Search for BSM physics in multilepton final states with the CMS Detector

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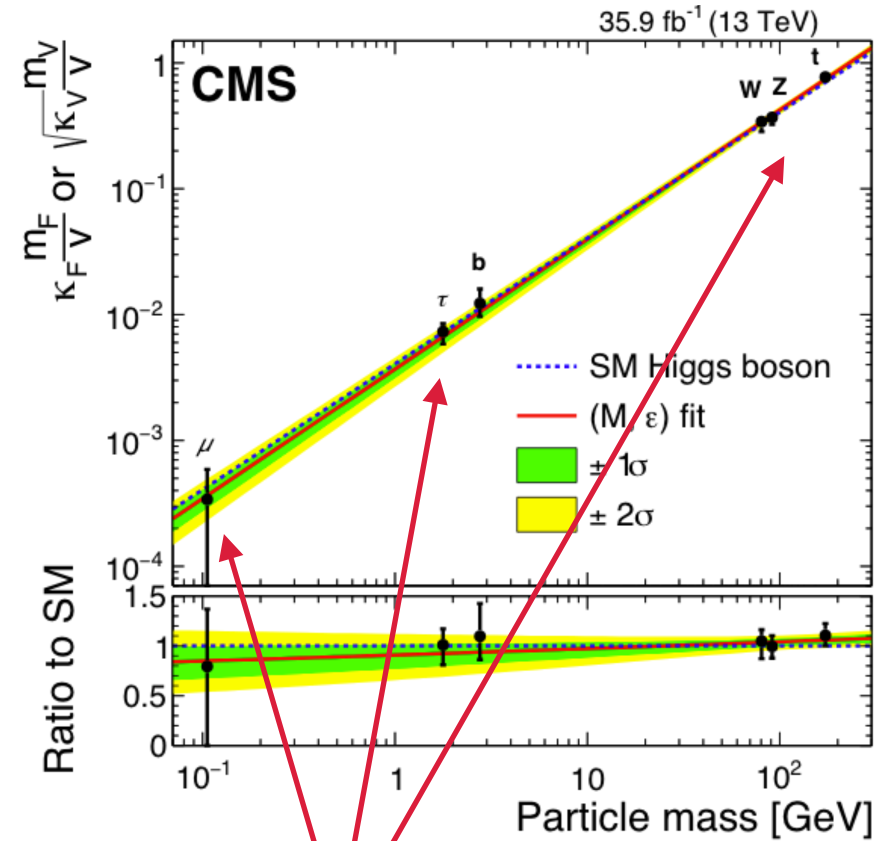
June 4, 2019 - 31st Rencontres de Blois

Leptons at a "Hadron" Collider

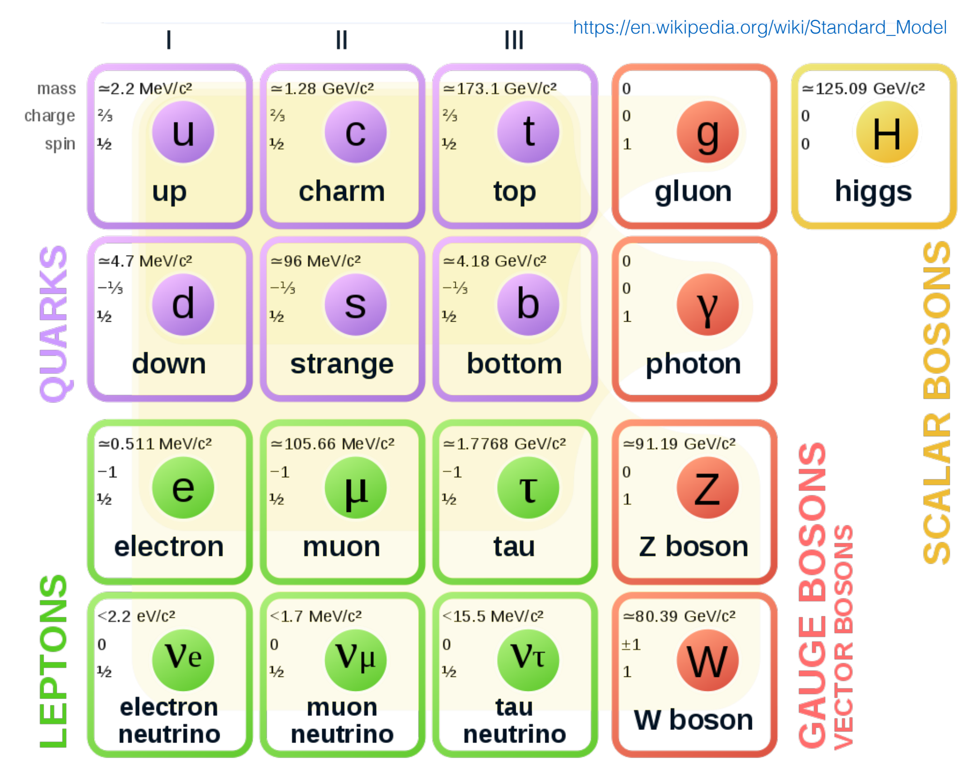
- The LHC has been designed to:
  - find (*or..*) the Higgs boson.
  - probe the electroweak sector of the SM.

- After a ~decade of intense work:
  - A Higgs boson is found at 125 GeV!
    (looking increasingly **like a SM Higgs boson**)
  - **Constraints are placed on** some of the leading contenders for **Beyond the SM physics.**



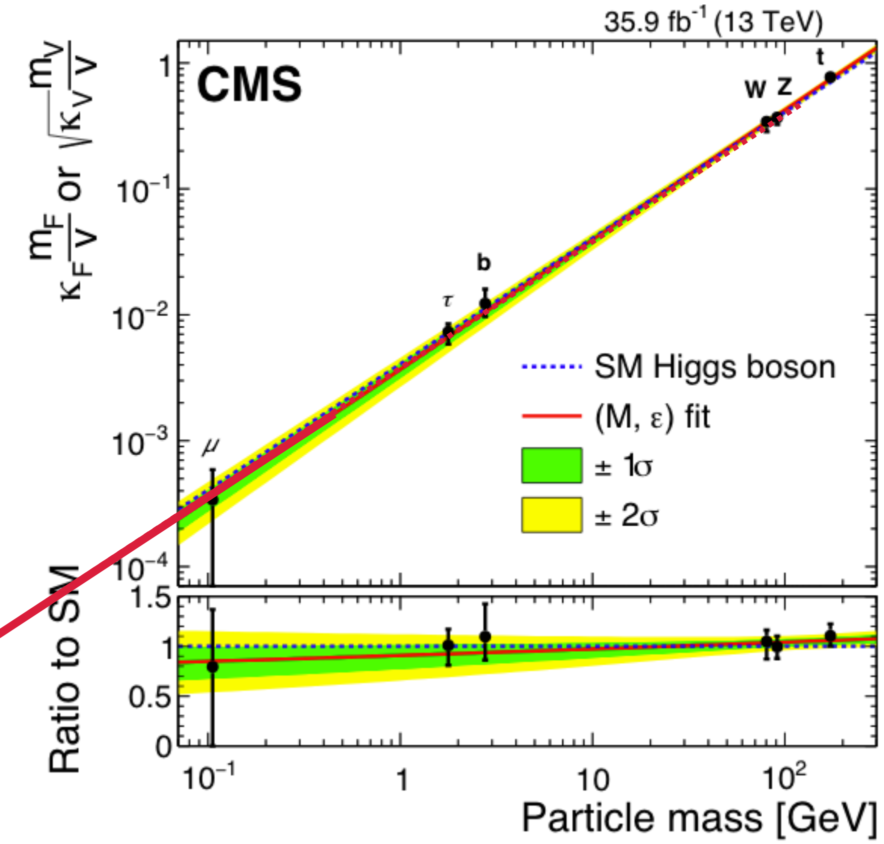
Leptonic final states

- In all these efforts, **leptonic signatures are ubiquitous**
  - All known "heavy" particles decay into leptons! →
  - Clean final states & triggers, excellent S/B
  - **A precious probe of BSM physics in busy pp collisions**



Setting the stage: Seesaw & Neutrinos

- The "standard model" is **not** a theory of everything.
- Neutrino masses are non-zero, $<\mathcal{O}(0.1)$eV (oscillations ~ Δm^2)
- Neutrinos are massless in SM in LO.
- **New heavy SU(2) fermions** with Majorana mass terms **(non-EWSB)** can mix with neutrinos give ~naturally light mass states



Type-I	SU(2) singlet fermion	ν_R
Type-II	SU(2) triplet scalar	$\Delta^{0,\pm,\pm\pm}$
Type-III	SU(2) triplet fermion	$\Sigma^{0,\pm}$

LR Symmetry, SO(10), SU(5), GUT, …

"seesaw mechanism"

$$m_\pm = \frac{\sqrt{m_M + 4m_D^2} \pm m_M}{2} \rightarrow \begin{cases} m_+ \simeq m_M \\ m_- \simeq m_D^2/m_M \end{cases}$$

$m_+ \simeq m_M$ ← New heavy state

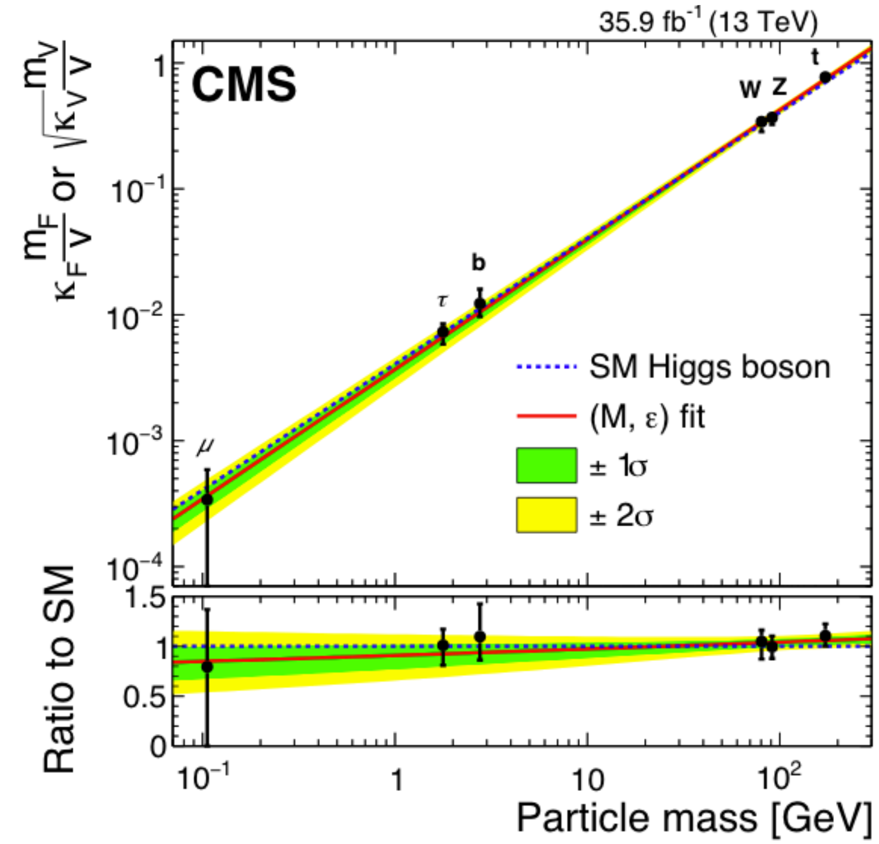
$m_- \simeq m_D^2/m_M$ ← "SM" neutrino

- Seesaw mechanism allows new heavy fermions with masses around $\mathcal{O}(1)$TeV

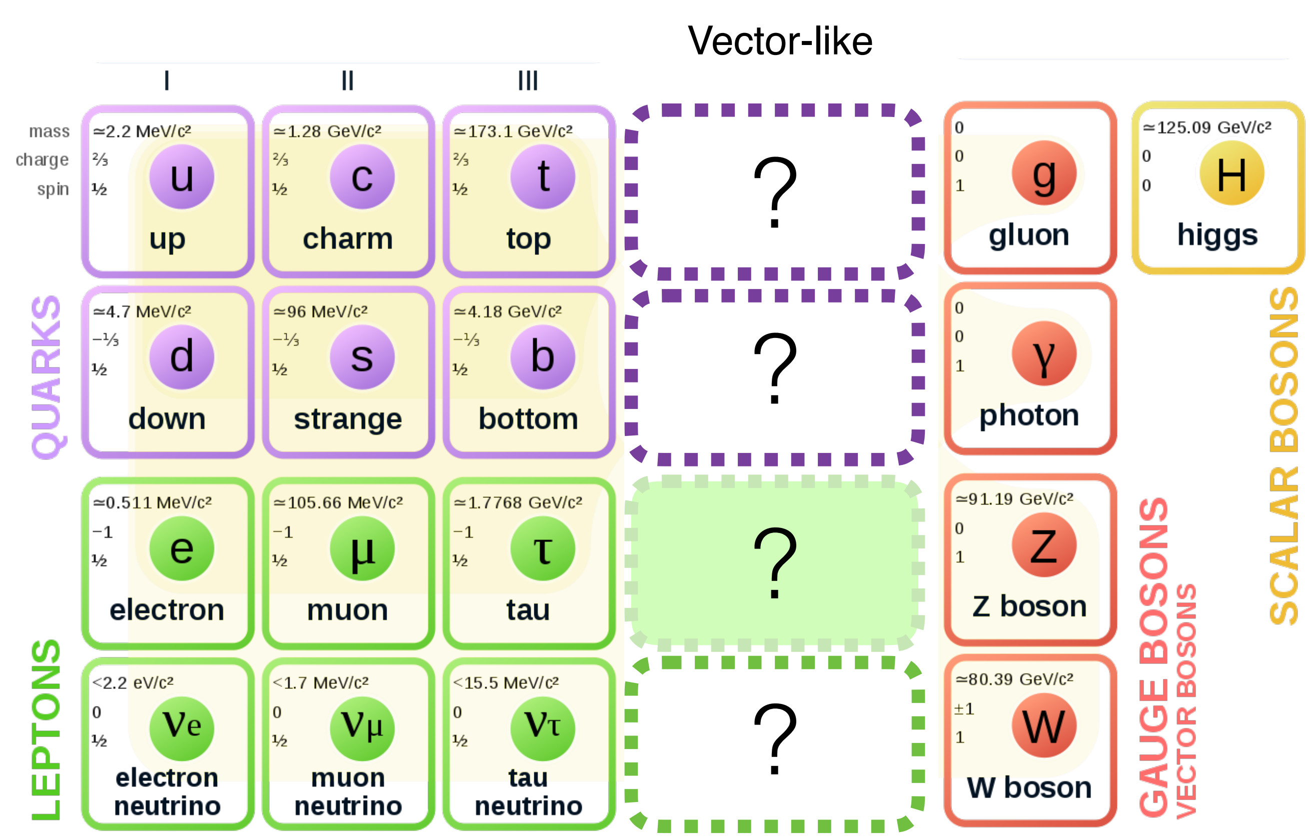
Setting the stage: Vectorlike leptons

- The "standard model" is **not** a theory of everything.

- Multiplicity and mass hierarchy of fermion families is arbitrary
  - **not a prediction of the SM** (built in "by hand")
  - **vectorlike leptons (VLL)** can explain this hierarchy via their mixings with SM leptons (extra dimensions, supersymmetry…)
  - VLL masses can again be **decoupled from EWSB**

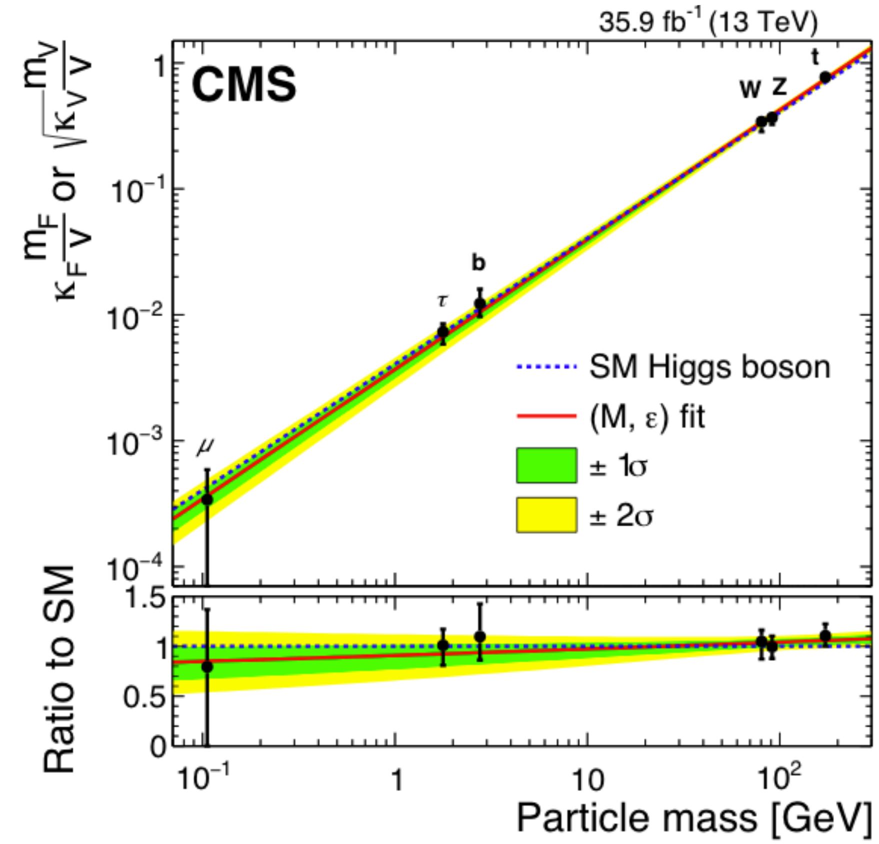


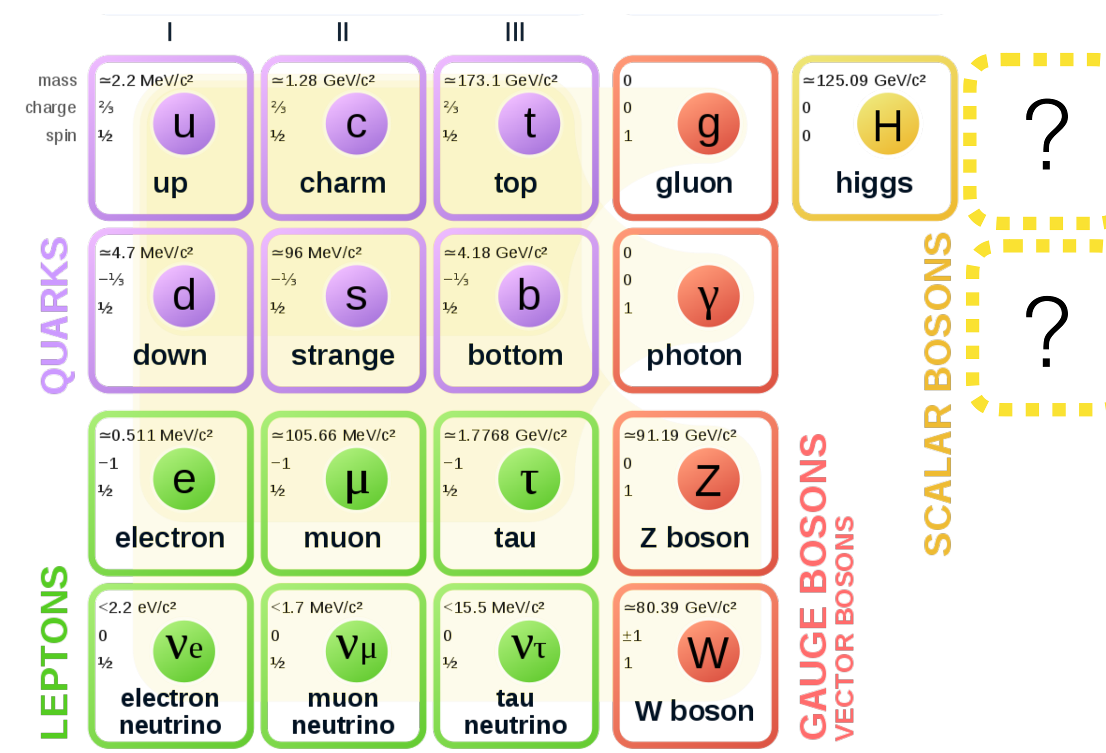
- Vectorlike leptons can be as light as ~$\mathcal{O}(100)$GeV



