Precision QCD simulations for the LHC

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HEP Monday Seminar

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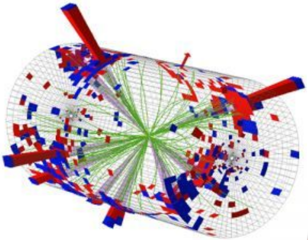
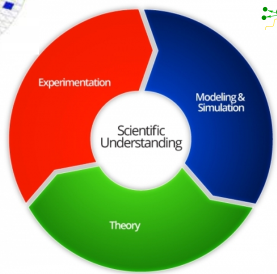
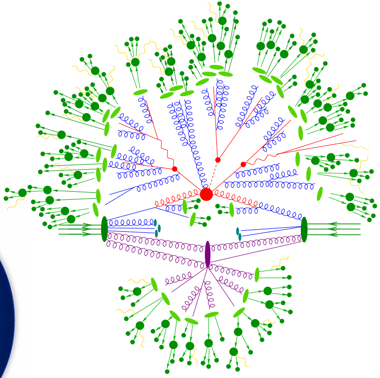
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

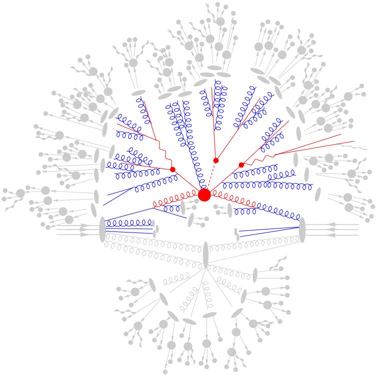
QCD at the LHC







$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c.$$



Aspects of the theory

- Perturbative QCD
  - Hard processes
  - Radiative corrections
- Non-perturbative QCD
  - Hadronization
  - Particle decays

Divide et Impera

- Quantity of interest: Total interaction rate
- Convolution of short & long distance physics

$$\sigma_{p_1 p_2 \to X} = \sum_{i,j \in \{q,g\}} \int \mathrm{d}x_1 \mathrm{d}x_2 \underbrace{f_{p_1,i}(x_1,\mu_F^2) f_{p_2,j}(x_2,\mu_F^2)}_{\text{long distance}} \underbrace{\hat{\sigma}_{ij\to X}(x_1 x_2, \mu_F^2)}_{\text{short distance}}$$

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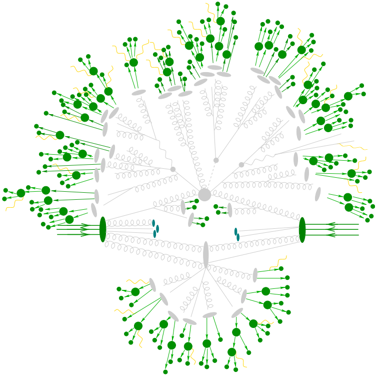

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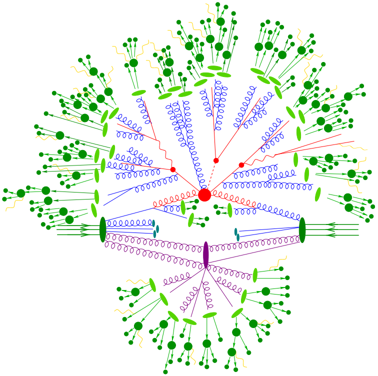

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Toolkit inventory

SLAC

All processes of interest

- Parton shower Monte Carlo (Herwig,Pythia,Sherpa,...)
- Automated tree-level calculations & merging with PS (Alpgen,CompHEP,Helac,MadGraph,Sherpa,...)
- Automated NLO virtual corrections (BlackHat,GoSam,Helac,MadLoop,MadGolem,NJet,OpenLoops,...)
- Matching to parton shower (aMC@NLO,POWHEG Box,Sherpa,...)
- Merging at NLO (aMC@NLO,Pythia,Sherpa,...)

Selected processes

- Inclusive NNNLO (gg$\rightarrow$H)
- Inclusive NNLO (jets,H+jet,W+jet,single top,...)
- Differential NNLO (W,Z,gg$\rightarrow$H,$t\bar{t}$,Vγ,VV,VH,...)
- NNLO+N^{x}LL resummation (e^+e^- $\rightarrow$2/3 jets, gg$\rightarrow$H,...)
- NNLO matching to PS (W,Z,gg$\rightarrow$H)

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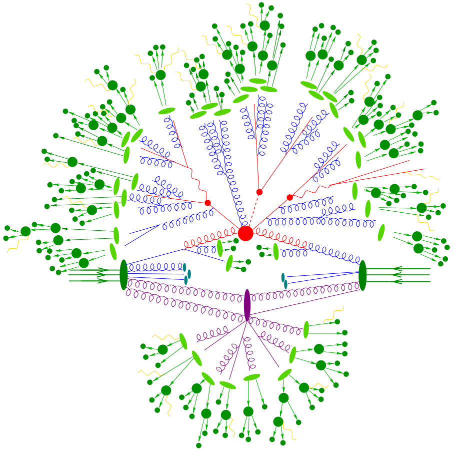
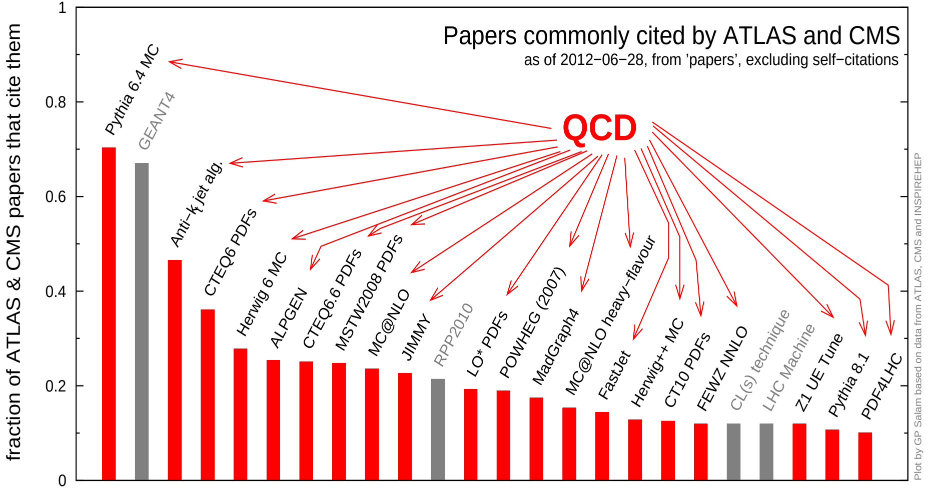
Simulation Cookbook

1. Matrix Element (ME) generators
   simulate "hard" part of scattering
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



