Recent results of exotic physics searches at the CMS experiment

Hui Wang (王徽)

Nanjing Normal University

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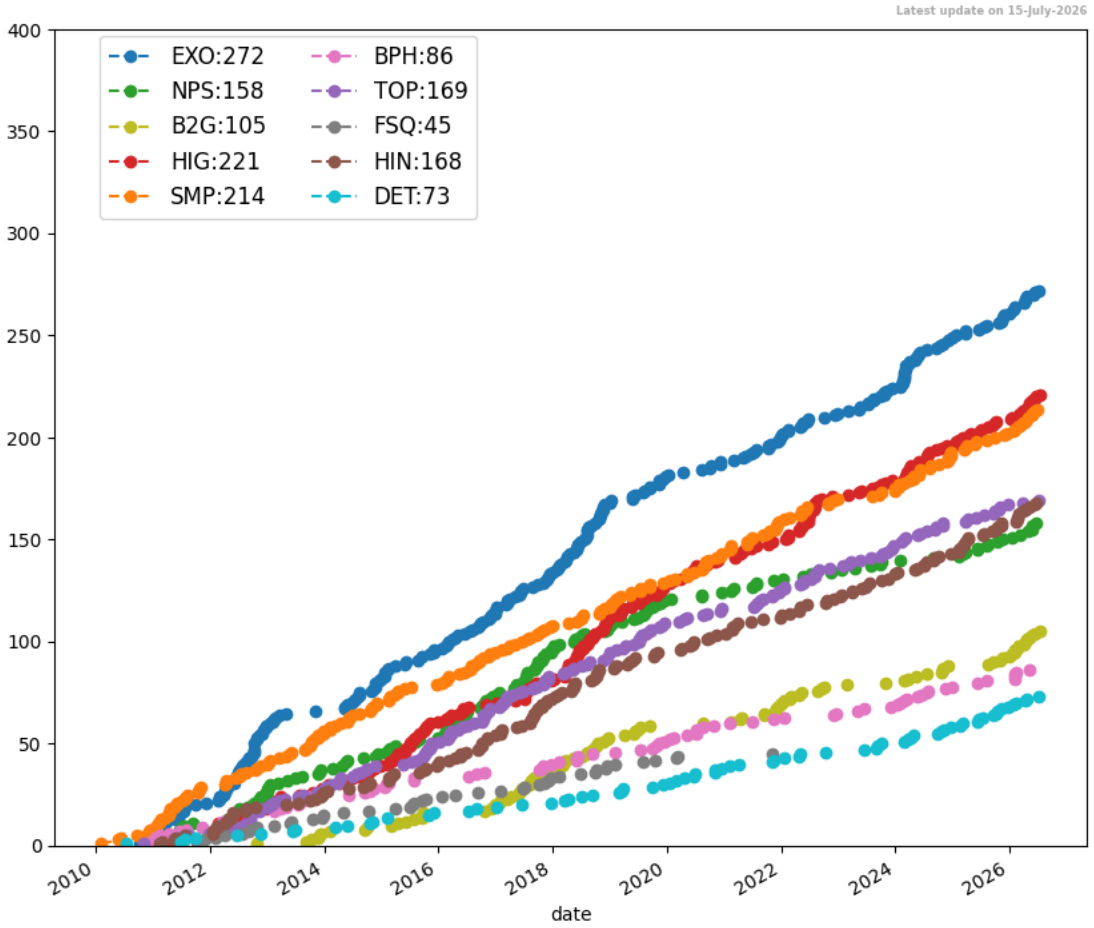
Introduction



- EXO is the largest analysis group in CMS
- This talk selects latest and interesting results of exotic physics searches
- Latest: most results are in preprint or PAS (physics analysis summary) status
- Interesting: using novel technique or observed hint of excess

Other models

Compositeness

Dark matter

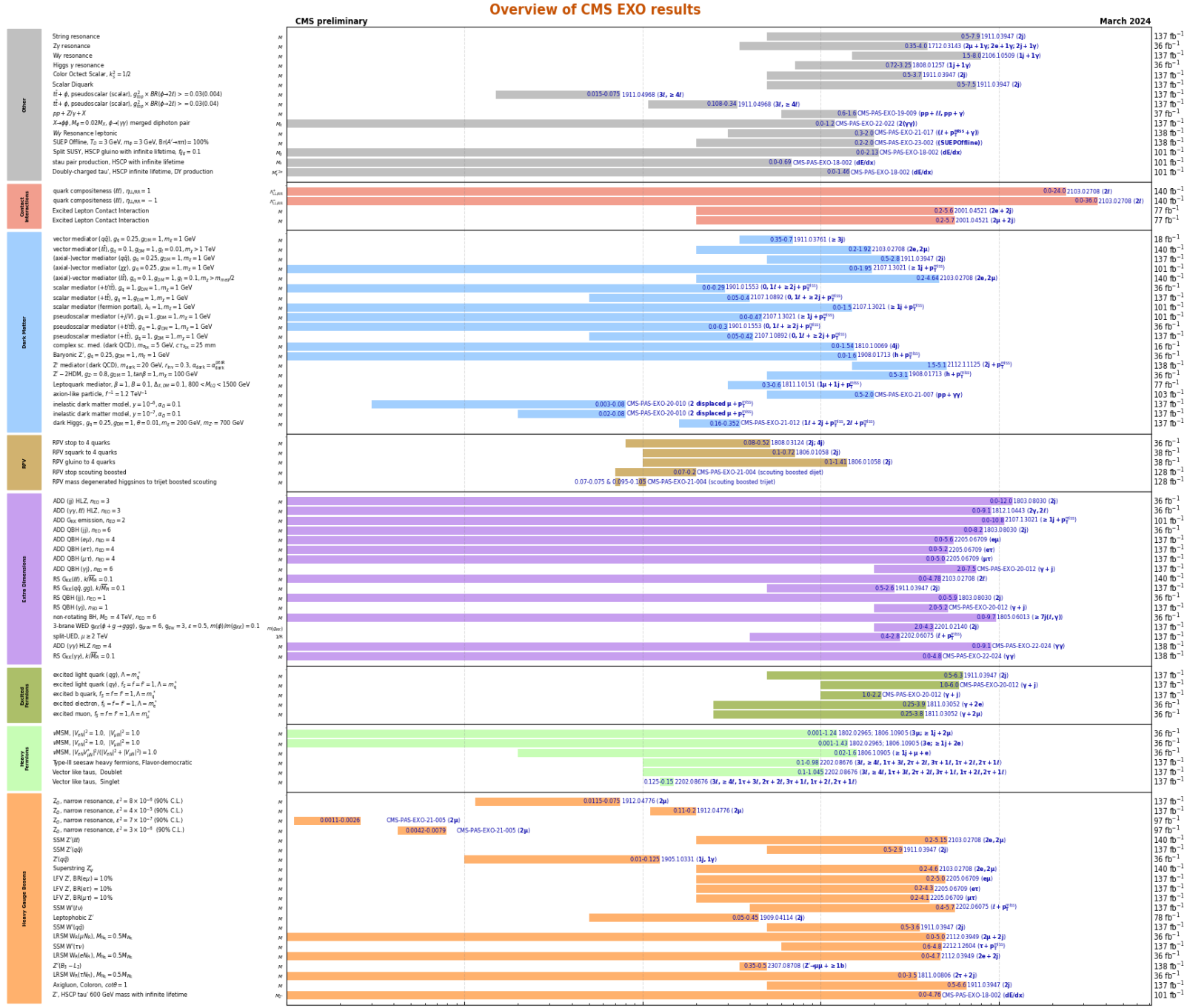
RPV SUSY

Extra Dimensions

Excited fermions

Heavy fermions

Heavy gauge bosons



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

link

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

Status: March 2023

ATLAS Preliminary

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

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt$[fb^{-1}]	Limit		Reference
Extra dimen.	ADD $G_{KK} + g/q$	0 e, μ, τ, γ	1 – 4 j	Yes	139	M_D 11.2 TeV	$n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	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 γ	–	–	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, μ	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥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, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	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, μ	≥1 b, ≥2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	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, μ	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, μ	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, μ	2 j / 1 J	Yes	139	Z' mass 3.9 TeV	$g_V = 3$	2004.14636
	LRSM $W_R \to \mu N_R$	2 μ	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	Λ 21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	Λ 35.8 TeV	η_{LL}^-	2006.12946
	CI $eebs$	2 e	1 b	–	139	Λ 1.8 TeV	$g_* = 1$	2105.13847
	CI $\mu\mu bs$	2 μ	1 b	–	139	Λ 2.0 TeV	$g_* = 1$	2105.13847
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ 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_χ=1, $m(\chi)$=10 TeV	ATL-PHYS-PUB-2022-036
	Pseudo-scalar med. (Dirac DM)	0 e, μ, τ, γ	1 – 4 j	Yes	139	m_{med} 376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	0 e, μ	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_χ=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 μ	≥2 j	Yes	139	LQ mass 1.7 TeV	$\beta = 1$	2006.05872
	Scalar LQ 3rd gen	1 τ	2 b	Yes	139	LQ_3^u mass 1.49 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	2303.01294
	Scalar LQ 3rd gen	0 e, μ	≥2 j, ≥2 b	Yes	139	LQ_{3u}^e mass 1.24 TeV	$\mathcal{B}(LQ_3^u \to t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	≥2 e, μ, ≥1 τ	≥1 j, ≥1 b	–	139	LQ_{3d}^e mass 1.43 TeV	$\mathcal{B}(LQ_3^d \to t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	0 e, μ, ≥1 τ	0 – 2 j, 2 b	Yes	139	LQ_{3d}^μ mass 1.26 TeV	$\mathcal{B}(LQ_3^d \to b\nu) = 1$	2101.12527
	Vector LQ mix gen	multi-channel	≥1 j, ≥1 b	Yes	139	$LQ_{1/3}^V$ 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, μ, τ	≥1 b	Yes	139	LQ_3^V mass 1.96 TeV	$\mathcal{B}(LQ_3^V \to b\tau) = 1$, Y-M coupl.	2303.01294
Vector-like fermions	VLQ $TT \to Zt + X$	2e/2μ/≥3e,μ	≥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,μ	≥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, μ	≥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, μ	≥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,μ	≥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	τ' 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 γ	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 τ^*	2 τ	≥2 j	–	139	τ^* mass 4.6 TeV	$\Lambda = 4.6$ TeV	2303.09444
Other	Type III Seesaw	2,3,4 e, μ	≥2 j	Yes	139	N^0 mass 910 GeV		2202.02039
	LRSM Majorana ν	2 μ	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, μ (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, μ (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

