Uncertainties in NLO+PS matched calculations of inclusive jet and dijet production

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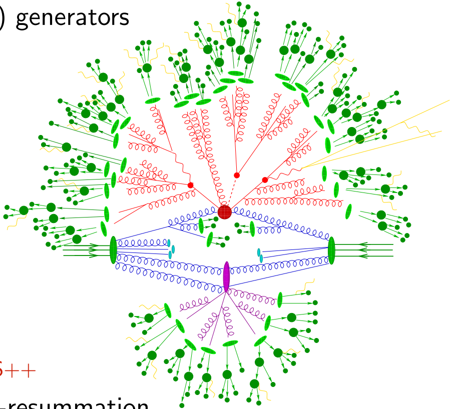
The SHERPA event generator framework



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Sherpa's traditional strength is the perturbative part of the event
MEPS (CKKW), MC@NLO, MENLOPS, MEPS@NLO
→ full analytic control mandatory for consistency/accuracy

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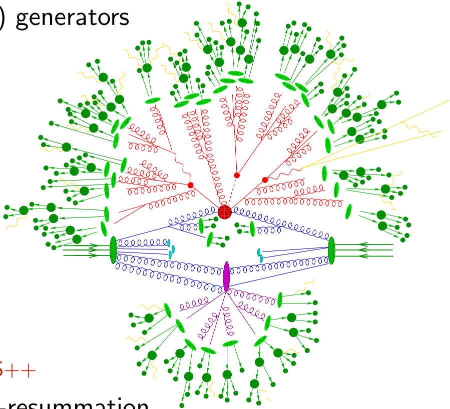

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Mc@Nlo

Frixione, Webber JHEP06(2002)029

$$\langle O\rangle^{\text{NLO+PS}} = \int \mathrm{d}\Phi_B\, \bar{\mathrm{B}}^{(\mathsf{A})}(\Phi_B)\Bigg[\Delta^{(\mathsf{A})}(t_0,\mu_Q^2)\,O(\Phi_B) + \sum_i \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_i^{(\mathsf{A})}(\Phi_B,\Phi_1)}{\mathrm{B}(\Phi_B)}\,\Delta^{(\mathsf{A})}(t,\mu_Q^2)\,O(\Phi_R)\Bigg] + \int \mathrm{d}\Phi_R\Big[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R)\Big]\,O(\Phi_R)$$

Höche, Krauss, MS, Siegert arXiv:1111.1220

- NLO weighted Born configuration $\bar{\mathrm{B}}^{(\mathsf{A})} = \mathrm{B} + \tilde{\mathrm{V}} + \mathrm{I} + \int \mathrm{d}\Phi_1 [\mathrm{D}^{(\mathsf{A})} - \mathrm{D}^{(\mathsf{S})}]$
- use $\mathrm{D}_i^{(\mathsf{A})}$ as resummation kernels $\Delta^{(\mathsf{A})}(t,t') = \exp\left[\int_t^{t'} \mathrm{d}\Phi_1\, \mathrm{D}^{(\mathsf{A})}/\mathrm{B}\right]$
- resummation phase space limited by $\mu_Q^2 = t_{\text{max}}$
  → starting scale of parton shower evolution
  → should be of the order of the hard resummation scale
  ⇒ **first implementation to allow to study μ_Q uncertainty**

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every term is well defined and NLO and NLL accuracy maintained if:

- $\mathrm{D}^{(\mathsf{A})} = \sum_i \mathrm{D}_i^{(\mathsf{A})}$ is full colour correct in soft limit
- $\mathrm{D}^{(\mathsf{A})} = \sum_i \mathrm{D}_i^{(\mathsf{A})}$ contains all spin correlations in collinear limit
- $\mathrm{D}_i^{(\mathsf{A})}$ and $\mathrm{D}_i^{(\mathsf{S})}$ have identical parton maps

⇒ **conventional parton showers need to be improved for that**

e.g. choose $\mathrm{D}_i^{(\mathsf{A})} = \mathrm{D}_i^{(\mathsf{S})}$ up to phase space constraints

