Search for Heavy Neutral Leptons in events with three charged leptons in pp collision at $\sqrt{s}$ = 13 TeV at CMS detector

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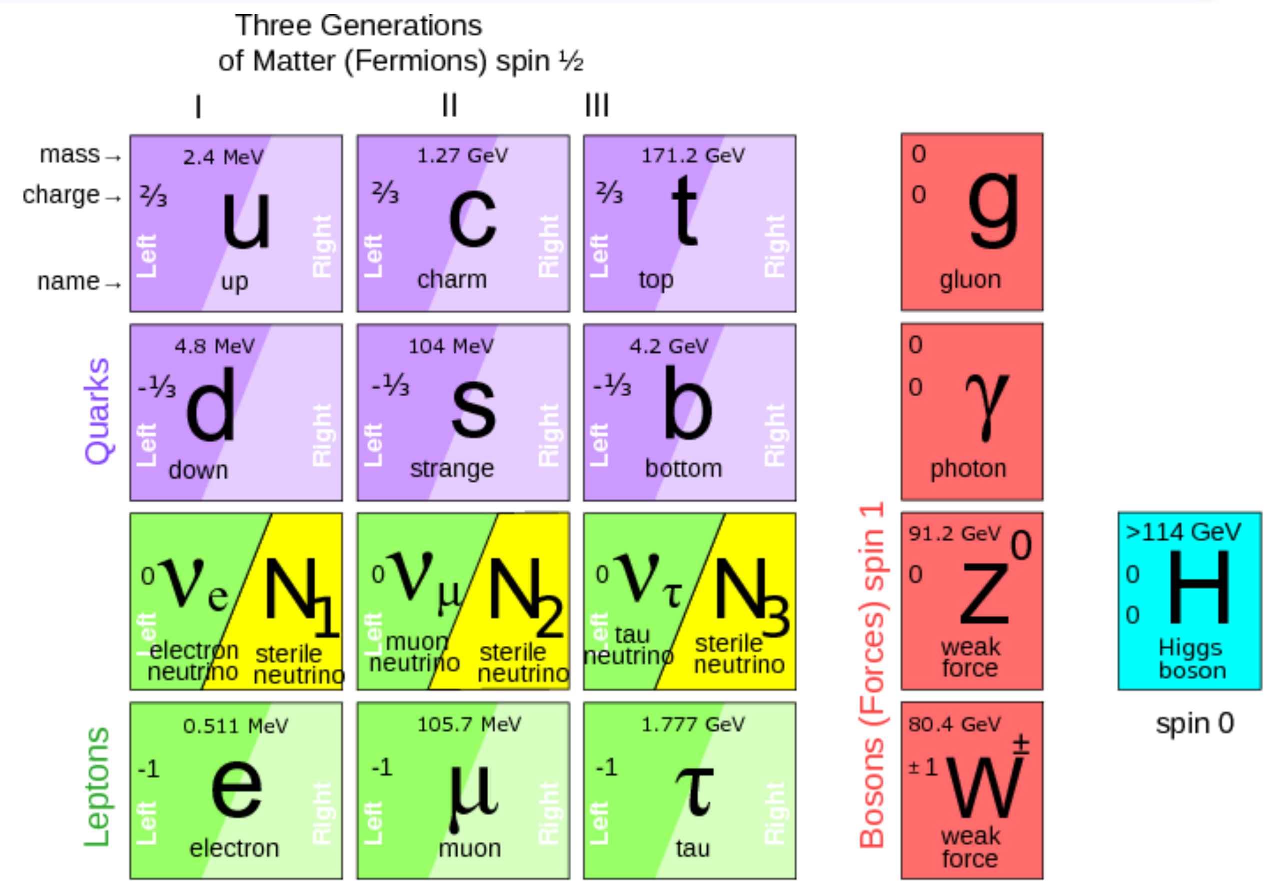
Heavy neutral leptons (HNL)

Right-handed **HNL** as potential solution for some of the outstanding problems of the SM.

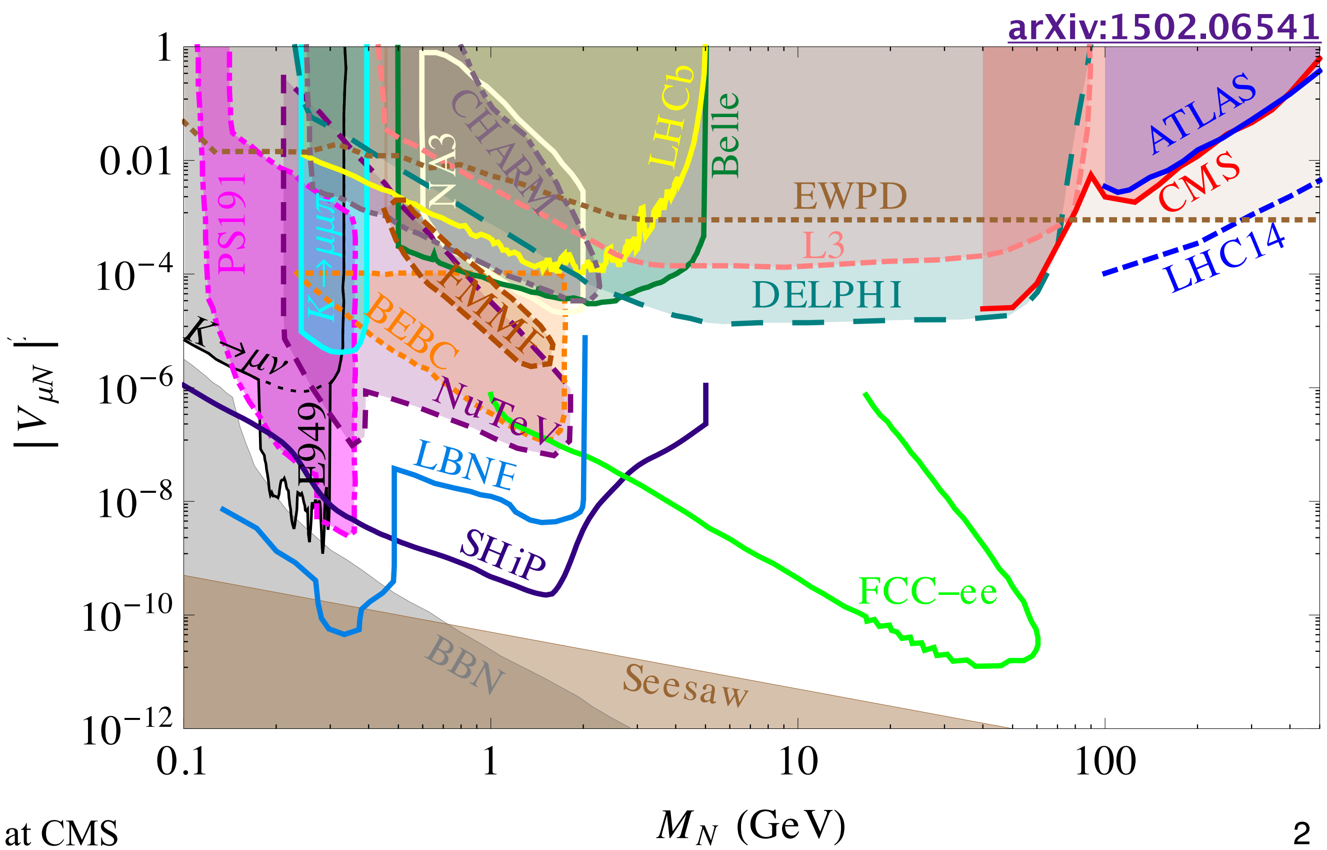
- Origin of the **SM neutrino masses (seesaw mechanism)**;
- **dark matter candidate**;
- **matter-antimatter asymmetry.**

arXiv:hep-ph/0503065



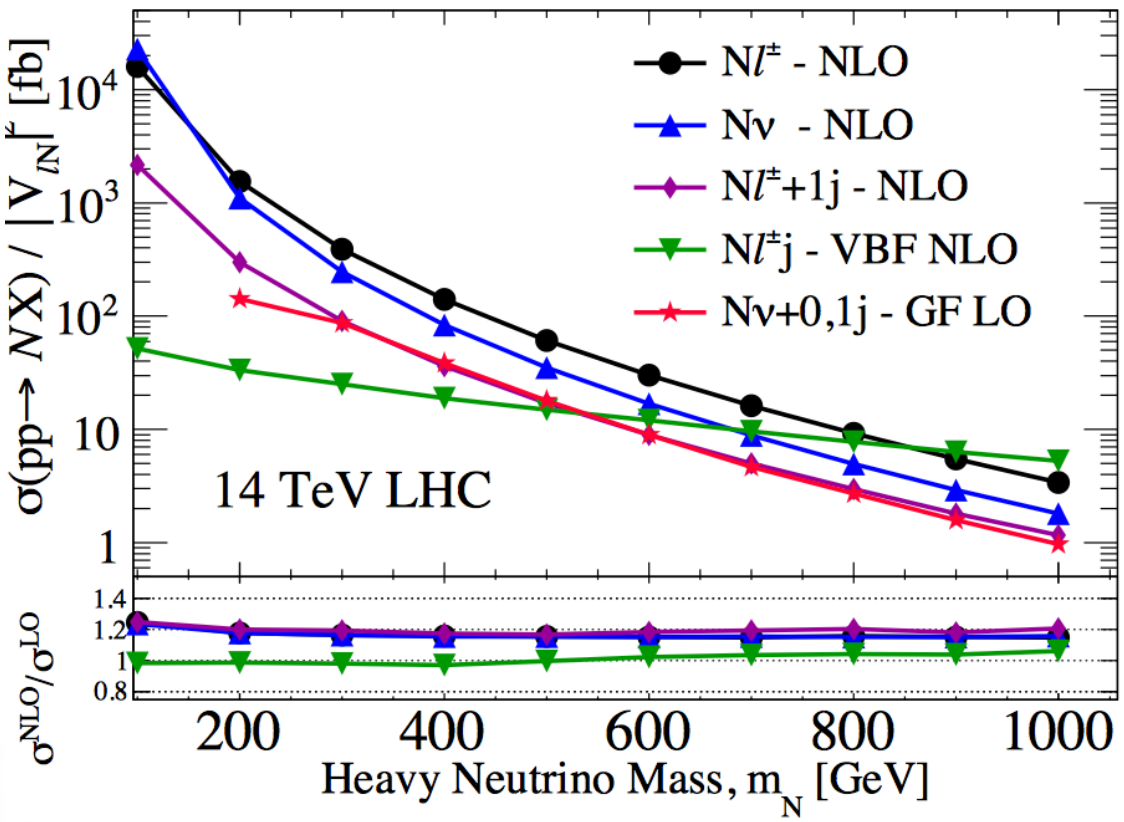
- N are sterile:
  - only interact with ν_{SM} through mixing: $\nu_{SM} \longrightarrow N$
- very low rate of $\nu \to N$: due to small mixing parameter $|V_{\ell N}|^2$ between ν_ℓ and N

Direct searches provide existing constraints and future projections on the mass and couplings with ν_{SM}
(filled areas - excluded; contours - projected experiments)

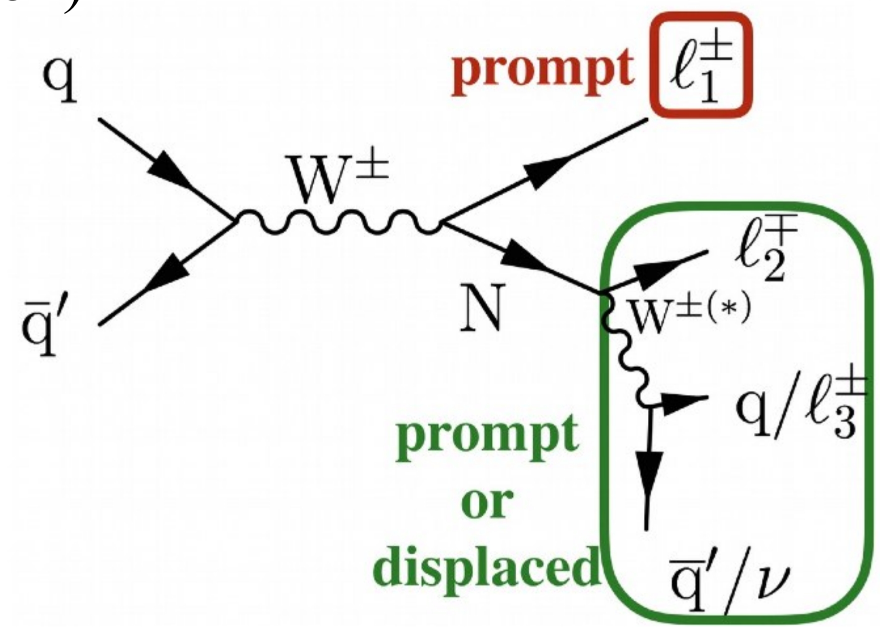


HNL production at LHC

- production of ν: $W \to \ell\nu$, $Z \to \nu\nu$, $b \to c\ell\nu$.
  - for high N masses VBF channel (Wγ fusion) becomes important
- decays: $N \to W\ell$ or $N \to Z\nu$ or $N \to H\nu$
- Final states with multiple charged-leptons ($N\ell^{\pm}$) are experimentally more accessible
  - charged DY current
  - VBF (Wγ fusion)



arXiv:1602.06957



- the smaller N mass or N-ν mixing – the longer N lives: $\tau \propto \sum_i |V_{iN}|^{-2} m_N^{-5}$

⇨ from very small (prompt decays) to macroscopic distances from production vertex (displaced decays) at very low mass and couplings.

