

Towards an NLO parton shower and improved uncertainty estimates

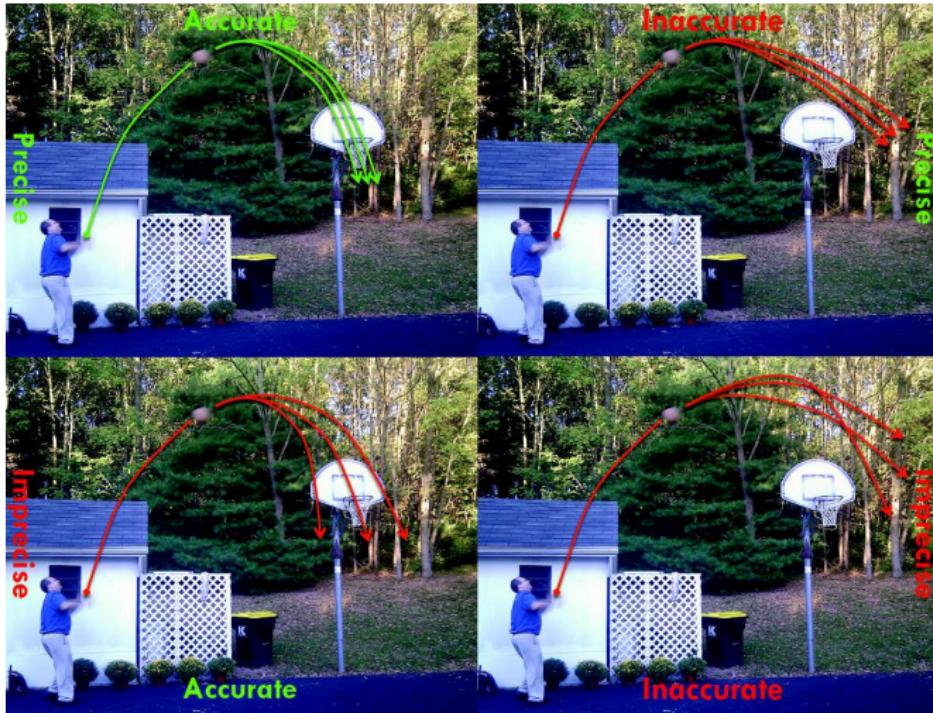
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ATLAS $h \rightarrow bb$ / Flavor Tagging Workshop

Stony Brook, 09/05/2017

Accuracy and Precision (A. David)

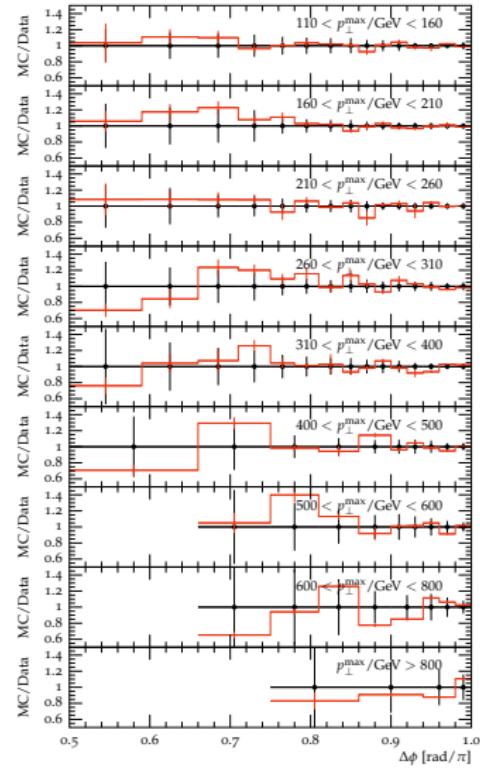
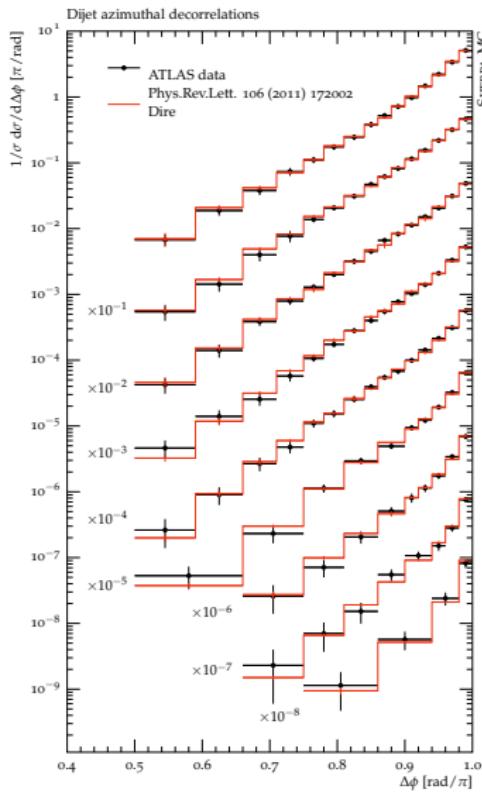
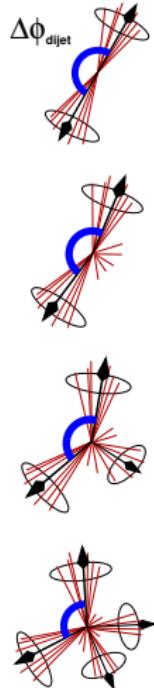


[N. Glover at Scales Workshop, 2017]

Accuracy of parton showers - Example: Jets at LHC

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[Prestel,SH] arXiv:1506.05057



How can we make parton showers more precise?

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- ▶ Formulate parton-shower algorithm at NLO [Nagy,Soper] arXiv:1705.08093
Naturally, NLO DGLAP evolution must be part of the full solution
- ▶ NLO DGLAP splitting kernels known since long
 - [Curci,Furmanski,Petronzio] NPB175(1980)27, PLB97(1980)437
 - [Floratos,Kounnas,Lacaze] NPB192(1981)417
- ▶ So far not implemented in parton showers because
 - ▶ Kernels are scheme dependent (easy)
 - ▶ Overlap with soft-gluon resummation (hard)
- ▶ Focus on purely collinear corrections (\leftrightarrow B2) for a start
 - ▶ Redefine time-like Sudakovs to recover NLO DGLAP evolution
[Jadach,Skrzypek] hep-ph/0312355
 - ▶ Negative NLO corrections require weighted veto algorithm
[Schumann,Siegert,SH] arXiv:0912.3501, [Lönnblad] arXiv:1211.7204
 - ▶ Flavor changing splitting functions require $2 \rightarrow 4$ transitions
[Prestel,SH] arXiv:1705.00742
- ▶ Flavor-changing case is simplest but requires all the technology

Parton-shower interpretation of the DGLAP equations

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- DGLAP equation for fragmentation functions

$$\frac{dx D_a(x, t)}{d \ln t} = \sum_{b=q,g} \int_0^1 d\tau \int_0^1 dz \frac{\alpha_s}{2\pi} [z P_{ab}(z)]_+ \tau D_b(\tau, t) \delta(x - \tau z)$$

- Define plus prescription $[z P_{ab}(z)]_+ = \lim_{\varepsilon \rightarrow 0} z P_{ab}(z, \varepsilon)$

$$P_{ab}(z, \varepsilon) = P_{ab}(z) \Theta(1 - z - \varepsilon) - \delta_{ab} \sum_{c \in \{q, g\}} \frac{\Theta(z - 1 + \varepsilon)}{\varepsilon} \int_0^{1-\varepsilon} d\zeta \zeta P_{ac}(\zeta)$$

- Rewrite for finite ε

$$\frac{d \ln D_a(x, t)}{d \ln t} = - \sum_{c=q,g} \int_0^{1-\varepsilon} d\zeta \zeta \frac{\alpha_s}{2\pi} P_{ac}(\zeta) + \sum_{b=q,g} \int_x^{1-\varepsilon} \frac{dz}{z} \frac{\alpha_s}{2\pi} P_{ab}(z) \frac{D_b(x/z, t)}{D_a(x, t)}$$

- First term is derivative of Sudakov factor

$$\Delta_a(t_0, t) = \exp \left\{ - \int_{t_0}^t \frac{d\bar{t}}{\bar{t}} \sum_{c=q,g} \int_0^{1-\varepsilon} d\zeta \zeta \frac{\alpha_s}{2\pi} P_{ac}(\zeta) \right\}$$

Parton-shower interpretation of the DGLAP equations

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- ▶ Use generating function $\mathcal{D}_a(x, t, \mu^2) = D_a(x, t)\Delta_a(t, \mu^2)$ to write

$$\frac{d \ln \mathcal{D}_a(x, t, \mu^2)}{d \ln t} = \sum_{b=q,g} \int_x^{1-\varepsilon} \frac{dz}{z} \frac{\alpha_s}{2\pi} P_{ab}(z) \frac{D_b(x/z, t)}{D_a(x, t)}.$$

- ▶ A similar probability density is used to generate initial-state emissions
But final-state showers are typically unconstrained (hadrons not identified)
In this case the probability density is modified to

$$\frac{d}{d \ln t} \ln \left(\frac{\mathcal{D}_a(x, t, \mu^2)}{D_a(x, t)} \right) = \sum_{b=q,g} \int_0^{1-\varepsilon} dz z \frac{\alpha_s}{2\pi} P_{ab}(z).$$

