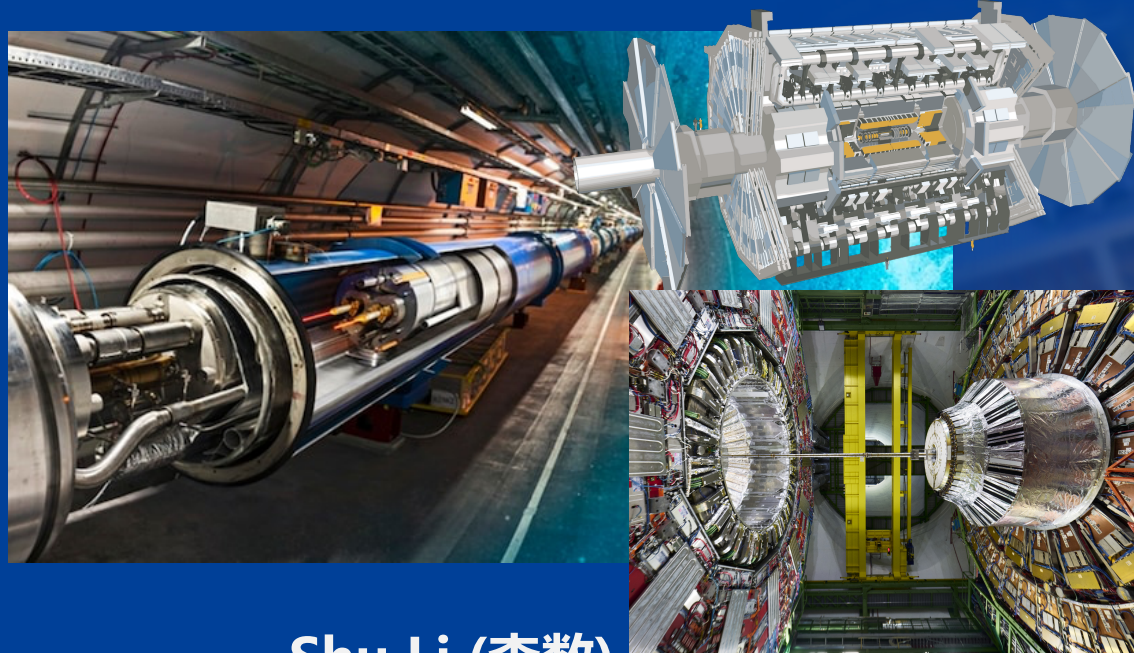


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Dark matter and unconventional searches at the LHC



Shu Li (李数)

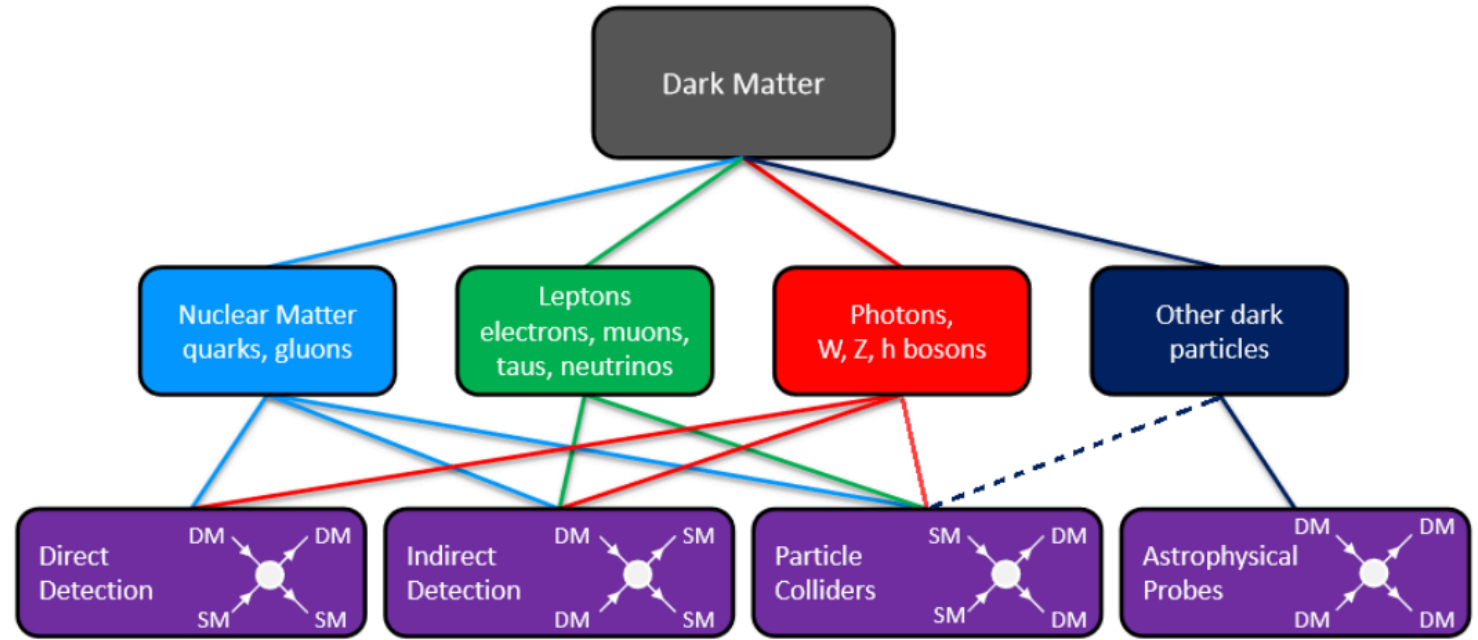
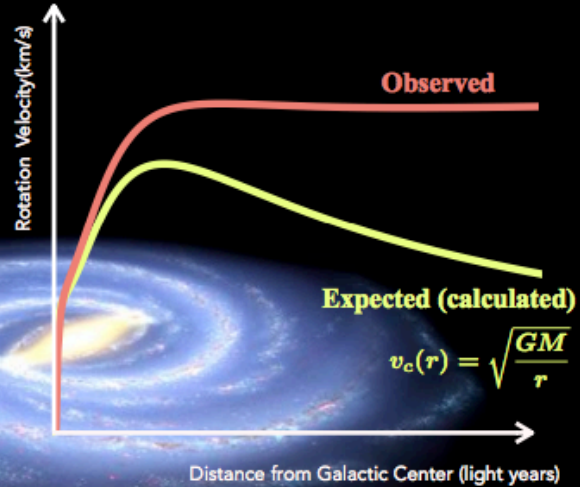
shuli@sjtu.edu.cn

27/11/2022

Chinese LHC Physics Workshop 2022 @ Nanjing

● Dark Matter Evidence and Theory Context in a nutshell

Galactic Rotation



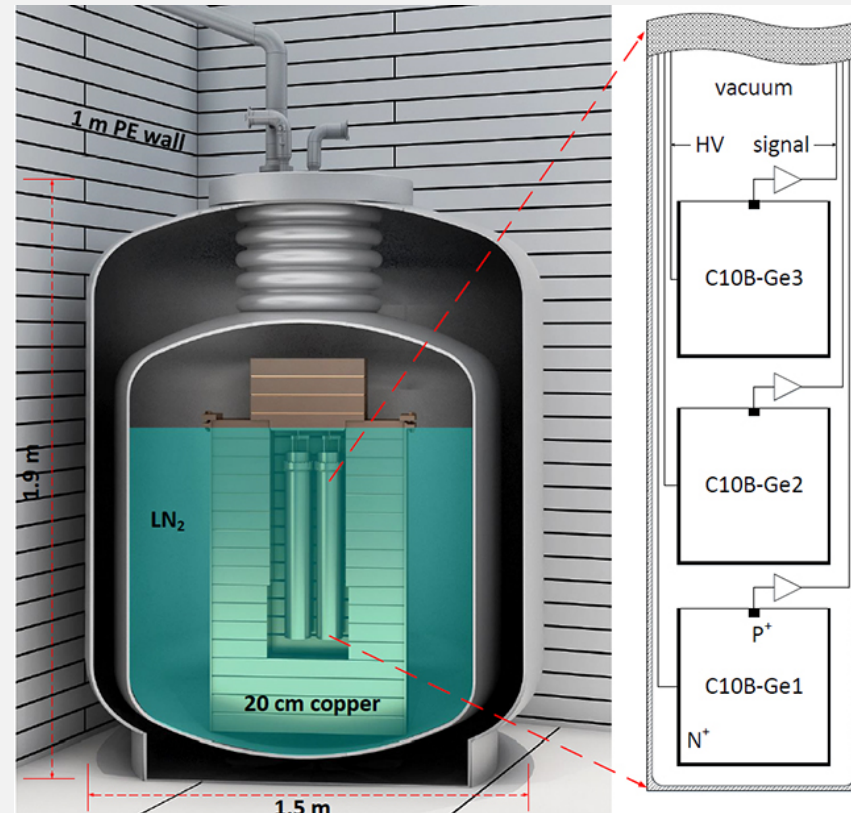
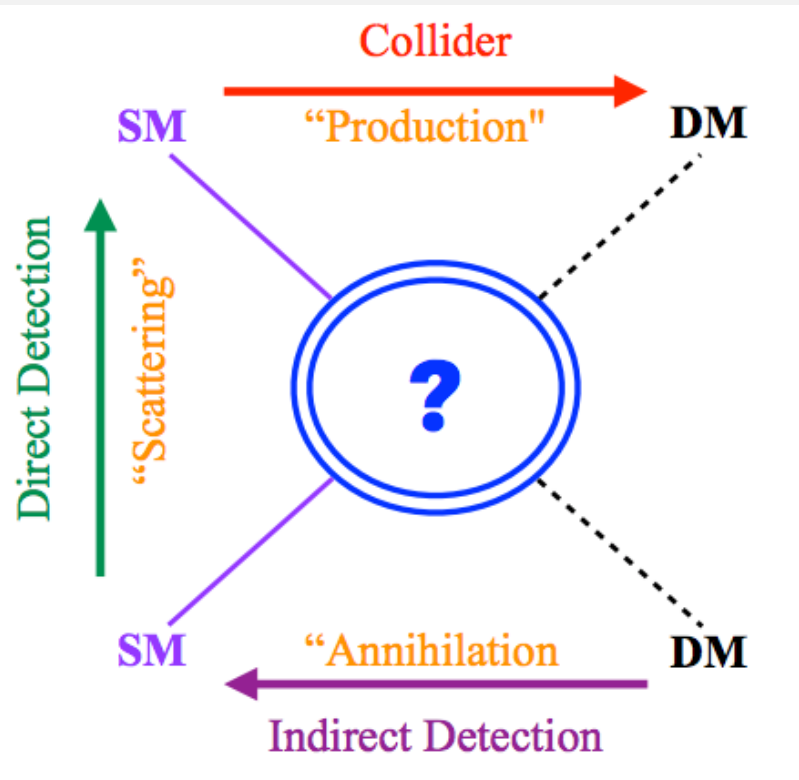
- DM evidence from astronomical observations and gravitational effects:
 - Galactic rotation curves, Gravitational lensing, Cosmic Microwave Background anisotropies, ...
- Characteristics: Non-baryonic, massive, electrically neutral, gravitational, stable → WIMP context
- BSM models predict weakly interacting massive particle (WIMP) -> Dark Matter Candidate. In SUSY models, the lightest SUSY particle LSP is a candidate for dark matter. Being LSP stable in most Models.
- Any WIMP DM produced at collider experiments will interact weakly and pass invisibly through detectors. Inferred through 'Missing E_T ' when event does not balance in plane transverse to beam.

● Frontiers that DM can reach out



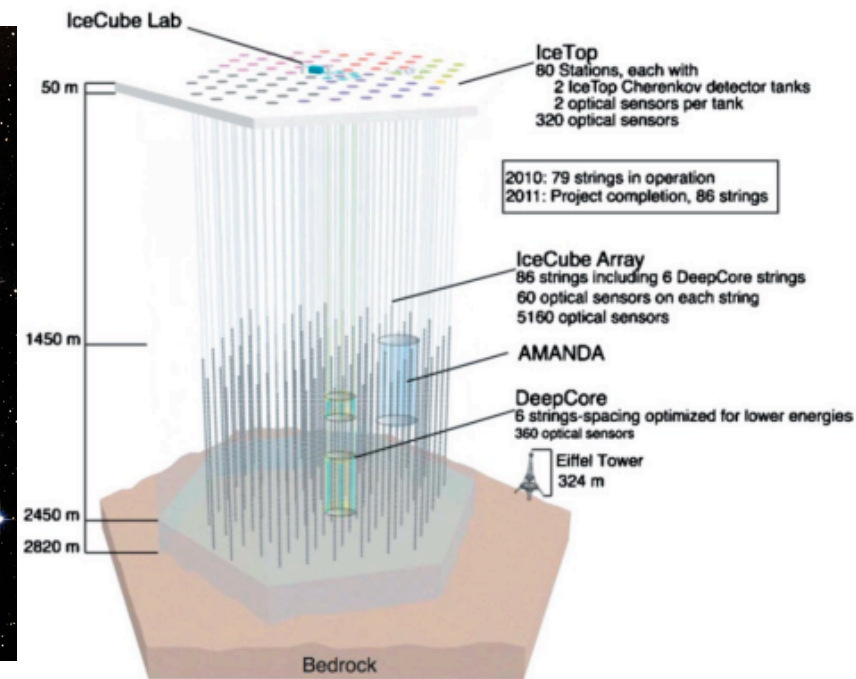
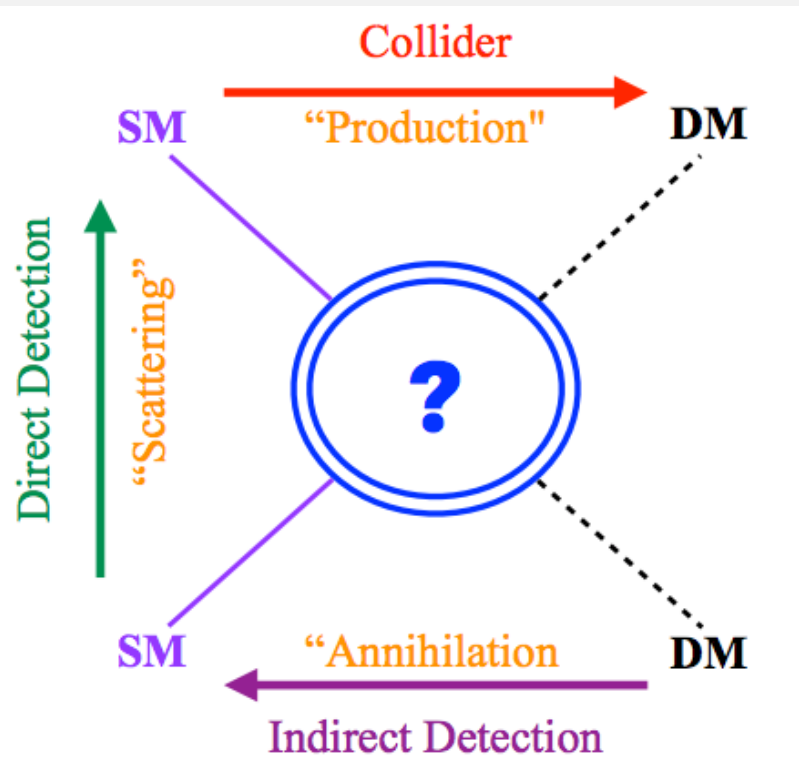
● Dark Matter Direct Detections

- Direct Detection (DD): nuclear recoils from DM-nuclei scattering (CDEX, PandaX, LZ, XenonNT, ...)
- Indirect Detection (ID): products from DM annihilation (DAMPE, HESS, IceCube, ..)
- Colliders: DM production in high-energy collisions, focusing on the productions of a SM particle(s) (X) with large missing E_T



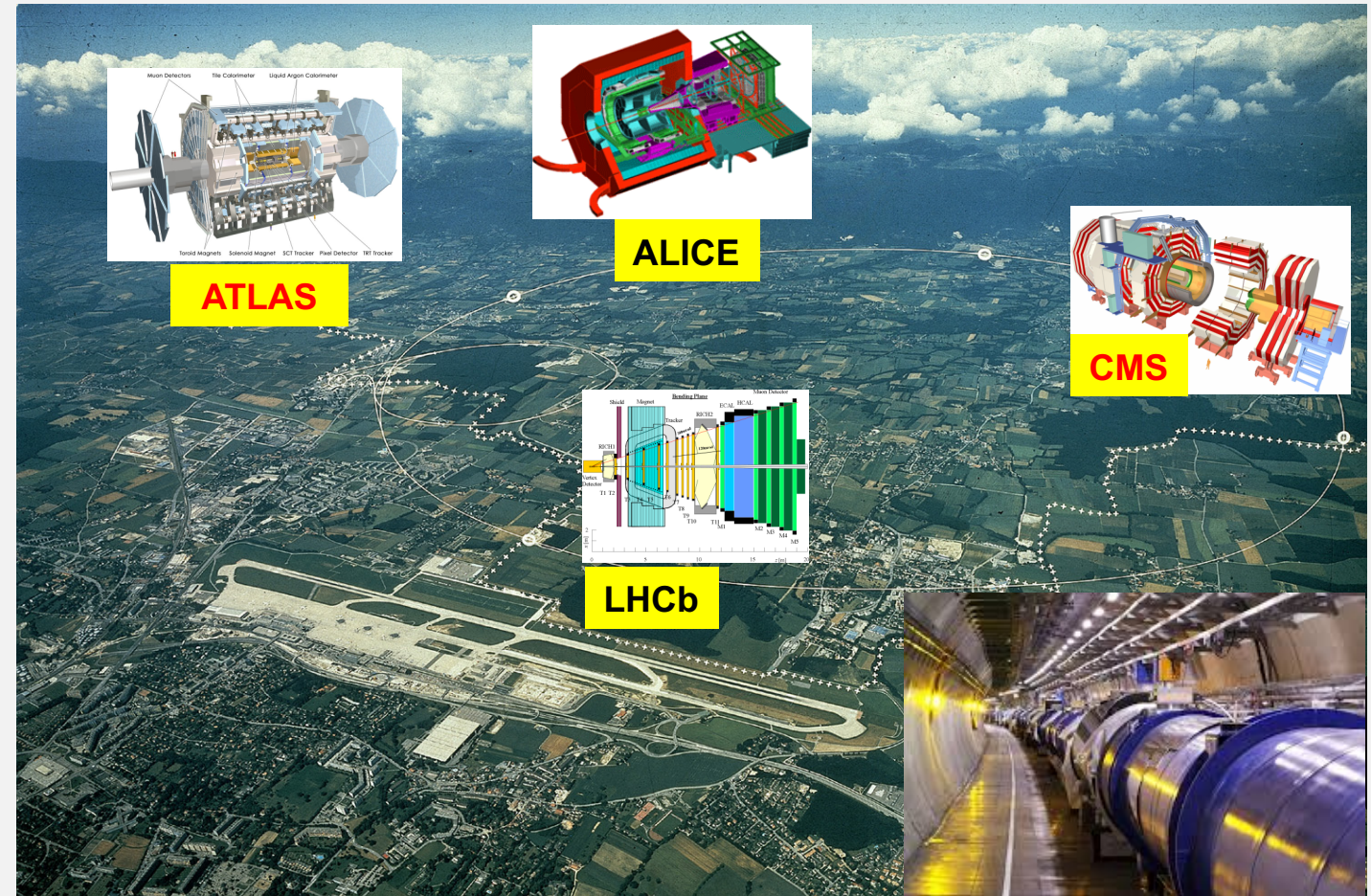
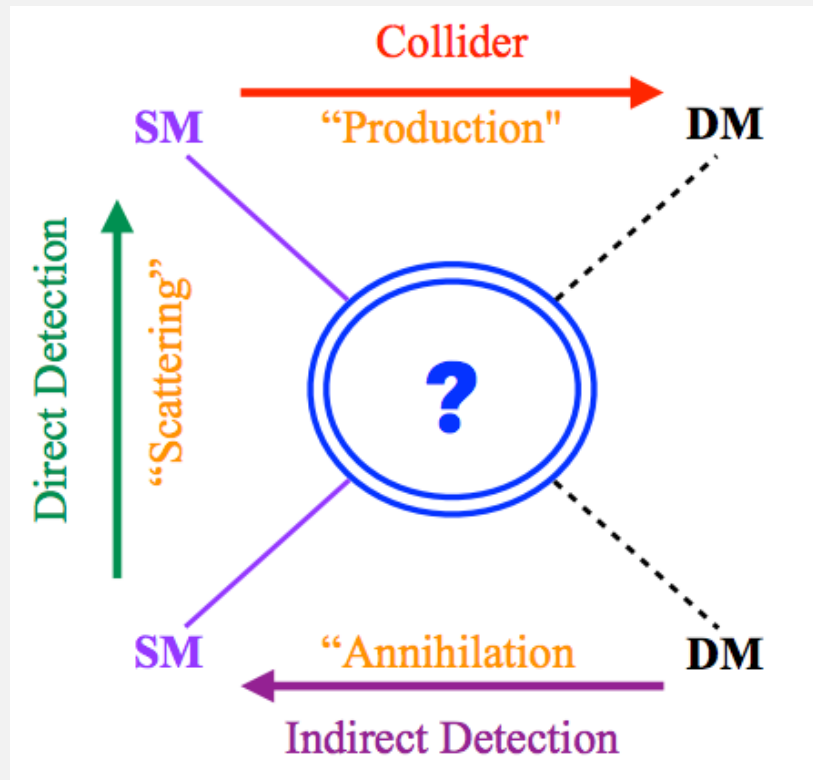
● Dark Matter Indirect Detections

- Direct Detection (DD): nuclear recoils from DM-nuclei scattering (CDEX, PandaX, LZ, XenonNT, ...)
- Indirect Detection (ID): products from DM annihilation (DAMPE, HESS, IceCube, ..)
- Colliders: DM production in high-energy collisions, focusing on the productions of a SM particle(s) (X) with large missing E_T



● Dark Matter Collider productions

- Direct Detection (DD): nuclear recoils from DM-nuclei scattering (CDEX, PandaX, LZ, XenonNT, ...)
- Indirect Detection (ID): products from DM annihilation (DAMPE, HESS, IceCube, ..)
- Colliders: DM production in high-energy collisions, focusing on the productions of a SM particle(s) (X) with large missing E_T



