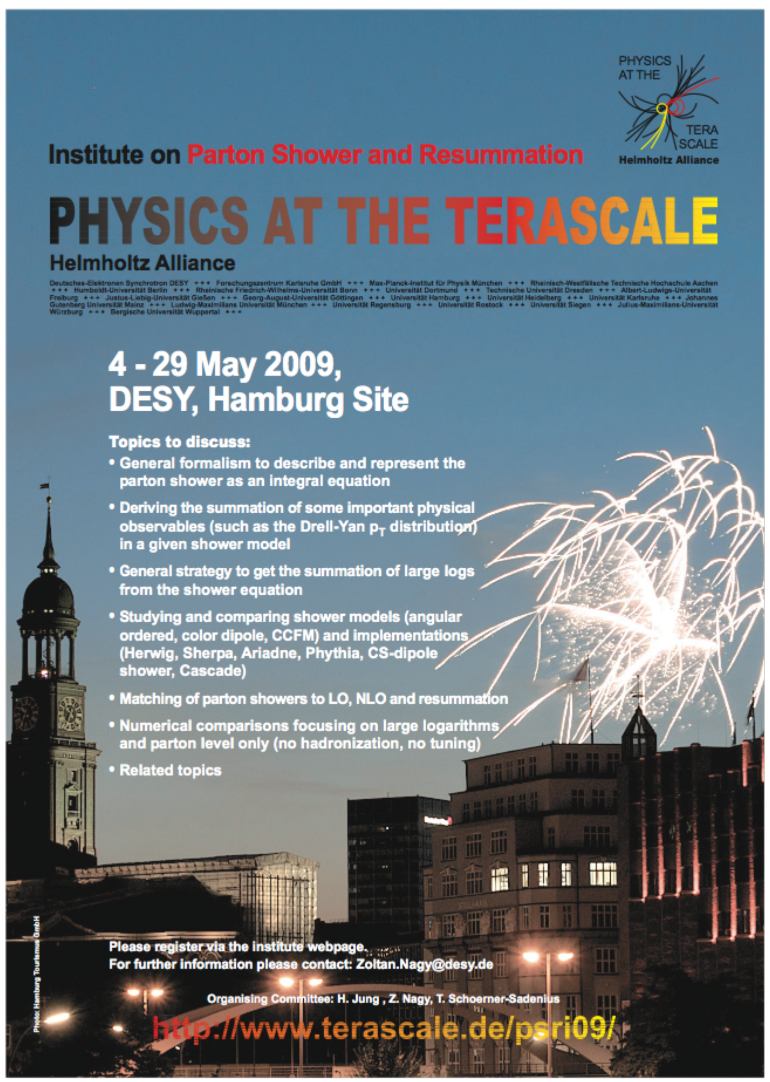
PHYSICS AT THE TERA SCALE

Helmholtz Alliance

QCD vs. Monte Carol Event Generators

http://www.terascale.de/mc



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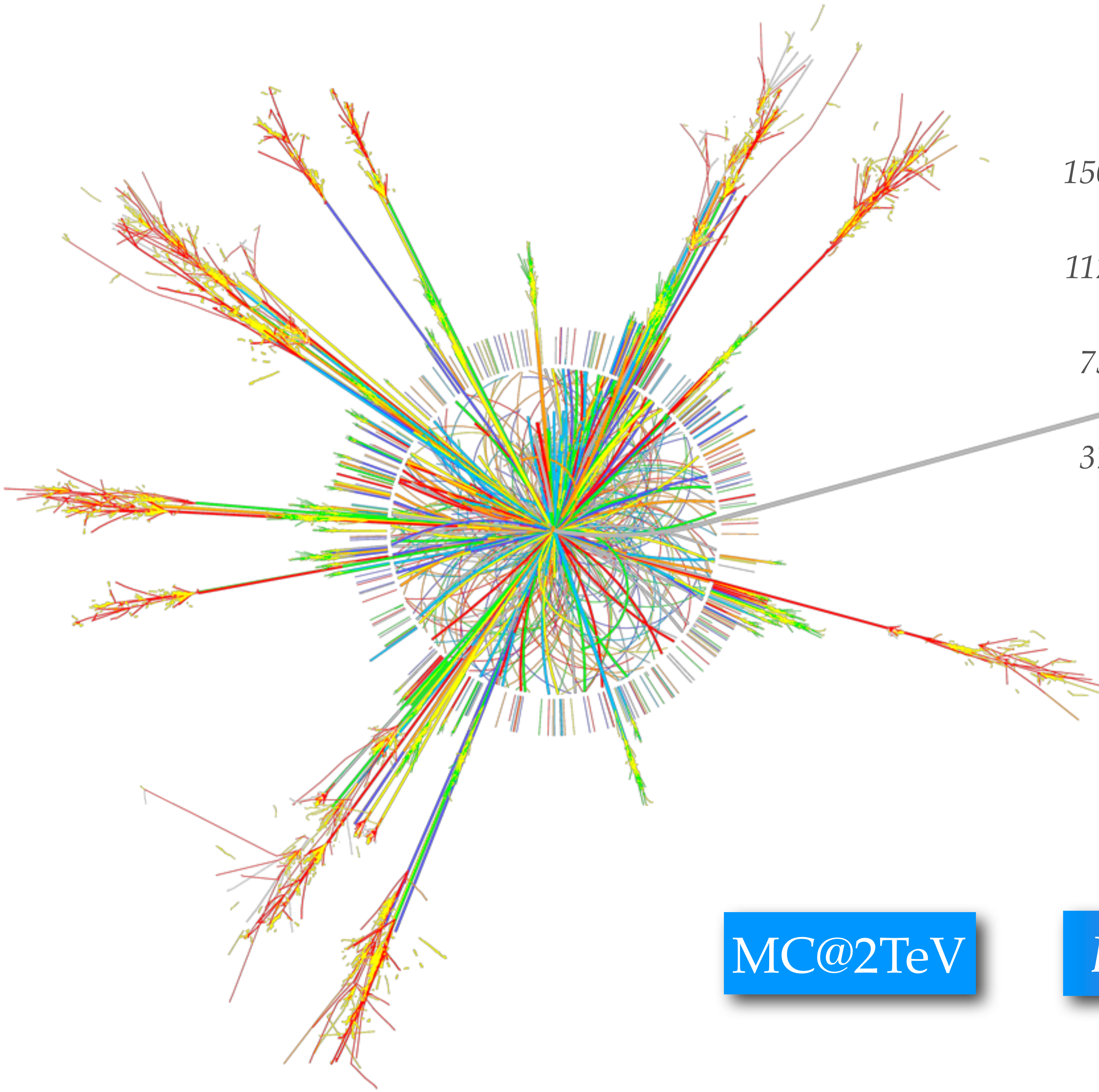
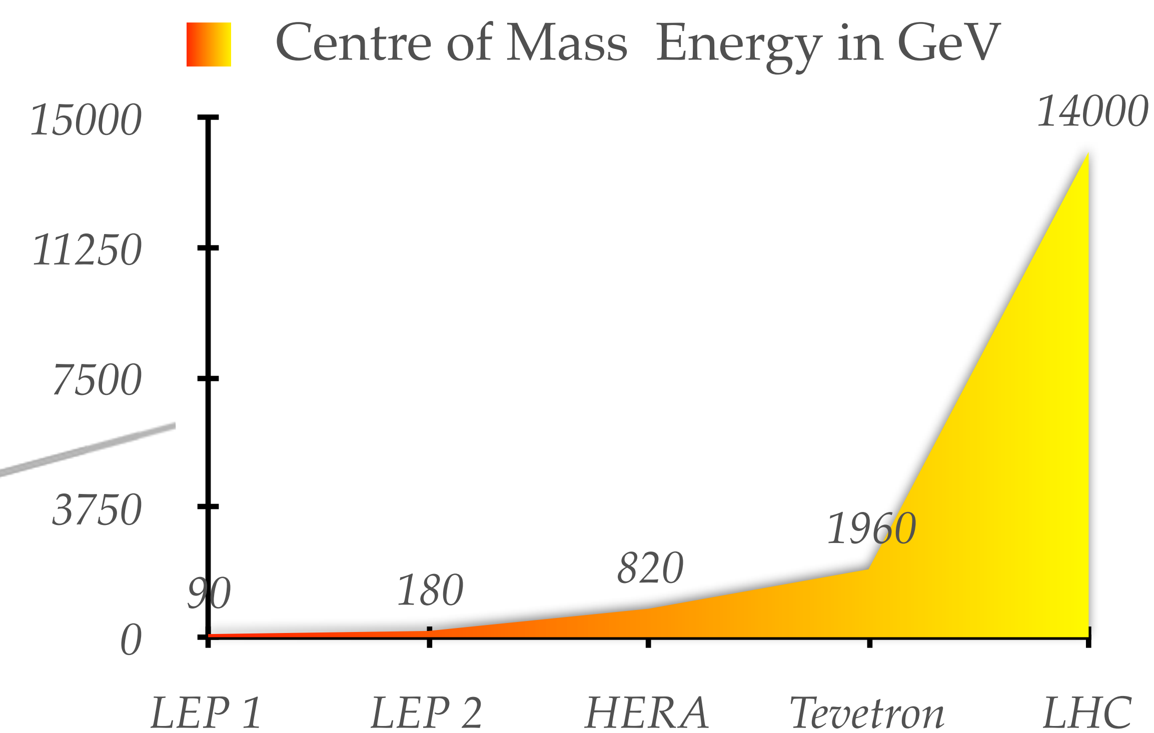
-- DESY Colloquium --

