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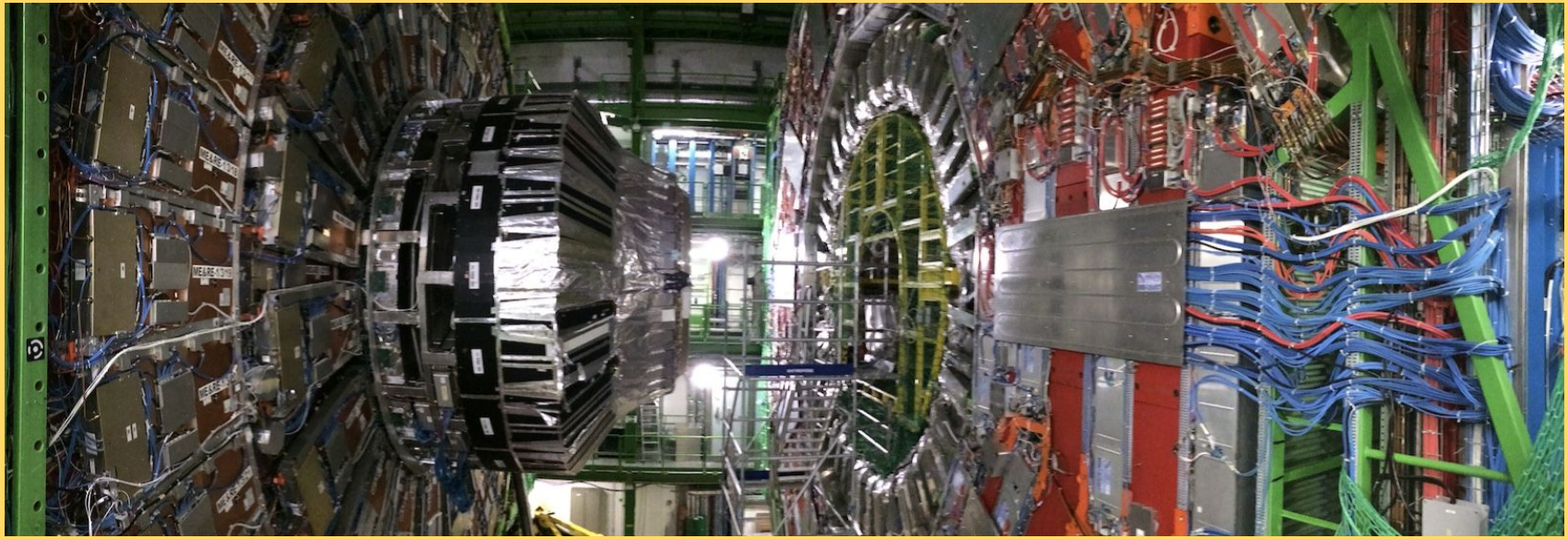
RUTGERS THE STATE UNIVERSITY OF NEW JERSEY

CMS

Searches in CMS for new physics in the final states with leptons

Olena Karacheban on behalf of CMS Collaboration (olena.karacheban@cern.ch)

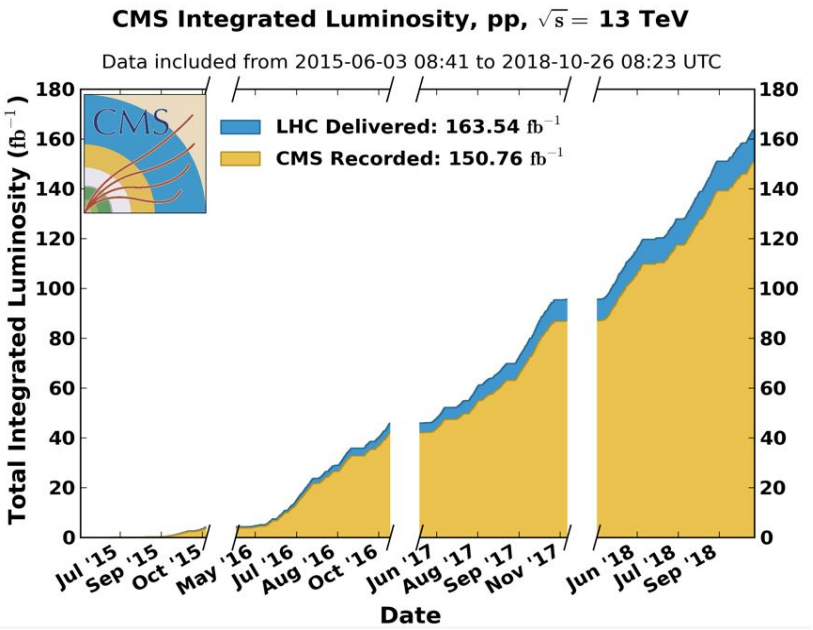


Introduction

- Standard Model is elegant theory and so far it withstands many tests carried out at collider experiments
- However SM can not explain
  - Asymmetry of the matter in the universe
  - Neutrino mass
  - Mass hierarchy between SM particles generations …

- **Wide range of models probing Beyond the Standard Model physics**:
  - Heavy gauge bosons and neutrino
  - Extended Higgs sector
  - Dark Matter
  - Unification theories
  - Extra Dimensions …

- **Full Run 2 data** set is available to examine these theories
- **Leptons are very clean probes** to explore the phasespace for new physics



Several latest EXO searches with leptons in the final states

Search for new physics in τ plus missing transverse momentum final state *(EXO-21-009)*

Key points:
- Hadronic tau + MET
- Multiple interpretations, including LQ, quantum black holes and nonuniversal gauge interaction model and more

FIRST RELEASE

The search for a third-generation leptoquark coupling to a τ lepton and a b quark *(EXO-19-016)*

Key points:
- Final state with $\boldsymbol{\tau}$ leptons
- Single, pair and LQ3 nonresonant production

FIRST RELEASE

Search for dilepton resonances from decays of (pseudo)scalar light bosons *(EXO-21-018)*

Key points:
- Three or four leptons in the final state
- Different coupling scenarios and variety of signatures
- Associated production with W/Z posonts or ttbar pair

FIRST RELEASE

Inclusive nonresonant multilepton search (EXO-21-002)

Key points:
- Three or four leptons in the final state
- Model independent tables
- Model specific MVA
- Seesaw type III, third-generation LQ and VLL models

Common terms and similarities for lepton analysis

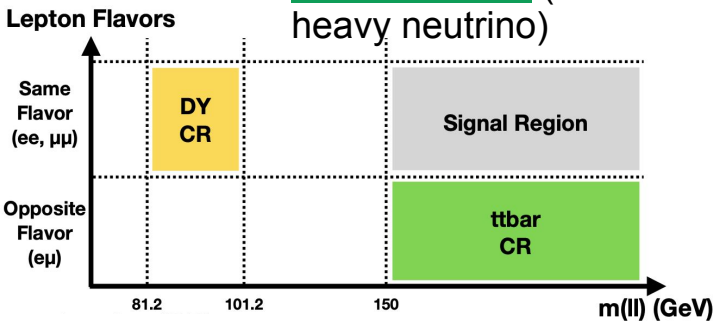
- Based on Run 2 LHC data (full Run 2) collected with CMS detector.
- Triggers: include single / double electron or muon, single / double photon.

- Main **prompt backgrounds** are normally normalized in the dedicated control regions orthogonal to signal region.

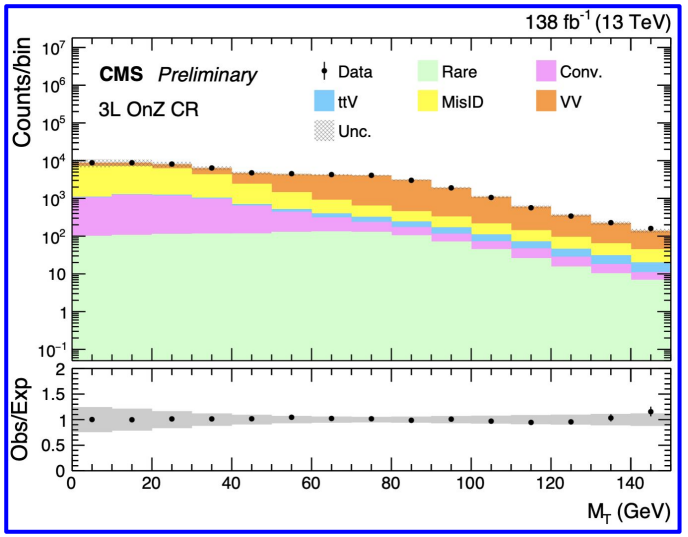
- **Fake (misidentification) backgrounds** are measured from data in bins of pT and η, when possible in several control regions:
  - Drell-Yan+Jets and ttbar+Jets rates are parameterized using sideband events with loose isolation.
  - τ fake backgrounds have different nature and are measured separately from light leptons.

