Doubly Charged Higgs from VBF at NLO with MG5aMC@NLO

BSM in VBS - VBSCan@LIP - Lisbon

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[1] with B. Fuks, O. Mattelaer, and M. Nemevšek [1912.abcde] + VBSCan COST Action support

BSM in VBS Processes

Idea: *a concrete new physics scenario (Type II Seesaw) and ways in which the vector boson scattering can improve searches for its predictions*

- New production mechanisms, new Monte Carlo (MC) tools, and new MC modeling

Today:

1. Motivation for new physics from the ν sector
2. LHC searches for doubly charged Higgs $\Delta^{\pm\pm}$ (see L. Barak's talk)
3. Room for improvements
4. VBF@NLO in `MadGraph5aMC@NLO` (this is the cool bit!)
5. Outlook

Motivation for new physics from ν physics

Neutrinos Masses and New Physics

To generate Dirac masses for ν like other SM fermions, we need N_R

$$\mathcal{L}_{\nu\ \text{Yuk.}} = -y_\nu \overline{L}\tilde{\Phi} N_R + H.c. = -y_\nu \begin{pmatrix} \overline{\nu_L} & \overline{\ell_L} \end{pmatrix} \begin{pmatrix} \langle \Phi \rangle + h \\ 0 \end{pmatrix} N_R + H.c.$$

$$= \underbrace{-y_\nu \langle \Phi \rangle}_{=m_D} \overline{\nu_L} N_R + H.c. + \ldots$$

However, N_R^i do not exist in the SM, implying $m_D = 0$

Significance of Neutrino Oscillations:

- Neutrino masses $\implies \mathcal{L}_{\text{Universe}} \neq \mathcal{L}_{\text{SM}} \quad (+\mathcal{L}_{\text{gravity}})$
- Instead, $\mathcal{L}_{\text{Universe}} \approx \mathcal{L}_{\text{SM}} + \underbrace{\mathcal{L}_{\nu\ \text{masses}}}_{BSM\ physics!} + \ldots$

Neutrino masses $\implies$ existence of physics beyond the SM!

Neutrinos Masses and New Particles

Nonzero neutrino masses $\implies$ new degrees of freedom exist [Ma'98]:

$$m_\nu \neq 0 + \text{LH currents}$$

$$\swarrow \qquad \searrow$$

$$\text{LH Majorana Mass}: m_\nu^L \overline{\nu_L} \nu_L^c \quad \text{and/or} \quad \text{Dirac Mass}: m_\nu^D \overline{\nu_L} N_R$$

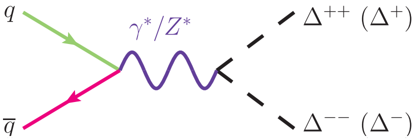
$$\downarrow \qquad \qquad \downarrow$$

$$m_\nu^L = y\langle\Delta\rangle \text{ or strong dynamics} \qquad m_\nu^D = y\langle\Phi_{\text{SM}}\rangle$$

$m_\nu \neq 0$ **+ renormalizability + gauge inv.** $\implies$ **new particles!**

- New particles might be charged under new or old gauge symm.
  E.g., N_R may have $U(1)_{B-L}$ charge and Δ_L is scalar $SU(2)_L$ triplet

Type II Seesaw[2]



[2] Konetschny and Kummer ('77); Schechter and Valle ('80); Cheng and Li ('80); Lazarides, et al ('81); Mohapatra and Senjanovic ('81)

Type II Seesaw Mechanism

Hypothesize an $SU(2)_L$ **scalar** triplet with lepton number $L = -2$

$$\hat{\Delta} = \frac{1}{\sqrt{2}} \begin{pmatrix} \Delta^{+} & \sqrt{2}\Delta^{++} \\ \sqrt{2}\Delta^{0} & -\Delta^{+} \end{pmatrix}, \quad \text{with} \quad \mathcal{L}_{\Delta\Phi} \ni \mu_{h\Delta}\left(\Phi^{\dagger}\hat{\Delta}\cdot\Phi^{\dagger} + \text{H.c.}\right)$$