-- June 2, 2009 & DESY HH ---

Introduction

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



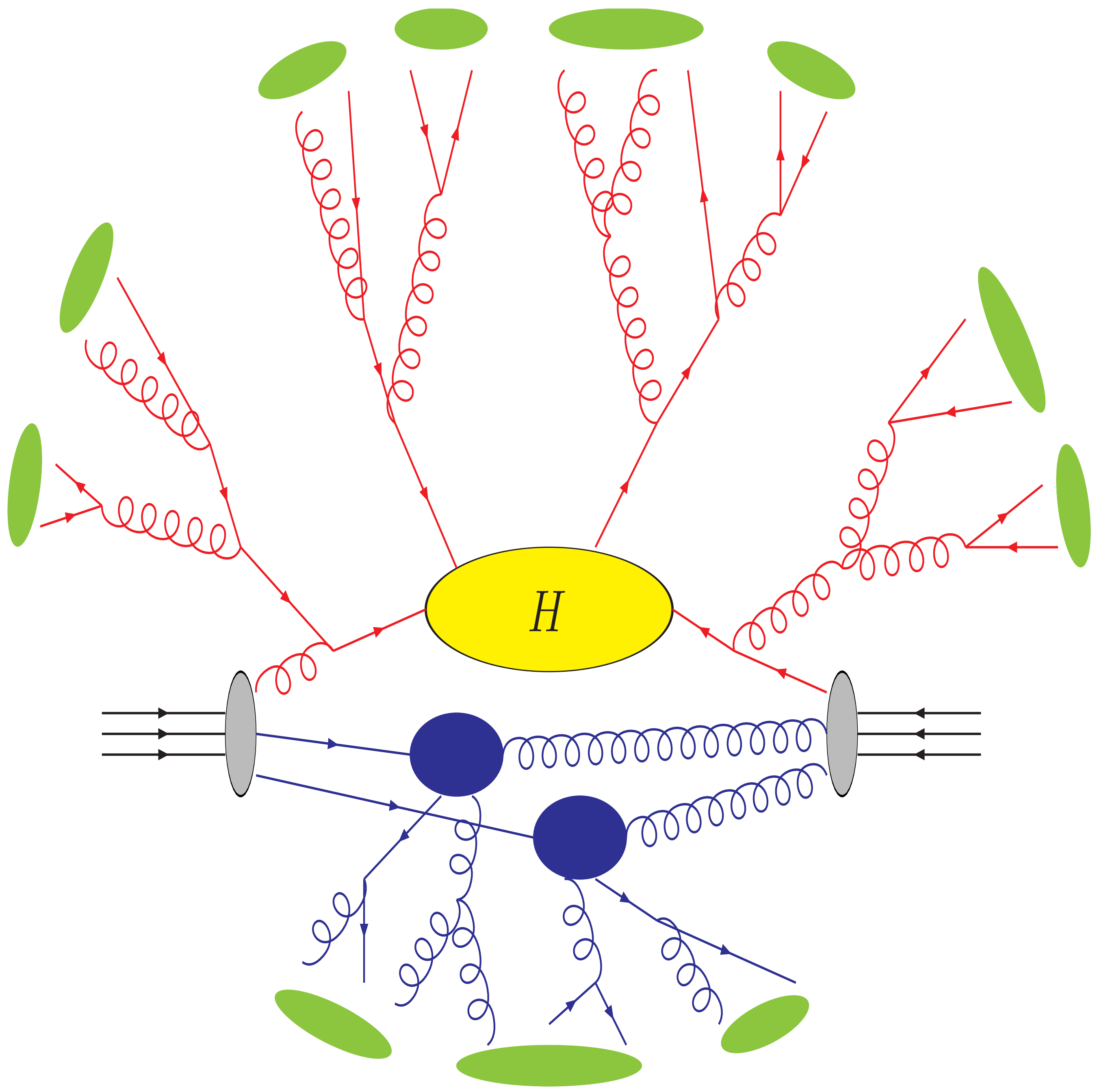


MC@2TeV → *Extrapolation* → MC@14TeV

Picture: ATLAS simulation

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

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)*

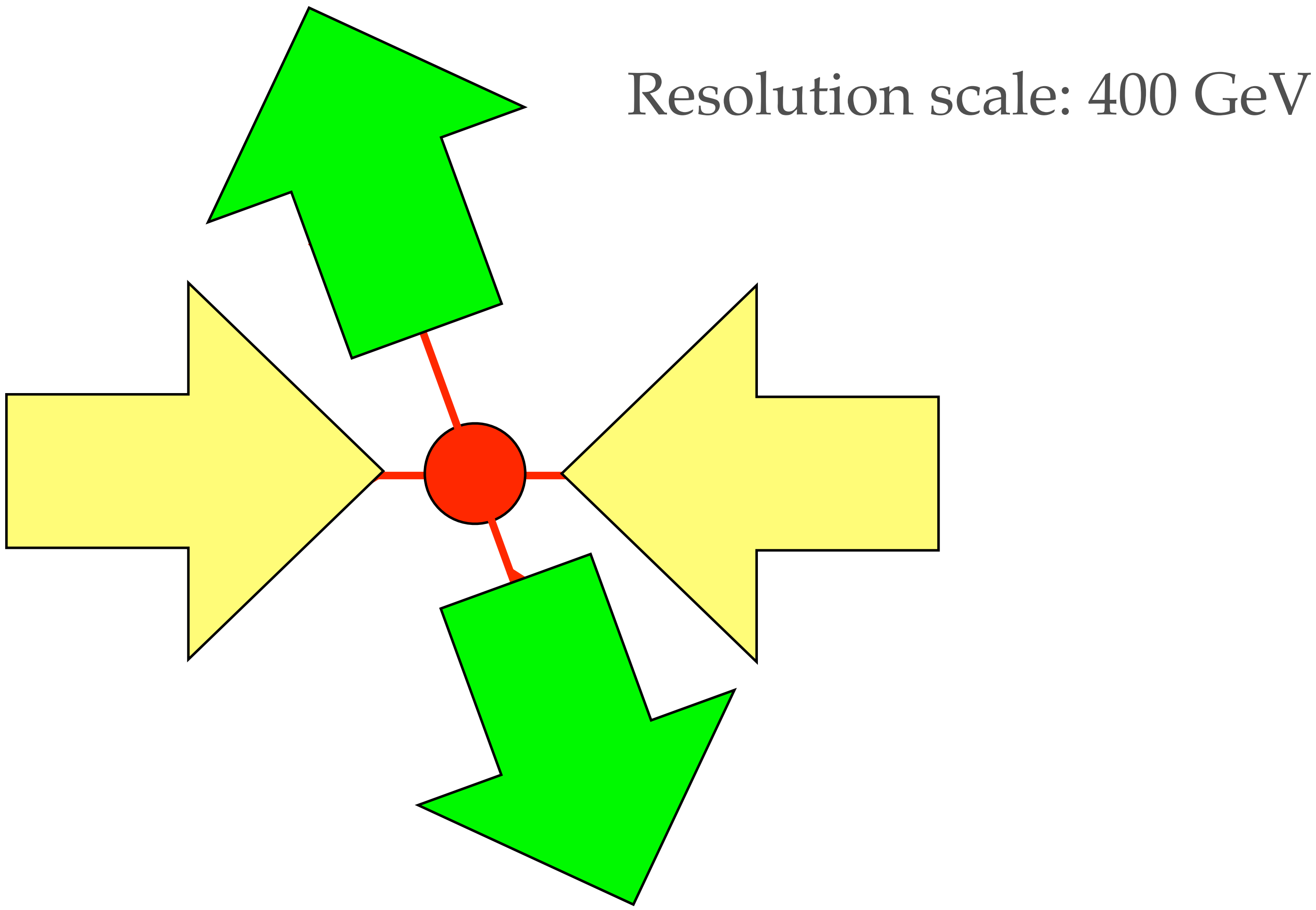
Master equation of the Monte Carlo program:

Data (no new physics) = [Hard part $\otimes$ Shower + MPI $\otimes$ Shower] $\otimes$ Hadronization

Well defined   Needs some work   Only model

Iterative Algorithm

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



Decreasing the resolution scale, more and more partons are visible and less absorbed by the incoming hadrons and the final state jets.

This intuitive picture is usually called *Wilsonian renormalisation technique* in theoretical physics.

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

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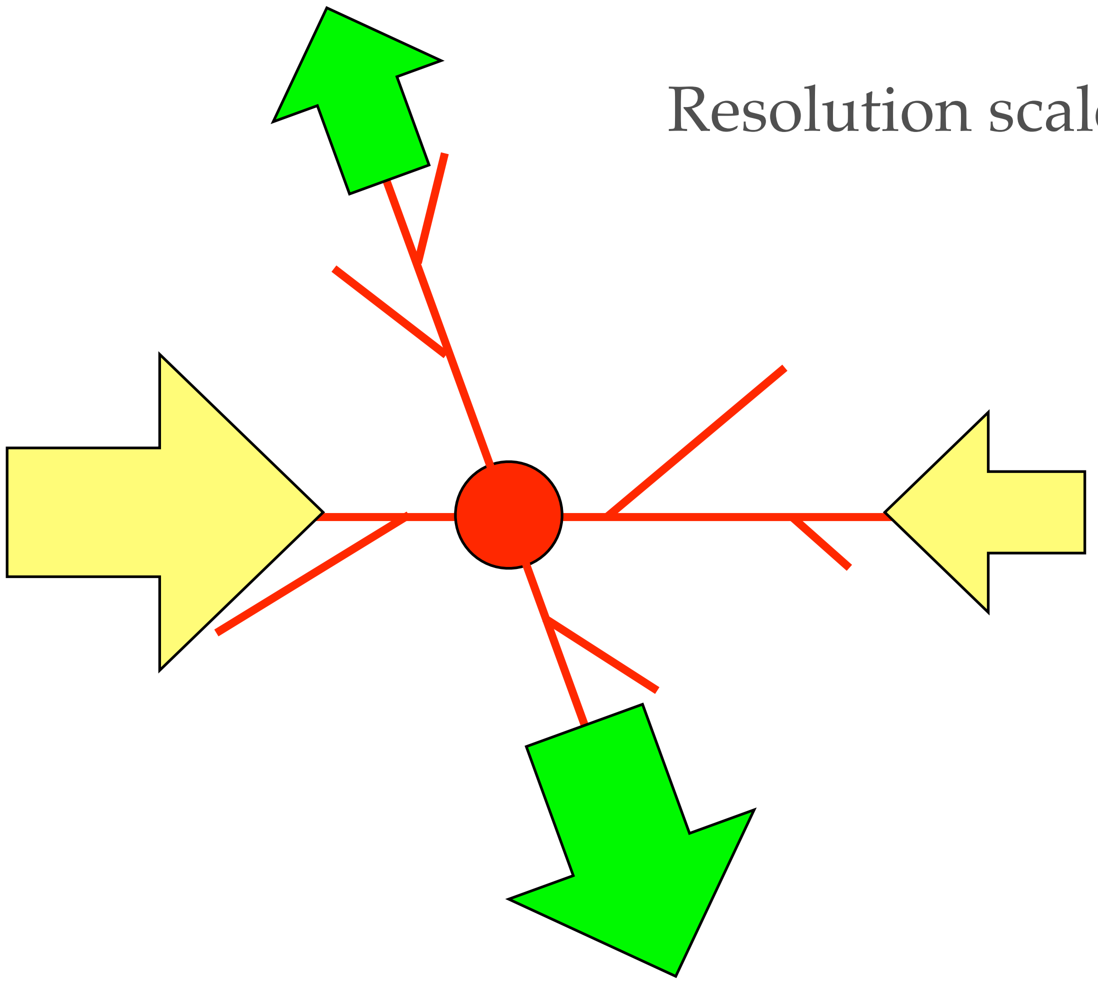

Resolution scale: 100 GeV

Decreasing the resolution scale, more and more partons are visible and less absorbed by the incoming hadrons and the final state jets.

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$$\mathcal{U}(t_\mathrm{f}, t_2)\big|\mathcal{M}_2\big) = \underbrace{\mathcal{N}(t_\mathrm{f}, t_2)\big|\mathcal{M}_2\big)}_{\text{“Nothing happens”}} + \overbrace{\int_{t_2}^{t_\mathrm{f}} dt_3\, \mathcal{U}(t_\mathrm{f}, t_3)\mathcal{H}(t_3)\mathcal{N}(t_3, t_2)\big|\mathcal{M}_2\big)}^{\text{“Something happens”}}$$

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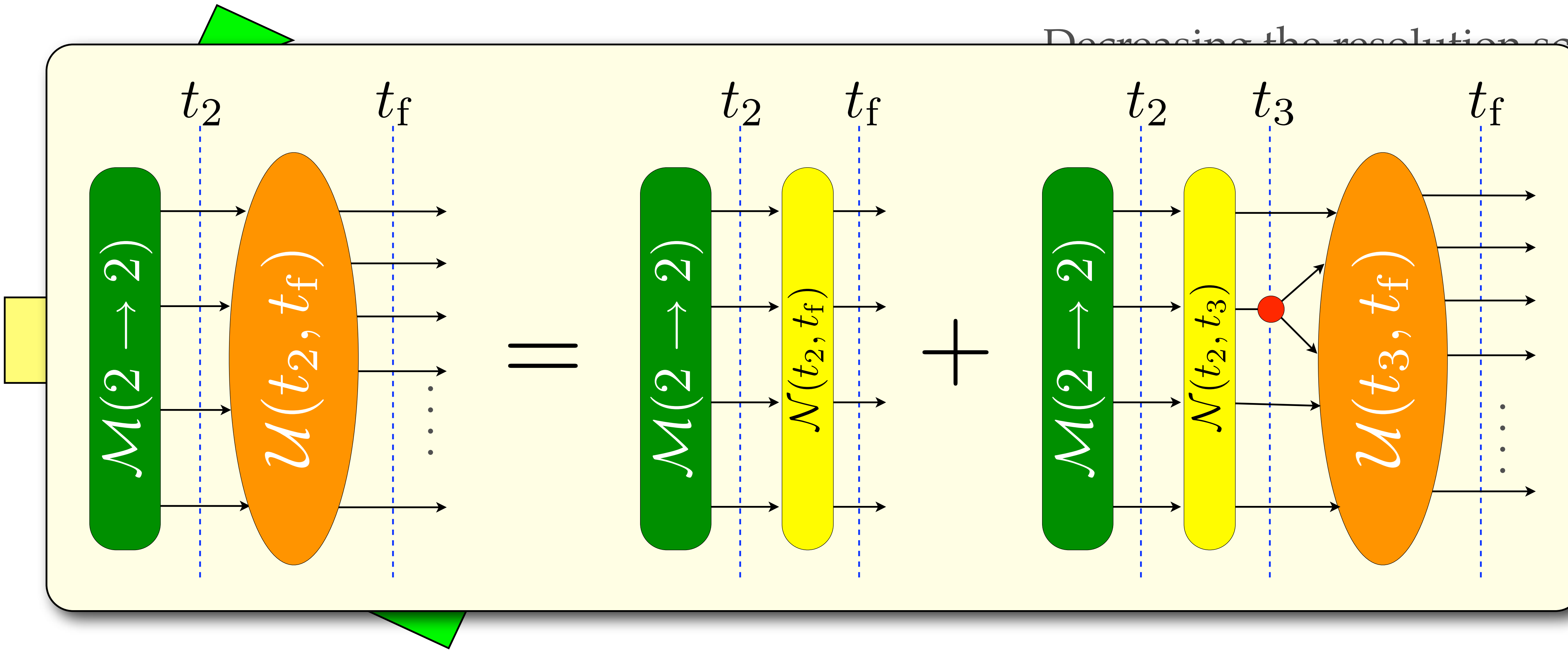


