PHYSICS AT THE TERA SCALE

Helmholtz Alliance

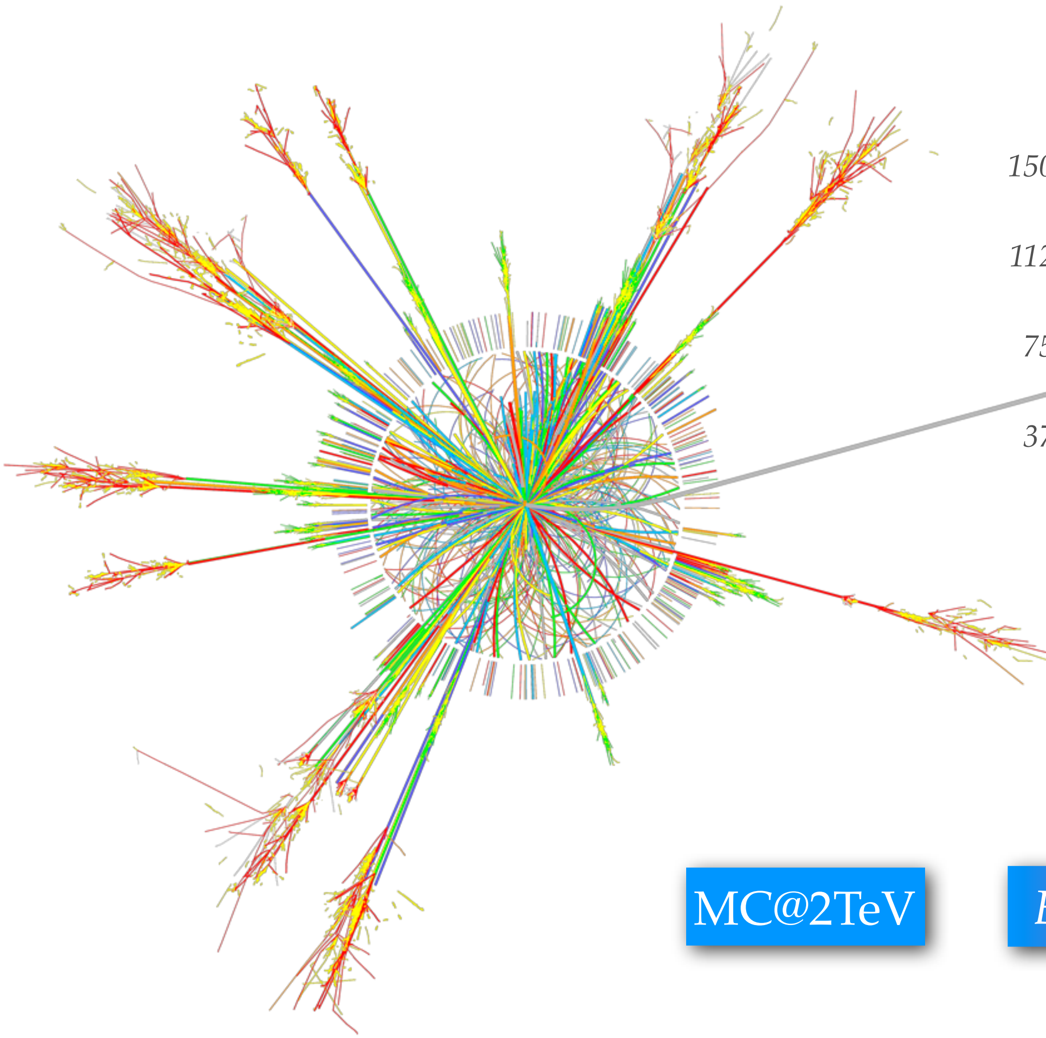
MC event generators -look from hard core QCD theorists