$\sqrt{s}$ = 13 TeV partial data

$\sqrt{s}$ = 13 TeV full data

10^{-1} 1 10 **Mass scale [TeV]**

*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

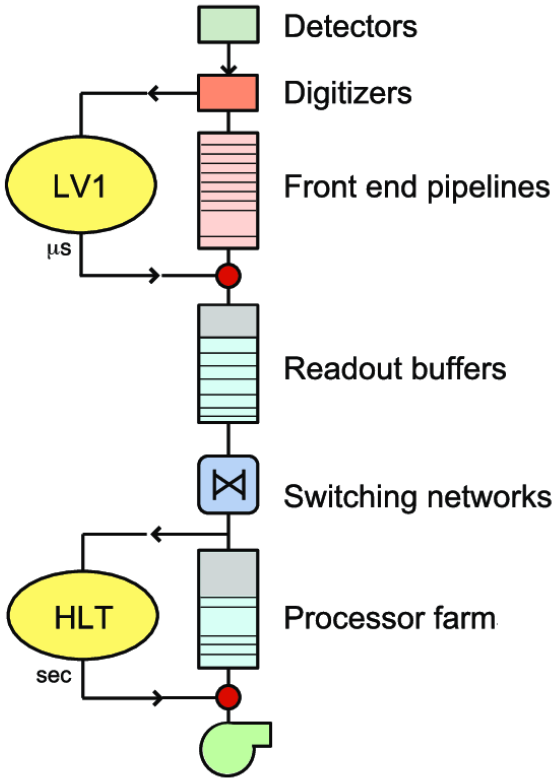
pp→Z’→tau'tau' heavy resonance

pp→ tau'tau' direct pair production

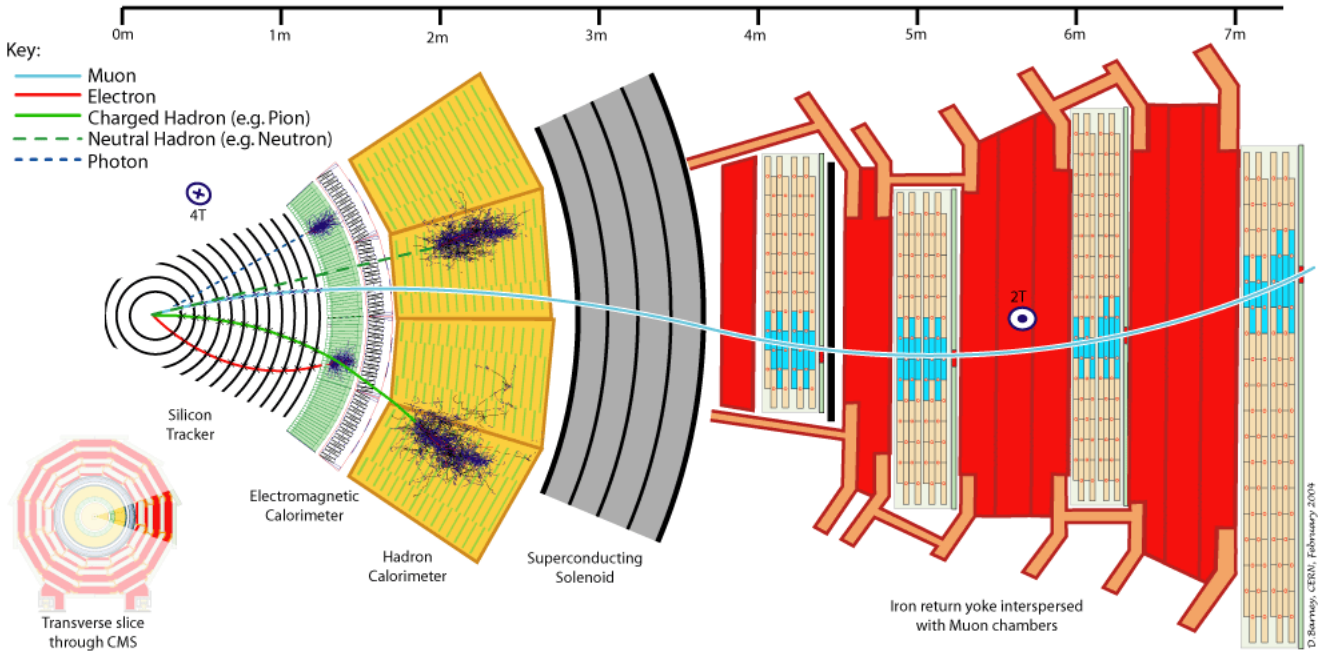
Challenges

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

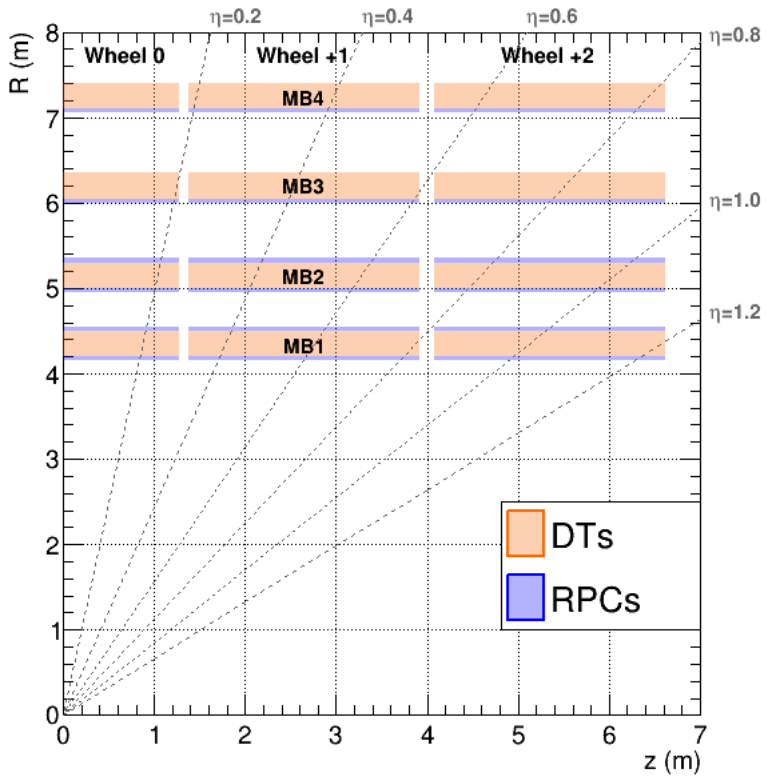
Solution



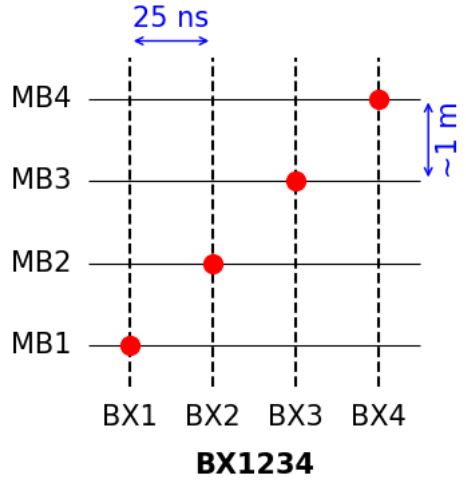
- [arXiv:2601.20063] the first analysis using L1 scouting data
- LHC collides at 40MHz = L1 input rate = L1 scouting rate
- Pros: high rate, saves all BXs in an orbit, perfect for slow-moving particles
- Cons: only L1 information, no tracker, no PF reconstruction

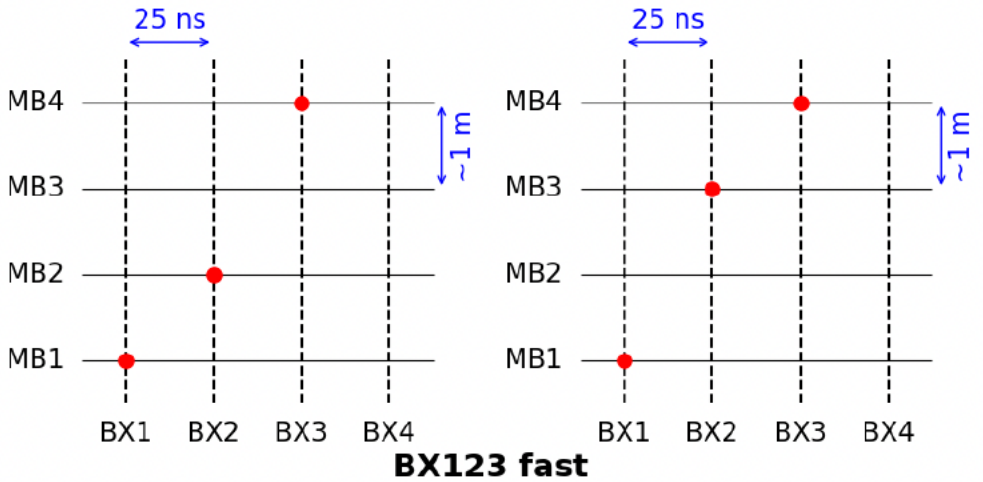


Search strategy

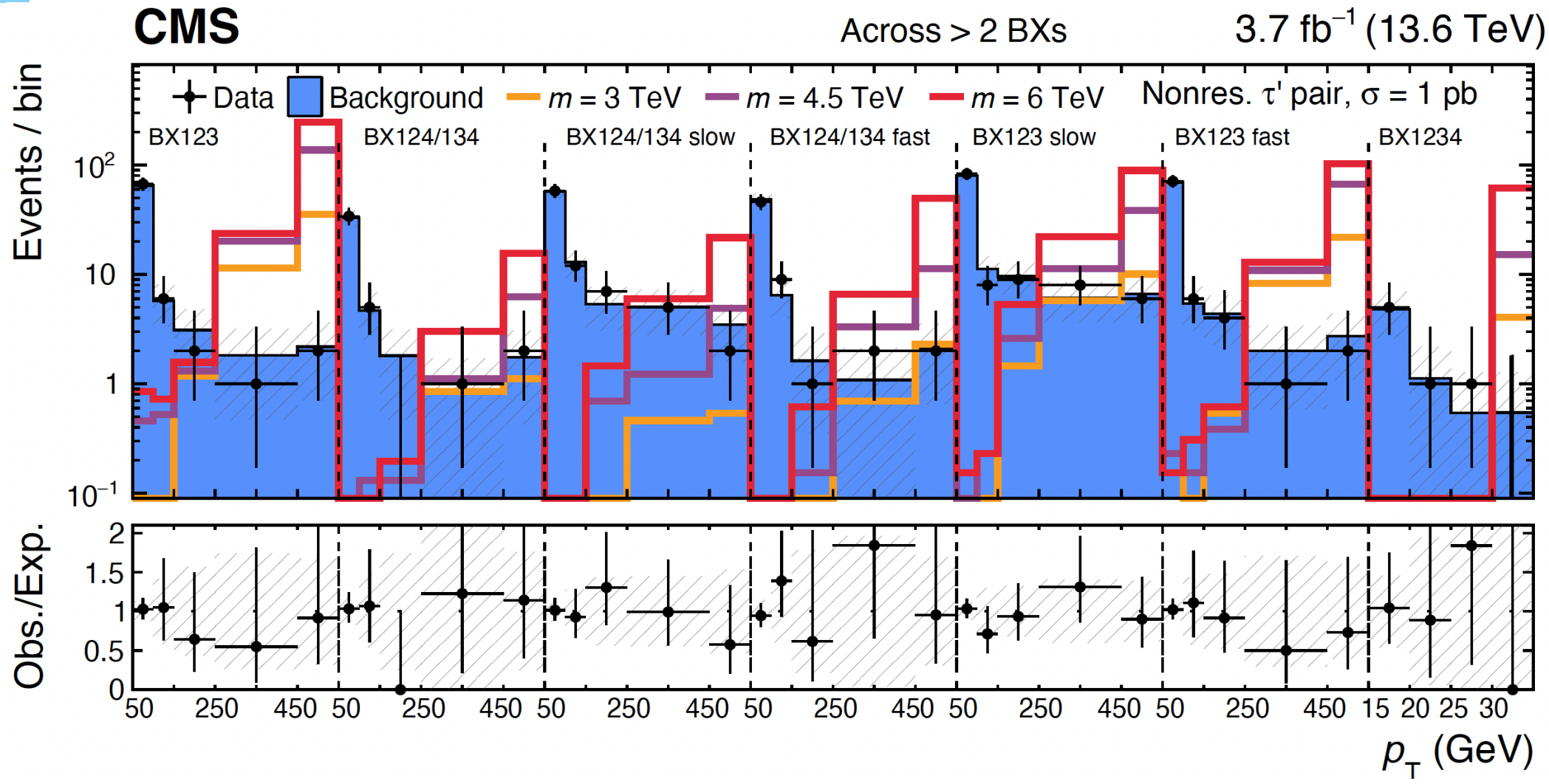


Stations / BXs	3/4	3/3 or 4/4	4/3	3/2	4/2
4 stubs	—	BX1234 BX124/134	BX123	—	BX1112 BX1122 BX1222
3 stubs, MB1 or MB4	BX124/134 slow	BX123 slow	—	BX112 slow BX122 slow	—
3 stubs, MB1 and MB4	—	BX124/134 fast	BX123 fast	—	BX112 fast BX122 fast

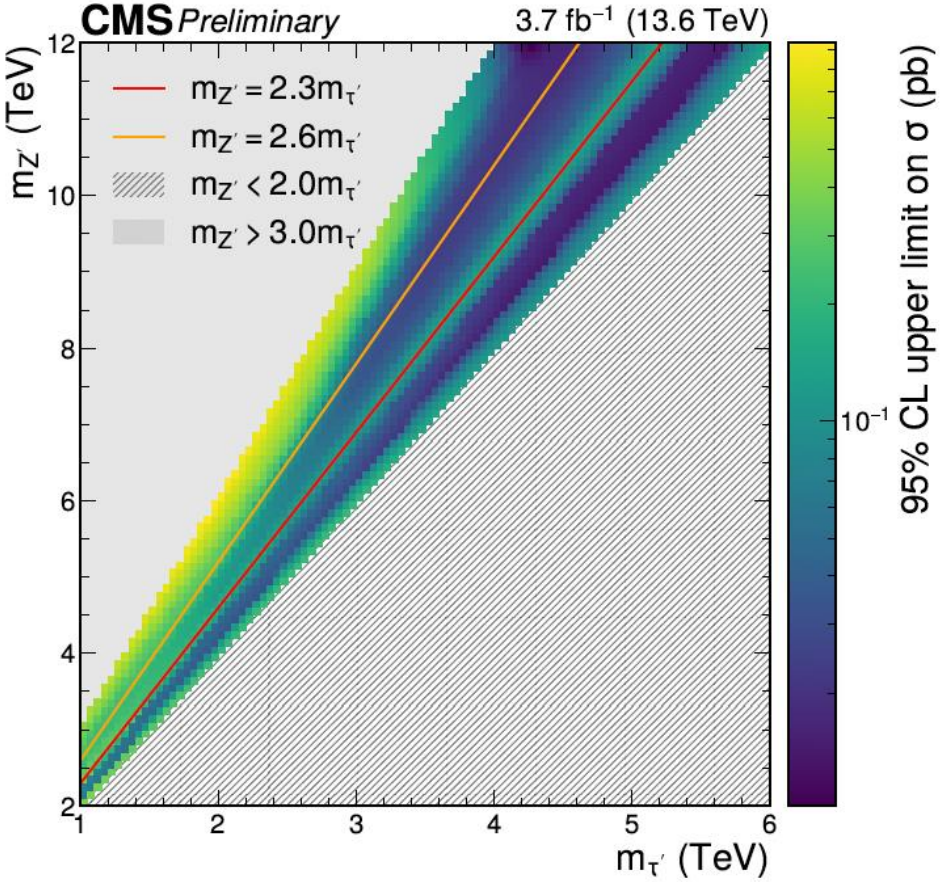




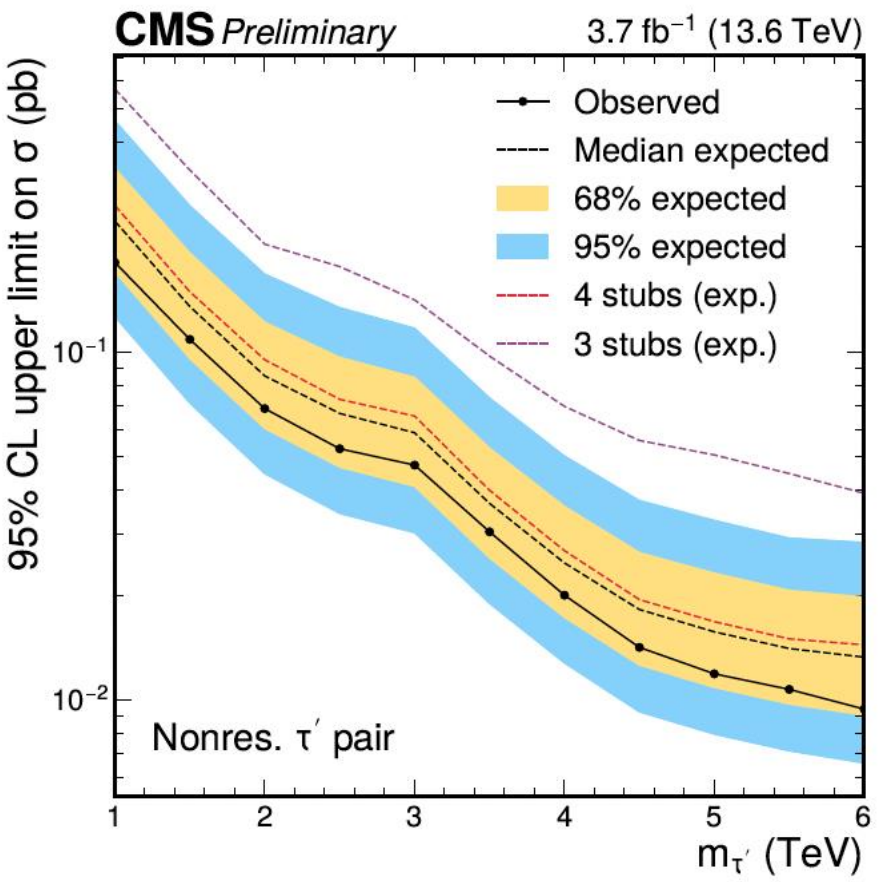
Results


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
Obs./Exp.
p_T (GeV)

Limits



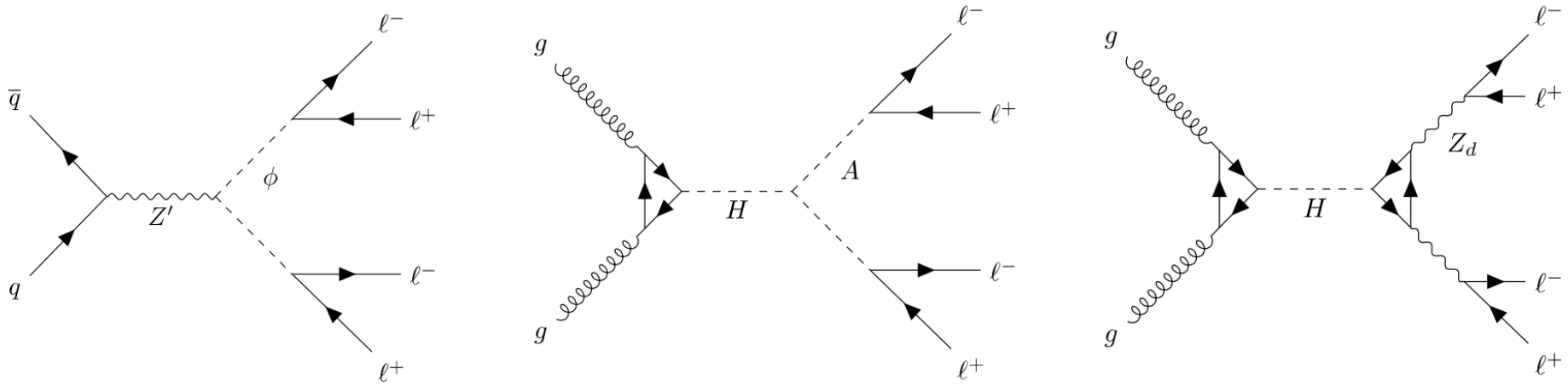
pp→Z'→tau'tau' heavy resonance



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.