Motivation to sit through this talk



[G.P. Salam, La Thuile 2012]

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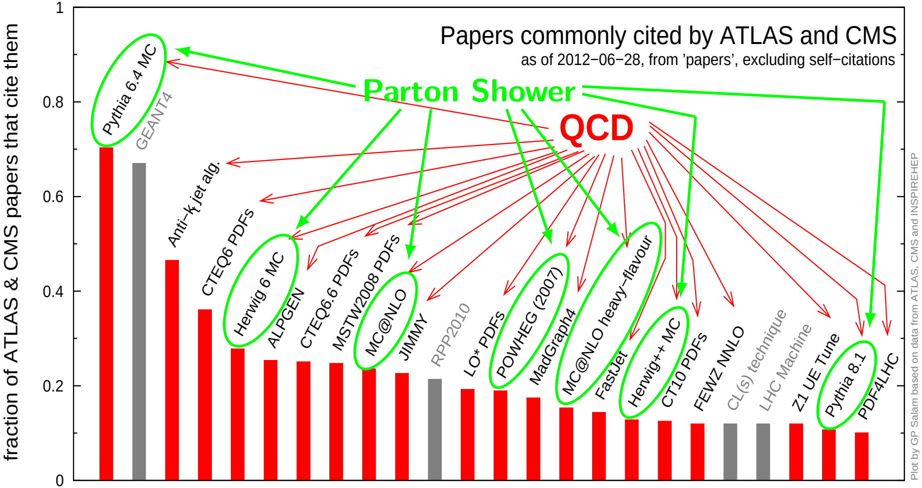
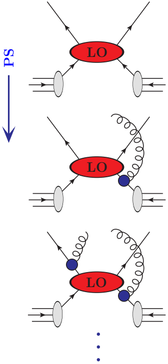


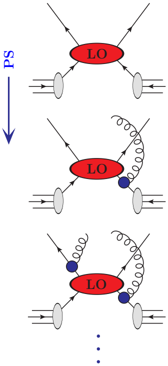
[G.P. Salam, La Thuile 2012]

Parton showers in a nutshell



$\sigma_{2\to 2}^{\text{incl}}\;\mathcal{F}_{\text{MC}}(Q^2)$

Parton showers in a nutshell



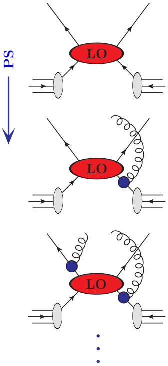
$$\sigma_{2\to2}^{\rm incl}\Bigg[\,\Delta(t_c,Q^2)$$

$$+\int\limits_{t_c}^{Q^2}\frac{{\rm d}t}{t}\int{\rm d}z\,\frac{\alpha_s}{2\pi}P(z)\;\Delta(t,Q^2)$$

$$+\,\frac{1}{2}\Bigg(\int\limits_{t_c}^{Q^2}\frac{{\rm d}t}{t}\int{\rm d}z\,\frac{\alpha_s}{2\pi}P(z)\Bigg)^2\Delta(t,Q^2)$$

$$+\ldots$$

Parton showers in a nutshell



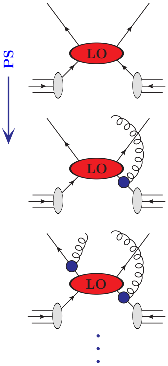
$$\sigma^{\text{incl}}_{2\to 2}\Bigg[\Delta(\tau_c)$$

$$+\int_{\tau_c}^{1}\frac{\mathrm{d}\tau}{\tau}\int \mathrm{d}z\,\frac{\alpha_s}{2\pi}P(z)\,\Delta(\tau)$$

$$+\frac{1}{2}\left(\int_{\tau_c}^{1}\frac{\mathrm{d}\tau}{\tau}\int \mathrm{d}z\,\frac{\alpha_s}{2\pi}P(z)\right)^2\Delta(\tau)$$

$$+\ldots$$

Parton showers in a nutshell



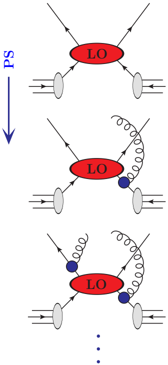
$$\sigma_{2\to 2}^{\text{incl}} \Bigg[\Delta(\tau_c)$$

$$+ \int_{\tau_c}^{1} \mathrm{d}\tau \, \frac{\alpha_s}{\tau} \big(A \log \tau + B \big) \, \Delta(\tau)$$

$$+ \frac{1}{2} \left(\int_{\tau_c}^{1} \mathrm{d}\tau \, \frac{\alpha_s}{\tau} \big(A \log \tau + B \big) \right)^2 \Delta(\tau)$$

$$+ \ldots$$

Parton showers in a nutshell



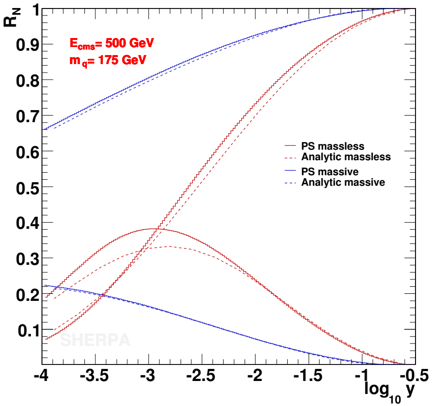
$$\sigma_{2\to2}^{\rm incl}\Bigg[\,\exp\left\{-\int_{\tau_c}^{1}{\rm d}\tau'\,\frac{\alpha_s}{\tau'}\,\big(A\log\tau'+B\big)\right\}$$

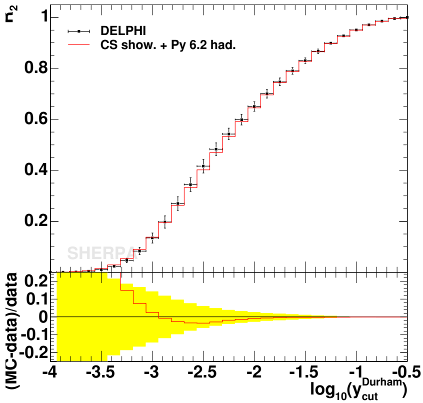
$$+\int_{\tau_c}^{1}{\rm d}\tau\,\frac{\alpha_s}{\tau}\,\big(A\log\tau+B\big)\,\exp\left\{-\int_{\tau_c}^{1}{\rm d}\tau'\,\frac{\alpha_s}{\tau'}\,\big(A\log\tau'+B\big)\right\}$$

$$+\frac{1}{2}\left(\int_{\tau_c}^{1}{\rm d}\tau\,\frac{\alpha_s}{\tau}\,\big(A\log\tau+B\big)\right)^2\exp\left\{-\int_{\tau_c}^{1}{\rm d}\tau'\,\frac{\alpha_s}{\tau'}\,\big(A\log\tau'+B\big)\right\}$$

$$+\ldots$$

Parton showers in a nutshell

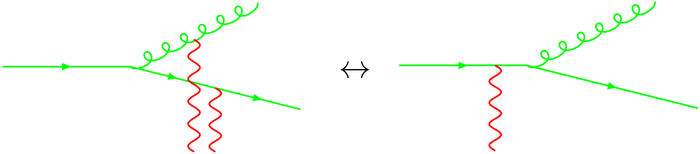




Color coherence and angular ordering

[Marchesini,Webber] NPB310(1988)461

- Gluons with large wavelength not capable of resolving charges of emitting color dipole individually

