THEORY UNCERTAINTIES and SIMULATIONS REPORT

HXSWG OFFSHELL INTERPRETATIONS 4th JOINT MEETING

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23 September 2020

Outline

- NNLO QCD + NLO EW corrections to *VV* production
- Reweighting techniques for signal processes
- Jet merging in $gg \rightarrow ZZ$
- Other work and recent progress
- Discussion: way forward

NNLO QCD + NLO EW

- Talk by Jonas Lindert at meeting in July, based on [Grazzini, Kallweit, Lindert, Pozzorini, Wiesemann, hep-ph/1912.00068]
- EW corrections particularly important in high-energy regime:
  - Soft/collinear logs from virtual EW bosons;
  - Soft/collinear logs from QED radiation;
  - Initial state photons.
- Mixed QCD-EW corrections extremely challenging → approximate using NNLO QCD + NLO EW.
- NNLO QCD + NLO EW in MATRIX+OpenLoops (parton-level) program [beta version on request]

NNLO QCD + NLO EW

- Additive and multiplicative procedures of combining QCD and EW corrections:

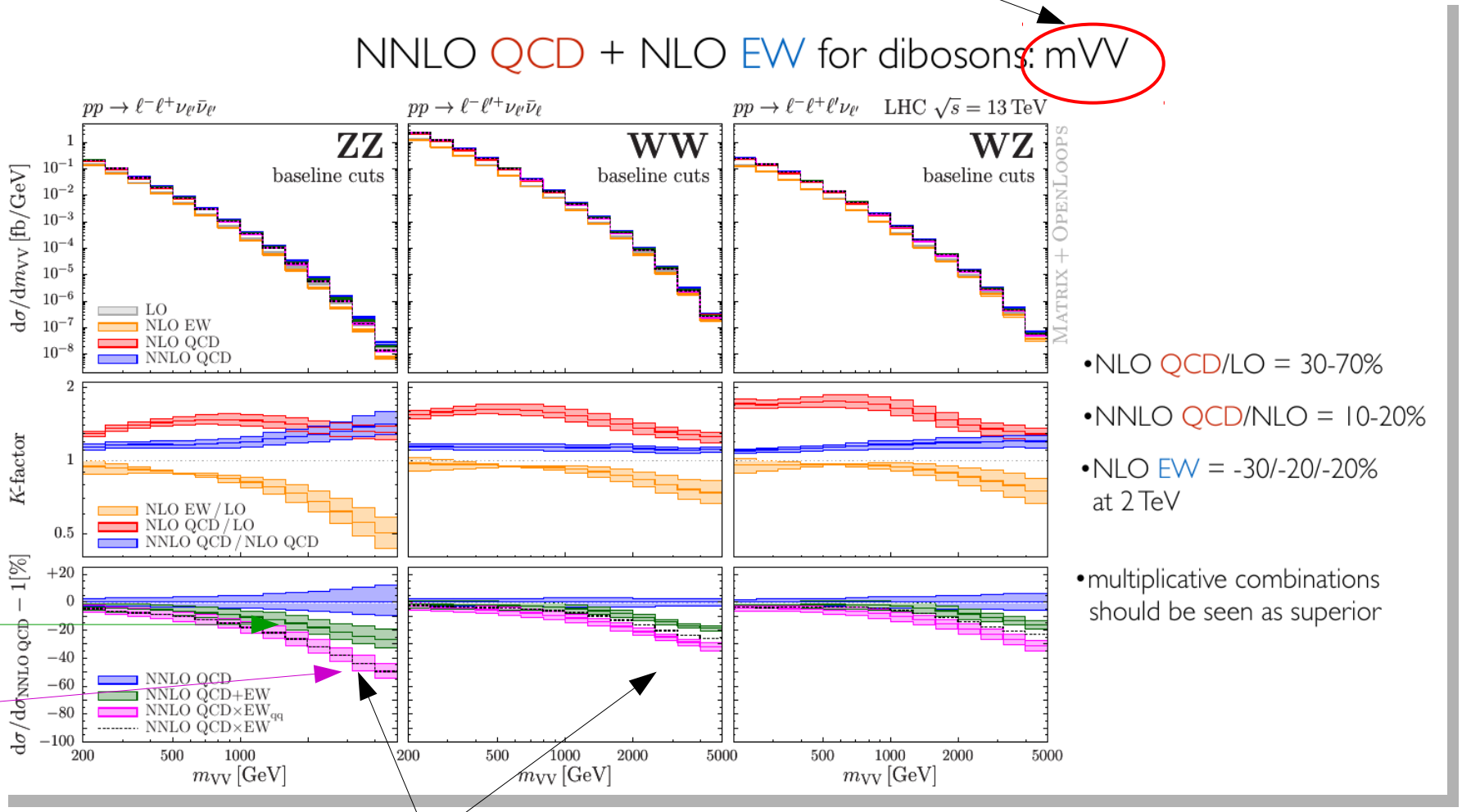
$$\mathrm{d}\sigma_{\mathrm{QCD+EW}} = \mathrm{d}\sigma_{\mathrm{LO}}\left(1 + \delta_{\mathrm{QCD}} + \delta_{\mathrm{EW}}\right) + \mathrm{d}\sigma^{gg}_{\mathrm{LO}}$$

