(Soft) QCD effects in VBS/VBF

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at the
MBI workshop
Thessaloniki | 27 August 2019
Hierarchy in energy scales: Factorization dictates work flow.

Hard partonic scattering
Jet evolution
Multiple interactions
Hadronization

Event generators and analytic methods share the same paradigm.

- Analytic: Accurate for a single observable.
- Event generator: Universal, accuracy limited or impossible to quantify.

\[ d\sigma \sim d\sigma_{\text{hard}}(Q) \times PS(Q \rightarrow \mu) \times \text{Had}(\mu \rightarrow \Lambda) \times \ldots \]
Motivation & Outline

Partonic predictions well understood at NLO+PS.

Realistic predictions need to include

- Multi-parton interactions
- Colour reconnection
- Hadronization

Far from first-principles assignment of uncertainties, so need to rely on different models/tunes.

Central jet vetoes, and more inclusive jets at hadron colliders especially sensitive to these effects.

Outline:

- Overview of showers, non-perturbative models and their interplay (~ Herwig-centric)
- Towards quantifying the impact and uncertainties on VBF/VBS selection

[Work in progress with Carsten Bittrich, Stefanie Todt, Patrick Kirchgaesser, Richard Ruiz, ...]

Colour flow selection for the hard process $\leftrightarrow$ large-angle soft radiation pattern. **Globally** constrained collinear jets radiate soft gluons as dictated by colour flow of hard process.

$$|\mathcal{M}\rangle = \sum_{\sigma} \mathcal{M}_\sigma |\sigma\rangle$$

Sum of Feynman graphs in a colour basis. Colour flows selected with weights according to squared subamplitudes $\leftrightarrow$ large-$N$ limit.
Eikonal radiation pattern guaranteed through initial conditions: large-angle soft gluons first. Subsequent evolution collapses into splitting functions in the collinear limit.

- Constructive interference in each collinear region
- Branchings order in \( \sim \) angle
- Dipoles order in \( \sim p_T \)

Large-angle gluons isolate colour.

\[
\frac{d\sigma_{n+1}}{dq} \sim \frac{dq}{q} d\bar{z} \frac{\alpha_s}{2\pi} P(\bar{z}) d\sigma_n
\]

Recoil strategies can ruin coherence initial conditions.
Initial conditions need to be supplemented by a hard veto scale to switch off resummation. Main source of shower variations.

Probes phasespace where shower becomes unreliable, significant improvements through matching with NLO.

Impact on soft physics is in hardness of emissions and length of evolution: Need to pin down cross talk.
Outside of tight VBF selection: presence and mixing of different colour flows changes large-angle (soft) radiation pattern.

Non-global nature of jet vetoes might require even more sophisticated partonic evolution.

summary of 3$^{rd}$ jet observables vs VBF approximation
Multi-parton Interactions & Colour Reconnection

Hard scattering accompanied by several additional partonic scatters.

Assume some matter distribution in the proton, and effective multiplicity distribution of additional scatters.

Colour reconnection crucial to describe MinBias and UE data ↔ lack knowledge on colour correlations.

Clear impact on interjet activity and jet shapes.

Interplay of MPI & colour reconnection → watch out for compensation patterns.

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Gather experts on jet vetoes, MPI, event generators and experimentalists to discuss soft QCD effects in VBF/VBS and to identify cornerstones of a study evaluating how reliable current predictions/models are.

In-depth discussions on handling of colour flows, colour evolution and its role within the VBF approximation, colour reconnection, impact of QCD corrections, ...

https://indico.cern.ch/event/806009/

Core group:

- Carsten Bittrich
- Jeff Forshaw
- Patrick Kirchgaesser
- Andreas Papaefstathiou
- Juergen Reuter
- Richard Ruiz
- Stefanie Todt
- Dieter Zeppenfeld
Impact of (soft) QCD effects

Soft QCD effects are not absent: on/off will only hint at their relative importance.

Questions to be raised:

- Quantify impact (and how certain this is)
- Quantify how reliable the model predictions are
- Determine interplay of shower variations and models
- Pinpoint signs of lack of perturbative dynamics beyond current NLO+PS

Benchmark

VBF Z production, plus QCD induced background if possible. Ideally at NLO+PS for reliable modeling of hard jet activity.

