New low-mass scalars and Higgs decays to BSM particles at the LHC

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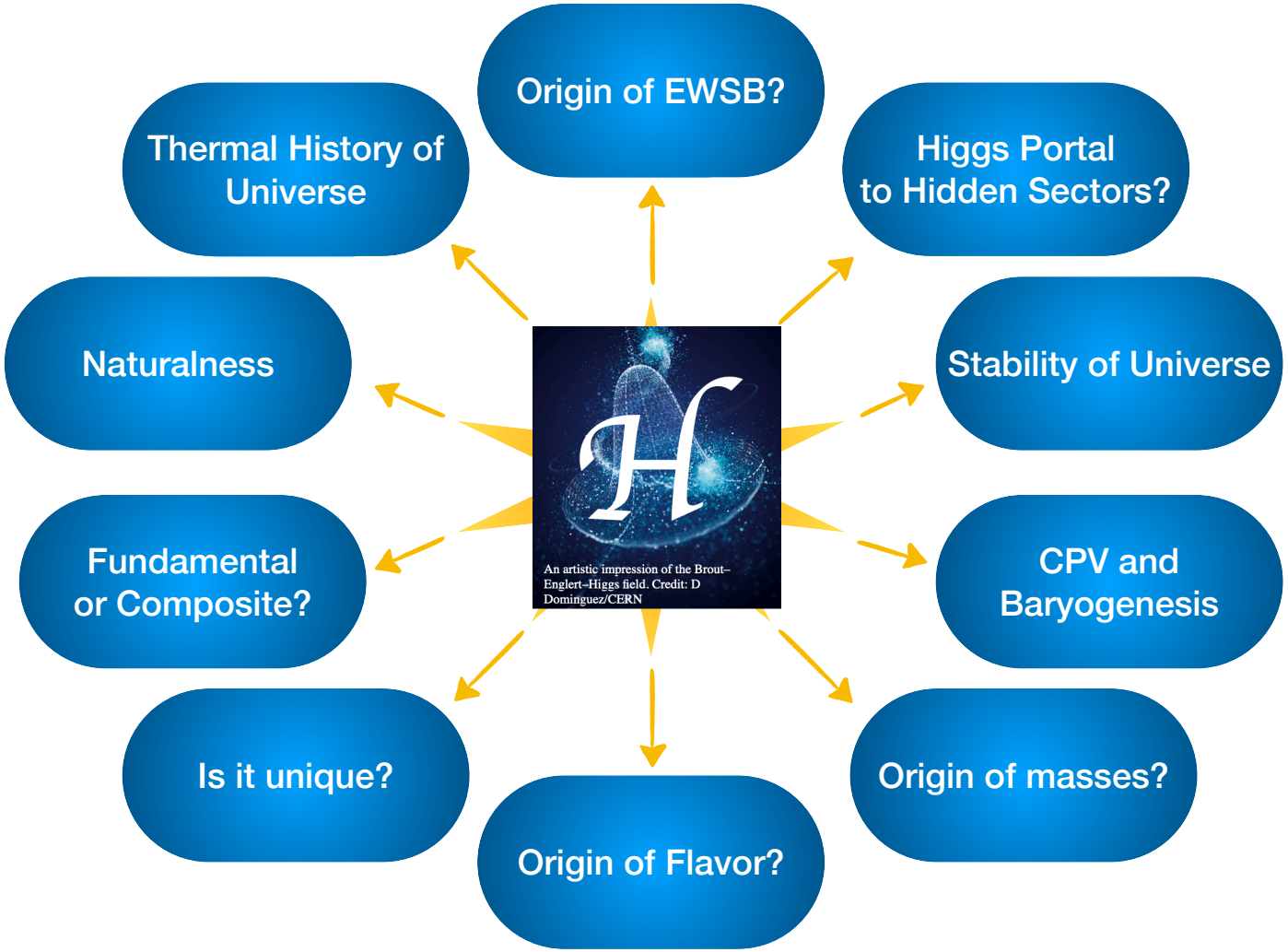
on behalf of ATLAS and CMS Collaborations

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

THE Higgs

The end of the puzzle or the start of the journey



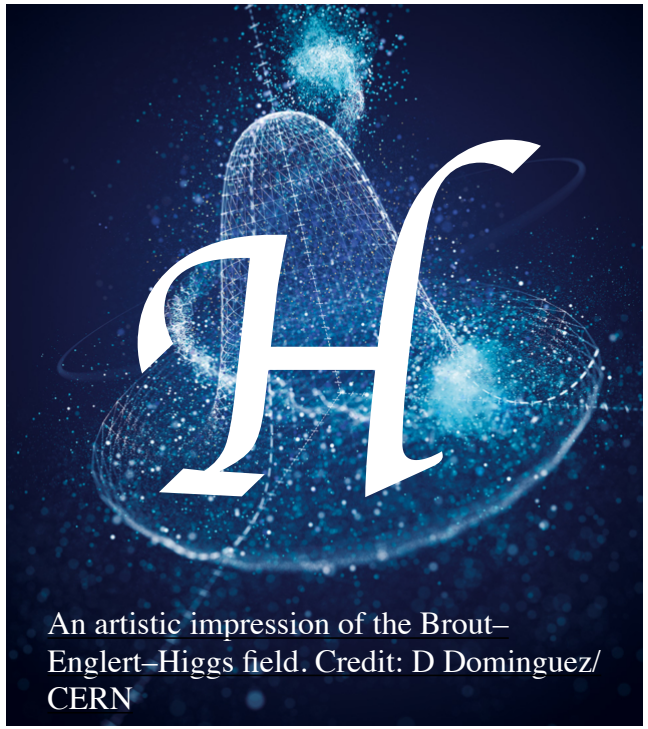
Precision measurements

Searches

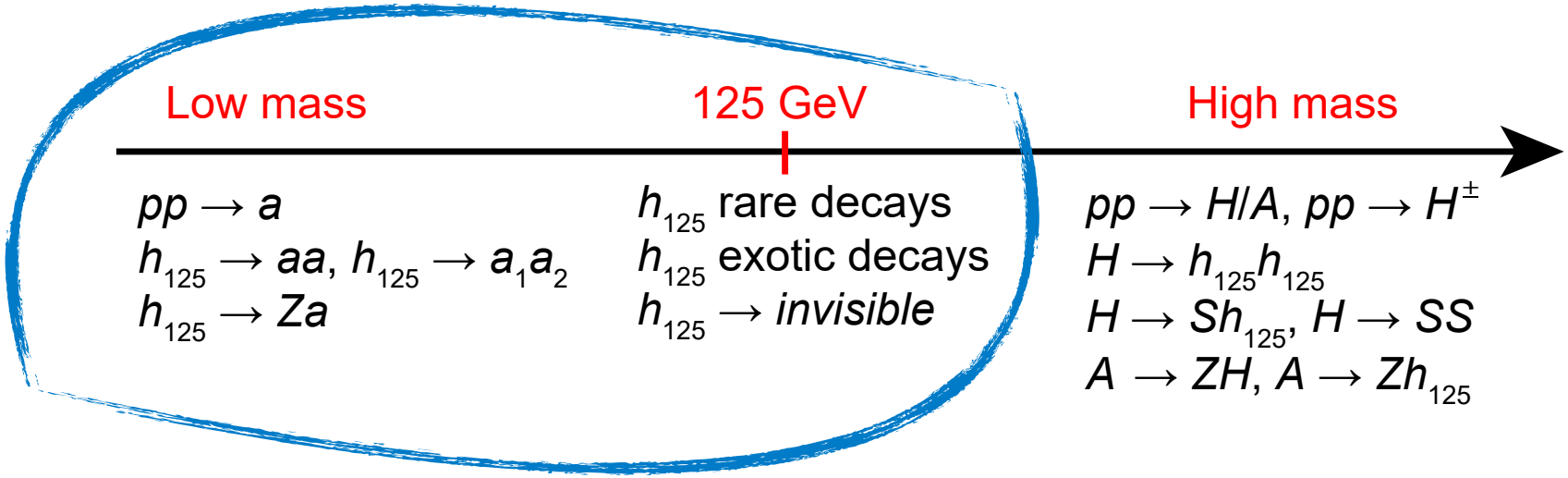
Snowmass arxiv:2211.11084

THE Higgs

The start of the journey - a searches perspective



focus of this talk

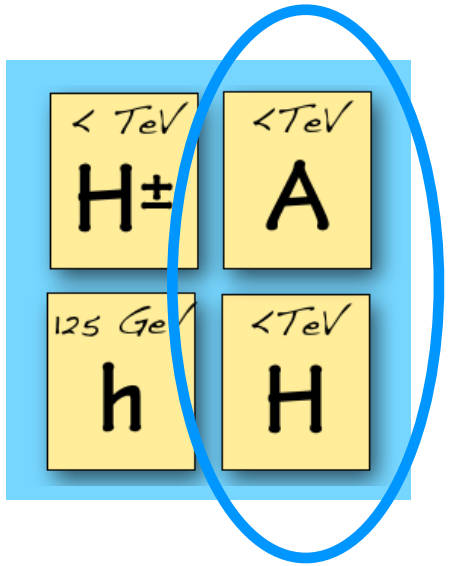


next two talks

More Higgses

theoretical framework

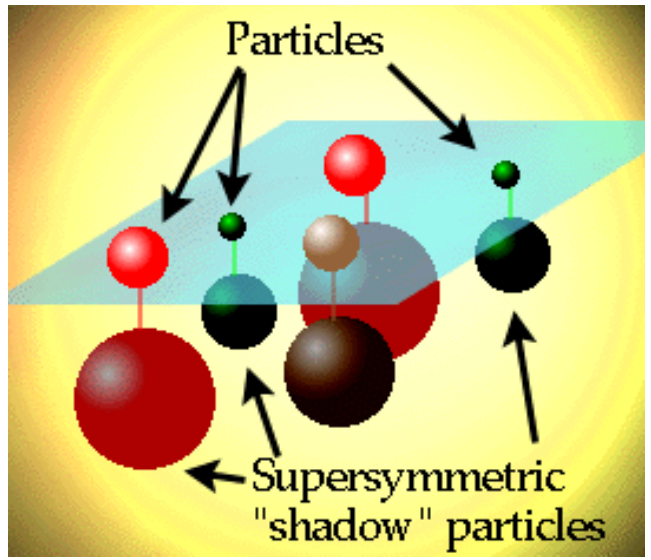
EXTENDED HIGGS SECTORS **2HDM**



scalar/pseudoscalar

ewkinos
NMSSM
2HDM+S
….

SUPERSYMMETRY



NOMENCLATURE
a (light pseudo scalar)
H (SM Higgs)
φ or s (light scalar)

2HDM+a
Higgs Portal

DARK MATTER /
DARK SECTOR

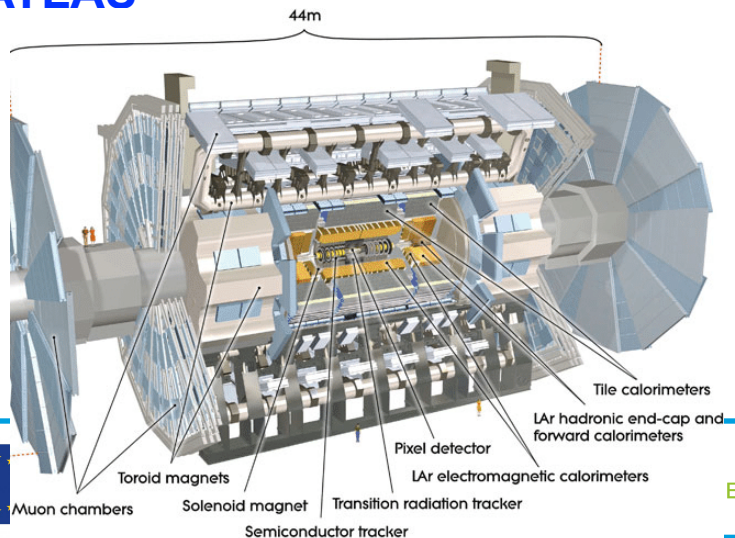
Credit slide

new since Higgs 2023

Signature	Exp.	Reference
h->γγ	ATLAS	HIGG-2023-12
S->ZdZd->4lep	ATLAS	HDBS-2021-13
H->Za, a->jj	ATLAS	HDBS-2021-09
A->ττ	ATLAS	HDBS-2021-08
H->aa, bbττ	ATLAS	HDBS-2021-07
H->aa, 4γ	ATLAS	HDBS-2019-19
H->Za, a->γγ	ATLAS	HDBS-2019-09
tta, a->μμ	ATLAS	HDBS-2020-12
rare decays	ATLAS	HDBS-2019-33
H->aa, bbμμ	ATLAS	HDBS-2021-03
H->SUSY	ATLAS	HDBS-2018-07

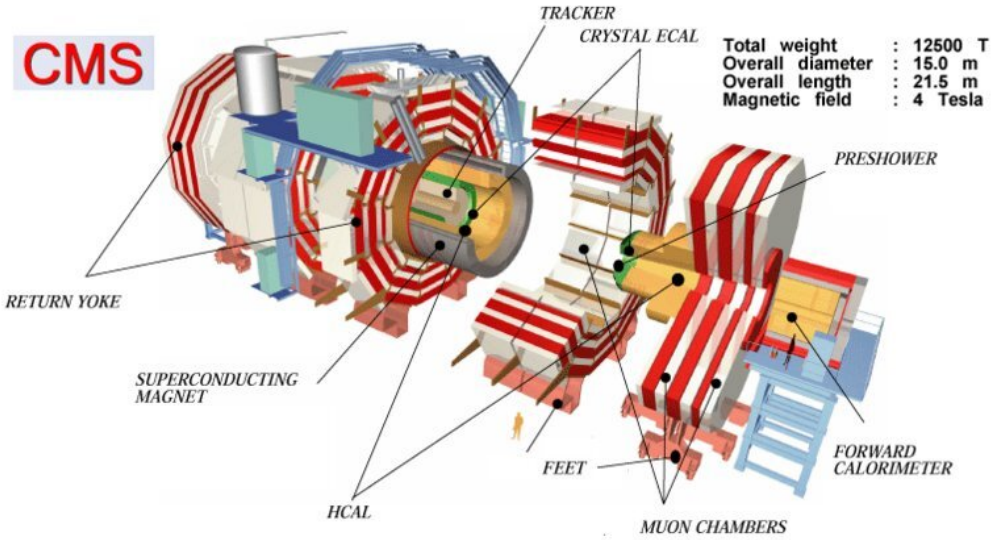
Signature	Exp.	Reference
phi->ll (tt/W/Z)	CMS	EXO-21-018
displaced μμ	CMS	HIG-21-004
h->γγ	CMS	HIG-20-002
H->aa, μμττ	CMS	HIG-18-024
H->aa, μμ+2tracks	CMS	HIG-18-006
H->aa, μμbb	CMS	HIG-18-011,
H->aa, μμττ	CMS	HIG-17-024,
H->aa,μμττ	CMS	HIG-17-029,
bba(μμ)	CMS	HIG-15-009,
VH, H->aa->4b	CMS	HIG-18-026
H -> ττ	CMS	HIG-21-001
H->aa, a->γγ	CMS	HIG-21-016
H->Za, a->γγ	CMS	HIG-22-003
H->aa μμbb/ττbb	CMS	HIG-22-007
H->aa 4τ / 2μ2τ	CMS	SUS-24-002