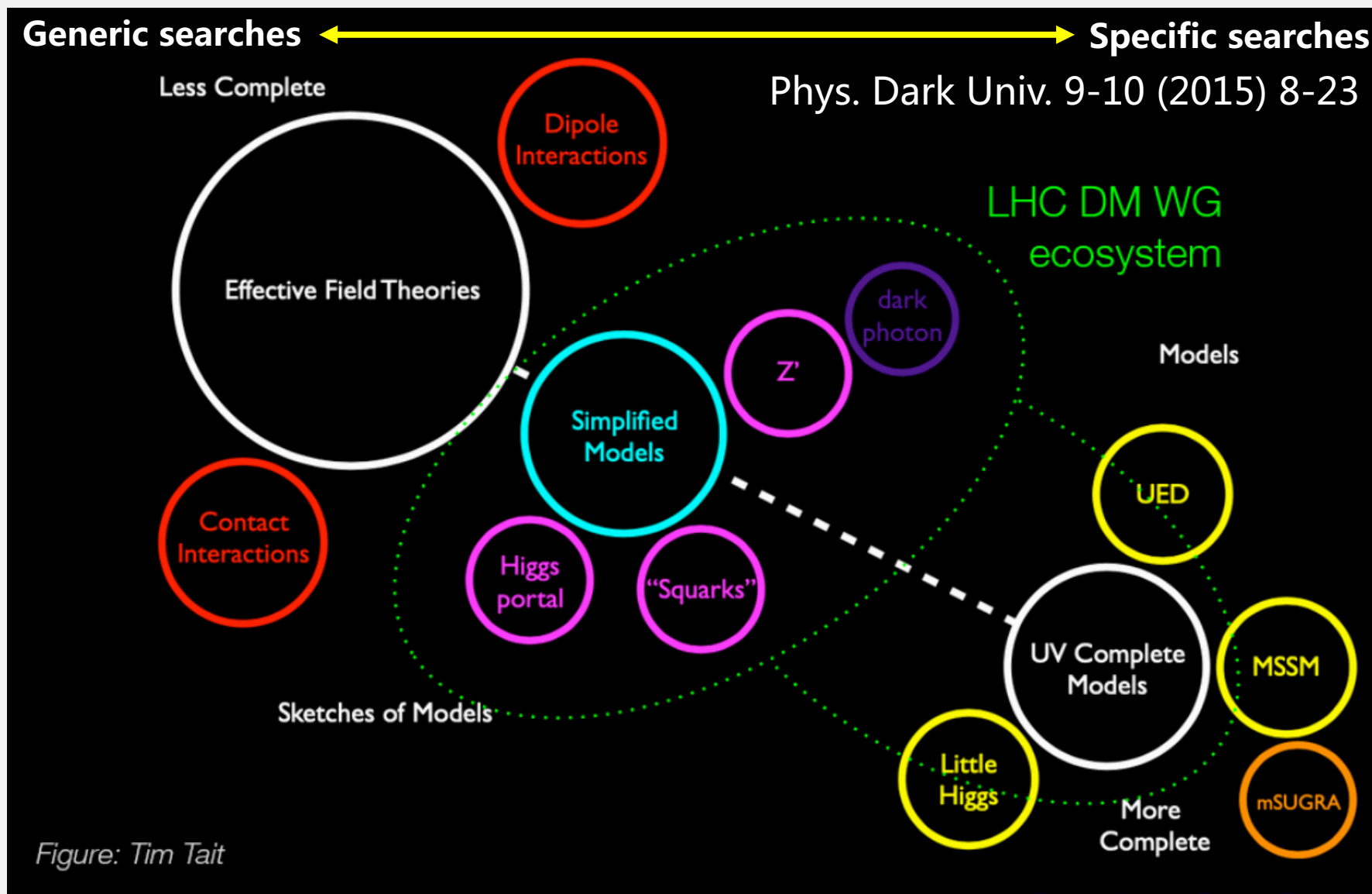
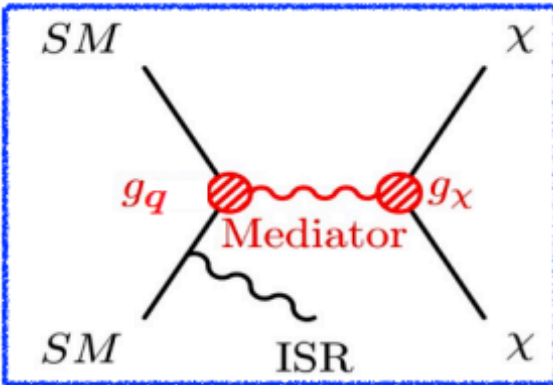


Figure: Tim Tait

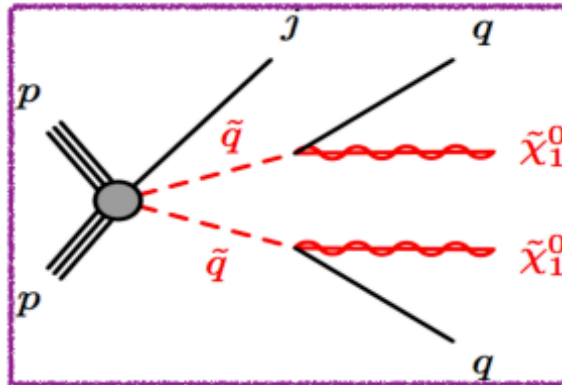
Dark Matter Search programs at LHC

Simplified models



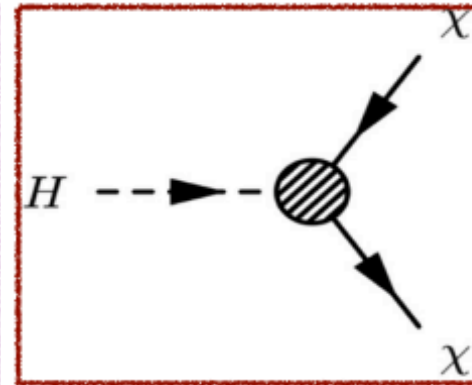
- SM-DM boson mediator:
- Spin-0: Scalar (S) or pseudo-scalar (a)
 - Spin-1: Vector (V/Z') or axial-vector (A)
 - Minimal set of parameters: $M_\chi, M_{\text{mediator}}, g_\chi, g_q, g_\ell$

SUSY



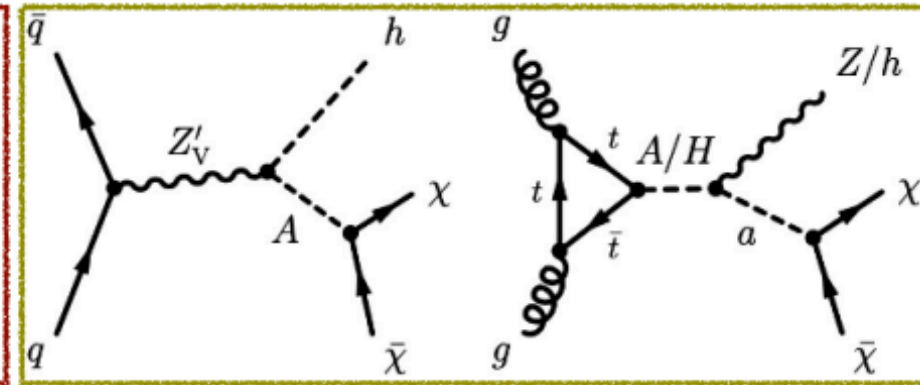
- Provides good candidate for DM
- R-parity conservation
- Lightest supersymmetric Particle (LSP)
- Model-dependent limit on DM candidate

Higgs portal



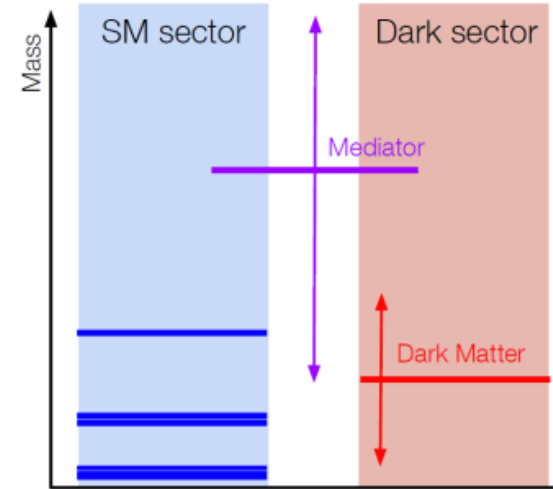
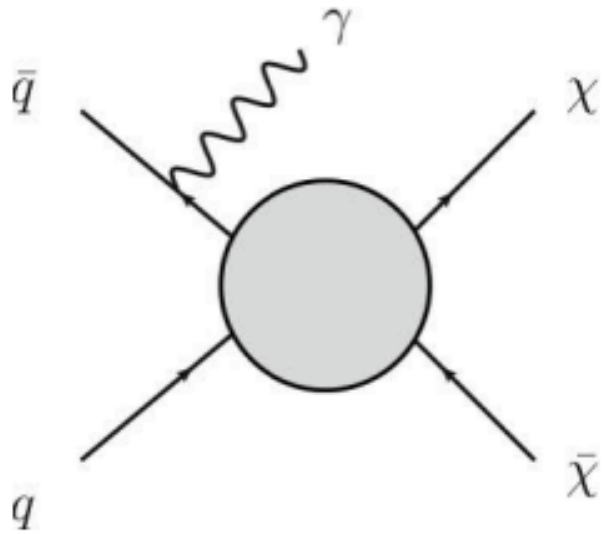
- Higgs boson mediates DM-SM interaction:
 $H \rightarrow \text{invisible}$
- Parameters: m_χ, χ spin

Extended Higgs sector

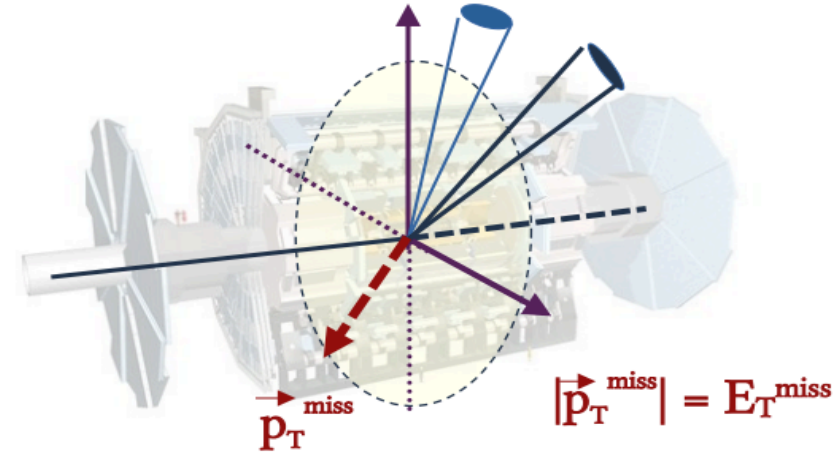


- More complete models (more free parameters and better sensitivity) involving several Higgs-like (or scalar) bosons: 2HDMa, Dark Higgs, ..

● S-channel Mediator Simplified Models



DM produced together with a visible object
e.g. γ , jet, Z-boson, W-boson, Higgs-boson



Escape
Detection

Simplified model:

- Starting point to build complete theories
- Colliders can search for the mediator directly
- Benchmark model @ Run II

Two complementary approaches:

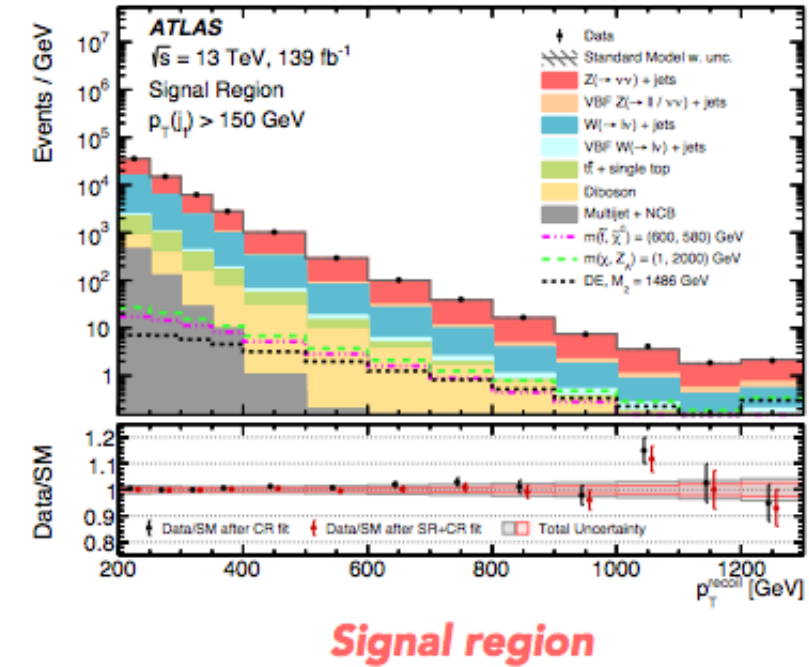
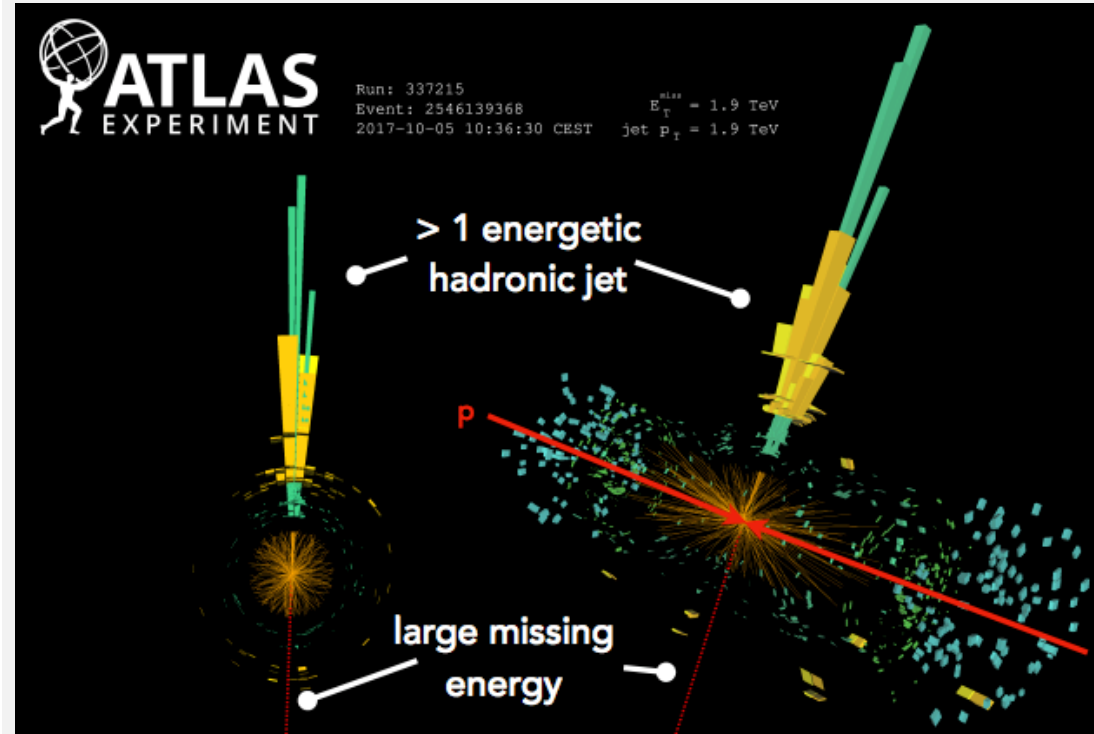
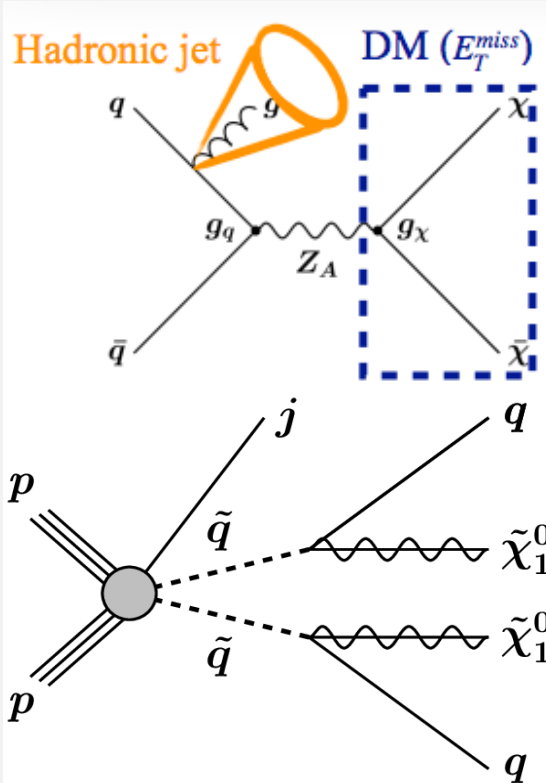
- Look for DM - mono-X signature
- Look for mediator - resonance search

● Mono-Jet search (Jet + E_T^{miss})

ATLAS: *Phys. Rev. D* 103 (2021) 112006
CMS: *JHEP* 11(2021)153



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- Diverse Interpretations
- Simplified Models:
 - Fix coupling; Fix ratio
 - T-channel models
 - Generic sensitivity
 - SUSY, leptoquarks, extra dimensions, ...

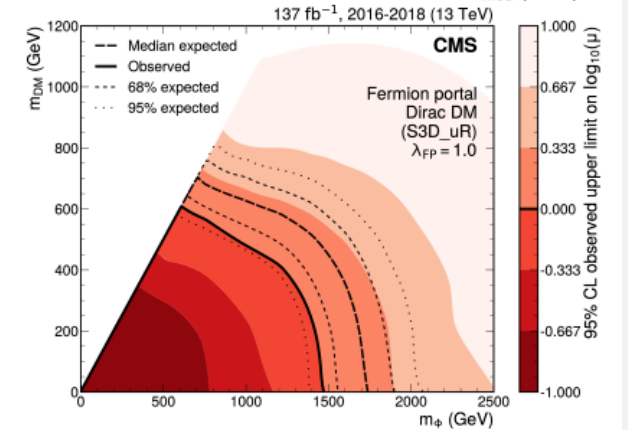
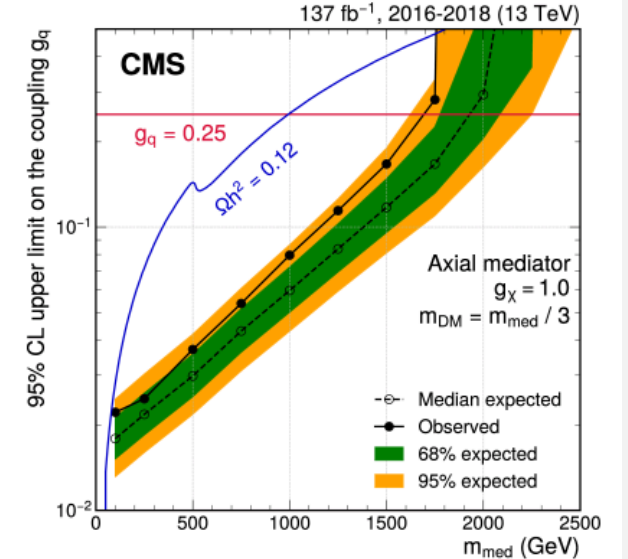
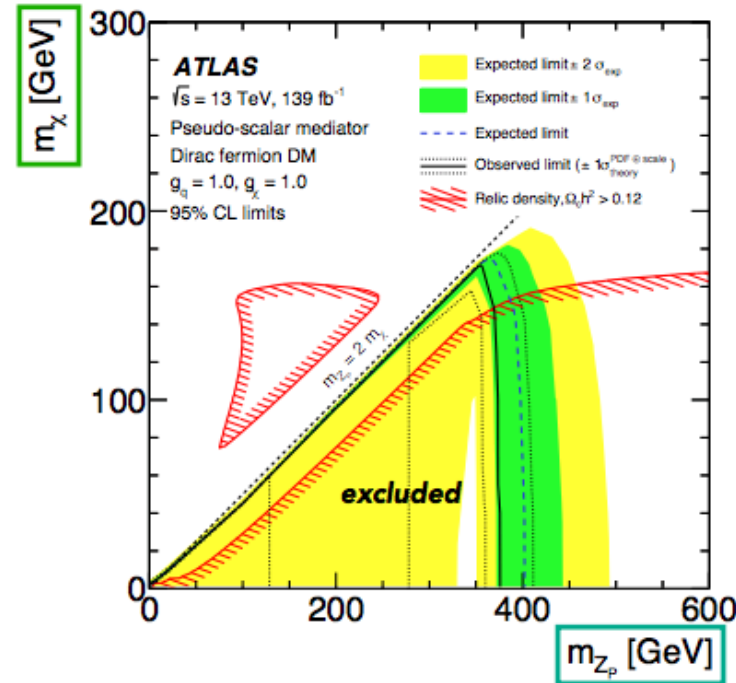
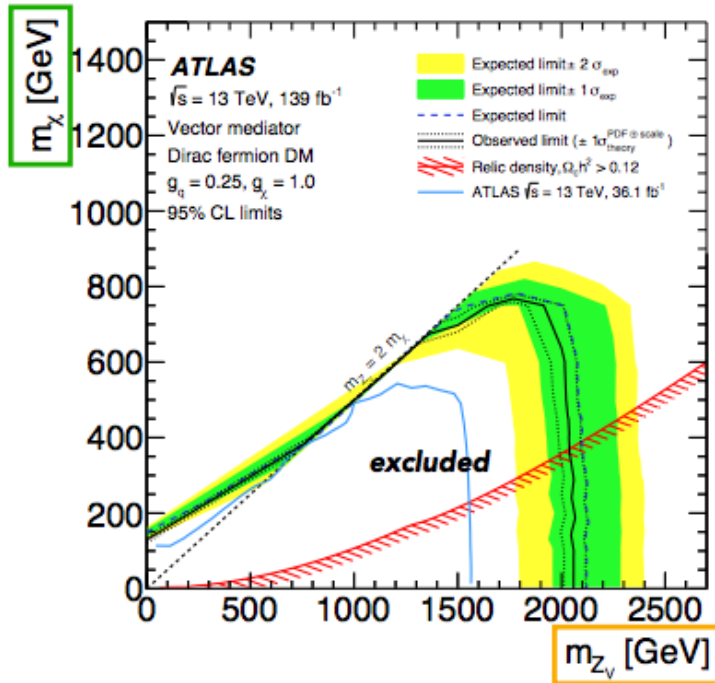
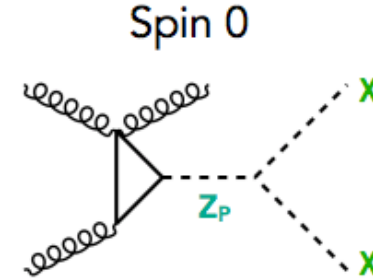
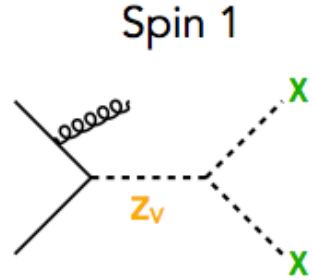
Main backgrounds