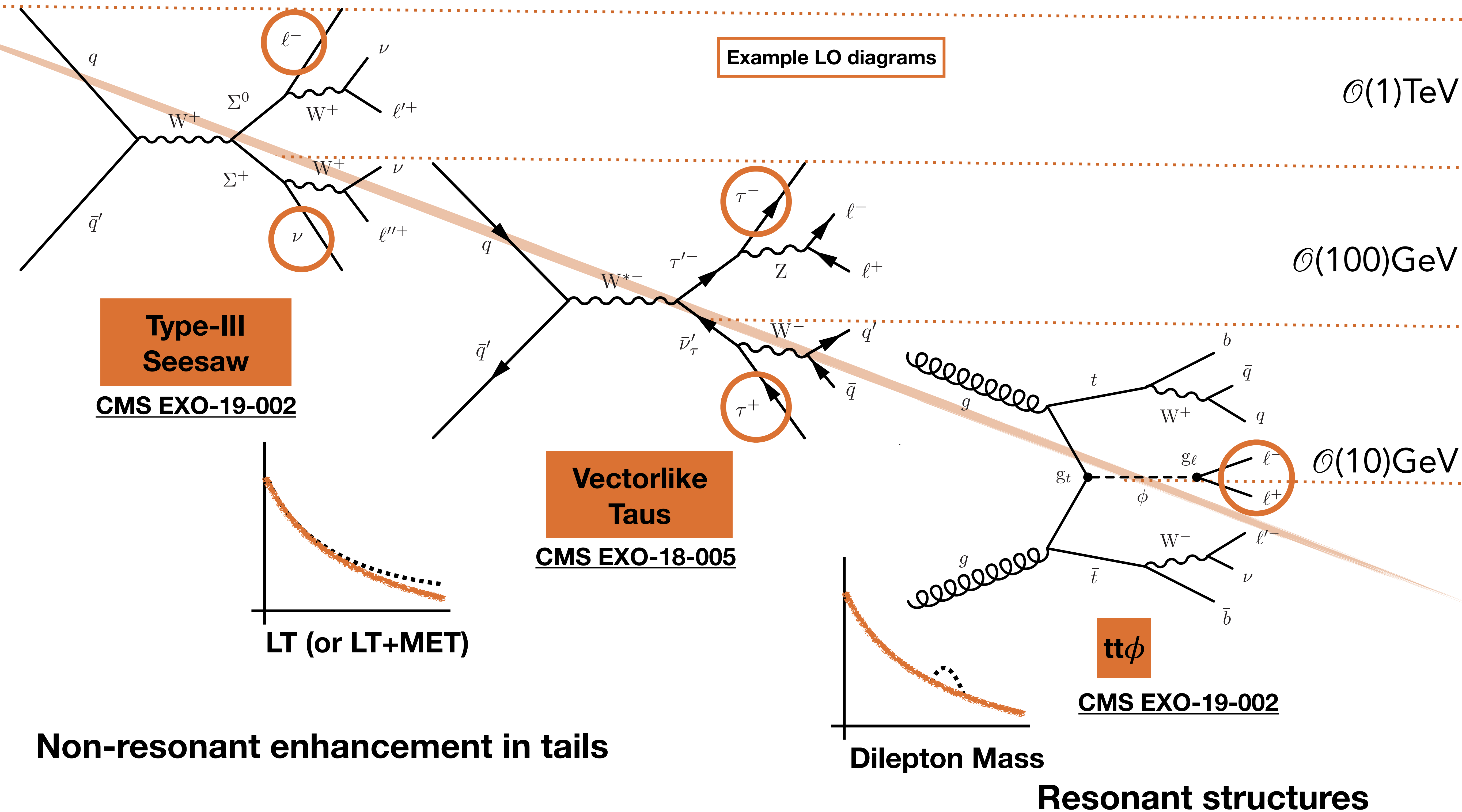
Setting the stage: Extended Scalar Sector

- The "standard model" is **not** a theory of everything.
- The 125 GeV Higgs boson might be the first of **multiple scalar sector particles.**
  - Supersymmetric models
  - N-Higgs Doublet models
  - Higgs portal models with scalar mediators..
- Masses of (pseudo)scalars could be as light as $\mathcal{O}(10)$ GeV
- A **minimal model** where a new **(pseudo)scalar,** only with nonzero couplings to **top quarks and charged leptons**
  - *"To a person with a hammer, everything looks like a nail"*



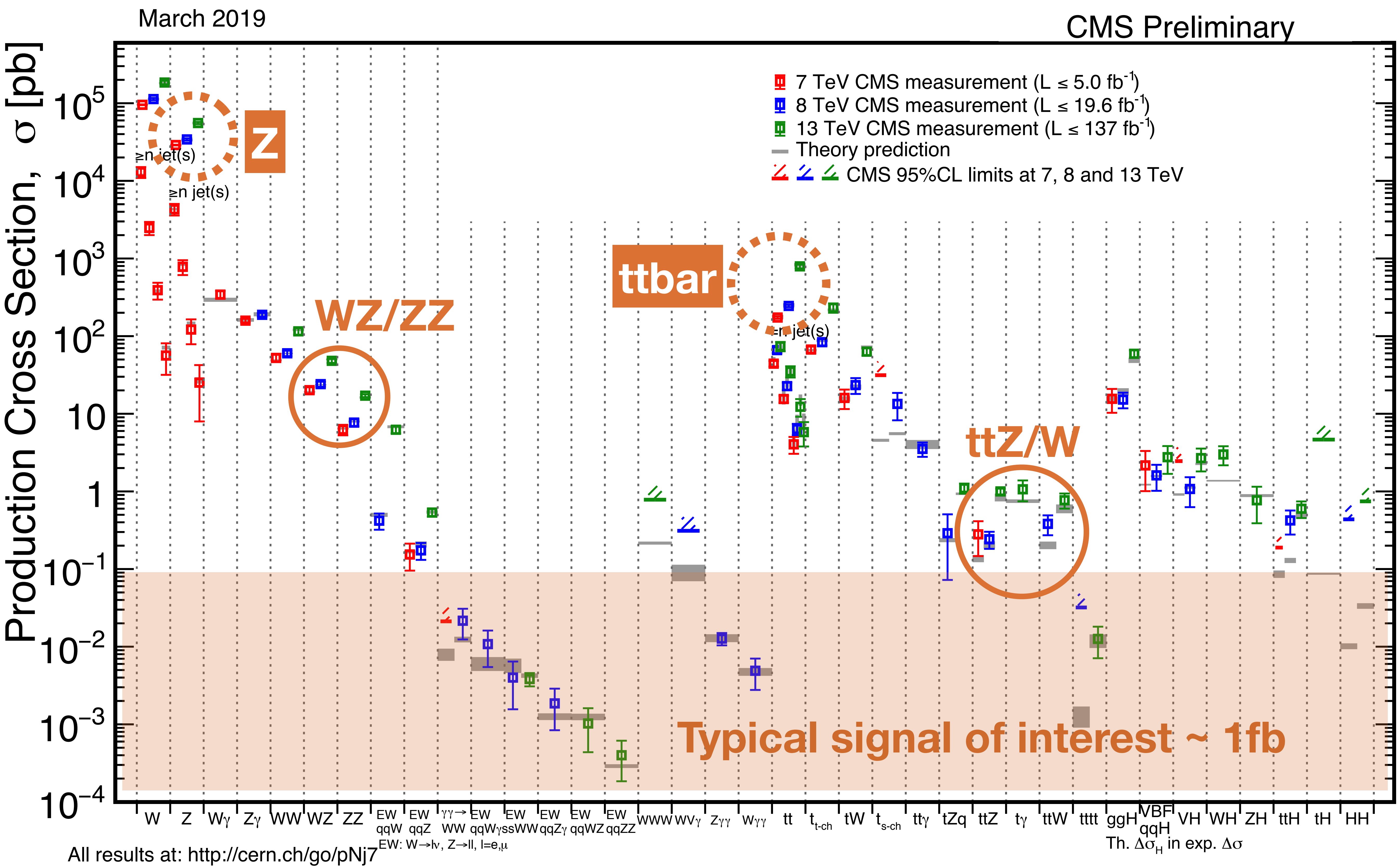


BSM models “to scale”

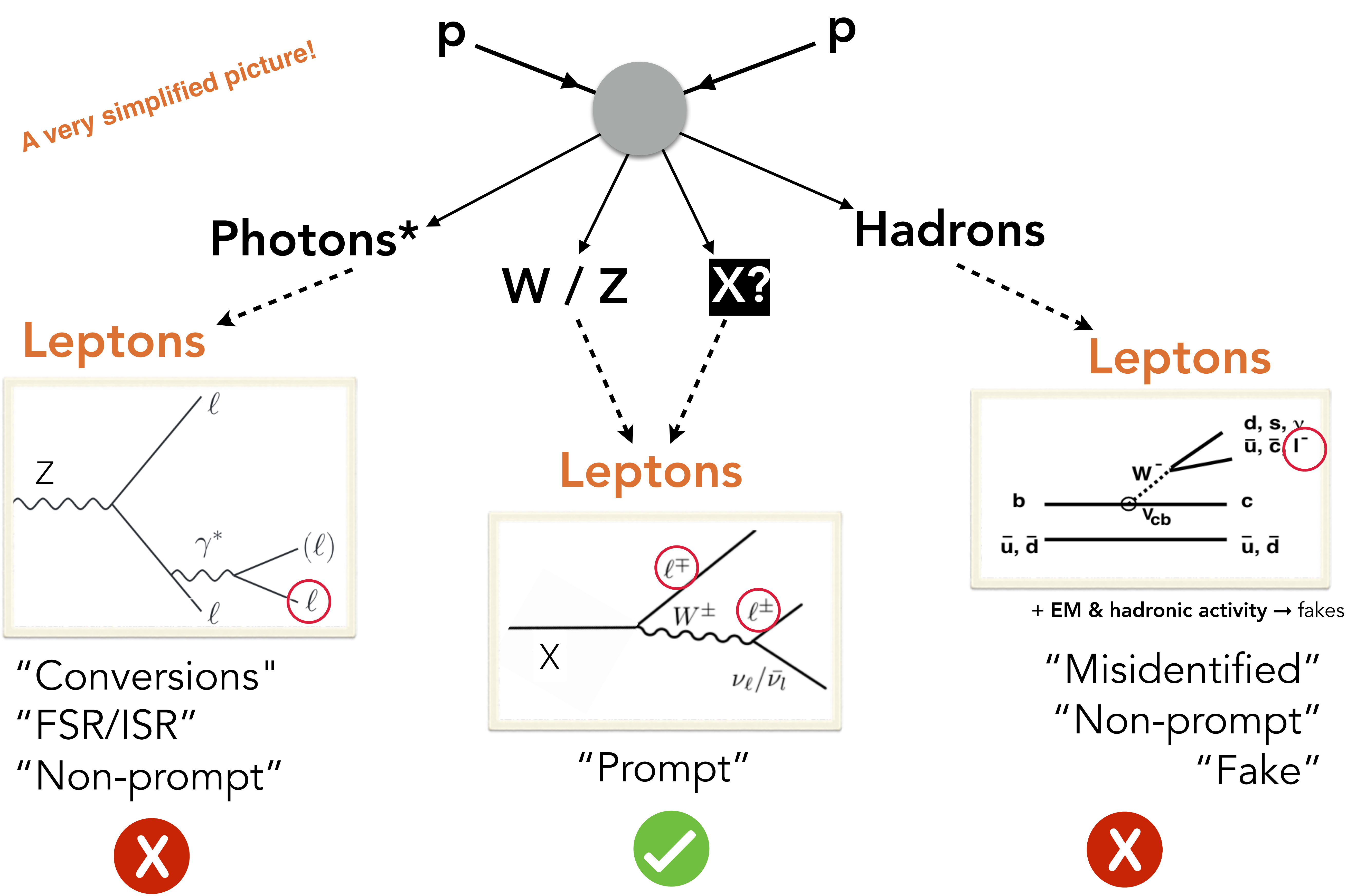


Excellent generators of **striking multi-leptonic signatures at the LHC**, around the EWK scale!

The Multilepton Landscape



Lepton Origins (and some jargon)



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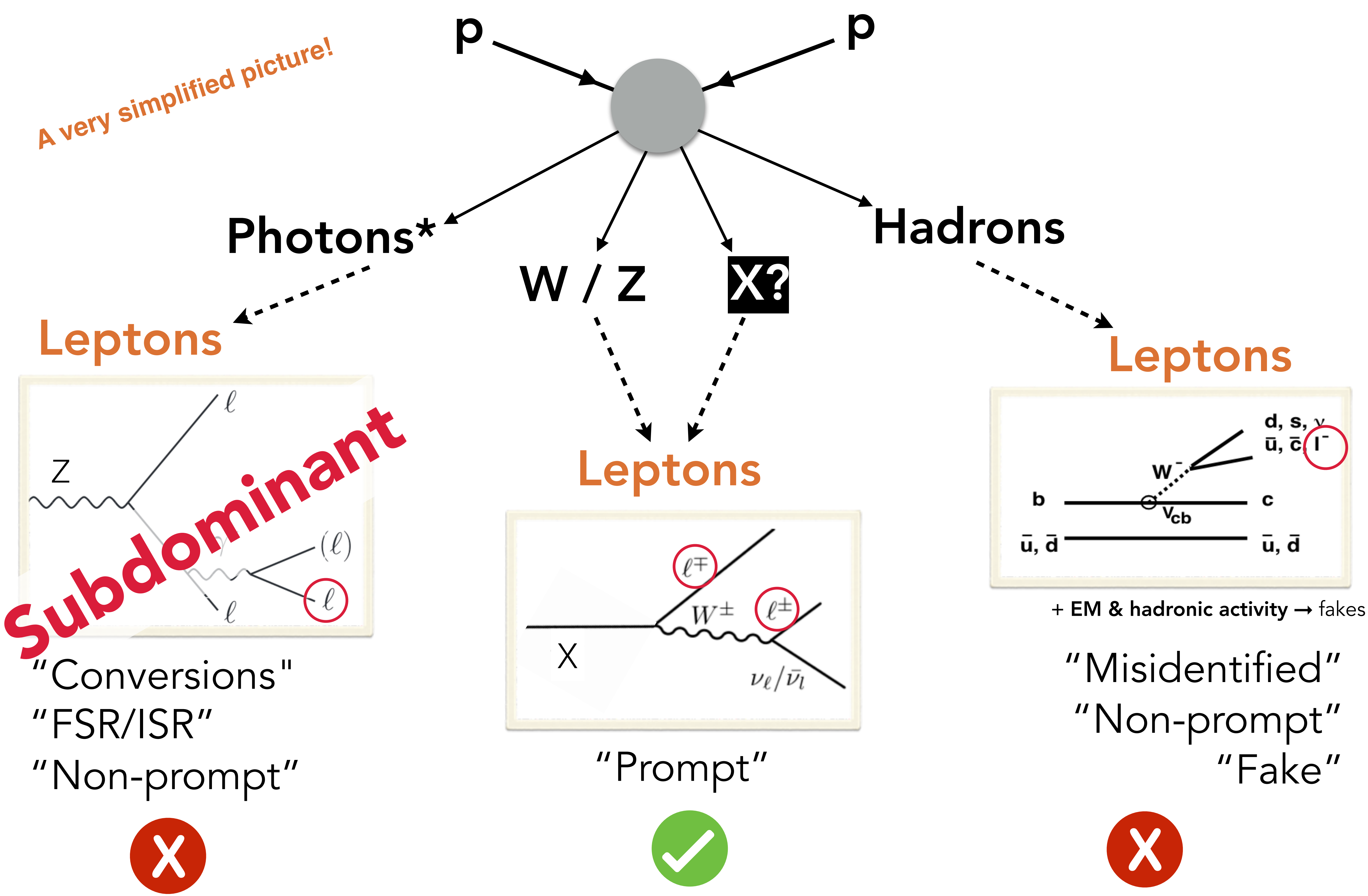
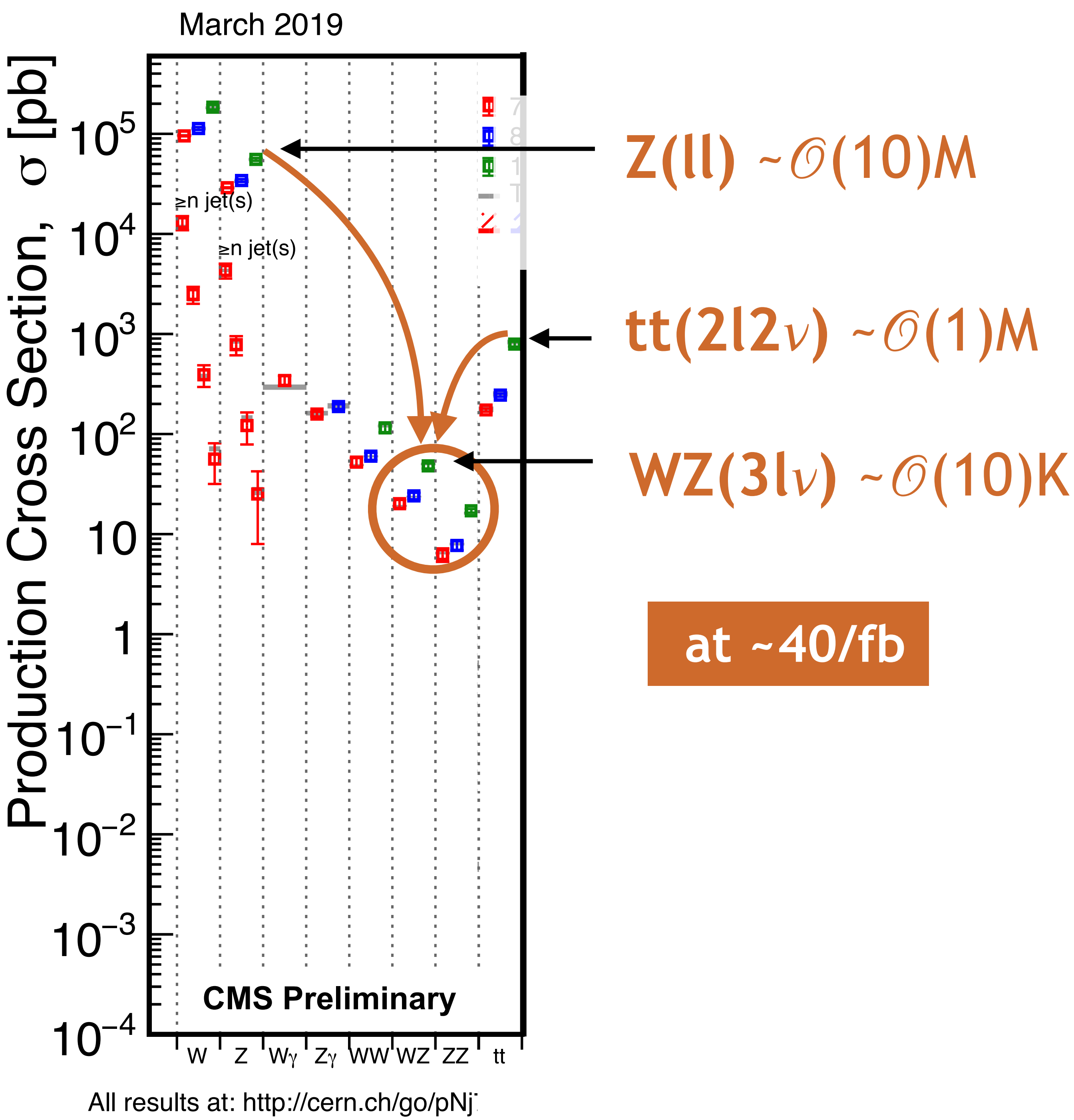


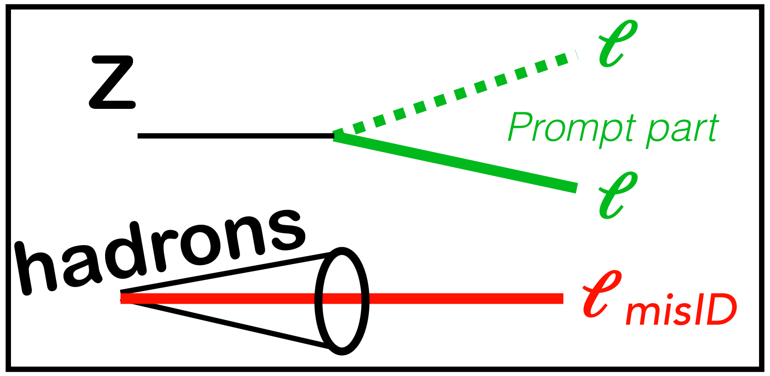
From the SM "peaks"..

