

Partons versus Dipoles

A biased view of recent progress on showers

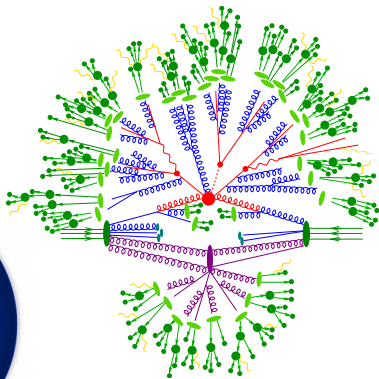
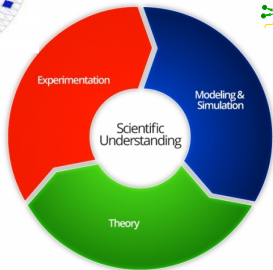
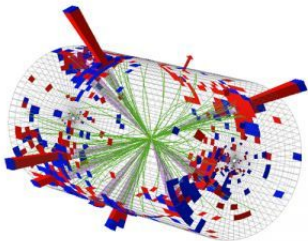
Stefan Höche

SLAC National Accelerator Laboratory

Workshop on QCD Factorization

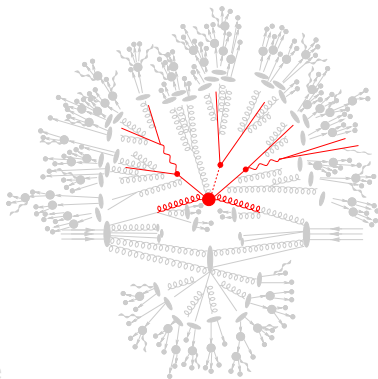
Buffalo, 11/03/2015

Motivation to stay for this talk



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

- ▶ Short distance interactions
 - ▶ Signal process
 - ▶ Radiative corrections
- ▶ Long-distance interactions
 - ▶ Hadronization
 - ▶ Particle decays

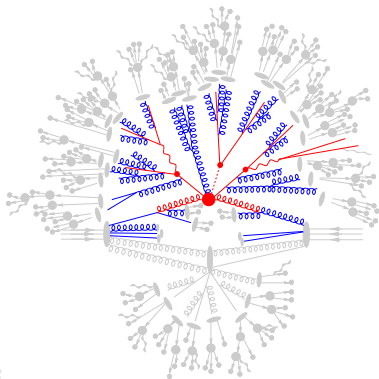


Factorization

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

$$\sigma_{p_1 p_2 \rightarrow X} = \sum_{i,j \in \{q,g\}} \int dx_1 dx_2 \underbrace{f_{p_1,i}(x_1, \mu_F^2) f_{p_2,j}(x_2, \mu_F^2)}_{\text{long distance}} \underbrace{\hat{\sigma}_{ij \rightarrow X}(x_1 x_2, \mu_F^2)}_{\text{short distance}}$$

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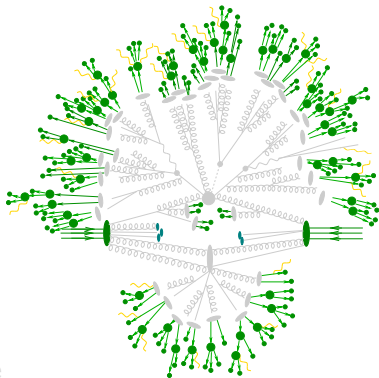


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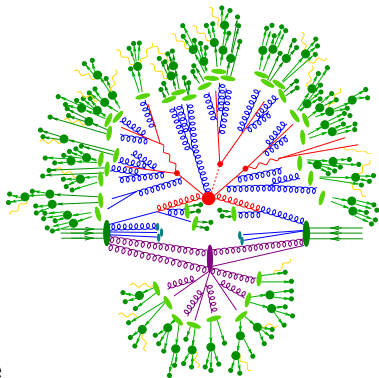


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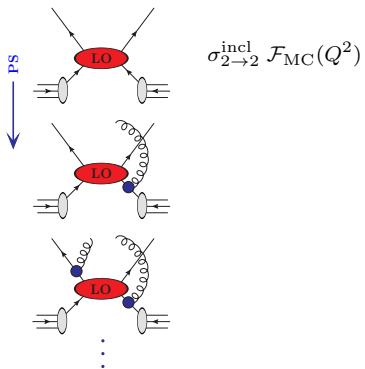
- ▶ Short distance interactions
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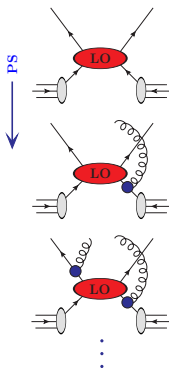


