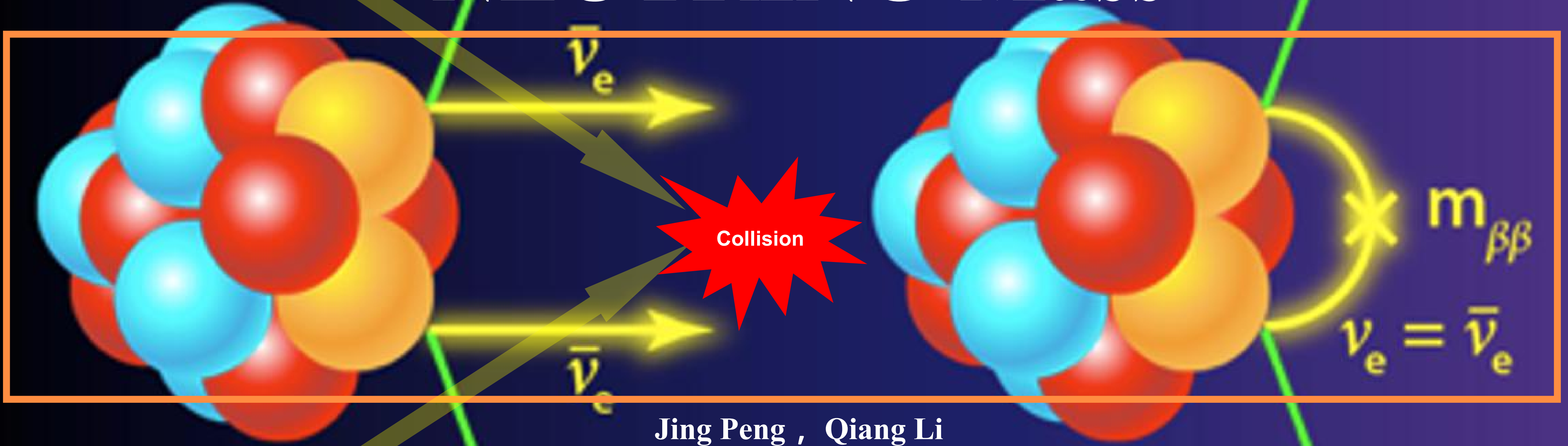
Vector boson scattering and NEUTRINO Mass



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On behalf of CMS Collaboration &Peking University

Outline

- ➢ Introduction
- ➢ Vector boson scattering process
- ➢ Heavy Majorana neutrinos & Weinberg operator
- ➢ Summary

PHYSICAL REVIEW LETTERS

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Accepted Paper

Probing heavy Majorana neutrinos and the Weinberg operator through vector boson fusion processes in proton-proton collisions at $\sqrt{s}$ = 13 TeV

Phys. Rev. Lett.

A. Tumasyan et al.

Accepted 31 August 2022

ABSTRACT

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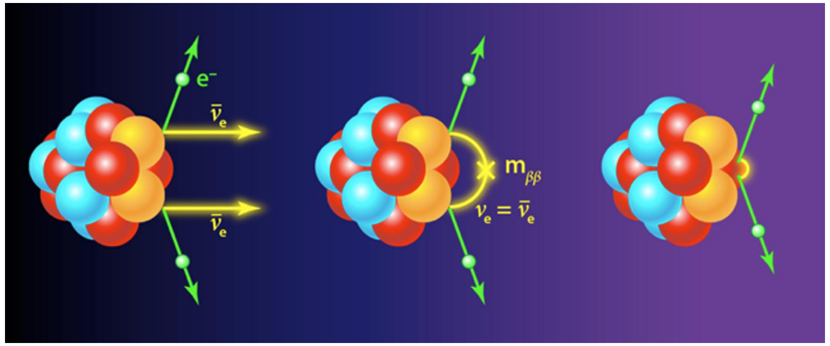
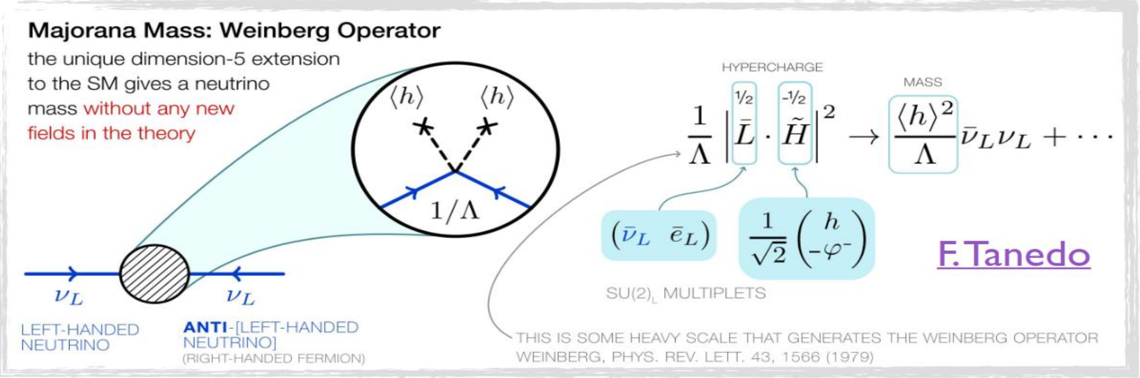
The first search exploiting the vector boson fusion process to probe heavy Majorana neutrinos and the Weinberg operator at the LHC is presented. The search is performed in the same-sign dimuon final state using a proton-proton collision data set recorded at $\sqrt{s} = 13$\TeV, collected with the CMS detector and corresponding to a total integrated luminosity of 138. The results are found to agree with the predictions of the standard model. For heavy Majorana neutrinos, constraints on the squared mixing element between the muon and the heavy neutrino are derived in the heavy neutrino mass range 50\GeV–25\TeV; for masses above 650these are the most stringent constraints from searches at the LHC to date. A first test of the Weinberg operator at colliders provides an observed upper limit at 95% confidence level on the effective \PGm\PGm Majorana neutrino mass of 10.8.

