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(Soft) QCD effects in VBS/VBF

Simon Plätzer

Particle Physics, University of Vienna

at the
MBI workshop
Thessaloniki | 27 August 2019

VBSCAN inside

cost
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY

MCnet

Setting the Scene: Structure of QCD Cross Sections

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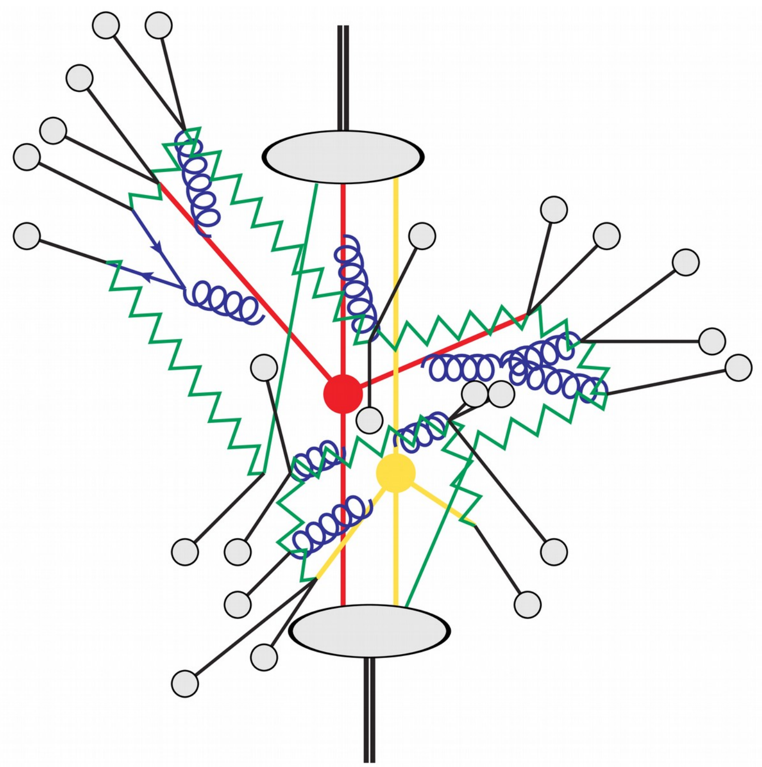
Hierarchy in energy scales:
Factorization dictates work flow.

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.

$$\mathrm{d}\sigma \sim \mathrm{d}\sigma_{\mathrm{hard}}(Q) \times \mathrm{PS}(Q \to \mu) \times \mathrm{Had}(\mu \to \Lambda) \times \ldots$$

Motivation & Outline

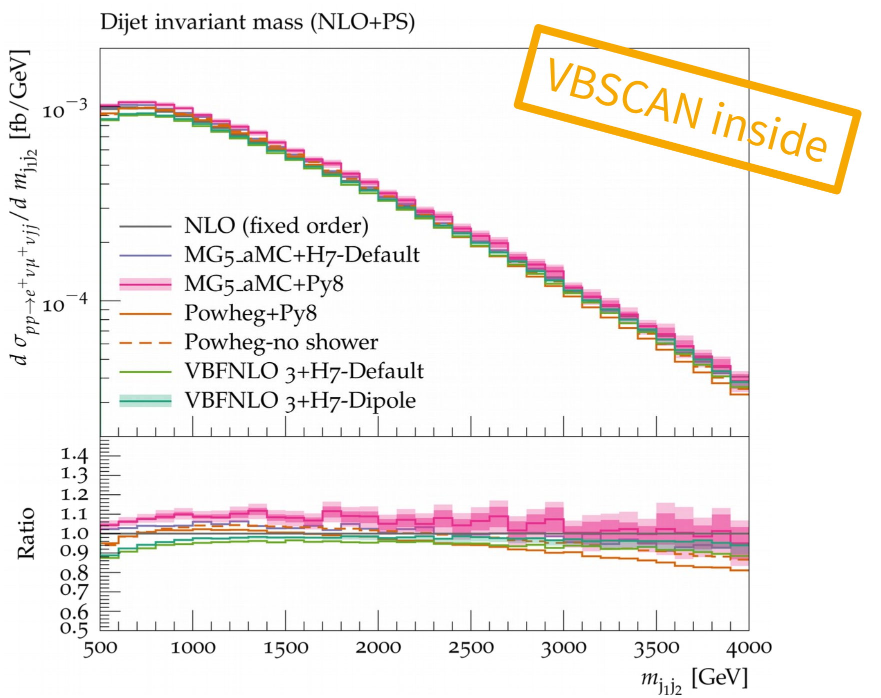
Partonic predictions well understood at NLO+PS.

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.



[Rauch et al. For VBSCAN study – EPJ C78 (2018) 671]

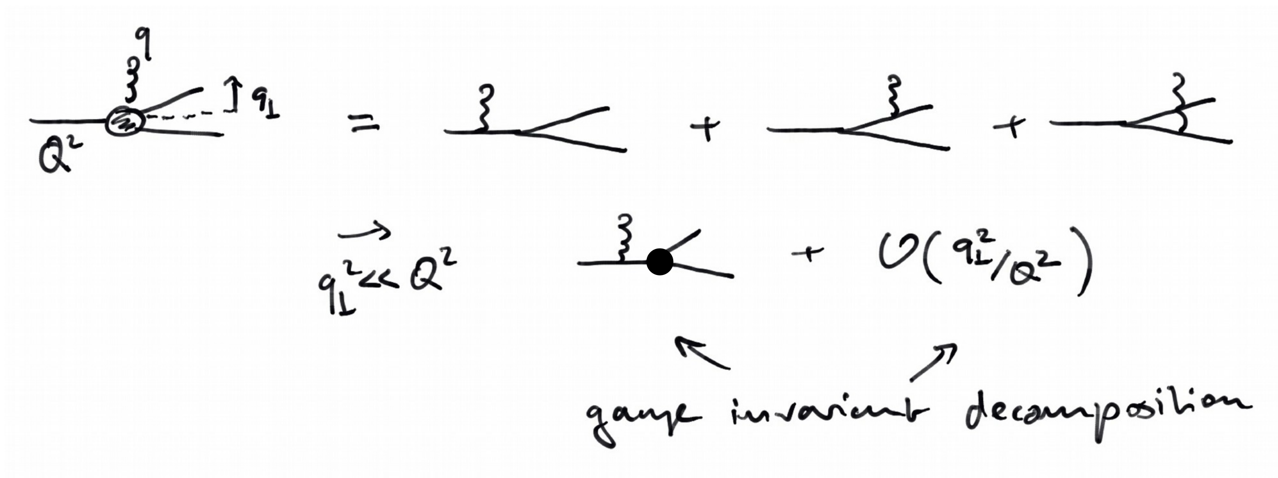
Outline:

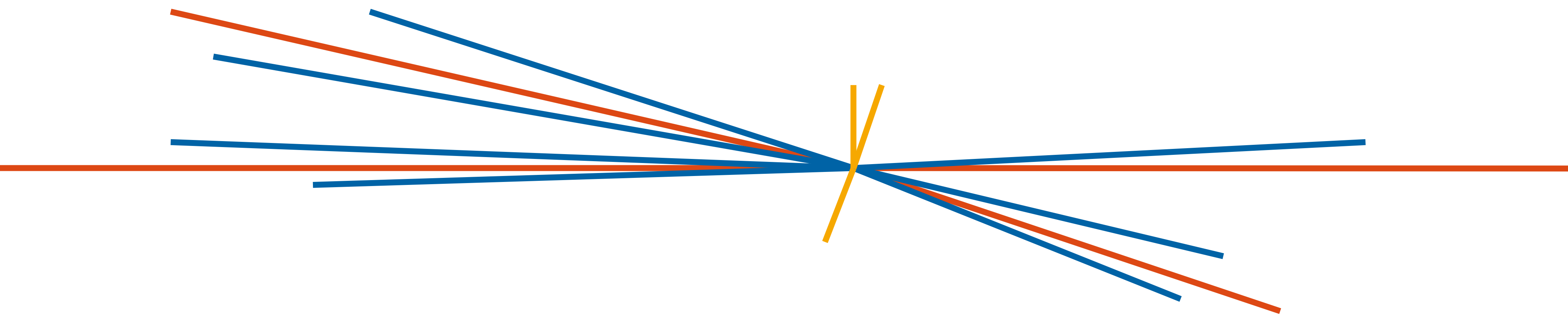
- Overview of showers, non-perturbative models and their interplay (~ Herwig-centric)
- Towards quantifying the impact and uncertainties on VBF/VBS selection

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

QCD Coherence & Colour Flows

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



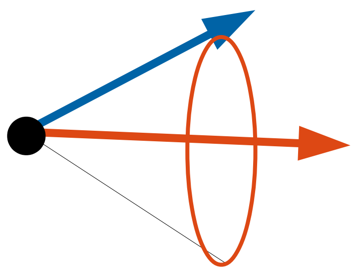


$$|\mathcal{M}\rangle = \sum_\sigma \mathcal{M}_\sigma |\sigma\rangle$$

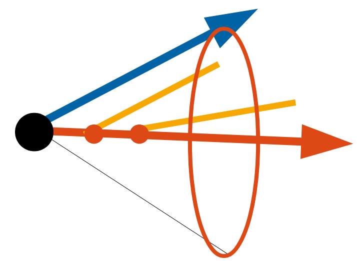
Sum of Feynman graphs in a colour basis. Colour flows selected with weights according to squared subamplitudes ↔ large-N limit.

QCD Coherence & Colour Flows

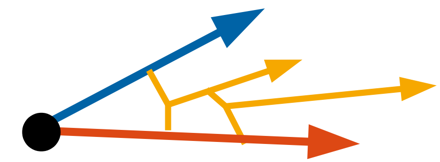
Eikonal radiation pattern guaranteed through initial conditions: large-angle soft gluons first.
Subsequent evolution collapses into splitting functions in the collinear limit.



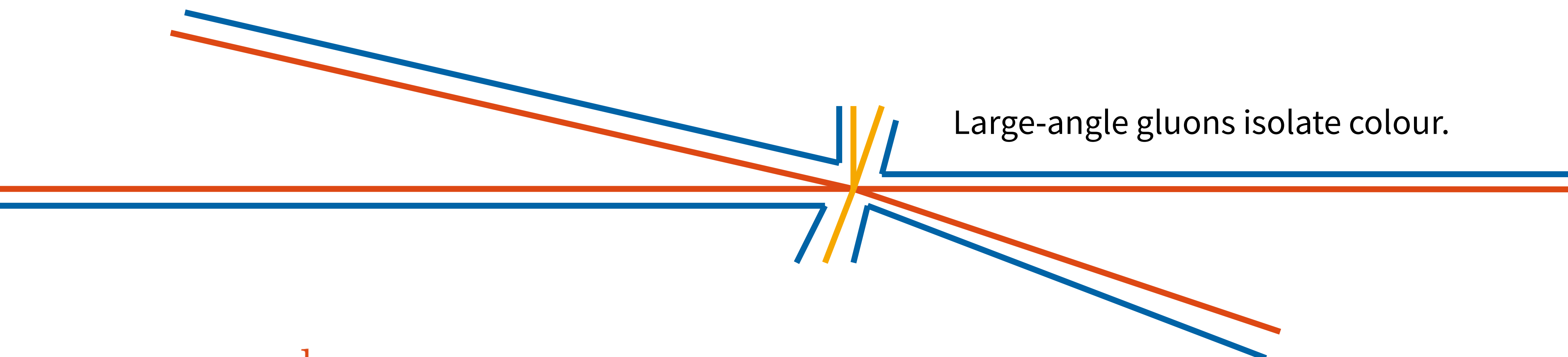
constructive interference
in each collinear region



branchings
order in ~ angle



dipoles
order in ~ p_T



Large-angle gluons isolate colour.

$$\mathrm{d}\sigma_{n+1} \sim \frac{\mathrm{d}q}{q}\mathrm{d}z\frac{\alpha_s}{2\pi}P(z)\mathrm{d}\sigma_n$$

Recoil strategies can ruin coherence initial conditions.

