Heavy neutral lepton searches at CMS and ATLAS

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on behalf of the ATLAS and CMS Collaborations

15th Rencontres du Vietnam *"3 Neutrinos and Beyond"*

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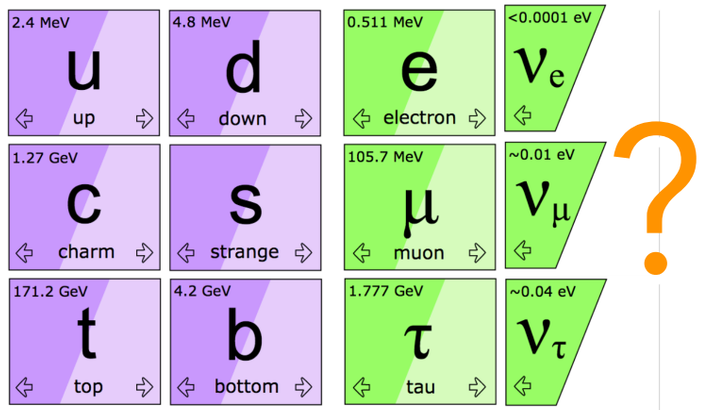
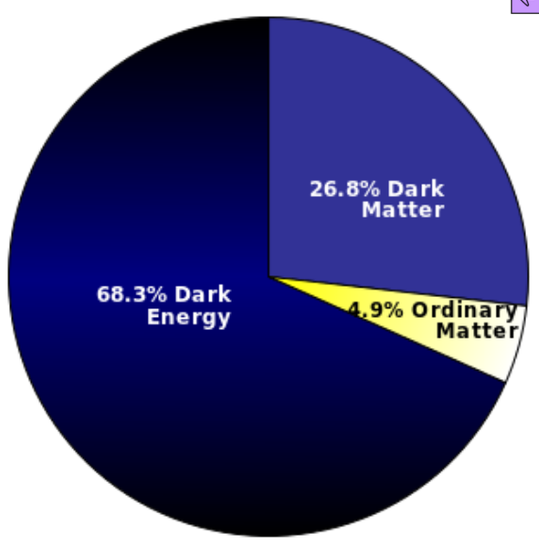
Why heavy neutral leptons?

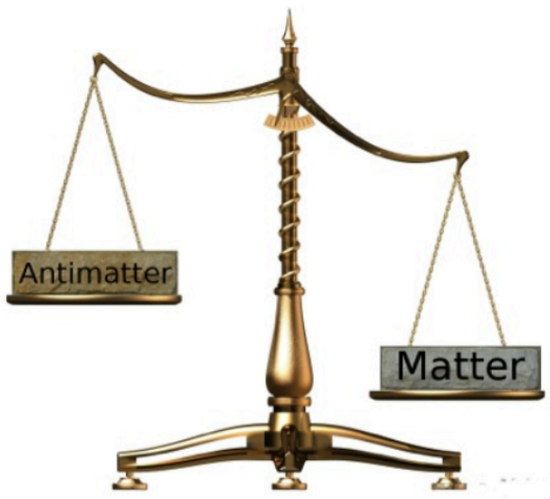
- Heavy neutral leptons (HNL) can provide an explanation to several unanswered questions, such as...
  - ... neutrino masses
    - generated via a seesaw mechanism



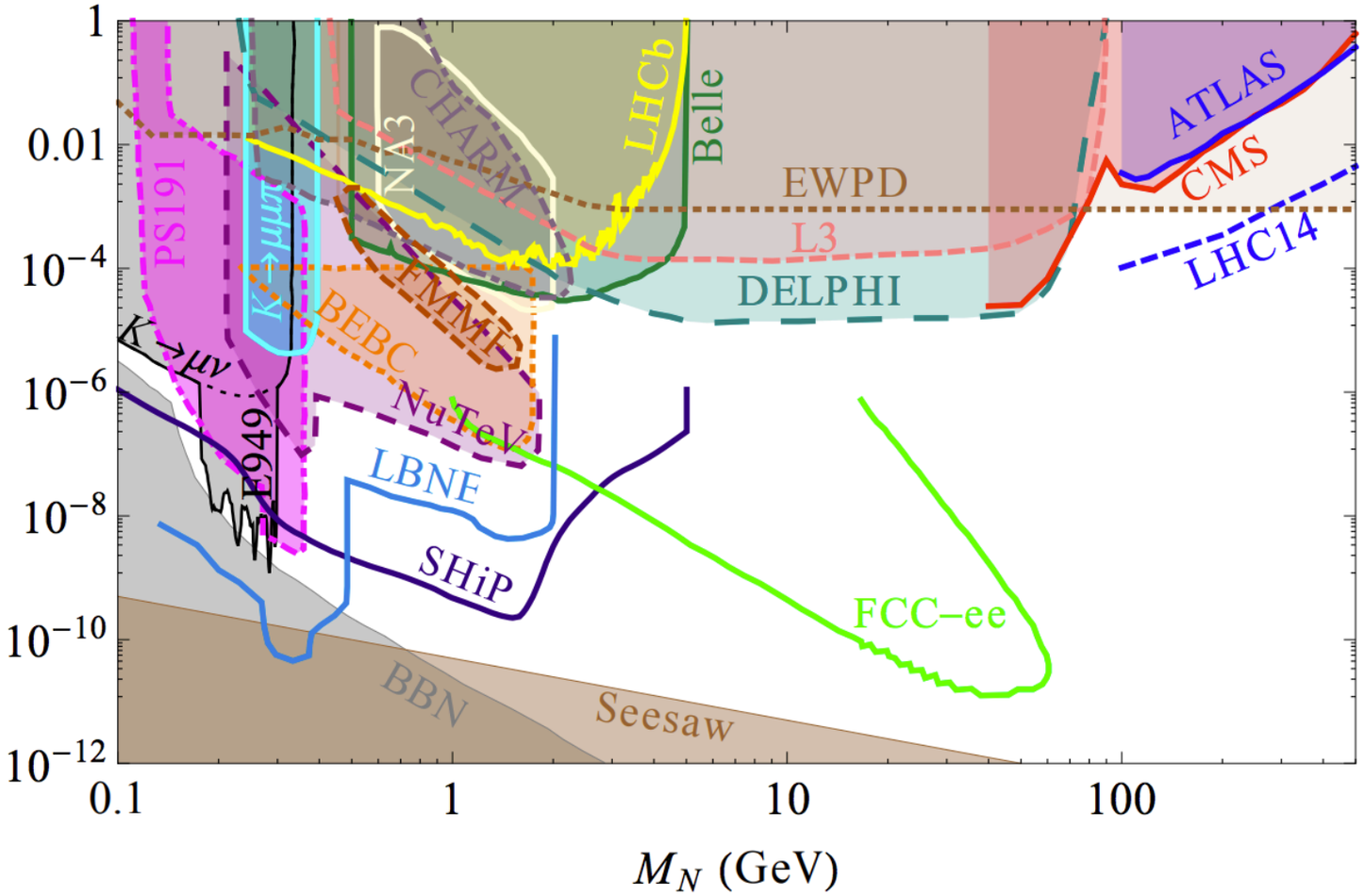
  - ... dark matter
    - the lightest HNL might make a suitable candidate



  - ... matter-antimatter asymmetry of the universe
    - multiple mass-degenerate HNLs may lead to a significant CP violation



Direct HNL searches



arXiv:1502.06541 [hep-ph]

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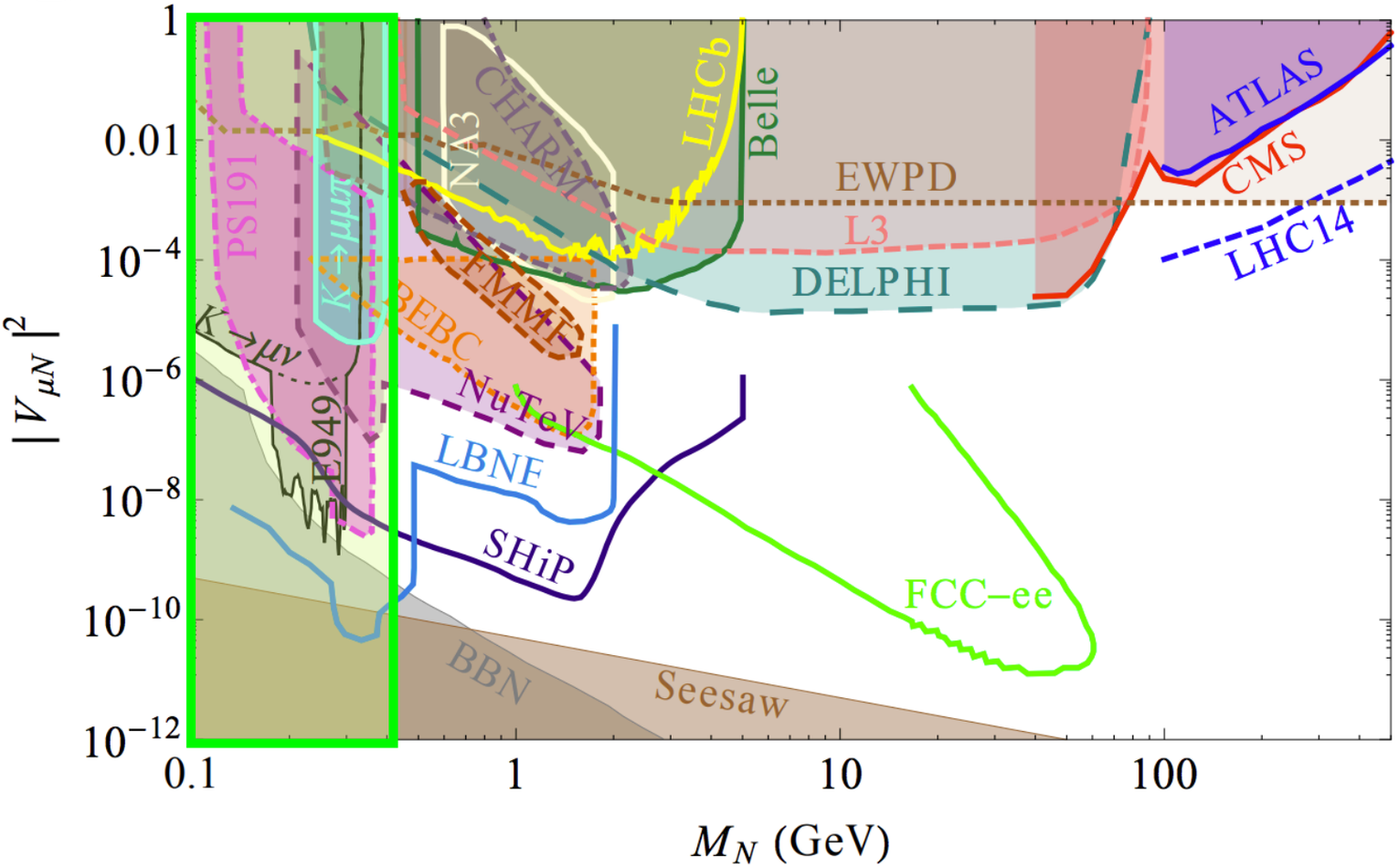

- $m_N < m_K$ (~500 MeV)
- Using K decays, such as $K^{\pm} \to \ell N$, $K^{\pm} \to \mu\mu\pi$
- E.g. beam-dump exp. (NuTeV, NA62, SHiP...)

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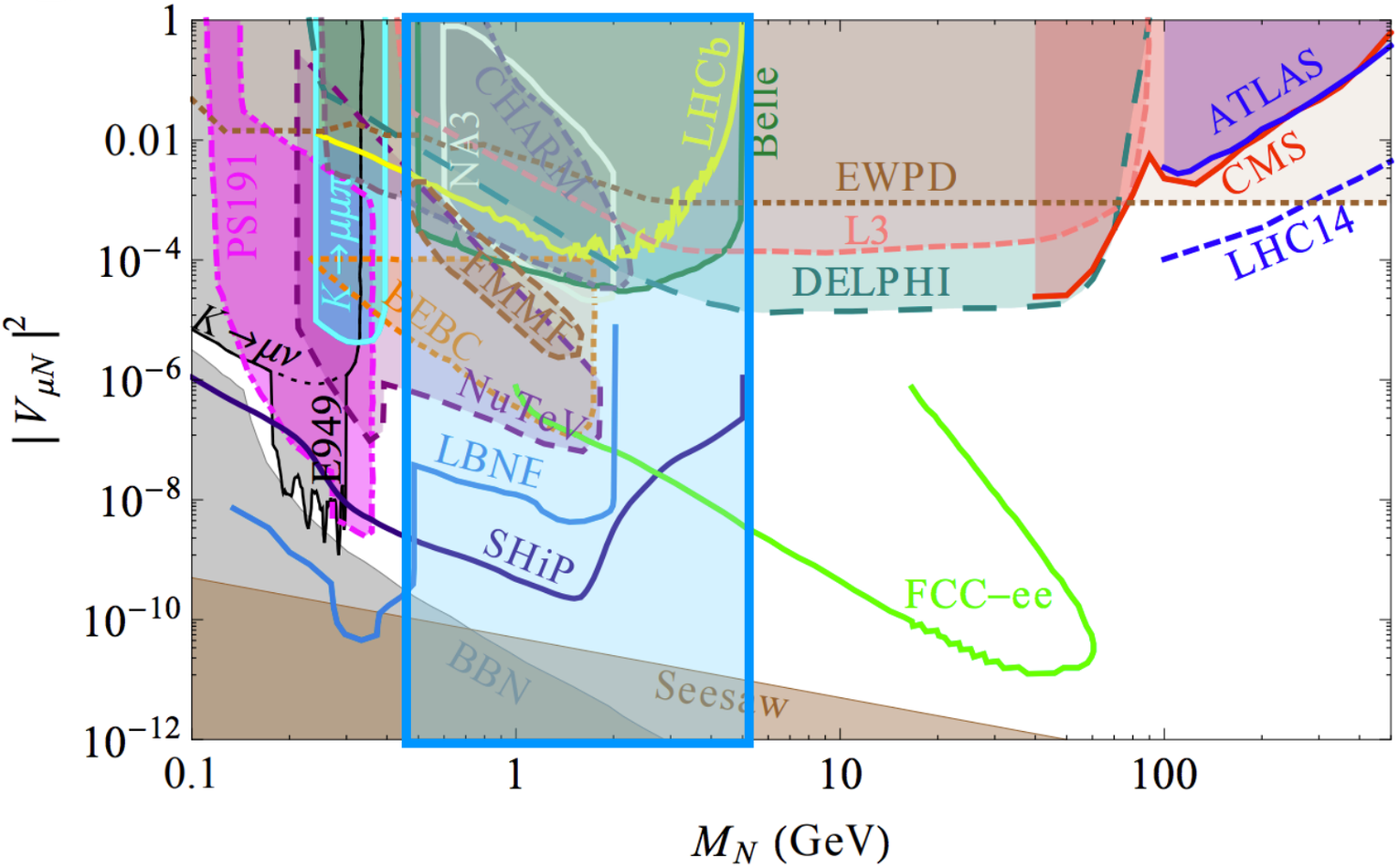

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- Explored at colliders (e.g. Belle, LHC*b*) or beam-dump experiments (e.g. SHiP)

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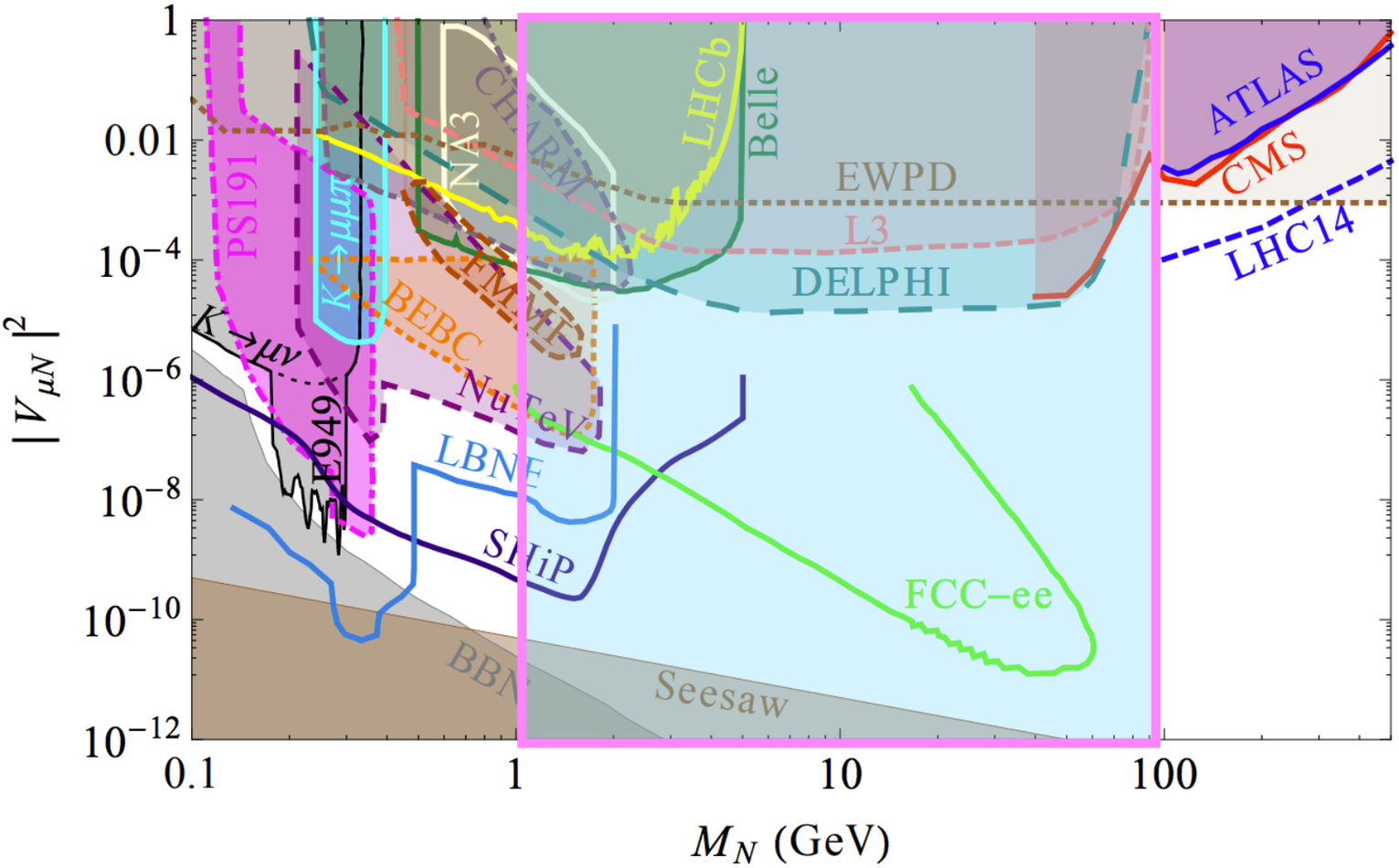

- $m_N < m_Z$ (~91 GeV)
- Results from LEP ($Z \to \nu N$)
- Currently explored at the LHC (ATLAS, CMS)

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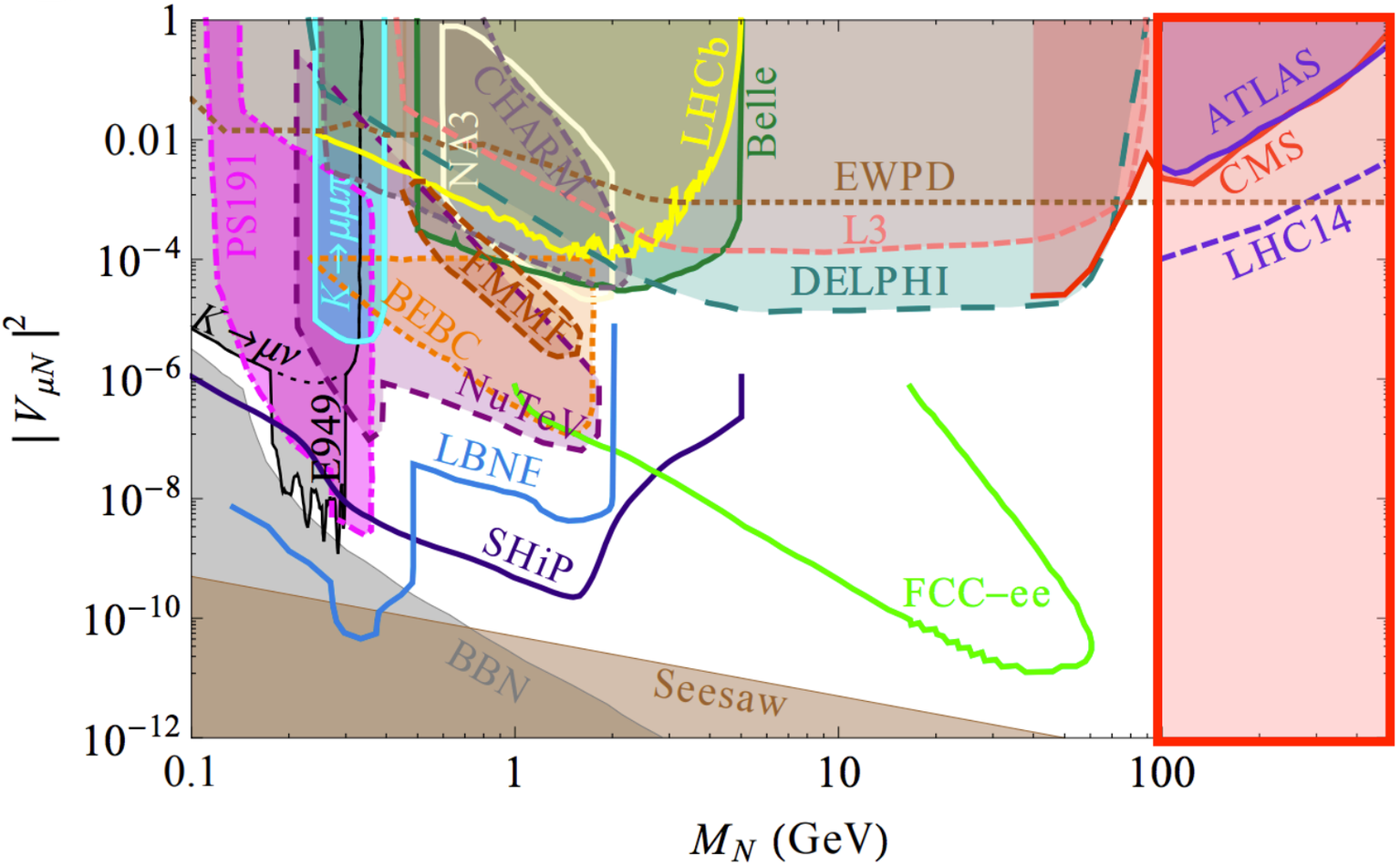

- $m_N > m_Z$ (~91 GeV)
- LHC can exceed the limits from electroweak precision data

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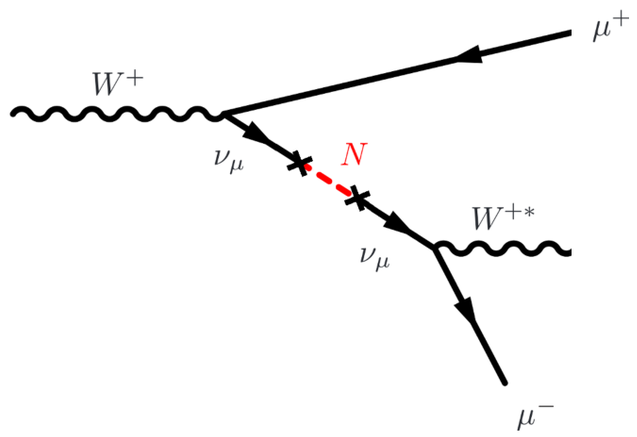
Main searches at the LHC