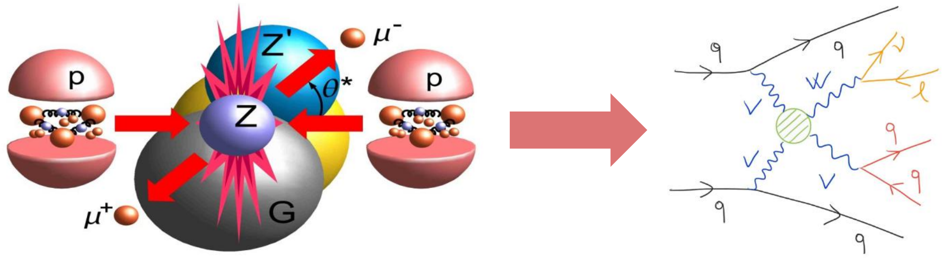
Introduction

- **Neutrino mass**
  - Confirmed by Neutrino Oscillation experiments
    <u>Oscillation of Atmospheric Neutrinos, Solar Neutrinos...</u>
- **In particle physics**
  - Beyond the Standard Model (SM) description
    - *New physics !*
    - Import **model** independent operators from effective field theory to explain the neutrino mass
  - Vector boson scattering (VBS) process
    - LHC & CMS
    - Same-sign WW to mumu

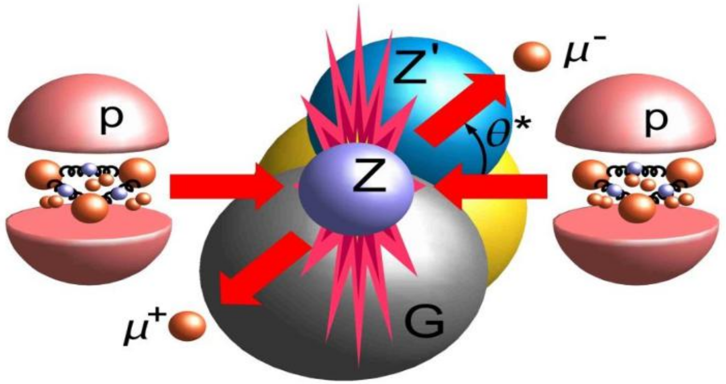


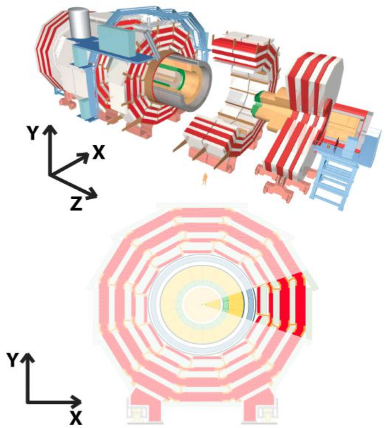


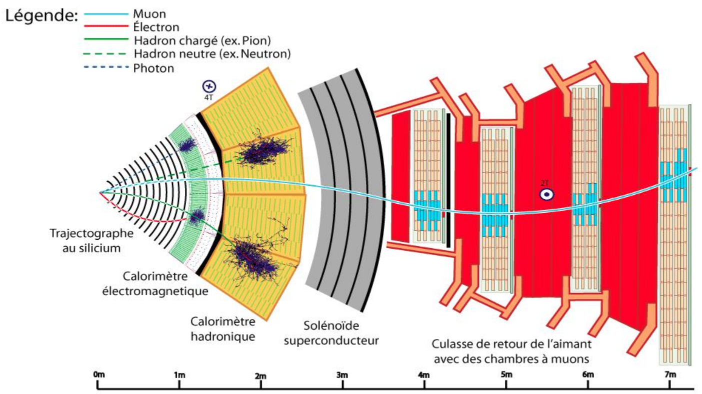
VBS process in LHC: vector boson collider !



Introduction







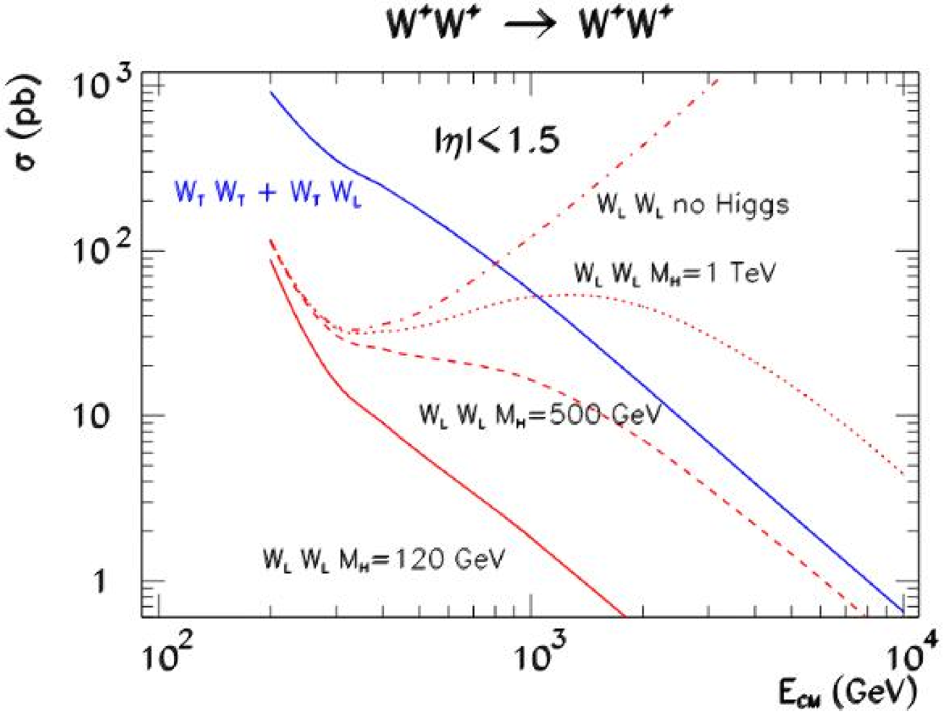
IN CMS Jargon: LHE –> GEN –> SIM –> DIGI –> RECO

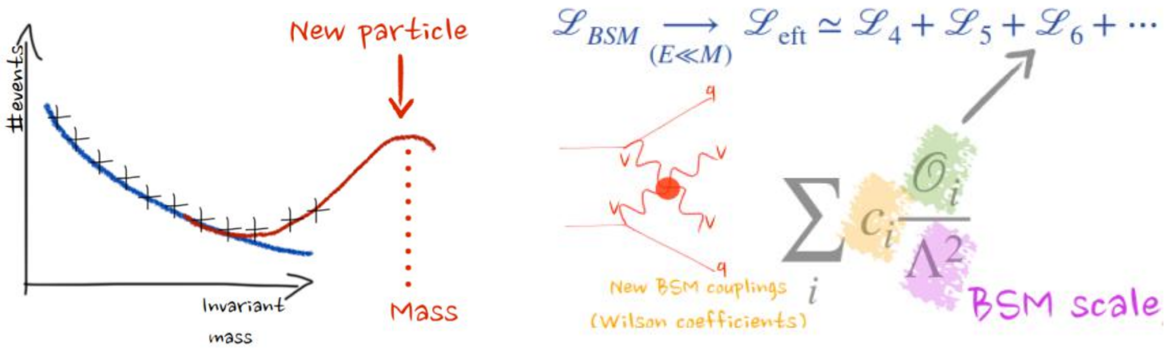
- The CMS experiment is a general-purpose particle physics detector built on the LHC at CERN
- Analyses in this report are based on the Run-2 (2016-2018) proton-proton collisions data at $\sqrt{s}$=13 TeV
- Corresponding to an integrated luminosity of ~138 fb^{-1}

