

Developments in Sherpa and BlackHat

Stefan Höche



SLAC

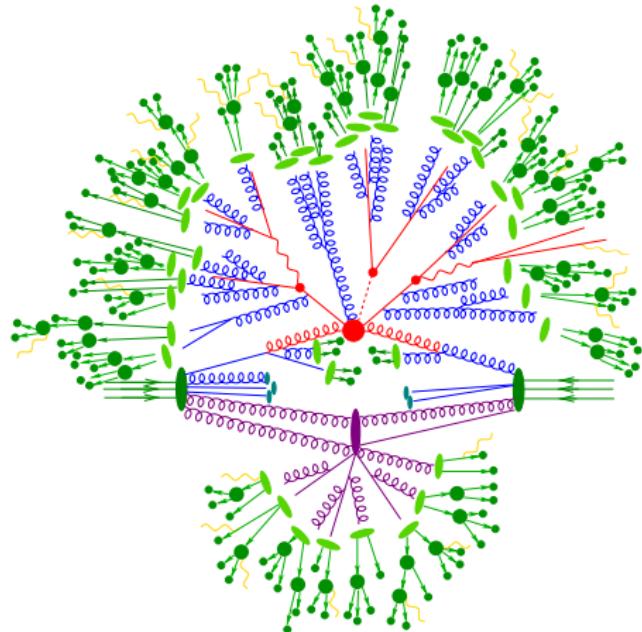


US ATLAS Workshop on LHC Searches

LBL, 01/27/14

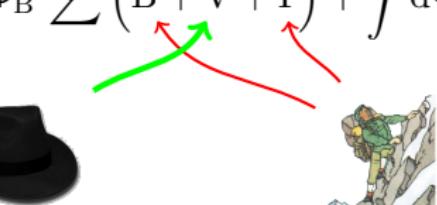
Event Generator Cookbook

1. Matrix Element (ME) generators simulate “hard” part of an event
2. Parton Showers (PS) produce Bremsstrahlung
3. Multiple interaction models simulate “secondary” interactions
4. Fragmentation models “hadronize” QCD partons
5. Hadron decay packages simulate unstable hadron decay
6. YFS generators produce QED Bremsstrahlung



NLO calculations: The art of collaboration

Share the workload

$$\sigma_{\text{NLO}} = \int d\Phi_B \sum (B + \tilde{V} + I) + \int d\Phi_R \sum (R - S)$$


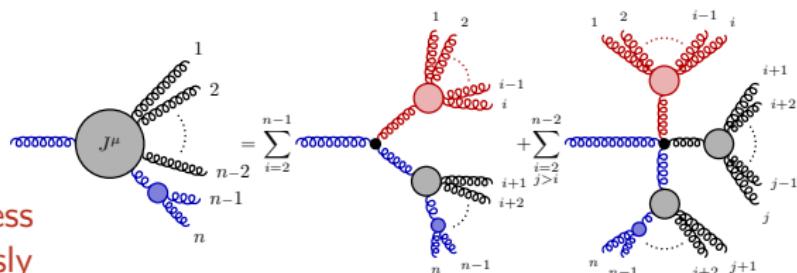
- ▶ One-Loop Engines (OLEs) provide virtual piece
- ▶ ME generator takes care of Born, real emission, subtraction phase-space integration and event generation
- ▶ Interface provided by BLHA(2)

[Binoth et al.] arXiv:1001.1307 [Alioli et al.] arXiv:1308.3462

Born, real radiation and subtraction terms

One-Loop codes capable of computing very high multiplicity processes
→ need to compute real-radiation & infrared subtraction terms efficiently

- ▶ Naively computational effort in dipole subtraction method grows like N^3 with number of external QCD particles
- ▶ Can be reduced by recursive computation similar to Berends-Giele technique at LO
- ▶ Fix spectator parton as “final” leg in amplitude
- ▶ Recycle subamplitudes from real-radiation process and dipoles simultaneously
- ▶ Implemented in ME generator **Comix** [Gleisberg,SH] arXiv:0808.3674



Virtual contribution

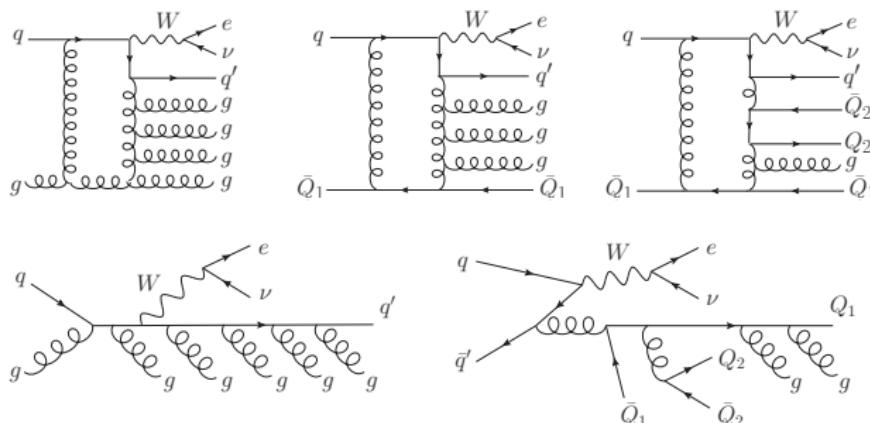
Plethora of (semi-)automated programs to compute virtual correction
Rough classification based on technique to evaluate loop integrals

- ▶ **Tensor reduction** [Denner,Dittmaier] hep-ph/0509141
[Binoth,Guillet,Pilon,Heinrich,Schubert] hep-ph/0504267
 - ▶ Golem95 [Binoth,Cullen,Greiner,Guffanti,Guillet,Heinrich,Karg,Kauer,Reiter,Reuter]
 - ▶ MadGolem [Binoth,Goncalves Netto,Lopez-Val,Mawatari,Plehn,Wigmore]
 - ▶ NLOX [Reina,Schutzmeier]
 - ▶ OpenLoops [Cascioli,Maierhöfer,Pozzorini]
- ▶ **Generalized unitarity** [Bern,Dixon,Dunbar,Kosower] hep-ph/9409265 hep-ph/9708239
[Ossola,Papadopoulos,Pittau] hep-ph/0609007, [Forde] arXiv:0704.1835
 - ▶ BlackHat [Bern,Dixon,Febres-Cordero,Ita,Kosower,LoPresti,Maître,Ozeren,SH]
 - ▶ GoSam [Cullen,Greiner,Heinrich,Luisoni,Mastrolia,Ossola,Reiter,Tramontano]
 - ▶ HelacNLO [Bevilacqua,Czakon,Garzelli,vanHameren,Kardos,Papadopoulos,Pittau,Worek]
 - ▶ MadLoop [Hirschi,Frederix,Frixione,Garzelli,Maltoni,Pittau]
 - ▶ NJet [Badger,Biedermann,Uwer,Yundin]
 - ▶ OpenLoops [Cascioli,Maierhöfer,Pozzorini]
 - ▶ Rocket [Ellis,Giele,Kunszt,Melnikov,Zanderighi]
- ▶ **Numerical integration** [Becker,Goetz,Reuschle,Schwan,Weinzierl] arXiv:1111.1733

