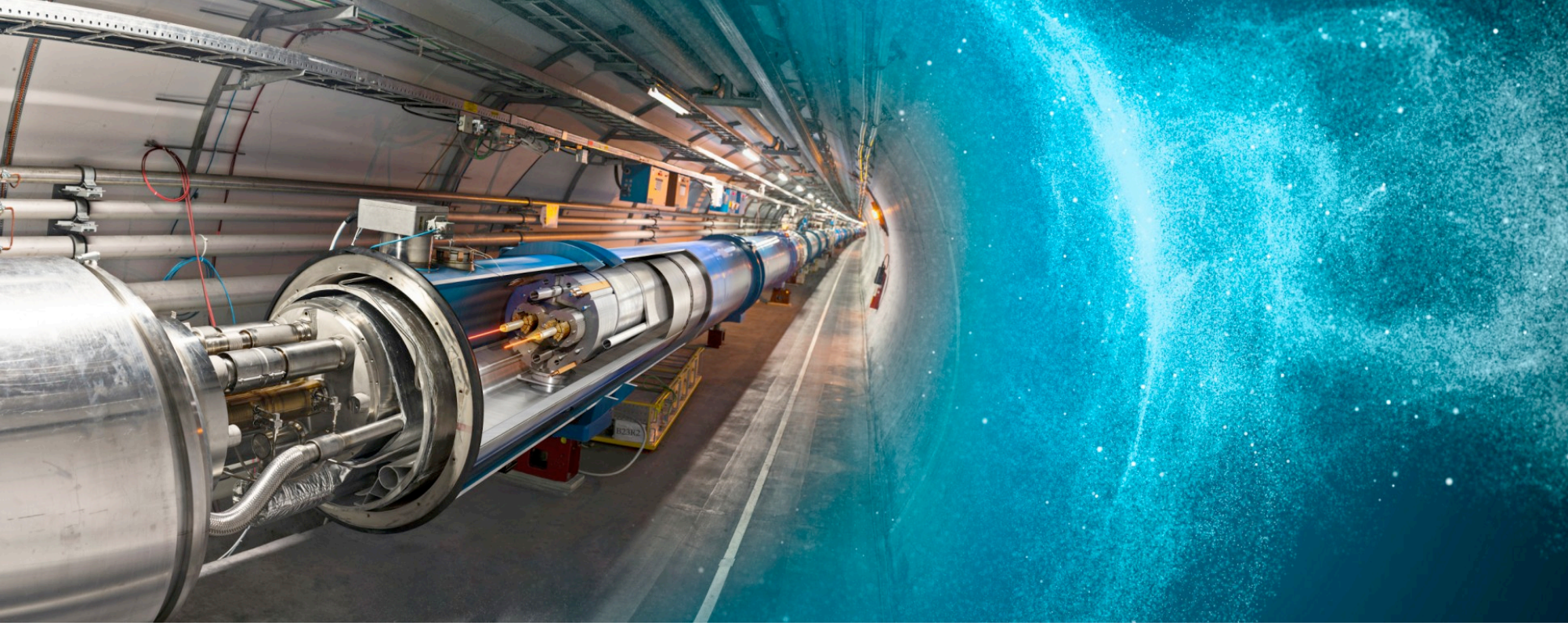


Search for heavy neutral leptons in the trilepton final state at CMS (arXiv:1802.02965)

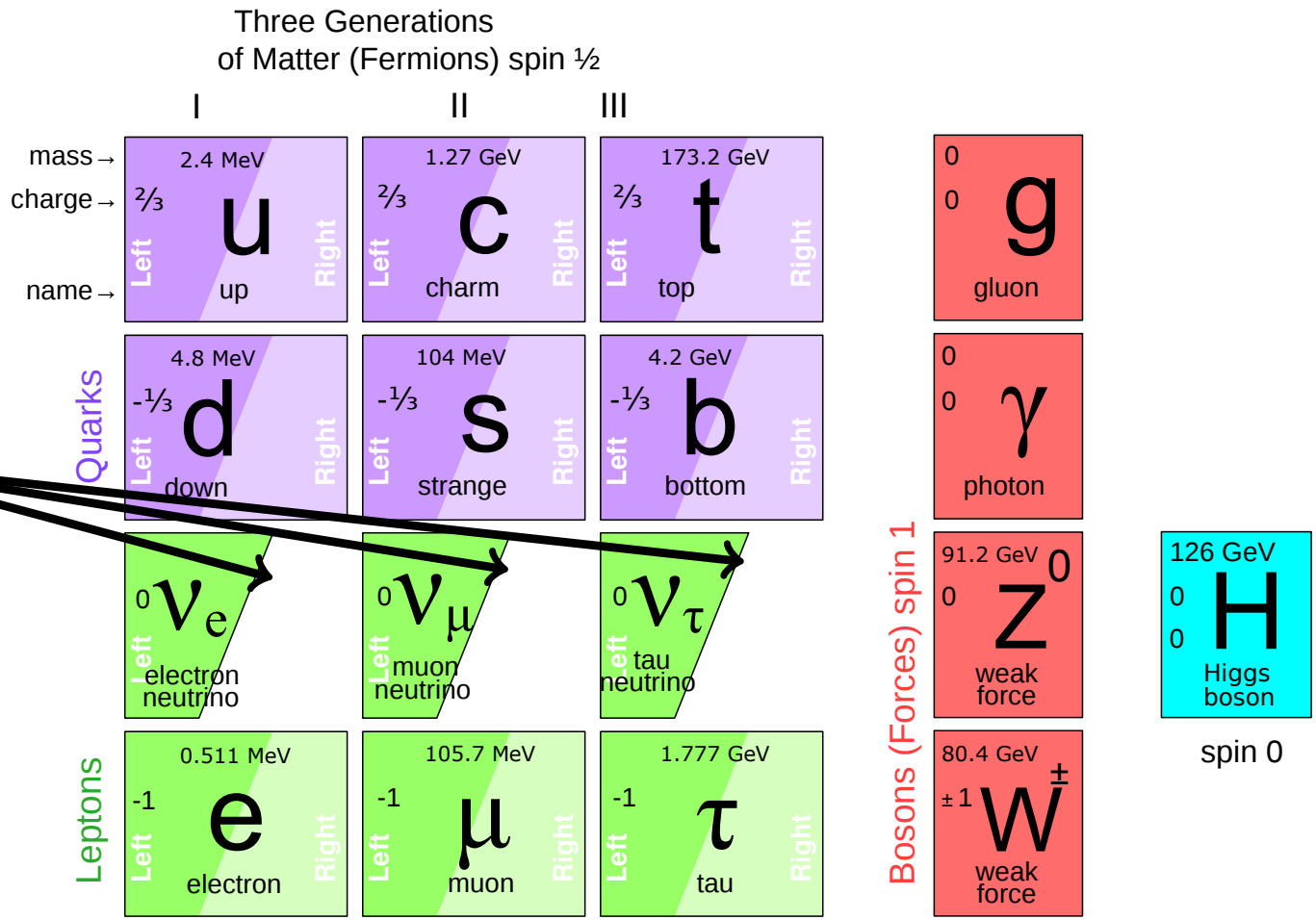
Lesya Shchutska
ETH Zürich
on behalf of the CMS Collaboration

CERN LHC Seminar
February 6, 2018

European Research Council
Established by the European Commission

The standard model of particle physics

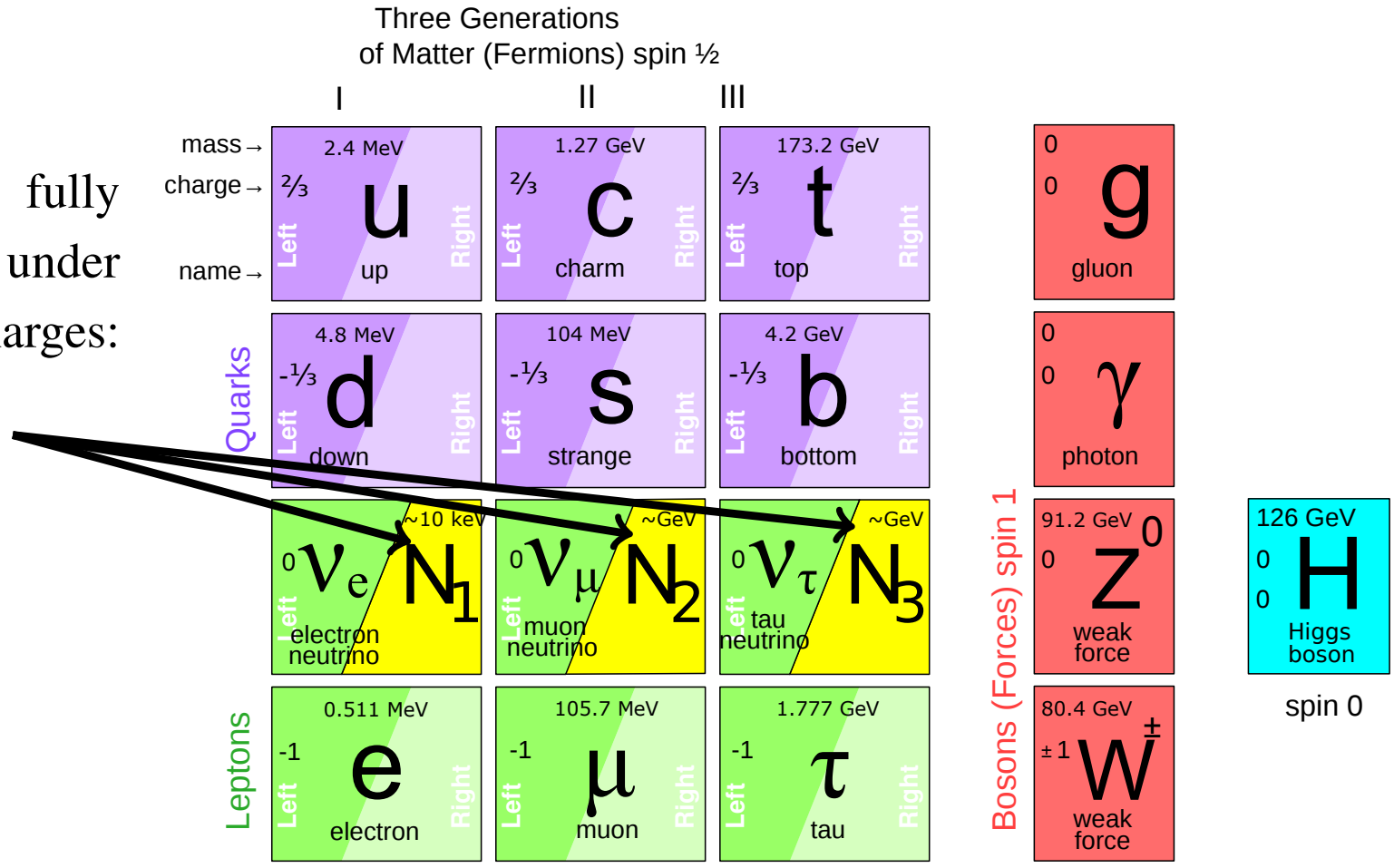
Right-handed neutrinos N are missing in the standard model



What are the consequences of their existence?
What are their properties?

Heavy neutral leptons (HNL) – “sterile” neutrinos

N are fully neutral under all SM charges: “sterile”



Can add both Dirac and Majorana mass terms for N:

$$\mathcal{L}_{\text{HNL}} = \mathcal{L}_{\text{SM}} + i\bar{N}\not{\partial}N + Y\bar{N}(\widetilde{H}\cdot L) + \frac{1}{2}\bar{N}MN^{C}$$

Phenomenological implications

Can add both Dirac and Majorana mass terms for N:

$$\mathcal{L}_{\text{HNL}} = \mathcal{L}_{\text{SM}} + i\bar{N}\not{\partial}N + Y\bar{N}(\widetilde{H}\cdot L) + \frac{1}{2}\bar{N}MN^{C}$$

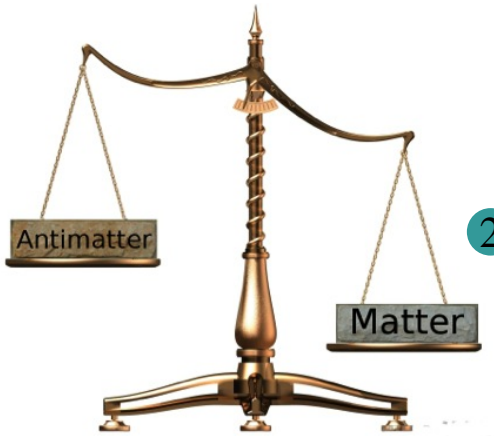
- if $M \gg m_{\text{Dirac}}$ get two types of particles:
  1. light neutrino (ν_{SM}) with mass $m_\nu \approx m_{\text{Dirac}}\dfrac{m_{\text{Dirac}}}{M}$ (**seesaw mechanism**)
  2. heavy neutrino (N) with mass $m_{\text{N}} \approx M$
- mixture between states ν_{SM} and N is governed by the mixing angle:

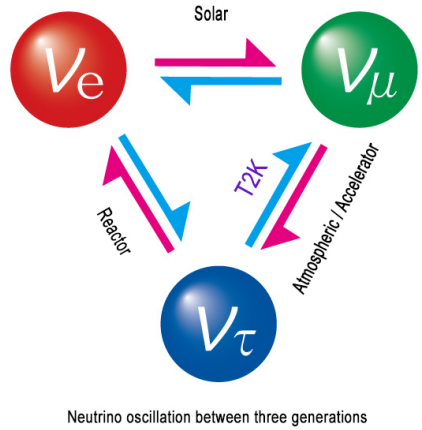
$$\sin V_{\nu\text{N}} \approx V_{\nu\text{N}} = \frac{m_{\text{Dirac}}}{M} \ll 1$$

  - $V_{\nu\text{N}}$ defines N production rate, e.g. $\Gamma(\text{W} \to \mu\text{N}) = |V_{\mu\text{N}}|^2\Gamma(\text{W} \to \mu\nu_\mu)$

More solutions to the long-standing puzzles

1. **origin of the SM neutrino masses:**
   - seesaw mechanism

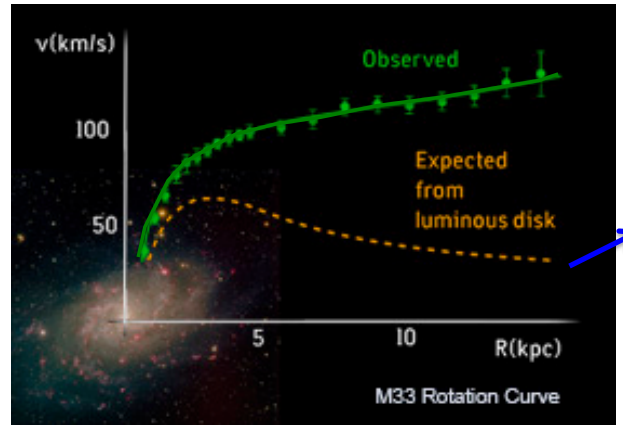




Neutrino oscillation between three generations

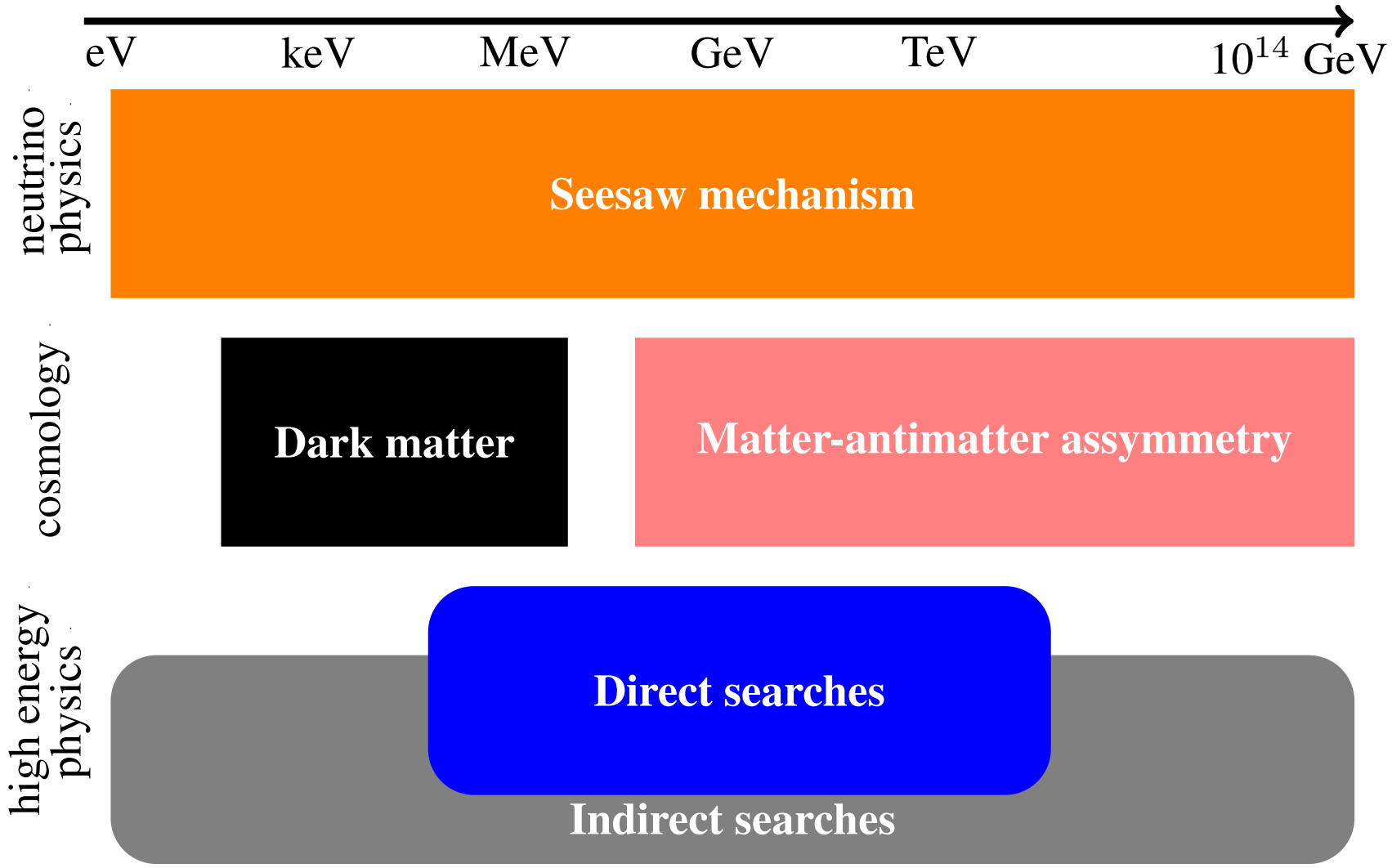
2. **matter-antimatter asymmetry of the universe:**
   - degenerate N_2 and N_3 (m_N from ~ 1 to $\sim 10^2$ GeV) could lead to dramatic increase of CP violation

