# Experimental overview

# BSM physics searches

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Workshop on New Physics Searches at Colliders, Apr 2026

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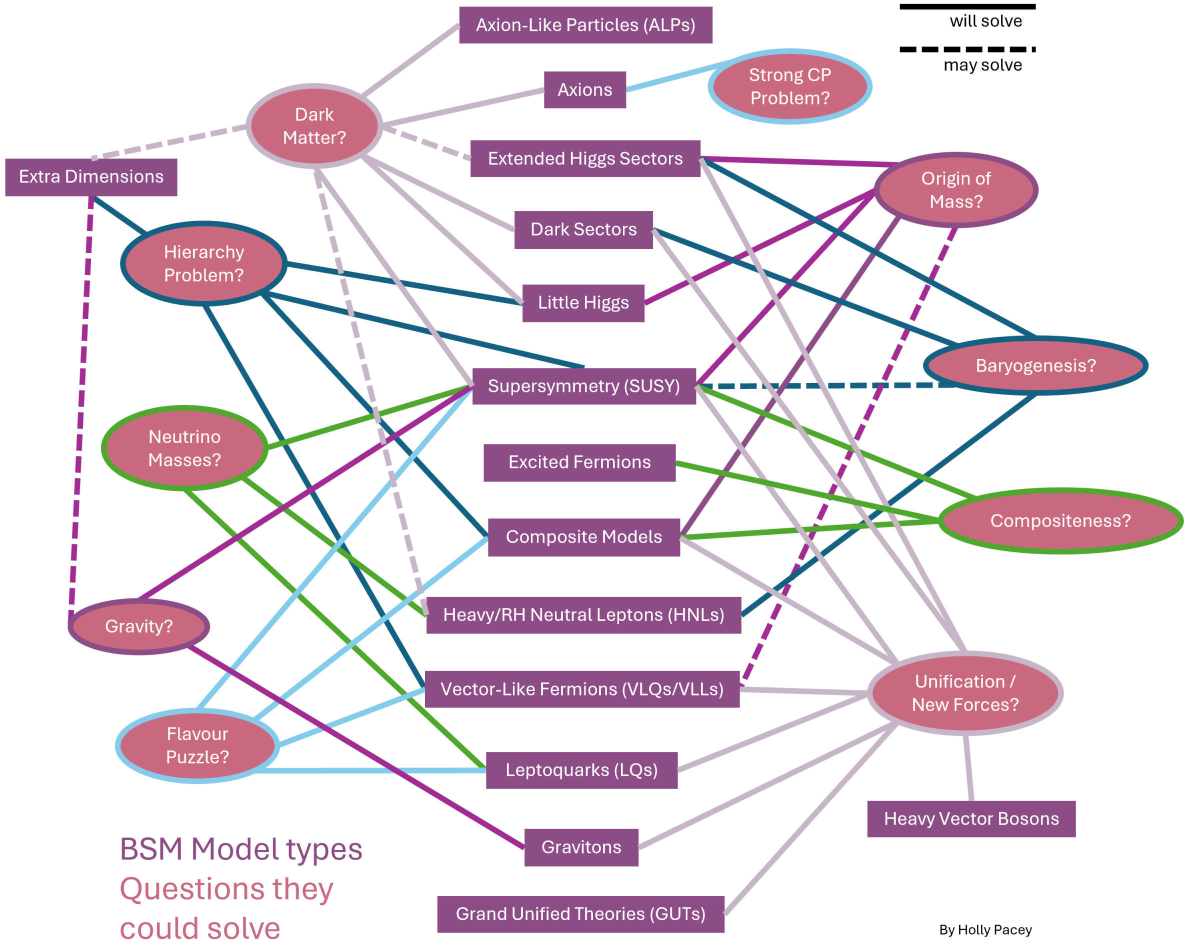
# Introduction



Graph by Holly Pacey

BSM physics searches is a huge topic

This talk selects latest and interesting results of exotic physics by CMS and ATLAS.

Latest: most results are in preprint or PAS (physics analysis summary) status

Interesting: using novel technique or observed hint of excess

Exotic: SUSY, BSM higgs etc will be covered in dedicated sessions

Other models

Compositeness

Dark matter

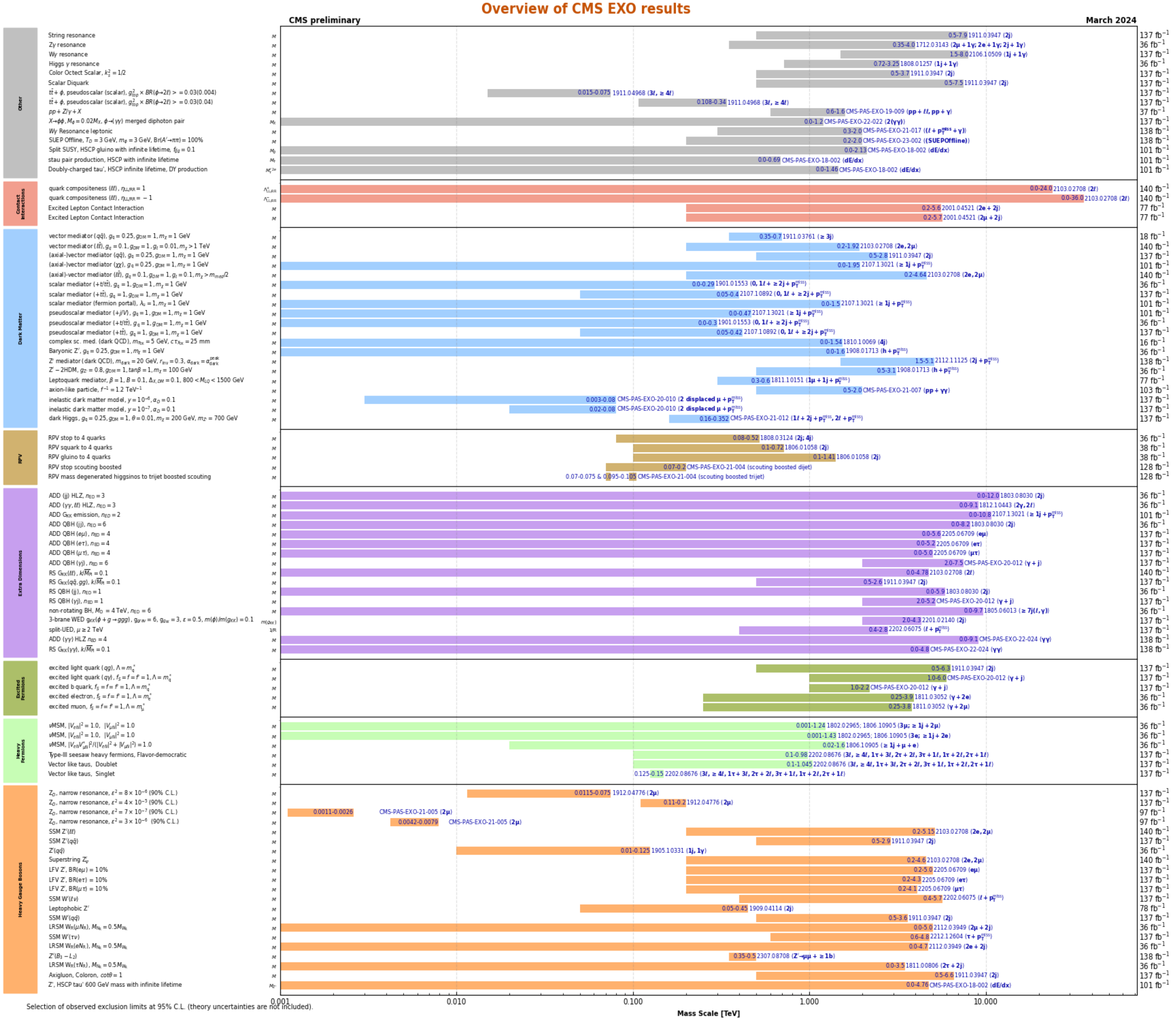
RPV SUSY

Extra Dimensions

Excited fermions

Heavy fermions

Heavy gauge bosons



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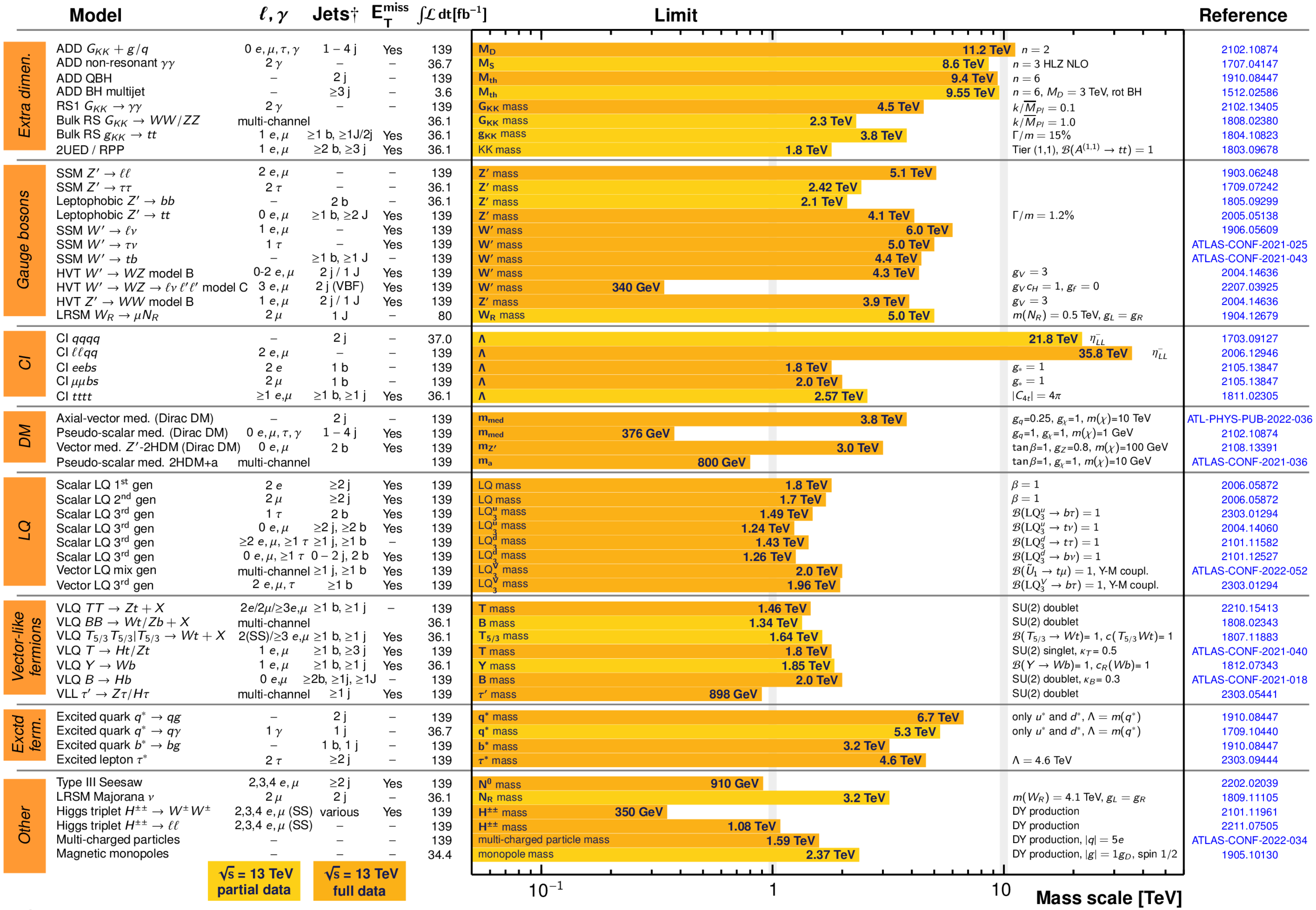
# ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

**ATLAS** Preliminary

$\int\mathcal{L}\,dt = (3.6 - 139)\ \text{fb}^{-1}$ $\sqrt{s} = 13$ TeV



| | Model | $\ell,\gamma$ | Jets† | $E_T^{miss}$ | $\int\mathcal{L}\,dt[\text{fb}^{-1}]$ | Limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| Extra dimen. | ADD $G_{KK}+g/q$ | 0 $e,\mu,\tau,\gamma$ | 1 – 4 j | Yes | 139 | $M_D$ 11.2 TeV | $n=2$ | 2102.10874 |
| | ADD non-resonant $\gamma\gamma$ | 2 $\gamma$ | – | – | 36.7 | $M_S$ 8.6 TeV | $n=3$ HLZ NLO | 1707.04147 |
| | ADD QBH | – | 2 j | – | 139 | $M_{th}$ 9.4 TeV | $n=6$ | 1910.08447 |
| | ADD BH multijet | – | ≥3 j | – | 3.6 | $M_{th}$ 9.55 TeV | $n=6$, $M_D=3$ TeV, rot BH | 1512.02586 |
| | RS1 $G_{KK}\to\gamma\gamma$ | 2 $\gamma$ | – | – | 139 | $G_{KK}$ mass 4.5 TeV | $k/\overline{M}_{Pl}=0.1$ | 2102.13405 |
| | Bulk RS $G_{KK}\to WW/ZZ$ | multi-channel | | | 36.1 | $G_{KK}$ mass 2.3 TeV | $k/\overline{M}_{Pl}=1.0$ | 1808.02380 |
| | Bulk RS $g_{KK}\to tt$ | 1 $e,\mu$ | ≥1 b, ≥1J/2j | Yes | 36.1 | $g_{KK}$ mass 3.8 TeV | $\Gamma/m=15\%$ | 1804.10823 |
| | 2UED / RPP | 1 $e,\mu$ | ≥2 b, ≥3 j | Yes | 36.1 | KK mass 1.8 TeV | Tier (1,1), $\mathcal{B}(A^{(1,1)}\to tt)=1$ | 1803.09678 |
| Gauge bosons | SSM $Z'\to\ell\ell$ | 2 $e,\mu$ | – | – | 139 | $Z'$ mass 5.1 TeV | | 1903.06248 |
| | SSM $Z'\to\tau\tau$ | 2 $\tau$ | – | – | 36.1 | $Z'$ mass 2.42 TeV | | 1709.07242 |
| | Leptophobic $Z'\to bb$ | – | 2 b | – | 36.1 | $Z'$ mass 2.1 TeV | | 1805.09299 |
| | Leptophobic $Z'\to tt$ | 0 $e,\mu$ | ≥1 b, ≥2 J | Yes | 139 | $Z'$ mass 4.1 TeV | $\Gamma/m=1.2\%$ | 2005.05138 |
| | SSM $W'\to\ell\nu$ | 1 $e,\mu$ | – | Yes | 139 | $W'$ mass 6.0 TeV | | 1906.05609 |
| | SSM $W'\to\tau\nu$ | 1 $\tau$ | – | Yes | 139 | $W'$ mass 5.0 TeV | | ATLAS-CONF-2021-025 |
| | SSM $W'\to tb$ | – | ≥1 b, ≥1 J | – | 139 | $W'$ mass 4.4 TeV | | ATLAS-CONF-2021-043 |
| | HVT $W'\to WZ$ model B | 0-2 $e,\mu$ | 2 j / 1 J | Yes | 139 | $W'$ mass 4.3 TeV | $g_V=3$ | 2004.14636 |
| | HVT $W'\to WZ\to\ell\nu\,\ell'\ell'$ model C | 3 $e,\mu$ | 2 j (VBF) | Yes | 139 | $W'$ mass 340 GeV | $g_V c_H=1$, $g_f=0$ | 2207.03925 |
| | HVT $Z'\to WW$ model B | 1 $e,\mu$ | 2 j / 1 J | Yes | 139 | $Z'$ mass 3.9 TeV | $g_V=3$ | 2004.14636 |
| | LRSM $W_R\to\mu N_R$ | 2 $\mu$ | 1 J | – | 80 | $W_R$ mass 5.0 TeV | $m(N_R)=0.5$ TeV, $g_L=g_R$ | 1904.12679 |
| CI | CI $qqqq$ | – | 2 j | – | 37.0 | $\Lambda$ 21.8 TeV | $\eta_{LL}^-$ | 1703.09127 |
| | CI $\ell\ell qq$ | 2 $e,\mu$ | – | – | 139 | $\Lambda$ 35.8 TeV | $\eta_{LL}^-$ | 2006.12946 |
| | CI $eebs$ | 2 $e$ | 1 b | – | 139 | $\Lambda$ 1.8 TeV | $g_*=1$ | 2105.13847 |
| | CI $\mu\mu bs$ | 2 $\mu$ | 1 b | – | 139 | $\Lambda$ 2.0 TeV | $g_*=1$ | 2105.13847 |
| | CI $tttt$ | ≥1 $e$,$\mu$ | ≥1 b, ≥1 j | Yes | 36.1 | $\Lambda$ 2.57 TeV | $\lvert C_{4t}\rvert=4\pi$ | 1811.02305 |
| DM | Axial-vector med. (Dirac DM) | – | 2 j | – | 139 | $m_{med}$ 3.8 TeV | $g_q$=0.25, $g_\chi$=1, $m(\chi)$=10 TeV | ATL-PHYS-PUB-2022-036 |
| | Pseudo-scalar med. (Dirac DM) | 0 $e,\mu,\tau,\gamma$ | 1 – 4 j | Yes | 139 | $m_{med}$ 376 GeV | $g_q$=1, $g_\chi$=1, $m(\chi)$=1 GeV | 2102.10874 |
| | Vector med. $Z'$-2HDM (Dirac DM) | 0 $e,\mu$ | 2 b | Yes | 139 | $m_{Z'}$ 3.0 TeV | $\tan\beta$=1, $g_Z$=0.8, $m(\chi)$=100 GeV | 2108.13391 |
| | Pseudo-scalar med. 2HDM+a | multi-channel | | | 139 | $m_a$ 800 GeV | $\tan\beta$=1, $g_\chi$=1, $m(\chi)$=10 GeV | ATLAS-CONF-2021-036 |
| LQ | Scalar LQ 1st gen | 2 $e$ | ≥2 j | Yes | 139 | LQ mass 1.8 TeV | $\beta=1$ | 2006.05872 |
| | Scalar LQ 2nd gen | 2 $\mu$ | ≥2 j | Yes | 139 | LQ mass 1.7 TeV | $\beta=1$ | 2006.05872 |
| | Scalar LQ 3rd gen | 1 $\tau$ | 2 b | Yes | 139 | $\text{LQ}_3^u$ mass 1.49 TeV | $\mathcal{B}(\text{LQ}_3^u\to b\tau)=1$ | 2303.01294 |
| | Scalar LQ 3rd gen | 0 $e,\mu$ | ≥2 j, ≥2 b | Yes | 139 | $\text{LQ}_3^u$ mass 1.24 TeV | $\mathcal{B}(\text{LQ}_3^u\to t\nu)=1$ | 2004.14060 |
| | Scalar LQ 3rd gen | ≥2 $e,\mu$, ≥1 $\tau$ | ≥1 j, ≥1 b | – | 139 | $\text{LQ}_3^d$ mass 1.43 TeV | $\mathcal{B}(\text{LQ}_3^d\to t\tau)=1$ | 2101.11582 |
| | Scalar LQ 3rd gen | 0 $e,\mu$, ≥1 $\tau$ | 0 – 2 j, 2 b | Yes | 139 | $\text{LQ}_3^d$ mass 1.26 TeV | $\mathcal{B}(\text{LQ}_3^d\to b\nu)=1$ | 2101.12527 |
| | Vector LQ mix gen | multi-channel | ≥1 j, ≥1 b | Yes | 139 | $\text{LQ}_3^V$ mass 2.0 TeV | $\mathcal{B}(\tilde{U}_1\to t\mu)=1$, Y-M coupl. | ATLAS-CONF-2022-052 |
| | Vector LQ 3rd gen | 2 $e,\mu,\tau$ | ≥1 b | Yes | 139 | $\text{LQ}_3^V$ mass 1.96 TeV | $\mathcal{B}(\text{LQ}_3^V\to b\tau)=1$, Y-M coupl. | 2303.01294 |
| Vector-like fermions | VLQ $TT\to Zt+X$ | 2$e$/2$\mu$/≥3$e$,$\mu$ | ≥1 b, ≥1 j | – | 139 | T mass 1.46 TeV | SU(2) doublet | 2210.15413 |
| | VLQ $BB\to Wt/Zb+X$ | multi-channel | | | 36.1 | B mass 1.34 TeV | SU(2) doublet | 1808.02343 |
| | VLQ $T_{5/3}T_{5/3}\lvert T_{5/3}\to Wt+X$ | 2(SS)/≥3 $e$,$\mu$ | ≥1 b, ≥1 j | Yes | 36.1 | $T_{5/3}$ mass 1.64 TeV | $\mathcal{B}(T_{5/3}\to Wt)$= 1, $c(T_{5/3}Wt)$= 1 | 1807.11883 |
| | VLQ $T\to Ht/Zt$ | 1 $e,\mu$ | ≥1 b, ≥3 j | Yes | 139 | T mass 1.8 TeV | SU(2) singlet, $\kappa_T$= 0.5 | ATLAS-CONF-2021-040 |
| | VLQ $Y\to Wb$ | 1 $e,\mu$ | ≥1 b, ≥1 j | Yes | 36.1 | Y mass 1.85 TeV | $\mathcal{B}(Y\to Wb)$= 1, $c_R(Wb)$= 1 | 1812.07343 |
| | VLQ $B\to Hb$ | 0 $e$,$\mu$ | ≥2b, ≥1j, ≥1J | – | 139 | B mass 2.0 TeV | SU(2) doublet, $\kappa_B$= 0.3 | ATLAS-CONF-2021-018 |
| | VLL $\tau'\to Z\tau/H\tau$ | multi-channel | ≥1 j | Yes | 139 | $\tau'$ mass 898 GeV | SU(2) doublet | 2303.05441 |
| Exctd ferm. | Excited quark $q^*\to qg$ | – | 2 j | – | 139 | $q^*$ mass 6.7 TeV | only $u^*$ and $d^*$, $\Lambda=m(q^*)$ | 1910.08447 |
| | Excited quark $q^*\to q\gamma$ | 1 $\gamma$ | 1 j | – | 36.7 | $q^*$ mass 5.3 TeV | only $u^*$ and $d^*$, $\Lambda=m(q^*)$ | 1709.10440 |
| | Excited quark $b^*\to bg$ | – | 1 b, 1 j | – | 139 | $b^*$ mass 3.2 TeV | | 1910.08447 |
| | Excited lepton $\tau^*$ | 2 $\tau$ | ≥2 j | – | 139 | $\tau^*$ mass 4.6 TeV | $\Lambda=4.6$ TeV | 2303.09444 |
| Other | Type III Seesaw | 2,3,4 $e,\mu$ | ≥2 j | Yes | 139 | $N^0$ mass 910 GeV | | 2202.02039 |
| | LRSM Majorana $\nu$ | 2 $\mu$ | 2 j | – | 36.1 | $N_R$ mass 3.2 TeV | $m(W_R)=4.1$ TeV, $g_L=g_R$ | 1809.11105 |
| | Higgs triplet $H^{\pm\pm}\to W^\pm W^\pm$ | 2,3,4 $e,\mu$ (SS) | various | Yes | 139 | $H^{\pm\pm}$ mass 350 GeV | DY production | 2101.11961 |
| | Higgs triplet $H^{\pm\pm}\to\ell\ell$ | 2,3,4 $e,\mu$ (SS) | – | – | 139 | $H^{\pm\pm}$ mass 1.08 TeV | DY production | 2211.07505 |
| | Multi-charged particles | – | – | – | 139 | multi-charged particle mass 1.59 TeV | DY production, $\lvert q\rvert=5e$ | ATLAS-CONF-2022-034 |
| | Magnetic monopoles | – | – | – | 34.4 | monopole mass 2.37 TeV | DY production, $\lvert g\rvert=1g_D$, spin 1/2 | 1905.10130 |

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

link

# Search for heavy fermions

# Search for heavy stable charged leptons

Strong theoretical motivation, e.g.

