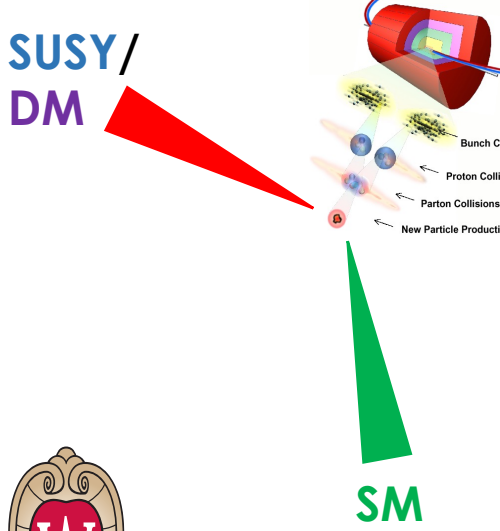
SUSY and Dark Matter search results at the CMS Experiment



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on behalf of the CMS collaboration

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

CMS Compact Muon Solenoid

31st Lepton Photon Conference 2023
MELBOURNE CONVENTION & EXHIBITION CENTRE
17 - 21 JULY

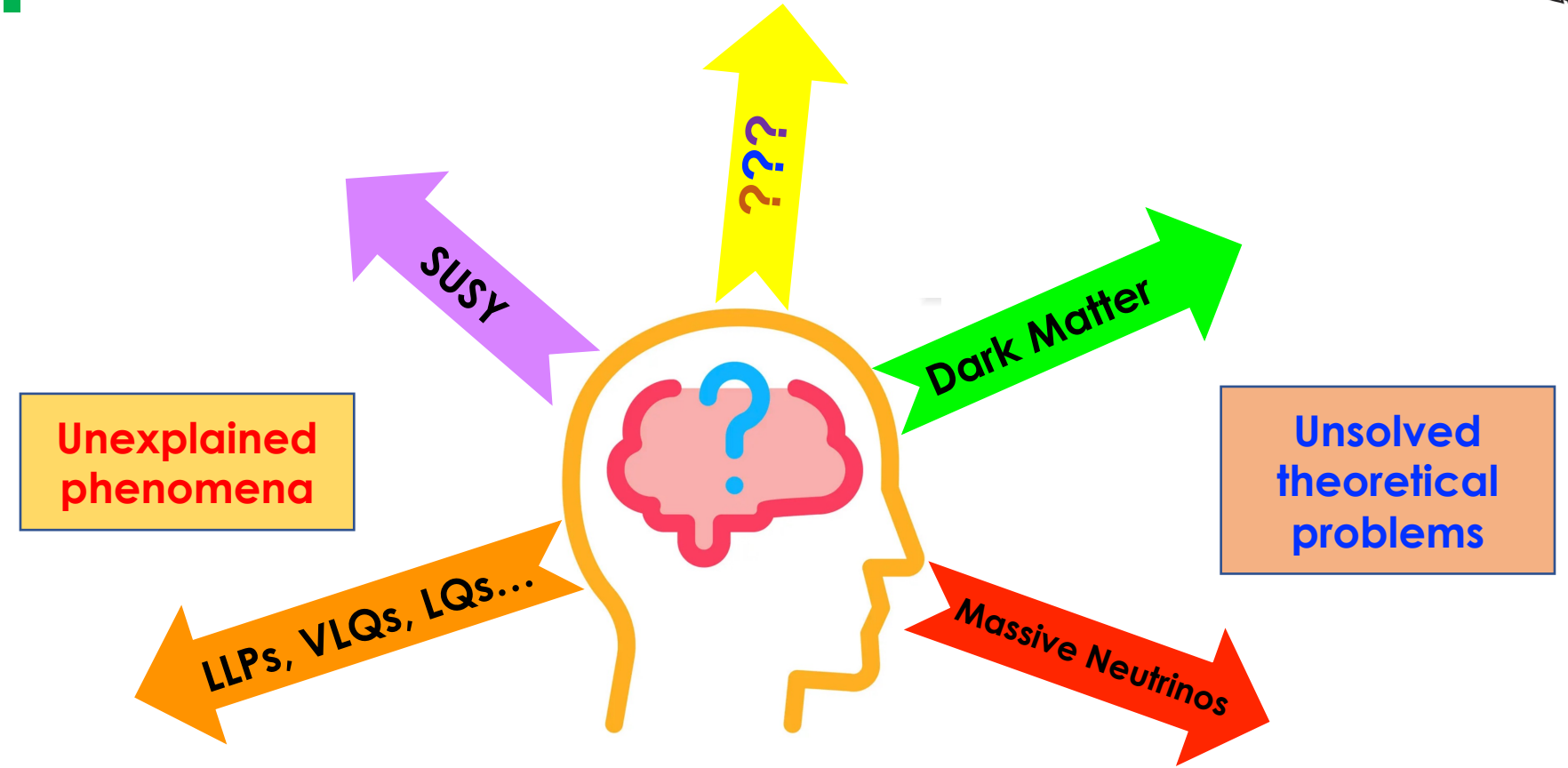
CMS @ LHC

- **Standard model:** successful theory of particle physics, thoroughly tested at the experimental level **but still far from complete**

- **LHC: Large Hadron Collider**
  - A 27 km collider designed to create rare processes happening in nature
  - Mostly collide protons, currently at $\sqrt{s}$ = 13.6 TeV

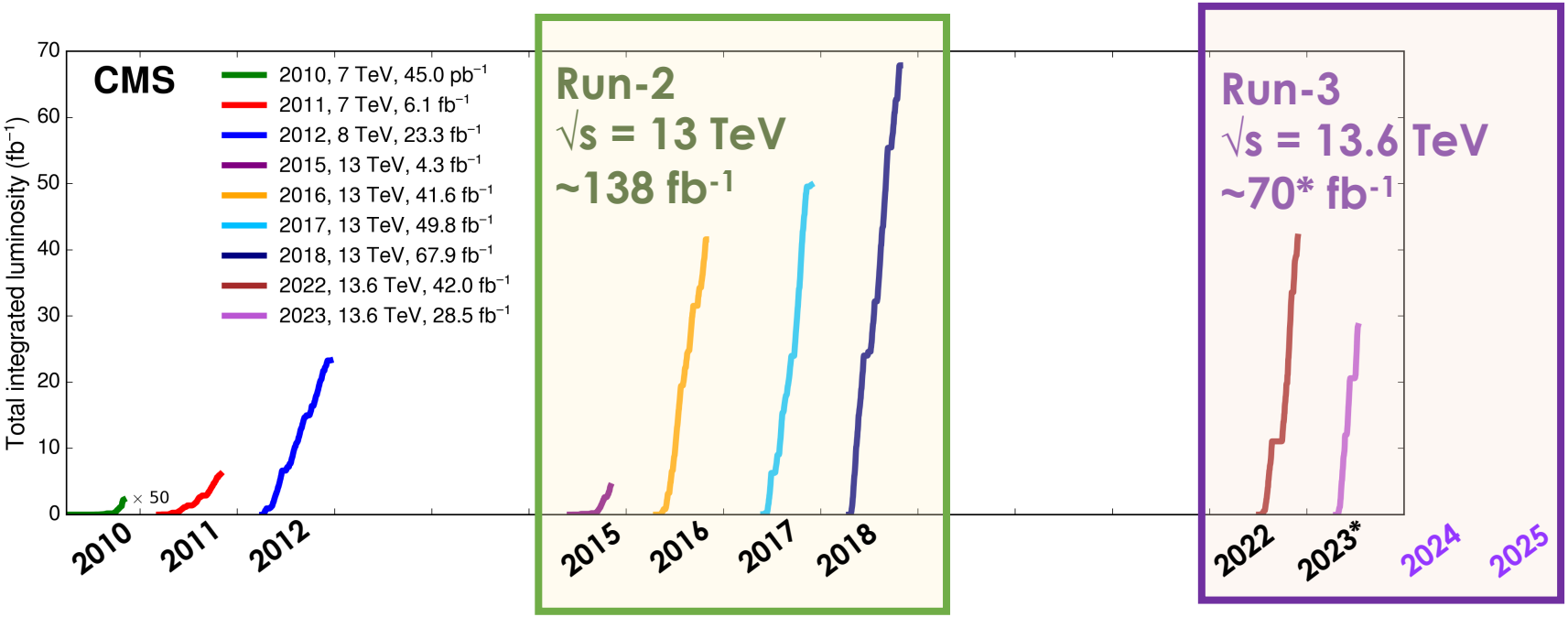
- **CMS: Compact Muon Solenoid Experiment**
  - One of four big detector at the LHC collision point (p5)
  - Record hadron collisions to unravel the unexplained phenomena of nature

