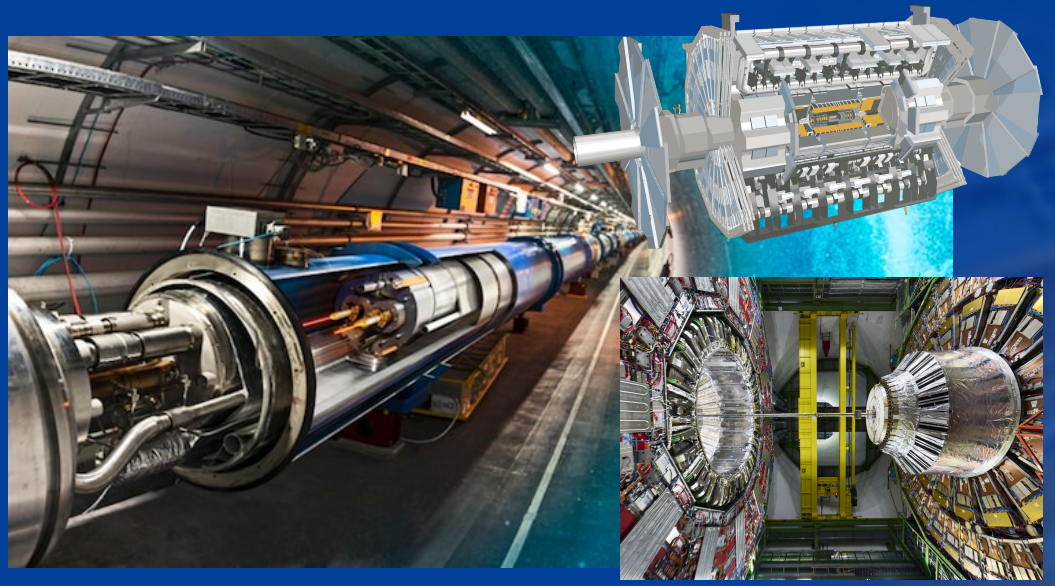
New physics searches at the LHC



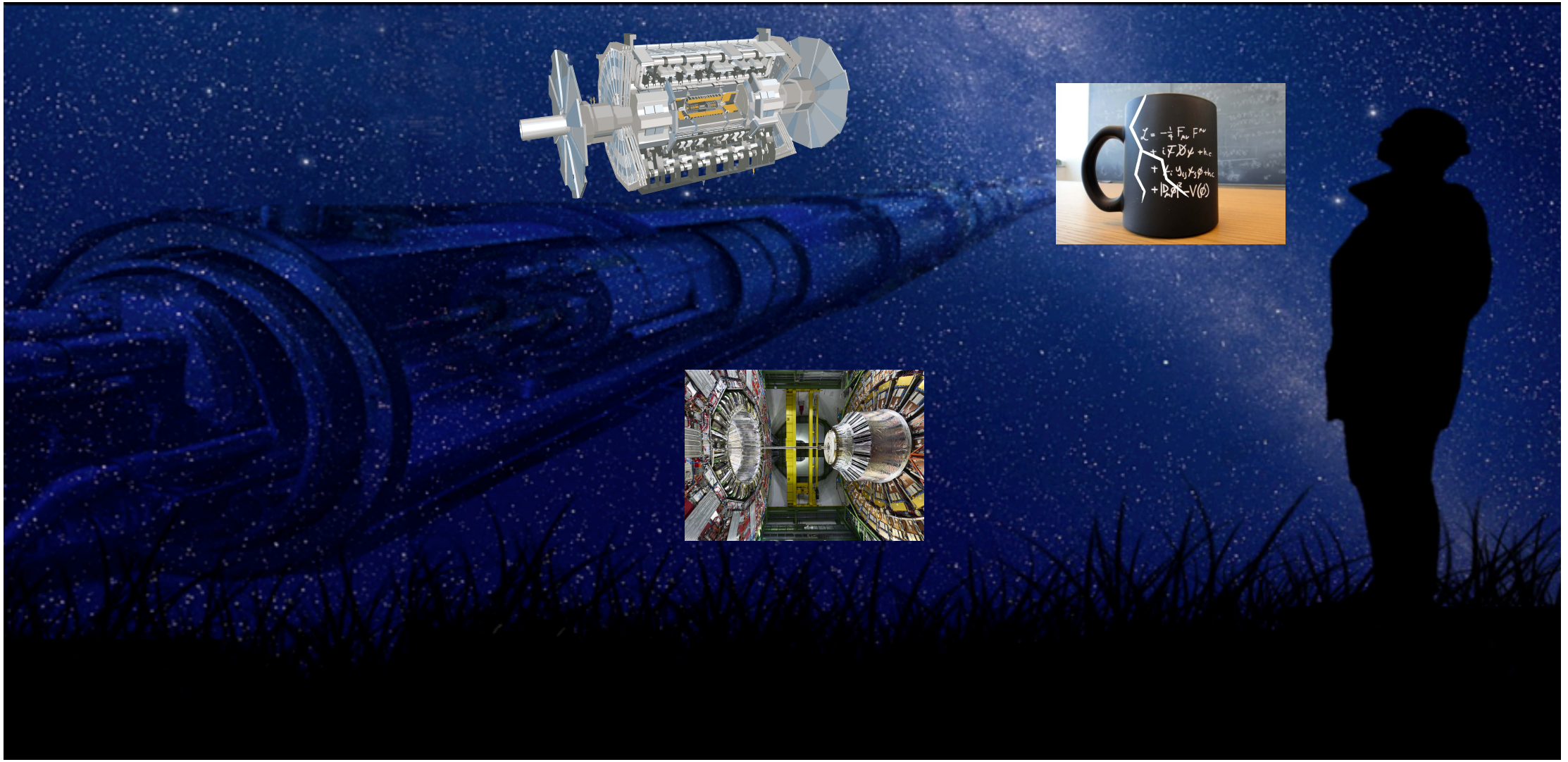
李数

shuli@sjtu.edu.cn

20/01/2024

27th Mini-workshop on the frontier of LHC @ SYSU, Zhuhai

LHC primary goals: looking into the “unknowns”



ATLAS and CMS Data Taking

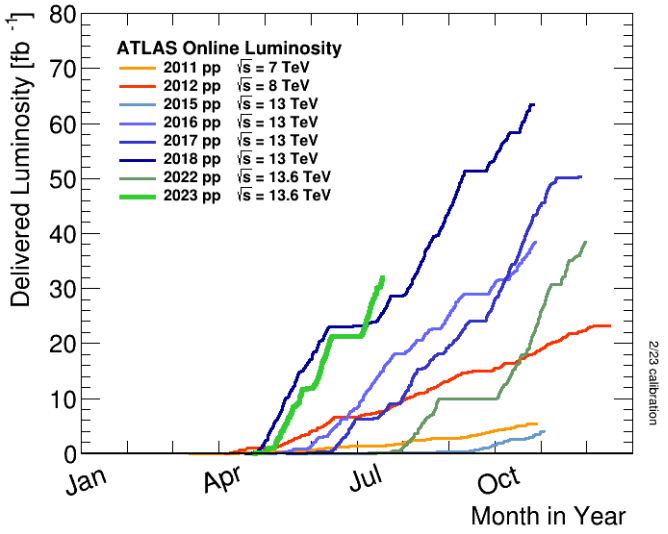
- Run2 legacy @ 13 TeV:

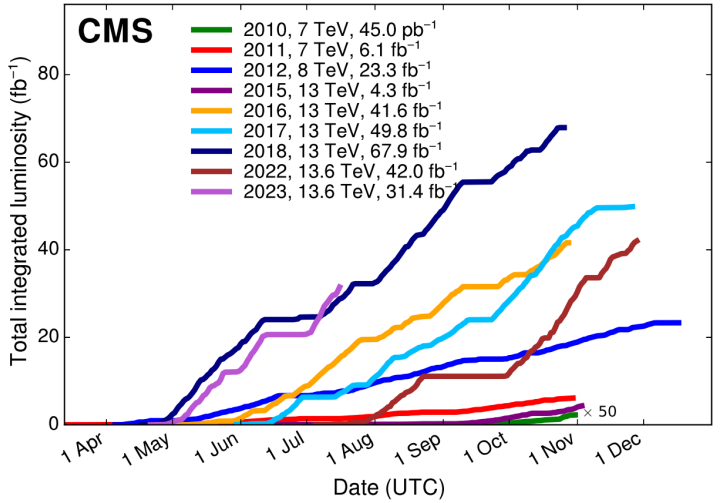
ATLAS and CMS recorded ~140fb^{-1} independent dataset of pp collisions

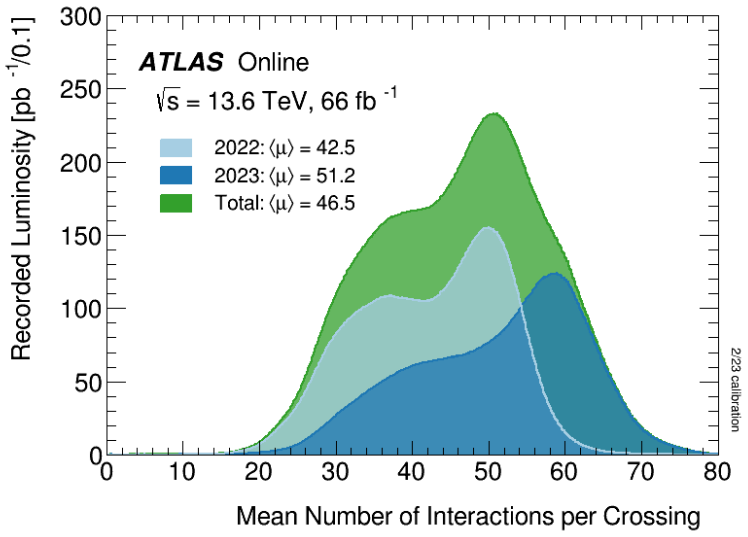
- RUN3 DATA taking status
  - ~70 fb^{-1} is already delivered @ 13.6 TeV during the RUN3
  - >60 fb^{-1} is recorded by both ATLAS and CMS
  - data-taking efficiency >90% “good for physics”
  - number of pp interactions per beam crossing (Pile-Up): $\langle\mu\rangle$ > 50 for 2023

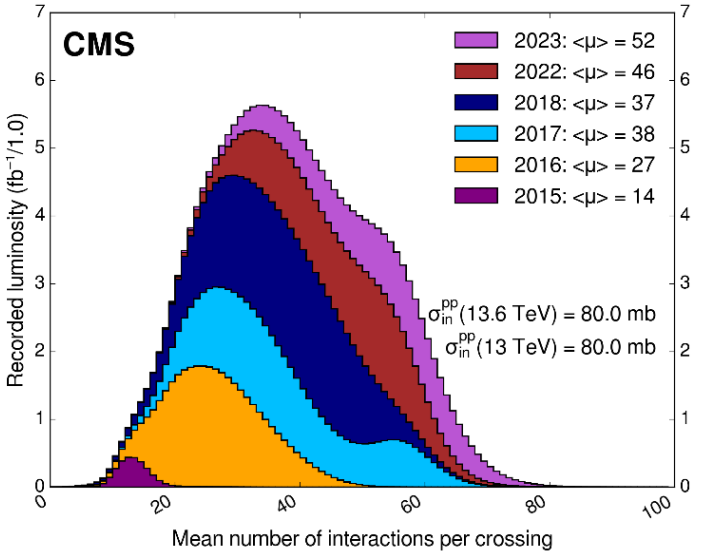
- >250 fb^{-1} expected @ 13.6 TeV

- ~450 fb^{-1} in total for RUN1/2/3

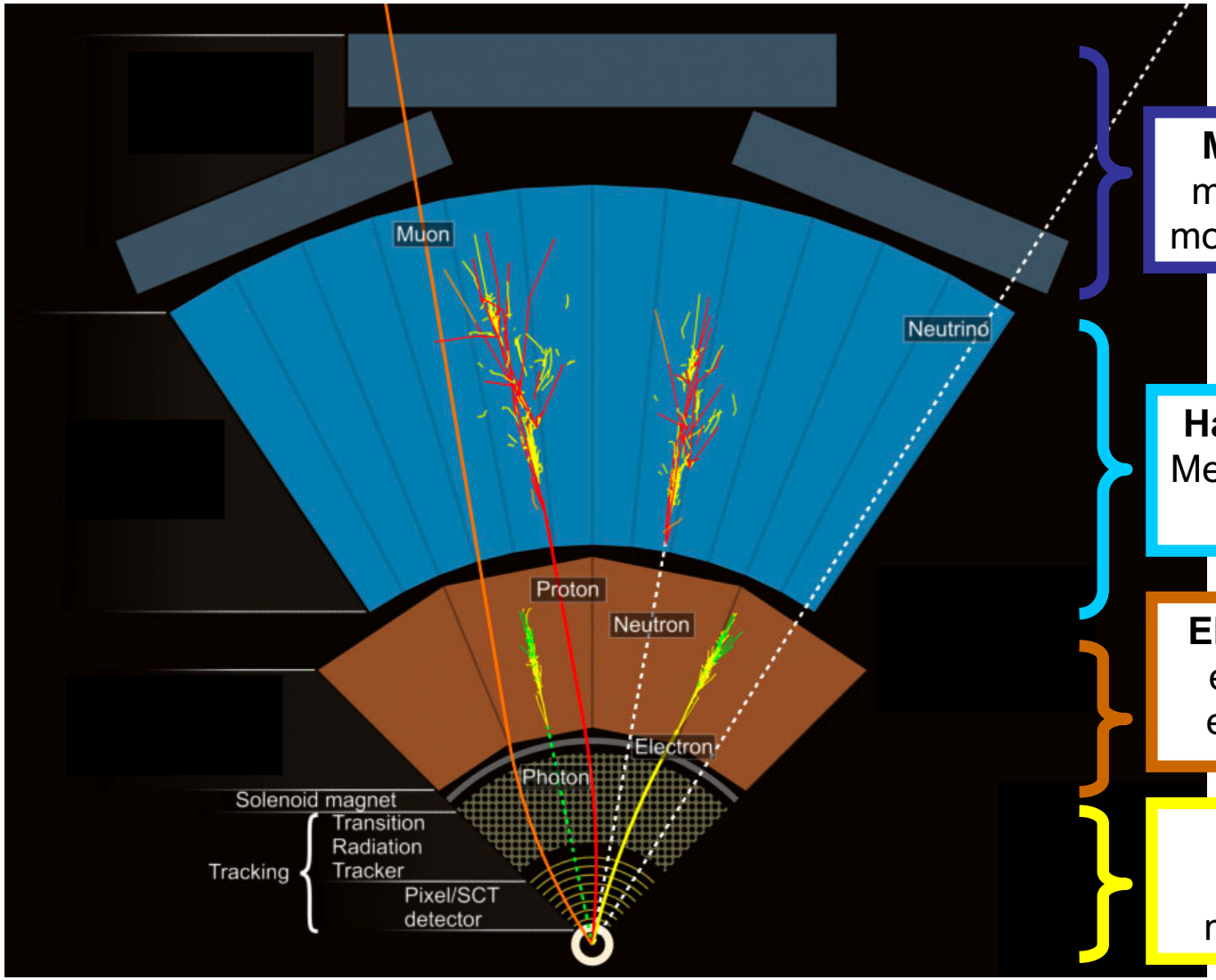








Particle Detection Potential



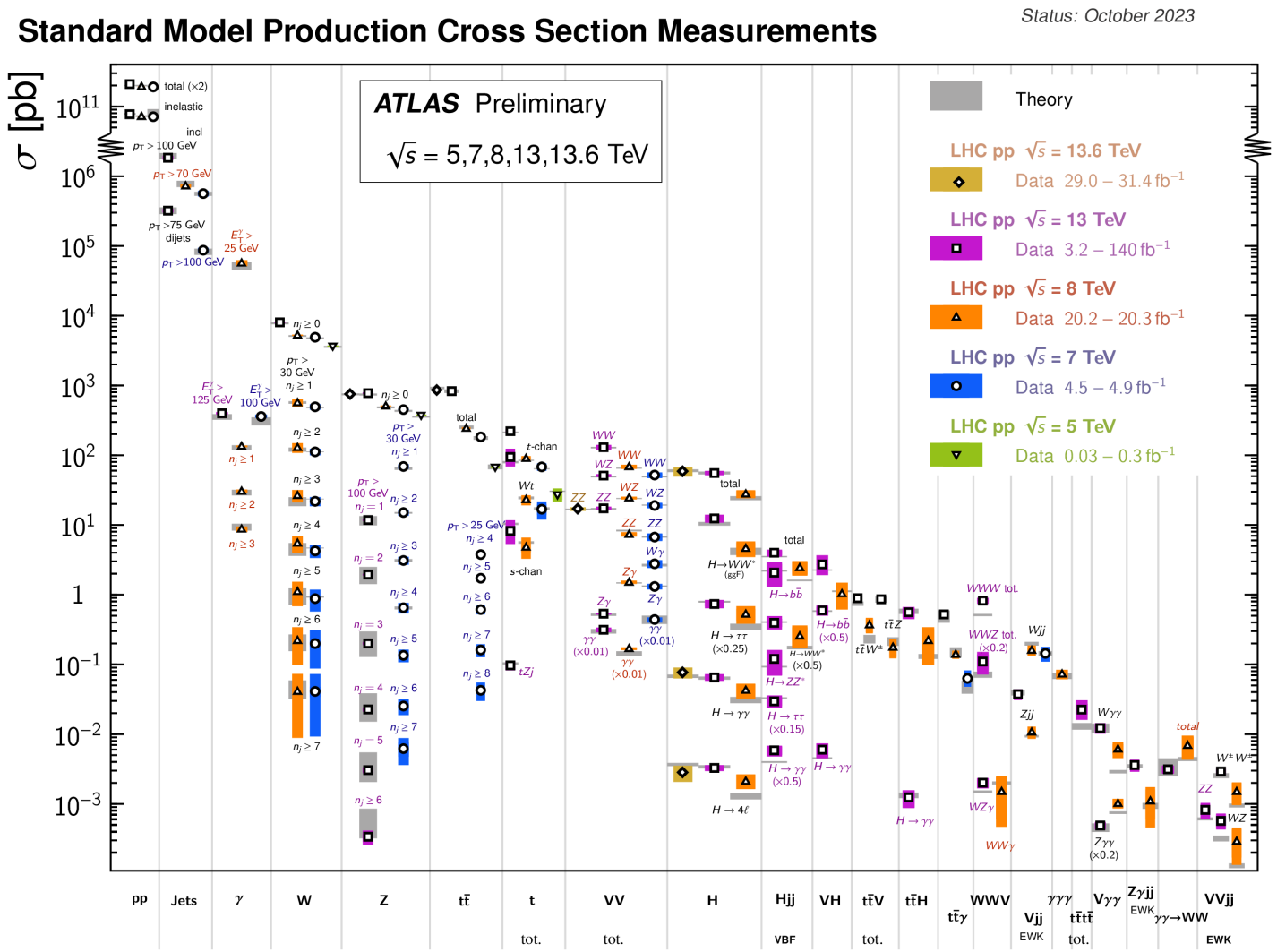
Muon Spectrometer:
muon identification and momentum measurement

Hadronic calorimeter:
Measurement of jets and missing energy

Electromagnetic calo:
e/γ identification and energy measurement

Tracking system:
Charged particle momentum, vertexing

Standard Model measured with unprecedented precision



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2023-039/

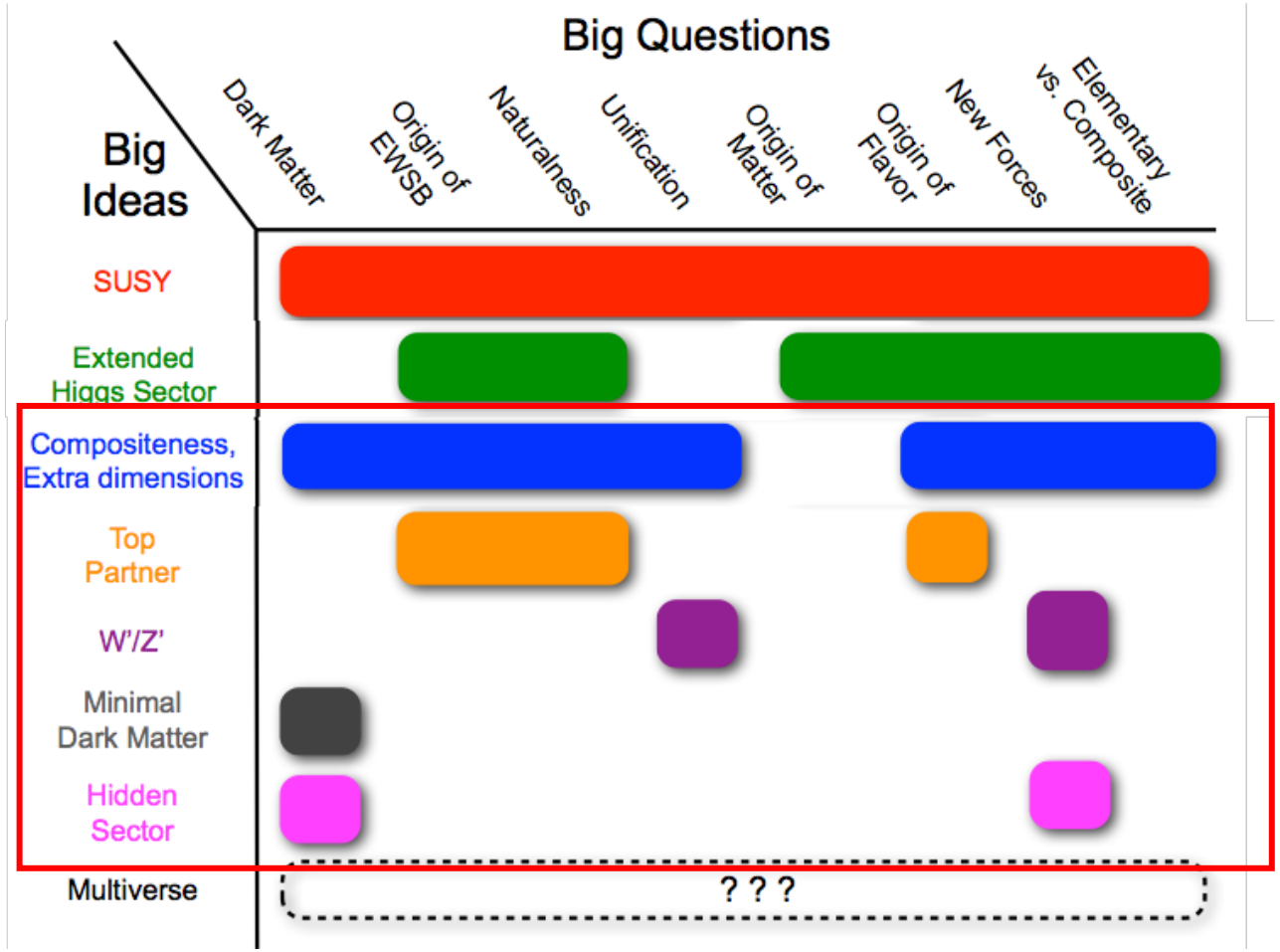
BSM searches targeting big questions

“Exotic” basically
cover the searches of
any BSM new physics signatures at
ATLAS, except: SUSY

Big questions request a better
and bigger ideas, as well as broader
analysis topics at the TeV scale hadron
colliders to explore the new phenomena
of the “unknowns”

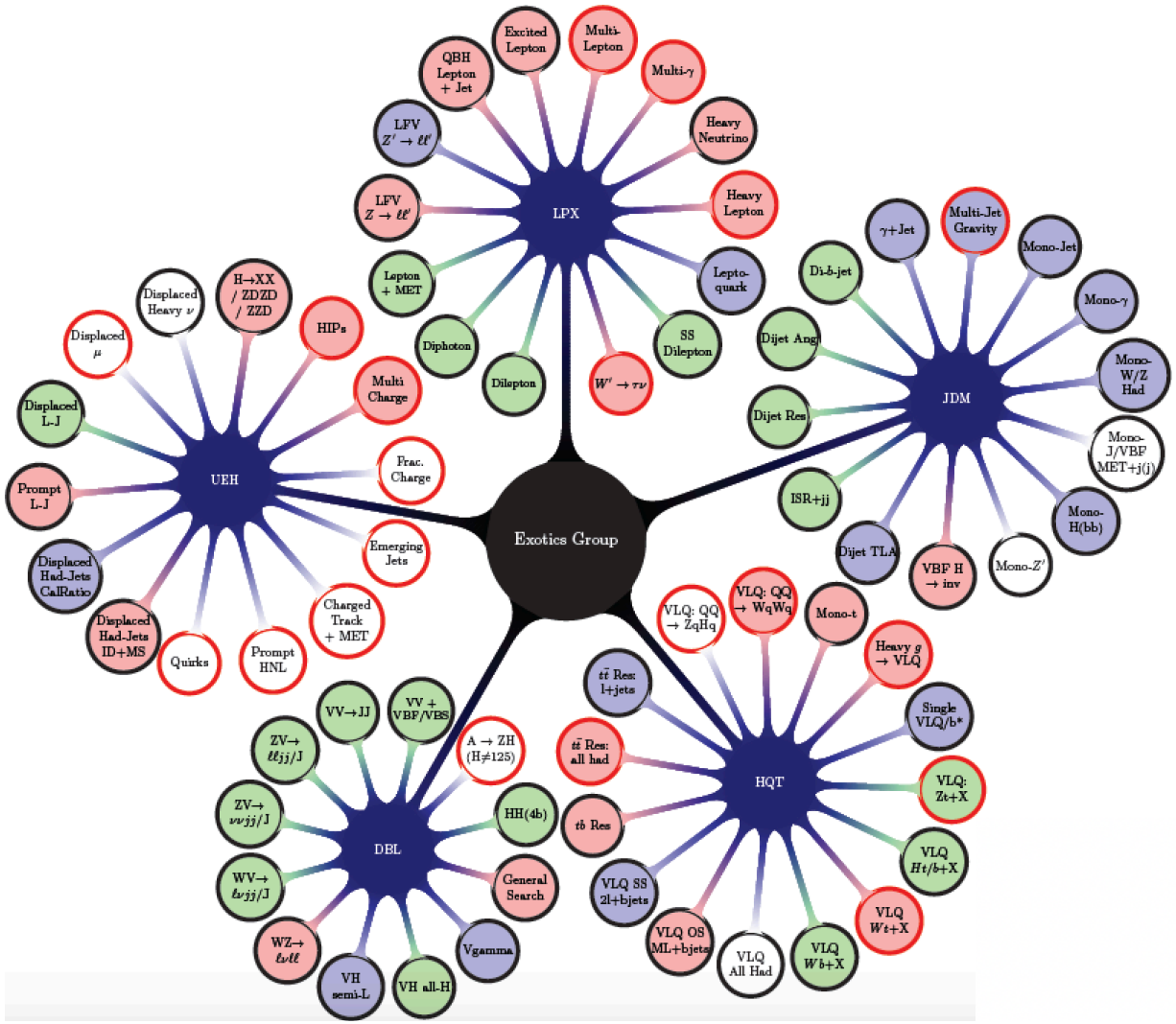
- ✓ Model guidance
- ✓ Signature driven
- ✓ Benchmark model interpretation

arXiv:1311.0299



BSM search program at LHC (ATLAS) in a nutshell

- Apology for not covering everything, only selected and recent topics are presented from ATLAS+CMS
- Separate talks for indirect search w/ SM precision measurements and dedicated searches with flavor physics and SUSY, and for LHCb/ALICE/…



PART 01

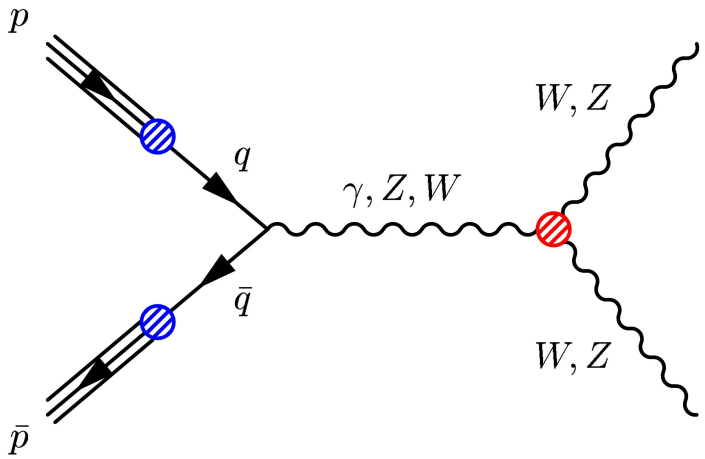
Resonance searches

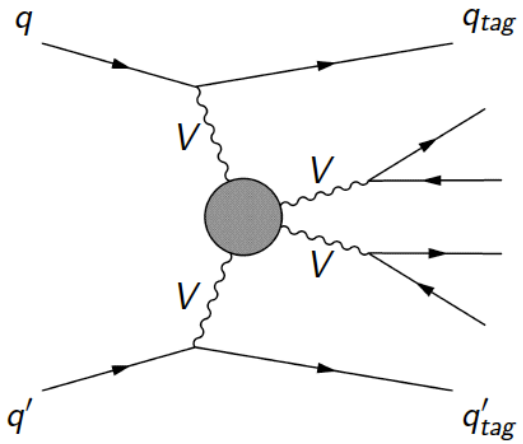
TSUNG-DAO LEE INSTITUTE

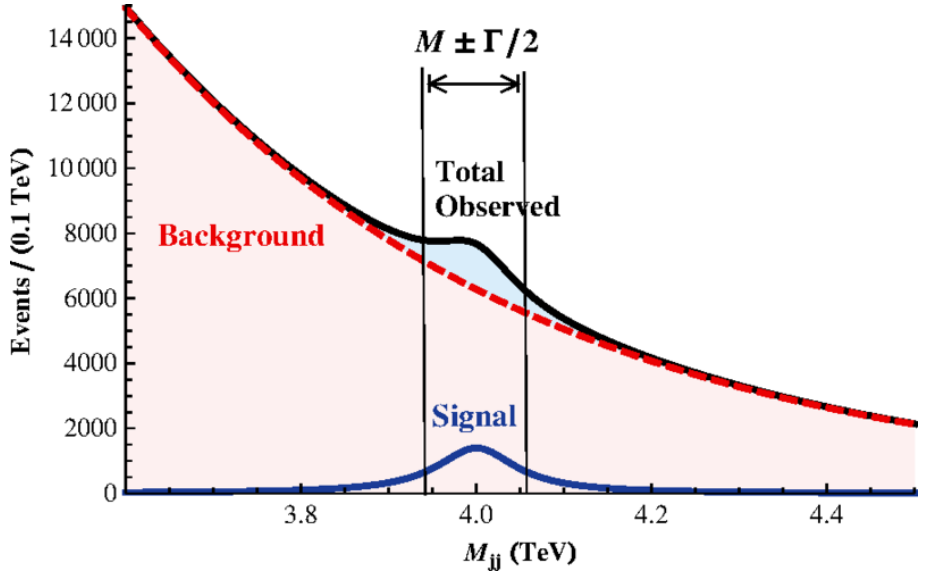
Why resonance searches

Two general ways:

- ***Direct search of new particles***
- ***New interactions of known particles of SM***
  - anomalous coupling
  - Effective field theory approach
  - Non-resonant interpretations



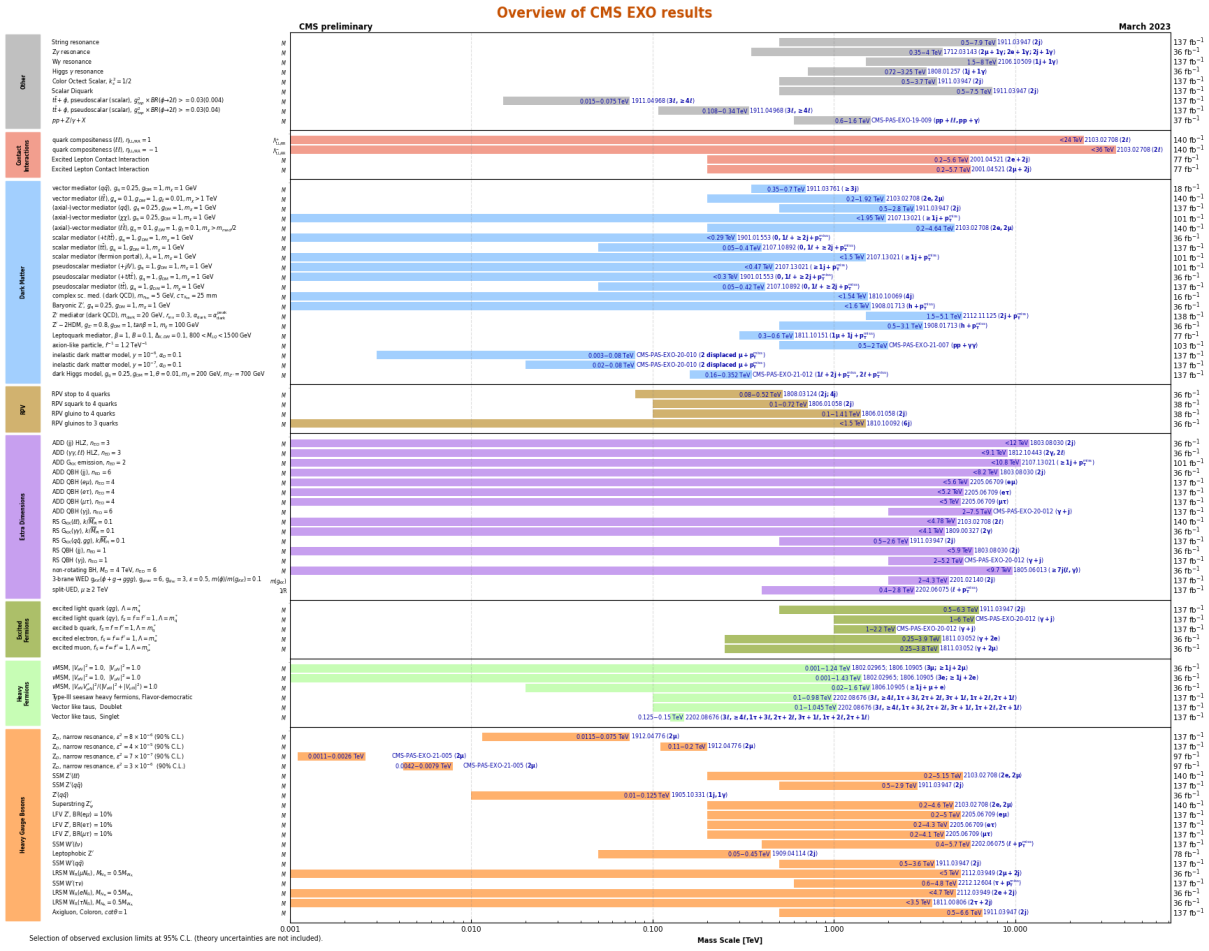


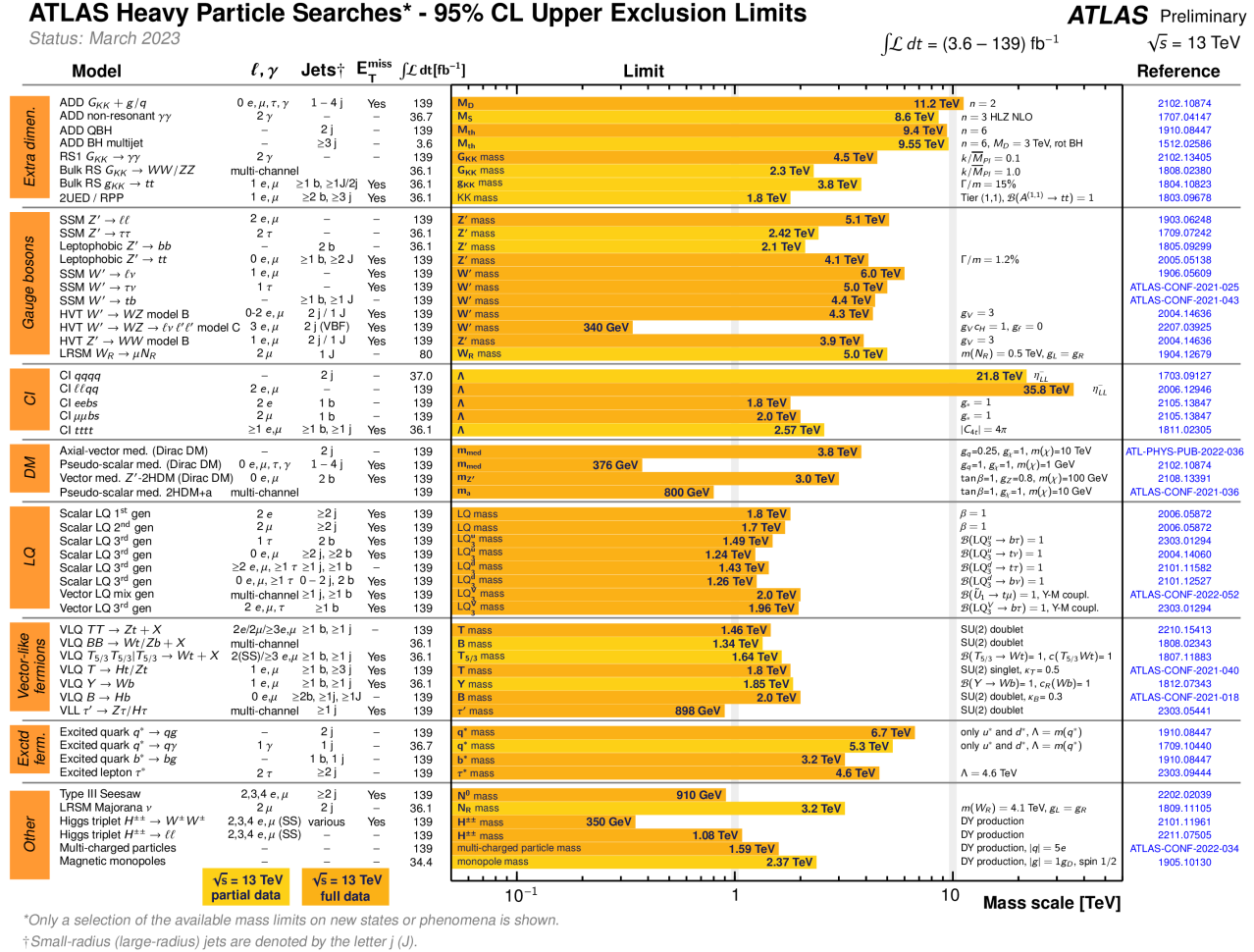


Heavy Resonance signatures

- Motivated by extended gauge models, extra dimensions, extra Higgs-like scalars, technicolor, …
- dileptons, dijets, diphotons, ttbar, W/Z→lep/jets

Direct searches at LHC





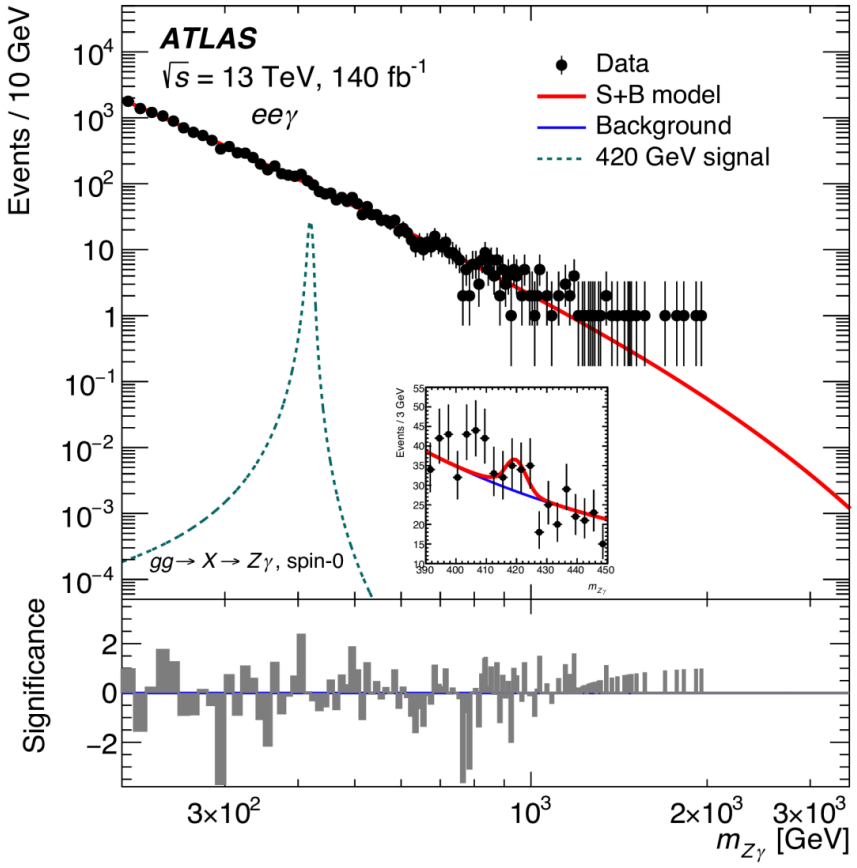
https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV

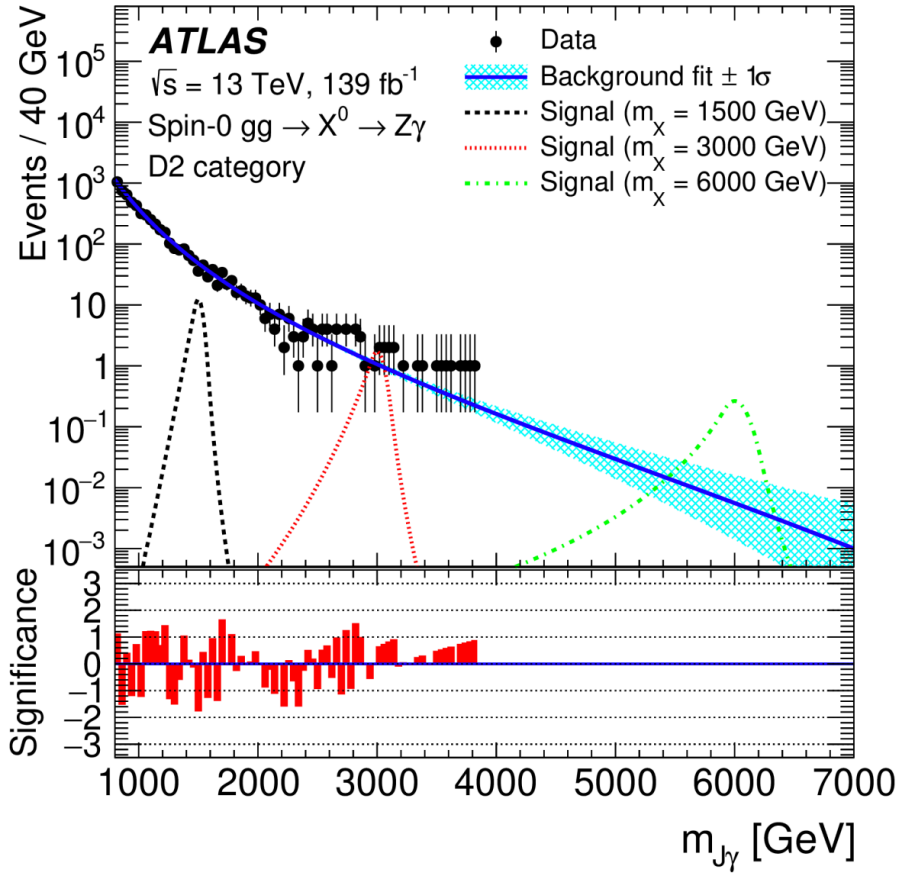
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

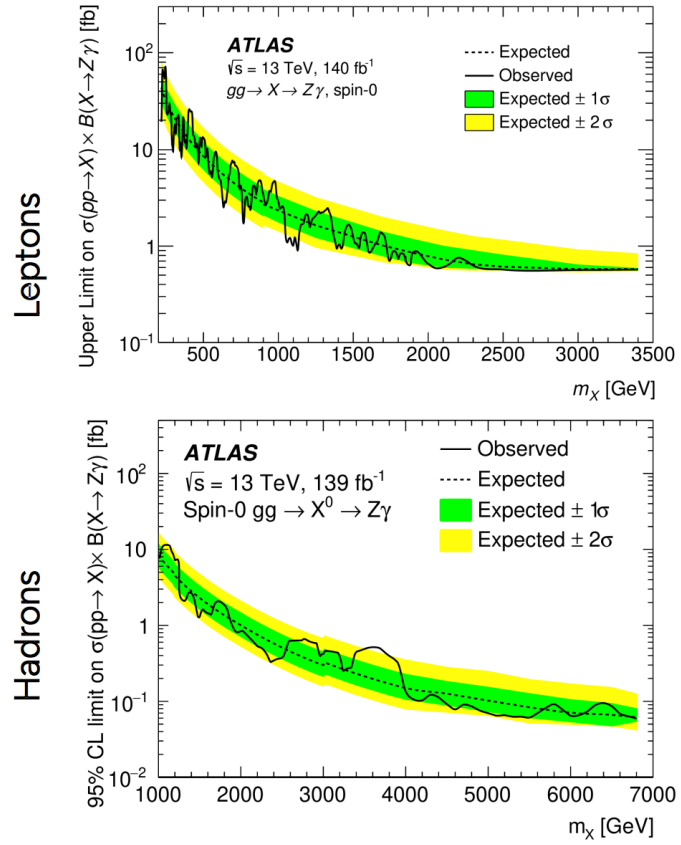
X→Zγ searches (Example)

arXiv:2309.04364
JHEP 07 (2023) 125

- Survey high mass signatures with X→Zγ via both leptonic decays and hadron decays
- Examine Spin-0/2 hypothesis, and both gg and qq-initiate production modes
- Accomplish full exclusion limits from 100GeV ~ 7 TeV, narrow width approximation





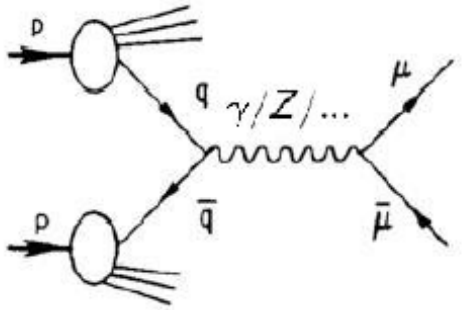


Heavy resonance search to probe BSM heavy boson signatures

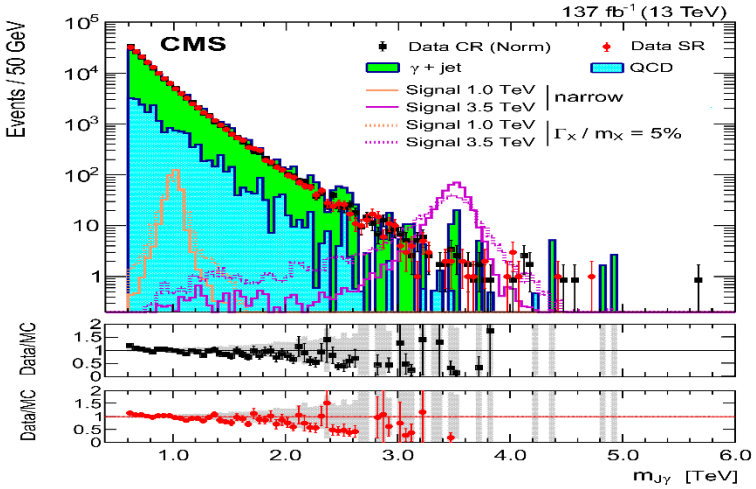
JHEP 07 (2021) 208

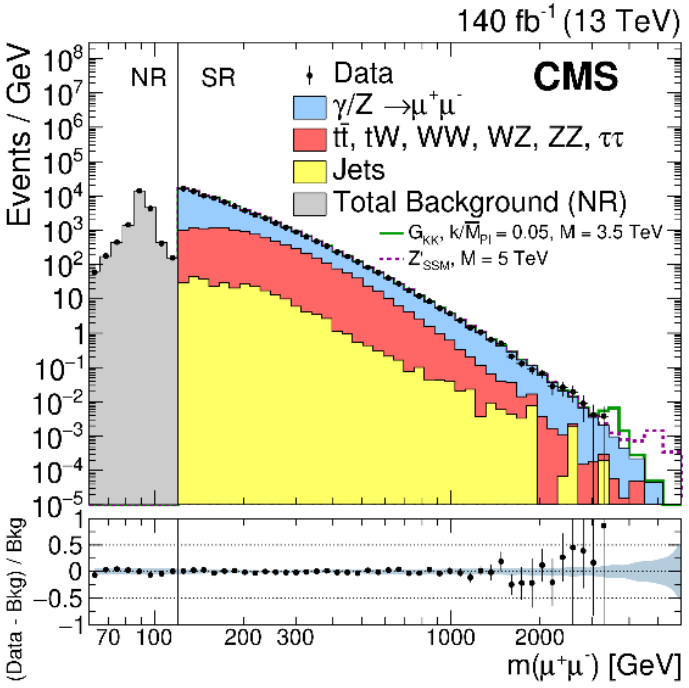
PLB 826 (2022) 136888

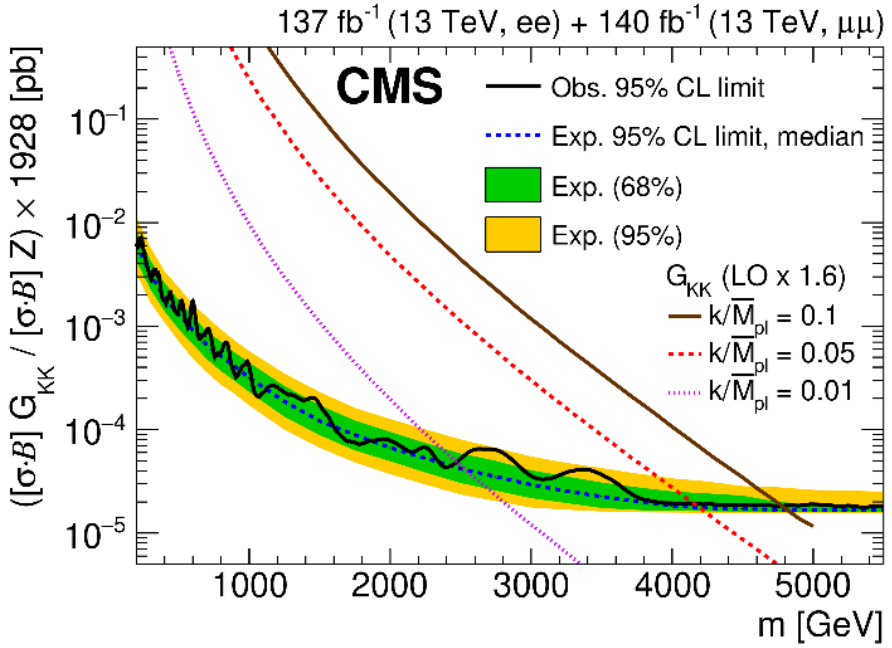
BSM new Physics contributions to SM processes via $Z'/Z_{KK}/G_{KK}$ hypothesis

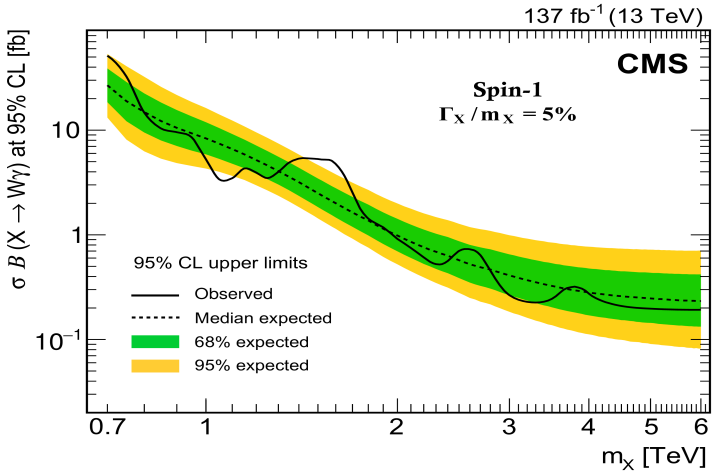


X→Wγ heavy resonance searches with Heavy Vector Triplet model







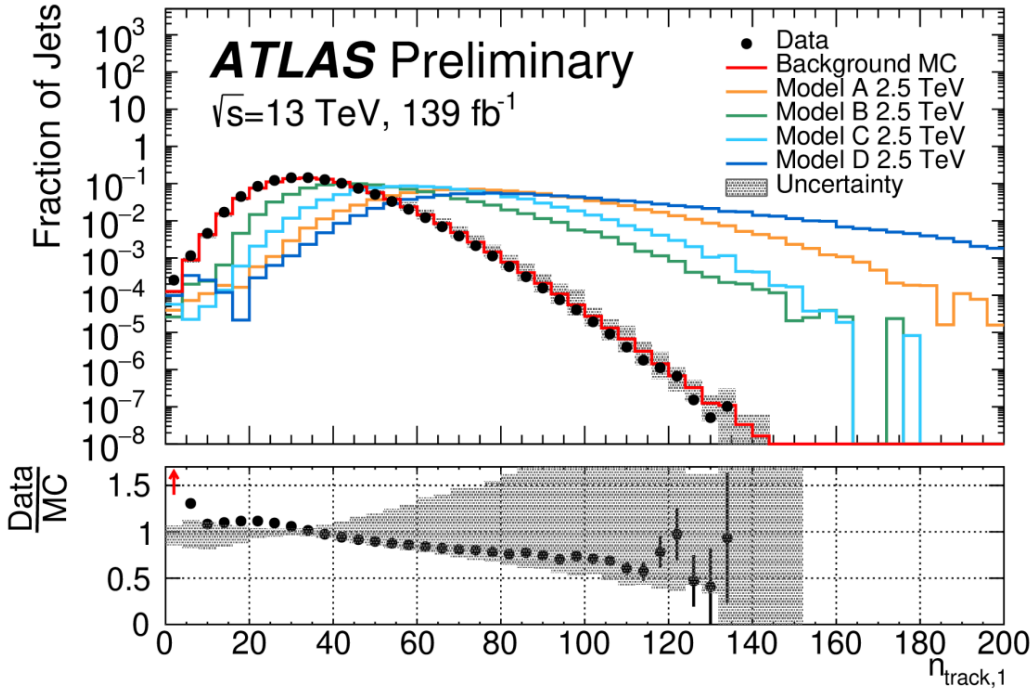


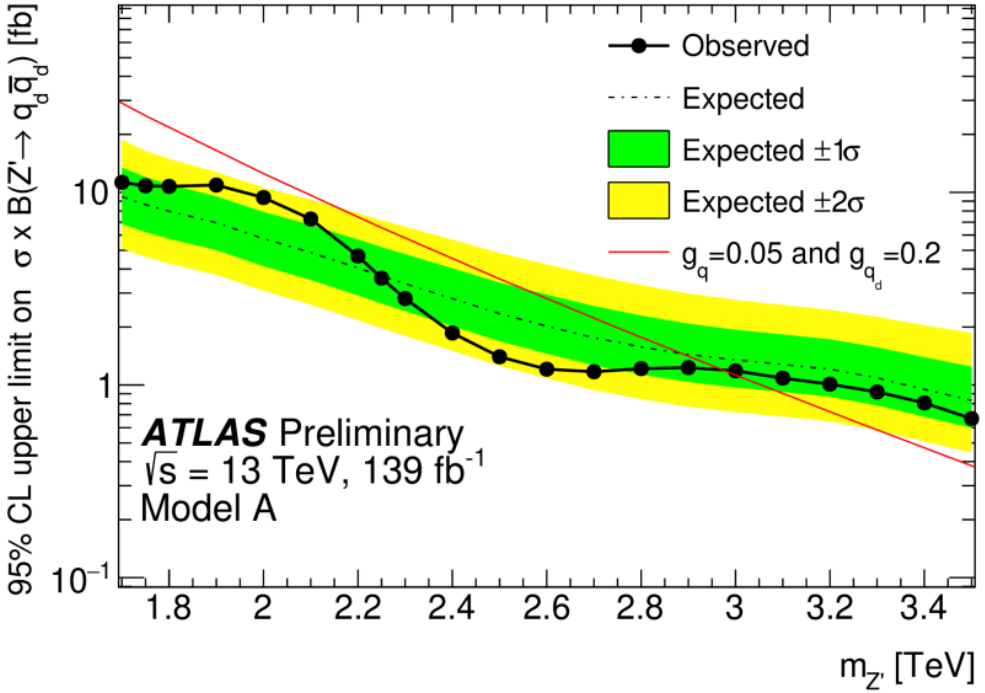
Dark quarks in di-jet final states

ATLAS-CONF-2023-047

- Dark QCD sector hadronizing to dark hadrons (DM candidates) decaying into semi-visible jets, emerging jets,…
  - $Z' \rightarrow q_d \bar{q}_d$
  - Wider jets due to SM and Dark hadronic components
  - Jets with higher particle multiplicity

- Bump hunt in the invariant mass spectrum of the two large-R jet system
- Analysis probes 1.3 TeV < m_{JJ} < 4.8 TeV





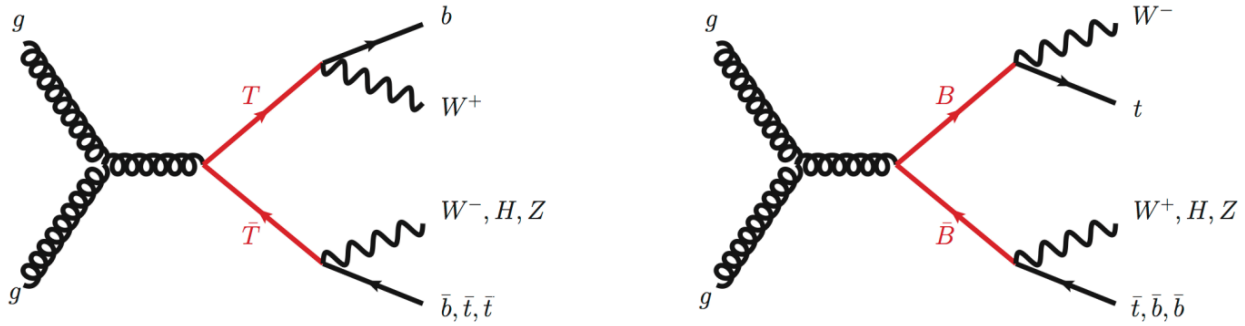
Vector Like Quarks

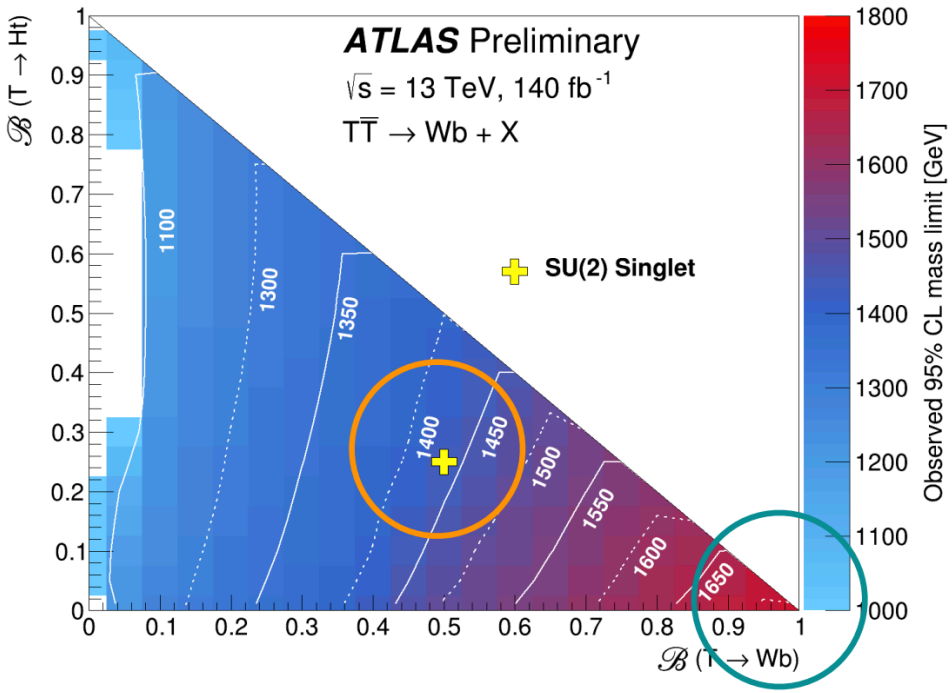
ATLAS-CONF-2023-070

- Postulated as isospin singlets, doublets or triplets ($T^{2/3}$, $B^{-1/3}$, $X^{5/3}$, $Y^{-4/3}$)
  - **Pair production** by strong interaction dominates for < 1TeV
  - **Single production** via EWK vertices, significant at high mass, scales with couplings to SM and multiplet model

