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CMS
Compact Muon Solenoid

Search for vector-like leptons with the CMS detector

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on behalf of *CMS collaboration*

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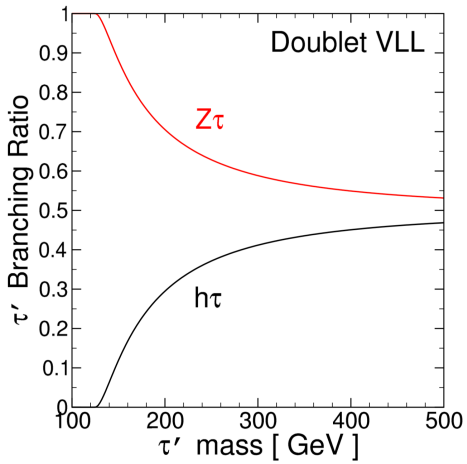
Introduction

- **Vector-like leptons (VLL)** are the leptonic counterparts to vector-like quarks
  - CMS has **extended program for VLQ**, but not for VLL so far (Talk by Orso today)
  - Vector-like fermions are less constrained by SM/Higgs properties and can be part of variety of beyond SM physics
  - Additional SU(2) doublet (singlet) which couples to SM leptons: **4 (2) new, mass degenerate fermions** (N. Kumar & S. Martin)
  - Coupling to SM lepton generations is arbitrary → possible lepton flavor violation

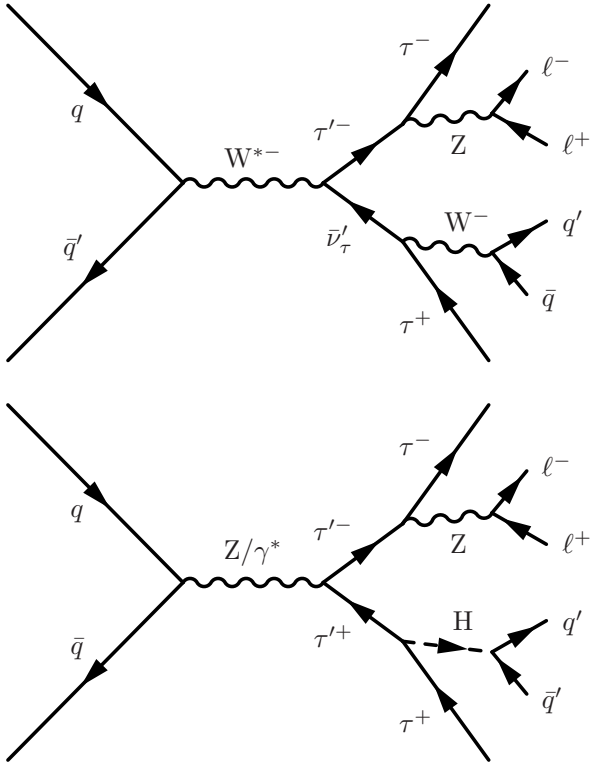
- **CMS-EXO-18-005** analysis:
  - Search for vector-like leptons in **multilepton final states**
  - Using 41.4 fb^{-1} of p-p collision data collected by CMS in 2017
  - VLL model: SU(2) doublet coupling only to **3rd generation**
  - **First analysis** to search for VLL doublet model at LHC and in general for 13 TeV

Phenomenology

- Production through EWK interaction at LHC: $\tau'^{+}\tau'^{-}$, $\tau'^{\pm}\nu'_{\tau}$ & $\nu'_{\tau}\nu'_{\tau}$
- Decays of VLL $\tau'^{\pm}$ & ν'_{τ}:
  - $\tau'^{\pm} \rightarrow Z\tau^{\pm}$ or $H\tau^{\pm}$
  - $\nu'_{\tau} \rightarrow W^{\mp}\tau^{\pm}$



arXiv:1510.03456 (Kumar & Martin)



- Leptonic decays of intermediate bosons lead to multilepton final states → search in **3ℓ, ≥4ℓ, 2ℓ+τ** channels (ℓ = e, μ)

Event selection

Inclusive approach: Binning rather than cutting in event kinematics

	E_T^{miss}	Control region veto
3ℓ	< 150 GeV, > 150 GeV	(a) MOSSF on-Z, E_T^{miss} < 100 GeV (b) MOSSF below-Z, $M_{3\ell}$ on-Z
$\geq 4\ell$	< 50 GeV, > 50 GeV	2 MOSSF on-Z, E_T^{miss} < 50 GeV
2ℓ(OS)+τ	< 150 GeV, > 150 GeV	E_T^{miss} < 50 GeV
2ℓ(SS)+τ	< 150 GeV, > 150 GeV	E_T^{miss} < 50 GeV

- Final binning in L_T (sum of all lepton momenta P_T)
- OS / SS: opposite / same sign
- MOSSF: mass of opposite sign same flavor pair (on-Z: 91 ± 10 GeV)
- P_T tresholds: 28 / 20 / … GeV (μ), 38 / 20 / … GeV (e), 20 GeV (τ)

