Polarized Parton Scattering in MG5_aMC@NLO

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[1] w/ Diogo Buarque Franzosi, Olivier Mattelaer, and Sujay Shil [191X.YYYYY]

Outline

Something New: Polarized, external parton scattering has been implemented in the event generation package `MadGraph5_aMC@NLO`

- Who? What? Why? How? When?

Something Cool: Case Study: $pp \to WZ$ production at the LHC

- Radiation Amplitude Zeros, Helicity Suppression, and Large QCD Corrections

Something Disclaimer: lots of references here omitted for space :(

(please complain if reference is missing in the paper!)

MadGraph5_aMC@NLO (mg5amc) in a Nutshell

In a Nutshell

MG5aMC is the 5th (or 6th) iteration of the Monte Carlo (MC) event generator `MadisonGraph` (or `MadGraph`) by Stelzer and Long at Wisconsin [hep-ph/9401258]

- For a given scattering process, generates Feynman Graphs and helicity amplitudes (`HELAS` routines) for *fast* numerical determination of rates

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- Merger with `MC@NLO` for NLO in QCD [1405.0301] and NLO in EW [1804.10017]

Then and Now (Publicity Plots)

(L) Early practioners of MadGraph

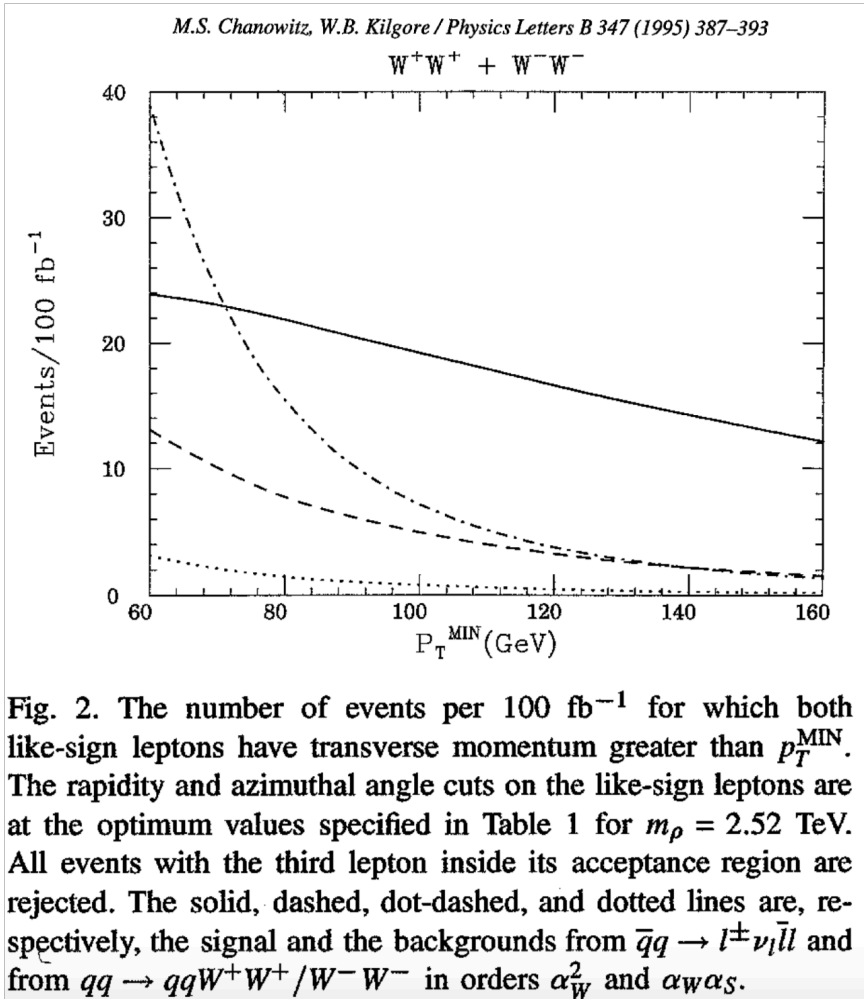
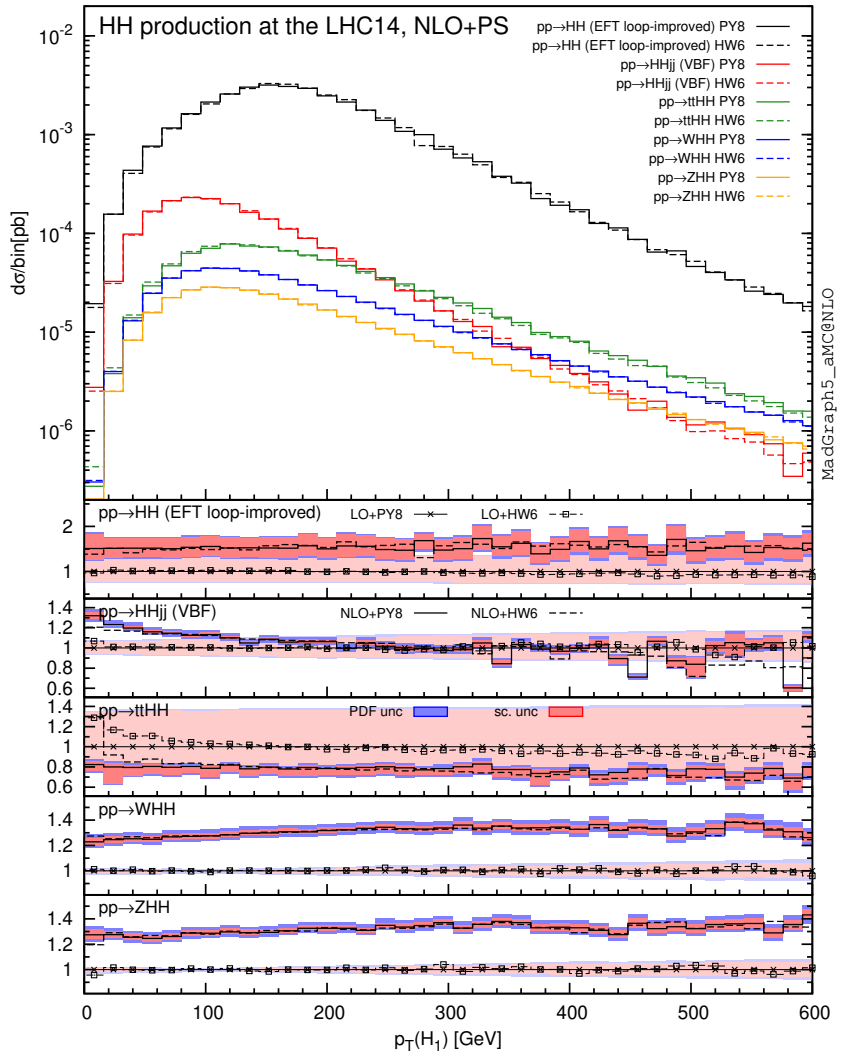