The mass scale $\mu_{h\Delta}$ explicitly breaks lepton number, and induces $\langle\Delta\rangle$:

$$\sqrt{s}\langle\hat{\Delta}\rangle = v_{\Delta} \approx \frac{\mu_{h\Delta} v_{\text{EW}}}{\sqrt{2}m_{\Delta}^{2}}$$

This induces a left-handed Majorana mass for neutrinos

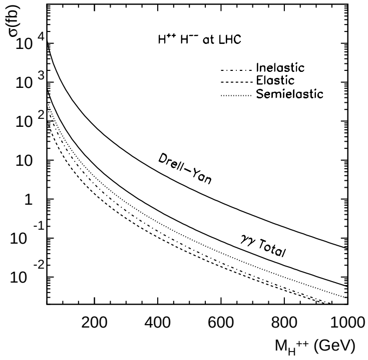
$$\Delta\mathcal{L} = -\frac{y_{\Delta}^{ij}}{\sqrt{2}}\overline{L^{c}}\hat{\Delta}L = -\frac{y_{\Delta}^{ij}}{\sqrt{2}}\begin{pmatrix}\overline{\nu^{jc}} & \overline{\ell^{jc}}\end{pmatrix}\begin{pmatrix}0 & 0 \\ v_{\Delta} & 0\end{pmatrix}\begin{pmatrix}\nu^{i} \\ \ell^{i}\end{pmatrix}$$

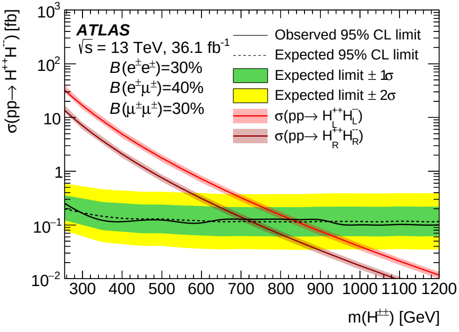
$$\ni -\frac{1}{2}\underbrace{\left(\sqrt{2}y_{\Delta}^{ij}v_{\Delta}\right)}_{=m_{\nu}^{ij}}\overline{\nu^{jc}}\nu^{i}$$

Generates light ν_m masses via vev **WITHOUT** invoking a sterile N!

Type II Seesaw is characterized by new scalars $\Delta^0,\ \Delta^\pm,\ \Delta^{\pm\pm}, \chi^0$

- Couples directly to W, Z, γ (unambiguous xsec prediction)





LHC searches for $\Delta^\pm,\ \Delta^{\pm\pm}$ are on going!

- See nice talk by L. Barak

Room For Improvements

Searches for Δ are classic LHC exotica, but room for improvement exists[3]

Monte Carlo generation:

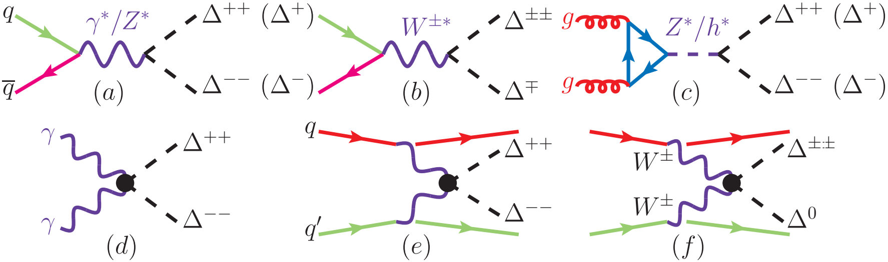
- Pythia 8.2 for Drell-Yan production of $pp \to \Delta^{++}\Delta^{--}$ but in context of Left-Right Symmetric Model
- CalcHEP for Drell-Yan production of $pp \to \Delta^{\pm\pm}\Delta^{\mp}$
- NLO K-factor / normalization with CTEQ6

Modeling Woes:

- VBS production $\Delta^{++}\Delta^{--}$ biased by LRSM Higgs sector (not same at Type II)
- CalcHEP event generation and CTEQ6 normalization do not describe associated soft hadronic and jet activity
- Uncertainty propagation and control over evt gen. limited, etc.

