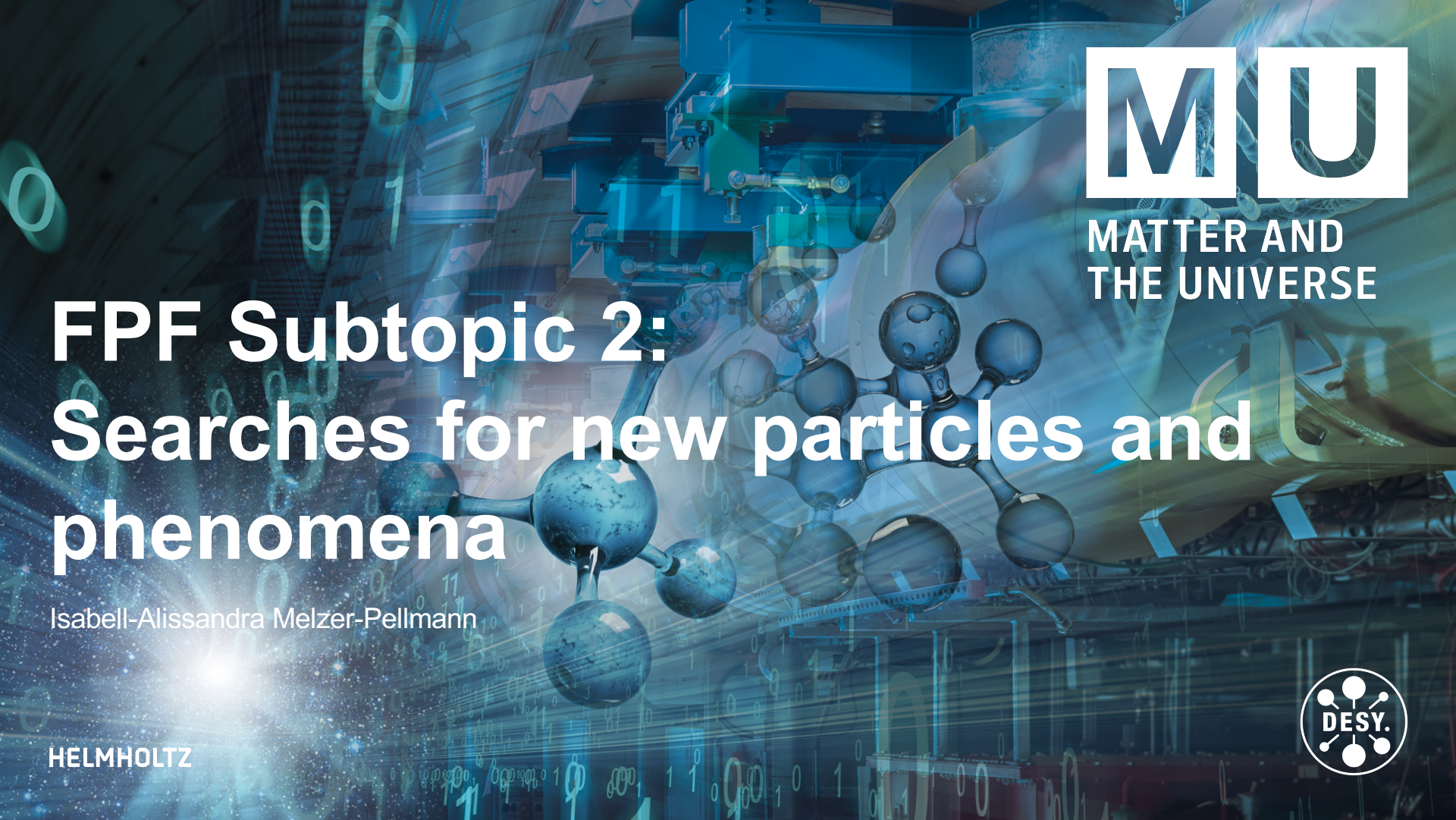


MATTER AND THE UNIVERSE

FPF Subtopic 2: Searches for new particles and phenomena

Isabell-Alissandra Melzer-Pellmann

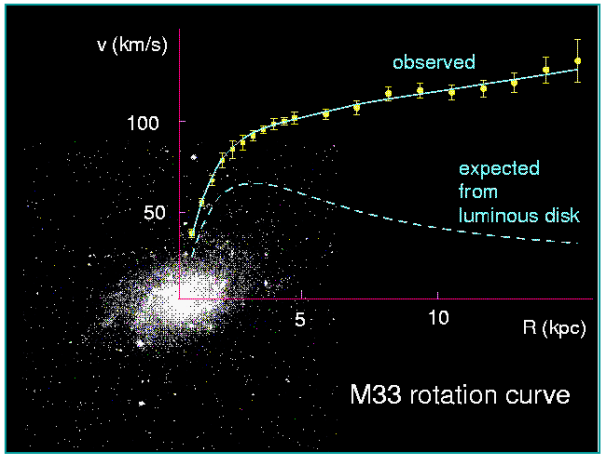
HELMHOLTZ

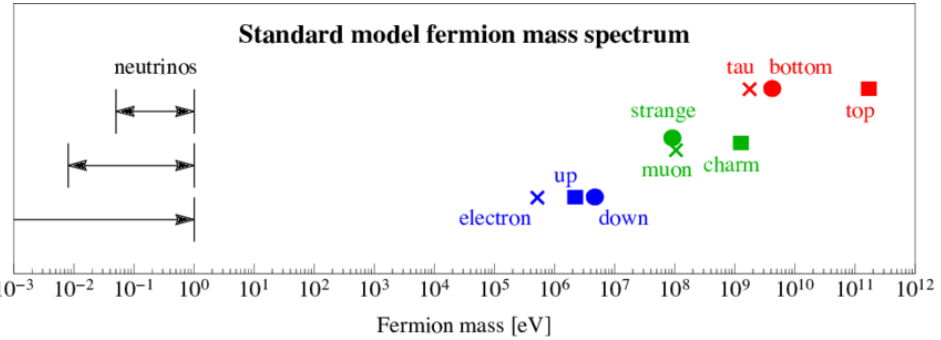
DESY.

Introduction

A decade after the discovery of the Higgs boson

- No other new particles found despite many open questions:
  - Nature of dark matter
  - Abundance of anti-matter
  - Neutrinos masses
  - Three particle families with very different masses
  - Higgs boson mass very light compared to the Plack scale
  - Gravity
- Extension of the Standard Model needed!





Extended Higgs Sector

2 Higgs doublet models

Additional Higgs doublet
→ 5 physical Higgs bosons

2HDMs could:

- Explain matter-antimatter asymmetry through baryogenesis (adding CP violation in the scalar sector)
- Can accommodate a strong first-order electroweak phase transition

Required by SUSY (MSSM)

Extended Higgs Sector

Highlight: Search in ττ channel

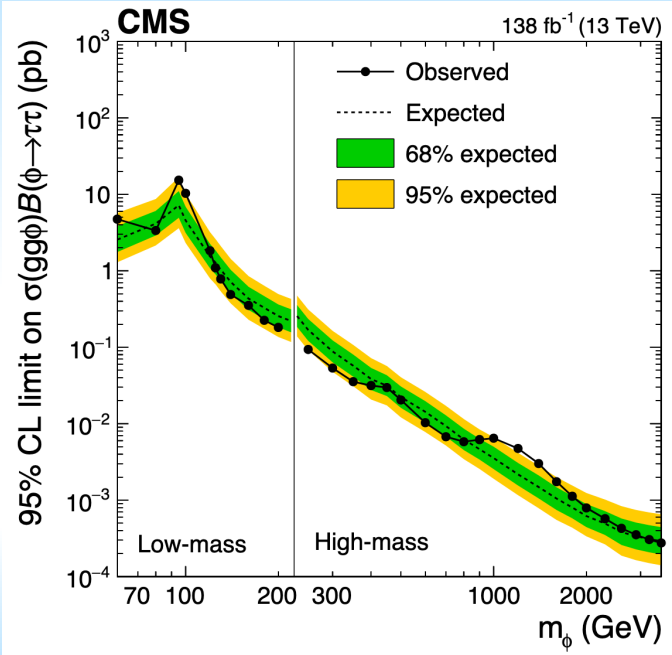
Additional Higgs doublet
→ 5 physical Higgs bosons

2HDMs could:

- Explain matter-antimatter asymmetry through baryogenesis (adding CP violation in the scalar sector)
- Can accommodate a strong first-order electroweak phase transition