- ▶ **Net result:** Unitarity implies that forward-branching Sudakovs must include a ‘symmetry factor’ z [Jadach,Skrzypek] hep-ph/0312355
- ▶ Convenient interpretation as “tagging” of evolving parton
- ▶ Equivalent to standard technique at LO due to symmetry of $P_{ab}(z)$
More care is needed at NLO [Prestel,SH] arXiv:1705.00742

2 → 4 kinematics mapping, massless FF case

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- ▶ Define evolution & splitting variables

$$t = \frac{4 p_j p_{ai} p_{ai} p_k}{q^2}, \quad z_a = \frac{2 p_a p_k}{q^2}$$

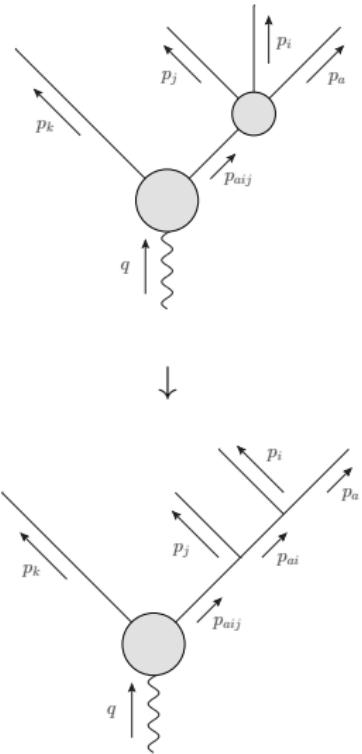
$$s_{ai} = 2 p_a p_i, \quad x_a = \frac{p_a p_k}{p_{ai} p_k}$$

- ▶ First branching $(\tilde{aij}, \tilde{k}) \rightarrow (ai, j, k)$
constructed with $m_{ai}^2 \rightarrow s_{ai}$, using
 [Catani,Dittmaier,Seymour,Trocsanyi] hep-ph/0201036
 [Prestel,SH] arXiv:1506.05057

$$y = \frac{t x_a / z_a}{q^2 - s_{ai}}, \quad \tilde{z} = \frac{z_a / x_a}{1 - y} \frac{q^2}{q^2 - s_{ai}}.$$

- ▶ Second step now a decay $(ai, k) \rightarrow (a, i, k)$
can use CDST algorithm with

$$y' = \left[1 + \frac{z_a}{x_a} \frac{q^2}{s_{ai}} \right]^{-1}, \quad \tilde{z}' = x_a$$



$2 \rightarrow 4$ phase space, massless FF case

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- Phase space factorization derived similar to [Dittmaier] hep-ph/9904440
→ s-channel factorization over p_{aij} , subsequently over p_{ai}

$$\begin{aligned}\int d\Phi(p_a, p_i, p_j, p_k | q) &= \int \frac{ds_{aij}}{2\pi} \int d\Phi(p_{aij}, p_k | q) \int d\Phi(p_a, p_i, p_j | p_{aij}) \\ &= \int d\Phi(\tilde{p}_{aij}, \tilde{p}_k | q) \int [d\Phi(p_a, p_i, p_j | \tilde{p}_{aij}, \tilde{p}_k)]\end{aligned}$$

- Nearly reduces to iterated $2 \rightarrow 3$ phase space

$$\int [d\Phi(p_a, p_i, p_j | \tilde{p}_{aij}, \tilde{p}_k)] =$$
$$\underbrace{\frac{1}{4(2\pi)^3} \int \frac{dt}{t} \int dz_a \int d\phi_j}_{\text{emission of } j} \underbrace{\frac{1}{4(2\pi)^3} \int ds_{ai} \int \frac{dx_a}{x_a} \int d\phi_i}_{\text{emission of } i} 2 p_{ai} p_j$$

- Fully massive case worked out for all dipoles [Prestel,SH] arXiv:1705.00742

Collinear factorization and resummation

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- ▶ Combination with massless matrix element in collinear limit leads to

$$\begin{aligned} & \int d\Phi(p_a, p_i, p_j, p_k | q) |M_{n+2}(a, i, j, k | q)|^2 \\ &= \int \frac{dt}{t} \int dz_a \int ds_{ai} \int \frac{dx_a}{x_a} \int \frac{d\phi_i}{2\pi} \frac{2p_{ai}p_j}{s_{aij}} \\ & \quad \times \left(\frac{\alpha_s}{2\pi}\right)^2 \frac{P_{(aij)a}(p_a, p_i, p_j)}{s_{aij}} \int d\Phi(\tilde{p}_{aij}, \tilde{p}_k | q) |M_n(\tilde{aij}, \tilde{k} | q)|^2 \end{aligned}$$

- ▶ Write as differential branching probability

$$\frac{d \ln \Delta_{(aij)a}^{1 \rightarrow 3}}{d \ln t} = \int dz_a \frac{z_a z_i}{1 - z_a} \int ds_{ai} \int \frac{dx_a}{x_a} \int \frac{d\phi_i}{2\pi} \left(\frac{\alpha_s}{2\pi}\right)^2 \frac{P_{(aij)a}(p_a, p_i, p_j)}{s_{aij}^2 / 2 p_{ai} p_j}$$

- ▶ LO PS accounts for iterated collinear limit, hence we must subtract

$$\frac{d \ln \Delta_{(aij)a}^{(1 \rightarrow 2)^2}}{d \ln t} = \int dz_a \frac{z_a z_i}{1 - z_a} \int \frac{ds_{ai}}{s_{ai}} \int \frac{d\xi}{\xi} \left(\frac{\alpha_s}{2\pi}\right)^2 \frac{\sum_{(ai)} P_{(aij)(ai)}^{(0)}(\xi) P_{(ai)a}^{(0)}(z_a/\xi)}{s_{aij} / 2 p_{ai} p_j}$$

Collinear factorization and resummation

- ▶ Simplest possible configuration $q \rightarrow q'$ [Catani,Grazzini] hep-ph/9908523

$$P_{qq'} = \frac{1}{2} C_F T_R \frac{s_{aij}}{s_{ai}} \left[-\frac{t_{ai,j}^2}{s_{ai}s_{aij}} + \frac{4z_j + (z_a - z_i)^2}{z_a + z_i} + (1 - 2\varepsilon) \left(z_a + z_i - \frac{s_{ai}}{s_{aij}} \right) \right]$$

where $(z_a + z_i)t_{ai,j} = 2(z_a s_{ij} - z_i s_{aj}) + (z_a - z_i)s_{ai}$

- ▶ Apparent collinear singularity in s_{ai} that cancels upon azimuthal averaging against iterated LO splitting
- ▶ But integrand locally divergent \rightarrow Not amenable to MC simulation
- ▶ Solved by subtraction of spin-correlated LO splitting functions
[Somogyi,Trocsanyi,del Duca] hep-ph/0502226

$$P_{qg}^{\mu\nu} = C_F \left[-2 \frac{z}{1-z} \frac{k_T^\mu k_T^\nu}{k_T^2} + \frac{1-z}{2} \left(-g^{\mu\nu} + \frac{p^\mu n^\nu + p^\nu n^\mu}{np} \right) \right]$$

$$P_{gq}^{\mu\nu} = T_R \left[-g^{\mu\nu} + 4z(1-z) \frac{k_T^\mu k_T^\nu}{k_T^2} \right]$$

- ▶ Leads to additional subtraction term

$$\Delta P_{qq'} = C_F T_R \frac{4z_a z_i z_j}{(1-z_j)^3} (1 - 2 \cos^2 \phi) , \quad \cos \phi = \frac{s_{ai}s_{jk} + s_{ak}s_{ij} - s_{aj}s_{ik}}{\sqrt{4 s_{ai}s_{ak} s_{ij}s_{jk}}}$$

Collinear factorization and resummation

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- ▶ Reference for $q \rightarrow q'$ upon integration over s_{ai}, x_a, ϕ_j given by NLO kernel

$$P_{qq'}(z) = C_F T_R \left[(1+z) \ln^2 z - \left(\frac{8}{3} z^2 + 9z + 5 \right) \ln z + \frac{56}{9} z^2 + 4z - 8 - \frac{20}{9z} \right]$$

- ▶ So far we only have

$$P_{qq'}(z) = -C_F T_R \left[5(1-z) + 2(1+z) \ln z \right]$$

- ▶ Remainder scheme-dependent, must be computed in D dimensions
- ▶ Key is to realize that we just set up a local, modified subtraction method

$$P_{qq'}(z) = \left(\mathbf{I} + \frac{1}{\epsilon} \mathcal{P} - \mathcal{I} \right)_{qq'}(z) + \int d\Phi_{+1} (\mathbf{R} - \mathbf{S})_{qq'}(z, \Phi_{+1})$$

where

$$I_{qq'}(z) = \int d\Phi_{+1} S_{qq'}(z, \Phi_{+1}), \quad \mathcal{P}_{qq'}(z) = \int_z \frac{dx}{x} P_{qg}^{(0)}(x) P_{gq}^{(0)}(z/x)$$

$$\mathcal{I}_{qq'}(z) = 2 \int_z \frac{dx}{x} C_F \left(\frac{1 + (1-x)^2}{x} \ln(x(1-x)) + x \right) P_{gq}(z/x)$$