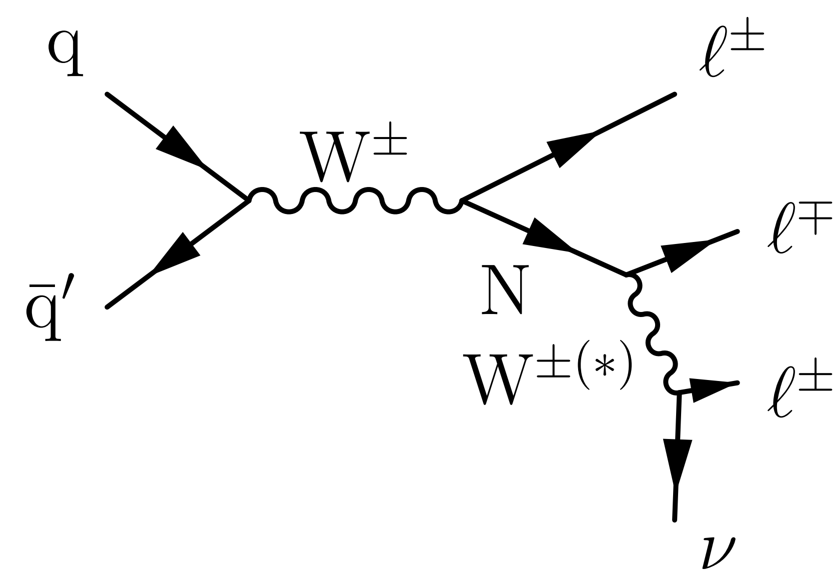
Search for HNL in 3 leptons final states

arXiv:1802.02965

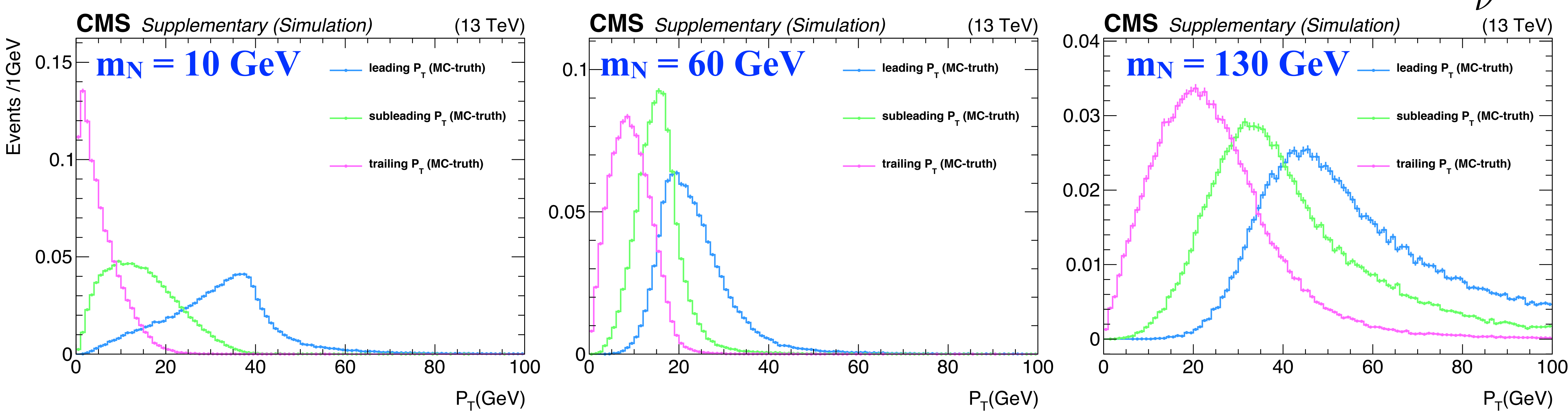
3Leptons final state

The data were collected in proton-proton collisions at a center-of-mass energy of 13 TeV, with an integrated luminosity of 35.9 fb^{-1} during 2016 Run.

- **considering the W —> ℓN —> 3$\ell\nu$ production mode (ℓ = e, μ);**
- sensitive to both **LeptonNumberViolation** and **LeptonNumberConserving** N decays;
- leptons from HNL decay assumed to be **prompt**;
- no clear N mass peak due to escaping of the ν;
- can detect decay products of very **light N** (lepton $P_T > 5$ GeV);
- moderate E_T^{miss}, very small hadronic activity;
- lepton $\boldsymbol{P_T}$ **spectra are compressed** for low masses ($m_N < m_W$).

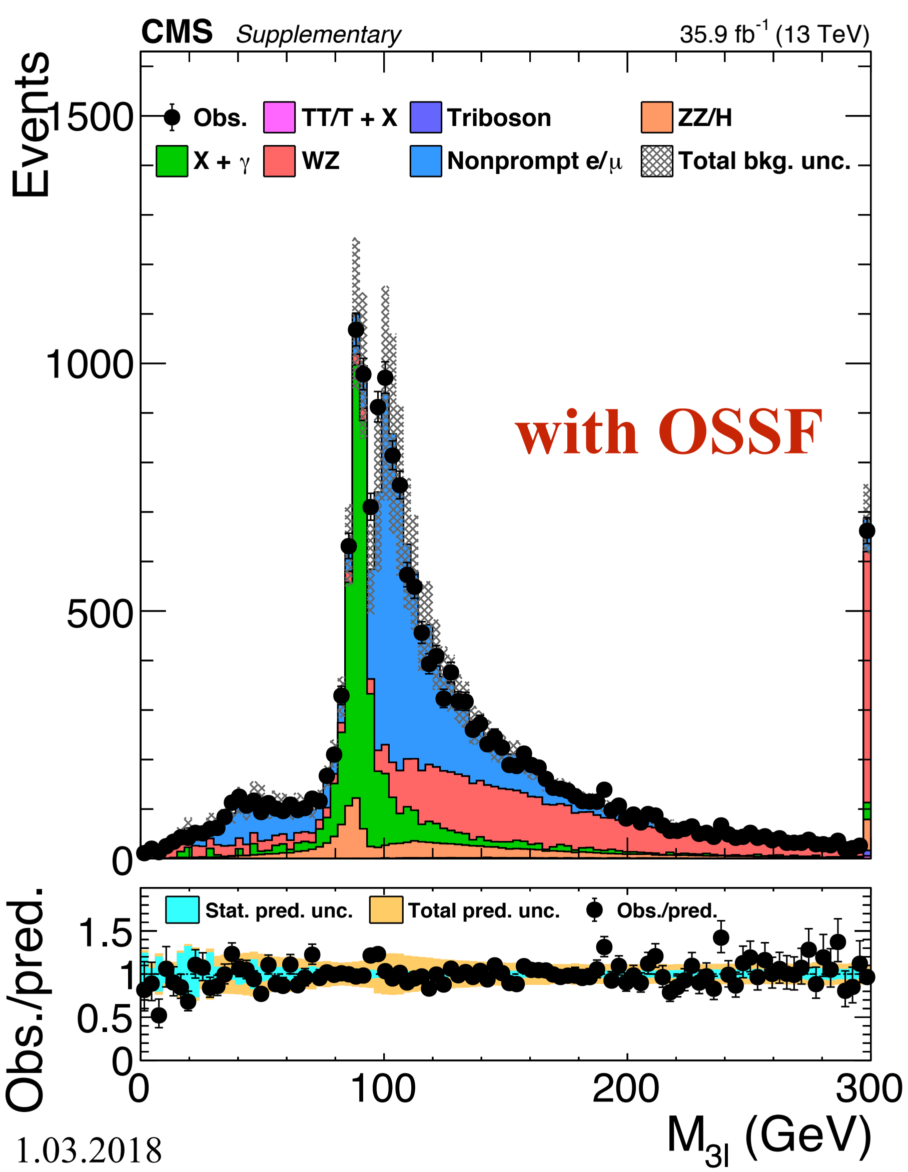


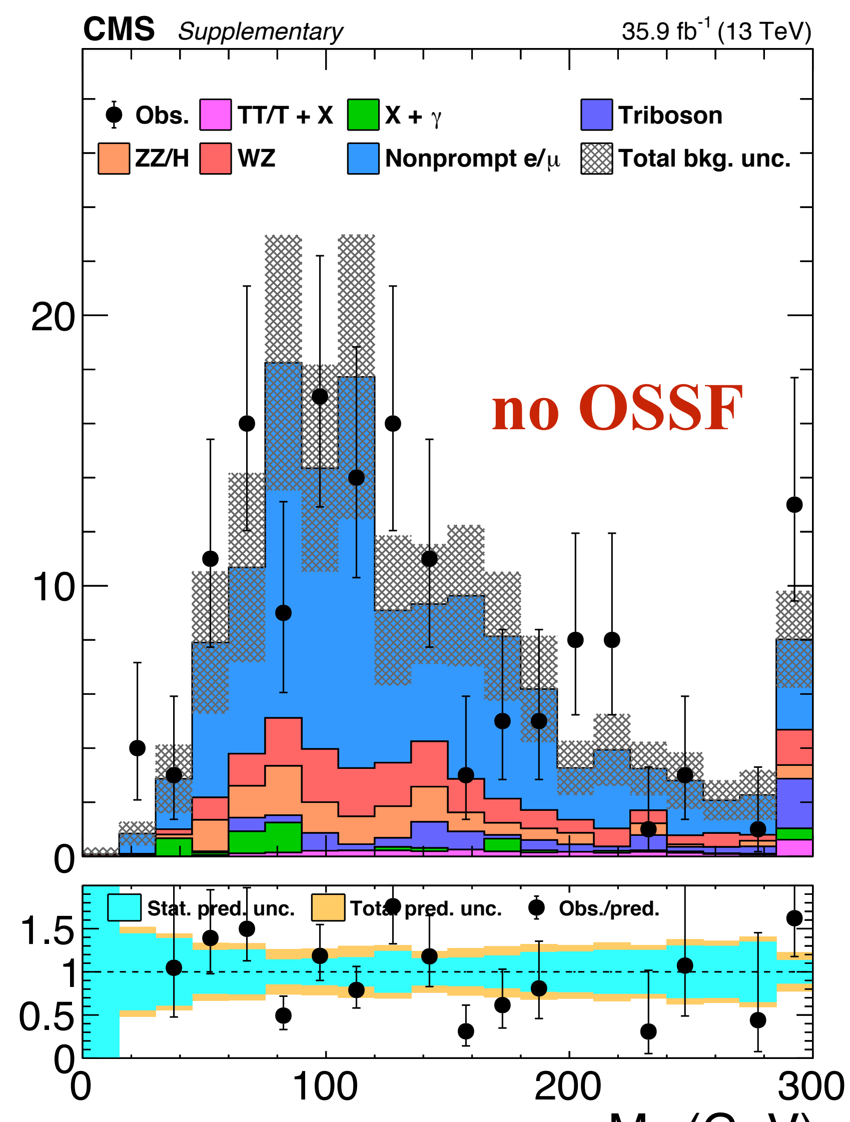
arXiv:hep-ph/0503065



Backgrounds

- **non-prompt ℓ**
  - reducible background
  - mainly $t\bar{t} \rightarrow 2\ell$ and/or DY$\rightarrow 2\ell$ with a 3rd ℓ from jet fragmentation
- **rare processes**:
  - tribosons, ttX
- **WZ —> $3\ell\nu$, ZZ —> 4ℓ**:
  - three signal-like leptons
  - almost always opposite-sign same flavor (OSSF) pair from Z —> 2ℓ
- **conversions:**
  - dominated by Zγ* with γ* —> 2ℓ
  - almost always with an OSSF pair



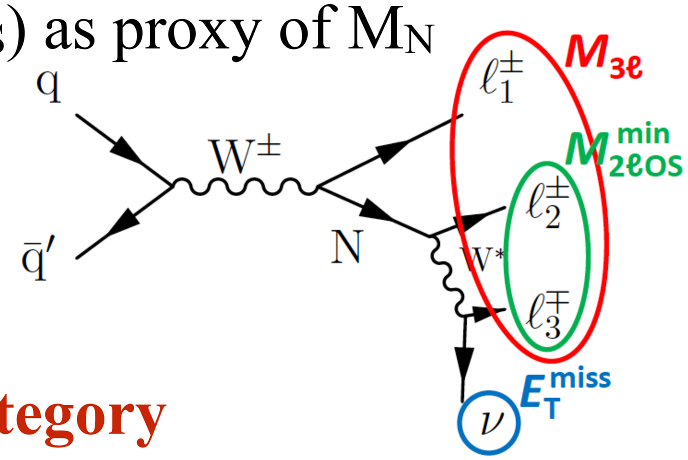


Two categories: with or without an OppositeSignSameFlavor pair. There is a difference of two orders of magnitude higher in final state with an OSSF lepton pair mainly due to:
- DY+jets
- Zγ* and WZ processes.

