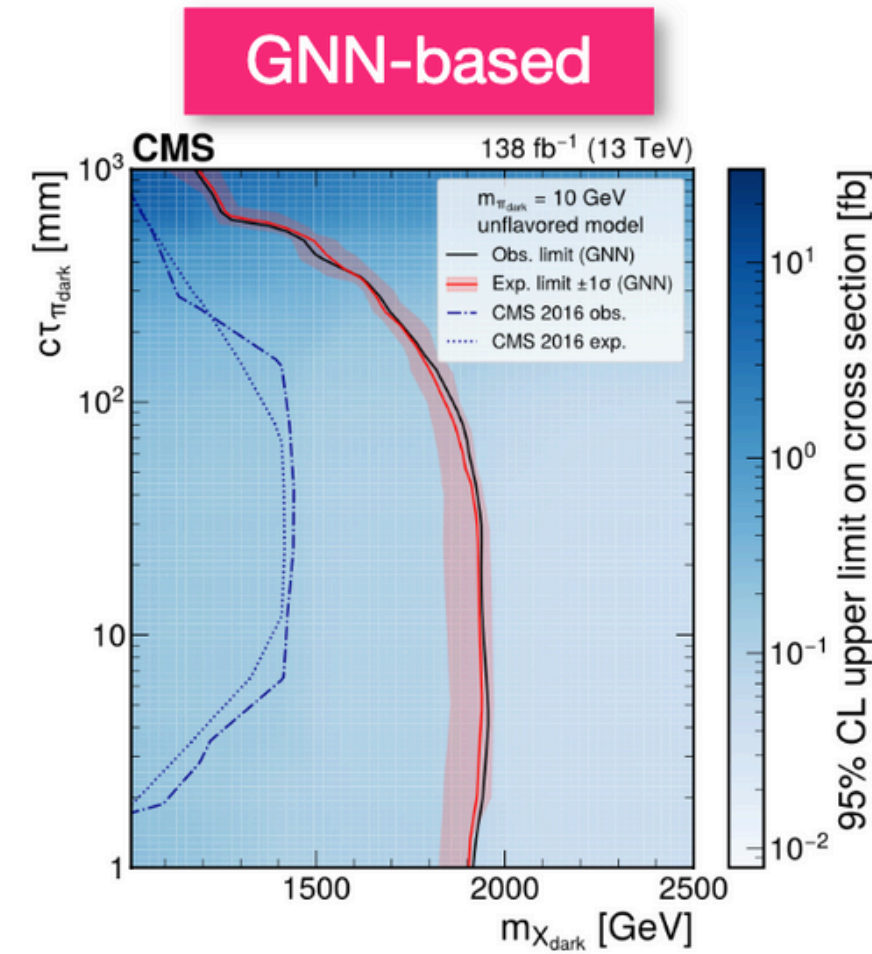
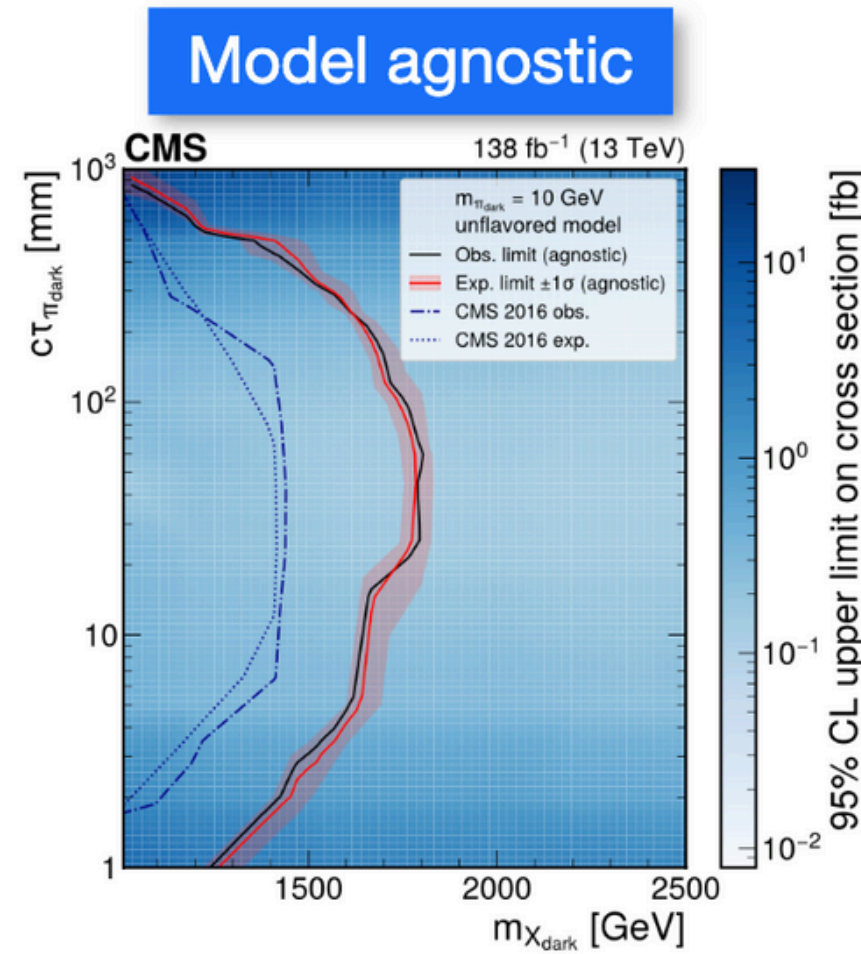


Emerging jets

JHEP07(2024)142

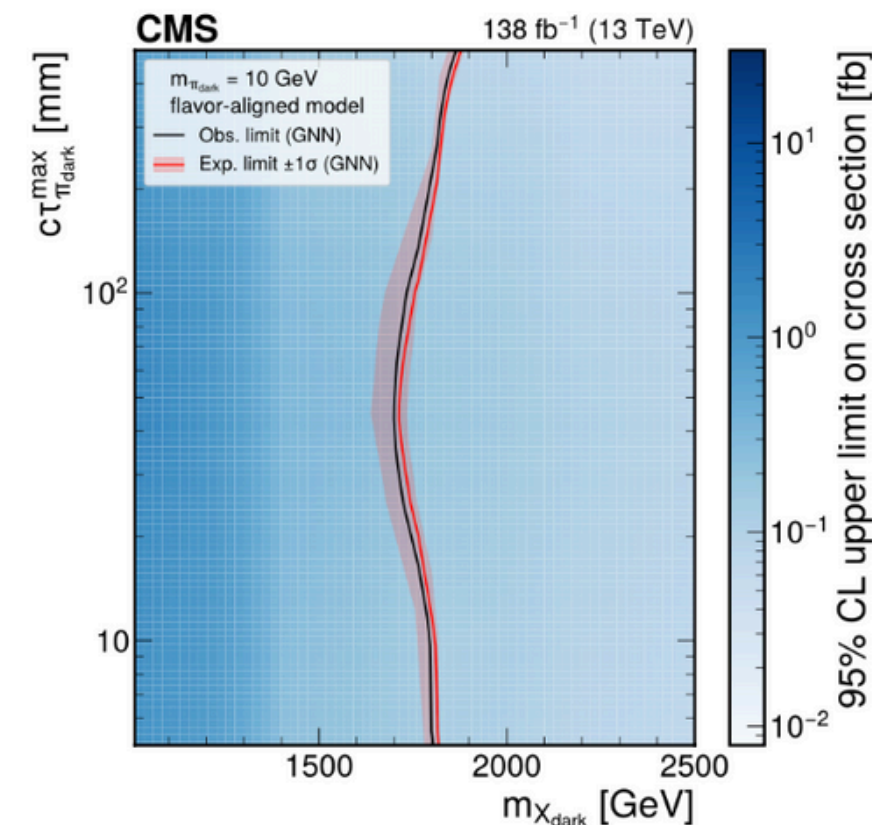
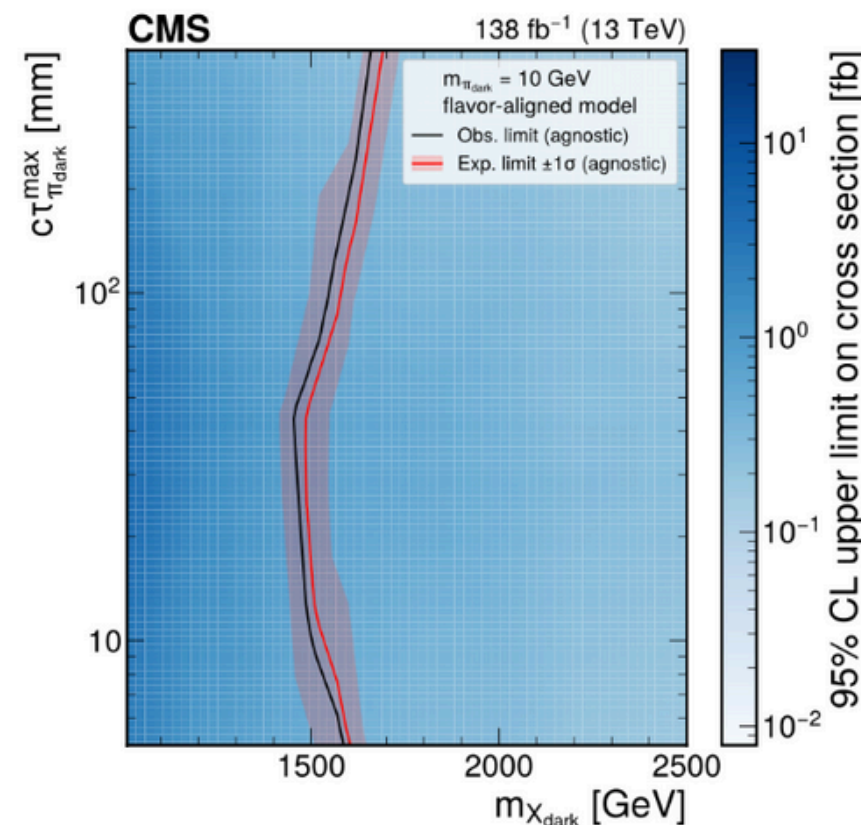
at CMS

limits depending on
track displacement
within jets



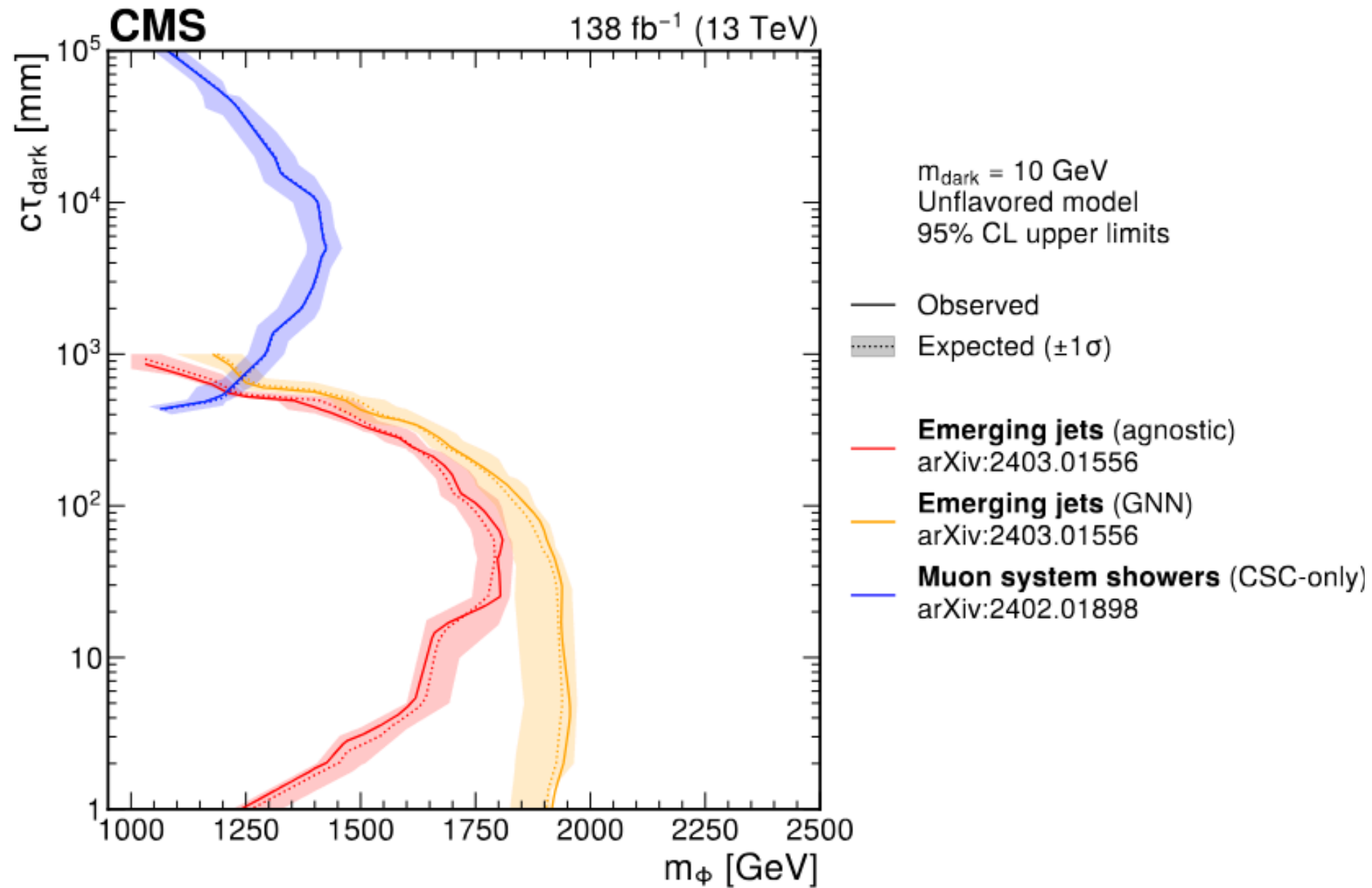
improves sensitivity
at short dark pion
lifetimes