Fig. 2. The number of events per 100 fb^{-1} for which both like-sign leptons have transverse momentum greater than $p_T^{\rm MIN}$. The rapidity and azimuthal angle cuts on the like-sign leptons are at the optimum values specified in Table 1 for $m_\rho = 2.52$ TeV. All events with the third lepton inside its acceptance region are rejected. The solid, dashed, dot-dashed, and dotted lines are, respectively, the signal and the backgrounds from $\bar{q}q \to l^\pm \nu_l \bar{l} l$ and from $qq \to qqW^+W^+/W^-W^-$ in orders α_W^2 and $\alpha_W \alpha_S$.

(R) MadGraph5_aMC@NLO today



Frederix, et al [1401.7340]

What is new?

What is new?

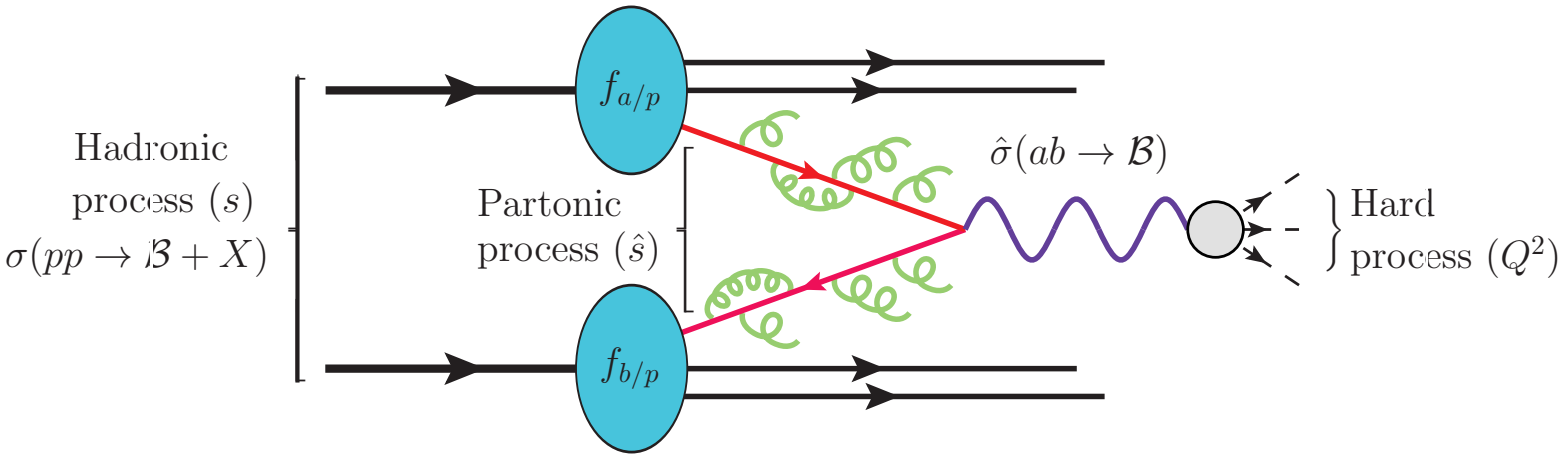
Polarized External Parton Scattering

To get pp scattering rates, mg5amc uses the Collinear Factorization Thm

Collins, Soper, Sterman ('85,'88,'89); Collins, Foundations of pQCD (2011)

$$d\sigma(pp \to W\gamma + X) = \sum_{i,j} f_i \otimes f_j \otimes \Delta_{ij} \otimes d\hat{\sigma}(ij \to W\gamma) + \mathcal{O}\left(\Lambda^p_{\rm NP}/Q^{p+2}\right)$$