ATLAS



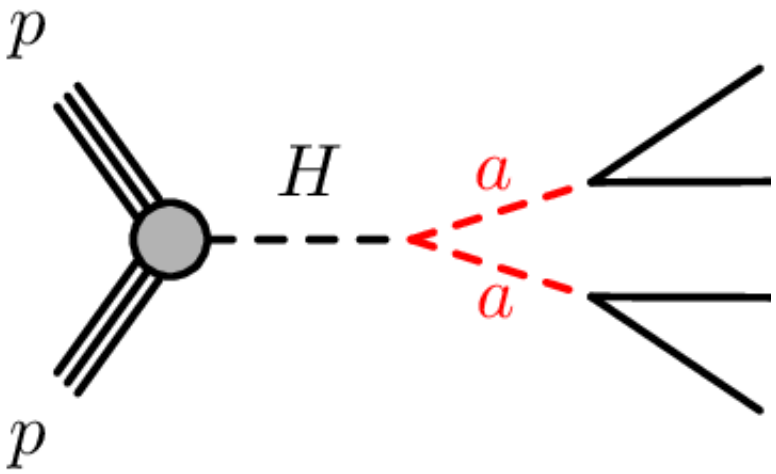
our experimental tools

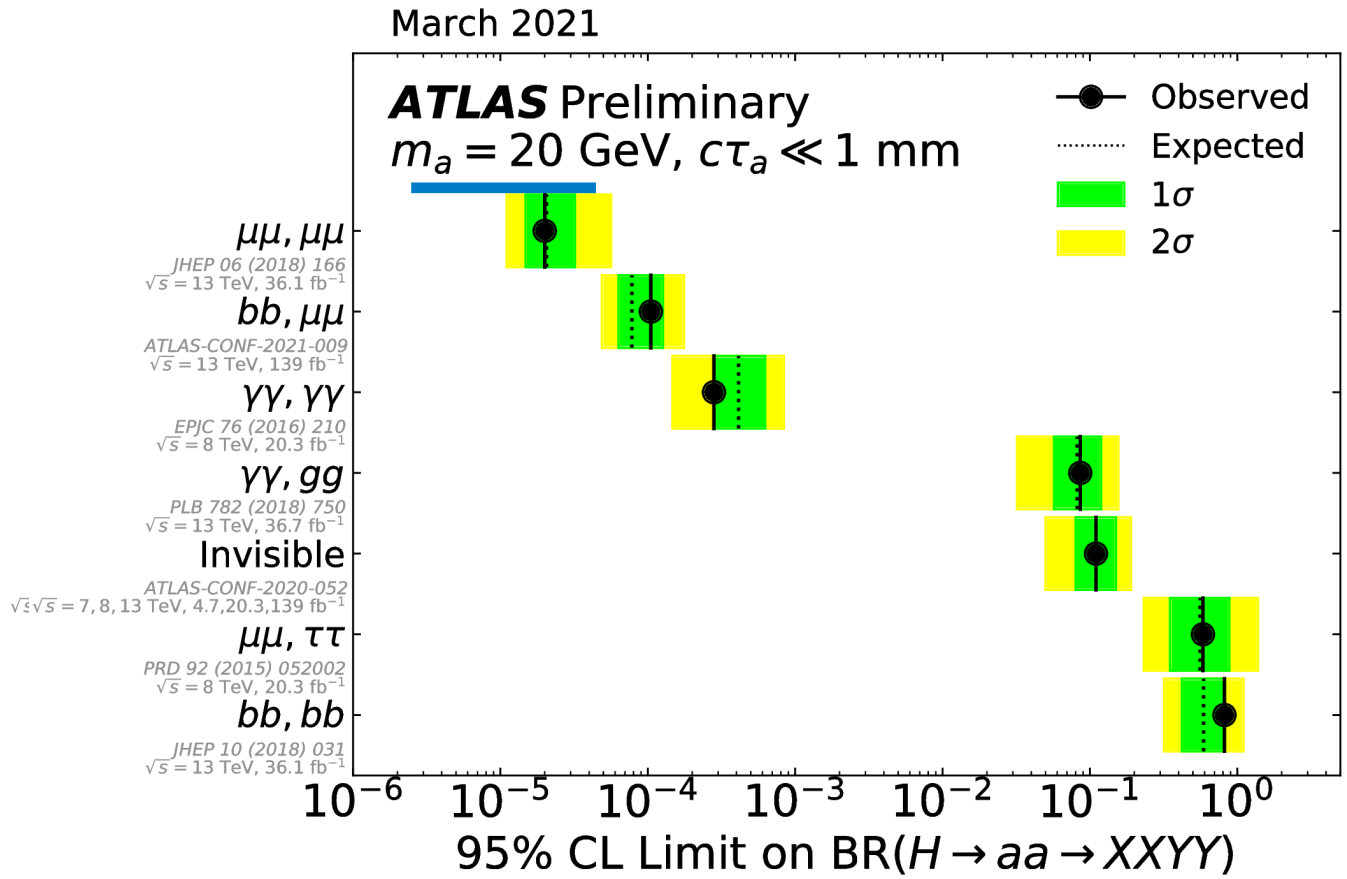
CMS



Pseudoscalars (a) via Higgs decays

channels





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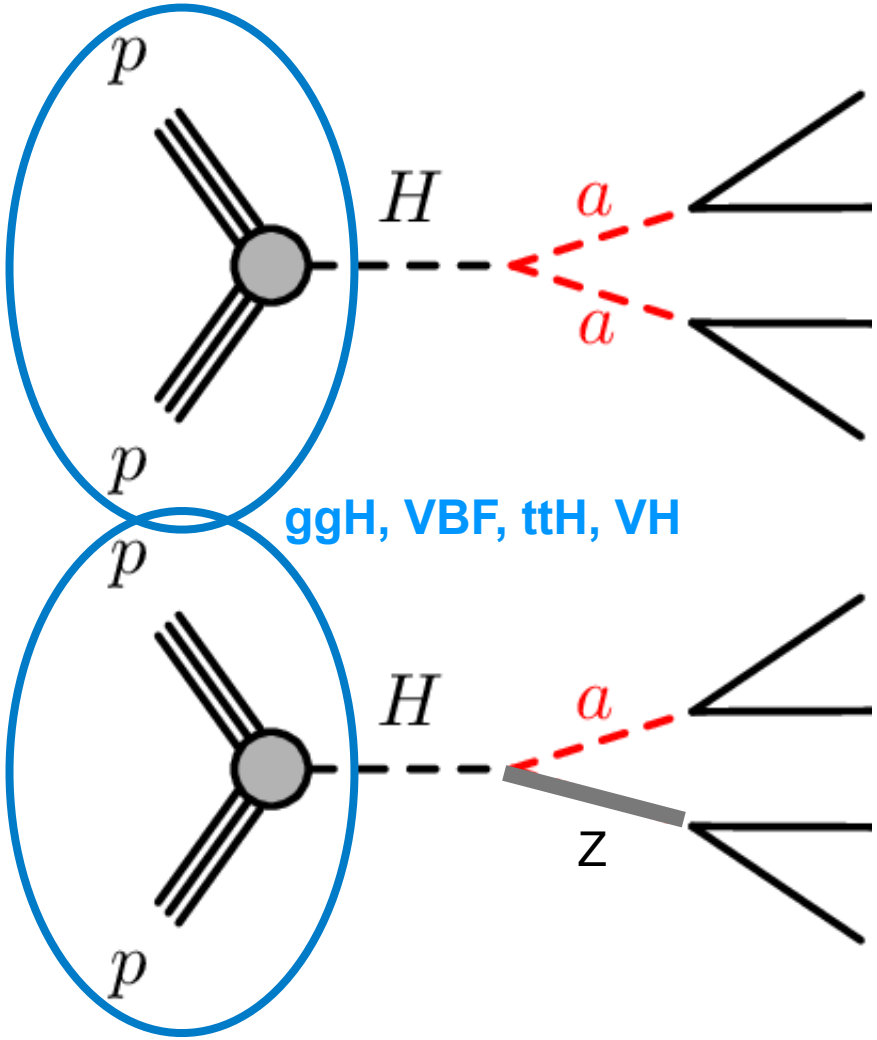


Particle identification performance

- muons
- bjets
- taus

PERFORMANCE ↑

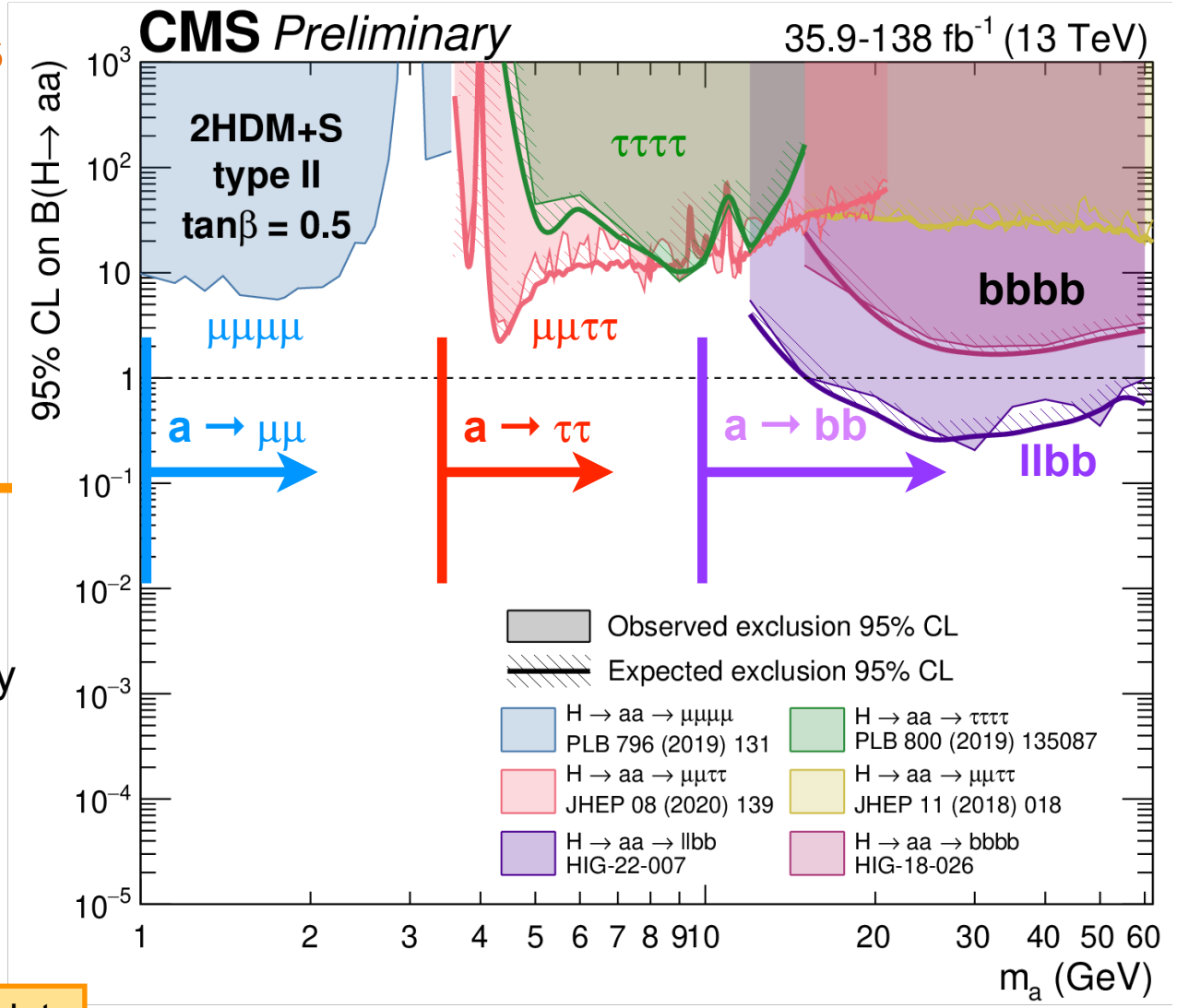
BRANCHING RATIO ↓

TRIGGER THRES. ↓

(*) Also valid for $\gamma\gamma$, but considered more in the context of ALPs

Pseudoscalars (a) via Higgs decays

vs mass



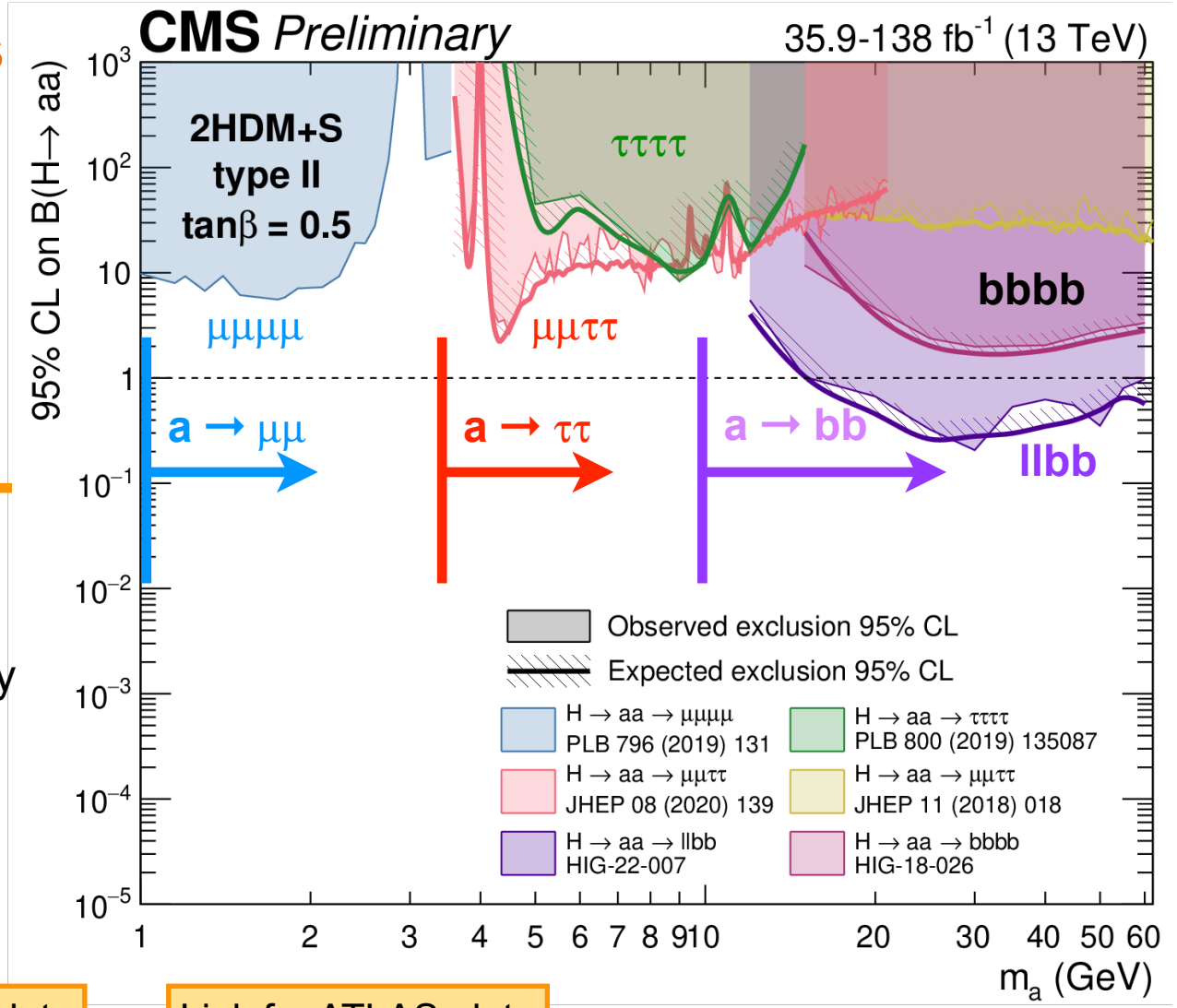
allowed by H→inv.

Link for CMS plots

- all consider H→aa
- channels are complementary
- BR(a) defined by model
- y=1 means Higgs decays 100% into new scalars

Pseudoscalars (a) via Higgs decays

vs mass

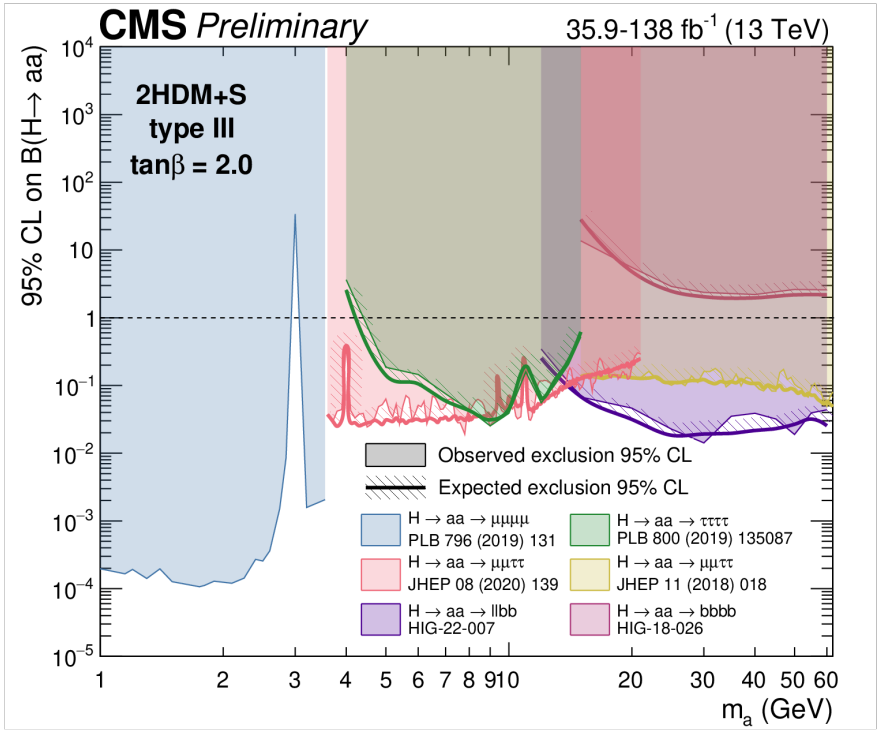


allowed by H→inv.

Link for CMS plots

Link for ATLAS plots

different tanb, type III



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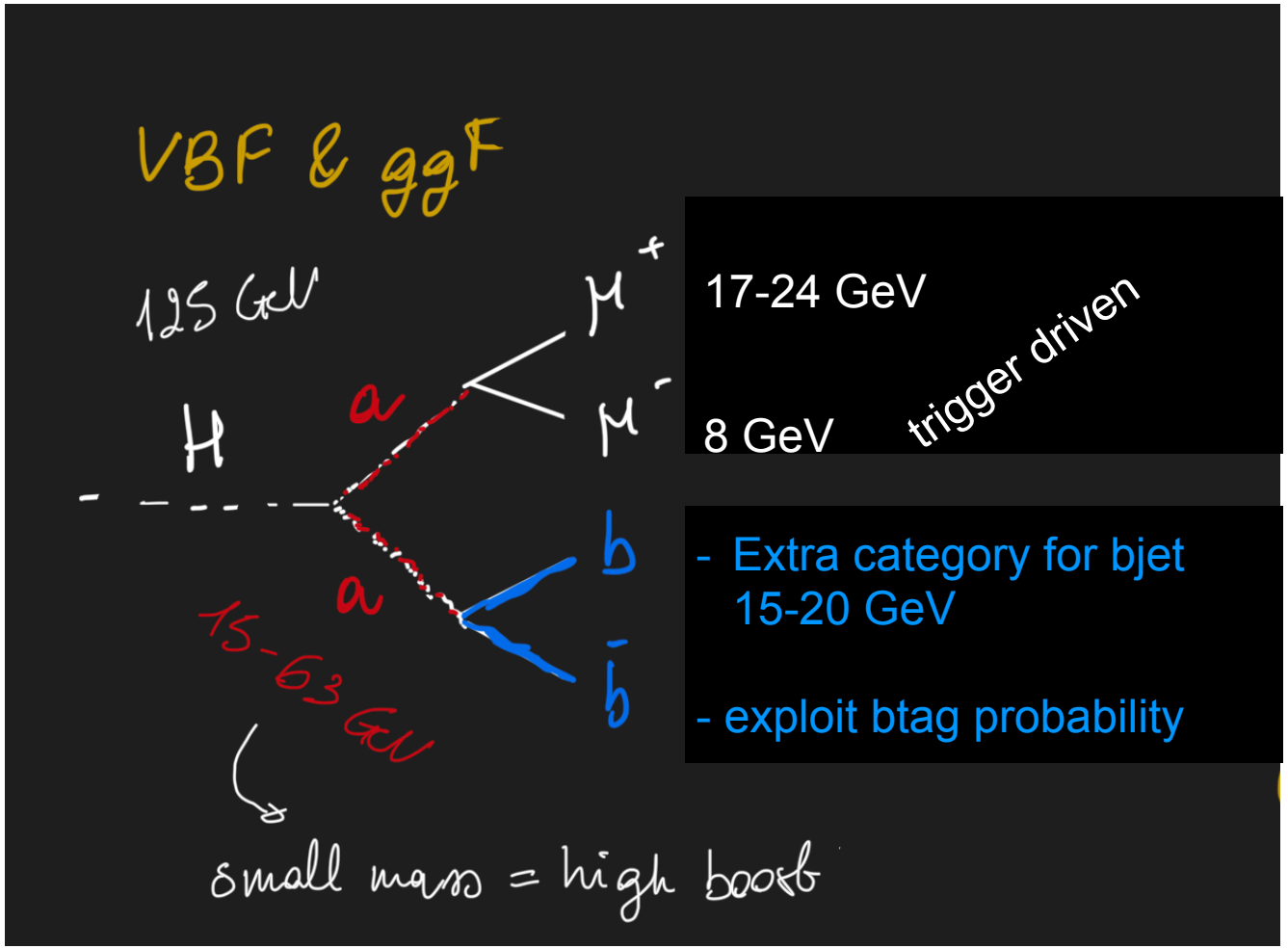
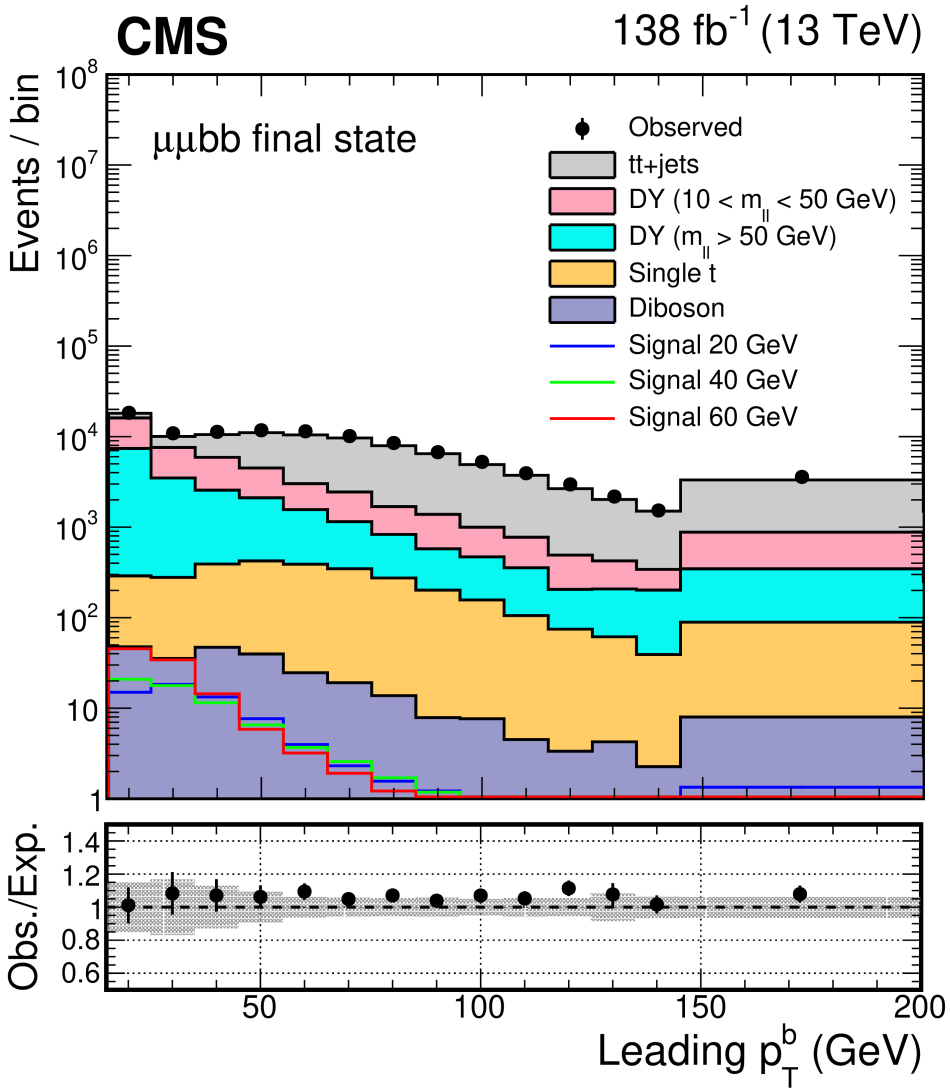
Highlight #1: H → aa → μμbb / ττbb