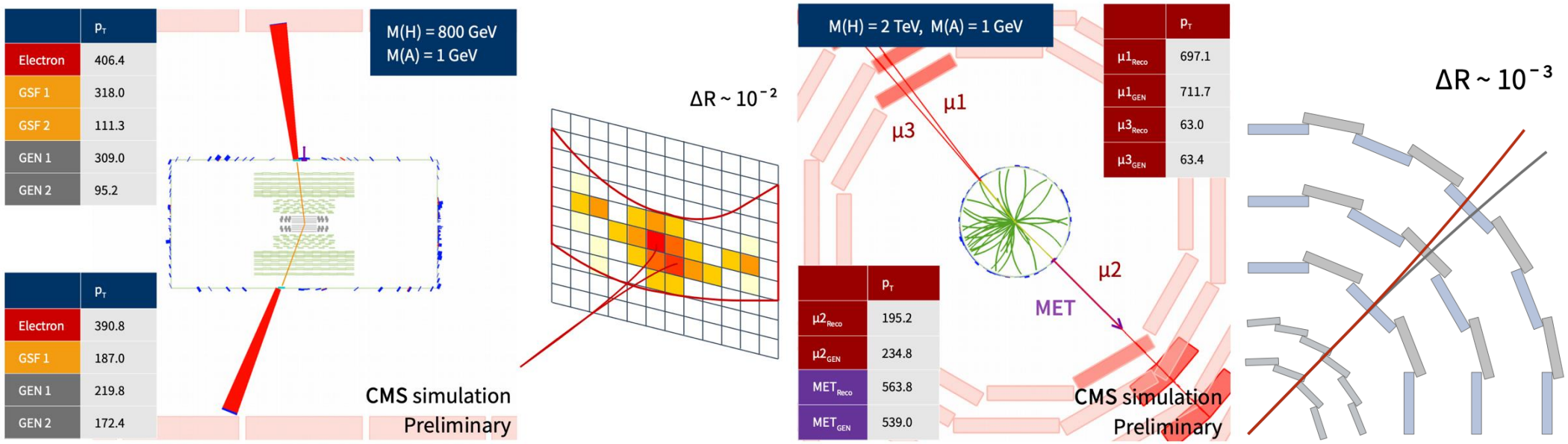
- U(1) extension of SUSY (UMSSM), [PRD 85 (2012) 055030]
- 2HDM, [Phys. Rep. 516 (2012) pp. 1-102]
- Dark photon models, [JHEP 02 (2015) 157]

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)



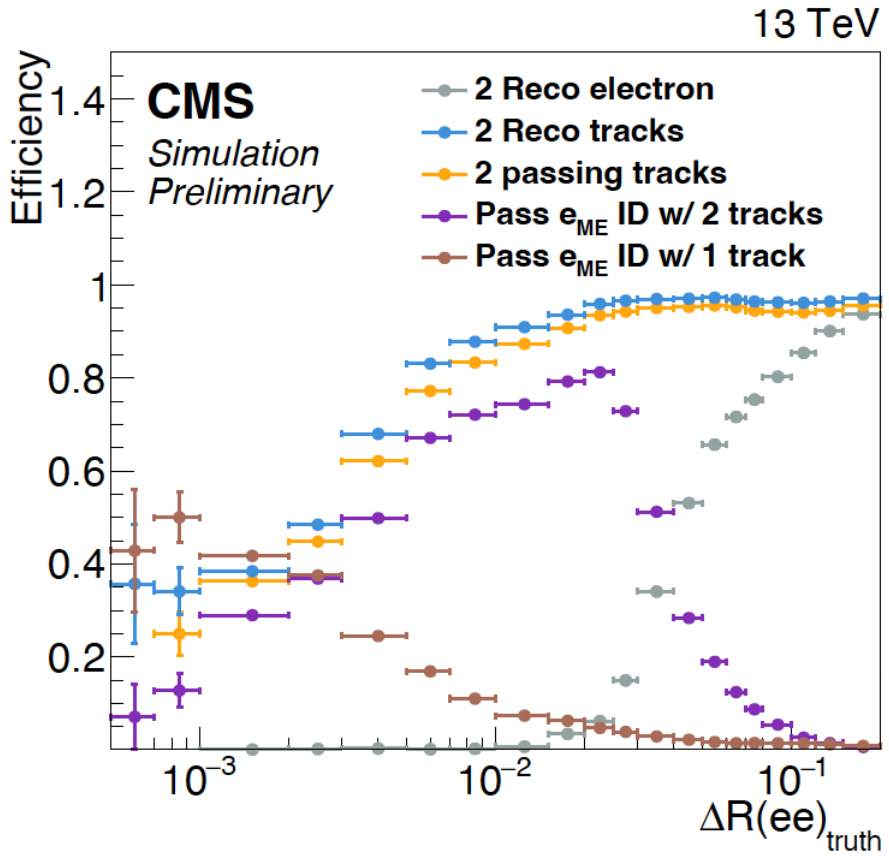
Solution

- 4-lep (truth) observed in detector as

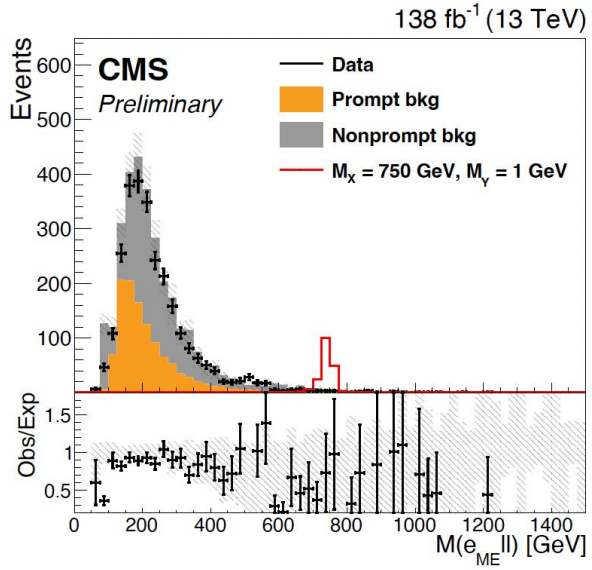
  1. 4-lep, 2. e_{ME} + ll, 3. mu+MET+ll,

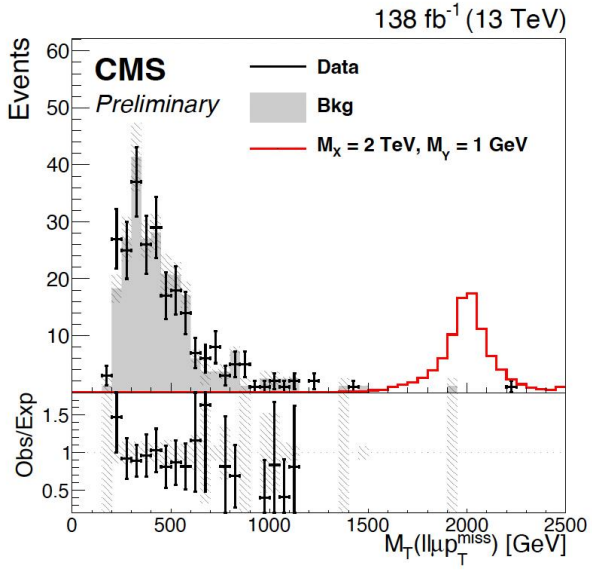
  4. 2 e_{ME} , 5. e_{ME} + mu+MET

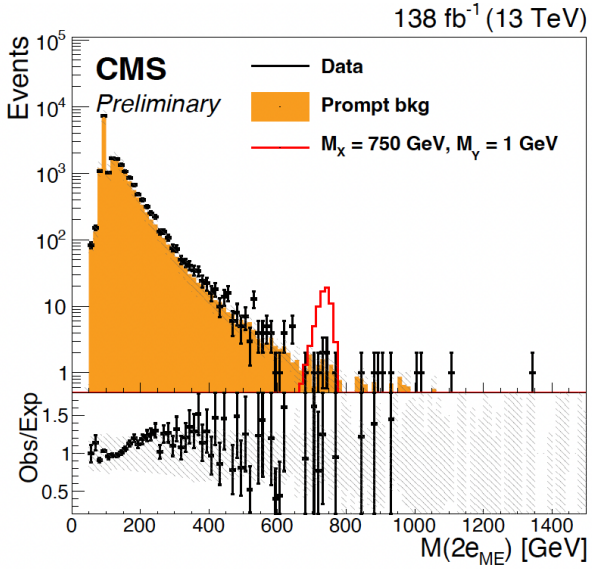
- Merged electrons (e_{ME})
  - Match secondary track to (super)cluster based on track pT, dZ to PV, number of hits, track quality, etc
  - Modify electron MVA reconstruction
- Merged muons (mu+MET)
  - use mu+MET to reconstruct mass of Y boson

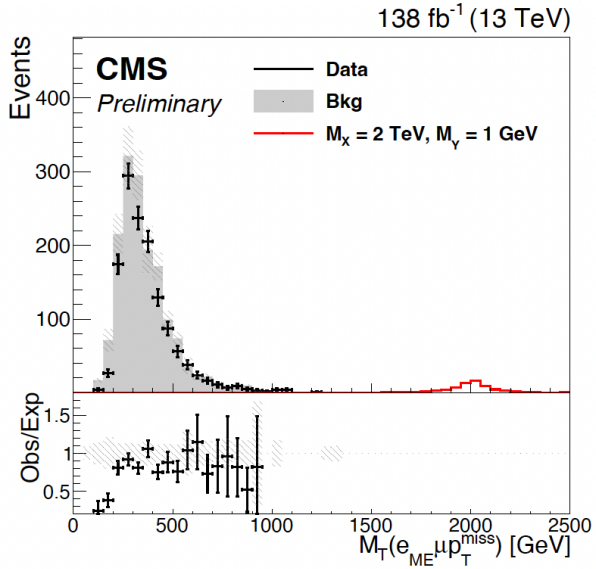


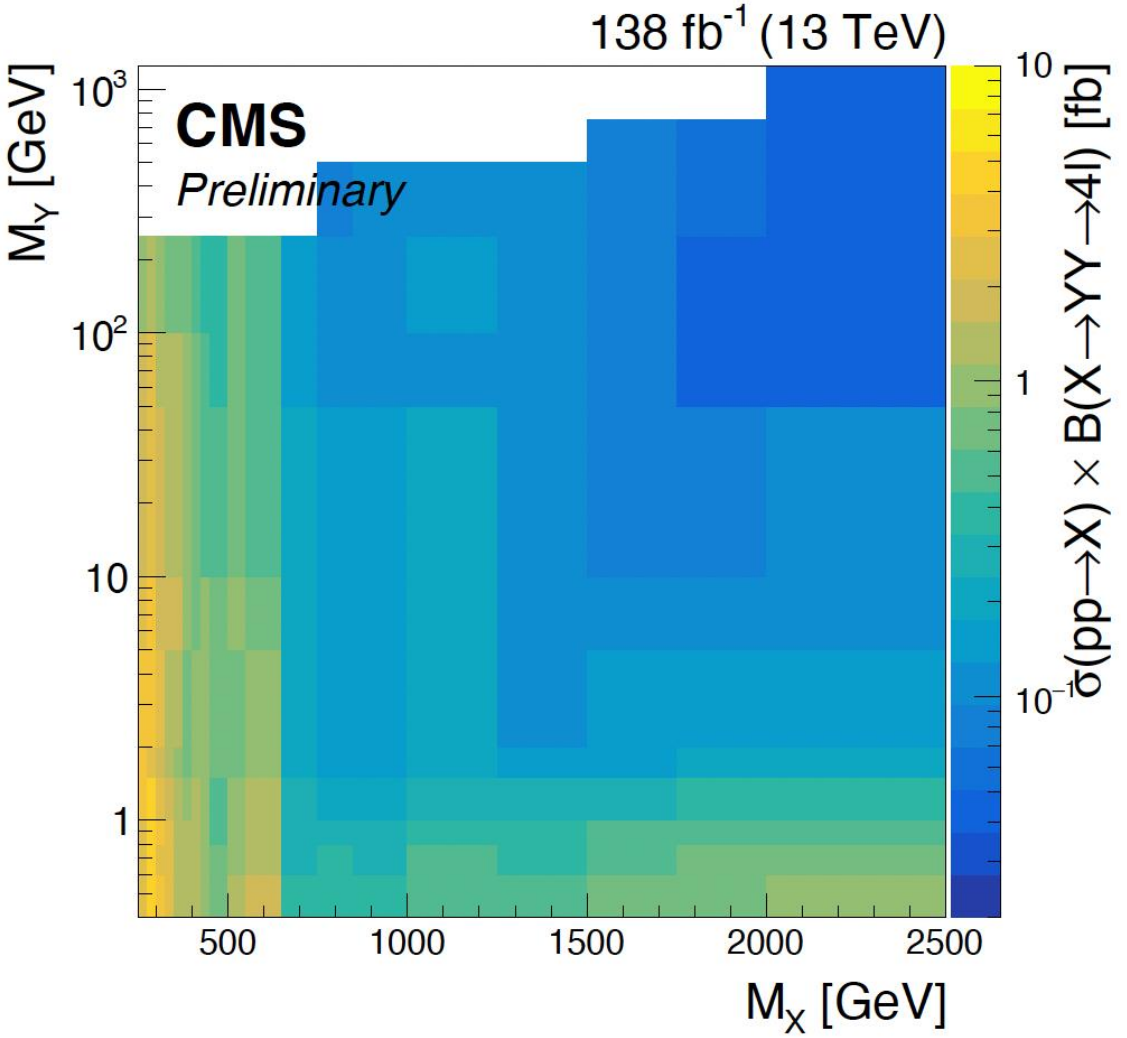
Results


138 fb-1 (13 TeV)
CMS
Preliminary
Data
Prompt bkg
Nonprompt bkg
MX = 750 GeV, MY = 1 GeV
Events
Obs/Exp
M(eME ll) [GeV]


138 fb-1 (13 TeV)
CMS
Preliminary
Data
Bkg
MX = 2 TeV, MY = 1 GeV
Events
Obs/Exp
MT(llμpTmiss) [GeV]


138 fb-1 (13 TeV)
CMS
Preliminary
Data
Prompt bkg
MX = 750 GeV, MY = 1 GeV
Events
Obs/Exp
M(2eME) [GeV]

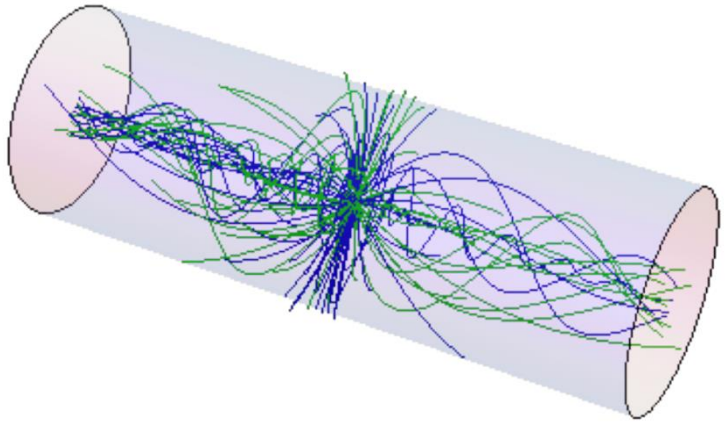

138 fb-1 (13 TeV)
CMS
Preliminary
Data
Bkg
MX = 2 TeV, MY = 1 GeV
Events
Obs/Exp
MT(eMEμpTmiss) [GeV]


