News on Monte Carlo Generators

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at the
XXVII Workshop on DIS and Related Subjects
Torino | 8 April 2019

(Apologies for any bias or omission – only a selection of things)

QCD Description of Collider Events

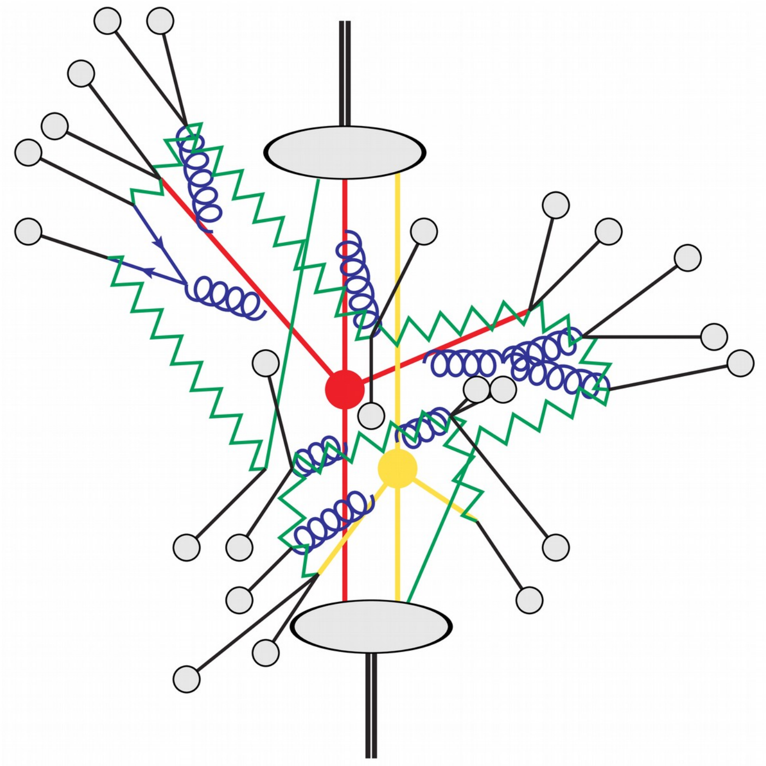
Indispensable input

for experiments & phenomenology.

Realistic, fully detailed description

spanning orders of magnitude in relevant energy scales.

Factorization dictates work flow.



Hard partonic scattering

Jet evolution

Multiple interactions

Hadronization

$$\mathrm{d}\sigma \sim \mathrm{d}\sigma_{\mathrm{hard}}(Q) \times \mathrm{PS}(Q \to \mu) \times \mathrm{Had}(\mu \to \Lambda) \times \ldots$$

The Big Workhorses

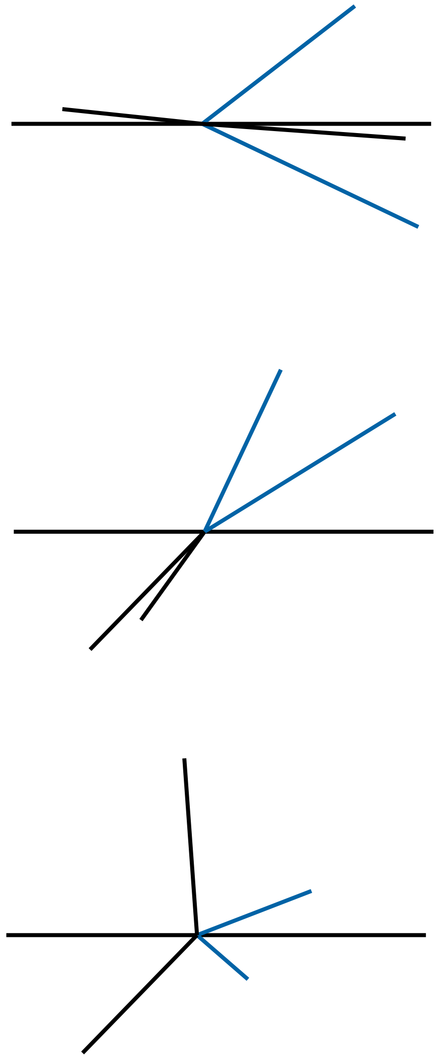
Multi-purpose generators covering all aspects of ee, ep and pp collisions

Herwig
Traditional focus on showers, Qtilde and Dipoles shower, cluster hadronization model, NLO matching and merging.

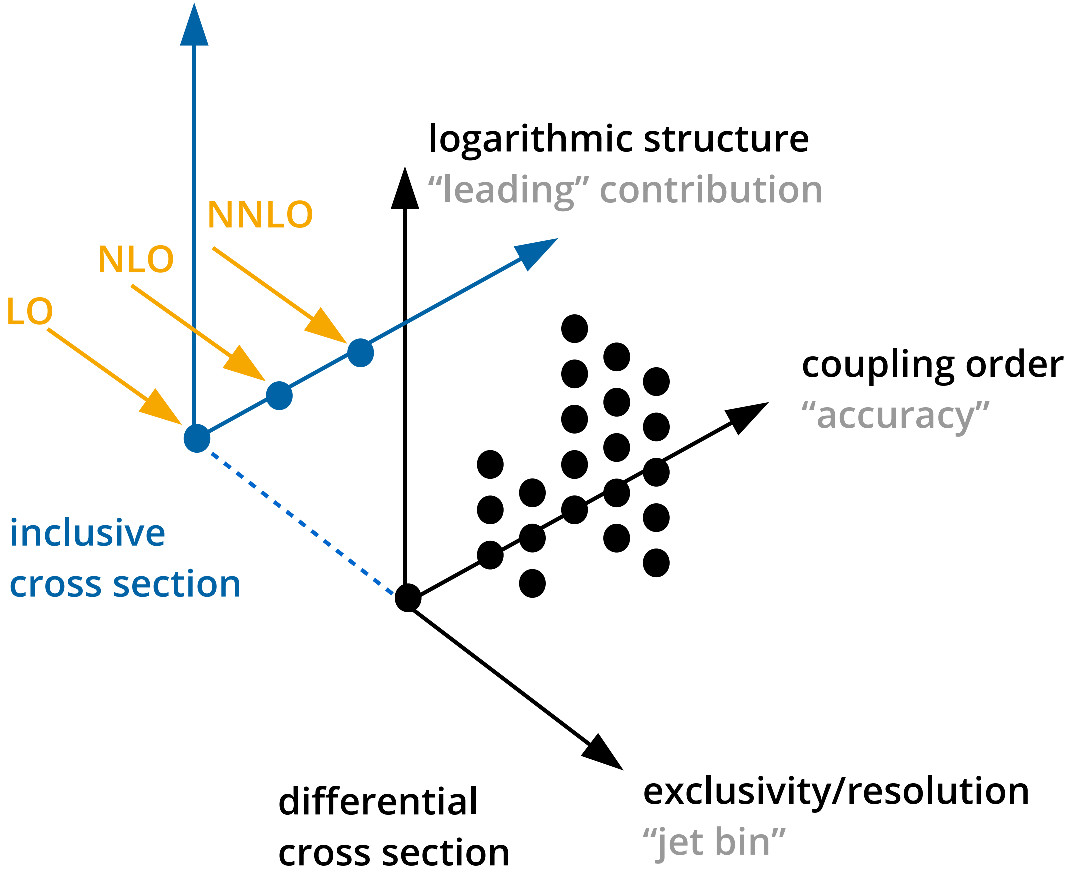
Pythia
Sophisticated soft physics, pt-ordered, DIRE and Vincia shower, string hadronization, NLO merging using event files.

Sherpa
Focus on perturbative improvements, CS and DIRE shower, cluster or string hadronization, NLO matching and merging.

Perturbative input



$$\sigma_n \sim \sum_k \sum_{l \leq 2k} \alpha_s^k C_{n,k,l} \ln^{2k-l}(\tau)$$



logarithmic structure
"leading" contribution

NNLO

NLO

LO

coupling order
"accuracy"

inclusive
cross section

differential
cross section

exclusivity/resolution
"jet bin"

Resummation and Parton Showers

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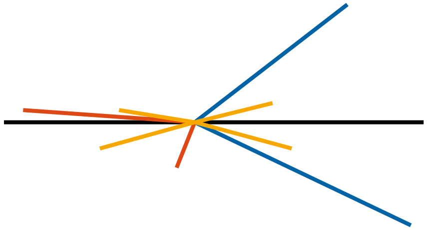