Vector boson scattering process

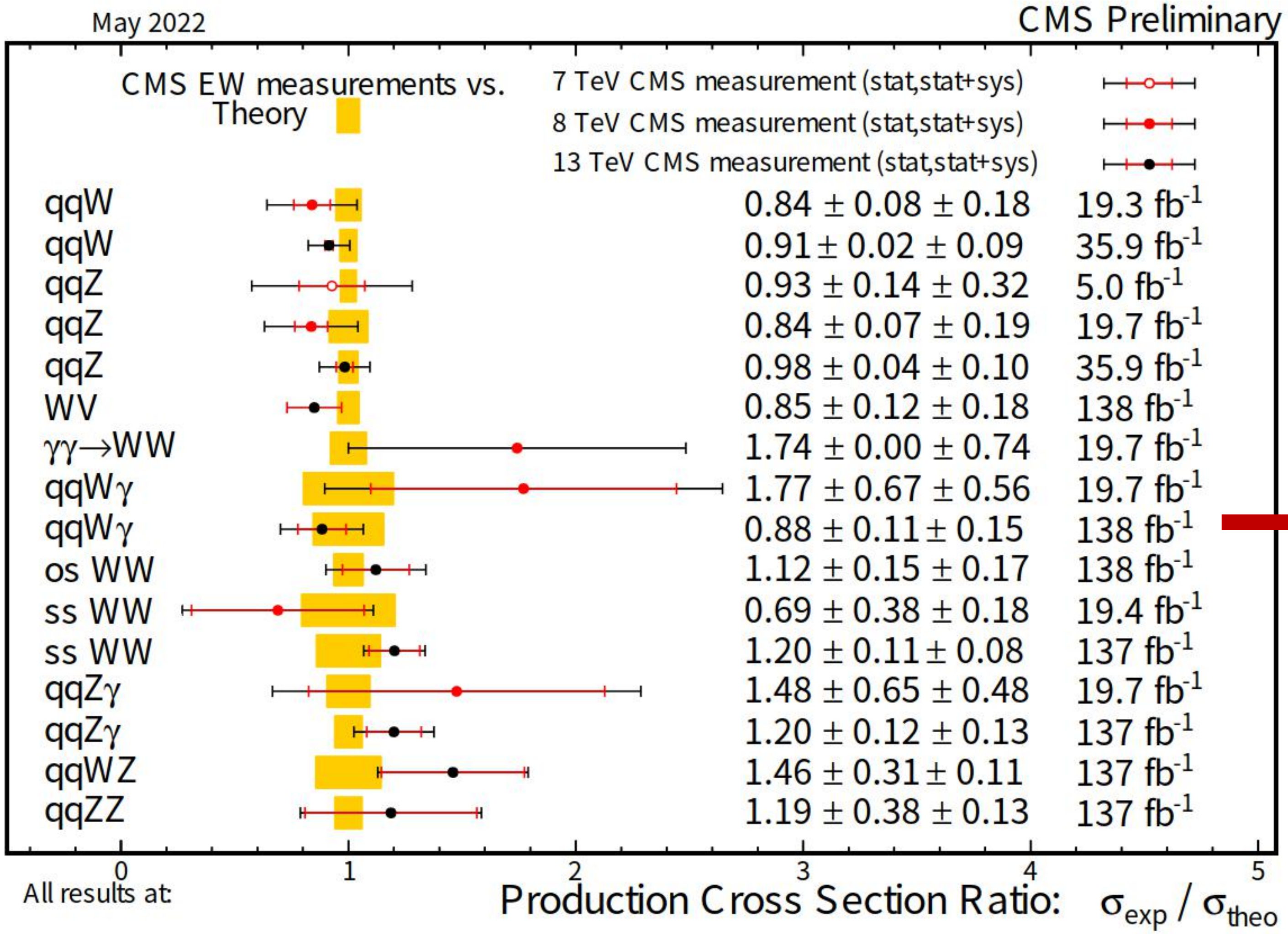
VBS process is very important!

- **At the heart of EWSB, probing non-abelian structure of the SM:** containing triple and quartic gauge couplings
- Studies of gauge invariance: this process is gauge invariant thanks to very delicate cancellations between diagrams
- Unitarity of the SM
- **Powerful portal test to BSM effects** in a model independent approach, usually parametrized as Effective Field Theory (EFT)