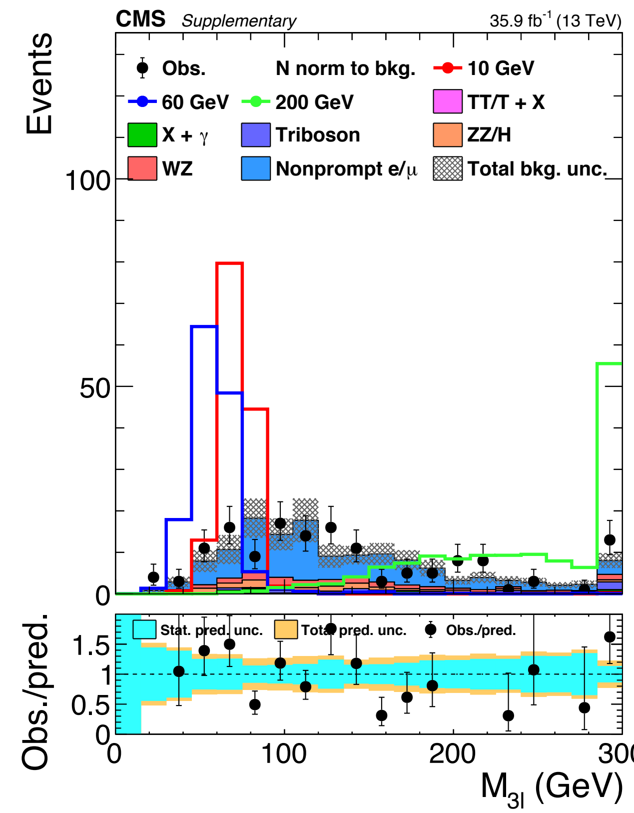
Search variables and strategy

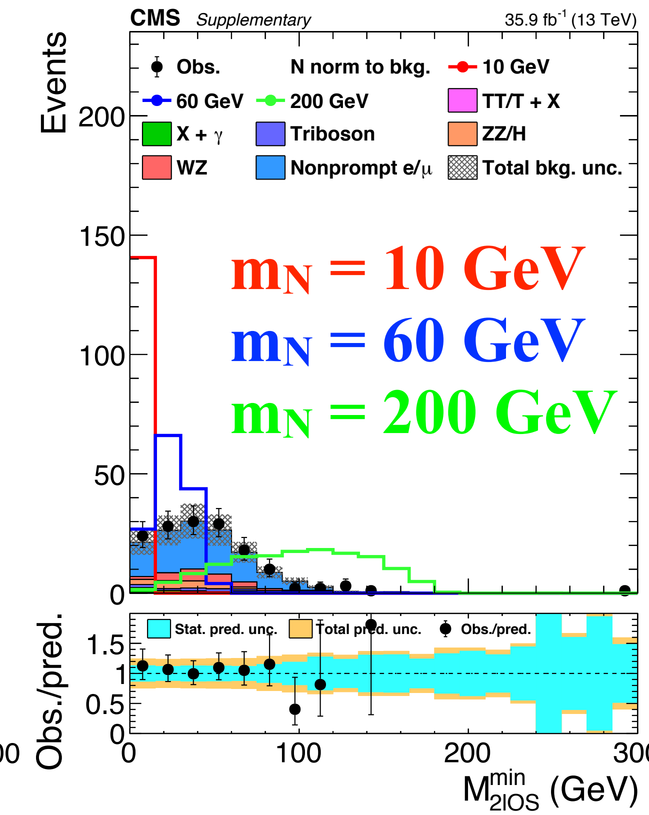
Low mass $m_N < m_W$

- ☑ categorize according to $P_{T(\text{leading})}$ < 30; $30 - 55\ GeV$
- ☑ $M_{3\ell} < m_W$, $E_T^{miss} < 75\ GeV$
- ☑ binning in $\min(M_{2lOS})$ as proxy of M_N
- ☑ bjet veto



only without OSSF category

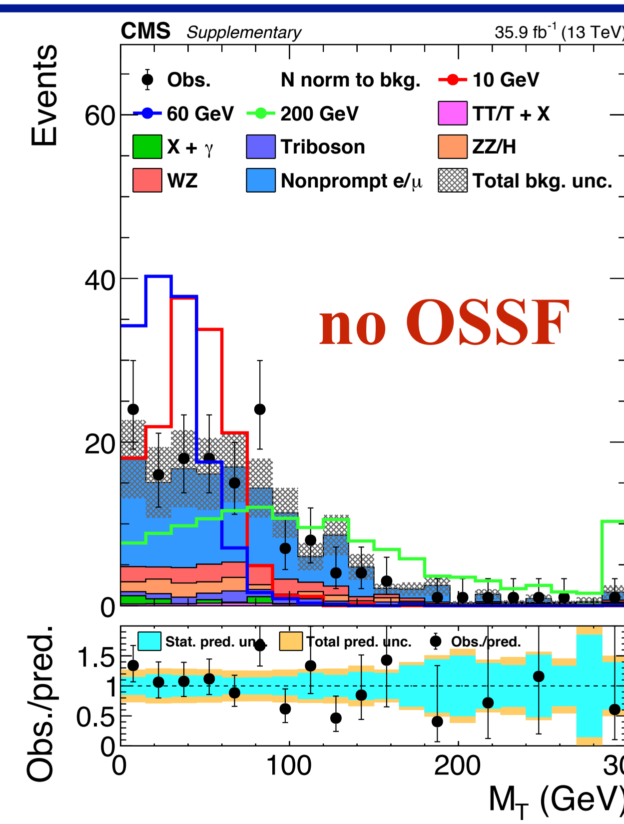


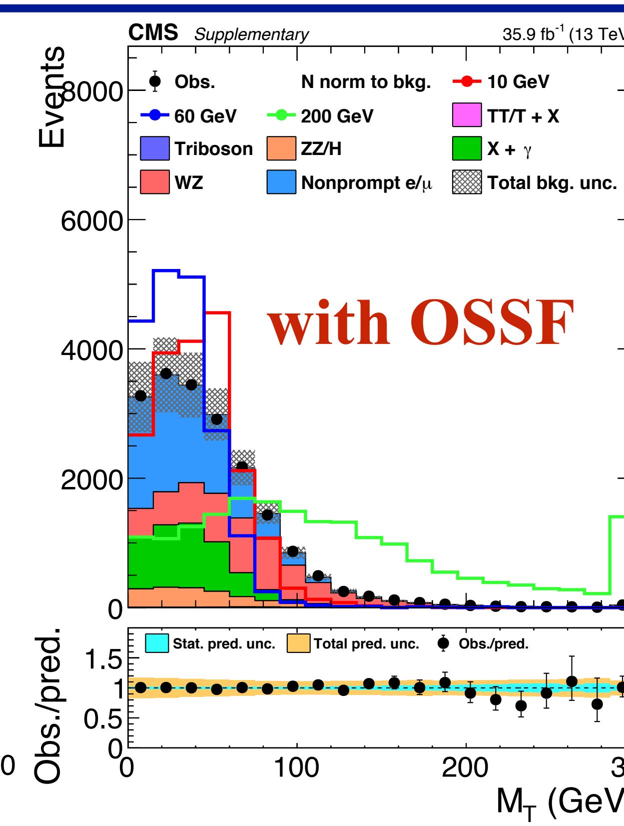


High mass $m_N > m_W$

- relatively soft trailing lepton, very hard leading lepton
- relatively high E_T^{miss} very high $M_{3\ell}$
- ☑ $P_T > 55, 15, 10\ GeV$
- ☑ bjet veto
- ☑ In OSSF category veto m_Z window in $M_{3\ell}$ and $M_{\ell\ell}$
- ☑ binning in $\min(M_{2lOS})$ and M_T(third)