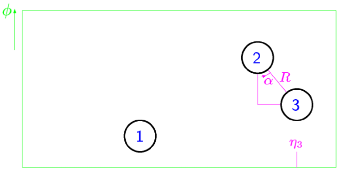


- Emission occurs with combined charge of mother parton instead
- Net effect is destructive interference outside cone with opening angle defined by emitting color dipole
- Soft anomalous dimension A is halved as a consequence of changed z-bounds

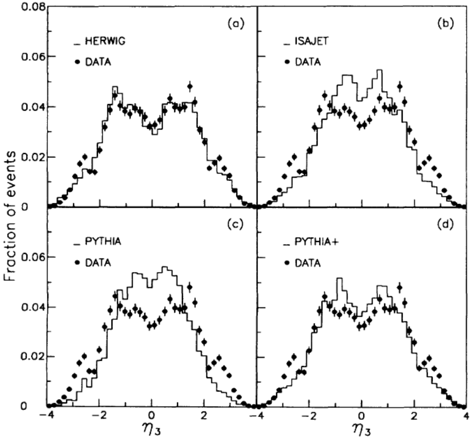
Color coherence and angular ordering

[CDF] PRD50(1994)5562

- Observed in 3-jet events
- Purely virtuality ordered PS's produced too much radiation in central region
- Angular ordered / angular vetoed PS's ok



$E_{T1} > 110$ GeV, $E_{T3} > 10$ GeV.



Color coherence and angular ordering

[Nagy] hep-ph/0601021 [Schumann,Krauss] arXiv:0709.1027
[Plätzer,Gieseke] arXiv:0909.5593

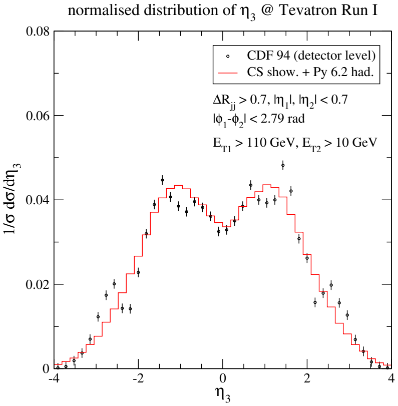
- Angular ordered PS does not fill full phase space → prefer alternative solution of coherence problem
- Coherence from eikonal factors
  Rewrite à la [Catani,Seymour] hep-ph/9605323

$$\frac{p_i p_k}{(p_i q)(q p_k)} \to \frac{1}{p_i q}\,\frac{p_i p_k}{(p_i + p_k) q} + \frac{1}{p_k q}\,\frac{p_i p_k}{(p_i + p_k) q}$$

- "Spectator"-dependent PS kernels

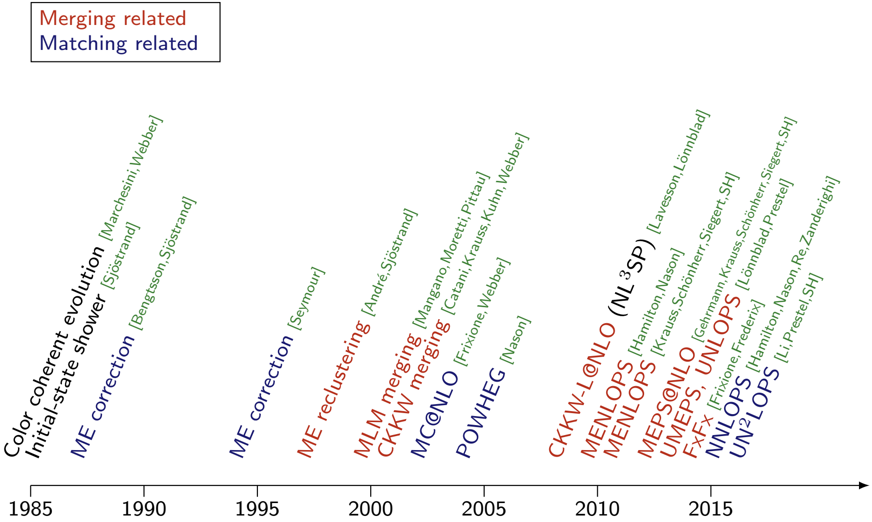
$$\frac{1}{1-z} \to \frac{1-z+k_\perp^2/Q^2}{(1-z)^2+k_\perp^2/Q^2}$$

  Singular in soft-collinear region only

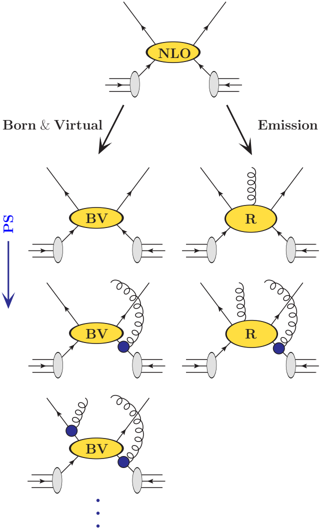


- Captures dominant coherence effects (3-parton correlations)
- Does not account for sub-leading color effects

Parton shower improvements



Restoring QCD coherence by matching



- Idea: Use real radiative corrections to improve PS approximation
- Methods: MC@NLO & POWHEG
  [Frixione,Webber] hep-ph/0204244 [Nason] hep-ph/0409146

Restoring QCD coherence by matching

- Leading-order calculation for observable O

$$\langle O \rangle = \int \mathrm{d}\Phi_B \, \mathrm{B}(\Phi_B) \, O(\Phi_B)$$

- NLO calculation for same observable

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

- Parton-shower result (until first emission)

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

Restoring QCD coherence by matching

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- Parton-shower result (until first emission)