- Multilepton searches:
  - Clean objects, well-defined SM backgrounds (SM EW sector: WZ/ZZ/..)
  - **But.. misidentified leptons complicate things!**



at ~40/fb

$(2\ell + j \rightarrow 2\ell + \ell_{misID})$



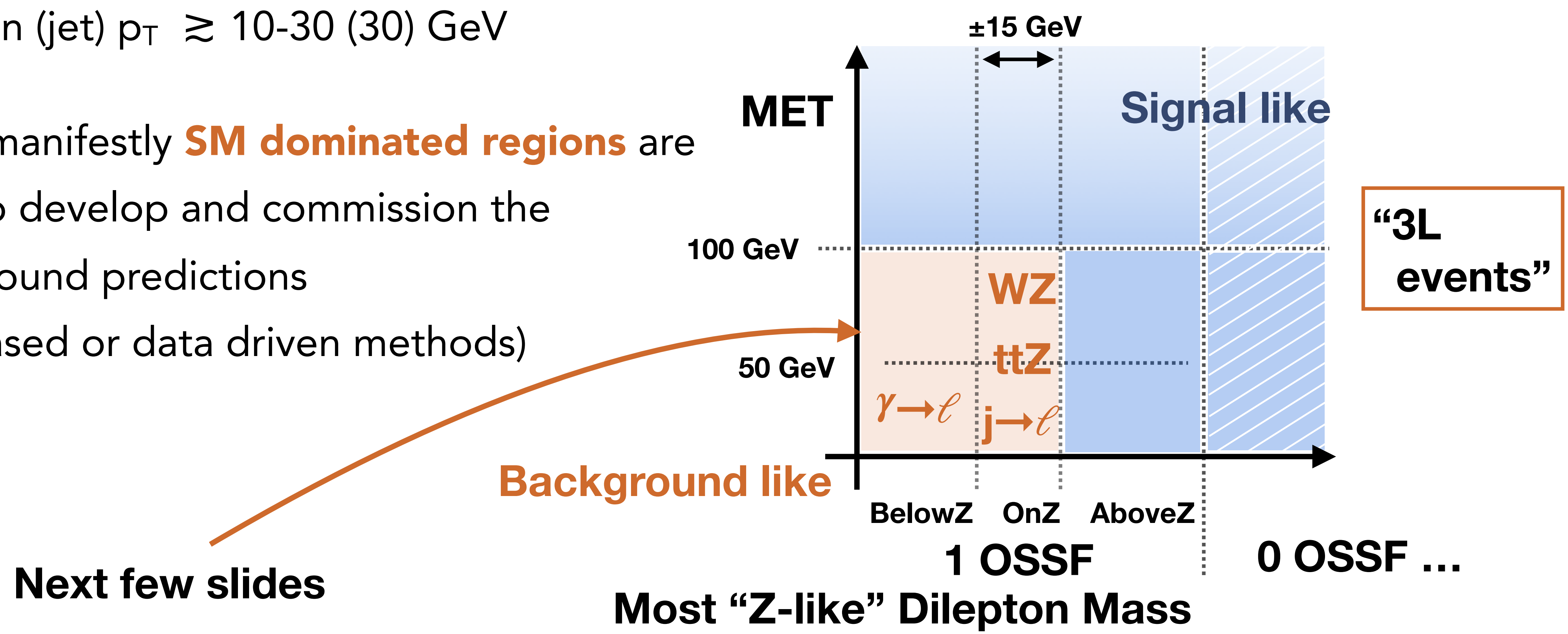
$$P(\text{hadrons} \rightarrow 10\ \text{GeV iso. e}/\mu) \sim 10^{-3}$$

$$P(\text{hadrons} \rightarrow 20\ \text{GeV iso. } \tau_h) \sim 10^{-2}$$

→ varies in Z+jets vs tt+jets environments

Anatomy of Multilepton Analyses

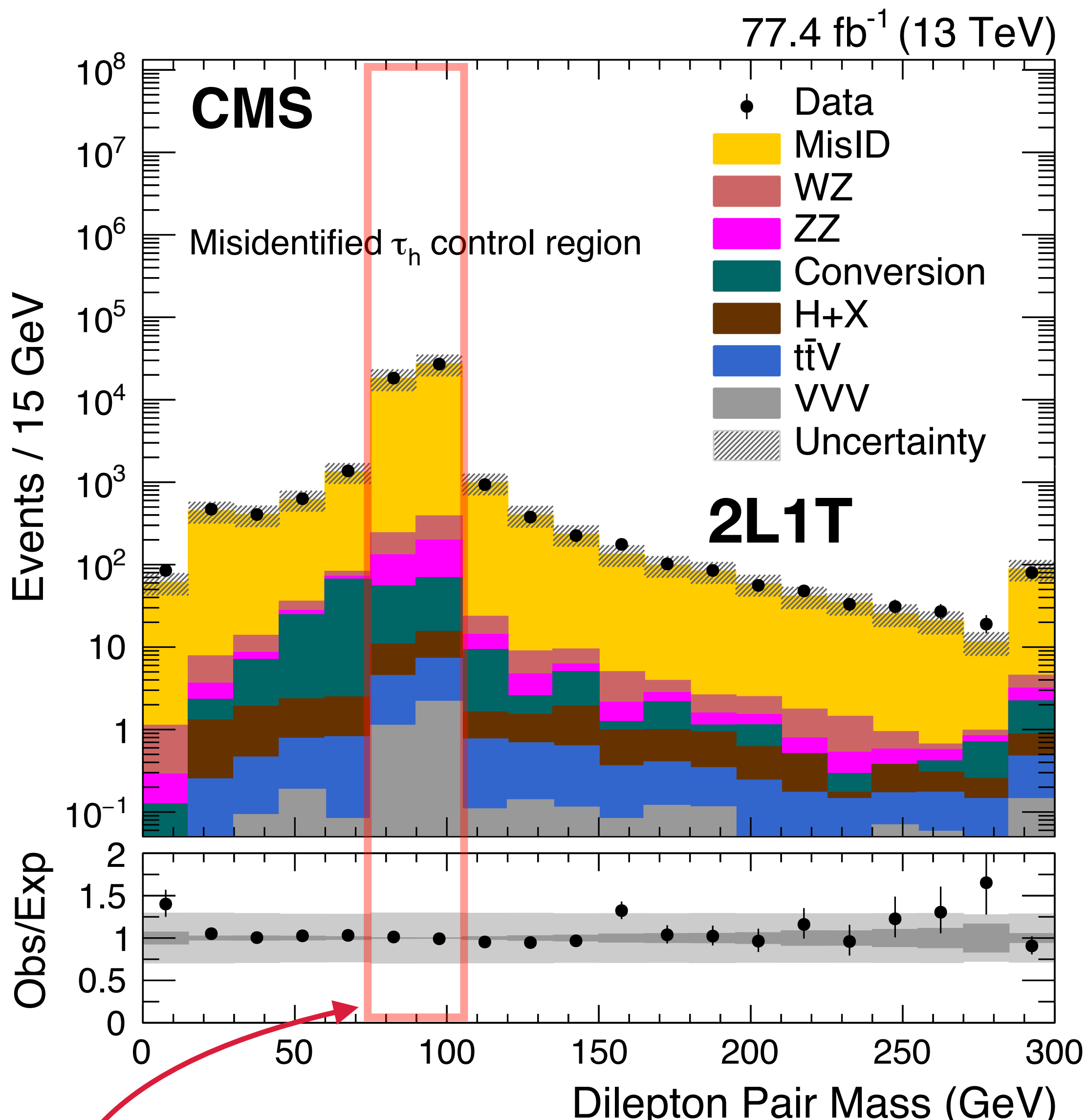
- Look for **"non-resonant" and "resonant" excesses** in multilepton events!
- "Bin, not cut!"
  - Comprehensive **consistency check of the SM** in 3 and 4 lepton final states
- Focus on a relatively few, "catch-it-all" parameters
  - **LT, MET (MT), ST, b-tagged jet multiplicity, dilepton mass,** … (continuous R&D)
- Use of single lepton triggers throughout to achieve near maximum efficiency
  - Lepton (jet) $p_T \gtrsim$ 10-30 (30) GeV
- Some manifestly **SM dominated regions** are used to develop and commission the background predictions (MC based or data driven methods)

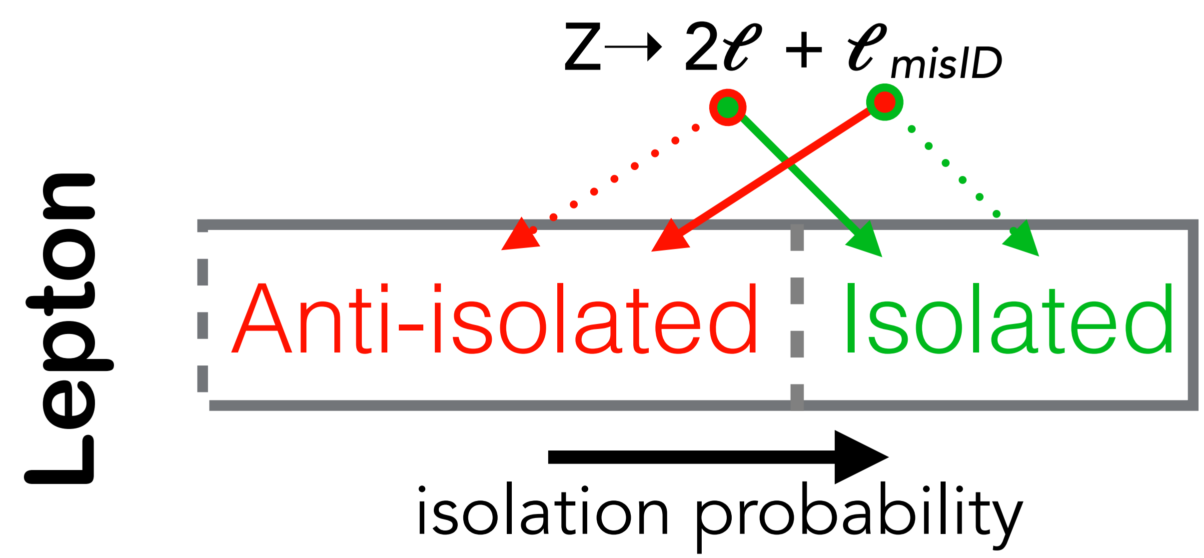


Misidentified Leptons

CMS EXO-18-005
https://arxiv.org/abs/1905.10853

- **Misidentified lepton** backgrounds are estimated via data-driven techniques
  - similarly for e/μ/τ





$n_P \cdot p + n_F \cdot f = \langle n_{iso} \rangle$

$n_P \cdot (1-p) + n_F \cdot (1-f) = \langle n_{anti\text{-}iso} \rangle$

→ varies in Z+jets vs tt+jets environments

Direct fake rate measurements:

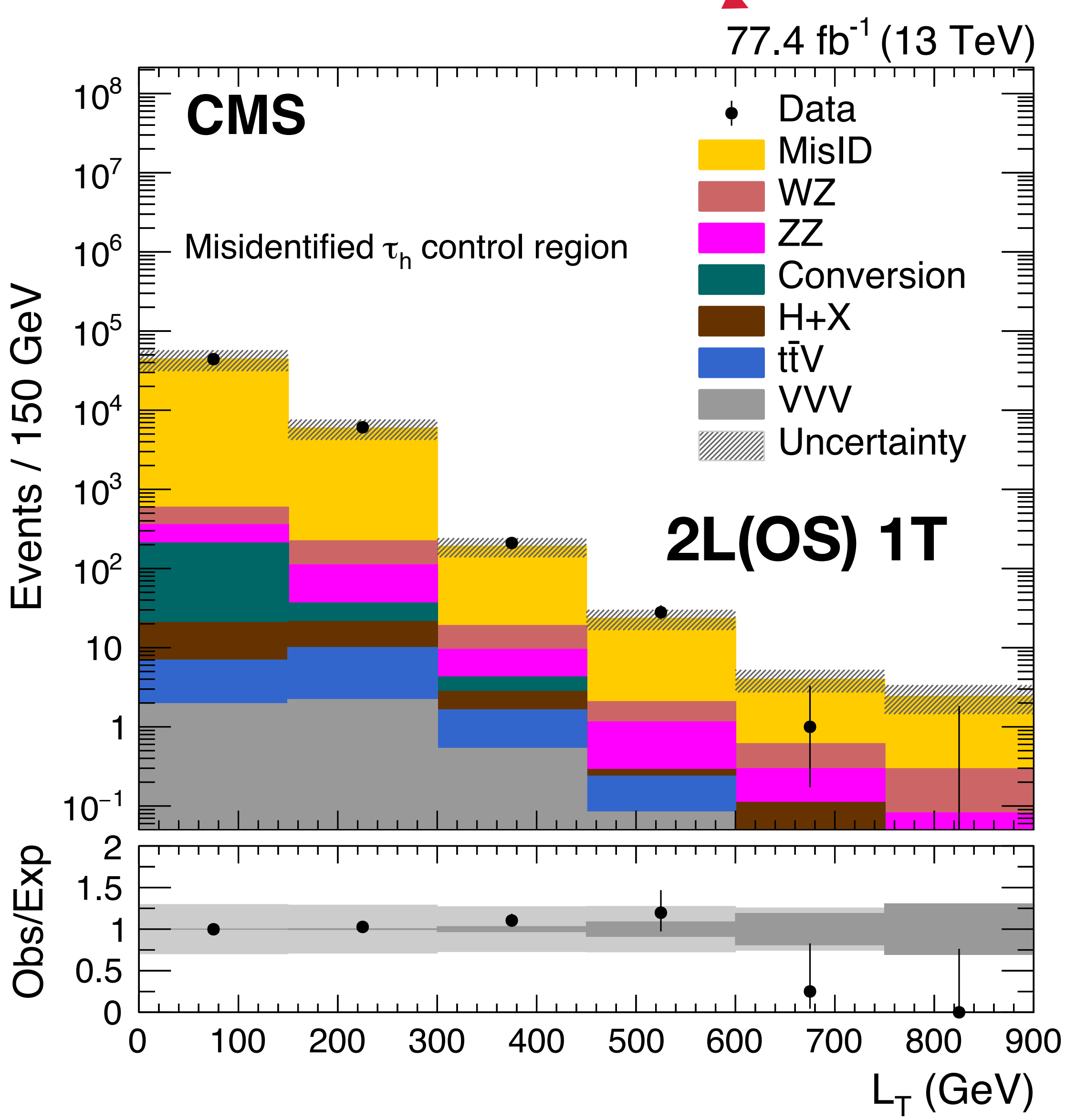
- Z-like: Trilepton (3L or 2L1T) with OSSF e/μ pair onZ, low MET
- tt-like: Same-sign dilepton

Misidentified Leptons

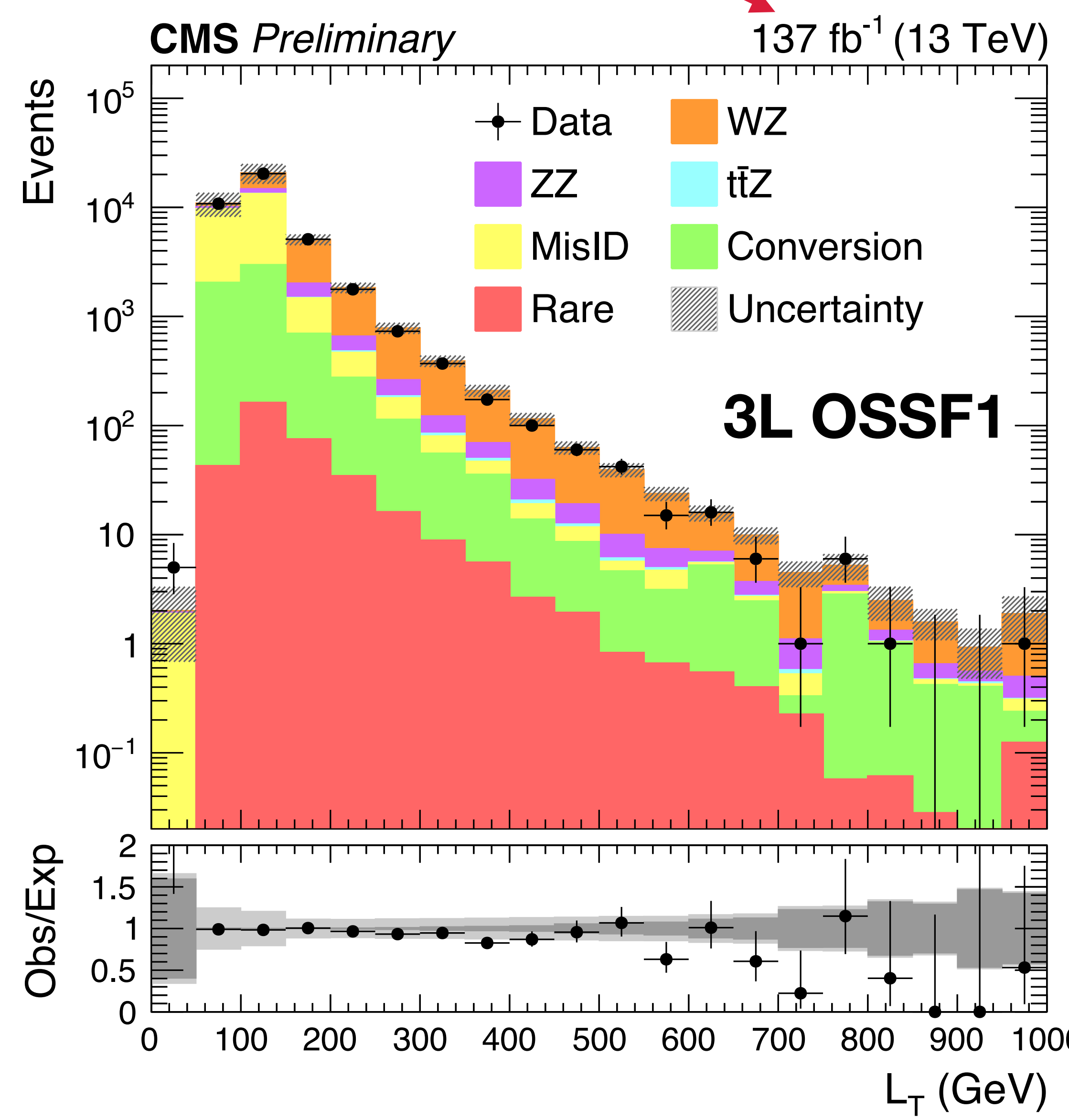
CMS EXO-18-005
CMS PAS-EXO-19-002

- **Misidentified lepton** backgrounds are estimated via data-driven techniques

2016+2017 luminosity



2016+2017+2018 luminosity



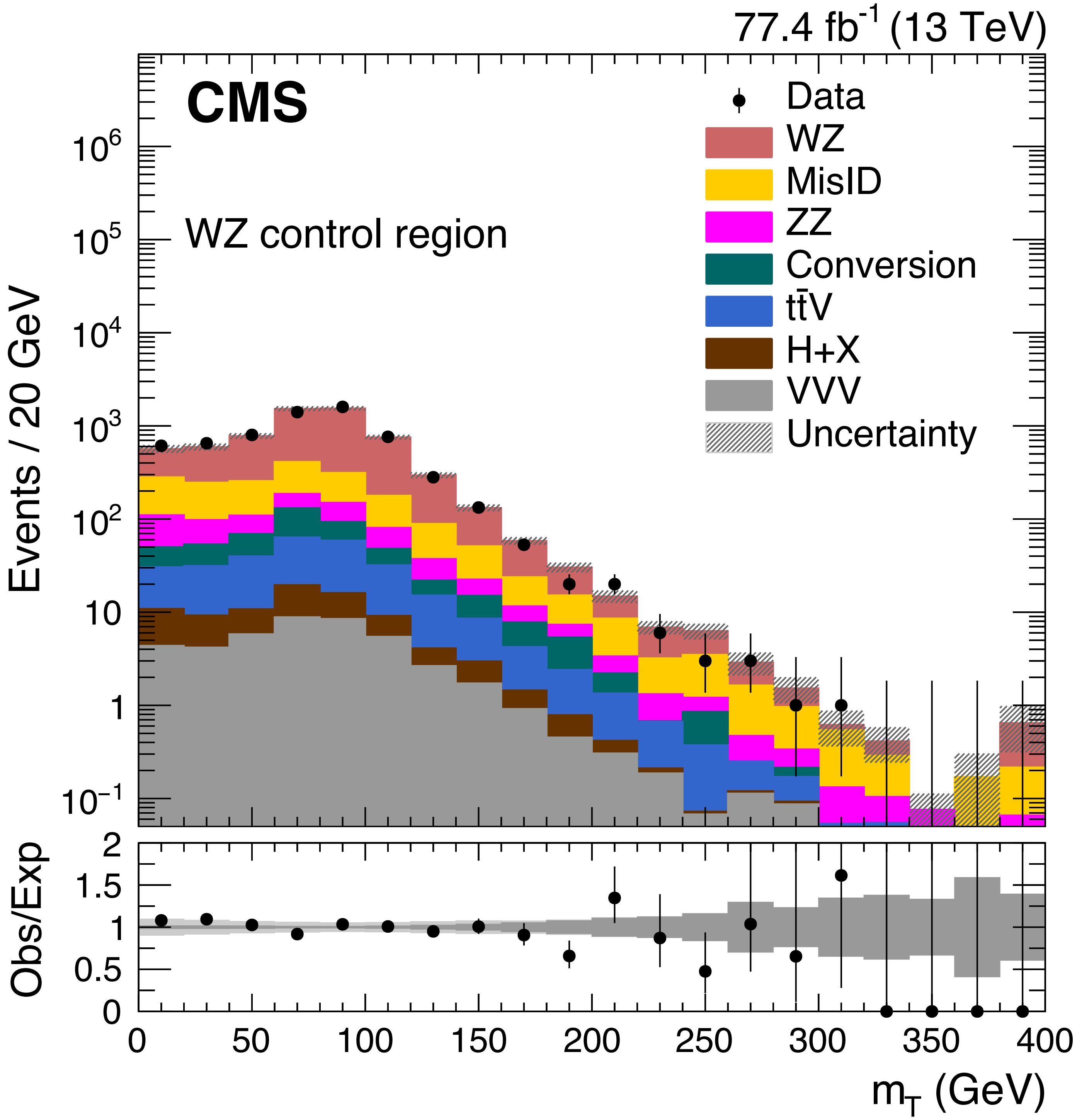
Misidentified Taus

Misidentified Electrons/Muons

~O(10) more dominant

Irreducible SM: WZ

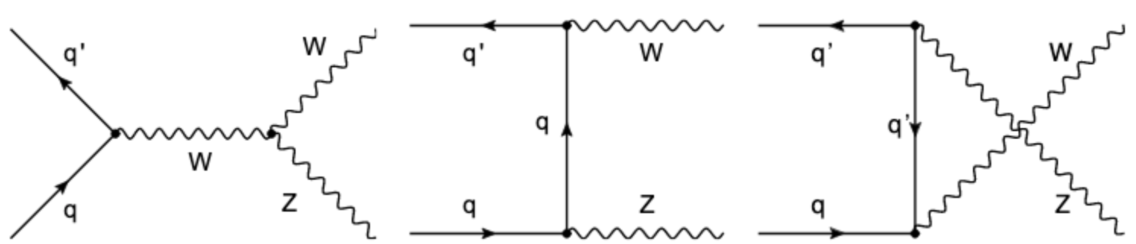
CMS EXO-18-005
https://arxiv.org/abs/1905.10853



σ(WZ) is normalized to data in CR

- both in yield, and jet multiplicity (0-3)
- reduces MC Generator sensitivity (aMC@NLO vs POWHEG)
- absorbs some higher order corrections
- relative norm. uncertainty is ~5%