Example of signal and control regions separation:

EXO-20-006 (Z' and heavy neutrino)



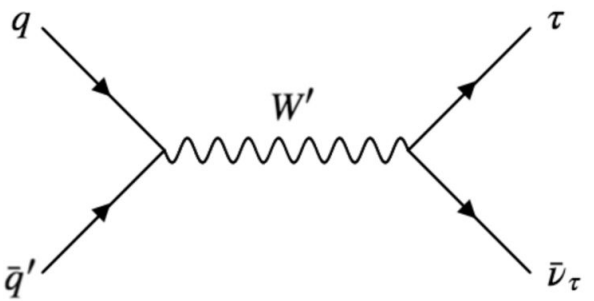
EXO-21-002 (nonresonant multilepton)

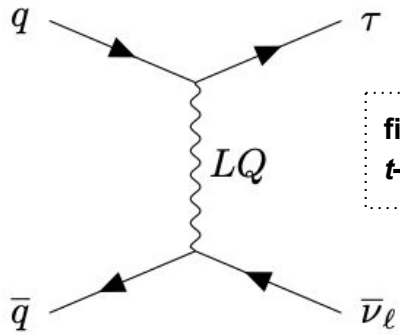


Search for new physics in τ plus MET final state (EXO-21-009)

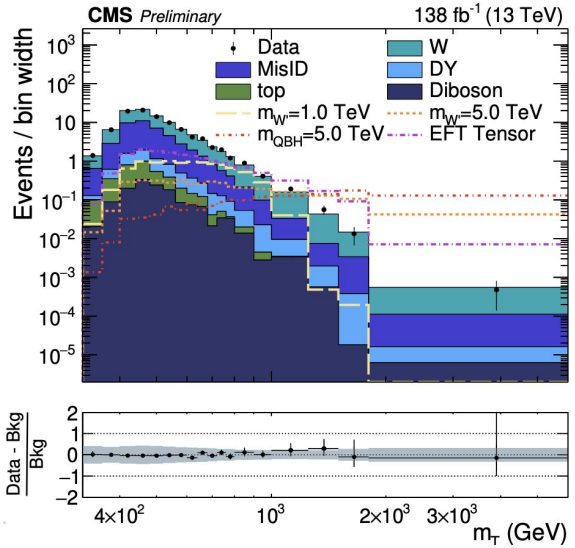
FIRST RELEASE

- A new charged gauge boson (W′) is one possible signature of the **sequential SM (SSM)**.
- W′ fermion couplings are similar to those of the SM W with **additional decay W′⇒tb, if mass W′ >180 GeV.**
- The **W′ coupling strengths** may differ from that of the SM W or the SSM W′ bosons.
  - $g_{W'}/g_W$ - impacts width and cross section
  - For $g_{W'}/g_W == 1$, this corresponds to Sequential Standard Model (benchmark)





first search for LQ *t*–channel exchange

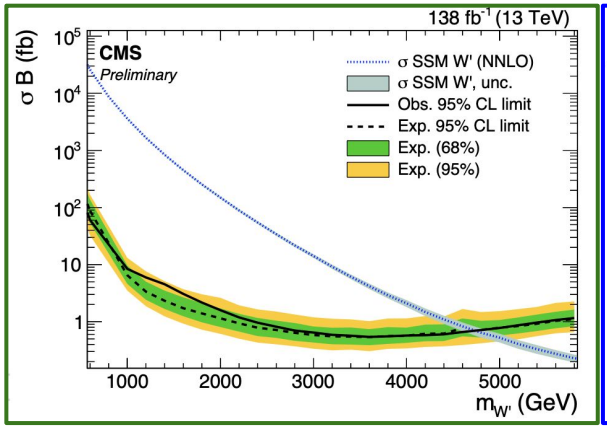


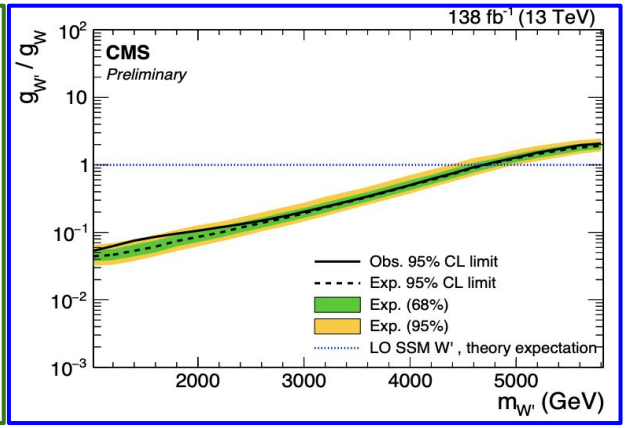
- **Final state:** one (hadronic) tau and missing transverse momentum
- p_T of tau and MET is balanced: expect back-to-back in azimuthal angle ϕ
- **Discriminant variable**: transverse mass m_T

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\tau_h} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi(\tau_{\mathrm{h}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}))}$$

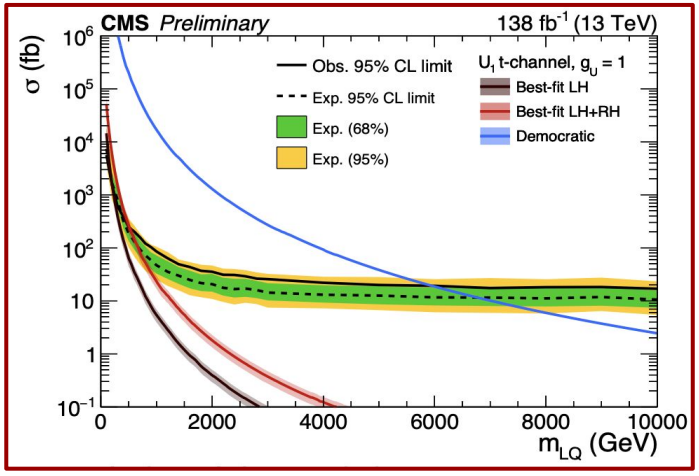
Results: Search for new physics in τ plus MET (EXO-21-009)

- Results are also interpreted for
  - Nonuniversal gauge interaction model (NUGIM)
  - Quantum black holes (QBH)
  - Effective field theory (EFT)
  - Vector leptoquark model: t-channel production
    - less dependence on mass of the LQ
    - First limit set on vector LQ model in this t-channel at the LHC.
- Taking background as a single bin ranging from min M_T to infinity also model independent limit is derived.



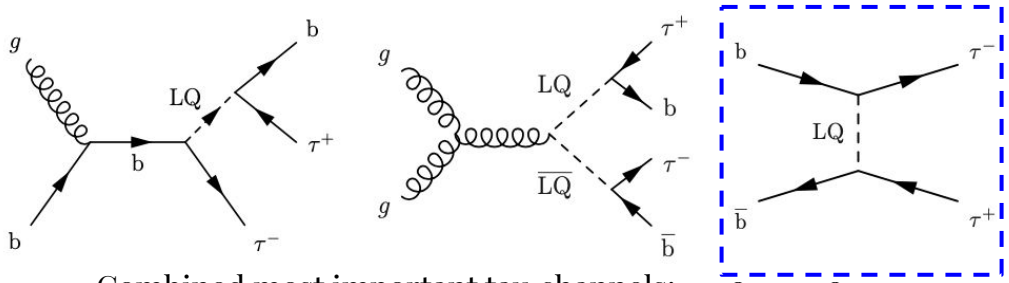


Model	Parameter	Expected Limit	Observed Run-2 Limit
SSM $W' \to \tau\nu$	$m_{W'}$	4.8 TeV	4.8 TeV
NUGIM $\cot(\theta_E)$=1	$m_{W'}$	4.8 TeV	4.8 TeV
NUGIM $\cot(\theta_E)$=5.5	$m_{W'}$	2.3 TeV	2.1 TeV
EFT ϵ_L=0.3	Signal strength	0.8	1.2
EFT ϵ_{SL}=1.0	Signal strength	0.1	0.2
EFT ϵ_T=0.3	Signal strength	0.5	1.0
LQ democratic, g_U=1.0	m_{LQ}	6.7 TeV	5.9 TeV
LQ Best-fit LH, g_U=1.0	m_{LQ}	145 GeV	205 GeV
LQ Best-fit LH, g_U=2.5	m_{LQ}	1.8 TeV	1.5 TeV
LQ Best-fit LH+RH, g_U=1.0	m_{LQ}	645 GeV	515 TeV
LQ Best-fit LH+RH, g_U=2.5	m_{LQ}	3.0 TeV	2.5 TeV
QBH	m_{QBH}	6.3 TeV	6.3 TeV

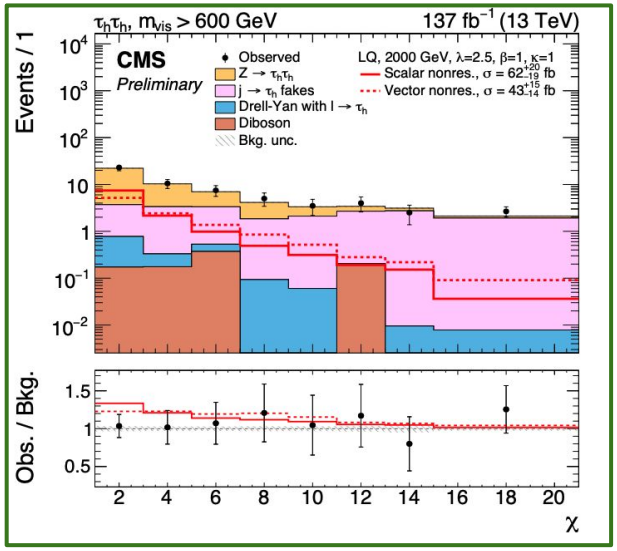


The search for a third-generation leptoquark coupling to a τ lepton and a b quark (EXO-19-016)

FIRST RELEASE



- Combined most important tau channels: $\tau\tau$, $e\tau$, $\mu\tau$, $e\mu$, $\mu\mu$
- Single, pair production and nonresonant production in t-channel
- 3 σ excess is observed arising from nonresonant channel



Summary of signal selections

$e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$ and $e\mu$ pre-selections ($e/\mu/\tau_h$ p_T > 50 GeV)

≥1 jet (p_T > 50 GeV)

Loose DeepCSV

0 b tag | ≥1 b tag

discriminating variable:

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

0 jet (p_T > 50 GeV)

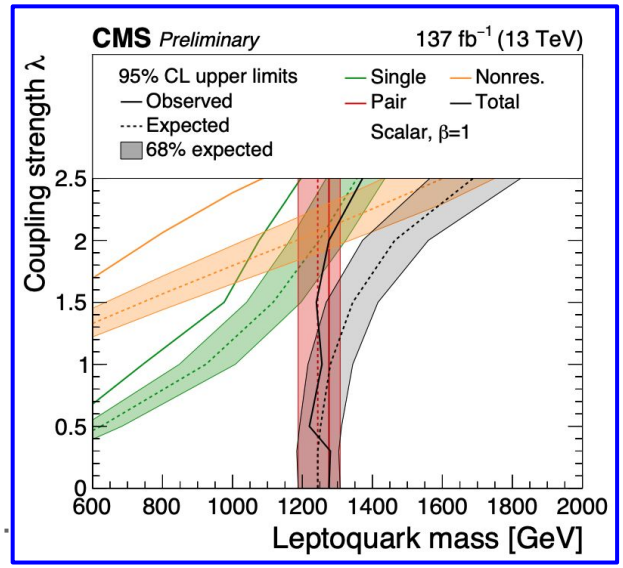
m_{vis} bins

200–400 | 400–600 | >600

discriminating variable:

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

angular separation between two taus



See this EXO-19-016 analysis in detail in Erini's talk:

Searches in CMS for new physics in final states with jets	*Eirini Tziaferi*
Bologna, Italy	10:00 - 10:15

Inclusive nonresonant multilepton probes of new phenomena (EXO-21-002)

- A **multi-bin, inclusive, model-independent** multilepton analysis with full Run2 data
- Covering light leptons, hadronic taus, and b-tags
- Categories by number of leptons:
  - Trilepton categories: 3L, 2L1T, 1L2T (L for light lepton and T for hadronic tau)
  - Quadlepton categories: 4L, 3L1T, 2L2T, 1L3T
- Each of the trilepton categories is split in 0, 1 and 2 or more b-jets categories (statistics permitting)
- Several signal models exploring high energy signatures (ST range up to 2 TeV)

and
FIRST RELEASE

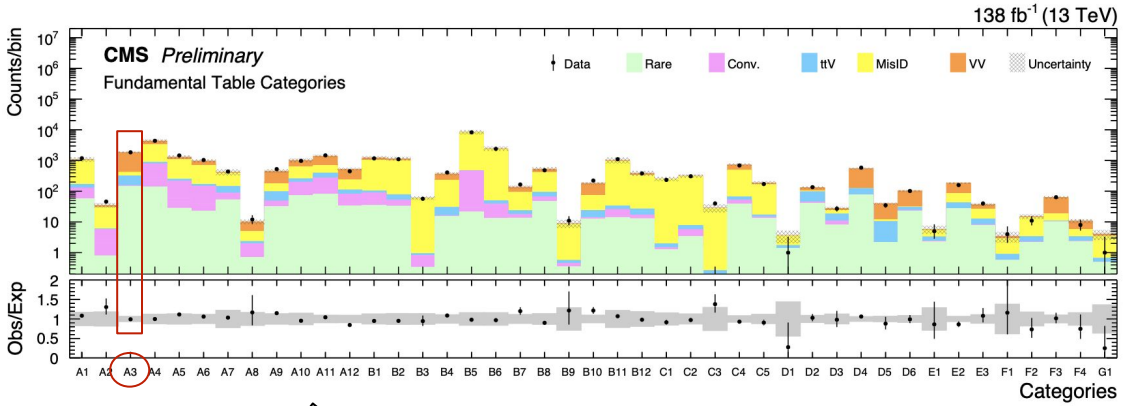
Search for dilepton resonances from decays of (pseudo)scalar light bosons (EXO-21-018)

- **Resonant part** of the analysis, **not inclusive**
  - natural extension of the multilepton analysis to the low energy
- Backgrounds are shared between nonresonant and resonant analyses
- Event selection has been reoptimized for light bosons search

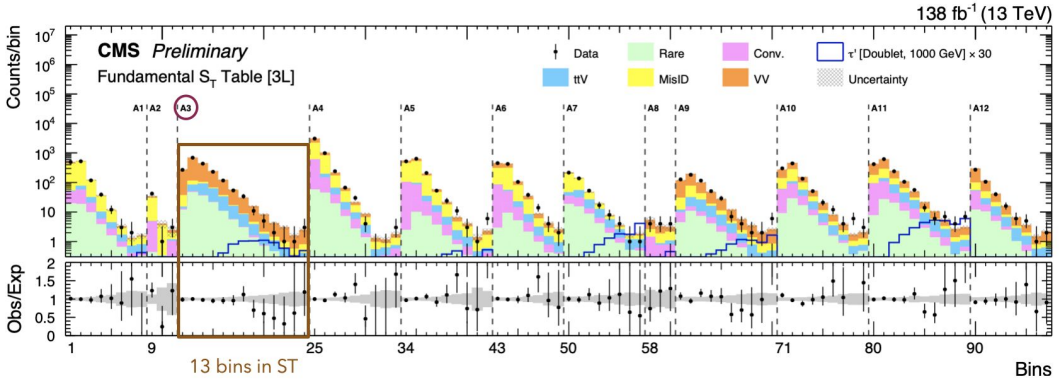
Inclusive cut based tables (EXO-21-002)

- Very detailed, SM-centric binning scheme to **probe dataset in many dimensions**
- Bins in ST and LT+MET

		OSSF0			OSSF1				OSSF2		
		BelowZ	AboveZ	SS	OnZ	BelowZ	AboveZ	MixedZ	Single-OnZ	Double-OnZ	OffZ
3L	Low p_T/M_T	A1*		A2	A3	A4	A5	A6	–	–	–
	High p_T/M_T	A7*		A8	A9	A10	A11	A12	–	–	–
2L1T	Low p_T	B1	B2	B3	B4	B5	B6	–	–	–	–
	High p_T	B7	B8	B9	B10	B11	B12	–	–	–	–
1L2T		C1	C2	C3	–	C4	C5	–	–	–	–
4L		D1*			D2	D3*			D4	D5	D6
3L1T		E1*			E2	E3*			–	–	–
2L2T		F1*			F2*			–	F3	–	F4
1L3T		G1*			–	G1*		–	–	–	–



- On top of this infrastructure several theory models are tested that provide complementary coverage of signature space
- **New physics could manifest itself as an excess in the tails of pT distributions**



Fundamental ST table in 3L

EXO-21-002

Complementary nonresonant signal models (EXO-21-002)

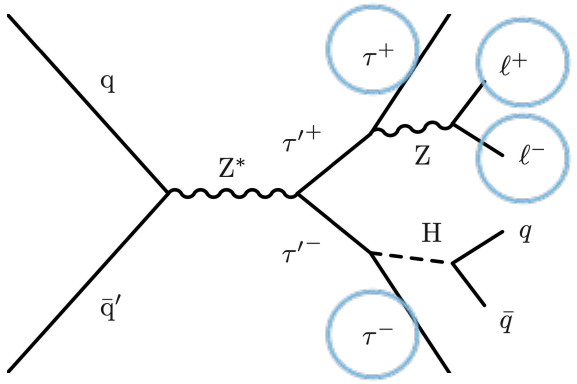
Tables in LT+MET and ST bins in this analysis create **regions of sensitivity for wide range of signatures.**

Results will be interpreted in the context of three signal models:

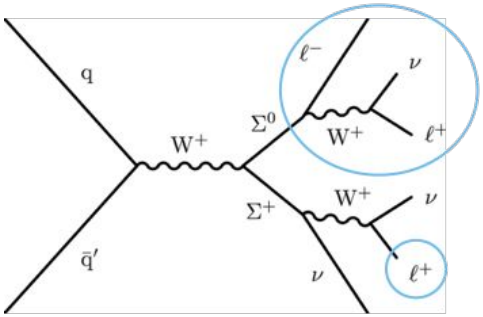
- Type-III Seesaw
- Vector-like leptons (singlet and doublet)
- Scalar leptoquarks (coupling to top quark and a charged lepton)

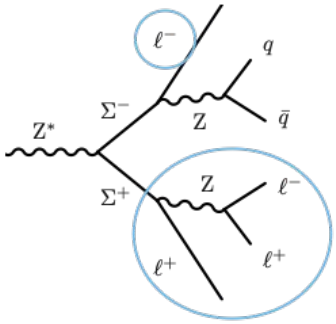
These models provide complementary signatures and cover different corners of the phase space of multilepton landscape: with high/low hadronic activity and transverse momentum, with and without b-jets.

Vector-like leptons: (τ'), or (τ', ν')



Type-III Seesaw: $\Sigma^{\pm}$, Σ^0





$$B_e + B_\mu + B_\tau = 1$$

B_e = **BR**($\Sigma \rightarrow e/\nu_e$ + V), B_μ = **BR**($\Sigma \rightarrow \mu/\nu_\mu$ + V) or B_τ = **BR**($\Sigma \rightarrow \tau/\nu_\tau$ + V),