Observables

- Large variety of third jet properties and jet vetoes
- Jet radius and VBF cut bin dependence

Herwig 7, Pythia 8 (with MG5_aMC), Sherpa 2

[MG5_aMC plot by Richard Ruiz]
Shower & Tune Variations with Herwig 7 + VBFNLO 3

Strategy

- Vary colour reconnection and MPI parameters to stay within ~ 10% agreement of typical tuning observables
- Vary shower hard scale by factors of $\frac{1}{2}$ and 2
- Currently LO, NLO will significantly improve on shower variations

Tagging jet distributions very stable, mostly independent of VBF cut bin.
loose VBF, R=1.0, just for illustration

loose VBF selection, R=0.4

tight VBF selection, R=0.4

[Work in progress with Carsten Bittrich, Stefanie Todt, Patrick Kirchgaesser, Richard Ruiz, ...]
Coherence paradigm fails in general – for any realistic measurement:

- Unconstrained systems of non-collinear partons radiate into observed region.
- The full complexity of QCD amplitudes and interference strike back.

**Gaps-between-jet vetoes specifically sensitive** to these physics. Evolution at the amplitude level is crucial, will include 1/N corrections.

[Caron-Huot – JHEP 1803 (2018) 036]
1/N Corrections, Colour Mixing & Amplitude Evolution

Restore exact colour correlations in factorization of emission rate

\[ d\sigma_{n+1} \sim |\mathcal{M}_{n+1}|^2 = \langle \mathcal{M}_{n+1} | \mathcal{M}_{n+1} \rangle \sim P \, d\sigma_n \rightarrow \frac{\text{Tr} \left[ |\mathcal{M}_n\rangle \langle \mathcal{M}_n| P \right]}{|\mathcal{M}_n|^2 P} \quad P \, d\sigma_n \]

\[ |\mathcal{M}\rangle = \sum_{\sigma} \mathcal{M}_\sigma |\sigma\rangle \]

Sum of Feynman diagrams, sorted by SU(3) tensor structures → vector space of colour structures

Dipole branching algorithms can be supplemented by correction factors for real emission, but still lack virtual contributions beyond leading-N.

Some subleading-N corrections can be restored.


Soon out with Herwig 7.2
Parton branching at the amplitude level

Universal framework requires evolution at the amplitude level:

\[
\sigma = \sum_n \int \text{Tr} \left[ A_n(\mu) \right] u(p_1, \ldots, p_n) \, d\phi_n
\]

`density operator` \( A_n(\mu) = |M_n(\mu)\rangle \langle M_n(\mu)| \) \text{ observable} \text{ phase space}

Virtual corrections and colour mixing in all orders perturbation theory.

\[
|M_n(\mu)\rangle = Z^{-1}(\mu, \epsilon) |\tilde{M}_n(\epsilon)\rangle
\]

\[
A_n(E) = V(E, E_n) D_n A_{n-1}(E_n) D_n^\dagger V^\dagger(E, E_n) \theta(E - E_n)
\]

Analytically proven one-to-one correspondence with renormalization group equations in colour space, both in direct QCD analysis and within EFT.

Can systematically expand around the large-N limit, and sum classes of terms enhanced by \( \alpha_s N \) – detailed control of subleading-N effects.
**CVolver library**

- Resummation tool based on RG equations in colour space
- Also able to host full parton shower algorithms

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A fresh look at colour reconnection

\[ |\mathcal{M}\rangle = e^\Gamma |\text{clusters}\rangle \]

\[ P_{\text{reco}} \sim |\langle \text{clusters}' |\mathcal{M}\rangle|^2 \]

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Conclusions

Soft models are detailed probes of soft gluon evolution of the hard process:
- Cannot be looked at independently from shower and its variations.
- Shower algorithms and soft gluon interference effects need to be carefully assessed.

No a priori recipe on how to assign uncertainties to phenomenological models:
- Vital to compare different tunes and/or variations around central tunes.
- Mind that a decent description of data does not imply a negligible theoretical uncertainty.

Comprehensive study in progress.

Amplitude level evolution significant to precision predictions of the central jet veto, interesting connections to colour reconnection models → work in progress, with VBF/VBS top of the agenda.
Thank you!