● Mono-Jet search (Jet + E_T^{miss})

ATLAS: *Phys. Rev. D* 103 (2021) 112006
CMS: *JHEP* 11(2021)153



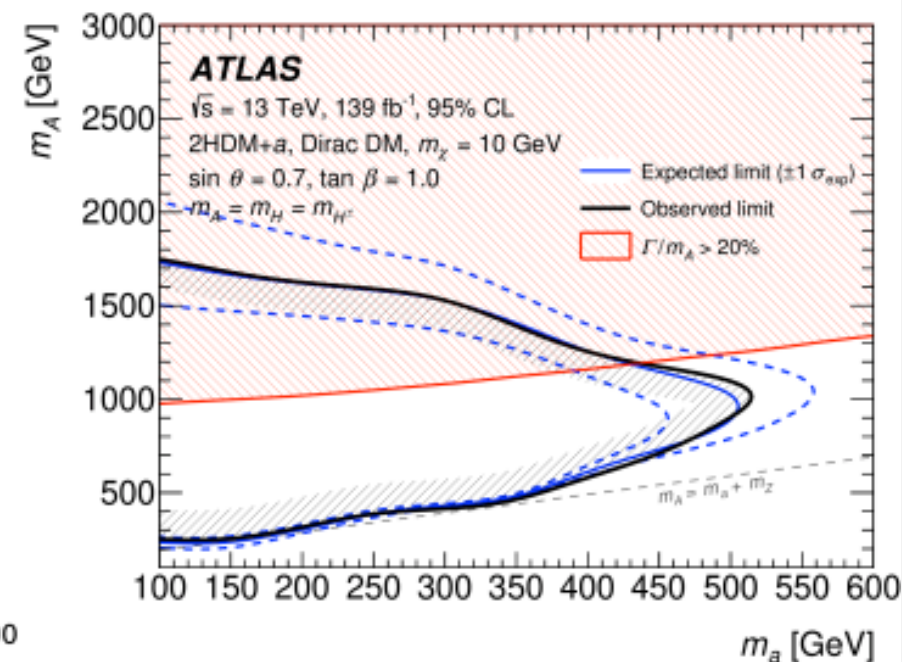
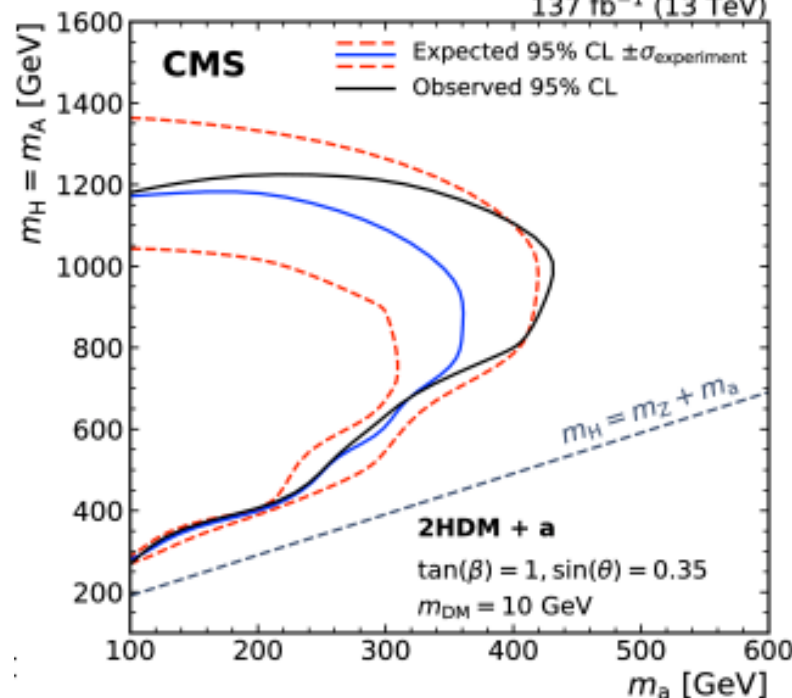
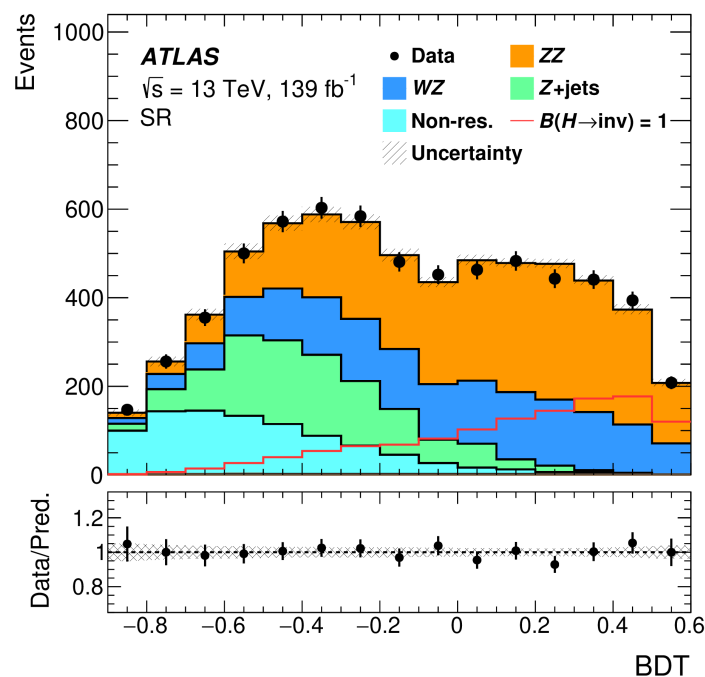
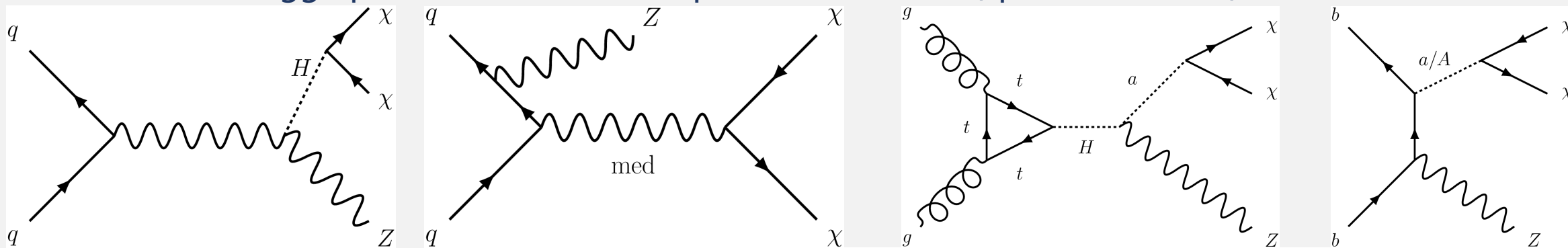
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● Mono-Z(II) ($Z + E_T^{\text{miss}}$)

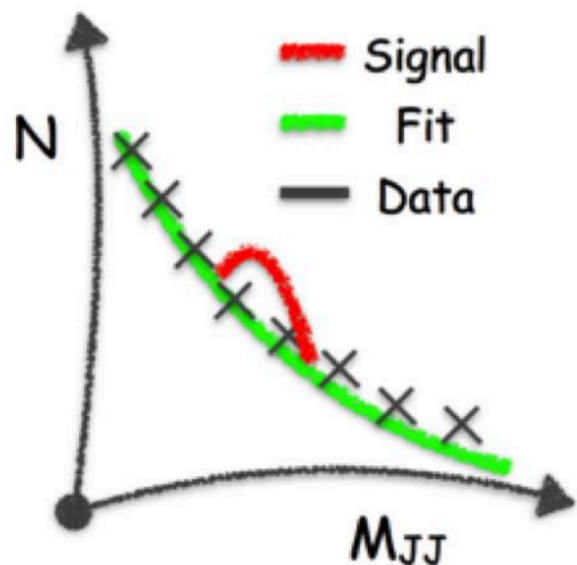
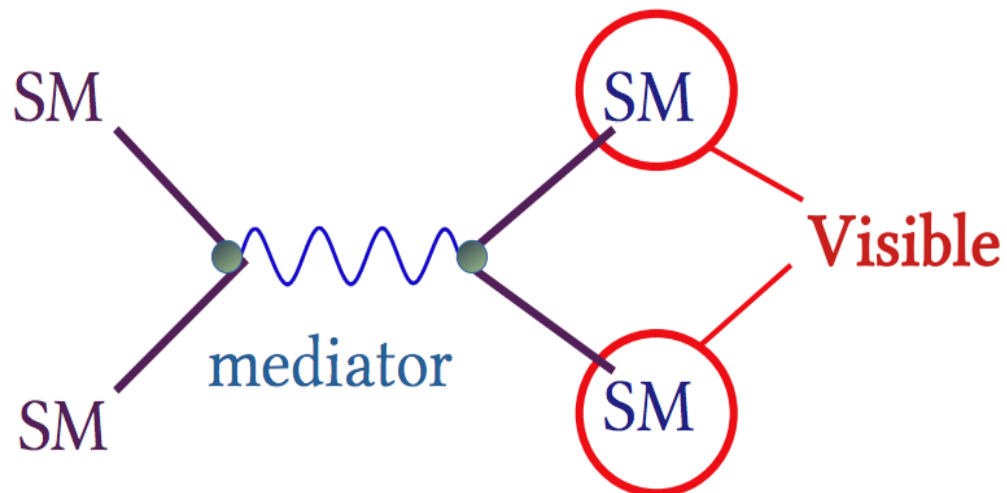
ATLAS: *Phys. Lett. B* 829 (2022) 137066
CMS: *Eur. Phys. J. C* 81 (2021) 13

Higgs-portal, 2HDM + a; simplified DM model (spin-1 mediator)

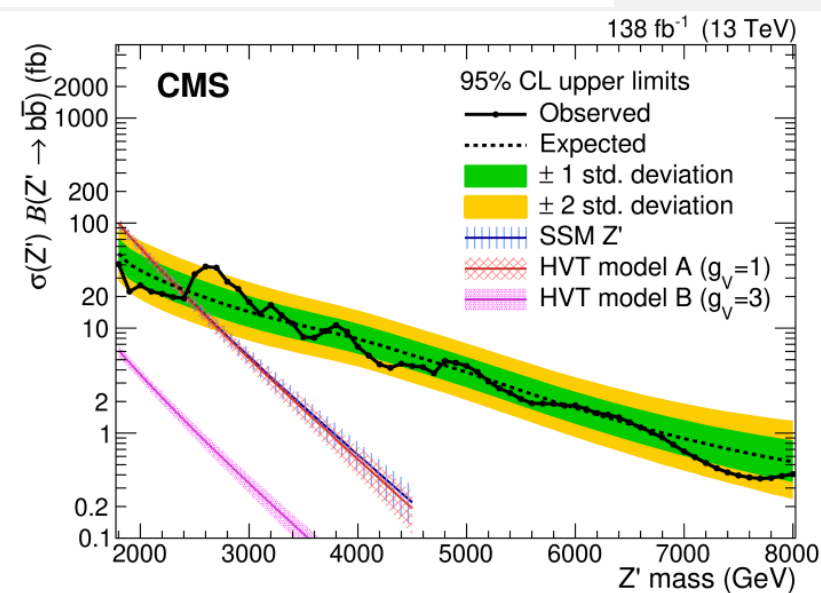
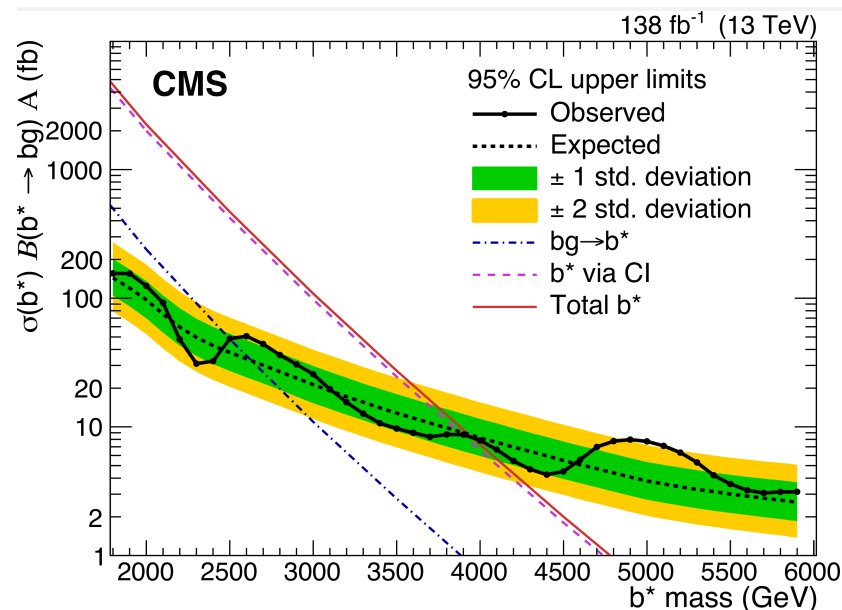
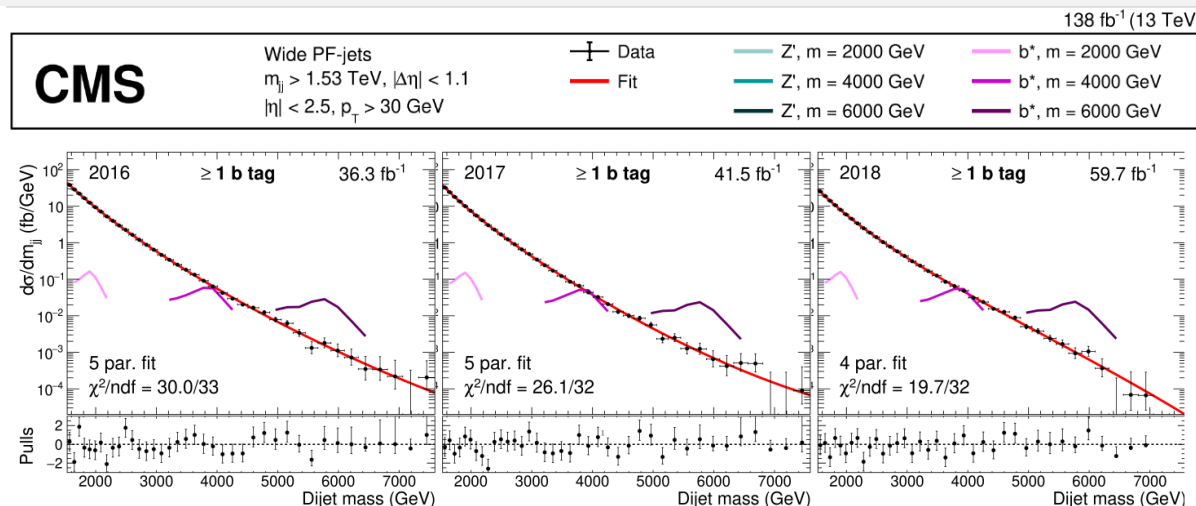


DM Mediator to Di-(b)jet search

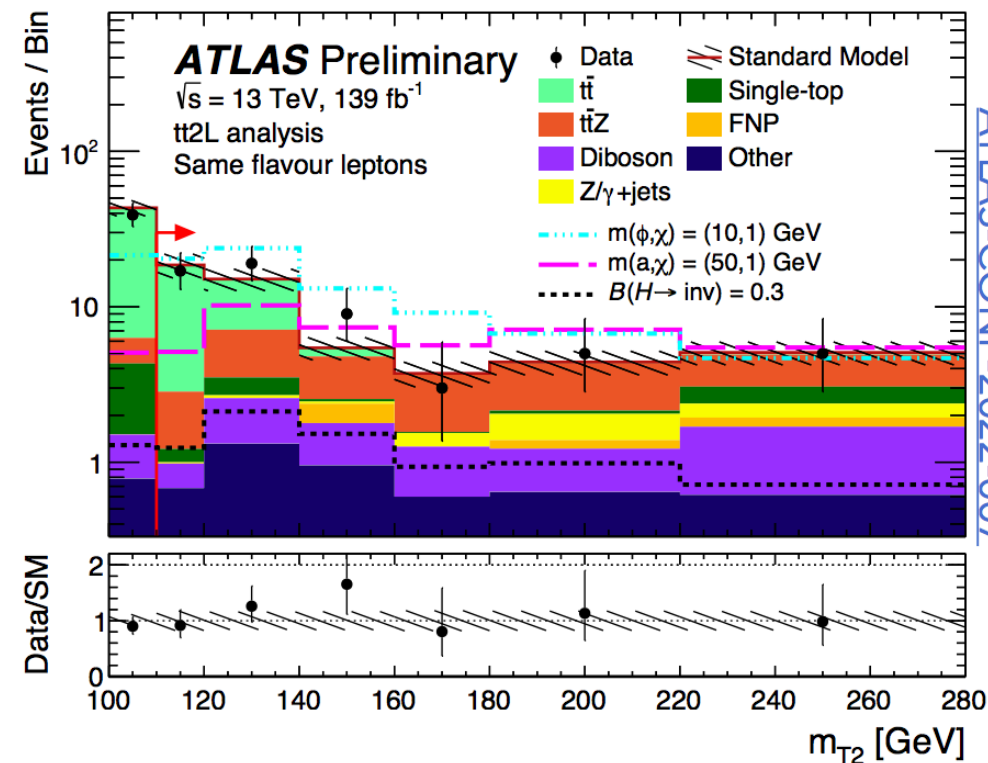
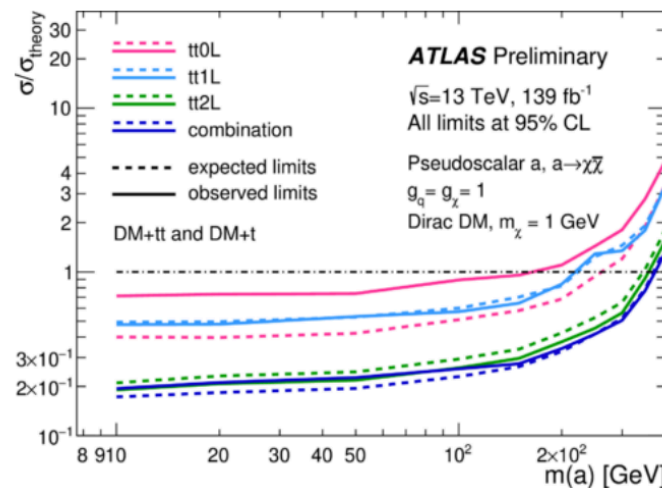
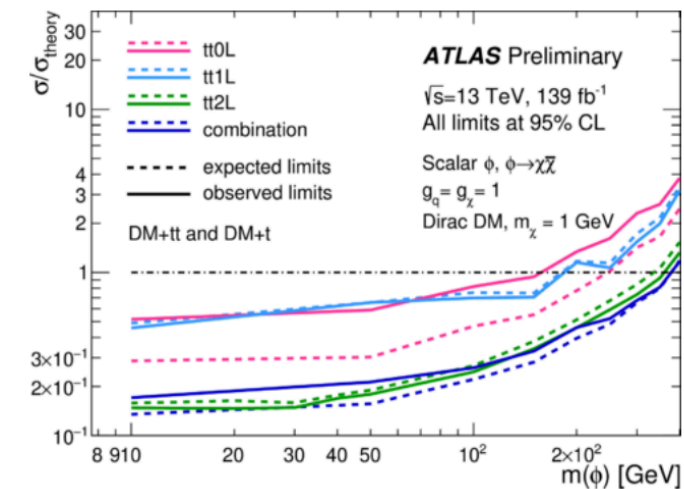
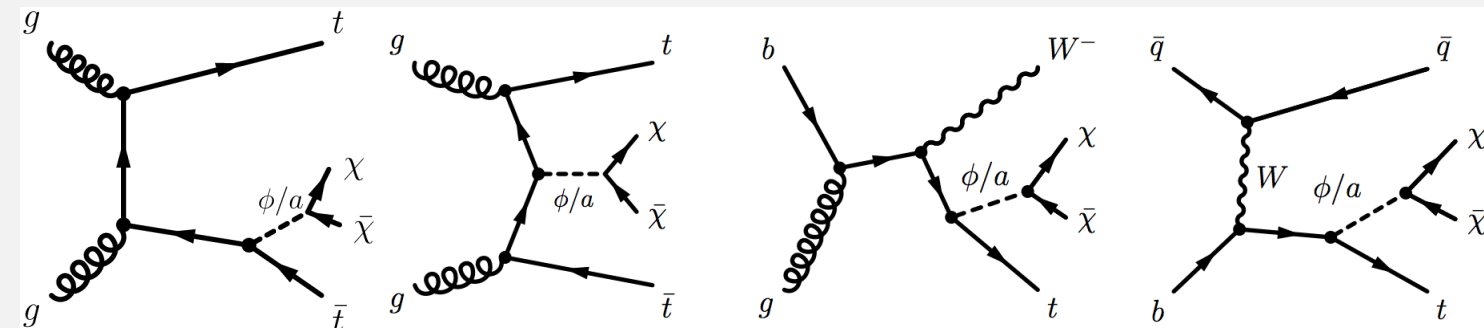
arXiv:2205.01835 (accepted by PRD)



Dijet



scalar mediators $\rightarrow$ Yukawa-like coupling with SM particles
sensitivity driven by 3rd generation



Combining 0, 1, 2 lepton channels
Also interpreted as results on $H \rightarrow \text{inv.}$

