Towards an NLO parton shower and improved uncertainty estimates

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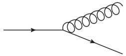
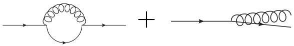
Radiative corrections as a branching process

[Marchesini,Webber] NPB238(1984)1, [Sjöstrand] PLB157(1985)321

- Make two well motivated assumptions
  - Parton branching can occur in two ways



\- observed



\- unobserved

  - Evolution conserves probability
- The consequence is Poisson statistics
  - Let the decay probability be λ
  - Assume indistinguishable particles $\to$ naive probability for n emissions

$$P_{\text{naive}}(n,\lambda) = \frac{\lambda^n}{n!}$$

  - Probability conservation (i.e. unitarity) implies a no-emission probability

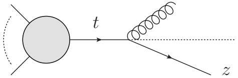
$$P(n,\lambda) = \frac{\lambda^n}{n!}\exp\{-\lambda\} \qquad \longrightarrow \qquad \sum_{n=0}^{\infty} P(n,\lambda) = 1$$

- In the context of parton showers $\Delta = \exp\{-\lambda\}$ is called Sudakov factor

Radiative corrections as a branching process

- Decay probability for parton state in collinear limit

$$\lambda \to \frac{1}{\sigma_n}\int_t^{Q^2} \mathrm{d}\bar{t}\,\frac{\mathrm{d}\sigma_{n+1}}{\mathrm{d}\bar{t}} \approx \sum_{\text{jets}} \int_t^{Q^2} \frac{\mathrm{d}\bar{t}}{\bar{t}} \int \mathrm{d}z\,\frac{\alpha_s}{2\pi} P(z)$$



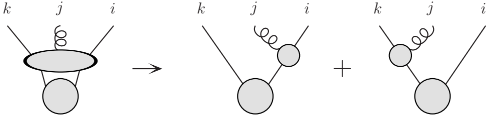
  Parameter t identified with evolution "time"

- Soft double counting problem [Marchesini,Webber] NPB310(1988)461
  full soft radiation probability in all collinear regions

$$\frac{1}{t}\,\frac{2\,z}{1-z} \longrightarrow \frac{p_i p_k}{(p_i q)(q p_k)}$$

- Can be solved for single emission by partial fractioning
  and matching to collinear sectors [Catani,Seymour] hep-ph/9605323

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



Color coherence and the dipole picture

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- Splitting kernels become dependent on anti-collinear direction usually defined by color spectator in large-N_c limit
- Singularity confined to soft-collinear region only captures soft coherence effects at leading color

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

- Complete set of leading-order splitting functions now given by

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

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

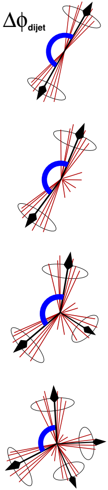
$$P_{gg}(z,\kappa^2) = 2\,C_A\left[\frac{1-z}{(1-z)^2+\kappa^2} + \frac{1}{z} - 2 + z(1-z)\right]$$

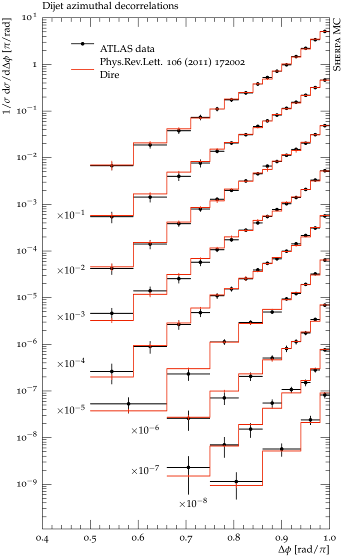
- Close correspondence to principal value regularization
  [Curci,Furmanski,Petronzio] NPB175(1980)27

Accuracy and precision

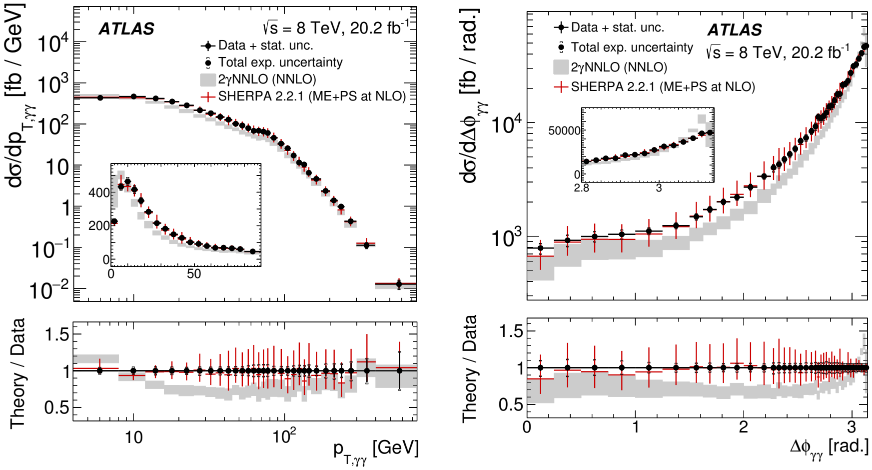
Accuracy of the parton shower: Jets at the LHC

