PHYSICS AT THE TERA SCALE

Helmholtz Alliance

We need just a program that describes the data, don't we?

http://www.terascale.de

Zoltán Nagy

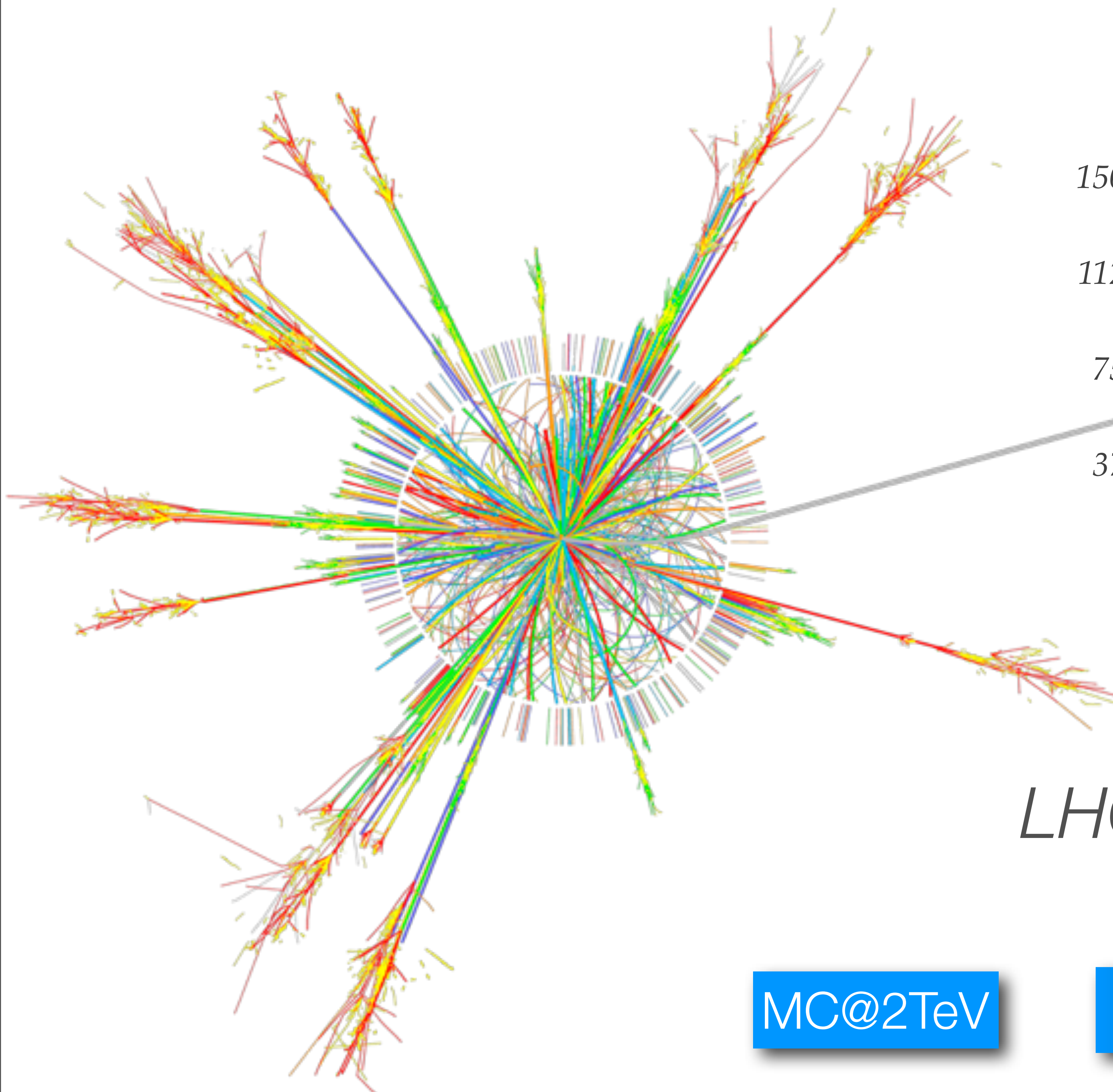
DESY, Terascale Analysis Center

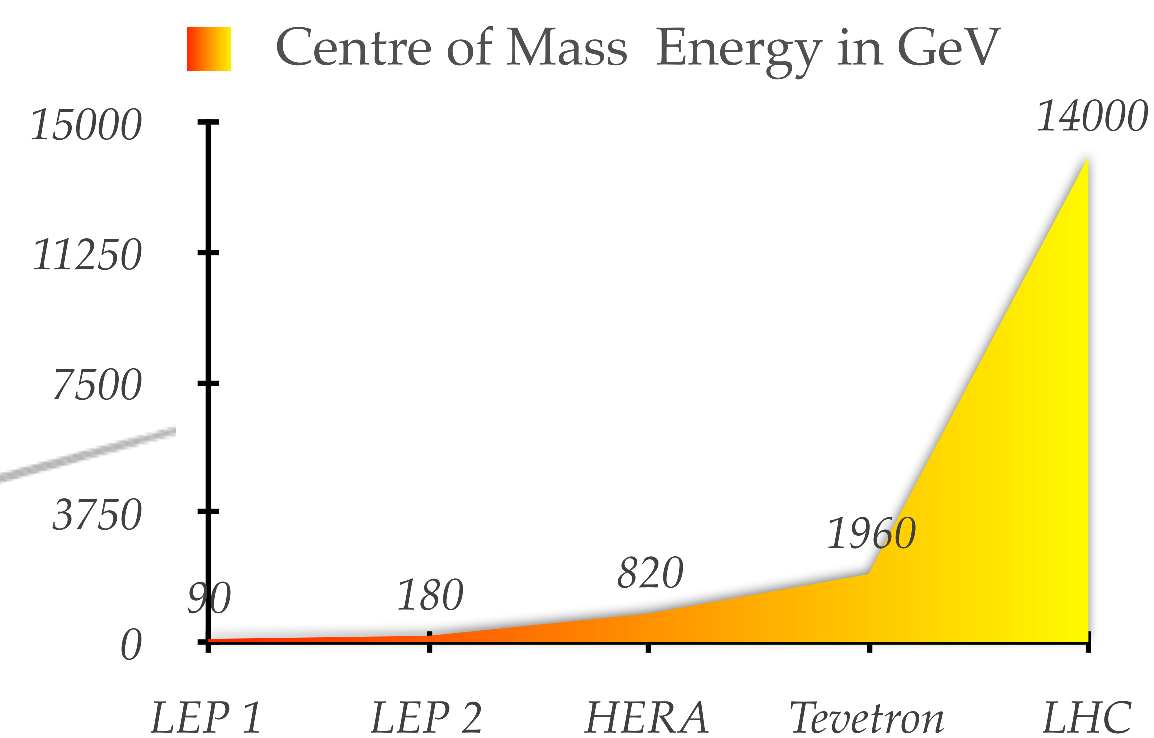
MPI Discussion

May 17, 2010, Hamburg

Introduction

