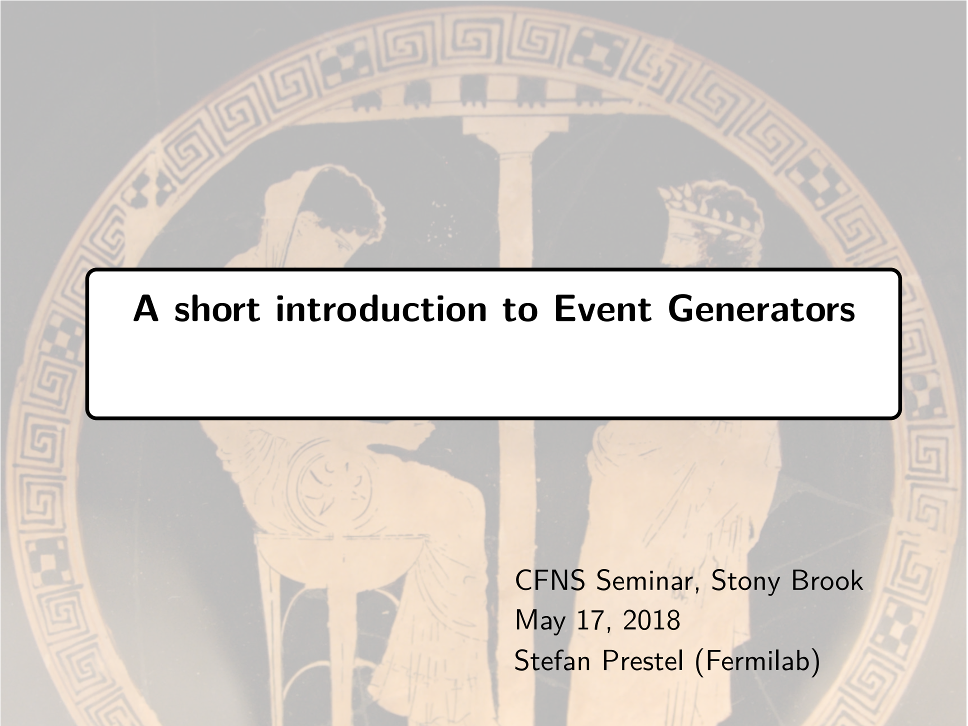
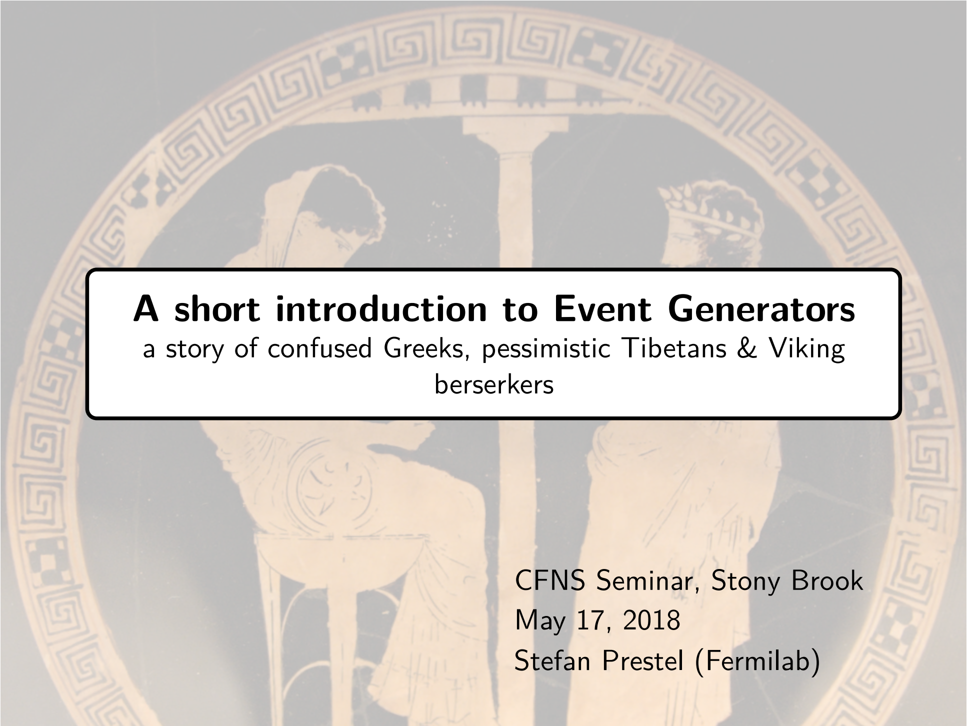