Multilepton backgrounds

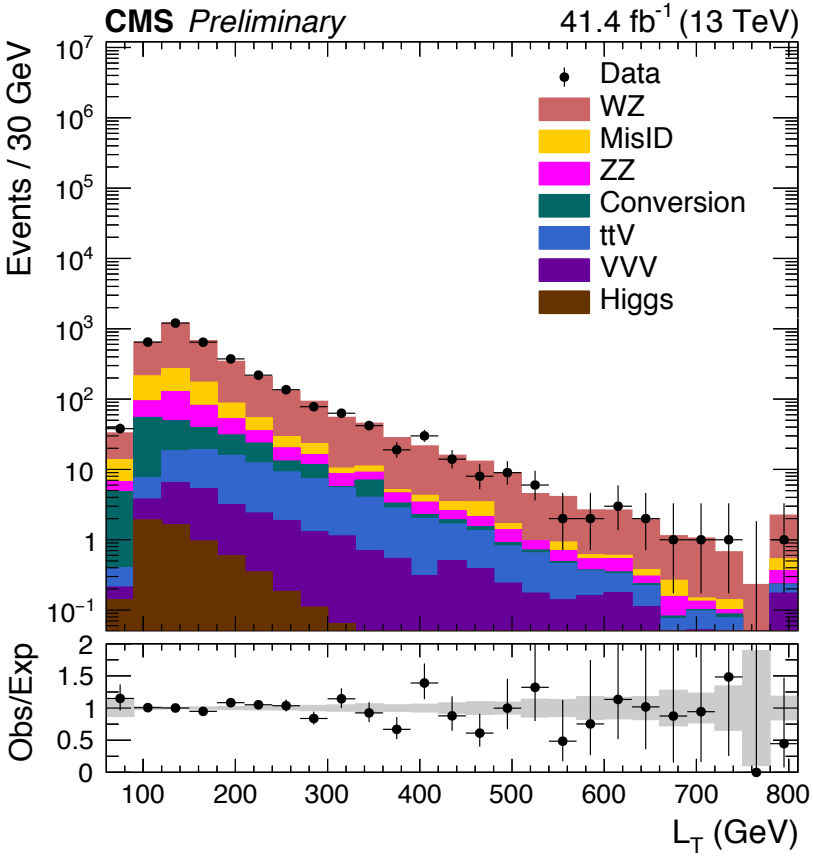
Background source	Leading processes	Estimation method	Notes
Irreducible	WZ, ZZ	MC	Normalized in 3ℓ & 4ℓ CR
Non-prompt	DY, ttbar	Data-driven (Matrix Method)	Developed in $2\ell+\tau$ & 3ℓ CR and MC
Photon conversion	DY, ttbar	MC	Normalized in 3ℓ CR

- Non-prompt leptons:
  - Lepton from heavy flavor decays
  - Jet misidentified as lepton
- Photon conversion: internal and external photon to lepton conversion

Backgrounds: WZ & ZZ

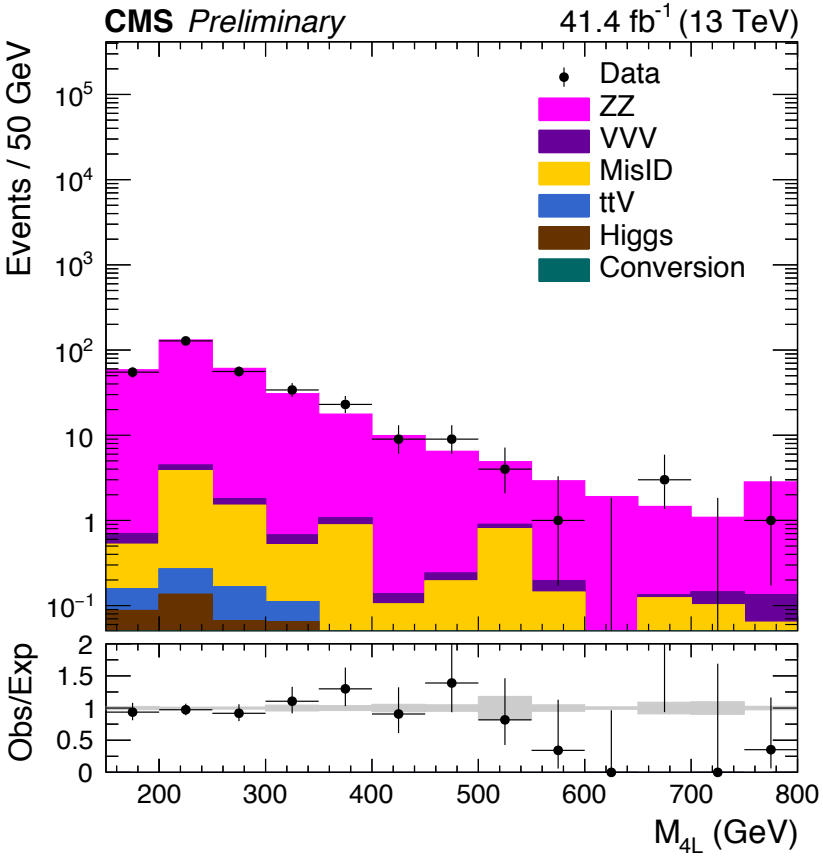
WZ control region:

3ℓ, on-Z, $50 < E_T^{miss} < 100$ GeV



ZZ control region:

4ℓ, 2 on-Z, $E_T^{miss} < 50$ GeV



Backgrounds: Misidentified

- Use **3D version of Matrix Method**: advanced tight-loose data-driven technique

In 2D:

$$\begin{pmatrix} N_{\mathrm{FF}} \\ N_{\mathrm{FP}} \\ N_{\mathrm{PF}} \\ N_{\mathrm{PP}} \end{pmatrix} = \frac{1}{(p_1 - f_1)(p_2 - f_2)} \begin{pmatrix} p_1 \cdot p_2 & -p_1 \cdot \hat{p}_2 & -\hat{p}_1 \cdot p_2 & \hat{p}_1 \cdot \hat{p}_2 \\ -p_1 \cdot f_2 & p_1 \cdot \hat{f}_2 & \hat{p}_1 \cdot f_2 & -\hat{p}_1 \cdot \hat{f}_2 \\ -f_1 \cdot p_2 & f_1 \cdot \hat{p}_2 & \hat{f}_1 \cdot p_2 & -\hat{f}_1 \cdot \hat{p}_2 \\ f_1 \cdot f_2 & -f_1 \cdot \hat{f}_2 & -\hat{f}_1 \cdot f_2 & \hat{f}_1 \cdot \hat{f}_2 \end{pmatrix} \begin{pmatrix} N_{\mathrm{LL}} \\ N_{\mathrm{LT}} \\ N_{\mathrm{TL}} \\ N_{\mathrm{TT}} \end{pmatrix}$$