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





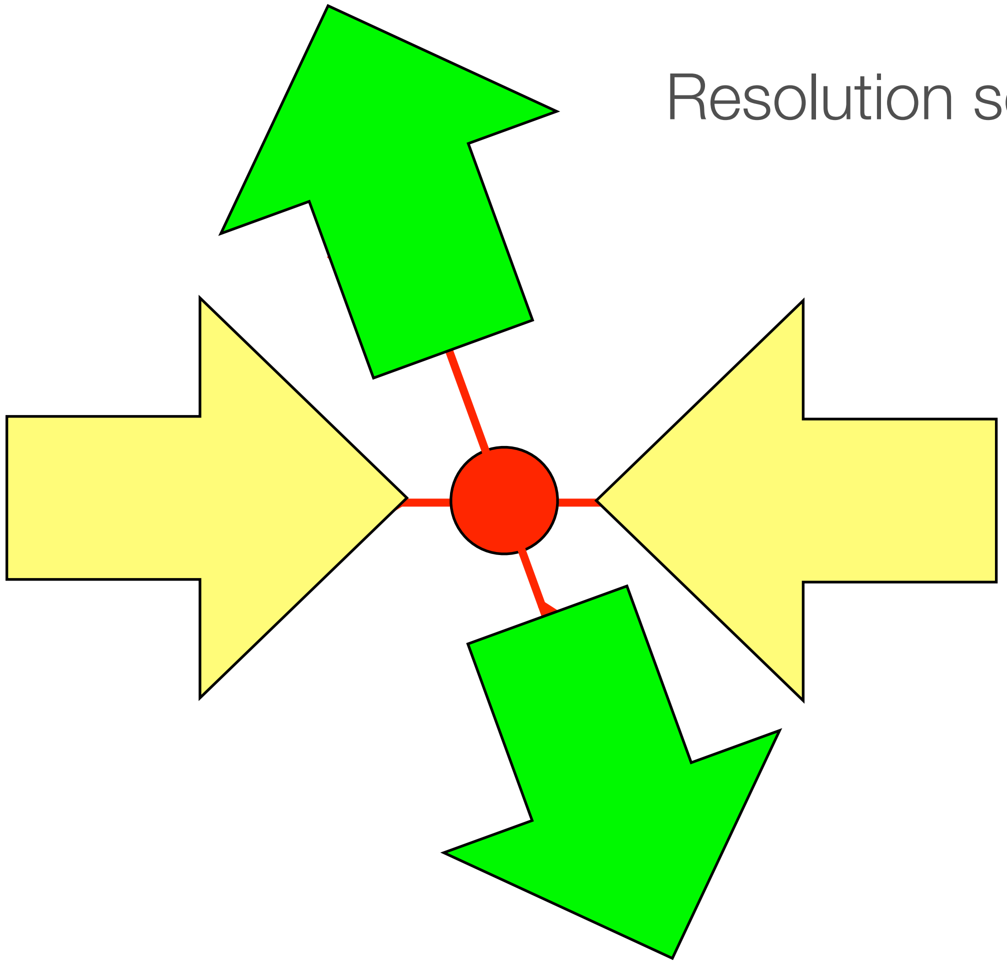
$$LHC = QCD + \varepsilon$$

MC@2TeV → *Extrapolation* → MC@14TeV

Picture: ATLAS simulation

Hadron-hadron Collision

In hardon-hadron collision the picture is more complicated.



Resolution scale: 400 GeV

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