Recent progress in BlackHat: $W+5\text{jets}$ at the LHC

[BlackHat] arXiv:1304.1253

- ▶ First $2 \rightarrow 6$ NLO calculation (plus decay $W \rightarrow l\nu$)
- ▶ Will be measured with good precision at LHC \rightarrow test of SM
- ▶ Can be used to understand jet scaling patterns \rightarrow BSM searches

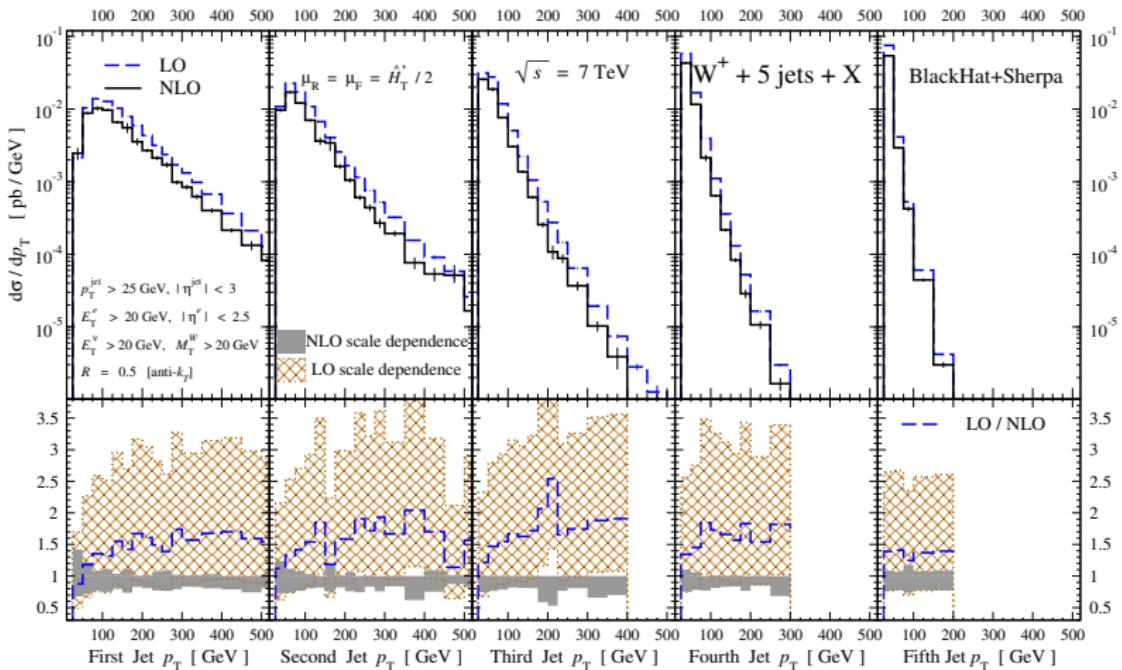


Approximations:

- ▶ Leading color in virtual piece (estimated $< 3\%$ correction)
- ▶ No real corrections with 8 quark lines ($< 1\%$ correction)

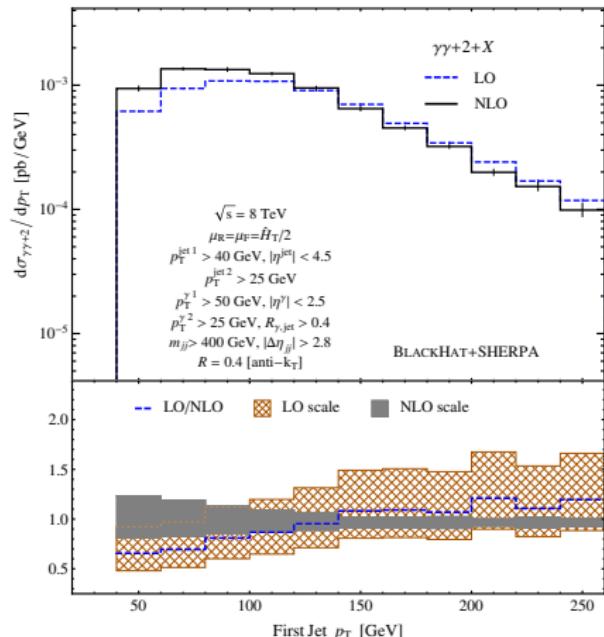
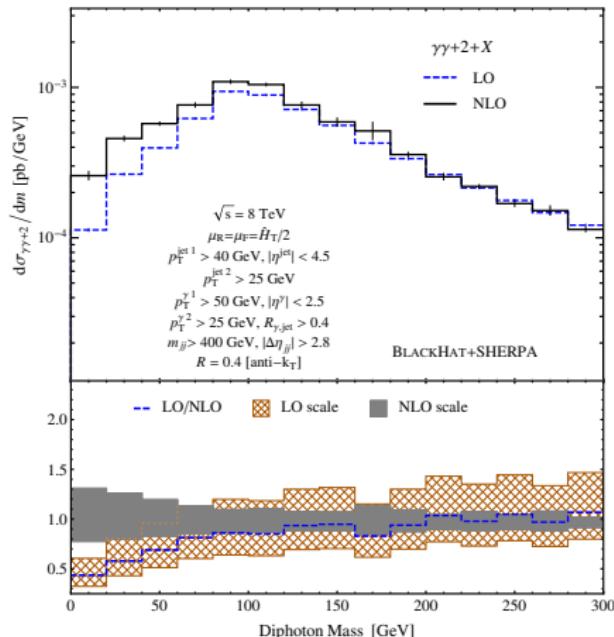
Recent progress in BlackHat: $W+5\text{jets}$ at the LHC

[BlackHat] arXiv:1304.1253



Recent progress in BlackHat: $\gamma\gamma+2\text{jets}$ at the LHC

[BlackHat] arXiv:1312.0592



- ▶ Significant reduction of scale dependence for VBF cuts
- ▶ Results will be available as NTuples [BlackHat] arXiv:1310.7439

Basics of NLO+PS matching

- ▶ Leading-order calculation for observable O

$$\langle O \rangle = \int d\Phi_B B(\Phi_B) O(\Phi_B)$$

- ▶ NLO calculation for same observable

$$\langle O \rangle = \int d\Phi_B \left\{ B(\Phi_B) + \tilde{V}(\Phi_B) \right\} O(\Phi_B) + \int d\Phi_R R(\Phi_R) O(\Phi_R)$$

- ▶ Parton-shower result

$$\langle O \rangle = \int d\Phi_B B(\Phi_B) \mathcal{F}_{\text{MC}}(\mu_Q^2, O)$$

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- ▶ Parton-shower result (until first emission)

$$\langle O \rangle = \int d\Phi_B B(\Phi_B) \left[\Delta^{(K)}(t_c) O(\Phi_B) + \int_{t_c} d\Phi_1 K(\Phi_1) \Delta^{(K)}(t(\Phi_1)) O(\Phi_R) \right]$$