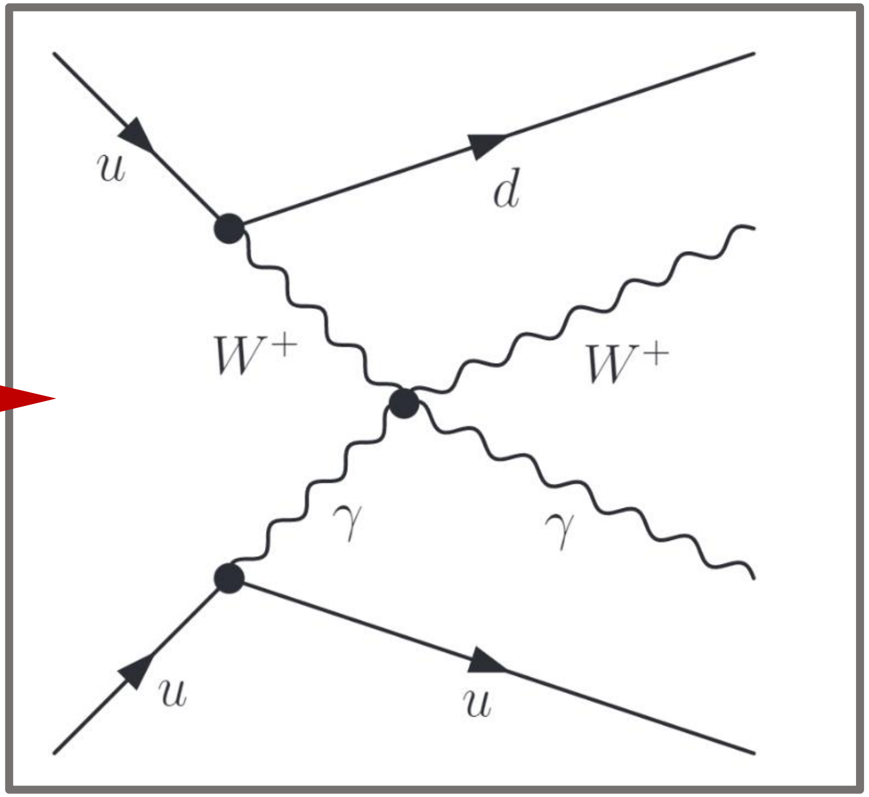




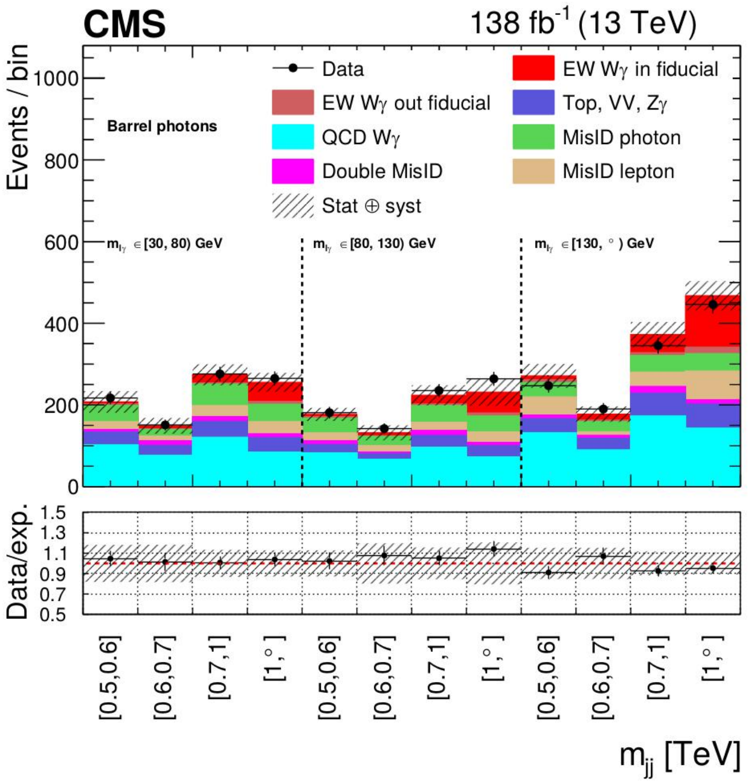
VBS process measurements in CMS

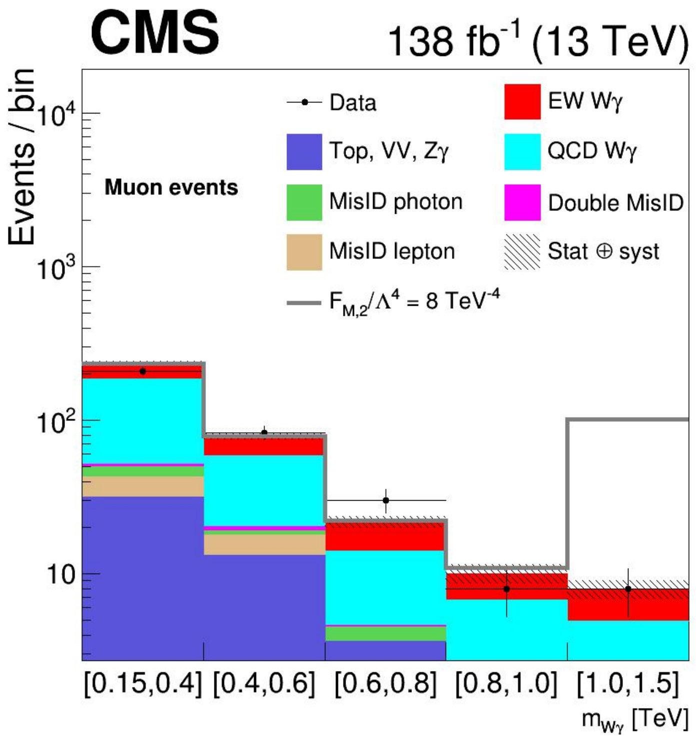


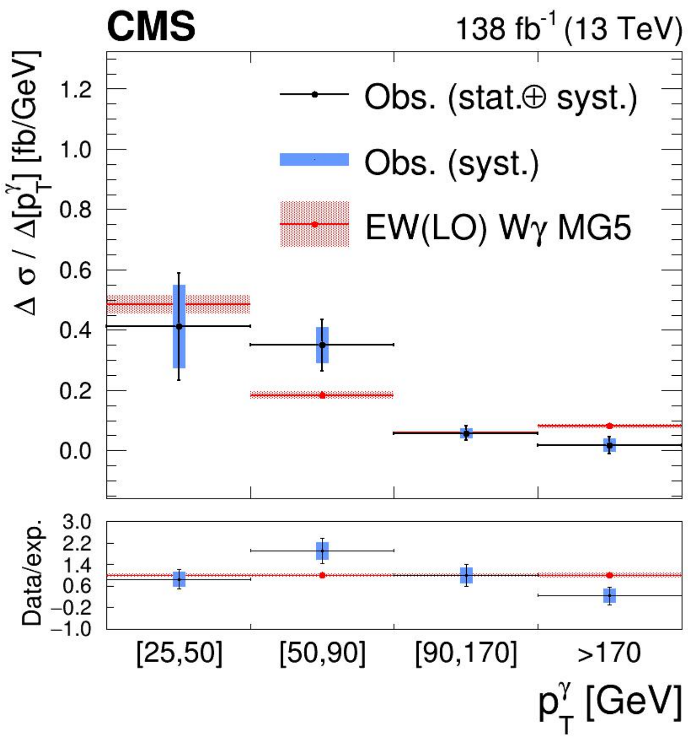
arXiv:2212.12592
PRD accepted



VBS process measurements in CMS







$\sigma^{fid}_{EW} = 19^{+4.0}_{-3.9}$fb,

$\sigma^{fid}_{EW+QCD} = 90^{+11}_{-10}$fb

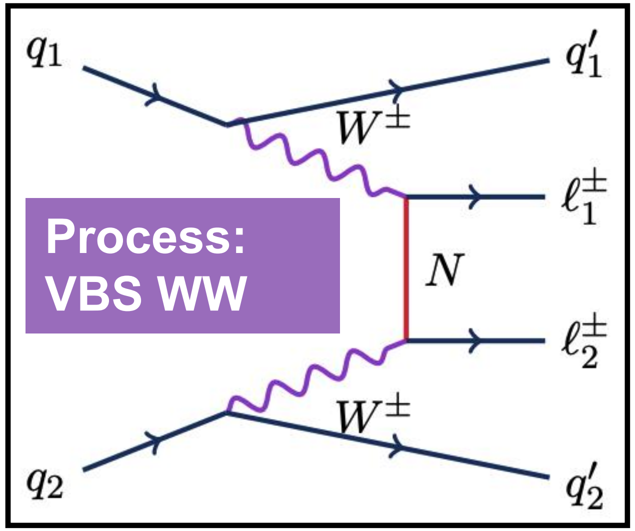
- Dimention 8 operators : LM0-7, LT0-2, LT5-7
- The most stringent limit for FM2-5, FT5-7

