On the Robustness of Type II seesaw Collider searches

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Co-authors

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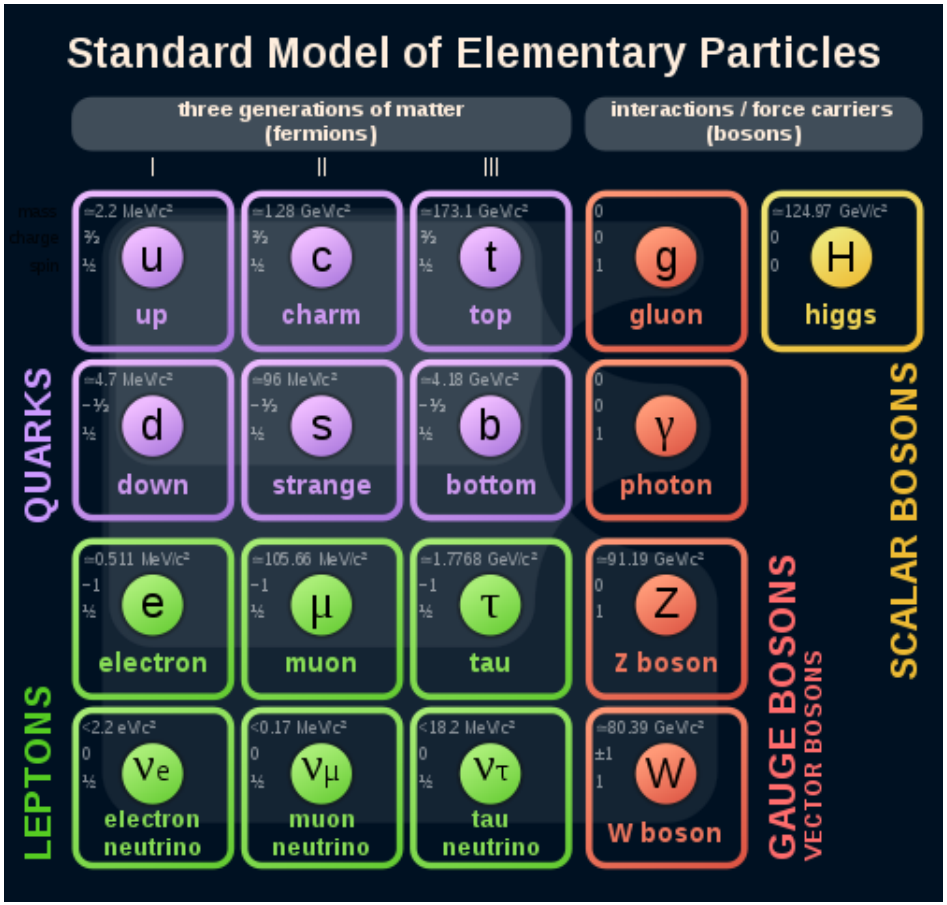
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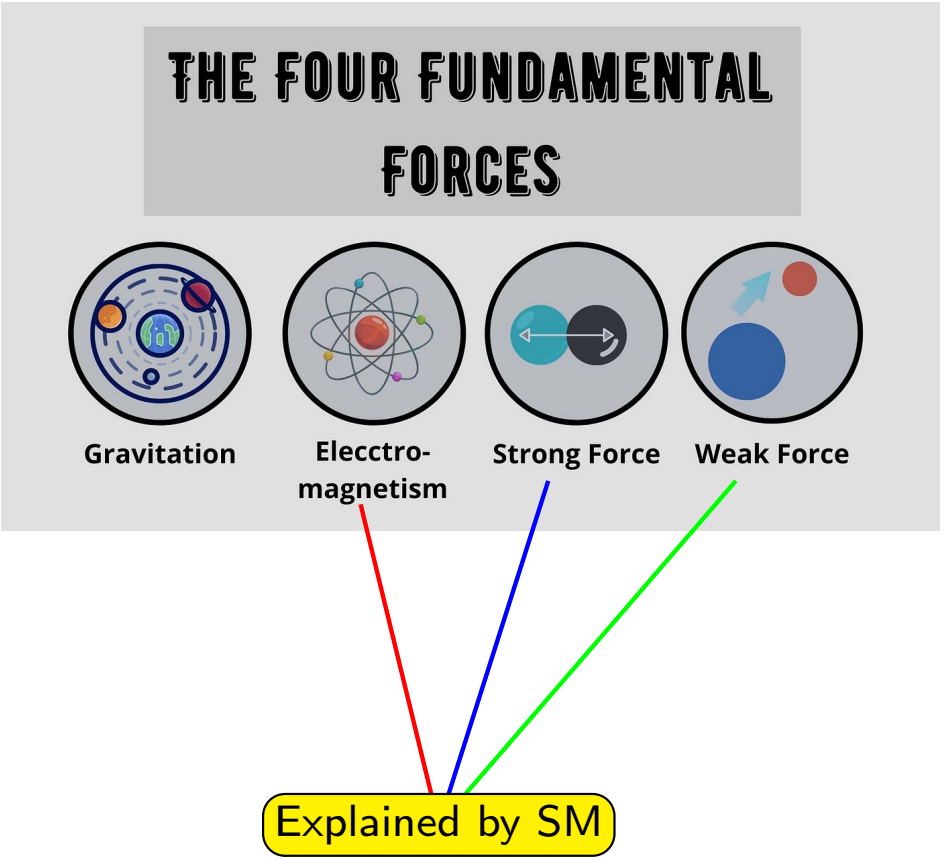
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Outline

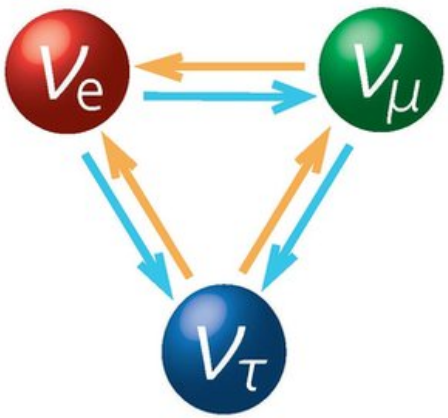
1. Standard Model and motivation to go beyond.
2. Type II seesaw and EFT extensions
3. Possible UV Completions
4. Effects of EFT on LHC constraints.
5. Discovery Prospect of Type II seesaw EFT.