$$\mathrm{d}\sigma_{\mathrm{QCD}\times\mathrm{EW}} = \mathrm{d}\sigma_{\mathrm{LO}}\left(1 + \delta_{\mathrm{QCD}}\right)\left(1 + \delta_{\mathrm{EW}}\right) + \mathrm{d}\sigma^{gg}_{\mathrm{LO}}$$

- Multiplicative method generally superior.
- Difference → (conservative) estimate of missing QCD-EW corrections

NNLO QCD + NLO EW

Key observable for offshell studies



Additive

Multiplicative

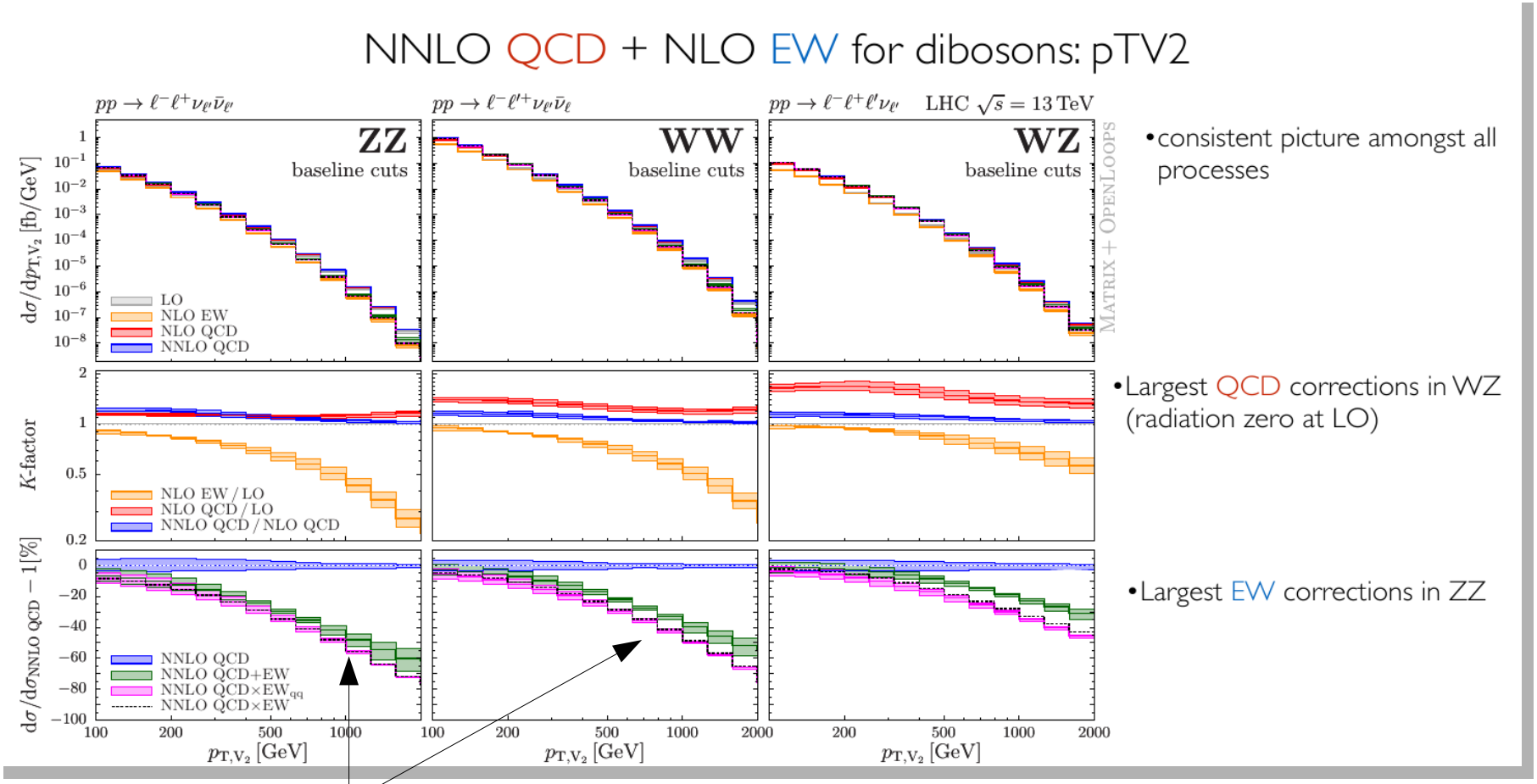
Two prescriptions consistent.