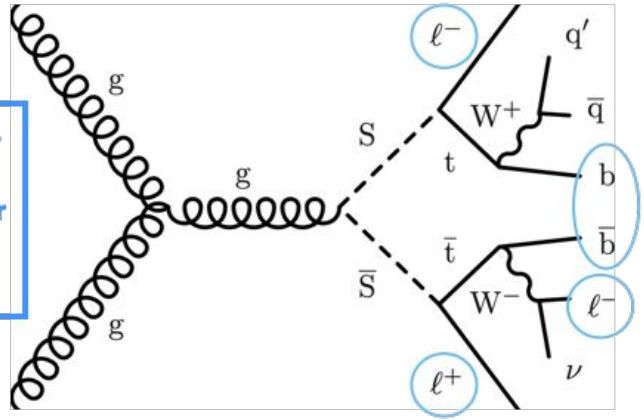
where V is W, Z or Higgs

Leptoquarks: S

$B_e = 1$ **or**

$B_\mu = 1$ **or**

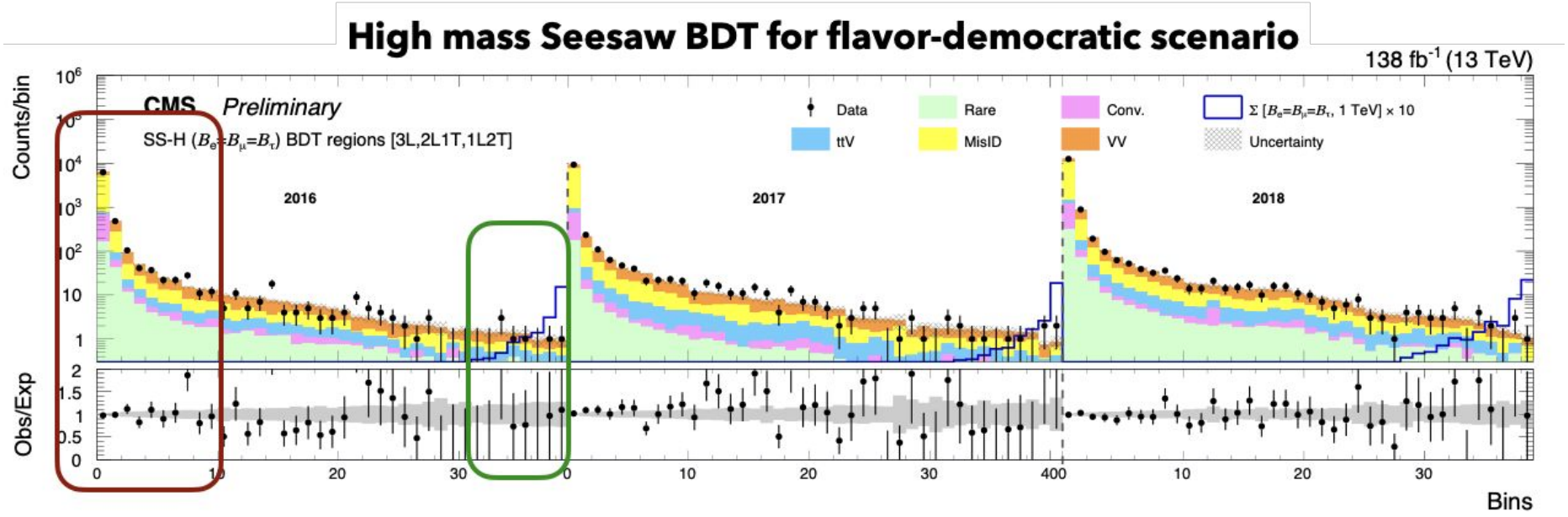
$B_\tau = 1$



B_e = **BR**(S → te) , B_μ = **BR**(S → tμ) or B_τ = **BR**(S → tτ)

Model specific MVA (EXO-21-002)

- **Signal specific BDT training** for range of masses.
- Increase signal sensitivity by creating a variable bin width for the BDT score (stretch high BDT score, compress low BDT score).
- **Complementary to table results.** Tables and MVAs acting as performance reference points for each other.



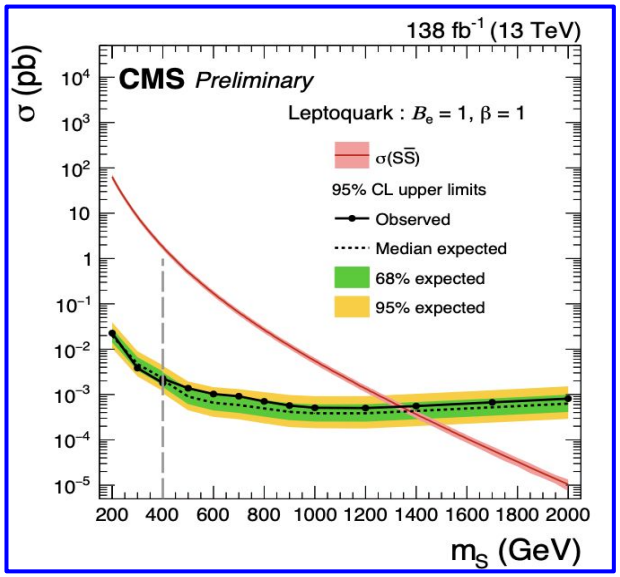
BDT score transformation: …

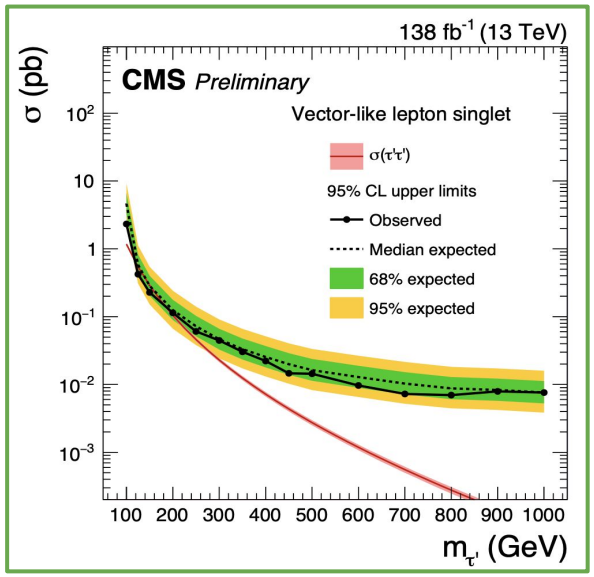
- Bin 1: [-1, -0.9115]
- Bin 2: [-0.9115, -0.8115]

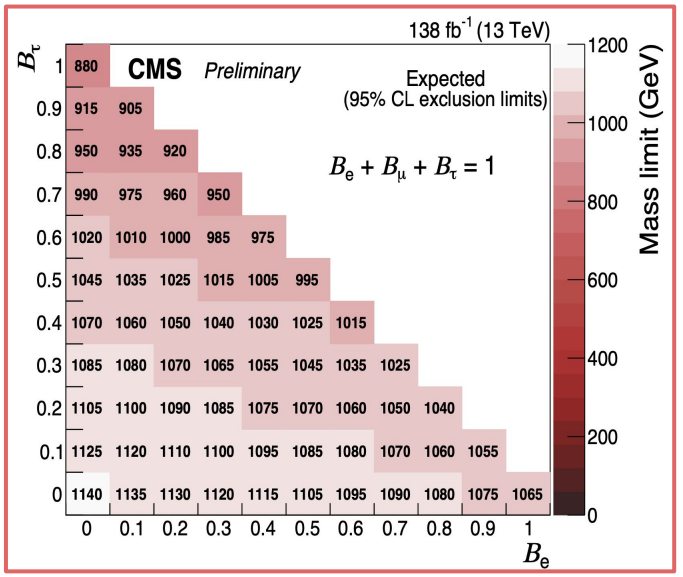
…

- Bin 19: [0.9755, 0.9925]
- Bin 20: [0.9925, 1]

Results on nonresonant search (EXO-21-002)







- **Expected and observed upper limits** on the production cross-section are computed using the asymptotic CLs criterion at 95% CL.
- Only the best exclusion among tables and MVA for each mass point is shown. The best expected limits are used to select between the cut-based tables and MVA based limits.
- Upper observed mass limits:
  - Leptoquarks assuming the $B_e = 1$ // $B_\mu = 1$ // $B_\tau = 1$ scenario 1340 GeV // 1425 GeV // 1120 GeV
  - Vector-like leptons assuming the doublet extension 1045 GeV, and the singlet extension 125-170 GeV
  - Seesaw assuming the flavor-democratic scenario 975 GeV
  - Seesaw assuming the $B_e = 1$ // $B_\mu = 1$ // $B_\tau = 1$ scenario 990 GeV // 1065 GeV // 890 GeV

Resonant Xϕ family (EXO-21-018)

FIRST RELEASE

- Search for resonant signature of ϕ boson in multilepton events.
- ϕ is produced in association with ttbar pair or W/Z bosons. Scalar, pseudoscalar and Higgs-like coupling scenarios are probed.
  - **ttϕ** (S/PS)
  - **Zϕ** (S/PS/H)
  - **Wϕ** (S/PS/H)
- Complementary signatures:
  - 0 / 1+ b-jets,
  - low/high ST,
  - 3 or 4 leptons,
  - with/without MET

Cross sections for each coupling:

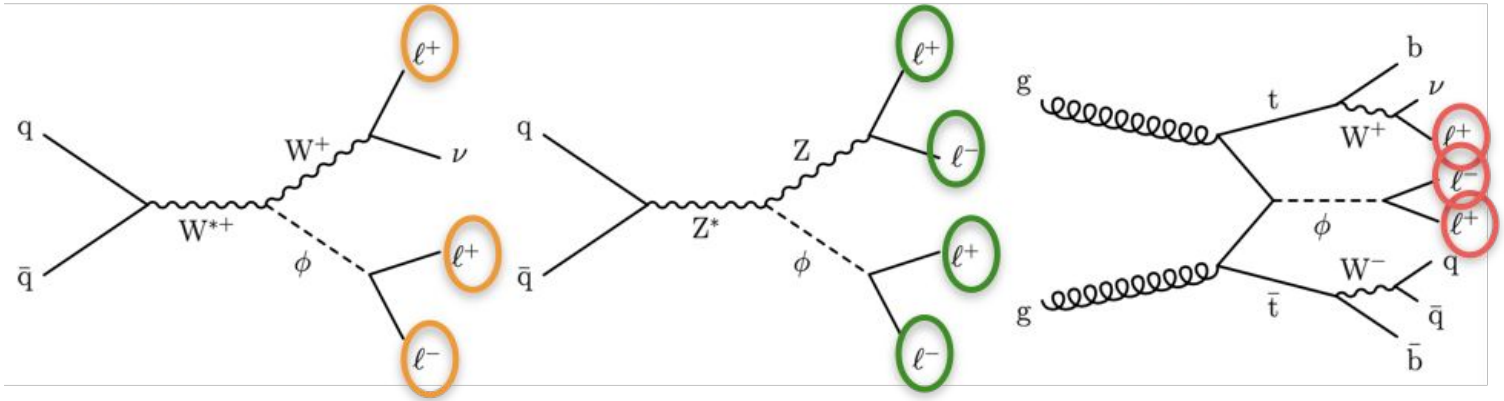
For S / PS: $\sigma(W\phi/Z\phi) \sim \Lambda^{-2}$

$\sigma(t\bar{t}\phi) \sim g_S^2$ or g_{PS}^2

For H-like: $\sigma(W\phi/Z\phi) \sim \sin^2\theta$

Λ is the effective coupling mass scale, θ is the mixing angle, g is Yukawa coupling to top quark.