Standard Model





Type-II Seesaw



$$|\Delta m^2_{21}| = (7.3 - 7.68) \times 10^{-5}\ \text{eV}^2,$$
$$|\Delta m^2_{31}| = (2.41 - 2.60) \times 10^{-3}\ \text{eV}^2,$$
$$\theta_{12} \sim 33.68^\circ,$$
$$\theta_{23} \sim 43.3^\circ,$$
$$\theta_{13} \sim 8.56^\circ$$

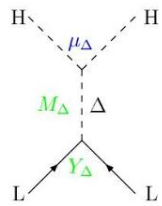
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Weignberg Op $\frac{c_{ij}}{\Lambda}(\tilde{H}^T L_i)(\tilde{H}^T L_j)$

UV completion
Type II seesaw

$\Delta \sim (1,3,1)$

$$\Delta \sim \begin{pmatrix} \delta^+ & \sqrt{2}\Delta^{++} \\ v_\Delta + \delta^0 + i\xi^0 & -\delta^+ \end{pmatrix}$$

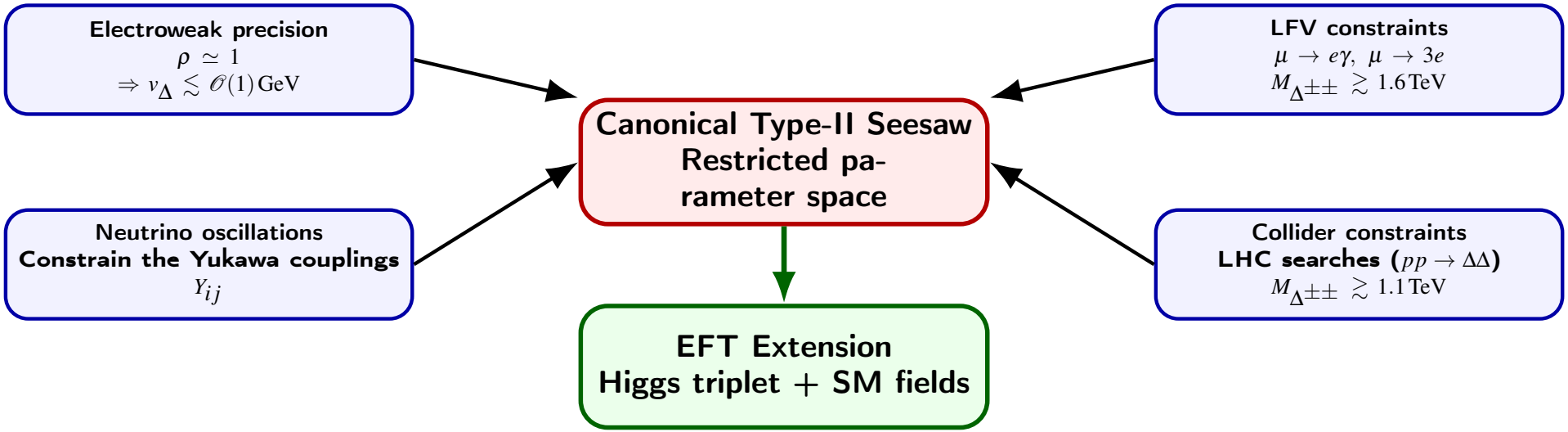


- $-Y_{ij}\overline{L^c_{L_i}}\Delta L_{L_j}$, $(m_\nu)_{ij} = \sqrt{2}Y_{ij}v_\Delta$

- No neutrino mass mechanism or flavour mixing.
- No viable dark matter candidate.
- Cannot explain the matter–antimatter asymmetry.
- Motivates physics Beyond the Standard Model (BSM).

- Neutrino oscillations $\rightarrow$ tiny neutrino masses.
- Type-II seesaw $\rightarrow$ Majorana neutrino masses $\rightarrow$ LNV.
- LNV signature in $\Delta^{\pm\pm}$ leptonic decay.

Type-II Seesaw EFT



Effective Interactions: $\Delta^{\pm\pm}$ pair production, $\Delta^{\pm\pm} \to \ell^\pm \ell^\pm \gamma$ decay

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$$\mathcal{O}_{G\Delta} = G^A_{\mu\nu} G^{A\mu\nu}\ \text{Tr}\left[\Delta^\dagger \Delta\right],$$

$$\mathcal{O}_{u\Delta D} = N_f^2 \bar{u}_{p\alpha} \gamma^\mu u_q^\alpha\ \text{Tr}\left[\Delta^\dagger i \overleftrightarrow{\mathscr{D}}_\mu \Delta\right],$$

$$\mathcal{O}^{(1)}_{Q\Delta\mathscr{D}} = N_f^2 \left(\overline{Q}_{p\alpha i} \gamma^\mu Q_q^{\alpha i}\right)\ \text{Tr}\left[\left(\Delta^\dagger i \overleftrightarrow{\mathscr{D}}_\mu \Delta\right)\right],$$

$$\mathcal{O}_{BL\Delta} = \frac{1}{2}(N_f^2 - N_f)(L_p^T C i\tau_2 \Delta \sigma_{\mu\nu} L_q) B^{\mu\nu}.$$