hadron-level scattering probabilities are the product (convolution) of parton-dist. (PDFs), -emission (Sudakov), and -scattering probs. ($|\mathcal{M}|^2$)



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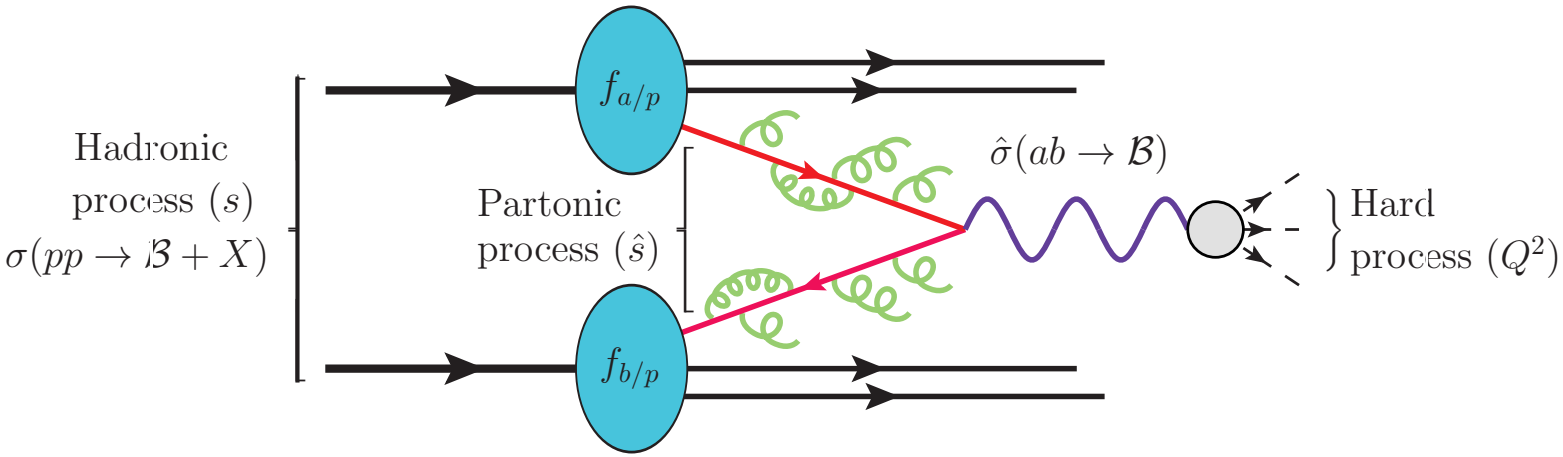

The partonic scattering rate is given by the usual (textbook) expression:

$$d\hat{\sigma}(ij \to W\gamma) = \underbrace{\frac{1}{2Q^2}}_{\text{hard scale}} \underbrace{\overline{|\mathcal{M}(ij \to W\gamma)|^2}}_{\text{dof avg./summed.}}$$

The *unpolarized* external parton scattering rate is given by the dof-averaged[2] (initial states) and dof-summed (final state) matrix element:

$$\overline{|\mathcal{M}(ij \to W\gamma)|^2} = \underbrace{\frac{1}{\mathcal{S}_i \mathcal{S}_j}}_{\text{spin dof}} \underbrace{\frac{1}{N_c^i N_c^j}}_{\text{color dof}} \sum_{\text{dof}} |\underbrace{\mathcal{M}(i_\lambda j_{\lambda'} \to W_{\tilde{\lambda}} \gamma_{\tilde{\lambda}'})}_{\text{ME in helicity basis}}|^2$$