Important observation: The total cross section *is independent of* the resolution of the measurement (or detector).

We have to also consider the evolution of the final state jets.

Does perturbative QCD support this nice intuitive picture?

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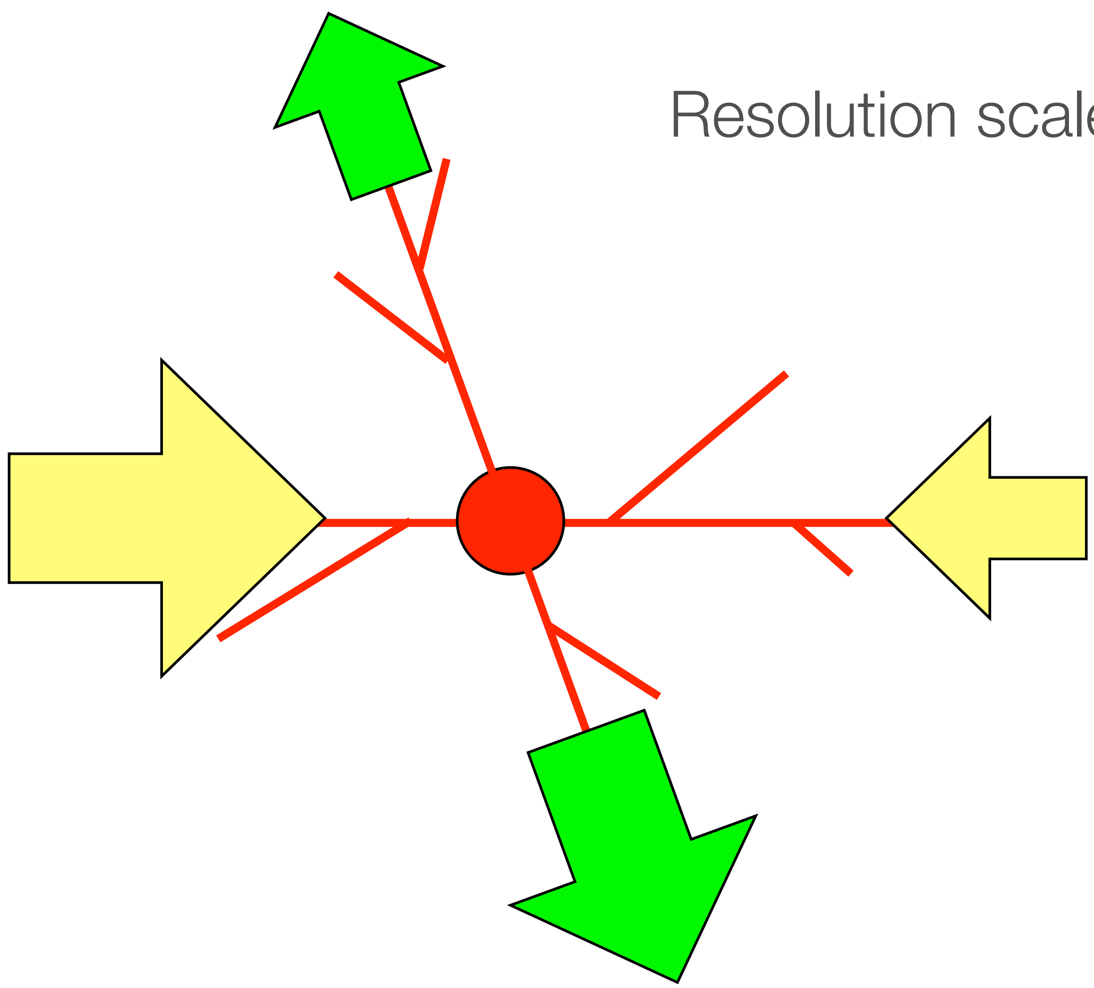

