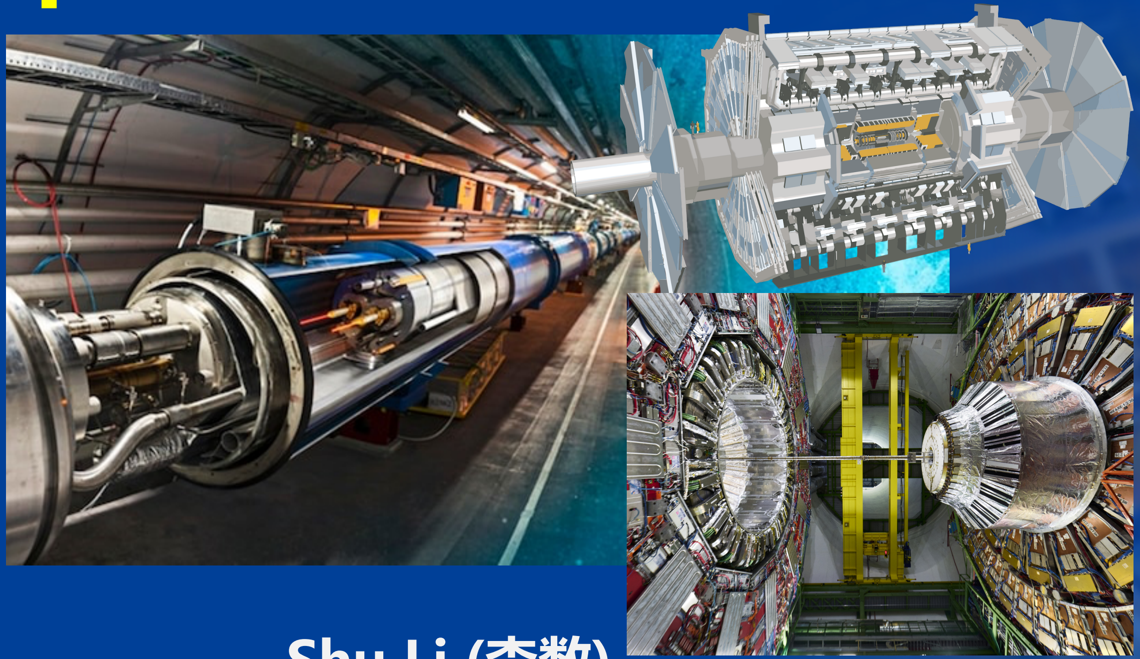
李政道研究所
TSUNG-DAO LEE INSTITUTE

中国高等科学技术中心
China Center of Advanced Science and Technology

ATLAS EXPERIMENT

Probing the BSM phenomena with Higgs portal at ATLAS and future colliders



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24/03/2023

Higgs Mini-Workshop 2023 @ CCAST

Outline: Higgs BSM Probe with selective topics

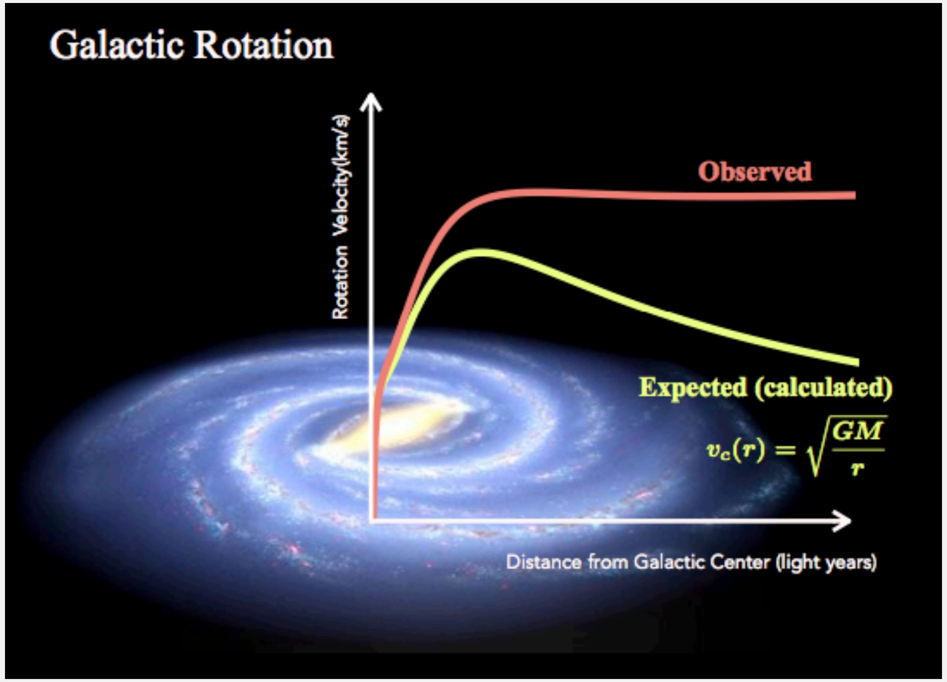
- Probing the Dark Sector with Higgs(-like) boson(s) at ATLAS
  - Dark Higgs searches with Mono-H/Mono-S
  - Invisible decay searches and Dark Photon searches with Higgs

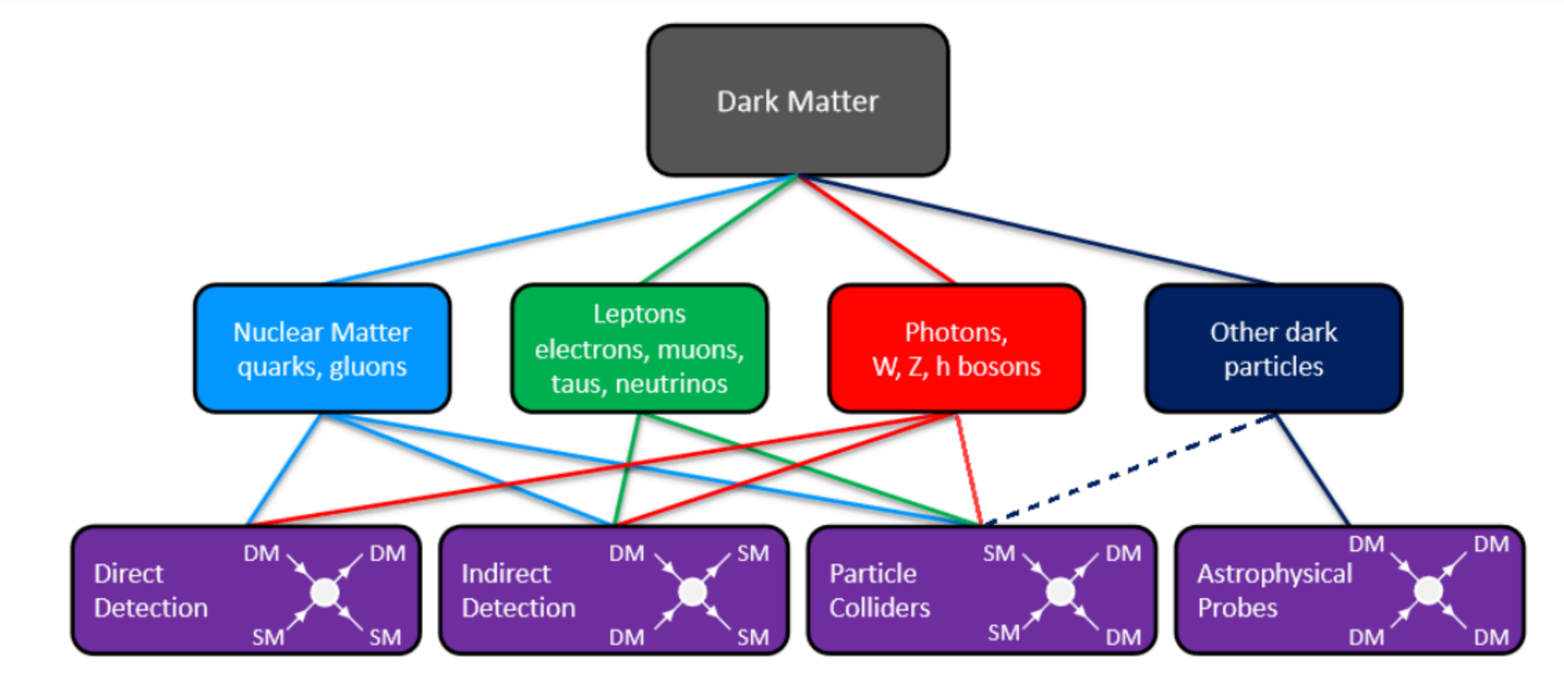
- Exotic Higgs Decays at LHC and Future Colliders
  - H→aa at ATLAS
  - H→aa at CEPC

- Composite Higgs search with VBF Di-Higgs and VBS Di-VectorBoson at ATLAS

Higgs and DM

Dark Matter Evidence and Theory Context in a nutshell





- 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.

Dark Matter Direct Detections

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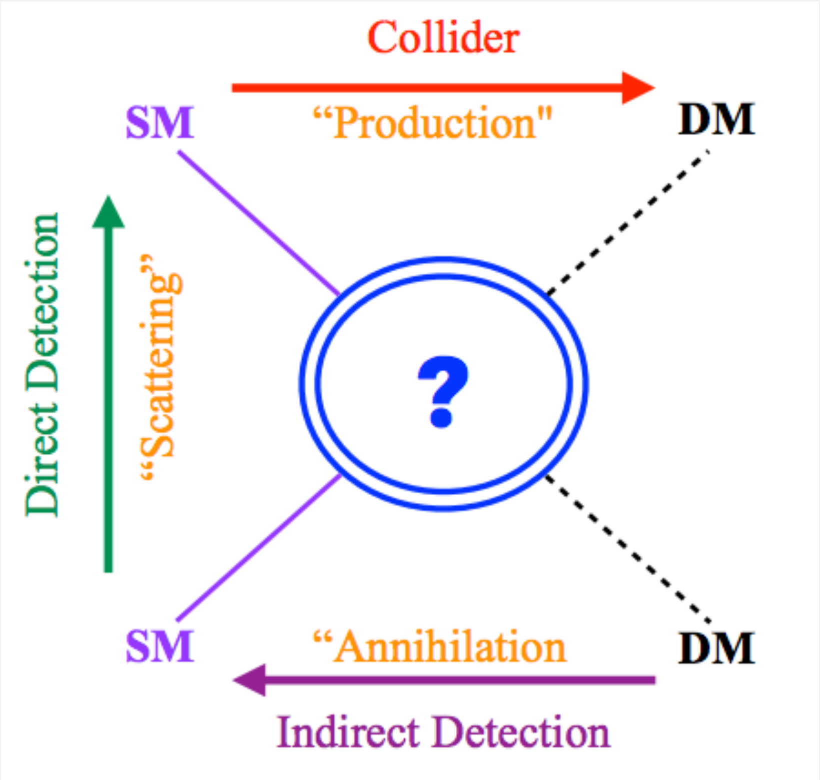
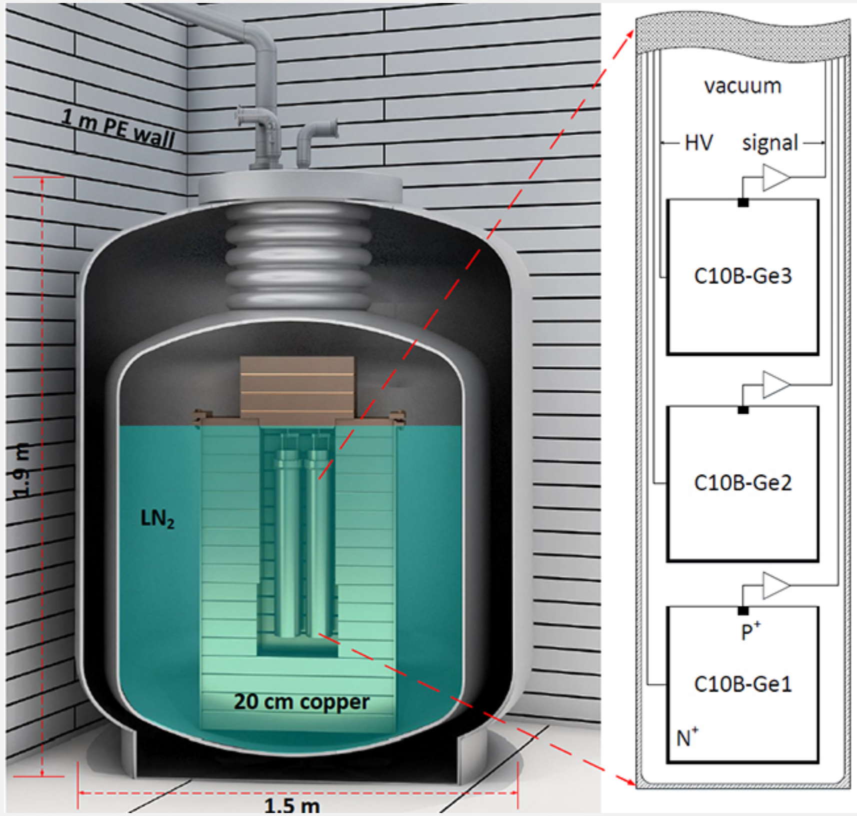
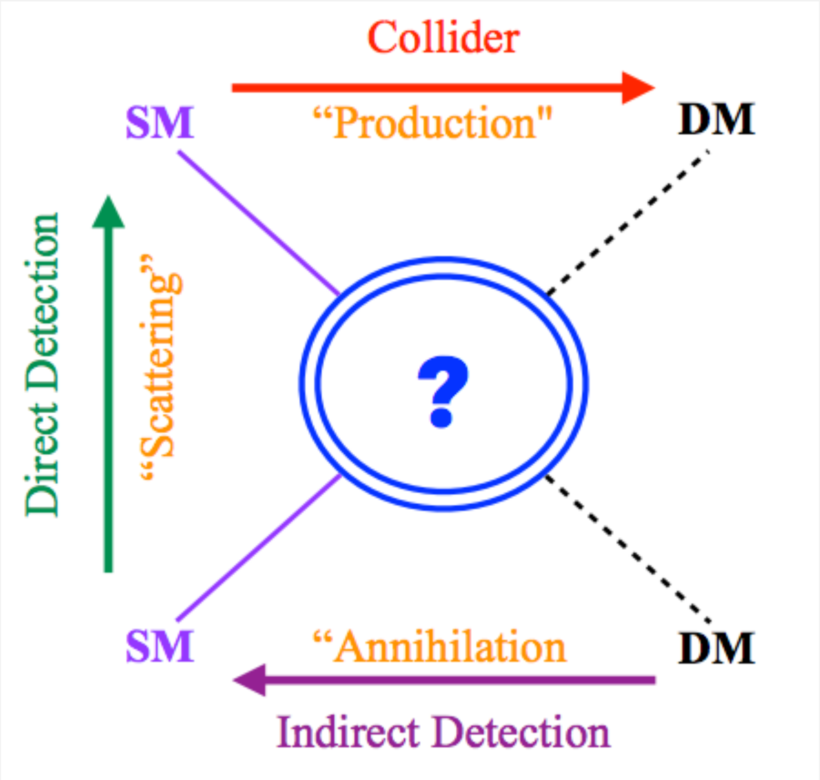
- Direct Detection (DD): nuclear recoils from DM-nuclei scattering (CDEX, PandaX, LZ, XENONnT, ...)
- Indirect Detection (ID): products from DM annihilation (DAMPE, HESS, IceCube, ..)
- Colliders: DM production in high-energy collisions, focusing on the productions of a SM particle(s) (X) with large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

