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QCD Effects in VBF/VBS

Simon Plätzer
Particle Physics — University of Graz / University of Vienna

At the
Multi-Boson-Interactions Conference
Milano/Online | 25 August 2021

[a personal overview]

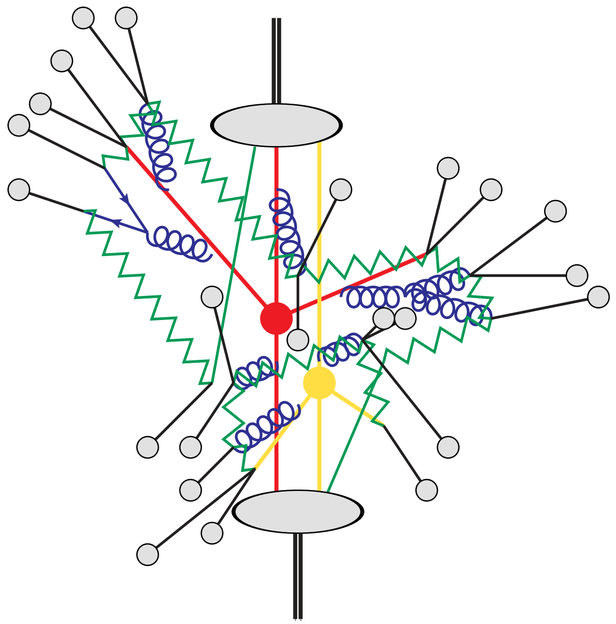
PP collisions are more complex

QCD description of collider reactions:
Complexity challenges precision.

Hard partonic scattering:
NLO QCD routinely

Jet evolution — parton showers:
NLL sometimes, mostly unclear

Multi-parton interactions
Hadronization



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

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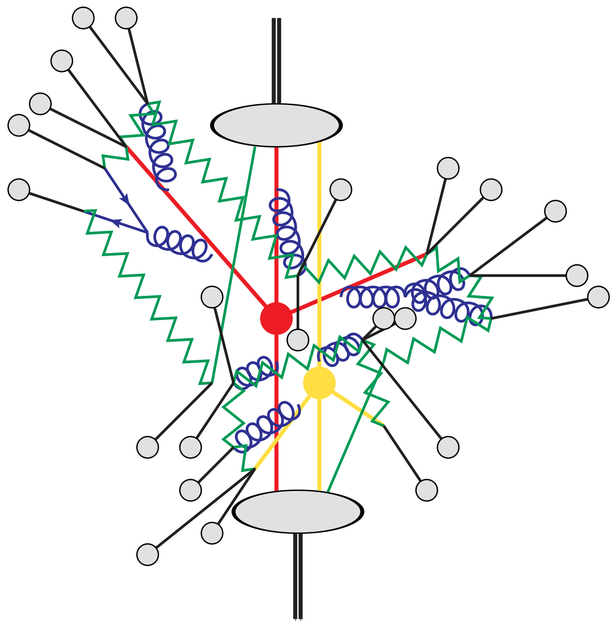
All challenged by VBF/VBS!



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Fixed order and the VBF approximation

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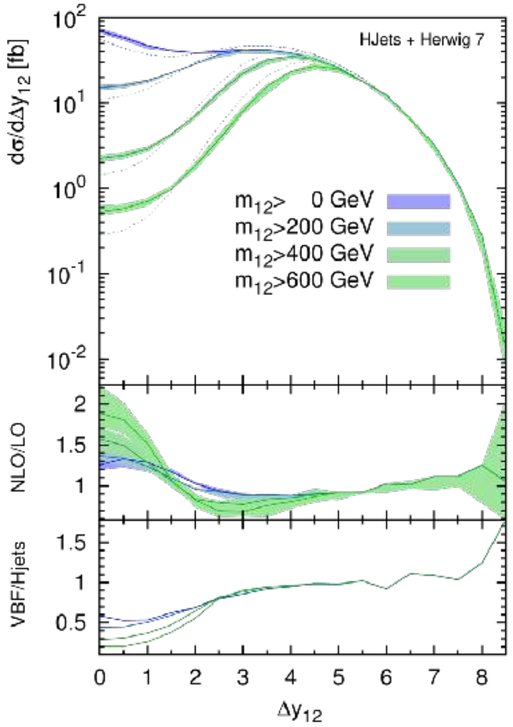
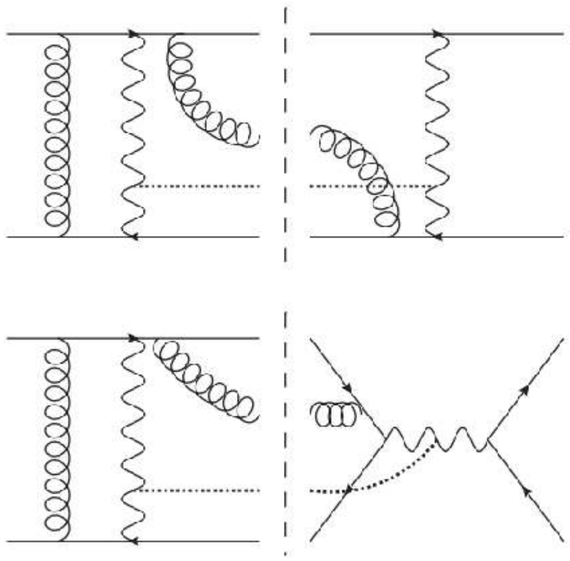
Approximation at NLO: acceptable in tight VBF selection. Challenge is in using full calculations throughout, and for anomalous couplings etc.

[Ballestero et al. — Eur.Phys.J.C 78 (2018) 8, 671]



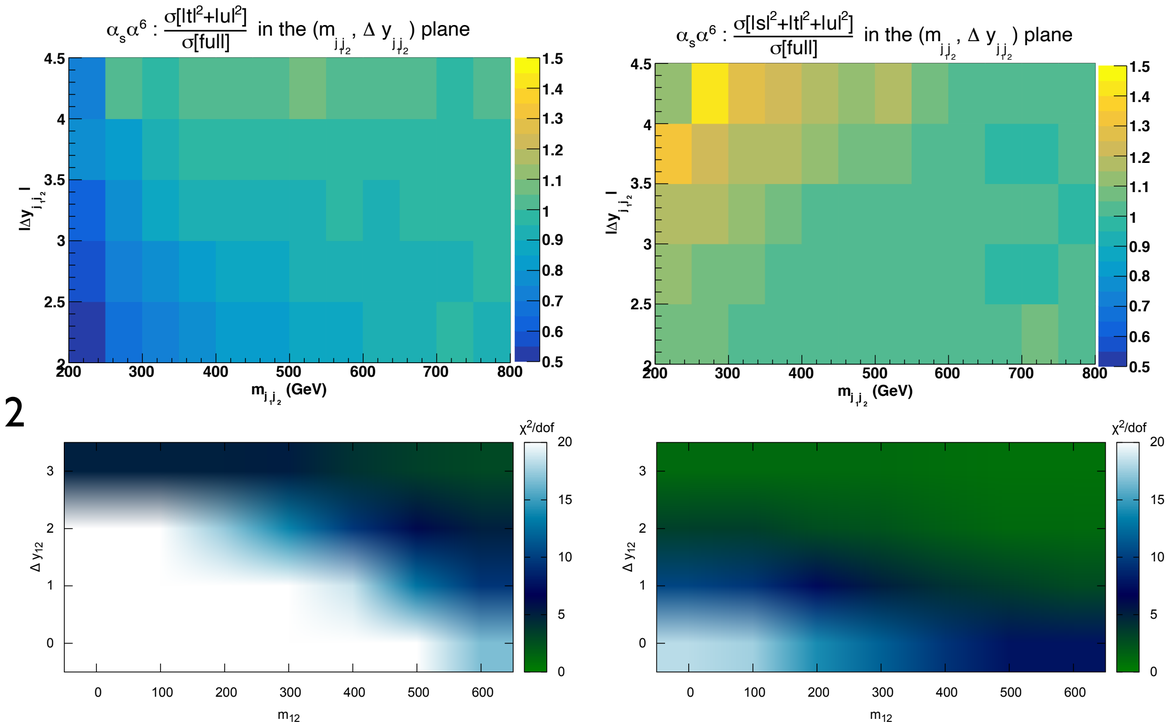
"non-factorizable"



"s channel"

no s channels

s channels in approximation



Δy_{12}

m_{12}

s channels un-suppressed

s channels vetoed

[Campanario, Figy, Plätzer, Sjödahl – PRL 111 (2013) 211802]

