Recent developments in parton showers

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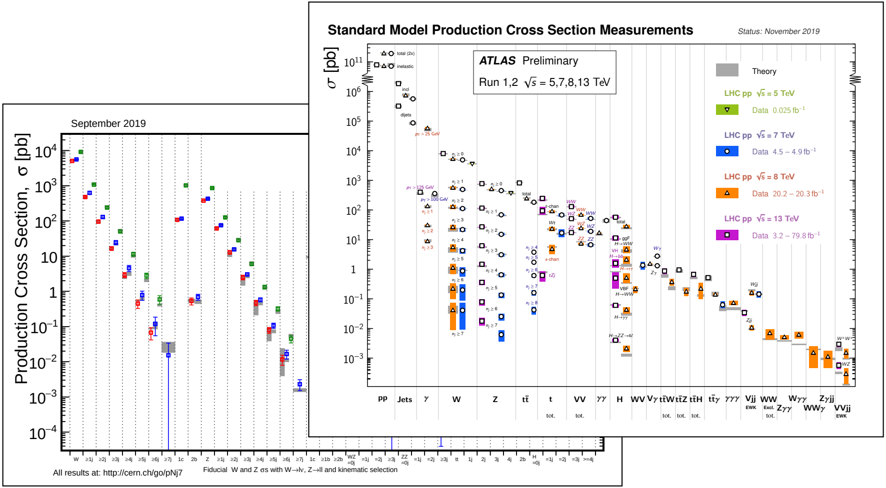
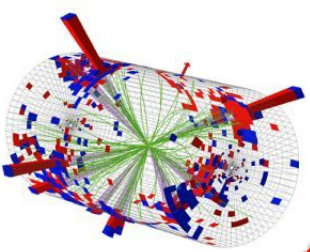
The Standard Model as we know it

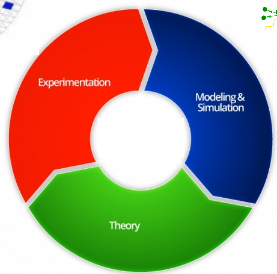


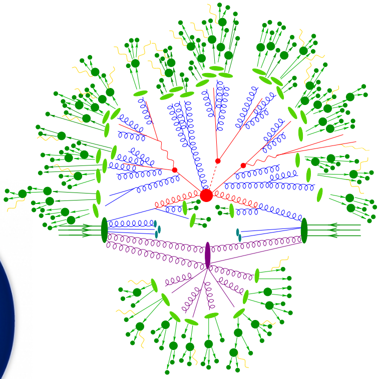
[ATLAS] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

[CMS] https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

How we measure it





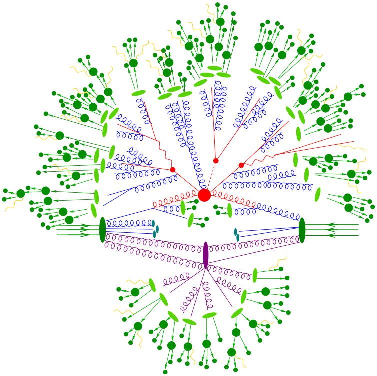


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c.$$

LHC event generators

[Buckley et al.] arXiv:1101.2599
[Campbell et al.] arXiv:2203.11110

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



Divide and Conquer

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

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

Connection to QCD theory

- $\hat{\sigma}_{ij\to n}(\mu_F^2) \to$ Collinearly factorized fixed-order result at N^{x}LO

  Implemented in fully differential form to be maximally useful

  Tree level: $\mathrm{d}\Phi_n \; B_n$

  - Automated ME generators + phase-space integrators

  1-Loop level: $\mathrm{d}\Phi_n \left(B_n + V_n + \sum C + \sum I_n\right) + \mathrm{d}\Phi_{n+1}\left(R_n - \sum S_n\right)$

  - Automated loop ME generators + integral libraries + IR subtraction

  2-Loop level: It depends ...

  - Individual solutions based on SCET, q_T subtraction, P2B

- $f_i(x, \mu_F^2) \to$ Collinearly factorized PDF at N^{y}LO

  Evaluated at $O(1\mathrm{GeV}^2)$ and expanded into a series above $1\mathrm{GeV}^2$

  DGLAP: $\frac{\mathrm{d}x\, x f_a(x,t)}{\mathrm{d}\ln t} = \sum_{b=q,g} \int_0^1 \mathrm{d}\tau \int_0^1 \mathrm{d}z \, \frac{\alpha_s}{2\pi} \left[z P_{ab}(z)\right]_+ \tau f_b(\tau, t)\, \delta(x - \tau z)$

  - Parton showers, dipole showers, antenna showers, ...

  Matching: $\mathrm{d}\Phi_n \, \frac{S_n}{B_n} \leftrightarrow \frac{\mathrm{d}t}{t} \mathrm{d}z \, \frac{\alpha_s}{2\pi} \, P_{ab}(z)$

  - MC@NLO, POWHEG, Geneva, MINNLO$_{\mathrm{PS}}$, ...

Directions of development

Much effort focused on parton-shower component recently

- Phenomenologically interesting: Drives jet production, b-tagging, ...
- Experimentally relevant: Often source of largest uncertainty
- The unique part of event generators (in perturbative QCD)

Fixed-order aspects

- Matching to NLO calculations
  - Negative weight fraction
  - Unweighting efficiency
- Matching to NNLO calculations
  - Semi-inclusive
  - Fully differential
- Matching to N^{3}LO calculations

All-order aspects

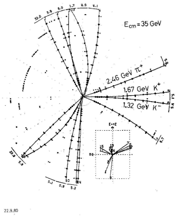
- NLL precision
- Splitting functions at NLO
- Spin correlations
- Sub-leading power corrections
- Sub-leading color effects
- Threshold effects
- Amplitude evolution