Factorization

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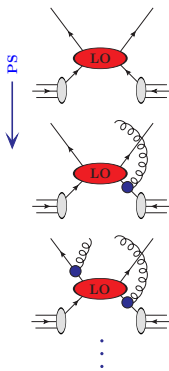


$$\sigma_{2 \rightarrow 2}^{\text{incl}} \left[\Delta(t_c, Q^2) \right.$$

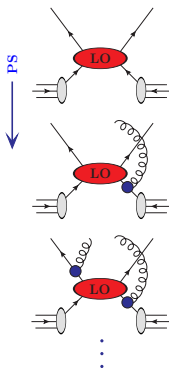
$$+ \int_{t_c}^{Q^2} \frac{dt}{t} \int dz \frac{\alpha_s}{2\pi} P(z) \Delta(t, Q^2)$$

$$+ \frac{1}{2} \left(\int_{t_c}^{Q^2} \frac{dt}{t} \int dz \frac{\alpha_s}{2\pi} P(z) \right)^2 \Delta(t, Q^2)$$

$$+ \dots$$



$$\begin{aligned}
 \sigma_{2 \rightarrow 2}^{\text{incl}} & \left[\Delta(\tau_c) \right. \\
 & + \int_{\tau_c}^1 \frac{d\tau}{\tau} \int dz \frac{\alpha_s}{2\pi} P(z) \Delta(\tau) \\
 & + \frac{1}{2} \left(\int_{\tau_c}^1 \frac{d\tau}{\tau} \int dz \frac{\alpha_s}{2\pi} P(z) \right)^2 \Delta(\tau) \\
 & + \dots
 \end{aligned}$$

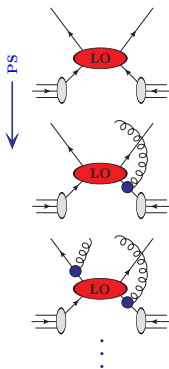


$$\sigma_{2 \rightarrow 2}^{\text{incl}} \left[\Delta(\tau_c) \right.$$

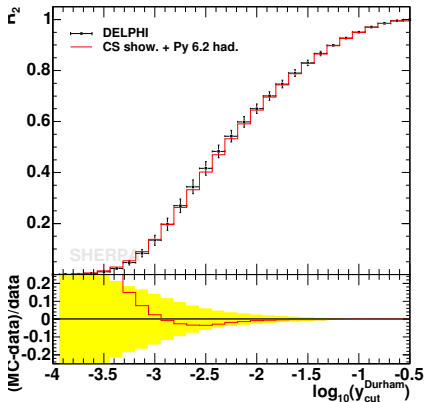
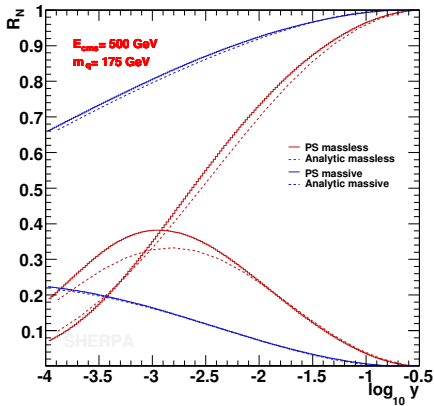
$$+ \int_{\tau_c}^1 d\tau \frac{\alpha_s}{\tau} (A \log \tau + B) \Delta(\tau)$$

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

$$+ \dots$$

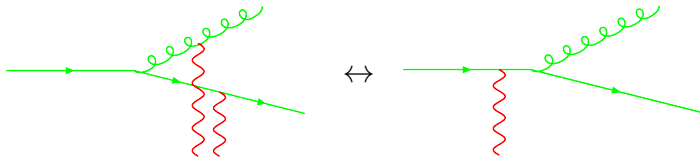


$$\begin{aligned}
 \sigma_{2 \rightarrow 2}^{\text{incl}} & \left[\exp \left\{ - \int_{\tau_c}^1 d\tau' \frac{\alpha_s}{\tau'} (A \log \tau' + B) \right\} \right. \\
 & + \int_{\tau_c}^1 d\tau \frac{\alpha_s}{\tau} (A \log \tau + B) \exp \left\{ - \int_{\tau_c}^1 d\tau' \frac{\alpha_s}{\tau'} (A \log \tau' + B) \right\} \\
 & + \frac{1}{2} \left(\int_{\tau_c}^1 d\tau \frac{\alpha_s}{\tau} (A \log \tau + B) \right)^2 \exp \left\{ - \int_{\tau_c}^1 d\tau' \frac{\alpha_s}{\tau'} (A \log \tau' + B) \right\} \\
 & + \dots
 \end{aligned}$$