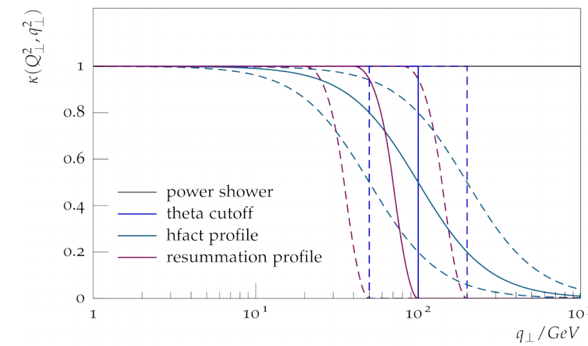
Parton Shower Variations

KINEMATIC LIMIT ~ S

HARD SCALE ~ μ^2

HARD SCALE IN 3 PHASE SPACE

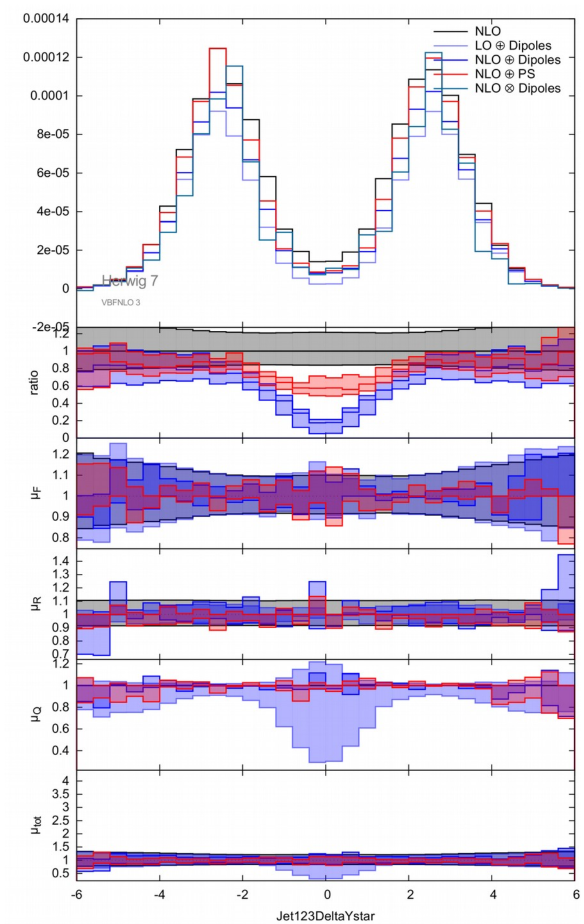
$$-\ln\Delta \sim \int_{p_\perp^2}^{R_\perp^2} \frac{dq_\perp^2}{q_\perp^2}\, \underbrace{\kappa(Q_\perp^2, q_\perp^2)}_{\text{CUTOFF ON RESUMMATION}}\, \ln\left(\frac{K_\perp^2}{q_\perp^2}\right)$$



Initial conditions need to be supplemented by a hard veto scale to switch off resummation. Main source of shower variations.

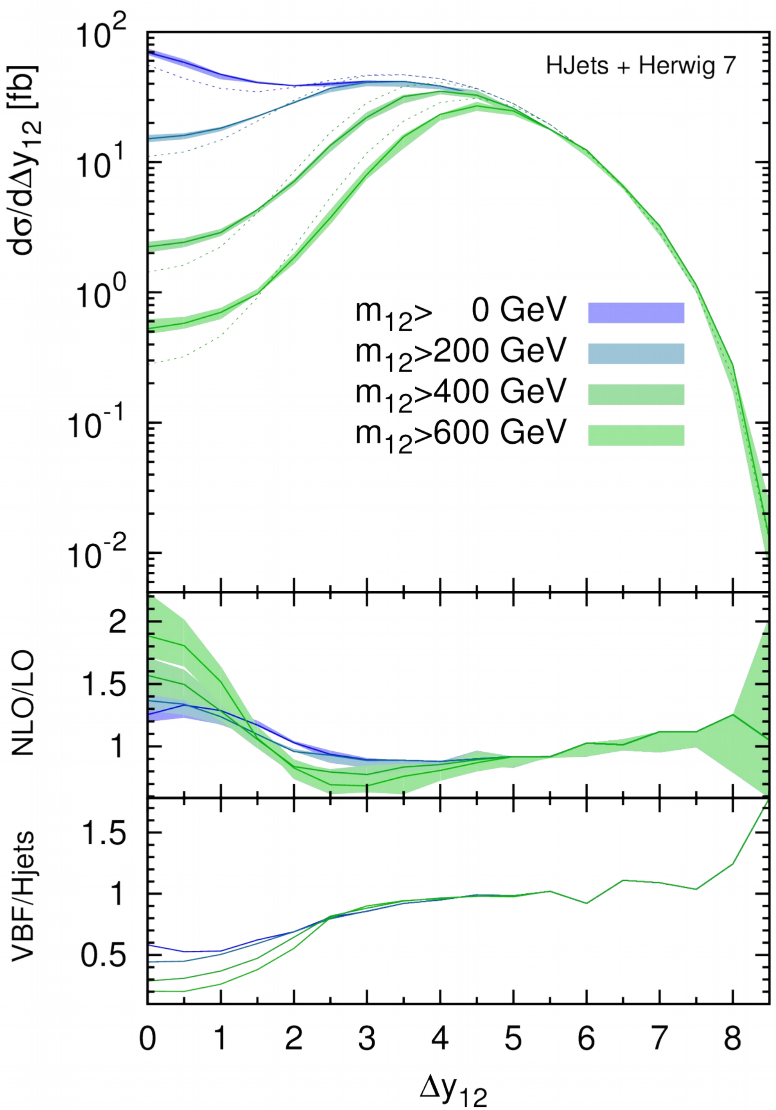
Probes phasespace where shower becomes unreliable, significant improvements through matching with NLO.

[Bellm, Nail, Plätzer, Schichtel, Siodmok – EPJ C76 (2016) 665]
[Rauch, Plätzer – EPJ C77 (2017) 293]



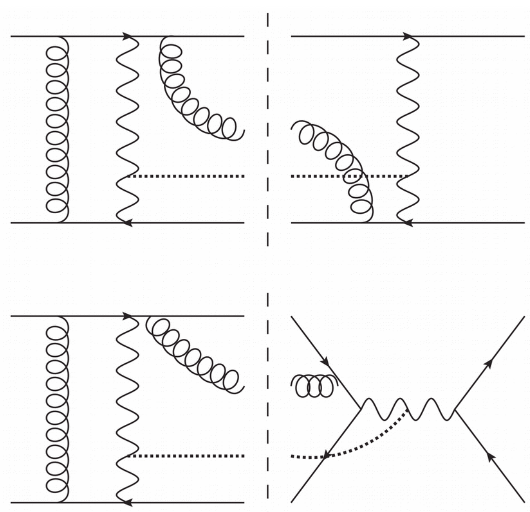
Impact on soft physics is in **hardness of emissions and length of evolution:** Need to pin down cross talk.

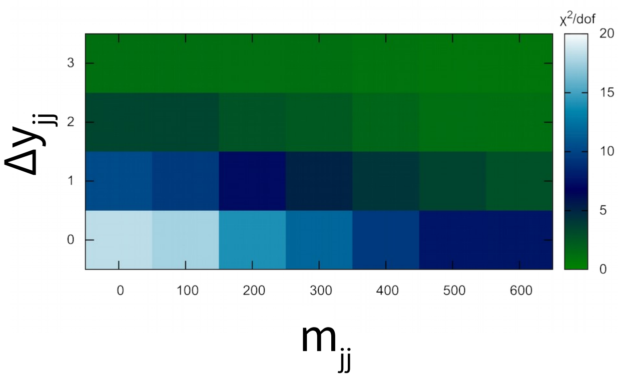
VBF Approximation



Outisde 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.