limits depending on
displaced tracks
multiplicities within
jets

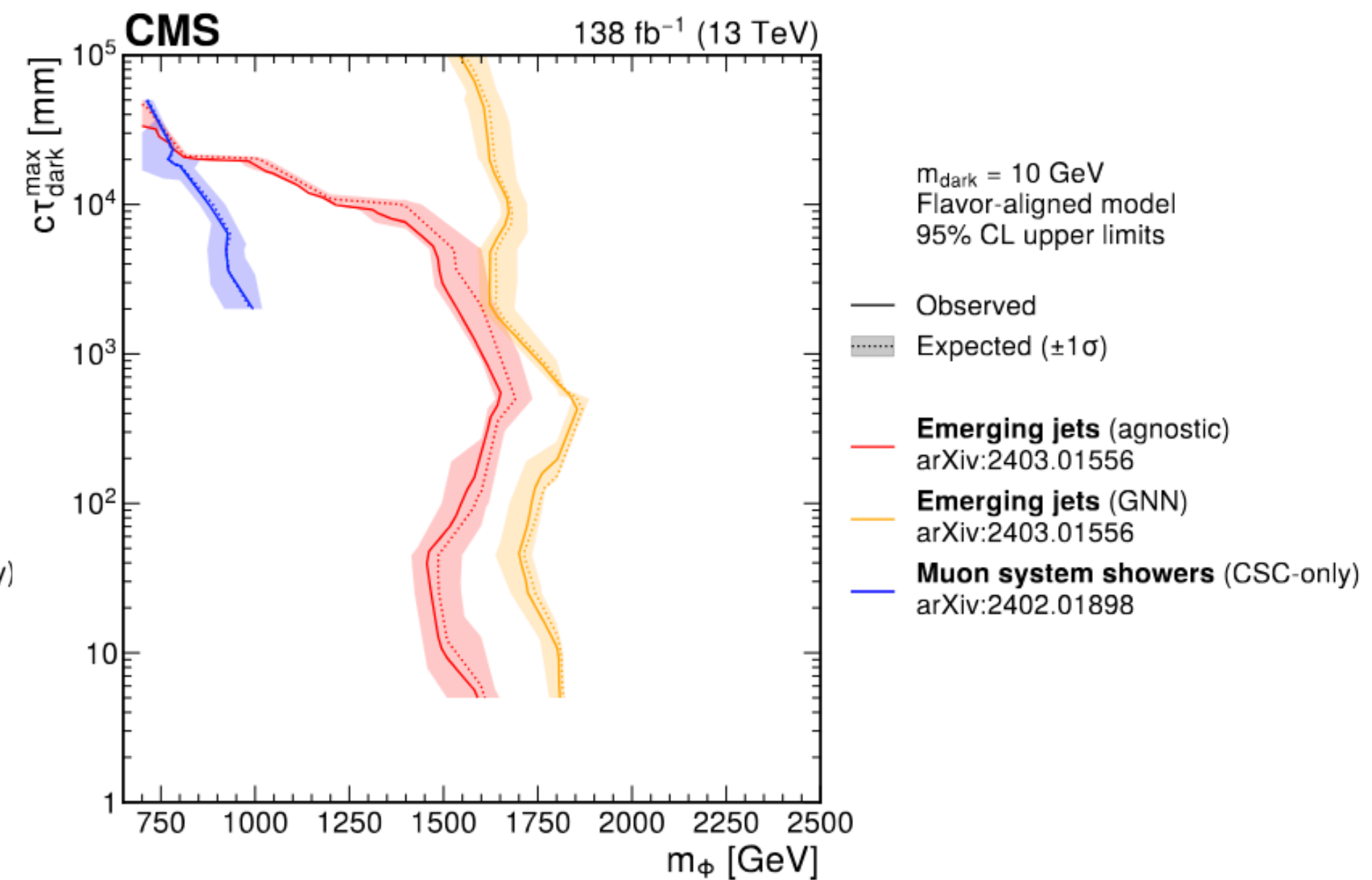


improves sensitivity
uniformly in the dark
pion lifetimes

unflavored



flavored-aligned



Semi Visible jets



EXO-24-029 at CMS

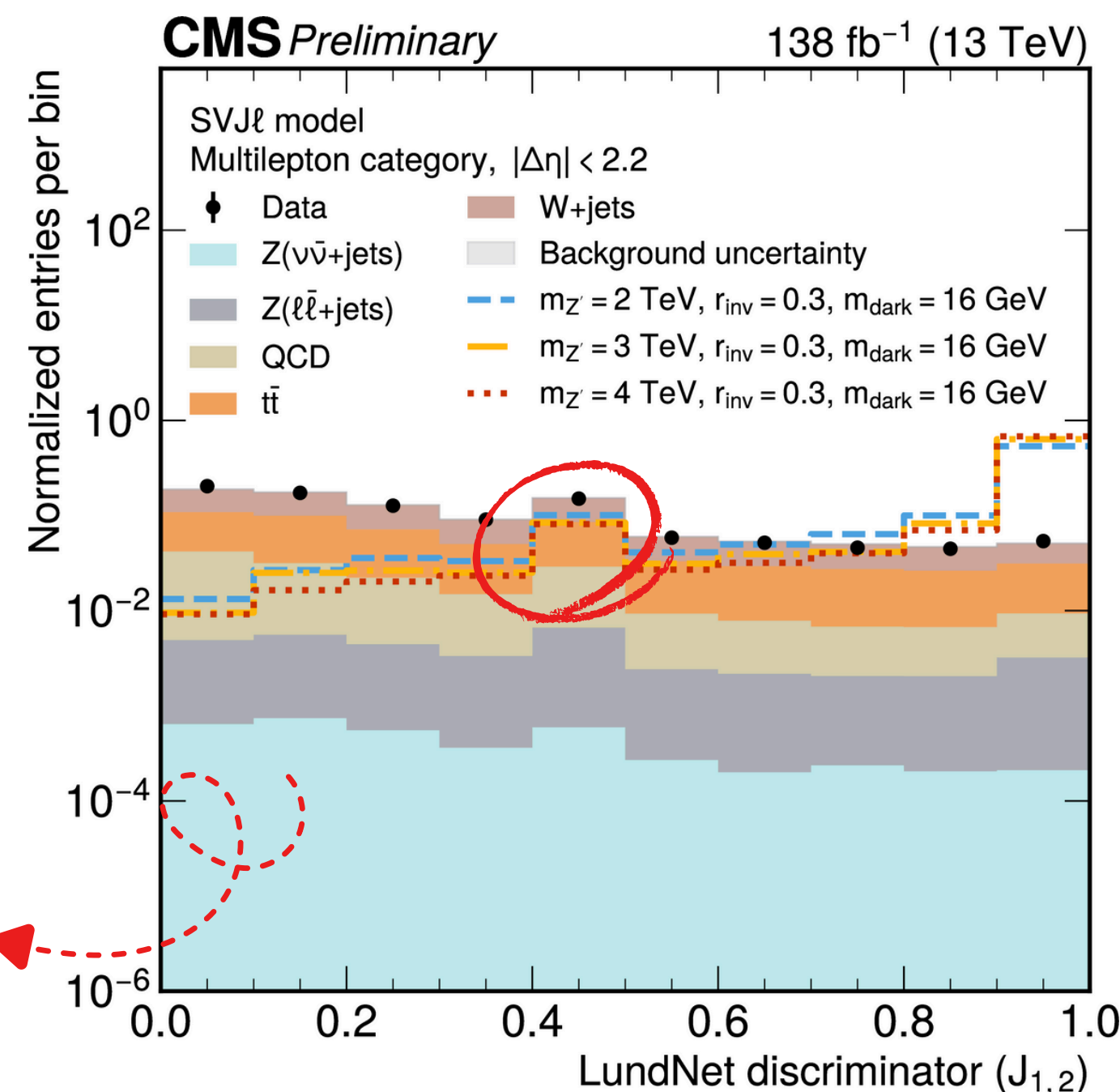
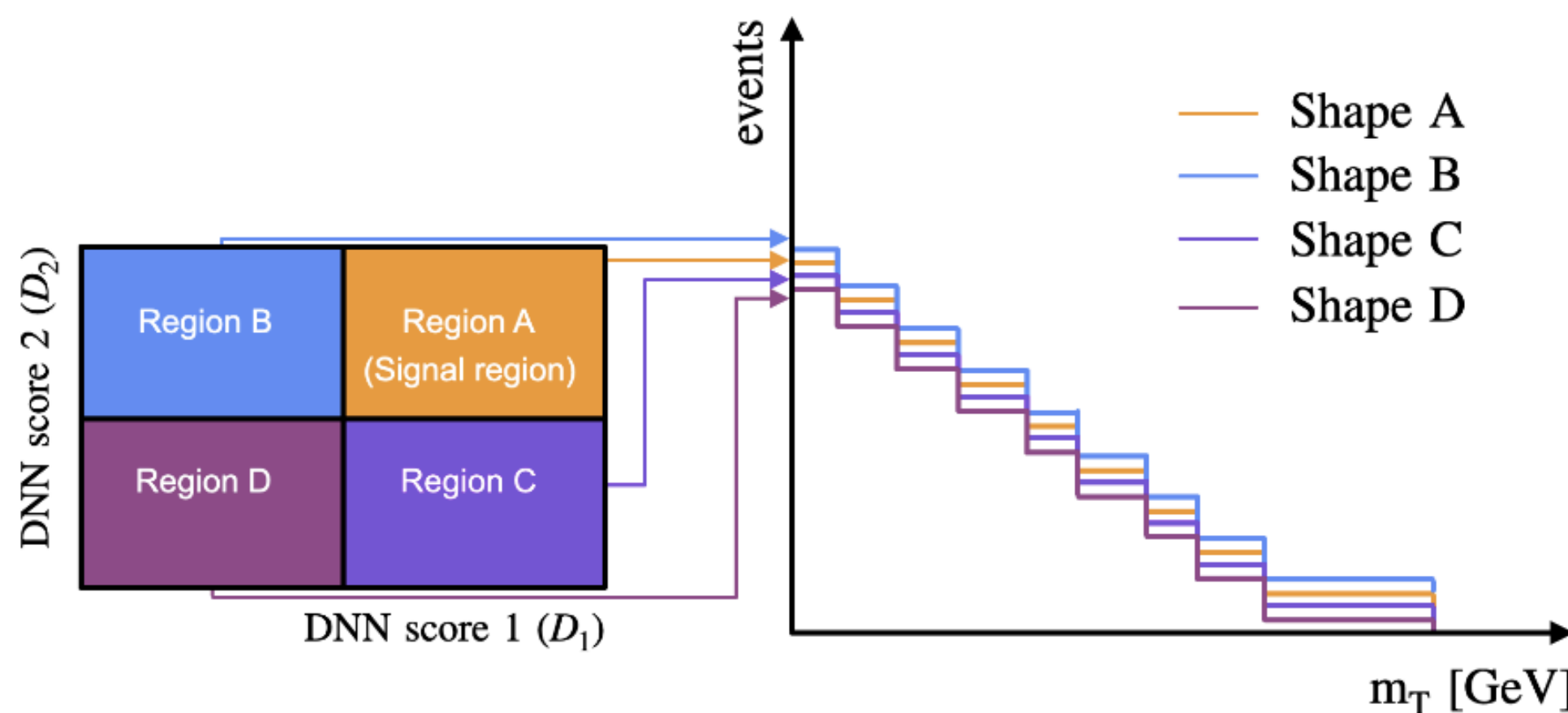
Goal: search for a peak in m_T

→ need DNNs decorrelated from m_T

→ now you can apply ABCD in bins of m_T

include explicit decorrelation terms
in the loss function

$$L_{\text{DisCo}}(D_1, D_2), L_{\text{DisCo}}(D_1, m_T), \text{ and } L_{\text{DisCo}}(D_2, m_T)$$



Draw-back of pruning: trees can be sometimes too shallow leading GNN to confuse bkg and sig jets

Semi Visible jets



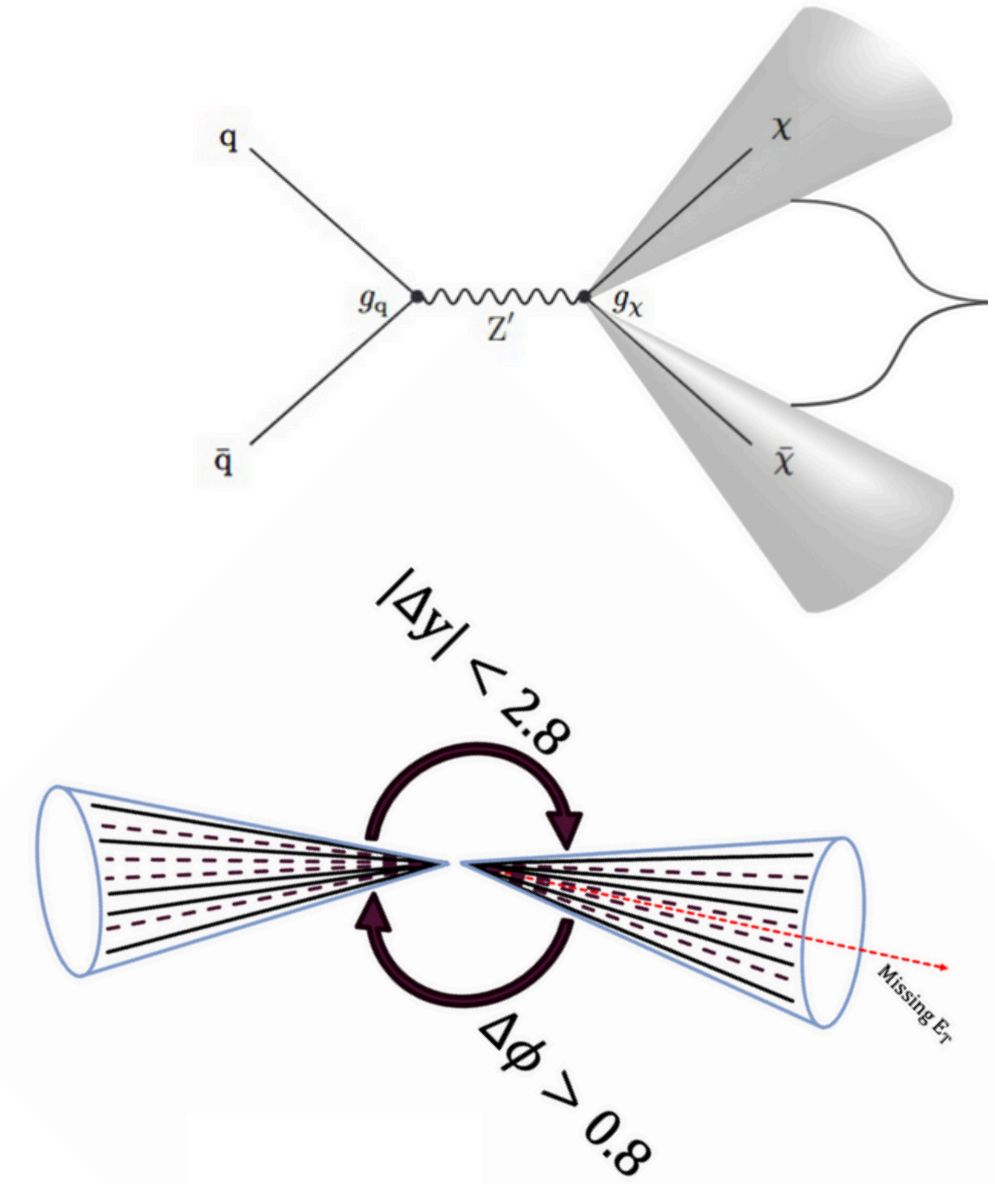
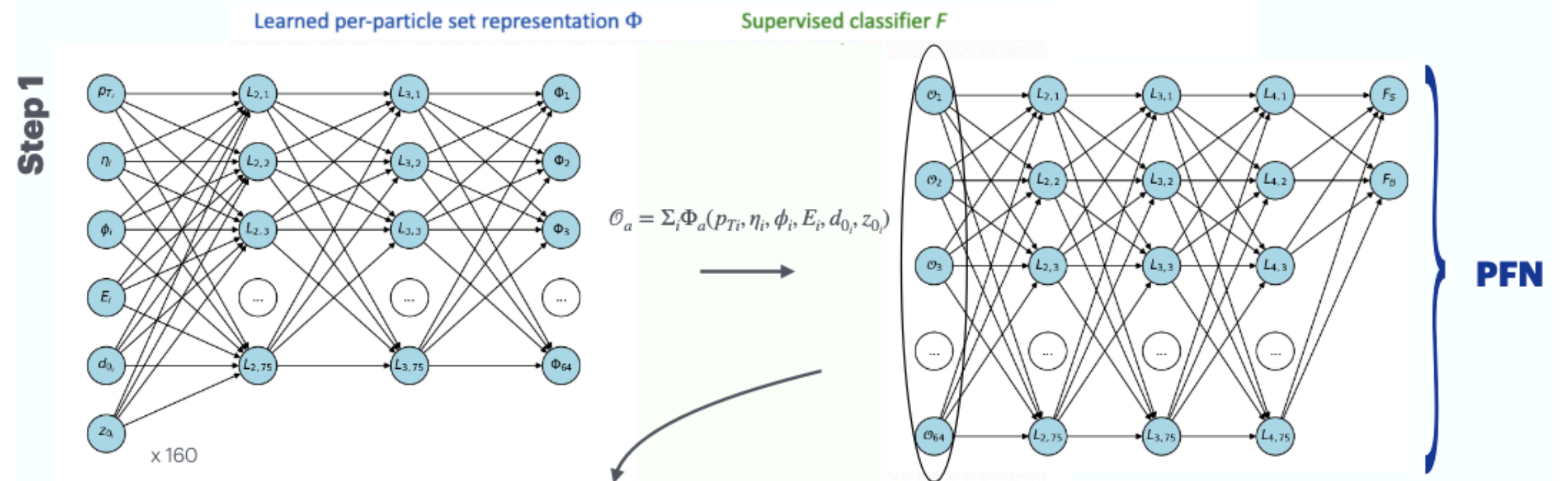
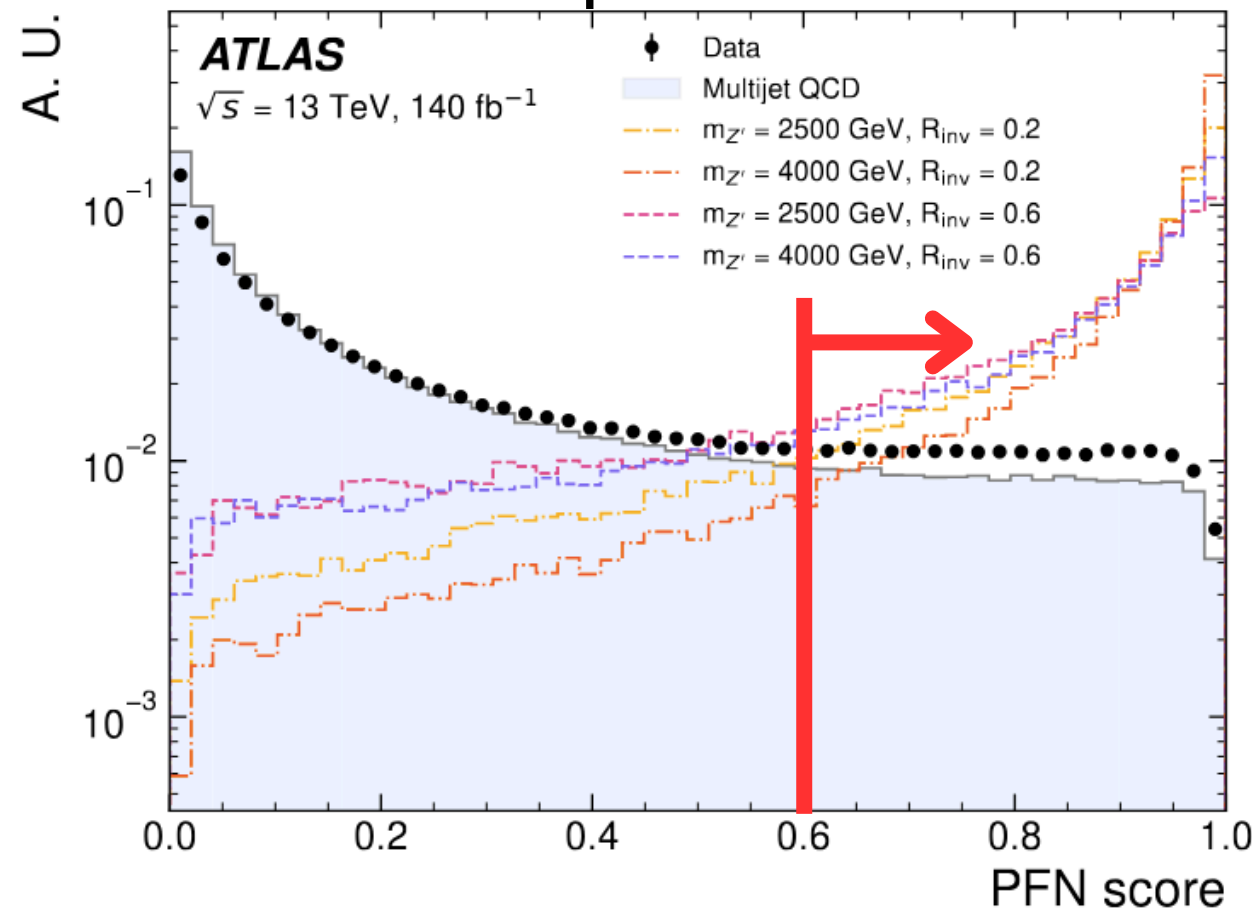
Phys. Rev. D 112 (2025) 012021 at **ATLAS**

ML analysis strategy: the tool should be:

- permutation-invariant (tracks not ordered)
- variable lengths of inputs (different # of tracks for each jet)

Particle Flow Network (PFN)

- supervised-training
- summing over all tracks ensures permutation-invariant
- model dependent



Semi Visible jets



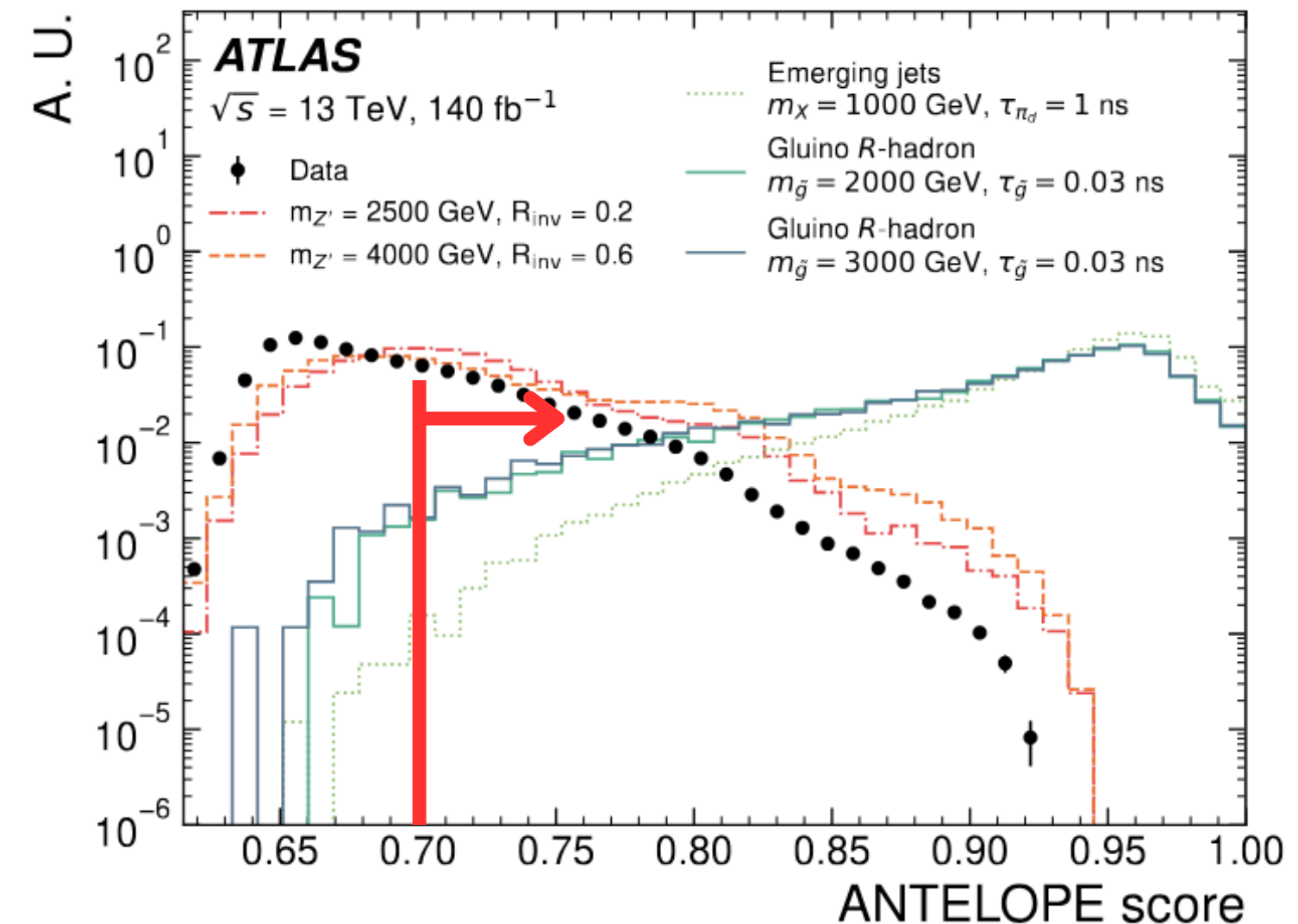
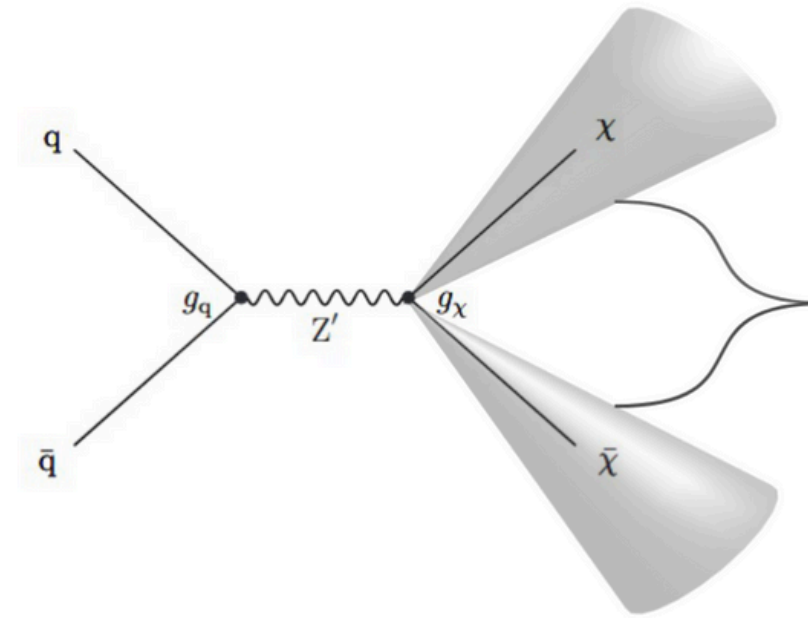
[Phys. Rev. D 112 \(2025\) 012021](#) at **ATLAS**