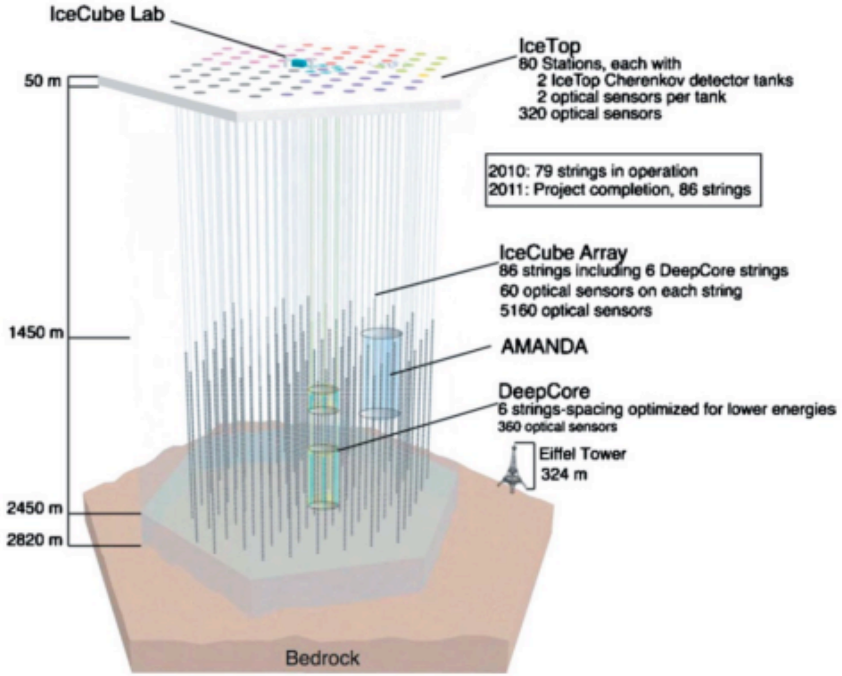




Dark Matter Indirect Detections

- 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, ..)
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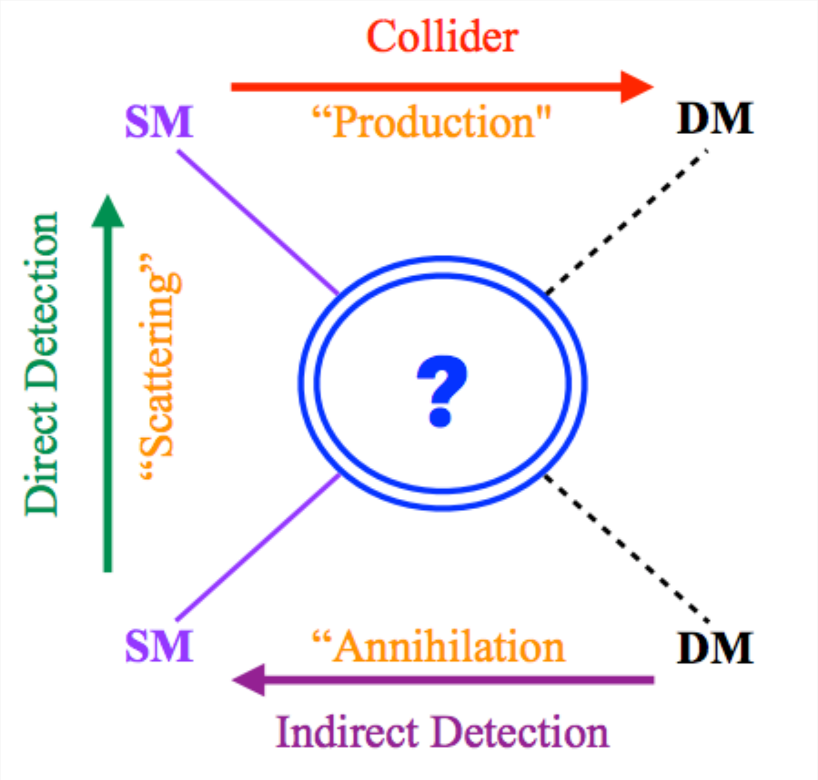
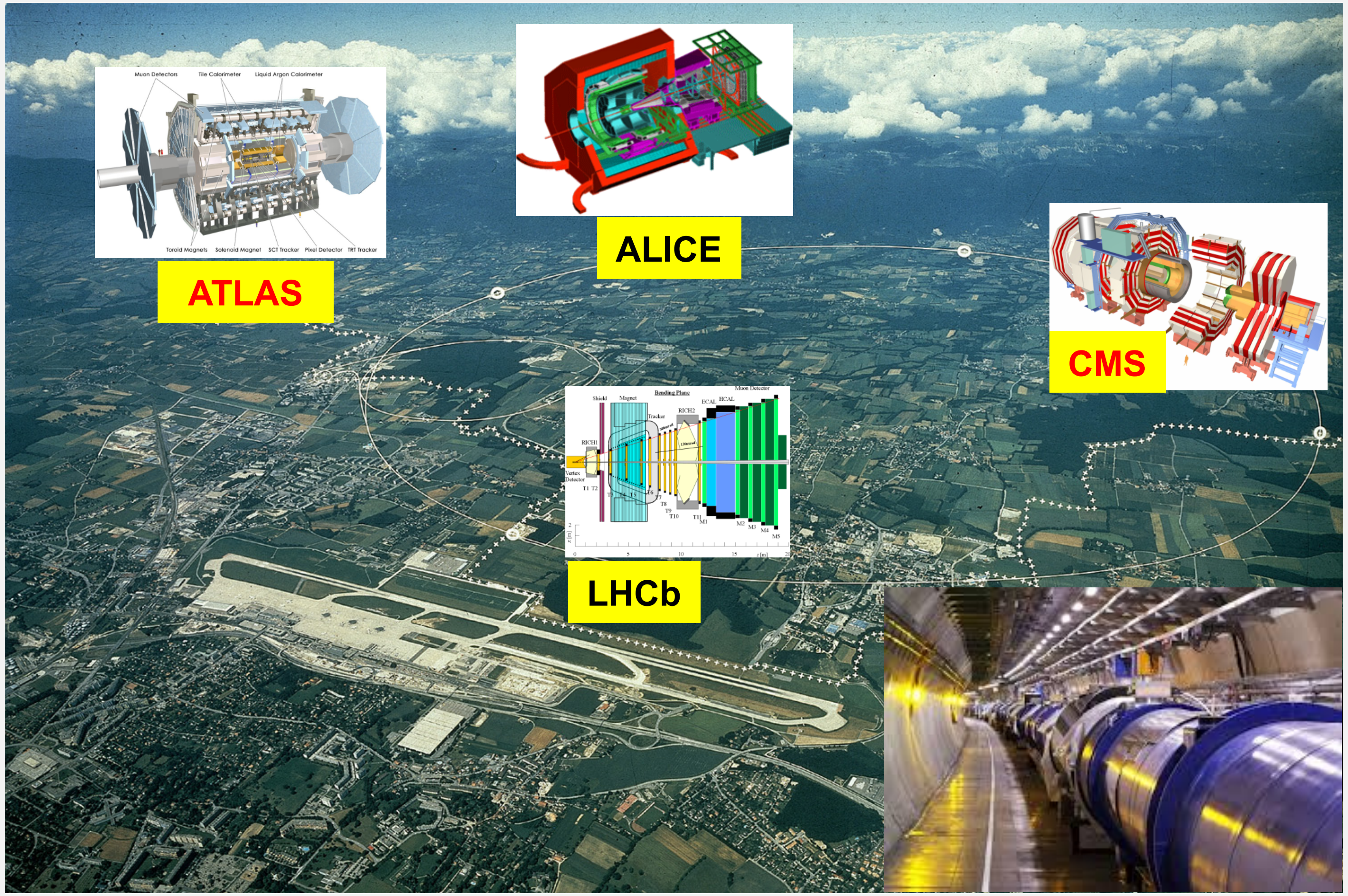
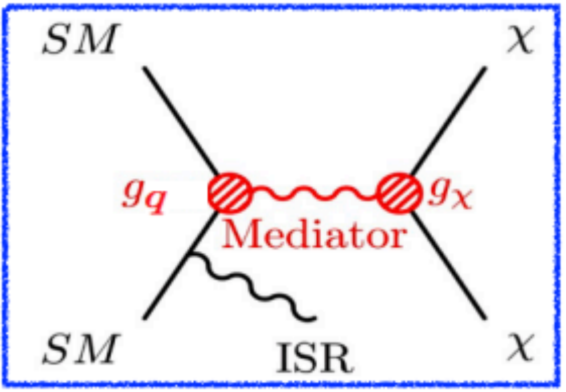


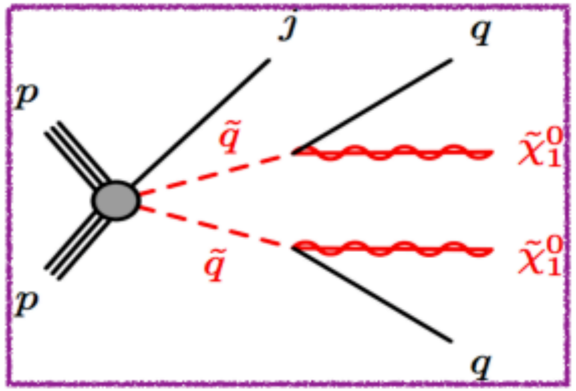


Dark Matter Search programs at LHC

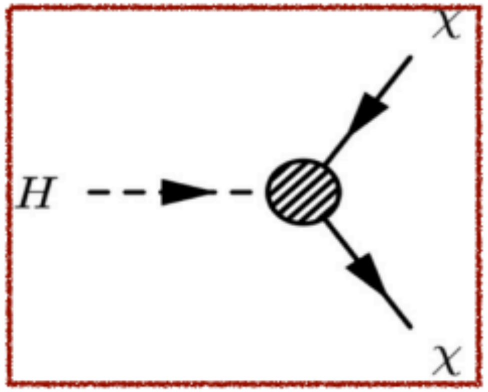
Simplified models | **SUSY** | **Higgs portal** | **Extended Higgs sector**



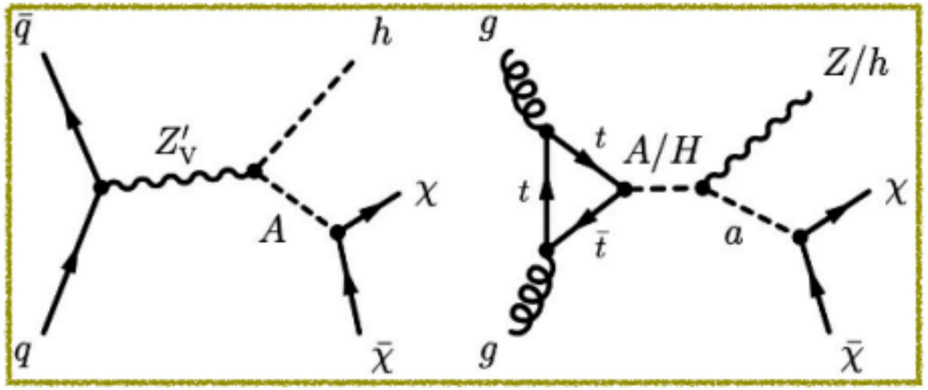
SM-DM boson mediator:
- Spin-0: Scalar (S) or pseudo-scalar (a)
- Spin-1: Vector (V/Z') or axial-vector (A)
- Minimal set of parameters: M_χ, $M_{mediator}$, g_χ, g_q, g_ℓ



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

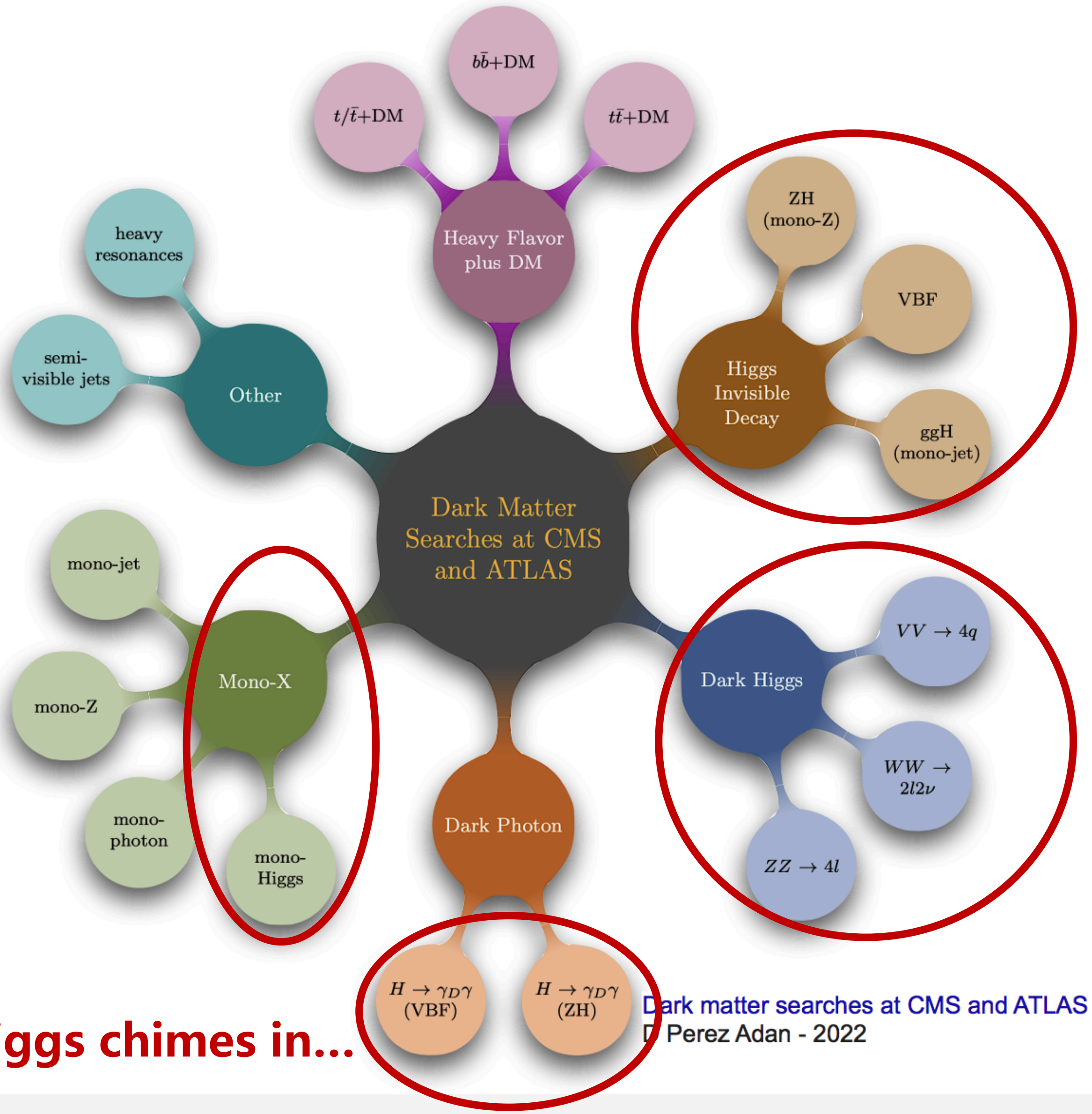


- Higgs boson mediates DM-SM interaction: $H \rightarrow invisible$
- Parameters: m_χ, χ spin



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

Frontiers that DM can reach out



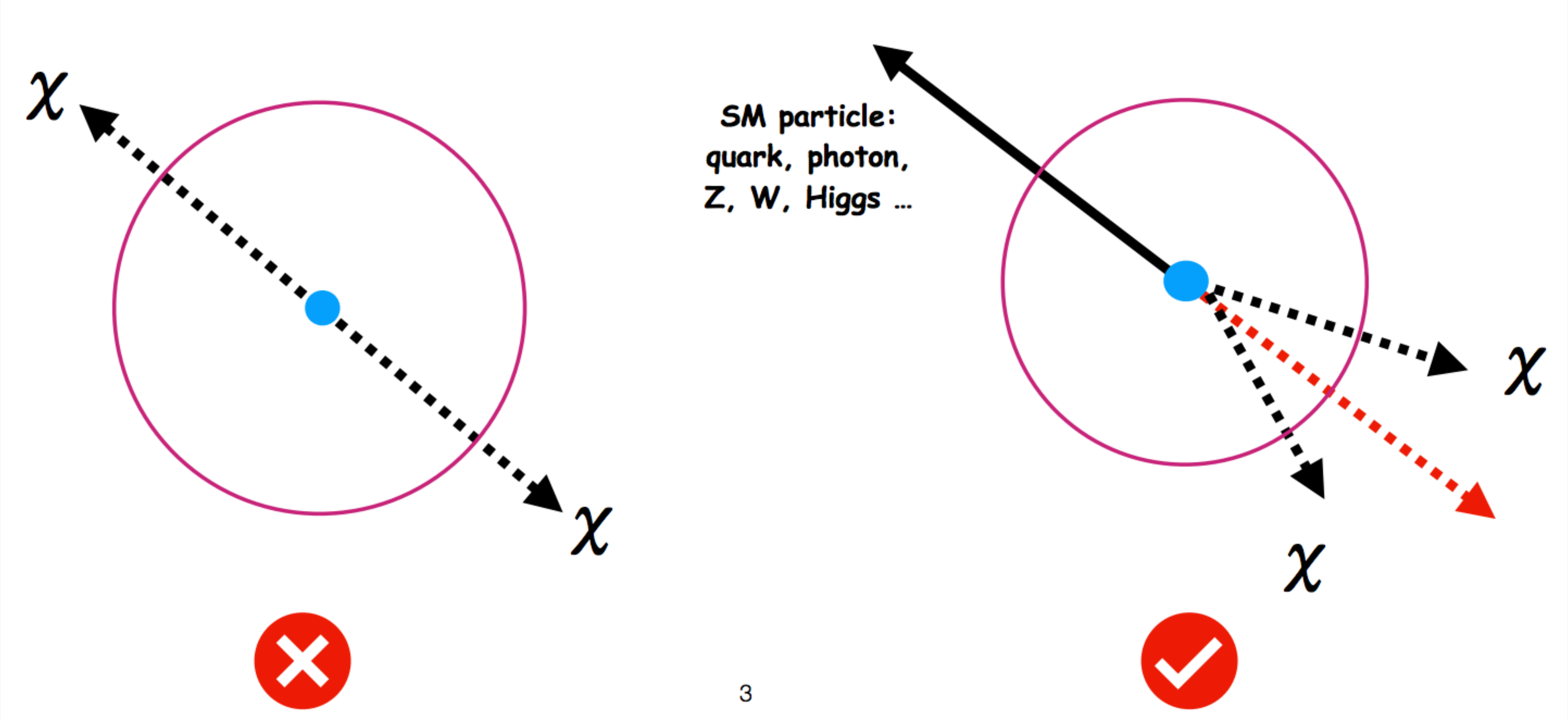
Where Higgs chimes in…

Dark matter searches at CMS and ATLAS
D Perez Adan - 2022

Probing the Dark Sector with Higgs(-like) boson(s) at ATLAS

DM search at ATLAS: ”Mono” signatures

- DM candidates give a missing momentum signature in detector
- We cannot directly observe it (i.e. trigger with nothing) → Need extra visible particles



Higgs portal to DM: Mono-H(γγ)

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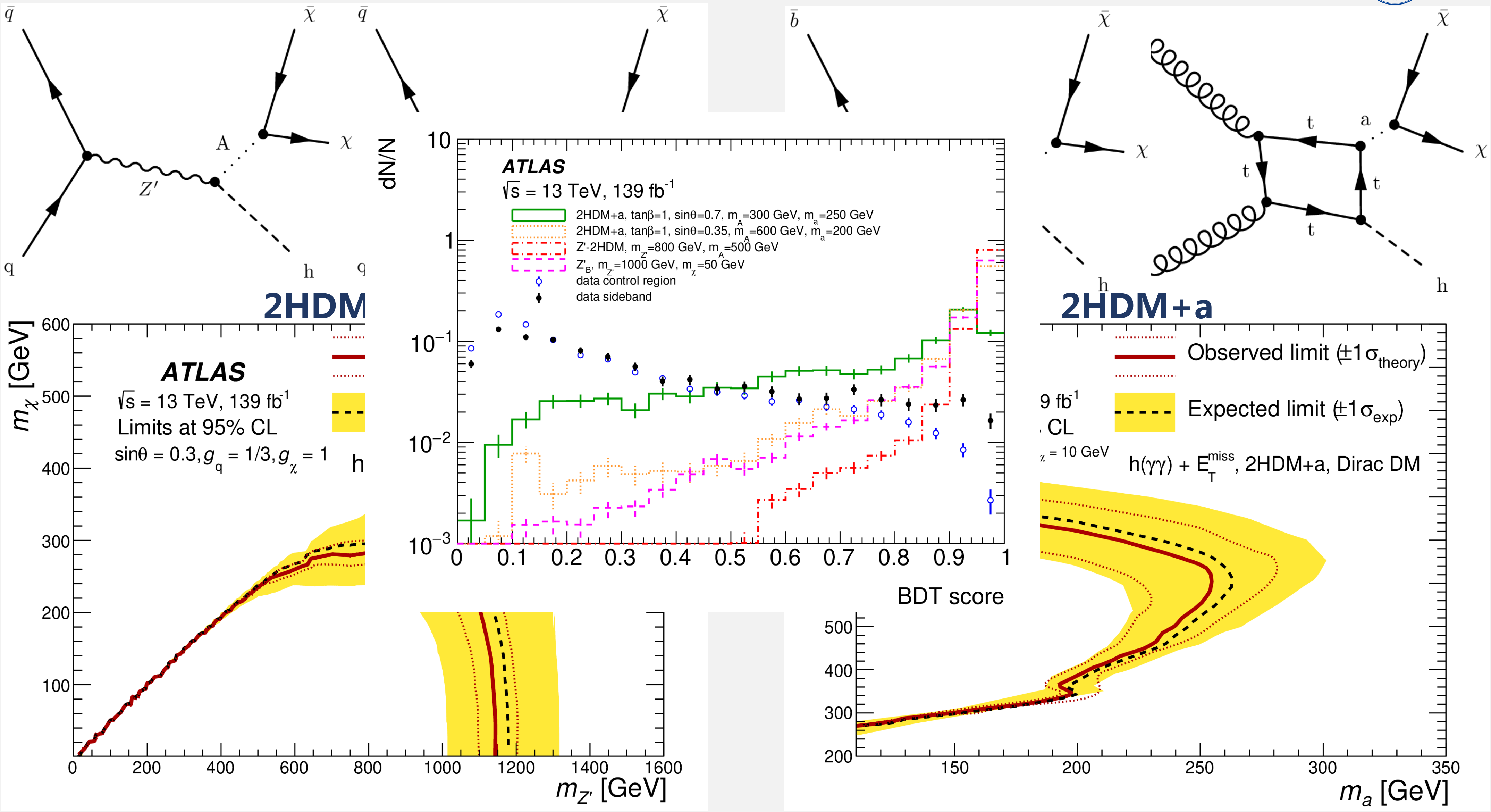

Higgs portal to DM: Mono-H(bb)