Calculated

Measured

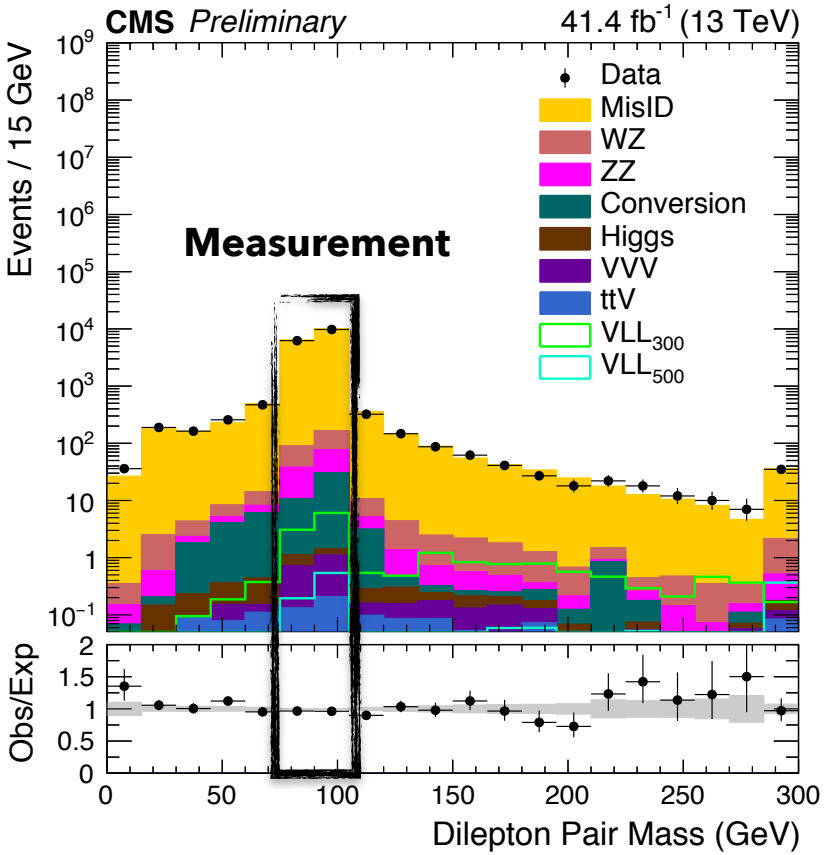
Observed

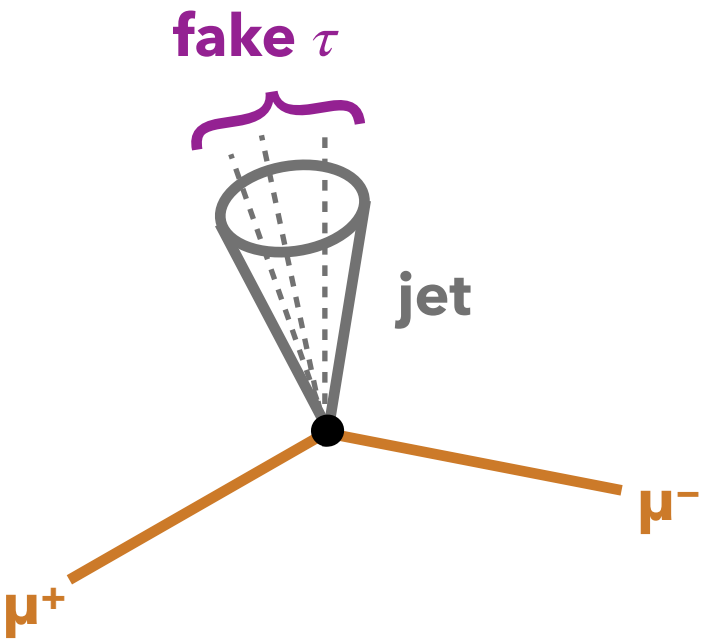
$$N_{\mathrm{TT}}^{\mathrm{Fake\ Bkg}} = f_1\ f_2\ N_{\mathrm{FF}} + f_1\ p_2\ N_{\mathrm{FP}} + p_1\ f_2\ N_{\mathrm{PF}}$$

- **Prompt leptons** come from bosons, **fake leptons** from hadronic activity
- Prompt & fake rates are measured via tag & probe in **data & MC**
- Parametrization of rates as functions of lepton P_T, lepton $|\eta|$, the P_T of the mother jet of the lepton and the number of isolated tracks in the event

