Recent Developments in Event Generators

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QCD@LHC

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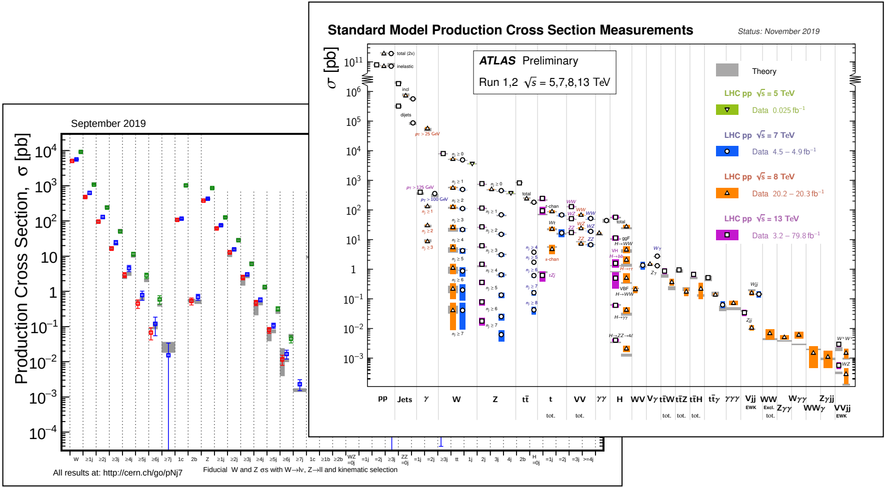
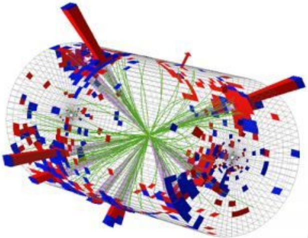
The Standard Model as we know it

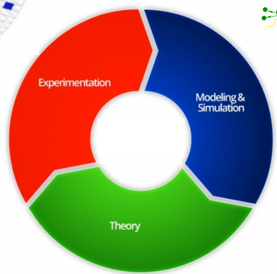


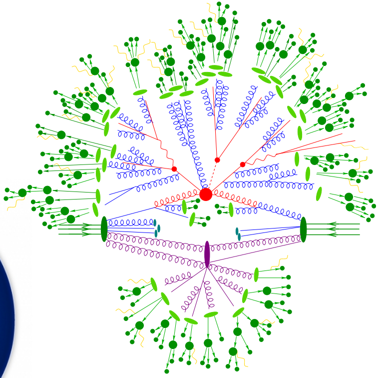
[ATLAS] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

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

The toolkit





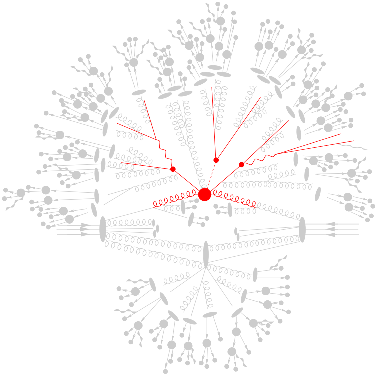


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i\bar{\psi}\not{D}\psi + h.c.$$

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

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

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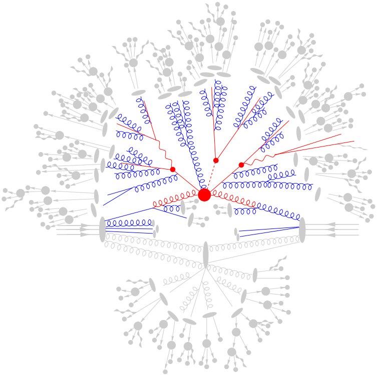

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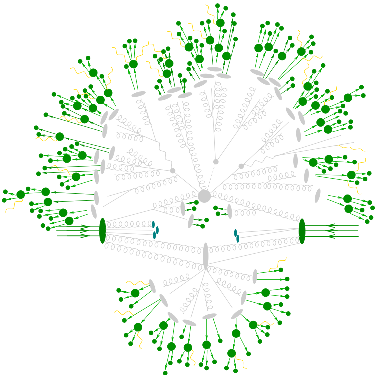

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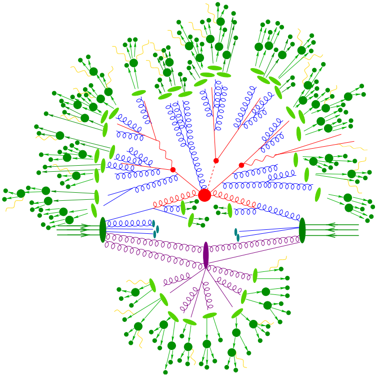