Evolution of parton-showers over time

Accuracy → Precision

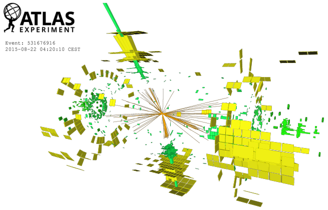
- 1985: Color coherent evolution; Backward evolution
- 1990: ME corrections; Color dipole formalism; Spin correlations
- 1995: Color dipole showers
- 2000: LO merging; NLO matching
- 2005: Dipole-like showers; Antenna showers; NLO merging
- 2010: Color ME corrections; NNLO matching
- 2015: Threshold effects; NLO splitting kernels; Higher-order PS framework
- 2018: Accuracy quantification; Amplitude evolution
- 2022: NLL & NGLs in one framework; Efficient $1/N_c$ corrections

1985 1990 1995 2000 2005 2010 2015 2018 2022



$\sqrt{s} \times 500$ →

e^+e^- vs. pp



Simulation of QCD dipole radiation

Approaches, problems & solutions

Semi-classical radiation pattern

[Marchesini,Webber] NPB310(1988)461

- Soft gluon radiator can be written in terms of energies and angles

$$J_\mu J^\mu \to \frac{p_i p_k}{(p_i p_j)(p_j p_k)} = \frac{W_{ik,j}}{E_j^2}$$

Angular "radiator" function

$$W_{ik,j} = \frac{1-\cos\theta_{ik}}{(1-\cos\theta_{ij})(1-\cos\theta_{jk})}$$

- Divergent as $\theta_{ij} \to 0$ and as $\theta_{jk} \to 0$

$\to$ Expose individual collinear singularities using $W_{ik,j} = \tilde{W}^i_{ik,j} + \tilde{W}^k_{ki,j}$

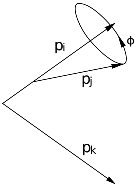
$$\tilde{W}^i_{ik,j} = \frac{1}{2}\left[\frac{1-\cos\theta_{ik}}{(1-\cos\theta_{ij})(1-\cos\theta_{kj})} + \frac{1}{1-\cos\theta_{ij}} - \frac{1}{1-\cos\theta_{kj}}\right]$$

  - Divergent as $\theta_{ij} \to 0$, but regular as $\theta_{kj} \to 0$
  - Convenient properties upon integration over azimuthal angle

Semi-classical radiation pattern

- Work in a frame where direction of $\vec{p}_i$ aligned with z-axis

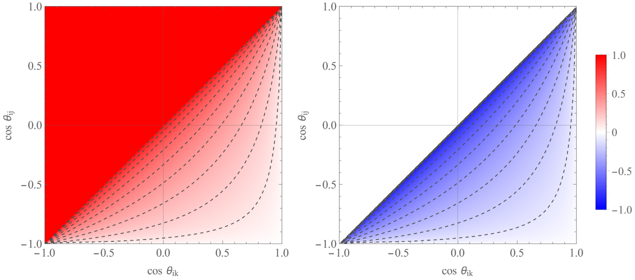
$$\cos\theta_{kj} = \cos\theta_k^i \cos\theta_j^i + \sin\theta_k^i \sin\theta_j^i \cos\phi_{kj}^i$$



- Integration over ϕ_j yields

$$\frac{1}{2\pi}\int_0^{2\pi} \mathrm{d}\phi_{kj}^i \tilde{W}_{ik,j}^i = \frac{1}{1-\cos\theta_j^i} \times \begin{cases} 1 & \text{if} \quad \theta_j^i < \theta_k^i \\ 0 & \text{else} \end{cases}$$

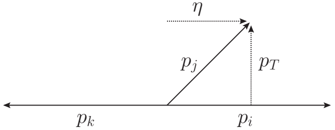
  - On average, no radiation outside cone defined by parent dipole
  - Differential radiation pattern more intricate:
    Positive & negative contributions outside cone sum to zero



Dual description and the Lund plane

[Gustafson] PLB175(1986)453

- Compute everything in center-of-mass frame of fast partons

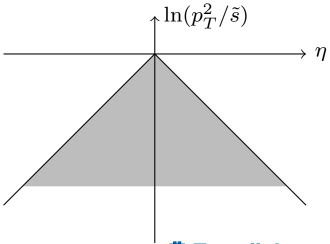


- Simple expressions for transverse momentum and rapidity

$$p_T^2 = \frac{2(p_i p_j)(p_k p_j)}{p_i p_k}\;, \qquad \eta = \frac{1}{2}\ln\frac{p_i p_j}{p_k p_j}$$

- In momentum conserving parton branching $(\tilde{p}_i, \tilde{p}_k) \to (p_i, p_k, p_j)$

$$-\ln \tilde{s}_{ik}/p_T^2 \le 2\eta \le \ln \tilde{s}_{ik}/p_T^2$$



- Differential phase-space element $\propto \mathrm{d}p_T^2\,\mathrm{d}\eta$
- Visualized in Lund plane
  - Phase space bounded by diagonals
  - Single-emission semi-classical radiation probability a constant

Angular ordered parton showers

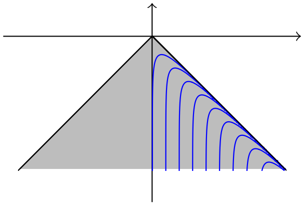
[Marchesini,Webber] NPB238(1984)1, ...

- Differential radiation probability

$$\mathrm{d}\mathcal{P} = \mathrm{d}\Phi_{+1}|M|^2 \approx \frac{\mathrm{d}\tilde{q}^2}{\tilde{q}^2}\,\mathrm{d}z\,\frac{\alpha_s}{2\pi}\,P_{\widetilde{ij}i}(z)$$

  - Ordering parameter $\tilde{q}^2 = \frac{2p_ip_j}{z(1-z)} \approx 4E_{\widetilde{ij}}^2 \sin^2\frac{\theta_{ij}}{2}$
  - Splitting variable $z = \frac{1+\cos\theta_{ik}}{2} = \frac{p_ip_k}{(p_i+p_j)p_k}$

- Lund plane filled from center to edges
  - Random walk in p_T^2
  - Color factors correct for observables insensitive to azimuthal correlations
  - Small dead zone at $\ln(p_T^2/\tilde{s}) \approx 0$



- Usually disfavored due to dead zones
  Not suitable to resum non-global logartihms

Dipole showers

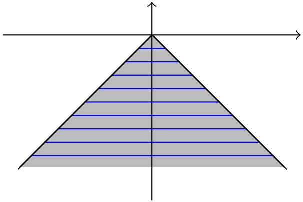
[Gustafson,Pettersson] NPB306(1988)746, ...