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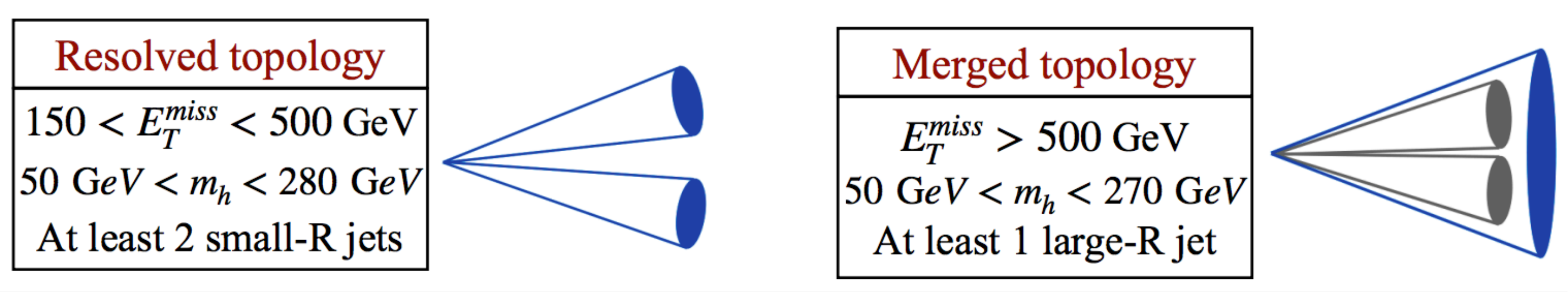
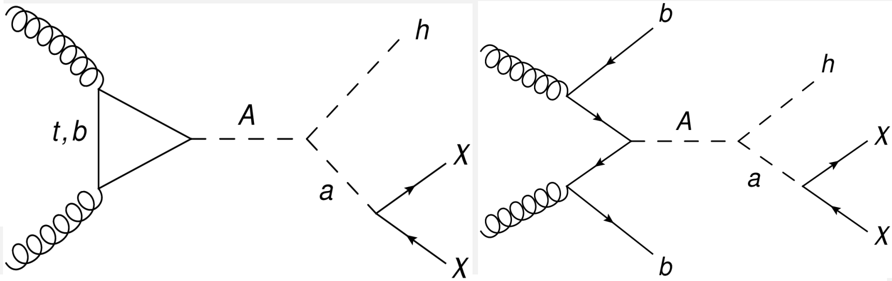
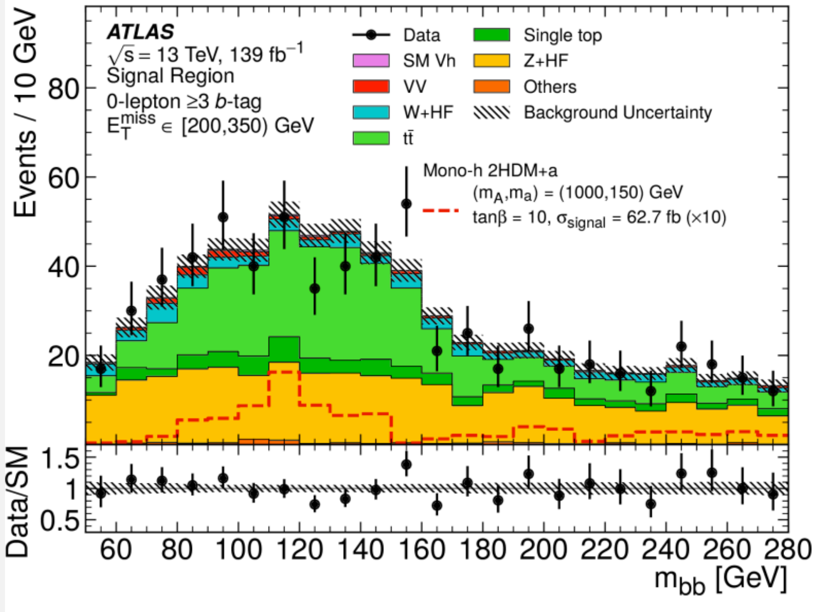
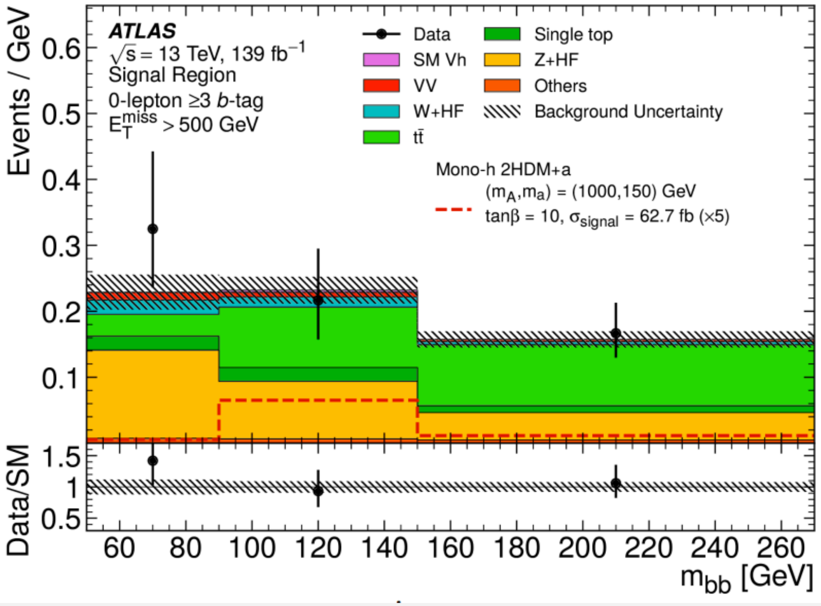
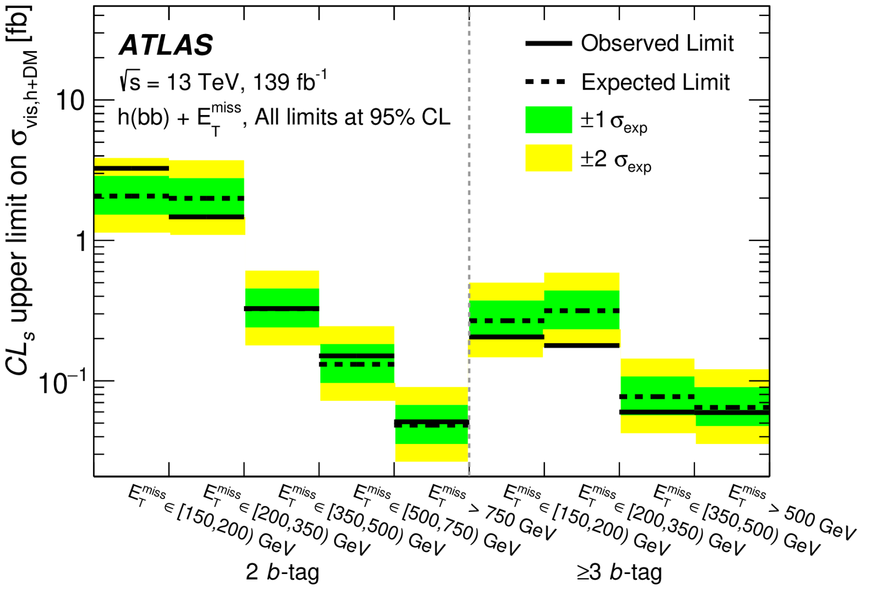
- Interpreted with 2HDM+Z′ , 2HDM+a in both ggF and bbH.
- Also Model-independent upper limits on the visible cross-section





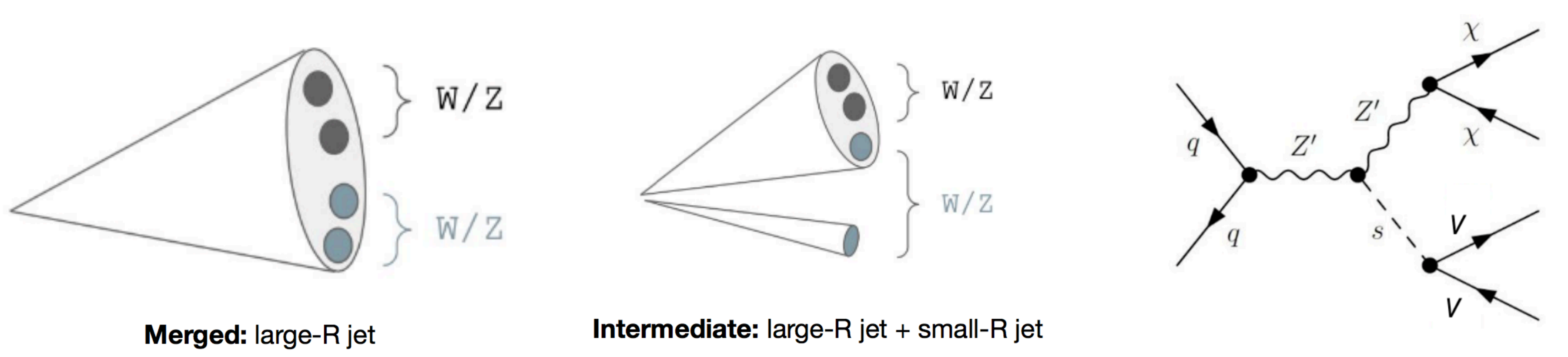


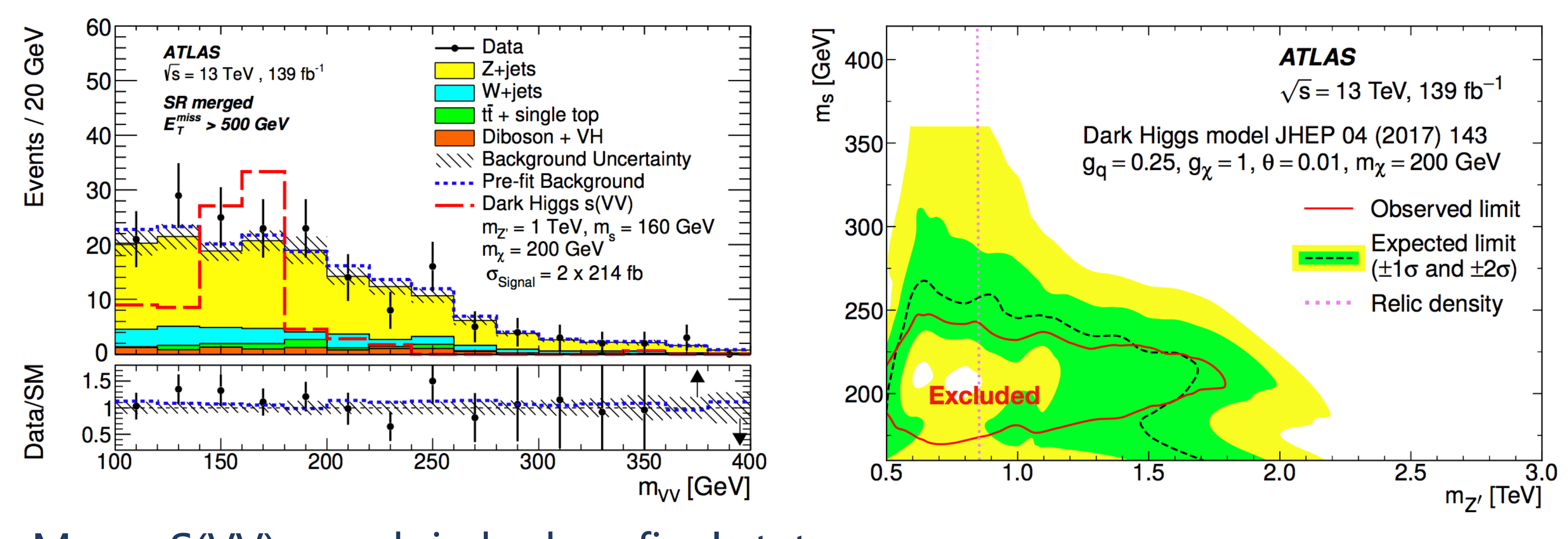




Phys. Rev. Lett. 126 (2021) 121802

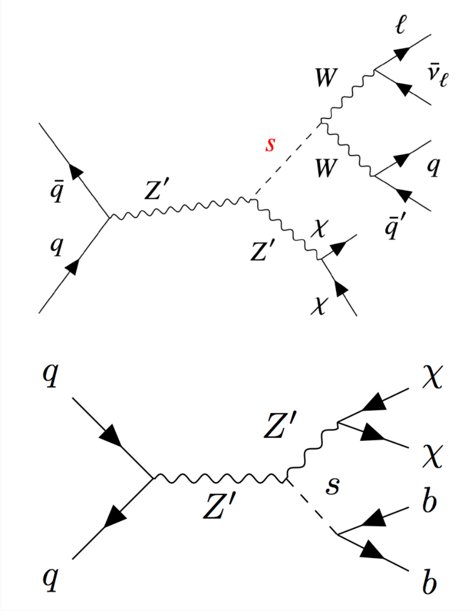
Dark Higgs search: Mono-S(VV) hadronic



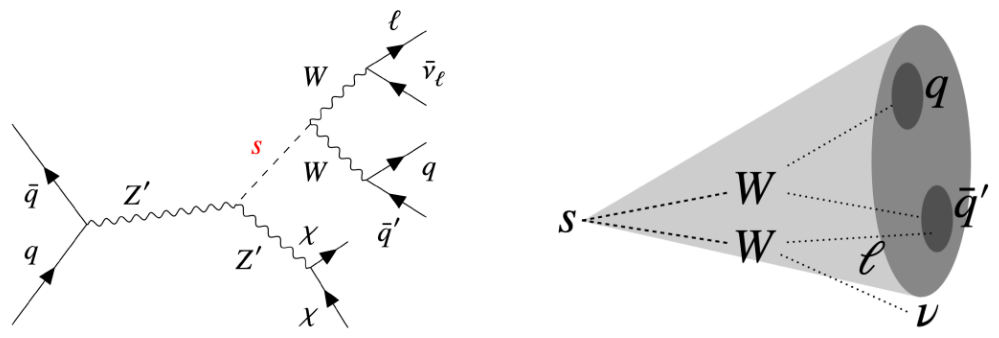


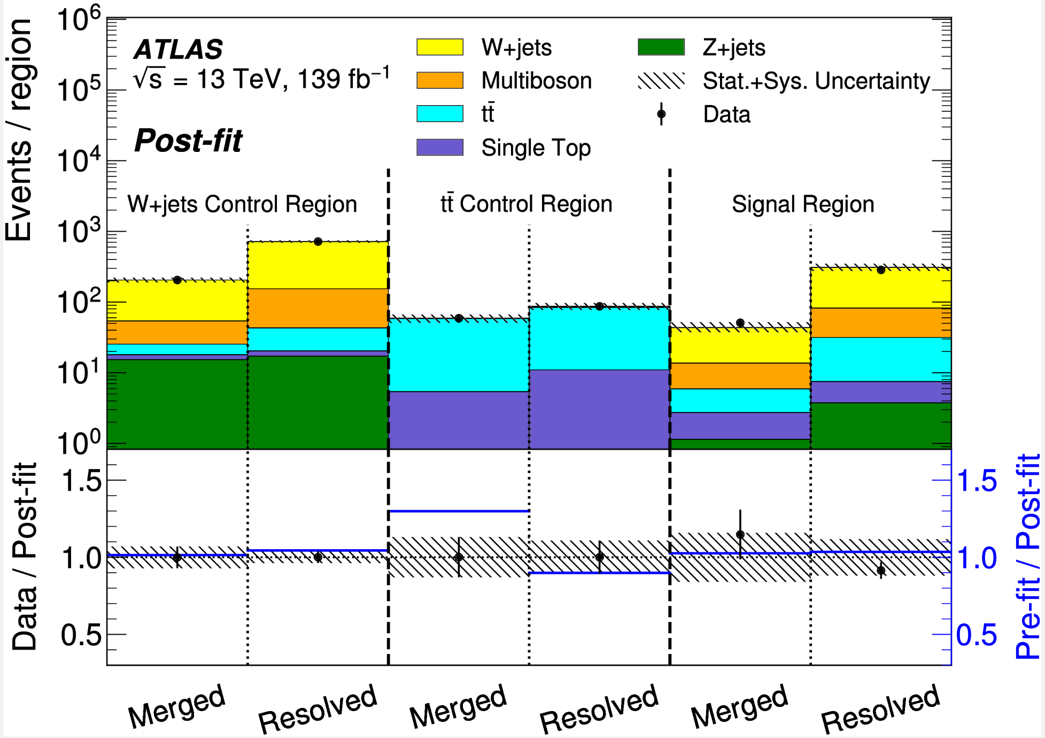
Mono-S(VV) search in hadron final states
- Fitted on the reconstructed mass of the dark Higgs candidate
- Exclusion contour obtained on ms-mZ′ plane

Dark Higgs model
- Specify a mechanism for generating mass of the dark particle and Z′ boson by spontaneous symmetry breaking, associated with a dark Higgs boson
- Predict a novel signature of dark matter production at the LHC: dark Higgs



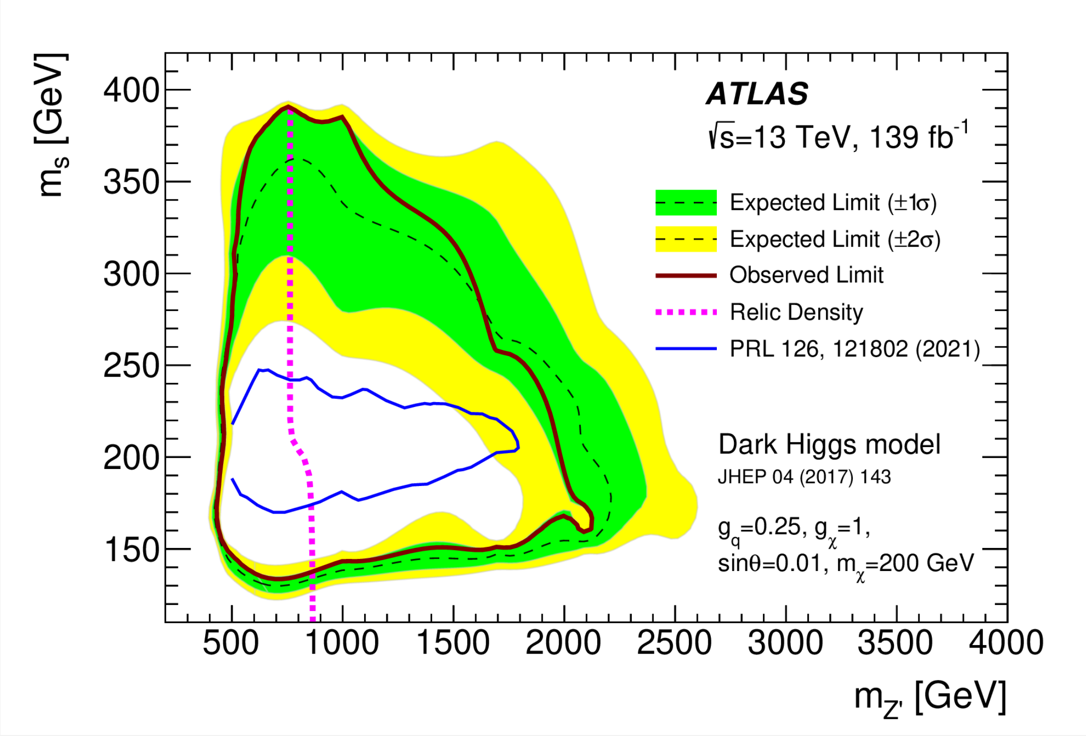
Dark Higgs Search: Mono-S(WW) semileptonic





- 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.