Collinear factorization and resummation

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- ▶ Analytical computation of I not needed, as $I + \mathcal{P}/\varepsilon$ finite
- ▶ Simulate as endpoint, starting from $\mathcal{O}(\varepsilon)$ coefficient of integrand
 - ▶ Generate point in triple collinear phase space,
but retroactively project onto $s_{ai} = 0$
 - ▶ Guarantees phase-space coverage
identical to fully differential simulation
- ▶ Kernel for endpoint contribution defined by $\Delta I_{qq'} = \tilde{I}_{qq'} - \tilde{\mathcal{I}}_{qq'}$, where

$$\tilde{I}_{qq'} = C_F T_R \left[\frac{1+z_j^2}{1-z_j} + \left(1 - \frac{2 z_a z_i}{(z_a + z_i)^2} \right) \left(1 - z_j + \frac{1+z_j^2}{1-z_j} \right) \left(\ln(z_a z_i z_j) - 1 \right) \right]$$
$$\tilde{\mathcal{I}}_{qq'} = 2C_F \left[\frac{1+z_j^2}{1-z_j} \ln((z_a + z_i) z_j) + (1 - z_j) \right] P_{gq}^{(0)} \left(\frac{z_a}{z_a + z_i} \right).$$

- ▶ Cross-checked method analytically using phase space from
[Gehrmann, Gehrmann-DeRidder, Heinrich] hep-ph/0311276 (timelike)
[Ellis, Vogelsang] hep-ph/9602356 (spacelike)

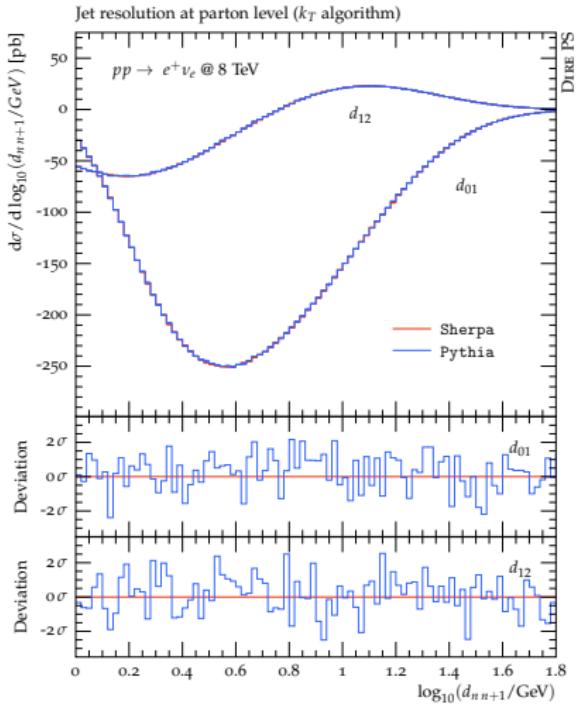
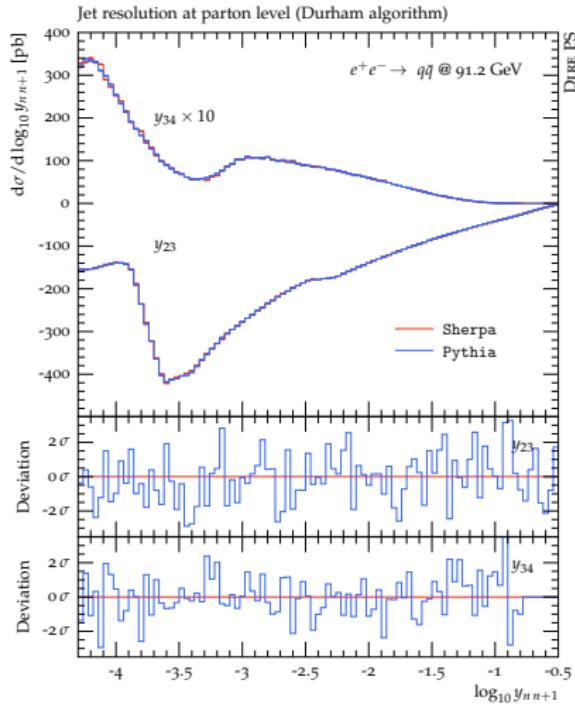
Basic layout of Dire [Prestel,SH] arXiv:1506.05057

- ▶ Dipole-like parton shower, kernels as close as possible to DGLAP
- ▶ Partial fraction soft eikonal à la Catani-Seymour, evolve in dipole- k_T
- ▶ Two independent implementations (Pythia & Sherpa)
- ▶ Cross-validation at particle level

New developments

- ▶ MC counterterms implemented in Amegic & Comix [SH]
- ▶ MC@NLO matching & NLO subtraction in Sherpa [SH]
- ▶ UNLOPS / MEPS@NLO merging in Pythia / Sherpa [Prestel,SH]
- ▶ Flavor-changing triple collinear splitting functions [Prestel,SH] arXiv:1507.00742
- ▶ NLO DGLAP kernels & 3-loop cusp [Krauss,Prestel,SH] arXiv:1507.00982

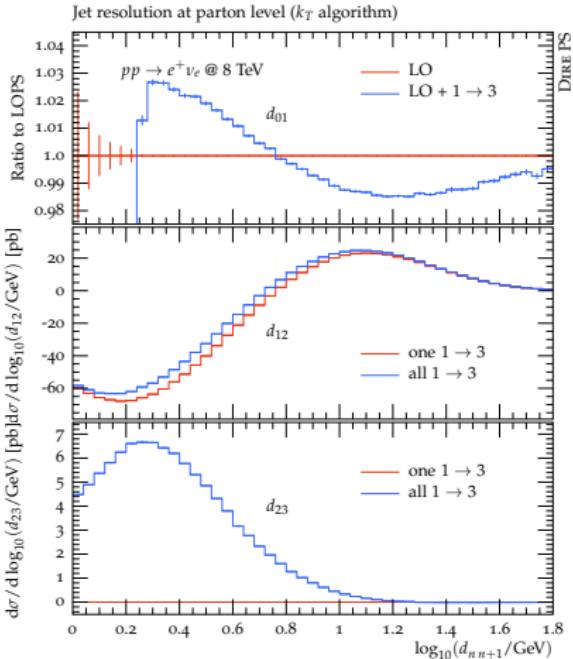
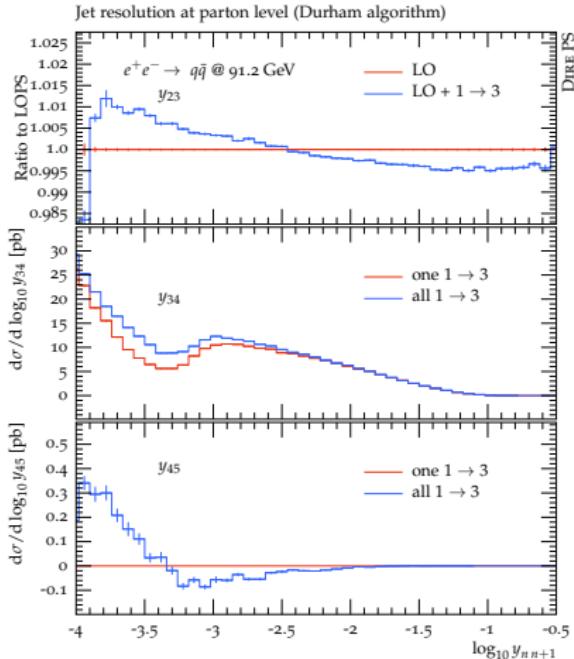
Validation



- Effect of single $1 \rightarrow 3$ emission on leading and next-to-leading jet rate

Impact on leading-order PS prediction

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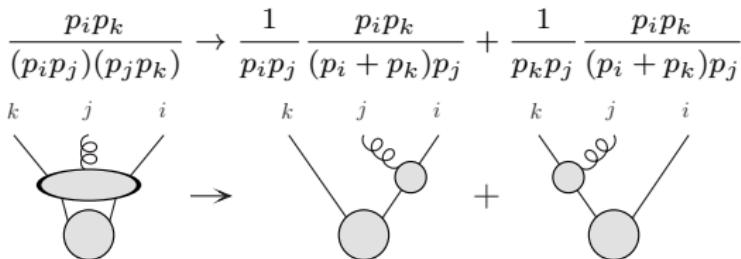


- Effect of $1 \rightarrow 3$ emissions on leading jet rate
- Impact of multiple $1 \rightarrow 3$ emissions

Soft-gluon radiation at LO

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- Soft eikonal partial fractioned to account for coherence effects
(3-parton correlations) [Catani,Seymour] hep-ph/9605323



- “Spectator”-dependent kernels, singular in soft-collinear region only
→ Soft enhanced term of splitting functions replaced as

$$2C_a \frac{1}{1-z} \rightarrow 2C_a \frac{1-z}{(1-z)^2 + \kappa_{j,ik}^2} \quad \kappa_{j,ik}^2 = \frac{k_{\perp,j \leftrightarrow ik}^2}{Q^2} = \frac{4 p_i p_j p_j p_k}{Q^4}$$

- For correct soft FS evolution, color correlations must be respected

$$P_{gg} \rightarrow P_{gg}(1 - z_j, \kappa_{j,ik}^2) + P_{gg}(1 - z_i, \kappa_{i,jk}^2)$$

$$P_{gg}(z, \kappa^2) = 2C_A \left[\frac{1-z}{(1-z)^2 + \kappa^2} - 1 + \frac{z(1-z)}{2} \right]$$