- Differential radiation probability for the dipole

$$\mathrm{d}\mathcal{P} = \mathrm{d}\Phi_{+1}|M|^2 \approx \frac{\mathrm{d}p_T^2}{p_T^2}\,\mathrm{d}\eta\,\frac{\alpha_s}{2\pi}\,\tilde{P}_{\widetilde{ij}}(z)$$

  - Ordering parameter p_T^2
  - Splitting variable $z = 1 - \frac{s_{ij}}{s - s_{ij}}\,\mathrm{e}^{-2\eta}$

- Lund plane filled from top to bottom
  - Random walk in η
  - Color factors in CFFE approximation
  - Pairs of partons evolve simultaneously
  - No dead zones

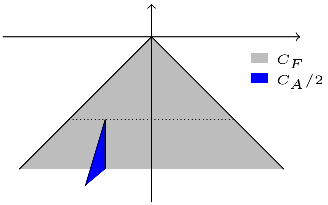


- Solves problem of dead zones
  Known issues with color coherence

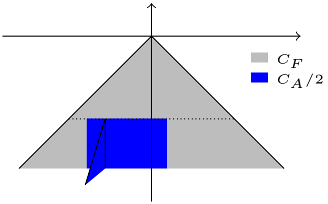
Problems with average color charges

[Gustafsson] NPB392(1993)251

- In angular ordered showers angles are measured in the event center-of-mass frame $\rightarrow$ coherence effects modeled by angular ordering variable agree on average with matrix element



- In dipole-like showers angles effectively measured in center-of-mass frame of emitting color dipole $\rightarrow$ angular coherence not reflected by setting average QCD charge

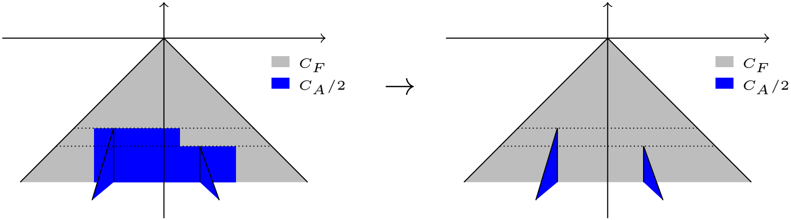


- Emission off "back plane" in Lund diagram should be associated with C_F, but is partly associated with $C_A/2$ in dipole showers
- All-orders problem that appears first in 2-gluon emission case

Solutions for average color charges

[Gustafsson] NPB392(1993)251
[Hamilton,Medves,Salam,Scyboz,Soyez] arXiv:2011.10054

- Analyze rapidity of gluon emission in event center-of-mass frame
- Sectorize phase space and assign gluon to closest parton
  $\rightarrow$ choose corresponding color charge for evolution
- Same technology for higher number of emissions

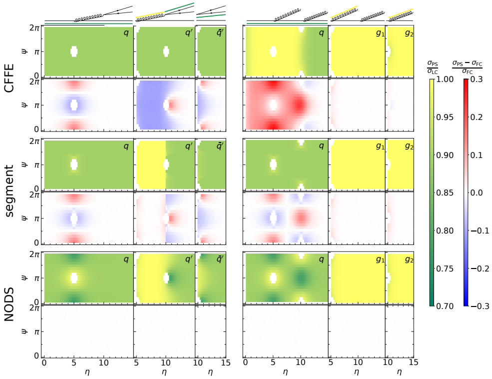


- Starting with 4 emissions, there be "color monsters"
  [Dokshitzer,Troian,Khoze] SJNP47(1988)881, YF47(1988)1384
  - Quartic Casimir operators (easy)
  - Non-factorizable contributions (hard)

Solutions for average color charges

[Hamilton,Medves,Salam,Scyboz,Soyez] arXiv:2011.10054

- Can include double-soft corrections via reweighting [Giele,Kosower,Skands] arXiv:1102.2126
- Algorithm scales as N^2 but can be simplified while retaining formal accuracy
- Implementation as nested corrections in rapidity segments of parent dipole
- Excellent agreement with full matrix element



- Good agreement with full-color evolution [Hatta,Ueda] arXiv:1304.6930

Problems with momentum mapping

[Dasgupta,Dreyer,Hamilton,Monni,Salam] arXiv:1805.09327

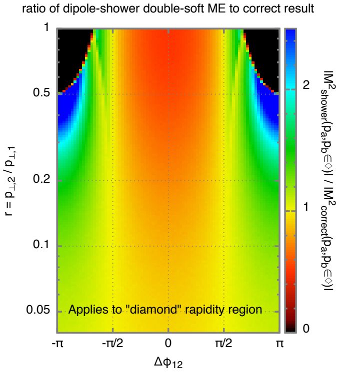
- Subtle problems in standard dipole-like momentum mapping

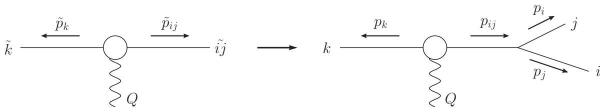
$$p_k^\mu = \left(1 - \frac{p_{ij}^2}{2\tilde{p}_{ij}\tilde{p}_k}\right)\tilde{p}_k^\mu$$

$$p_i^\mu = \tilde{z}\,\tilde{p}_{ij}^\mu + (1-\tilde{z})\frac{p_{ij}^2}{2\tilde{p}_{ij}\tilde{p}_k}\tilde{p}_k^\mu + k_\perp^\mu$$

$$p_j^\mu = (1-\tilde{z})\,\tilde{p}_{ij}^\mu + \tilde{z}\frac{p_{ij}^2}{2\tilde{p}_{ij}\tilde{p}_k}\tilde{p}_k^\mu - k_\perp^\mu$$