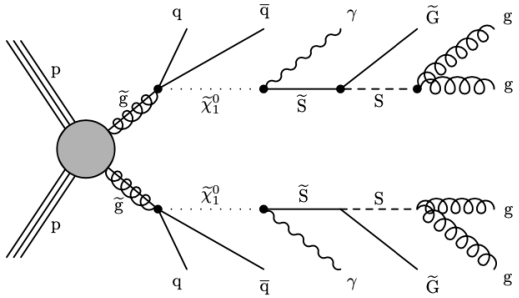
Beyond the Standard Model

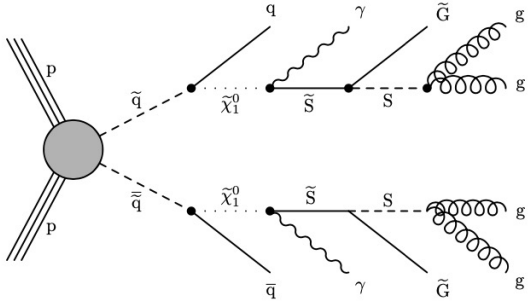


Today's talk

Some of the recent results on SUSY and DM searches with Run-2 data collected by CMS experiment







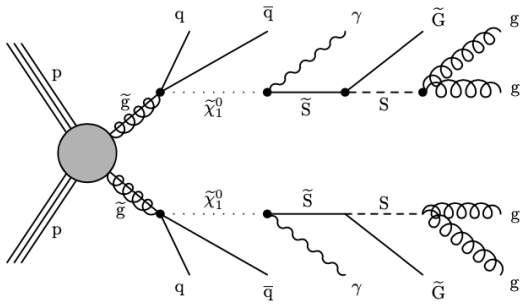
Stealth SUSY: Diphotons + jets + low MET

CMS SUS-19-001 | **to be submitted soon**

Stealth SUSY in diphotons + jets + low MET

CMS SUS-19-001

- **Model: MSSM augmented with a light hidden sector**
  - SUSY violation is weak in this hidden sector
  - Super partners are nearly mass degenerate
- **Simplest hidden sector has a single scalar singlet (S) and its super partner, singlino ($\tilde{S}$)**
  - **$|\ m_S - m_{\tilde{S}}\ |$ = small ⇒ Low MET (requirement for 'Stealth' SUSY)**
  - **Gravitino ($\tilde{G}$) is the LSP, has low momentum**
- **R-parity conserved**
- Signature truly low-MET: robust against ISR boost



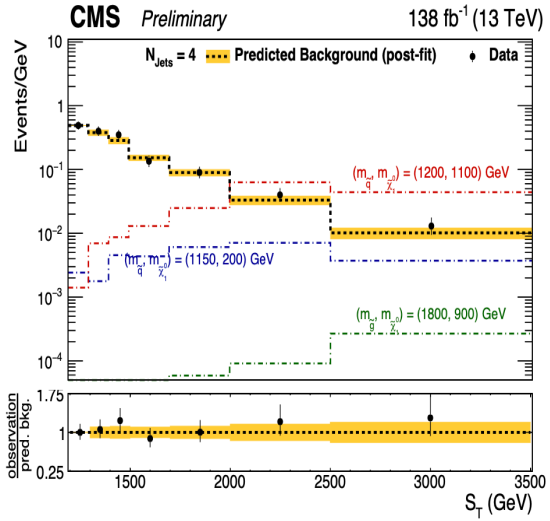
No special fine tuning!

- **S_T : Scalar pT sum of jets, photons and MET in event**
- **Events catergorization:**
  - High jet multipicity
  - Two photons ($m_{\gamma\gamma}$ > 90 GeV), pT > 35, 25 GeV
  - S_T > 1200 GeV

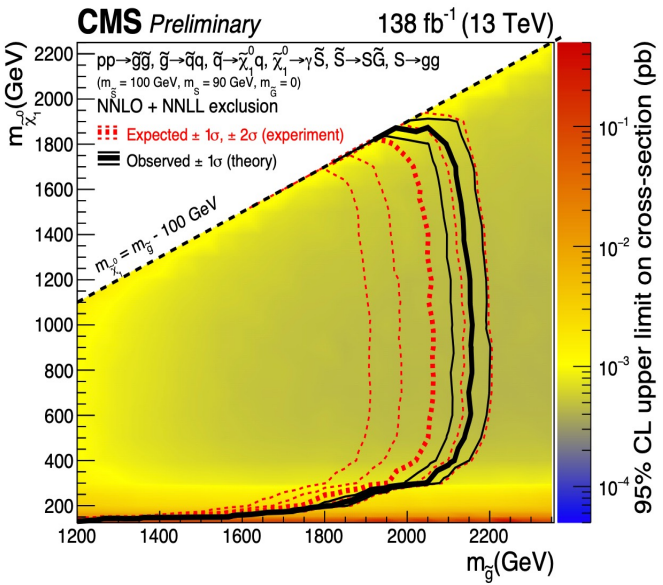
- **m_s = 100 GeV**
- **$m_{\tilde{S}}$ = 90 GeV**
- **$\tilde{g}$ = {1250, 2350} GeV**
- **$\tilde{q}$ = {1100, 2000} GeV**

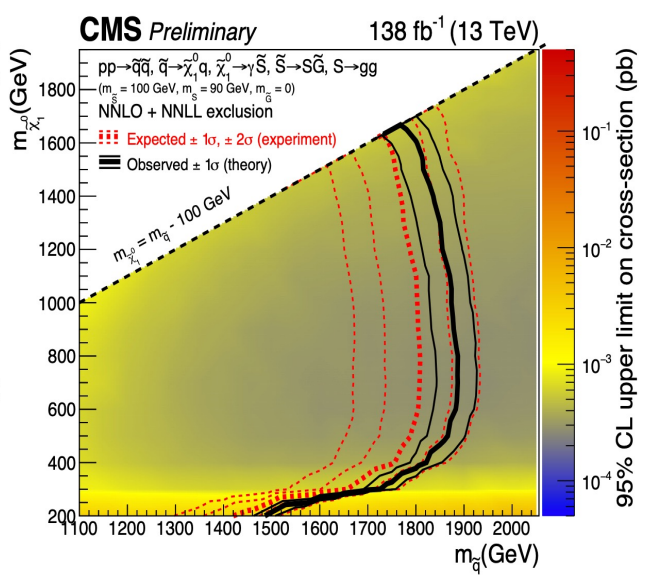
Stealth SUSY in diphotons + jets + low MET