[3] Rizzo ('82); Huitu, et al ('96); Muhlleitner and Spira ('03); Akeroyd and Aoki ('05); Perez, Han, et al ('08); etc

`TypeIISeesaw@NLO`[4]



[4] with B. Fuks, O. Mattelaer, and M. Nemevšek [1912.abcde], feynrules.irmp.ucl.ac.be/wiki/TypeIISeesaw

TypeIISeesaw@NLO FeynRules Libraries

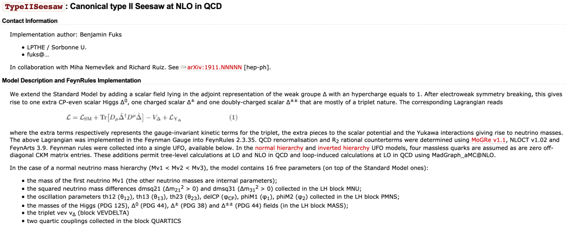
The lack of MC support for Type II Seesaw was an oversight

- HeavyN, MLFVtIIIseesaw, EffLRSM Universal FeynRules Object (UFO) libraries exist[5]
- UFOs work as plugins for mainstream MC event generators to simulate BSM at high energy experiments (not just colliders)

After a request by a certain hep-ex group, we wrote TypeIISeesaw@NLO

- Already available online and paper out in 1-2 weeks

```
> import model TypeII_NLO_UFO
> generate p p > d++ d-- [QCD]
> output TypeIInlo_DYX_DxxDxx_NLO
> launch
> order=NLO
> fixed_order=ON
> set mdpp scan1:range(100,2001,50)
> set dynamical_scale_choice -1
> set no_parton_cut
> set jetalgo    -1
> set jetradius 0.4
```



TypeIISeesaw : Canonical type II Seesaw at NLO in QCD

Contact Information

Implementation author: Benjamin Fuks

- LPTHE / Sorbonne U.
- fuks@...

In collaboration with Miha Nemevšek and Richard Ruiz. See arXiv:1911.NNNNN [hep-ph].

Model Description and FeynRules Implementation

We extend the Standard Model by adding a scalar field lying in the adjoint representation of the weak groupe Δ with an hypercharge equals to 1. After electroweak symmetry breaking, this gives rise to one extra CP-even scalar Higgs Δ^0, one charged scalar $\Delta^\pm$ and one doubly-charged scalar $\Delta^{\pm\pm}$ that are mostly of a triplet nature. The corresponding Lagrangian reads

$$\mathcal{L} = \mathcal{L}_{\rm SM} + {\rm Tr}\big[D_\mu \hat{\Delta}^\dagger D^\mu \hat{\Delta}\big] - V_\Delta + \mathcal{L}_{Y_\Delta} \qquad (1)$$

where the extra terms respectively represents the gauge-invariant kinetic terms for the triplet, the extra pieces to the scalar potential and the Yukawa interactions giving rise to neutrino masses. The above Lagrangian was implemented in the Feynman Gauge into FeynRules 2.3.35. QCD renormalisation and R_2 rational counterterms were determined using MoGRe v1.1, NLOCT v1.02 and FeynArts 3.9. Feynman rules were collected into a single UFO, available below. In the normal hierarchy and inverted hierarchy UFO models, four massless quarks are assumed as are zero off-diagonal CKM matrix entries. These additions permit tree-level calculations at LO and NLO in QCD and loop-induced calculations at LO in QCD using MadGraph_aMC@NLO.

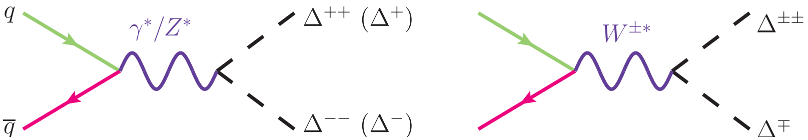
In the case of a normal neutrino mass hierarchy (Mv1 < Mv2 < Mv3), the model contains 16 free parameters (on top of the Standard Model ones):