3. **dark matter candidate:** $N_1(\sim\text{keV})$
   - observable decay mode $N_1 \to \nu\gamma$
   - search for mono-line in galactic photon spectrum, $E_\gamma = M_N/2$

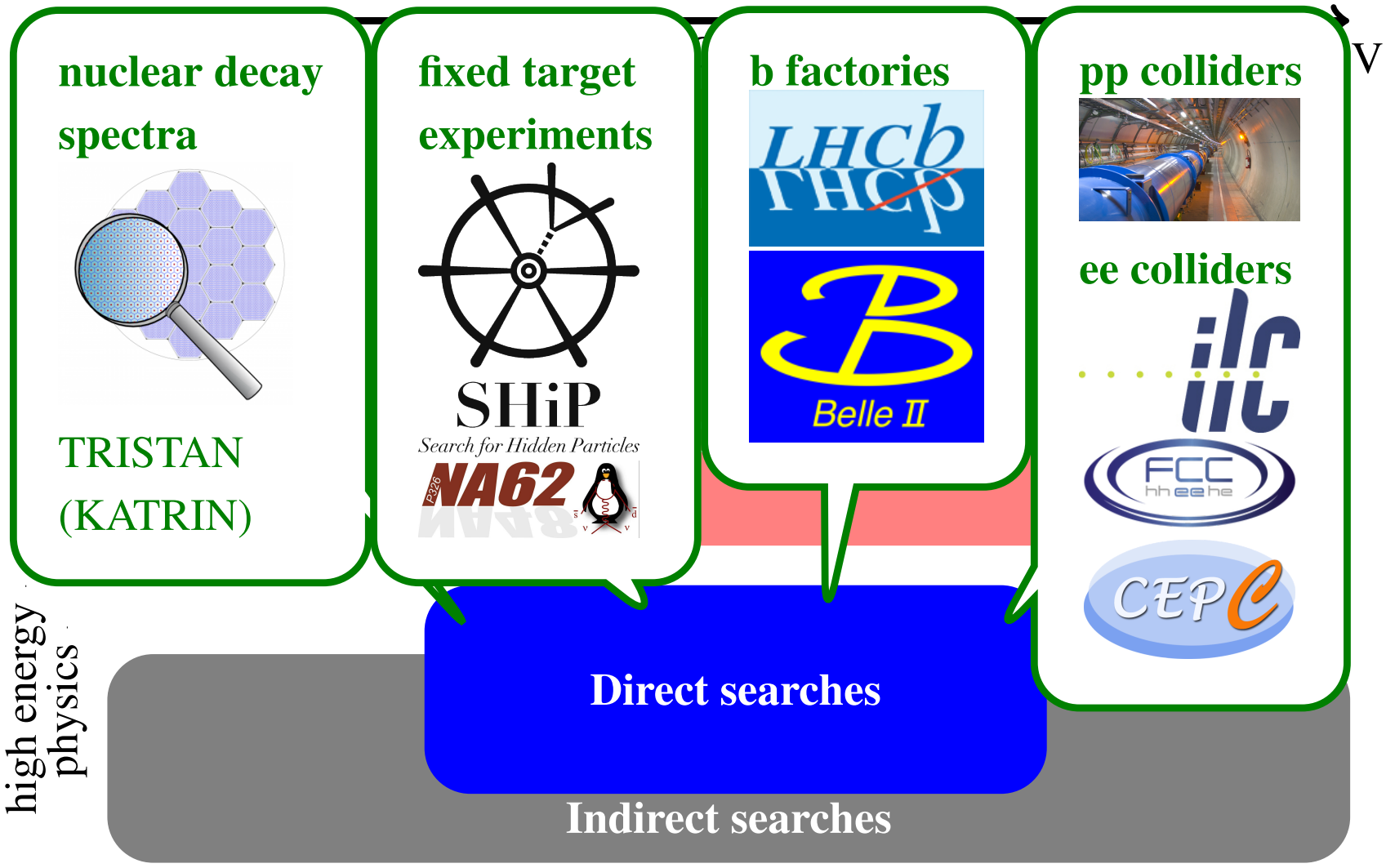


$v^2 \propto \frac{M}{r}$

Possible masses of N

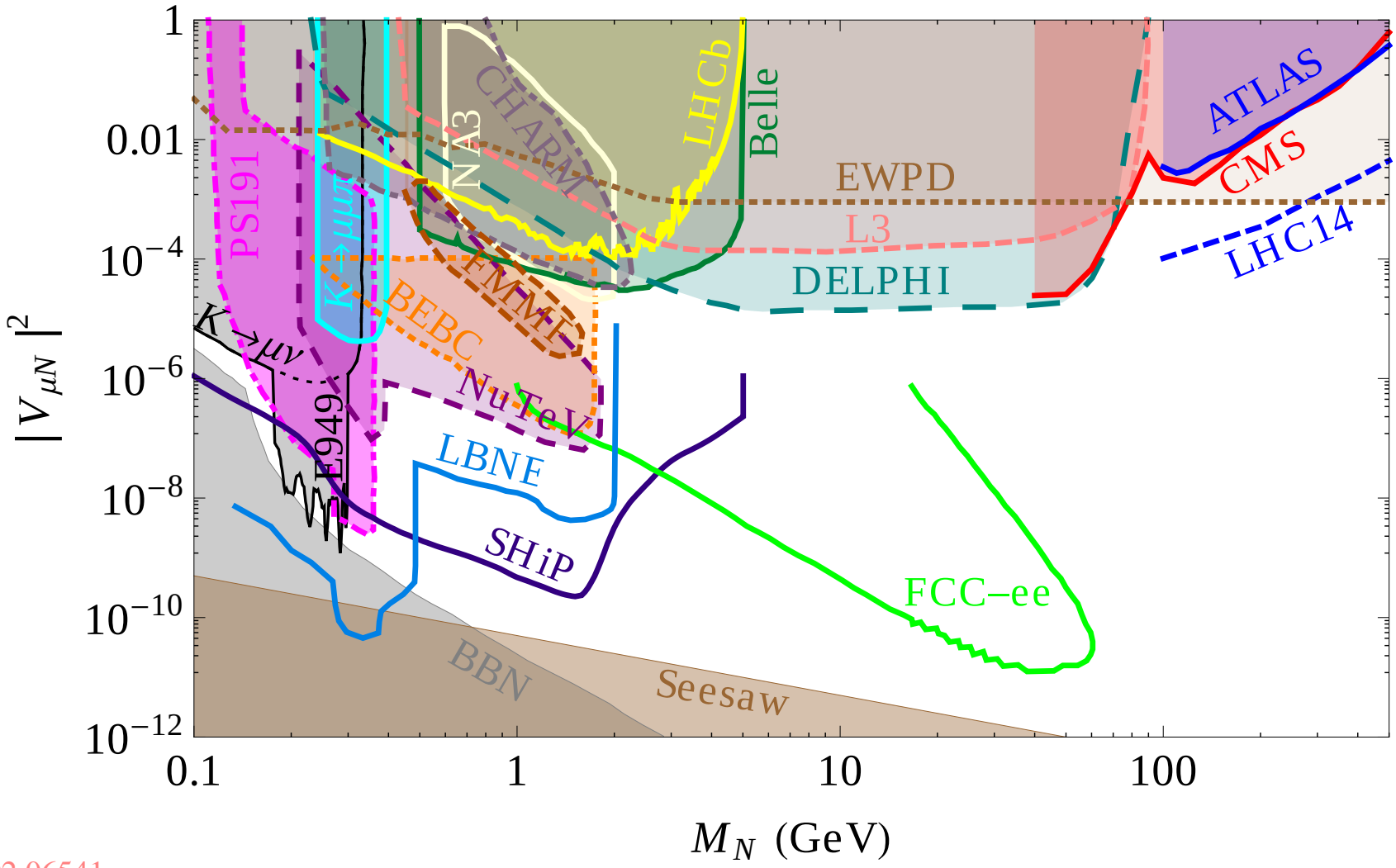


Possible masses of N: tools to find them



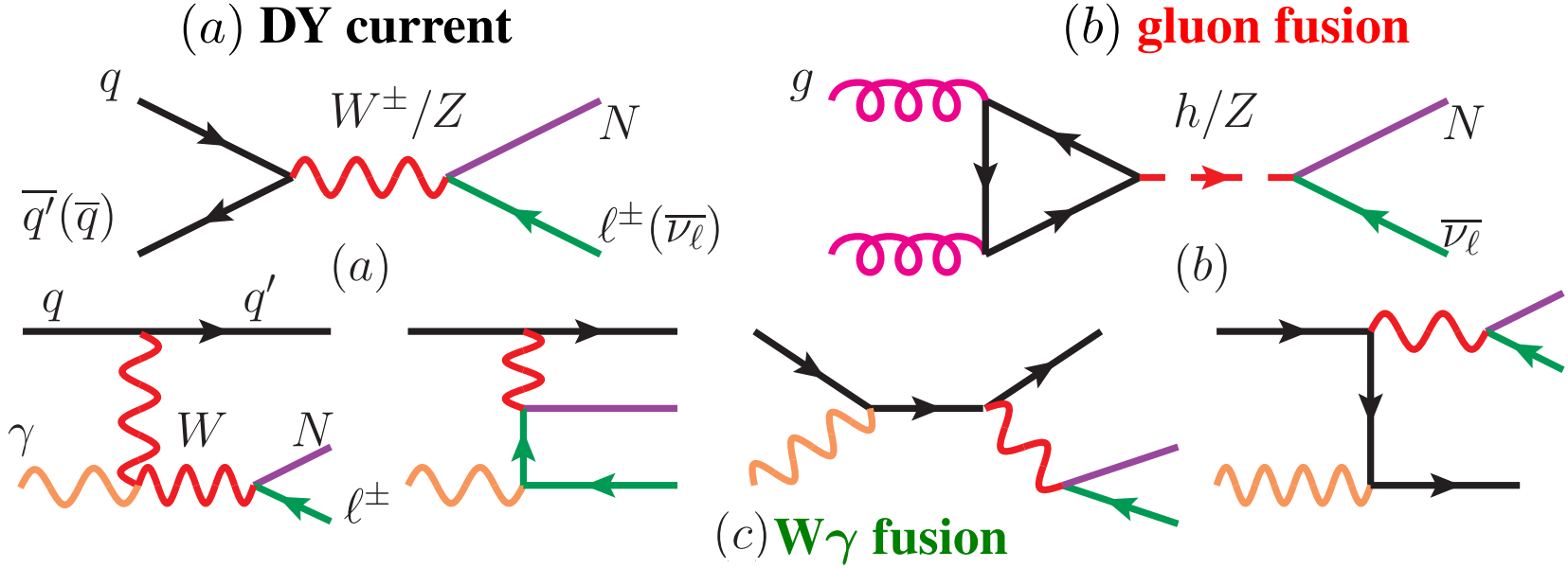
Existing constraints and some projections

- LHC just starts to probe region not excluded by the electroweak precision data (EWPD) (*filled areas - excluded; contours - projected experiments*)

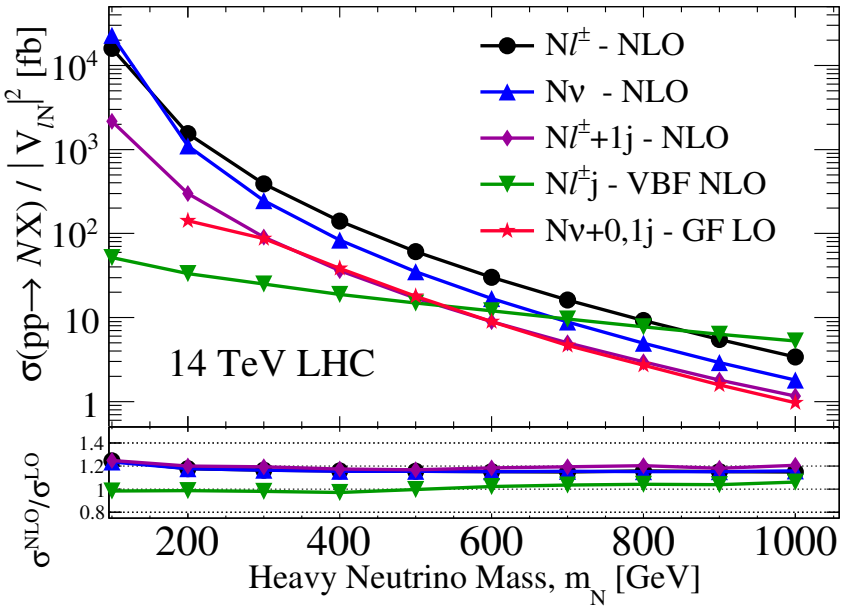


arXiv:1502.06541

Heavy neutrino production at the LHC

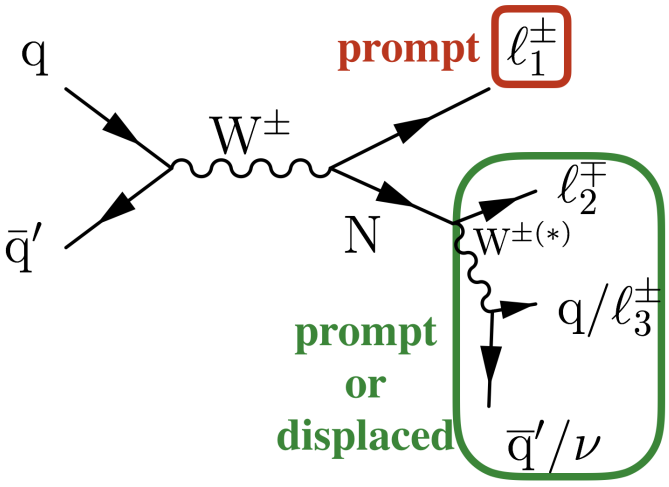


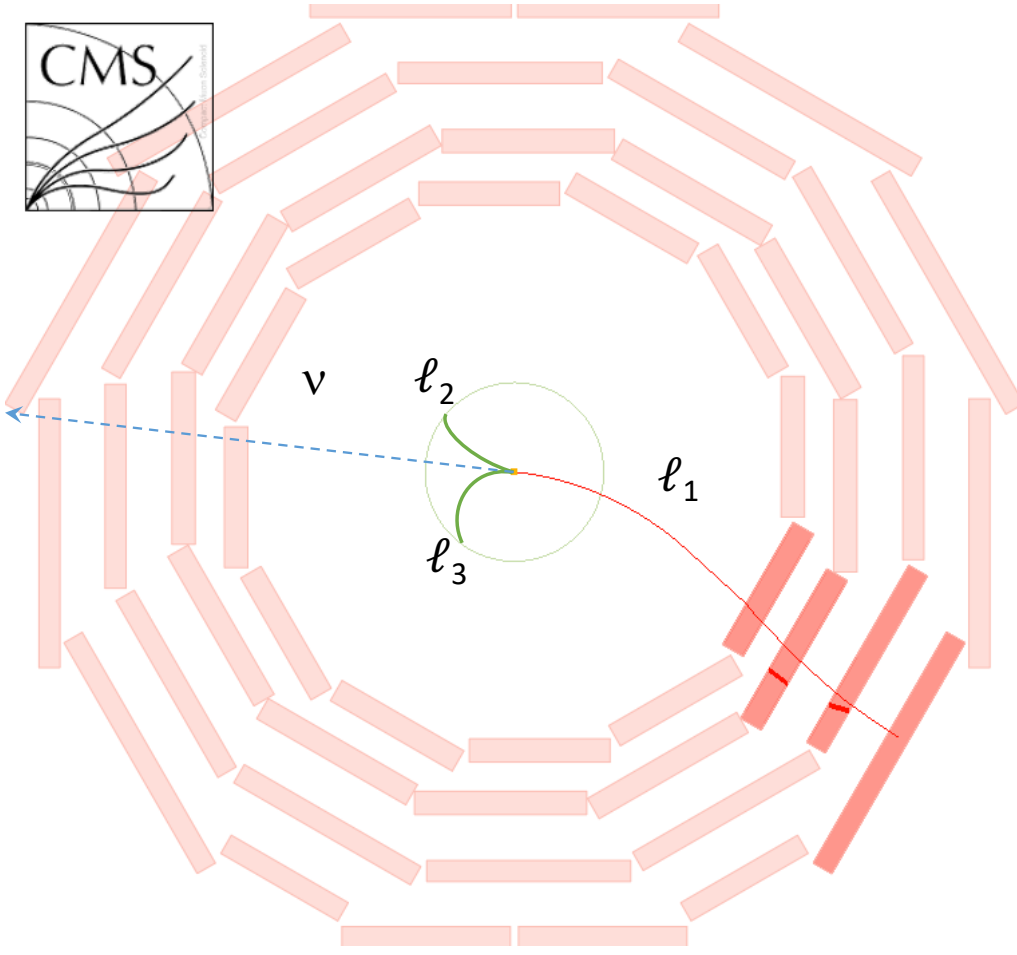
- produced in decays of W or Z bosons
- for high N masses VBF channel (Wγ fusion) becomes important
- N$\ell^\pm$ final states experimentally are more accessible:
  - charged DY current
  - VBF (Wγ fusion)