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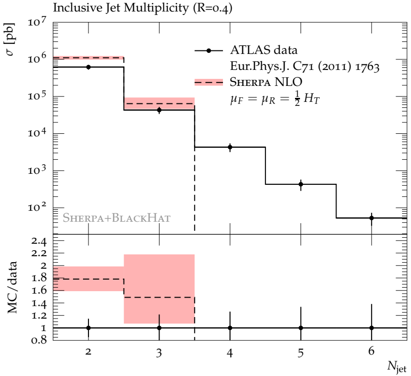
Powheg and Mc@Nlo differ in choice of $\mathrm{D}_i^{(\mathsf{A})}$ and μ_Q

Powheg $\mu_Q^2 = \frac{1}{4}\,S_{\text{had}}$, $\mathrm{D}_i^{(\mathsf{A})} = \rho_i \mathrm{R}$
ρ_i suitable projector on single soft-collinear singular region
→ exponentiates process-specific non-logarithmic terms

Mc@Nlo $\mu_Q^2 = t_{\text{max}}$, $\mathrm{D}_i^{(\mathsf{A})} = \mathrm{B}\cdot\mathcal{K}_i$
modify to $\mathrm{D}_i^{(\mathsf{A})} = f\cdot\mathrm{B}\cdot\mathcal{K}_i$ for non-trivial colour structures
→ exponentiates same as parton shower

Short-comings of fixed-order QCD

- poor description in phase space regions with strongly hierarchical scales
- poor perturbative jet-modeling (at most two constituents)
- no hadronisation, MPI effects
- very pronounced in inclusive & dijet production
- jet-$p_\perp$ turn negative in forward region unless y-dependent scale is used (e.g. $H_T^{(y)}$)



cuts: $p_\perp^{j_1} > 80$ GeV, $p_\perp^{j_{\geq 2}} > 60$ GeV

no. jets	ATLAS	LO	ME+PS	NLO	NP factor	NLO+NP
≥ 2	$620 \pm 1.3^{+110}_{-66} \pm 24$	$958(1)^{+316}_{-221}$	$559(5)$	$1193(3)^{+130}_{-135}$	$0.95(0.02)$	$1130(19)^{+124}_{-129}$
≥ 3	$43 \pm 0.13^{+12}_{-6.2} \pm 1.7$	$93.4(0.1)^{+50.4}_{-30.3}$	$39.7(0.9)$	$54.5(0.5)^{+2.2}_{-19.9}$	$0.92(0.04)$	$50.2(2.1)^{+2.0}_{-18.3}$
≥ 4	$4.3 \pm 0.04^{+1.4}_{-0.79} \pm 0.24$	$9.98(0.01)^{+7.40}_{-3.95}$	$3.97(0.08)$	$5.54(0.12)^{+0.08}_{-2.44}$	$0.92(0.05)$	$5.11(0.29)^{+0.08}_{-2.32}$

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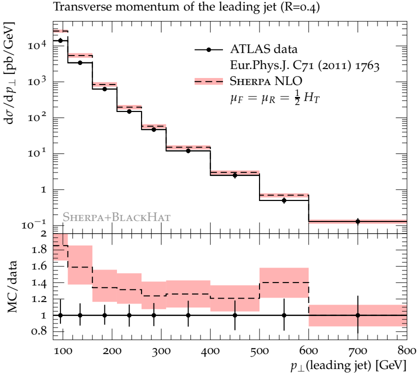

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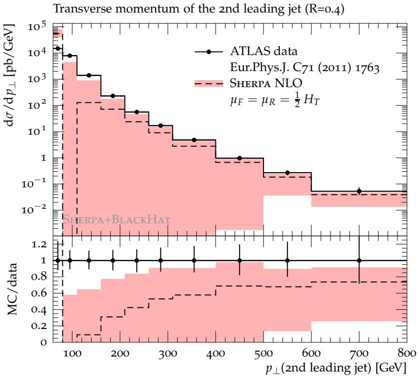

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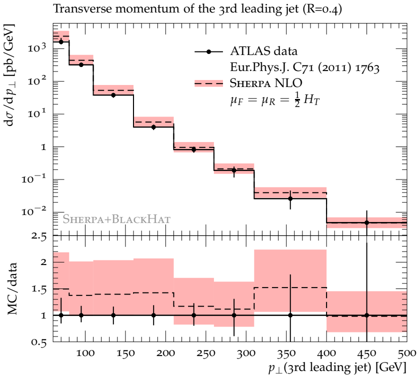