- VLQs assumed to decay to 3rd generation SM quarks via charged and neutral currents but BR not fixed by theory regulated by parameters dependent on multiplet model

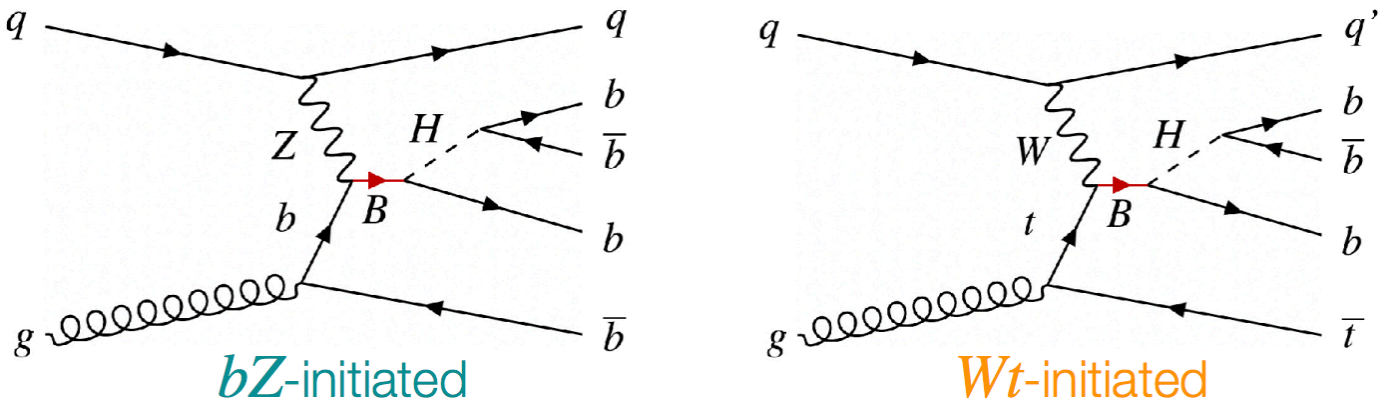
- All possible VLQ decays searched in many final states





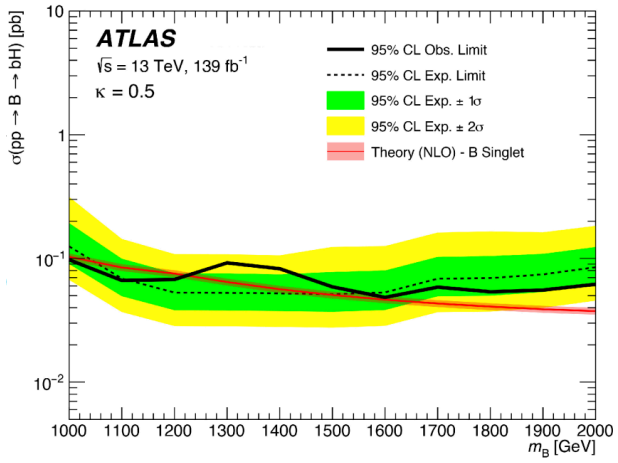
Vector-like B → bH(bb̄)

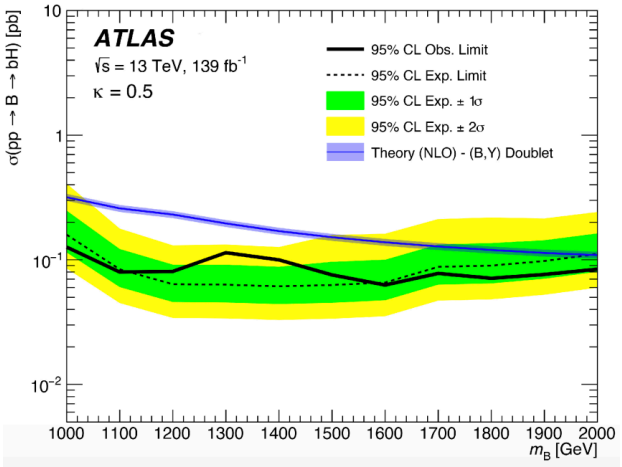
arxiv:2308.02595

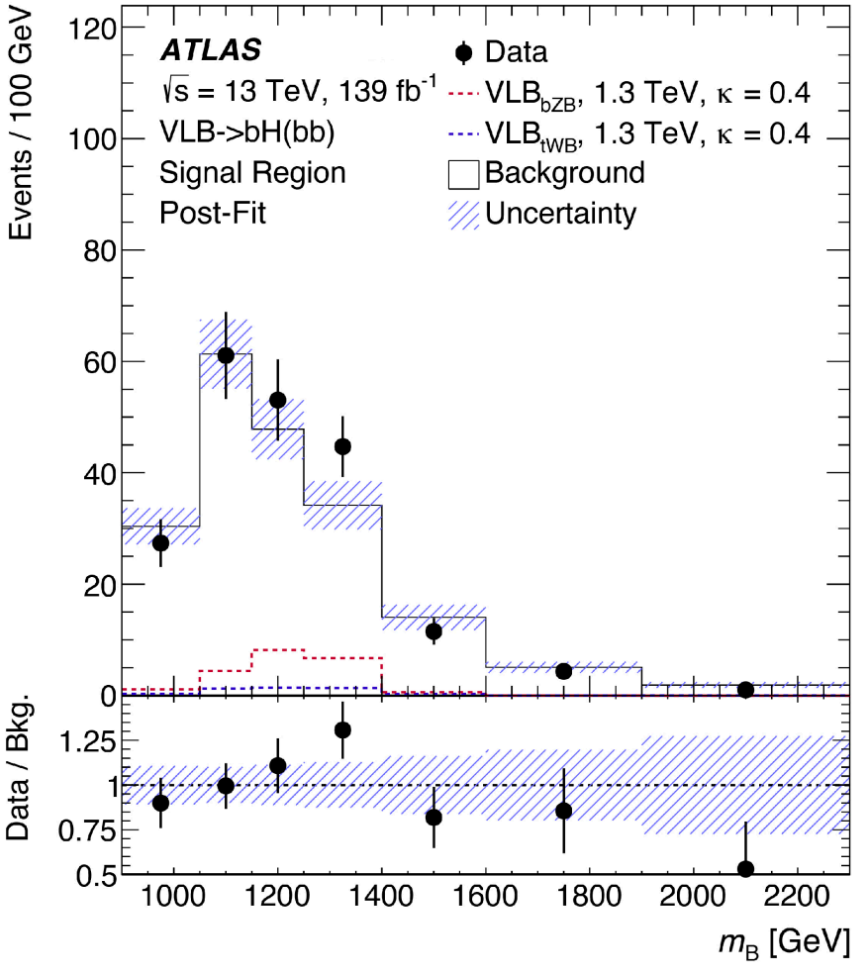


bZ-initiated: dominant for singlet model initiated diagram

Wt-initiated: forbidden for (B, Y) doublet (ξ_W=0)



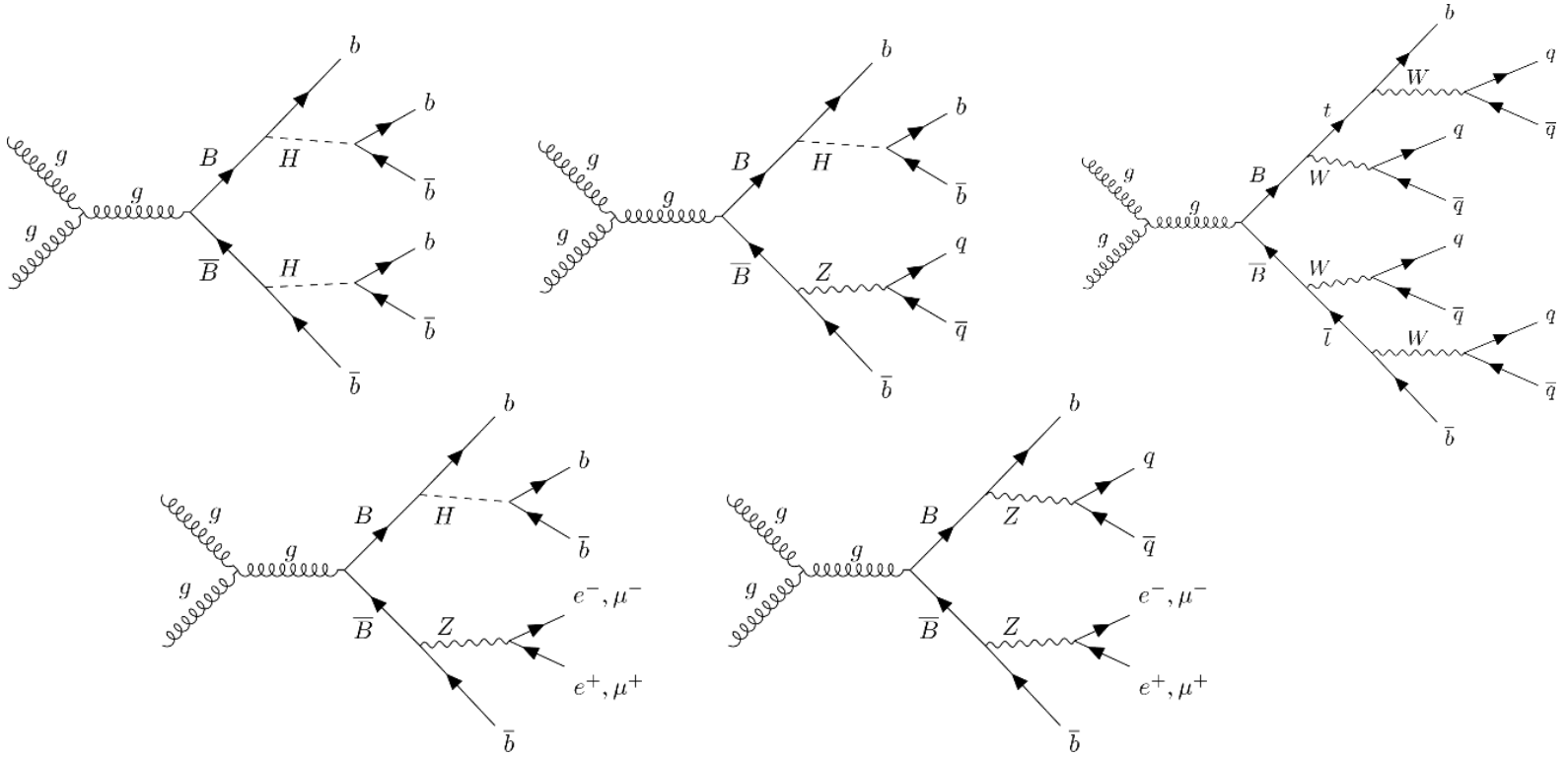


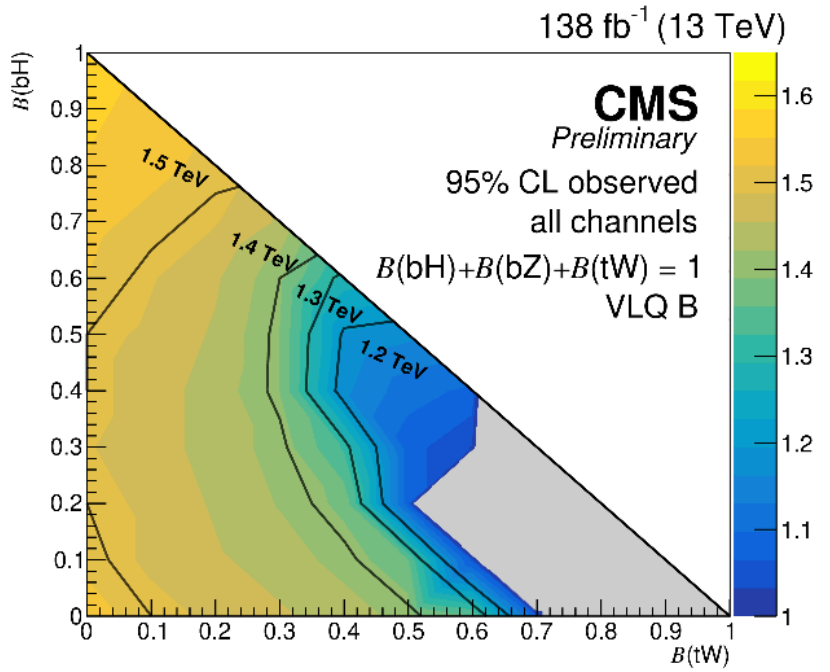


Reconstructed with large radius H(bb)-jets plus b-jets

VLQ → b + H/Z, t + W

CMS-PAS-B2G-20-014

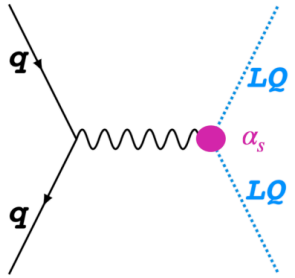




- Search for a pair of bottom-type vector-like quarks: VLQ → b + H/Z, t + W
- both fully hadronic final states and those containing a lepton pair from a Z boson decay
- hadronic decays can be resolved as two distinct jets or merged into a single jet

Leptoquark searches

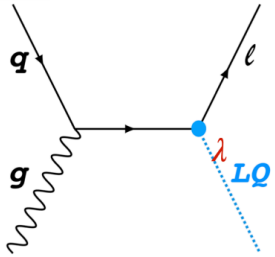
arxiv:2306.17642



Pair Production

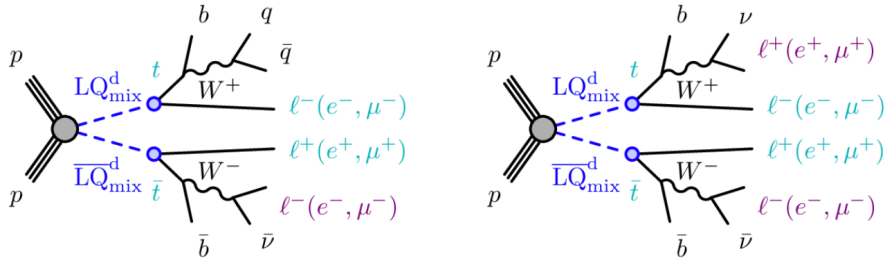
Governed by QCD

σ depends on m_{LQ}

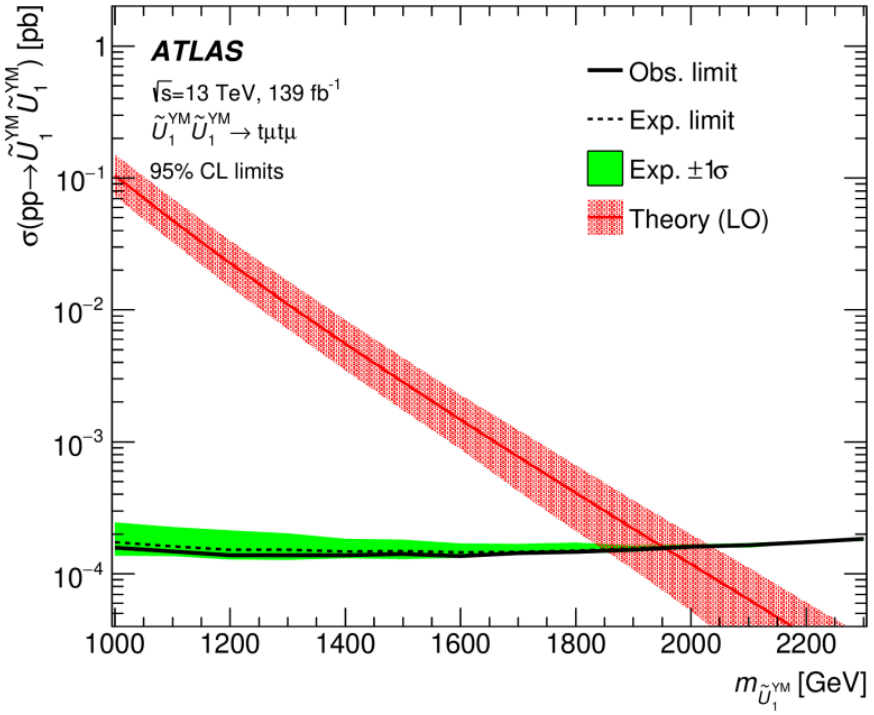


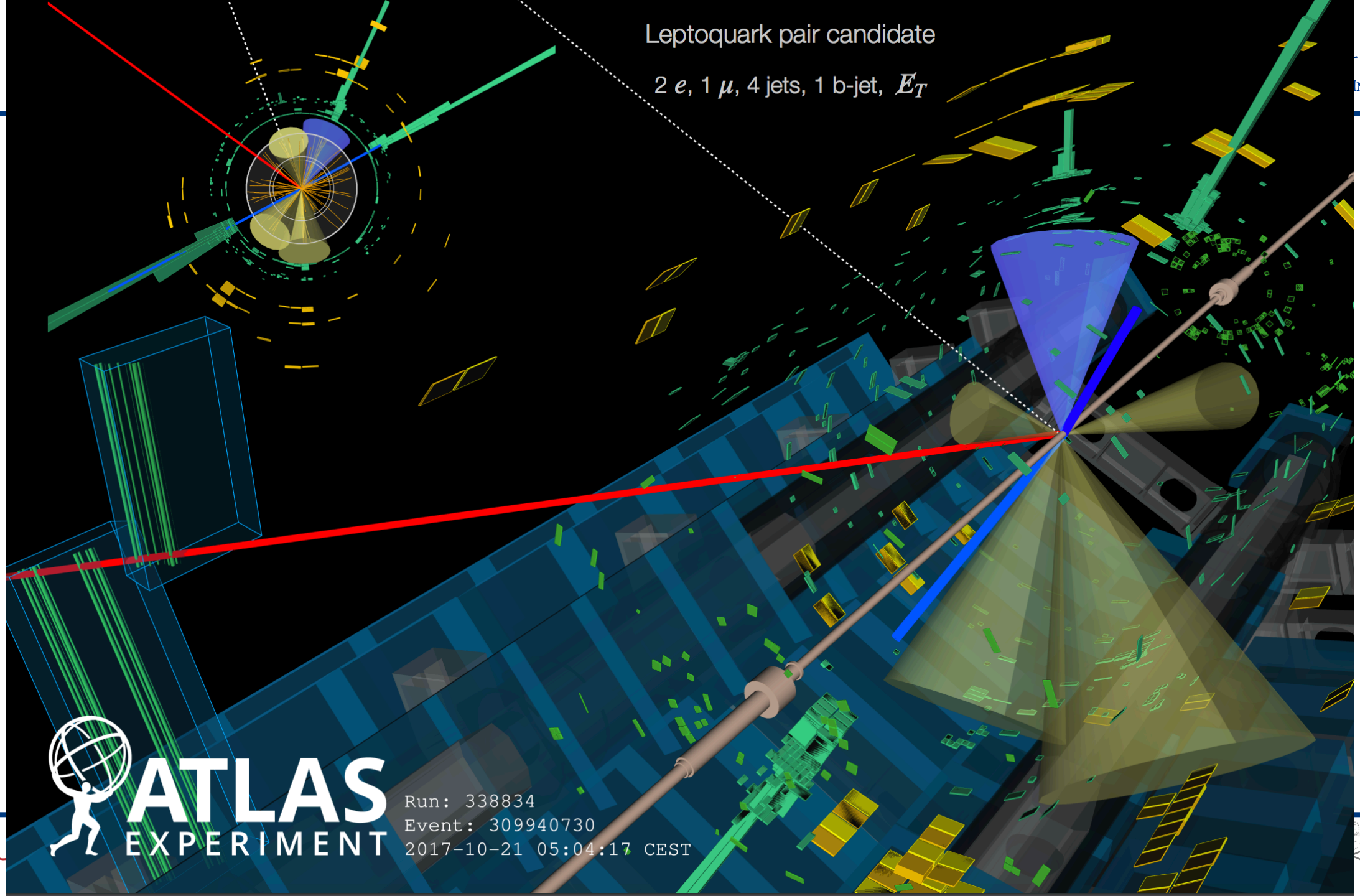
Single production

σ proportional to λ^2

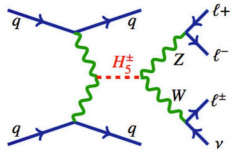


- Color-triplet scalar or vector bosons with lepton and baryon number
- Couple SM quarks and leptons directly through Yukawa λ interaction and can mediate lepton-flavor violation
- Can explain B-anomalies and anomalous muon dipole moment g_μ-2, present in GUTs
- Rich phenomenology and many searches depending on decay diversities
- Broad program of searches for pair production, single production starting to be searched too




Leptoquark pair candidate
2 e, 1 μ, 4 jets, 1 b-jet, E_T
ATLAS
EXPERIMENT
Run: 338834
Event: 309940730
2017-10-21 05:04:17 CEST

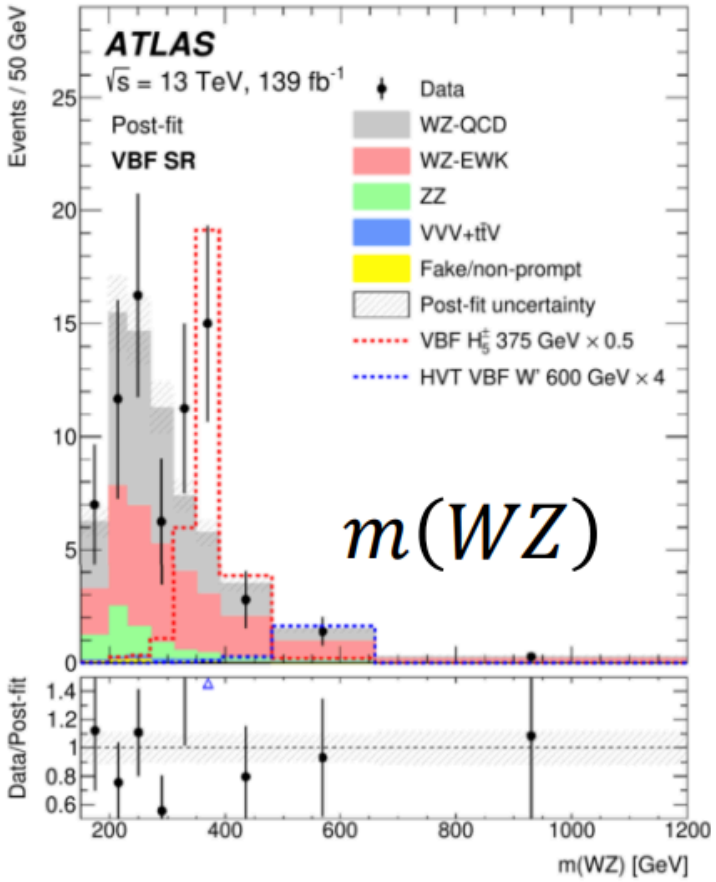
(Doubley-)charged Higgs searches



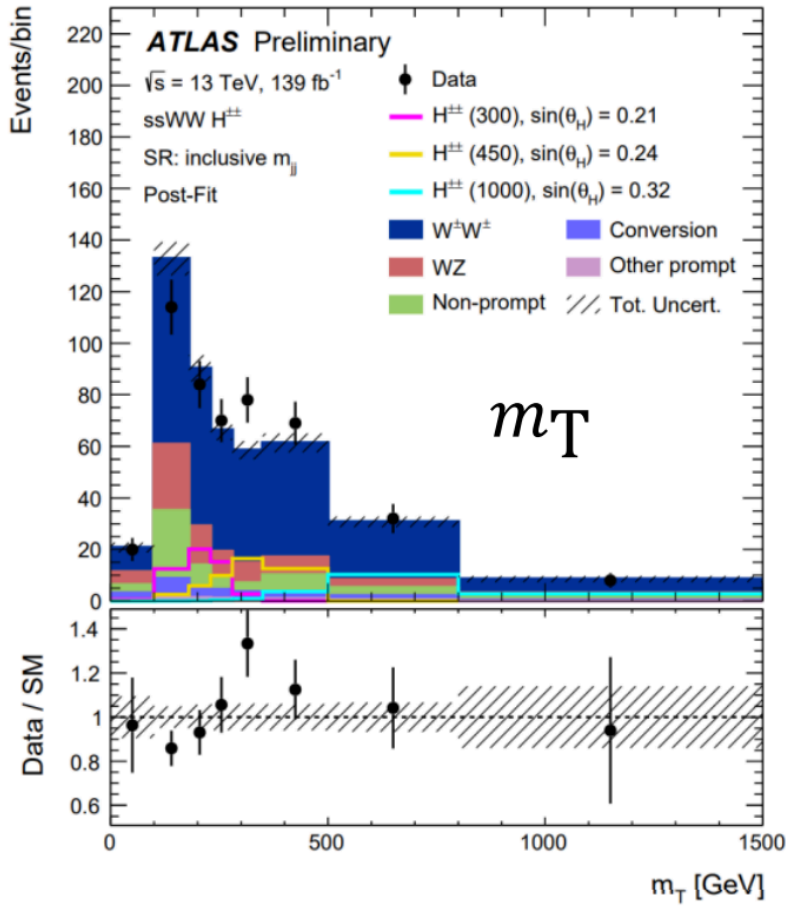
EPJC 83 (2023) 633
ATLAS-CONF-2023-023

Motivated by Georgi-Machacek model (Fermiophobic Higgs fiveplet)