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

Colour in VBS/VBF

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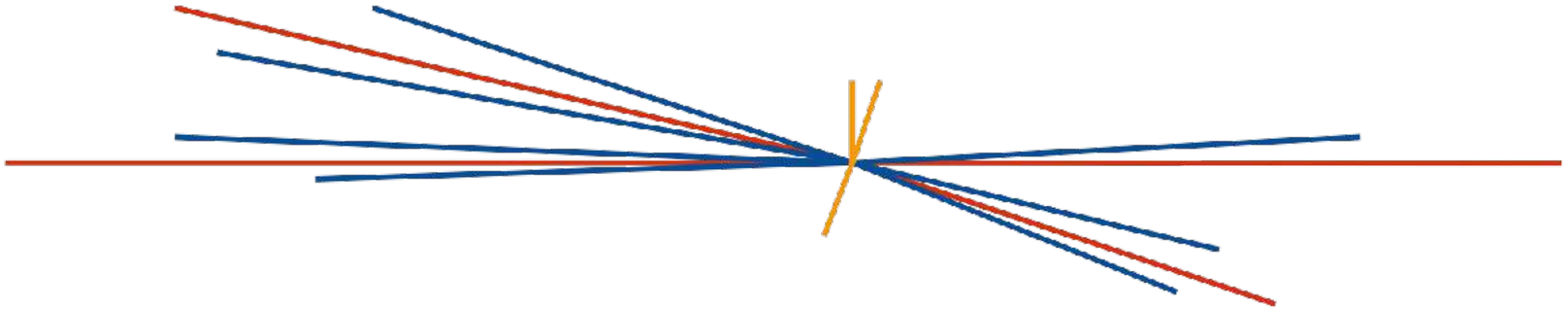
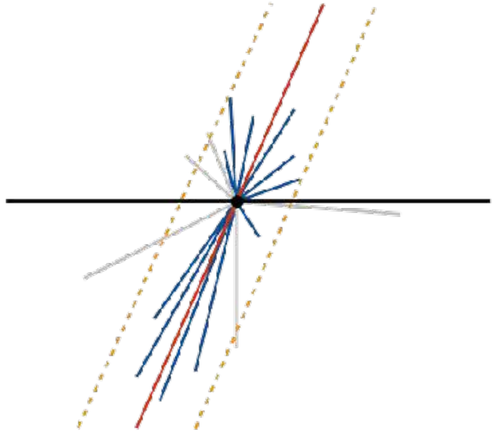
Coherent emission of soft large angle gluons from systems of collinear partons.

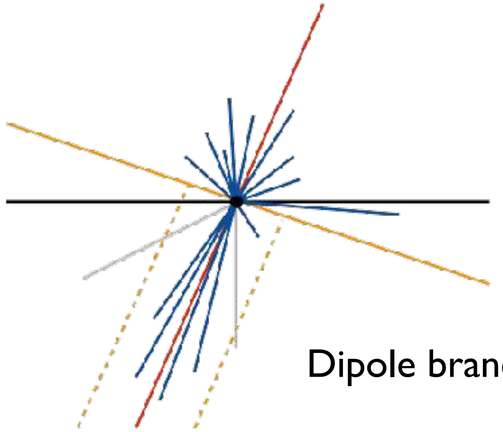


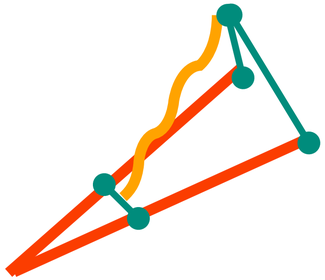
Parton showers: dipoles vs angular ordered, issues of accuracy.
Can formulate dipole showers which reproduce coherent branching.

[Salam et al. — JHEP 09 (2018) 033]
[Forshaw, Holguin, Plätzer – JHEP 09 (2020) 014]



Parton branchings order in angle:
accurate for global observables.





Dipole branchings order in transverse momentum:
accurate for non-global observables.

Colour in VBS/VBF

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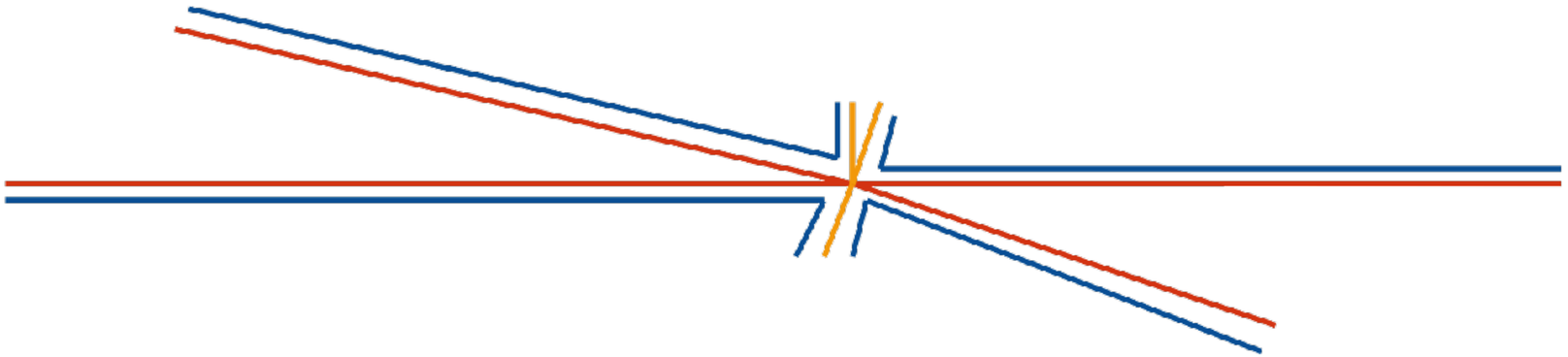

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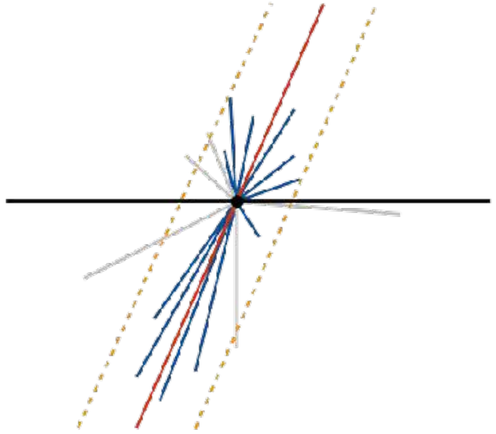

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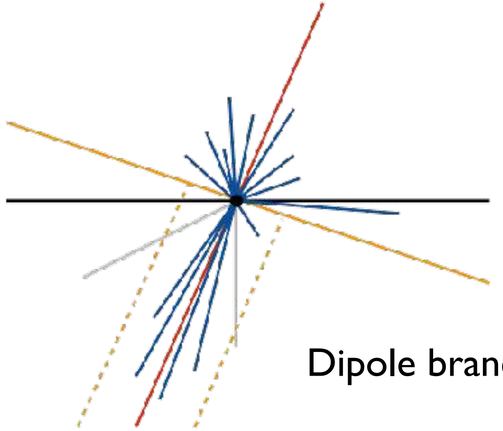

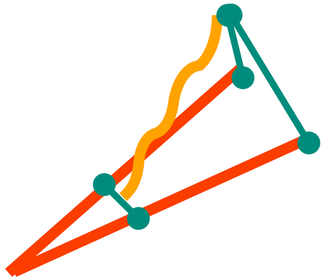

Dipole branchings order in transverse momentum:
accurate for non-global observables.

Challenges for Matching and Merging

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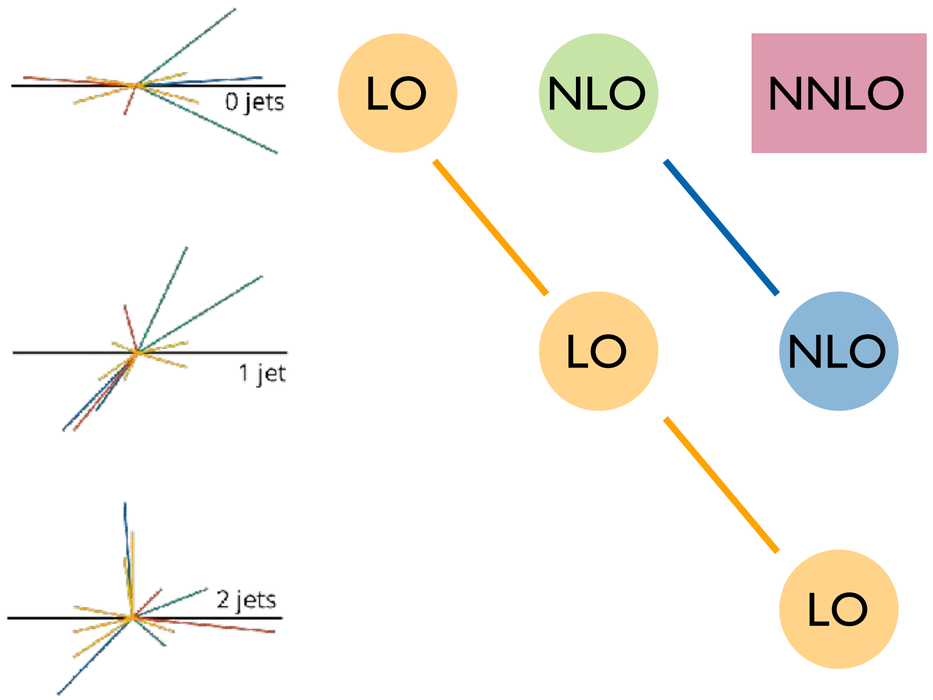
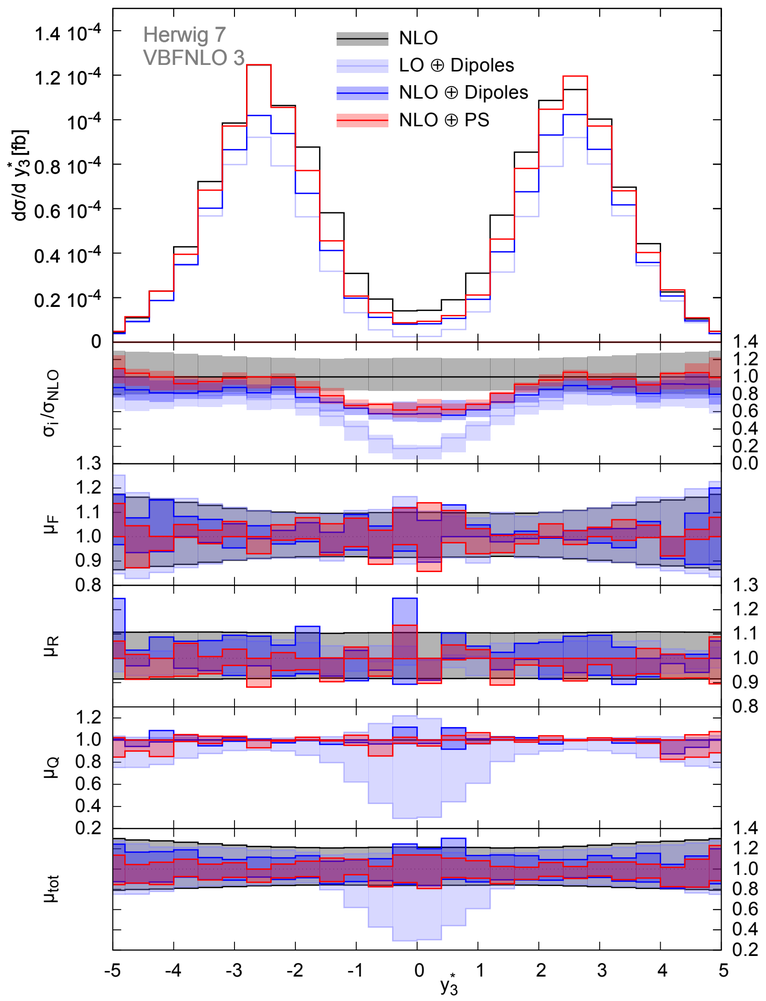
Jets at Born level:

- Generation cut uncertainties
- Merging algorithms specifically challenged — solved within modified unitarized merging.

[Bellm, Gieseke, Plätzer — EPJ C78 (2018) 244]



Merging & matching
NLO merging



[Rauch, Plätzer – EPJ C77 (2017) 293]

Challenges for Matching and Merging

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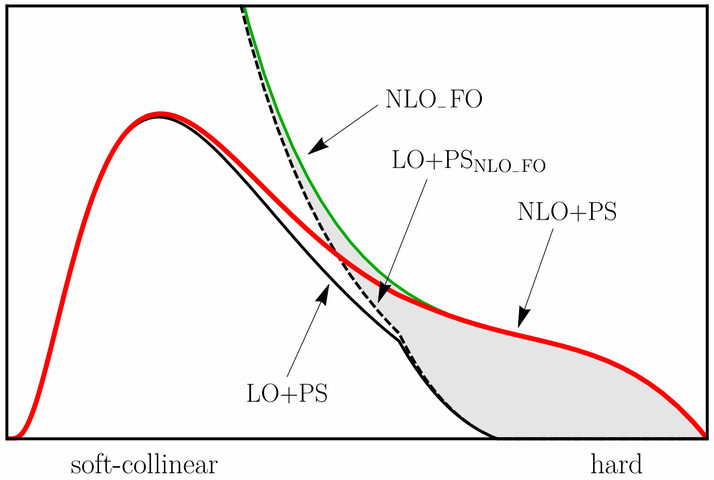
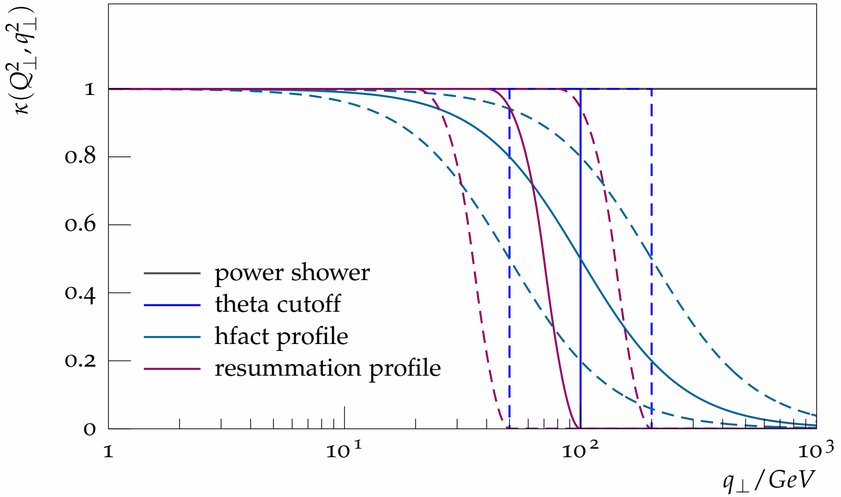
Jets at Bor

- Genera
- Merging
  modifie



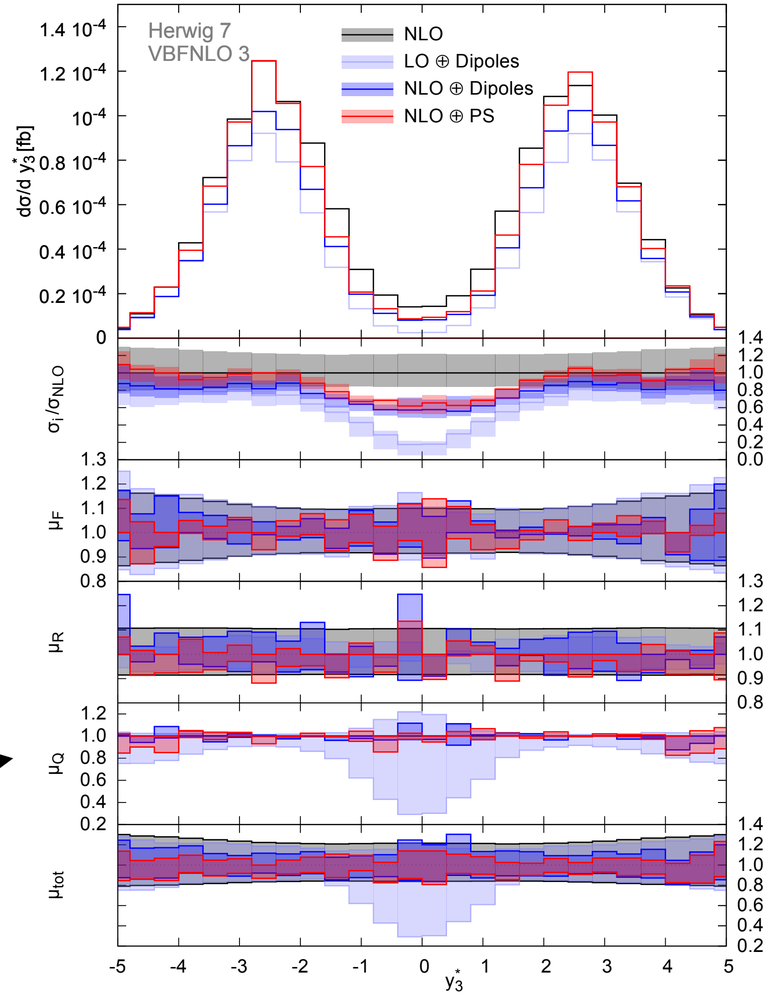


[Bellm, Nail, Plätzer, Schichtel, Siodmok – EPJ C76 (2016) 665]

thin

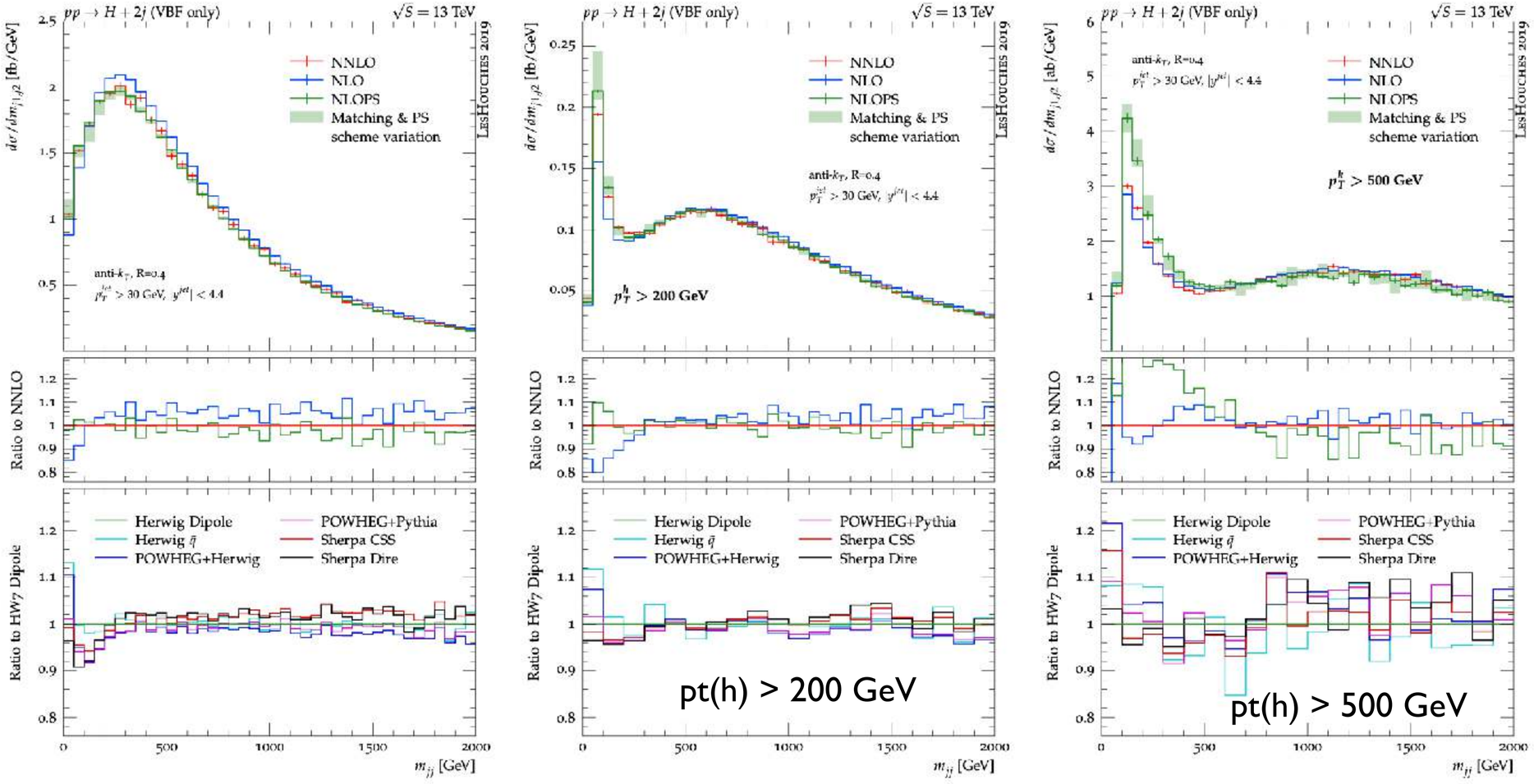
J C78 (2018) 244]