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Connection to QCD theory

- $\hat{\sigma}_{ij\to n}(\mu_F^2)$ → 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

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

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

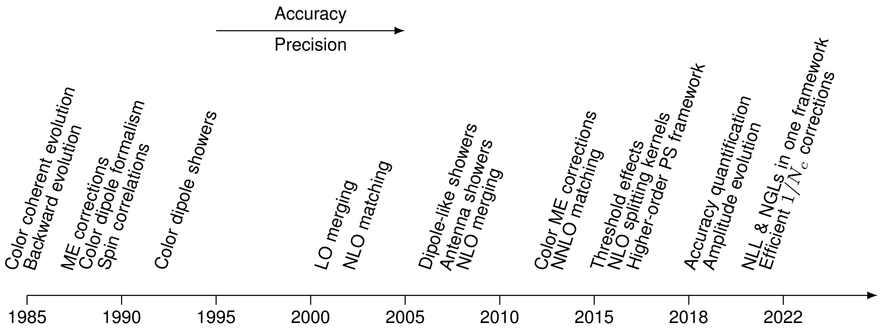
  DGLAP: $\frac{\mathrm{d}x\, x f_a(x,t)}{\mathrm{d}\ln t} = \sum_{b=q,g}\int_0^1 \mathrm{d}\tau \int_0^1 \mathrm{d}z\, \frac{\alpha_s}{2\pi}\left[zP_{ab}(z)\right]_+ \tau f_b(\tau,t)\,\delta(x-\tau z)$

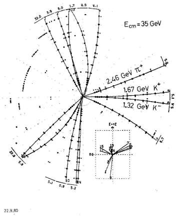
  - Parton showers, dipole showers, antenna showers, ...

  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$_{\mathrm{PS}}$, ...

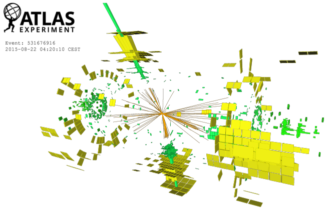
Co-design of simulations over the years





$\sqrt{s} \times 500$

e^+e^- vs. pp



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
- Next to hadronization, probably the most important component of MCs

Fixed-order aspects

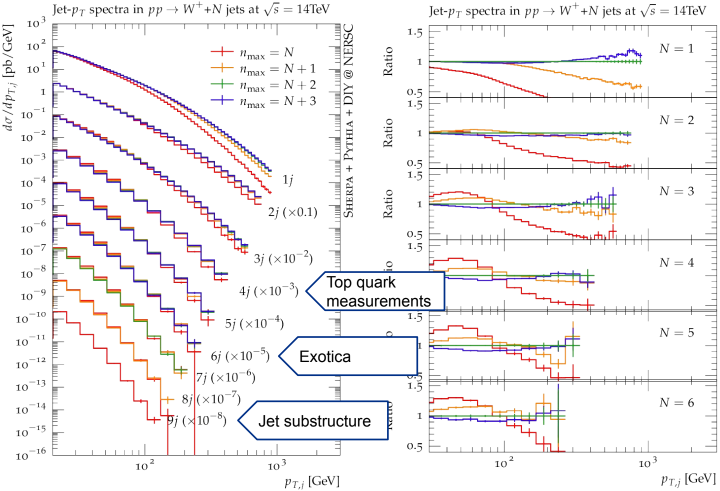
- Matching to NLO & merging
  - Negative weight fraction
  - Computing efficiency
- Matching to NNLO calculations
  - Semi-inclusive (Geneva, MINNLO$_{PS}$)
  - Fully differential (Vincia)
- Matching to N^{3}LO calculations
  - Fully differential (TOMTE)

All-order aspects

- NLL precision
- NLO splitting functions
- Kinematic edge effects
- Spin correlations in collinear & soft limit
- Sub-leading color effects
- Threshold effects
- Amplitude evolution

Why matching & merging?

[Prestel,Schulz,SH] arXiv:1905.05120

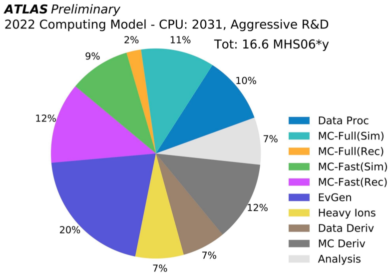


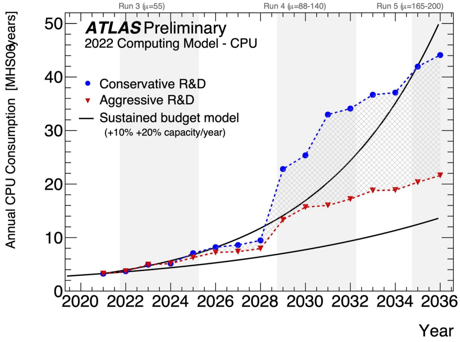
- Predictions for measured N-jet rates stabilize for $\approx N$+2 LO ME-level jets
- Poor man's version of NNLO (loops emulated by legs + unitarity constraint)