Required by SUSY (MSSM)

Excess with global (local) p-value of 2.7σ (3.1σ) at 100 GeV, coinciding with a similar excess in the γγ final state at 95 GeV



JHEP 07 (2023) 073

Extended Higgs Sector

Highlight: Theory study

Additional Higgs doublet
→ 5 physical Higgs bosons

2HDMs could:

- Explain matter-antimatter asymmetry through baryogenesis (adding CP violation in the scalar sector)
- Can accommodate a **strong first-order electroweak phase transition**

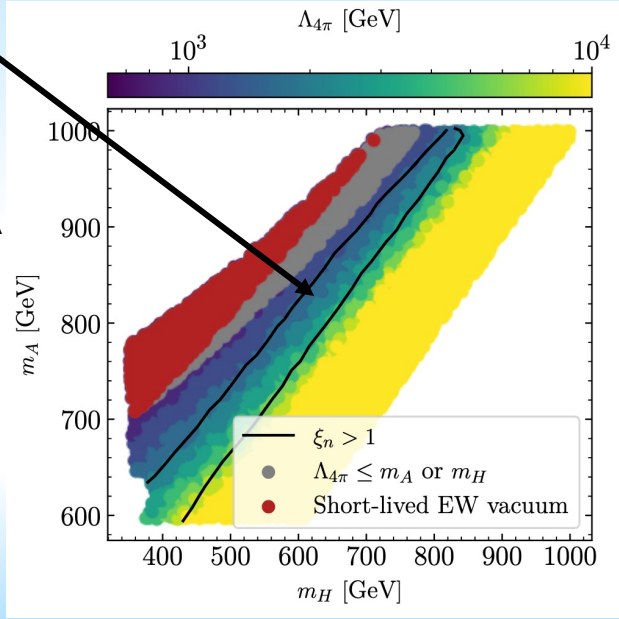
Required by SUSY (MSSM)

Analyis of the thermal history of the 2HDM:
Determine the parameter regions featuring strong first-order electroweak phase transition (EWPT)

→ Can produce a primordial gravitational wave

→ Potentially detectable at LISA

→ Enhance trilinear Higgs self-coupling



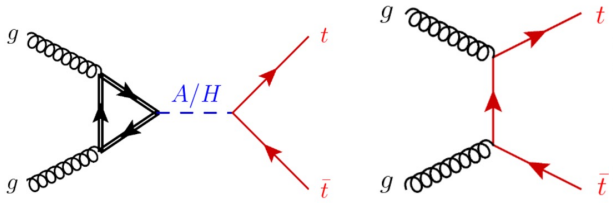
JCAP 03 (2023) 031

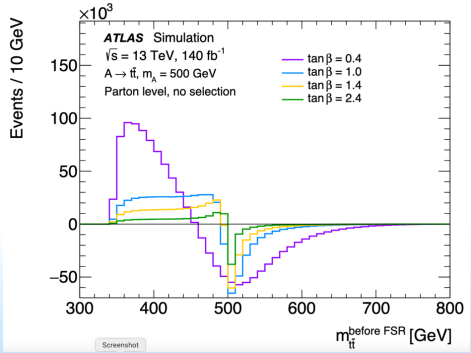
Extended Higgs Sector

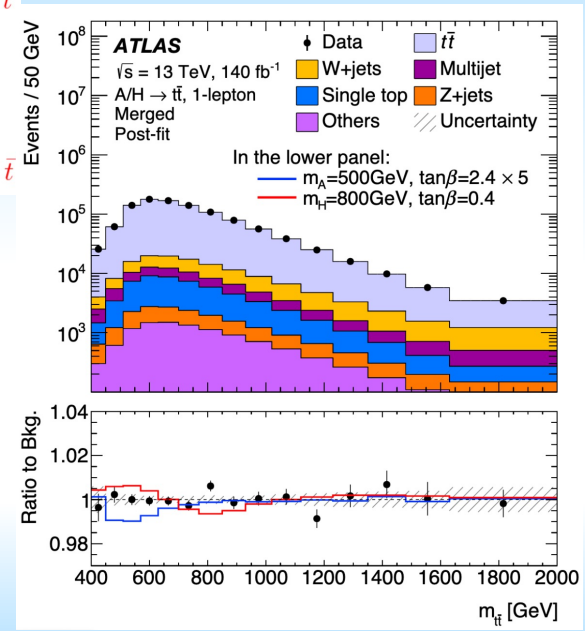
Highlight : Search in $t\bar{t}$ channel

Difficult analysis because of interference with SM $t\bar{t}$ production

→ need to search for peak-dip structure







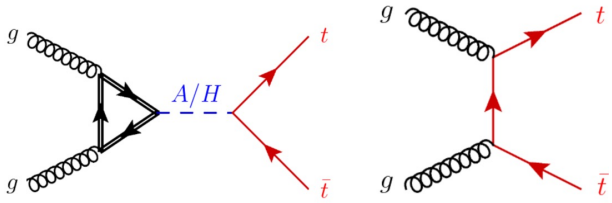
JHEP 08 (2024) 013

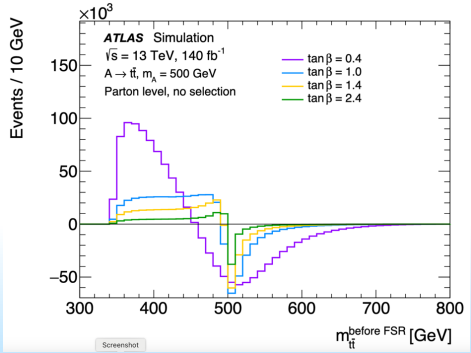
Extended Higgs Sector

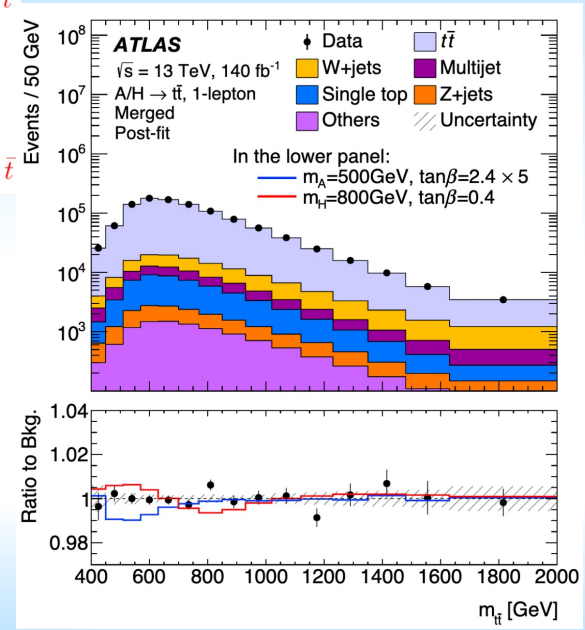
Highlight: Search in $t\bar{t}$ channel

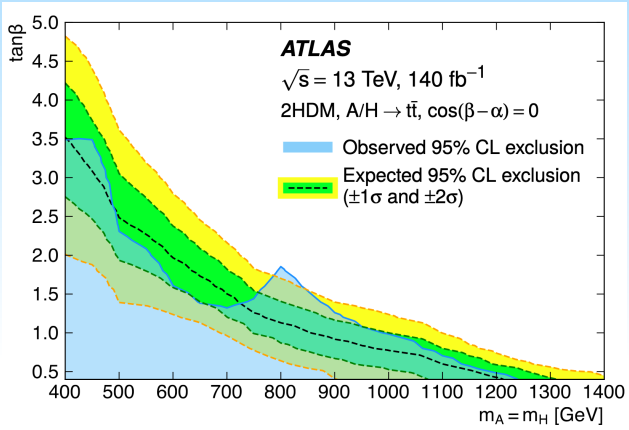
Difficult analysis because of interference with SM $t\bar{t}$ production

