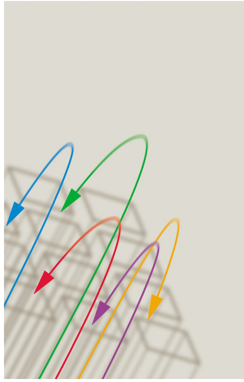
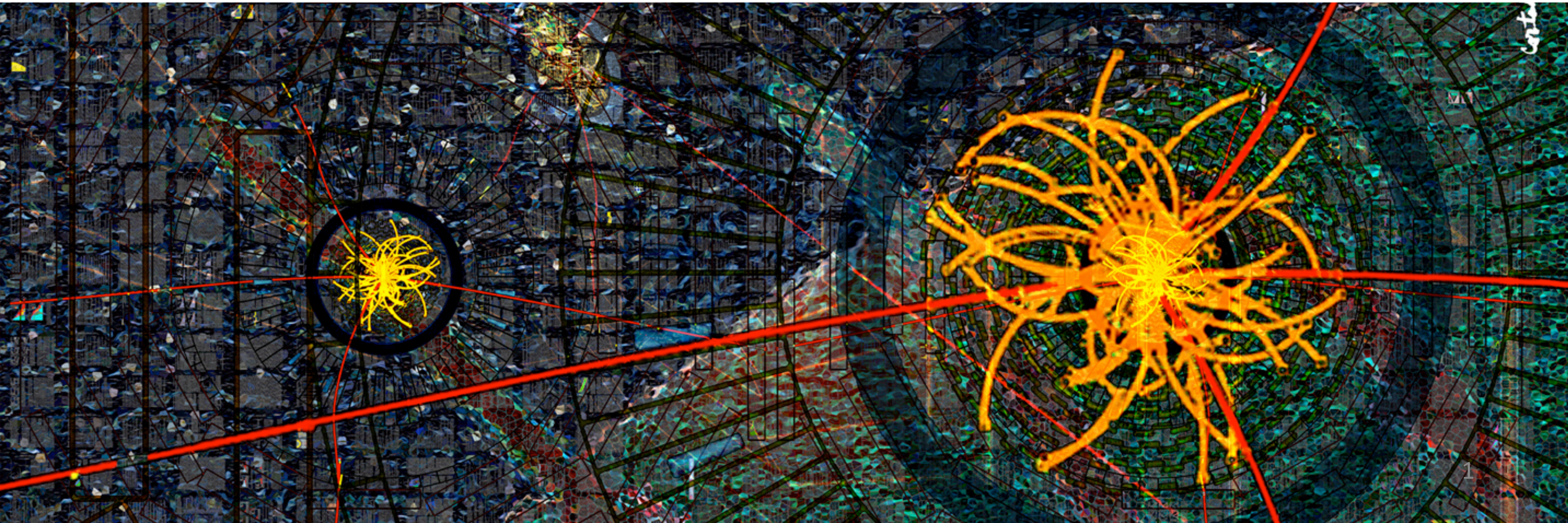
LHC with multi-leptons: from SM to new physics



Didar Dobur
University of Ghent



Outline

- Search for tt+H (CMS-PAS-HIG-17-004)
- tt+W and tt+Z measurement (arXiv:1711.02547)
- Search for SUSY via Electroweak production
  (arXiv:1709.05406)
- Search for sterile neutrinos at the LHC
  - (soon to appear in arxiv)

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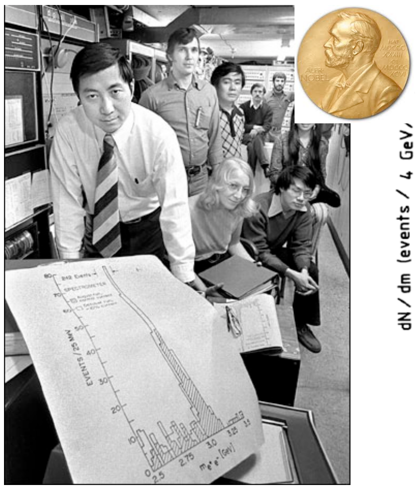
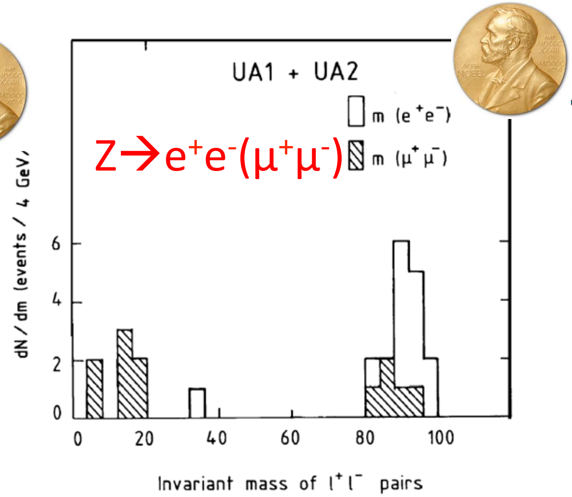
…all that with multi-lepton signatures

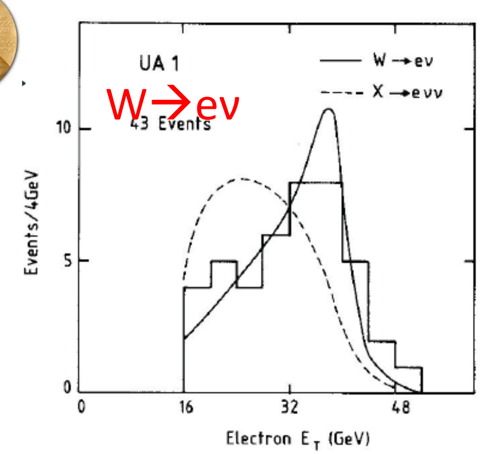
Discoveries with leptons

1974 A narrow resonance
$J/\Psi \rightarrow e^+e^-$

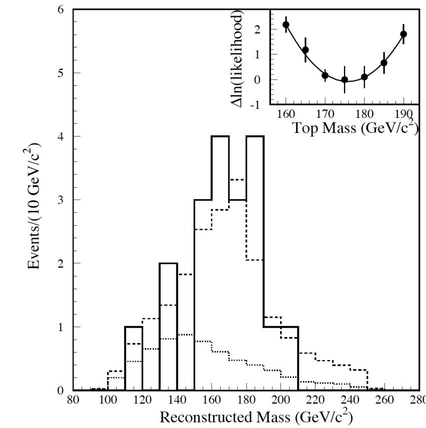


1983 first observation of W and Z at CERN

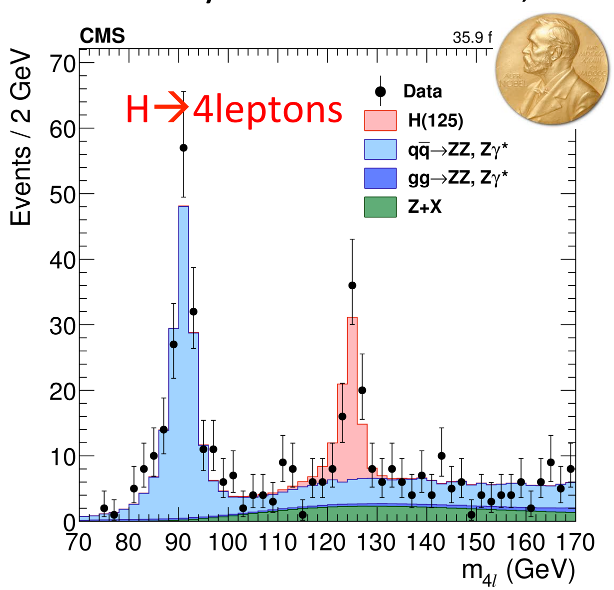


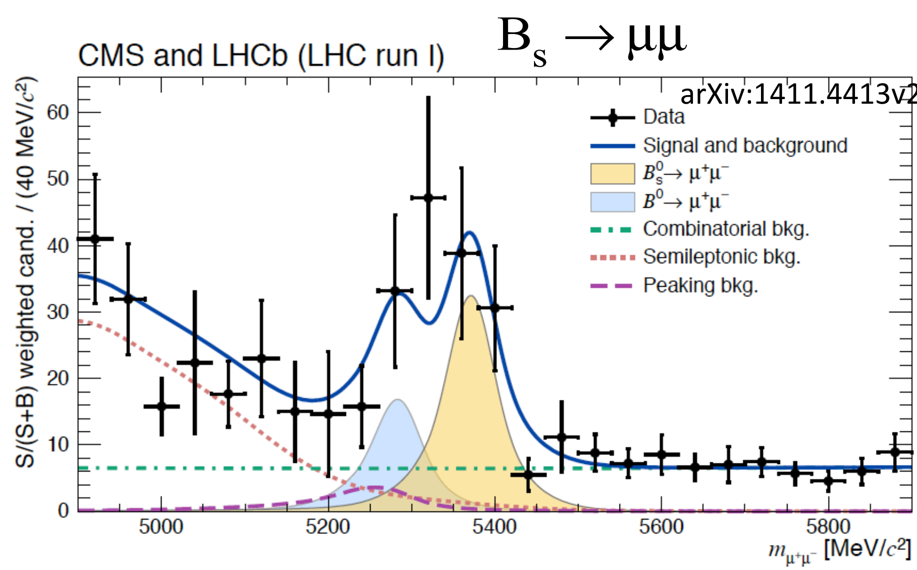


1995, the top quark, FNAL $t\bar{t} \rightarrow e,\mu$+jets)

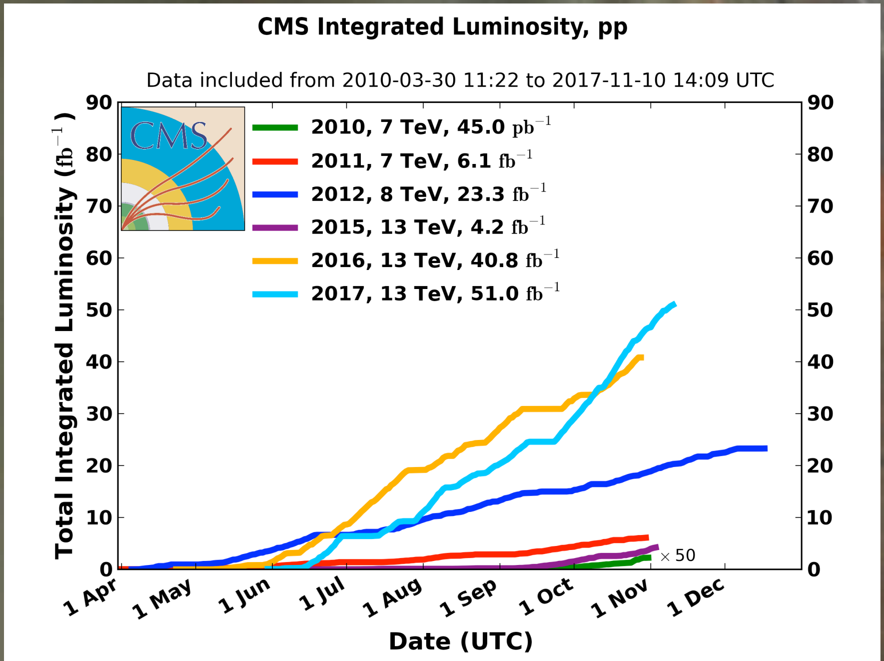


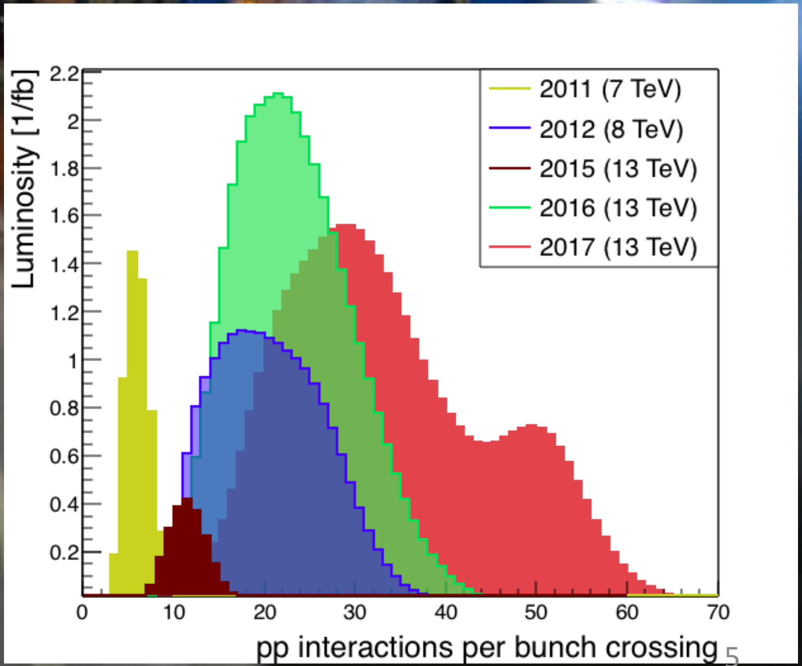
2012 Discovery of a scalar boson, CERN



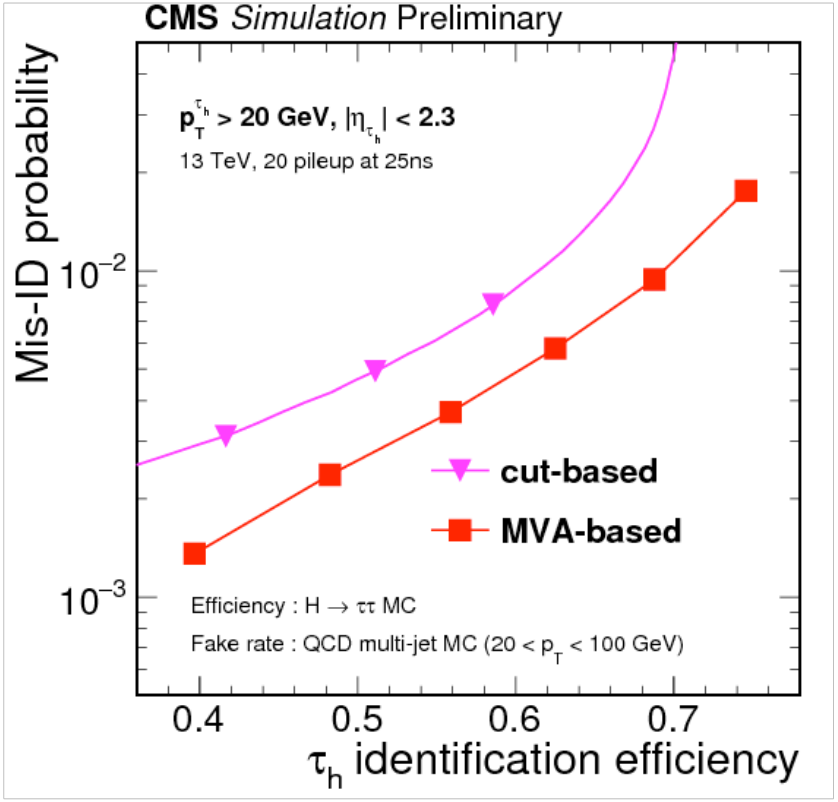


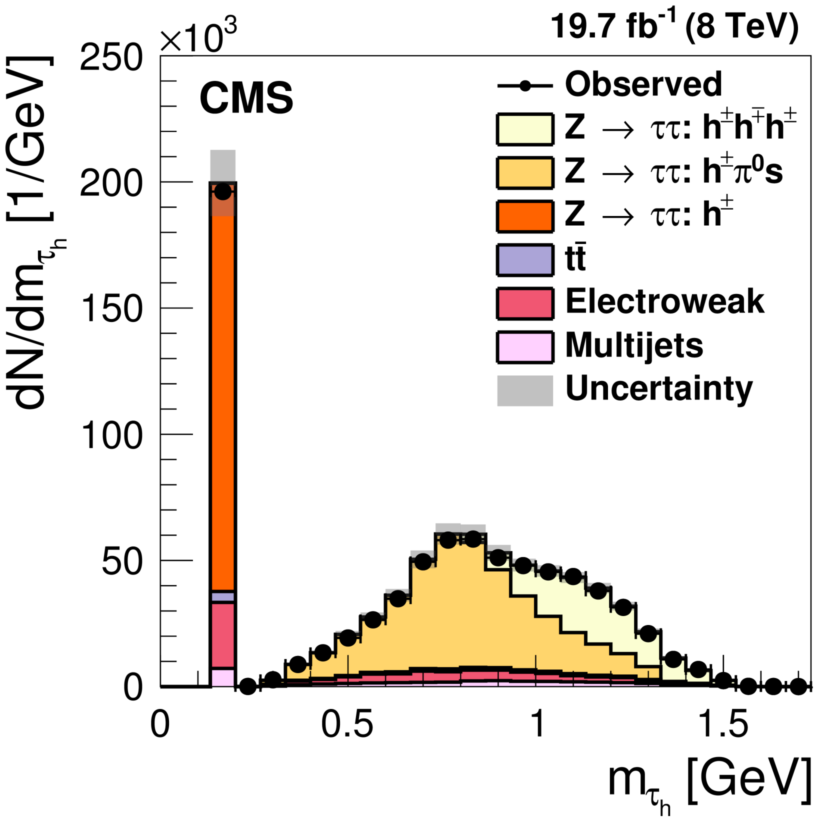
What do we have in hand ?