[Phys. Rept. 438 (2007) 1], [Phys. Lett. B 690 (2010) 280]

Long history of searches

CERN LEP [1] -> Fermilab Tevatron [2] -> CERN LHC [3]

[1] ALEPH Collaboration, “Search for pair production of longlived heavy charged particles in e+e− annihilation”, Phys. Lett. B 405 (1997) 379
[2] CDF Collaboration, “Search for long-lived massive charged particles in 1.96 TeV pp collisions”, Phys. Rev. Lett. 103 (2009) 021802
[3] CMS Collaboration, “Search for heavy stable charged particles in pp collisions at 7 TeV”, JHEP 03 (2011) 024

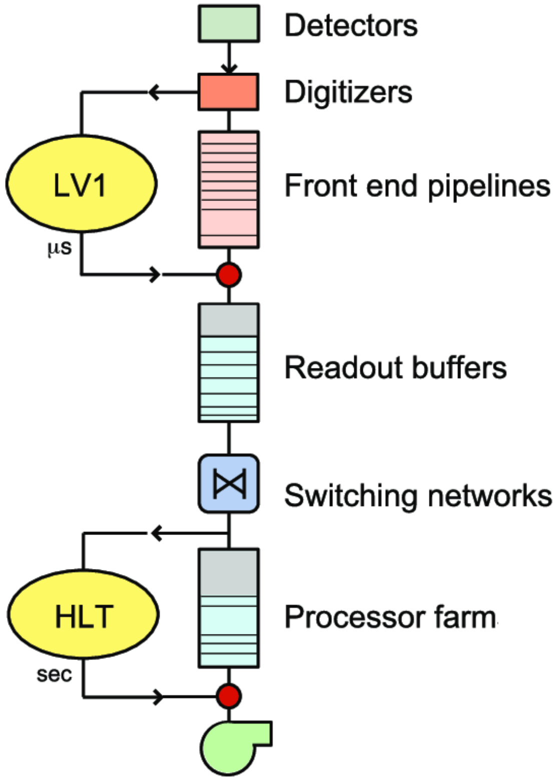
[arXiv:2601.20063] searches for TeV scale charged leptons (noted as tau’) in

- pp→Z’→tau'tau' heavy resonance
- pp→ tau'tau' direct pair production

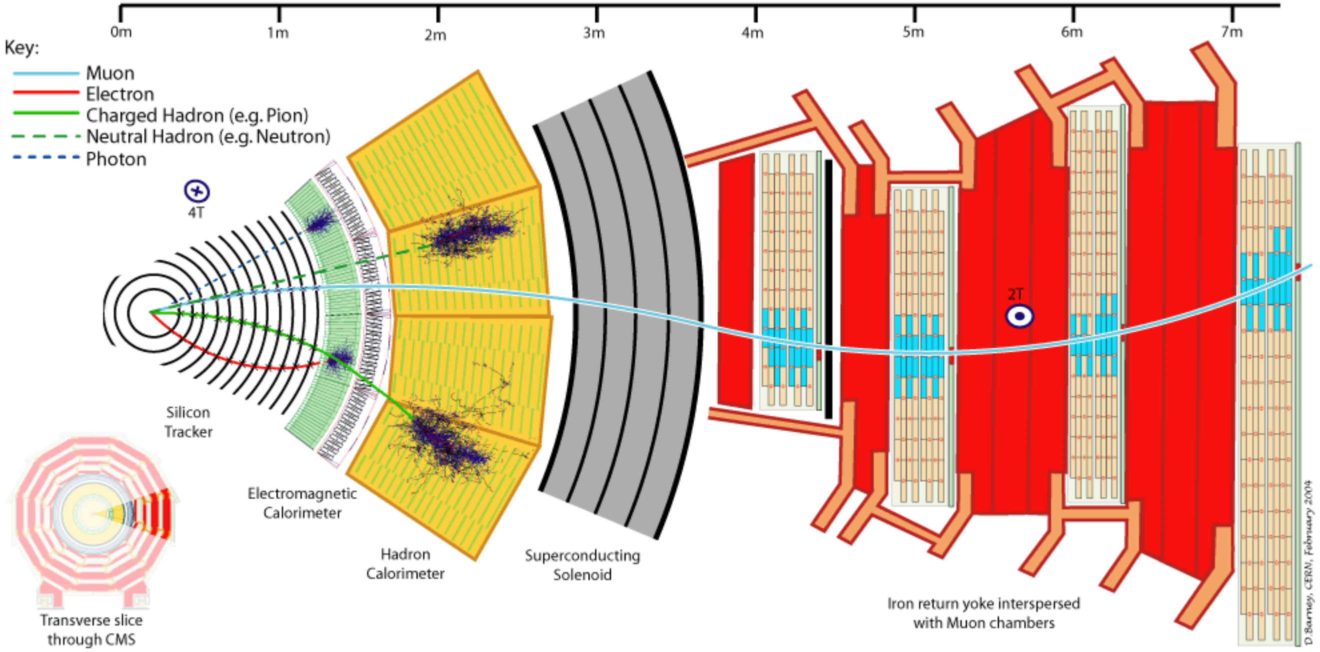
Challenges

1. Small cross section, low statistics using traditional trigger
2. Slow-moving, detector hits across several LHC bunch crossings (BX)

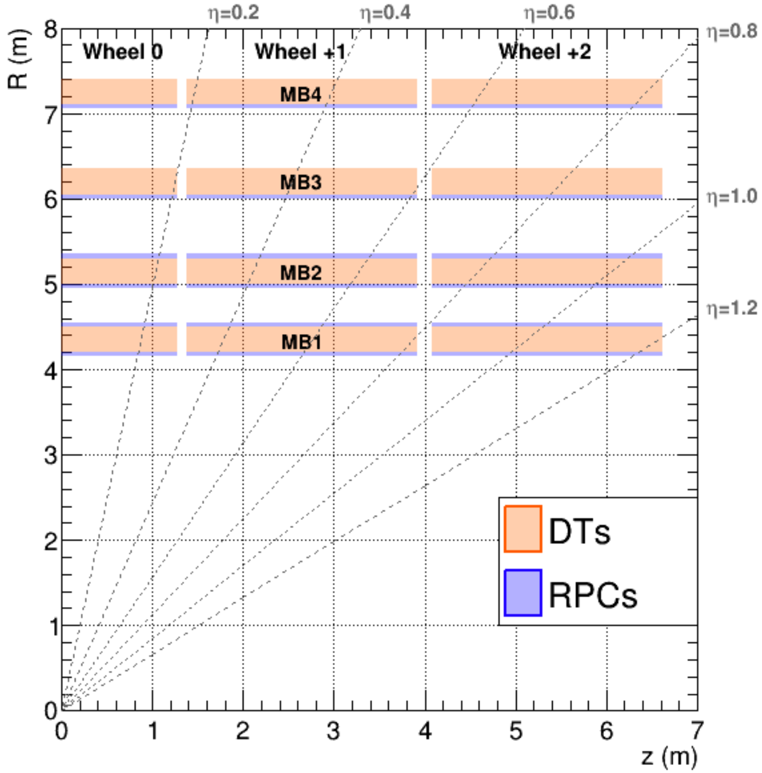
# Solution



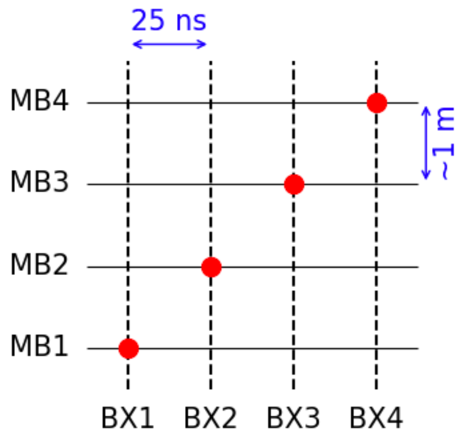
- [arXiv:2601.20063] the first analysis using L1 scouting data
- LHC collides at 40MHz = L1 input rate = L1 scouting rate
- Pros: high rate, saves all BXs in an orbit, perfect for slow-moving particles
- Cons: only L1 information, no tracker, no PF reconstruction



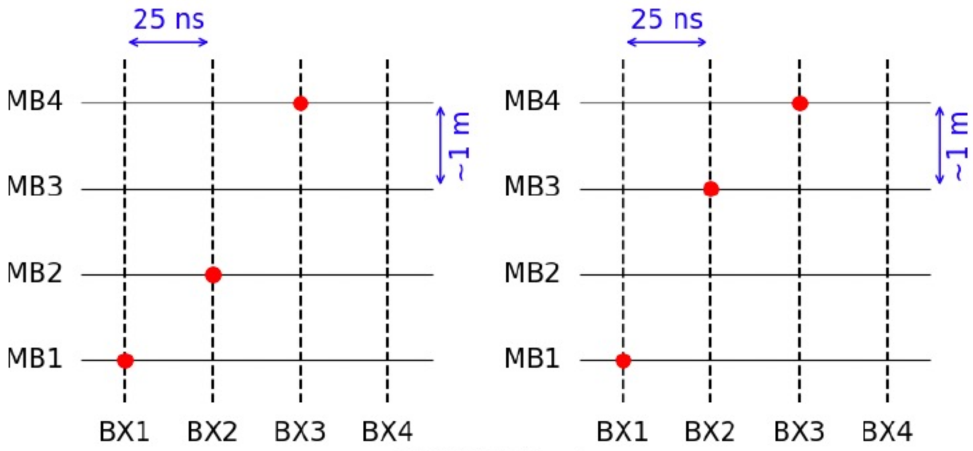
# Search strategy



| Stations / BXs | 3/4 | 3/3 or 4/4 | 4/3 | 3/2 | 4/2 |
|---|---|---|---|---|---|
| 4 stubs | — | BX1234<br>BX124/134 | BX123 | — | BX1112<br>BX1122<br>BX1222 |
| 3 stubs, MB1 or MB4 | BX124/134 slow | BX123 slow | — | BX112 slow<br>BX122 slow | — |
| 3 stubs, MB1 and MB4 | — | BX124/134 fast | BX123 fast | — | BX112 fast<br>BX122 fast |

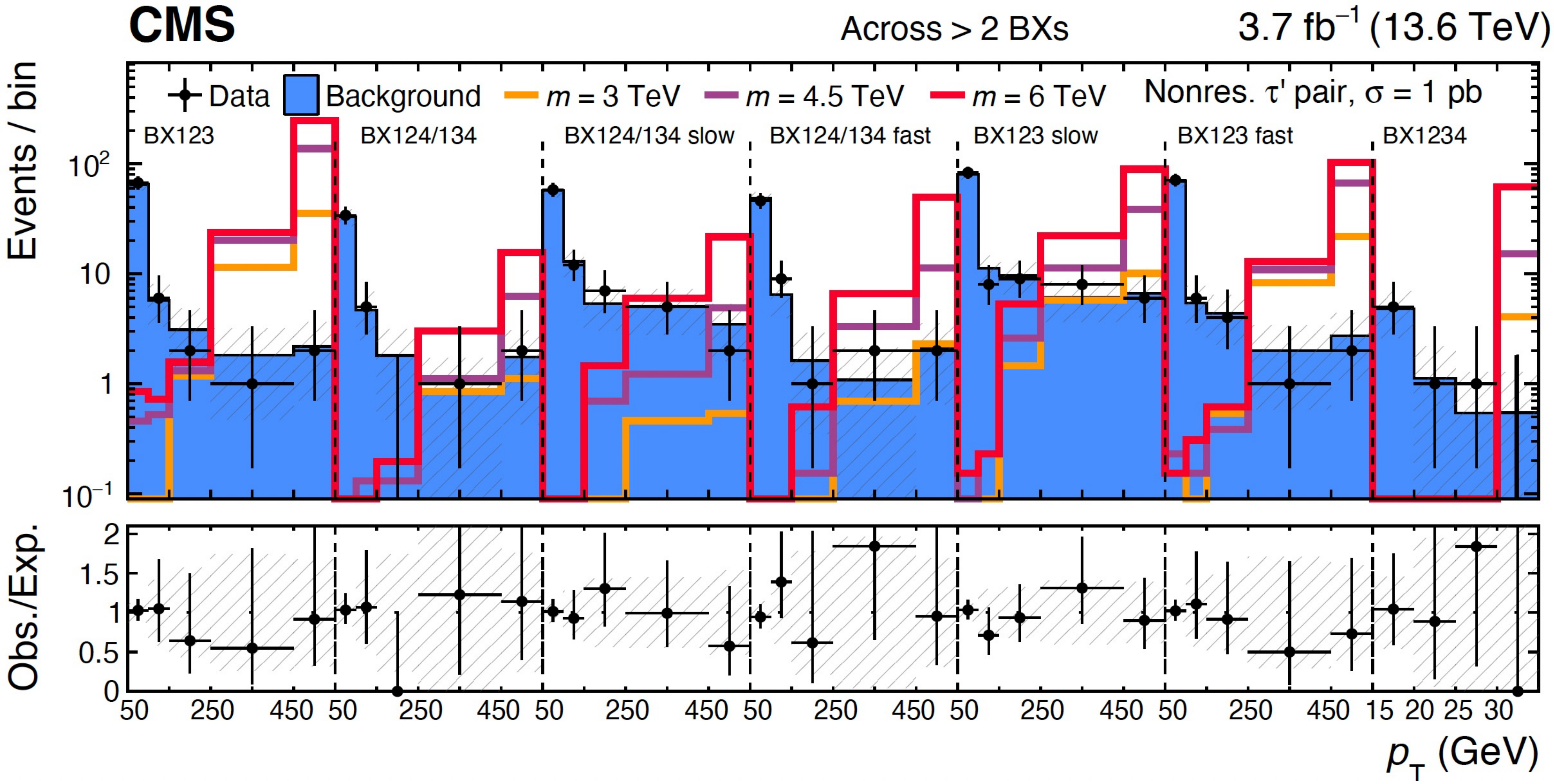


**BX1234**

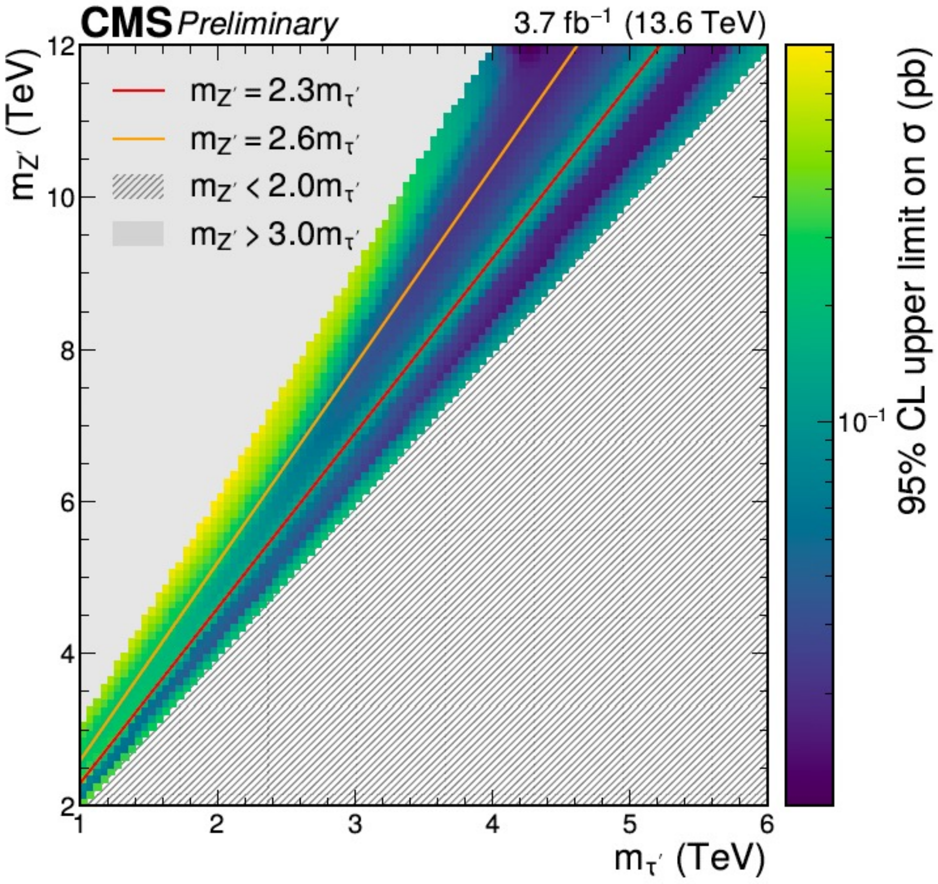


**BX123 fast**

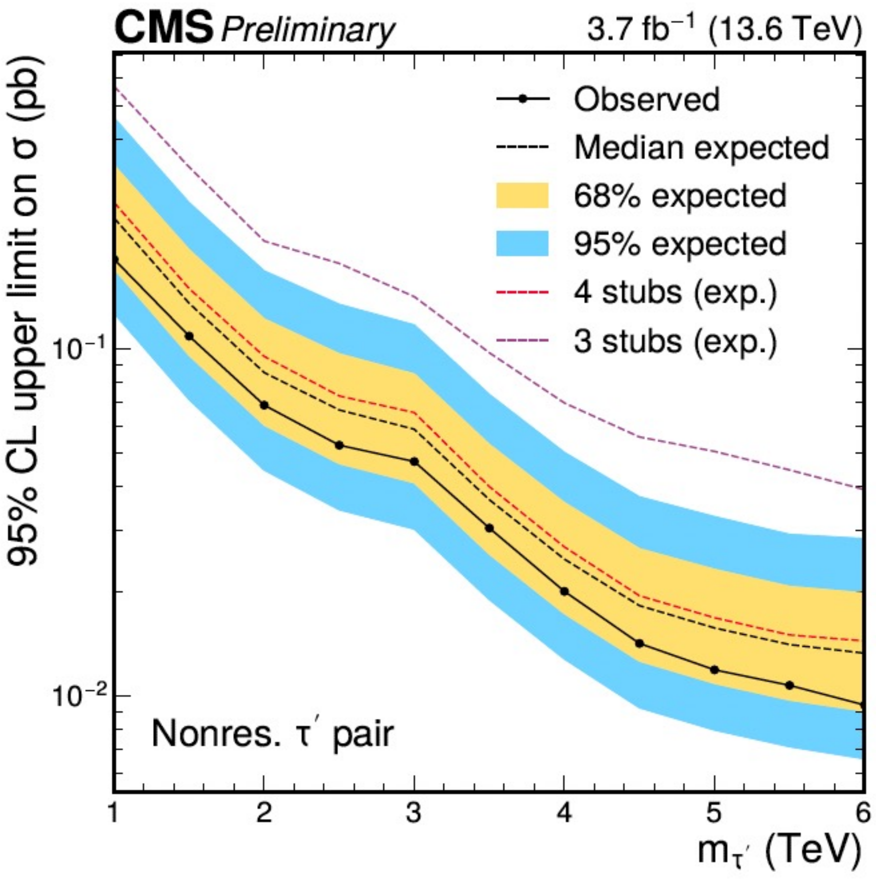
# Results


CMS
Across > 2 BXs
3.7 fb$^{-1}$ (13.6 TeV)
Data
Background
$m$ = 3 TeV
$m$ = 4.5 TeV
$m$ = 6 TeV
Nonres. τ' pair, σ = 1 pb
BX123
BX124/134
BX124/134 slow
BX124/134 fast
BX123 slow
BX123 fast
BX1234
Events / bin
$10^{2}$
10
1
$10^{-1}$
Obs./Exp.
2
1.5
1
0.5
0
50 250 450 50 250 450 50 250 450 50 250 450 50 250 450 50 250 450 15 20 25 30
$p_T$ (GeV)

# Limits



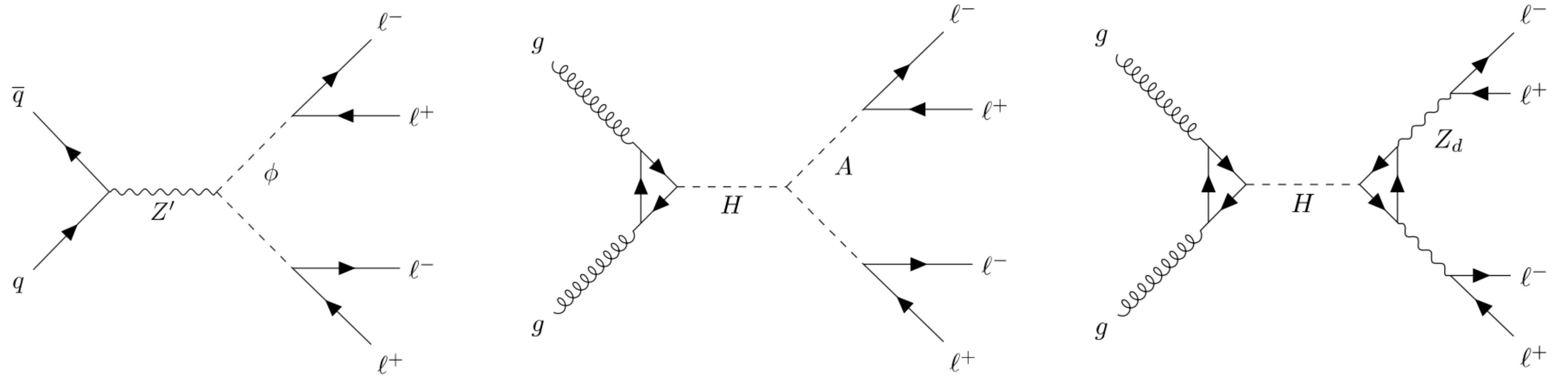
pp→Z'→tau'tau' heavy resonance



pp→ tau'tau' direct pair production

# Search for heavy gauge bosons

# Search for heavy 4-lepton resonance



Many models predict BSM processes of X → YY → 4-lep and X → YZ → 4-lep

where X, Y, Z are new bosons, e.g.