→ need to search for peak-dip structure









Exclude large parameter range for small tan β

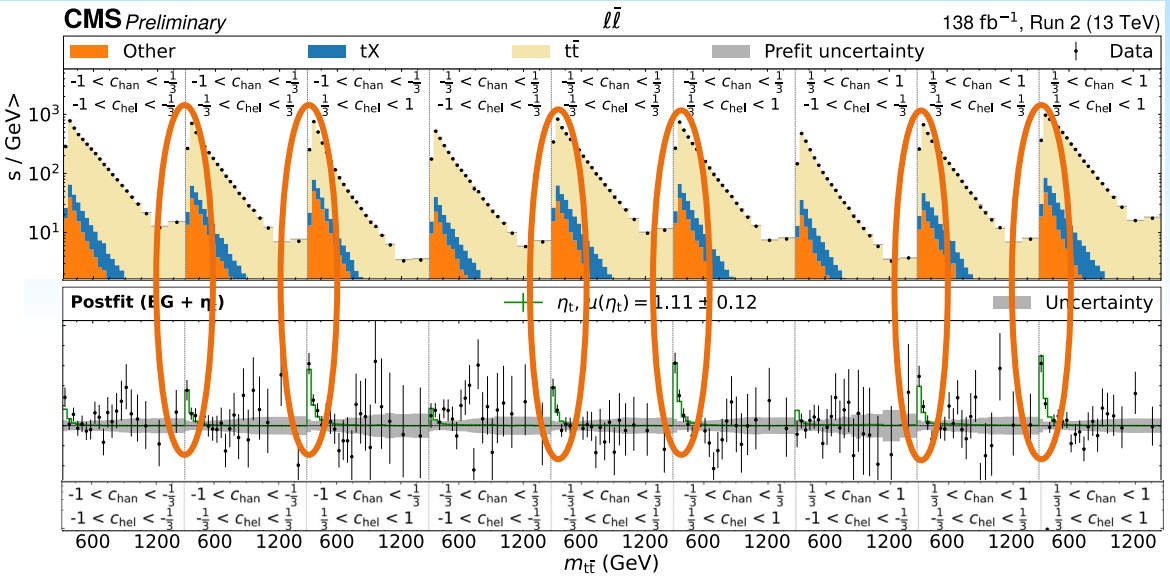
JHEP 08 (2024) 013

Extended Higgs Sector

Highlight: Search in $t\bar{t}$ channel

Extend search in $t\bar{t}$ channel to lower di-top masses

3D search using 2 spin observables and m_{tt}



- **Deviations observed in close to the $t\bar{t}$ production threshold**
- **Not yet well understood region (non-relativistic QCD)**
  → strong exchange with theorists

CMS-PAS-HIG-22-013

Extended Higgs Sector

Highlight: Search in $t\bar{t}$ channel

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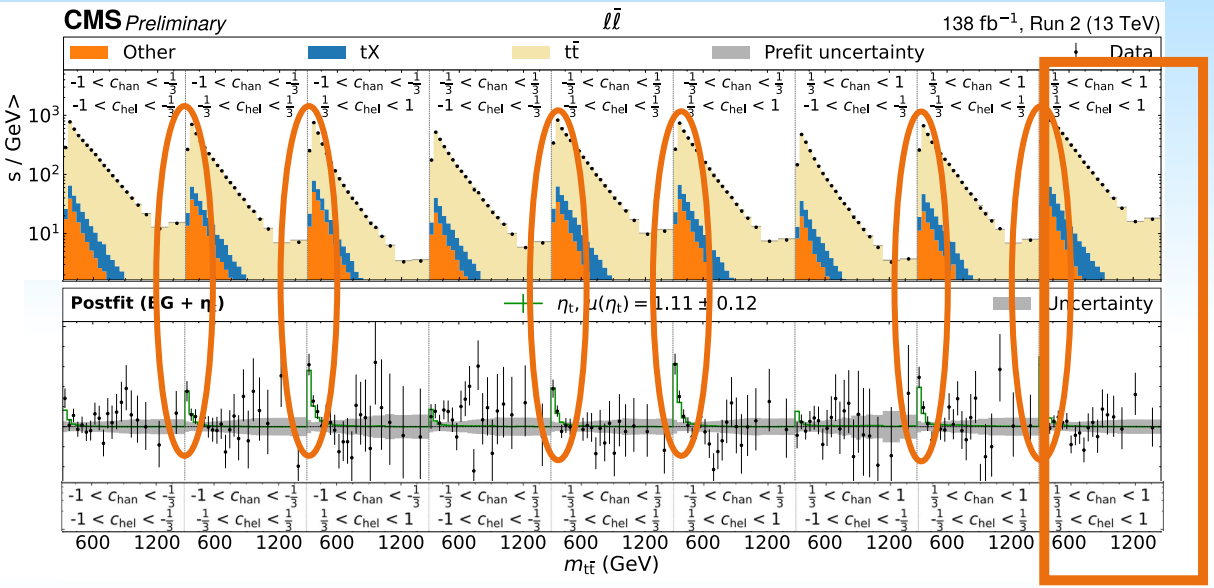

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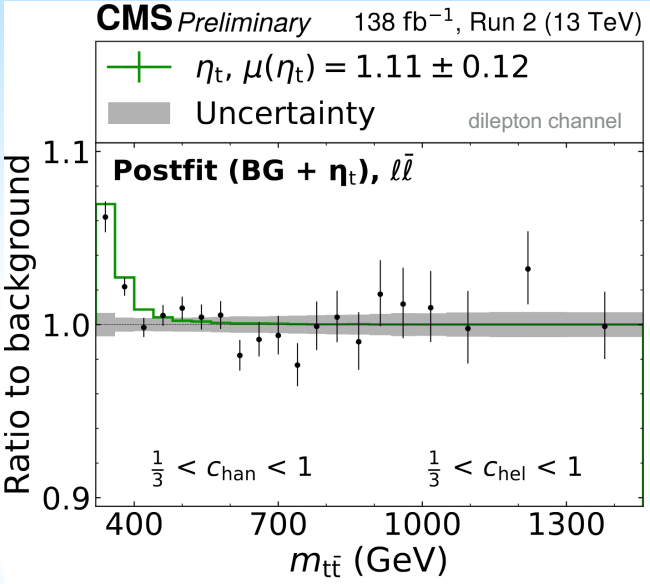
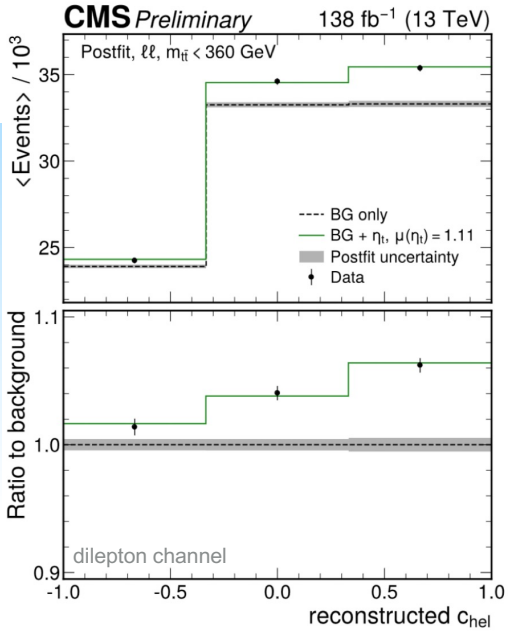


Simplified pseudoscalar bound state model:

- fits well to data in threshold region
- cannot be separated from pseudoscalar toponium



Spin observable

Caution: Yet a simplified model!