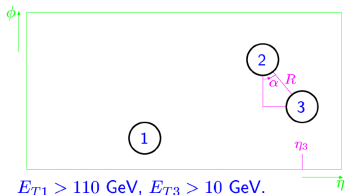
[Marchesini,Webber] NPB310(1988)461

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

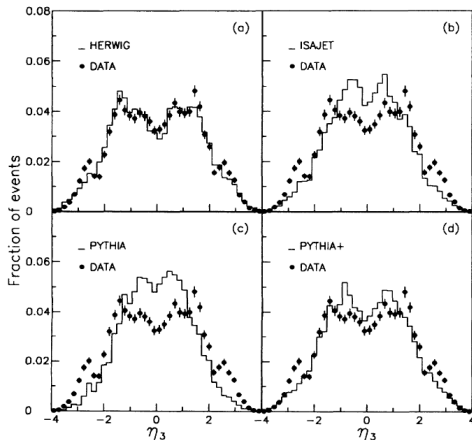


- ▶ Emission occurs with combined charge of mother parton instead
- ▶ Net effect is destructive interference outside cone with opening angle defined by emitting color dipole
- ▶ Soft anomalous dimension A is halved as a consequence of changed z -bounds

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



[CDF] PRD50(1994)5562



[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

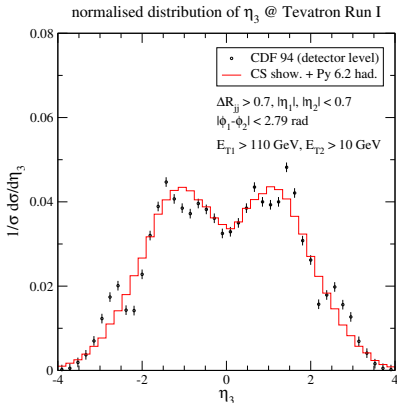
$$\frac{p_i p_k}{(p_i q)(q p_k)} \rightarrow \frac{1}{p_i q} \frac{p_i p_k}{(p_i + p_k) q} + \frac{1}{p_k q} \frac{p_i p_k}{(p_i + p_k) q}$$

- ▶ “Spectator”-dependent PS kernels

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

Singular in soft-collinear region only

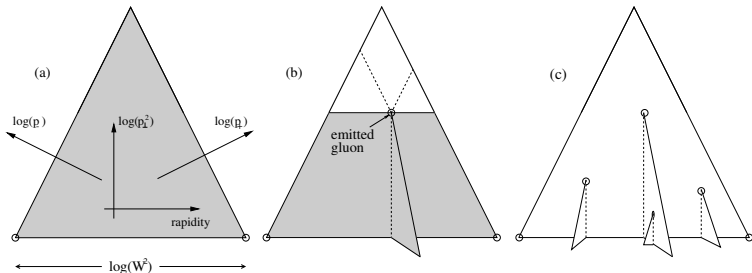
- ▶ Captures dominant coherence effects (3-parton correlations)
- ▶ Does not account for sub-leading color effects



[Gustafsson, Pettersson] NPB306(1988)746

[Kharraziha, Lönnblad] hep-ph/9709424

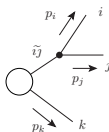
- ▶ To obtain correct soft evolution, ordering variable must be identical for both “dipole ends” (\rightarrow recombine eikonal at integrand level)



- ▶ Solution found in LDC model, but initial state treated non-perturbatively
- ▶ Alternative approach [Winter, Krauss] arXiv:0712.3913