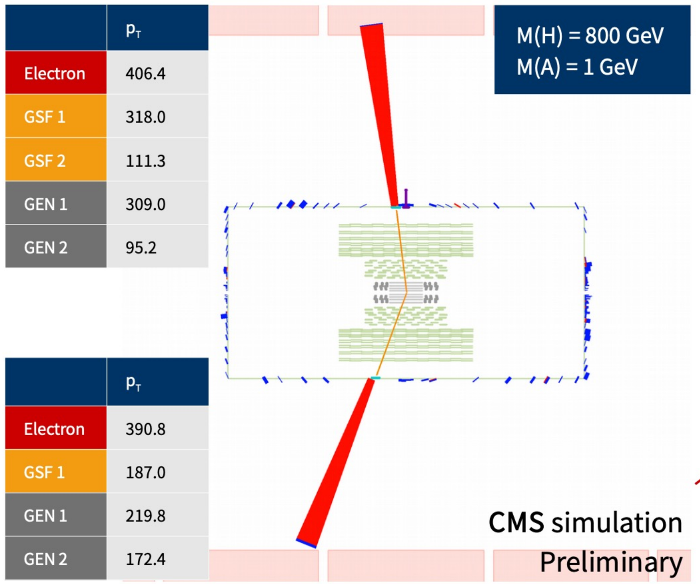
- U(1) extension of SUSY (UMSSM), [PRD 85 (2012) 055030]
- 2HDM, [Phys. Rep. 516 (2012) pp. 1-102]
- Dark photon models, [JHEP 02 (2015) 157]

EXO-24-006-pas

# Challenges

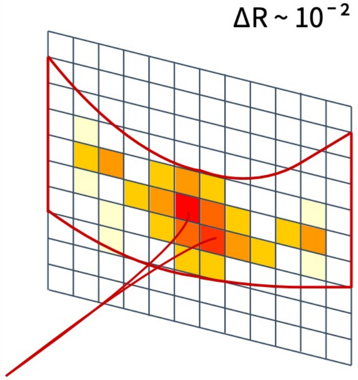
- Collimated electrons merged via (super)cluster
- Collimated muons share tracker hits, trajectory cleaner removes either of the two tracks

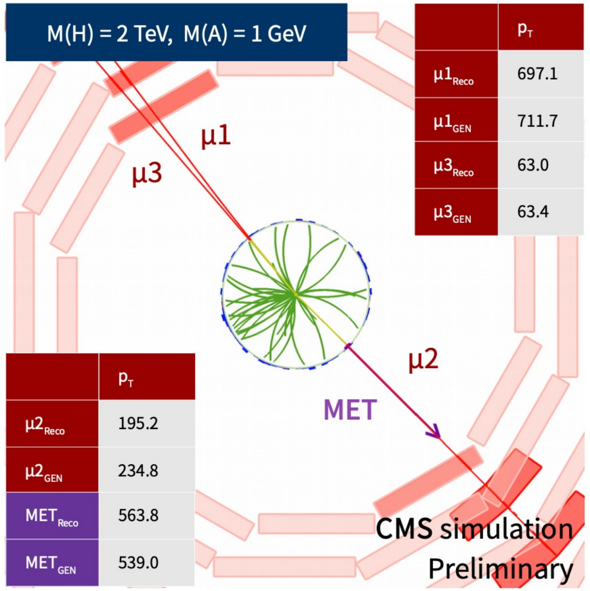
  → the missing track observed as missing ET (MET)



| | $p_T$ |
|---|---|
| Electron | 406.4 |
| GSF 1 | 318.0 |
| GSF 2 | 111.3 |
| GEN 1 | 309.0 |
| GEN 2 | 95.2 |

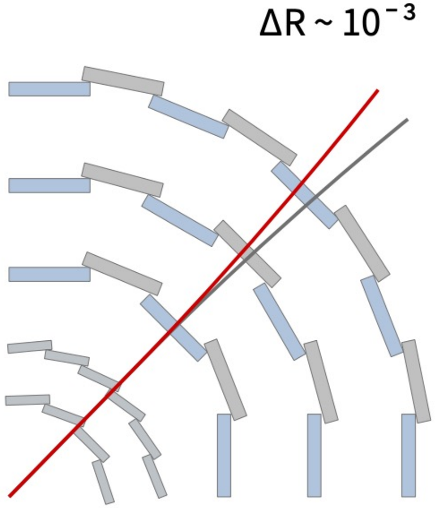
| | $p_T$ |
|---|---|
| Electron | 390.8 |
| GSF 1 | 187.0 |
| GEN 1 | 219.8 |
| GEN 2 | 172.4 |





| | $p_T$ |
|---|---|
| $\mu1_{Reco}$ | 697.1 |
| $\mu1_{GEN}$ | 711.7 |
| $\mu3_{Reco}$ | 63.0 |
| $\mu3_{GEN}$ | 63.4 |

| | $p_T$ |
|---|---|
| $\mu2_{Reco}$ | 195.2 |
| $\mu2_{GEN}$ | 234.8 |
| $MET_{Reco}$ | 563.8 |
| $MET_{GEN}$ | 539.0 |



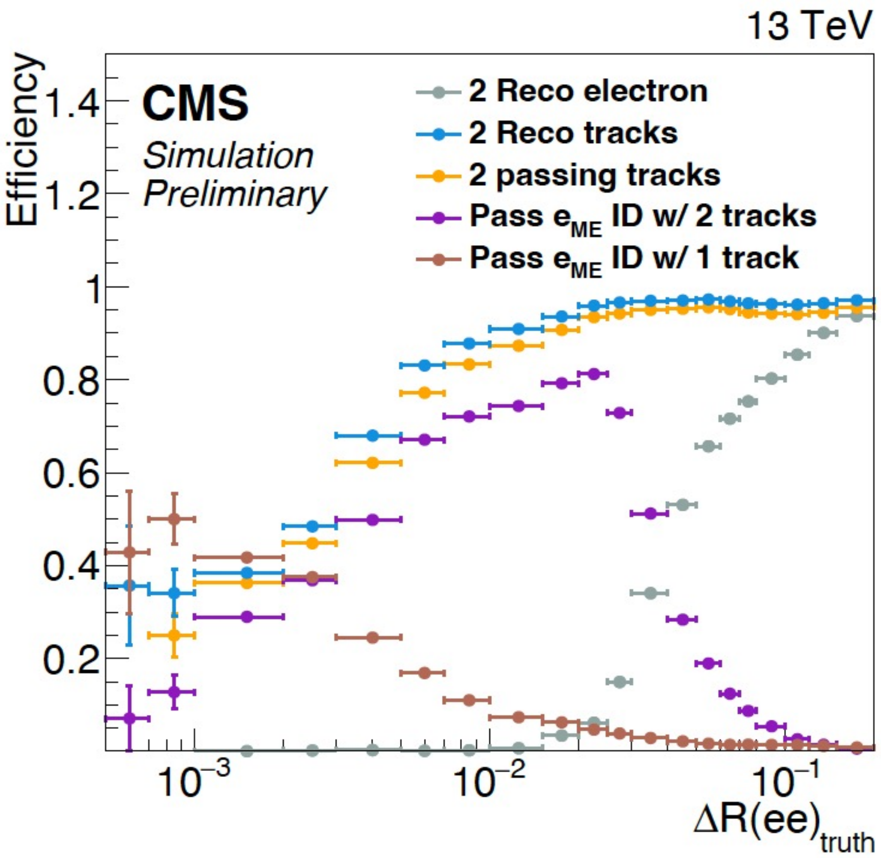
# Solution

- 4-lep (truth) observed in detector as

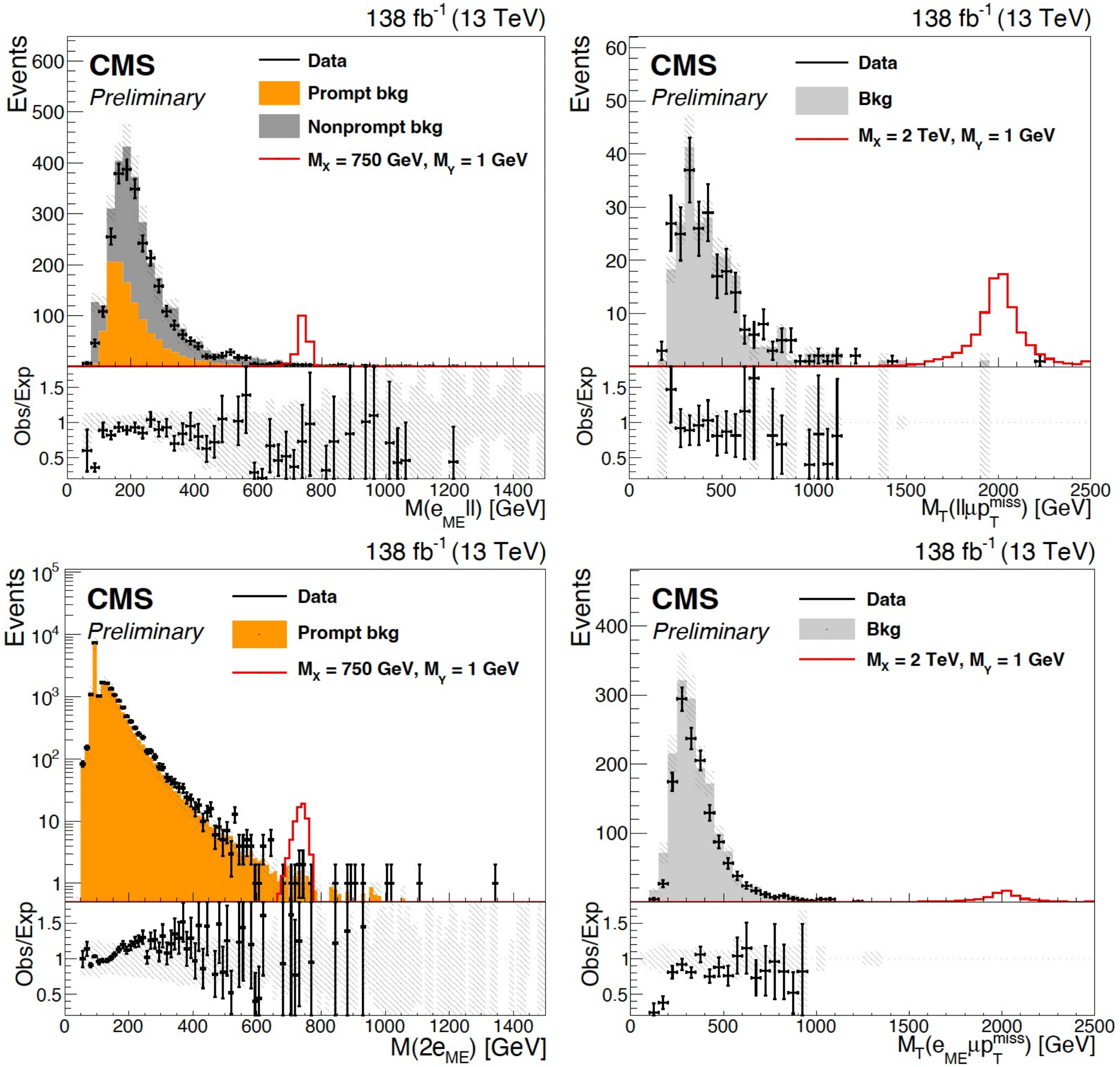
  1. 4-lep, 2. $e_{ME}$ + ll, 3. mu+MET+ll,

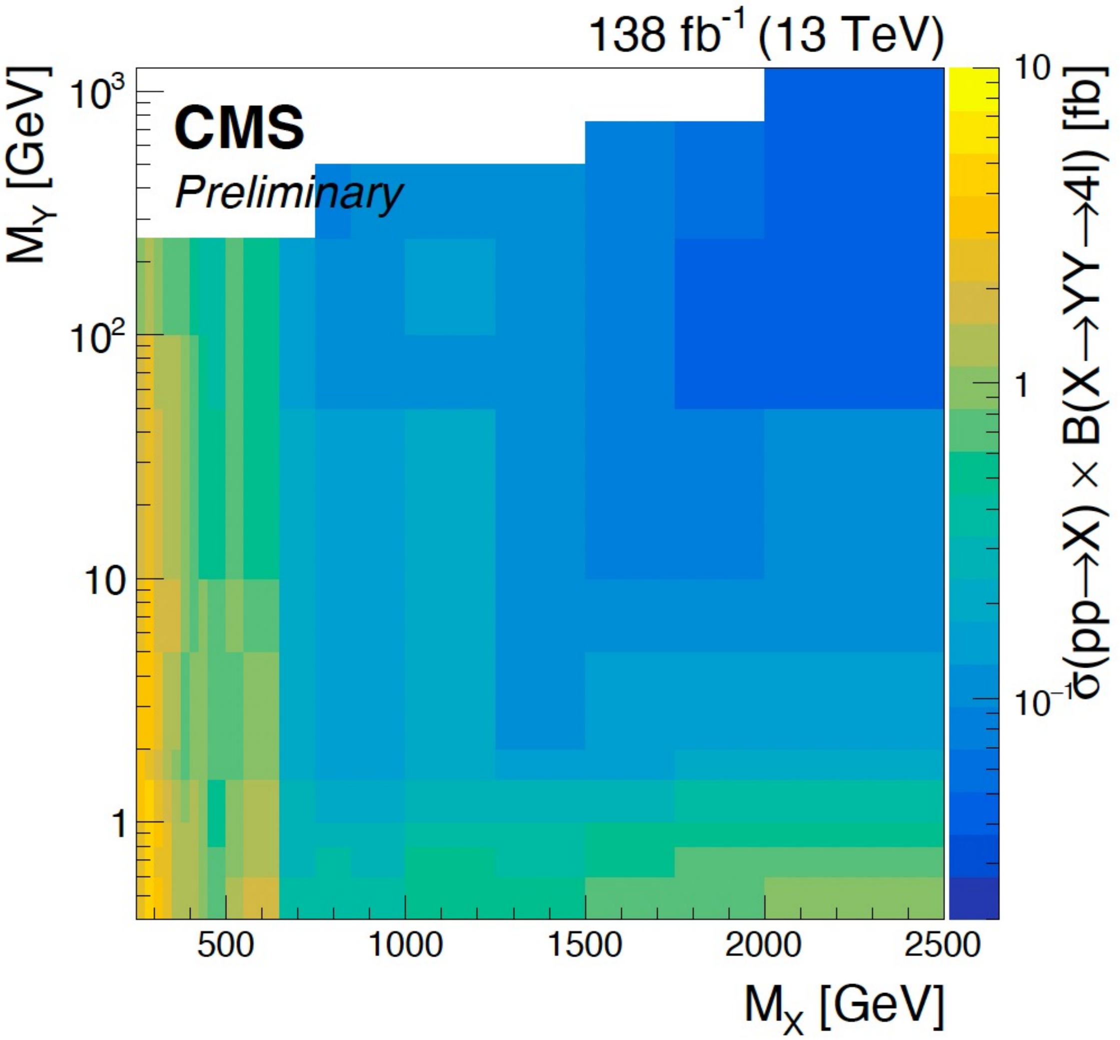
  4. 2 $e_{ME}$ , 5. $e_{ME}$ + mu+MET

- Merged electrons ($e_{ME}$)
  - Match secondary track to (super)cluster based on track pT, dZ to PV, number of hits, track quality, etc
  - Modify electron MVA reconstruction
- Merged muons (mu+MET)
  - use mu+MET to reconstruct mass of Y boson



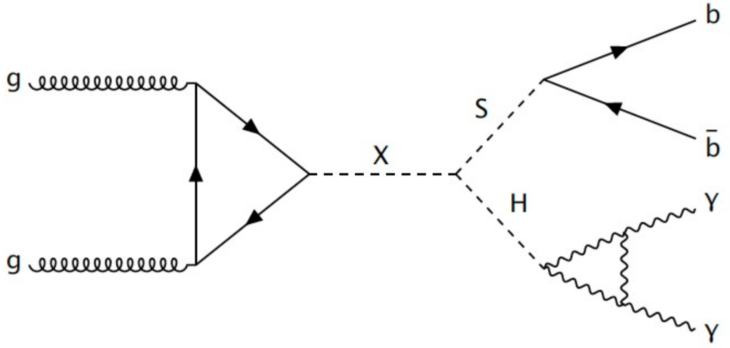
# Results


138 fb$^{-1}$ (13 TeV)
CMS
Preliminary
Data
Prompt bkg
Nonprompt bkg
$M_X$ = 750 GeV, $M_Y$ = 1 GeV
Events
Obs/Exp
$M(e_{ME}ll)$ [GeV]
138 fb$^{-1}$ (13 TeV)
CMS
Preliminary
Data
Bkg
$M_X$ = 2 TeV, $M_Y$ = 1 GeV
Events
Obs/Exp
$M_T(ll\mu p_T^{miss})$ [GeV]
138 fb$^{-1}$ (13 TeV)
CMS
Preliminary
Data
Prompt bkg
$M_X$ = 750 GeV, $M_Y$ = 1 GeV
Events
Obs/Exp
$M(2e_{ME})$ [GeV]
138 fb$^{-1}$ (13 TeV)
CMS
Preliminary
Data
Bkg
$M_X$ = 2 TeV, $M_Y$ = 1 GeV
Events
Obs/Exp
$M_T(e_{ME}\mu p_T^{miss})$ [GeV]


138 fb$^{-1}$ (13 TeV)
CMS
Preliminary
$M_Y$ [GeV]
$10^3$
$10^2$
10
1
500
1000
1500
2000
2500
$M_X$ [GeV]
10
1
$10^{-1}$
$\sigma(pp\rightarrow X) \times B(X\rightarrow YY\rightarrow 4l)$ [fb]

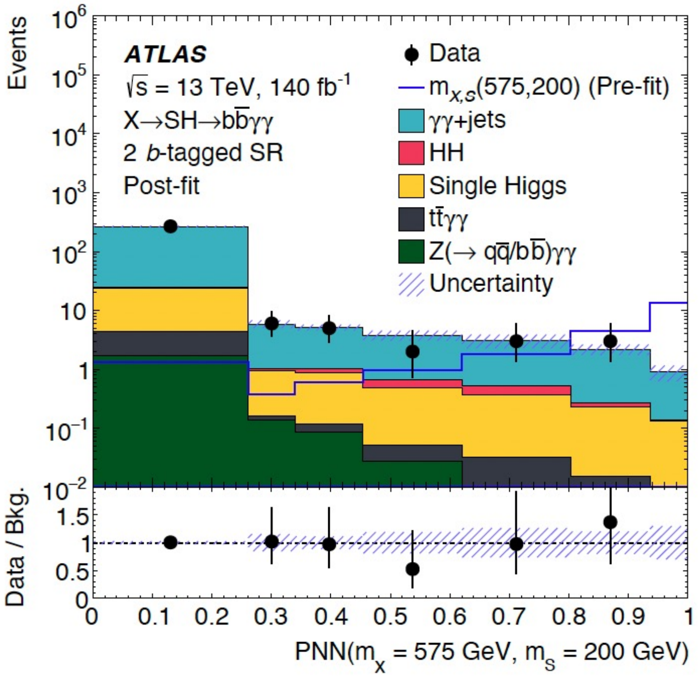
# Search for heavy scalar X→SH

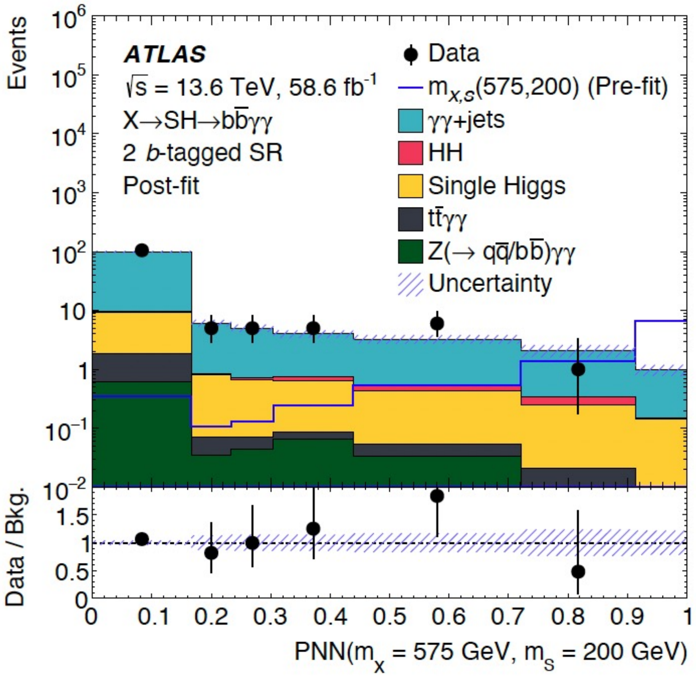
- Many models predict processes of heavy scalar X to light scalar S + SM higgs, e.g.
  - One complex singlet extension of SM [PRD 79 (2009) 015018]
  - Two real scalar singlet extension of SM [EPJC 80 (2020) 151]
  - NMSSM [Phys. Rept. 496 (2010) 1], etc