CMS SUS-19-001

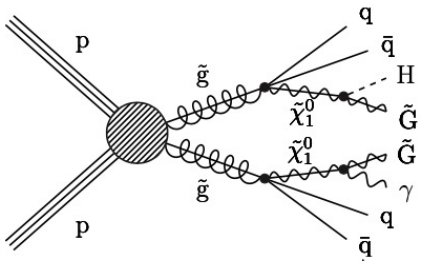


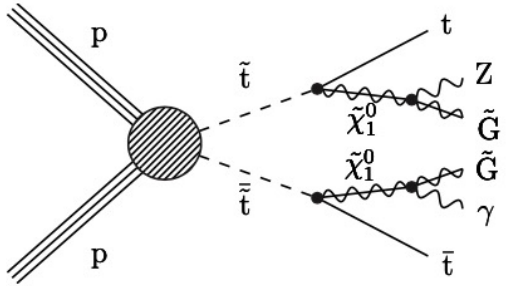
Background constraints rely on small correlation between S_T shape & nJets





- Exclude $m_{\tilde{g}}$ ($m_{\tilde{q}}$) upto 2.15 (1.85) TeV
- 70% improvement in the reach of the exclusion contour in the ($m_{\tilde{q}}$, $m_{\tilde{\chi}^0}$)
- Most stringent limits on these models





SUSY in photon + jets + large MET

CMS SUS-21-009 | **to be submitted soon**

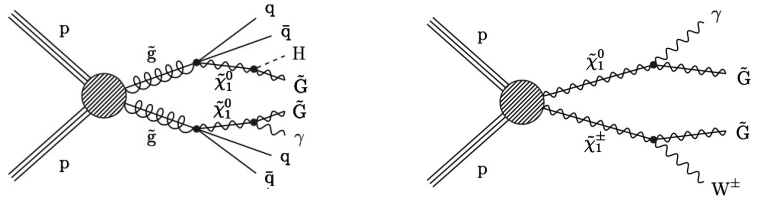
SUSY in photon + jets + large MET

CMS SUS-21-009

Gauge mediated SUS breaking (GMSB) scenarios using both EWK and strong SUSY production models

- **LSP: Gravitino ($\tilde{G}$), assumed here to be 1 GeV**
- **Photon decays of neutralinos are prominent**

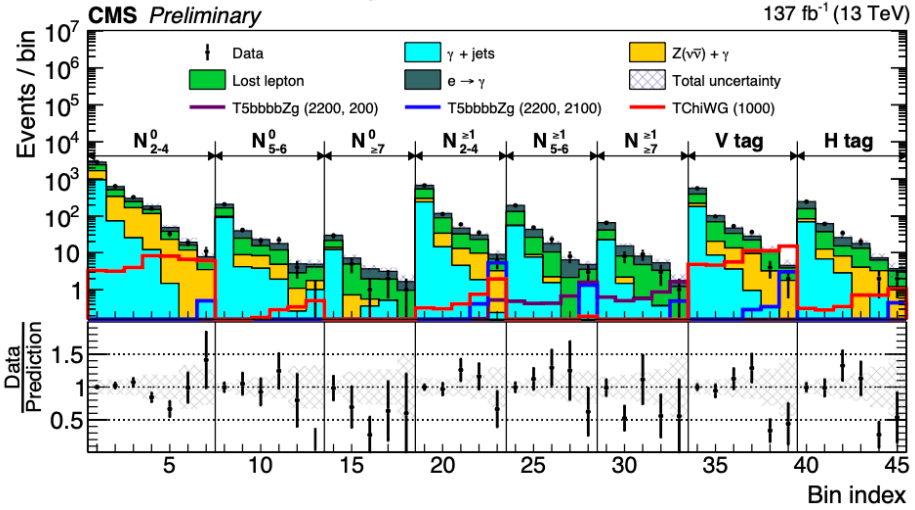
Several possible models are explored



$m_{\tilde{G}}$ = 1 GeV

Events: ≥ 1 photon, ≥ 2 jets and large MET

- **Veto events with leptons**
- **S_T: Scalar sum of photon + jets > 300 GeV**
- **$\Delta\phi$(Jet, MET) > 0.3 (leading 2 jets)**
- **Photon pT > 100 GeV**



Search categories: With/without a tagged W/Z/H boson

- **Binned in MET & N_{jets}**

Main background: lost lepton (Wγ+jets, ttγ+jets)

Results: GMSB – Gluino/Stop

CMS SUS-21-009

95% CL upper limits on the production cross sections for $\tilde{g}$ pairs

Observed (expected) limits on gluon mass for small NLSP masses:

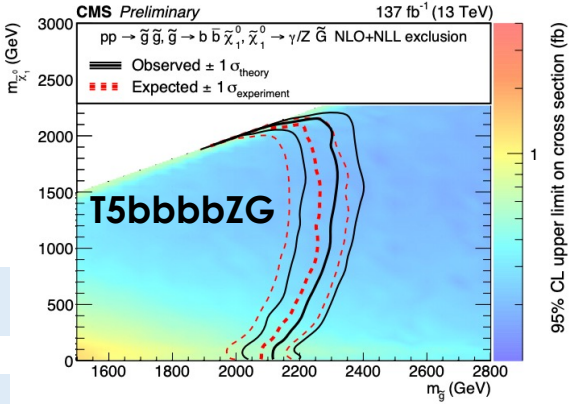
T5bbbbZG: $m_{\tilde{g}} < 2.32\ (2.27)$ TeV

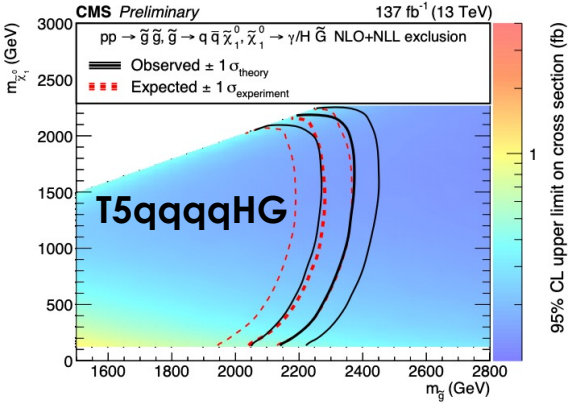
T5bbbbHG: $m_{\tilde{g}} < 2.35\ (2.30)$ TeV

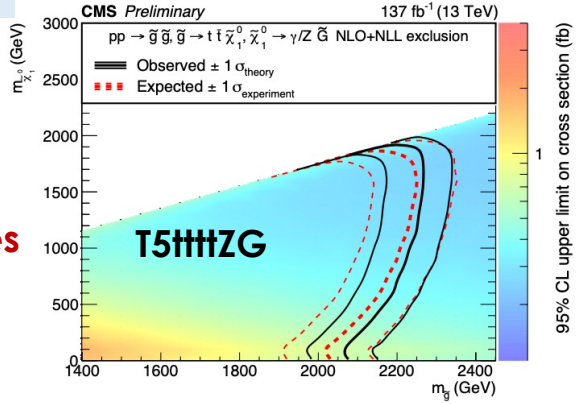
T5ttttZG: $m_{\tilde{g}} < 2.26\ (2.25)$ TeV