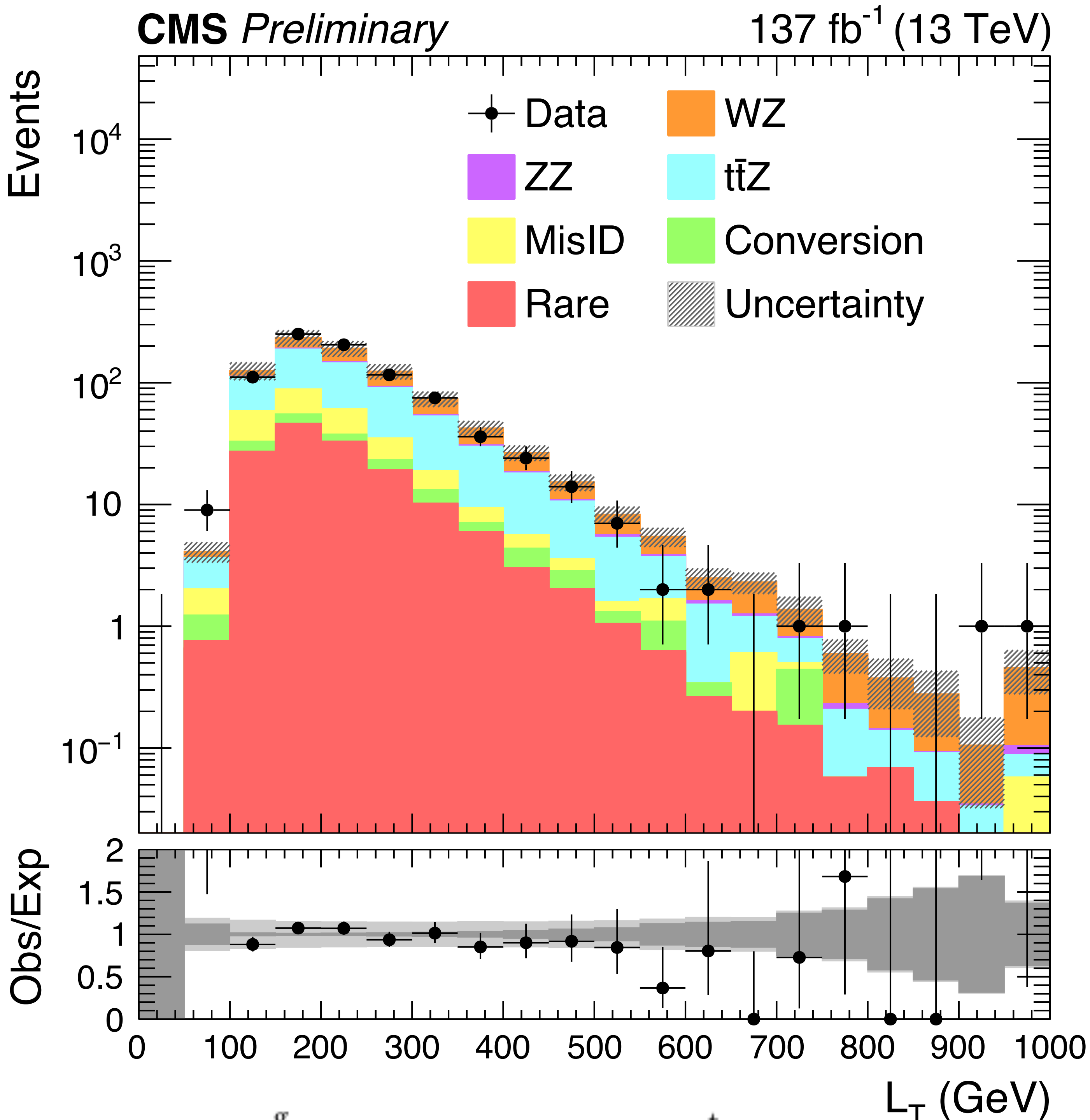
Exactly 3 leptons
On-Z pair
50<MET<100 GeV
(0 btags)



A "ZZ CR" follows similarly in 4L

Irreducible SM: ttZ

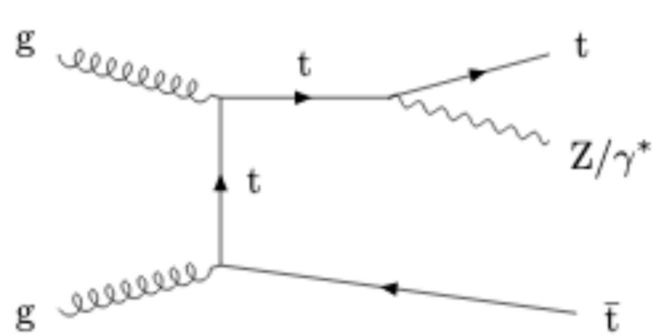
CMS PAS-EXO-19-002
http://cds.cern.ch/record/2668721

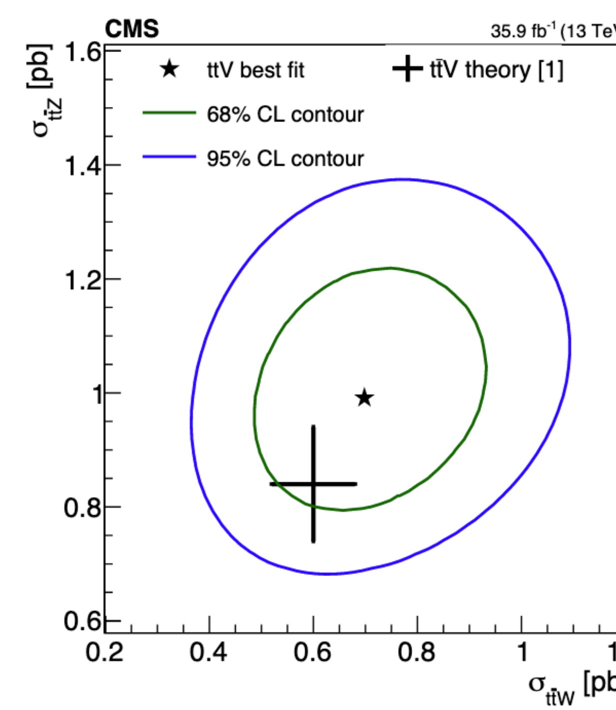


σ(ttZ) is normalized to data in CR

- both in yield, and jet multiplicity (0-2)
- reduces MC Generator sensitivity (aMC@NLO vs POWHEG)
- absorbs some higher order corrections
- relative norm. uncertainty is ~20%

Exactly 3 leptons, with an On-Z pair
MET<100 GeV
ST>350 GeV
1 b-tagged jet





https://arxiv.org/abs/1711.02547

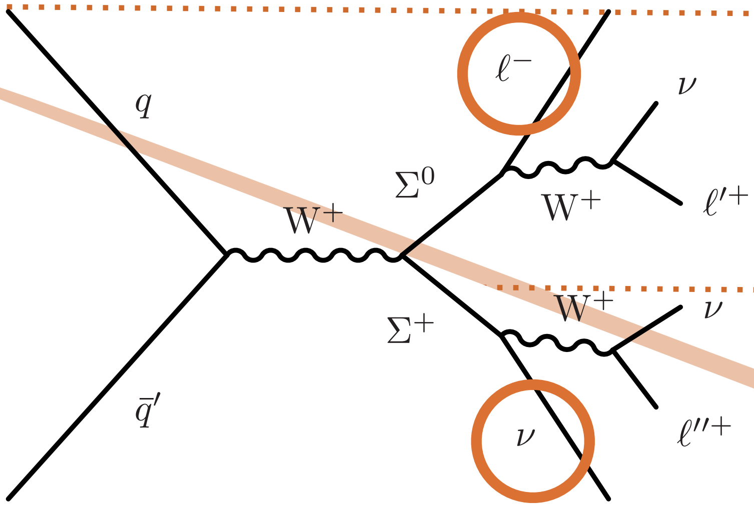
BSM models "to scale"

Example LO diagrams

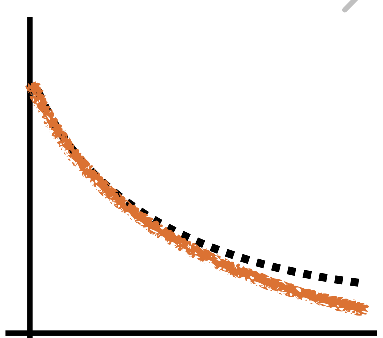
$\mathcal{O}$(1)TeV

$\mathcal{O}$(100)GeV

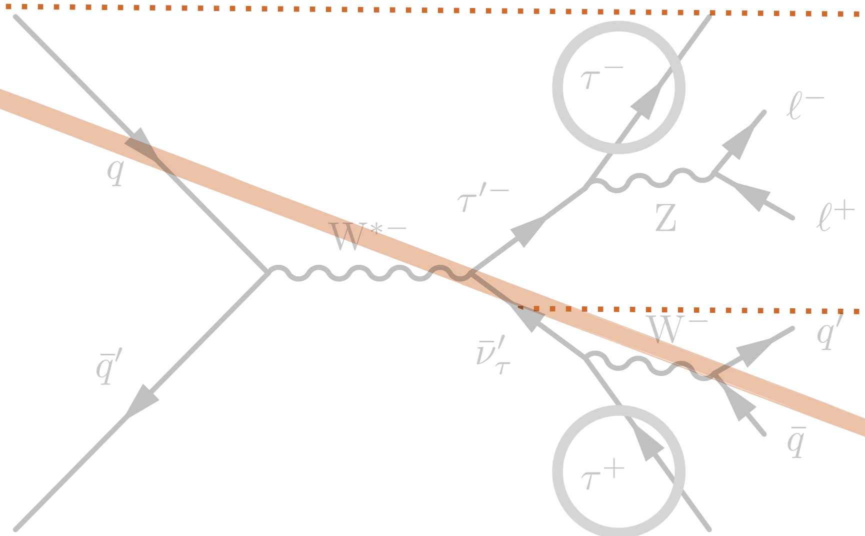
$\mathcal{O}$(10)GeV



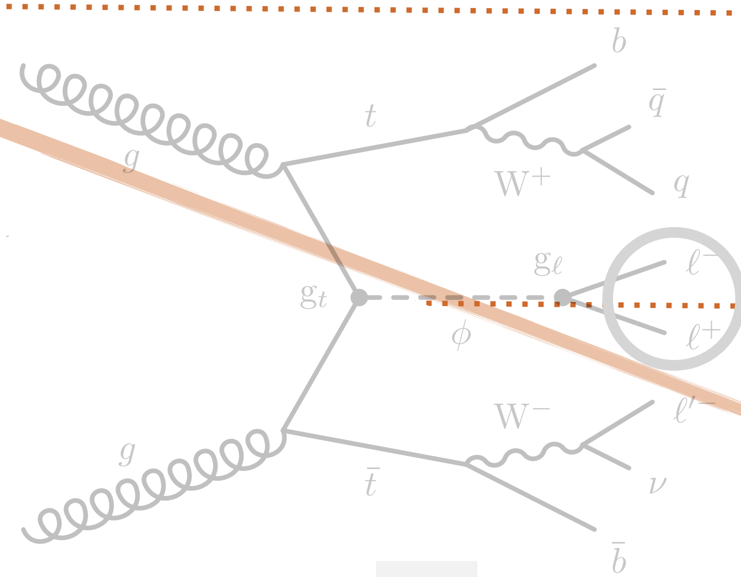
Type-III Seesaw



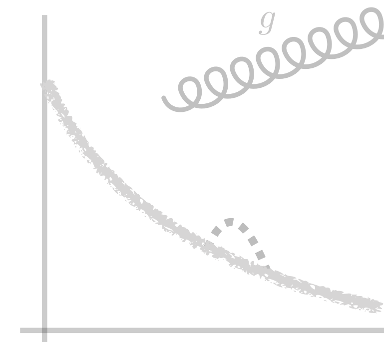
Non-resonant enhancement in tails



Vectorlike Taus



ttφ



Resonant structures

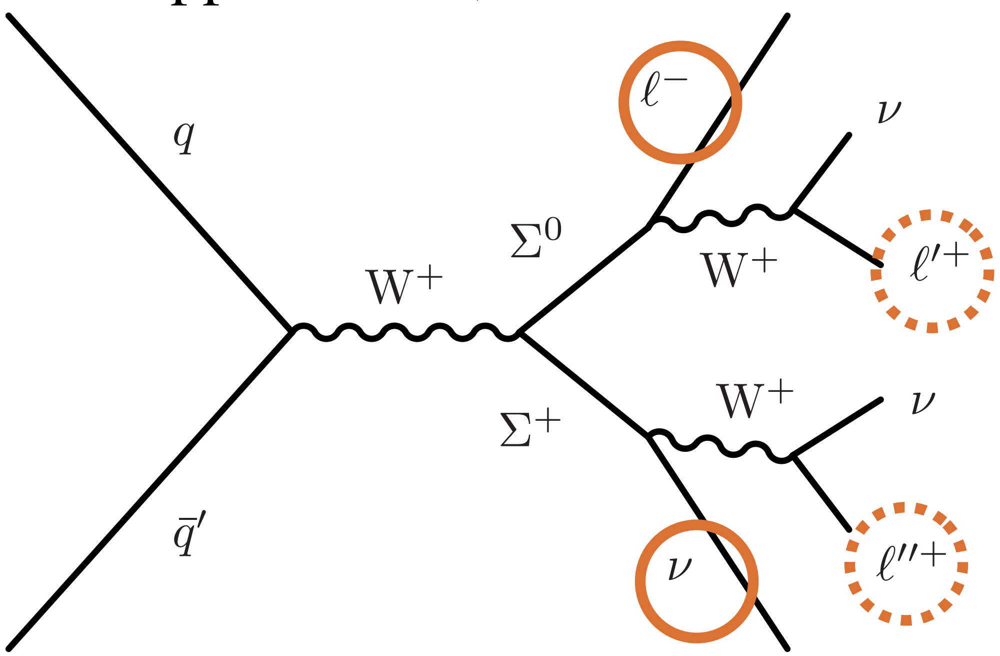
Excellent generators of **striking multi-leptonic signatures at the LHC**, around the EWK scale!

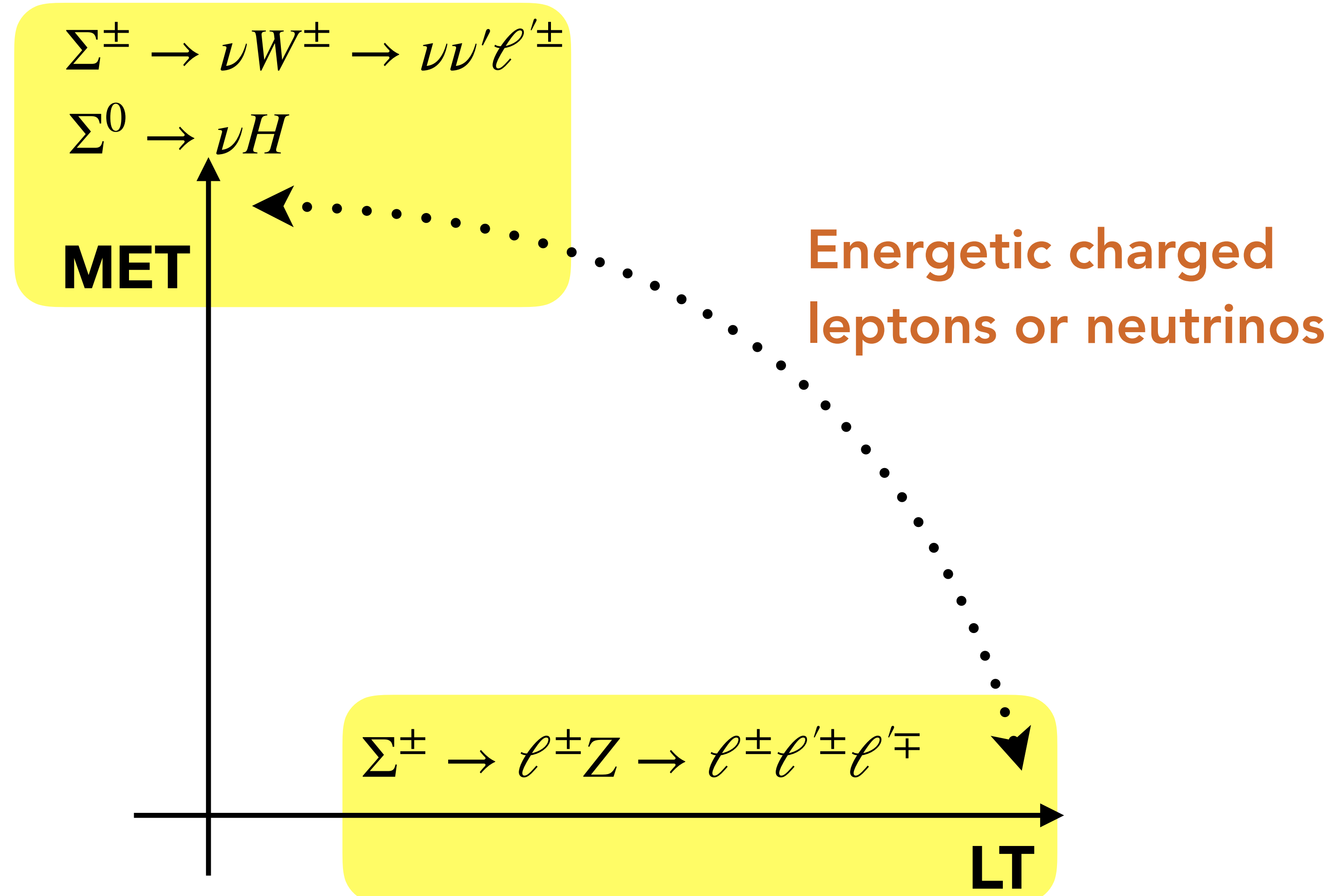
Type-III Seesaw

CMS PAS-EXO-19-002
http://cds.cern.ch/record/2668721

Heavy Lepton Triplets

$pp \rightarrow \Sigma^{\pm}\Sigma^{\mp},\ \Sigma^{\pm}\Sigma^{0}$





Biggio, Bonnet
https://arxiv.org/abs/1107.3463

Categorize by the mass of "most Z-like OSSF pair"

Label	N_ℓ	N_{OSSF}	M_{OSSF}	N_{b}	$p_{\mathrm{T}}^{\mathrm{miss}}$	Variable
Signal model: type-III seesaw						
3L below-Z	3	1	< 76 GeV	–	–	$L_{\mathrm{T}} + p_{\mathrm{T}}^{\mathrm{miss}}$
3L on-Z	3	1	$76 - 106$ GeV	–	> 100 GeV	M_{T}
3L above-Z	3	1	> 106 GeV	–	–	$L_{\mathrm{T}} + p_{\mathrm{T}}^{\mathrm{miss}}$
3L OSSF0	3	0	–	–	–	$L_{\mathrm{T}} + p_{\mathrm{T}}^{\mathrm{miss}}$
4L OSSF1	≥ 4	1	–	–	–	$L_{\mathrm{T}} + p_{\mathrm{T}}^{\mathrm{miss}}$
4L OSSF2	≥ 4	2	–	–	> 100 GeV if double on-Z	$L_{\mathrm{T}} + p_{\mathrm{T}}^{\mathrm{miss}}$