- Induces angular correlations across multiple emissions
- Spoils agreement w/ analytic resummation





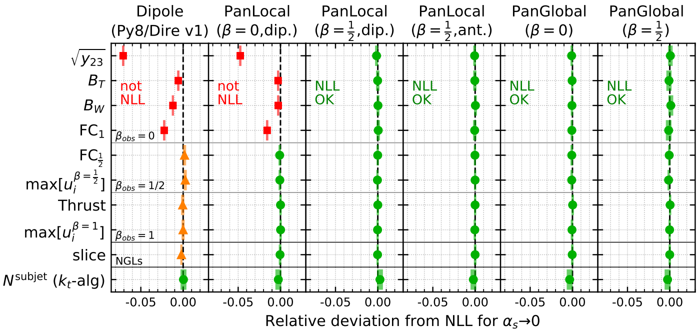
Solutions for momentum mapping

[Dasgupta,Dreyer,Hamilton,Monni,Salam,Soyez] arXiv:2002.11114

- Problem can be solved by partitioning of antenna radiation pattern and choosing a suitable evolution variable ($\beta \sim 1/2$)

$$k_T = \rho v e^{\beta|\bar{\eta}|} \qquad \rho = \left(\frac{s_i s_j}{Q^2 s_{ij}}\right)^{\beta/2}$$

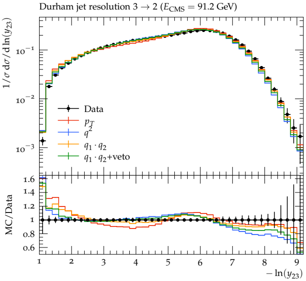
- Different recoil schemes can lead to NLL result if β chosen appropriately: Local dipole, local antenna, and global antenna
- NLL correct for global and non-global observables in $e^+e^- \to$hadrons

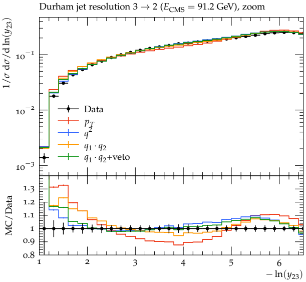


Solutions for momentum mapping

[Bewick,Ferrario-Ravasio,Richardson,Seymour] arXiv:1904.11866

- Recoil schemes affect logarithmic accuracy but impact also phase-space coverage
- In context of angular ordered Herwig 7 (NLL accurate for global observables)
  - q_T preserving scheme:
    Maintains logarithmic accuracy
    Overpopulates hard region
  - q^2 preserving scheme:
    Breaks logarithmic accuracy
    Good description of hard region
  - Dot product preserving scheme (new):
    Maintains logarithmic accuracy
    Good description of hard radiation

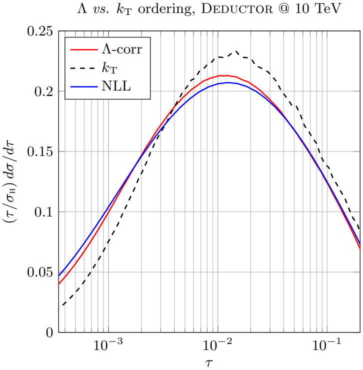


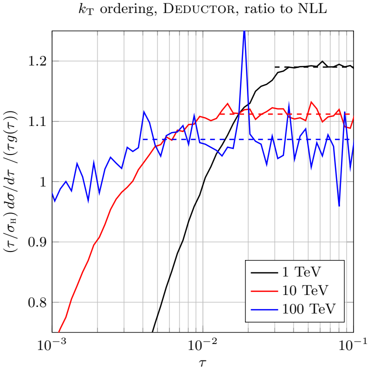


Solutions for momentum mapping

[Nagy,Soper] arXiv:2011.04773

- Local transverse recoil, global longitudinal recoil
- Analytic proof of NLL correctness, based on kinematics in $s \to \infty$ limit





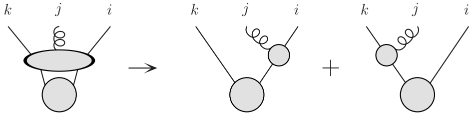
A new perspective on old ideas

Identified partons & azimuthal angle dependence

The semi-classical matrix element revisited

- Alternative to additive matching: partial fraction matrix element & match to collinear sectors [Ellis,Ross,Terrano] NPB178(1981)421, [Catani,Seymour] hep-ph/9605323

$$\frac{W_{ik,j}}{E_j^2} \quad \rightarrow \quad \frac{1}{p_ip_j}\,\frac{p_ip_k}{(p_i+p_k)p_j} + \frac{1}{p_kp_j}\,\frac{p_ip_k}{(p_i+p_k)p_j}$$



  - Captures matrix element both in angular ordered and unordered region
  - Caveat: Oversampling difficult for certain kinematics maps

- Separate into energy & angle first [Herren,Krauss,Reichelt,Schönherr,SH] arXiv:2208.06057
  Partial fraction angular radiator only: $W_{ik,j} = \bar{W}^i_{ik,j} + \bar{W}^k_{ki,j}$

$$\bar{W}^i_{ik,j} = \frac{1-\cos\theta_{ik}}{(1-\cos\theta_{ij})(2-\cos\theta_{ij}-\cos\theta_{kj})}$$

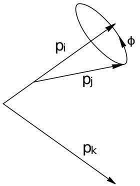
  - Bounded by $(1-\cos\theta_{ij})\bar{W}^i_{ik,j} < 2$
  - Strictly positive