$$\sigma(\eta_t) = 7.1 \pm 0.8\,\text{pb}$$

NRQCD: $\sigma(\eta_t)^{\text{pred}} = 6.43\,\text{pb}$ PRD 104 (2021) 034023

CMS-PAS-HIG-22-013

Extended Higgs Sector

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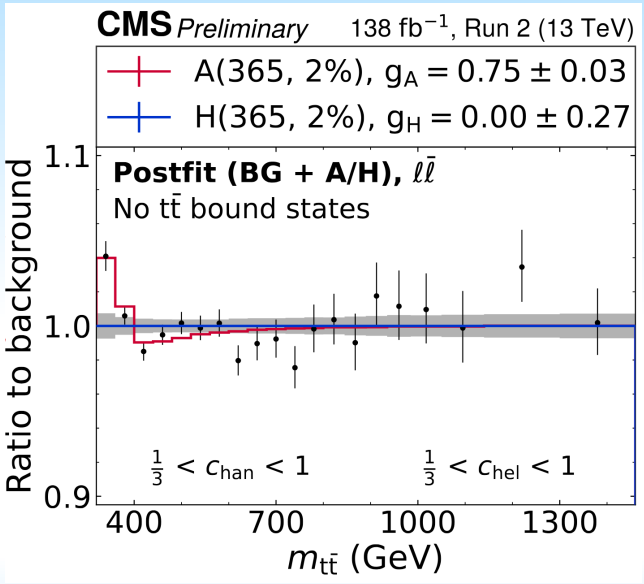
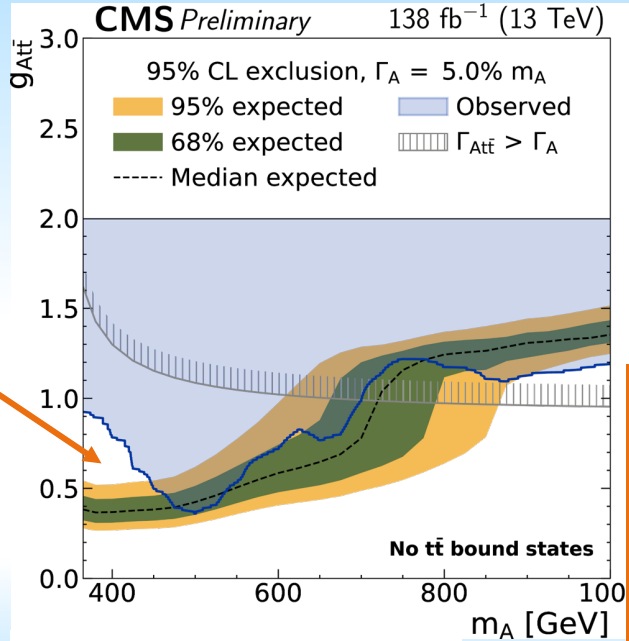
Extend search in $t\bar{t}$ channel to lower di-top masses



Interpretation in 2HDM:
Combined fit shows data excess > 5σ



Result consistent with ATLAS at higher masses

CMS-PAS-HIG-22-013

Supersymmetry

An additional space-time symmetry: new partner particles with spin differing by 1/2

Supersymmetry could explain:

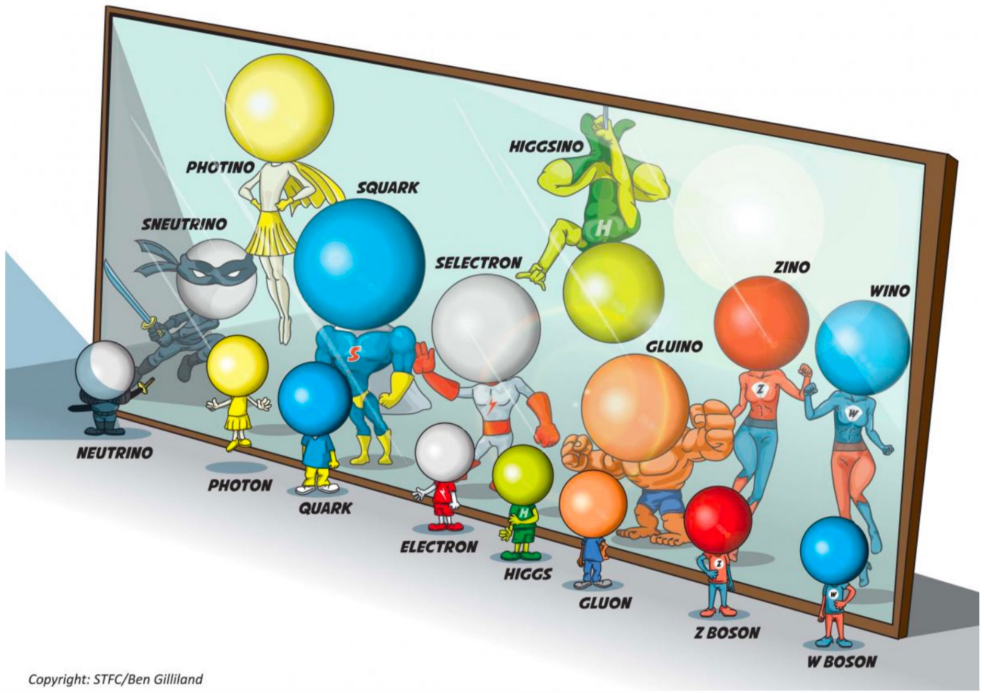
- Dark matter
  (DM = lightest SUSY particle)
- Neutrino masses

Implications for theory:

- Hierarchy problem
- Unification of forces possible
- Gravity can be included

However, not yet observed:

- Broken symmetry
  → expect partner particles
  with higher masses



Supersymmetry

Strong contributions to many SUSY searches, excluding strong-coupling partners in the TeV range

Supersymmetry could explain:

- Dark matter
  (DM = lightest SUSY particle)
- Neutrino masses

Implications for theory:

- Hierarchy problem
- Unification of forces possible
- Gravity can be included

However, not yet observed:

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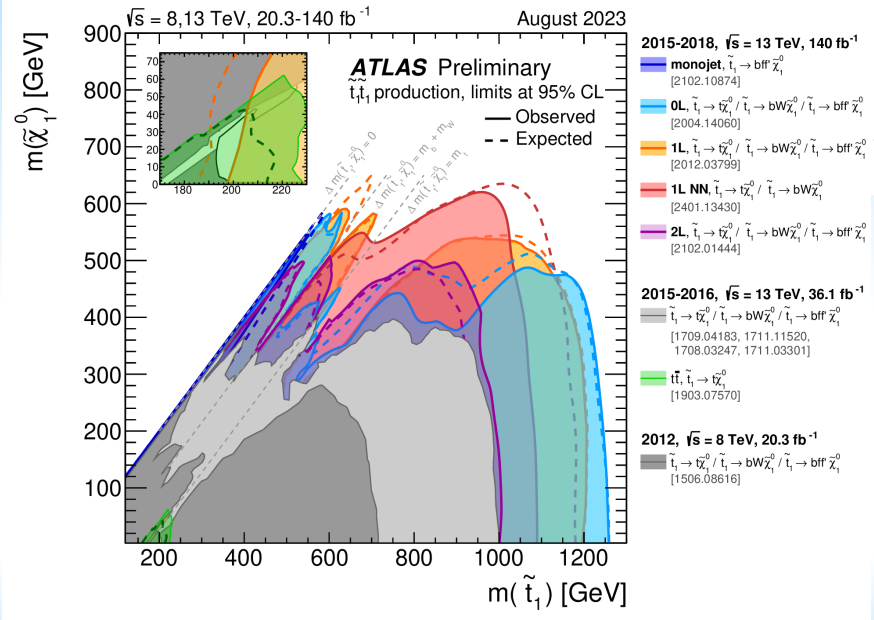
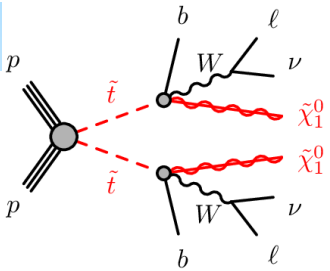
Highlight: top squark search





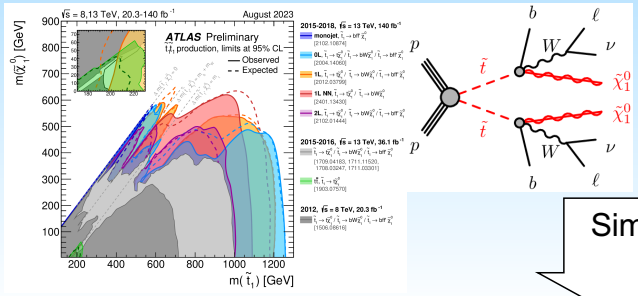
JHEP 04 (2021) 165
arxiv.2403.02455

Diverse set of searches needed to cover full phase space

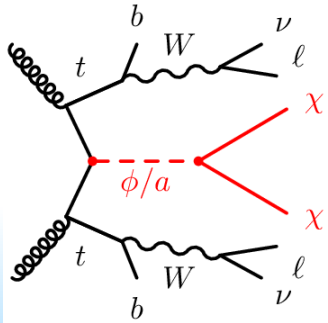
Supersymmetry

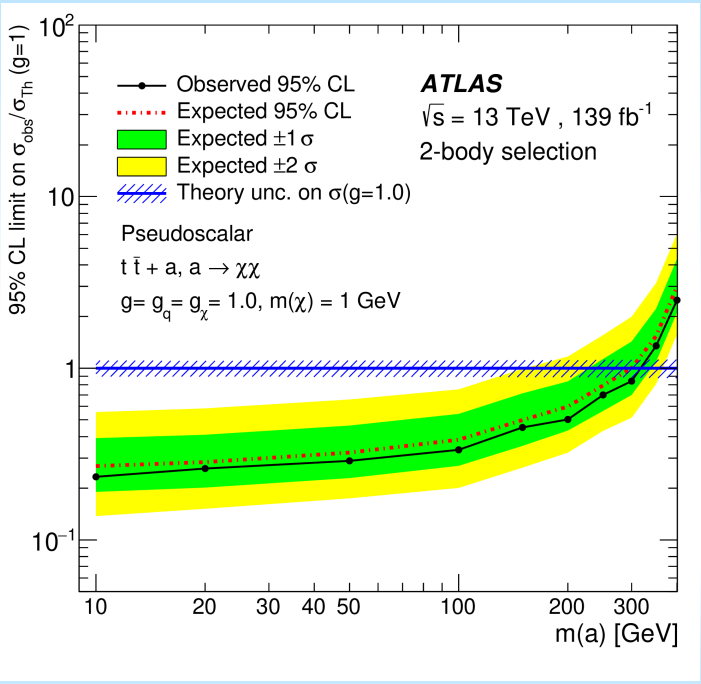
Reinterpretation in other (more generic) models

