Searches for Supersymmetry and Dark Matter

Christian Herwig, on behalf of the ATLAS+CMS Collaborations

Recontres du Vietnam 30th Anniversary: Windows on the Universe

August 8, 2023

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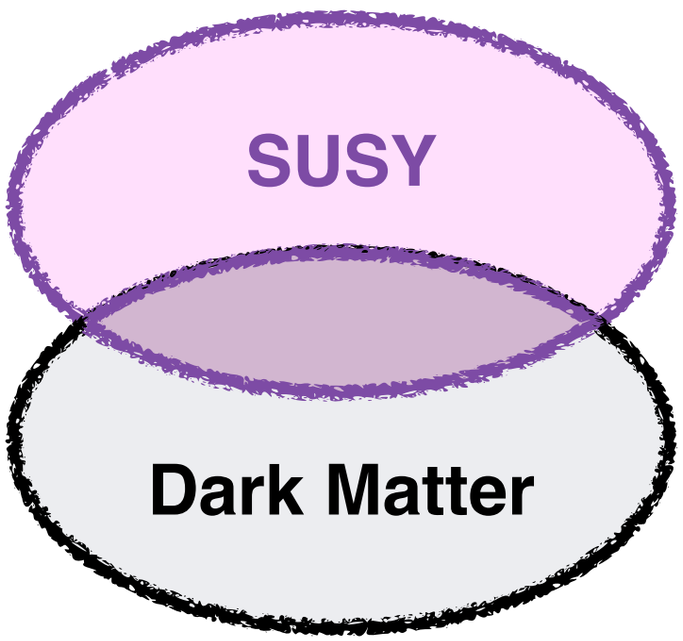
Setting the context

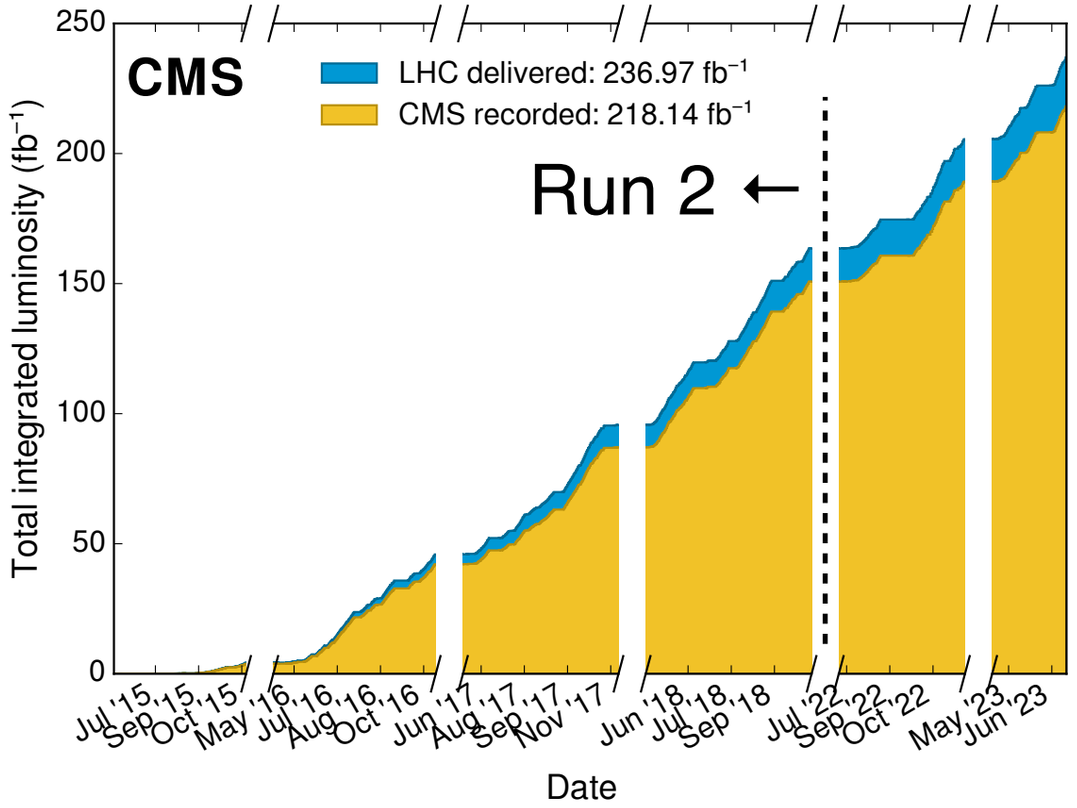
10 years after the Higgs discovery, we continue to face **deep questions**:



- Is there additional structure to the mechanism of electroweak symmetry breaking?
- Is Dark Matter part of such a deeper theory?
- How exhaustively can we test the possibility of a GeV-TeV scale thermal relic?

LHC Run 2 has provided a large dataset of high-energy collisions to probe weakly-coupled theories.

- We are pushing our detectors to their limits; new capabilities (more next talk)
- Strong theory collaborations → new signatures & search techniques.



Supersymmetry

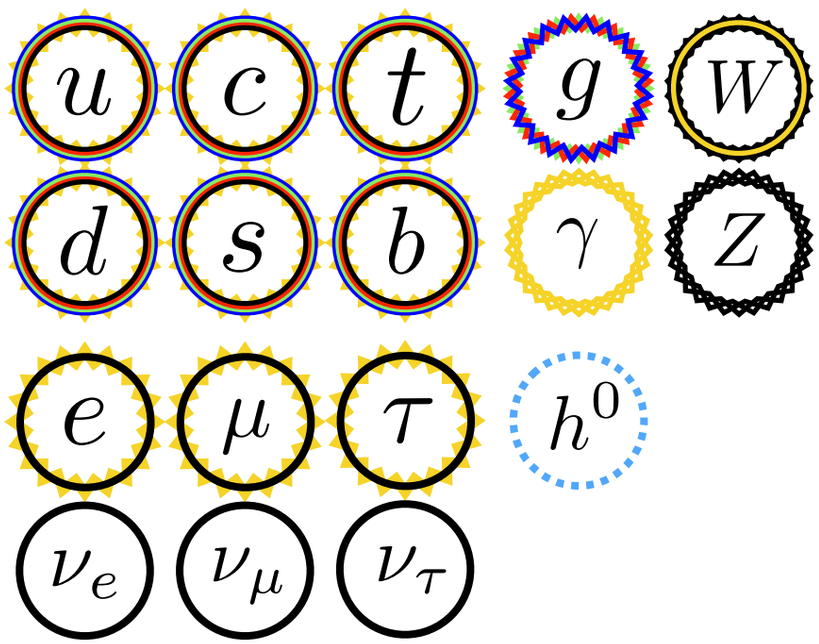
SUSY@LHC pheno crash course

✓ New spacetime symmetry.

✓ ~ Double the SM particle content.

✓ Lightest SUSY Particle = DM?

✓ Direct Sparticle production at LHC.



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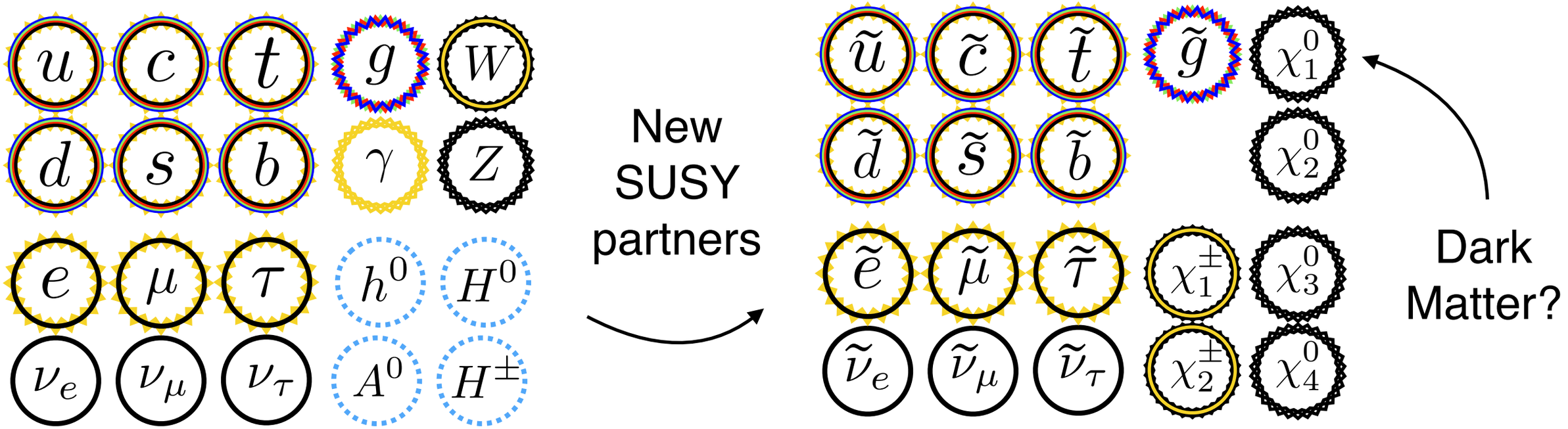

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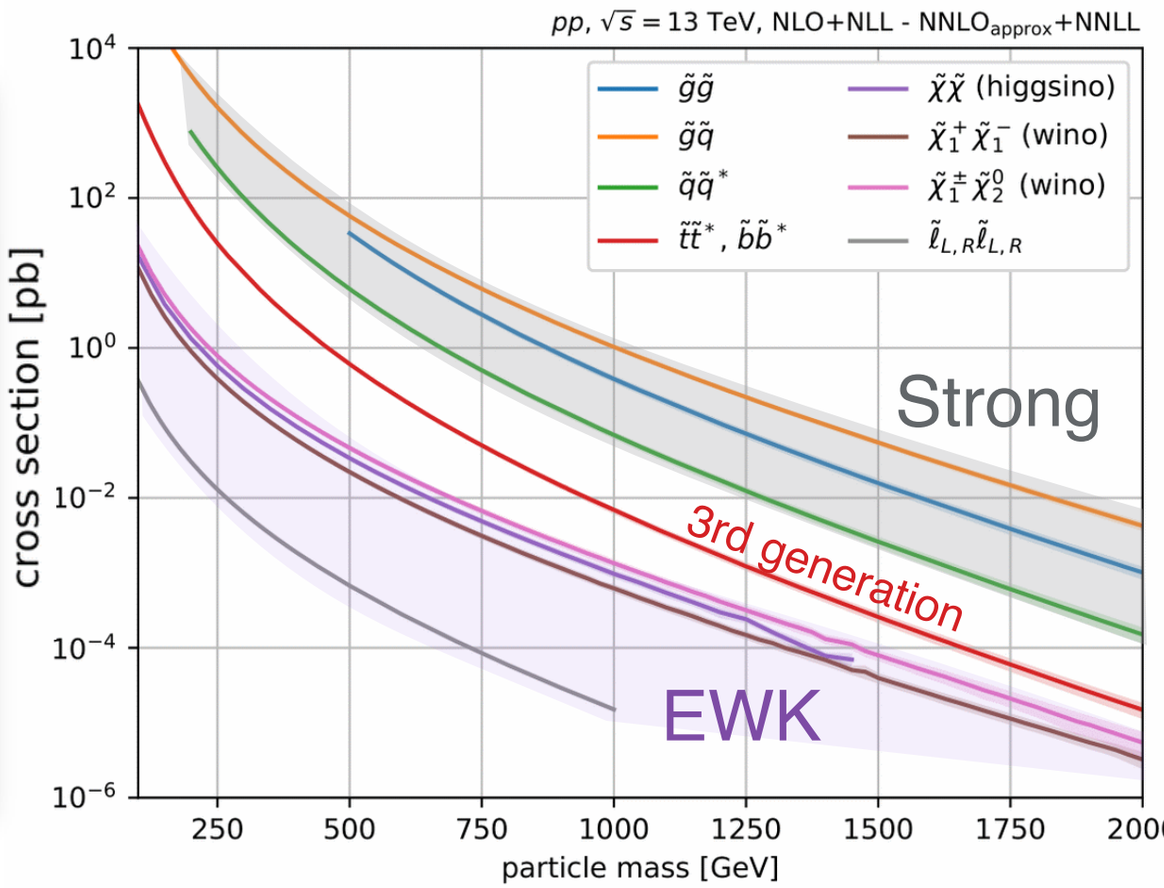
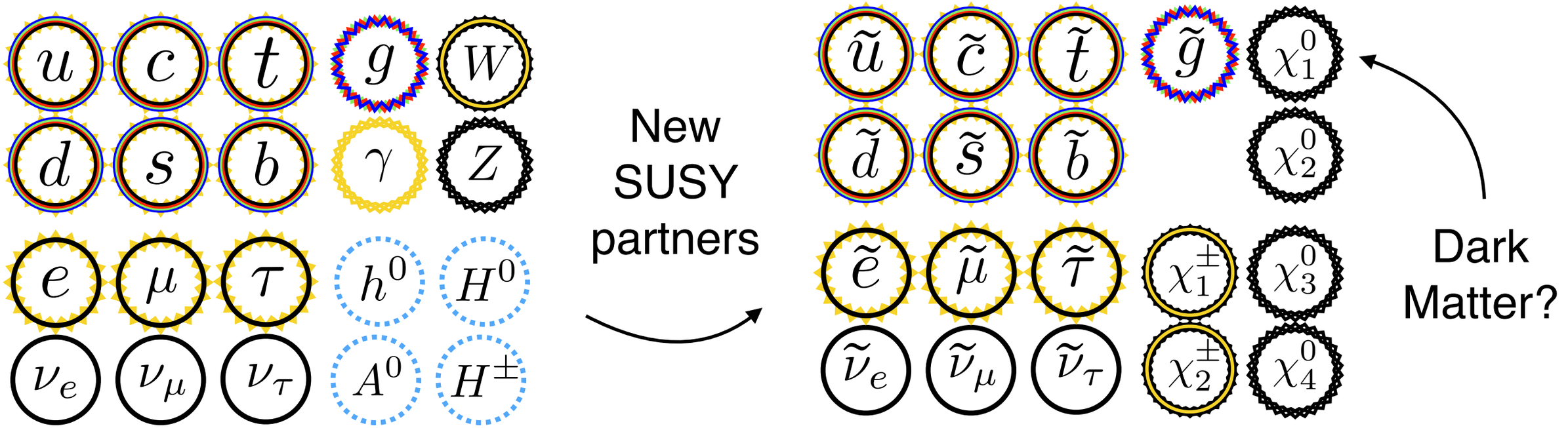
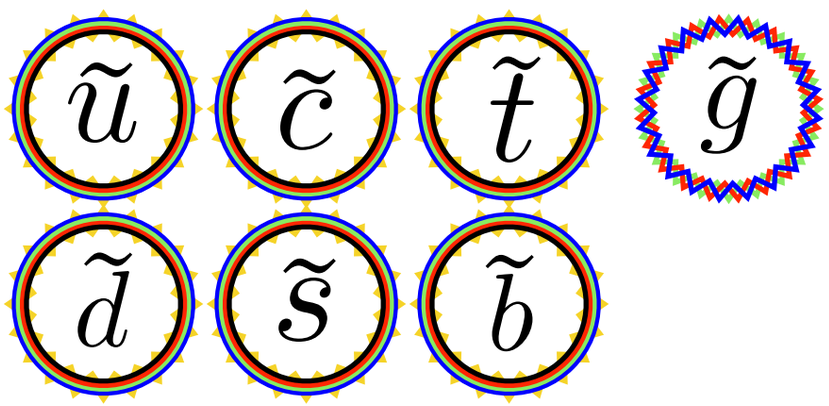


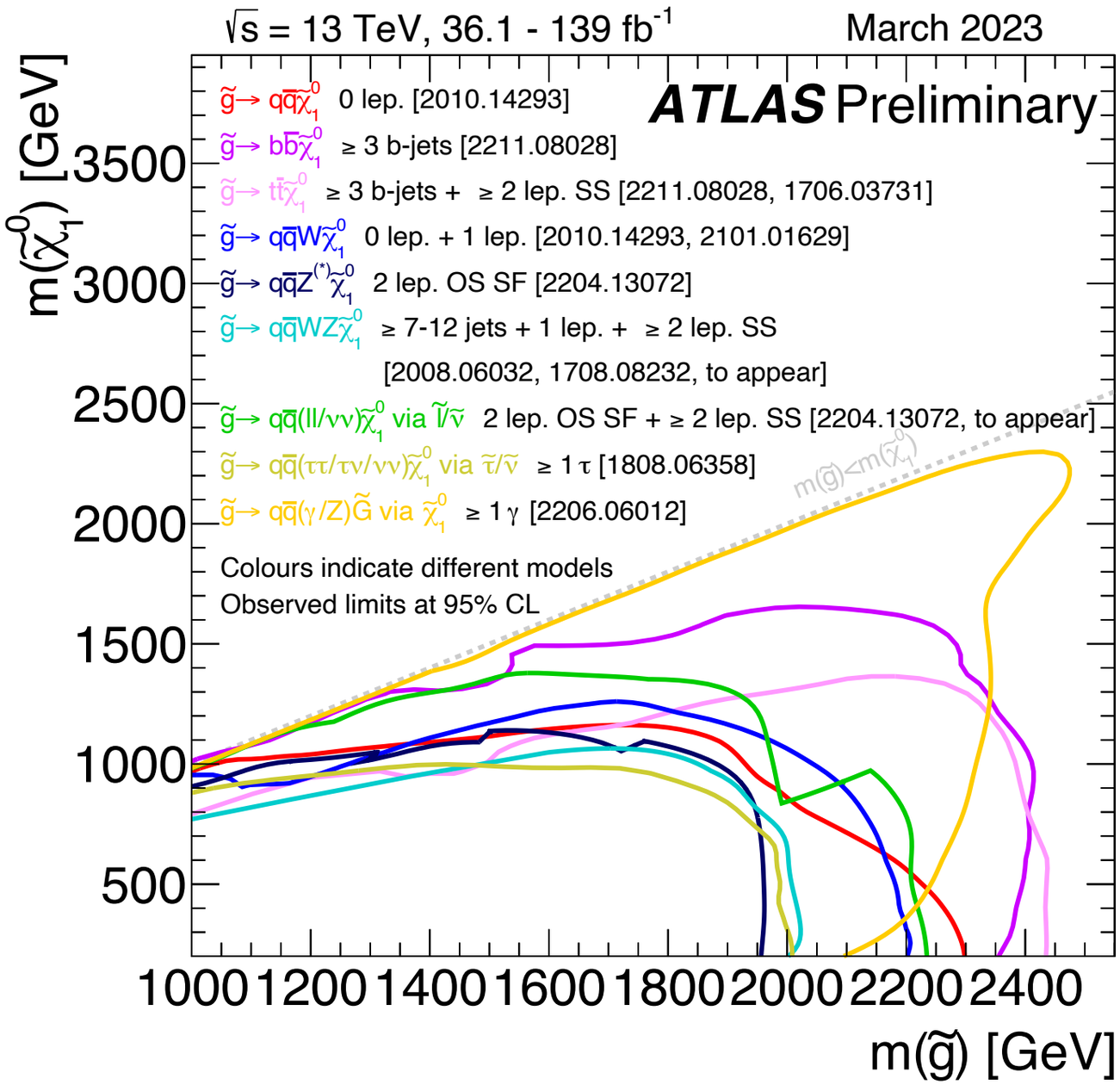


SUSY: where are we today?