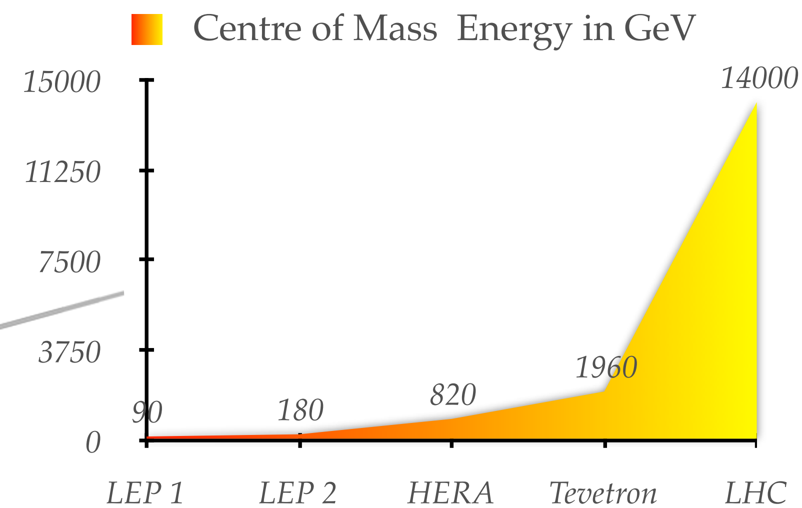
Zoltán Nagy

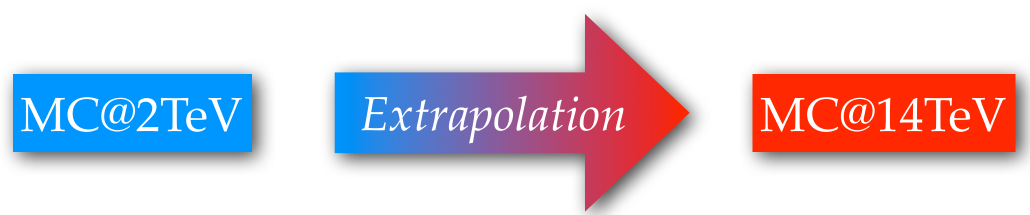
DESY, Terascale Analysis Center

Introduction

The LHC is almost running and we will have to deal with the data soon.







Picture: ATLAS simulation

Introduction

Master equation for LHC discovery:

New Physics = Data (experimental) - Background (theory)

EXPERIMENT

- Collecting raw data
- Detector corrections
- Converting to hadron level
- Converting to parton level

← MC event generators

THEORY

- Calculate at least at NLO level *(if it is available)*
- Resum the large logarithms and match it to NLO *(if it is available)*

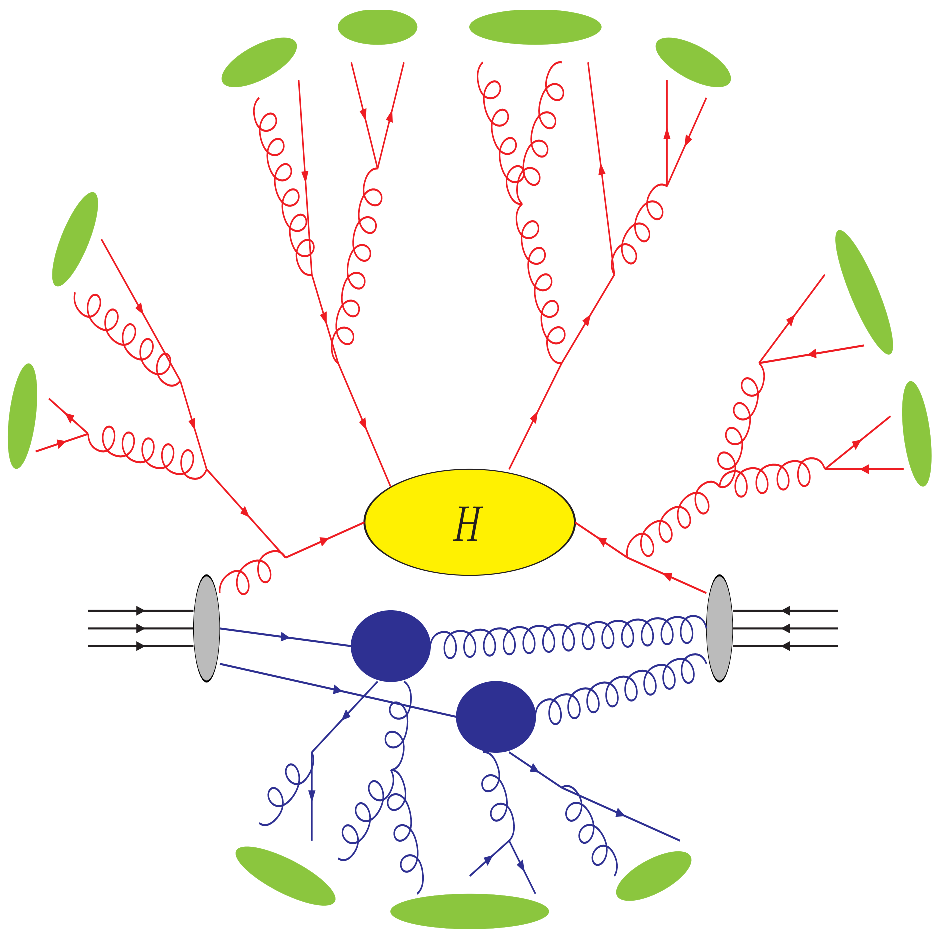
Master equation of the Monte Carlo program:

Data (no new physics) = [Hard part ⊗ Shower + MPI ⊗ Shower] ⊗ Hadronization

■ Well defined ■ Needs some work ■ Only model

Introduction

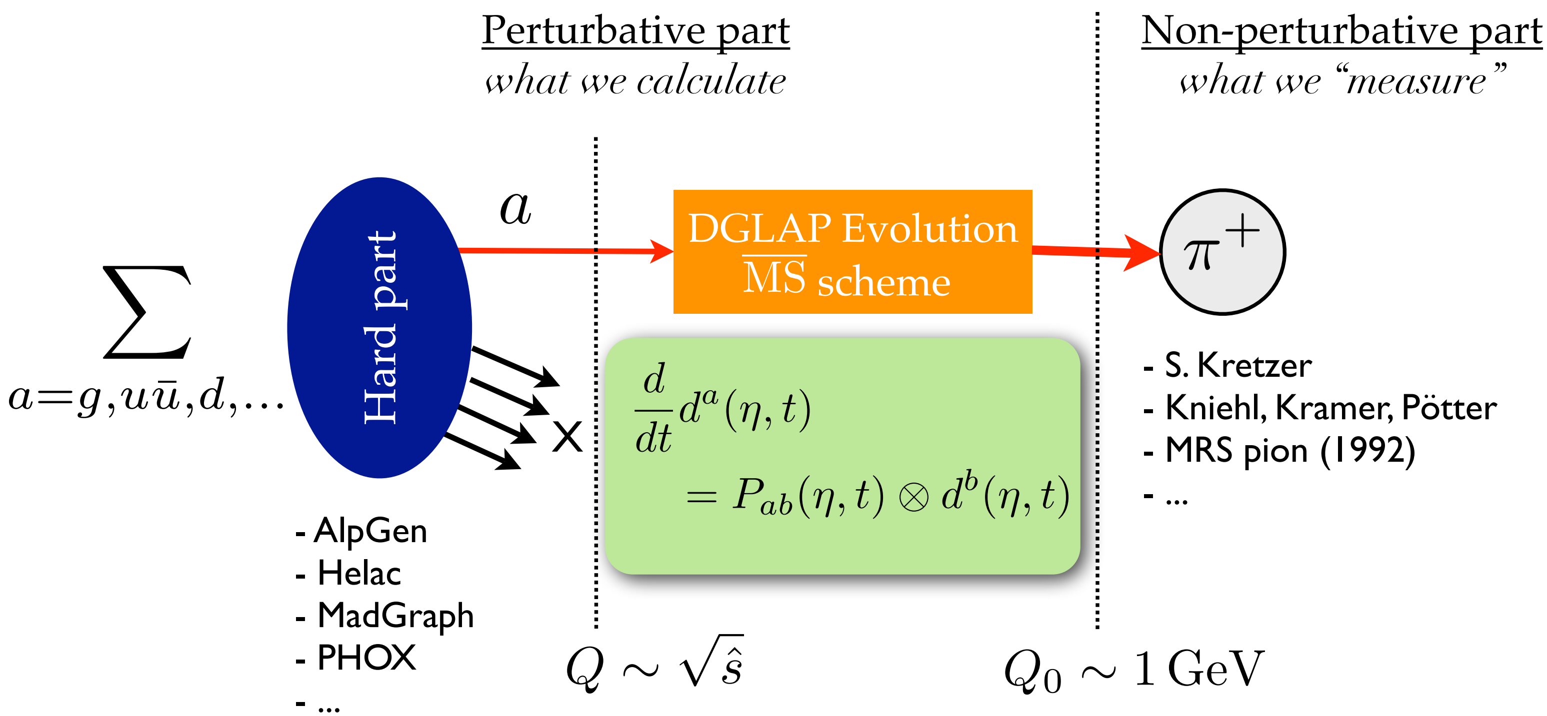
The structure of the Monte Carlo event generators



1. Incoming hadron *(gray bubbles)*
   - Parton distribution function
2. Hard part of the process *(yellow bubble)*
   - Matrix element calculation, cross sections at LO, NLO, NNLO level
3. Radiations *(red graphs)*
   - Parton shower calculation
   - Matching to the hard part
4. Underlying event *(blue graphs)*
   - Models based on multiple interaction
5. Hardonization *(green bubbles)*
   - Universal models

Inclusive hadron production

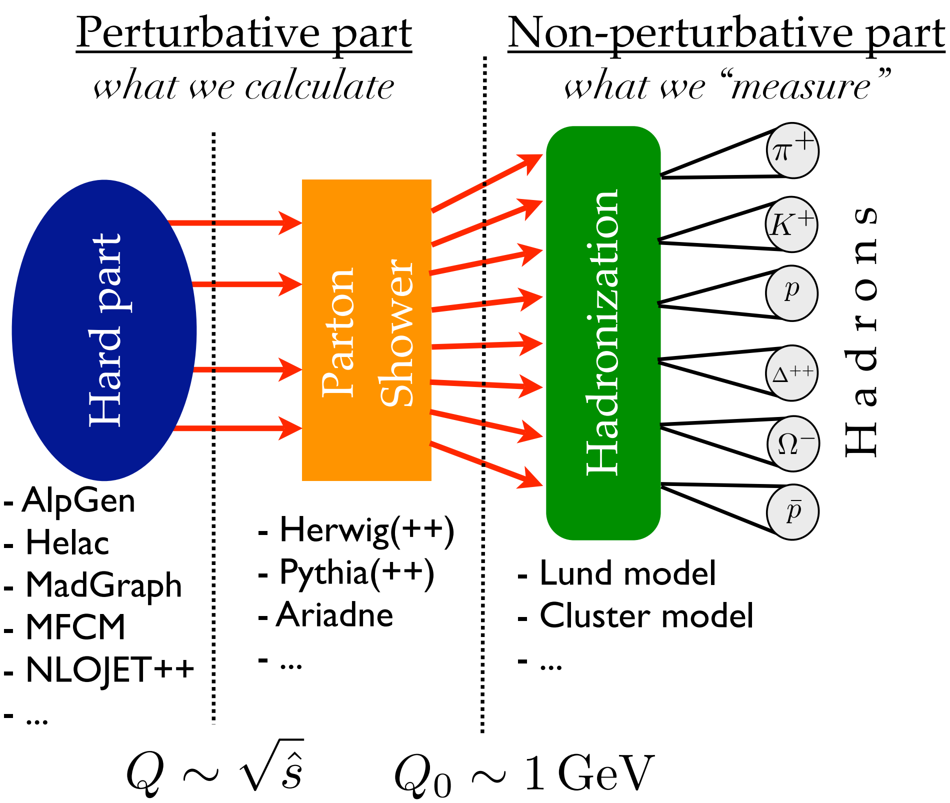
Structure of the one-hadron inclusive cross section