Backgrounds: Misidentified

2ℓ(OS)+τ, E_T^{miss} < 50 GeV

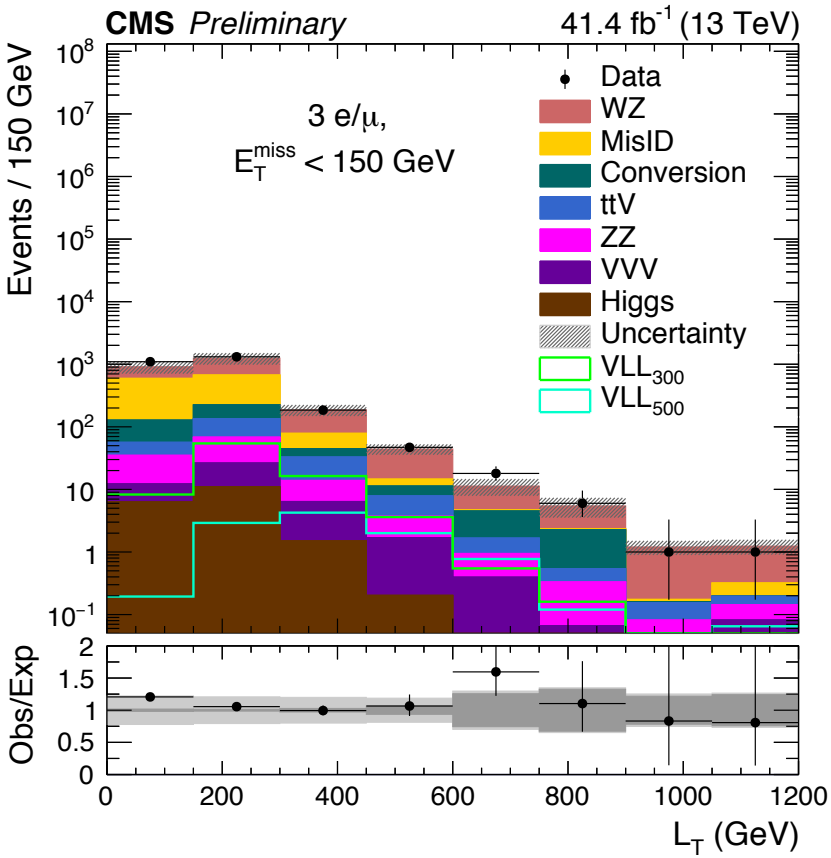




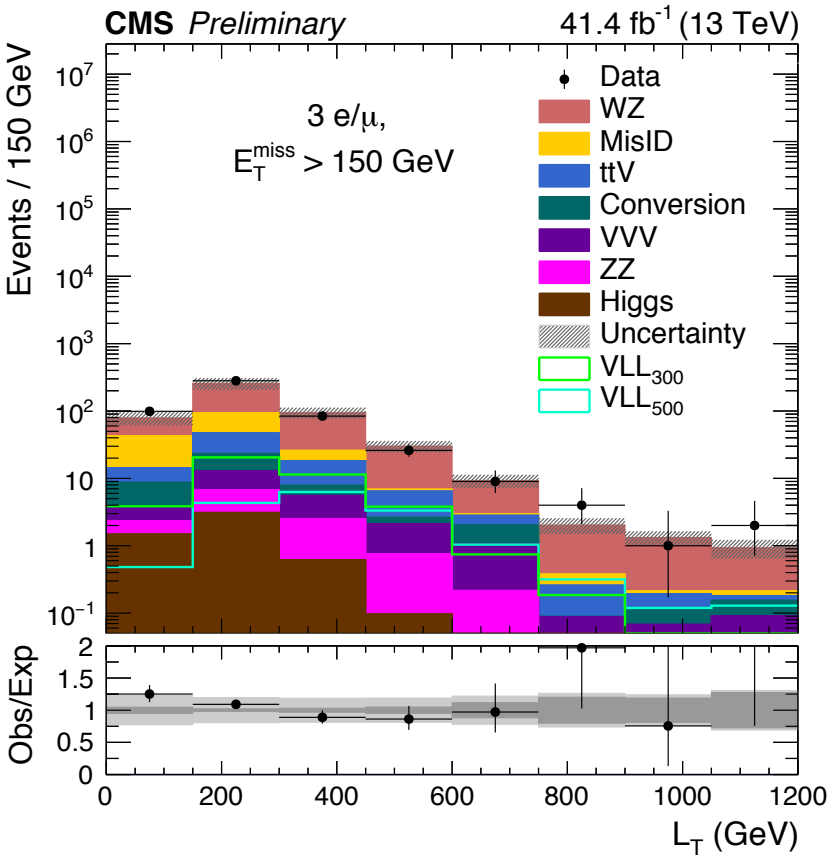
Similar procedure for light lepton fakes in fake enriched 3ℓ region