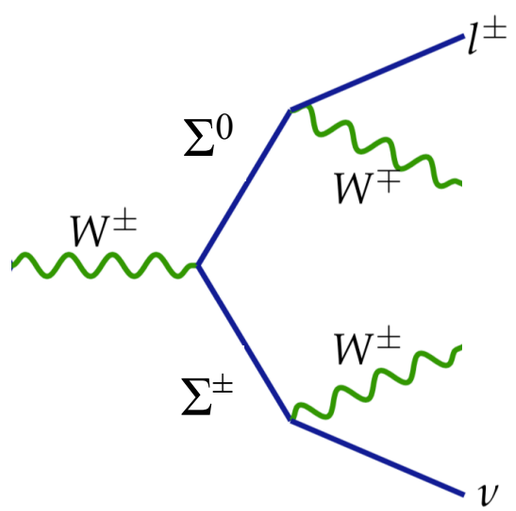
	ATLAS	CMS
Type-I seesaw	Search for heavy Majorana neutrinos with the ATLAS detector in pp collisions at √s = 8 TeV, JHEP07(2015)162	Search for heavy Majorana neutrinos in $\mu^{\pm}\mu^{\pm}$ + jets events in proton-proton collisions at √s = 8 TeV, PLB748(2015)144
	Search for heavy neutral leptons in decays of W bosons produced in 13 TeV pp collisions using prompt and displaced signatures with the ATLAS detector, arXiv:1905.09787	Search for heavy Majorana neutrinos in $e^{\pm}e^{\pm}$ + jets and $e^{\pm}\mu^{\pm}$ + jets events in proton-proton collisions at √s = 8 TeV, JHEP(2016)2016:169
		Search for Heavy Neutral Leptons in Events with Three Charged Leptons in Proton-Proton Collisions at √s = 13 TeV, PRL120(2018)221801
		Search for heavy Majorana neutrinos in same-sign dilepton channels in proton-proton collisions at √s = 13 TeV, JHEP(2019)2019:122
Type-III seesaw	Search for type-III seesaw heavy leptons in pp collisions at √s = 8 TeV with the ATLAS detector, PRD92(2015)032001	Search for Evidence of the Type-III Seesaw Mechanism in Multilepton Final States in Proton-Proton Collisions at √s = 13 TeV, PRL119(2017)221802
	Search for heavy lepton resonances decaying to a Z boson and a lepton in pp collisions at √s = 8 TeV with the ATLAS detector, JHEP(2015)2015:108	
	Search for type-III seesaw heavy leptons in proton-proton collisions at √s = 13 TeV with the ATLAS detector, ATLAS-CONF-2018-020	
Left-Right Symmetric Model	Search for heavy neutrinos and right-handed W bosons in events with two leptons and jets in pp collisions at √s = 7 TeV with the ATLAS detector, EPJC(2012)72:2056	Search for heavy neutrinos and W bosons with right-handed couplings in proton-proton collisions at √s = 8TeV, EPJC(2014)74:3149
	Search for heavy Majorana neutrinos with the ATLAS detector in pp collisions at √s = 8 TeV, JHEP07(2015)162	Search for a heavy right-handed W boson and a heavy neutrino in events with two same-flavor leptons and two jets at √s = 13 TeV, JHEP05(2018)148
	Search for heavy Majorana or Dirac neutrinos and right-handed W gauge bosons in final states with two charged leptons and two jets at √s = 13 TeV with the ATLAS detector, JHEP(2019)2019:16	Search for heavy neutrinos or third-generation leptoquarks in final states with two hadronically decaying τ leptons and two jets in proton-proton collisions at √s = 13 TeV, JHEP03(2017)077
	Search for a right-handed gauge boson decaying into a high-momentum heavy neutrino and a charged lepton in pp collisions with the ATLAS detector at √s = 13 TeV, arXiv:1904.12679	Search for third-generation scalar leptoquarks and heavy right-handed neutrinos in final states with two tau leptons and two jets in proton-proton collisions at √s = 13 TeV, JHEP07(2017)121
Composite neutrino		Search for a heavy composite Majorana neutrino in the final state with two leptons and two quarks at √s = 13 TeV, PLB775(2017)315

Main models explored at the LHC

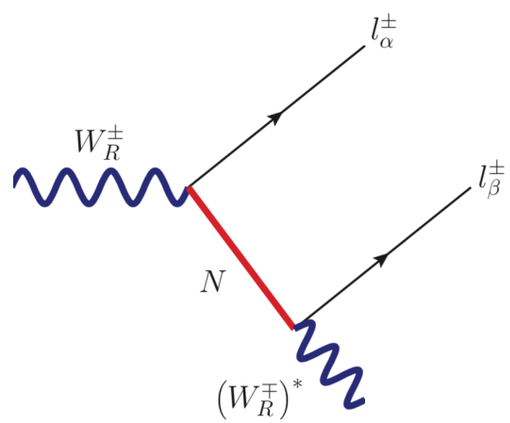
- Type-I seesaw
  - minimal SM extension: 2–3 right-handed neutrinos (N_i), Dirac and Majorana masses
  - $SU(2)_{\mathrm{L}}$ singlets ⇒ sterile, only mix with SM ν



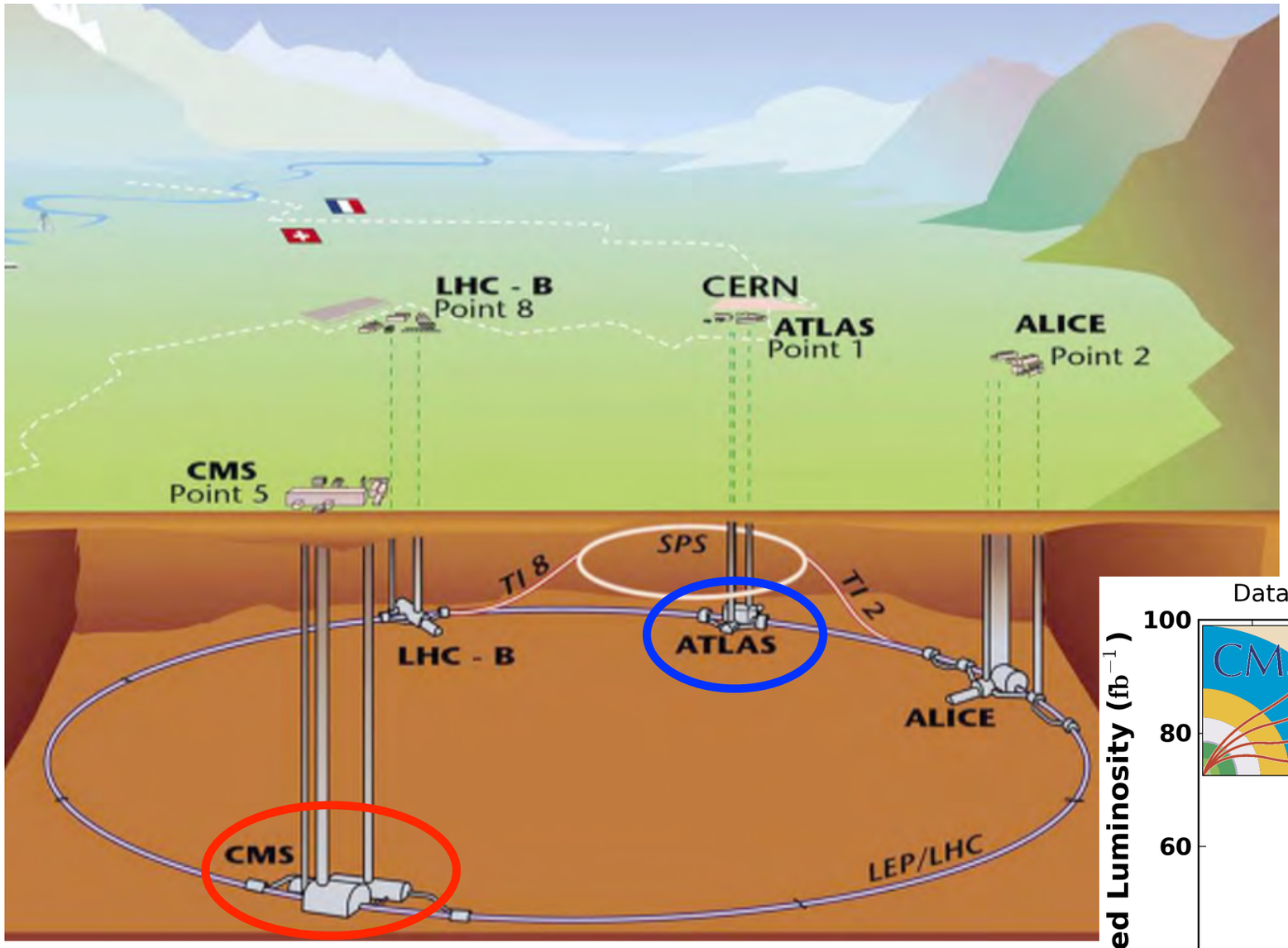
- Type-III seesaw
  - at least two $SU(2)_{\mathrm{L}}$ triplets ($\Sigma^{\pm}$, Σ^0), coupled to SM gauge bosons



- Left-Right Symmetric Models
  - $SU(2)_{\mathrm{R}}$ as right-handed analogue of $SU(2)_{\mathrm{L}}$
  - RH N_i coupled to RH gauge bosons $\mathrm{W_R}$, $\mathrm{Z_R}$

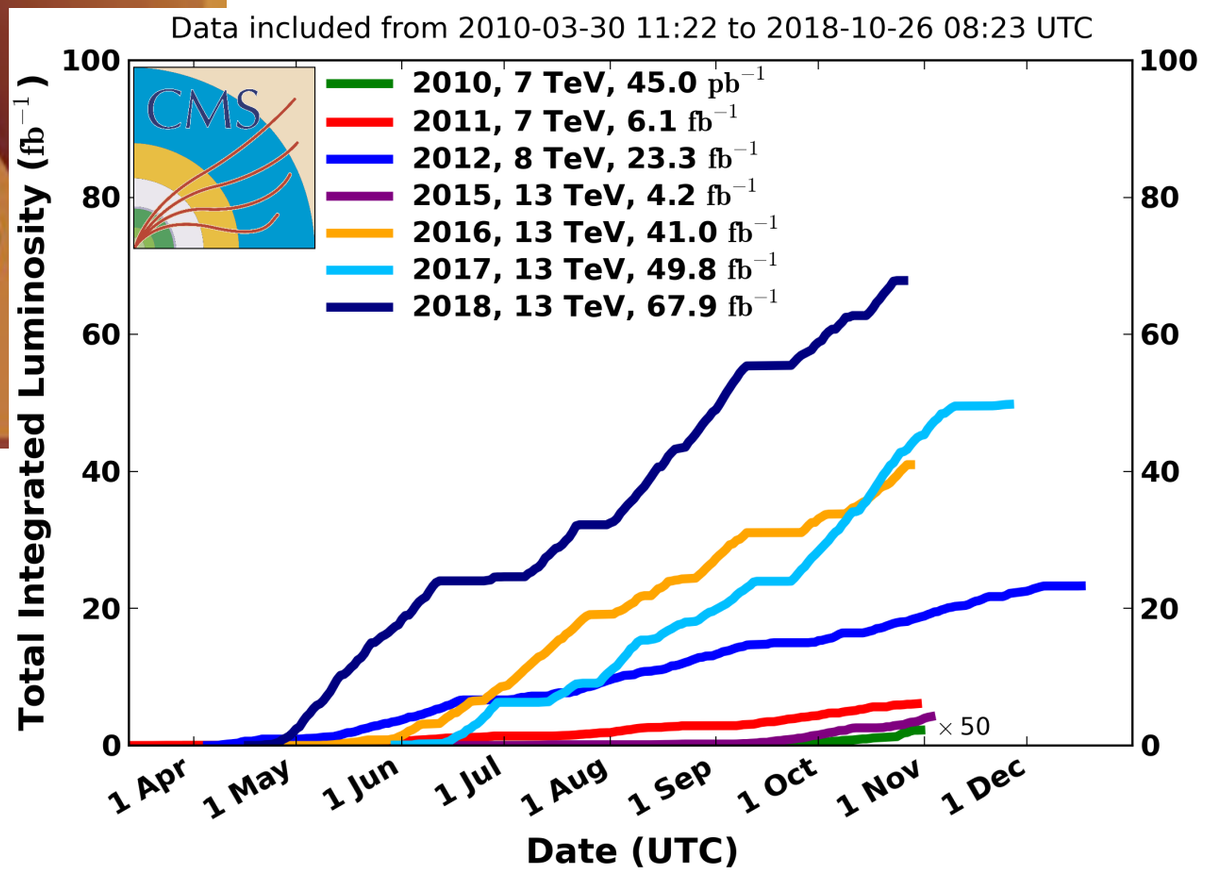


The Large Hadron Collider

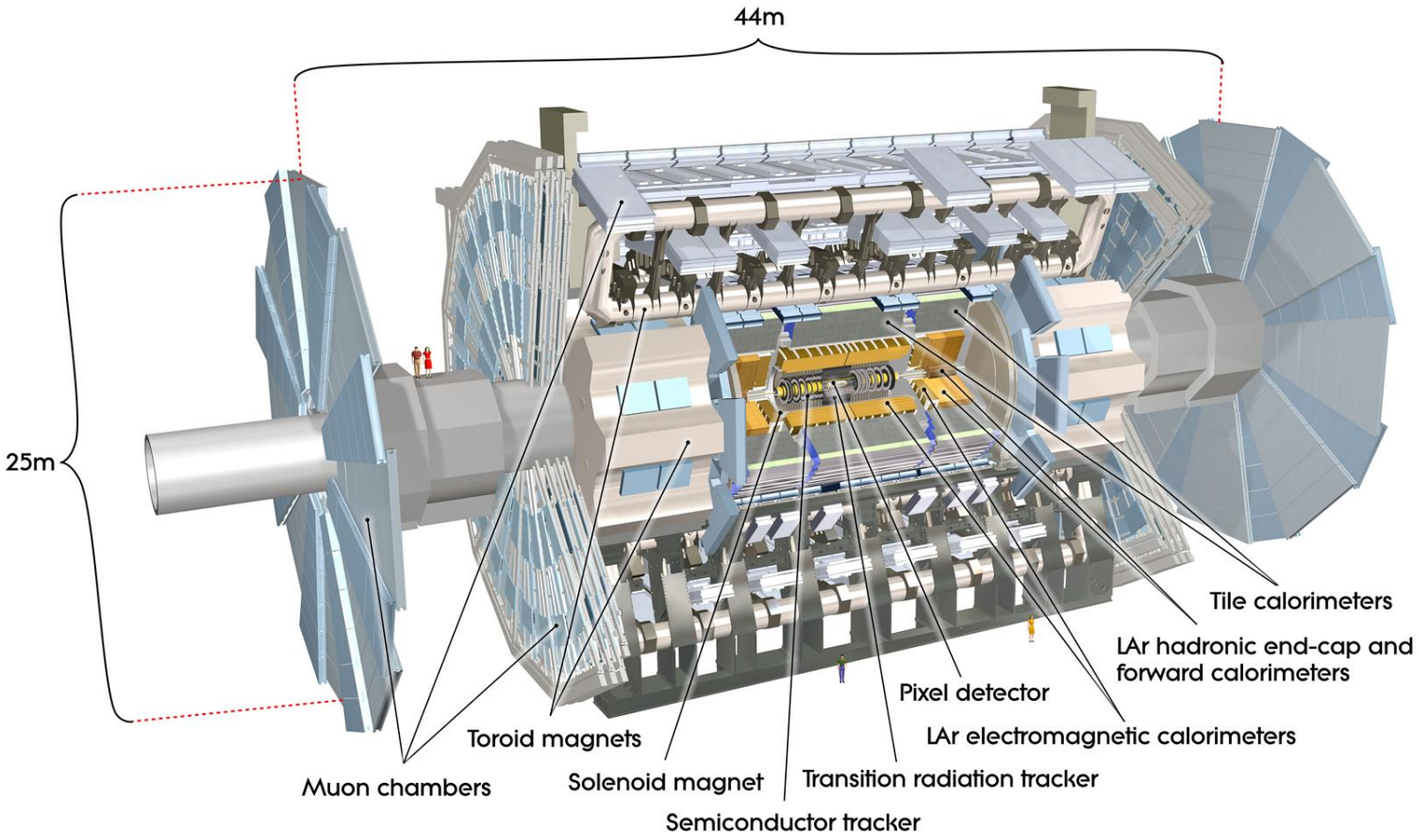


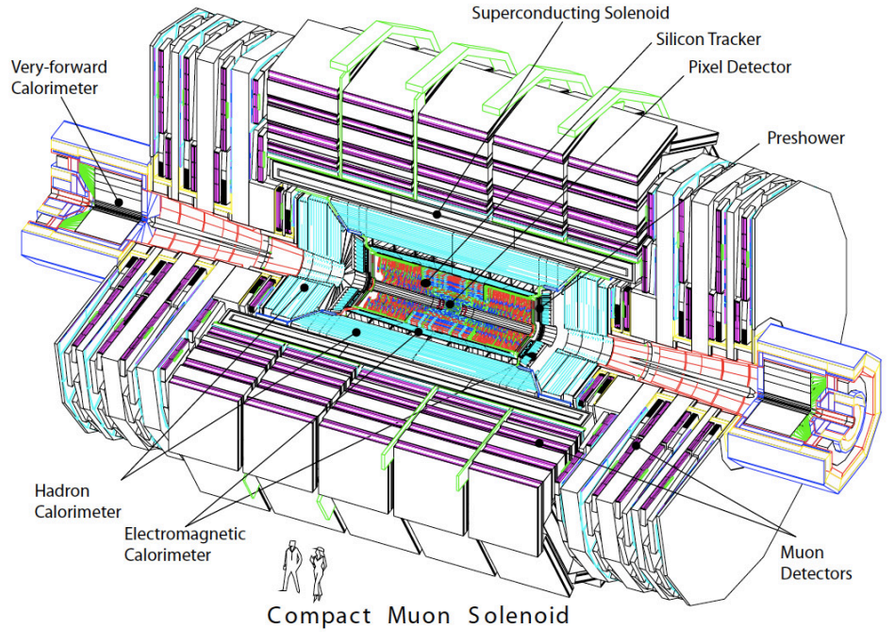
- **LHC:** proton-proton collisions at various c.o.m. energies
- **Run-II (2015–18):** ~140 fb^{-1} at 13 TeV

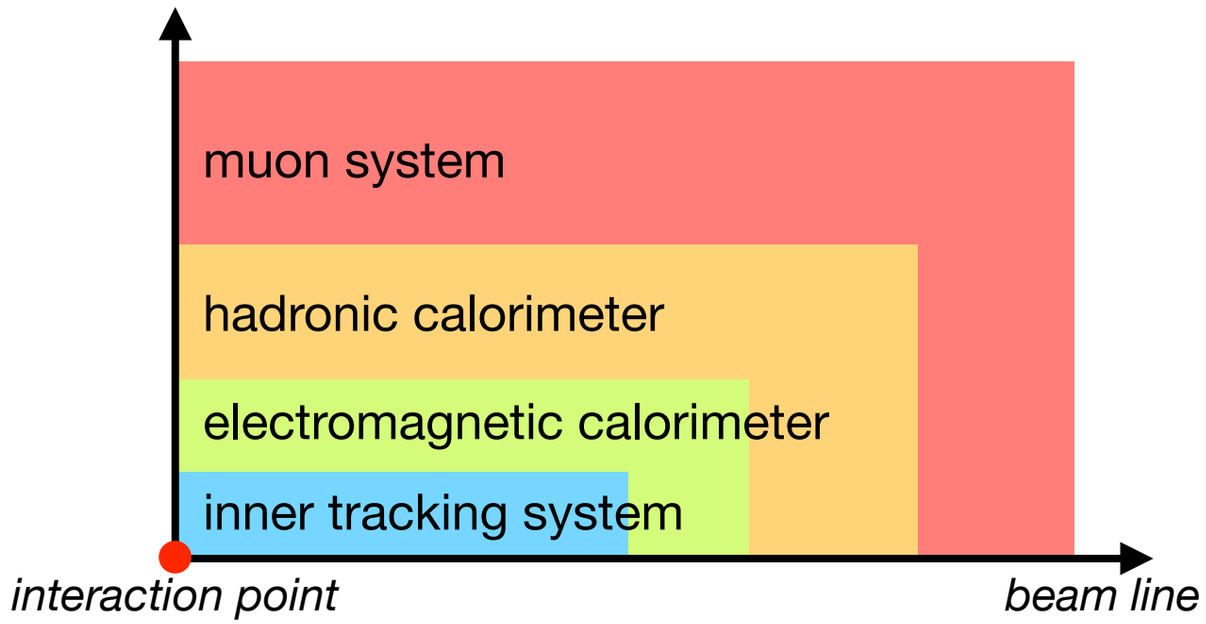
- **CMS** and **ATLAS:** two general-purpose detectors, cross check of each other's results