- the mass of the first neutrino Mv1 (the other neutrino masses are internal parameters);
- the squared neutrino mass differences dmsq21 ($\Delta m_{21}^2 > 0$) and dmsq31 ($\Delta m_{31}^2 > 0$) collected in the LH block MNU;
- the oscillation parameters th12 (θ_{12}), th13 (θ_{13}), th23 (θ_{23}), delCP (φ_{CP}), phiM1 (φ_1), phiM2 (φ_2) collected in the LH block PMNS;
- the masses of the Higgs (PDG 125), Δ^0 (PDG 44), $\Delta^\pm$ (PDG 38) and $\Delta^{\pm\pm}$ (PDG 44) fields (in the LH block MASS);
- the triplet vev v_Δ (block VEVDELTA)
- two quartic couplings collected in the block QUARTICS

[5] See FeynRules database feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage

Some Results

Charged Current and Neutral Current Drell-Yan



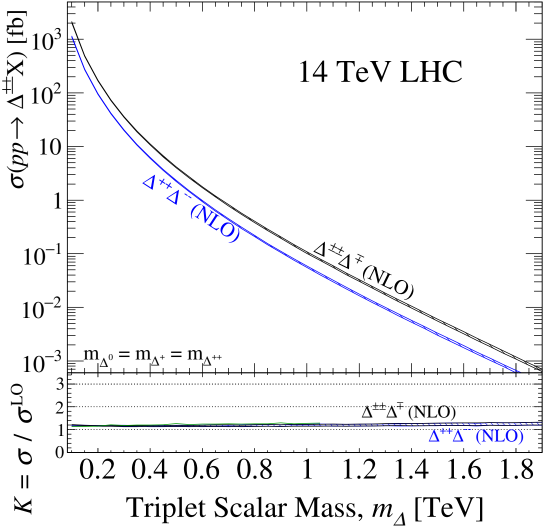
Charged Current and Neutral Current Drell-Yan

Drell-Yan production at NLO in QCD is sanity check[6]

- With one event generator, all the following can be computed: $pp \to \Delta^{++}\Delta^{--}$, $\Delta^{\pm\pm}\Delta^{\mp}$, $\Delta^{+}\Delta^{-}$, $\Delta^{\pm}\Delta^{0}$, $\Delta^{\pm}\chi^{0}$, $\Delta^{0}\chi^{0}$ (← *unexplored*)

- Other channels necessary to determine gauge quantum numbers and discriminate against Georgi-Machacek

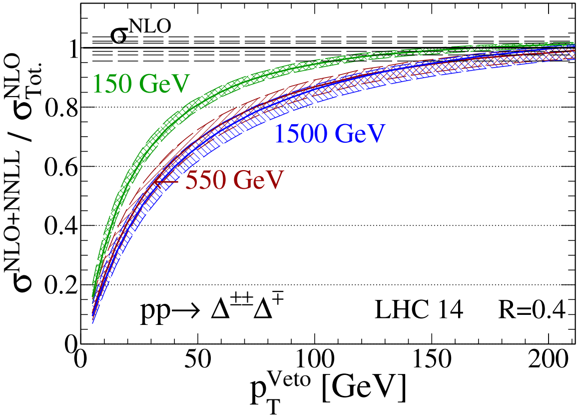
- At NLO, jet vetoes can be modeled / implemented (yay!)



[6] Only other group to compute this is Muhlleitner and Spira ('03)

Unfortunately, for high-mass BSM, jet vetoes $\implies$ poor signal efficiency :

Plotted:[7] jet veto efficiency $\varepsilon = \sigma^{\mathrm{NLO+NNLL}}(p_T^j < p_T^{\mathrm{Veto}}) \ / \ \sigma^{\mathrm{NLO}}_{\mathrm{Tot.}}$



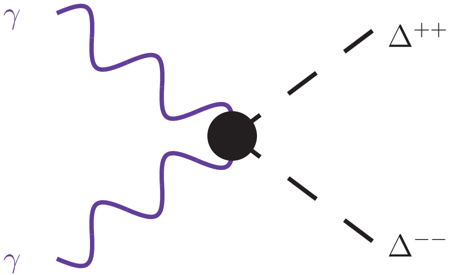
Signal veto efficiency is pretty terrible for $p_T^{\mathrm{Veto}} = 20 - 50$ GeV