ML analysis strategy: the tool should be:

- permutation-invariant (tracks not ordered)
- variable lengths of inputs (different # of tracks for each jet)

ANomaly deTEction on particLe fLOW latent sPacE (ANTELOPE)

- semi-supervised training: training on data events, but PFN used for basis change
- sum all tracks ensures permutation-invariant
- model-independent  works also for other signatures

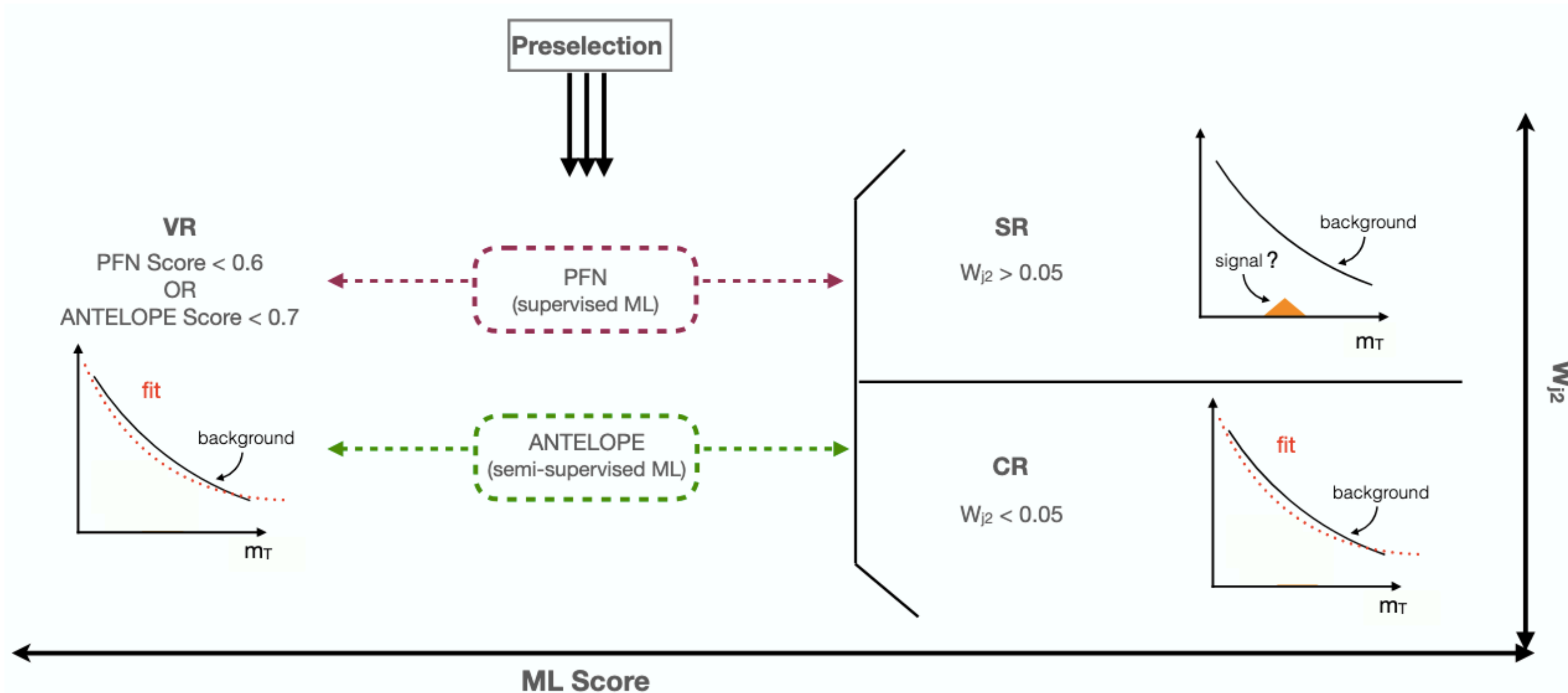


Semi Visible jets



[Phys. Rev. D 112 \(2025\) 012021](#) at **ATLAS**

- SR and CR defined on width of subleading jet
- VR defined by cutting on PFN/ANTELOPE score
- fit performed on transverse mass, computed from 2 leading jets and $p_{T\text{miss}}$

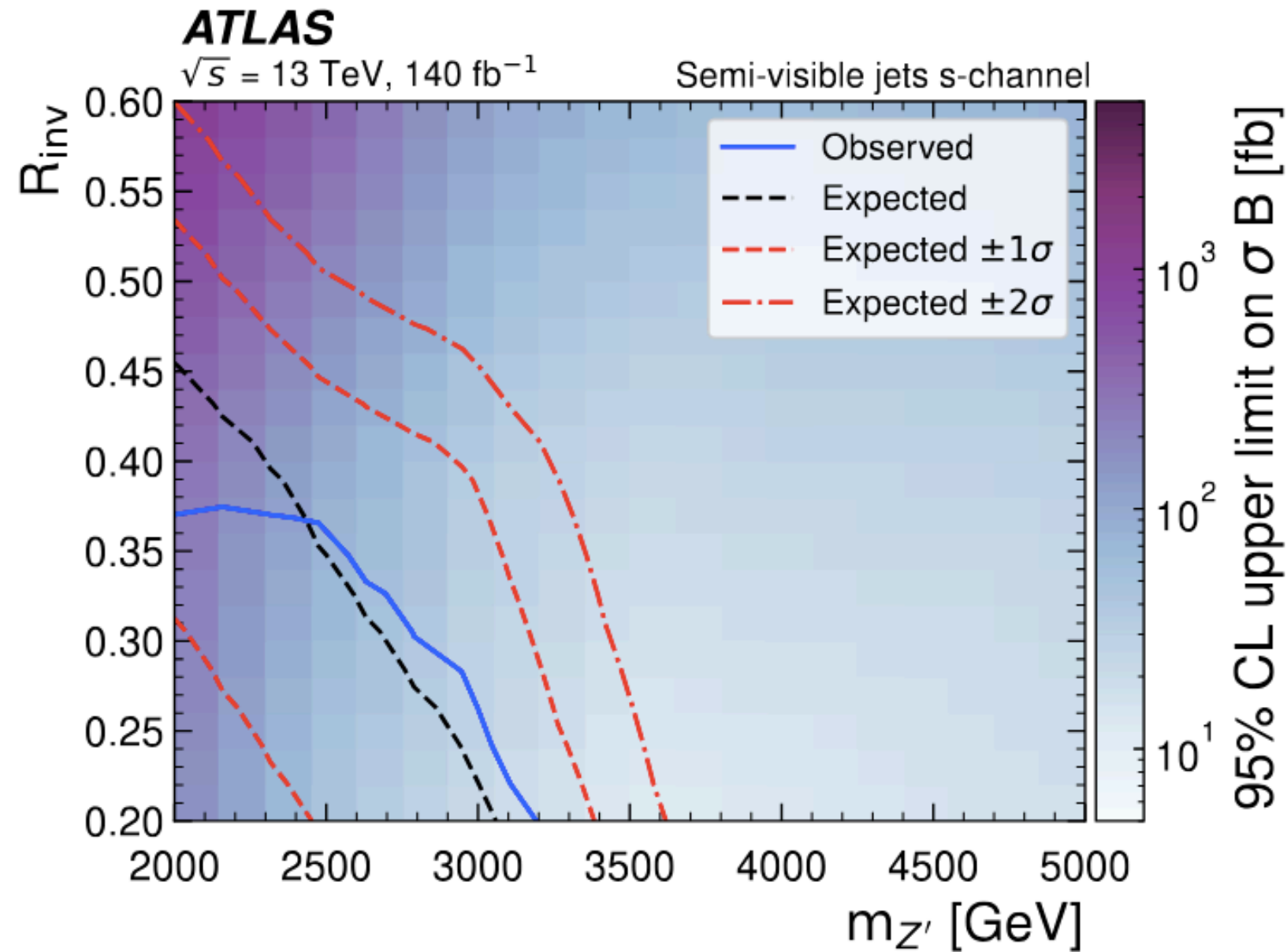


Semi Visible jets

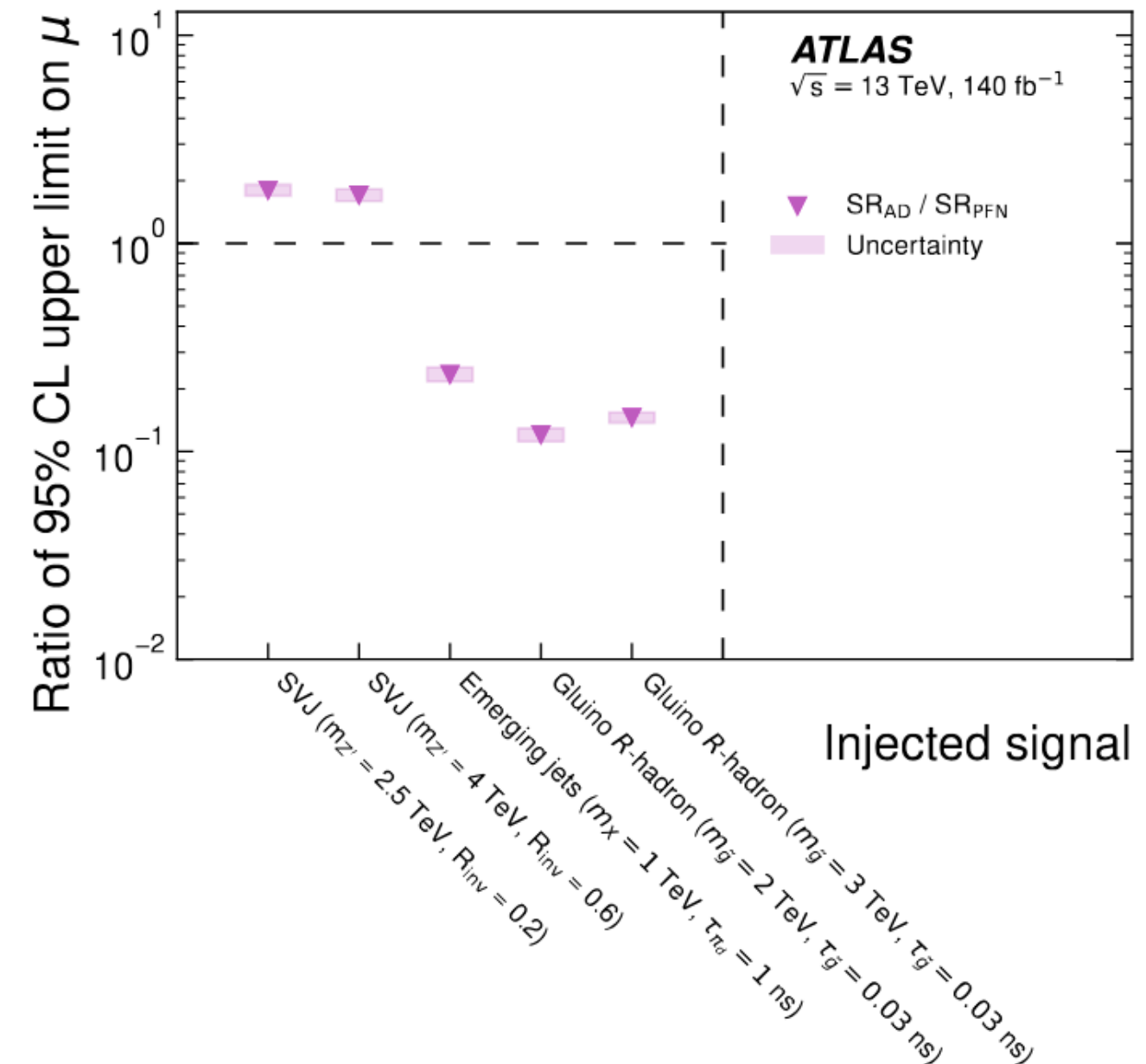


[Phys. Rev. D 112 \(2025\) 012021](#) at **ATLAS**

Results for PFN and ANTELOPE strategies



Higher R_{inv} less excluded

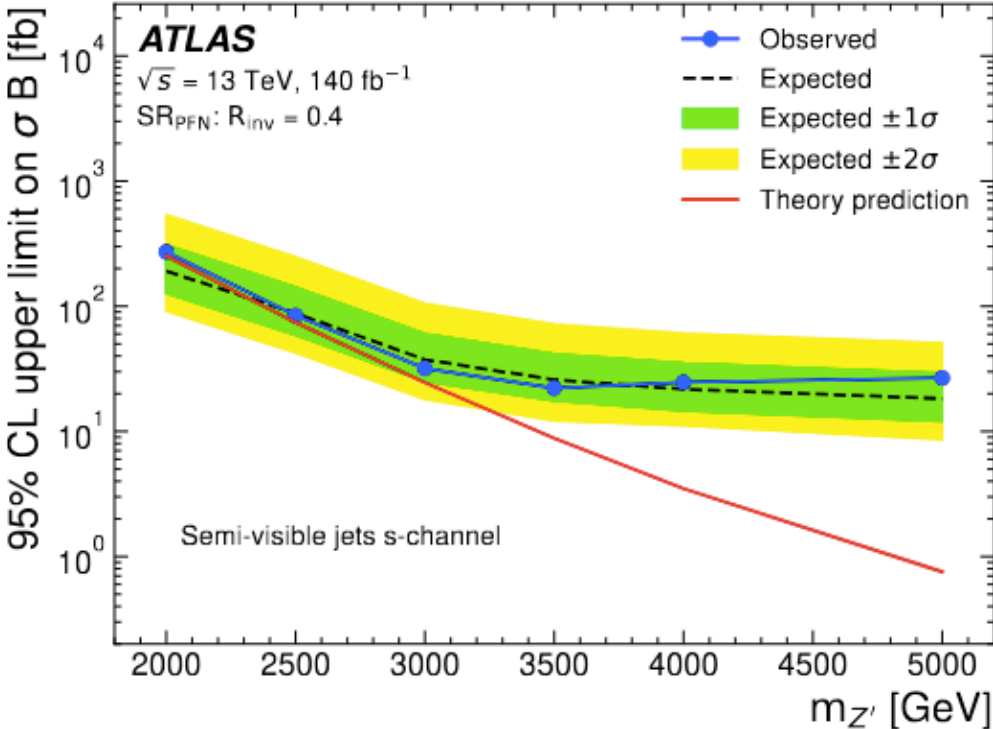
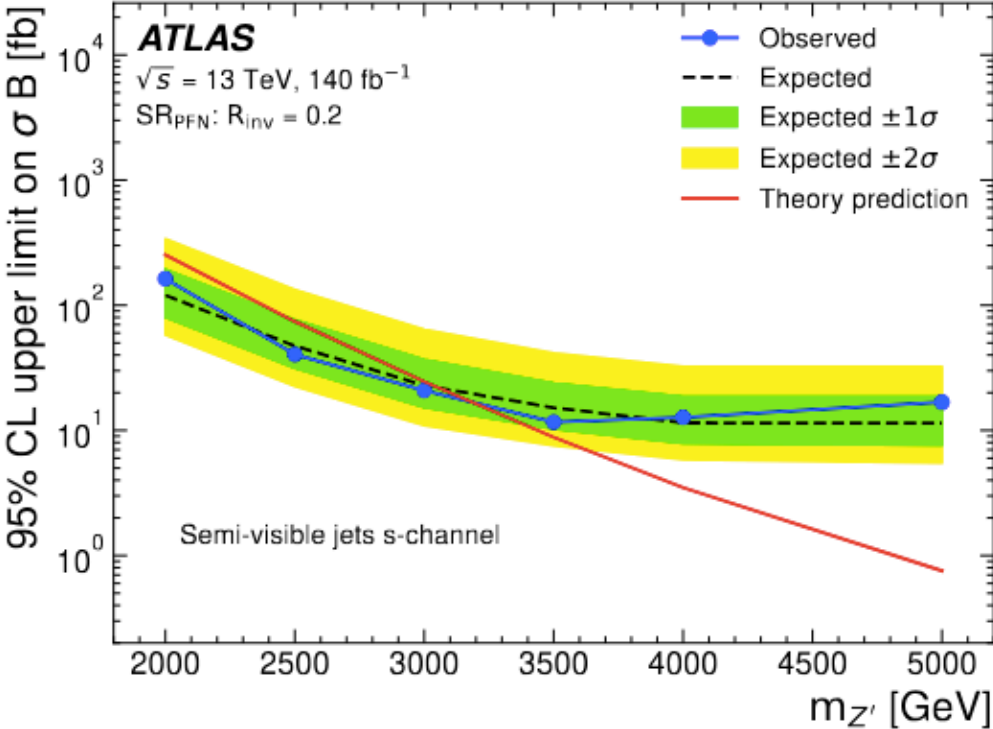