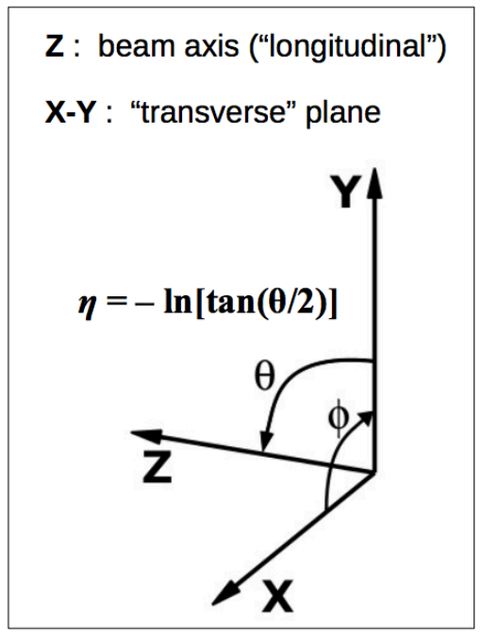


The ATLAS and CMS detectors

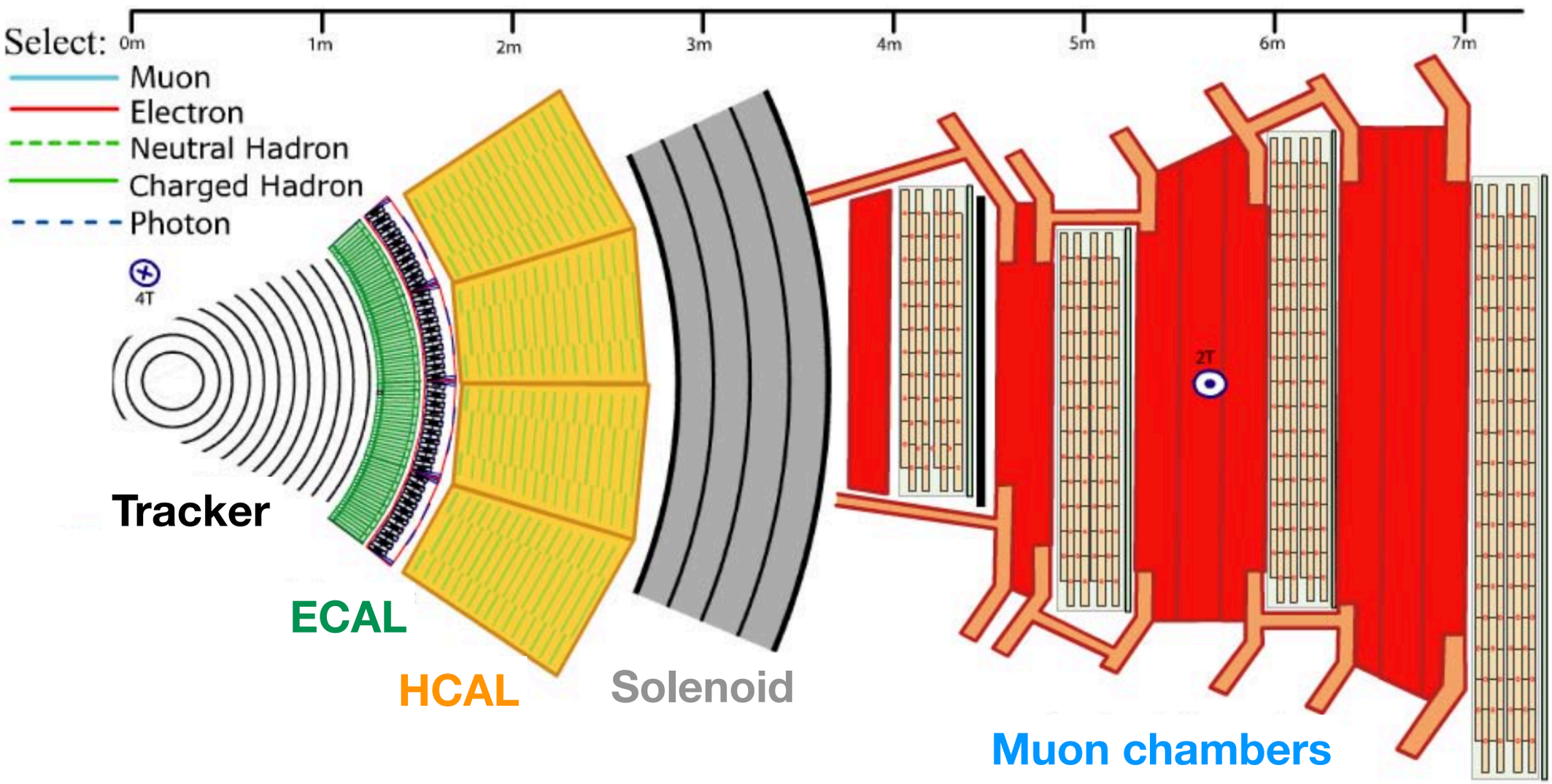






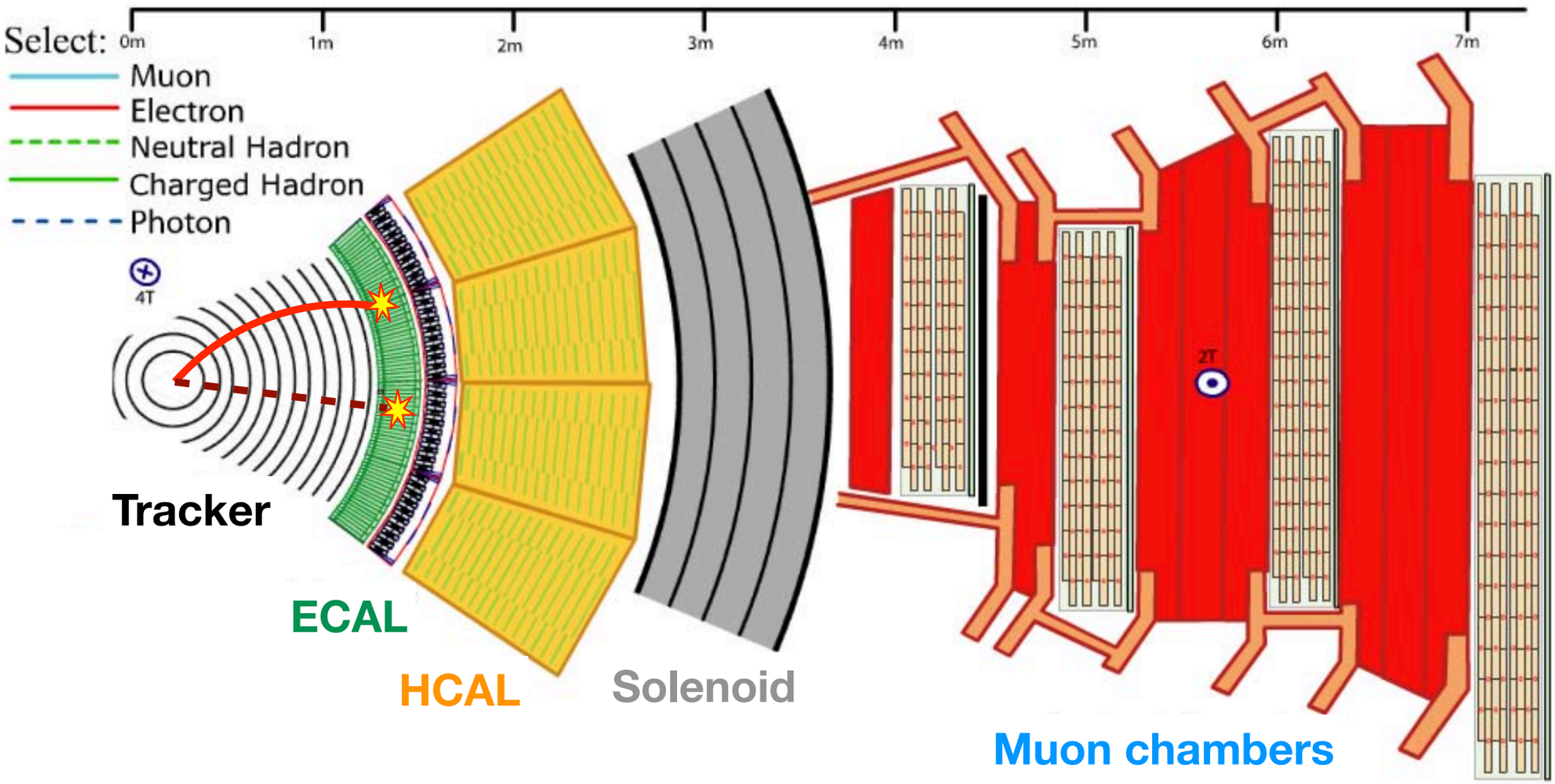


Particle and event reconstruction



Particle and event reconstruction

Electrons, photons ⇨ ECAL + tracker



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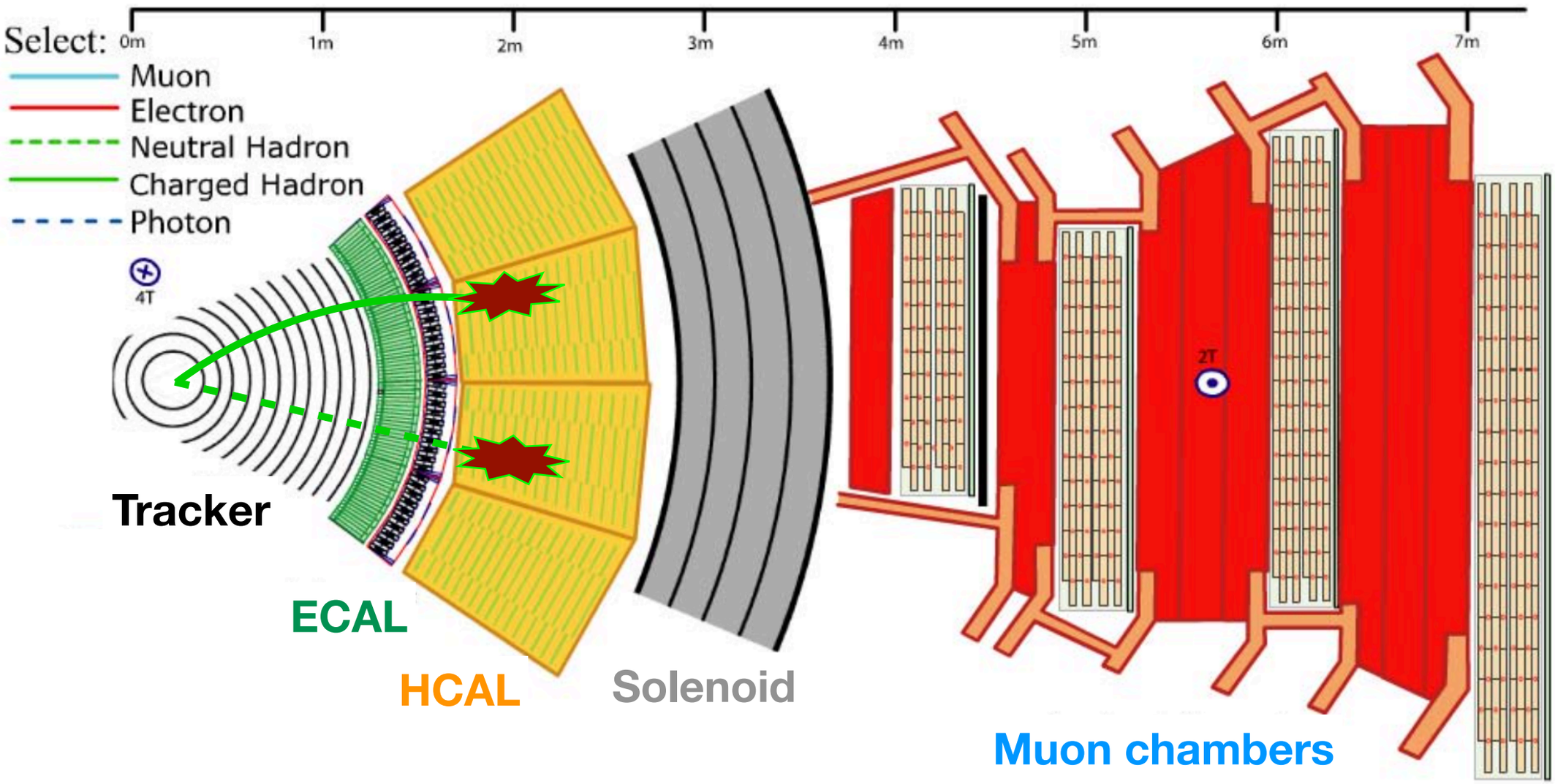
Hadrons (π, K, p, n) ⇨ HCAL + tracker

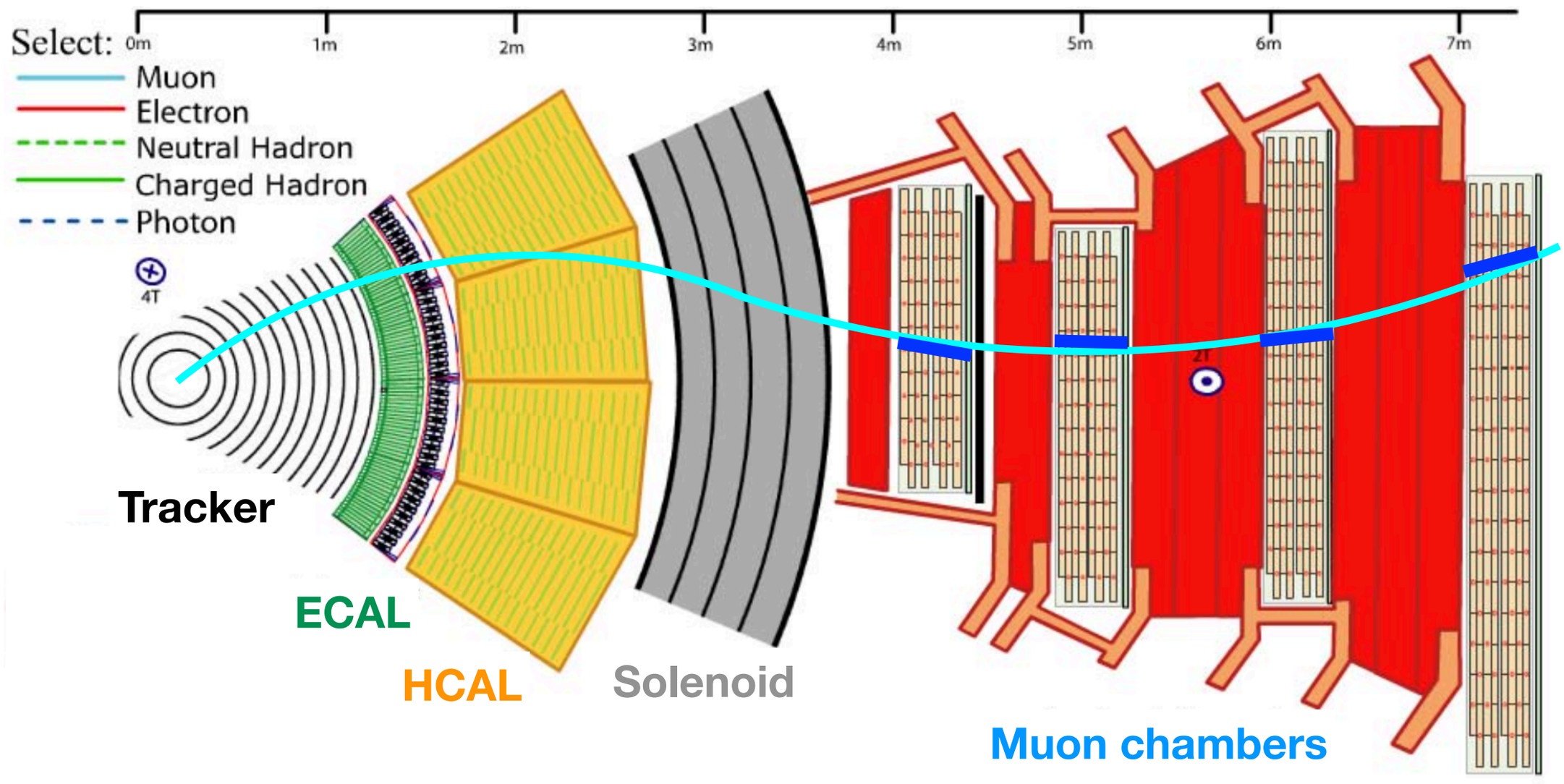


Particle and event reconstruction

Electrons, photons ⇨ ECAL + tracker

Hadrons (π, K, p, n) ⇨ HCAL + tracker

Muons ⇨ Muon chambers + tracker

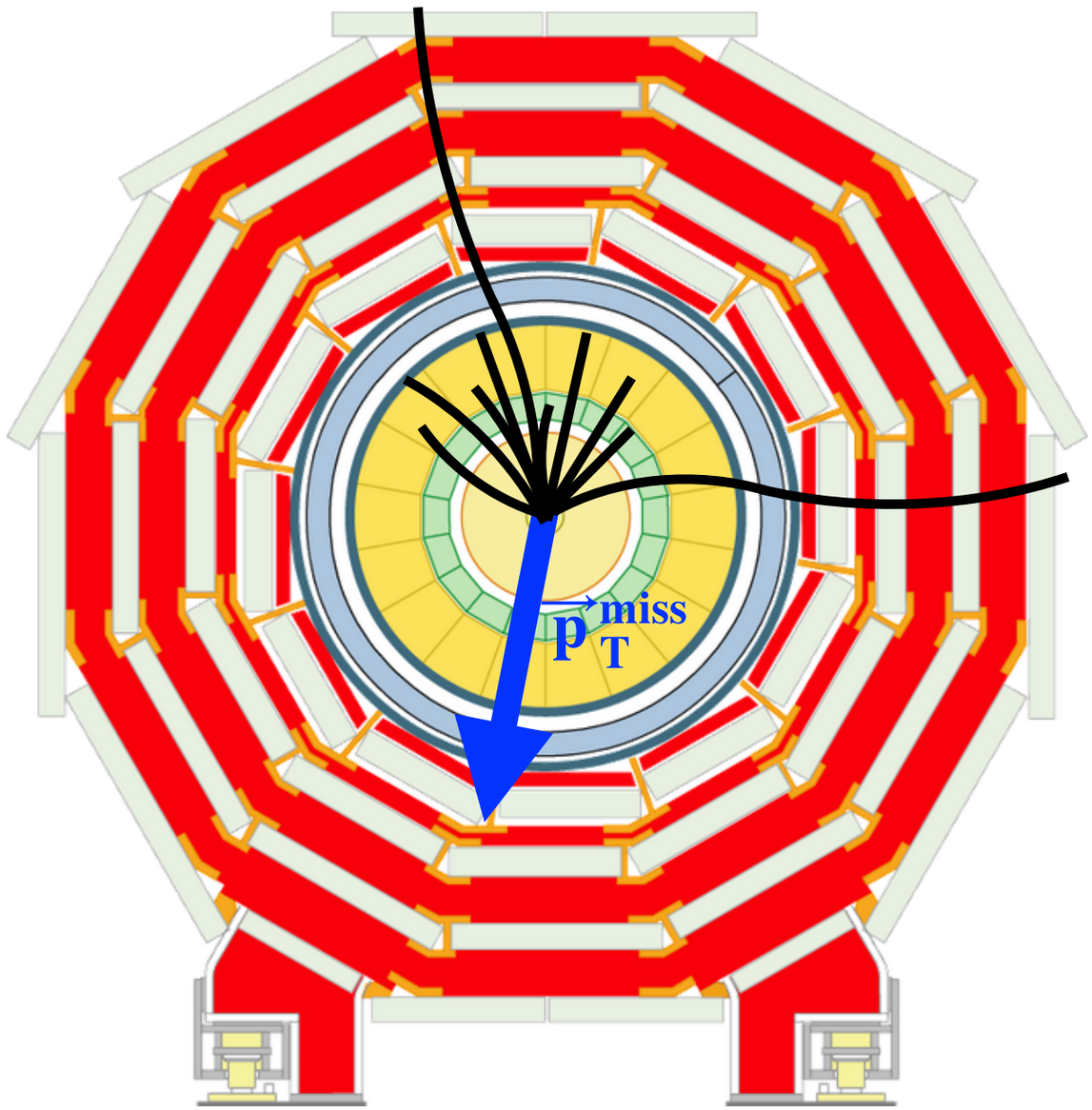


Particle and event reconstruction

Undetectable particles (neutrinos) can be measured collectively as an imbalance in the transverse momentum of all detected particles

⇒ missing transverse momentum: $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\sum_i \vec{p}_{\mathrm{T}}^{\,i}$

$$\mathrm{MET} = \left| \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} \right|$$



Prompt leptons

- HNL signatures at the LHC are rich in charged leptons
  - Typically from decays of the HNL or W, Z, H bosons

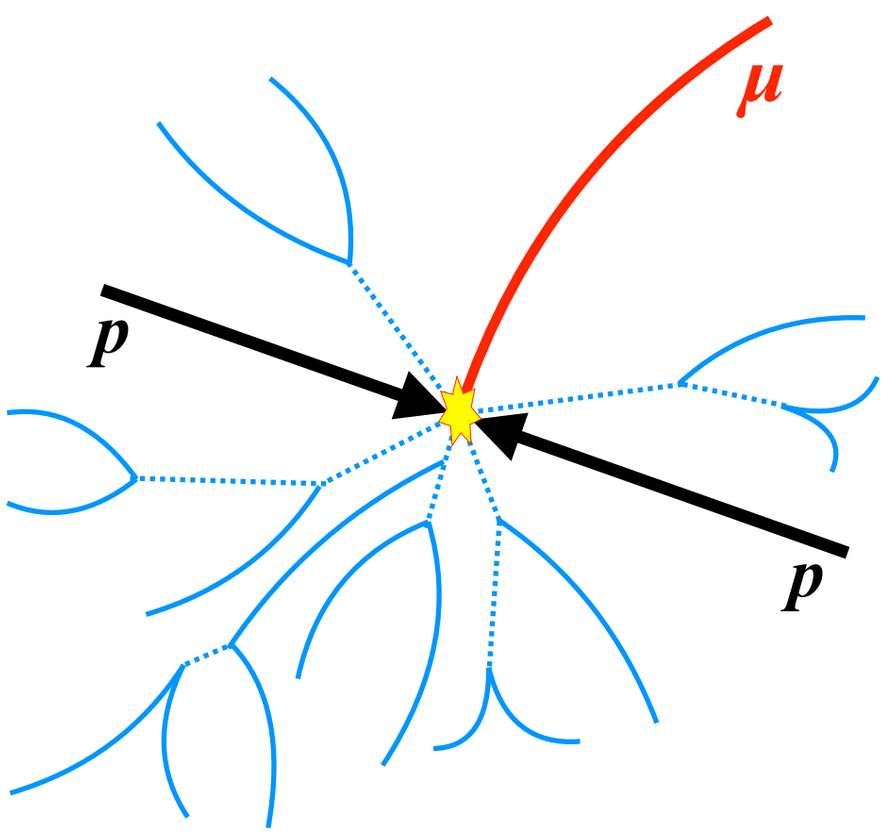
prompt

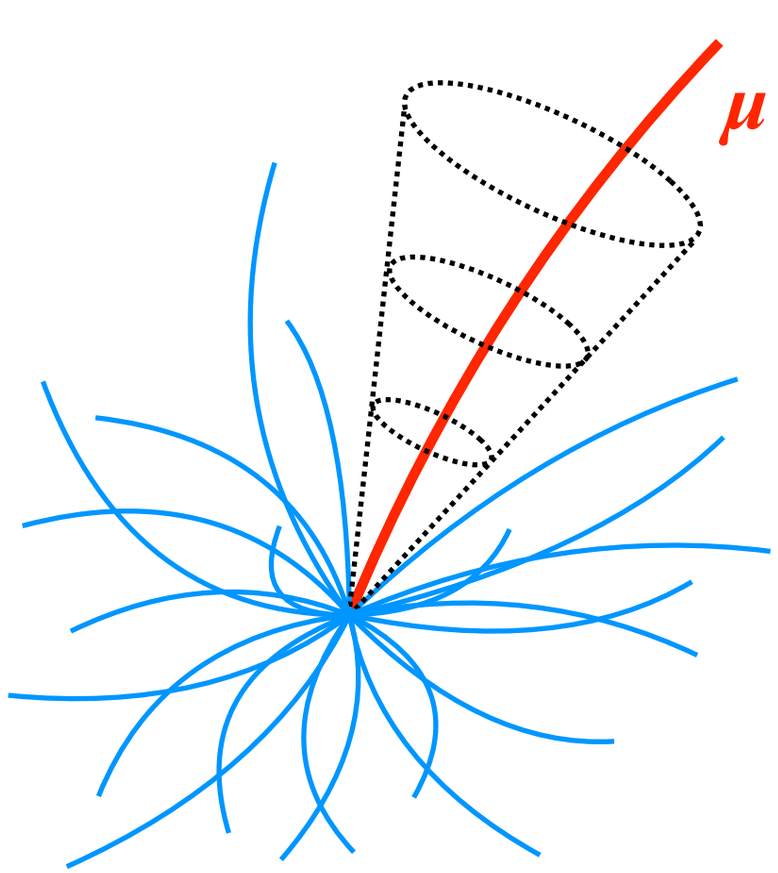
emerging directly from the primary proton-proton interaction vertex

isolated

from hadronic activity

(other particles, tracks, energy deposits)





Common backgrounds

- Other SM processes can mimic HNL signatures

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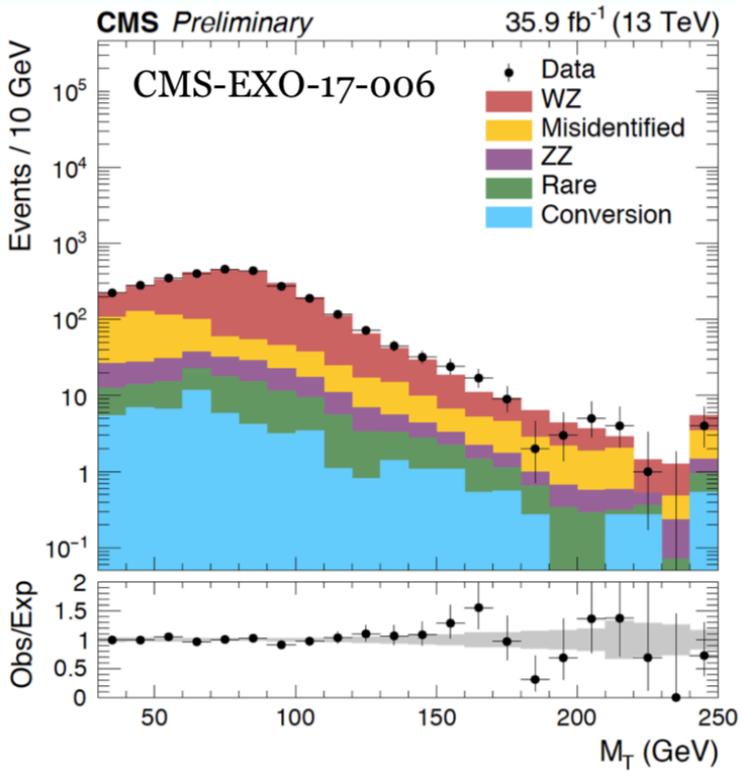
Prompt leptons from multiple gauge-boson, top, or Higgs production: WW, WZ, ZZ, ttW, ttZ, ttH, etc.