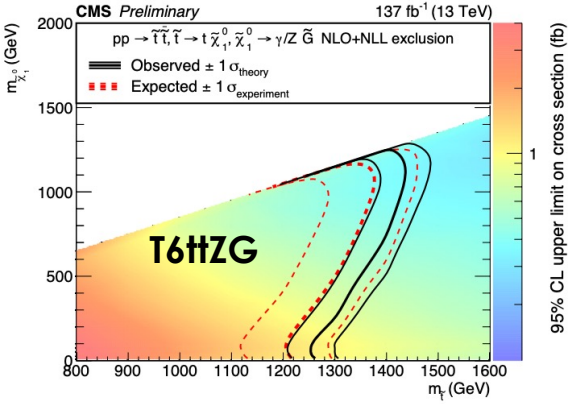
Exclusion upper limits degrade for very high and very low NLSP masses

T6ttZG: $m_{\tilde{g}} < 1.43\ (1.38)$ TeV



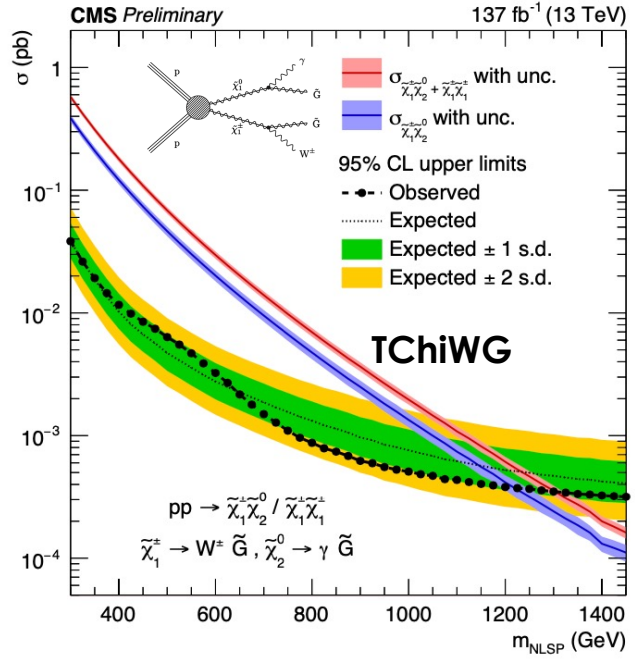


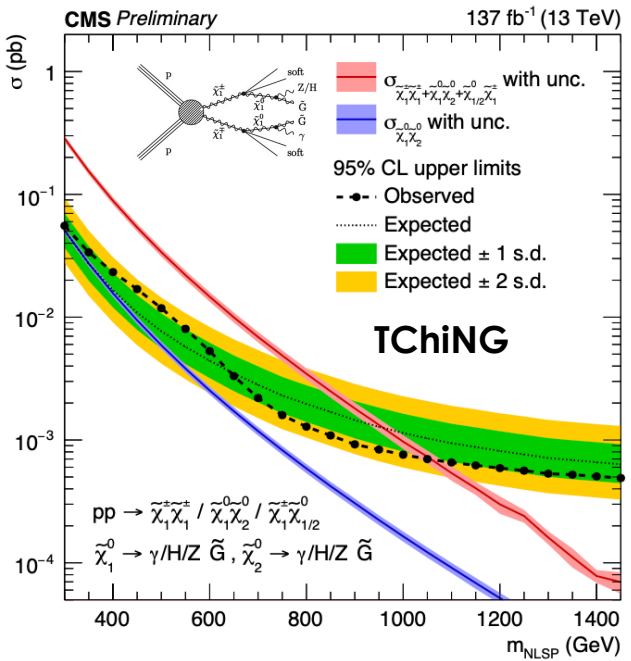


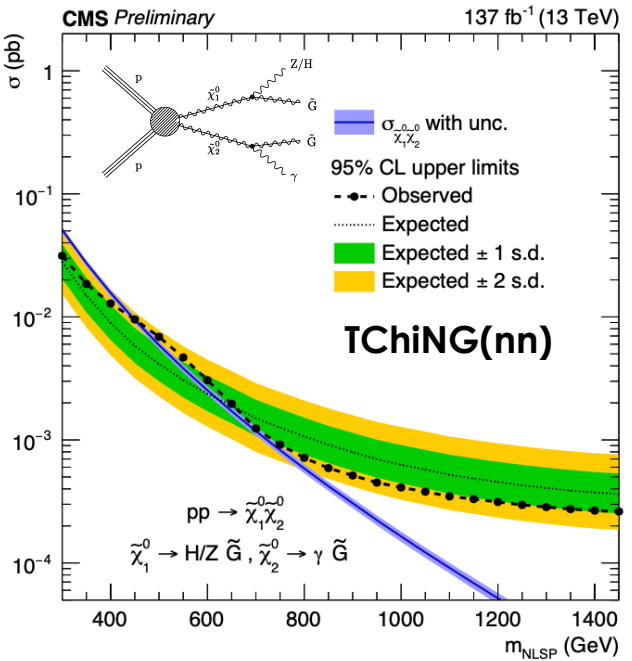


Results: GMSB – Electroweakinos

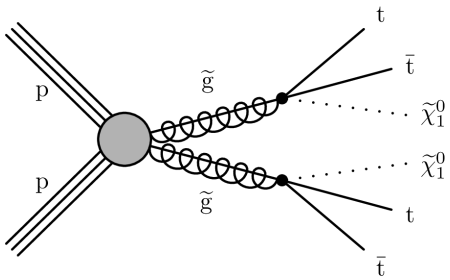
CMS SUS-21-009

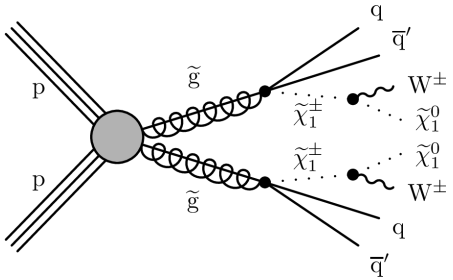






Limits assume all possible production modes or nearly degenerate triplet of chargino & neutralino states





SUSY with angular correlations

CMS SUS-21-007 | **Submitted to JHEP** | **arXiv:2211.08476**

SUSY with angular correlations

CMS SUS-21-007

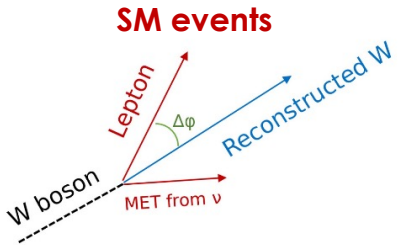
Benchmark model: R-parity conserving gluino-pair production simplified models

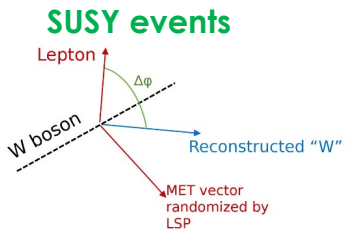
- 1 lepton from W boson decay,
- W from a top decay (multi-b) or chargino decay (0-b)

Events with 1 lepton, a large # of jets and high MET

Main discriminating observable: $\Delta\phi$ (l, W_{reco})

$\Delta\phi$ b/w lepton & reconstructed W (W=lepton and MET)

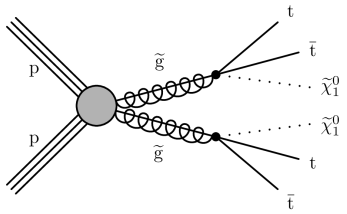




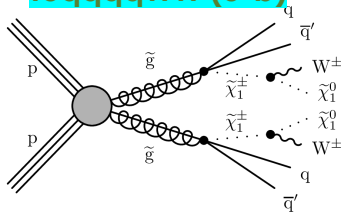
$\Delta\phi$ between lepton & MET is usually small

