Di-Vector-Boson Production in Association with Multiple Jets at the LHC.

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Outline

Motivation: W W+Jets

NLO with Unitarity: BlackHat

Predictions
Quests at LHC

Explore the 1 TeV mass scale:

- Origin of electroweak symmetry breaking.
- Searches for Dark-Matter particles (e.g. SUSY).

$WW + \text{jets}$ important in Standard Model:

- Measurements of Higgs & vector bosons.
- As backgrounds to New-Physics searches.
**WW + Jets Signatures**

Rich phenomenology including many jets:

- **Cubic and quartic couplings** of electroweak vector bosons.
- **Top-pair production** with top decays to W-bosons and b-quarks.
- **Higgs** phenomenology: Higgs coupling to vector-boson pairs.
- In particular, WW+2,3-jet production is background to **vector-boson-fusion** (VBF) mechanism: understand **radiation** between tagging jets.
- **BSM** models; decay chains of heavy colored particles to leptons and jets.
• Impressive agreement of theory and experiment.
• Jet towers help to understand QCD.
• Small cross section for WW+jets.
• Similar results from CMS.
Hadron Collisions

Theory based on QCD improved parton model:

- Parton level prediction.
- Truncated perturbative expansion introduces scale dependence at high multiplicity.
- Process dependence in hard partonic cross sections.
- Quantum corrections important: next-to-leading-order (NLO) effects in strong-coupling expansion.
In practice, perturbation theory is complicated:

- Factorial growth of diagrams, exponential growth of spin sums.
- Many interesting processes needed (Higgs, W/Z, top, jets, photons, susy, etc.).
- Numerical challenges: gauge cancellations, tensor reduction, soft and collinear cancellations, integrals.

⇒ Must find the right approach!
Origins in bootstrap program for strong interactions in 60s which aims to construct amplitudes directly from analytic properties.

Replaced in 70s by rise of field theory (QCD) and Feynman rules. Return of analyticity as boost for field theory unitarity method.

- Built from analytic inspiration: N=4 super Yang-Mills.
- Poles explained by factorisation.
- Branch cuts from optical theorem, generalised cuts.
- Spinor helicity, color ordering.

Numerical unitarity methods are algorithm to construct loop amplitudes from tree amplitudes:

- Good numerical stability.
- Multiplicity independent setup.

Many contributors: [Arkani-Hamed, Badger, Berger, Bern, Bjerrum-Bohr, Brandhuber, Britto, Cachazo, Dixon, Dunbar, Ellis, Febres-Cordero, Feng, Forde, Giele, Harmeren, HI, Kosower, Kunszt, Maitre, Mastrolia, Melnikov, Ossola, Papadopoulos, Pittau, Schwinn, Spence, Travaglini, Weinzierl, Witten]

Reviews: e.g. [Britto; HI; Ellis, Kunszt, Melnikov, Zanderighi]
**NLO with BlackHat**

**BlackHat:**
- A loop matrix element generator based on unitarity & on-shell methods.
- Linked to SHERPA Monte-Carlo for partonic cross sections
  - [Hoeche, Krauss, Kuttimalai, Schoenherr, Schumann, Siegert, Thompson, Winter, Zapp]
- Recent results: $W/Z +3, 4, 5$ jets; $4$ jets; $\gamma\gamma + 2$ jet; $N$ tuples

**WW + 0, 1, 2, 3 jets:**
- New infrastructure & tree input
  - [Diploma thesis of P. Hofmann]
- Cross checks: UV/IR-structure, factorisation, 2nd implementation using off-shell recursion
  - [Brends, Giele], literature for $WW + 1, 2$ jets
  - [GOSAM; Melia, Menikov, Zanderighi], consistent dipole subtraction.
Parton-level predictions $WW+\text{Jets}$

$W-W+$:

- **LO (1979):** [Brown, Michaelin]
- **NLO (1991):** [Ohnemus; Frixione; Campbell, Ellis; Dixon, Kunszt, Signer; Campbell, Ellis, Williams]
- **NNLO (2014):** [Gehrmann, Grazzini, Kallweit, Maierhoefer, von Manteuffel, Pozzorini, Rathlev, Tancreedi]

$W+W- + 1\text{jet}$:

- **NLO (2007):** [Campbell, Ellis, Zanderighi; Dittmaier, Kallweit, Uwer; Campbell, Miller, Robens]

$W+W- + 2\text{ jets}$:

- **NLO (2011):** [Melia, Melnikov, Rontsch, Zanderighi; Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano; Alwall, Frederix, Frixione, Hirschi, Maltoni, et al.]

$W+W+ + 2\text{ Jets}$:

- **NLO (2010):** [Melia, Melnikov, Rontsch, Zanderighi; Campanario, Kerner, Ninh, Zeppenfeld]
WW+Jets Setup

Work @ Uni Freiburg [in preparation: Febres Cordero, HI, Hofmann].

Matrix elements:

- BlackHat for WW+1,2, 3-jets
- Omitted sub-leading-color terms (good at percent level; better than PDFs)
- Double resonant contributions.

Standard kinematical cuts:

- $\text{PT } e, \mu > 20 \text{ GeV}, |\eta_{e, \mu}| < 2.4, \text{ETmiss} > 30 \text{GeV}, \text{PT } e\mu > 30 \text{GeV}, m_{e\mu} > 10 \text{GeV},$
- Jets: anti-$k_T$ algorithm, $R=0.4, \ p_{\text{jet}} > 30 \text{GeV}, |\eta_{\text{jet}}| < 4.5$
- Scale $\mu_r = \mu_f = H_T$ and MSTW2008 set of PDFs,
Scale Sensitivity

- Total cross sections as function of unphysical scales.
- Small scale sensitivity at NLO.
- Large multiplicity needs NLO corrections.
- Reduction of sensitivity from 45% to 15%.

PRELIMINARY
Jet PT Spectra

- Jet PT of softer jets fall more steeply.
- Quantum corrections shift PT of softest jet.
- More structure in harder jets.
- Similar to QCD NLO corrections for V+jets.
Conclusions

• Precision theory plays an important role to exploit the potential of the LHC.

• New methods such as unitarity approaches extend theorists’ reach.

• Presented first NLO QCD predictions for WW+3-jet production. This adds to very few such predictions for processes with more than 5 objects in the final state (V + 4, 5 Jets from BlackHat+Sherpa and 5-Jet production from NJet).

• NLO QCD corrections provide reliable predictions at large multiplicity.

• All is in place to explore di-vectors (Z, W & photons) in association with jets.

• Future: more detailed phenomenology will follow including VBF studies and jet production ratios.
**WW + Jets @ CDF**

- Based on full dataset [CDF: 1505.00801].
- Differential cross sections.
- Approximate agreement between theory and experiment.
- At Tevatron tt background is small.