PFN works better for SVJ while
ANTELOPE for emerging jets & gluinos

Semi Visible jets

Comparison of ATLAS and CMS results

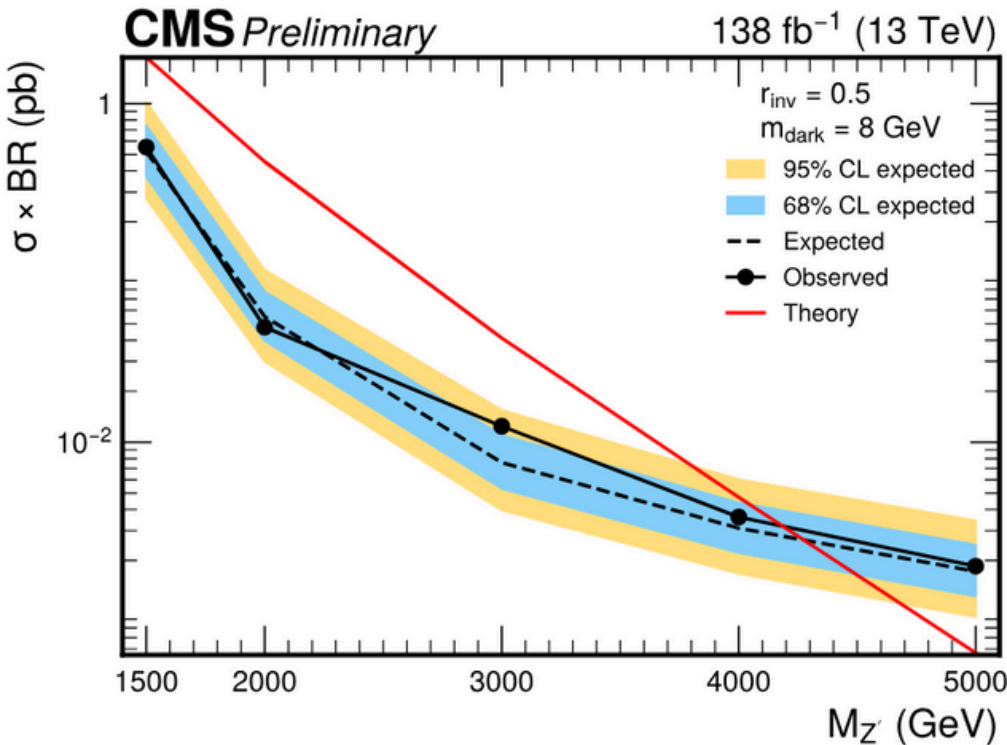
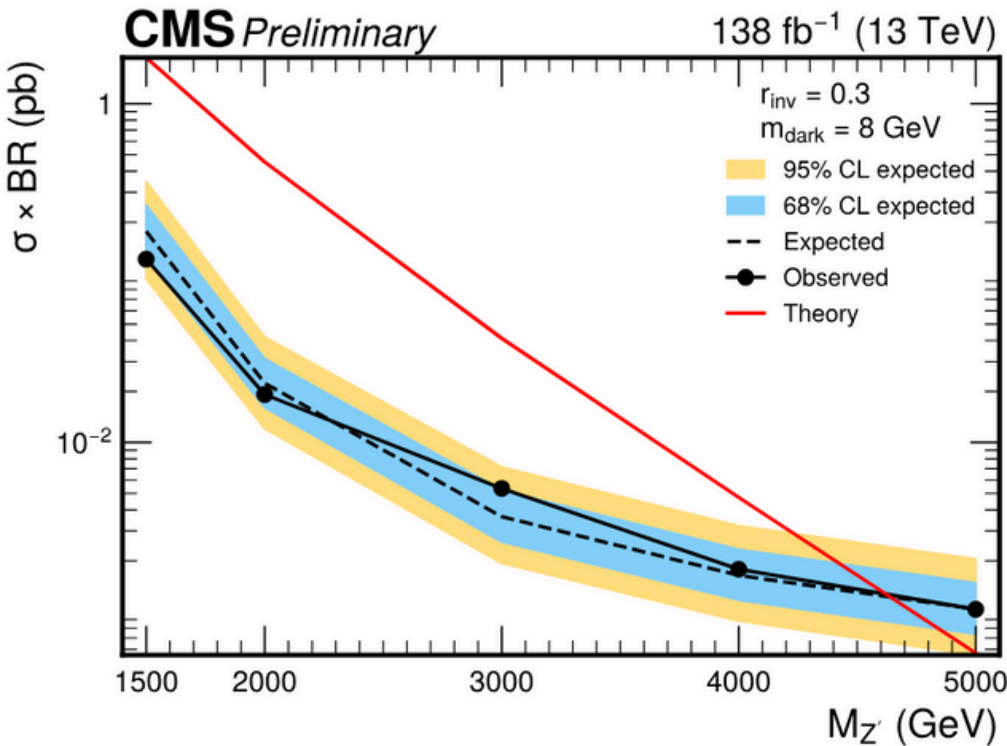
$$m_{\chi} = 10\text{GeV}$$



Phys. Rev. D 112 (2025) 012021 at **ATLAS**

EXO-24-029 at **CMS**

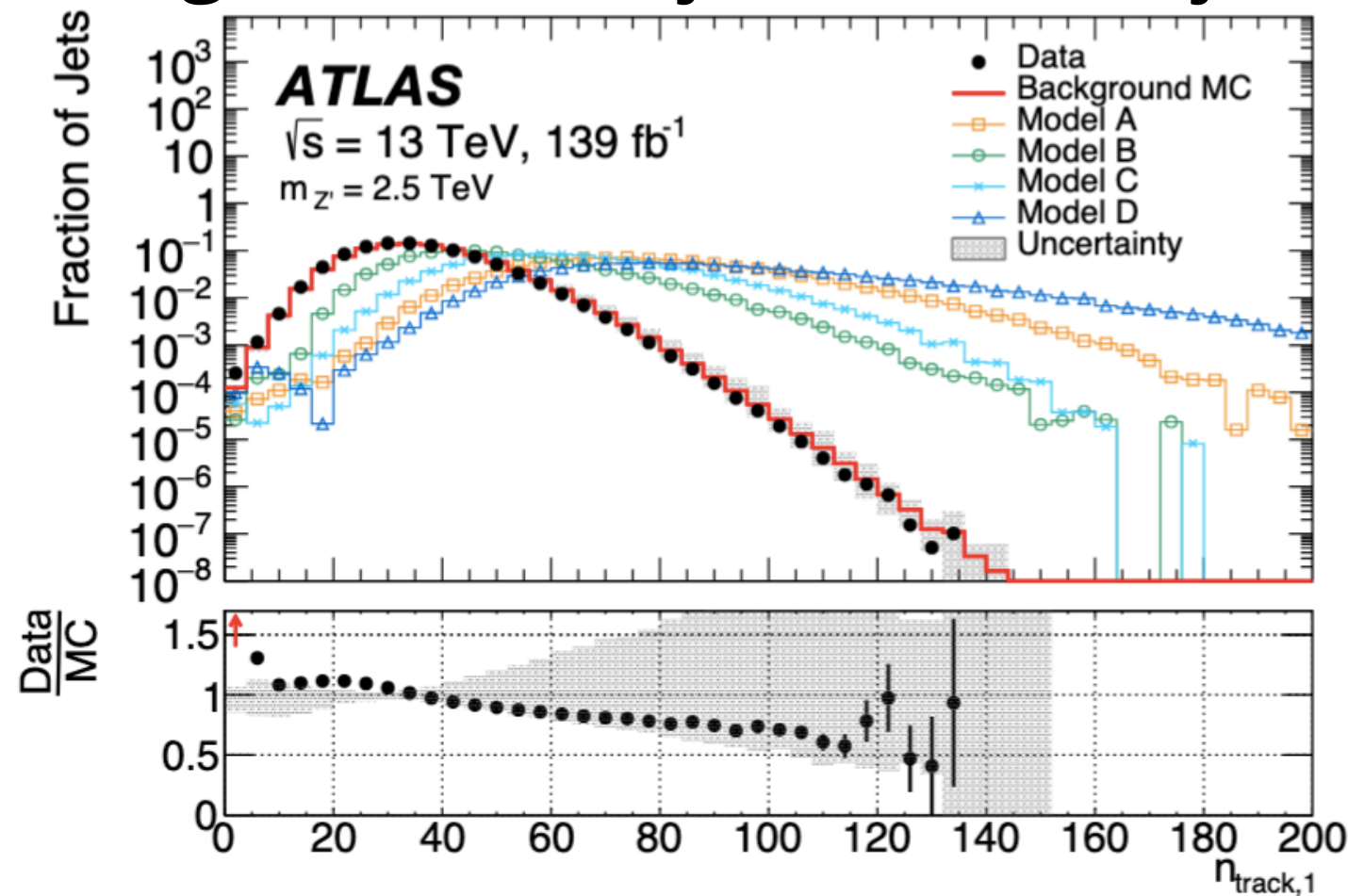
$$m_{\chi} = 8\text{GeV}$$



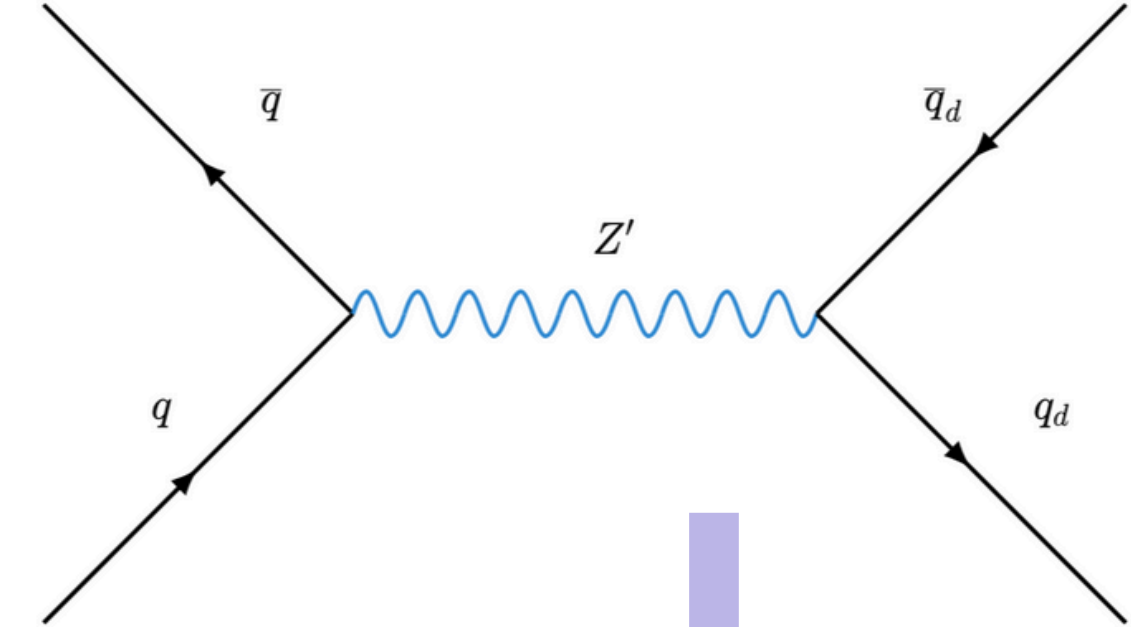
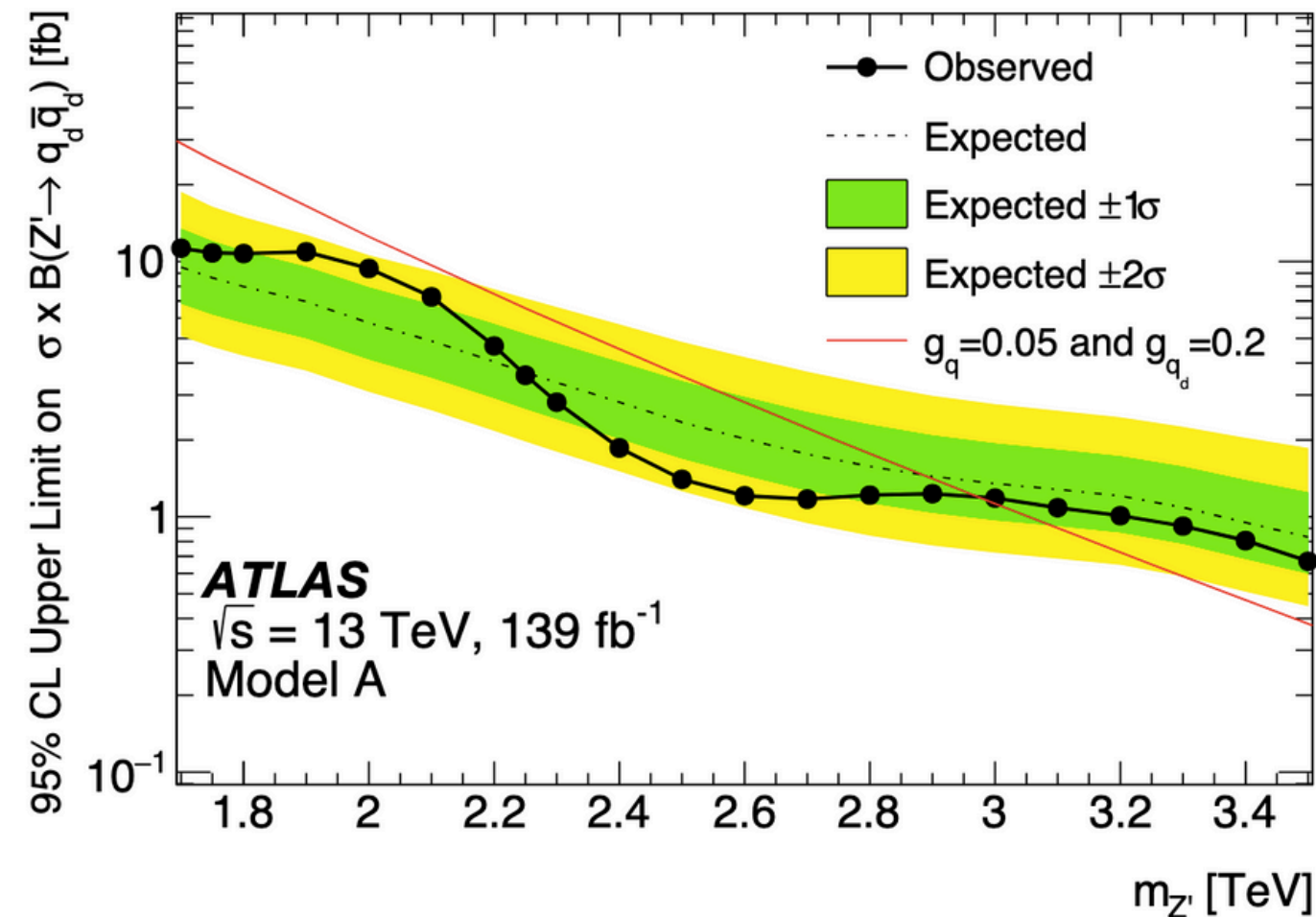
Dark jets

- Double hadronization, first in dark sector and then in SM $\rightarrow$ larger jets
- higher running coupling $\rightarrow$ higher charged-particle multiplicity

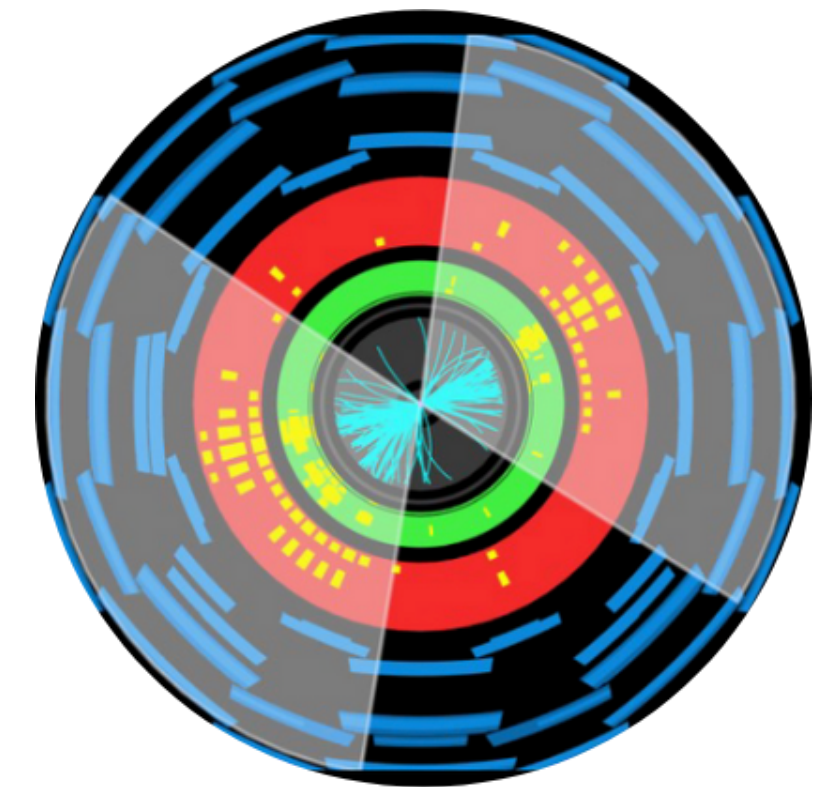
of charged tracks in leading jet
higher in dark jets than SM jets



intervals of $m_{Z'}$ excluded
in different dark QCD models



dijet final state



Dark Higgs model: Motivation

- Naturally satisfied observed relic density via $\chi\chi \rightarrow ss \rightarrow SM$
- Explains massive DM via dark sector Higgs mechanism

Dark Higgs model parameters

- coupling to quarks 0.25
- coupling to DM 1 (ensure high DM production rate)
- mixing angle 0.01 ensure prompt decay and to have no observable effect on coupling of SM Higgs

Two-Mediator DM(2MDM) model

Dark Higgs model can be inserted in a wider model where Majorana DM(χ) interacts with two different mediators:

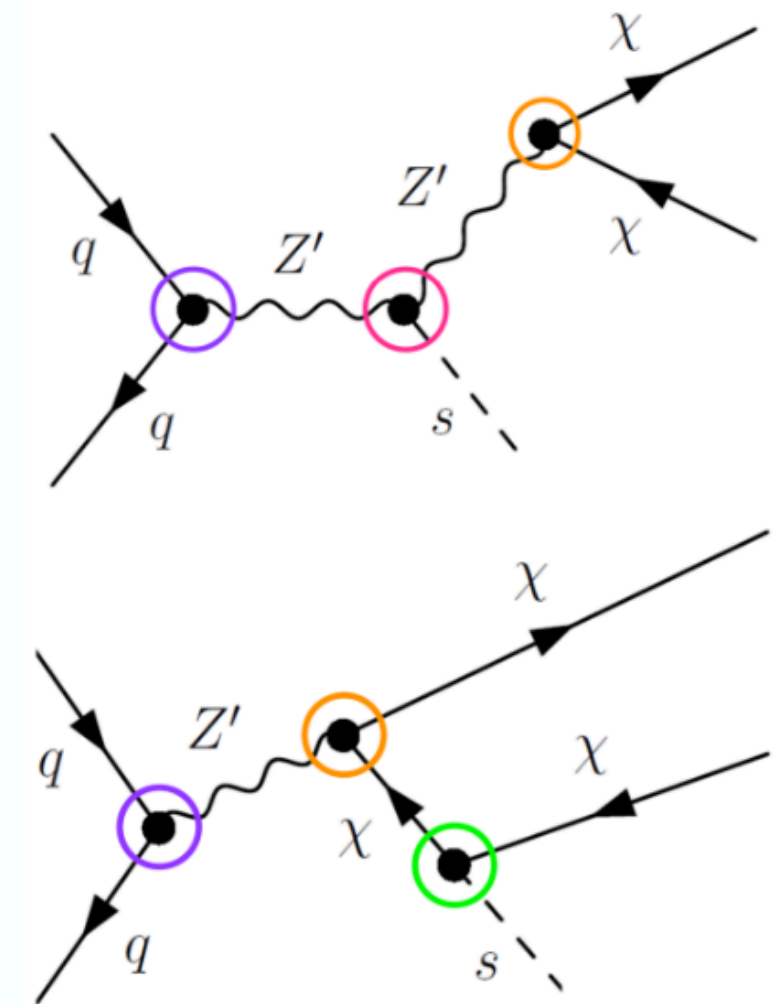
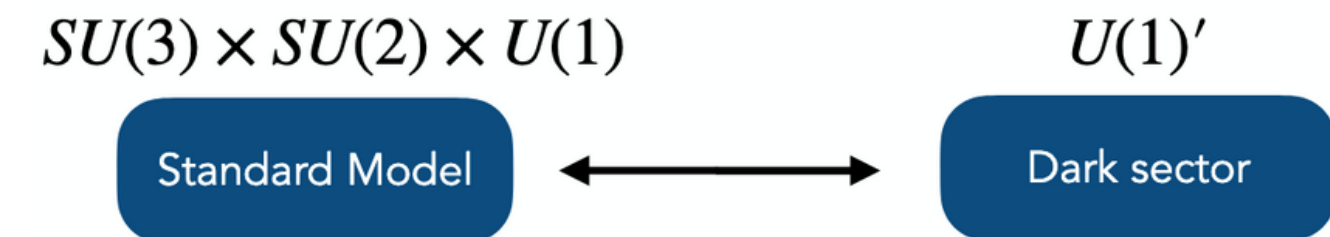
- Massive spin-1 vector boson Z' of a broken $U(1)'$ symmetry
- Dark Higgs s