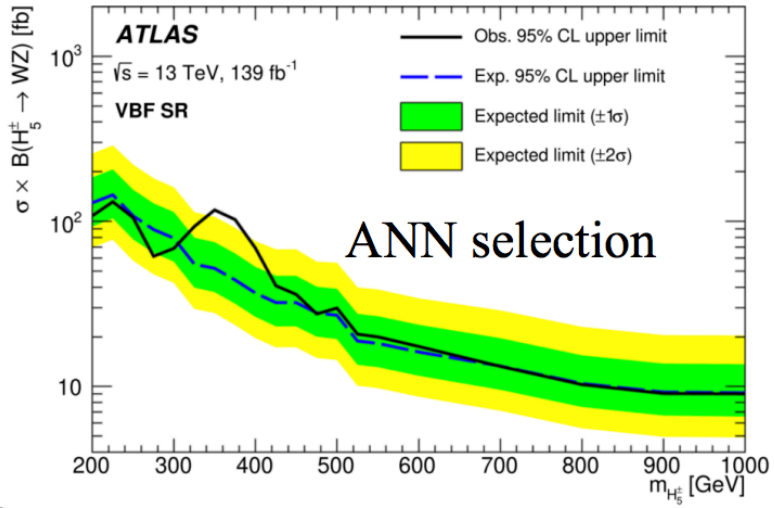
$H^+ \rightarrow WZ$

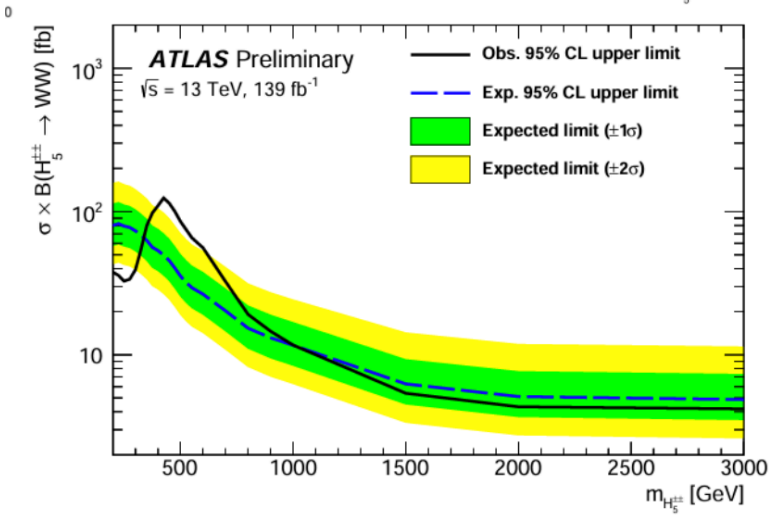


$H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$



2.8σ local signif. @ 375 GeV





3.2σ local signif. @ 450 GeV

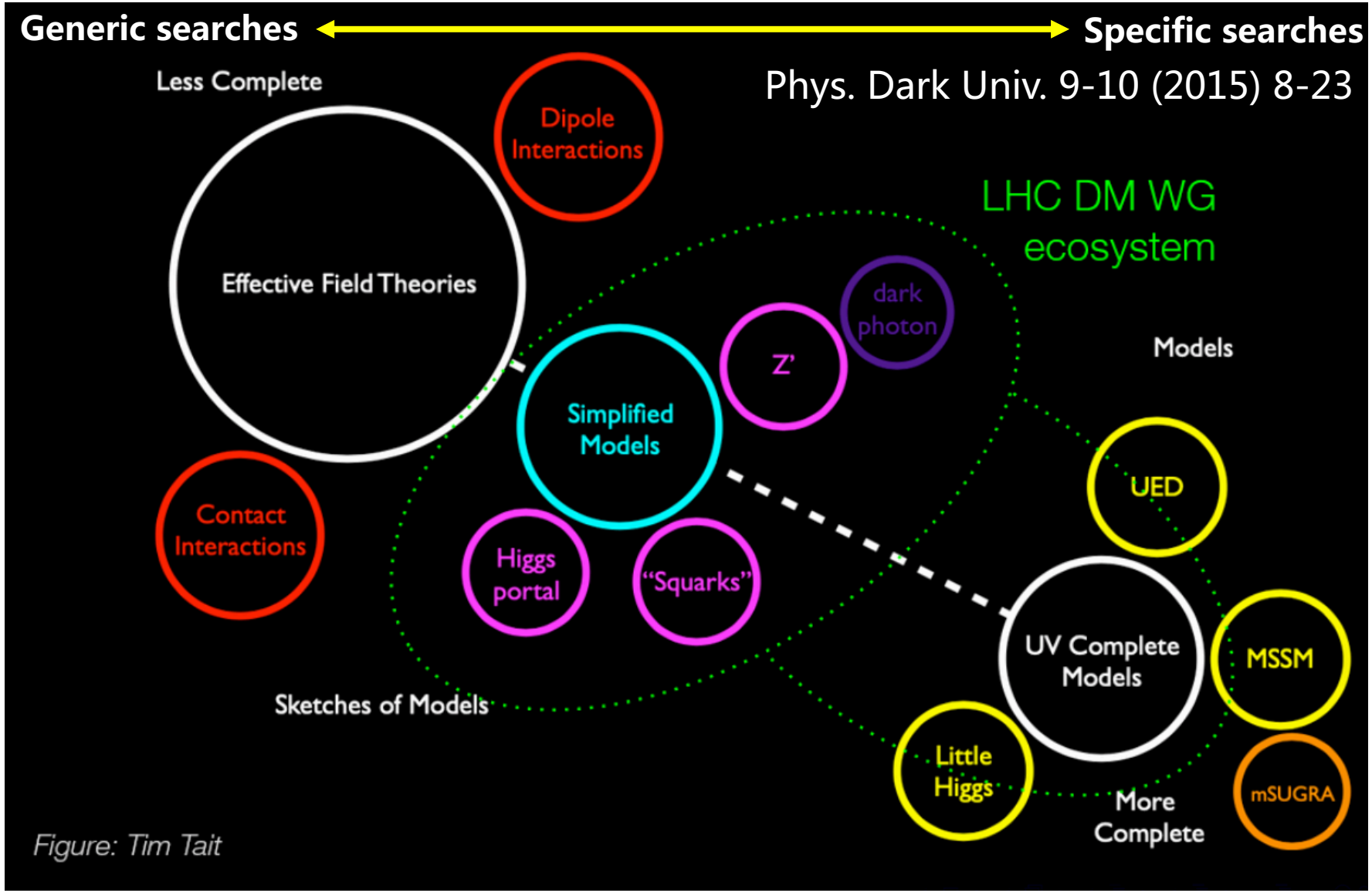
PART 02

Dark Matter Searches

TSUNG-DAO LEE INSTITUTE

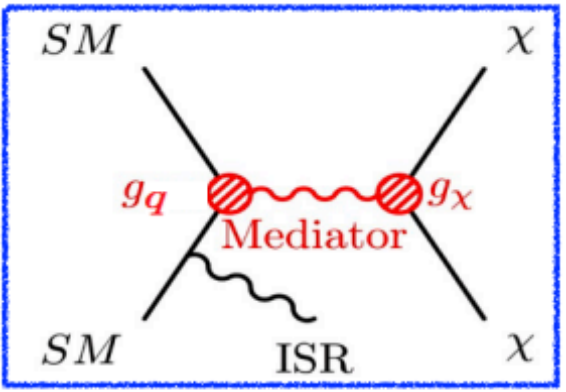
Frontiers that DM can reach out

Dark Matter Models for LHC



Dark Matter Search programs at LHC

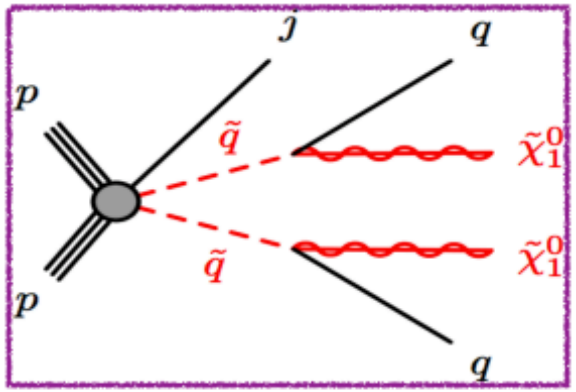
Simplified models



SM-DM boson mediator:

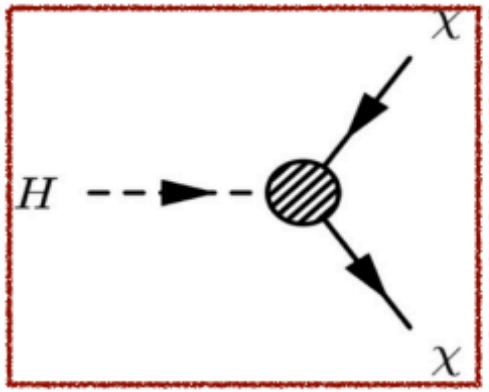
- Spin-0: Scalar (S) or pseudo-scalar (a)
- Spin-1:
  Vector (V/Z') or axial-vector (A)
- Minimal set of parameters:
  M_χ, $M_{mediator}$, g_χ, g_q, g_ℓ

SUSY



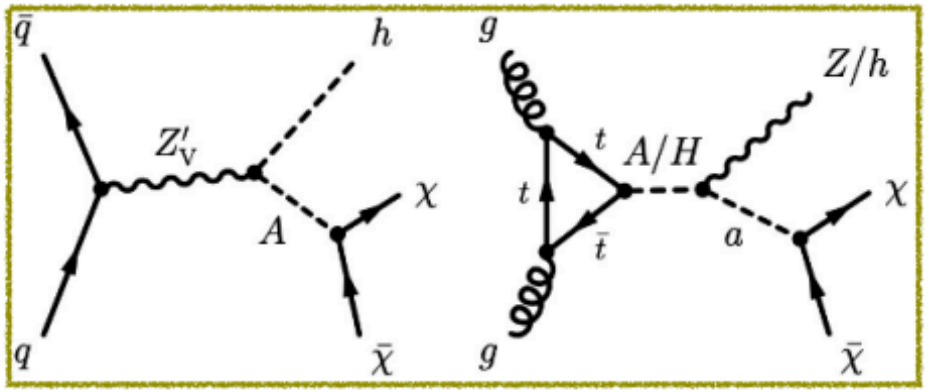
- Provides good candidate for DM
- R-parity conservation
- Lightest supersymmetric Particle (LSP)
- Model-dependent limit on DM candidate

Higgs portal



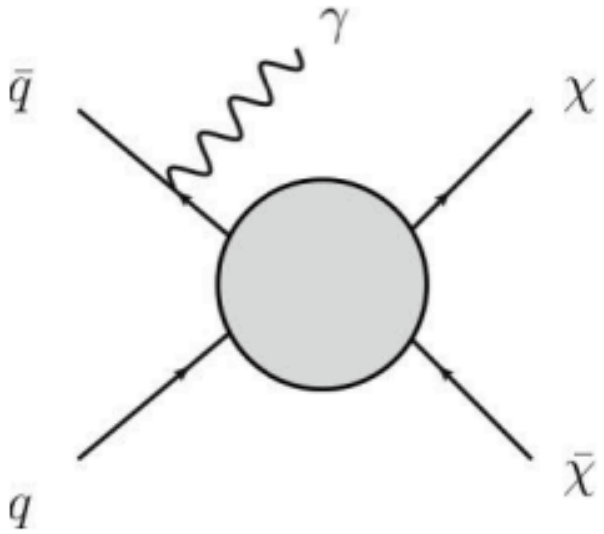
- Higgs boson mediates DM-SM interaction:
  $H \rightarrow invisible$
- Parameters: m_χ, χ spin

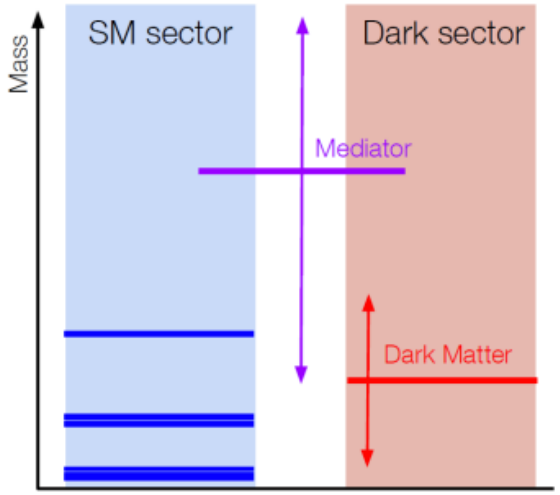
Extended Higgs sector



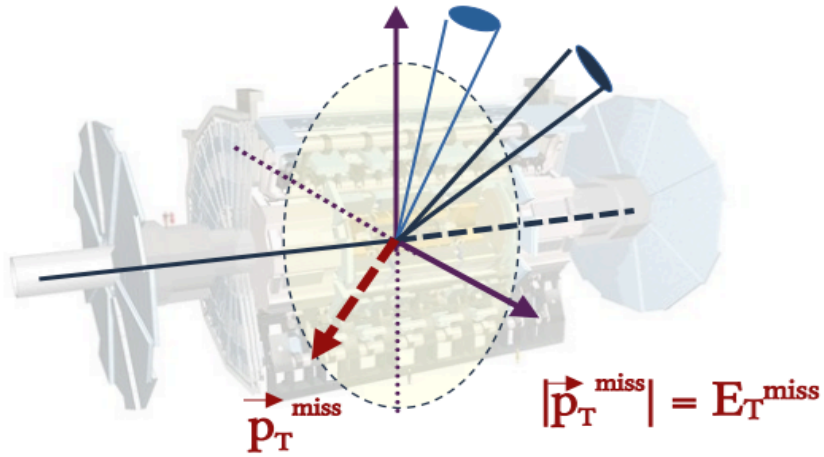
- More complete models (more free parameters and better sensitivity) involving several Higgs-like (or scalar) bosons: 2HDMa, Dark Higgs, ..

S-channel Mediator Simplified Models





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



Escape
Detection

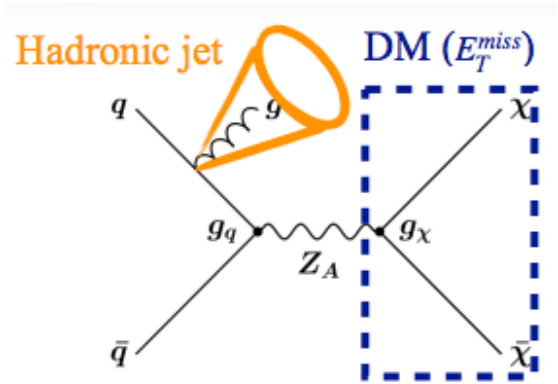
Missing transverse momentum inferred from momentum conservation

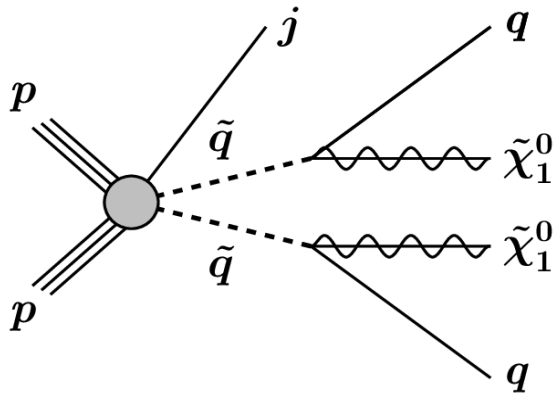
Simplified model:
- Starting point to build complete theories
- Colliders can search for the mediator directly
- Benchmark model @ Run II

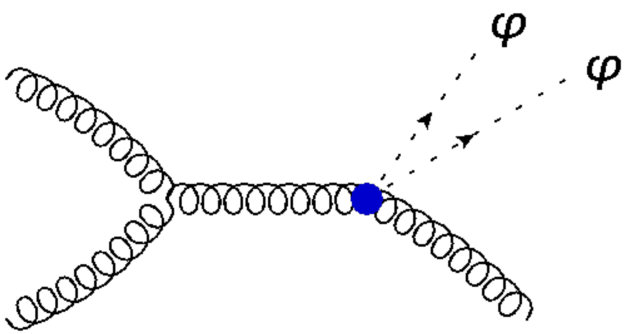
Two complementary approaches:
- Look for DM - mono-X signature
- Look for mediator - resonance search

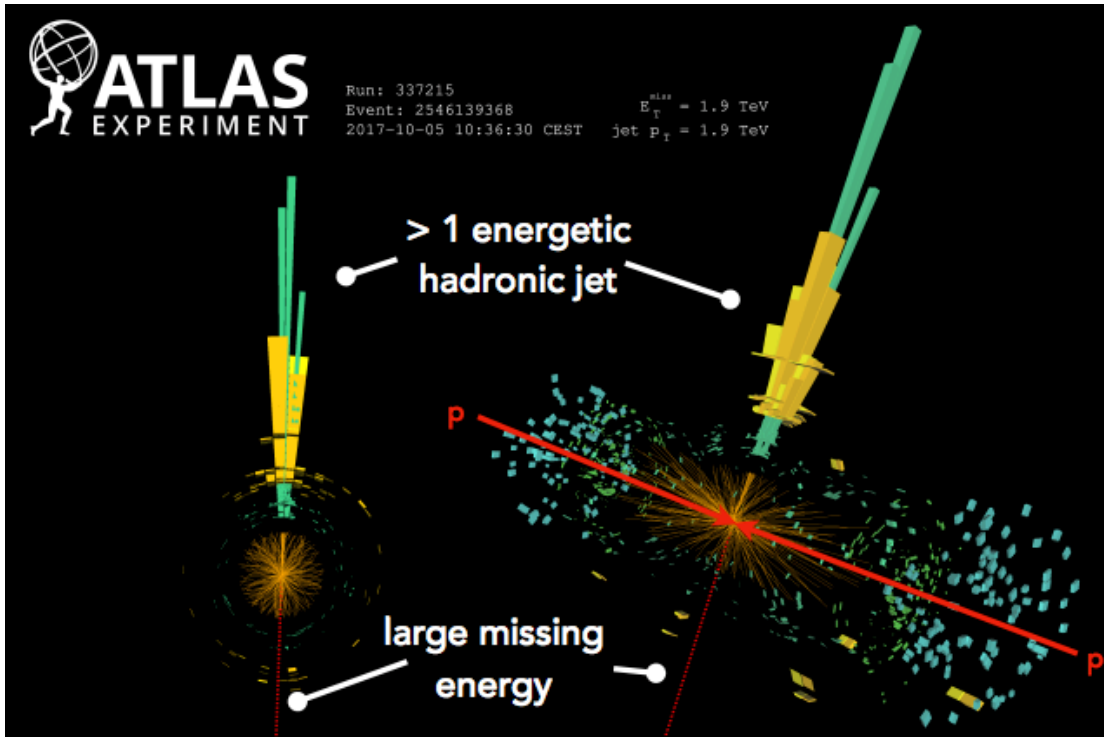
Mono-Jet search (Jet + E_T^{miss})

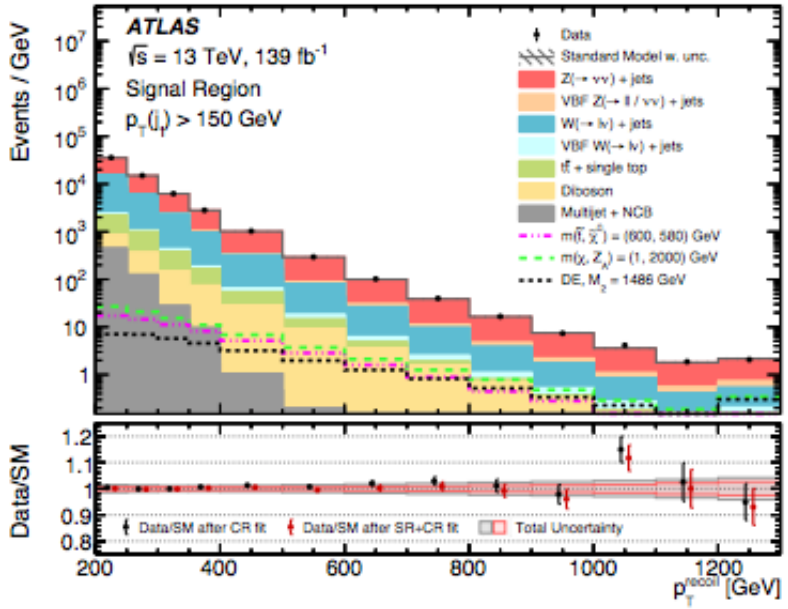
Phys. Rev. D 103 (2021) 112006



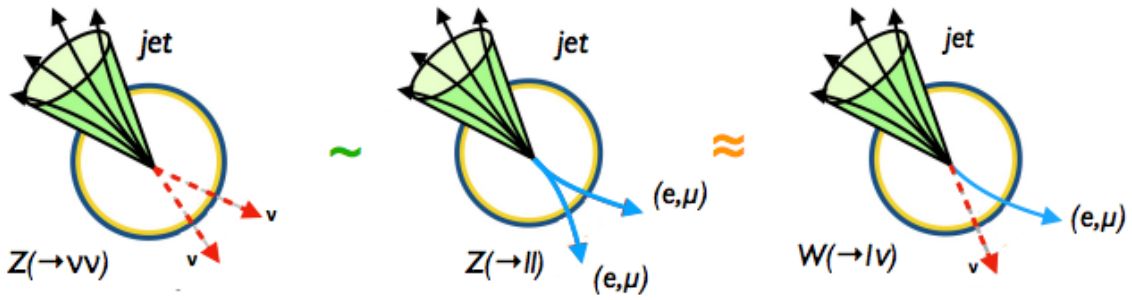








Signal region



Main backgrounds

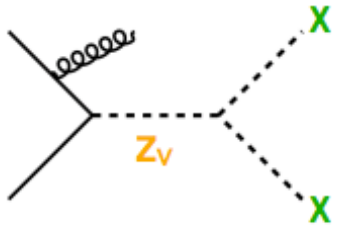
Diverse Interpretations

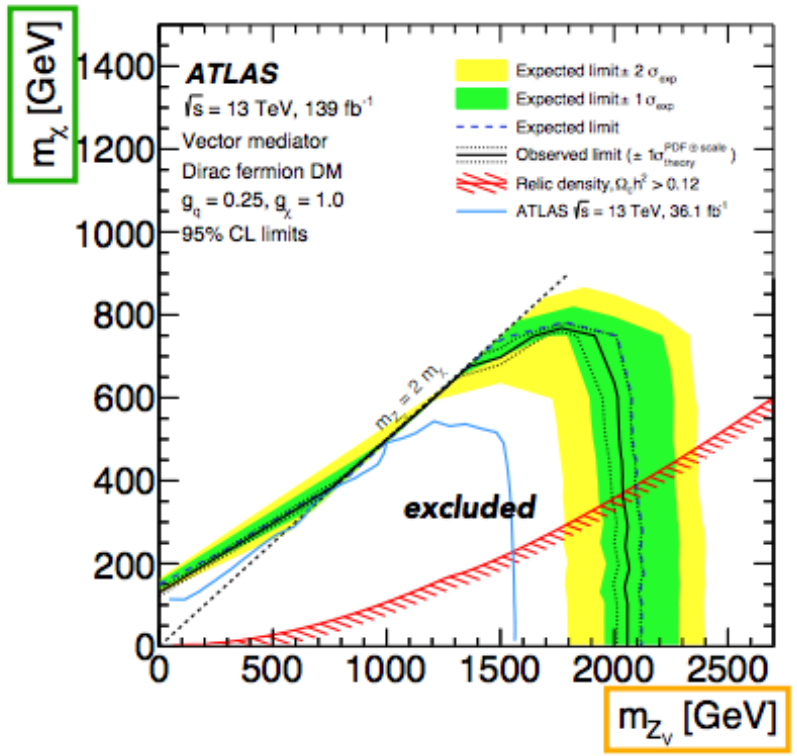
- Simplified Models:
  - Fix coupling; Fix ratio
- T-channel models
- Generic sensitivity
  - SUSY, leptoquarks, extra dimensions, …

Mono-Jet search (Jet + E_T^{miss})

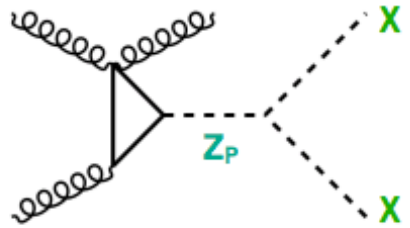
Phys. Rev. D 103 (2021) 112006

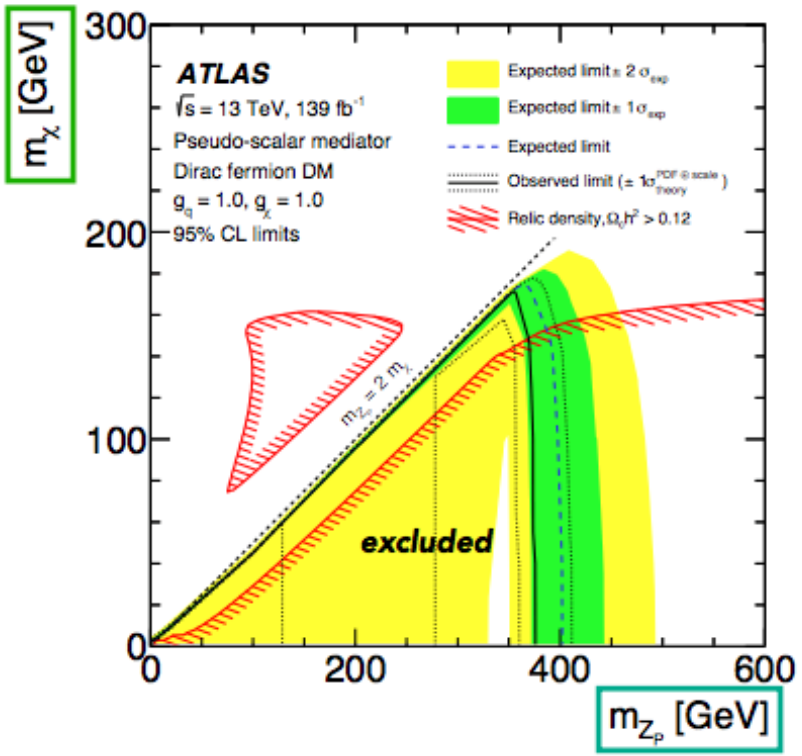
Spin 1





Spin 0





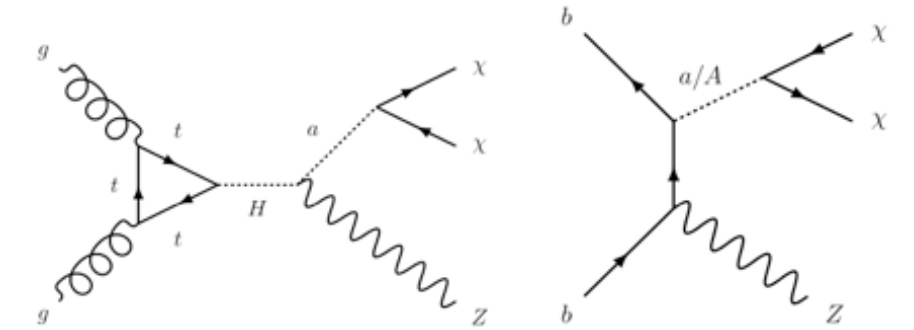
E_T^{miss}+Z(ll) signature

Phys. Lett. B 829 (2022) 137066

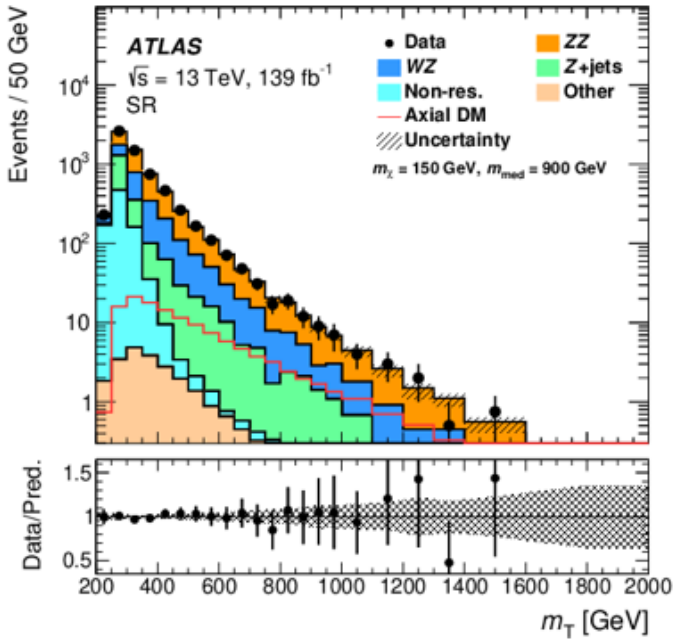
- **Signal region**:
  - Z boson recoiling against large $E_{\mathrm{T}}^{\mathrm{miss}} > 90$ GeV
  - Presence of a pair of high-p_{T}, same flavour, oppositely charged leptons with angular separation < 1.8

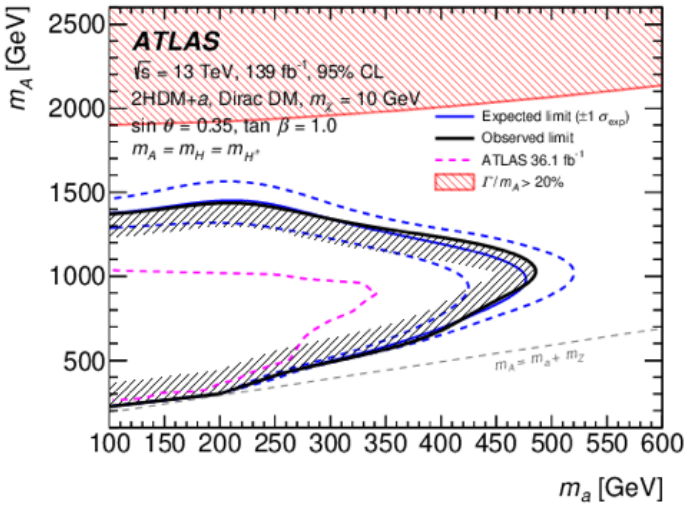
- Dominant bkgs ZZ, WZ and non-resonant bkgs estimated using **4l, 3l, and eμ Control Regions.**

- Fit to data is performed on $m_{\mathrm{T}}^{\mathrm{lep}}$ (in SR and $e\mu$ CR) + $E_{\mathrm{T}}^{\mathrm{miss}}$ (in 4l and 3l CRs).