matching
ging



[Rauch, Plätzer – EPJ C77 (2017) 293]

Matching & Showers



Larger differences at large Higgs pt.

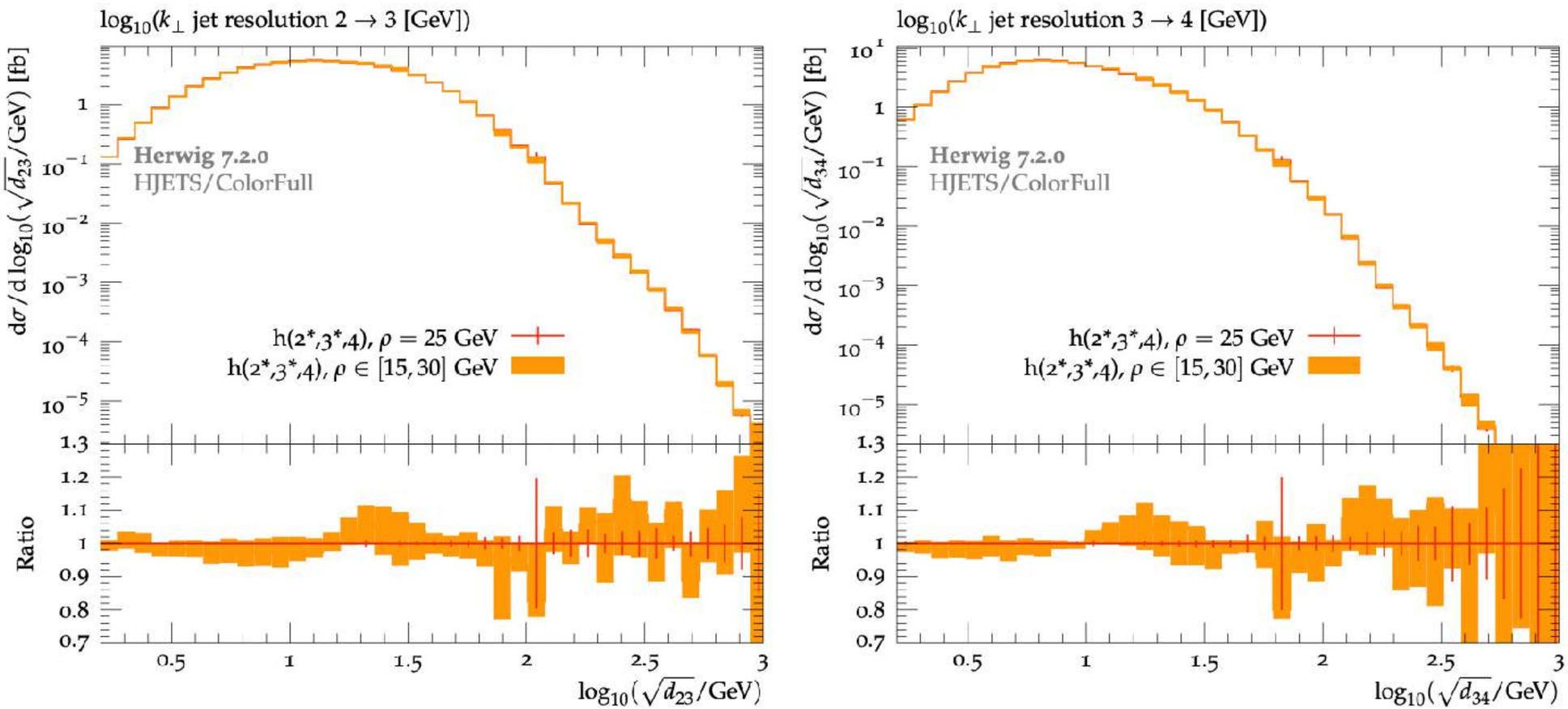
Good agreement in between showers.
Matched showers ~ NNLO.

[Ferrario-Varasio et al. (LH 2019) — arXiv:2105.11399]
also see [Jäger, Karlberg, Plätzer, Scheller, Zaro — EPJ C80 (2020) 756]

Merging

[Chen, Figy, Plätzer — arXiv:soon]

Unitarized merging with VBF up to H+3jet at NLO



Stable under merging scale variations — transition between jet bins NLO(2), NLO(3) and LO(4)

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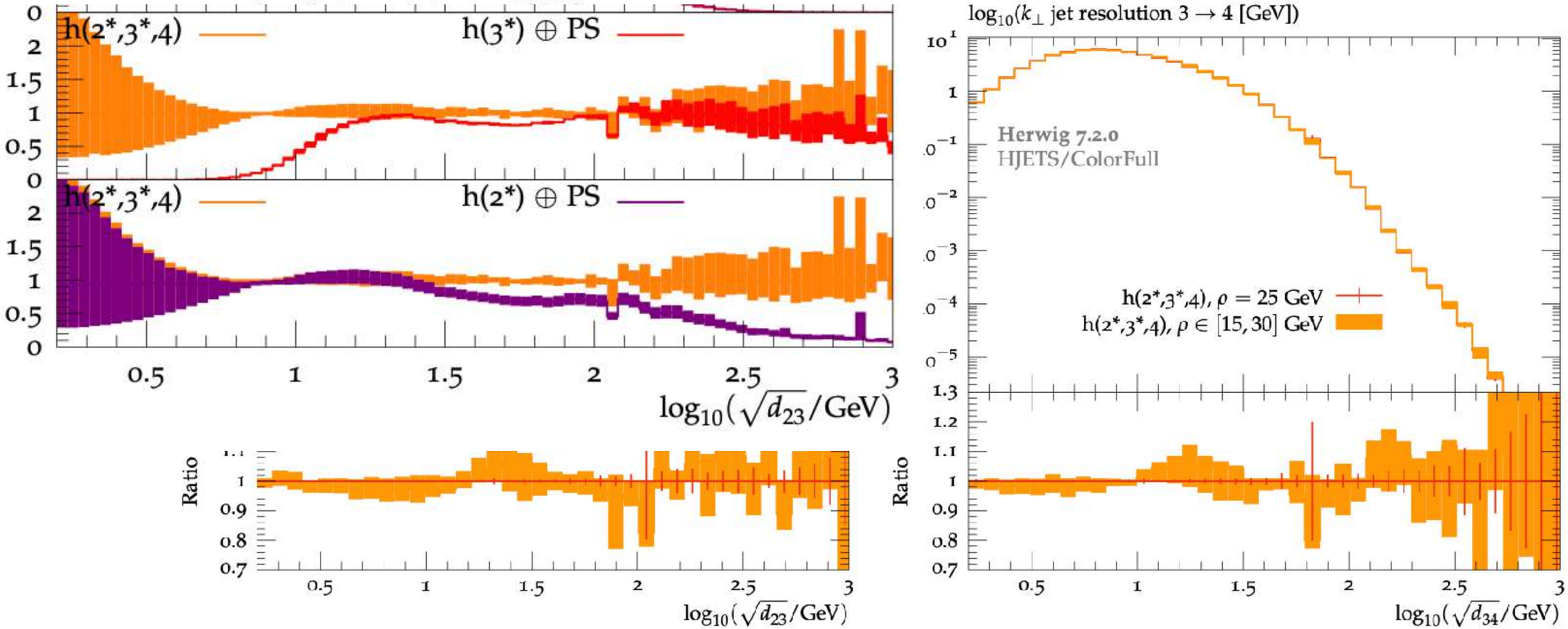


Stable under merging scale variations — transition between jet bins NLO(2), NLO(3) and LO(4)

Merging

[Chen, Figy, Plätzer — arXiv:soon]

Delicate interplay of VBF approximation and subsequent showering even within VBF phase space.