The semi-classical matrix element revisited

- Integration over ϕ_j yields

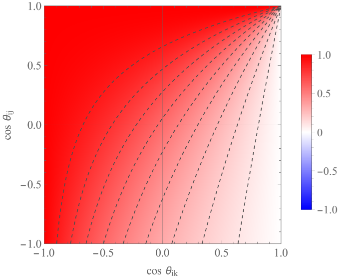
$$\frac{1}{2\pi}\int_0^{2\pi} \mathrm{d}\phi_{kj}^i \bar{W}_{ik,j}^i = \frac{1}{1-\cos\theta_j^i}\frac{1}{\sqrt{(\bar{A}_{ij,k}^i)^2-(\bar{B}_{ij,k}^i)^2}}$$

  - Radiation across all of phase space
  - Probabilistic radiation pattern

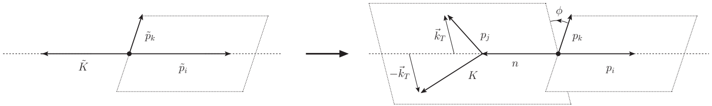


$$\bar{A}_{ij,k}^i = \frac{2-\cos\theta_j^i(1+\cos\theta_k^i)}{1-\cos\theta_k^i}$$

$$\bar{B}_{ij,k}^i = \frac{\sqrt{(1-\cos^2\theta_j^i)(1-\cos^2\theta_k^i)}}{1-\cos\theta_k^i}$$



Kinematics mapping revisited



- In collinear limit, splitting kinematics defined by ($n \to$ auxiliary vector)

$$p_i \xrightarrow{i||j} z\,\tilde{p}_i\;, \qquad p_j \xrightarrow{i||j} (1-z)\,\tilde{p}_i \qquad \text{where} \qquad z = \frac{p_i n}{(p_i + p_j)n}$$

- Parametrization, using hard momentum $\tilde{K}$

$$p_i = z\,\tilde{p}_i\;, \qquad n = \tilde{K} + (1-z)\,\tilde{p}_i$$

- Using on-shell conditions & momentum conservation ($\kappa = \tilde{K}^2/(2\tilde{p}_i\tilde{K})$)

$$\begin{aligned} p_j &= (1-z)\,\tilde{p}_i + v\big(\tilde{K} - (1-z+2\kappa)\,\tilde{p}_i\big) + k_\perp \\ K &= \qquad\qquad \tilde{K} - v\big(\tilde{K} - (1-z+2\kappa)\,\tilde{p}_i\big) - k_\perp \end{aligned}$$

- Momenta in $\tilde{K}$ Lorentz-boosted to new frame K [Catani,Seymour] hep-ph/9605323

$$p_l^\mu \to \Lambda^\mu_{\ \nu}(K,\tilde{K})\,p_l^\nu\;, \qquad \Lambda^\mu_{\ \nu}(K,\tilde{K}) = g^\mu_{\ \nu} - \frac{2(K+\tilde{K})^\mu (K+\tilde{K})_\nu}{(K+\tilde{K})^2} + \frac{2\tilde{K}^\mu K_\nu}{K^2}\;.$$

Logarithmic accuracy – Analytic proof

- Logarithmic accuracy of parton shower can be quantified by comparing results to (semi-)analytic resummation e.g. [Banfi,Salam,Zanderighi] hep-ph/0407286
- Example: Thrust or FC_0 in $e^+e^- \to$hadrons

- Define a shower evolution variable $\xi = k_T^2/(1-z)$
- Parton-shower one-emission probability for $\xi > Q^2\tau$

$$R_{\rm PS}(\tau) = 2\int_{Q^2\tau}^{Q^2}\frac{d\xi}{\xi}\int_{z_{\rm min}}^{z_{\rm max}}dz\,\frac{\alpha_s\big(k_T^2\big)}{2\pi}\,C_F\left[\frac{2}{1-z}-(1+z)\right]\Theta(\eta)$$

- Approximate to NLL accuracy

$$R_{\rm NLL}(\tau) = 2\int_{Q^2\tau}^{Q^2}\frac{d\xi}{\xi}\left[\int_0^1 dz\,\frac{\alpha_s\big(k_T^2\big)}{2\pi}\frac{2\,C_F}{1-z}\Theta(\eta)-\frac{\alpha_s(\xi)}{\pi}\,C_F B_q\right]$$

Logarithmic accuracy – Analytic proof

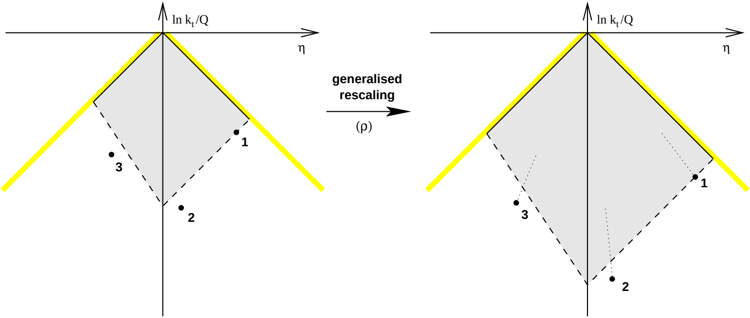
- Cumulative cross section $\Sigma(\tau) = e^{-R(\tau)}\mathcal{F}(\tau)$ obtained from all-orders resummed result by Taylor expansion of virtual corrections in cutoff ε

$$\mathcal{F}(\tau) = \int \mathrm{d}^3k_1 |M(k_1)|^2\, e^{-R'\ln\frac{\tau}{\varepsilon v_1}} \sum_{m=0}^{\infty} \frac{1}{m!}\left(\prod_{i=2}^{m+1}\int_{\varepsilon v_1}^{v_1} \mathrm{d}^3k_i |M(k_i)|^2\right) \times \Theta\big(\tau - V(\{p\}, k_1, \ldots, k_n)\big)$$

  - $\mathcal{F}(\tau)$ is pure NLL & accounts for (correlated) multiple-emission effects
- In order to make $\mathcal{F}(\tau)$ calculable, make the following assumptions
  - Observable is recursively infrared and collinear safe
  - Hold $\alpha_s(Q^2)\ln\tau$ fixed, while taking limit $\tau \to 0$
    $\to$ Can factorize integrals and neglect kinematic edge effects