- Clear that dynamic / safe jet veto schemes[8] are meritted

[7] Using MG5aMC@NLO+SCET. See Becher, et al [1412.8408]

[8] See with Pascoli and Weiland [1805.09335, 1812.08750], as well as with Fuks, Nordstrom, and Williamson [1901.09937]

Photon Fusion



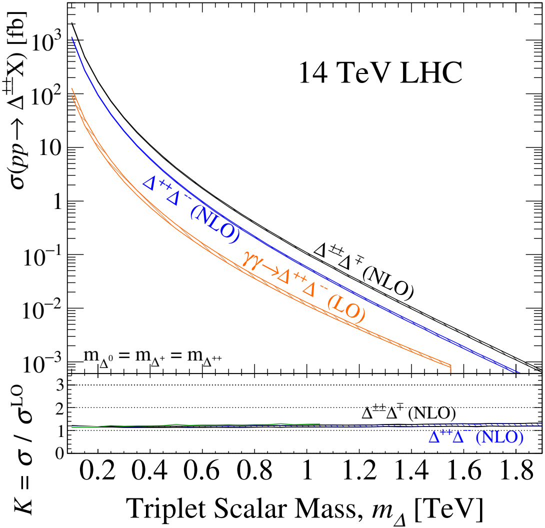
$\gamma\gamma \to \Delta^{++}\Delta^{--}$ is wickedly cool!

(see talk by M. Gallinaro on $\gamma\gamma$ scattering at the LHC)

- Modern γ PDFs match LUXqed (elastic PDF) and perturbative QCD (inelastic PDF) formalisms

- LO+Pythia8* can match γ to $q \to \gamma q$ splitting, i.e., match to forward jets

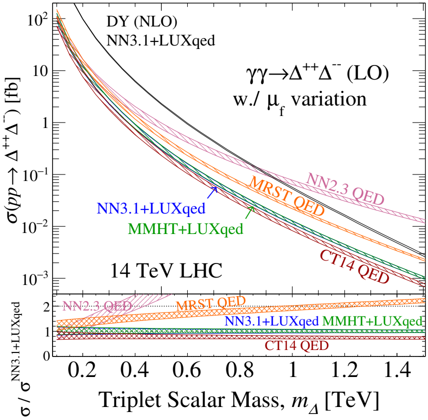
- How do different γ PDFs compare?

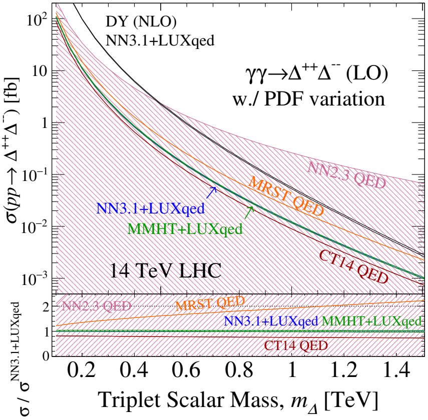


*For details, see home.thep.lu.se/ torbjorn/pythia81html/SpacelikeShowers.html

Historically, back-and-forth about importance of $\gamma\gamma \to \Delta^{++}\Delta^{--}$

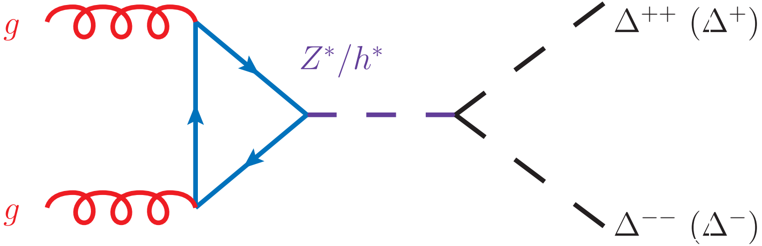
- How do different γ PDFs compare?