In this calculation the only free parameters are choice factorization scheme and scale. We have a well defined and systematically improvable structure.

Parton Shower

Structure of the Monte Carlo algorithm:



HADRONIZATION MODELL

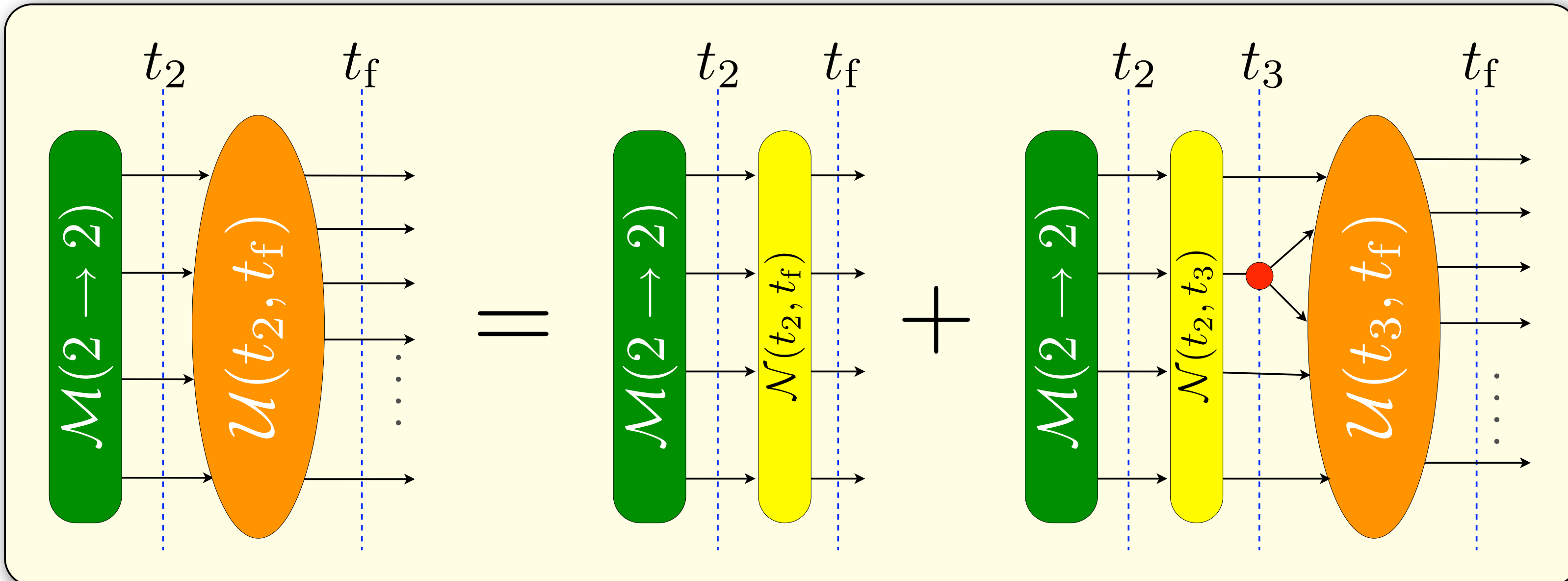
- Universal object. One can consider it as a measurement function. It measures the partonic color flow.
- In *principle* the LEP measurement determines.
- Model with tuning parameters.

Here we need 40 error set of the hadronization to estimate the uncertainties.

It would be nice to have Tune A0-40.

Iterative Algorithm

The parton shower evolution starts from the simplest hard configuration, that is usually 2→2 like.



$$\mathcal{U}(t_f, t_2)|\mathcal{M}_2) = \underbrace{\mathcal{N}(t_f, t_2)|\mathcal{M}_2)}_{\text{"Nothing happens"}} + \overbrace{\int_{t_2}^{t_f} dt_3\, \mathcal{U}(t_f, t_3)\mathcal{H}(t_3)\mathcal{N}(t_3, t_2)|\mathcal{M}_2)}^{\text{"Something happens"}}$$

Classical Parton Shower

- The parton shower relies on the universal soft and collinear factorization of the QCD matrix elements. It is universal property and true at all order. This should be the only approximation ...