Notable differences above ~ 1 TeV

Slide from J. Lindert

NNLO QCD x NLO EW

Transverse momentum of softer vector boson



Two prescriptions consistent.

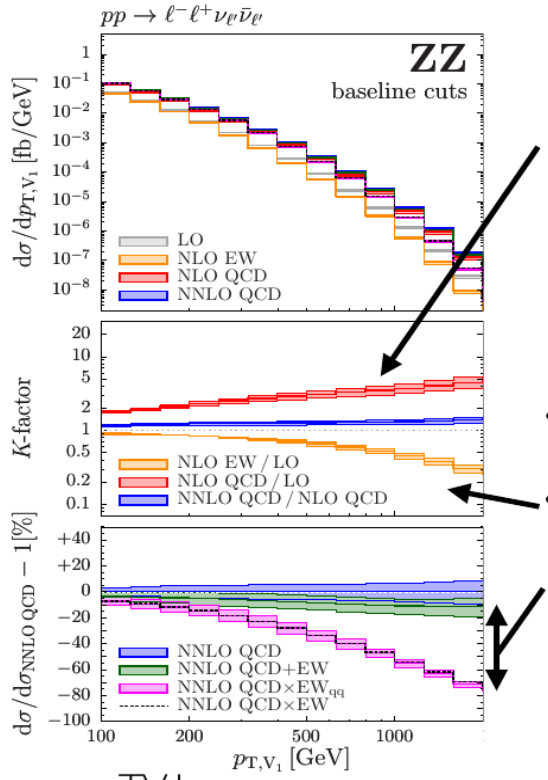
Slide from J. Lindert

NNLO QCD + NLO EW

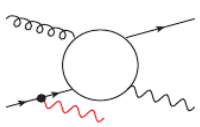
Not always the case!

E.g. transverse momentum of hardest EW boson

Giant QCD K-factors and EW corrections: pTV1



- NLO QCD/LO=2-5! ("giant K-factor")
- at large pTV1:VV phase-space is dominated by V+jet (w/ soft V radiation)