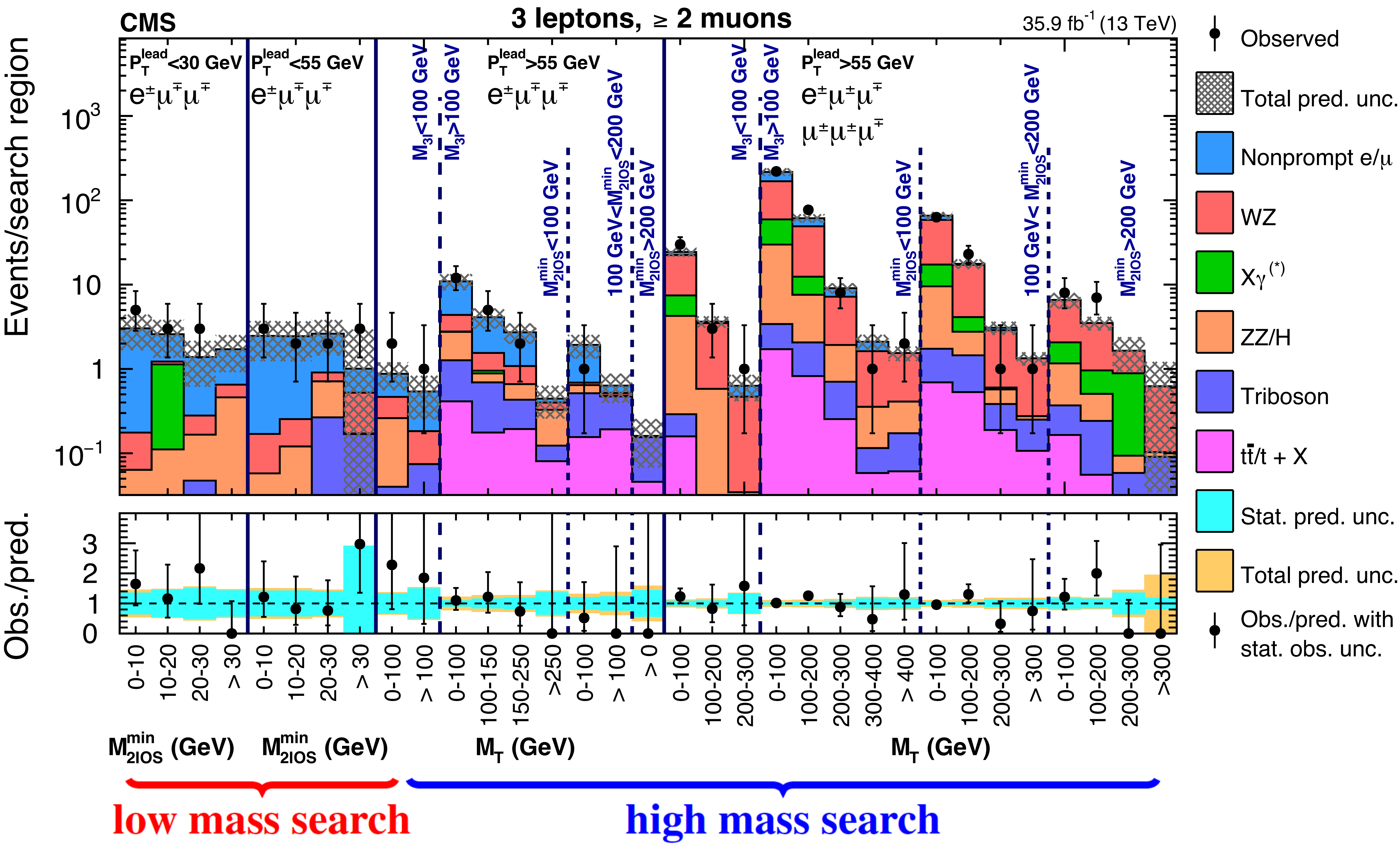
with and without OSSF categories





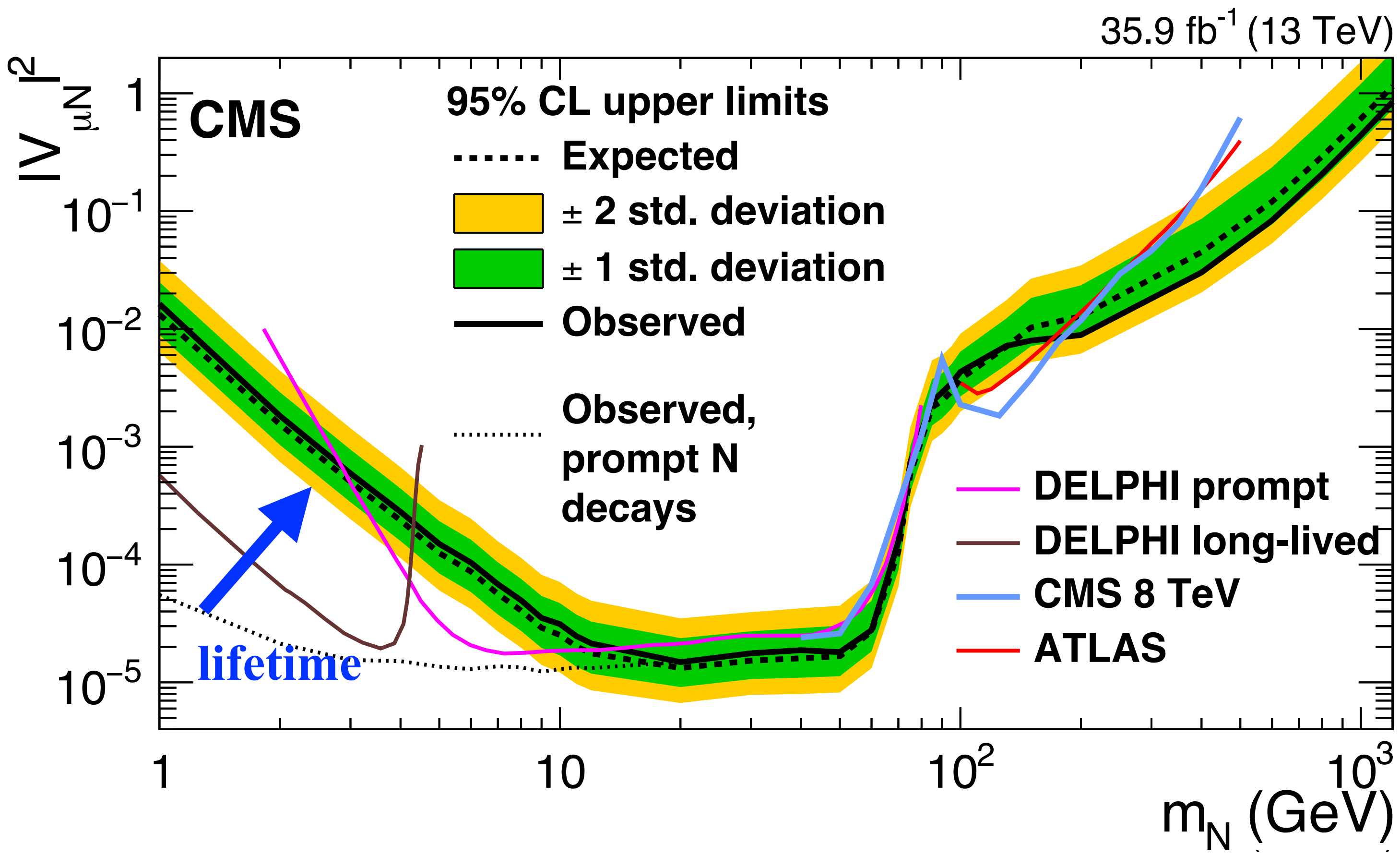
Results

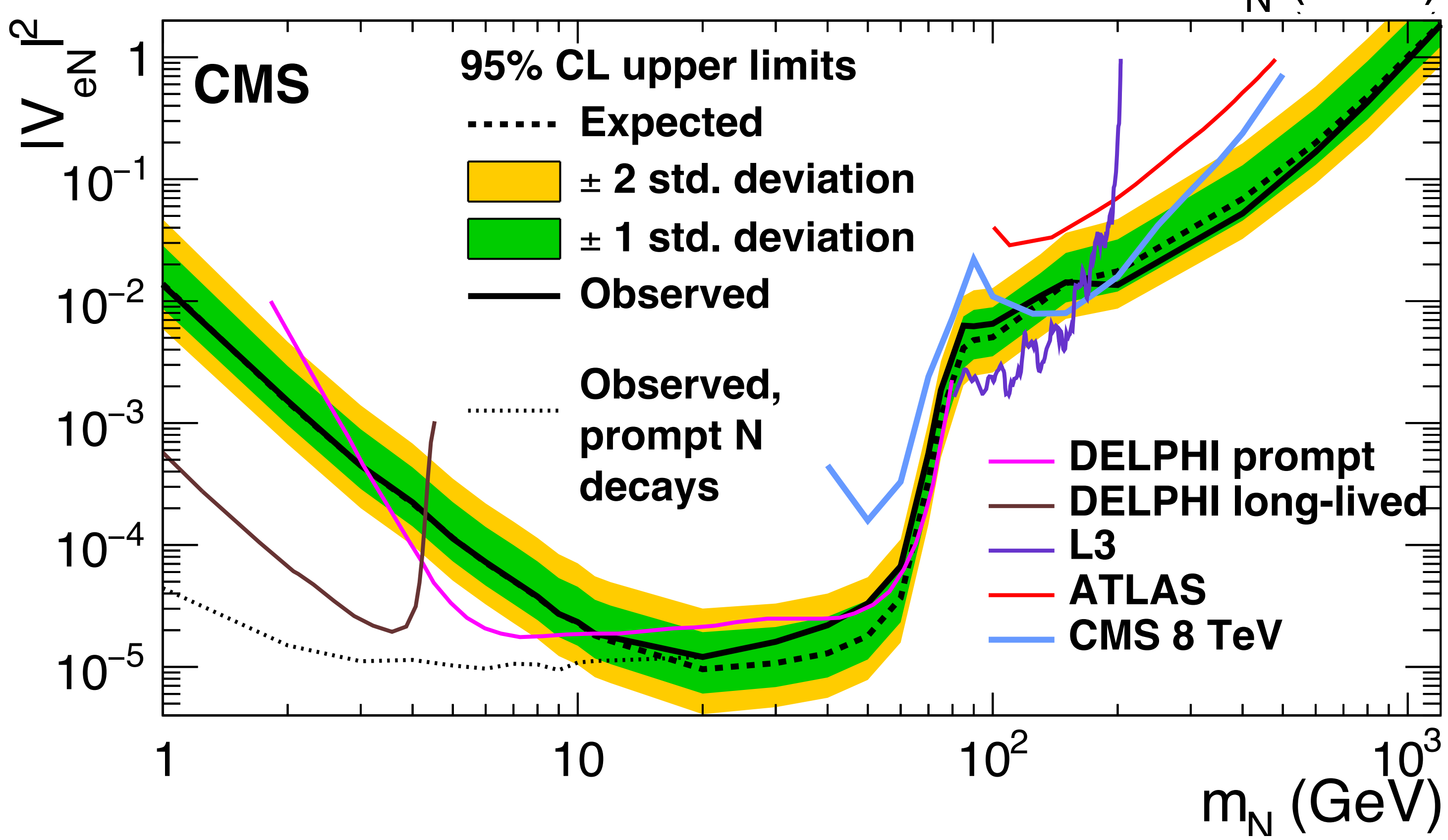
Search regions



No deviations from the SM are observed

Final results





No deviations from the SM are observed; upper limits set on $\nu_{SM}N$ coupling strengths V_{eN} and $V_{\mu N}$

New sensitivity

These are the **first direct limits** for N masses **above 500 GeV** and the first limits obtained at a hadron collider for **N masses below 40 GeV**

Lifetime correction

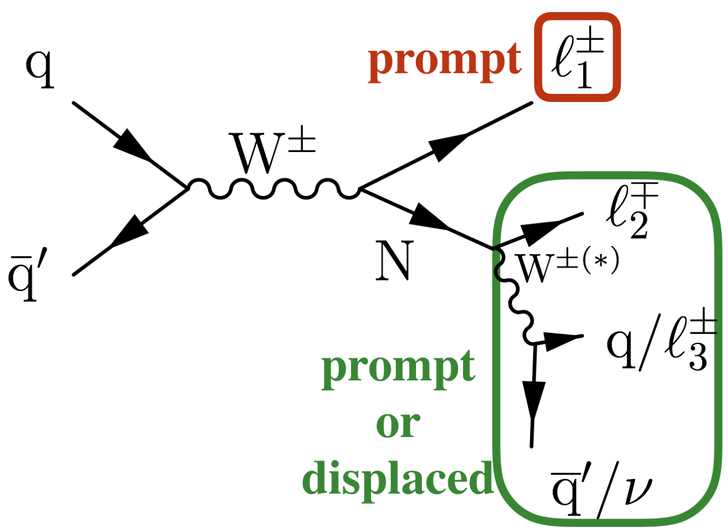
- For **small N** mass and couplings, the **decay length can be significantly large**;
  —> reduced acceptance for this specific search
- a-posteriori correction applied to account for the finite lifetime
  —> degraded sensitivity to $|V_{\ell N}|^2$
- effect is partially compensated by signal cross section growth $\propto |V_{\ell N}|^2$