[Prestel,SH] arXiv:1506.05057





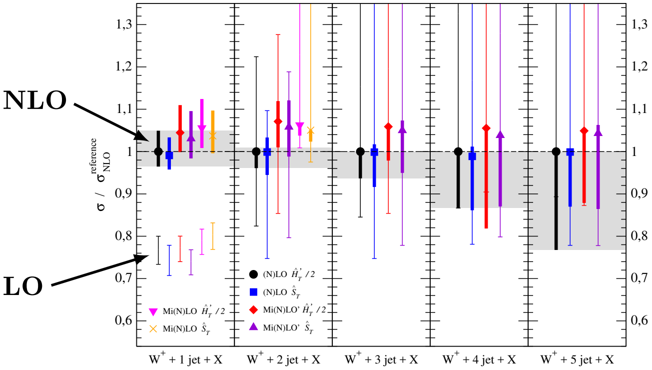
[ATLAS] arXiv:1704.03839



Precision of fixed-order calculations: $W^\pm$ at the LHC

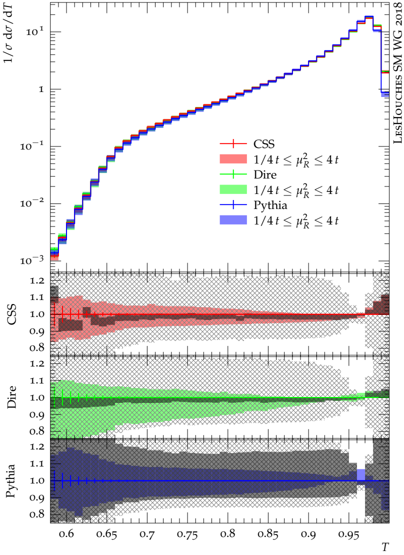
[Bern et al.] arXiv:1304.1253, arXiv:1412.4775
[Anger,Febres Cordero,Maître,SH] arXiv:1712.08621

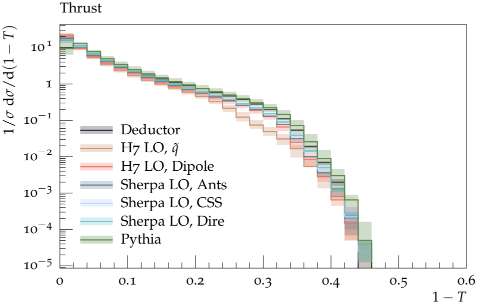
- $W^\pm$+jets at 13 TeV LHC, computed with BlackHat+Sherpa
- Largely reduced uncertainties at NLO, but more importantly good agreement for different functional forms of scale, including several variants of MINLO [Hamilton,Nason,Zanderighi] arXiv:1206.3572



Precision of parton-showers?

[LesHouches] arXiv:1605.04692, arXiv:1803.07977





- Assessment of PS uncertainties assuming they can be covered by varying evolution variable t in 2nd order soft emission term

$$\frac{1}{t}\left(\frac{\alpha_s(t)}{2\pi}\right)^2\left[\beta_0(t)\log\frac{k_T^2}{t}+K(t)\right]\frac{2}{1-z}$$

Lessons learned and motivation of this talk

- Fueled by the NLO revolution, large parts of the MC community worked on precision fixed-order calculations during the past decade(s)
- This lead to much improved agreement with data and tremendous new capabilities of event generators $\to$ parton showers to catch up
- Many of the challenges at higher luminosity / energy require increased precision in the parton-shower simulation (we cannot hope to compute, say, 8-jet final states at NLO)

- Must understand what precision means in context of parton showers and how to quantify it ↗ Talks by Daniel and Pier Francesco
- Here: Start to improve formal precision of parton shower by adding higher-order corrections to evolution kernels
- There are many other questions, but we have to start somewhere We know that what's done here *must* feed into any full solution

How to make parton showers more precise?
Part I: Collinear limit

How to make parton showers more precise?