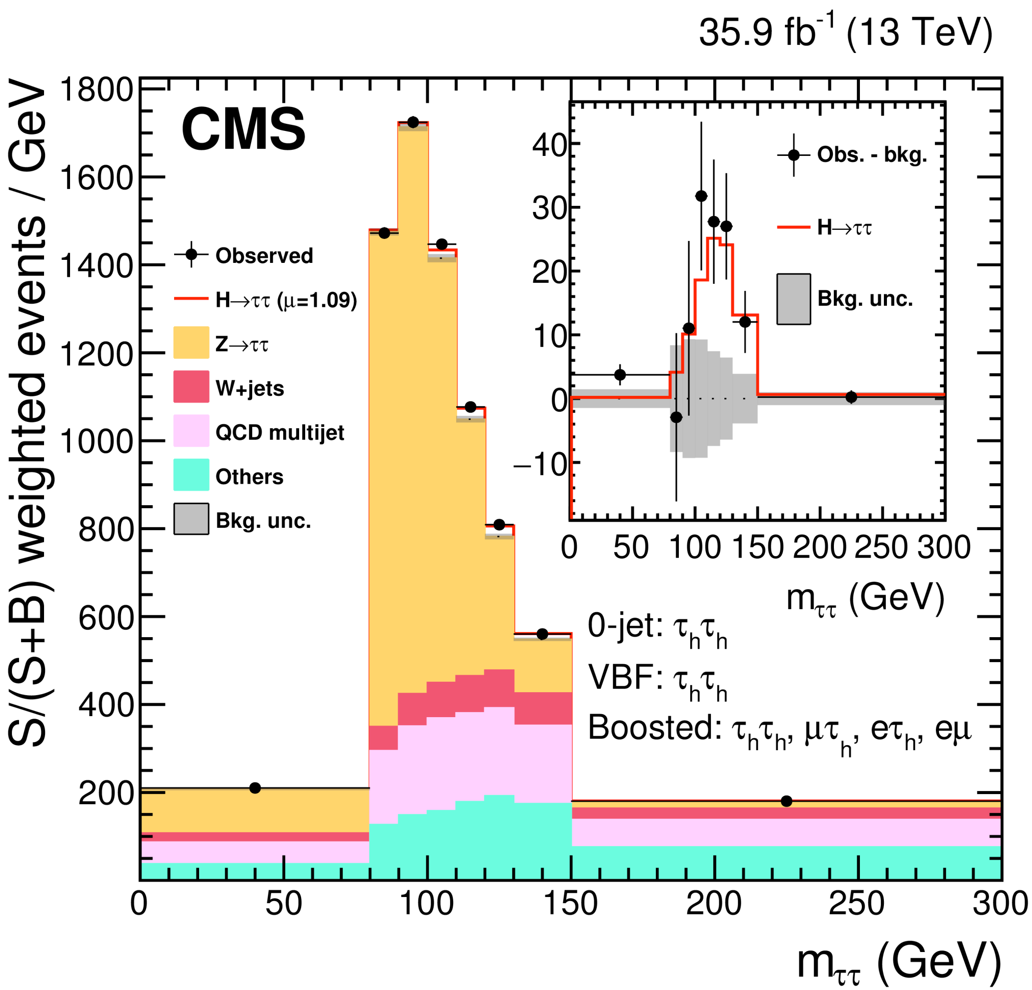
Lepton identification: τ





- Hadronicly decaying tau identification with high purity & efficiency
- Excellent description of the visible mass by the simulation

Lepton identification: τ



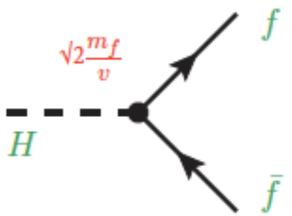
$H \rightarrow \tau\tau$

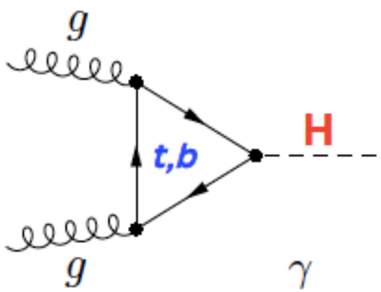
Observed (expected) significance:

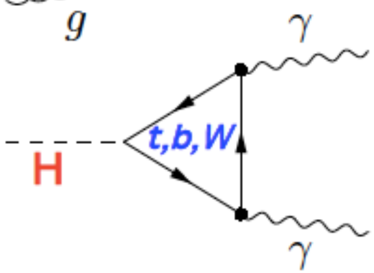
- 13 TeV : 4.9 (4.7) σ
- 7+8+13 TeV : 5.9 (5.9) σ

arXiv:1708.00373

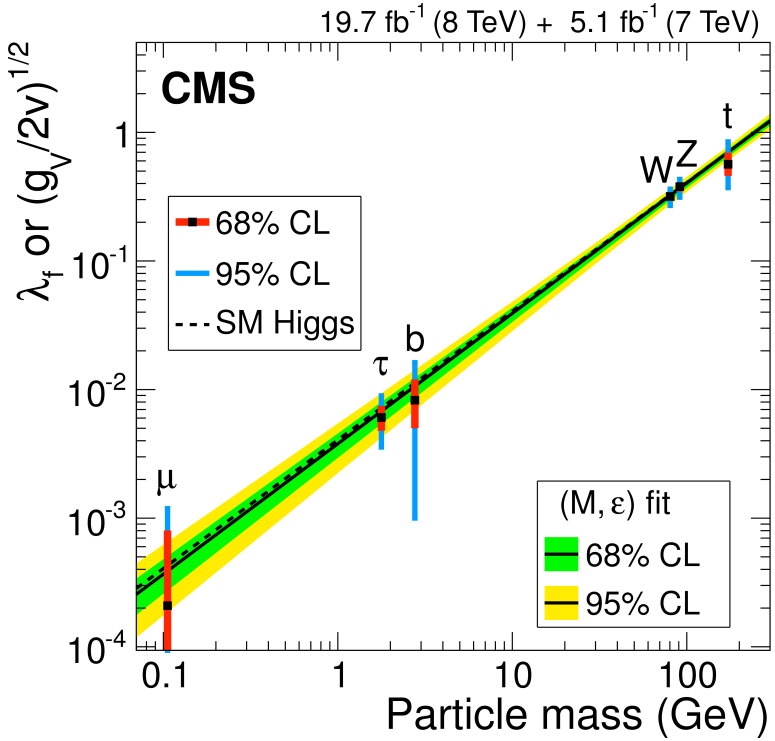
$t\bar{t} + H$ production







- Higgs coupling to the fermions through Yukawa interactions
- Large M(top) → Largest Yukawa coupling: $\lambda_t \approx 1$
- λ_t can be extracted from H production via gg and its decay to γγ



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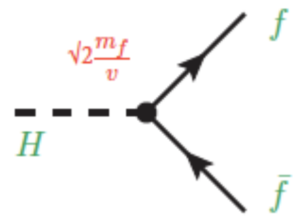

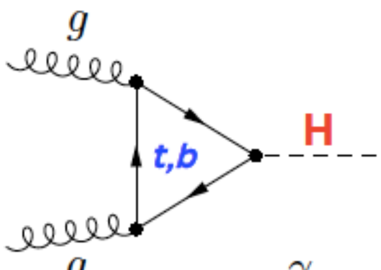

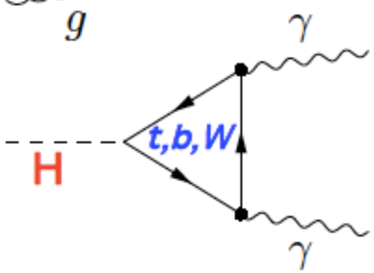

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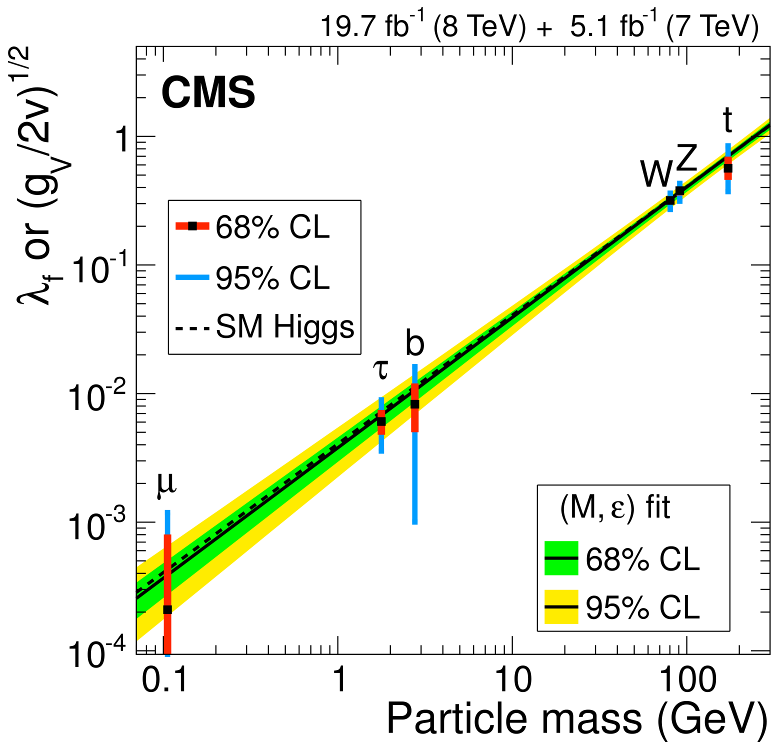

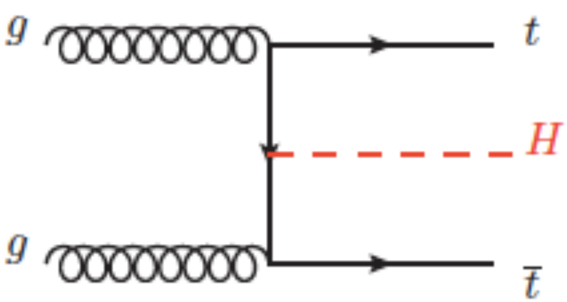

$t\bar{t} + H$ production :

- best way to directly measure the top quark yukawa coupling

$$\sigma \propto \lambda_t^2$$

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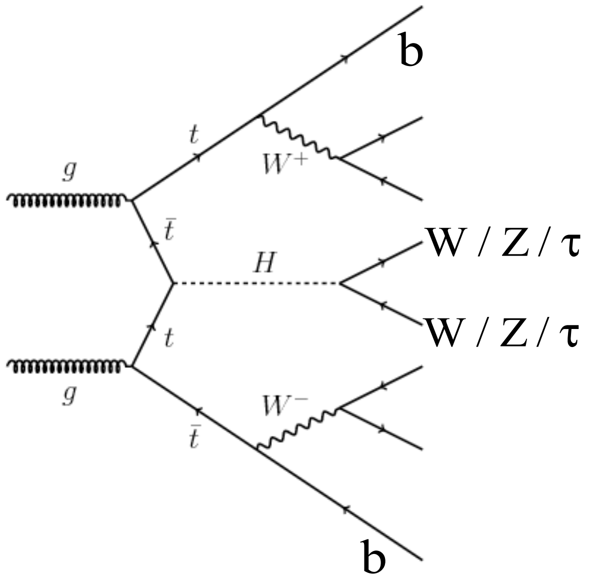
$t\bar{t} + H$ search strategy

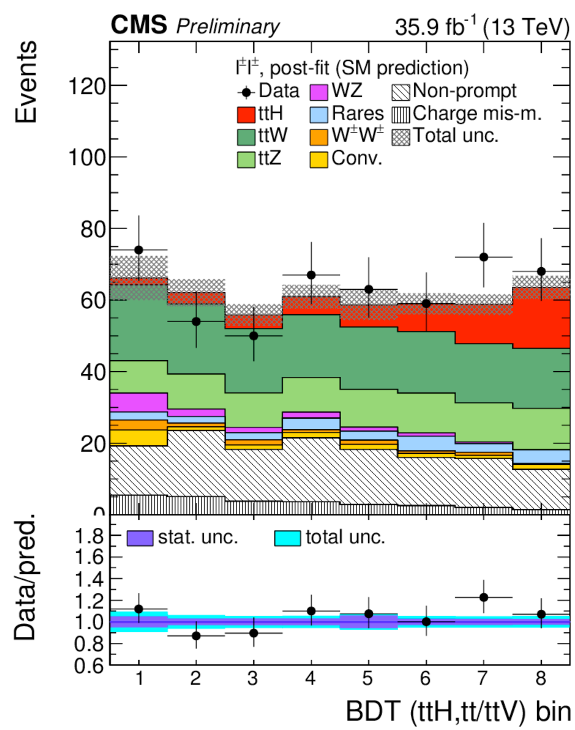


- Large $\sigma(t\bar{t}H) \sim 1\text{fb}$
- All H decays are explored
- Most sensitive channel is multi-leptons

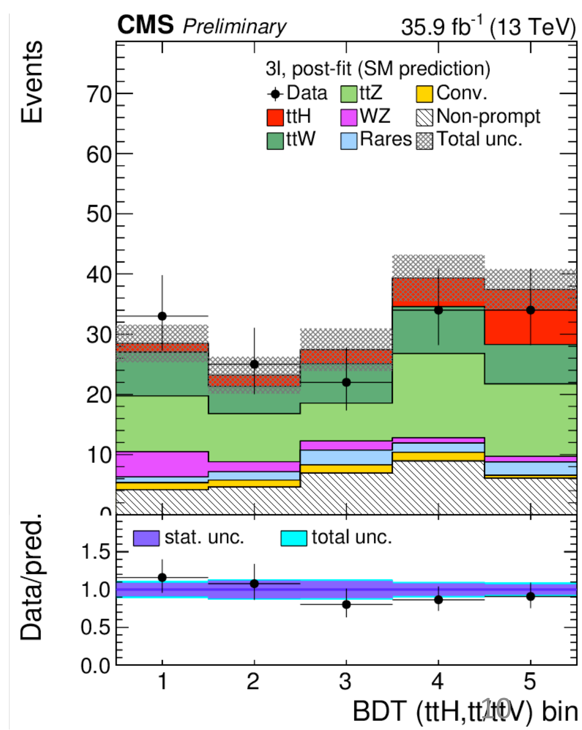
$\ell^{\pm}\ell^{\pm}$ and $\geq 3\ell$ with multi – (b) jets

- Multivariate methods for both lepton selection and signal extraction
- Main backgrounds are tt+W and tt+Z
- Misidentified leptons

Same-sign di-leptons



three-leptons



$t\bar{t}+H$: results

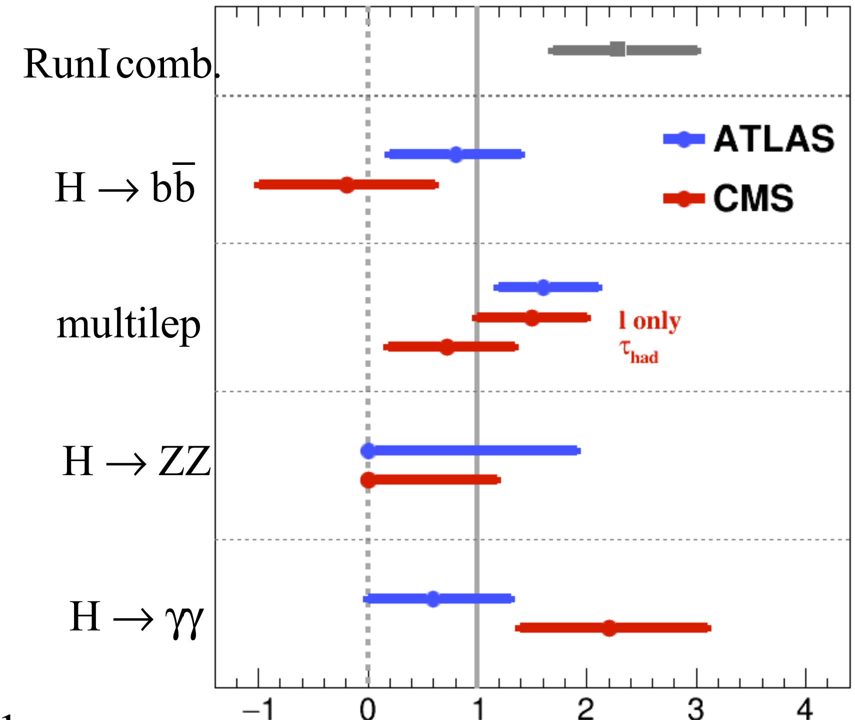
Expected and observed signal significance

$\mathrm{RunI(CMS+ATLAS)} \quad 4.4(2.0)\sigma$

	CMS	ATLAS
$H \to b\bar{b}$	$--$	$1.4(1.6)\sigma$
$H \to \mathrm{multilep}$	$3.3(2.5)\sigma$	$4.1(2.8)\sigma$
$H \to \gamma\gamma$	$3.3(1.5)\sigma$	$1.0(1.8)\sigma$

- Comparable expected sensitivity from both experiments
- Most significant channels tend to show $\mu_{\mathrm{ttH}} > 1$
- Analysis of 2017 in combination with 2016 might lead to observation

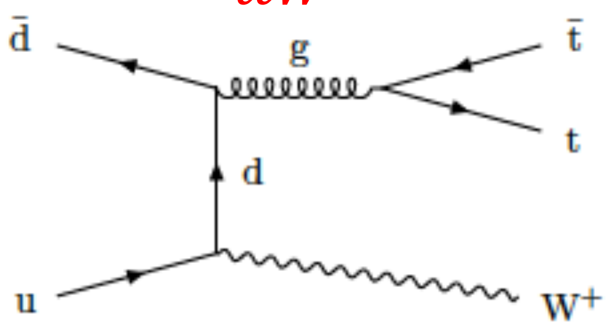
Measured signal strength by CMS & ATLAS



$$\mu_{\mathrm{ttH}} = \sigma(t\bar{t}H)/\sigma(ttH)_{\mathrm{theo}}$$

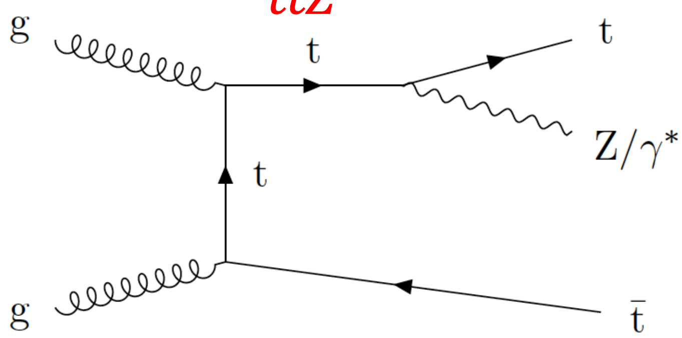
$t\bar{t} + W$ and $t\bar{t} + Z$ production