[2] Degrees of freedom = all discrete quantum numbers, e.g., color, spin, electric charge

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For *polarized* scattering, truncate the spin averaging/summing

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The two are related by reintroducing spin averaging/summing

$$\overline{|\mathcal{M}(ij \to W\gamma)|^2} = \underbrace{\frac{1}{\mathcal{S}_i \mathcal{S}_j}}_{\text{spin dof}} \sum_{\lambda,\lambda',\tilde{\lambda}\tilde{\lambda}'} \overline{|\mathcal{M}(i_\lambda j_{\lambda'} \to W_{\tilde{\lambda}} \gamma_{\tilde{\lambda}'})|^2}$$

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Polarized External Parton Scattering (3/3)

Polarized parton scattering in LHC collisions is given by

$$d\sigma(pp \to W_{\tilde{\lambda}}\gamma_{\tilde{\lambda}'} + X)|_{i_\lambda, j_{\lambda'}} = f_{i_\lambda} \otimes f_{i_{\lambda'}} \otimes \Delta_{i_\lambda j_{\lambda'}} \otimes d\hat{\sigma}(i_\lambda j_{\lambda'} \to W_\lambda \gamma_{\tilde{\lambda}'})$$

- f_{i_λ} is the PDF for parton i with helicity λ in *unpolarized proton* p
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Again, unpolarized scattering is recovered by spin averaging/summing

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Hence, for unpolarized initial states and polarized final states:

$$d\sigma(pp \to W_{\tilde{\lambda}}\gamma_{\tilde{\lambda}'} + X) = \sum_{i_\lambda, j_{\lambda'}} \underbrace{\frac{1}{\mathcal{S}_i \mathcal{S}_j}}_{\text{spin dof}} \sum_{\lambda,\lambda'} d\sigma(pp \to W_{\tilde{\lambda}}\gamma_{\tilde{\lambda}'} + X)|_{i_\lambda, j_{\lambda'}}$$

WHY?!?!?!?!?!?!?!

Motivation for Polarized Parton Scattering in MG5aMC

Practical Considerations:

- Request by multiboson and VBF/VBS groups in ATLAS and CMS
- Polarization is excellent test of $V \pm A$ (chiral) structure in (B)SM
- Polarization is excellent test of gauge+unitarity structure in (B)SM

Future Proofing:

- W_0/Z_0 and W_T/Z_T PDFs (needed at $\sqrt{s} \gtrsim 50$ TeV) couple differently to bosons and massles fermions

  Note that rationale studies for $\sqrt{s} = 27 - 100$ TeV are being done today!

- (N)NLO QCD + NLO EW PDFs will eventually be needed to match precision of (N)NLO QCD + NLO EW predictions