Phase space: $d\Phi_1 = dt dz d\phi J(t, z, \phi)$

Splitting functions: $K(t, z) \rightarrow \alpha_s/(2\pi t) \sum P(z) \Theta(\mu_Q^2 - t)$

Sudakov factors: $\Delta^{(K)}(t) = \exp \left\{ - \int_t d\Phi_1 K(\Phi_1) \right\}$

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$$\xrightarrow{\mathcal{O}(\alpha_s)} \int d\Phi_B B(\Phi_B) \left\{ 1 - \int_{t_c} d\Phi_1 K(\Phi_1) \right\} O(\Phi_B) + \int_{t_c} d\Phi_B d\Phi_1 B(\Phi_B) K(\Phi_1) O(\Phi_R)$$

Phase space: $d\Phi_1 = dt dz d\phi J(t, z, \phi)$

Splitting functions: $K(t, z) \rightarrow \alpha_s/(2\pi t) \sum P(z) \Theta(\mu_Q^2 - t)$

Sudakov factors: $\Delta^{(K)}(t) = \exp \left\{ - \int_t d\Phi_1 K(\Phi_1) \right\}$

Basics of NLO+PS matching

- Subtract $\mathcal{O}(\alpha_s)$ PS terms from NLO result ($t_c \rightarrow 0$)

$$\langle O \rangle = \int d\Phi_B \left\{ B(\Phi_B) + \tilde{V}(\Phi_B) + B(\Phi_B) \int d\Phi_1 K(\Phi_1) \right\} O(\Phi_B)$$
$$+ \int d\Phi_R \left\{ R(\Phi_R) - B(\Phi_B) K(\Phi_1) \right\} O(\Phi_R)$$

- In DLL approximation both terms finite →
MC events in two categories, Standard and Hard

$$\mathbb{S} \rightarrow \bar{B}^{(K)}(\Phi_B) = B(\Phi_B) + \tilde{V}(\Phi_B) + B(\Phi_B) \int d\Phi_1 K(\Phi_1)$$
$$\mathbb{H} \rightarrow H^{(K)} = R(\Phi_R) - B(\Phi_B) K(\Phi_1)$$

- Full QCD has color & spin correlations → **NLO subtraction** needed
 $1/N_c$ corrections faded out in soft region by **smoothing function**

$$\bar{B}^{(K)}(\Phi_B) = B(\Phi_B) + \tilde{V}(\Phi_B) + I(\Phi_B) + \int d\Phi_1 \left[S(\Phi_R) - B(\Phi_B) K(\Phi_1) \right] f(\Phi_1)$$
$$H^{(K)}(\Phi_R) = \left[R(\Phi_R) - B(\Phi_B) K(\Phi_1) \right] f(\Phi_1)$$

- Add parton shower, described by generating functional \mathcal{F}_{MC}

$$\langle O \rangle = \int d\Phi_B \bar{B}^{(K)}(\Phi_B) \mathcal{F}_{\text{MC}}^{(0)}(\mu_Q^2, O) + \int d\Phi_R H^{(K)}(\Phi_R) \mathcal{F}_{\text{MC}}^{(1)}(t(\Phi_R), O)$$

Probability conservation $\leftrightarrow \mathcal{F}_{\text{MC}}(t, 1) = 1$

- Expansion of matched result until first emission

$$\langle O \rangle = \int d\Phi_B \bar{B}^{(K)}(\Phi_B) \left[\Delta^{(K)}(t_c) O(\Phi_B) \leftrightarrow \begin{array}{c} \text{B} \\ \text{---} \\ \text{= = =} \end{array} \right. \\ \left. + \int_{t_c} d\Phi_1 K(\Phi_1) \Delta^{(K)}(t(\Phi_1)) O(\Phi_R) \right] + \int d\Phi_R H^{(K)}(\Phi_{n+1}) O(\Phi_R)$$

- Parametrically $\mathcal{O}(\alpha_s)$ correct
- Preserves logarithmic accuracy of PS

Soft gluon effects - MC@NLO vs S-MC@NLO

Method 1 (MC@NLO)

[Frixione,Webber] hep-ph/0204244

- ▶ $f(\Phi_1) \rightarrow 0$ in soft-gluon limit
- ▶ Full NLO only in hard / collinear region
Missing subleading color terms in soft domain
- ▶ Only affects unresolved gluons \rightarrow no need to correct

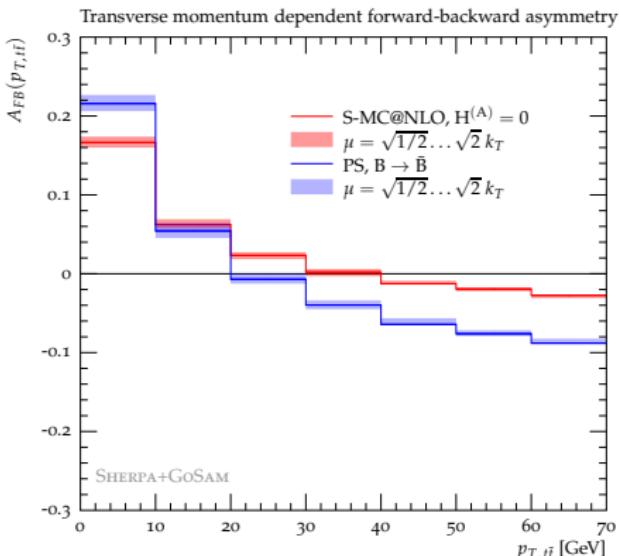
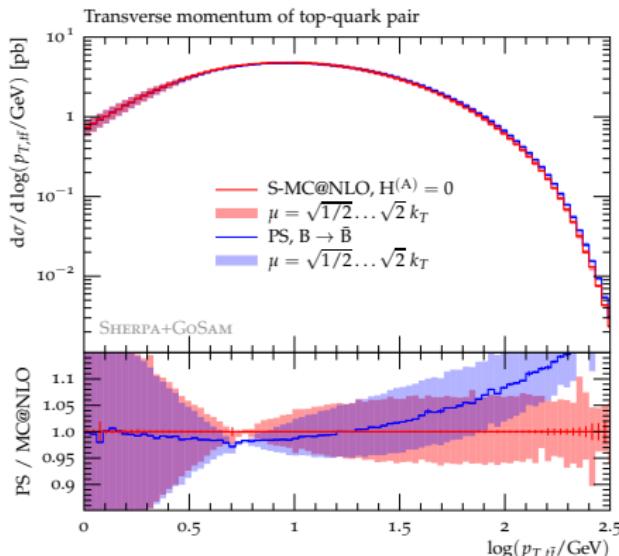
Method 2 (S-MC@NLO)