ttW



$\sigma(t\bar{t}W)_{Theory} = 0.61 \pm 0.08$ pb

ttZ



$\sigma(t\bar{t}Z)_{Theory} = 0.84 \pm 0.10$ pb

Three exclusive analyses

- **same-sign dileptons**

$-p_T(\mathrm{e}) > 27, p_T(\mu) > 25\ GeV$

$-N_{jet} \geq 2, N_{bjet} > 0$

$-\mathrm{MVA\ with:}\ N_{jets}, N_{bjets}, H_T, E_T^{miss},$

$p_T^{\ell}, p_T^{j}, M_T, \Delta R(\ell, j)$

- **3-lepton**

$-p_T > 10/20/40$ GeV

$-Z-candidate,\ N_{jet} \geq 2$

$-$Exclusive N_{jet} and N_{bjet} categories

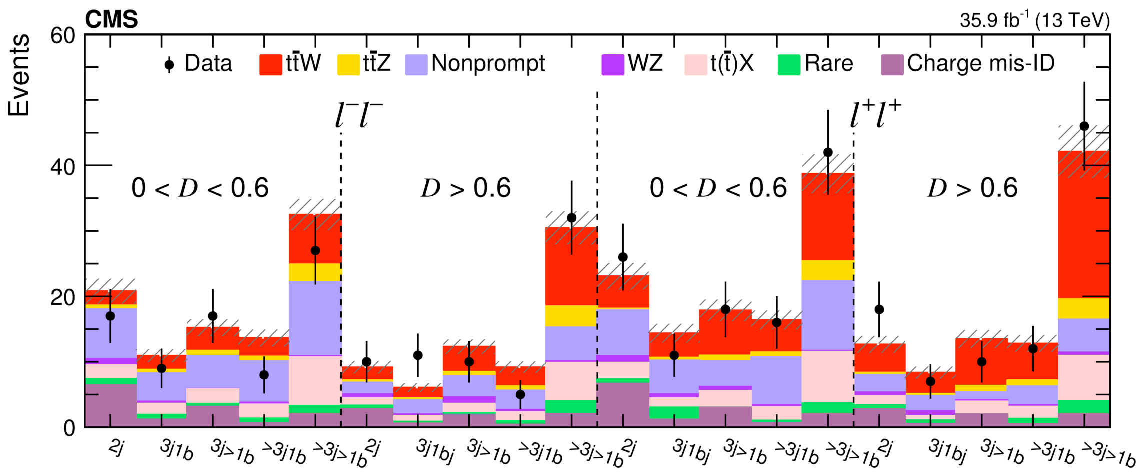
- **4-lepton**

$-\ \mathrm{p}_T > 10/10/10/40$

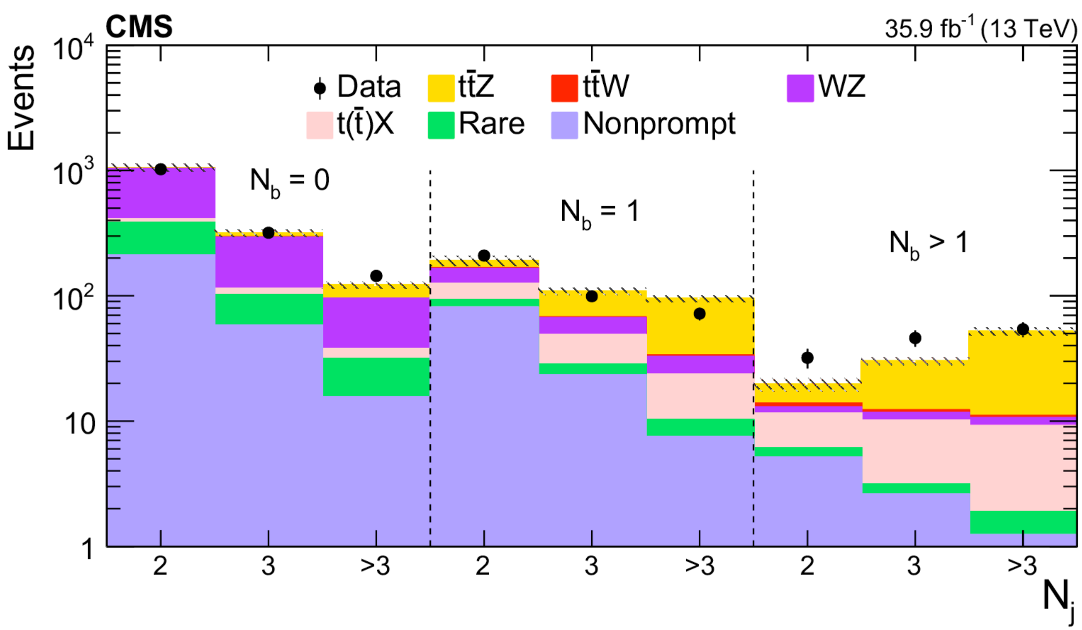
$-ONZ$, 2$^{\mathrm{nd}}$ Z-veto

$-N_{jet} \geq 2, N_{bjet} \geq 1$

$t\bar{t} + W$ and $t\bar{t} + Z$ production

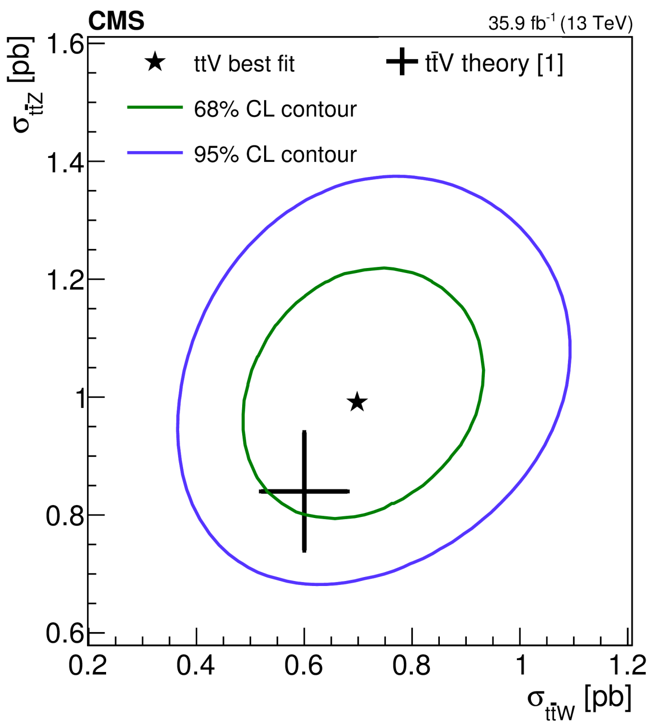


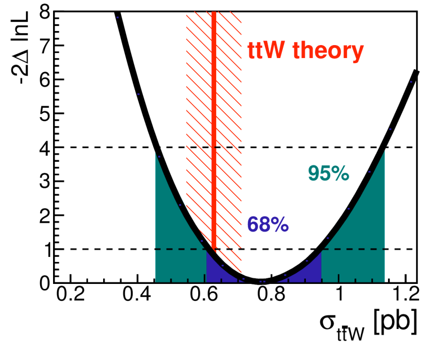
Same-sign dileptons (ttW)
- Backgrounds:
  - Leptons from b-decays
  - ttX: ttH, tWZ
  - Rare: multibosons

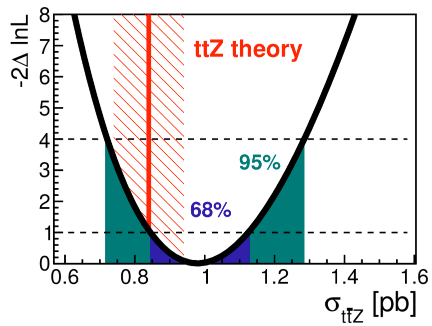


3ℓ and 4ℓ (ttZ)
- Backgrounds:
  - WZ, ZZ
  - Leptons from b-decays
  - ttX: ttH, tqZ
  - Rare: multibosons

$t\bar{t}+W$ and $t\bar{t}+Z$: results







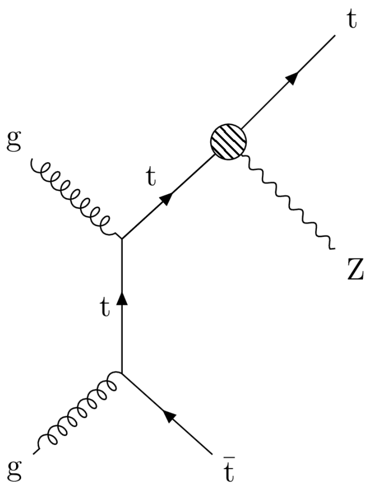
[arXiv:1711.02547](https://arxiv.org/abs/1711.02547)

$$\sigma(t\bar{t}W) = 0.77\underbrace{^{+0.12}_{-0.11}(\text{stat})}_{15\%}\ \underbrace{^{+0.13}_{-0.12}(\text{sys})}_{17\%}\ \text{fb}$$

$$\sigma(t\bar{t}Z) = 0.99\underbrace{^{+0.09}_{-0.08}(\text{stat})}_{9\%}\ \underbrace{^{+0.12}_{-0.10}(\text{sys})}_{11\%}\ \text{fb}$$

- Both ttW and ttZ processes are observed with > 5 sigma (first time!)
- Measured cross sections in agreement with SM
- From now on systematics matter, potential reduction is possible

$t\bar{t} + W$ and $t\bar{t} + Z$: EFT interpretation



- New physics(NP) effects on ttW and ttZ in a model independent way → Effective Field theory

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i + \cdots$$

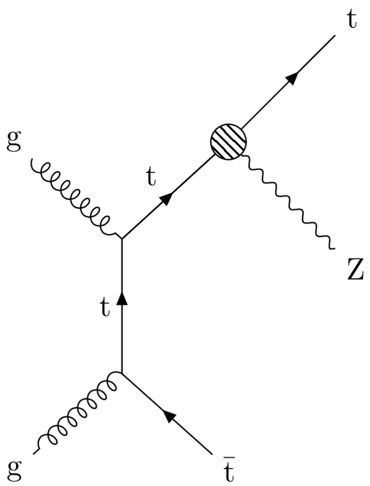
O_i : dimention – 6 operators

c_i : Wilson coefficient

Λ : NP scale

- Studied several of the Wilson coefficients that impact ttW/Z/H

$t\bar{t}+W$ and $t\bar{t}+Z$: EFT interpretation



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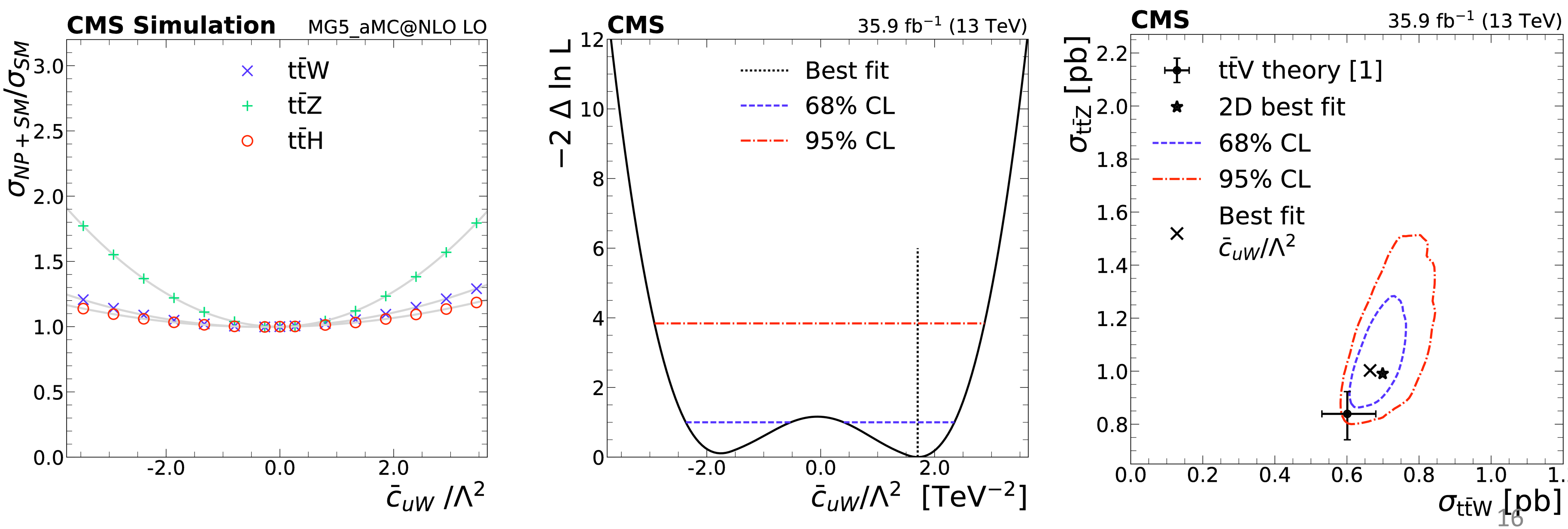
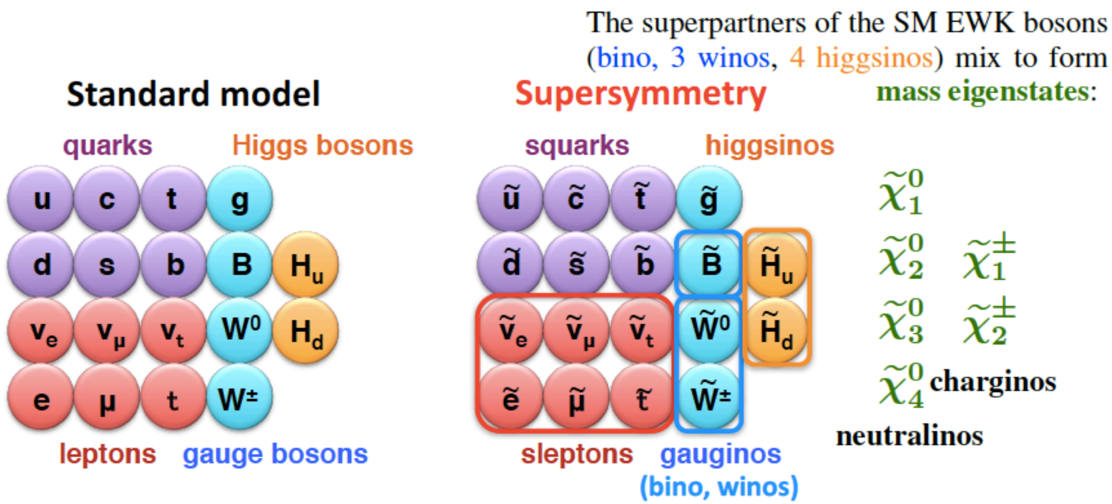
An example…

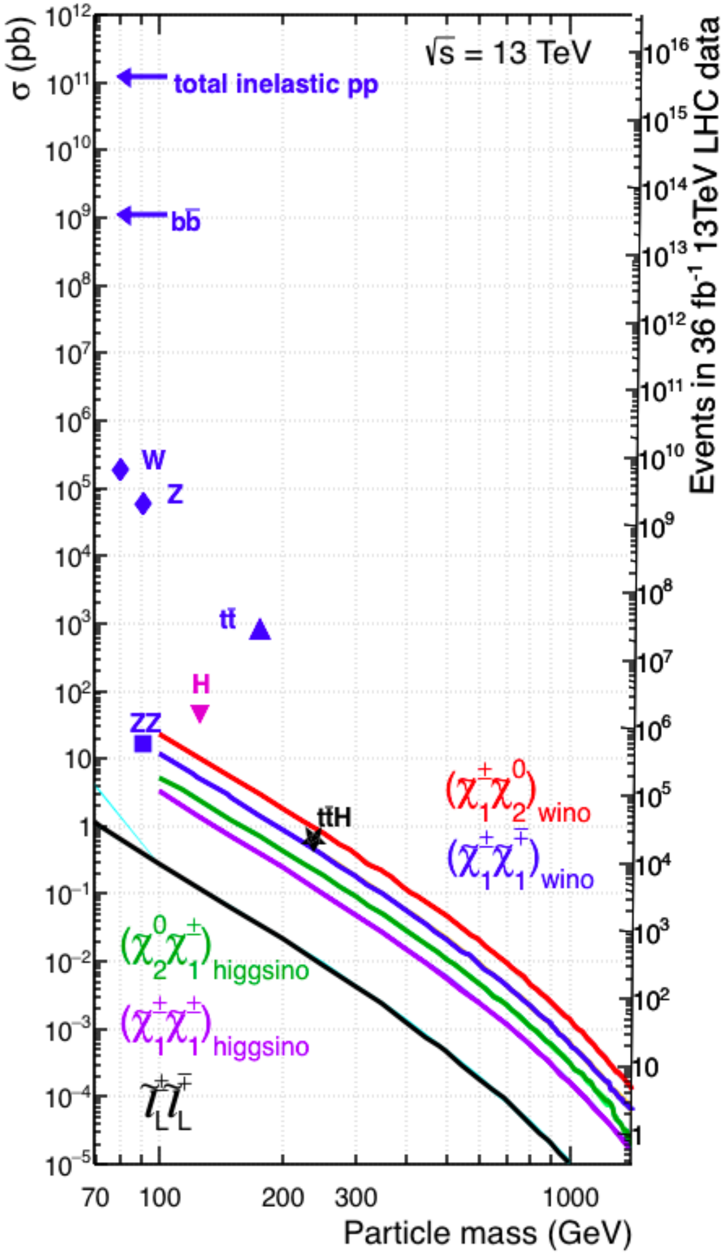


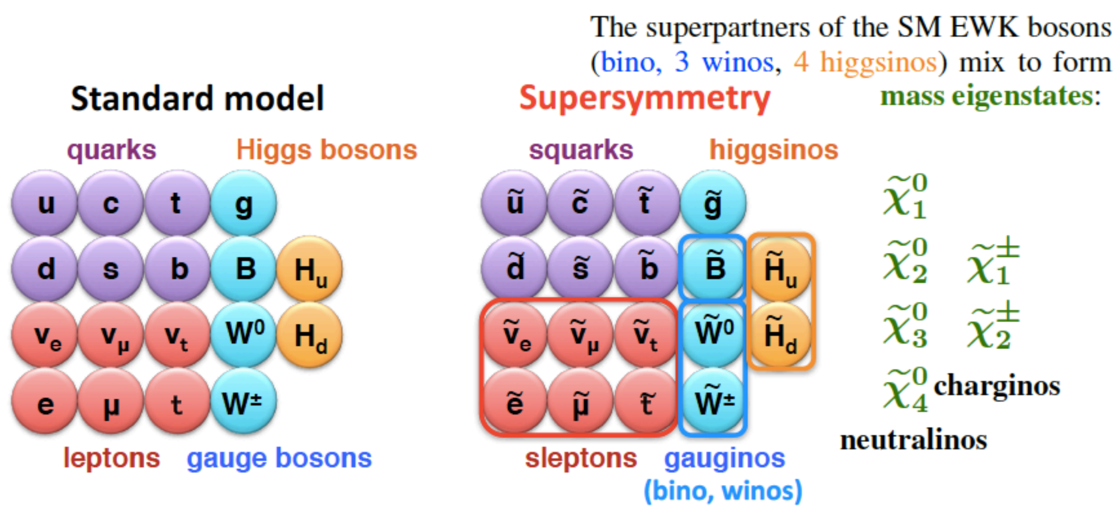
EWK production of $\tilde{\chi}^{\pm}\tilde{\chi}_1^0$



- Searches via strong production profits from large x-sectons
- Limits in squark/gluino sector ~1.5-2 TeV

EWK production of $\tilde{\chi}^{\pm}\tilde{\chi}^{0}_{1}$

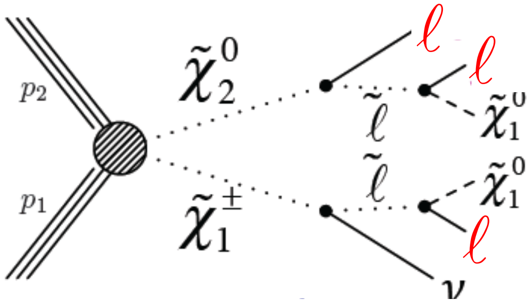




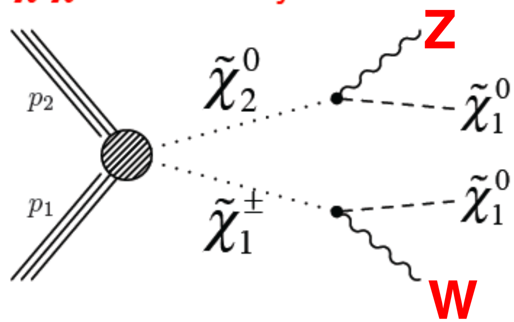
- Searches via strong production profits from large x-sectons
- Limits in squark/gluino sector ~1.5-2 TeV
- While cross sections for chargino/neutralino are lower than some SM processes still to be discovered
- Will certainly profit from luminosity

$\tilde{\chi}^{\pm}\tilde{\chi}_1^0$: experimental signatures

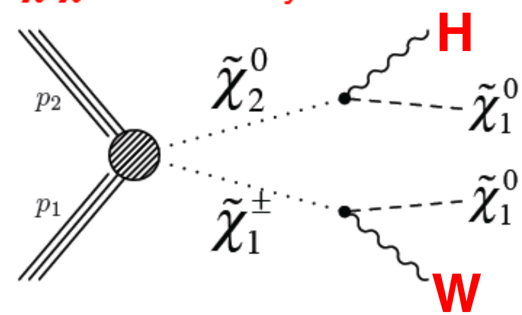
$\chi^{\pm}\chi^0$ with light sleptons



$\chi^{\pm}\chi^0$ with decays to W/Z



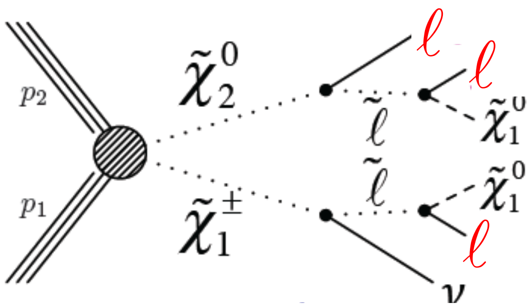
$\chi^{\pm}\chi^0$ with decays to W/H



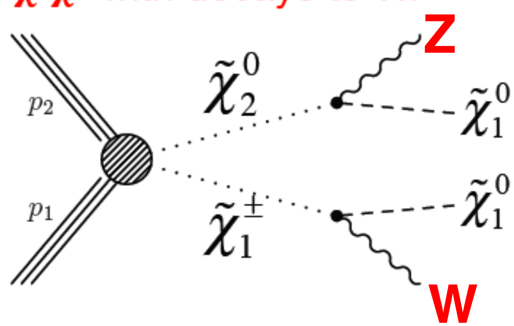
- 3 and 4 lepton events categorized according to:
  - number of hadronic tau
  - Number of Z - candidates