Results: 3 light leptons

E_T^{miss} < 150 GeV

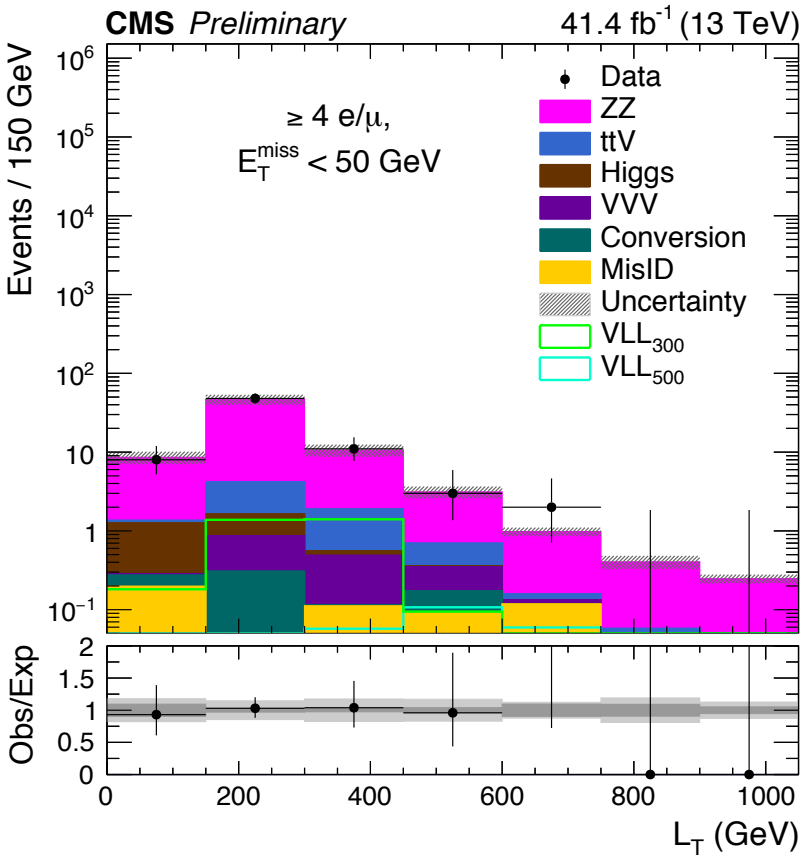


E_T^{miss} > 150 GeV

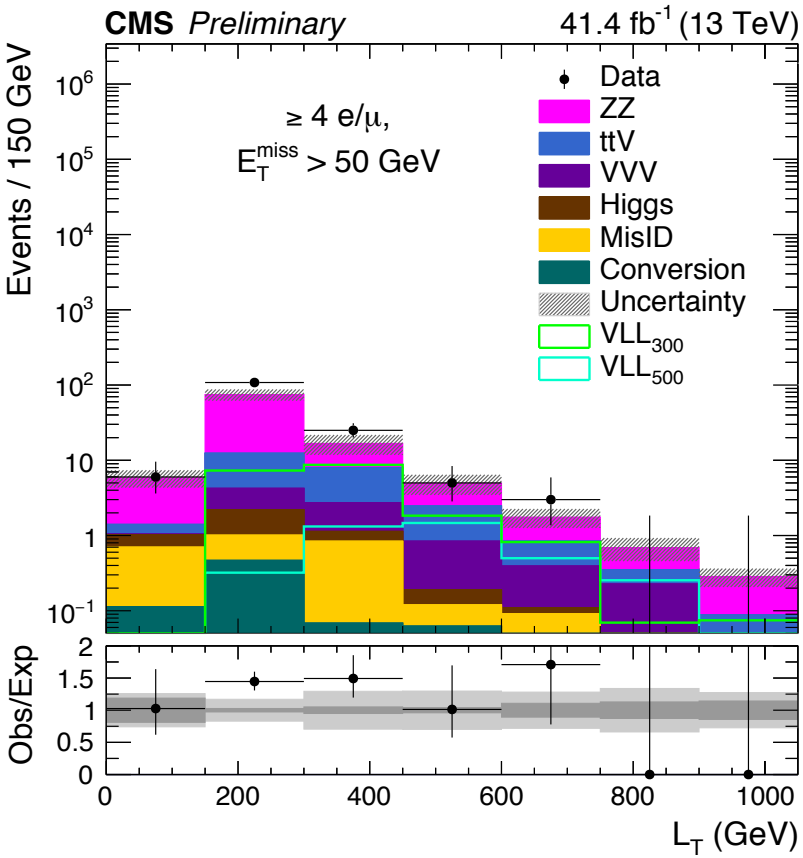


Results: ≥4 light leptons

E_T^{miss} < 50 GeV

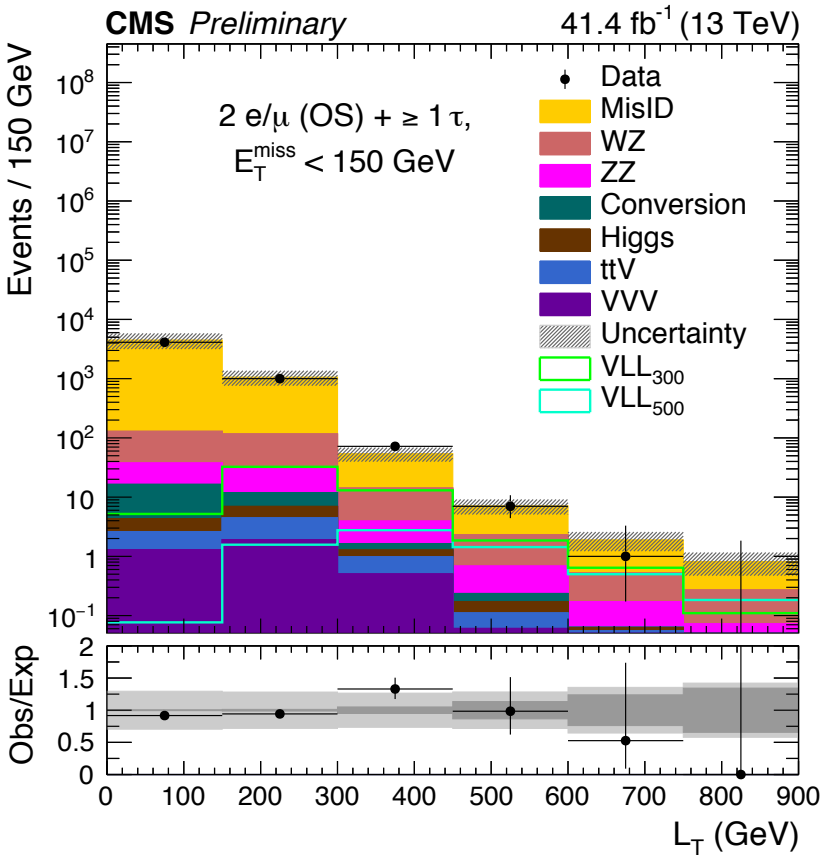


E_T^{miss} > 50 GeV

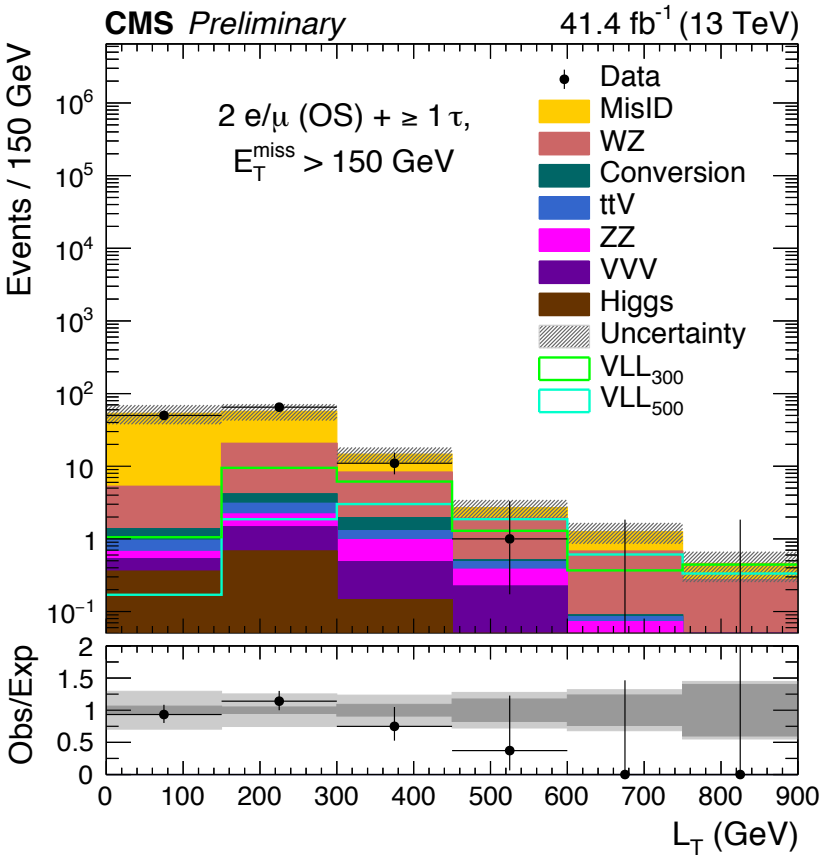