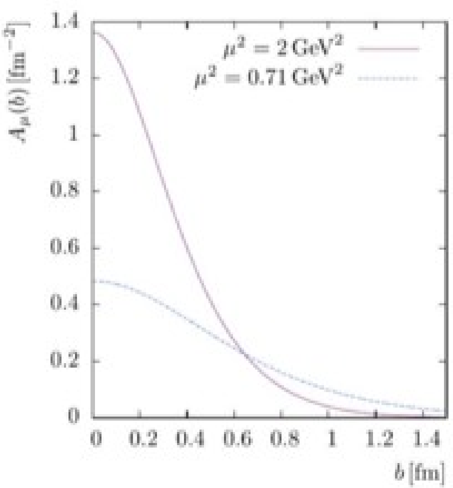


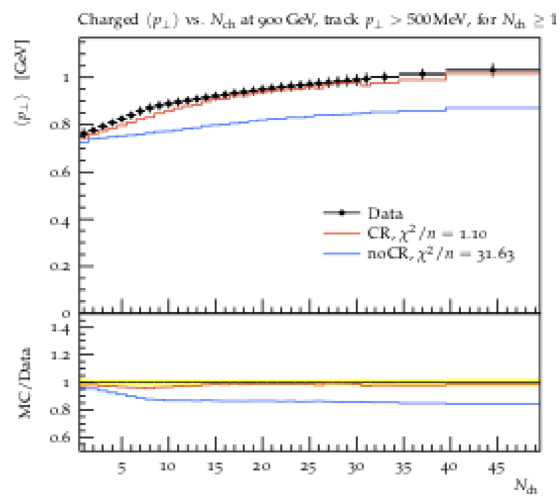
summary of 3rd jet observables vs VBF approximation

[Campanario, Figy, Plätzer, Sjödahl – PRL 111 (2013) 211802]
[Campanario, Figy, Plätzer, Rauch, Schichtel, Sjödahl – PRD 98 (2018) 033]

Multi-parton Interactions & Colour Reconnection

Hard scattering accompanied by several additional partonic scatters.

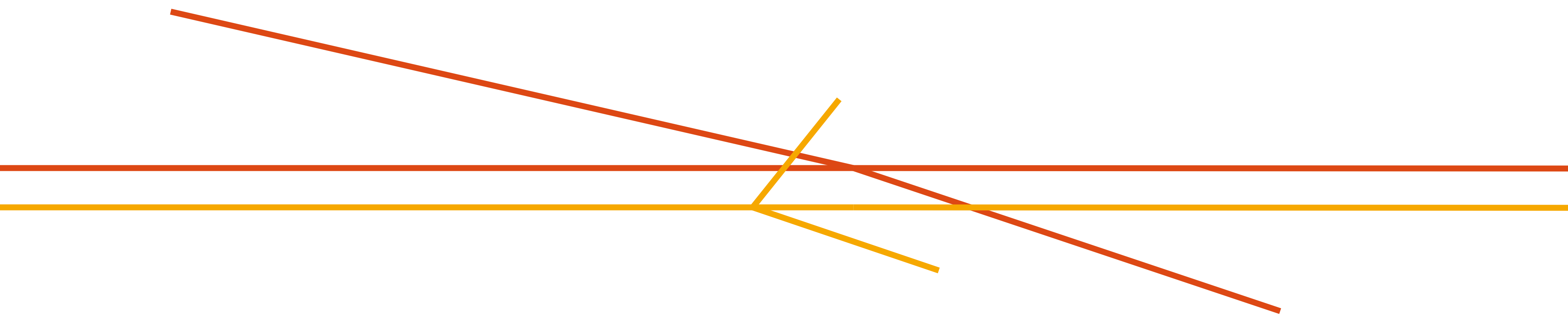




Assume some matter distribution in the proton, and effective multiplicity distribution of additional scatters.

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

[Gieseke, Röhr, Siodmok – EPJ C72 (2012) 2225]



Clear impact on interjet activity and jet shapes.

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

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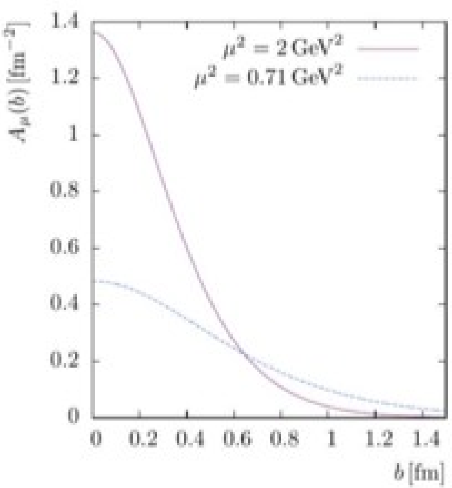

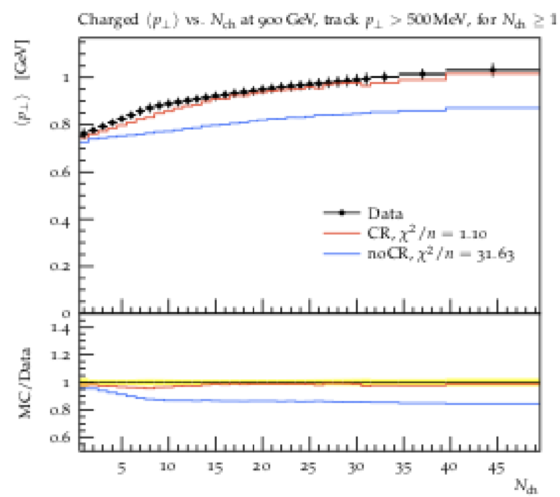

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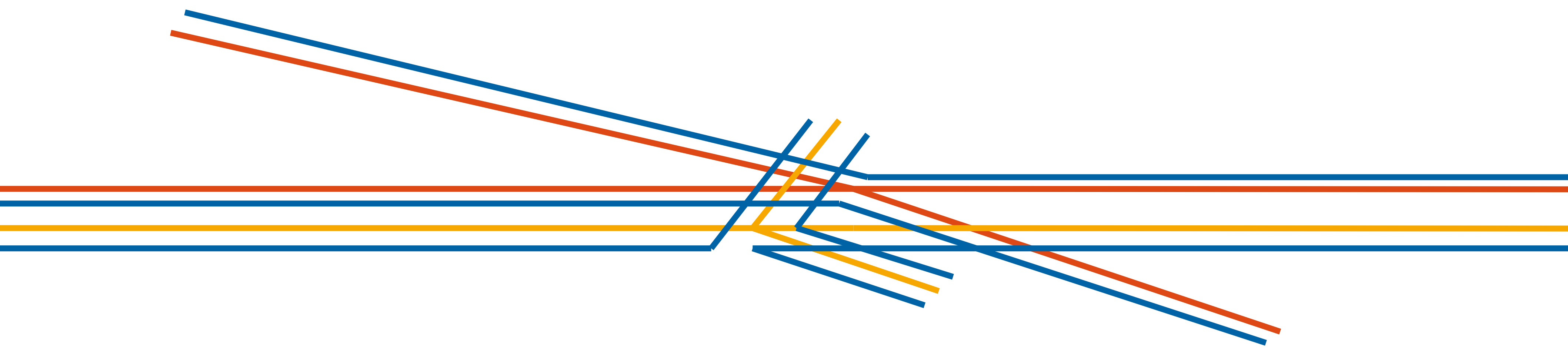