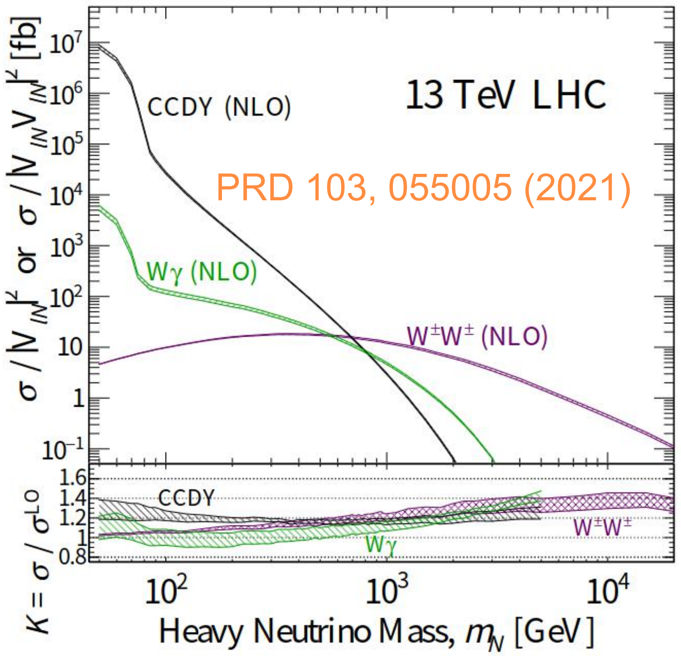
★Differential cross section are measured :

- EW and EW+QCD
- p_T^l, p_T^γ, p_T^{j1}, $m_{l\gamma}$, m_{jj}, $\Delta\eta_{jj}$

Motivation

- In the context of SM, neutrinos have to be massless because:
  - SU(2)×U(1) symmetry group for EW theory & Dimension-4 operators only
  - Economical particle content:
    - Only left handed neutrinos: Dirac mass term is forbidden
    - Only one neutral Higgs doublet: Majorana mass is forbidden
- Neutrino mass can be explained with:
  - Model independent operators from effective field theory:
    - Example: Majorana mass term introduced by the dimension-5 Weinberg Operator





Neutrino mass model

Latest results from CMS on neutrino mass models!

- **Type-I seesaw model**:
  - Probing heavy Majorana neutrinos & Weinberg Operator via Vector Boson Fusion (VBF)
  - Long-lived heavy neutral leptons with displaced vertices
- Type-III seesaw model:
  - Inclusive nonresonant multilepton probe for new physics
- Heavy Composite Majorana Neutrino
  - Two same-flavor lepton and two jets final state
- Left-Right Symmetric Model
  - decay to heavy right handed neutrino
  - Z boson decaying to pairs of heavy Majorana neutrino
- Prospects of High Luminosity LHC (HL-LHC)
  - Inclusive nonresonant multilepton probes of type-I and type-II seesaw models

arXiv: 2206.08956

JHEP07(2022)081

PhysRevD.105.112007

JHEP04(2022)047

Signal simulation

- Only the lightest heavy Majorana neutrino n1, denoted as N, is considered. All n2, n3 contributions are forbidden.
- Only dimuon channel is generated.
- Due to the mass dependence, **a scan** over the hypothesis heavy Majorana neutrino mass from 50 GeV to 20000 GeV is performed.

Process syntax

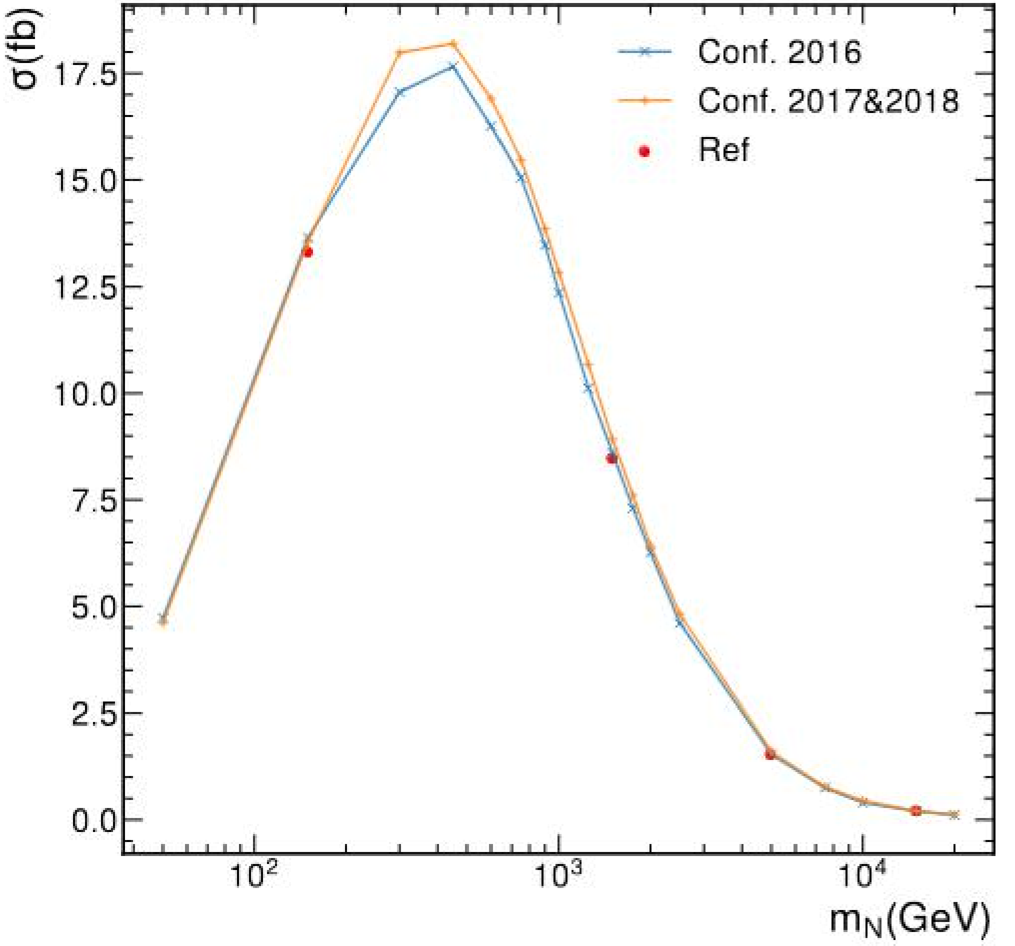
```
import model SM_HeavyN_NLO
define p = g u c d s ūc̄d̄s̄
define j = p
generate p p > mu+ mu+ j j QED=4 QCD=0 $$ w+ w- / n2 n3 [QCD]
add process p p > mu- mu- j j QED=4 QCD=0 $$ w+ w- / n2 n3 [QCD]
```