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

Phase space: $\mathrm{d}\Phi_1 = \mathrm{d}t\,\mathrm{d}z\,\mathrm{d}\phi\,J(t,z,\phi)$
Splitting functions: $\mathrm{K}(t,z) \to \alpha_s/(2\pi t)\sum \mathrm{P}(z)\,\Theta(\mu_Q^2 - t)$
Sudakov factors: $\Delta^{(\mathrm{K})}(t) = \exp\left\{-\int_t \mathrm{d}\Phi_1 \mathrm{K}(\Phi_1)\right\}$

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

Phase space: $\mathrm{d}\Phi_1 = \mathrm{d}t\,\mathrm{d}z\,\mathrm{d}\phi\,J(t,z,\phi)$

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

Restoring QCD coherence by matching

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

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

$$+ \int \mathrm{d}\Phi_R \left\{ \mathrm{R}(\Phi_R) - \mathrm{B}(\Phi_B)\,\mathrm{K}(\Phi_1) \right\} O(\Phi_R)$$

- In DLL approximation both terms finite $\to$
  MC events in two categories, $\mathbb{S}$tandard and $\mathbb{H}$ard

$$\mathbb{S} \;\to\; \bar{\mathrm{B}}^{(\mathrm{K})}(\Phi_B) = \mathrm{B}(\Phi_B) + \tilde{\mathrm{V}}(\Phi_B) + \mathrm{B}(\Phi_B) \int \mathrm{d}\Phi_1 \mathrm{K}(\Phi_1)$$

$$\mathbb{H} \;\to\; \mathrm{H}^{(\mathrm{K})} = \mathrm{R}(\Phi_R) - \mathrm{B}(\Phi_B)\mathrm{K}(\Phi_1)$$

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

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

$$\mathrm{H}^{(\mathrm{K})}(\Phi_R) = \left[\mathrm{R}(\Phi_R) - \mathrm{B}(\Phi_B)\,\mathrm{K}(\Phi_1) \right] f(\Phi_1)$$

Restoring QCD coherence by matching

[Frixione,Webber] JHEP06(2002)029

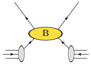
- Add parton shower, described by generating functional $\mathcal{F}_{\rm MC}$

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

  Probability conservation $\leftrightarrow$ $\mathcal{F}_{\rm MC}(t,1)=1$
- Expansion of matched result until first emission

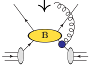
$$\langle O\rangle = \int \mathrm{d}\Phi_B\bar{\mathrm{B}}^{(\mathrm{K})}(\Phi_B)\Bigg[\Delta^{(\mathrm{K})}(t_c)\,O(\Phi_B)$$

$\leftrightarrow$

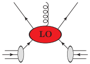


$$+\int_{t_c}\mathrm{d}\Phi_1\mathrm{K}(\Phi_1)\Delta^{(\mathrm{K})}(t(\Phi_1))\,O(\Phi_r)\Bigg] + \int \mathrm{d}\Phi_R\,\mathrm{H}^{(\mathrm{K})}(\Phi_{n+1})\,O(\Phi_R)$$

$\updownarrow$



$\updownarrow$



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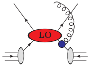


- Parametrically $\mathcal{O}(\alpha_s)$ correct
- Preserves logarithmic accuracy of PS

Treatment of soft singularities

Method 1 [Frixione,Webber] JHEP06(2002)029

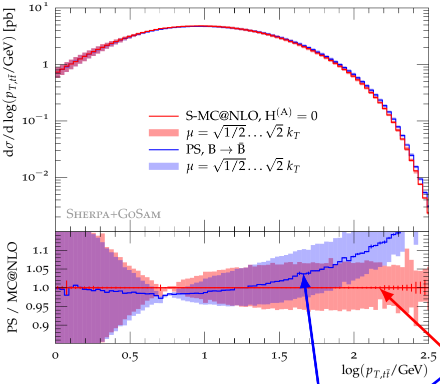
- $f(\Phi_1) \to 0$ in soft-gluon limit
- Full NLO only in hard / collinear region
  Missing subleading color terms in soft domain
- Only affects unresolved gluons $\to$ no need to correct in principle

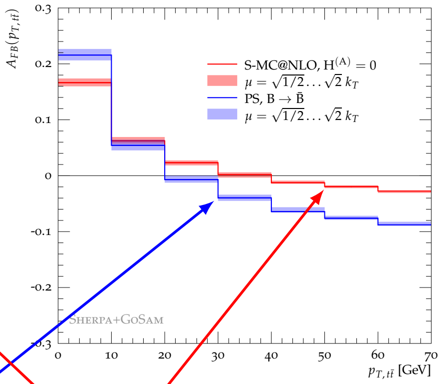
Method 2 [Krauss,Schönherr,Siegert,SH] JHEP09(2012)049

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

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

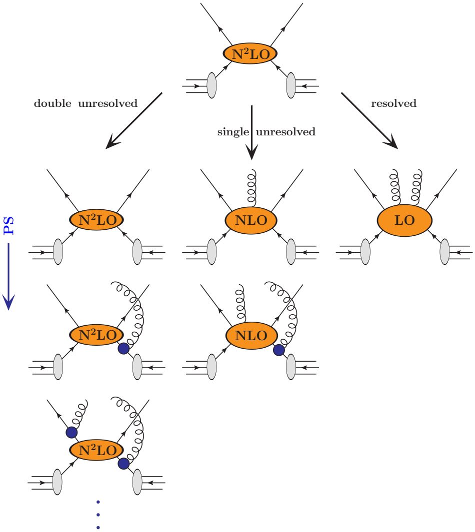
- Top-quark pair p_T
- Forward-backward asymmetry





leading color **full color** (first shower step)

Restoring QCD coherence, Part II: NNLO Matching



Restoring QCD coherence, Part II: NNLO Matching

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[Lönnblad,Prestel] arXiv:1211.4827

- PS expression for infrared safe observable, O

$$\langle O\rangle = \int \mathrm{d}\Phi_0\,\mathrm{B}_0\,\mathcal{F}_0(\mu_Q^2,O)$$

$$\mathcal{F}_n(t,O) = \Delta_n(t_c,t)\,O(\Phi_n) + \int_{t_c}^{t}\mathrm{d}\hat{\Phi}_1\,\mathrm{K}_n\,\Delta_n(\hat{t},t)\,\mathcal{F}_{n+1}(\hat{t},O)$$

- Add ME correction to first emission $(\mathrm{B}_0\mathrm{K}_0 \to \mathrm{B}_1)$ & unitarize

$$+\int_{t_c}\mathrm{d}\Phi_1\,\Delta_0(t_1,\mu_Q^2)\,\mathrm{B}_1\,\mathcal{F}_1(t_1,O) - \int_{t_c}\mathrm{d}\Phi_1\,\Delta_0(t_1,\mu_Q^2)\,\mathrm{B}_1\,O(\Phi_0)$$