CMS: arXiv:2402.13358 (HIG-22-007)



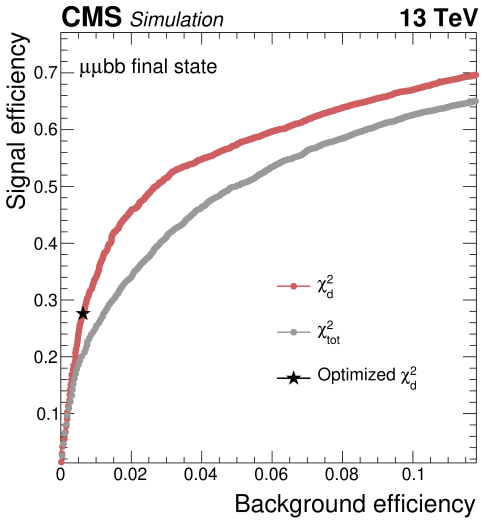


Highlight #1: H → aa → μμbb / ττbb

CMS: arXiv:2402.13358 (HIG-22-007)

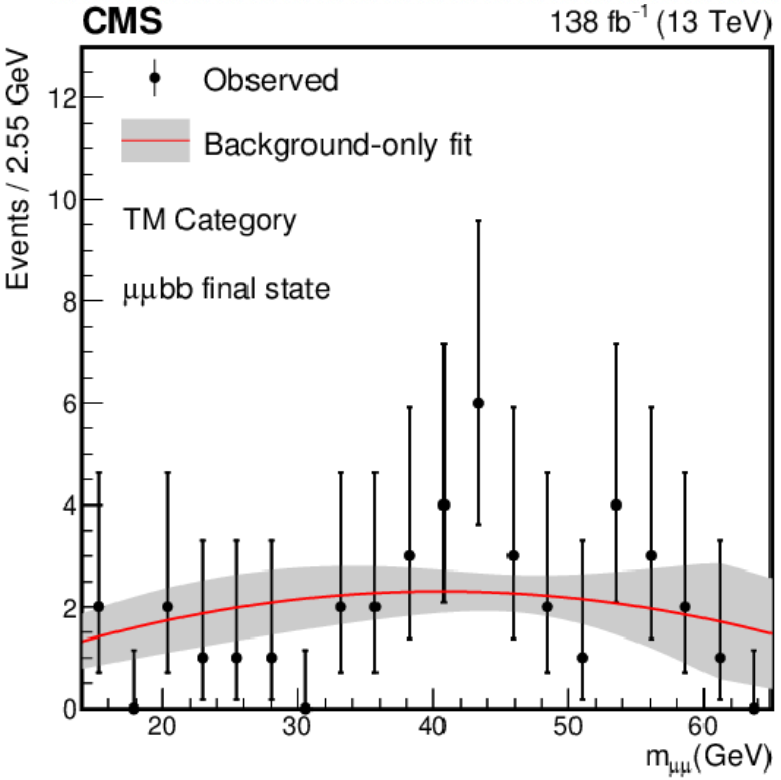
$$\chi_{bb} = \frac{(m_{bb} - m_{\mu\mu})}{\sigma_{bb}} \oplus \chi_H = \frac{(m_{\mu\mu bb} - 125\,\text{GeV})}{\sigma_H}.$$

Decorrelation for improved performance

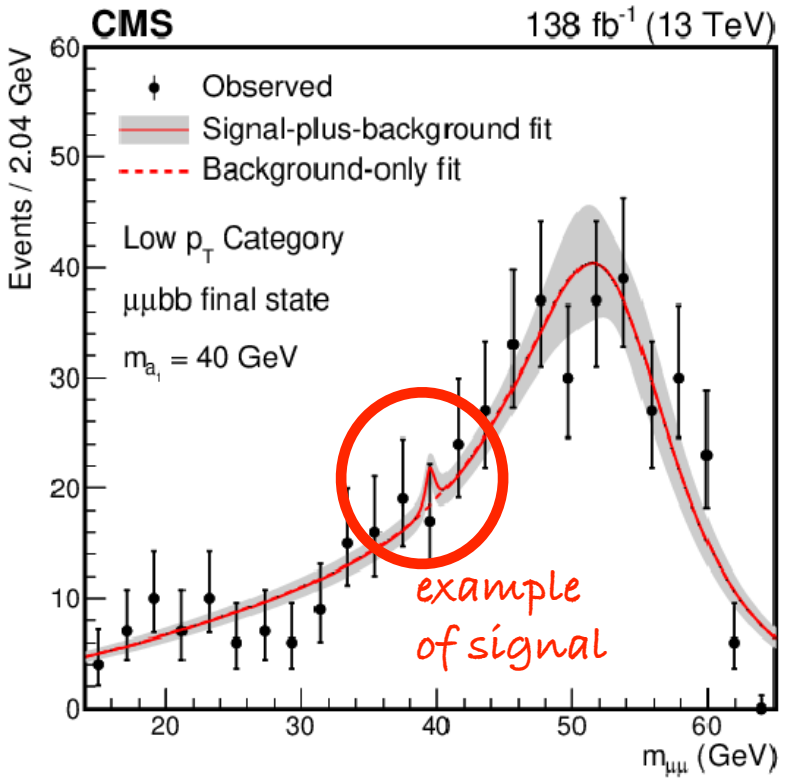


$$\begin{pmatrix} \chi_H \\ \chi_{bb} \end{pmatrix}_d = \begin{pmatrix} \frac{a}{\sqrt{\lambda_1}} & \frac{b}{\sqrt{\lambda_1}} \\ \frac{-b}{\sqrt{\lambda_2}} & \frac{a}{\sqrt{\lambda_2}} \end{pmatrix} \begin{pmatrix} \chi_H \\ \chi_{bb} \end{pmatrix}_c,$$

$$\chi^2_d \equiv \chi^2_{H,d} + \chi^2_{bb,d}$$



S/B = 0.3 @60 GeV

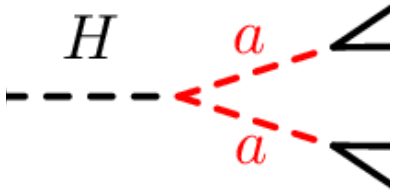


S/B = 0.02 @40 GeV

No excess in any category, very stringent limits in various scenarios

Highlight #2: bjets reconstruction developments

performance highlight



Momentum of decay products
~ (m(H) - m(a))

- small Δm: reduce the threshold of final-state objects (TC-LVT)

  ATLAS: arXiv:2405.03253 (FTAG-2023-02)

- large Δm: identify merged b-jets (DeXTer)

  ATLAS: ATL-PHYS-PUB-2022-042

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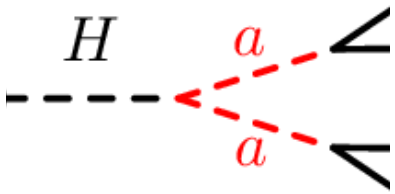
performance highlight



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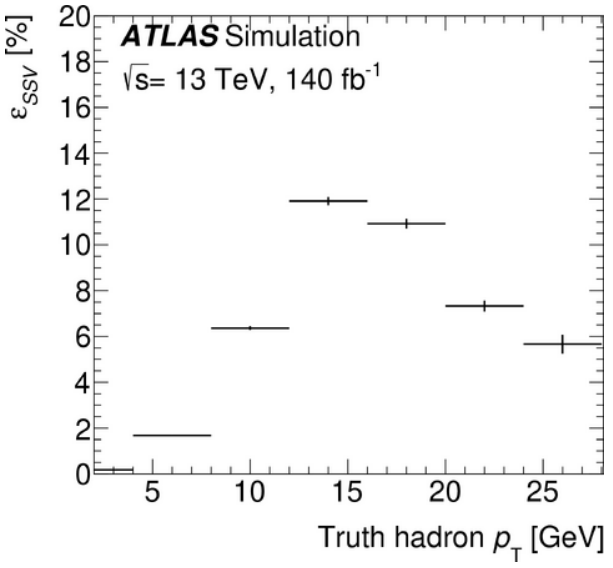
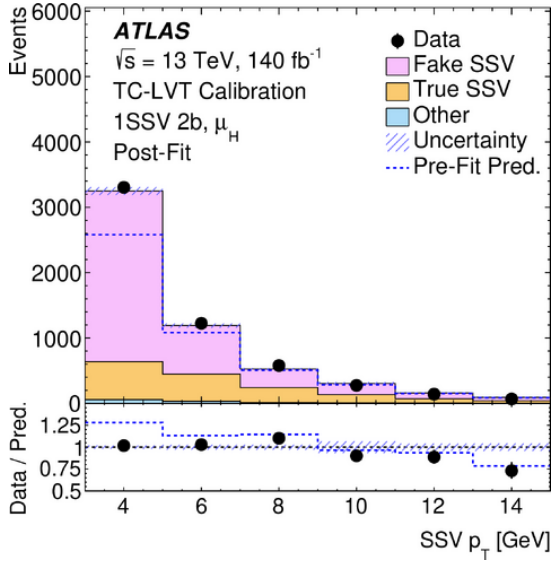
ATLAS TC-LVT algorithm for the reconstruction of soft secondary vertices outside jets



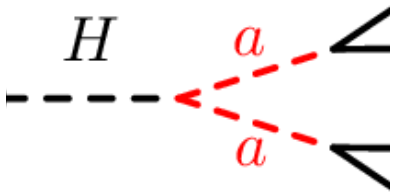


Calibration Scale Factors	
SF_{eff}	0.86 ± 0.10
$SF_{fake}^{\mu_L}$	1.63 ± 0.15
$SF_{fake}^{\mu_H}$	1.58 ± 0.13

Stay tuned to see the algorithm used in light BSM higgs searches

Highlight #2: bjets reconstruction developments

performance highlight



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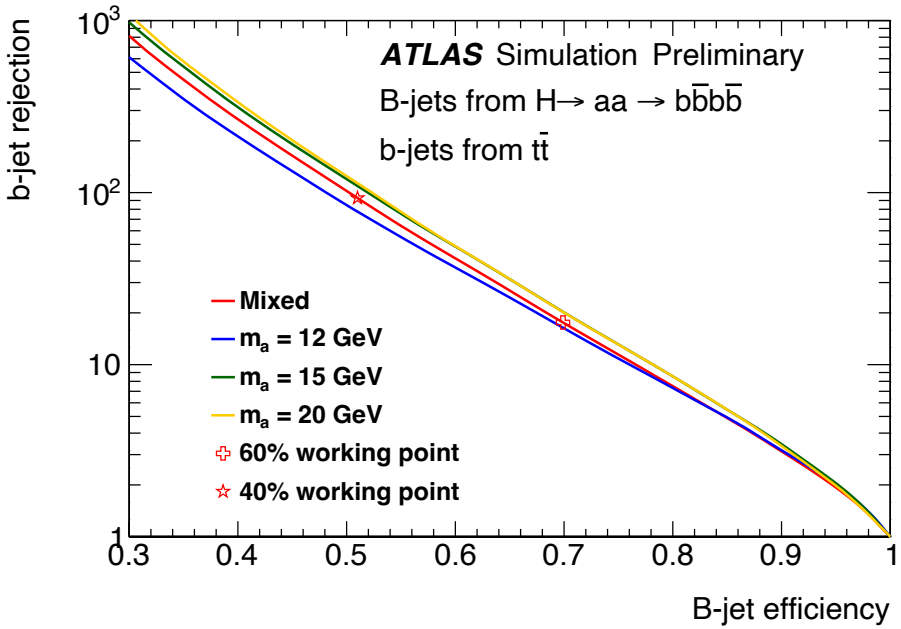
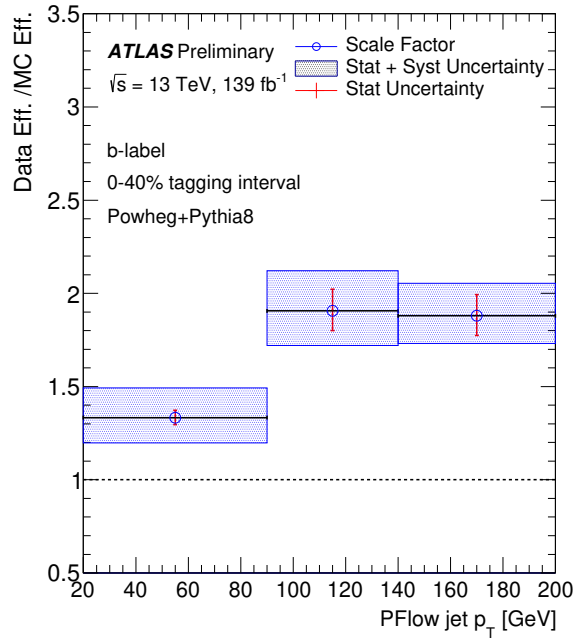
ATLAS DeXter algorithm is a deep-learning double-b tagger for jets below 200 GeV





Highlight #2: bjets reconstruction developments

performance highlight

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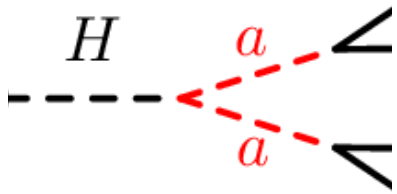


Momentum of dec
~ (m(H) - m(a))

- small Δm: reduc
  of final-state obj

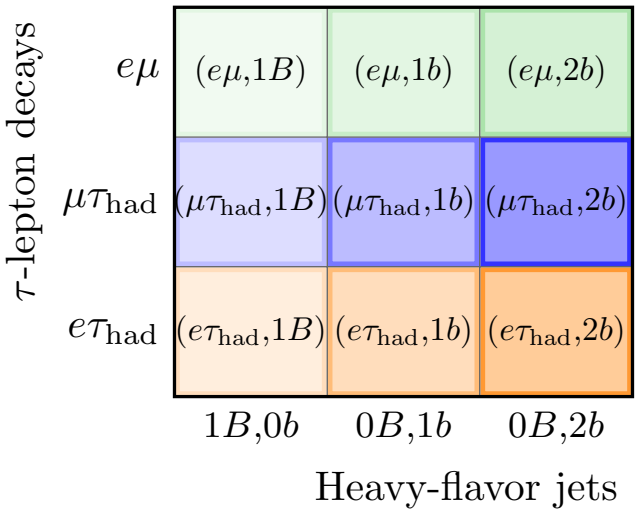
ATLAS:

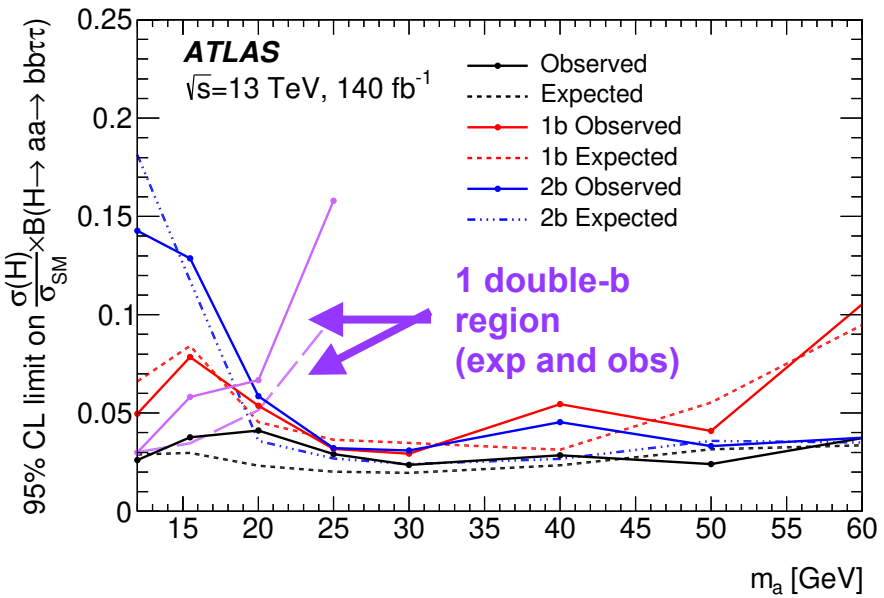
- large Δm: identif

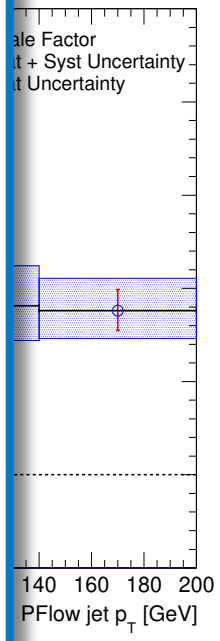
ATLAS: ATL-PHYS-PUB-2022-042

ATLAS: arXiv:2407.01335 (HDBS-2021-07)

$$H \to aa \to b\bar{b}\tau^+\tau^-$$

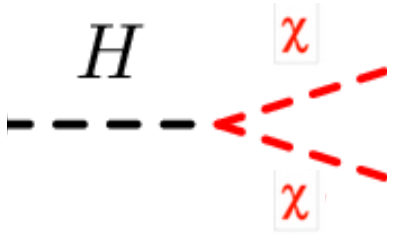


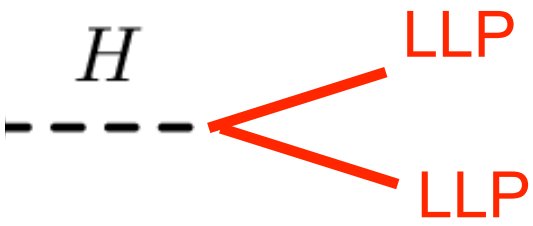


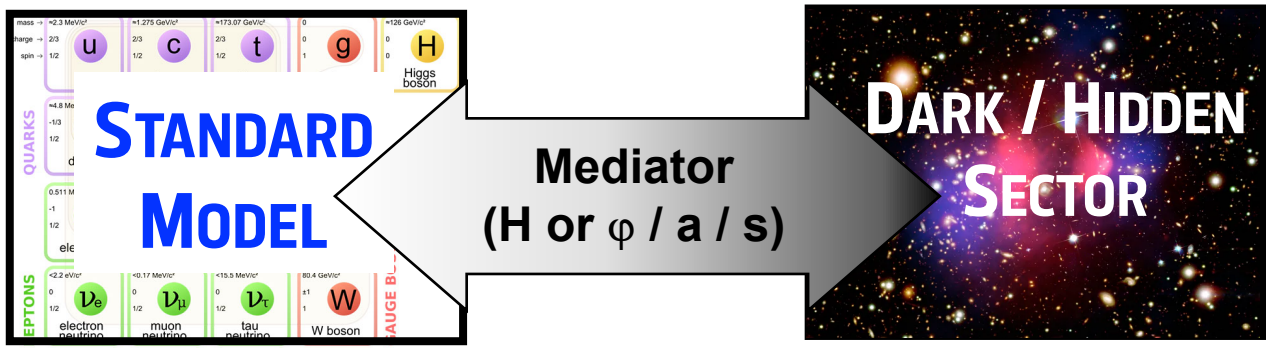


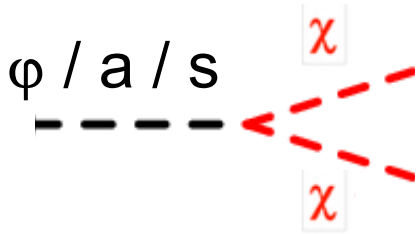
(*) check out also the beautiful performance of the di-t missing mass calculator [1012.4686] used in this analysis

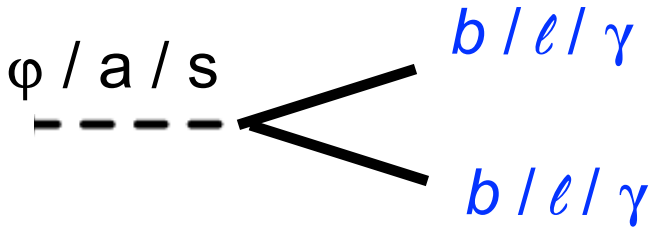
Dark Sectors and Hidden Sectors via Higgs or scalars



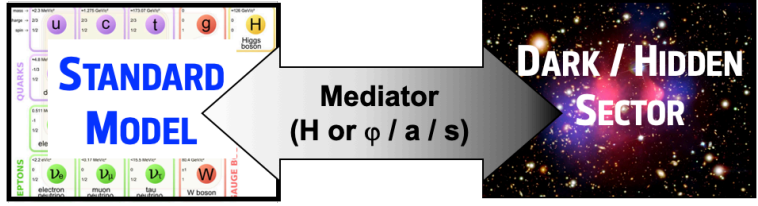


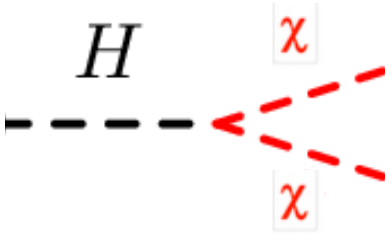


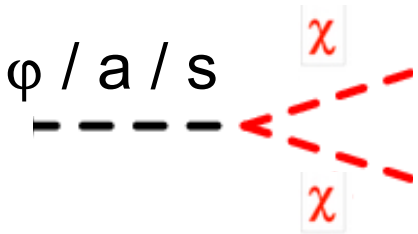




Light Higgs bosons and Dark Matter





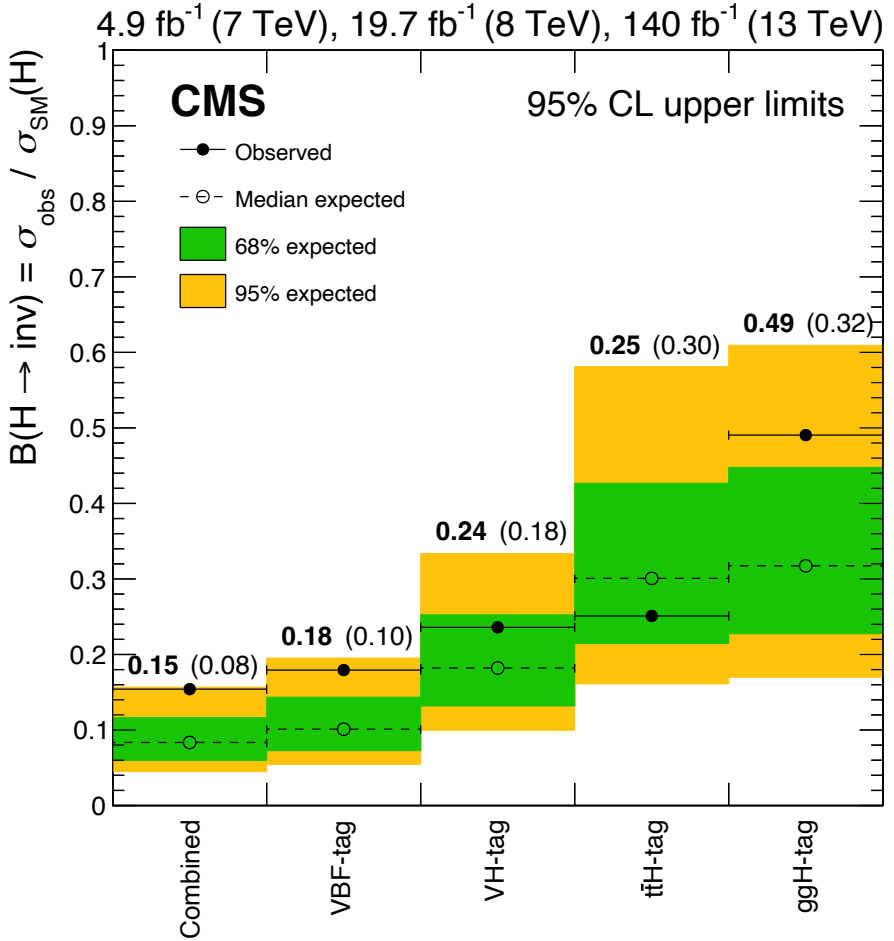


1) The SM Higgs mediates the interaction to the dark sector (H → invisible)

CMS:arXiv:1809.05937

ATLAS:arXiv:2301.10731

Great results in constraining H → invisible < 10-15%



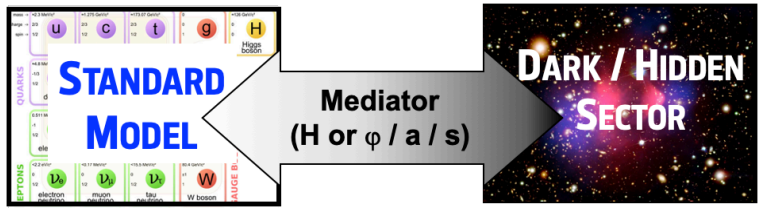
2) Interaction mediated by a light scalar/pseudoscalar (somewhat simplistic model but interesting final states)

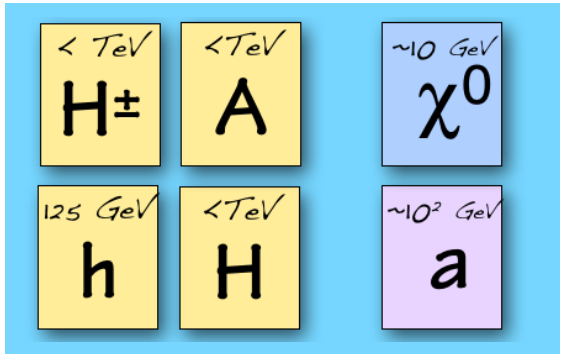
CMS: arXiv:2405.13778 (EXO-2023-005)

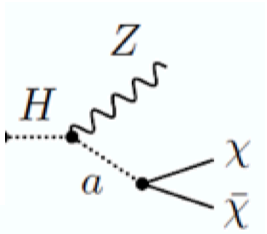
ATLAS: arXiv:2404.15930 (EXOT-2018-62)

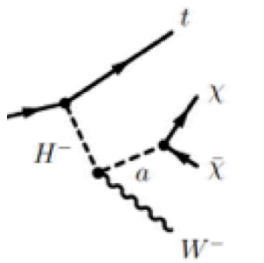
Highlight #3: 2HDM+a

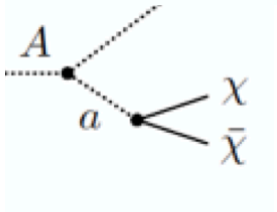
A more realistic model for Dark Matter

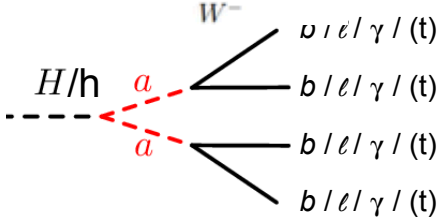












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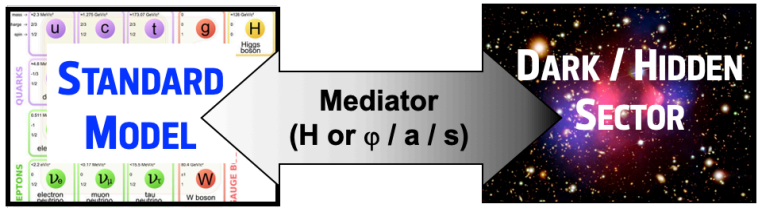
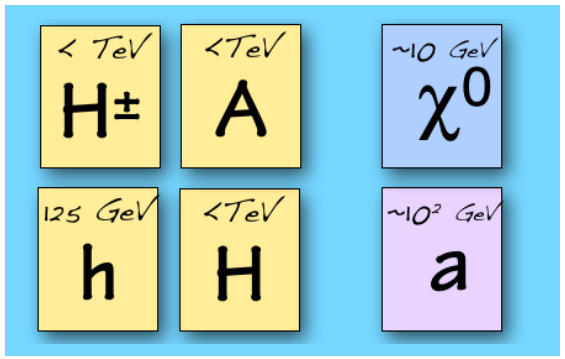
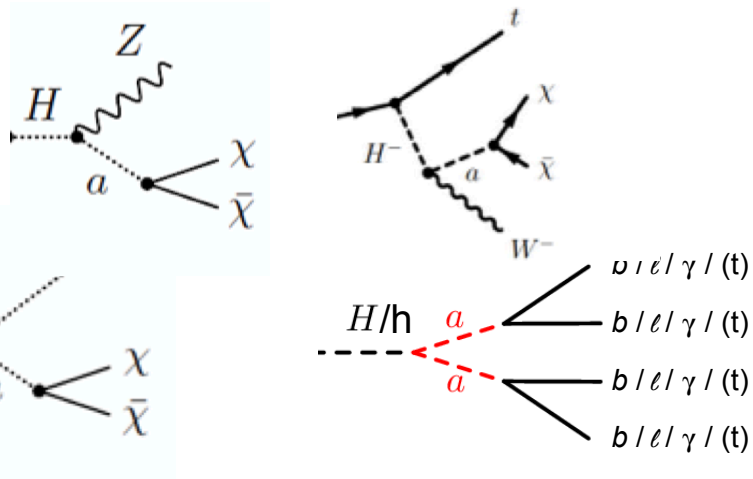
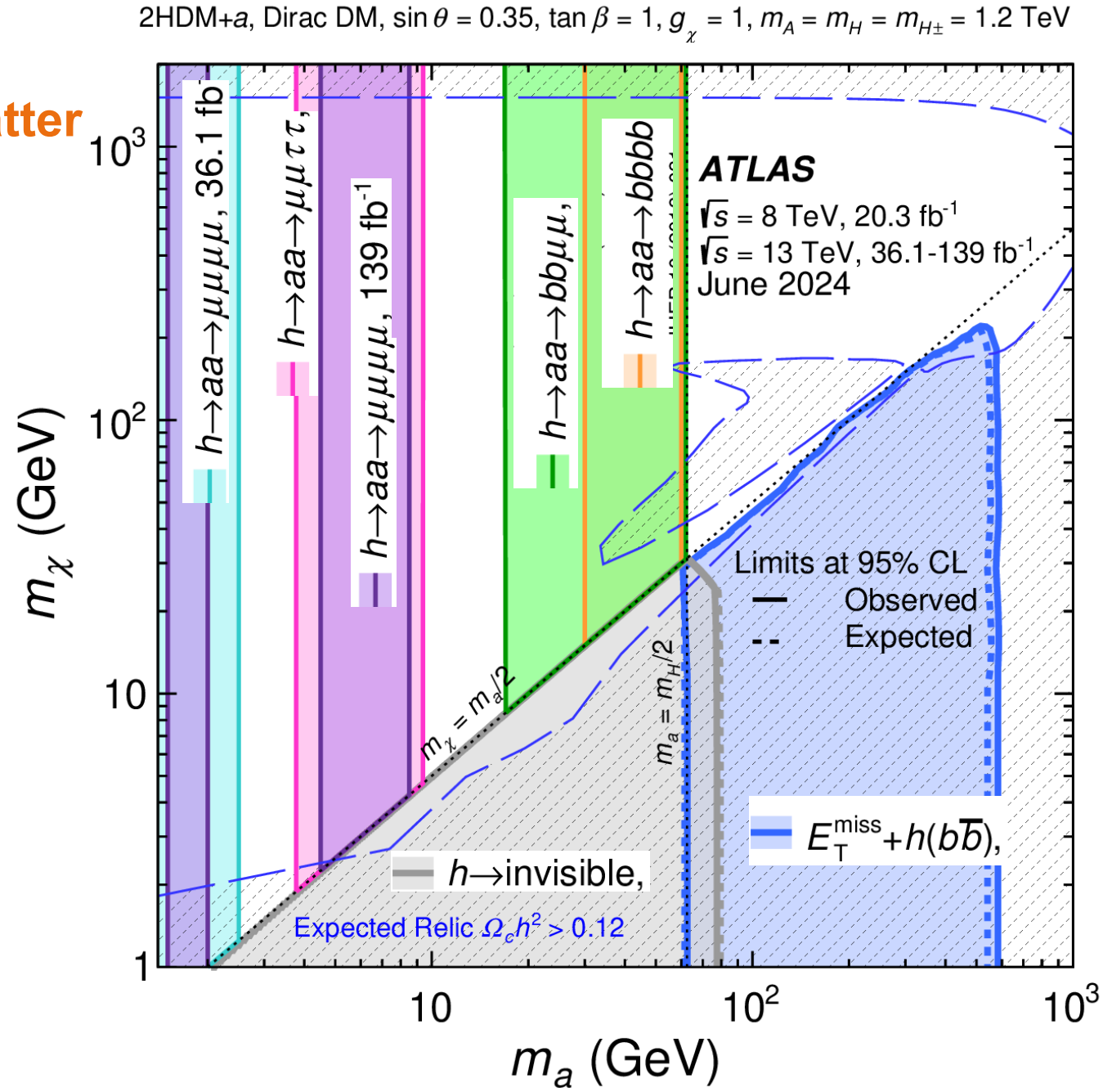
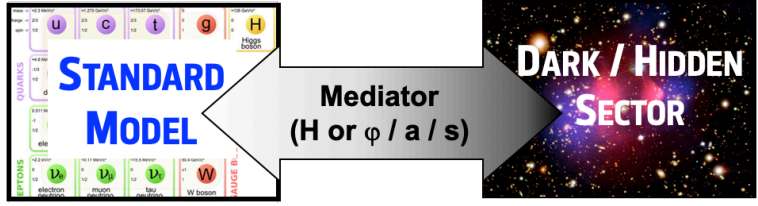