Results: 2 light leptons (OS) + tau

E_T^{miss} < 150 GeV

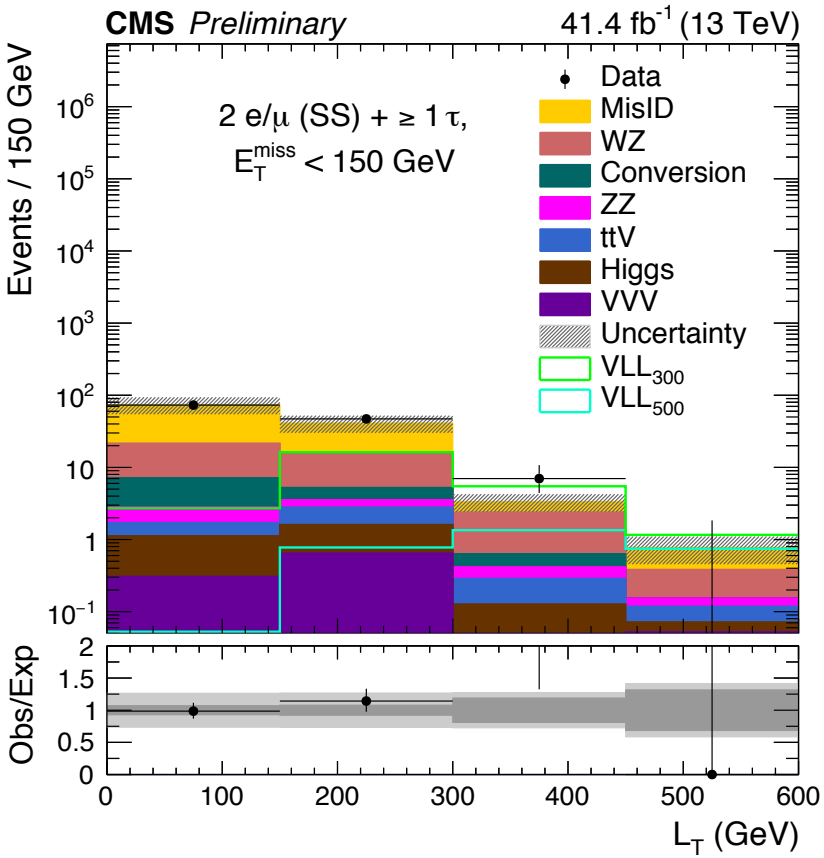


E_T^{miss} > 150 GeV

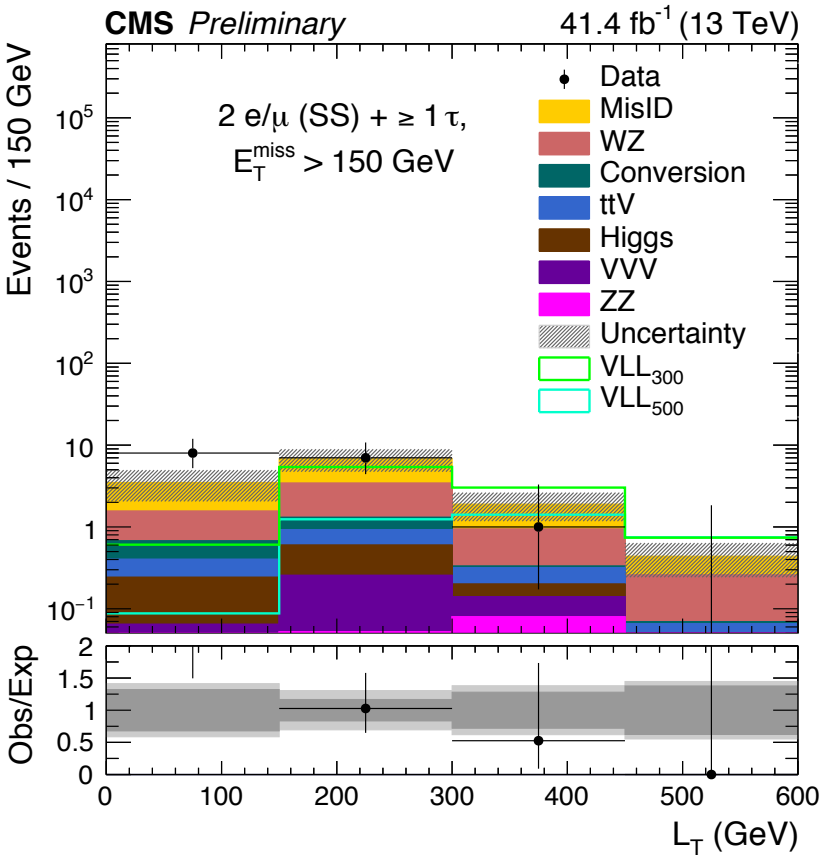


Results: 2 light leptons (SS) + tau

E_T^{miss} < 150 GeV

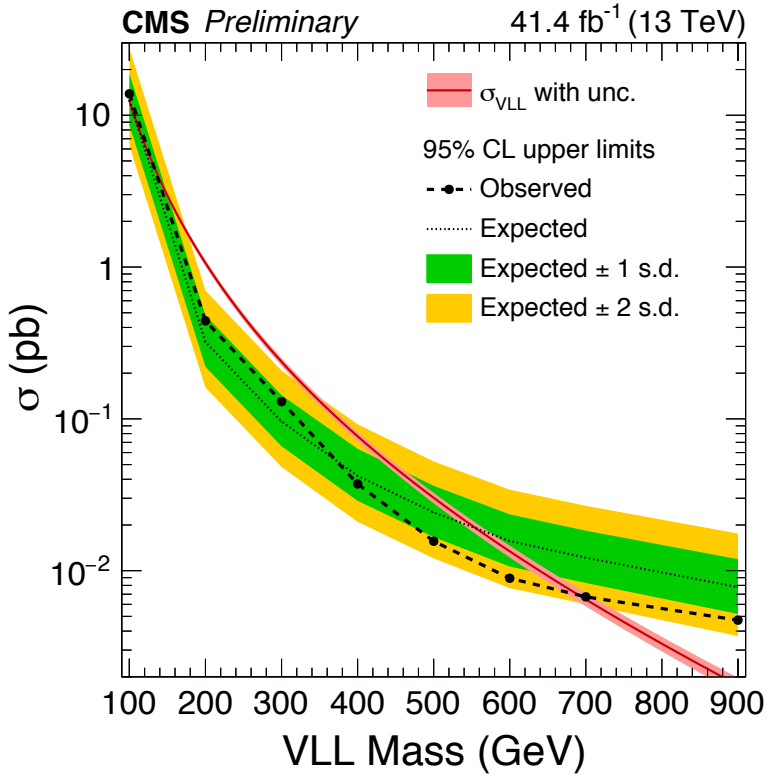


E_T^{miss} > 150 GeV



Interpretation

- **No evidence** of vector-like lepton signal has been observed
- We compute 95 % CL_S exclusion limits on the signal production cross section
- Exclude vector-like leptons in SU(2) doublet model coupling to 3rd generation with **masses 130-690 GeV** (expected: 110-560 GeV)