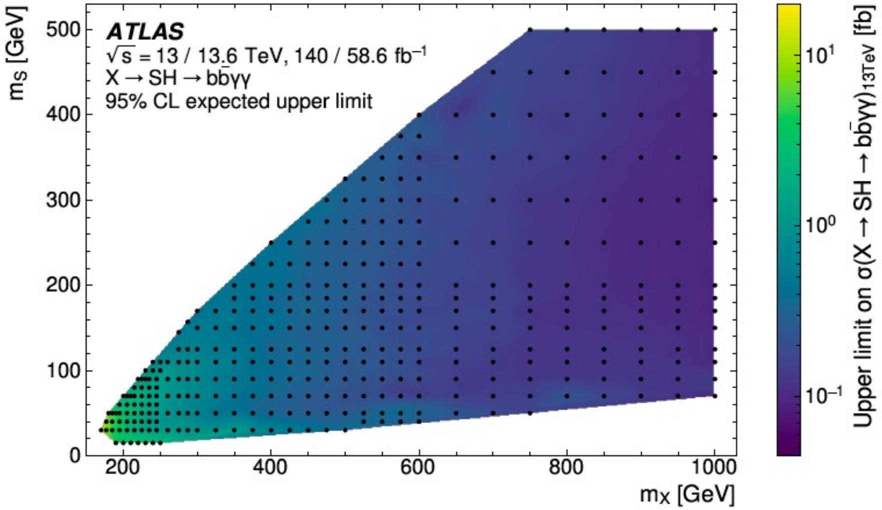


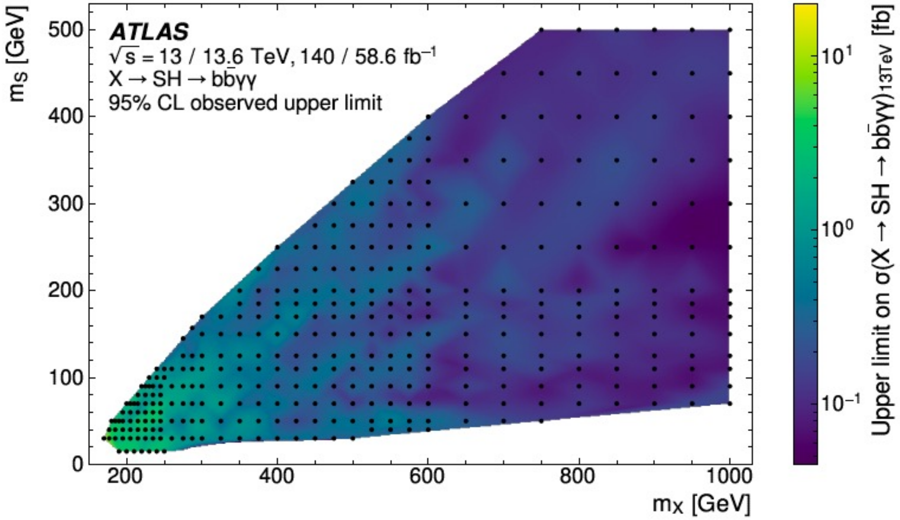
- [arXiv:2510.02857] focuses on X→SH→bbγγ final state
- Signal-background discriminant based on Parameterised neural network (PNN) [EPJC 76 (2016) 235]
- Traditional NN: learns a function of event characteristics $\vec{x}$
- PNN: learns a function of event characteristics $\vec{x}$ and phase space parameters $\vec{\theta}$ ($m_X$ and $m_S$ in this case)
  - Able to interpolate between trained parameter points
  - Suitable for searches where both mother and daughters mass unknown

# Results







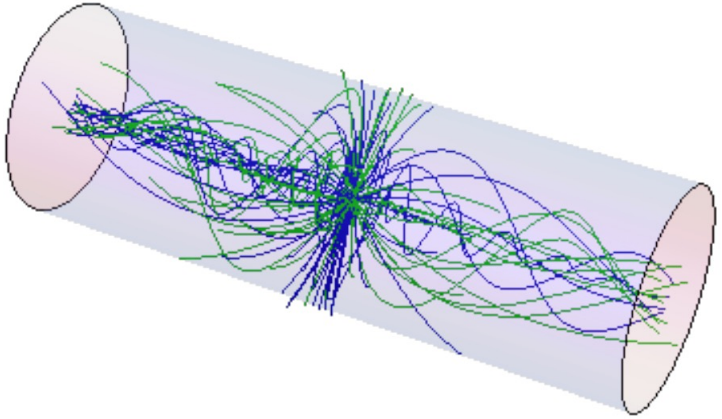


Using PNN, search sensitivity increased by 15-73% w.r.t. previous analysis

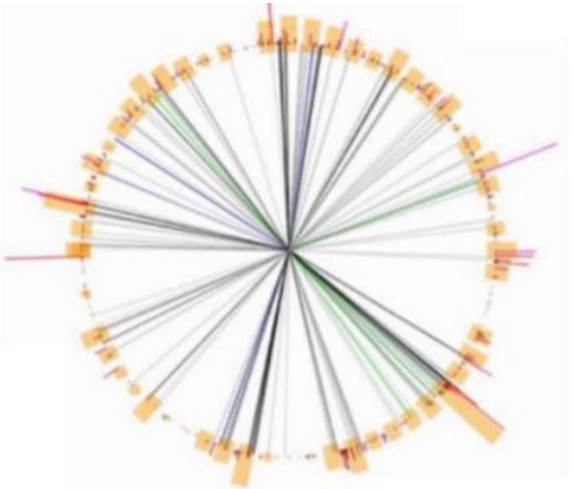
# Search for Soft Unclustered Energy Patterns

# Soft Unclustered Energy Patterns

- Motivated by Hidden Valley Model
  - [PRL 96 (2006) 231802], [Phys. Lett. B 651 (2007) 374], [Phys. Lett. B 696 (2011) 262]
  - Probe the dark sector extension of SM, dark parton showing similar to QCD
- Soft Unclustered Energy Patterns (SUEPs) searche for unique detector signatures
  - Large t' Hooft coupling: large number of particles and large angle emission in the shower
  - Final state looks like plain QCD, or pileup
    Signal events usually rejected by trigger

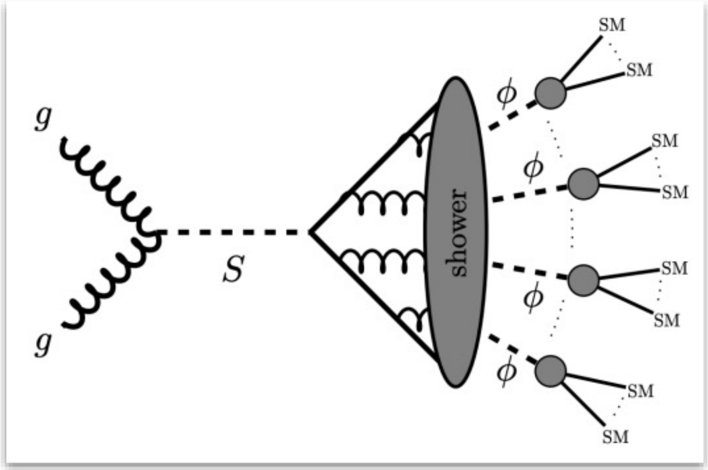


SUEP signal in lab frame (up) and CoM frame (down)



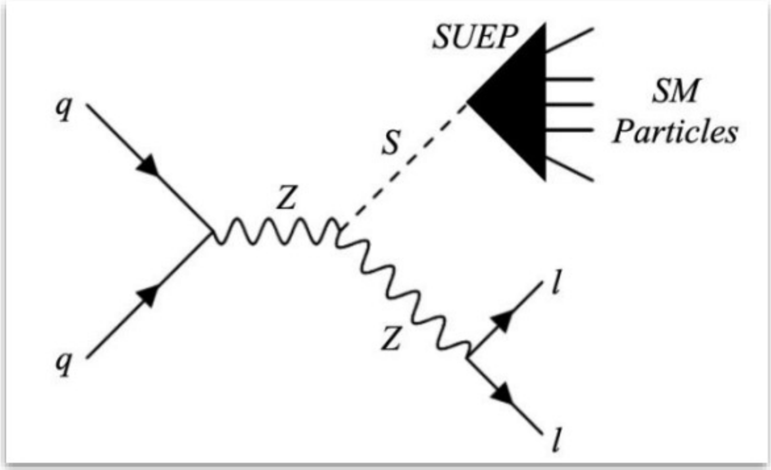
# Signal Models

### Gluon Fusion Channel (ggF)



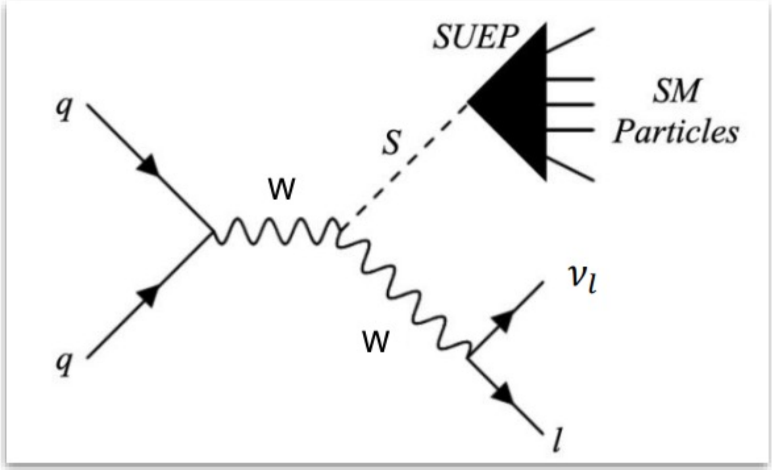
[PRL 133 (2024) 191902]

### Associated Production (ZH)



[EXO-23-003-pas]

### Associated Production (WH)

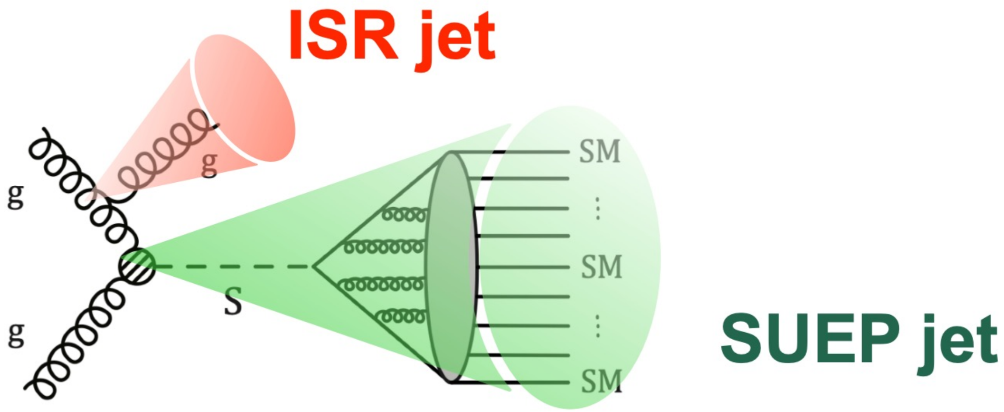


[EXO-24-030-pas]

- The scalar mediator (S) showers into several dark mesons (Φ).
  - Φ are the lightest bounded state of dark QCD, akin to SM pions.
  - Shower modeled with Boltzmann distribution with an effective temperature $T_D$

$$\frac{dN_\phi}{dp} \sim e^{-\sqrt{p^2+m_\phi^2}/T_D}$$

# Search strategy - ggF

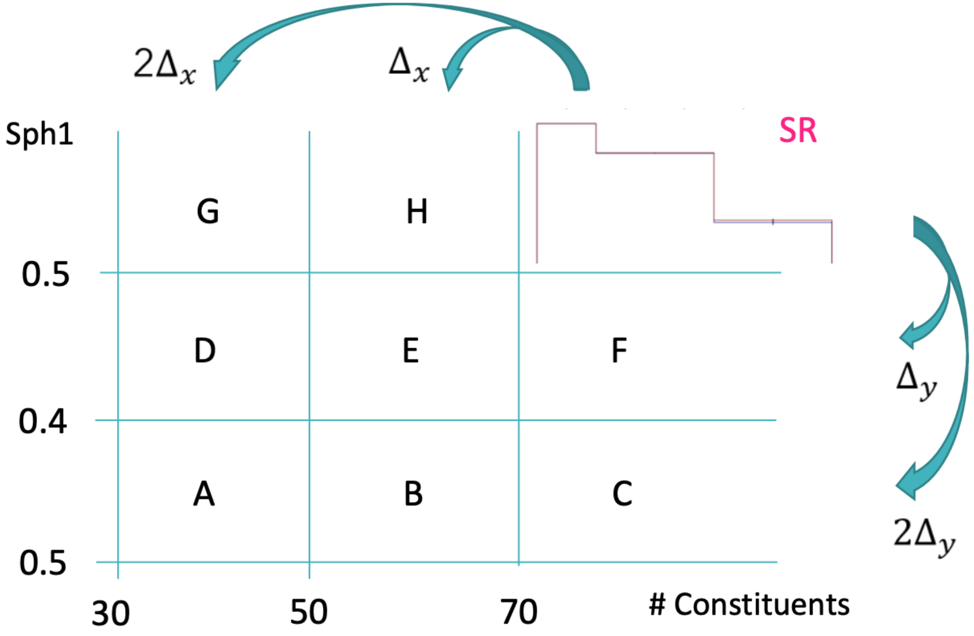


Signal looks like soft QCD, hardly pass trigger

Require high pT ISR jet to recoil the entire system

Cluster SUEP candidates from selected tracks using

anti-kt algorithm with R=1.5



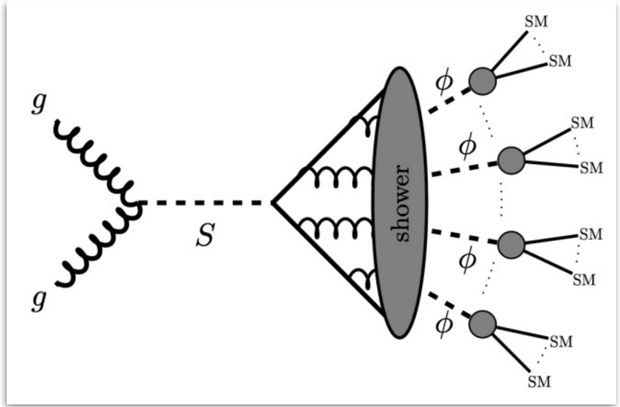
SUEP candidate signatures:

(1) cluster shape close to sphere

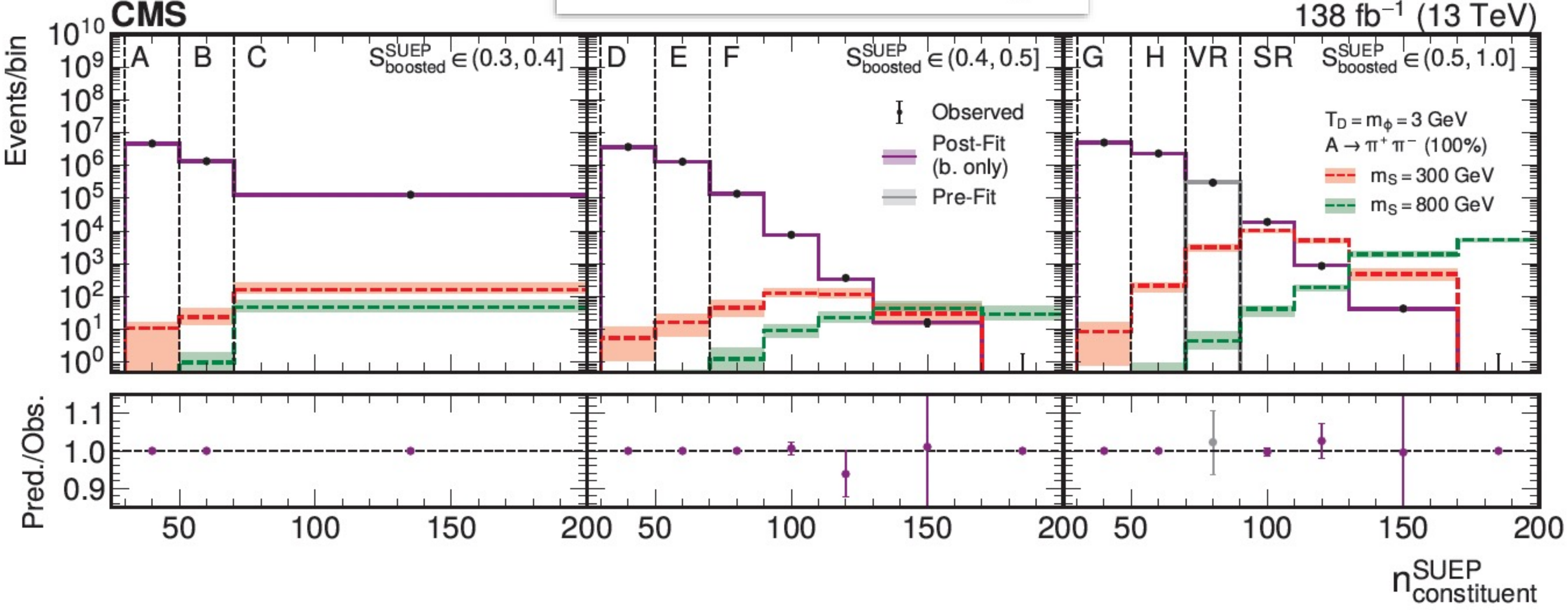
(2) high number of constituents in cluster

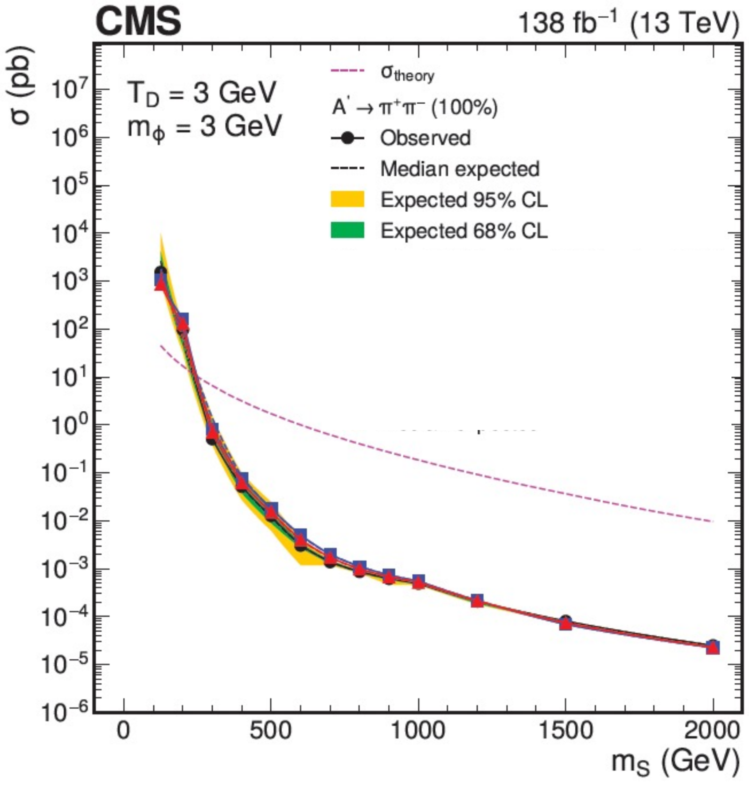
# Results - ggF

Gluon Fusion Channel (ggF)

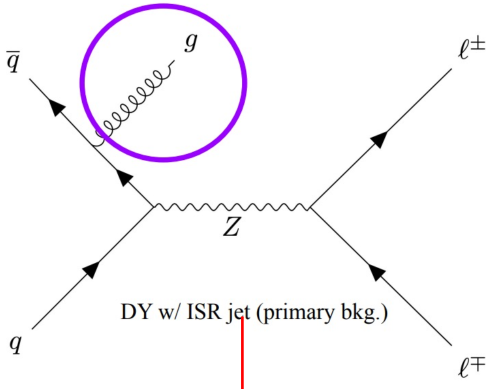


PRL 133 (2024) 191902

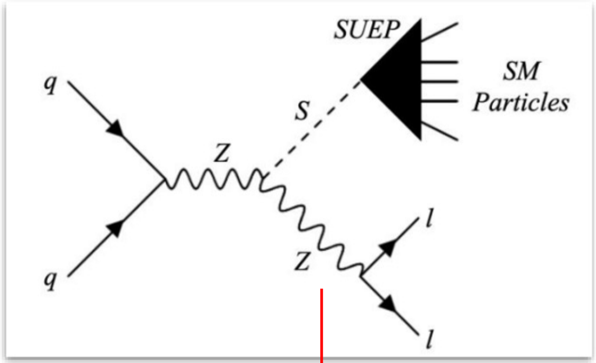


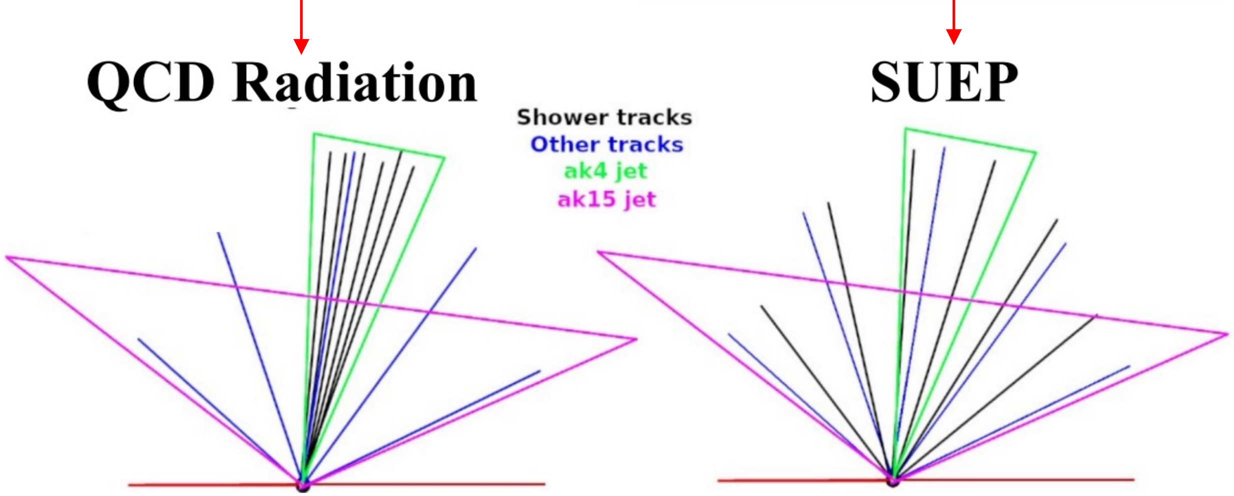


# Search strategy - ZH



Associated Production (ZH)