arXiv:1602.06957

Heavy neutrino decays

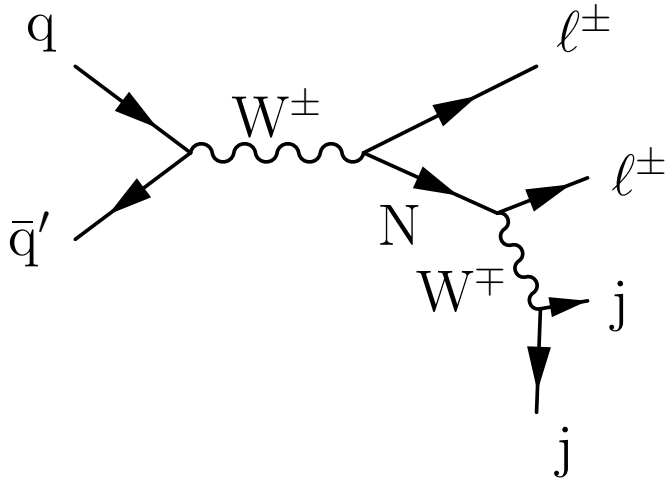




- **N decays**: $N \to W^{(*)}\ell$ or $N \to Z^{(*)}\nu$ or $N \to H\nu$
- **N$\to$Wℓ** experimentally is the most accessible
- **N lifetime**: from very small (**prompt** decays) to macroscopic distances from production vertex (**displaced** decays) as $\tau_N \propto |V_{\ell N}|^{-2} m^{-5}$

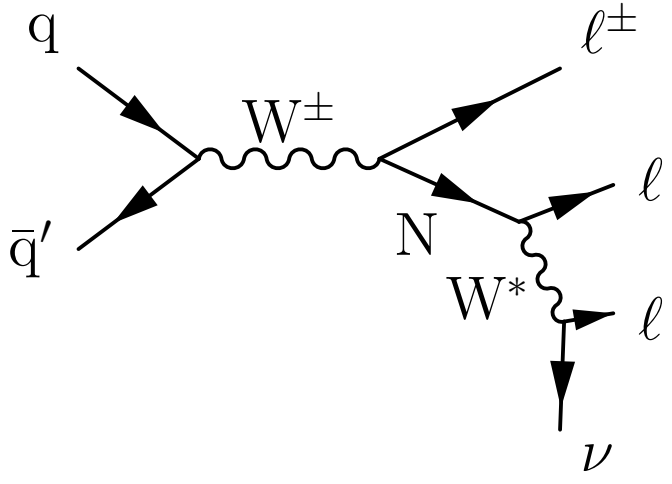
Signatures with prompt N decays

Same-sign dileptons + 2 jets:



- allows to fully reconstruct N mass peak
- N has to be heavy (jet $p_T > 30$ GeV)
- sensitive only to **lepton-number-violating (LNV)** N decays

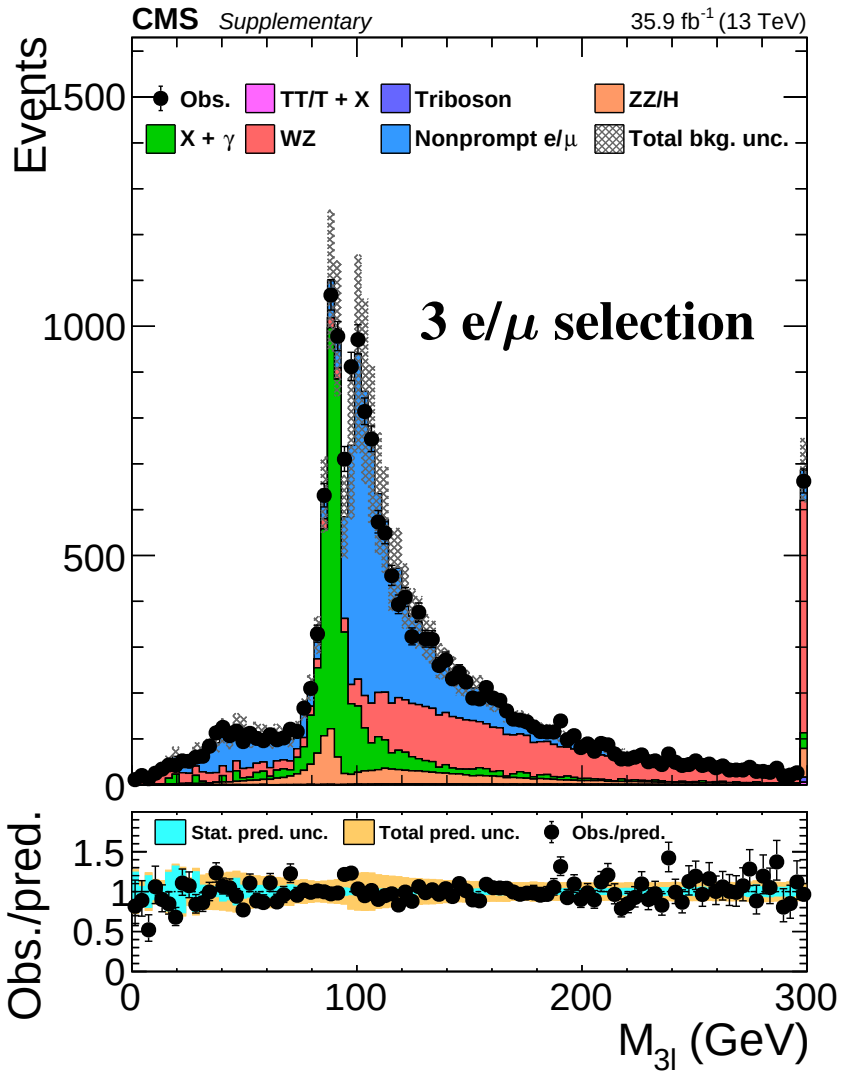
Trileptons (+ E_T^{miss}):



- no clear N mass peak due to escaping ν
- can detect decay products of very light N (lepton $p_T > 5$ GeV)
- sensitive to both LNV and **LN-conserving (LNC)** N decays

Explore a new territory with looking at the prompt trilepton (e, μ) final state!

Standard model background in trileptons



Nonprompt leptons:

- reducible background
- $t\bar{t} \rightarrow 2\ell$ and/or DY$\rightarrow 2\ell$ with a 3rd ℓ from jet fragmentation

WZ$\rightarrow 3\ell\nu$, **ZZ**$\rightarrow 4\ell$:

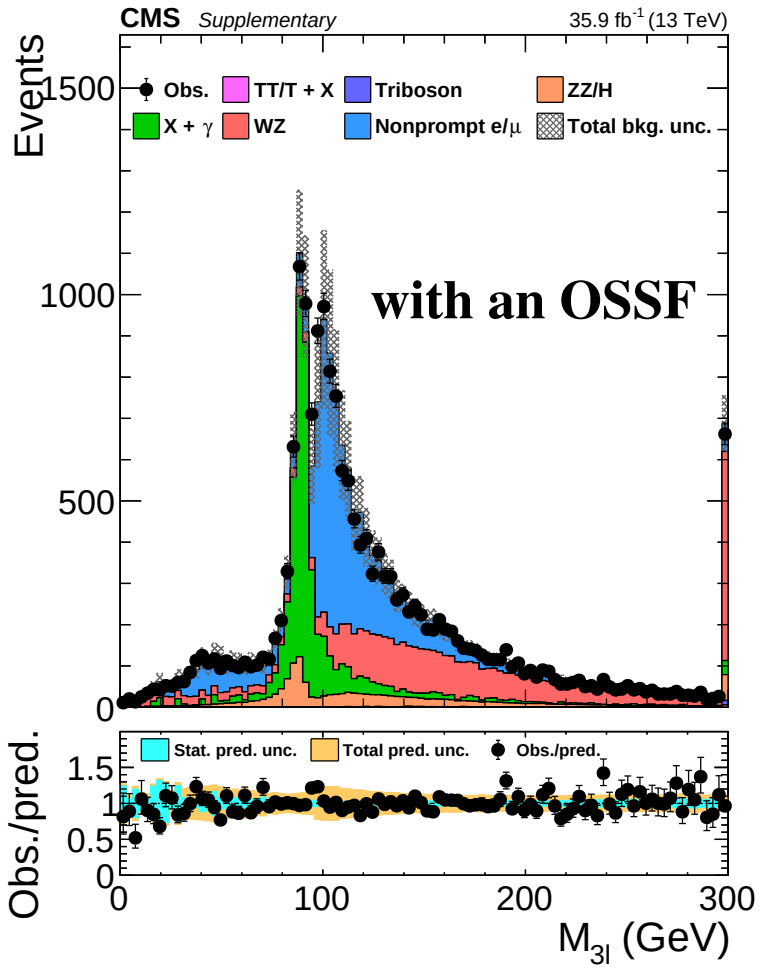
- three signal-like leptons
- almost always an opposite-sign same flavor (OSSF) pair from Z$\rightarrow \ell\ell$ is present

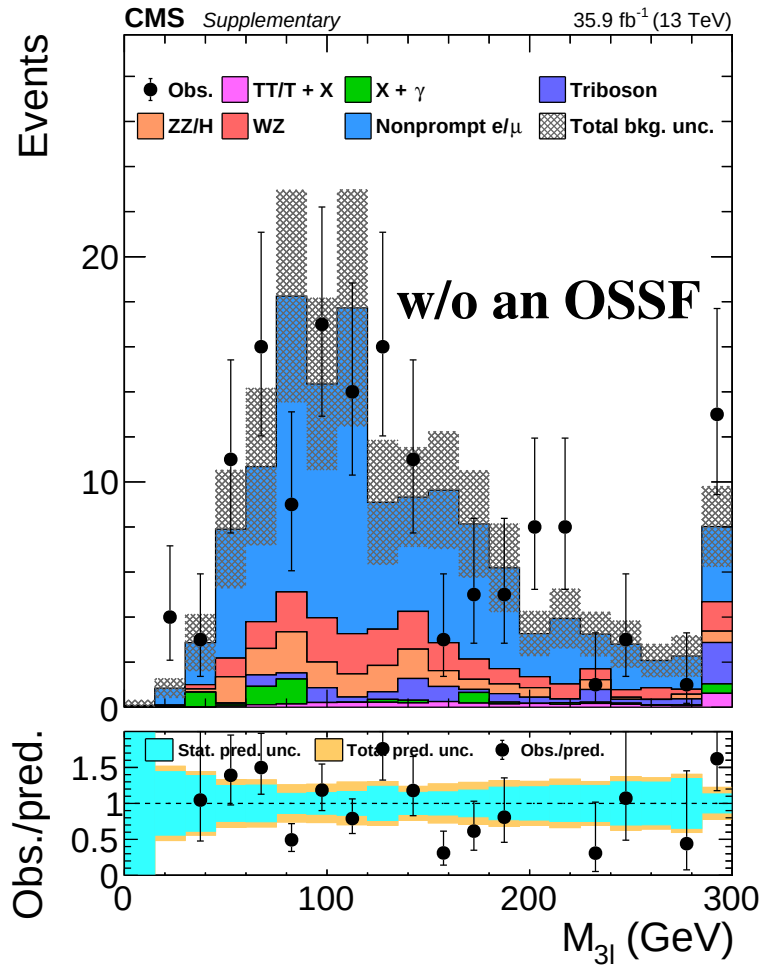
Conversions (Xγ):

- dominated by Zγ^* with $\gamma^* \rightarrow \ell\ell$
- almost always has an OSSF pair

Rare processes: tribosons, $t\bar{t}$X:

Importance of the charge: OSSF wrt no OSSF leptons

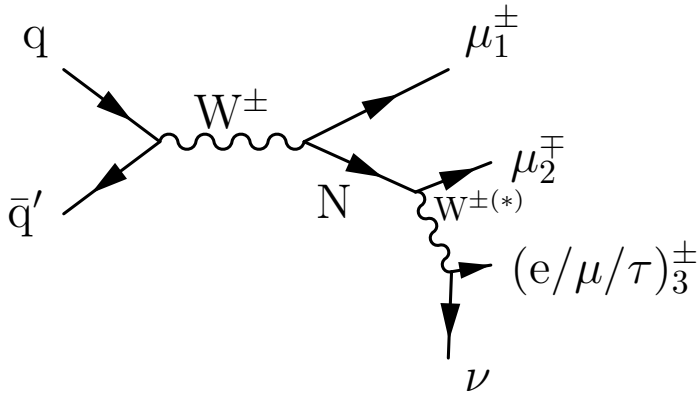




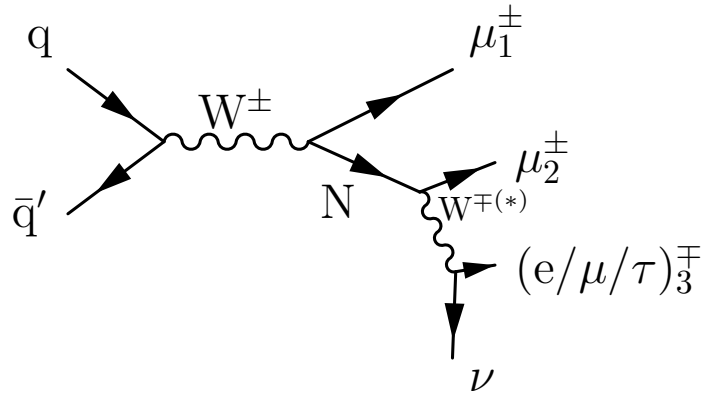
Two orders of magnitude higher in final state with an OSSF lepton pair: mainly DY+jets, Zγ^* and WZ processes

Trilepton final states with one coupling: e.g. $V_{\mu N} \neq 0$

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

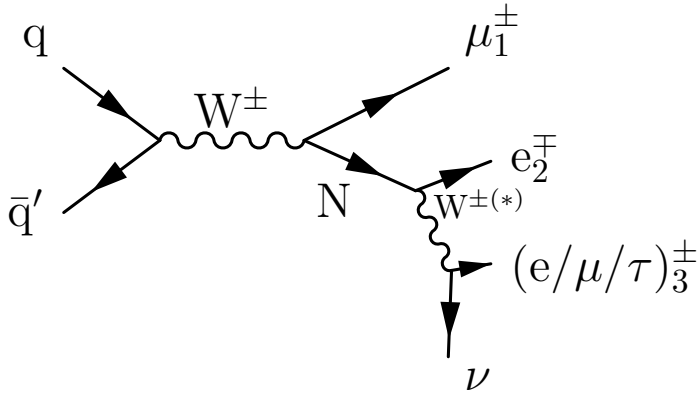
1/6 of all fully leptonic decays lead to a final state with 3 e/μ w/o an opposite-sign same-flavor pair*