... but we have some further approximations:

- ✗ Interference diagrams are treated approximately with the angular ordering
- ✗ Color treatment is valid in the $N_c \to \infty$ limit
- ✗ Spin treatment is usually approximated.
- ✗ Approximation in the phase space

... non-systematic approximations lead to systematically NOT improvable algorithm.

Parton shower as classical statistical mechanics

"Quantum Parton Shower"

- The parton shower relies on the universal soft and collinear factorization of the QCD matrix elements. It is universal property and true at all order. This should be the only approximation ...

⇒ Parton shower as Quantum statistical mechanics

ZN and D. Soper: **JHEP** 0709:114 (2007)
JHEP 0803:030 (2008)
JHEP 0807:025 (2008)

Conventional Shower Scheme

What would be the requirements for a conventional shower scheme?

Shower must be fully exclusive.

- Full color evolution with quantum interference.
  This goes beyond the leading color approximation.
- Spin correlations.

Splitting operator must be as *exact* as possible.

- Possibly based on exact Feynman graphs

Don't mix the kinematical and dynamic effects.

- Mapping based on exact phase space factorization.
- Recoil strategy must be independent of the dynamics.
  e.g.: Don't choose the recoiled parton to the color connected one.
- Don't use explicit angular ordering or angular veto.

Choice of the evolution variable

- Must be soft and collinear sensitive.
- Should be as simple as possible (e.g.: virtuality)
- Should give the best phase space phase space coverage

How to do the matching to LO and NLO matrix elements systematically?

QCD vs. Parton Shower

Recent paper by Marchesini and Dokshitzer indicates that the color dipole based showers are not consistent with the parton evolution picture. They studied the quark energy distribution. Good news, there is no problem.

From shower equation

$$\frac{d}{dt}\big(x,q\big|\mathcal{U}(t,t')\big|M_2\big) = \big(x,q\big|[\mathcal{H}_I(t)-\mathcal{V}(t)]\,\mathcal{U}(t,t')\big|M_2\big)$$

No approximation and assumptions.
Only algebraic manipulations.

to DGLAP

$$\frac{d}{dt}D_q(t,t',x) = \int_x^1 \frac{dz}{z} P_{qq}(z) D_q(t,t',x/z) + \mathcal{O}(e^{-t})$$

Drell-Yan pT distribution

Building a shower based on the Catani-Seymour splitting functions and mappings can lead to the loss of accuracy.

$$\frac{d}{dt}\sigma(t,t';p_T) = K(t,p_T) \otimes \sigma^B(p_T = 0) + \cdots$$

This is effectively an approximated NLO calculation. No resummation of the large logarithms correctly. We got wrong equation because of the choice of the momentum mapping. This can be fixed, but...

$$\frac{d}{dt}\sigma(t,t';p_T) = \underbrace{K(t,p_T)} \otimes \sigma(t,t';p_T) + \cdots$$

Still depends on the momentum mapping.