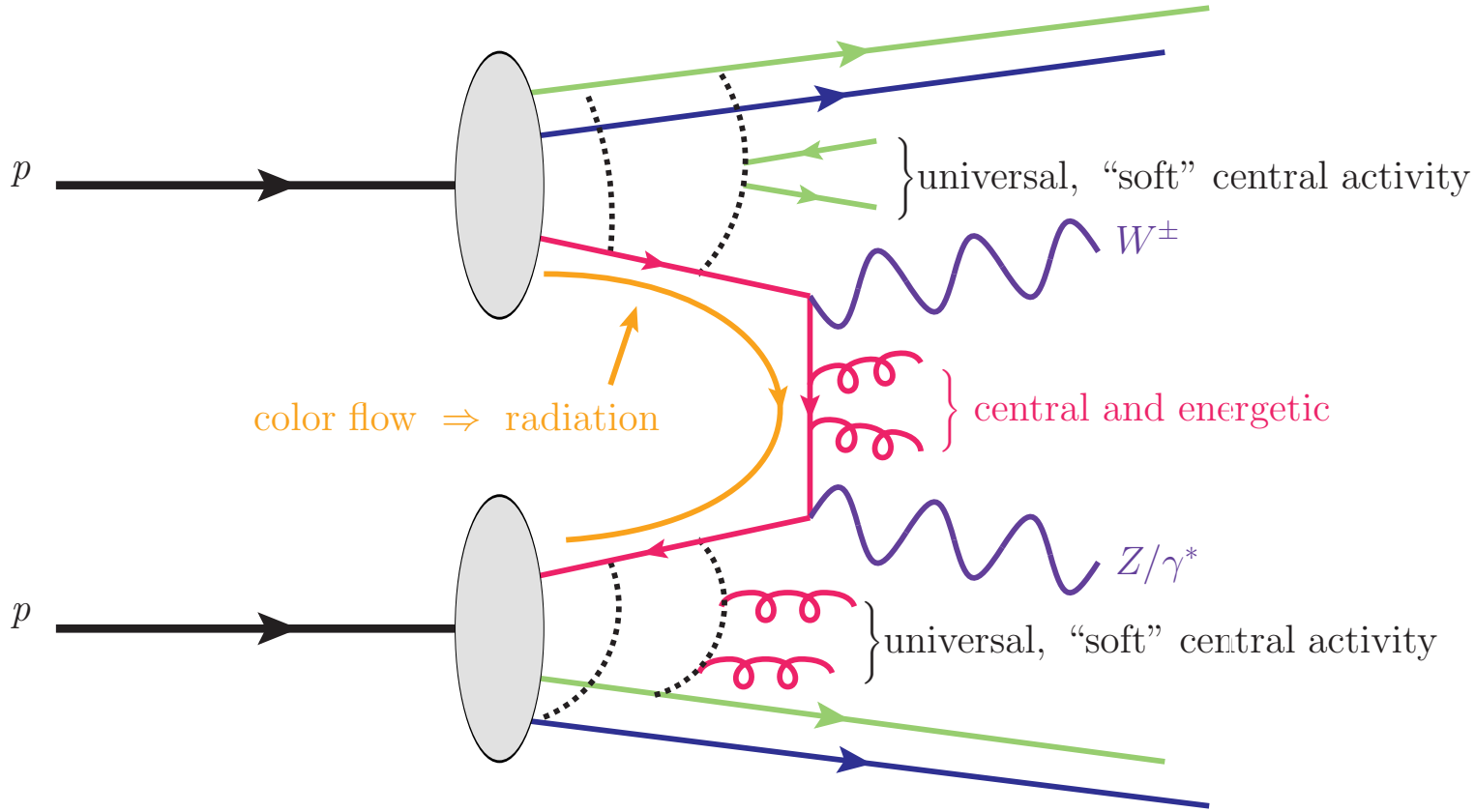
  DGLAP evolution for LH/RH quarks is asymmetric $\Longrightarrow$ polarized PDFs

Important: While formally clear, technical implementation is *difficult* due to relaxing of Lorentz invariance / reference frame independence

Case Study: Polarized WZ Production

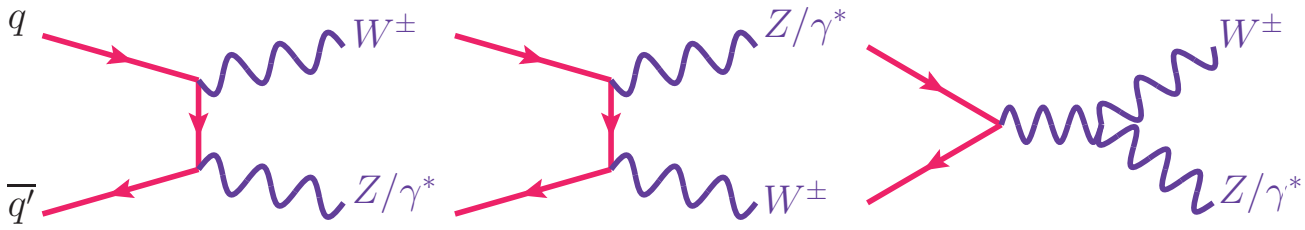
Di- / triboson processes contain *huge amounts* of hadronic activity