$\tilde{\chi}^{\pm}\tilde{\chi}_1^{0}$: experimental signatures

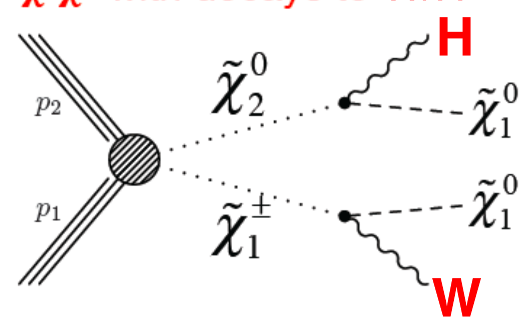
$\chi^{\pm}\chi^{0}$ with light sleptons



$\chi^{\pm}\chi^{0}$ with decays to W/Z



$\chi^{\pm}\chi^{0}$ with decays to W/H



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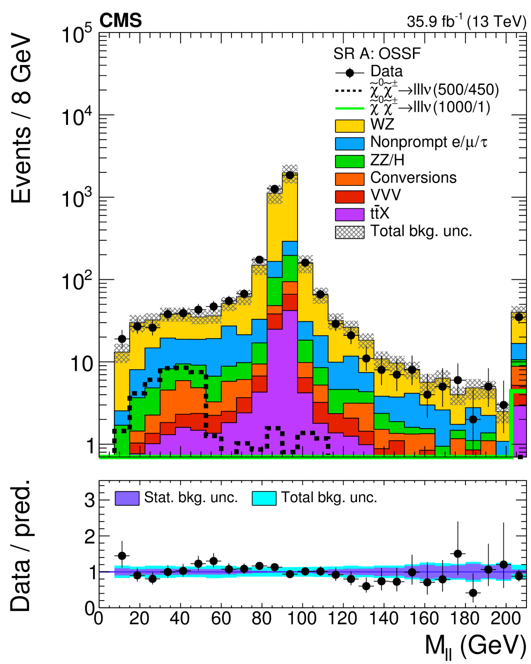
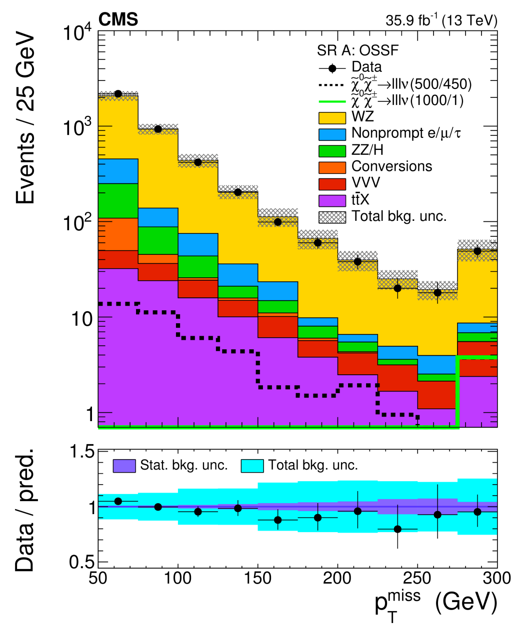
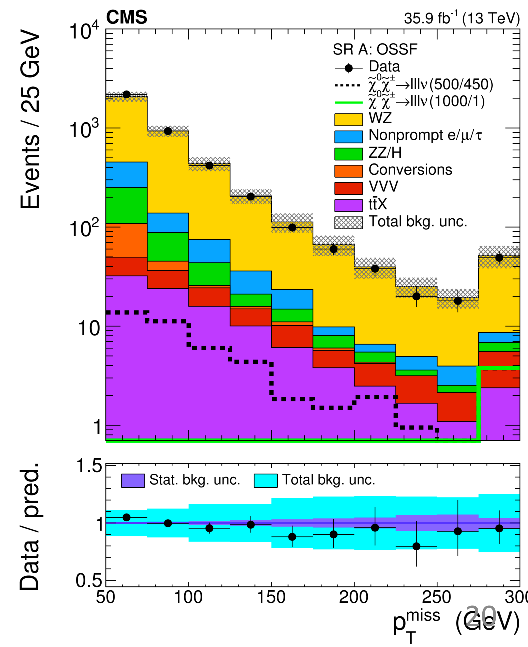
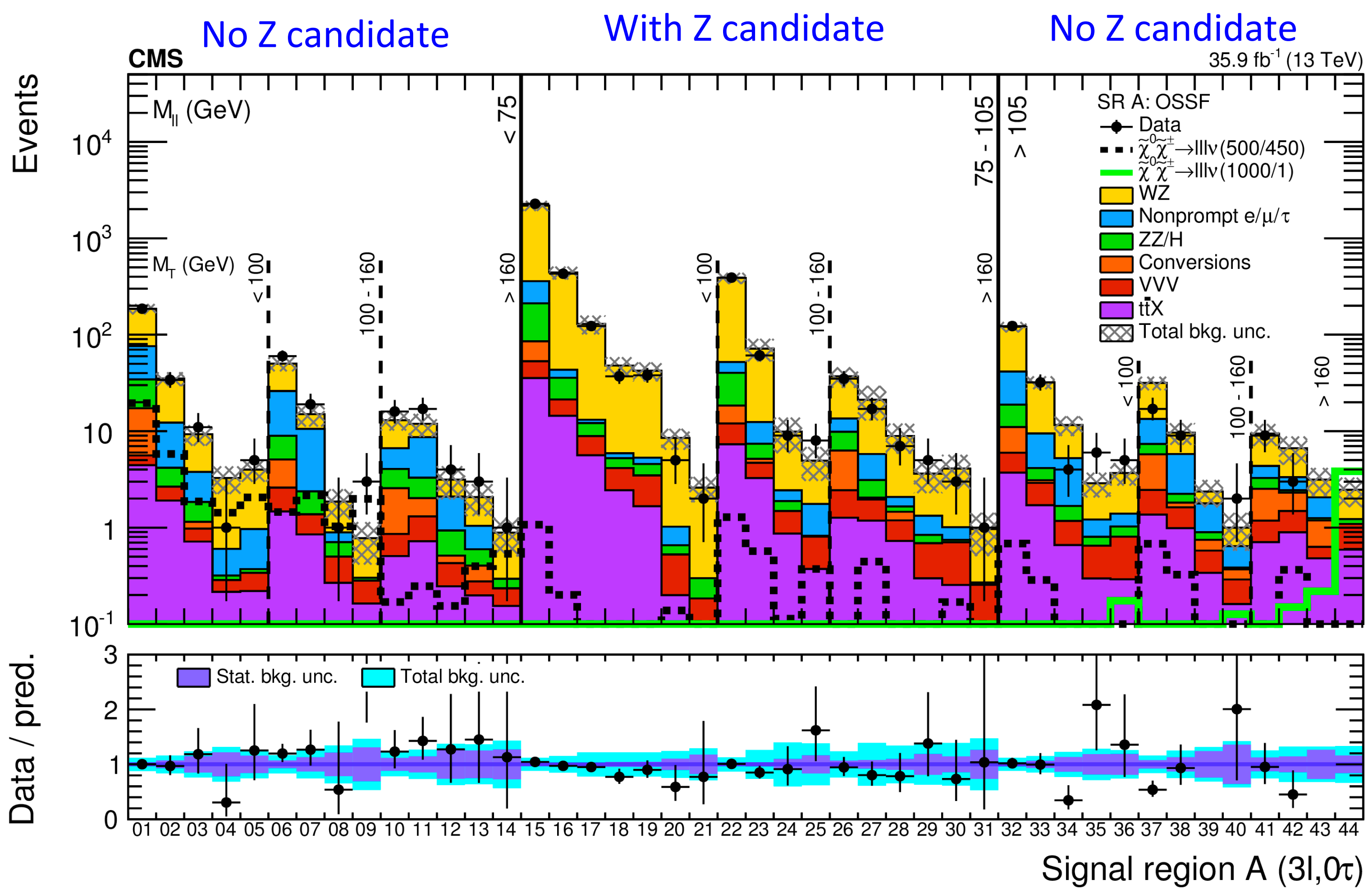






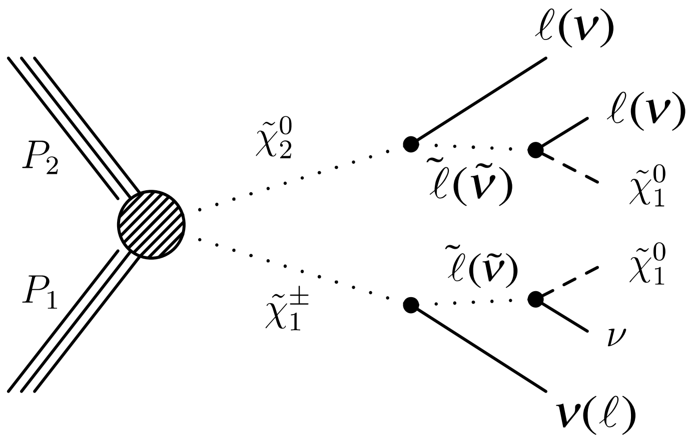
$\tilde{\chi}^{\pm}\tilde{\chi}_1^0$ search results

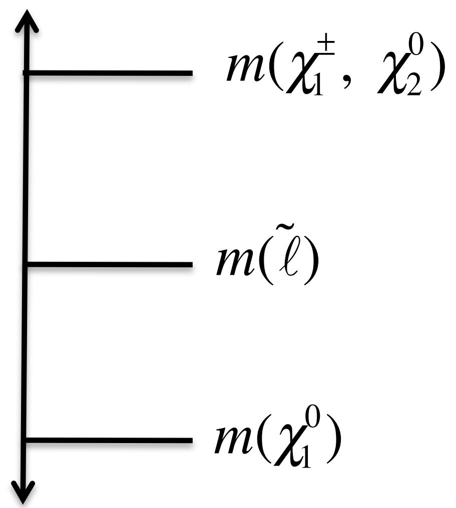
One of the several categories: three light light lepton, 0 τ



Bottomline: data agrees very well with the expected background

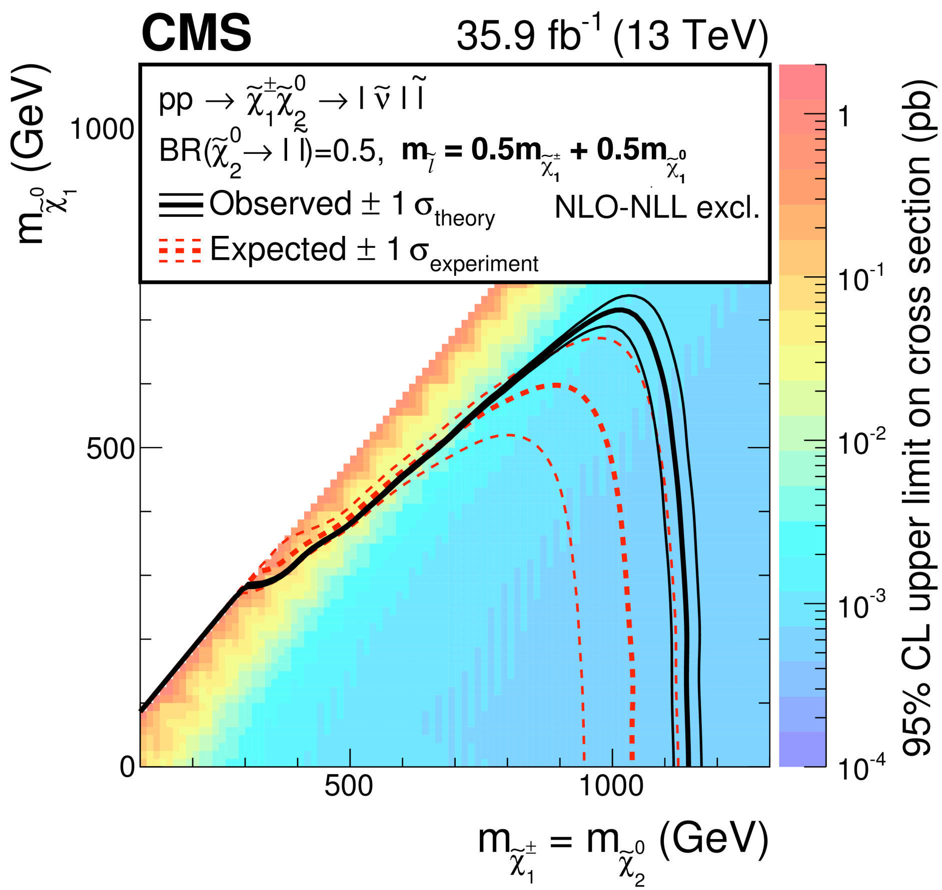
EWK production of $\tilde{\chi}^{\pm}\tilde{\chi}_1^0$



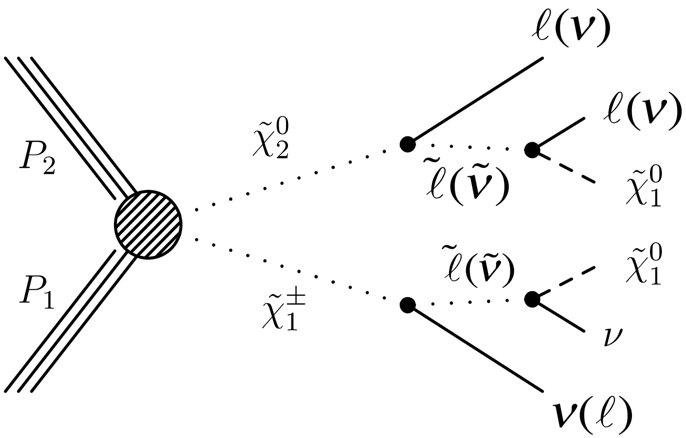


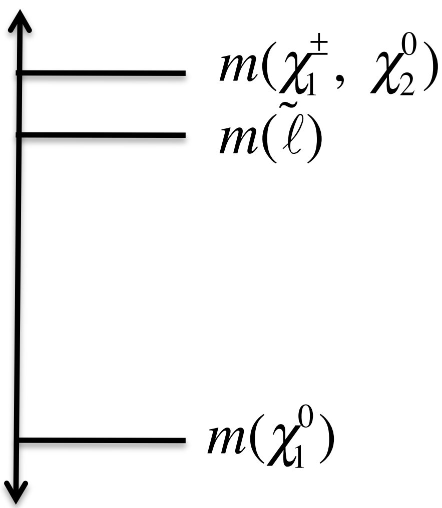
Scenario 1: Left handed sleptons

- $M(\tilde{\ell}_L) << M(\tilde{\ell}_R)$
- Equal BR to e,μ,τ



EWK production of $\tilde{\chi}^{\pm}\tilde{\chi}_1^0$





Scenario 2: Left handed sleptons

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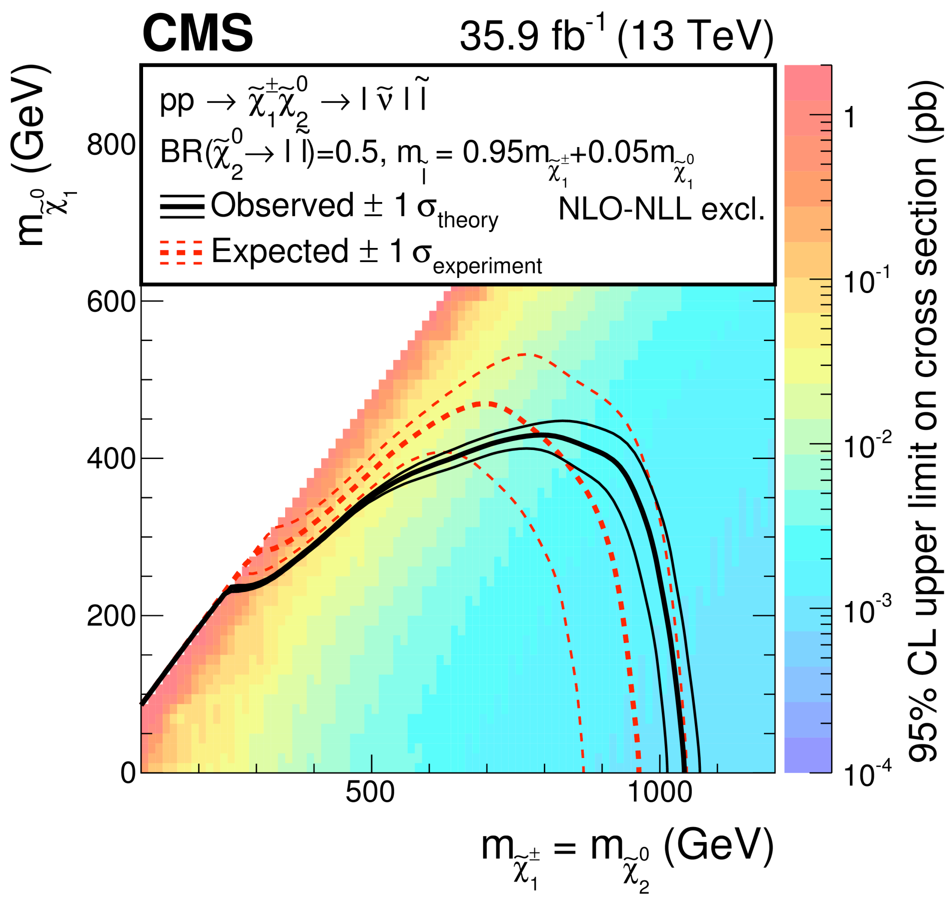
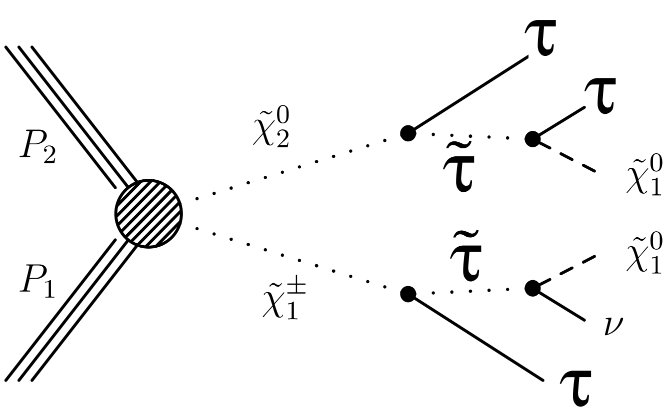
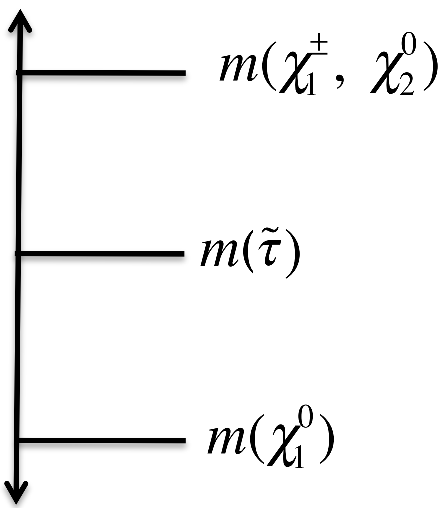