- Well reproduced by Monte Carlo generators
- Estimated with simulations



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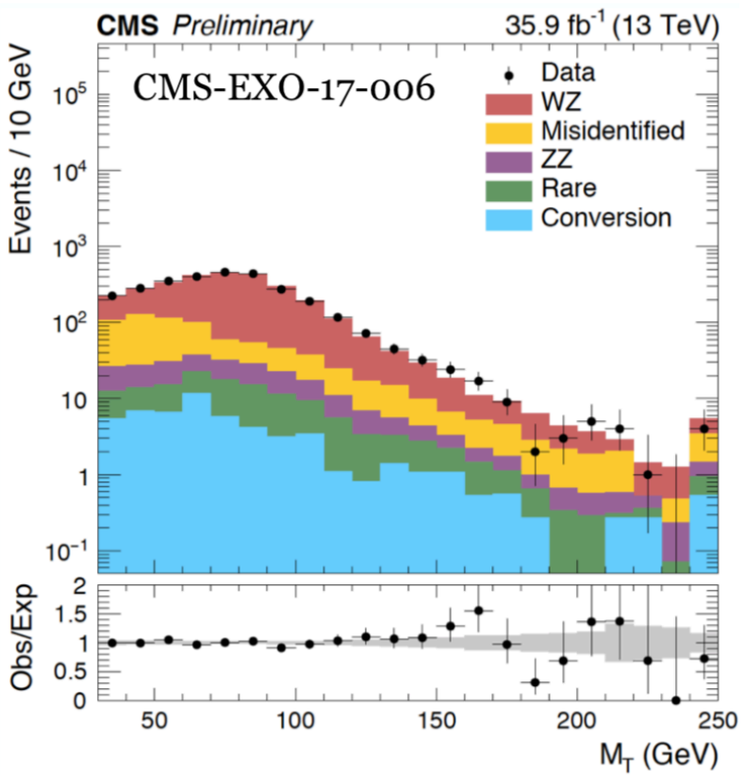
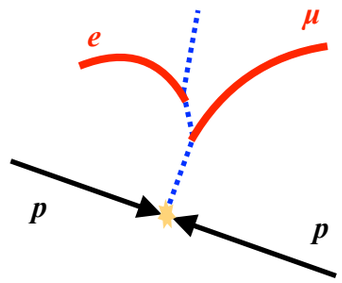
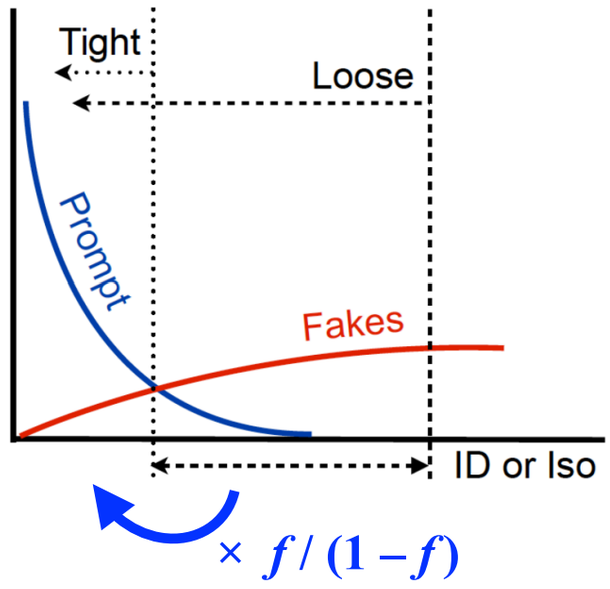


Nonprompt leptons from hadron decays (e.g. B) or **misidentified hadrons and jets**
→ generally called "*fake leptons*"



- Measured in data side-bands using the mis-ID probability or "fake-rate" f



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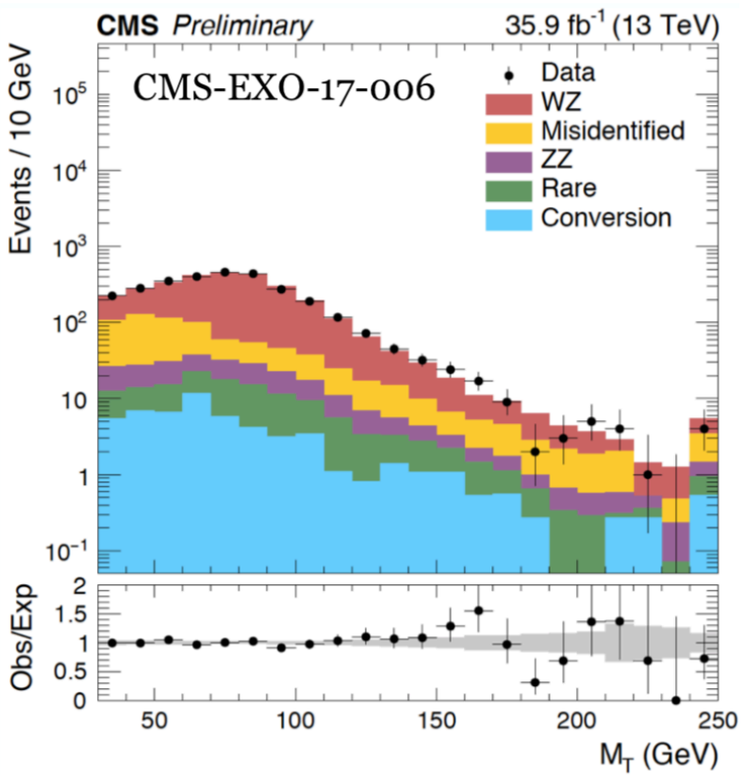

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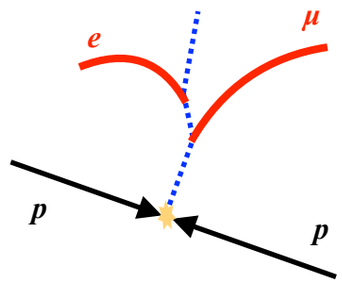

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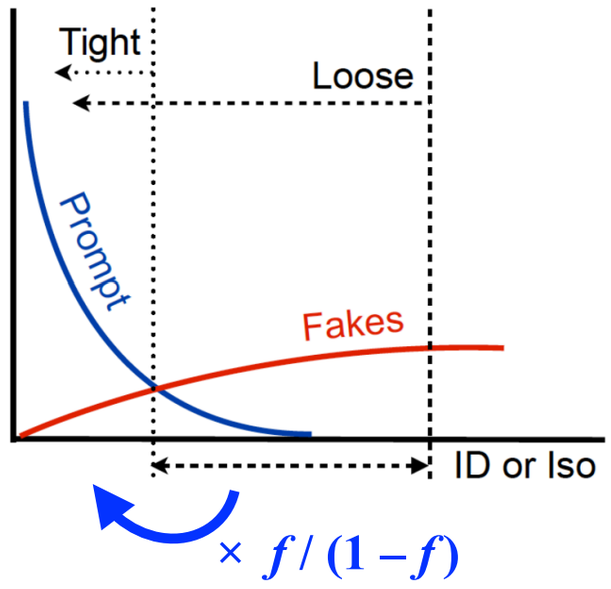
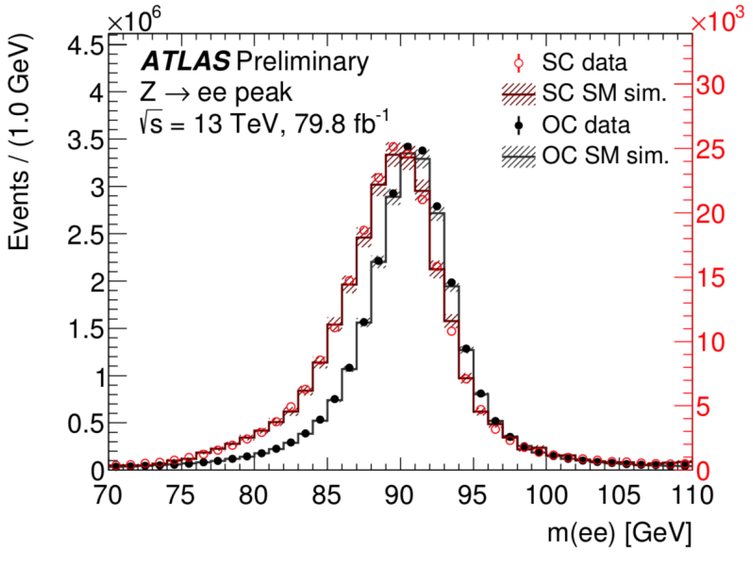


Leptons (esp. electrons) with **mis-measured charge** can give rise to same-sign (SS) leptons — typical indicator of Majorana neutrinos

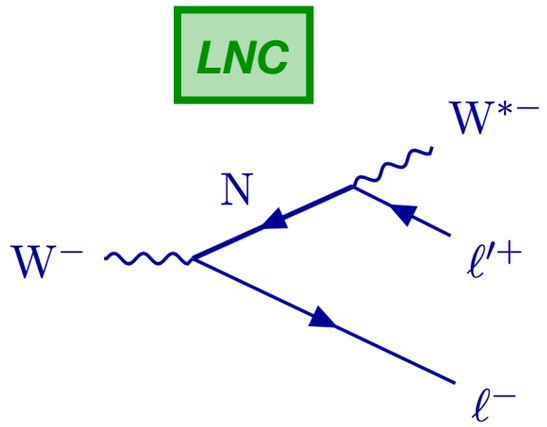
- Charge mis-ID probability measured from Z → ee events
- Simultaneous fit to OS $Z \to e^+e^-$ and SS $Z \to e^\pm e^\pm$ peaks



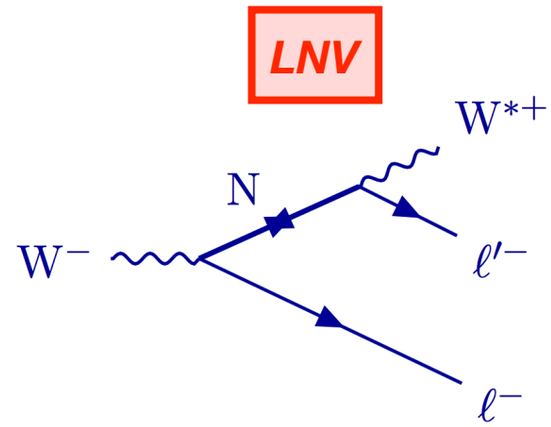
Type-I seesaw

Type-I: HNL production & decay

- Two parameters: HNL mass m_N and ν_ℓ-N mixing angle $|V_\ell|^2$
- Produced from W boson decays
- **Conserving** or **violating** lepton number



Dirac *or* ***Majorana***



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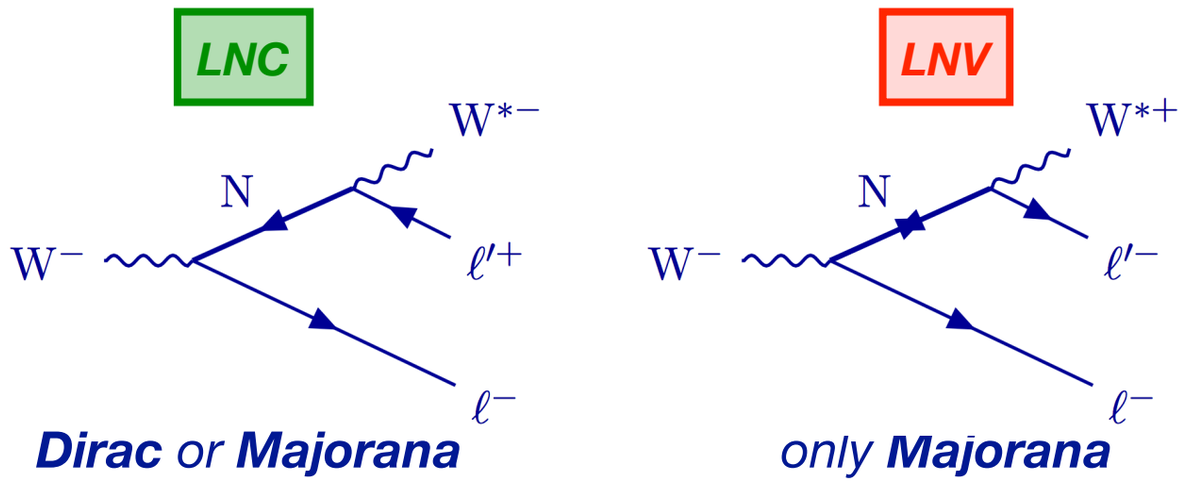
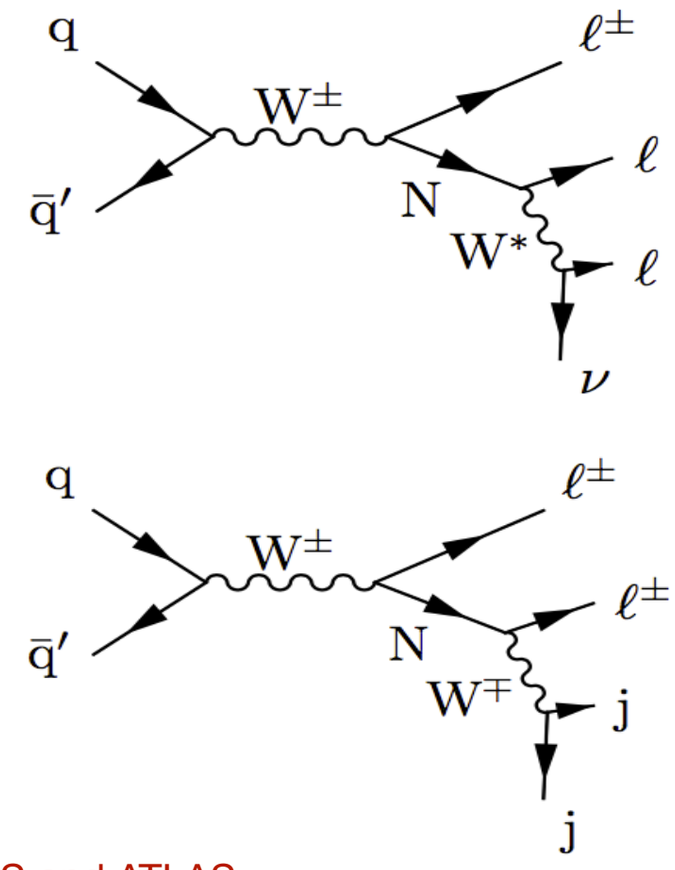


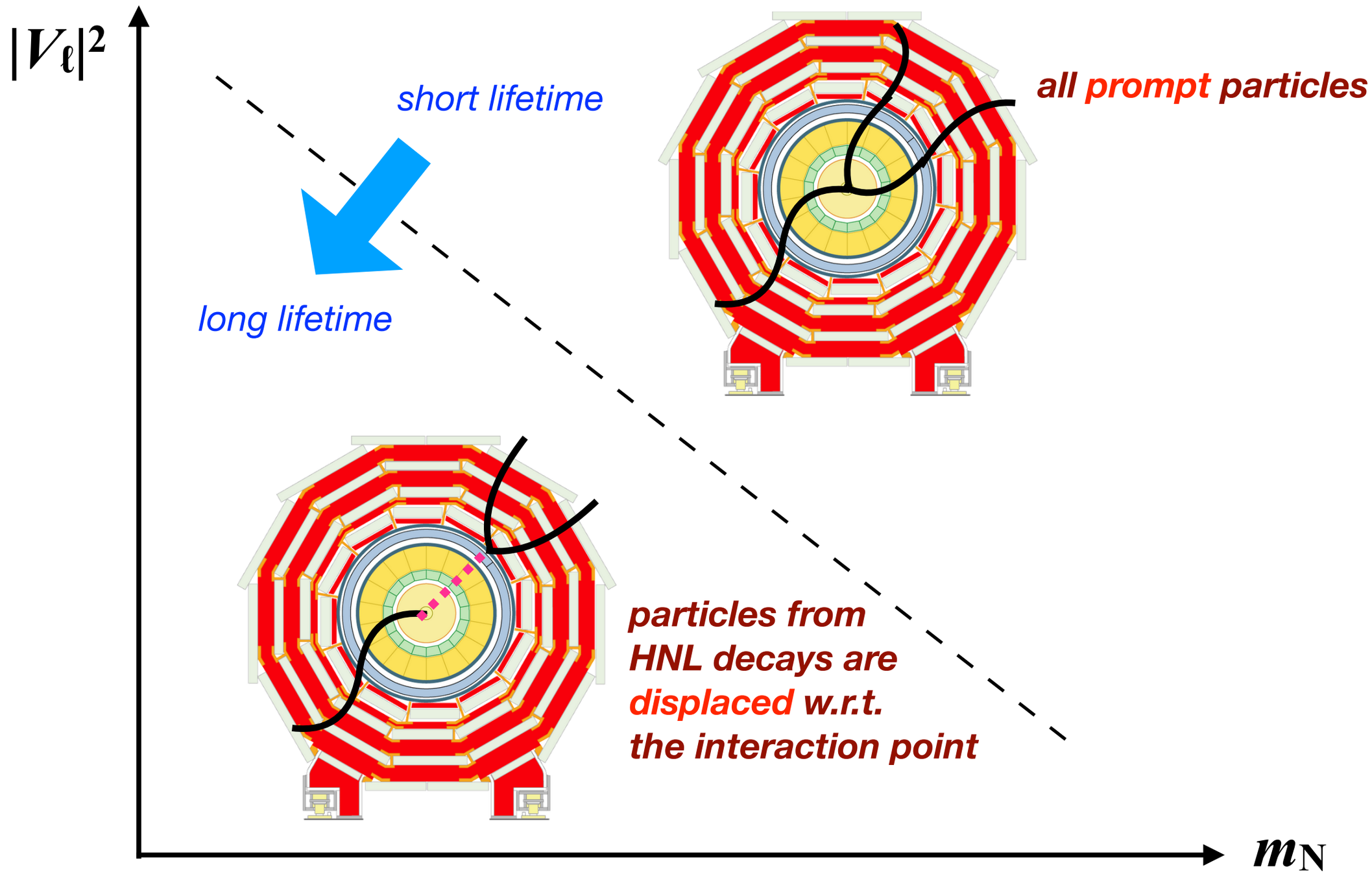
Dirac *or* ***Majorana*** *only* ***Majorana***

- Possible final states
  - **3ℓ + ν:** lower background, but no m_N peak
  - **2ℓ + 2q:** large background, m_N measurable



Type-I: HNL lifetime

- HNL lifetime $\tau \sim m_N^{-5} \, |V_\ell|^{-2}$



Type-I: trilepton channel (CMS)

- Search for Majorana HNLs mixing with e and μ, with $m_{\mathrm{N}} = 1\ \mathrm{GeV}–1.2\ \mathrm{TeV}$
  - 33 search categories to target a large variety of kinematics ($m_{\mathrm{N}} < m_{\mathrm{W}}$ or $m_{\mathrm{N}} > m_{\mathrm{W}}$)
  - categorize by lepton p_{T}, 2ℓ and 3ℓ invariant mass, MET, presence of a lepton pair with opposite sign and same flavor (OSSF)

Phys. Rev. Lett. 120, 221801 (2018)

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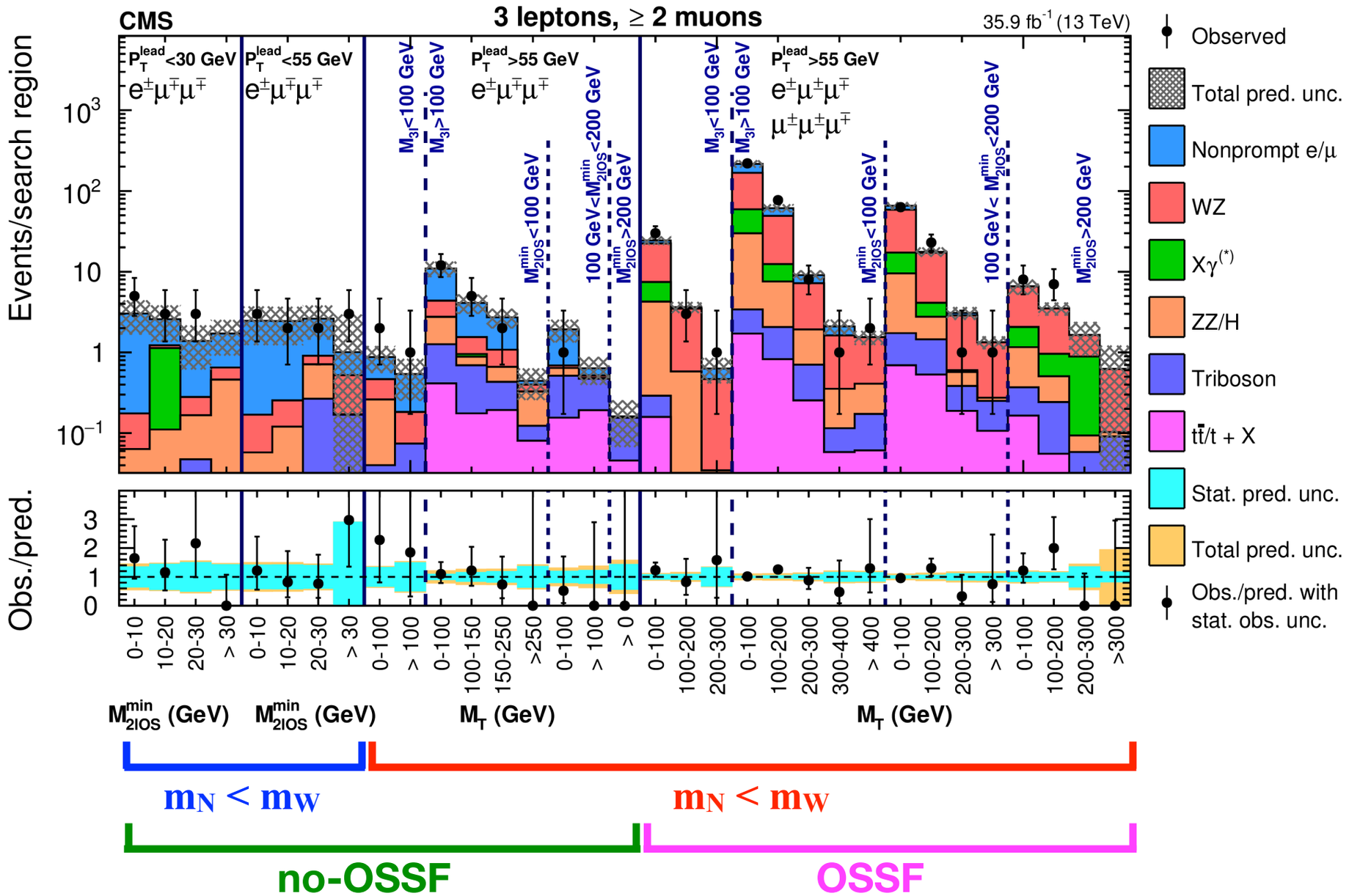
$\int L = 36\ \mathrm{fb}^{-1}$