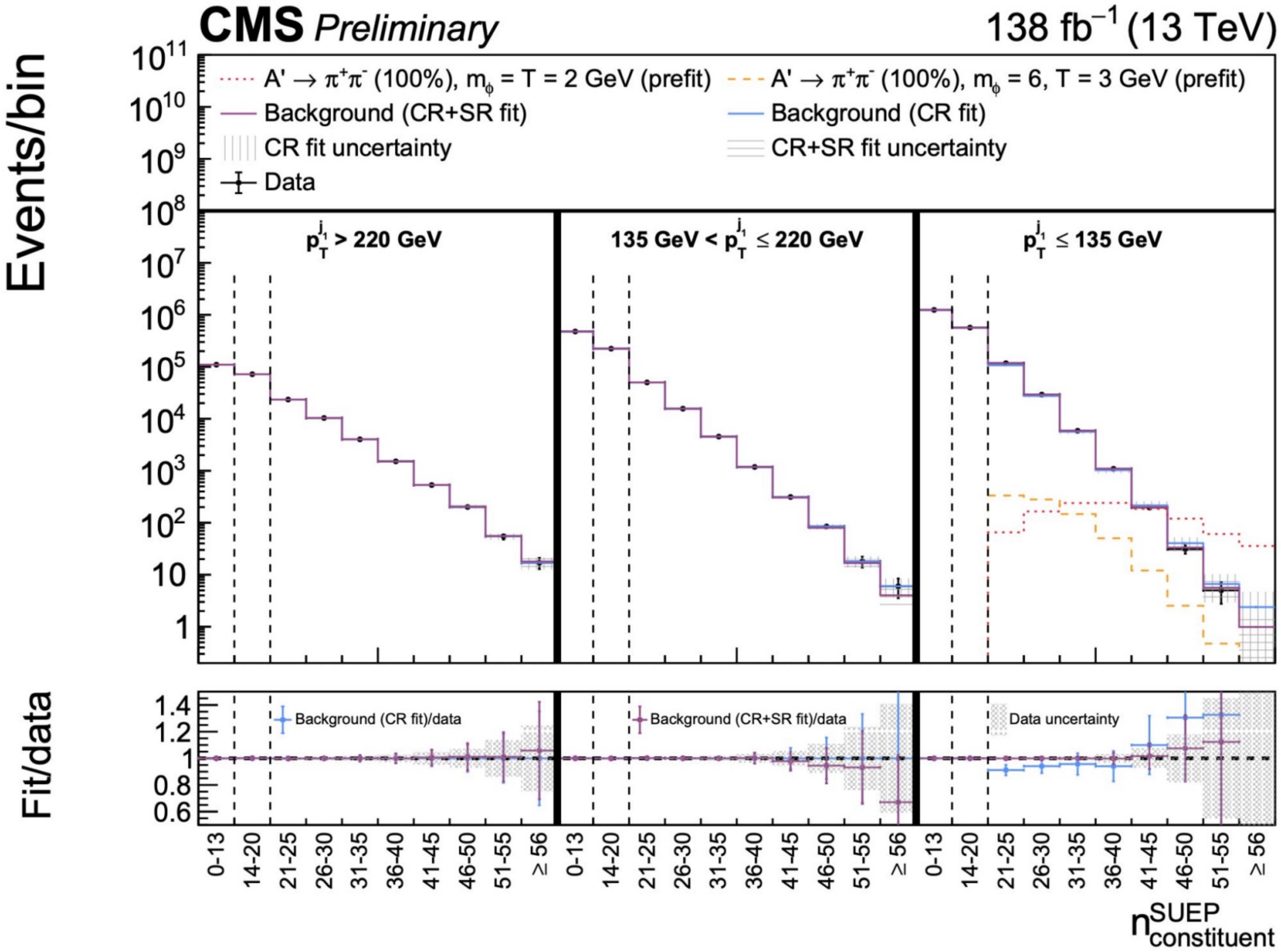


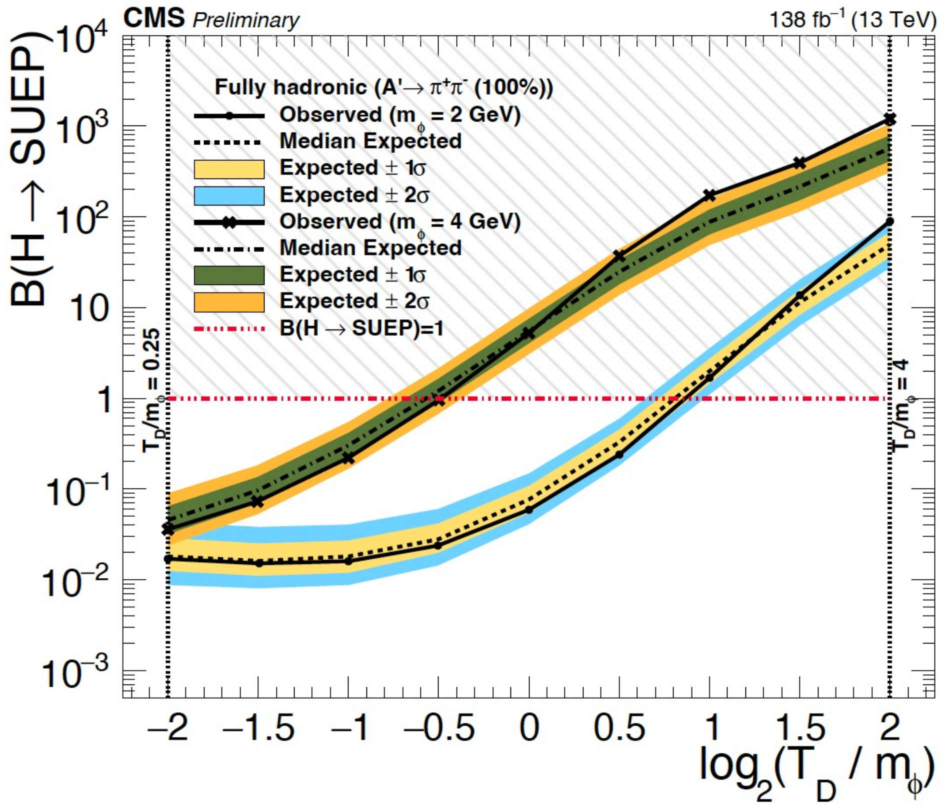
trigger on Z boson, i.e.
OS double electron / muon

| | QCD Radiation | SUEP |
|---|---|---|
| Ak4 | High pT | Low pT |
| Ak15 | Low NTracks | High NTracks |

ABCD background prediction method using Ak4 jet pT and AK15 jet number of consituents

# Results - ZH

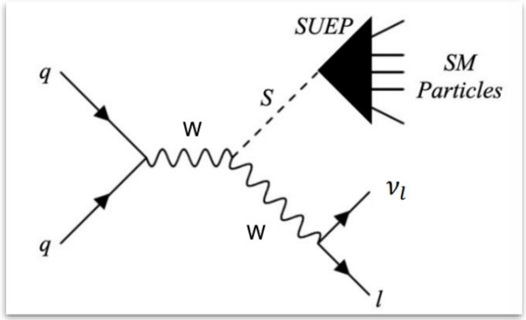


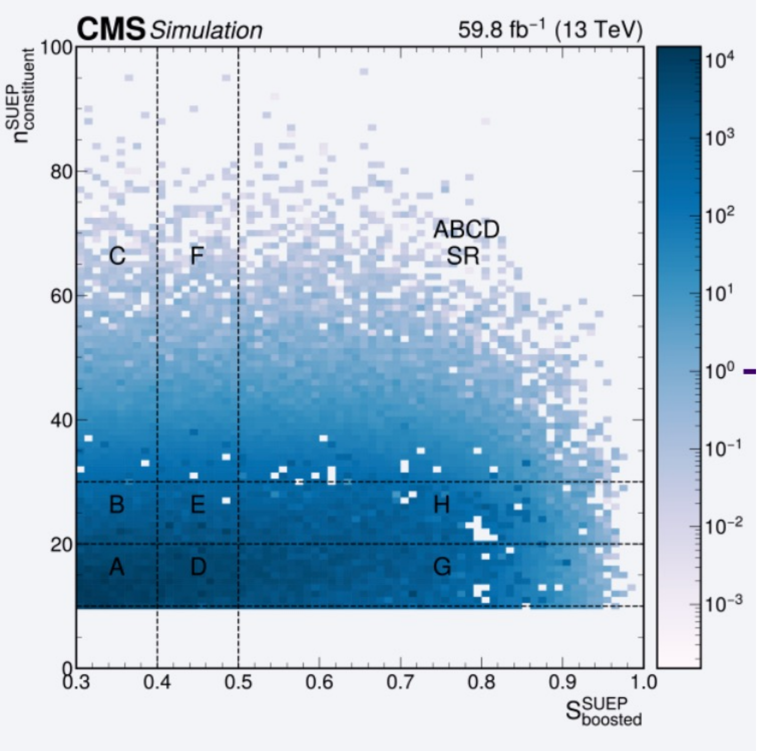


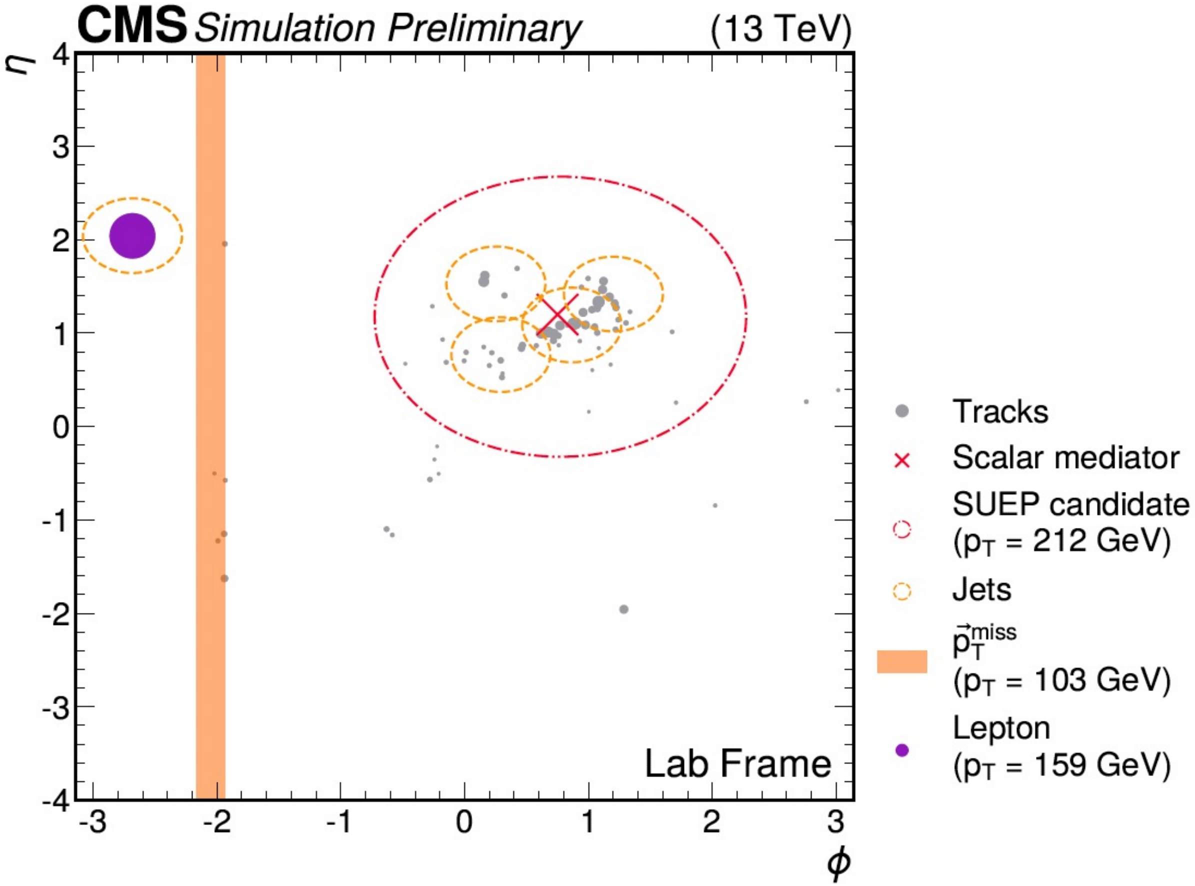
EXO-23-003-pas

# Search strategy - WH

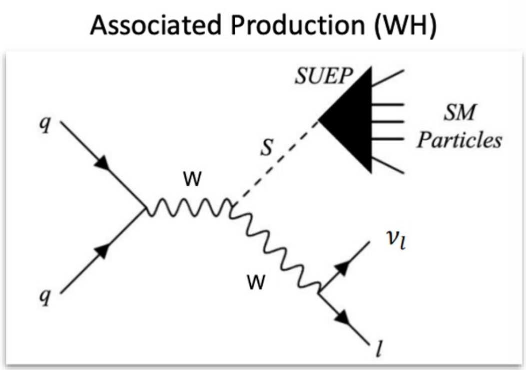
Associated Production (WH)



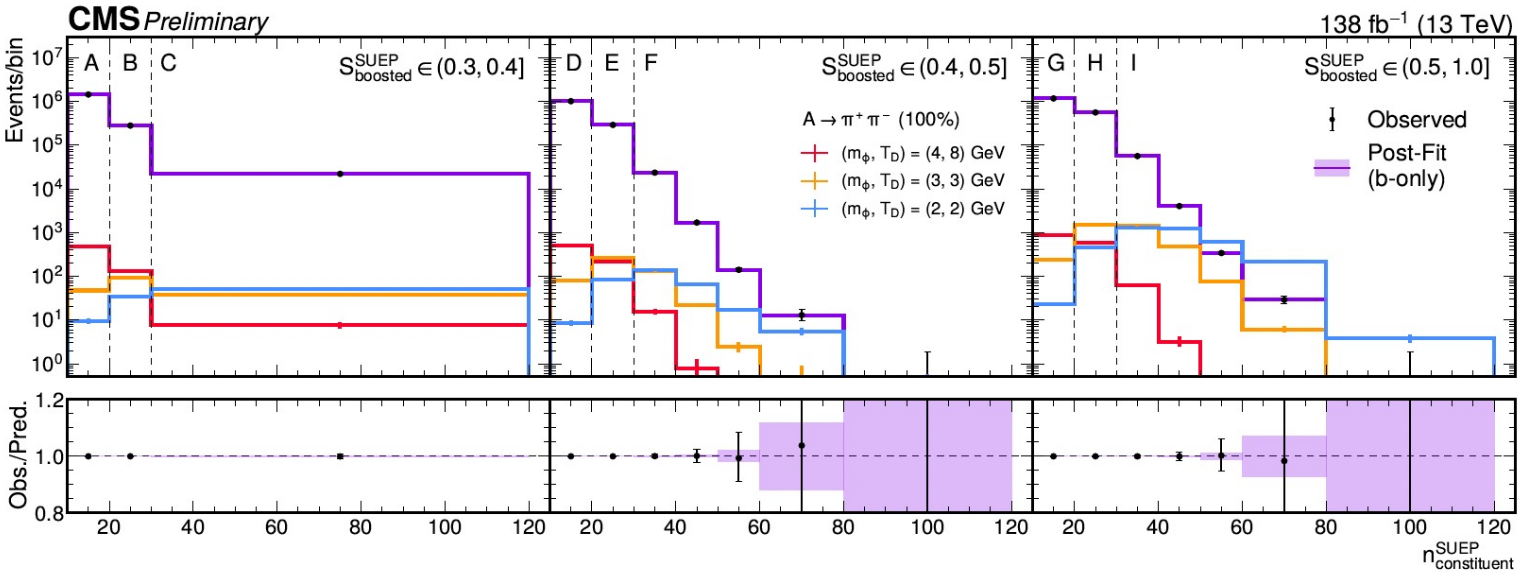


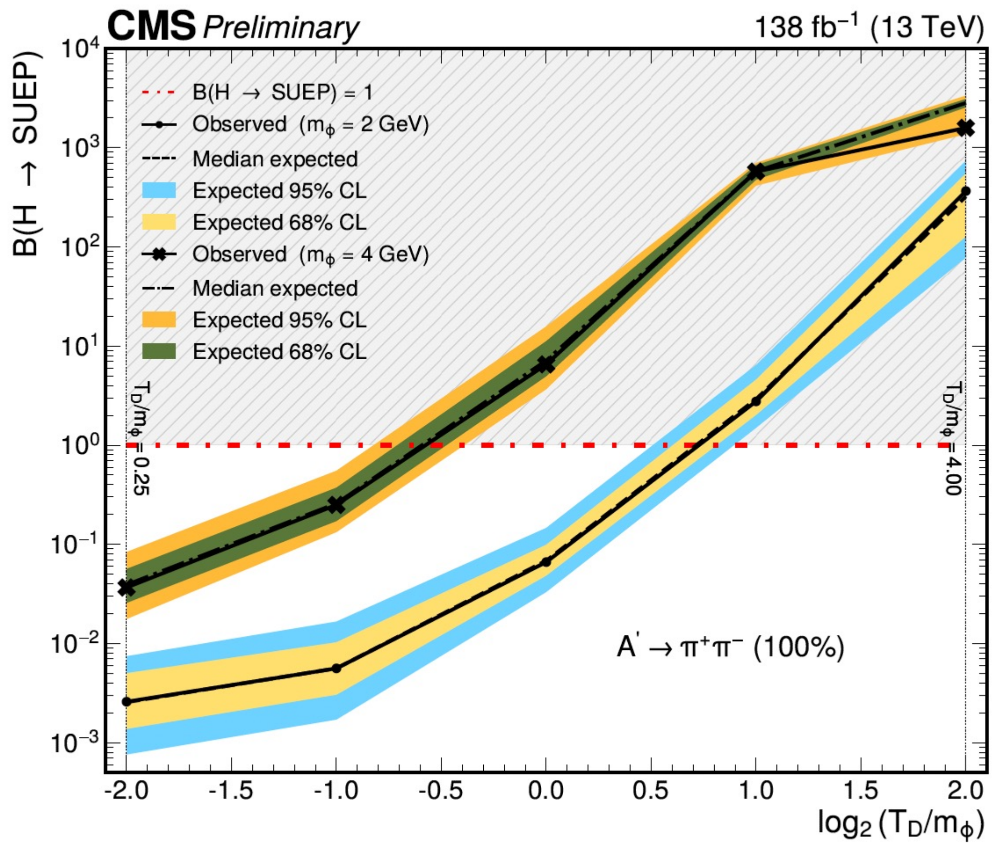


# Results - WH

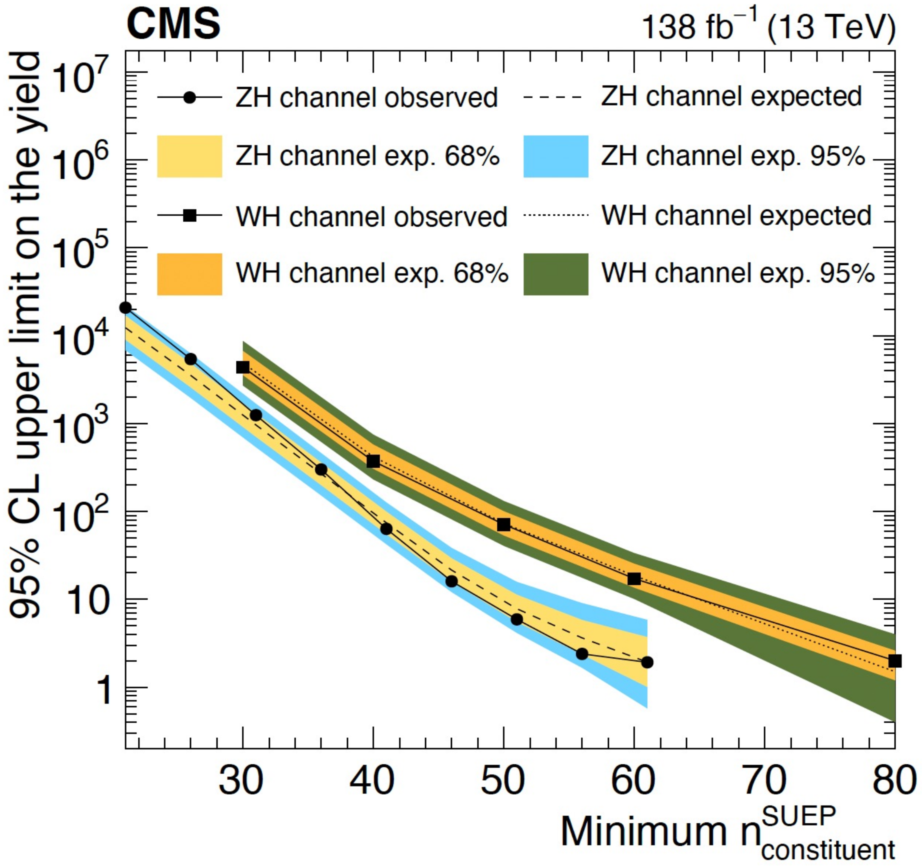

Associated Production (WH)