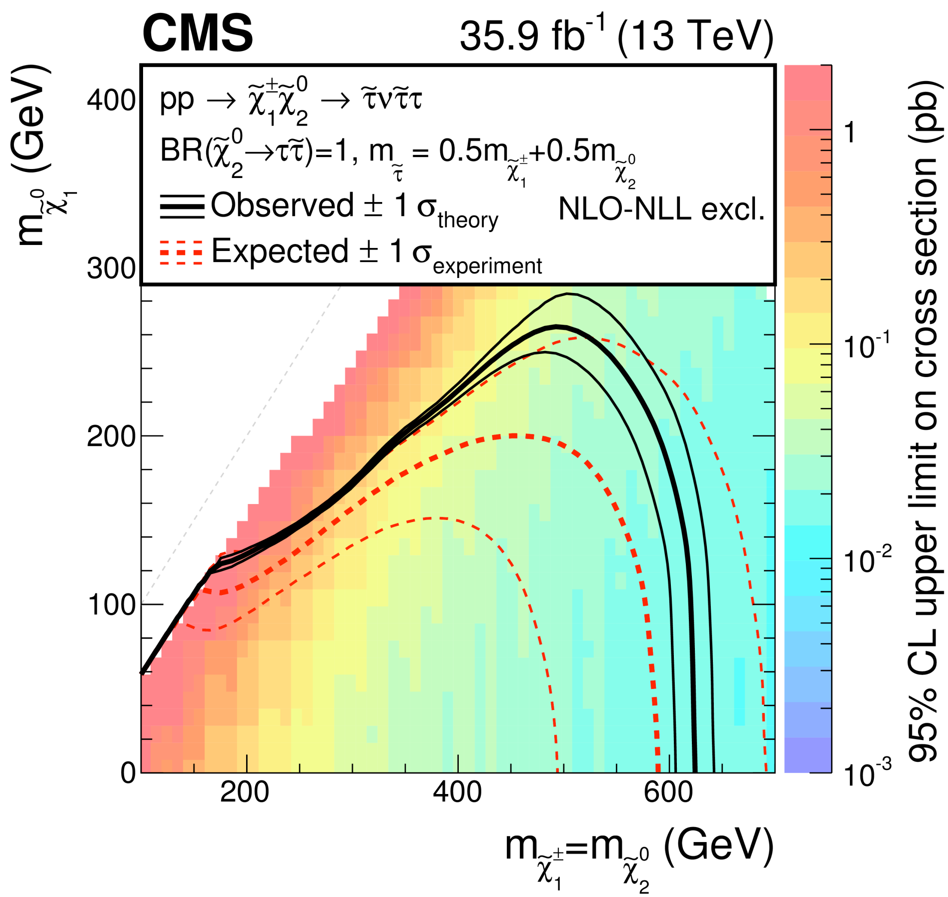
EWK production of $\tilde{\chi}^{\pm}\tilde{\chi}^{0}_{1}$



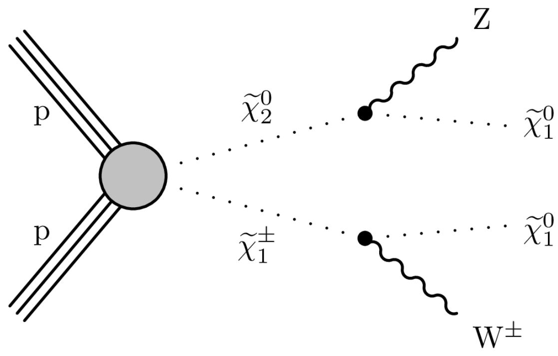


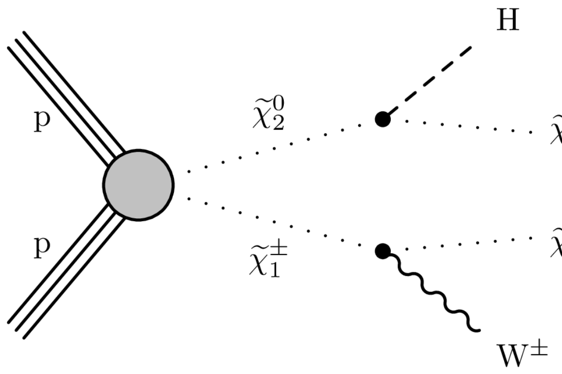
Scenario 3: **Right handed sleptons**

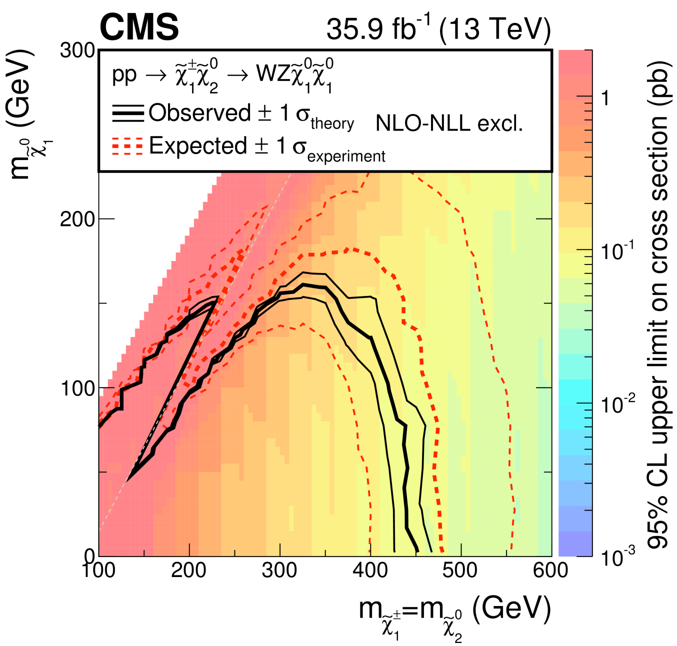
- $M(\tilde{\ell}_R) << M(\tilde{\ell}_L)$
- $\chi^\pm$ and χ^0 decays to **τ** with BR(100%)

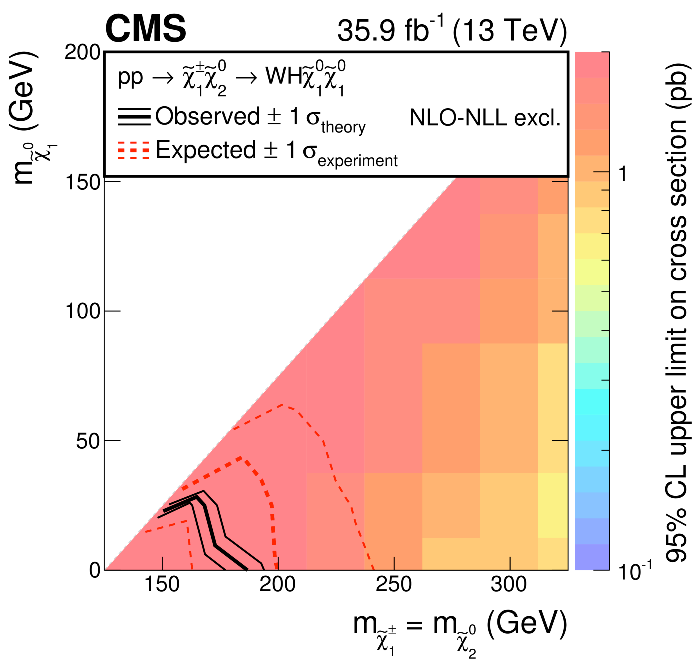


EWK production of $\tilde{\chi}^{\pm}\tilde{\chi}_1^0$





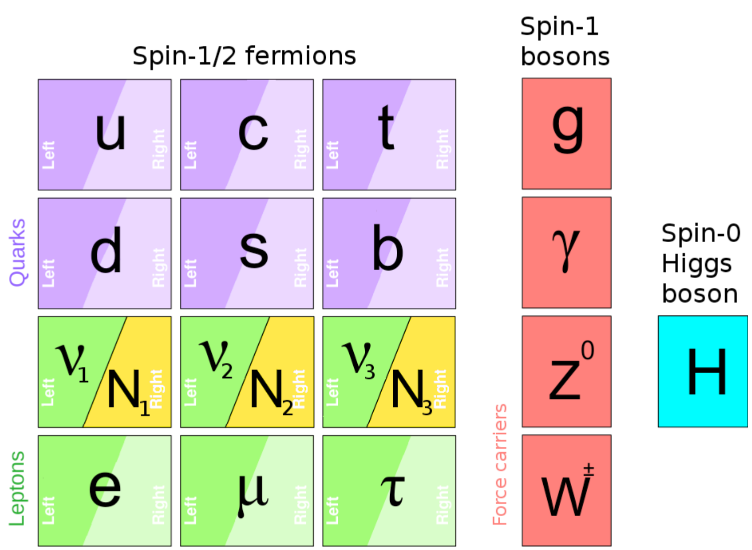




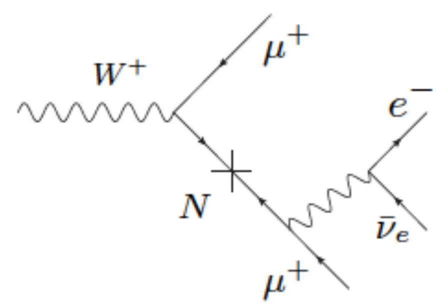
Still large phase-space unreached

Sterile neutrinos

- Neutrino oscillations suggest $m(\nu) > 0$
- Not naturally included in SM
- Minimal extensions (ie. νMSM) with additional right-handed sterile neutrinos
- Type-I seesaw mechanism to give masses to active neutrinos
- $m(N_1) \approx \mathrm{keV}$ potential DM candidate, N_2, N_3 ($m \approx 1 - 100$ GeV) large CP violation[1]
- N_2, N_3 can be searched at the LHC



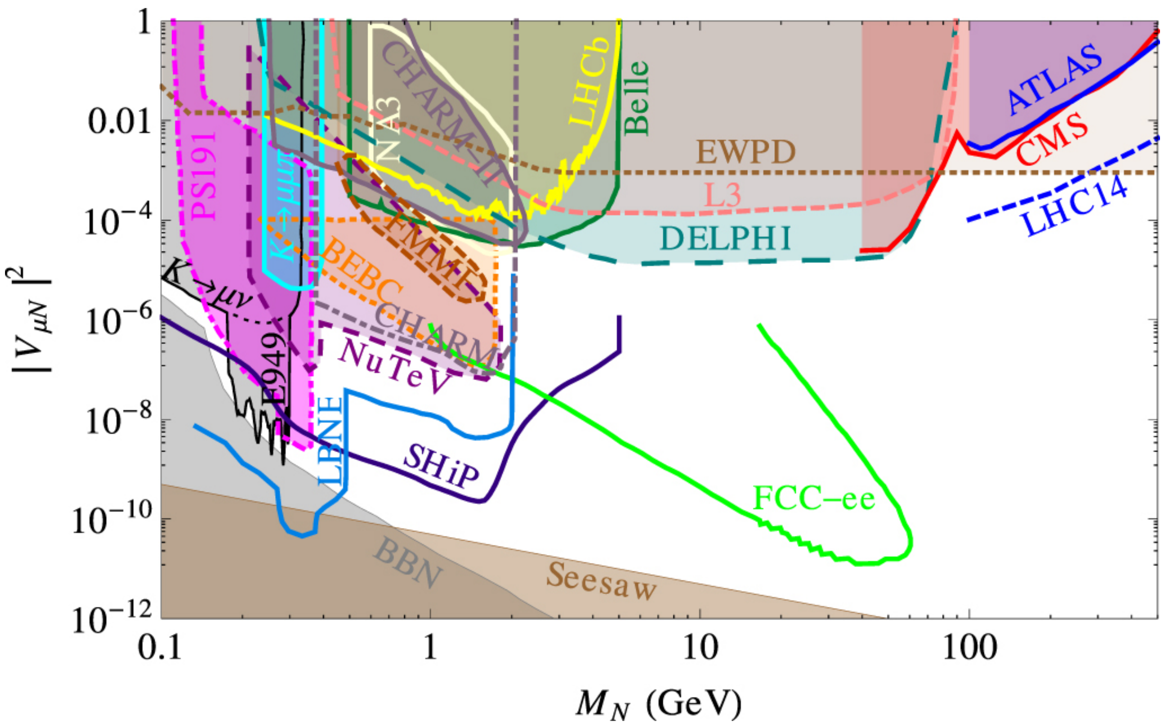
- N are sterile: interact only with ν through mixing
- production of ν: $W \to \ell\nu$, $Z \to \nu\nu$, $b \to c\ell\nu$...
- very low rate of $\nu \to N$: due to small mixing parameter $|V_{\ell N}|^2$ between ν_ℓ and N
- decays: $N \to W\ell$ or $N \to Z\nu$ or $N \to H\nu$



[1] arXiv:hep-ph/0505013

Sterile Neutrinos: state of the art

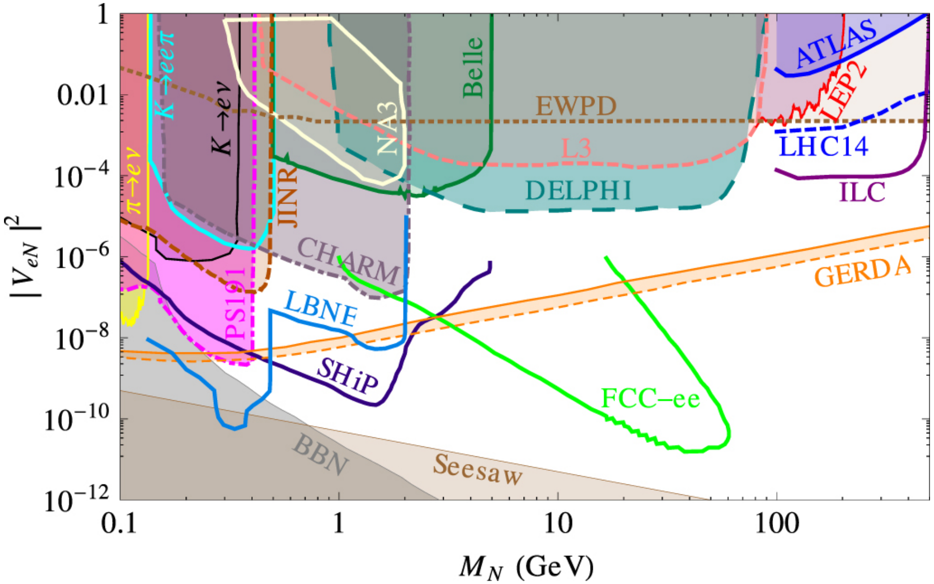
Coupling to muon neutrino



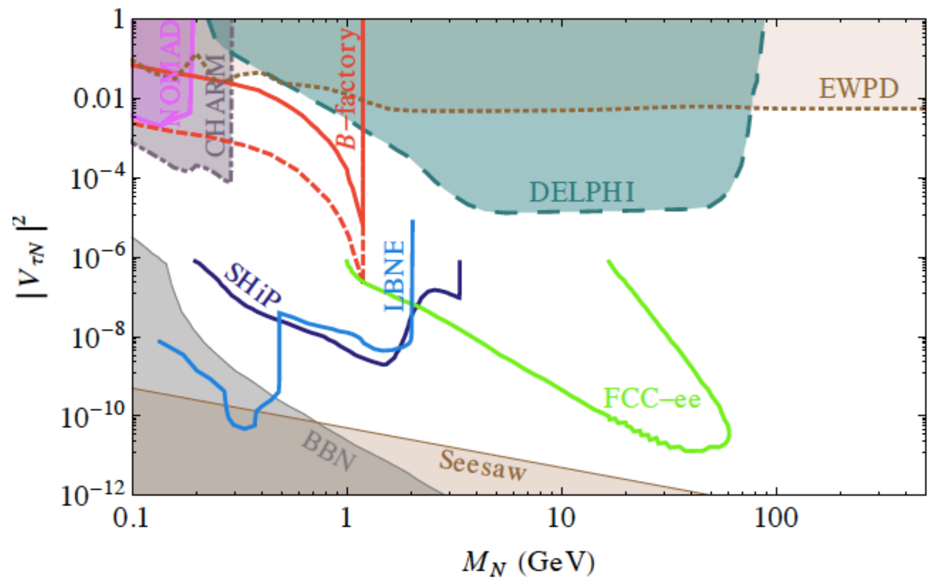
- $m_N < M_{kaon}$ is pretty much excluded
- $m_N < M_{heavyflavour}$ explored LHCb, Belle…
- $m_N < M_Z$ results from LEP
- Earlier results from LHC just starts probing interesting phase-space