A short introduction to Event Generators

CFNS Seminar, Stony Brook
May 17, 2018
Stefan Prestel (Fermilab)



A short introduction to Event Generators

a story of confused Greeks, pessimistic Tibetans & Viking berserkers

CFNS Seminar, Stony Brook
May 17, 2018
Stefan Prestel (Fermilab)

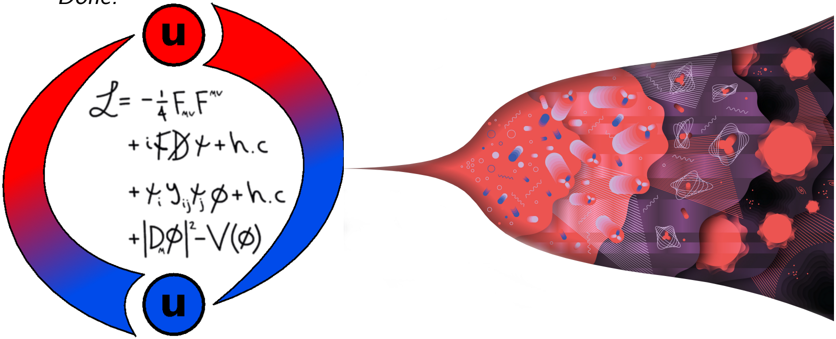
Particle physics ambitions

The roadmap to knowledge is simple:

Find all Particles ("matter") & how they are related ("symmetries")

Derive equations of motion in Quantum Field Theory ("interactions")

Done!

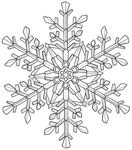


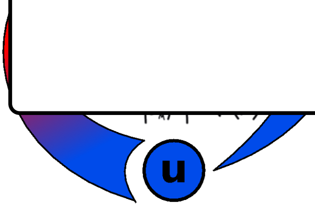
Particle physics ambitions

The roadmap to knowledge is simple:

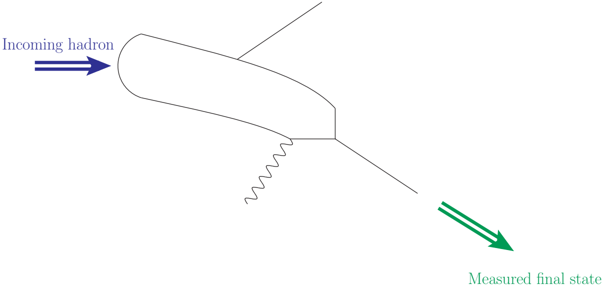
Find all Particles ("matter") & how they are related ("symmetries")

BUT HOW DO INTERESTING PHENOMENA EMERGE?





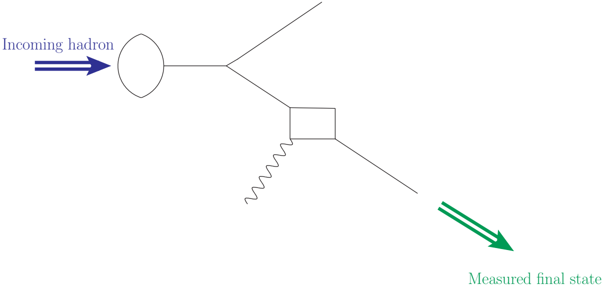
What are interesting phenomena?



Parton inside a hadron scatters off an electromagnetic potential.
Final-state hadrons are slightly misaligned with the incoming hadron.
⇒ Semi-inclusive measurements then allow to map the proton structure.