$\Delta\phi$ distribution is flat due to additional MET from two LSPs

T1tttt (Multi-b)

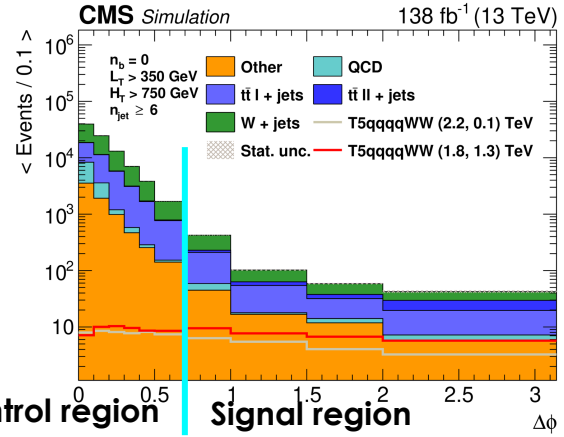


T5qqqqWW (0-b)



L_T: Scalar sum of Lepton pT + MET

H_T: Scalar sum of hadronic jets



SUSY with angular correlations

CMS SUS-21-007

Analysis region is binned in H_T, L_T, njets, nb-tags(multi-b), ntop-tag (multi-b), nW-tag (0b)

Baseline selection:
Exactly 1 lepton (e or μ), pT > 25 GeV
H_T > 500 GeV
L_T > 250 GeV
At least 2 jets with pT > 80 GeV
Number of AK4jets ≥ 3
$n_b \geq 1$ & $n_t \geq 1$ (multi-b) or $n_b = 0$ (0-b)

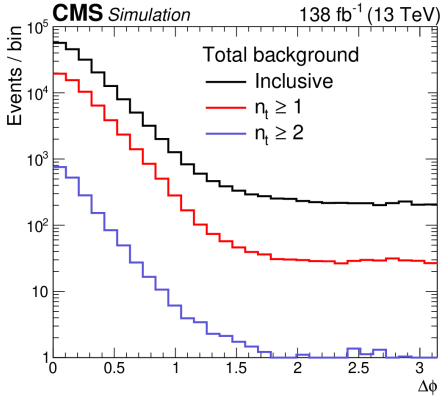
Search region is defined by large $\Delta\phi$

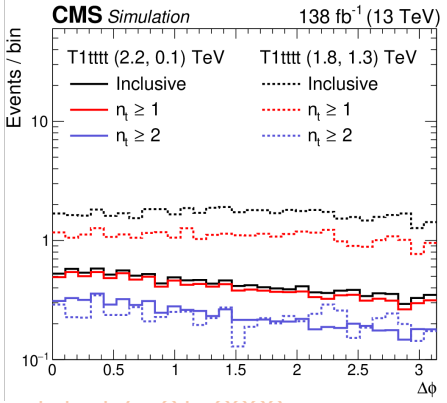
In multi-b signal, there are 3 hadronic top decays and 1 semileptonic top decay

- A combination of DNN based AK8 jet tagger and BDT based AK4 jet tagger are used

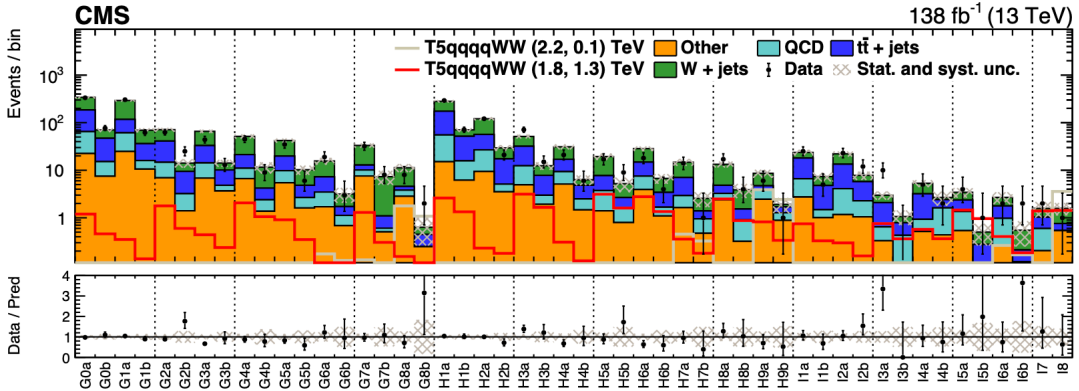
Zero-b: Hadronically decaying W bosons are identified using AK8 tagger

Selection on ntop-tag reduces background significantly in signal region



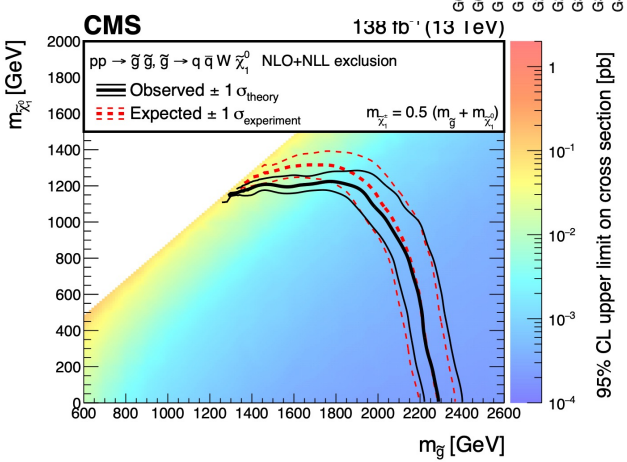


Results: SUSY with angular correlations



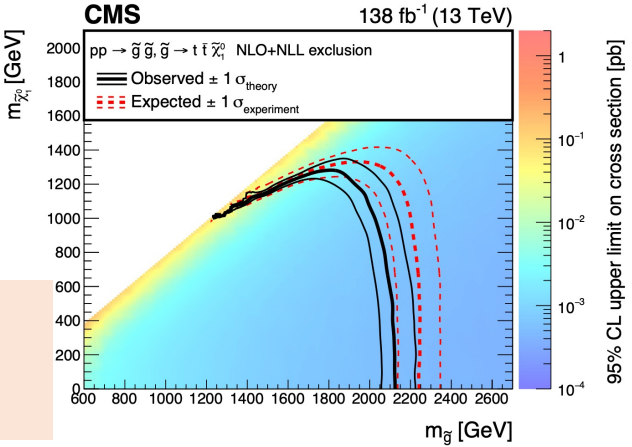
No deviation from SM

Exclusions



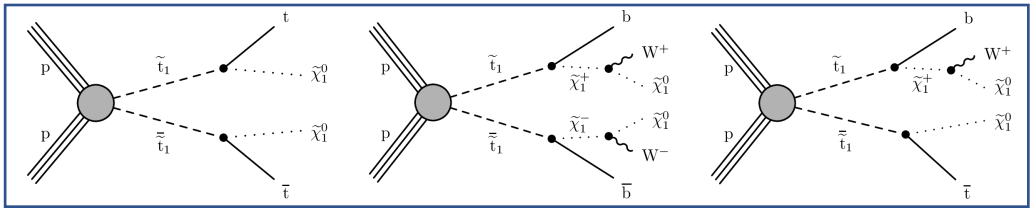
T1tttt

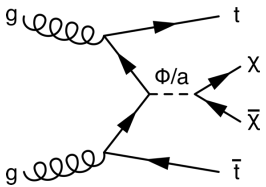
- $m_{\tilde{g}} < 2.13$ TeV
- $m_{LSP} < 1.27$ TeV