Sterile Neutrinos: state of the art

Coupling to electron neutrino

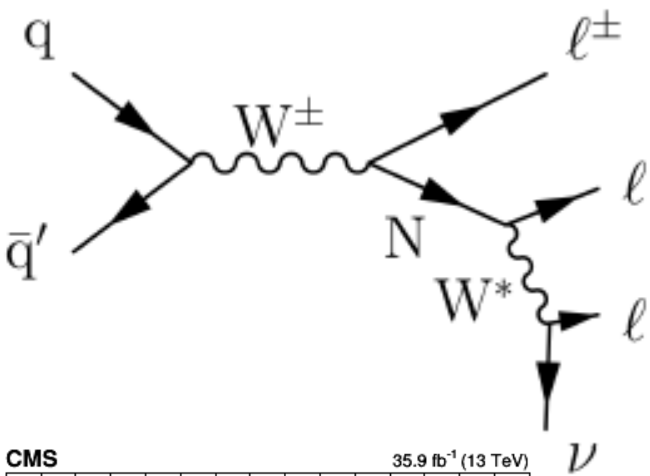


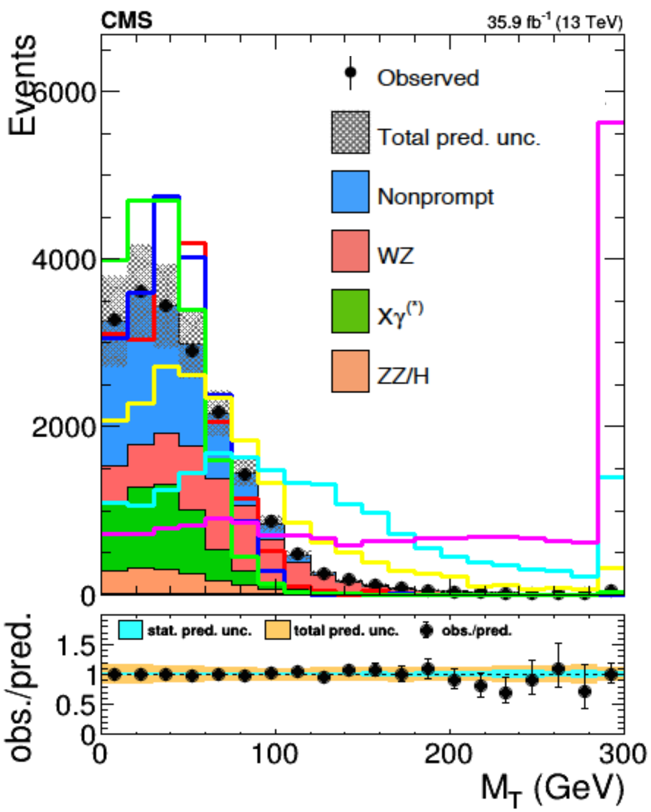
Coupling to tau neutrino



- Strong results from GERDA $0\nu\beta\beta$
- Couplings to tau are barely explored
- $m_N < M_{kaon}$ is pretty much excluded
- $m_N < M_{heavyflavour}$ explored LHCb, Belle…
- $m_N < M_Z$ results from LEP
- Earlier results from LHC just starts probing interesting phase-space

a new search at the LHC

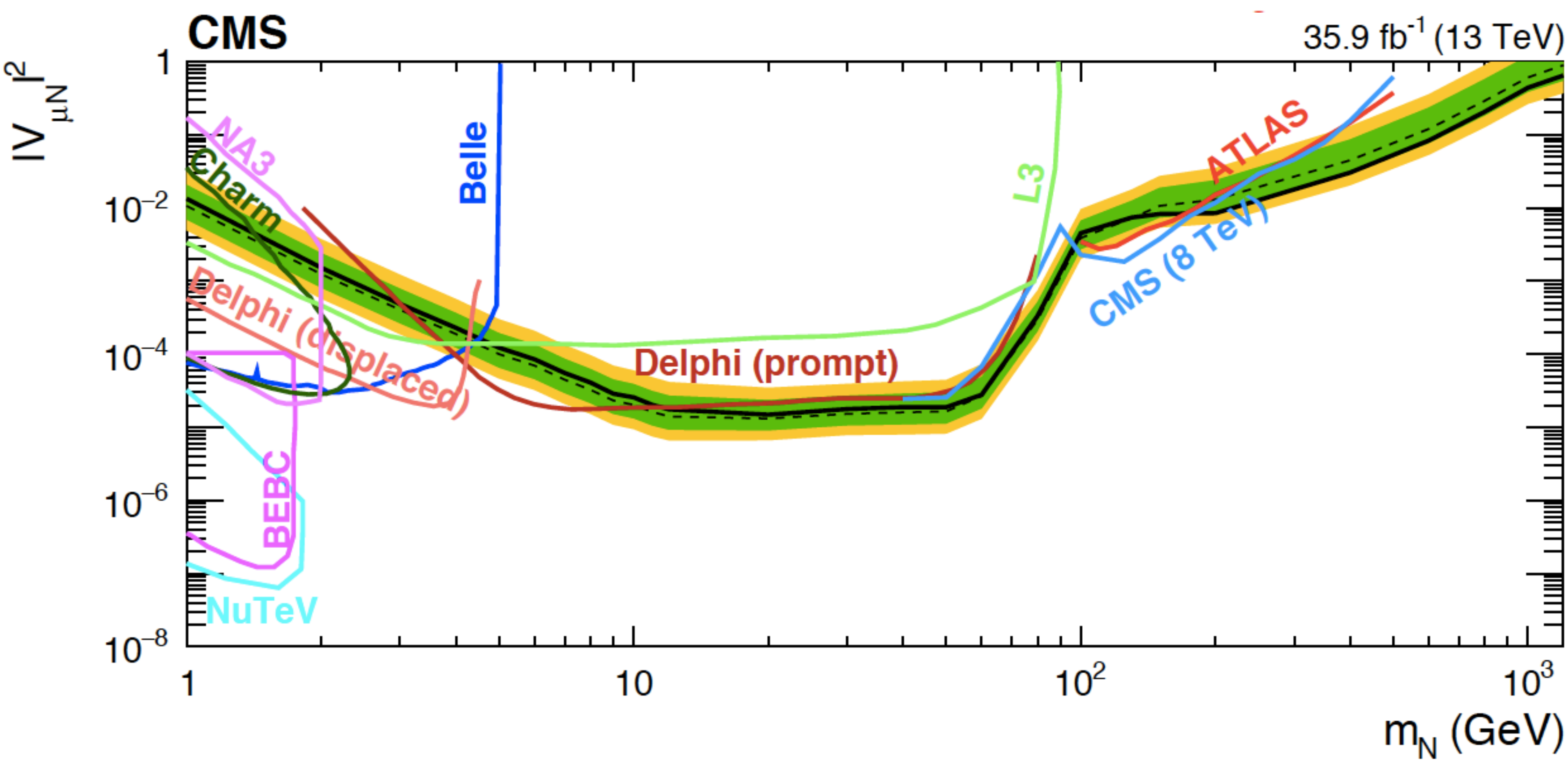




- W production and leptonic decays
- Final state with 3-leptons (e/μ)
- Kinematics dramatically change vs. m_N
  - $m_N < M_W$
    - Soft leptons, low missing E_T
    - $m_{\ell\ell\ell} \leq M_W$
    - Backgrounds: nonprompt leptons (DY, ttBar), γ-conversions
  - $m_N > M_W$
    - One high p_T lepton, large missing E_T
    - lower x-section
    - Backgrounds: WZ production & nonprompt leptons (DY, ttBar)

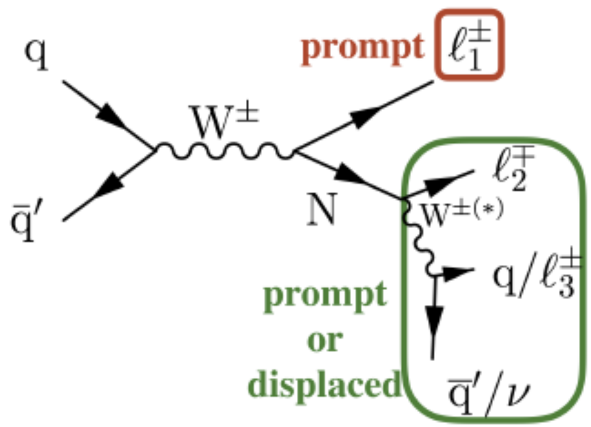
Sterile neutrinos :results

consider **only** $\mu\mu e$, $\mu\mu\mu$ **events to probe** $|V_{\mu N}|^2$

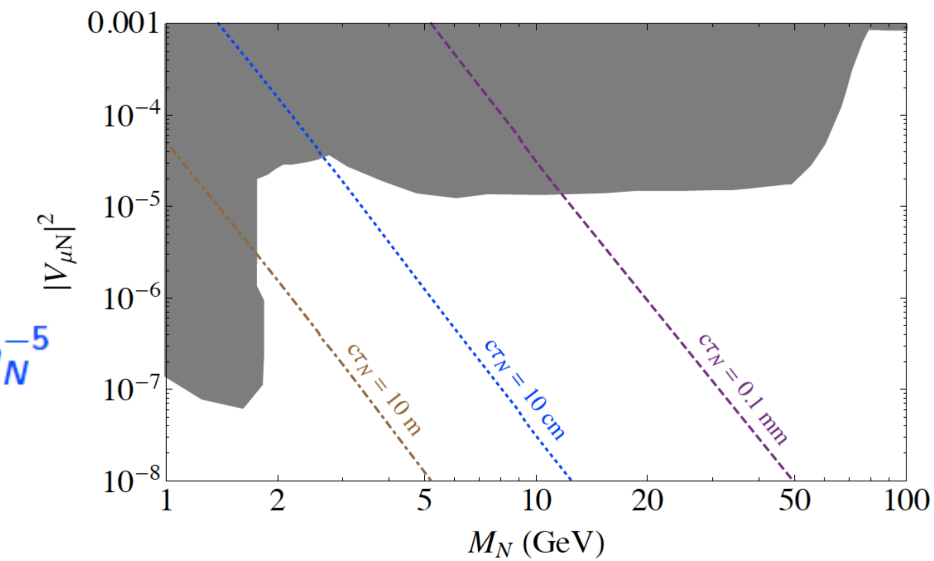


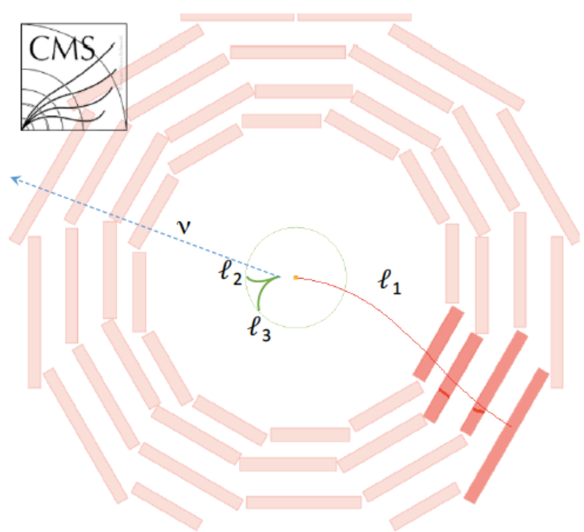
- First time a single experiment probes masses from 1 GeV – 1 TeV
- Extend sensitivity in large parameter-space
- Results will appear soon in arxiv

Sterile neutrinos : What is next ?



$$\tau \propto |V_{\ell N}|^{-2}\, m_N^{-5}$$





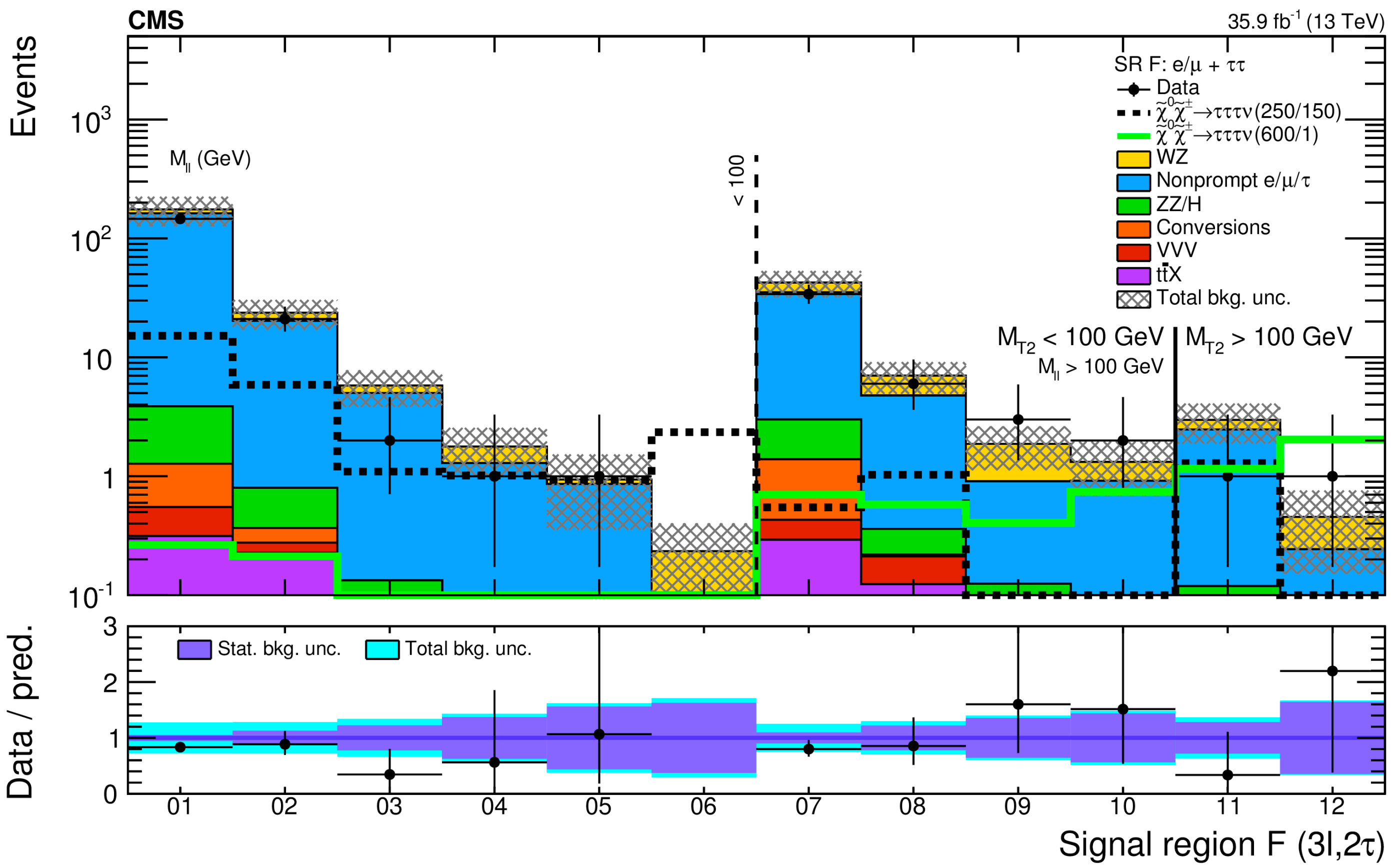
- Long lived N via displaced leptons/jets → important for low mass region
- Explore boosted lepton-jets
- Couplings to tau by analyzing hadronic tau
- Explore $b \rightarrow_{\tau} c\ell\nu$? O(5) larger x-section

Summary

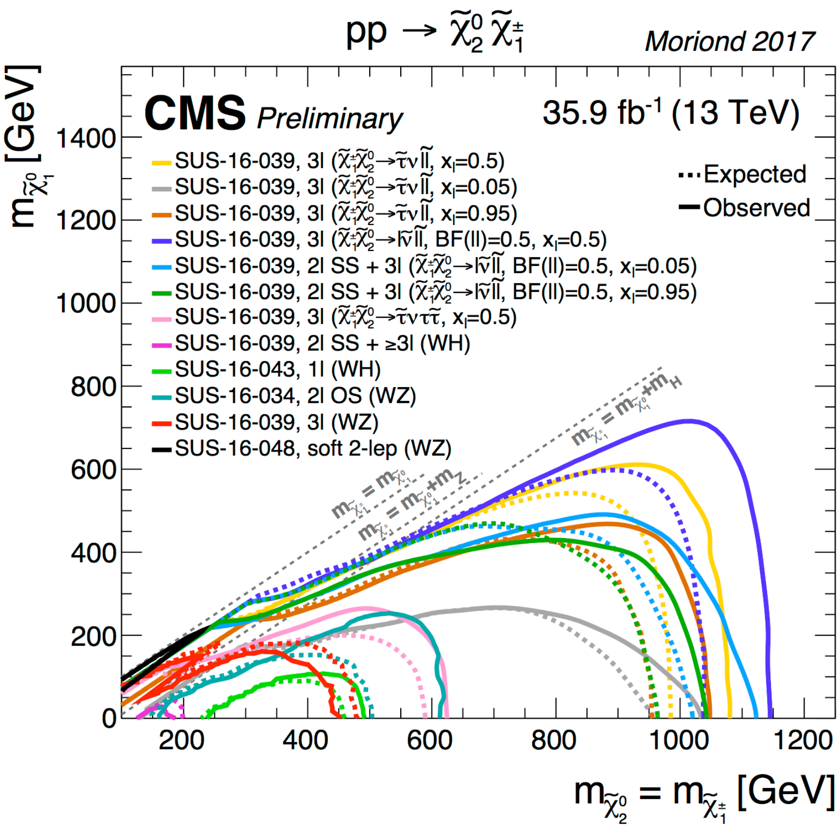
- Leptonic final states: clean exp. signatures both for SM measurements and searches
  - ttH :
    - Not yet observed, expected(observed) significances ~3(2.5) sigma
    - 2017 data and combination with ATLAS might yield observation
  - ttW, ttZ:
    - First observation of both processes
    - Measurements are already systematics dominated
    - NP search via EFT
  - EWK production of SUSY
    - Rich experimental signatures, limited by x-section, compressed mass spectrum
  - Search for sterile neutrinos
    - Interesting phase-space available for LHC data
    - First results are about to come out