Measurable, by now good non-perturbative fits.

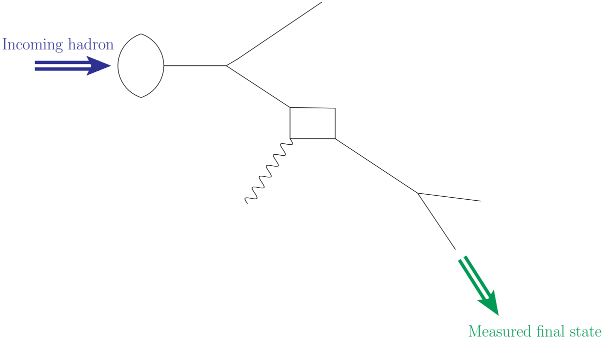
What are interesting phenomena?



Parton inside a hadron scatters off an electromagnetic potential.
Final-state hadrons are slightly misaligned with the incoming hadron.
⇒ Semi-inclusive measurements then allow to map the proton structure.

Non-perturbative fits more universal when including evolution.

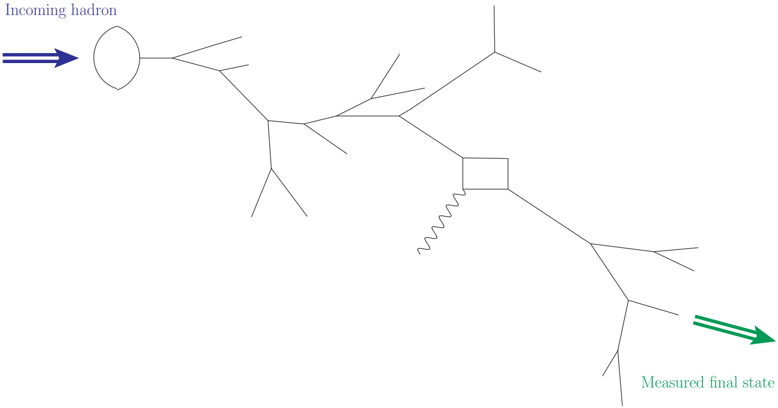
What are interesting phenomena?



"Initial-state" and "final-state evolution" are not easy to separate – long-wavelength "soft" gluons see everything!

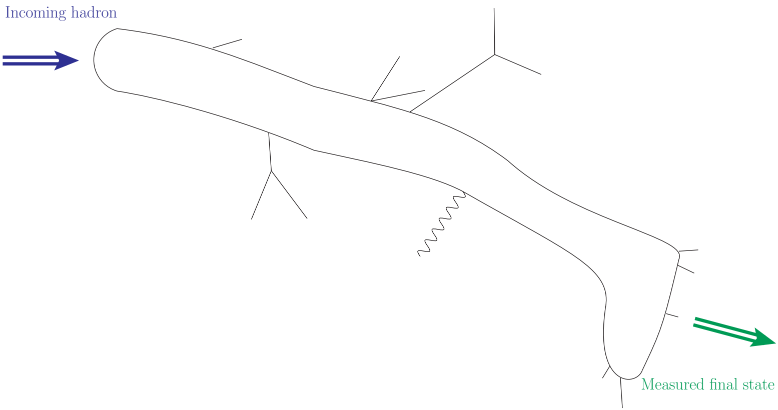
Tough to disentangle in experiment & factorization scheme dependent.

What are interesting phenomena?



The “full” final state is much more complicated, and the state evolution is complicated.
⇒ Exploit the evolution as much as possible

What are interesting phenomena?



The “full” final state is much more complicated, and the state evolution is complicated.
⇒ Exploit the evolution as much as possible before we have to parametrize the whole system & abandon predictivity!

Factorization

The asymptotic states of QCD are not explicit in its Lagrangian. The confinement of high-energy partons into hadrons cannot be calculated.