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

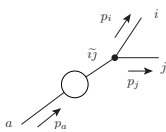
(1) FF



$$\kappa^2 = \frac{p_i p_j p_j p_k}{(p_{\tilde{ij}} p_{\tilde{k}})^2}$$

$$z_j = \frac{p_j p_k}{p_{\tilde{ij}} p_{\tilde{k}}}$$

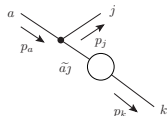
(2) FI



$$\kappa^2 = \frac{p_i p_j p_j p_a}{(p_{ij} p_a)^2}$$

$$z_j = \frac{p_j p_a}{p_{ij} p_a}$$

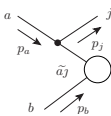
(3) IF



$$\kappa^2 = \frac{p_a p_j p_j p_k}{(p_{jk} p_a)^2}$$

$$z_j = \frac{p_j p_k}{p_{jk} p_a}$$

(4) II



$$\kappa^2 = \frac{p_a p_j p_j p_b}{(p_a p_b)^2}$$

$$z_j = \frac{p_j p_b}{p_a p_b}$$

- Phase-space factorization from [Catani,Seymour] hep-ph/9605323
- z_j can be interpreted as light-cone momentum fraction of emitted parton
→ mapping onto collinear limit becomes trivial

Construction principles for a hybrid shower

- ▶ Dipole-like picture (emitter & spectator identified)
- ▶ Properties of evolution variables from dipole cascades
- ▶ Collinear anomalous dimensions unchanged
- ▶ Flavor and momentum sum rules preserved

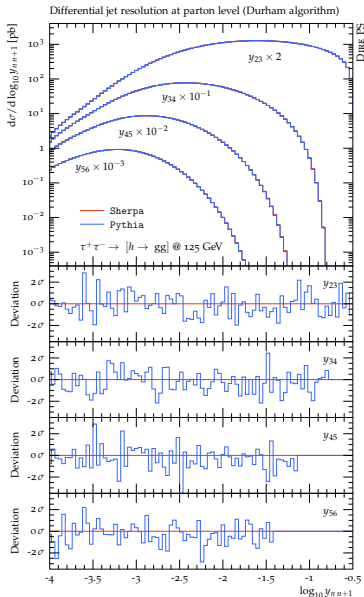
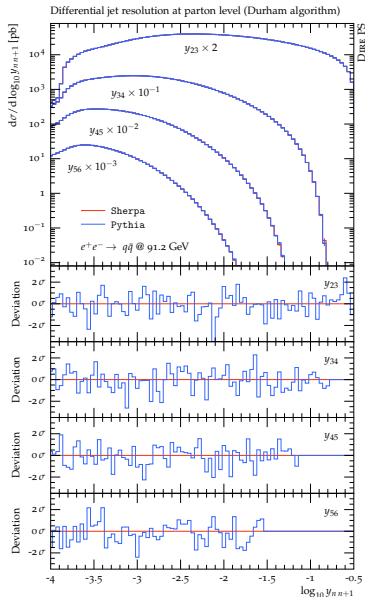
Defines complete set of LO splitting functions

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

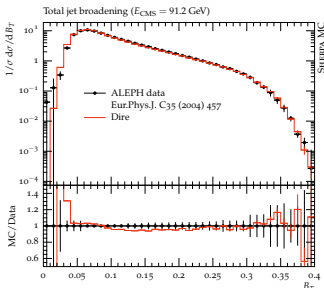
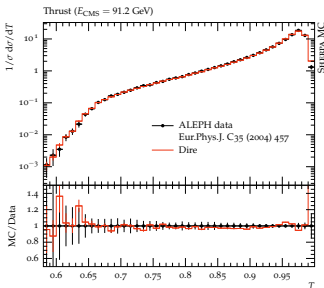
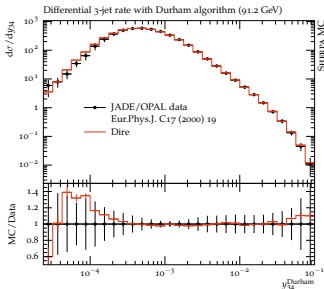
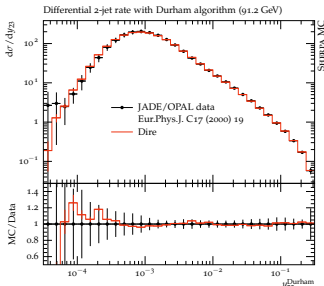
$$P_{gg}(z, \kappa^2) = 2C_A \left[\left(\frac{1-z}{(1-z)^2 + \kappa^2} \right)_+ + \frac{z}{z^2 + \kappa^2} - 2 + z(1-z) \right] + \gamma_g \delta(1-z)$$