Computing efficiency: The cost of multi-jet merging

[HSF Generator WG] arXiv:2004.13687, arXiv:2109.14938

- Event generation will consume significant fraction of resources at LHC soon
- Need to scrutinize both generator usage and underlying algorithms
- Dedicated effort in HEP Software Foundation (HSF)



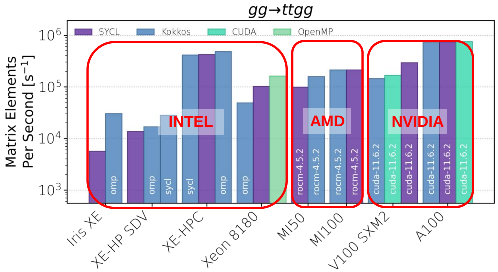


[ATLAS] CERN-LHCC-2022-005 / LHCC-G-182

Computing efficiency: MadGraph Developments

[A. Valassi et al., ACAT'22 & QCD@LHC 2022]

- New code-generator in MadGraph 5 to generate CUDA, SYCL, Kokkos output for ME computation
- Vectorized code for computations on CPUs
- Included in improved MadEvent framework



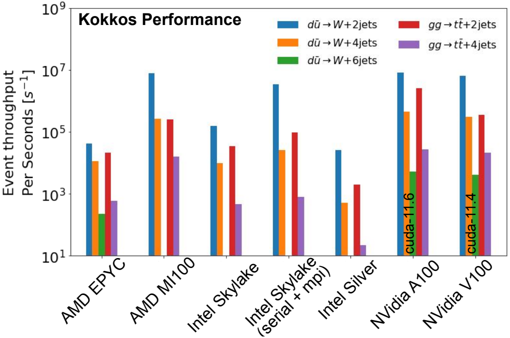
- Performances of SYCL and Kokkos comparable to direct CUDA
- New computing strategy delivers both portability and performance

		ACAT2022 madevent			standalone	
CUDA grid size		8192				16384
$gg\to t\bar{t}ggg$	MEs precision	$t_{TOT} = t_{Mad} + t_{MEs}$ [sec]	N_{events}/t_{TOT} [events/sec]	N_{events}/t_{MEs} [MEs/sec]		
Fortran	double	1228.2 = 5.0 + 1223.2	7.34E1 (=1.0)	7.37E1 (=1.0)	—	—
CUDA	double	19.6 = 7.4 + 12.1	4.61E3 (x63)	7.44E3 (x100)	9.10E3	9.51E3 (x129)
CUDA	float	11.7 = 6.2 + 5.4	7.73E3 (x105)	1.66E4 (x224)	1.68E4	2.41E4 (x326)
CUDA	mixed	16.5 = 7.0 + 9.6	5.45E3 (x74)	9.43E3 (x128)	1.10E4	1.19E4 (x161)

Computing efficiency: Sherpa Developments

[R. Wang et al., ACAT'22]

- Study of a variety of algorithms & assessment of practicality for LHC background simulations
- First use of new color basis [Melia] arXiv:1509.03297 in a generator
- Cuda for benchmarks, portability through Kokkos



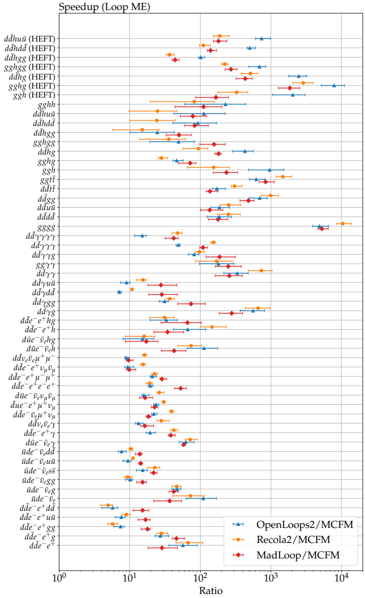
- Factor $\sim$10 speedup at low multiplicity, factor $\sim$4 at high multiplicity (fully loaded E5620 CPU (MPI) and V100 GPU)
- Currently being combined with integrator and event generation framework