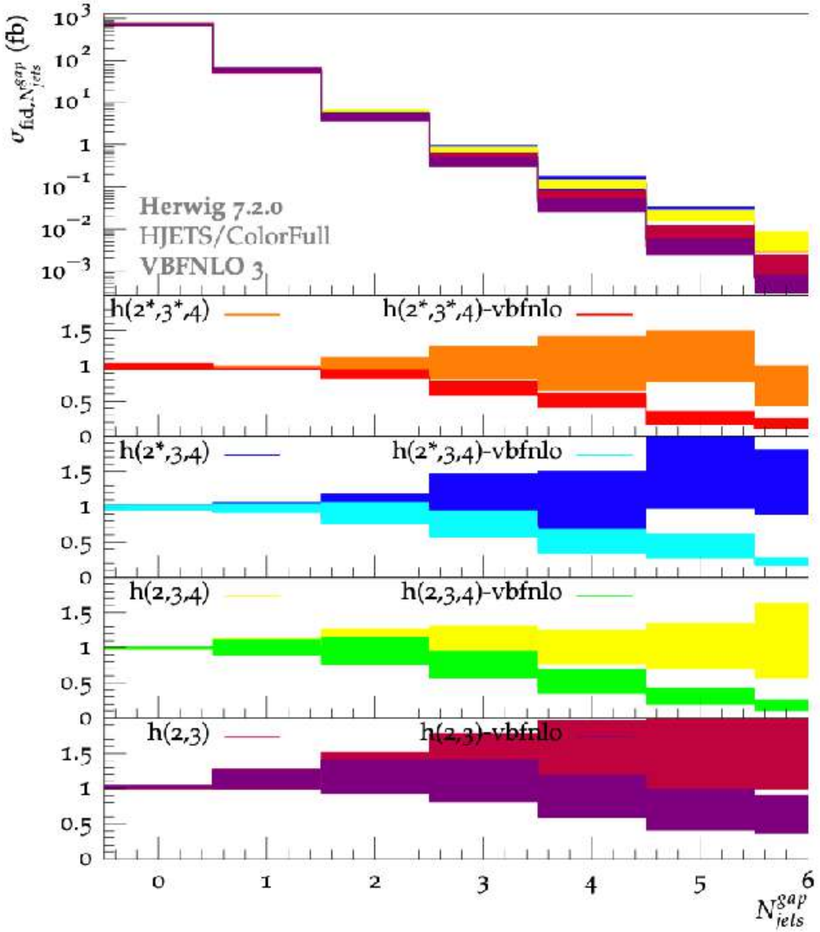
NLO(2) / NLO (3) / LO (4)

NLO(2) / LO (3) / LO (4)

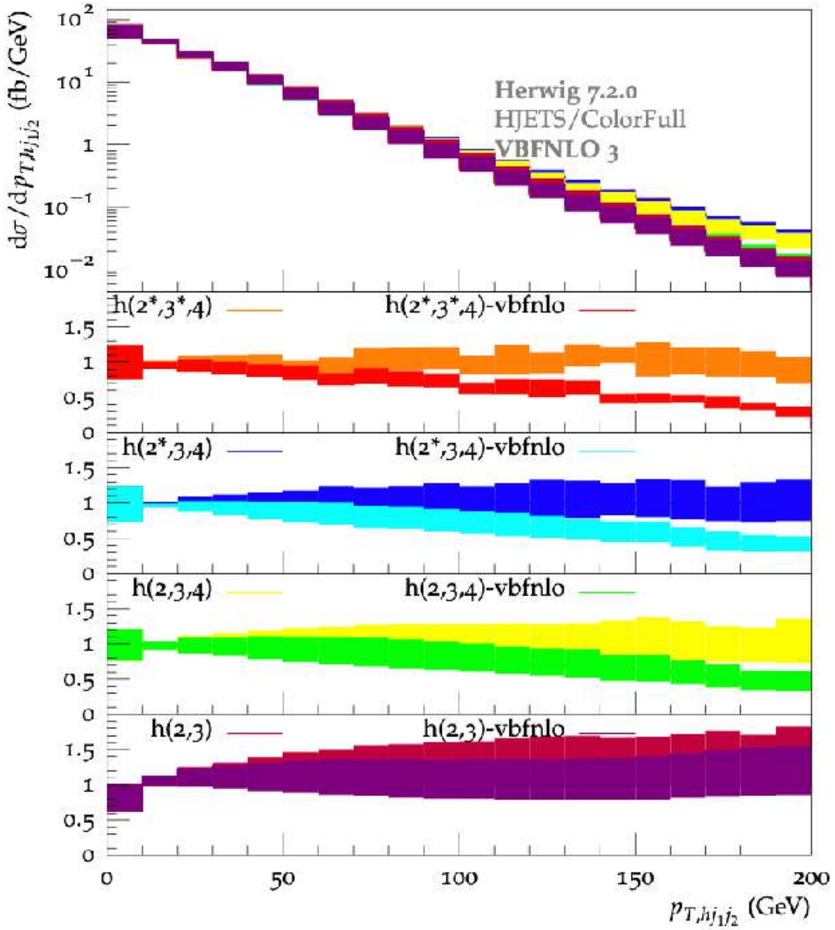
LO(2) / LO (3) / LO (4)

LO(2) / LO (3) / PS (4)

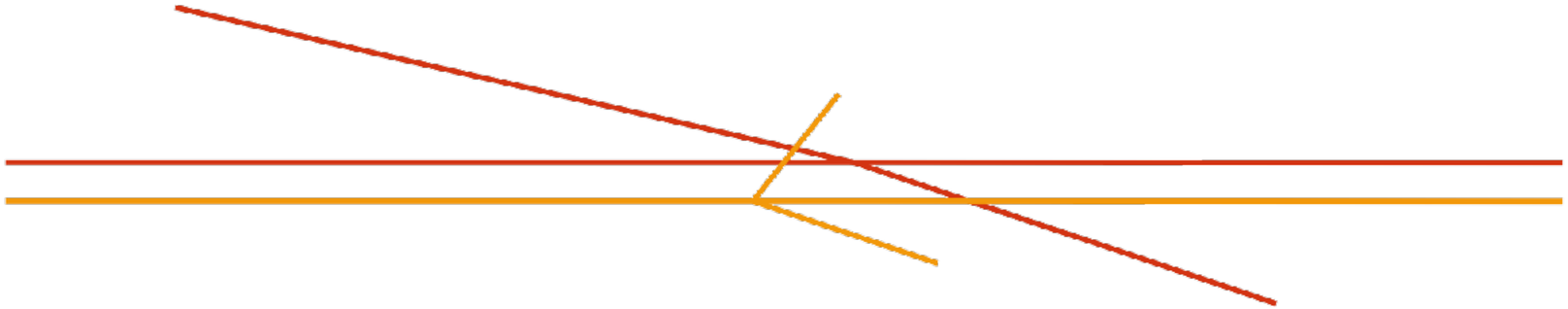
Gap jet multiplicities (tight VBF).



pt(hjj) ~ radiation recoil (loose VBF).

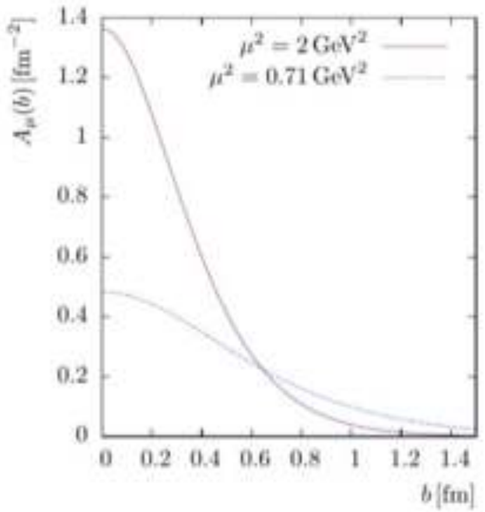


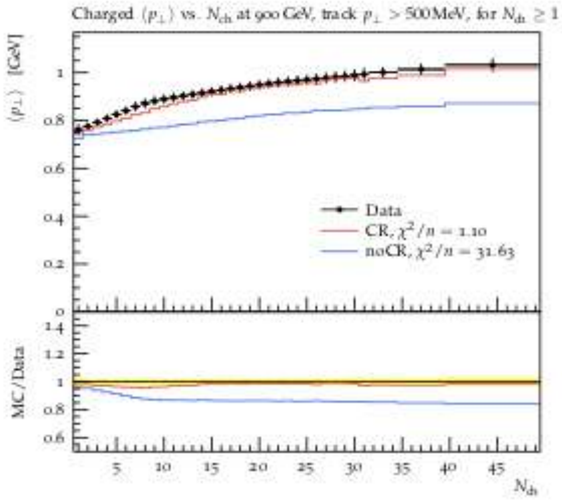
MPI & Colour Reconnection



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

Colour reconnection crucial to describe MinBias and UE data: lack of knowledge about colour correlations.