- ME evaluated at fixed scales $\mu_{R/F}$ $\longrightarrow$ need to adjust to PS

$$w_1 = \frac{\alpha_s(b\,t_1)}{\alpha_s(\mu_R^2)}\,\frac{f_a(x_a,t_1)}{f_a(x_a,\mu_F^2)}\,\frac{f_{a'}(x_{a'},\mu_F^2)}{f_{a'}(x_{a'},t_1)}$$

- Replace B_0 by vetoed xs $\bar{\mathrm{B}}_0^{t_c} = \mathrm{B}_0 - \int_{t_c}\mathrm{d}\Phi_1\mathrm{B}_1$

$$\langle O\rangle = \left\{\int \mathrm{d}\Phi_0\,\bar{\mathrm{B}}_0^{t_c} + \int_{t_c}\mathrm{d}\Phi_1\left[1-\Delta_0(t_1,\mu_Q^2)\,w_1\right]\mathrm{B}_1\right\}O(\Phi_0)$$

$$+\int_{t_c}\mathrm{d}\Phi_1\,\Delta_0(t_1,\mu_Q^2)\,w_1\,\mathrm{B}_1\,\mathcal{F}_1(t_1,O)$$

Restoring QCD coherence, Part II: NNLO Matching

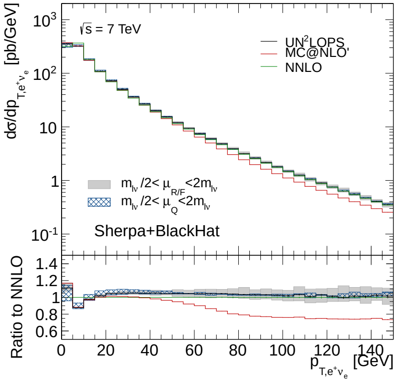
[Lönnblad,Prestel] arXiv:1211.7278
[Li,Prestel,SH] arXiv:1405.3607

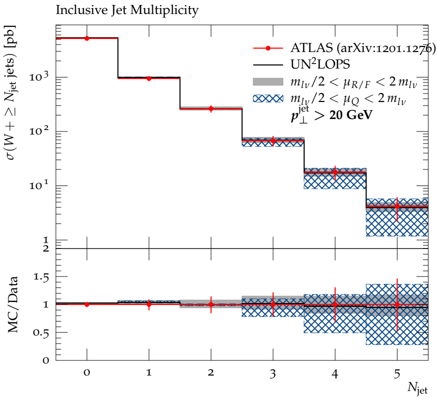
- Promote vetoed cross section to NNLO
- Add NLO corrections to B_1 using S-MC@NLO
- Subtract $\mathcal{O}(\alpha_s)$ term of w_1 and Δ_0

$$
\begin{aligned}
\langle O\rangle = & \int \mathrm{d}\Phi_0\, \bar{\bar{\mathrm{B}}}_0^{t_c}\, O(\Phi_0) \\
& + \int_{t_c} \mathrm{d}\Phi_1 \left[1-\Delta_0(t_1,\mu_Q^2)\left(w_1 + w_1^{(1)} + \Delta_0^{(1)}(t_1,\mu_Q^2)\right)\right] \mathrm{B}_1\, O(\Phi_0) \\
& + \int_{t_c} \mathrm{d}\Phi_1\, \Delta_0(t_1,\mu_Q^2)\left(w_1 + w_1^{(1)} + \Delta_0^{(1)}(t_1,\mu_Q^2)\right) \mathrm{B}_1\, \bar{\mathcal{F}}_1(t_1,O) \\
& + \int_{t_c} \mathrm{d}\Phi_1 \left[1-\Delta_0(t_1,\mu_Q^2)\right] \tilde{\mathrm{B}}_1^{\mathrm{R}}\, O(\Phi_0) + \int_{t_c} \mathrm{d}\Phi_1 \Delta_0(t_1,\mu_Q^2)\, \tilde{\mathrm{B}}_1^{\mathrm{R}}\, \bar{\mathcal{F}}_1(t_1,O) \\
& + \int_{t_c} \mathrm{d}\Phi_2 \left[1-\Delta_0(t_1,\mu_Q^2)\right] \mathrm{H}_1^{\mathrm{R}}\, O(\Phi_0) + \int_{t_c} \mathrm{d}\Phi_2\, \Delta_0(t_1,\mu_Q^2)\, \mathrm{H}_1^{\mathrm{R}}\, \mathcal{F}_2(t_2,O) \\
& + \int_{t_c} \mathrm{d}\Phi_2\, \mathrm{H}_1^{\mathrm{E}}\, \mathcal{F}_2(t_2,O)
\end{aligned}
$$

- $\tilde{\mathrm{B}}_1^{\mathrm{R}} = \bar{\mathrm{B}}_1 - \mathrm{B}_1 = \tilde{\mathrm{V}}_1 + \mathrm{I}_1 + \int \mathrm{d}\Phi_{+1}\mathrm{S}_1\Theta(t_2-t_1)$
  $\mathrm{H}_1^{\mathrm{R}}$ ($\mathrm{H}_1^{\mathrm{E}}$) $\rightarrow$ regular (exceptional) double real configurations

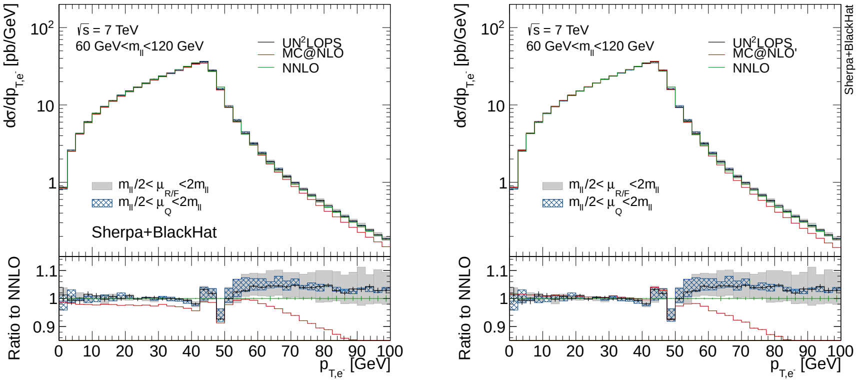
Restoring QCD coherence, Part II: NNLO Matching