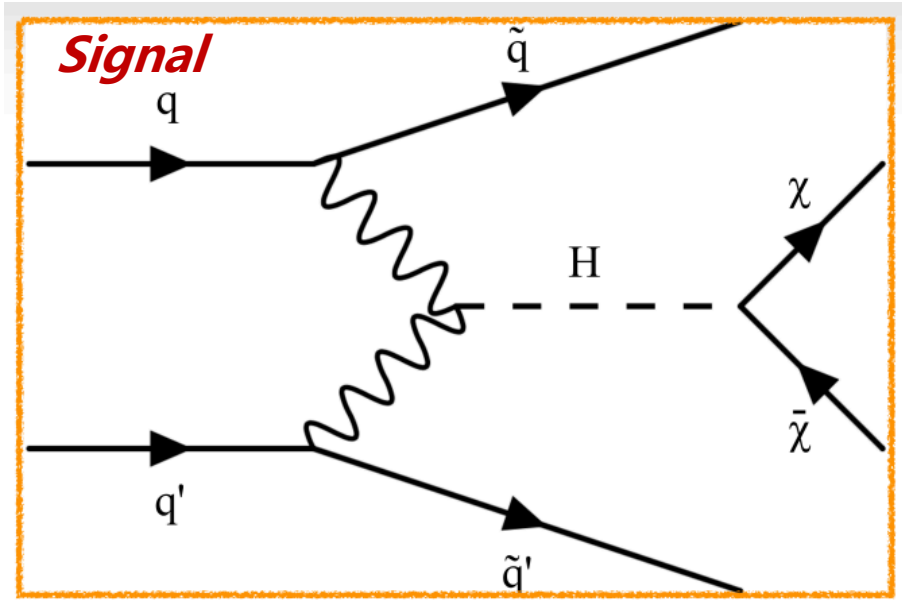
gg-initiated bb-initiated





Higgs portal to DM: invisible decays

Phys. Rev. D 105 (2022) 092007



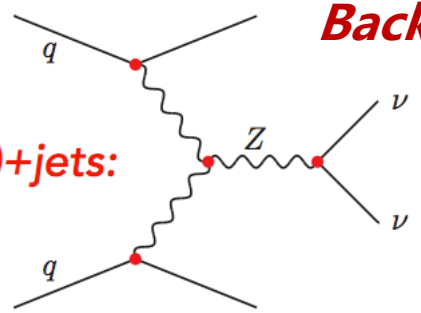
Observed Limit from the combination

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

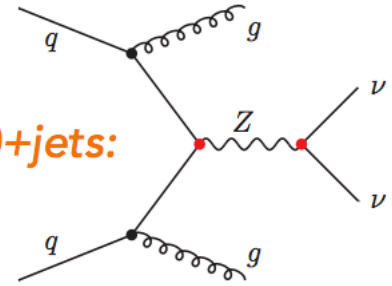
- Signature: Vector-Boson Fusion
- Two SR triggers:
  - MTR with missing momentum trigger
  - VTR with VBF jet trigger

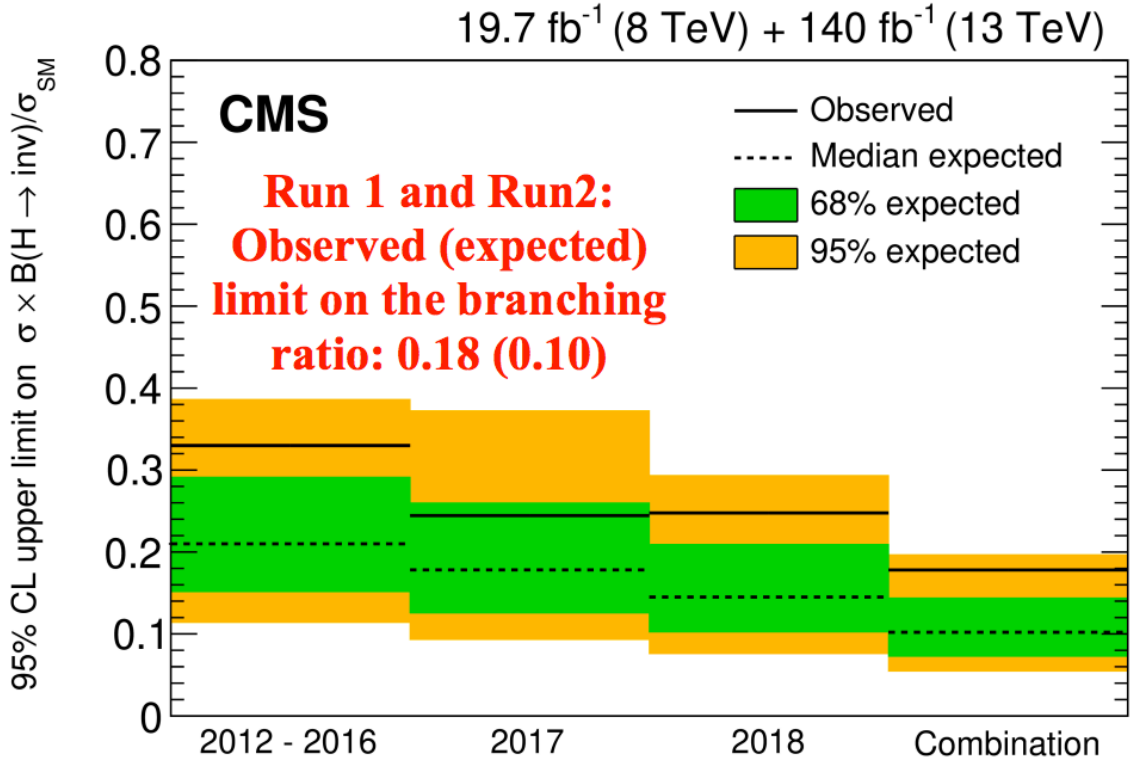
Backgrounds

EW Z(νν)+jets:



QCD Z(νν)+jets:



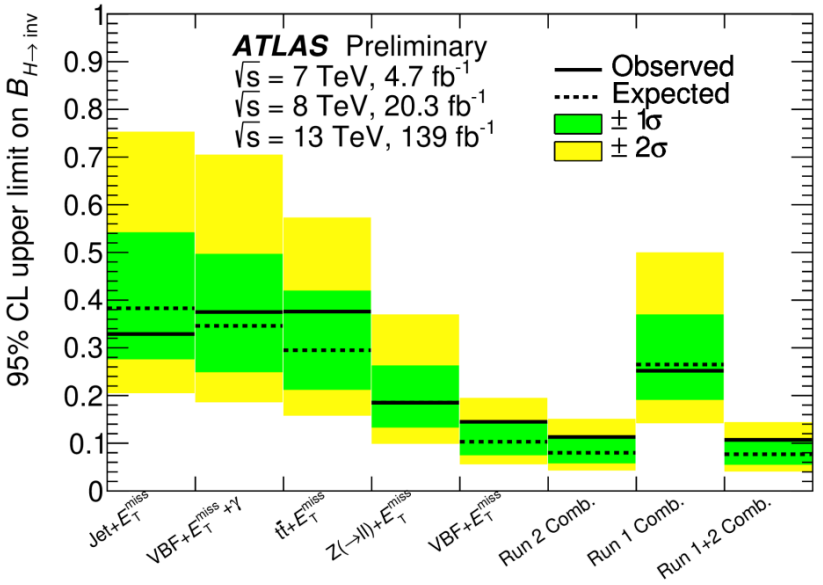


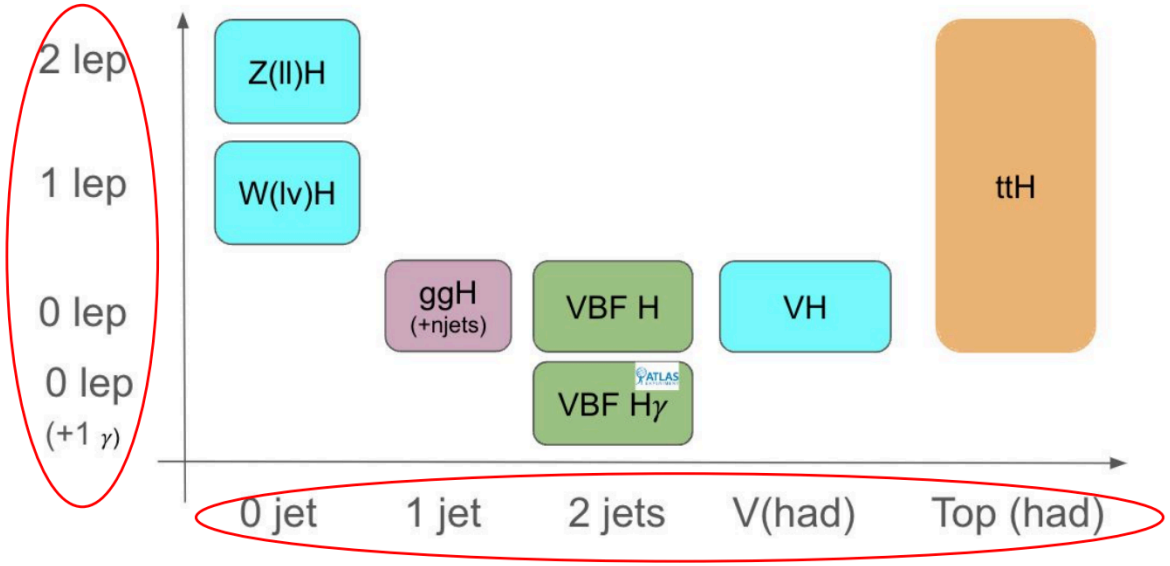
Higgs portal to DM: invisible decays

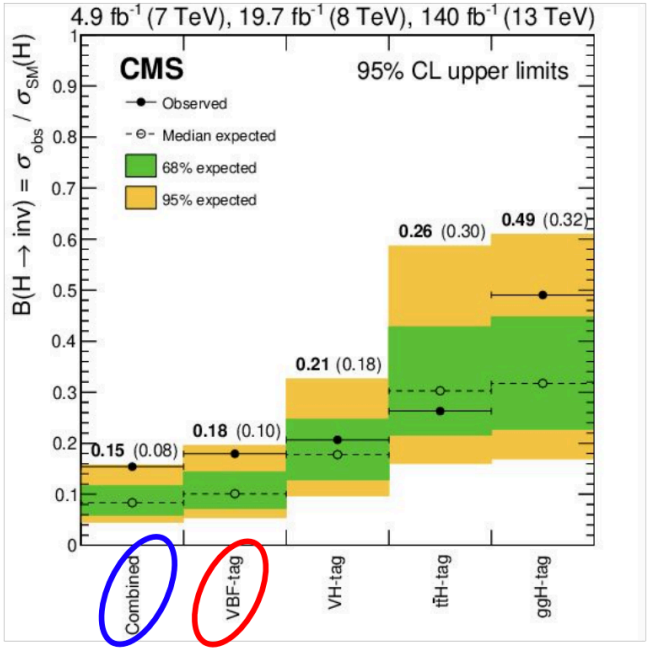
Phys. Lett. B 842 (2023) 137963
EPJC 83 (2023) 933

Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	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** - used to constrain Z+j with W+j
- Probing BR(H→ Inv) at 10% level



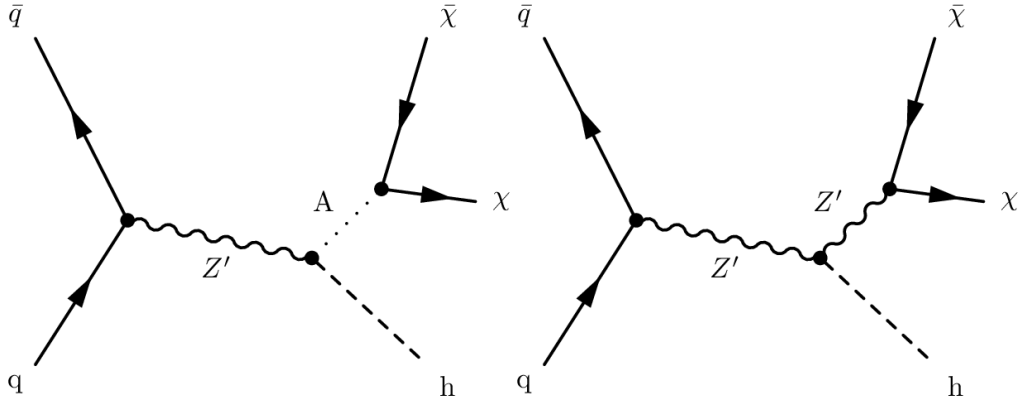




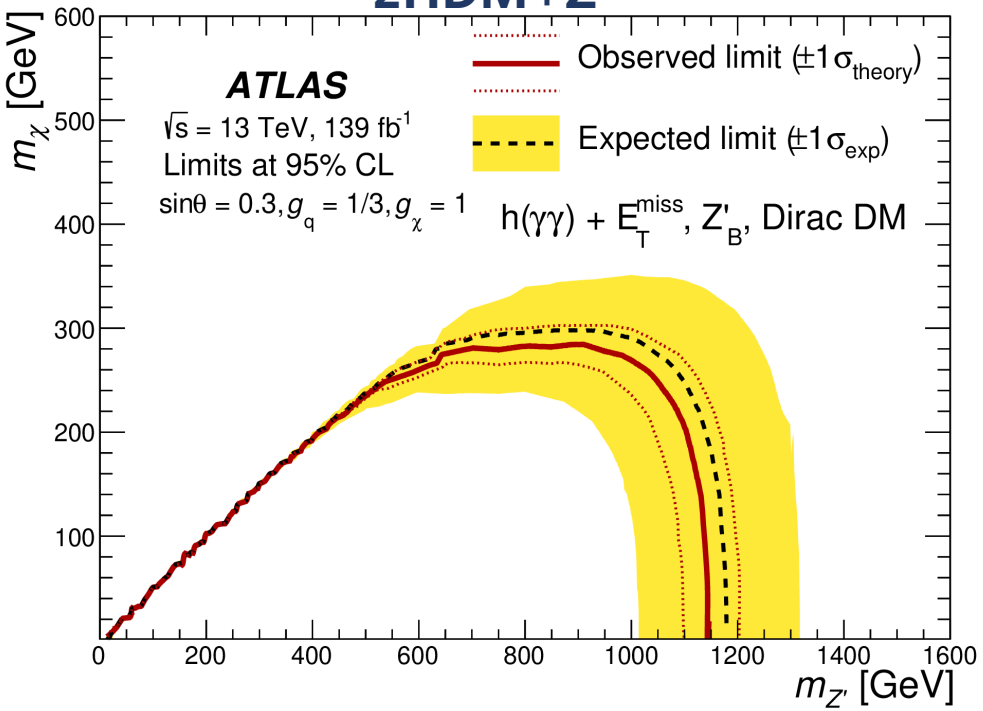
- ATLAS B(H → inv) 95% limit : 10.7% (7.7%)
- CMS B(H → inv) 95% limit : 15% (8%)

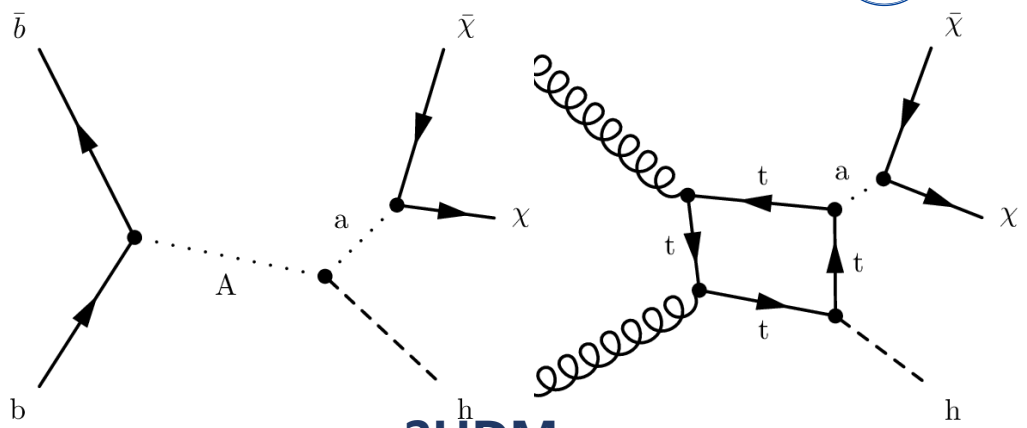
Higgs portal to DM: Mono-H($\gamma\gamma$)

JHEP 10 (2021) 13

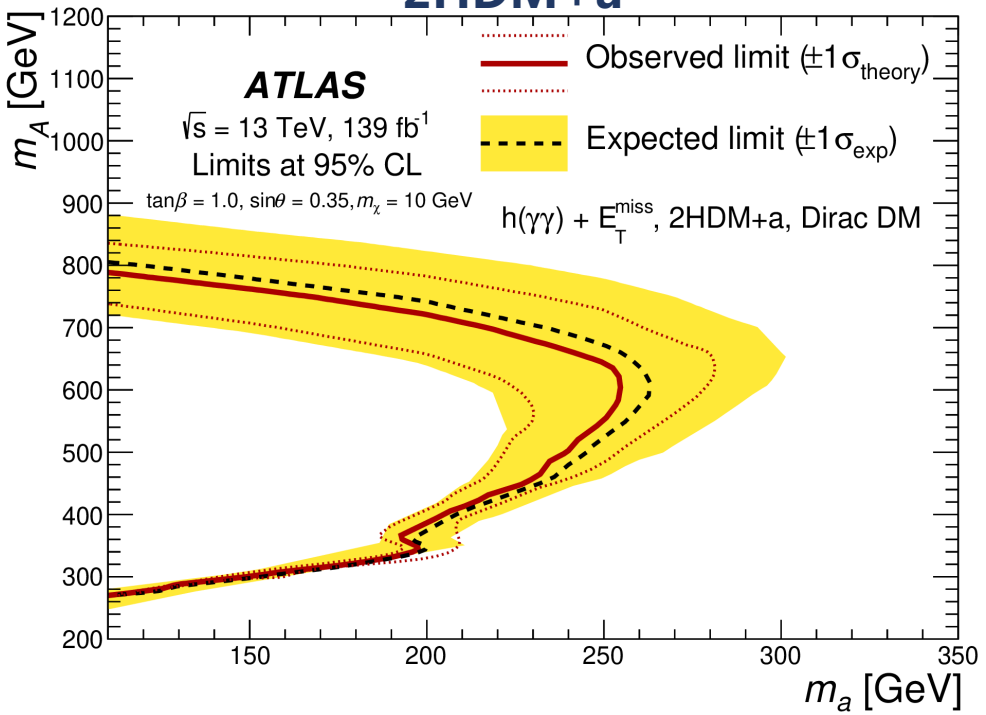


2HDM+Z'





2HDM+a

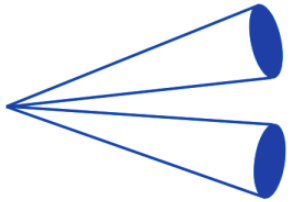


Higgs portal to DM: Mono-H(bb)

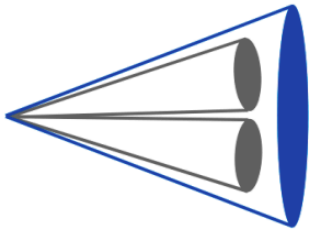
JHEP 11 (2021) 209

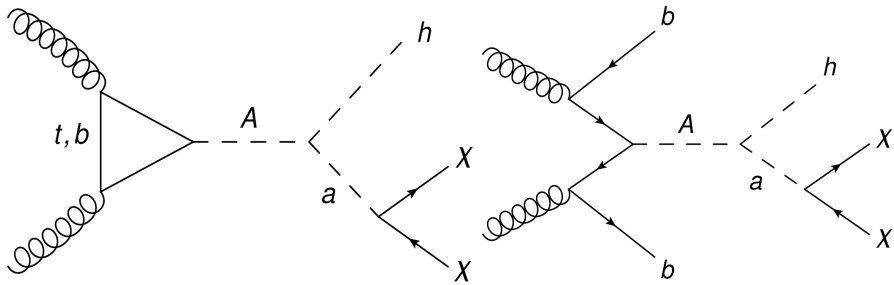
- Interpreted with 2HDM+Z′ , 2HDM+a in both ggF and bbH.
- Also Model-independent upper limits on the visible cross-section

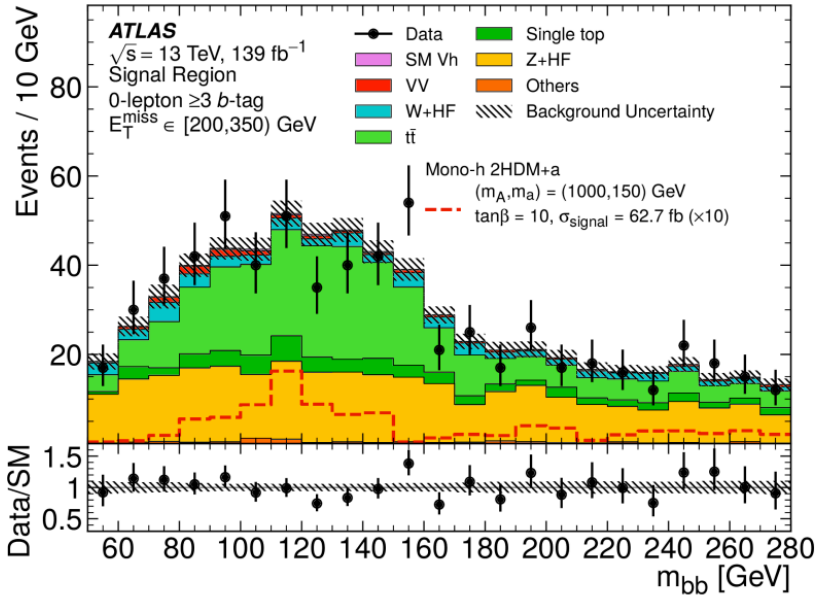
Resolved topology
$150 < E_T^{miss} < 500$ GeV
$50\ GeV < m_h < 280\ GeV$
At least 2 small-R jets

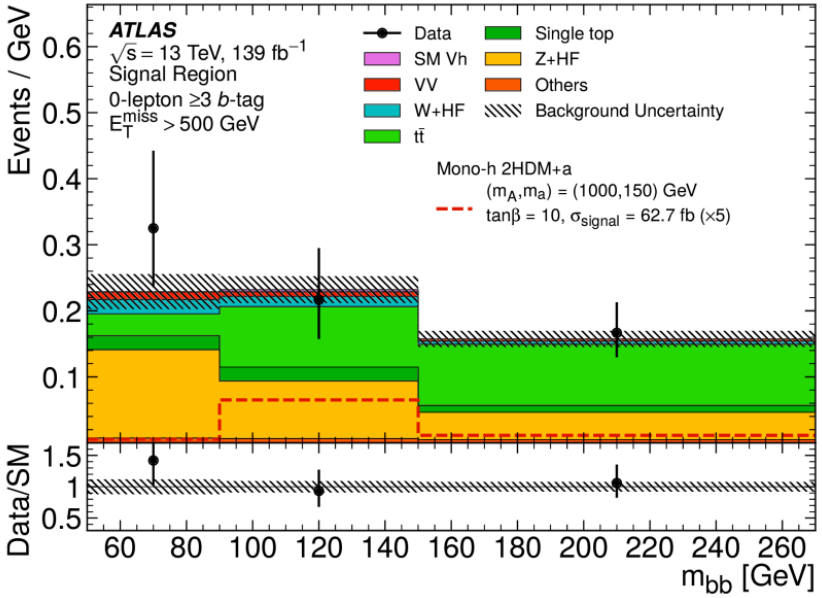


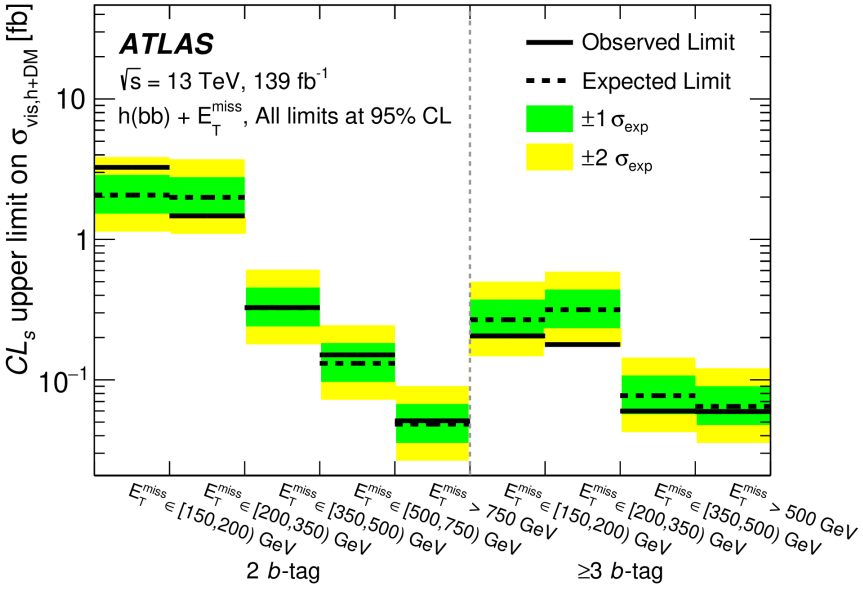
Merged topology
$E_T^{miss} > 500$ GeV
$50\ GeV < m_h < 270\ GeV$
At least 1 large-R jet





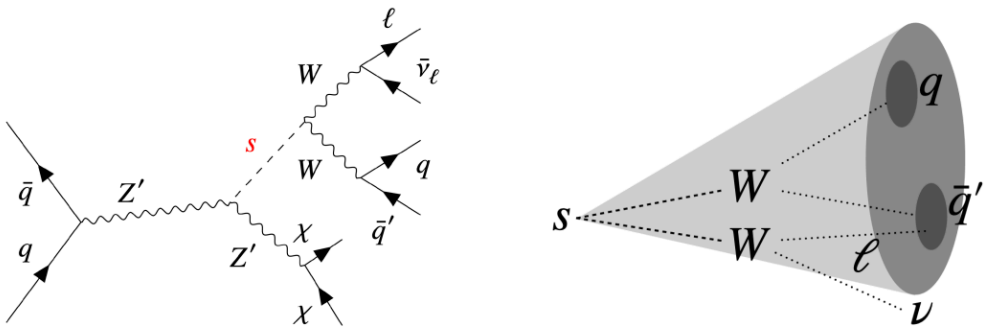






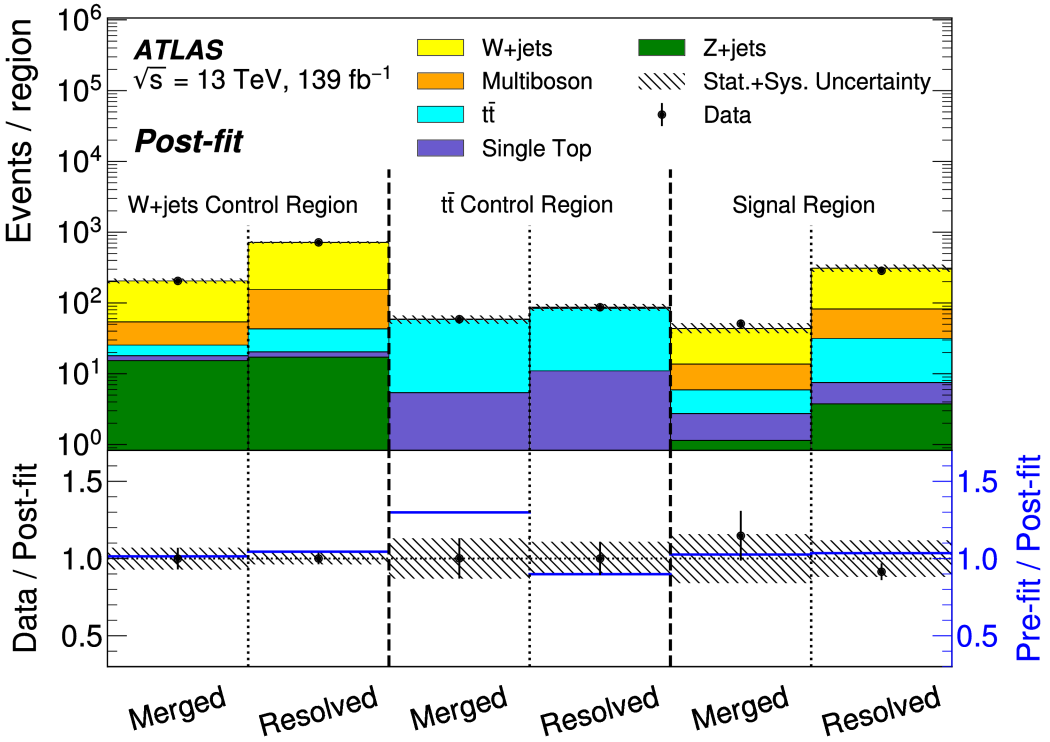
Dark Higgs Search: s→WW semileptonic

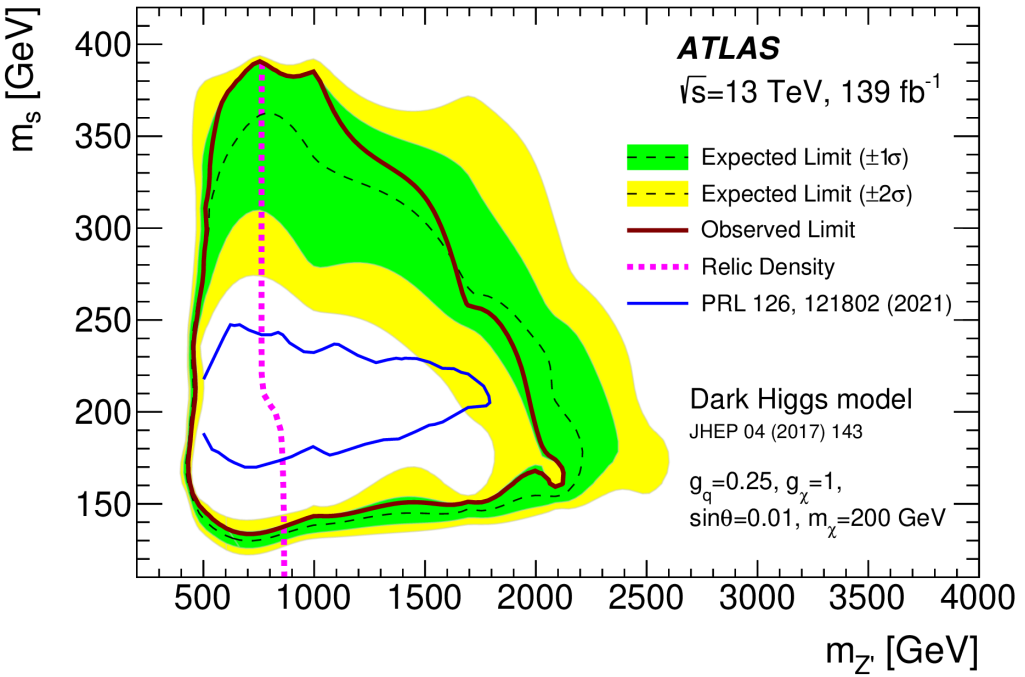
JHEP 07 (2023) 116



- 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.