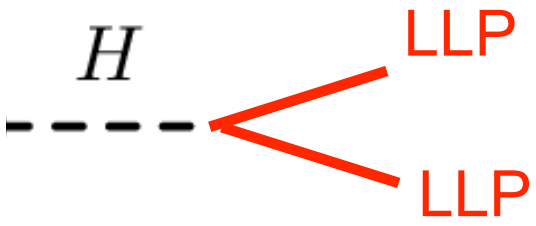






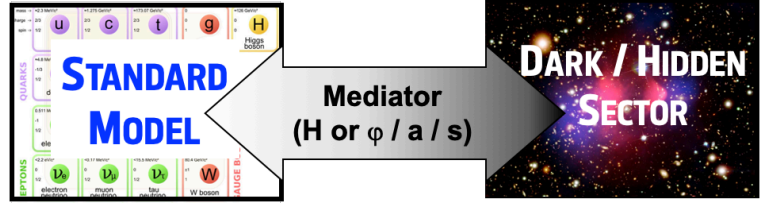
Highlight #4: Long Lived Particles

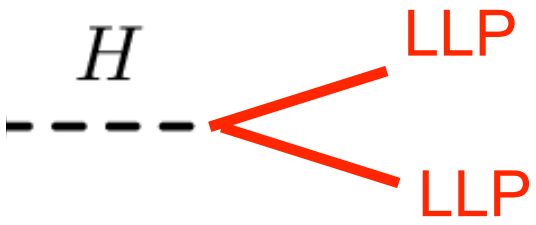




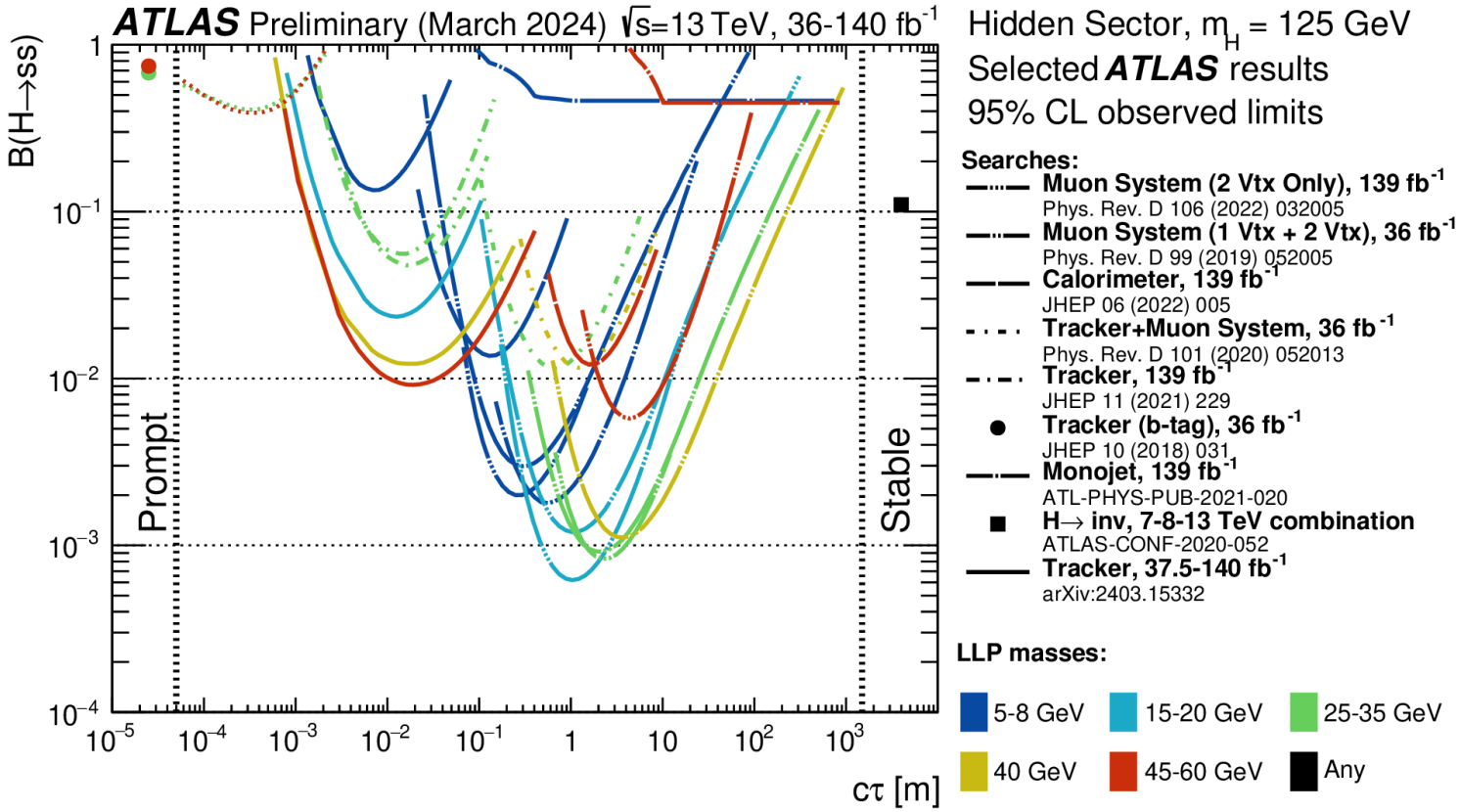
3) The SM Higgs mediates the interaction to the hidden sector and decays into long lived particles

Highlight #4: Long Lived Particles

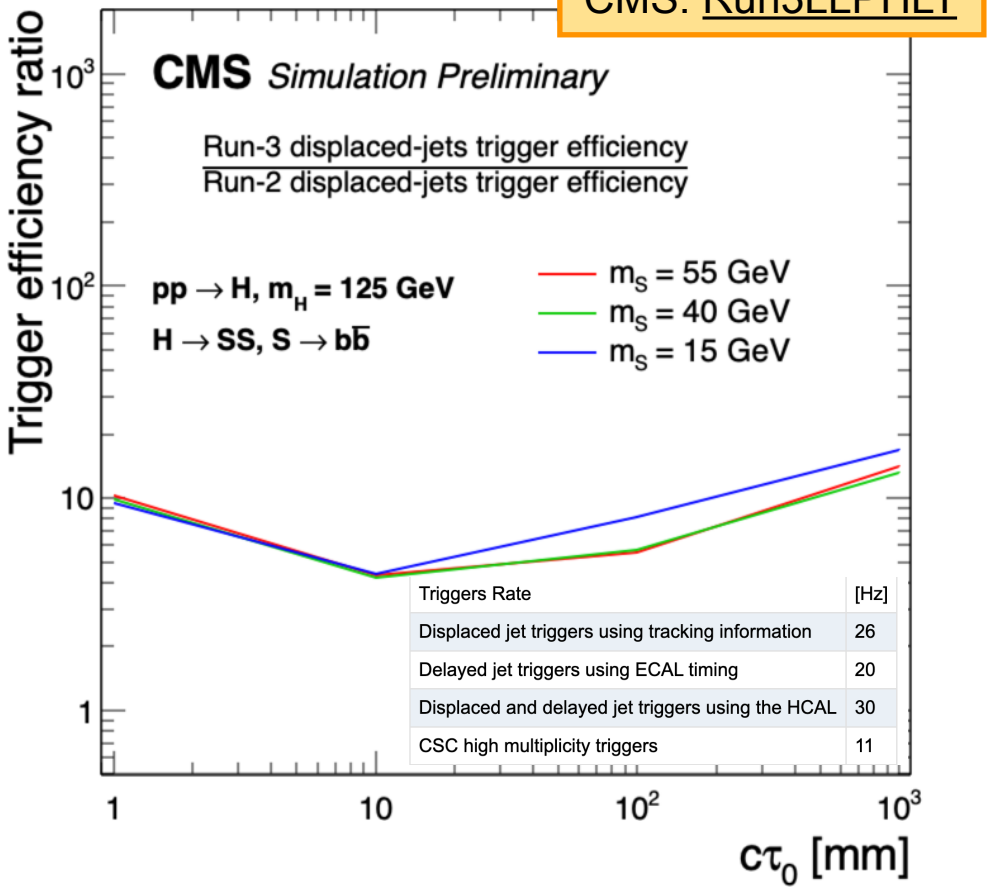




3) The SM Higgs mediates the interaction to the hidden sector and decays into long lived particles



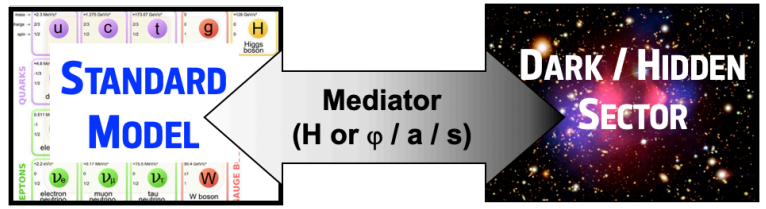
CMS: Run3LLPHLT

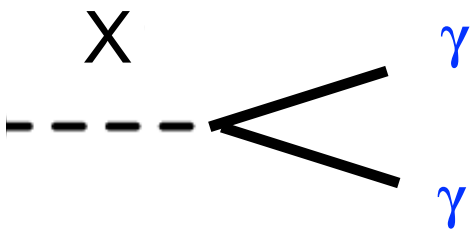


ATLAS: arXiv:2405.04914 (HDBS-2023-15)

Highlight #4: Intermediate mass searches

di-photon searches 70 < mγγ <110 GeV



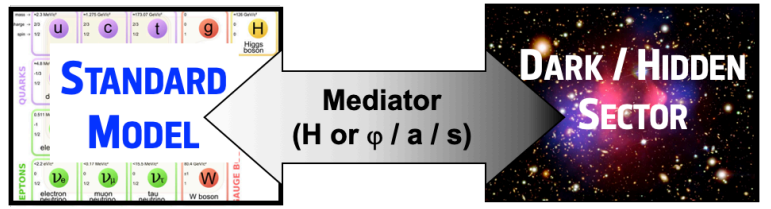


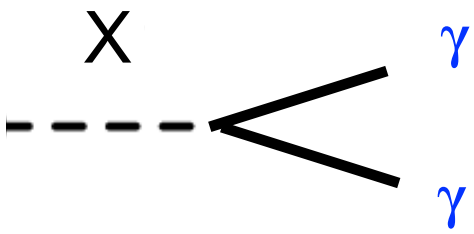
4) All new mediators decay back into the SM and can be reconstructed as resonances in all allowed SM final states

- These searches provide unique access to intermediate mass regimes

Highlight #5: Intermediate mass searches

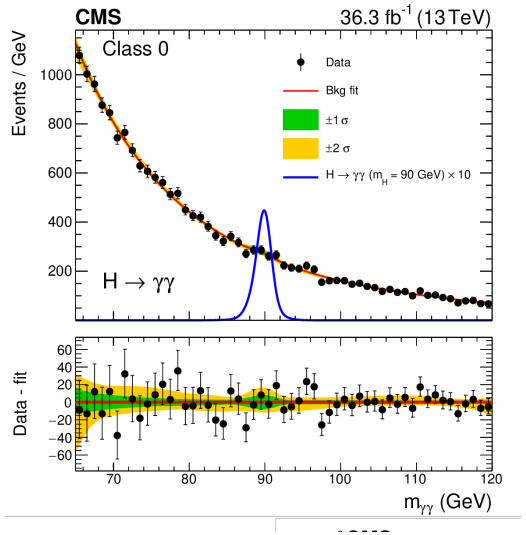
di-photon searches 70 < mγγ <110 GeV



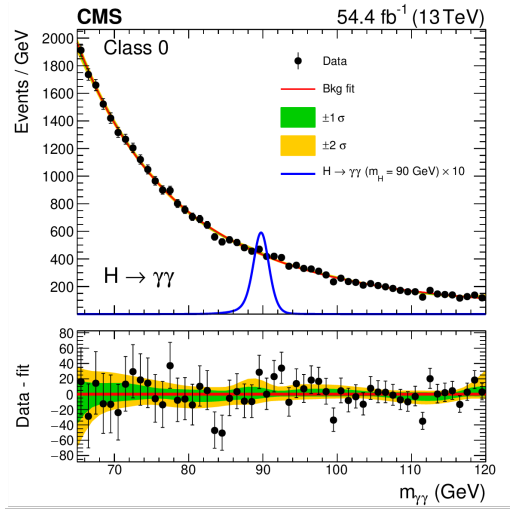


4) All new mediators decay back into the SM and can be searched as resonances in all allowed SM final states

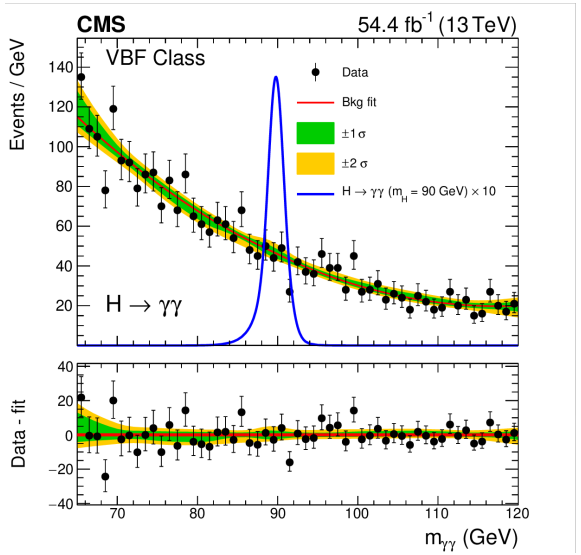
- These searches provide unique access to intermediate mass regimes



2016 data



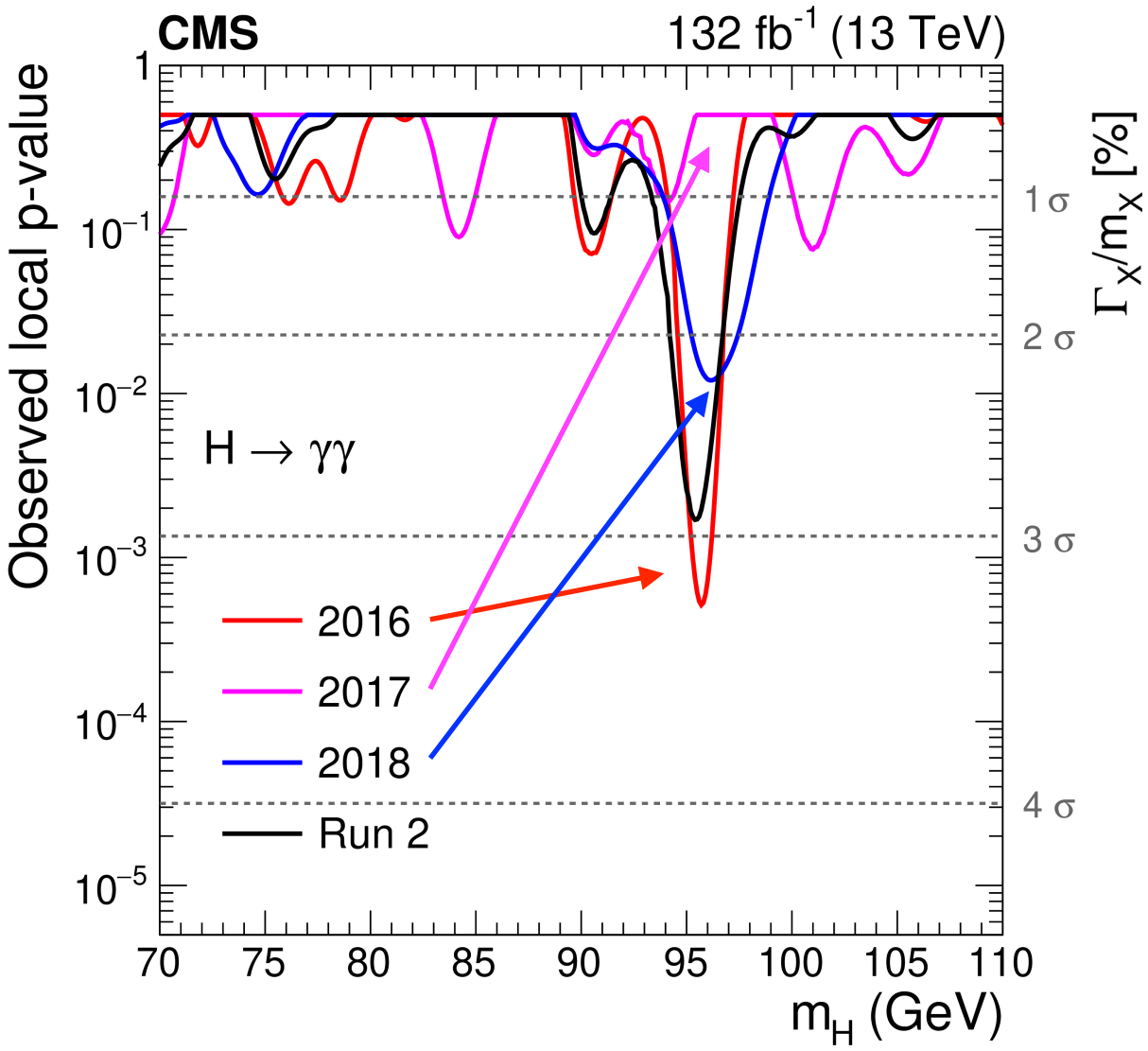
2018 data

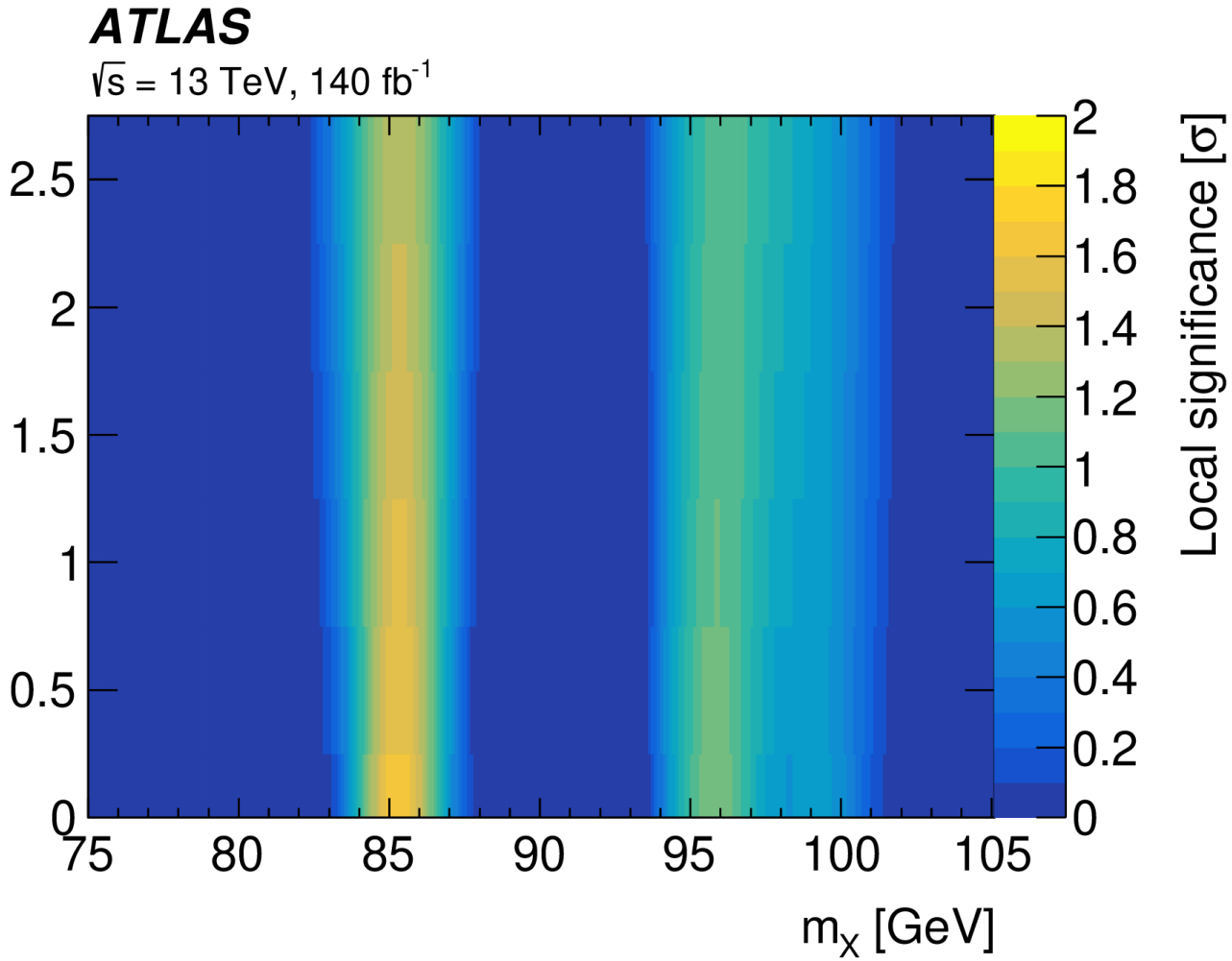


new 2018 VBF selection

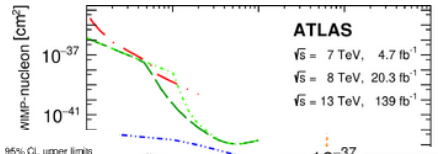
- Complete and improved re-analysis of the entire dataset
- Events divided in various categories, VBF newly added for 2017-2018 data

