KRUGER 2022

# BSM searches at CMS: Highlights and prospects

- Introduction
- Highlights
- Prospects
- Conclusion

Eric Chabert
On behalf the CMS collaboration

# Goals

- Complement the panorama of BSM searches given by Greg Landsberg showing selected CMS results
- Highlight some recent results sometimes with (*mild*) **excesses**
- Show how CMS increase its **model coverage**
- Trends of **reconstruction** methods
- Include few SUSY-motivated searches

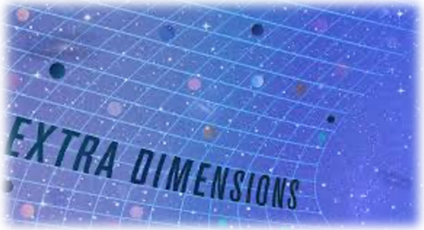
Remarks:

- Do not cover BSM-Higgs
- Do not review current limits
- Due to lack of time, I won't cover bkg estimation methods which are data-driven for the main contributions in all analyses presented

More results in SUSY (5) – EXO (17) – B2G (8) (new results in 2022)

http://cms-results.web.cern.ch/cms-results/public-results/publications/

# Simplified BSM Phenomenology



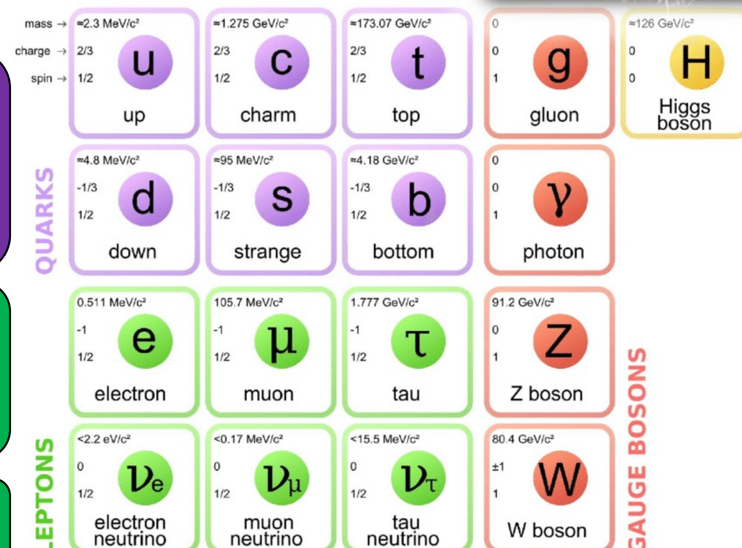

- KK excitations
- Quantum black holes


compositeness

**New heavy quarks:**
- Vector-Like Quark
- Excited quarks

**New heavy lepton**
- Vector-Like Lepton
- Excited lepton

**Heavy Neutral Lepton**




**Extended Higgs sector:**
- 2 HDM
- NMSSM …

**Extended gauge sector:**
- W', Z'

**Leptoquarks**

SUSY | RPV

\+ ….

## Beyond standard reconstruction

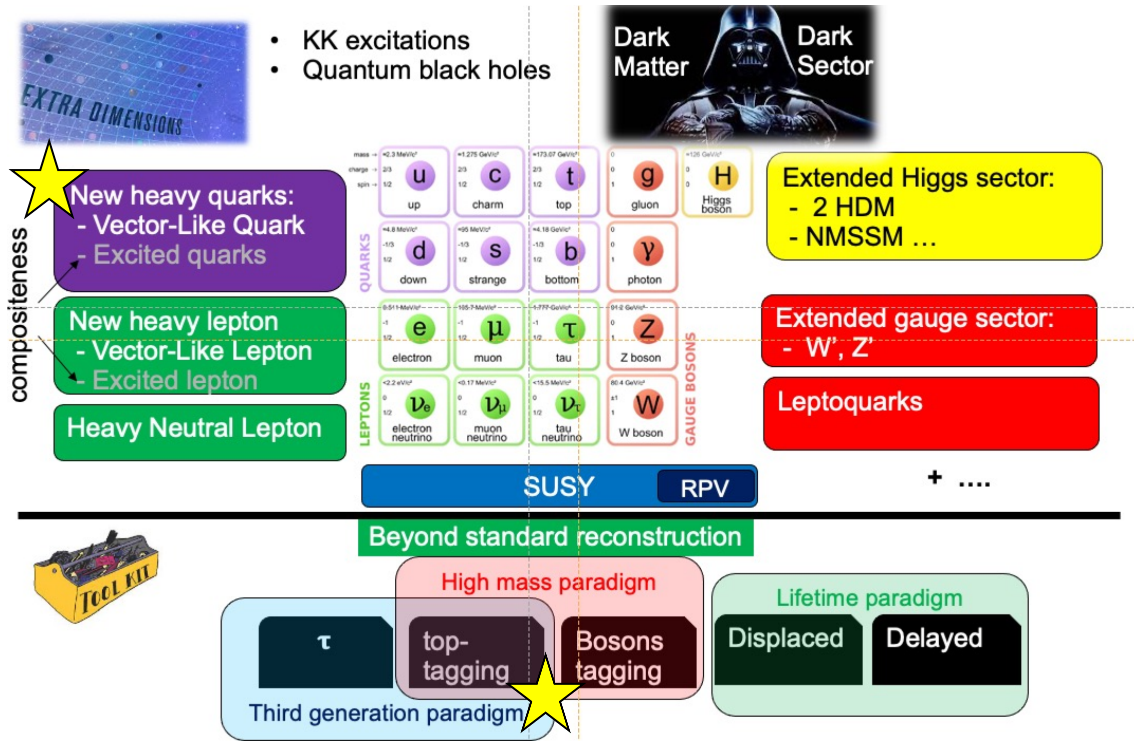

DeepJet (b)

**High mass paradigm**
- top-tagging
- Bosons tagging

**Third generation paradigm**
- τ DeepTau
- top-tagging

**Lifetime paradigm**
- Displaced
- Delayed

# VLQ

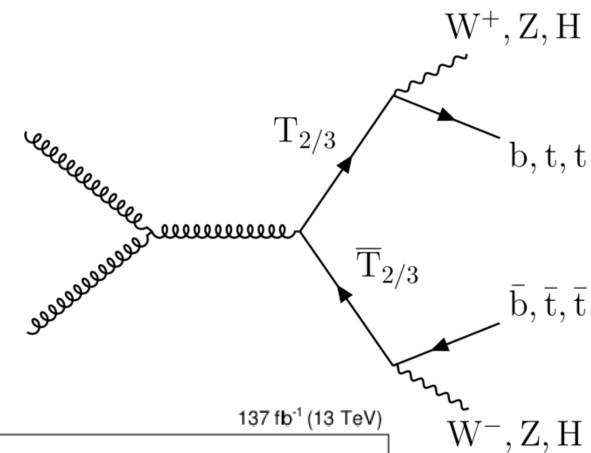

EXTRA DIMENSIONS
KK excitations
Quantum black holes
Dark Matter
Dark Sector
compositeness
New heavy quarks:
- Vector-Like Quark
- Excited quarks
New heavy lepton
- Vector-Like Lepton
- Excited lepton
Heavy Neutral Lepton
QUARKS
LEPTONS
GAUGE BOSONS
u up
c charm
t top
g gluon
H Higgs boson
d down
s strange
b bottom
γ photon
e electron
μ muon
τ tau
Z Z boson
νe electron neutrino
νμ muon neutrino
ντ tau neutrino
W W boson
Extended Higgs sector:
- 2 HDM
- NMSSM …
Extended gauge sector:
- W', Z'
Leptoquarks
SUSY
RPV
+ ….
Beyond standard reconstruction
TOOL KIT
High mass paradigm
τ
top-tagging
Bosons tagging
Third generation paradigm
Lifetime paradigm
Displaced
Delayed

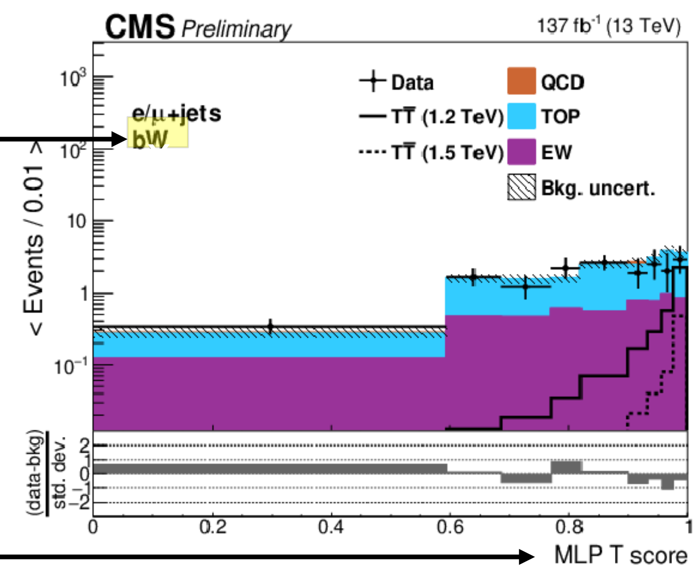
# VLQ: Vector-like quark

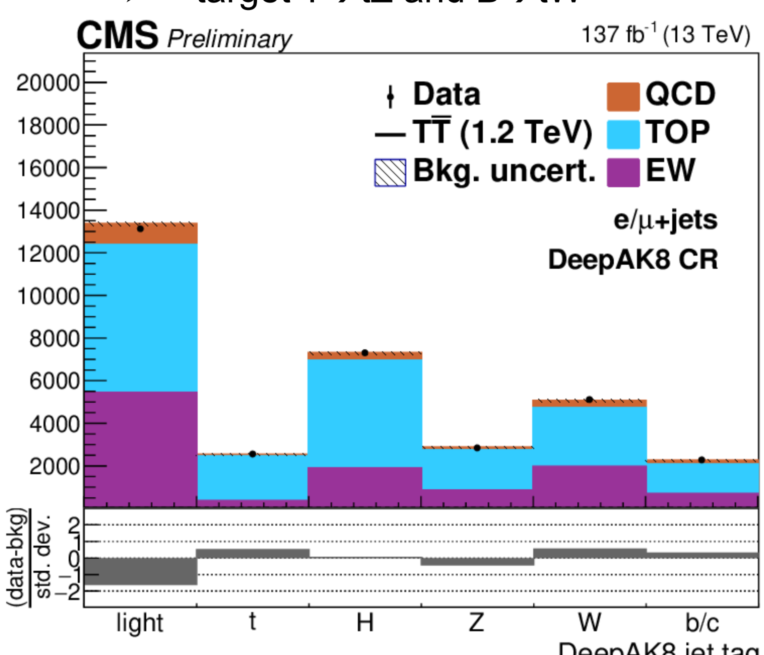
May 2022

B2G-20-011

- Search for $\mathbf{T_{2/3}}$ or $B_{-1/3}$ in pair production
- Focused on **leptonic** final states (e,μ), combining:
  - **single lepton**
    - ≥ 3 large-radius jets with tagging (DeepAK8 Puppi) + MET
    - NN (MLP with 13 input var.) for discrimination:
    - Categorization based on jet-tags
  - **same-sign dilepton (ee,μμ,eμ)**
    - Target T→tH (H→WW) and B→tW
  - **≥ 3 leptons:**
    - target T→tZ and B→tW




**Strongest limits to date:**

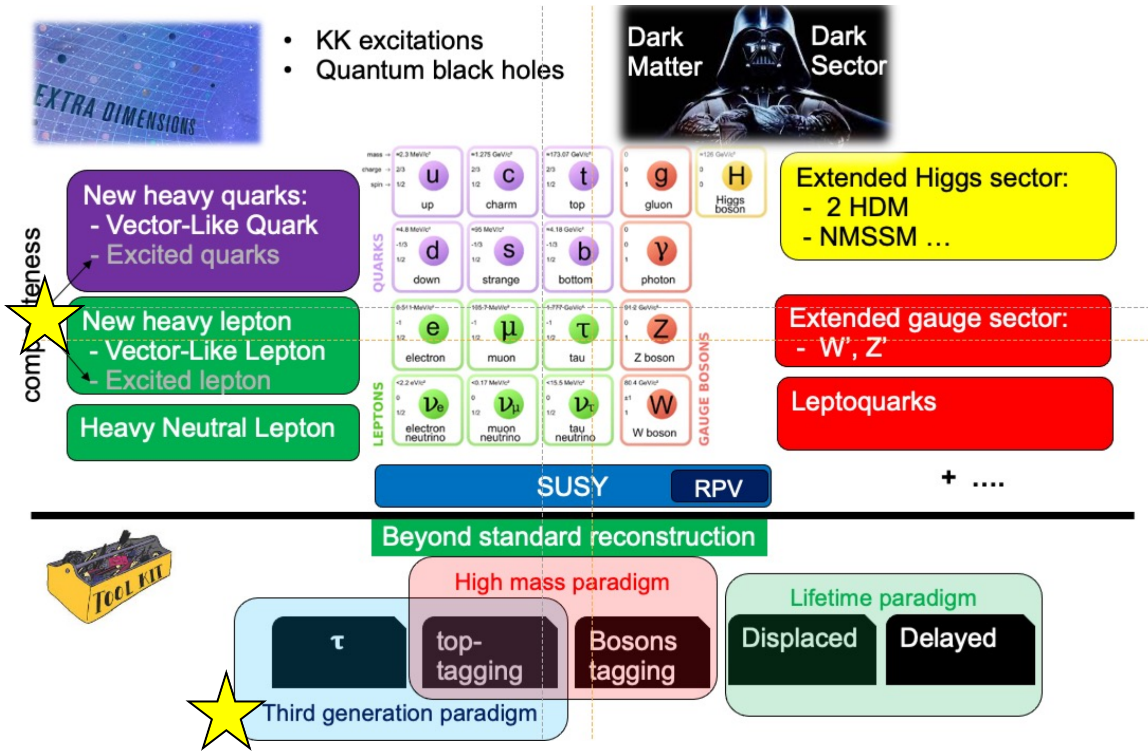
Excluding T quark masses:

[1.48 -1.58 (bW) TeV] depending in BR

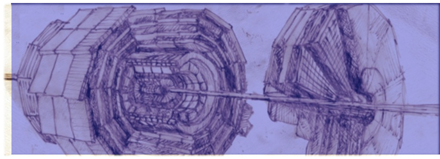
Excluded B quark masses:

[1.11-1.56 (tW) TeV] depending in BR

# VLL



KK excitations
Quantum black holes
Dark Matter
Dark Sector
New heavy quarks:
- Vector-Like Quark
- Excited quarks
New heavy lepton
- Vector-Like Lepton
- Excited lepton
Heavy Neutral Lepton
compositeness
Extended Higgs sector:
- 2 HDM
- NMSSM …
Extended gauge sector:
- W', Z'
Leptoquarks
SUSY
RPV
+ ….
Beyond standard reconstruction
High mass paradigm
Lifetime paradigm
τ
top-tagging
Bosons tagging
Displaced
Delayed
Third generation paradigm



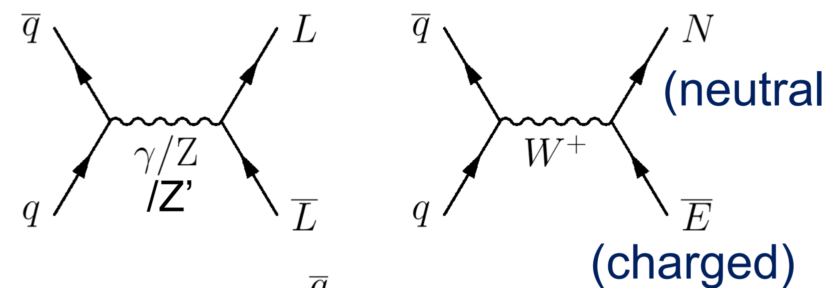
# VLL: Vector-like lepton

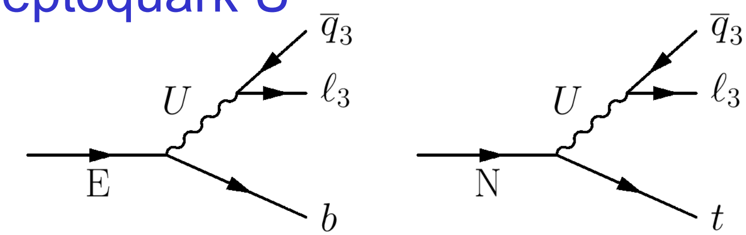
March 2022

B2G-21-004

- Search in the context of 4321 model: $SU(4)\times SU(3)'\times SU(2)_L\times U(1)$

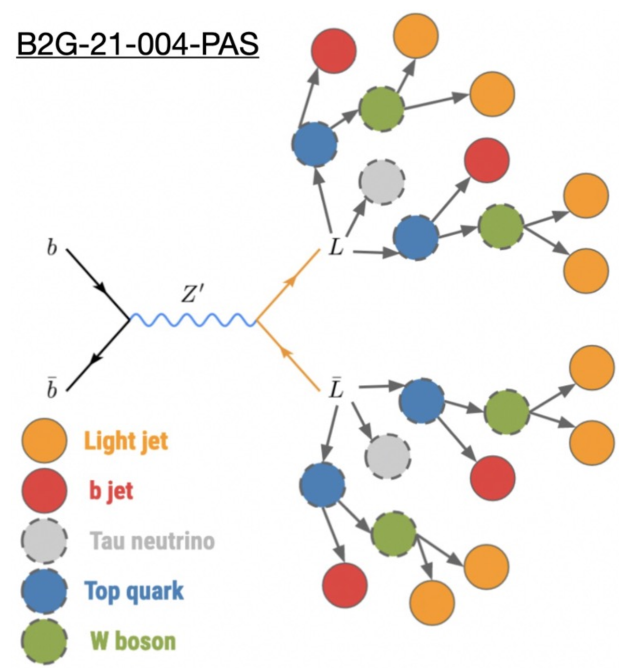
  → UV-complete model motivated by B physics excess
- Search for a VLL **doublet** (N,E) - L = N|E
- VLL production through EW processes
- Coupling to SM via vector leptoquark U




- B-anomalies favor **3rd gen coupling**,
- **Final states**: ≥ 3 **b-jets** – 0,1,2 $\tau$ - ≥ 4 jets - MET
- Signal Region per #$\tau$ and year (2017-2018)
- Use of a **Graphical NN** (10 objects/event)
  - Inputs: $\eta$,$\phi$,log($p_T$), log(m), Q, DeepJet score