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

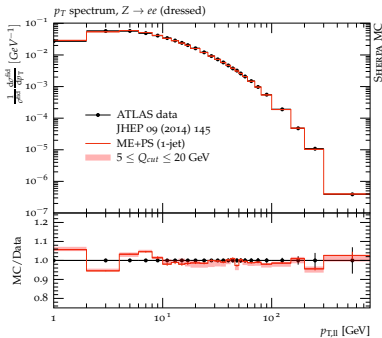
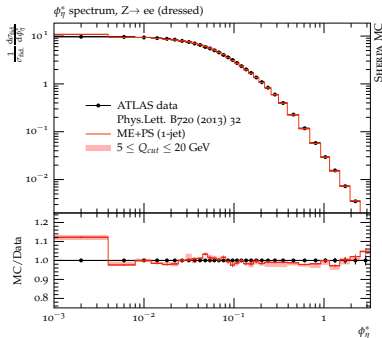
The midpoint between dipole and parton showers



The midpoint between dipole and parton showers

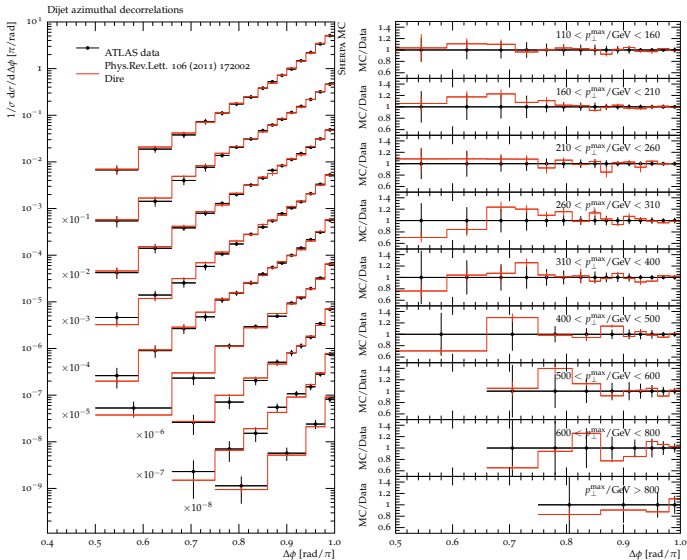


The midpoint between dipole and parton showers



- ▶ Parton shower merged with 1-jet tree-level ME using CKKW-L

The midpoint between dipole and parton showers



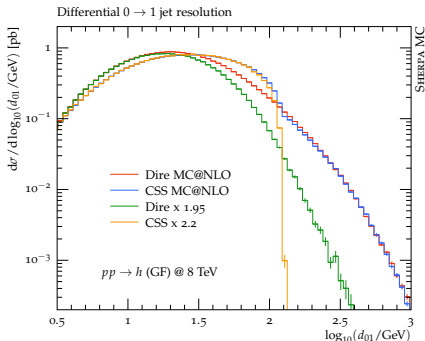
- ▶ Can view new shower model as modification of CS subtraction
- ▶ IR-finite counterterms computed and implemented in Sherpa (improved cancellation in $pp \rightarrow h + j$ due to regulated $1/z$ terms)

- ▶ Sherpa MC@NLO based on exponentiation of CS dipole subtraction terms

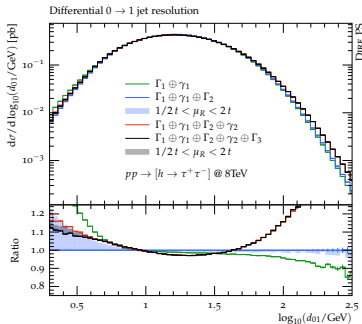
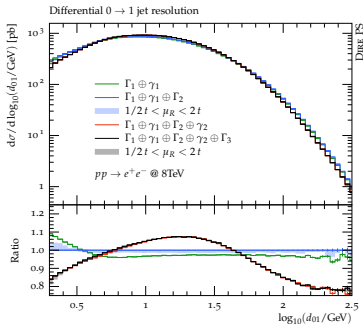
[Krauss,Siegert,Schönherr,SH]

arXiv:1111.1220, arXiv:1208.2815

- ▶ Dire modified CS subtraction automatically available for MC@NLO matching
- ▶ Interesting differences due to evolution variables and kernels