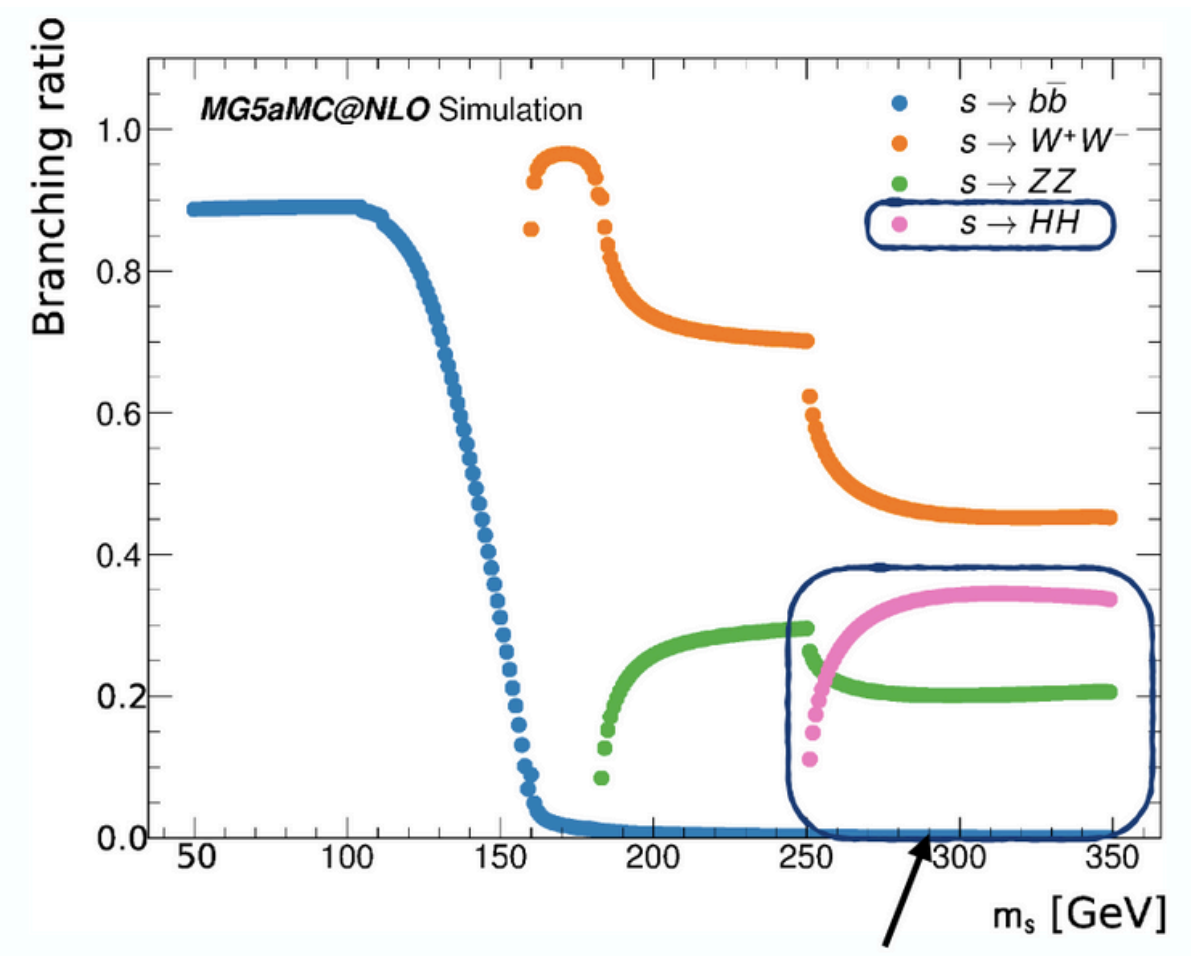
$$\mathcal{L}_\chi = -g_q Z'^\mu \bar{q} \gamma_\mu q$$

$$\mathcal{L}_\chi = -\frac{1}{2} g_\chi Z'^\mu \bar{\chi} \gamma^5 \gamma_\mu \chi - g_\chi \frac{m_\chi}{m_{Z'}} s \bar{\chi} \chi + 2 g_\chi Z'^\mu Z'_\mu (g_\chi s^2 + m_{Z'} s)$$

Dark Higgs

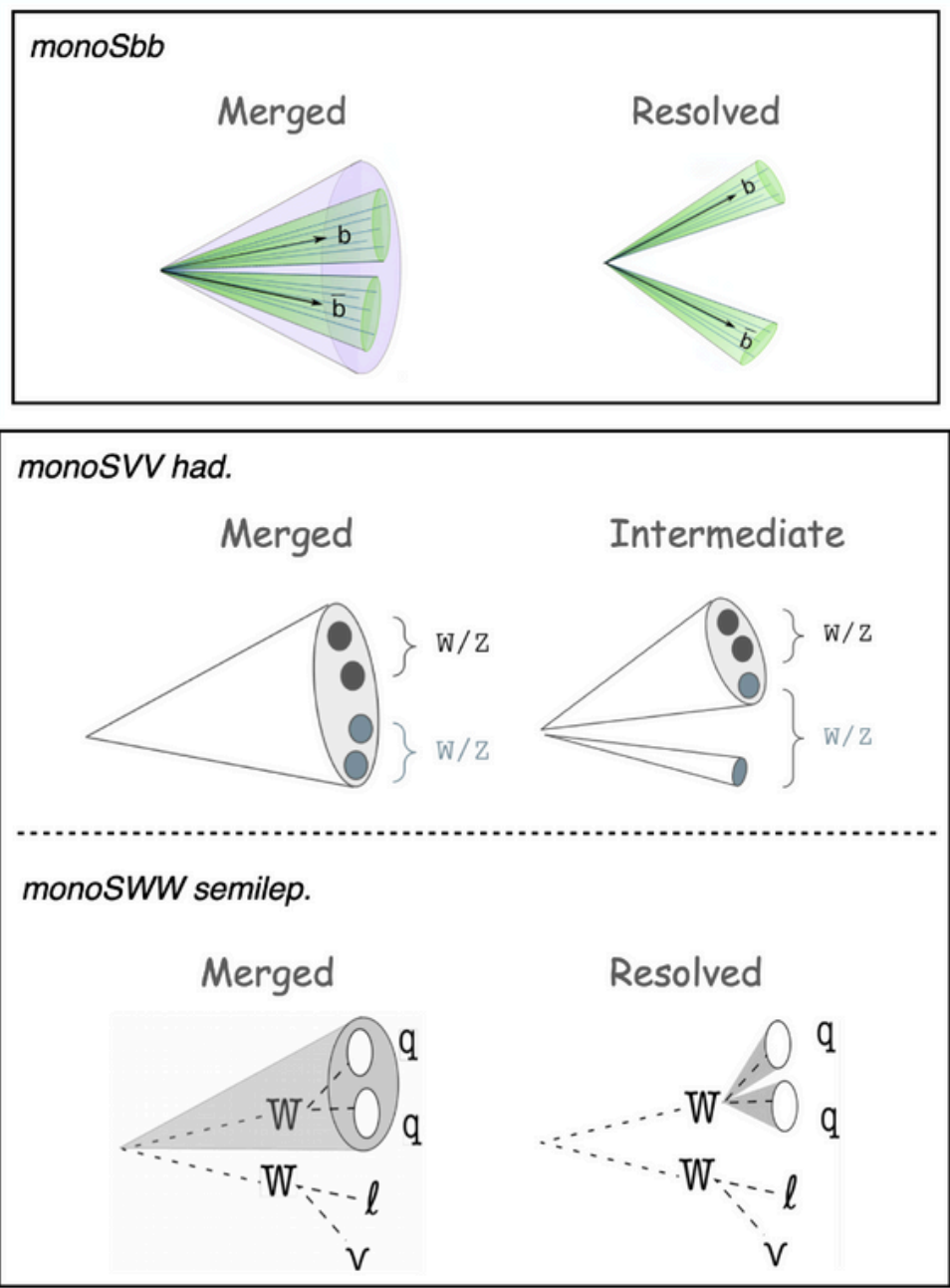
$g_q = 0.25, g_\chi = 1, \theta_h = 0.01$
Free: $m(Z'), m(\chi), m(H_D)$





HH is the resolved final-state with higher expected BR at high masses
Other channels:

- $\Rightarrow m_s \leq 150 \text{ GeV}$
 - Dark Higgs s(bb) analysis
Final states: $E_T^{miss} + b\bar{b}$
Dominates in low m_s
- $\Rightarrow m_s > 150 \text{ GeV}$
 - Dark Higgs s(VV) hadronic analysis
Final states: $E_T^{miss} + VV(qqqq)$
 - Dark Higgs s(WW) semileptonic analysis
Final states: $E_T^{miss} + WW(l\nu qq)$
Higher cross section than fully-leptonic

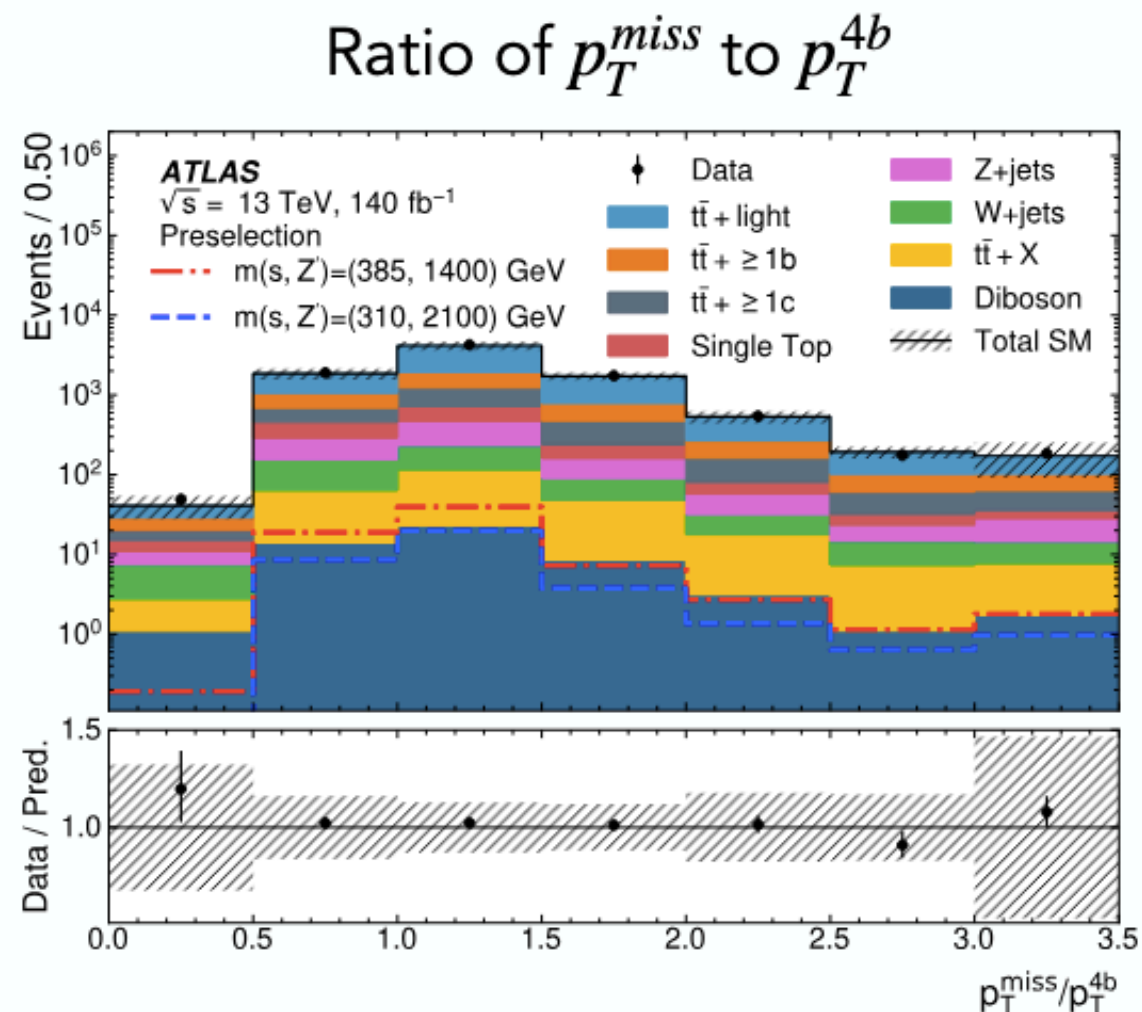


s->HH analysis: DNN

Example of input variables:

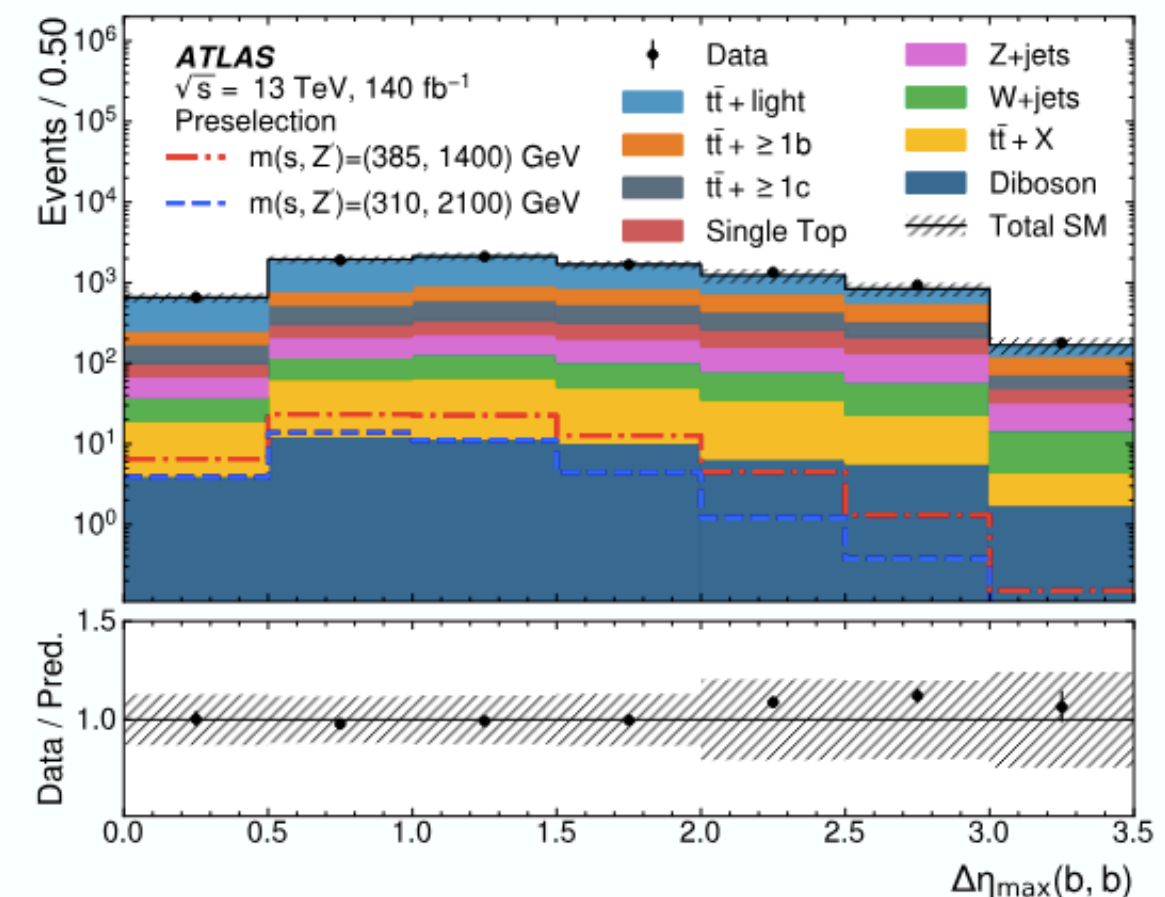
- p_T^{miss} and 4b system back-to-back
- maximum pseudorapidity difference will be lower for signal

Loss function contain a decorrelation term ensuring NN score and m_{hh} are decorrelated



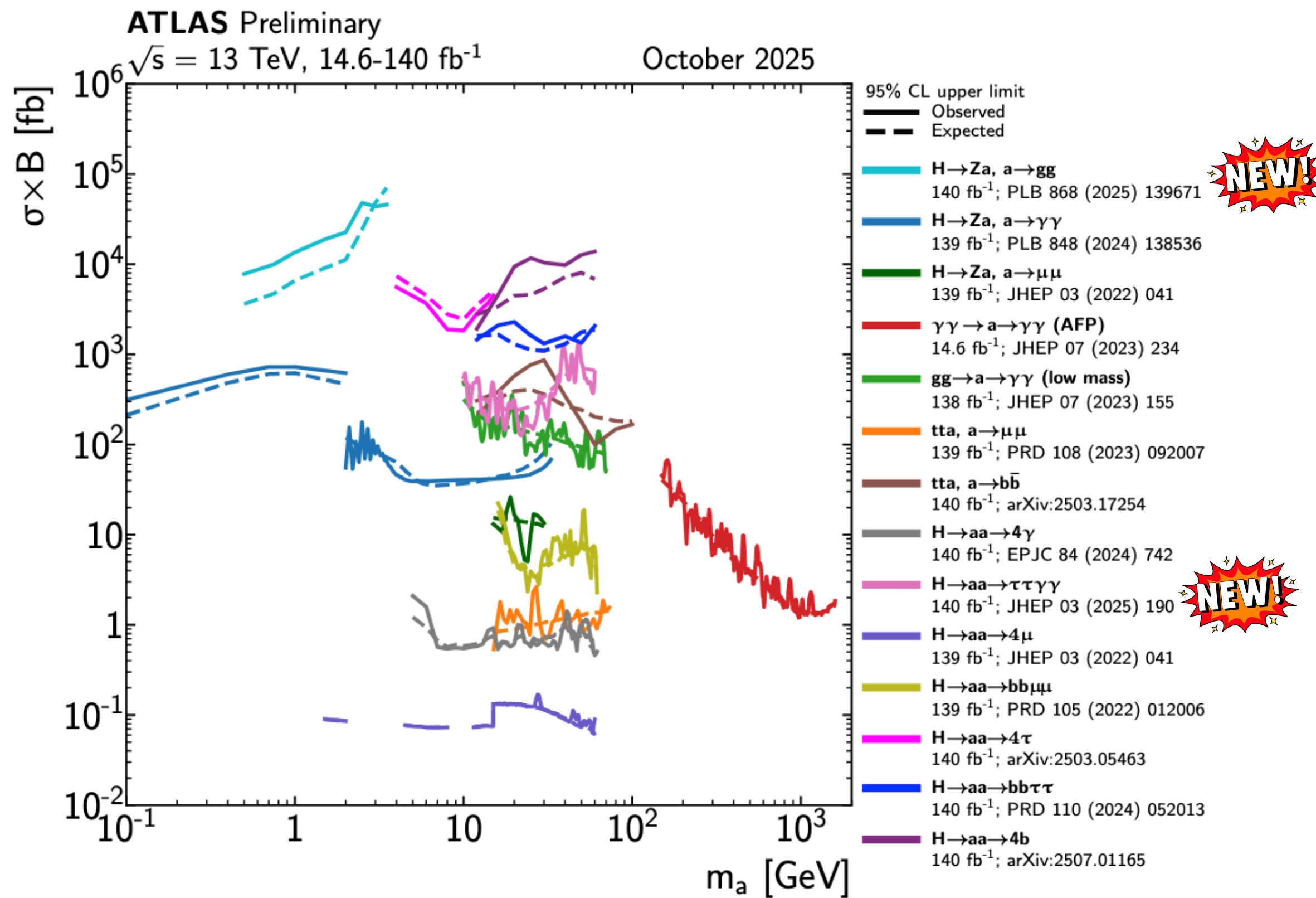
Signal 4b back-to-back with p_T^{miss} : $p_T^{4b} \sim p_T^{\text{miss}}$