- $p_T^{\mu_1}(\mu_2) > 27(10)$ GeV, $|\eta^{\mu}| < 2.7$, $n_{\mu} = 2$
- $p_T^{j} > 25$GeV, $|\eta^{j}| < 4.5$, $n_j \geq 2$
- $Q_{\mu_1} \times Q_{\mu_2} = 1$

Mass effect

Cross sections for heavy Majorana neutrino with different masses.

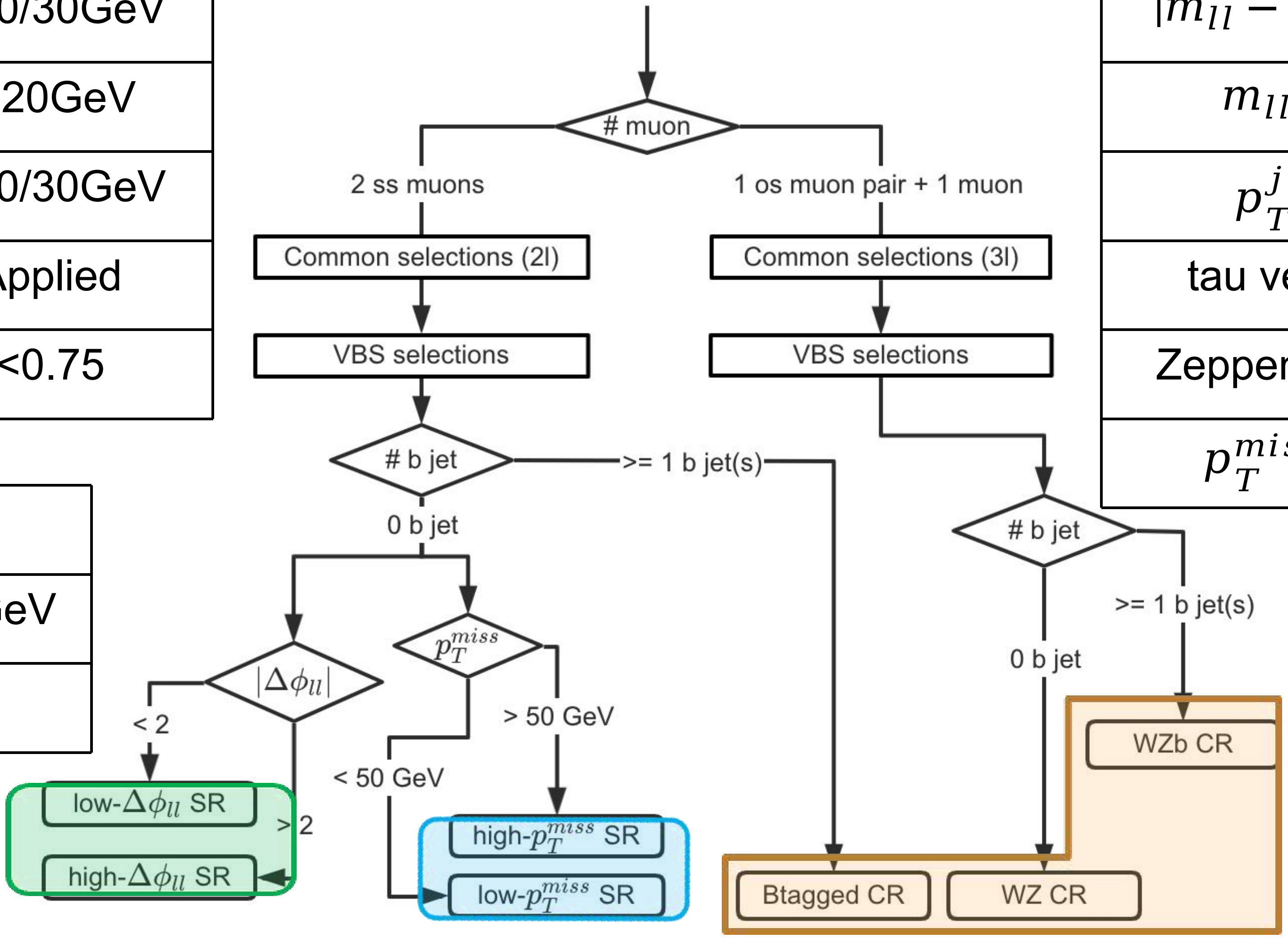
m_N(GeV)	σ^{2016}(fb)	$\sigma^{2017(8)}$(fb)	m_N(GeV)	σ^{2016}(fb)	$\sigma^{2017(8)}$(fb)
50	4.725	4.606	1500	8.598	8.918
150	13.66	13.57	1750	7.303	7.612
300	17.06	17.99	2000	6.264	6.425
450	17.66	18.20	2500	4.602	4.811
600	16.26	16.91	5000	1.536	1.598
750	15.05	15.47	7500	0.7521	0.7736
900	13.48	13.86	10000	0.3977	0.4480
1000	12.36	12.84	15000	0.2018	0.2052
1250	10.12	10.67	20000	0.1089	0.1165



Event selection

Common selection $2l$	
p_T^l	> 30/30GeV
m_{ll}	> 20GeV
p_T^j	> 30/30GeV
tau veto	Applied
Zeppenfeld	<0.75

VBS selection	
m_{jj}	> 750GeV
$\|\eta_{jj}\|$	2.5



Common selection $3l$	
p_T^l	> 25/10/25GeV
$\|m_{ll} - m_Z\|$	< 15GeV
m_{lll}	> 100GeV
p_T^j	> 30/30GeV
tau veto	Applied
Zeppenfeld	< 1.0
p_T^{miss}	> 30GeV