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Case study: Inclusive jet & dijet production

Describe wealth of experimental data with a single sample (LHC@7TeV)

MC@NLO di-jet production:

Höche, MS arXiv:1208.2815

- $\mu_{R/F} = \frac{1}{4}\, H_T$, $\mu_Q = \frac{1}{2}\, p_\perp$
- CT10 PDF $(\alpha_s(m_Z) = 0.118)$
- hadron level calculation
  fully hadronised including MPI
- virtual MEs from BLACKHAT
  Giele, Glover, Kosower Nucl.Phys.B403(1993)633-670
  Bern et.al. arXiv:1112.3940
- $p_\perp^{j_1} > 20$ GeV, $p_\perp^{j_2} > 10$ GeV

Uncertainty estimates:

- $\mu_{R/F} \in [\frac{1}{2}, 2]\, \mu_{R/F}^{\text{def}}$
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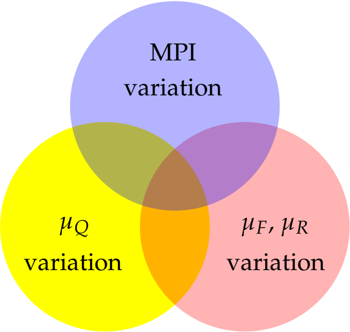
- MPI activity in tr. region ± 10%



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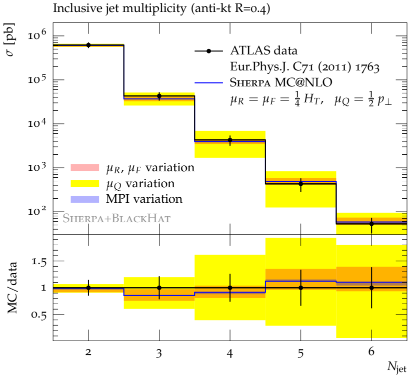

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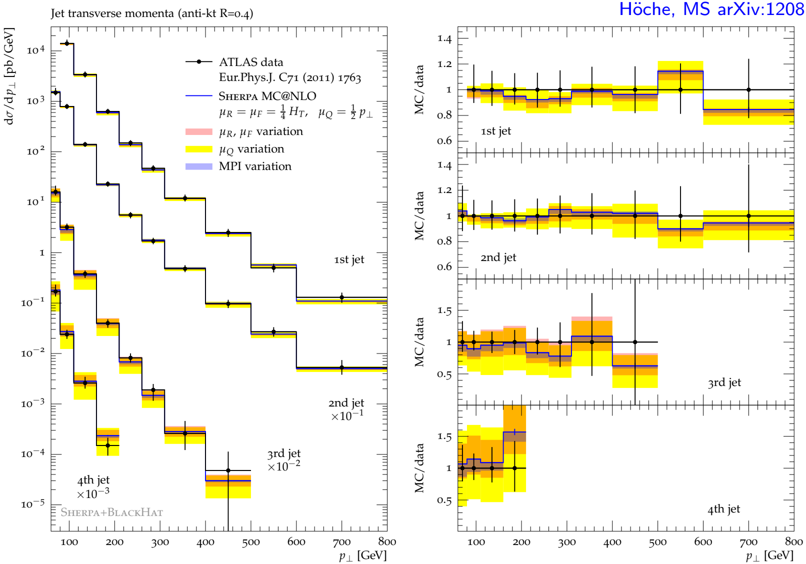