T5qqqqWW

- $m_{\tilde{g}} < 2.2$ TeV
- $m_{LSP} < 1.2$ TeV





Combination of searches: "top squarks"

CMS SUS-20-002 | **Eur. Phys. J. C 81 (2021) 970**

0-lepton: CMS SUS-19-010 | PRD 104 (2021) 052001

+

1-lepton: SUS-19-009 | JHEP 05 (2020) 032

+

2-lepton: SUS-19-011 | EPJC 81 (2021) 3

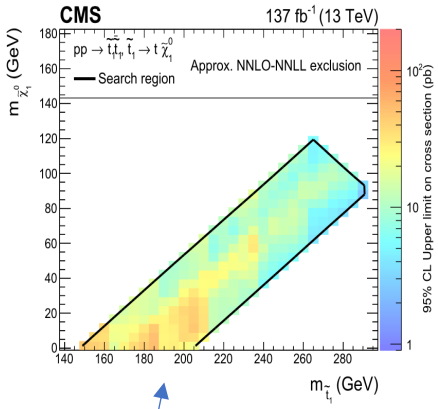
Top squarks "in the corridor"

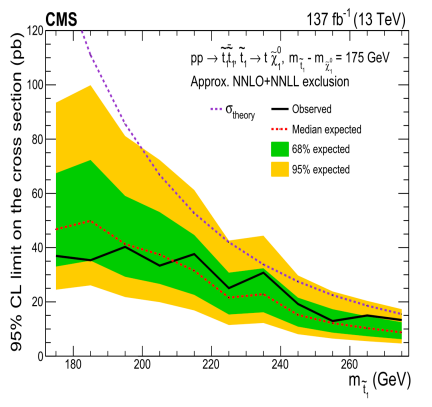
CMS SUS-20-002

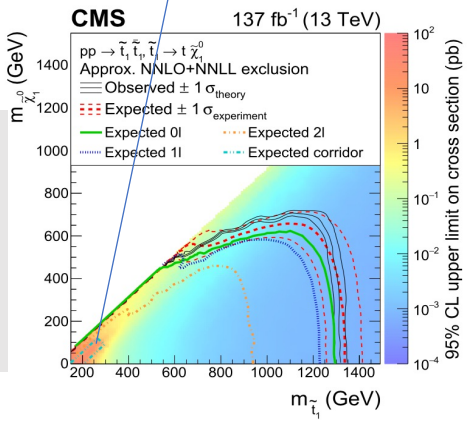
- Search targets simplified models of top squark pair production with three different models (T2tt, T2bW, T2bWt)
- Results are combined for final states with 0,1 and 2 leptons + new search in top corridor with opposite signed leptons (T2tt)
- Top corridor: Δm_{cor}: $|\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) - m_t| < 30$ GeV
  - Top corridor was not included in previous searches
- Sensitivity in top corridor is extended using a DNN to discriminate signal from similar SM ttbar events
  - Oppositely charged leptons, > 2 jets, 1 b-jet, MET> 50 GeV, $m_{T2}(ll) > 80$ GeV

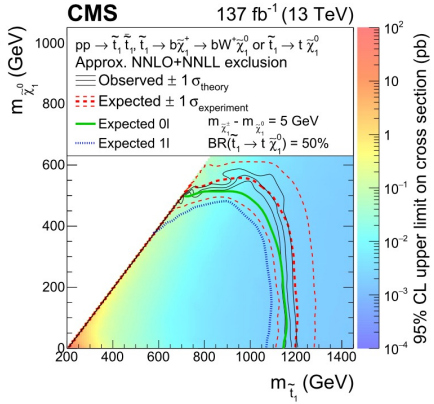
Corridor results exclusion (first time with CMS data):
$145 < m_{\tilde{t}} < 275$ GeV, $0 < m_{\tilde{\chi}_1^0} < 100$ GeV ($\Delta m_{cor} < 30$ GeV)

Combined results:
$m_{\tilde{t}} < 1.3$ TeV ($m_{\tilde{\chi}_1^0} = 0$), $m_{\tilde{\chi}_1^0} < 700$ GeV ($m_{\tilde{t}} = 1.15$ TeV)





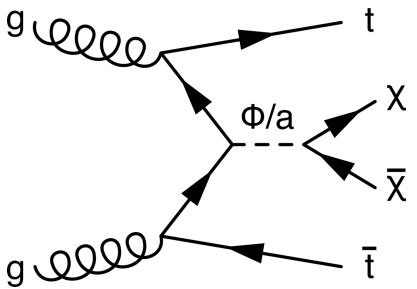




Dark Matter Interpretation

CMS SUS-20-002

The results of the inclusive top squark search are interpreted in an alternative dark matter signal model

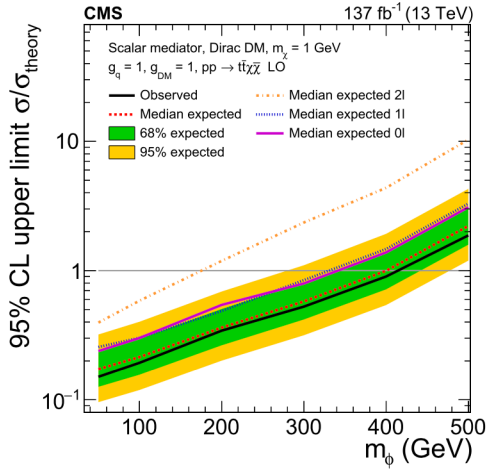


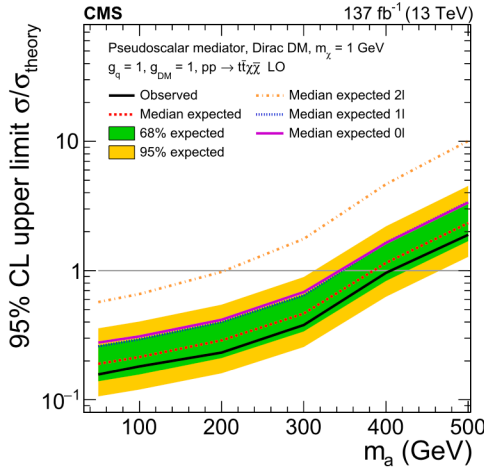
Simplified $t\bar{t}$+DM model: DM produced by a spin 0 mediator (scalar or pseudoscalar) in association with a top quark pair

m_ϕ = 50 – 500 GeV
m_χ = 1 GeV
g_q : coupling strength b/w mediator and SM quarks = 1
g_{DM} : coupling strength b/w mediator and DM quarks = 1

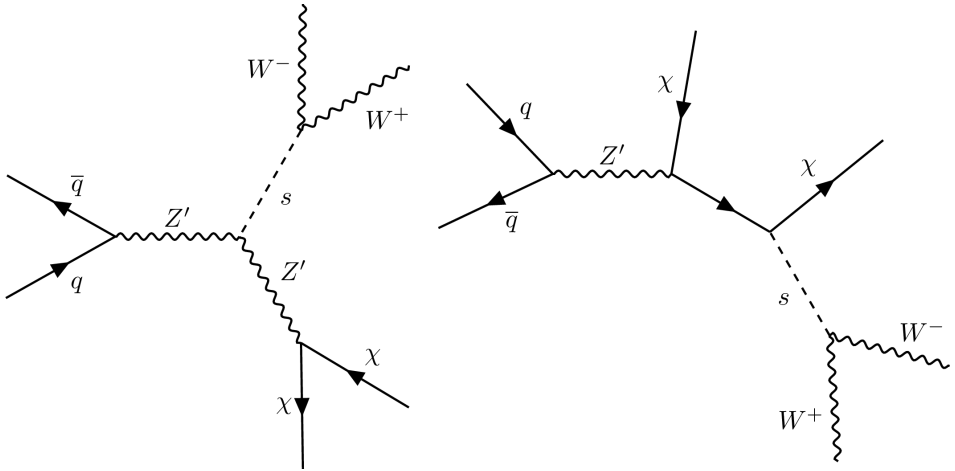
Scalar (ϕ) and pseudoscalar (a) mediators with a mass up to 400 GeV & 420 GeV are excluded, respectively