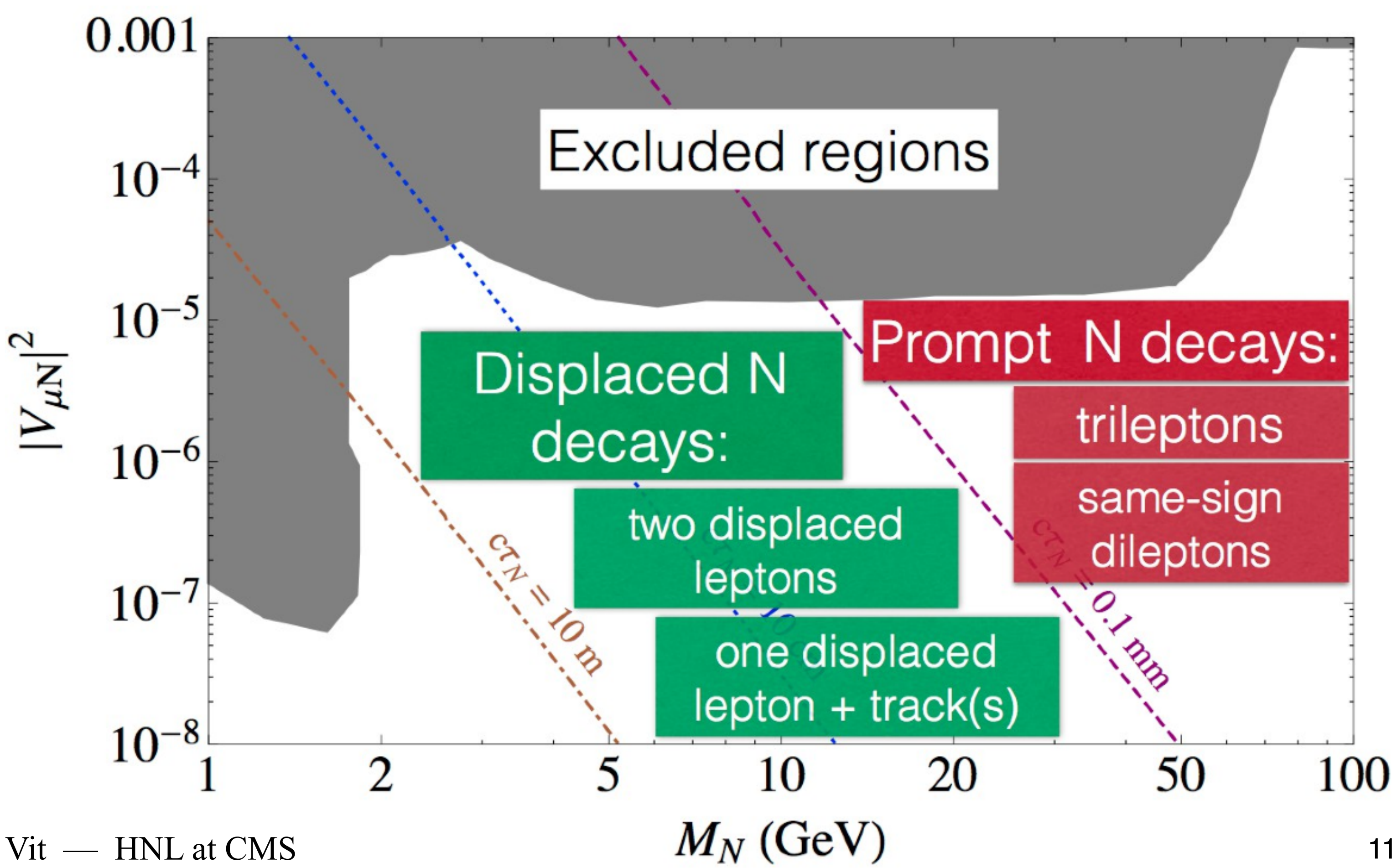
arXiv:1802.02965

Conclusions

The unprecedented amount of data collected at the LHC, and to the capabilities of CMS to detect leptons in a very wide energy range, allowed us to **extend the direct search for HNLs to regions so far unexplored**.

To increase our sensitivity to lower HNL masses and couplings, signatures with **displaced vertices** will have to be considered





to be continued…

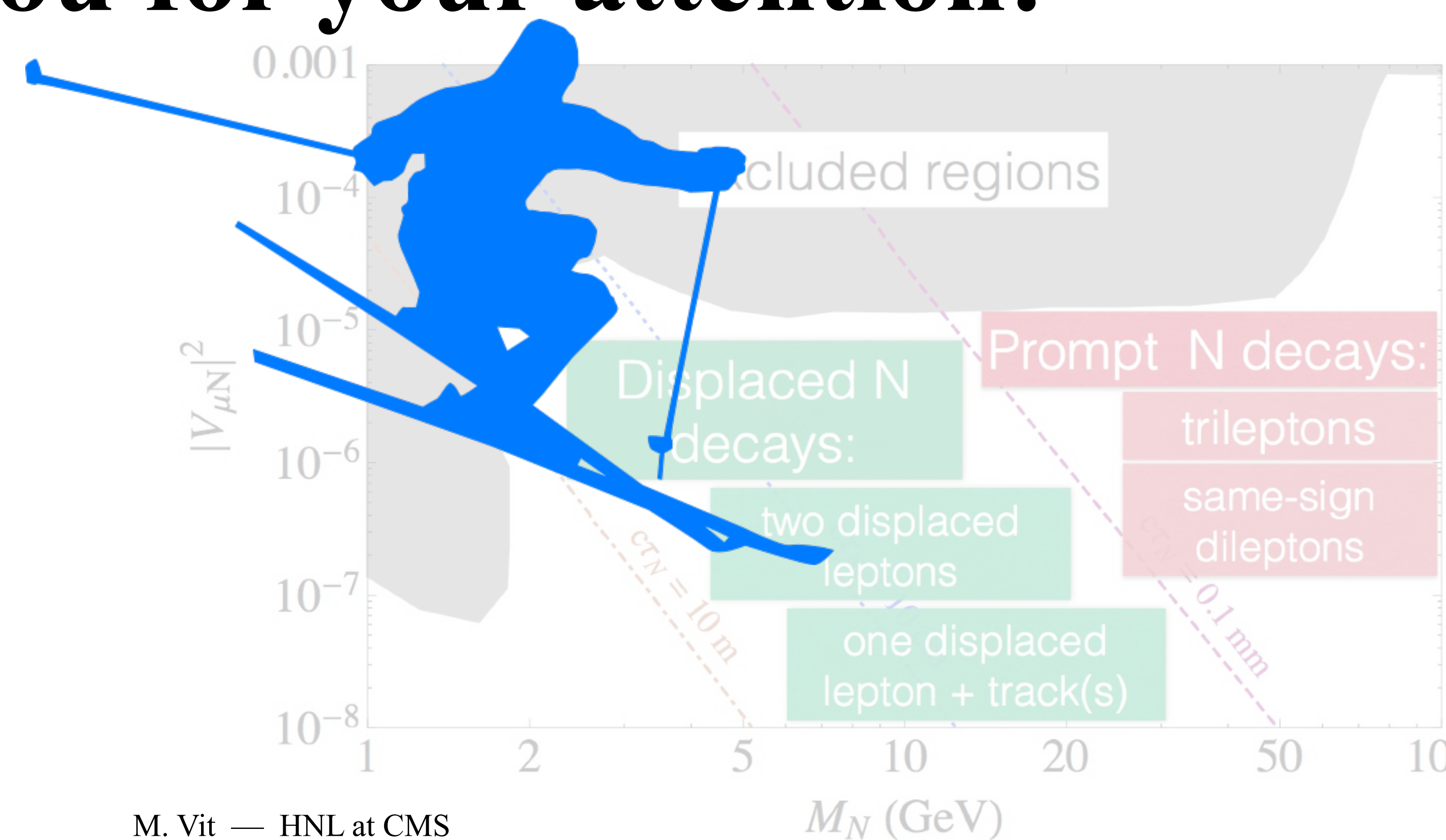
Conclusions

The unprecedented amount of data collected at the LHC, and to the capabilities of CMS to detect leptons in a very wide energy range, allowed us to **extend the direct search for HNLs to regions so far unexplored**.

To increase our sensitivity to lower HNL masses and couplings, signatures with **displaced vertices** will have to be considered

Thank you for your attention!

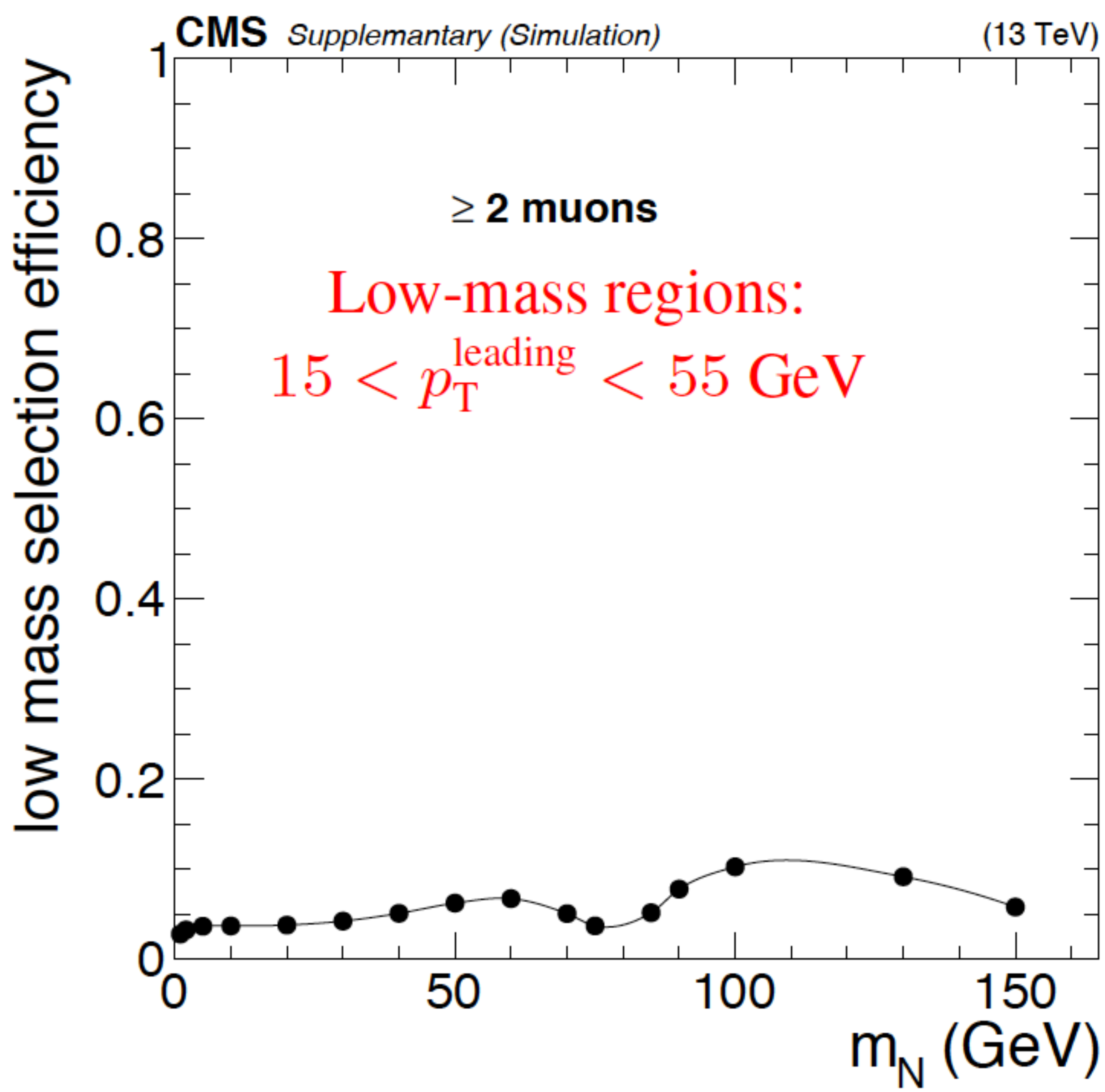
to be continued…

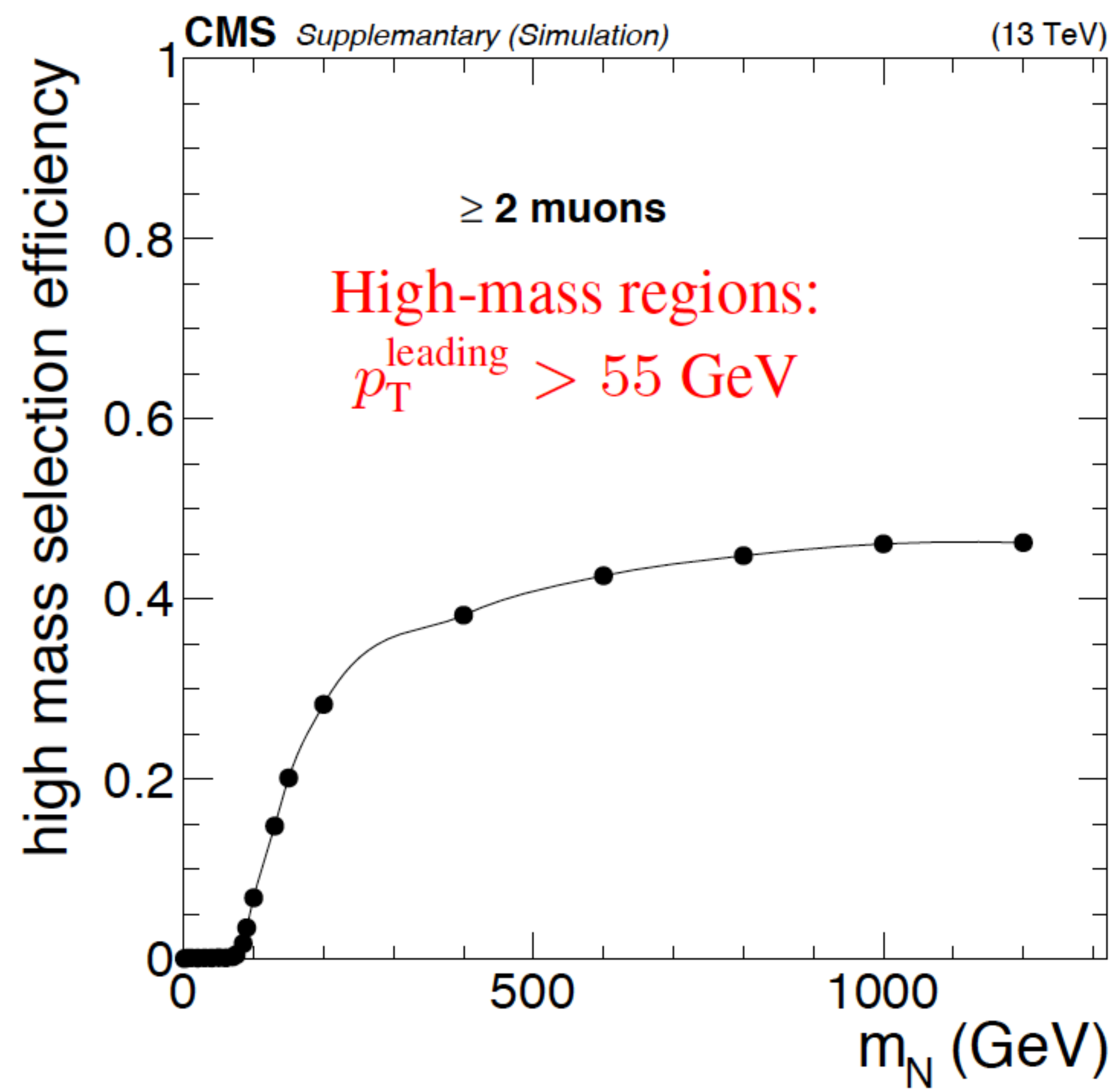


Backup

Signal efficiency

Low signal efficiencies because of the selection on lepton p_T and isolation.