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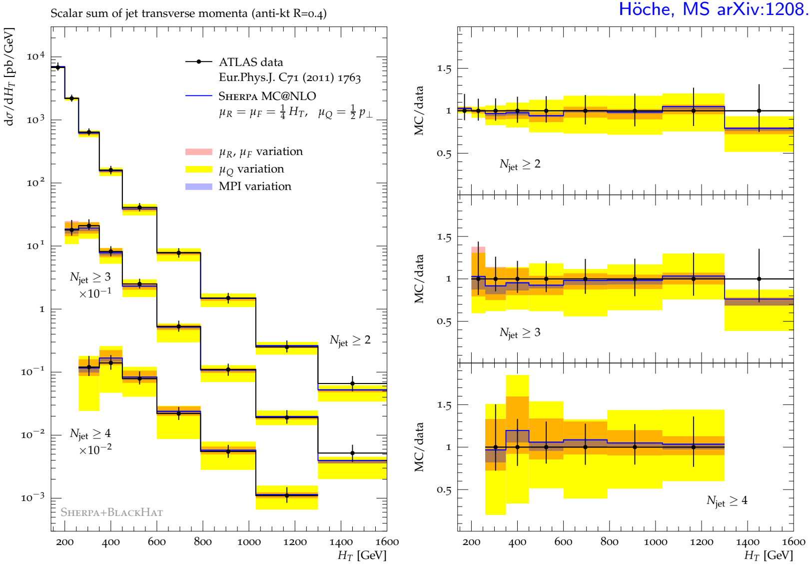

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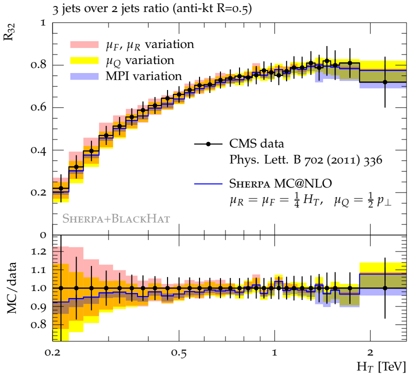

3-jet-over-2-jet ratio

- determined from incl. sample
  2-jet rate at NLO+NLL
  3-jet rate at LO+LL
- common scale choices
  → varied simultaneously
- at large H_T large MPI uncertainties
  → better MPI physics needed (soft QCD)
- similar description of related ATLAS observables

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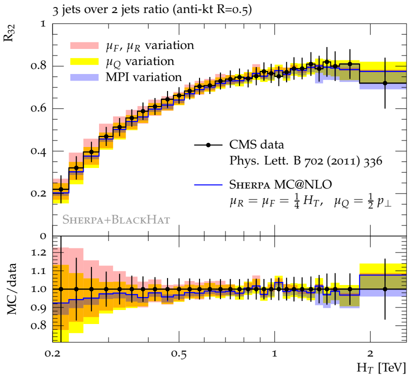

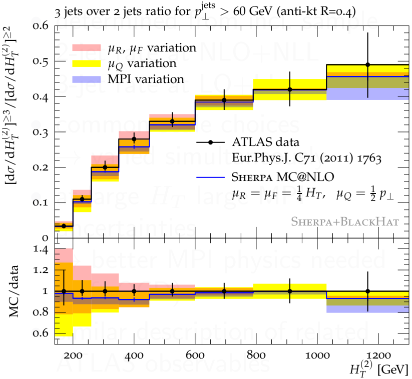

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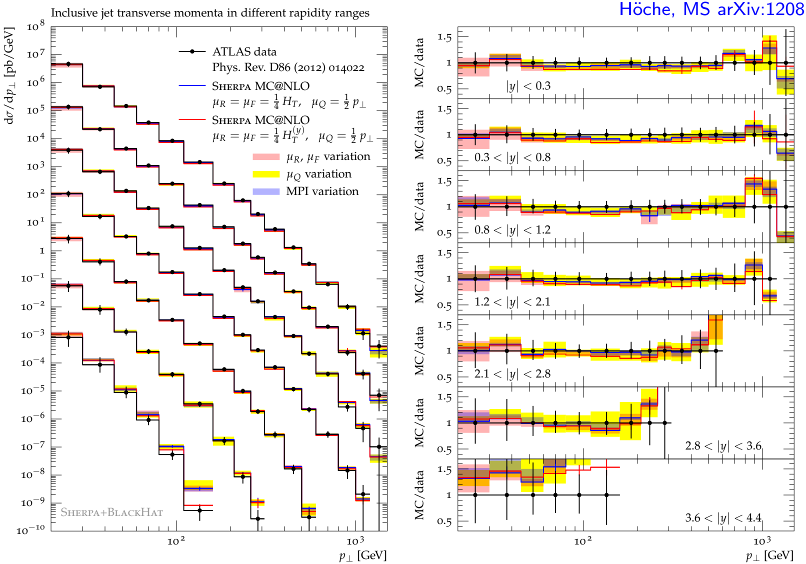