Possible UV Completions of the EFT Operators

$\mathcal{O}_{G\Delta}$

Possible mediators

- Vector-like quarks (VLQs)

$$X \sim (\mathbf{3}/\bar{\mathbf{3}}, \mathbf{2}/\mathbf{3}, Y)$$

Coupling:

$$\bar{X}\Delta Q,\ \bar{X}\Delta u_R,\ \bar{X}\Delta d_R$$

- Colored scalars

$$S(\mathbf{R_C}, \mathbf{R_L}, Y)$$

Coupling:

$$(S^\dagger S)(\Delta^\dagger \Delta)$$

Generates

$$gg \to \Delta^{++}\Delta^{--}$$

$\mathcal{O}_{Q\Delta D}$ & $\mathcal{O}_{u\Delta D}$

Possible mediator

$$Z'$$

Couples to

$$q\bar{q} \quad \text{and} \quad \Delta^{++}\Delta^{--}$$

After integrating out the heavy Z'

$$q\bar{q} \longrightarrow \Delta^{++}\Delta^{--}$$

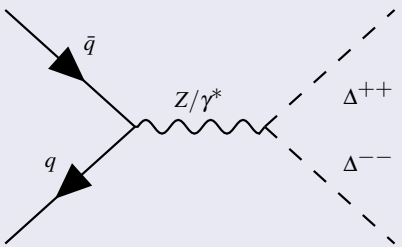
Underlying BSM Frameworks

Partial Compositeness | Extended Higgs Sectors | $U(1)'$ Models | GUTs

Possible Pair Production Topologies

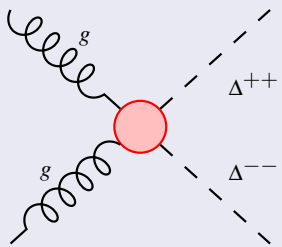
Different production mechanisms for $\Delta^{++}\Delta^{--}$ at the LHC