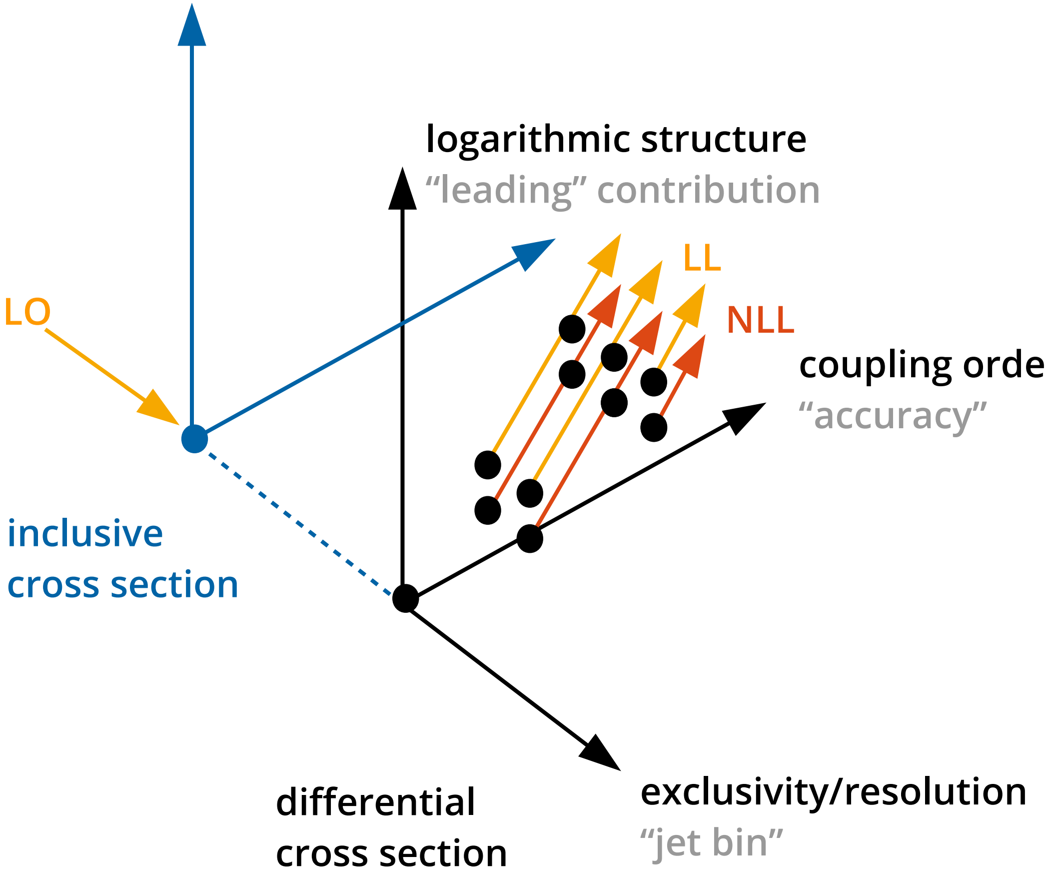

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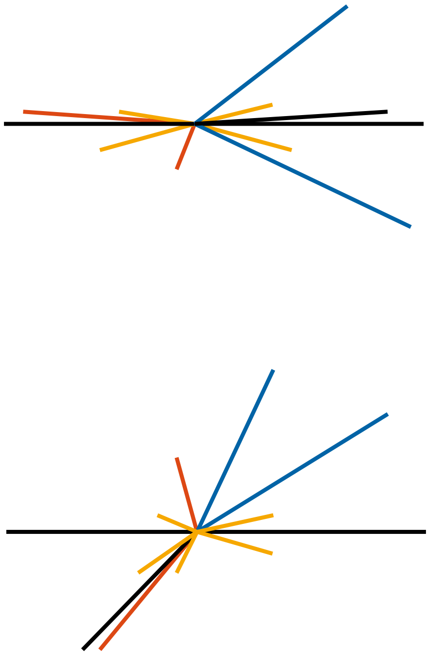

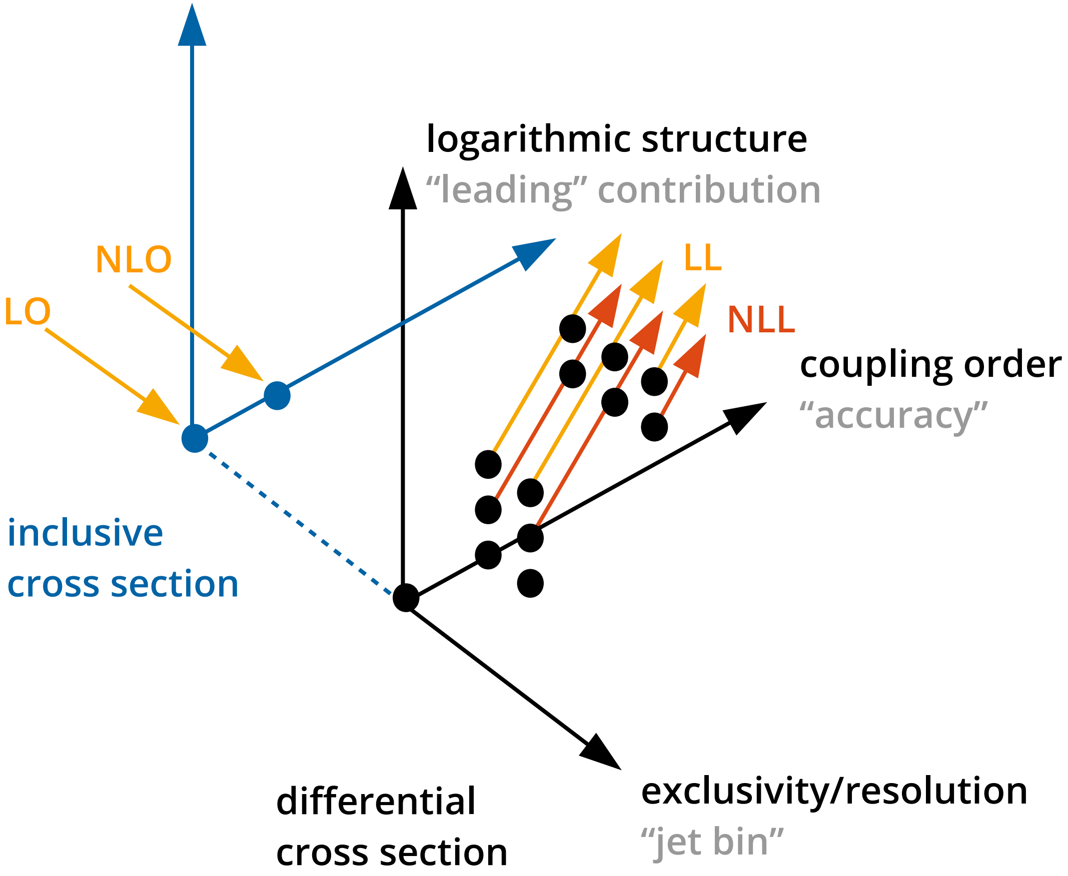

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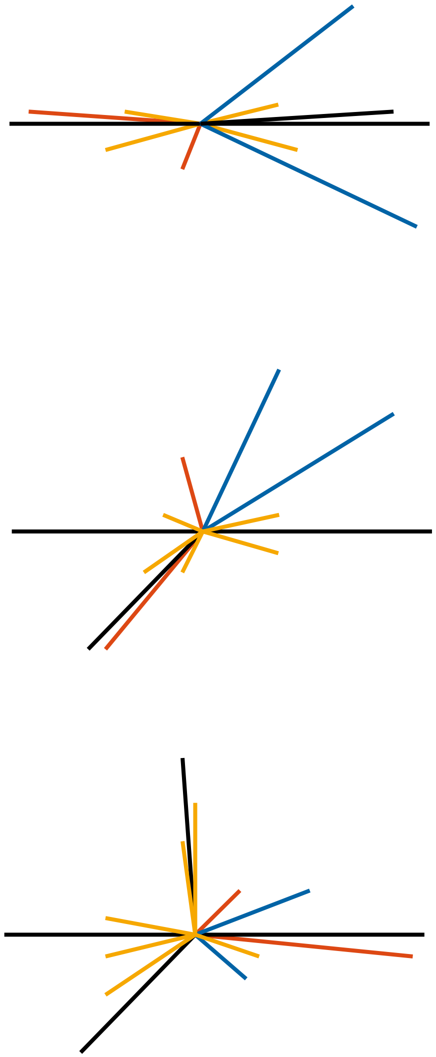