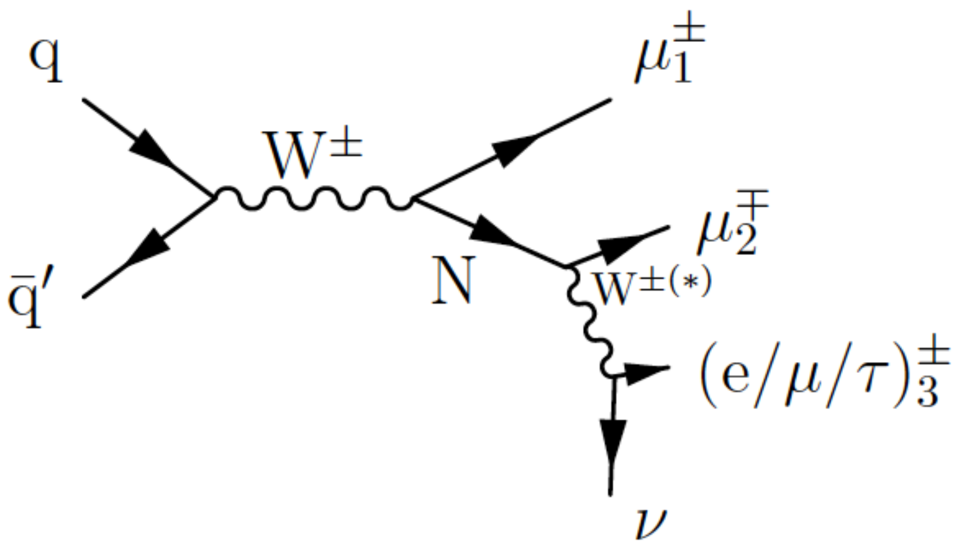




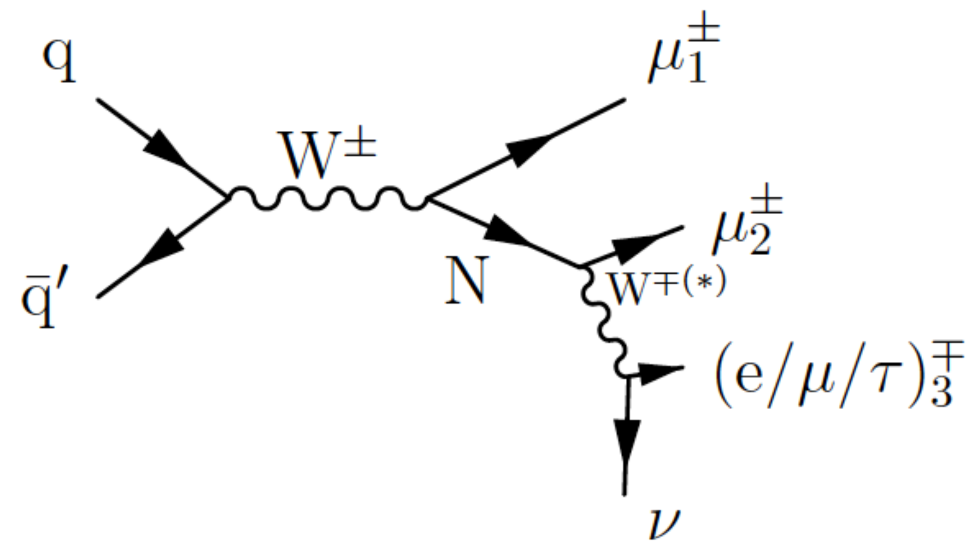
3l final states with one coupling

e.g. $V_{\mu \mathrm{N}} \neq 0$

LNC decay



LNV decay



$\mu^+\mu^-e^+$: OSSF pair
$\mu^+\mu^-\mu^+$: OSSF pair
$\mu^+\mu^-\tau^+$: no 3 light leptons

$\mu^+\mu^+e^-$: **no OSSF pair**
$\mu^+\mu^+\mu^-$: OSSF pair
$\mu^+\mu^+\tau^-$: no 3 light leptons

1/6 of all fully leptonic decays lead to a final state with 3 e/μ w/o an opposite-sign same-flavor pair*

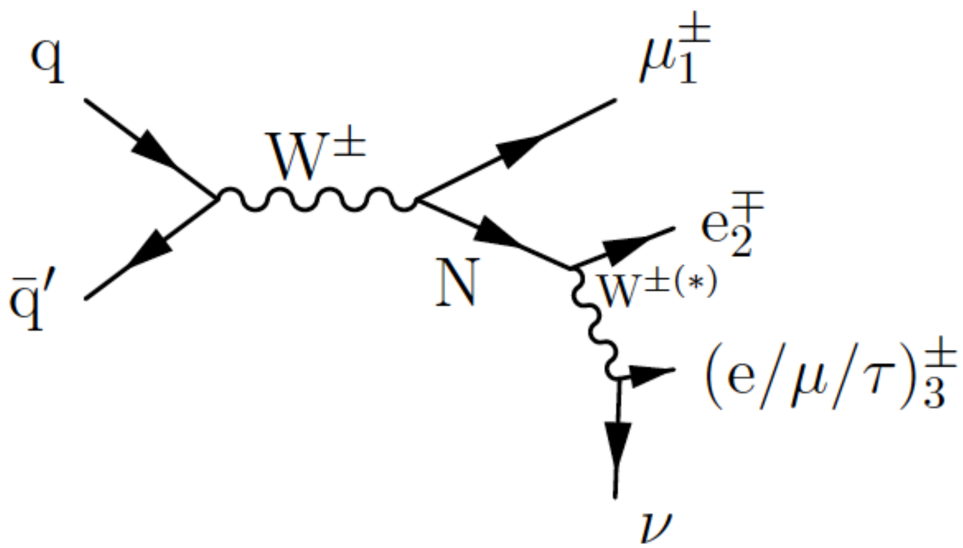
* *if N is a Majorana particle (and LNV decays are open)!*

3l final states with two couplings

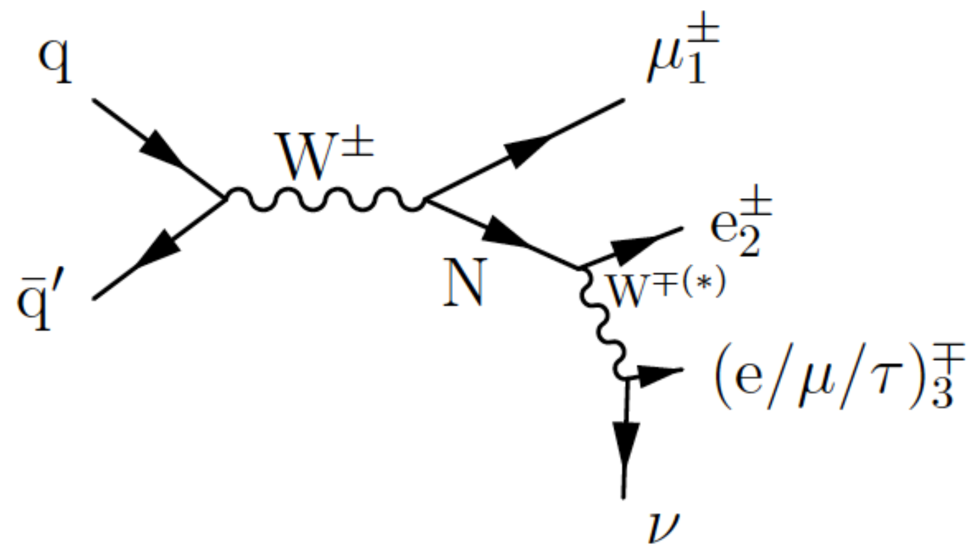
e.g. $V_{eN} \neq 0$
and $V_{\mu N} \neq 0$

Get **in addition** (+ the decays W→eN):

LNC decay



LNV decay



$\mu^+ e^- e^+$: OSSF pair
$\mu^+ e^- \mu^+$: **no OSSF pair**
$\mu^+ e^- \tau^+$: no 3 light leptons

$\mu^+ e^+ e^-$: OSSF pair
$\mu^+ e^+ \mu^-$: OSSF pair
$\mu^+ e^+ \tau^-$: no 3 light leptons

1/6 of all fully leptonic decays lead to a final state with 3 e/μ w/o an opposite-sign same-flavor pair*

* *for both Majorana (LNV+LNC decays) and Dirac (LNC decay) N!*

Flavor combinatorics

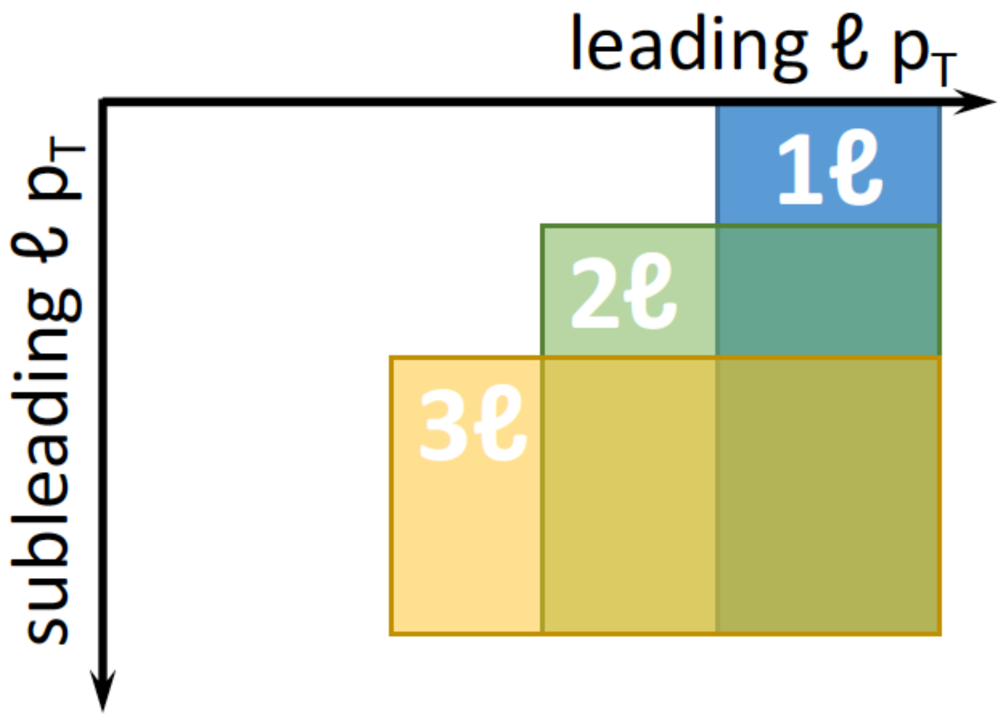
- split all events by the presence of an OSSF pair of leptons
- profit from the reduced background in searches

ME	OSSF		noOSSF		OSSF	
	eee	$e^{\pm}e^{\mp}\mu$	$e^{\pm}e^{\pm}\mu$	$\mu^{\pm}\mu^{\pm}e$	$\mu^{\pm}\mu^{\mp}e$	$\mu\mu\mu$
$\lvert V_{eN}\rvert^2$	×	×	×			
$\lvert V_{\mu N}\rvert^2$				×	×	×
$\lvert V_{eN}V_{\mu N}\rvert$		×	×	×	×	
bkg level	high		low		high	

- in noOSSF channel probe $|V|^2 = |V_{eN}|^2 + |V_{\mu N}|^2 + 2|V_{eN}V_{\mu N}|$
- provide limits on each $|V_{\ell N}|^2$ separately assuming other couplings 0

Trigger strategy

To have access to all kinematic regimes combine several trigger algorithms:



- single lepton: very high leading lepton p_T, any trailing lepton p_T
- dilepton: moderate leading and subleading lepton p_T, any trailing lepton p_T
- trilepton: low leading, subleading, and trailing lepton p_T

Target all three mass scenarios outlined previously!