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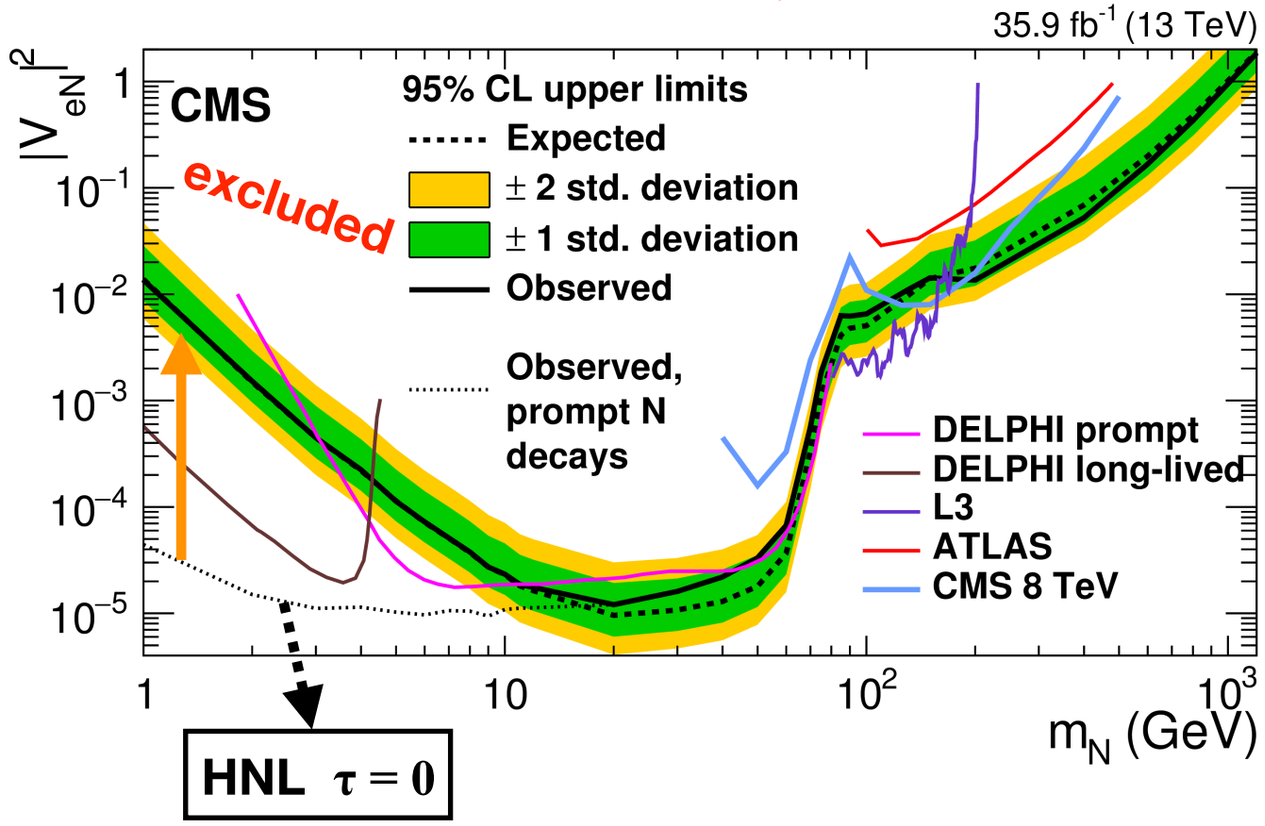
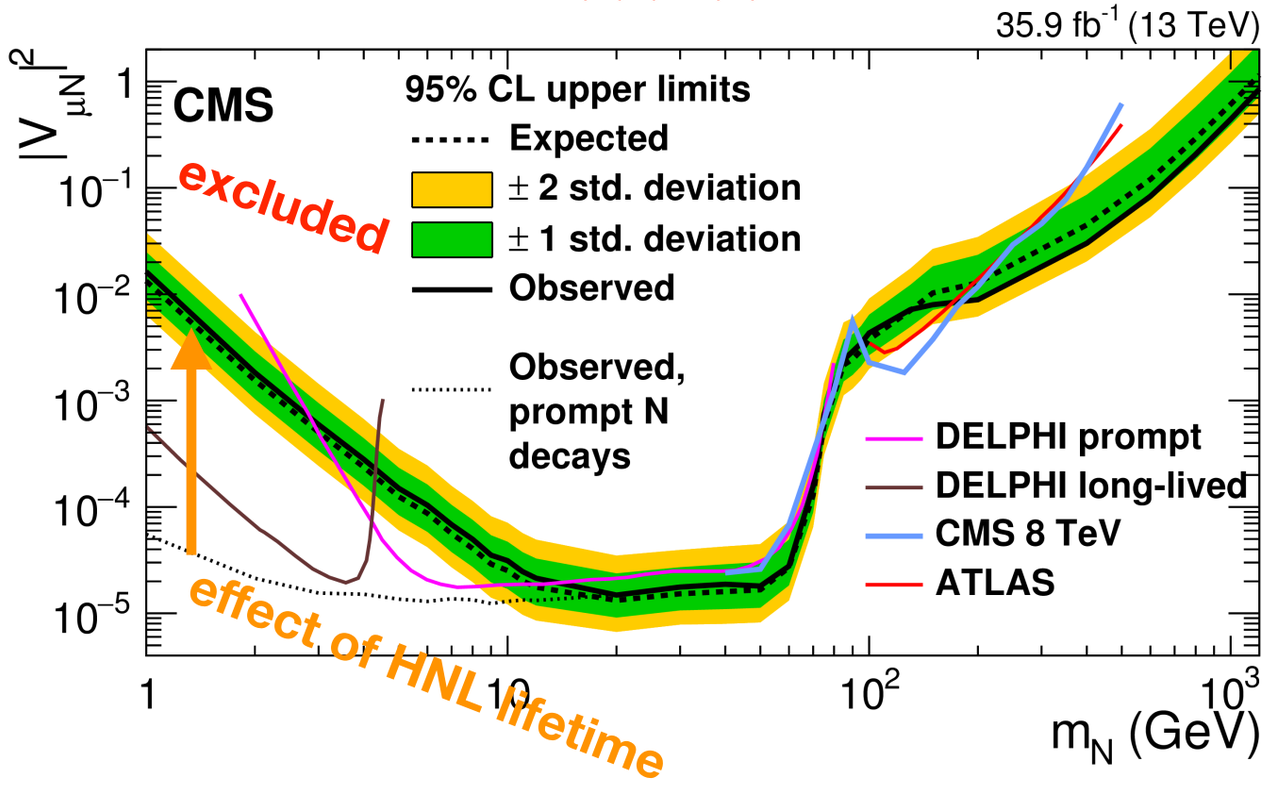
$|V_{eN}|^2$

eee, eeμ



$|V_{\mu N}|^2$

μμμ, μμe



- Limits over 3 orders of magnitude in m_N, first results for $m_N > 500$ GeV
- Analysis optimized for prompt lepton signatures ⇒ drastic loss of sensitivity for $m_N < 20$ GeV

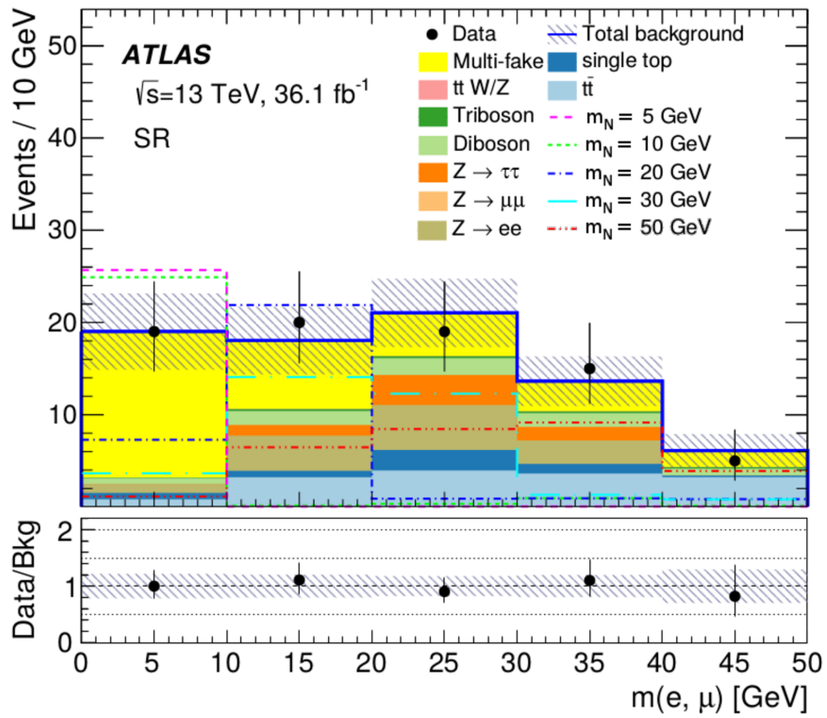
Phys. Rev. Lett. 120, 221801 (2018)

Type-I: trilepton channel (ATLAS)

- Similar search, focused on the region of highest sensitivity
  - $m_N = 5–50$ GeV, no OSSF pairs (only LNV decays)
  - selections on trilepton mass, MET, b-jet veto
  - main backgrounds controlled in data:
    top (normalization),
    W+jets and multi-jet (normalization and shape)
  - simultaneous fit to signal and control regions

$\int L = 36\ fb^{-1}$

$e^{\pm}e^{\pm}\mu^{\mp}$



arXiv:1905.09787v1 [hep-ex]

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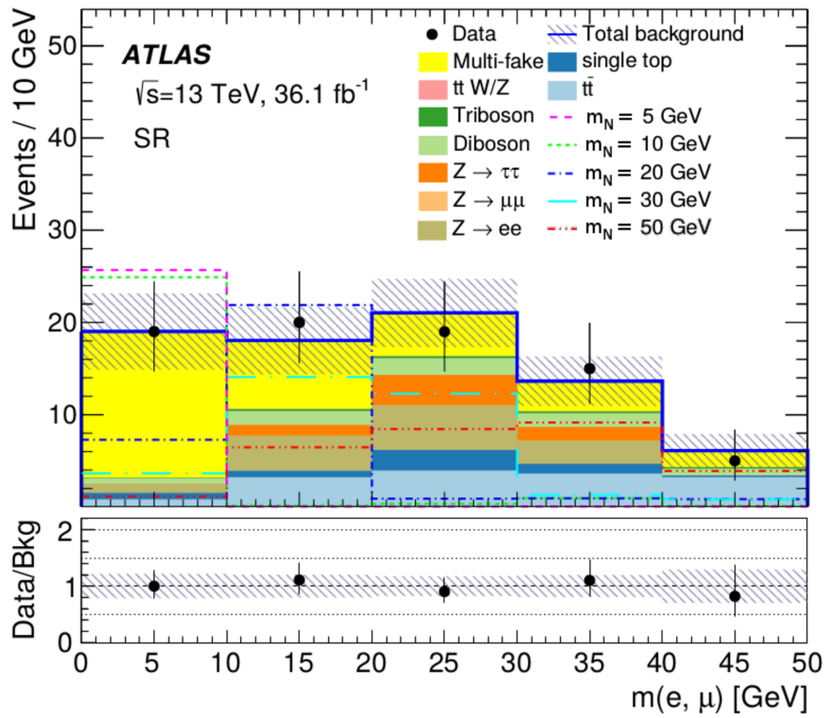
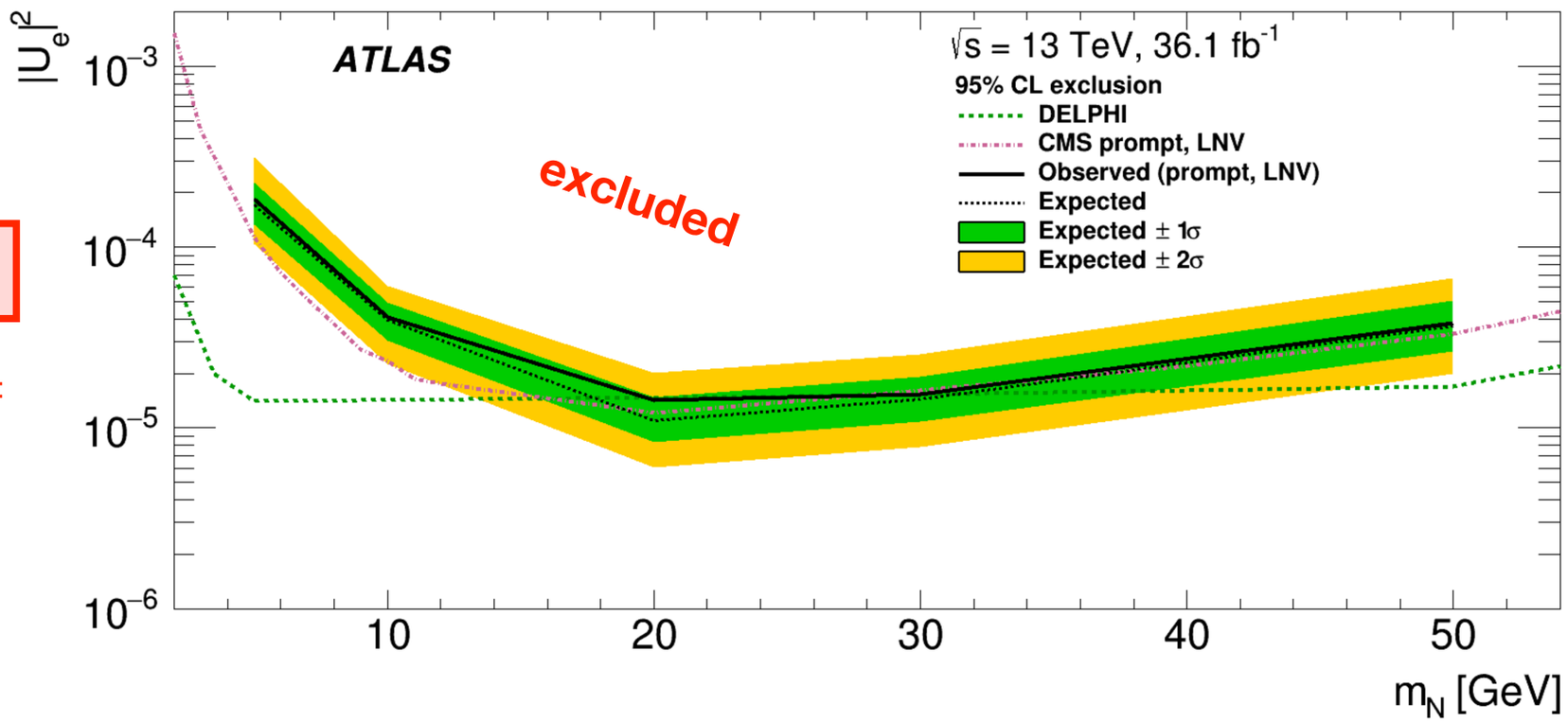




$|V_{eN}|^2$

$e^{\pm}e^{\pm}\mu^{\mp}$

CMS

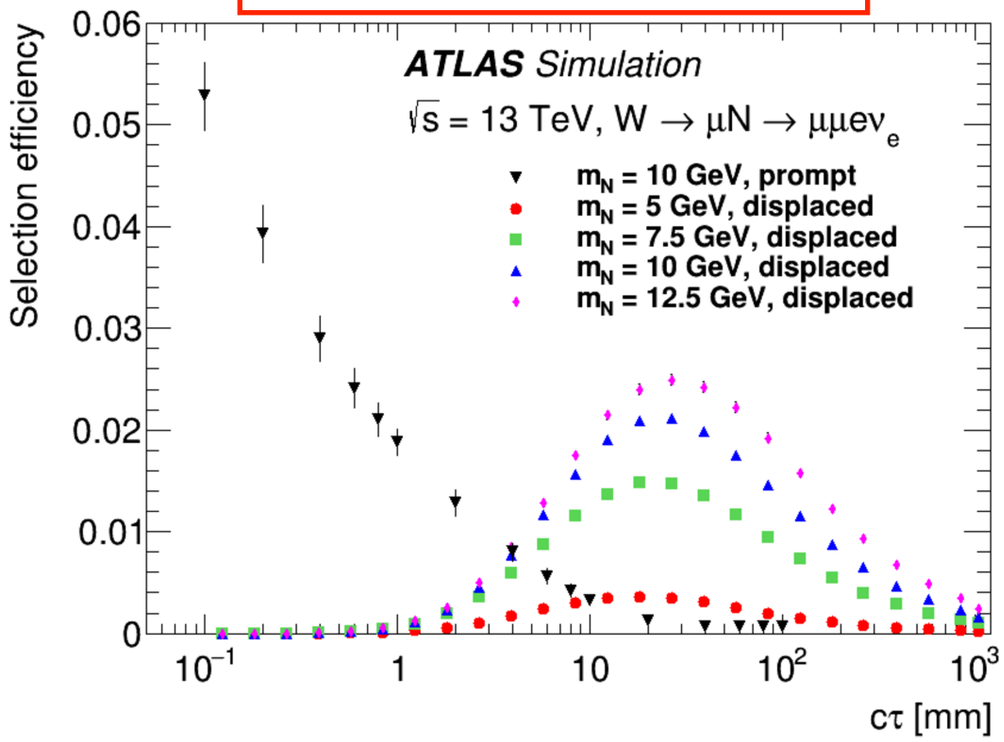
DELPHI

arXiv:1905.09787v1 [hep-ex]

Type-I: trilepton channel (ATLAS)

- For $m_{\mathrm{N}} = 4.5$–10 GeV (long-lived HNL), dedicated large-radius tracking for nonprompt leptons
  - Only muon couplings $V_{\mathrm{N}\mu}$, both LNV and LNC decays
  - Dilepton displaced vertex (DV):
    - radius $r_{\mathrm{DV}} = 4$–300 mm
    - mass $m_{\mathrm{DV}} > 4$ GeV

Selection efficiency *vs* cτ



- Nonstandard backgrounds, carefully controlled in data
  - decays of metastable particles, hadron interactions in the material, and cosmic muons: negligible for $m_{\mathrm{DV}} > 4$ GeV
  - contribution from accidental particle crossings estimated using SS two-track DVs

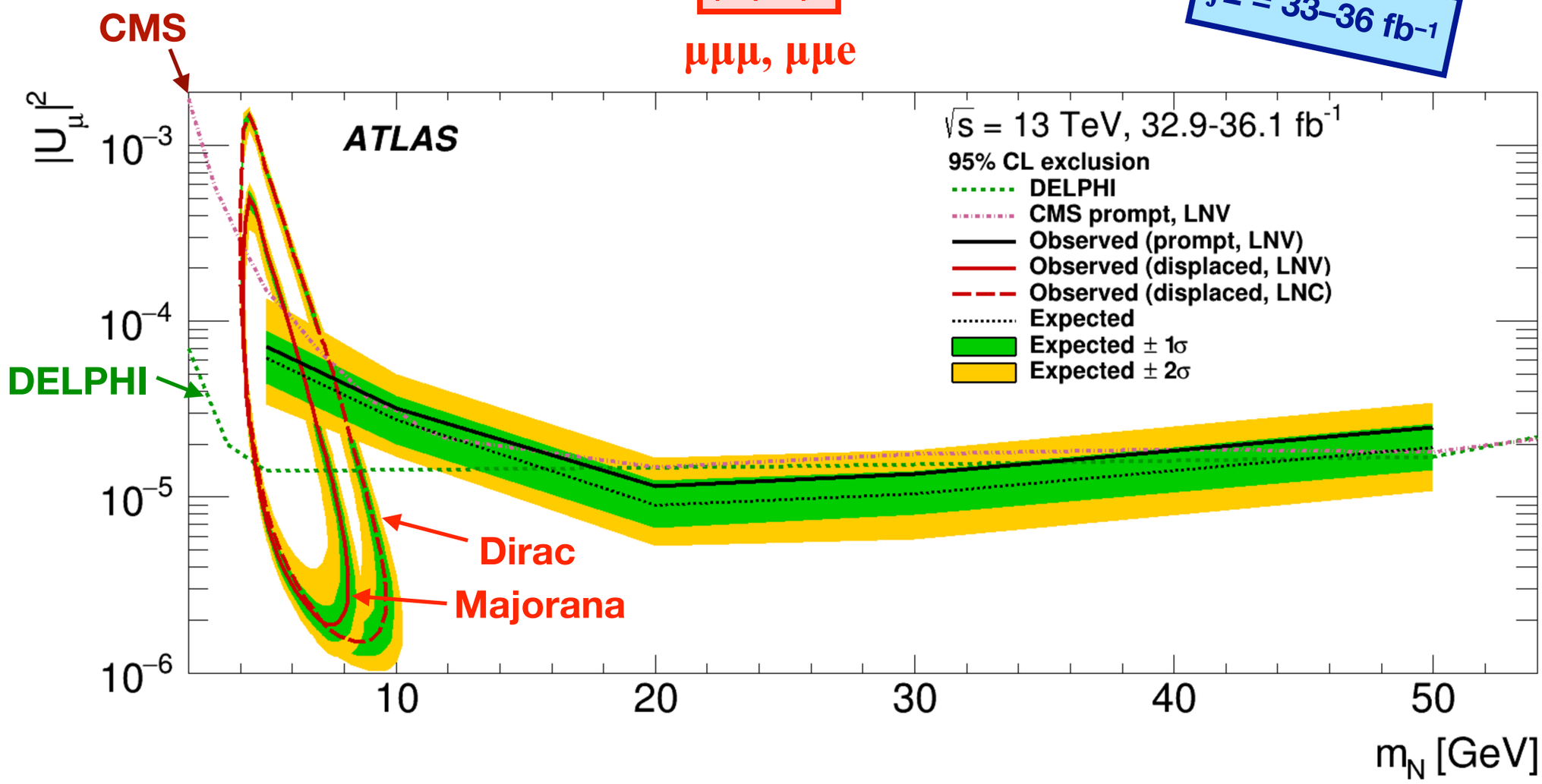
arXiv:1905.09787v1 [hep-ex]

Type-I: trilepton channel (ATLAS)

$|V_{\mu N}|^2$

μμμ, μμe

$\int L = 33\text{–}36\ fb^{-1}$

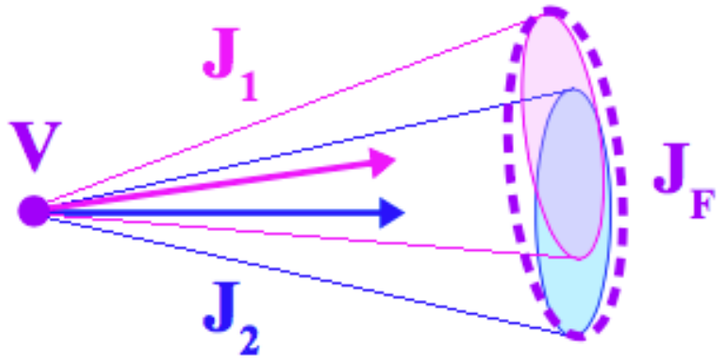


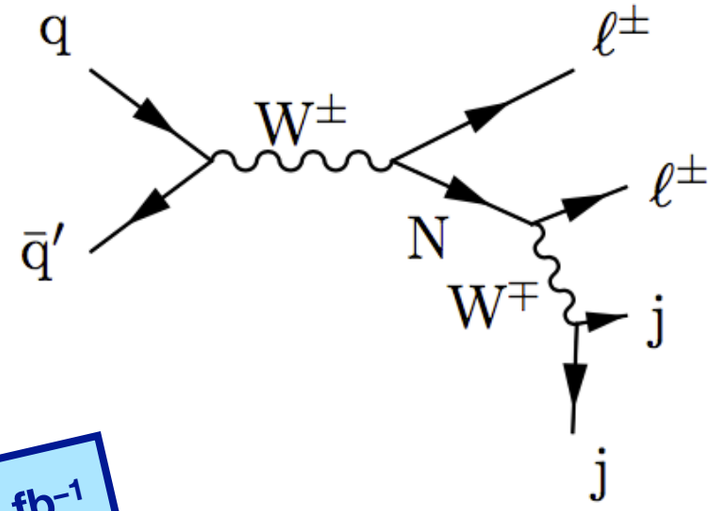
- First HNL search at ATLAS+CMS using displaced vertices!
- Majorana HNL has 1/2 lifetime than Dirac HNL ⇒ weaker limits
- Width of the limit contour corresponds to decay lengths of 1–30 mm

arXiv:1905.09787v1 [hep-ex]