- 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
  - NLO-calculation 4-2ε dimensional, but parton showers firmly 4D
  - Overlap with soft-gluon resummation must be treated at NLO
- Focus on purely collinear corrections for a start
  Flavor-changing case is simplest but requires all the technology:
  - Redefine time-like Sudakovs to recover NLO DGLAP evolution
    [Jadach,Skrzypek] hep-ph/0312355
  - Phase-space factorization and kinematics for $2 \to 4$ transitions
    [Prestel,SH] arXiv:1705.00742
  - Negative NLO corrections $\to$ weighted veto algorithm
    [Schumann,Siegert,SH] arXiv:0912.3501, [Lönnblad] arXiv:1211.7204

Time-like parton showers and the DGLAP equation

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- DGLAP equation for fragmentation functions

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

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

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

- Rewrite for finite ε

$$\frac{\mathrm{d}\ln D_a(x,t)}{\mathrm{d}\ln t}=-\sum_{c=q,g}\int\limits_0^{1-\varepsilon}\mathrm{d}\zeta\,\zeta\,\frac{\alpha_s}{2\pi}P_{ac}(\zeta)+\sum_{b=q,g}\int\limits_x^{1-\varepsilon}\frac{\mathrm{d}z}{z}\,\frac{\alpha_s}{2\pi}\,P_{ab}(z)\,\frac{D_b(x/z,t)}{D_a(x,t)}$$

- First term is logarithmic derivative of Sudakov factor

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

Time-like parton showers and the DGLAP equation

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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

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

- 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

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

- **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

$2 \to 4$ kinematics mapping, massless FF case

- Define evolution & splitting variables

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

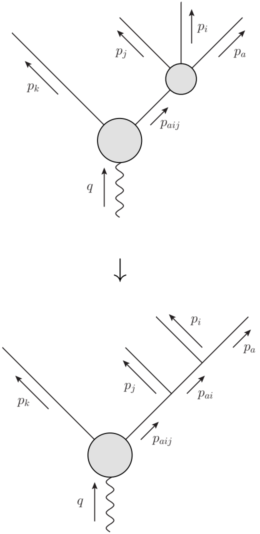
$$s_{ai} = 2\,p_a p_i\ , \qquad x_a = \frac{p_a p_k}{p_{ai} p_k}$$

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

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

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

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



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

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

$$\int \mathrm{d}\Phi(p_a,p_i,p_j,p_k|\,q) = \int \frac{\mathrm{d}s_{aij}}{2\pi} \int \mathrm{d}\Phi(p_{aij},p_k|\,q) \int \mathrm{d}\Phi(p_a,p_i,p_j|\,p_{aij})$$
$$= \int \mathrm{d}\Phi(\tilde{p}_{aij},\tilde{p}_k|\,q) \int \left[\mathrm{d}\Phi(p_a,p_i,p_j|\,\tilde{p}_{aij},\tilde{p}_k)\right]$$

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

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

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

Collinear parton evolution at NLO

[Curci,Furmanski,Petronzio] NPB175(1980)27, [Floratos,Kounnas,Lacaze] NPB192(1981)417

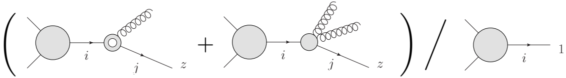
- Higher-order DGLAP evolution kernels obtained from factorization

$$D_{ji}^{(0)}(z,\mu) = \delta_{ij}\delta(1-z) \qquad \leftrightarrow$$

$$D_{ji}^{(1)}(z,\mu) = -\frac{1}{\varepsilon}P_{ji}^{(0)}(z) \qquad \leftrightarrow$$

$$D_{ji}^{(2)}(z,\mu) = -\frac{1}{2\varepsilon}P_{ji}^{(1)}(z) + \frac{\beta_0}{4\varepsilon^2}P_{ji}^{(0)}(z) + \frac{1}{2\varepsilon^2}\int_z^1 \frac{\mathrm{d}x}{x}P_{jk}^{(0)}(x)P_{ki}^{(0)}(z/x)$$

$\leftrightarrow$

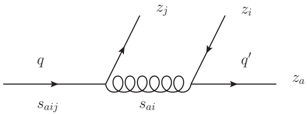


- $P_{ji}^{(n)}$ not probabilities, but sum rules hold ($\leftrightarrow$ unitarity constraint)
  In particular: Momentum sum rule identical between LO & NLO
- **Goal**: Perform the NLO computation of $P_{ji}^{(1)}$ fully differentially using modified dipole subtraction [Catani,Seymour] hep-ph/9605323

Collinear parton evolution at NLO

[Prestel,SH] arXiv:1705.00742

- Simulation of exclusive states requires computing splitting functions on the fly using differential NLO calculation & collinear factorization
- Schematically very similar to Catani-Seymour dipole subtraction
- Simplest example: Flavor-changing configuration $q \to q'$



Tree-level expression[1] $\leftrightarrow$ real-emission correction in CS

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

Subtraction term (q→g)⊗(g→q') $\leftrightarrow$ differential subtraction term in CS

$$\tilde{P}_{qq'} = C_F T_R \frac{s_{aij}}{s_{ai}} \left(\frac{1 + \tilde{z}_j^2}{1 - \tilde{z}_j} - \varepsilon(1 - \tilde{z}_j) \right) \left(1 - \frac{2}{1 - \varepsilon} \frac{\tilde{z}_a \tilde{z}_i}{(\tilde{z}_a + \tilde{z}_i)^2} \right) + \dots$$