[Gieseke, Kirchgaesser, Plätzer – EPJ C 78 (2018) 99]

[Gieseke, Röhr, Siodmok – EPJ C 72 (2012) 2225]

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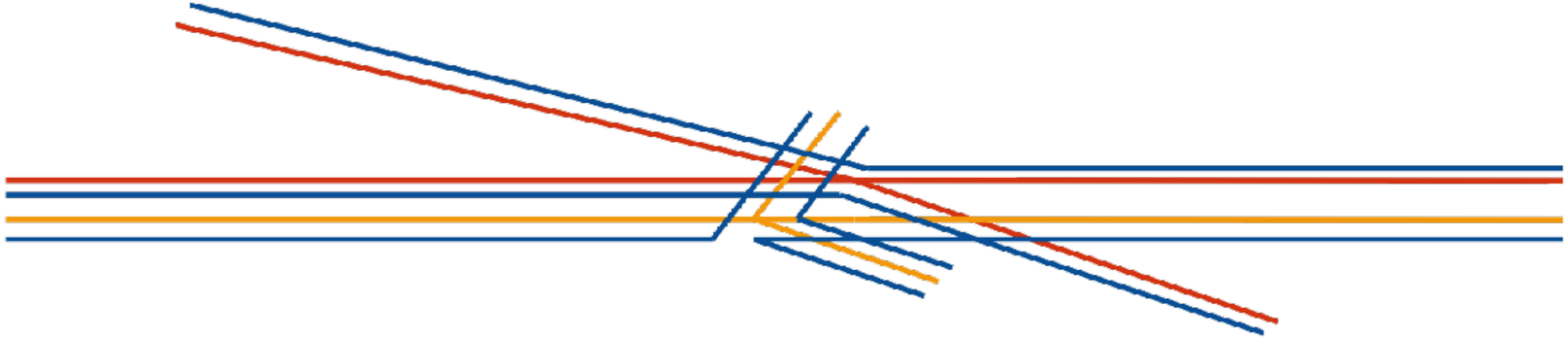

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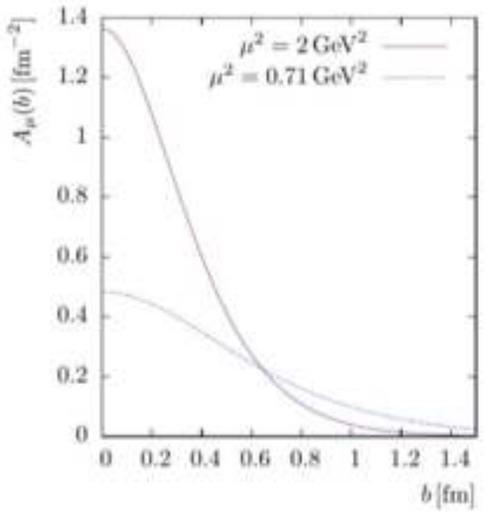

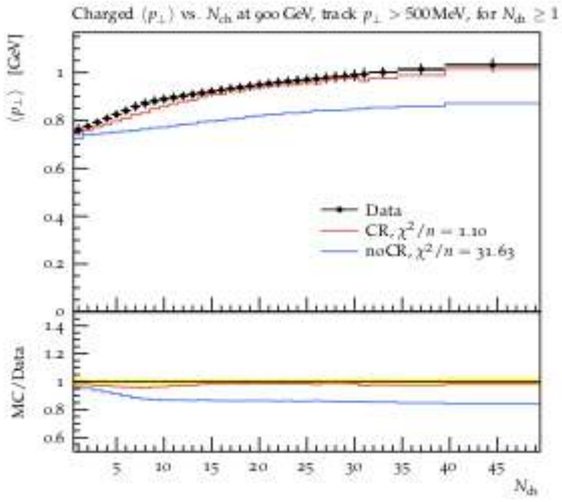

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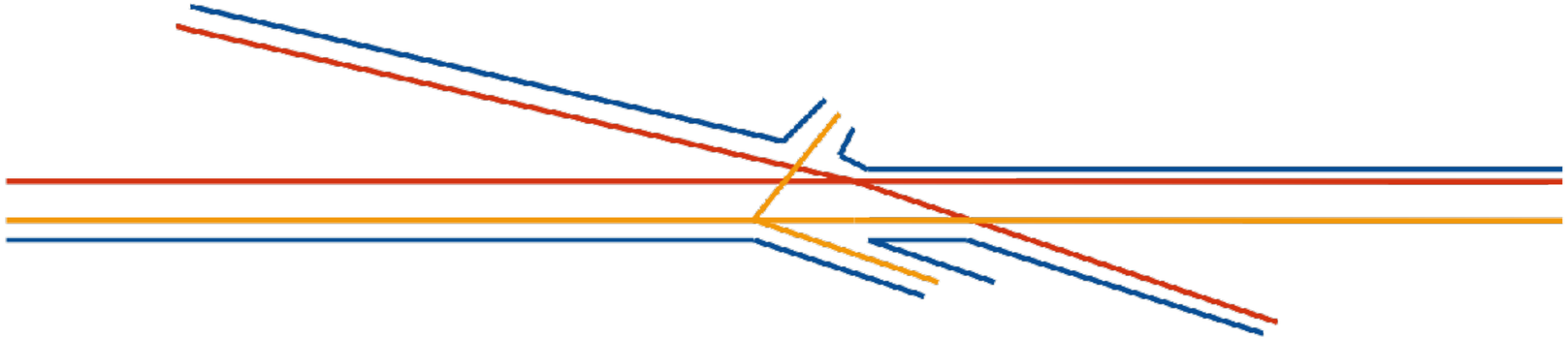

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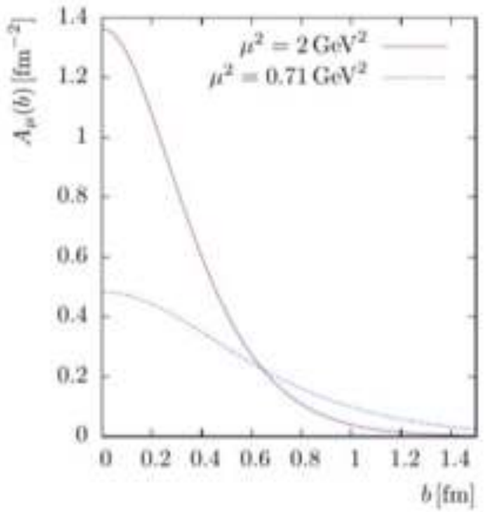

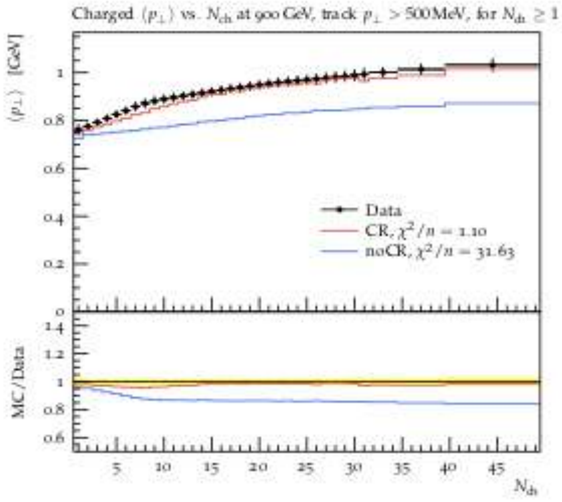

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MPI & Colour Reconnection

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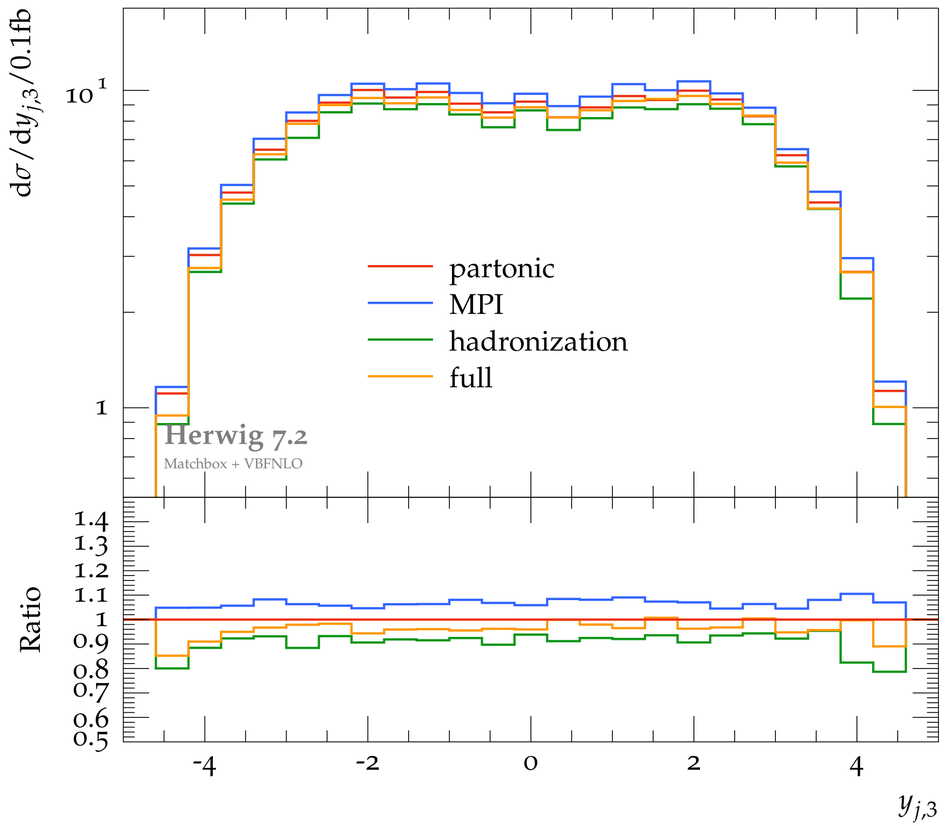
[Bittrich, Kirchgaesser, Papaefstathiou, Plätzer, Todt — arXiv:soon]

Soft QCD effects are not absent: significant impact on interjet activity and jet shapes. On/off exercise will only hint at their relative importance.