(a) Vanilla Type-II



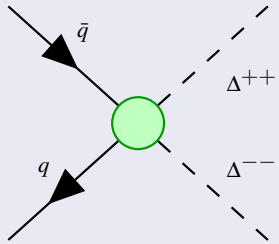
Standard Type-II seesaw

(b) $\mathcal{O}_{G\Delta}$



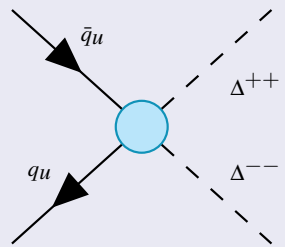
Gluon fusion

(c) $\mathcal{O}^{(1)}_{Q\Delta\mathscr{D}}$



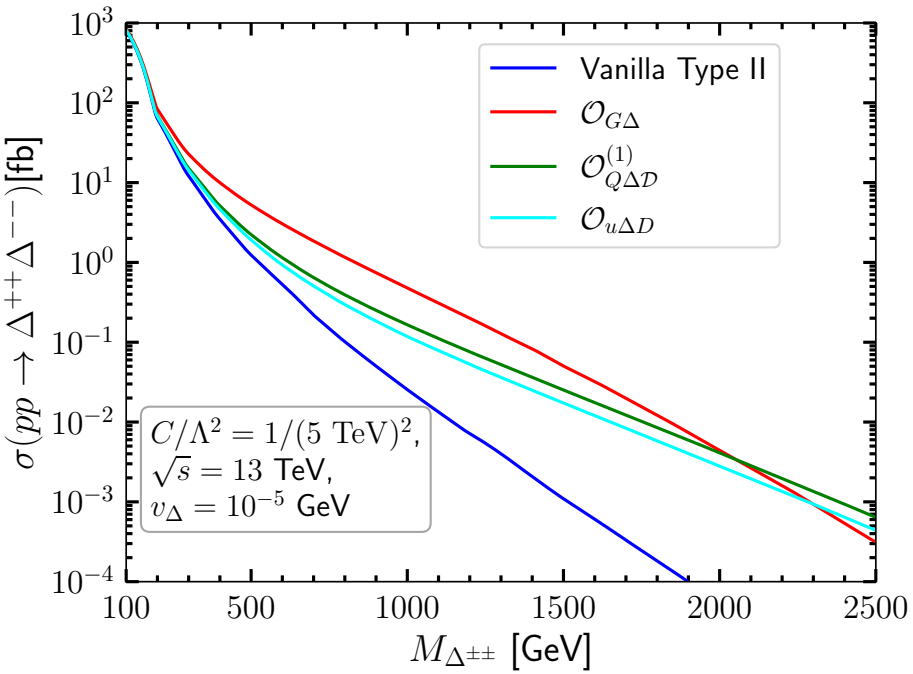
Quark contact interaction

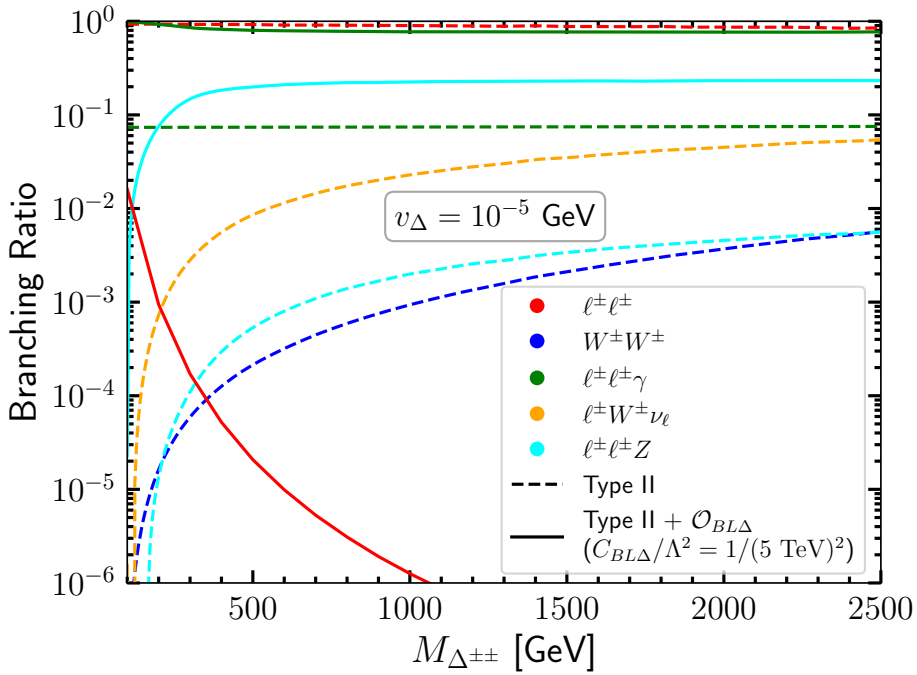
(d) $\mathcal{O}_{u\Delta\mathscr{D}}$



Up-quark interaction

Production cross section and Branching Ratio





- EFT contributions dominate over the minimal Type-II seesaw for the chosen Λ, with $\mathscr{O}_{G\Delta}$ providing the largest enhancement to $\Delta^{++}\Delta^{--}$ production.
- The hierarchy $\mathscr{O}_{G\Delta} > \mathscr{O}^{(1)}_{Q\Delta D} > \mathscr{O}_{u\Delta D}$ is driven by the different gluon and quark PDFs inside the proton.
- When $C_{BL\Delta} = 0.0$: $\ell^\pm\ell^\pm$ dominates, When $C_{BL\Delta} = 1.0/(5TeV)^2$: $\ell^\pm\ell^\pm\gamma$ dominates.

Impact on LHC Experimental Constraints

How do EFT operators modify collider limits:

- Validation of the **Eur. Phys. J. C 83 (2023) 605** selection criteria for canonical type II seesaw.
- Finding the fitting variable $M_{\ell^\pm\ell^\pm}$ distribution in presence of EFT operators.
- Fit these distribution bin by bin for all SRs and get exclusion limit using `pyhf` package.

S1 Vanilla type-II + operator $\mathcal{O}_{G\Delta}$.

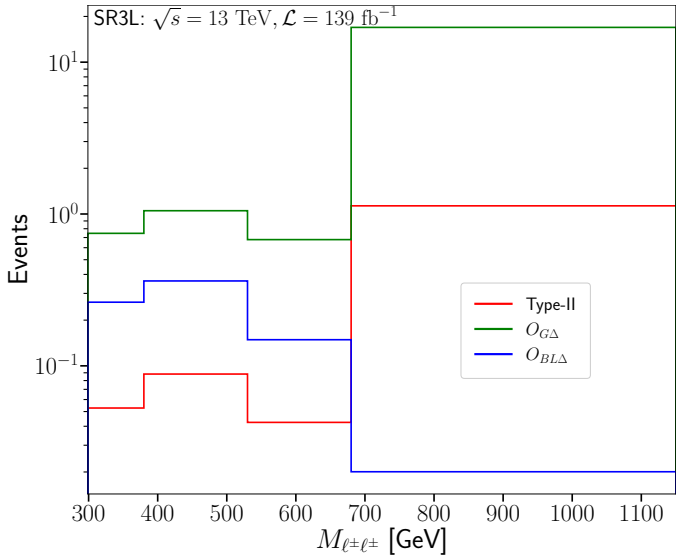
S2 Vanilla type-II + operator $\mathcal{O}_{BL\Delta}$.

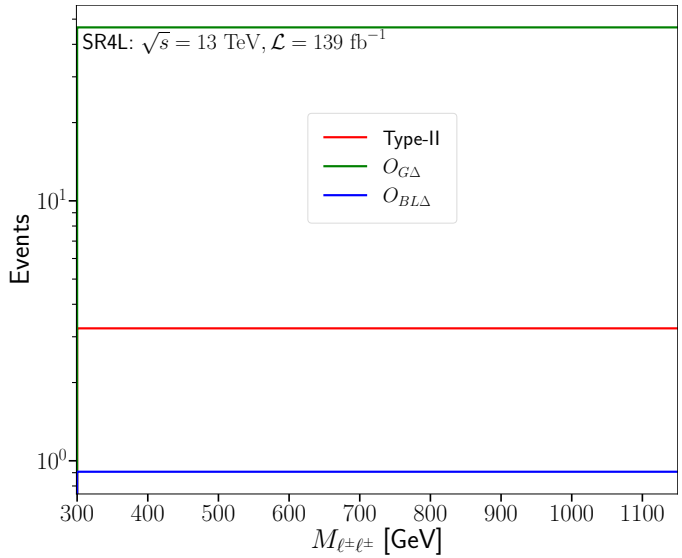
S3 Vanilla type-II + both operators, $\mathcal{O}_{G\Delta}$ and $\mathcal{O}_{BL\Delta}$.