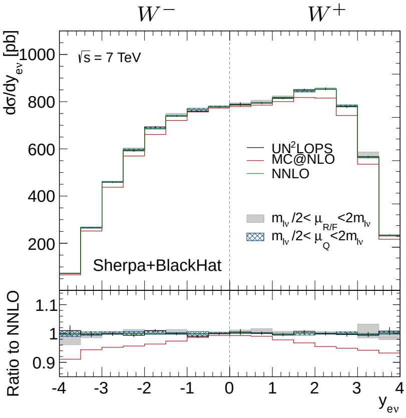
- Good agreement with S-MC@NLO at low $p_{T,W}$
- W+1-jet K-factor at high $p_{T,W}$

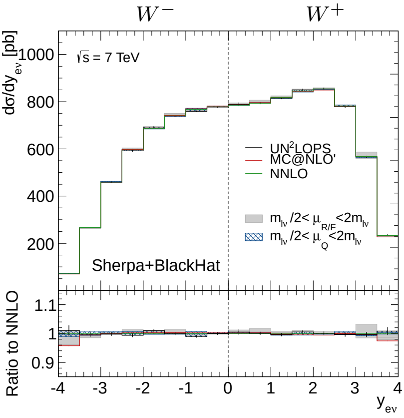
Impact of PDFs



- S-MC@NLO with NLO PDFs
- S-MC@NLO with NNLO PDFs

Impact of PDFs





- S-MC@NLO with NLO PDFs
- S-MC@NLO with NNLO PDFs

Soft evolution with more color

- In soft limit real-emission amplitudes factorize as

$$|\mathcal{M}_0(1,\ldots,j,\ldots,n)|^2 \overset{j\to\text{soft}}{\longrightarrow} -\sum_{i,k\neq i}\frac{8\pi\mu^{2\varepsilon}\alpha_s}{p_ip_j}$$
$$\times\langle m_0(1,\ldots,i,\ldots,k,\ldots,n)|\frac{\mathbf{T}_i\cdot\mathbf{T}_k\;p_ip_k}{p_ip_j+p_kp_j}|m_0(1,\ldots,i,\ldots,k,\ldots,n)\rangle\;.$$

  $\mathbf{T}_i$ - color insertion operator for parton i
  $|m_0(1,\ldots,i,\ldots,k,\ldots,n)\rangle$ - Born amplitude

- Parton showers use $\mathbf{T}_i\cdot\mathbf{T}_k\approx-\mathbf{T}_i^2/\sum_{k\neq i}$
- Matched shower uses $\mathbf{T}_i\cdot\mathbf{T}_k$ in first emission
- Full matrix exponentiation is work in progress
  Comparison to analytic resummation is a starting point

Soft evolution with more color

SLAC

[Banfi,Salam,Zanderighi] hep-ph/0407286, arXiv:1001.4082

- Generic NLL resummation framework exists (CAESAR)
- Observable dependence parametrized as

$$V\left(\{\tilde{p}\};k\right) = d_l \left(\frac{k_t^{(l)}}{Q}\right)^a e^{-b_l \eta^{(l)}} g_l\left(\phi^{(l)}\right)$$

- Resummed integrated spectrum for $V\left(\{\tilde{p}\};k\right) < v$ given by

$$\frac{1}{\sigma}\int_0^v \frac{d^2\sigma}{d\mathcal{B}dv'}dv' = \sum_{\delta\in\text{partonics}} \frac{d\sigma_0^{(\delta)}}{d\mathcal{B}} e^{Lg_1^{(\delta)}(\alpha_s L)+g_2^{(\delta,\mathcal{B})}(\alpha_s L)}\left[1+\mathcal{O}(\alpha_s)\right]\,, \quad L = \log\frac{1}{v}$$

- LL / NLL coefficients g_1 and g_2 arise from 1- and 2-emission integrals
- g_2 depends on soft function $\mathcal{S}$ through

$$\log\mathcal{S}(T(L/a))\,, \qquad \text{where} \quad T(L) = \frac{1}{\pi\beta_0}\log\frac{1}{1-2\alpha_s\beta_0 L}$$

Soft evolution with more color

SLAC

[Gerwick,SH,Marzani,Schumann] arXiv:1411.7325

- Soft function known analytically for low-multiplicity final states
- Generic structure in terms of anomalous dimension Γ is

$$\mathcal{S}(\xi) = \frac{\langle m_0|e^{-\frac{\xi}{2}\mathbf{\Gamma}^\dagger}e^{-\frac{\xi}{2}\mathbf{\Gamma}}|m_0\rangle}{\langle m_0|m_0\rangle}\;, \quad \mathbf{\Gamma} = -2\sum_{i<j}\mathbf{T}_i\cdot\mathbf{T}_j\,\log\frac{Q_{ij}}{Q_{12}} + i\pi\sum_{i,j=II,FF}\mathbf{T}_i\cdot\mathbf{T}_j$$

- Insertion of color projectors $|c_\alpha\rangle\langle c^\alpha|$ leads to matrix structure

$$\mathcal{S}(\xi) = \frac{c_{\alpha\beta}H^{\gamma\sigma}\mathcal{G}^\dagger_{\gamma\rho}c^{\rho\beta}c^{\alpha\delta}\mathcal{G}_{\delta\sigma}}{c_{\alpha\beta}H^{\alpha\beta}}\;, \qquad \mathcal{G}_{\alpha\beta}(\xi) = c_{\alpha\gamma}\exp\left(-\frac{\xi}{2}\,c^{\gamma\delta}\,\Gamma_{\delta\beta}\right)$$

  where $H^{\alpha\beta} = \langle m_0|c^\alpha\rangle\langle c^\beta|m_0\rangle$ and $\Gamma_{\alpha\beta} = \langle c_\alpha|\mathbf{\Gamma}|c_\beta\rangle$
- $c_{\alpha\beta} = \langle c_\alpha|c_\beta\rangle$ - color "metric", $H^{\alpha\beta}$ - hard matrix
- Much effort in the literature is spent on choosing orthogonal bases
  [Sjödahl] arXiv:0906.1121, arXiv:1211.2099, [Keppeler] arXiv:1207.0609

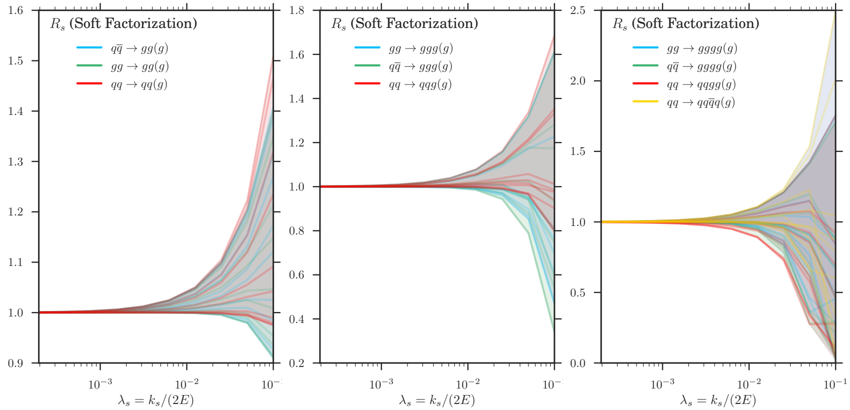
High-multiplicity NLL resummation & matching