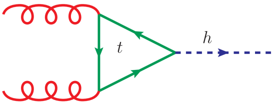
With LUXqed, discrepancies have disappeared (again)

Gluon Fusion

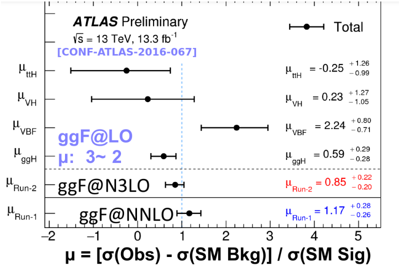


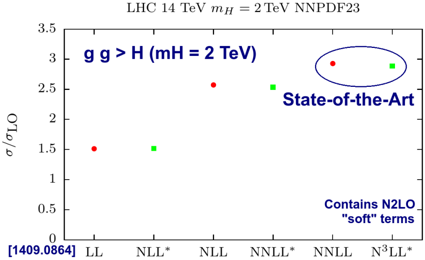
Threshold Resummation for Gluon Fusion

QCD corrections to $gg \to h_{\rm SM}$ are *large*



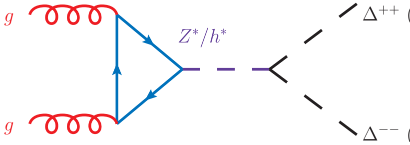
GF@LO is **excluded** by LHC data!





Corrections also *large* for heavy $H^0,\ A^0$

Resummation captures leading FO corrections Bonvini, et al, [1409.0864]



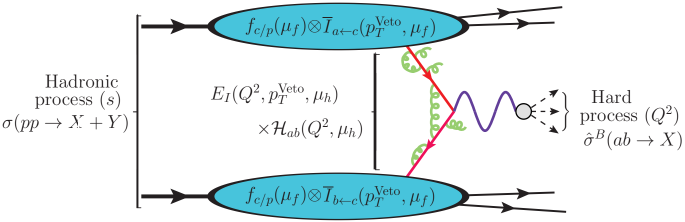
Use SM technology for Δ production!

Threshold Resummation in SCET

Each component of the Factorization Theorem obeys $\mathcal{D}X = \Gamma X$

Collecting like-terms shows scattering rates have the form[9]:

$$d\sigma(pp \to \mathcal{B} + X) = f(\mu_f) \times f(\mu_f) \times \Delta(\mu_s) \times \underbrace{U(\mu_f, \mu_s, \mu_h)}_{Messy,\ but\ universal} \times d\hat{\sigma}(\mu_h)$$



This expression is known as "RG-improved" factorization theorem (SCET)

- Sudakov-like factors act as "dressing" functions, in QFT sense

[9] Contopanagos, et al; Becher, Neubrt etc; Bauer, Stewart, Tackmann etc

Threshold resummation at (approximately) N^3LL captures leading normalization at N^2LO in QCD

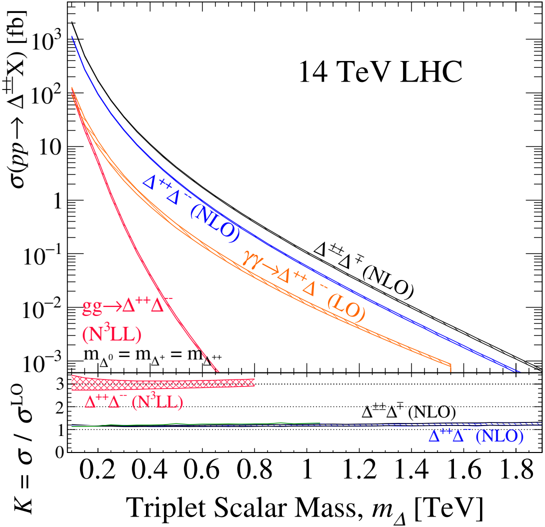
Loop-induced $gg \to \Delta\Delta$ is possible at LO with new UFO - N^3LL a bit more work

For lower masses, gg and $\gamma\gamma$ are competitive, but $\gamma\gamma$ becomes more relevant