Questions to be raised:

- Quantify impact (and how certain that is)
- Determine interplay with perturbative variations and models
- Watch out for lack of perturbative dynamics beyond current NLO+PS



Benchmark is VBF Z production, but findings should be ~ universal.

MPI & Colour Reconnection

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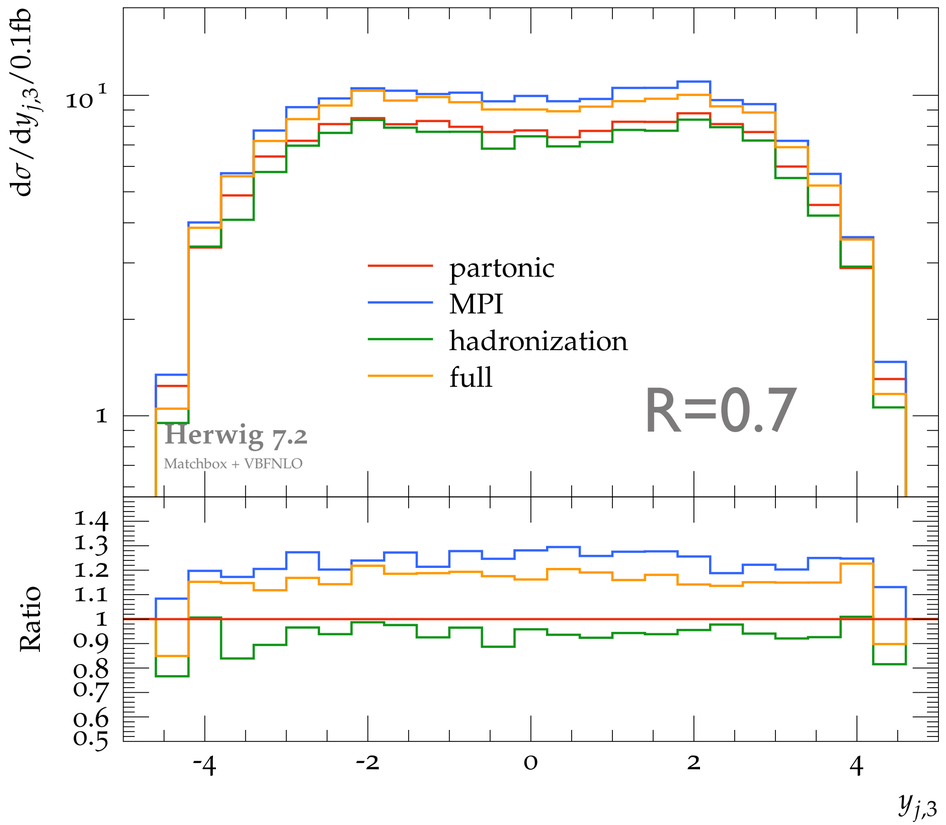

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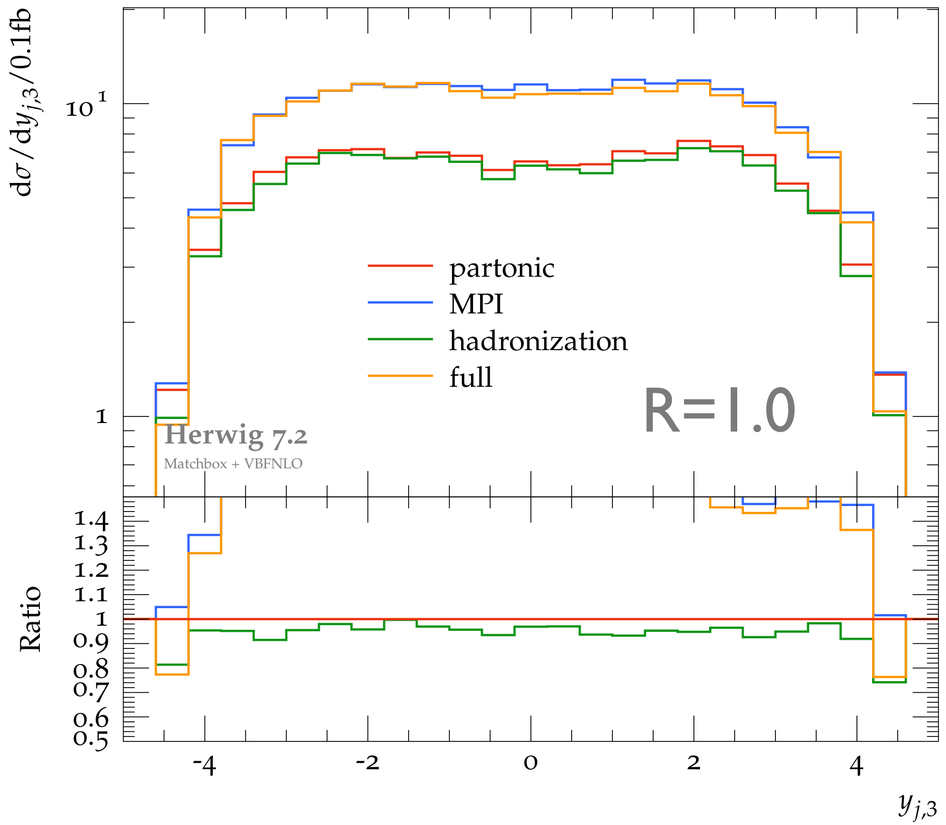

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Model variations

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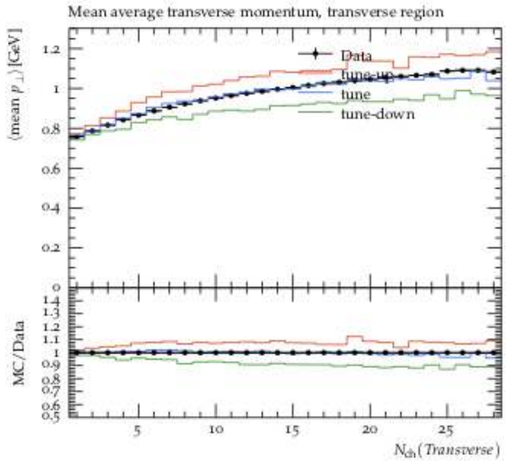
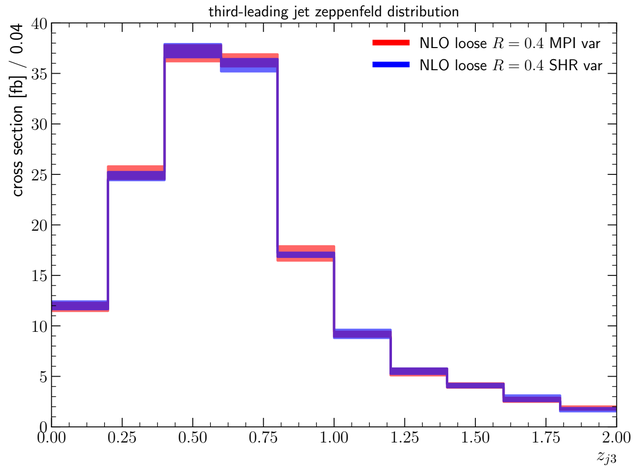
Strategy

- Vary colour reconnection and MPI parameters to stay within ~ 10% agreement of typical tuning observables
- Vary perturbative scales, specifically shower hard scale