➢ **Highlight: top squark search with reinterpretation in DM limits**



Similar final state





Reinterpretation in dark matter model, excluding mediators < 300 GeV

JHEP 04 (2021) 165
arxiv.2403.02455

Heavy neutral leptons

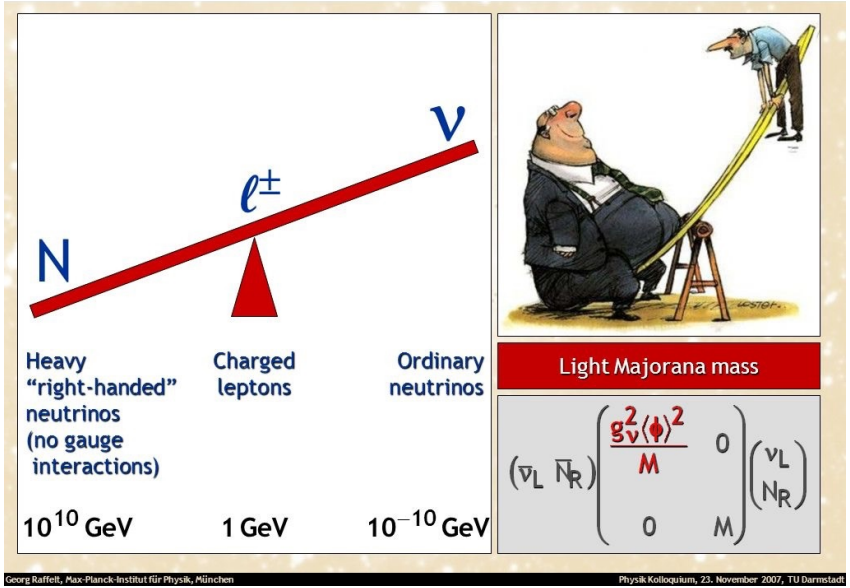
Neutrino oscillations are BSM → require small neutrino mass

Heavy sterile neutrinos could explain:

- Neutrino masses
- Baryon asymmetry of the universe (through leptogenesis)
- Dark matter (warm DM)

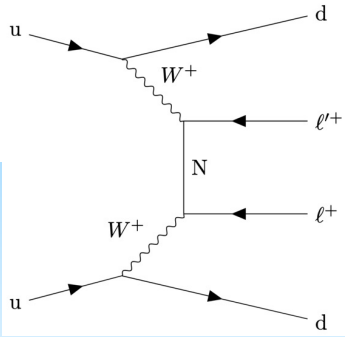
Cosmological impact on:

- Big bang nucleosynthesis
- Cosmic microwave background



Heavy neutral leptons

Highlight: Search in the phenomenological type-I seesaw model



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Cosmological impact on:

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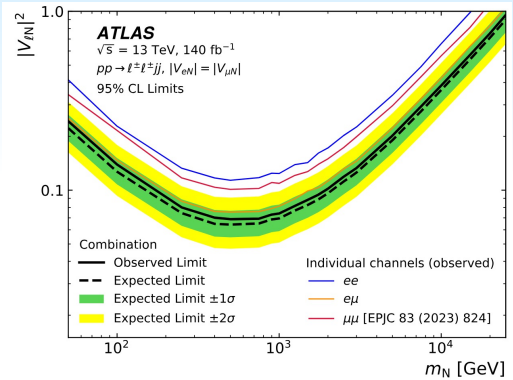
Search for right-handed sterile neutrinos N with

- a large SM gauge-invariant Majorana mass
- coupled via Yukawa interactions to the left-handed active neutrinos

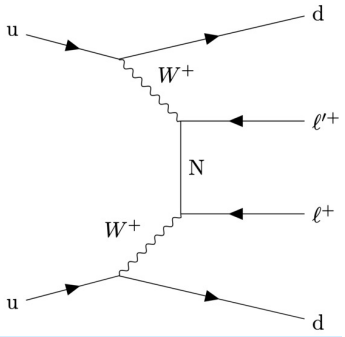


- **Strong bounds on $|V_{lN}|$** (matrix element describing the mixing of the mass eigenstate of N with the SM ν_e or ν_μ)

PLB 856 (2024)138865

Heavy neutral leptons

Highlight: Search in the phenomenological type-I seesaw model



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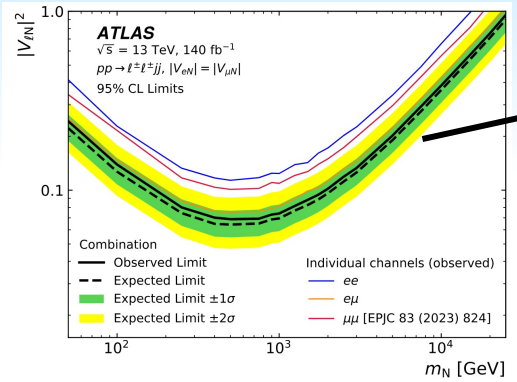
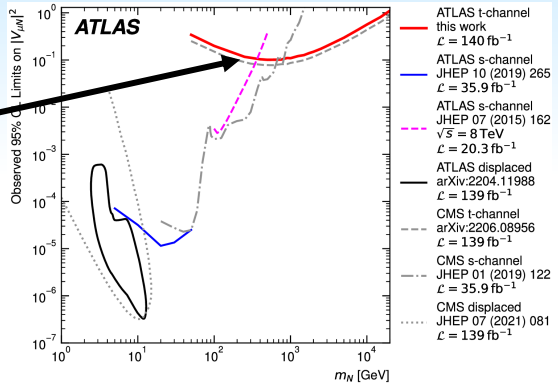




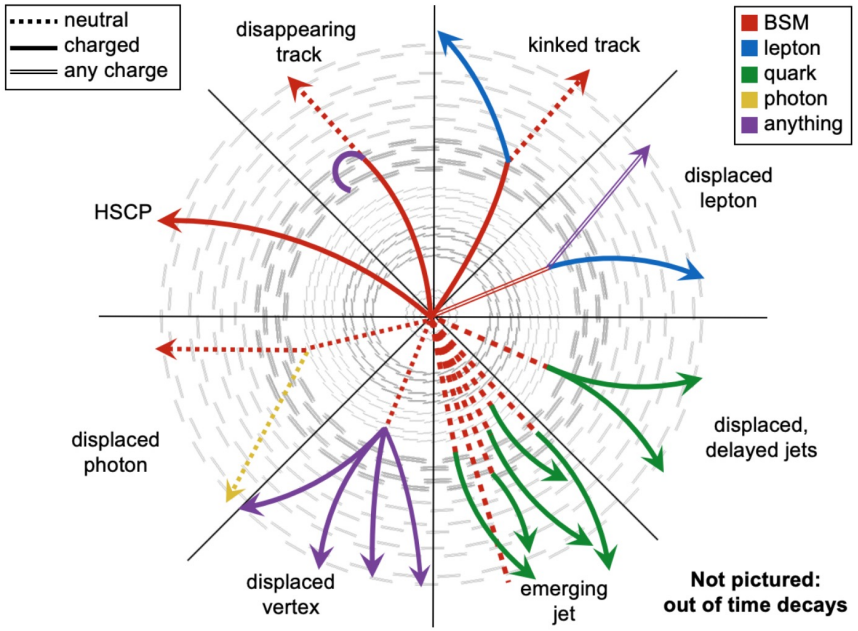
- **Strong bounds on $|V_{lN}|$** (matrix element describing the mixing of the mass eigenstate of N with the SM ν_e or ν_μ)
- **Extend phase space to higher masses**

PLB 856 (2024)138865

Long-lived particles

Extending to long-lived signatures

- **Expected in many BSM scenarios** (not only HNL)
- Might escape standard reconstruction!



