$\Delta^{\pm\pm}$ (or $H^{\pm\pm}$) Production at Hadron Colliders

HPNP 2021 - Osaka University

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25 March 2021

[1] with B. Fuks and M. Nemevšek [1912.08975] + review with Y. Cai, T. Han, and T. Li [1711.02180]

what is this talk about?

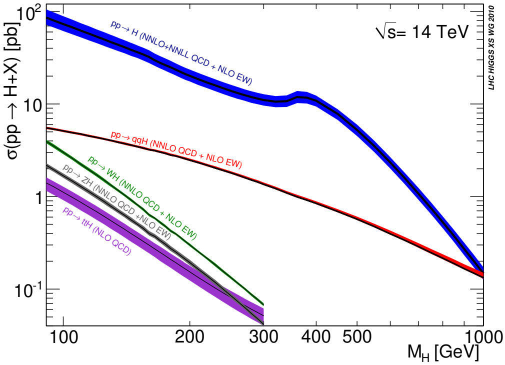
how to best make doubly charged Higgs bosons ($\Delta^{\pm\pm}$) at colliders

Cross section predictions not updated since publication of total NLO rates for the neutral current Drell-Yan process Muhlleitner & Spira [hep-ph/0305288]

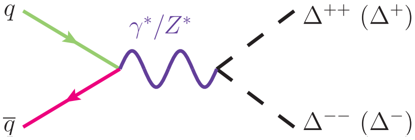
- K-factors for $m_\Delta < 1$ TeV at $\sqrt{s} = 14$ TeV with one PDF

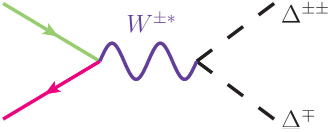
Missing from the lit.: differential information at NLO, clarity (again) on size of $\gamma\gamma$ fusion, and systematic comparison of production channels

- Where is the $\Delta^{\pm\pm}$ equivalent of this????



why? because $\Delta^{\pm\pm}$, $\Delta^{\pm}$ are important[2]





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

Example: Type II Seesaw Mechanism for Neutrino Masses

Hypothesize a **scalar** $\text{SU}(2)_L$ 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 $\mu_{h\Delta}$ breaks lepton number, and induces $\langle\hat{\Delta}\rangle \neq 0$:

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

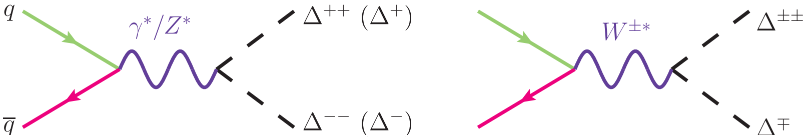
which leads to **left-handed Majorana masses** for neutrinos

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

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

Generates light ν_m masses via vev **WITHOUT** invoking sterile N_k!

$\Delta^{\pm\pm}$, $\Delta^{\pm}$ couple directly to W, Z, γ (unambiguous xsec prediction)



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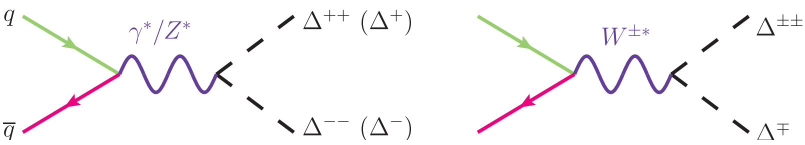
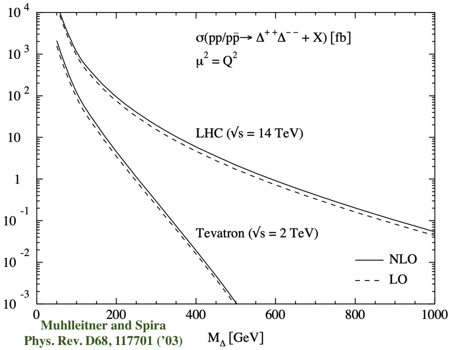