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

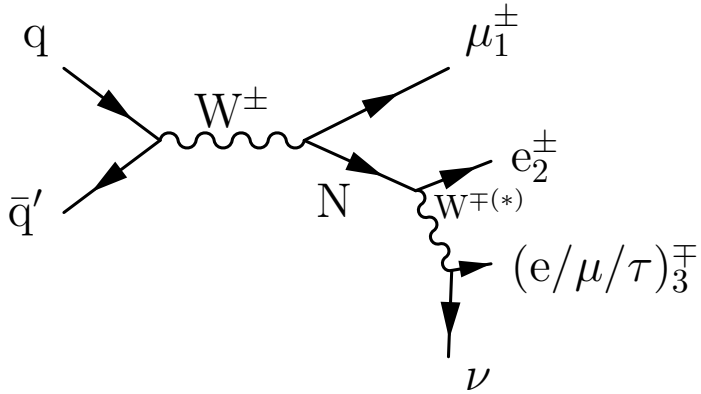
Trilepton final states with two couplings: e.g. $V_{eN} \neq 0$ and $V_{\mu N} \neq 0$

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

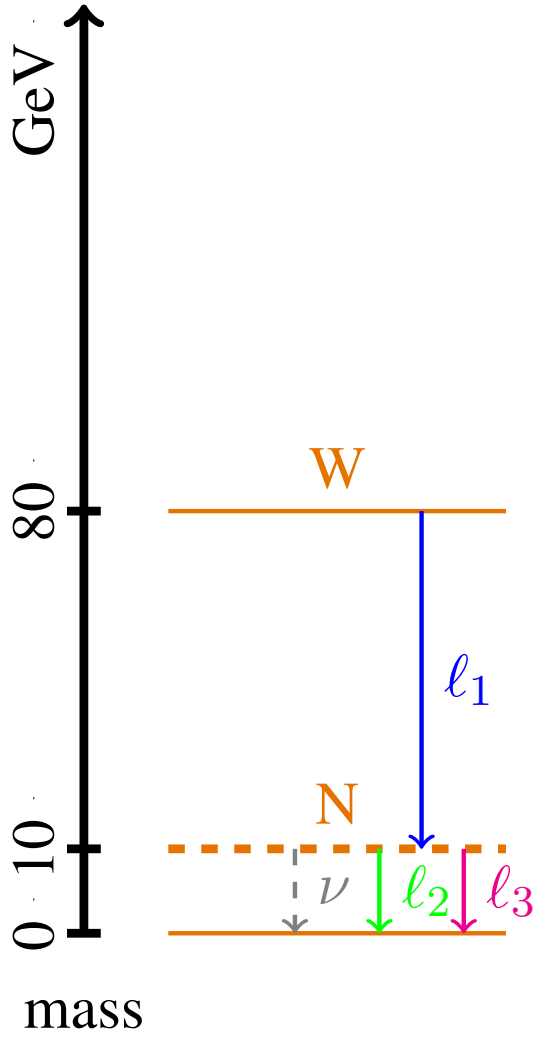
- split all events by the presence of an OSSF pair of leptons
- profit from the reduced background in searches

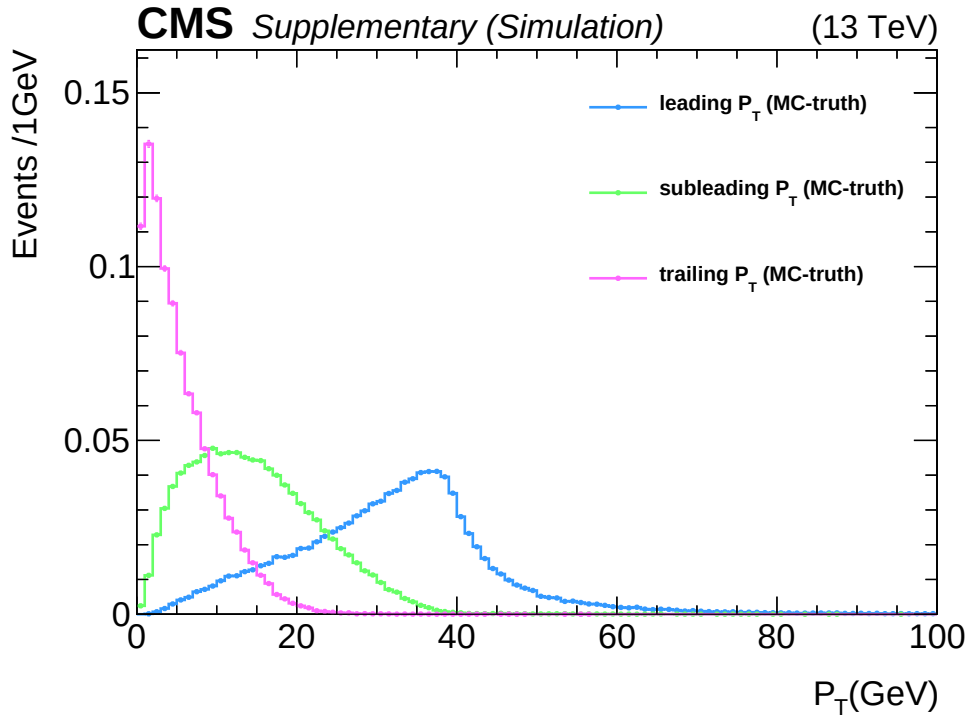
ME	OSSF		noOSSF		OSSF	
	eee	$e^{\pm}e^{\mp}\mu$	$e^{\pm}e^{\pm}\mu$	$\mu^{\pm}\mu^{\pm}e$	$\mu^{\pm}\mu^{\mp}e$	$\mu\mu\mu$
$\lvert V_{eN}\rvert^2$	$\times$	$\times$	$\times$			
$\lvert V_{\mu N}\rvert^2$				$\times$	$\times$	$\times$
$\lvert V_{eN}V_{\mu N}\rvert$		$\times$	$\times$	$\times$	$\times$	
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

Lepton spectrum

depends on the N mass: **low mass case**

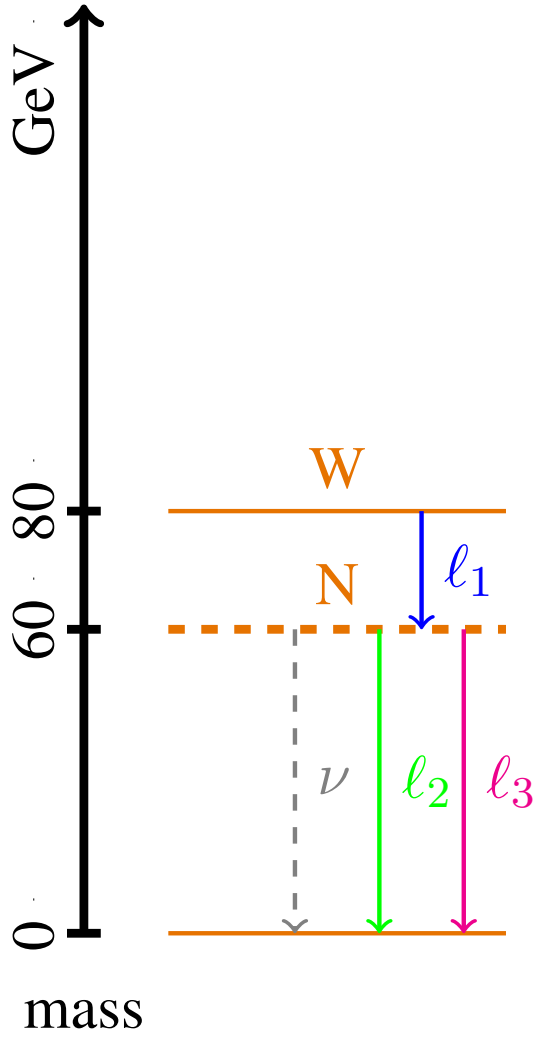


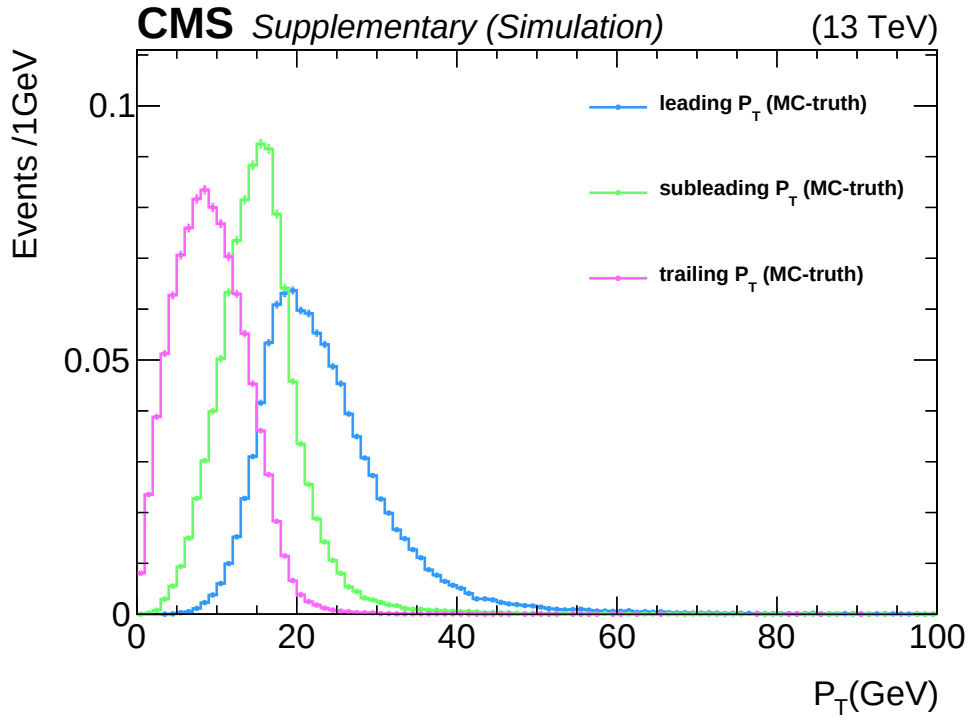


- very soft trailing lepton
- hard leading lepton

Lepton spectrum

depends on the N mass: **intermediate mass case**

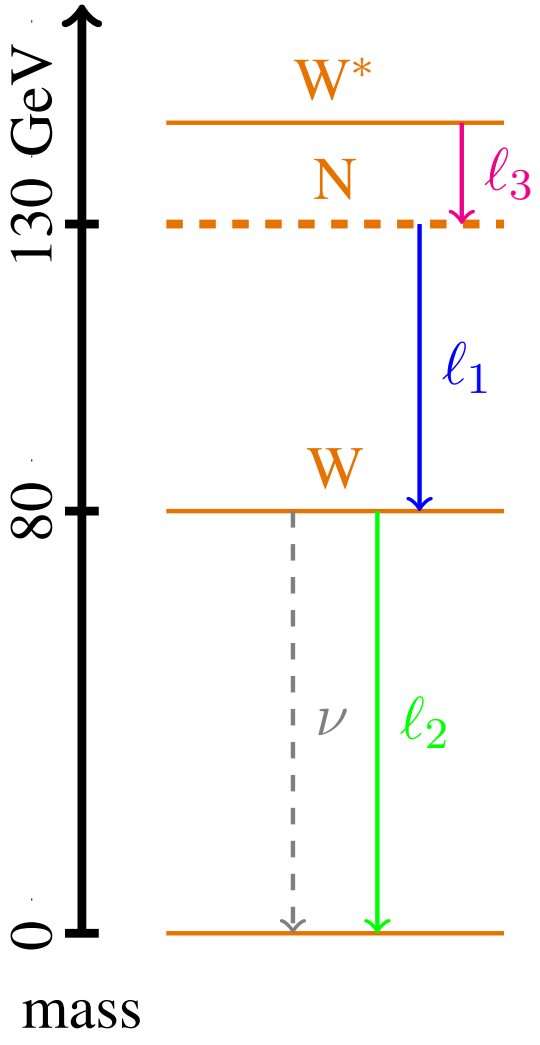


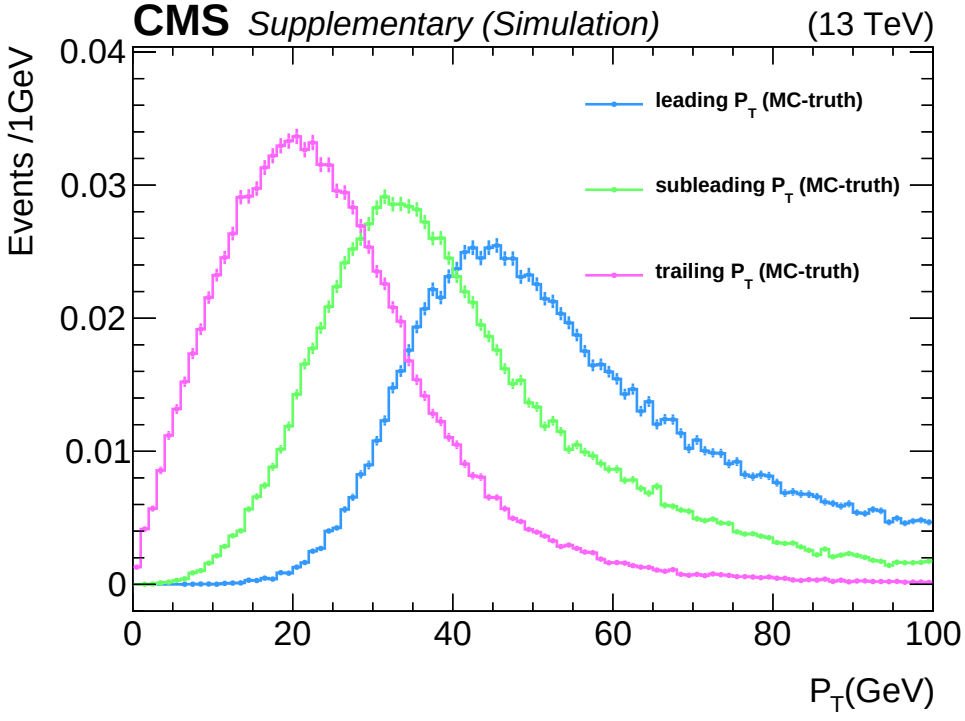


- all leptons have moderate p_T
- softer leading lepton

Lepton spectrum

depends on the N mass: **high mass case**

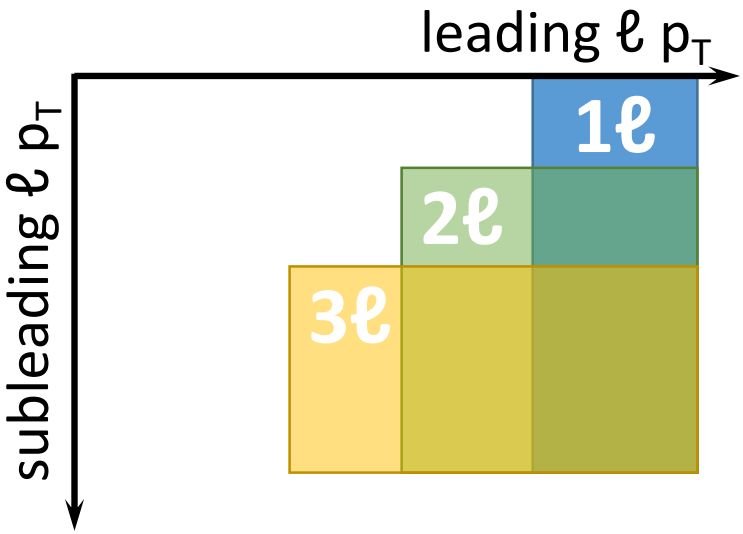




- trailing lepton has moderate p_T
- very hard leading lepton

Trigger strategy

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



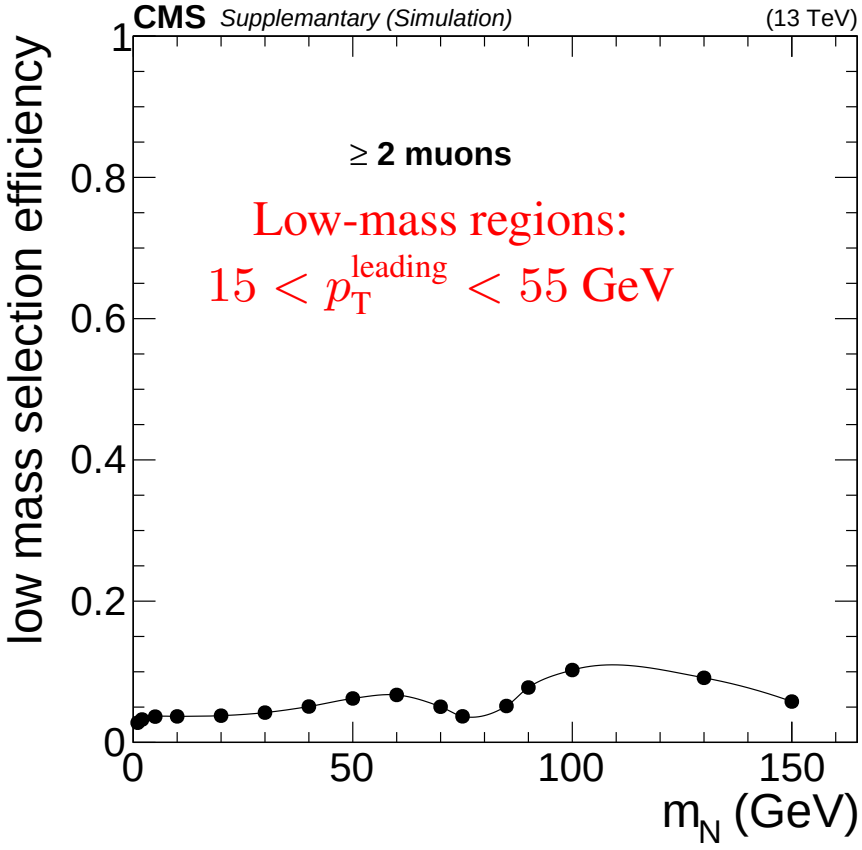
- single lepton: very high leading lepton p_T, any trailing lepton p_T
- dilepton: moderate leading and subleading lepton p_T, any trailing lepton p_T
- trilepton: low leading, subleading, and trailing lepton p_T