[Krauss,Schönherr,Siegert,SH] arXiv:1111.1220

- ▶ Replace $B(\Phi_B)K(\Phi_1) \rightarrow S(\Phi_R)$, i.e. include color & spin correlations
- ▶ May lead to non-probabilistic Sudakov factor $\Delta^{(S)}(t)$
Requires modification of veto algorithm
- ▶ Exact cancellation of all divergences without additional smoothing
Equivalent to one-step full colour parton shower algorithm

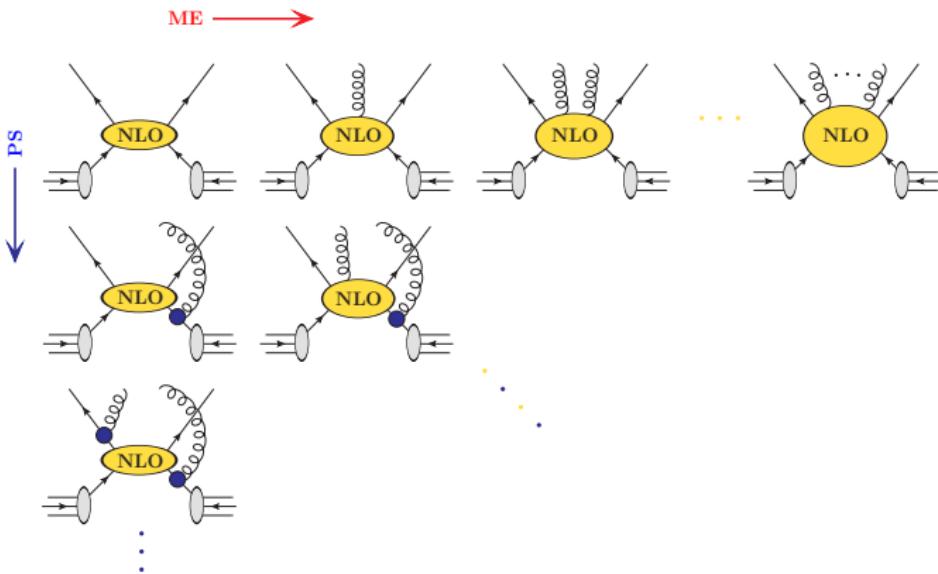
Does it make a difference?

[Huang,Luisoni,Schönherr,Winter,SH] arXiv:1306.2703



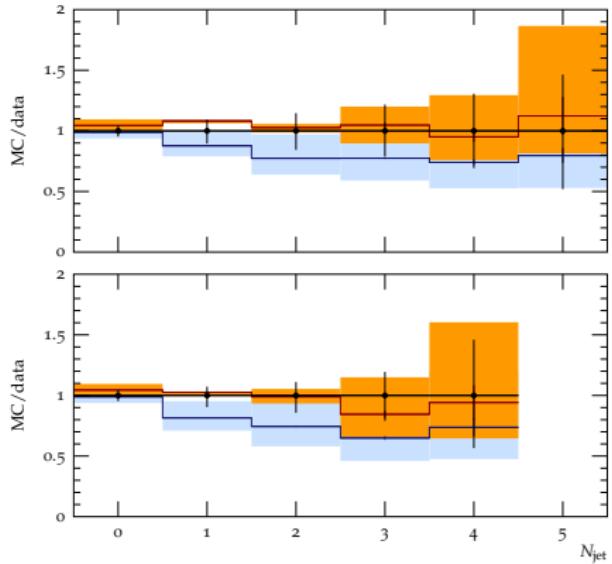
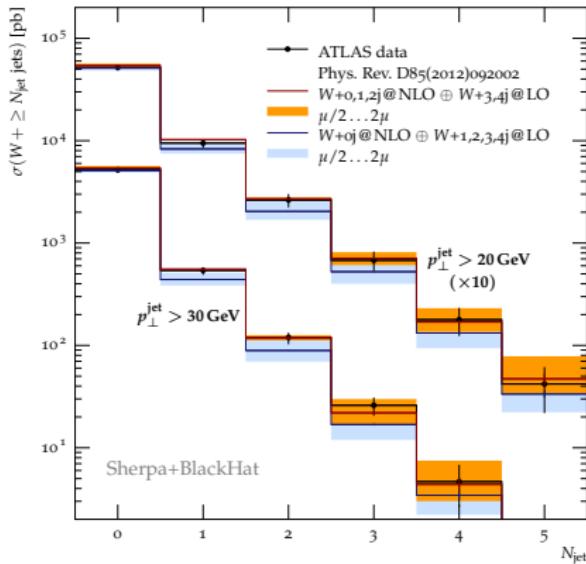
- Effect of sub-leading color corrections typically $\mathcal{O}(10\%)$
- In most cases also well within parton shower uncertainty
- Can have larger impact on some observables, e.g. $A_{FB}(p_T)$

ME+PS merging at next-to-leading order



$W+jets$ production at the LHC

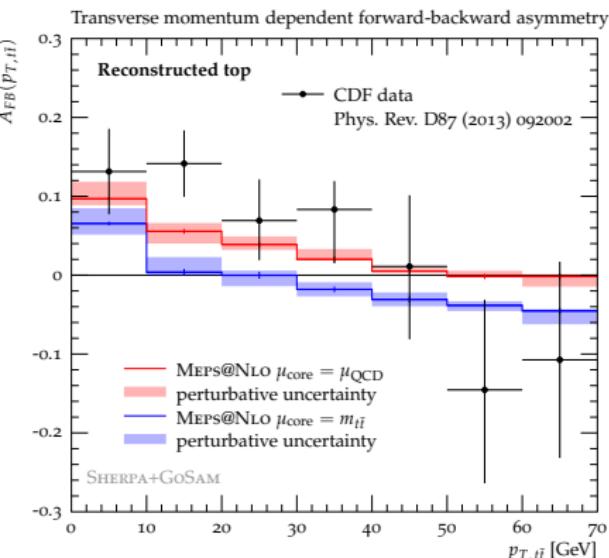
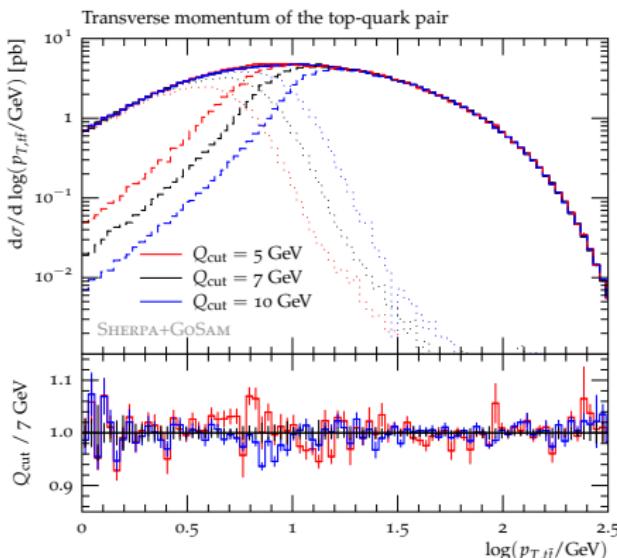
[SH,Krauss,Schönherr,Siegert] arXiv:1207.5030