ATL-PHYS-PUB-2019-032

Dark Higgs Search: Mono-S(bb) with novel

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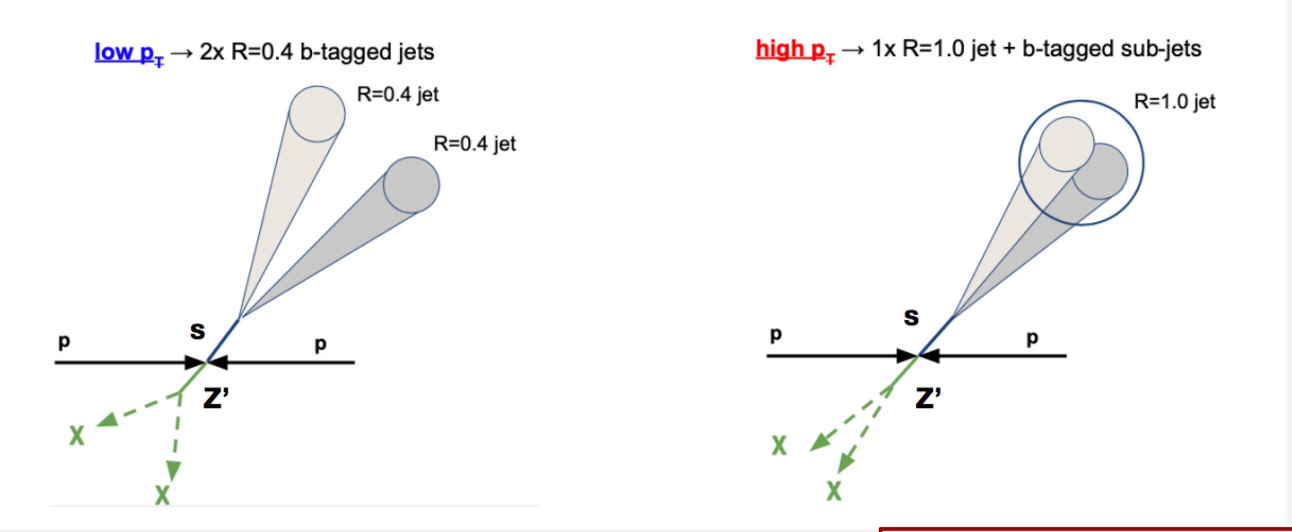
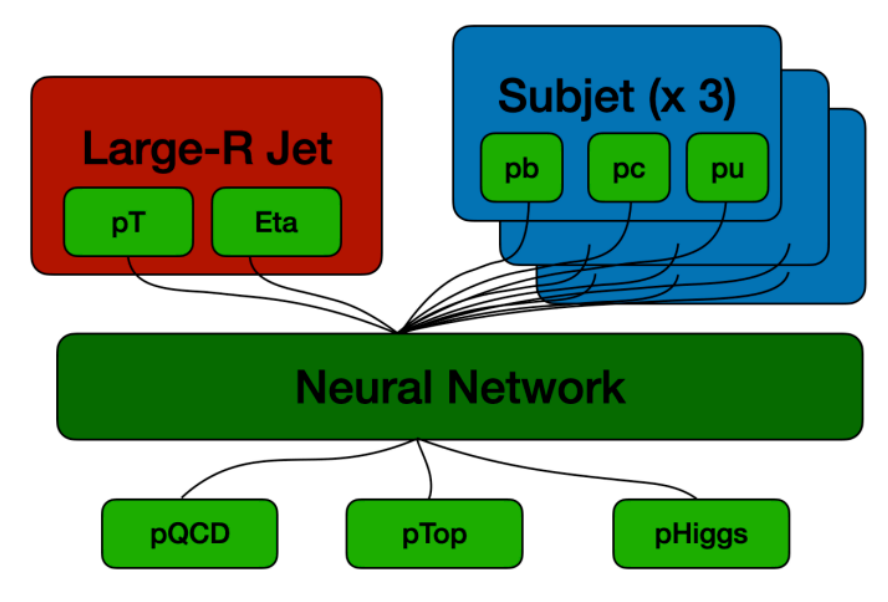
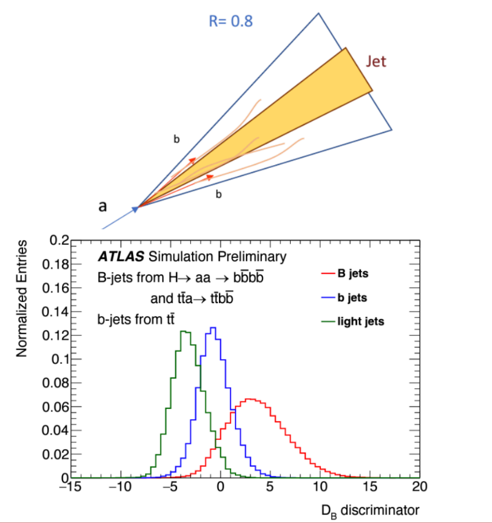
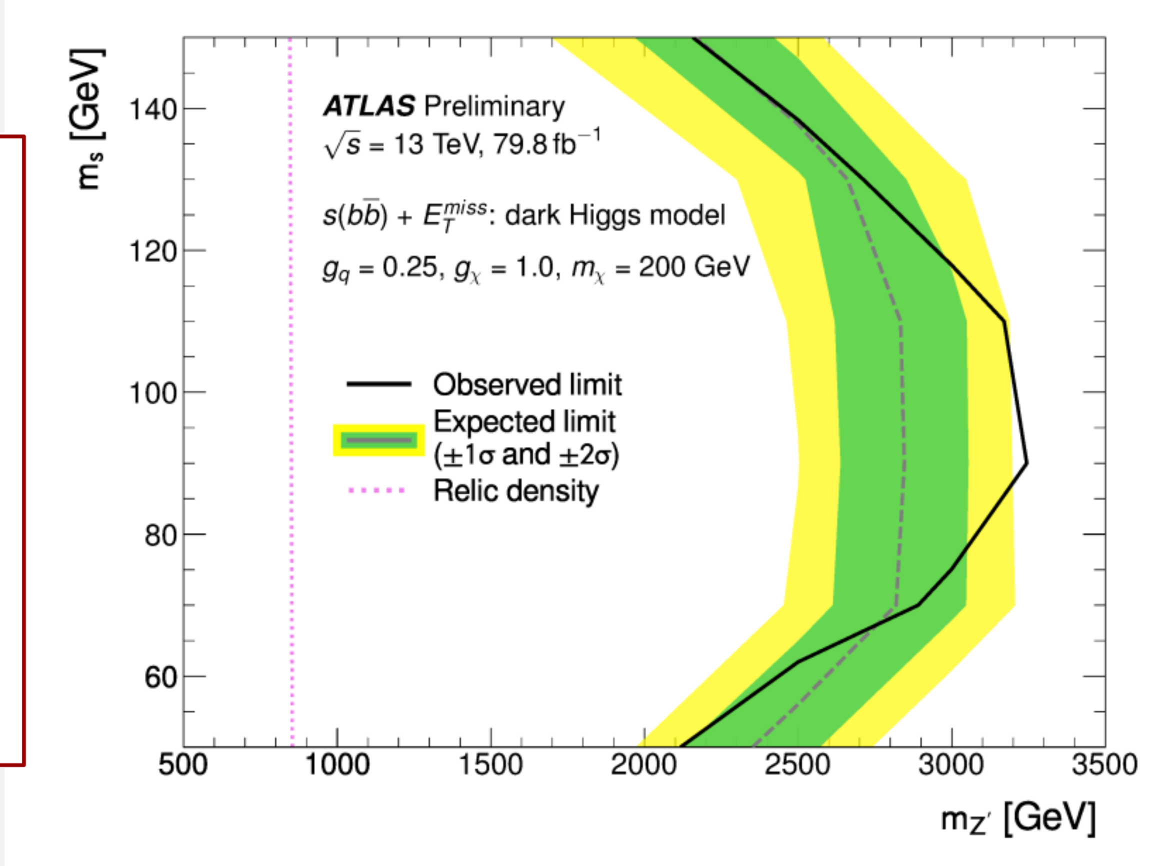


- The previous analysis is the reinterpretation of ATLAS mono-H(bb) result
  - not optimal for dark Higgs signal → require further optimization
  - Floated mS rather than fixed mH = 125 GeV → require high s(→bb) tagging efficiency for all mass range → Dxbb tagger introduced



DeXTer: Deep Set $X \to bb$ Tagger
ATL-PHYS-PUB-2022-042





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Higgs → ” undetected”

Higgs portal to undetected particles

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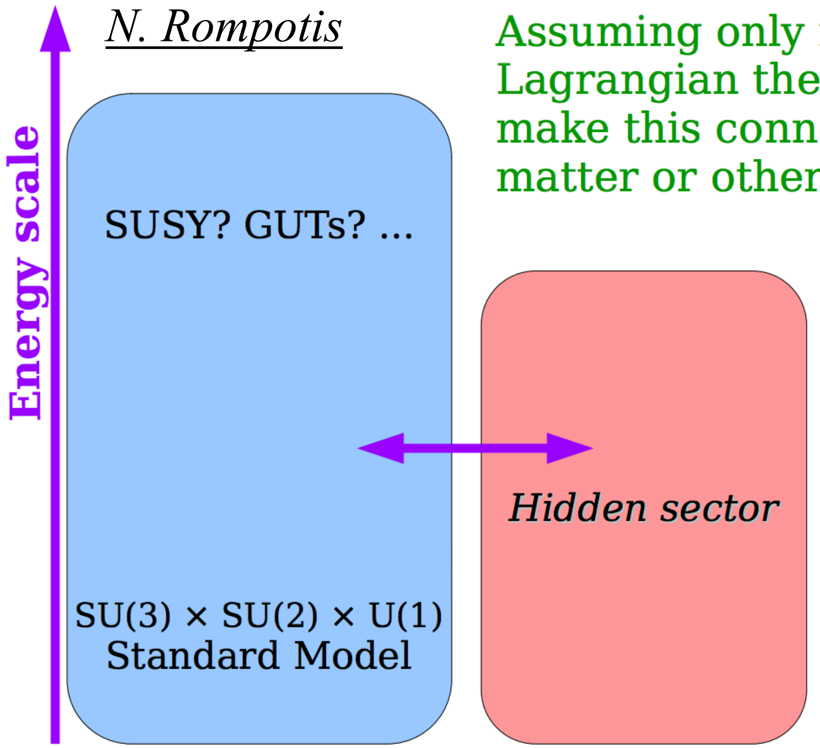
One way to do that would be to consider the Higgs coupling measurements and then see how much space is left for "left-out" decays ("undetected")

95% CL limits on Higgs to "undetected":
ATLAS: < 12% [Nature 607, 52–59 (2022)]
CMS: < 16% [Nature 607, 60–68 (2022)]

N. Rompotis

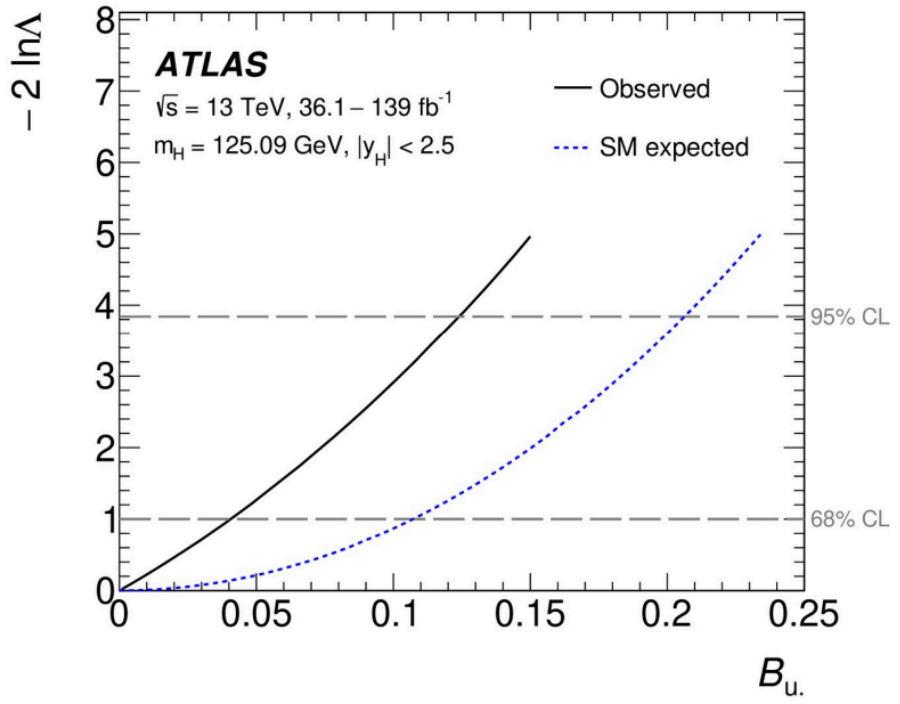


Assuming only renormalizeable terms in the Lagrangian there are only a handful of ways to make this connection! Potential access to Dark matter or other new physics in colliders

$\phi\phi SS$ — **Higgs portal**

$\phi L \psi$ — Neutrino portal

$F_{\mu\nu}F'^{\mu\nu}$ — Vector and Axion portal



Higgs portal to DM: invisible decays

ATLAS:arXiv:2301.10731
CMS: arXiv:2303.01214

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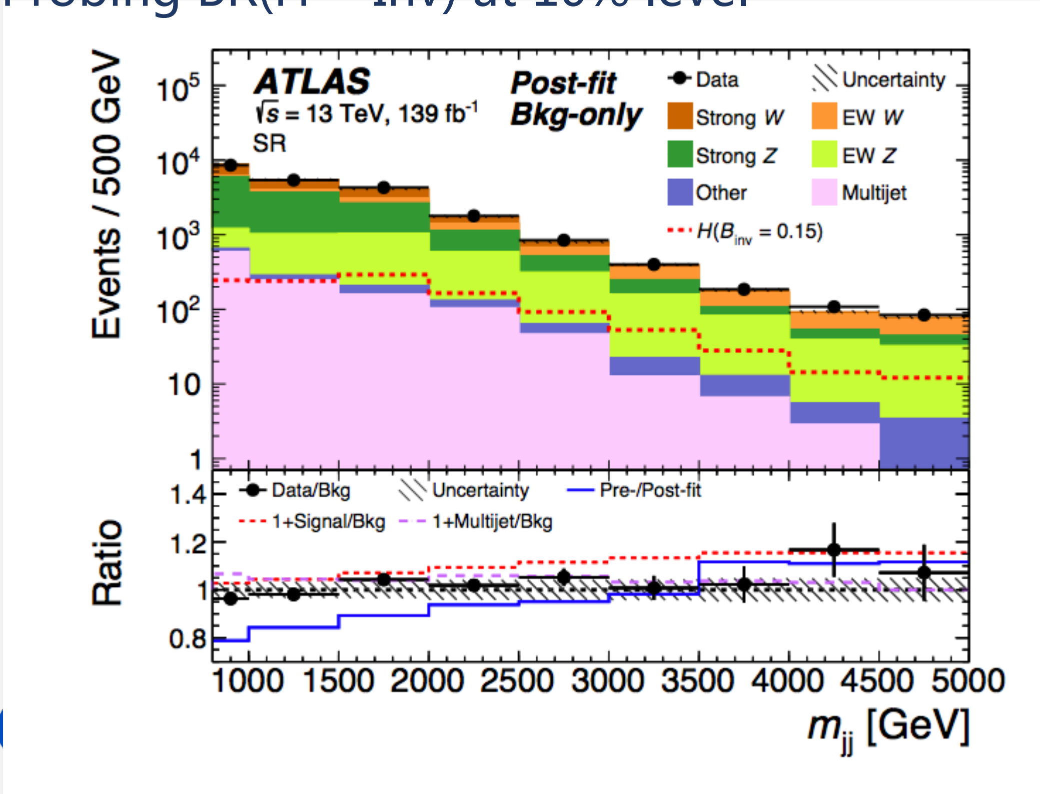
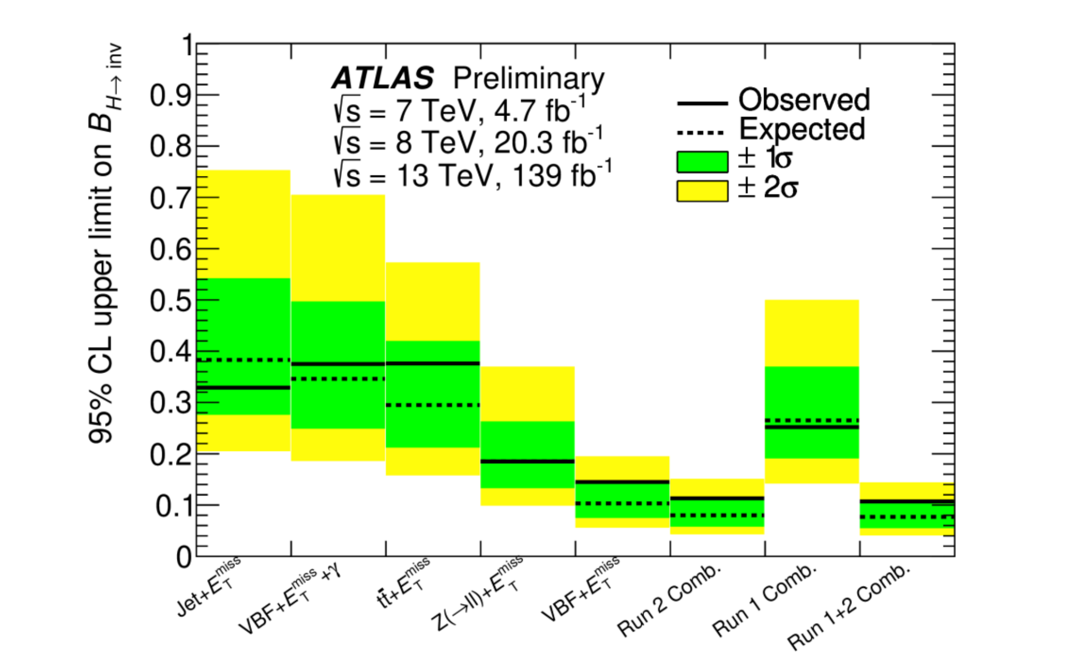
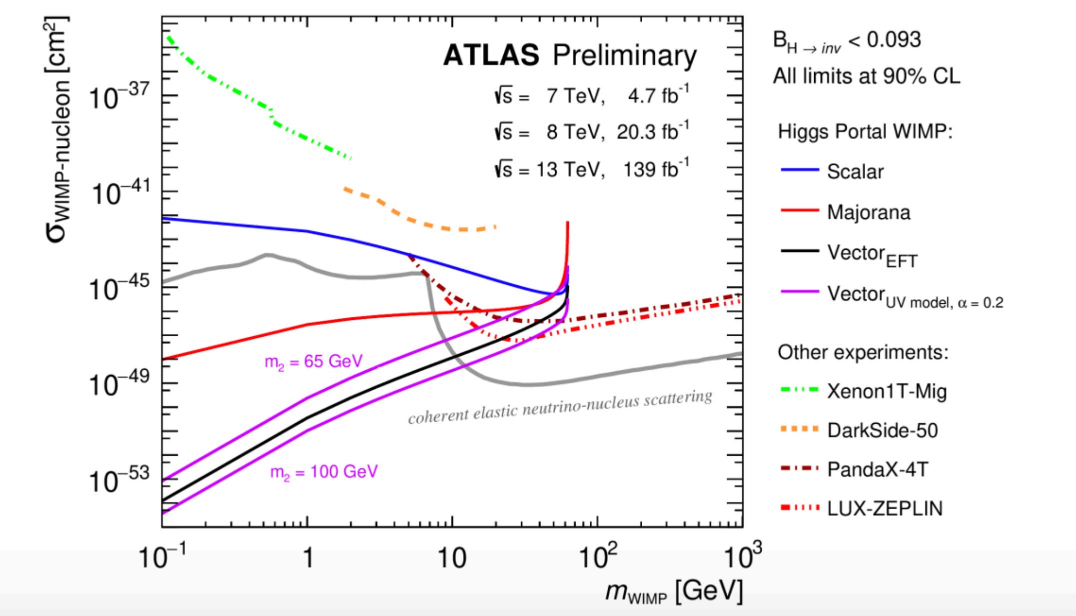
Analysis	Best fit $\mathcal{B}_{H\to \text{inv}}$	Observed 95% U.L.	Expected 95% U.L.
Run 2 Comb.	0.04 ± 0.04	0.113	$0.080^{+0.031}_{-0.022}$
Run 1 Comb.	$-0.02^{+0.14}_{-0.13}$	0.252	$0.265^{+0.105}_{-0.074}$
Run 1+2 Comb.	0.04 ± 0.04	0.107	$0.077^{+0.030}_{-0.022}$

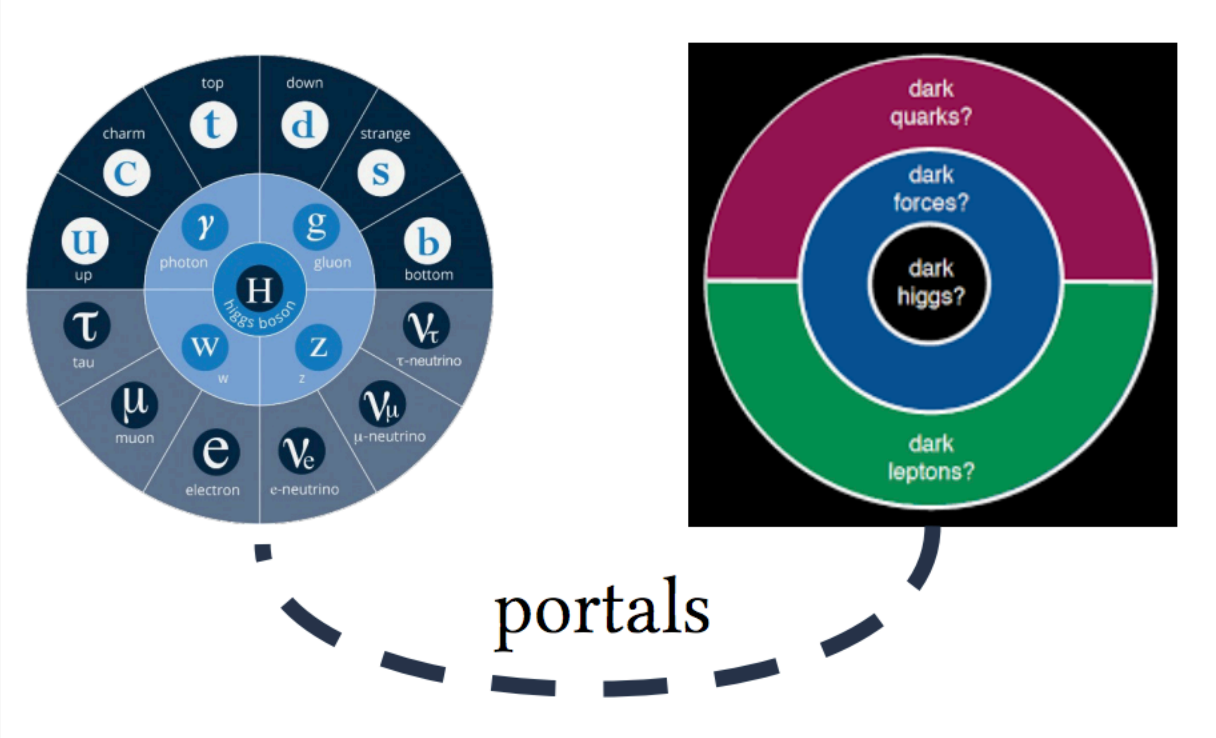
- Z to W ratio predictions @NLO QCD, NLO EW - **arXiv:2204.07652** - used to constrain Zjets with Wjets
- Probing BR(H→ Inv) at 10% level