Since *early 13 TeV data*, the most spectacular signatures face tight constraints.

→ Most notably Strong SUSY





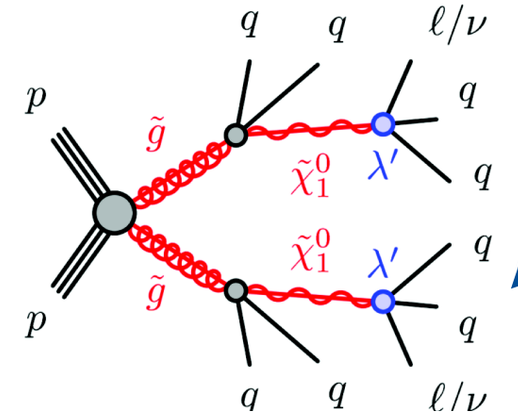
Each color in the plot represents a different model, probed by one or more analyses.

ATLAS Strong 2 Same-Sign & 3L

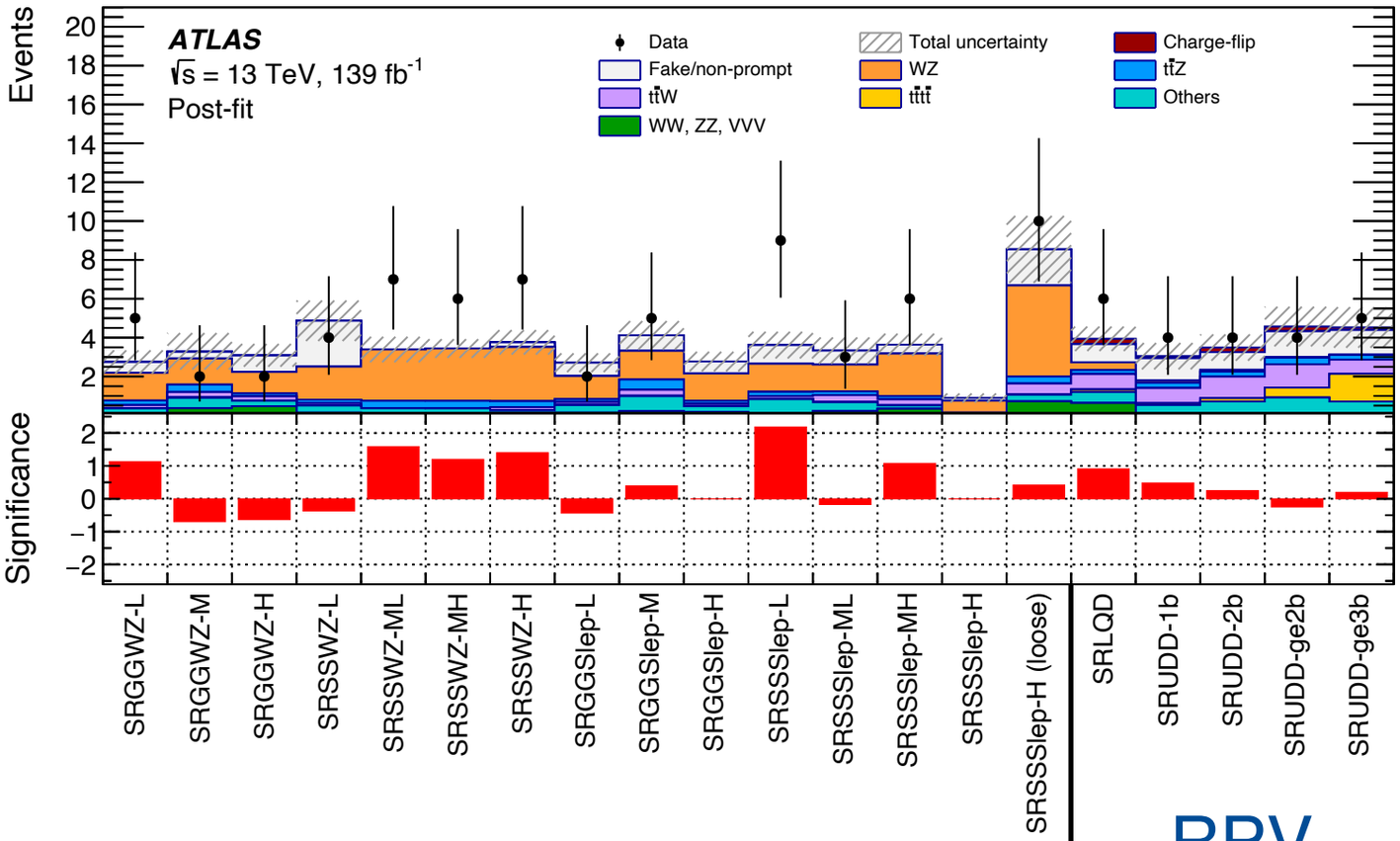
SUSY-2020-27

Workhorse final state: excellent for scenarios with long decay chains, complex spectra, and/or RPV couplings due to small SM background.

Craft dedicated Signal Regions for each target model based on #leptons, (b-)jets, $p_{T,miss}$, hadronic energy.

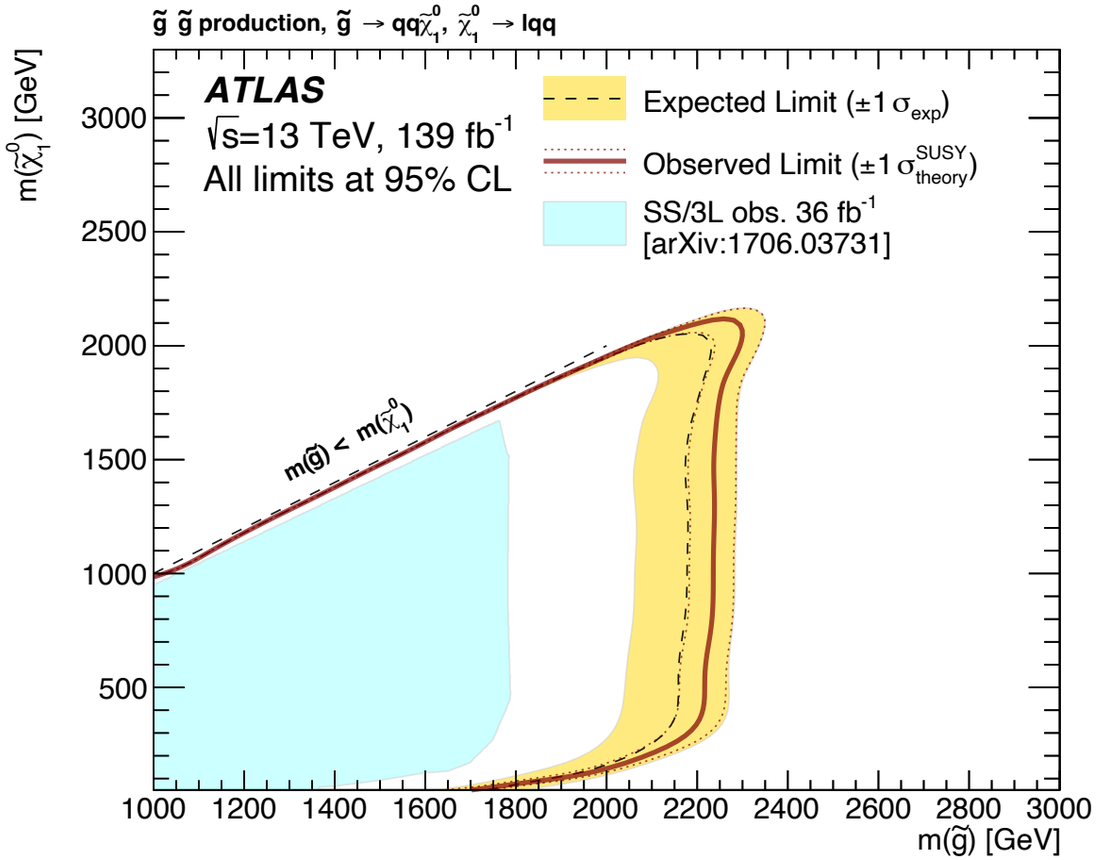


"LQD"



R-parity conserving model SRs

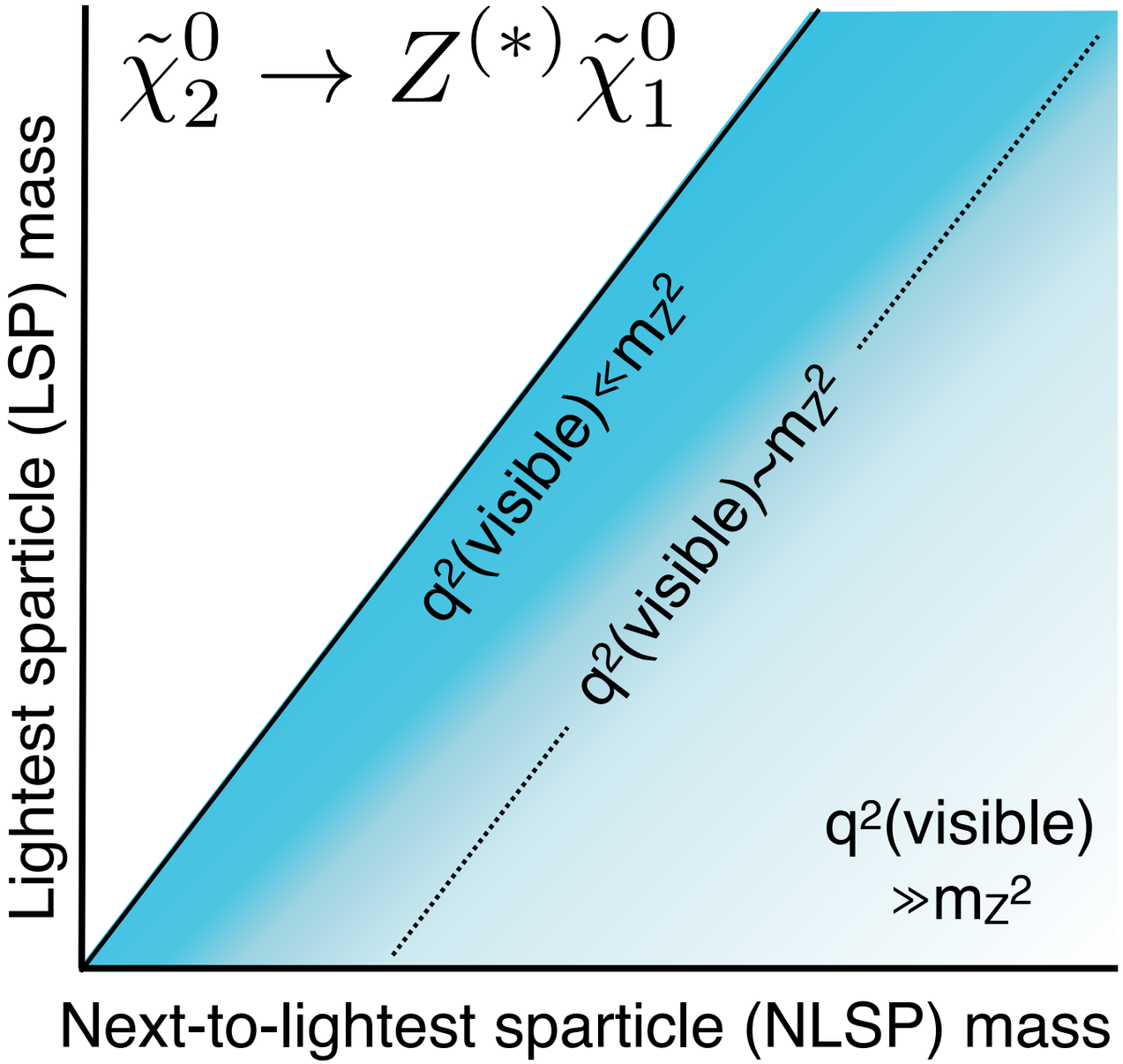
RPV regions



Targeting the electroweak sector

LHC signatures will be dictated by the few (lightest) sparticles.

→ target Simplified Models, where the heavier sparticles decouple.



Higgsino (μ) χ_3^0 $\chi_2^\pm$ χ_4^0

Wino (M_2) χ_2^0 $\chi_1^\pm$

Bino (M_1) χ_1^0

n.b. mass-ordering not known a-priori

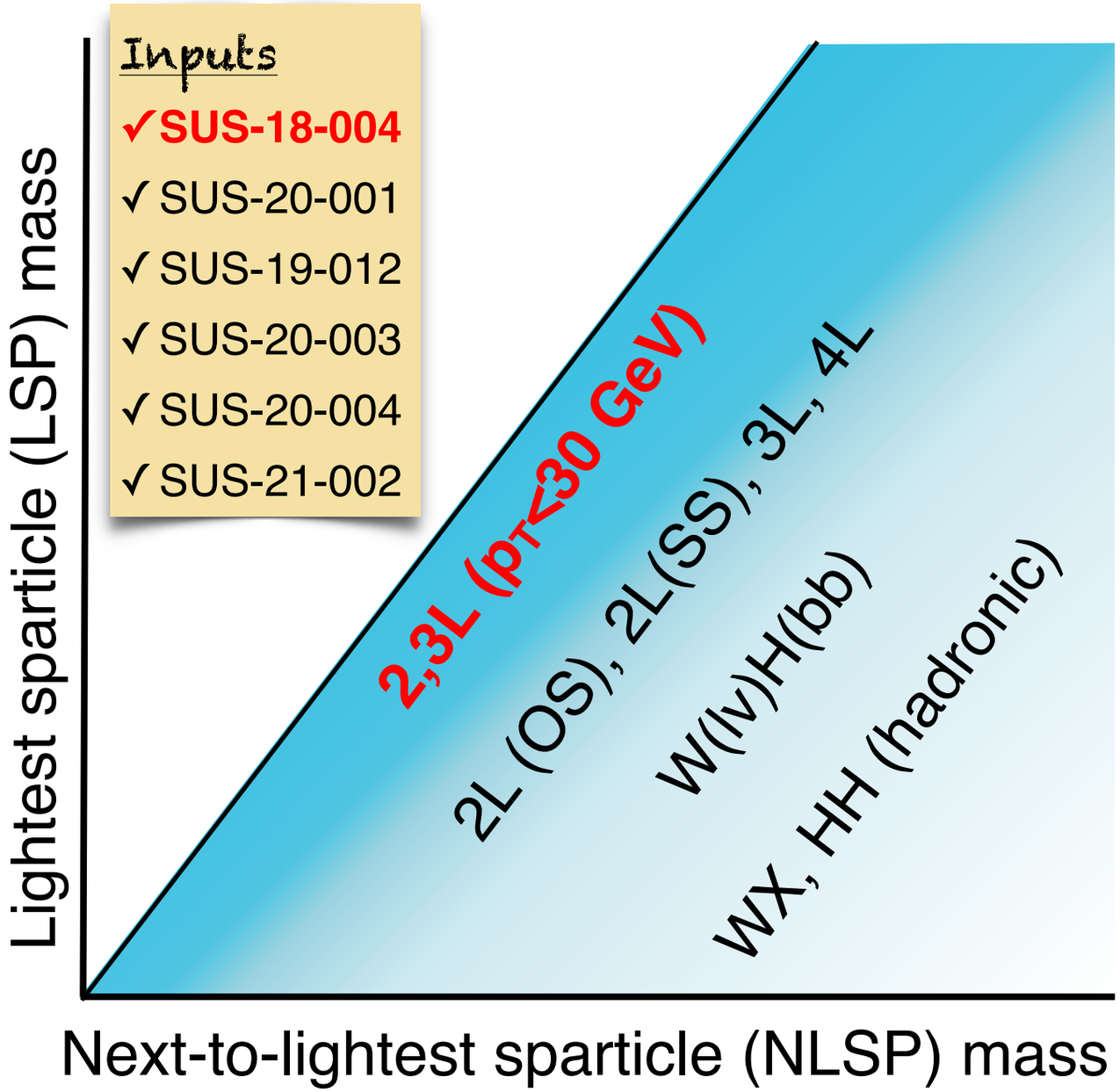
Aim to systematically cover all production channels, and mass spectra