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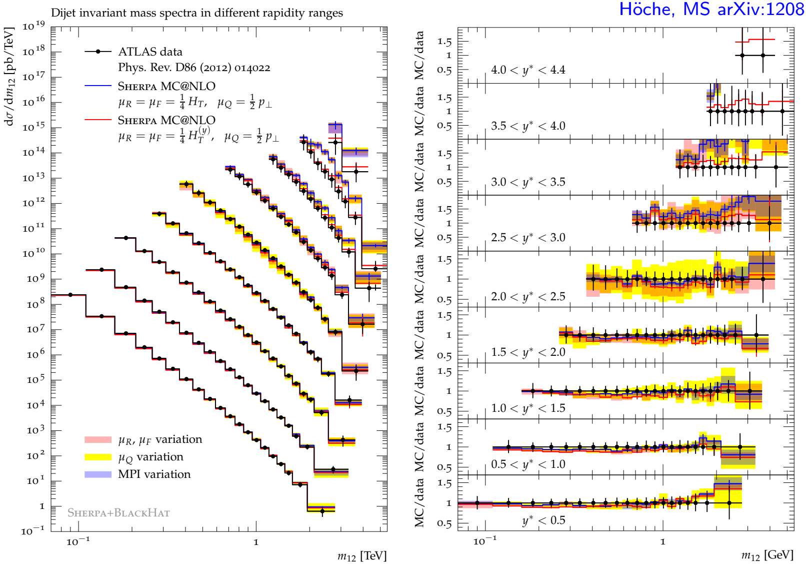

Case study: Inclusive jet & dijet production

Try different scale

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- reduces to $\mu_{R/F} = \frac{1}{2}\,p_\perp\, e^{0.3y^*}$ with $y^* = \frac{1}{2}|y_1-y_2|$ for $2\to 2$ and captures real emission dynamics

  Ellis, Kunszt, Soper PRD40(1989)2188
- better description of data at large rapidities, as expected
- description of most other observables worsened
- need proper description of forward physics (e.g. (B)FKL)

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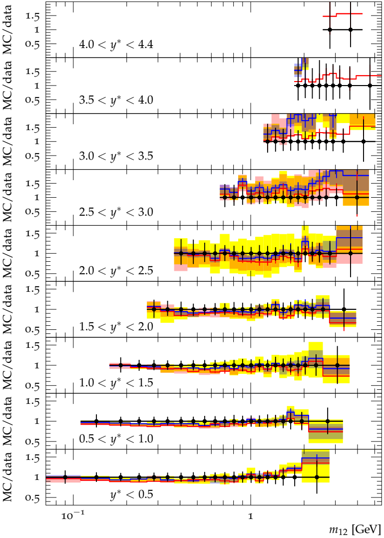

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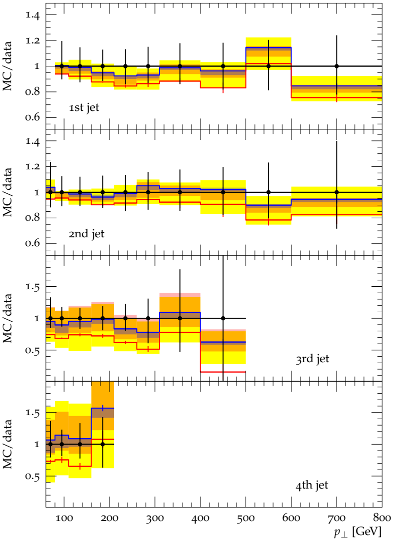