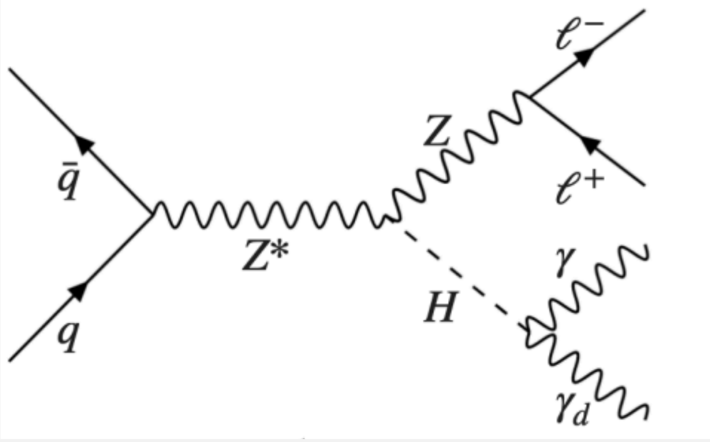


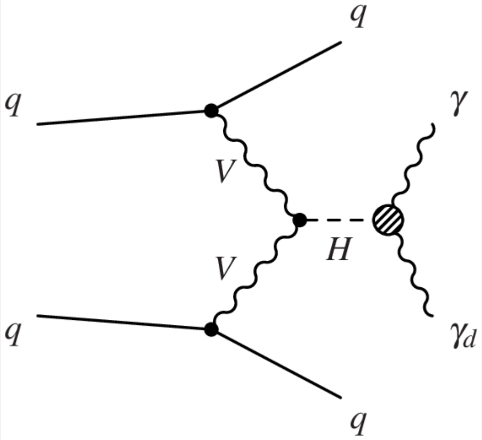


Dark Higgs → more Dark Portals connecting hidden sectors



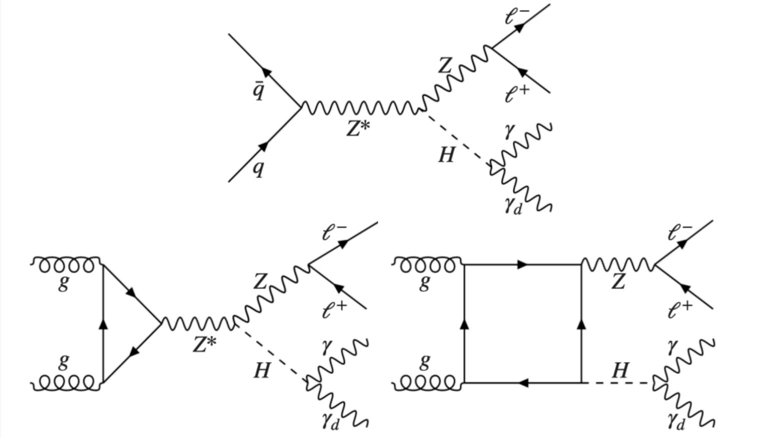
- Dark Photon BSM extensions:
  - U(1) extension of the SM
  - Hidden gauge boson A′ → kinetic mixing (ε) with the SM photon
  - the magnitude of ε affects production rate and lifetime





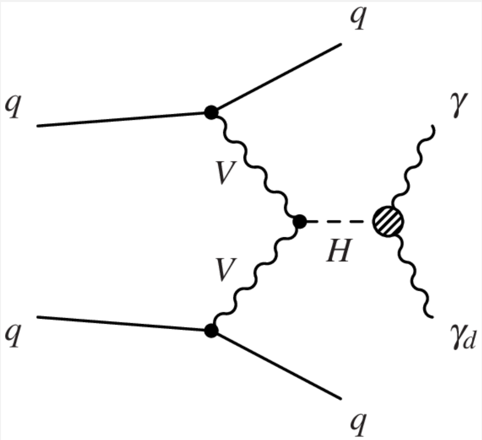
- Vector portal – dark photons
- Scalar portals - dark Higgs
- Neutrino portal
- Axion portal

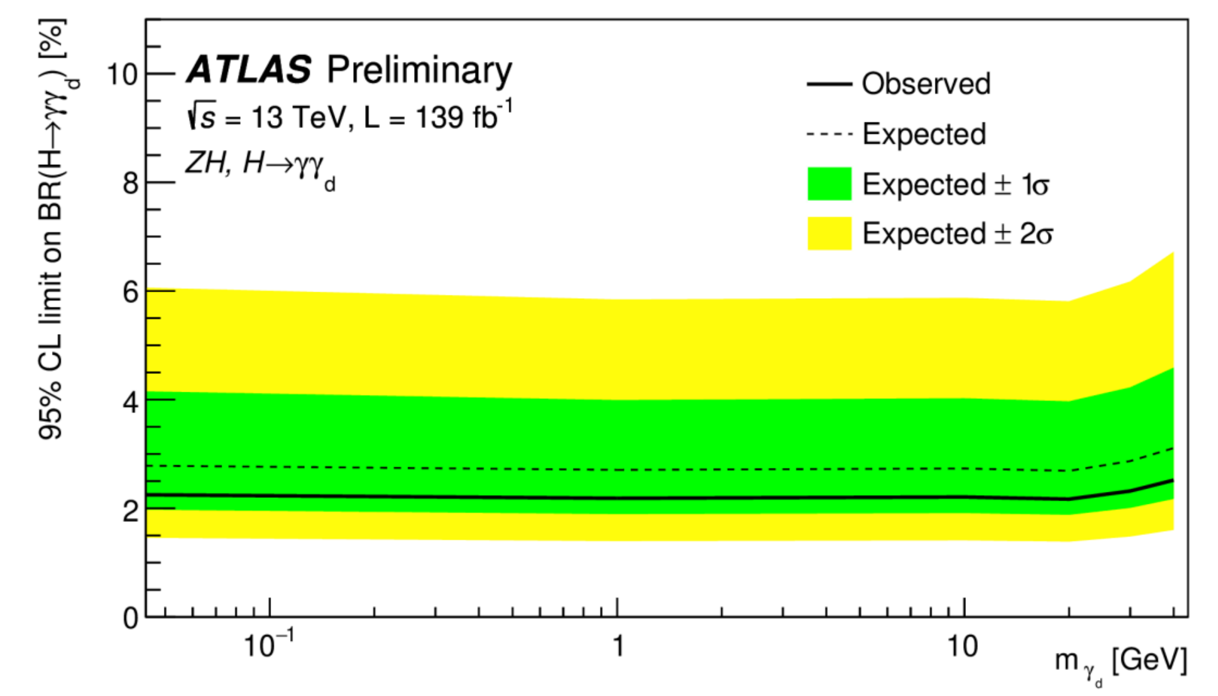
Dark Photon searches: ZH and VBF

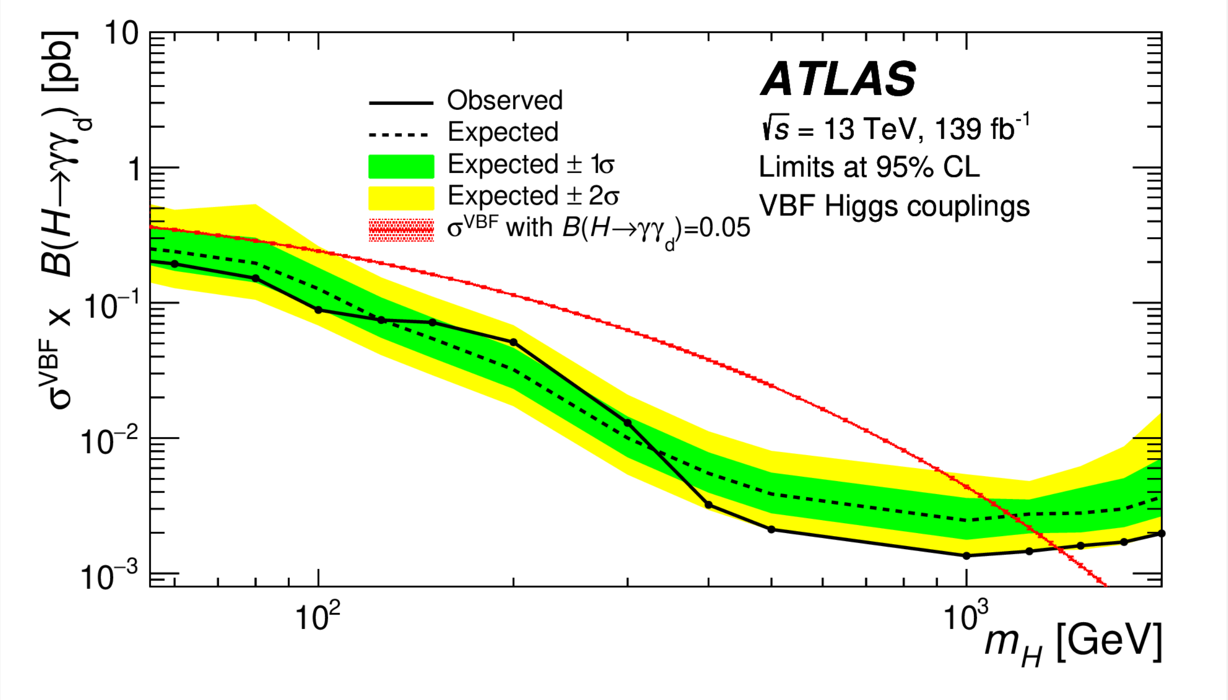


For massless γ_d

		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



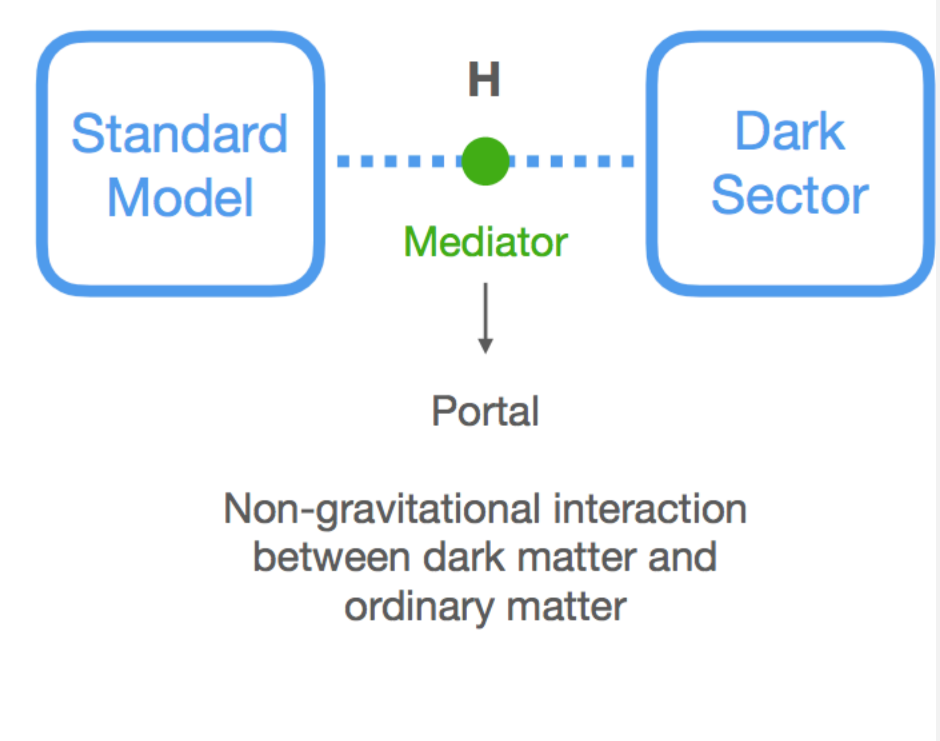




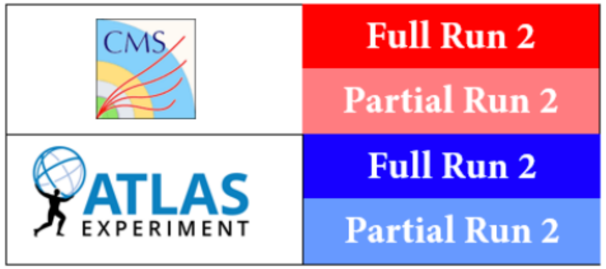
More on Higgs Exotic Decays

Higgs exotic decays in a nutshell

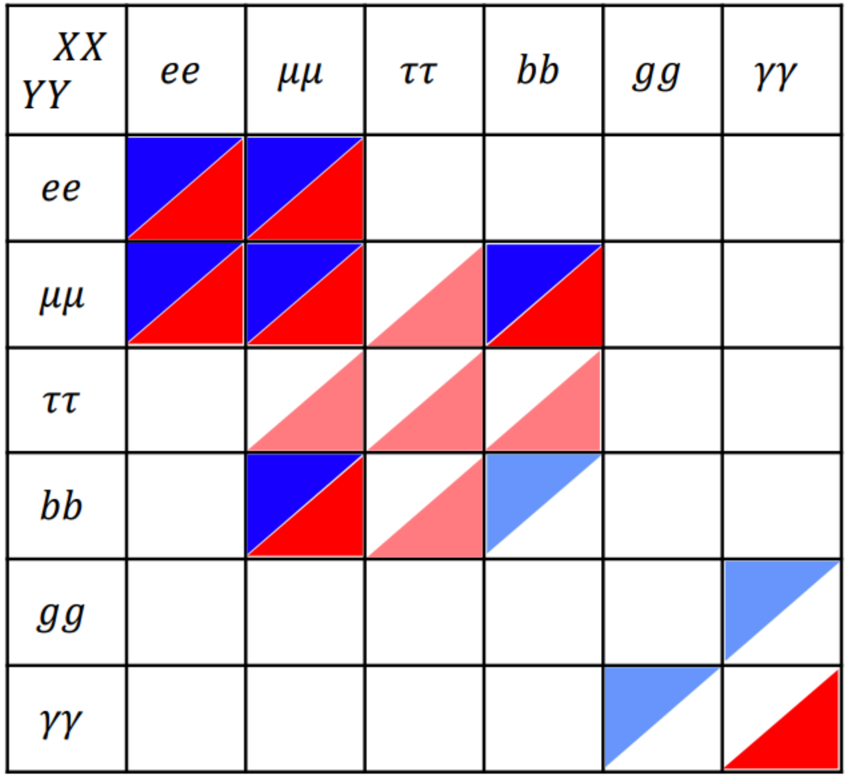
- Higgs has very small total width.
- Very weakly-coupled new particles can generate sizable $H \to ss$ BR to new low-mass particles
- CP-odd scalars decays ($H \to aa$) common in ALP



Extended Higgs sectors predicted by many theories of beyond the Standard Model (BSM) physics: naturalness, axions, SUSY, DM …

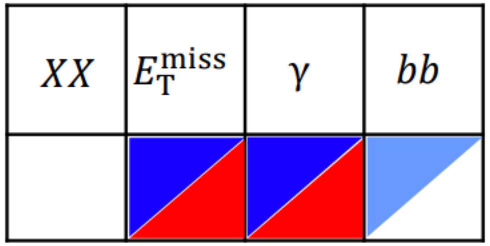


$H \to aa, a \to XX, a \to YY$

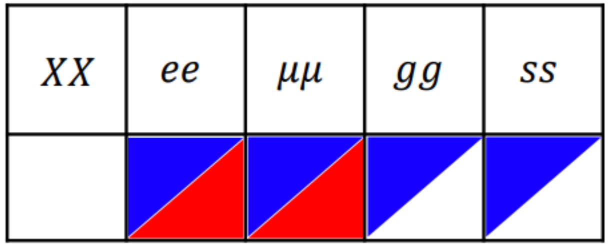


Landscape of ATLAS/CMS Exotic Higgs Decays

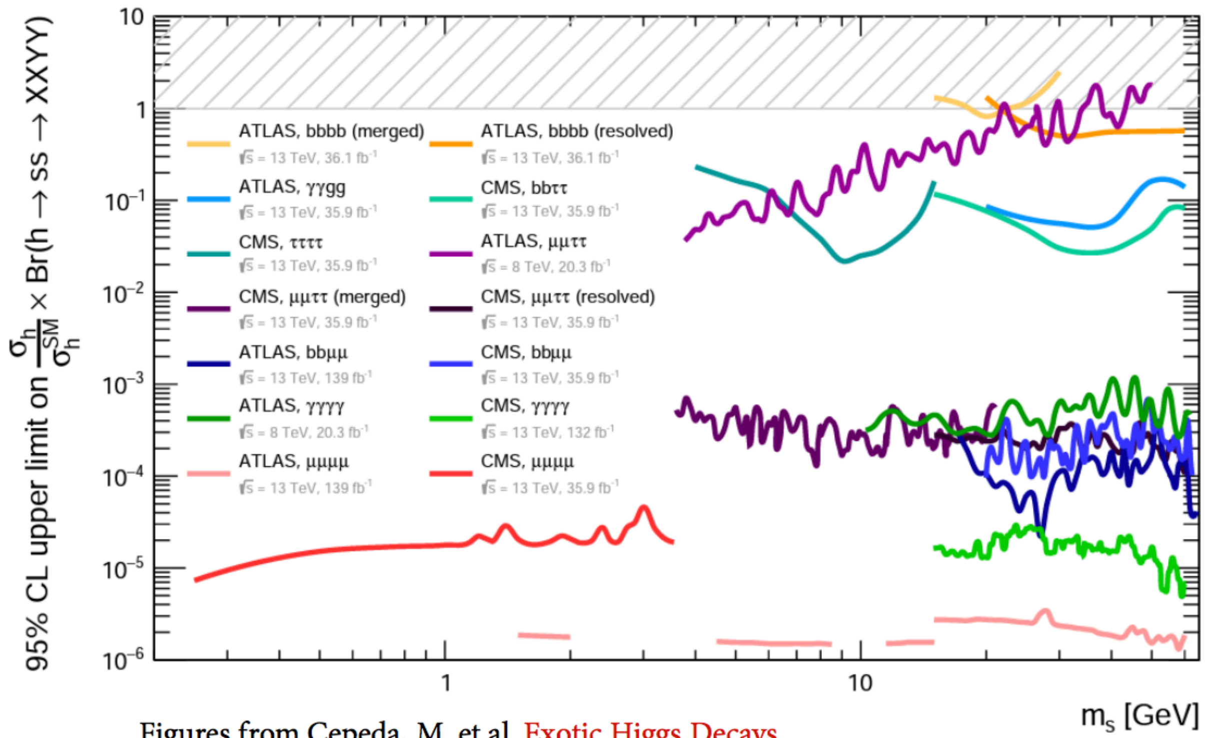
$H \to a + E_T^{miss}, a \to XX$



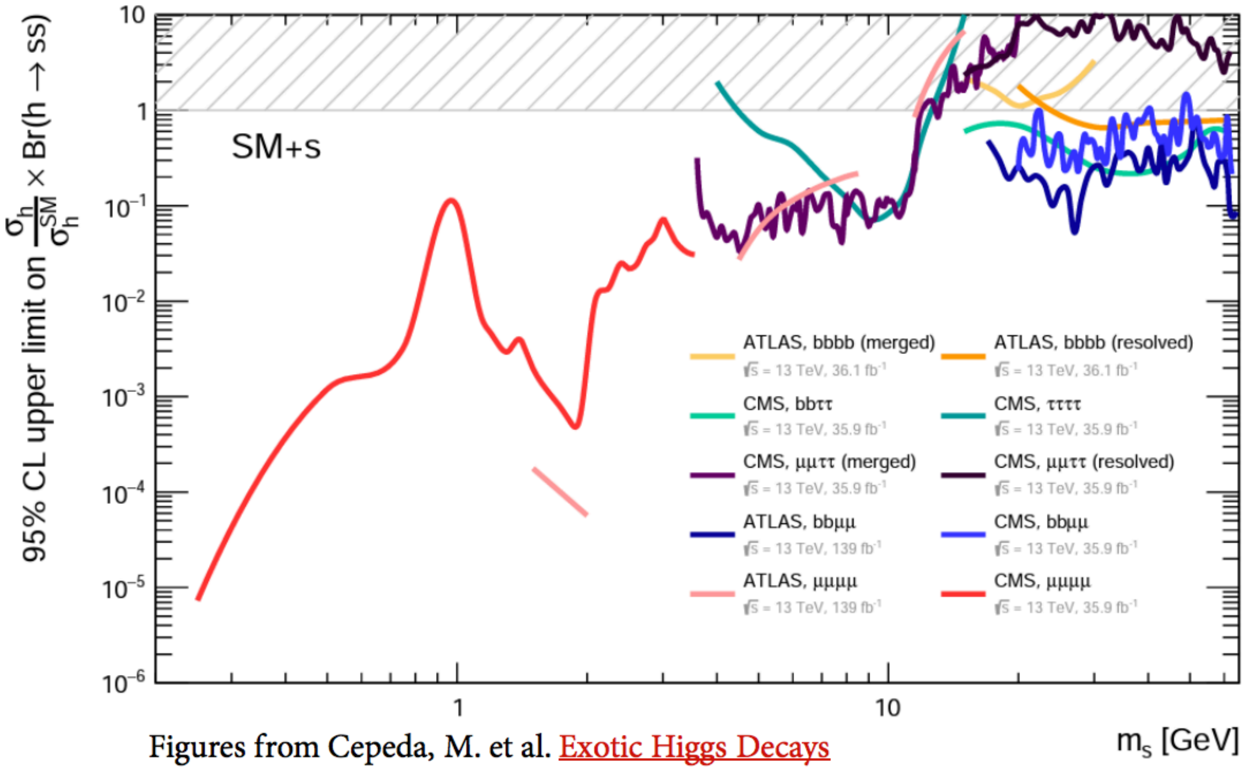
$H \to Za, a \to XX$



Overview of Exotic Higgs decays at ATLAS and CMS



Figures from Cepeda, M. et al. Exotic Higgs Decays
[Annual Review of Nuclear and Particle Science, Volume 72, 2022]