We rely on factorization of long-distance (hadronic) effects from short-distance (partonic) physics:

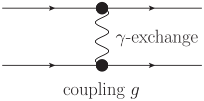
$$\begin{aligned}\sigma \quad = \quad & \int d\sigma_{(ab\to X+N\ \text{partons})}(\text{high energy}) \\ & \otimes\ f_{a\in\mathrm{A}}(\{x\}_a, \text{high energy}) \otimes\ f_{b\in\mathrm{B}}(\{x\}_b, \text{high energy}) \\ & \otimes\ \mathcal{D}(p_A, p_B, p_1, \ldots, p_N)\end{aligned}$$

$f(\{x\}, \text{energy}) \mathrel{\widehat{=}}$ Parton density in colliding hadron at “resolution” $1/$energy
$\mathcal{D} \mathrel{\widehat{=}}$ Fragmentation mechanism
Measure f and $\mathcal{D}$ where radiative corrections are small (low energy).

Hard scattering cross sections

...can be calculated systematically:

Tree-level



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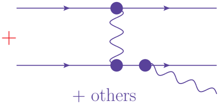
Real correction



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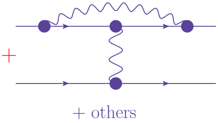
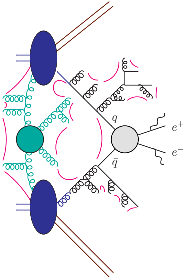
Virtual correction



Requirements on numerical cancellation of IR divergences
→ IR treated differently from “structure function renormalization”
→ Finite remainders (factorization scheme change)

Modelling of non-perturbative structure



PDFs: Parametrization of longitudinal hadron structure. Extracted where phase space is small, low energy

Beam/target remnant: Modeling of $k_\perp$ of partons inside of the colliding hadrons.

Multiparton interactions: Many "perturbative" $2 \to 2$ scatterings as model of the inelastic cross section.

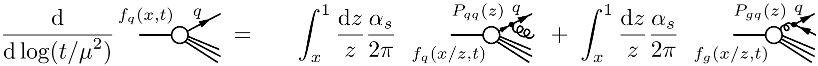
Hadronization model: Color strings or clusters as confinement model, with an IR-safe matching to perturbation theory.

Limit phase space (i.e. impact) for modeling by covering the phase space with perturbative dynamics **as much as possible**.
Accurate perturbative dynamics ensure universality.

The evolution of distribution functions

Short distance scattering cross sections can be calculated in fixed-order coupling expansion. Fixed-order corrections apply at a high energy.
But distribution functions are extracted at low energy.

→ Transport extracted $f(x,$ low energy$)$ to the desired $f(x',$ high energy$)$ by (DGLAP) evolution equations:

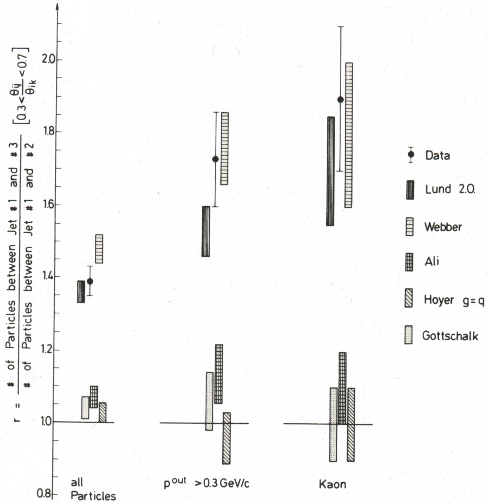


$$\frac{\mathrm{d}}{\mathrm{d}\log(t/\mu^2)} \quad = \quad \int_x^1 \frac{\mathrm{d}z}{z}\frac{\alpha_s}{2\pi} \quad + \int_x^1 \frac{\mathrm{d}z}{z}\frac{\alpha_s}{2\pi}$$

⇒ Allows to calculate the fixed-order “hard scattering” cross section at large momentum transfers.

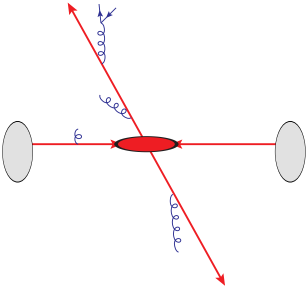
The inversion high energy → low energy is called parton shower.