Use three lepton p_T categories where for a leading lepton:

- **high mass N**, $p_T^{leading} > 55$ GeV: select with 1ℓ, 2ℓ and 3ℓ triggers
- **low mass N**, $30 < p_T^{leading} < 55$ GeV: select with 1ℓ, 2ℓ and 3ℓ triggers
- **low mass N**, $15 < p_T^{leading} < 30$ GeV: select with 2ℓ and 3ℓ triggers

Trailing leptons with $p_T > 5$ GeV for μ and $p_T > 10$ GeV for e.

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Systematics

Total SM background uncertainty is dominated by stat. uncertainty. Following sources of systematic uncertainties are considered:

Source	Estimated uncertainty (%)	Treatment
e/μ selection	2 per lepton	normalization
Trigger efficiency	2–5	normalization
Jet energy scale	0–3	shape
b tag veto	1–5	shape
Pileup	1–5	shape
Integrated luminosity	2.5	normalization
Scale variations	1–15	shape & normalization
PDF variations	0.1–1	shape
Other backgrounds	50	normalization
MC samples statistical precision	1–30	normalization
Nonprompt leptons (normalization)	30	normalization
Nonprompt leptons (W, Z bkg. subtraction)	5–20	shape
Conversions normalization	15	normalization
WZ normalization	8.5	normalization
ZZ normalization	10	normalization
ZZ normalization for $M_T > 75$ GeV	25	normalization
Scale variations for signal processes	1–2	shape

Non-prompt leptons

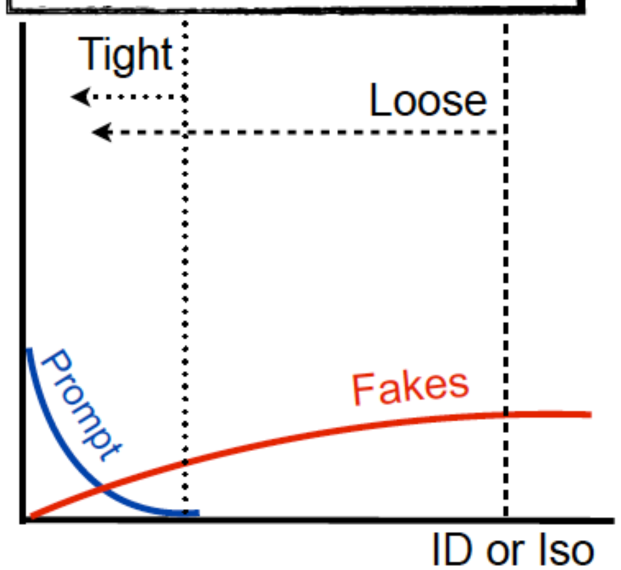
If no OSSF: main background is nonprompt (1) or misidentified (2) leptons:

1. e.g., $t\bar{t} \rightarrow W^{+}(\rightarrow \ell_1^{+}\nu)W^{-}(\rightarrow \ell_2^{-}\nu)b(\rightarrow X\ell_3^{-}\nu)\bar{b}$
2. e.g., DY+jets $\rightarrow \tau^{+}\tau^{-}$+jets $\rightarrow e^{+}\mu^{-}e^{+}_{\mathrm{misID}} + X$

when they accidentally get isolated and pass *tight* selection criteria.

Use events where at least one lepton fails tight criteria to derive yields in SR:

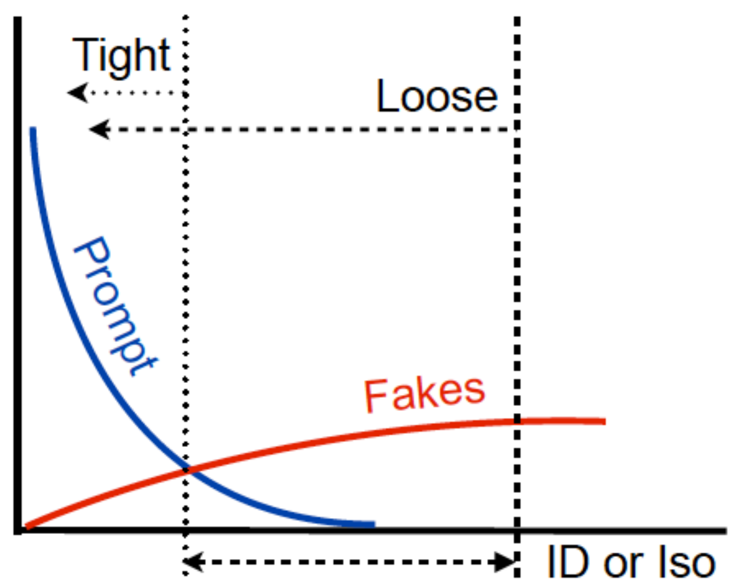
Measurement Region (Fake dominated)



$\leftarrow$ data multijet: measure $f = \frac{\text{tight}}{\text{loose}}$

control region $\rightarrow$ apply $\frac{f}{1-f}$ to (loose – tight)

Signal Region / Application Region



Main challenge: parameterize f to be **universal for any process**

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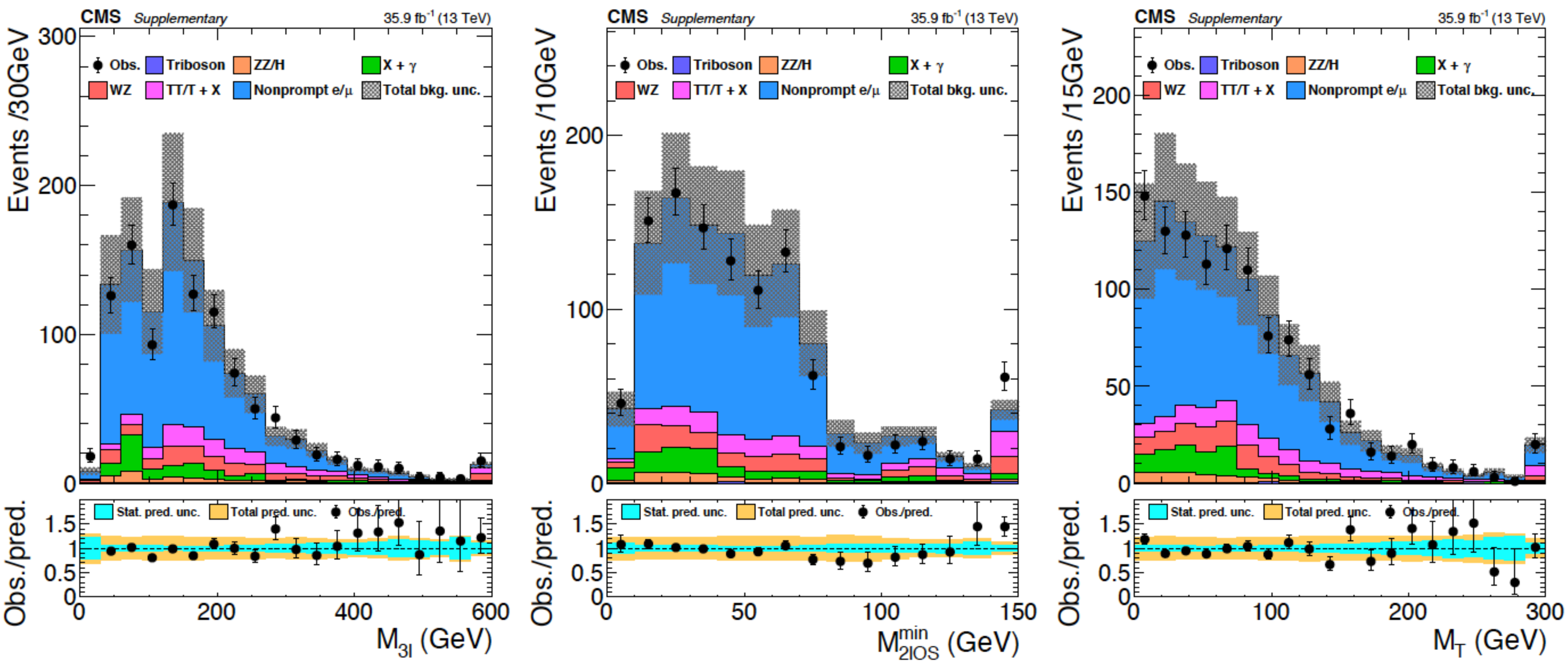
Validation nonprompt in $t\bar{t}$

- enriched with $\mathrm{b} \to \mathrm{X}\ell\nu$
- check f performance
- validate all analysis kinematical variables

- if OSSF pair present;
  - $|M_{\ell\ell} - m_{\mathrm{Z}}| > 15$ GeV (suppress Z)
  - $|M_{3\ell} - m_{\mathrm{Z}}| > 15$ GeV (suppress conversions)
  - $\min M(\mathrm{OSSF}) > 12$ GeV (suppress conversions)
- ≥ 1 b-jet;
- $p_{\mathrm{T}} > 15, 10, 5(10)$ GeV;



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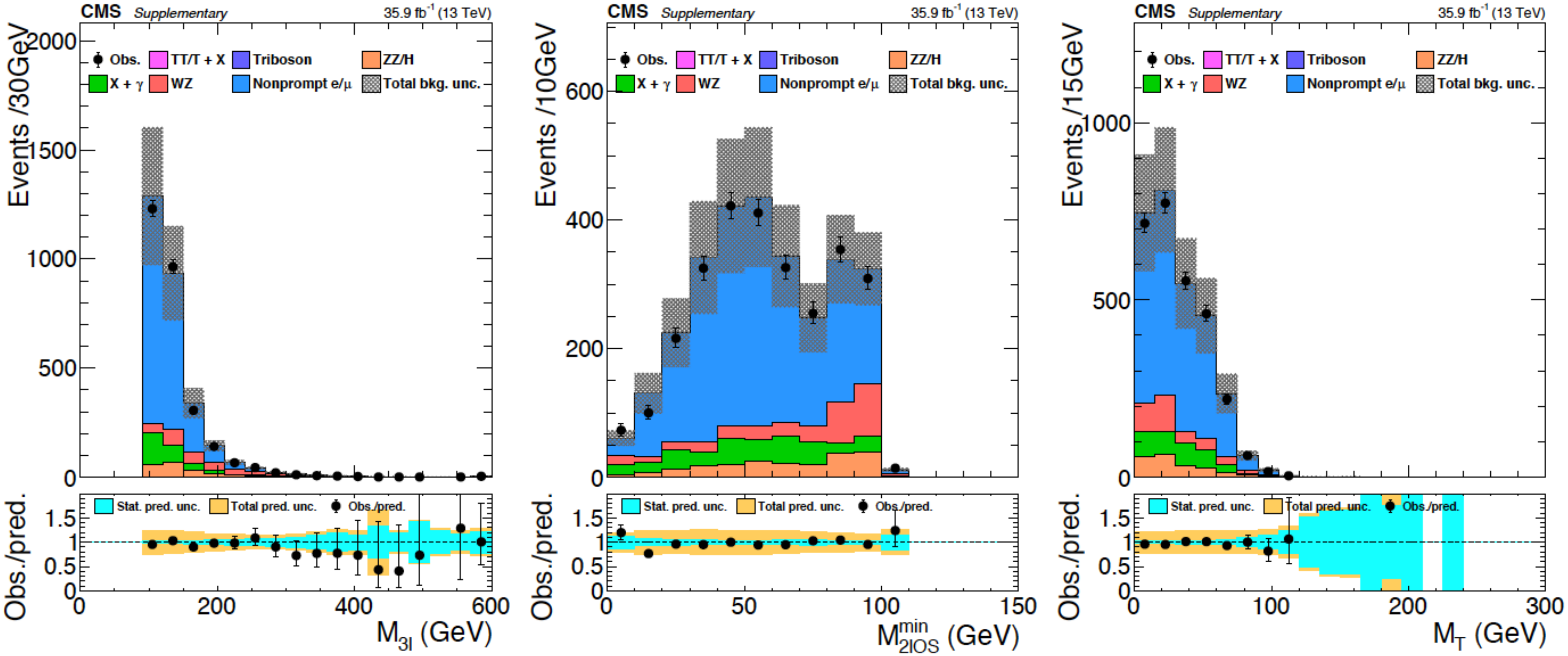
Validation nonprompt in DY