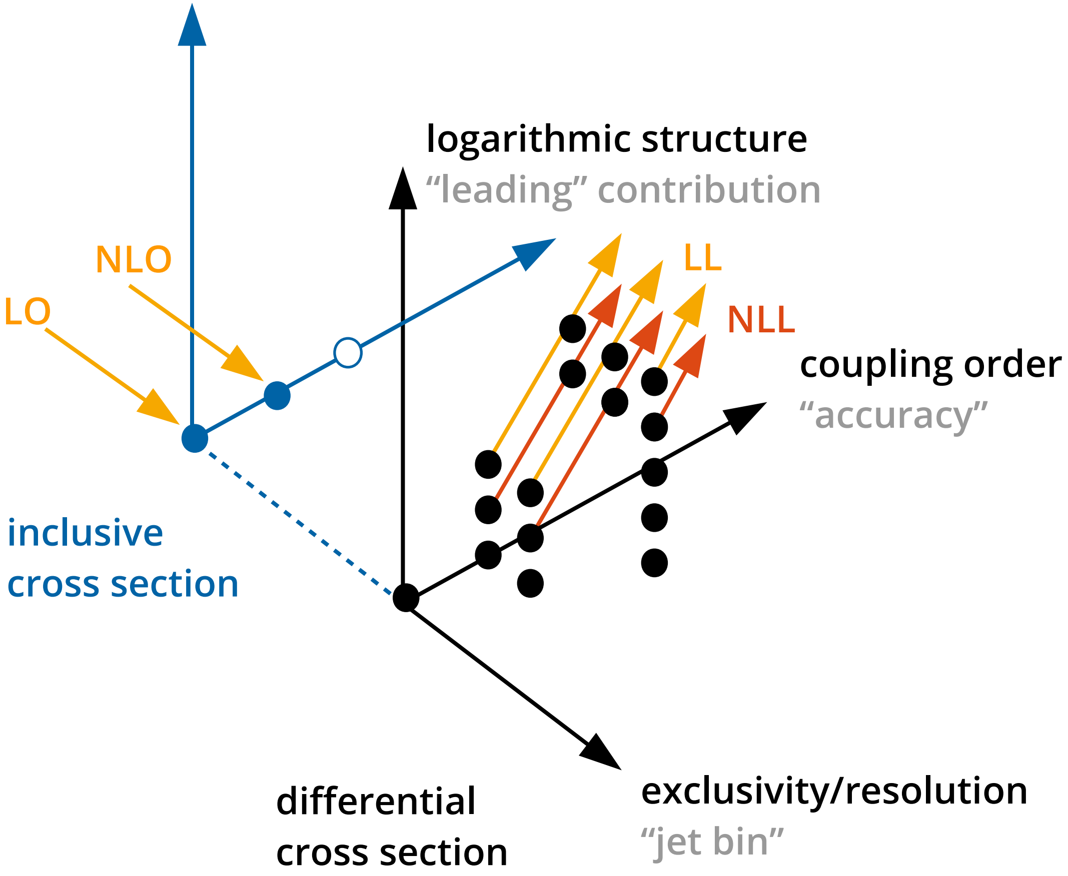

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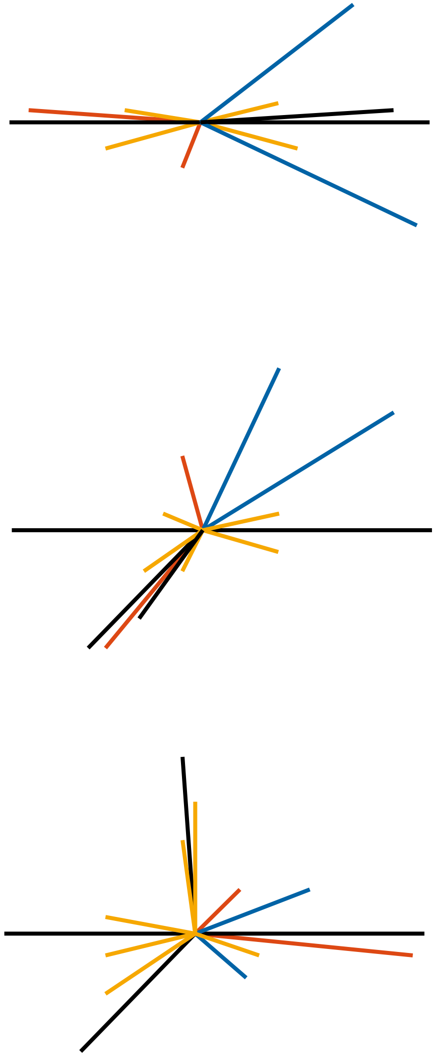

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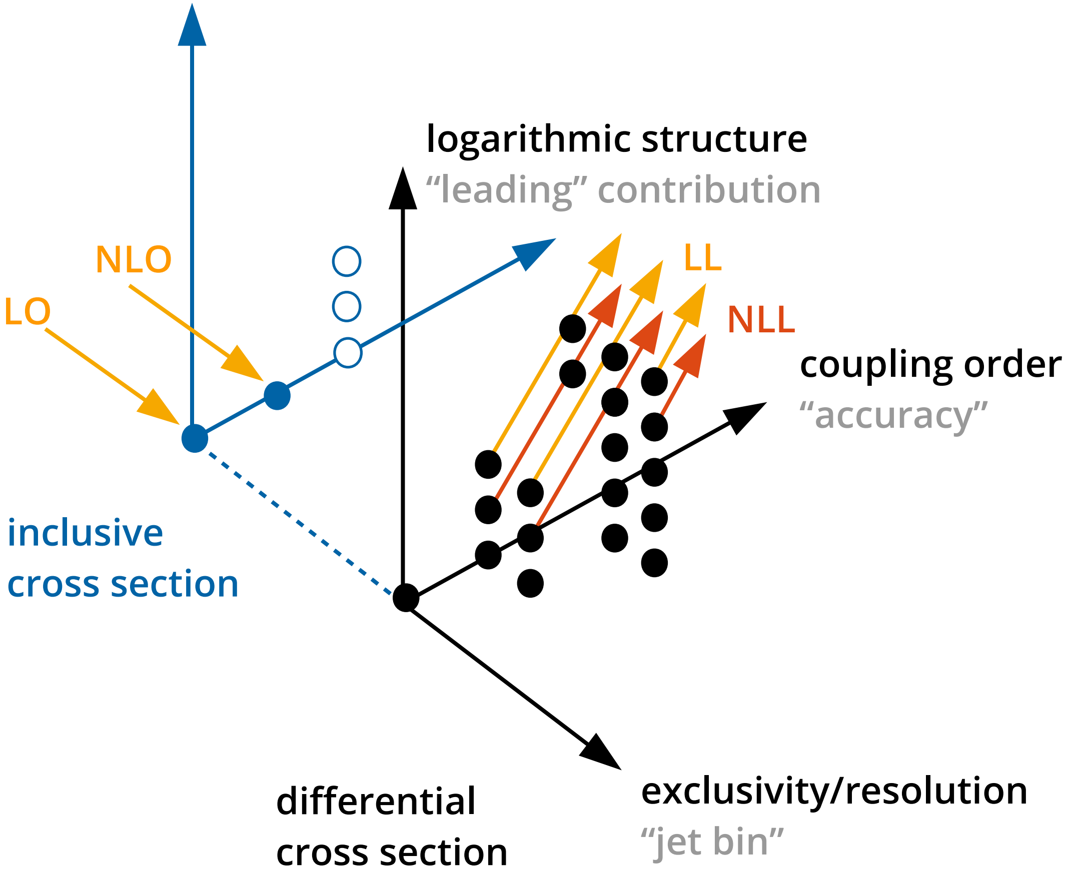

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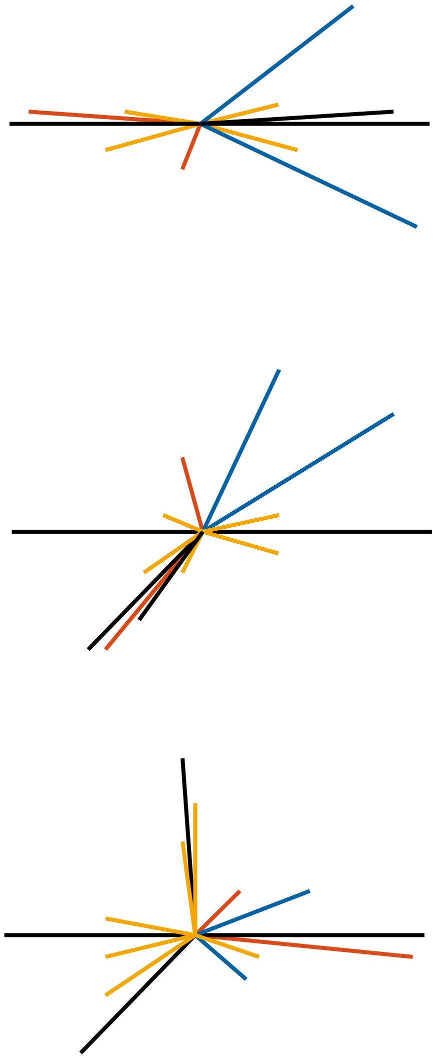

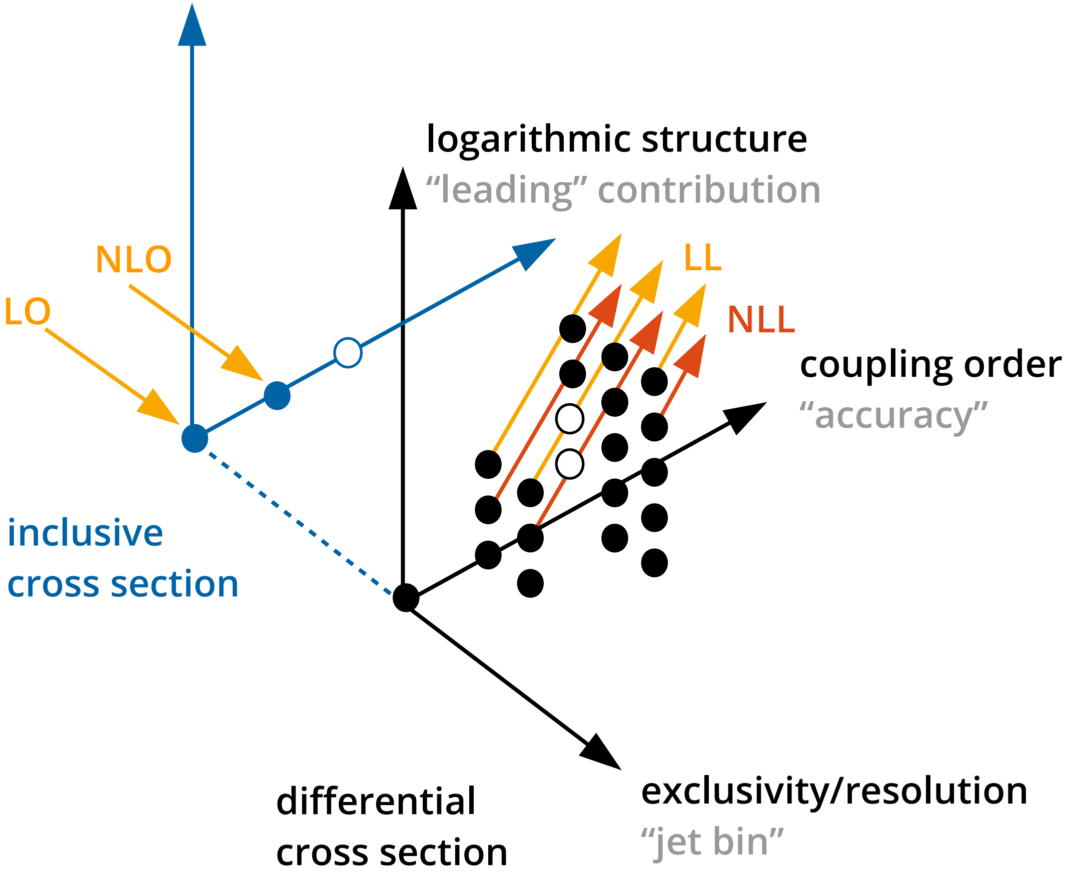

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Unitarized Merging and Combination with NNLO