Type-I: dilepton channel (CMS)

- HNL with mass 20 GeV–1.7 TeV in events with
  - 2 same-sign leptons (only LNV decays)
  - 2 jets or 1 boosted, large-cone jet

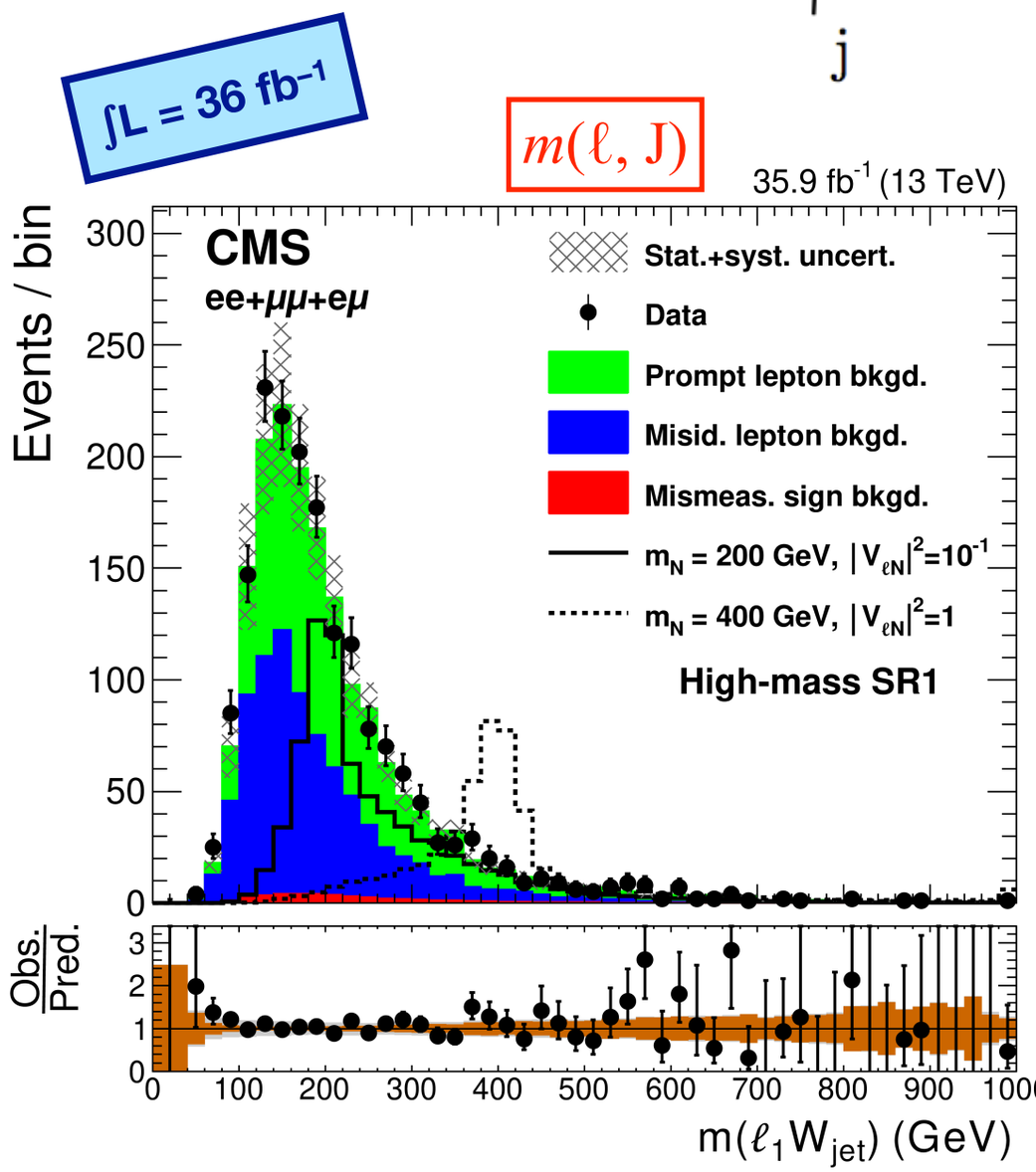




- flavor combinations:

$e^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$, $e^{\pm}\mu^{\pm}$

$|V_{eN}|^2$, $|V_{\mu N}|^2$, $\dfrac{|V_{eN}V_{\mu N}^*|^2}{|V_{eN}|^2 + |V_{\mu N}|^2}$.

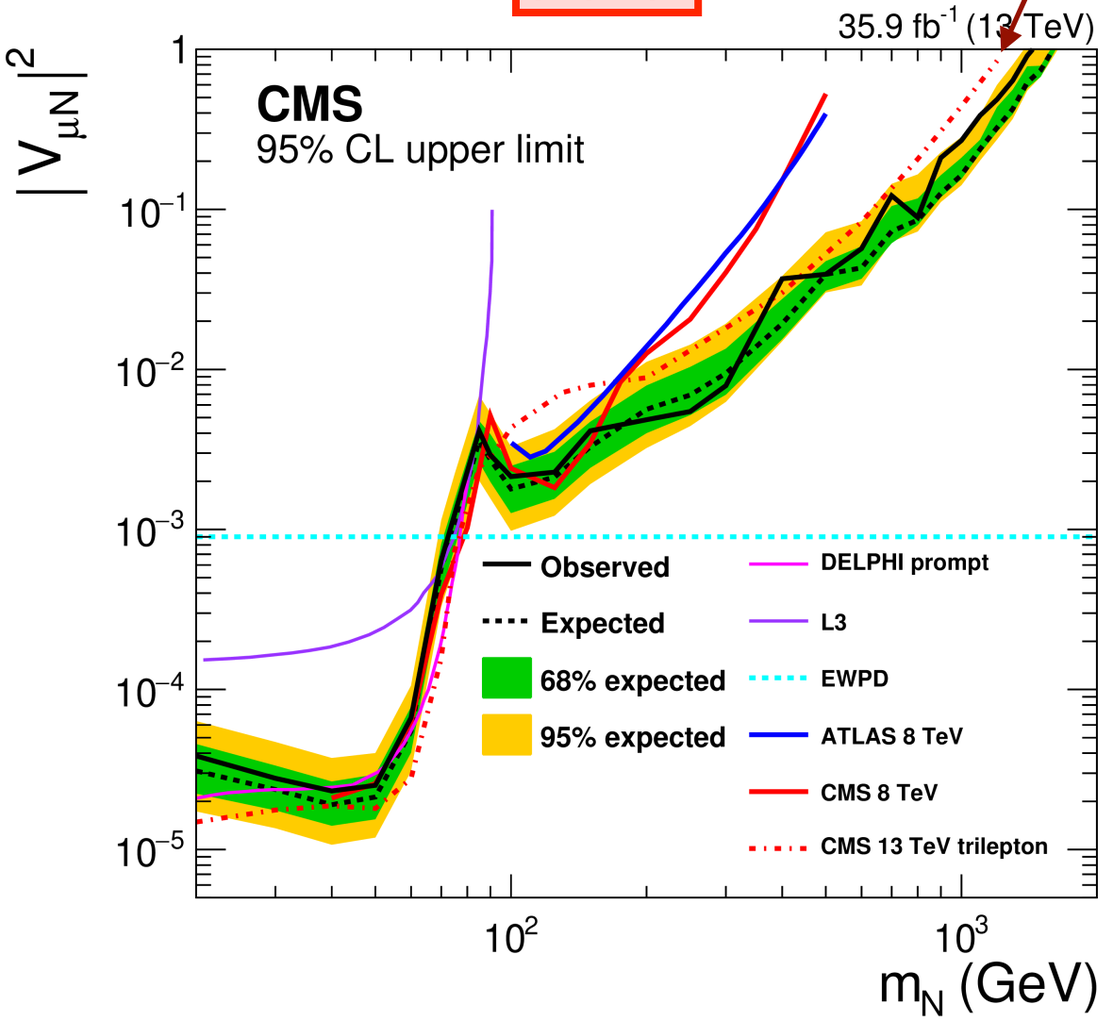


J. High Energ. Phys. (2019) 2019: 122

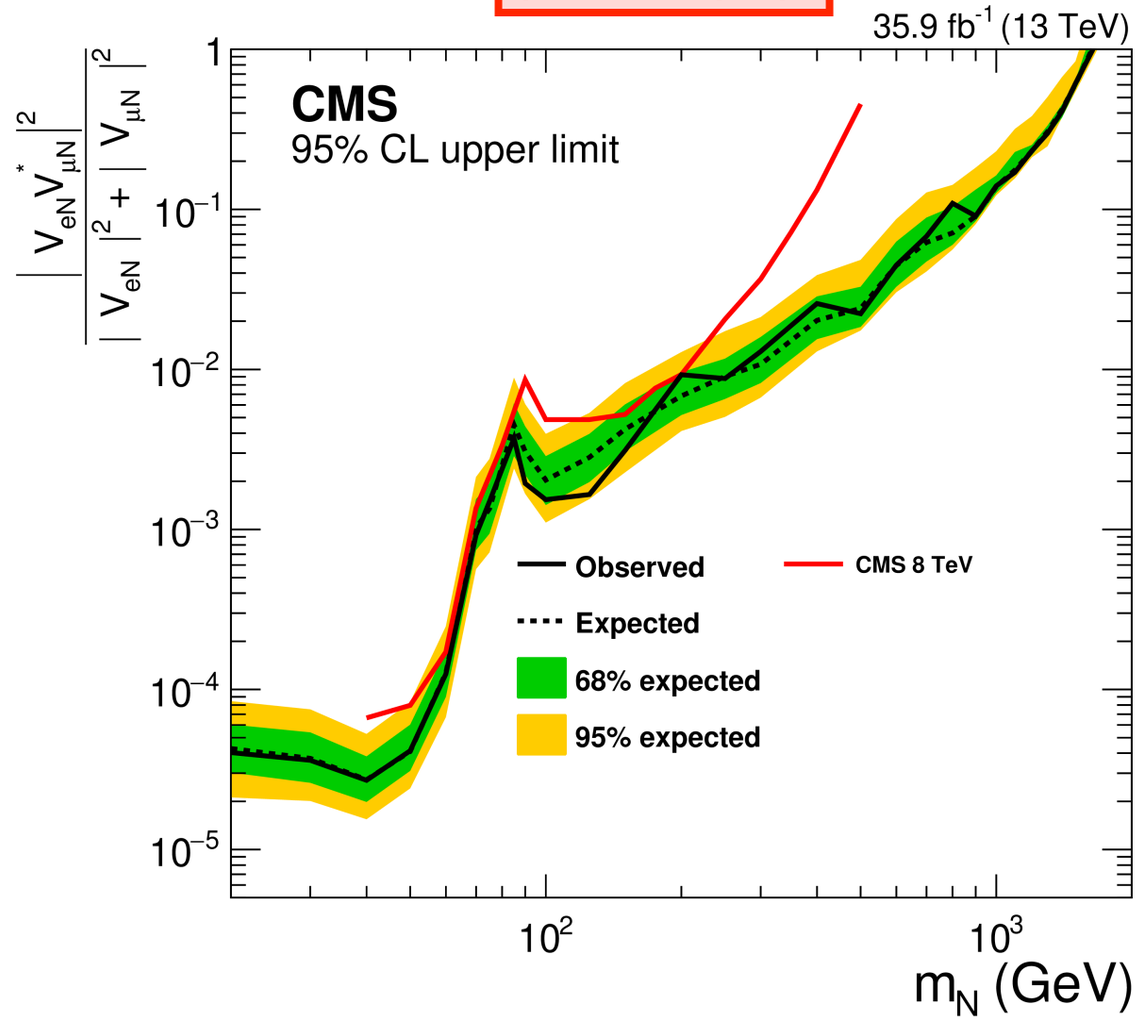
Type-I: dilepton channel (CMS)

$|V_{\mu N}|^2$

CMS trilepton



$|V_{eN} \cdot V^*_{\mu N}|^2$



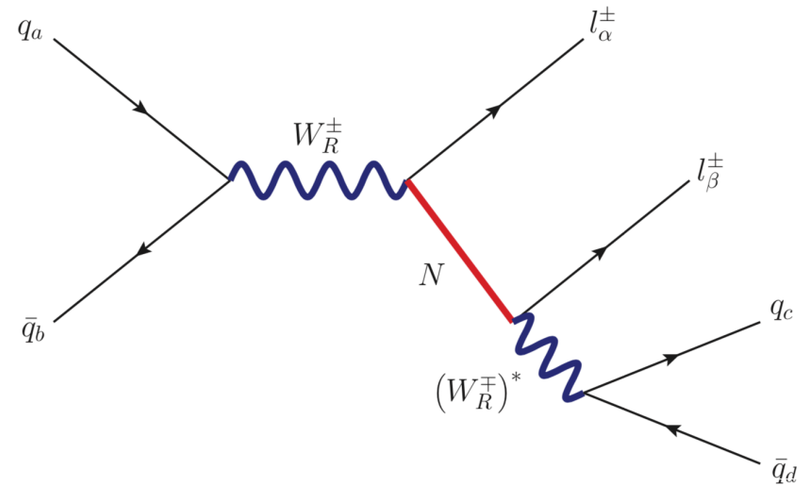
J. High Energ. Phys. (2019) 2019: 122

- Largest range of m_N ever tested by a single analysis!
- Stronger limits than 3ℓ search for $m_N > m_W$
- Limits on the lepton-flavor violating coupling $|V_{eN}\, V^*_{\mu N}|^2$

Left-Right Symmetric Model

Left-Right Symmetric Model

- Signature: 2ℓ + 2 jets
  - ℓ = e, μ: same flavor, any charge combo
  - strict LR symmetry: $g_R = g_L$
  - free parameters: W_R and N_R masses



CMS

- no distinction between OS and SS pairs (only N_R Majorana interpretation)
- main backgrounds (top, Z+jets) measured in data
- for each W_R mass hypothesis, simple counting experiment in a $m(\ell\ell jj)$ window

JHEP05(2018)148

ATLAS

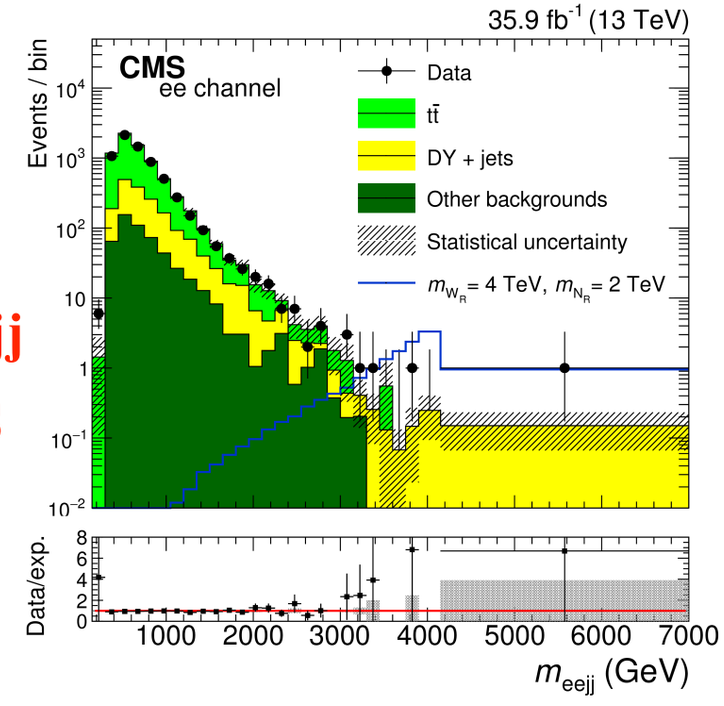
- separate OS and SS for Majorana/Dirac interpretation
- background control regions fitted simultaneously with signal region
- shape analysis using different variables for different mass regimes, in part. $m(\ell\ell jj)$ and $m(jj)$

J. High Energ. Phys. (2019) 2019: 16

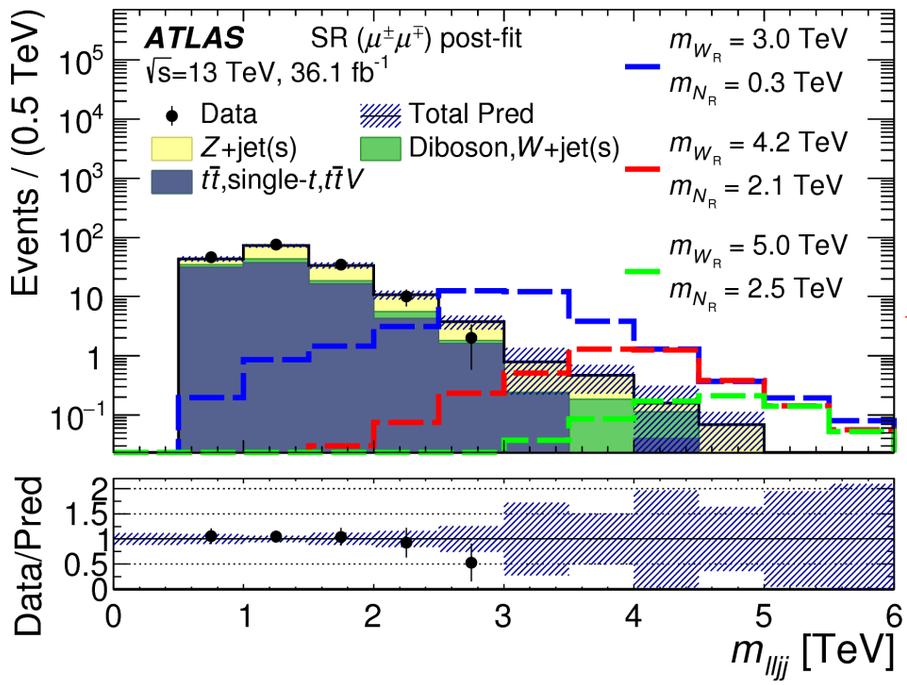
Left-Right Symmetric Model

CMS, eejj

OS + SS



Mass of W_R candidate



$\int L = 36$ fb^{-1}

ATLAS, μμjj

OS only

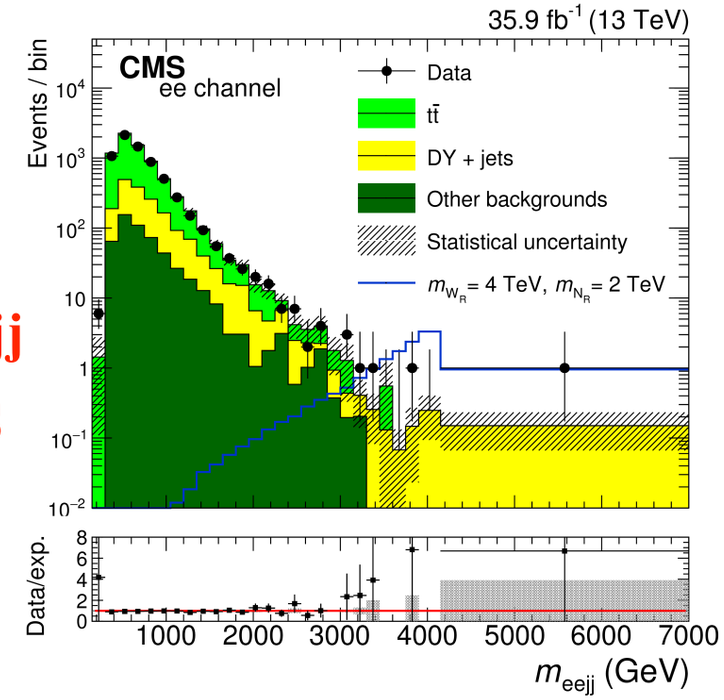
JHEP05(2018)148

J. High Energ. Phys. (2019) 2019: 16

Left-Right Symmetric Model

CMS, eejj

OS + SS



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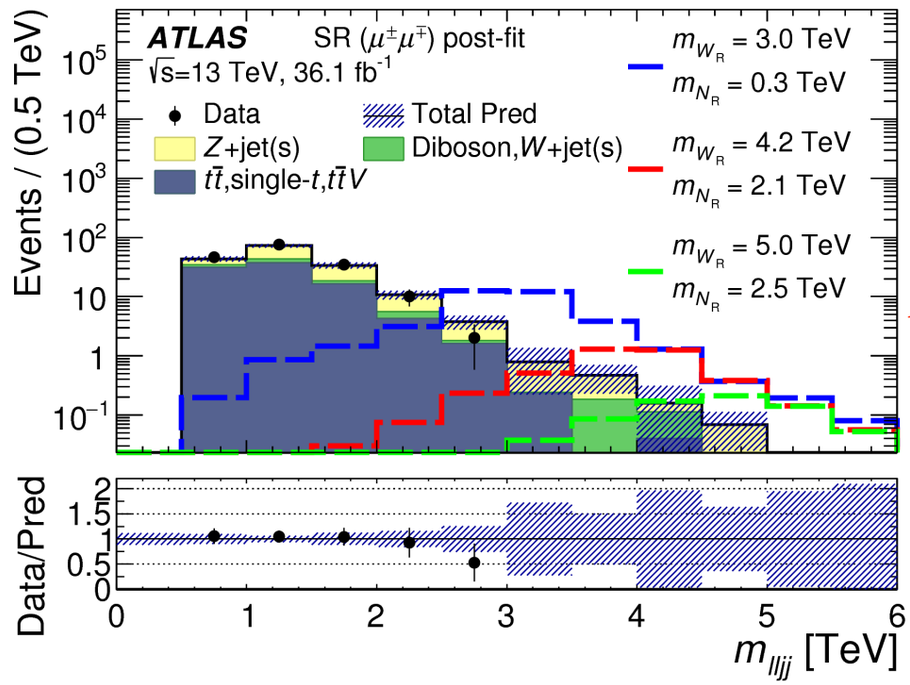
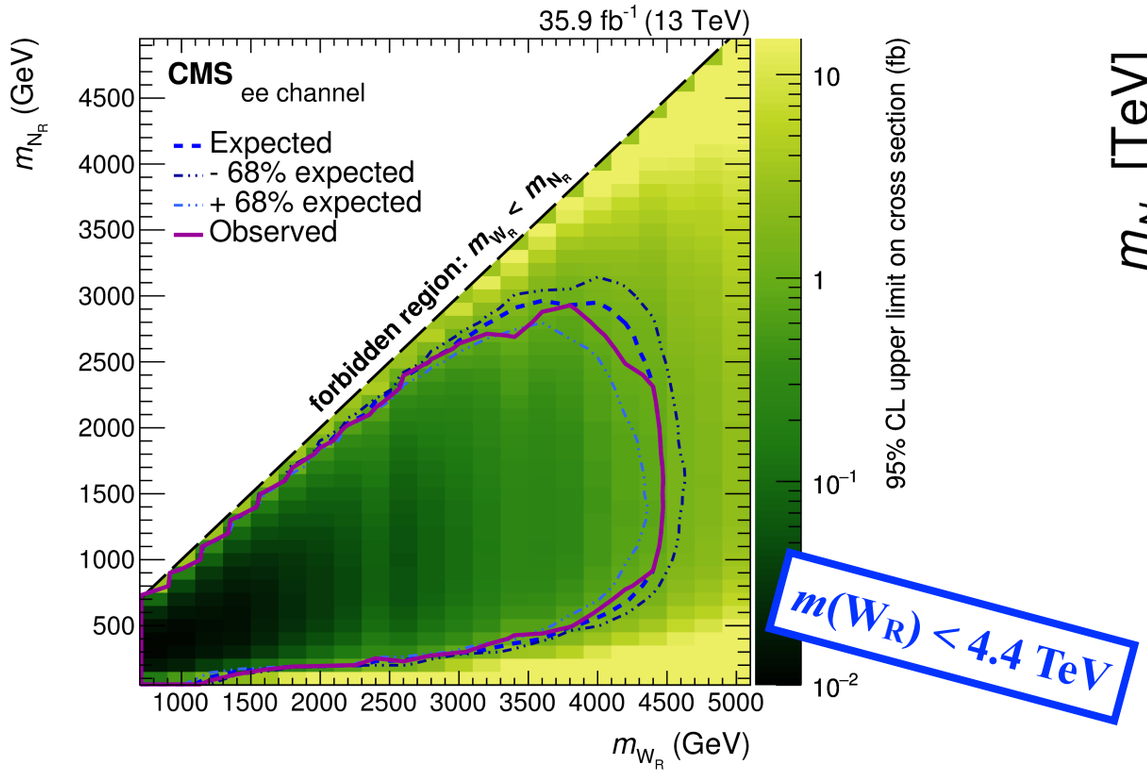