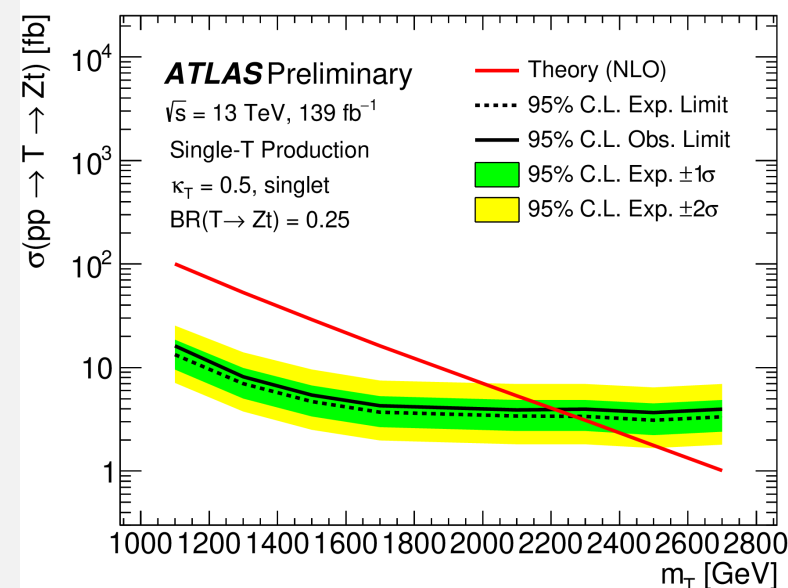
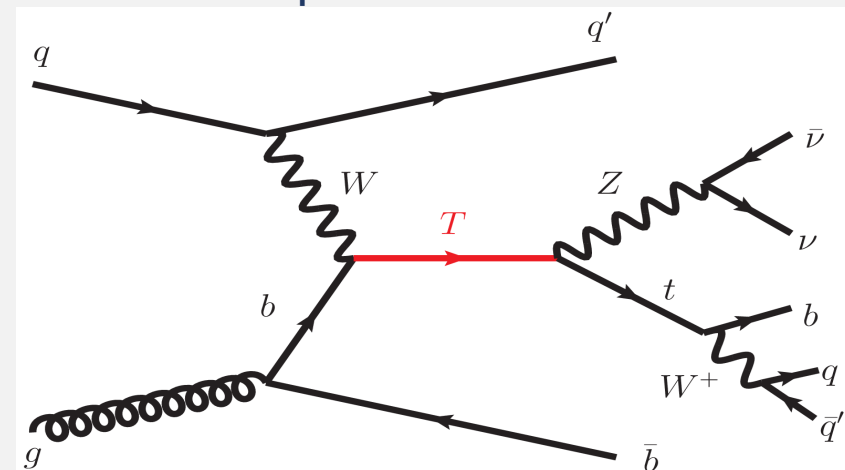
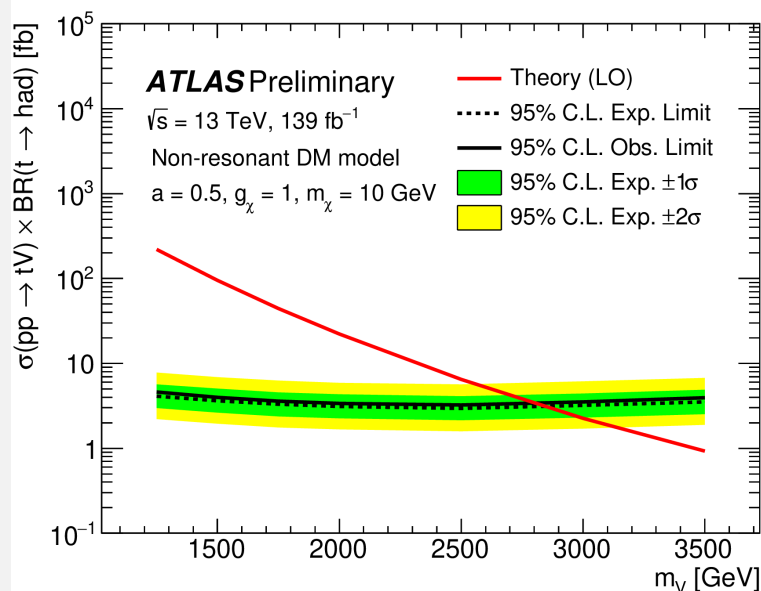
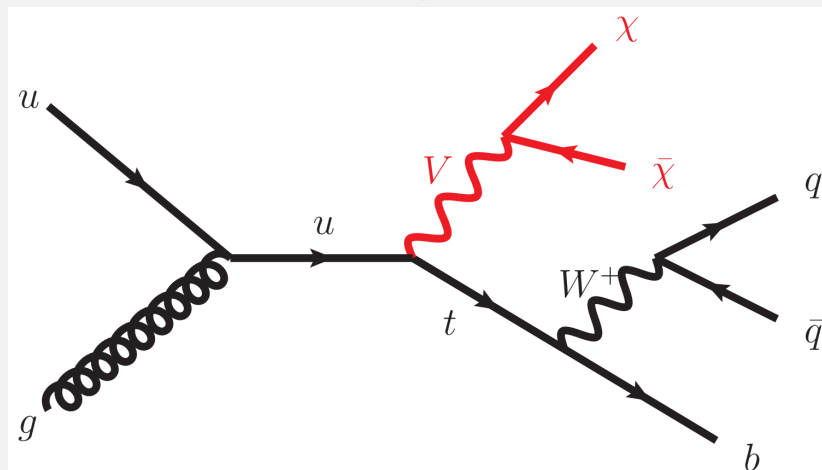
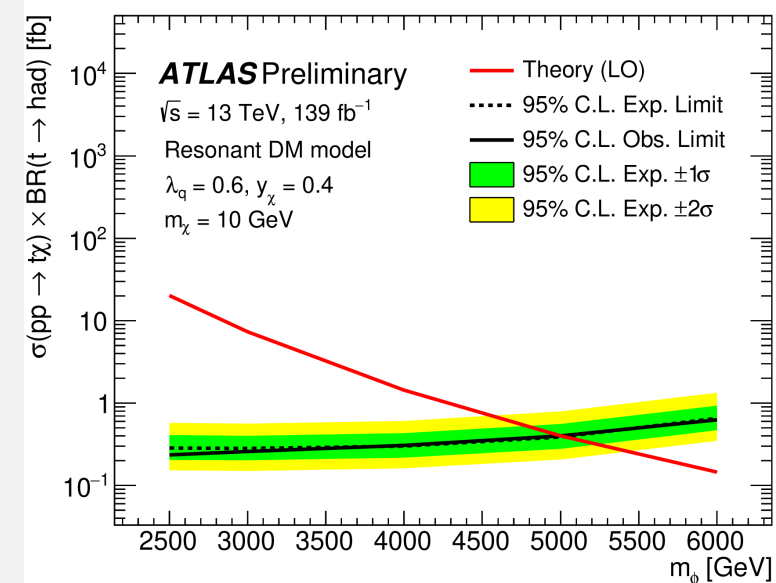
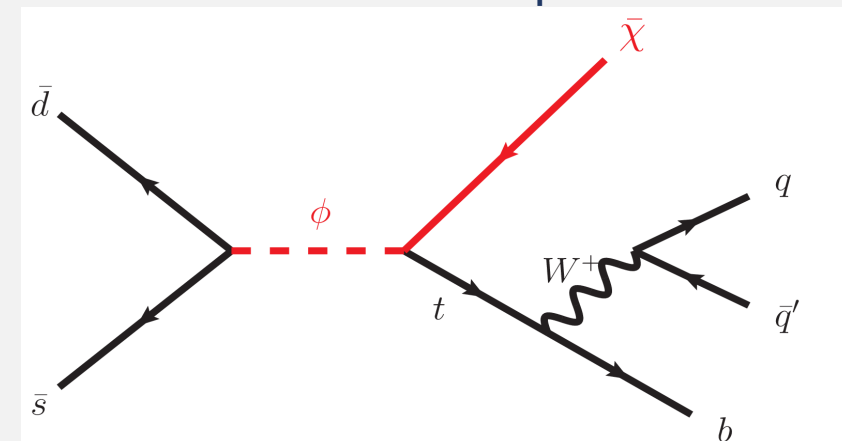
Single Top + E_T^{miss}

ATLAS-CONF-2022-036



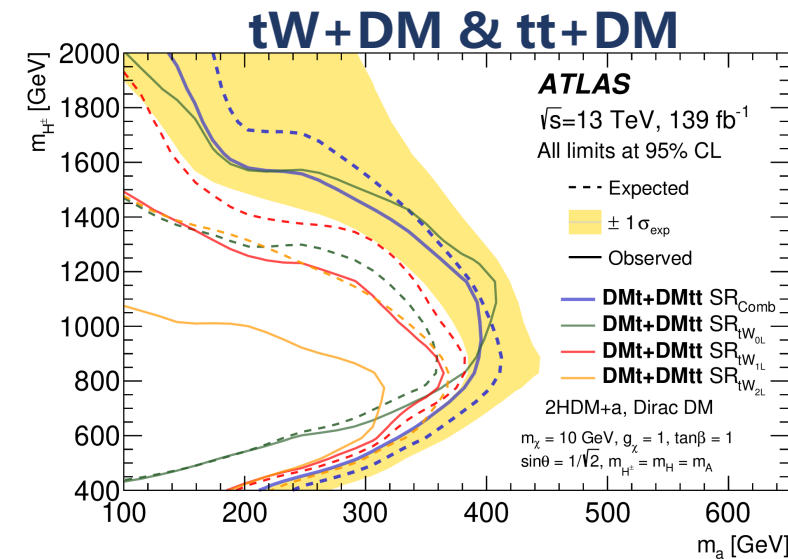
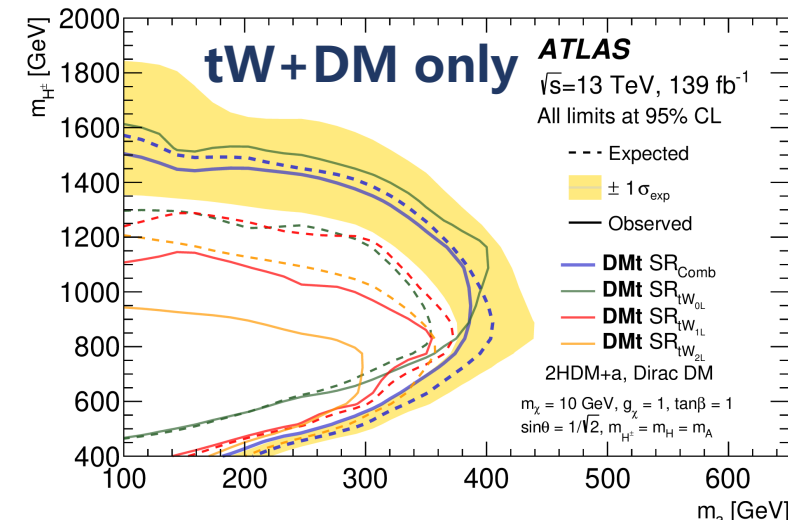
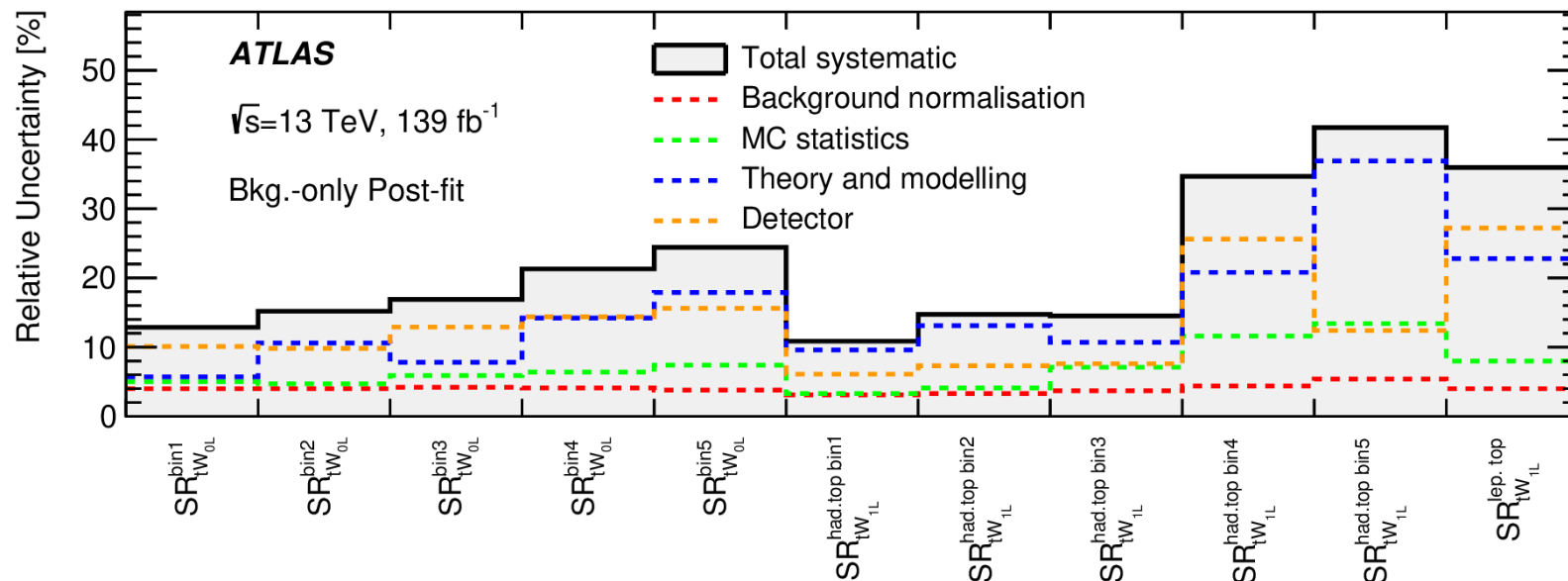
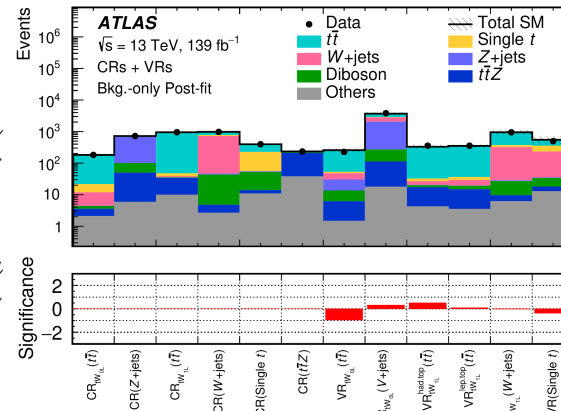
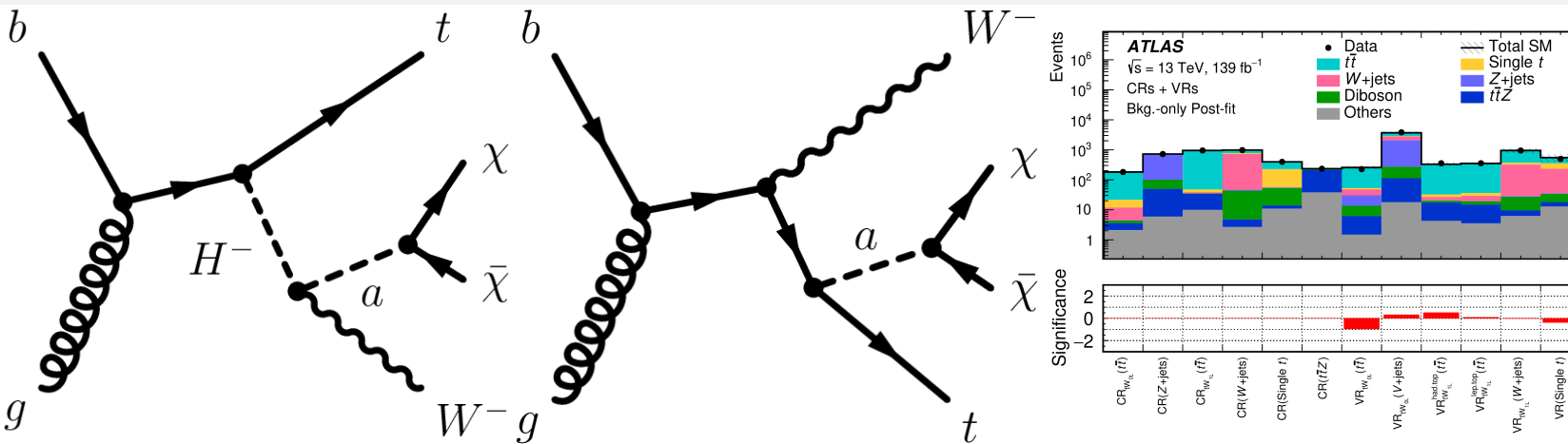
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Interpretations in context of resonant/non-resonant and vector like quark

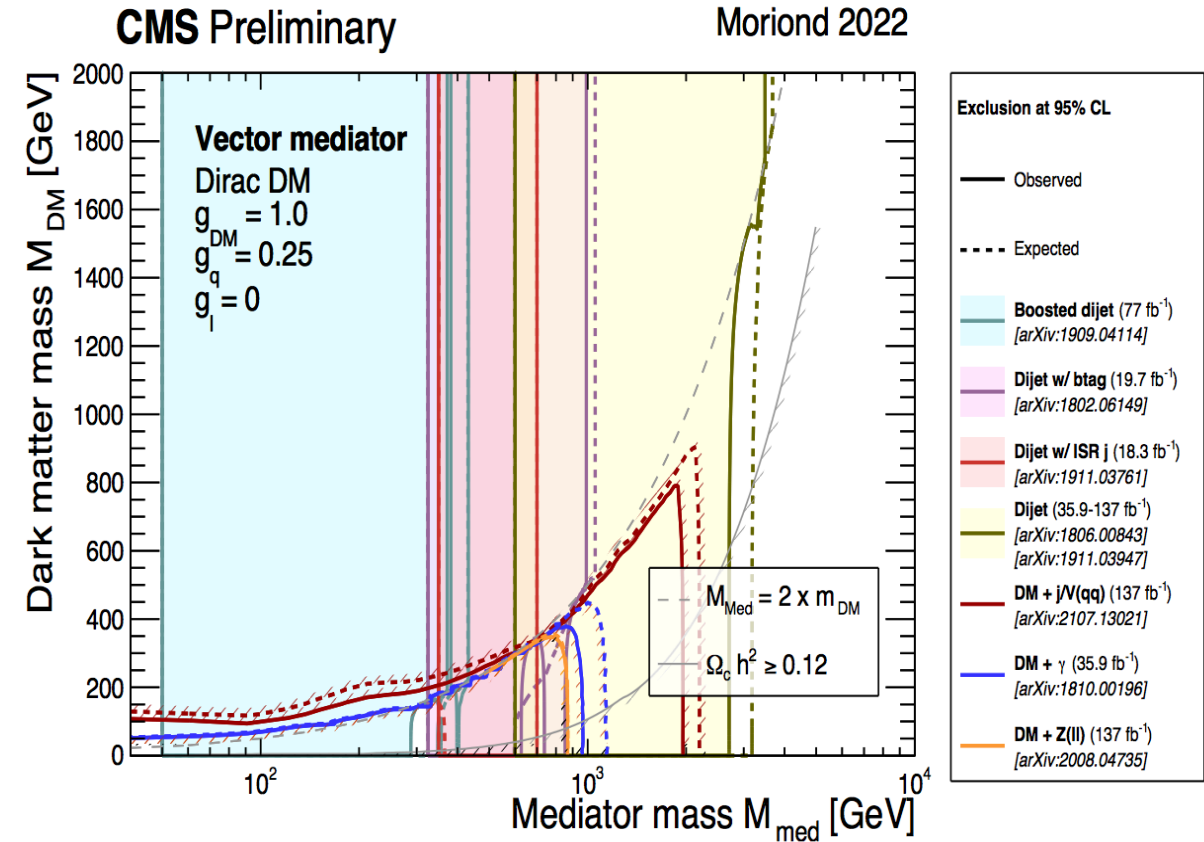
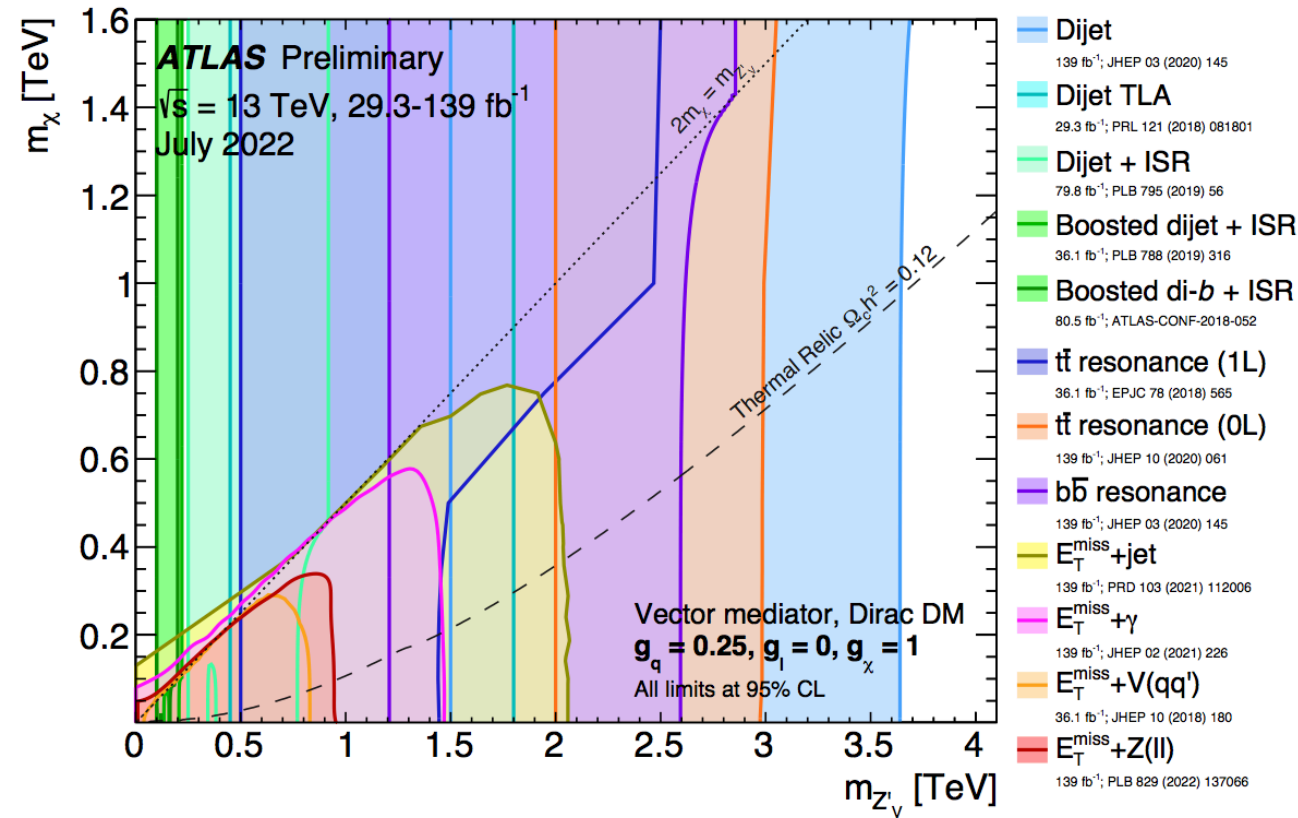