Type-III Seesaw

CMS PAS-EXO-19-002
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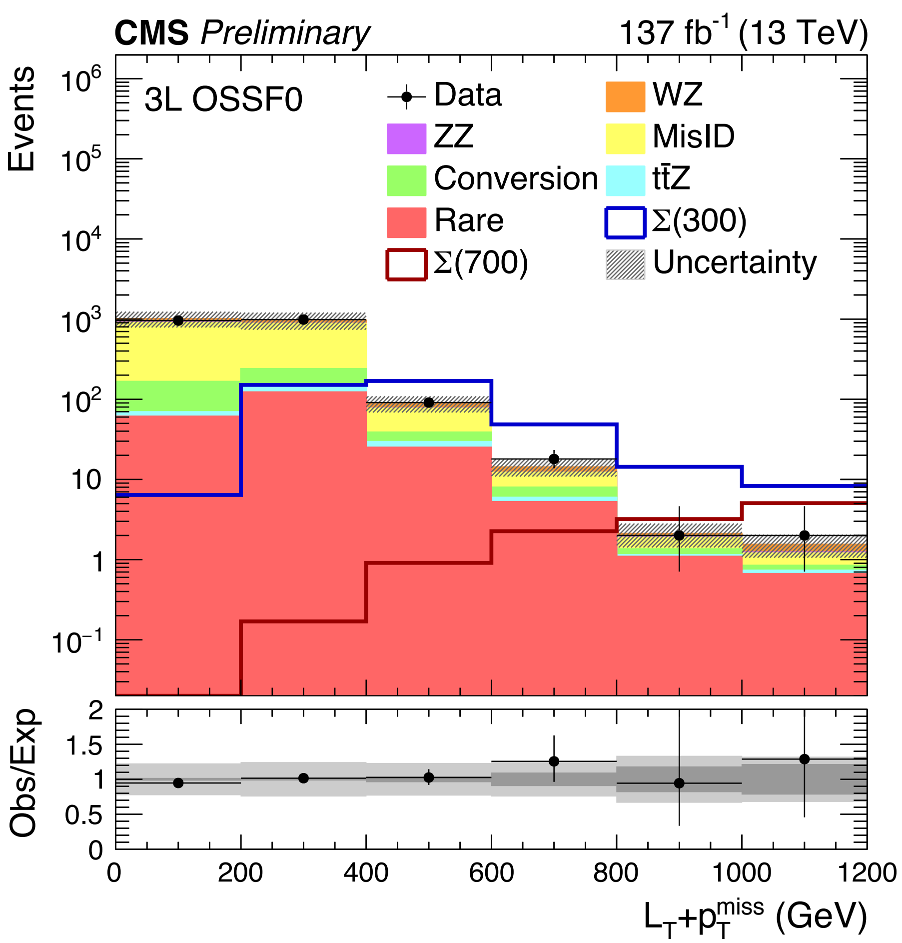
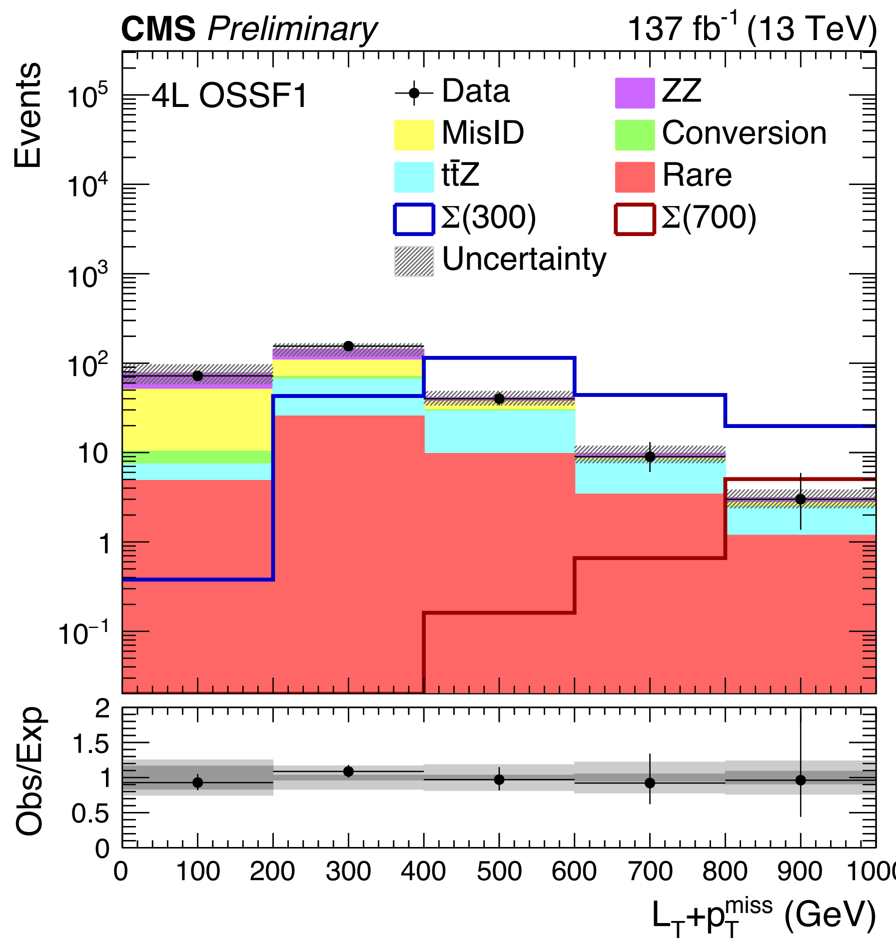
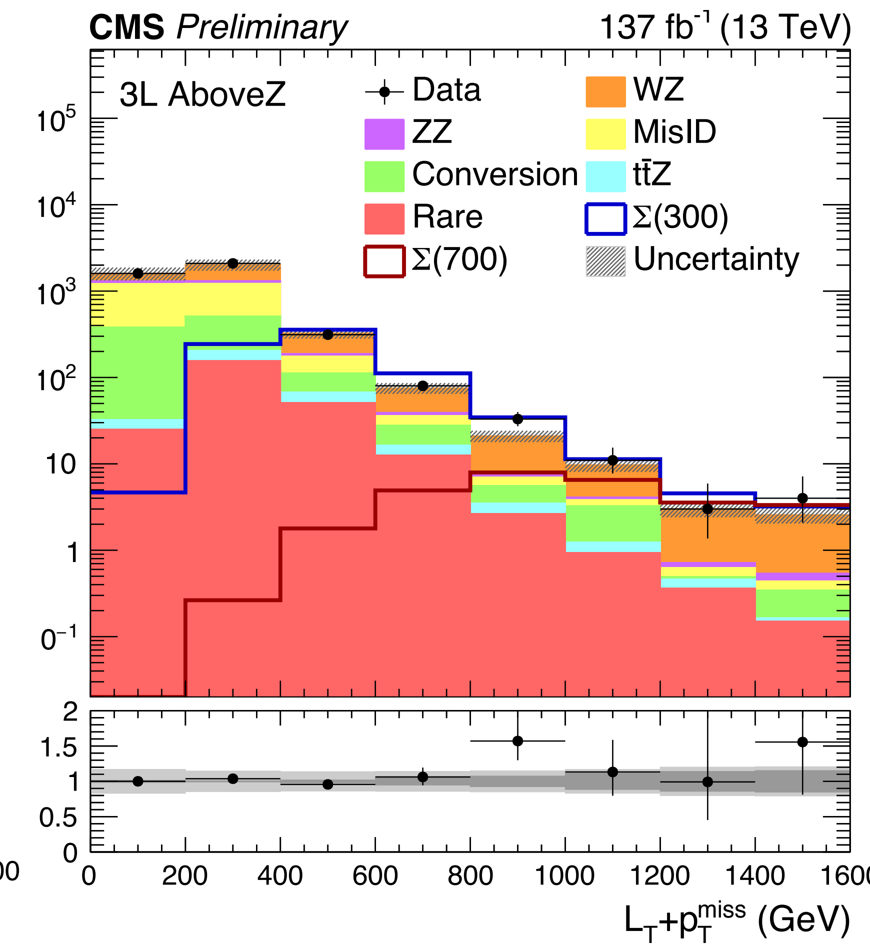


3L OSSF0



4L OSSF1



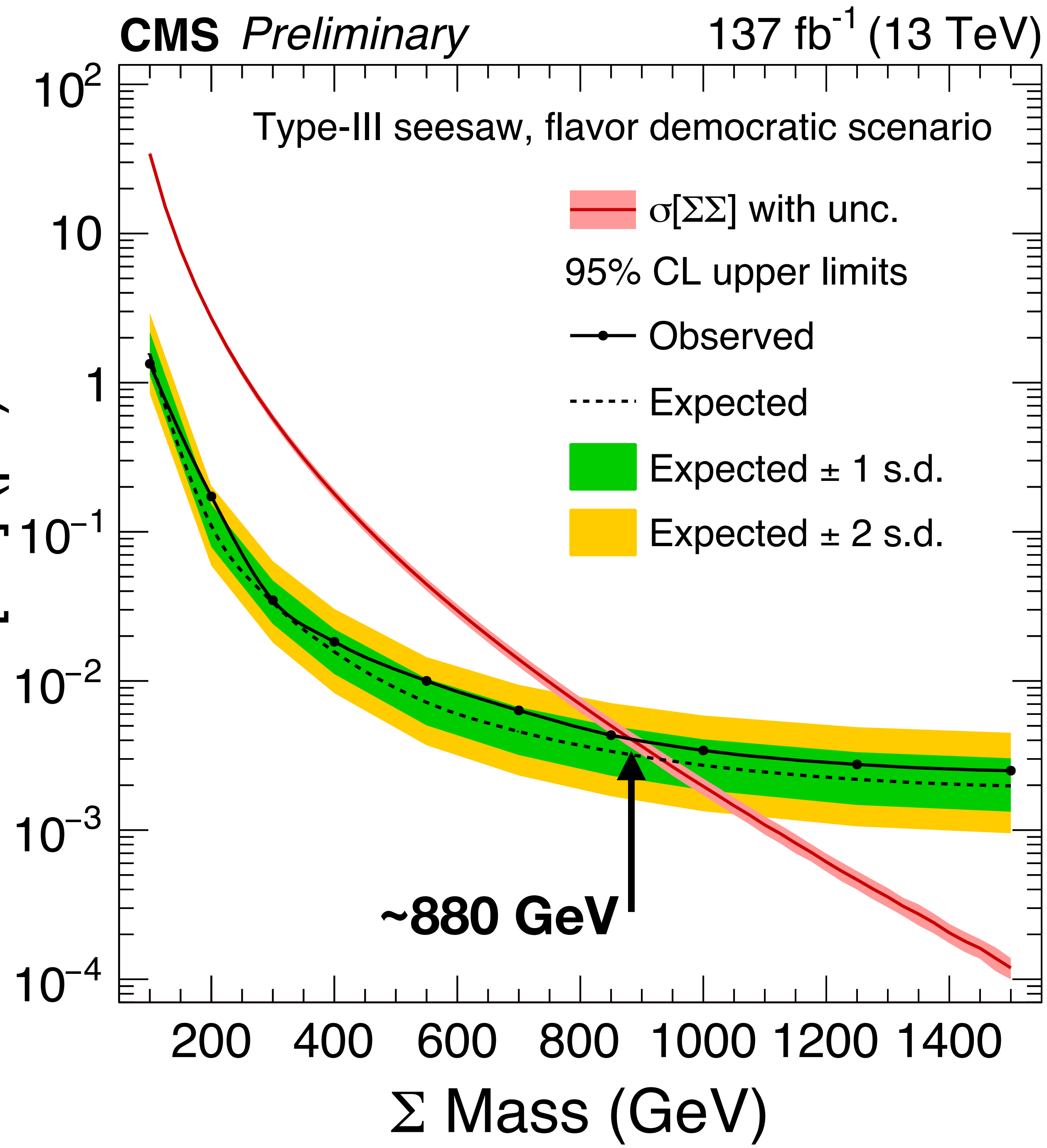
3L OSSF1 AboveZ

Dominant SM process:

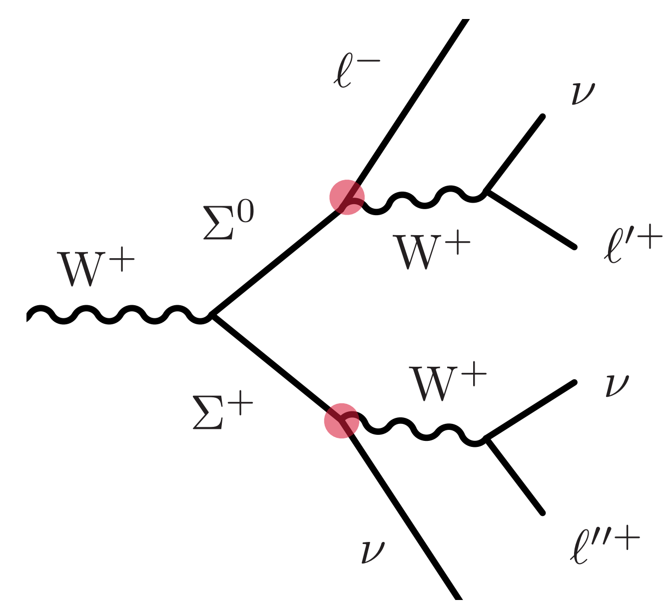
Misidentified leptons | ttZ | WZ

Type-III Seesaw

CMS PAS-EXO-19-002
http://cds.cern.ch/record/2668721



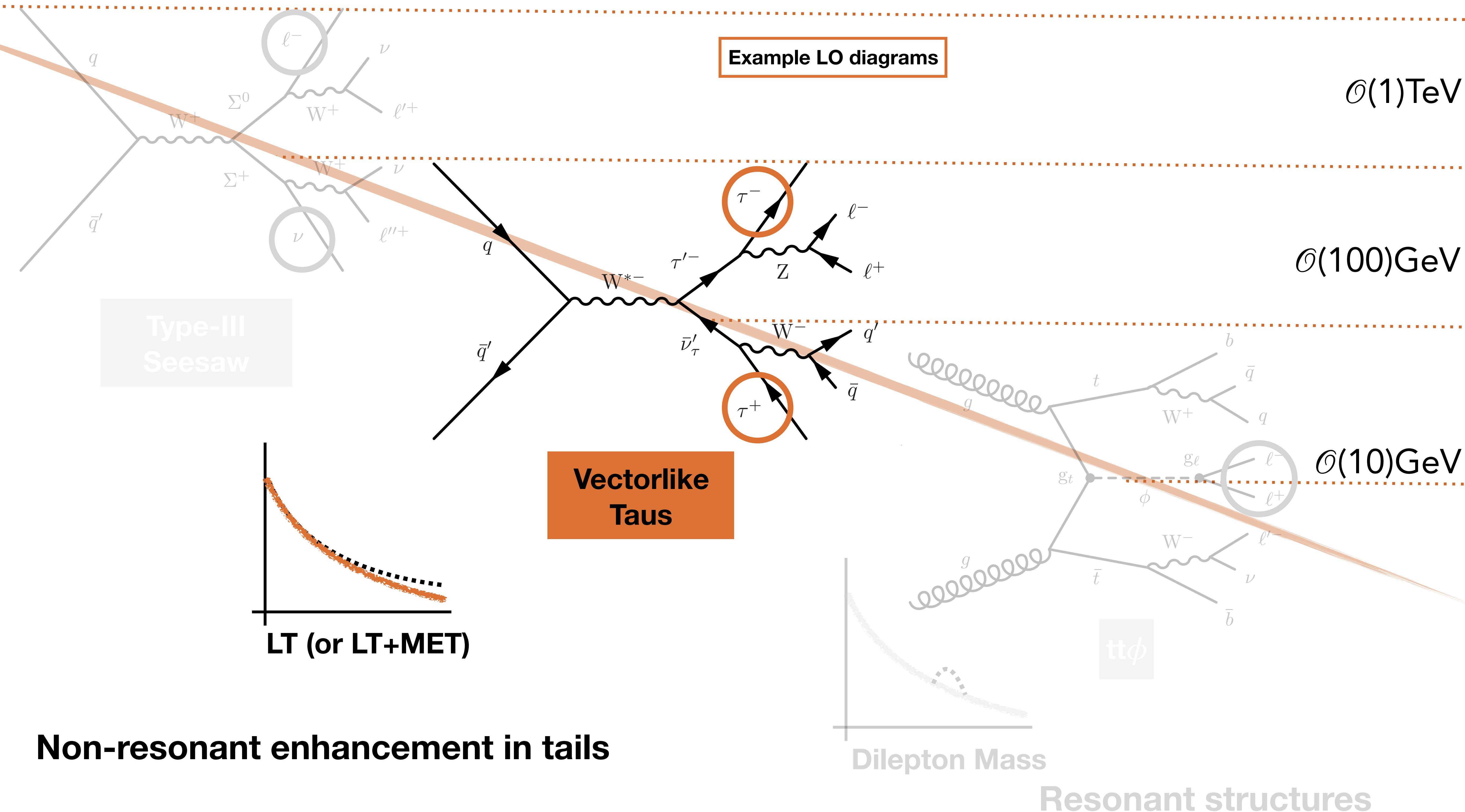
"Prompt decays" in detector



$$V_\ell \sim 10^{-4}$$

- **Production primarily via gauge interactions**
- **Mixing to SM leptons controls Σ lifetime and BR**

BSM models "to scale"



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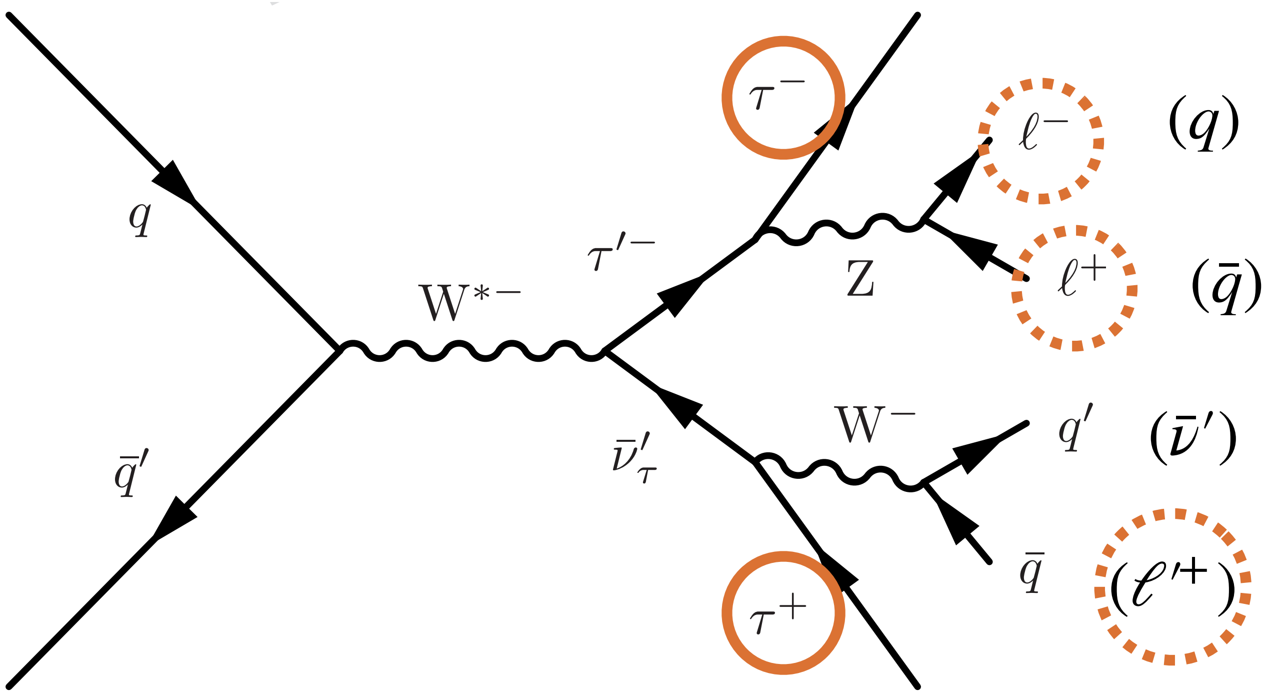
Vectorlike Taus

CMS EXO-18-005
https://arxiv.org/abs/1905.10853

Vector-like Tau Doublet



$$pp \to \tau'\tau',\ \ \tau'\nu',\ \ \nu'\nu'$$

$$\tau' \to Z\tau, H\tau$$

$$\nu' \to W\tau$$

Energetic taus (hadronic) in each event

No direct decays to neutrinos!

- *not necessarily of high MET*

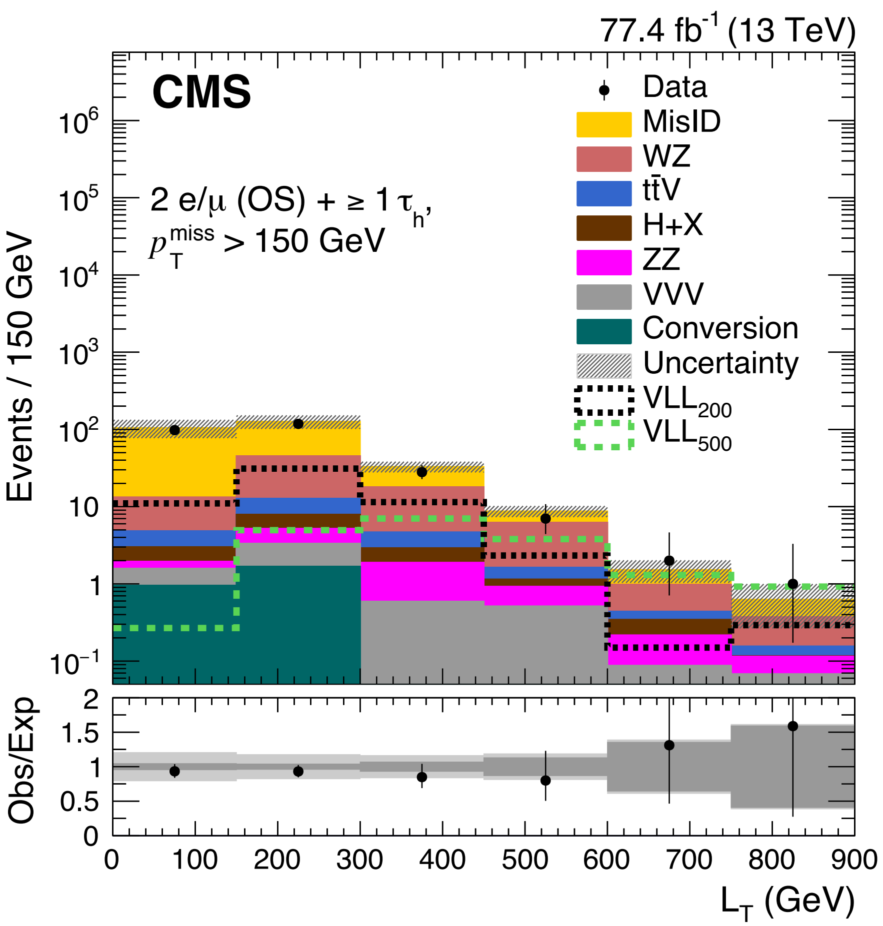
Kumar, Martin.
https://arxiv.org/abs/1510.03456

$N_{leptons}$	p_T^{miss} (GeV)	CR veto
$\geq$4e/μ	<50 >50	2 OSSF on-Z pairs and $p_T^{miss} < 50$ GeV
3e/μ	<150 >150	OSSF on-Z pair and $p_T^{miss} < 100$ GeV, or OSSF below-Z pair and $p_T^{miss} < 50$ GeV, or OSSF below-Z pair and on-Z $m_{3\ell}$
2e/μ OS (or SS) + $\geq 1\tau_h$	<150 >150	$p_T^{miss} < 50$ GeV

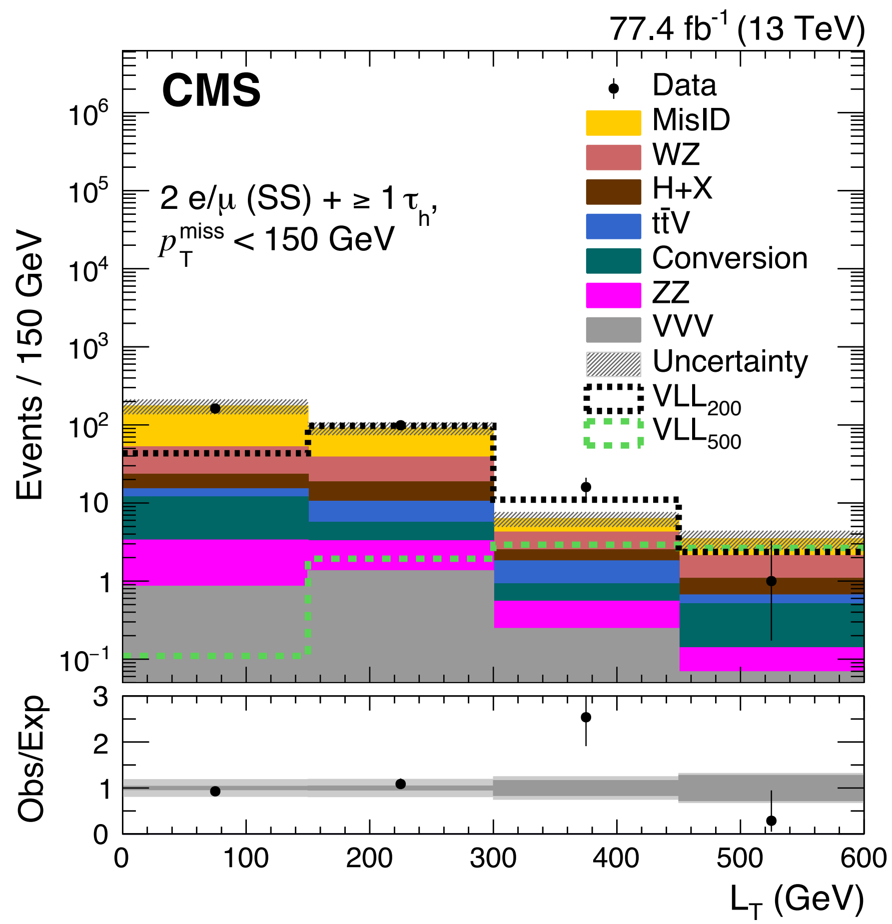
Same-sign dilepton (e/μ) + tau is the golden channel