B2G-21-004-PAS



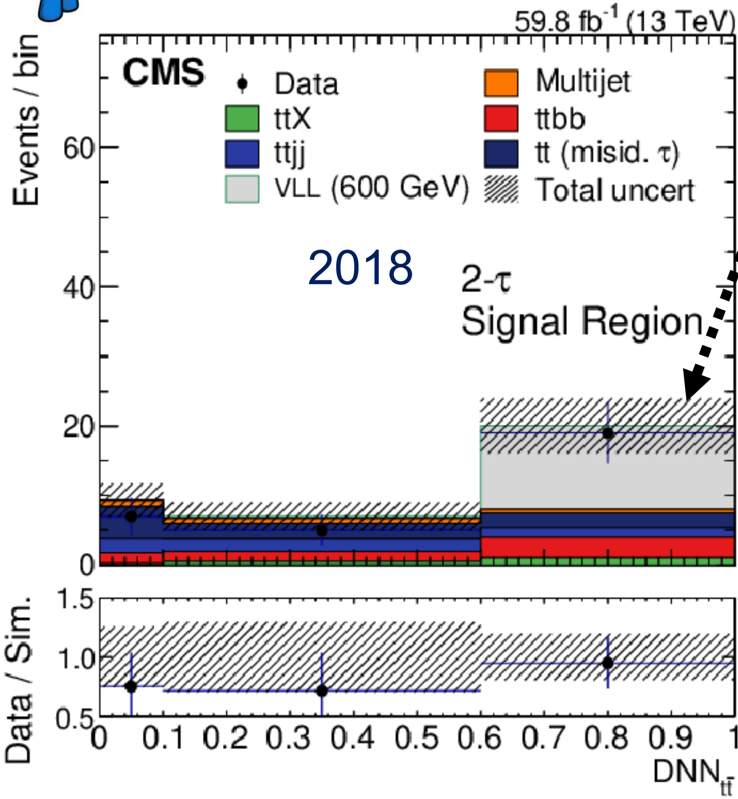
# VLL: Vector-like lepton

**Excess** of 2.8 σ (favorizing 600 GeV VLL)

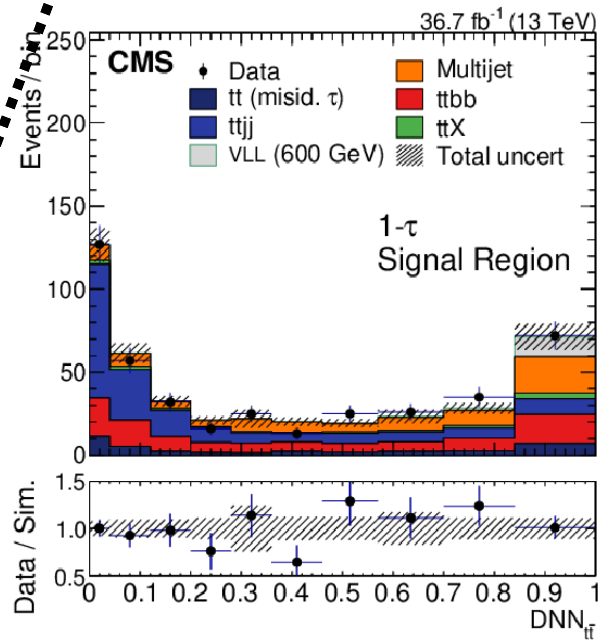
B2G-21-004

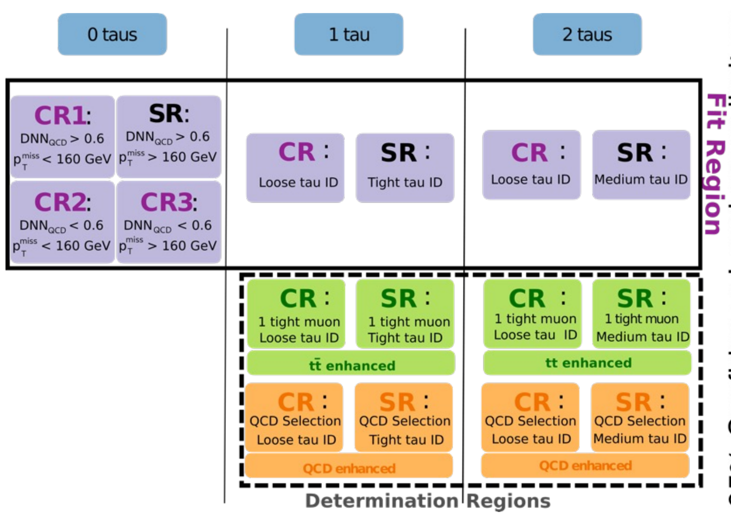
March 2022

2018

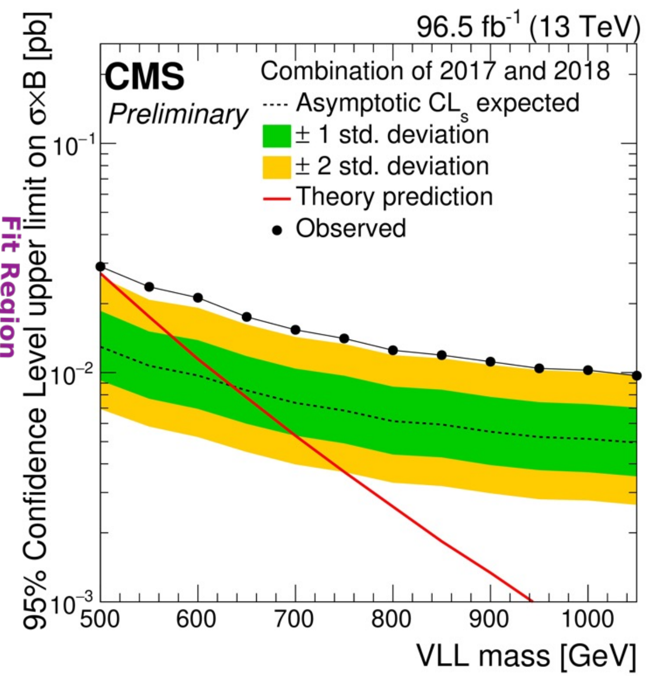



2017

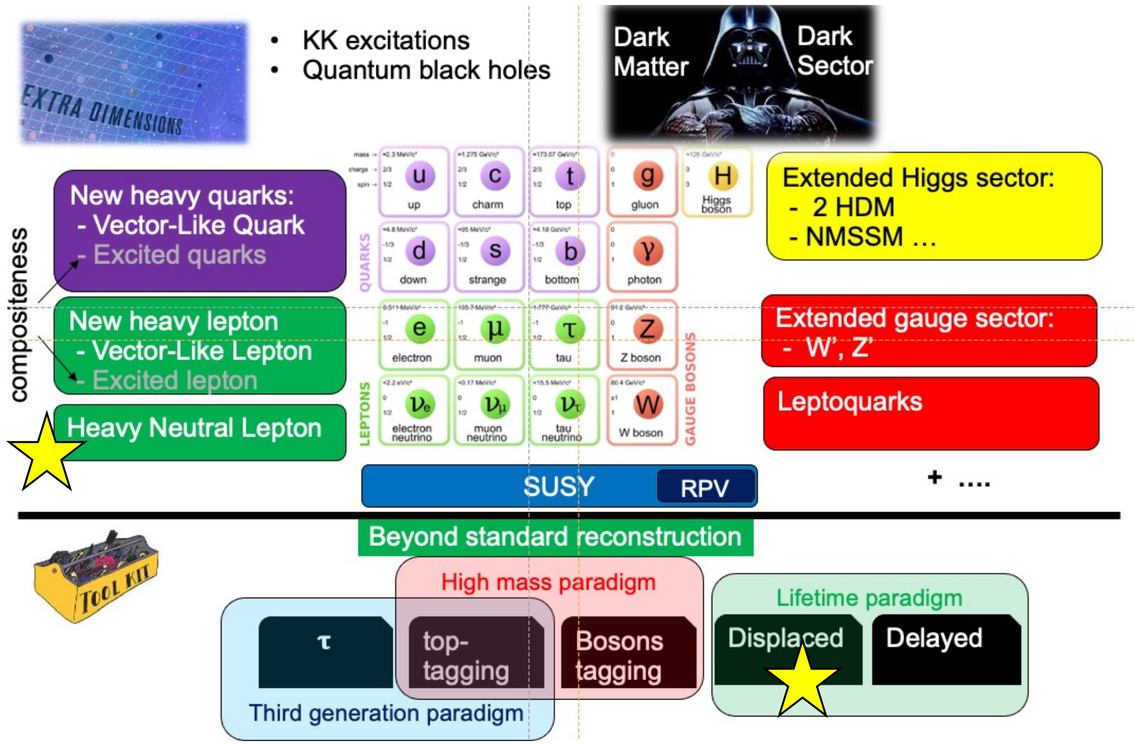



Set limits on VLL mass
Combining years & regions



# HNL


EXTRA DIMENSIONS
• KK excitations
• Quantum black holes
Dark Matter
Dark Sector
New heavy quarks:
- Vector-Like Quark
- Excited quarks
compositeness
New heavy lepton
- Vector-Like Lepton
- Excited lepton
Heavy Neutral Lepton
u up
c charm
t top
g gluon
H Higgs boson
d down
s strange
b bottom
γ photon
e electron
μ muon
τ tau
Z Z boson
$\nu_e$ electron neutrino
$\nu_\mu$ muon neutrino
$\nu_\tau$ tau neutrino
W W boson
QUARKS
LEPTONS
GAUGE BOSONS
Extended Higgs sector:
- 2 HDM
- NMSSM …
Extended gauge sector:
- W', Z'
Leptoquarks
SUSY
RPV
+ ….
Beyond standard reconstruction
TOOL KIT
High mass paradigm
τ
top-tagging
Bosons tagging
Third generation paradigm
Lifetime paradigm
Displaced
Delayed

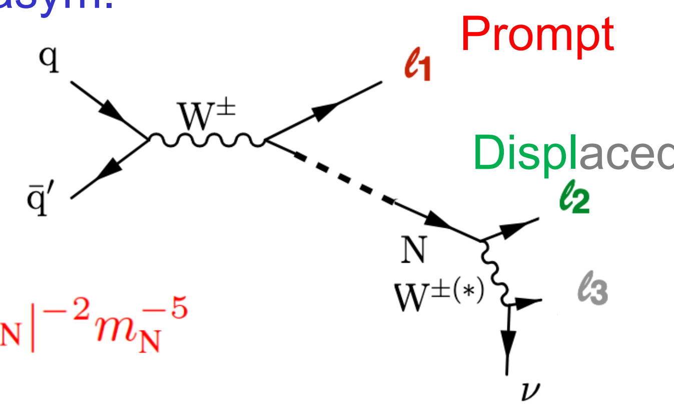
# Heavy Neutral Lepton

July 2021

EXO-20-009

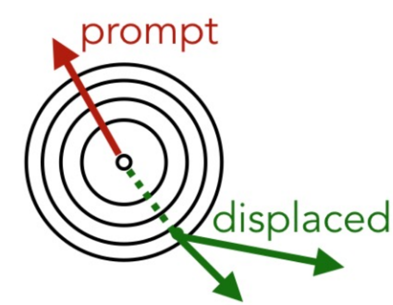
- HLN = RH Dirac or Majorana (→ lepton number violation) neutrinos
- Motivations: **ν** mass (seesaw) – DM candidate - (anti-)matter asym.
- Sterile = only interact through kinetic mixing with SM **ν**
- Decay through **W*** or Z*
- For $m_{HLN}$<20 GeV & HLN-**ν** mixing within $10^{-7}$ -$10^{-2}$

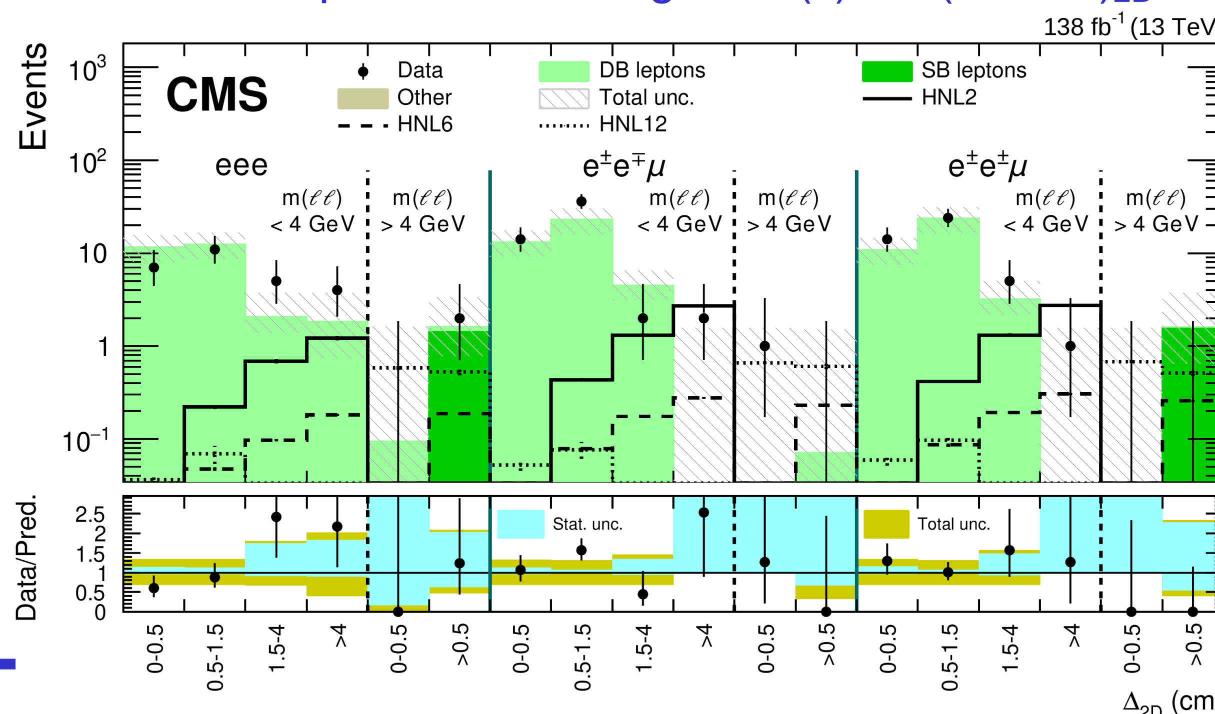
  → **Displaced vertex** resolved by silicon tracker




$$\tau \propto \sum_i |V_{iN}|^{-2} m_N^{-5}$$

- **Final state**: ≥ 3l, 0 b-jets, 2,3-bodies angular and mass constraints
- Categorization as function of lepton flavor/charge – m(ll) - $\Delta(PV\text{-}SV)_{2D}$