Cutting edge: Merge jet cross sections and shower at NLO for different multiplicities.

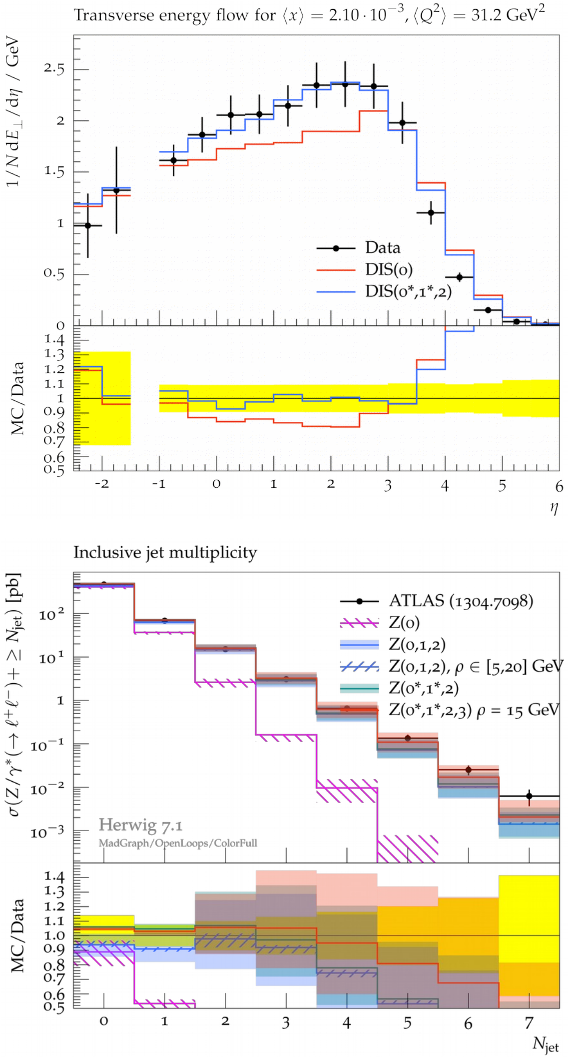
- Unitarized merging techniques: approximate higher order corrections through constraining inclusive cross sections.

[Plätzer – '12]
[Lönnblad, Prestel – '12]

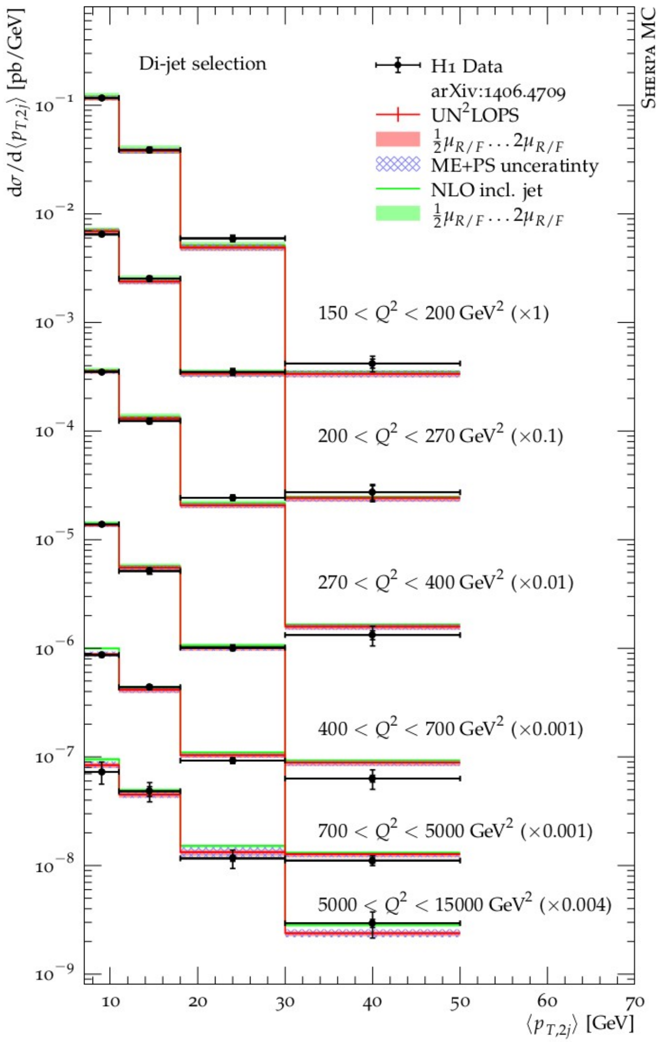
- Crucial to address when going from LO to NLO merging

- Use to combine with NNLO, in presence of merging scale.

[Höche, Li, Prestel – '15]



[Bellm, Gieseke, Plätzer – '17]



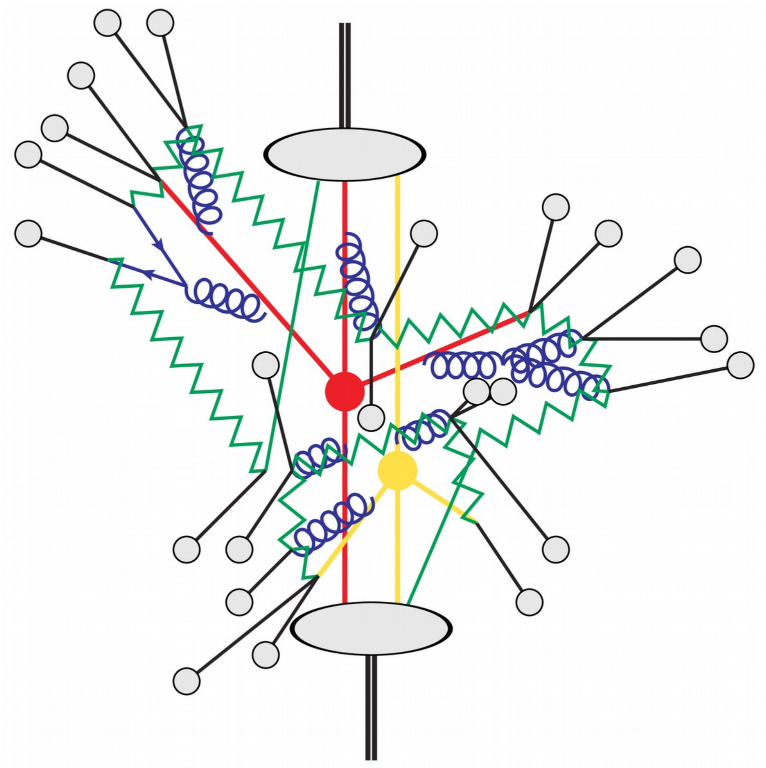
[Höche, Kuttimalai, Li – '18]

Parton Showers

Central component of all event generators, luckily now receive much more attention than the previous activity on improving the description of the hard process.

Precision collider phenomenology demands reliable simulations with the highest level of theoretical control.