Remember: Independent evolution is only an approximation!



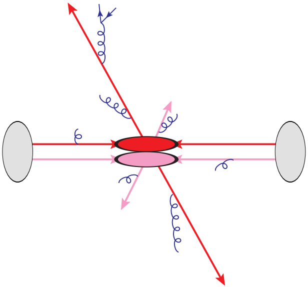
Data shows that jets at LEP “talk to each other”. The phenomenon is called string effect, a.k.a. *color coherence*.

Now, let's design a Monte Carlo Event Generator



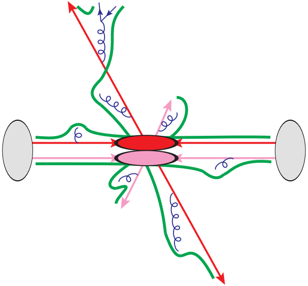
Hard interaction
+ Radiative cascade

Now, let's design a Monte Carlo Event Generator



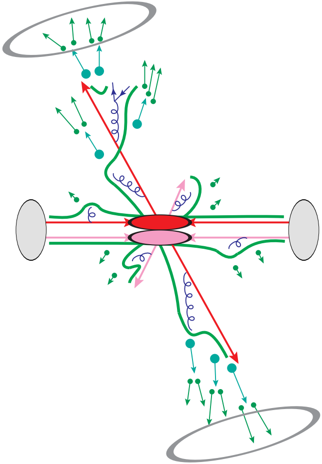
Hard interaction
+ Radiative cascade
+ Multiple interactions of initiators

Now, let's design a Monte Carlo Event Generator



Hard interaction
+ Radiative cascade
+ Multiple interactions of initiators
+ Hadron formation

Now, let's design a Monte Carlo Event Generator



Hard interaction

\+ Radiative cascade

\+ Multiple interactions of initiators

\+ Hadron formation

\+ Hadron decays

⇒ Particles as measured in detector

\+ Beam spectrum, detector & material effects

Monte Carlo integration is our friend!

Parton showers are the glue between long- and short distance

Parton showers solve evolution equations

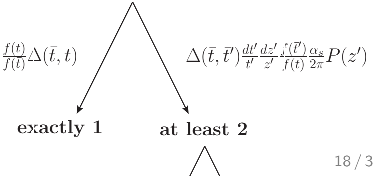
$$\frac{\mathrm{d}\, f_a(x,t)}{\mathrm{d}\ln t} = \sum_{b=q,g} \int_0^1 \frac{\mathrm{d}z}{z}\, \frac{\alpha_s}{2\pi} \left[P_{ab}(z)\right]_+ f_b\left(\frac{x}{z}, t\right)$$

...and define the factorization and evolution procedure,
...distribute simple theory calculations over multiplicities,
...set the starting conditions for non-perturbative effects.

no decay **radiate at least once**

$$H(\mu)f(\mu) \to \; H(\mu)\Delta(\mu,t)f(t) \; + \; H(\mu)\int\limits_t^\mu \frac{d\bar{t}}{\bar{t}} \int \frac{dz}{z} f(\bar{t})\frac{\alpha_s}{2\pi}P(z)\Delta(\mu,\bar{t}) \; + \; ..$$

When increasing the resolution, we
$a)$ can still find the same parton, or
$b)$ may find parton → parton decay.
At lowest order Δ and P are probabilities.



What is a good parton shower?

Iteration requires completely differential, physical intermediate states at any stage!

The construction of a parton shower is not arbitrary. PS provides a good representation of all-order QCD **if it...**

Recovers eikonal in soft limit, AP kernels in collinear limit

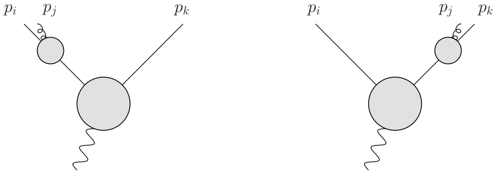
Obeys flavor/momentum sum rules.

Employs exact phase space factorization, in the completely general massive case.