$$\mathcal{U}(t_\mathrm{f},t_2)|\mathcal{M}_2) = \underbrace{\mathcal{N}(t_\mathrm{f},t_2)|\mathcal{M}_2)}_{\text{“Nothing happens”}} + \overbrace{\int_{t_2}^{t_\mathrm{f}} dt_3\,\mathcal{U}(t_\mathrm{f},t_3)\mathcal{H}(t_3)\mathcal{N}(t_3,t_2)|\mathcal{M}_2)}^{\text{“Something happens”}}$$

Statistical space

In QCD a m-patron system is described by the density operator

$$\rho(\{p,f\}_m) = \big|\mathcal{M}(\{p,f\}_m)\big\rangle\big\langle\mathcal{M}(\{p,f\}_m)\big|$$
$$= \sum_{s,c,s',c'} \big|\{s',c'\}_m\big\rangle\big(\{p,f,s',c',s,c\}_m\big|\rho\big)\big\langle\{s,c\}_m\big|$$

In the statistical space it is represented by a vector

$$\big|\rho\big) = \sum_m \frac{1}{m!}\int \big[d\{p,f,s',c',s,c\}_m\big]\,\big|\{p,f,s',c',s,c\}_m\big)\,\big(\{p,f,s',c',s,c\}_m\big|\rho\big)$$

Measurement operators can be also represented by vectors in the statistical space

$$\big|F\big) = \sum_m \frac{1}{m!}\int \big[d\{p,f,s',c',s,c\}_m\big]\,\big|\{p,f,s',c',s,c\}_m\big)\,F(\{p,f\}_m)$$

E.g.: Total cross section $\qquad \big|1\big) \Leftrightarrow F(\{p,f\}_m) = 1$

Transverse momentum in Drell-Yan: $\qquad \big|\boldsymbol{p}_\perp\big) \Leftrightarrow F(\{p,f\}_m) = \delta(\boldsymbol{p}_\perp - \boldsymbol{p}_{\perp,Z})$

QCD vs. MC

SHOWER CROSS SECTION

$$\sigma^S[F] = \big(F\big|\rho\big)$$

- It is an all order but approximated calculation
- Based on soft and collinear factorization of the amplitudes
- Usually more approximation considered (e.g: large Nc,...)
- Implemented in general purpose MC programs (HERWIG, PHYTIA,...)
- *Sums up large logarithms*

QCD CROSS SECTION

$$\sigma^{QCD}[F]$$

- It is an all order but approximated calculation
- Based on soft and collinear factorization of the amplitudes
- Precise in color
- Case-by-case rather elaborate calculation
- *Sums up large logarithms, correctly*

Let us compare them!

QCD vs. MC

Shower cross section

$$\sigma^S[F] = (F|\rho)$$

- It is an all order but approximated calculation
- Based on soft and c… factorization of the…
- Usually more appr… considered (e.g: lar…
- Implemented in general purpose MC programs (Herwig, Phytia,…)
- *Sums up large logarithms*

Herwig has been tested for

- e+e-: thrust, C-parameter, Durham jet rates, jet mass distribution, …
- DIS, DY: large x

QCD cross section

$$\sigma^{QCD}[F]$$

- It is an all order but approximated
- …and collinear …of the amplitudes
- …r
- …rather elaborate calculation
- *Sums up large logarithms, correctly*

Let us compare them!

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.

This has been checked both analytically and numerically and the shower is consistent with the DGALP equation.

Stefan Weinzierl presented numerical results

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.

$$\big(\boldsymbol{p}_\perp\big|\mathcal{U}(t,0)\big|M_2\big) = \big(\boldsymbol{p}_\perp\big|\mathcal{N}(t,0)\big|M_2\big) + \int_0^t d\tau\,\big(\boldsymbol{p}_\perp\big|\mathcal{H}(\tau)\mathcal{N}(\tau,0)\big|M_2\big)$$

This is effectively an approximated NLO calculation with summation of the virtual emissions. No resummation of the large logarithms correctly. We got wrong equation because of the choice of the momentum mapping.

Simon Plaetzer reported modified version where this kinematical issue is fixed.

The correct equation is

$$\big(\boldsymbol{p}_\perp\big|\mathcal{U}(t,0)\big|M_2\big) = \big(\boldsymbol{p}_\perp\big|\mathcal{N}(t,0)\big|M_2\big) + \int_0^t d\tau\,\big(\boldsymbol{p}_\perp\big|\mathcal{U}(t,\tau)\mathcal{H}(\tau)\mathcal{N}(\tau,0)\big|M_2\big)$$

We have to study analytically and test against known QCD results.

QCD: Drell-Yan process

The NLL expression of the pT distribution was obtained using the renormalization group technique and the result at NLL level is

$$\frac{d\sigma}{d\boldsymbol{p}_\perp\, dY} = \int \frac{d\boldsymbol{b}}{(2\pi)^2}\, e^{\mathrm{i}\boldsymbol{p}_\perp\cdot\boldsymbol{b}} \exp\left\{ -C_{\mathrm{F}} \int_{C^2/\boldsymbol{b}^2}^{M^2} \frac{d\boldsymbol{k}^2}{\boldsymbol{k}^2} \frac{\alpha_{\mathrm{s}}(\boldsymbol{k}^2)}{\pi} \left[\log\frac{M^2}{\boldsymbol{k}^2} - \frac{3}{2}\right]\right\}$$
$$\times \sum_{a,b} H^{(0)}_{a,b}\, f_{a/A}\left(x_{\mathrm{A}}, \frac{C^2}{\boldsymbol{b}^2}\right) f_{b/B}\left(x_{\mathrm{A}}, \frac{C^2}{\boldsymbol{b}^2}\right)$$

where

$$x_{\mathrm{A}} = \sqrt{\frac{M^2}{s}} e^{Y} \qquad x_{\mathrm{B}} = \sqrt{\frac{M^2}{s}} e^{-Y} \qquad C = 2e^{-\gamma_E}$$

Let's try to calculate this formulae from the shower equation!

Anna Kulesza had a nice overview on the current progress on the summation of large logarithms in the processes with color singlet in the final state

MC: Drell-Yan process

The result and the derivation strongly depends on the shower algorithm, so it is useful to stick at one. My choice an shower algorithm with quantum interference.