[1] $(z_a + z_i)\, t_{ai,j} = 2(z_a s_{ij} - z_i s_{aj}) + (z_a - z_i) s_{ai}$

Collinear parton evolution at NLO

[Prestel,SH] arXiv:1705.00742

- Complete NLO result schematically given by

$$P^{(1)}_{qq'}(z) = \mathrm{C}_{qq'}(z) + \mathrm{I}_{qq'}(z) + \int \mathrm{d}\Phi_{+1} \Big[\mathrm{R}_{qq'}(z, \Phi_{+1}) - \mathrm{S}_{qq'}(z, \Phi_{+1}) \Big]$$

- Real correction $R_{qq'}$ and subtraction terms $S_{qq'}$ $\nearrow$ previous slide
  Difference finite in 4 dimensions $\to$ amenable to MC simulation
- Integrated subtraction term and factorization counterterm given by

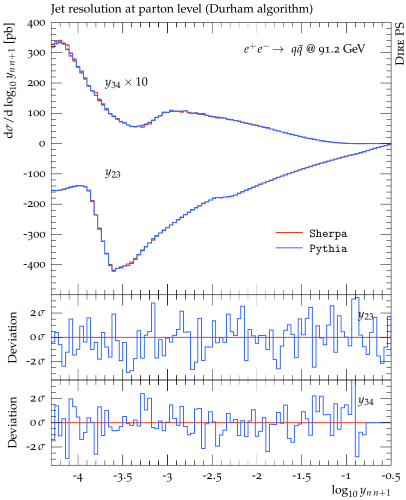
$$\mathrm{I}_{qq'}(z) = \int \mathrm{d}\Phi_{+1} S_{qq'}(z, \Phi_{+1})$$

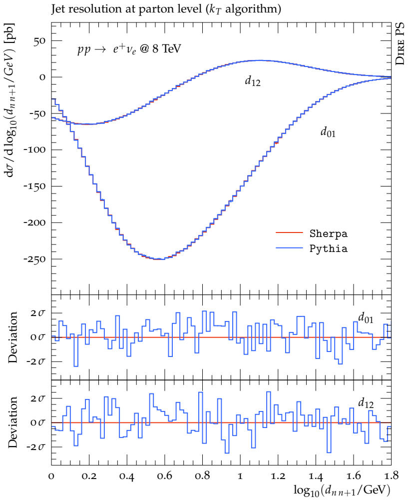
$$\mathrm{C}_{qq'}(z) = \int_z \frac{\mathrm{d}x}{x} \left(P^{(0)}_{qg}(x) + \varepsilon \mathcal{J}^{(1)}_{qg}(x) \right) \frac{1}{\varepsilon} P^{(0)}_{gq}(z/x)$$

$$\mathcal{J}^{(1)}_{qg}(z) = 2C_F \left(\frac{1 + (1-x)^2}{x} \ln(x(1-x)) + x \right)$$

- Analytical computation of I not needed, as $\mathrm{I} + \mathrm{C}$ finite
  generate as endpoint at $s_{ai} = 0$, starting from integrand at $\mathcal{O}(\varepsilon)$
- All components of $P^{(1)}_{qq'}$ eventually finite in 4 dimensions
  Can be simulated fully differentially in parton shower

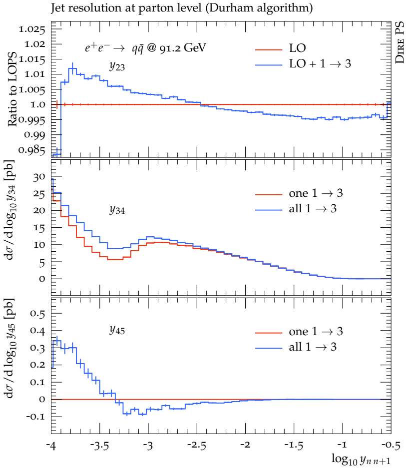
Validation

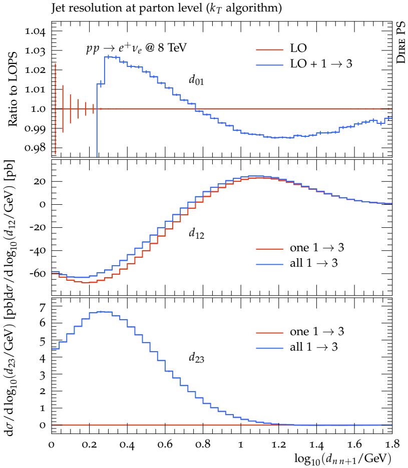




- Effect of single $1 \to 3$ emission on leading and next-to-leading jet rate

Impact relative to leading-order prediction





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

How to make parton showers more precise?
Part II: Soft limit

Soft evolution at the next-to-leading order

[Marchesini,Korchemsky] PLB313(1993)433, hep-ph/9210281

- Soft-gluon resummed expression of Drell-Yan or DIS cross section

$$\frac{1}{\sigma}\frac{d\sigma(z,Q^2)}{d\log Q^2} = \mathcal{H}(Q^2)\,\widetilde{W}(z,Q^2)$$