Flavor non-changing splittings at NLO

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- ▶ Two-loop cusp anomalous dimension included at LO in CMW prescription [Catani,Marchesini,Webber] NPB349(1991)635

$$P_{ab}^{(0)} \rightarrow P_{ab}^{(0)} + \delta_{ab} 2C_a \frac{1-z}{(1-z)^2 + \kappa^2} \frac{\alpha_s}{2\pi} \Gamma^{(2)}, \quad \Gamma^{(2)} = \left[\frac{67}{18} - \frac{\pi^2}{6} \right] C_A - \frac{10}{9} T_F$$

Can add structurally identical 3-loop term [Moch,Vermaseren,Vogt] hep-ph/0403192

- ▶ Subtract $\Gamma^{(2)}$ from 2-loop splitting function to avoid double-counting

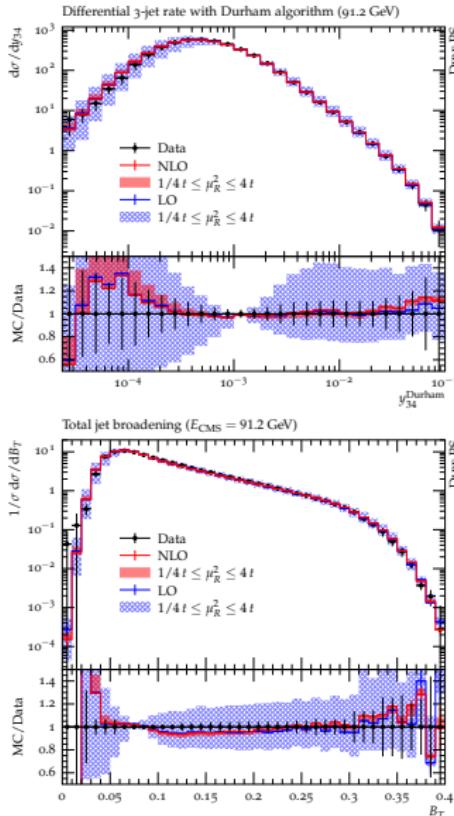
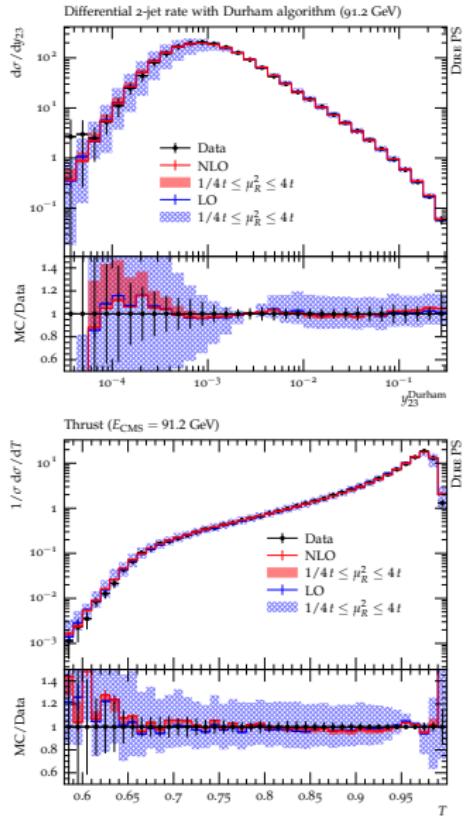
$$P_{ab}^{(1)}(z, \kappa^2) \rightarrow P_{ab}^{(1)}(z) - \delta_{ab} \frac{2C_a}{1-z} \Gamma^{(2)}$$

- ▶ Scale variation on soft-enhanced part of splitting functions relies on [Amati,Bassetto,Ciafaloni,Marchesini,Veneziano] NB173(1980)429
(renormalization scale set by $k_T^2 \leftrightarrow$ limit on gluon virtuality)

First results

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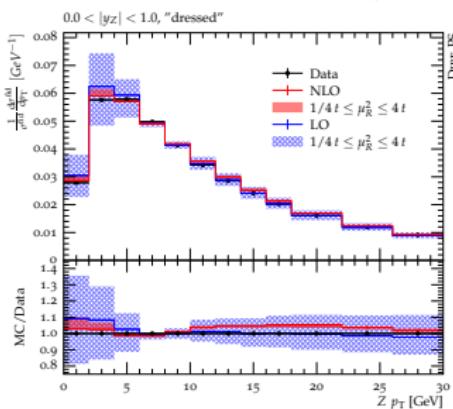
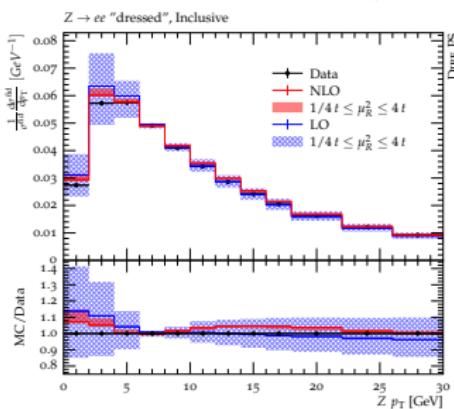
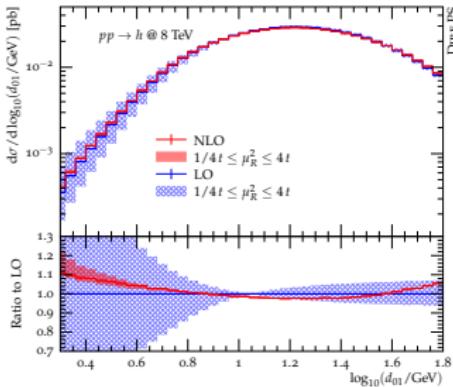
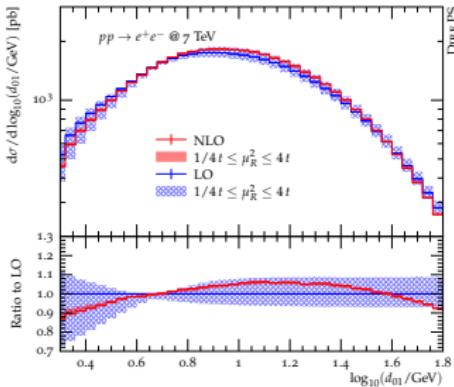
[Krauss,Prestel,SH] arXiv:1705.00982



First results

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[Krauss,Prestel,SH] arXiv:1705.00982



Summary

- ▶ Developed MC algorithm to implement $2 \rightarrow 4$ splittings that recovers integrated NLO splitting functions for $q \rightarrow q' / q \rightarrow \bar{q}$
- ▶ Cross-validated implementation Pythia \leftrightarrow Sherpa
- ▶ Flavor non-changing splitting kernels included in integrated form

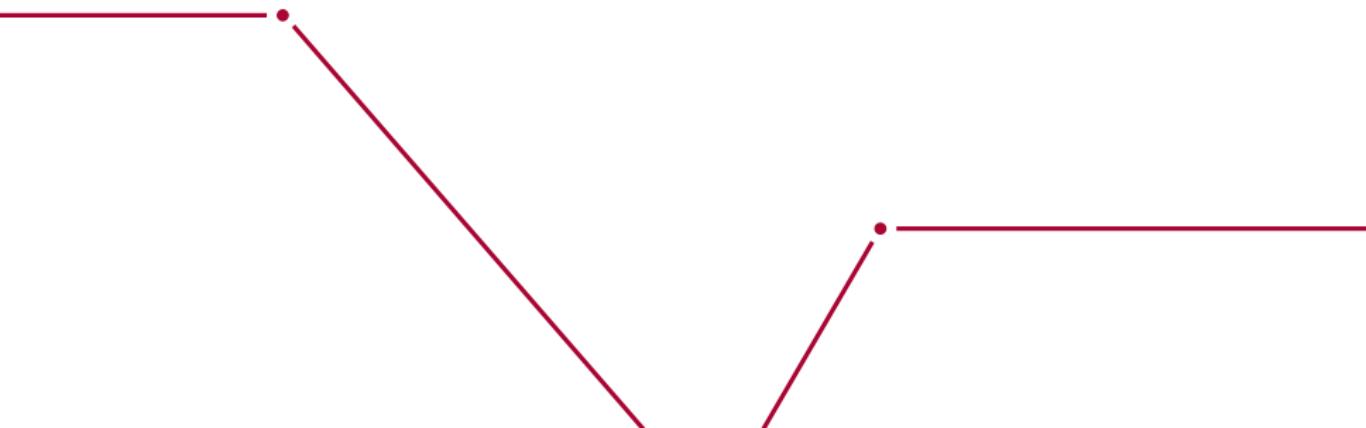
Next steps

- ▶ Extension of differential simulation to flavor non-changing kernels
- ▶ Simulation of soft-gluon radiation at NLO (single emission)
- ▶ Color correlations in soft-gluon emissions (multiple emissions)