EFT limits are rescaled using the ratio between our vanilla Type-II result and the corresponding ATLAS limit to account for detector and systematic effects.

Implication on $m_{\ell^\pm\ell^\pm}$ Distribution

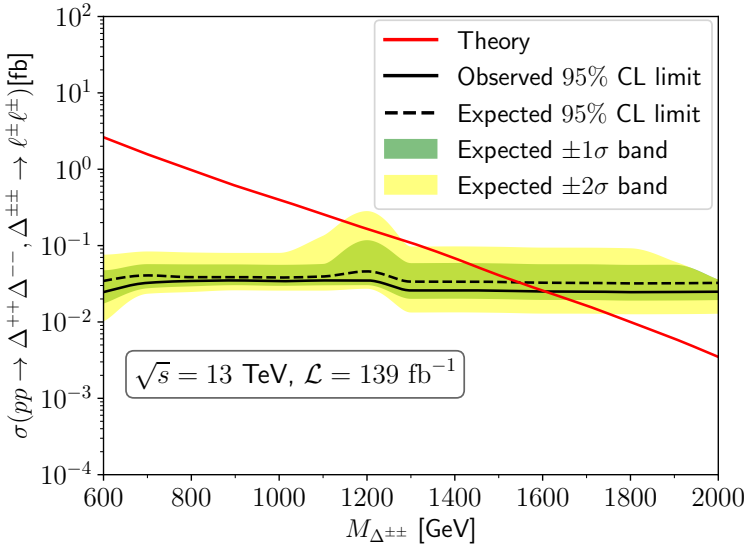
$$\frac{C}{\Lambda^2} = \frac{1.0}{(5\ \text{TeV})^2}$$

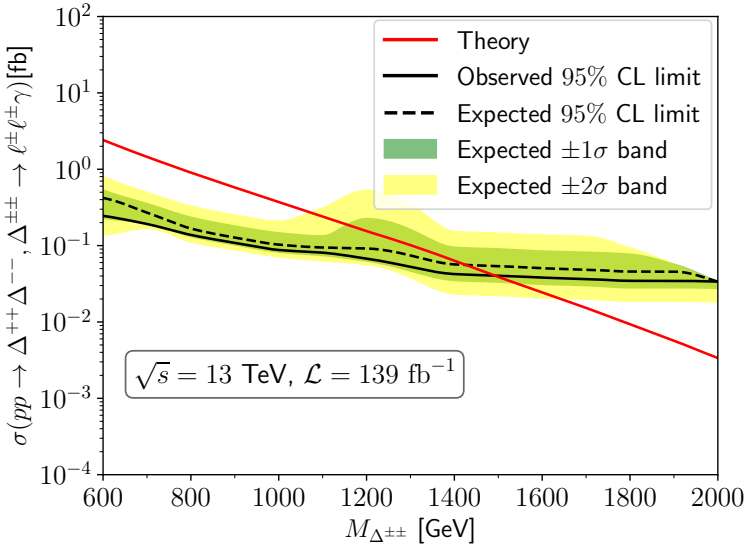


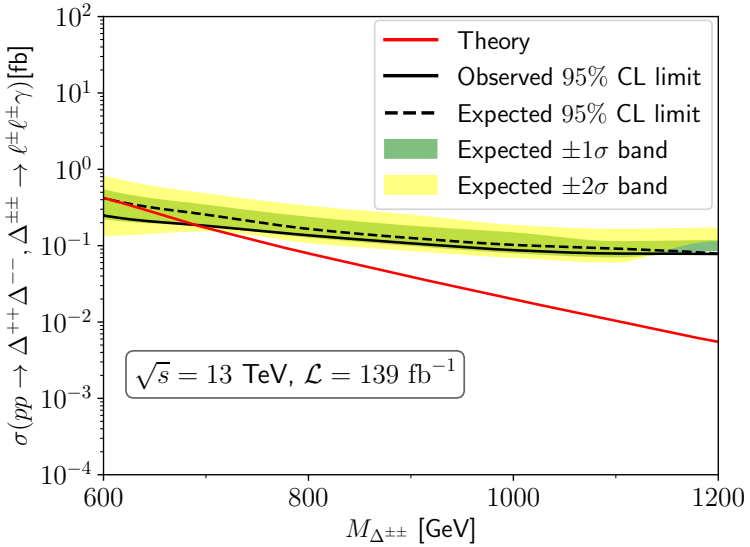


- EFT operators modify the shape of the distribution.
- The resulting distortions alter the signal-region efficiencies.
- Consequently, the ATLAS sensitivity is affected.

Exclusion limits







Observations

- **S1 ($\mathcal{O}_{G\Delta}$):** Enhanced pair production strengthens the exclusion, ruling out $M_{\Delta^{\pm\pm}} \lesssim 1.6$ TeV.
- **S2 ($\mathcal{O}_{BL\Delta}$):** Modified $\Delta^{\pm\pm} \to \ell^{\pm}\ell^{\pm}\gamma$ kinematics reduce cut efficiency, weakening the exclusion to ~ 700 GeV.
- **S3 ($\mathcal{O}_{G\Delta} + \mathcal{O}_{BL\Delta}$):** Increased production compensates for the efficiency loss, excluding $M_{\Delta^{\pm\pm}} \lesssim 1.5$ TeV.
- $\mathcal{O}_{G\Delta}$ has the dominant impact on the collider sensitivity, while $\mathcal{O}_{BL\Delta}$ mainly modifies the event kinematics.