Computing efficiency: Usage of analytics

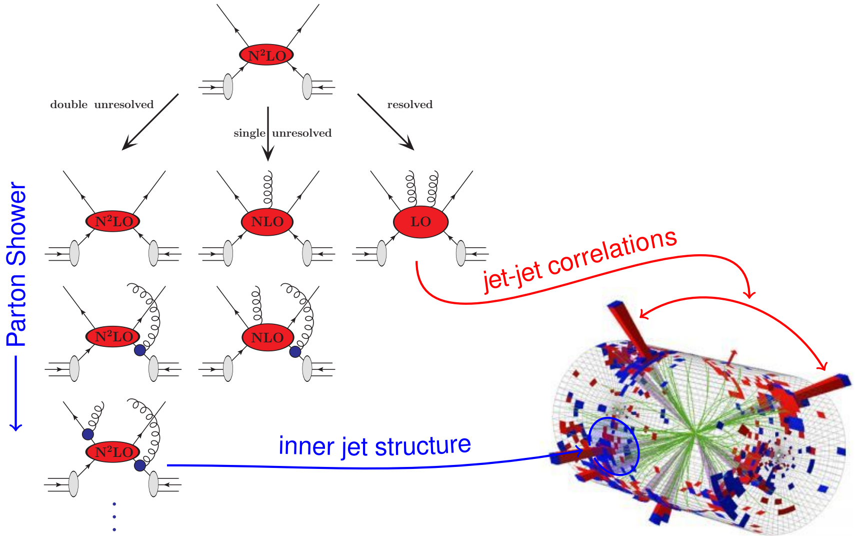
[Campbell,Preuss,SH] arXiv:2107.04472, [↗ M. Knobbe's talk]

- At HL-LHC, accuracy and precision requirements for a small number of processes drive computing demands:
  - $W^\pm/Z/\gamma$+jets
  - $t\bar{t}$+jets
  - ...
- Up to 2 jets, NLO matrix elements for $W/Z/\gamma/h$ are known *analytically*
- Significant speedup out of the box
  (analytic vs numeric 1-loop ME only)

Merged Process $n \le 2$ @ NLO $n \le 5$ @ LO	Sherpa+ OpenLoops2/MCFM	Sherpa+ MadLoop5/MCFM
$pp \to Z + nj$	$1.83^{+0.20}_{-0.12}$	$3.01^{+0.26}_{-0.18}$
$pp \to W^+ + nj$	$1.34^{+0.06}_{-0.07}$	$1.36^{+0.03}_{-0.03}$
$pp \to W^- + nj$	$1.38^{+0.06}_{-0.04}$	$1.38^{+0.07}_{-0.11}$



Fixed-order matching: Basic idea



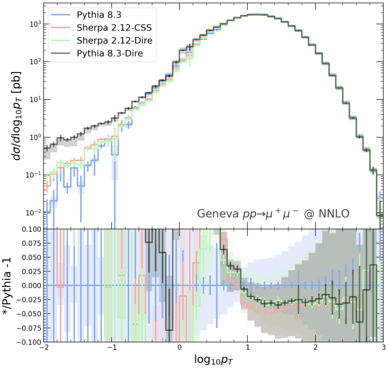
Fixed-order matching: Geneva

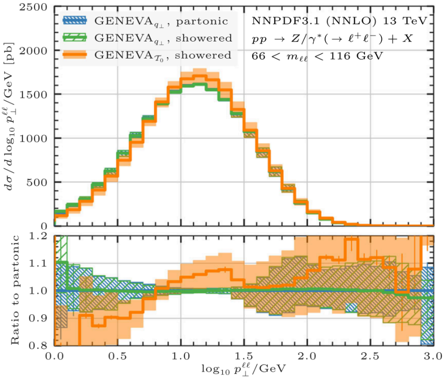
[D. Napoletano's talk at HP[2]]

- Use known resummation in jettiness / q_T & match to NNLO

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi\,\mathrm{d}r} = \frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi\,\mathrm{d}r} - \frac{\mathrm{d}\sigma^{\mathrm{res.exp.}}}{\mathrm{d}\Phi\,\mathrm{d}r} + \frac{\mathrm{d}\sigma^{\mathrm{FO}}}{\mathrm{d}\Phi\,\mathrm{d}r}$$

- Match to shower by vetoing events with $r_N(\Phi_{N+M}) > r_N$



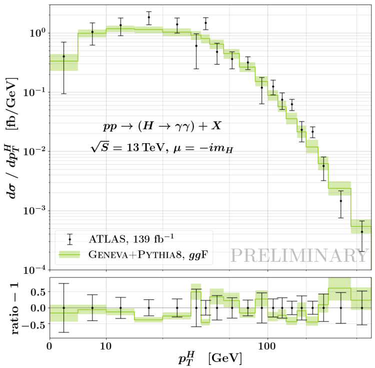


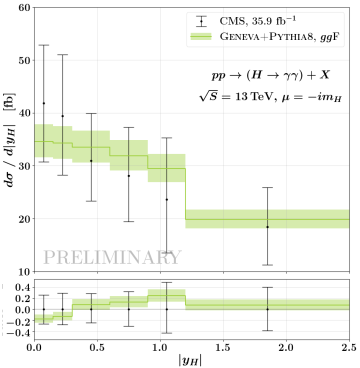
- Parton shower scheme uncertainty
- Choice of resolution variable