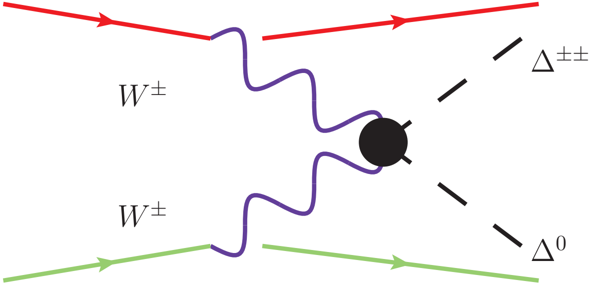
(again, cool)

Caveat: we assume all Δ masses degenerate

$\Longrightarrow$ scalar-scalar couplings are small (probably not justified)



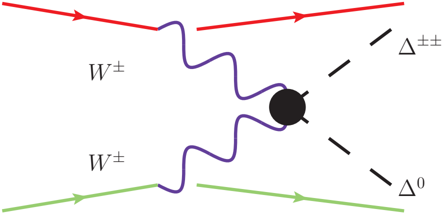
Weak Boson Fusion



$\Delta^{\pm\pm}$ from Vector Boson Scattering

Weak boson fusion is a useful production mechanism of $\Delta^{\pm\pm}$ (See R. Santo's talk)

- Except $W^\pm W^\pm \to \Delta^{\pm\pm}$ is vev/coupling-suppressed
- Except $VV \to \Delta^{++}\Delta^{--}$ is mass-suppressed



$W^\pm W^\pm \to \Delta^{\pm\pm}\Delta^0$ for $m_{\Delta^0} \ll m_{\Delta^{++}}$ keeps important features

- LNV/LFV dilepton signature with resonant invariant mass
- Difficulty is modeling beyond NLO in QCD (needed for jet veto modeling)

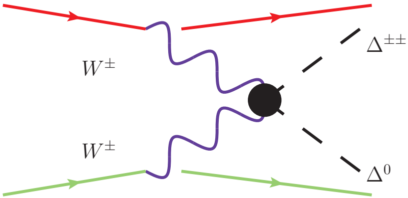
Vector Boson Scattering beyond LO

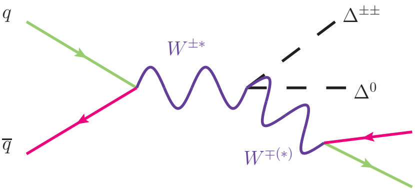
NLO+PS(LL) is necessary to describe leading QCD radiation in

$$q_1\overline{q_2} \rightarrow \Delta^{\pm\pm}\Delta^0 q_1'\overline{q_2'} \quad \text{at} \quad \mathcal{O}(\alpha^4)$$

Difficulties are **not** NLO corrections to VBF topology; difficulties are coping with MC inefficiency and interference (interference is numerically large)

- Numerical instabilities due to t- vs s-channel momentum flow
- New poles and resonances from EW gauge bosons
- Non-VBF/S topologies dominate event generation

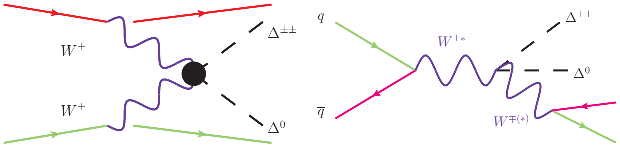




Vector Boson Scattering at LO

MC inefficiency controlled at LO using generator-level cuts

- Cuts: $m_{q_1 q_2} \gtrsim 200 - 500$ GeV, $|\Delta\eta(q_1, q_2)| \gtrsim 1 - 3$, etc
- New poles and resonances regulated and/or removed
- VBF/S topologies dominate event generation



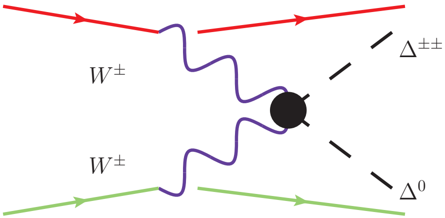
At NLO, one works with parton-clusters to retain infrared safety