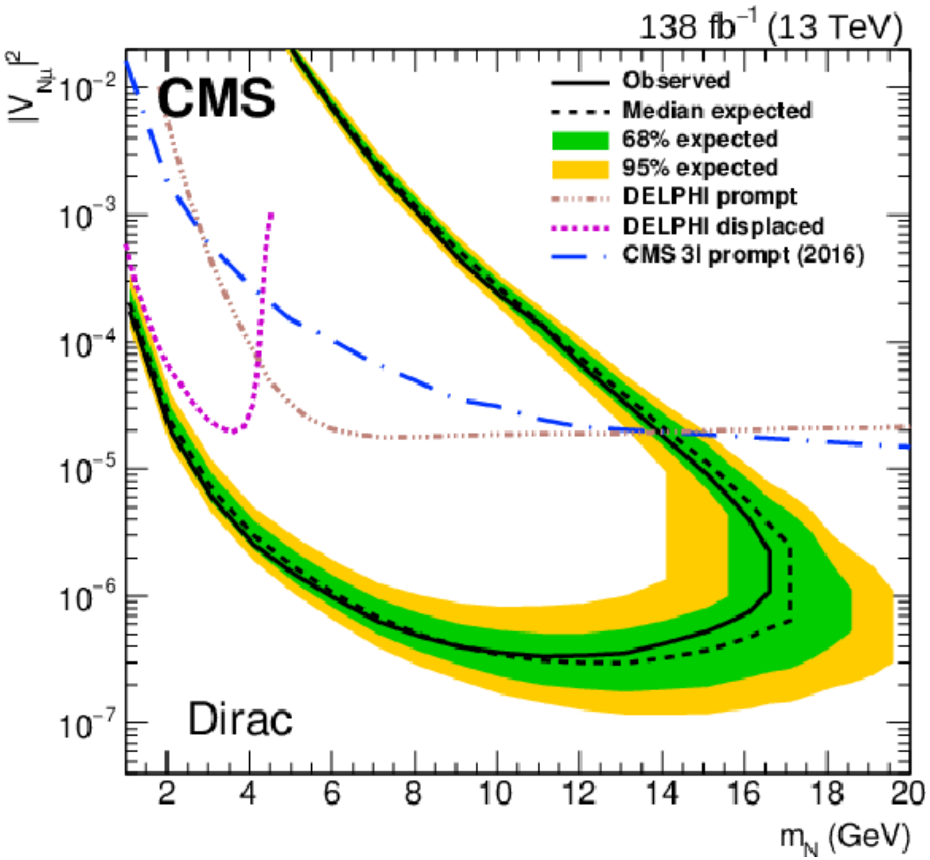



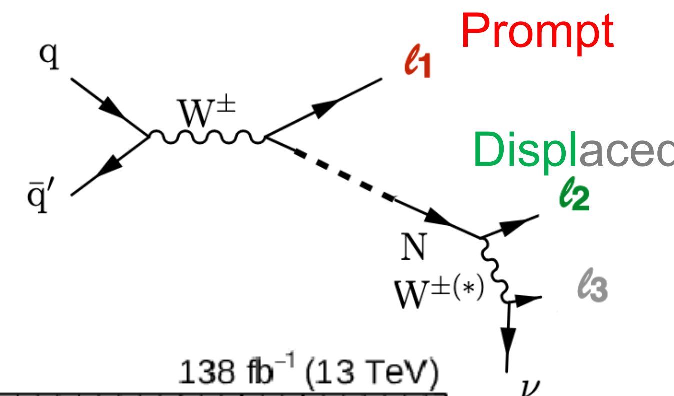
# Heavy Neutral Lepton

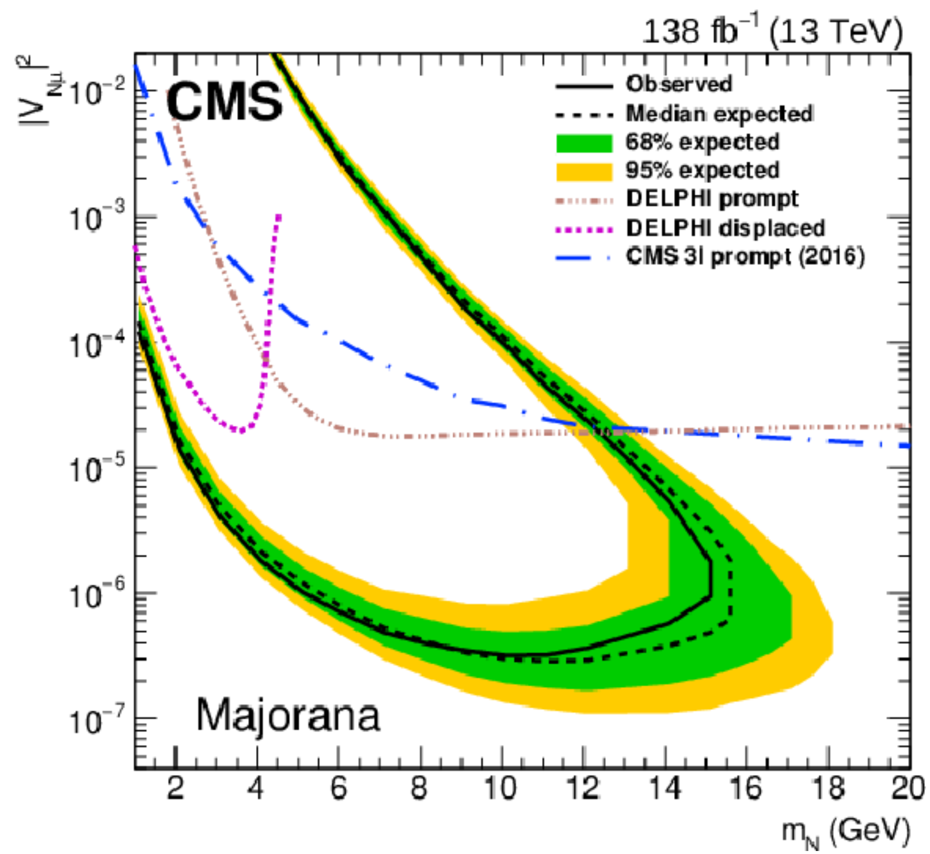
July 2021

Results of Dirac and Majorana HNe and HNμ superseed former constraints

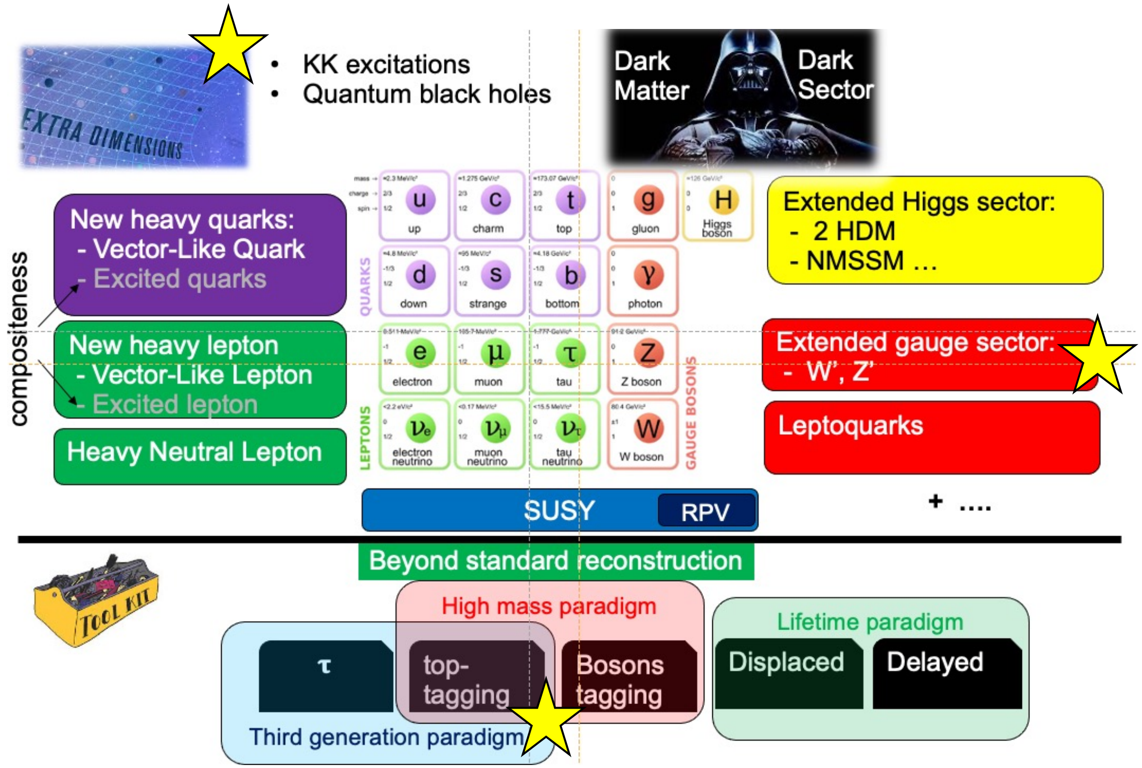
EXO-20-009



# Extended gauge sector



# Extended gauge sector: di-jet pairs

June 2022

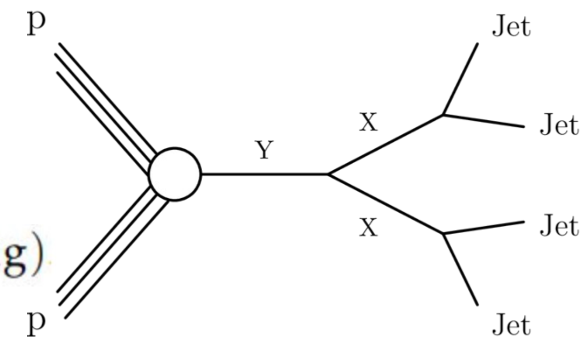
EXO-21-010

- First search for di-jet pairs production

**Resonant**:
Could be interpreted in Diquark model

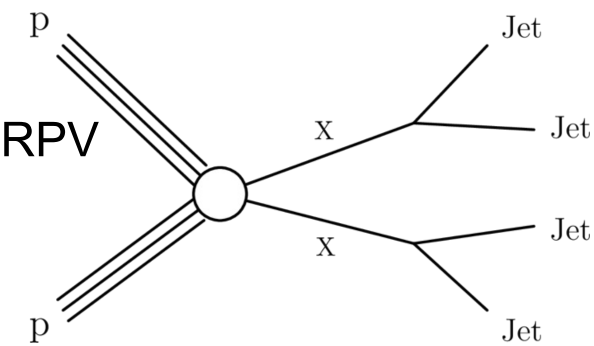
$$uu \to S \to \chi\chi \to (ug)(ug)$$

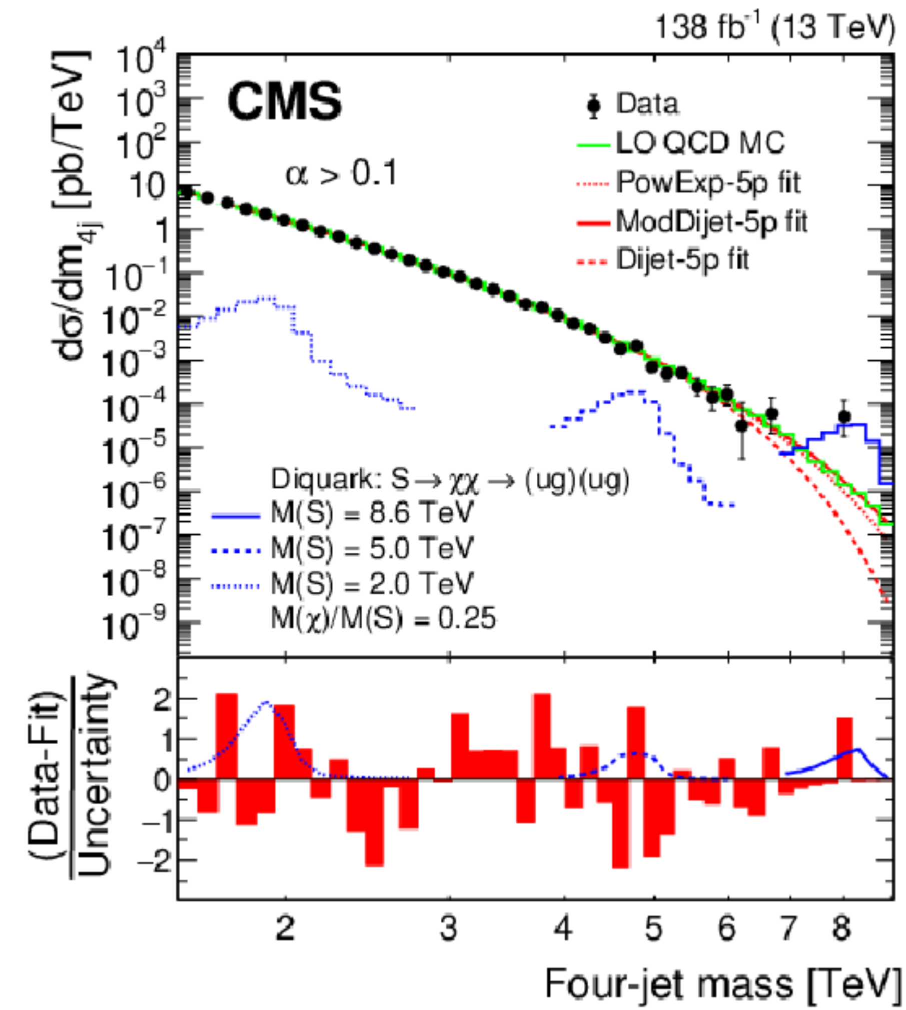
↳ VLQ




**Non-resonant:**
Could be interpreted in RPV

$$pp \to \tilde{t}\tilde{t}^* \to (\bar{d}\bar{s})(ds)$$



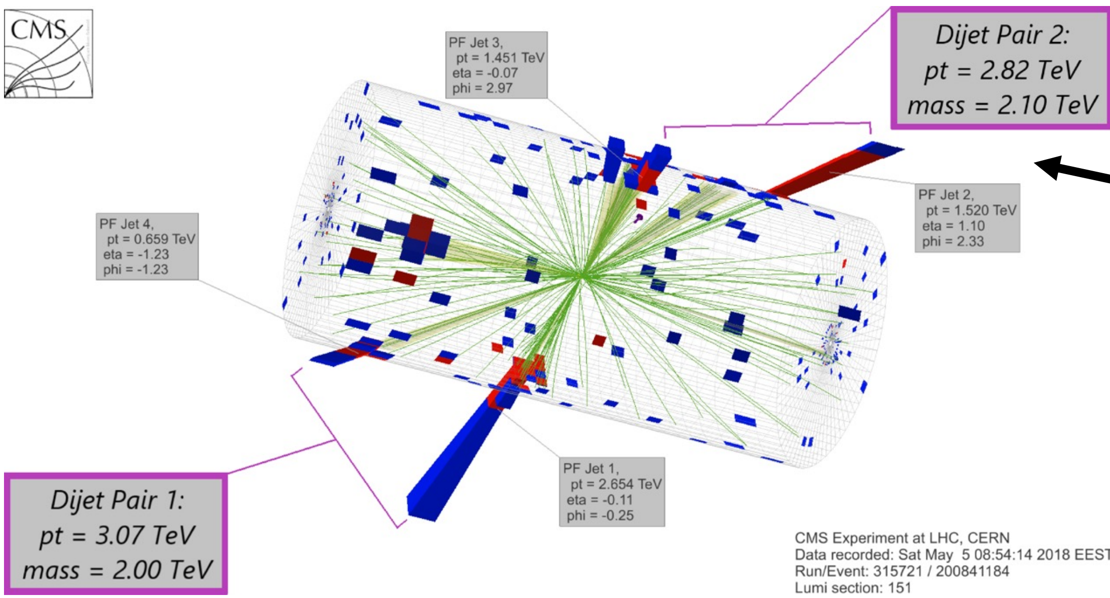



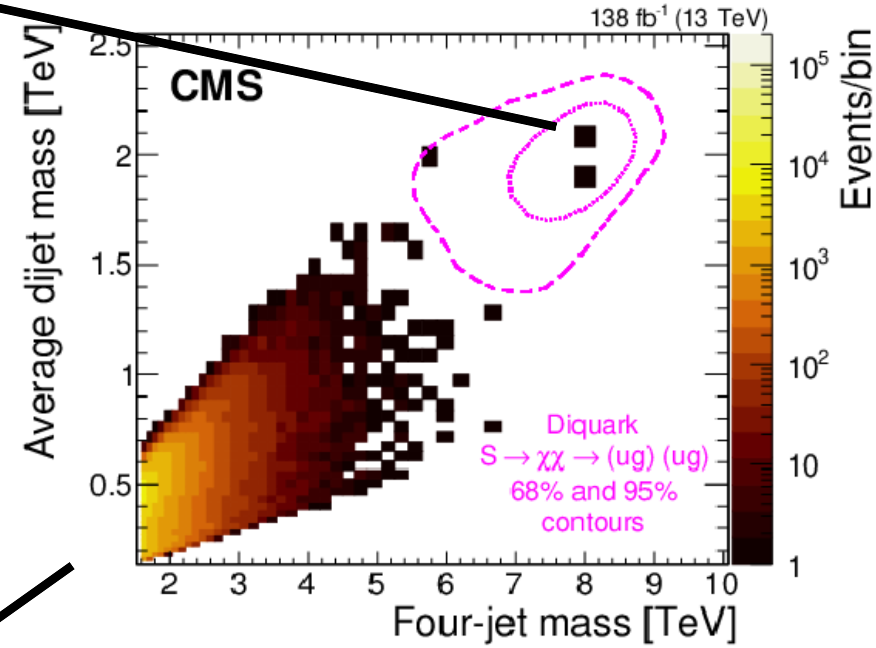

- Optimal dijet pairing with small $M_{asym}$, $\Delta R^{pair}_{jj}$, $\Delta\eta$
- Background-fit in various $\alpha$ bins (=$\langle m_{X=jj}\rangle / m_{Y=4j}$)

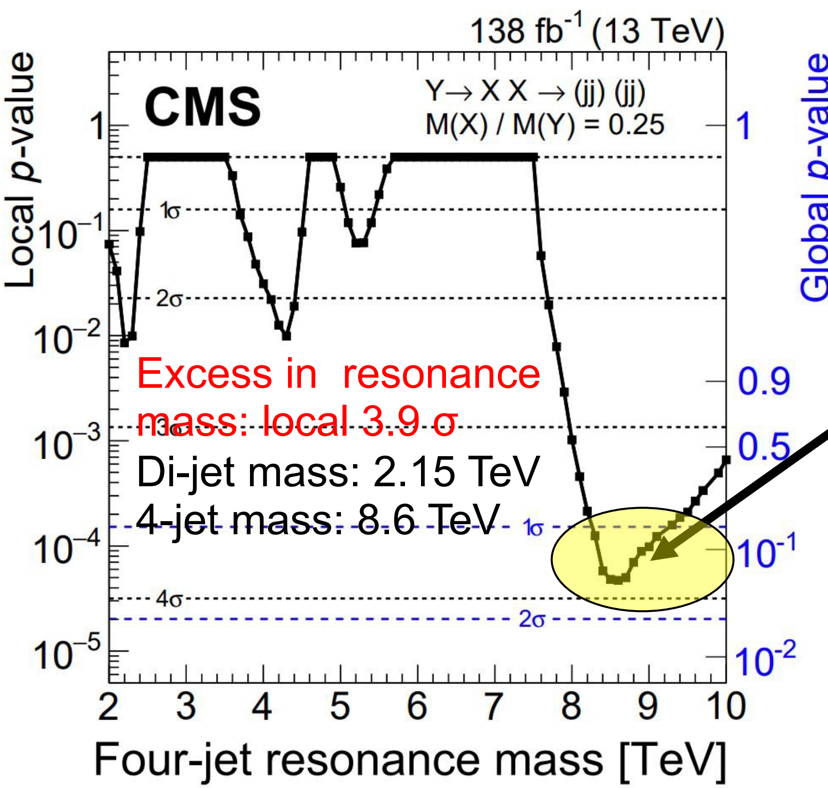
# Extended gauge sector: di-jet pairs

June 2022

EXO-21-010



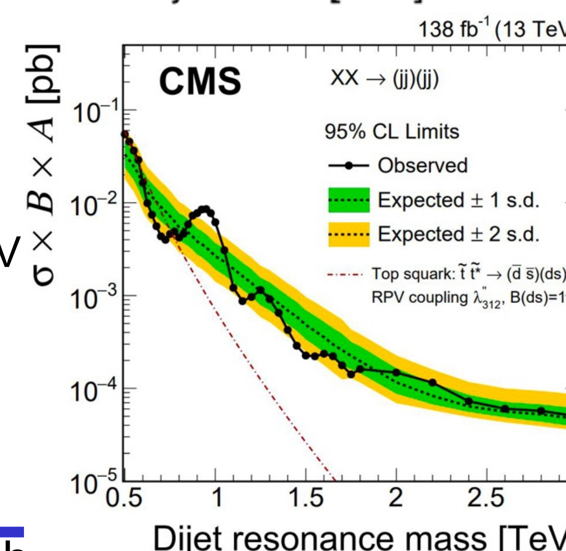




Excess in resonance mass: local 3.9 σ

Di-jet mass: 2.15 TeV

4-jet mass: 8.6 TeV

Limits for the interpretation in RPV SUSY for non resonant search

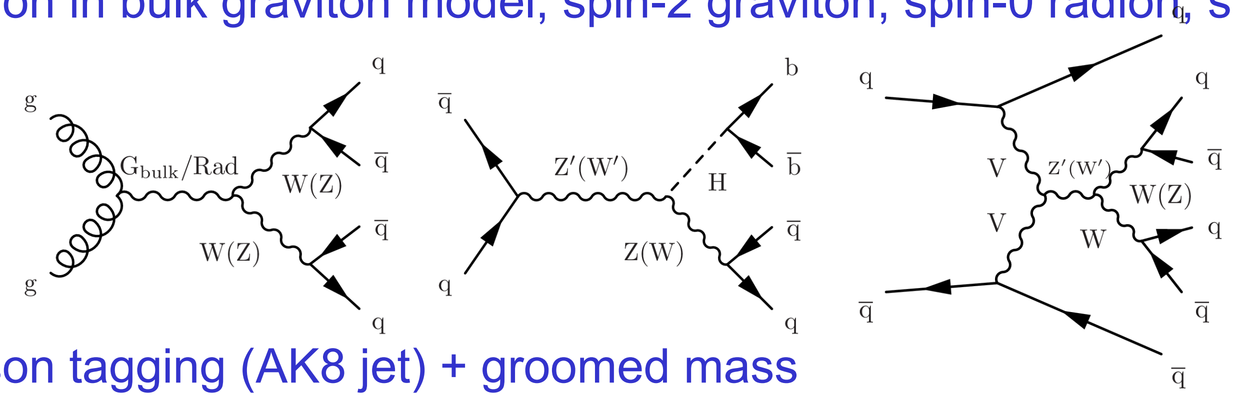


# Extended gauge sector: di-boson pairs

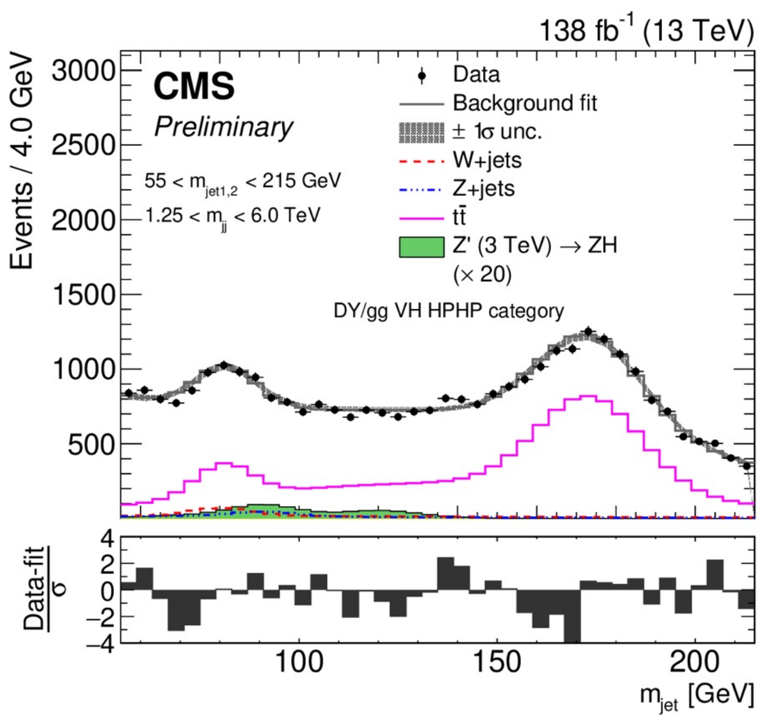
Sept. 2022

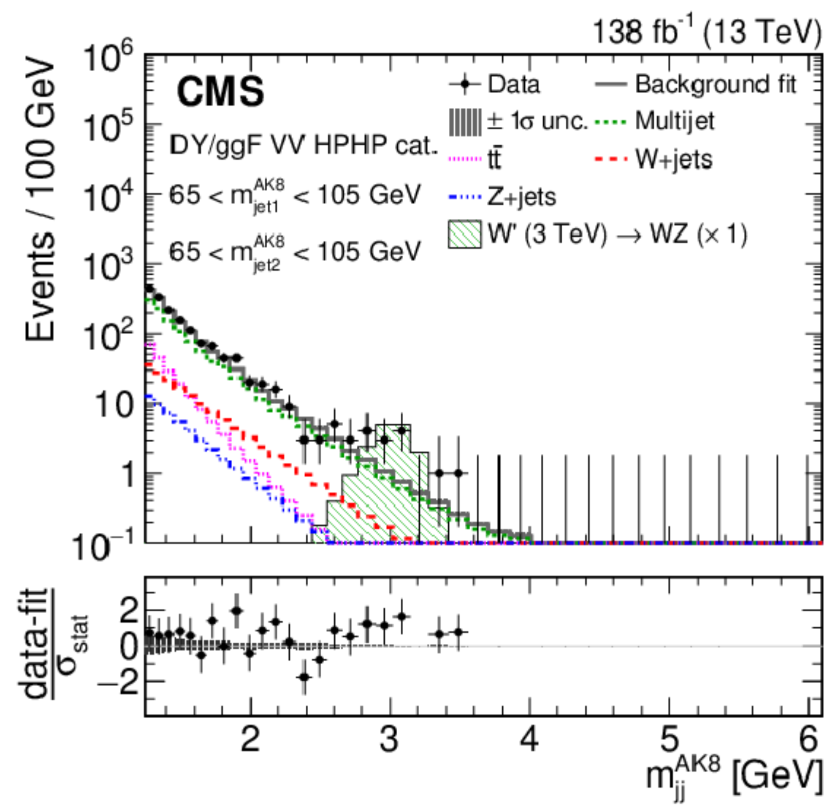
B2G-20-009

- Search for heavy resonances decaying into VV or VH (V=W or Z)
- Interpretation in bulk graviton model, spin-2 graviton, spin-0 radion, spin 1 W' or Z'




- Use of boson tagging (AK8 jet) + groomed mass



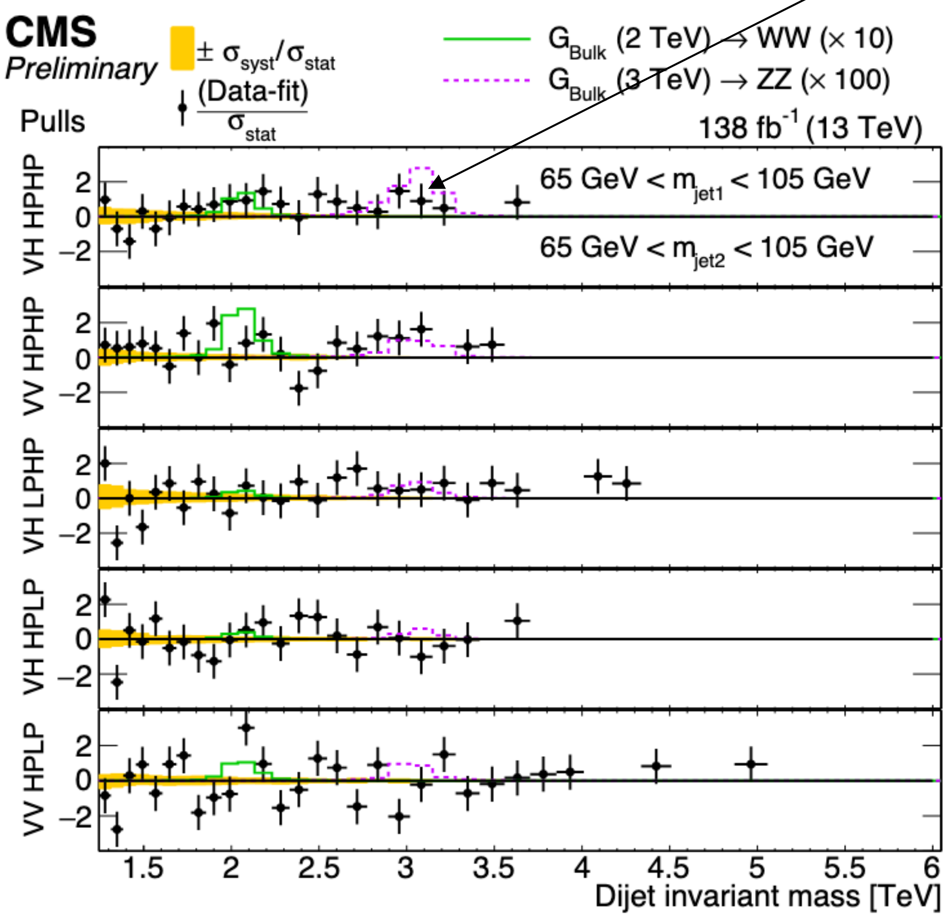

Enough signal-like V and top merged jets to constrain tagger and jet mass scale systematics