Fixed-order matching: Geneva

[G. Marinelli's talk at HP^2]

- Comparison against experimental data



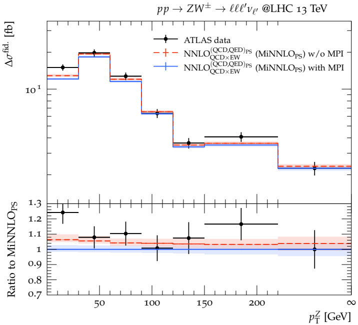


- $p_{T,H}$ and ATLAS data
- y_H and CMS data

Fixed-order matching: MINNLO$_{PS}$

[Lindert,Lombardi,Wiesemann,Zanderighi,Zanoli] arXiv:2208.12660

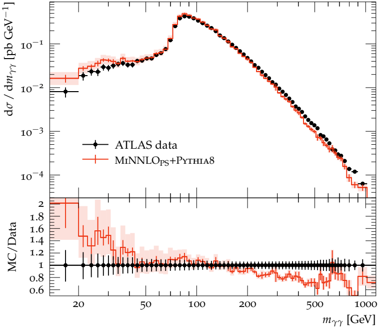
- WZ production at NNLO QCD $\times$ NLO EW
- Various schemes to combine QCD & EW corrections
  $\rightarrow$ associated uncertainty estimates

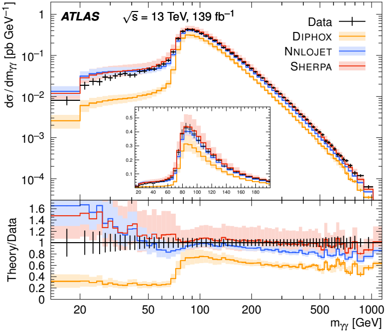


Fixed-order matching: MINNLO$_{PS}$

[Gavardi,Oleari,Re] arXiv:2204.12602

- Di-photon production at the LHC
- QED singular contributions in real-emission corrections treated as fixed order → split off by damping function



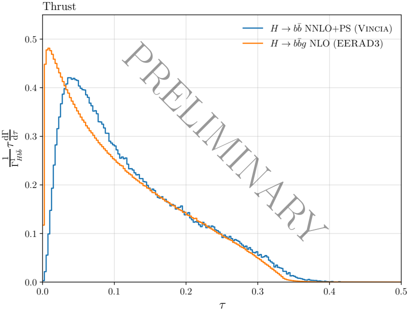


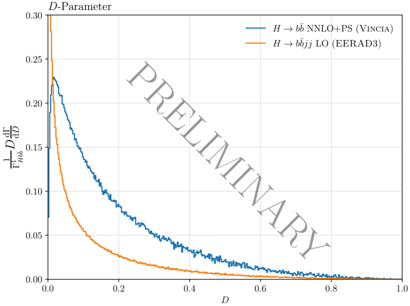
- Comparison between ATLAS data and MINNLO$_{PS}$
- Previous experimental analysis
  [ATLAS] arXiv:2107.09330

Fixed-order matching: Vincia

[C. Preuss' talk at HP^2]
[Campbell,Li,Preuss,Skands,SH] arXiv:2108.07133

- Fully differential matching technique akin to POWHEG
- Technical implementation based on sector antenna framework
- Configurations absent in antenna-shower approximation simulated using direct $2 \to 4$ branchings

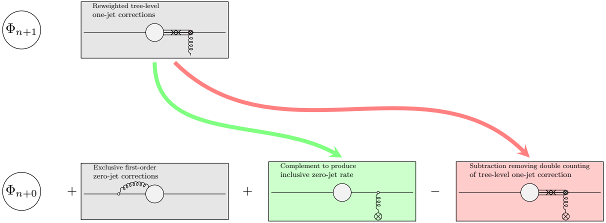




Fixed-order matching: N^3LO

[Lönnblad,Prestel] arXiv:1211.4827, [Plätzer] arXiv:1211.5467

U(N)LOPS

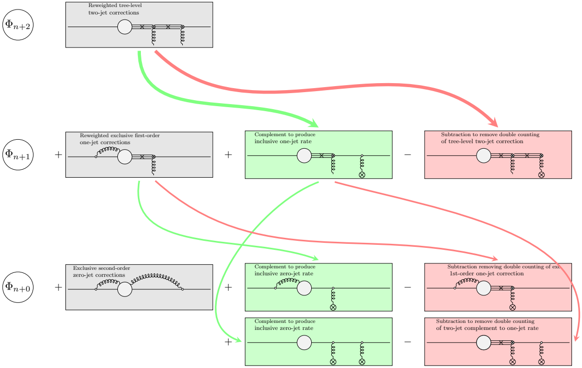


- Compute vetoed cross section & complete with real-emission
- Add Sudakov vetoed real-emission cross section & projection
- Can be implemented based on only two inputs (gray boxes)