138 fb-1 (13 TeV)
CMS
Preliminary
MY [GeV]
MX [GeV]
σ(pp→X) × B(X→YY→4l) [fb]

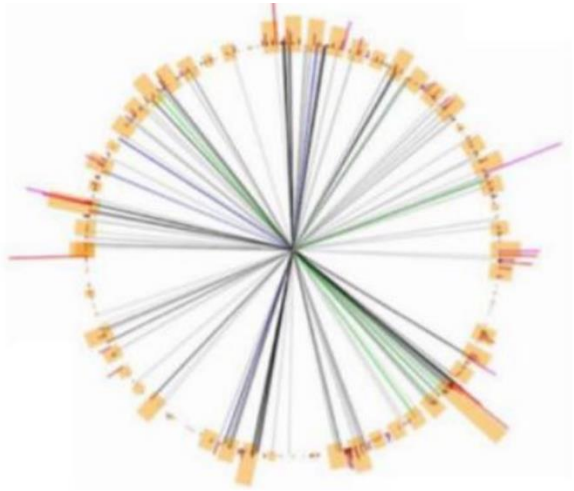
Search for Soft Unclustered Energy Patterns

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) search 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

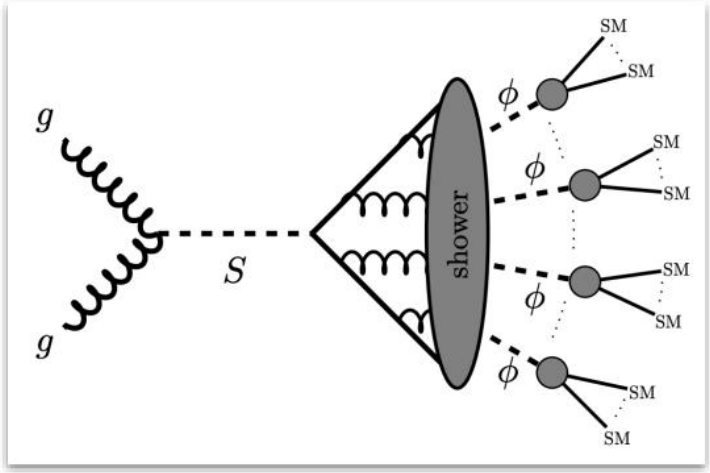


SUEP signal in lab frame (up) and CoM frame (down)



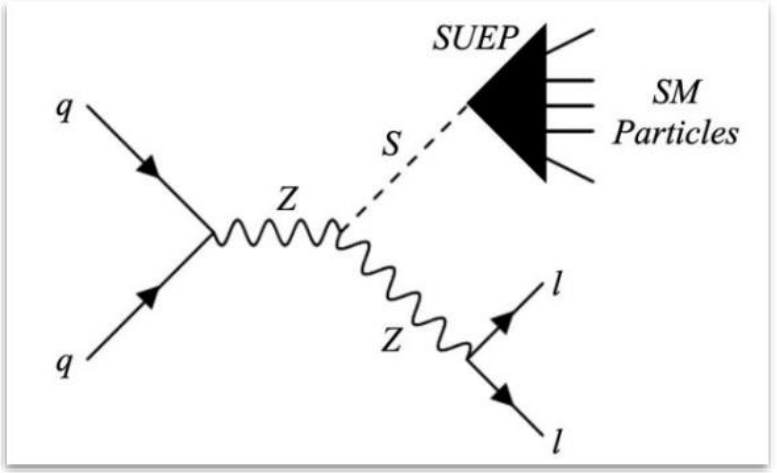
Signal Models

Gluon Fusion Channel (ggF)



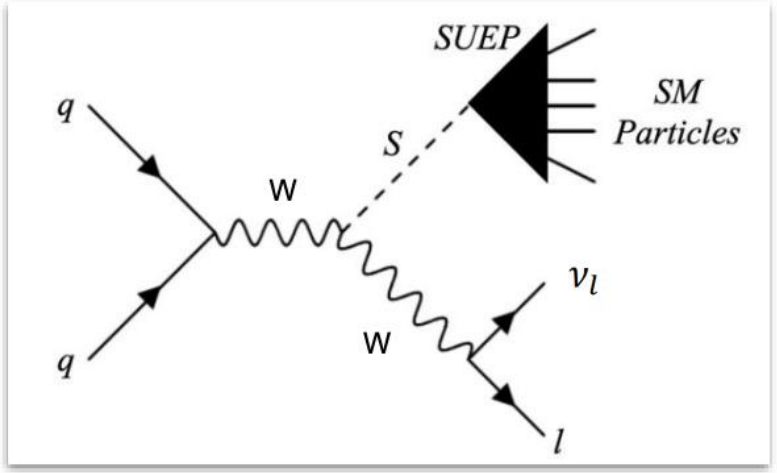
PRL 133 (2024) 191902

Associated Production (ZH)



EXO-23-003-pas

Associated Production (WH)

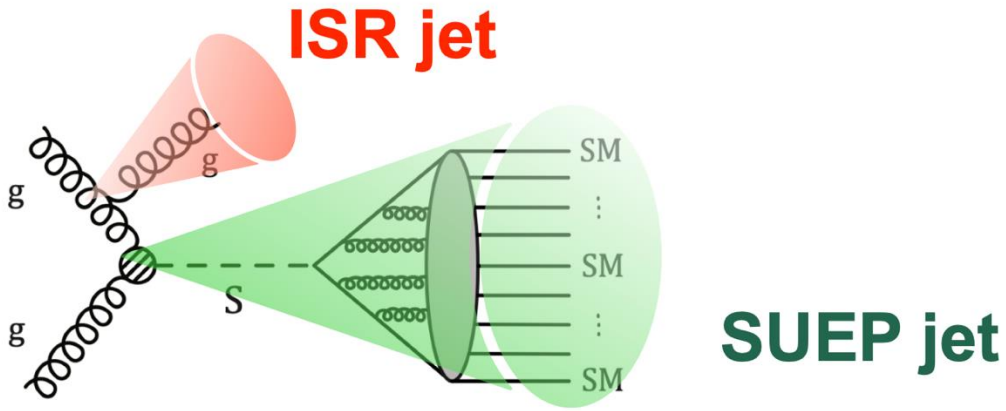


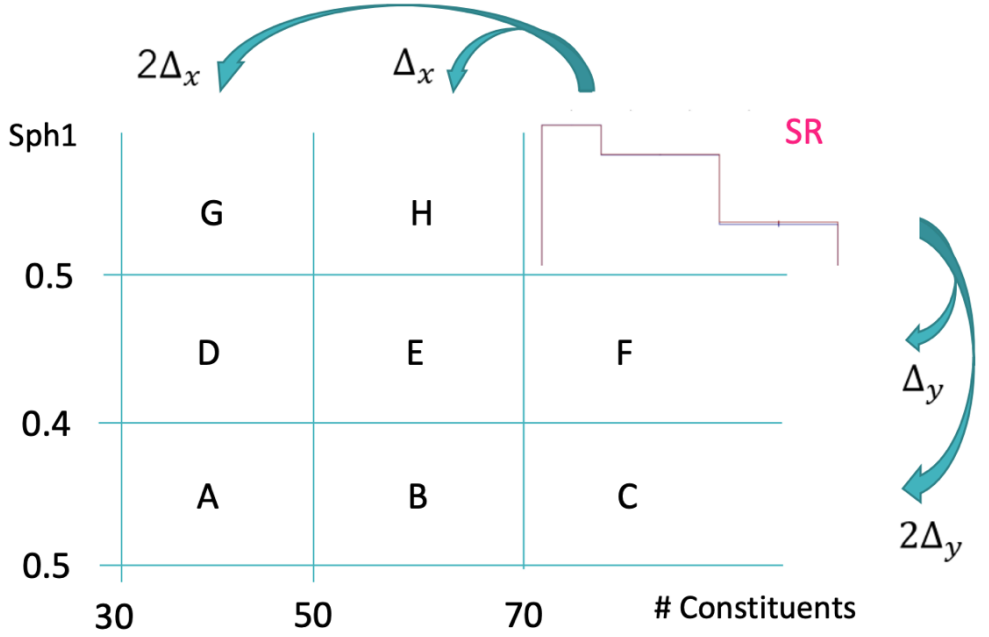
EXO-24-030-pas

- 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

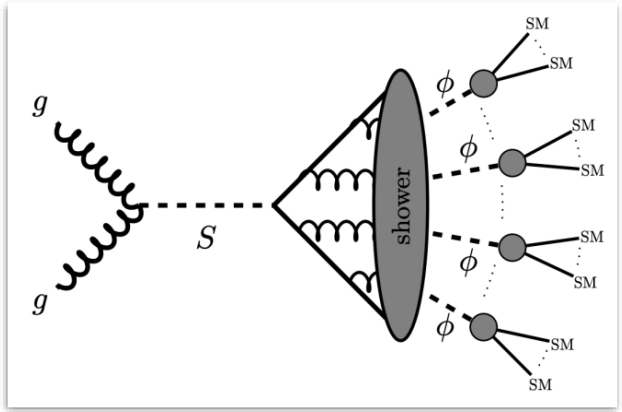
SUEP candidate signatures:

(1) cluster shape close to sphere

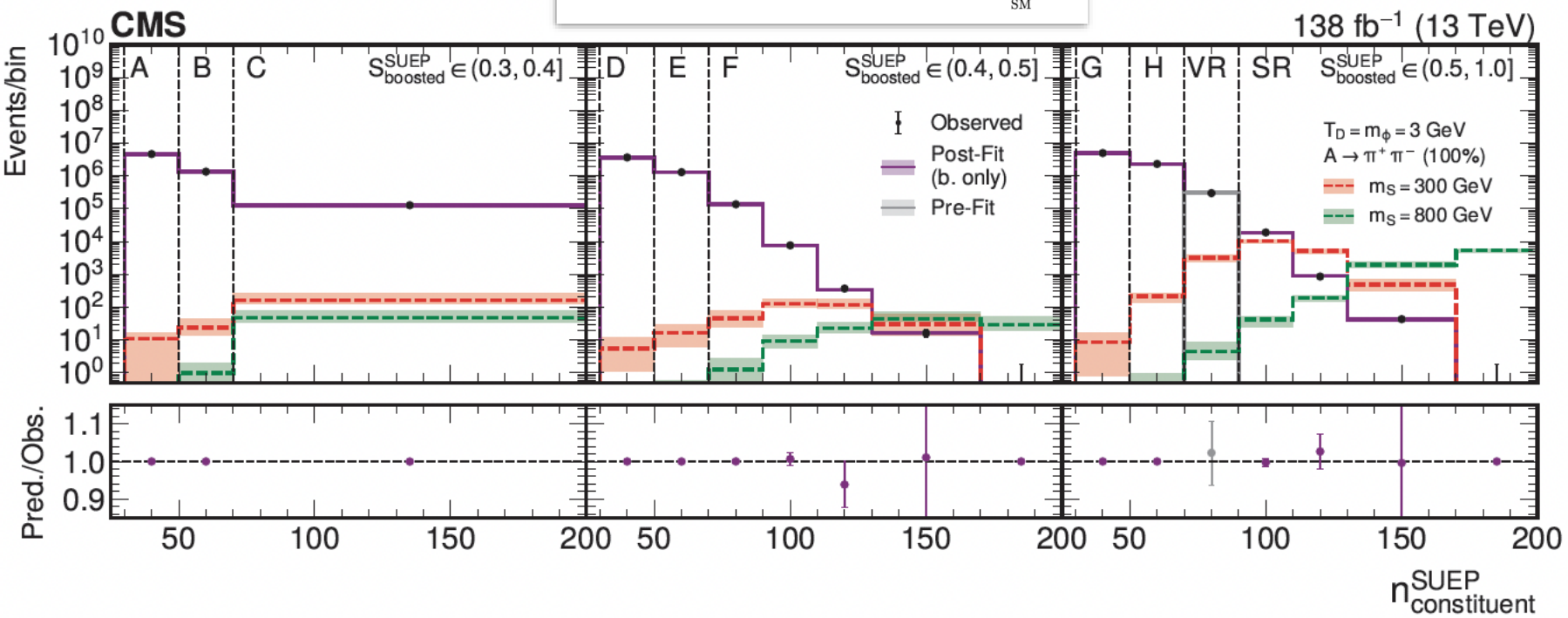
(2) high number of constituents in cluster

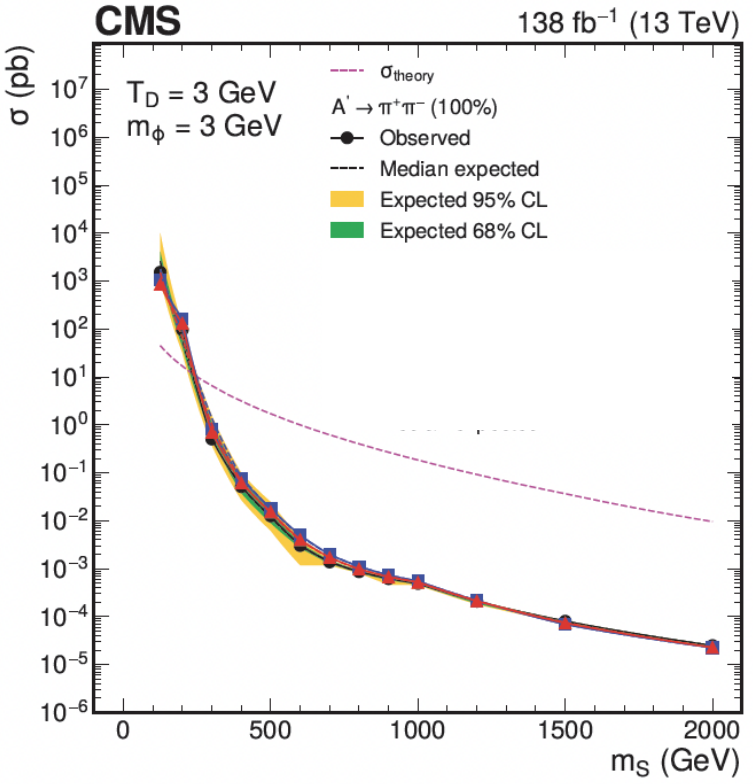
Results - ggF

Gluon Fusion Channel (ggF)