Particle and Nuclear Physics Division
粒子与核物理研究部

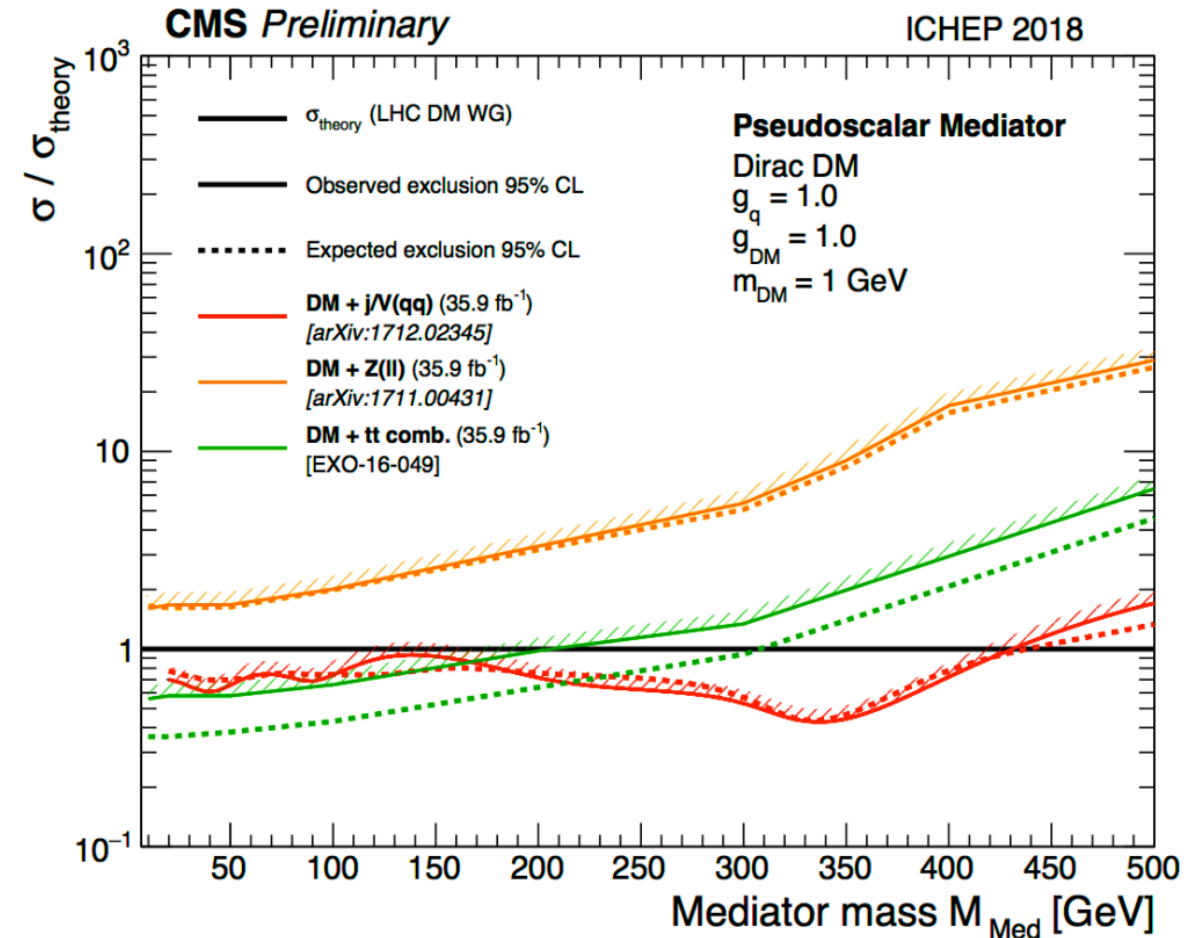
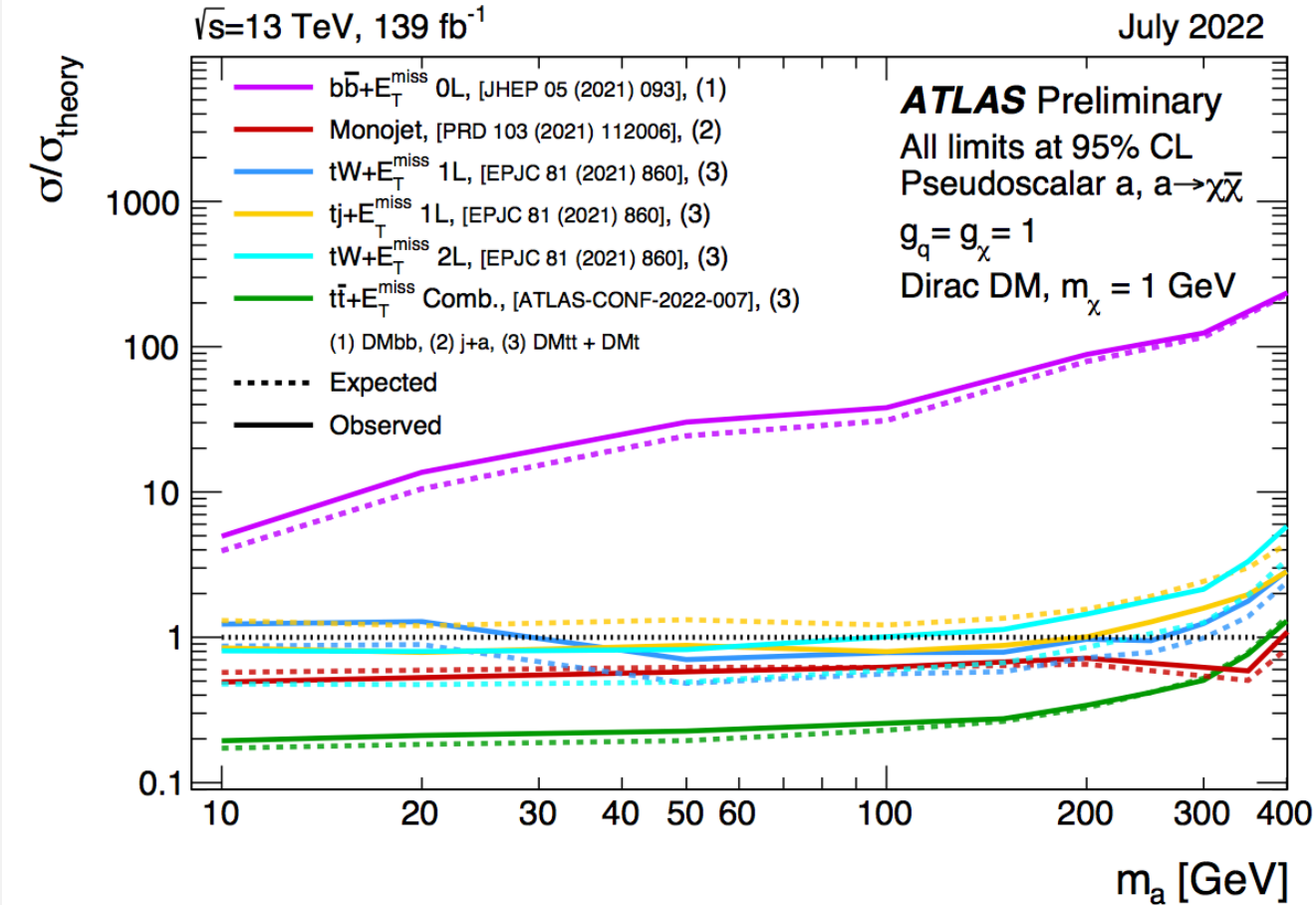
BDT (XGBoost) is used to discriminate signal/ background (E_T^{miss} based variables and ΔR_{max} among the most important features in the training)



● (Axial-)Vector Mediator summary



● (Pseudo-)Scalar mediator sensitivity summary

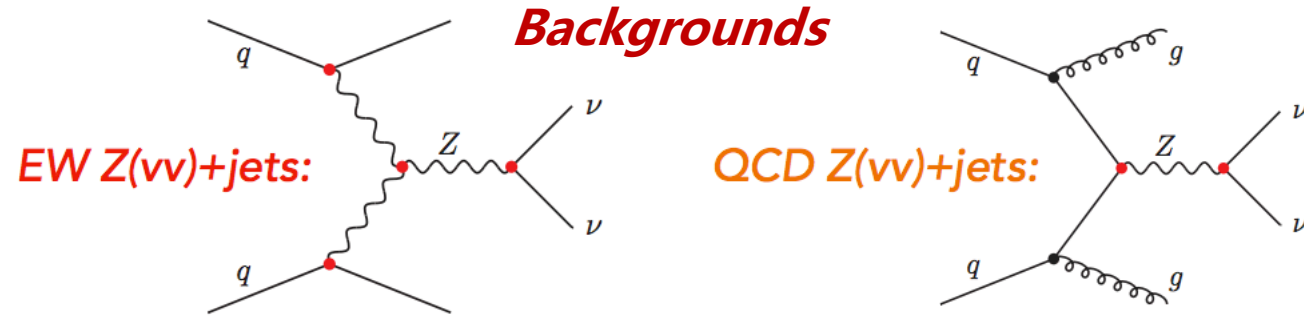
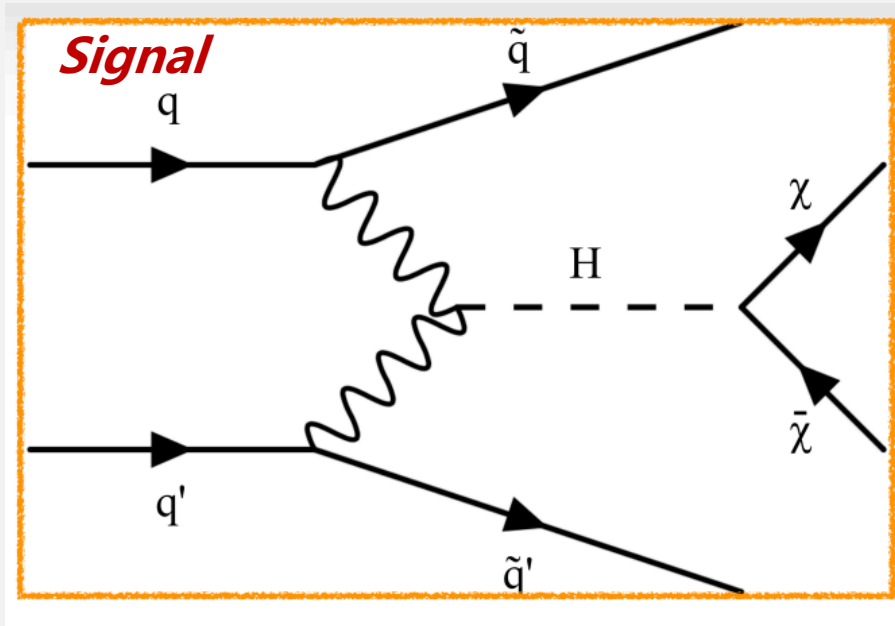


● Higgs portal to DM: invisible decays

Phys. Rev. D 105 (2022) 092007



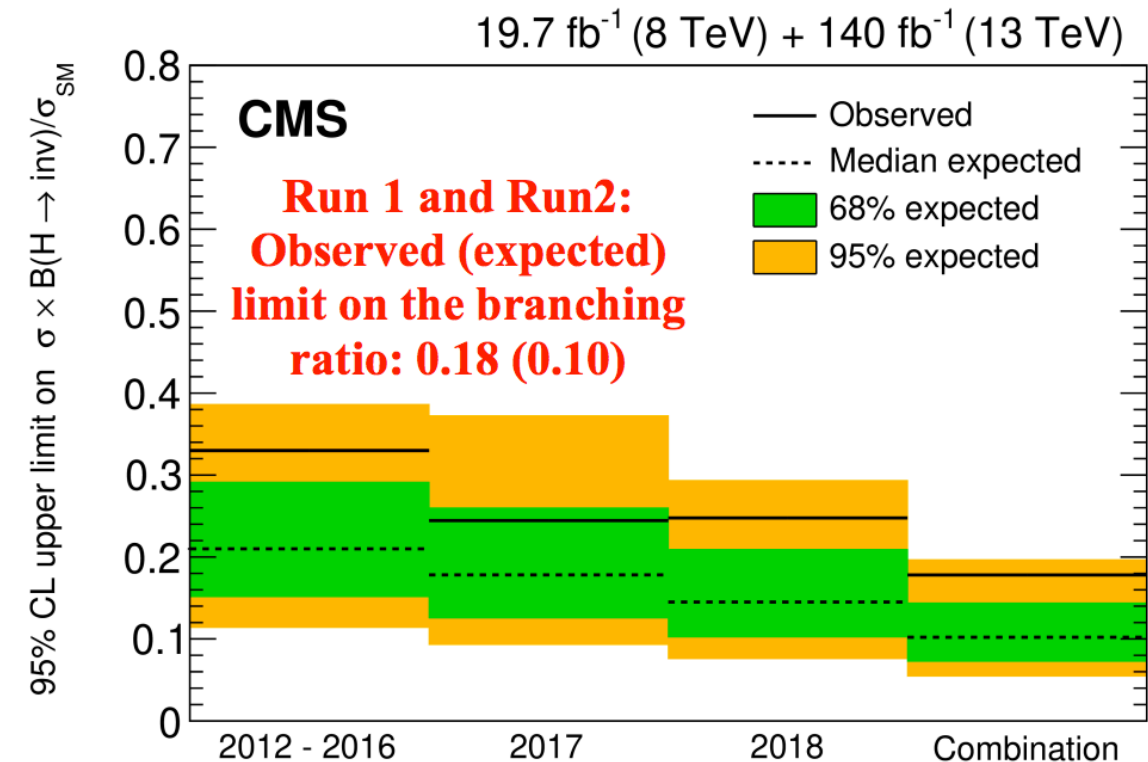
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Observed Limit from the combination

$$\mathcal{B}(H \rightarrow \text{inv}) < 0.18 \text{ (0.12) at the 95\% CL,}$$

- Signature: Vector-Boson Fusion
- Two SR triggers:
 - MTR with missing momentum trigger
 - VTR with VBF jet trigger



Higgs portal to DM: invisible decays

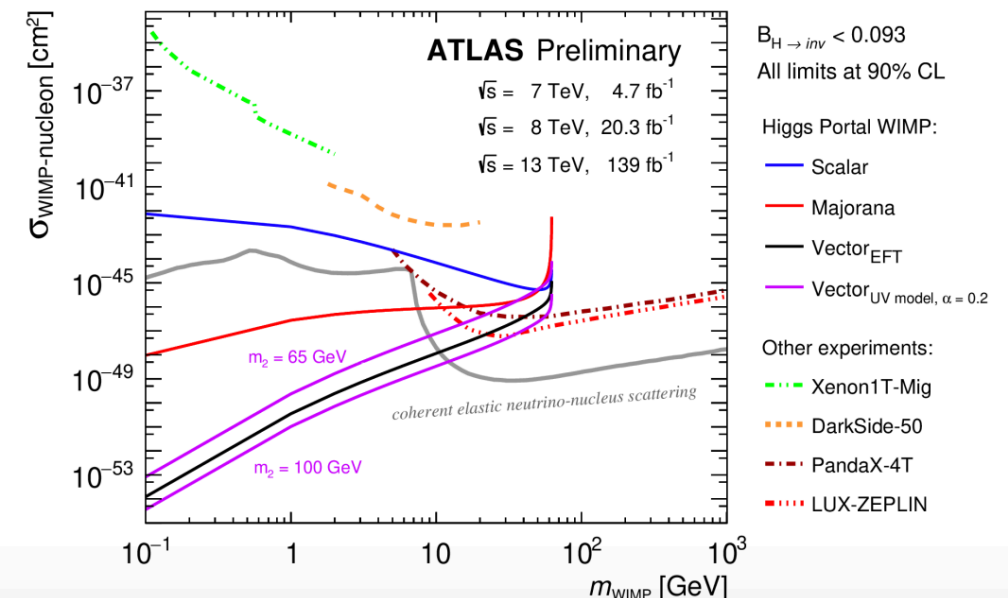
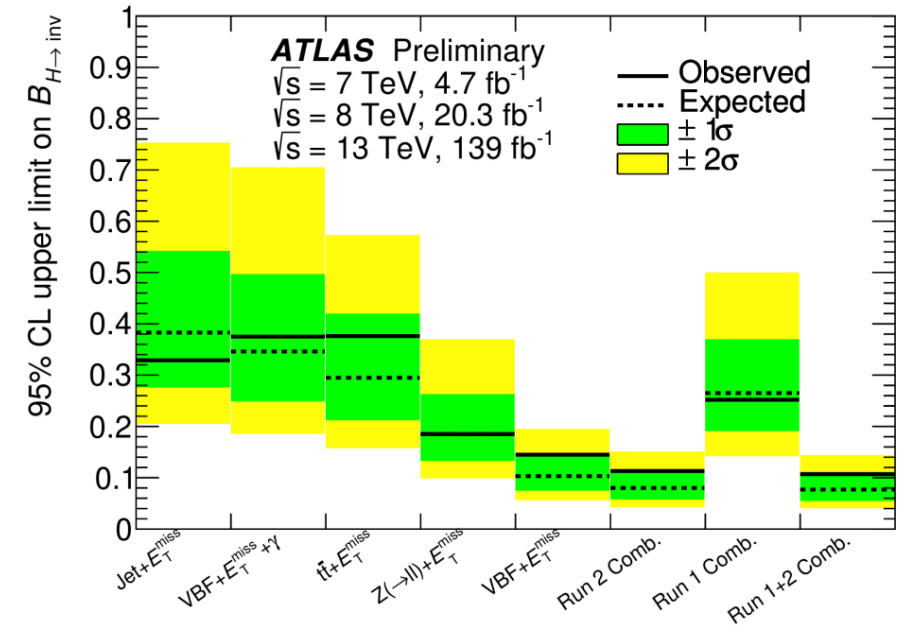
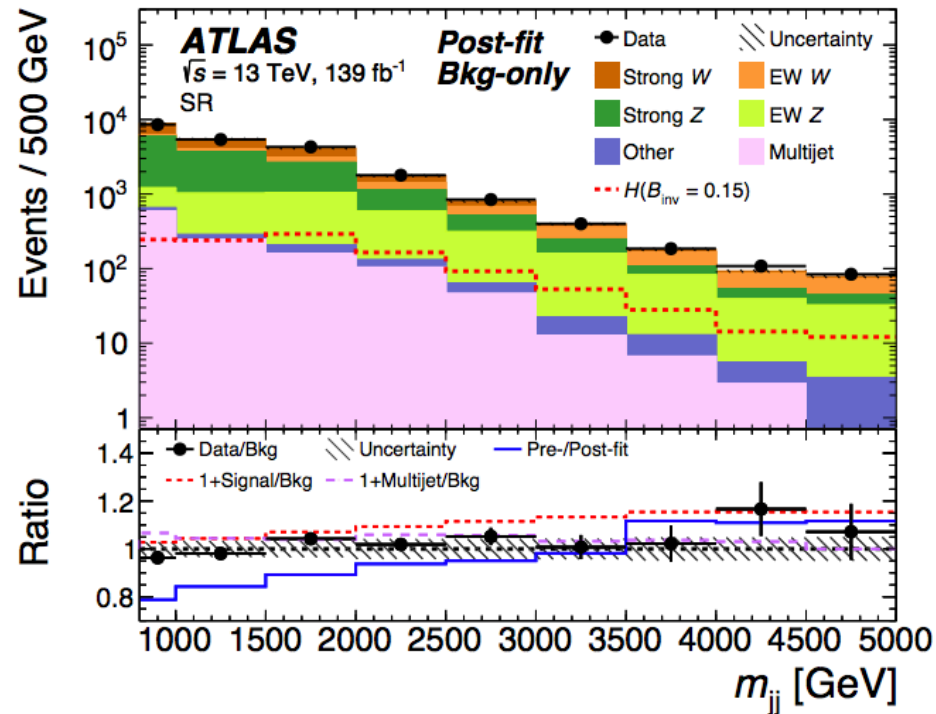
HIGG-2021-05



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Analysis	Best fit $\mathcal{B}_{H \rightarrow \text{inv}}$	Observed 95% U.L.	Expected 95% U.L.
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	$0.077^{+0.030}_{-0.022}$

- Z to W ratio predictions @NLO QCD, NLO EW - [arXiv:2204.07652](https://arxiv.org/abs/2204.07652) - used to constrain Zjets with Wjets
- Probing BR(H → Inv) at 10% level

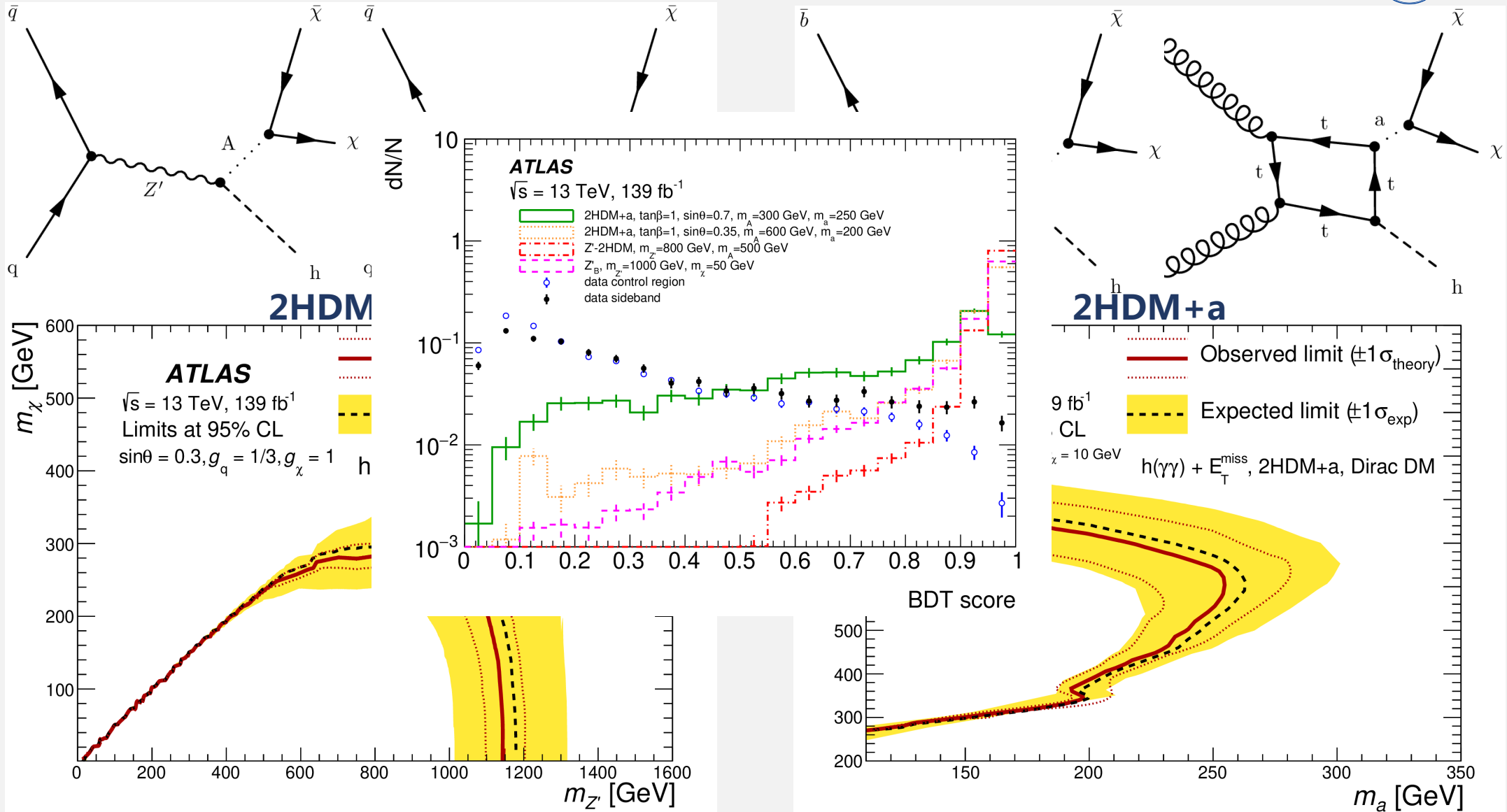


Higgs portal to DM: Mono-H($\gamma\gamma$)