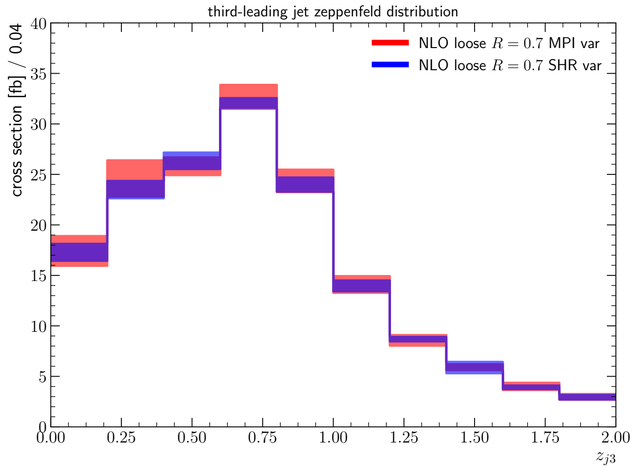


Loose selection

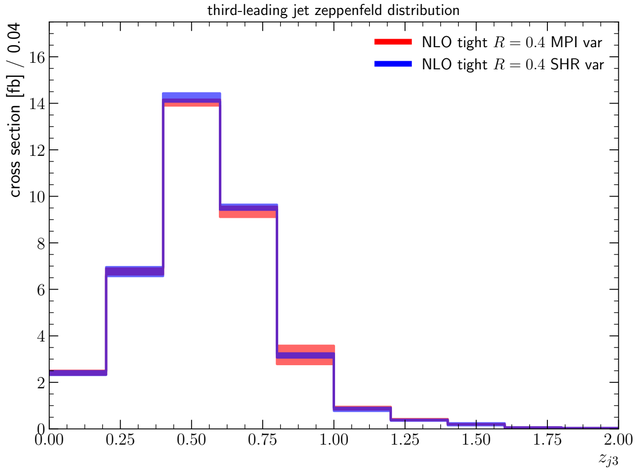
R=0.4

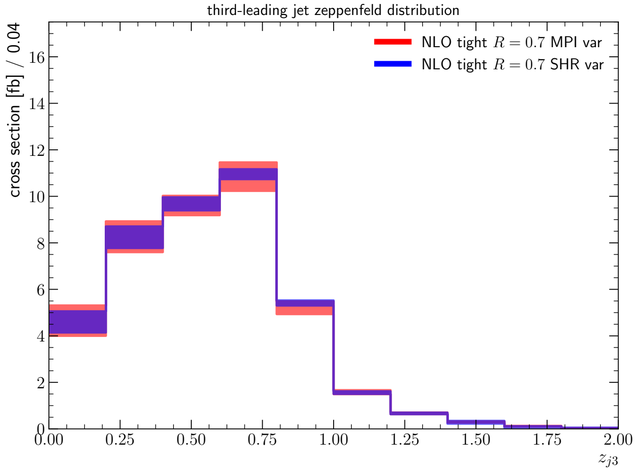


R=0.7



Tight selection





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Colour Evolution in VBF

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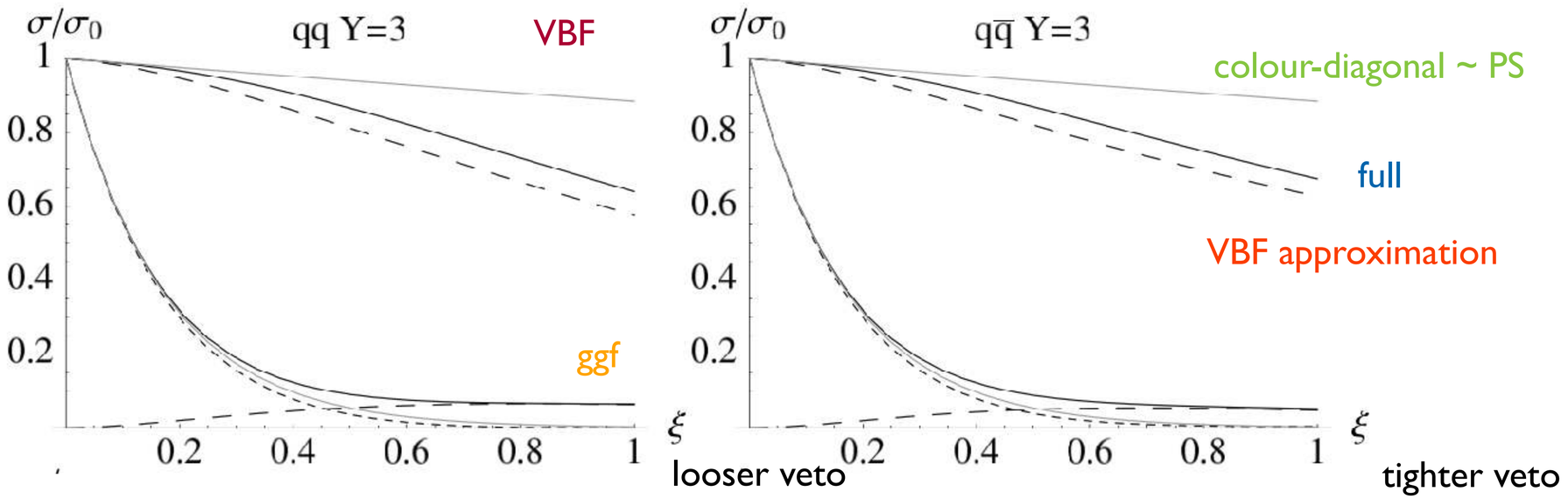
Parton showers with colour matrix element corrections can account for subleading N effects from real emissions.

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

Virtual exchanges can be resumed at fixed jet multiplicity.

[Forshaw, Sjödahl — JHEP 09 (2007) 119]



Neither one gives a complete picture.

Jet vetos & Non-global Observables

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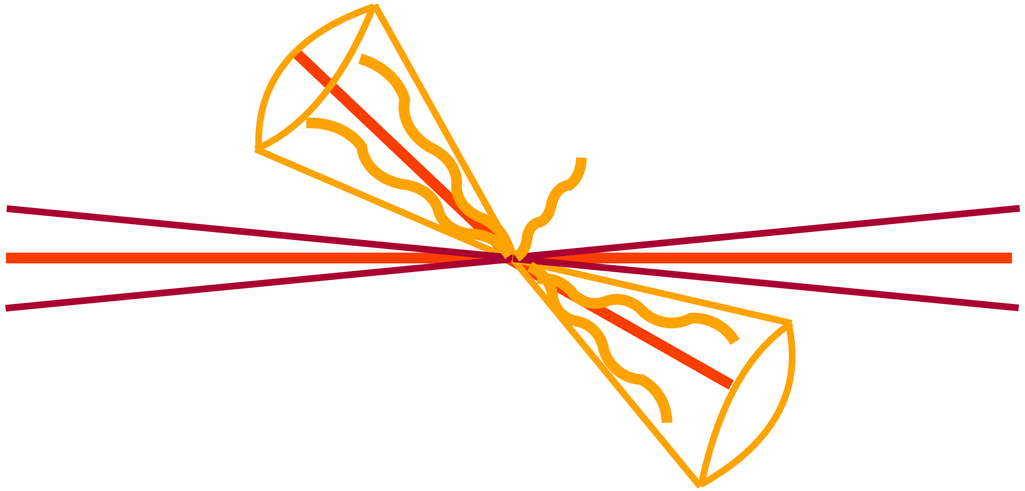
Jet vetos beyond leading-N and Glauber phases require amplitude level evolution. [Liu, Melnikov, Penin]

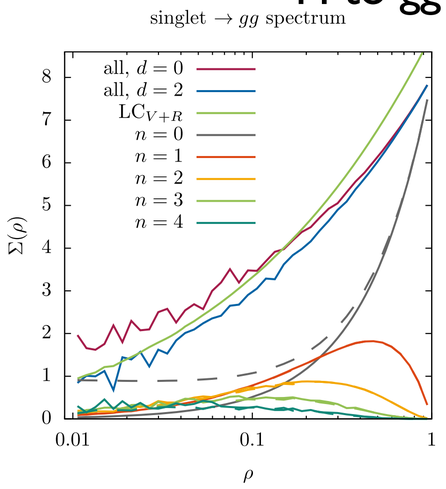
[Forshaw, Holguin, Plätzer – JHEP 1908 (2019) 145]



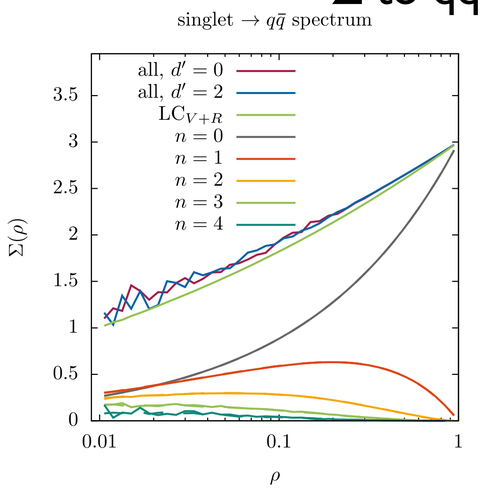
Recent results on jet vetos from CVolver on jet vetos in e+e- collisions.

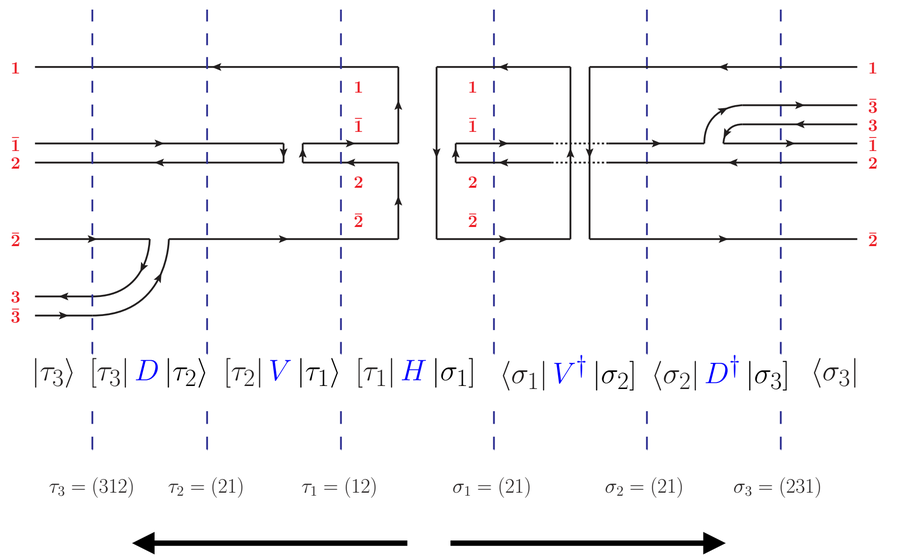
[De Angelis, Forshaw, Plätzer — PRL 126 (2021) 11]

H to gg



Z to qq





amplitude ← → conjugate amplitude

Complementary approach through Langevin dynamics, but not in form of an event generator.

[Hatta et al. — Nucl.Phys.B 962 (2021) 115273]

Summary

VBS and VBF processes provide unique challenges for QCD description.

Fixed order and parton showers established, uncertainties and interplay with non-perturbative contributions needs careful understanding.

Standard event generators not capable of reproducing all relevant effects, specifically mixing of colour structures and beyond leading-N contributions to non-global jet vetos.

Thank you!