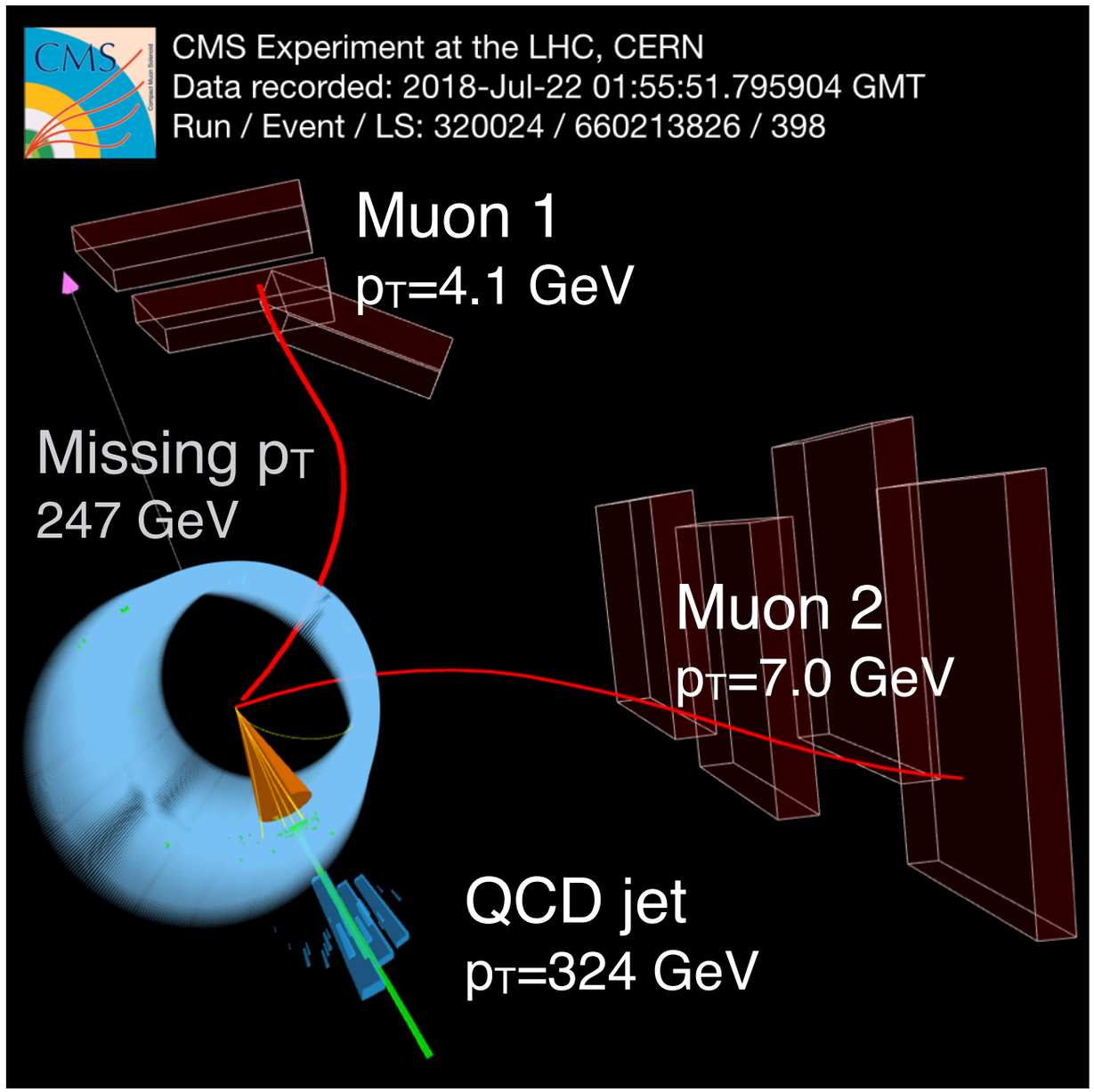
CMS Electroweakino combination

SUS-21-008

Statistical combination of six analyses targeting "$p_{T,miss}$ + (W/Z/h)" final-states.

Complementary low/high-p_T, leptonic/hadronic channels.





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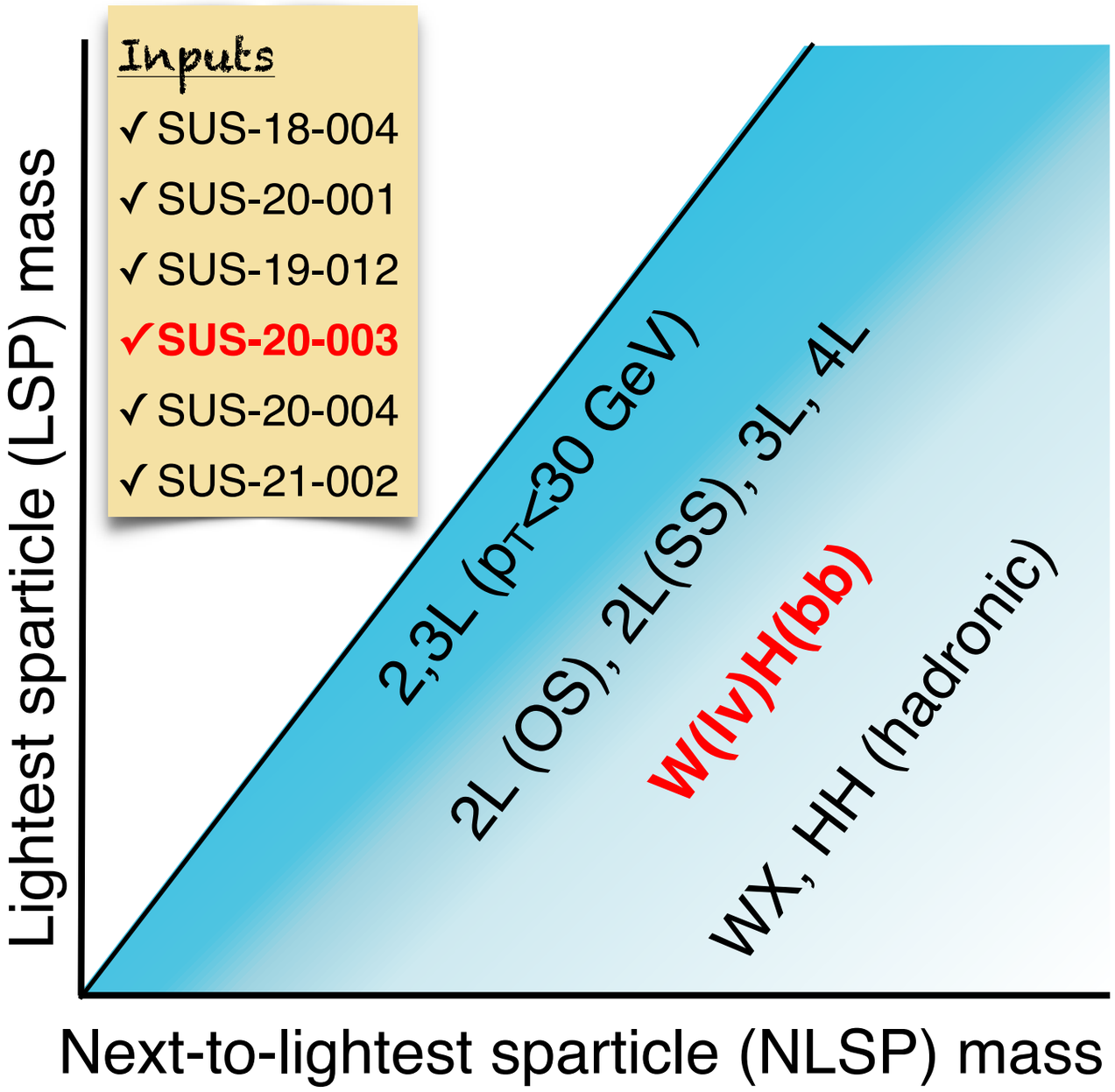

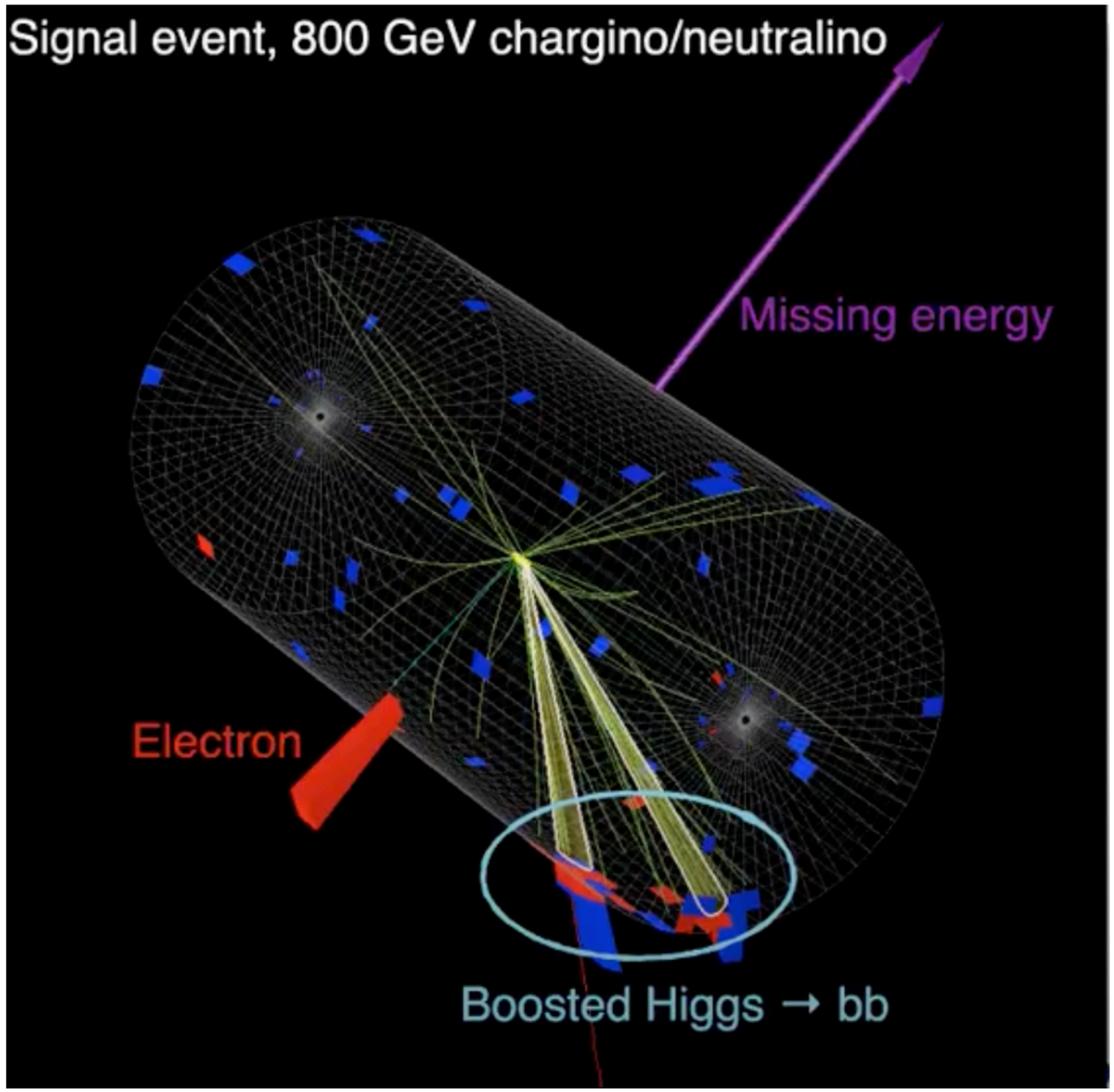

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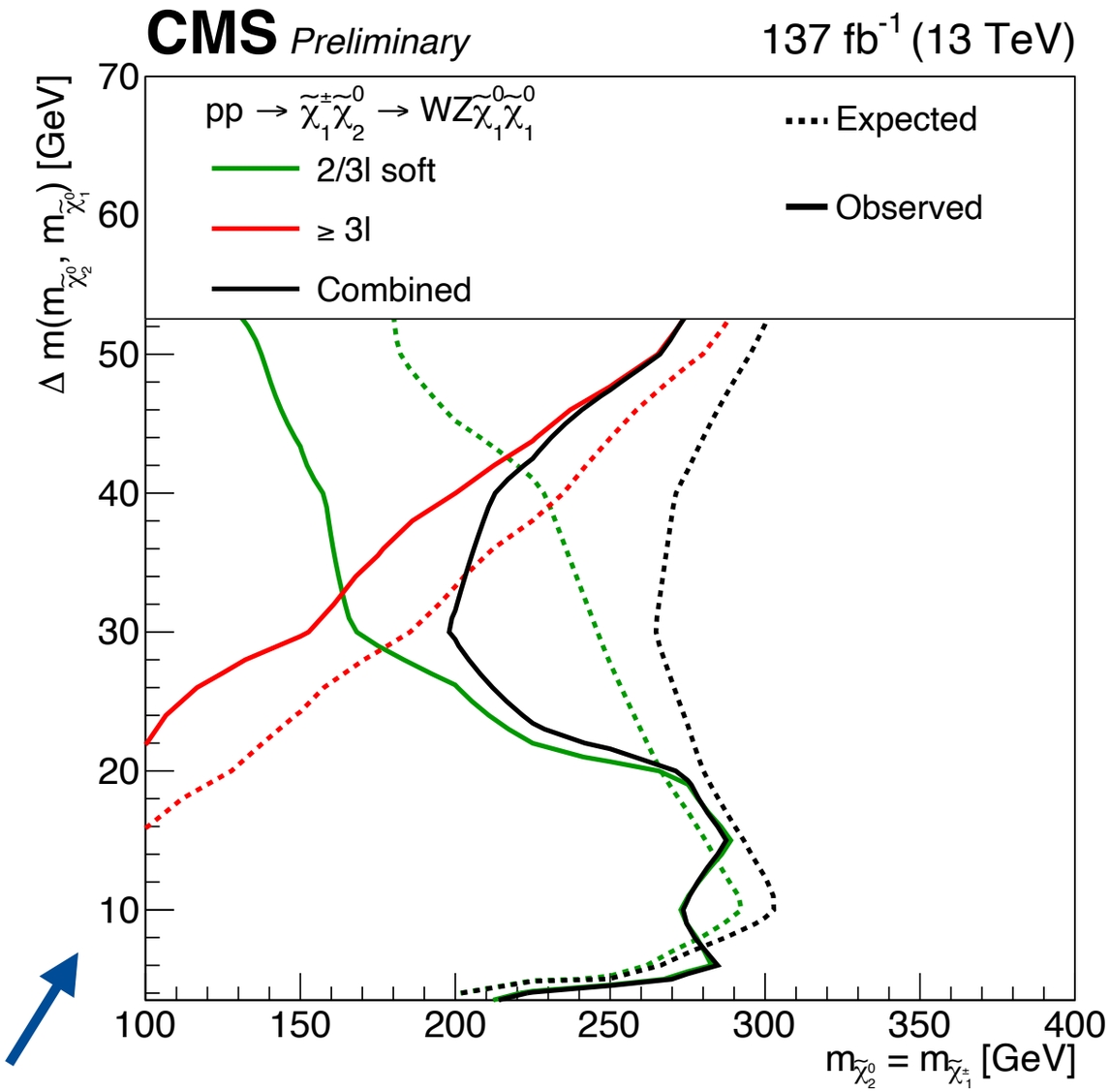
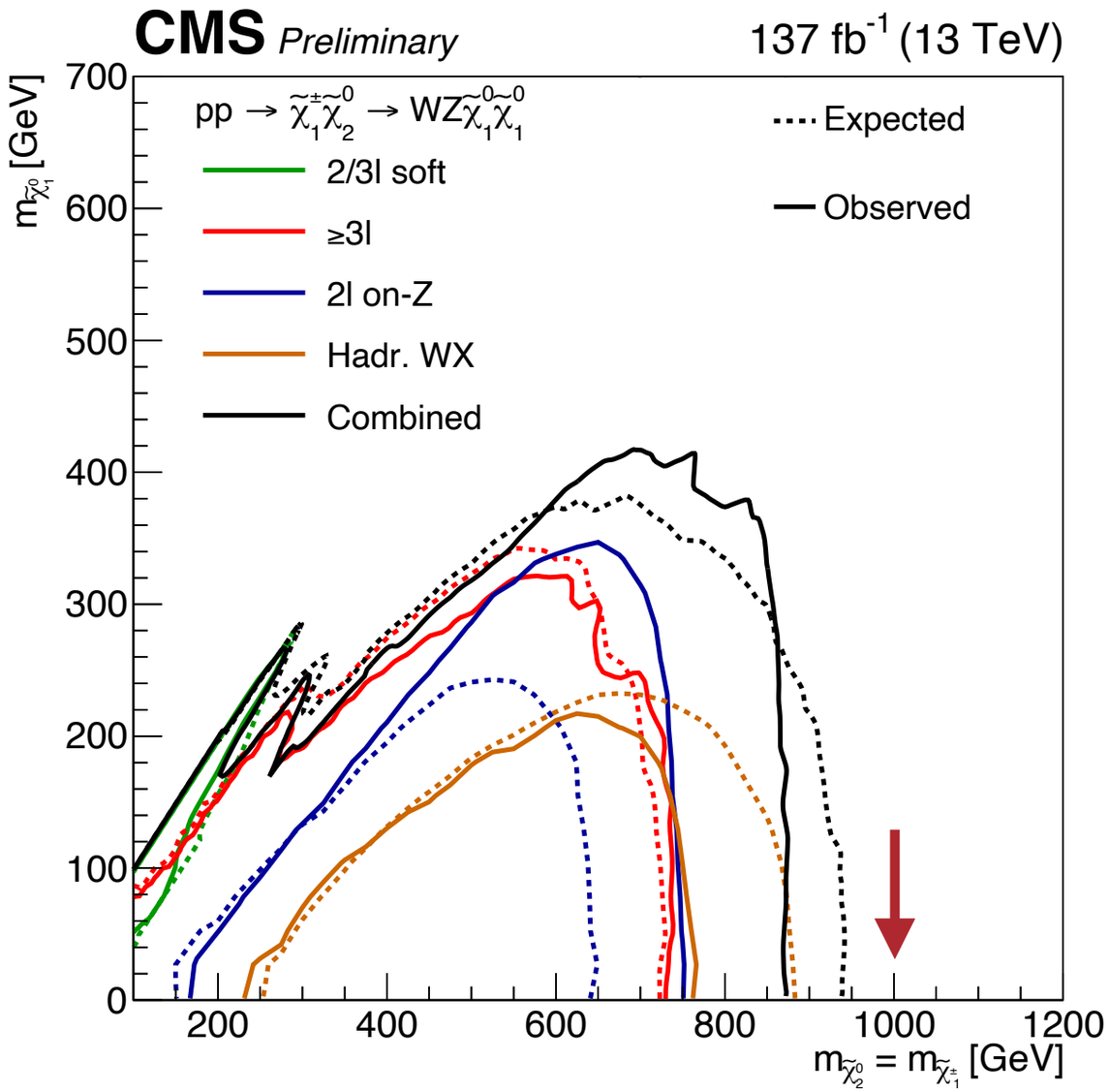




Broad sensitivity to Δm of 3-50 GeV.