Limits are independent of dark matter mass as mediator is produced on-shell





Dark Higgs



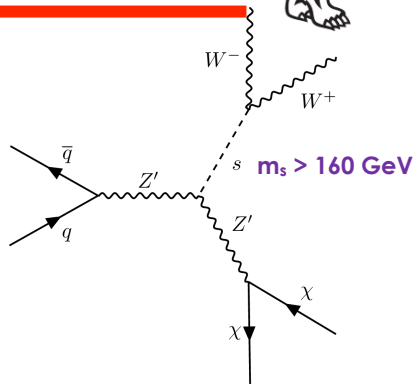
CMS EXO 21-012 | to be submitted soon

Common DM signature in collider searches: one or more SM particles + MET

Dark Higgs to WW

CMS EXO-21-012

- New collider approach to probe DM rooted in the dark sector
  - scenario where the DM particle acquires mass through its interaction with a dark Higgs boson (s)
- Benchmark model: Majorana DM particle, yield dark Higgs singlet (s) + additional massive spin-1 vector boson (Z')
  - Z' could be responsible for establishing thermal equilibrium b/w visible & dark sector in early universe
- Signature: s(WW) + $\chi\chi$; W decays leptonically or semi-leptonically



Exploits dependence of the kinematics of the final state objects on three model parameters, $m_{Z'}$, m_s, m_χ

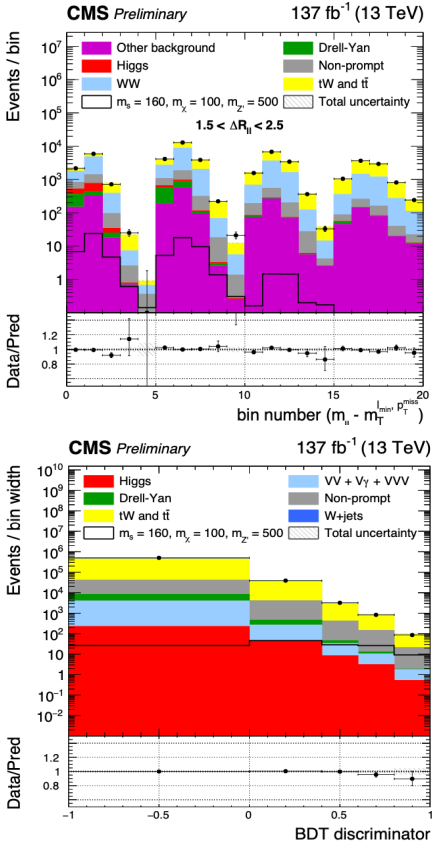
Leptonic category:
- Discriminating variable: Transverse mass b/w trailing lepton + MET

Semi-leptonic category (low cross section, irreducible background)
- Discriminating variable: BDT based on several kinematic variables

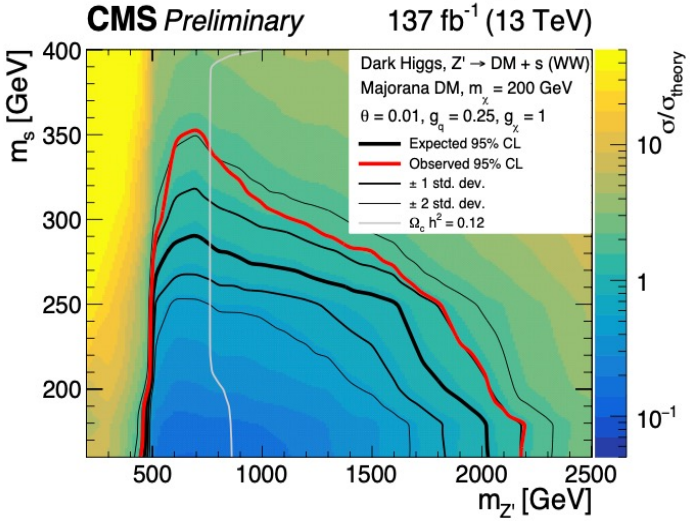
$100\ \text{GeV} \leq m_\chi \leq 300\ \text{GeV}$
$200\ \text{GeV} \leq m_{Z'} \leq 2500\ \text{GeV}$
$160\ \text{GeV} \leq m_s \leq 400\ \text{GeV}$
$g_q = 0.25;\ g_\chi = 1$

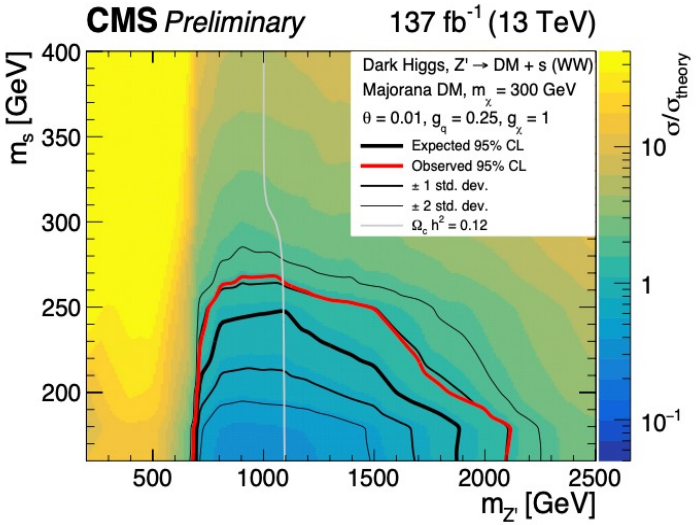
Results: Dark Higgs

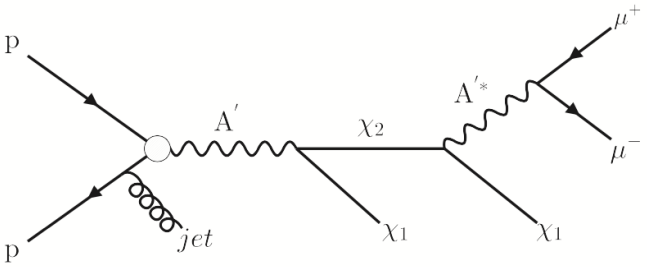
CMS EXO-21-012

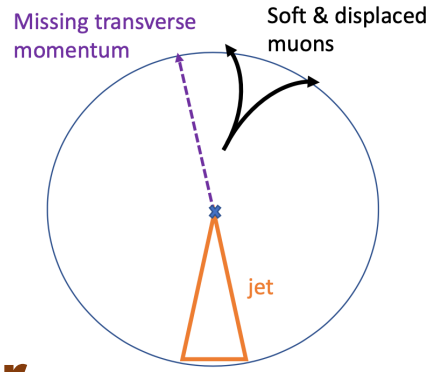


The most stringent limit is set for a m_{DM} = 200GeV, excluding m_s up to ≈ 350 GeV at $m_{Z'}$ = 700 GeV, and up to $m_{Z'}$ ≈ 2200 GeV for a m_s = 160 GeV