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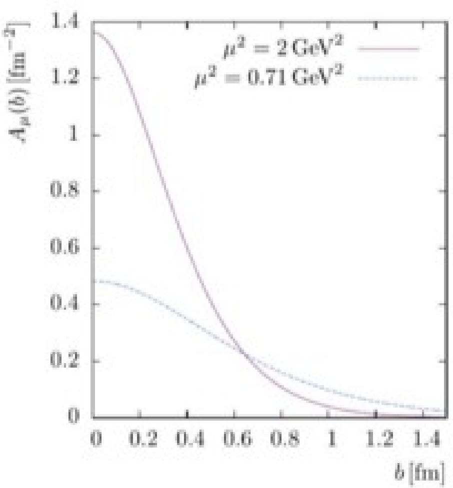

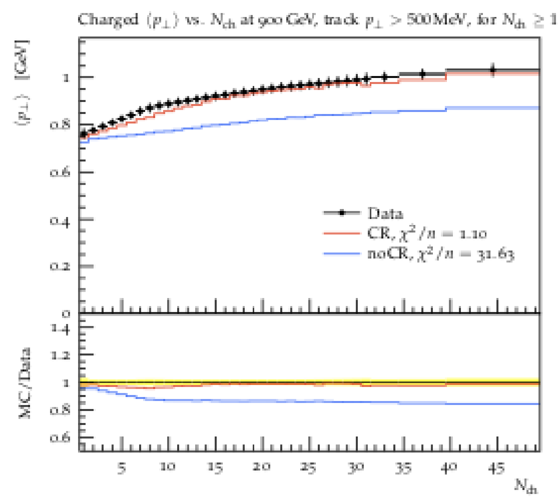

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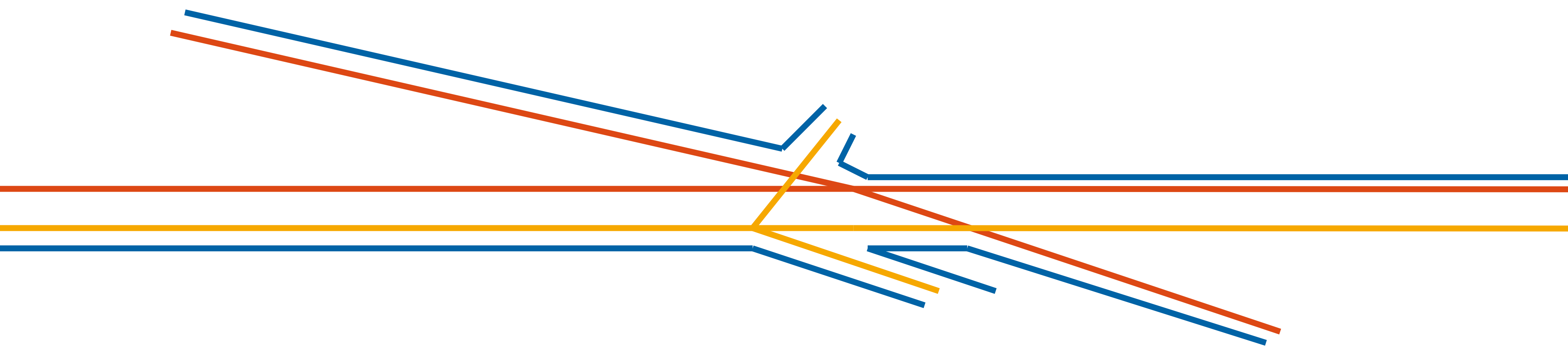


Clear impact on interjet activity and jet shapes.

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

QCD @ VBS workshop

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

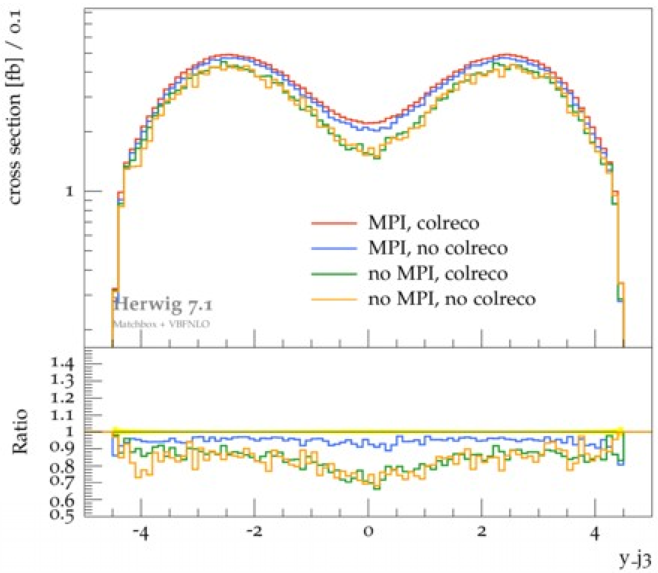
Benchmark

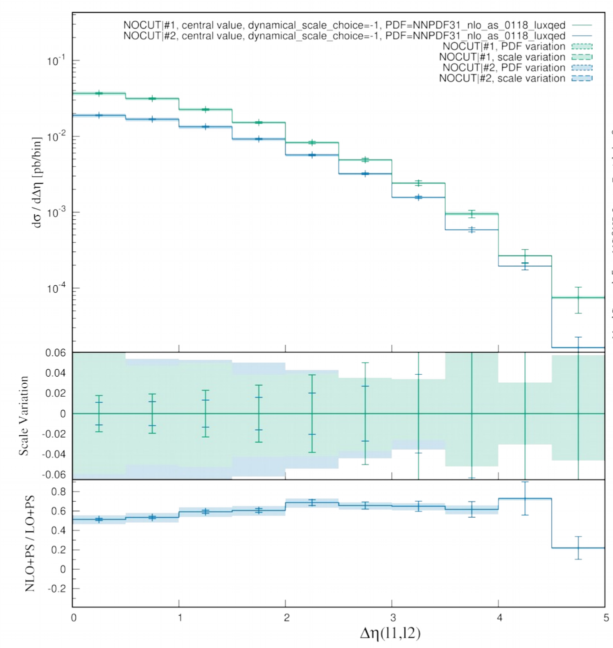
VBF Z production, plus QCD induced background if possible
Ideally at NLO+PS for reliable modeling of hard jet activity.