- ME \oplus PS@NLO with 0,1&2 jet at NLO plus 3&4 jet at LO
- vs 0 jet at NLO plus up to 4 jets at LO (ME \ominus NLOPS)

Top quark pair production at the Tevatron

[Huang,Luisoni,Schönherr,Winter,SH] arXiv:1306.2703

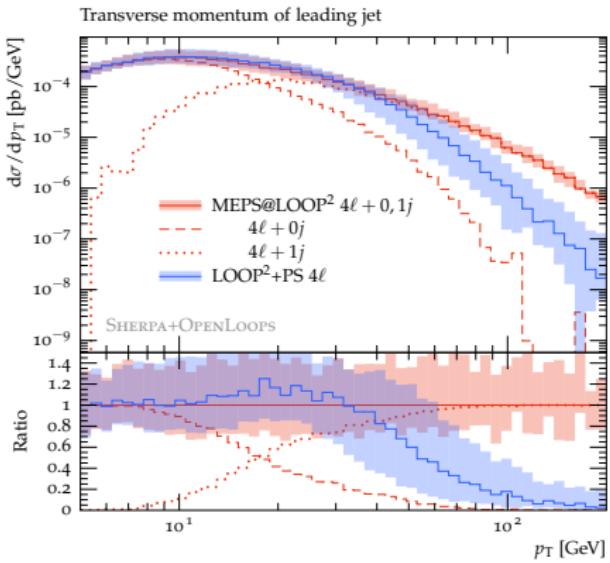
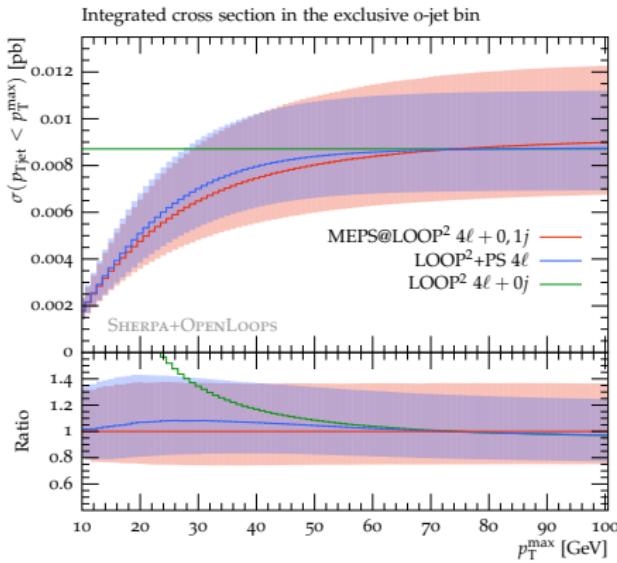
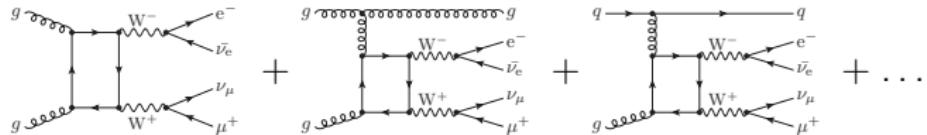


- ME \oplus PS@NLO with 0&1 jet at NLO and central merging cut at 7GeV
- Leads to NLO-accurate prediction of $A_{FB}(p_T)$ except in first bin
- Large dependence on functional form of scale, despite NLO

Detour: Squared-loop ME \oplus PS merging

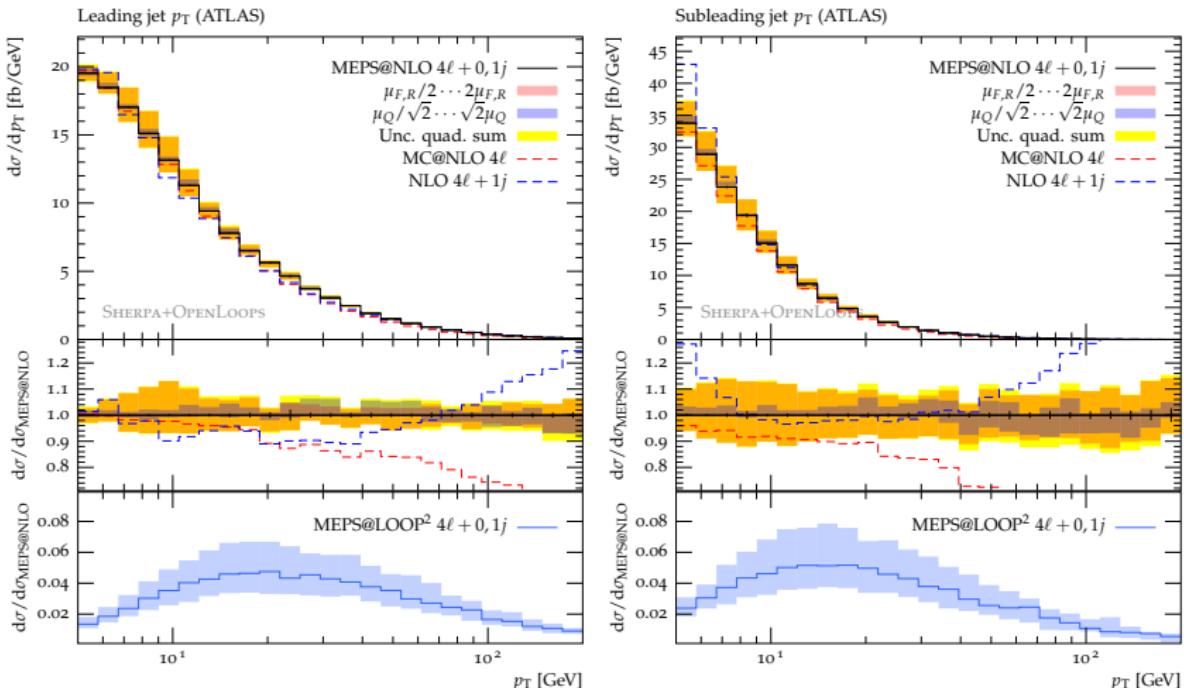
[Cascioli,Krauss,Maierhöfer,Pozzorini,Siegert,SH] arXiv:1309.0500