This we mostly only have for the fixed order input.



$$\mathrm{d}\sigma \sim \mathrm{d}\sigma_{\mathrm{hard}}(Q) \times \mathrm{PS}(Q \to \mu) \times \mathrm{Had}(\mu \to \Lambda) \times \ldots$$

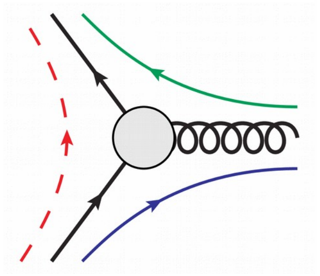
Improving Existing Showers

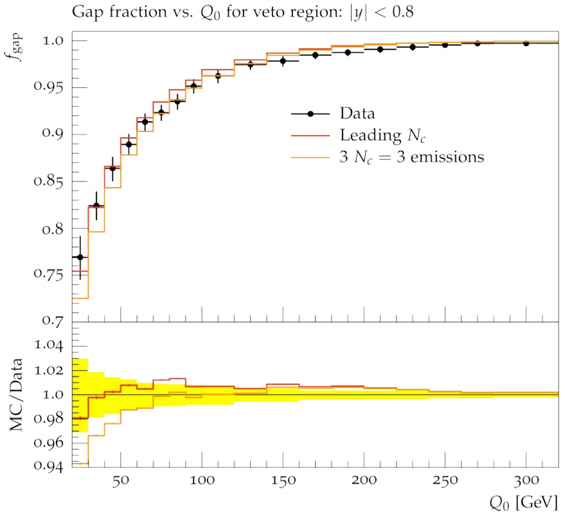
Some recent development in improving existing shower algorithms

- Colour correlations to correct the radiation pattern

$$V_{ij,k} \to -\frac{\langle \mathcal{M}|\mathbf{T}_{ij}\cdot\mathbf{T}_k|\mathcal{M}\rangle}{\mathbf{T}_{ij}^2|\mathcal{M}|^2} V_{ij,k}$$

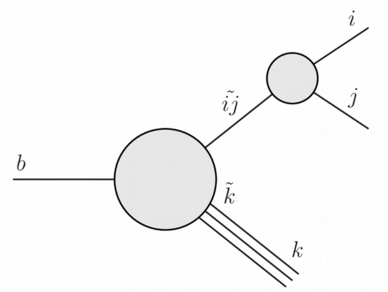
[Plätzer, Sjödahl, Thoren – '18]
[Prestel, Isaacson – '18]





- Colour in successive soft emissions

[Bellm – '18]

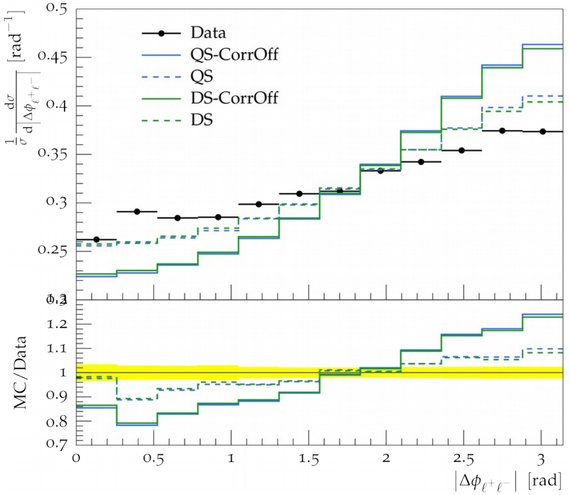


- Mass effects, matching in decays

[Cormier, Plätzer, Reuschle, Richardson, Webster – '18]

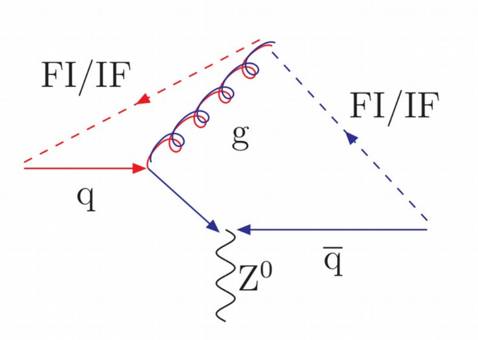
- Spin correlations in shower evolution

[Webster, Richardson – '18]
[Fischer, Lifson, Skands – '17]



- Recoil in different colour flows

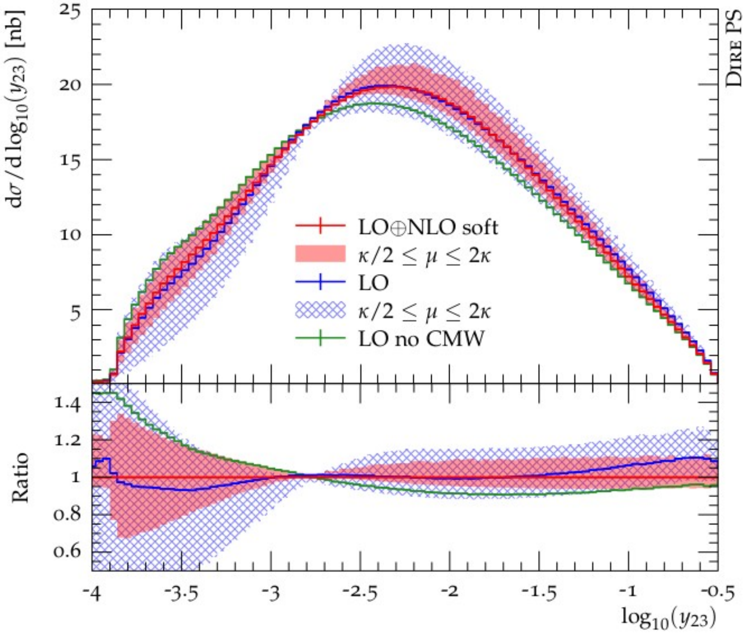
[Cabaout, Sjöstrand – '17]



Open Ends

Inclusion of 1 → 3 splittings:
Testing out first ingredients for a full evolution at the next order.

[Dulat, Prestel, Höche – ‘18]



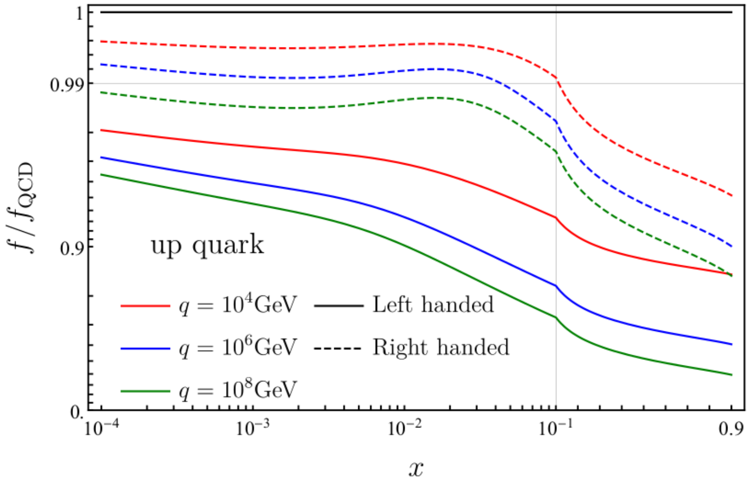
Combination in between different soft/collinear limits does not yet seem to be in reach.

Inclusion of electroweak effects. At high energies: double logarithmis.

$$\alpha \ln^2 \frac{M_W^2}{p_\perp^2}$$

PDFs at highest energies available, full shower picture yet missing.

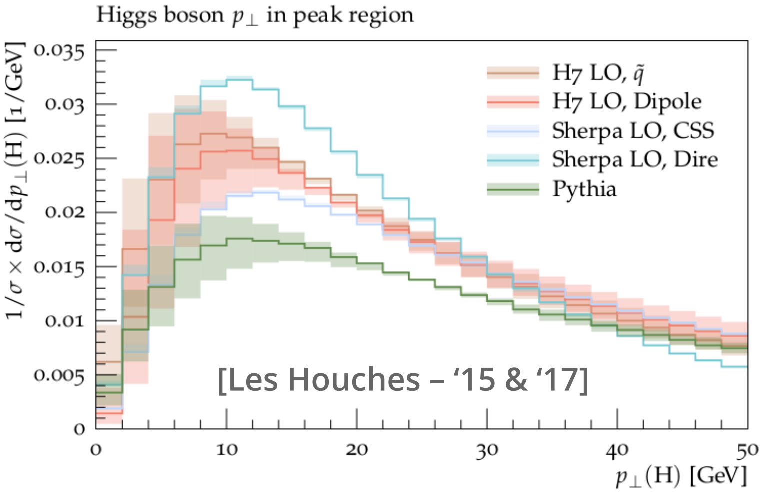
[Bauer, Ferland, Webber – ‘17]



Understanding Existing Showers

(Scale) variations in showers only provide an indication of their intrinsic accuracy: Need to investigate interplay of all ingredients to make decisive statements.

[NB Variations now mostly available with on-the-fly weights.]



[Les Houches – '15 & '17]

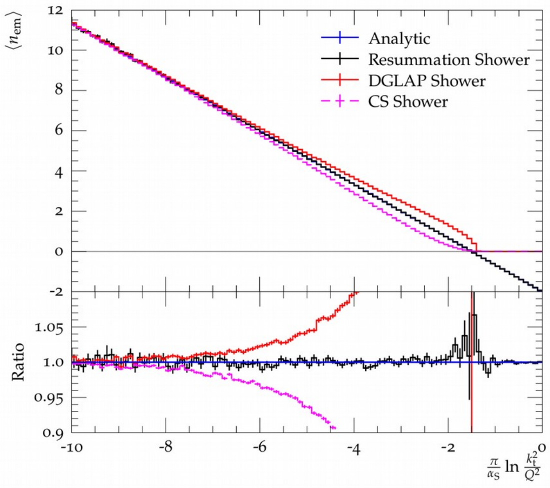
Analytic & numeric studies are vital to determine the accuracy per observable.