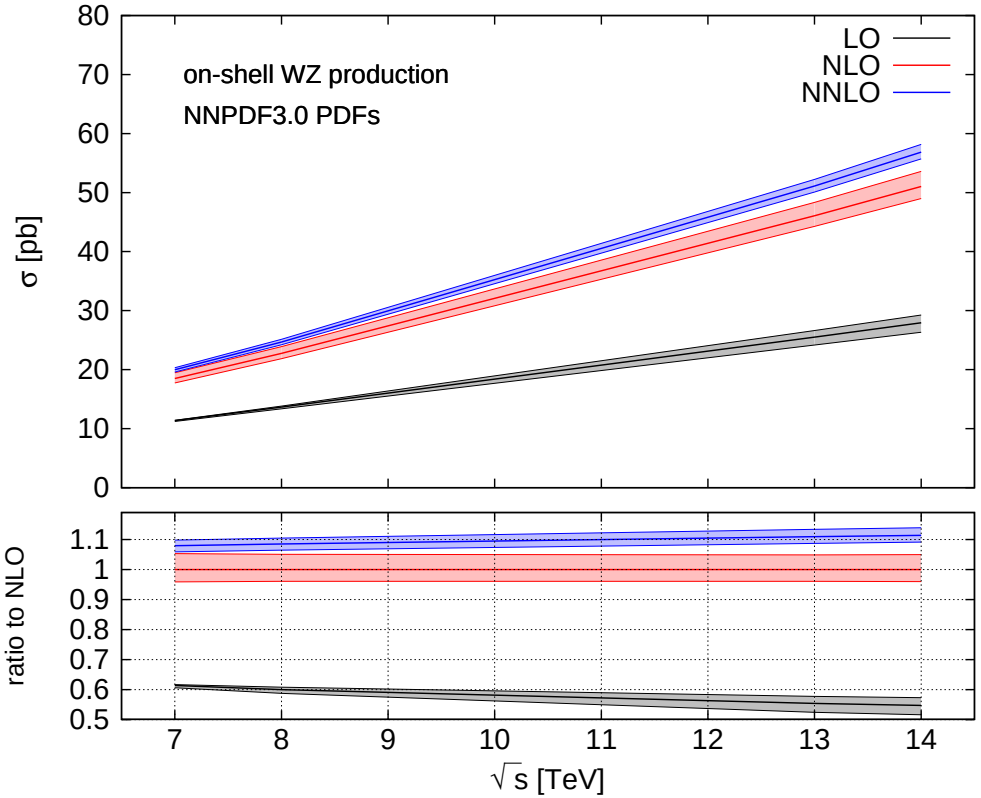
- Significant s- and t-channel cancelations for Born-like configurations[3]
- Nontrivial color flow, despite naïve, color-singlet nature



[3] i.e., Radiation zeros (super interesting!) Mikaelian ('78); +Brown, et al ('78-'79); Zhu ('80); Brodsky, et al ('82,'83); Baur, Han, Ohnemus [PRL ('94), hep-ph/9403248]

Radiation amplitude zeros follow from strong destructive interference between (electric) dipoles in special configurations of, e.g., $u\bar{d} \to W^+$





Gauge cancellation broken in $qg \to VV'q \implies$ inclusive VV' production mostly qg scattering

Breaking manifests as large K-factor in $pp \to W^\pm Z$ at NNLO [1604.08576]

$q\bar{q} \to W\gamma/WZ$ dominated by $(\lambda_W, \lambda_V) = (T, T)$ and $(0, 0)$
$(0, T)$ is helicity suppressed

Except $(T, 0)$ is **not** suppressed in $qg \implies$ expect larger jump at NLO

Calculating Polarized WZ Production with `mg5amc`

Generating polarized events at LO or NLO in QCD with mg5amc is as difficult as unpolarized computations now

```
MG5_aMC>
MG5_aMC>define ww = w+ w-
Defined multiparticle ww = w+ w-
MG5_aMC>generate p p > ww{0} z{T}
INFO: Checking for minimal orders which gives processes.
INFO: Please specify coupling orders to bypass this step.
INFO: Trying coupling order WEIGHTED<=4: WEIGTHED IS 2*QED+QCD
INFO: Trying process: u d~ > w+ z WEIGHTED<=4 @1
INFO: Process has 3 diagrams
INFO: Trying process: u s~ > w+ z WEIGHTED<=4 @1
INFO: Trying process: c d~ > w+ z WEIGHTED<=4 @1
INFO: Trying process: c s~ > w+ z WEIGHTED<=4 @1
INFO: Process has 3 diagrams
INFO: Trying process: d u~ > w- z WEIGHTED<=4 @1
INFO: Process has 3 diagrams
INFO: Trying process: d c~ > w- z WEIGHTED<=4 @1
INFO: Trying process: s u~ > w- z WEIGHTED<=4 @1
INFO: Trying process: s c~ > w- z WEIGHTED<=4 @1
INFO: Process has 3 diagrams
INFO: Process u~ d > w- z added to mirror process d u~ > w- z
INFO: Process c~ s > w- z added to mirror process s c~ > w- z
INFO: Process d~ u > w+ z added to mirror process u d~ > w+ z
INFO: Process s~ c > w+ z added to mirror process c s~ > w+ z
4 processes with 12 diagrams generated in 0.070 s
Total: 4 processes with 12 diagrams
MG5_aMC>generate p p > ww{0} z{T} [QCD]
INFO: Generating FKS-subtracted matrix elements for born process: u d~ > w+ z [ all = QCD ] (1 / 8)
INFO: Generating FKS-subtracted matrix elements for born process: c s~ > w+ z [ all = QCD ] (2 / 8)
```