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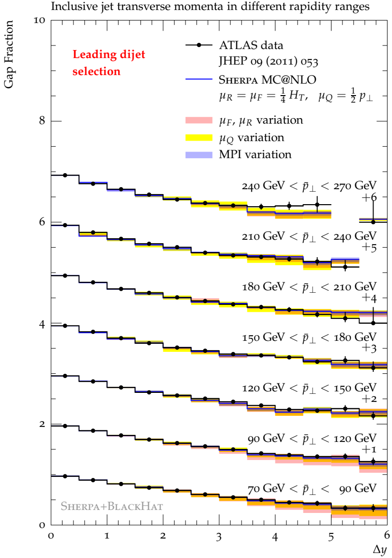

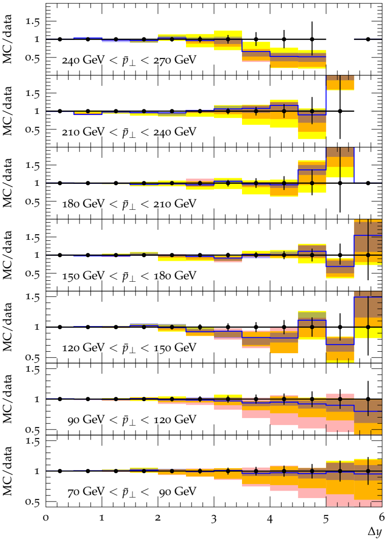

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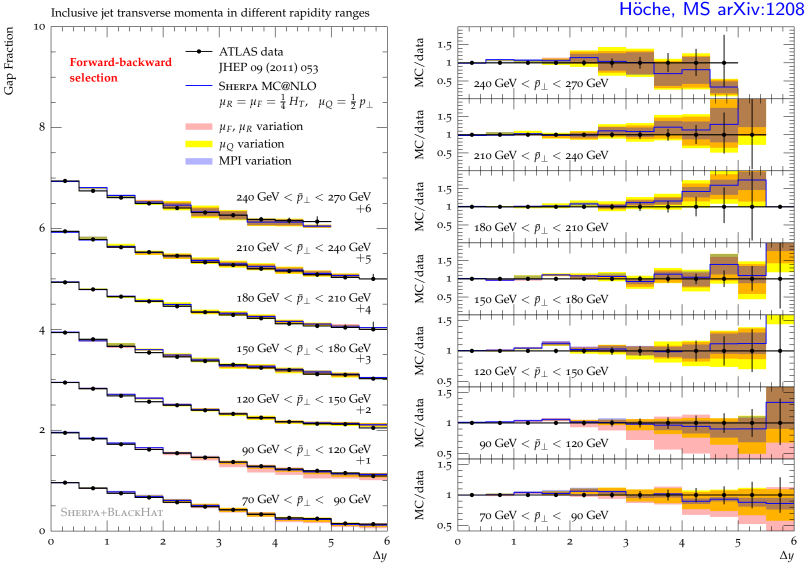

Case study: Inclusive jet & dijet production

- small-Δy region
  $\Rightarrow$ small uncertainty on additional jet production
- large-Δy region
  $\Rightarrow$ all uncertainties sizable

- small-$\bar{p}_\perp$ region
  $\Rightarrow$ dominated by perturbative uncertainties
- large-$\bar{p}_\perp$ region
  $\Rightarrow$ non-perturbative uncertainties as large as perturbative uncertainties

Reduction of theoretical uncertainty necessitates better understanding of soft QCD and non-factorisable contributions

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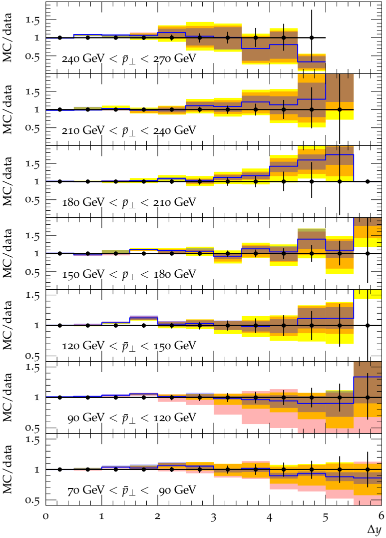