[Gerwick,SH,Marzani,Schumann] arXiv:1411.7325

- Missing ingredients for resummation at higher multiplicity
  - Hard matrix → ME generator Comix
  - Soft anomalous dimension → Mathematica scripts
- Remaining problems
  - Non-orthogonality of color bases
    Solved by incorporation of inverse metric $c^{\alpha\beta} = (c_{\alpha\beta})^{-1}$
  - $N_c = 3$ pathologies in overcomplete color bases
    Solved by numeric matrix inversion at $N_c = 3 + \varepsilon$

High-multiplicity NLL resummation & matching

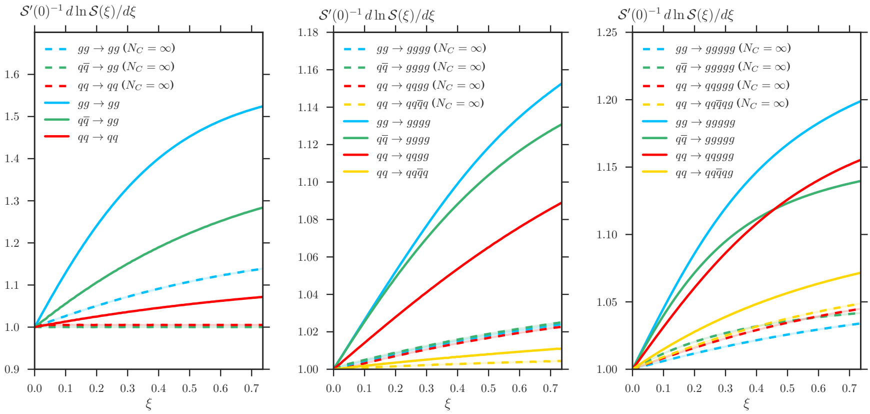
[Gerwick,SH,Marzani,Schumann] arXiv:1411.7325



- Ratio of sum-over-dipole dressed Born to exact matrix elements
- Checks correctness of soft anomalous dimension and color metric

High-multiplicity NLL resummation & matching

[Gerwick,SH,Marzani,Schumann] arXiv:1411.7325



- Size of sub-leading color contributions for "circle kinematics" (all outgoing partons at $\eta = 0$, equally spaced in $\Delta\phi$)

High-multiplicity NLL resummation & matching

SLAC

[Banfi,Salam,Zanderighi] hep-ph/0407286, arXiv:1001.4082

- Resummed integrated spectrum for $V(\{\tilde{p}\};k) < v$ given by

$$\frac{1}{\sigma}\int_0^v \frac{d^2\sigma}{d\mathcal{B}dv'}dv' = \sum_{\delta\in\text{partonics}} \frac{d\sigma_0^{(\delta)}}{d\mathcal{B}} e^{Lg_1^{(\delta)}(\alpha_s L)+g_2^{(\delta,\mathcal{B})}(\alpha_s L)}\left[1+\mathcal{O}(\alpha_s)\right]$$

- Expansion to NLO leads to LL and NLL coefficients

$$G_{12} = -\sum_{l=1}^{n} \frac{C_l}{a(a+b_l)}$$

$$G_{11} = -\left[\sum_{l=1}^{n} C_l\left(\frac{B_l}{a+b_l}+\frac{1}{a(a+b_l)}\left(\ln\bar{d}_l - b_l\ln\frac{2E_l}{Q}\right)+\frac{1}{a}\ln\frac{Q_{12}}{Q}\right)\right.$$
$$\left. +\frac{1}{a}\frac{\mathrm{Re}[\Gamma_{\alpha\beta}]\,H^{\alpha\beta}}{c_{\alpha\beta}H^{\alpha\beta}} + \sum_{l=1}^{n_\text{initial}} \frac{\int_{x_l}^1 \frac{dz}{z}P_{lk}^{(0)}\left(\frac{x_l}{z}\right)q^{(k)}(z,\mu_F^2)}{2(a+b_l)q^{(l)}(x_l,\mu_F^2)}\right].$$

- Missing ingredient for resummation at higher multiplicity
  - Generic matching method $\rightarrow$ Quasi-local subtraction

[Gerwick,SH,Marzani,Schumann] arXiv:1411.7325

- Compare soft factorization with Catani-Seymour dipole factorization

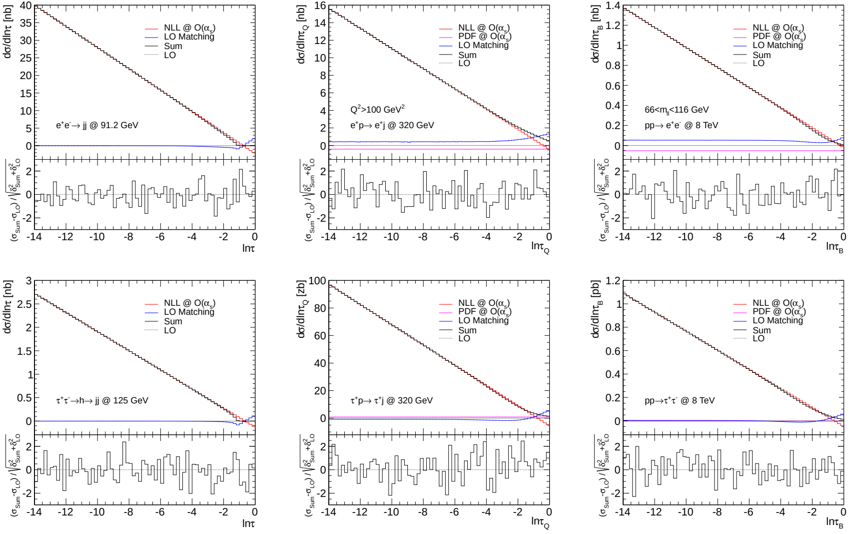
$$\mathcal{D}_{ij,k}(1,\ldots,n) \;=\; -\frac{1}{2p_ip_j}$$
$$\times\,\langle m_0(1,\ldots,ij,\ldots,k,\ldots,n)|\,\frac{\mathbf{T}_i\cdot\mathbf{T}_k}{\mathbf{T}_{ij}^2}\,\hat{V}_{ij,k}(z,k_T,\varepsilon)\,|m_0(1,\ldots,ij,\ldots,k,\ldots,n)\rangle\;.$$