"State of the Art" Event Generation

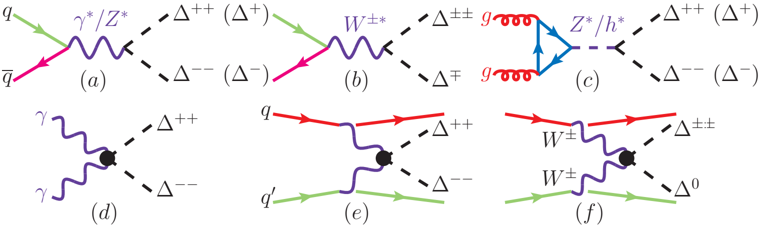
- Hard coded pair production of $\Delta^{\pm\pm}\Delta^{\mp(\mp)}$ in `Pythia8` and `CalcHEP` (no longer actively supported)

- Event generation at LO+PS (no MLM matching, etc)

- Normalized to NLO with CTEQ6 $\rightarrow$ (sizable PDF uncertainties)



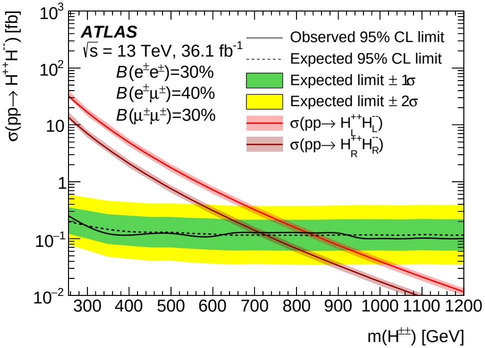
Limitations of "State of the Art"



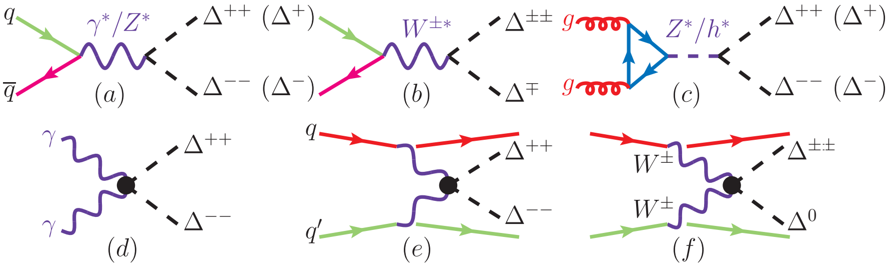
- Fixed production channels do not reflect full parameter spaces

- Fixed decay modes do not utilize potential of full LHC datasets

- does not facilitate newer analysis techniques e.g., jet vetoes or fast recasting tool chains



TypeIISeesaw@NLO[3]



3 with B. Fuks, O. Mattelaer, and M. Nemevšek [1912.08975], feynrules.irmp.ucl.ac.be/wiki/TypeIISeesaw

The lack of Monte Carlo support for $\Delta^{\pm\pm}, \Delta^{\pm}$ was an oversight

- Universal FeynRules Object (UFO) libs exist for many other models

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

- UFOs encode Feynman rules for mainstream event generators, e.g. MadGraph, to simulate BSM in HEP experiments (not just colliders)