    Can be interpreted as $\alpha_s \to 0$ or $s \to \infty$ limit

Logarithmic accuracy – Analytic proof



- $\alpha_s \to 0$ / $s \to \infty$ limit taken by similarity transformation of Lund plane
- Can be parametrized in terms of scaling parameter ρ

$$k_{t,l} \to k'_{t,l} = k_{t,l}\,\rho^{(1-\xi_l)/a+\xi_l/(a+b)}$$

$$\eta_l \to \eta'_l = \eta - \xi_l \frac{\ln\rho}{a+b}\,, \qquad \text{where} \qquad \xi = \frac{\eta}{\eta_{\max}}$$

observable parametrization at one-emission level: $v = (k_t^2/Q^2)^a \exp(-b\eta)$

- NLL precision requires scaling to be maintained after additional emissions

Logarithmic accuracy – Analytic proof

- Lorentz transformation defined by shift $\tilde{K} \to K$

$$K^\mu = \tilde{K}^\mu - X^\mu\ , \qquad \text{where} \qquad X^\mu = p_j^\mu - (1-z)\,\tilde{p}_i^\mu$$

- X is small, but is it small enough? Rewrite

$$\Lambda^\mu_{\ \nu}(K,\tilde{K}) = g^\mu_\nu + \tilde{K}^\mu A_\nu + X^\mu B_\nu$$

- In NLL limit, coefficients scale as

$$A^\nu \xrightarrow{\rho\to 0} 2\,\frac{\tilde{K}X}{\tilde{K}^2}\,\frac{\tilde{K}^\nu}{\tilde{K}^2} - \frac{X^\nu}{\tilde{K}^2}\ , \qquad \text{and} \qquad B^\nu \xrightarrow{\rho\to 0} \frac{\tilde{K}^\nu}{\tilde{K}^2}\ .$$

- Simplify situation by taking $a=1$, $b=0$ (worst offenders)
  Relative momentum shift of soft emission particle l becomes

$$\Delta p_l^{0,3}/\tilde{p}_l^{0,3} \sim \rho^{1-\max(\xi_i,\xi_j)} \quad \xrightarrow{\rho\to 0} \quad 0$$

$$\Delta p_l^{1,2}/\tilde{p}_l^{1,2} \sim \rho^{1-\xi_l} \quad \xrightarrow{\rho\to 0} \quad 0$$

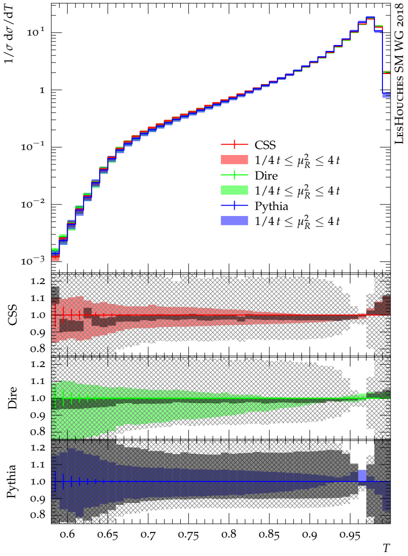
- For hard momenta, leading terms in X^μ cancel exactly
  Remaining components scale as ρ or stronger

The elusive parton-shower uncertainty

Scale variations

[LesHouches] arXiv:1605.04692, arXiv:1803.07977

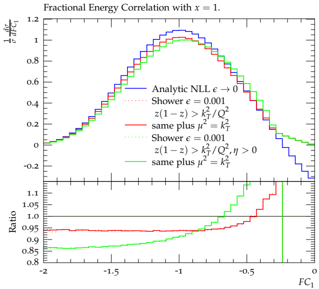
- First systematic attempt to estimate PS variations by MCnet groups at LesHouches 2015/2017 $\rightarrow$
- Renormalization scale uncertainties based on order α_s^2 corrections to soft enhanced part of kernels
- Kinematics and evolution variable remain similar among contenders

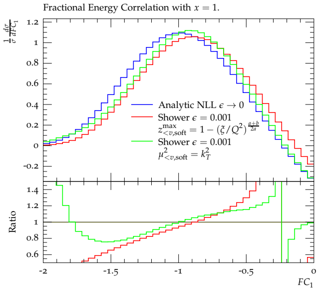


Momentum conservation

[Reichelt,Siegert,SH] arXiv:1711.03497

- Sizeable differences between NLL & PS away from $s \to \infty$ limit
- "guesstimate" of uncertainty from momentum mapping
  NLP resummation needed to improve systematically





Single emission effects

- 4-mom conservation
- PS sectorization
- k_T scale in coll. terms

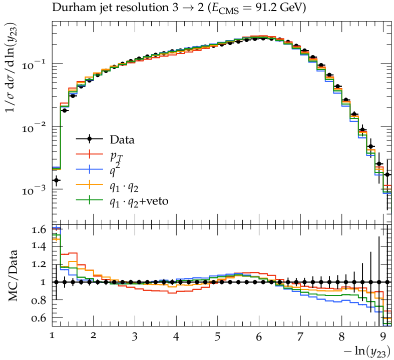
Multiple emission effects

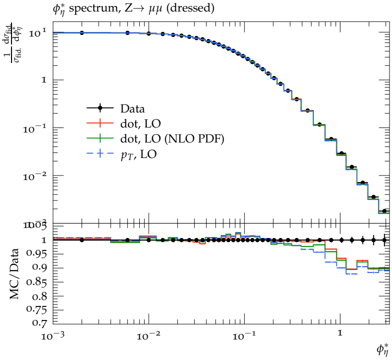
- z bounds by unitarity
- k_T scale by unitarity