- Obtain $\mathrm{Re}[\Gamma_{\alpha\beta}]\,H^{\alpha\beta}/c_{\alpha\beta}H^{\alpha\beta}$ from replacement $\hat{V}_{ij,k}(z,k_T,\varepsilon)\to\log Q_{(ij)k}/Q_{12}$, and rescaling by $1/a$
- Obtain G_{12} and B_l-dependent term in G_{11} from replacement $\hat{V}_{ij,k}\to P_{ij,i}$, restricting LL terms to $z^a>v$, and rescaling by $1/(a+b_l)$
- Need to identify observable with CS phase space variables:

$$v=\begin{cases} y_{ij,k} & \text{FF dipoles}\\ \dfrac{1-x_{ij,a}}{1-x_B} & \text{FI dipoles}\\ u_i & \text{IF dipoles}\\ \dfrac{v_i}{1-x_B} & \text{II dipoles}\end{cases}\;,\qquad z=\begin{cases} \tilde{z}_j \text{ or } \tilde{z}_i & \text{FF dipoles}\\ \tilde{z}_j \text{ or } \tilde{z}_i & \text{FI dipoles}\\ \dfrac{1-x_{ik,a}}{1-x_B} & \text{IF dipoles}\\ \dfrac{1-x_{i,ab}}{1-x_B} & \text{II dipoles}\end{cases}\;.$$

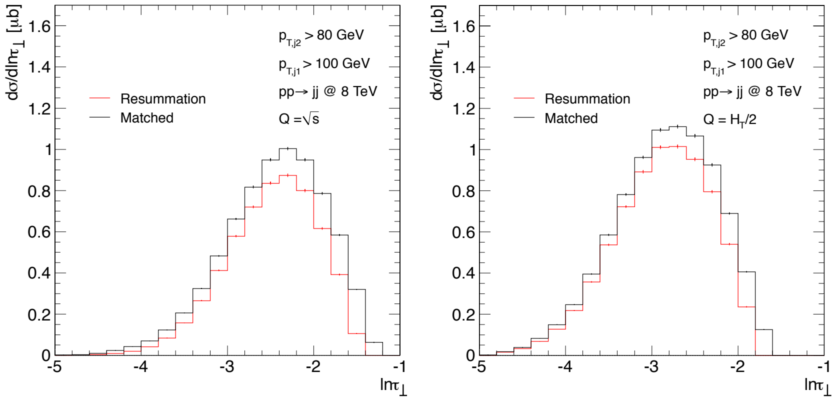
High-multiplicity NLL resummation & matching

[Gerwick,SH,Marzani,Schumann] arXiv:1411.7325



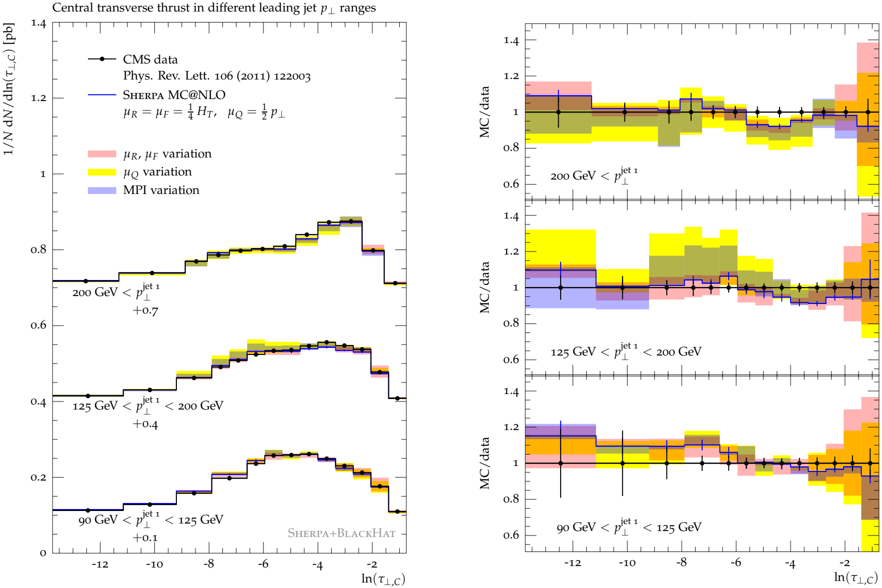
High-multiplicity NLL resummation & matching

[Gerwick,SH,Marzani,Schumann 2014]



- Full result (NLL resummed and matched) for transverse thrust in $pp \to jj$

Back to the parton shower



Outlook

- Parton showers are indispensable tools for
  - phenomenology
  - experimental analysis
  - experiment design
- Matching at (N)NLO & merging at (N)LO
  can improve PS approximation at fixed jet multiplicity
- Genuine reduction of uncertainties
  can only be achieved by improved resummation
- New tool for NLL resummation at high multiplicity
  will allow detailed study of sub-leading color effects
- Another interesting topic under investigation
  is incorporation of sub-leading logarithms
- All this is ongoing work, stay tuned!

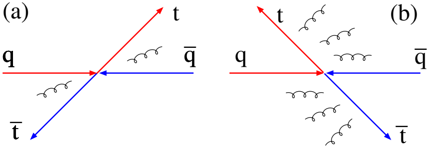
Thank you for your attention!

A_{FB} from a parton shower viewpoint

SLAC

[Skands,Webber,Winter] arXiv:1205.1466
[Huang,Luisoni,Schönherr,Winter,SH] arXiv:1306.2703

- Parton-shower unitarity broken by splitting of emission phase space
- Events with $\Delta y_{t\bar{t}} > 0$ have fewer phase space for radiation



- But inclusive asymmetry is mainly generated by momentum mapping

$$\Delta\sigma_{+-} = -2\int \underbrace{\mathrm{d}\sigma_{LO}|_{\Delta y>0}(1-\Delta_+)P_{+-}}_{\text{subdominant as } \Delta_- < \Delta_+ \text{ ((b) vs. (a))}} + 2\int \underbrace{\mathrm{d}\sigma_{LO}|_{\Delta y<0}(1-\Delta_-)P_{-+}}_{\text{dominant as } \Delta_+ > \Delta_- \text{ ((a) vs. (b))}}$$

P_{-+}/P_{+-} - probabilities for Δy to increase / decrease in splitting

- Dipole showers generate positive rapidity shift in each emission

$$\Delta y_t = \frac{1}{2}\ln\left(1 + \frac{p_q p_g}{p_q p_t}\left(\frac{1-z}{z} + \frac{m_t^2}{p_q p_t}\right)\frac{\tilde{p}_q^+}{\tilde{p}_t^+}\right) > 0$$

Similar finding for any dipole-like recoil scheme $\rightarrow$ positive asymmetry