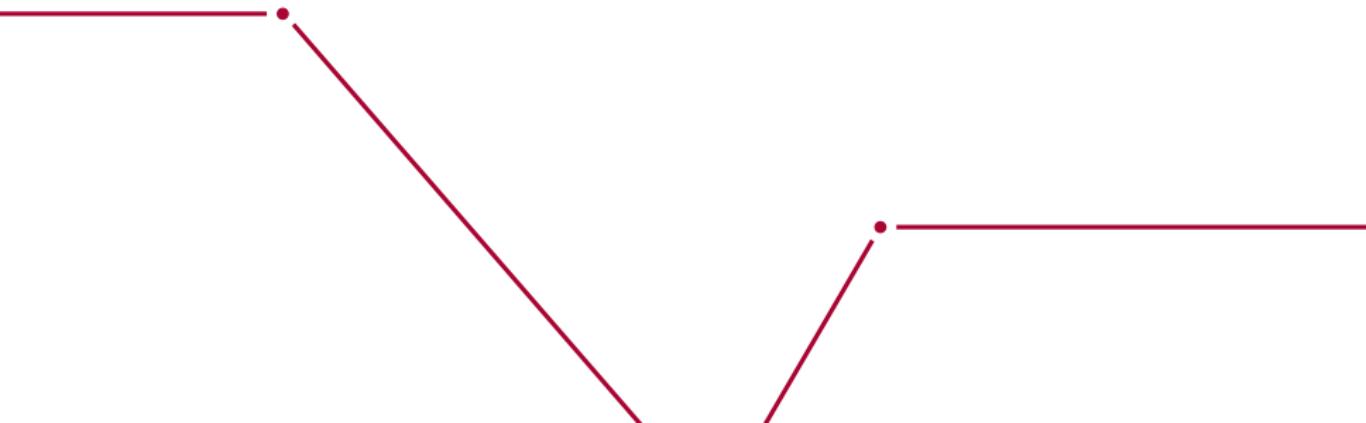
Possible benefits

- ▶ Parton showers with more realistic uncertainty estimates
- ▶ Comparison to analytic resummation at higher precision
- ▶ Same shower algorithm in two different generators

Thank you for your attention



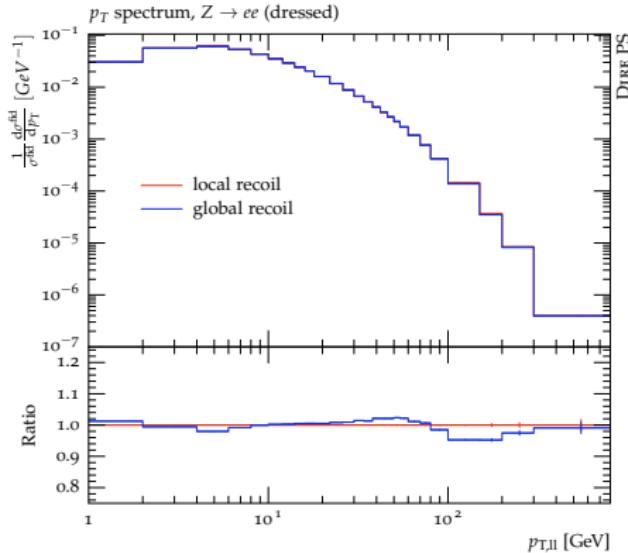
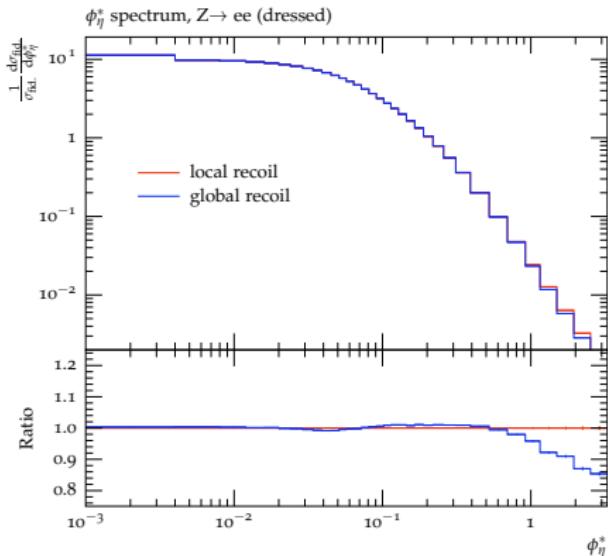
Slides for discussion



Parton shower uncertainties – Kinematics

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[Prestel,SH] arXiv:1506.05057



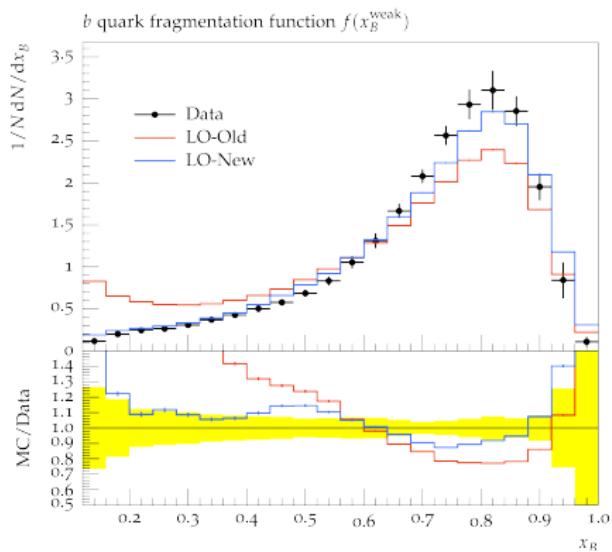
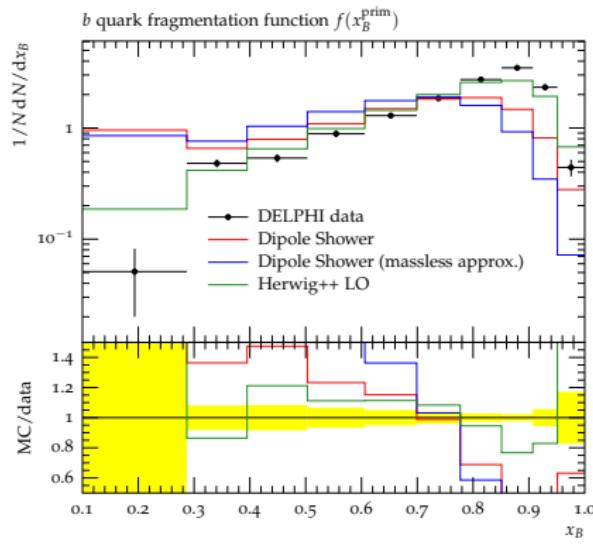
- ▶ Two mapping schemes for IF dipoles \rightarrow local [Catani,Seymour] hep-ph/9605323 and global [Plätzer,Gieseke] arXiv:0909.5593, [Schumann,Siegert,SH] arXiv:0912.3501
- ▶ Negligible impact e.g. on q_T -spectrum of Drell-Yan lepton pairs
- ▶ Less well investigated in more exclusive observables and heavy flavor

Parton shower uncertainties – Shower model

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[Stoll (Diploma thesis)], [Plätzer (IPPP HF WS '16)]
[Plätzer (PSR WS '17)]

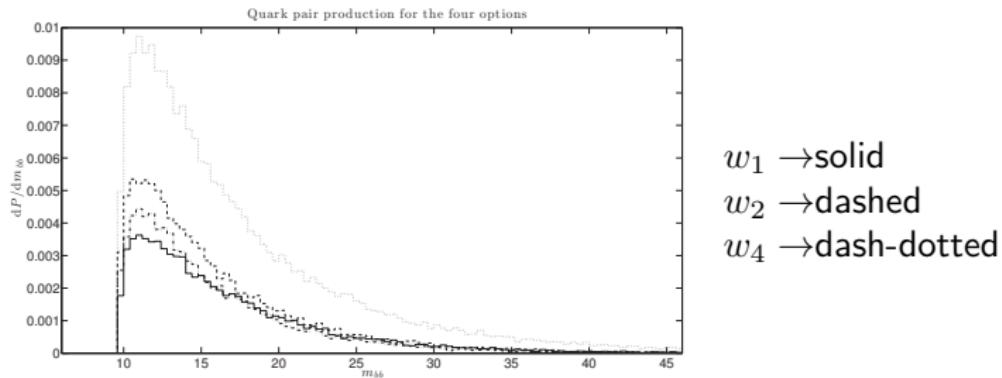
- ▶ Something odd in dipole-like shower models for $g \rightarrow b\bar{b}/c\bar{c}$ splittings
 - ▶ Not a bug, consistent between generators (Herwig7, Sherpa, ...)
 - ▶ Not a kinematical effect
 - ▶ Possibly fixed by evolution variable (collinear p_T , ↗ [S. Plätzer, PSR '17])



Parton shower uncertainties – Splitting functions

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- ▶ Splitting functions for heavy flavor ambiguous
- ▶ Example: FSR $g \rightarrow Q\bar{Q}$ in Pythia8 [Jimenez (Masters Thesis) LU-TP 14-15]
 - ▶ $w_1 = \beta [1 - 2z(1 - z)]$, $\beta = \sqrt{1 - 4m_Q^2/Q^2}$
 - ▶ $w_2 = \beta [1 - 2z(1 - z)(1 - 8m_Q^2/Q^2)]$
 - ▶ $w_4 \rightarrow$ full $\gamma^* \rightarrow Q\bar{Q}$ ME correction