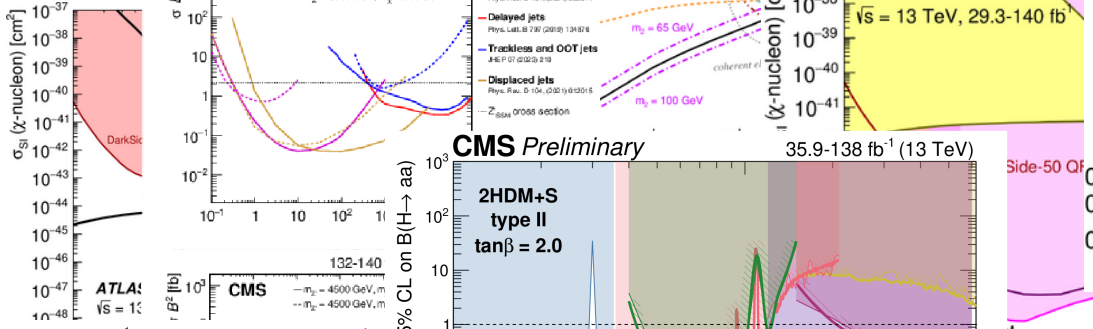
Highlight #5: di-photon searches 70 < mγγ <110 GeV



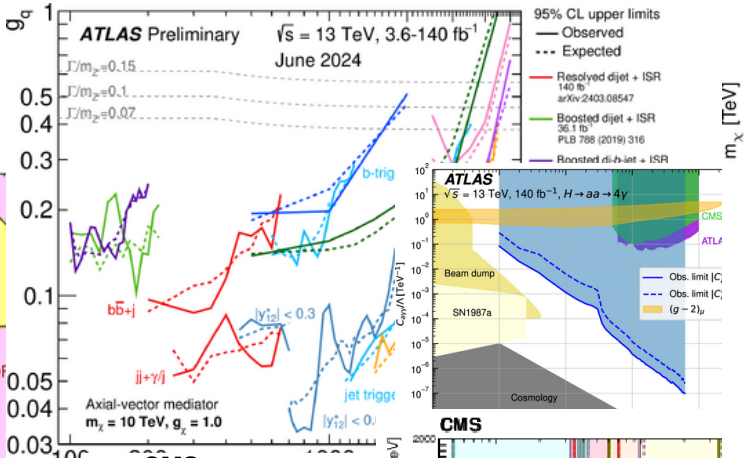


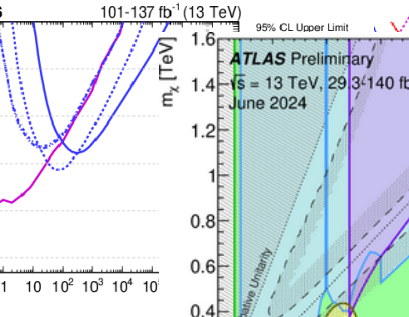
Wrap-up


ATLAS
All limits at 90% CL
Higgs Portal WIMP:
Scalar
Majorana

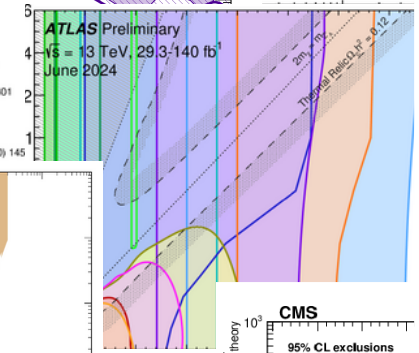

CMS
132-140 fb-1 (13 TeV)
Displaced vertices
Delayed jets
Trackless and OOT jets
Displaced jets
ATLAS
√s = 13 TeV, 29.3-140 fb-1

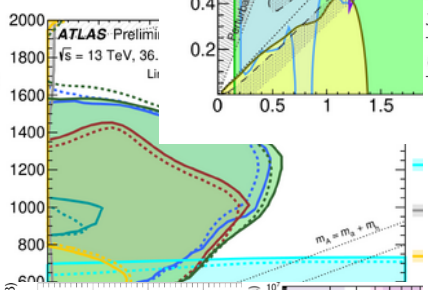
CMS Preliminary
35.9-138 fb-1 (13 TeV)
2HDM+S
type II
tanβ = 2.0
95% CL on B(H→ aa)

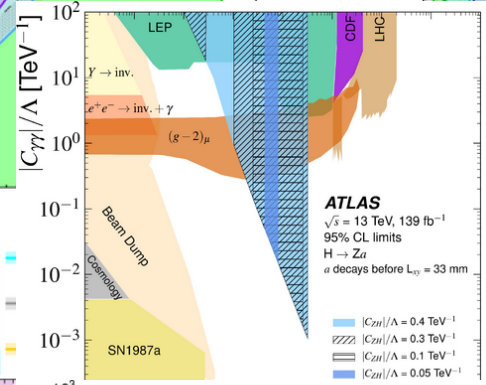

ATLAS Preliminary
√s = 13 TeV, 3.6-140 fb-1
June 2024
95% CL upper limits
Observed
Expected
Axial-vector mediator
mχ = 10 TeV, gχ = 1.0
b-trig
jet trigge
Beam dump
SN1987a
Cosmology

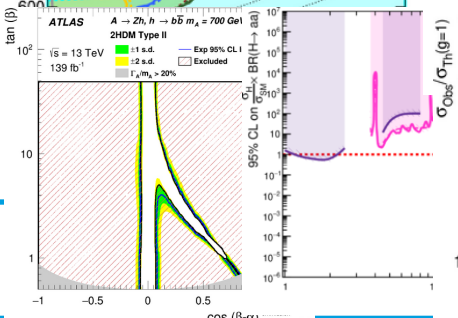

101-137 fb-1 (13 TeV)
95% CL Upper Limit

ATLAS Preliminary
√s = 13 TeV, 29.3-140 fb-1
June 2024
Dilepton
Dijet resonance
bb̄ resonance
Perturbative Unitarity
Thermal Relic Ω1h2 = 0.12

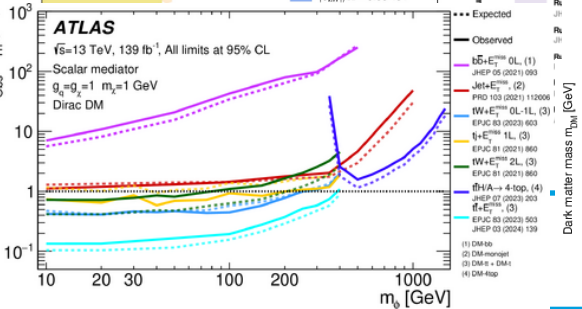

ATLAS Preliminary
√s = 13 TeV, 29.3-140 fb-1
June 2024

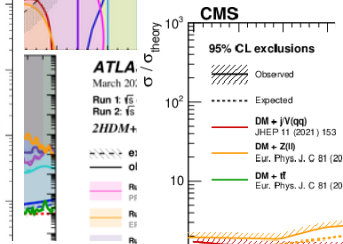

ATLAS Preliminary
√s = 13 TeV, 36.


LEP
CDF
LHC
ATLAS
√s = 13 TeV, 139 fb-1
95% CL limits
H → Za
a decays before Lxy = 33 mm
Beam Dump
Cosmology
SN1987a

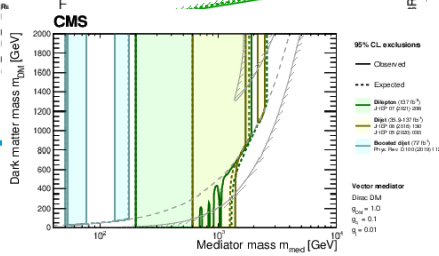

ATLAS
√s = 13 TeV
139 fb-1
2HDM Type II

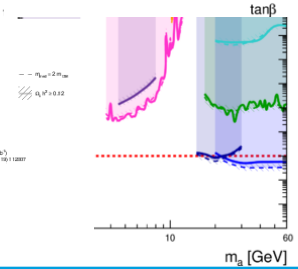
95% CL on σH/σSM BR(H→ aa)

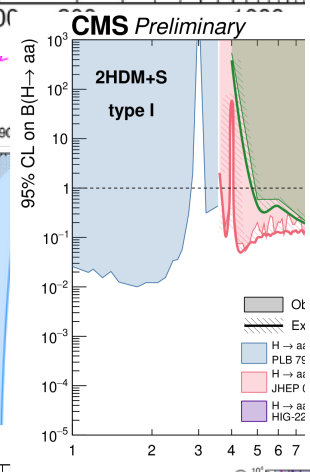

ATLAS
√s=13 TeV, 139 fb-1, All limits at 95% CL
Scalar mediator
gq=gχ=1 mχ=1 GeV
Dirac DM
σObs/σTh(g=1)
mϕ [GeV]

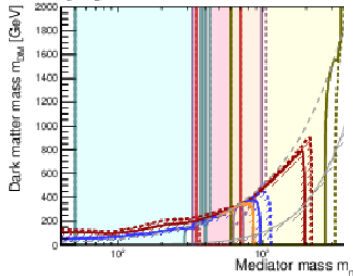

ATLAS
March 2021
Run 1: √s = 8 TeV
Run 2: √s = 13 TeV
2HDM+S Type-III, ma = 40 GeV
expected ± 1 σ
observed

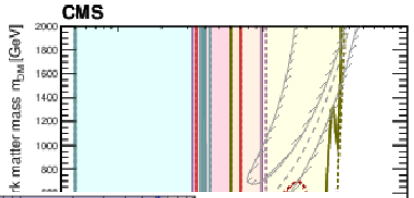
CMS
95% CL exclusions
Observed
Expected
DM + jV(qq)
DM + Z(ll)
DM + tt̄
Scalar Mediator
Dirac DM
gq = 1.0
gDM = 1.0
mDM = 1 GeV
σ / σtheory
tanβ

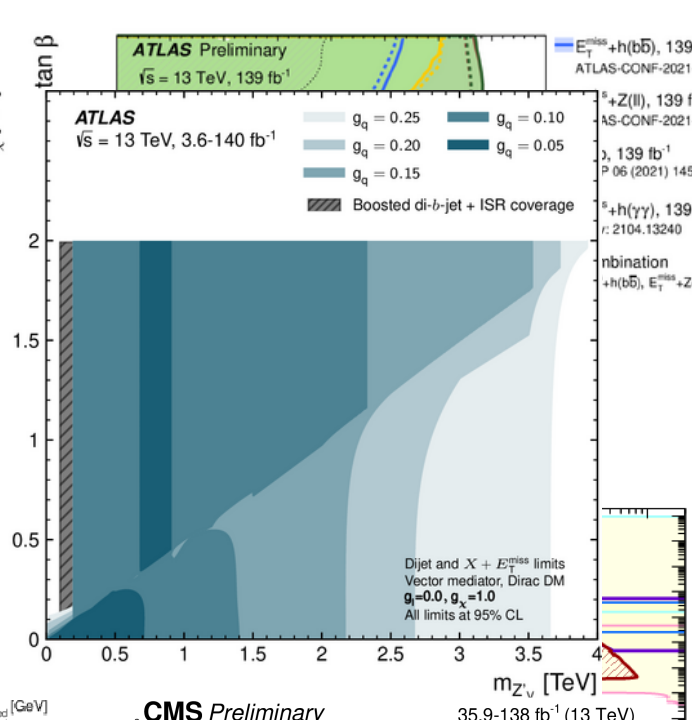

CMS
95% CL exclusions
Observed
Expected
Dilepton
Vector mediator
Dirac DM
Dark matter mass mDM [GeV]
Mediator mass mmed [GeV]

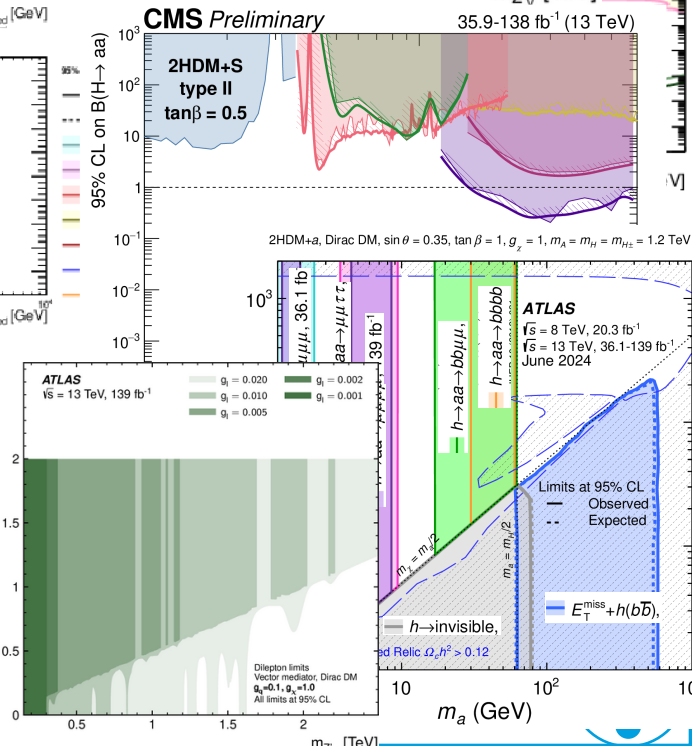

2HDM+S Type-IV, t
expected ± 1
observed
ma [GeV]


CMS Preliminary
2HDM+S
type I
95% CL on B(H→ aa)

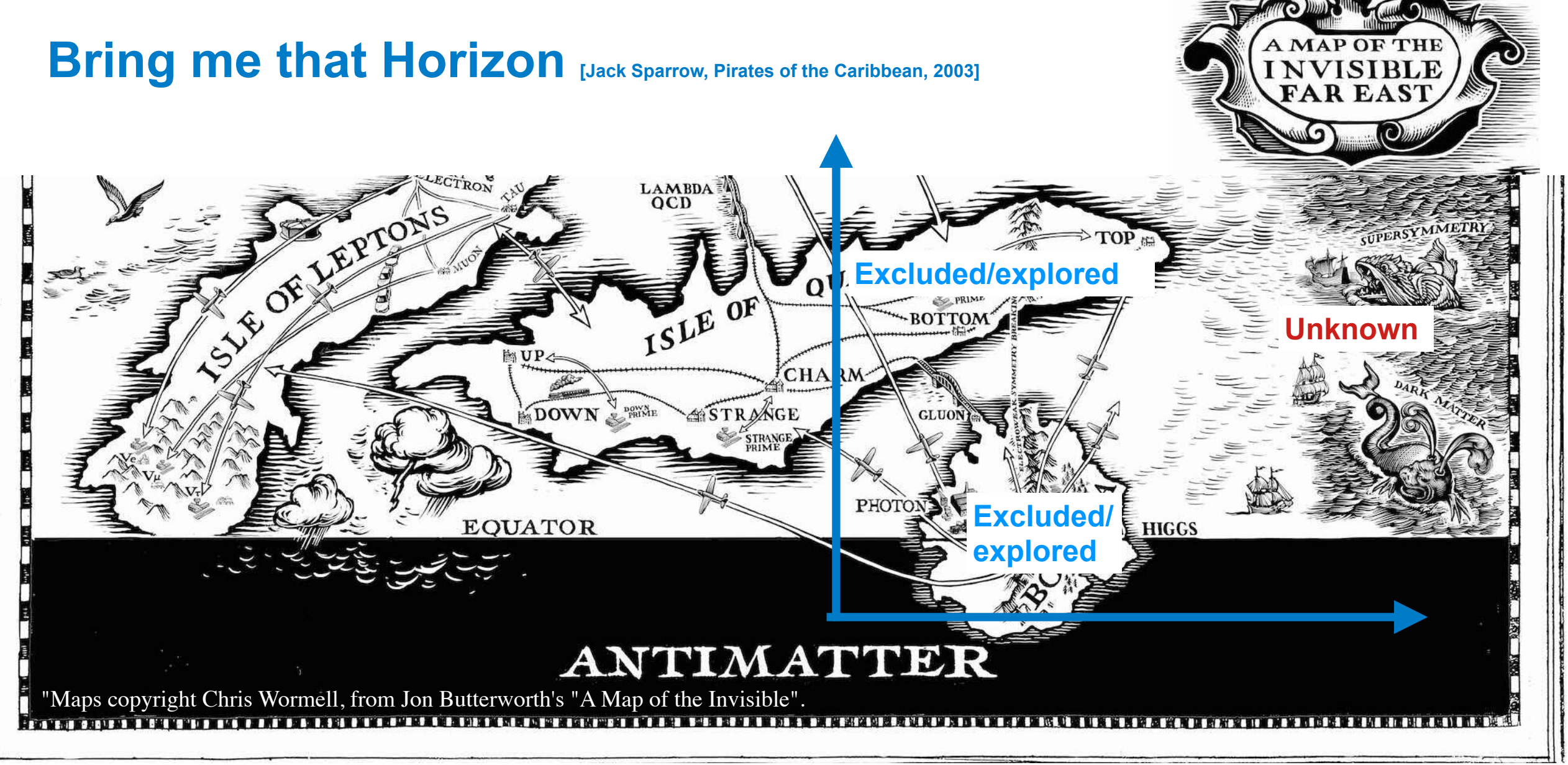

CMS
Dark matter mass mDM [GeV]
Mediator mass mmed [GeV]


CMS
Dark matter mass mDM [GeV]


ATLAS Preliminary
√s = 13 TeV, 139 fb-1
ATLAS
√s = 13 TeV, 3.6-140 fb-1
gq = 0.25
gq = 0.20
gq = 0.15
gq = 0.10
gq = 0.05
Boosted di-b-jet + ISR coverage
Dijet and X + ETmiss limits
Vector mediator, Dirac DM
gq=0.0, gχ=1.0
All limits at 95% CL
tan β
mZ'v [TeV]