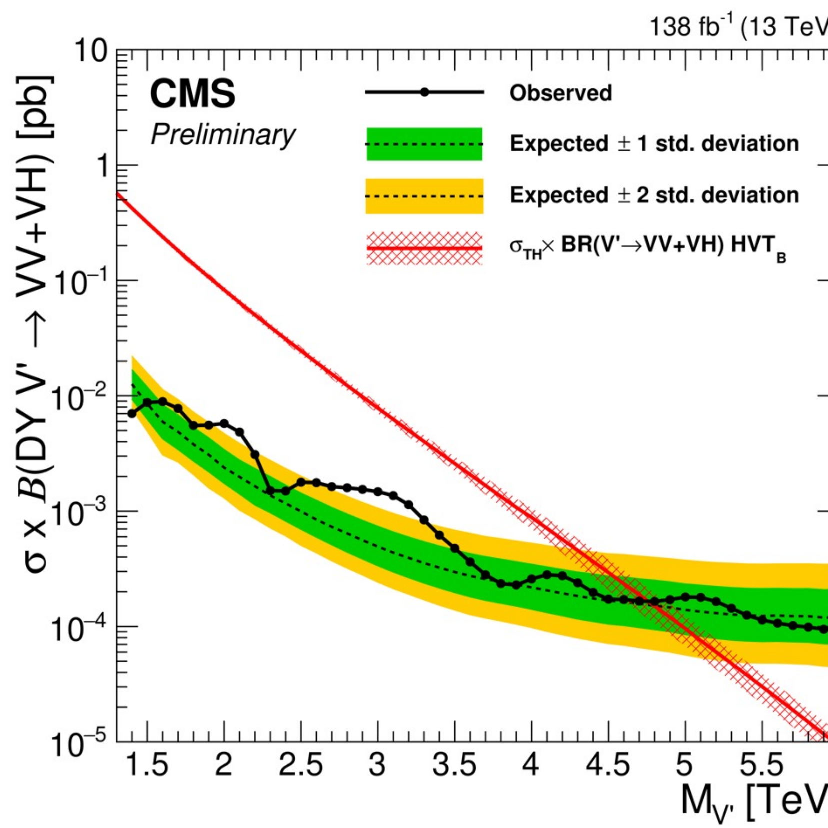
# Extended gauge sector: di-boson pairs

Sept. 2022

B2G-20-009

- Search for heavy resonances decaying into VV or VH (V=W or Z)
- Interpretation in bulk graviton model, spin-2 graviton, spin-0 radion, spin 1 W' or Z'
- Local (global) **excess** of 3.6 σ (2.3 σ) for mass 2.1 & 2.9 TeV
    - Limit at 4.8 TeV on V' through DY



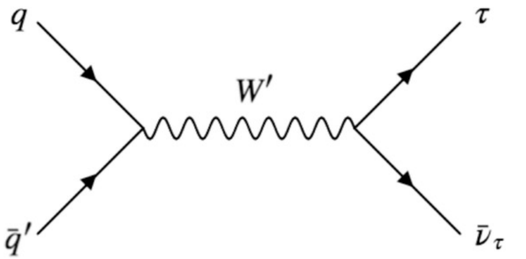

Limits on $G_{bulk}$ mass ~ 1.4 TeV
Limits on Radion mass ~ 2.7 TeV

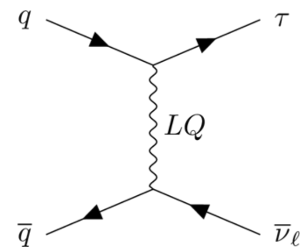
# Extended gauge sector: $\tau_{had}$ + MET

July 2022

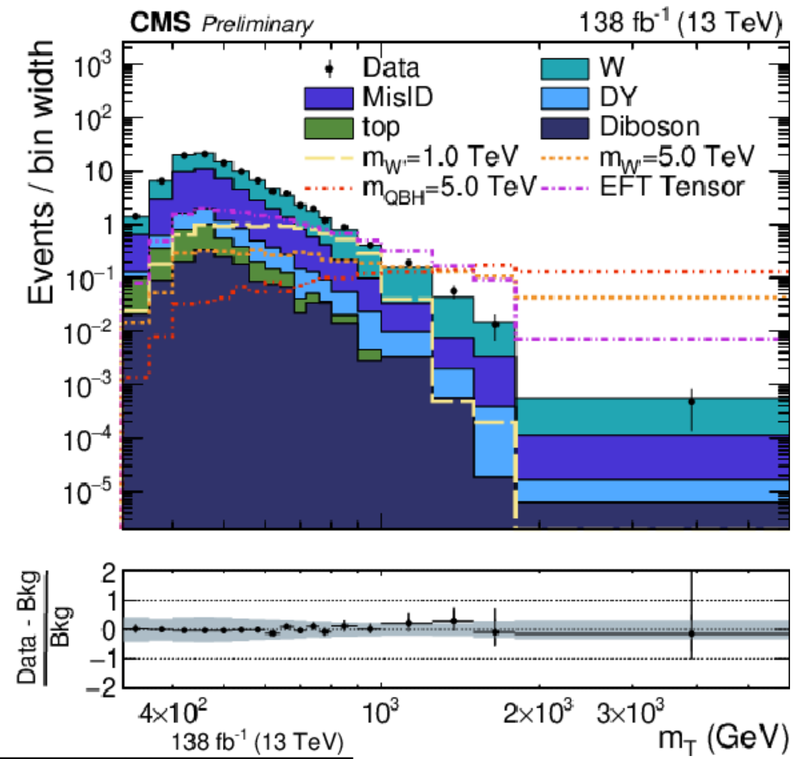
EXO-21-009

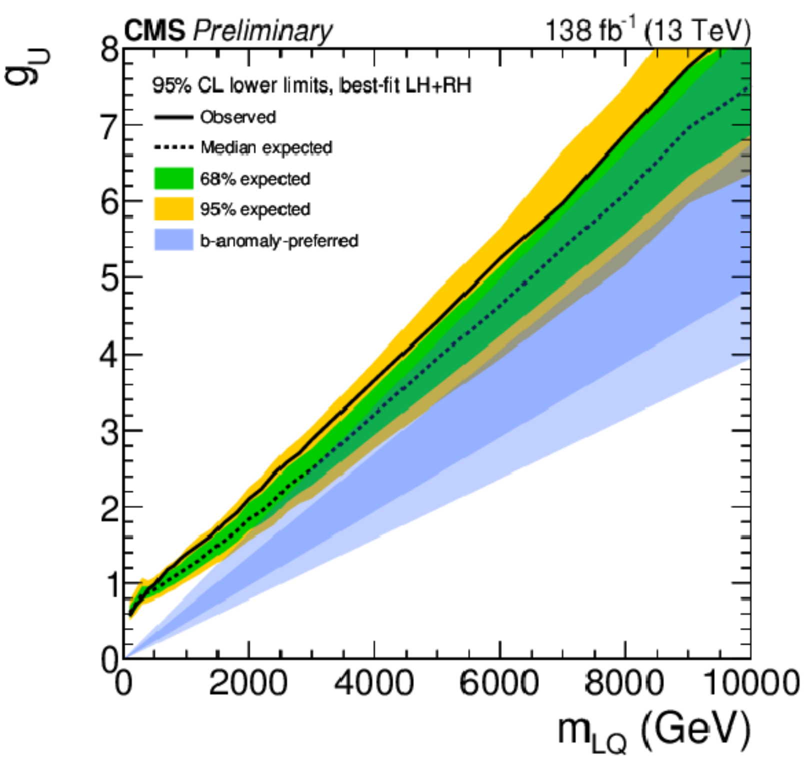
- Search for W' decaying into $\tau\nu$ & LQ in t-channel

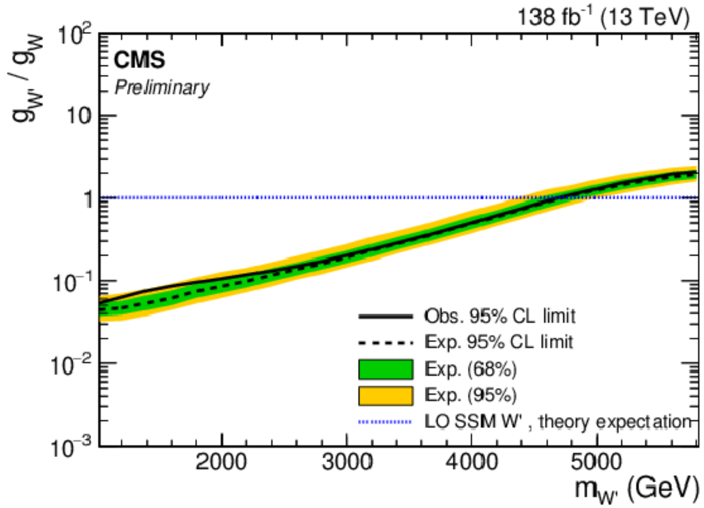


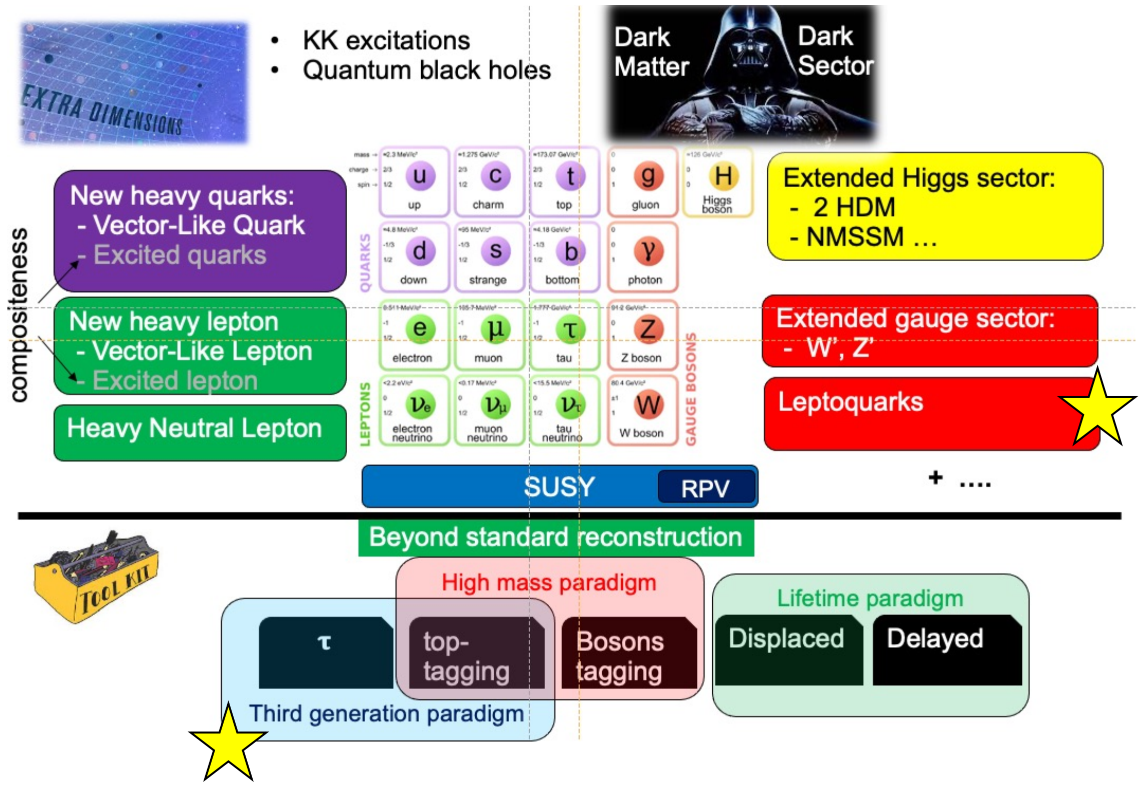

- Final state $\tau_{had}$ + MET



# Extended gauge sector



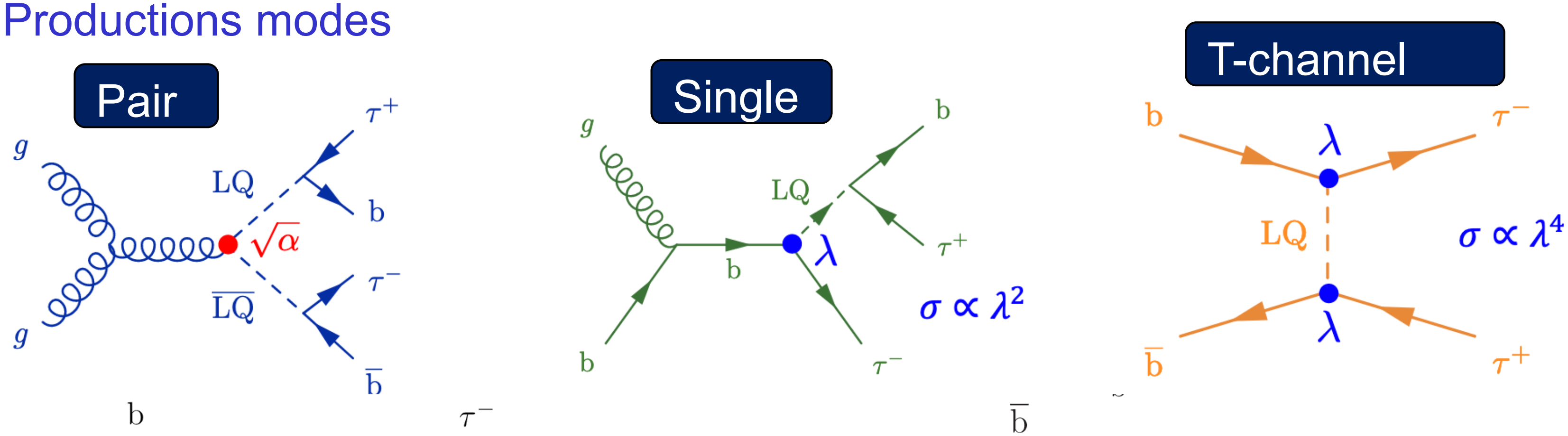
# Leptoquarks

July 2022

EXO-19-016

- LQ couple to both leptons & quarks: can be scalar or vector bosons
- Can be source of Lepton Flavor Universality Violation

  → interest is related to anomalies observed in **B**-physics
- Search focused on 3rd generation LQ coupling to b and **τ**
- Productions modes




- Final states depends on production mode
- Results depends on LQ **spin** (scalar or vector), λ (LQ,b,**τ**), β(BR in lq) , κ (non-minimal coupling for vector LQ)

# Leptoquarks

July 2022

EXO-19-016

- Event selection rely on ≥ 1 $\tau$ (e$\nu$ μ$\nu$ or hadr) and ≥ 1 b-jet
- Categorization in $\tau$ decays – 0 jet / 0/1 b-jet - ≥1 jet / $m_{vis}$
- Use of discriminating variables:

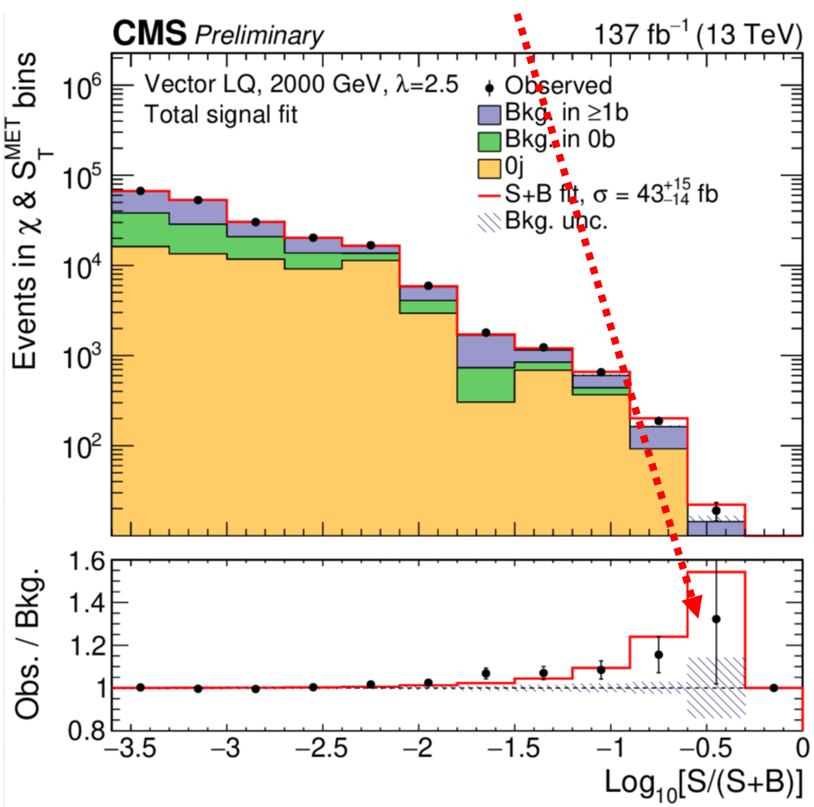
discriminating variable:

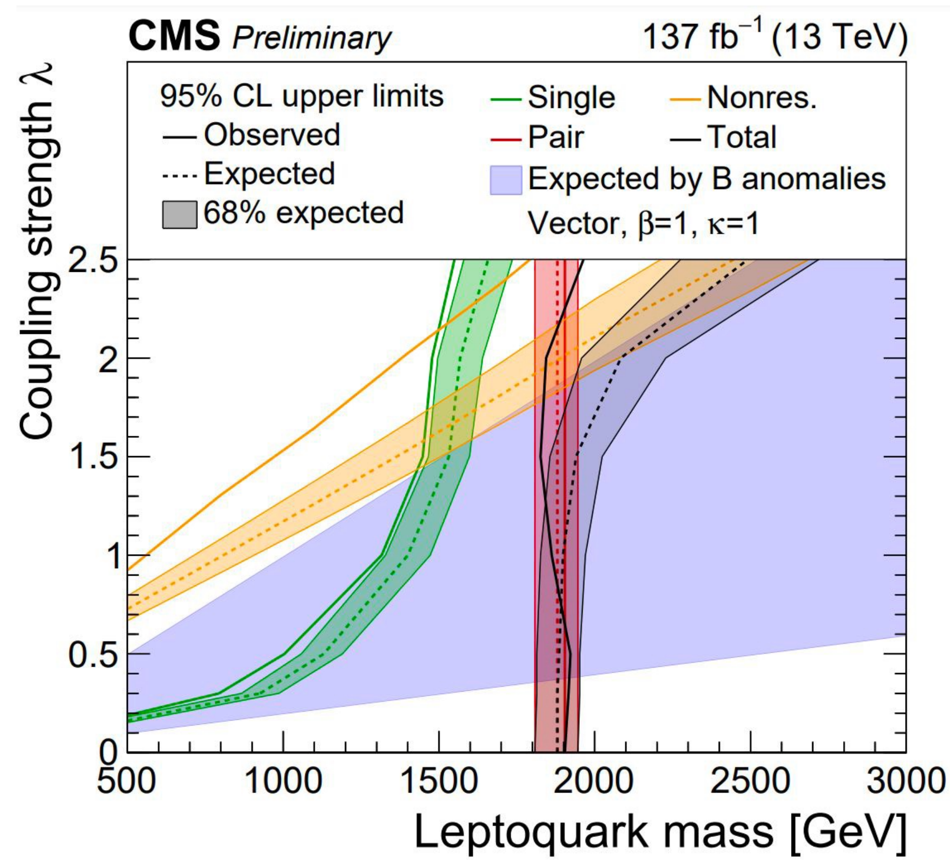
$$S_T^{MET} = p_T^{\tau_1} + p_T^{\tau_2} + p_T^{j} + MET$$

discriminating variable:

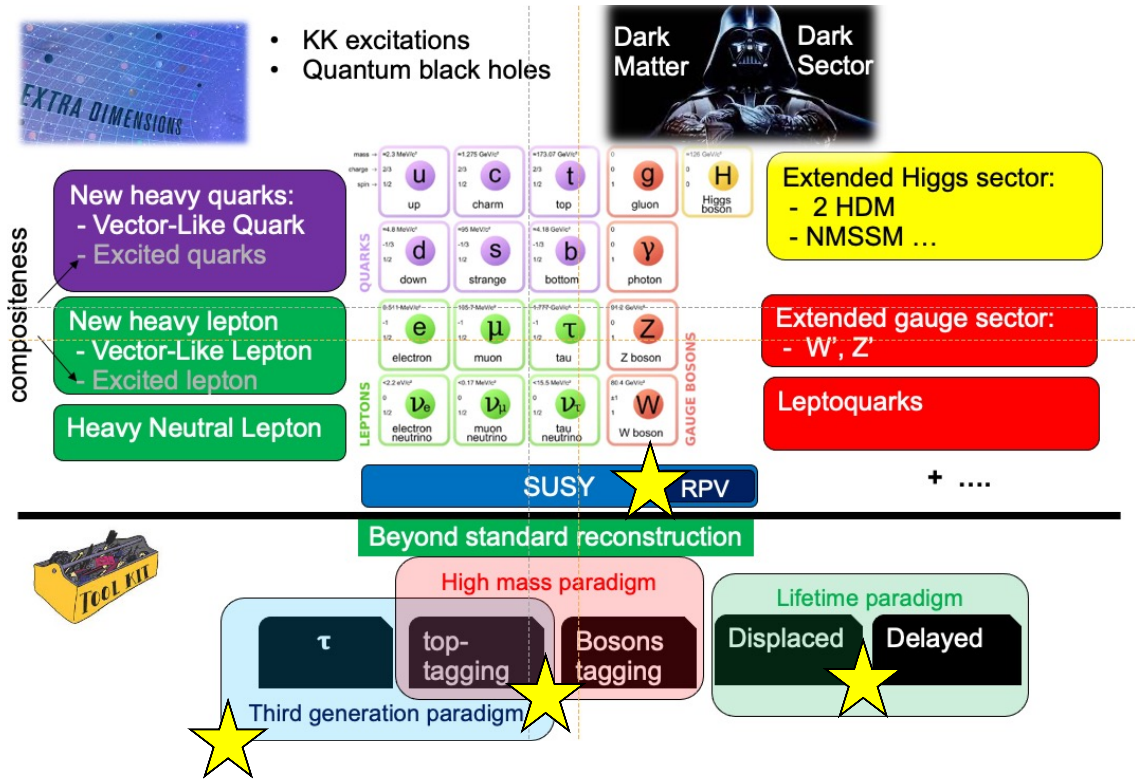
$$\chi = e^{\Delta\eta}$$

- Limits on scalar with scalar & vectors LQs with various coupling λ and M
- **Excess** of **3.4 σ** for 2 TeV LQ with λ = 2.5



# Extended gauge sector



# SUSY: gluino search

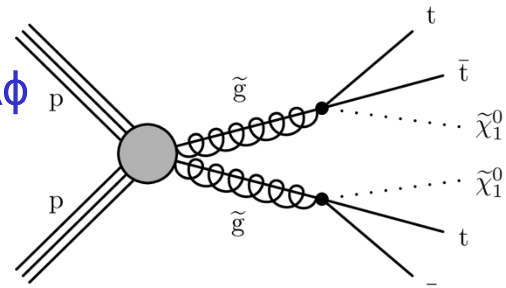
March 2022

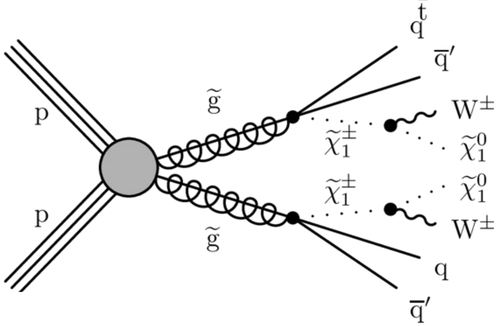
SUS-21-007

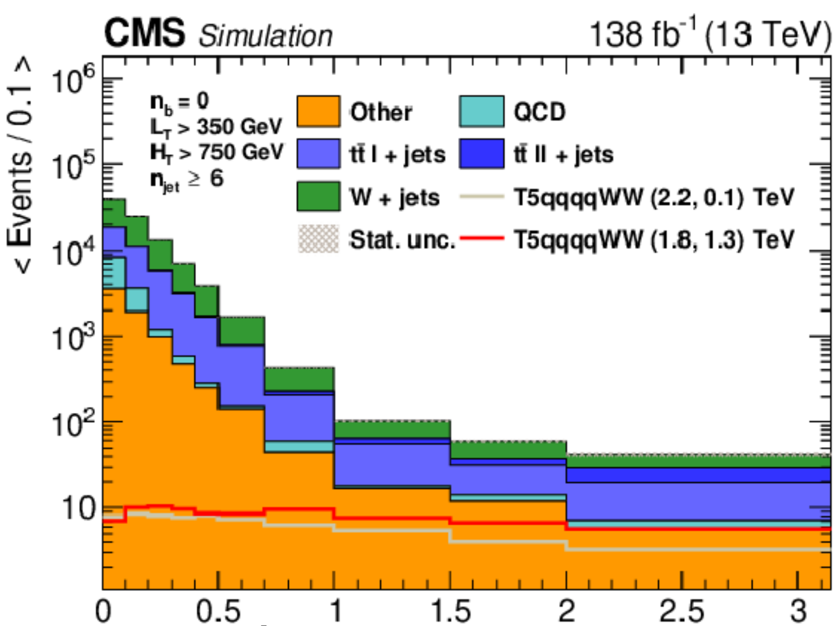
- Gluino search w or w/o intermediate chargino
- Signature: 1 e or μ (+veto) + ≥ 3 jets - heavy object tagging + Δϕ
- Δϕ(l,$W_{reco}$) cut suppress dominant W/tt+j

→ collimated for SM – 2 sources of MET in signal

- AK8 PUPPI jets with multiclass CNN (V & top-tagging)
  - top(W)-tagging: ε = 68% (62%) – fake rate = 8% (7%)

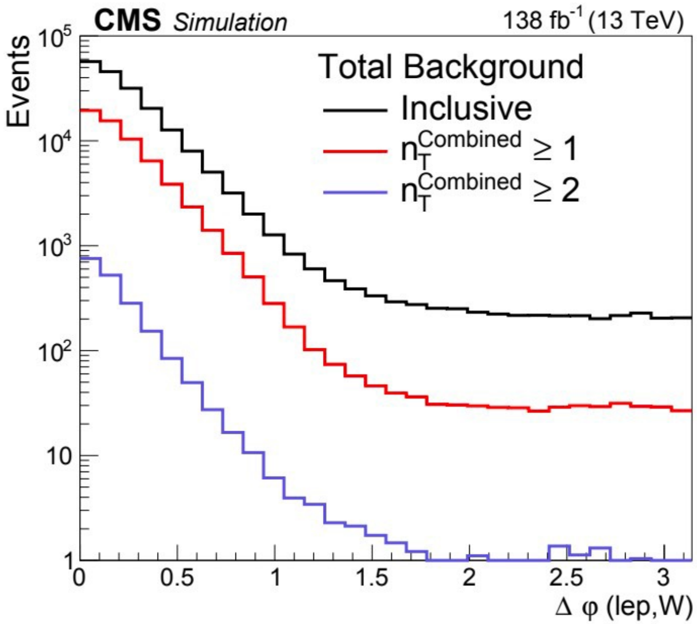







Control Region Δφ<0.75 | Search Region Δφ>0.75

In multi-b



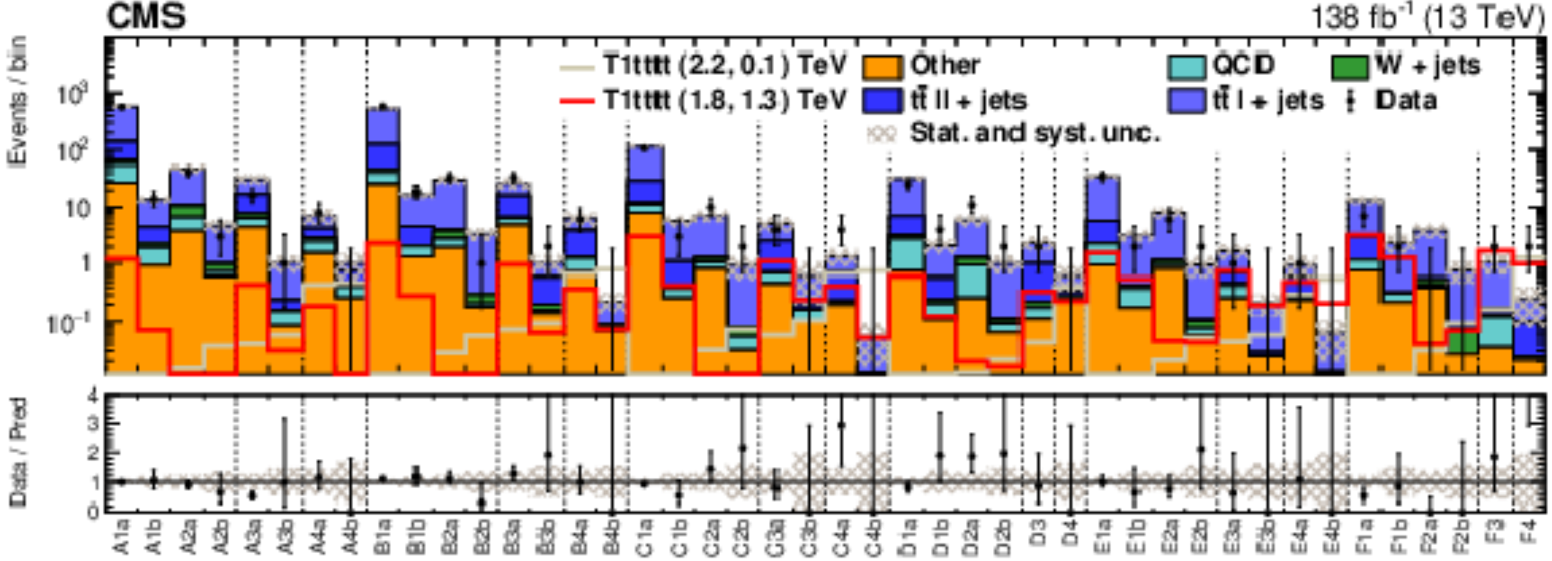
# SUSY: gluino search

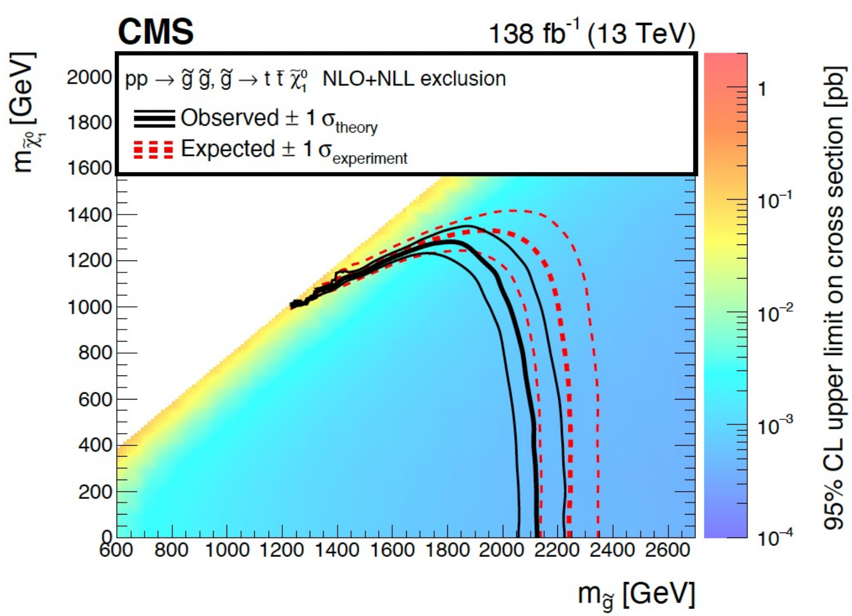
SR (w chargino): 0 b-jet: n-jets, $L_T$, $H_T$

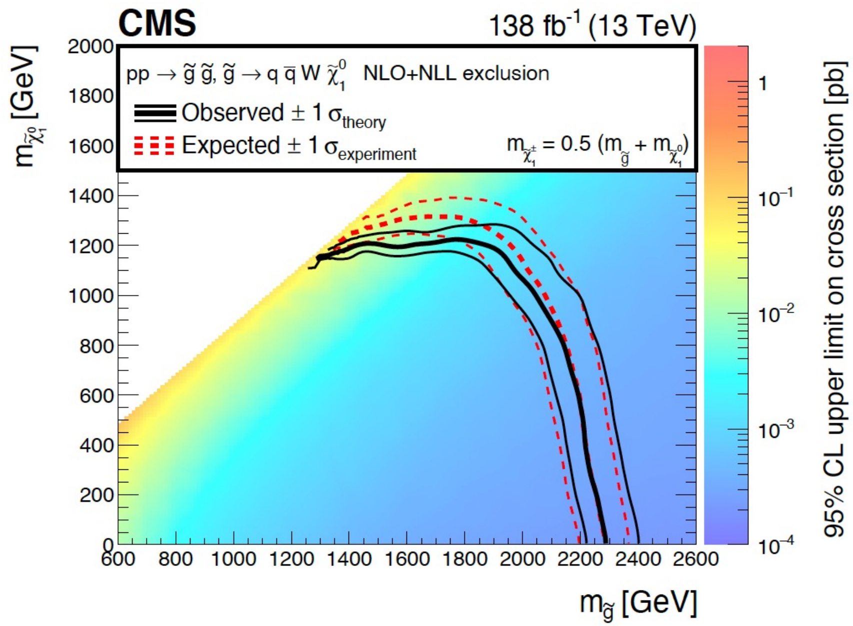
SR (wo) multi-b-jets: idem + n-bjets, n-top, (n-W)

March 2022

SUS-21-007



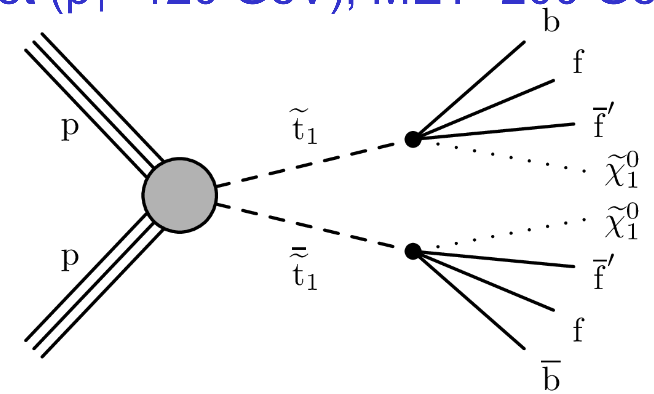



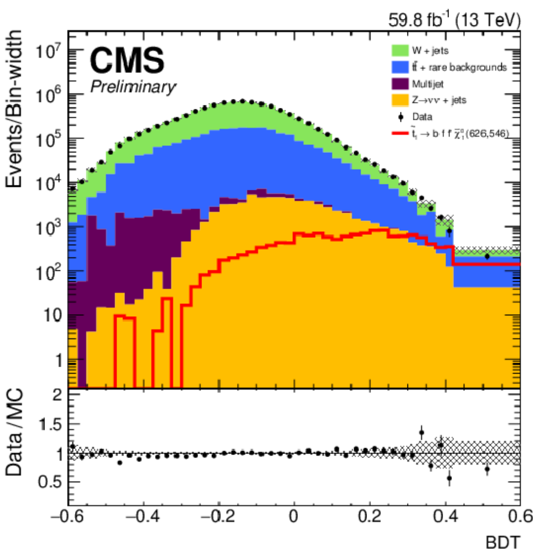
# SUSY: stop in 4-body – compressed spectra

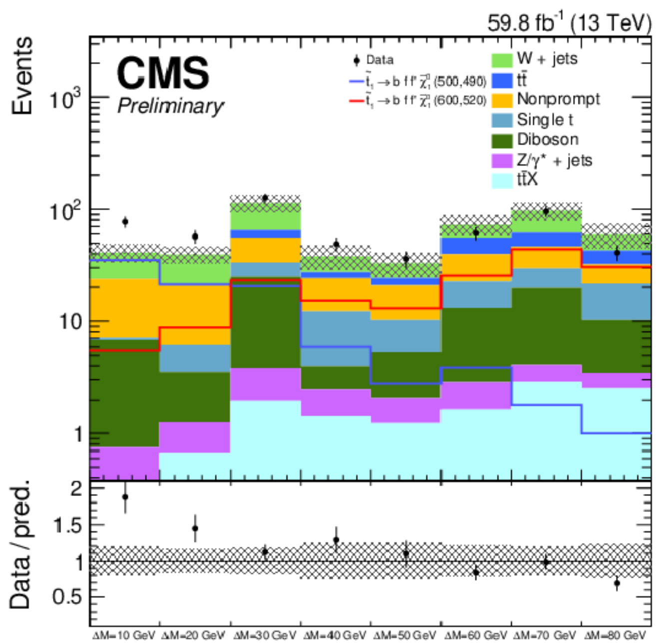
June 2022

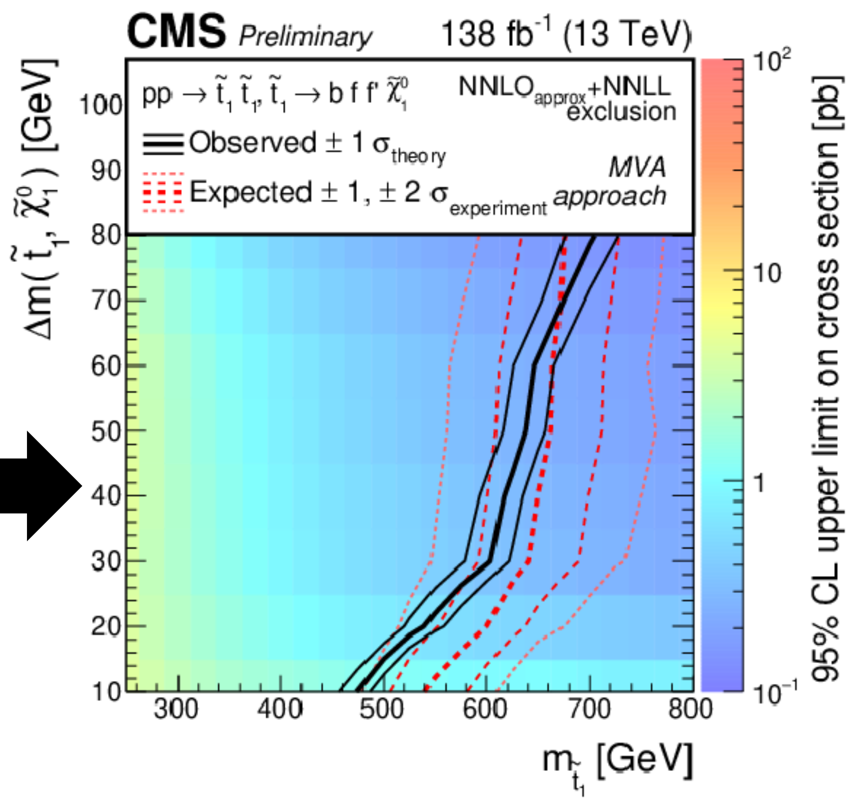
SUS-21-003

- Target 4-body decay for $\Delta m(\text{stop}, \chi^0) < m_W$
- **Selection**: one soft e ($5<p_T<30$) or μ ($3.5<p_T<30$), ISR jet ($p_T>120$ GeV), MET>200 GeV
- Signal regions based on 8 BDT adapted to Δm
  - 21 input variables: $p_T(l)$, $p_T(j)$, $H_T$, MET, …
  - Eff ~ 5% - bkg rejection: $5.10^3$



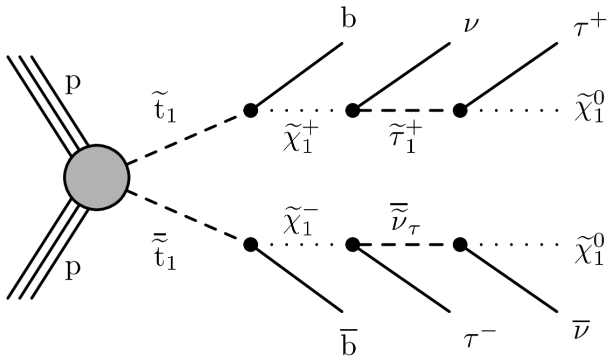
# SUSY: stop with τ

SUS-21-004

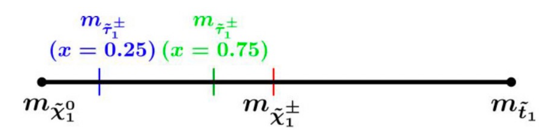
- Search for stop pair production with one hadronically decaying tau
- Highly sensitive to high tan β or higgsino-like scenarios