Fixed-order matching: N^{3}LO

[Lönnblad,Prestel] arXiv:1211.4827, [Li,Prestel,SH] arXiv:1405.3607

UN^{2}LOPS

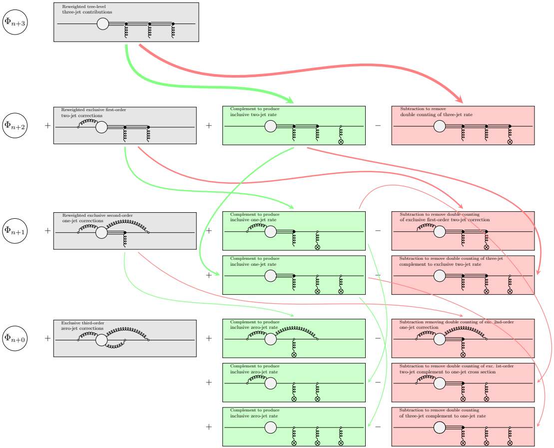


- Same idea as in ULOPS, but now also adding 2-loop contribution

Fixed-order matching: N^{3}LO

[Prestel] arXiv:2106.03206, [Bertone,Prestel] arXiv:2202.01082

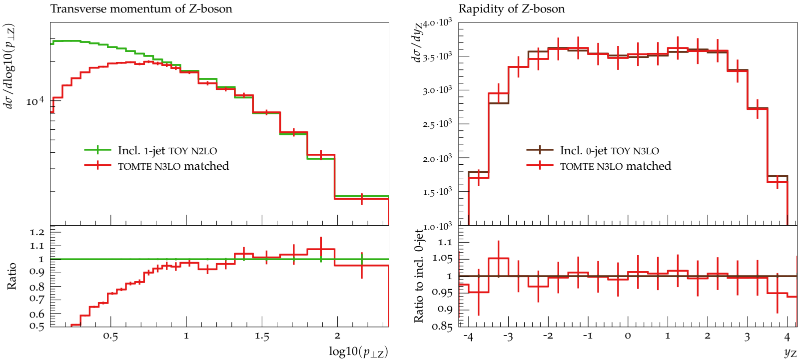
TOMTE



- Same idea as in UN^{2}LOPS, but now also adding 3-loop contribution
- Must pay careful attention to projections (relevant for all UN^{X}LOPS)

Fixed-order matching: N^{3}LO

[Bertone,Prestel] arXiv:2202.01082



- Drell-Yan lepton pair production at LHC
- Stand-in fixed-order calculation for closure tests

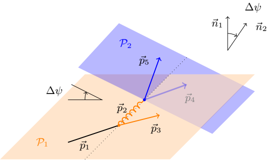
All-order aspects: Parton showers at NLL precision

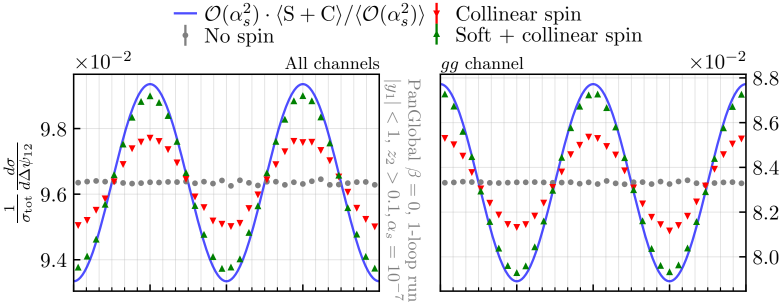
- How to quantify logarithmic precision of parton showers?
  [Dasgupta,Dreyer,Hamilton,Monni,Salam] arXiv:1805.09327
- Angular ordered parton showers provably NLL accurate for global observables, but wrong recoil may invalidate this
  [Bewick,Ferrario Ravasio,Richardson,Seymour] arXiv:1904.11866
- Two problems in commonly used dipole showers [↗ talk by S. Ferrario-Ravasio]
  - Correlations across multiple emissions due to recoil strategy
  - Color charge of initial quarks not reflected in soft, wide angle region
- Kinematics problem can be solved by
  - Partitioning of antenna radiation pattern, combined with local or semi-global recoil scheme [Dasgupta,Dreyer,Hamilton,Monni,Salam,Soyez] arXiv:2002.11114
    [vanBeekveld,Ferrario Ravasio,Hamilton,Salam,Soto-Ontoso,Soyez] arXiv:2205.02237, arXiv:2207.09467
  - Additive matching of soft to collinear radiator, combined with global recoil scheme [Forshaw,Holguin,Plätzer] arXiv:2003.06400
  - Multiplicative matching of soft to collinear radiator, combined with semi-global recoil scheme [Nagy,Soper] arXiv:2011.04773
  - Multiplicative matching of soft to collinear radiator, combined with global recoil scheme [Herren,Krauss,Reichelt,Schönherr,SH] arXiv:2208.06057