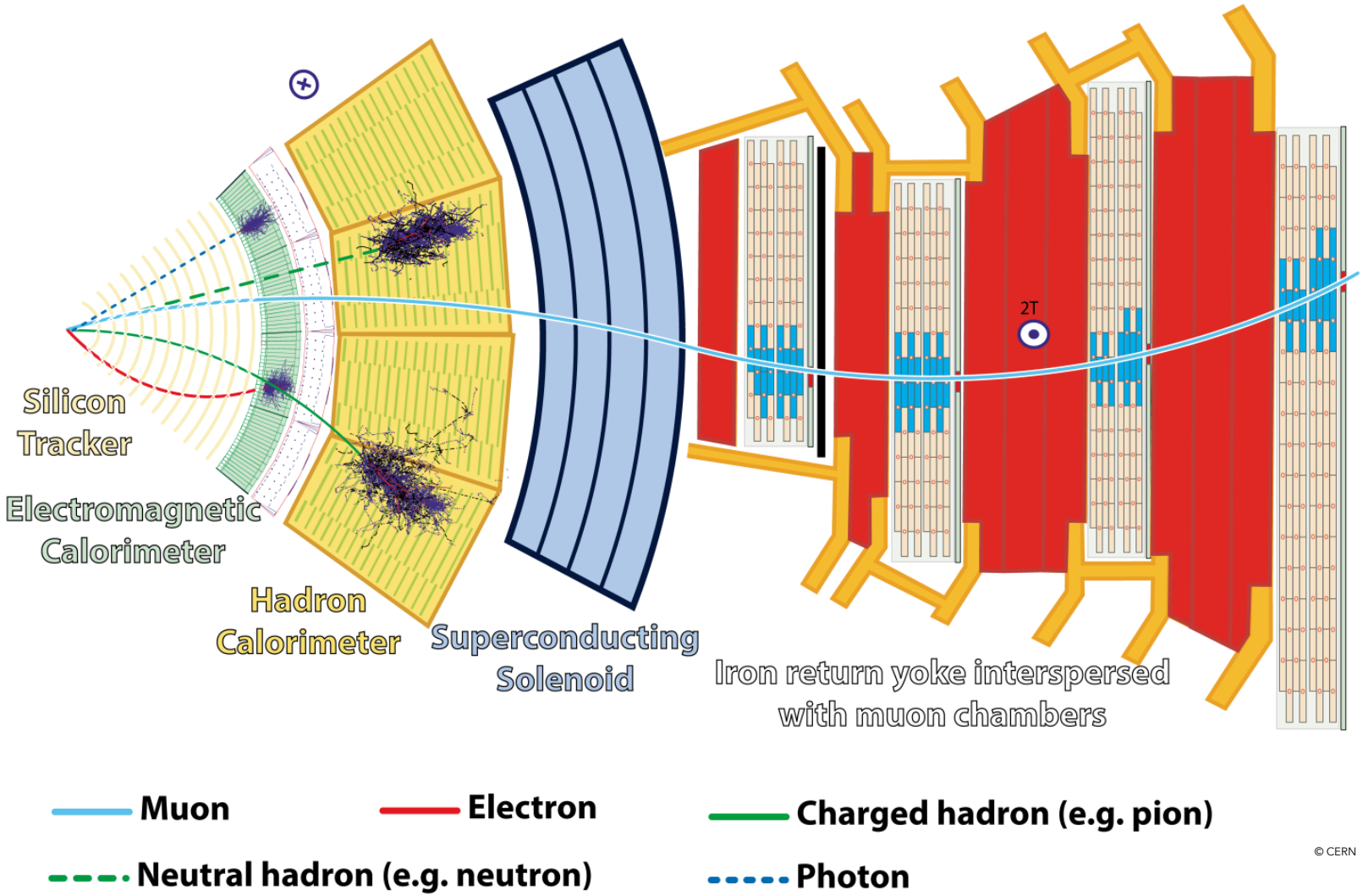
Closing remarks

- We conducted a search for vector-like leptons in SU(2) doublet model coupling only to 3rd generation in multilepton final states with 2017 data collected with the CMS detector
- This analysis was the first of its kind at 13 TeV and for the vector-like lepton doublet model in general
- Since no evidence for the signal was found, we excluded vector-like leptons with masses 130-690 GeV
- Work is ongoing to extend the analysis with 2016 data and probe this model close to the TeV scale
- Comparison to VLQ: latest exclusions go beyond mass of 1 TeV (higher cross-sections and acceptance than 3rd generation VLL)

BACKUP

I. CMS detector
II. Datasets & trigger
III. Objects ID's & selection
IV. More Matrix Method
V. Systematic uncertainties

CMS detector



Datasets & trigger

Datasets:

- SingleMuon Run2017B-F (version: 17Nov2017)
- SingleElectron Run2017B-F (version: 17Nov2017)

Trigger:

- Single isolated muon: $P_T > 27$ GeV
- Single isolated electron (tight WP): $P_T > 35$ GeV

General selection:

- min. MOSSF > 12 GeV (veto low mass resonances)
- min. $\Delta R > 0.4$ between all leptons

Objects ID's & selection

- Electrons:
  - medium cut-based WP with tight ID H/E and 1/E-1/P cuts
  - $d_z < 0.1$ / 0.2 cm & $d_{xy} < 0.05$ / 0.1 cm in EB / EE
  - $P_T > 20$ GeV, $|\eta| < 2.5$
- Muons:
  - medium ID with tight DBcorr. PF isolation
  - $d_z < 0.1$ cm & $d_{xy} < 0.05$ cm
  - $P_T > 20$ GeV, $|\eta| < 2.4$
- Taus:
  - 1+3 prong decay mode with very tight MVA-based isolation
  - tight anti-electron & anti-muon discriminator
  - $P_T > 20$ GeV, $|\eta| < 2.3$
- Jets:
  - loose ID AK4 PF jets
  - $P_T > 30$ GeV, $|\eta| < 2.4$
- E_T^{miss}:
  - Type 1 corrected PF MET
  - AK4 PF jets with $P_T < 70$ GeV & $2.5 < |\eta| < 3.0$ removed

More Matrix Method

- Definition prompt & fake rate: N_{tight} / N_{loose}
- Any of the three leptons is allowed to be fake simultaneously and independently
- Parametrization helps minimizing DY vs. ttbar spread and dependency on the recoil against the Z boson
- MC closure test before measurement in data
- Final prompt / fake rate:

$$p = k^{\mathrm{p}}_{\mathrm{data}} \cdot \frac{p^{\mathrm{DY\ MC}} + p^{\mathrm{t\bar{t}\ MC}}}{2},$$

$$f = k^{\mathrm{f}}_{\mathrm{data}} \cdot \frac{f^{\mathrm{DY\ MC}} + f^{\mathrm{t\bar{t}\ MC}}}{2}.$$

- Systematic unc. based on combined statistical, kinematic and DY vs. ttbar variation

Lepton flavor	Typical fake rates	Relative unc. on fake rates	Prompt rates
Electrons	5-20%	10-25%	75-100 %
Muons	5-20%	10-25%	75-100 %
Taus	10-20%	10-25 %	55-60%

Systematics uncertainties

Source of uncertainty	Typical magnitude (%)	Processes
MisID lepton backgrounds (matrix method)	20-40	Misidentified
Rare MC backgrounds ($t\bar{t}$ V, VVV, Higgs)	50	Rare
Conversion MC backgrounds normalization	8	DY/ $t\bar{t}$
WZ MC normalization	7	WZ
ZZ MC normalization	5	ZZ
Single lepton trigger	<3	WZ/ZZ/Rare/Signal
Lepton ID & isolation	$6-8$	WZ/ZZ/Rare/Signal
Electron energy scale and resolution	2-5	WZ/ZZ/Rare/Signal
Muon momentum scale and resolution	2-10	WZ/ZZ/Rare/Signal
Tau Energy Scale	<5	WZ/ZZ/Rare/Signal
Jet energy scale	5-10	WZ/ZZ/Rare/Signal
Jet energy resolution	5-10	WZ/ZZ/Rare/Signal
Unclustered energy scale	2-10	WZ/ZZ/Rare/Signal
Integrated luminosity	2.3	Rare/Signal
Pileup	<4	WZ/ZZ/Rare/Signal