(Improved signal extraction procedure w.r.t. the initial paper result.)

Together the 2L, 3L, & hadronic channels probe (nearly) **TeV Winos**.

For the latest ATLAS results on EWK SUSY, see talk by S. Passagio.

CMS Photon + Jets + $p_{T,miss}$

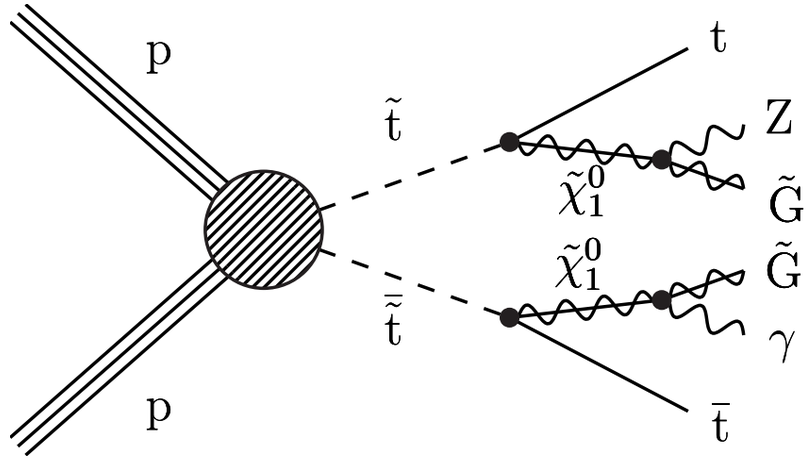
SUS-21-009

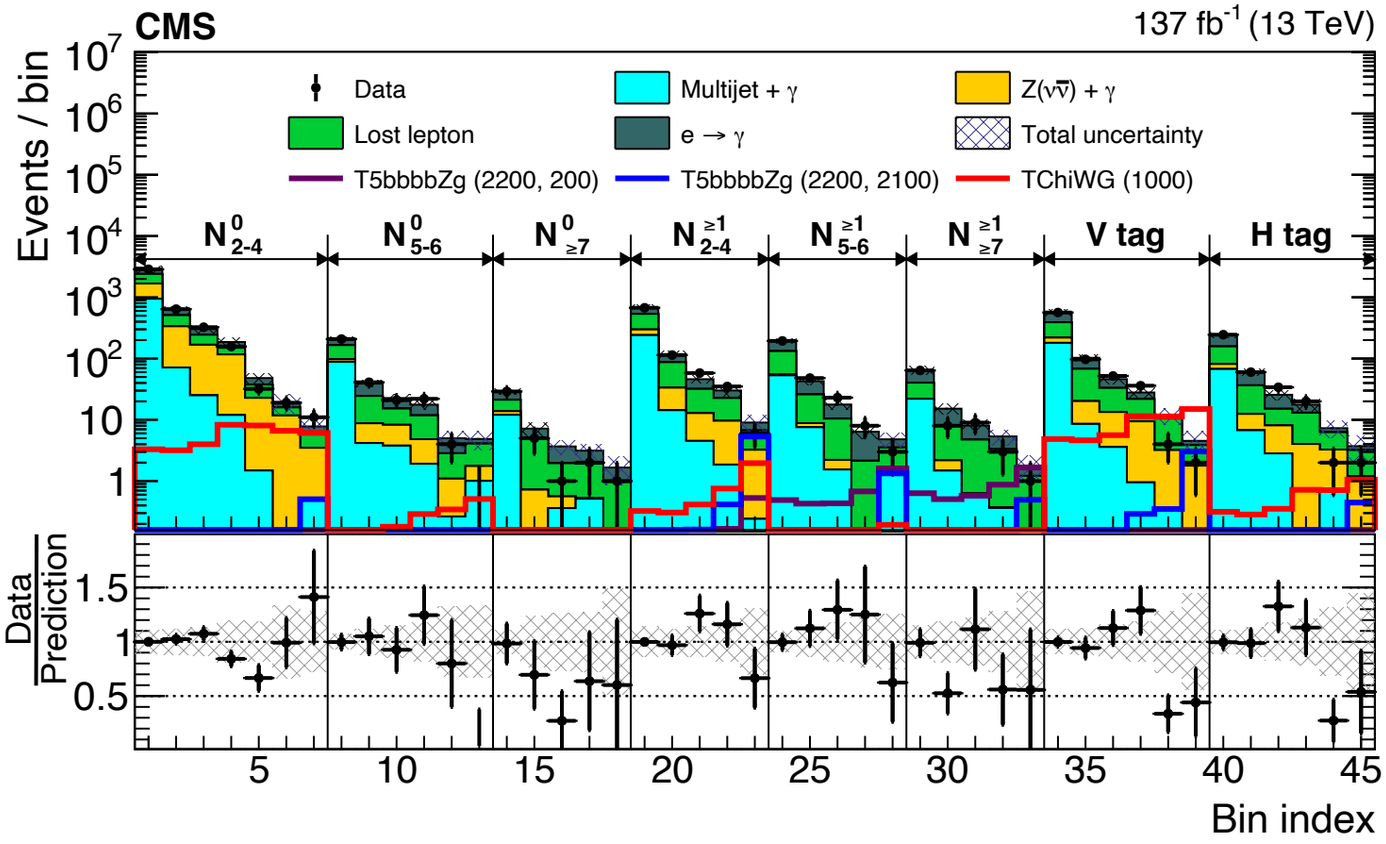
GMSB scenario: EWKinos decay to γ + Gravitino

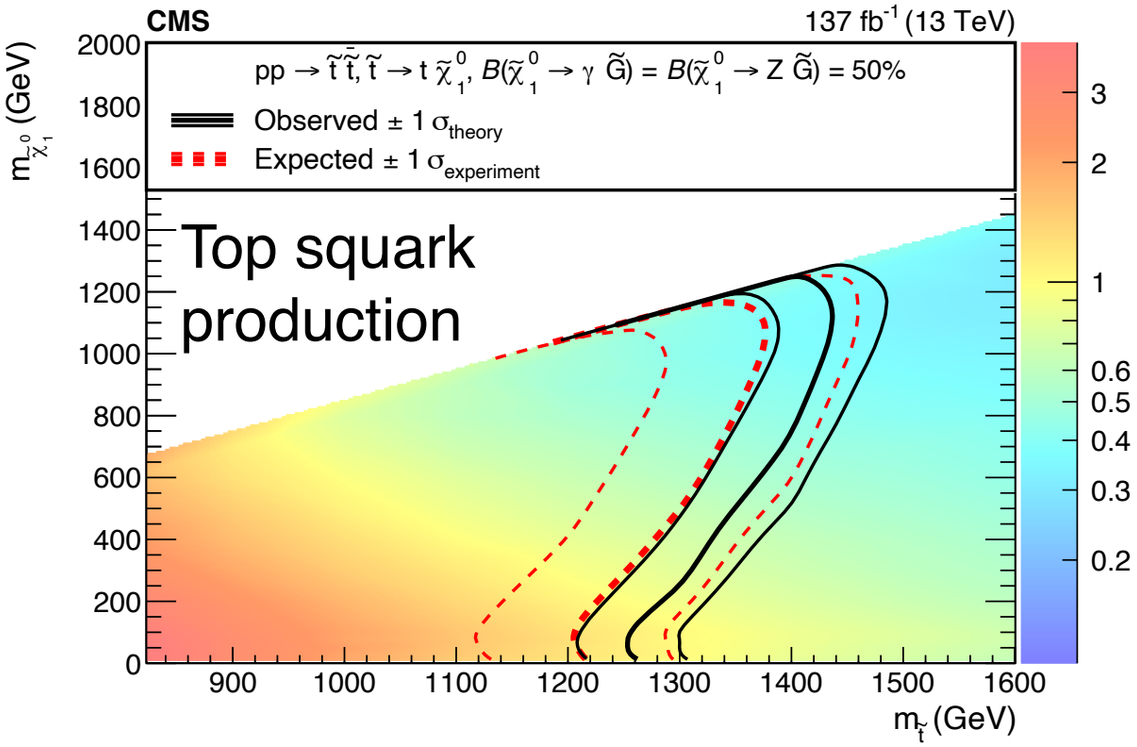
- Search considers both strong+weak production.

Selection: 100 GeV photon and ≥2 jets

- Categories ($p_{T,miss}$, #(b-)jets, and W/Z/h-jets) probe a range of production modes.







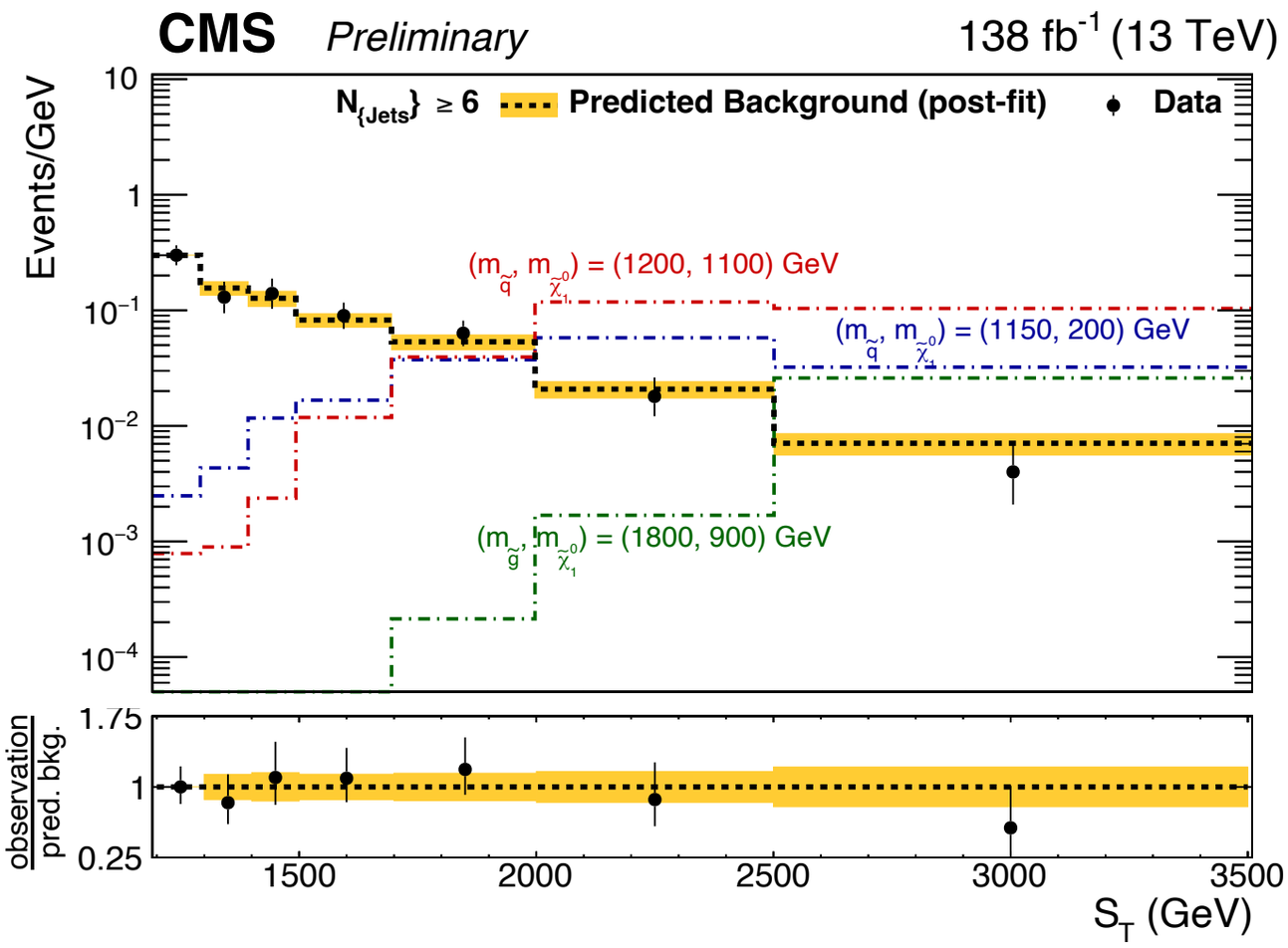
Limits placed on gluinos, squarks, 3rd generation, EWKinos.

CMS Stealth DiPhoton, low $p_{T,miss}$ SUS-19-001

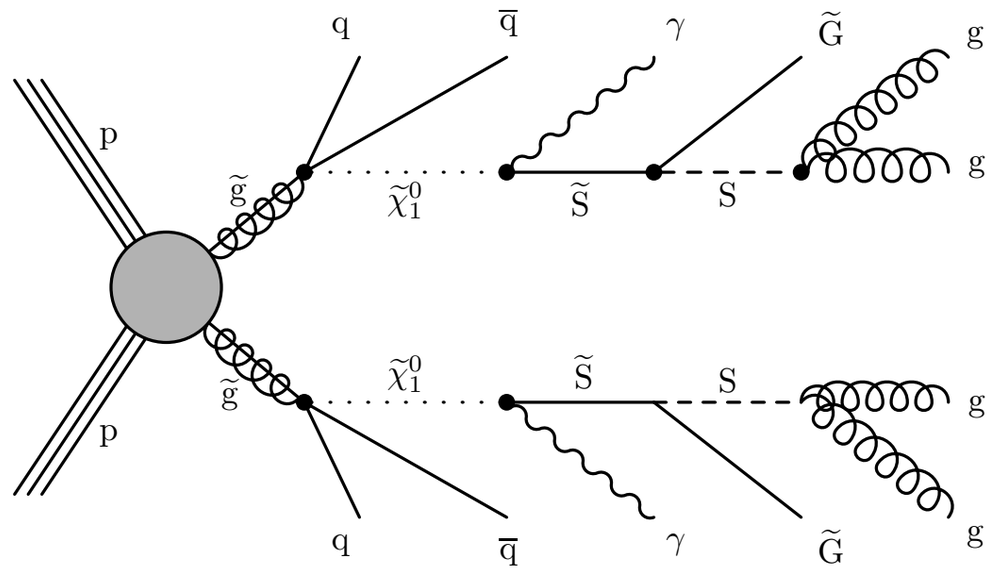
"Stealth" SUSY extends MSSM w/ (~mass degenerate) Singlet+Singlino

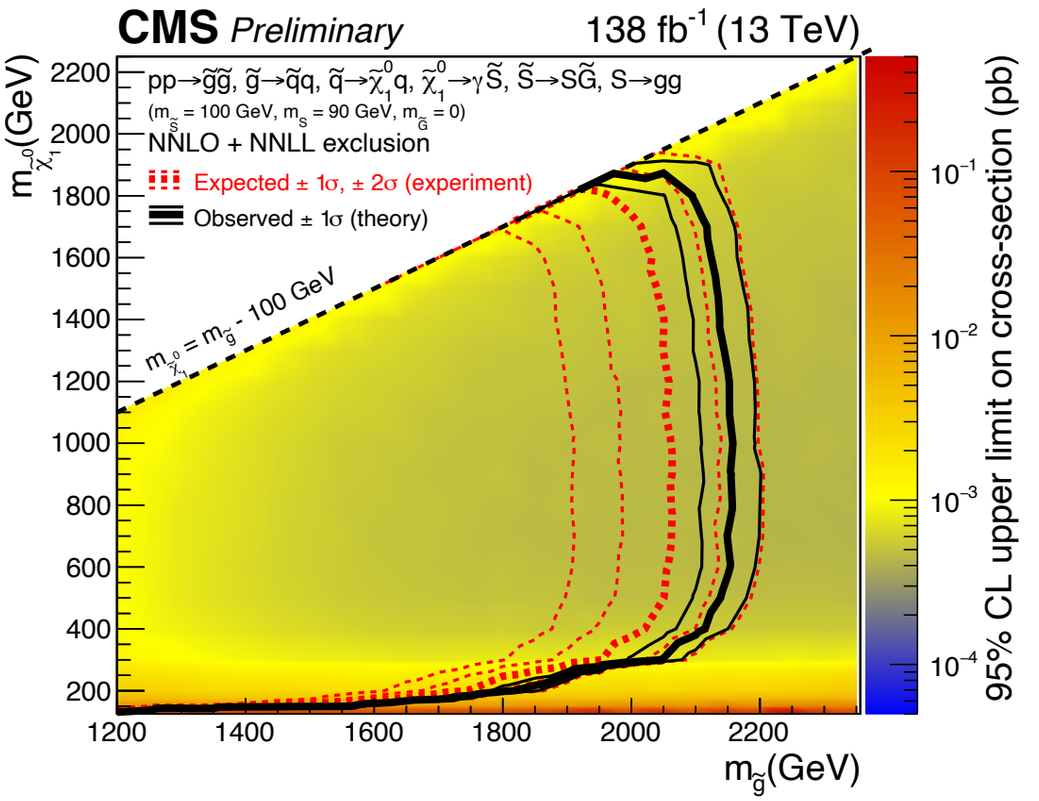
Experimental signature without $p_{T,miss}$!

Targets events with 2γ, significant energy.