Figures from Cepeda, M. et al. Exotic Higgs Decays
[Annual Review of Nuclear and Particle Science, Volume 72, 2022]

Recent $H \to ss \to XXXX$ results at LHC

Interpreting result in SM+s model

H→2a→2b2μ (ALP)

Phys. Rev. D 105 (2022) 012006

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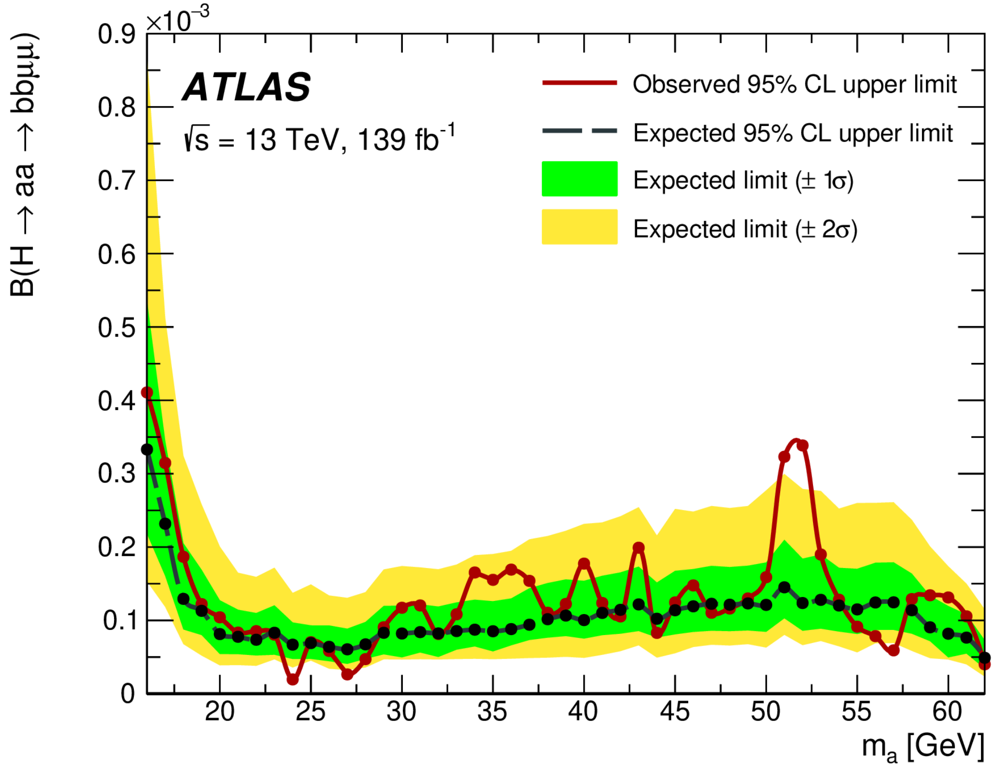
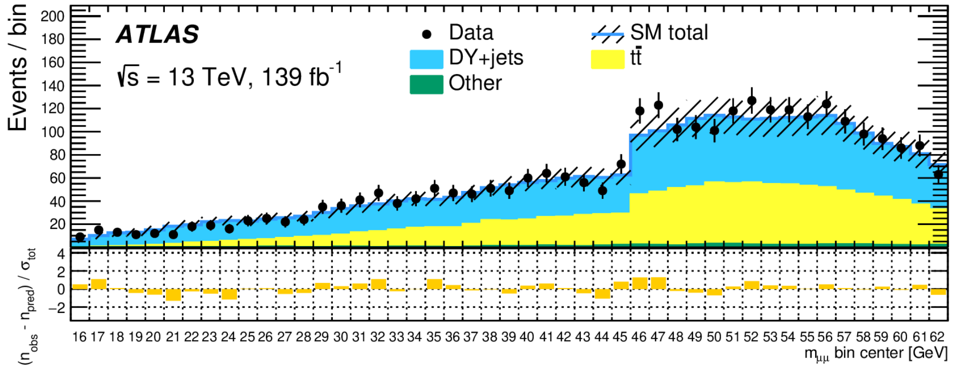
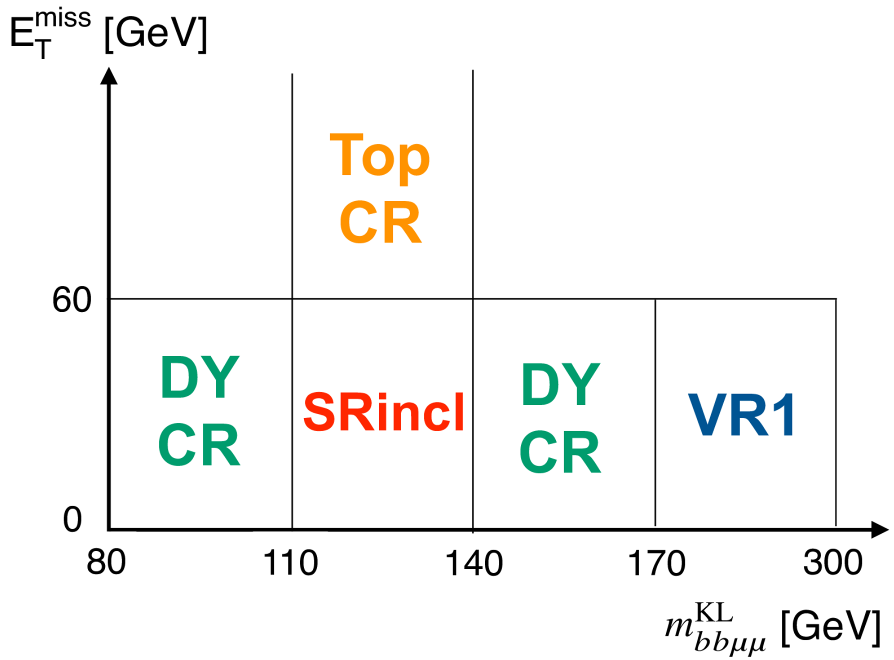




- Search for a narrow resonance in the $m_{\mu\mu}$ spectrum (16GeV<$m_{\mu\mu}$<62GeV) and train BDTs to separate the signal from the DY and ttbar backgrounds

- Kinematic likelihood fit (KLM) used to constrain the mbbto the mμμ mass
- Improve b-jet resolution maximising the likelihood Cut on the KLM score (L^{max}) to select best $m_{\mu\mu}$ ~ m_{bb} events
- Bump hunt over the m_mm invariant mass distribution



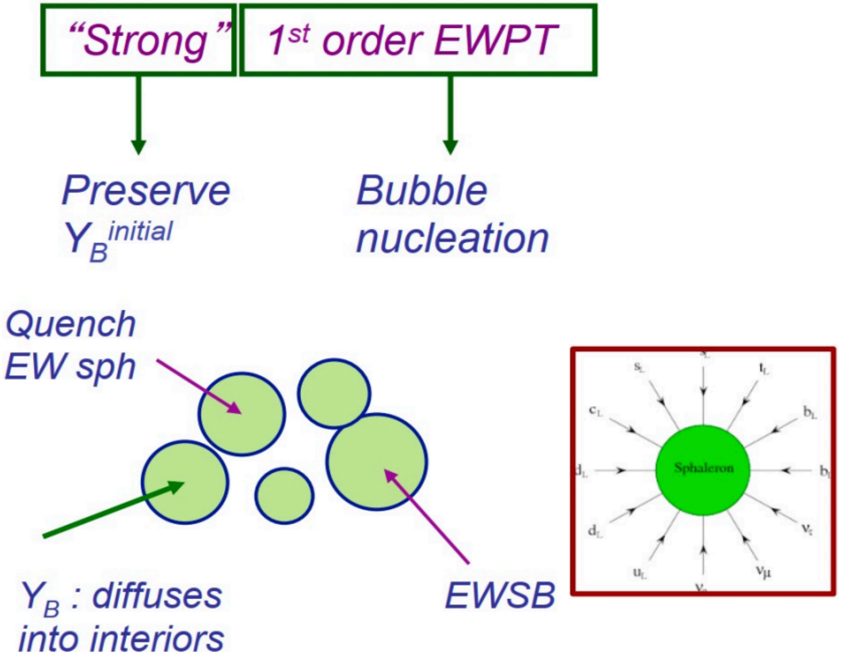
ma 52 GeV:
local sig 3.27 sigma
global sig 1.67 sigma

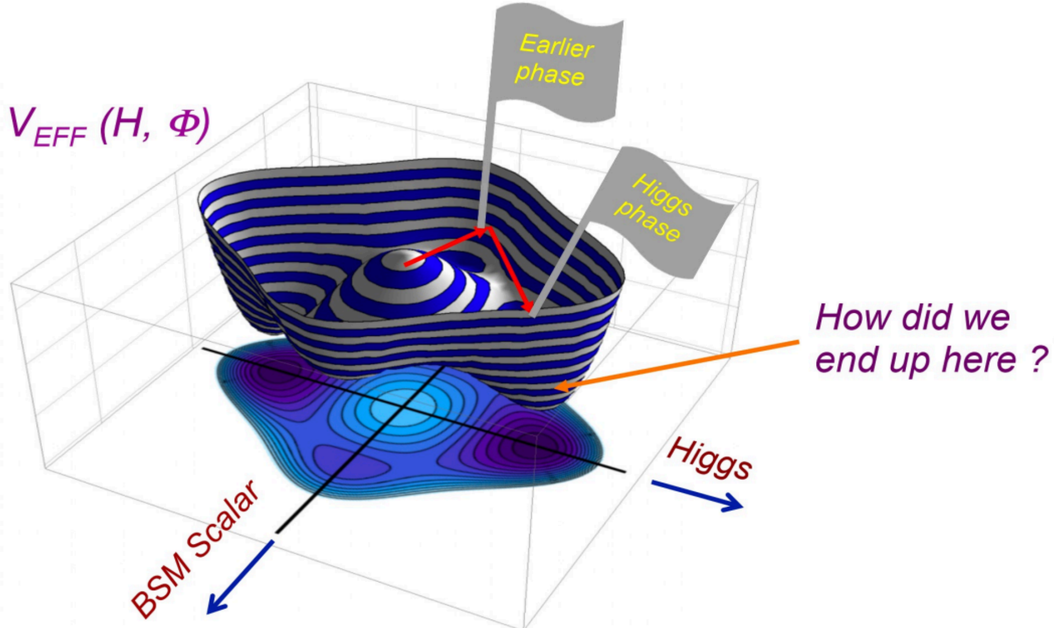
Exotic Higgs motivated by SFOEWPT

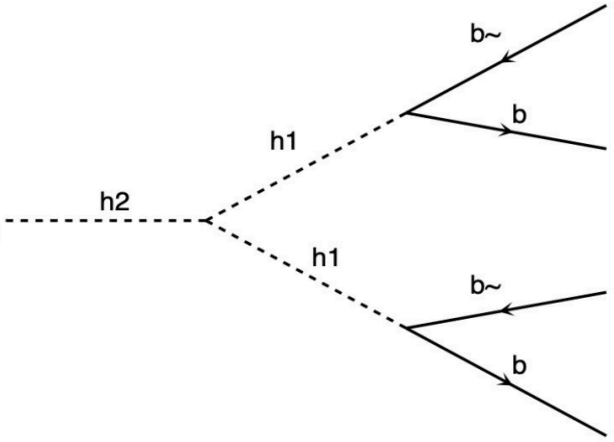
- We are interested in the strong first-order electroweak phase transition in the "SM Higgs + Light Real Singlet Scalar" model:

$$V = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}a_1|H|^2S + \frac{1}{2}a_2|H|^2S^2 + b_1S + \frac{1}{2}b_2S^2 + \frac{1}{3}b_3S^3 + \frac{1}{4}b_4S^4$$

- Mass eigenstates: $h_1 = h\cos\theta + s\sin\theta$ (h_1 : singlet-like)
  $h_2 = -h\sin\theta + s\cos\theta$ (h_2 : SM-like Higgs)





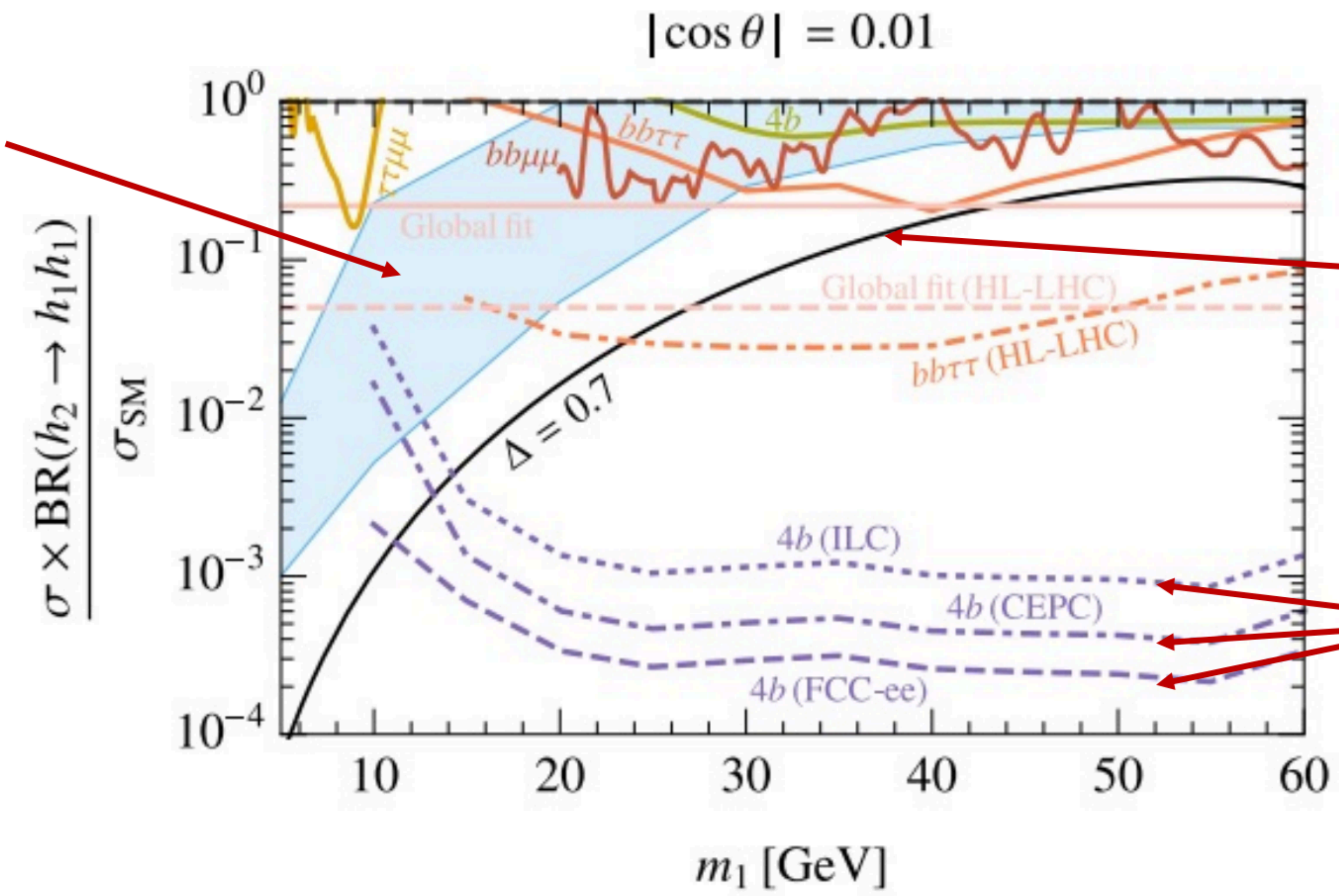


Extrema can evolve differently as T evolves
→ Rich possibilities for symmetry breaking

H→ss→4b phenomenology at LHC and beyond

$H \to ss \to 4b$

EWPT viable: numerical



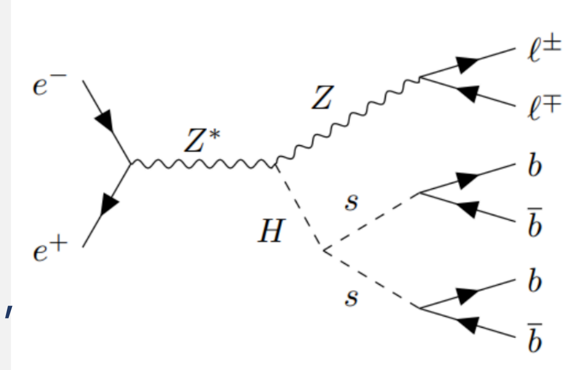
EWPT viable: semi analytic

Future e^+e^-

J. Kozaczuk, M. J. Ramsey-Musolf, and J. Shelton *Phys. Rev. D* **101**, 115035 (2020).
Z. Liu *et al., Chinese Phys. C* **41**, 063102 (2017).