$W\phi\ (\phi \to \ell^+\ell^-)$ $Z\phi\ (\phi \to \ell^+\ell^-)$ $t\bar{t}\phi\ (\phi \to \ell^+\ell^-)$



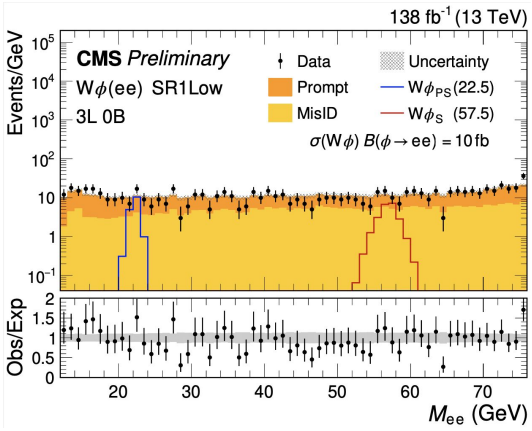
Analysis strategy and results (EXO-21-018)

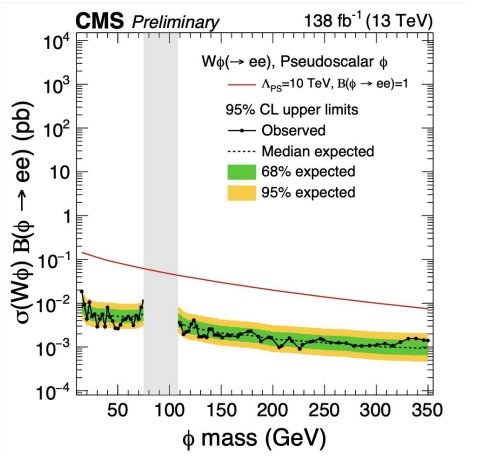
FIRST RELEASE

Resonant $X\phi \to ee/\mu\mu$

- **Dilepton mass is the final discriminator distribution**: M_{ee} for $\phi \to e^+e^-$ and $M_{\mu\mu}$ for $\phi \to \mu^+\mu^-$ search.
- Z boson mass window 91±15 GeV is excluded due to high SM background contamination. ϕ mass is probed in the mass range of 15-76 GeV and 106-366 GeV.

Example of dielectron mass distribution with $W\phi$ signal ($\phi \to ee$)

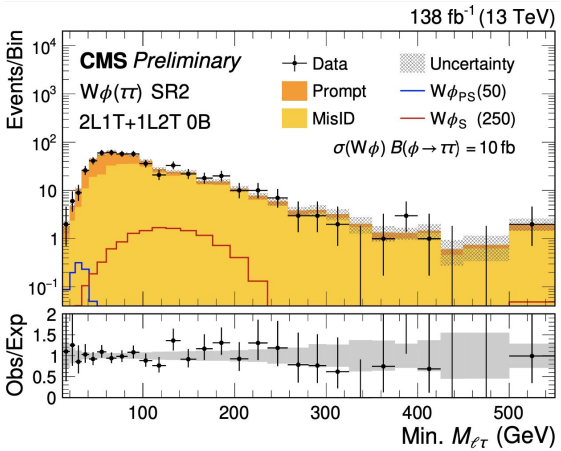


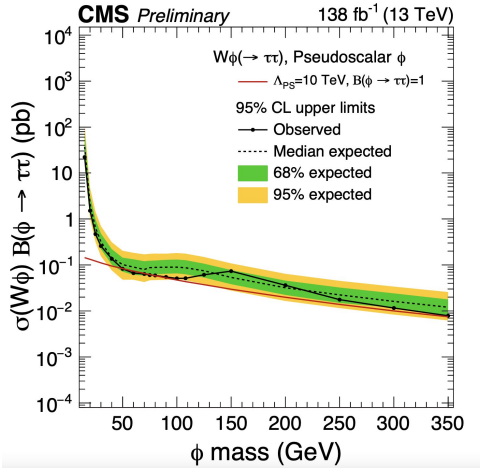


Semiseronant $X\phi \to \tau\tau$

- **Mass spectra** are defined depending on the flavor of leptons used to reconstruct the ϕ mass:
  - $M_{\tau\tau}$ when two τ_h leptons are used
  - $M_{l\tau}$ when light lepton and τ_h lepton are used
  - M_{ll} when two light leptons are used (ee, $\mu\mu$ or eμ)

Example of the min $M_{l\tau}$ mass variable with $W\phi$ signal ($\phi \to \tau\tau$).



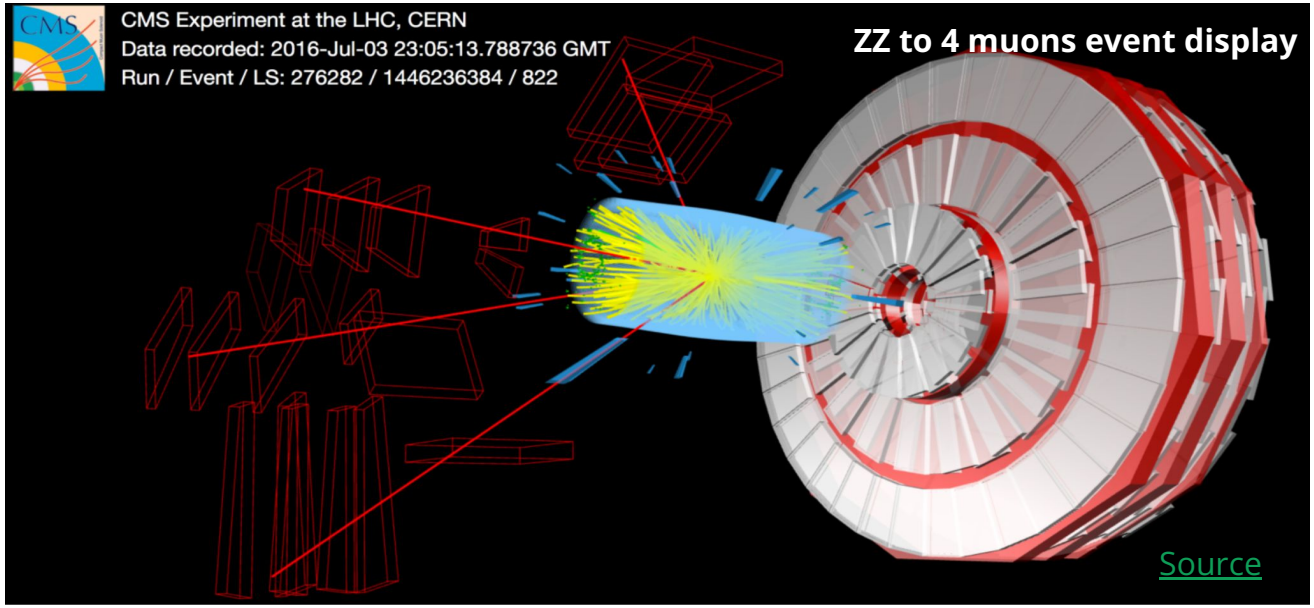


- No significant excess of data consistent with the models probed.
- **$tt\phi \to ee/\mu\mu$** are the most restrictive limits. **$W\phi$, $Z\phi$** and **$tt\phi \to \tau\tau$** are the first direct constraints on an extension of the SM with light boson in leptonic decay channels and this mass range.

Conclusions

- CMS performed many resonant and nonresonant searches beyond Standard Model with leptons in the final state.
- Only several latest publications were discussed today. **Full list of publications** can be found here and preliminary results here.
- **Run 3** will bring: more data, new triggers, analysis techniques!

Looking forward to new exciting results!



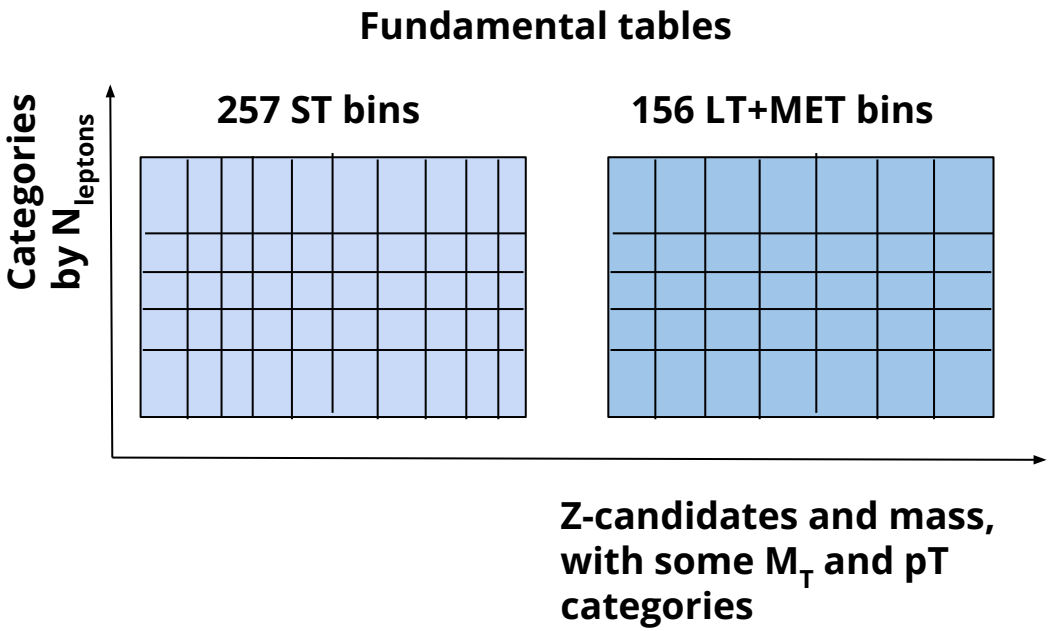
See more CMS analyses with leptons in the final stats in Celia's talk:

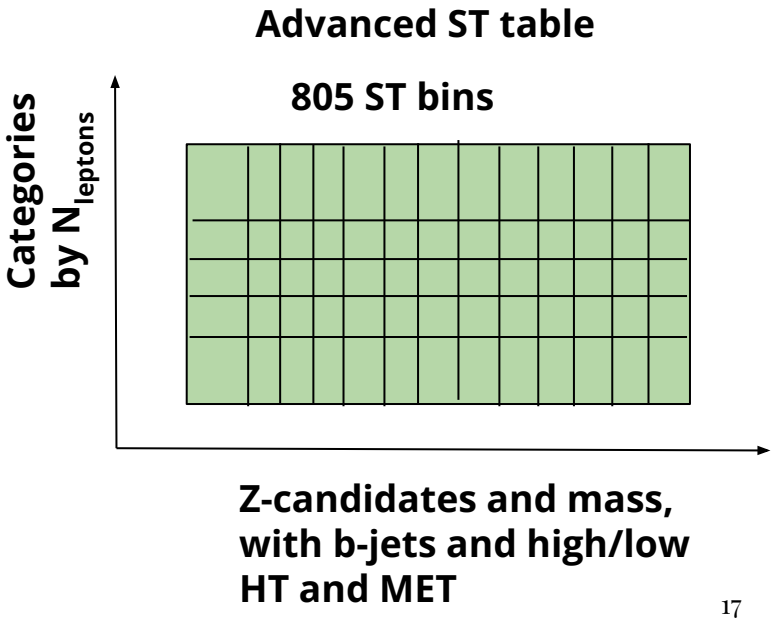
Searches in CMS for long-lived particles and other non-conventional signatures	*Celia Fernández Madrazo*
Room 10 (Magenta B)	12:00 - 12:15

Backup

Inclusive nonresonant multilepton probes of new phenomena (EXO-21-002)

- A **multi-bin, inclusive, model-independent** multilepton analysis with full Run2 data.
- Covering light leptons, hadronic taus, and b-tags.
- Categories by number of leptons:
  - Trilepton categories: 3L, 2L1T, 1L2T (L for light lepton and T for hadronic tau)
  - Quadlepton categories: 4L, 3L1T, 2L2T, 1L3T
- Each of the trilepton categories is split in 0, 1 and 2 or more b-jets categories (statistics permitting)





Inclusive fundamental tables (EXO-21-002, full Run 2)

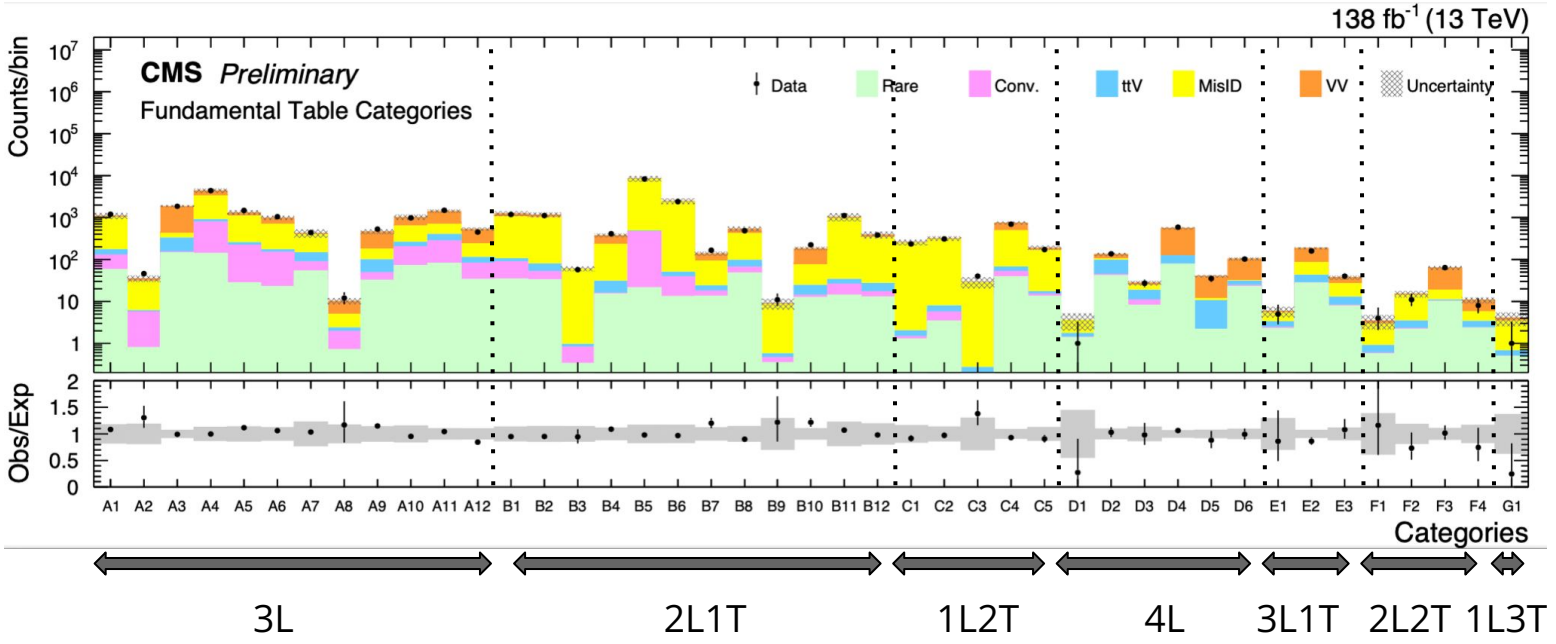
Fundamental scheme

Flavor based Categories

		OSSF0			OSSF1				OSSF2		
		BelowZ	AboveZ	SS	OnZ	BelowZ	AboveZ	MixedZ	Single-OnZ	Double-OnZ	OffZ
3L	Low p_T/M_T	A1*		A2	A3	A4	A5	A6	–	–	–
	High p_T/M_T	A7*		A8	A9	A10	A11	A12	–	–	–
2L1T	Low p_T	B1	B2	B3	B4	B5	B6	–	–	–	–
	High p_T	B7	B8	B9	B10	B11	B12	–	–	–	–
1L2T		C1	C2	C3	–	C4	C5	–	–	–	–
4L		D1*			D2	D3*			D4	D5	D6
3L1T		E1*			E2	E3*			–	–	–
2L2T		F1*			F2*			–	F3	–	F4
1L3T		G1*			–	G1*		–	–	–	–

Z-candidates

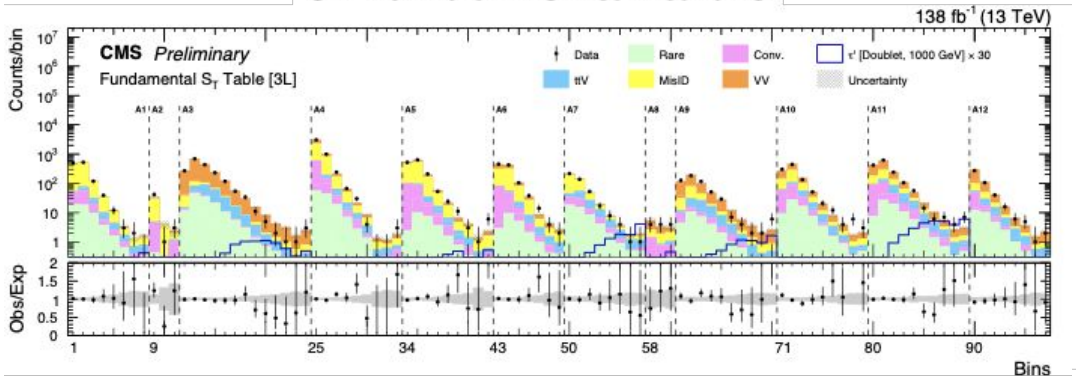
Multiplicity



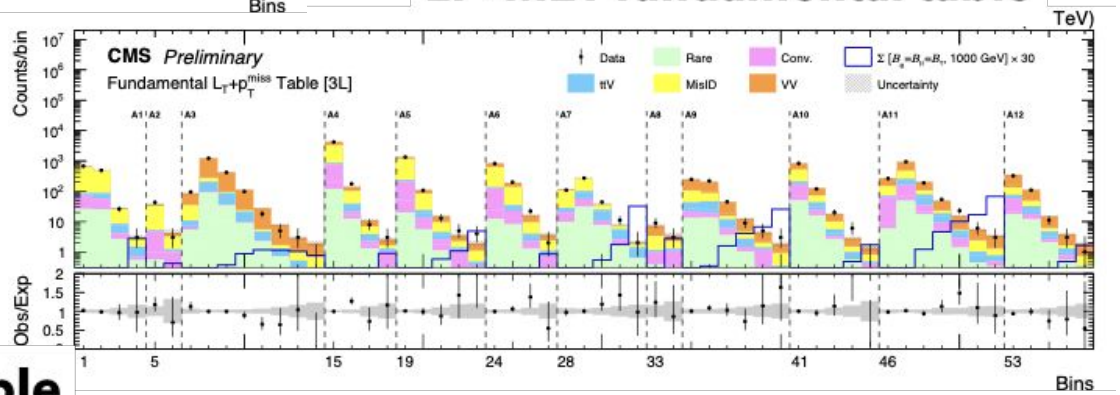
Signal regions tables (EXO-21-002)