Herwig angular ordered parton showers

[Bewick,Ferrario-Ravasio,Richardson,Seymour] arXiv:1904.11866, arXiv:2107.04051

- Comparison of q_T, q^2 & dot product preserving recoil schemes

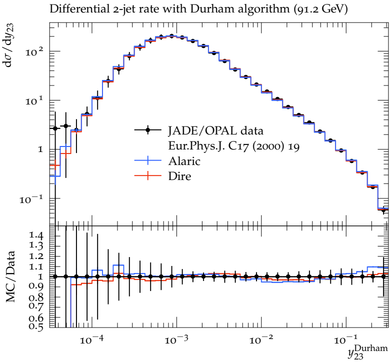


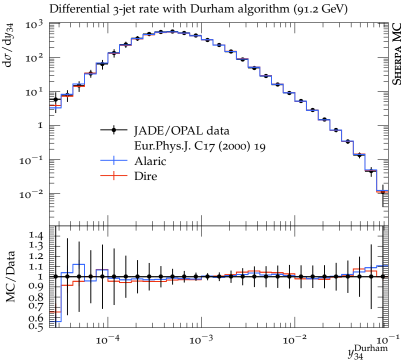


Alaric parton shower

[Herren,Krauss,Reichelt,Schönherr,SH] arXiv:2208.06057

- Comparison to experimental data from LEP

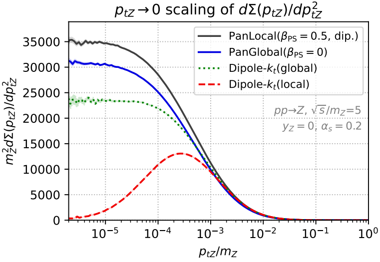


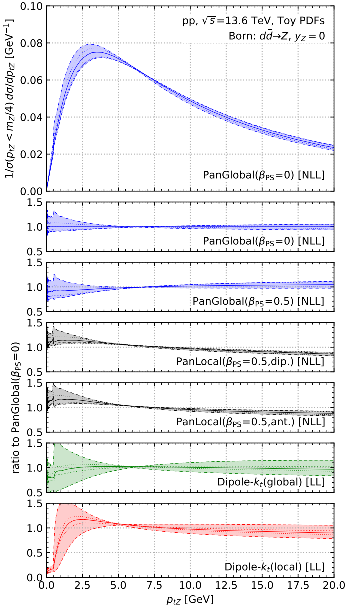


PanScales parton shower

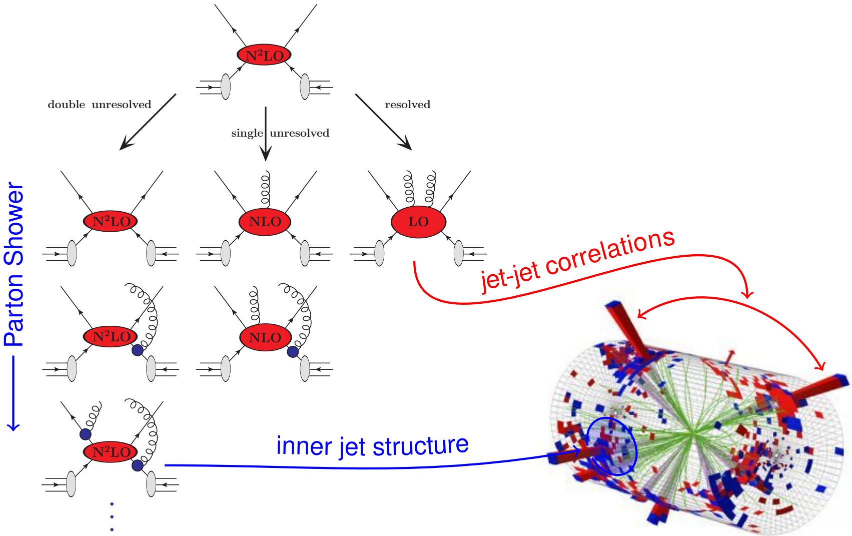
[van Beekveld,Ferrario Ravasio,Hamilton,Salam, Soto-Ontoso,Soyez,Verheyen] arXiv:2207.09467

- Comparison of different PanScales showers all provably NLL accurate
- Toy PDF, fixed flavor initial state
- Conventional dipole schemes do not reproduce [Parisi,Petronzio] NPB154(1979)427





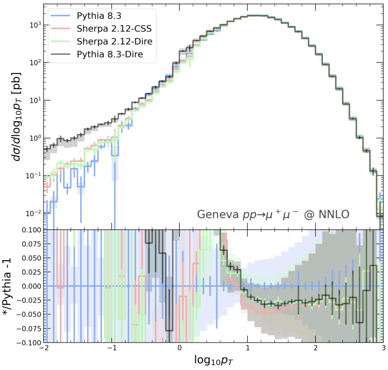
Impact of parton-shower variations on matching