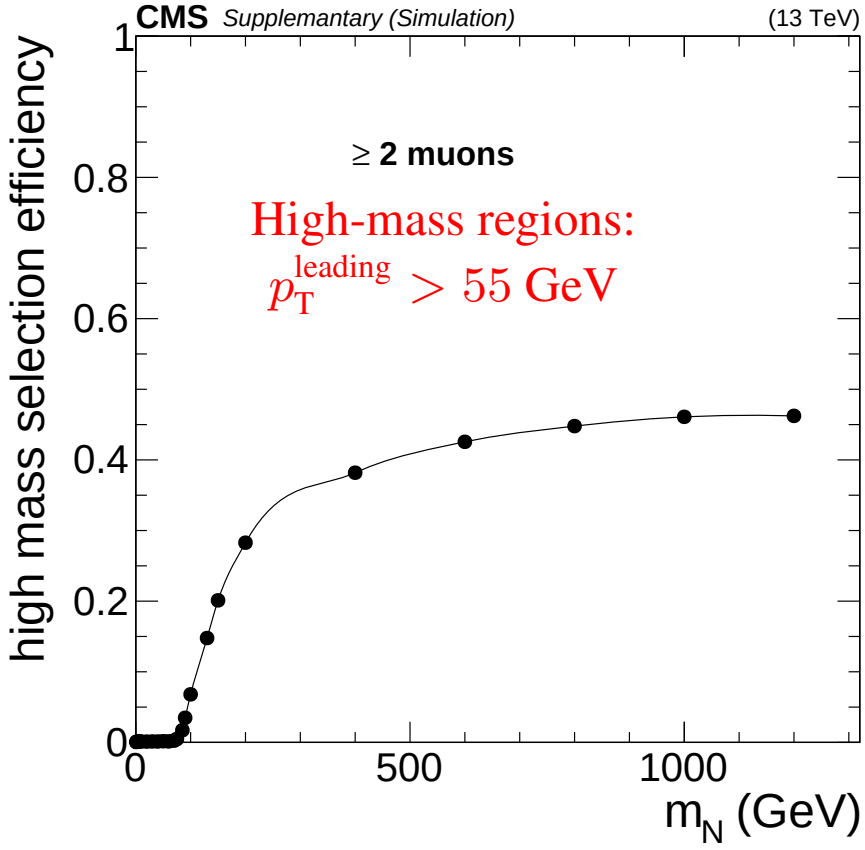
Target all three mass scenarios outlined previously!
Use three lepton p_T categories where for a leading lepton:

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

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

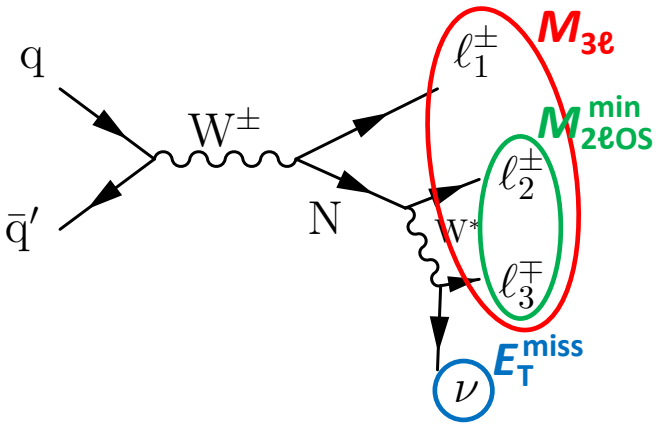
Signal efficiencies



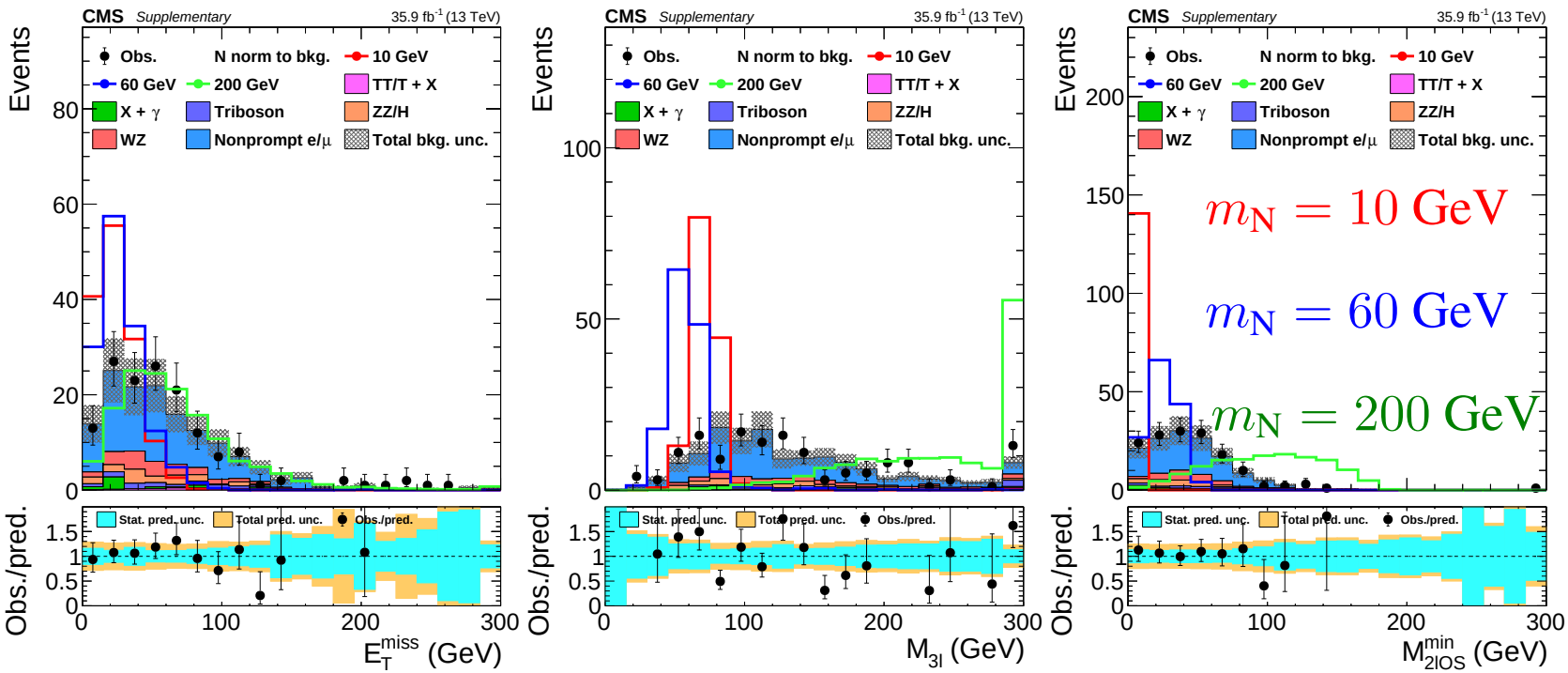


- computed with respect to trilepton (e or μ) final state
- in low mass: no OSSF requirement is imposed
- in high mass: any charge combination of leptons is allowed (Z-veto is imposed)
- low signal efficiencies because of the selection on lepton p_{T} and lepton identification inefficiencies

Search variables: low mass N ($< m_{\mathrm{W}}$)

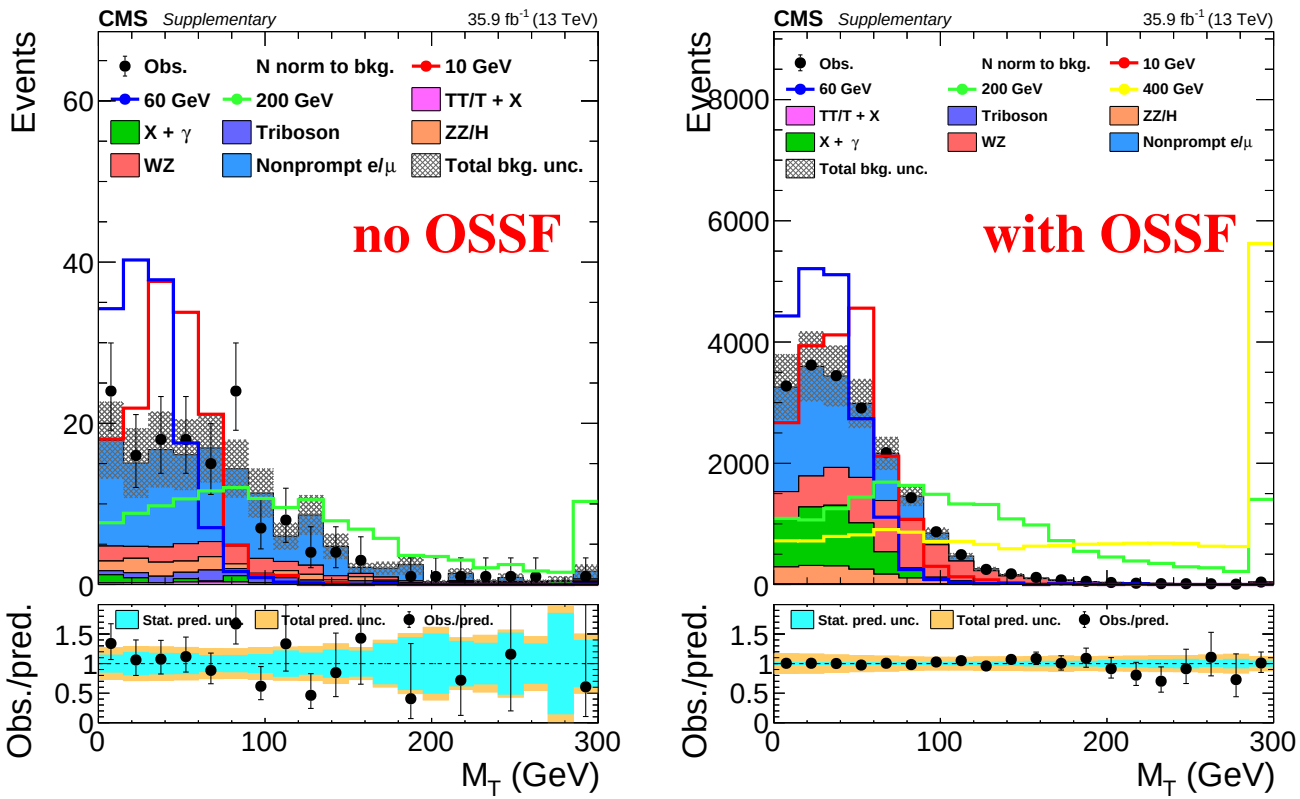


- two ranges for leading lepton p_{T}: $15 - 30$ GeV and $30 - 55$ GeV
- low $E_{\mathrm{T}}^{\mathrm{miss}} < 75$ GeV
- low $M_{3\ell} < 80$ GeV
- b jet veto
- $M_{2\ell\mathrm{OS}}^{\mathrm{min}}$ as a proxy for M_{N}



Search variables: high mass N $(> m_{\mathrm{W}})$

- higher lepton p_{T} thresholds: $p_{\mathrm{T}} > 55, 15, 10$ GeV
- b jet veto
- due to lower nonprompt and conversion backgrounds use both OSSF and no OSSF events
- in OSSF category veto Z-mass window in $M_{3\ell}$ and $M_{\ell\ell}$
- use $M_{2\ell\mathrm{OS}}^{\mathrm{min}}$ and M_{T} shapes to differentiate signal and background



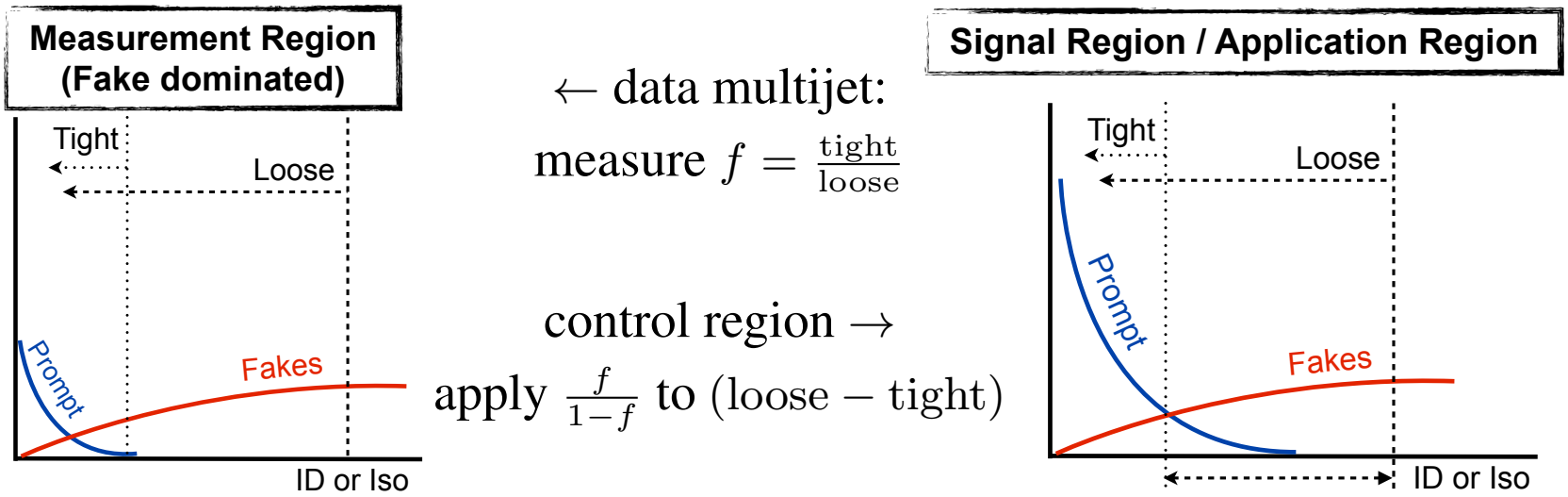
SM backgrounds: nonprompt leptons

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

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

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

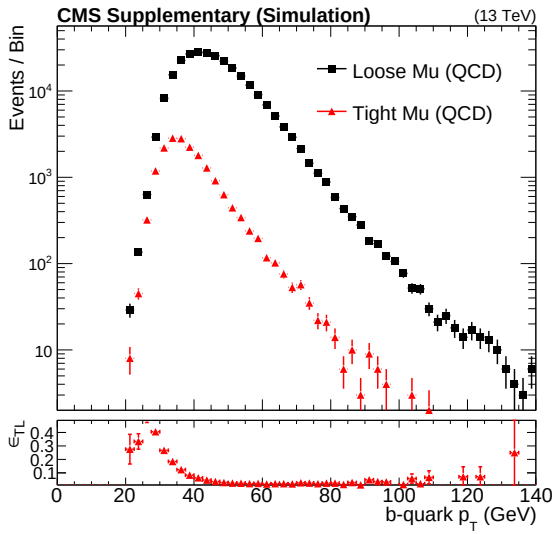
Use events where at least one lepton fails tight criteria to derive yields in SR:



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

SM backgrounds: nonprompt leptons estimation

1. for leptons from heavy-flavor decays:



- probability to get isolated depends on mother parton p_{T}
- for *tight* leptons mother parton $p_{\mathrm{T}} \approx$ lepton p_{T}
- for *loose* leptons take lepton p_{T}+energy in the isolation cone: $p_{\mathrm{T}}^{\mathrm{cone}} = p_{\mathrm{T}} \times (1 + I_{\mathrm{rel}} - I_{\mathrm{rel}}^{\mathrm{tight}})$
- parameterize $f = f(p_{\mathrm{T}}^{\mathrm{cone}})$ to remove dependence on jet spectrum