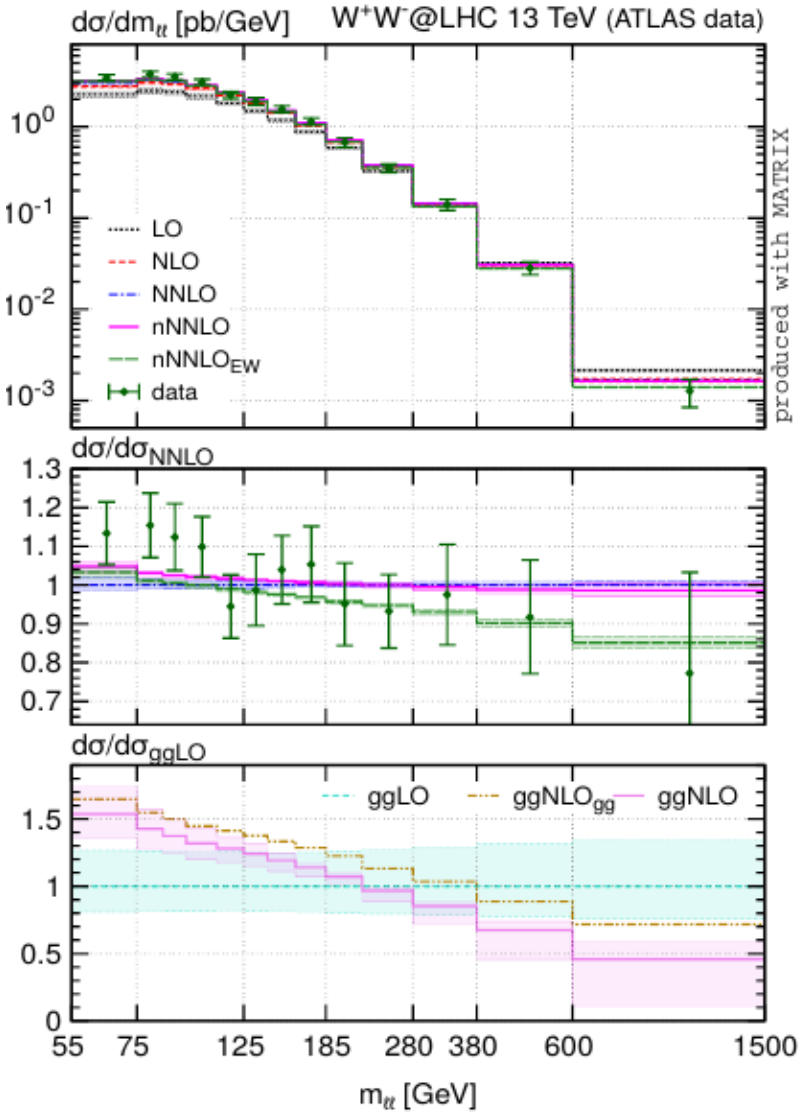


$$\frac{d\sigma^{V(V)j}}{d\sigma^{\text{LO}}_{VV}} \propto \alpha_S \log^2\left(\frac{Q^2}{M_W^2}\right) \simeq 3 \quad \text{at} \quad Q = 1\,\text{TeV}$$

- NNLO / NLO QCD moderate and NNLO uncert. 5-10%
- NLO EW/LO=-(40-50)%
- Very large difference $d\sigma_{\text{NNLO QCD+EW}}$ vs. $d\sigma_{\text{NNLO QCD}\times\text{EW}}$
- Problems:
  1. In additive combination dominant Vj topology does not receive any EW corrections
  2. In multiplicative combination EW correction for VV is applied to Vj hard process
- Pragmatic solution: take average as nominal and spread as uncertainty
- Rigorous solution: merge VVj incl. EW corrections with VV retaining NNLO QCD + EW

Slide from J. Lindert

NNLO QCD + EW



- Comparison of NNLO QCD + NLOgg + NLO EW with ATLAS data.

  [Grazzini, Kallweit, Yook, Wiesemann, hep-ph/2002.01877]

- Most sophisticated fixed-order results for diboson production.

NNLO QCD + NLO EW

Open issues:

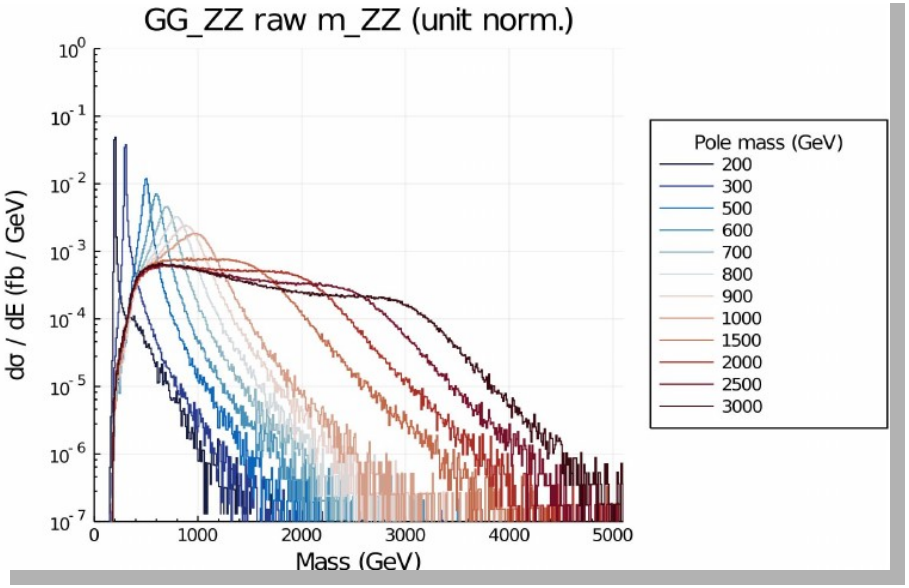
- Are the problems in $p_{T,V1}$ relevant for offshell studies? If so, can they be handled using a jet veto, e.g. $H_T^{\mathrm{j}} < 0.2 H_T^{\mathrm{lep}}$
- How to include corrections in practice?
  - Overall k-factor/differential k-factor? How many distributions are relevant?
  - Combine with multi-jet merged samples including NLO EW corrections?
  - See [Bräuer, Denner, Pellen, Schönherr, Schumann, hep-ph/2005.12128]