Background estimation

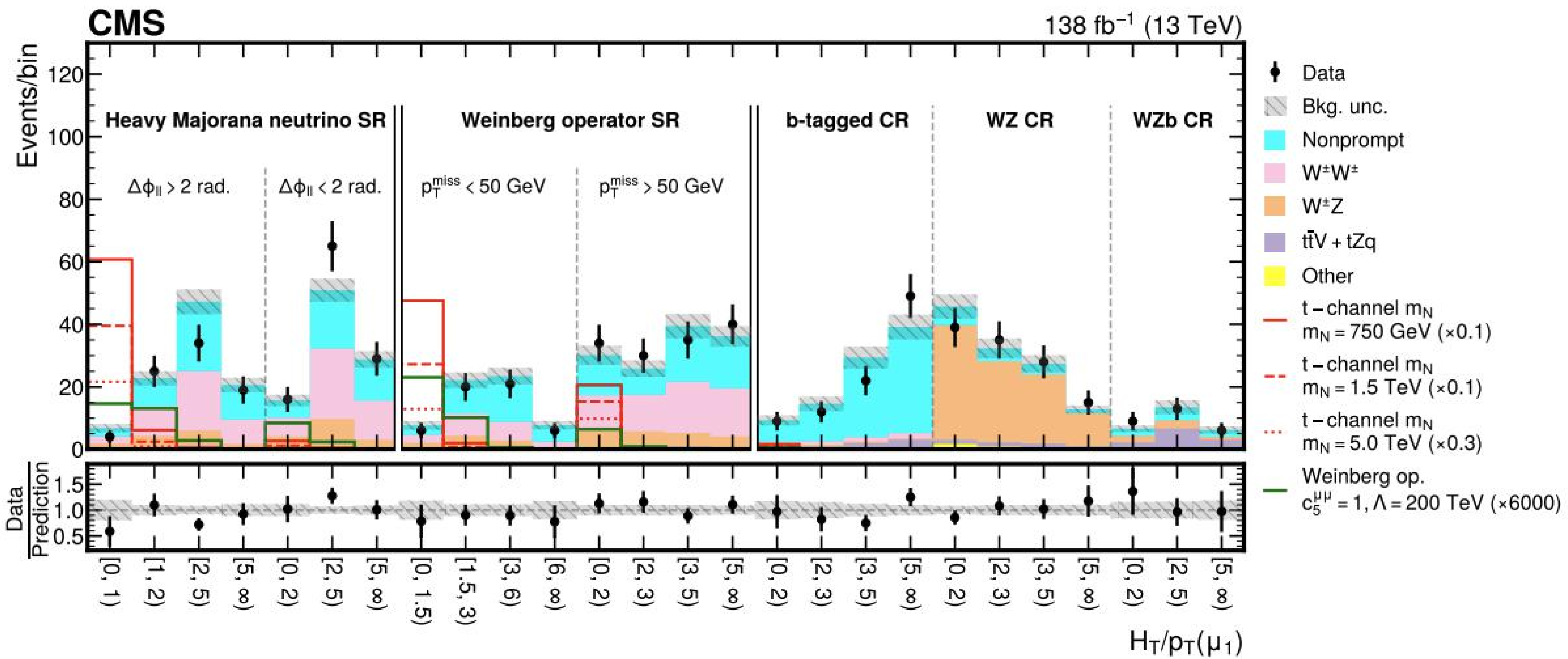
Background	Description	Estimation
$W^{\pm}W^{\pm}jj$	One of the dominant backgrounds	Simulation
WZ	The fraction of EW WZ jj is small, the NLO QCD and EW corrections are considered	Simulation
ZZ, TVX, Vγ , WW DPS and tribosons	Tiny backgrounds	Simulation
Non-prompt lepton	One of the dominant backgrounds	Data-driven

Uncertainties

Unsertainties	
Integrated luminosity	Uncertainties on MC only
Muon momentum scale and resolution	➢ These uncertainties arise due to different detector effects and are p_T and η dependent. ➢ Uncertainties on both the scale and resolution in-dividually amount to about 0.2% for muons.
Theoretical uncertainties	The re-normalization and factorization scale (QCD) and parton distribution function (PDF) uncertainties are considered for the heavy Majorana neutrino samples, the Weinberg operator sample and EW $W^{\pm}W^{\pm}jj$ processes.
Other uncertainties	Trigger efficiency, Prefiring correction, Jet energy scale/resolution (JES/R) uncertainties, p_T^{miss} unclustered component, Jet PU ID SF, b-tagging, and Pileup reweighting.

Signal Extraction

- Data collected on CMS run 2. All uncertainties introduced have been considered
- Simultaneously fit the signal and control regions.
  The fitted distribution is $\boldsymbol{H_T / p_T^{\mu 1}}$ (where $H_\mathrm{T} = \sum p_\mathrm{T}^{i}(jet), (i \in p_\mathrm{T}(jet) > 30\mathrm{GeV})$)
- Floating normalizations of the BKGs: SM SSWW, WZ, tZq



Signal Extraction

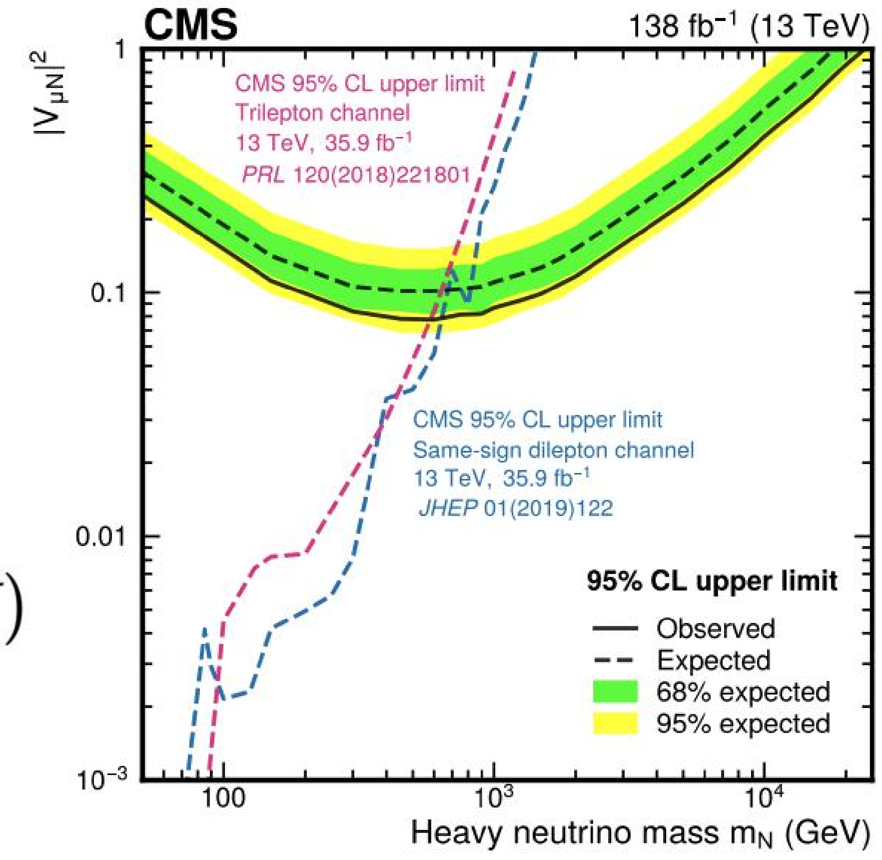
- Interpretations of limits
  - Parameter of interest (POI) in fit: signal strength μ