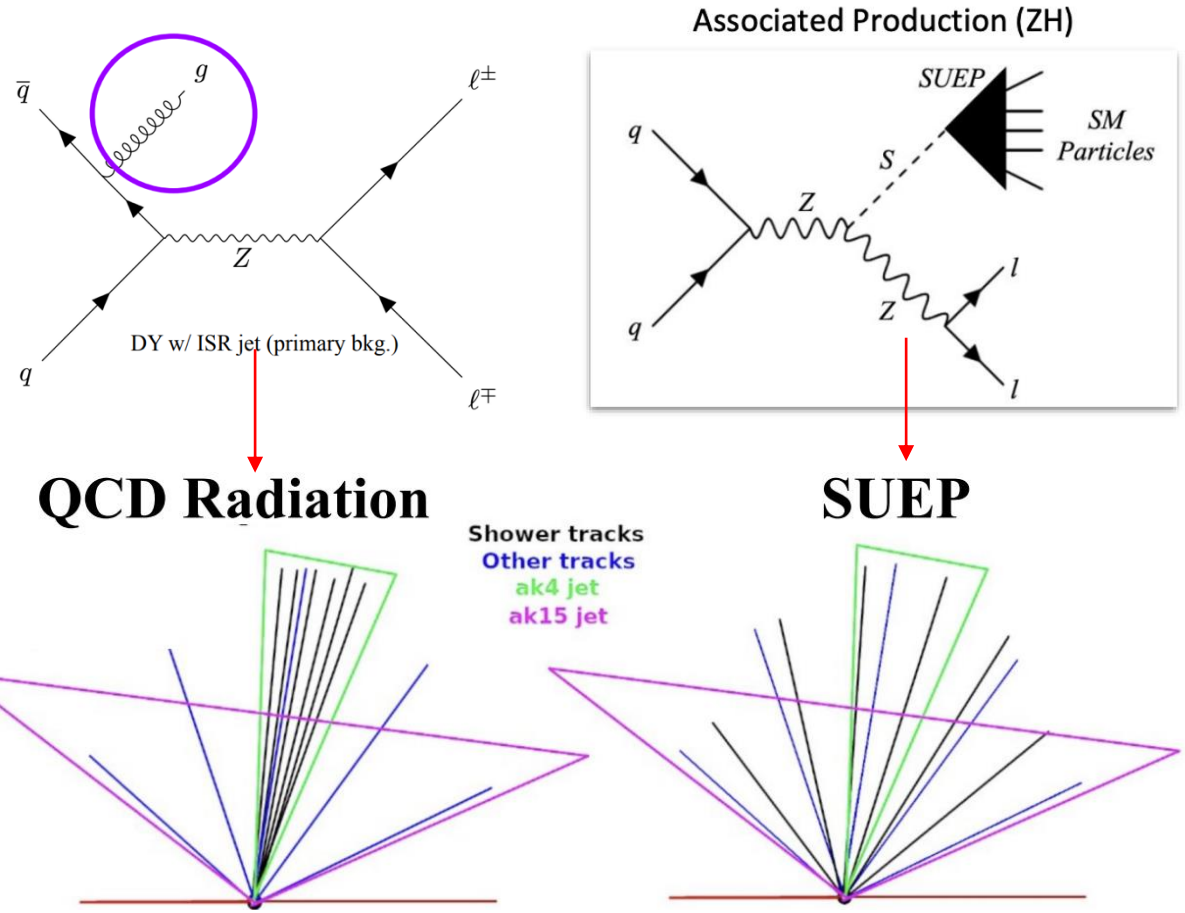


PRL 133 (2024) 191902





Search strategy - ZH

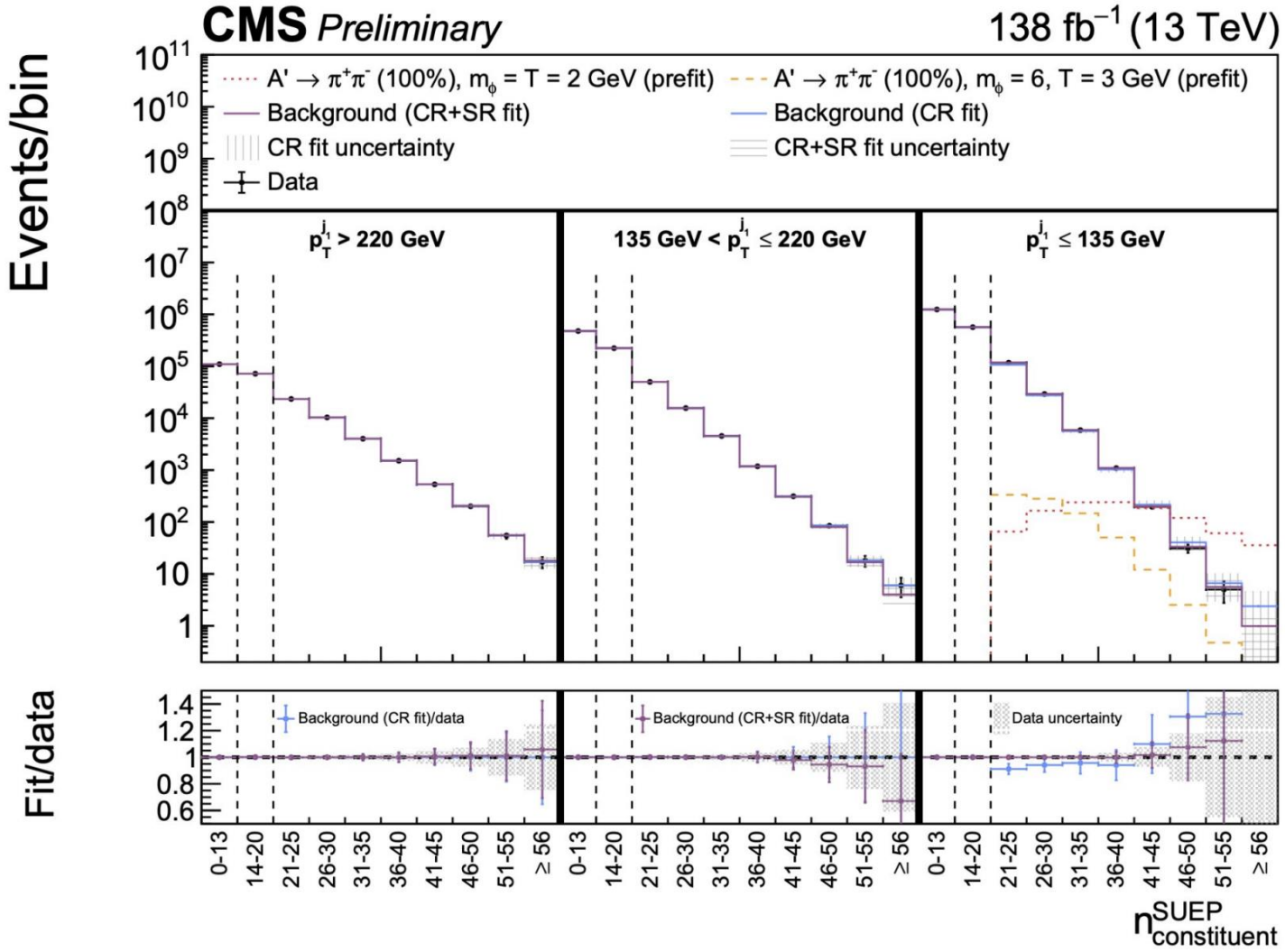


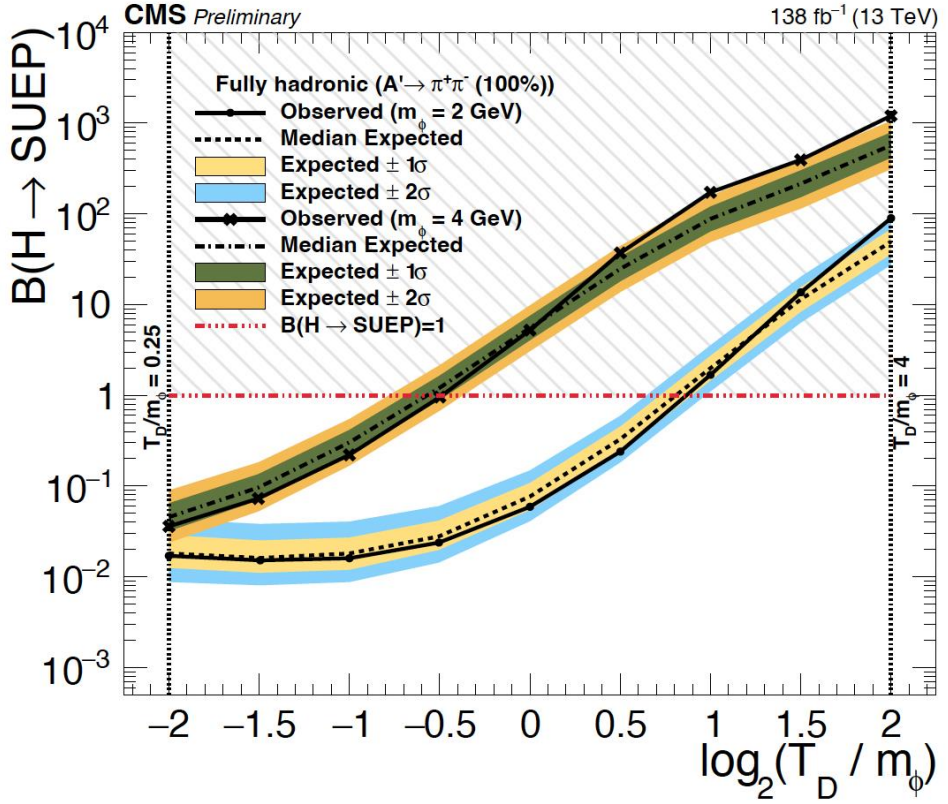
trigger on Z boson, i.e.
OS double electron / muon