Z.N, D.E. Soper: JHEP 0709:114,2007; JHEP 0803:030,2008; JHEP 0807:025,2008

Now, the shower equation is

$$\frac{d}{dt}\big(\hat{\boldsymbol{p}}, Y\big|\rho(t)\big) = \big(\hat{\boldsymbol{p}}, Y\big|\mathcal{H}_{\rm I}(t) - \mathcal{V}(t)\big|\rho(t)\big)$$

After some harmless approximations, algebraic manipulations and about 2 months of hard work the result is

$$\frac{d\sigma}{d\boldsymbol{p}_\perp\, dY} = \int \frac{d\boldsymbol{b}}{(2\pi)^2}\, e^{{\rm i}\boldsymbol{p}_\perp\cdot\boldsymbol{b}} \exp\left\{-C_{\rm F}\int_{C^2/\boldsymbol{b}^2}^{M^2} \frac{d\boldsymbol{k}^2}{\boldsymbol{k}^2}\, \frac{A_s(\boldsymbol{k}^2)}{\pi}\left[\log\frac{M^2}{\boldsymbol{k}^2} - \frac{3}{2}\right]\right\}$$
$$\times \sum_{a,b} H_{a,b}^{(0)}\, f_{a/A}\left(x_{\rm A}, \frac{C^2}{\boldsymbol{b}^2}\right)\, f_{b/B}\left(x_{\rm A}, \frac{C^2}{\boldsymbol{b}^2}\right)$$

With the support of the DGLAP equation for the PDFs:

$$\mu_F^2 \frac{d}{d\mu_F^2} f_{a/{\rm A}}(x, \mu_F^2) = -\sum_{\hat{a}} \int_0^1 \frac{dz}{z}\, \frac{\alpha_{\rm s}(\mu_{\rm R}^2)}{2\pi}\, P_{\hat{a},a}(z)\, f_{\hat{a}/{\rm A}}(x/z, \mu_F^2)$$

MC: Drell-Yan process

The result is strongly depends on the choice of the *argument of the α_s in the shower*:

$$\frac{A_s(\boldsymbol{k}^2)}{\pi} = \frac{\alpha_{\rm s}(M^2)}{\pi}\left(1 - A^{(1)}\,\beta_0 \frac{\alpha_{\rm s}(M^2)}{2\pi}\log\frac{M^2}{\boldsymbol{k}^2}\right)$$

Using transverse momentum then we have, $A^{(1)} = 1$

$$\frac{A_s(\boldsymbol{k}^2)}{\pi} = \frac{\alpha_{\rm s}(\boldsymbol{k}^2)}{\pi}$$

$\Rightarrow$ *NLL result in the exponent*

We need a modified LO PDF

$$\mu_F^2 \frac{d}{d\mu_F^2} f_{a/\mathrm{A}}(x,\mu_F^2) = \sum_{\hat{a}} \int_0^1 \frac{dz}{z} \frac{\alpha_{\rm s}((1-z)\mu_{\rm F}^2)}{2\pi} P_{\hat{a},a}(z)\, f_{\hat{a}/\mathrm{A}}(x/z,\mu_F^2)$$

Modified LO PDF

Expanding the strong coupling, we have

$$\mu_F^2 \frac{d}{d\mu_F^2} f_{a/\mathrm{A}}\left(x, \mu_F^2\right) = \sum_{\hat{a}} \int_0^1 \frac{dz}{z} \frac{\alpha_{\mathrm{s}}(\mu_{\mathrm{F}}^2)}{2\pi} P_{\hat{a},a}(z)\, f_{\hat{a}/\mathrm{A}}\left(x/z, \mu_F^2\right)$$

$$- \sum_{\hat{a}} \int_0^1 \frac{dz}{z} \left[\frac{\alpha_{\mathrm{s}}(\mu_{\mathrm{F}}^2)}{2\pi}\right]^2 \beta_0 \log(1-z) P_{\hat{a},a}(z)\, f_{\hat{a}/\mathrm{A}}\left(x/z, \mu_F^2\right)$$

- Adds some NLO correction to the standard LO PDFs.
- The LO part is the standard evolution. The NLO piece violate the momentum sum rule dynamically.
- This violation is less important at large scale.
- This is *not a universal* PDF, other shower models might prefer other solution.
- With this choice of the PDFs and renormalization scale we can sum up all the LL and NLL contributions only for the pT Drell-Yan distribution there is *no guarantee* that this works for other observable.
- In principle shower *has chance to* sum up all the *LL and the LO NLL* contributions.
- Shower is only an exponentiated LO (*let's call it eLO*) calculation.

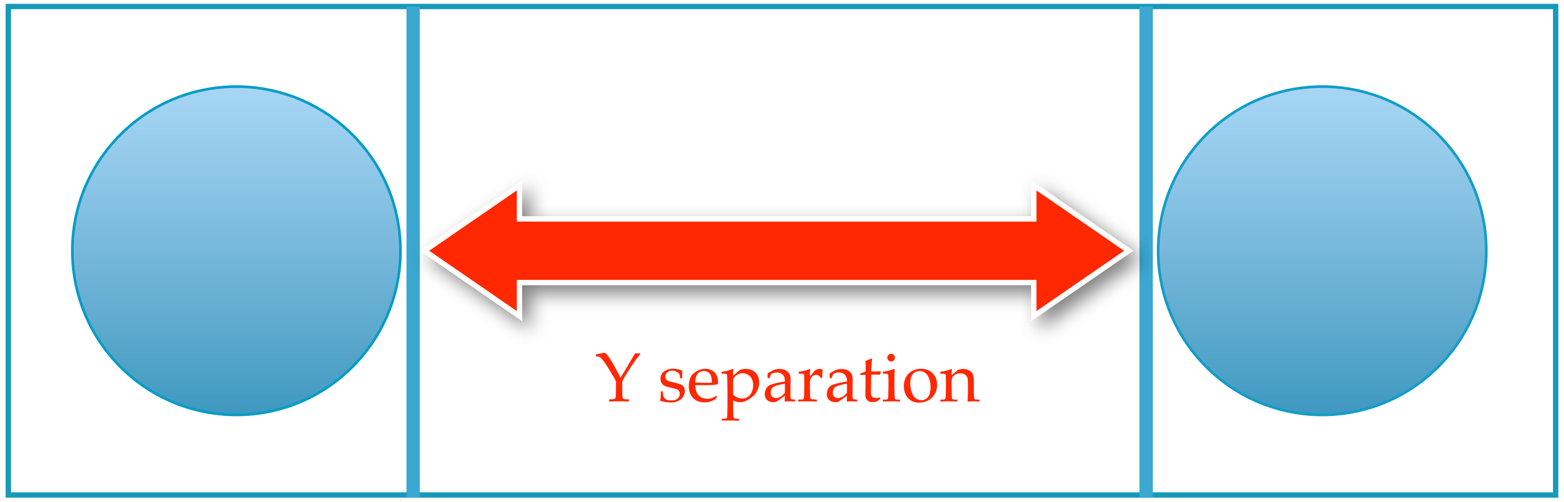
"has chance to" $\neq$ *"does"*

Non-global Observables

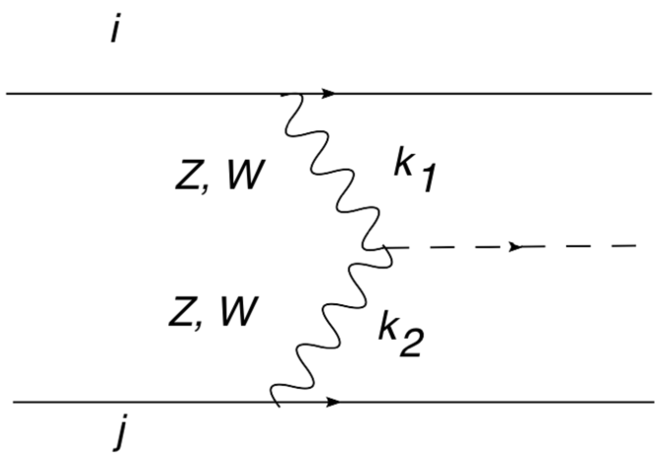
Simone Marzani had a overview on the gap between jet probles

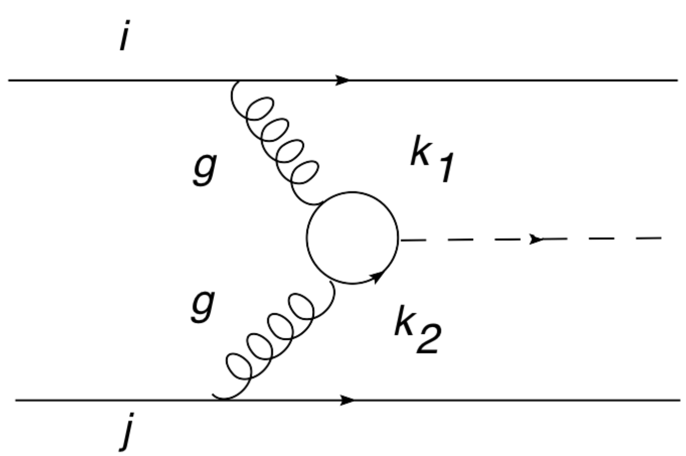
Production of two jets:

- with transverse momentum Q
- with rapidity separation Y
- emissions with $k_T > Q_0$



Motivation:





- Possible Higgs discovery channel
- Important to extract the VVH coupling
- Different QCD radiation in the interjet region

What happens if we dress the hard scattering with soft gluons?