After these prerequisites, we can start building bridges to e.g. CSS and the TMD formalism (e.g. by comparing anomalous dimensions)

Remember: Colors glue together!

PS needs to describe both soft from collinear radiation.



$$dP_{\text{PS rad}} \quad \sim \quad \frac{dp_\perp^2}{p_\perp^2} dz \left[\; P_{ij}(z_i) + P_{kj}(z_k) \;\right]$$

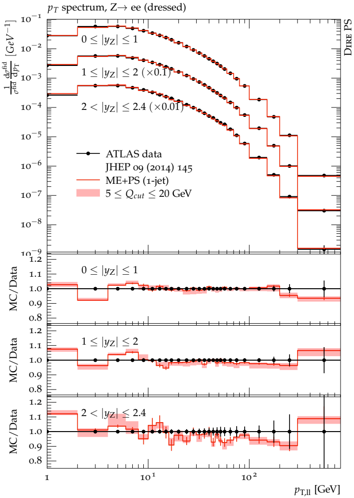
Idea: Use $p_\perp^2 \sim \frac{(p_i p_j)(p_j p_k)}{\mu^2}$ and splitting probabilities

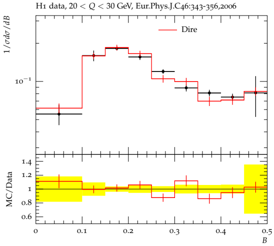
$$P_{ij}(z_i) \propto \begin{cases} \text{diverges like } 1/(p_i p_j) & \text{for } p_j \parallel p_i \quad \text{(collinear limit)} & (1) \\ \text{no divergence} & \text{for } p_j \parallel p_k \quad \text{(no double counting)} & (2) \end{cases}$$

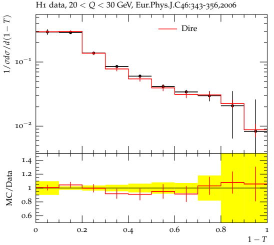
(2) not fulfilled by AP kernels of collinear factorization

Solution 1: Get the integral "right" $\Rightarrow$ Angular ordering
Solution 2: Get the integrand "right" $\Rightarrow$ Dipole PS $P(z, p_\perp^2) \sim \frac{(1-z)}{(1-z)^2 + p_\perp^2/\mu^2}$

Parton shower predictions







→ Reproduces $p_\perp$-like spectra, based on two types of non-perturbative inputs: collinear PDFs and primordial $k_\perp$ parametrization.
...but MC deliberately does not "do standard CSS". Great opportunity!

How does factorization work at differential level?

To understand how the PS factorizes, we need to understand
...how kinematics (real-emission recoil) correlates partons
...how multi-parton correlations affect factorization
...how multi-parton correlations should “disappear” after integration

Need to go beyond leading order to find out!

Extending showers beyond lowest order… and beyond codes!

Dire PS, arXiv:1705.00742, arXiv:1805.03757 (S. Höche, SP)

Definition of shower evolution beyond LO needs an analytically simple phase space for LO-like $(1 \rightarrow 2)$ and higher-order $(1 \rightarrow 3)$ transitions.

With this, a NLO-corrected PS amounts to

1. *Formulating a consistent leading-order result*
2. *Applying a fully differential NLO calculation, at all orders:*

$$\Delta_{\text{NLO}}(t_0, t_1) = e^{-\int_{t_1}^{t_0} \frac{dt}{t} \int d\tilde{z} \left[\left(\mathrm{I} + \frac{1}{\varepsilon}\,\mathcal{P} - \mathcal{I} \right)(\tilde{z}) + \int \mathrm{d}\Phi_{+1} (\mathrm{R}-\mathrm{S})(\tilde{z}, \Phi_{+1}) \right]}$$

$\uparrow$ Born-like event, a.k.a. endpoint

$\uparrow$ Real-emission event

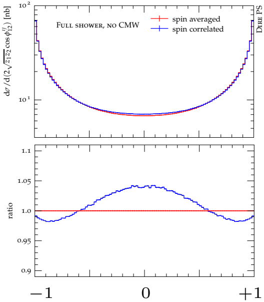
Pros: On-the-fly numerical recalculation of NLO transitions.
Can account for kinematic differences between real and virtual, and factorization scheme dependence.