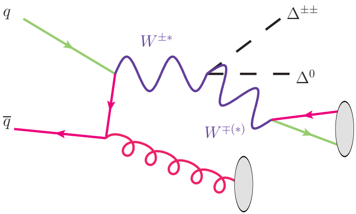
1. After phase space point generated in `mg5amc@nlo`, run all final-state QCD partons through k_T-algorithm
2. Soft/collinear, i.e., unresolved, QCD rad. are clustered with parent
3. Apply p_T^j, $|\eta^j|$ cuts to clusters, not partons

Pathologies at NLO

At NLO, one works with parton-clusters to retain infrared safety

- **Cut on leading clusters**: $m_{j_1 j_2} \gtrsim 200$ GeV, $|\Delta\eta(j_1, j_2)| \gtrsim 1$, etc
- **Pathologies** appear when $q\overline{q'}$ are clustered (leads to resonant V or worse)





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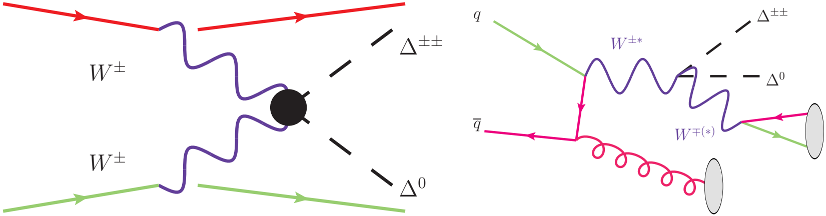


Idea: veto clustering of isospin partners

- Effectively a phase space cut on p_T of $W/Z/\gamma^*$ ($p_T^V \lesssim 2M_V/R$)
- Analogous of on-the-fly flavor-tagging jets
- **Turn off** hard-coded change of variables in `mg5amc@nlo`

$pp \to \Delta^{\pm\pm}\Delta^0 jj$ + VBS Cuts at NLO is under control!

$\sigma_{\rm DY}/\sigma_{\rm VBF} \sim 10^3$difference hides three things:

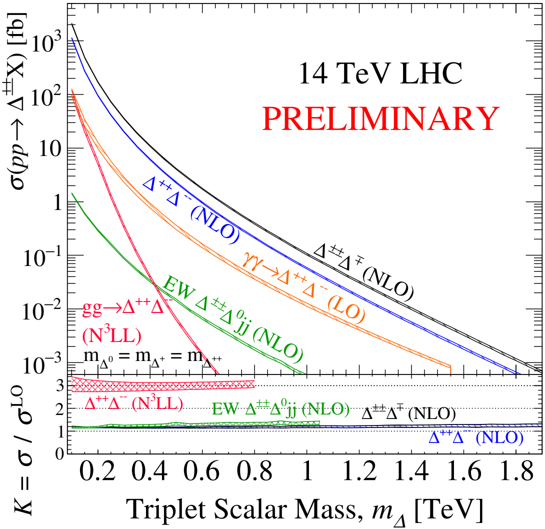
- VBF cuts already applied at generator-level

- Scalar-scalar couplings are small since mass degenerate

- Larger mass splittings $\implies$ higher mass reach

This is being investigated

(give me 1 week)



Summary

nonzero neutrino masses are clear evidence of physics beyond the SM

- Lack of guidance from $0\nu\beta\beta$, oscillation data, flavor factories, etc
  $\implies$ broad hep-ex/ph/th approaches are needed

1. Colliders are *incredibly complementary* to oscillation facilities:

   see review with Yi Cai, Tao Han, Tong Li for details! [1711.02180]

   - Direct production of Seesaw particles
   - Direct test of LNV/LFV and UV realizations of neutrino EFTs / NSIs

2. Type II Seesaw is an excellent and viable candidate to explain $m_\nu \neq 0$
   - No N as m_ν originate from new set of Higgs: $\Delta^0,\ \Delta^+,\ \Delta^{\pm\pm}, \chi^0$
   - LHC searches are ongoing but room for improvement exists

3. Report update for tools and modeling Type II Seesaw at colliders
   - `TypeIIScalars@NLO` UFO allows reliably modeling of jet vetoes
   - VBS channels probe unexplored $W^\pm W^\pm \to \Delta^{\pm\pm}\Delta^0$, etc.
   - Propose procedure for generator-level VBF cuts in `MG5_aMC@NLO`

Thank you.