Color Evolution

In the naive approach the real and virtual contributions are cancelled everywhere except in the gap region where $k_T > Q_0$.
One only needs to consider virtual contributions in the gap region

$$Q_0 < k_T < Q$$

$$\mathcal{M} = e^{-\alpha_s \log \frac{Q}{Q_0} \boldsymbol{\Gamma}} \mathcal{M}_B$$

anomalous dimension:
its an operator in the color space

Needs color evolution!

✗ All the classical showers (HERWIG, PHYTIA, ARIADNE, CS-dipole) fails to do color evolution

✓ There is a fully defined shower algorithm that can consider quantum interferences

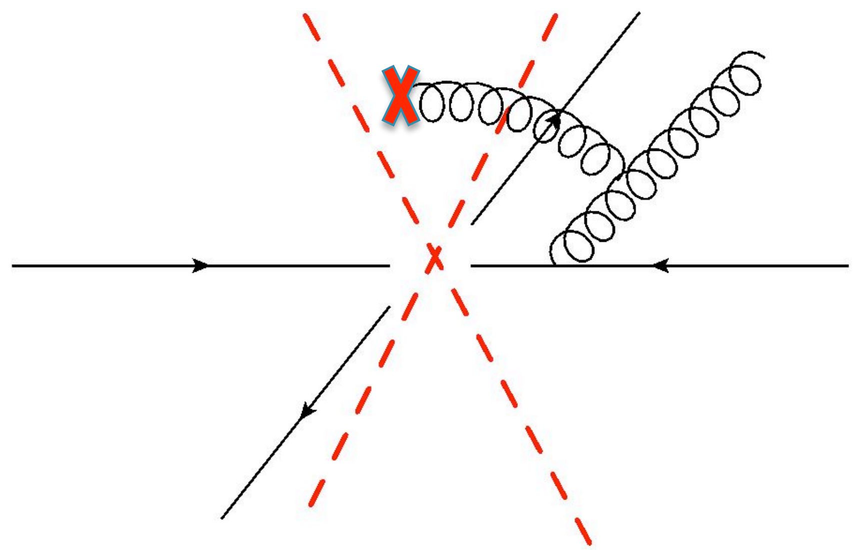
Z.N, D.E.Soper: JHEP 0709:114,2007; JHEP 0803:030,2008; JHEP 0807:025,2008

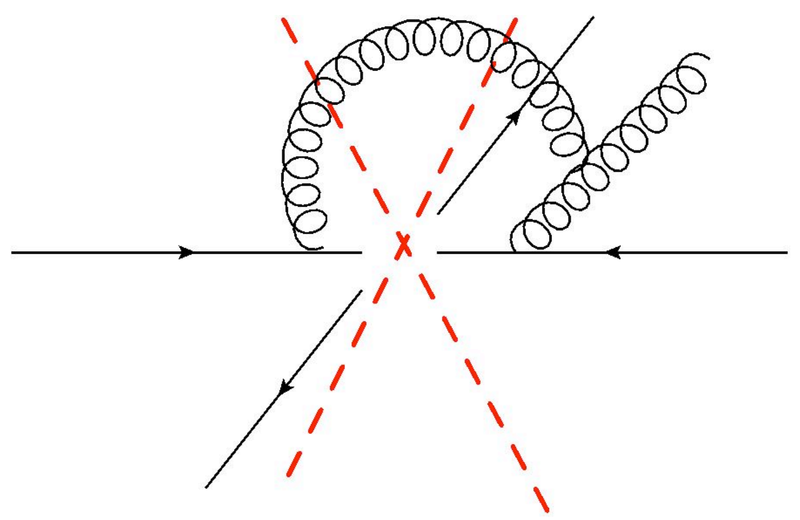
✗ You still have to wait for the implementation...

Non-global Effects

Virtual contributions are not the whole story because real emissions out of the gap are forbidden to remit back into the gap

Dasgupta and Salam: hep-ph/0104277





This configurations lead to the so-called *Super-Leading Logs (SLL)*

$$\sigma^{(1)} \sim -\alpha_s^4 L^5 \pi^2 + \cdots$$

Forshaw, Kyrieleis, Seymour hep-ph/0604094

This logarithms are entirely due to the emission of the Coulomb gluons:

$$\mathbf{\Gamma} = i\pi\, \boldsymbol{T}_1 \cdot \boldsymbol{T}_2 + \cdots$$

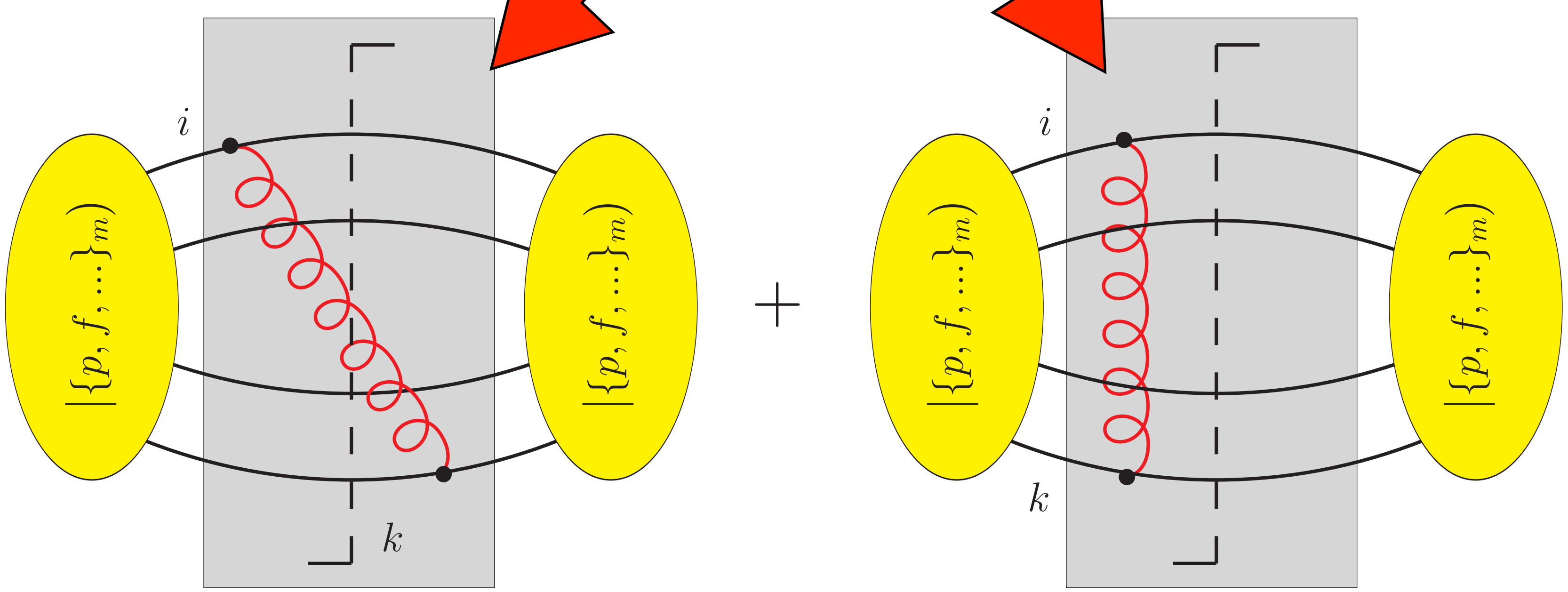
Do the "Quantum Shower" or any other shower know about these logarithms?