	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 constituents

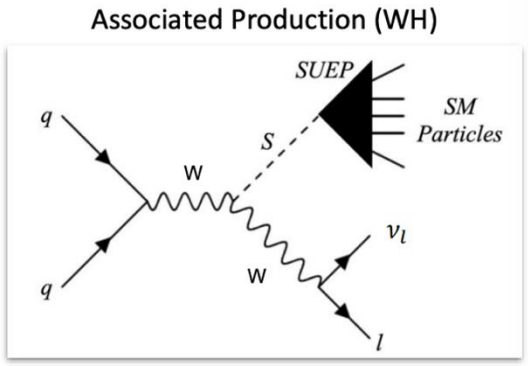
Results - ZH

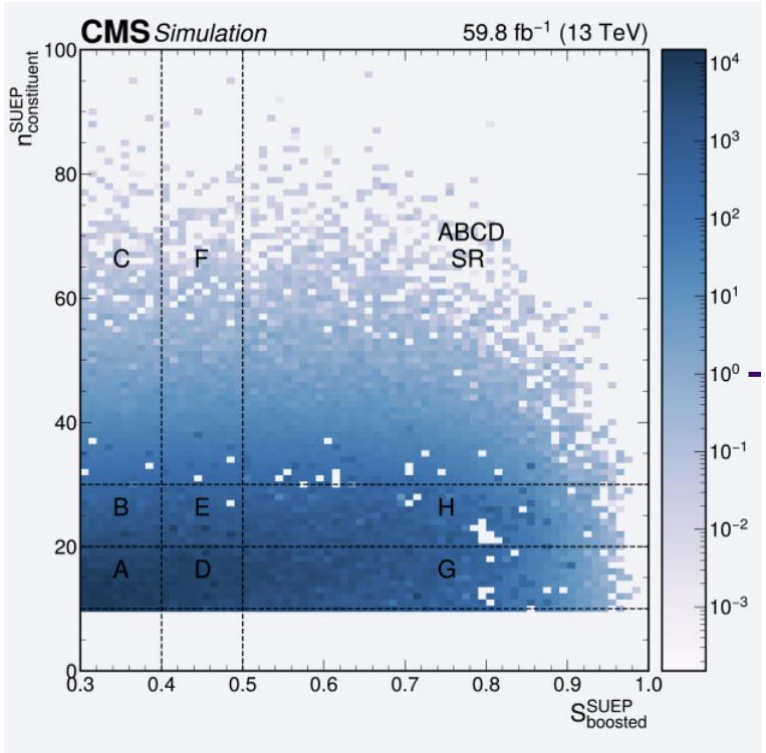


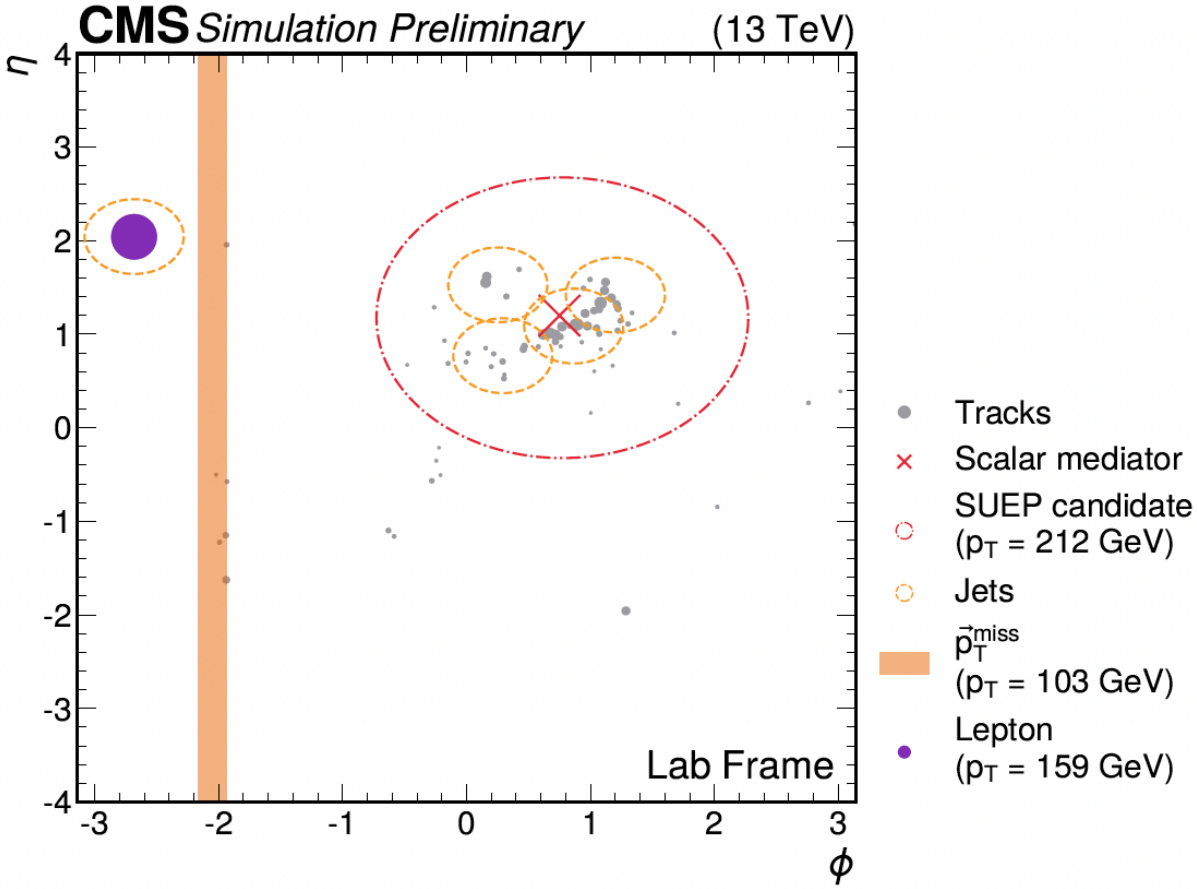


EXO-23-003-pas

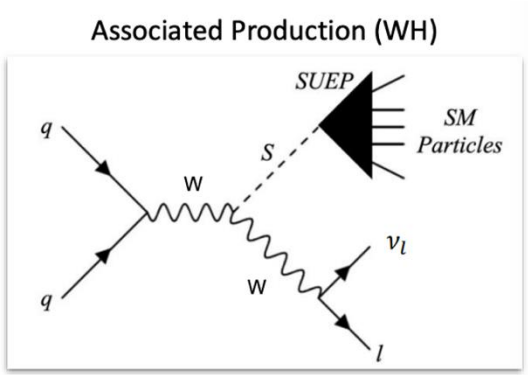
Search strategy - WH



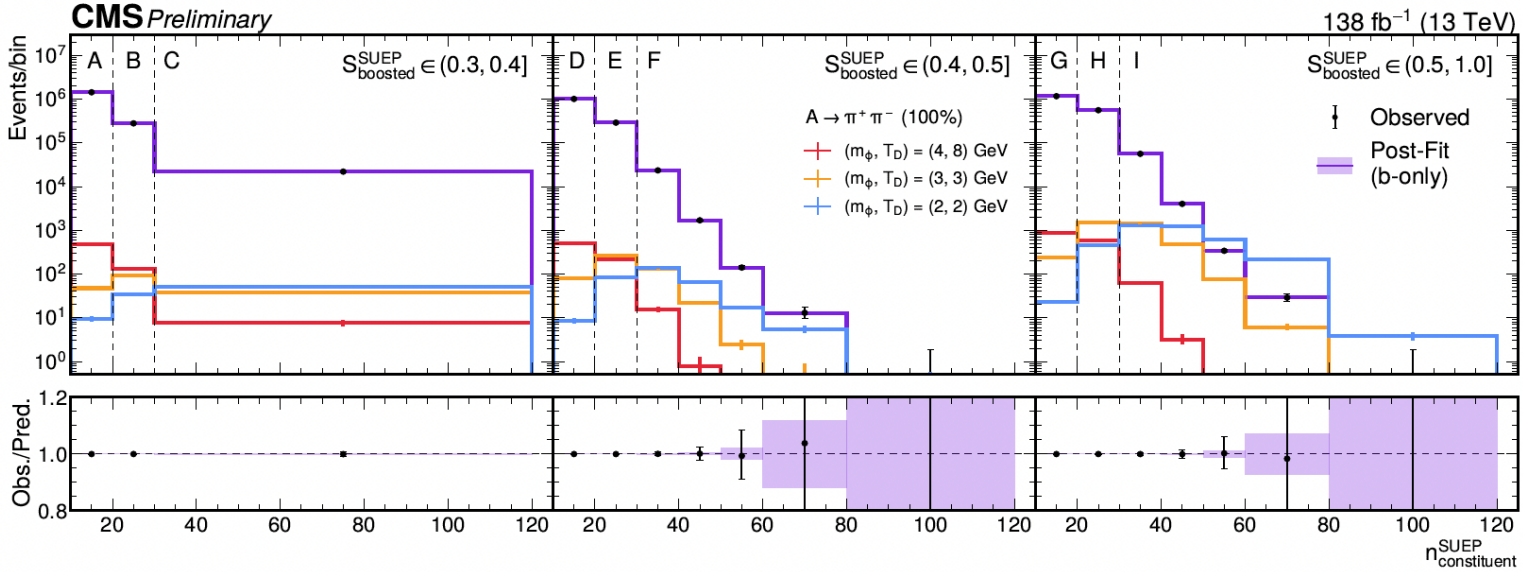


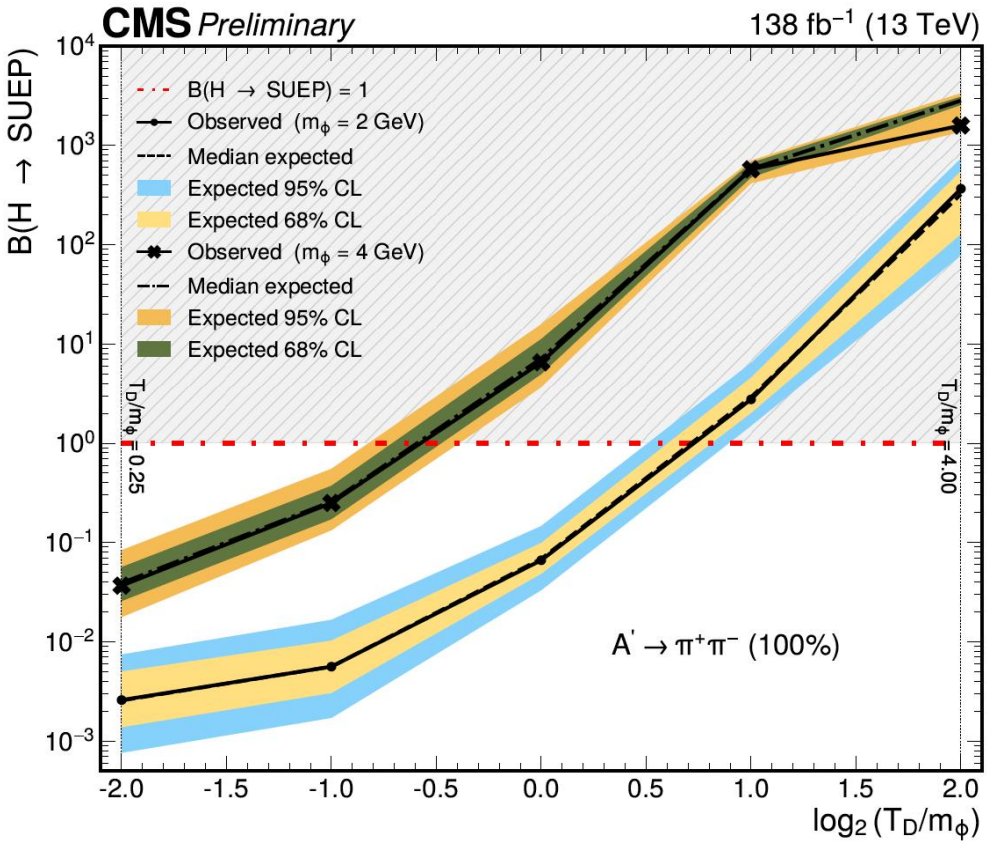


Results - WH

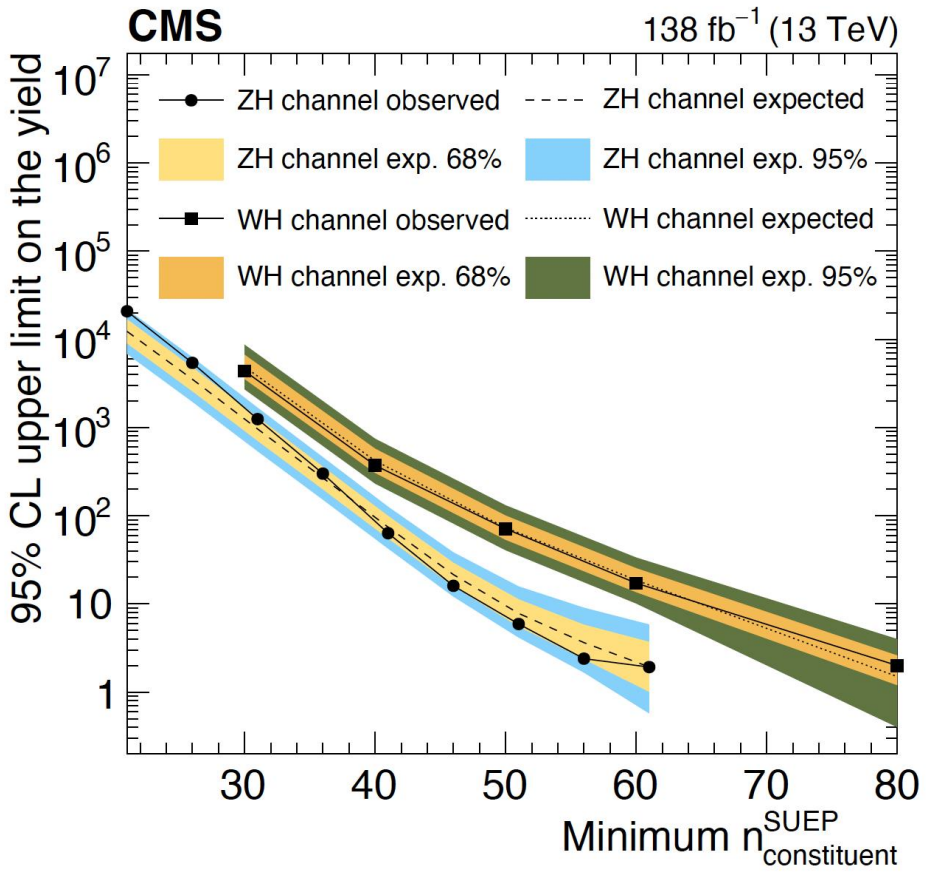


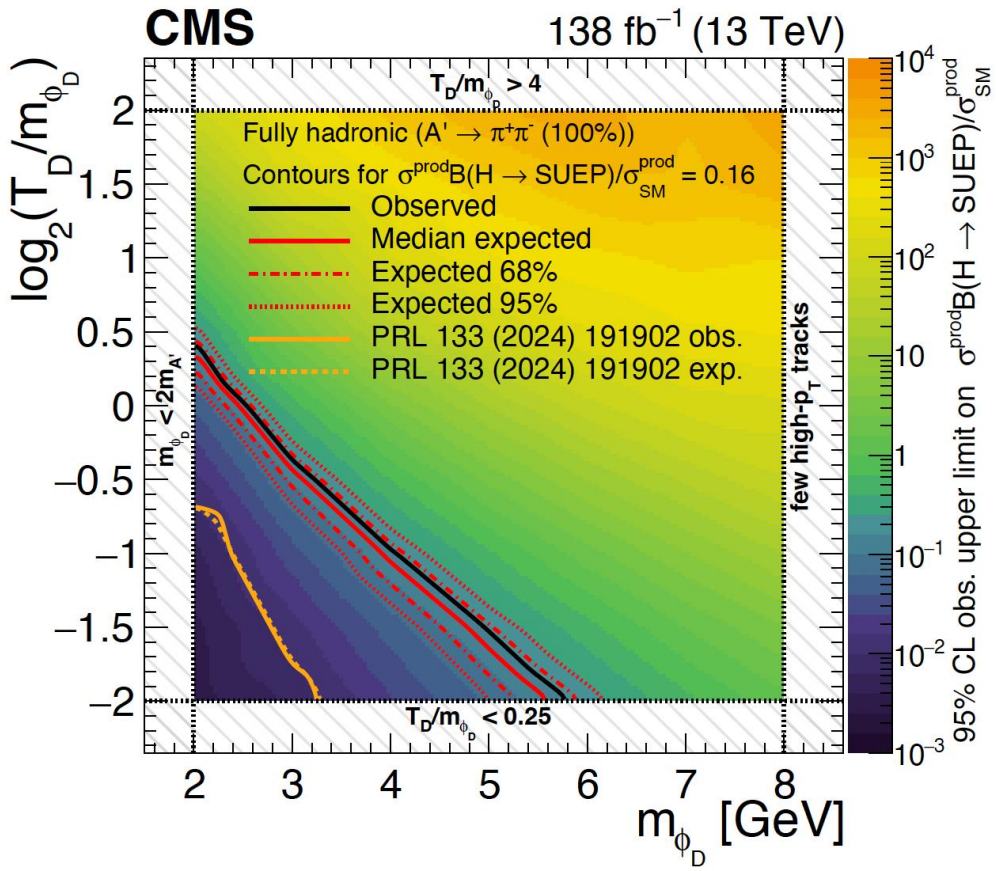
EXO-24-030-pas





Combined results





arXiv:2604.05996 combined results for SUEP searches

ggH with HLT scouting

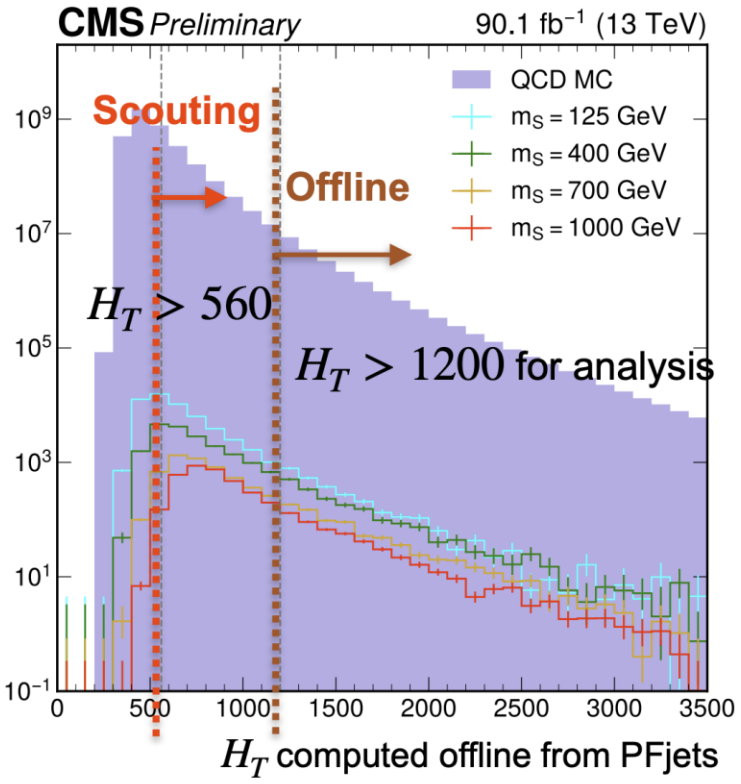
Challenge for SUEP search:
no dedicated trigger-level variables for SUEP signals