Simulation and Analysis Setup

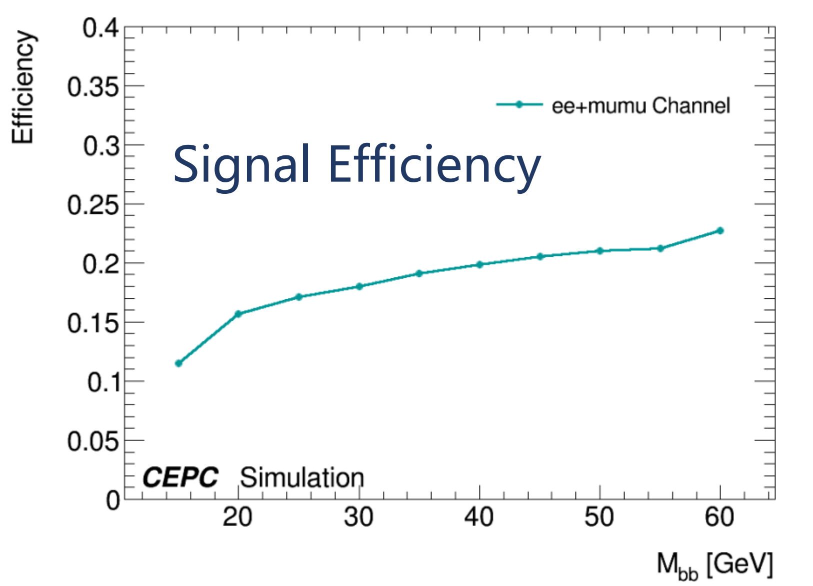
- Signal: [5, 60]GeV mass points, C.M.E.@240GeV
- Generator: Madgraph5 and Pythia8
- Framework: cepcsoft 0.1.1 , CEPC_v4
- Background : 2-Fermion, 4-Fermion, eeH, mumuH as our background

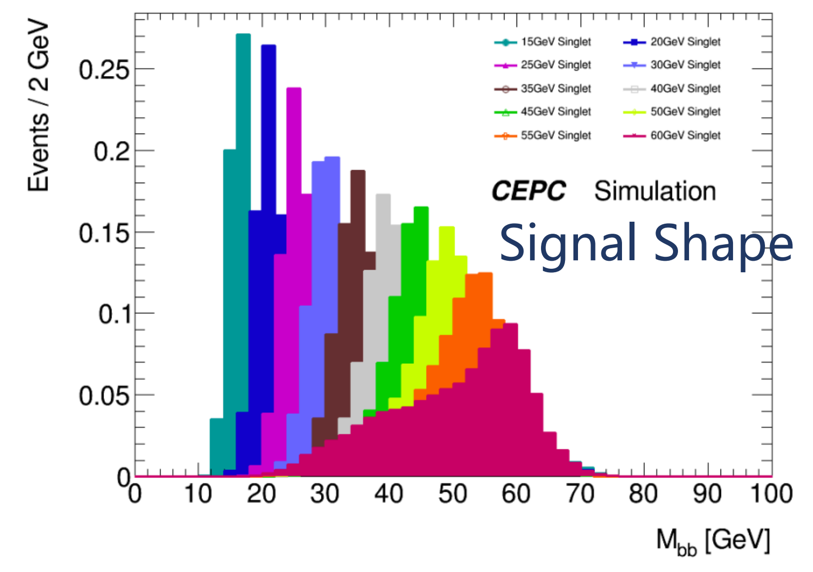


Process	$\int L$	Final states	X-sections (fb)	Comments
	5 ab^{-1}	ffH	203.66	all signals
	5 ab^{-1}	e^+e^-H	7.04	including ZZ fusion
	5 ab^{-1}	$\mu^+\mu^-H$	6.77	
	5 ab^{-1}	$\tau^+\tau^-H$	6.75	
	5 ab^{-1}	$\nu\bar{\nu}H$	46.29	all neutrinos (ZH+WW fusion)
	5 ab^{-1}	$q\bar{q}H$	136.81	all quark pairs (Z→ $q\bar{q}$)

2 fermion backgounds

Process	$\int L$	Final states	X-sections (fb)	Comments
$e^+e^- \to e^+e^-$	5 ab^{-1}	e^+e^-	24770.90	



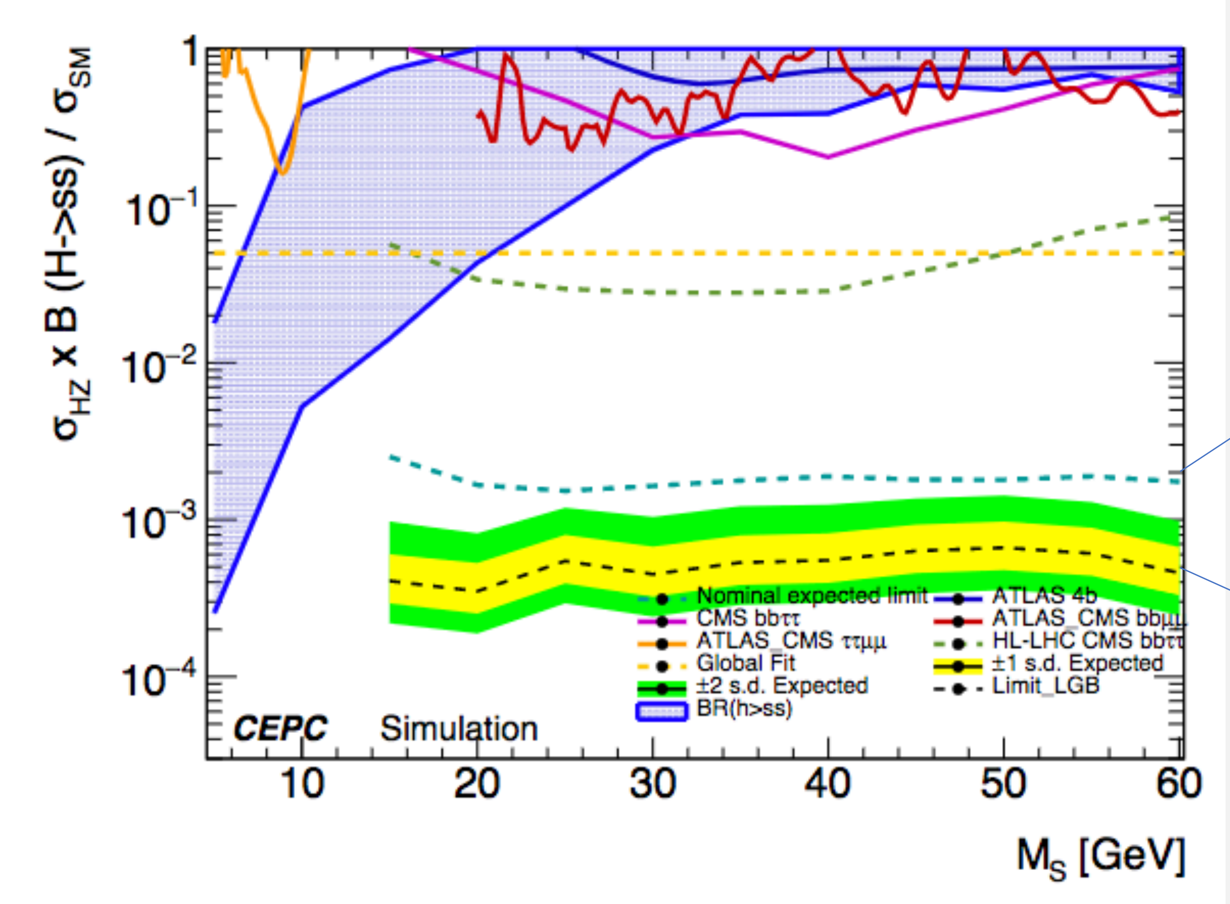


Particle and Nuclear Physics Division
粒子与核物理研究部

GBDT-based b-jet tagging algorithm in use [Chinese Phys. C 44, 013001 (2020)]

H→ss→4b search sensitivity at CEPC

arXiv:2203.10184 (SnowMass White Paper)
In submission to LHEP Higgs-10 special issue

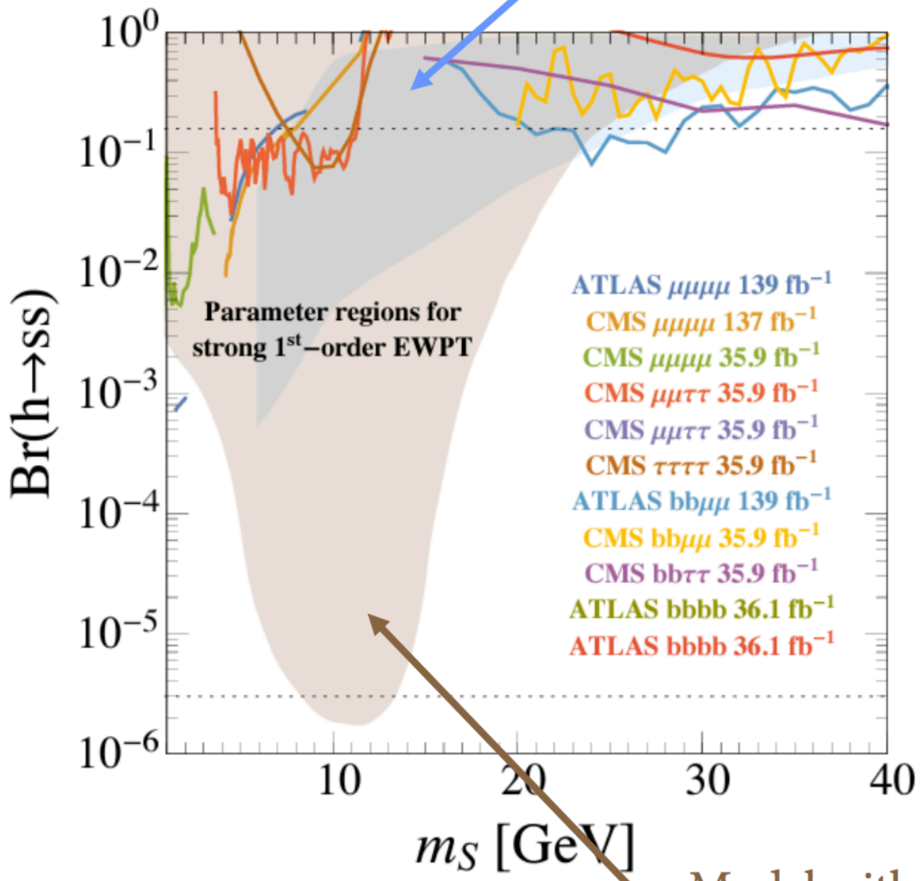


Lepton colliders have better sensitivity compared to hadron colliders: promising for e+e- machine BSM merits besides Higgs precision factory

Cut-based limits
BDT limits

BDT limits

Model with $s-H$ mixing with $\sin\theta = 0.01$ from Kozaczuk et al. [Phys. Rev. D 101, 115035 (2020)]



Probing the Electroweak Phase Transition with Exotic Higgs Decays

Marcela Carena,[1,2,3] Jonathan Kozaczuk,[4] Zhen Liu,[5] Tong Ou,[2]
Michael J. Ramsey-Musolf,[6,7,8] Jessie Shelton,[9] Yikun Wang,[10] and Ke-Pan Xie[11]

- Models of SFOEWPT with $m_s > 25$ GeV are disfavored by LHC searches
- Region $10 < m_s < 25$ GeV can be probed with $H \to ss \to bbbb$ and $H \to ss \to bb\tau\tau$
- Region with $m_s < 10$ GeV can be probed with $H \to ss \to \tau\tau\tau\tau$ and $H \to ss \to \tau\tau\mu\mu$

Model with Z_2 symmetry spontaneously broken by Carena et al. [arXiv:2210.14352]

Carena, M. et al. arXiv:2203.08206

(to) probe the composite Higgs hypothesis with VBS VV and VBF HH

More on Higgs→BSM Portal: the Higgs Puzzle

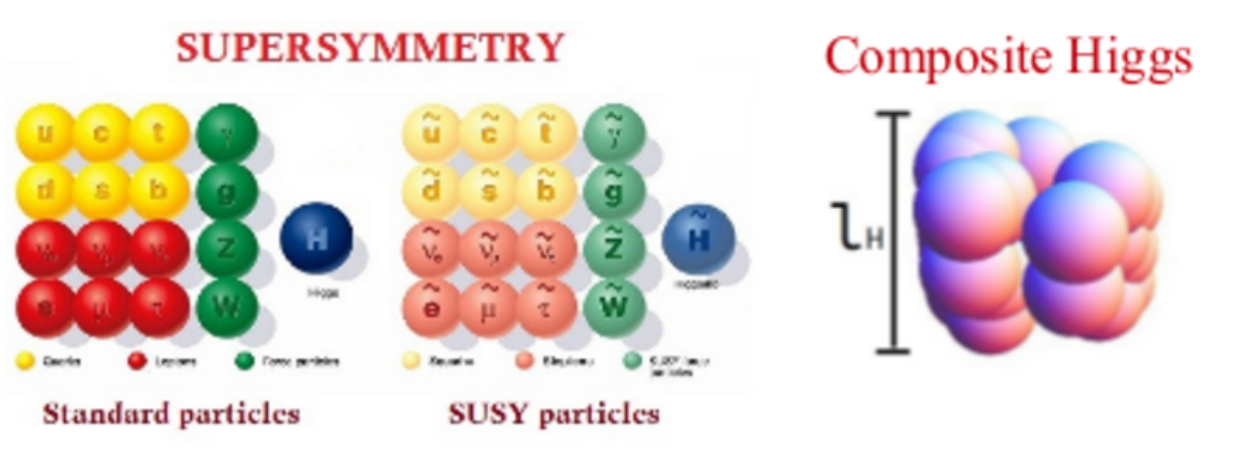
- First fundamental (?) scalar field to be discovered
- Spontaneous symmetry breaking by development of a VeV
  - But VeV is induced parametrically by ad-hoc Higgs potential, no dynamics
- Parameters of Higgs potential are not stable under radiative corrections
  - First time that the radiative correction to a particle mass is additive and quadratically divergent
  - Gauge boson masses are protected by gauge invariance
  - Fermion masses are protected by chiral symmetry of massless fermions
- Single scalar Higgs field is a strange beast, compared to fermions and gauge bosons
- Additional symmetries and/or dynamics strongly motivated by Higgs discovery

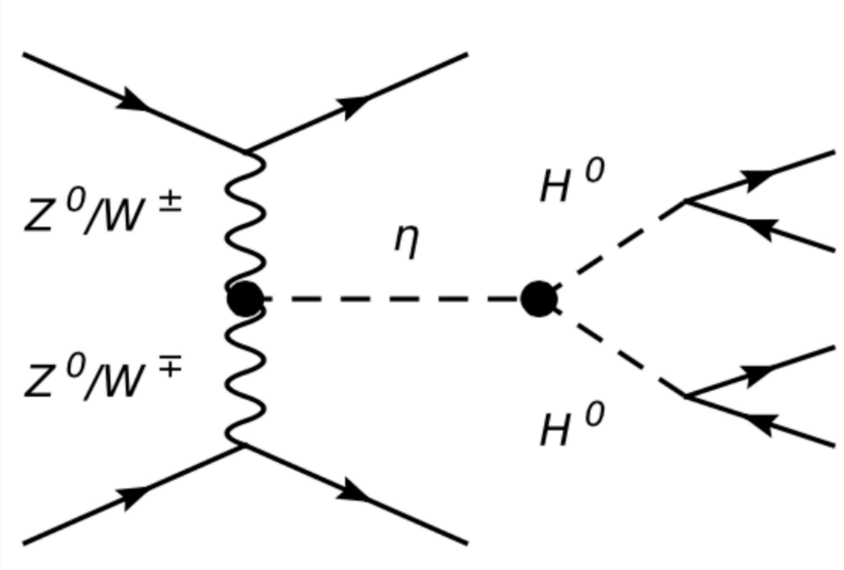
$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4}h^4 \quad \text{or} \quad V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4}h^4 + \frac{1}{\Lambda^2}h^6$$

- Ad-hoc potential, similar to and motivated by Landau-Ginzburg theory of superconductivity
- Higgs potential in SM can be extrapolated to Planck scale without additional parameters
  - but no a-priori reason for a parameterization to respect this condition

Composite Higgs, VBS-VV and VBF Di-Higgs

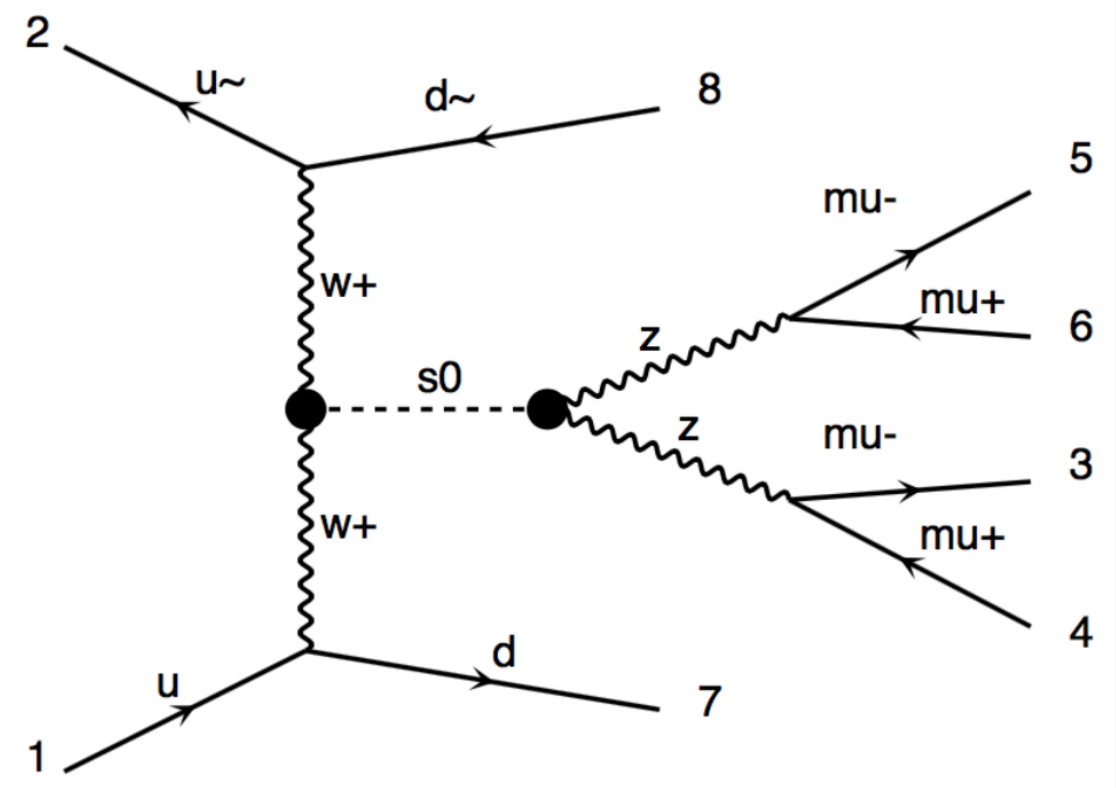
- Old idea: Higgs doublet (4 fields) is a Goldstone mode generated from the spontaneous breaking of a larger global symmetry
- But assuming there is a strong dynamics at the energy scale "f" which causes a condensate to form and break the SO(5) symmetry
- Resonances will be associated with this strong dynamics
- Lightest resonance will decay to the "pseudo-Goldstones" which are much lighter, i.e. longitudinal gauge bosons and Higgs bosons
  - Similar to QCD $\rho \rightarrow \pi\pi$
- Simplified model: arXiv:1109.1570 (Contino et al.) "On the effect of resonances in composite Higgs phenomenology"
  - Scalar resonance: $\eta \rightarrow hh, V_L V_L$

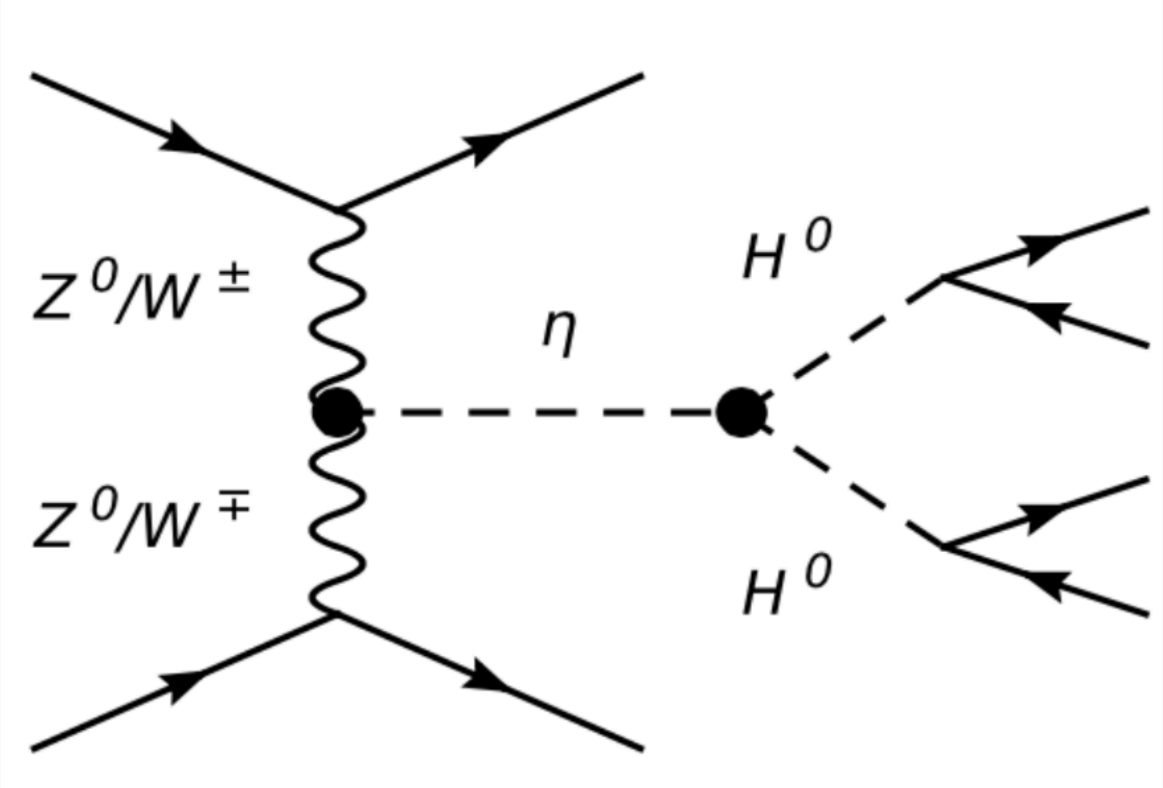




VBS-VV vs VBF HH

Joint interpretation of latest resonant VBF HH and VBS VV: upcoming and stay tuned