Maximum $\Delta\eta$ between b-jet candidates

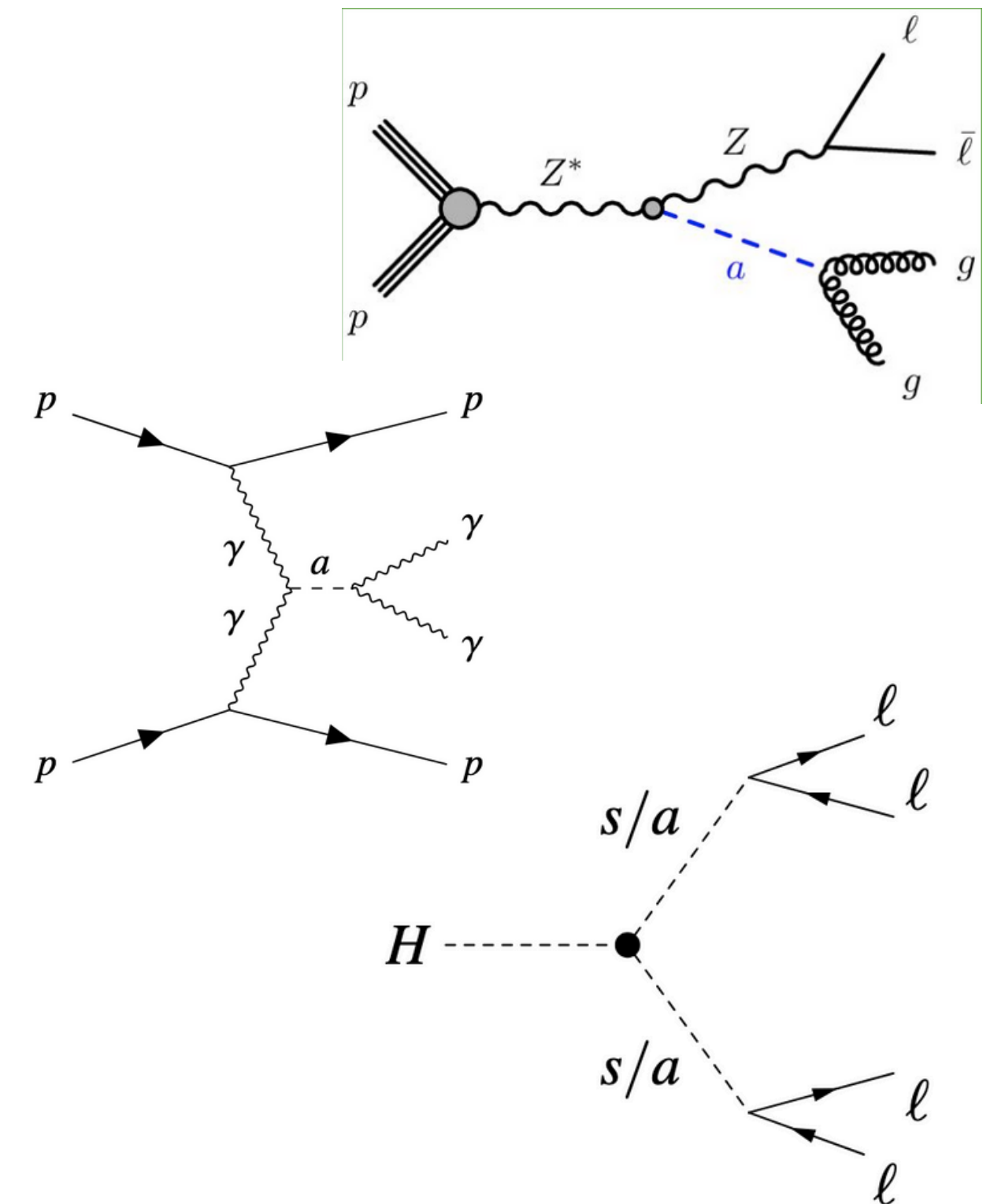


Signal low: 4b from resonant system

ALPs searches

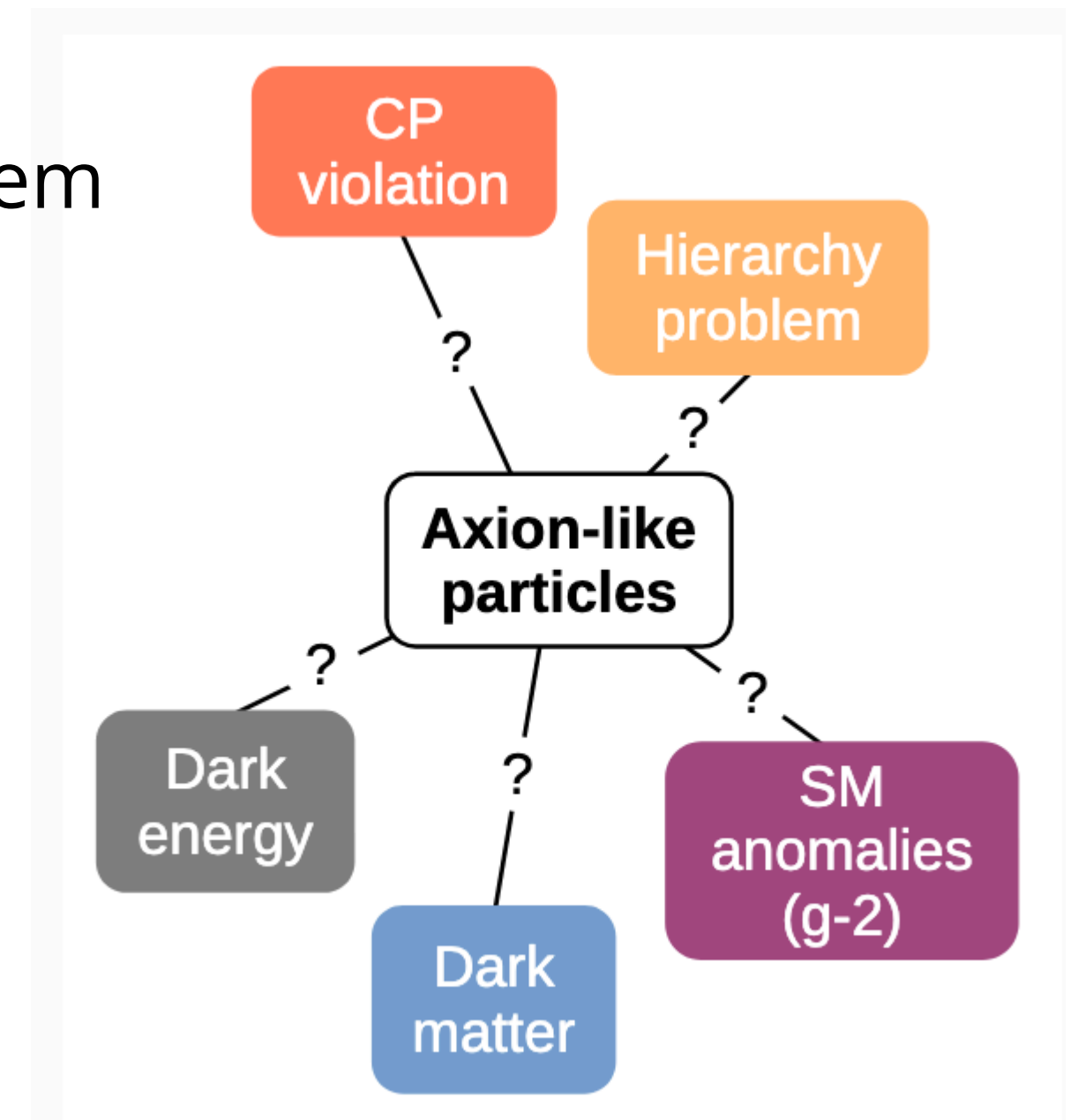
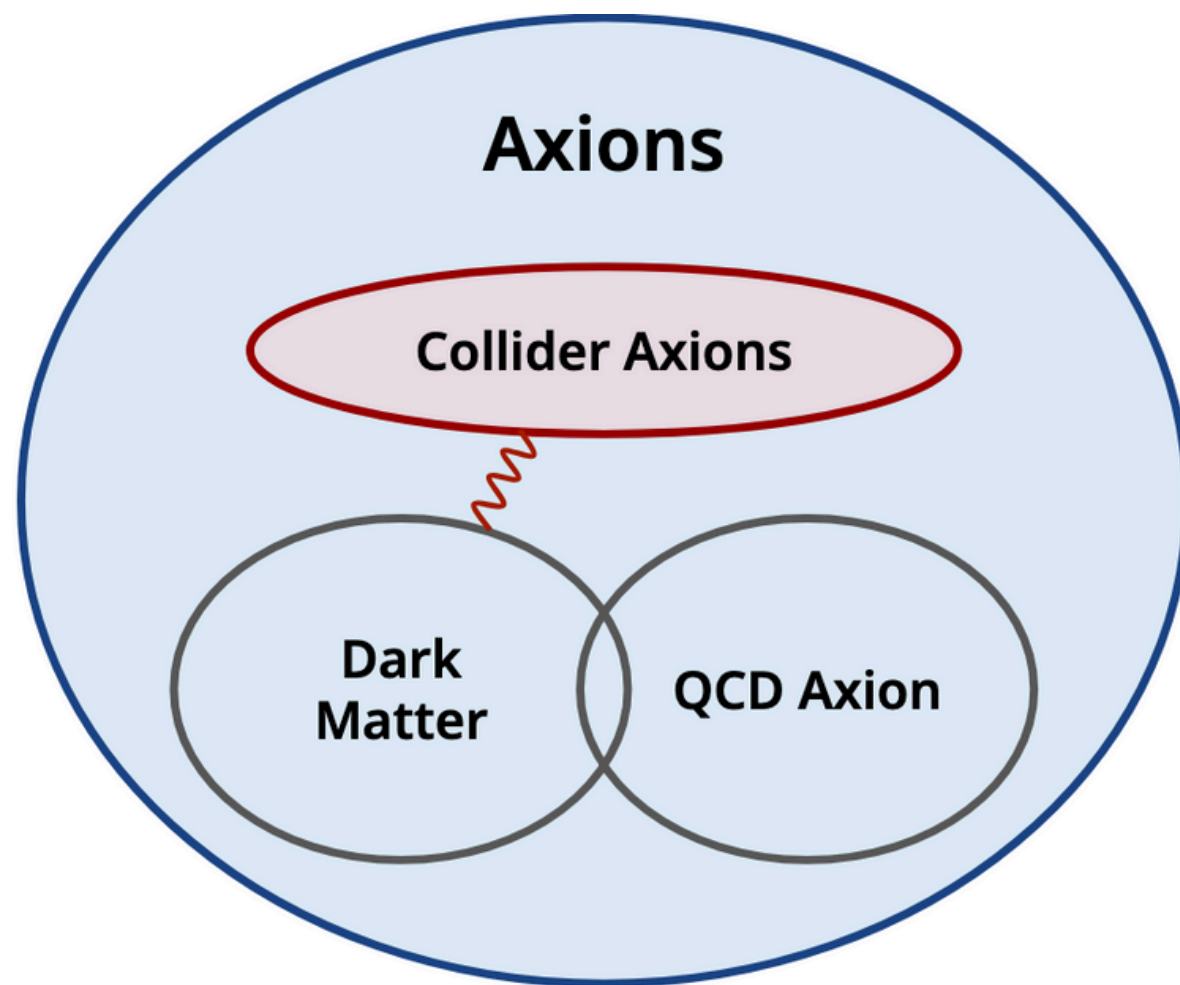


Huge variety of signatures



ALPs motivation

- Axion-like particles (ALPs) are hypothetical pseudoscalar bosons predicted in many BSM theories, especially as bosons of spontaneously broken global symmetries.
- viable mediators to the dark sector
- can be naturally light w.r.t. EW scale → DM candidate
- promising candidates for solving the strong CP problem



HNL motivation

SM Extension with 3 HNLs

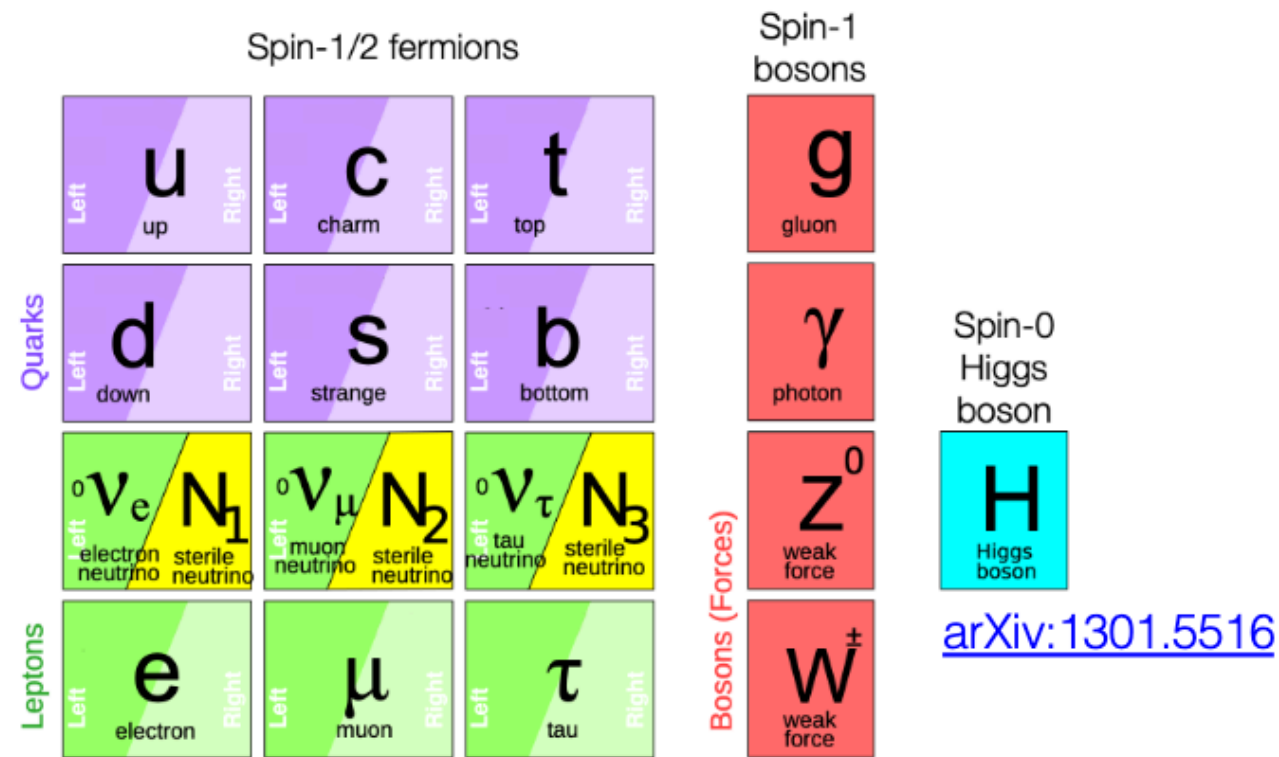


Image credit: M. Francis

Model predicts an **inverse relationship** between heavy neutrino mass and SM neutrino masses.