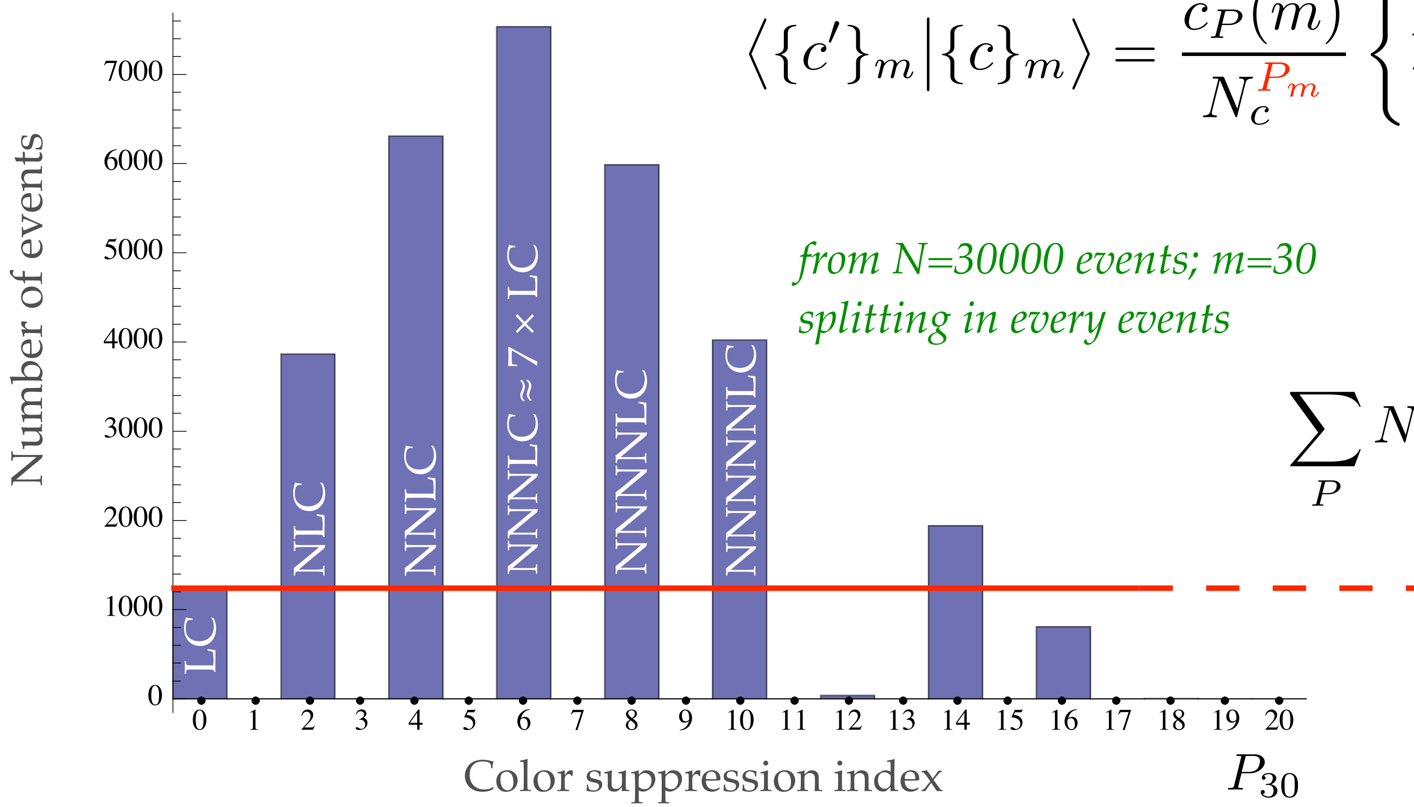
We have to study and test against known results our shower algorithm analytically at parton level not just numerically.

Color Correlations

With a simple "color shower" we can estimate the importance of the subleading color contributions.

$$N_m(P) = \frac{1}{N}\sum_{i=1}^{N} \langle \{c_i'\}_m | \{c_i\}_m \rangle \, \delta(P - P_m(\{c_i', c_i\}_m))$$

$$\langle \{c'\}_m | \{c\}_m \rangle = \frac{c_P(m)}{N_c^{P_m}} \left\{ 1 + \mathcal{O}\left(\frac{1}{N_c^2}\right) \right\}$$



from N=30000 events; m=30 splitting in every events

$$\sum_P N_m(P) = 1$$

Multi Parton Interaction

Back to our master equation:

Data (no new physics) = [Hard part ⊗ Shower + MPI ⊗ Shower] ⊗ Hadronization

The MPI models based on the eikonal model. This is a model to calculate total cross section.

$$\sigma_{\text{tot}} = 2\pi \int_0^\infty db\, b(1 - \exp(-A(b)\sigma_{QCD}))$$

The parton showers basically exclusive implementation of total cross section based on eikonal model. The number of the hard interactions selected according to the Poisson distribution:

$$P_n = \frac{2\pi}{\sigma_{tot}} \int_0^\infty db\, b \frac{[A(b)\sigma_{QCD}]^n}{n!} \exp(-A(b)\sigma_{QCD})$$

Basically only two tuning parameters.

No momentum conservation is built in this formula.

HERWIG++: Vetoing unwanted events
PYTHIA: PDF rescaling

Factorization Theorem

Deep inselastic scattering we can proof the factorization of the cross section:

$$\sigma[F] = \sum_a \int_0^1 d\eta f_{a/H}(\eta, \mu) \int d\hat{\sigma}_a[F]$$

In hadro-hadron collision we cannot proof the factorization in general. It is understood only for some simple quantity, like Drell-Yan cross section. For other (more exclusive quantities) we can assume and check it by order by order.

$$\sigma[F] = \sum_{ab} \int_0^1 d\eta_a f_{a/H}(\eta_a, \mu) \int_0^1 d\eta_b f_{b/H}(\eta_b, \mu) \int d\hat{\sigma}_{ab}[F]$$

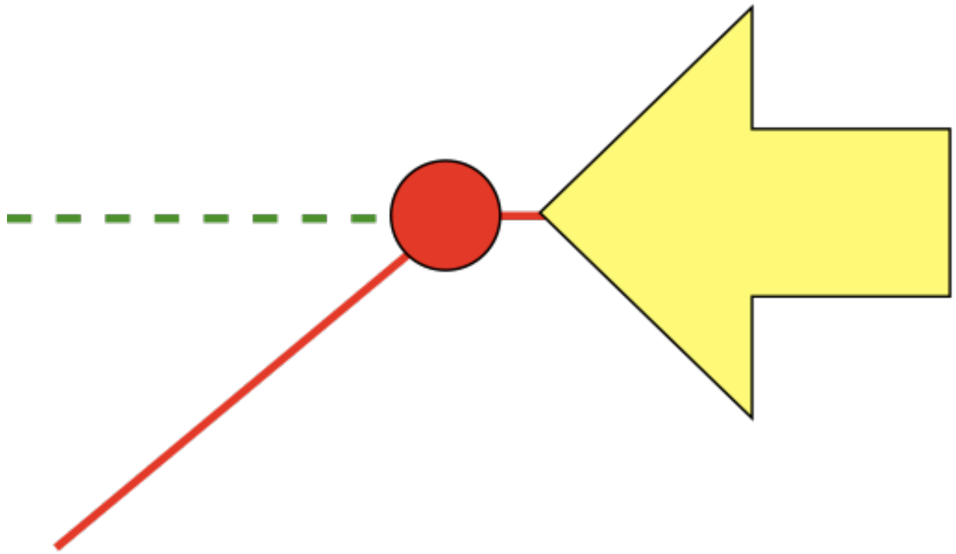
Now the questions:

- If now factorization at hard level, what can we expect in the multiple interaction case?
- Can we understand something at least order-by-order basis?

Deep Inelastic Scattering

The physical picture behind the evolution equation

$\mu = 100\,\mathrm{GeV}$



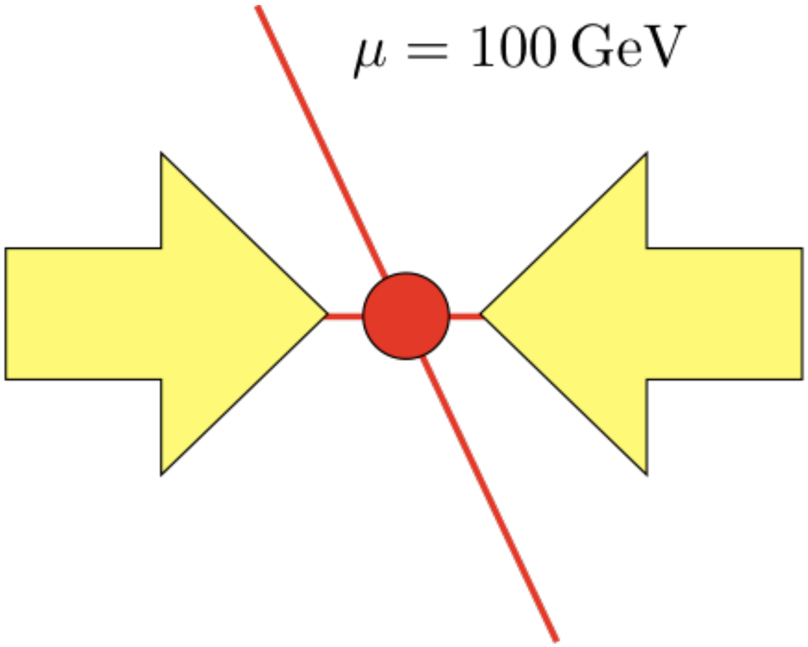
Decreasing the resolution scale more and more partons are visible and less absorbed by the incoming hadron.

This picture is consistent with the pQCD and leads to the DGLAP evolution equation

$$\mu \frac{d}{d\mu} f_{a/H}(\eta, \mu) = \sum_b [P_{a,b} \otimes f_{b/H}](x, \mu)$$

Hadron Collision

Let us see how it looks at hadron collider



In hadron-hadron collision the parton distribution function also absorbs the contribution of the secondary interactions.

This is a more complicated evolution than in the DIS case.

- Is there factorization or can we define in a systematic way?
- If yes, how does it work?
- What is the evolution equation?