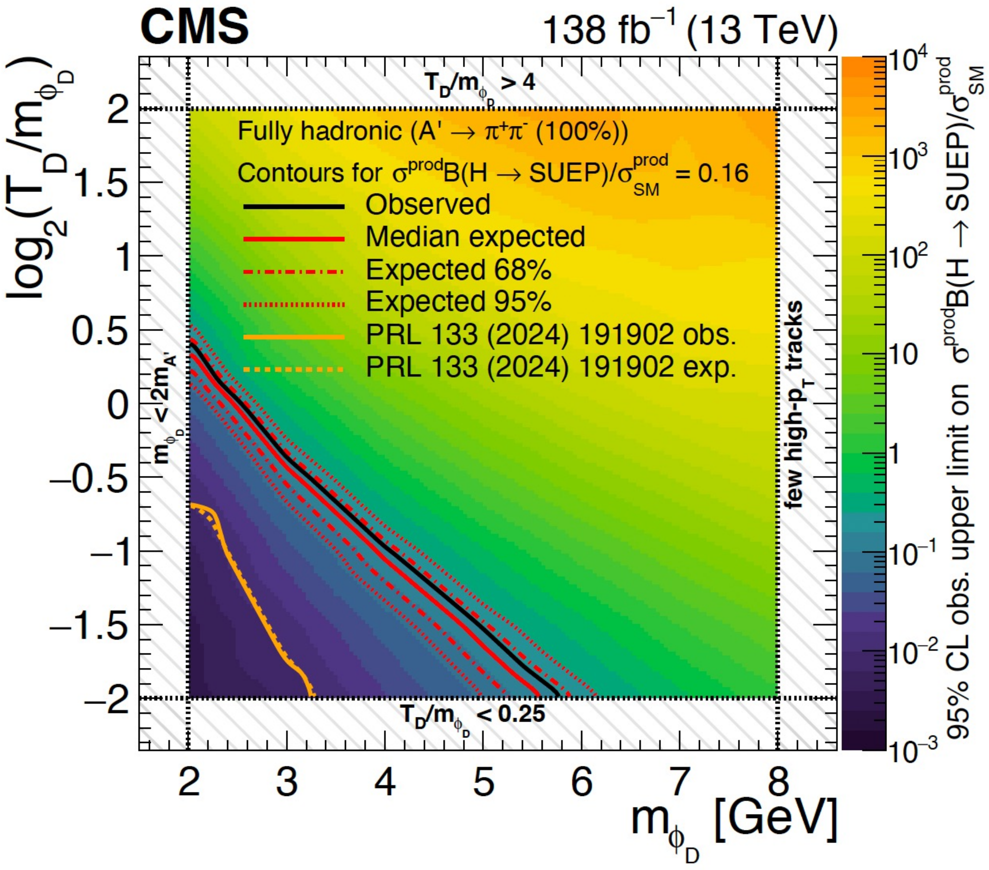
EXO-24-030-pas





# Combined results



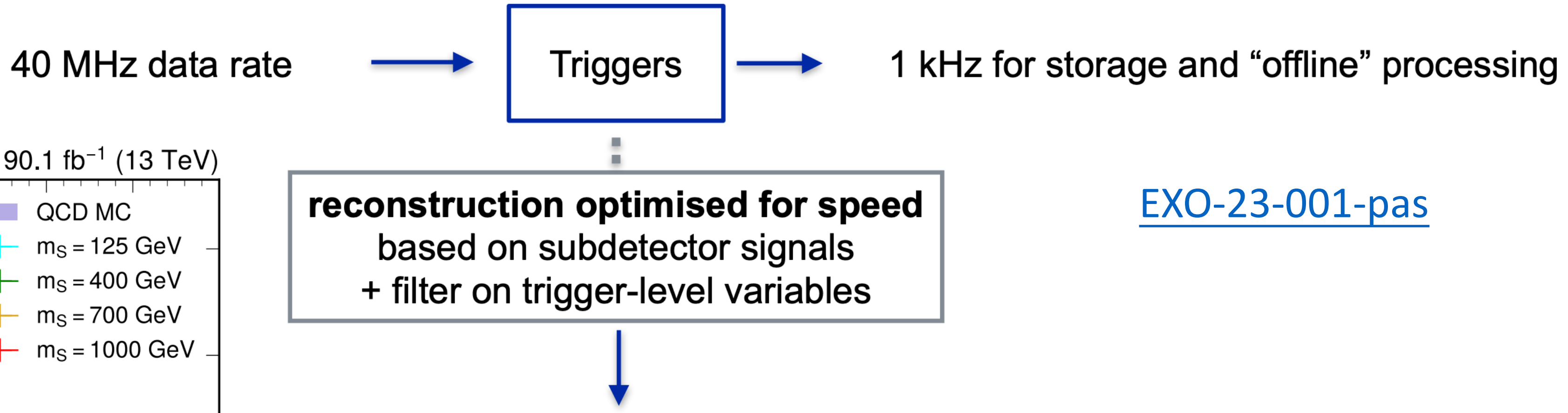


arXiv:2604.05996 combined results for SUEP searches

# ggH with HLT scouting

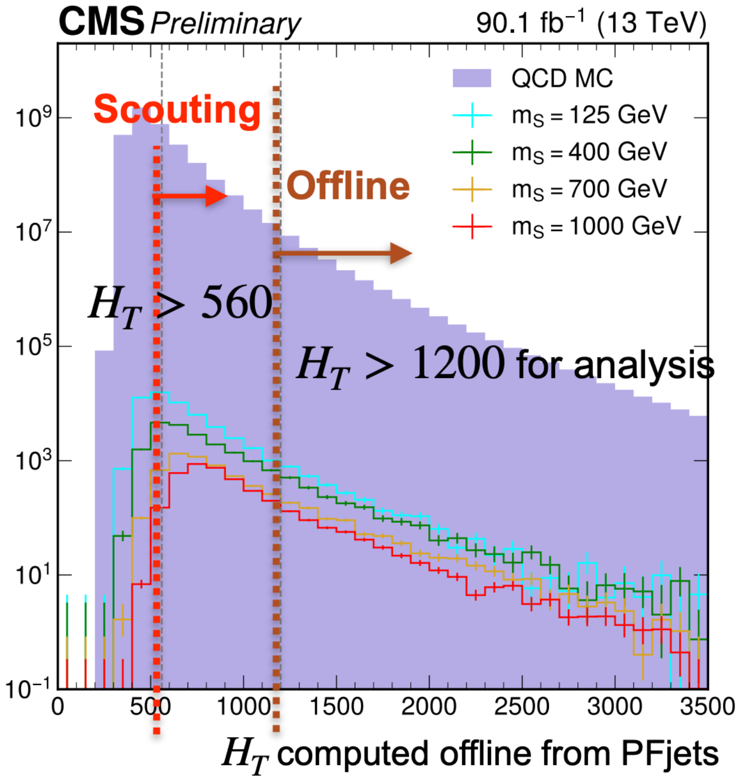
**Challenge for SUEP search:**
no dedicated trigger-level variables for SUEP signals

**Strategy:**
use data selected by **high $H_T$ triggers** (high hadronic activities)



40 MHz data rate → Triggers → 1 kHz for storage and "offline" processing

**reconstruction optimised for speed**
based on subdetector signals
+ filter on trigger-level variables



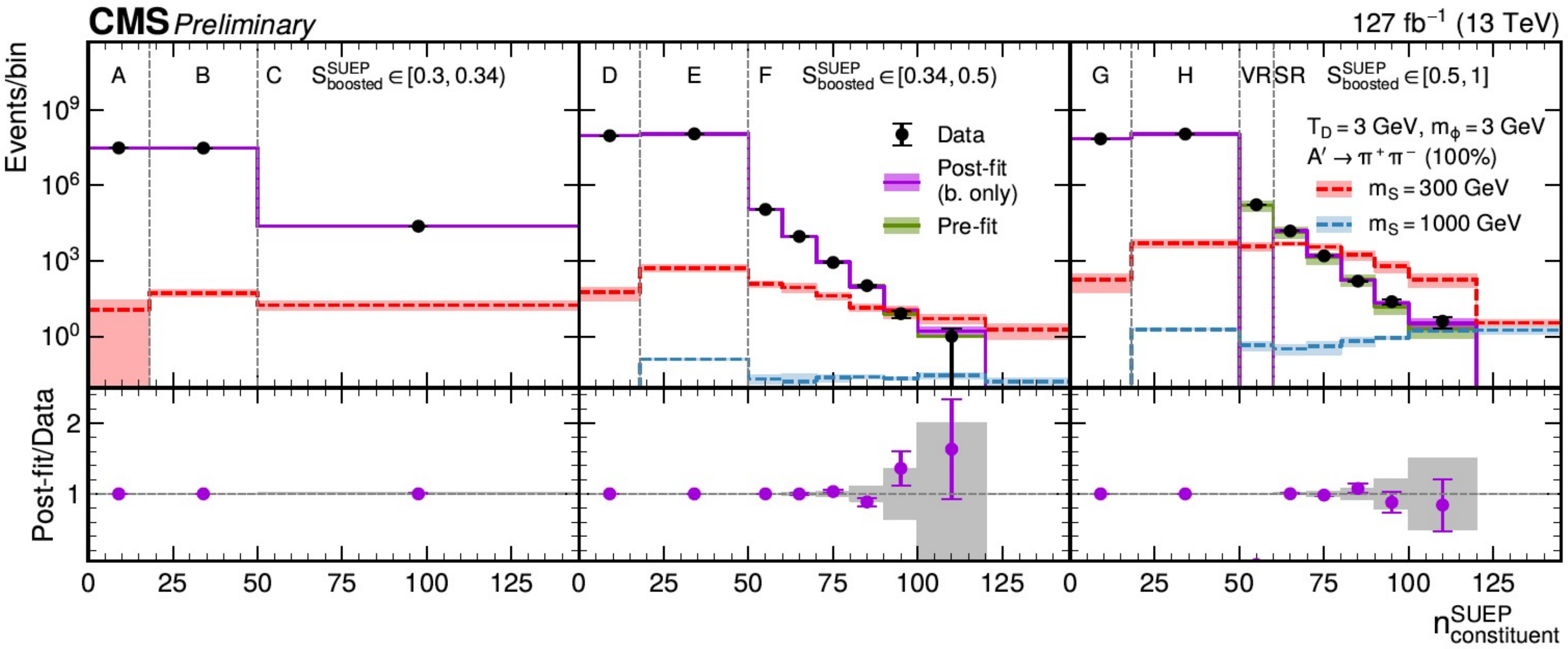
[EXO-23-001-pas](EXO-23-001-pas)

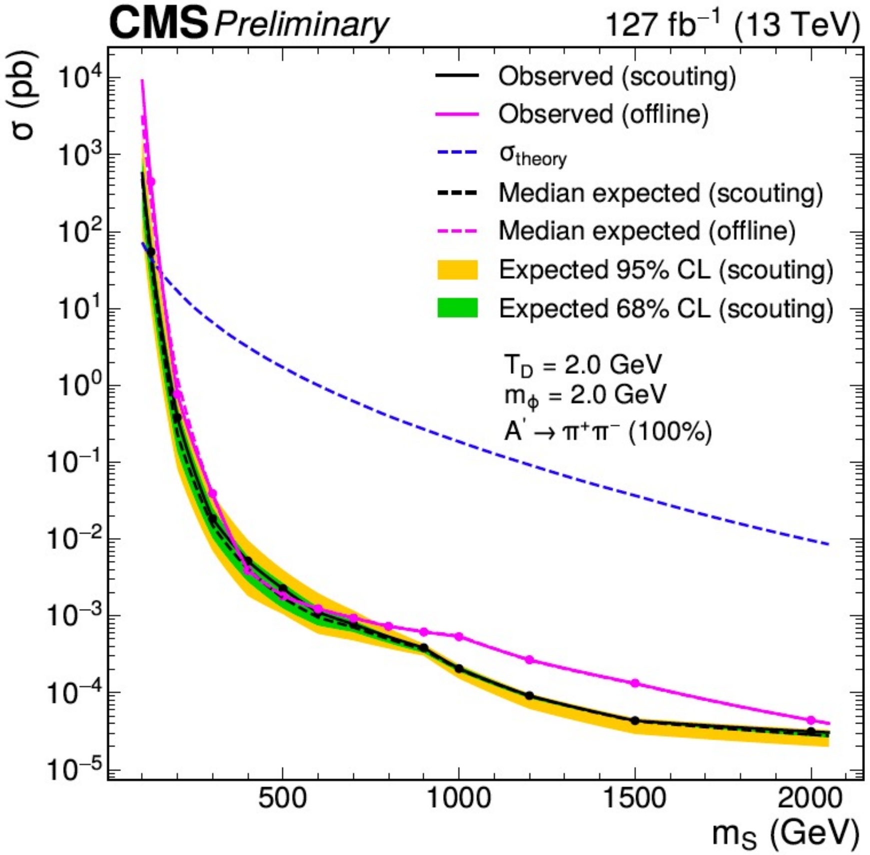
**Scouting** stream:
directly store the reconstructed objects at HLT

$H_T$ cut ~ 1000 GeV for "offline" analysis

Drop the raw data contents in scouting
→ 100-1000 times smaller event size
→ Allow for higher trigger rates (bandwidth = event size × trigger rate)
→ **Lower trigger threshold** (calojet $H_T > 410$ GeV)

# ggH with HLT scouting



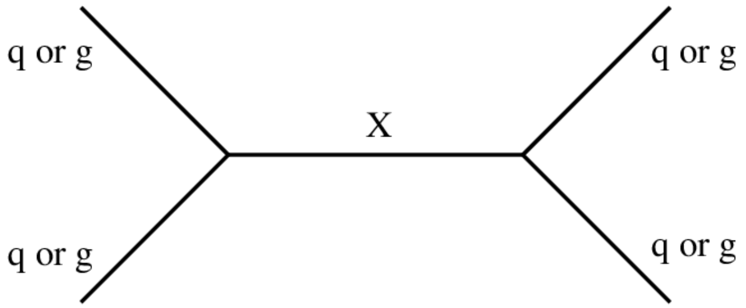


Better limits with HLT scouting

EXO-23-001-pas

# General search
# dijet and 4-jet resonance

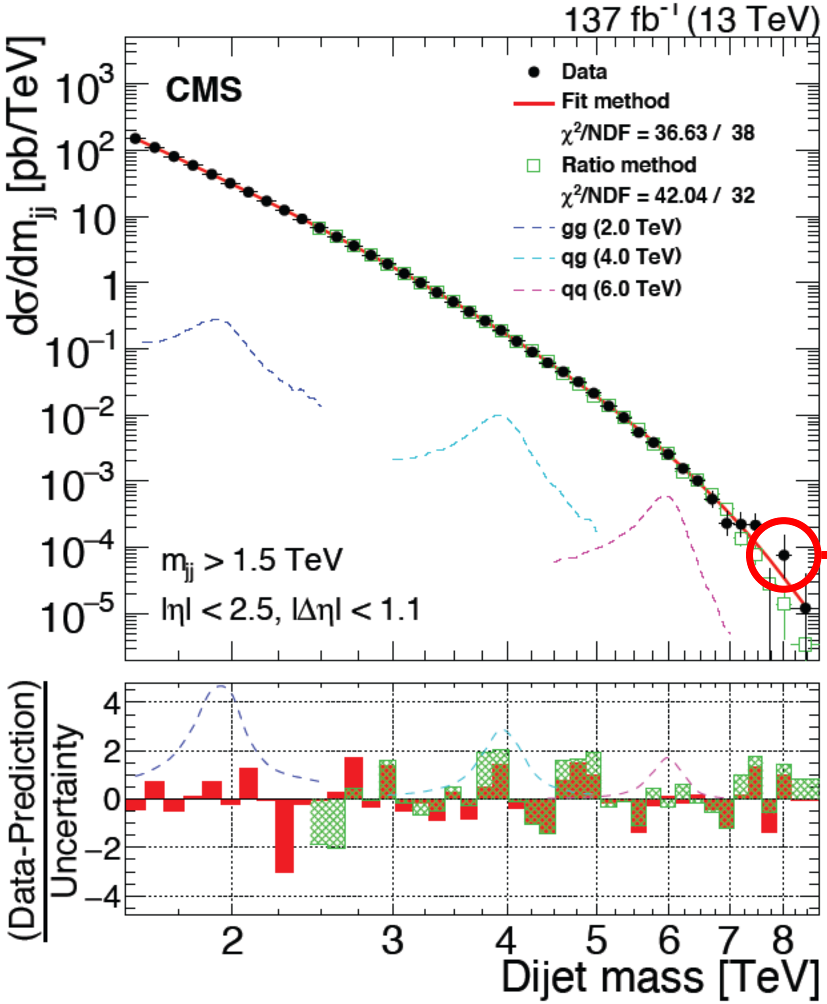
# Search for dijet resonance

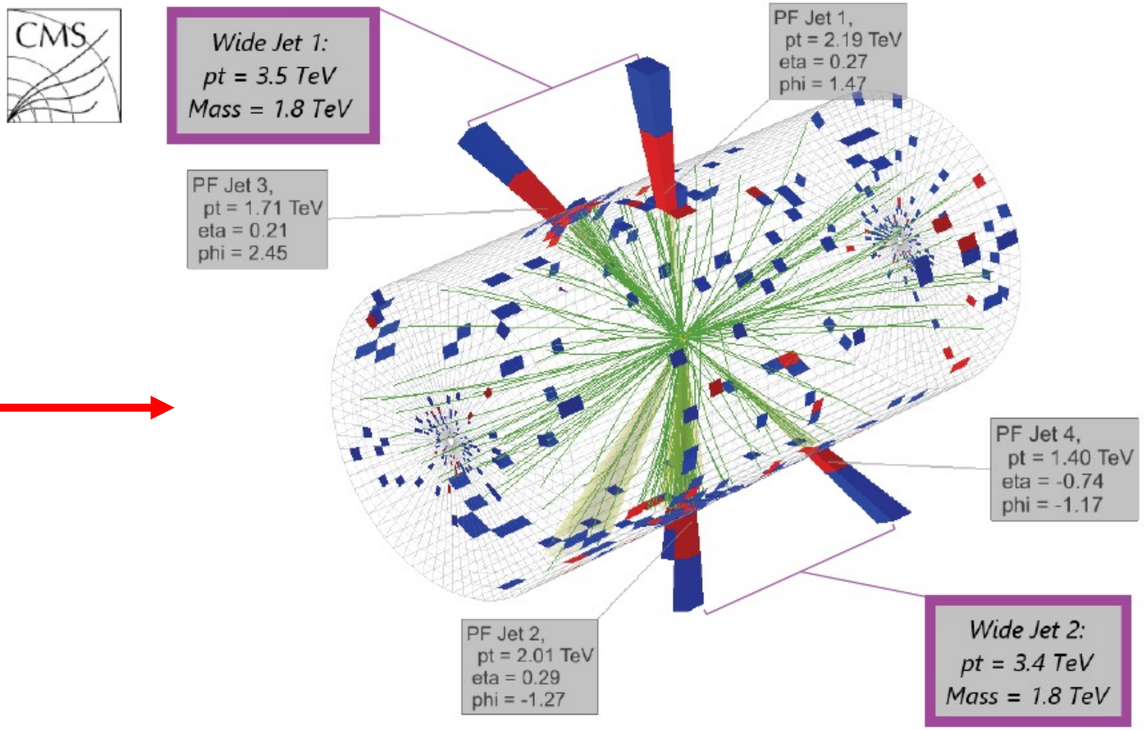


[1] UA1 Collaboration, Two-jet mass distributions at the CERN proton-antiproton collider, Phys. Lett. B 209 (1988) 127.
[2] CDF Collaboration, Two-jet invariant mass distribution at √s=1.8 TeV, Phys. Rev. D 41 (1990) 1722.
[3] CMS Collaboration, Search for Dijet Resonances in 7 TeV pp Collisions at CMS, Phys.Rev.Lett. 105 (2010) 211801.

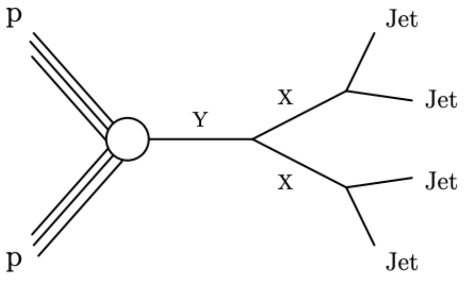
- General search for resonances of two wide jets
- Long history in hadron colliders
  - CERN SPS [1] -> Fermilab Tevatron [2] -> CERN LHC [3]
- Benchmark models
  - New gauge bosons [Rev. Mod. Phys. 58 (1986) 1065]
  - Randall–Sundrum gravitons [PRL 83 (1999) 4690]
  - Dark matter mediators [JHEP 1507 (2015) 089]
- Search strategy
  - Reconstruct two wide (AK11) jets from the two leading AK4 jets in each event, for final-state radiations
  - Fit the dijet invariant mass in data with a smooth curve modeled with QCD

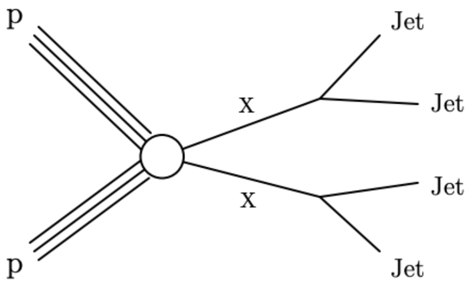
# Results

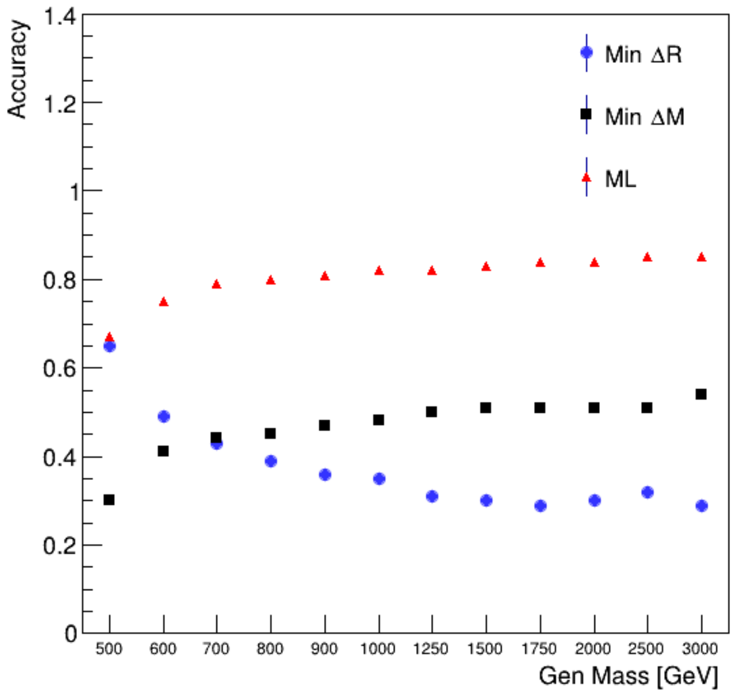

137 fb$^{-1}$ (13 TeV)
CMS
Data
Fit method
$\chi^2$/NDF = 36.63 / 38
Ratio method
$\chi^2$/NDF = 42.04 / 32
gg (2.0 TeV)
qg (4.0 TeV)
qq (6.0 TeV)
$m_{jj}$ > 1.5 TeV
$|\eta|$ < 2.5, $|\Delta\eta|$ < 1.1
$d\sigma/dm_{jj}$ [pb/TeV]
$10^3$
$10^2$
10
1
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
(Data-Prediction) / Uncertainty
4
2
0
−2
−4
2
3
4
5
6
7
8
Dijet mass [TeV]


CMS
Wide Jet 1:
pt = 3.5 TeV
Mass = 1.8 TeV
PF Jet 1,
pt = 2.19 TeV
eta = 0.27
phi = 1.47
PF Jet 3,
pt = 1.71 TeV
eta = 0.21
phi = 2.45
PF Jet 4,
pt = 1.40 TeV
eta = -0.74
phi = -1.17
PF Jet 2,
pt = 2.01 TeV
eta = 0.29
phi = -1.27
Wide Jet 2:
pt = 3.4 TeV
Mass = 1.8 TeV