Not public yet

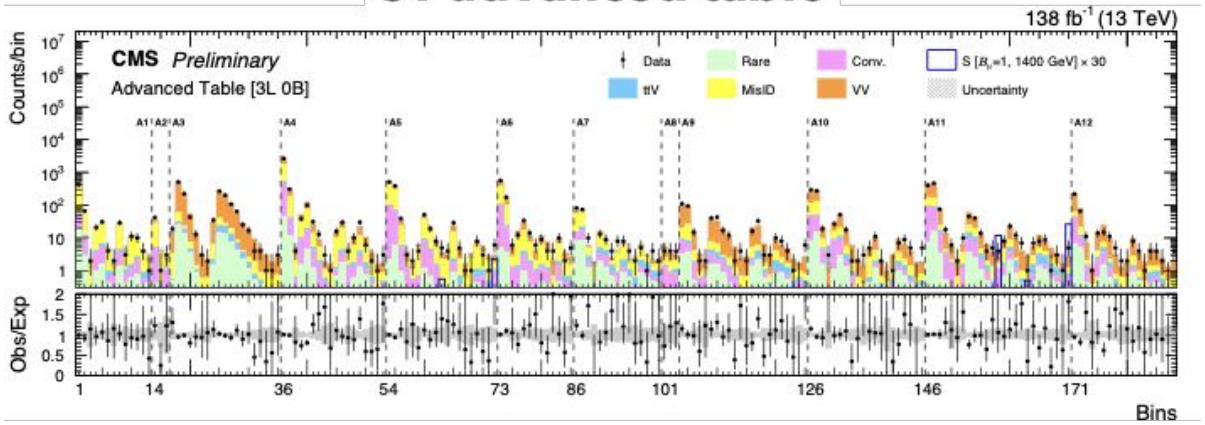
ST fundamental table



LT+MET fundamental table



ST advanced table



Other recent EXO searches with leptons in the final states

Search for Z prime and heavy neutrino in events with two same flavor leptons and at least two jets (EXO-20-006)

Key points:
- Neutral current
- Dielectron and dimuon final states

Right-handed W boson and heavy neutrino (EXO-20-002)

Key points:
- Charged current
- Dielectron and dimuon final states
- Boosted and resolved topologies

Lepton-flavor violating decays of heavy resonances and quantum black holes to $e\mu$, $e\tau$, $\mu\tau$ (EXO-19-014)

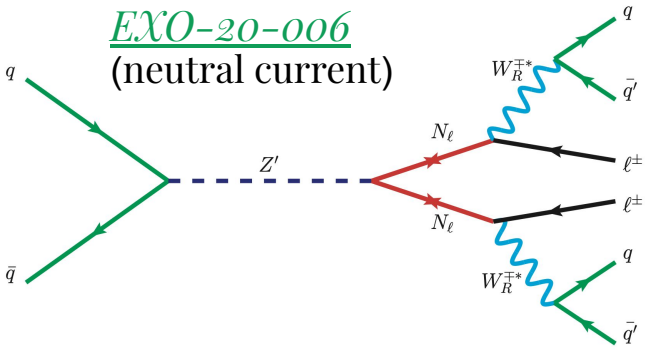
Key points:
- Final state with light leptons and taus
- Model specific and model independent exclusions

Search for Z', W_R and heavy Majorana neutrinos (EXO-20-006, EXO-20-002)

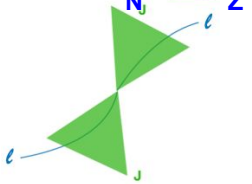
- The left-right symmetric model (LRSM) is an extension of SM by a right-handed SU(2) group: $\mathbf{W_R}^{\pm}$ and **Z'** and three right handed neutrinos.
- Two searches for extra gauge bosons and heavy Majorana neutrinos:
  - Dilepton (ee and $\mu\mu$) plus jets final state
  - **Z'** mass range 400-4400 GeV
  - $\mathbf{W_R}$, mass range 200-7000 GeV
  - **heavy neutrino** (**N**, mass between 100 GeV and **Z' or $\mathbf{W_R}$** mass)

- Kinematics varies dramatically depending on ratio between masses of extra gauge bosons and heavy Majorana neutrinos

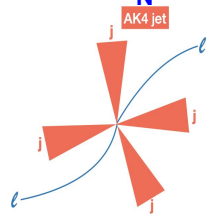
EXO-20-006 (neutral current)



Boosted: $M_{N_\ell} \ll M_{Z'}$

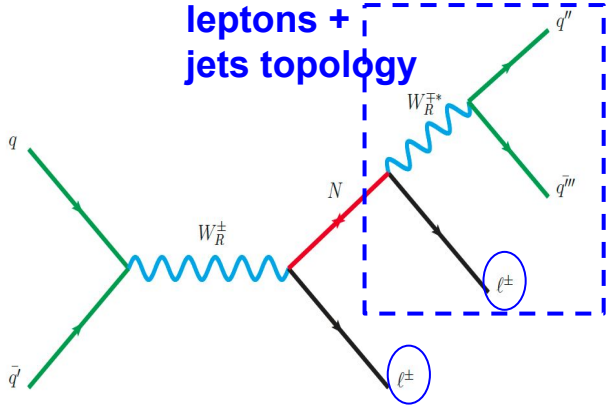


Resolved: $M_N \sim M_{Z'}$

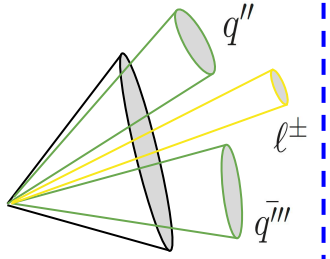


EXO-20-002 (charged current)

Resolved leptons + jets topology



Boosted lepton + jets topology

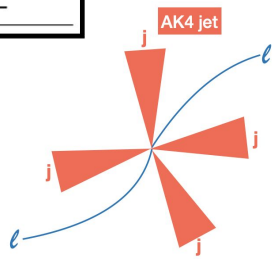


See more on EXO-20-002 and heavy neutrino new Run2 results in dedicated Basile's talk:

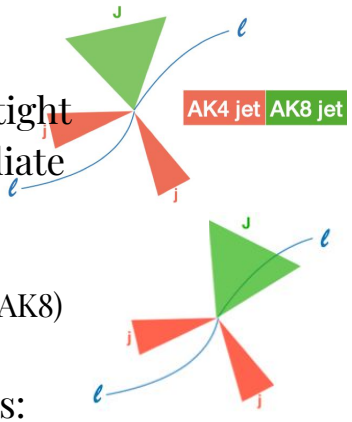
Searches for Heavy Neutral Leptons in CMS	*Basile Vermassen*
Bologna, Italy	17:45 - 18:00

Reconstruction of Z' and N

SR	N(AK8 jet)	N(tight leptons)	N(AK4 jet)
SR1 (0AK8)	$= 0$	$= 2$	≥ 4
SR2 (1AK8)	$= 1$	≥ 1	≥ 2
SR3 (2AK8)	≥ 2	—	—

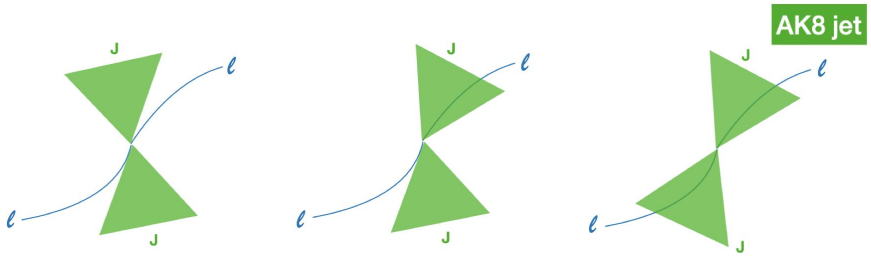


- Leading four AK4 jets and two tight leptons: Good sensitivity for resolved signals
  - Two N(= a tight lepton + two AK4 jets) with the smallest Δ(mN1, mN2)
  - Z'=N1+N2

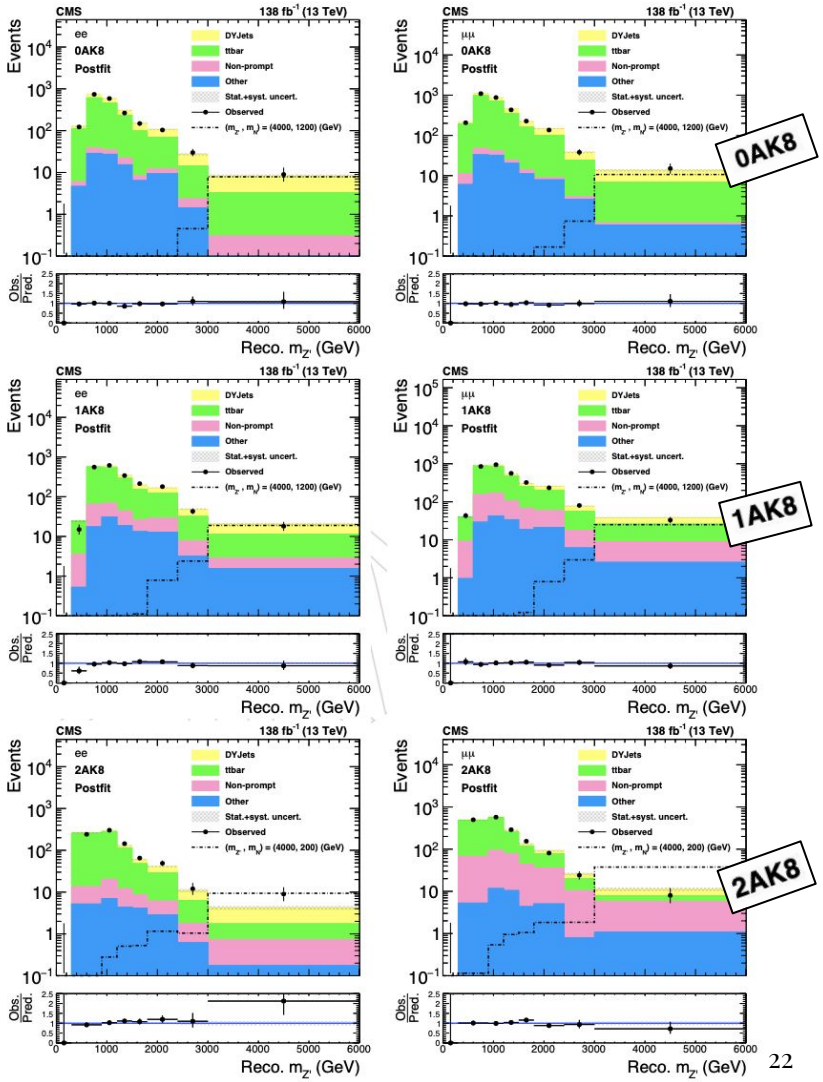


- An AK8 jet, leading two AK4 jets, and tight leptons: good sensitivity for intermediate signals
  - N1 = two jest and tight laptop
  - N2 = AK8 jet and tight lepton (or just AK8)