Vectorlike Taus

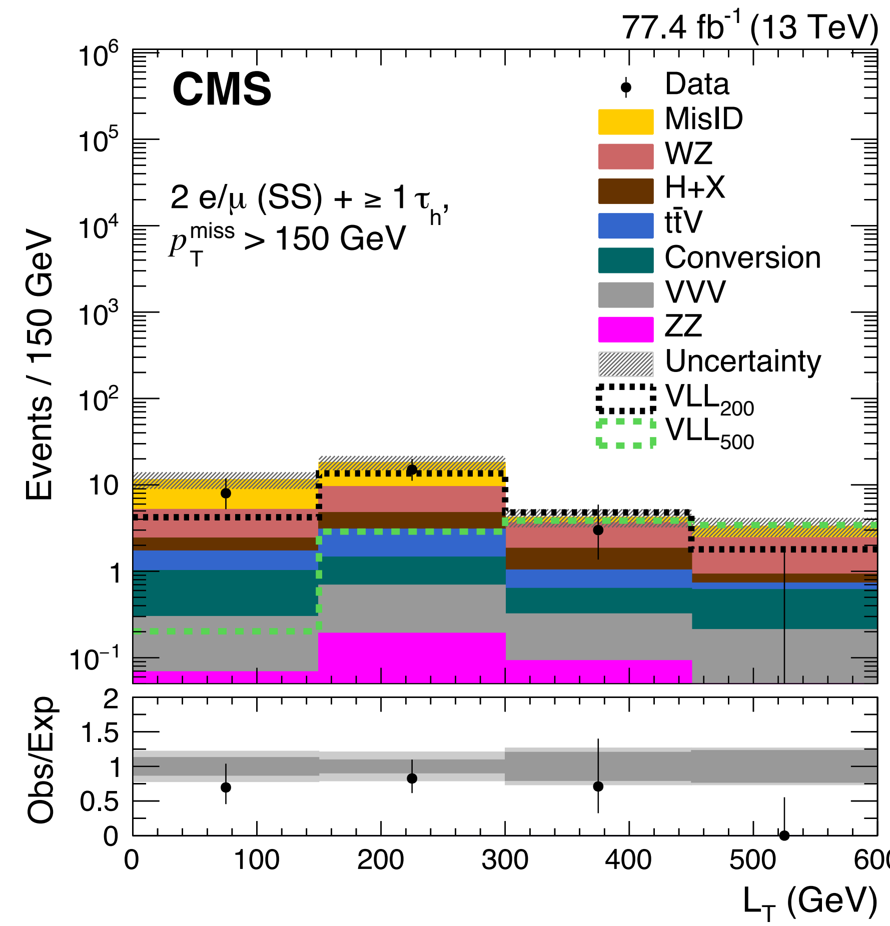
CMS EXO-18-005
https://arxiv.org/abs/1905.10853



2LOS+Tau, high MET



2LSS+Tau, low MET



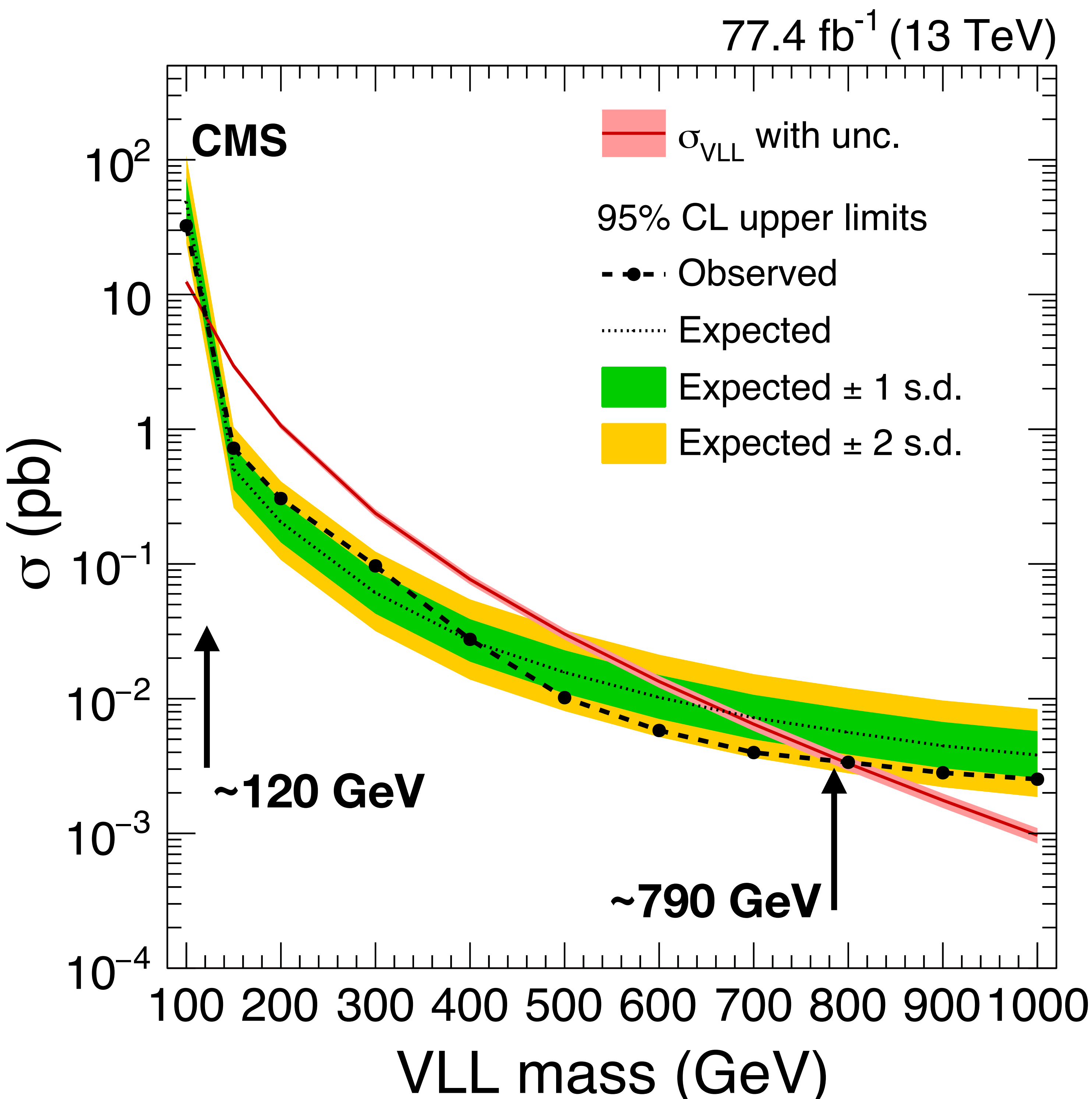
2LSS+Tau, high MET

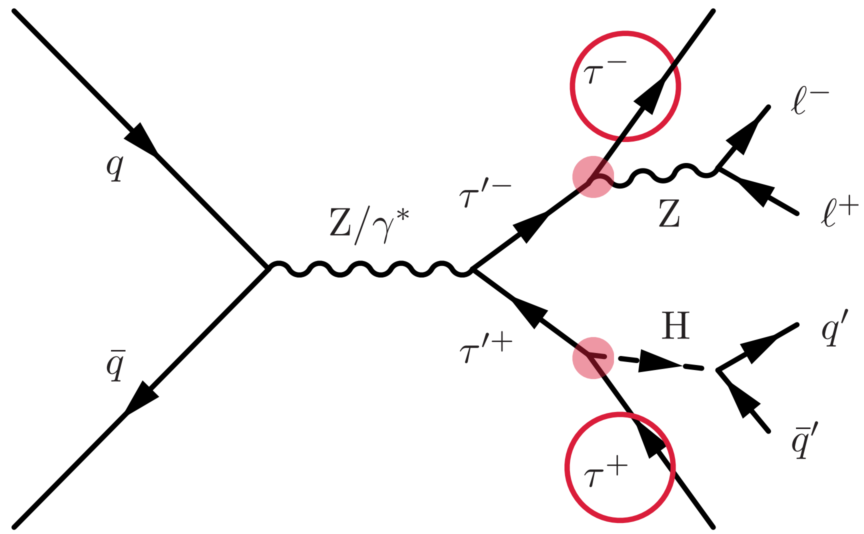
<u>**Dominant SM process:**</u>

Misidentified Tau **WZ**

Vectorlike Taus

CMS EXO-18-005
https://arxiv.org/abs/1905.10853



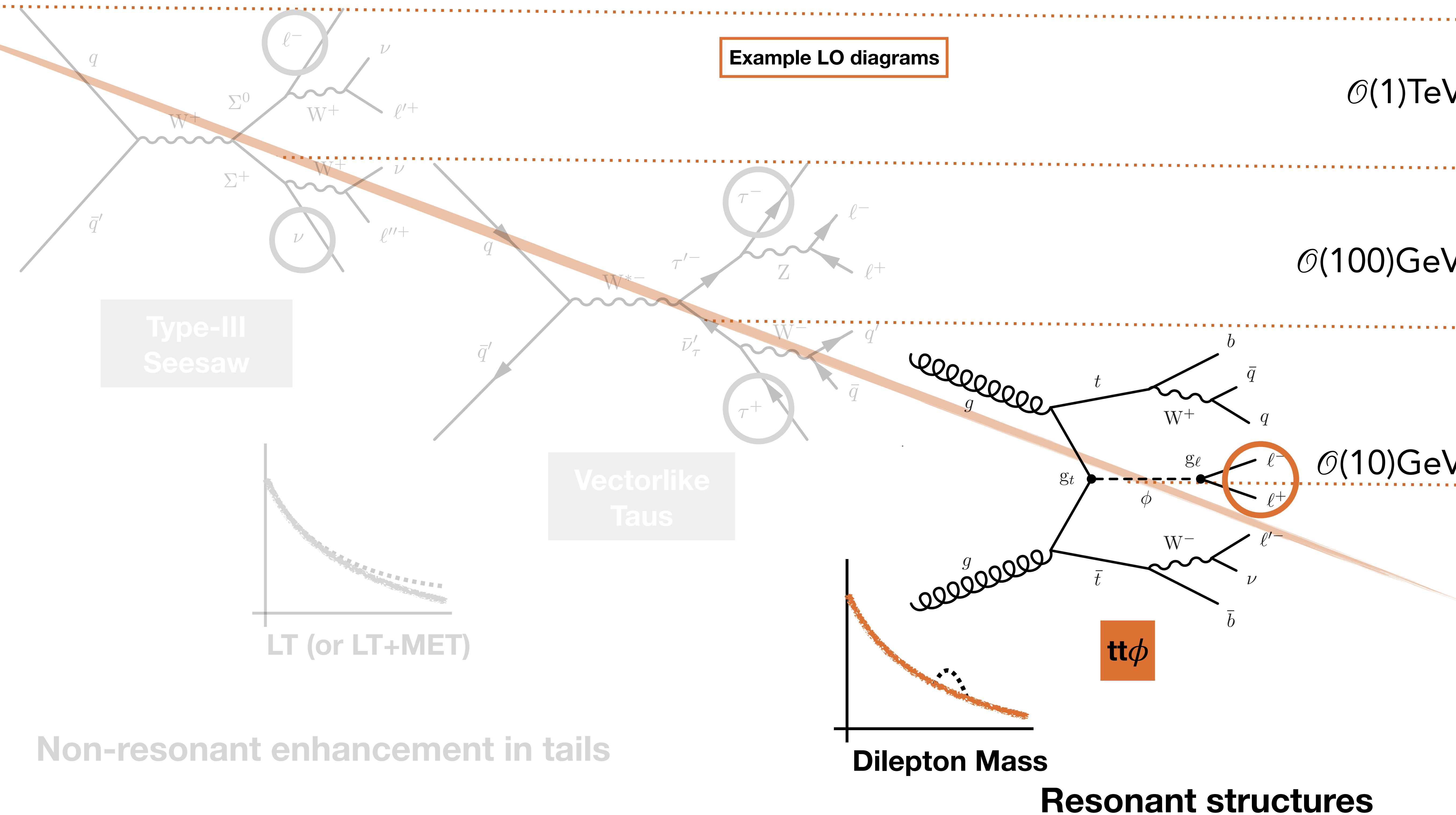


$\epsilon > 2 \times 10^{-7}$

- **Production primarily via gauge interactions**
- **Mixing to SM leptons controls τ' lifetime and BR**

"Prompt decays" in detector

BSM models "to scale"

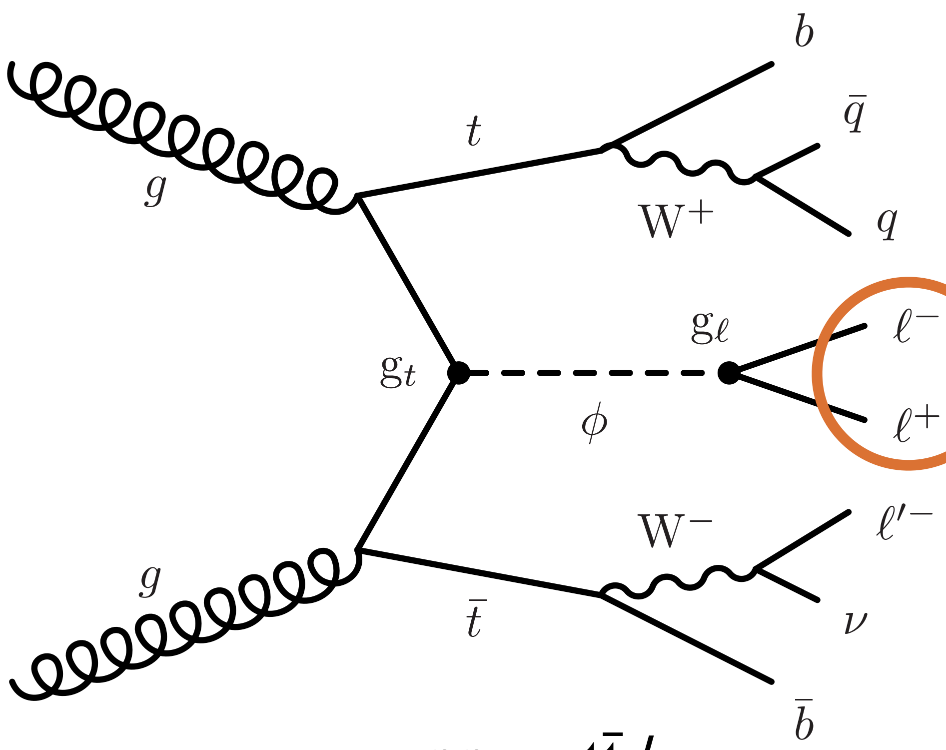


Excellent generators of striking multi-leptonic signatures at the LHC, around the EWK scale!

Extended scalar sector: ttϕ

CMS PAS-EXO-19-002
http://cds.cern.ch/record/2668721

Light Scalars/Pseudoscalars



$pp \rightarrow t\bar{t}\phi$

$\phi \rightarrow ee/\mu\mu$

Label	N_ℓ	N_{OSSF}	M_{OSSF}	N_b	p_T^{miss}	Variable
Signal model: $t\bar{t}\phi$						
$3L(\ell\ell)^\star$ 0B	3	1	off-Z	0	–	M_{OSSF}^{20} M_{OSSF}^{300}
$3L(\ell\ell)^\star$ 1B	3	1	off-Z	≥ 1	–	M_{OSSF}^{20} M_{OSSF}^{300}
$4L(\ell\ell)^\star$ 0B	≥ 4	≥ 1	off-Z	0	–	M_{OSSF}^{20} M_{OSSF}^{300}
$4L(\ell\ell)^\star$ 1B	≥ 4	≥ 1	off-Z	≥ 1	–	M_{OSSF}^{20} M_{OSSF}^{300}

* ℓ = e or μ

Casolino et al.
https://arxiv.org/abs/1507.07004
Chang et al.
https://arxiv.org/abs/1711.05722

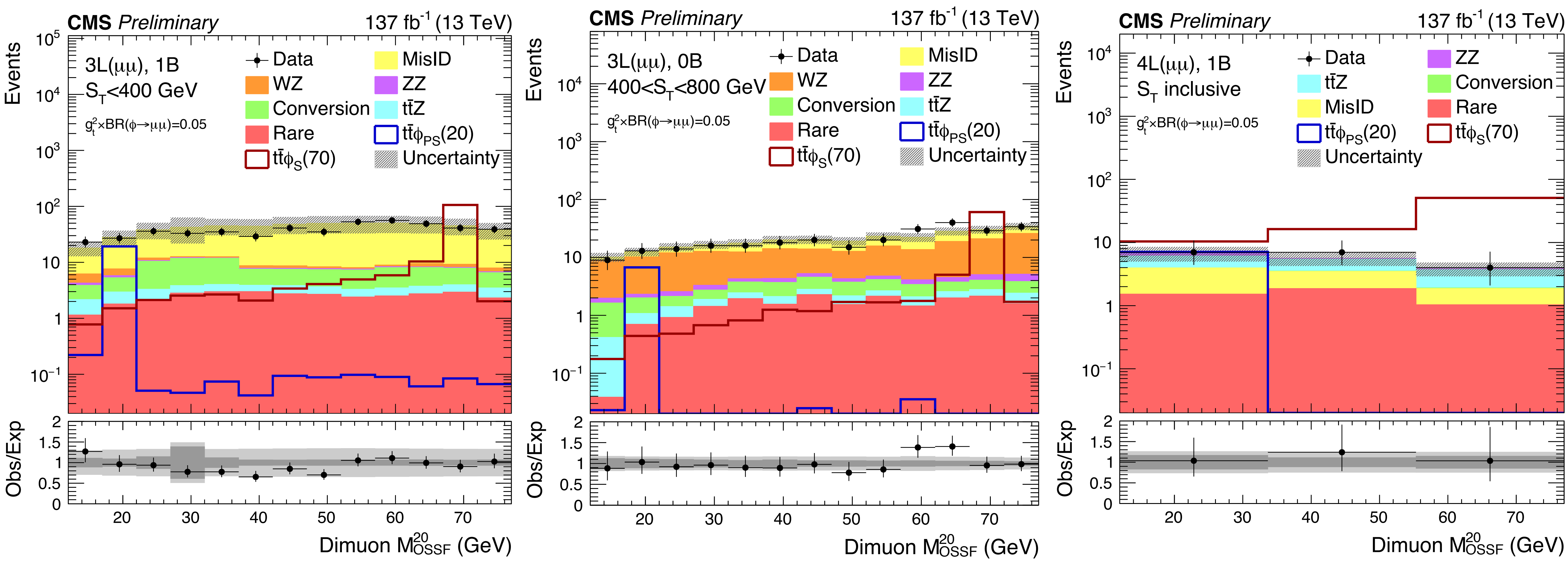
"Phi leptons" could be soft

Here we choose **one low, one high** mass OSSF pair in each event

In a nutshell:
Veto events with OSSF onZ (requires special treatment of WZ/ttZ normalization)
Look for a consistent resonant bump in ST and b-tagged jet multiplicity "slices"

Extended scalar sector: ttϕ

CMS PAS-EXO-19-002
http://cds.cern.ch/record/2668721



3L μμe+μμμ, low ST, 1B | **3L μμe+μμμ, med. ST, 0B** | **4L μμee++μμμe+μμμμ, 1B**