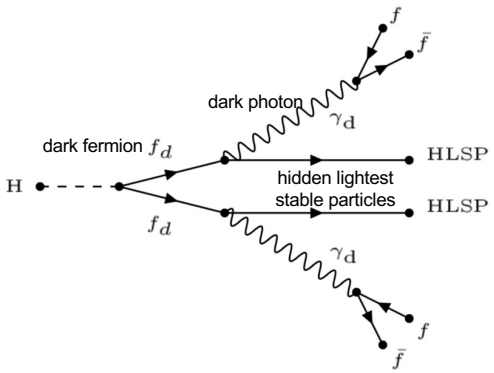
Long-lived particles

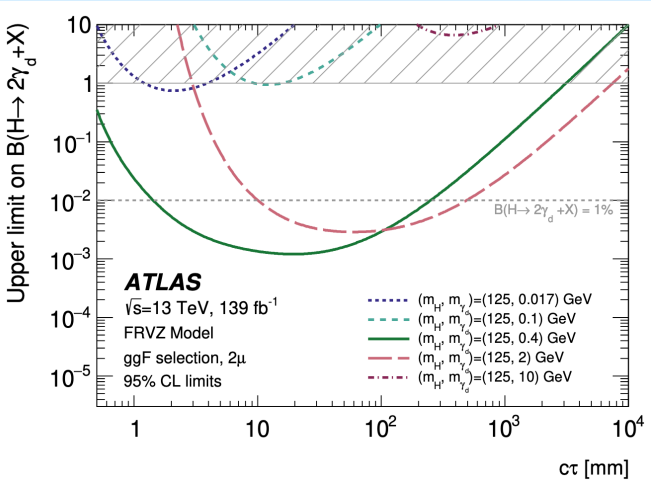
Extending to long-lived signatures

- **Expected in many BSM scenarios**
- Might escape standard reconstruction!

Highlight: Search for events with **displaced collimated SM fermions** reconstructed in the calorimeter or muon spectrometer

→ Development of **special reconstruction** for dark photon jets





Exclude long-lived dark photons with 0.4 GeV < $m_{\gamma d}$ < 2 GeV for Higgs BR of 𝒪(1%) and 10 mm < cτ < 250 mm

JHEP 06 (2023) 153

Search for the rare decay $B^{\pm} \to K^{\pm}\nu\nu$

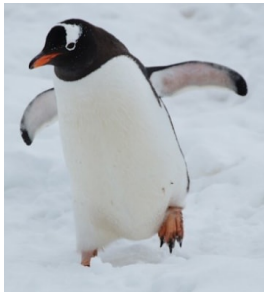
Looking for enhanced branching ratio

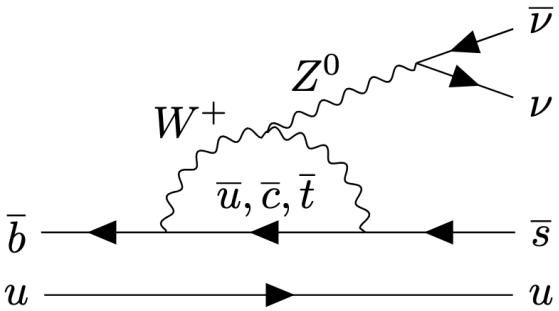
Prohibited at tree level in the SM

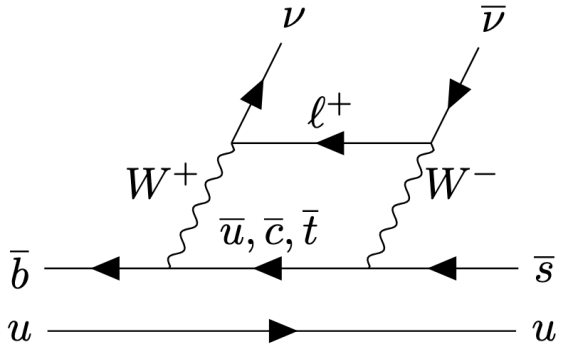
- known with high accuracy in the SM: $(5.6 \pm 0.4) \times 10^{-6}$
- Unique for Belle II

Significant enhancements from new physics

- New invisible particles in final state
- New mediators in the loop
- Common explanations of R(D$^{(*)}$), muon g-2 anomaly







First evidence for the rare decay $B^{\pm} \to K^{\pm}\nu\nu$

Branching ratio 2.7σ higher than expected by SM

Prohibited at tree level in the SM

- known with high accuracy in the SM: $(5.6 \pm 0.4) \times 10^{-6}$
- Unique for Belle II

Significant enhancements from new physics

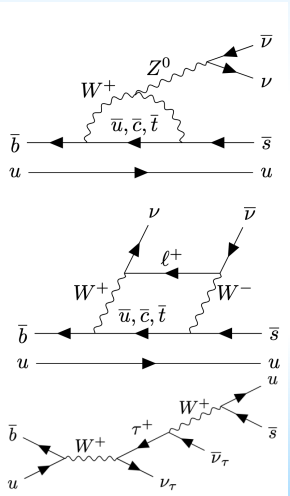
- New invisible particles in final state
- New mediators in the loop
- Common explanations of R(D$^{(*)}$), muon g-2 anomaly

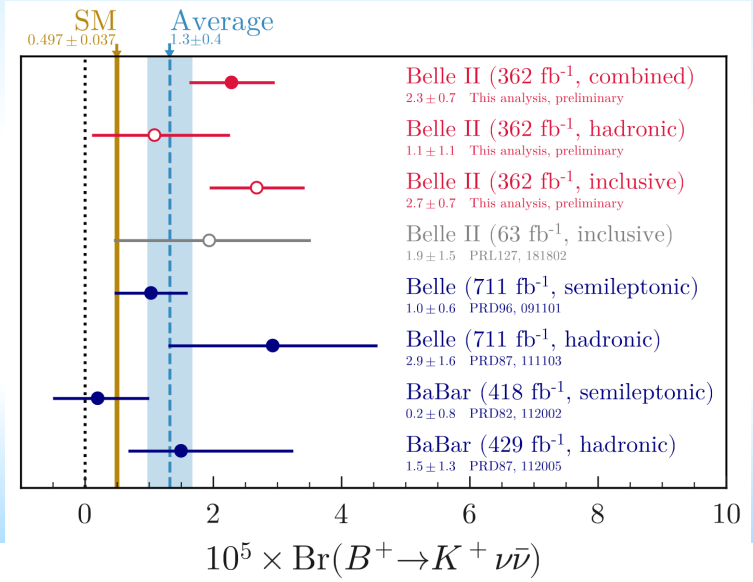
Result of combination of two independent analyses:

$$\mu = 4.6 \pm 1.0\,(\text{stat}) \pm 0.9\,(\text{syst})$$

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = [2.3 \pm 0.5\,(\text{stat})^{+0.5}_{-0.4}\,(\text{syst})] \times 10^{-5}$$

- 3.5σ significance wrt the background-only hypothesis
- **First evidence**





PRD 109 (2024) 112006

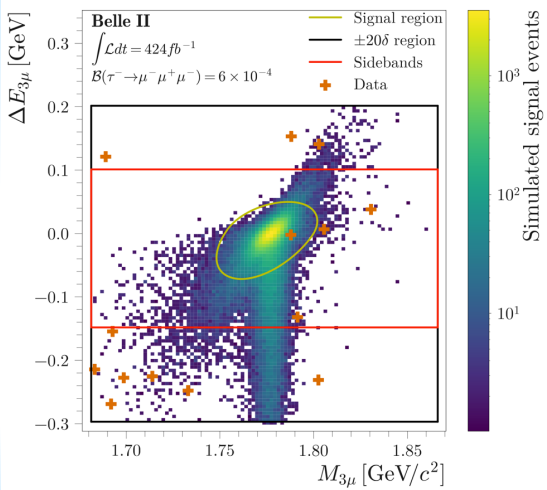
Search for τ→μμμ

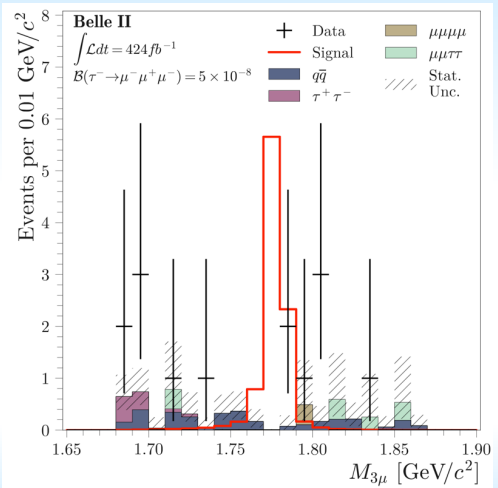
Most stringent limit to date

- Neutrino oscillations: first sign of lepton flavor violation
- How about charged leptons?
- Immeasurable small rate in standard model
- Enhancement possible through new particles

Search at Belle II with 424 fb-1

- μ identification is the most powerful discriminating variable
- Observed limit on branching ratio: 1.9×10^{-8} at 90% C.L.