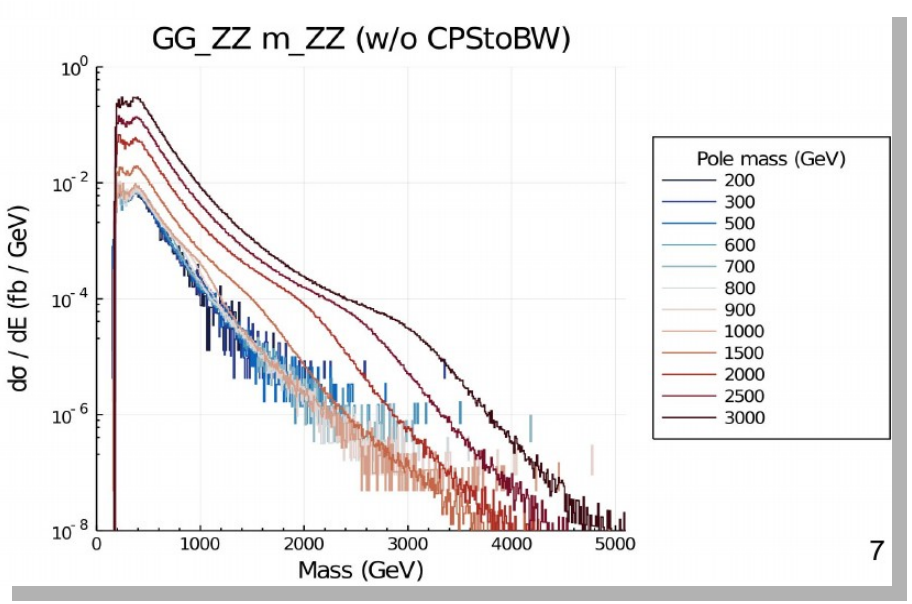
Reweighting Techniques

- Talk by Jerry Ling at meeting in July on reweighting signal samples.
- Signal samples generated onshell for a range of Higgs masses, and then reweighted to give offshell distributions.
  - Gluon fusion;
  - VBF;
  - VH.

Reweighting Techniques

- Start with NLO gg→H→ZZ using POWHEG for different m_H.
- Reweight by LO ME using JHUGen+MCFM with m_H=125 GeV with overall NNLO k-factor.