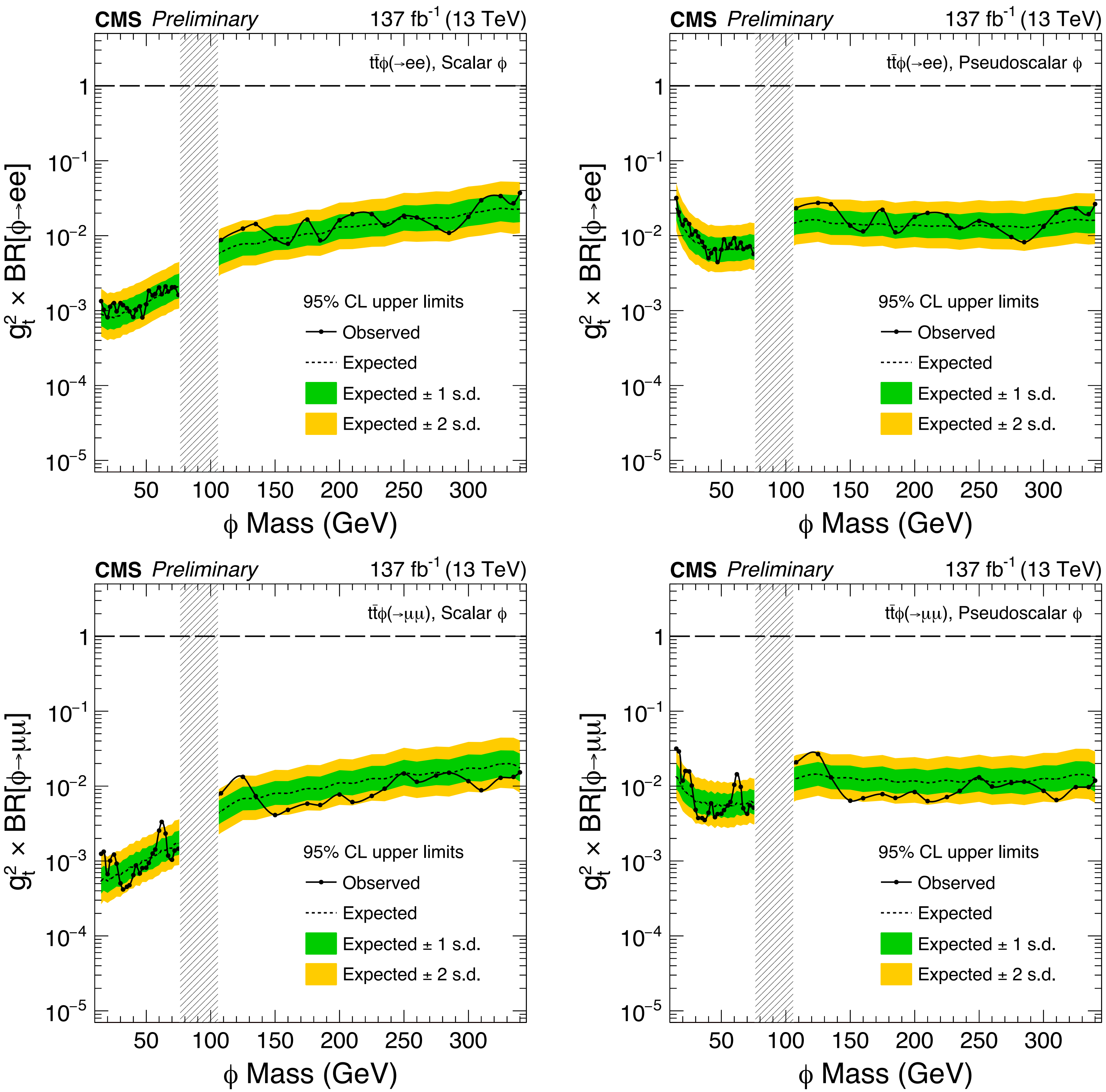
<u>Dominant SM process:</u>

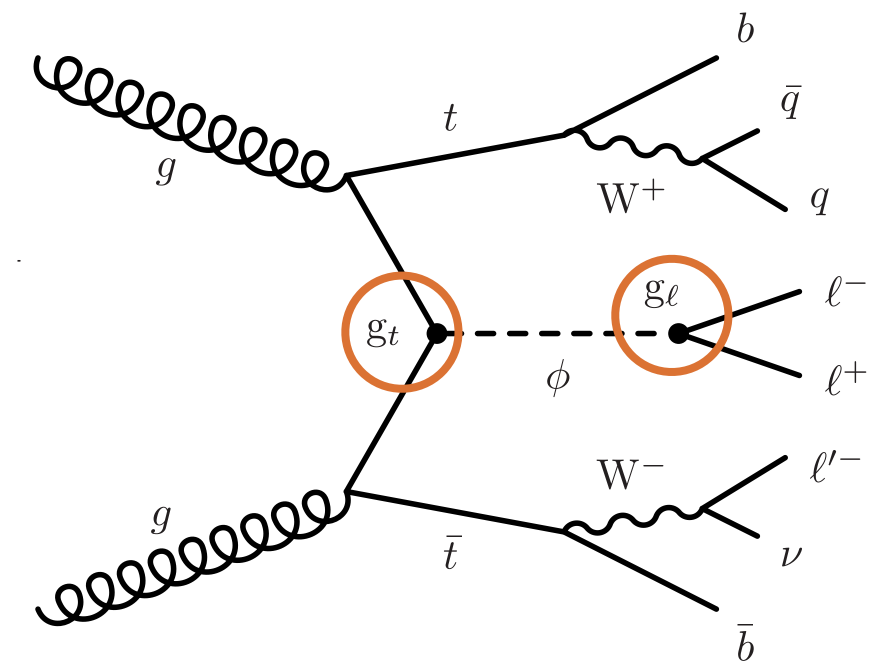
Misidentified lepton | WZ | ttZ

Also probed: → high masses (108-340)
→ "dielectron+X" channels

The ttϕ parameter space

CMS EXO-19-002





For $m_\phi < 2m_t$:

$$BR(\phi \to \ell\ell) \sim \frac{|g_\ell|^2}{\Sigma |g_\ell|^2}$$

For $g_t \sim 1$, we exclude BR(ϕ→ee/μμ) above ~0.1-1% level.

Limits on absolute cross-cross-section are also provided!

In lieu of conclusions

- **Seesaw** : M > 880 GeV

  Vectorlike Taus : M > 790 GeV

  Scalars in ttbar associated production : BR $\lesssim$ 0.1-1% for 15<M<340 GeV

- Signature driven program:

  - low vs high **lepton pT**
  - low vs high **MET**
  - lepton **charge**, **flavor**, and **mass**
  - …

- Target **many** flavor and kinematic combinations

  - Arguably, an “experimentally driven” era in high energy physics

- Signatures are **exotic**, but backgrounds are **standard**

  - Is everything behaving as it should?

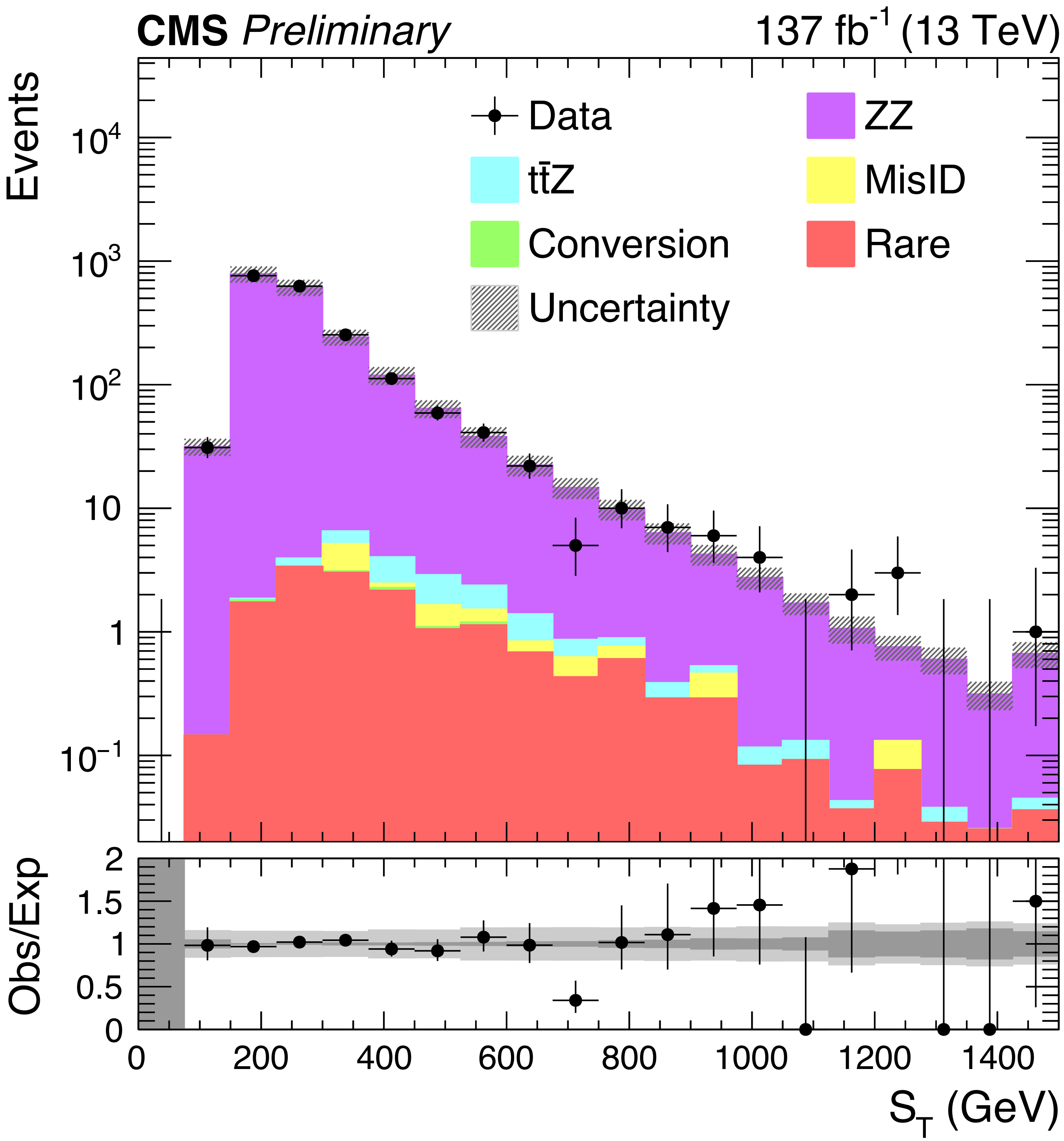
- We have **just scratched off the surface of the LHC Run-2 dataset**

  - Early days of ~$\mathcal{O}$(100)/fb era

Additional Material

Irreducible SM: ZZ

CMS PAS-EXO-19-002
http://cds.cern.ch/record/2668721



2016+2017+2018 luminosity

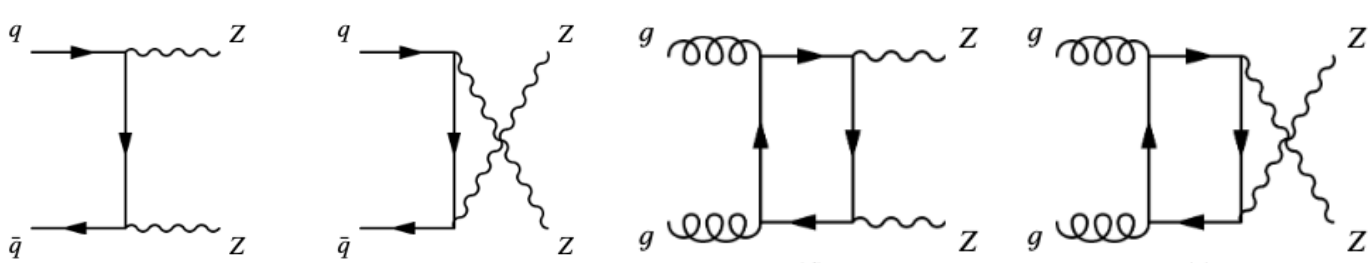
σ(ZZ) is normalized to data in CR

- both in yield, and jet multiplicity (0-2)
- reduces MC Generator sensitivity (aMC@NLO vs POWHEG)
- absorbs some higher order corrections
- relative norm. uncertainty is ~5%

Exactly 4 leptons

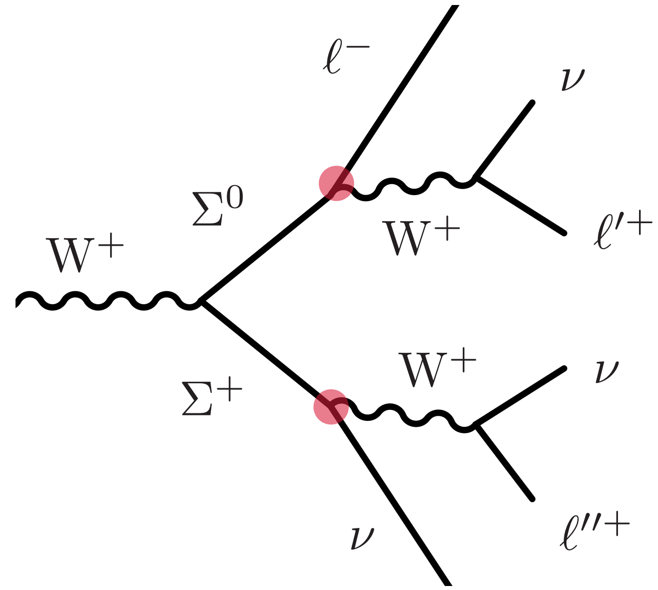
2 distinct On-Z pairs

MET<100 GeV

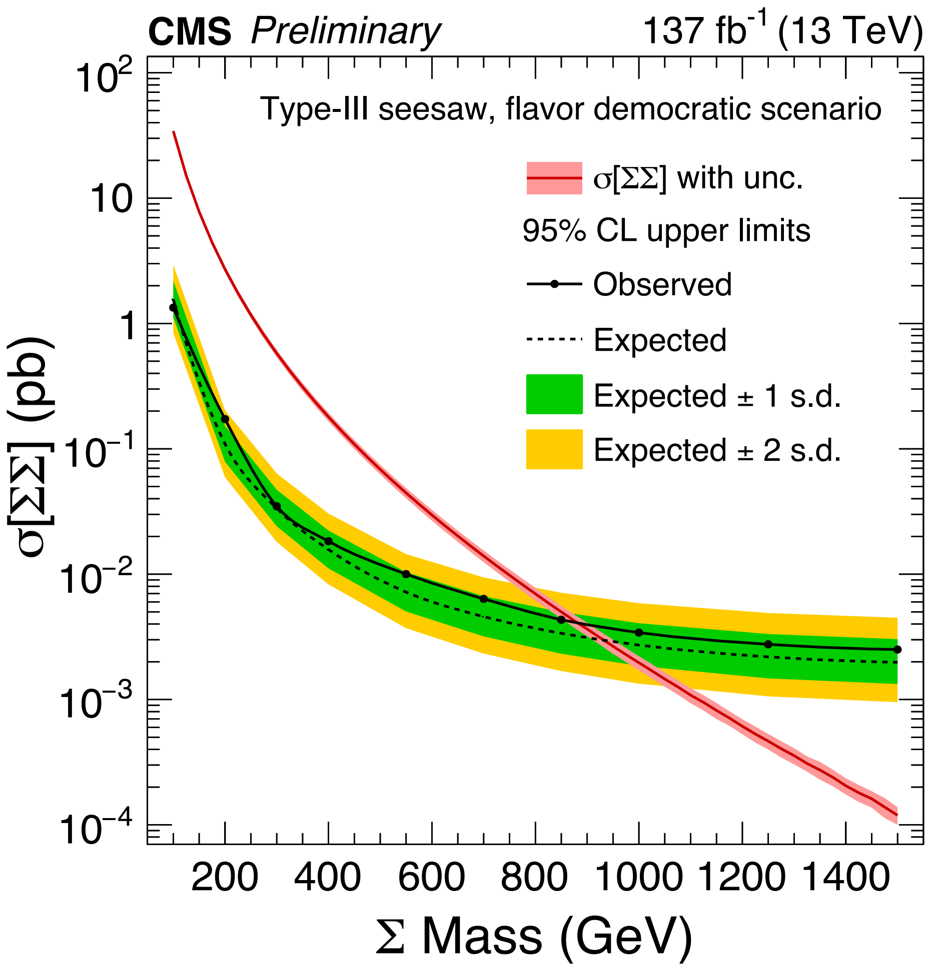


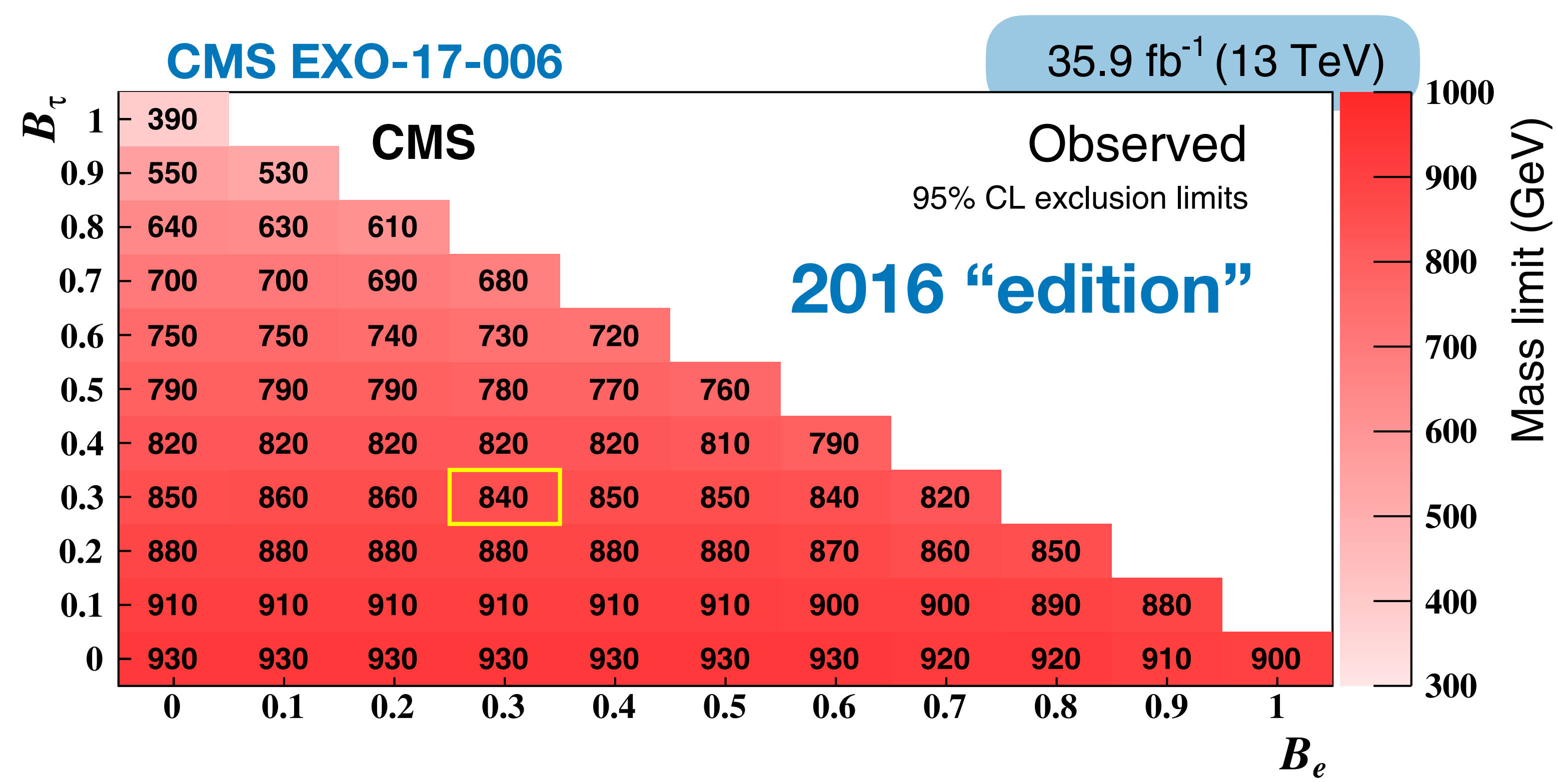
Type-III Seesaw

CMS PAS-EXO-19-002
http://cds.cern.ch/record/2668721



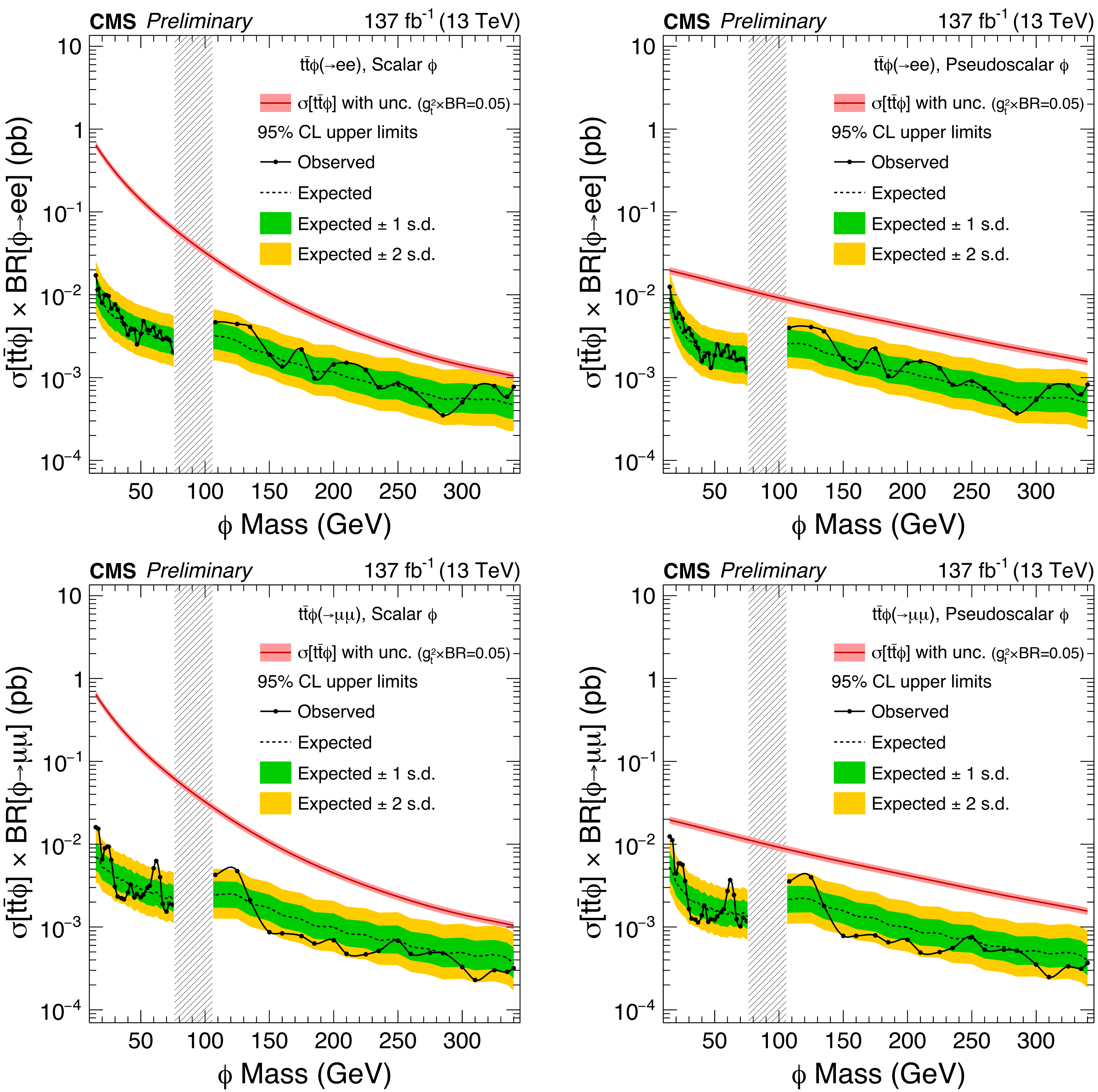
$$V_\ell \sim 10^{-4}$$





Flavor democratic mixings

Extended scalar sector: $t\bar{t}\phi$



Uncertainties in EXO-19-002

Uncertainty source	Signal/Background process	Variation (%)	Correlation
Luminosity	Signal/Rare/Non-$Z\gamma$ conversion	$2.3-2.5$	No
Lepton reco, ID and iso. efficiency	Signal/Background*	$4-5$	No
Lepton displacement efficiency (only in 3L)	Signal/Background*	$3-5$	Yes
Trigger efficiency	Signal/Background*	<3	No
B tag efficiency	Signal/Background*	<5	No
Minbias cross section (pileup)	Signal/Background*	<3	Yes
Factorization/renormalization scale & PDF	Signal/Background*	<10	Yes
Jet energy scale	Signal/Background*	<5	Yes
Unclustered energy scale	Signal/Background*	<5	Yes
Muon energy scale and resolution	Signal/Background*	<5	Yes
Electron energy scale and resolution	Signal/Background*	<2	Yes
WZ normalization (0/1/2/$\geq$3 jets)	WZ	$5-10$	Yes
ZZ normalization (0/1/$\geq$2 jets)	ZZ	$5-10$	Yes
$t\bar{t}Z$ normalization	$t\bar{t}Z$	$15-20$	Yes
Conversion normalization	Conversion	$20-50$	Yes
Rare normalization	Rare	50	Yes
Lepton misidentification rates	Misidentified lepton	$30-40$	Yes
Electron charge misidentification	WZ/ZZ†	<20	No