After a request by hep-ex'ers, we wrote TypeIISeesaw@NLO UFO libraries

available at feynrules.irmp.ucl.ac.be/wiki/TypeIISeesaw

```
> 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 electrowe
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 Lagra

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

where the extra terms respectively represents the gauge-invariant kinetic terms for the triplet, the extra pieces to the scalar potential and the Yukawa interactio
The above Lagrangian was implemented in the Feynman Gauge into FeynRules 2.3.35. QCD renormalisation and R_2 rational counterterms were determined using
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
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_a

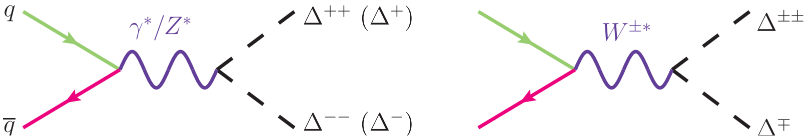
In the case of a normal neutrino mass hierarchy (Mv1 < Mv2 < Mv3), the model contains 16 free parameters (on top of the Standard Model ones):

- 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

some newish results[4]

[4] with B. Fuks and M. Nemevšek [1912.08975]

Neutral Current and Charged Current Drell-Yan



Charged Current and Neutral Current Drell-Yan

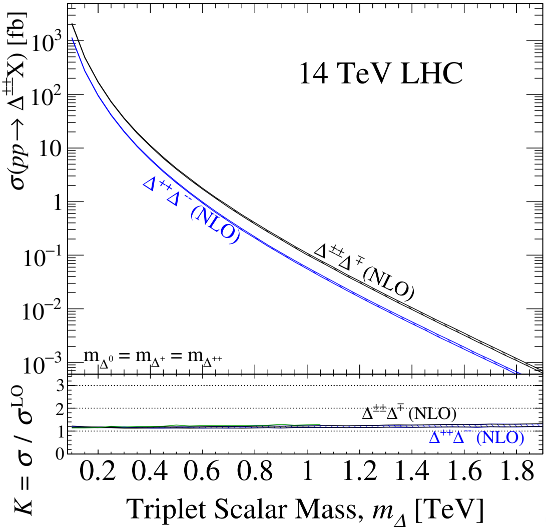
Drell-Yan production at NLO(+PS) in QCD is sanity check

- 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*)

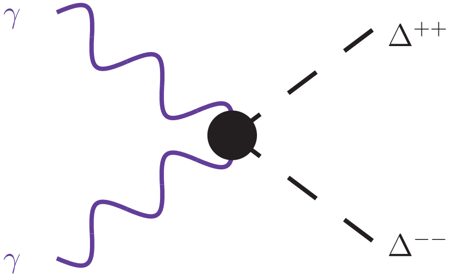
- These other channels needed to check quantum numbers and discriminate against Georgi-Machacek, etc.

- At NLO, jet vetoes can be implemented (yay!) (see backup)

only other group to compute this is Muhlleitner and Spira ('03)



photon fusion

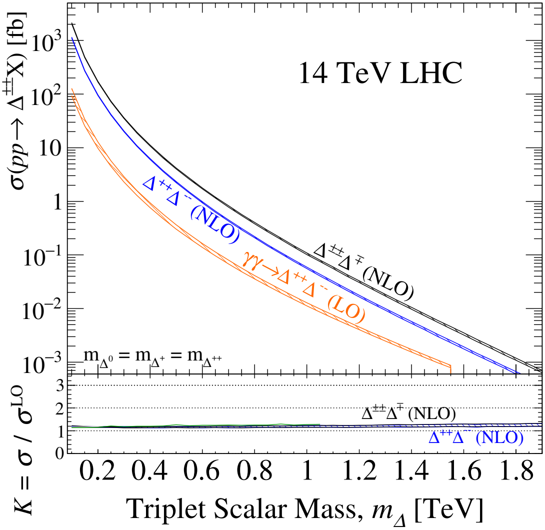


$\gamma\gamma \to \Delta^{++}\Delta^{--}$ is wickedly cool!

- **Subleading** but ultra peripheral collisions have *tiny* backgrounds