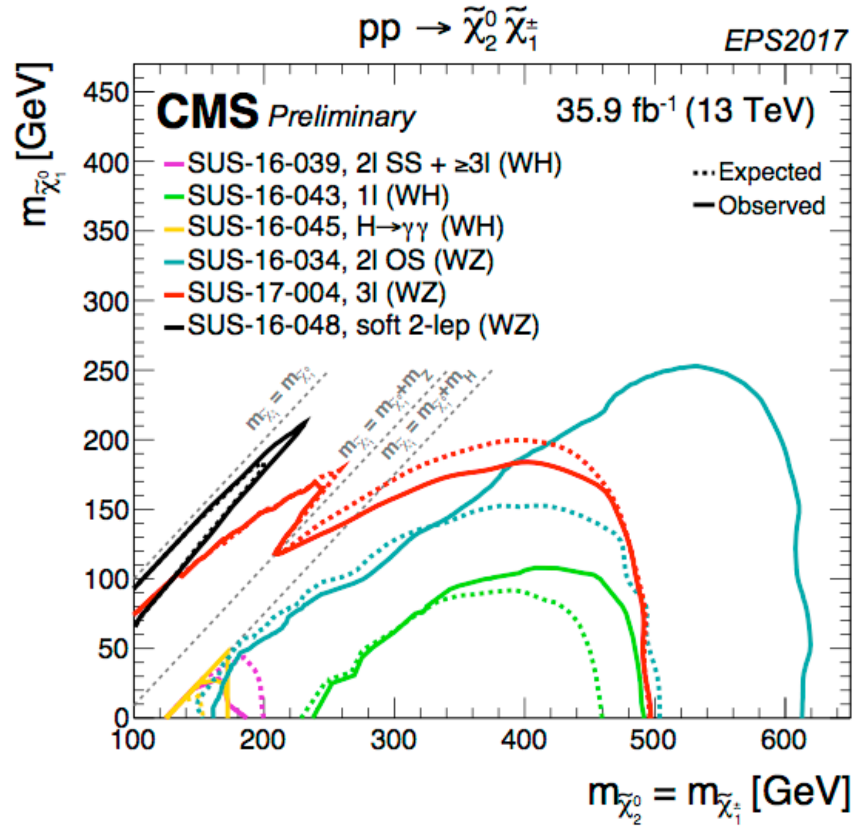
backup

$\tilde{\chi}^{\pm}\tilde{\chi}_1^0$ search results

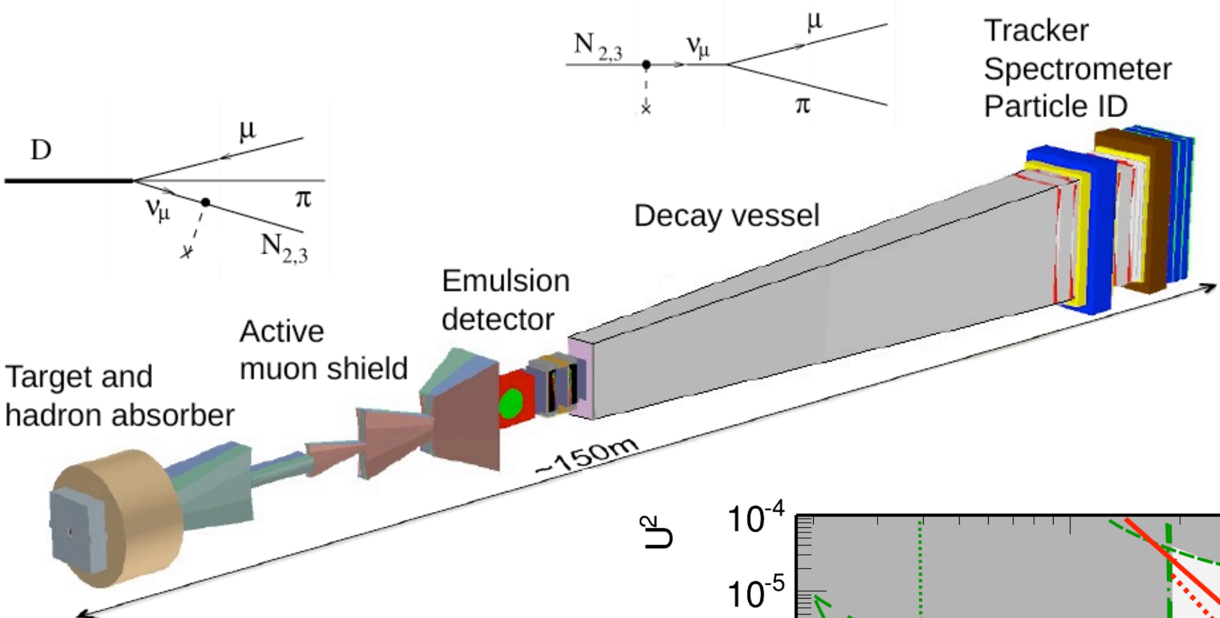


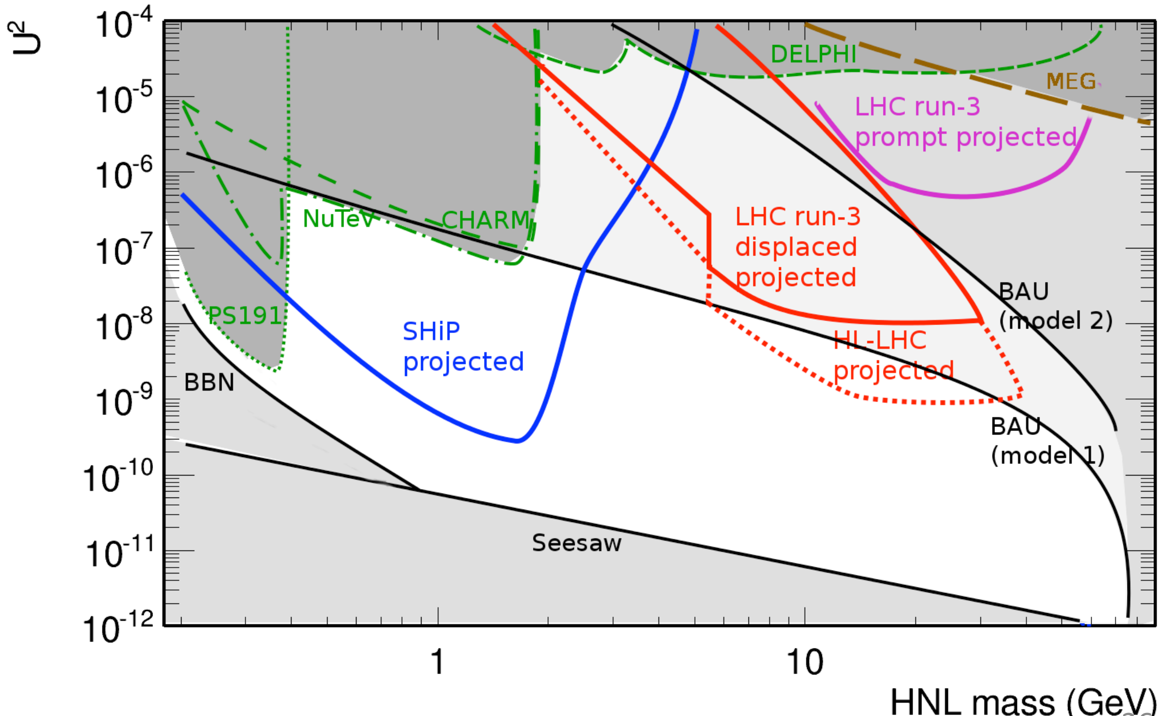
Search for $\tilde{\chi}^{\pm}\tilde{\chi}_1^0$: summary





Sterile Neutrinos : SHIP





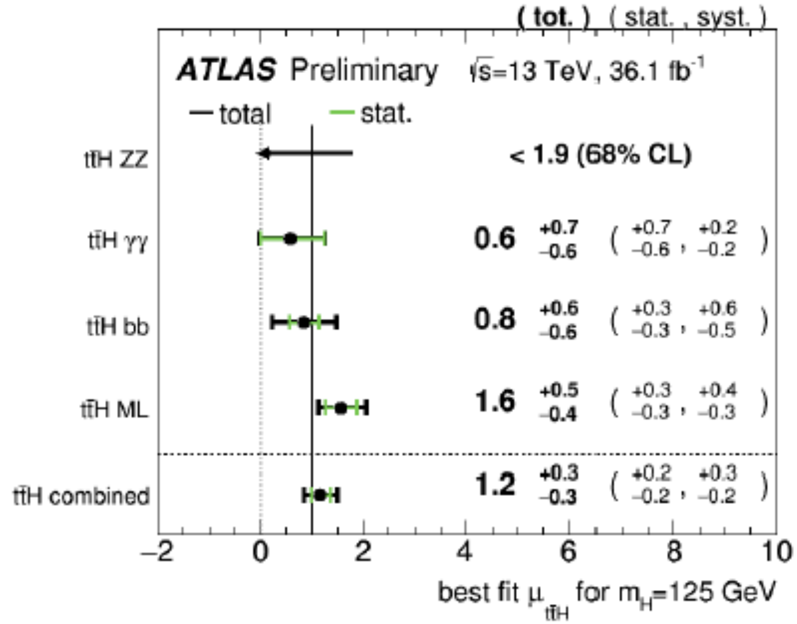
Combination

- Combining $b\bar{b}$, multilepton, $\gamma\gamma$ and $ZZ \to 4\ell$ channels
  - Only $t\bar{t}H$ enhanced categories in $\gamma\gamma$ and 4ℓ included
- $tHjb$ and tWH treated as backgrounds and fixed to the SM prediction
- Non-$t\bar{t}H$ production mechanisms also fixed to the SM predictions
- Correlating almost all signal, background and detector uncertainties
- Best-fit value:

$$\mu_{t\bar{t}H} = 1.17 \pm 0.19(\text{stat}) \,^{+0.27}_{-0.23}(\text{syst})$$

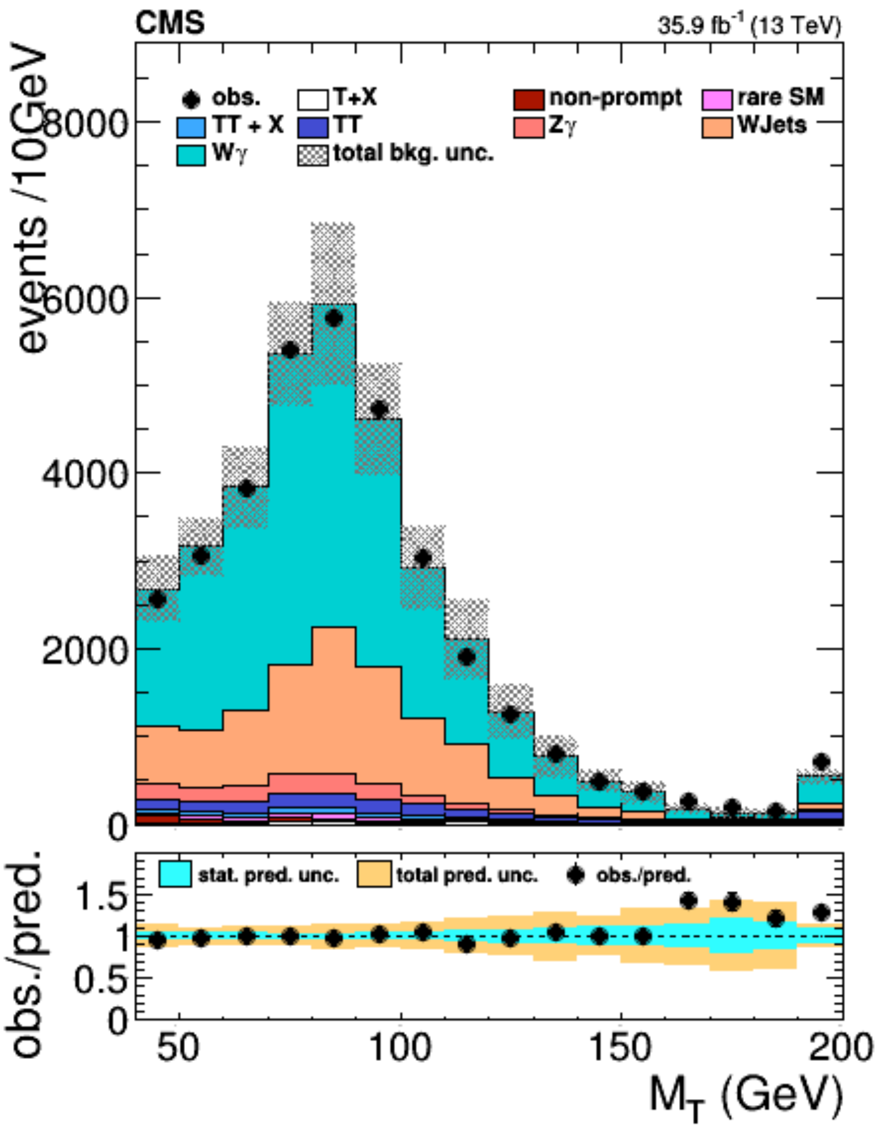
$$\sigma_{t\bar{t}H} = 590^{+160}_{-150} \text{ fb}$$

- Significance: 4.2σ (exp: 3.8σ)



Channel	Significance	
	Observed	Expected
Multilepton	4.1σ	2.8σ
$H \to b\bar{b}$	1.4σ	1.6σ
$H \to \gamma\gamma$	0.9σ	1.7σ
$H \to 4\ell$	—	0.6σ
Combined	4.2σ	3.8σ

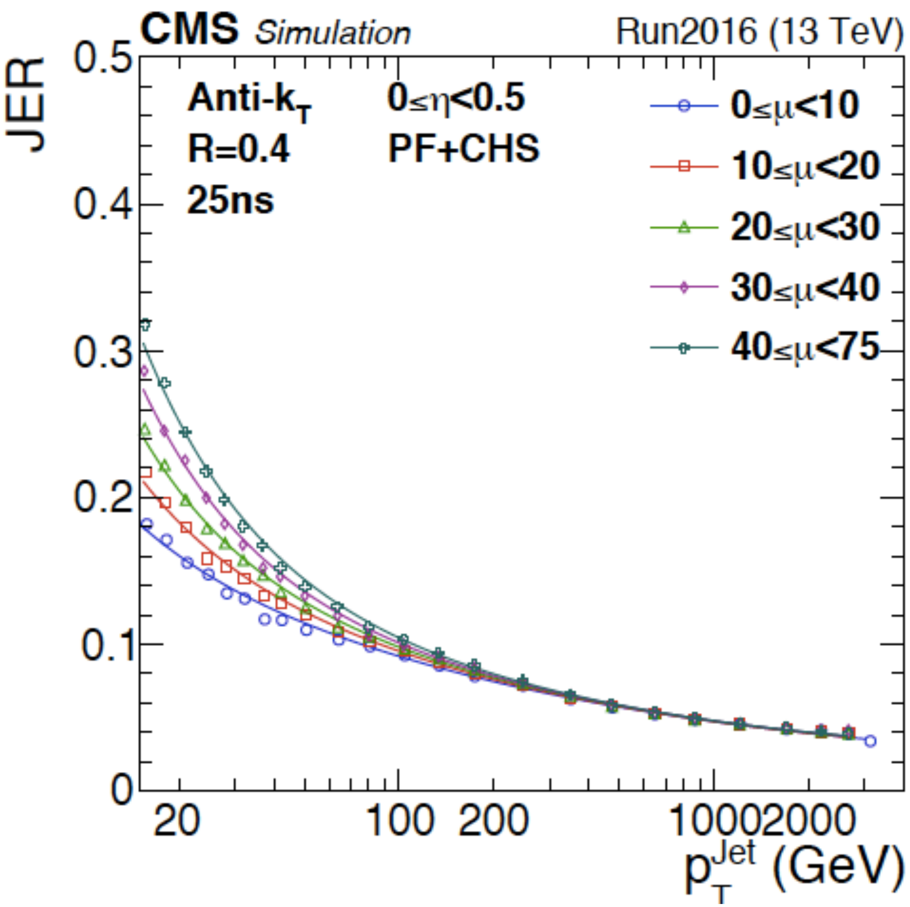
W+gamma

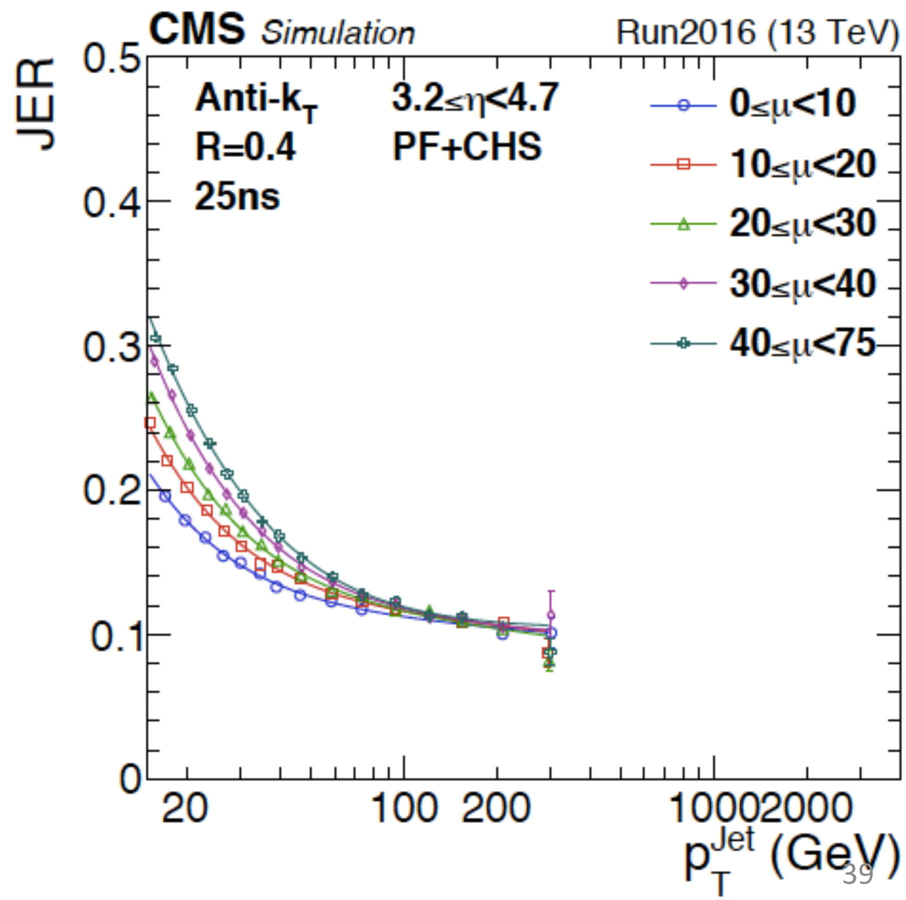

CMS
35.9 fb-1 (13 TeV)
obs.
T+X
non-prompt
rare SM
TT + X
TT
Zγ
WJets
Wγ
total bkg. unc.
events /10GeV
8000
6000
4000
2000
0
stat. pred. unc.
total pred. unc.
obs./pred.
obs./pred.
1.5
1
0.5
0
50
100
150
200
MT (GeV)

Jet Energy resolution (JER)

- Resolutions stable against pileup above jet p_T=100 GeV
- Better than 10% (5%) resolution above p_T=100 GeV (1 TeV)
- Degradation of 50% at p_T=20 GeV for very high pileup of up to μ=75

$$\mathrm{JER} = \sigma\left(\frac{\langle p_\mathrm{T}\rangle}{\langle p_\mathrm{T,ptcl}\rangle}\right)$$





EFT operator selection

There are two major changes with respect to the selection performed for the TOP-17-005 PAS: the scan windows are not arbitrarily restricted to $\bar{c}_j = [-1, 1]$, and four new rare backgrounds have been added: tttt, tHq, tHW, tWZ. The eight operators proportional to $\bar{c}_{uW}$, $\bar{c}_{uB}$, $\bar{c}_H$, $\widetilde{c}_{3G}$, $\bar{c}_{3G}$, $\bar{c}_{Hu}$, $\bar{c}_{2G}$, and $\bar{c}_{uG}$ now pass the selection (note that the operator proportional to $\bar{c}_u$ which passed the previous version now fail due to effects on tHq and tHW).

$$
\begin{aligned}
\mathcal{L}_{\rm SILH} = & \boxed{\frac{\bar{c}_H}{2v^2}\partial^\mu[\Phi^\dagger\Phi]\partial_\mu[\Phi^\dagger\Phi]} + \frac{\bar{c}_T}{2v^2}[\Phi^\dagger \overleftrightarrow{D}^\mu \Phi][\Phi^\dagger \overleftrightarrow{D}_\mu \Phi] - \frac{\bar{c}_6 \lambda}{v^2}[\Phi^\dagger\Phi]^3 \\
& - \left[\frac{\bar{c}_u}{v^2} y_u \Phi^\dagger\Phi\ \Phi^\dagger \cdot \bar{Q}_L u_R + \frac{\bar{c}_d}{v^2} y_d \Phi^\dagger\Phi\ \Phi \bar{Q}_L d_R + \frac{\bar{c}_l}{v^2} y_\ell\ \Phi^\dagger\Phi\ \Phi \bar{L}_L e_R + \text{h.c.}\right] \\
& + \frac{ig\ \bar{c}_W}{m_W^2}[\Phi^\dagger T_{2k} \overleftrightarrow{D}^\mu \Phi] D^\nu W^k_{\mu\nu} + \frac{ig'\ \bar{c}_B}{2m_W^2}[\Phi^\dagger \overleftrightarrow{D}^\mu \Phi]\partial^\nu B_{\mu\nu} \\
& + \frac{2ig\ \bar{c}_{HW}}{m_W^2}[D^\mu\Phi^\dagger T_{2k} D^\nu\Phi] W^k_{\mu\nu} + \frac{ig'\ \bar{c}_{HB}}{m_W^2}[D^\mu\Phi^\dagger D^\nu\Phi] B_{\mu\nu} \\
& + \frac{g'^2\ \bar{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\ \bar{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu}\,,
\end{aligned}
\tag{2.5}
$$

$$
\begin{aligned}
\mathcal{L}_{CP} = & \frac{ig\ \tilde{c}_{HW}}{m_W^2} D^\mu\Phi^\dagger T_{2k} D^\nu \Phi \widetilde{W}^k_{\mu\nu} + \frac{ig'\ \tilde{c}_{HB}}{m_W^2} D^\mu\Phi^\dagger D^\nu\Phi \widetilde{B}_{\mu\nu} + \frac{g'^2\ \tilde{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}\widetilde{B}^{\mu\nu} \\
& + \frac{g_s^2\ \tilde{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}\widetilde{G}_a^{\mu\nu} + \frac{g^3\ \tilde{c}_{3W}}{m_W^2}\epsilon_{ijk}W^i_{\mu\nu}W^{\nu j}{}_\rho \widetilde{W}^{\rho\mu k} + \boxed{\frac{g_s^3\ \tilde{c}_{3G}}{m_W^2} f_{abc} G^a_{\mu\nu} G^{\nu b}{}_\rho \widetilde{G}^{\rho\mu c}}\,,
\end{aligned}
\tag{2.9}
$$