- Leading two AK8 jets and tight leptons: good sensitivity for boosted signals

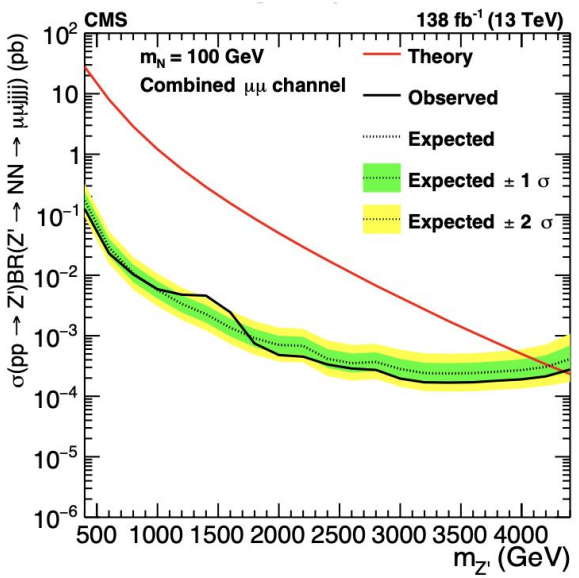


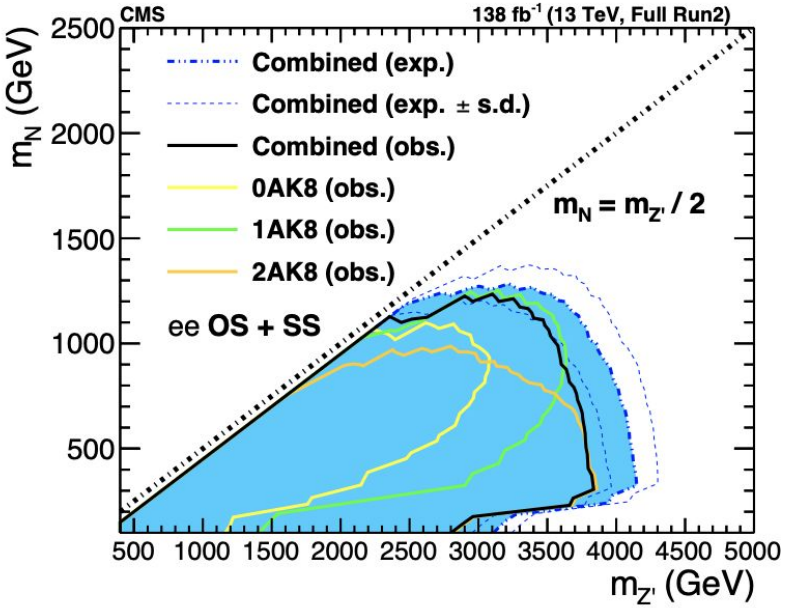
- **Final discriminant** for binned maximum-likelihood fit is invariant mass:

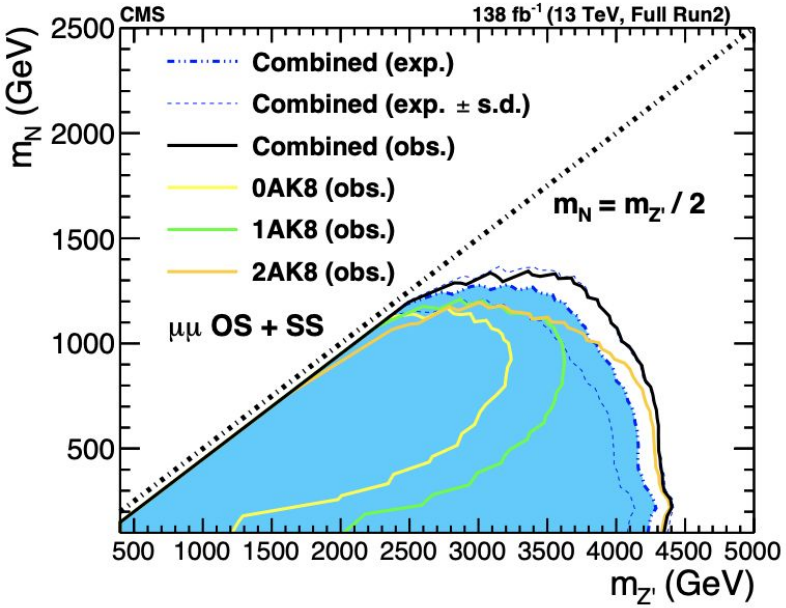


Results (EXO-20-006)

- No significant excess for Z': upper limit are set on cross section times brach fraction
- Exclusion regions are set using signal cross sections:
  - Up to mZ' = 2.8 TeV in electron channel, and 4.4 TeV in muon channel
  - Significant improvement in sensitivity compared to the previous ATLAS results (2.2 TeV based on 8 TeV data from Run 1)

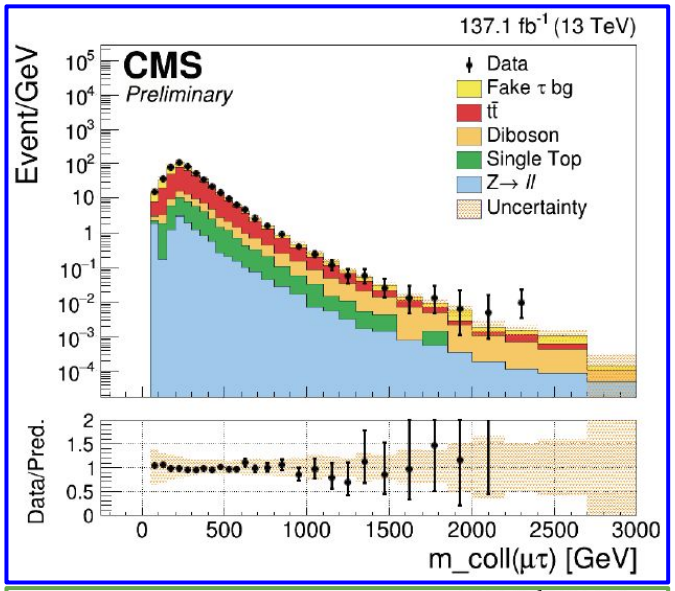


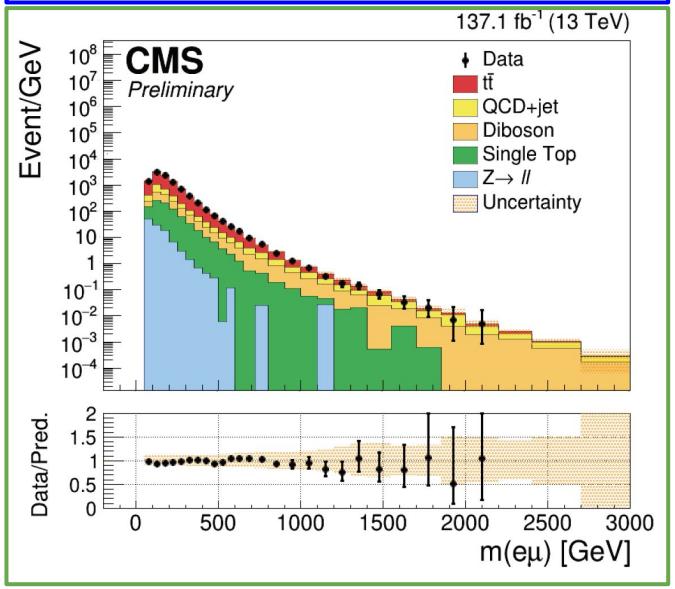




Search for lepton-flavor violating decays of heavy resonances and quantum black holes to eμ, eτ, $\mu\tau$ final states (EXO-19-014)

- Trigger
  - single-muon pT > 50 GeV
  - single-photon pT > 175 GeV.
- pT requirements in events selection
  - Electrons in the event have min pT of 35 GeV (50 GeV in eτ channel) and muons min pT of 53 GeV, leading hadronic τ min pT is 50 GeV.
- The statistical interpretation is done based on the shape of the **invariant eμ mass and collinear eτ, $\mu\tau$ distributions.**





- Analysis is designed to be as model independent as possible and tested various lepton-flavor violating signals:
  - Resonant **τ-sneutrino** production in R-parity violating supersymmetric models (RPV SUSY).
  - Resonant **heavy Z'** gauge vector bosons with lepton-flavor violating transitions: Z' ↠ eμ // eτ // $\mu\tau$ with BR 10% each.
  - Non-resonant **quantum black-hole** production in models with extra spatial dimensions (QBH).

Results (EXO-19-014, full Run 2)

- Upper limits on the $\sigma \times BR$ are determined using a Bayesian method with a uniform positive prior probability density for the signal cross section.
  - Z' boson with LFV couplings is excluded up to mass 4.1 // 4.2 // 5.0 TeV in the $\mu\tau$ // eτ // eμ channels.
  - τ-sneutrino derived from RPV SUSY is excluded up to mass 3.7 TeV in the $\mu\tau$ and eτ channels, and up to 4.2 TeV in the eμ channel, for the coupling hypothesis $\lambda = 0.1$ (λ controls decay of τ-sneutrino).
  - The cross section limit is translated into **exclusion bounds in the mass vs coupling plane** (using the narrow width approximation formula of the RPV signal cross section).
  - Quantum black holes derived from an ADD model with n=4 extra dimensions are excluded up to threshold mass 5.1 // 5.3 // 5.7 TeV in the $\mu\tau$ // eτ // eμ channels.
- Also model independent cross section limits ($\sigma \times BR \times A \times \epsilon$) are derived.