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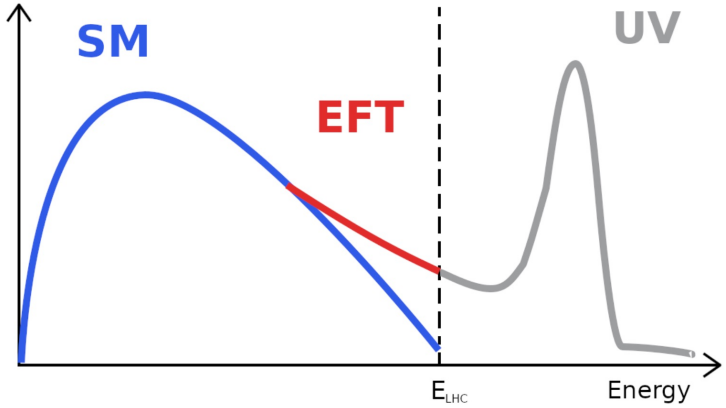
SMEFT

Searching for signs of resonances that are too heavy to be produced at the LHC

- **Model independent framework**
  - Assumes new-physics states are heavy
  - Write effective Lagrangian with only light (SM) particles
  - BSM effects can be incorporated as a momentum expansion
- Intensively studied by theory
- Interpretation also by LHC analyses



dimension-6 dimension-8

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4} \mathcal{O}_i^{d=8} + \dots$$

BSM effects SM particles

SMEFT

Searching for signs of resonances that are too heavy to be produced at the LHC

- **Model independent framework**
  - Assumes new-physics states are heavy
  - Write effective Lagrangian with only light (SM) particles
  - BSM effects can be incorporated as a momentum expansion
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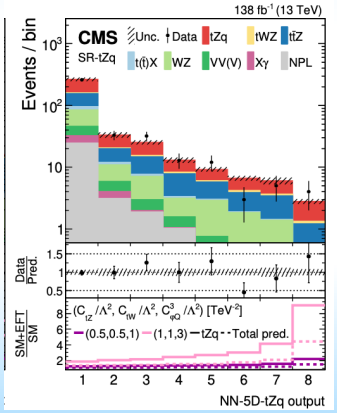
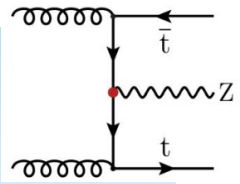
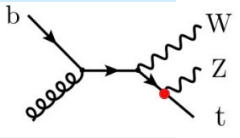
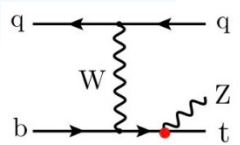
Highlight: Probing t-Z couplings with EFT

- t-Z coupling modified by various BSM scenarios
- Novel approach: constrain several t-Z EFT operators in a simultaneous analysis of ttZ, tWZ, & tZq events:
  - Consider up to 5 EFT operators simultaneously
  - Pioneer use of Deep Learning techniques to target EFT effects









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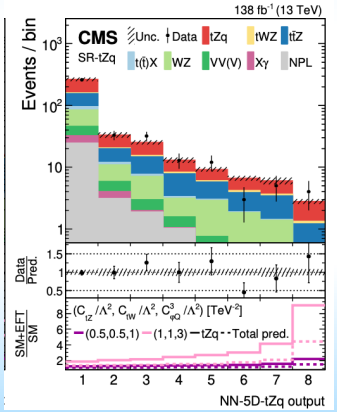
SMEFT

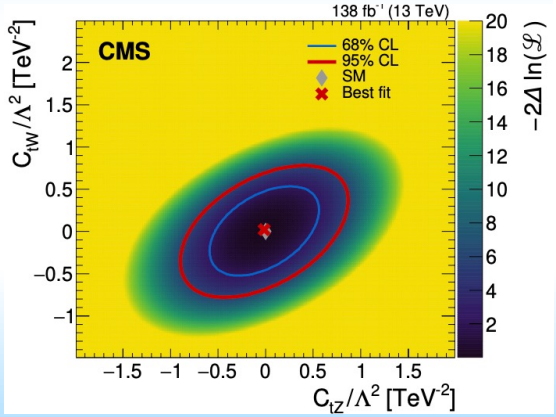
Searching for signs of resonances that are too heavy to be produced at the LHC

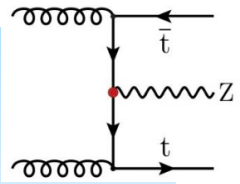
- **Model independent framework**
  - Assumes new-physics states are heavy
  - Write effective Lagrangian with only light (SM) particles
  - BSM effects can be incorporated as a momentum expansion
- Intensively studied by theory
- Interpretation also by LHC analyses

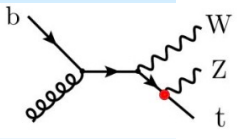
Highlight: Probing t-Z couplings with EFT

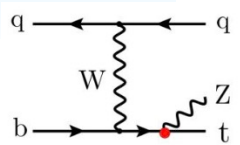
- t-Z coupling modified by various BSM scenarios
- Novel approach: constrain several t-Z EFT operators in a simultaneous analysis of ttZ, tWZ, & tZq events:
  - Consider up to 5 EFT operators simultaneously
  - Pioneer use of Deep Learning techniques to target EFT effects











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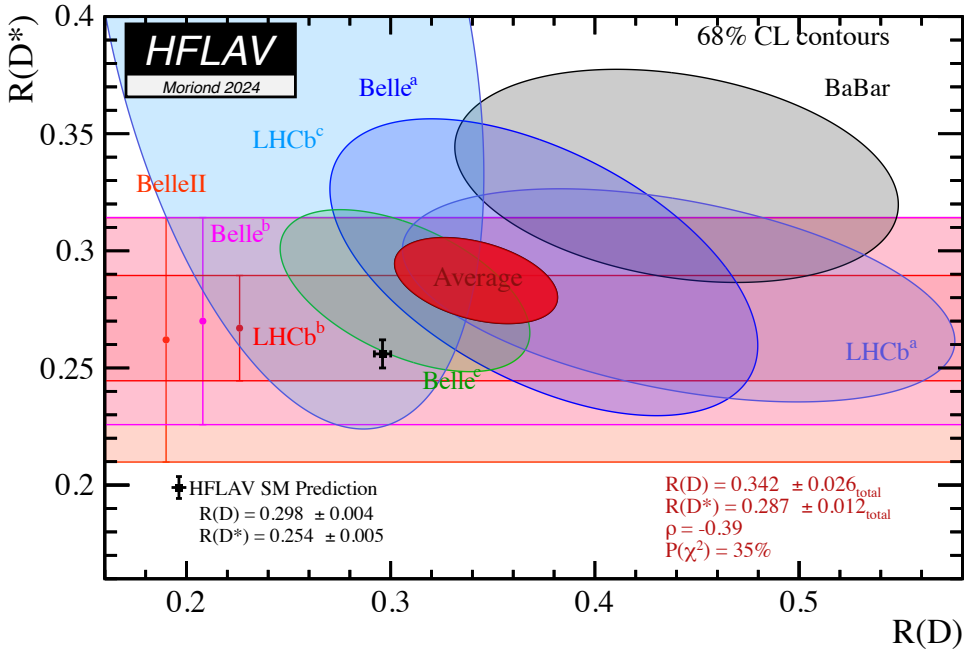
Summary

Many searches done, important contributions from theory

- ATLAS, CMS and Belle II have been performing a diverse set of searches
- Theory provides important guidelines and frameworks, e.g. SMEFT
- Trying to turn all stones, so far only a few exciting excesses
- More data to be analyzed, stay tuned!