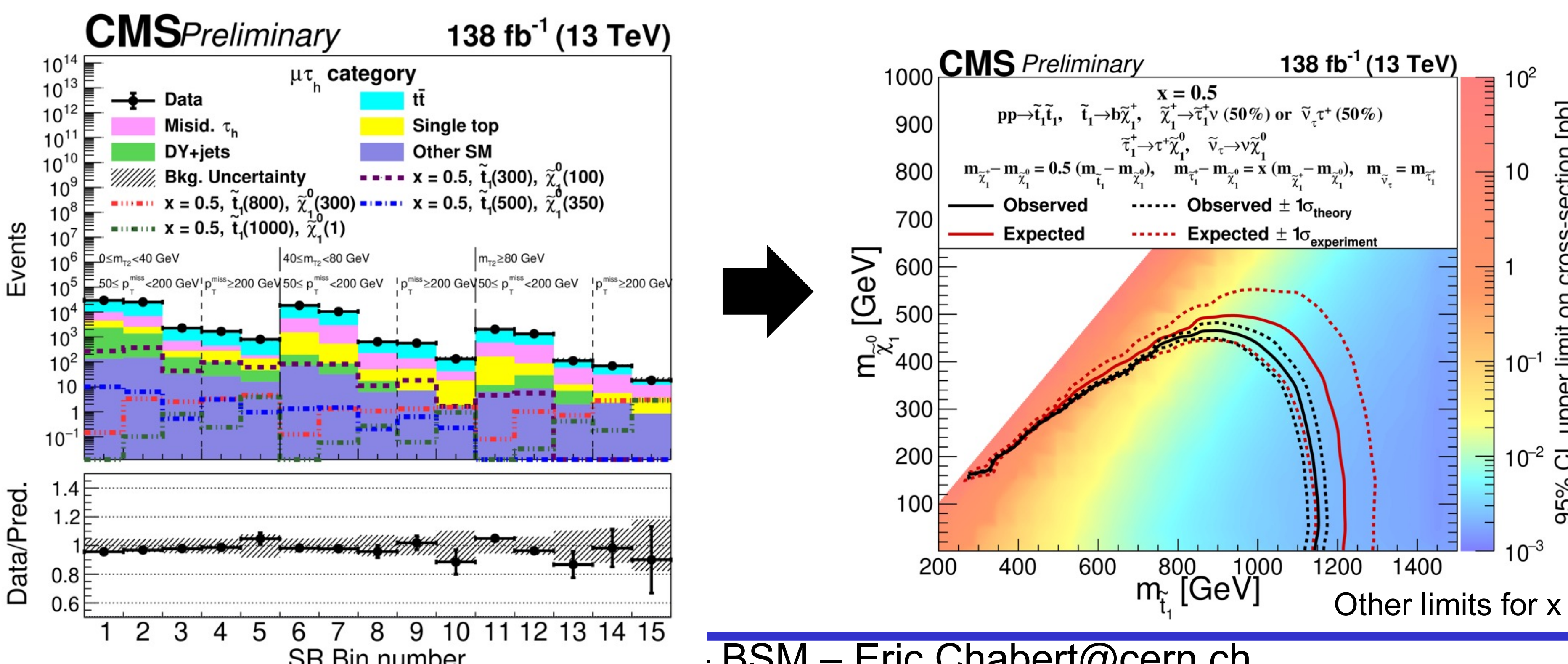
→ charginos are mainly couple to 3rd generation

- Study intermediate staus or sneutrino (+mixte)
- Hypotheses on masses and BR($\chi^{\pm}$) for interpretation
- Selection: $\tau_h$ (DeepTau), e, μ, b-jets (DeepJet), MET, $H_T$ or $S_T$
- Categorization for $\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, with 15 SR using $M_{T2}$ and MET



Ex: diagram with intermediate stau & sneutrimo






Other limits for x = 0.25, 0.75

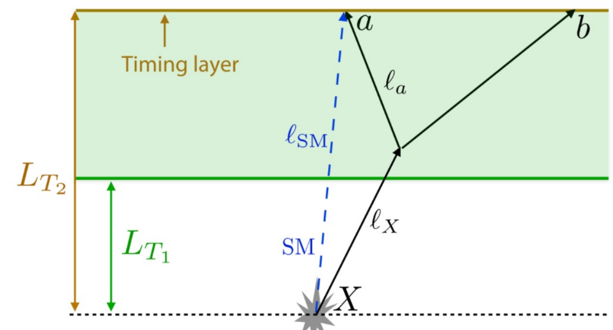
# SUSY: neutral LLP→ trackless/delayed jet

Oct. 2022

EXO-21-014

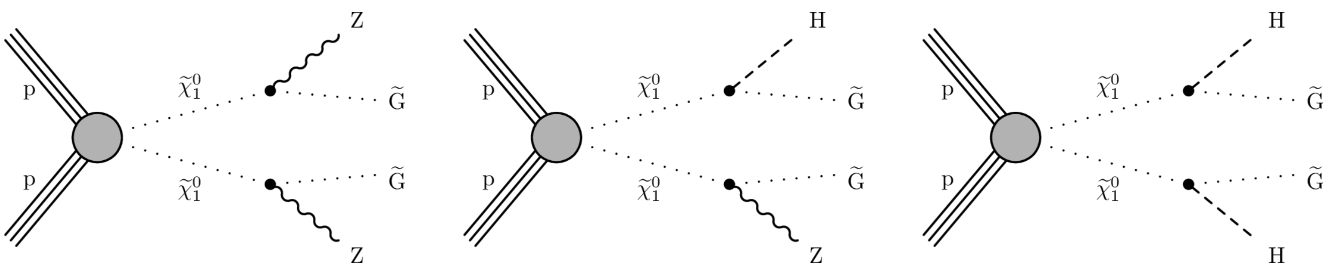
- Search for LLP decaying in outer regions of tracker or in calorimeters
- **Novel technique** using **trackless and delayed jet information** combined in a DNN

delay from slow-moving LLPs and path length increase due to displacement

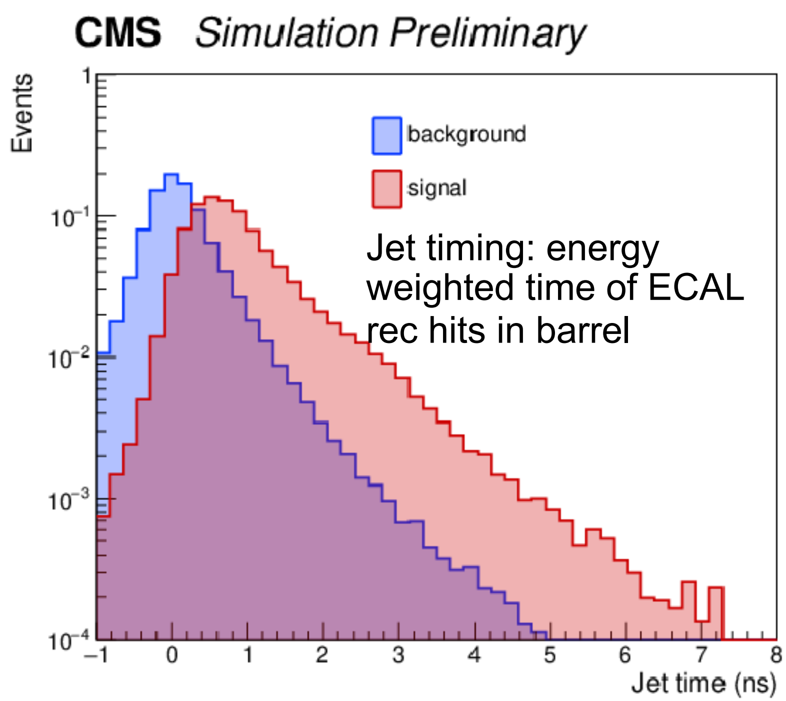



PhysRevLett.122.131801

- Interpretation in GMSB

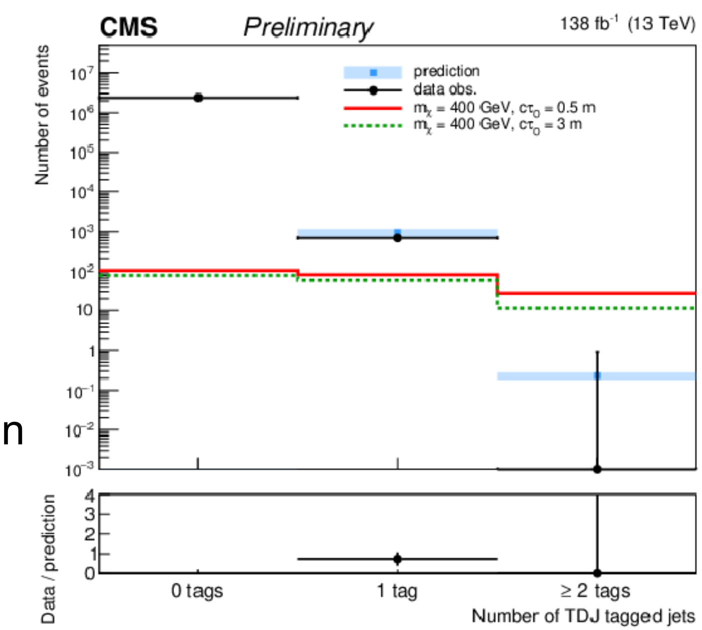



- DNN uses 21 variables such as energy fractions, number of constituents, jet time, …




DNN WP:
82% eff
4e-4 fake rat

~Stable perf on Signal (m,cτ)



# SUSY: neutral LLP→ trackless/delayed jet

Oct. 2022

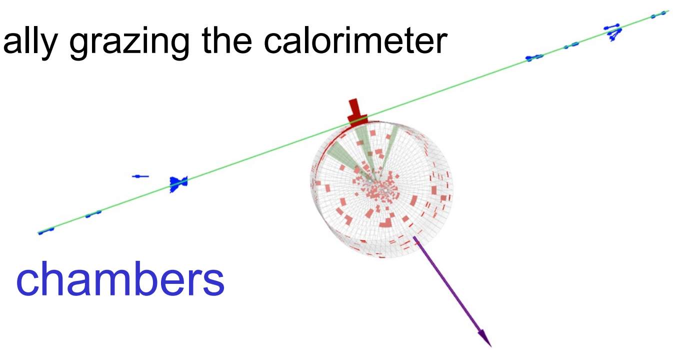
EXO-21-014

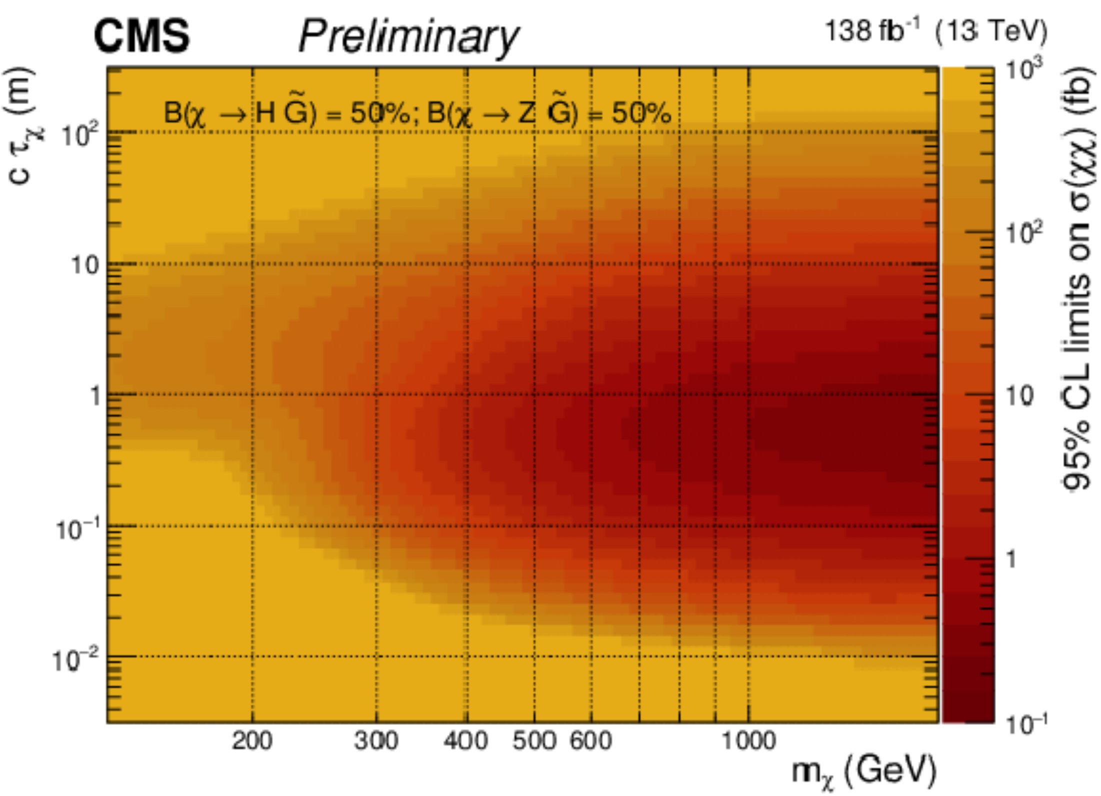
- Trigger/offline selection based on MET + jets (QCD remove through $\Delta\phi$ cut)
- Cosmic rays & beam halo are remaining backgrounds suppressed through dedicated cuts and estimated from data
- Interpretation in GMSB

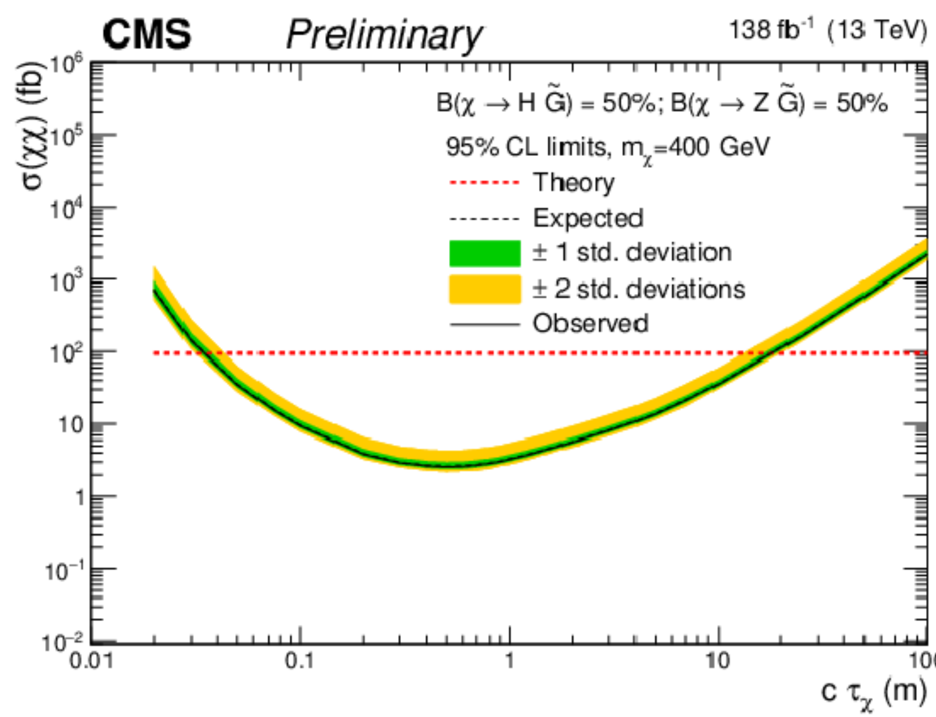
→ Sensitivity in “intermediate” $c\tau$

→ Complementary to displaced tracks & search in muon chambers

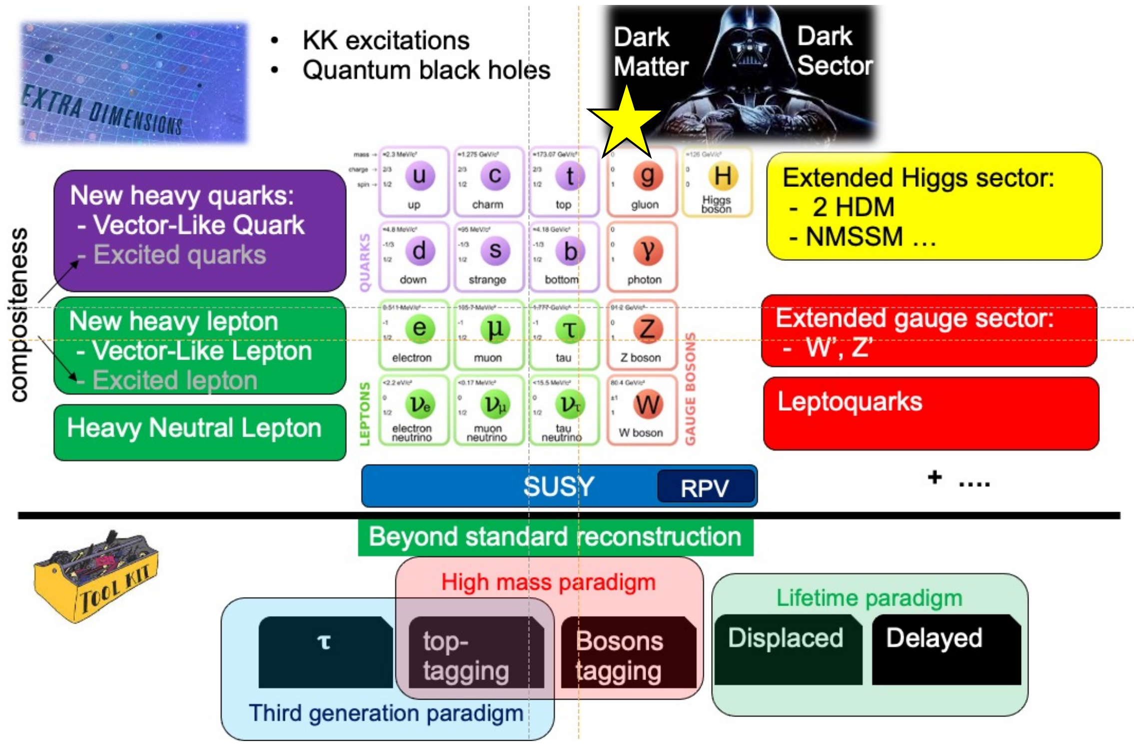
Cosmic muons tangentially grazing the calorimeter





# Extended gauge sector

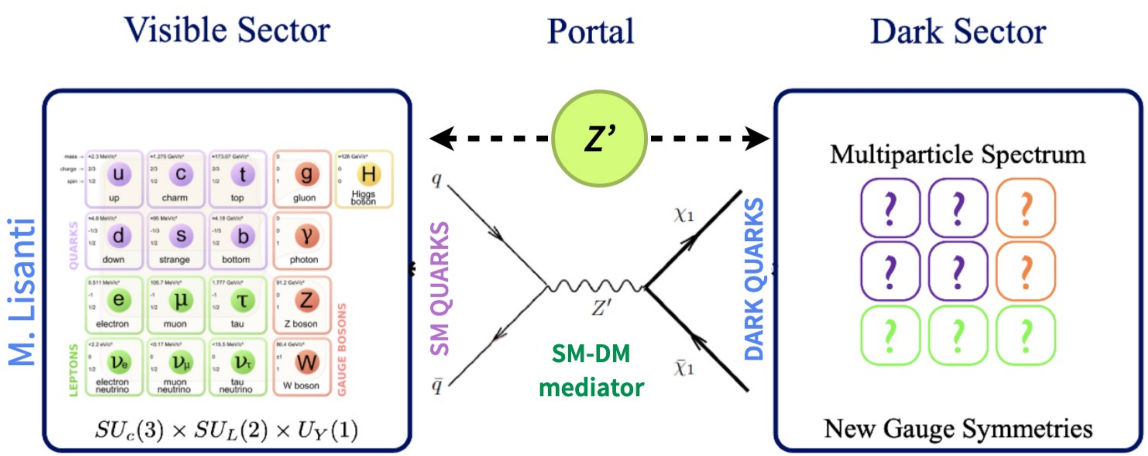


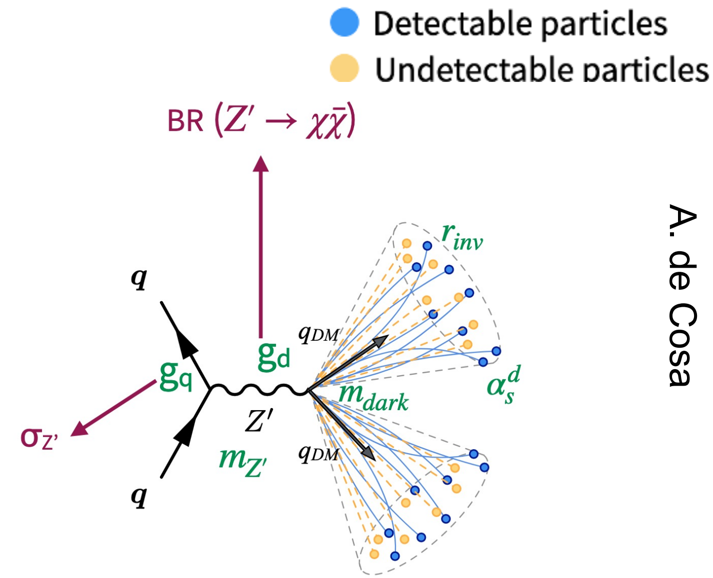
# Dark matter: ~~WIMP~~ SIMP

Aug. 2021

EXO-19-020

- First collider search of DM arising from a **strongly** coupled hidden sector
- Dark QCD: assume a SU(n) in the dark sector