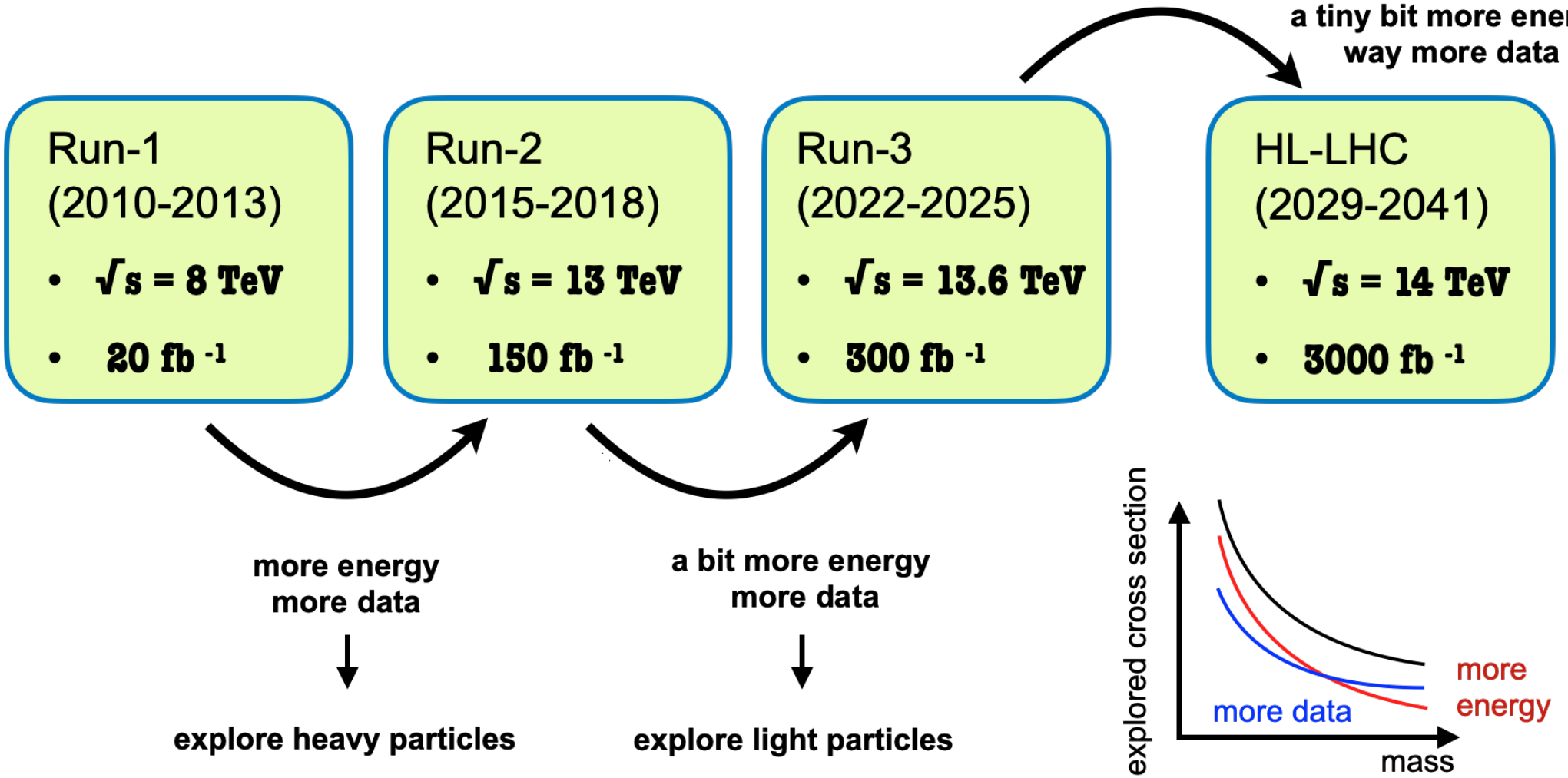

CMS Preliminary
2HDM+S
type II
tanβ = 0.5
35.9-138 fb-1 (13 TeV)
95% CL on B(H→ aa)
2HDM+a, Dirac DM, sin θ = 0.35, tan β = 1, gχ = 1, ma = mH = mH± = 1.2 TeV
ATLAS
√s = 8 TeV, 20.3 fb-1
√s = 13 TeV, 36.1-139 fb-1
June 2024
Limits at 95% CL
Observed
Expected
h→invisible,
ETmiss+h(bb̄),
ma (GeV)

Bring me that Horizon [Jack Sparrow, Pirates of the Caribbean, 2003]



"Maps copyright Chris Wormell, from Jon Butterworth's "A Map of the Invisible".

The importance of focusing on low masses



Conclusions and credits (again)

CMS:"Dark sector searches with the CMS experiment", arXiv:2405.13778 (EXO-2023-005)

ATLAS:"ATLAS searches for additional scalars and exotic Higgs boson decays [..]" arXiv:2405.04914 (HDBS-2023-15)

Signature	Exp.	Reference
phi->ll (tt/W/Z)	CMS	EXO-21-018
displaced μμ	CMS	HIG-21-004
h->γγ	CMS	HIG-20-002
H->aa, μμττ	CMS	HIG-18-024
H->aa, μμ+2tracks	CMS	HIG-18-006
H->aa, μμbb	CMS	HIG-18-011,
H->aa, μμττ	CMS	HIG-17-024,
H->aa,μμττ	CMS	HIG-17-029,
bba(μμ)	CMS	HIG-15-009,
VH, H->aa->4b	CMS	HIG-18-026
H -> ττ	CMS	HIG-21-001
H->aa, a->γγ	CMS	HIG-21-016
H->Za, a->γγ	CMS	HIG-22-003
H->aa μμbb/ττbb	CMS	HIG-22-007

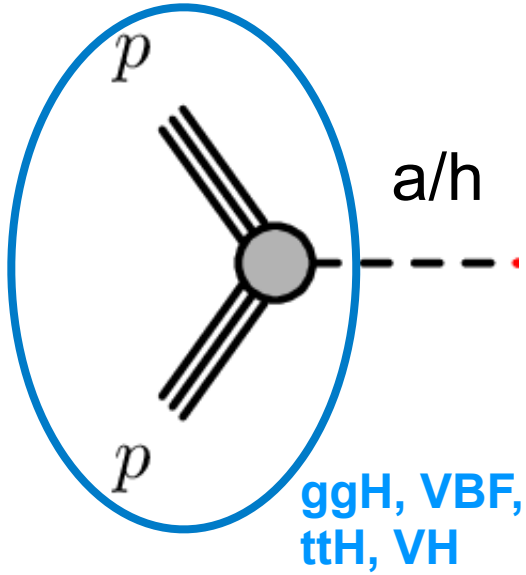
Signature	Exp.	Reference
h->γγ	ATLAS	HIGG-2023-12
S->ZdZd->4lep	ATLAS	HDBS-2021-13
H->Za, a->jj	ATLAS	HDBS-2021-09
A->ττ	ATLAS	HDBS-2021-08
H->aa, bbττ	ATLAS	HDBS-2021-07
H->aa, 4γ	ATLAS	HDBS-2019-19
H->Za, a->γγ	ATLAS	HDBS-2019-09
tta, a->μμ	ATLAS	HDBS-2020-12
rare decays	ATLAS	HDBS-2019-33
H->aa, bbμμ	ATLAS	HDBS-2021-03
H->SUSY	ATLAS	HDBS-2018-07

- Exploration of low-mass BSM Higgs and exotics decays well advanced - congratulations to the experiments for the extensive effort!
- Looking forward to new ideas, Run-3 exploitation and HL-LHC

Thank you

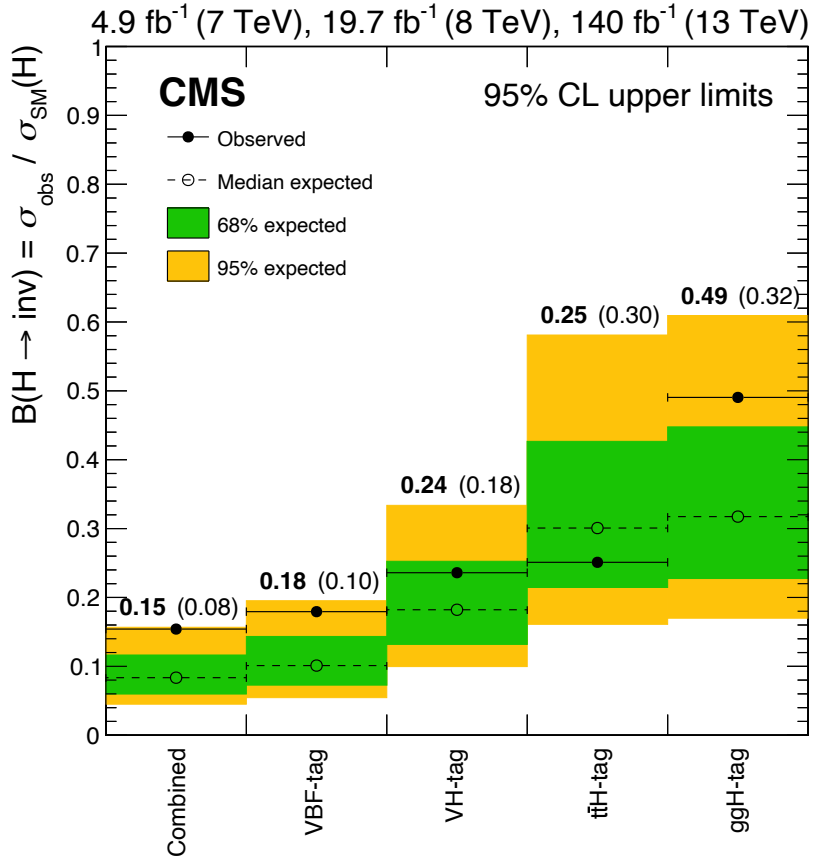
Backup slides

Single BSM higgs searches



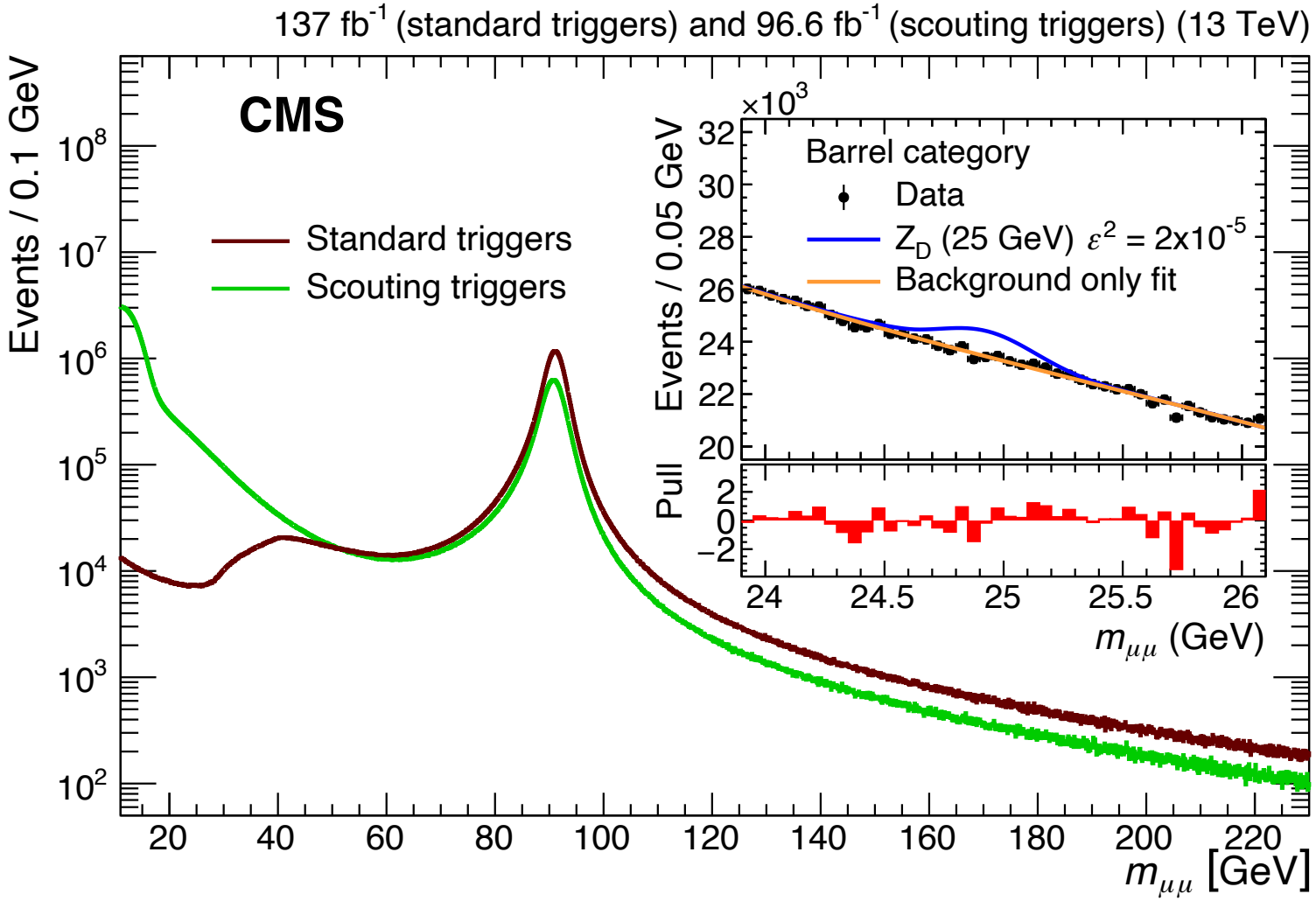
- Great results in constraining H → invisible < 10-15%
- Trigger requirements and large backgrounds are often challenging in some other final states
- Unique probe of intermediate mass regime (60-200 GeV) - *synergies with data scouting and b-jet TLA (?)*
- Increasing efforts in non-standard final states: Long Lived particles (LLPs) and SUSY decays -*latter to be extended?*

H → invisible

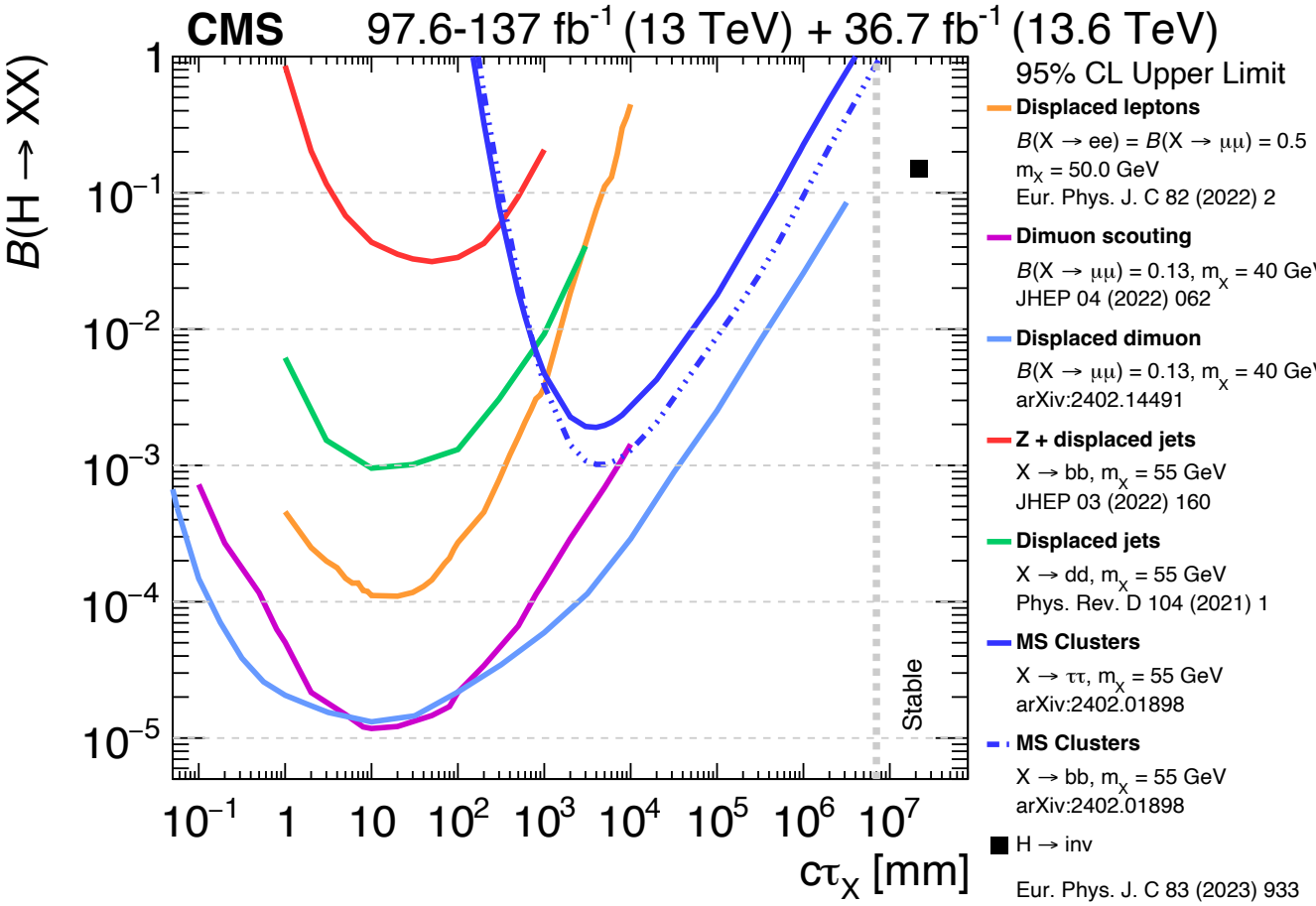


CMS:arXiv:1809.05937

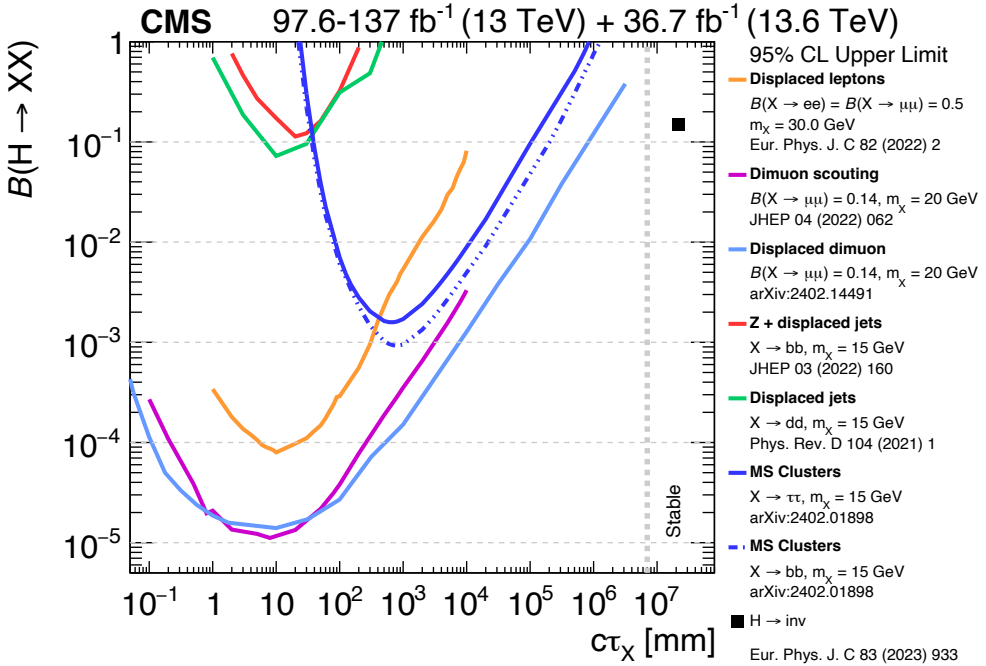
ATLAS:arXiv:2301.10731

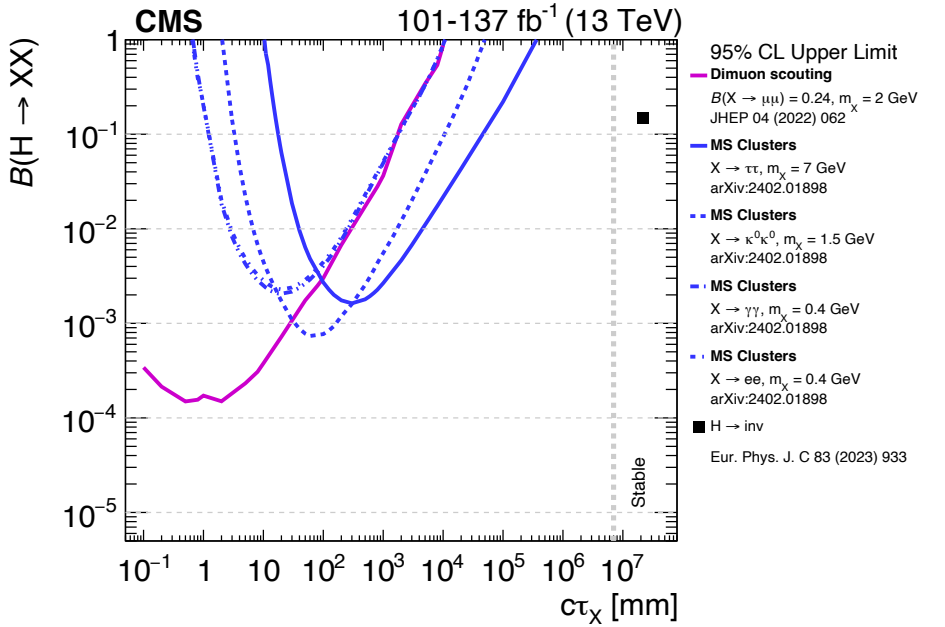

137 fb^{-1} (standard triggers) and 96.6 fb^{-1} (scouting triggers) (13 TeV)
CMS
Standard triggers
Scouting triggers
Events / 0.1 GeV
$m_{\mu\mu}$ [GeV]
Barrel category
Data
Z_D (25 GeV) $\varepsilon^2 = 2\text{x}10^{-5}$
Background only fit
Events / 0.05 GeV
Pull
$m_{\mu\mu}$ (GeV)