- ▶ Also: Effects of massive recoil partners in momentum mapping

Matching – Full vs leading color

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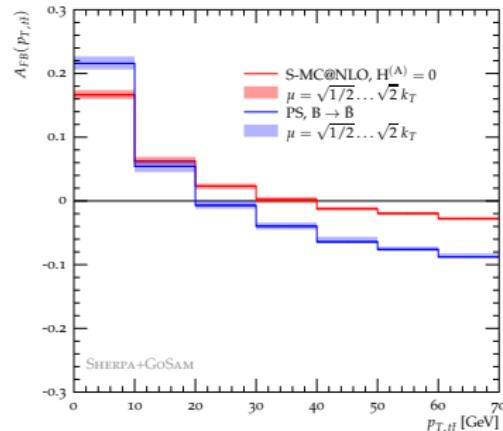
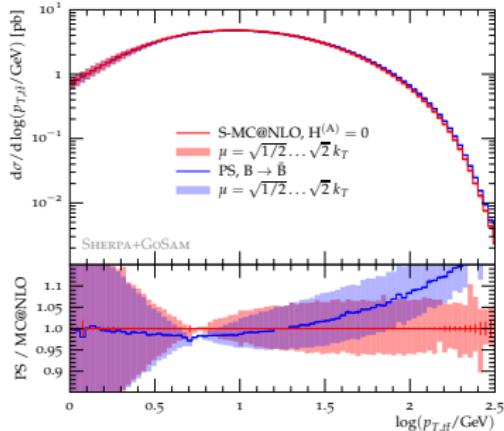
[Huang,Luisoni,Schönherr,Winter,SH] arXiv:1306.2703

- Standard MC@NLO: Soft-gluon kinematics ignored by fading out real-emission correction to account for leading color **MC subtraction terms**

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

$$\bar{B}^{(K)} = B + \tilde{V} + I + \int d\Phi_1 [S - BK] f(\Phi_1), \quad H^{(K)} = [R - BK] f(\Phi_1)$$

- Appropriate for sufficiently inclusive observables, problematic e.g. for A_{FB}
Similar issues could arise in other observables that break PS unitarity

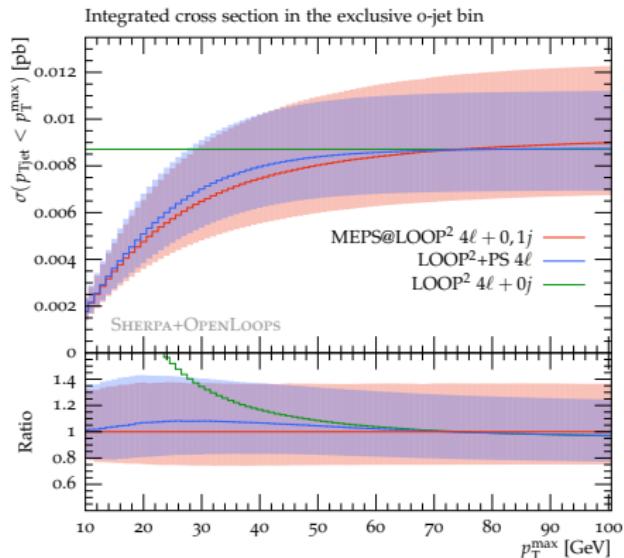
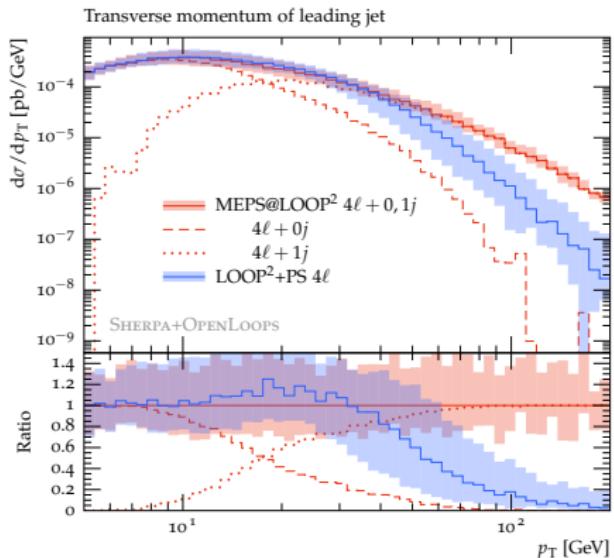
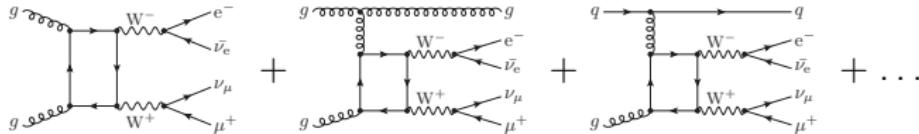


Squared-loop merging in $gg \rightarrow WW$

SLAC

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

► Combine

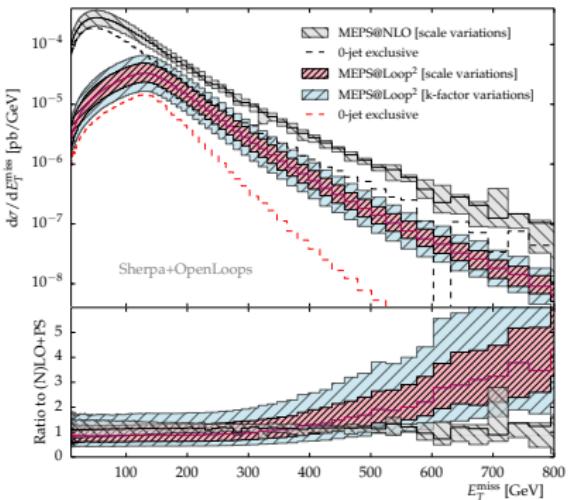
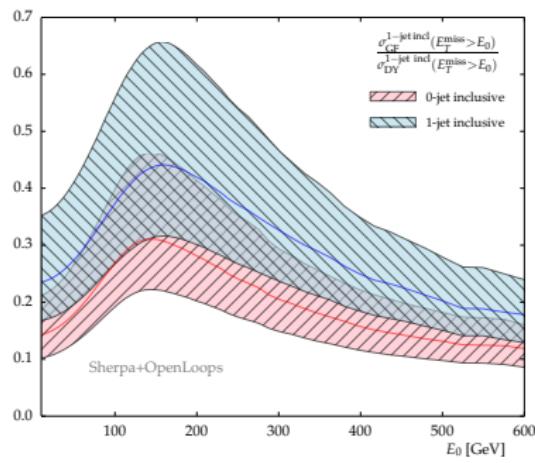
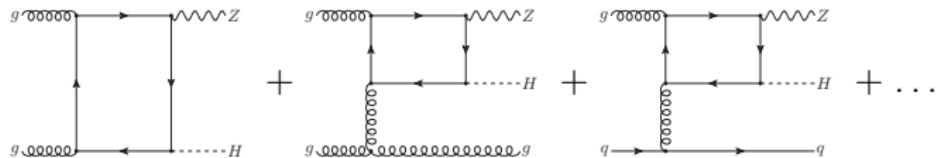


Squared-loop merging in $gg \rightarrow HZ$

SLAC

[Goncalves,Krauss,Kuttmalai,Maierhöfer] arXiv:1509.01597, arXiv:1605.08039

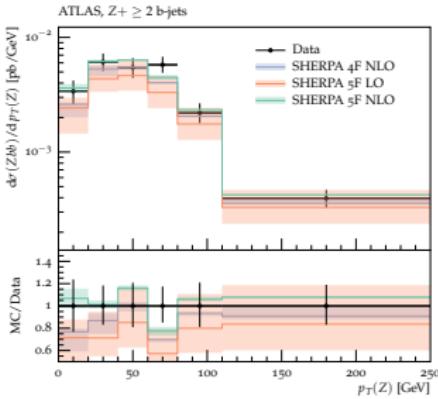
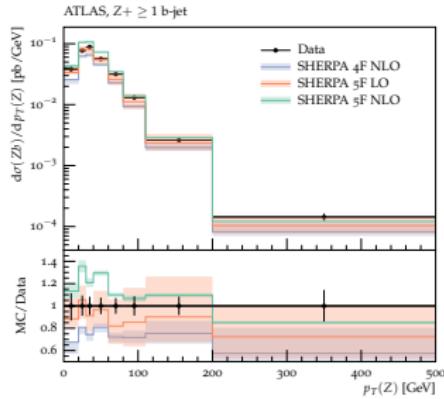
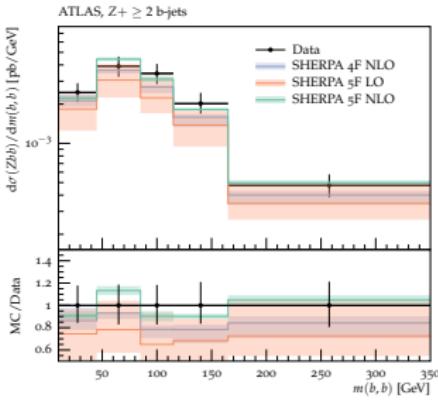
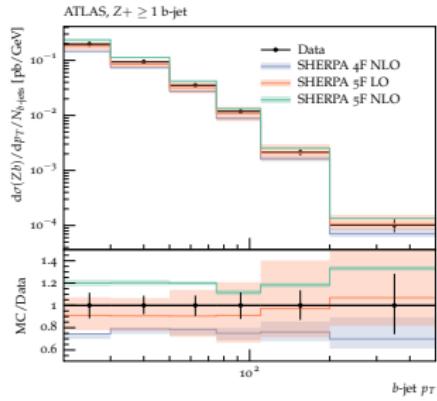
► Combine