Thank you

Extended Higgs Sector

2 Higgs doublet model: Search in $t\bar{t}$ channel

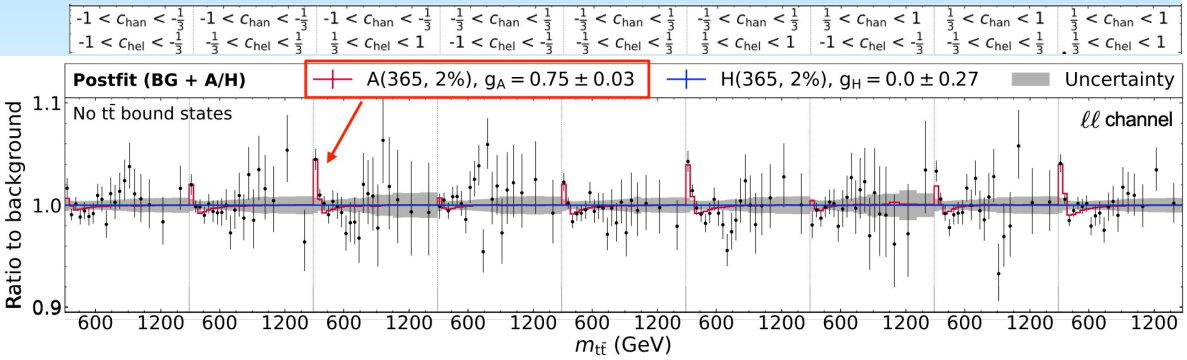
Additional Higgs doublet
→ 5 physical Higgs bosons

2HDMs could:

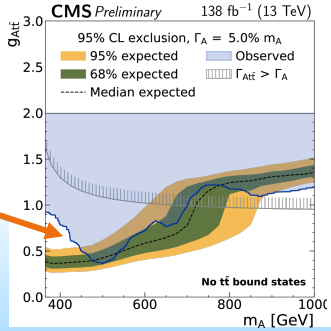
- Explain fermion masses and mixings by different couplings to the different bosons
- Explain matter-antimatter asymmetry through baryogenesis (adding CP violation in the scalar sector)
- Accommodate a strong first-order electroweak phase transition

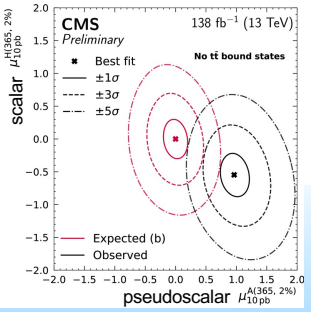
2HDM are a natural extension in SUSY (MSSM)

Highlight: Extended search in $t\bar{t}$ channel to lower di-top masses by CMS: 3D search using 2 spin observables and m_{tt} Dilepton & lepton+jets



Dilepton & lepton+jets combined fit shows data excess > 5σ





Data prefer pseudoscalar over scalar hypothesis

HIG-22-013

Extended Higgs Sector

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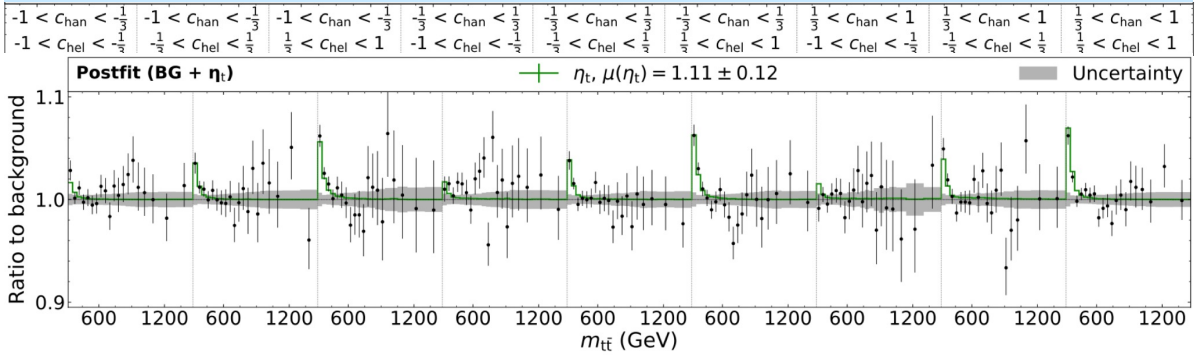
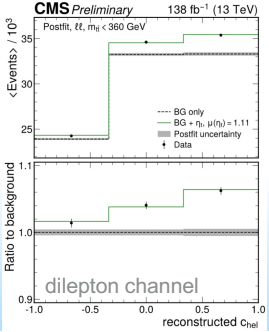


Simplified pseudoscalar bound state model:

- fits well to data well in threshold region
- cannot be separated from pseudoscalar toponium



Caution: Yet a simplified model!

$$\sigma(\eta_t) = 7.1 \pm 0.8\,\text{pb}$$

NRQCD: $\sigma(\eta_t)^{\text{pred}} = 6.43\,\text{pb}$ PRD 104 (2021) 034023

HIG-22-013

Heavy Z’

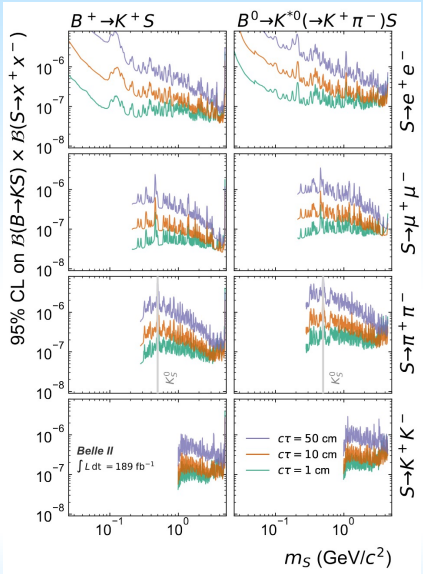
- [85] ATLAS Collaboration, Search for top-philic heavy resonances in pp collisions at √s = 13 T eV with the ATLAS detector. Eur. Phys. J. C 84, no. 2, 157 (2024). doi: 10.1140/epjc.a10052-023-12318-9
- [86] ATLAS Collaboration, Search for heavy resonances decaying into a pair of Z bosons in the ℓ+ℓ−ℓ′+ℓ′− and ℓ+ℓ−ν̄ν final states using 139 fb−1 of proton–proton collisions at √s = 13 TeV with the ATLAS detector. Eur. Phys. J.C 81, no. 4, 332 (2021). doi: 10.1140/epjc.s10052-021-09013-y
- 87 ATLAS Collaboration, Search for dark matter produced in association with a Standard Model Higgs boson
- decaying into b-quarks using the full Run 2 dataset from the ATLAS detector, JHEP 11 (2021) 209. doi:
- 10.1007/JHEP11(2021)209

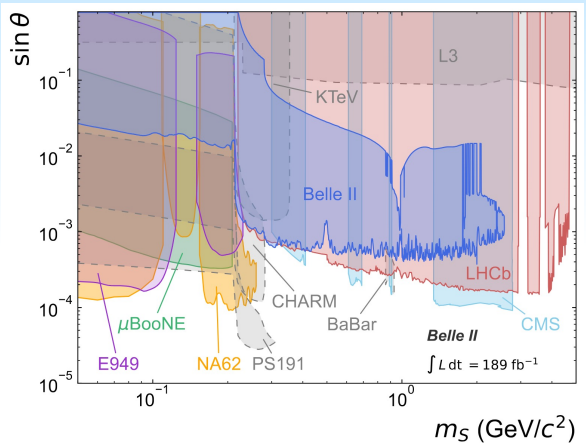
Long-lived particles

Extending to long-lived signatures

- Expected in many BSM scenarios, also at Belle II
- Might escape standard reconstruction because of:
  - Displaced vertices
  - Disappearing tracks
  - Emerging jets
  - Displaced photons
  - Out-of-time decays

Highlight: Search for long-lived spin-0 particles S in B-meson decays mediated by a b → s quark transition





Model-independent upper limits on
B(B⁰ → K*(892)⁰(→ K⁺π⁻)S) × B(S → x⁺x⁻) and
B(B⁺ → K⁺S) × B(S → x⁺x⁻), with (x = e, μ, π, K)

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Subheading, optional

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