- `z{T}` denotes LH and RH transverse Z bosons
- `ww{0}` denotes longitudinal $W^{\pm}$ bosons
- Just be careful to know in which frame the polarizations are defined

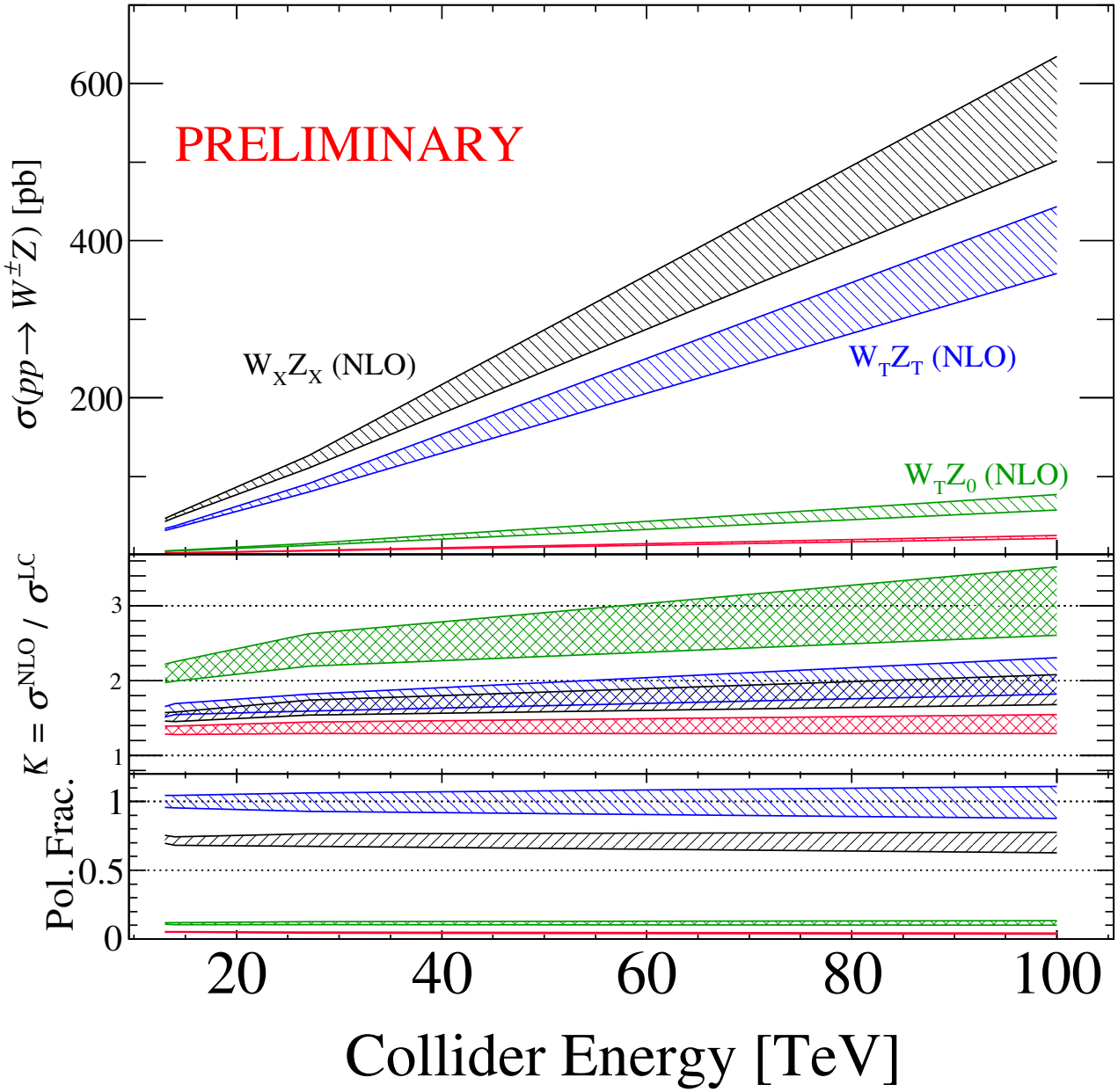
Polarized WZ Production in MG5aMC

$\sqrt{s}$	13 TeV			14 TeV			100 TeV		
Process	$\sigma^{\rm NLO}$ [pb]	K	$f^{\rm NLO}_{\lambda,\lambda'}$ $(f^{\rm LO}_{\lambda,\lambda'})$	$\sigma^{\rm NLO}$ [pb]	K	$f^{\rm NLO}_{\lambda,\lambda'}$ $(f^{\rm LO}_{\lambda,\lambda'})$	$\sigma^{\rm NLO}$ [pb]	K	$f^{\rm NLO}_{\lambda,\lambda'}$ $(f^{\rm LO}_{\lambda,\lambda'})$
	K = NLO / LO		Region I: Inclusive $pp \to W^\pm_\lambda Z_{\lambda'}$						
WZ	$44.7^{+4\%}_{-4\%}$	1.59	...	$50.2^{+5\%}_{-5\%}$	1.62	...	$571^{+11\%}_{-12\%}$	2.08	...
W_TZ_T	$32.4^{+4\%}_{-4\%}$	1.51	73% (76%)	$35.8^{+4\%}_{-4\%}$	1.52	71% (76%)	$404^{+10\%}_{-11\%}$	1.90	71% (77%)
W_0Z_T	$5.43^{+6\%}_{-6\%}$	2.05	12% (9%)	$6.05^{+6\%}_{-6\%}$	2.07	12% (9%)	$72.0^{+15\%}_{-15\%}$	3.00	13% (9%)
W_TZ_0	$5.06^{+6\%}_{-6\%}$	2.10	11% (9%)	$5.63^{+6\%}_{-6\%}$	2.12	11% (9%)	$67.1^{+15\%}_{-15\%}$	3.06	12% (8%)
W_0Z_0	$2.31^{+4\%}_{-4\%}$	1.34	5% (6%)	$2.52^{+4\%}_{-4\%}$	1.34	5% (6%)	$23.3^{+7\%}_{-10\%}$	1.44	4% (6%)
	Region II: $p_T(W^\pm)$, $p_T(Z) > 200$ GeV								
WZ	$0.531^{+6\%}_{-5\%}$	1.55	...	$0.617^{+6\%}_{-5\%}$	1.60	...	$16.3^{+7\%}_{-7\%}$	2.82	...
W_TZ_T	$0.409^{+8\%}_{-6\%}$	1.72	77% (70%)	$0.475^{+7\%}_{-6\%}$	1.76	77% (70%)	$13.3^{+8\%}_{-8\%}$	3.12	82% (74%)
W_0Z_T	$25.6 \times 10^{-3}\ ^{+8\%}_{-6\%}$	1.71	5% (4%)	$29.5 \times 10^{-3}\ ^{+8\%}_{-6\%}$	1.75	5% (4%)	$0.882^{+8\%}_{-8\%}$	4.25	5% (4%)