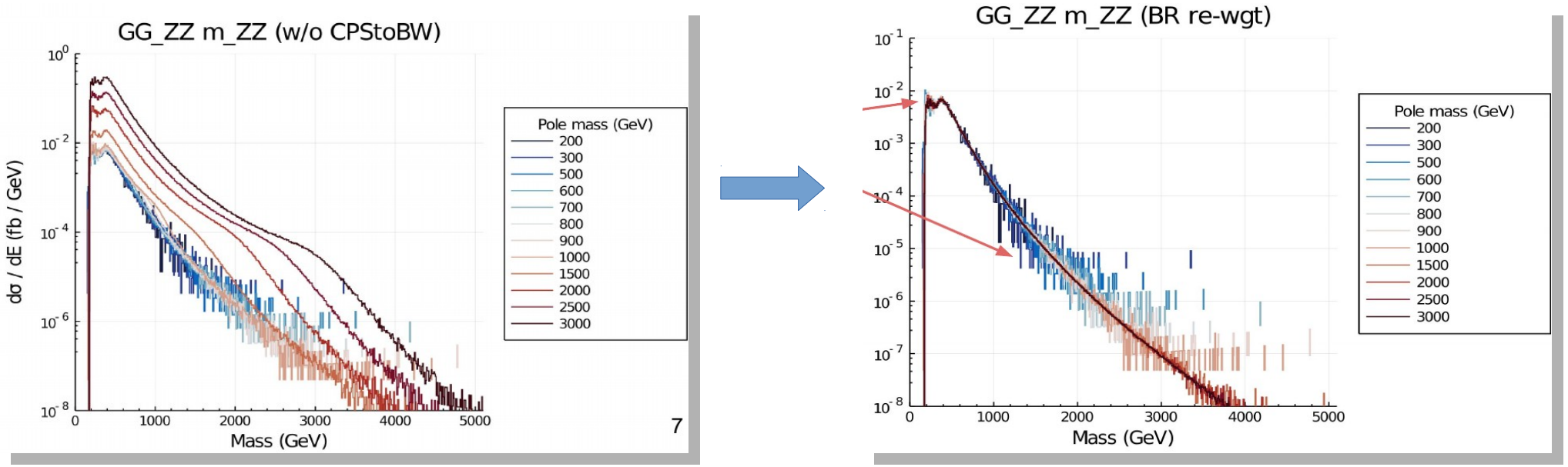




Plots from J. Ling

Reweighting Techniques

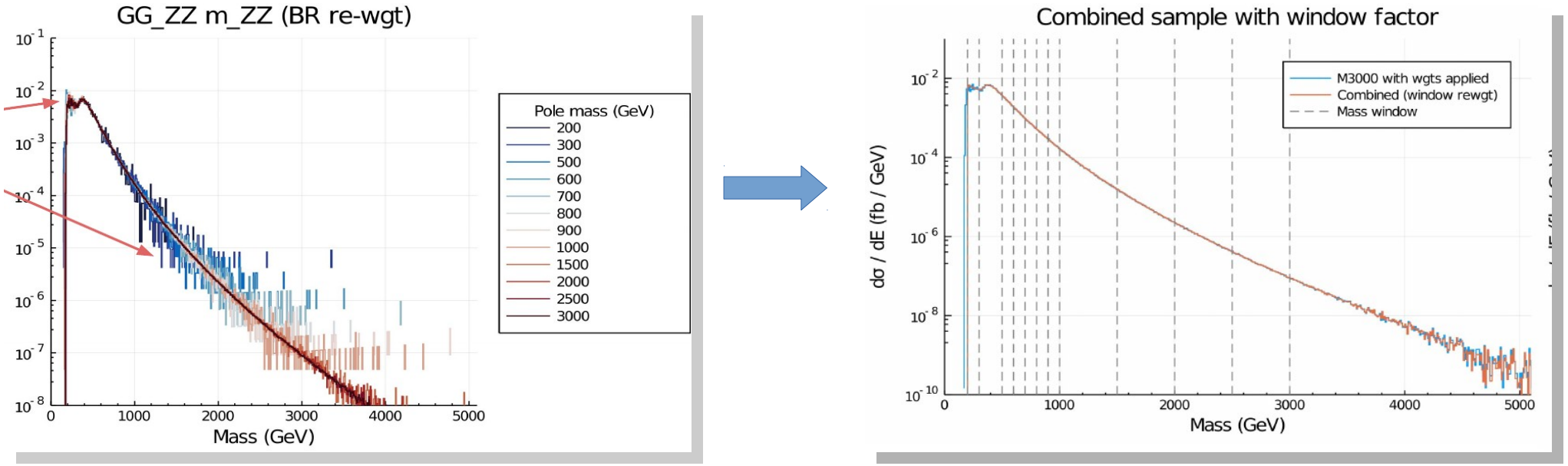
Reweight from CPS to Breit-Wigner for m_H=125 GeV.