JHEP 10 (2021) 13



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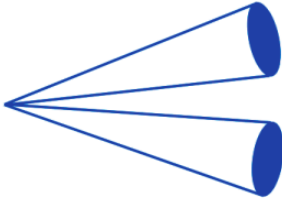
● Higgs portal to DM: Mono-H(bb)

JHEP 11 (2021) 209

- Interpreted with 2HDM+Z' , 2HDM+a in both ggF and bbH.
- Also Model-independent upper limits on the visible cross-section

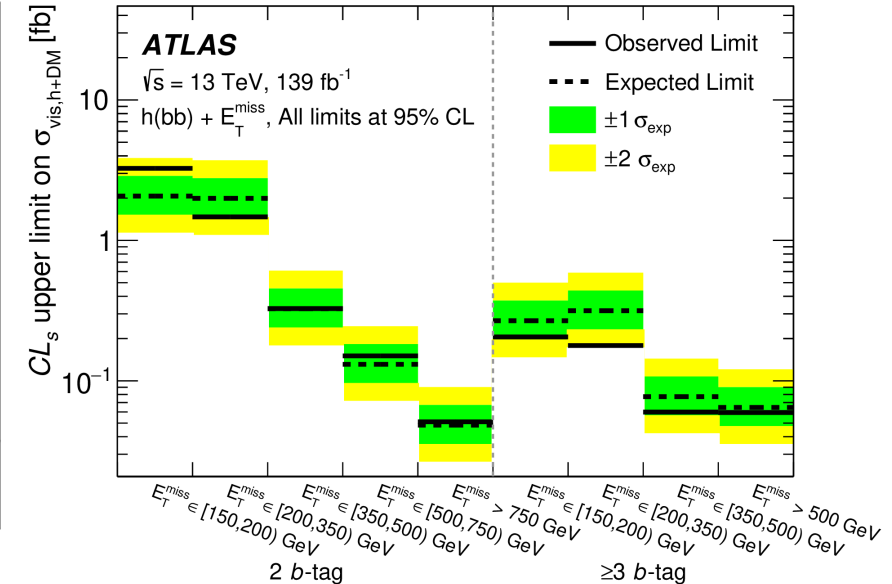
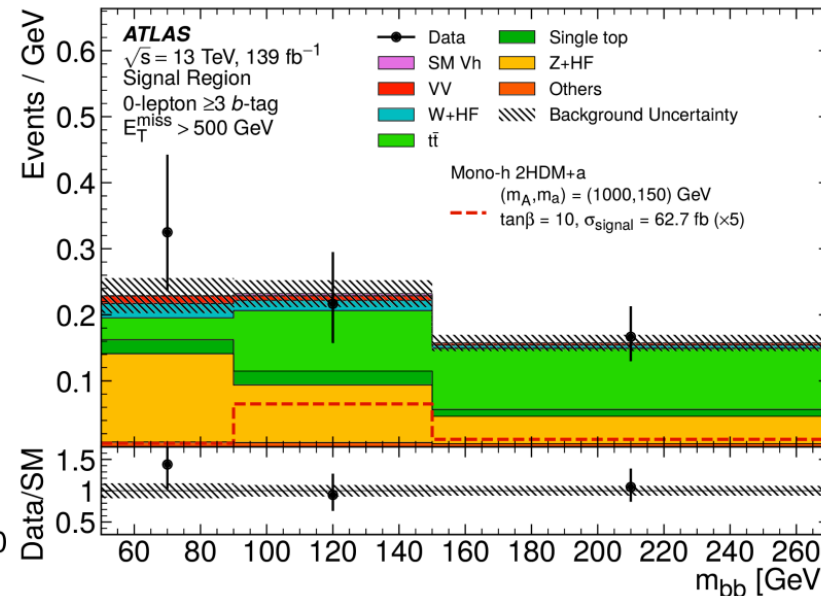
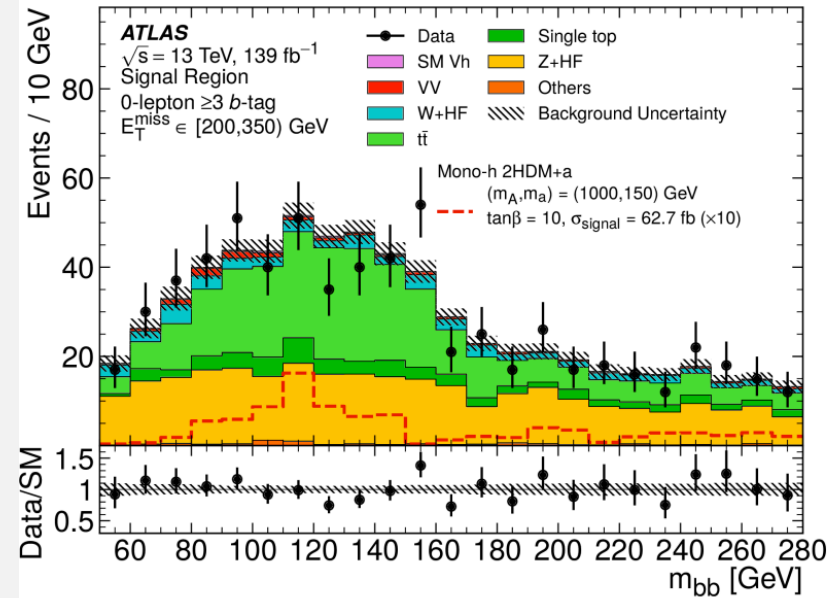
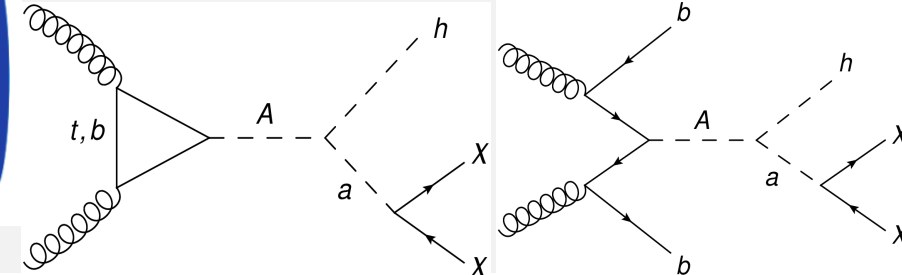
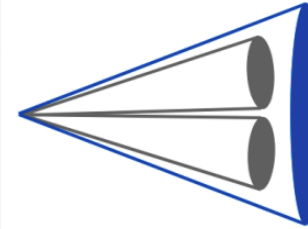
Resolved topology

$150 < E_T^{miss} < 500 \text{ GeV}$
 $50 \text{ GeV} < m_h < 280 \text{ GeV}$
 At least 2 small-R jets

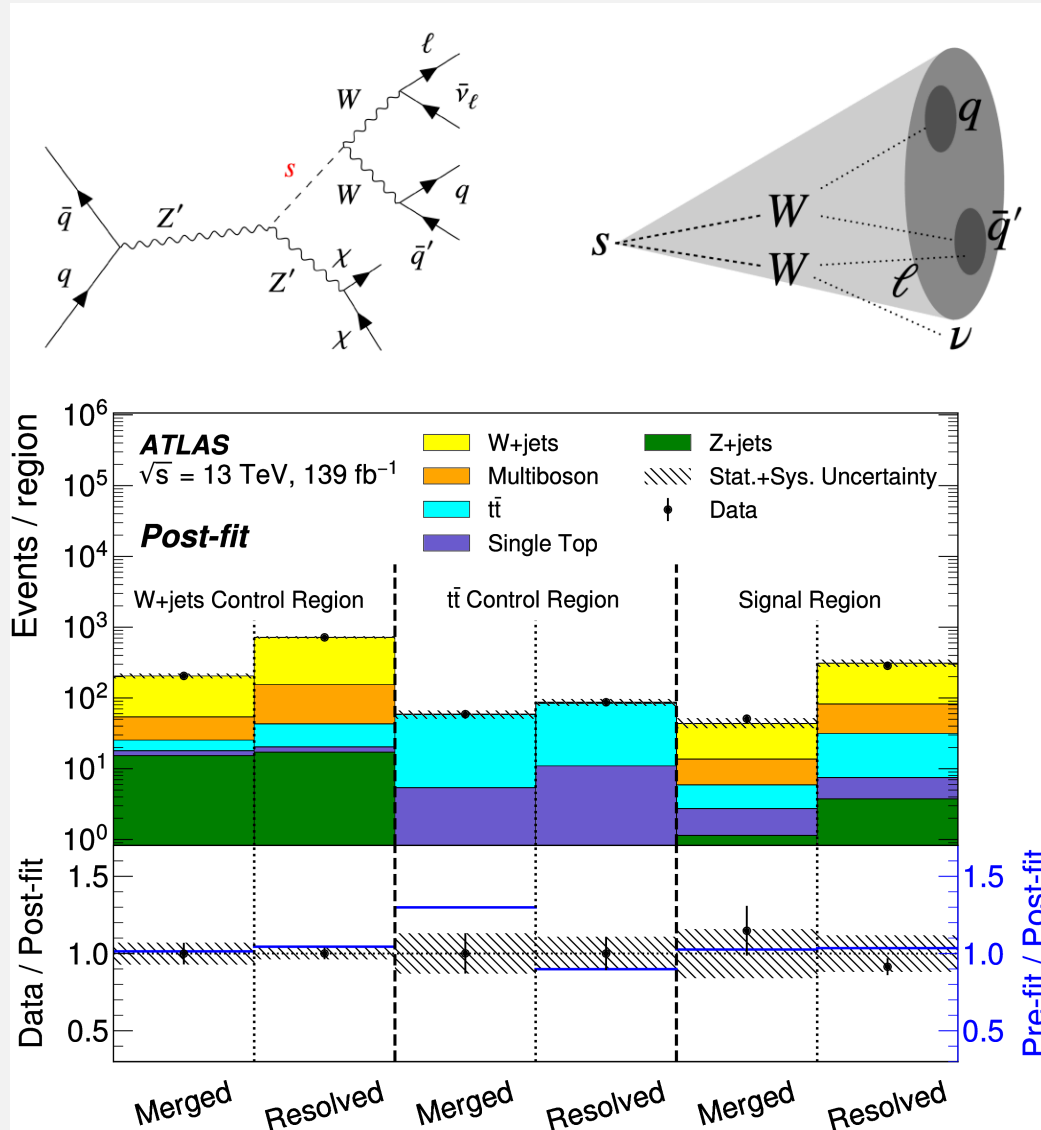


Merged topology

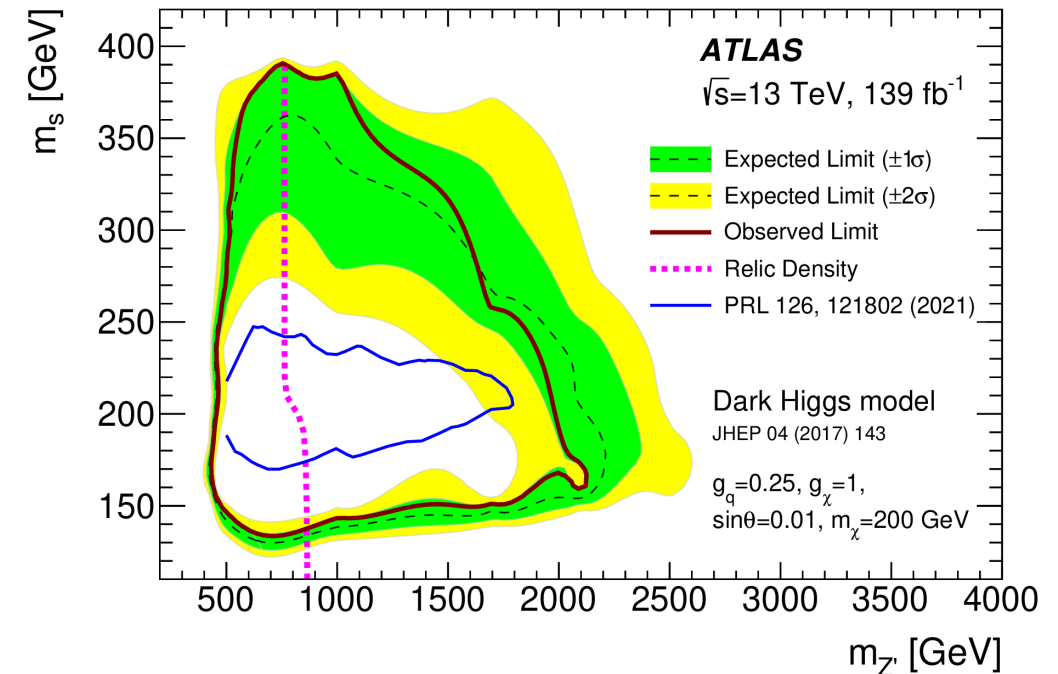
$E_T^{miss} > 500 \text{ GeV}$
 $50 \text{ GeV} < m_h < 270 \text{ GeV}$
 At least 1 large-R jet



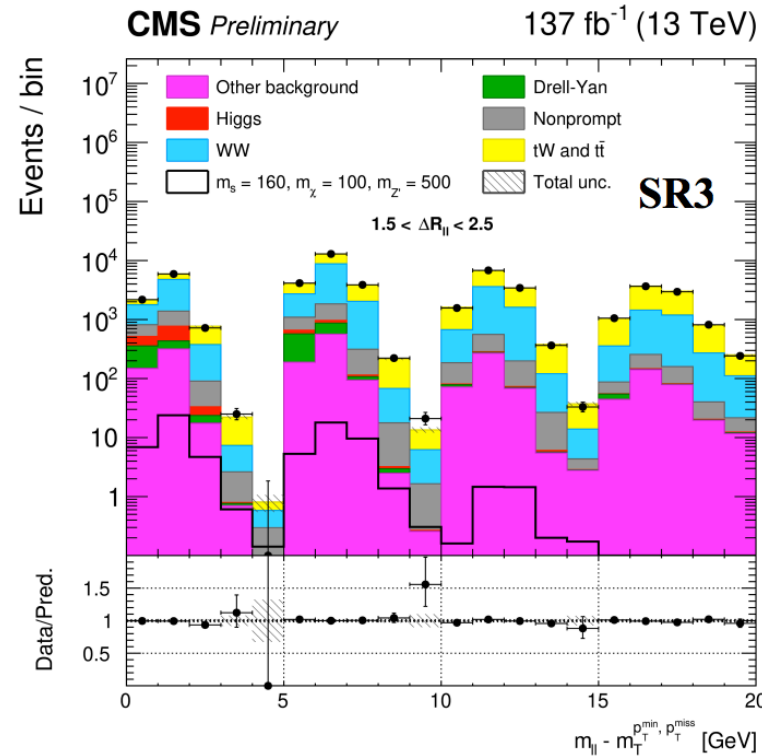
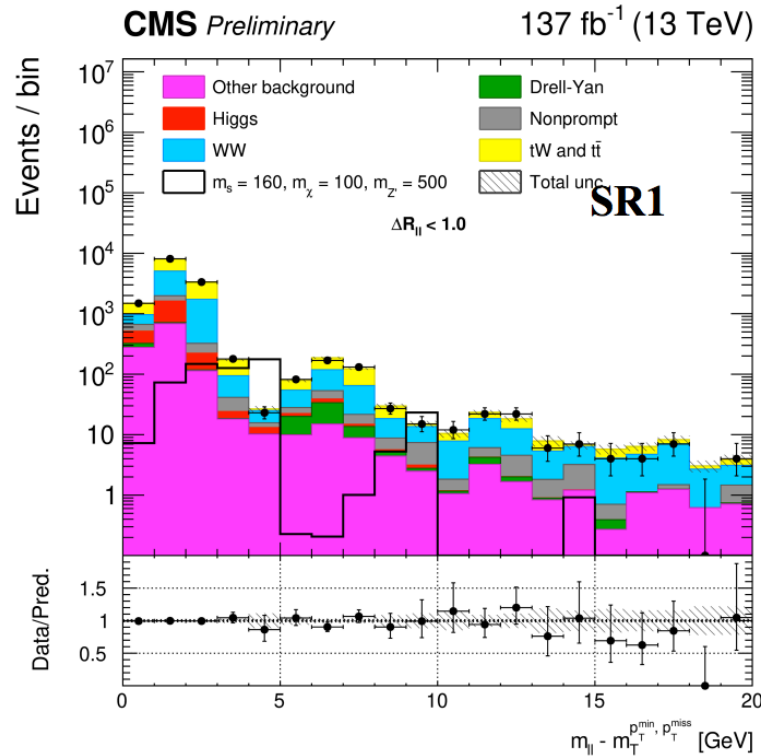
Dark Higgs Search: $s \rightarrow WW$ semileptonic [arXiv:2211.07175](https://arxiv.org/abs/2211.07175)



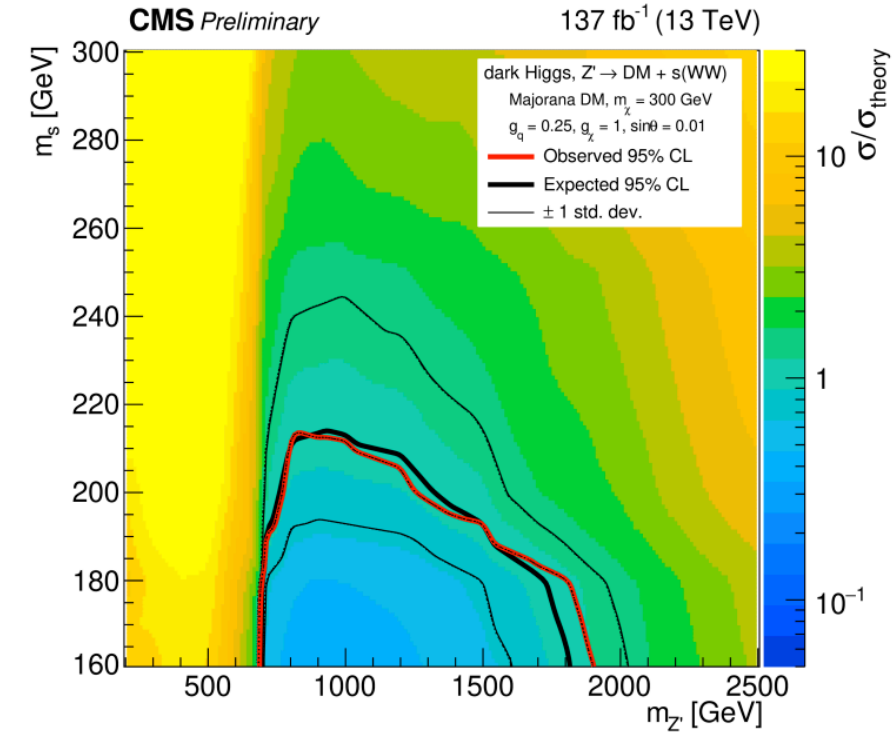
- Two mediator model: Z' + Dark Higgs
- Utilize both resolved calorimeter-measured jet pair or merged from track-assisted reclustered jets
- Scenarios with dark Higgs boson masses ranging between 140 and 390 GeV are excluded.