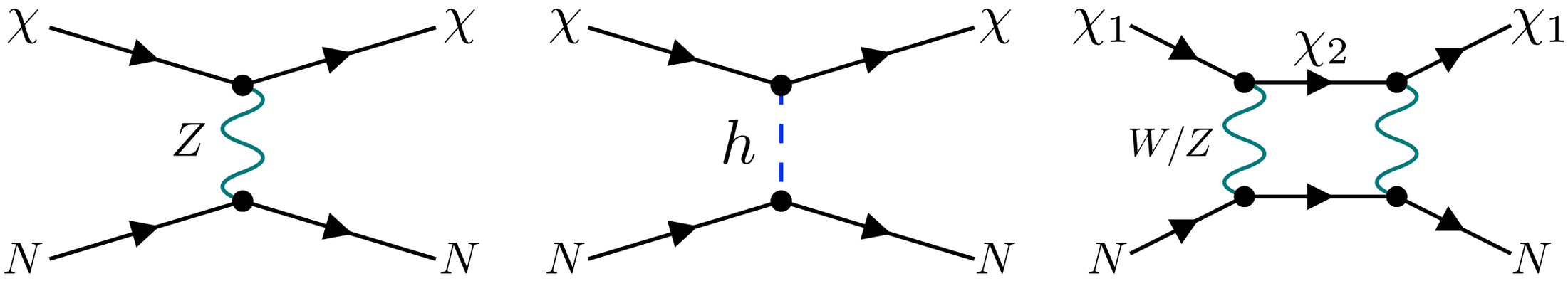
Background prediction from universal scaling functions in $S_T = \sum_{all} |p_T|$.



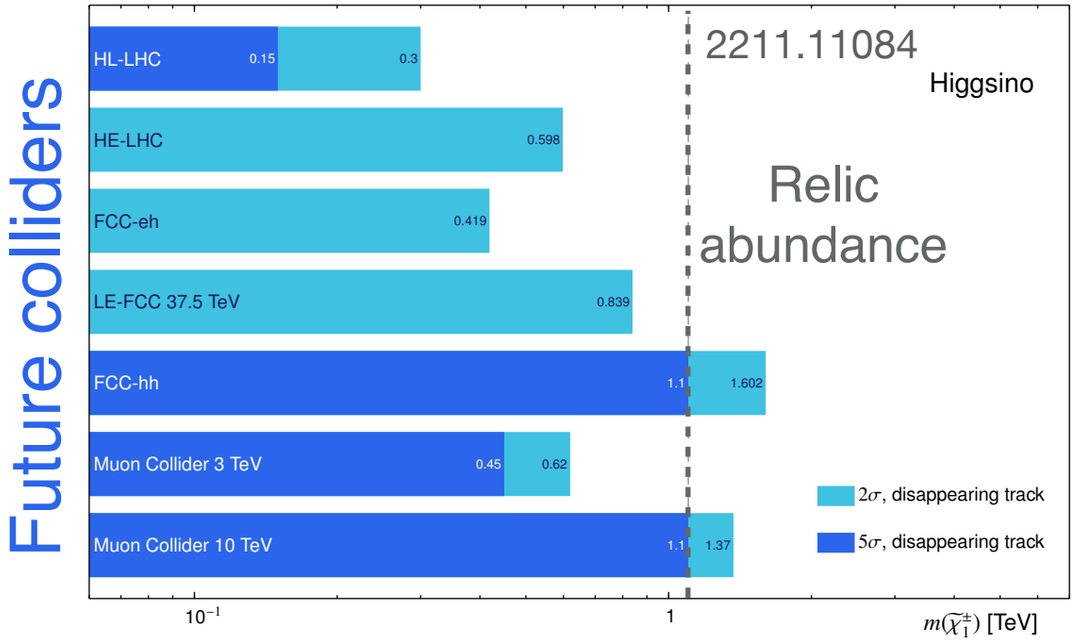


Dark Matter searches at the LHC

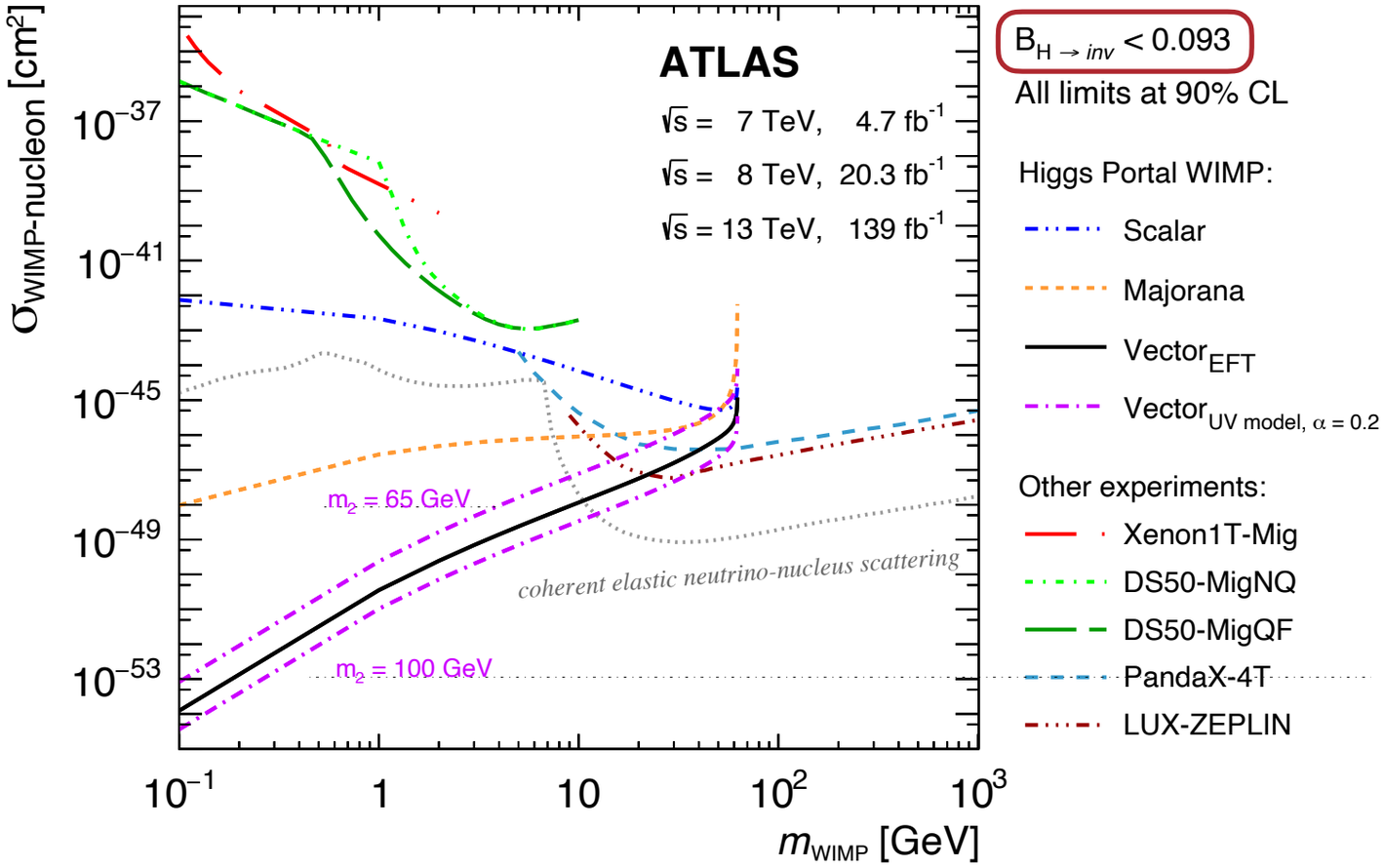
Simplest WIMP scenario adds only 1 new state: the DM candidate itself.



Future colliders



For weak N-plet m_{DM}~1-3 TeV, likely requiring larger √s collider.

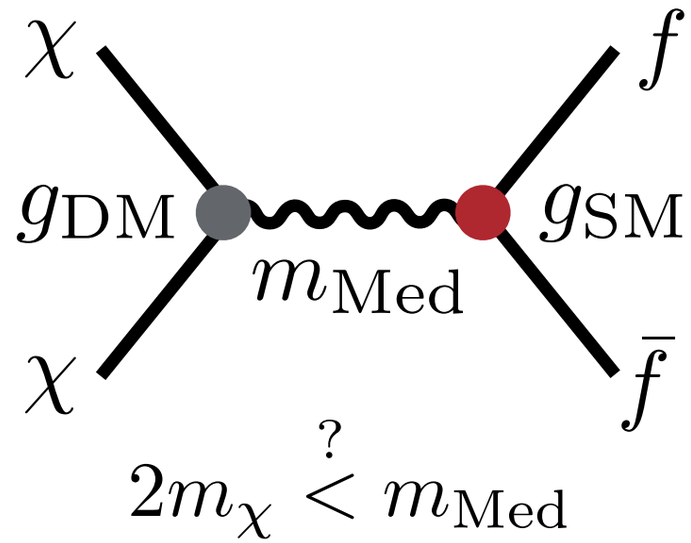


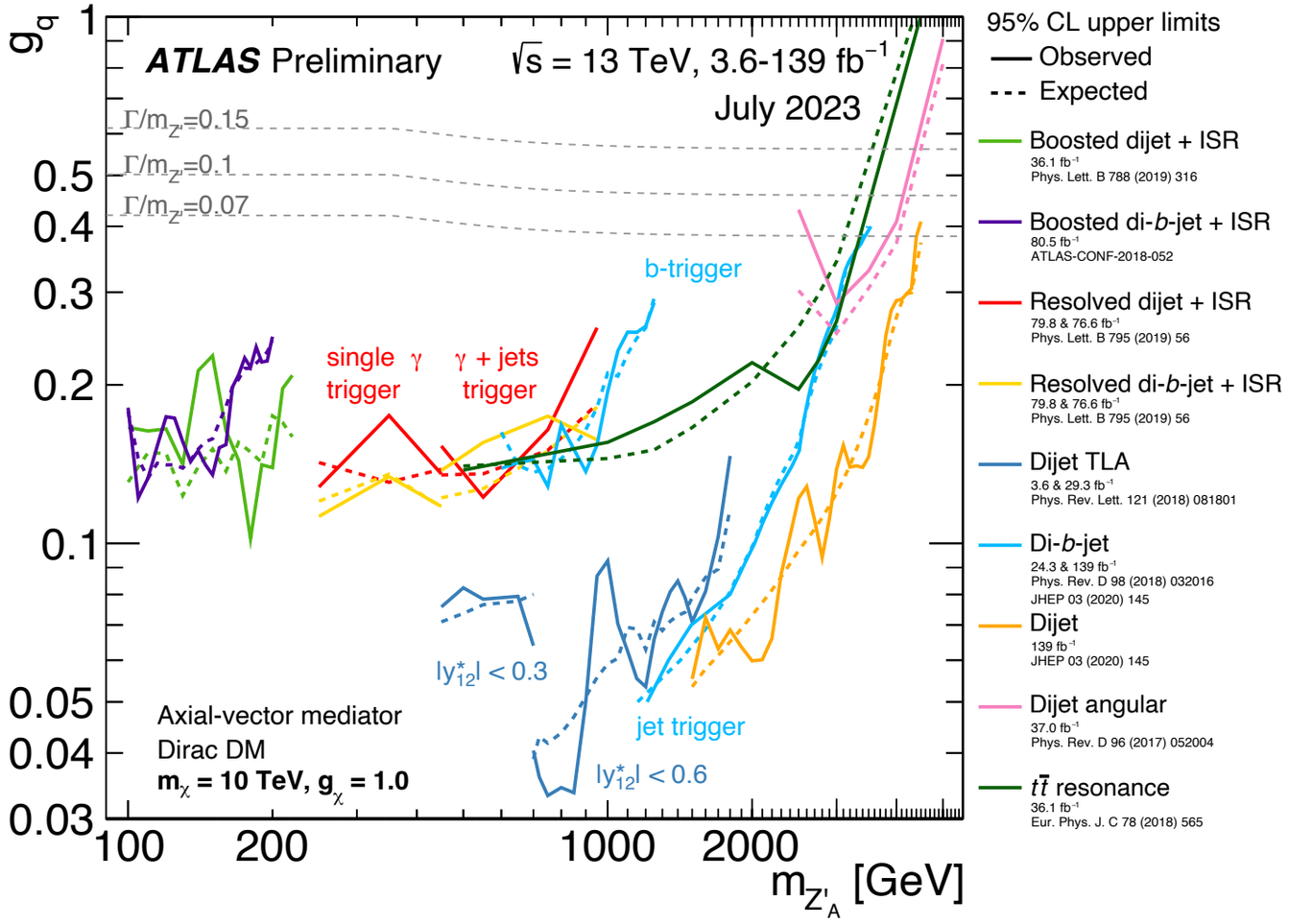
Minimal s-channel models

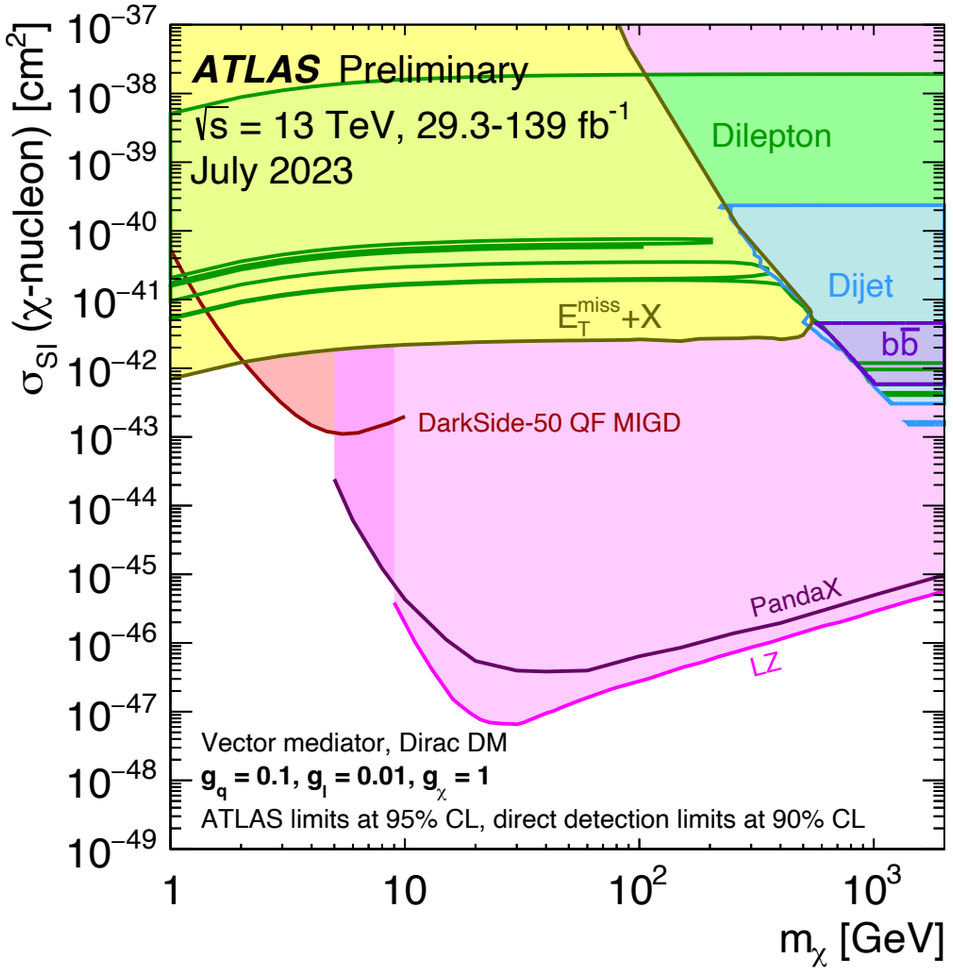
ATLAS summary
CMS summary

New mediators may facilitate SM-DM interaction, leading to several degrees of freedom:

- m_{DM}, mediator masses, couplings to DM, SM.
- Mediator: (Pseudo-)scalar, (Axial-)Vector?
- DM: Dirac, majorana, (scalar, vector)?







CMS WW+$p_{T,miss}$

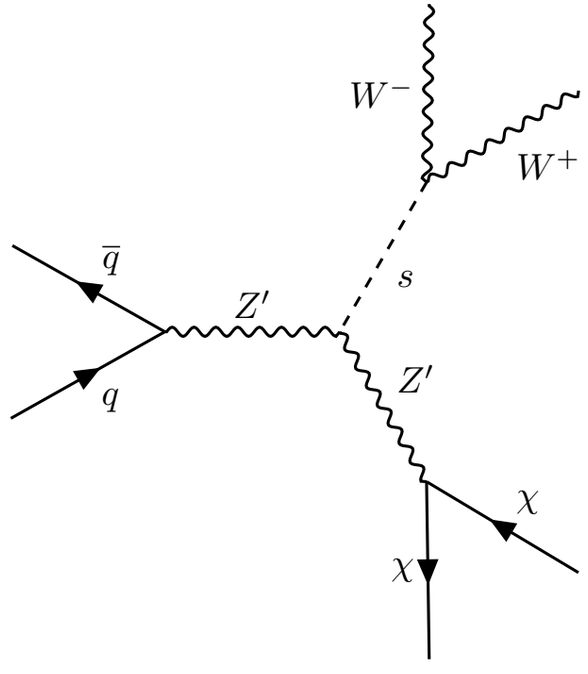
EXO-21-012
ATLAS summary

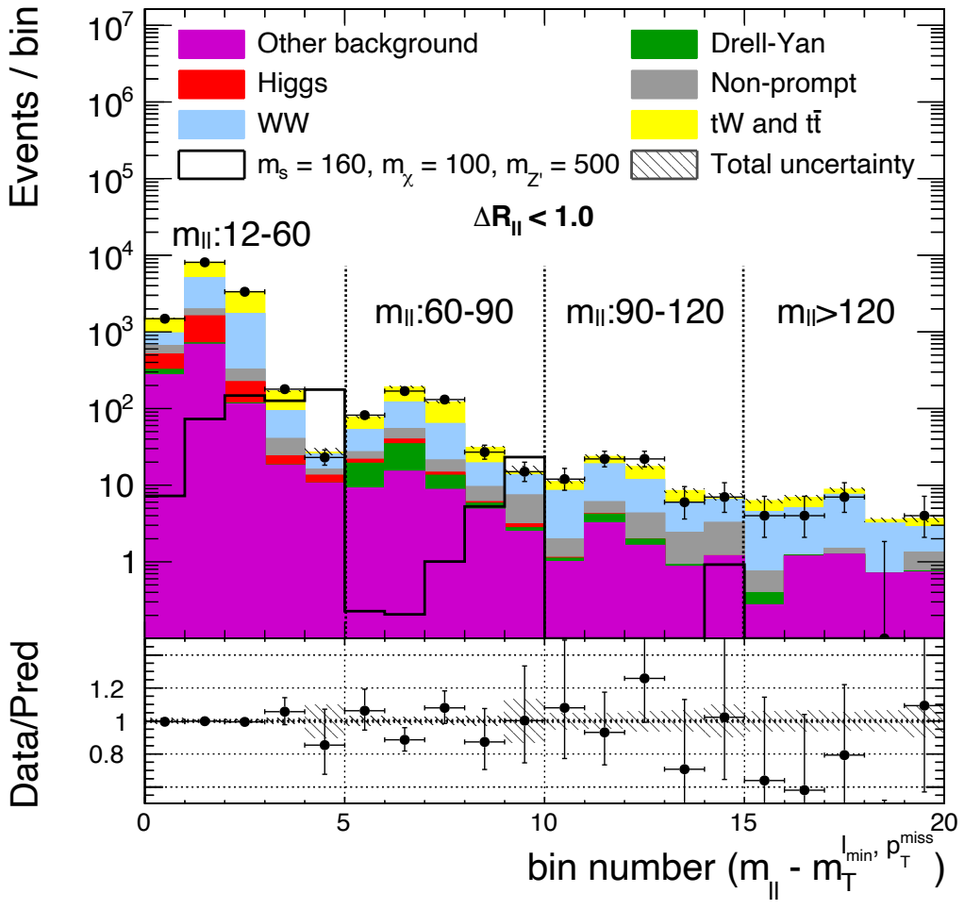
Dark Higgs model adds a light scalar that can't decay invisibly ($m_s<2m_\chi$, 'secluded annihilation').