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





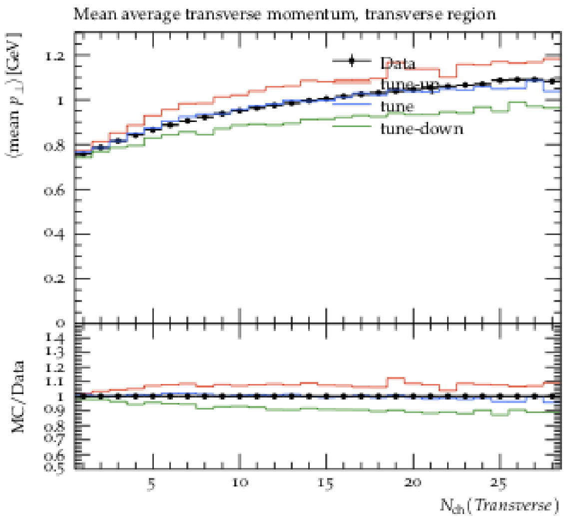
[MG5_aMC plot by Richard Ruiz]

Shower & Tune Variations with Herwig 7 + VBFNLO 3

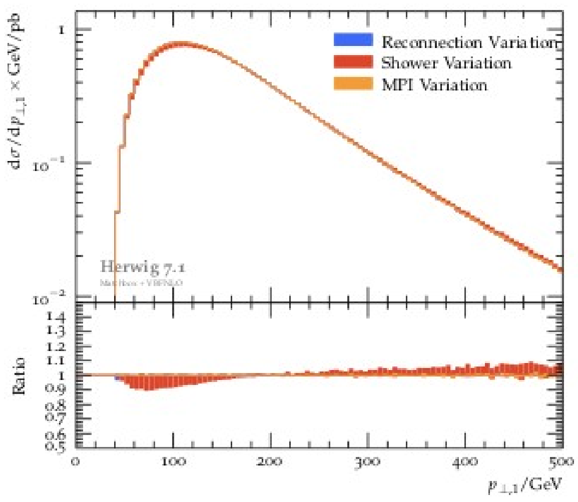
[Work in progress with Carsten Bittrich, Stefanie Todt, Patrick Kirchgaesser, Richard Ruiz, ...]

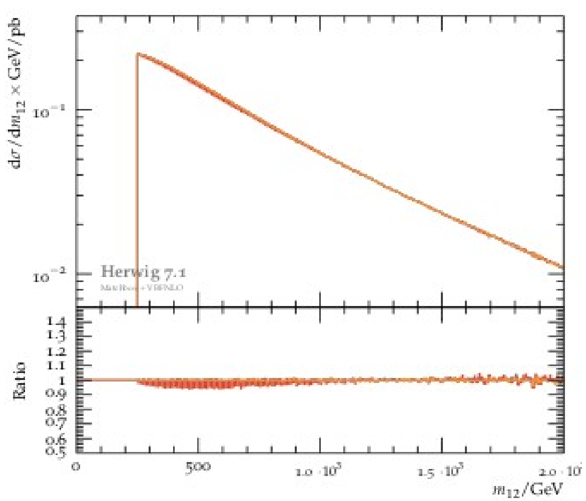
Strategy

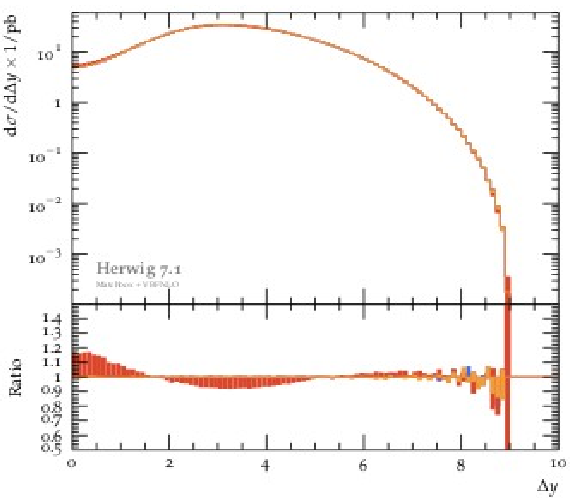
- Vary colour reconnection and MPI parameters to stay within ~ 10% agreement of typical tuning observables
- Vary shower hard scale by factors of ½ and 2
- Currently LO, NLO will significantly improve on shower variations



Tagging jet distributions very stable, mostly independent of VBF cut bin.