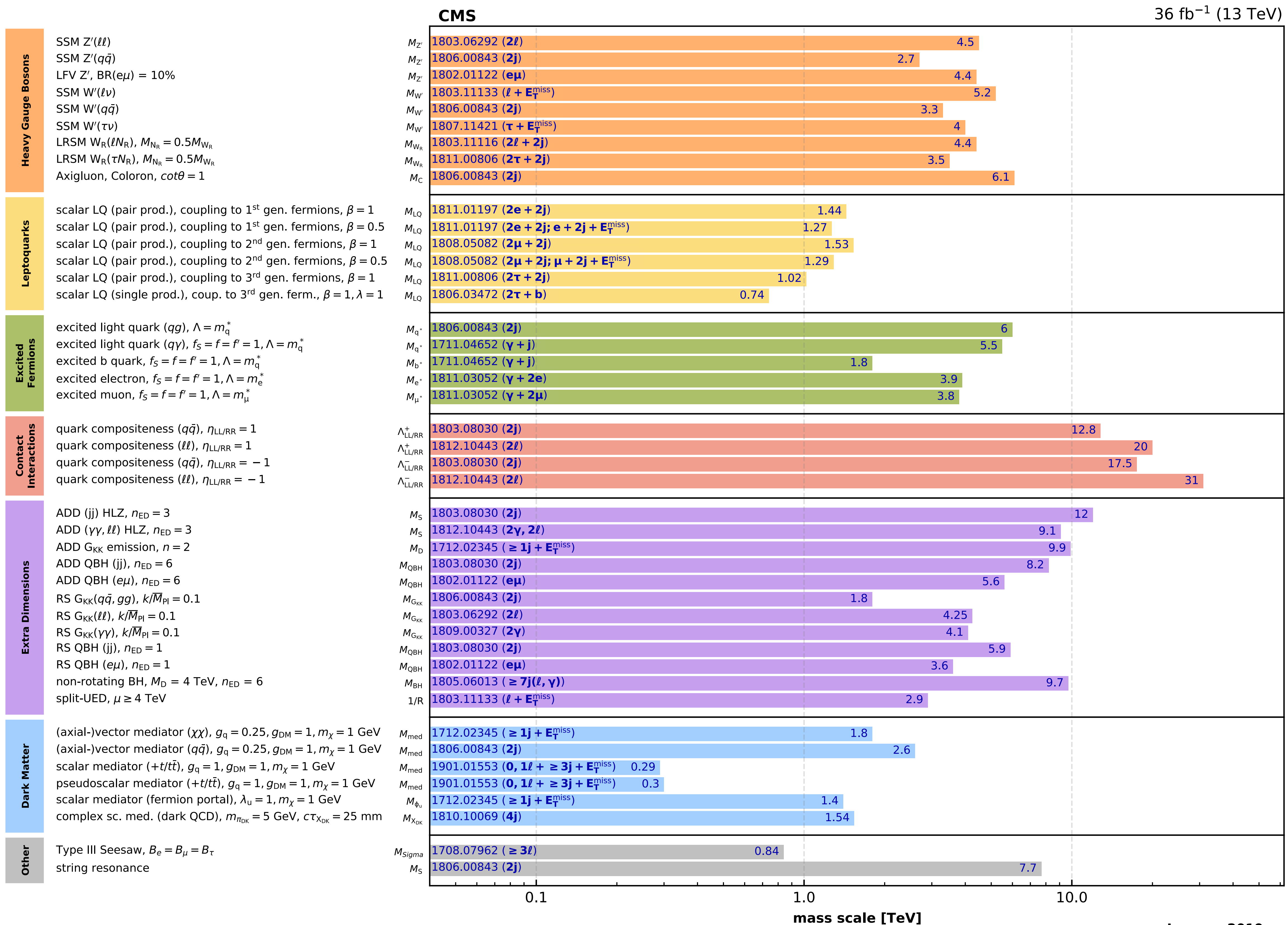
*WZ, ZZ, $t\bar{t}Z$, rare, and conversion background processes.
†Only in 3L OSSF0 and 4L OSSF1 signal regions.

Uncertainties in EXO-18-005

Source of uncertainty	Typical variations (%)	Processes
MisID background	20–35	—
Rare background normalization	50	—
Conversion background normalization	11	—
WZ background normalization	5	—
ZZ background normalization	4–5	—
Lepton identification & isolation	6–8	ALL
Single lepton trigger	<3	ALL
Electron energy scale and resolution	2–5	ALL
Muon momentum scale and resolution	2–10	ALL
Hadronic τ lepton energy scale	<5	ALL
Jet energy scale	5–10	ALL
Unclustered energy scale	1–10	ALL
Integrated luminosity	2.3–2.5	Rare/Signal
Pileup modeling	<4	ALL

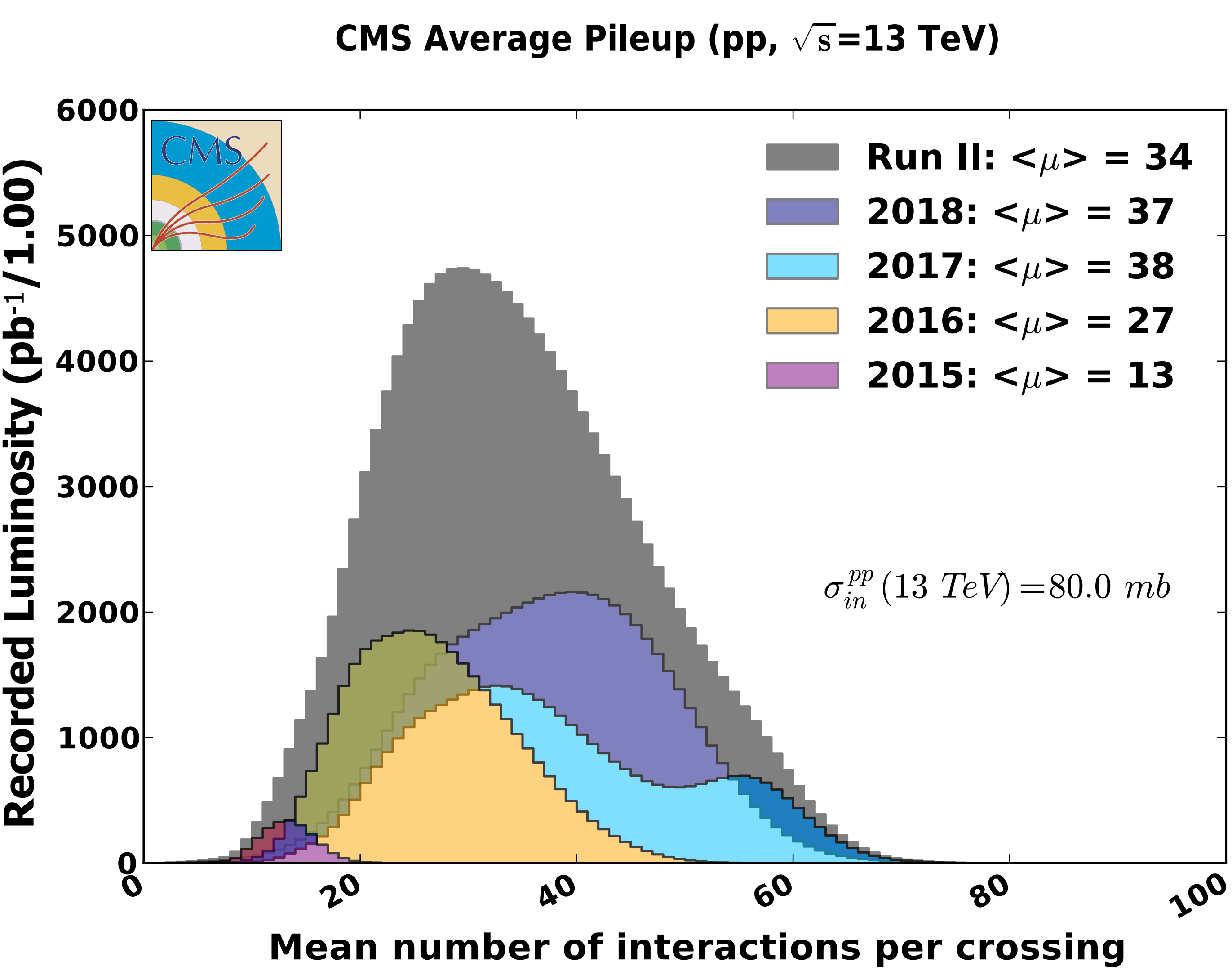
Status of Exotic Searches in CMS

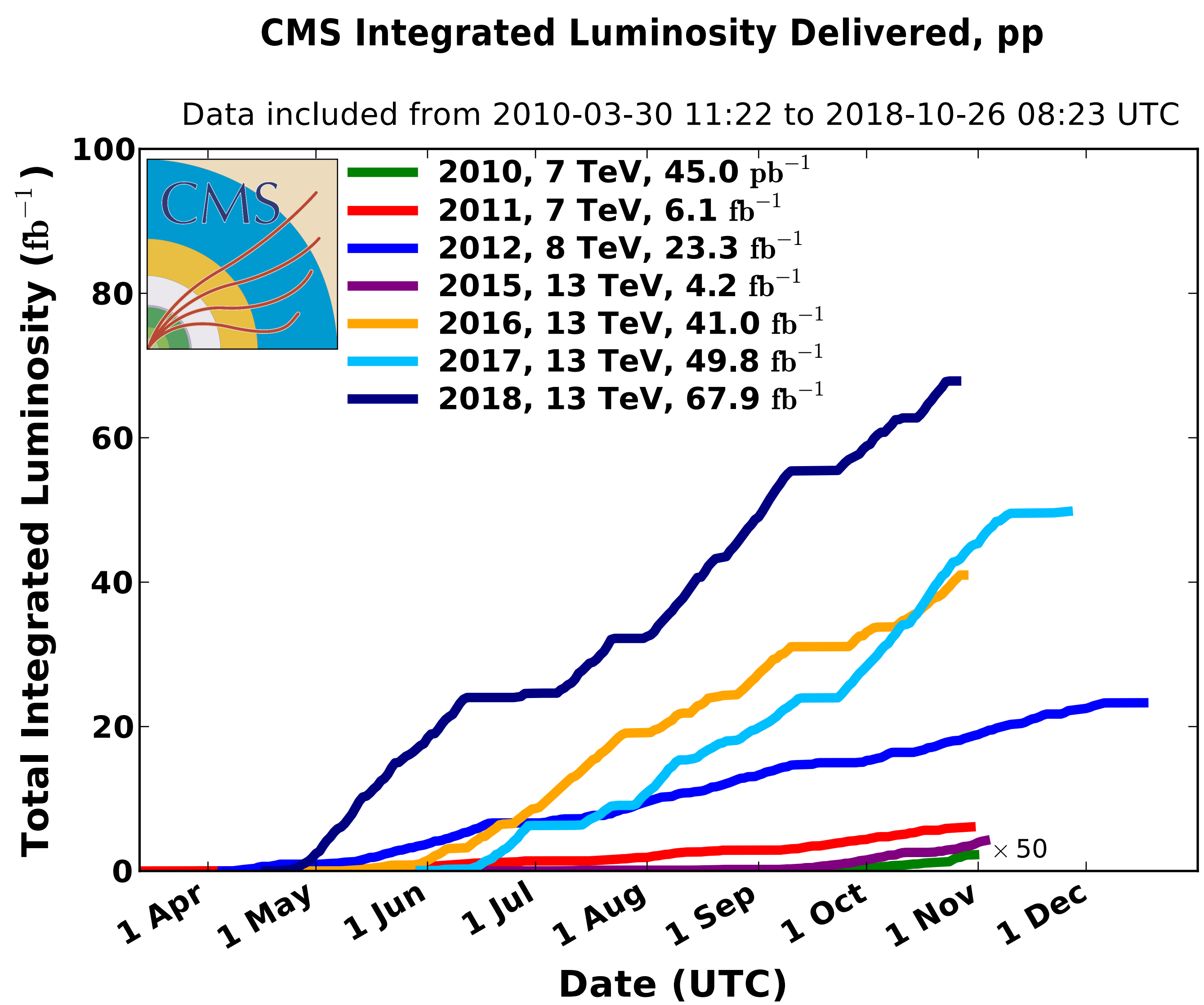
Overview of CMS EXO results



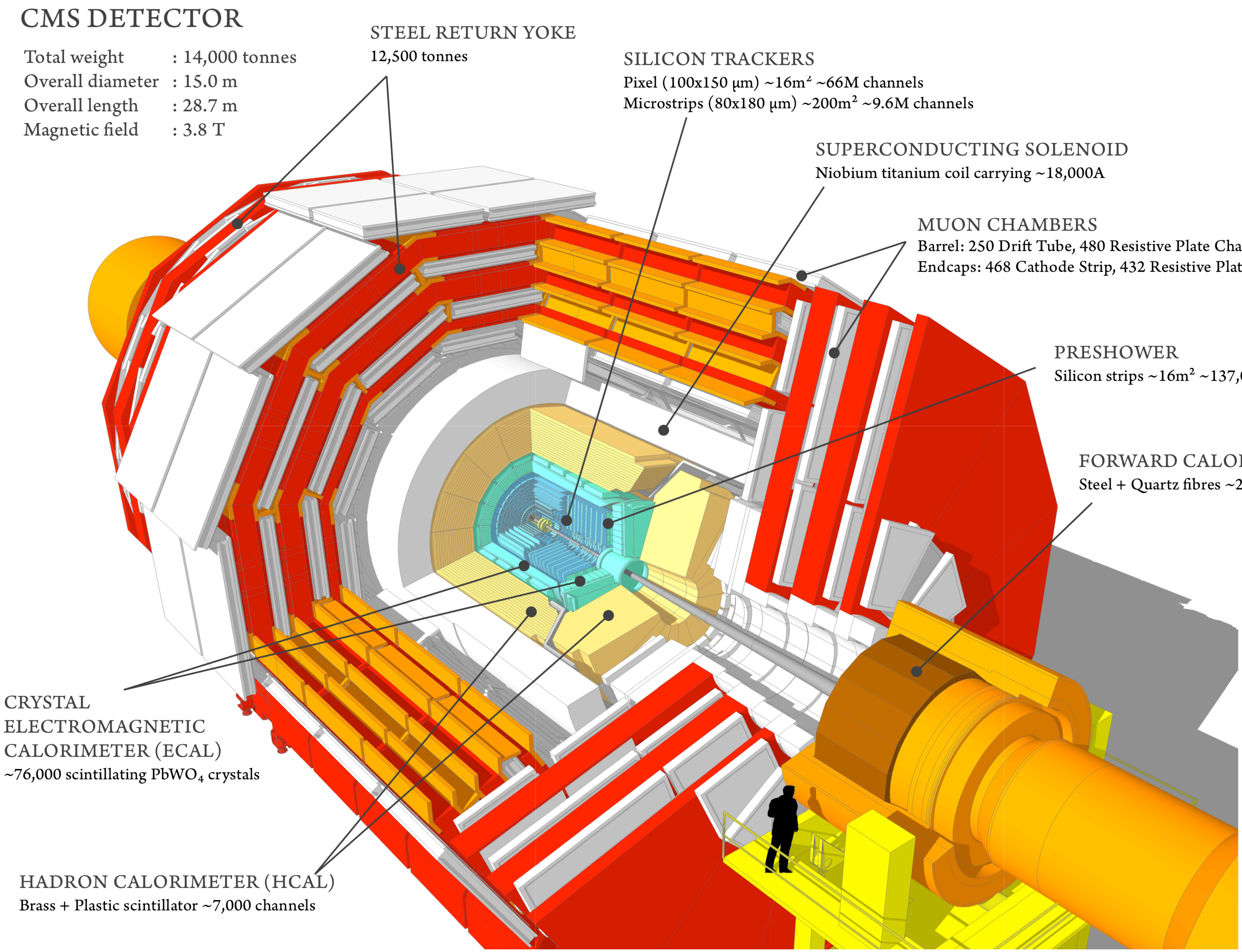
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

Luminosity and Pileup in LHC Run-2



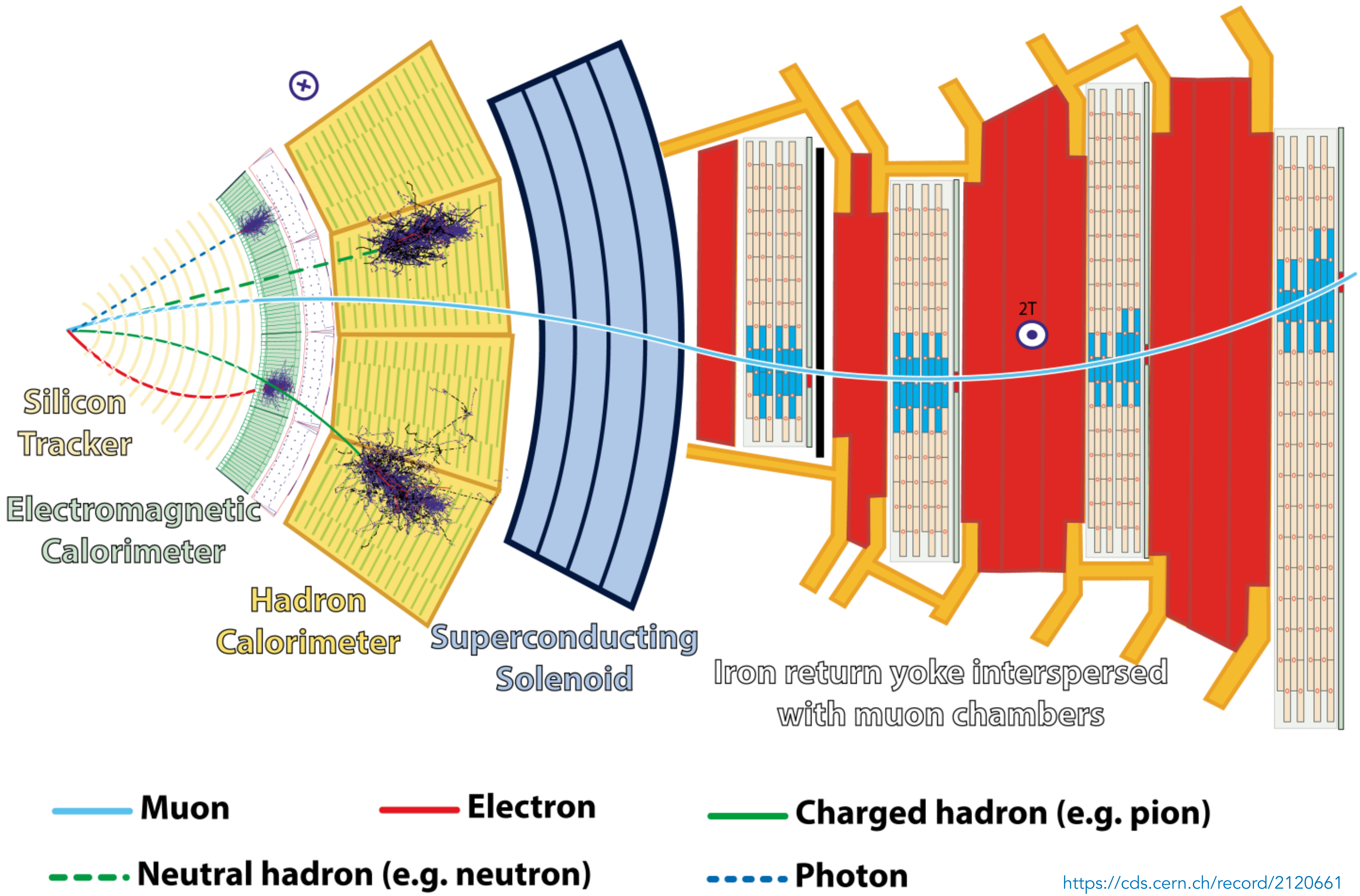


The CMS Detector



Electron (muon) reconstruction efficiency ≳90-95%
Tau reconstruction efficiency ~70%
Muon/electron/tau p_T resolution 1-3/3-5/<5% (for p_T <100 GeV)

Particle Signatures in CMS



https://cds.cern.ch/record/2120661

Hadronic Taus in CMS

Decay mode	Meson resonance	$\mathcal{B}$ [%]
$\tau^- \to e^- \overline{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$		17.4
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other modes with hadrons		3.2
All modes containing hadrons		64.8