Cons: LO must recover all soft/coll. limits for one *and two* emissions.

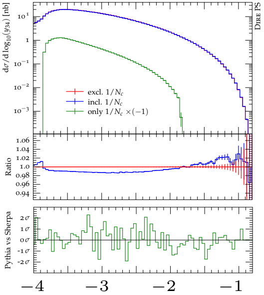
Consistent leading order showers... for PYTHIA and SHERPA

Correct all soft and collinear limits *for one and two (or more) emissions* requires

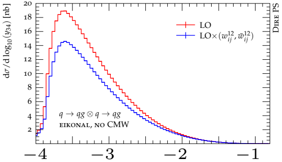
Spin correlations:



Color correlations:



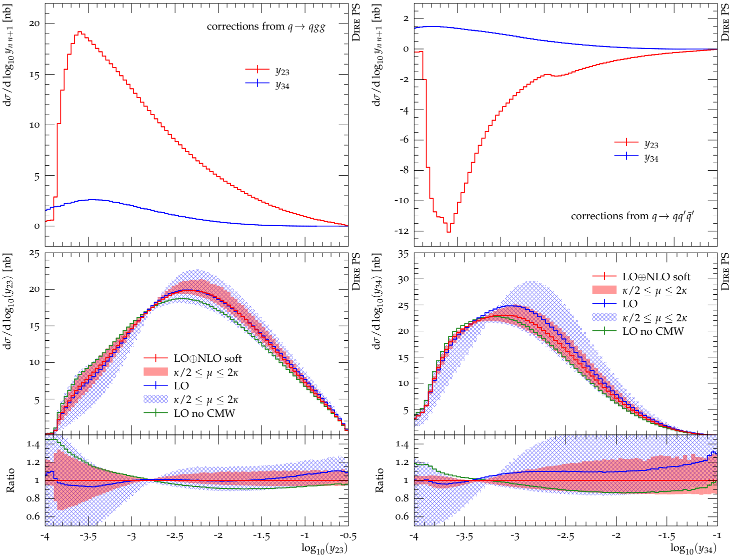
Recoil corrections:



→ Enables completely differential definition of NLO corrections, which allows inclusion of remainders of IR regularization as in factorization.

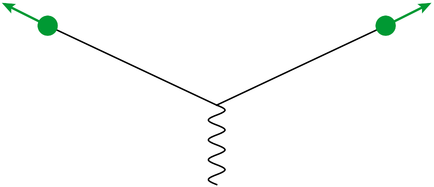
NLO shower results

Almost NLO: arXiv:1805.03757 (S. Höche, F. Dulat, SP)



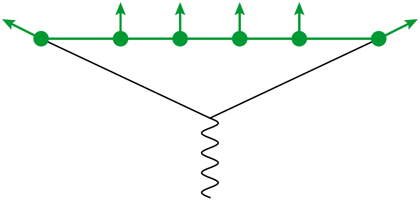
→ Reduced uncertainty, but similar to LO.
More importantly, might allow event-based definition of factorization.

Why bother with showers? Non-perturbative physics!



Color or flavor are not “destroyed” by confinement, only contained.
A parton can never fragment into a hadron.

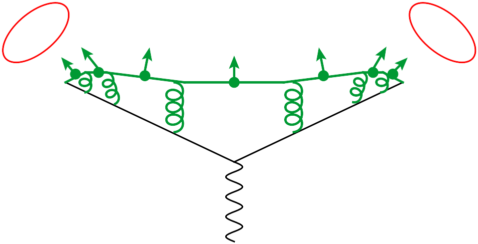
Why bother with showers? Non-perturbative physics!



When do partons convert to hadrons?
If they have small relative momenta and a virtuality $\sim \Lambda_{qcd}$.
Widely separated partons cannot couple to hadron vertices and allow $\mathcal{O}(\Lambda_{qcd})$ momentum flow.