# Search for paired dijet resonance







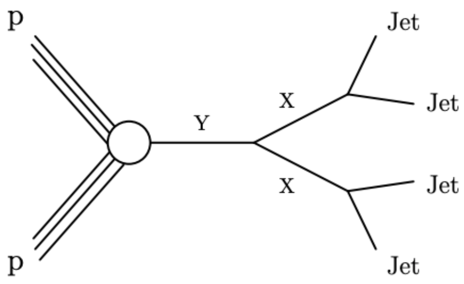
- General search for resonances of paired dijets
- Benchmark models
  - Resonant production: Suu diquark model [ref]
  - Nonresonant production: RPV top squark model [ref]
- Three possible pairings of dijets:

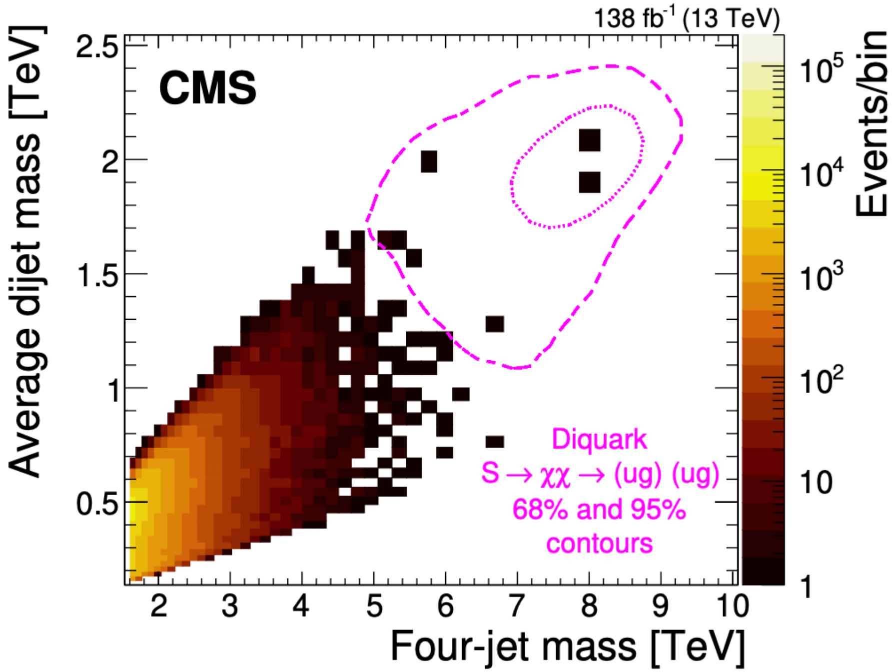
  (J12, J34), (J13, J24) and (J14, J23)
- Traditional pairing:
  - Minimize dR of the two jets in dijets

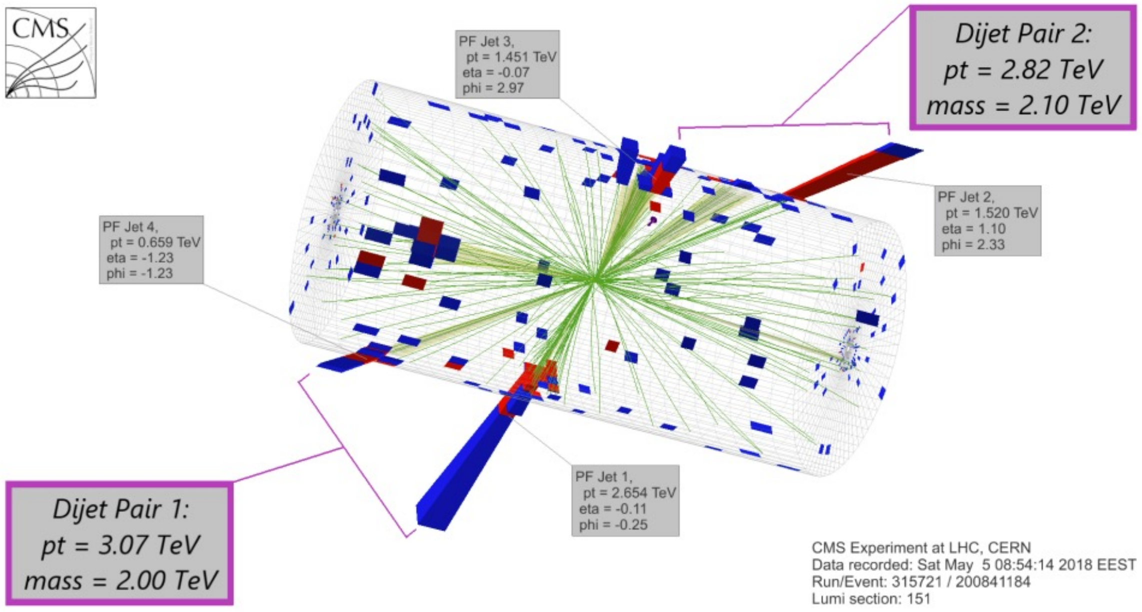
    Works well for boosted signals (i.e. low mass points)
  - Minimize dijets mass asymmetry $\frac{|M_{x1} - M_{x2}|}{M_{x1} + M_{x2}}$

    Relatively flat accuracy for different mass points

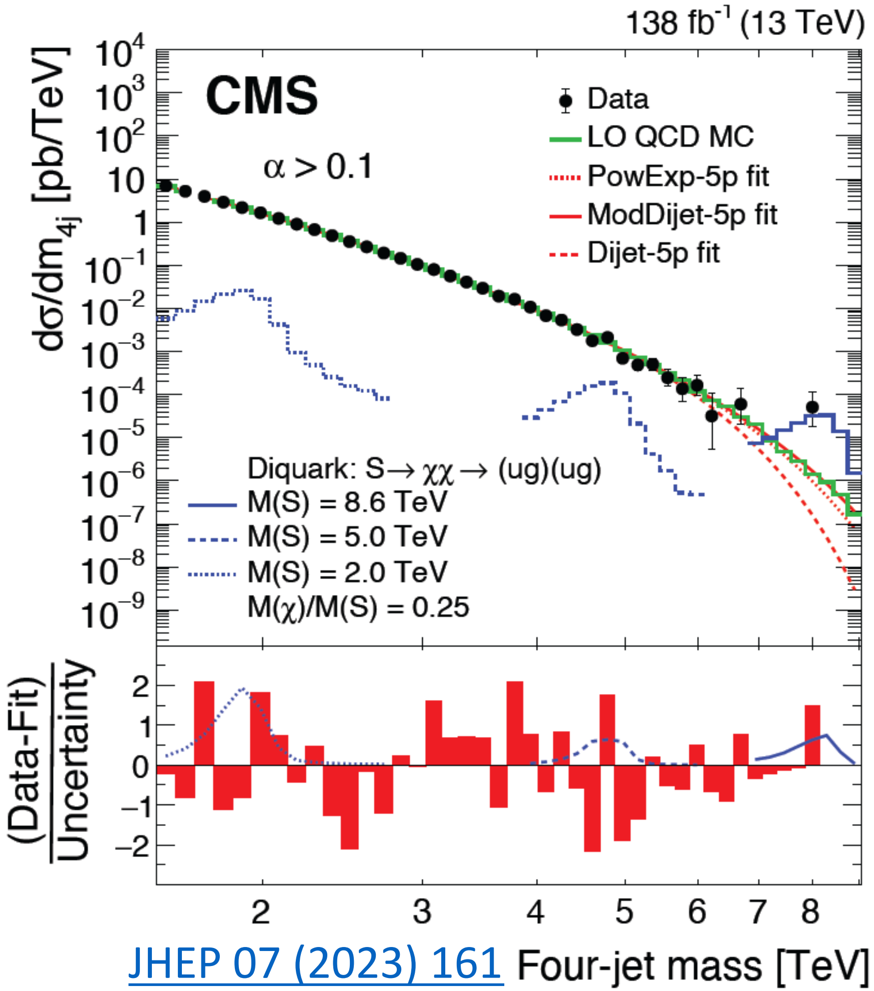
# Two candidate event at 8 TeV



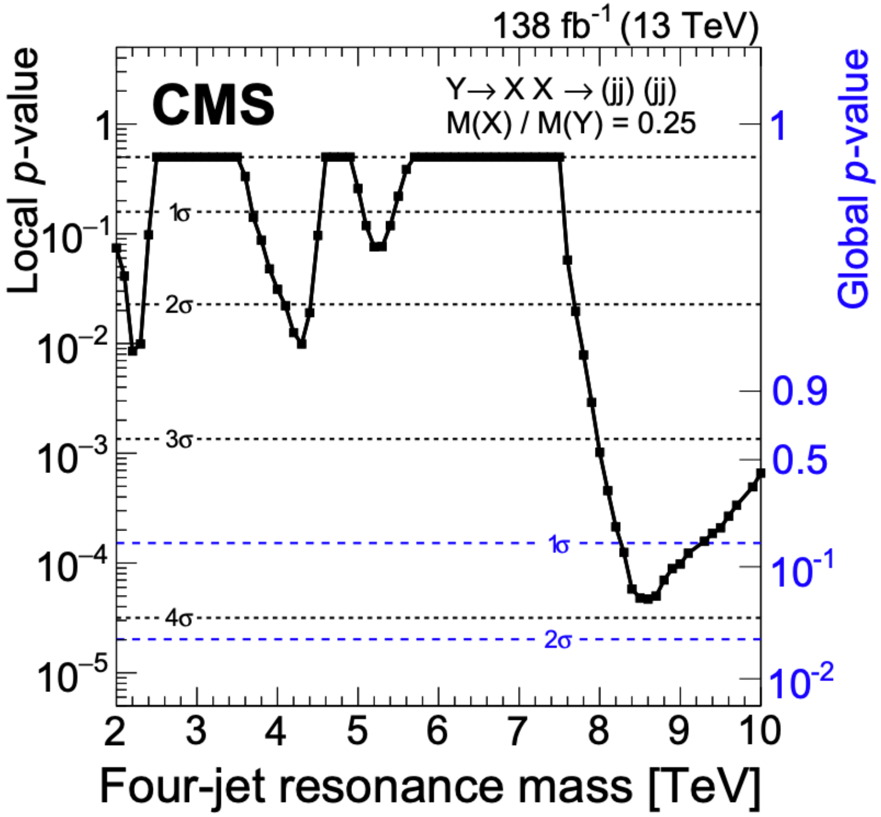




# Results

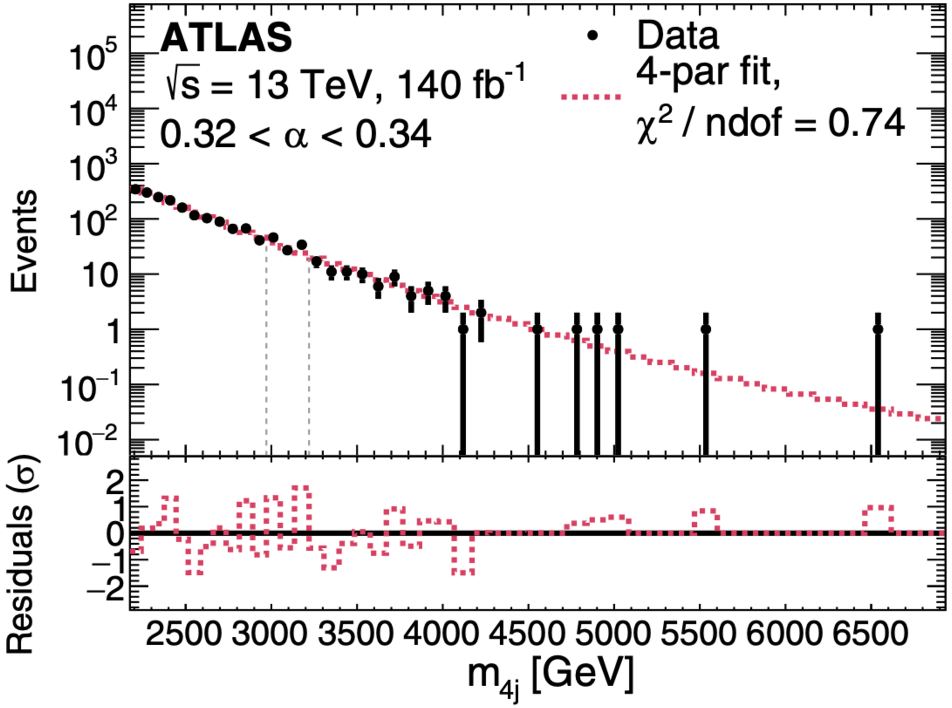


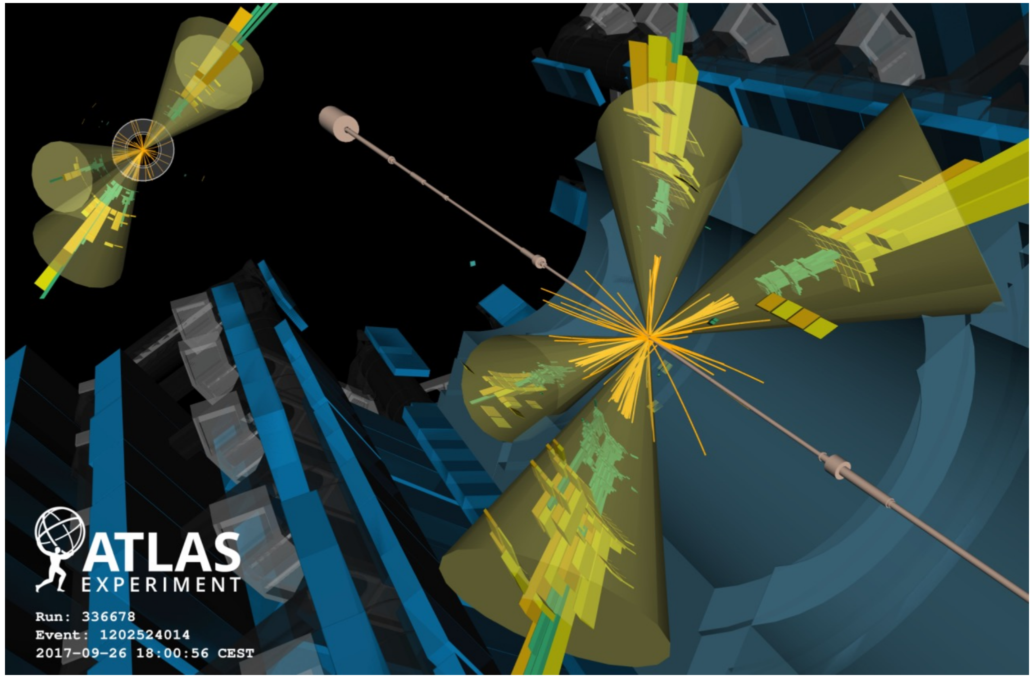
JHEP 07 (2023) 161



Two candidate events at 8 TeV result in a local significant of 3.9σ, highlighted in CERN news

# ATLAS results

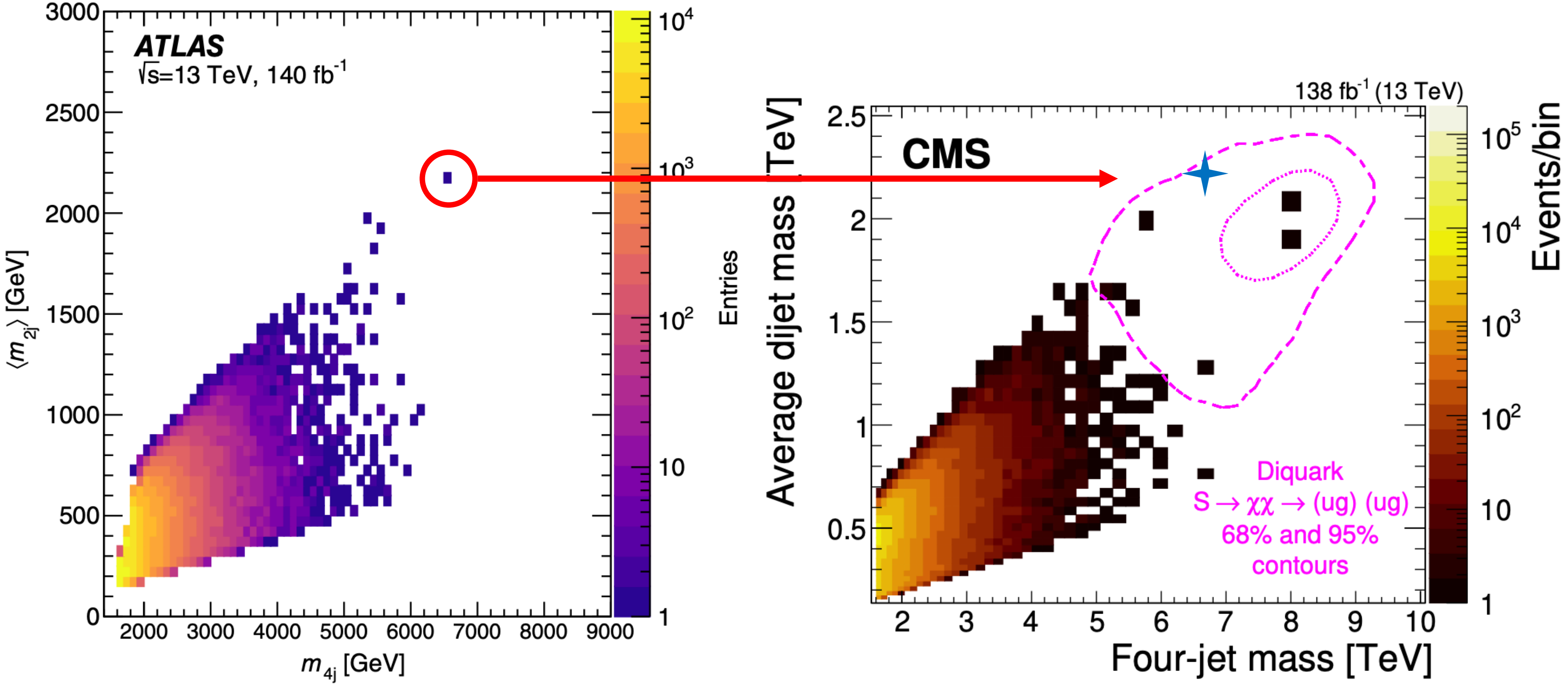




The highest four jet mass observed by ATLAS in Run2 is 6.5 TeV

PRD 108 (2023) 112005

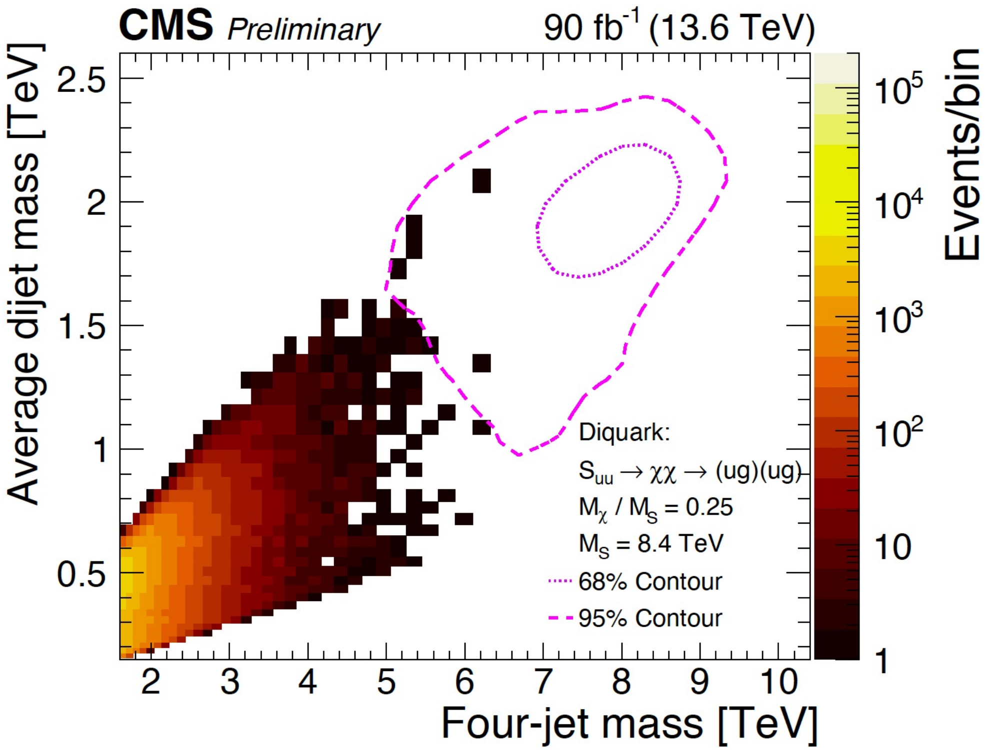
# ATLAS results

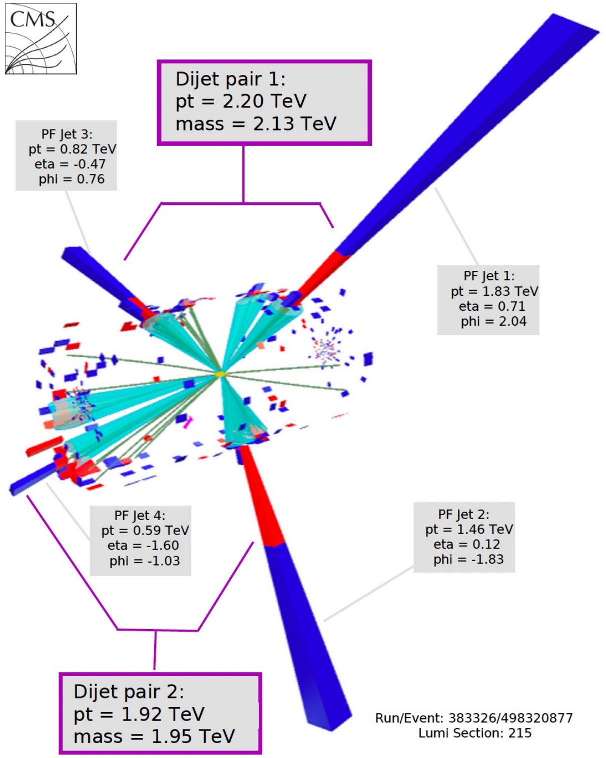


PRD 108 (2023) 112005

JHEP 07 (2023) 161

# Run3 results



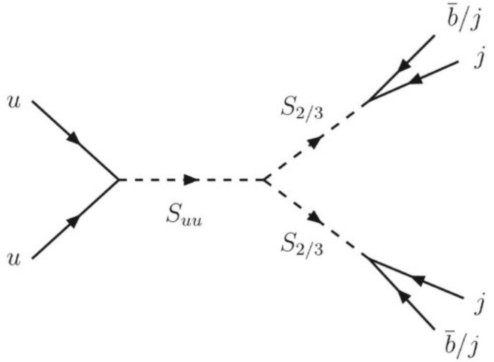


Latest result using 2024 data (CMS 2022, 2023 data unusable because of trigger prefiring)