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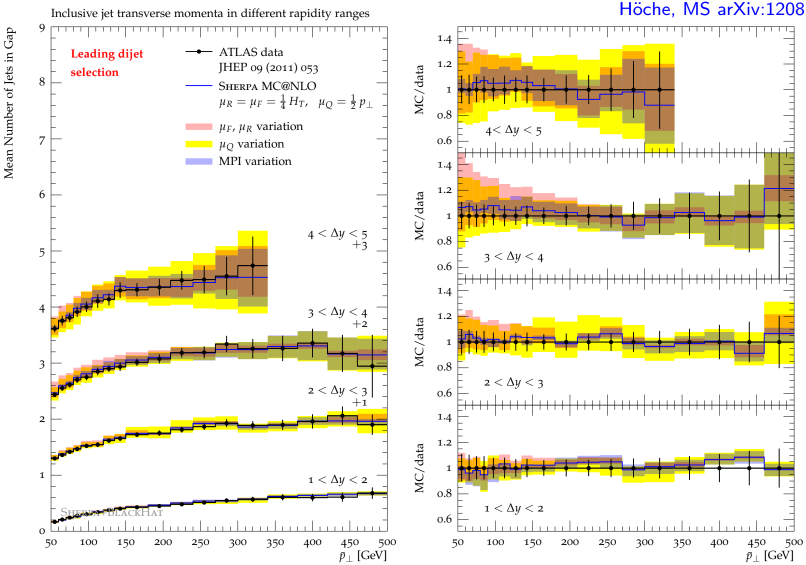

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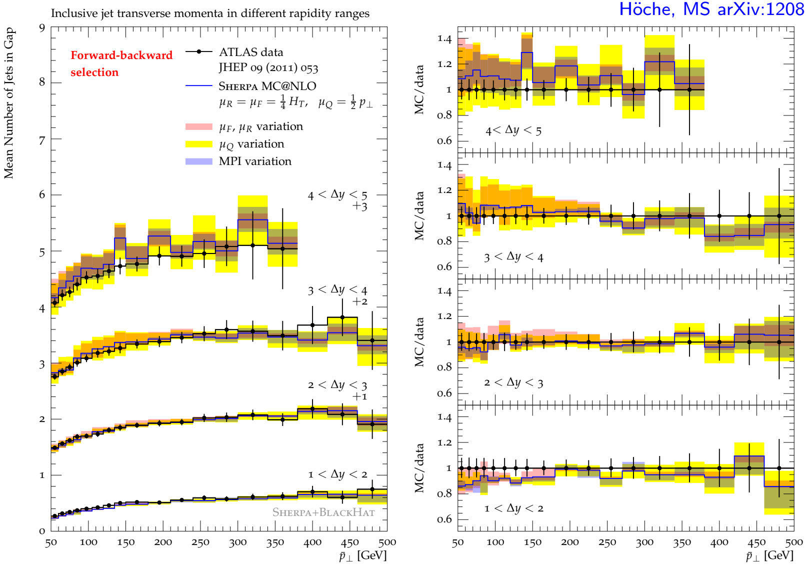
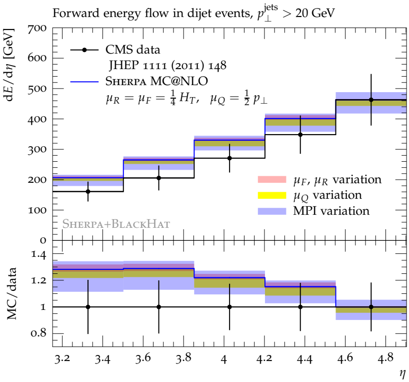


Case study: Inclusive jet & dijet production



Höche, MS arXiv:1208.2815

Forward energy flow

- energy flow in rapidity interval per event with a central back-to-back di-jet pair
- normalisation reduces $\mu_{R/F}$ and μ_Q dependence
- dominated by MPI modeling uncertainty

Complete estimate of theoretical uncertainties

Perturbative uncertainties:

- unphysical scales of perturbative calculation μ_F, μ_R, μ_Q in any fixed-order-resummation matched calculation (LoPs, NloPs, etc.)
  → central value fits surprisingly good given perturbative uncertainties
- PDF uncertainties individually through respective error sets or replica globally through PDF4LHC accord (needs individual tunes for non-perturbative physics modelling for at least every central set)

Non-perturbative uncertainties:

- modelling uncertainties for non-perturbative physics with only little first principles basis
  proper: use full set of eigentunes obtainable through e.g. Professor
  approximate: use canonical variation of characteristic activity measure
    - MPI: $\langle N_{\text{ch}}\rangle \pm 10\%$ of plateau in transverse region
    - hadronisation: $\langle N_{\text{ch}}\rangle \pm 1$ at LEP
    - intrinsic $k_\perp$, beam remnants, ... ?