Simulation of $Wbb\bar{b}$

SLAC

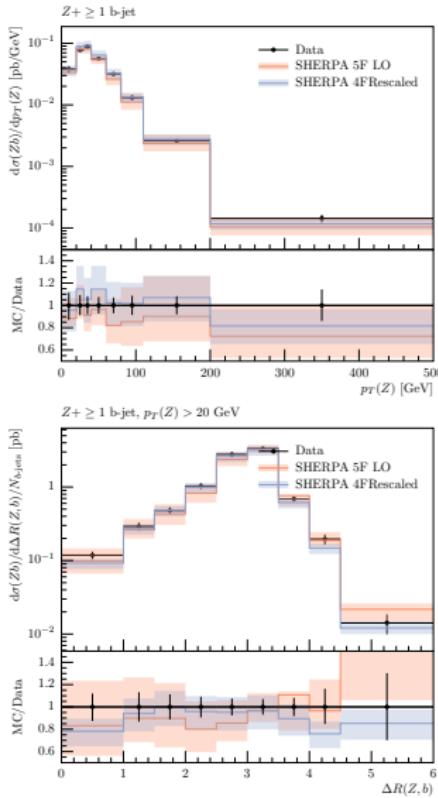
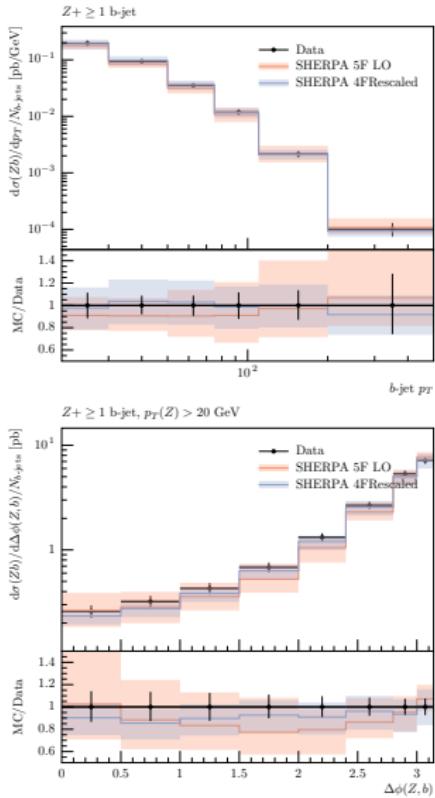
[Krauss,Napoletano,Schumann] arXiv:1605.04692, arXiv:1612.04640



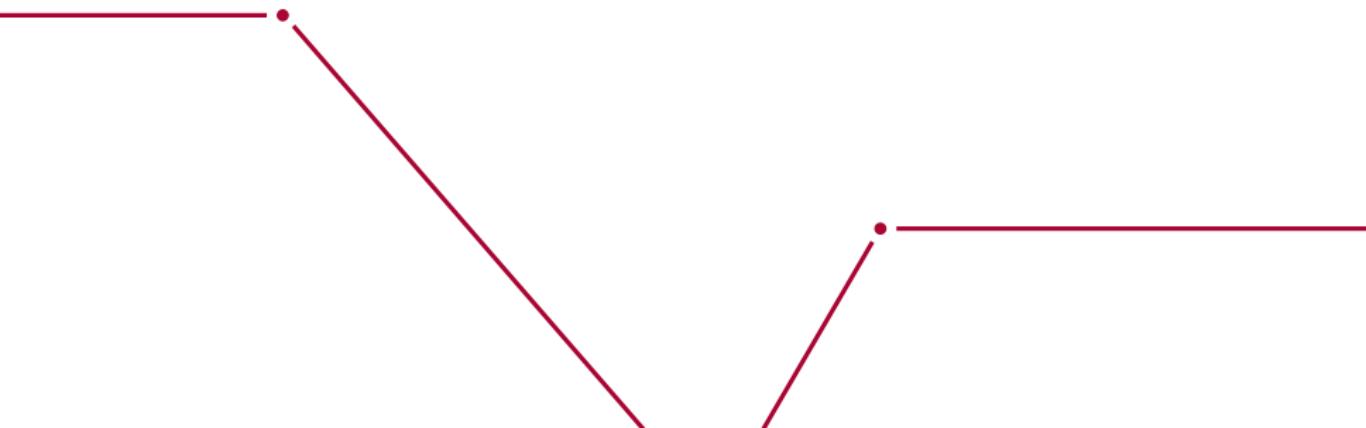
Simulation of $Wbb\bar{b}$

SLAC

[Krauss,Napoletano,Schumann] arXiv:1605.04692, arXiv:1612.04640



Backup slides



Negative branching “probabilities” in Markov Chains

- ▶ Problem in NLO splitting kernels, sub-leading color terms, etc. lies in negative weights → no-emission probability *locally* exceeds unity
- ▶ Recall standard veto algorithm: $\mathcal{P}_{\text{no}}(t, t') = \exp\{F(t) - F(t')\}$
Exact MC solution $t = F^{-1}[F(t') + \ln R]$, R – random number
- ▶ Don't want or can't compute $F(t) = - \int_t d\bar{t} f(\bar{t})$,
instead find simple function $g(t) > f(t)$ with integral $G(t)$
- ▶ Generate points according to $g(t)$ and accept with $f(t)/g(t)$

Standard probability for one acceptance with n rejections

$$\frac{f(t)}{g(t)} g(t) \exp \left\{ - \int_t^{t_1} d\bar{t} g(\bar{t}) \right\} \prod_{i=1}^n \left[\int_{t_{i-1}}^{t'} dt_i \left(1 - \frac{f(t_i)}{g(t_i)} \right) g(t_i) \exp \left\{ - \int_{t_i}^{t_{i+1}} d\bar{t} g(\bar{t}) \right\} \right]$$

Split weight into MC and analytic part using auxiliary function $h(t)$

$$\frac{f(t)}{h(t)} g(t) \exp \left\{ - \int_t^{t_1} d\bar{t} g(\bar{t}) \right\} \prod_{i=1}^n \left[\int_{t_{i-1}}^{t'} dt_i \left(1 - \frac{f(t_i)}{h(t_i)} \right) g(t_i) \exp \left\{ - \int_{t_i}^{t_{i+1}} d\bar{t} g(\bar{t}) \right\} \right]$$

$$w(t, t_1, \dots, t_n) = \frac{h(t)}{g(t)} \prod_{i=1}^n \frac{h(t_i)}{g(t_i)} \frac{g(t_i) - f(t_i)}{h(t_i) - f(t_i)}$$

Negative branching “probabilities” in Markov Chains

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Looks trivial, surprisingly it's not: It allows to

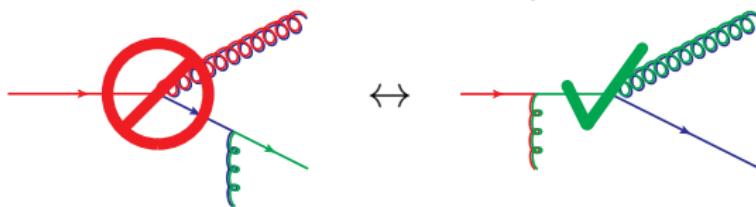
- ▶ Resum sub-leading color terms in MC@NLO and POWHEG
[Krauss,Schönherr,Siegert,SH] arXiv:1111.1220
- ▶ Implement triple-collinear splitting functions in parton showers
[Prestel,SH] arXiv:1705.00742
- ▶ Use PDFs with negative values in parton showers
[Prestel,SH] arXiv:1506.05057
- ▶ Enhance branching probabilities in parton showers
[Schumann,Siegert,SH] arXiv:0912.3501, [Lönnblad] arXiv:1211.7204
- ▶ Reweight parton showers [Bellm,Plätzer,Richardson,Siódlok,Webster] arXiv:1605.08256
[Mrenna,Skands] arXiv:1605.08352, [Bothmann,Schönherr,Schumann] arXiv:1606.08753

Color coherence and the dipole picture

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[Marchesini,Webber] NPB310(1988)461

- ▶ Individual color charges inside a color dipole cannot be resolved by gluons of wavelength larger than the dipole size
→ emission off combined mother parton instead



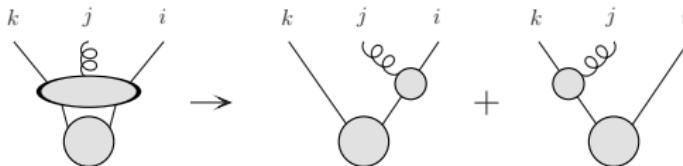
- ▶ Net effect is destructive interference outside cone with opening angle defined by emitting color dipole
→ Soft anomalous dimension halved due to reduced phase space
- ▶ Formerly implemented by angular ordering / angular veto
[Webber at al.] hep-ph/0210213, [Sjöstrand et al.] hep-ph/0603175
- ▶ Alternative description in terms of color dipoles
[Gustafsson,Pettersson] NPB306(1988)746, [Kharraziha,Lönnblad] hep-ph/9709424
[Winter,Krauss] arXiv:0712.3913