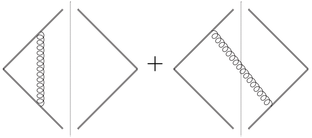
RGE governed by Wilson loop $\widetilde{W}$ ($Q(1-z)$ - total soft gluon energy)

- Non-abelian exponentiation theorem allows to expand as

$$\widetilde{W} = \exp\left\{\sum_{i=1}^{\infty} w^{(\mathrm{n})}\right\}$$

- One-loop result given by

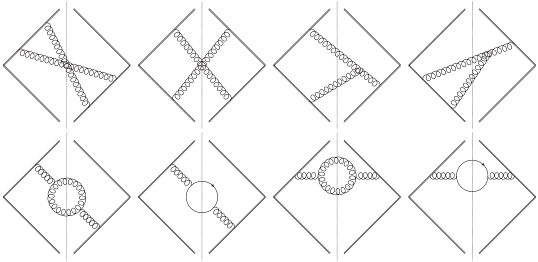
$$w^{(1)} = C_F\,\frac{\alpha_s(\mu)}{2\pi}\left[\ln^2 L + \frac{\pi^2}{6}\right] \quad \leftrightarrow$$



where $L = -b_+ b_- / b_0^2$ and $b_0 = 2\,e^{-\gamma_E}/\mu$

Soft evolution at the next-to-leading order

- 2-loop contribution $w^{(2)}$ computed from (reals only) [Belitsky] hep-ph/9808389



- Renormalized result in position space

$$w^{(2)} = C_F \frac{\alpha_s^2(\mu)}{(2\pi)^2} \left[-\frac{\beta_0}{6} \ln^3 L + \Gamma^{(2)}_{\text{cusp}} \ln^2 L + 2 \ln L \left(\Gamma^{(2)}_{\text{soft}} + \frac{\pi^2}{12} \beta_0 \right) + \ldots \right]$$

$$\Gamma^{(2)}_{\text{cusp}} = \left(\frac{67}{18} - \frac{\pi^2}{6} \right) C_A - \frac{10}{9} T_R n_f \,, \qquad \beta_0 = \frac{11}{6} C_A - \frac{2}{3} T_R n_f$$

$$\Gamma^{(2)}_{\text{soft}} = \left(\frac{101}{27} - \frac{11}{72} \pi^2 - \frac{7}{2} \zeta_3 \right) C_A - \left(\frac{28}{27} - \frac{\pi^2}{18} \right) T_R n_f$$

- This is the benchmark to be reproduced by exclusive MC simulation

Separation of soft and collinear sectors

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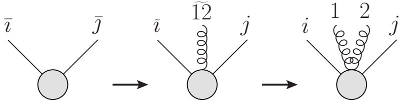
[Dulat,Prestel,SH] arXiv:1805.03757

- Phase space parametrized in terms of total soft momentum $q = p_1 + p_2$



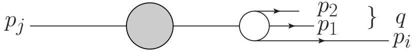
- Momentum space result expanded in Laurent series using

$$\frac{1}{q_\pm^{1+\varepsilon}} = -\frac{1}{\varepsilon}\,\delta(q_\pm) + \sum_{i=0}^{\infty} \frac{\varepsilon^n}{n!} \left(\frac{\ln^n q_\pm}{q_\pm}\right)_+$$

- Unitarity implies that factorized plus distributions like $[1/q_+]_+[1/q_-]_+$ have no PS analogue $\rightarrow$ define double-plus distributions instead

$$\big[f(q_+, q_-)\big]_{++}\, g(q_+, q_-) = f(q_+, q_-)\Big(g(q_+, q_-) - g(0,0)\Big)$$

- Re-organize entire calculation in terms of pure soft & collinear terms
Key observation: $q_\pm = 0$ implies collinear limit both for 1 & 2 emissions