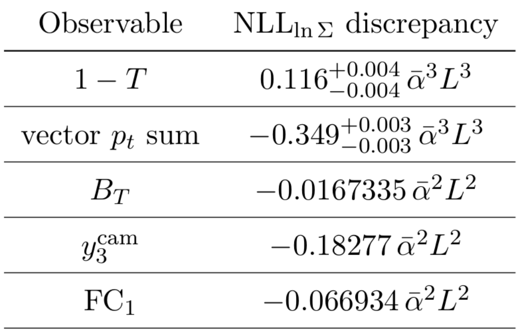
- Compare analytic results and (dedicated) shower implementations

  [Höche, Reichelt, Siegert – '17]

- Dedicated calculation of fixed order expansions, where analytic all-order solution not feasible

  [Dasgupta, Dreyer, Hamilton, Monni, Salam – '18]





Observable	$\mathrm{NLL}_{\ln\Sigma}$ discrepancy
$1-T$	$0.116^{+0.004}_{-0.004}\,\bar{\alpha}^3 L^3$
vector p_t sum	$-0.349^{+0.003}_{-0.003}\,\bar{\alpha}^3 L^3$
B_T	$-0.0167335\,\bar{\alpha}^2 L^2$
$y_3^{\rm cam}$	$-0.18277\,\bar{\alpha}^2 L^2$
FC_1	$-0.066934\,\bar{\alpha}^2 L^2$

Understanding Existing Showers

[Hoang, Plätzer, Samitz – ‘18]

Analytic insight important also in interpreting underlying parameters:
E.g. calculate massive event shapes predicted by Herwig/coherent branching.

Shift in peak position from cutoff change

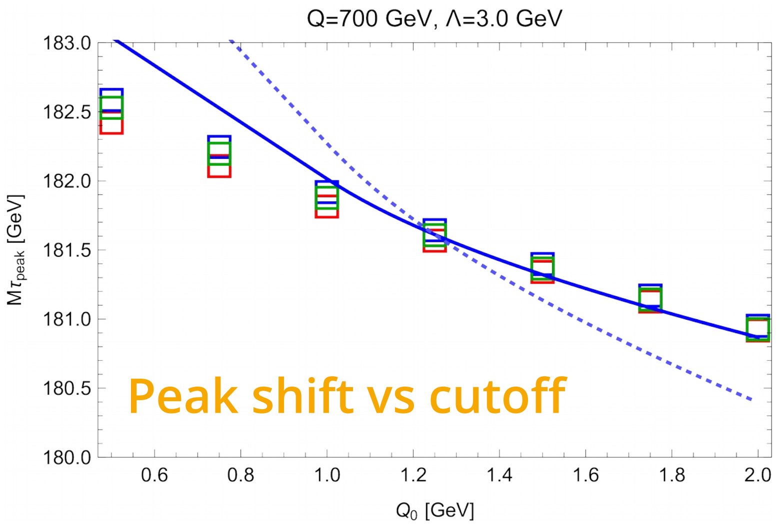
$$\tau_{\text{peak}}(Q_0) = \tau_{\text{peak}}(Q_0') - \frac{1}{Q}\left(16C_F - 8\pi C_F\frac{m}{Q}\right)\int_{Q_0'}^{Q_0} \mathrm{d}R\,\frac{\alpha_s(R)}{4\pi}$$

large-angle soft

ultra-collinear

Allows to interpret top mass parameter in comparison to effective field theory, which analytically agrees with Herwig result.

$$m_t^{\text{CB}}(Q_0) = m_t^{\text{pole}} - \frac{2}{3}Q_0\;\alpha_s(Q_0) + \mathcal{O}(\alpha_s^2)$$



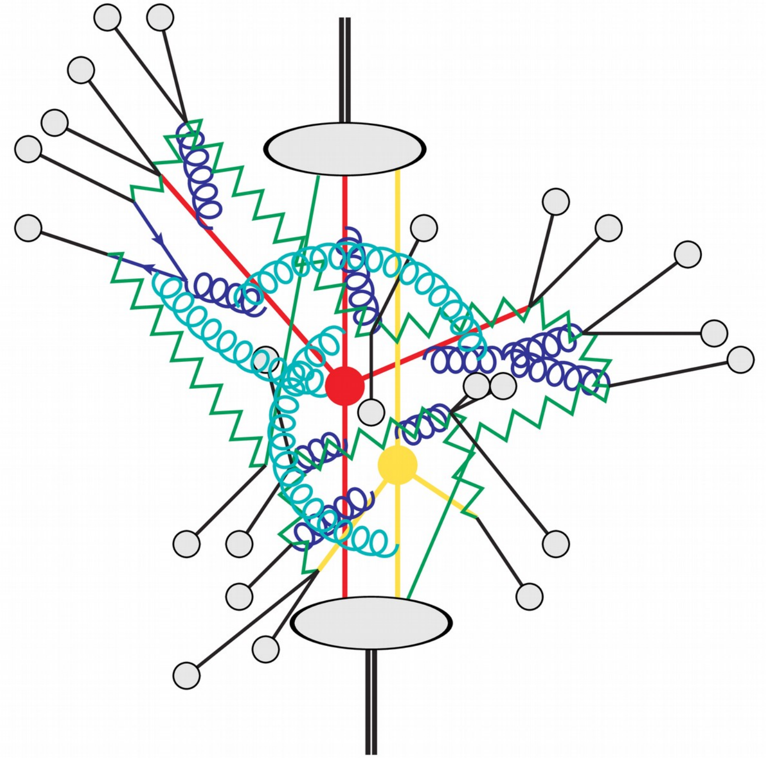
Peak shift vs cutoff

The Bottlenecks Remain

Parton shower algorithms
Lack a systematic expansion, obstruct systematic matching for the hard process.

Hadronization models
Lack constraints from perturbative evolution: Hiding perturbative effects?

Rethink foundations of parton showers:
Systematic picture including virtual corrections and quantum mechanical interference.

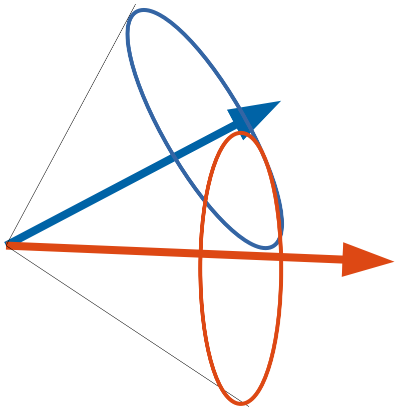


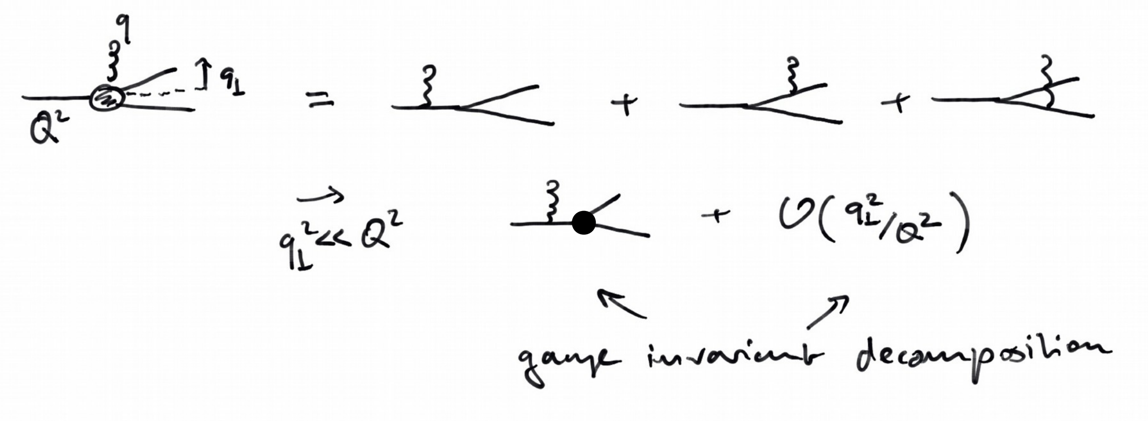
$$\mathrm{d}\sigma \sim \mathrm{d}\sigma_{\mathrm{hard}}(Q) \times \mathrm{PS}(Q \to \mu) \times \mathrm{Had}(\mu \to \Lambda) \times \ldots$$

Resummation and Parton Showers

Coherent branching algorithms essential to direct QCD resummation of global event shapes, and to designing parton shower algorithms.

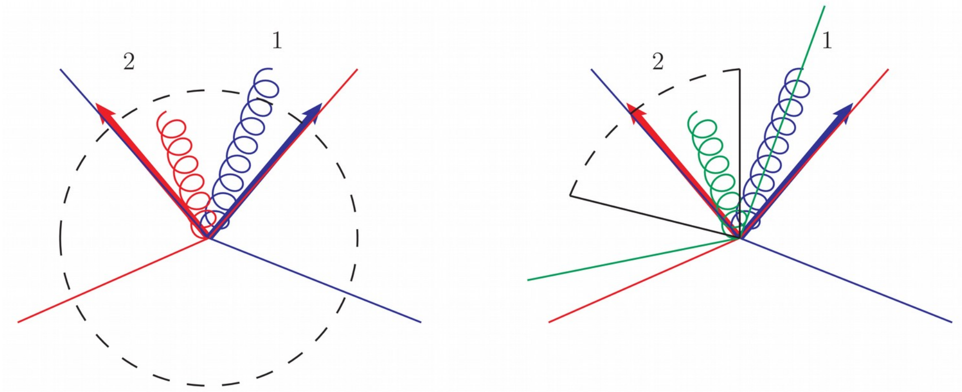
[Catani, Marchesini, Webber]
[Gieseke, Stephens, Webber]





Large-angle soft effects included on average by a clever choice of ordering variable.