The midpoint between dipole and parton showers

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- ▶ Angular ordered / vetoed parton shower does not fill full phase space
Dipole shower lacks parton interpretation → prefer alternative to both
- ▶ Can preserve parton picture by partial fractioning soft eikonal
↔ soft enhanced part of splitting function [Catani,Seymour] hep-ph/9605323

$$\frac{p_i p_k}{(p_i p_j)(p_j p_k)} \rightarrow \frac{1}{p_i p_j} \frac{p_i p_k}{(p_i + p_k)p_j} + \frac{1}{p_k p_j} \frac{p_i p_k}{(p_i + p_k)p_j}$$



- ▶ “Spectator”-dependent kernels, singular in soft-collinear region only
→ capture dominant coherence effects (3-parton correlations)

$$\frac{1}{1-z} \rightarrow \frac{1-z}{(1-z)^2 + \kappa^2} \quad \kappa^2 = \frac{k_\perp^2}{Q^2}$$

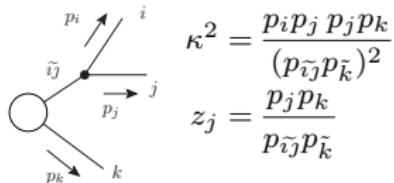
- ▶ For correct soft evolution, ordering variable must be identical at both “dipole ends” (→ recover soft eikonal at integrand level)

The midpoint between dipole and parton showers

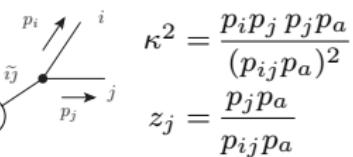
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Choose parametrization such that soft term is $\frac{1-z}{(1-z)^2 + \kappa^2}$ in all dipole types

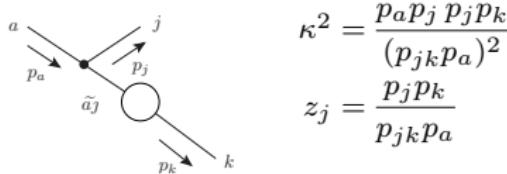
(1) FF



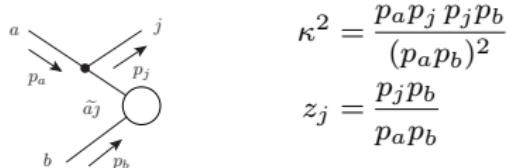
(2) FI



(3) IF



(4) II



Preserve collinear anomalous dimensions & sum rules \rightarrow splitting functions fixed

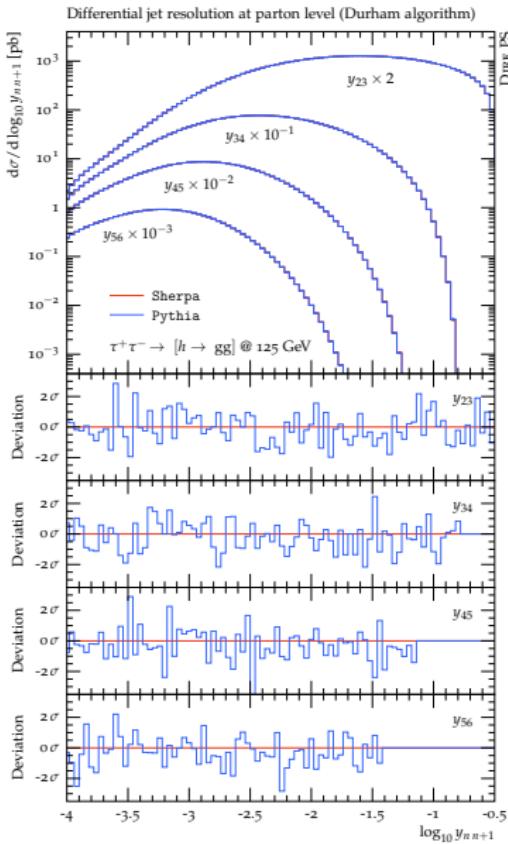
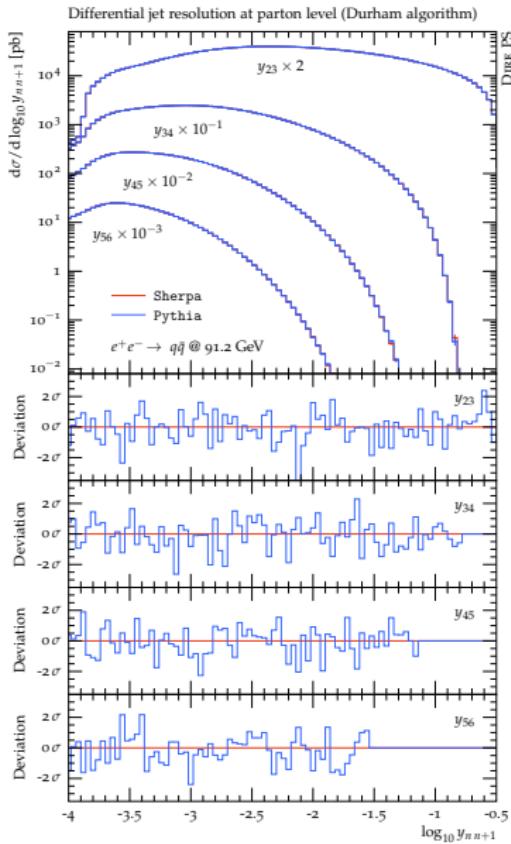
$$P_{qq}(z, \kappa^2) = 2 C_F \left[\left(\frac{1-z}{(1-z)^2 + \kappa^2} \right)_+ - \frac{1+z}{2} \right] + \gamma_q \delta(1-z)$$

$$P_{gg}(z, \kappa^2) = 2 C_A \left[\left(\frac{1-z}{(1-z)^2 + \kappa^2} \right)_+ + \frac{z}{z^2 + \kappa^2} - 2 + z(1-z) \right] + \gamma_g \delta(1-z)$$

$$P_{qg}(z, \kappa^2) = 2 C_F \left[\frac{z}{z^2 + \kappa^2} - \frac{2-z}{2} \right]$$

$$P_{gq}(z, \kappa^2) = T_R \left[z^2 + (1-z)^2 \right]$$

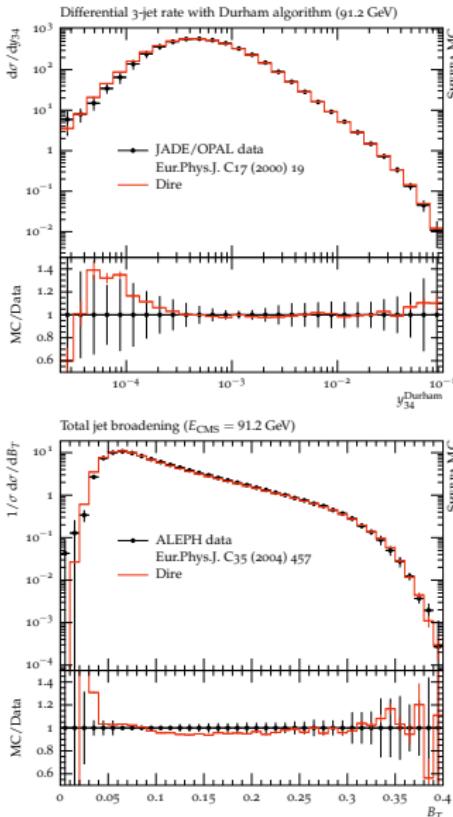
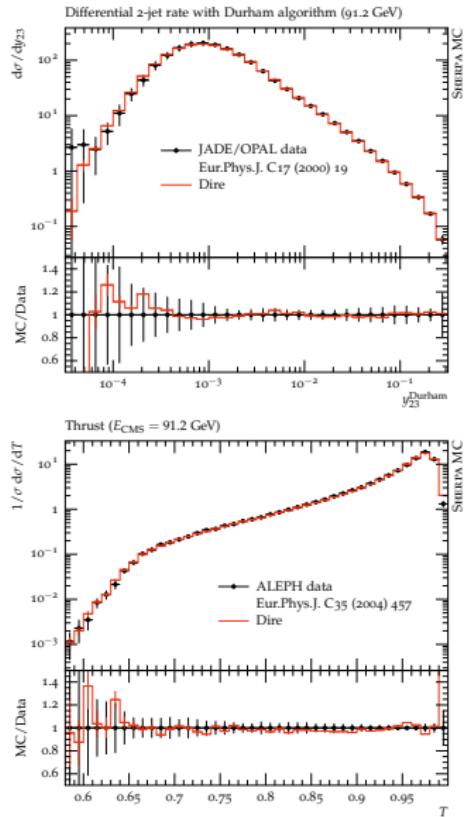
Validation in $e^+e^- \rightarrow$ hadrons



Comparison to LEP data

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[Prestel,SH] arXiv:1506.05057



Dire as an NLO subtraction method and MC@NLO

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[SH] TBP?

- ▶ Can view new shower model as modification of CS subtraction
- ▶ IR counterterms computed and implemented in Sherpa
(improved cancellation in $pp \rightarrow h + j$ due to regulated $1/z$ terms)
- ▶ Sherpa MC@NLO based on exponentiation of CS dipole subtraction terms
[Krauss,Siegert,Schönherr,SH]
arXiv:1111.1220, arXiv:1208.2815
- ▶ Dire modified CS subtraction automatically available for MC@NLO matching
- ▶ Interesting differences due to evolution variables and kernels