- Coupling through a heavy leptophobic Z' which decay in 2 **"semivisible" jets** contain SM matter (from decay of unstable dark hadrons) and DM (stable dark hadrons)

Assumptions in benchmark model used: n=2, 2 flavors, mass degenerated, …

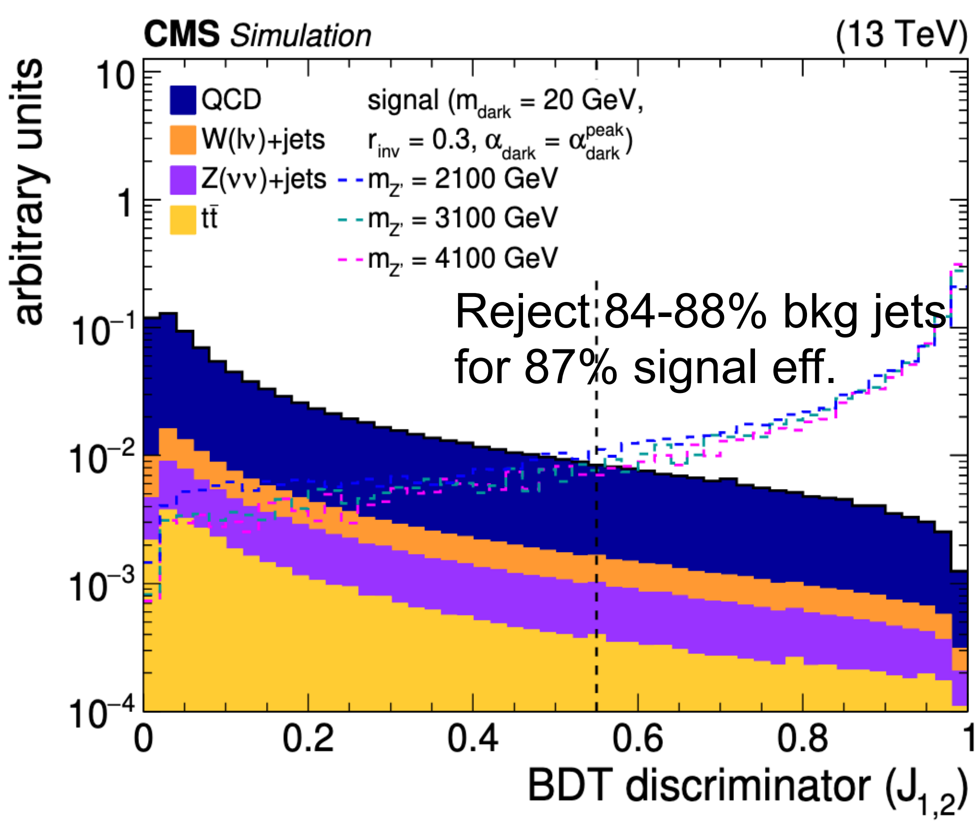
- 4 parameters: $m_{Z'}$, $m_{dark}$, $\alpha_{dark}$, $r_{inv}$
- $R_{inv}$ is fraction of invisible (stable) dark-hadron: [0-1]

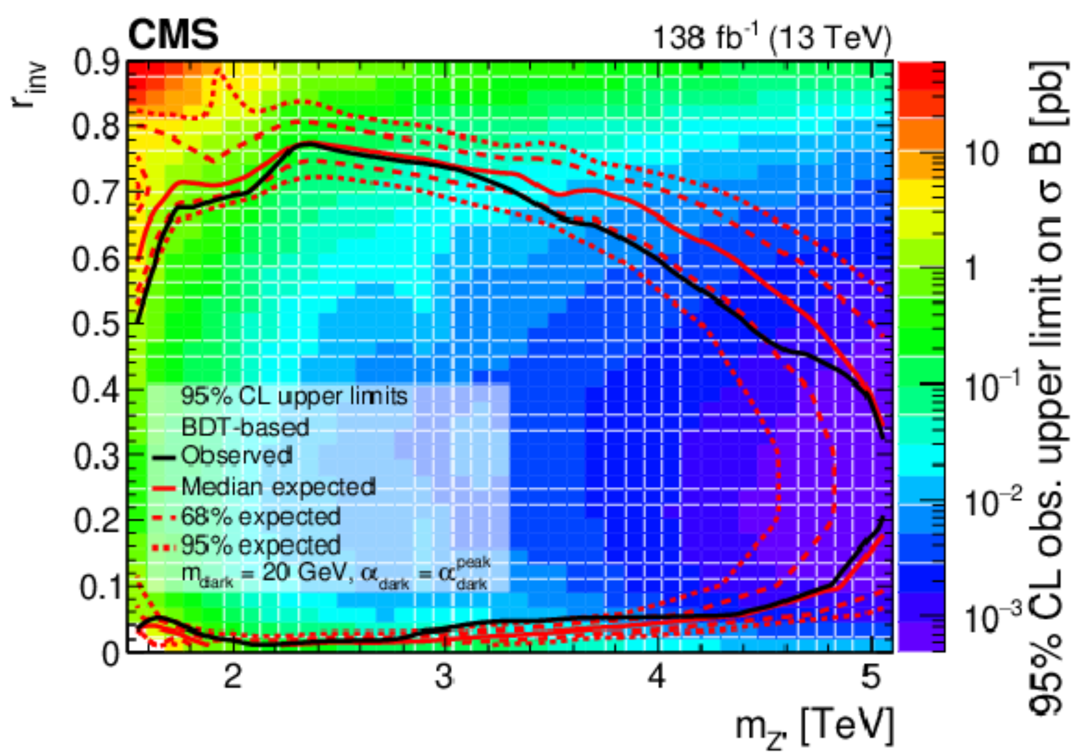
# Dark matter: ~~WIMP~~ SIMP

Aug. 2021

EXO-19-020

- Signature based on 2 high $p_T$ AK8 PUPPI - dijet transverse mass ($M_T$) - moderate MET aligned with the jets ($\Delta\phi$)
- Split data into 2 bins in $R_T$ = MET/$M_T$
- 2 versions of the analysis: cut-based & **BDT-based**
- SV-jet BDT with 15 variables using jet substructure variables such as $m_{SD}(J_{1,2})$ or $D_{pT}(J_{1,2})$ used to distinguish semivisible jet to SM jets as well as pf energy fractions




*More interpretations provided in the paper*

# Other …

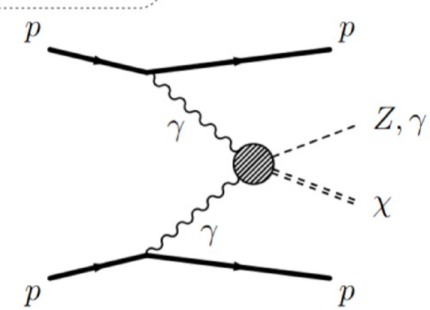
EXO-19-019

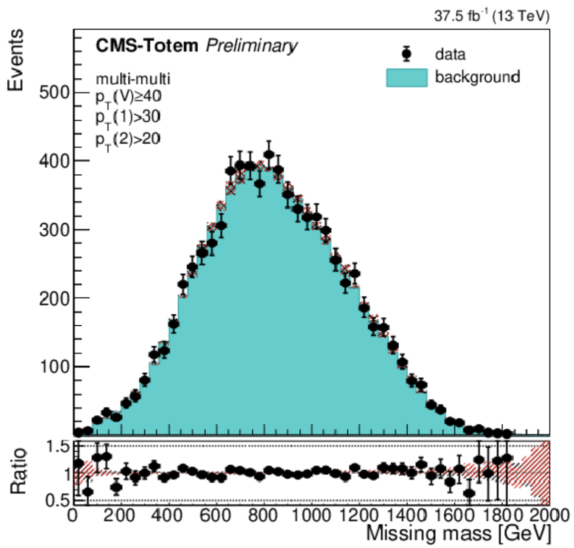
- Generic search of CMS and CMS-TOTEM precision proton spectrometer
- Search for an additional unspecified massive particle in proton tagged events
- Reconstruct the **missing mass spectrum**

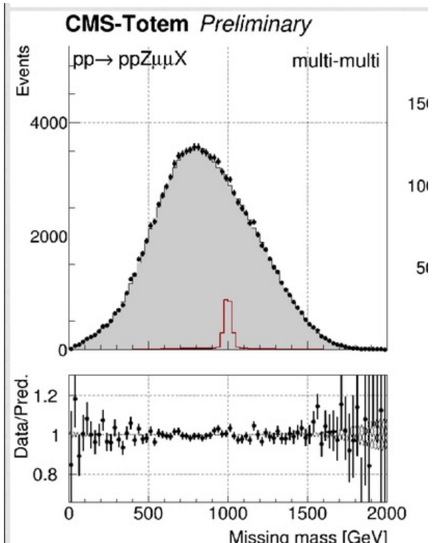
$$m^2_{\text{miss}} = \Big[\underbrace{(P^{\text{in}}_{p_1} + P^{\text{in}}_{p_2})}_{LHC} - (\underbrace{P_V}_{CMS} + \underbrace{P^{\text{out}}_{p_1} + P^{\text{out}}_{p_2}}_{PPS})\Big]^2$$

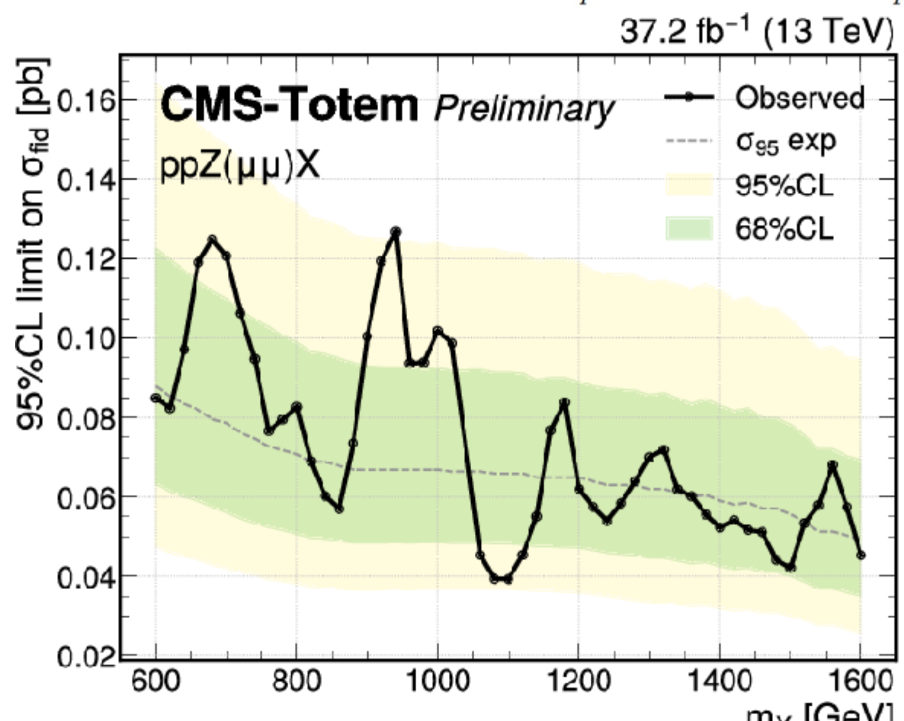
- Use 2017 data: 37 $pb^{-1}$
- Selection: Z→ee or μμ || γ in CMS – 1 p in each PPS arm
- Bump search in multiple possible final states
- Validation of shape in CR
- No excess – generic interpretations