MC: Non-global Effects

Answer: None of them knows.

Using the factorization properties of the QCD the approximated order by order calculation can be organized according to

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



- ➡ Real emissions
  - ✓ Based on the soft and collinear factorization
  - ✓ True matrix elements considered
- ➡ Virtual emissions
  - ✓ Obtained from the unitary condition, $(1|\mathcal{H}_I(t) = (1|\mathcal{V}(t)$
  - ✗ No 1-loop amplitudes considered explicitly
  - ✗ Missing genuine 1-loop contributions

Do we need this precision?

Color & Spin Evolution

Classical probabilistic picture

- positiveness
- unweighted shower

Quasi-classical probabilities

- still can be organized as a Markovian process
- real weighted for color ($w \approx 1$)
- complex weights for spins

Non-global effects

Quantum probabilities

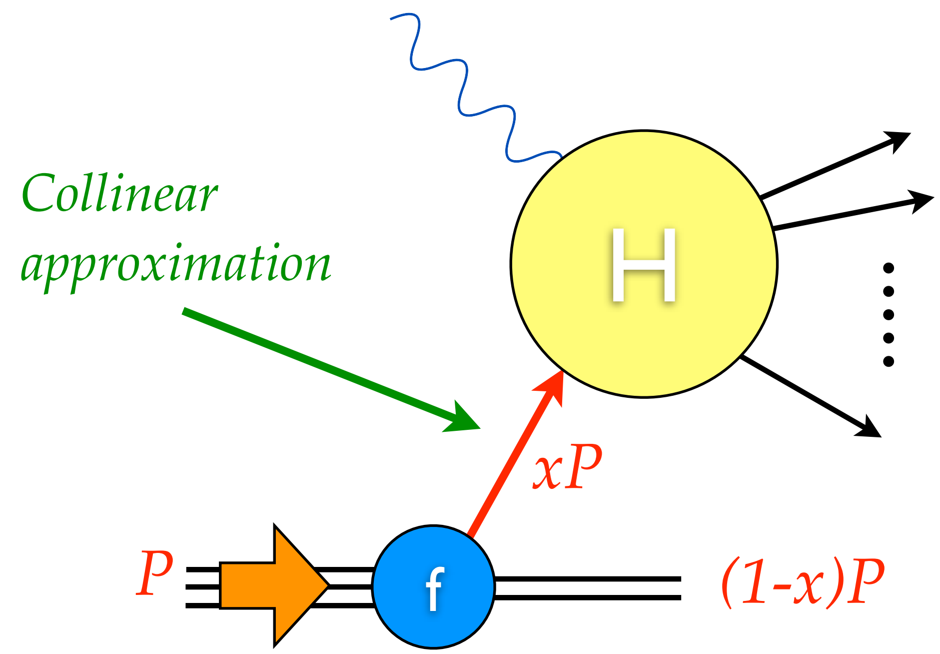
- *quantum Markovian process ???*
- complex weights everywhere
- .....

$$\sigma^{MC}[F] = \big(F\big|\underbrace{\mathcal{D}(t_f)}_{\text{Hadronization}}\big|\rho(t_f)\big)$$

- Hadronization can be considered as a implicit measurement of the partonic color flow. The quantum effects could be important.
- Interesting physics from non-global observable
- Better understanding of QCD dynamics
- In QCD *"Q"* stands for *"Quantum"* ....

Factorization Theorem

STANDARD COLLINEAR FACTORIZATION



$$\sigma = \int_0^1 dx\, f(x, \mu_F^2)\, \hat{\sigma}(xP) + \mathcal{O}(\Lambda/Q)$$

- With the collinear approximation we are able to write the cross section in simple factorized form. This factorization can be proofed.
- The PDF depends only on the momentum fraction variable.

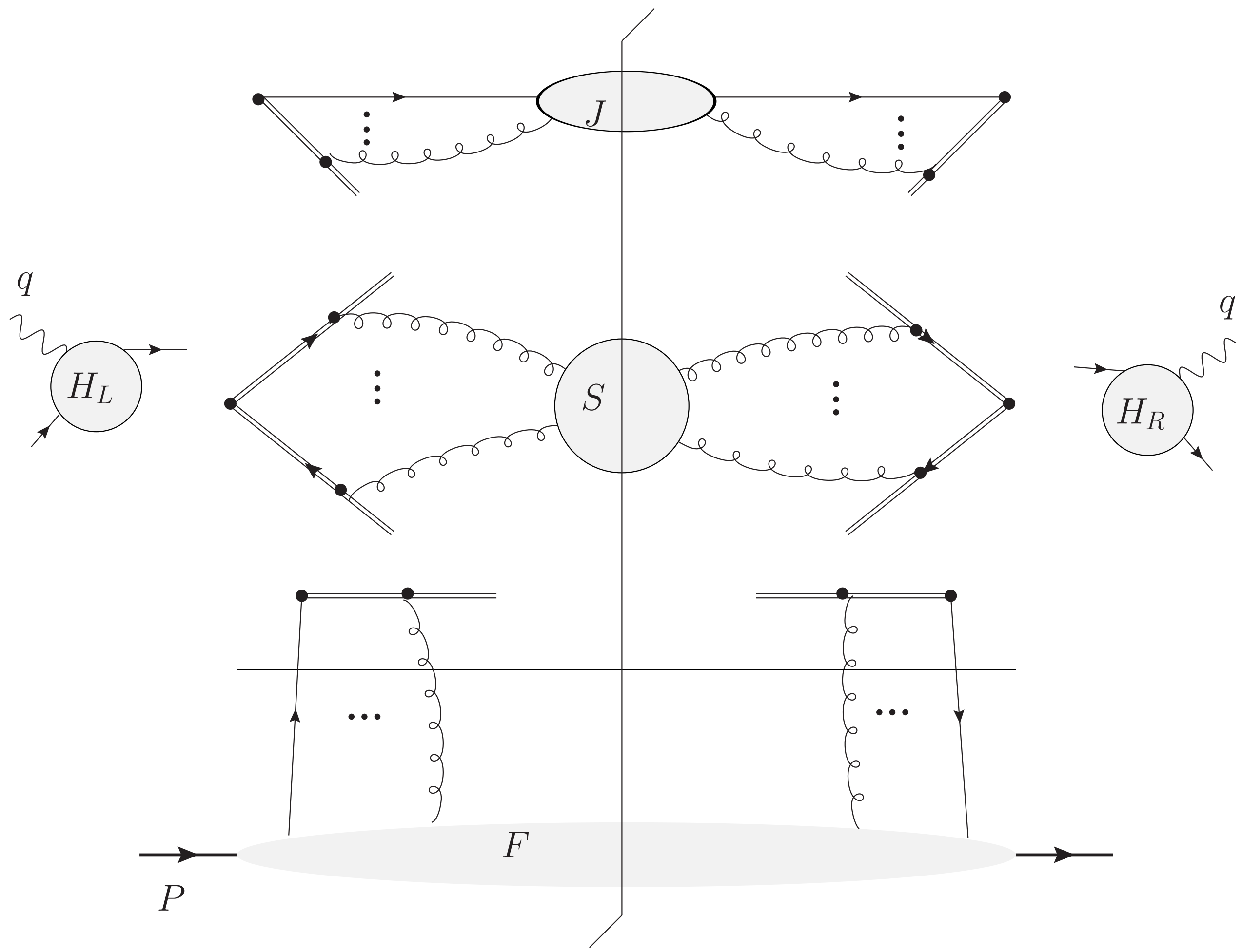
- *We might loose important kinematical effect with the collinear approximation in the initial state.*
- *Can we proof factorization if we consider the full kinematics correctly?*

Fully Unintegrated PCF

Ted Rogers had a overview on fully unintegrated parton correlation functions

Francesco Hautmann talk about unintegrated (kT dependent) PDFs

The factorization is proofed by Collins and Rogers in Abelian gauge theory. There are some indication that it works for QCD.