$$\mu = \frac{Data - Bkgs}{Signal}$$

- For VBF production of HMN
  - The cross section dependence reads:

$$\sigma(pp \to \ell_i^{\pm}\ell_j^{\pm} + X) \equiv \left|V_{\ell_i N} V_{\ell_j N}\right|^2 \times \sigma_0(pp \to \ell_i^{\pm}\ell_j^{\pm} + X)$$

  - Upper limits on signal strength can be translated to the squared mixing element $|V_{\mu N}|^2 = \sqrt{\mu}$
- m_N up to around 23TeV is excluded
- Better constraints on $|V_{\mu N}|^2$ for $m_N \gtrsim 650\text{GeV}$



Signal Extraction

- Interpretations of limits
  - POI in fit: signal strength μ
- For Weinberg op. processes
  - The cross-section dependence reads:

$$\hat{\sigma}(W^+W^+ \to \ell^+\ell'^+) = \frac{(2-\delta_{\ell\ell'})}{2\pi 3^2}\left|\frac{C_5^{\ell\ell'}}{\Lambda}\right|^2 + \mathcal{O}\left(\frac{m_W^2}{M_{WW}^2}\right)$$

  - Effective Majorana Mass is given by:

$$m_{\ell\ell'} = C_5^{\ell\ell'} v^2 / \Lambda$$

  - Interpretation: translate to EFT scale limit with Wilson coefficient fixed to unit, thus $\Lambda = 200 \times \mu^{-\frac{1}{2}}$ GeV, and translate to effective Majorana mass limit $m_{\mu\mu} = \nu^2 |C_5^{\mu\mu}| / \Lambda$

- Results
  - Observed (expected) lower bond on EFT scales Λ: 5.6 (4.7) TeV (assuming $C_5^{\mu\mu} = 1$)
  - Observed (expected) upper limits of effective Majorana mass $m_{\mu\mu}$: 10.8 (12.8) GeV

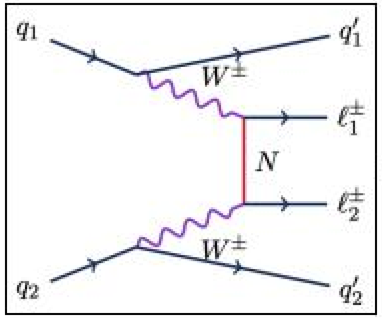
Summary

★ Performed analysis on VBF production of same-sign muon pairs associated with two jets

- **Heavy Majorana neutrino** from Type-I Seesaw Model
  - Upper limits on $|V_{\mu N}|^2$ for m_N up to around 23 TeV
  - Better constraints on $|V_{\mu N}|^2$ for $m_N \gtrsim 650$ GeV
- First direct search at collider on dimension-5 **Weinberg operator**
  - Upper limit of effective Majorana mass $m_{\mu\mu}$, observed (expected): 10.84 (12.84) GeV

Thank you!

Backup



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Mixing matrix

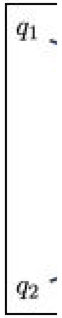
$$V_{lN} = \begin{pmatrix} V_{eN_1} & V_{eN_2} & V_{eN_3} \\ V_{\mu N_1} & V_{\mu N_2} & V_{\mu N_3} \\ V_{\tau N_1} & V_{\tau N_2} & V_{\tau N_3} \end{pmatrix}$$

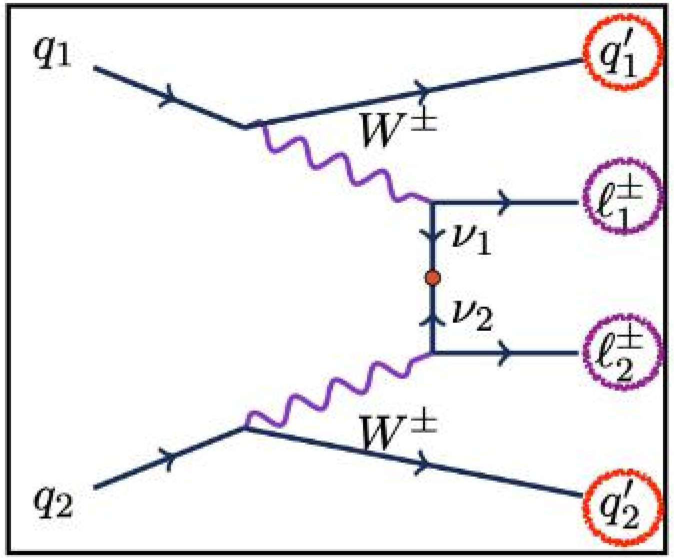
→

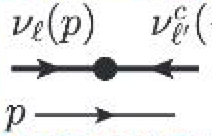
Cross section

$$\sigma(pp \to \ell_i^\pm \ell_j^\pm + X) \equiv |V_{\ell_i N} V_{\ell_j N}|^2 \times \sigma_0(pp \to \ell_i^\pm \ell_j^\pm + X)$$

→







$$= \frac{i\not{p}}{p^2}\,\frac{-iC_5^{\ell\ell'}v^2}{\Lambda}\,\frac{i\not{p}}{p^2} = \frac{im_{\ell\ell'}}{p^2}$$

$$\sigma \sim \left|m_{\ell\ell'}\right|^2 \propto \left|C_5^{\ell\ell'}/\Lambda\right|^2$$

Wilson Coefficients

$$\mathcal{L}_5 = \frac{C_5^{\ell\ell'}}{\Lambda}\left[\Phi\cdot\overline{L_\ell^c}\right]\left[L_{\ell'}\cdot\Phi\right] + \text{H.c.}$$

EFT Scale

$$v = \sqrt{2}\langle\Phi\rangle \approx 246\ \text{GeV}$$

$$m_{\ell\ell'} = C_5^{\ell\ell'}v^2/\Lambda$$

Effective Majorana Mass

Phys. Rev. D 103, 115014

First ever direct examination of Weinberg Operator at colliders!