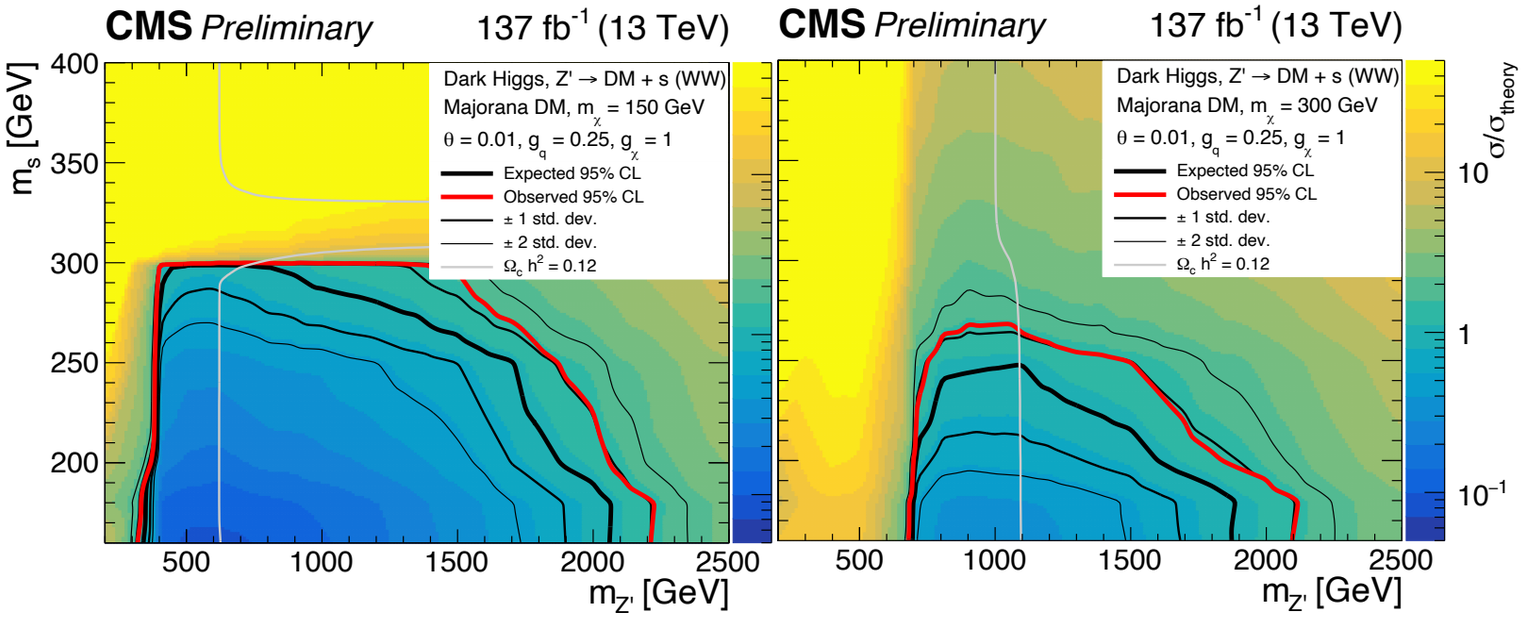
- Relic favors large s-Z' couplings → dark h-strahlung.

New CMS result: s→WW for 2l2v + lvqq' channels.

- Template fit to $m_{ll}/m_{T,min}$ (2L) and BDT analysis (1L).







Results are interpreted for range of m_χ values.

CMS WW+$p_{T,miss}$

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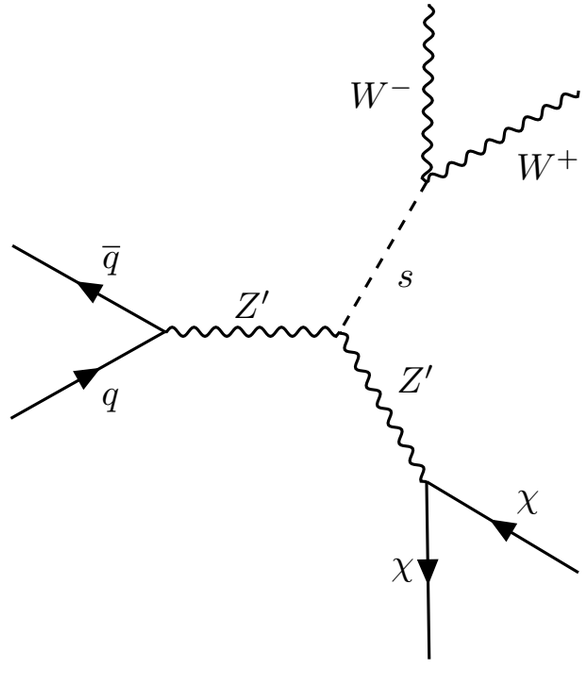
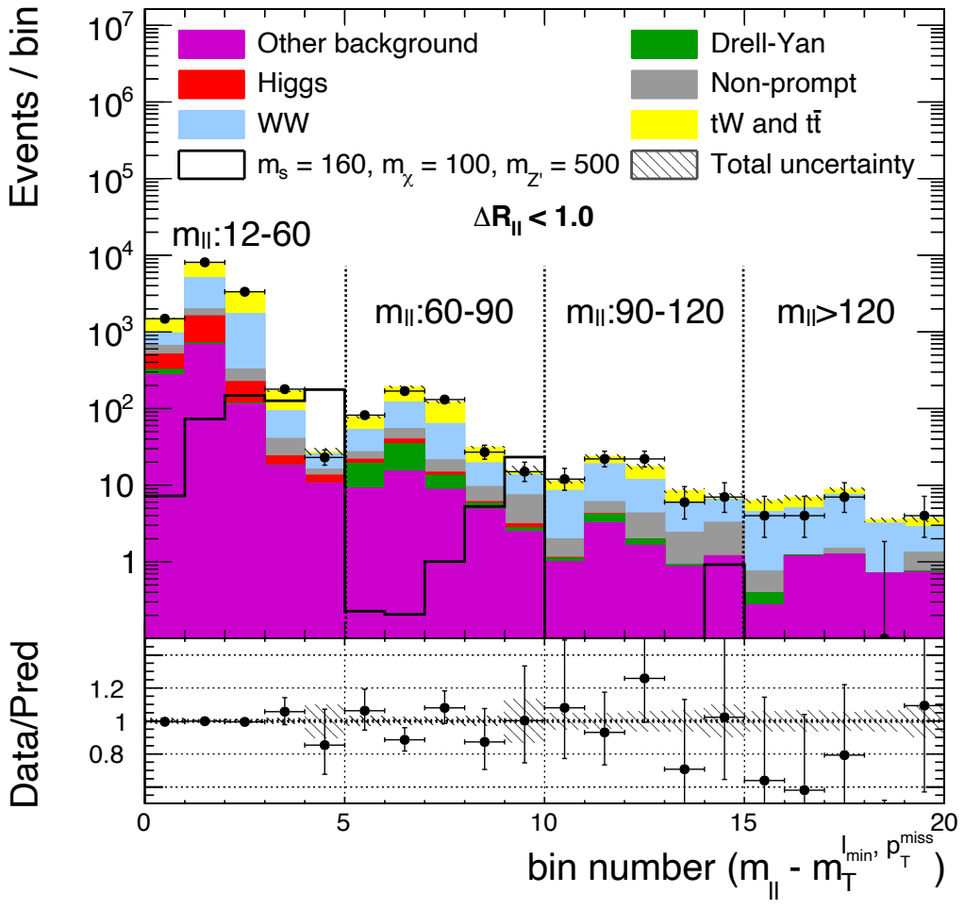
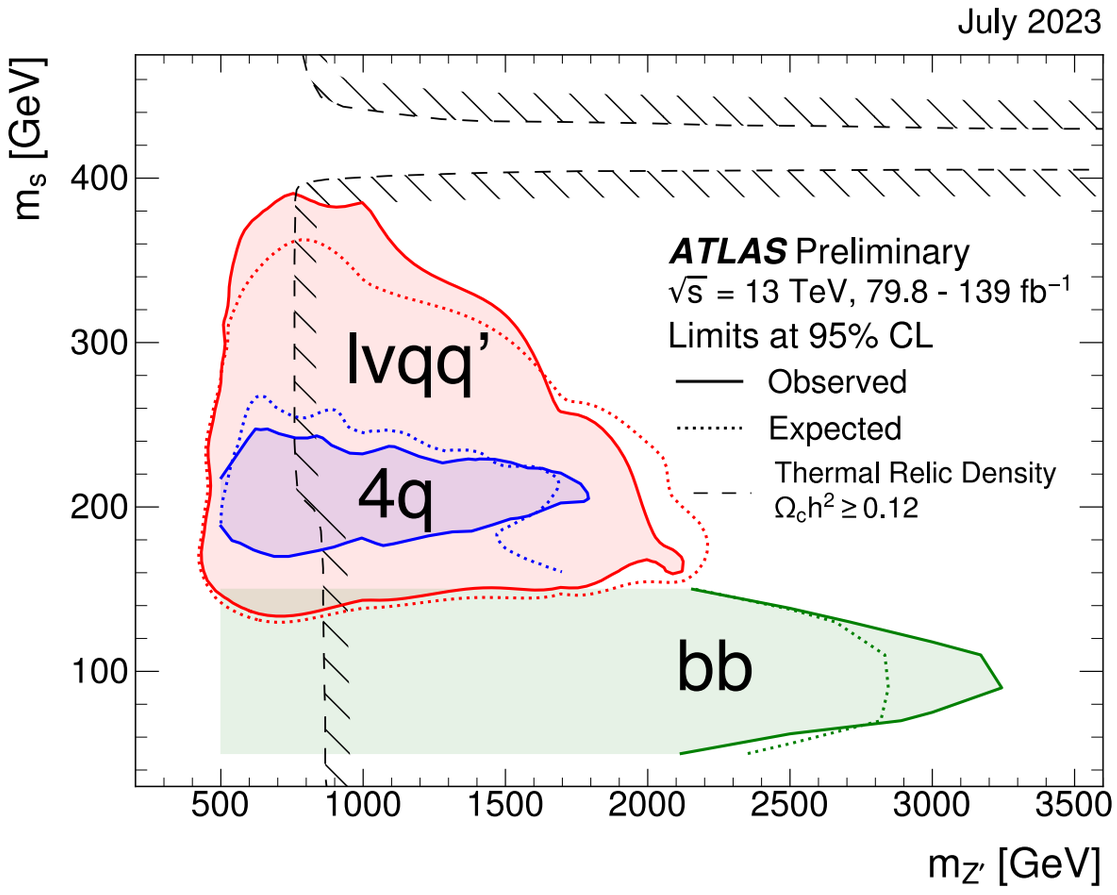






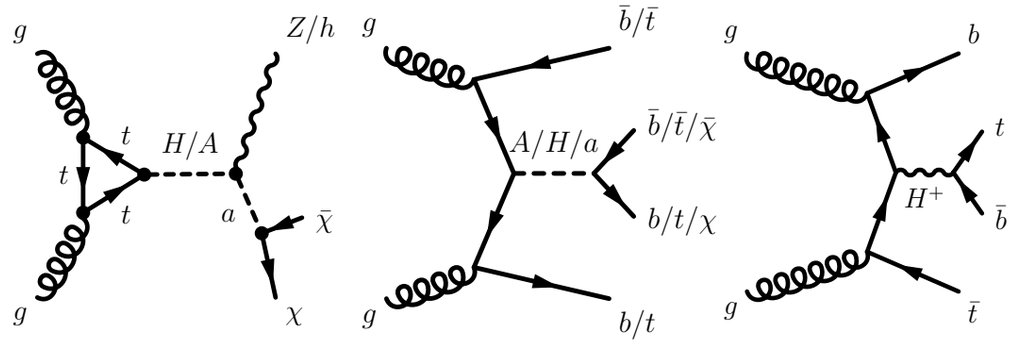
Summary of ATLAS search channels.

UV complete models: 2HDM+a

EXOT-2018-64

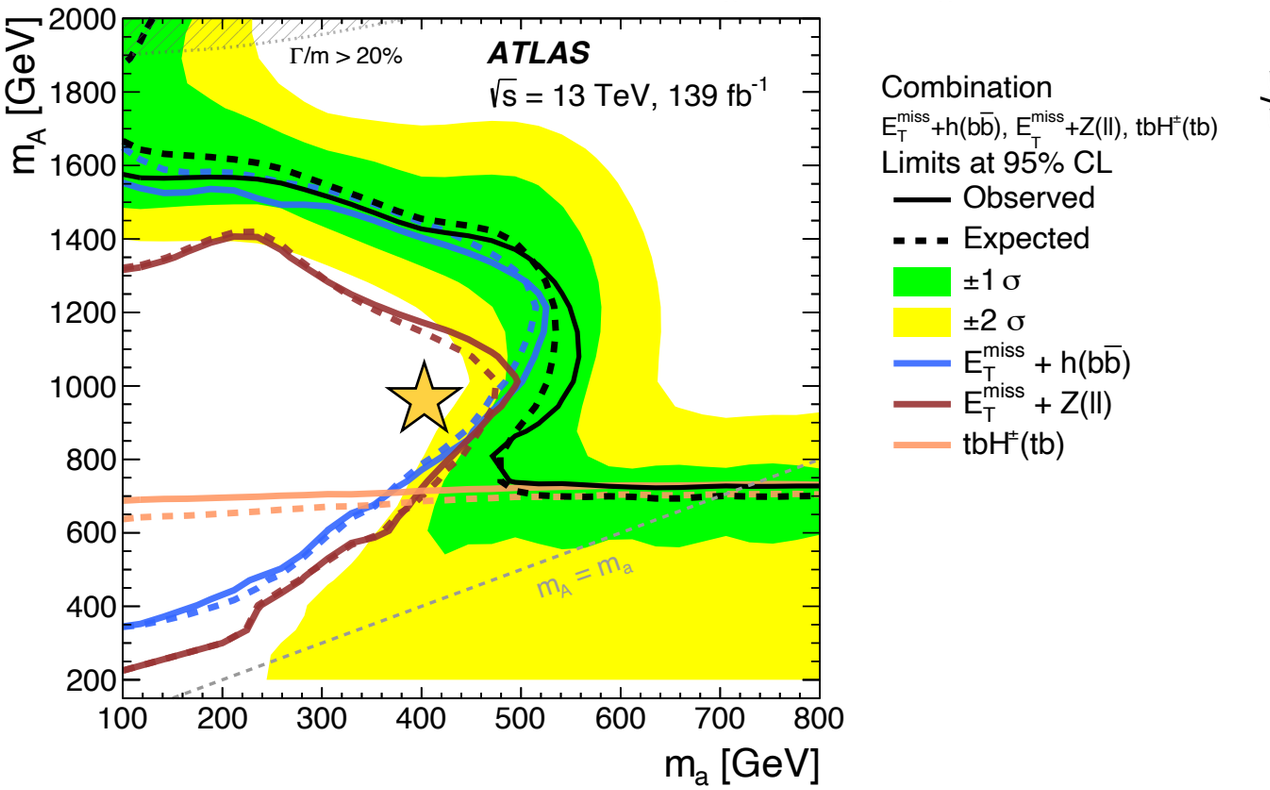
Model adds Type-II 2HDM (h, H, H±, A) plus pseudo-scalar mediator and DM (a, χ).