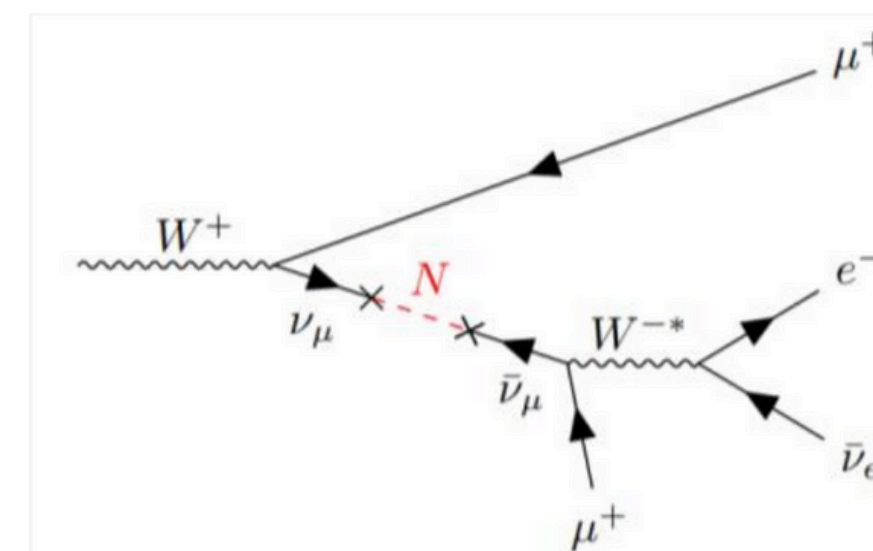
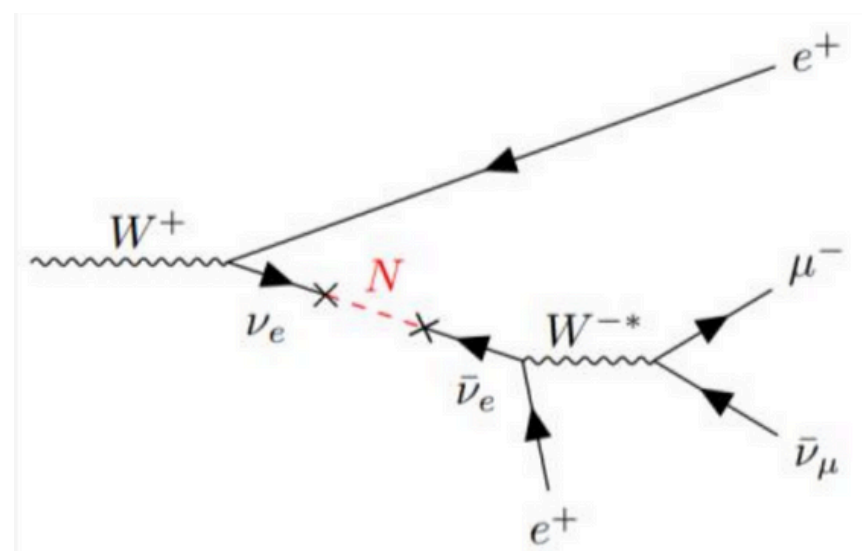
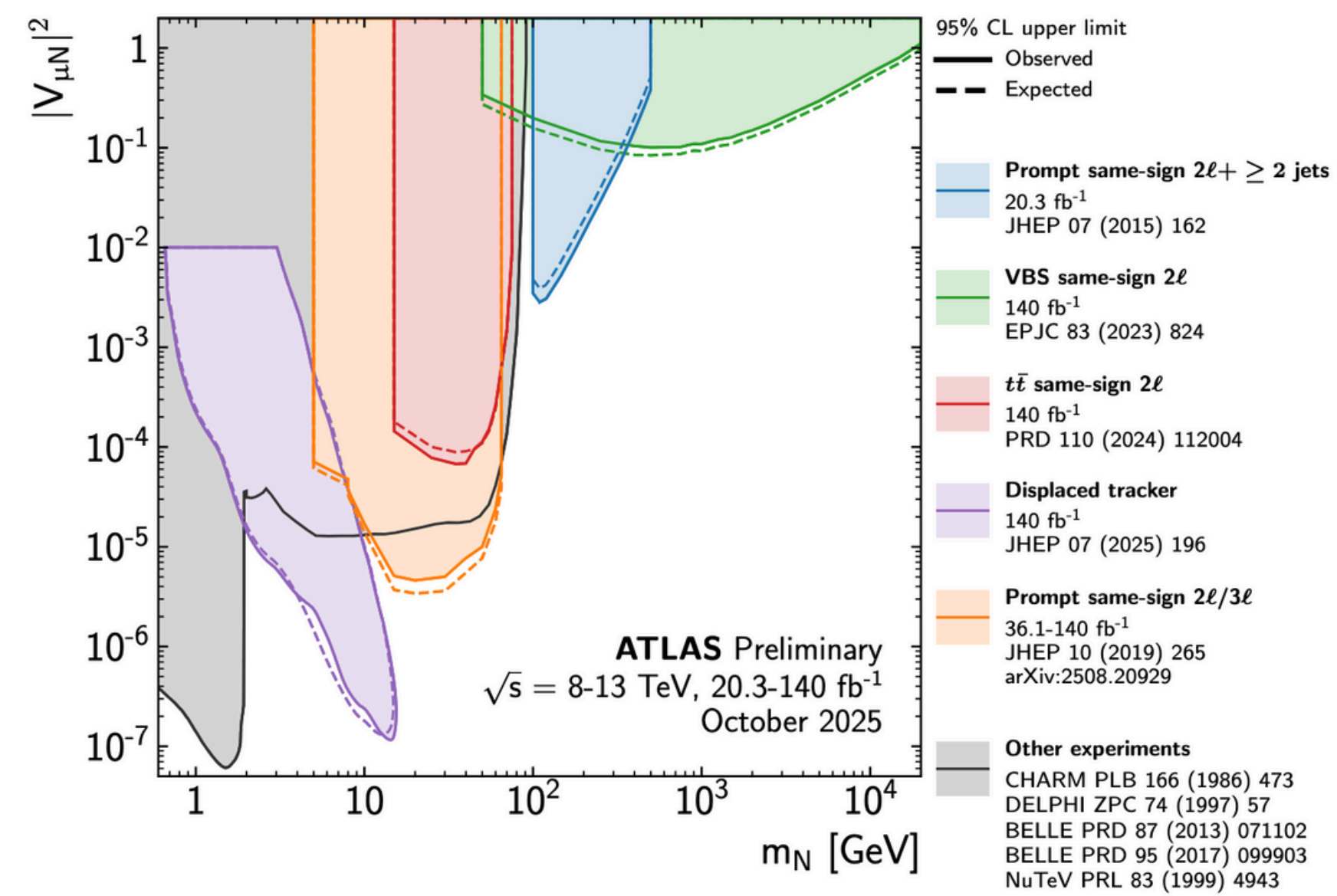
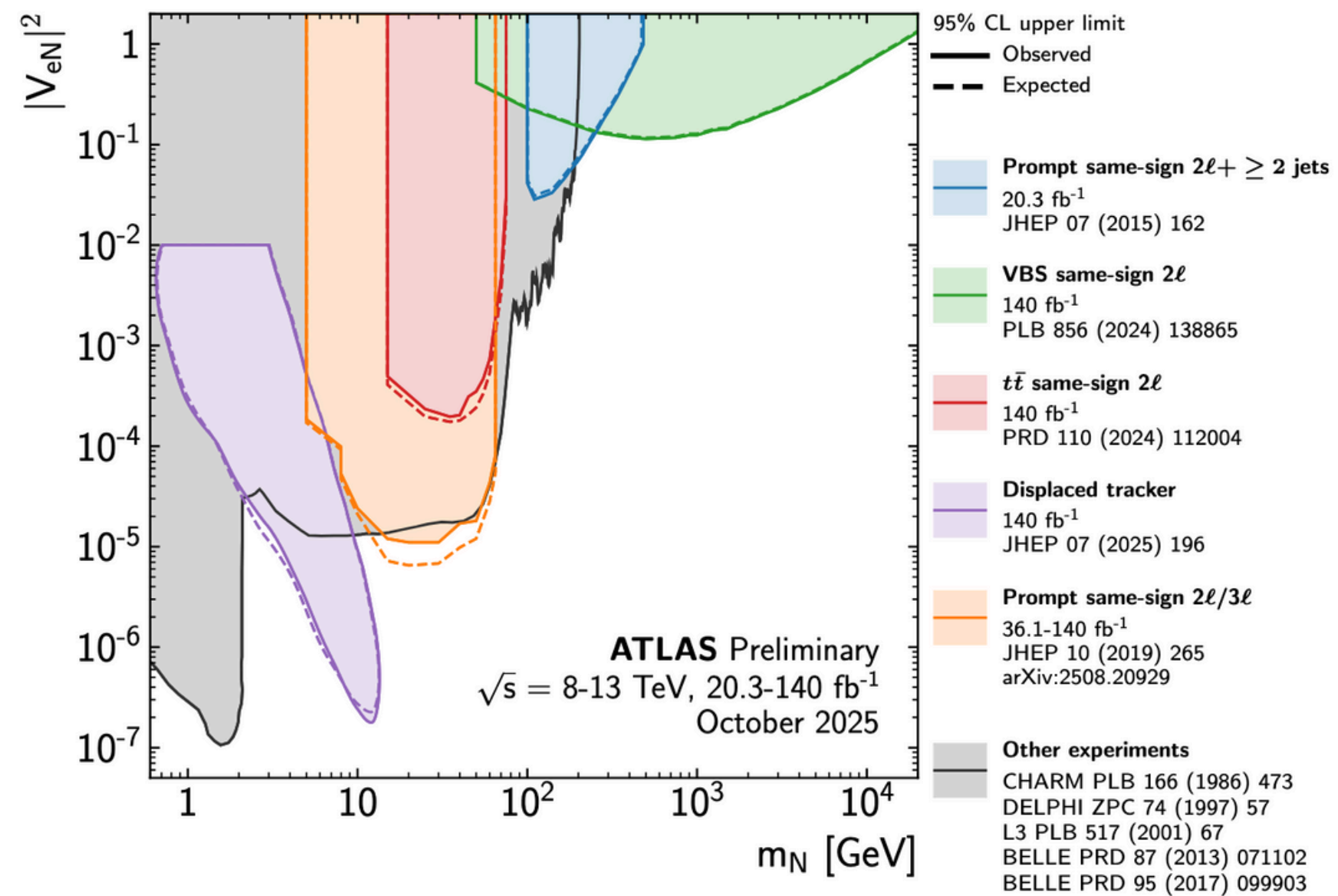
→ Heavy N gives rise to a very light neutrino!

$$\tau_N \propto \frac{1}{m_N^5 |U_\alpha|^2}$$

Introducing right-handed sterile neutrino states or Heavy Neutral Leptons (HNL) can explain:

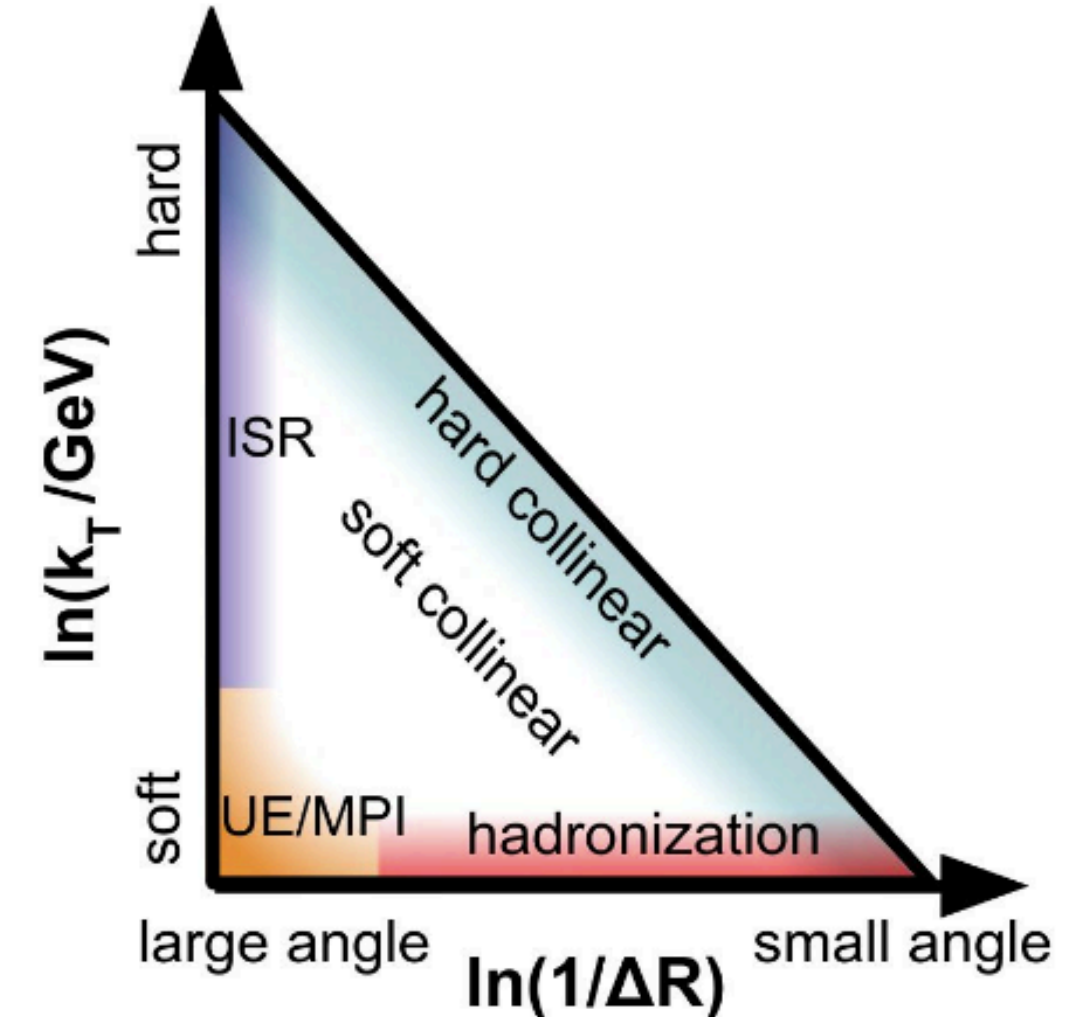
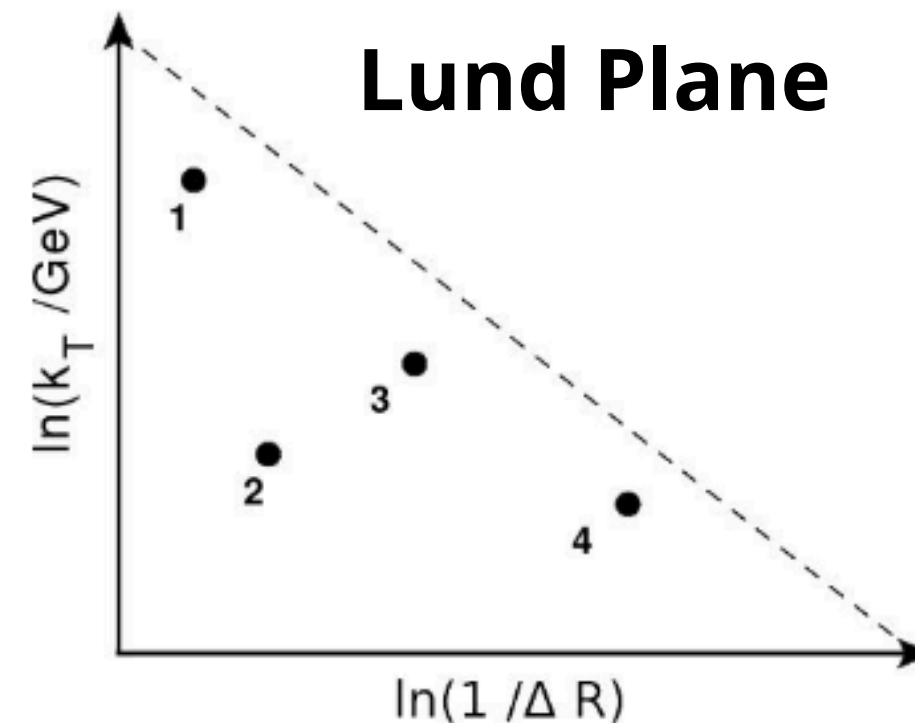
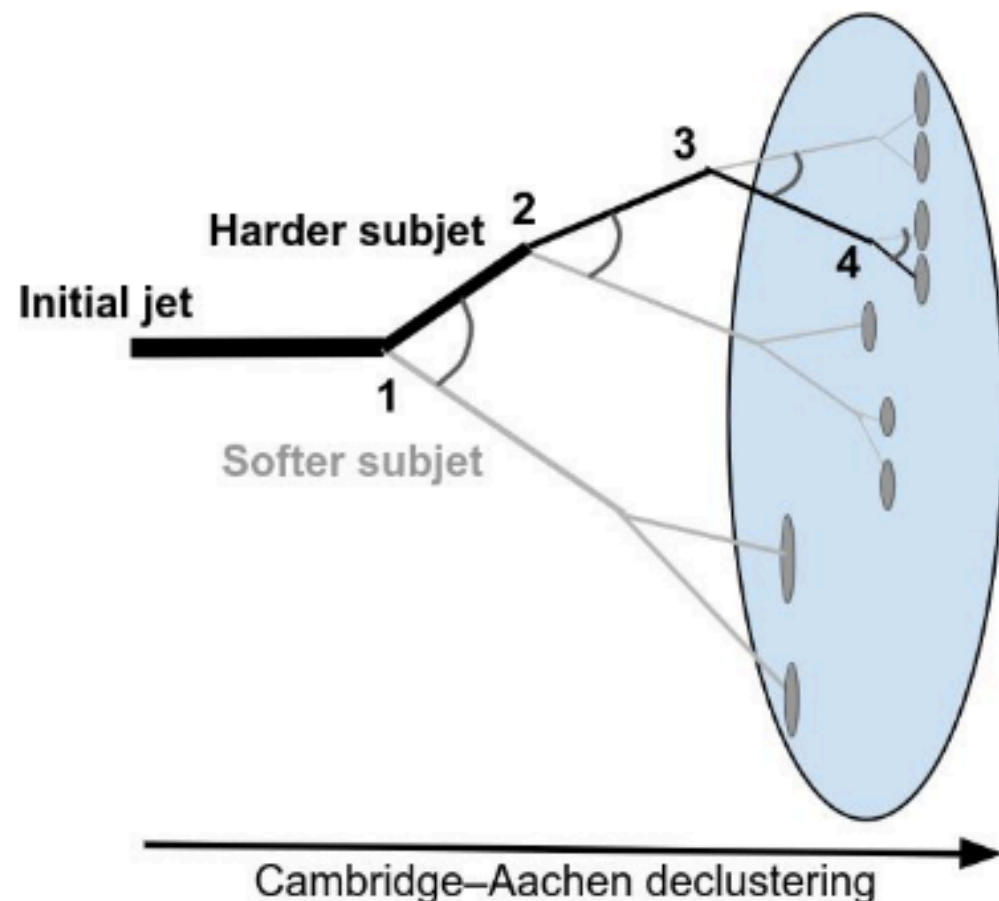
- origin of neutrino masses: see-saw mechanism
- matter-antimatter asymmetry: CP violation increase due to neutrino oscillations in early universe
- dark matter candidate: models with at least 3 HNLs can have keV-order sterile neutrinos