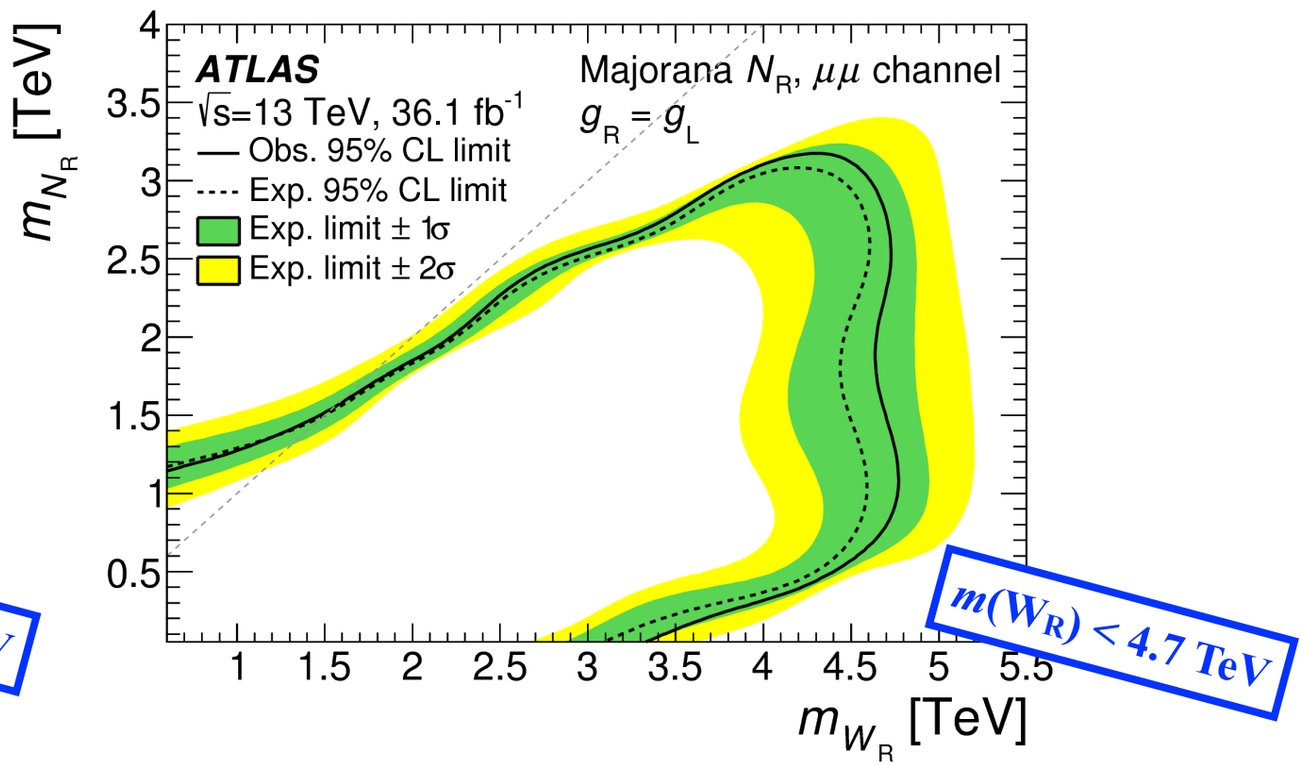
∫L = 36 fb⁻¹

ATLAS, μμjj

OS only



$m(W_R) < 4.4$ TeV



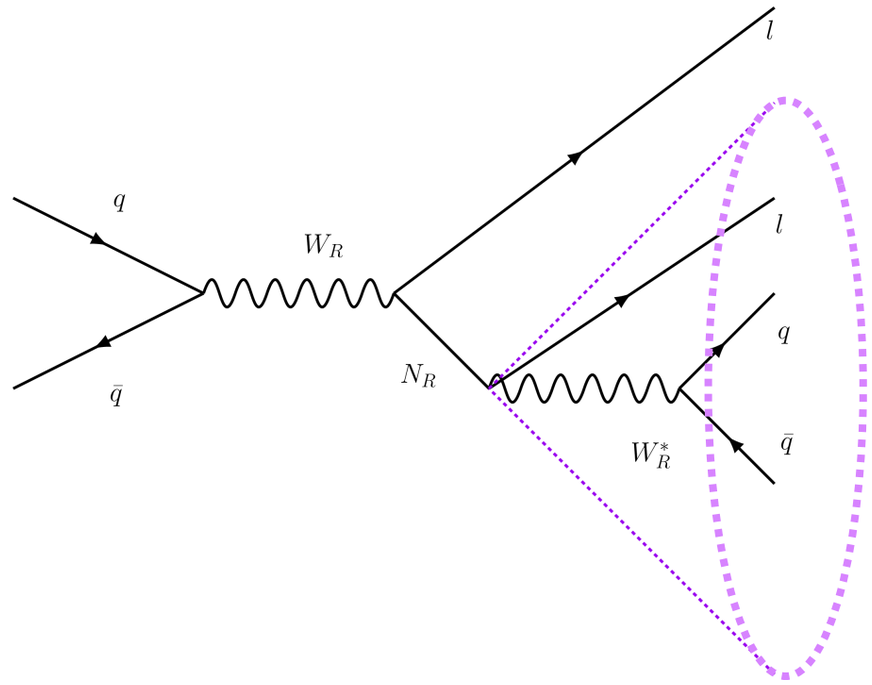
$m(W_R) < 4.7$ TeV

JHEP05(2018)148

J. High Energ. Phys. (2019) 2019: 16

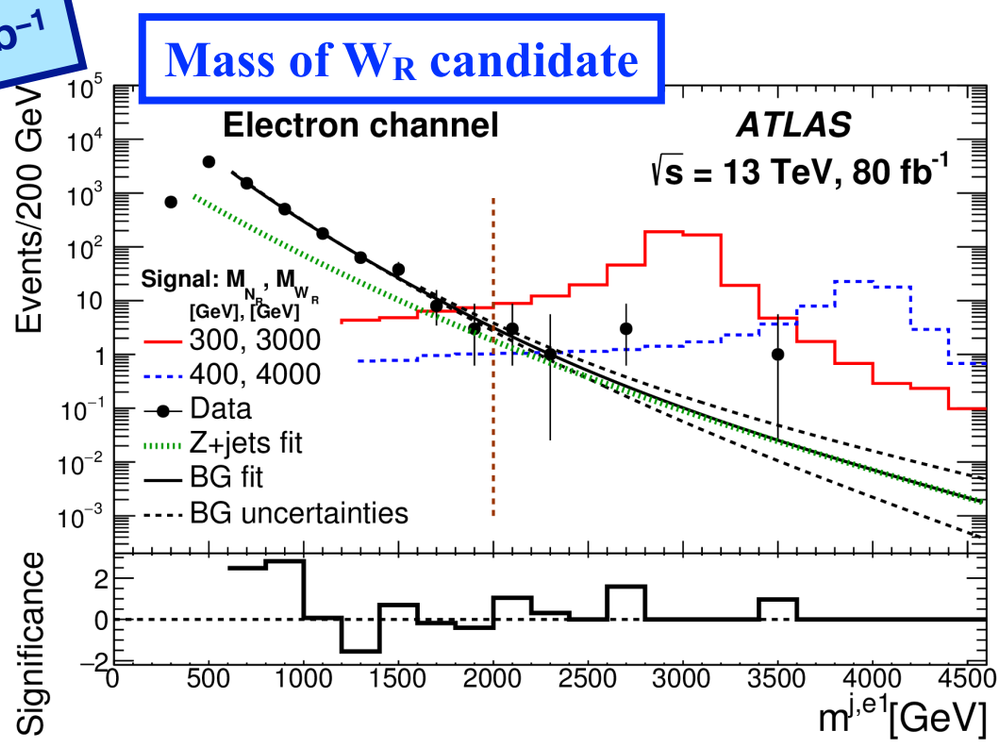
LRSM: boosted topology (ATLAS)

- If $m(N_R) \ll m(W_R)$, N_R is very boosted
  - The two jets are not resolvable, but clustered into a single, large-radius jet
  - The lepton is also found inside the jet cone
    - electron energy naturally included
    - muon momentum added by hand



  - Careful calibration of large-jet energy and mass scales

$\int L = 80\ fb^{-1}$



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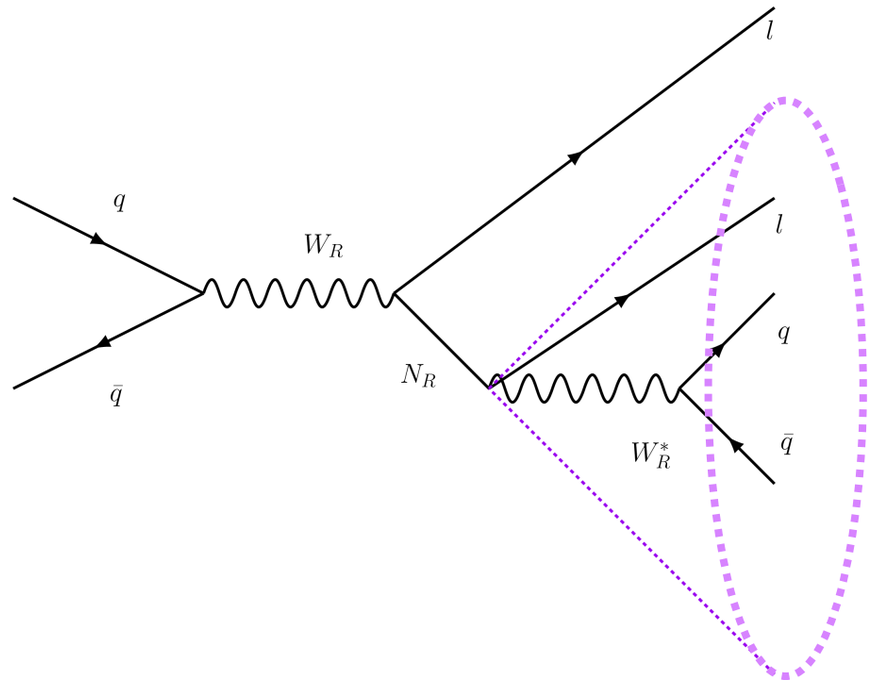

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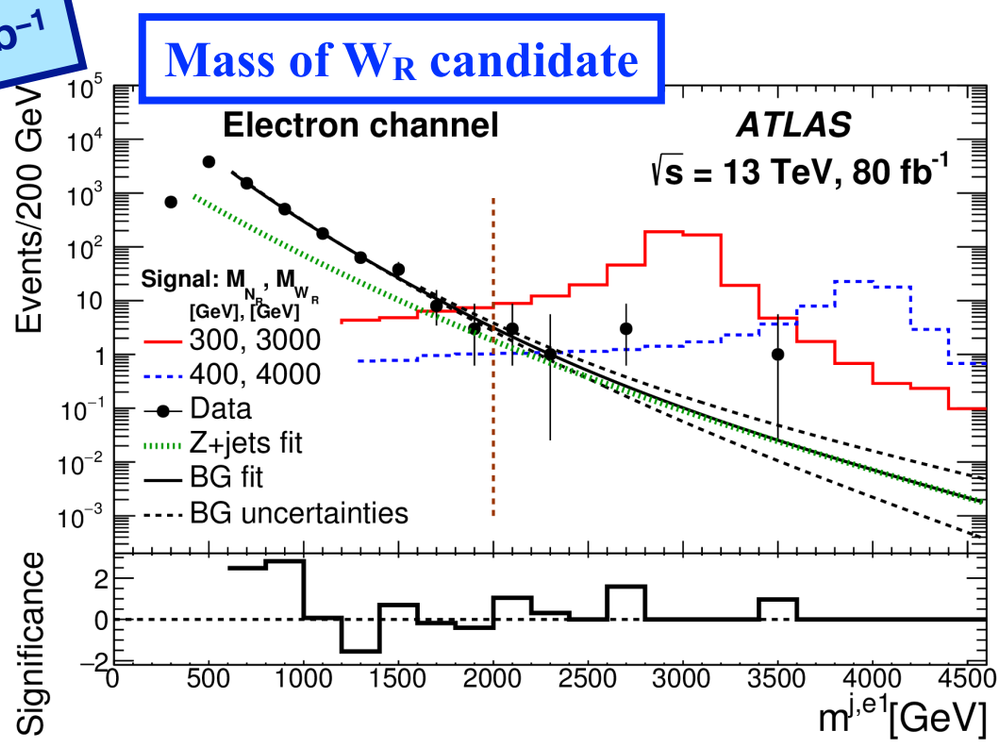
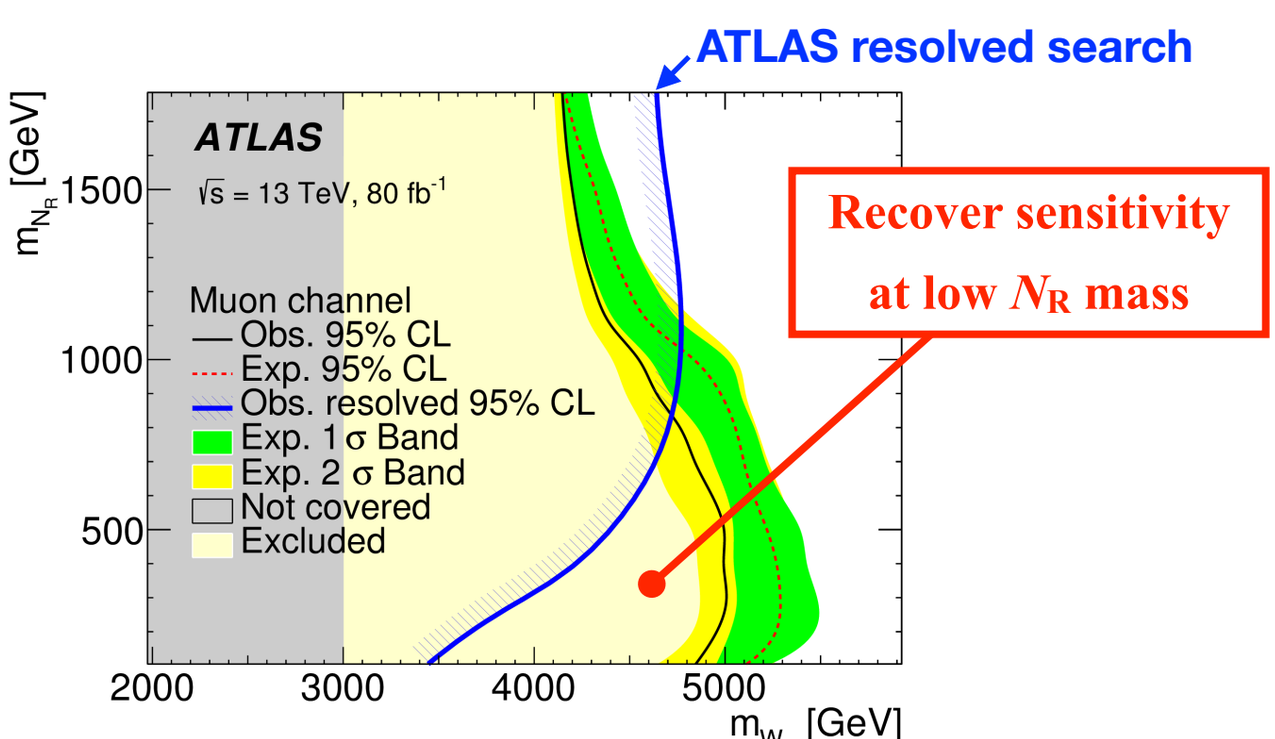
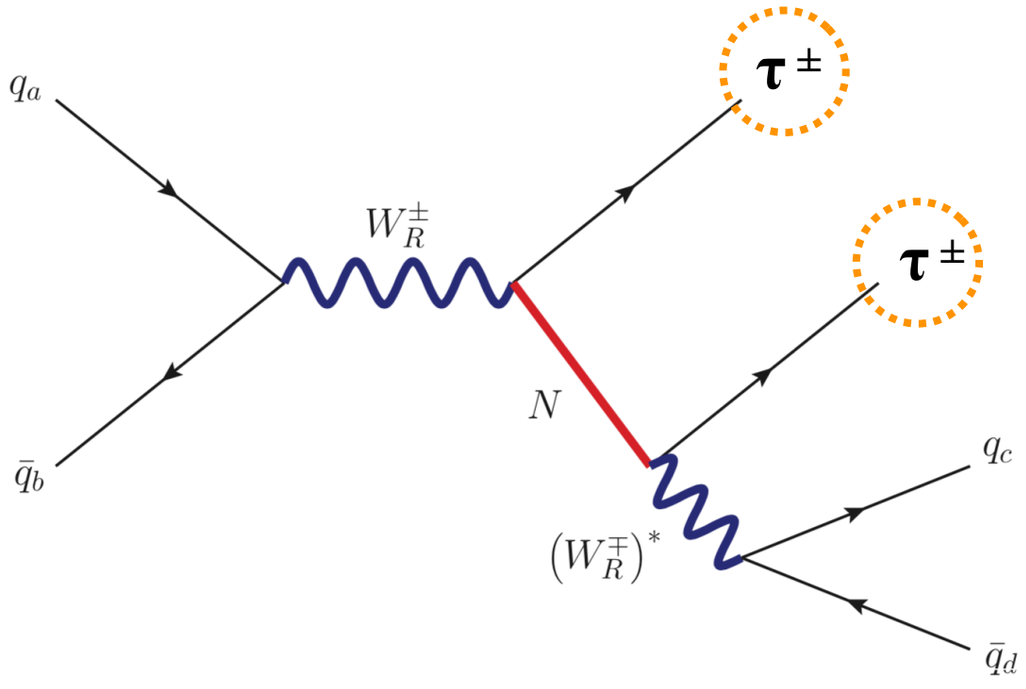




LRSM: τ couplings (CMS)

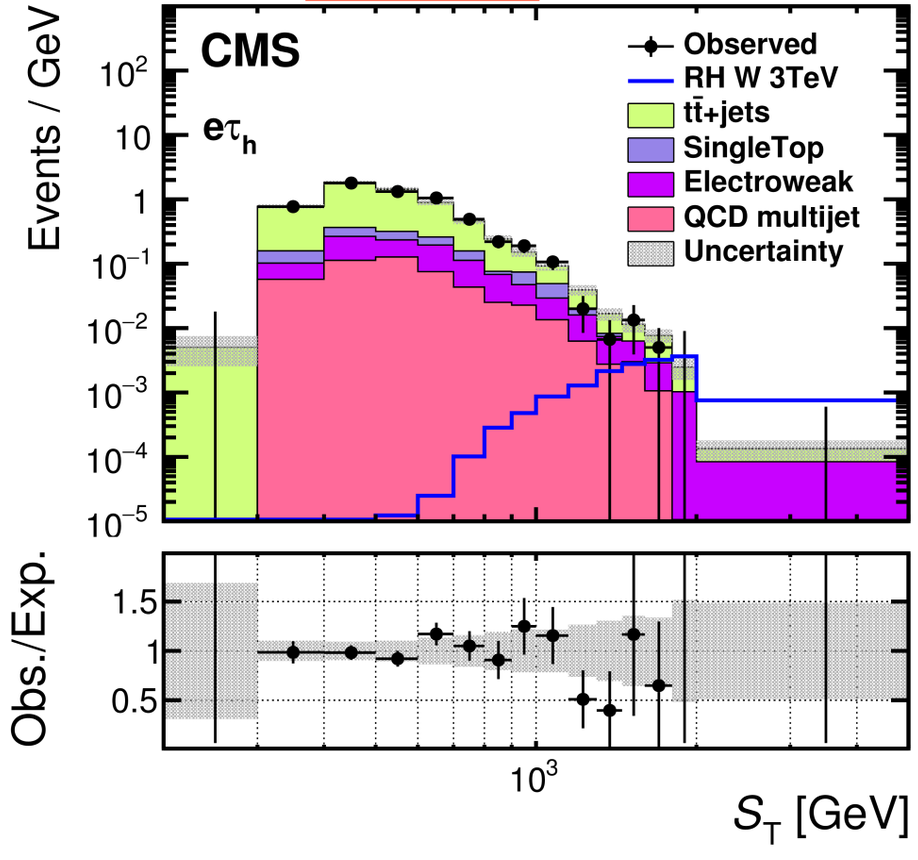
- Production of $\tau\tau qq$
  - JHEP03(2017)077: both τ's decay hadronically (τ_h)
  - JHEP07(2017)121: one τ_h and one decaying leptonically → $\ell\nu\,\tau_h\,qq$ (ℓ = e, μ)
    - ℓ allows for efficient triggering, τ_h has larger branching fraction
    - Discriminating variable: S_T = scalar sum of p_T of ℓ, τ_h, jets, MET



$e\nu\,\tau_h\,qq$

$\int L = 13\ fb^{-1}$

12.9 fb^{-1} (13 TeV)