Discovery Prospects of a Heavy $\Delta^{\pm\pm}$ at the HL-LHC

Signal

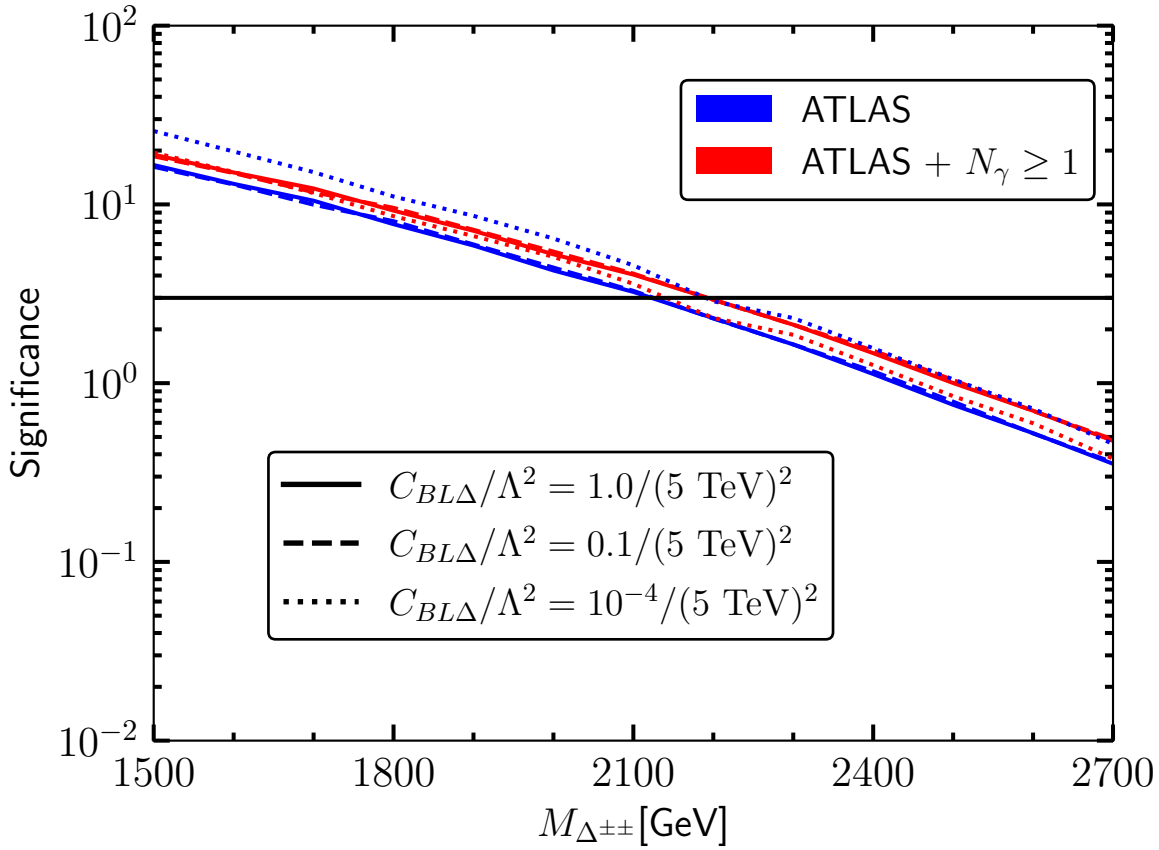
$pp \to \Delta^{++}\Delta^{--}$ with $\Delta^{\pm\pm} \to \ell^\pm\ell^\pm/\ell^\pm\ell^\pm\gamma$.
$C_{G\Delta} = 1.0, v_\Delta = 10^{-5}$.

backgrounds

VV, $VV\gamma$, $VV\gamma\gamma$, VVV, $VVV\gamma$, $VVV\gamma\gamma$, $t\bar{t}V$, $t\bar{t}V\gamma$, and $t\bar{t}V\gamma\gamma$, where $V = W^\pm, Z$

Kinematic cuts

- **ATLAS (SR4L):** $N_\ell = 4$, $m^{\text{lead}}_{\ell^\pm\ell^\pm} > 300$ GeV, $\bar{m} > 300$ GeV, and $m_{\ell^+\ell^-} \notin [71.2, 111.2]$ GeV.
- **ATLAS + Photon:** SR4L selection + $N_\gamma \geq 1$ with $p_T^\gamma > 20$ GeV.



- **ATLAS (SR4L):** The standard dilepton selection is most sensitive for small $C_{BL\Delta}$, where the conventional $\Delta^{\pm\pm} \to \ell^\pm\ell^\pm$ decay dominates.
- **ATLAS + Photon:** Requiring $N_\gamma \geq 1$ significantly enhances the sensitivity for large $C_{BL\Delta}$, extending the 3σ reach up to $M_{\Delta^{\pm\pm}} \simeq 2.2$ TeV.

Conclusions

- Developed an EFT extension of the Type-II seesaw and investigated the collider impact of the operators $\mathscr{O}_{G\Delta}$ and $\mathscr{O}_{BL\Delta}$.
- Recast the ATLAS doubly charged Higgs search, showing that $\mathscr{O}_{G\Delta}$ significantly strengthens the exclusion limits on $M_{\Delta^{\pm\pm}}$.
- Demonstrated that the EFT-induced decay $\Delta^{\pm\pm} \to \ell^{\pm}\ell^{\pm}\gamma$ provides a complementary discovery channel, with a 3σ reach up to $M_{\Delta^{\pm\pm}} \simeq 2.2$ TeV at the HL-LHC.
- Highlights the importance of EFT effects in modifying Type-II seesaw phenomenology and motivating dedicated future collider searches.

Future outlook

Match EFT operators with UV model to have more robust theoretical motivation.