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

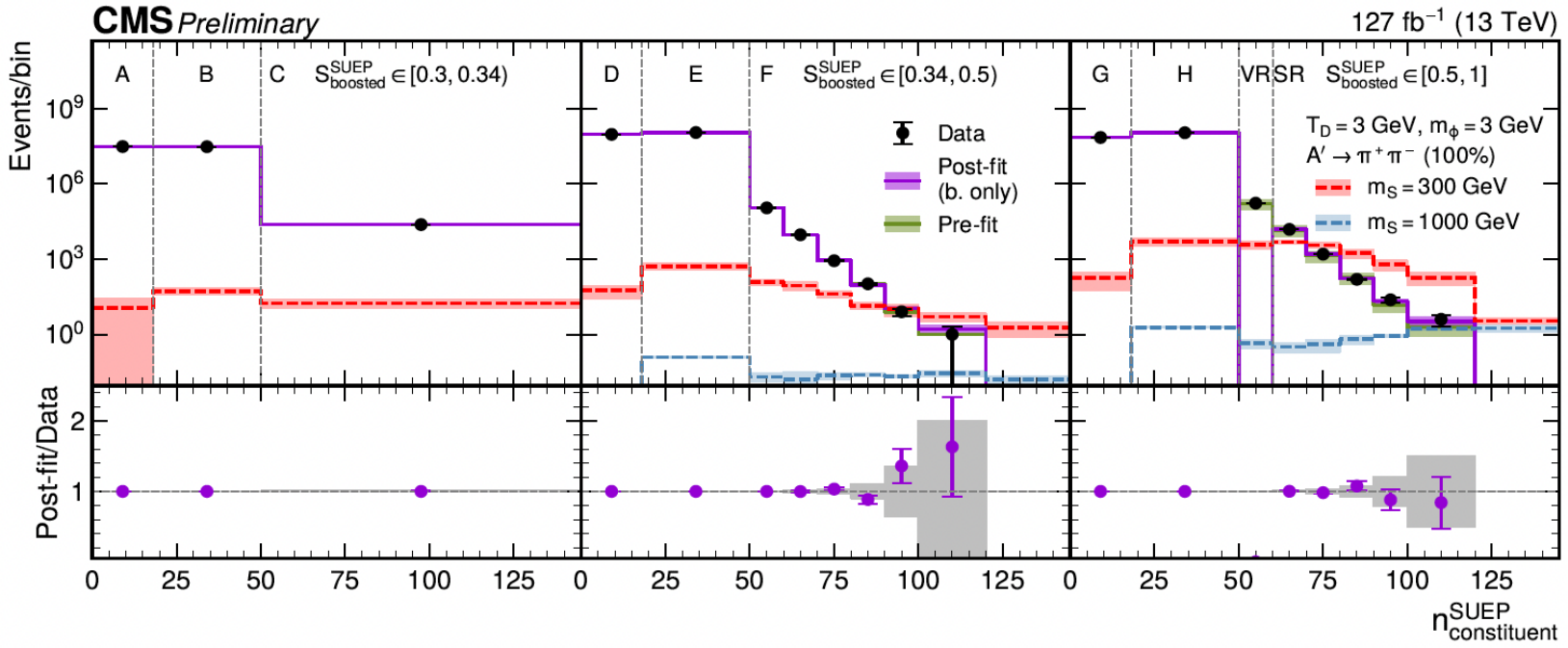


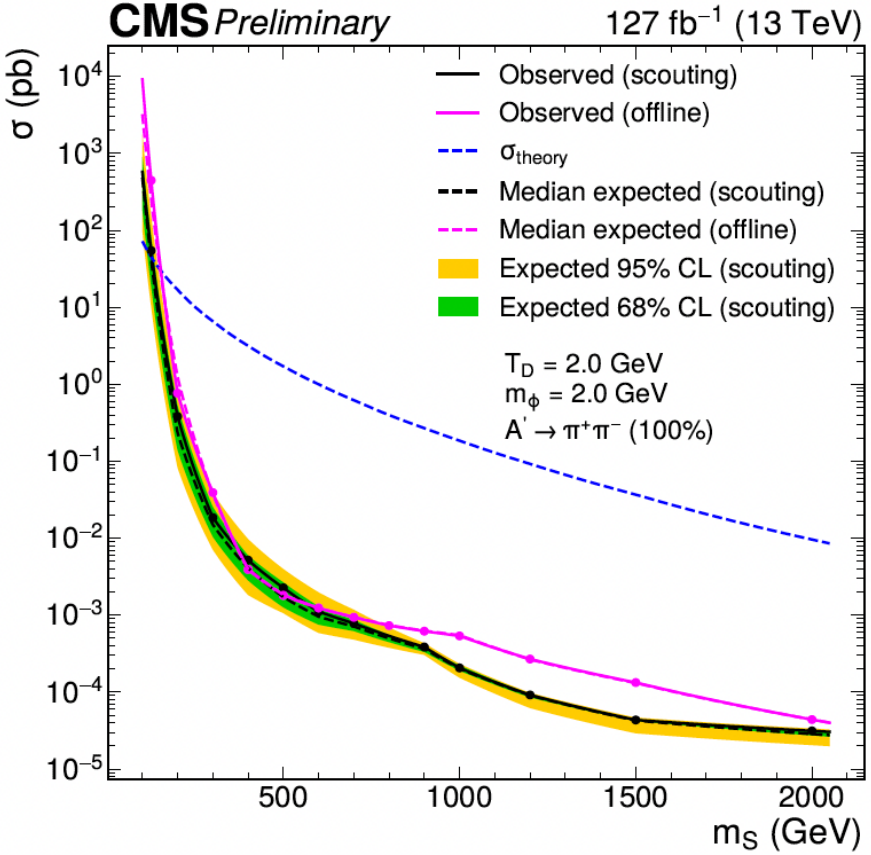
Scouting stream:
directly store the reconstructed objects at HLT

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



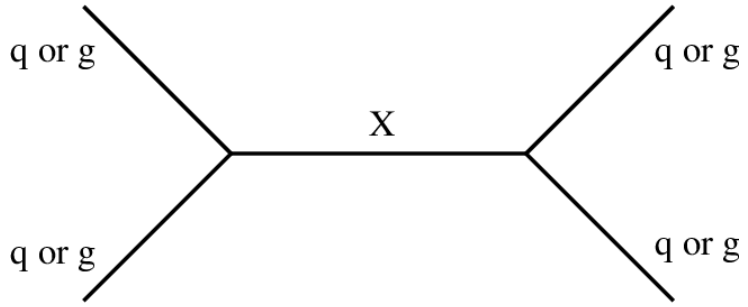


Better limits with HLT scouting

EXO-23-001-pas

General search
dijet and 4-jet resonance

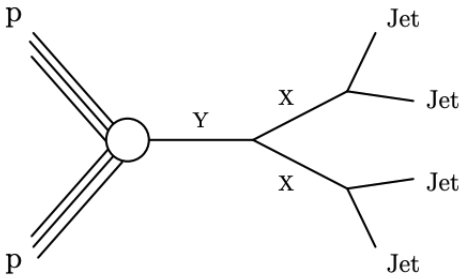
Search for dijet resonance

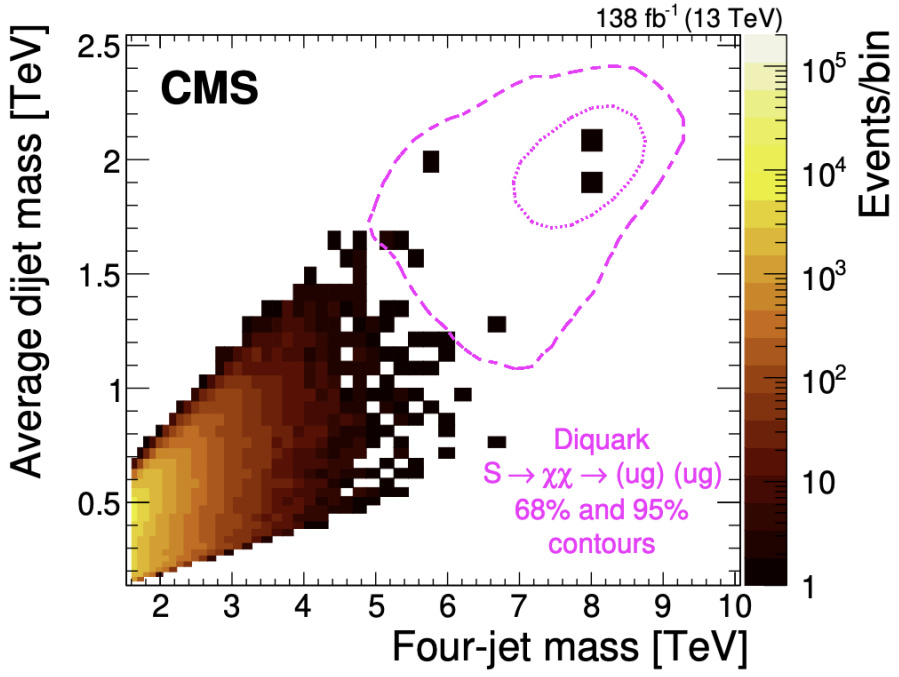


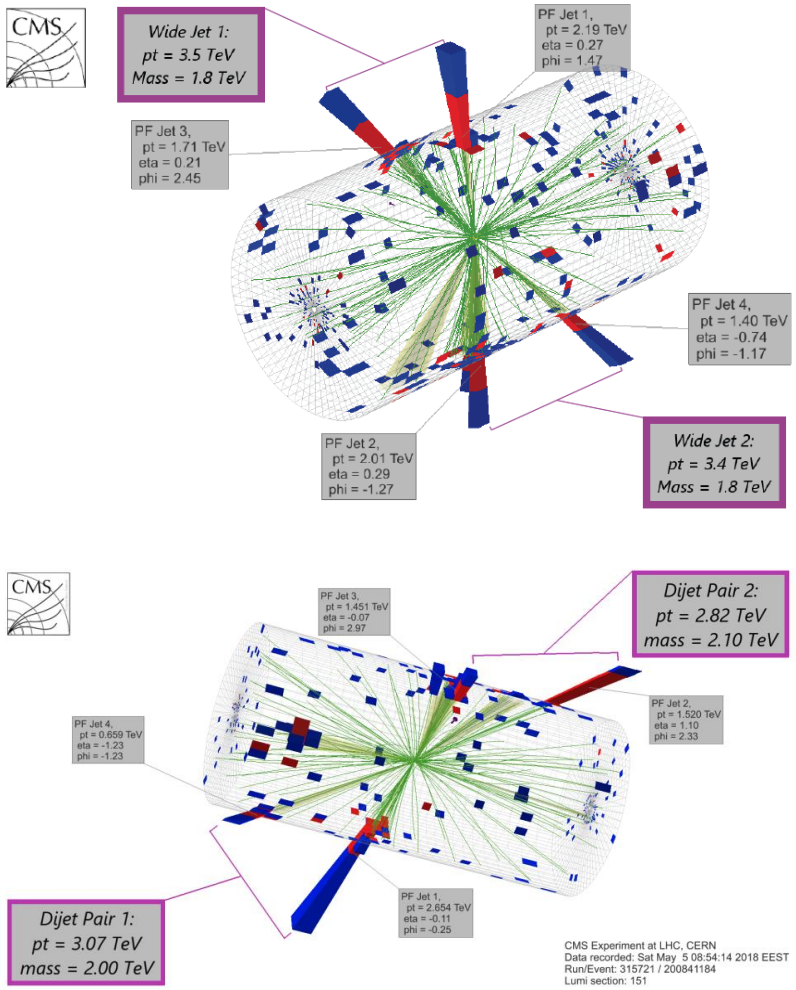
[1] UA1 Collaboration, Two-jet mass distributions at the CERN proton-antiproton collider, Phys. Lett. B 209 (1988) 127.
[2] CDF Collaboration, Two-jet invariant mass distribution at √s=1.8 TeV, Phys. Rev. D 41 (1990) 1722.
[3] CMS Collaboration, Search for Dijet Resonances in 7 TeV pp Collisions at CMS,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