W_TZ_0	$25.3 \times 10^{-3}\ ^{+8\%}_{-7\%}$	1.84	5% (4%)	$29.8 \times 10^{-3}\ ^{+9\%}_{-7\%}$	1.92	5% (4%)	$0.902^{+9\%}_{-8\%}$	4.69	6% (3%)
W_0Z_0	$74.6 \times 10^{-3}\ ^{+0.5\%}_{-<0.5\%}$	1.01	14% (22%)	$83.4 \times 10^{-3}\ ^{+<0.5\%}_{-<0.5\%}$	1.00	14% (22%)	$1.07^{+1.5\%}_{-1.8\%}$	1.00	7% (19%)

TABLE II: Upper: Total cross section [pb] at NLO for inclusive, unpolarzation $pp \to W^\pm Z$ production, with scale variation [%], and NLO in QCD K-factor, as well as the same for individual $W_\lambda, Z_{\lambda'}$ polarizations along with their fractional contribution $f^{\rm NLO\ (LO)}_{\lambda,\lambda'}$ [%] at NLO (LO). Lower: Same as upper but with $p_T(W)$, $p_T(Z) > 200$ GeV phase space cuts applied.

- For inclusive rate, big jump in $(\lambda_W, \lambda_Z) = (0, T),\ (T, 0)$, with $K = \sigma^{\rm NLO}/\sigma^{\rm LO} \gtrsim 2 - 3$ (fractions mostly the same)
- For $p_T(W), p_T(Z) > 200$ GeV, nontrivial shift in polarization fractions between NLO and LO

Polarized WZ Production in MG5aMC (In Pictures)



Summary

We report the implementation of polarized external parton scattering in the MC event generator `MadGraph5_MC@NLO` [191?.?????]

- Formalism **ready** for multiboson, VBF/VBS, etc, tests of (B)SM, and in place for future studies (and future colliders!)
- Case study in WZ at NLO in QCD shows little (significant) change for inclusive (fiducial) polarization fractions
  - Evidence of "Giant K-Factors" from breaking helicity cancellation (not just, gauge cancellation or new kinematic channels)
- Lots not shown: polarization propagation via `MadSpin`, polarization at NLO+PS, polarization in different reference frames, VBF/S

Stay Tuned! The paper will be out very soon!

Thank you.