V=Z,γ



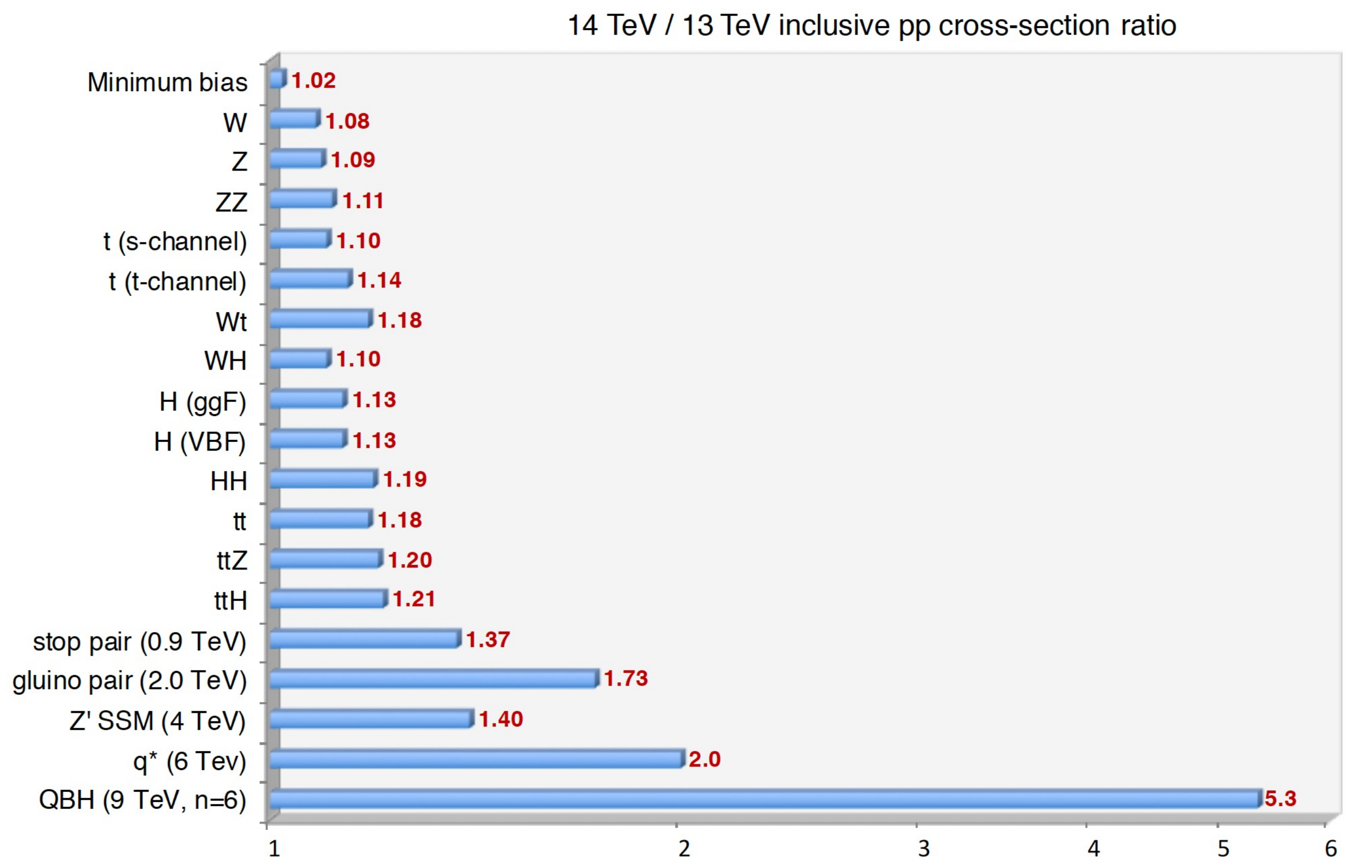



# Prospects for run 3

Energy | Luminosity | Detector | Reconstruction

**Energy:** 13 → 13.6 TeV
→ ~ in between run II and HL-LHC
→ ex: +20-40% for SUSY strong production of σ

**Luminosity:** ~ 260 $fb^{-1}$
(run 2 analyses ~ 140 $fb^{-1}$)

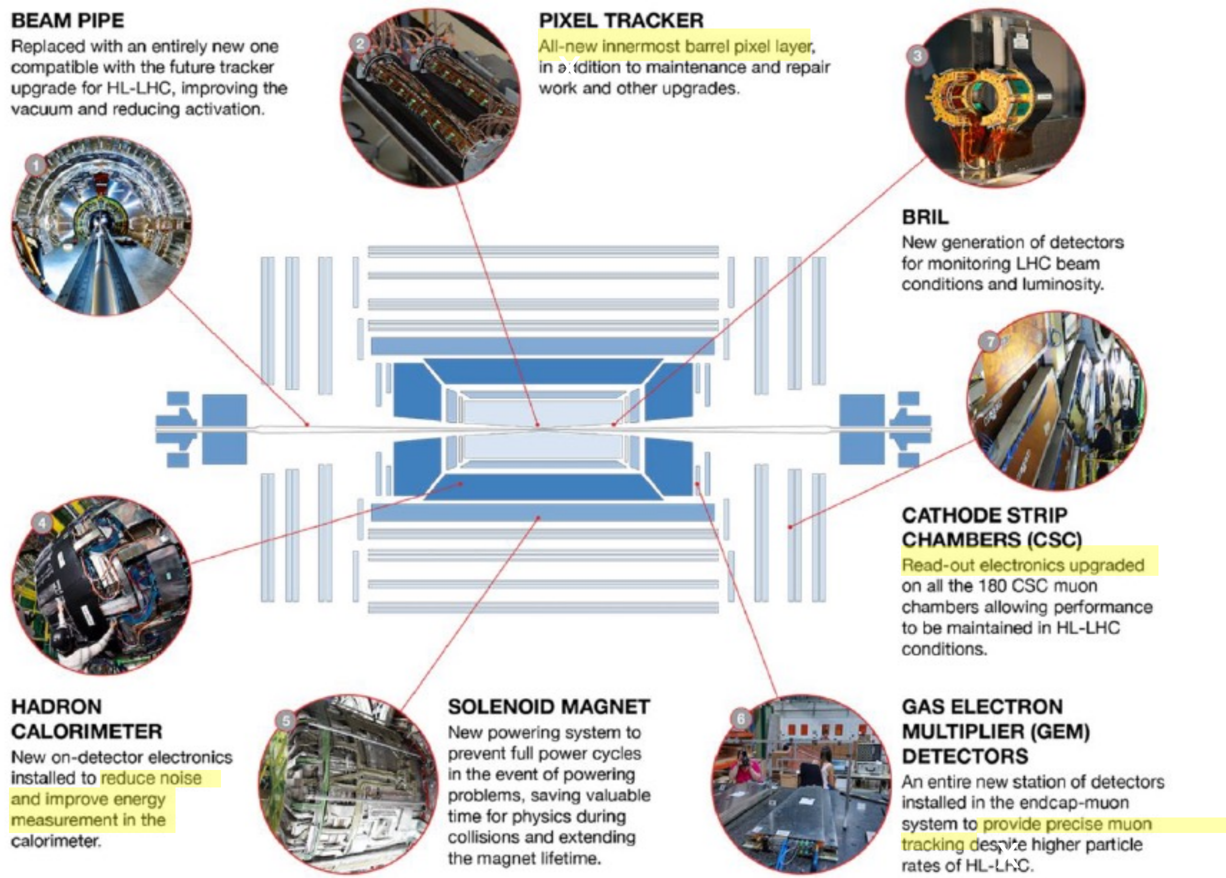


# Prospects for run 3

Energy | Luminosity | **Detector** | **Reconstruction**

**Detector upgrade:**
- Maintain performance
- Prepare HL-LHC conditions
- Detector improvements → object reconstruction

**Improvements** can be expected in trigger / reconstruction / machine-learning



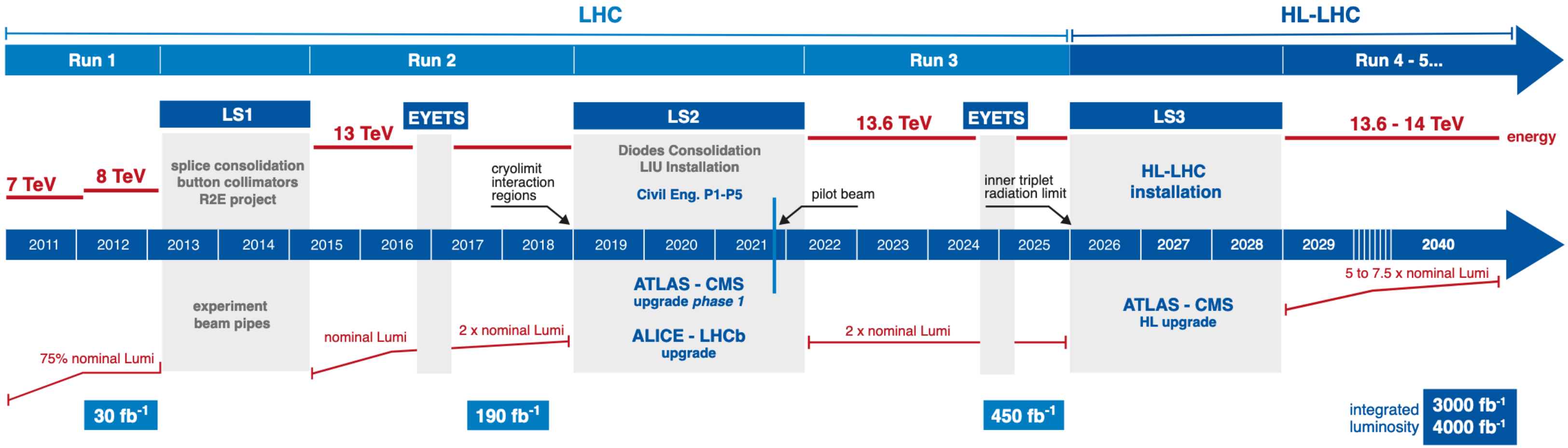
# Prospects for HL-LHC

Energy: 13.6-14 TeV

Luminosity: $3ab^{-1}$

Detector

Reconstruction

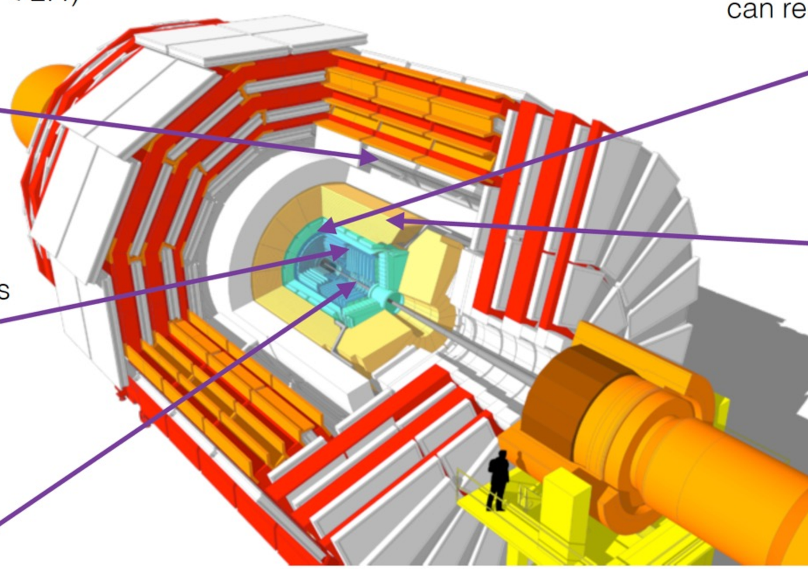


# Prospects for HL-LHC

Energy: 13.6-14 TeV | Luminosity: $3ab^{-1}$ | **Detector** | Reconstruction

**Improved muon coverage and trigger**
increased RPC coverage ($1.5 < |\eta| < 2.4$)
new electronics

**New endcap calorimeters**
high granularity
can reconstruct showers in 3D



**Updates to calorimeter and trigger**
higher granularity
electronics for trigger

**New precision timing detector**
Timing resolution of 30-40 ps for MIPs
full coverage of $|\eta| < 3.0$

**New inner tracker**
all silicon tracker
4 layers of pixels
5 layers of strips
coverage to $|\eta| < 4$

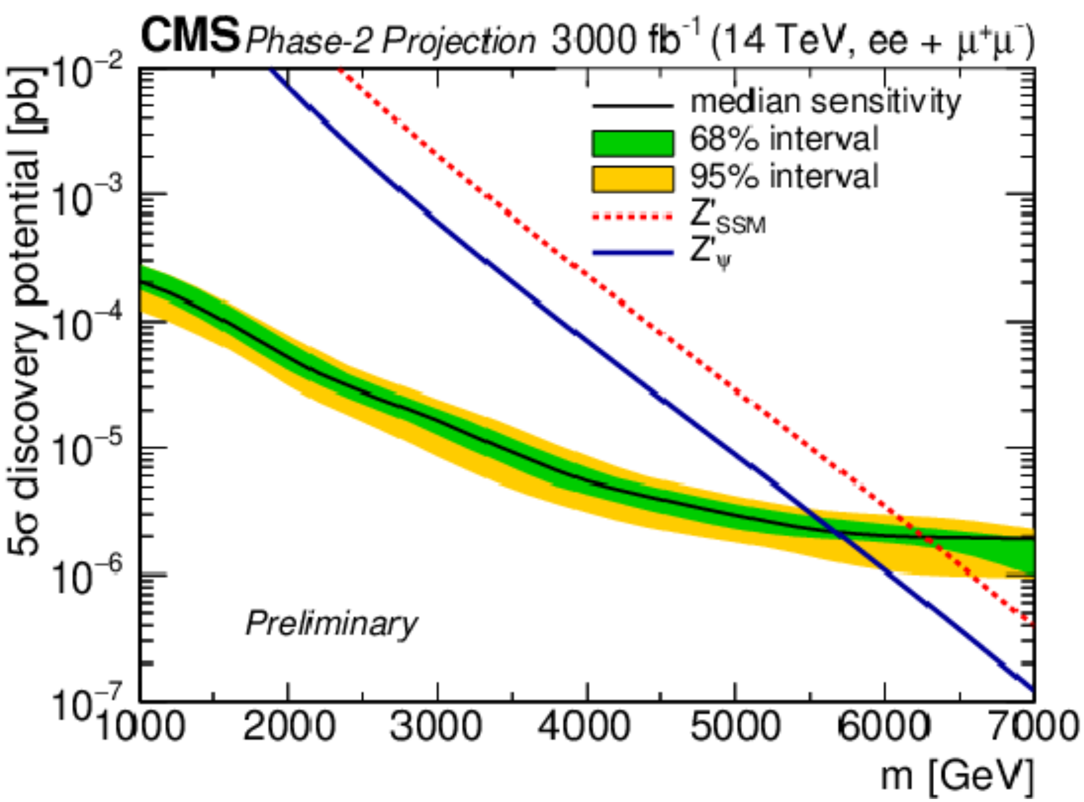
**Upgrade to trigger and DAQ**
L1 rate increased to 750 kHz
High Level trigger rate to 7.5 kHz
Track information at L1

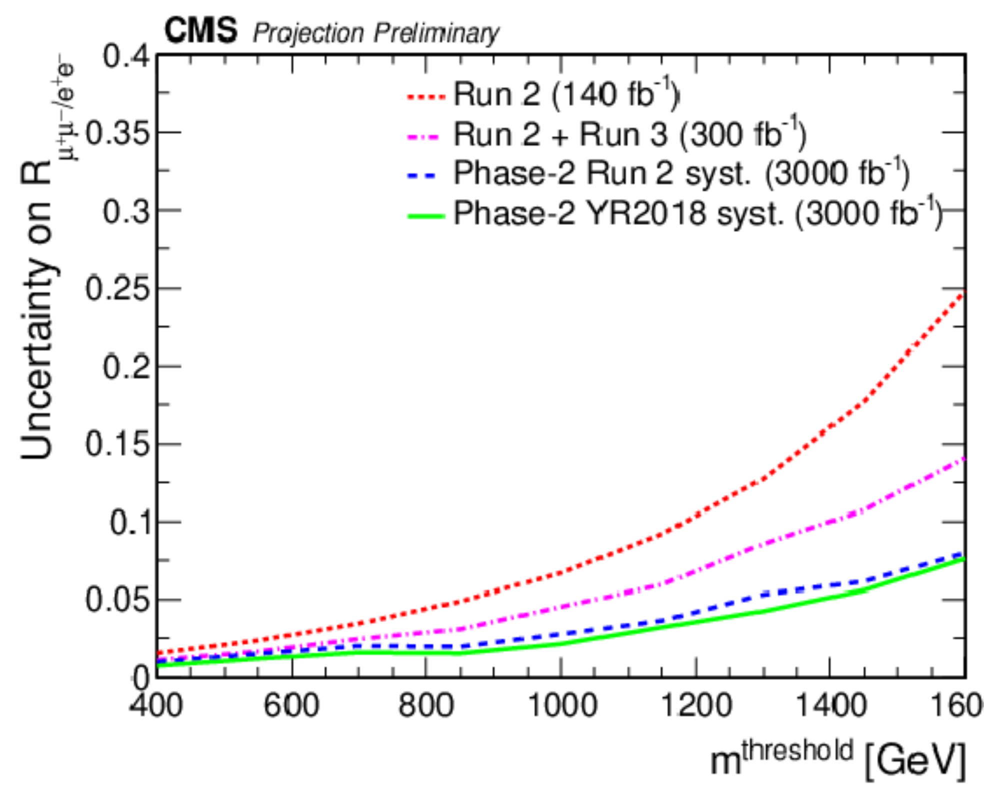
6

# Prospect for HL-LHC: dilepton mass

**CMS-PAS-FTR-21-005** (22/03): new phenomena at high dilepton mass

- Example or interpretation with $Z'_{SSM}$ 95%CL mass limit:
  - Current mass limit: 5.15 TeV - HL-LHC projection: 6.83 TeV
  - Forward acceptance increased: $|\eta_\mu|< 2.4 \rightarrow 2.8$ - $|\eta_e|< 2.5 \rightarrow 3.0$ (+5-10% in signal acceptance for ee)
- Test Lepton Flavor Universality through flavor ratio measurement

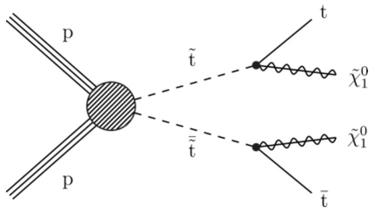


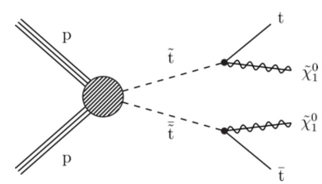
# Prospect for HL-LHC: SUSY: gluinos/stops

**CMS-PAS-FTR-18-037** (2019): searches for new physics in hadronic final states with boosted W bosons or top quarks using razor variables

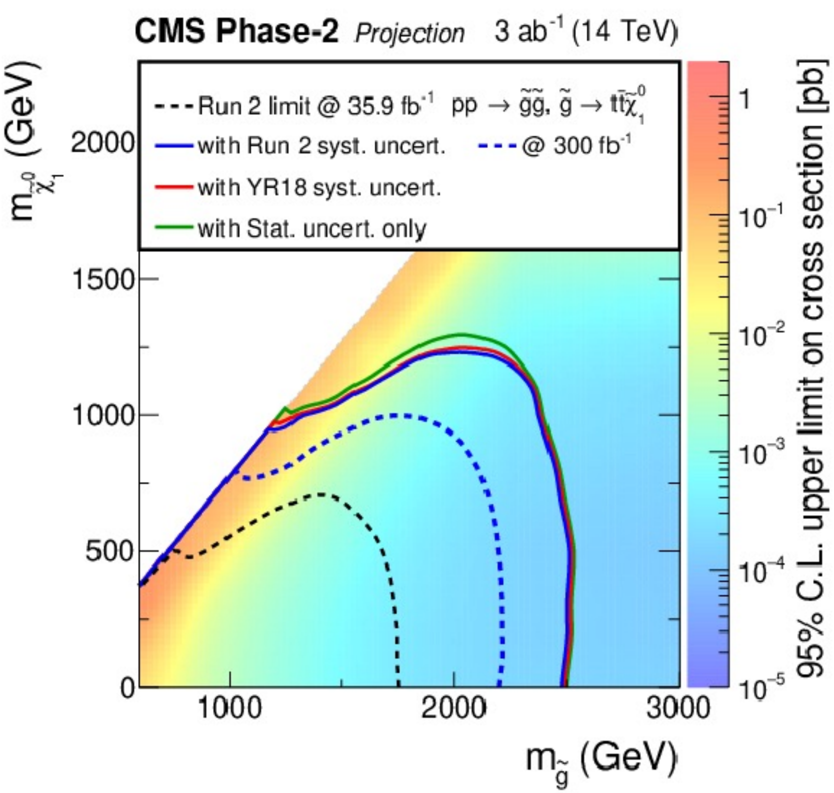
- Study done in 2019 based on 2016 analysis
- Give an idea of sensitivity in term of significance & exclusion

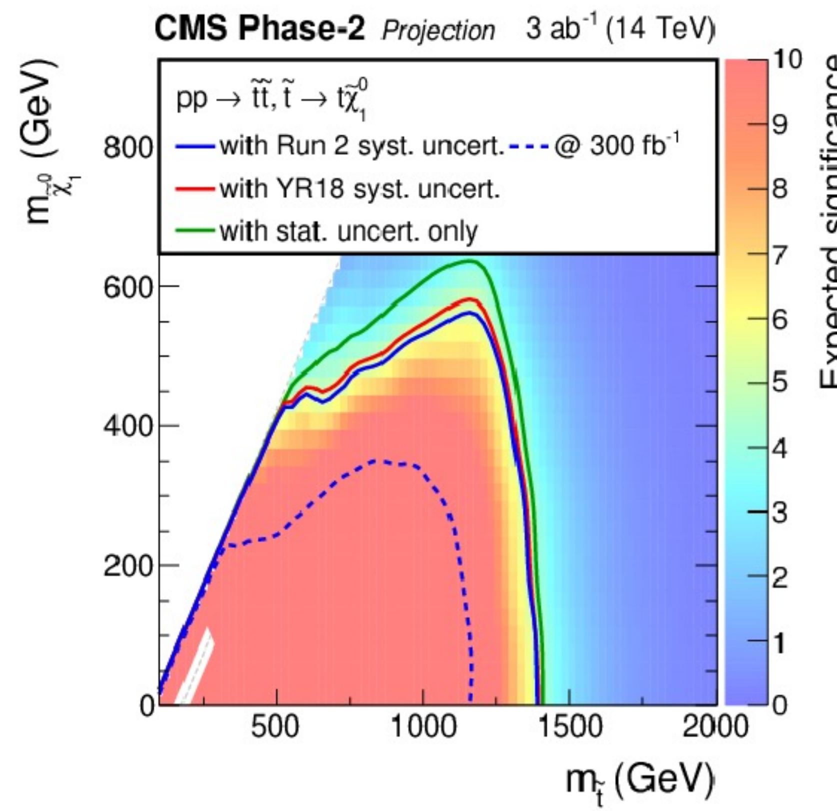


$3\sigma$ up to $m_g$~2.3 TeV



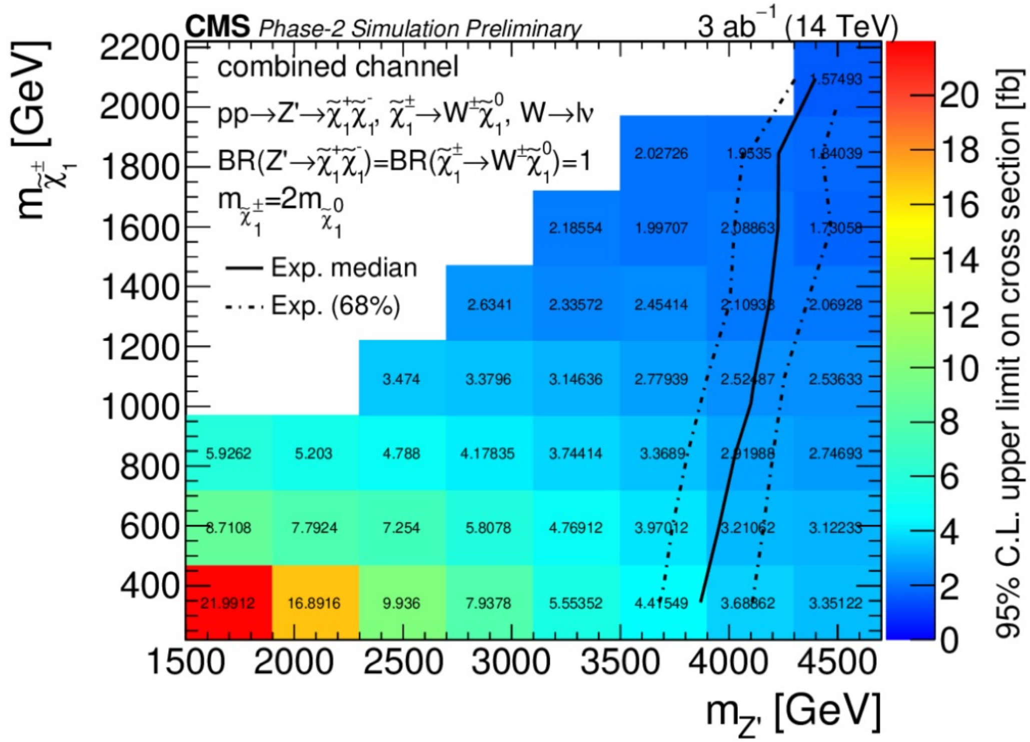
95% CL exclusion up to $m_t$~ 1.5 TeV (now: ~1.3 TeV)

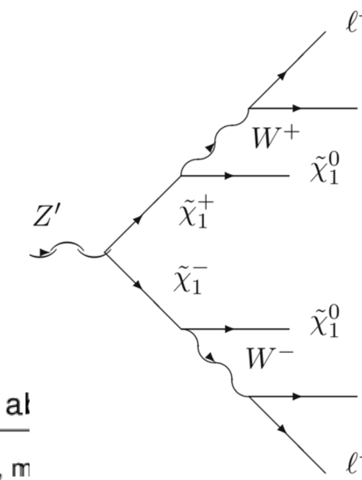


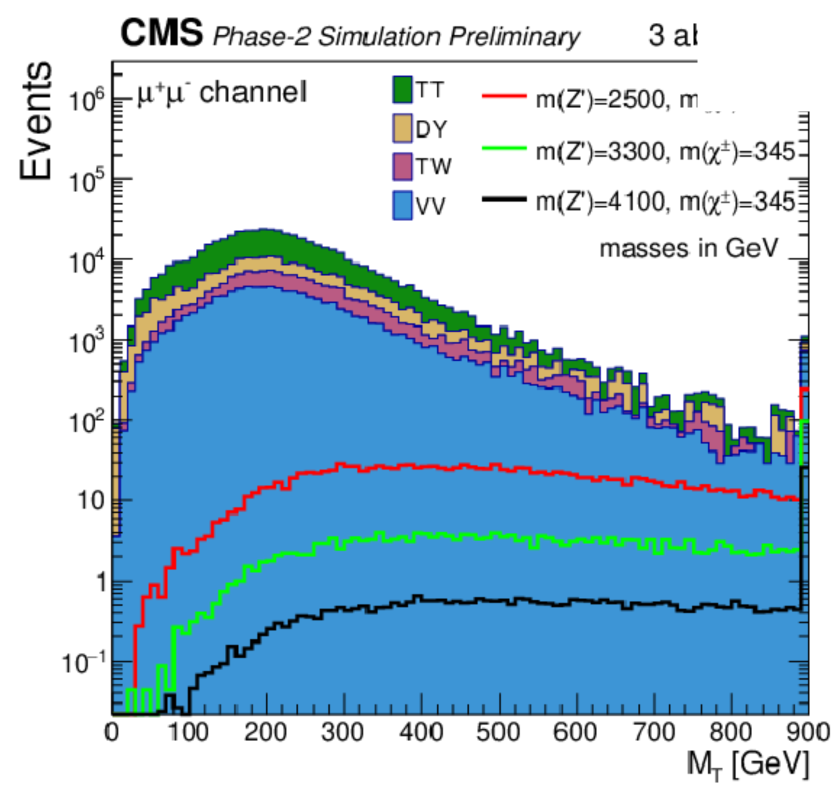



**CMS-PAS-FTR-21-011** (22/03): ): leptophobic Z' decaying into charginos in the dilepton + MET final state

- Study ee,μμ,eμ channels – Use of a DNN



# Conclusions

- CMS continues to increase its model coverage
- Beyond prompt/high-mass searches, it covers broader range of lifetime, low mass/momenta, …
- Use of **ML-based** objects and event reconstruction technics  allow to reach sensitivity **beyond initial projections**
- Few ***mild* excess** are reported which need to be confirmed (complementary searches - run III data)
- Thanks to higher sqrt(s) & higher luminosity & and few detector upgrades, improvements are expected for run III
- A bigger jump will arrive at HL-LHC !
- Meanwhile some run 2 analyses have not yet fully released and should appear soon