Resolution scale: 100 GeV

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

Important observation: The total cross section *is independent of* the resolution of the measurement (or detector).

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Does perturbative QCD support this nice intuitive picture?

Approx. of the Density Operator

The *m+1* parton physical state is represented by density operator in the quantum space and by the statistical state in the statistical space.

$$\rho\big(\{p,f\}_{m+1}\big) \Leftrightarrow \big|\rho(\{p,f\}_{m+1})\big)$$

This is based on the *m+1* parton matrix elements. They are very complicated (especially the loop matrix elements). We try to approximate them by using their *soft collinear factorization properties*. For this we introduce operators in the statistical space:

$$\big|\rho(\{\hat{p},\hat{f}\}_{m+1})\big) \approx \int_{t_m}^{\infty} dt\,\Big[\underbrace{\mathcal{H}_C(t)}_{\text{Collinear and soft-collinear contribution}} + \overbrace{\mathcal{H}_S(t)}^{\text{Wide angle soft contributions}}\Big]\big|\rho(\{p,f\}_m)\big)$$

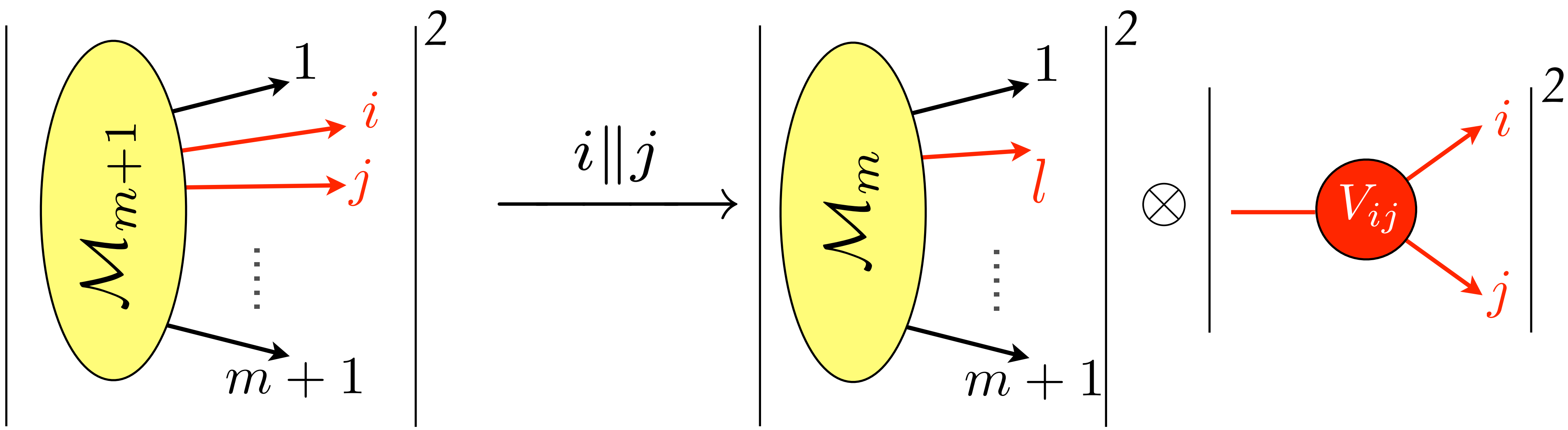
This parameter represents the hardness of the splitting. We will call it ***shower time****.*