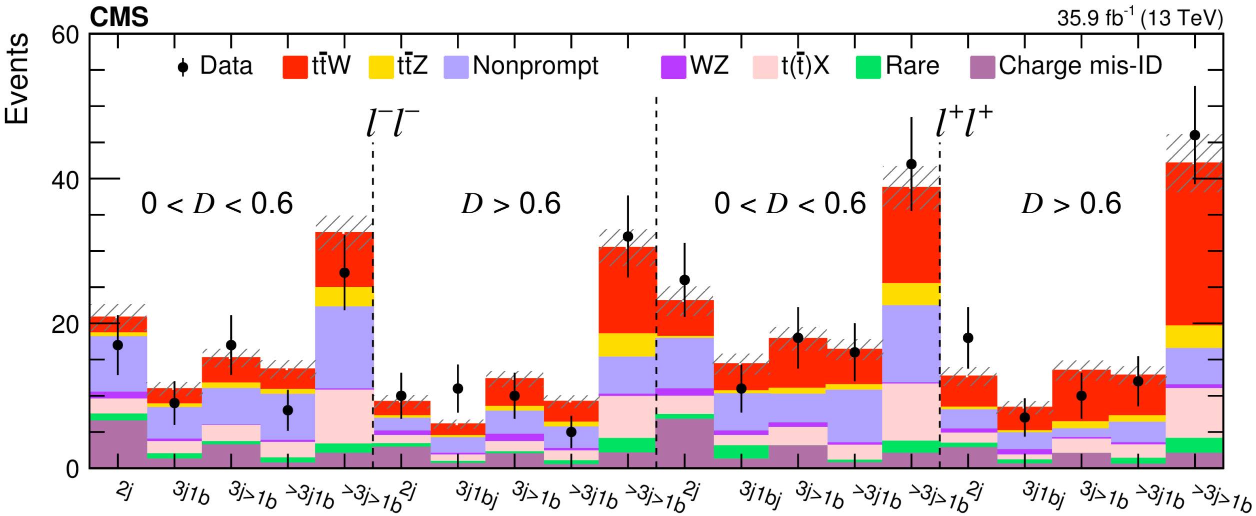
$$
\begin{aligned}
\mathcal{L}_{F_1} = & \frac{i\bar{c}_{HQ}}{v^2}[\bar{Q}_L\gamma^\mu Q_L][\Phi^\dagger \overleftrightarrow{D}_\mu \Phi] + \frac{4i\bar{c}'_{HQ}}{v^2}[\bar{Q}_L\gamma^\mu T_{2k} Q_L][\Phi^\dagger T_2^k \overleftrightarrow{D}_\mu \Phi] \\
& + \boxed{\frac{i\bar{c}_{Hu}}{v^2}[\bar{u}_R\gamma^\mu u_R][\Phi^\dagger \overleftrightarrow{D}_\mu \Phi]} + \frac{i\bar{c}_{Hd}}{v^2}[\bar{d}_R\gamma^\mu d_R][\Phi^\dagger \overleftrightarrow{D}_\mu \Phi] \\
& - \left[\frac{i\bar{c}_{Hud}}{v^2}[\bar{u}_R\gamma^\mu d_R][\Phi \cdot \overleftrightarrow{D}_\mu \Phi] + \text{h.c.}\right] \\
& + \frac{i\bar{c}_{HL}}{v^2}[\bar{L}_L\gamma^\mu L_L][\Phi^\dagger \overleftrightarrow{D}_\mu \Phi] + \frac{4i\bar{c}'_{HL}}{v^2}[\bar{L}_L\gamma^\mu T_{2k} L_L][\Phi^\dagger T_2^k \overleftrightarrow{D}_\mu \Phi] \\
& + \frac{i\bar{c}_{He}}{v^2}[\bar{e}_R\gamma^\mu e_R][\Phi^\dagger \overleftrightarrow{D}_\mu \Phi]\,,
\end{aligned}
\tag{2.11}
$$

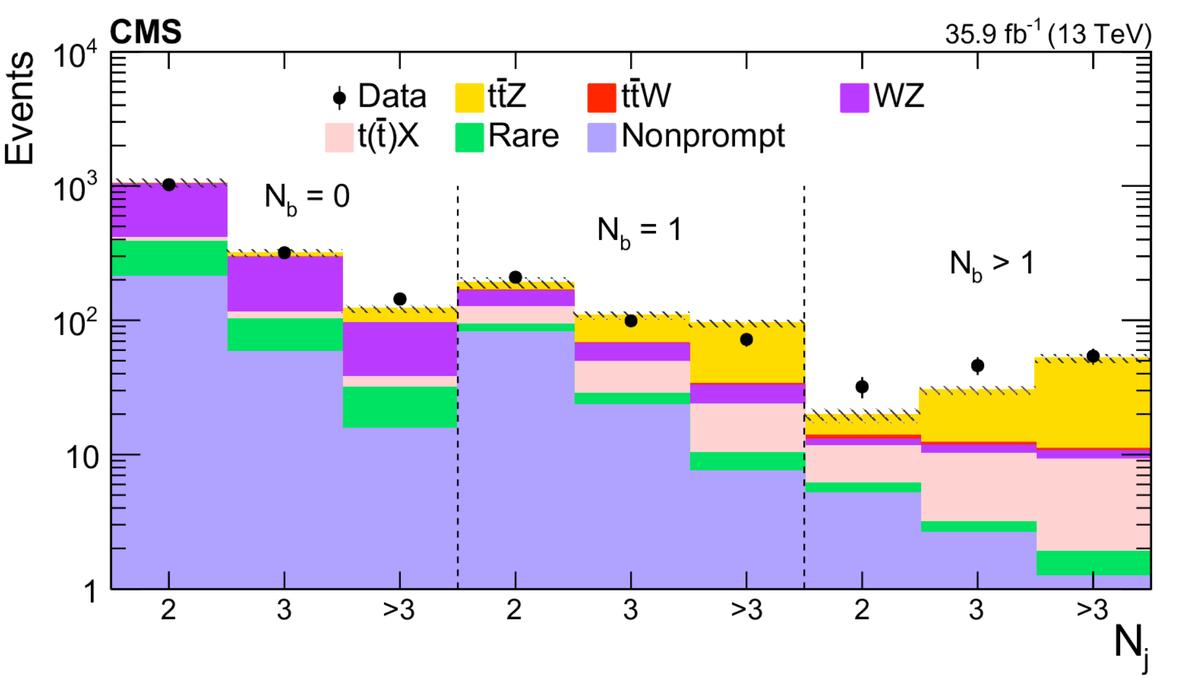
$$
\begin{aligned}
\mathcal{L}_{F_2} = \Bigg[& \boxed{-\frac{2g'\ \bar{c}_{uB}}{m_W^2} y_u\ \Phi^\dagger \cdot \bar{Q}_L\gamma^{\mu\nu} u_R\ B_{\mu\nu}} \boxed{-\frac{4g\ \bar{c}_{uW}}{m_W^2} y_u\ \Phi^\dagger \cdot (\bar{Q}_L T_{2k})\gamma^{\mu\nu} u_R\ W^k_{\mu\nu}} \\
& \boxed{-\frac{4g_s\ \bar{c}_{uG}}{m_W^2} y_u\ \Phi^\dagger \cdot \bar{Q}_L\gamma^{\mu\nu} T_a u_R G^a_{\mu\nu}} + \frac{2g'\ \bar{c}_{dB}}{m_W^2} y_d\ \Phi \bar{Q}_L\gamma^{\mu\nu} d_R\ B_{\mu\nu} \\
& + \frac{4g\ \bar{c}_{dW}}{m_W^2} y_d\ \Phi(\bar{Q}_L T_{2k})\gamma^{\mu\nu} d_R\ W^k_{\mu\nu} + \frac{4g_s\ \bar{c}_{dG}}{m_W^2} y_d\ \Phi \bar{Q}_L\gamma^{\mu\nu} T_a d_R G^a_{\mu\nu} \\
& + \frac{2g'\ \bar{c}_{eB}}{m_W^2} y_\ell\ \Phi \bar{L}_L\gamma^{\mu\nu} e_R\ B_{\mu\nu} + \frac{4g\ \bar{c}_{eW}}{m_W^2} y_\ell\ \Phi(\bar{L}_L T_{2k})\gamma^{\mu\nu} e_R\ W^k_{\mu\nu} + \text{h.c.}\Bigg]\,.
\end{aligned}
\tag{2.12}
$$

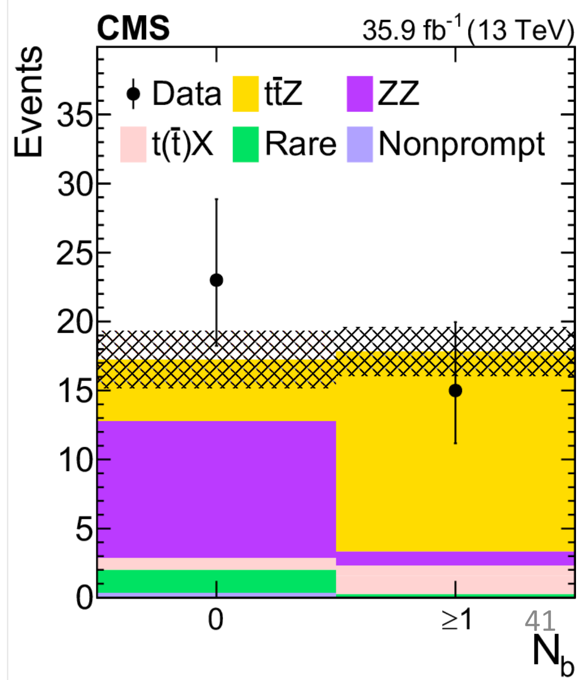
$$
\begin{aligned}
\mathcal{L}_G = & \frac{g^3\ \bar{c}_{3W}}{m_W^2}\epsilon_{ijk}W^i_{\mu\nu}W^{\nu j}{}_\rho W^{\rho\mu k} + \boxed{\frac{g_s^3\ \bar{c}_{3G}}{m_W^2} f_{abc} G^a_{\mu\nu} G^{\nu b}{}_\rho G^{\rho\mu c}} + \frac{\bar{c}_{2W}}{m_W^2} D^\mu W^k_{\mu\nu} D_\rho W_k^{\rho\nu} \\
& + \frac{\bar{c}_{2B}}{m_W^2}\partial^\mu B_{\mu\nu}\partial_\rho B^{\rho\nu} + \boxed{\frac{c_{2G}}{m_W^2} D^\mu G^a_{\mu\nu} D_\rho G_a^{\rho\nu}}\,,
\end{aligned}
\tag{2.14}
$$

7

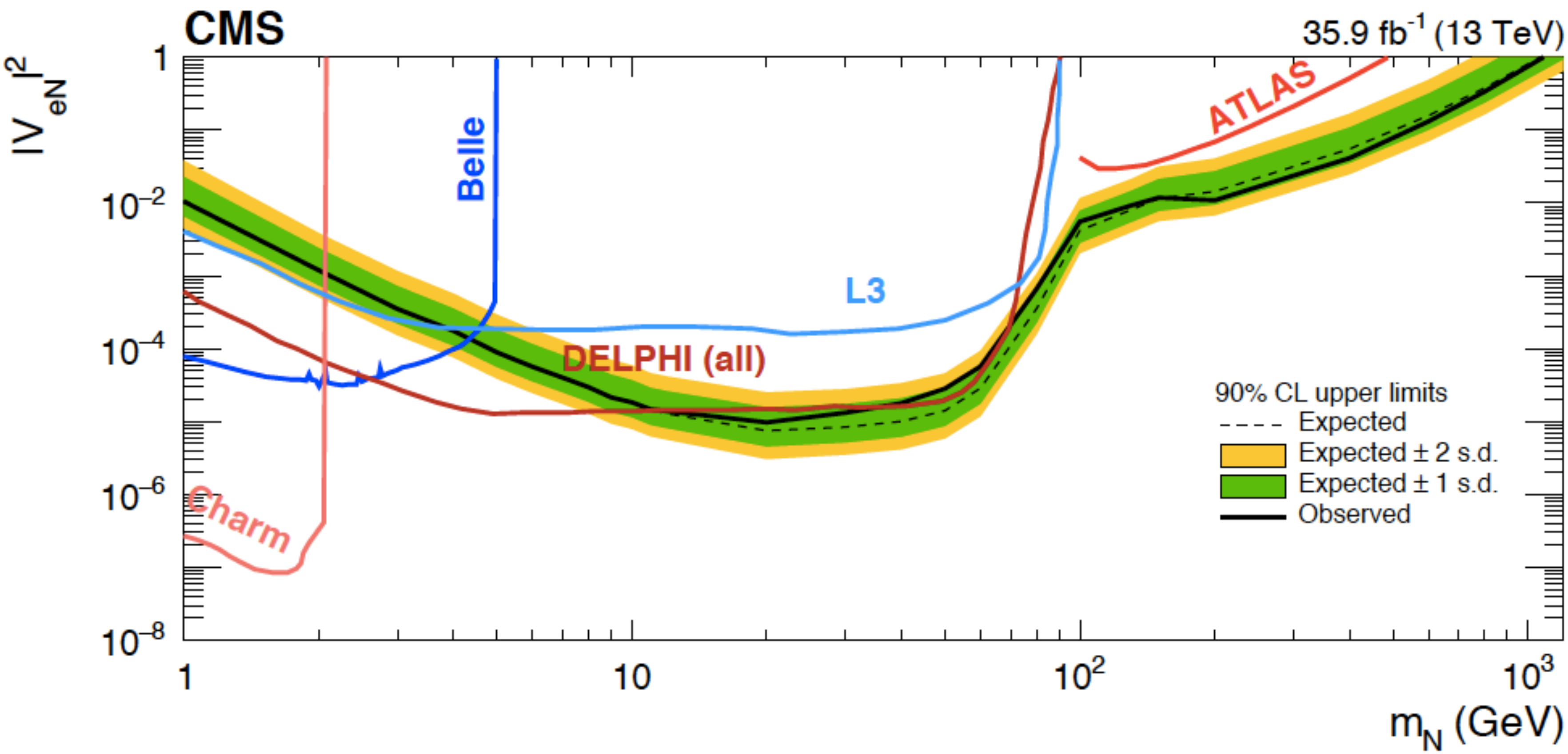
ttV


CMS
35.9 fb^{-1} (13 TeV)
Events
Data
$t\bar{t}W$
$t\bar{t}Z$
Nonprompt
WZ
$t(\bar{t})X$
Rare
Charge mis-ID
l^-l^-
l^+l^+
$0 < D < 0.6$
$D > 0.6$
$0 < D < 0.6$
$D > 0.6$
2j
3j1b
3j>1b
>3j1b
>3j>1b

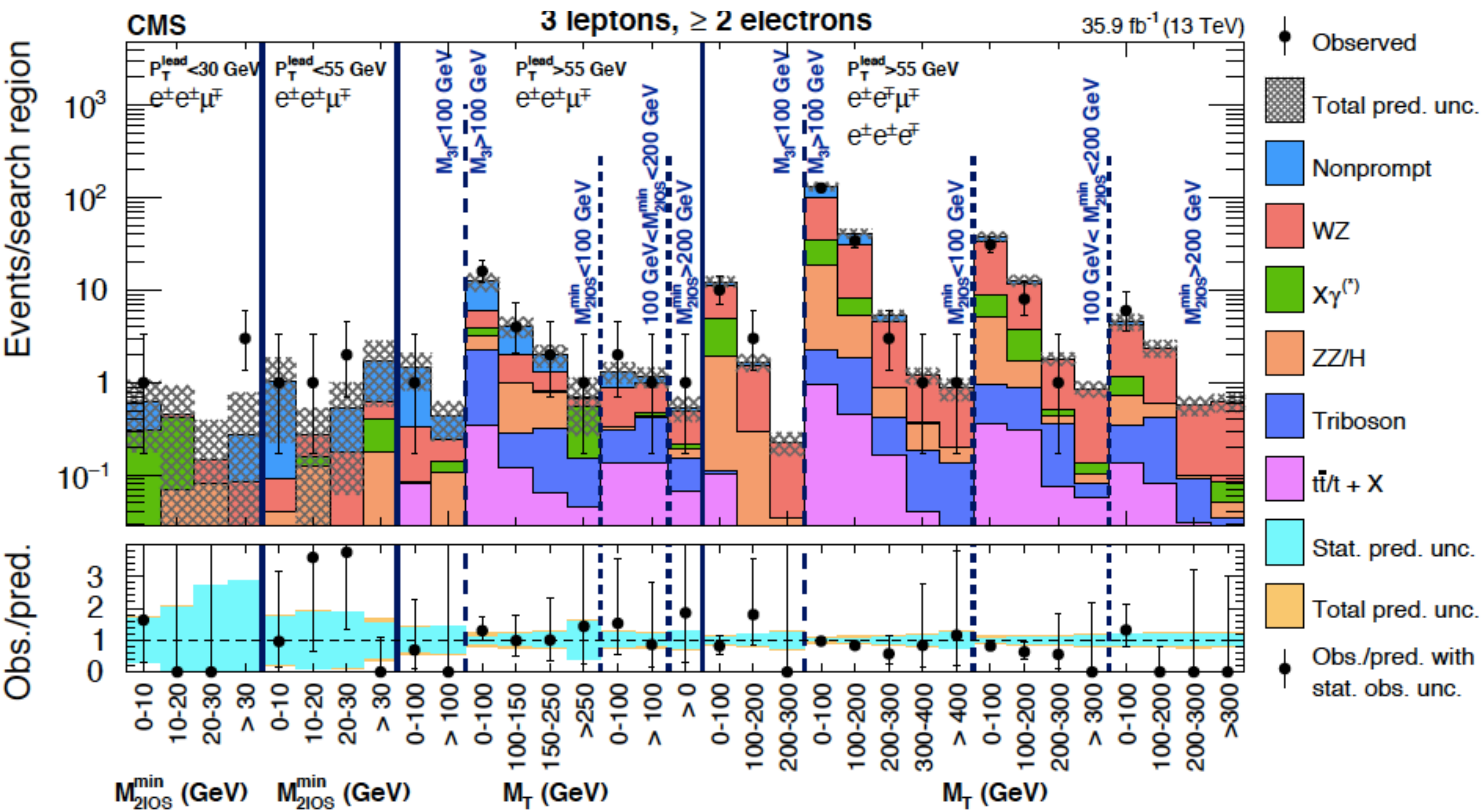

CMS
35.9 fb^{-1} (13 TeV)
Events
Data
$t\bar{t}Z$
$t\bar{t}W$
WZ
$t(\bar{t})X$
Rare
Nonprompt
$N_b = 0$
$N_b = 1$
$N_b > 1$
N_j


CMS
35.9 fb^{-1} (13 TeV)
Events
Data
$t\bar{t}Z$
ZZ
$t(\bar{t})X$
Rare
Nonprompt
N_b

Sterile Neutrinos



Sterile Neutrinos :results



Bottomline: data agrees very well with the expected background