Plots from J. Ling

Reweighting techniques

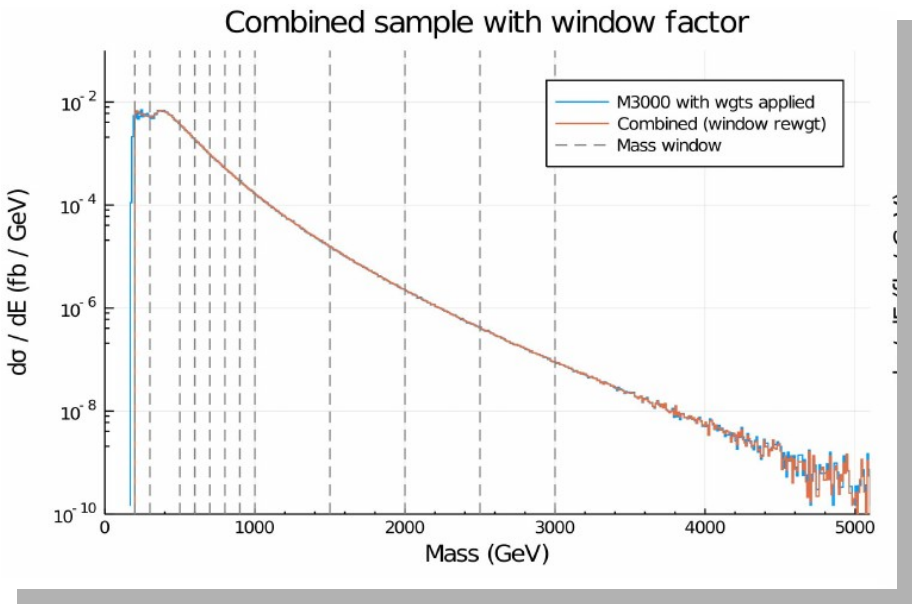
Statistical window reweighting

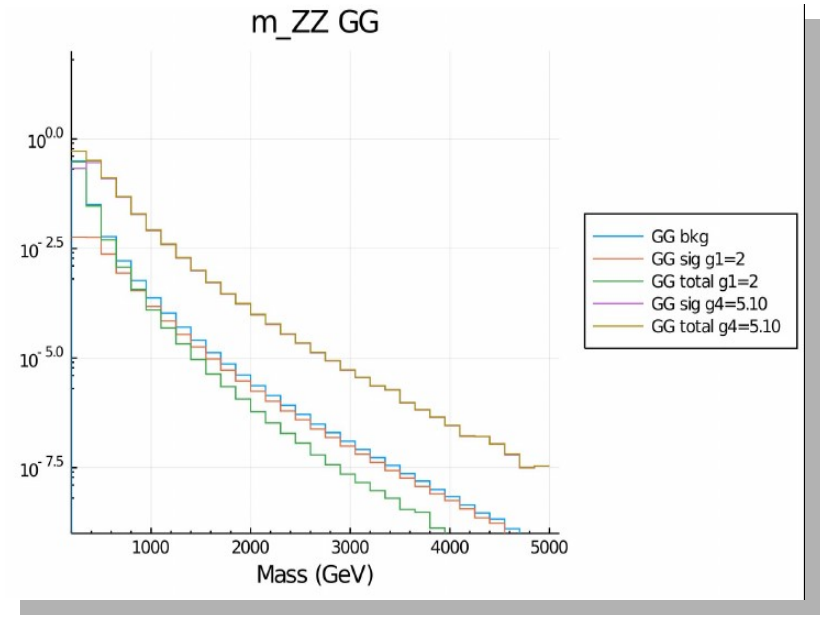


Plots from J. Ling

Reweighting techniques

Use different matrix element (with signal/background/pseudoscalar signal etc.) in reweighting.

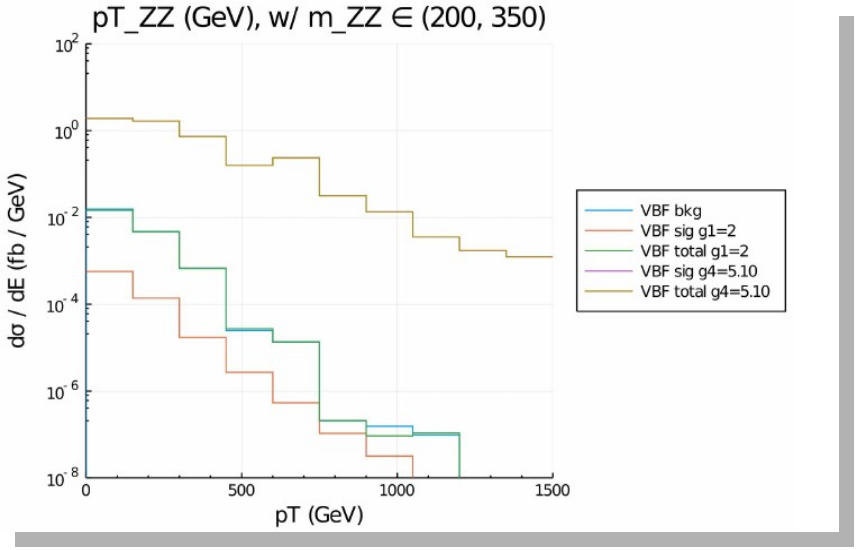




Plots from J. Ling

Reweighting Techniques

- Procedure can be used for other observables, e.g. $p_{T,ZZ}$.
- Results also for VBF.



Plot from J. Ling

Remaining issues:

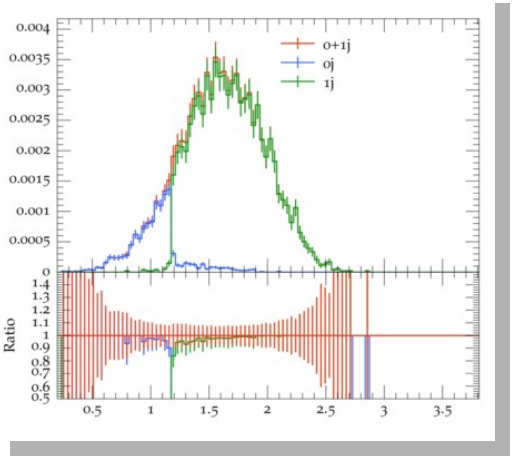
- Comparison with LO simulation including PS effects.
- Results for *VH* production available but subject to internal approval.

Jet merging in *gg* → *ZZ*

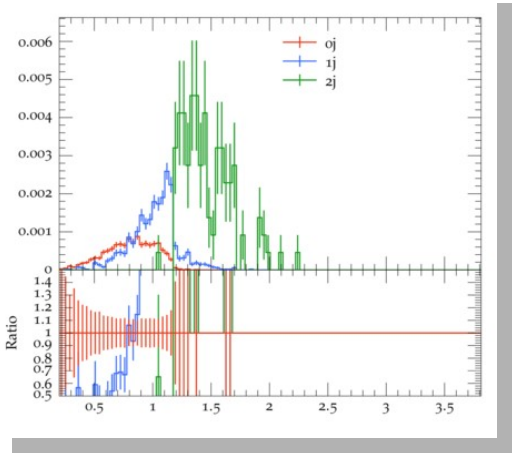
- Produce *gg* →*(H)* → *ZZ* sample with up to 2 matrix element jets.
  - MadGraph+Pythia
  - merged using kT-MLM