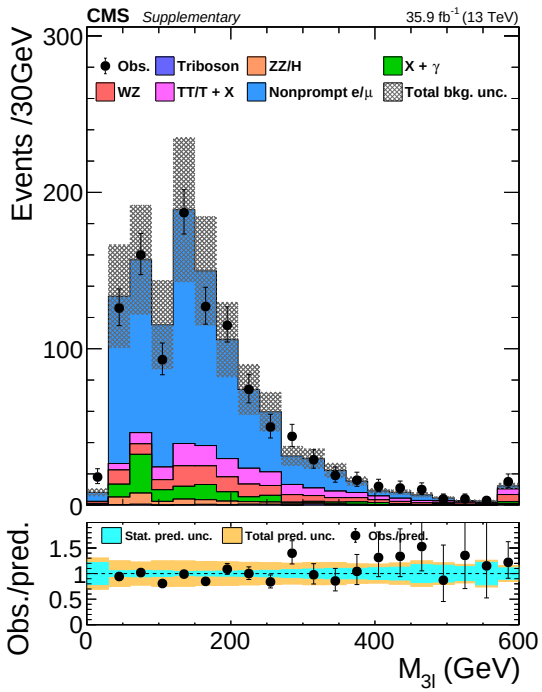
2. for misidentified electrons:

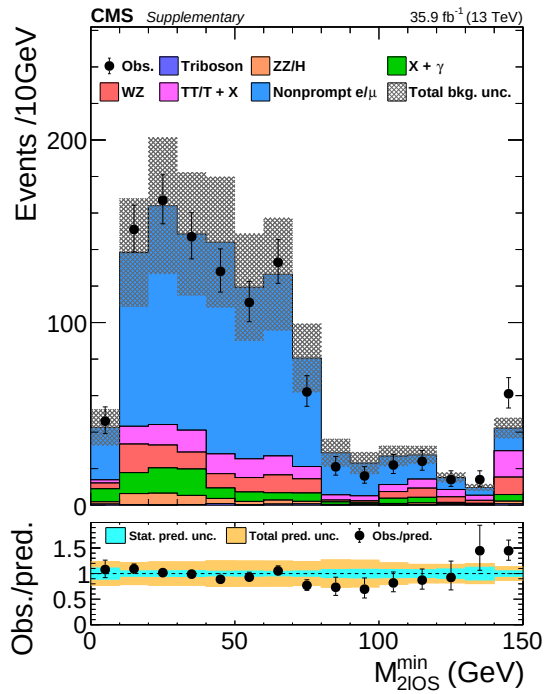
- include into *loose* electron definition ID interpolation
- select it in such a way that numerically f for heavy-flavor decays and misidentification is the same

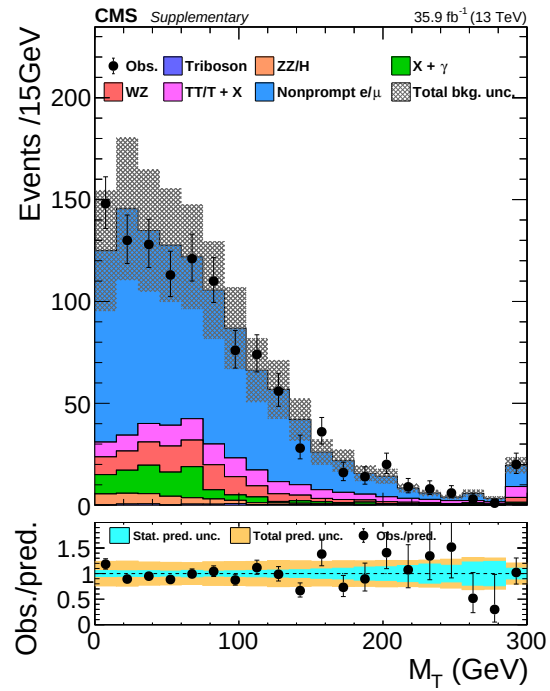
Validation: nonprompt leptons from $t\bar{t}$

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

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



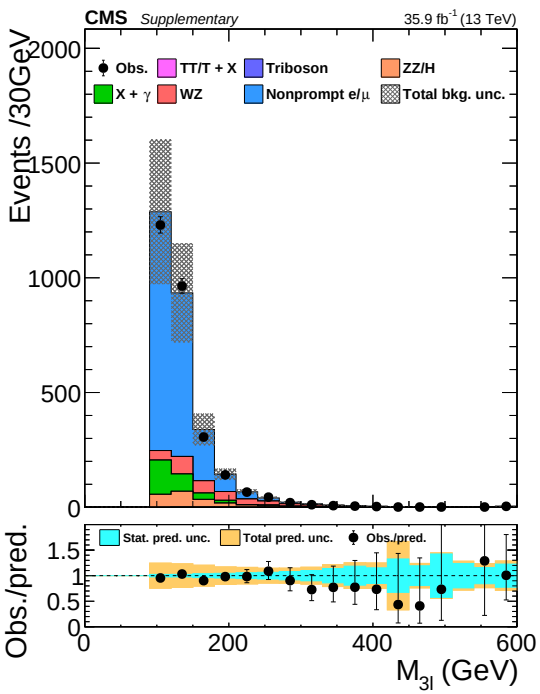


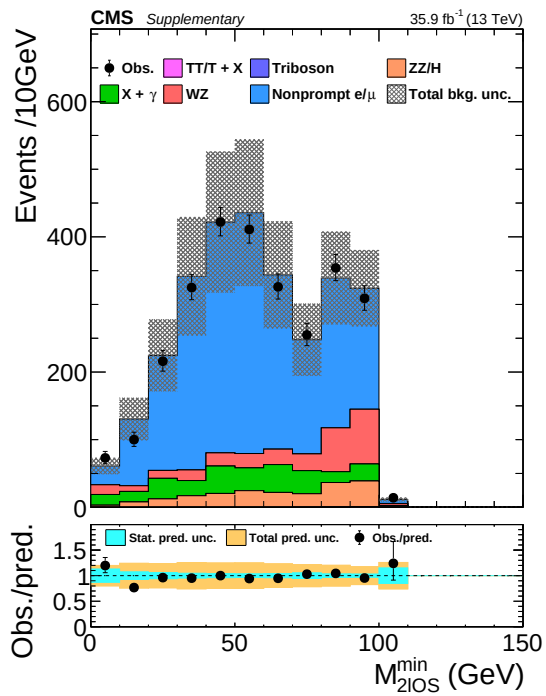


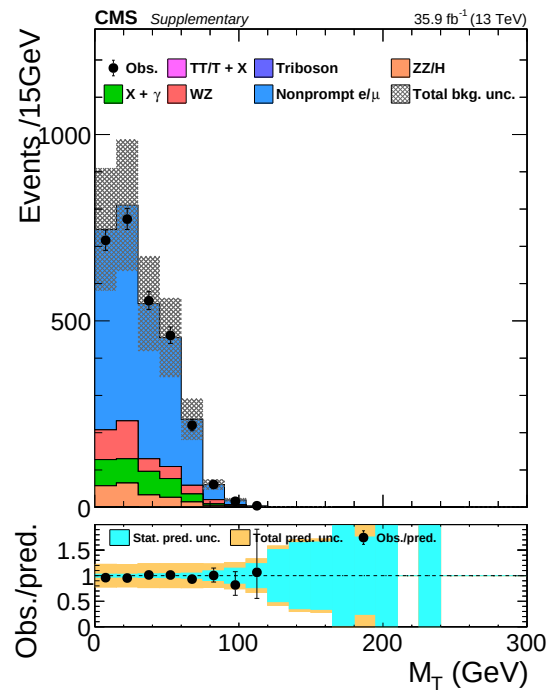
Validation: nonprompt leptons from DY

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

- OSSF pair present;
- $|M_{\ell\ell} - m_{\mathrm{Z}}| < 15$ GeV;
- $|M_{3\ell} - m_{\mathrm{Z}}| > 15$ GeV;
- 0 b-jets;
- $p_{\mathrm{T}} > 15, 10, 5(10)$ GeV;
- $E_{\mathrm{T}}^{\mathrm{miss}} < 30$ GeV;
- $M_{\mathrm{T}} < 30$ GeV





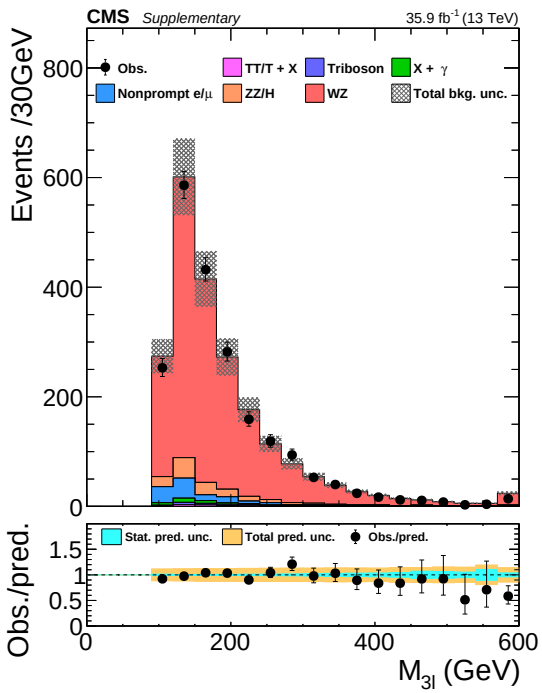


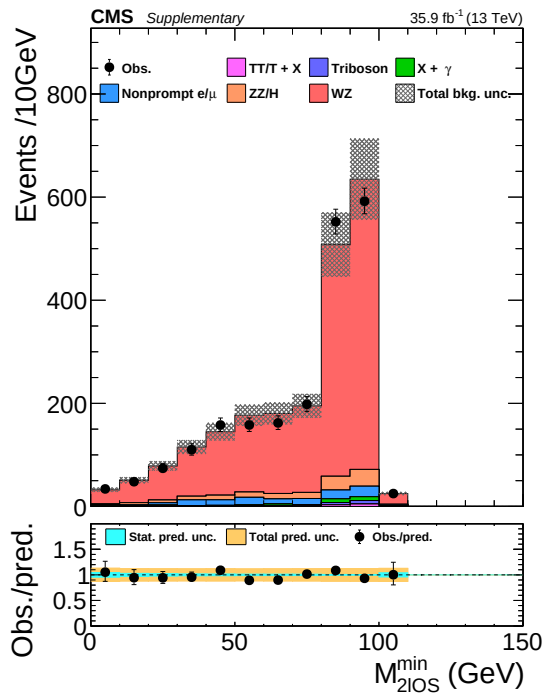
SM backgrounds: WZ

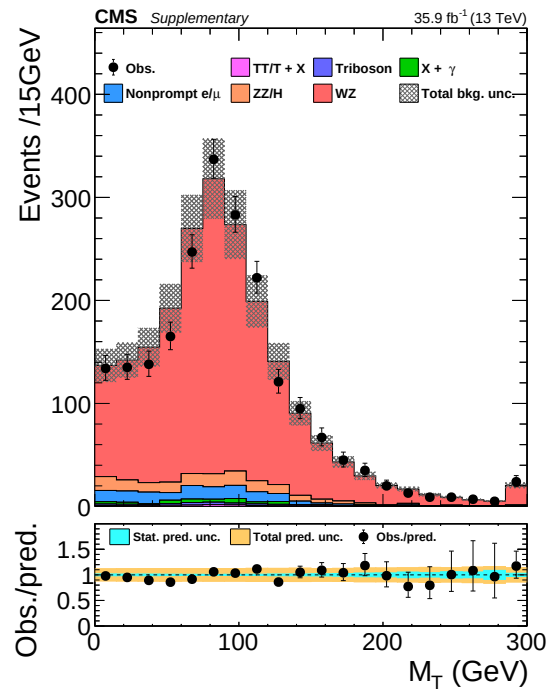
Subdominant background in most regions: important only in high-mass SR with OSSF.

- derive process normalization
- measured SF = 1.08 ± 0.09

- OSSF pair present;
- $|M_{\ell\ell} - m_{\mathrm{Z}}| < 15$ GeV;
- $|M_{3\ell} - m_{\mathrm{Z}}| > 15$ GeV;
- 0 b-jets;
- $p_{\mathrm{T}} > 25, 15, 10$ GeV;
- $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV;





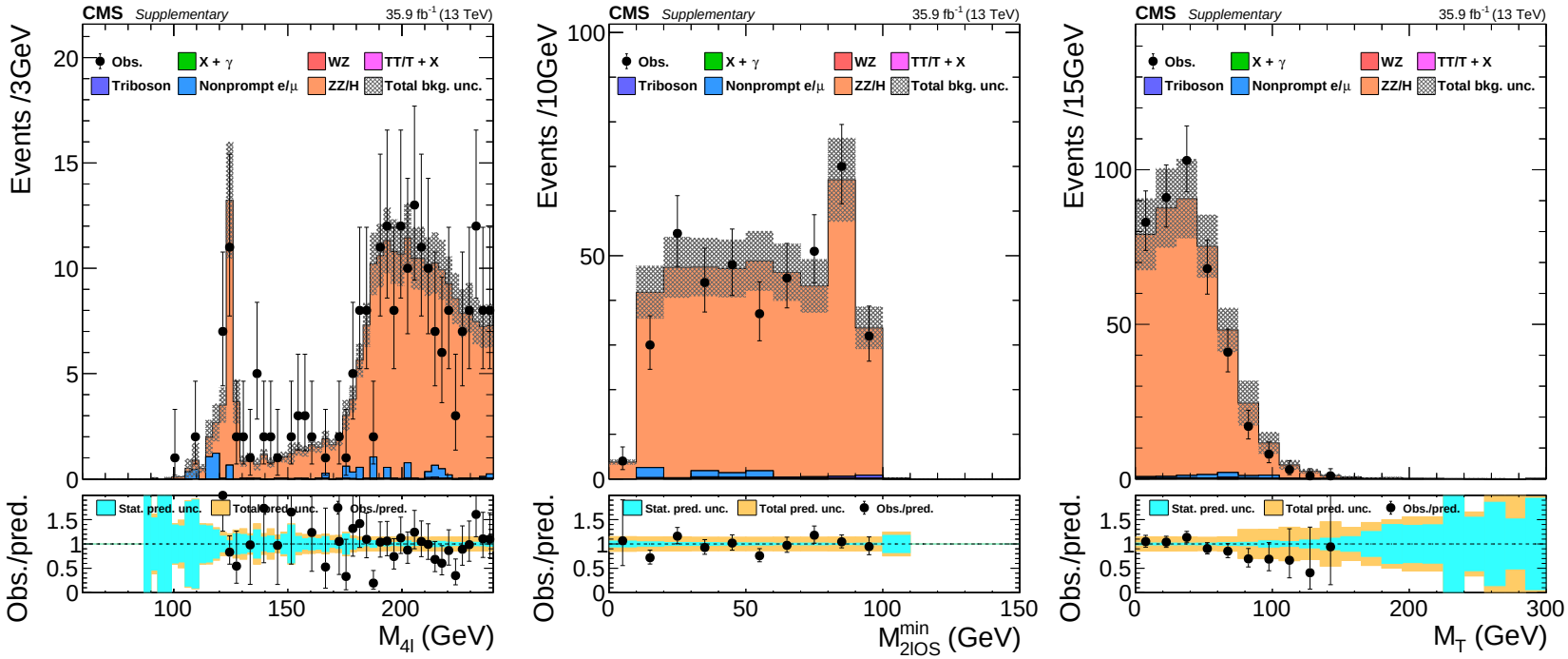


SM backgrounds: ZZ

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

- derive process normalization
- measured SF = 1.03 ± 0.10
- additional uncertainty for $M_{\mathrm{T}} > 75$ GeV

- 2 OSSF pairs present;
- $|M_{\ell\ell} - m_{\mathrm{Z}}| < 15$ GeV for both;
- 0 b-jets;
- $p_{\mathrm{T}} > 15, 10, 5(10)$ GeV;