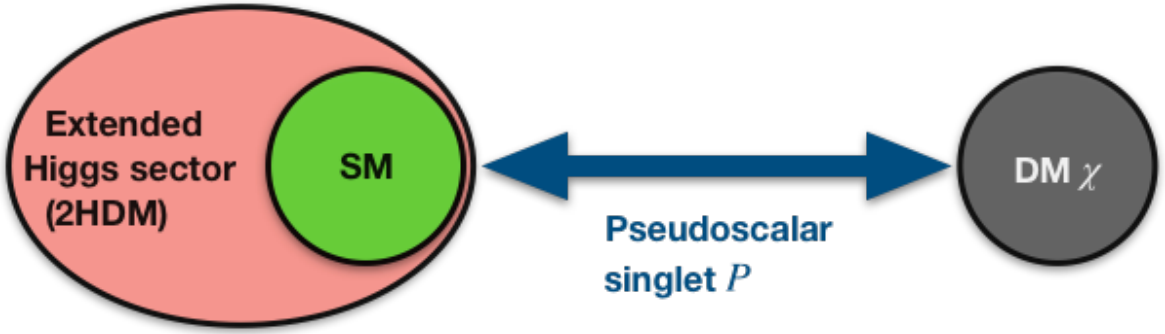




2HDM+a context

arXiv:2306.00641
(Science Bulletin Accepted)

- One of the popular ATLAS DM benchmark context
  - Searches interpreted in Two-Higgs-Doublet Model plus a pseudo-scalar mediator (2HDM+a):
  - Minimal, UV-complete extension.
  - EWK Symmetry Breaking:
    - 5 Higgs: h, H, $H^{\pm}$, A
    - 1 light pseudo-scalar: a



2HDM+a fully defined by 14 parameters

$$v,\ M_h,\ M_A,\ M_H,\ M_{H^\pm},\ M_a,\ m_\chi$$
$$\cos(\beta-\alpha),\ \tan\beta,\ \sin\theta,$$
$$y_\chi,\ \lambda_3,\ \lambda_{P1},\ \lambda_{P_2}$$

EWK, flavour constraints and to simplify parameter space

5 unconstrained parameters

$m_A = m_H = m_{H^\pm}$	masses of heavy Higgs
m_a	mass of pseudo-scalar mediator
m_χ	DM mass
$\sin\theta$	mixing angle between CP-odd states a and A
$\tan\beta$	ratio of 2 Higgs doublet VEVs

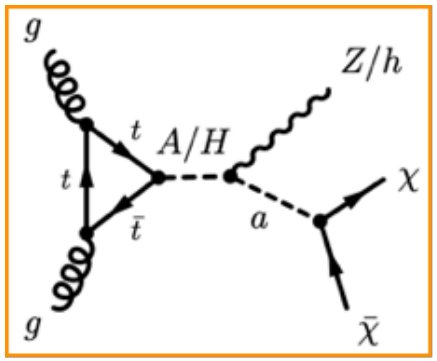
LHC Dark Matter Working Group
Phys. Dark Univ. 27 (2020) 100351
Bauer, Haisch, Kahlhoefer
JHEP05(2017) 138

*h: SM-like CP-even Higgs with mass of 125 GeV

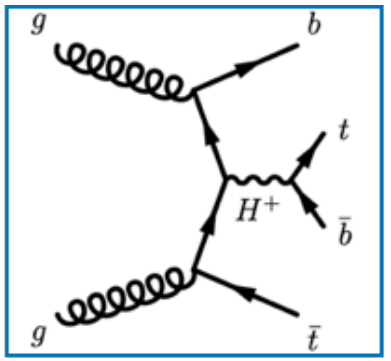
2HDM+a Experimental Signatures at ATLAS

arXiv:2306.00641
(Science Bulletin Accepted)

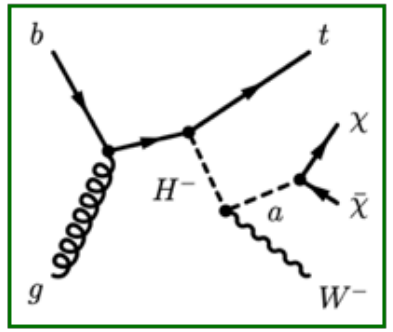
- 2HDM+a has rich phenomenology predicting wide range of signatures with both visible and invisible decays
  - resonantly production of E_T^{miss} +Z/h
  - additional (pseudo-)scalar bosons, e.g. tbH$^{\pm}$(tb)
  - new signatures, e.g. E_T^{miss} +tW



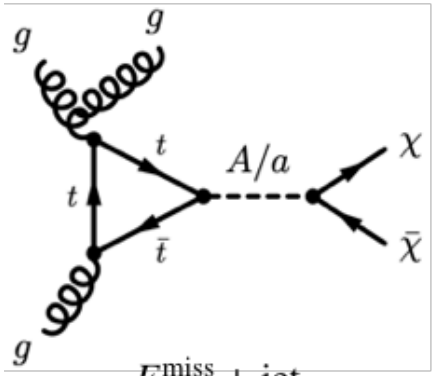
$E_T^{miss} + Z/h$



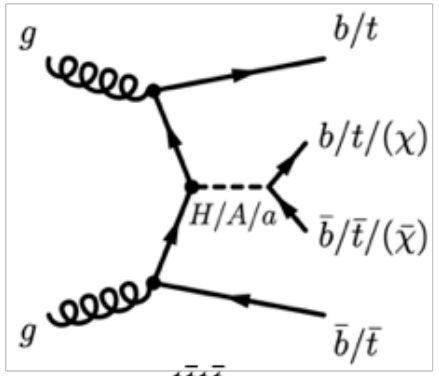
$tbH^{\pm}(tb)$



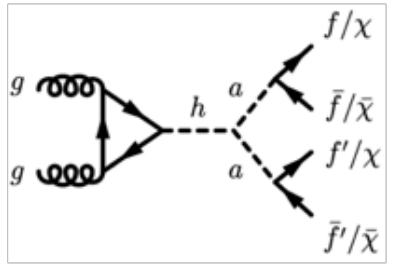
$E_T^{miss} + tW$



E_T^{miss} + jet



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

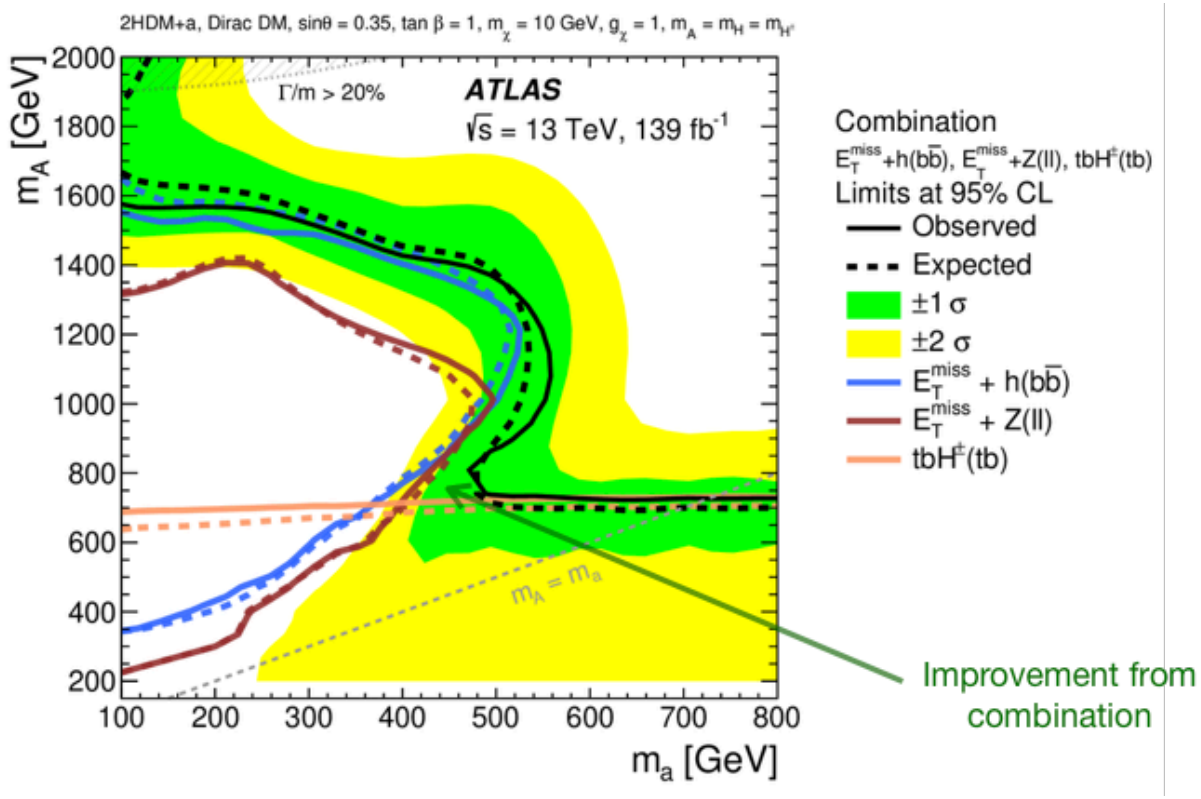


$h \to aa \to 4f\,/\,h \to$ invisible

Statistical Combination

arXiv:2306.00641
(Science Bulletin Accepted)

- $E_{\mathrm{T}}^{\mathrm{miss}} + h(bb)$, $E_{\mathrm{T}}^{\mathrm{miss}} + Z(ll)$ and $tbH^{\pm}(tb)$: Most constraining signatures of 2HDM+a.
  - $tbH^{\pm}(tb)$ gives significant complementarity to sensitivities of $E_{\mathrm{T}}^{\mathrm{miss}} + X$
  - stat. combination of 3 channels to maximize 2HDM+a constraints in parameter space.
- Combined exclusion limits obtained from **profile likelihood ratio** corresponding to **3-channel-combined likelihood**.
- Decorrelate over-constrained/pulled uncertainties to avoid any phase-space-specific biases across channels.



Summary of constraints on 2HDM+a

- constraints on 2HDM+a interpreted in 6 benchmark scenarios.
  - highlight diverse phenomenology of 2HDM+a.
  - study the interplay and complementarities between different signatures.

Scenario		Fixed parameter values				Varied parameters
		$\sin\theta$	m_A [GeV]	m_a [GeV]	$\tan\beta$	
1	a	0.35	–	–	1.0	(m_a, m_A)
	b	0.70	–	–	1.0	
2	a	0.35	–	250	–	$(m_A, \tan\beta)$
	b	0.70	–	250	–	
3	a	0.35	600	–	–	$(m_a, \tan\beta)$
	b	0.70	600	–	–	
4	a	–	600	200	1.0	$\sin\theta$
	b	–	1000	350	1.0	
5		0.35	1000	400	1.0	m_χ
6		0.35	1200	–	1.0	(m_a, m_χ)

shows interplay due to mass hierarchies

motivated by similar scans done for general 2HDMs

illustration a-A mixing parameter effect

connection with cosmological constraints and direct/indirect searches

showed for the 1st time

m_χ set to 10 GeV in all scenarios, except 5 and 6

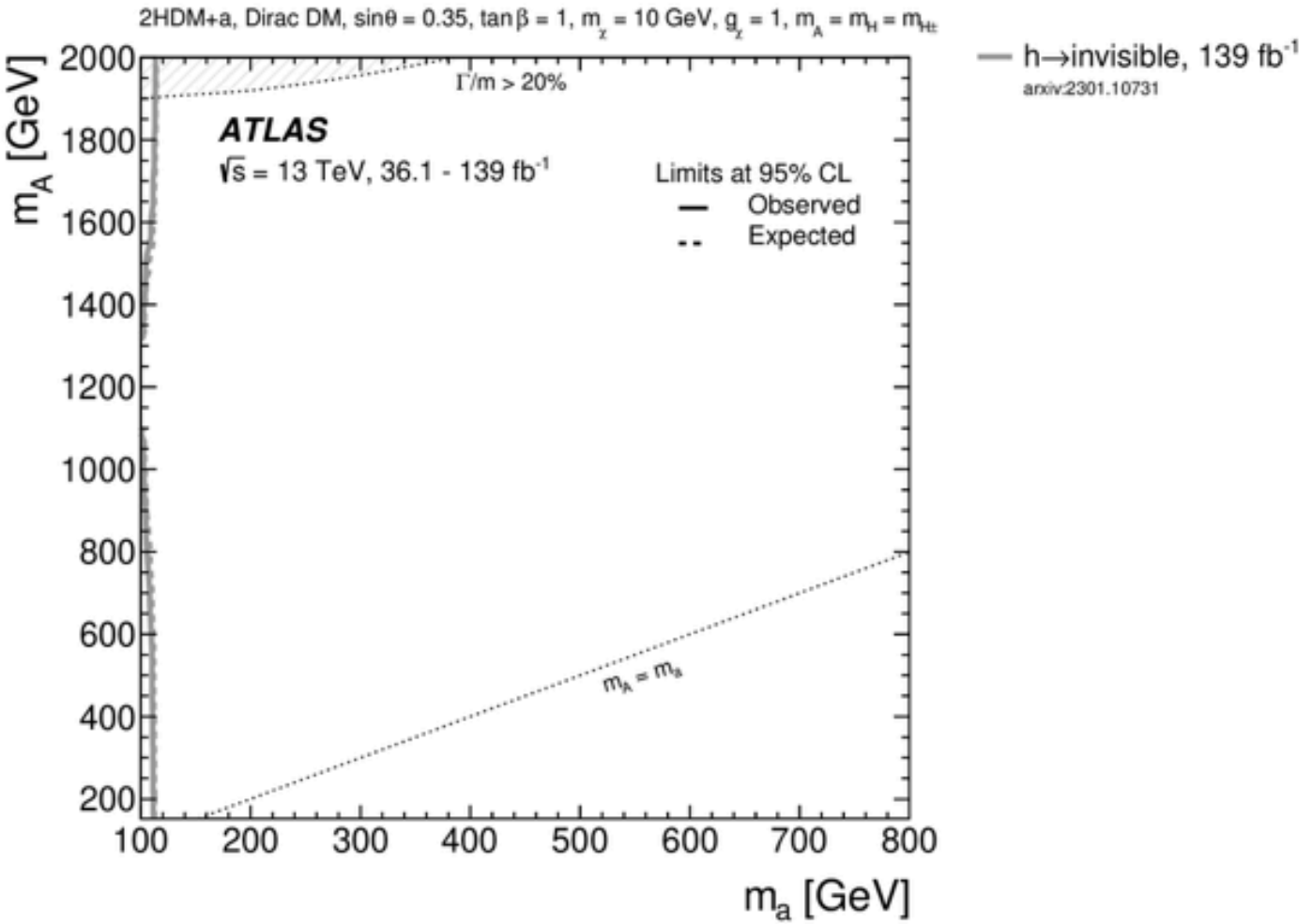
Summary of constraints on 2HDM+a

Variety of searches interpreted in the context of different 2HDM+a benchmark scenarios

Analysis/Scenario	1a	1b	2a	2b	3a	3b	4a	4b	5	6
$E_{\mathrm{T}}^{\mathrm{miss}} + Z(\ell\ell)$ [74]	x	x	x	x	x	x	x	x	x	
$E_{\mathrm{T}}^{\mathrm{miss}} + h(b\bar{b})$ [75]	x	x	x	x	x	x	x	x	x	x
$E_{\mathrm{T}}^{\mathrm{miss}} + h(\gamma\gamma)$ [84]	x	x			x	x	x	x		
$E_{\mathrm{T}}^{\mathrm{miss}} + h(\tau\tau)$ [78]	x			x						
$E_{\mathrm{T}}^{\mathrm{miss}} + tW$ [77]	x	x	x	x	x	x	x	x		
$E_{\mathrm{T}}^{\mathrm{miss}} + j$ [45]	x	x			x	x	x	x		
$h \to$ invisible [86]	x	x			x					x
$E_{\mathrm{T}}^{\mathrm{miss}} + Z(q\bar{q})$ [127]	x						x	x		
$E_{\mathrm{T}}^{\mathrm{miss}} + b\bar{b}$ [128]							x	x		
$E_{\mathrm{T}}^{\mathrm{miss}} + t\bar{t}$ [128,129]							x	x		
$t\bar{t}t\bar{t}$ [85]	x	x	x	x	x	x	x	x	x	
$tbH^{\pm}(tb)$ [76]	x	x	x	x	x	x	x	x	x	
$h \to aa \to f\bar{f}f'\bar{f}'$ [79,80,81,82,83]										x

Scenario 1a: sinθ=0.35, m_A - m_a plane

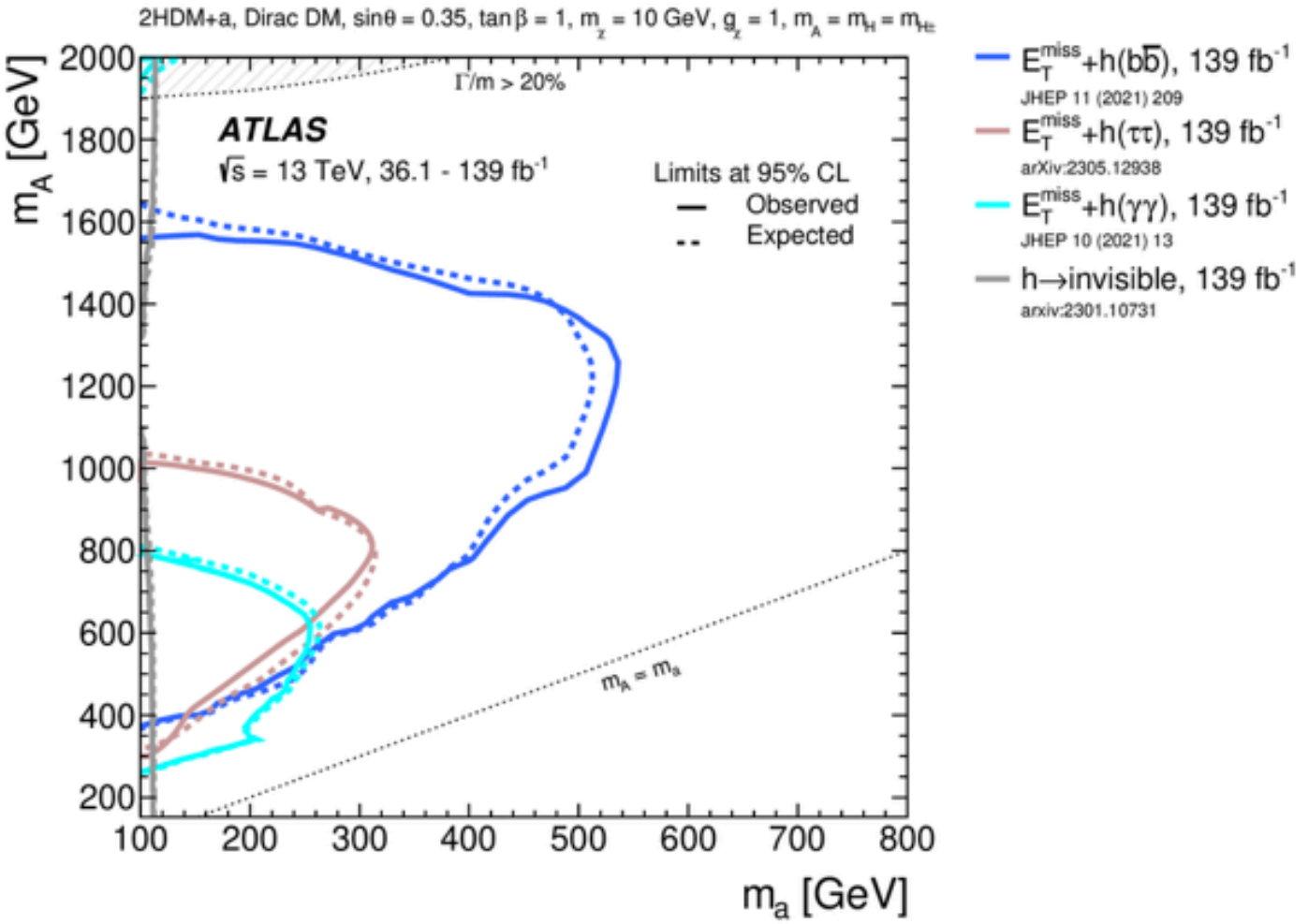
- $h \rightarrow$ invisible constrains very low m_a.



Scenario 1a: sinθ=0.35, m_A - m_a plane

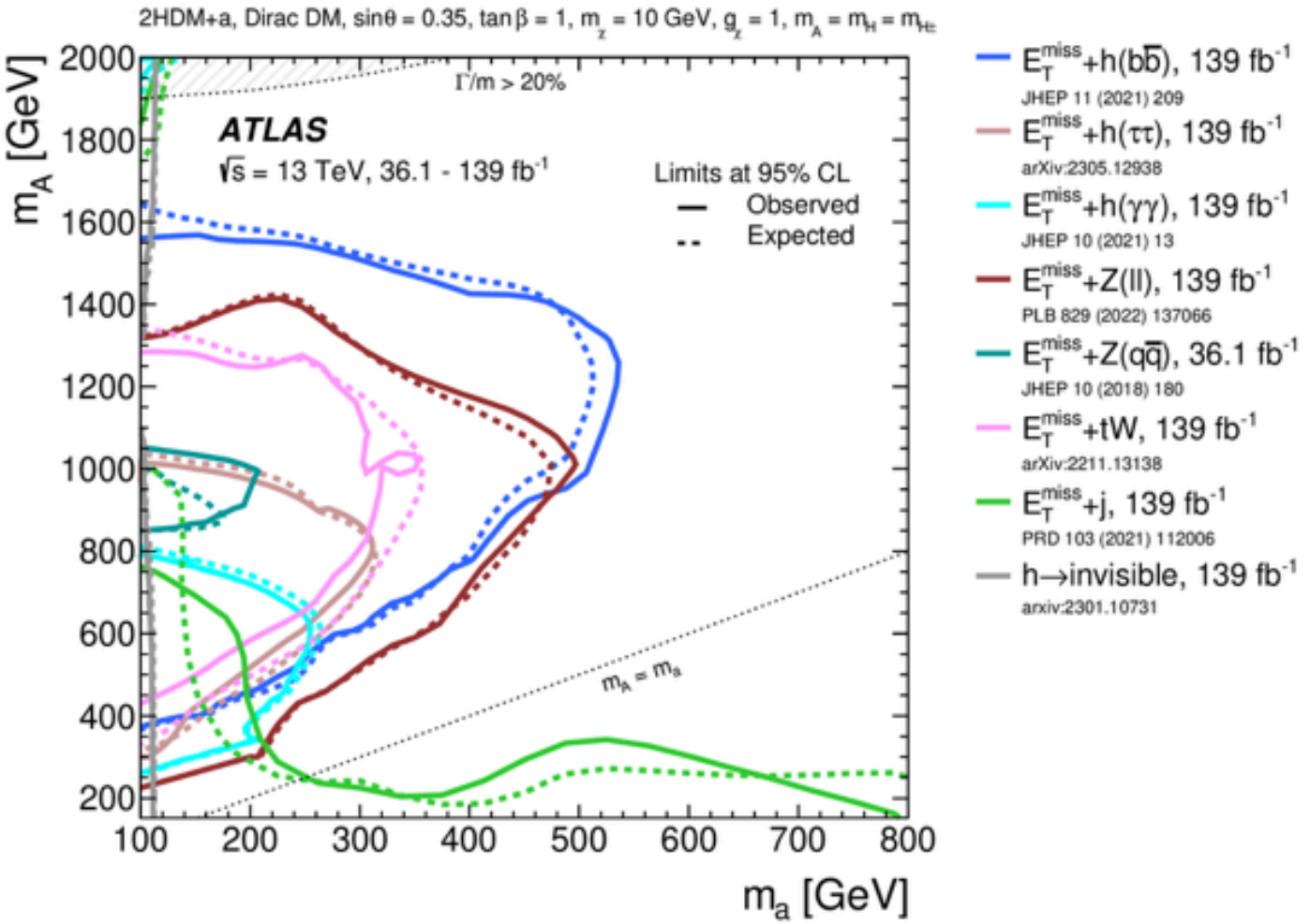
- $h \rightarrow$ invisible constrains very low m_a.

- constraints from $E_{\mathrm{T}}^{\mathrm{miss}} + h$ signatures: similar m_A-m_a dependence, with $h \rightarrow bb$ most sensitive.



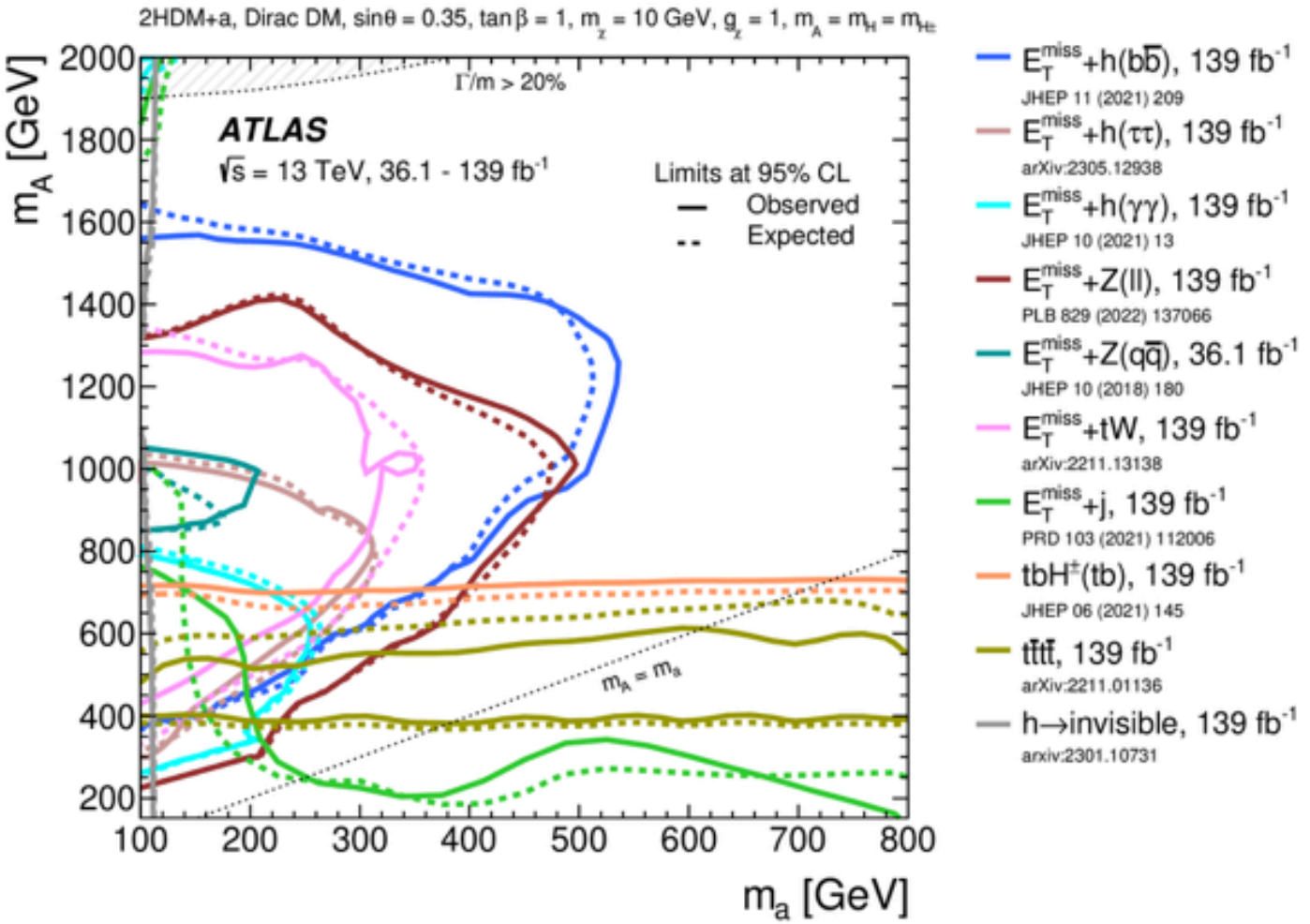
Scenario 1a: sinθ=0.35, m_A - m_a plane

- $h \rightarrow$ invisible constrains very low m_a.
- constraints from $E_{\mathrm{T}}^{\mathrm{miss}} + h$ signatures: similar m_A-m_a dependence, with $h \rightarrow bb$ most sensitive.
- $E_{\mathrm{T}}^{\mathrm{miss}} + tW$ similar to $E_{\mathrm{T}}^{\mathrm{miss}} + Z(ll)$ but with smaller excl. region.
- $E_{\mathrm{T}}^{\mathrm{miss}} +$ jet sensitivity notably different from those of $E_{\mathrm{T}}^{\mathrm{miss}} + Z$ and $E_{\mathrm{T}}^{\mathrm{miss}} + h$.



Scenario 1a: sinθ=0.35, m_A - m_a plane

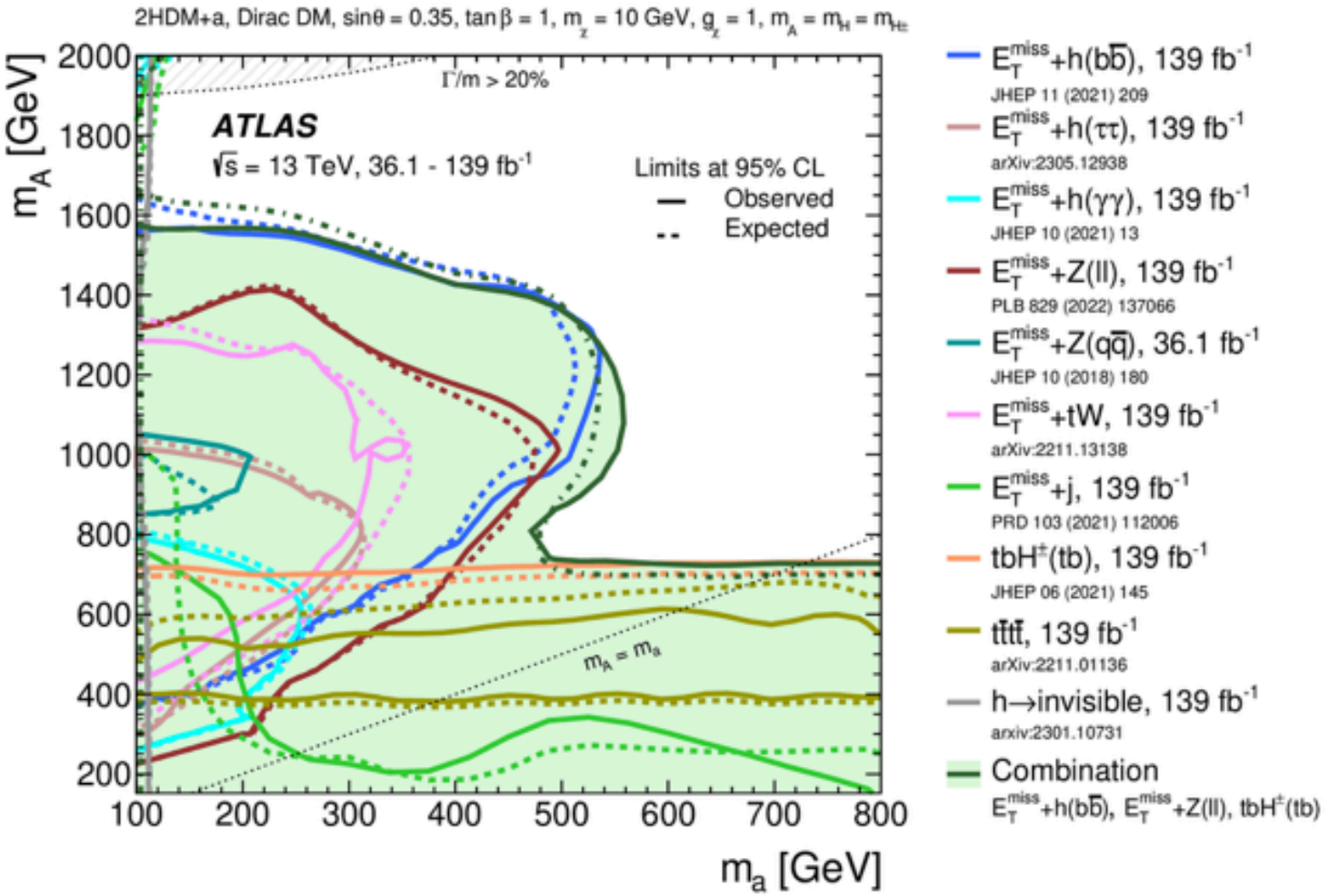
- $h \rightarrow$ invisible constrains very low m_a.
- constraints from $E_{\mathrm{T}}^{\mathrm{miss}} + h$ signatures: similar m_A-m_a dependence, with $h \rightarrow bb$ most sensitive.
- $E_{\mathrm{T}}^{\mathrm{miss}} + tW$ similar to $E_{\mathrm{T}}^{\mathrm{miss}} + Z(ll)$ but with smaller excl. region.
- $E_{\mathrm{T}}^{\mathrm{miss}} +$ jet sensitivity notably different from those of $E_{\mathrm{T}}^{\mathrm{miss}} + Z$ and $E_{\mathrm{T}}^{\mathrm{miss}} + h$.
- Complementary constraints from searches not targeting DM.