► Combine



Four lepton production at the LHC

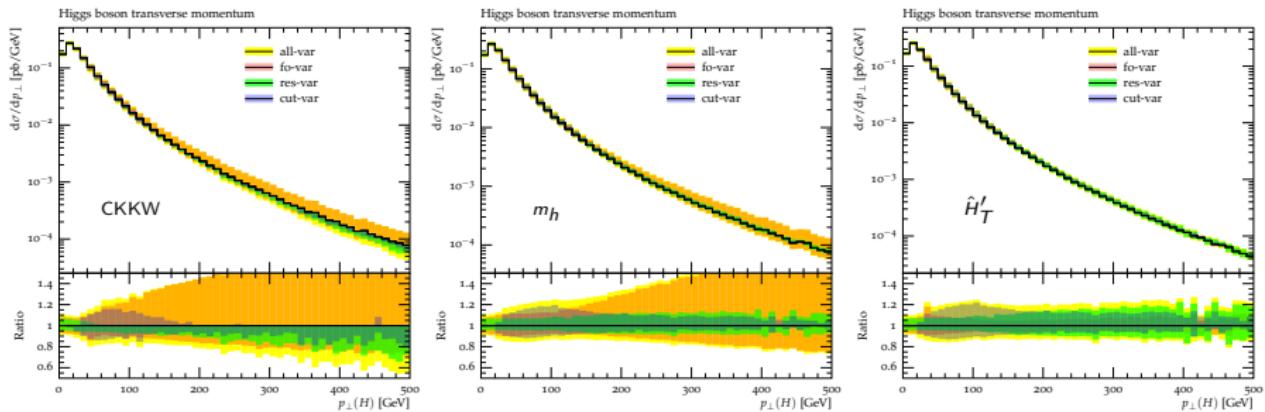
[Cascioli,Krauss,Maierhöfer,Pozzorini,Sieger,SH] arXiv:1309.0500



- ME \oplus PS@NLO with 0&1 jet at NLO plus 2 jet at LO
- ME \oplus PS@LOOP² with 0&1 jet at LOOP²

Higgs+jets production at the LHC

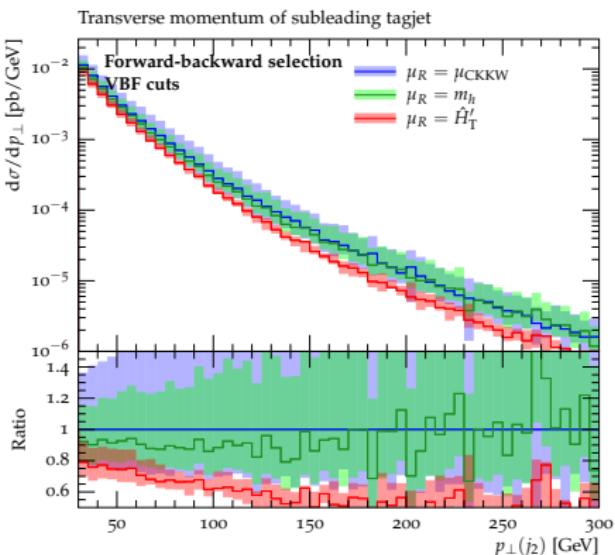
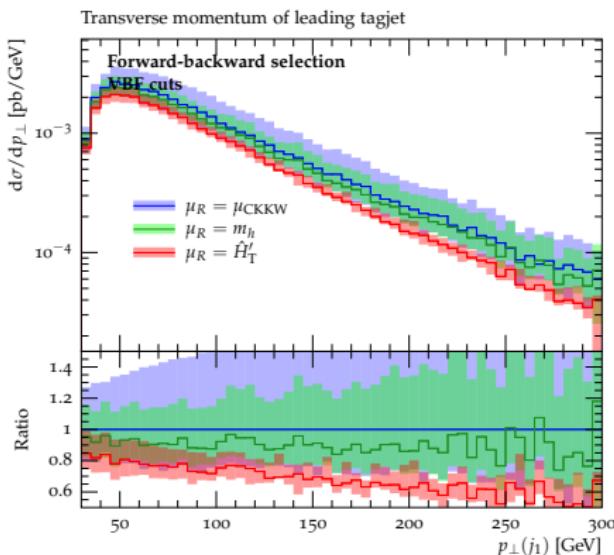
[Krauss,Schönherr,Siegert,SH] TBP



- ▶ ME \oplus PS@NLO with 0,1&2 jet at NLO plus 3 jet at LO
- ▶ Compare three different functional forms of scale
 - ▶ CKKW $\rightarrow \alpha_s(\mu_R^2) = \alpha_s^2(\mu_{\text{core}}^2) \prod \alpha_s(k_{T,i}^2)$
 - ▶ $\mu_R = m_h$ (in between CKKW and \hat{H}'_T)
 - ▶ $\mu_R = \hat{H}'_T = \sum m_{\perp}$

Higgs+jets production at the LHC

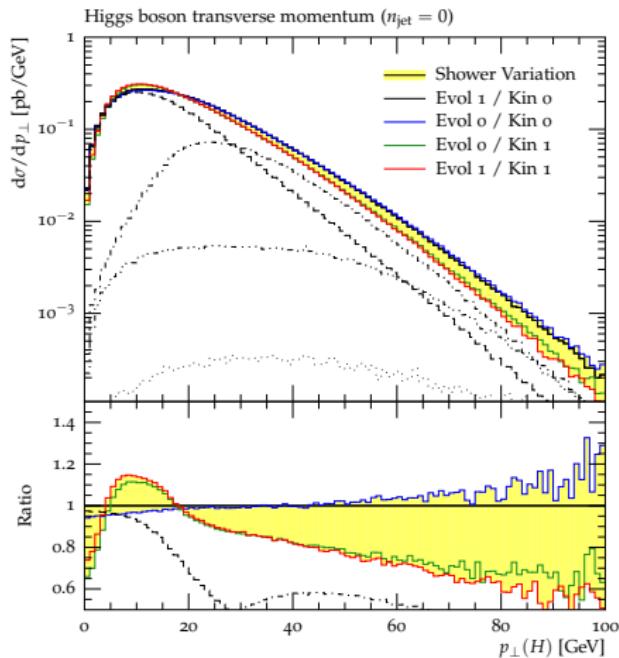
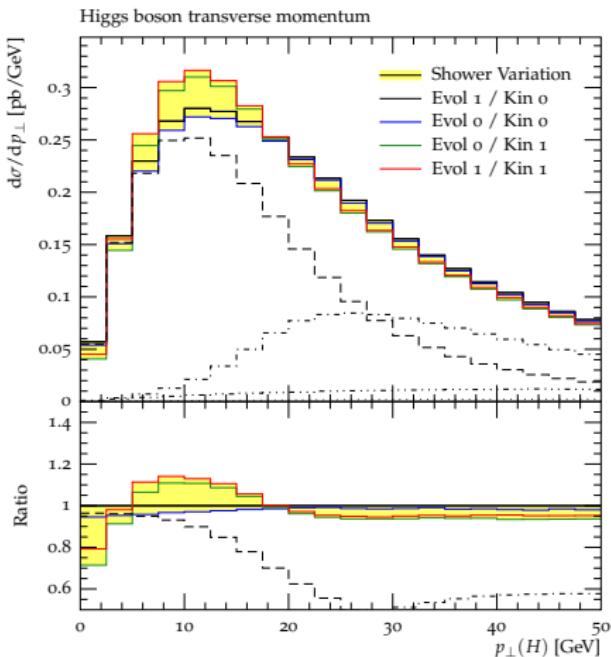
[Krauss,Schönherr,Siegert,SH] TBP