The total splitting operator is

$$\mathcal{H}_I(t) = \mathcal{H}_C(t) + \mathcal{H}_S(t)$$

Collinear Singularities

The QCD matrix elements have universal factorization property when two external partons become collinear

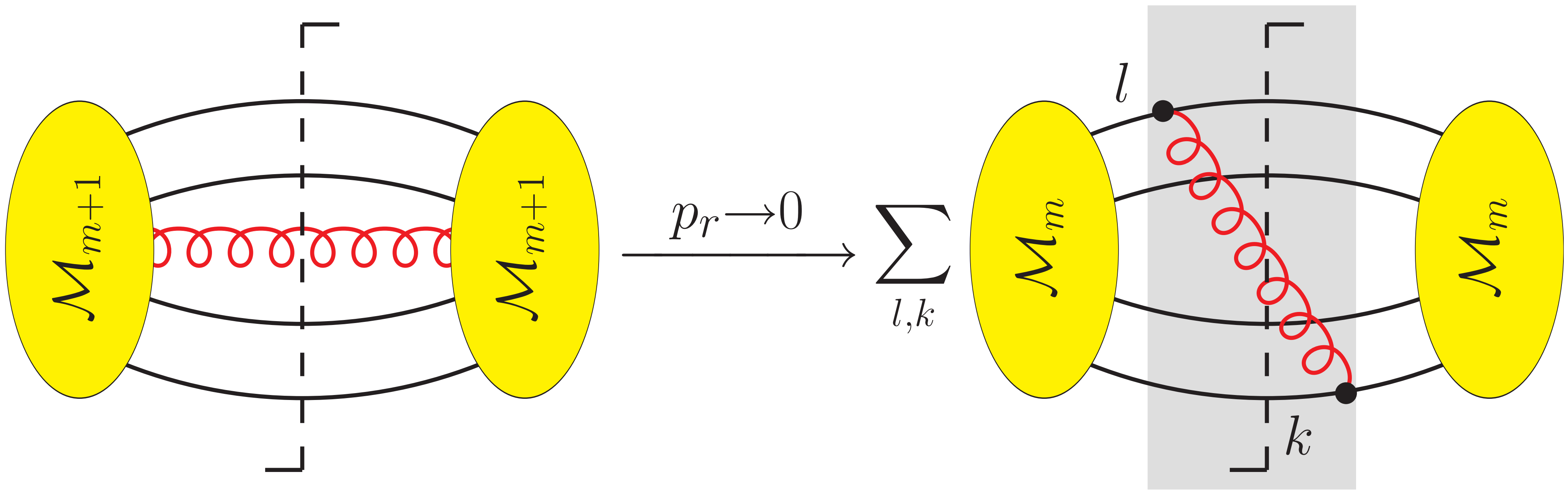


$$\mathcal{H}_C \sim \sum_l t_l \otimes t_l^\dagger \, V_{ij}(s_i, s_j) \otimes V_{ij}^\dagger(s'_i, s'_j) \Leftrightarrow \frac{\alpha_s}{2\pi} \sum_l \frac{1}{p_i \cdot p_j} P_{f_l, f_i}(z) + \dots$$

Altarelli-Parisi splitting kernels

Soft Singularities

The QCD matrix elements have universal factorization property when an external gluon becomes soft



$$\mathcal{H}_S \sim -\sum_{\substack{l,k \\ l \neq k}} \frac{\hat{p}_l \cdot \varepsilon(s)\, \hat{p}_k \cdot \varepsilon(s')}{\hat{p}_l \cdot \hat{p}_{m+1}\, \hat{p}_k \cdot \hat{p}_{m+1}}\, t_l \otimes t_k^{\dagger}$$

Soft gluon connects everywhere and the color structure is not diagonal; quantum interferences in the color space.