Dark Higgs Search: $s \rightarrow WW$ fully leptonic



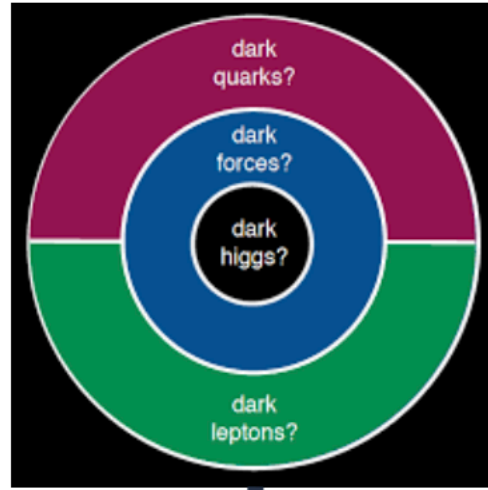
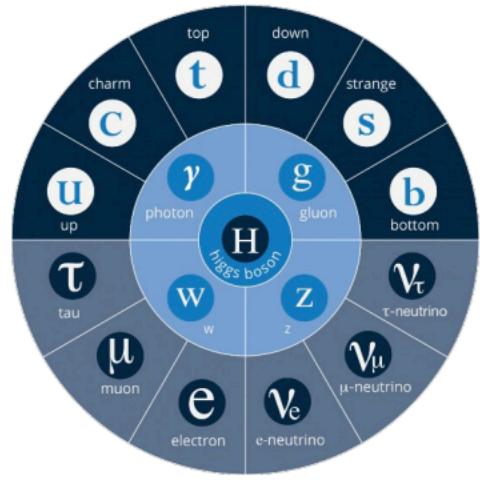
Dark Higgs model limit in the $(m_{Z'}, m_s)$ plane



3-dimensional fit performed using ΔR , $m_{||}$ and m_T

$$m_T^{\ell \min, p_T^{\text{miss}}} = \sqrt{2p_T^{\ell \min} p_T^{\text{miss}} \left[1 - \cos \Delta\phi(\vec{p}_T^{\ell \min}, \vec{p}_T^{\text{miss}}) \right]}$$

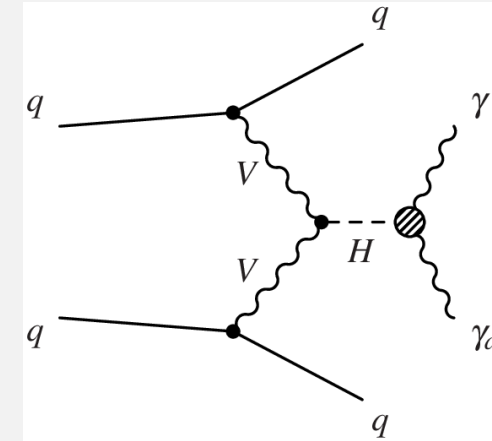
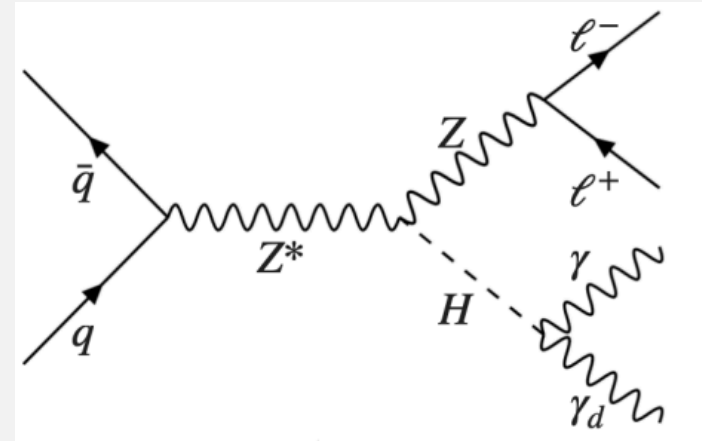
• Dark Higgs → more Dark Portals connecting hidden sectors



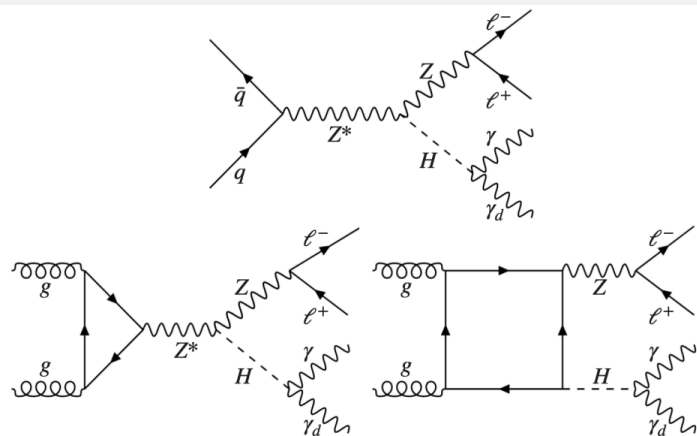
portals

- **Vector portal – dark photons**
- Scalar portals - dark Higgs
- Neutrino portal
- Axion portal

- **Dark Photon BSM extensions:**
 - U(1) extension of the SM
 - Hidden gauge boson A' → kinetic mixing (ϵ) with the SM photon
 - the magnitude of ϵ affects production rate and lifetime



Dark Photon searches: ZH and VBF



For massless γ_d

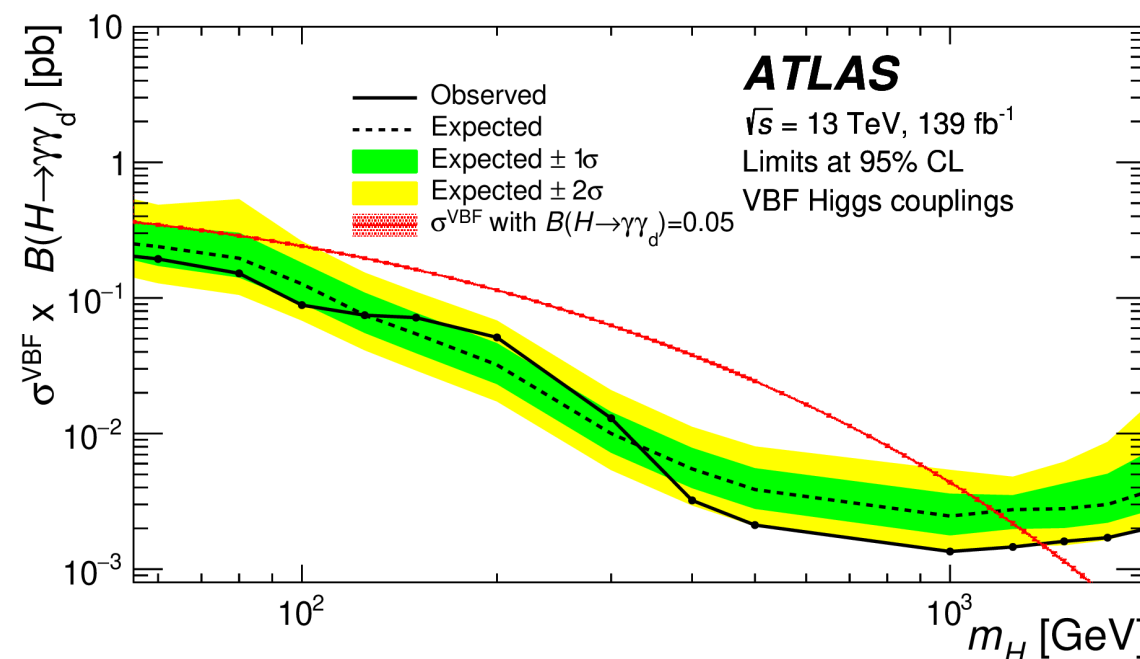
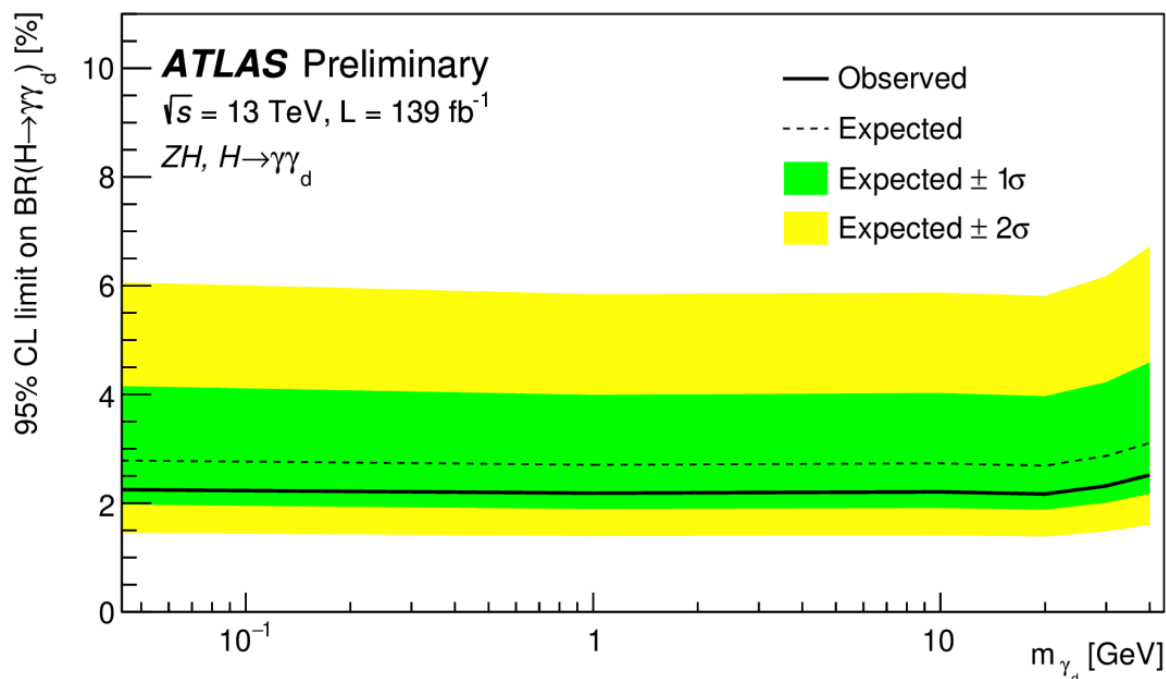
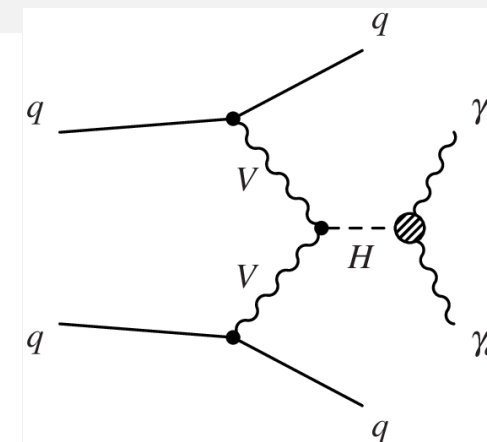
		Obs.	Exp.
CMS	VBF	3.5%	2.8%
CMS	ZH	4.6%	3.6%
ATLAS	VBF	1.8%	1.7%
ATLAS	ZH	2.3%	2.8%

[JHEP03\(2021\)011](#)

[JHEP10\(2019\)139](#)

[CERN-EP-2021-137](#)

[ATLAS-CONF-2022-064](#)

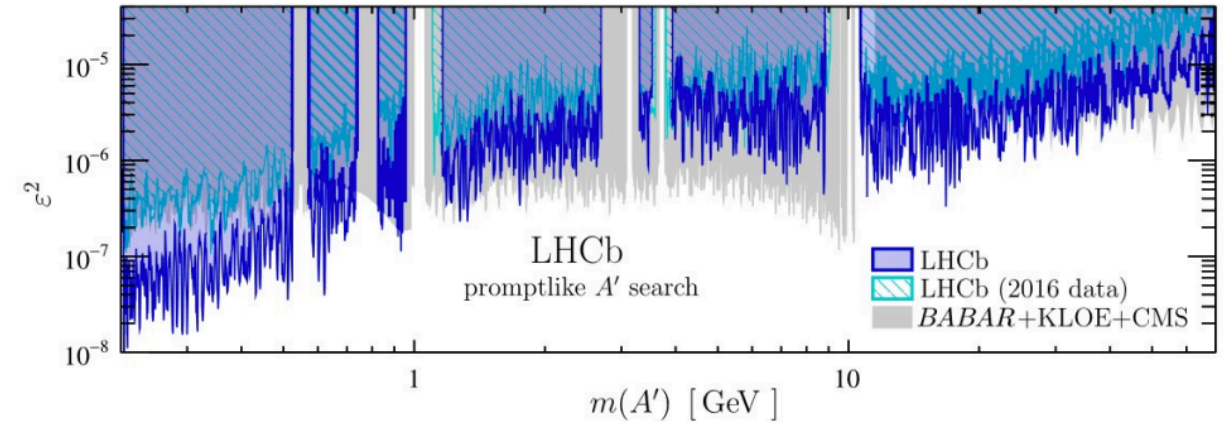
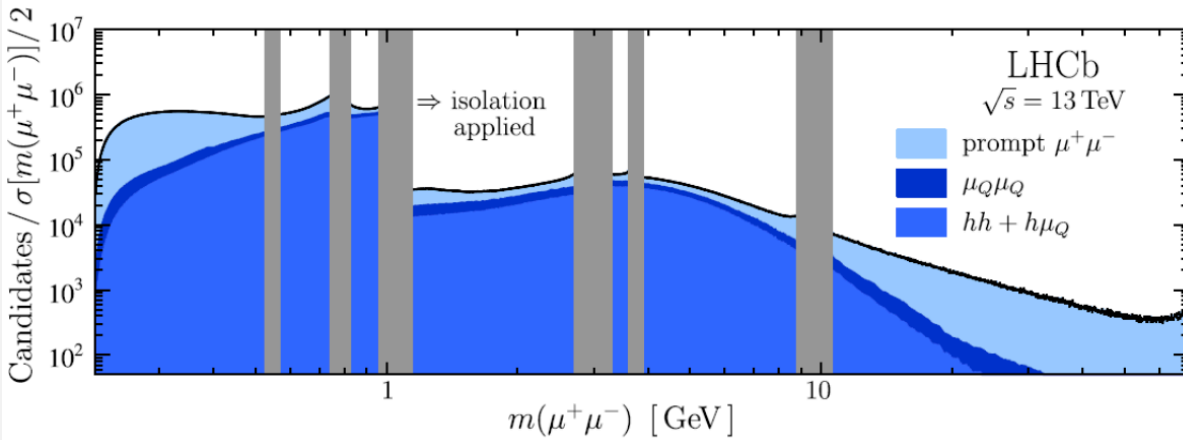


Dark Photon Search at LHCb

Phys. Rev. Lett. 124 (2020) 041801



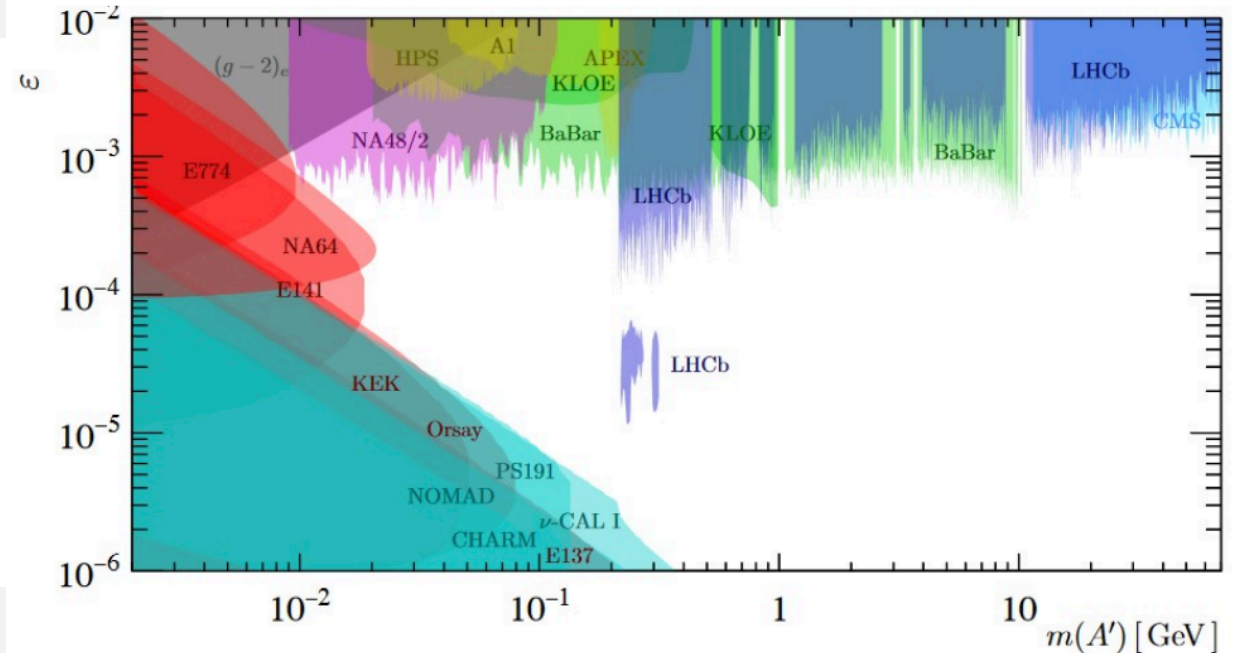
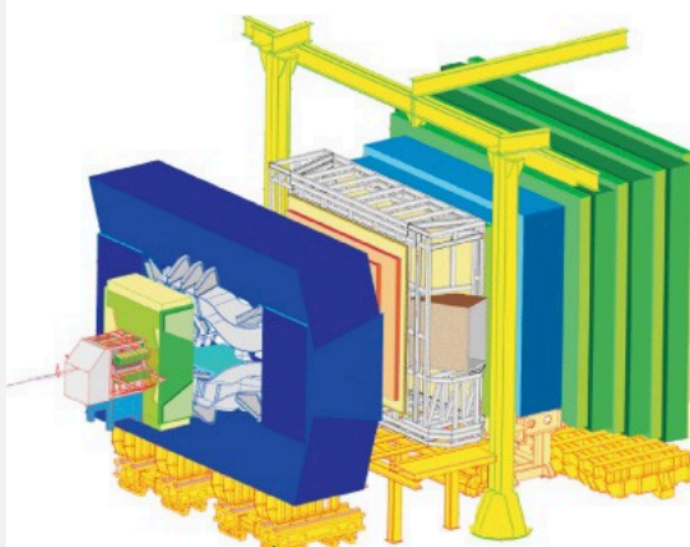
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TSUNG-DAO LEE INSTITUTE



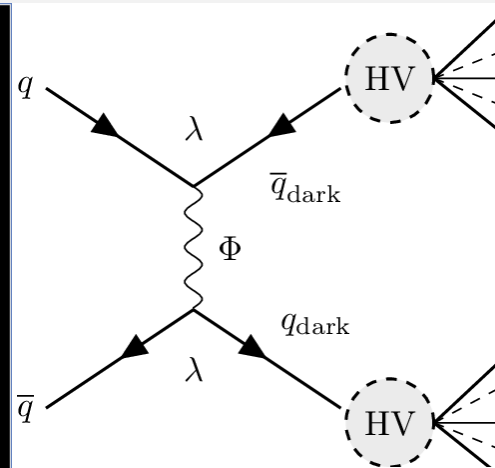
Search via di-muon final state

Two signature recipes:

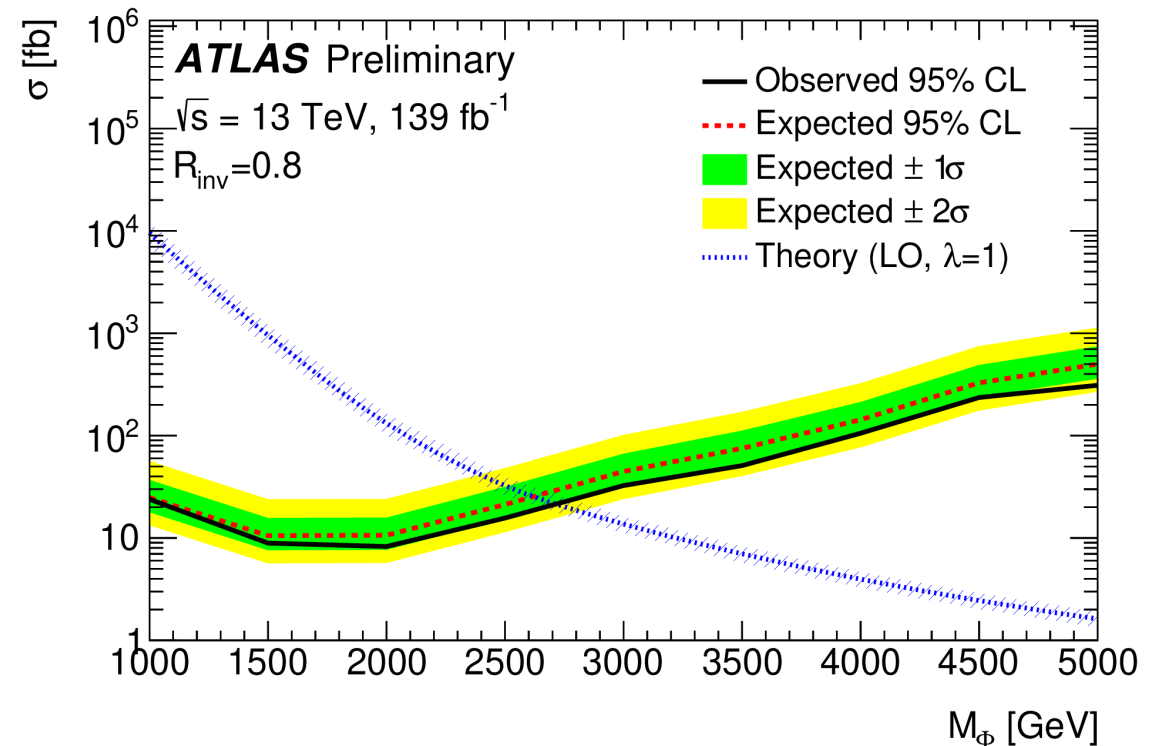
- Prompt search:
 $m_{A'} \lesssim 2m_\mu$ up to 70 GeV
- Displaced search:
 $m_{A'} \sim 214 - 350 \text{ MeV}$