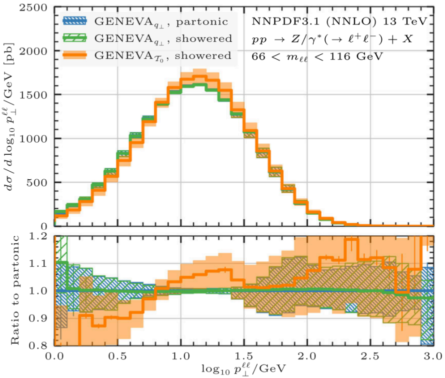


Impact of parton-shower variations on matching

[D. Napoletano, HP2 2022], [Alioli et al.] arXiv:2102.08390

- NNLO+PS precise predictions for $pp \to Z$ from Geneva



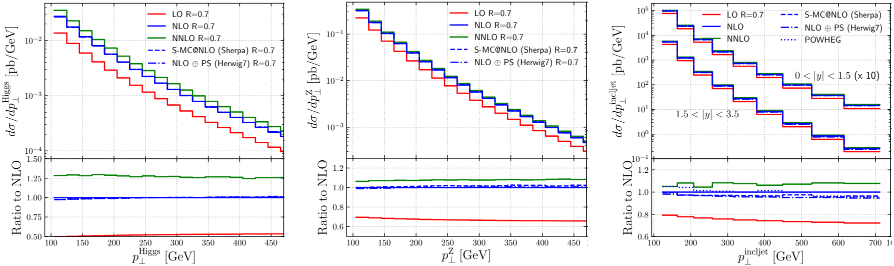


- Parton shower scheme uncertainty
- Choice of resolution variable

Impact of parton-shower variations on matching

[Bellm at al.] arXiv:1903.12563

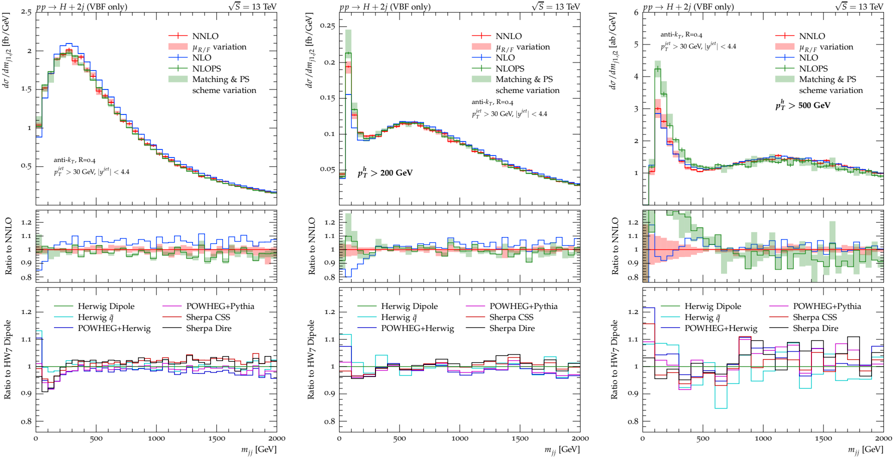
- Inclusive $p_\perp$ spectra for different processes
- Comparison between different MC (Herwig, Sherpa, POWHEG+Herwig)



Impact of parton-shower variations on matching

[Buckley et al.] arXiv:2105.11399

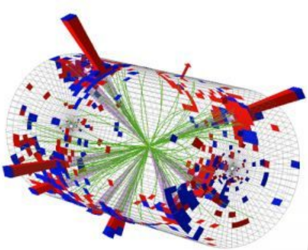
- m_{jj} of two leading jets in VBF Higgs production

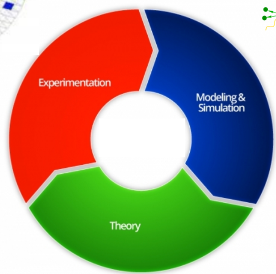


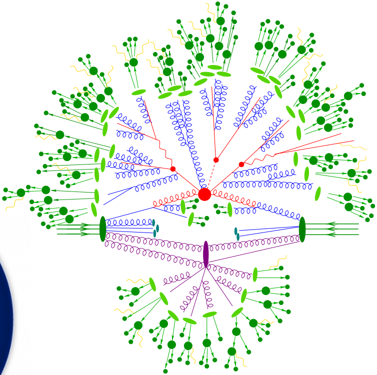
Summary and Outlook

- Lots of activity in parton shower development ...
  - Logarithmic precision [PanScales,Deductor,Herwig,Sherpa,...]
  - Higher-order kernels [Vincia,Sherpa,Herwig,...]
  - Interplay w/ NNLL, CMW [PanScales,Sherpa,...]
- ... and matching to fixed-order calculations
  - Improvements at NLO [Herwig,Pythia,Sherpa,...]
  - Resummation based [Geneva,MINNLO$_{PS}$]
  - Fully differential [Vincia,UN^{X}LOPS,TOMTE]
- Still, many questions remain [Campbell et al.] arXiv:2203.11110
  - Systematic treatment of power corrections
  - Massive quark production & evolution
  - Interplay with hadronization
  - ...

Exciting times ahead!



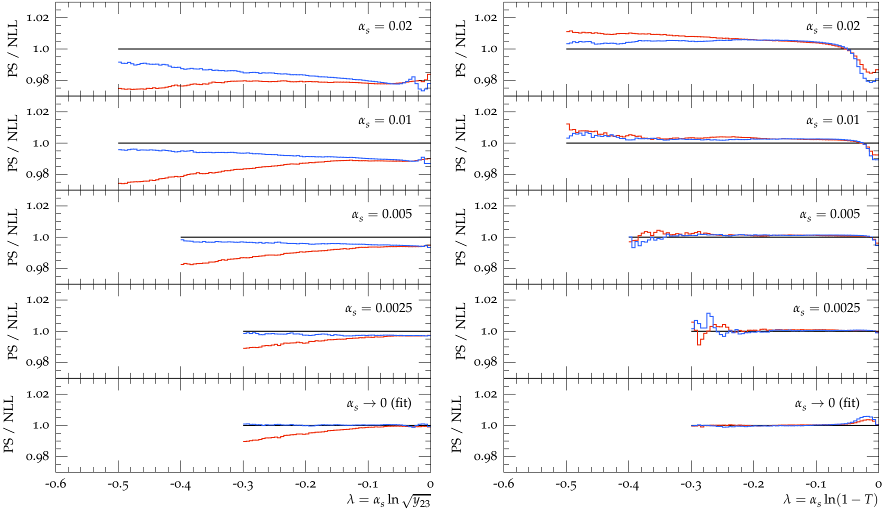




$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c.$$

Accuracy of Alaric scheme – Numerical checks

[Herren,Krauss,Reichelt,Schönherr,SH] arXiv:2208.06057



- At fixed $\lambda = \alpha_s \log v$, deviation from NLL should be proportional to α_s
- Dire algorithm (red) fails, Alaric (blue) passes

Comparison to experimental data: LEP I

[Herren,Krauss,Reichelt,Schönherr,SH] arXiv:2208.06057

- Comparison to experimental data from LEP