Soft evolution at the next-to-leading order

[Catani,Grazzini] hep-ph/9908523

- Real-emission corrections can be written in convenient form

$$\mathcal{S}_{ij}^{(q\bar{q})}(1,2) = -\frac{s_{ij}}{(s_{i1}+s_{i2})(s_{j1}+s_{j2})}\frac{T_R}{s_{12}}\Big(1-4\,z_1z_2\cos^2\phi_{12,ij}\Big)$$

$$\mathcal{S}_{ij}^{(gg)}(1,2) = \mathcal{S}_{ij}^{(\mathrm{s.o.})}(1,2)\,\frac{C_A}{2}\left(1+\frac{s_{i1}s_{j1}+s_{i2}s_{j2}}{(s_{i1}+s_{i2})(s_{j1}+s_{j2})}\right) + \frac{s_{ij}}{(s_{i1}+s_{i2})(s_{j1}+s_{j2})}\frac{C_A}{s_{12}}\Big(-2+4\,(1-\varepsilon)\,z_1z_2\cos^2\phi_{12,ij}\Big)$$

- Strongly ordered and spin correlation components

$$\mathcal{S}_{ij}^{(\mathrm{s.o.})}(1,2) = \frac{s_{ij}}{s_{i1}s_{12}s_{j2}}+\frac{s_{ij}}{s_{j1}s_{12}s_{i2}}-\frac{s_{ij}^2}{s_{i1}s_{j1}s_{i2}s_{j2}}$$

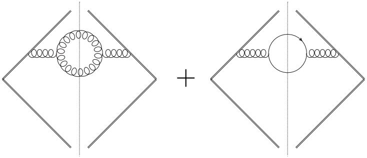
$$4\,z_1z_2\cos^2\phi_{12,ij} = \frac{(s_{i1}s_{j2}-s_{i2}s_{j1})^2}{s_{12}s_{ij}(s_{i1}+s_{i2})(s_{j1}+s_{j2})}$$

- Apparently simple structure, but unlike collinear NLO results not reflected by iterated leading-order splitting kernels
$\rightarrow$ not all denominators can be composed from LO expressions

NLO subtraction: Dipole approach

[Dulat,Prestel,SH] arXiv:1805.03757

- Nearly ok subtraction obtained from spin correlated parton shower



$$= \sum_{b=q,g} J_{ij,\mu}(p_{12}) J_{ij,\nu}(p_{12}) \, \frac{P^{\mu\nu}_{gb}(z_1)}{s_{12}}$$

- Building blocks are eikonal currents

$$J^{\mu}_{ij}(q) = \frac{p_i^{\mu}}{2p_i q} - \frac{p_j^{\mu}}{2p_j q}$$

and collinear splitting functions

$$P^{\mu\nu}_{gq}(z) = T_R \left(-g^{\mu\nu} + 4\, z(1-z)\, \frac{k_\perp^\mu k_\perp^\nu}{k_\perp^2} \right)$$

$$P^{\mu\nu}_{gg}(z) = C_A \left(-g^{\mu\nu} \left(\frac{z}{1-z} + \frac{1-z}{z} \right) - 2\,(1-\varepsilon) z(1-z)\, \frac{k_\perp^\mu k_\perp^\nu}{k_\perp^2} \right)$$

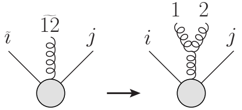
- Finite remainder has integrable singularities $\rightarrow$ not suitable for MC problem arises from interference of abelian & non-abelian diagrams

NLO subtraction: Antenna approach – Kinematics

[Dulat,Prestel,SH] arXiv:1805.03757

- In iterated emission $\bar{\imath}\,\bar{\jmath} \to \widetilde{\imath}\,\widetilde{12}\,j \to ij12$ emission probability of first step written in terms of momenta after second step is

$$\frac{\tilde{p}_i p_j}{2(\tilde{p}_i \tilde{p}_{12})(\tilde{p}_{12} p_j)} = \frac{s_{ij}}{(s_{i1}+s_{i2})(s_{j1}+s_{j2}) - s_{ij}s_{12}}$$



- Not identical to desired "eikonal" $s_{ij}/((s_{i1}+s_{i2})(s_{j1}+s_{j2}))$ in soft⊗collinear terms of $\mathcal{S}_{ij}$ but easily corrected by weight

$$w_{ij}^{12} = 1 - \frac{s_{ij}s_{12}}{(s_{i1}+s_{i2})(s_{j1}+s_{j2})} = \left(\frac{p_{\perp,12}^{(ij)}}{m_{\perp,12}^{(ij)}}\right)^2$$

- Iterated eikonals of type $s_{ij}/(s_{i1}s_{j1})$, $s_{j1}/(s_{12}s_{j2})$ in $\mathcal{S}_{ij}^{(\mathrm{s.o.})}$ reconstructed by partial fractioning & matching to LO^2 $\to$ additional weight

$$\bar{w}_{ij}^{12} = \frac{(s_{i1}+s_{i2})(s_{j1}+s_{j2}) - s_{ij}s_{12}}{s_{i1}s_{j1}+s_{i2}s_{j2}} = \frac{\left(p_{\perp,12}^{(ij)}\right)^2}{\left(p_{\perp,1}^{(ij)}\right)^2 + \left(p_{\perp,2}^{(ij)}\right)^2}$$