Unconventional searches with semi-visible jets

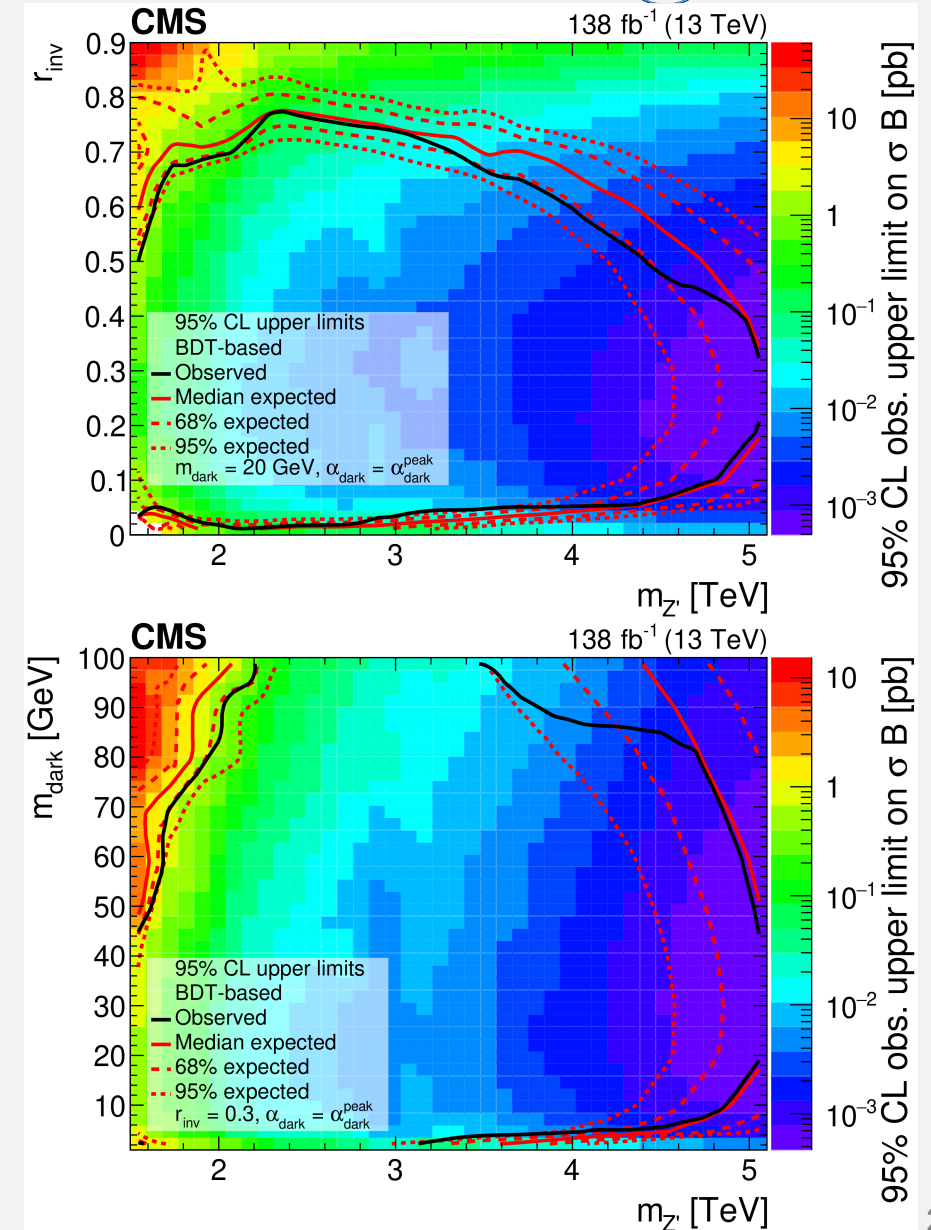
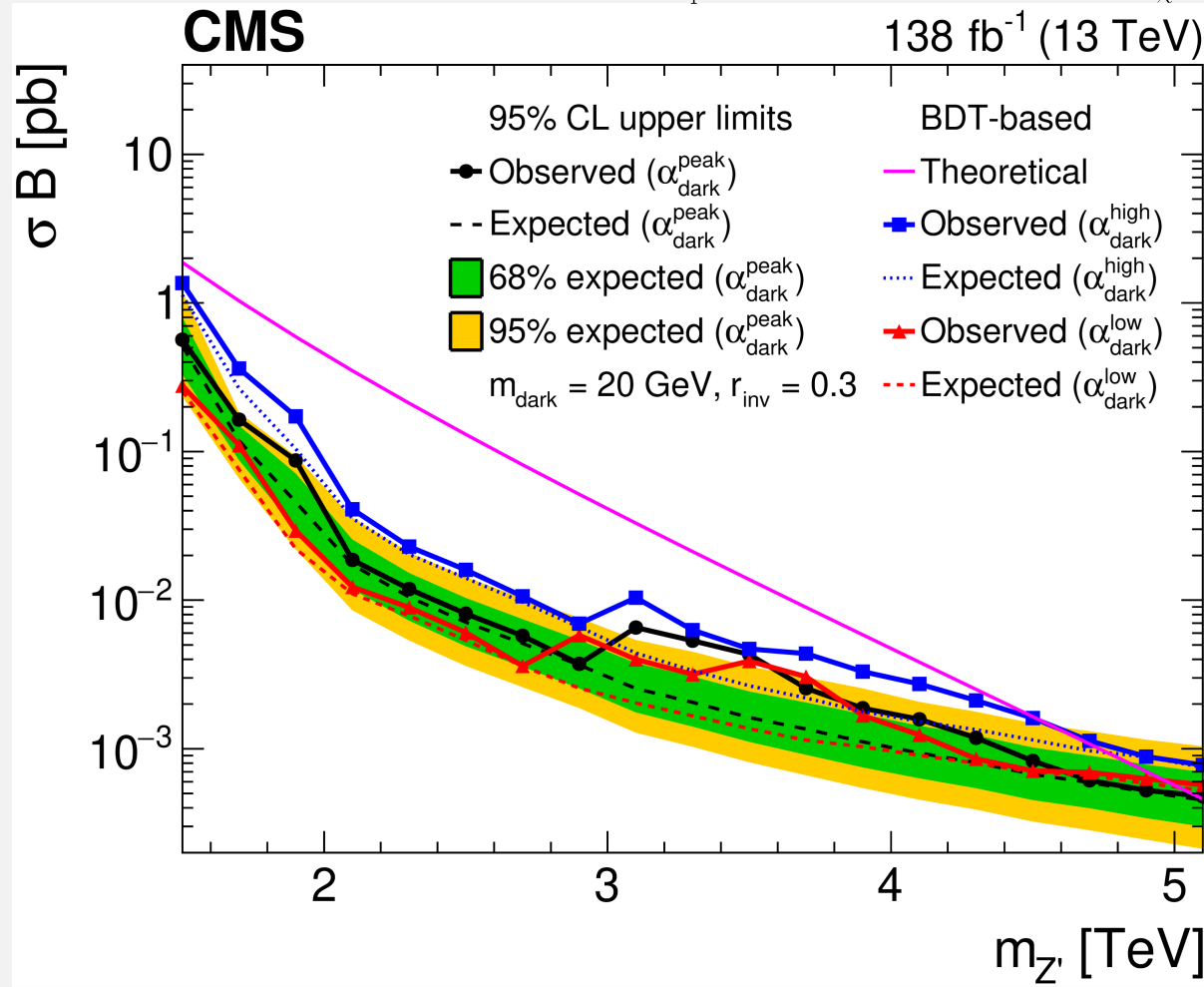
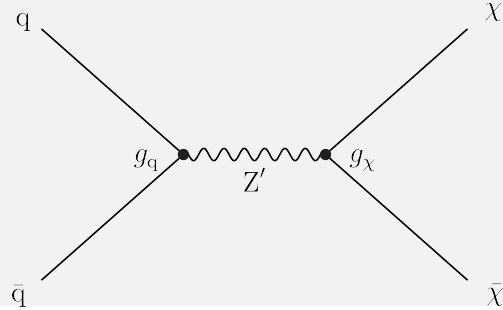


- Semi-visible jets arise in strongly-interacting dark sectors
- One of the jets is aligned with the missing transverse momentum direction: i.e. missing transverse momentum originates from the invisible components of the two semi-visible jets.



Unconventional searches with semi-visible jets

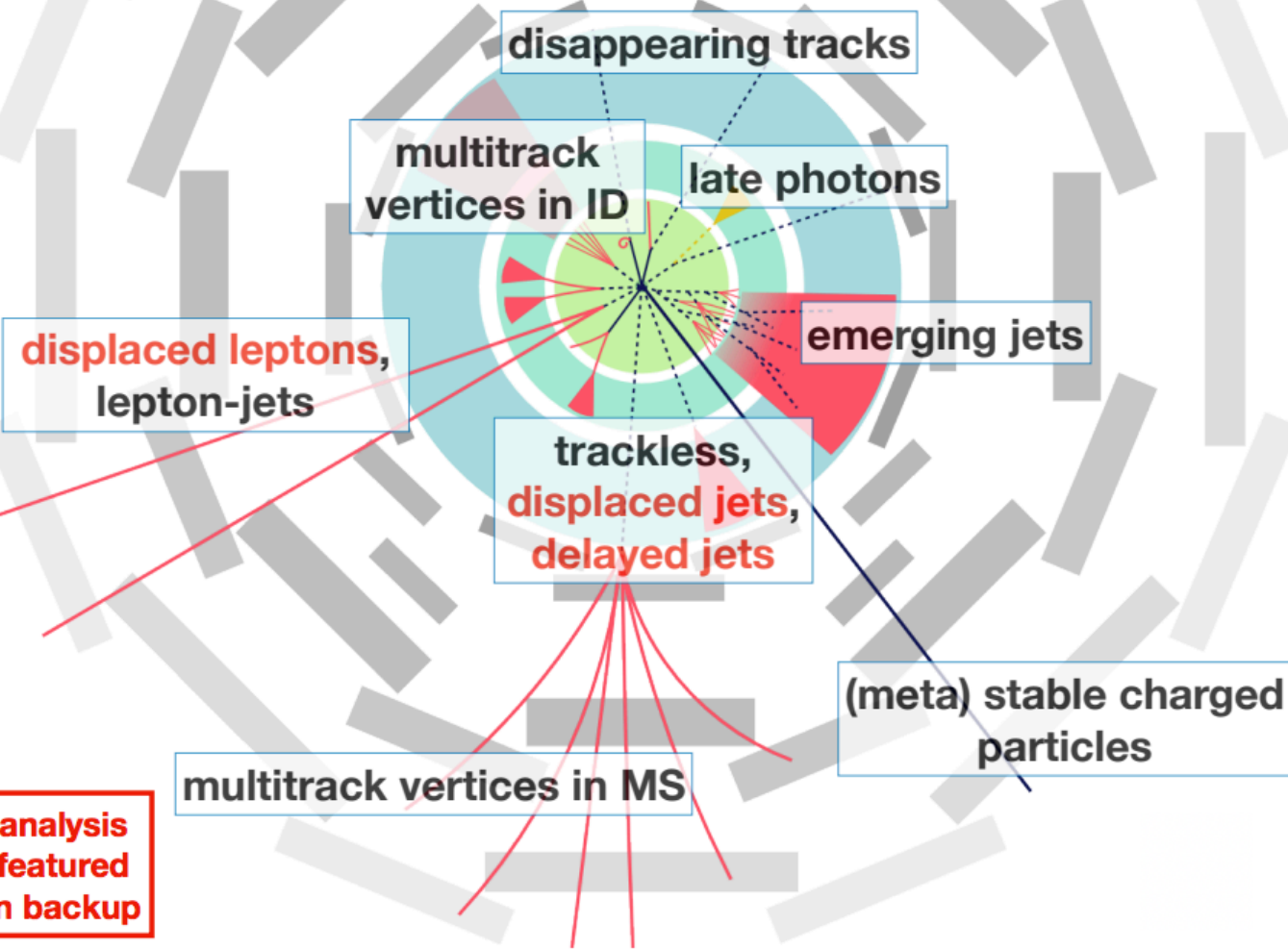
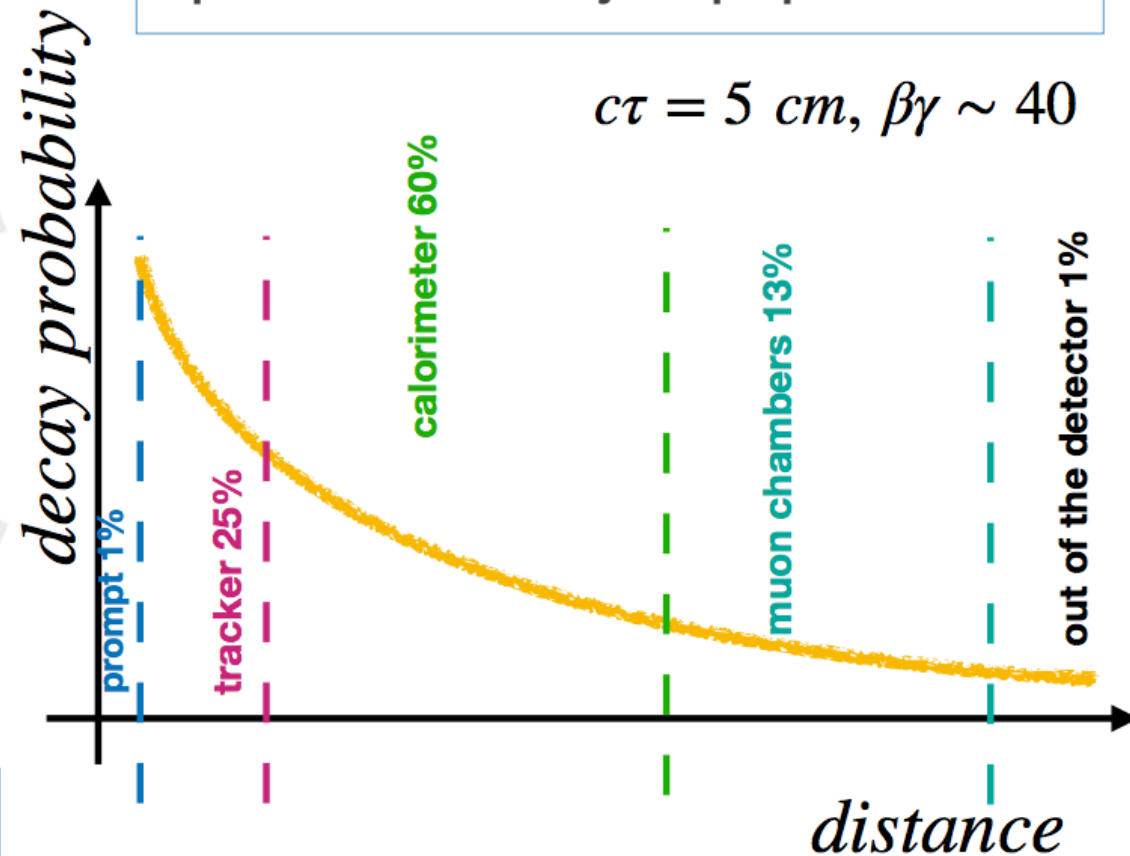
Search for s-channel resonant production of strongly coupled dark matter



Unconventional signatures

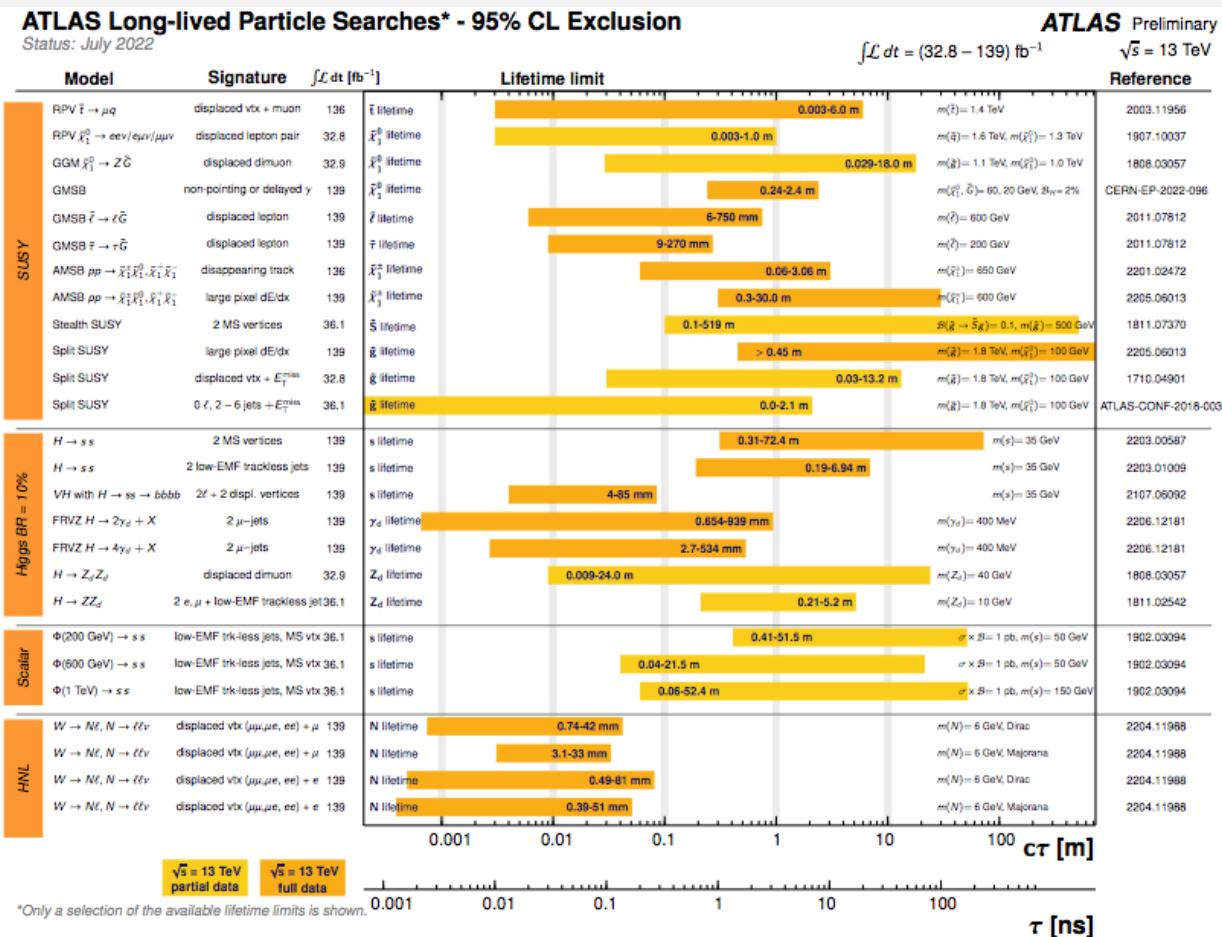
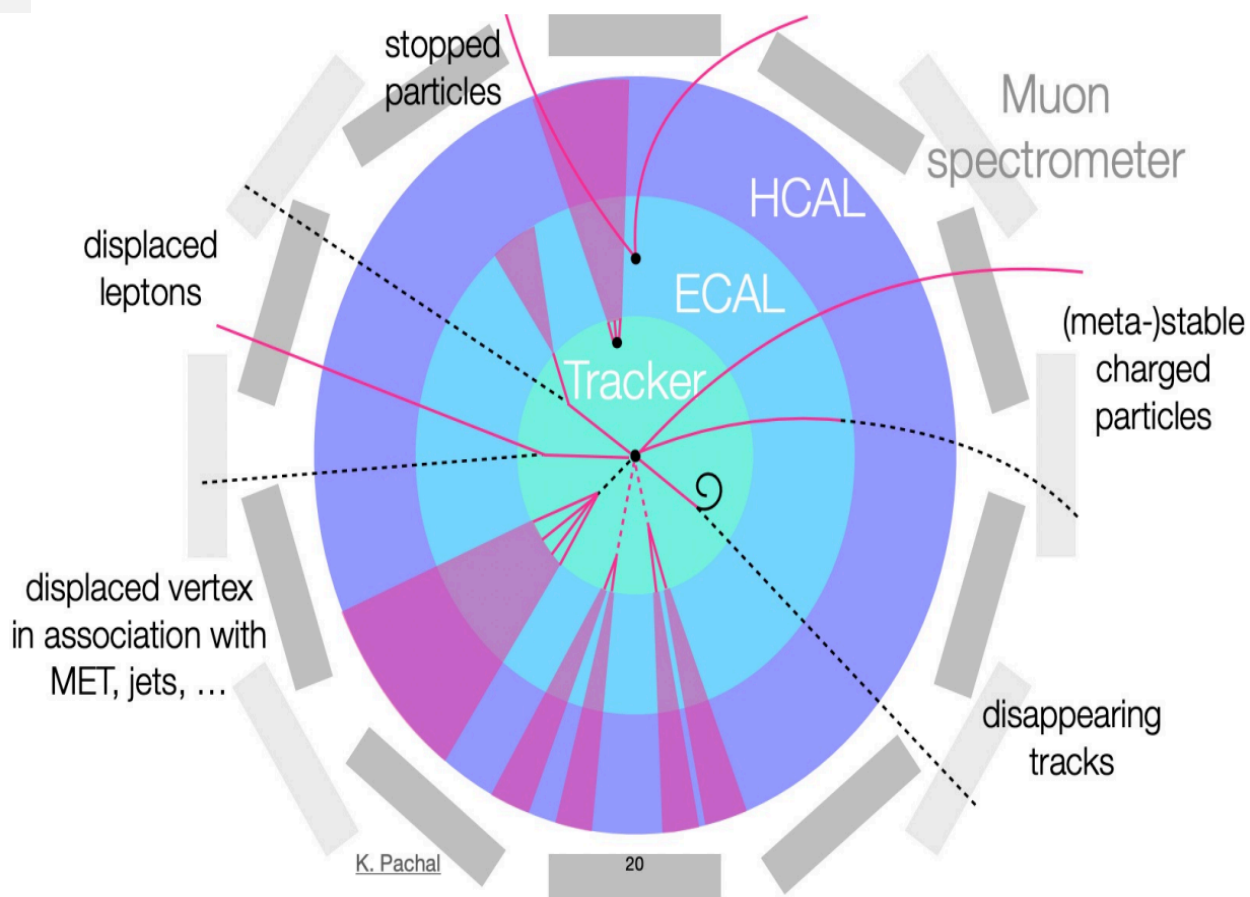
New particles can be long-lived:
observed lifetime is governed by an
exponential defined by the proper lifetime $c\tau$

$$c\tau = 5 \text{ cm}, \beta\gamma \sim 40$$



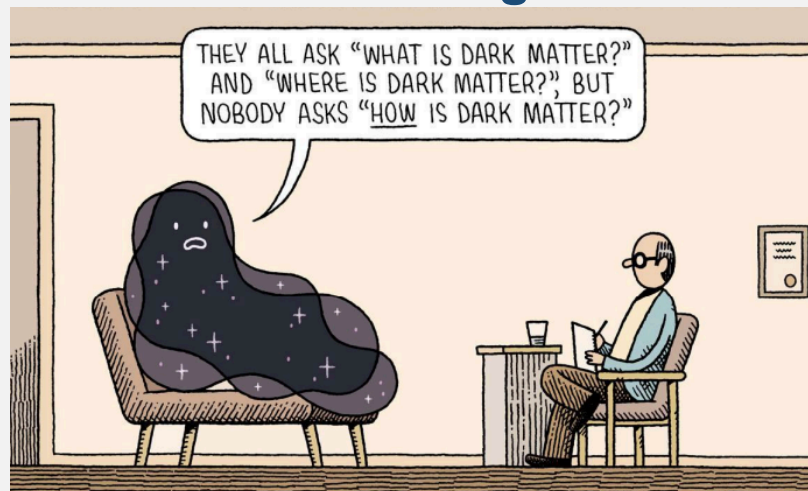
More unconventional searches

- LLP, displaced vertices, displaced leptons and jets, disappearing tracks, stopped particles
- Connecting more general untouched dark sector signatures, enlightening DM new prospects



Summary

- LHC continues to deliver highly valuable physical results while Run-3 is started with new results in the pipeline
- Dark Matter mystery remains puzzling while collider searches provide sensitivity complementarity with non-collider DM searches
- Many hypotheses, diverse processes and signatures are broadly surveyed and searched for but by far no hints of Dark Matter
- Need to further diversify the data mining aspects in the collisions covering more unconventional signatures and untouched stones





—— 谢 谢 ！ ——