HNL searches



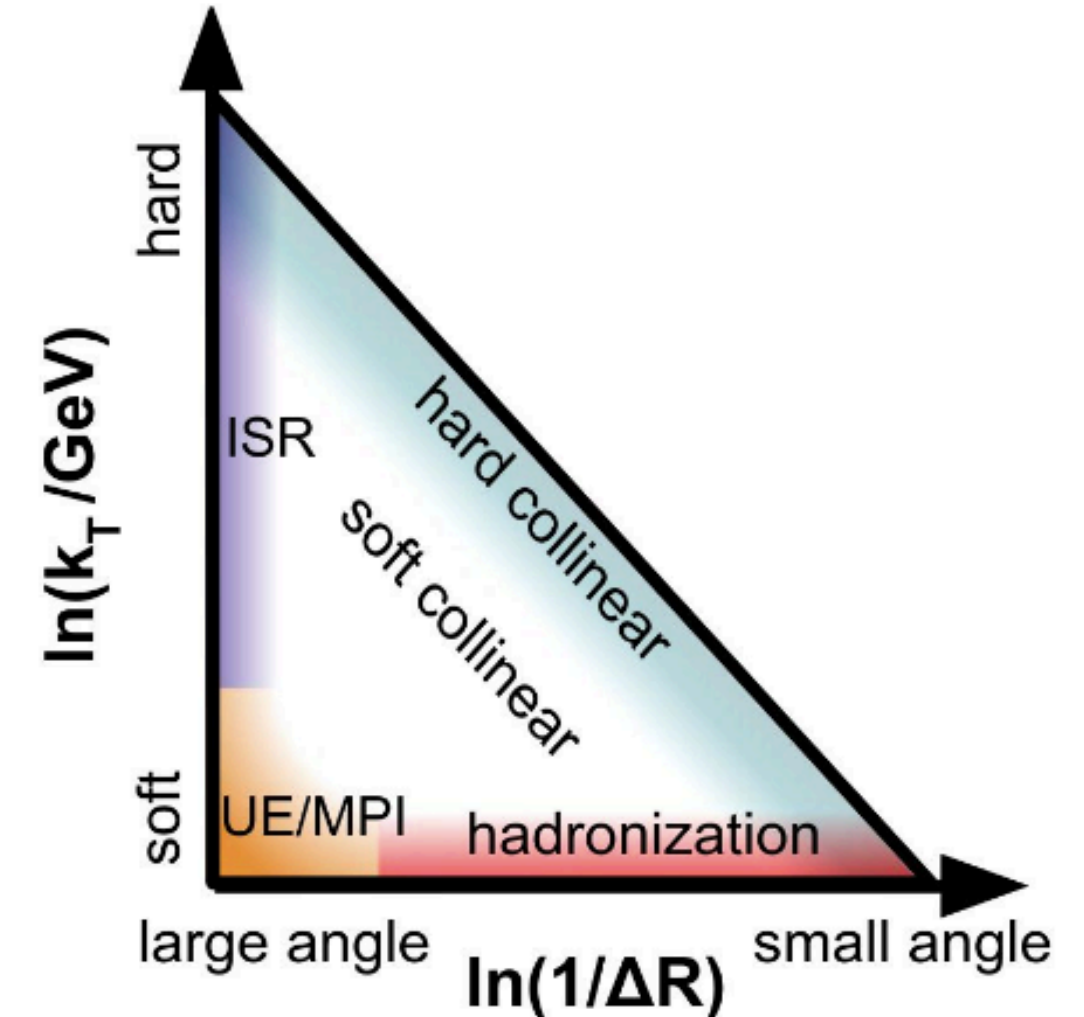
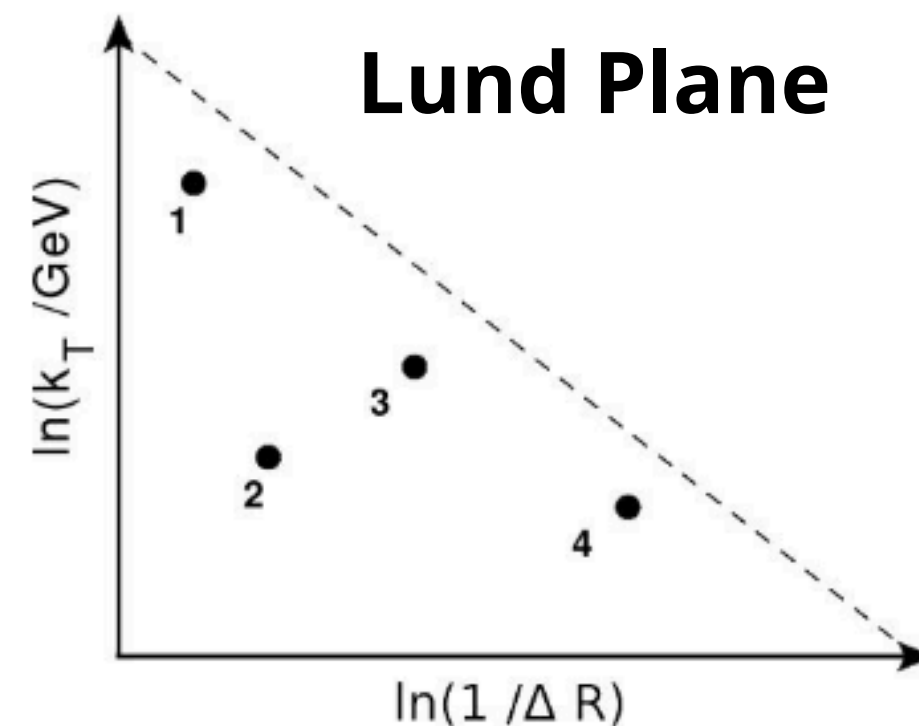
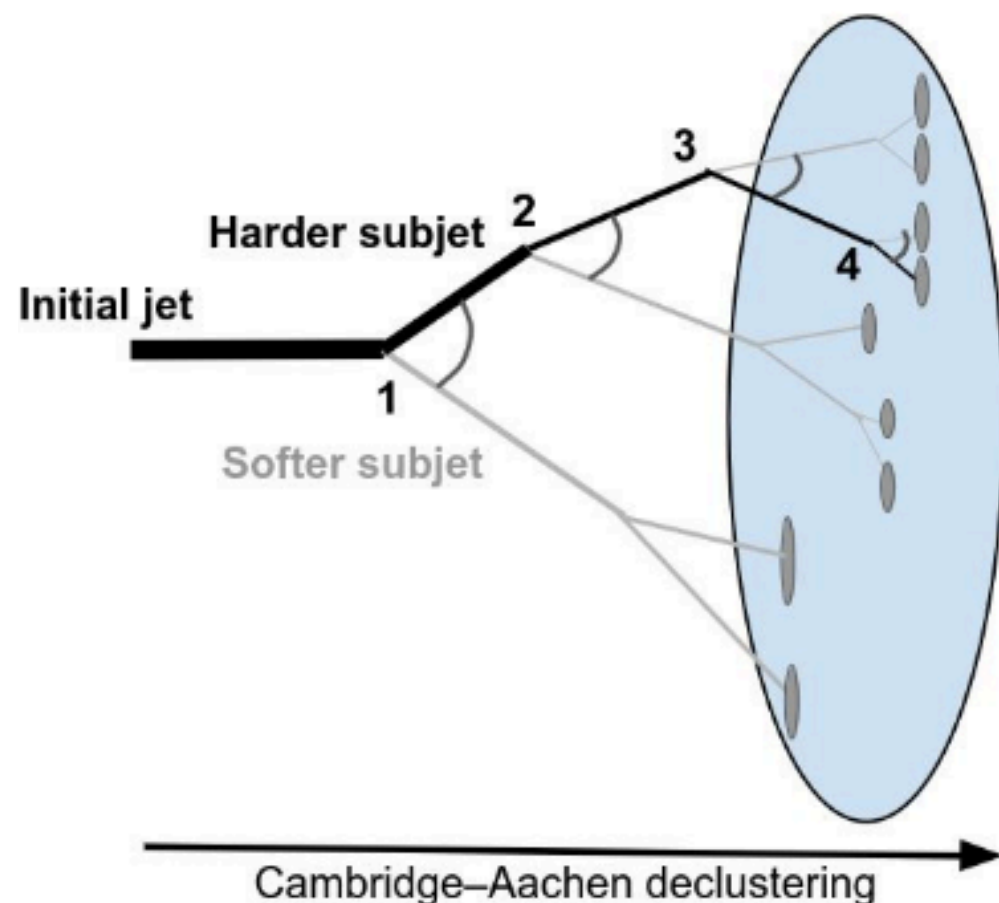
Lund plane

- Cambridge/Aachen algorithm to reverse the hadronization process and reconstruct jet clustering history
- Splitting variables:
 - k_T , transverse momentum
 - Delta, angle of the split
 - z , momentum fraction of the original p_T that went to the less energetic particle



Lund plane

- Each splitting is a node in the Lund tree and a dot in the Lund plane and is associated with a set of features encoding kinematic information of the splitting
- The Lund tree can be encoded in a GNN so that the network has an inductive physics-based bias.



Hypercharge (vectorial) portal

$$\tilde{\mathcal{L}} = -\frac{\varepsilon}{2 \cos \theta_W} \tilde{F}'_{\mu\nu} B^{\mu\nu}.$$

- Coupling B (hypercharge boson) and F' (dark photon) with strength epsilon
- After diagonalization, new couplings of the massive dark photon to the SM fermions appear for the photon and the Z gauge boson

$$\begin{pmatrix} W_\mu^3 \\ B_\mu \\ \tilde{A}'_\mu \end{pmatrix} = \begin{pmatrix} c_W & s_W & -s_W \varepsilon \\ -s_W & c_W & -c_W \varepsilon \\ t_W \varepsilon & 0 & 1 \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \\ A'_\mu \end{pmatrix}, \quad \mathcal{L} \supset -e \varepsilon J^\mu A'_\mu + e' \varepsilon t_W J'^\mu Z_\mu + e' J^{\mu'} A'_\mu,$$

$$\tilde{\mathcal{L}} = -\frac{\varepsilon}{2 \cos \theta_W} \tilde{F}'_{\mu\nu} B^{\mu\nu} \longrightarrow \begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos \theta_w & \sin \theta_w \\ -\sin \theta_w & \cos \theta_w \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix} \longrightarrow \mathcal{L} \ni \frac{\varepsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

- A further possibility is introducing a mass mixing with Z boson: $\epsilon_Z m_Z^2 Z Z_d$, with $\epsilon_Z = \delta m_{Z_d} / m_Z$

Dark photons decay rate

$$\mathcal{L} \ni \frac{\varepsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

Decay rate is proportional to the square of the coupling

$$\Gamma(A' \rightarrow \ell^+ \ell^-) = \frac{1}{3} \alpha \varepsilon^2 m_{A'} \sqrt{1 - \frac{4m_\ell^2}{m_{A'}^2}} \left(1 + \frac{2m_\ell^2}{m_{A'}^2} \right),$$

$$\Gamma(A' \rightarrow \text{hadrons}) = \frac{1}{3} \alpha \varepsilon^2 m_{A'} \sqrt{1 - \frac{4m_\mu^2}{m_{A'}^2}} \left(1 + \frac{2m_\mu^2}{m_{A'}^2} \right) R,$$

[The dark photon](#)

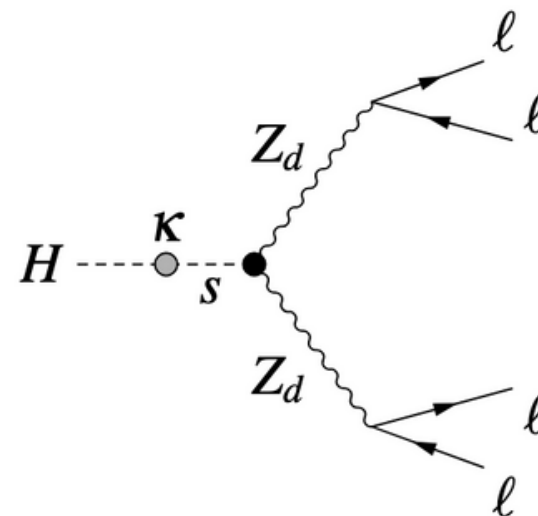
Fabbrichesì, Gabrielli, Lanfranchi

Scalar portal

$$(\mu S + \lambda S^2) H^\dagger H$$

- Coupling H (SM Higgs boson) and S (new scalar, sometimes called dark Higgs)
- The dark Higgs boson would inherit the Yukawa couplings from the SM Higgs boson and decay preferentially into high-mass fermion pairs.

This mechanism allows decays:

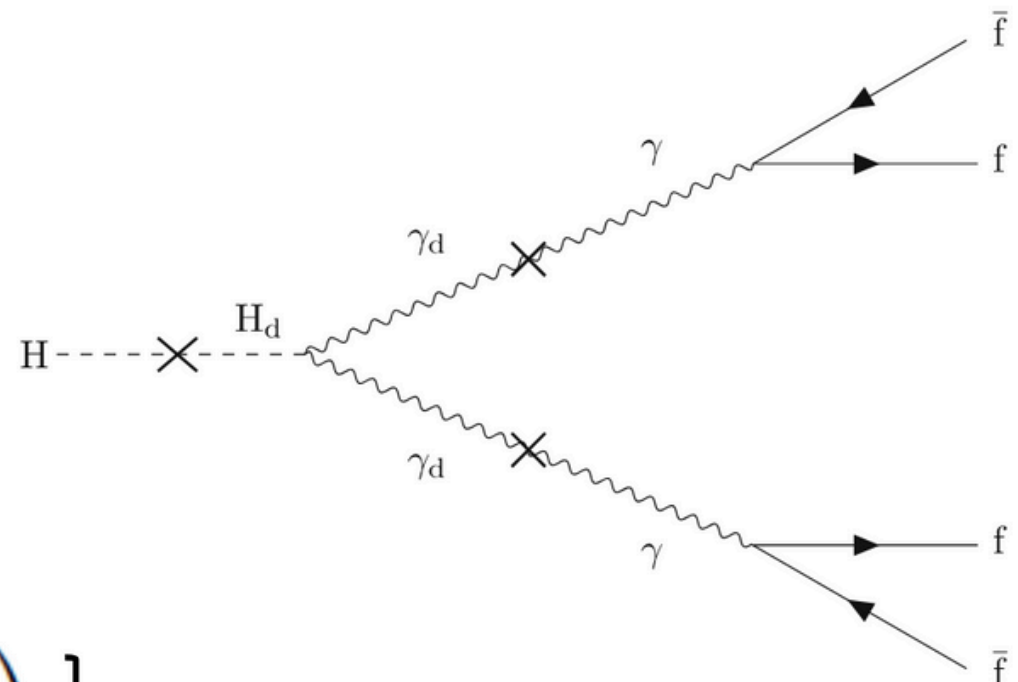


Hidden Abelian Higgs Model (HAHM)

Vectorial + scalar portal

- spontaneously broken dark U(1) group mediated by a dark photon Z'
- SM particles interact with Z' through kinematic mixing with the hypercharge boson
- Z' decays exclusively to SM leptons and can be long-lived if $\varepsilon < 10^{-4}$
- dark Higgs boson H_2 coupling with the SM higgs through κ

$$\begin{aligned} \mathcal{L}_\Phi = & |D_\mu \Phi_{\text{SM}}|^2 + m_{\Phi_{\text{SM}}}^2 |\Phi_{\text{SM}}|^2 - \lambda |\Phi_{\text{SM}}|^4 & \longrightarrow & \sim \text{SM} \\ & + |D_\mu \Phi_X|^2 + m_{\Phi_X}^2 |\Phi_X|^2 - \rho |\Phi_X|^4 & \longrightarrow & \text{Hidden sector} \\ & - \kappa |\Phi_{\text{SM}}|^2 |\Phi_X|^2 & \longrightarrow & \text{Mixing} \end{aligned}$$



$$\begin{pmatrix} \Phi_{\text{SM}} \\ \Phi_X \end{pmatrix} = \begin{pmatrix} c_h & s_h \\ -s_h & c_h \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

Mixing angle
Mass eigenstates

$$\begin{pmatrix} B \\ W^3 \\ X \end{pmatrix} = \begin{pmatrix} c_W & -s_W c_\alpha & s_W s_\alpha \\ s_W & c_W c_\alpha & -c_W s_\alpha \\ 0 & c_\alpha & s_\alpha \end{pmatrix} \begin{pmatrix} A \\ Z \\ Z' \end{pmatrix} \left\{ \begin{array}{l} \sim \text{SM} \\ \text{Hidden sector} \end{array} \right.$$

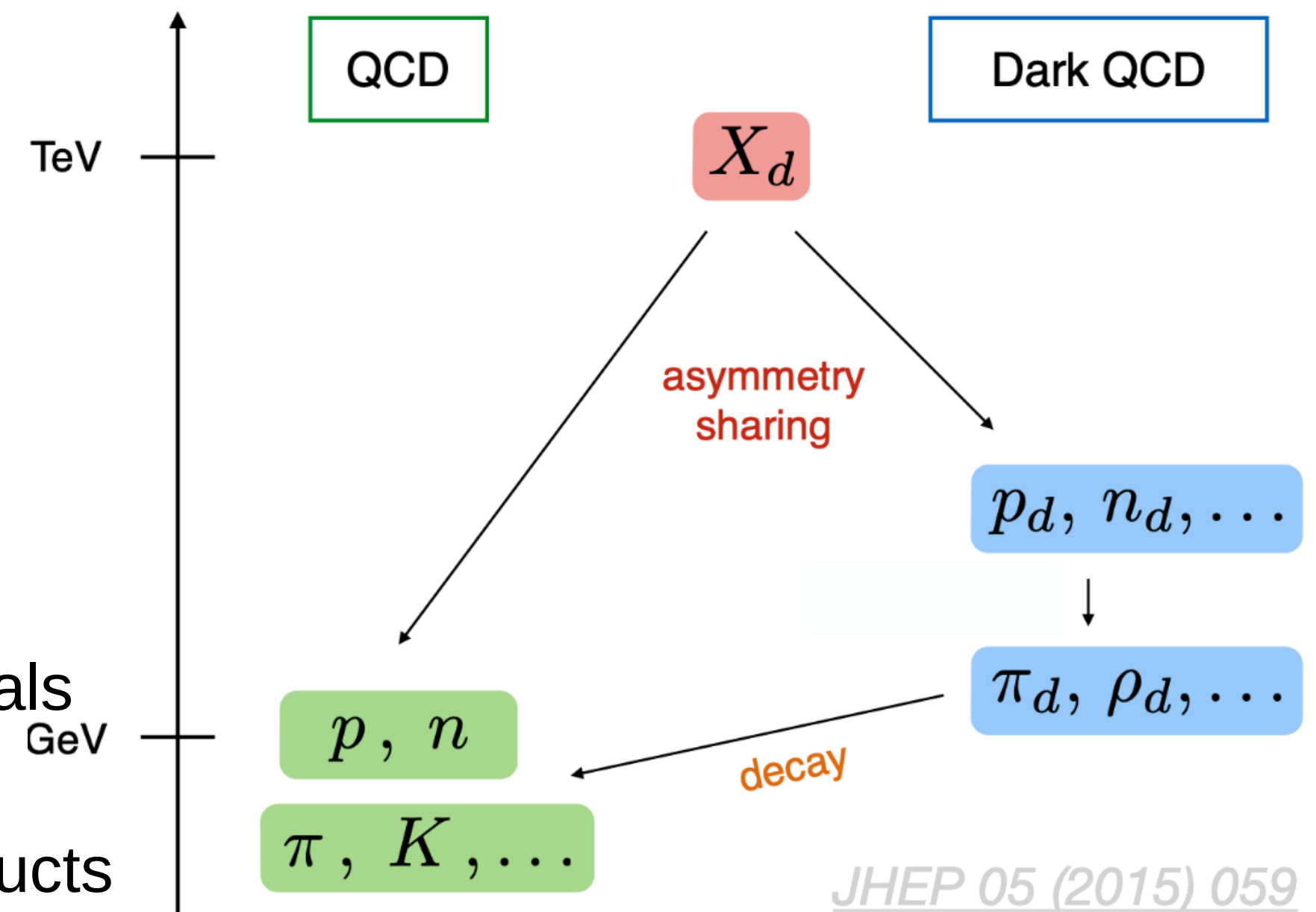
function of : η , hidden sector vev and coupling constants, Z and Z' boson masses
HAHM model, by Wess et al.

Dark QCD

- Dark QCD force governed by $SU(N_c^{dark})$ with N_f flavours
- Dark quarks hadronise to form dark baryons (DM candidate) & mesons (lightest particle)
- Hidden sector couples to SM weakly via mediators

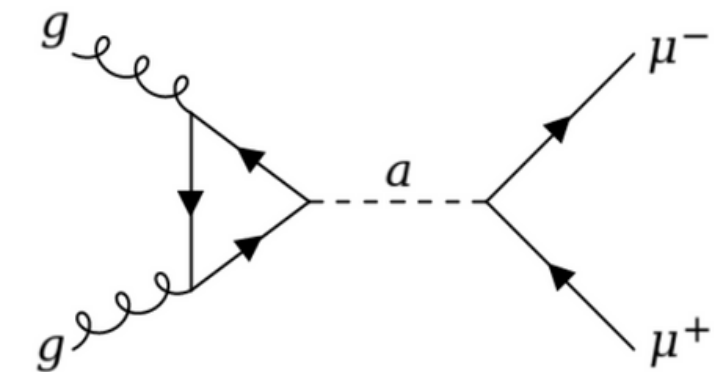
Why?

- Typical strategies focus on high- p_T + MET
 - dark showers may be rejected as noise
- Most visible matter is composite
 - DM might be too (dark baryons?)
- Similar densities: $\Omega_{DM} \approx 5 \times \Omega_{baryons}$
 - hints at a common origin
- Dark matter from asymmetric production
 - no indirect detection, no annihilation signals
- Ultra-weak couplings
 - no direct detection, no visible decay products



Two Higgs Doublets (2HDM)

- Each complex doublet contains four degrees of freedom, for a total of $2 \times 4 = 8$ degrees of freedom in the 2HDM.
- After the electroweak symmetry breaking, three of these are "eaten" to become the longitudinal components of the $W^\pm$ and Z bosons.
- The remaining five physical scalar states are:
 - Two CP-even (scalar) Higgs bosons (h and H): The lighter (h) is often identified with the 125 GeV Higgs boson discovered at the LHC.
 - One CP-odd (pseudoscalar) Higgs boson (A):
 - A pair of charged Higgs bosons ($H^\pm$).



An extension of the model is the 2HDM+S model, where there is an extra Complex Scalar Singlet (S). In this extension, there can be additional pseudoscalar and scalar arising from the mixing of S with h , H .

Why Higgs boson decays as a portal to the dark sector?

- The most stringent 95% CL upper limit on the branching ratio for the SM Higgs boson decay into undetected final states is 12%
- SM predicts a very narrow decay width for the Higgs boson: even a small coupling to a new light state could result in a significant BR to that state.