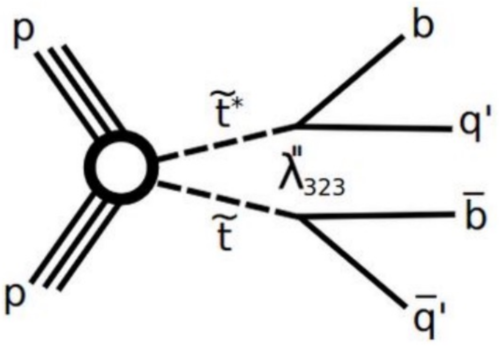
The highest four jet mass observed is 6.5 TeV EXO-25-004-pas

# Search for paired dijet with b-tag

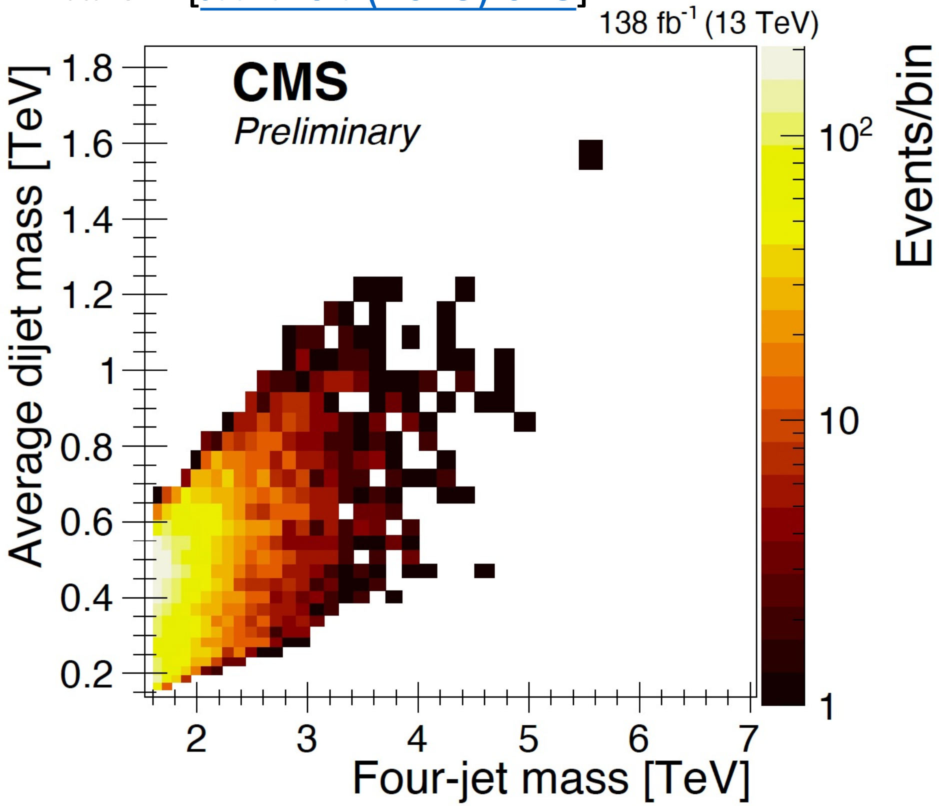
**Diquark-to-diquark (D2D)**



**RPV**



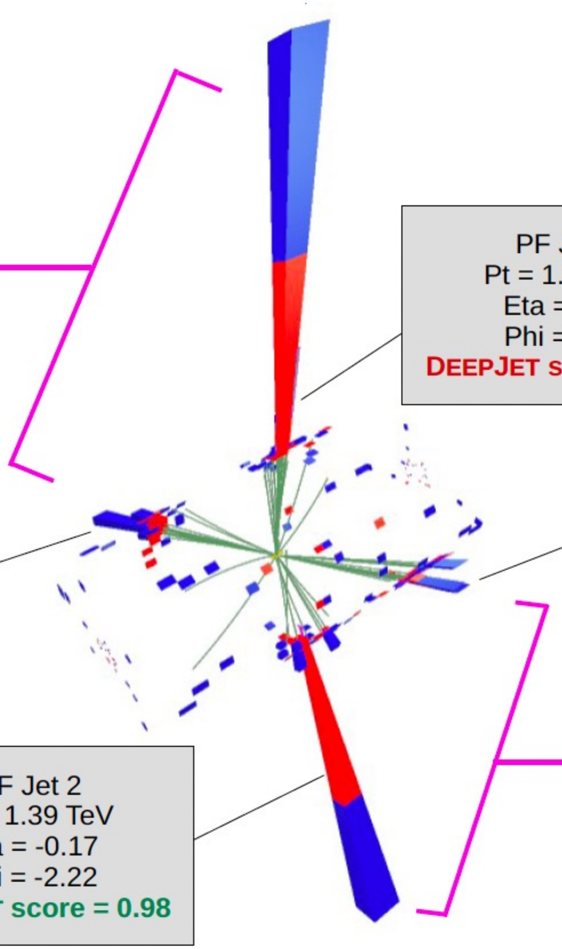
Benchmark models
D2D [arXiv:1912.13155]
RPV [JHEP 04 (2013) 028]



EXO-24-039-pas

# Results

EXO-24-039-pas



*Dijet Pair 1*
*Pt = 2.31 TeV*
*Mass = 1.54 TeV*

PF Jet 1
Pt = 1.98 TeV
Eta = 0.43
Phi = 1.00
**DEEPJET score = 0.14**

PF Jet 4
Pt = 0.48 TeV
Eta = -0.77
Phi = 0.11
**DEEPJET score = 0.61**

PF Jet 3
Pt = 0.87 TeV
Eta = 1.11
Phi = -2.40
**DEEPJET score = 0.02**

*Dijet Pair 2*
*Pt = 2.25 TeV*
*Mass = 1.54 TeV*

PF Jet 2
Pt = 1.39 TeV
Eta = -0.17
Phi = -2.22
**DEEPJET score = 0.98**

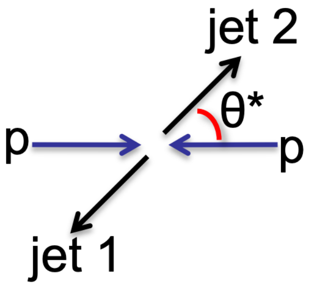
CMS Experiment at LHC, CERN
Run/Event : 320010 / 23731487
Lumi section: 18

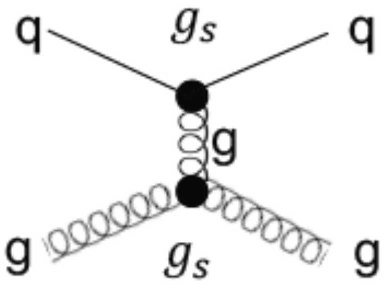
The highest four jet mass observed is 5.5 TeV, local significance ~2σ

# Dijet Search with Angular Analysis

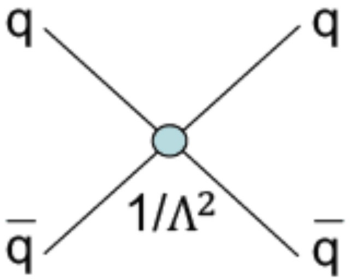
Dijet angular distributions probe parton-parton scattering angle

$$\chi_{\text{dijet}} = e^{|y_1-y_2|} \sim \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$





QCD background
- flat distribution
- independent of dijet mass



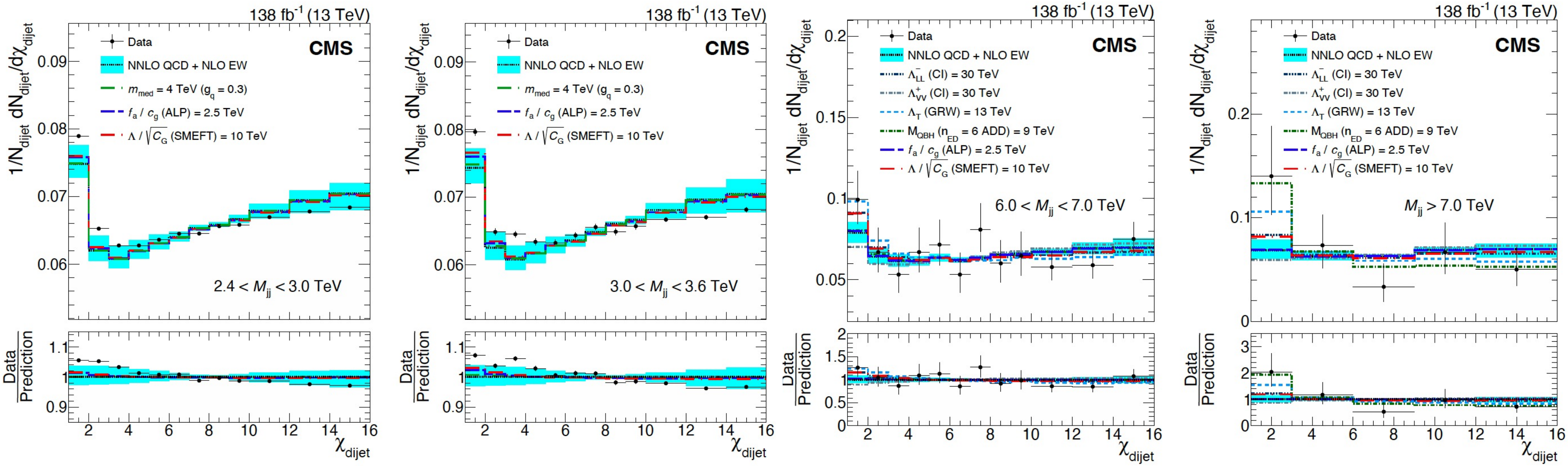
Signal
- peaks at low $\chi$
- Increase at high dijet mass

Benchmark models

- Quark compositeness
  [PRL 50 (1983) 811]
- Dark matter simplified model
  [arXiv:1506.03116]
- Quantum black holes (QBHs)
  [Phys. Lett. B 441 (1998) 96]
- Axion-like particles (ALPs)
  [Phys. Lett. B 169 (1986) 73]

arXiv:2603.25458

# Results



Two largest excesses in 3–3.6 TeV and >7 TeV bins, with local significance of 2.0 and 2.4σ

arXiv:2603.25458

# Summary

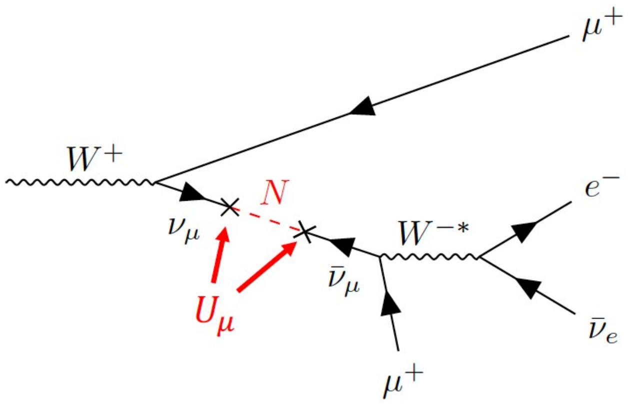
- Presented latest and interesting results of exotic searches by CMS and ATLAS
  - Search for heavy fermions - first search using L1 scouting data
  - Search for heavy gauge bosons - novel reconstruction and signal discrimination techniques
  - Search for Soft Unclustered Energy Patterns - unique detector signature, using HLT scouting data
  - General search - dijet and 4-jet resonance - observed hints of excess
- Thanks for your attention

# Backup Slides

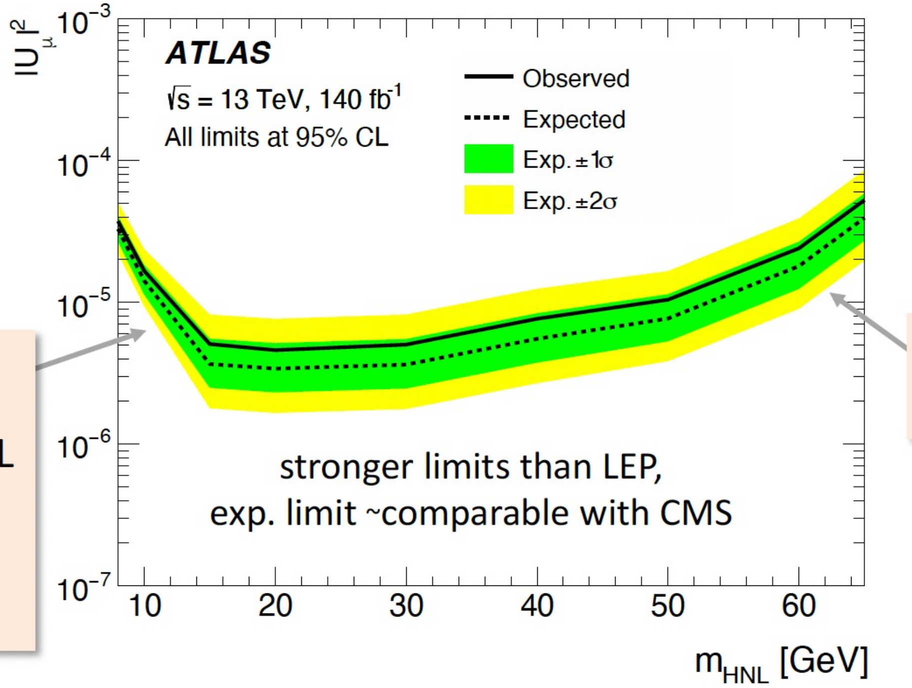
# Search for Majorana neutrino

**Heavy Neutral Lepton *N*** (Majorana neutrino) **mixing with SM neutrinos.**
Simplified model: *N* mixing with 1 lepton flavor
Free params: $m_{HNL}$, $U_\ell$ mixing param ($\ell = e, \mu$)
Focus on prompt decays, $e^\pm e^\pm \mu^\mp$ and $\mu^\pm \mu^\pm e^\mp$

Multiple SRs targeting different $m_{HNL}$ .



arXiv:2508.20929



stronger limits than LEP,
exp. limit ~comparable with CMS

Lifetime ~ $m_{HNL}^{-5}$ .

Leptons from long-lived HNL decay have track with large impact parameters, lower reco efficiency (LLP regime)

phase space suppression

# Anomaly detection with multilepton

**Model-agnostic search**

- **design SR without precise BSM model in mind:**
  $\geq 4\ell$ signatures arise from many BSM models, low SM bkg
- **look for outliers in tails of SM distributions:**
  **how to determine SM probability density $p(x)$ in SR?**

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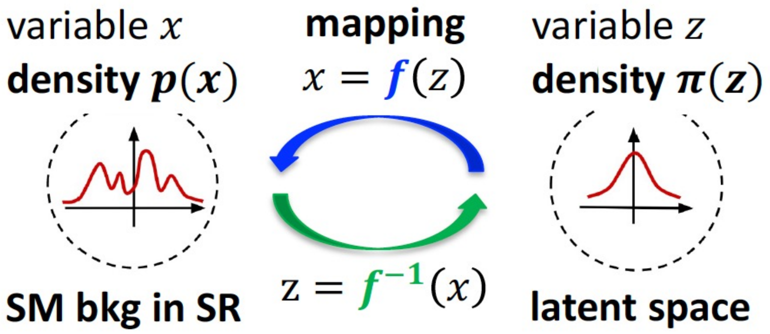
**Use nomalizing flow** (generative AI technique):

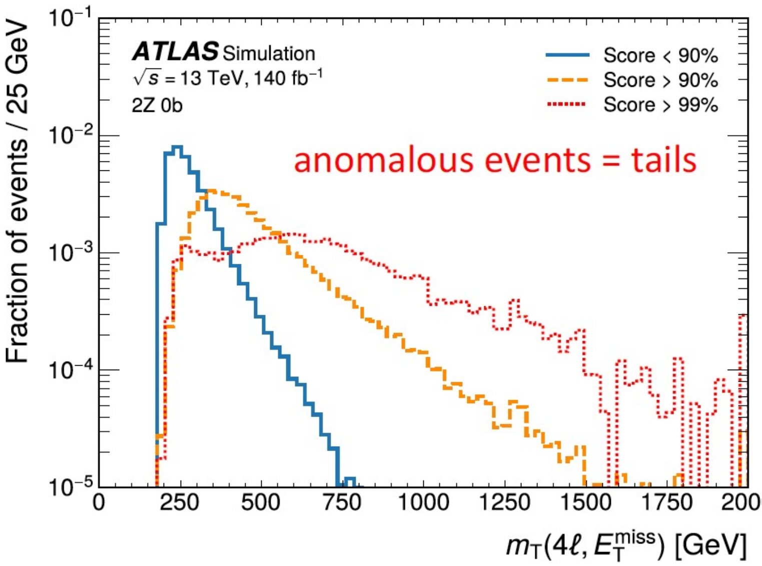
- introduce **invertible transformation function** $f$ **to map SR phase space onto latent space**
- choose Gaussian density $\pi(z)$ in latent space
- $f$: Real-valued Non-Volume Preserving flow, **trained on SM MC**
- **once $f$ is known, can compute $p(x)$:**

$$p(x) = \pi(z)\left|\frac{dz}{dx}\right| = \pi(f^{-1}(x))\left|\frac{df^{-1}}{dx}\right| = \pi(f^{-1}(x))|(f^{-1})'(x)|$$

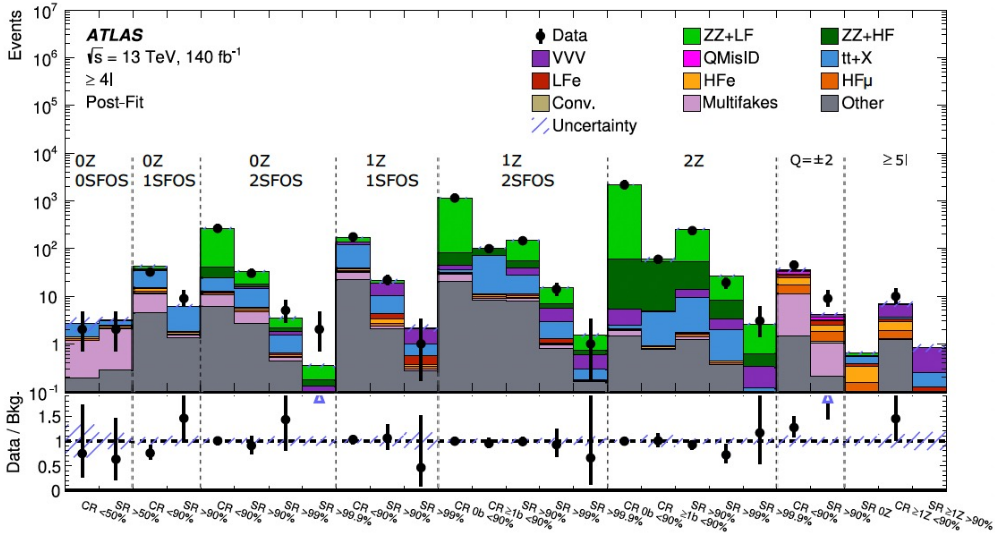
- **Anomaly score** $s(x) = \dfrac{\log p(x) - \log p_{\max}}{\log p_{\min} - \log p_{\max}}$



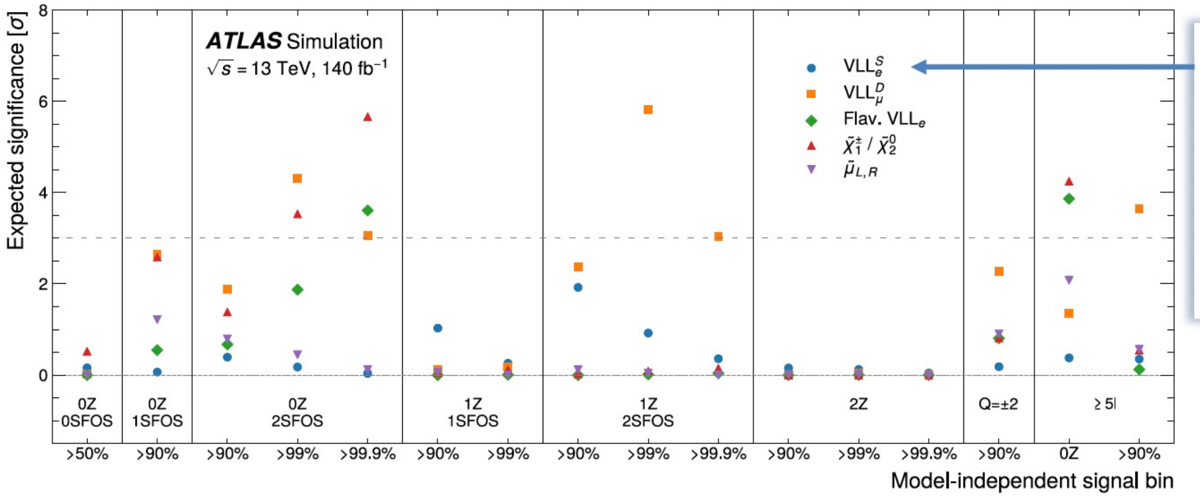
# Results

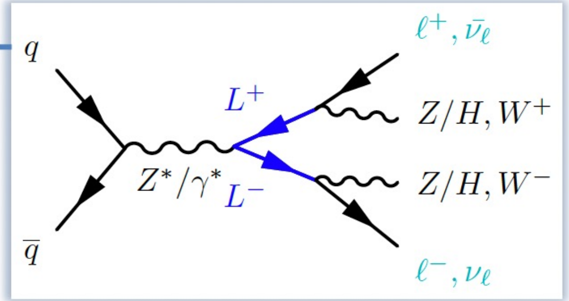


anomalous events = tails



SRs: $4\ell$ with |Q|=0,2, $\geq 5\ell$, low/high AD score





Example Vector-Like Lepton model, SU(2) singlet