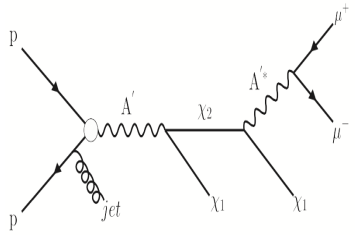
Inelastic dark matter with displaced muons pair

CMS EXO-21-010 | **Submitted to PRL** | arXiv:2305.11649

CMS EXO-21-010

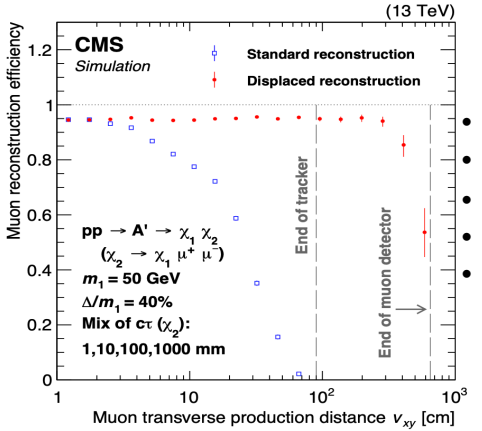
Inelastic dark matter with displaced muons

- First dedicated collider search for IDM
- Postulates: Two DM states (χ_1 & χ_2) accompanied by a dark photon (A') that kinetically mixes with SM hypercharge.
  - Inelastic senarios: DM states can't scatter elastically with other particles (eg. nucleons)
- Difference b/w lighter & heavier DM states lead to compressed phase-space & increased lifetime of the heavier state => LLP signatures
- Compatible with observed thermal-relic DM abundance
- Extend sensitivity from previous results (~ 1 GeV) to heavier DM masses (3-80 GeV)



Events with large MET (> 200 GeV)+ at least 1-jet (>80 GeV) + pair of displaced muons collimated with MET

- Specialized displaced standalone algorithm using only muon detectors info & does not require muon to originate from the interaction point
- ISR jet required to enhance MET from 2 χ_1 collimated with muons:
  - $\Delta R_{\mu\mu} < 0.9$, $\Delta\phi(\text{MET}, p_T^{\mu\mu}) < 0.5$ rad



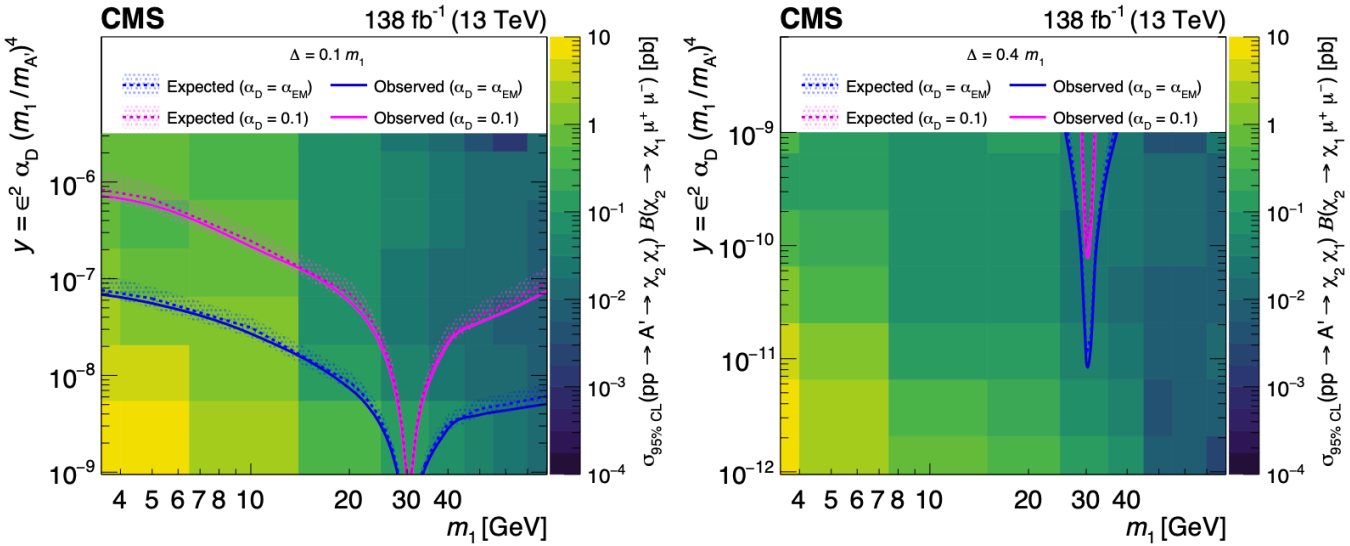
- m_1 = 1 – 80 GeV
- Δ: $m_2 - m_1$: {10%, 40%}m_1
- A' mass = $m_A = 3m_1$
- Dark sector $\alpha = \alpha_D$ = {0.1, α_{EM}}
- $c\tau$ = 1 – 1000 mm

CMS EXO-21-010

Inelastic dark matter with display muons

$\alpha_D = \alpha_{EM}$ scenario more sensitive

But $\alpha_D = 0.1$ scenario more cosmologically relevant



Upper limits are set on the product of the DM production cross section and decay branching fraction into muons as a function of DM mass m_1 and interaction strength

Resonant enhancement in the exclusion limit from mixing between A' and Z when when $m_{A'} \sim m_Z$

Other recent results

https://cms-results.web.cern.ch/cms-results/public-results/publications/SUS/index.html

https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS/index.html

https://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html

https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO/index.html

Closing Remarks

- Plethora of models tested for both Dark Matter & SUSY by CMS experiment using Run-2 data sample (~138 fb^{-1})
- New techniques being employed to improve the search strategies, identifications and background rejections
- Small deviations in few channels need to be resolved with a bigger data sample (Run-3: > 250 fb^{-1})

Stay Tuned!

ありがとう

Gracias

감사합니다

धन्यवाद

Thank you

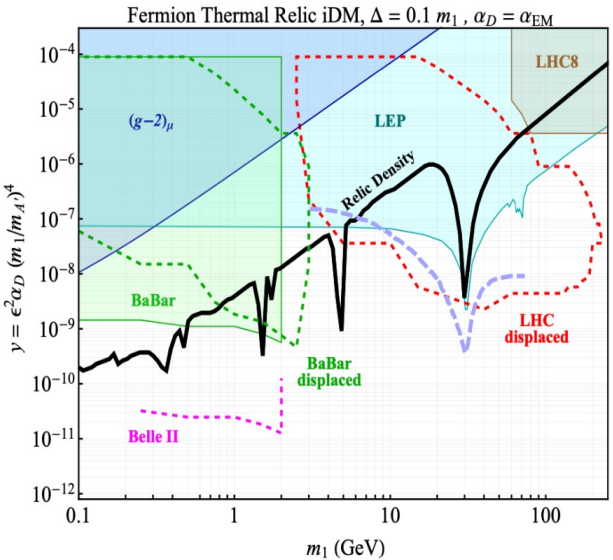
谢谢

Grazie

Merci beaucoup

EXO-20-010 (Comparison with theory)

arxiv:1508.03050



$\alpha_D = \alpha_{EM}$
$m_{A'} = 3\,m_1$

$\alpha_D = 0.1$
$m_{A'} = 3\,m_1$

Theory (300 fb^{-1})

This result (138 fb^{-1})