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

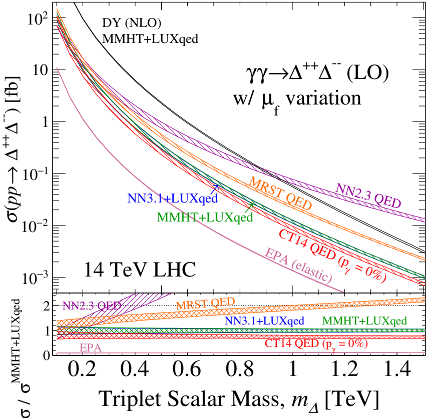
- Many modern γ PDFs on the market these days. How do different γ PDFs compare?

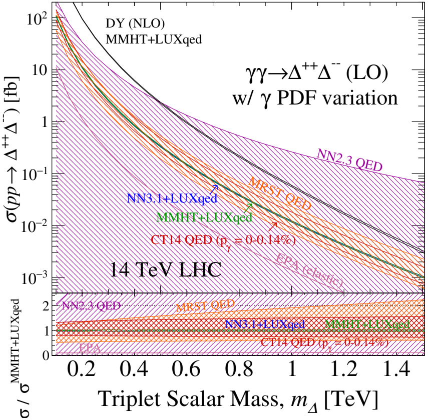


*For details, see home.thep.lu.se/ torbjorn/pythia81html/SpacelikeShowers.html

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

- How do different γ PDFs compare?



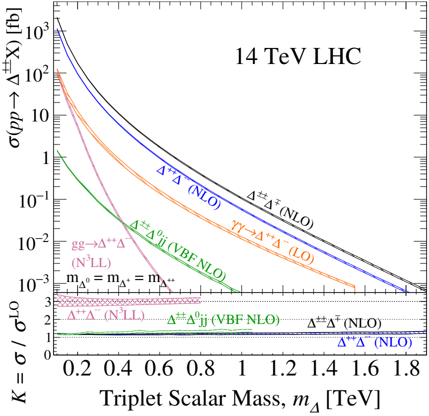


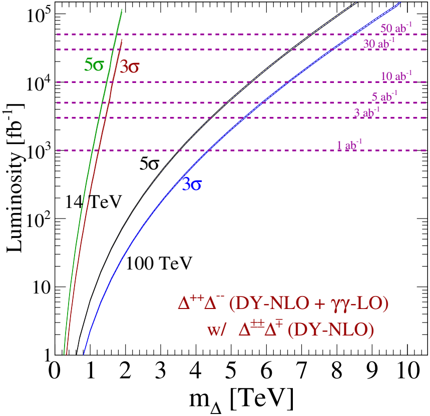
Most PDFs agree and discrepancies have disappeared (again)

- **Warning**: NNPDF 2.3 QED (default in MG5aMC) has poor description of γ PDF; well-known and due to limited statistics (not method)

outlook (see backup for more channels!)

NEW: a revised outlook for both $\sqrt{s} = 14$ TeV and 100 TeV!





- At LHC with $\mathcal{L} = 5$ ab^{-1}, 3σ sensitivity up to $m_\Delta \sim 1.5$ TeV
- At $\sqrt{s} = 100$ TeV with $\mathcal{L} = 30 - 50$ ab^{-1} $\implies$ $m_\Delta \approx 8 - 9$ TeV
- **Warning**: can be improve for specialized final state / parameter space

Lots not covered!

Theory uncertainties (see the paper! [1912.08975])

- Uncertainties at LO, NLO, NLO+NNLL(veto), NNNLL(threshold)
- PDF uncertainties (statistical PDF and modeling)
- 4FS vs 5FS scheme, with selection cuts

Monte Carlo recommendations (see the paper! [1912.08975])

- choices of scales, generator cuts, PDFs, etc. (care always needed)
- explit `MG5aMC@NLO` instructions and lots tables for checks

Sensitivity beyond *pp* colliders (reader exercise)

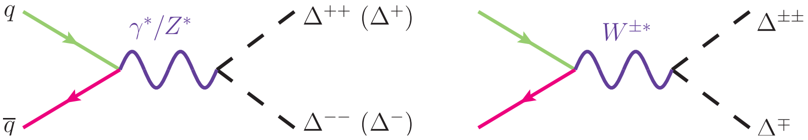
- `TypeIISeesaw` UFO + `MG5aMC@NLO` enables beam dump, DIS/ion, electron/muon colliders, astroparticle studies
- Useful since Δ^0 (CP even) and ξ^0 (CP odd) are under-studied, long-lived particles and stable, dark matter candidates