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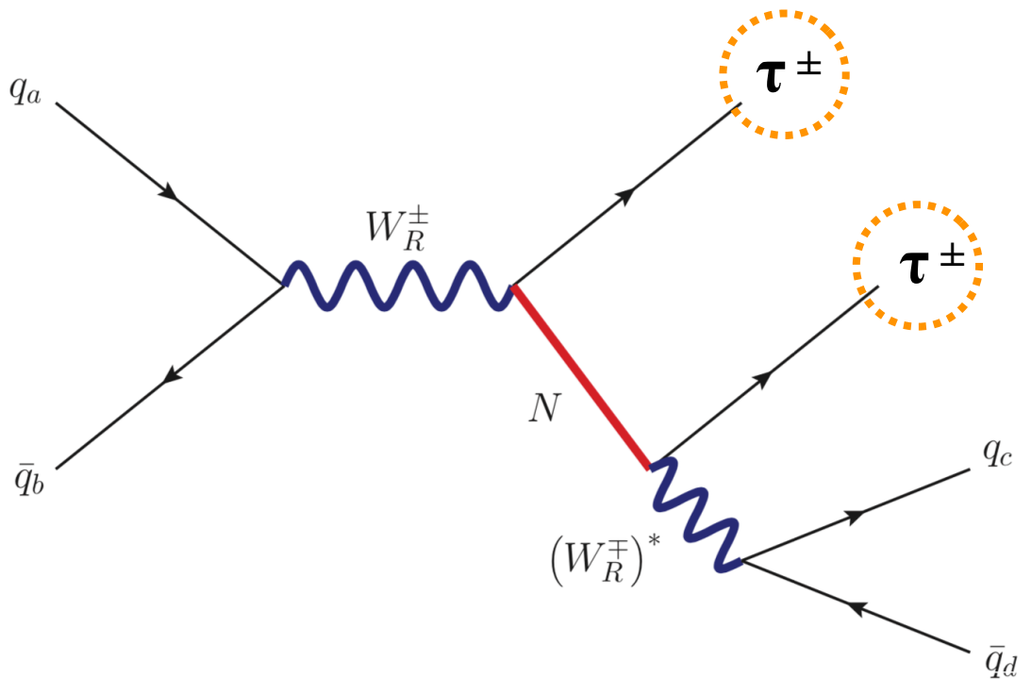
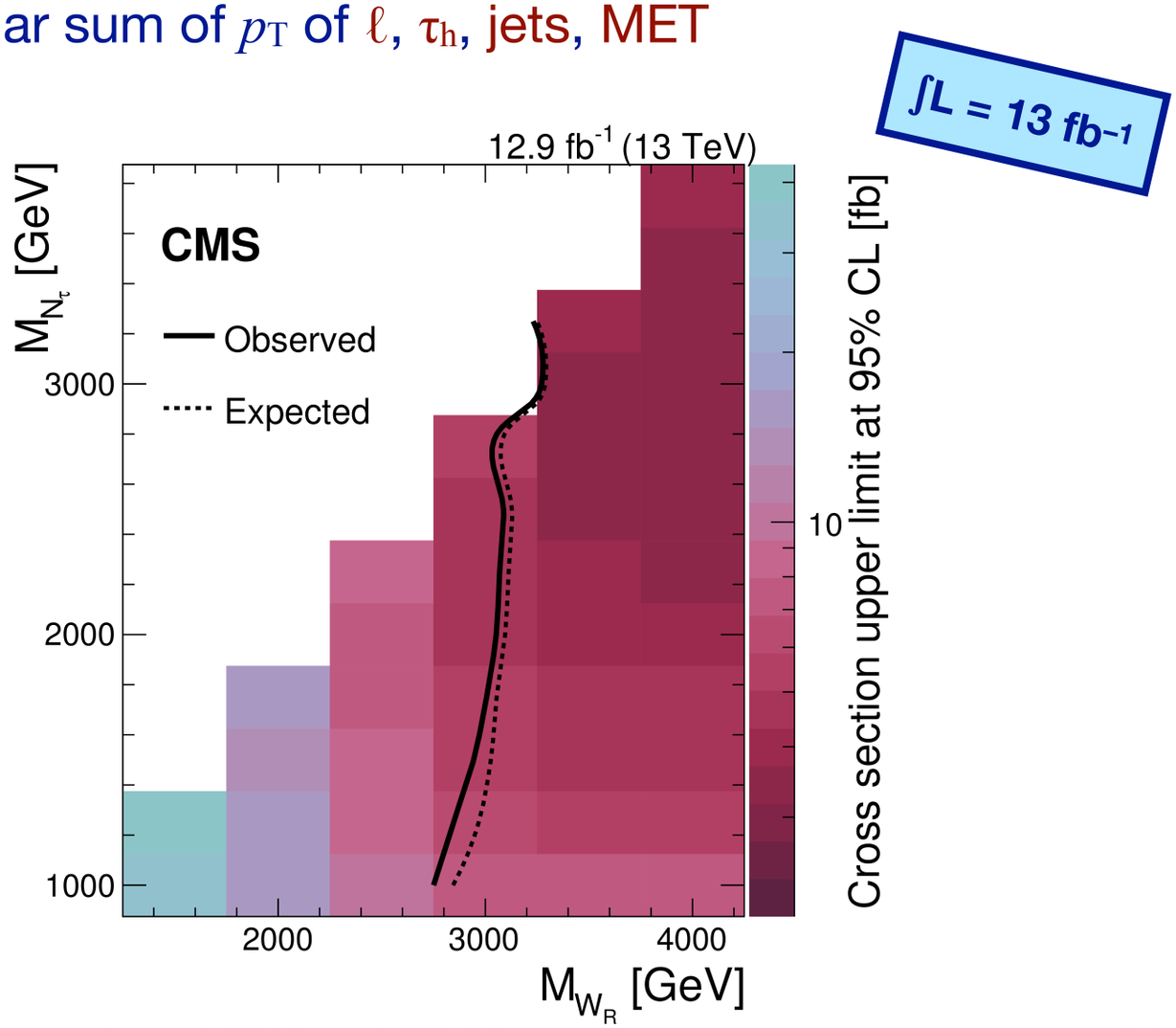


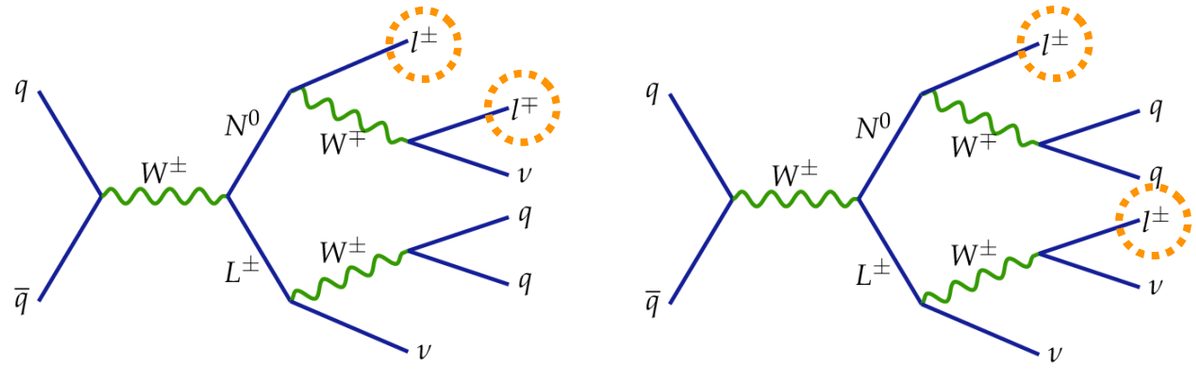


Type-III seesaw

Type-III: dilepton channel (ATLAS)

ATLAS-CONF-2018-020

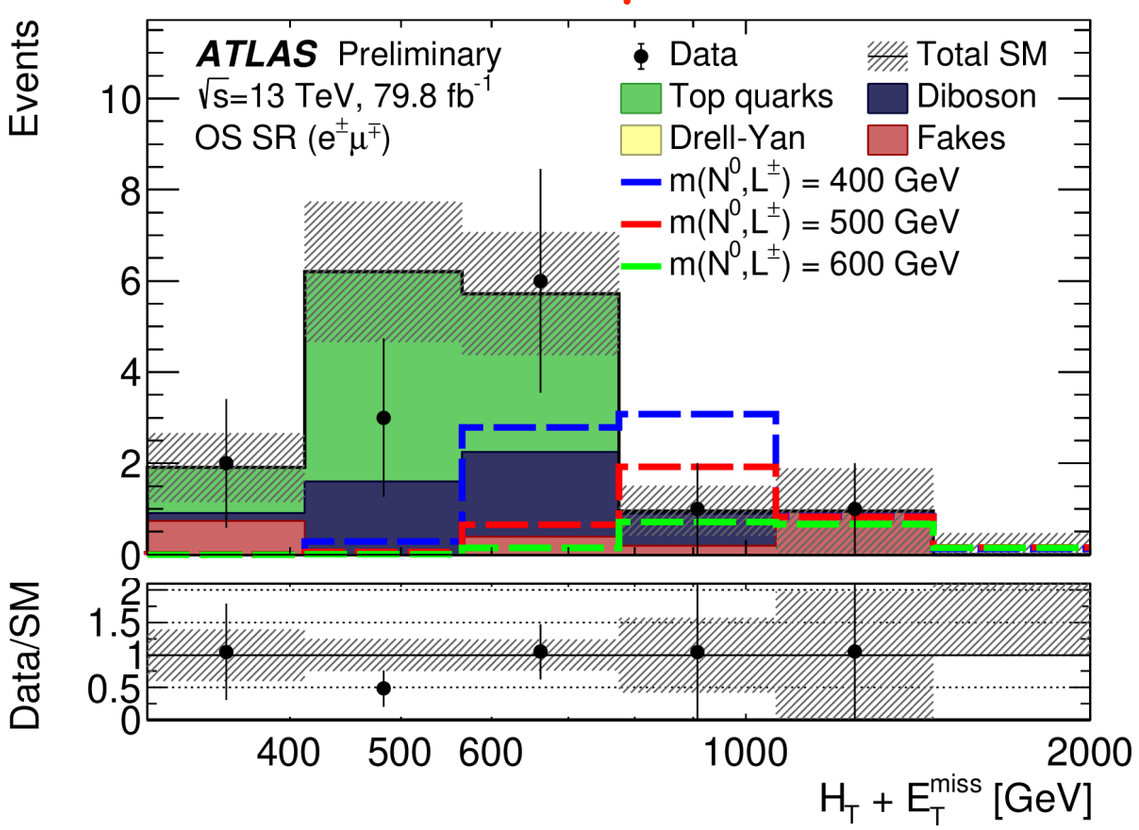
- Select $pp \to \Sigma^0\Sigma^\pm$ with 2ℓ final states, any flavor and charge combination
  ⇒ 6 final states



  - Σ^0 and $\Sigma^\pm$ have same mass
  - Flavor-democratic scenario: $B_\ell = 1/3$ for any ℓ
  - Discriminating variable: scalar sum of lepton p_T (H_T) + MET

OS $e^\pm\mu^\mp$

$\int L = 80\ fb^{-1}$



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ATLAS-CONF-2018-020

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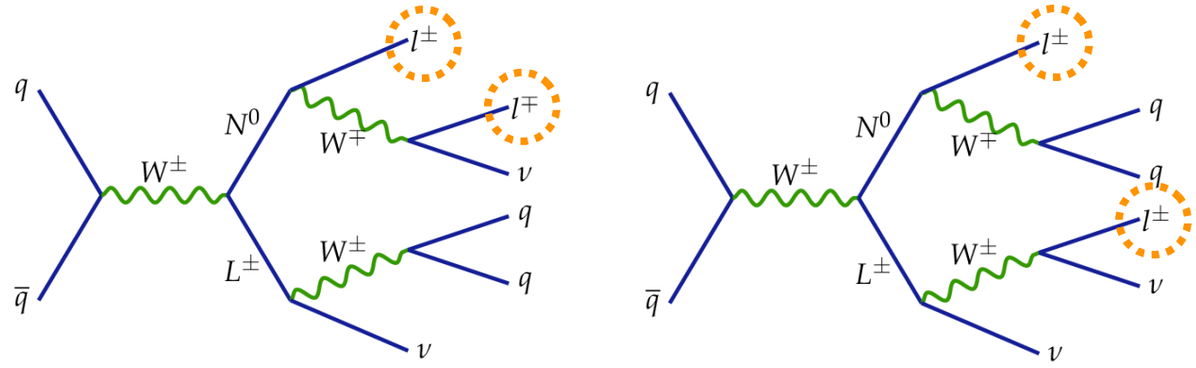

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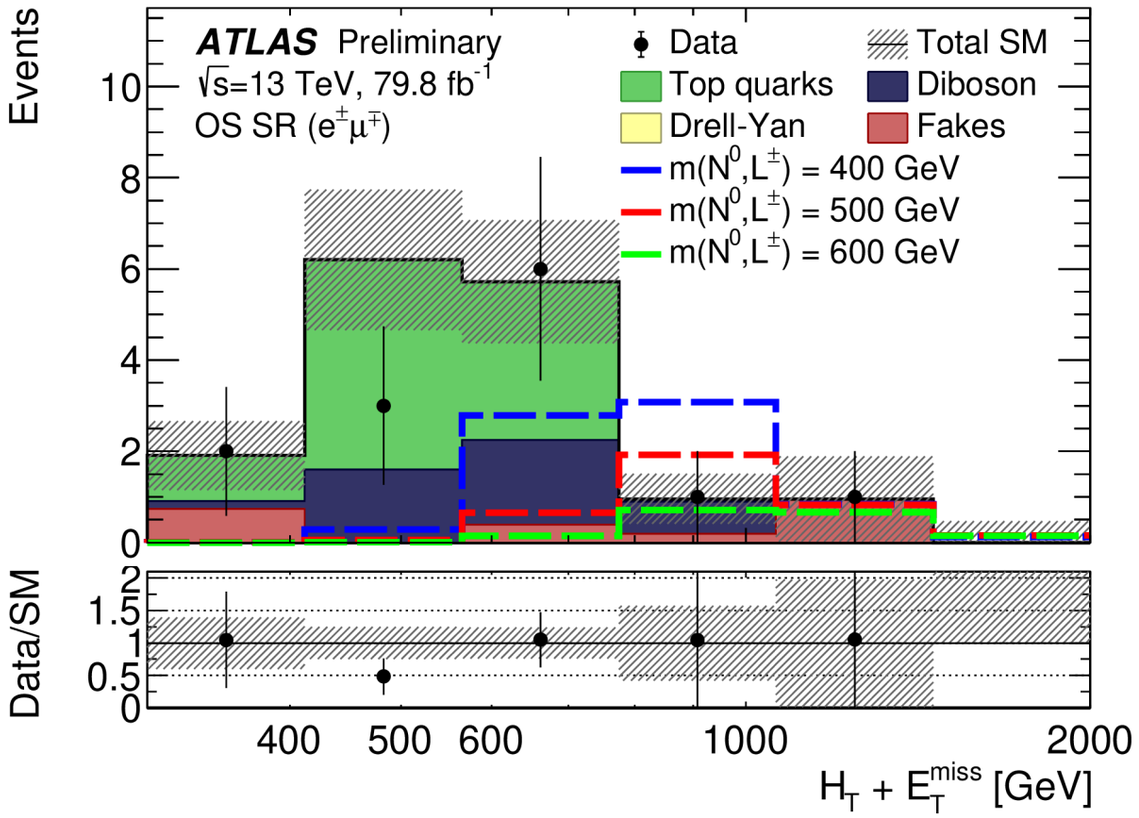
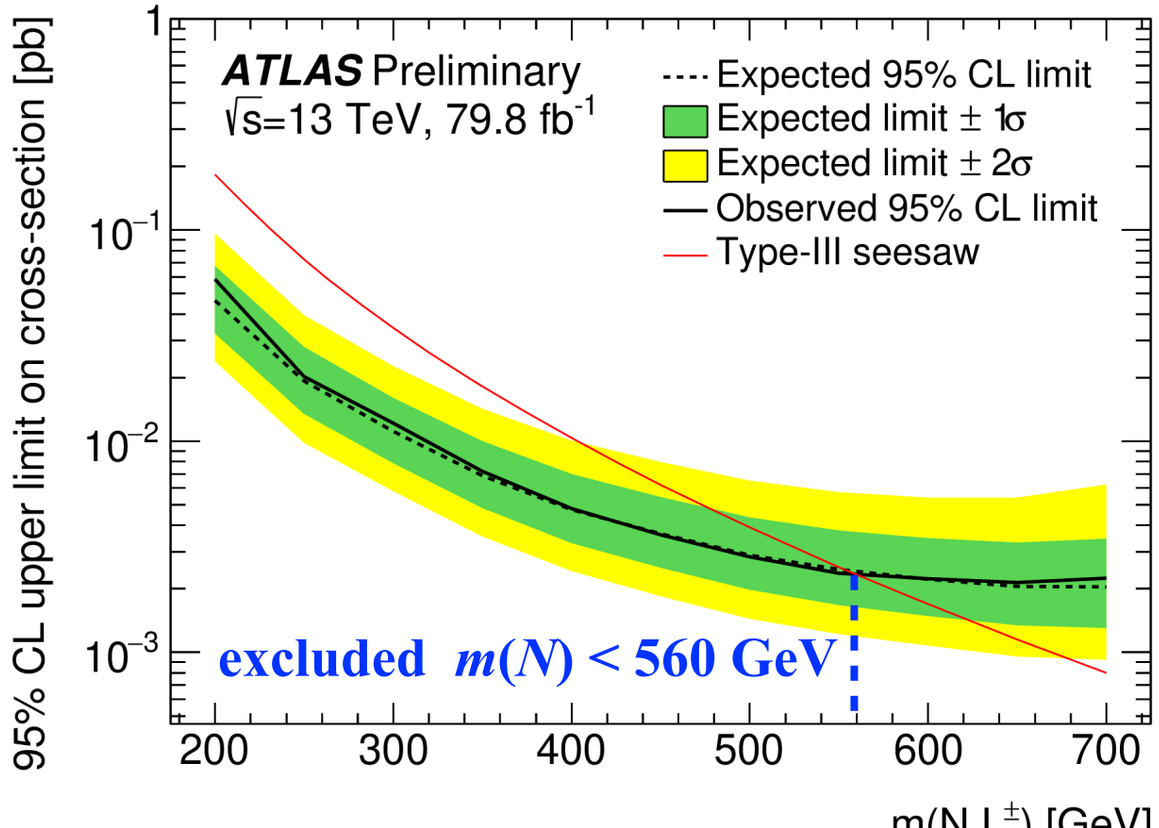


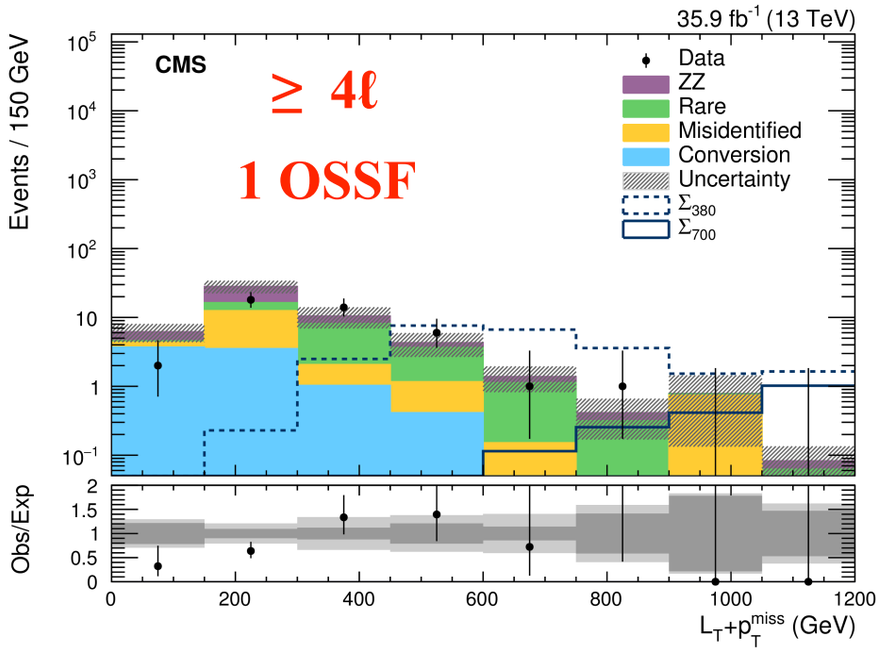


Type-III: multilepton channel (CMS)

PRL 119, 221802 (2017)

- $pp \to \Sigma^0\Sigma^\pm$ / $\Sigma^\pm\Sigma^\mp$ with fully leptonic final states (including τ leptonic decays) mediated by W/Z/H bosons ⇒ 27 final states, with 3 or more leptons
  - Events classified by number of leptons and number of OSSF pairs
  - Explore all possible $B_e / B_\mu / B_\tau$ combinations
  - Discriminating variable: scalar sum of lepton p_T (L_T) + MET

$\int L = 36\ fb^{-1}$



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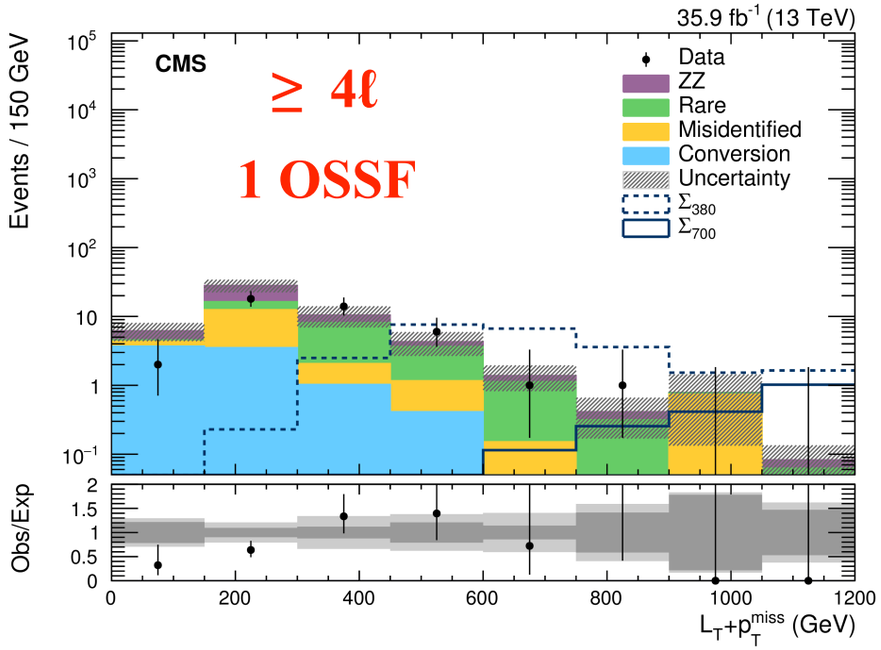
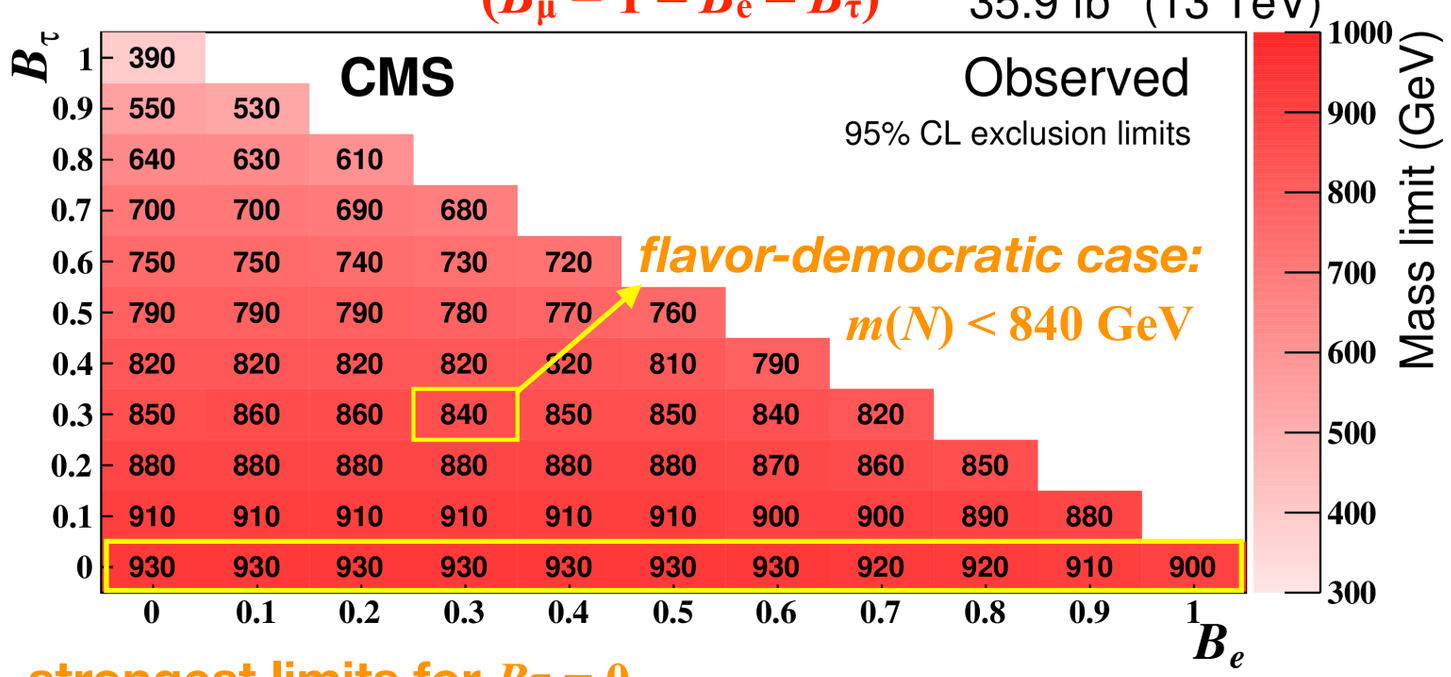


Limit on $m(N)$ *vs* B_e, B_τ

$(B_\mu = 1 - B_e - B_\tau)$



strongest limits for $B\tau = 0$

Conclusions

- ATLAS and CMS have been actively participating in the hunt for heavy neutral leptons
  - they have extended the search up to the TeV scale!

- Several models with HNLs have already been explored
- So far the focus has been put on short-lived HNLs and on electron and muon couplings
  - but first results with long-lived HNLs and τ couplings have been shown

- More to come with Run-II data, and even more to be expected from future runs... stay tuned!