Non-global logarithms require dipole-type soft gluon evolution to take into account change in colour structure after each emission.



Systematic inclusion of collinear effects needs to be addressed.

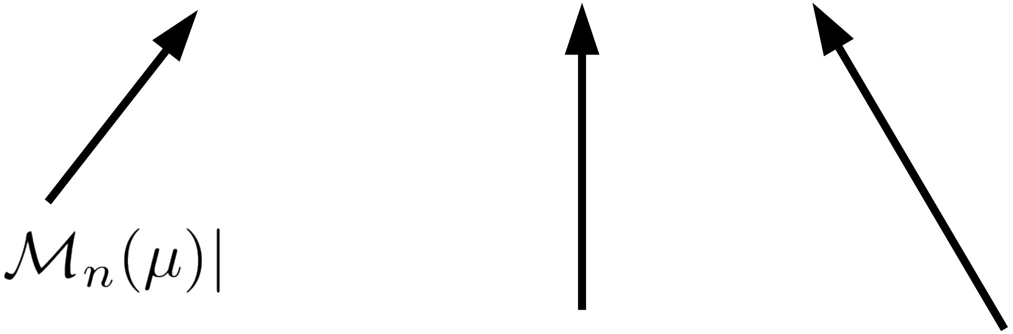
[Dasgupta, Salam] [Banfi, Marchesini, Smye]
[Angeles, DeAngelis, Forshaw, Plätzer, Seymour]

A New Point of View

[Angeles, De Angelis, Forshaw, Plätzer, Seymour – ‘18] [Nagy, Soper – ‘17 - ‘18]
[De Angelis, Forshaw, Holguin, Plätzer,.. – in progress]

Unified framework requires evolution at the amplitude level as most general basis:

$$\sigma = \sum_n \int \mathrm{Tr}\left[\mathbf{A}_n(\mu)\right] u(p_1, \ldots, p_n)\, \mathrm{d}\phi_n$$



$$\mathbf{A}_n(\mu) = |\mathcal{M}_n(\mu)\rangle\langle\mathcal{M}_n(\mu)|$$

Evolved `density operator`

Observable

Phase space

General expression of (partonic) cross section including all multiplicities and virtual corrections and colour mixing in all orders perturbation theory.

$$|\mathcal{M}_n(\mu)\rangle = \mathbf{Z}^{-1}(\mu, \epsilon)|\tilde{\mathcal{M}}_n(\epsilon)\rangle$$

[Sterman] [Becher, Neubert] [...]

Amplitude Level Evolution

[Angeles, De Angelis, Forshaw, Plätzer, Seymour – ‘18]

Parton shower picture encoded in recursive definition including emission and virtual evolution operators

$$\mathbf{A}_n(E) = \mathbf{V}(E, E_n)\mathbf{D}_n\mathbf{A}_{n-1}(E_n)\mathbf{D}_n^\dagger\mathbf{V}^\dagger(E, E_n)\theta(E - E_n)$$

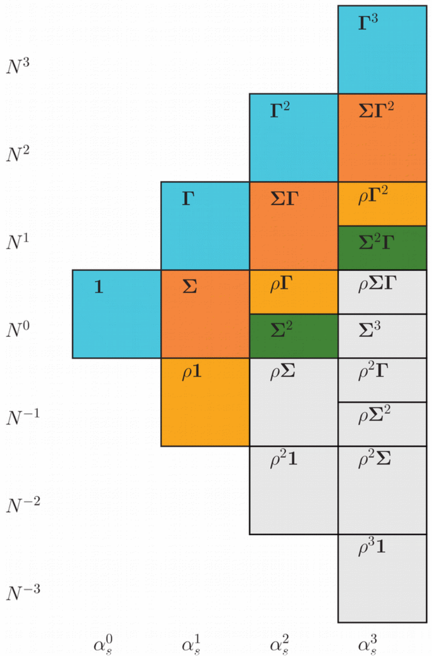
Corresponds to tower of evolution equations for each partonic multiplicity.

Sum terms enhanced by $\alpha_s N$ to all orders, insert perturbations in 1/N.

Take into account real emission contributions and the final suppression by the scalar product matrix element.

Recover BMS equation as well as other evolution equations.

[Weigert – Caron-Huot – Becher, Neubert, Rothen]



	virtuals	reals
🟦	$(0 \text{ flips}) \times 1 \times (\alpha_s N)^n$	$(\mathbf{t}[...]\mathbf{t}\|_{0 \text{ flips}})^{r-1}\ \mathbf{t}[...]\mathbf{t}\|_{2 \text{ flips}} \times 1$ $(\mathbf{t}[...]\mathbf{t}\|_{0 \text{ flips}})^{r-1}\ \mathbf{t}[...]\mathbf{s}\|_{1 \text{ flip}} \times N^{-1}$ $(\mathbf{t}[...]\mathbf{t}\|_{0 \text{ flips}})^{r-1}\ \mathbf{s}[...]\mathbf{s}\|_{0 \text{ flips}} \times N^{-2}$
🟧	$(1 \text{ flip}) \times \alpha_s \times (\alpha_s N)^n$	$(\mathbf{t}[...]\mathbf{t}\|_{0 \text{ flips}})^{r}$ $(\mathbf{t}[...]\mathbf{t}\|_{0 \text{ flips}})^{r-1}\ \mathbf{t}[...]\mathbf{s}\|_{1 \text{ flip}} \times N^{-1}$
🟨	$(0 \text{ flips}) \times \alpha_s N^{-1} \times (\alpha_s N)^n$	$(\mathbf{t}[...]\mathbf{t}\|_{0 \text{ flips}})^{r}$
🟩	$(0 \text{ flips}) \times \alpha_s^2 \times (\alpha_s N)^n$ $(2 \text{ flips}) \times \alpha_s^2 \times (\alpha_s N)^n$	$(\mathbf{t}[...]\mathbf{t}\|_{0 \text{ flips}})^{r}$ $(\mathbf{t}[...]\mathbf{t}\|_{0 \text{ flips}})^{r-1}\ \mathbf{t}[...]\mathbf{t}\|_{2 \text{ flips}}$

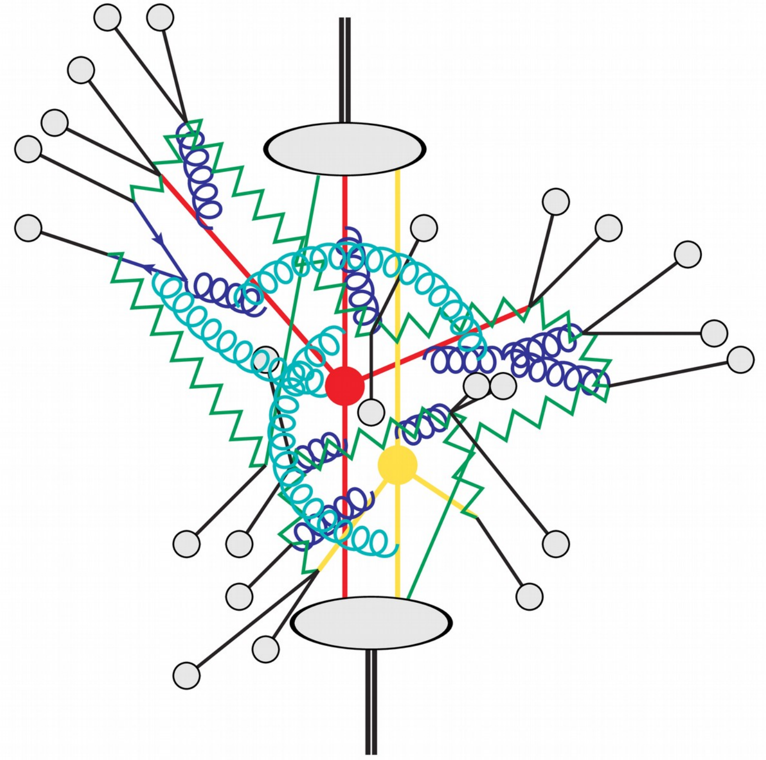
More on WG4 Wednesday afternoon.

Colour Reconnection & Hadronization

Constraining models requires to understand the interface between perturbative and non-perturbative physics.

Stated differently, we need to know how much perturbative dynamics can hide under the hood of phenomenological models.

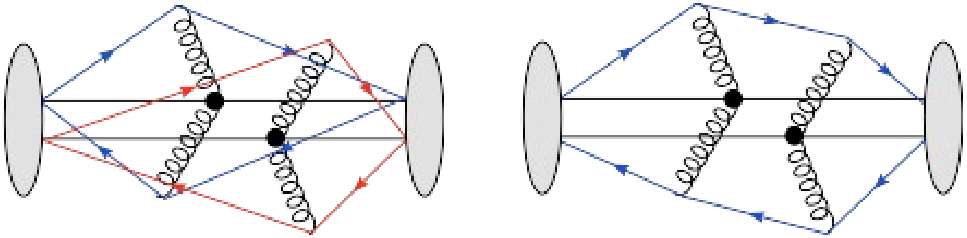
Colour reconnection is one of the key aspects here.