- ME \oplus PS@NLO with 0,1&2 jet at NLO plus 3 jet at LO
- Compare three different functional forms of scale
- VBF cuts ($|\Delta y_{jj}| > 2.8$, $m_{jj} > 800$ GeV)

Resummation uncertainties

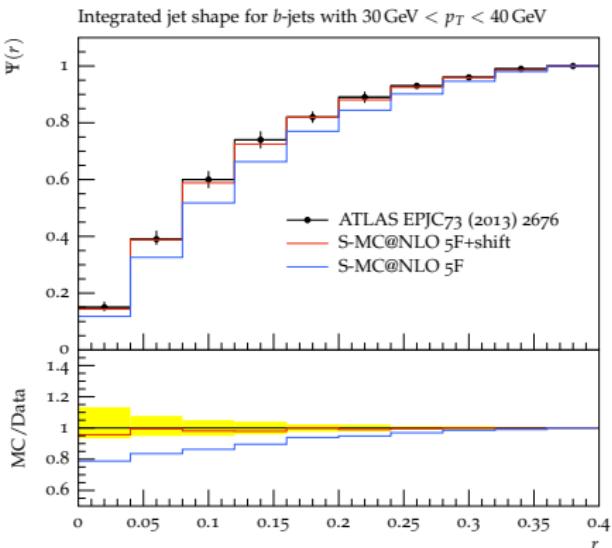
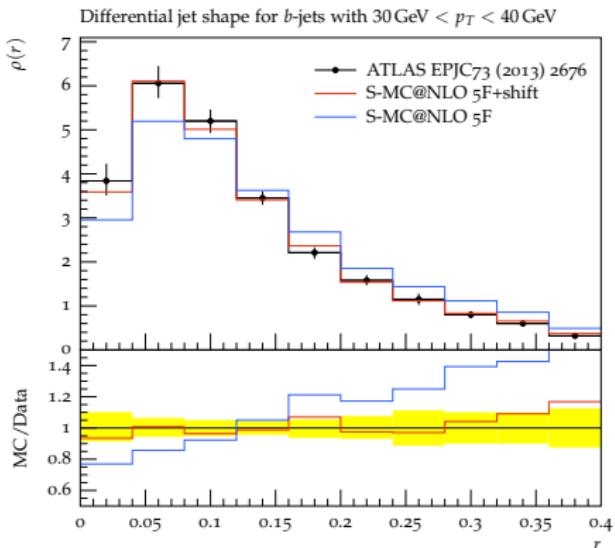
[Krauss,Schönherr,Sieger,SH] TBP



- ME \oplus PS@NLO with 0,1&2 jet at NLO plus 3 jet at LO
- Comparison of different evolution variables/momenta mappings

Heavy flavors

[Krauss,Schönherr,Siegert,SH] TBP



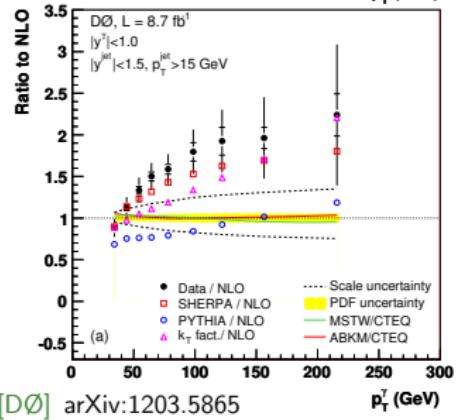
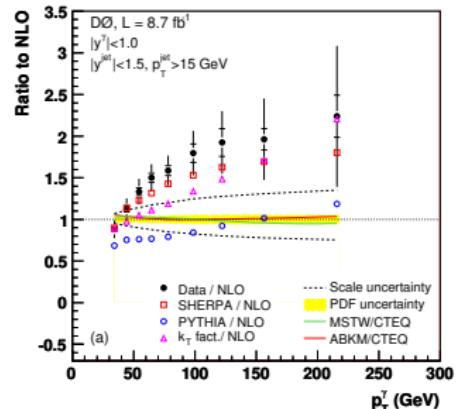
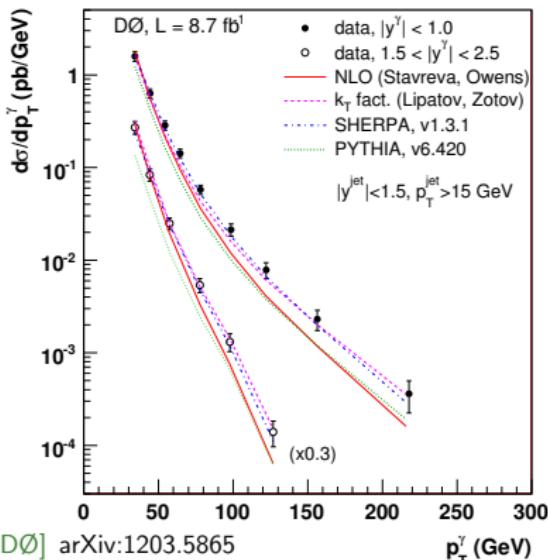
- ▶ Two options for treating heavy flavor in Sherpa
 - ▶ Option 1: True 5-flavor scheme (b -quarks massless throughout)
 - ▶ Option 2: 5-flavor scheme, but b -quarks become massive in PS
- ▶ Option 2 captures most mass effects in b -jet production/evolution

Heavy flavors

$Z + b$ cross section

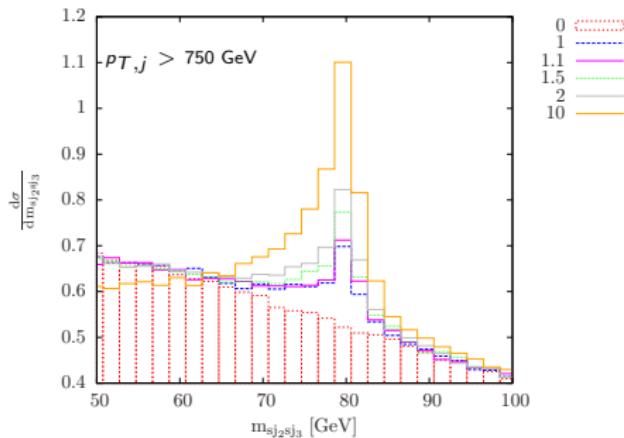
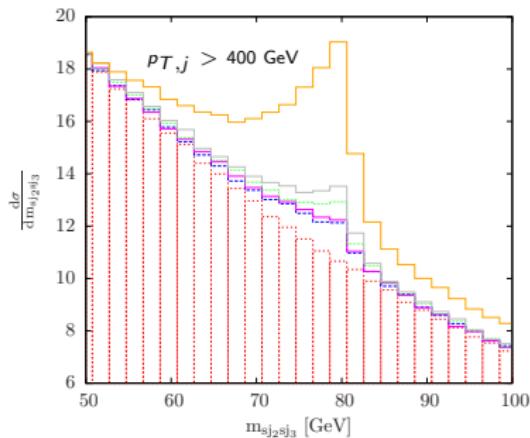
[ATLAS] arXiv:1109.1403