Conclusions

- SHERPA's MC@NLO formulation allows full evaluation of perturbative uncertainties (μ_F, μ_R, μ_Q)
- MC@NLO can be easily combined with MEPS → MENLOPS
- MC@NLO is a necessary input for NLO merging → MEPS@NLO
  ⇒ see Frank's talk

⇒ will be included in next major release

Current release: SHERPA-1.4.1

http://sherpa.hepforge.org

- precise theoretical calculations need to be confronted with data as differentially as possible over as large a phase space as possible to identify physics region that needs improvement

Thank you for your attention!

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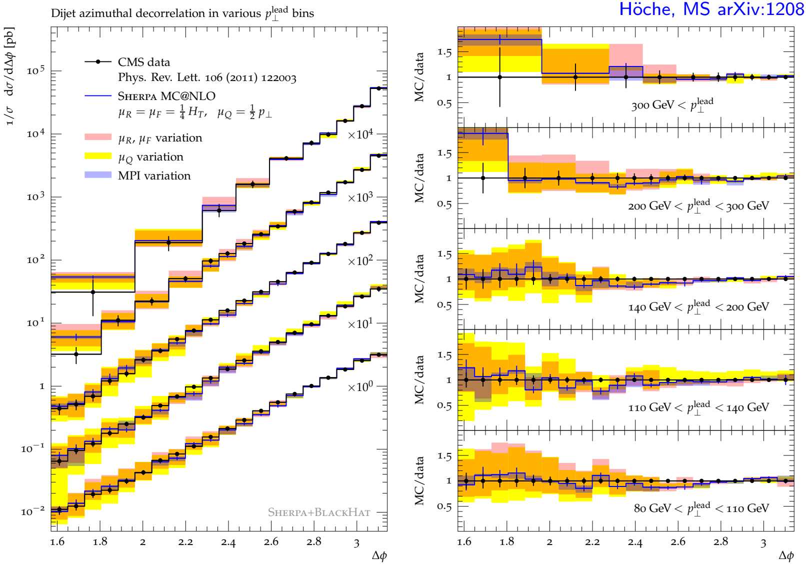
Dijet azimuthal decorrelation in various $p_\perp^{\rm lead}$ bins

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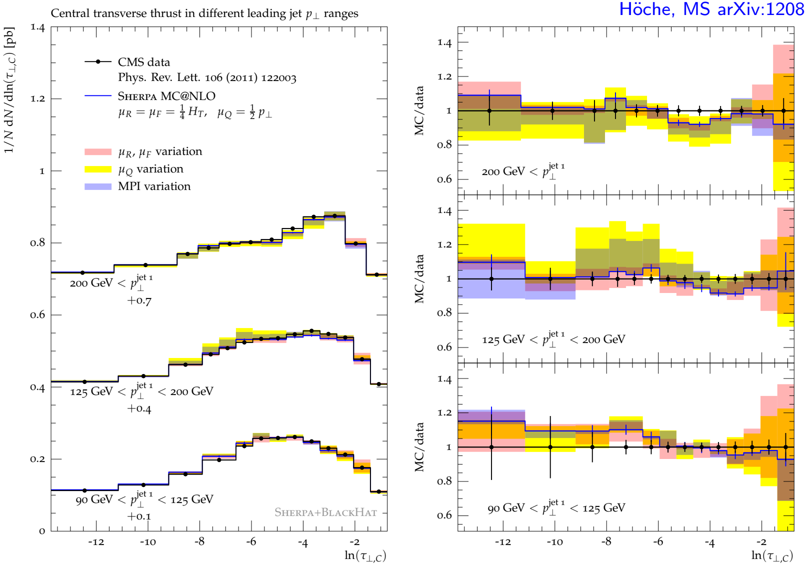

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