Scenario 1a: sinθ=0.35, m_A - m_a plane

arXiv:2306.00641
(Science Bulletin Accepted)

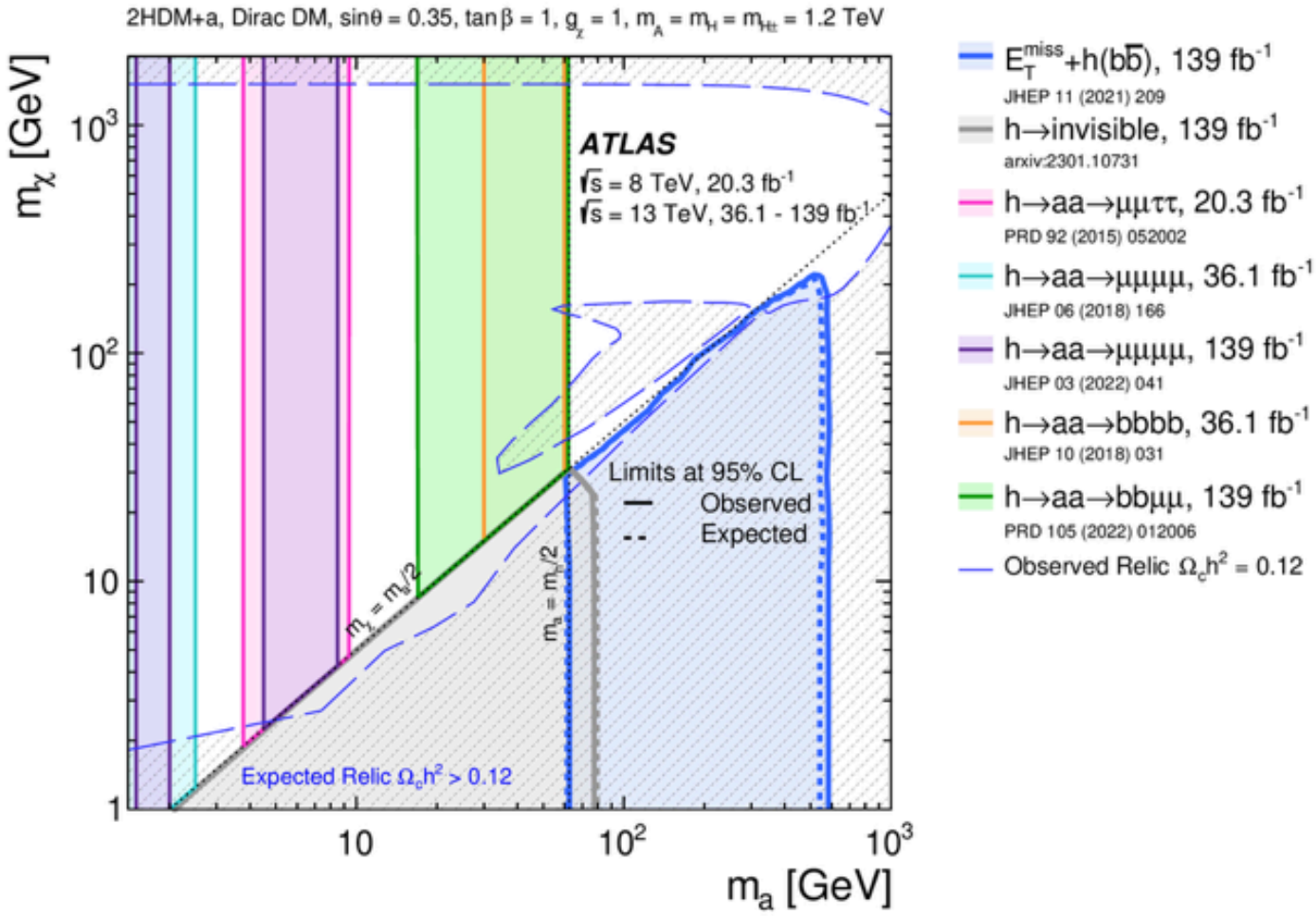
- $h \rightarrow$ invisible constrains very low m_a.
- constraints from $E_{\mathrm{T}}^{\mathrm{miss}} + h$ signatures: similar m_A-m_a dependence, with $h \rightarrow bb$ most sensitive.
- $E_{\mathrm{T}}^{\mathrm{miss}} + tW$ similar to $E_{\mathrm{T}}^{\mathrm{miss}} + Z(ll)$ but with smaller excl. region.
- $E_{\mathrm{T}}^{\mathrm{miss}} +$ jet sensitivity notably different from those of $E_{\mathrm{T}}^{\mathrm{miss}} + Z$ and $E_{\mathrm{T}}^{\mathrm{miss}} + h$.
- Complementary constraints from searches not targeting DM.
- Sensitivity of 2HDM+a driven by the combination.



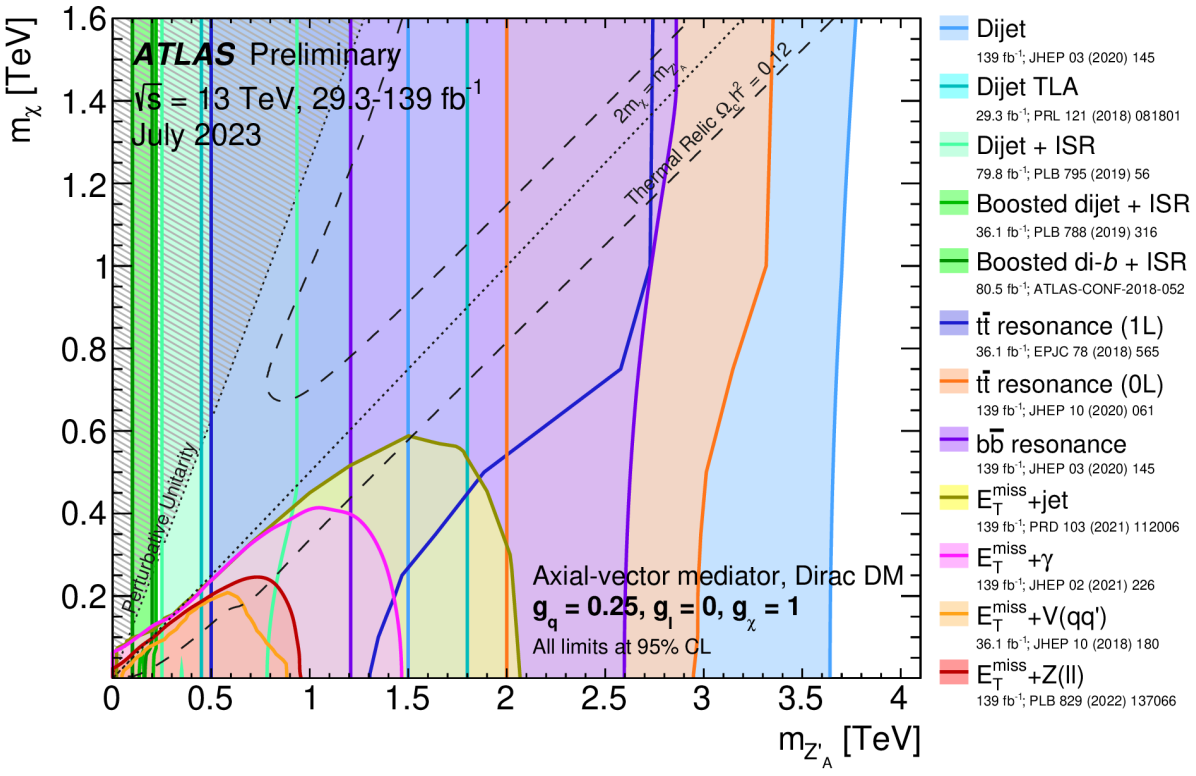
Scenario 6: m_a - m_χ plane

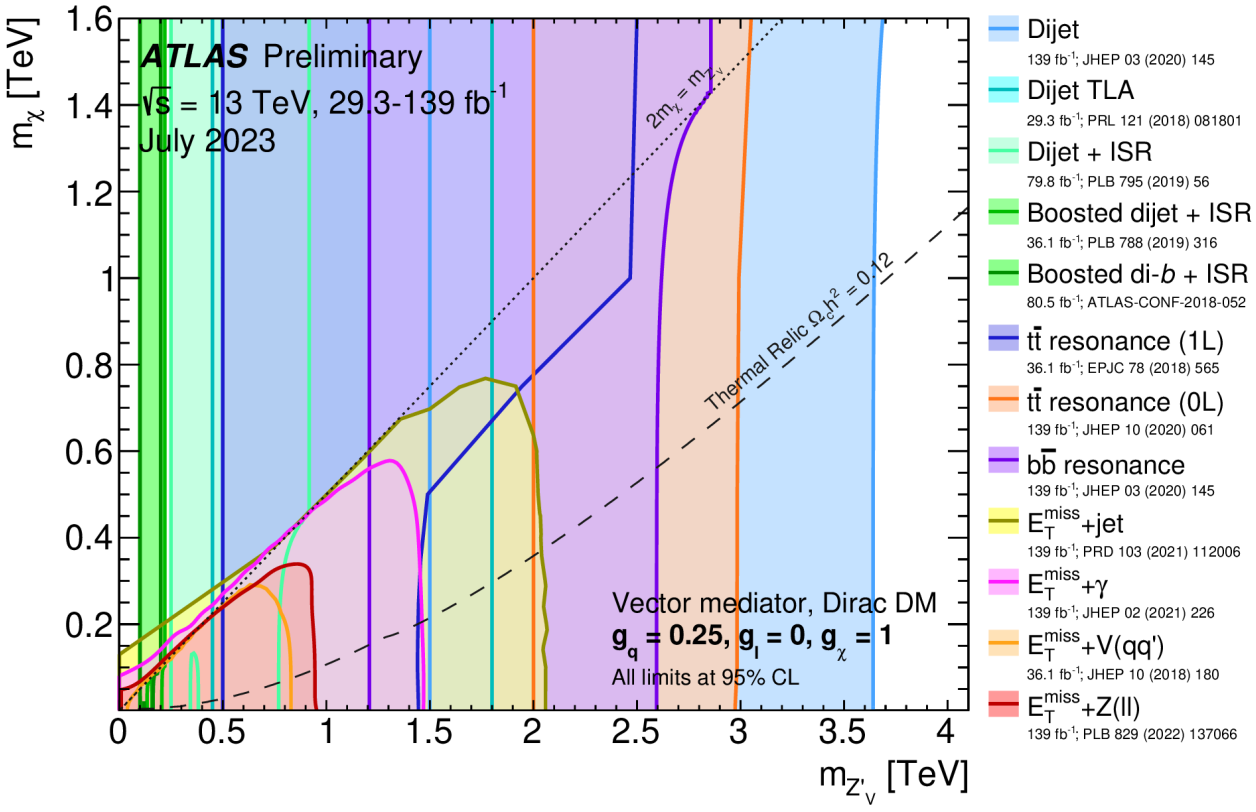
arXiv:2306.00641
(Science Bulletin Accepted)

- New interpretation in m_a - m_χ plane:
- Searches for SM Higgs decaying to 4 fermions via constrain previously unprobed region of 2HDM+a.
- Complementarity to h→inv. and E_T^{miss}+h(bb) searches.



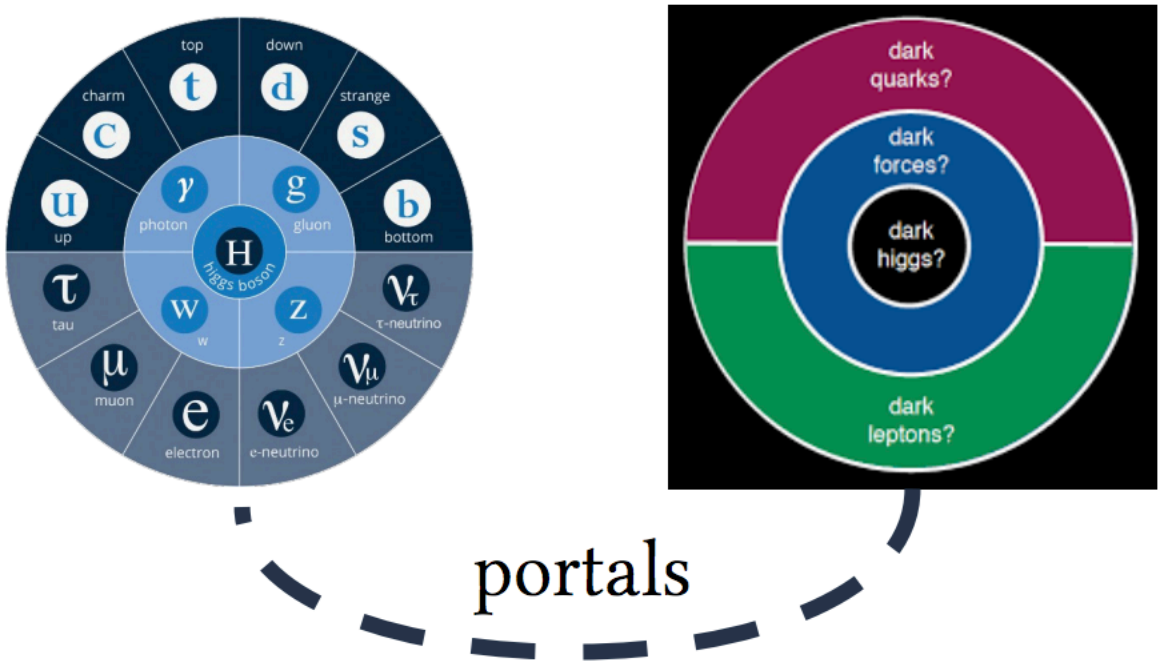
Auxiliary: (Axial-)Vector Mediator summary



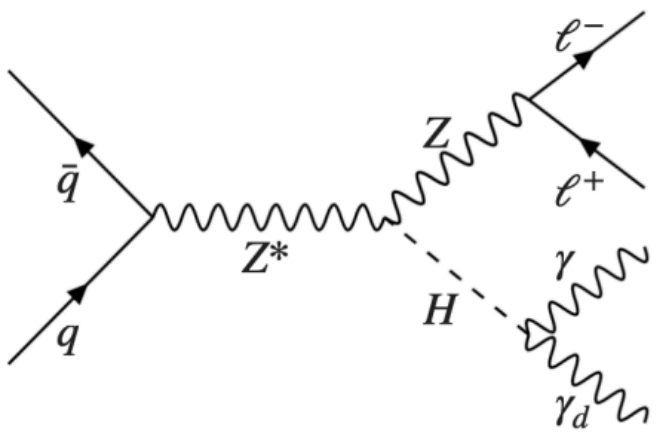


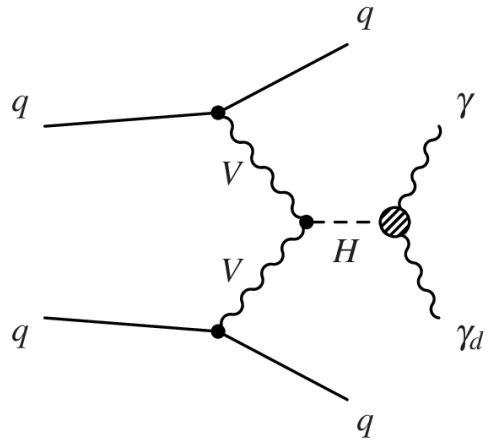
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2023-018/

Dark Higgs → more Dark Portals connecting hidden sectors



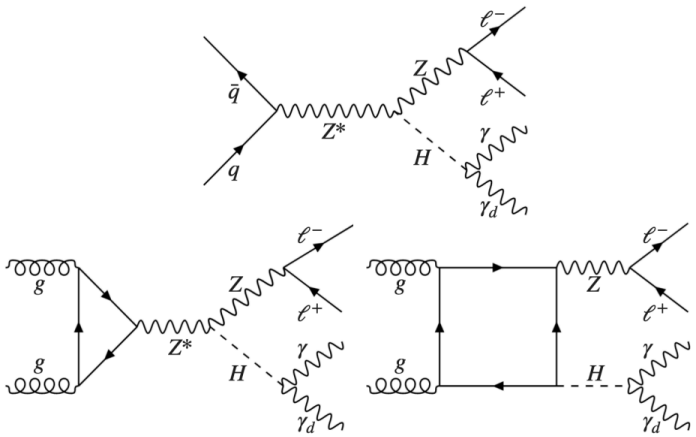
- Dark Photon BSM extensions:
  - U(1) extension of the SM
  - Hidden gauge boson A′ → kinetic mixing (ε) with the SM photon
  - the magnitude of ε affects production rate and lifetime





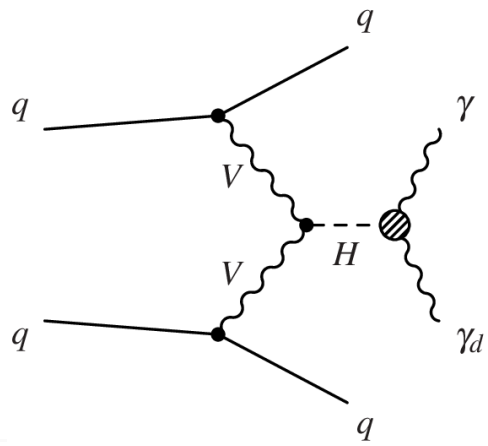
- Vector portal – dark photons
- Scalar portals - dark Higgs
- Neutrino portal
- Axion portal

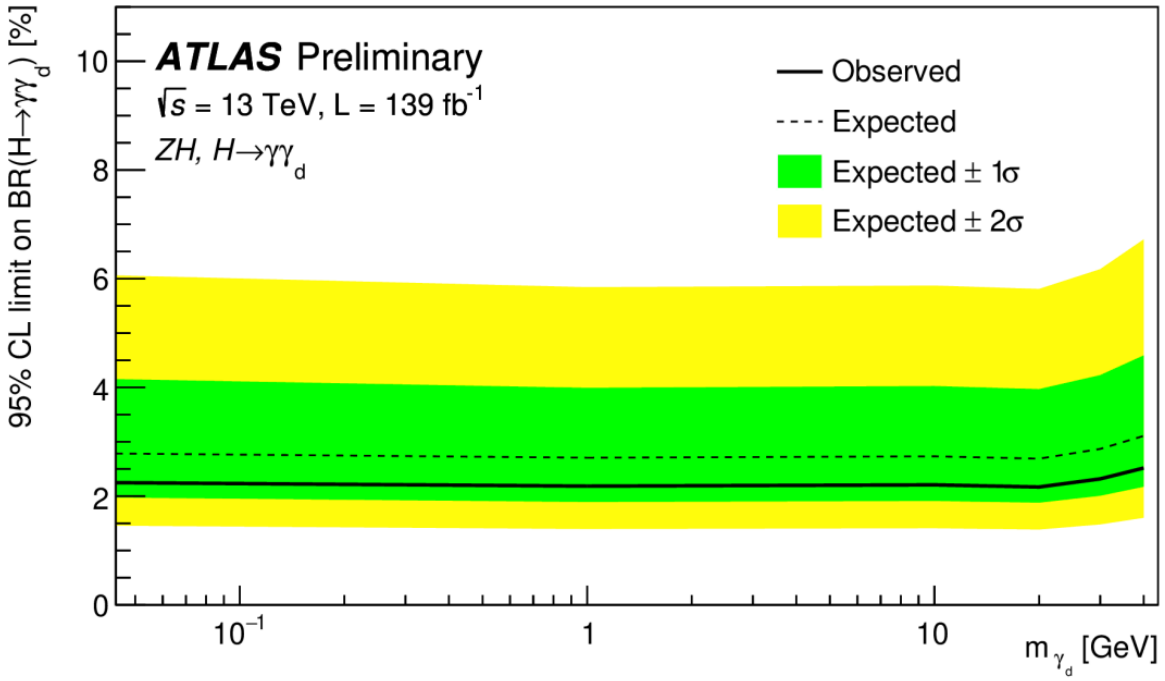
Dark Photon searches: ZH and VBF

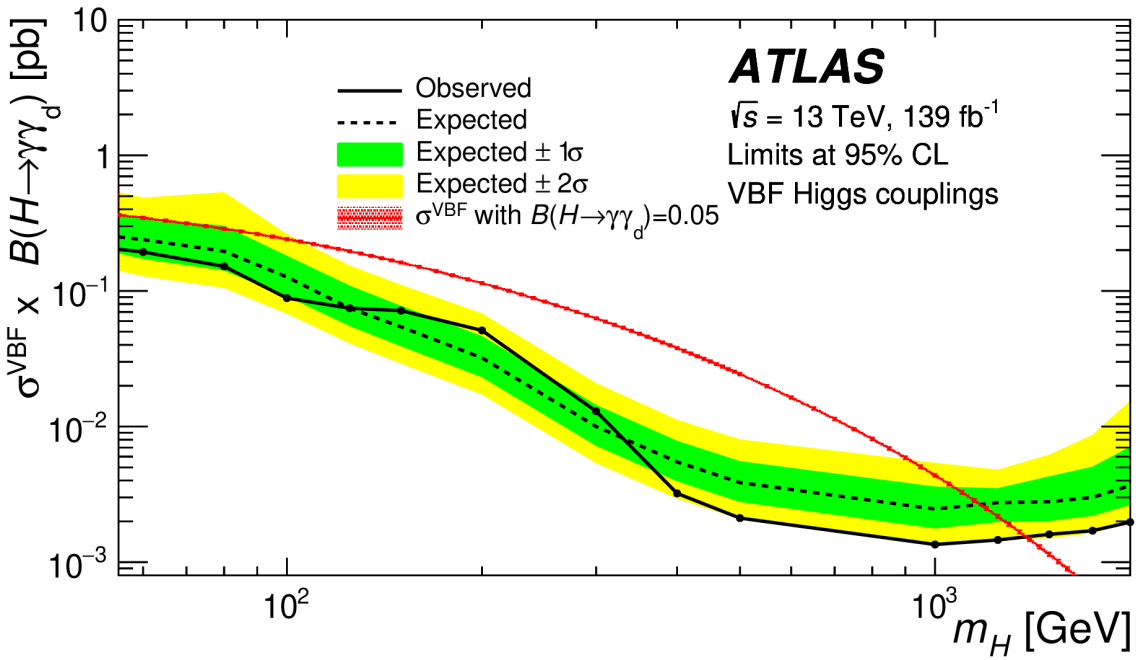


For massless γ_d

		Obs.	Exp.	
CMS	**VBF**	3.5%	2.8%	JHEP03(2021)011
CMS	**ZH**	4.6%	3.6%	JHEP10(2019)139
ATLAS	**VBF**	1.8%	1.7%	CERN-EP-2021-137
ATLAS	**ZH**	2.3%	2.8%	ATLAS-CONF-2022-064

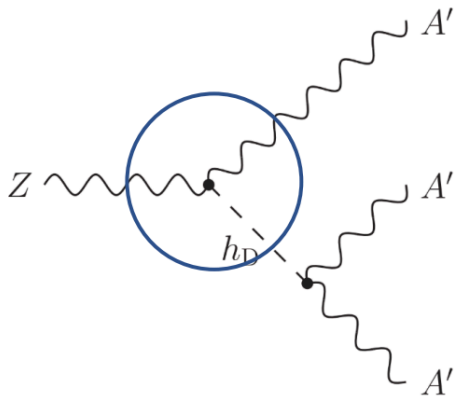






PRL 131 (2023) 251801

Dark Photon search with Z boson rare decay into Dark Higgs

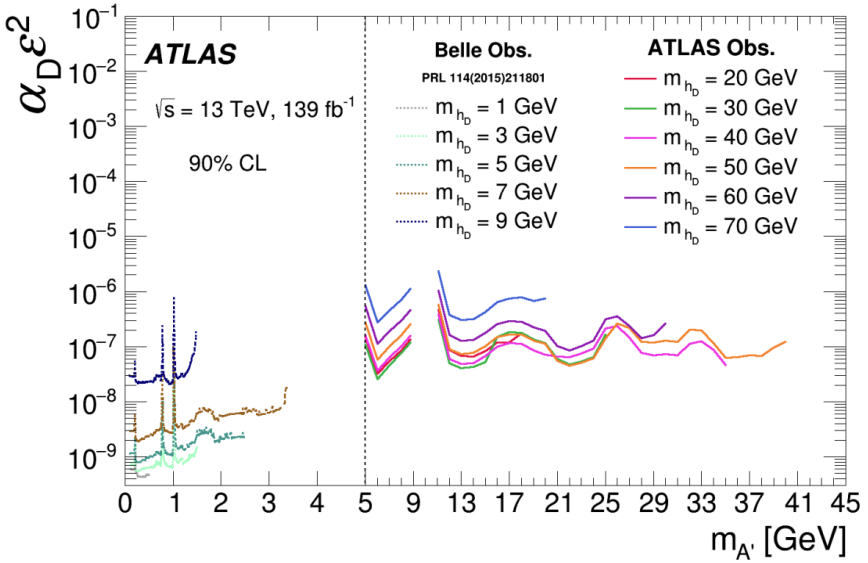


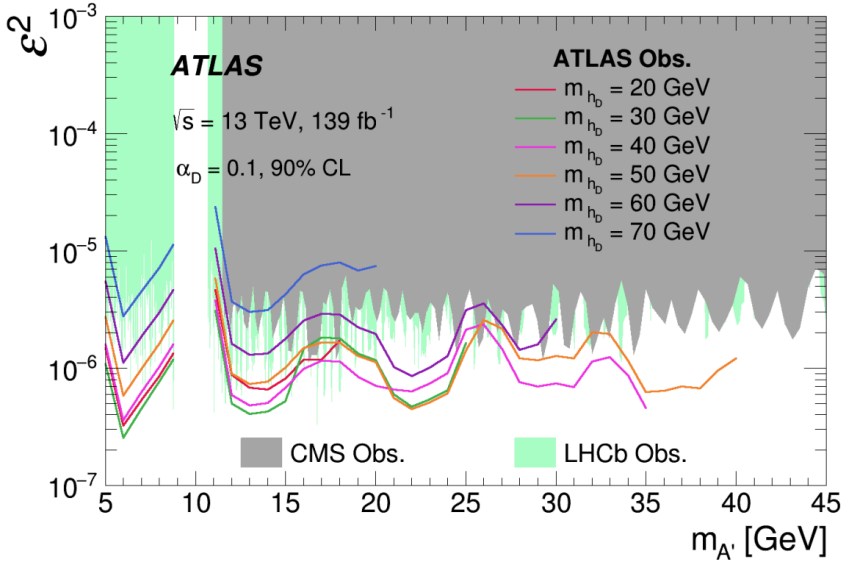
Decay rate ∝ $\alpha_D \varepsilon^2$

Assumptions:
(Minimal kinetically mixed)
- Br ($h_D \to A'\,A'$) = 100%
- A' is the lightest DS
- Br ($A' \to SM\ f\ \bar{f}$) = 100%

Benchmark parameter:
$\alpha_D = 0.1;\ \varepsilon = 10^{-3}$

- First search for the dark-Higgs-strahlung process at the LHC
  - Previous range (Belle): mA' < 5GeV
  - Extended significantly to 40 GeV
- Compare with CMS/LHCb (limits on ε^2):
  - Some assumptions on α_D (set it as 0.1)
  - Comparable (or even better)