Experiment	$3.55^{+0.82}_{-0.74}(\text{stat})^{+0.73}_{-0.55}(\text{syst}) \pm 0.12(\text{lumi}) \text{ pb}$
MCFM	$3.88 \pm 0.58 \text{ pb}$
ALPGEN	$2.23 \pm 0.01 \text{ (stat only) pb}$
SHERPA	$3.29 \pm 0.04 \text{ (stat only) pb}$



Electroweak showers

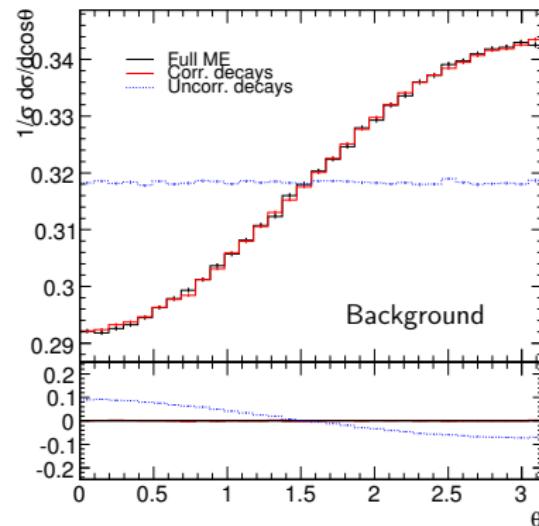
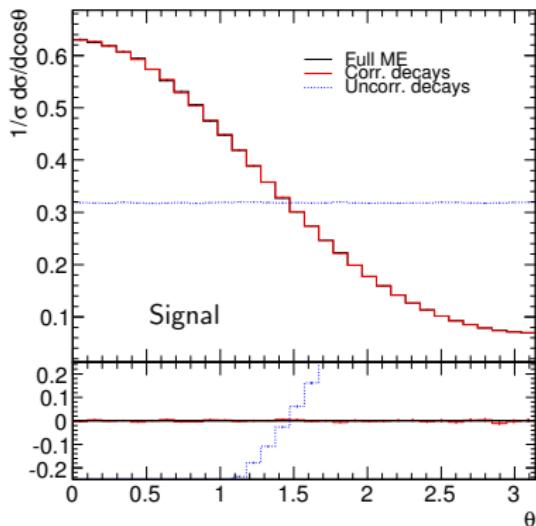
[Krauss,Petrov,Schönherr,Spannowsky] TBP



- ▶ W masses as reconstructed from sub-jets using different enhance factors for EW-splittings
- ▶ Spin averaged splitting functions
→ OK for a single W emission

Spin correlations

- ▶ Sherpa 2.1.x automatically simulates spin correlated decay chains
- ▶ Example: $\theta_{e^+\nu_e,\mu^-\nu_\mu}^{\text{cm}_h}$ in $pp \rightarrow h[\rightarrow W^+W^-]Z$



Summary

New with Sherpa 2.1.x ($\mathcal{O}(1\text{week})$)

- ▶ Spin correlated decay chains
- ▶ Improved(?) heavy flavor treatment (massive PS)
- ▶ More options to assess shower uncertainties

Other interesting topics

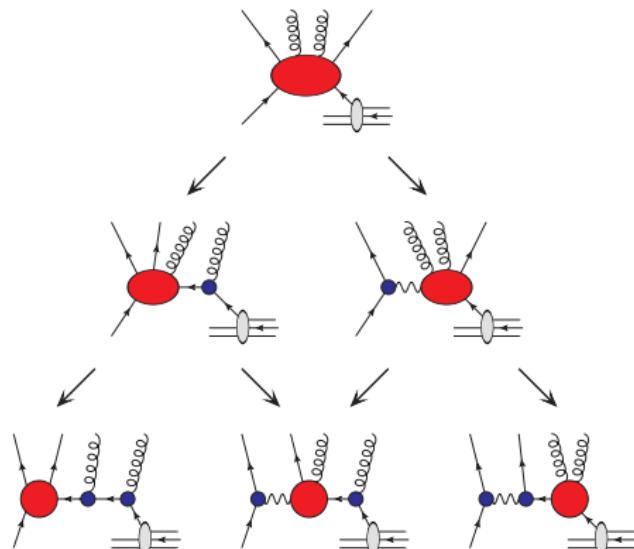
- ▶ $W^+ W^- b\bar{b}$ with S-MC@NLO in Sherpa – in the works!
- ▶ EW showers vs inclusive merging (\nearrow backup slides)

Partial alternative to EW showers: Inclusive ME \oplus PS

[Krauss,Schälicke] hep-ph/0409106

[Krauss,Schumann,Sieger,SH] arXiv:0903.1219

- ▶ Matrix element final states can have very different “PS histories”
- ▶ Must reduce full high-multi ME to either of these configurations in order to start PS
- ▶ Radiation off intermediate states must be included to account for QCD Sudakovs \rightarrow truncated PS
- ▶ Probability to identify splitting given by PS's branching eqns
- ▶ Reduced ME configuration defined by “inverted” PS kinematics
- ▶ Continue until $2 \rightarrow 2$ “core”
- ▶ Core process sets hardness scale $\rightarrow \mu_Q$ (resummation scale)



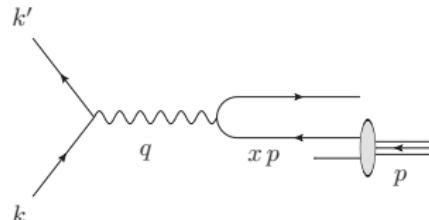
Detour: Lessons from HERA

Leading order $e^\pm p$ - scattering in collinear factorization (Breit frame)

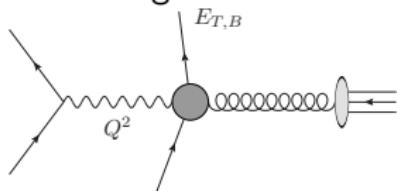
- There are no jets !
- Kinematical variables

$$Q^2 = -q^2 = (k' - k)^2 \text{ and } x = \frac{Q^2}{2 q \cdot p}$$

- Hadronic cm energy $W = Q \sqrt{(1-x)/x}$



DIS at higher orders



- Multiple QCD scales, e.g. $E_{T,B}^2$
- $e^\pm q \rightarrow e^\pm q$ if $E_{T,B}^2 \lesssim Q^2$
- $\gamma^* g \rightarrow \text{jets}$ if $Q^2 \lesssim E_{T,B}^2$

- Virtuality of exchanged photon preferentially close to zero
- Resummation scale is $Q^2 \rightarrow$ no phase space for PS emissions

Very similar to $pp \rightarrow e^+ e^-$ at large jet- p_T !

Inclusive ME \oplus PS Example: Inclusive jets in DIS

[Carli,Gehrmann,SH] arXiv:0912.3715

Variation of maximum matrix-element multiplicity, N_{\max} (\nearrow color code)