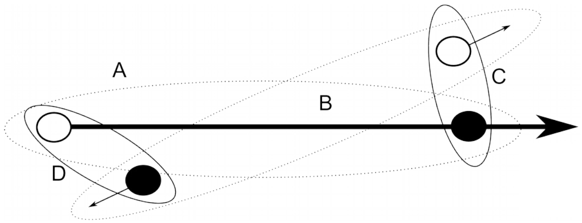


$$d\sigma \sim d\sigma_{\text{hard}}(Q) \times \mathrm{PS}(Q \to \mu) \times \mathrm{Had}(\mu \to \Lambda) \times \ldots$$

Colour Reconnection

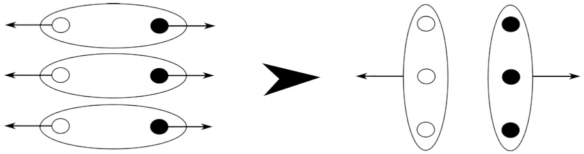
Colour reconnection is central to describing underlying event activity: colour correlations in between multiple scatters much more complex. [Sjöstrand, van Zijl]



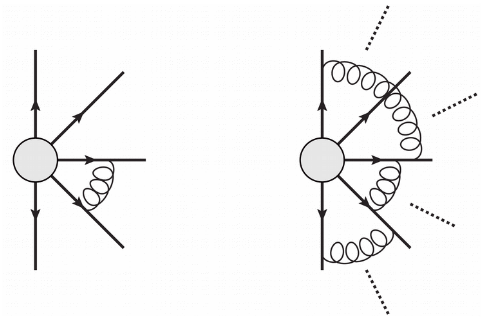


Recent focus on its role in Baryon production.

[Christiansen, Skands – ‘15] [Gieseke, Plätzer, Kirchgaesser – ‘17]



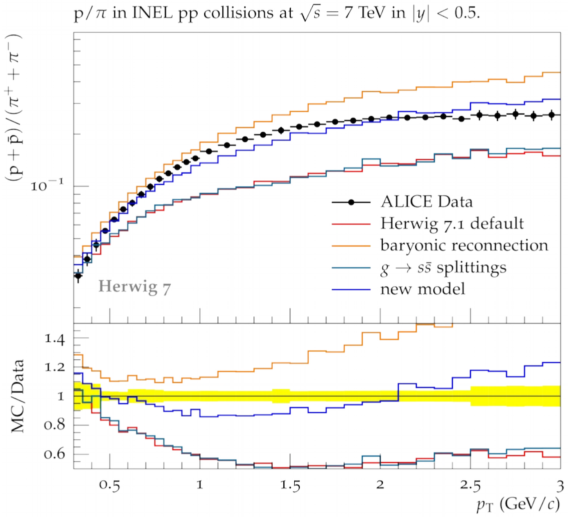
First indications of how colour reconnection links to structures in amplitude evolution.



$$|\mathcal{M}\rangle = e^{\mathbf{\Gamma}}|\text{clusters}\rangle$$

$$P_{\text{reco}} \sim |\langle\text{clusters'}|\mathcal{M}\rangle|^2$$

[Gieseke, Plätzer, Kirchgaesser, Siodmok – ‘18]

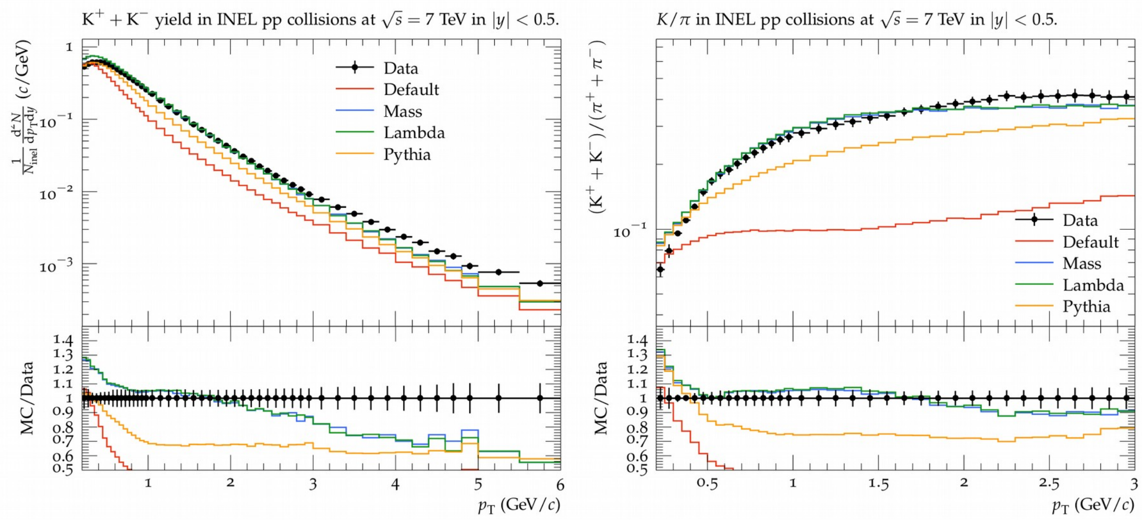


Hadronization Models

New mechanism of strange production in Cluster model:

$$w_s \to w_s(m_{\text{system}})$$

[Duncan, Kirchgaesser– ‘18]

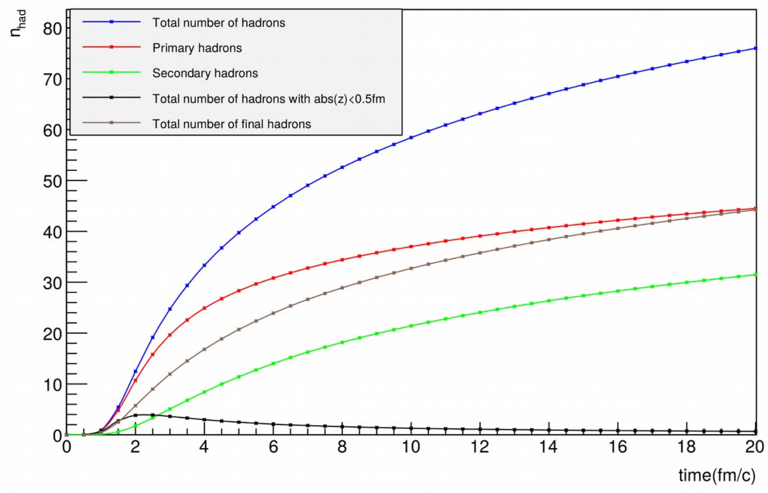


Heavy Ion collisions raise interest in space-time structure of hadronization models.

[Sjöstrand, Ferreres-Sole – ‘18]

Loads of effort underway for microscopic modeling of heavy ion collisions using multipurpose event generators.

[see e.g. Sjöstrand Nucl.Phys. A982 (2019) 43]



Temporal dependence of hadron multiplicities.

Summary

Multi-purpose event generators: tremendous development in recent years.

pp, ep, and ee collisions routinely handled, first steps to eA, pA, AA – also significant development in MPI and diffractive contributions (not covered), photoproduction …

Perturbative improvements now require a much more detailed focus on parton showers and subsequent phenomenological models.

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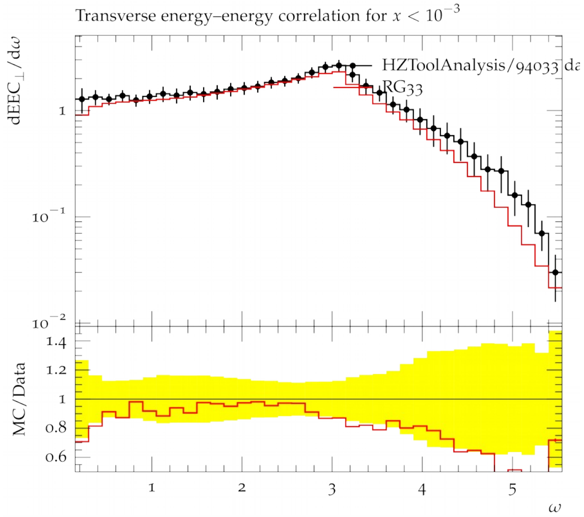
A truly DIS specific thing at this DIS conference:

[contact Hannes Jung or me for more details]

LHC-age Monte Carlos (desperately) seek conveniently available comparisons to ep data.

There is an effort going on to make Rivet fully ep aware, and to wrap HZTOOL into it. Please donate your analysis!

HZ94033



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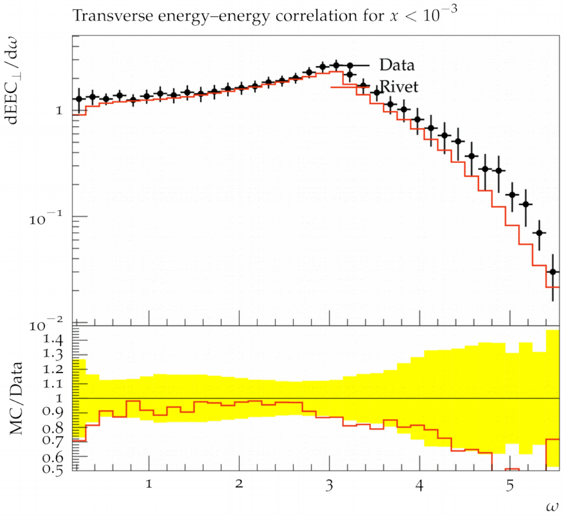

Thank you!

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