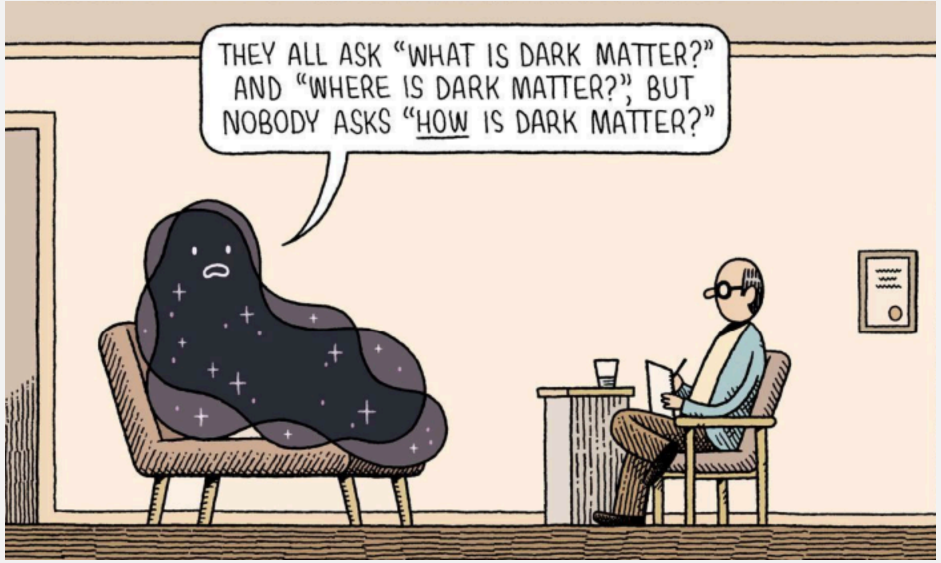


- Branching ratio to hh, W_LW_L and Z_LZ_L in the 1:2:1 ratio is a definitive prediction
- Resonance decaying to two Z_L bosons is a distinctive signature of the Goldstone nature of the Higgs boson

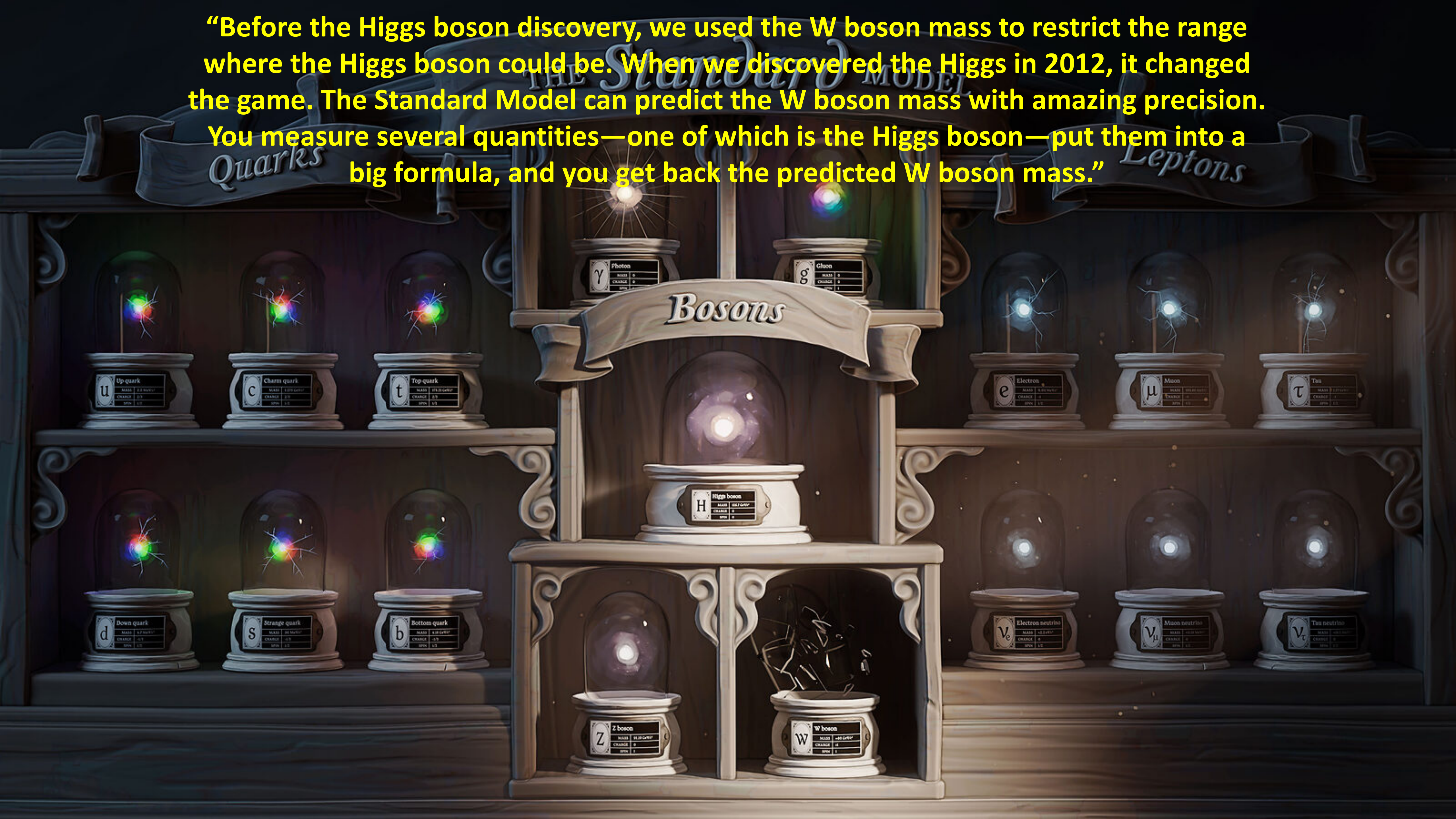
- Vector boson scattering topology
  - Quarks emit longitudinal vector bosons which interact with new (presumably strong) dynamics
  - Quarks scatter by small angle in the forward direction

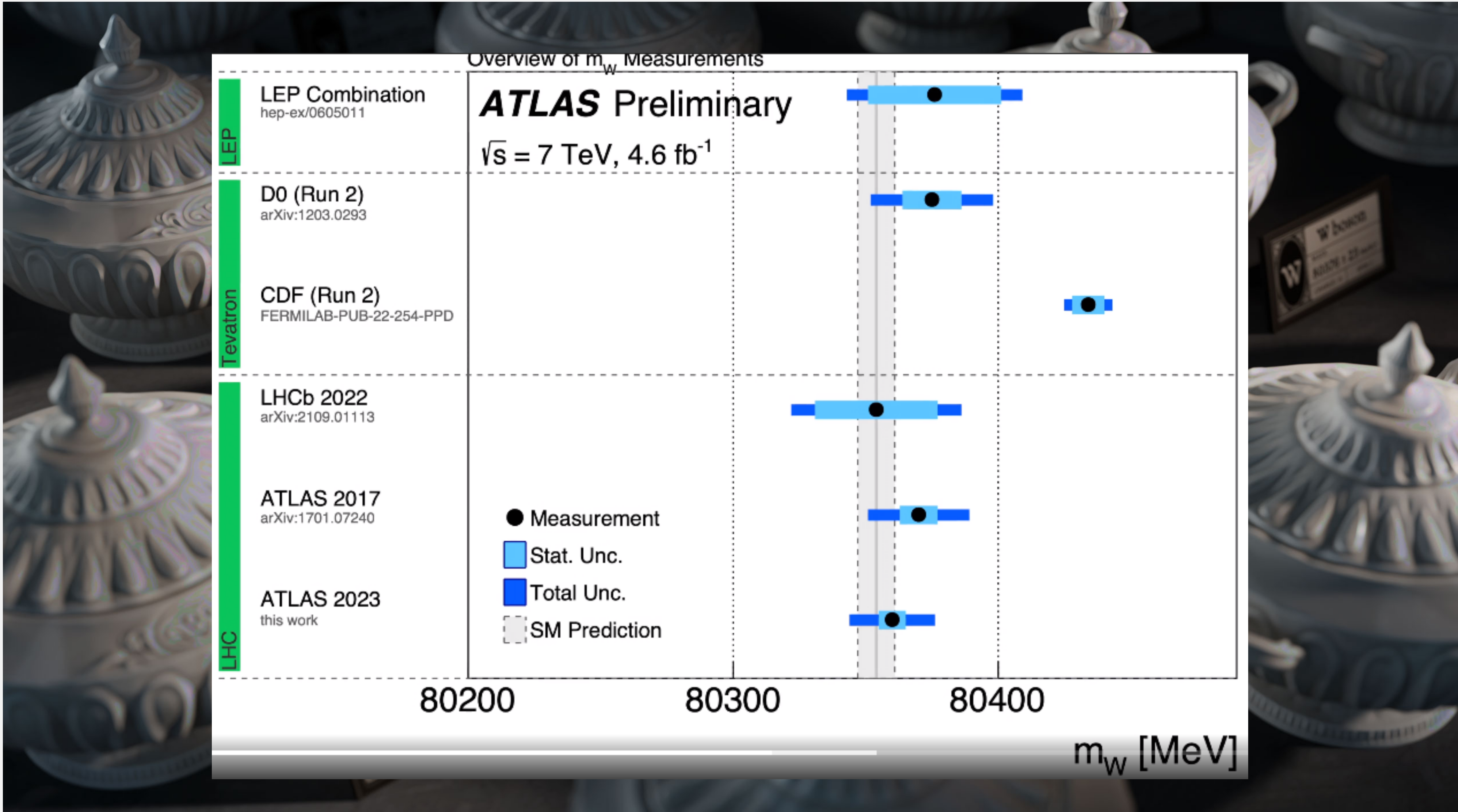
Summary

- 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
  - Higgs as a probe to DM plays one of the leading roles
- Higgs BSM probe unify and diversify the searches at LHC because its success and its puzzles
- Need to further diversify the data mining aspects in the collisions covering more unconventional signatures and untouched stones with and without Higgs

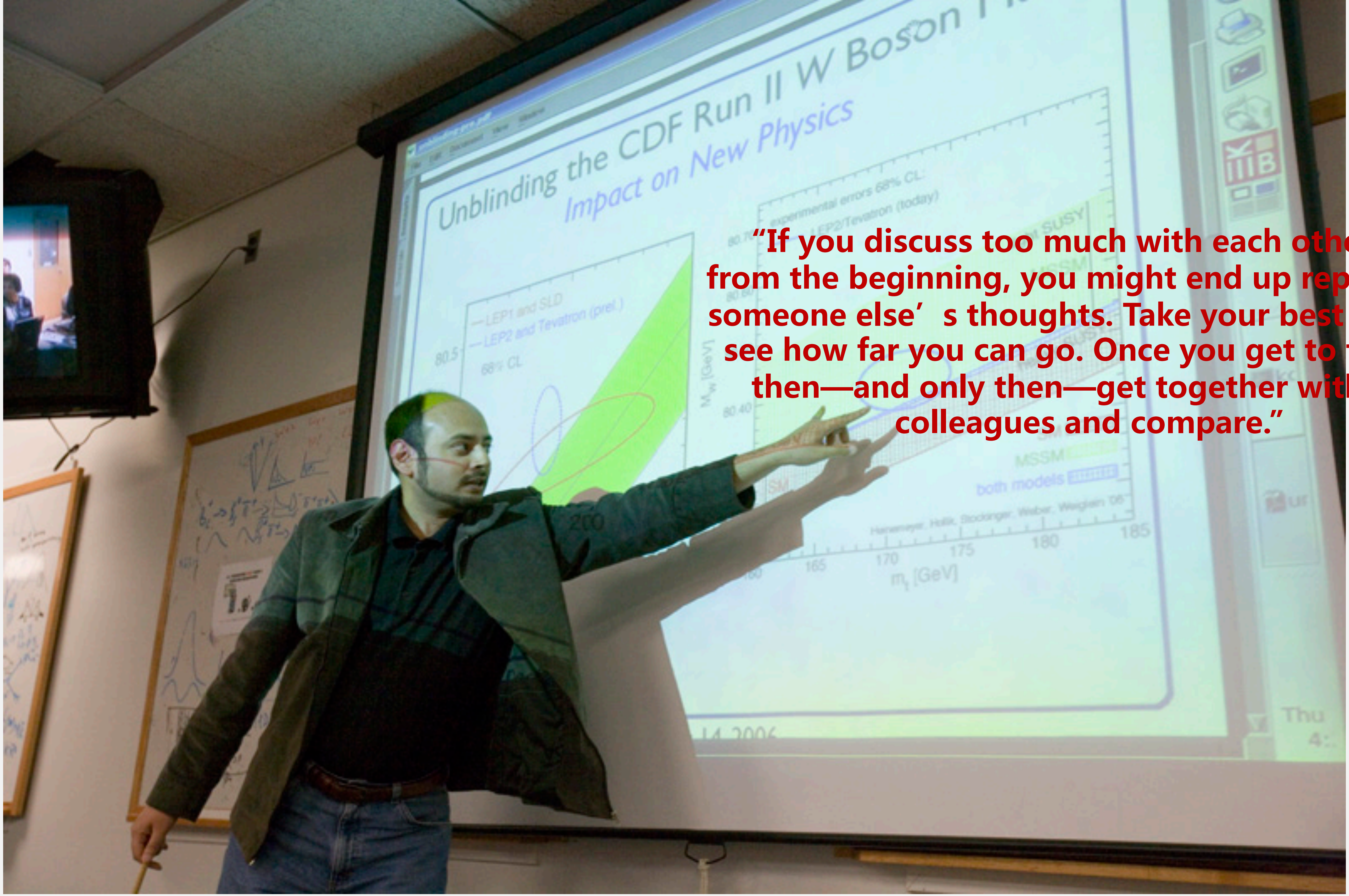


"Before the Higgs boson discovery, we used the W boson mass to restrict the range where the Higgs boson could be. When we discovered the Higgs in 2012, it changed the game. The Standard Model can predict the W boson mass with amazing precision. You measure several quantities—one of which is the Higgs boson—put them into a big formula, and you get back the predicted W boson mass."

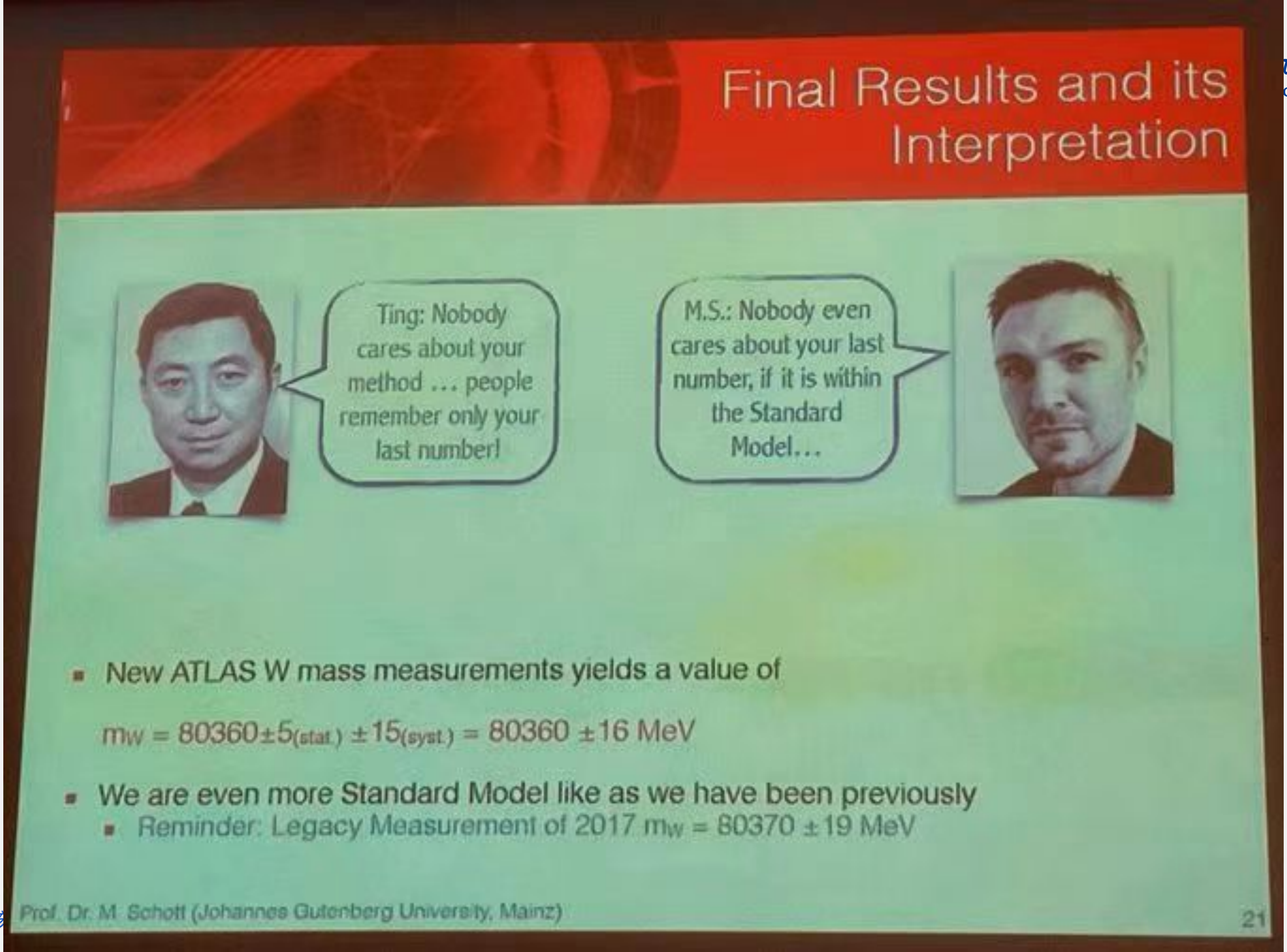




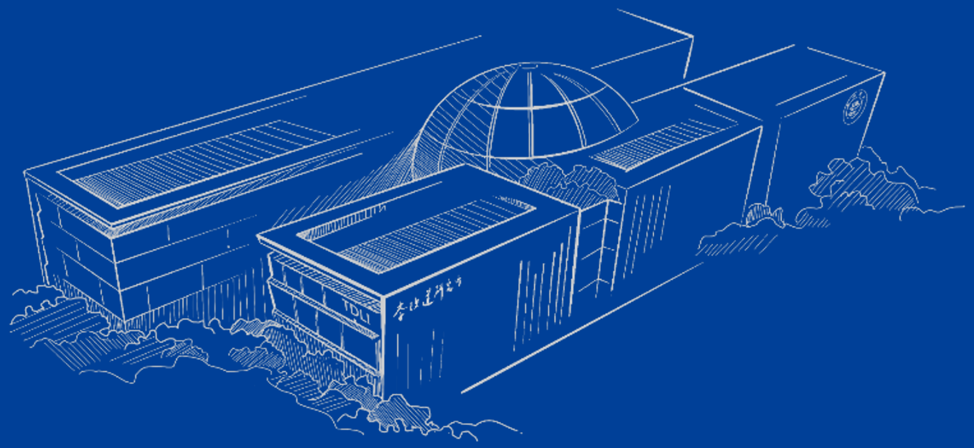
Overview of m_W Measurements
ATLAS Preliminary
$\sqrt{s}$ = 7 TeV, 4.6 fb^{-1}
LEP
LEP Combination
hep-ex/0605011
Tevatron
D0 (Run 2)
arXiv:1203.0293
CDF (Run 2)
FERMILAB-PUB-22-254-PPD
LHC
LHCb 2022
arXiv:2109.01113
ATLAS 2017
arXiv:1701.07240
ATLAS 2023
this work
Measurement
Stat. Unc.
Total Unc.
SM Prediction
80200
80300
80400
m_W [MeV]



"If you discuss too much with each other right from the beginning, you might end up reproducing someone else' s thoughts. Take your best shot and see how far you can go. Once you get to the end, then—and only then—get together with your colleagues and compare."


Final Results and its Interpretation
Ting: Nobody cares about your method … people remember only your last number!
M.S.: Nobody even cares about your last number, if it is within the Standard Model…
New ATLAS W mass measurements yields a value of
$m_W = 80360 \pm 5_{(stat.)} \pm 15_{(syst.)} = 80360 \pm 16$ MeV
We are even more Standard Model like as we have been previously
Reminder: Legacy Measurement of 2017 $m_W = 80370 \pm 19$ MeV
Prof. Dr. M. Schott (Johannes Gutenberg University, Mainz)
21

谢谢！



Motivation

- Lagrangian from Contino *et al.* for a scalar resonance η coupling to the Goldstones

$$\mathcal{L}^{(\eta)} = \frac{1}{2}(\partial_\mu \eta)^2 - \frac{1}{2}m_\eta^2 \eta^2 + \frac{f^2}{4}\left(2a_\eta \frac{\eta}{f} + b_\eta \frac{\eta^2}{f^2}\right) \mathrm{Tr}\left[d_\mu d^\mu\right]$$

$$(D_\mu \Phi)^T (D^\mu \Phi)$$

- Width of the resonance:

$$\Gamma_\eta = \frac{a_\eta^2 m_\eta^3}{8\pi f^2}$$

Unitary is fully preserved by setting $a_\eta = 1$, no need for ad-hoc unitarization

Eliminates the complications of unitarization for anomalous couplings and higher-dimensional operators

Two free parameters: mass and width of the resonance