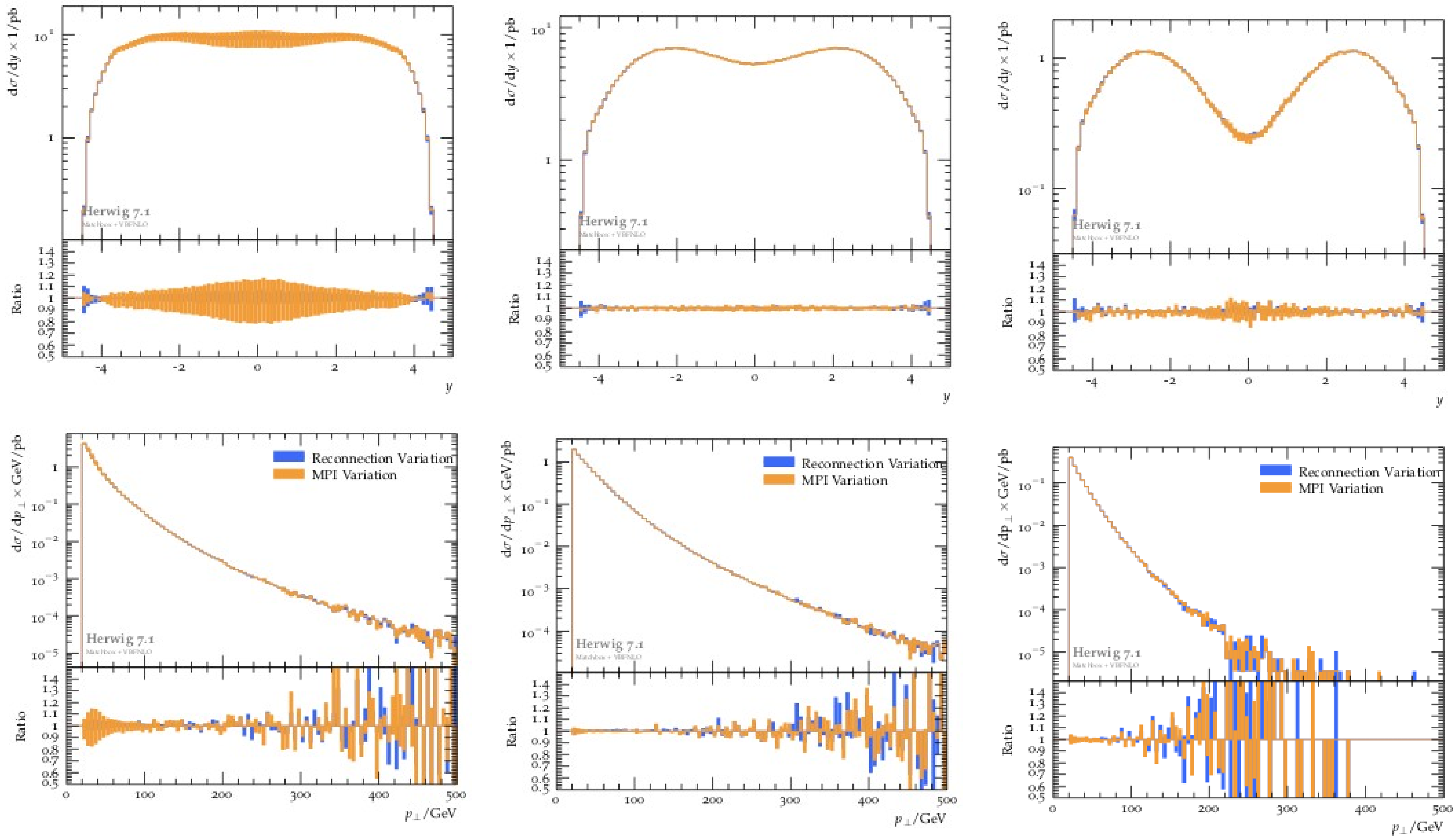
Shower & Tune Variations – 3rd Jet

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

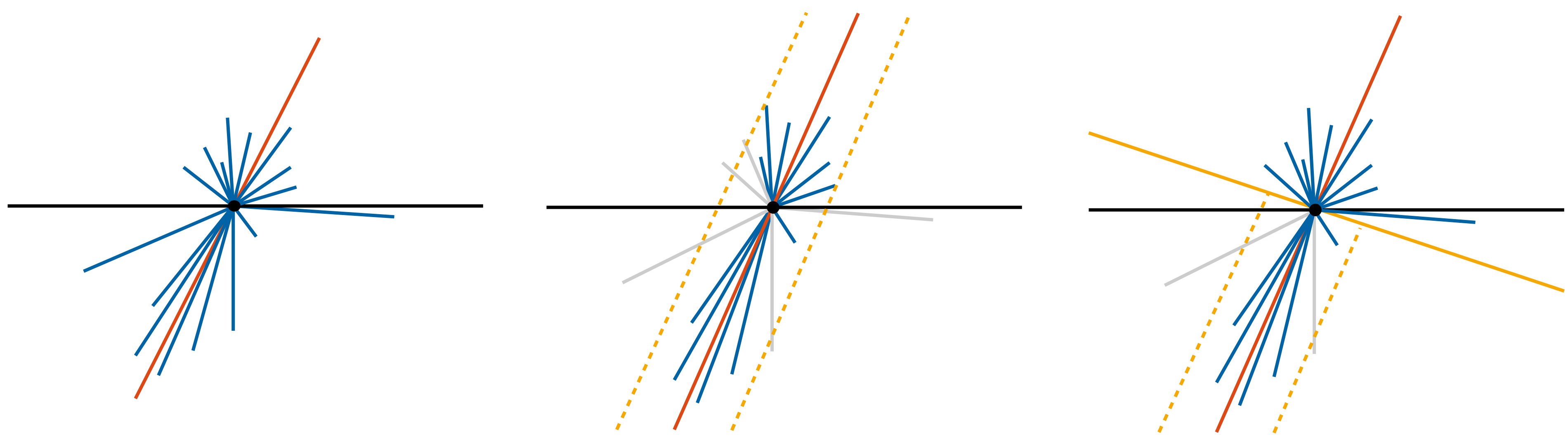
loose VBF, R=1.0, just for illustration

loose VBF selection, R=0.4

tight VBF selection, R=0.4



1/N Corrections, Colour Mixing & Amplitude Evolution



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.

[Dasgupta, Salam – Phys.Lett. B512 (2001) 323]
[Forshaw, Kyrieleis, Seymour – JHEP 0608 (2006) 059]
[Weigert – Nucl.Phys. B685 (2004) 321]
[Caron-Huot – JHEP 1803 (2018) 036]
[Becher, Neubert, Rothen, Shao – JHEP 1611 (2016) 019]

1/N Corrections, Colour Mixing & Amplitude Evolution

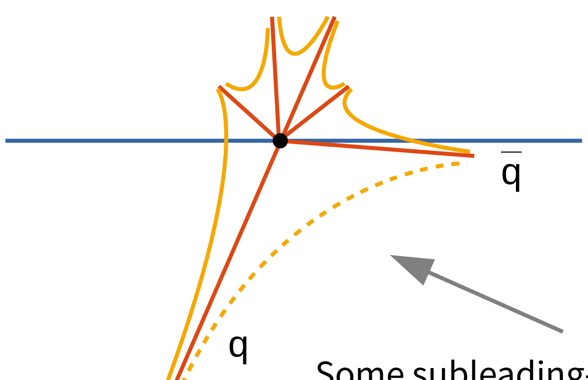
Restore exact colour correlations in factorization of emission rate

$$\mathrm{d}\sigma_{n+1} \sim |\mathcal{M}_{n+1}|^2 = \langle \mathcal{M}_{n+1} | \mathcal{M}_{n+1} \rangle \sim P \; \mathrm{d}\sigma_n \to \frac{\mathrm{Tr}\left[|\mathcal{M}_n\rangle\langle\mathcal{M}_n| \mathbf{P} \right]}{|\mathcal{M}_n|^2 P} \; P \; \mathrm{d}\sigma_n$$

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

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

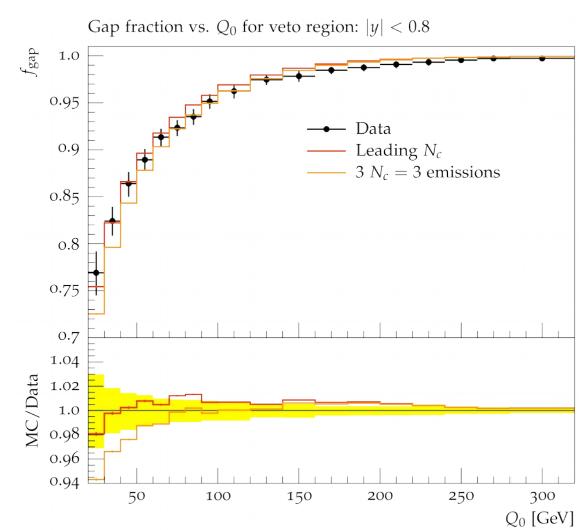
Dipole branching algorithms can be supplemented by correction factors for real emission, but still lack virtual contributions beyond leading-N.