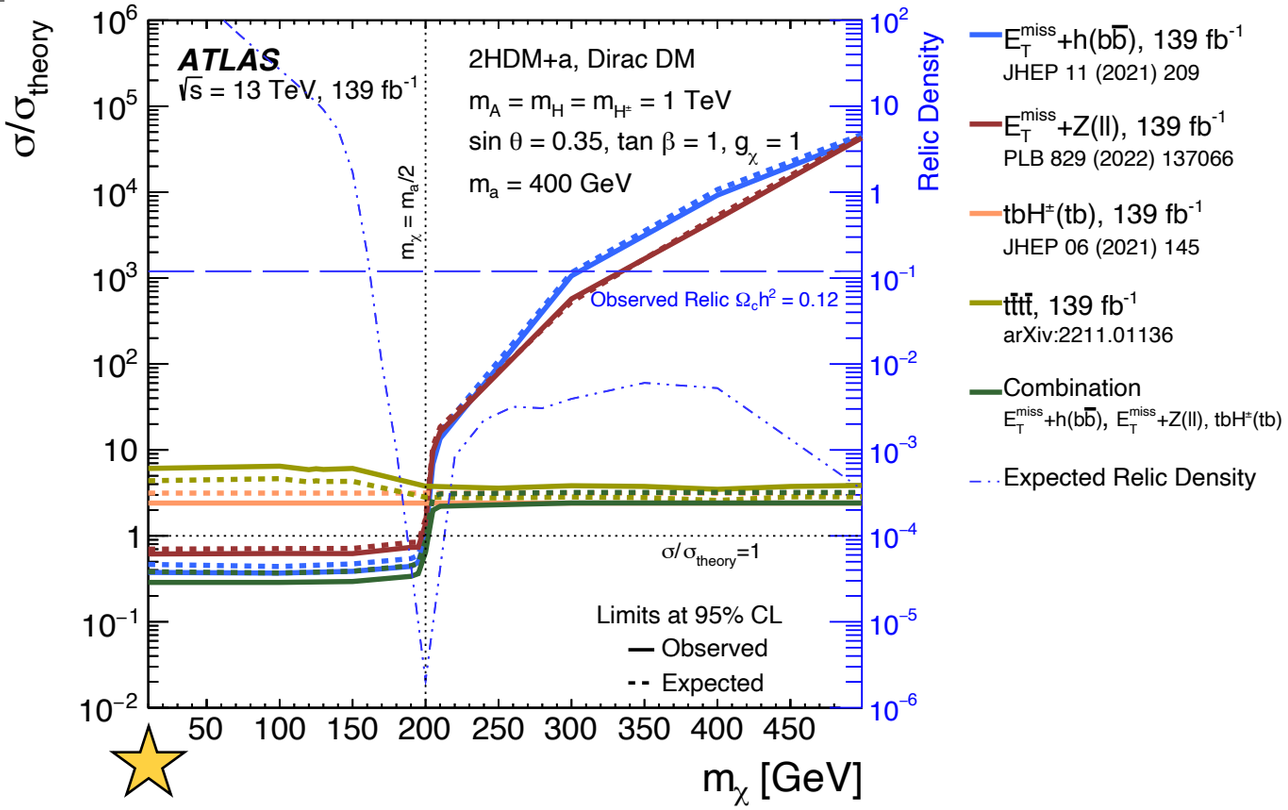
- Recent **ATLAS summary** considers several benchmark scenarios.
- Combines 3 of the leading channels.



$E_{\mathrm{T}}^{\mathrm{miss}} + Z(\ell\ell)$ [74]	$E_{\mathrm{T}}^{\mathrm{miss}} + h(\gamma\gamma)$ [84]	$h \to$ invisible [86]	$h \to aa \to f\bar{f}f'\bar{f}'$ [79–83]
$tbH^{\pm}(tb)$ [76]	$E_{\mathrm{T}}^{\mathrm{miss}} + h(\tau\tau)$ [78]	$E_{\mathrm{T}}^{\mathrm{miss}} + Z(q\bar{q})$ [126]	$E_{\mathrm{T}}^{\mathrm{miss}} + t\bar{t}$ [127, 128]
$E_{\mathrm{T}}^{\mathrm{miss}} + h(b\bar{b})$ [75]	$E_{\mathrm{T}}^{\mathrm{miss}} + tW$ [77]	$E_{\mathrm{T}}^{\mathrm{miss}} + b\bar{b}$ [127]	$t\bar{t}t\bar{t}$ [85]	$E_{\mathrm{T}}^{\mathrm{miss}} + j$ [45]

2HDM+a, Dirac DM, sinθ = 0.35, tan β = 1, m_χ = 10 GeV, g_χ = 1, $m_A = m_H = m_{H^\pm}$



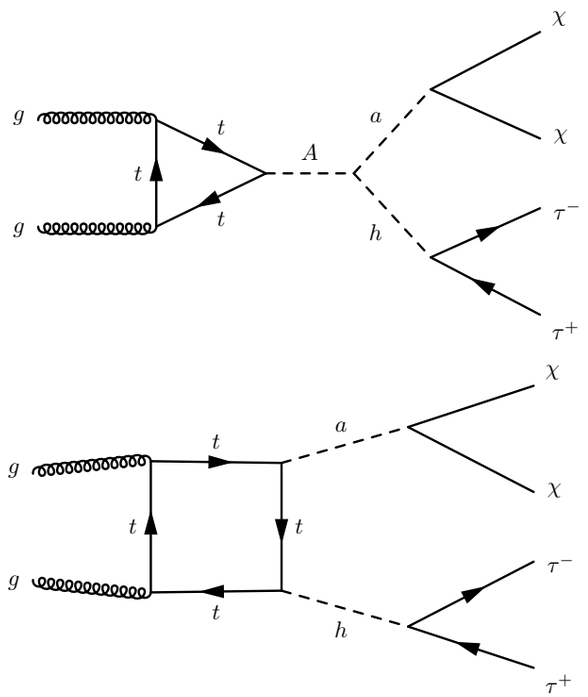


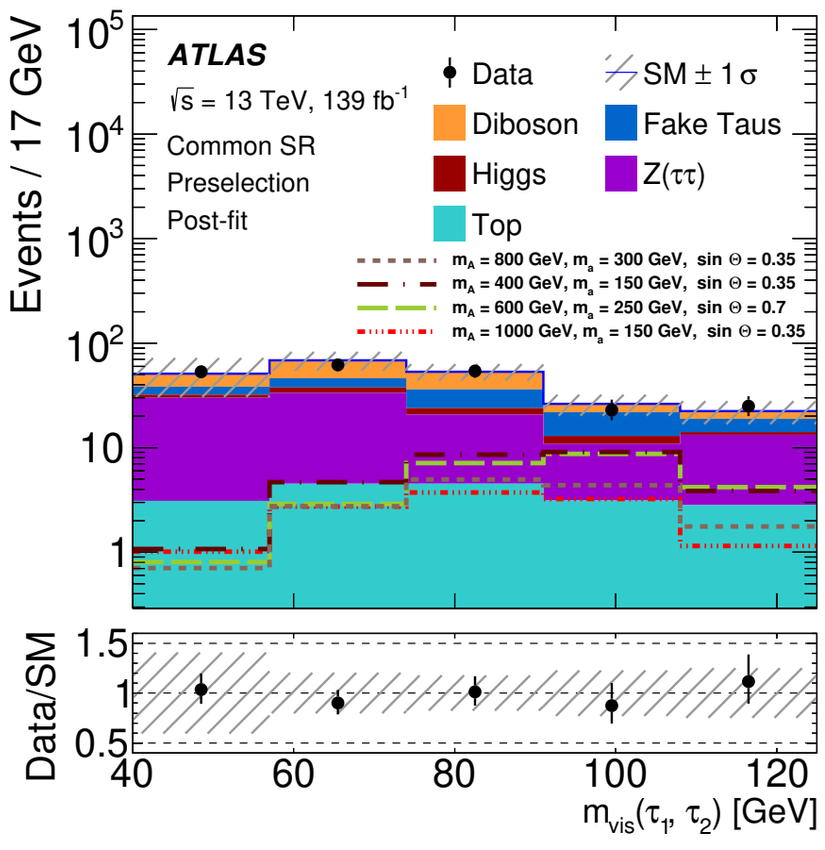
ATLAS 2HDM+a: mono-h(ττ)

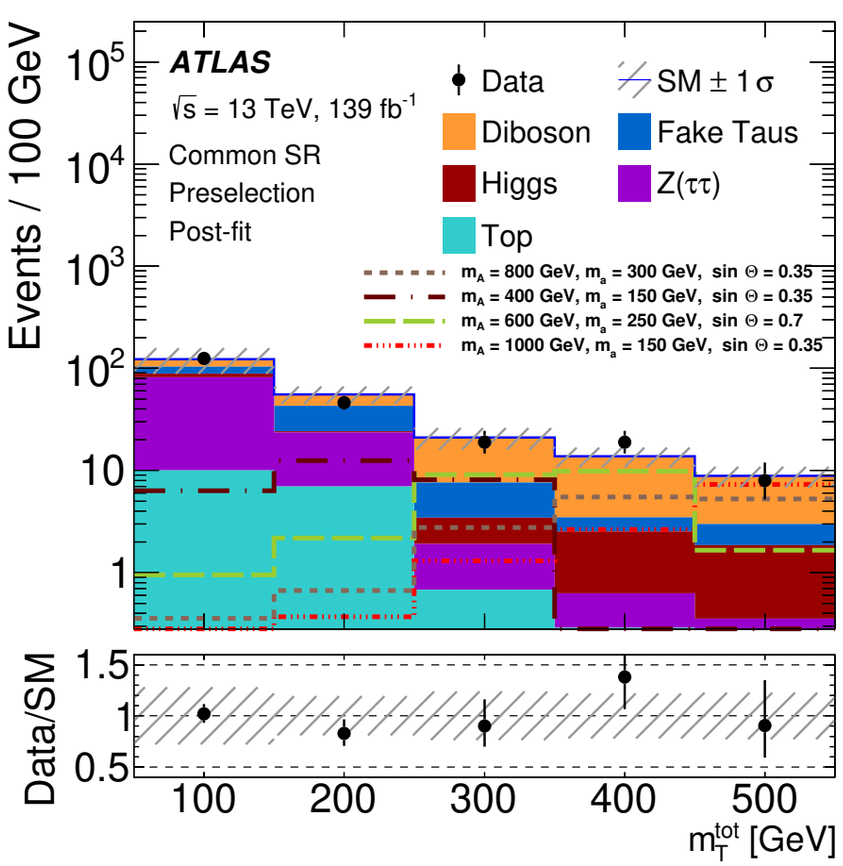
HDBS-2018-50

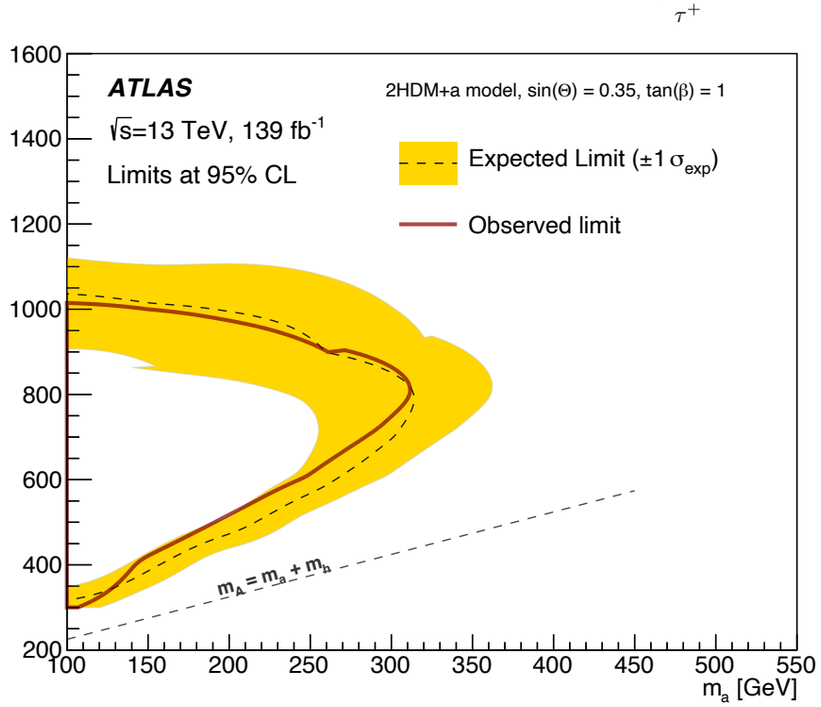
Most recent addition: mono-Higgs($\tau_{had}\tau_{had}$) channel, sensitive to a wide range of m_A and m_a.

- Challenges: broad Higgs mass peak (due to ν_τ), and Diboson (ττνν) background.
- Signal regions target high/low m_A-m_a based on the total transverse mass.









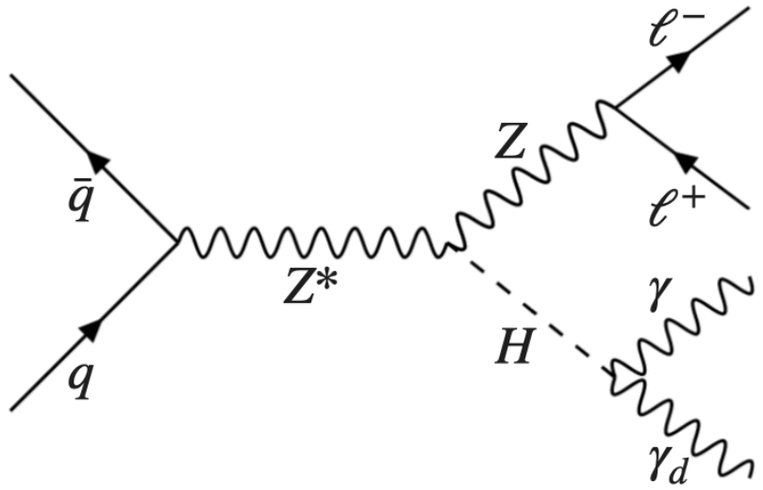
More results in the 2HDM combination.

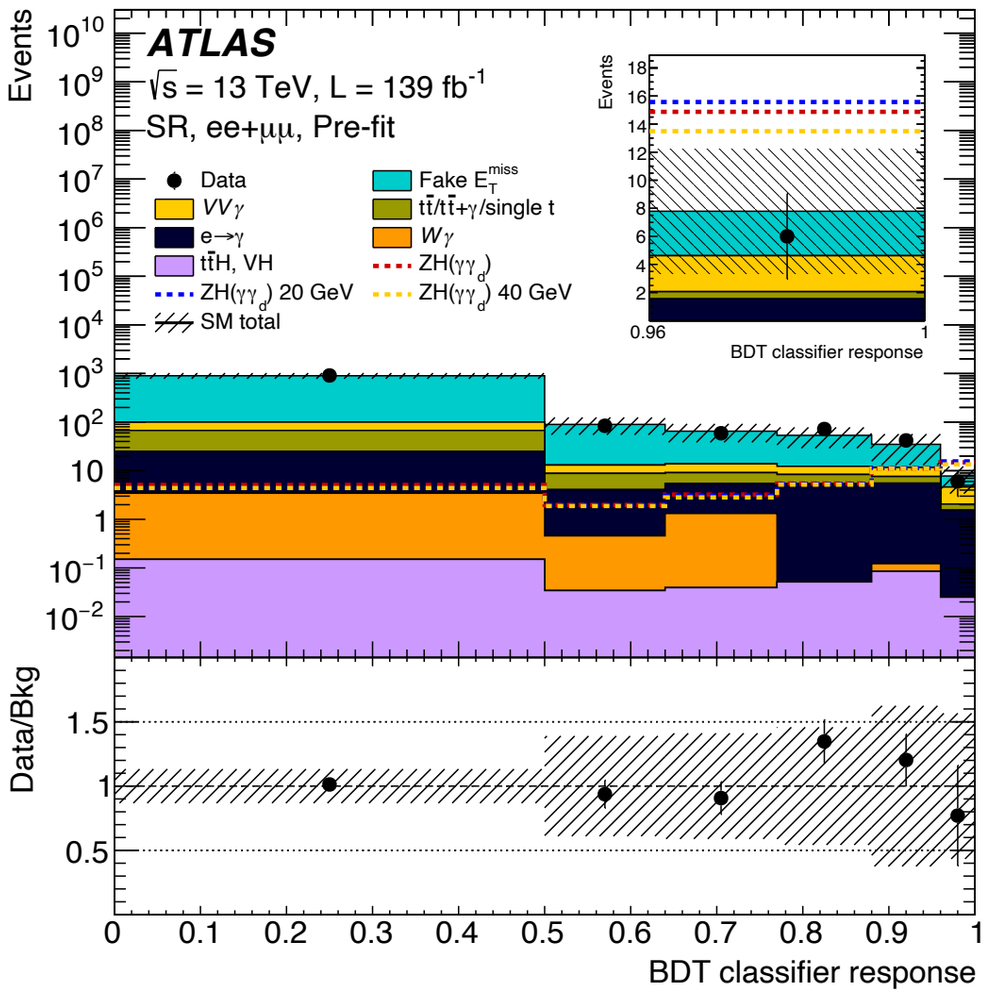
ATLAS ZH($\rightarrow \gamma\gamma_D$)

Search for invisible dark photons in Higgs decays, coupled through a new dark sector.

New ATLAS result in the ZH channel:

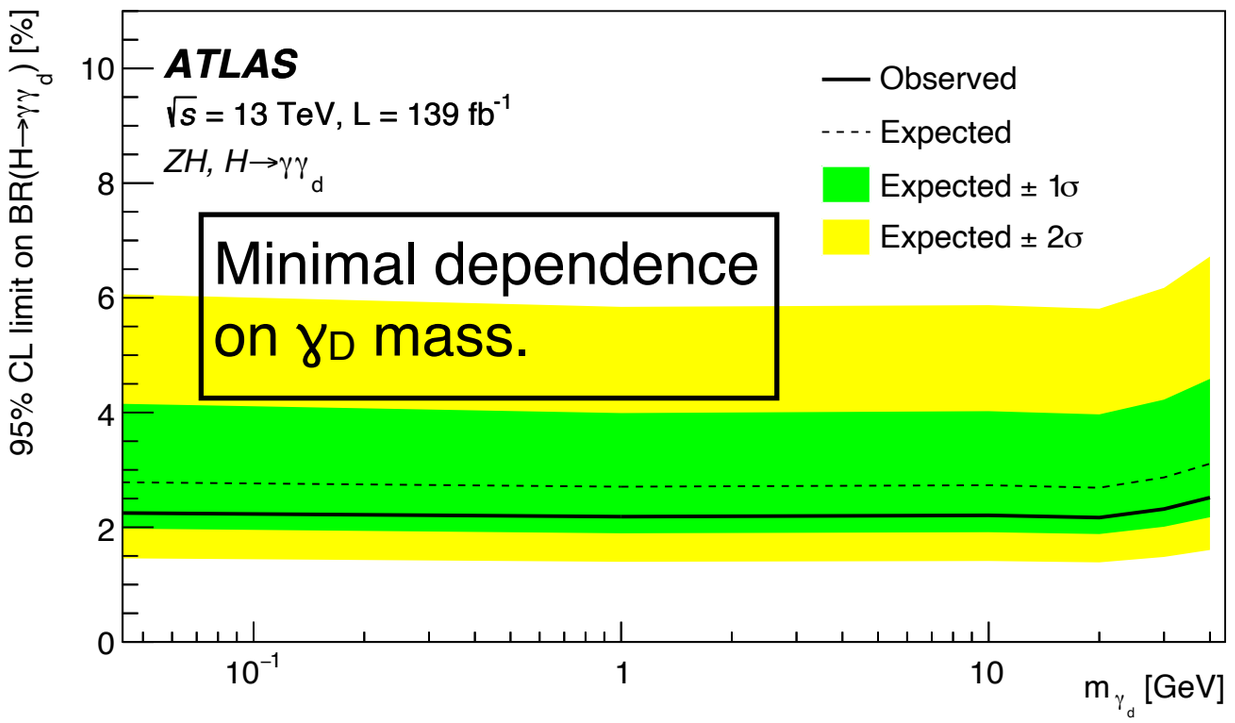
- BDT purifies signal region, mainly based on: $\sigma(p_{T,miss})$, $m_T(\gamma,p_{T,miss})$, and decay angles.