Ongoing work by Jay Sandesara

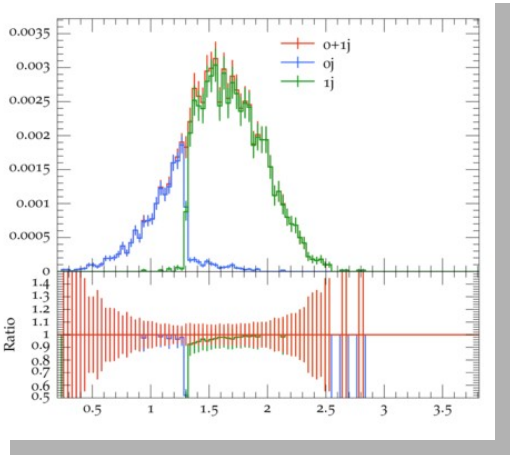
All plots preliminary



0, 1 merging
qCut=15 GeV



0, 1,2 merging
qCut=15 GeV

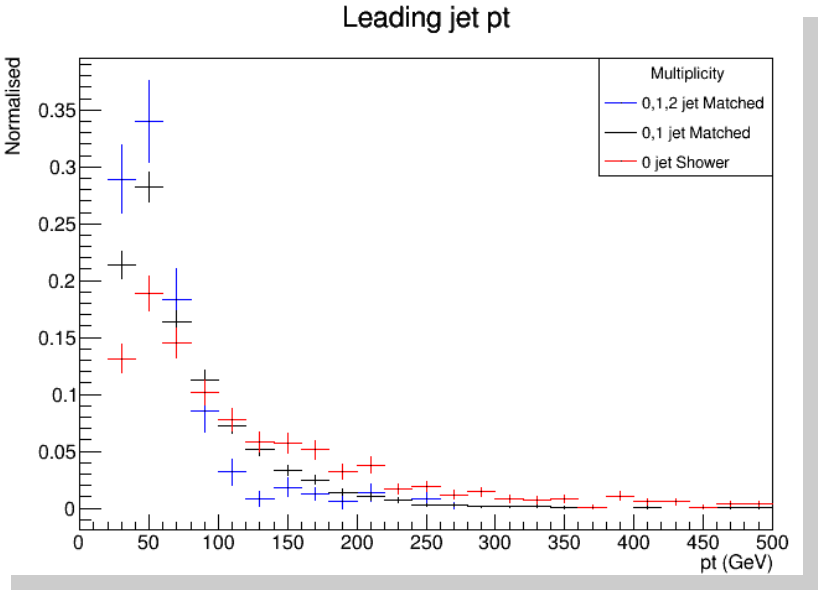


0, 1 merging
qCut=20 GeV

- **D**ifferential **J**et **R**ates distributions indicate that *qCut* between 15 GeV and 22 GeV yield physical results for 0 →1 transition.
- Ideal *qCut* for 1 → 2 transition still being investigated.

Jet merging in $gg \rightarrow ZZ$

Comparison for transverse momentum of leading jet for 0,1 jet samples.



with MadGraph

Other Work

- Offshell effects in VBF (Martina Javurkova)
  - Signal sample in s-channel, with $H \to 4l$ decay.
  - Cross section ~ 0.1 fb.
- EFT effects in offshell production through gluon fusion (Ashley McDougall)
  - SMEFT @ NLO in MadGraph (Warsaw basis).
  - Operators: ggH (cpG), ttH Yukawa (ctp), HVV couplings (cpWB and cpW).
  - Also looking into translating into Higgs basis.

Recent progress

- NLO QCD + NLO EW corrections to *WW* and *WWj* production, including jet merging with (approximate) NLO EW corrections.

  [Bräuer, Denner, Pellen, Schönherr, Schumann, hep-ph/2005.12128]

- NLO QCD + NLO EW corrections to *ZZ* production in VBS.

  [Denner, Franken, Pellen, Schmidt, hep-ph/2009.00411]

- Merging of 0,1,2 jet samples in $gg \to ZZ$ (background only)

  [Li, An, Charlot, Covarelli, Guan, Li, hep-ph/2006.12860]

- Massive two-loop amplitudes for $gg \to WW$

  [Brønnum-Hansen, Wang, hep-ph/2009.03742]

- *...*

Way forward

Deadline to produce first version of documentation: 31 October

Include in this document:

- Studies/recommendations on NNLO QCD + NLO EW effects in *VV* production. [R.R., ...]
- Jet merging in $gg \to ZZ$? [Jay Sandesara, …]
- Results from EFT effects in gluon fusion? [Ashley McDougall,...]
- Results from offshell effects in VBF? [Martina Javurkova, ...]

Beyond this document:

- Jet merging in *VV?* Including in $gg \to (H) \to ZZ$ and *VV* production with NLO EW effects.
- Corrections to VBF/VBS?
- Full NLO QCD corrections to $gg \to WW$?