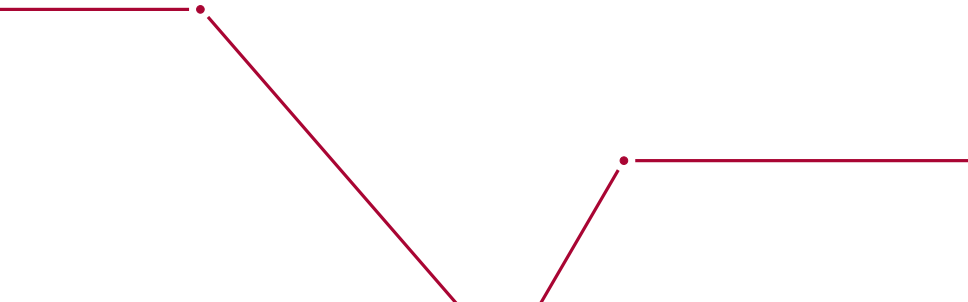


- ▶ Big drawback of parton showers is lack of higher-order kernels
- ▶ Start improving with spacelike NLO splitting functions
[Curci,Furmanski,Petronzio] NPB175(1980)27, PLB97(1980)437
- ▶ 2-loop cusp term subtracted & combined with LO soft contribution (similar to CMW rescaling [Catani,Marchesini,Webber] NPB349(1991)635)
- ▶ Implemented using weighting algorithms [Schumann,Siegert,SH] arXiv:0912.3501



- ▶ 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
→ focus area of development during past decade
- ▶ Genuine reduction of uncertainties can only be achieved by improved resummation
- ▶ Incorporation of sub-leading logarithms just started ... stay tuned!

Thank you for your attention!



In the notation of NPB244(1984)337, $\gamma_{ab}(N, \kappa^2) = \int_0^1 dz z^N P_{ab}(z, \kappa^2)$:

$$\gamma_{qq}(N, \kappa^2) = 2C_F \Gamma(N, \kappa^2) - \frac{C_F (2N + 3)}{(N + 1)(N + 2)} + \gamma_q$$

$$\gamma_{gq}(N, \kappa^2) = 2C_F K(N, \kappa^2) - \frac{C_F (N + 3)}{(N + 1)(N + 2)}$$

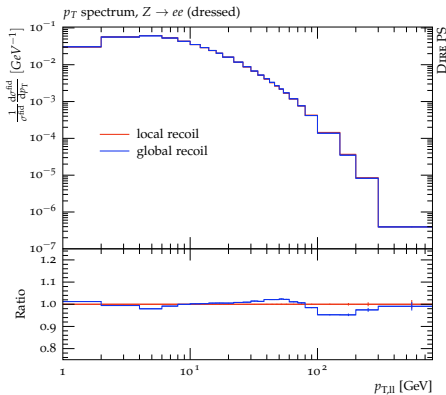
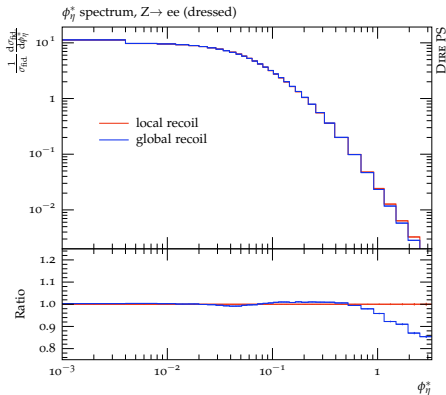
$$\gamma_{gg}(N, \kappa^2) = 2C_A \Gamma(N, \kappa^2) + 2C_A K(N, \kappa^2) - \frac{2C_A (N + 3)}{(N + 1)(N + 2)} - \frac{2C_A}{N + 3} + \gamma_g$$

$$\gamma_{qg}(N, \kappa^2) = -\frac{T_R N}{(N + 1)(N + 2)} + \frac{2T_R}{N + 3}$$

where

$$2\Gamma(N, \kappa^2) = \frac{{}_2F_2\left(1, 1, \frac{3}{2}; \frac{N+3}{2}, \frac{N+4}{2}; -\kappa^{-2}\right)}{(N + 1)(N + 2) \kappa^2} - \ln \frac{1 + \kappa^2}{\kappa^2}$$

$$2K(N, \kappa^2) = \frac{{}_2F_1\left(1, \frac{N+2}{2}; \frac{N+4}{2}; -\kappa^{-2}\right)}{(N + 2) \kappa^2}.$$