Designed to be user friendly but bother us with Q's or collaboration ideas!

Thank you.

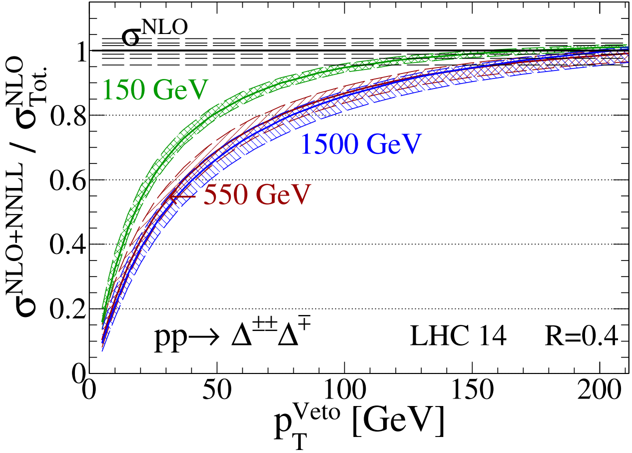
Backup

Jet Vetoes in Neutral Current and Charged Current Drell-Yan



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

using MG5aMC@NLO+SCET. See Becher, et al [1412.8408] for details!

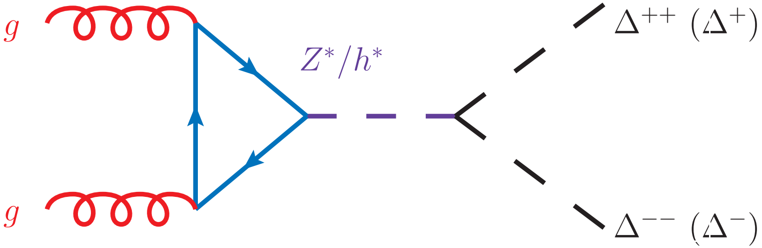


Signal veto efficiency is pretty terrible for $p_T^{\text{Veto}} = 20 - 50$ GeV

- Clear that dynamic / safe jet veto schemes are meritted

see, e.g., Pascoli, RR, et al [1805.09335, 1812.08750], as well as Fuks, Nordstrom, RR, and Williamson [1901.09937]

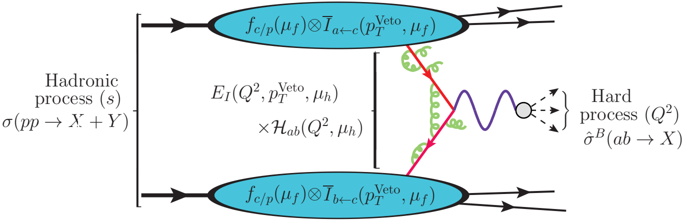
Gluon Fusion



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[5]:

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



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

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

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

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

for N^3LL details, see RR, Spannowsky, Waite [1706.02298]

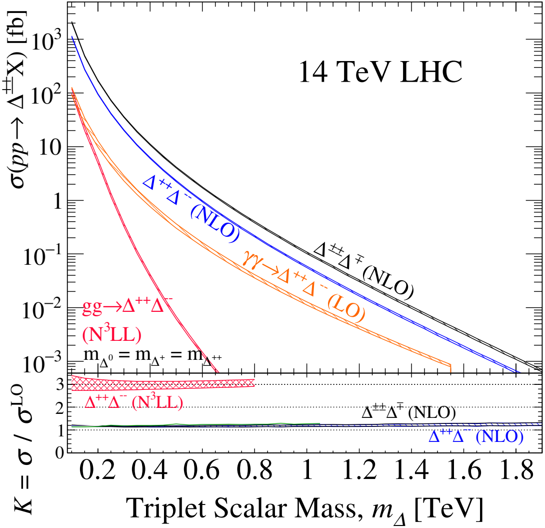
Loop-induced $gg \to \Delta\Delta$ is possible at LO with new UFO - N^3LL a bit more work

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

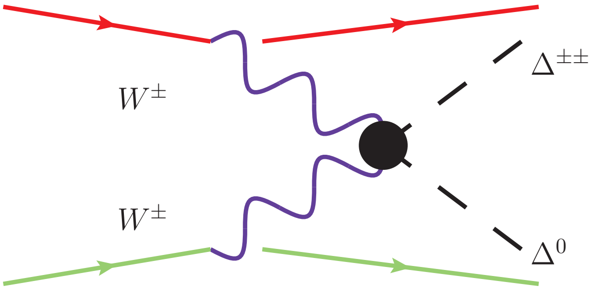
(again, cool)

Caveat: we assume all Δ masses degenerate

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



Weak Boson Fusion[6]



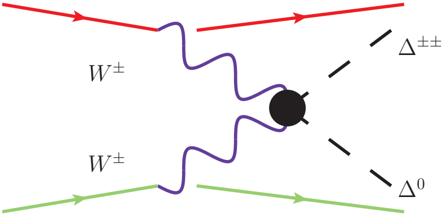
[6]many details being omitted!

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

Weak boson fusion is a useful production mechanism of $\Delta^{\pm\pm}$

- 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)

$pp \to \Delta^{\pm\pm}\Delta^{0}jj$ + 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