- These weights lie between zero and one and reduce emission rates

Leading color fully differential soft evolution at NLO

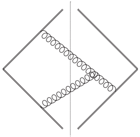
SLAC

[Dulat,Prestel,SH] arXiv:1805.03757

- Squared LO eikonal and negative term in $\mathcal{S}_{ij}^{(\mathrm{s.o.})}$ both have no parton-shower analogue $\to$ correct for both mismatches by adding sub-leading color contribution to $i1$-collinear splitting functions

$$P_{ij,A}^{(\mathrm{slc})}(1,2) = \frac{2\,s_{ij}}{s_{i1}+s_{j1}}\,\frac{w_{ij}^{12}+\bar{w}_{ij}^{12}}{2}\left(\bar{C}_{ij}-C_A\right)\,, \quad \bar{C}_{ij} = \begin{cases} 2C_F & \text{if } i \;\&\; j \text{ quarks} \\ C_A & \text{else} \end{cases}$$

- Second soft emission off Wilson lines occurs with color charge factor C_A due to interference with octet



$$P_{ij,B}^{(\mathrm{slc})}(1,2) = \frac{2\,s_{i2}}{s_{i1}+s_{12}}\,\frac{w_{ij}^{12}+\bar{w}_{ij}^{12}}{2}\left(C_A-\bar{C}_{ij}\right)$$

- Combined effect on $i1$-collinear matched splitting function

$$P_{ij}^{(\mathrm{slc})}(1,2) = \left(C_A-\bar{C}_{ij}\right)\left(\frac{2\,s_{i2}}{s_{i1}+s_{12}}-\frac{2\,s_{ij}}{s_{i1}+s_{j1}}\right)\frac{w_{ij}^{12}+\bar{w}_{ij}^{12}}{2}$$

- Non-singular in $i1$-collinear limit $\to$ color charges of Wilson lines in soft-collinear limit are C_i and C_j, in agreement with DGLAP

Leading color fully differential soft evolution at NLO

[Dulat,Prestel,SH] arXiv:1805.03757

- Complete NLO-weighted LO splitting functions

$$(P_{qq})_i^k(1,2) = C_F\left(\frac{2\,s_{i2}}{s_{i1}+s_{12}}\,\frac{w_{ik}^{12}+\bar{w}_{ik}^{12}}{2}\right) + P_{ik}^{(\mathrm{slc})}(1,2)$$

$$(P_{gg})_{ij}(1,2) = C_A\left(\frac{2\,s_{i2}}{s_{i1}+s_{12}}\,\frac{w_{ij}^{12}+\bar{w}_{ij}^{12}}{2} + w_{ij}^{12}\left(-1+z(1-z)\,2\cos^2\phi_{12}^{ij}\right)\right)$$

$$(P_{gq})_{ij}(1,2) = T_R\,w_{ij}^{12}\left(1-4z(1-z)\cos^2\phi_{12}^{ij}\right)$$

- Calculation completed by subtracted real correction, virtuals and factorization counterterms
- Counterterms are endpoint contributions, as in collinear limit

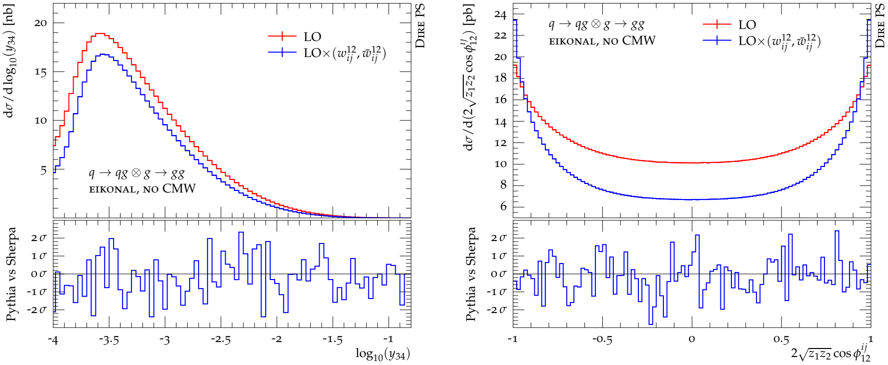
$$\tilde{\mathcal{S}}_{gq}^{(\mathrm{cusp})} = \delta(s_{12})\,\frac{2\,s_{ij}}{s_{i12}s_{j12}}\,T_R\Big[2z(1-z)+\big(1-2z(1-z)\big)\ln(z(1-z))\Big]$$

$$\tilde{\mathcal{S}}_{gg}^{(\mathrm{cusp})} = \delta(s_{12})\,\frac{2\,s_{ij}}{s_{i12}s_{j12}}\,2C_A\left[\frac{\ln z}{1-z}+\frac{\ln(1-z)}{z}+\big(-2+z(1-z)\big)\ln(z(1-z))\right]$$

$$\tilde{\mathcal{S}}_{wl}^{(\mathrm{cusp})} = -\,\delta(s_{i1})\,\frac{1}{2}\,\frac{C_A}{2}\,\frac{2\,s_{ij}}{s_{i12}s_{j12}}\left(\frac{\ln z_i}{1-z_i}+\frac{\ln(1-z_i)}{z_i}\right)+\big(\text{swaps}\big)$$