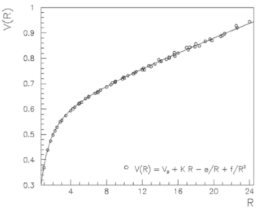
see e.g. Collins & Rogers arXiv:1801.02704 [hep-ph]

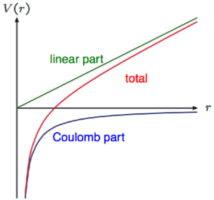
Why bother with showers? Non-perturbative physics!



Partons fragment together with their soft/collinear gluon field!
Gluons and soft/collinear partons from evolution make momentum
flow small and allow non-perturbative parton-hadron vertices.

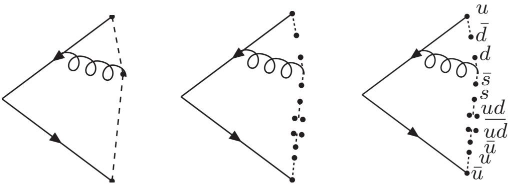
The Lund string model(s)



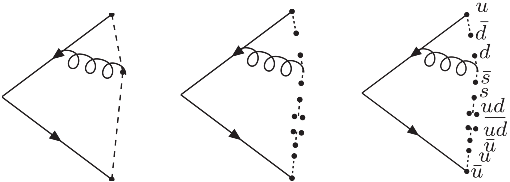


At large distances, the potential between color-anticolor is linear.

⇒ Similar to 1+1-dimensional, for which fragmentation mechanism is “known”!



The Lund string model(s)



The “vertices” are related to tunneling probabilities that define the Lund symmetric fragmentation function

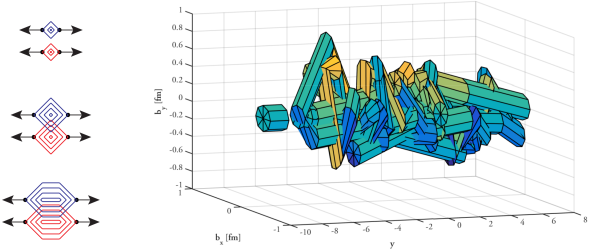
$$f(z) = \frac{(1-z)^a}{z} \exp\left(-\frac{bm_\perp^2}{z}\right)$$

Note the $p_\perp$-dependence required by momentum conservation! Gluons are just excitations of the string.

(Note: Flavor selection not very predictive, adds more parameters)

The evolution of strings

Figures from arxiv:1710.09725 [hep-ph] and C. Bierlich



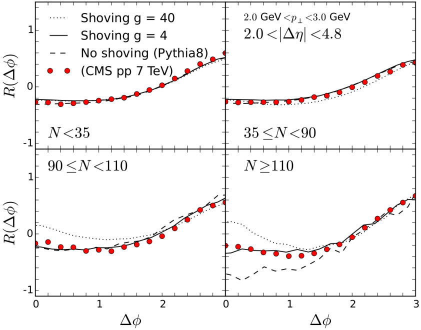
As color and anti-color move apart, strings will expand
…and at some point overlap.

Typical events for pp scattering at $\sqrt{s} = 7$ TeV are already very dense. Heavy-Ion collisions even more so!

Need microscopic model of collective effects!

Modelling collectivity...microscopically

Figures from arxiv:1710.09725 [hep-ph]



In dense environment, strings interact by

- forming collective states (ropes)
- repulsion, i.e. "shoving"
- reacting to pressure gradients

Implemented in Angantyr (Dipsy+Pythia).

Wrap-up

First and foremost: Event generators ♡ Data

- Scattering events often exhibit emergent phenonema such as jet formation and fragmentation
- Event generators aim at a complete, numerical model of scatterings.
- Parton-shower evolution glues soft- and long-distance physics together and defines how/if the calculation factorizes.
- NLO parton showers are on the horizon.
- Gluons are essential for a consistent fragmentation and are naturally included in thhe Lund string model.
- High-energy or heavy-ion collisions contain many overlapping strings, giving hints how collective effects might emerge.