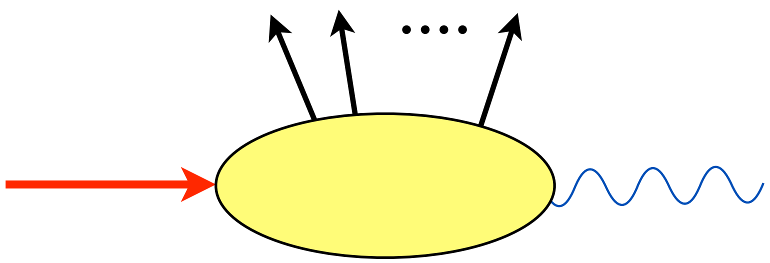


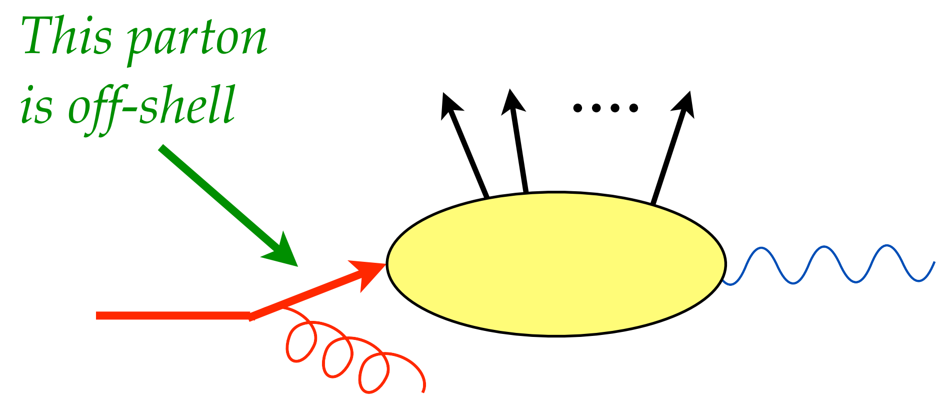
- ✓ There is factorization
- ✓ Two more non-perturbative universal functions.
- ✗ No evolution equation for them, so far.
- ✗ No model to calculate them
- ✗ Lots of theory difficulties
- *One can ask why to bother*

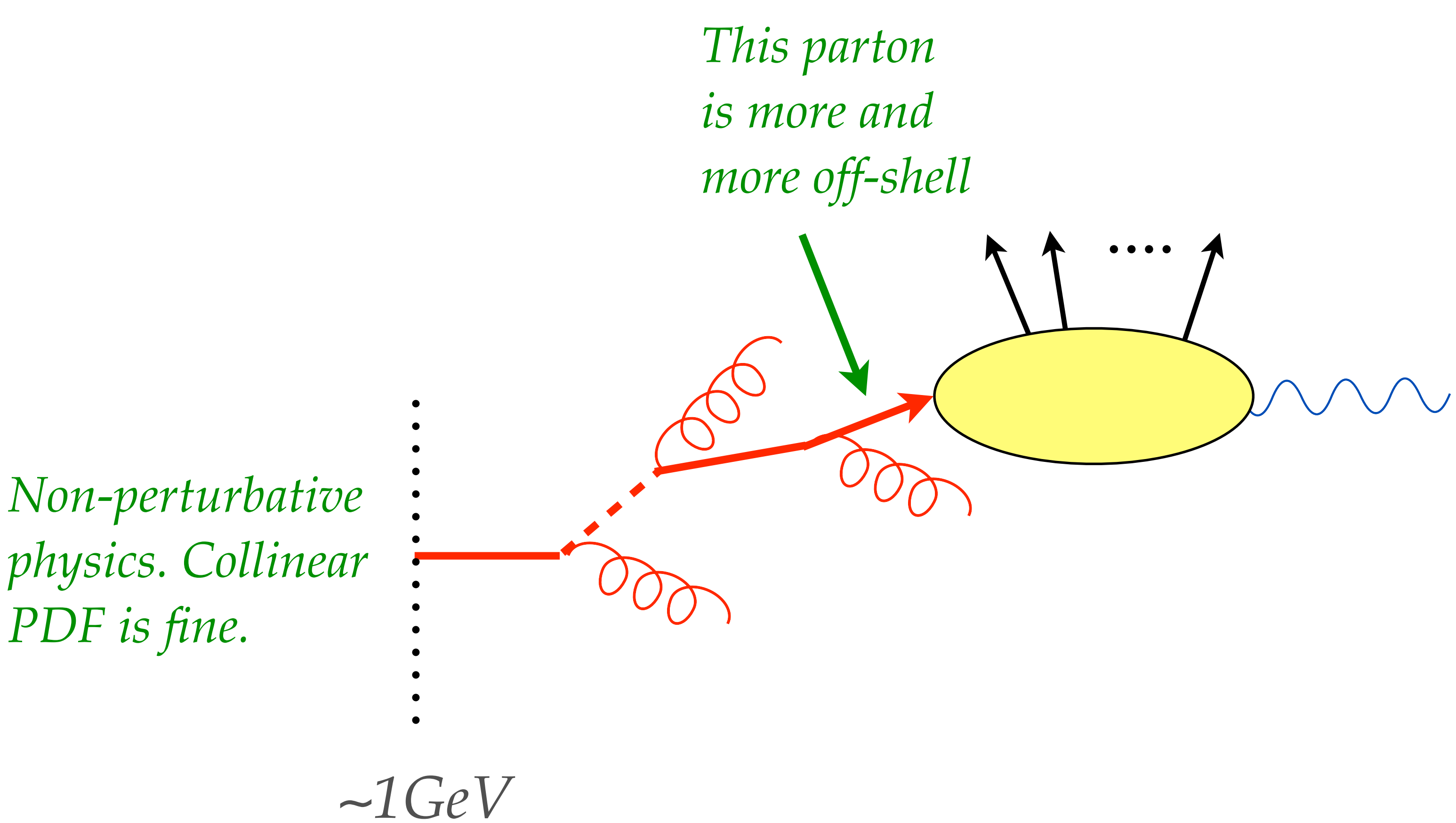
$$\sigma = \int \frac{d^4 k_{\rm T}}{(2\pi)^4} \frac{d^4 k_{\rm J}}{(2\pi)^4} \frac{d^4 k_S}{(2\pi)^4} (2\pi)^4 \delta^{(4)}(q + P - k_{\rm T} - k_{\rm J} - k_S)$$

$$\times |H(Q, \tilde{k}_T, \tilde{k}_J, \mu)|^2 \; S_2(k_S, y_s, \mu) \; F(k_{\rm T}, y_p, y_s, \mu) \; J(k_{\rm J}, y_s, \mu),$$

Shower Model PCF







- It seem to me that a *"carefully defined"* parton shower generates the fully unintegrated PCFs.
- Studying generalized factorization can help us to improve our MC models.

$$S_2(q+P-k_{\mathrm{T}}-k_{\mathrm{J}}, y_s, \mu)\ F(k_{\mathrm{T}}, y_p, y_s, \mu)\ J(k_{\mathrm{J}}, y_s, \mu) \sim \frac{\left(k_T, k_J \middle| \mathcal{U}(t_f, 0) \middle| H\right)}{|H(Q, \tilde{k}_T, \tilde{k}_J, \mu)|^2}$$

Summary

- It is important to test parton shower against resummed QCD calculation.
- This can help us to treat it more systematically.
- Modified parton distribution functions.
- Need more work on color evolution, spin correlations, non-global effect,...., more theory work required.
- *Important but I didn't talk about* NLO shower, matching to LO and NLO fix order matrix elements.