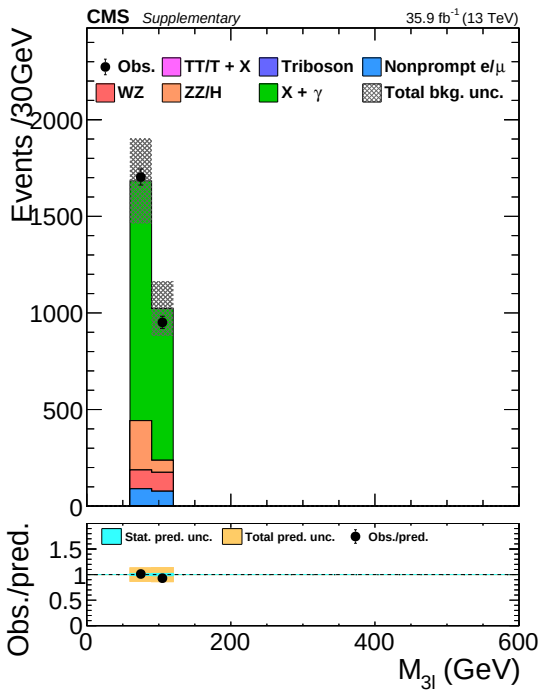


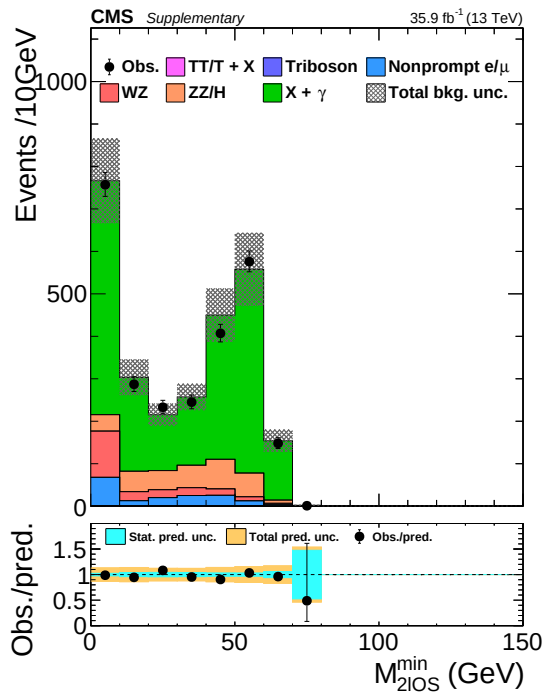
SM backgrounds: conversions

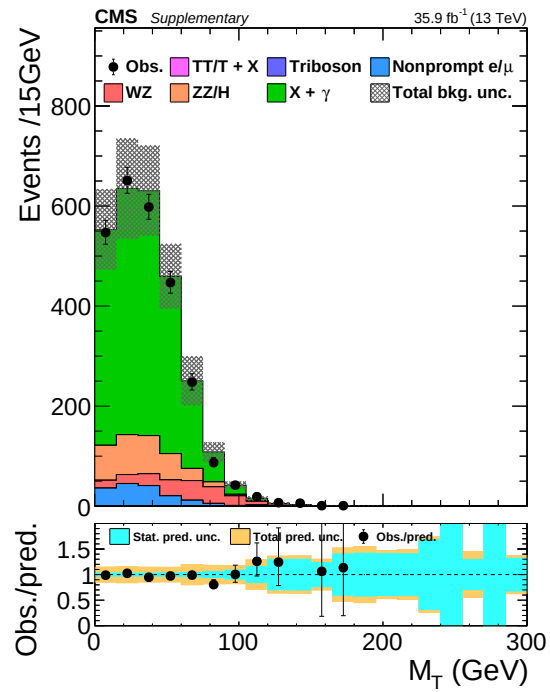
Subdominant background: more important for electron channel (external conversions).

- derive process normalization
- measured SF = 0.95 ± 0.08

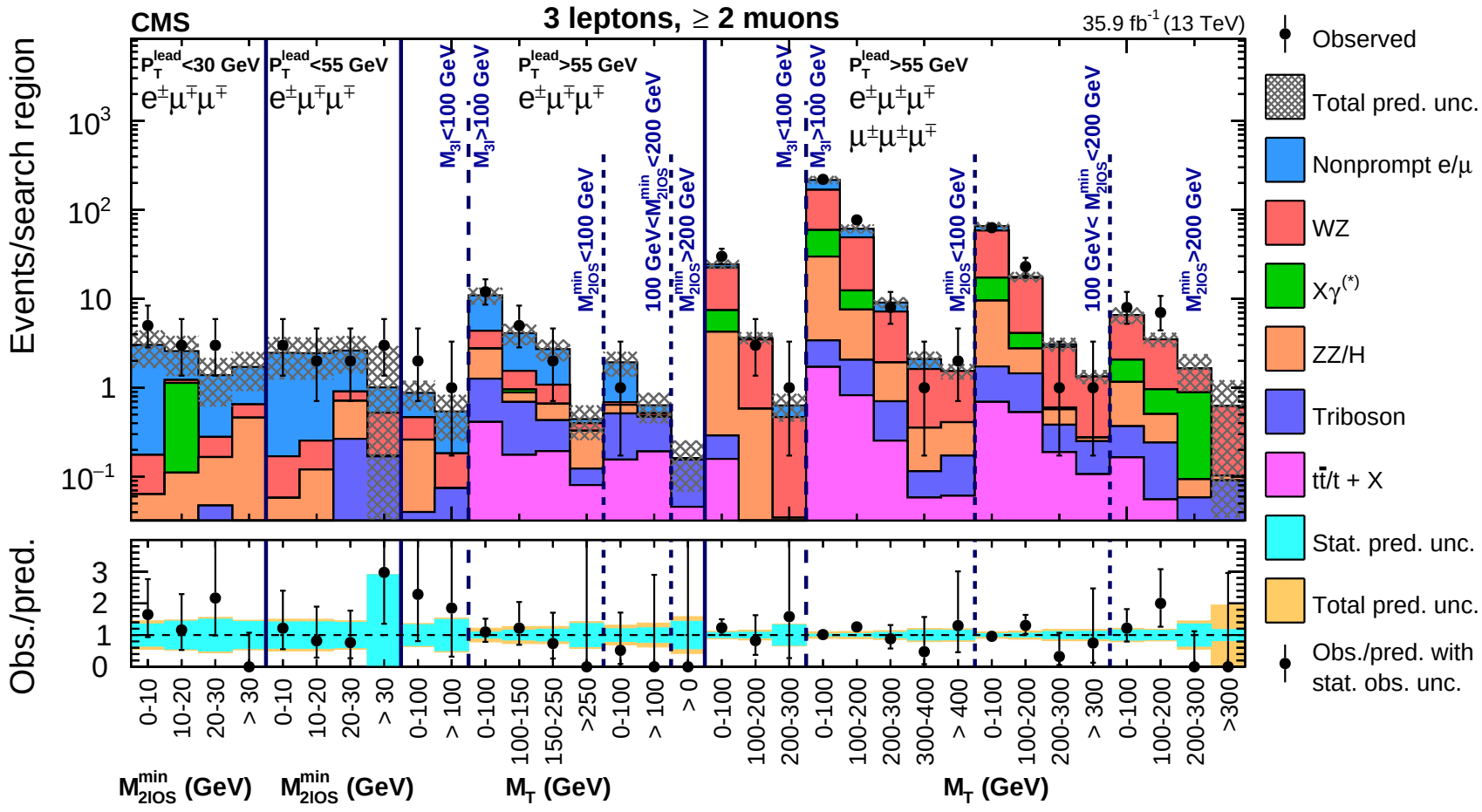
- OSSF pair present;
- $|M_{\ell\ell} - m_{\mathrm{Z}}| > 15$ GeV;
- $|M_{3\ell} - m_{\mathrm{Z}}| < 15$ GeV;
- 0 b-jets;
- $p_{\mathrm{T}} > 15, 10, 5(10)$ GeV;







All search regions: muon coupling

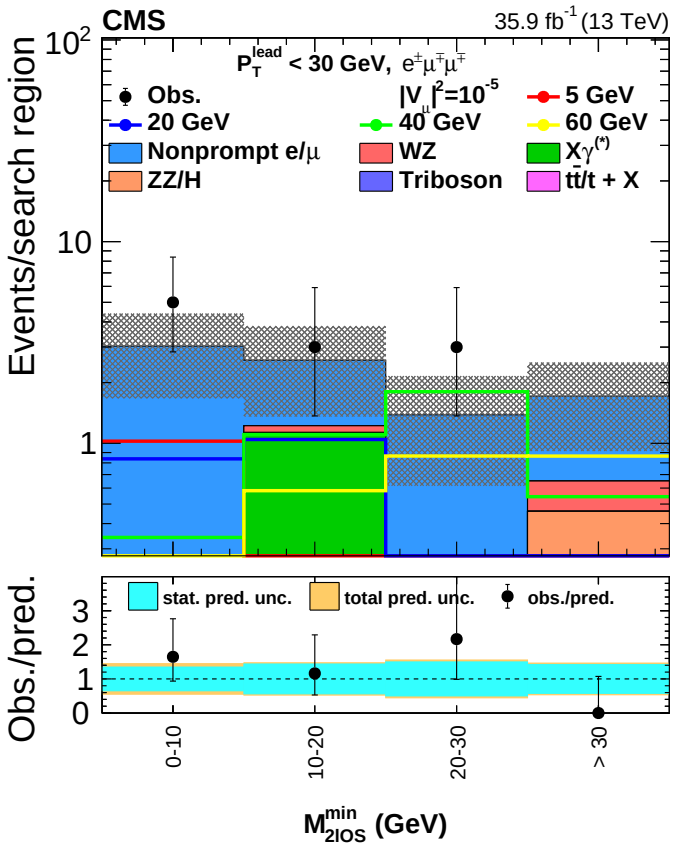


low mass search **high mass search**

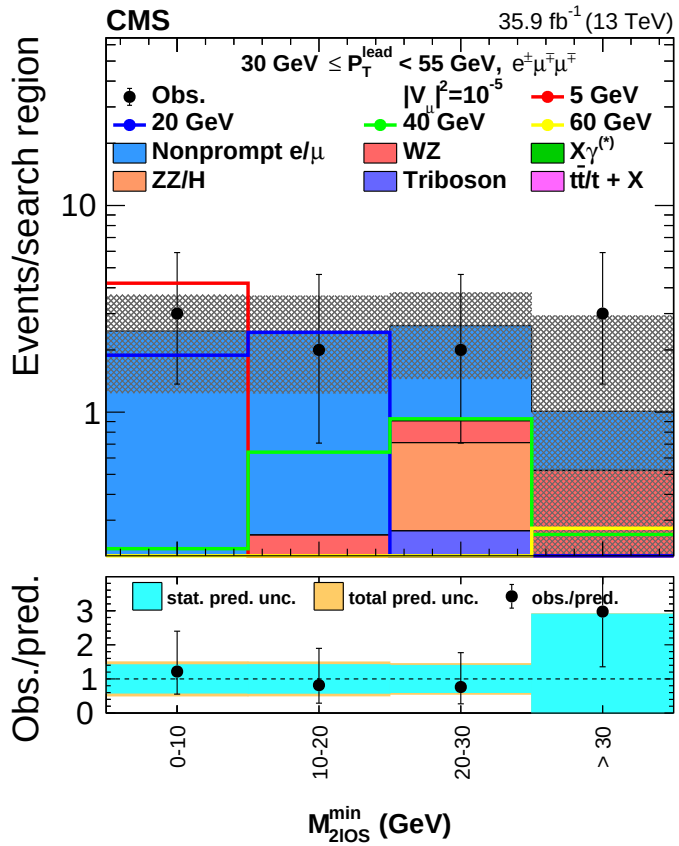
Muon coupling: deciphering

Low mass search

$15 < p_{\mathrm{T}}^{\mathrm{lead}} < 30$ GeV



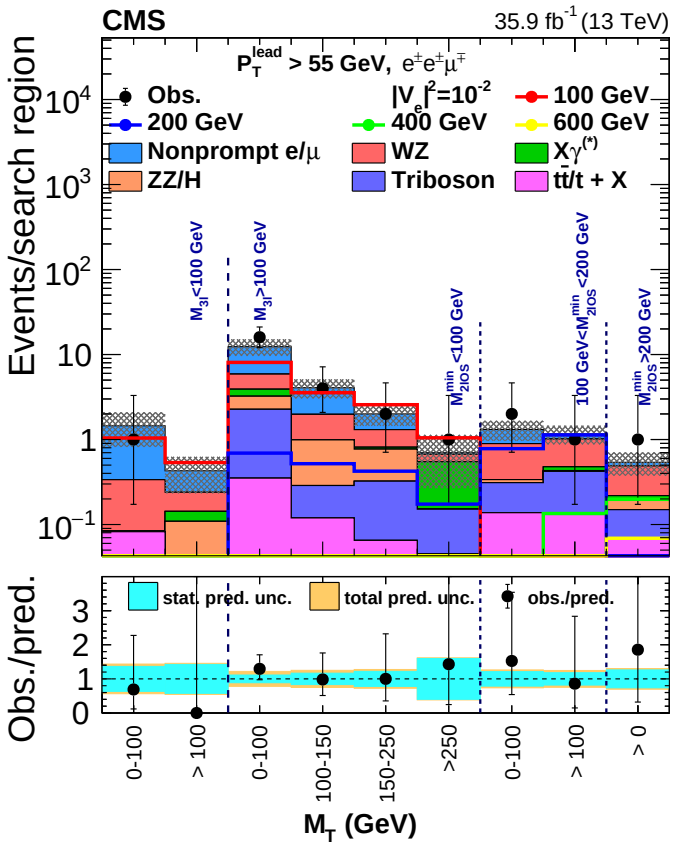
$30 < p_{\mathrm{T}}^{\mathrm{lead}} < 55$ GeV