	ATLAS	CMS
ZH	2.3%	2.9%
VBF	1.8%	

Limits on Higgs BR

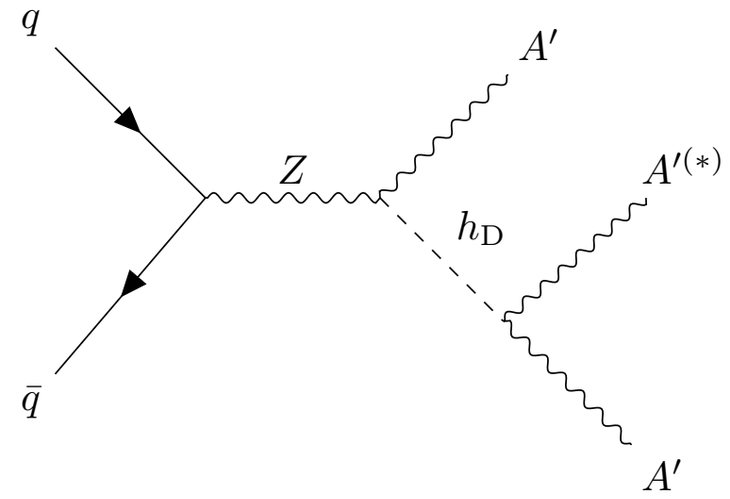


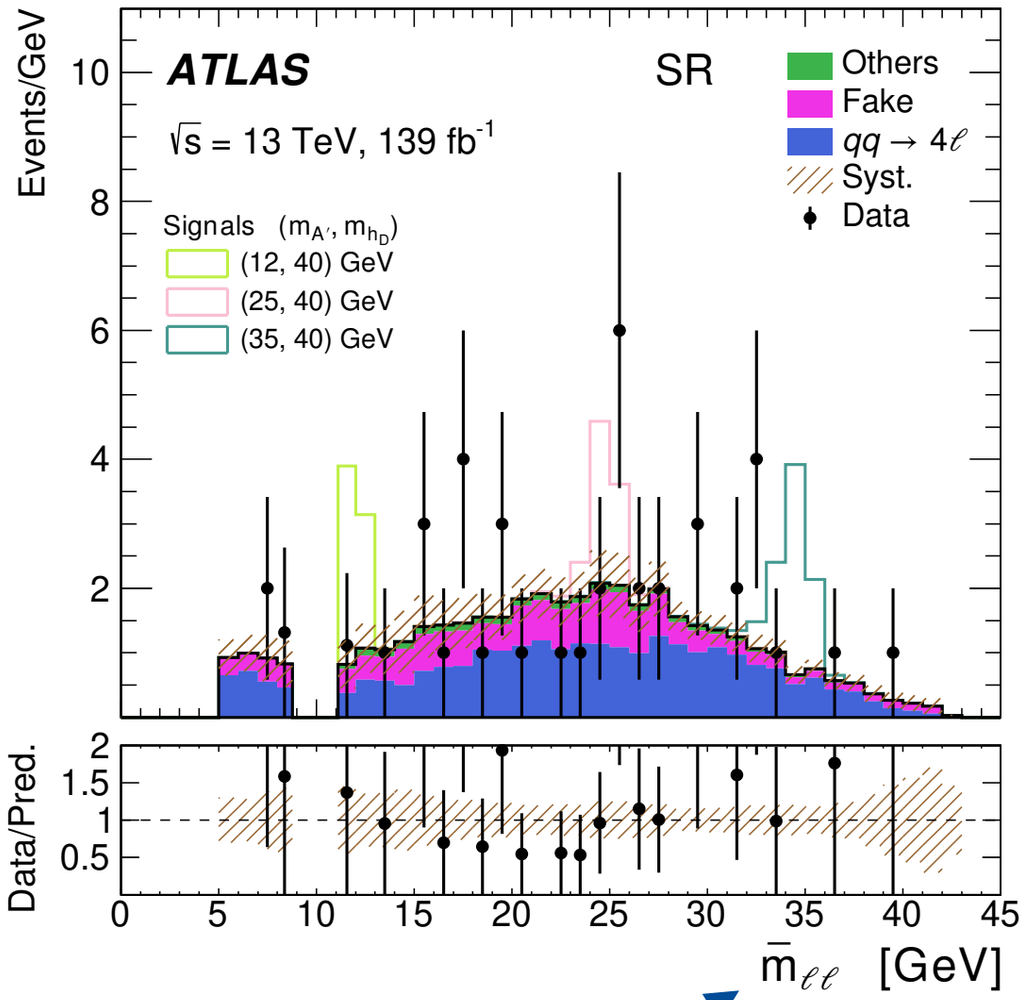
ATLAS Z→Dark photons

HDBS-2019-32

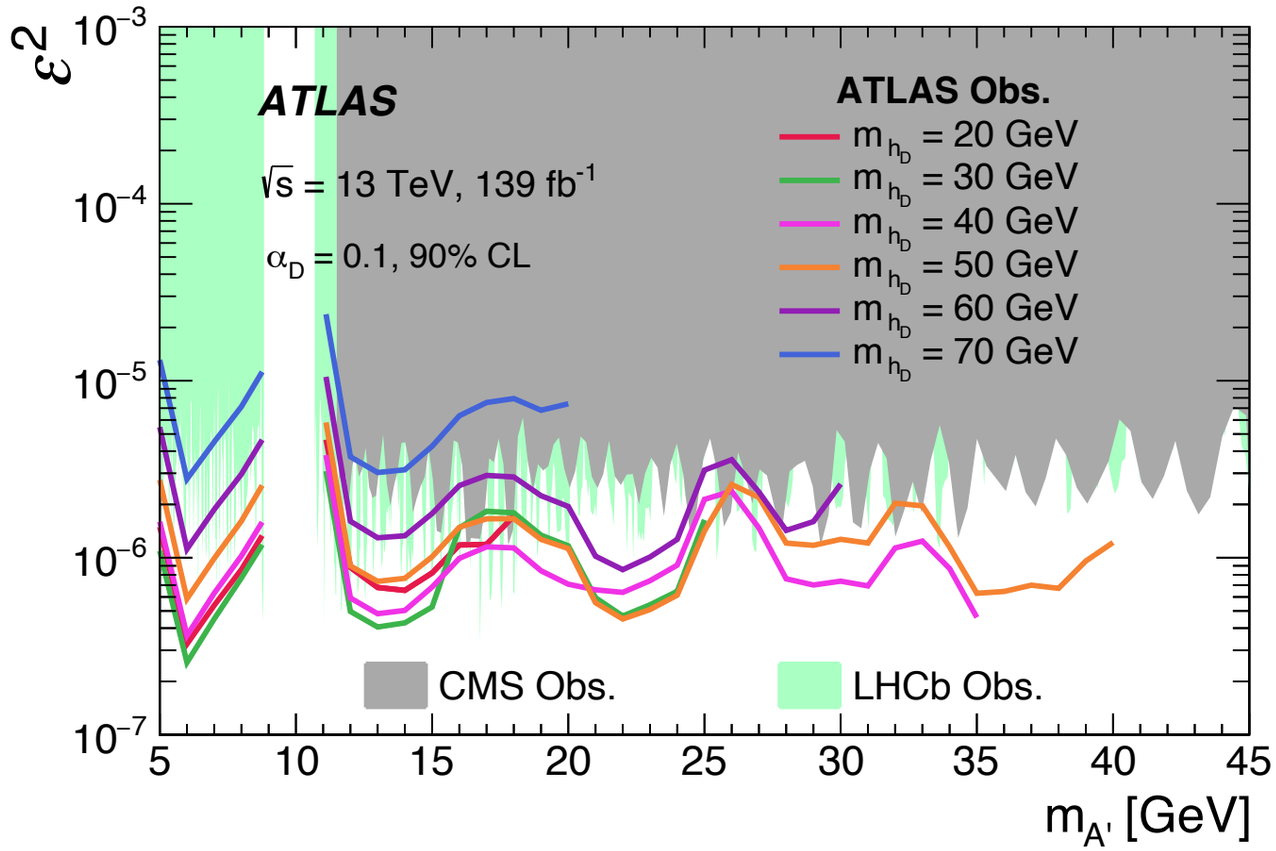
Search for Z →3A', mediated by a dark Higgs.

A minimal selection requires ≥4 leptons, with a pair of consistent 2-body (γ_D→ll) masses.





Average A' candidate mass



Compare to Belle & direct LHCb, CMS searches for the minimal A' (pp→A'→μμ).

ATLAS Semi-visible jets

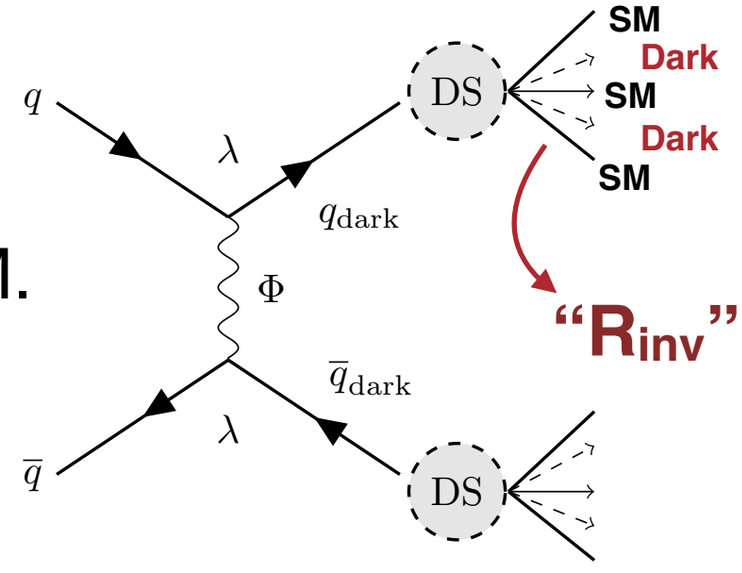
EXOT-2022-37

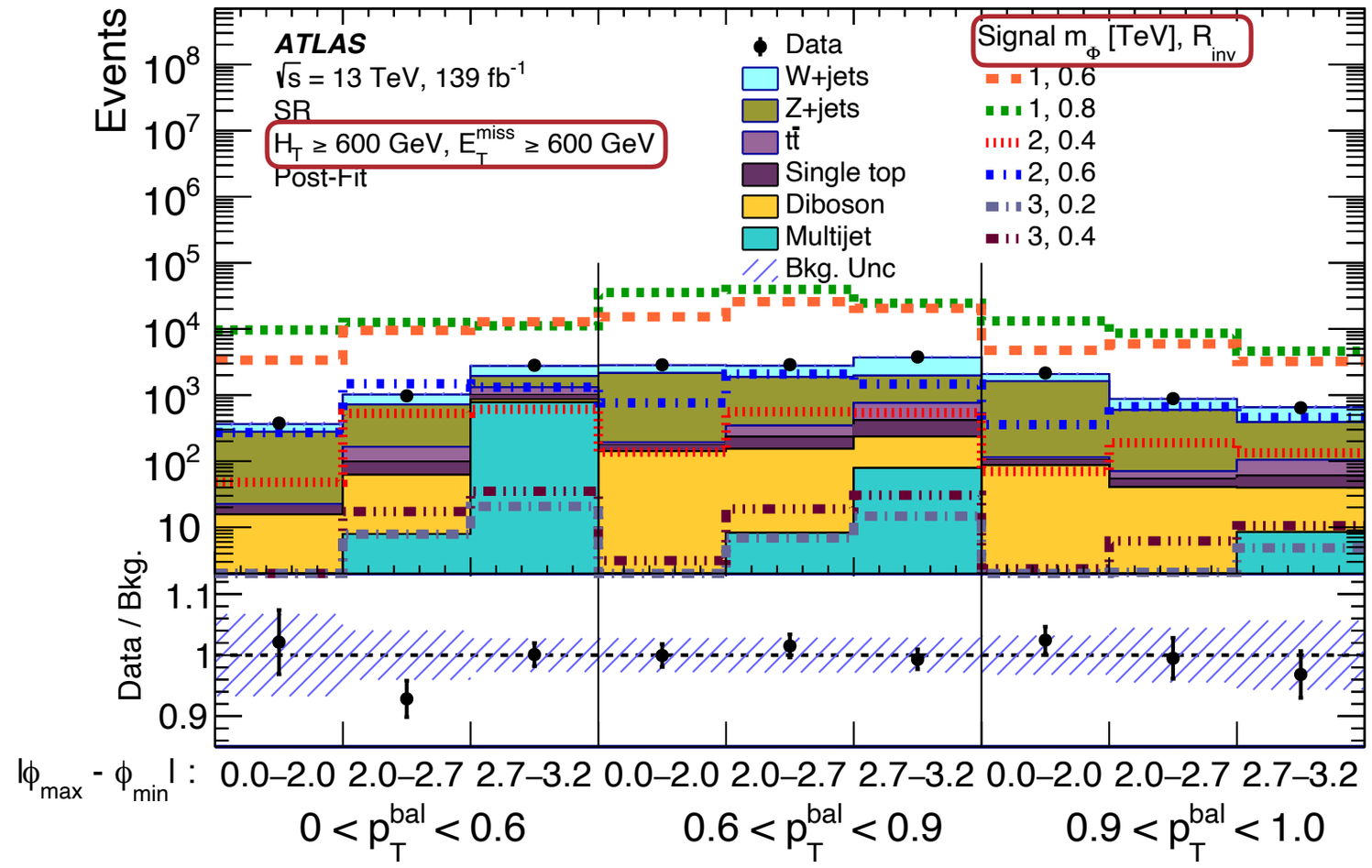
Strongly-coupled Dark Sectors may lead to **"Dark Showers"** analogous to the QCD parton shower.

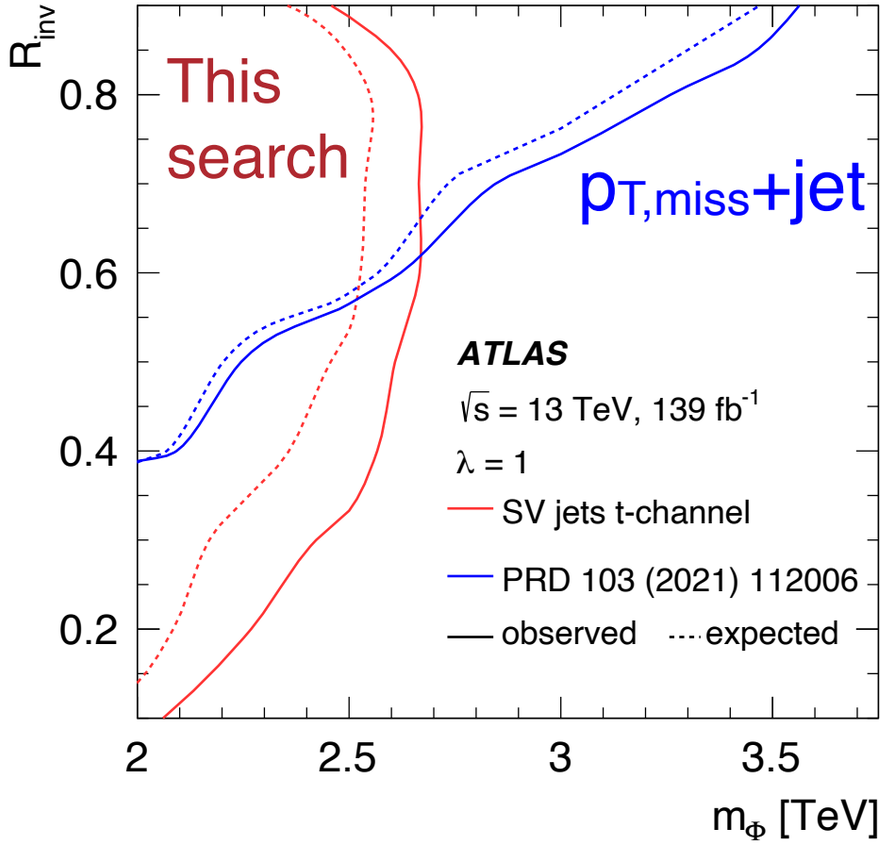
- Some fraction of the resulting π_D, ρ_D *may* decay to SM.

New ATLAS search for DS production in the t-channel.

- Categorize events by the min/max $d\phi$(jet,$p_{T,miss}$) jets.







Also see the CMS s-channel search.

Summary

- The significant 13 TeV dataset deliver by the LHC during Run 2 has lead to an expansive program of searches at ATLAS and CMS.
  - Many state-of-the-art efforts are only possible through an understanding of our detectors and reconstruction developed w/ 10+ years experience.
- Portfolio of SUSY and Dark Matter searches following similar trajectories:
  - A comprehensive program of searches, combinations, and new summary results target a critical set of benchmark models.
  - Meanwhile, new ideas in theory and novel reconstruction techniques expand our sensitivity to previously-unconsidered signatures.
- Looking ahead, more LHC data (and new triggers, upgraded detectors) in **Run 3 and the High Luminosity LHC will significantly extend our reach to new weakly-coupled states!**