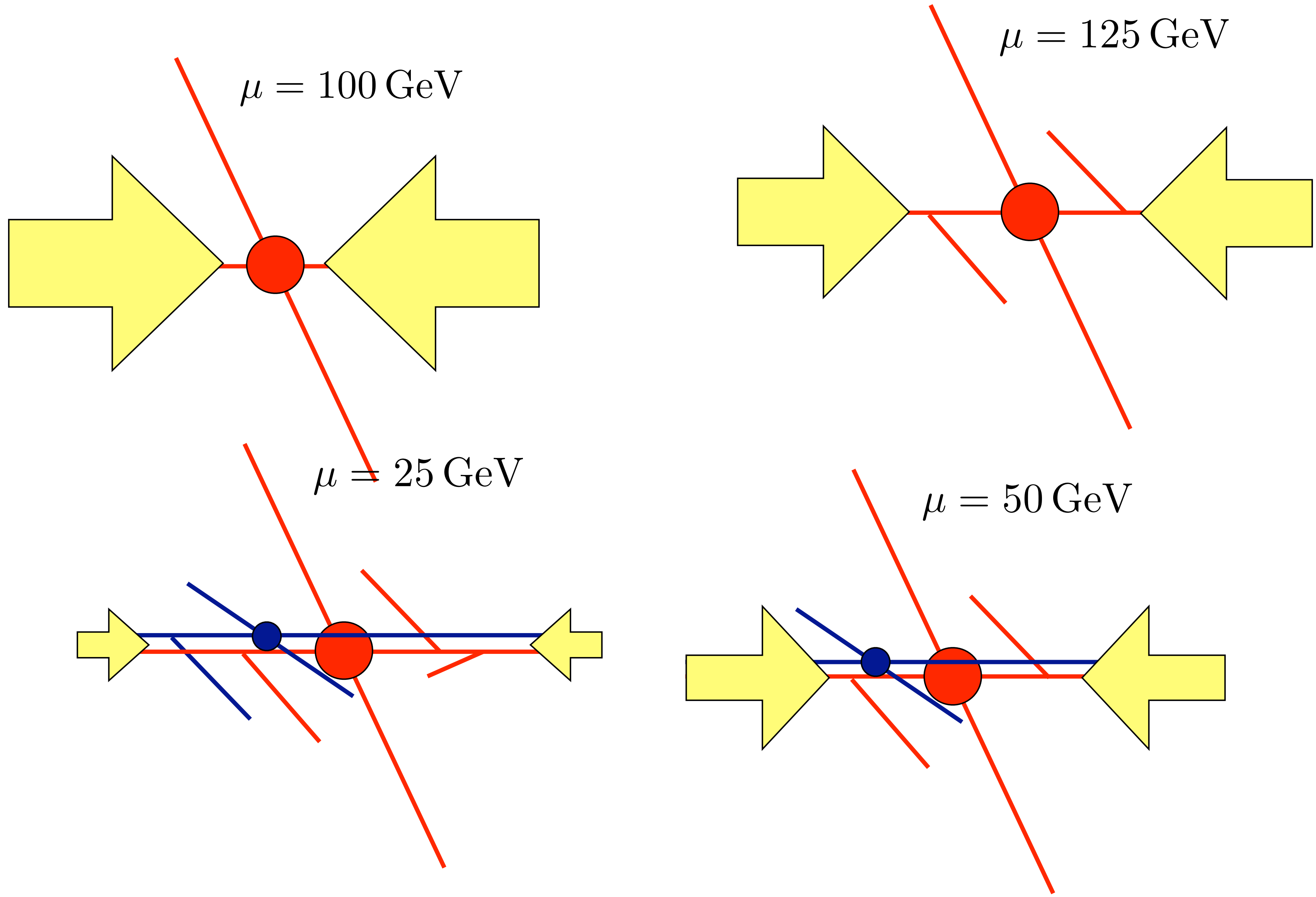
As a first guess, the evolution equations would be something like

$$\mu \frac{d}{d\mu} f_a(\eta, \mu) = \sum_b [(P_{a,b} + H_{a,b}) \otimes f_b](\eta, \mu) + G_a[D_{a',b'}, f_a](\eta, \mu)$$

$$\mu \frac{d}{d\mu} D_{a,b}(\eta_a, \eta_b, \mu) = F_{a,b}[D_{a'b'}, f_{a'}](\eta_a, \eta_b, \mu)$$

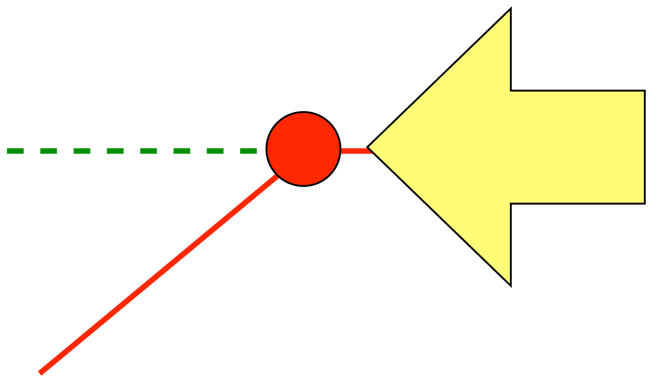
Conclusion

- A standardized parton shower scheme would be nice.
- Error set for hadronization model tunning (e.g.: Tune A0-40)
- We need a lot of theoretical study of the multiple interactions in hadron collisions.

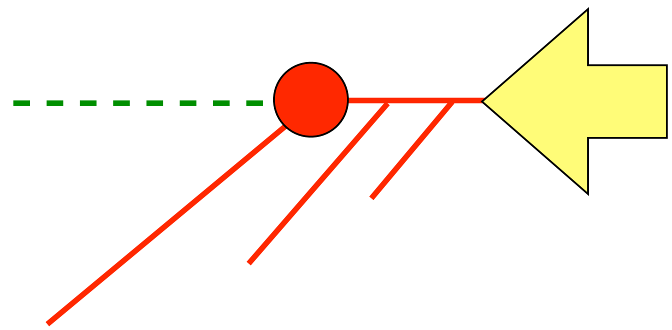


$\mu = 100\,\mathrm{GeV}$
$\mu = 125\,\mathrm{GeV}$
$\mu = 25\,\mathrm{GeV}$
$\mu = 50\,\mathrm{GeV}$

$\mu = 100\,\mathrm{GeV}$



$\mu = 50\,\mathrm{GeV}$



$\mu = 25\,\mathrm{GeV}$