- enriched with misidentified electrons
- check the same f for this source
- systematic uncertainty of the method 30%

- OSSF pair present;
- $|M_{\ell\ell} - m_Z| < 15$ GeV;
- $|M_{3\ell} - m_Z| > 15$ GeV;
- 0 b-jets;
- $p_T > 15, 10, 5(10)$ GeV;
- $E_T^{miss} < 30$ GeV;
- $M_T < 30$ GeV



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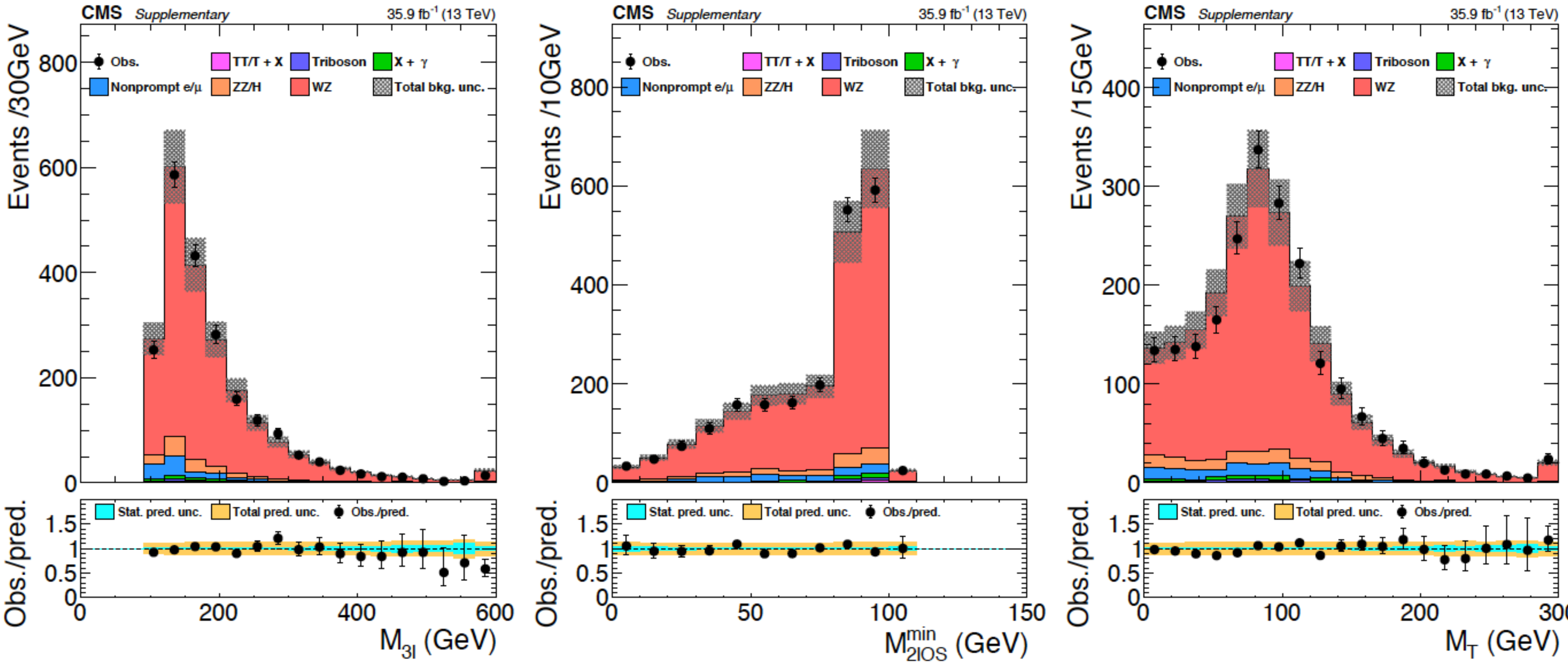
Validation WZ

Subdominant background in most regions: important only in high-mass SR with OSSF.

- derive process normalization
- measured SF = 1.08 ± 0.09

- OSSF pair present;
- $|M_{\ell\ell} - m_Z| < 15$ GeV;
- $|M_{3\ell} - m_Z| > 15$ GeV;
- 0 b-jets;
- $p_T > 25, 15, 10$ GeV;
- $E_T^{miss} > 50$ GeV;



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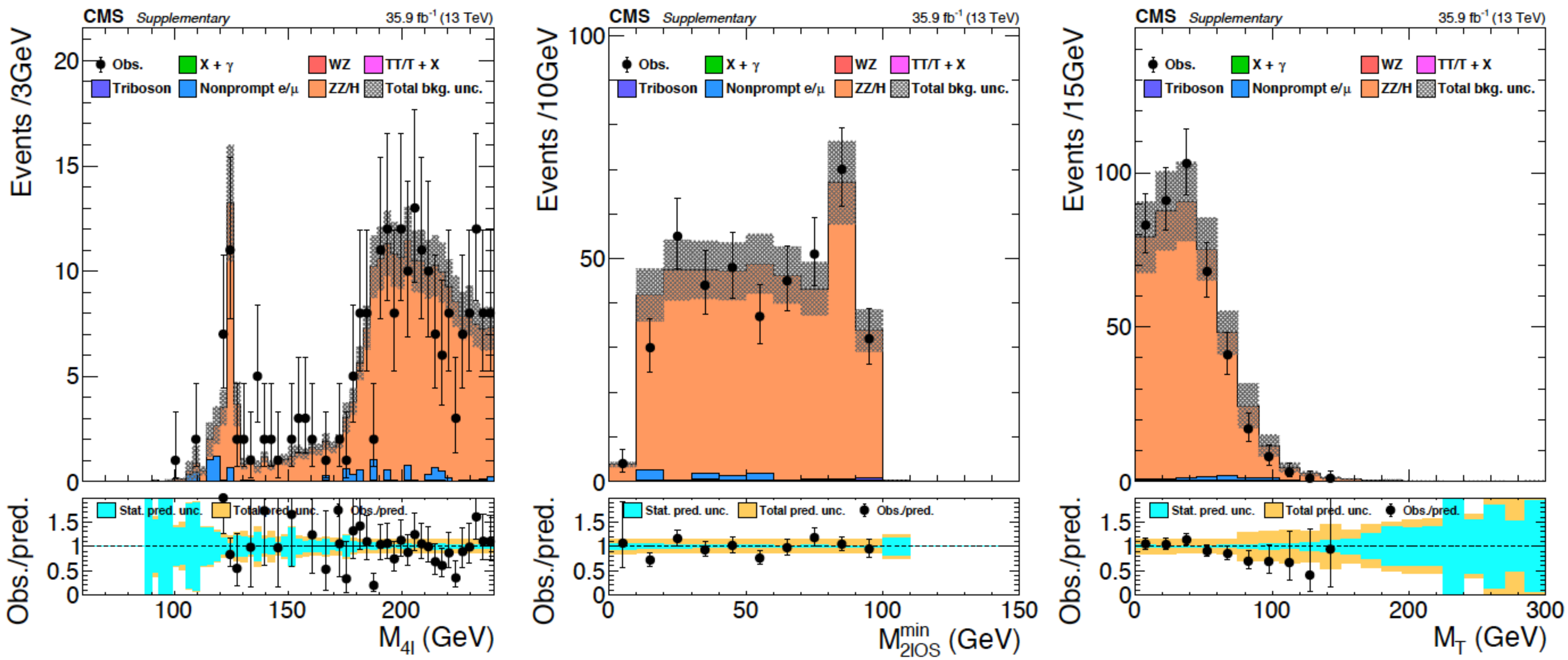
Validation ZZ

Subdominant background: contributes only when one of the leptons is lost.

- derive process normalization
- measured SF = 1.03 ± 0.10
- additional uncertainty for $M_T > 75$ GeV

- 2 OSSF pairs present;
- $|M_{\ell\ell} - m_Z| < 15$ GeV for both;
- 0 b-jets;
- $p_T > 15, 10, 5(10)$ GeV;



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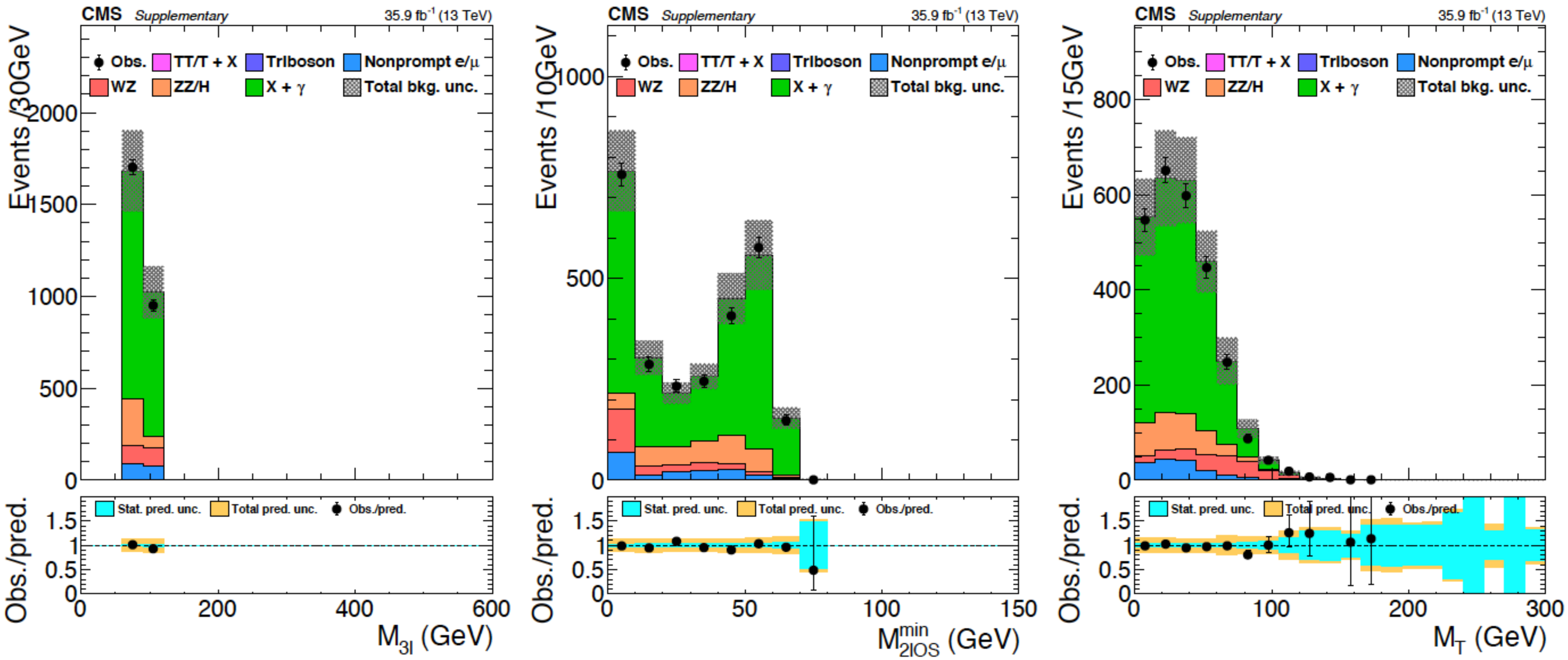
Validation conversion

Subdominant background: more important for electron channel (external conversions).

- derive process normalization
- measured SF = 0.95 ± 0.08

- OSSF pair present;
- $|M_{\ell\ell} - m_Z| > 15$ GeV;
- $|M_{3\ell} - m_Z| < 15$ GeV;
- 0 b-jets;
- $p_T > 15, 10, 5(10)$ GeV;



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