Thank You!
Ďakujem!

Mass matrix in Type II seesaw

$$m_H^2 = \lambda_H v^2 - \sqrt{2}\,\mu_\Delta v_\Delta + \frac{1}{2}(\lambda_{\Delta_3} + \lambda_{\Delta_4}) v_\Delta^2 \,, \tag{1}$$

$$m_\Delta^2 = \frac{\mu_\Delta v^2}{\sqrt{2} v_\Delta} - \frac{1}{2}(\lambda_{\Delta_3} + \lambda_{\Delta_4}) v^2 - (\lambda_{\Delta_1} + \lambda_{\Delta_2}) v_\Delta^2 \,. \tag{2}$$

$$M_{\Delta^{\pm\pm}}^2 \simeq m_\Delta^2 - \frac{\lambda_{\Delta_4}}{2} v^2 \,, \tag{3}$$

$$M_{\Delta^{\pm}}^2 \simeq m_\Delta^2 - \frac{\lambda_{\Delta_4}}{4} v^2 \,, \tag{4}$$

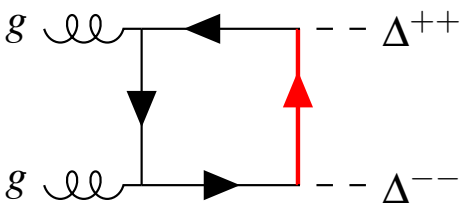
$$M_A^2 \simeq m_\Delta^2 \,, \tag{5}$$

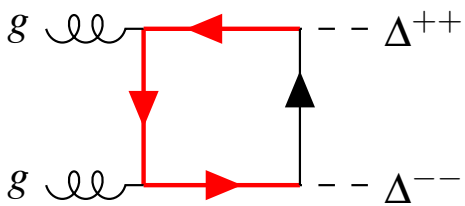
$$M_{\Delta^0, h}^2 \simeq \begin{pmatrix} 2\lambda_H v^2 & -\sqrt{2}\,\mu_\Delta v \\ -\sqrt{2}\,\mu_\Delta v & m_\Delta^2 \end{pmatrix} . \tag{6}$$

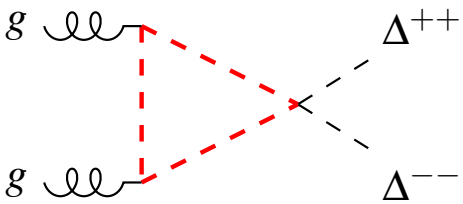
$$\tan 2\alpha \simeq \frac{2\sqrt{2}\,\mu_\Delta v}{m_\Delta^2 - 2\lambda_H v^2} \,, \tag{7}$$

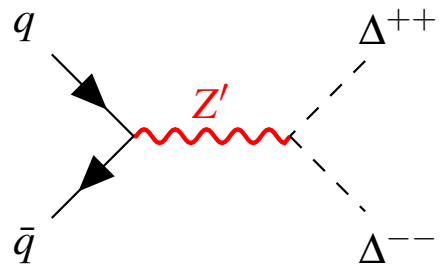
new physical states: a pair of doubly-charged scalars $\Delta^{\pm\pm}$, singly charged scalars $\Delta^{\pm}$, a CP-odd neutral pseudoscalar A, and two CP-even neutral scalars Δ^0, h.