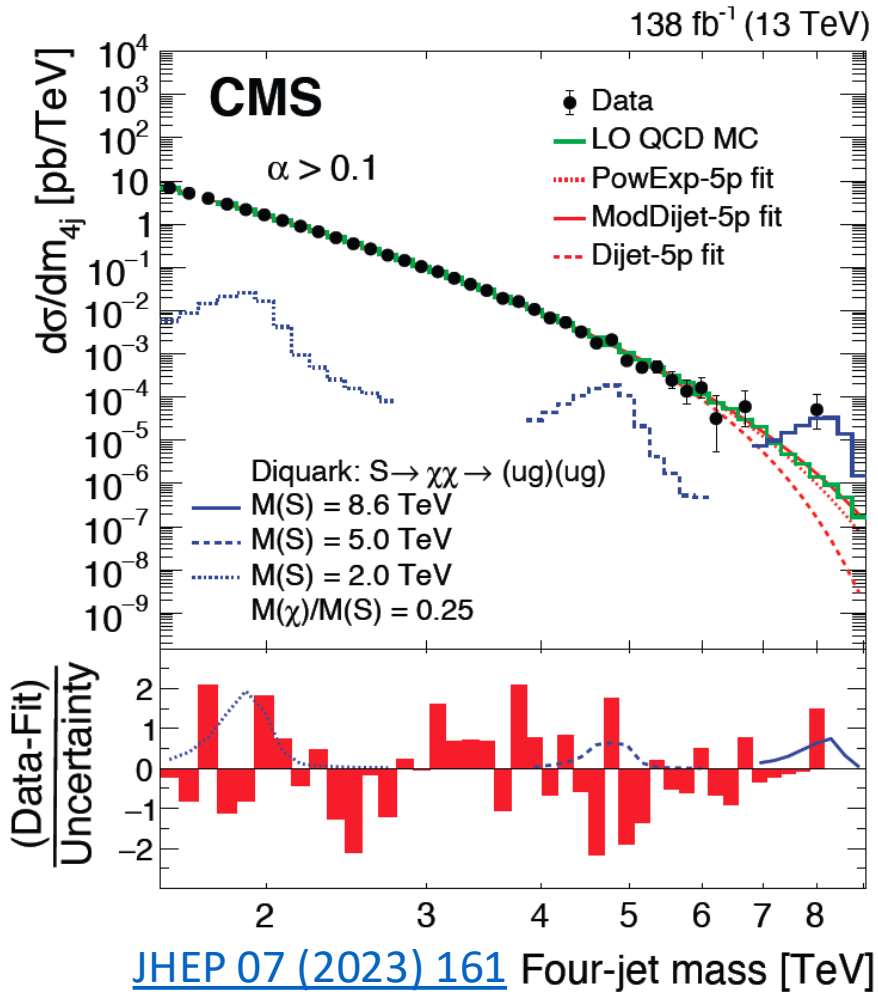
Search for 4-jet resonance



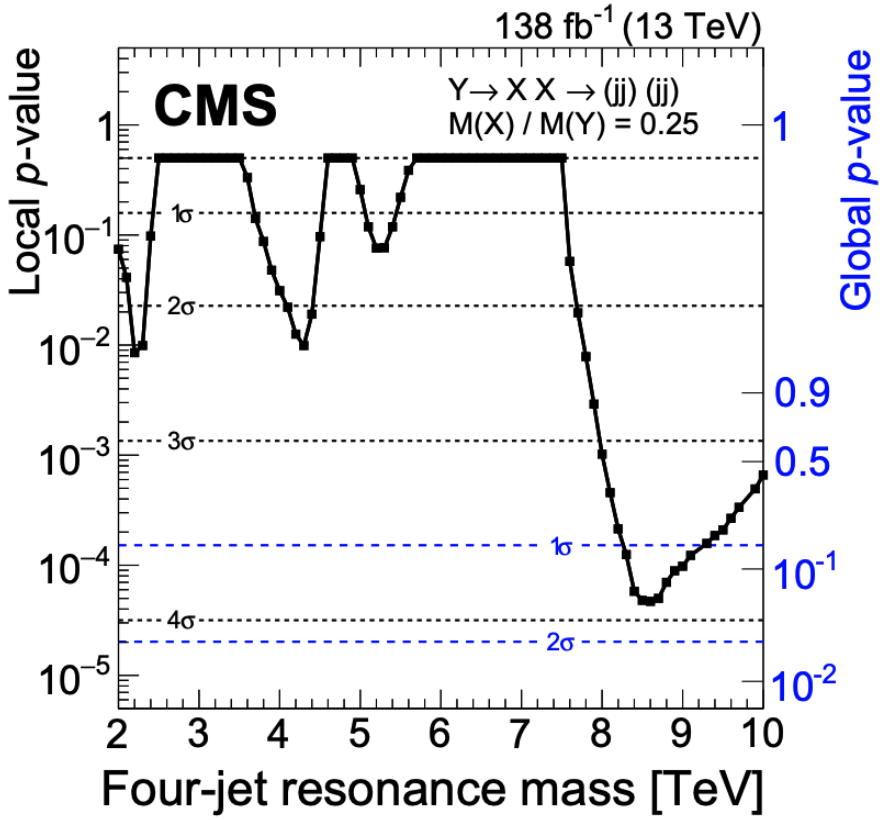




Results

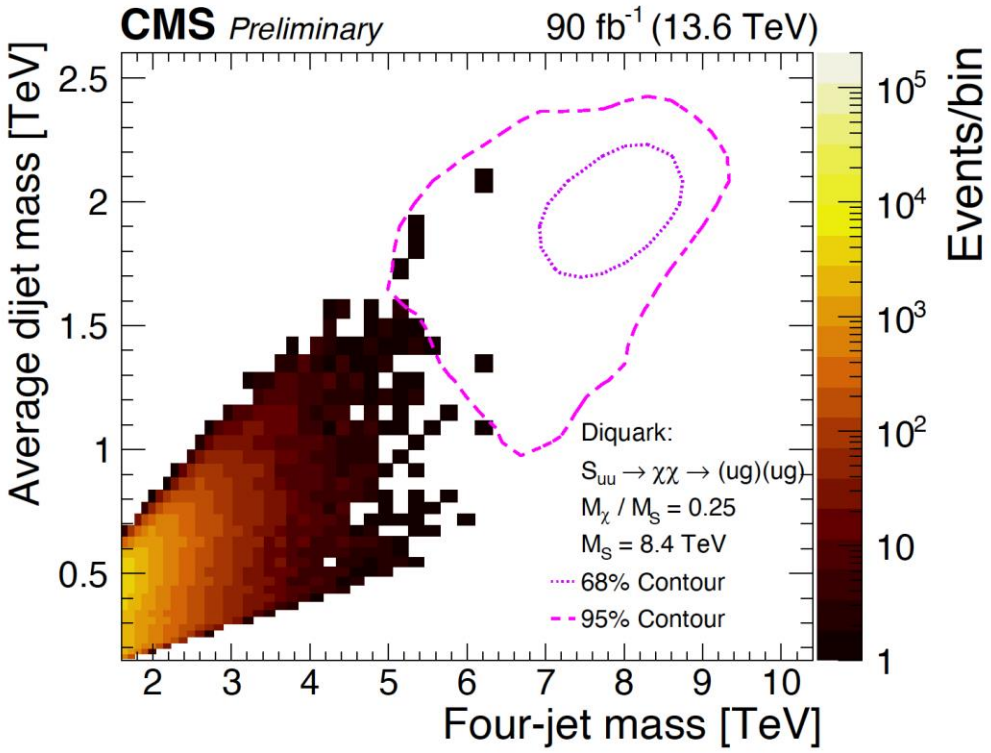


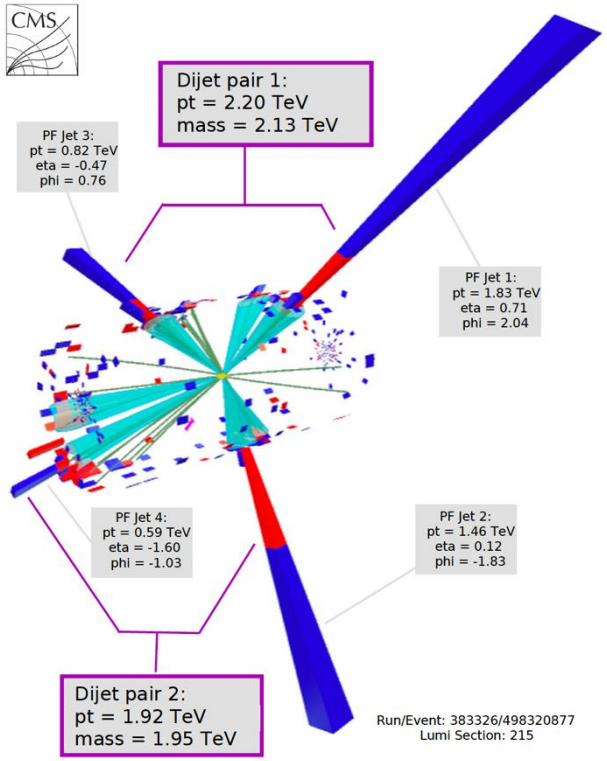
JHEP 07 (2023) 161



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

Run3 results





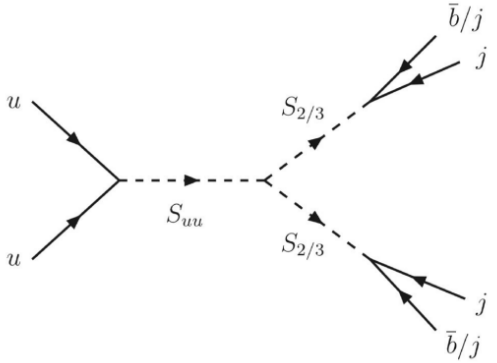
Latest result using 2024 data (CMS 2022, 2023 data unusable because of trigger prefiring)

The highest four jet mass observed is 6.5 TeV

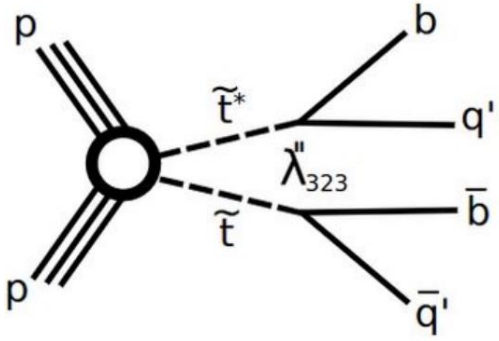
EXO-25-004-pas

Search for paired dijet with b-tag

Diquark-to-diquark (D2D)



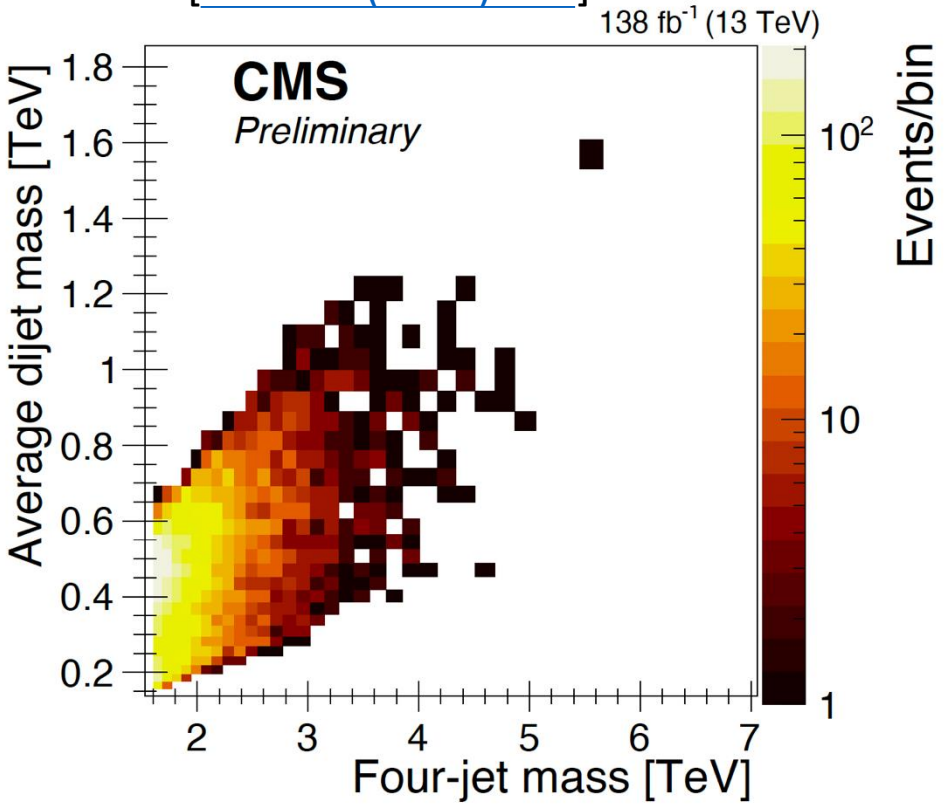
RPV



Benchmark models

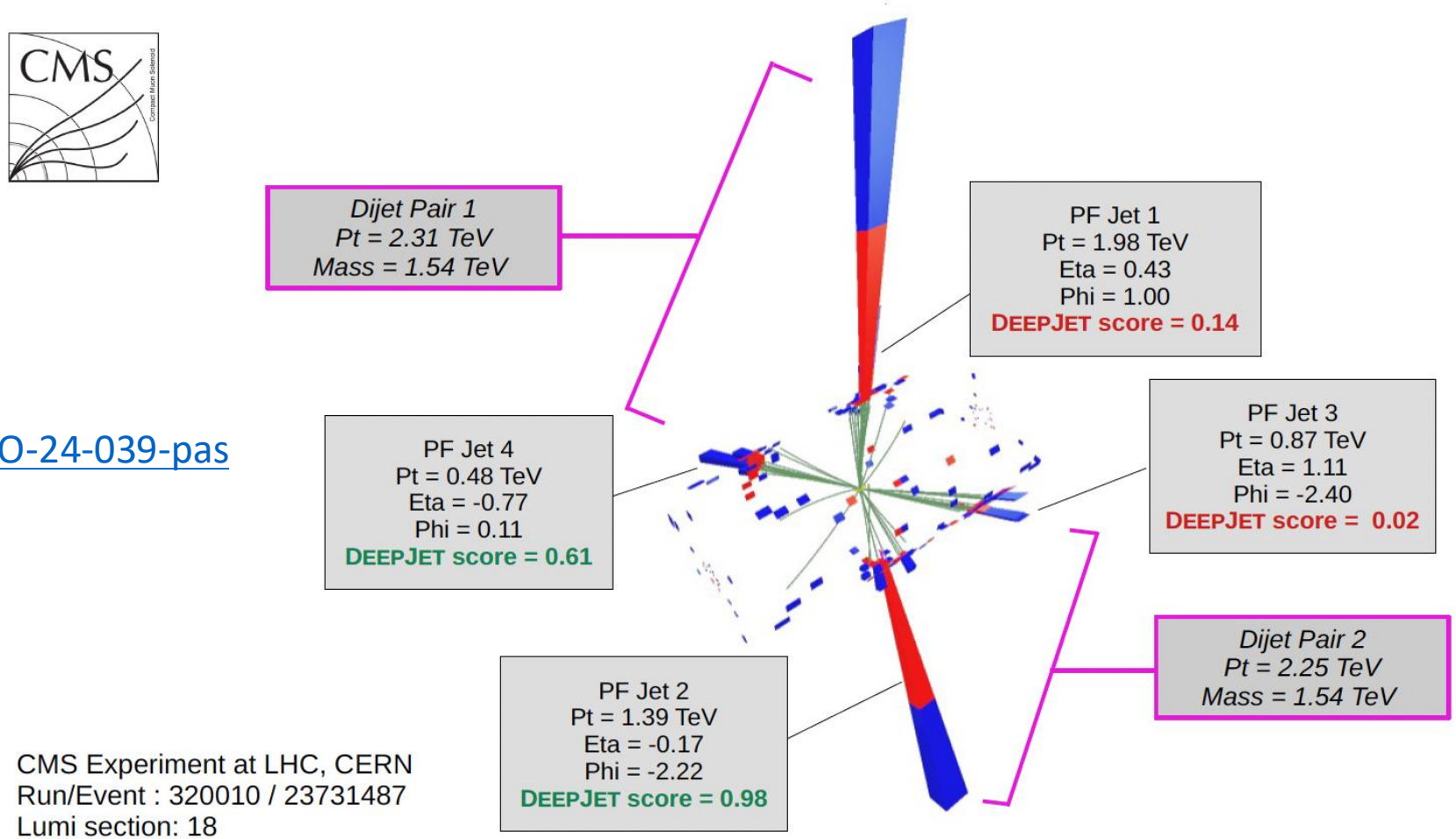
D2D [arXiv:1912.13155]

RPV [JHEP 04 (2013) 028]



EXO-24-039-pas

Results



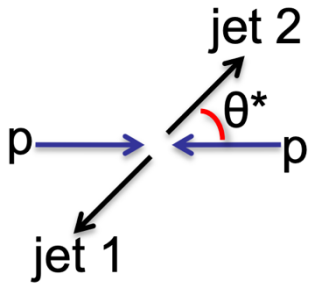
EXO-24-039-pas

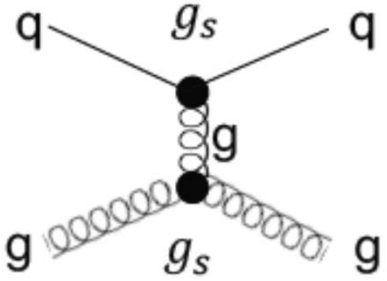
The highest four jet mass observed is 5.5 TeV, local significance ~2σ

Dijet Search with Angular Analysis

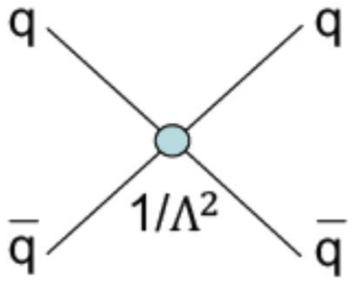
Dijet angular distributions probe parton-parton scattering angle

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





QCD background
- flat distribution
- independent of dijet mass



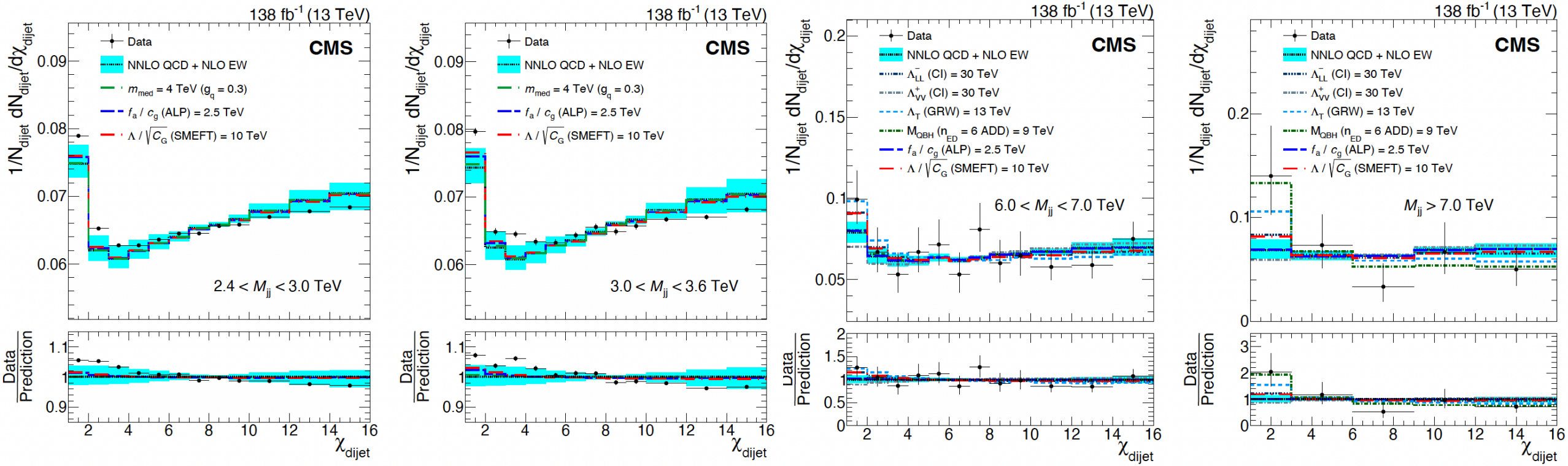
Signal
- peaks at low χ
- Increase at high dijet mass

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
  - 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