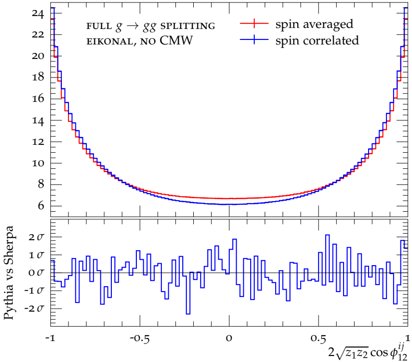
Sum integrates to CMW correction [Catani,Marchesini,Webber] NPB349(1991)635

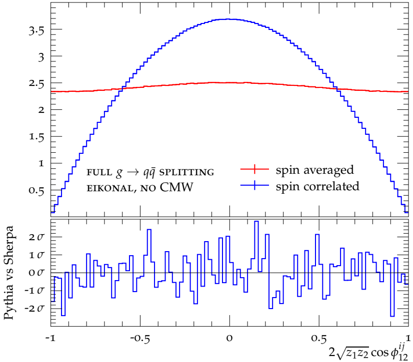
Leading color fully differential soft evolution at NLO



- Impact of weights w_{ij}^{12} and $\bar{w}_{ij}^{12}$ on $3 \to 4$ Durham jet rate and azimuthal angle between soft gluons at LEP I

Leading color fully differential soft evolution at NLO

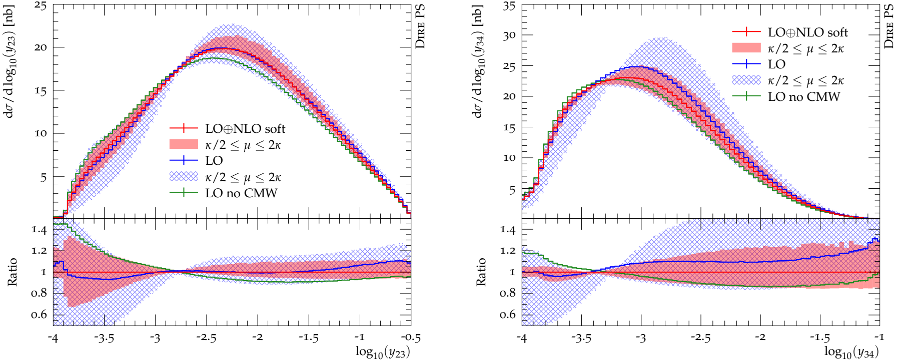




- Impact of spin correlations on azimuthal angle between soft gluons / quarks at LEP I

Leading color fully differential soft evolution at NLO

[Dulat,Prestel,SH] arXiv:1805.03757



- Impact on $2 \to 3$ and $3 \to 4$ Durham jet rate at LEP I
- Uncertainty bands no longer just estimates but perturbative QCD predictions for the first time
- Fair agreement with CMW scheme

Summary

- Double-soft & flavor-changing triple-collinear NLO corrections now added to parton-shower simulation in fully exclusive form
- Remaining collinear NLO corrections to be added by subtracting double-soft components as needed and using CS-like subtraction devised in flavor-changing case
- Relation to NLL resummation to be investigated in detail
  $\rightarrow$ benchmark using [Dasgupta,Dreyer,Hamilton,Monni,Salam] arXiv:1805.09327

Thank you for your attention

Collinear factorization and resummation

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

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

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 $\to$ Not amenable to MC simulation
- Solved by subtraction of spin-correlated LO splitting functions [Somogyi,Trocsanyi,del Duca] hep-ph/0502226

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

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

- Leads to additional subtraction term

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

Collinear factorization and resummation

- Reference for $q \to q'$ 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

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

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

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

where

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

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

Collinear factorization and resummation

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- Analytical computation of I not needed, as $\mathrm{I}+\mathcal{P}/\varepsilon$ 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 $\Delta\mathrm{I}_{qq'}=\tilde{\mathrm{I}}_{qq'}-\tilde{\mathcal{I}}_{qq'}$, where

$$\tilde{\mathrm{I}}_{qq'}=C_FT_R\left[\frac{1+z_j^2}{1-z_j}+\left(1-\frac{2\,z_az_i}{(z_a+z_i)^2}\right)\left(1-z_j+\frac{1+z_j^2}{1-z_j}\right)\Big(\ln(z_az_iz_j)-1\Big)\right]$$

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

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