LLP summary



ATLAS: arXiv:2405.13778 (CMS-EXO-23-005)

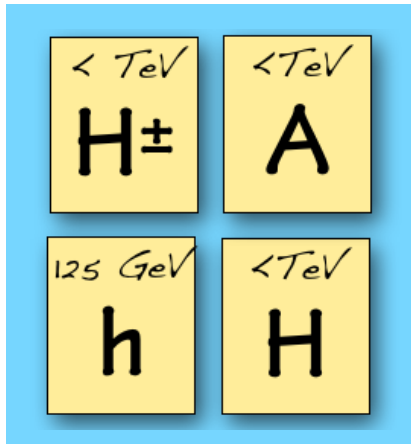




More Higgses

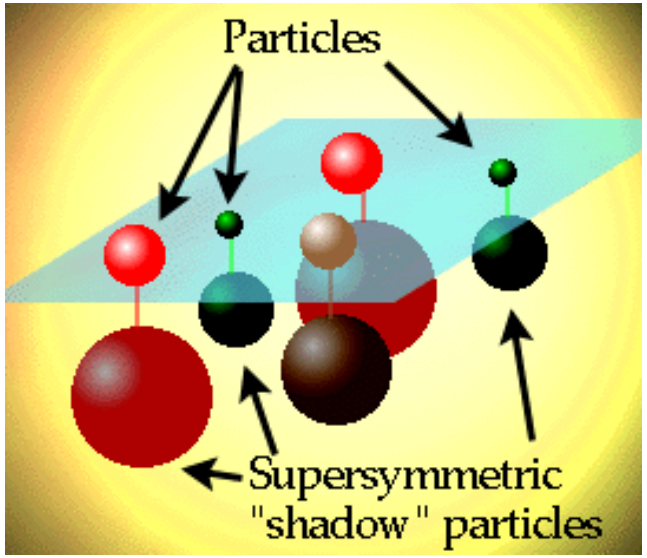
theoretical framework

EXTENDED HIGGS SECTORS **2HDM**



SUPERSYMMETRY

ewkinos
NMSSM
2HDM+S
….



2HDM+a
Higgs Portal

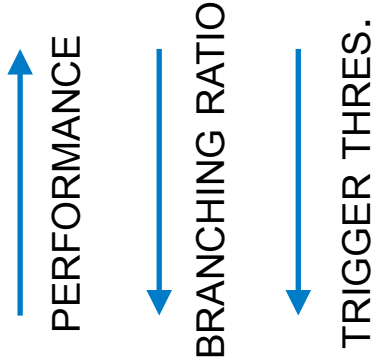
DARK MATTER /
DARK SECTOR

- Parameter : **mass**, **tanβ** (ratio of vev, v2/v1) , **α** (mixing angle between the h, H)
- **Type 1** : One doublet couples to V(fermiophobic), one to fermions
- **Type 2** : MSSM like model, one doublet couples to up-type quark, one to down-type quarks
- **Type 3** : Lepton-specific model, same coupling to quarks as Type 1 & to lepton as Type 2
- **Type 4** : Flipped model, same coupling to quarks as Type 2 & to lepton as Type 1

Key experimental ingredients

Particle identification performance

- muons
- bjets
- taus



(*) Also valid for $\gamma\gamma$, but considered more in the context of ALPs

Mass reconstruction

Background modelling

Systematic uncertainties

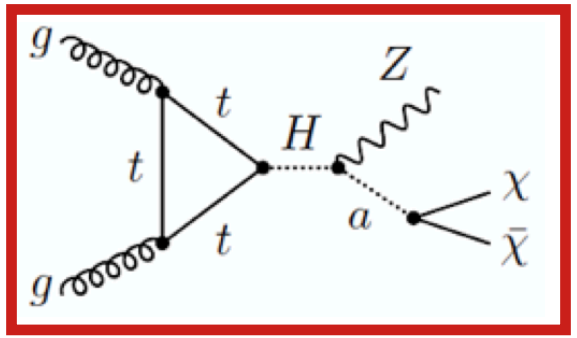
+ Rigorous blinding procedure,
+ non-discovery results interpreted as broadly as possible

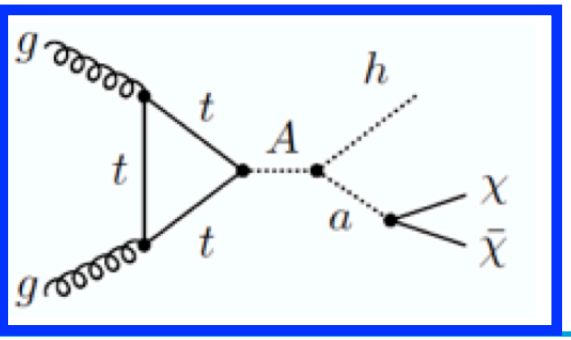
Higgs and Dark Matter

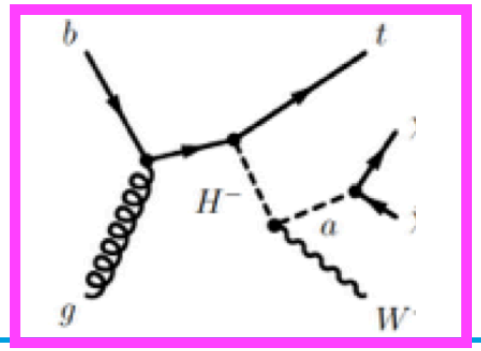
2HDM+a

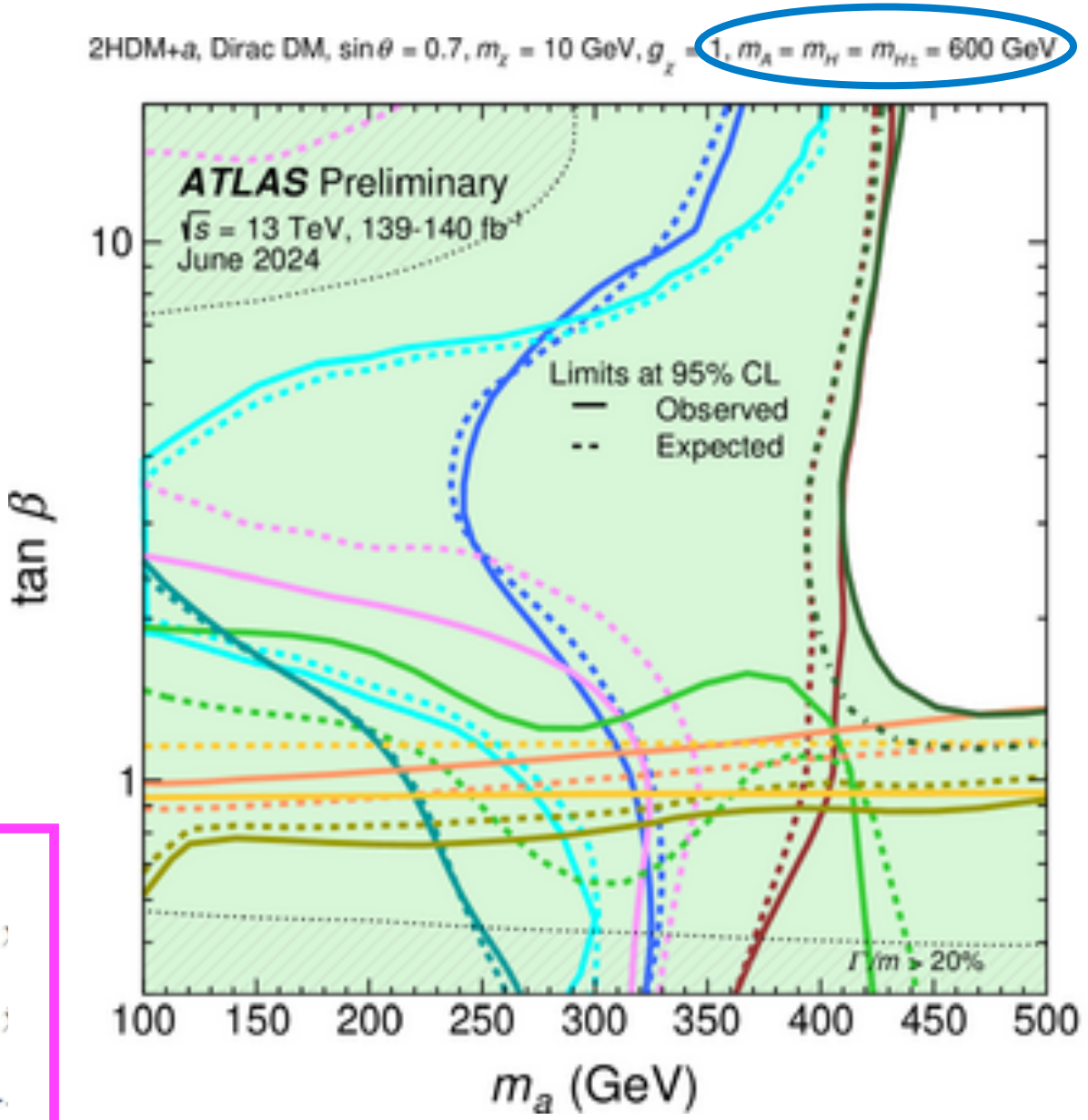
2HDM DM models

< TeV $H^{\pm}$	<TeV A	~10 GeV χ^0
125 GeV h	<TeV H	~10^2 GeV a

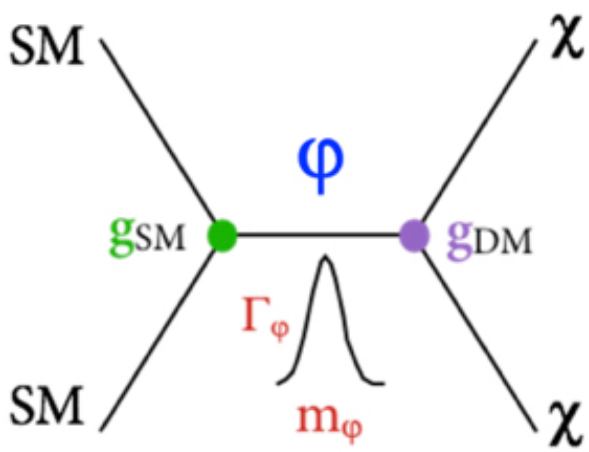


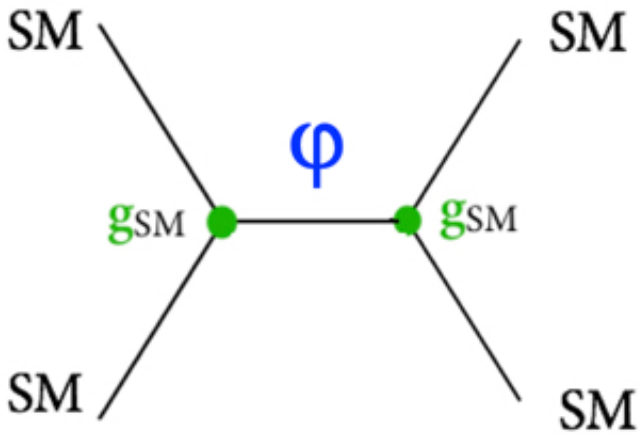






Light Higgs bosons and Dark Matter





1) Mediated by the SM Higgs (H → invisible)

2) Mediated by a light scalar/pseudoscalar (simplified and somewhat simplistic model)

$$\mathcal{L} \sim \sum_f i g_v \frac{y_f}{\sqrt{2}} a \bar{f} \gamma^5 f$$

→ **Enhanced cross-section for tops and bottoms**
(small cross section for light quarks)

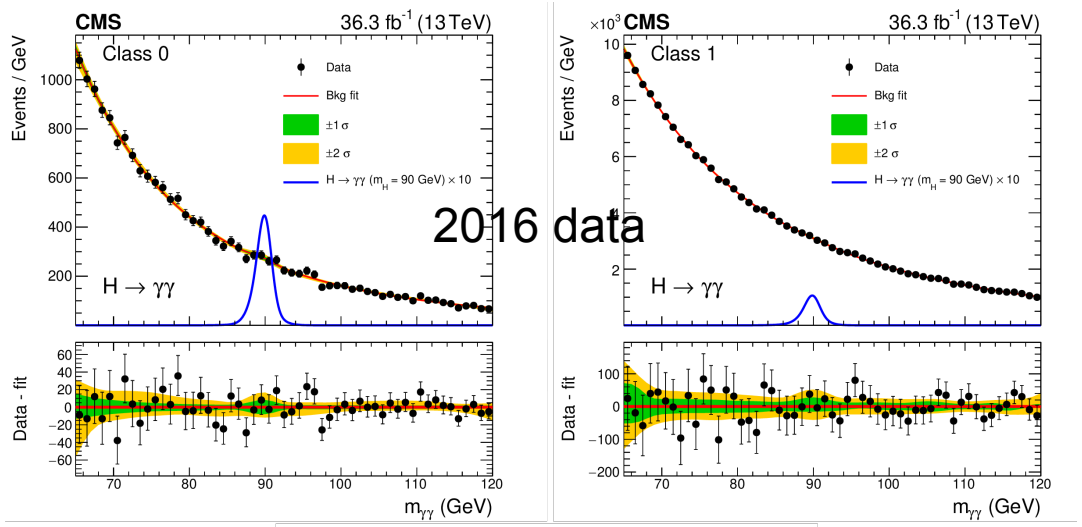
CMS: arXiv:2405.13778 (EXO-2023-005)

ATLAS: arXiv:2404.15930 (EXOT-2018-62)

3) Mediated by a light scalar/pseudoscalar within an extended Higgs sector (UV complete and rich phenomenology)

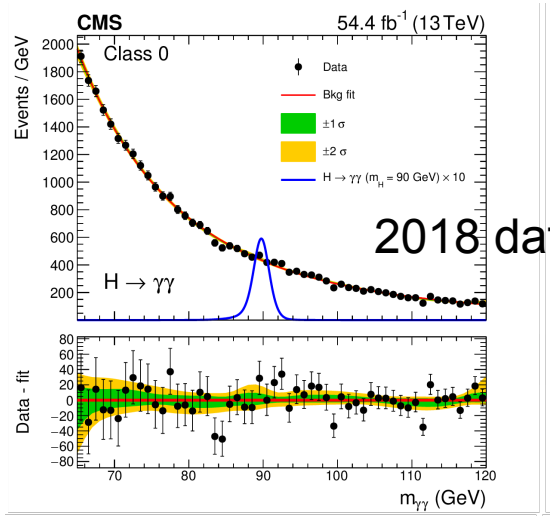
Results in the next slide

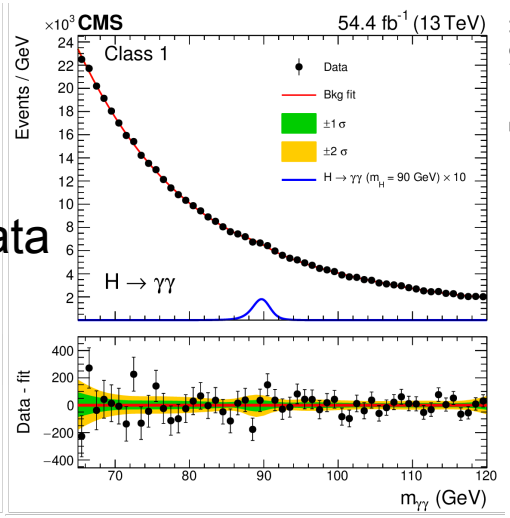
Highlight #4: di-photon searches 70 < mγγ <110 GeV



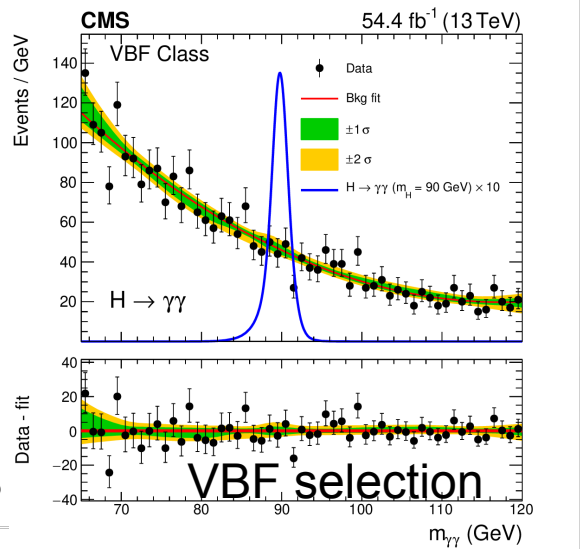
2016 data

- Complete and improved re-analysis of the entire dataset
- Events divided in various categories, VBF newly added for 2017-2018 data





2018 data



CMS: arXiv:2405.18149 (HIG-20-002)

ATLAS: arXiv:2407.07546 (HIGG-2023-12)