All-order aspects: Spin correlations

[Hamilton,Karlberg,Salam,Scyboz,Verheyen] arXiv:2111.01161

- Azimuthal dependence of radiation pattern due to spinning gluons should be implemented
- Linear time algorithm known & used in Herwig
  [Collins] NPB304(1988)794, [Knowles] NPB310(1988)571
- New: Matching to dipole radiation pattern



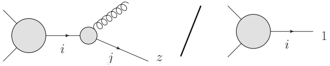


Higher-order corrections: Collinear evolution at NLO

- Higher-order DGLAP evolution kernels obtained from factorization

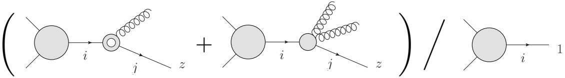
$$D_{ji}^{(0)}(z,\mu) = \delta_{ij}\delta(1-z) \qquad \leftrightarrow$$

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



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

$\leftrightarrow$



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

Higher-order corrections: Collinear evolution at NLO

[Prestel,SH] arXiv:1705.00742

- Example: Flavor-changing NLO splitting functions

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

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

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

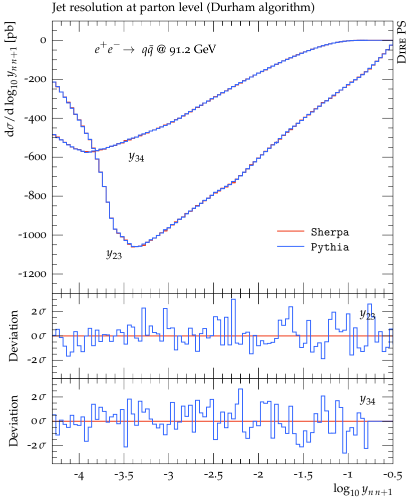
$$\mathrm{C}_{qq'}(z) = \int_z \frac{\mathrm{d}x}{x}\left(P^{(0)}_{qg}(x) + \varepsilon\mathcal{J}^{(1)}_{qg}(x)\right)\frac{1}{\varepsilon}P^{(0)}_{gq}(z/x)$$

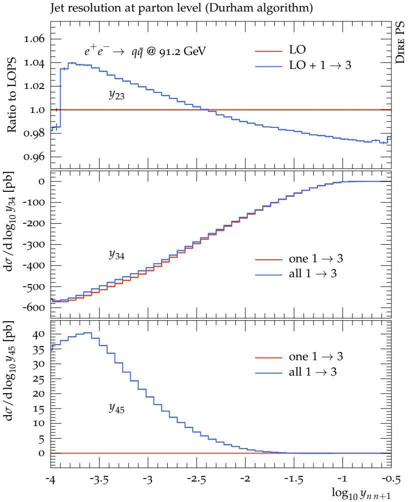
$$\mathcal{J}^{(1)}_{qg}(z) = 2C_F\left(\frac{1+(1-x)^2}{x}\ln(x(1-x)) + x\right)$$

- Analytical computation of I not needed, as $\mathrm{I} + \mathcal{P}/\varepsilon$ 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

Higher-order corrections: Collinear evolution at NLO

[Gellersen,Prestel,SH] arXiv:2110.05964



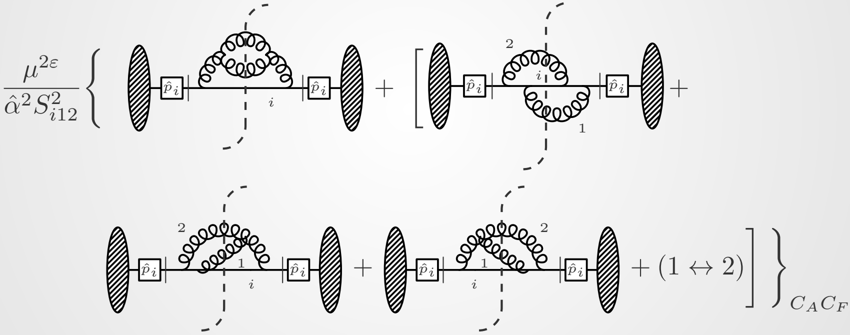


- Effects on jet rates in e^+e^- →hadrons at LEP

Higher-order corrections: Multi-Emission Kernels

[Löschner,Plätzer] arXiv:2112.14454

- Program to define higher-order splitting functions for parton showers
- Sudakov-like momentum decomposition $\rightarrow$ power counting
- Reproduces known soft & double-/triple-collinear splitting functions