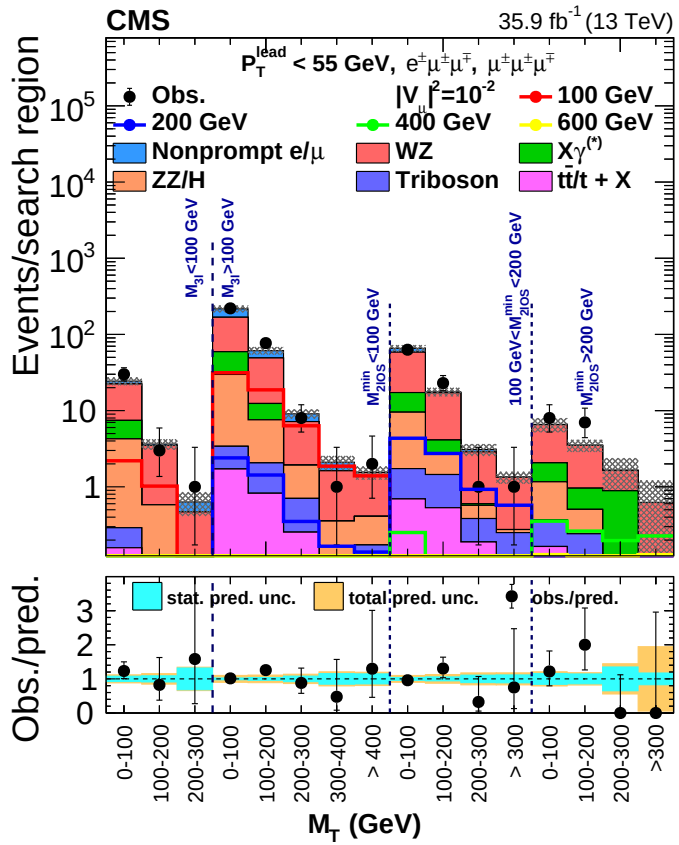
Muon coupling: deciphering

High mass search

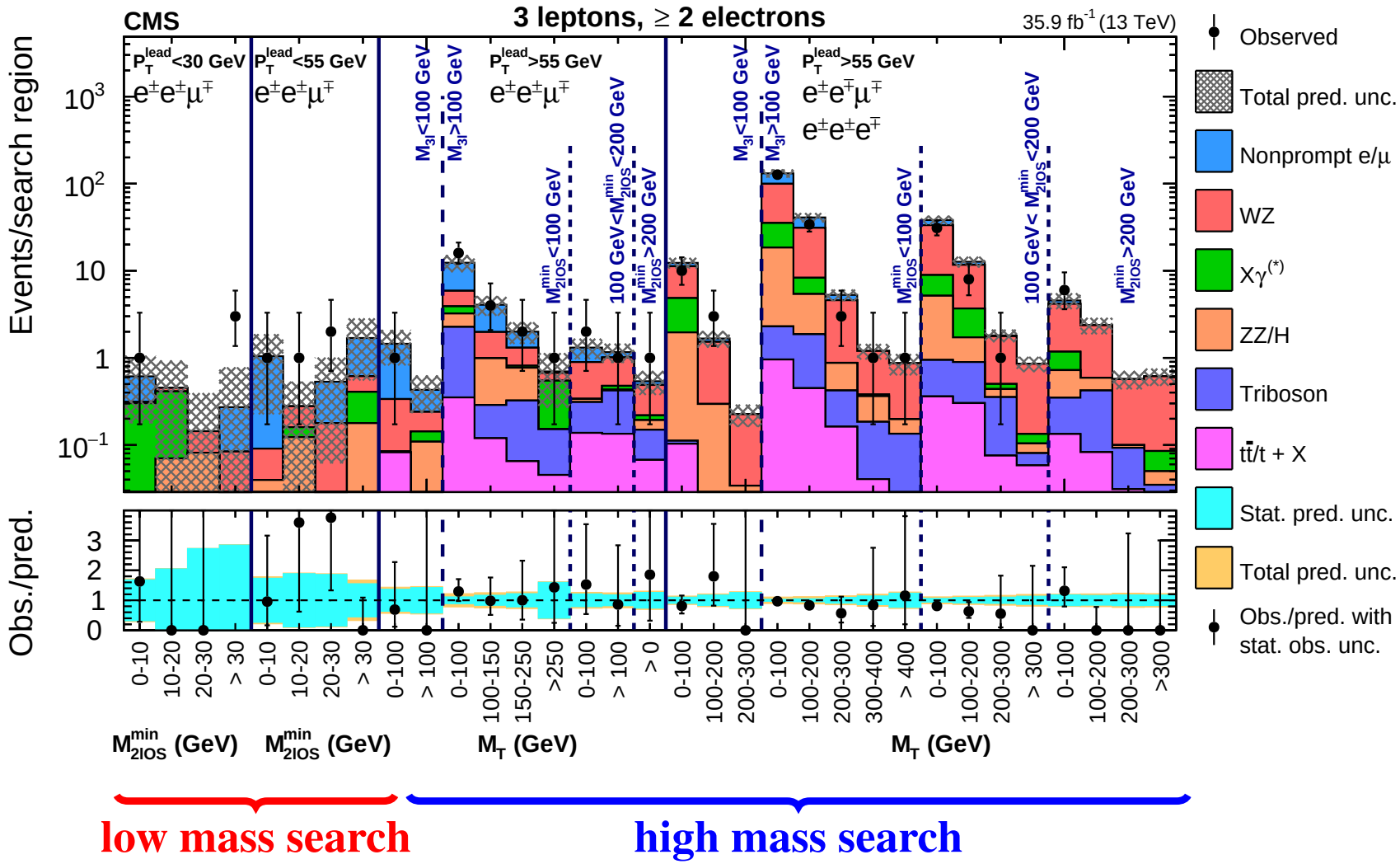
w/o OSSF leptons



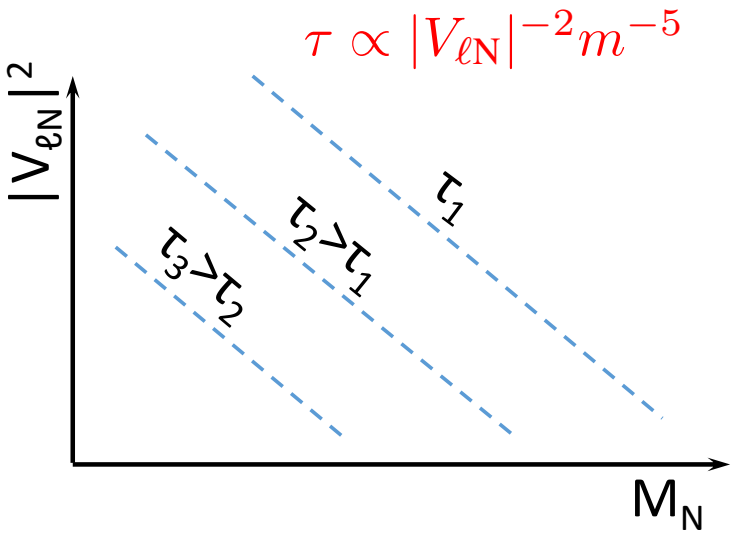
with OSSF leptons



All search regions: electron coupling

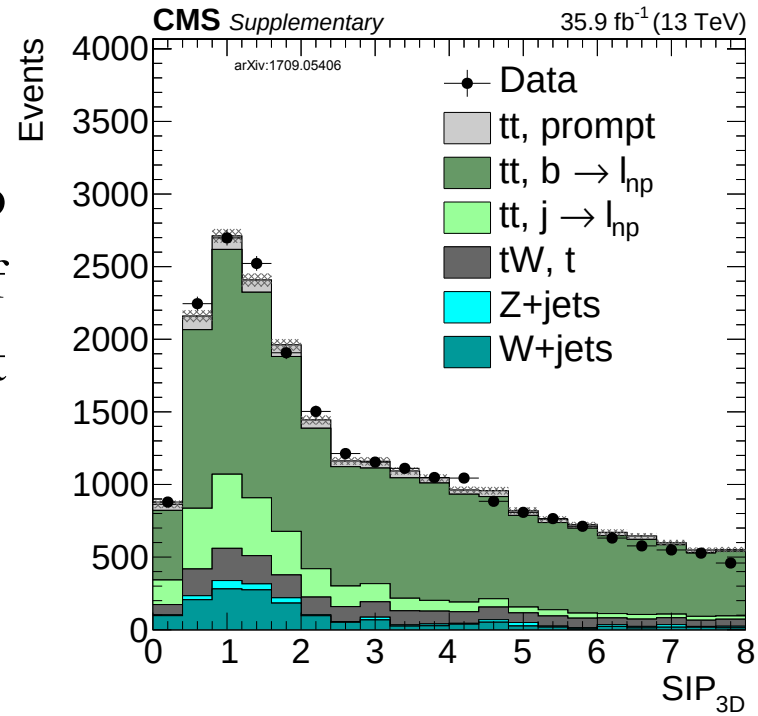


Lifetime correction

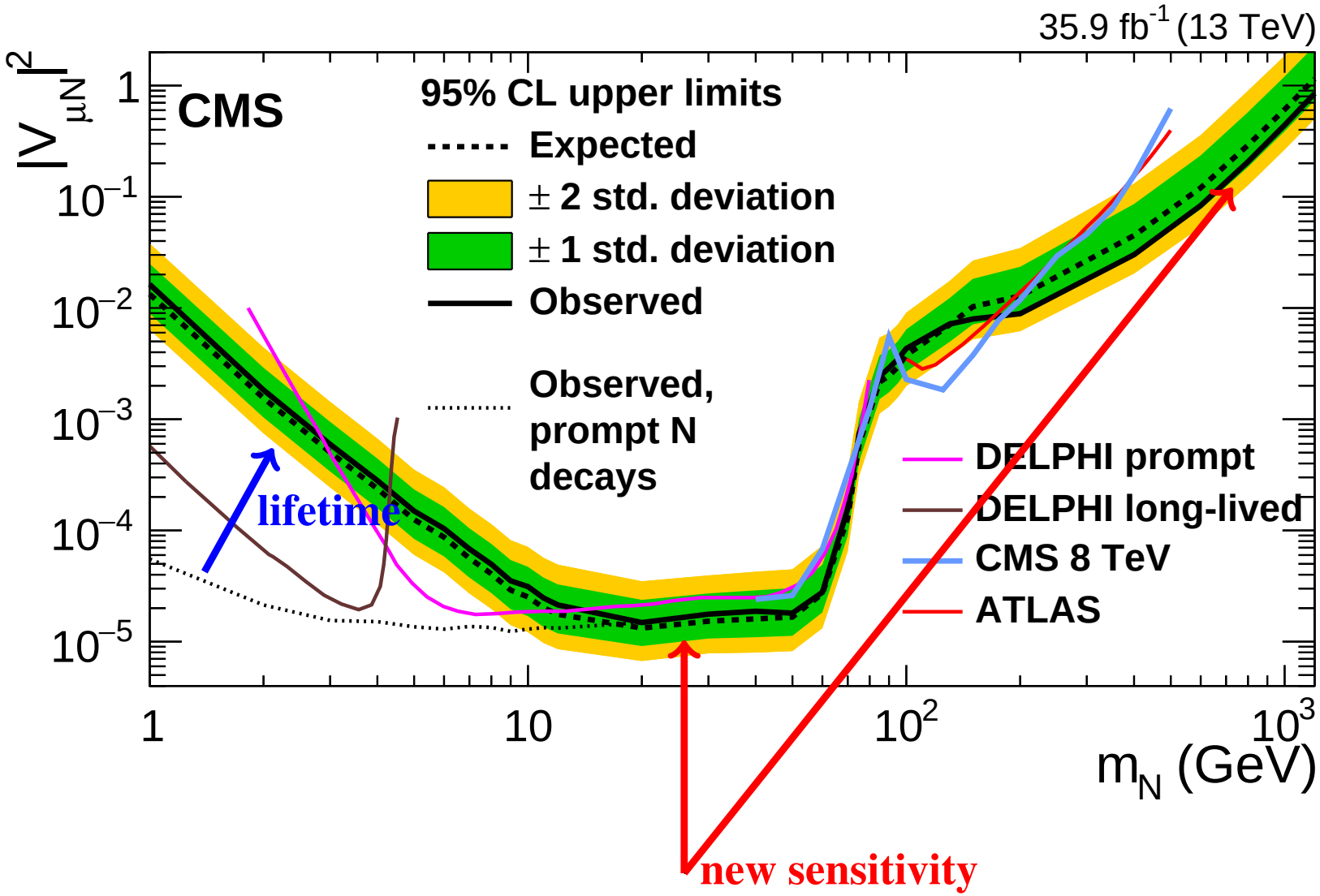


- if N are light or weakly coupled they travel macroscopical distance in the detector
- signal goes out of the analysis acceptance
- final sensitivity to $|V_{\ell N}|^2$ degrades
- effect is partially compensated by signal cross section growth $\propto |V_{\ell N}|^2$

Signal acceptance correction due to lifetime relies on good description of lepton pointing variables, e.g. impact parameter significance SIP_{3D}

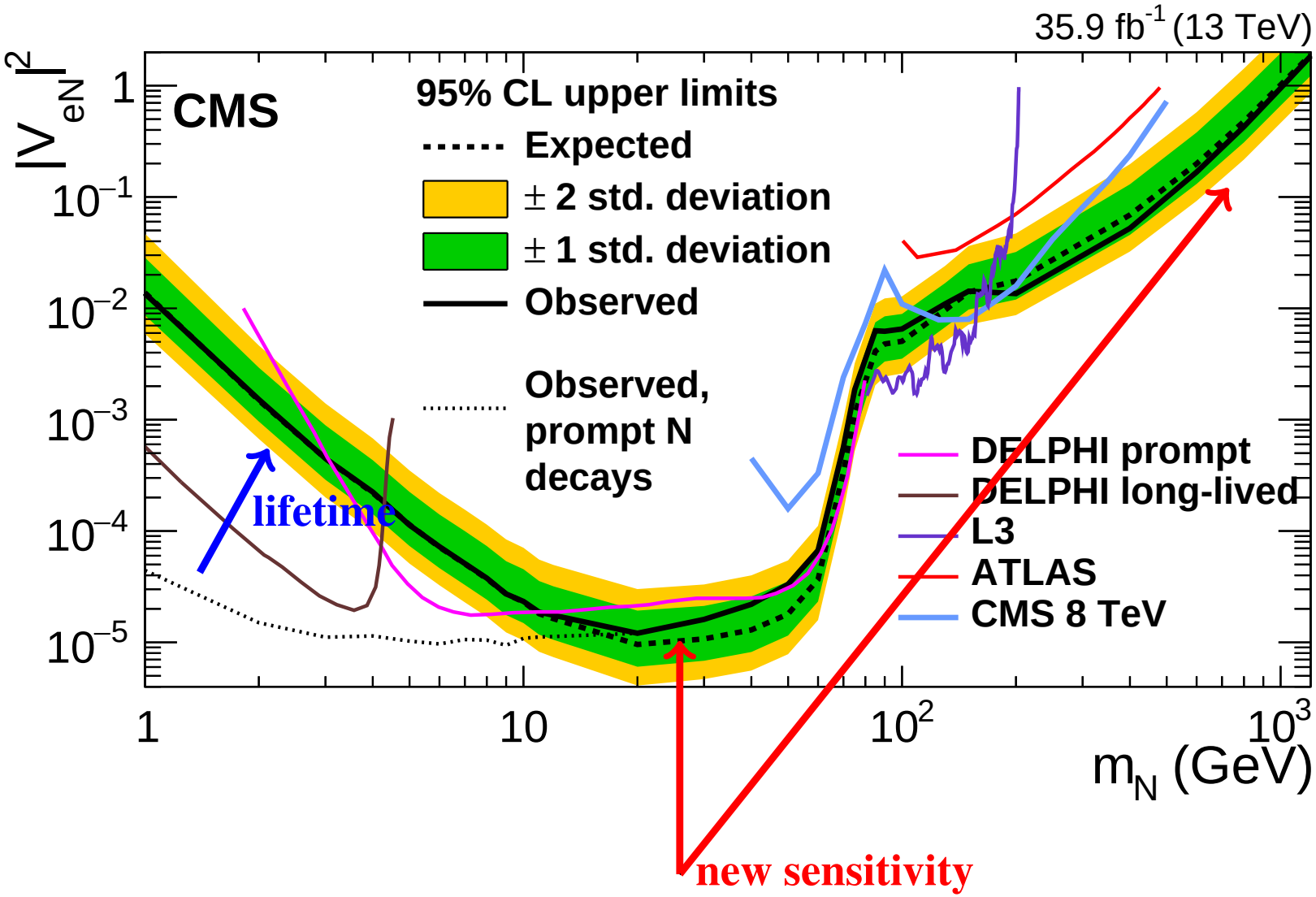


Final results: coupling to muons (LNV scenario)



High mass: VBF production channel drives production cross section.

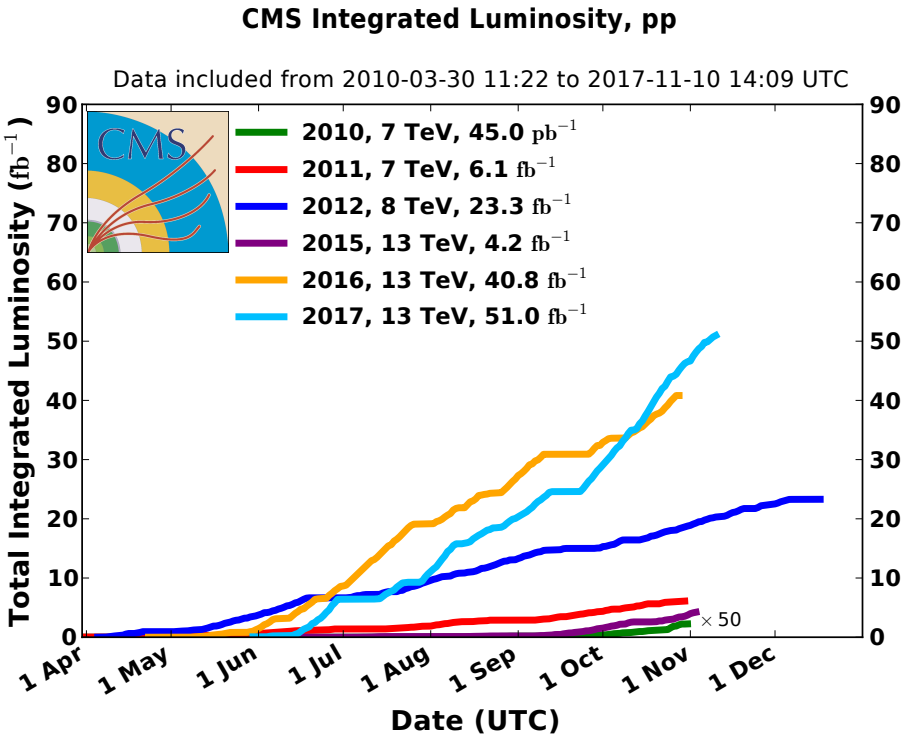
Final results: coupling to electrons (LNV scenario)



High mass: VBF production channel drives production cross section.

New era of searches at the LHC

- the amount of data collected up to now at LHC opens the possibility to search for **very rare processes**
- more data to be collected in next years will allow to explore a lot of new territory



- making use of the capability of CMS to trigger on and reconstruct soft leptons enables, for the first time at the LHC, to probe **Heavy Neutral Leptons at low mass**
- significantly lower couplings at low masses will become accessible by extending the analysis to incorporate **displaced signatures**

The opportunities for discoveries at LHC are by far not over!

Analysis 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 $M_{\mathrm{T}} > 75$ GeV	25	normalization
Scale variations for signal processes	1–2	shape

Analysis triggers

channel	HLT paths
3e	HLT_Ele16_Ele12_Ele8_CaloIdL_TrackIdL
2e, 1μ	HLT_Mu8_DiEle12_CaloIdL_TrackIdL
1e, 2μ	HLT_DiMu9_Ele9_CaloIdL_TrackIdL
3μ	HLT_TripleMu_12_10_5
2e	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ
1e, 1μ	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ
	HLT_Mu23_TrkIsoVVL_Ele8_CaloIdL_TrackIdL_IsoVL_DZ
	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ
	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL
	HLT_Mu23_TrkIsoVVL_Ele8_CaloIdL_TrackIdL_IsoVL
2μ	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ
	HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ
	HLT_TkMu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ
	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL
	HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL
	HLT_TkMu17_TrkIsoVVL_TkMu8_TrkIsoVVL
1e	HLT_Ele27_WPTight_Gsf
1μ	HLT_IsoMu24
	HLT_IsoTkMu24