- ▶ Two mapping schemes for IF dipoles → local [Catani,Seymour] hep-ph/9605323 and global [Plätzer,Gieseke] arXiv:0909.5593, [Schumann,Siegert,SH] arXiv:0912.3501
- ▶ Negligible impact on q_T -spectrum in low- q_T range (spectrum dominated by singlet evolution at LHC energies)

- ▶ 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 (until first emission)

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

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

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

- ▶ 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 \rightarrow
MC events in two categories, Standard and \mathbb{H} ard

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

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

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

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

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

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

- ▶ Expansion of matched result until first emission

$$\langle O \rangle = \int d\Phi_B \bar{B}^{(K)}(\Phi_B) \left[\Delta^{(K)}(t_c) O(\Phi_B) \leftrightarrow \text{Diagram 1} \right. \\ \left. + \int_{t_c} d\Phi_1 K(\Phi_1) \Delta^{(K)}(t(\Phi_1)) O(\Phi_1) \right] + \int d\Phi_R H^{(K)}(\Phi_{n+1}) O(\Phi_R) \\ \text{Diagram 2} - \text{Diagram 3}$$

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

Method 1

[Frixione,Webber] JHEP06(2002)029

- ▶ $f(\Phi_1) \rightarrow 0$ 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 in principle

Method 2

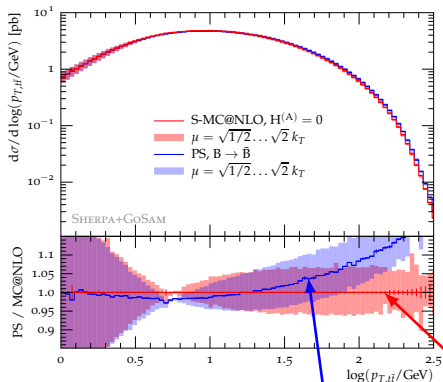
[Krauss,Schönherr,Siegert,SH] JHEP09(2012)049

- ▶ 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?

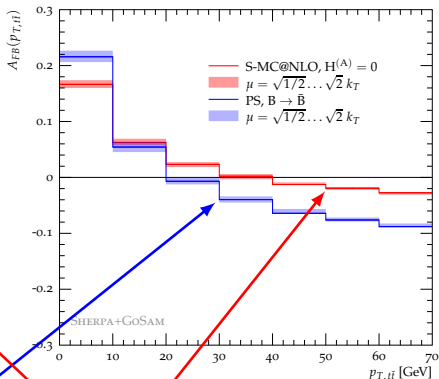
[Huang,Luisoni,Schönherr,Winter,SH] arXiv:1306.2703

▶ Top-quark pair p_T



leading color

▶ Forward-backward asymmetry



full color (first shower step)

[Siegert,Schumann,SH] arXiv:0912.3501

- ▶ In MC@NLO generate emission according to

$$\Delta^{(S)}(t, t') = \exp \left\{ - \int_t^{t'} d\Phi_1 \frac{S(\Phi_B; t, z, \phi)}{B(\Phi_B)} \right\}$$

- ▶ “dipole-term-correct” PS

$$f(t) \rightarrow \int dz d\phi J(t, z, \phi) \frac{S(\Phi_B; t, z, \phi)}{B(\Phi_B)}$$

$$g(t) \rightarrow \int dz d\phi J(t, z, \phi) K(t, z, \phi)$$

- ▶ $f(t)/g(t)$ may be negative e.g. due to subleading color dipoles
→ probabilistic interpretation not possible
- ▶ Split weight into MC and **analytic** part using auxiliary function $h(t)$

$$\frac{f(t)}{h(t)} g(t) \exp \left\{ - \int_t^{t_1} d\bar{t} g(\bar{t}) \right\} \prod_{i=1}^n \left[\int_{t_{i-1}}^{t_{i+1}} dt_i \left(1 - \frac{f(t_i)}{h(t_i)} \right) g(t_i) \exp \left\{ - \int_{t_i}^{t_{i+1}} d\bar{t} g(\bar{t}) \right\} \right]$$

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

- ▶ $h(t)$ can be chosen freely, as long as $\text{sgn}(h) = \text{sgn}(f)$, $|f| < |h|$