UV Completion Feynman Diagrams

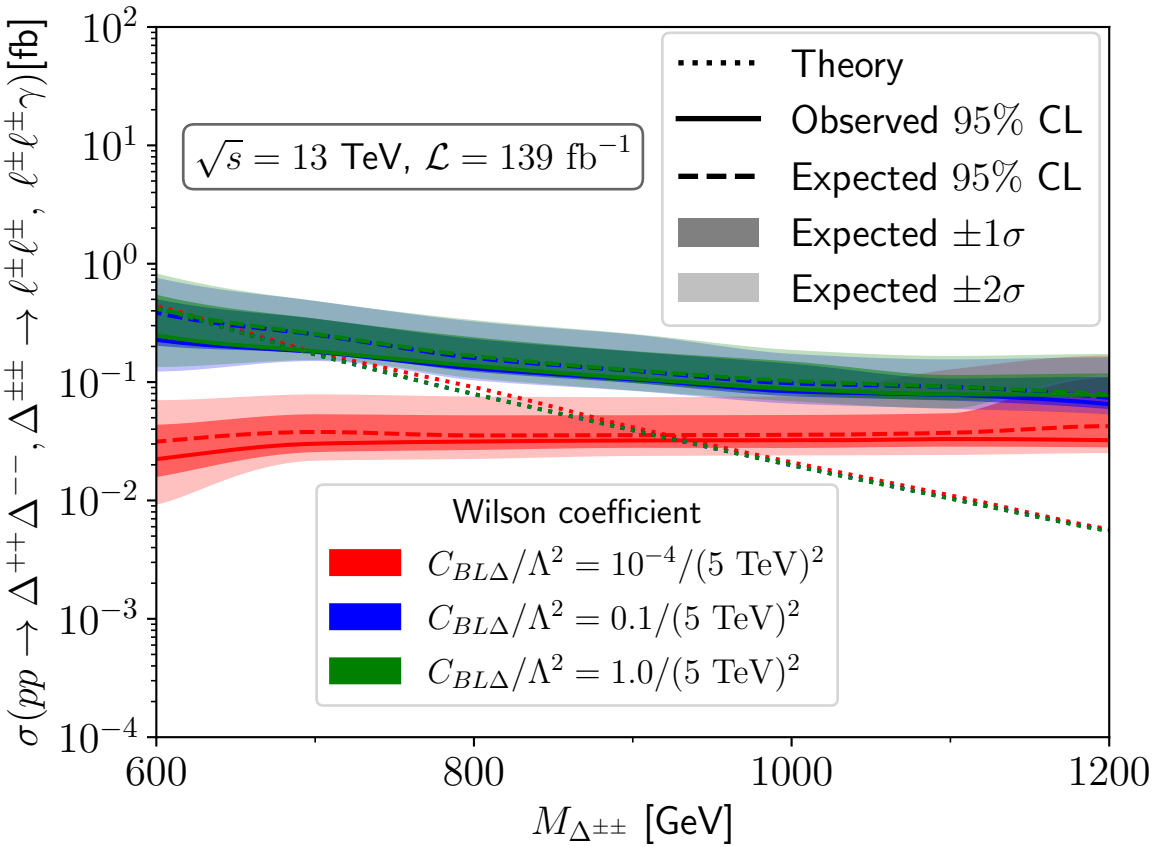








Exclusion with $C_{BL\Delta}$ variation



- Increasing the Wilson coefficient $C_{BL\Delta}$ enhances the $\Delta^{\pm\pm} \to \ell^\pm\ell^\pm\gamma$ branching ratio, reducing the efficiency of the standard dilepton search.
- Consequently, the exclusion limit weakens from ~ 937 GeV ($C_{BL\Delta} = 10^{-4}$) to ~ 690 GeV ($C_{BL\Delta} = 0.1, 1$).
- In the limit $C_{BL\Delta} \to 0$, the result reproduces the ATLAS exclusion of $M_{\Delta^{\pm\pm}} \simeq 1.1$ TeV.

EFT Validity

- Although $\sqrt{s} = 14$ TeV, the partonic centre-of-mass energy is reduced by parton distribution functions. We also consider $M_{\Delta^{\pm\pm}} < \Lambda = 5$ TeV.
- Following Refs. Phys. Lett. B 728 (2014) 412 we adopt the indicative perturbative unitarity criterion

$$\frac{Q_{\rm tr}}{4\pi} < \Lambda, \qquad Q_{\rm tr} \equiv M_{\Delta^{++}\Delta^{--}}.$$

- We examine the invariant-mass distributions at the HL-LHC ($\sqrt{s} = 14$ TeV) for $M_{\Delta^{\pm\pm}} = 1,\ 2,\ 2.7$ TeV.
- The distributions show that the majority of simulated events satisfy the adopted criterion, supporting the EFT validity in the dominant event region.
- We clarify that this is an indicative consistency check, not a strict, UV-independent bound.

HistFitter: From Distributions to an Exclusion Limit

1. **Inputs**
   - Observed data histogram: n_{ri}
   - Signal template: s_{ri}
   - Background templates: b_{rij}
   - Systematic variations and MC statistical uncertainties
   - Signal and control region definitions
2. **Expected events in each bin**

$$\nu_{ri}(\mu,\theta) = \mu s_{ri}(\theta) + \sum_j b_{rij}(\theta)$$

   - μ: signal-strength parameter
   - θ: nuisance parameters
3. **Construct the binned likelihood**

$$\mathscr{L}(\mu,\theta) = \prod_{r,i} \mathrm{Pois}\,(n_{ri} \mid \nu_{ri}) \prod_k C_k(\theta_k)$$

4. **Maximise the likelihood**

$$(\widehat{\mu},\widehat{\theta}) = \arg\max_{\mu,\theta} \mathscr{L}(\mu,\theta)$$

   - Vary μ and nuisance parameters to obtain the best fit.
   - For each tested μ, re-optimise nuisance parameters (profile likelihood).
5. **Calculate the signal limit**
   - Use the profile-likelihood test statistic and CL_s method.
   - Obtain observed and expected 95% CL upper limits: μ_{95}.

Interpretation

If $\mu_{95} < 1$, the nominal signal prediction ($\mu = 1$) is excluded at 95% CL, under the specified statistical model.

ATLAS: Event Selection and Signal Regions

Common Event Selection

- Integrated luminosity: $\mathscr{L} = 139$ fb^{-1} at $\sqrt{s} = 13$ TeV.
- Good-quality events with a reconstructed primary vertex.
- Dilepton trigger requirement.
- At least two selected electrons or muons.
- Apply lepton–jet overlap removal.
- Veto events containing a b-tagged jet.

Z-boson veto: Applied in SR3L and SR4L:

$$71.2 < m_{\ell\ell} < 111.2 \text{ GeV}$$

for same-flavour lepton pairs.

Common mass requirement:

$$\boxed{m_{\text{SS}}^{\text{lead}} > 300 \text{ GeV}}$$

Signal Region Definitions

SR2L: Two-lepton channel

- $m_{\text{SS}}^{\text{lead}} > 300$ GeV
- $p_T^{\text{pair}} > 300$ GeV
- $\Delta R_{\text{SS}} < 3.5$

SR3L: Three-lepton channel

- $m_{\text{SS}}^{\text{lead}} > 300$ GeV
- $p_T^{\text{pair}} > 300$ GeV
- Apply Z-boson veto

SR4L: Four-lepton channel

- $m_{\text{SS}}^{\text{lead}} > 300$ GeV
- $\overline{m}_{\text{SS}} > 300$ GeV
- Apply Z-boson veto

$$p_T^{\text{pair}} = |\vec{p}_{T,\ell_1} + \vec{p}_{T,\ell_2}|, \qquad \overline{m}_{\text{SS}} = \frac{m_{\ell^+\ell'^+} + m_{\ell^-\ell'^-}}{2}.$$