$$= \left(\frac{8\pi\alpha_S}{\hat{\alpha} S_{i12}}\mu^{\varepsilon}\right)^2 C_A C_F \, \langle \hat{P}^{\text{(non-Ab)}}_{ggq} \rangle_{\hat{\not{p}}_i} + \mathcal{O}\left(\beta_{il}^{-3/2}\right).$$

Looking beyond logarithmic accuracy

- Provably NLL accurate parton showers solve long-standing problem
  NNLL seems on the horizon, but is it the obvious target?
- Revisit well-established result: Thrust or $FC_{1-\beta}$ in $e^+e^- \to$hadrons

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

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

- Approximate to NLL accuracy

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

Origin of the $\alpha_s \to 0$ / $s \to \infty$ limit

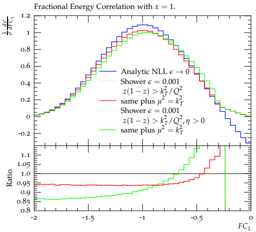
- Cumulative cross section $\Sigma(\tau) = e^{-R(\tau)}\mathcal{F}(\tau)$ obtained from all-orders resummed result by Taylor expansion of virtual corrections in cutoff ε

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

  - $\mathcal{F}(\tau)$ 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
- Breaks momentum conservation and unitarity for finite τ
  $\to$ Clean NLL result, but unknown kinematic corrections
- How large are effects in regions of a typical measurement?

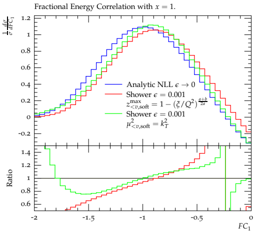
Numerical effects away from the limit

[Reichelt,Siegert,SH] arXiv:1711.03497



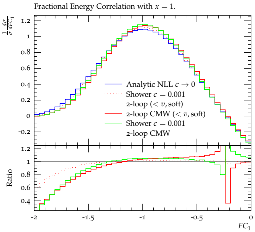
Single emission effects

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



Multiple emission effects

- z bounds by unitarity
- k_T scale by unitarity



Effects of scale choice

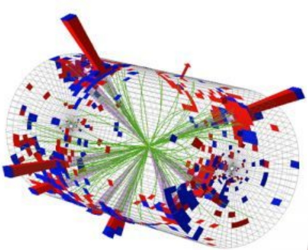
- 2-loop CMW in all soft terms
- 2-loop CMW overall

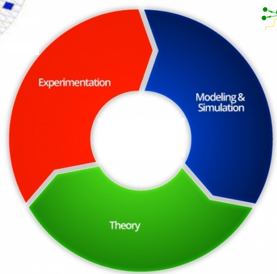
- Simplest process and simplest type of observable, still sizable differences away from $\tau \to 0$ limit
- How do we quantify the precision of event generators in the intermediate region ("between" NLL and NLO) ?

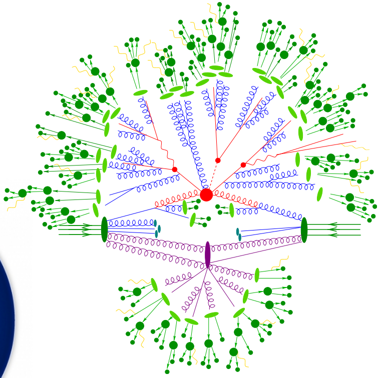
Summary and Outlook

- Lots of activity in event generator development ...
  - Logarithmic precision of parton showers [PanScales,Herwig,Sherpa,...]
  - Higher-order QCD evolution kernels [Vincia,Sherpa,Herwig,...]
  - Interplay of parton showers w/ NNLL [PanScales,Sherpa,...]
  - Improved & alternative hadronization models [↗ talk by T. Menzo]
- ... and matching to fixed-order calculations
  - Novel computing techniques [MadGraph5,Sherpa]
  - Resummation based NNLO matching [Geneva,MINNLO$_{PS}$]
  - Fully differential (N)NNLO matching [Vincia,UN^{X}LOPS,TOMTE]
- Still, many improvements needed [Campbell et al.] arXiv:2203.11110
  - Systematic treatment of kinematic edge effects
  - Massive quark production & evolution
  - Other exciting areas: νs, HI, EIC, ...
  - ...

Exciting times ahead!







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