Soon out with Herwig 7.2

Some subleading-N corrections can be restored.

[Plätzer, Sjödahl – JHEP 1207 (2012) 042]
[Plätzer, Sjödahl, Thoren – JHEP 11 (2018) 009]



Parton branching at the amplitude level

[Angeles, De Angelis, Forshaw, Plätzer, Seymour – JHEP 05 (2018) 044]
[Forshaw, Holguin, Plätzer – arXiv:1905.08686, to appear in JHEP]

Universal framework requires evolution at the amplitude level:

$$\sigma = \sum_n \int \mathrm{Tr}\left[\mathbf{A}_n(\mu)\right] u(p_1, ..., p_n)\ \mathrm{d}\phi_n$$

\`density operator\` $\mathbf{A}_n(\mu) = |\mathcal{M}_n(\mu)\rangle\langle\mathcal{M}_n(\mu)|$ observable phase space

Virtual corrections and colour mixing
in all orders perturbation theory.

$$|\mathcal{M}_n(\mu)\rangle = \mathbf{Z}^{-1}(\mu, \epsilon)|\tilde{\mathcal{M}}_n(\epsilon)\rangle$$

$$\mathbf{A}_n(E) = \mathbf{V}(E, E_n)\mathbf{D}_n\mathbf{A}_{n-1}(E_n)\mathbf{D}_n^\dagger\mathbf{V}^\dagger(E, E_n)\theta(E - E_n)$$

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.

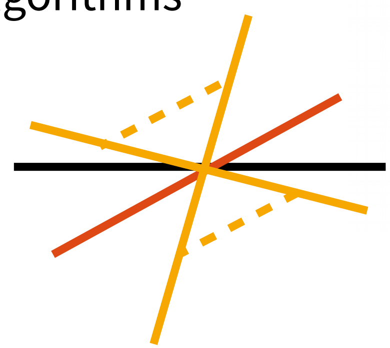
[Plätzer – EPJ C 74 (2014) 2907]

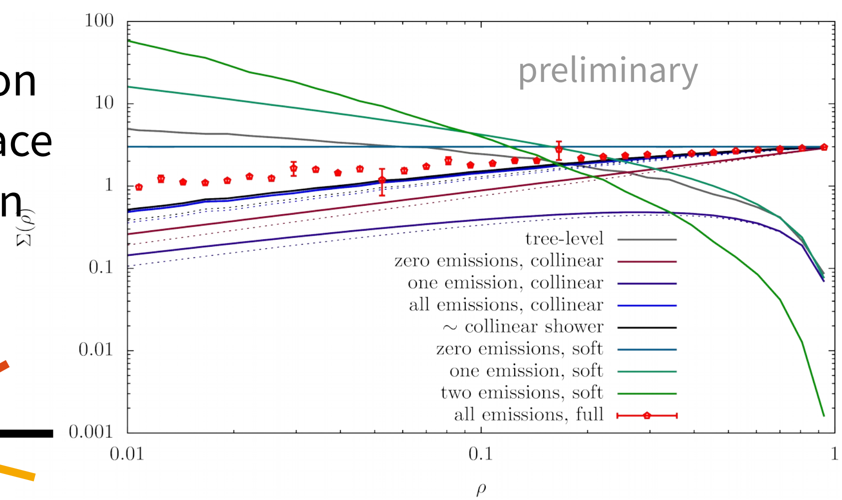
1/N Corrections, Colour Mixing & Amplitude Evolution

[work in progress with De Angelis, Forshaw, Kirchgaesser]

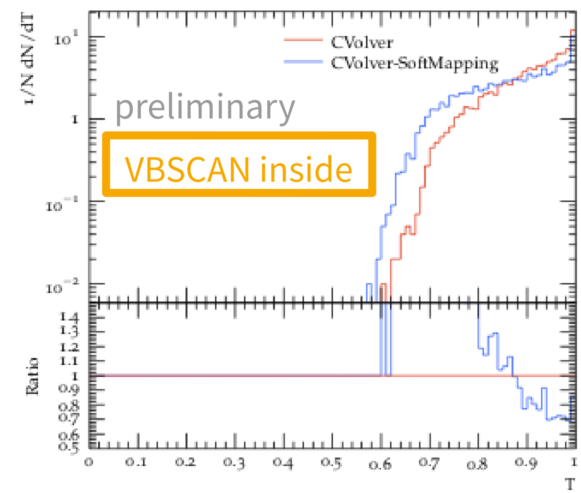
CVolver library

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





Gaps between jets (e+e-)

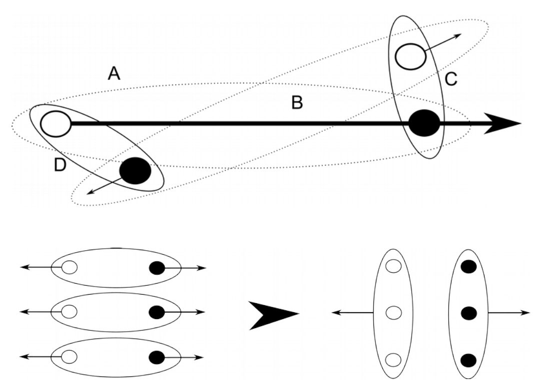


Event shapes (e+e-)

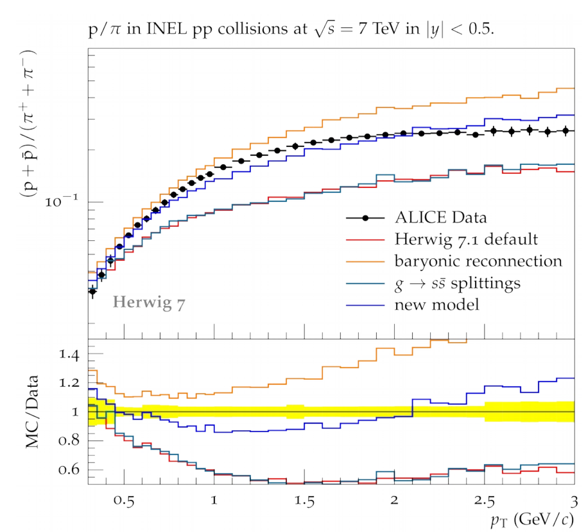
A fresh look at colour reconnection

$$|\mathcal{M}\rangle = e^{\mathbf{\Gamma}}|\text{clusters}\rangle$$

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



[Gieseke, Kirchgaesser, Plätzer – EPJ C 78 (2018) 99]
[Gieseke, Kirchgaesser, Plätzer, Siodmok – JHEP 11 (2018) 149]



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!