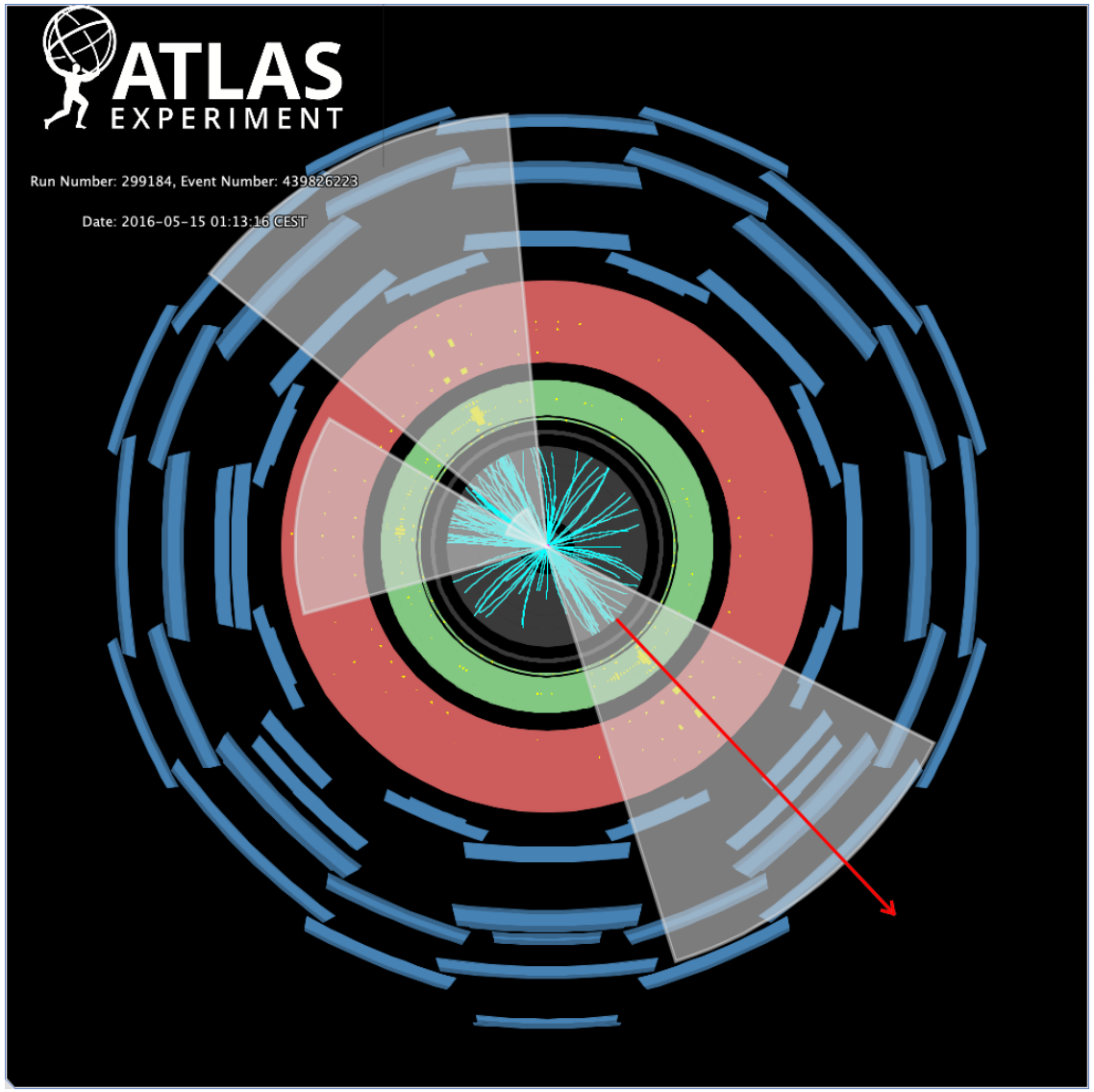


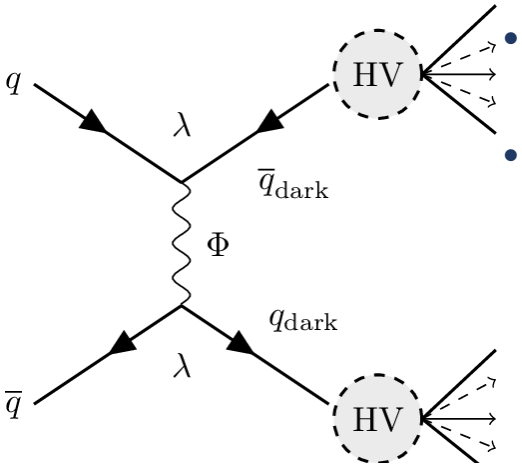
PART 03

Unconventional Searches (incomplete and selective)

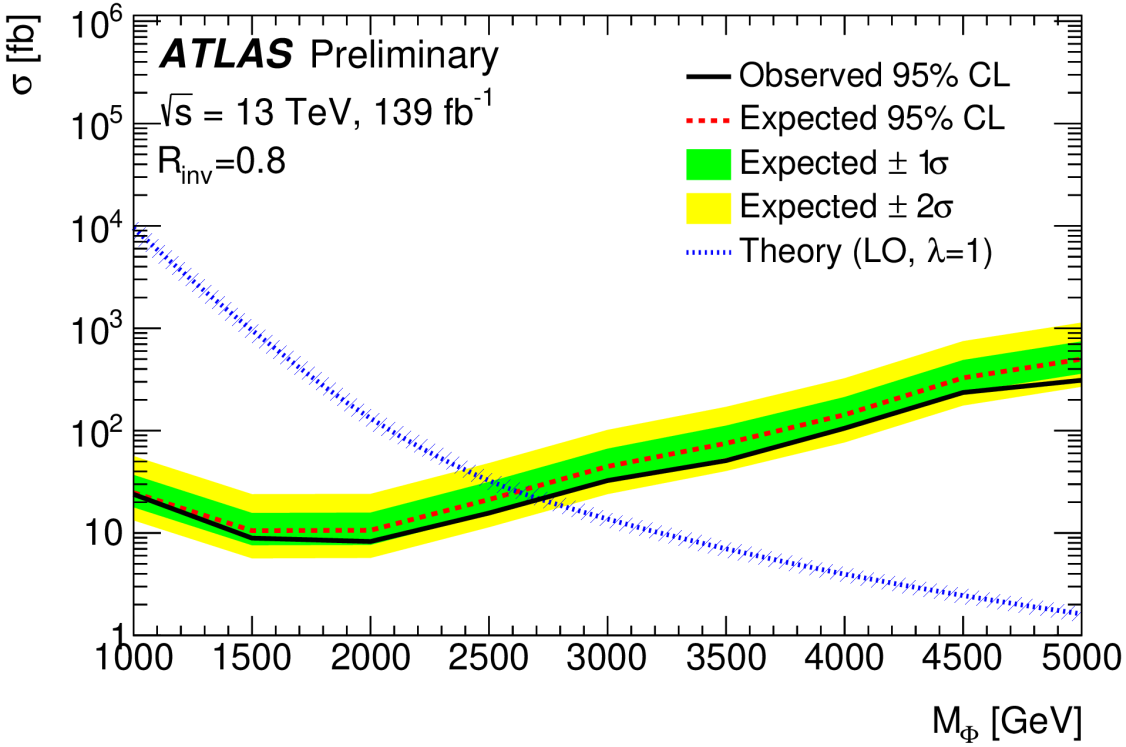
TSUNG-DAO LEE INSTITUTE

Unconventional searches with semi-visible jets





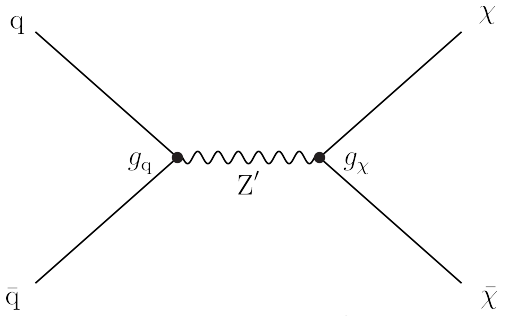
- Semi-visible jets arise in strongly-interacting dark sectors
- One of the jets is aligned with the missing transverse momentum direction: i.e. missing transverse momentum originates from the invisible components of the two semi-visible jets.

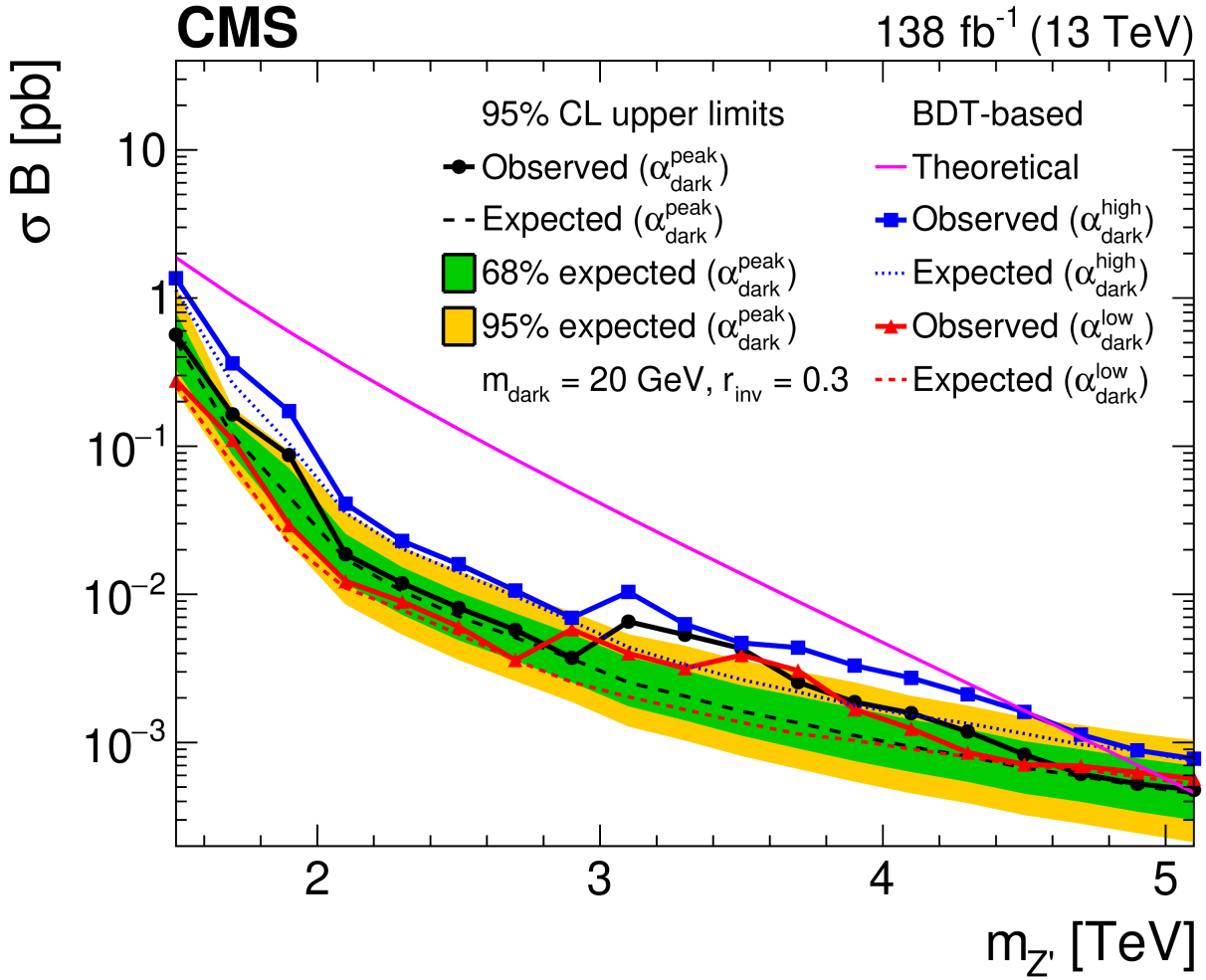


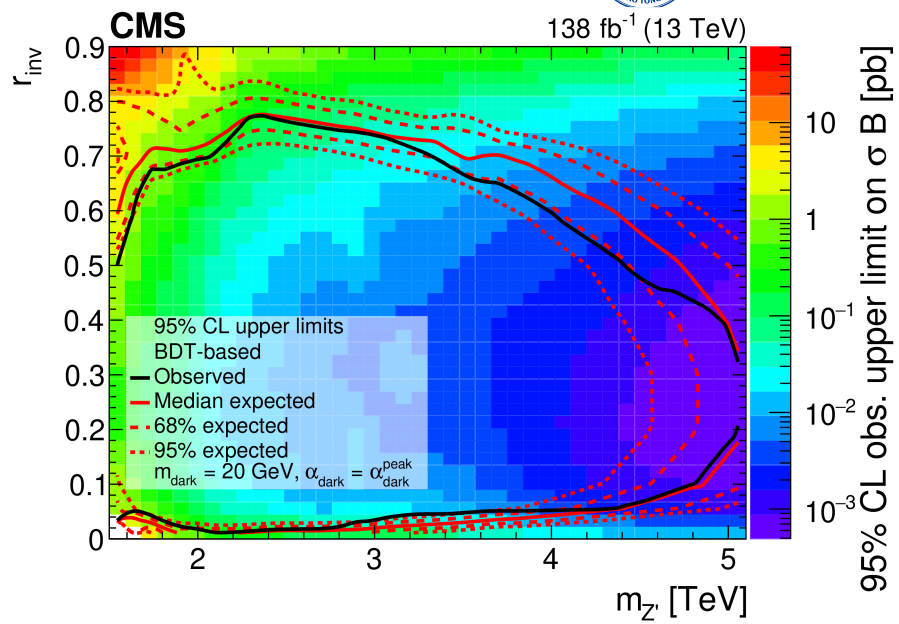
Unconventional searches with semi-visible jets

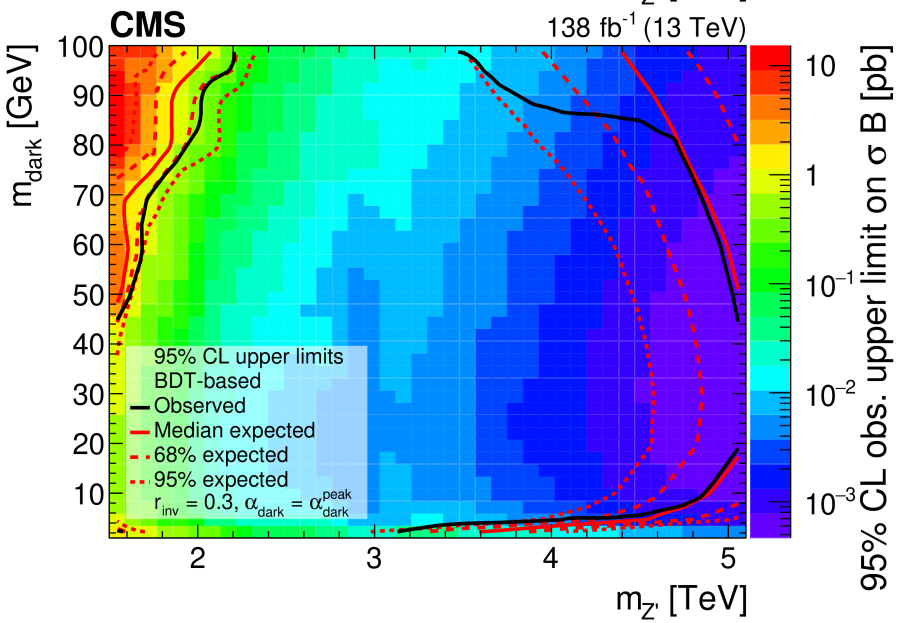
JHEP 06 (2022) 156

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

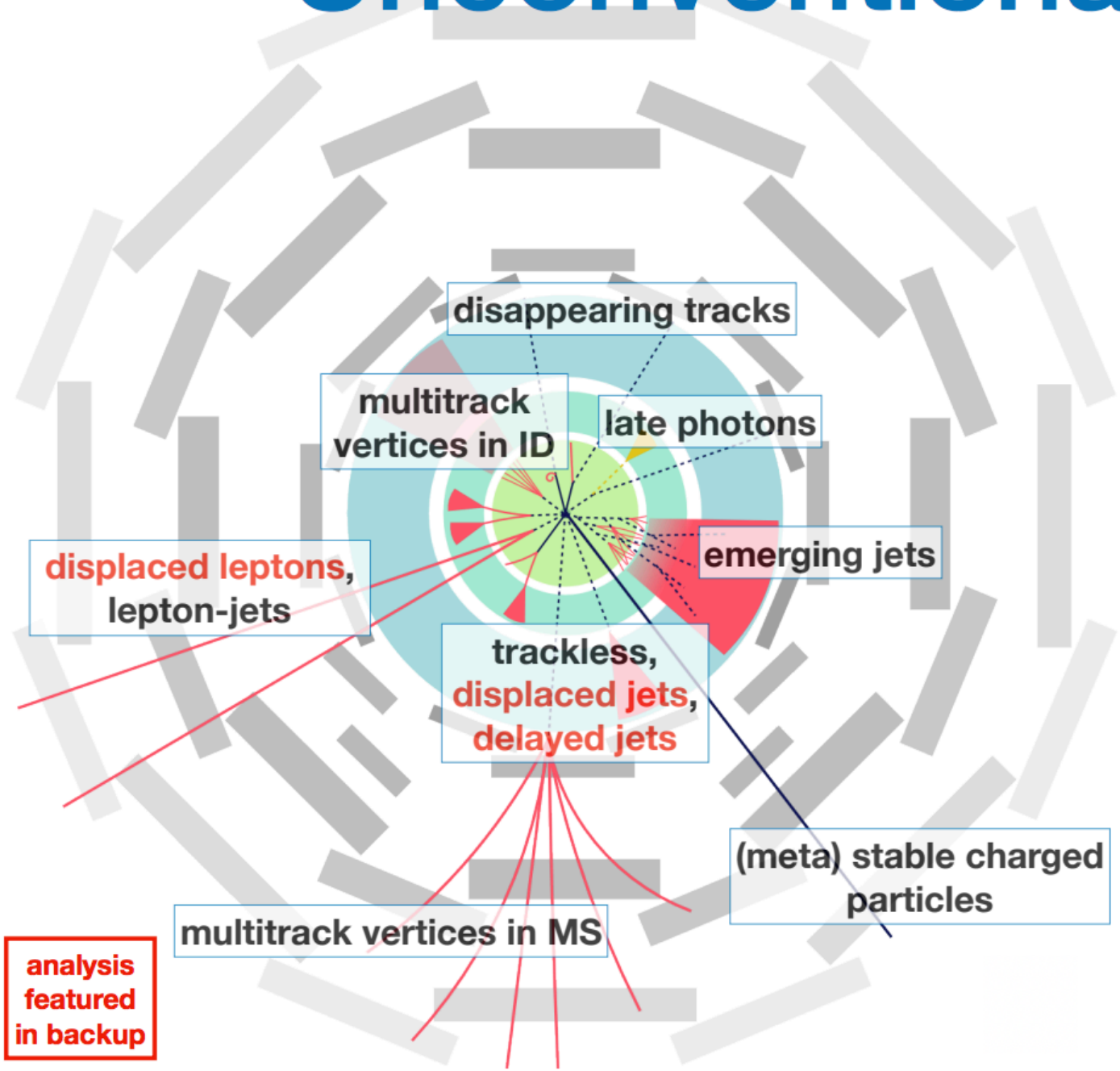






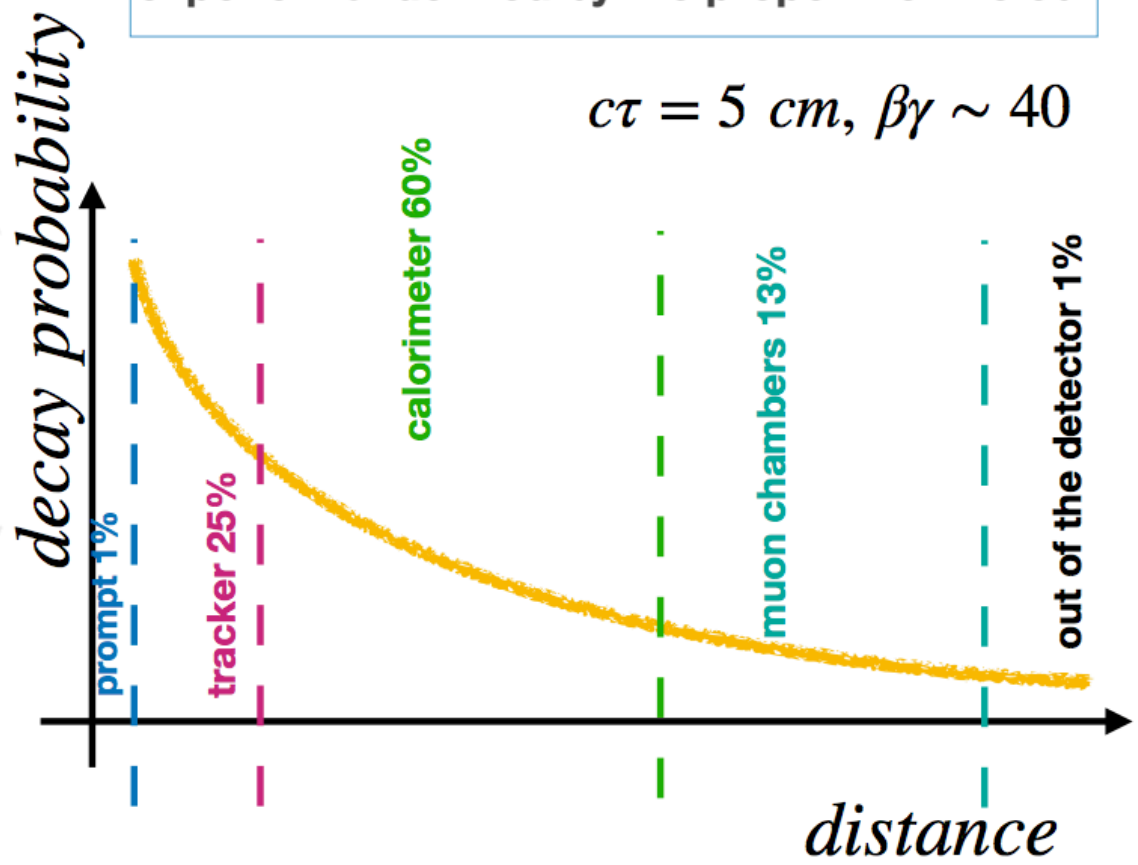


Unconventional signatures



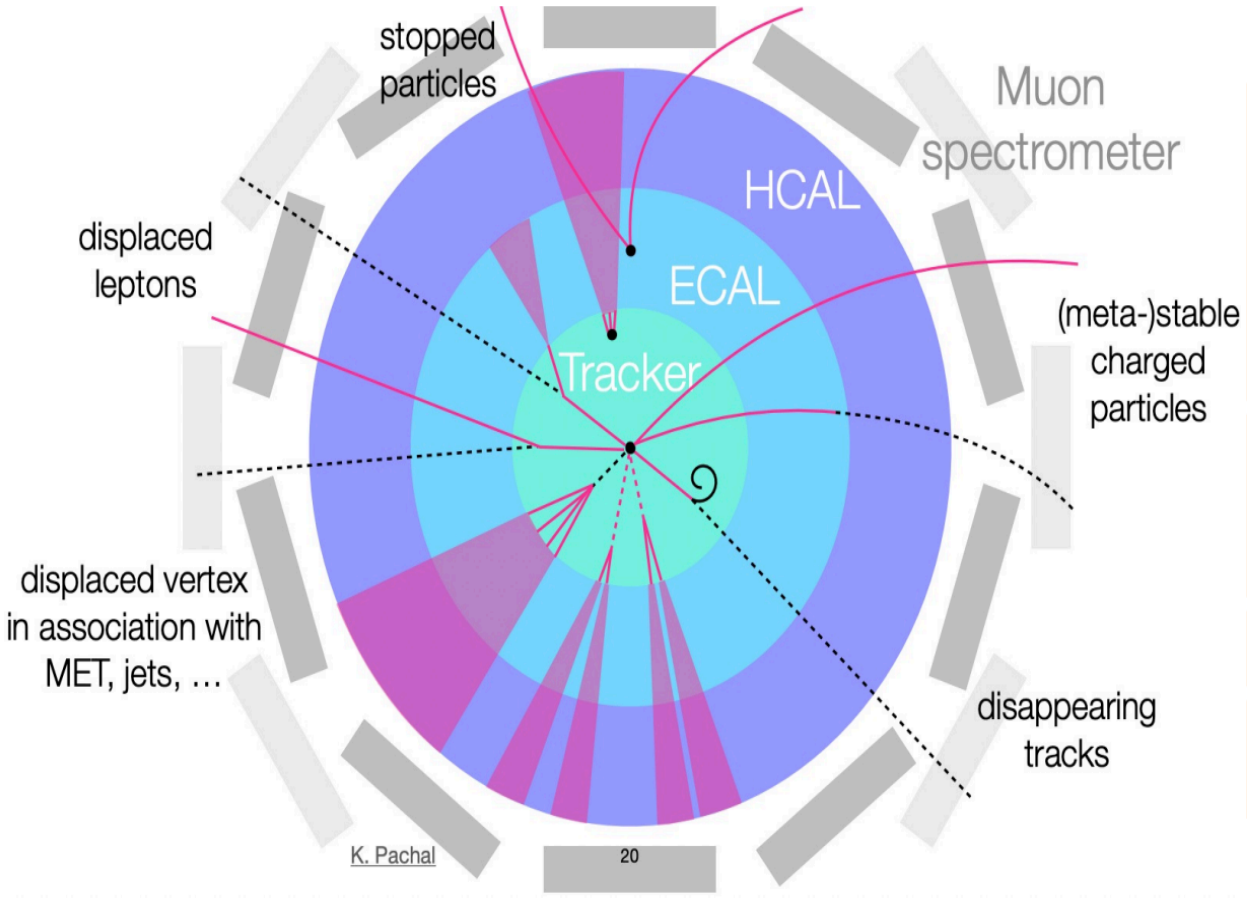
analysis featured in backup

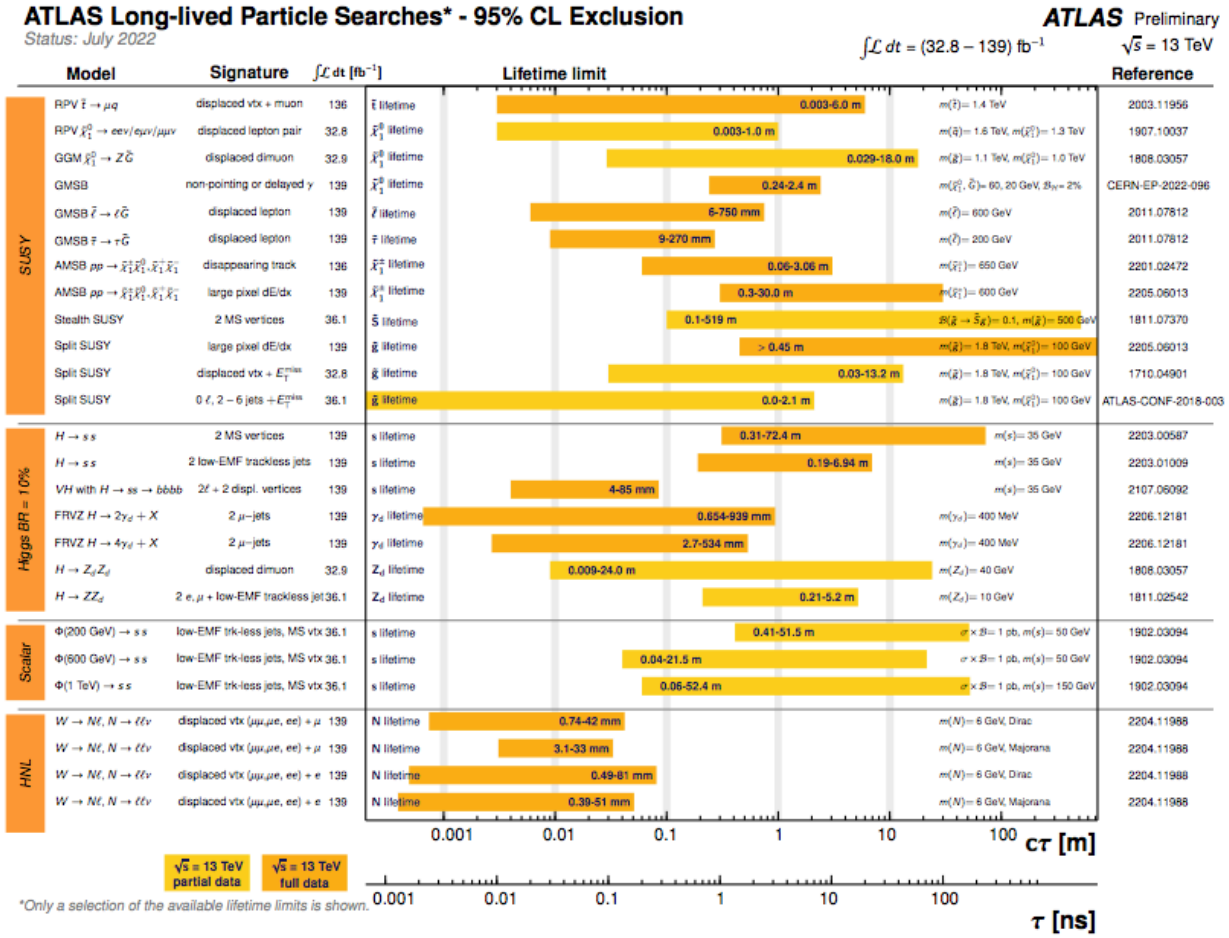
New particles can be long-lived: observed lifetime is governed by an exponential defined by the proper lifetime cτ



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 (ATLAS+CMS) continue to deliver highly valuable physical results while Run-3 is ongoing
- ATLAS reaches its 30-year birthday and Higgs has been discovered for 10-year
- We still don’ t know precisely where the BSM is hidden but we know more than ever the nature of SM and everything observed, despite:
  - Higgs is measured and combinedly measured with order of magnitudes improved precision after ten years
  - We know much better the Higgs cross sections, mass, width, CP, couplings to the other SM particles
  - Precision will progress further in HL-LHC
- Diversified BSM anomalies are being thoroughly hunted for with as less untounched stone as possible

谢 谢 ！