Resolvable Splittings

Let us consider a physical state at shower time t, $|\rho(t))$. This means every parton is resolvable at this time (this scale). Now, we apply the splitting operator:

$\mathcal{H}_I(t)$ *operator changes*

- the number of the partons, $m \to m+1$
- the color and spin structure
- flavors and momenta

$$|\rho^{\mathrm{R}}_{\infty}) = \int_t^{\infty} d\tau\, \mathcal{H}_I(\tau)\, |\rho(t))$$

This is good approximation if we allow only softer radiations than t, $\tau > t$

Now, let us consider a measurement with a resolution scale which correspond to shower time t'

$$|\rho^{\mathrm{R}}_{\infty}) \approx \underbrace{\int_t^{t'} d\tau\, \mathcal{H}_I(\tau)\, |\rho(t))}_{\textit{Resolved radiations}} + \underbrace{\int_{t'}^{\infty} d\tau\, \mathcal{V}_I^{(\epsilon)}(\tau)\, |\rho(t))}_{\textit{Unresolved radiations}}$$

This is a singular contribution

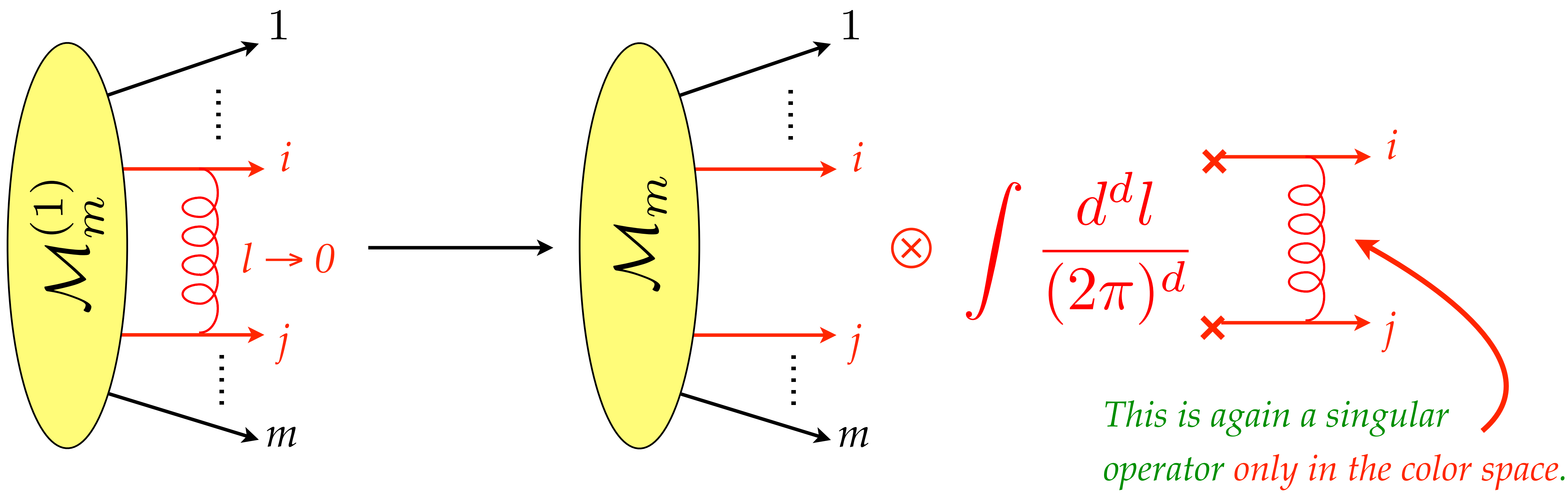
$\mathcal{V}_I(t)$ *operator*

- changes only the color structure
- $(1|\mathcal{V}_I(t) = (1|\mathcal{H}_I(t)$

What can we do about it?

Virtual Contributions

There is another type of the unresolvable radiation, *the virtual (loop graph) contributions.* We have *universal factorization properties* for the loop graphs. E.g.: in the soft limit, when the loop momenta become soft we have



We can use this factorization to *dress up* partonic states *with virtual radiation*. After careful analysis one can found that the virtual contribution can be approximated by

$$\big|\rho_\infty^{\mathrm{V}}\big) \approx -\int_t^\infty d\tau\, \mathcal{V}_I^{(\epsilon)}(\tau)\,\big|\rho(t)\big)$$

Same structure like in the real unresolved case but here with opposite sign.

Physical States

Combining the real and virtual contribution we have got

$$\big|\rho_\infty^{\mathrm{R}}\big) + \big|\rho_\infty^{\mathrm{V}}\big) = \int_t^{t'} d\tau \, [\mathcal{H}_I(\tau) - \mathcal{V}_I(\tau)] \big|\rho(t)\big)$$

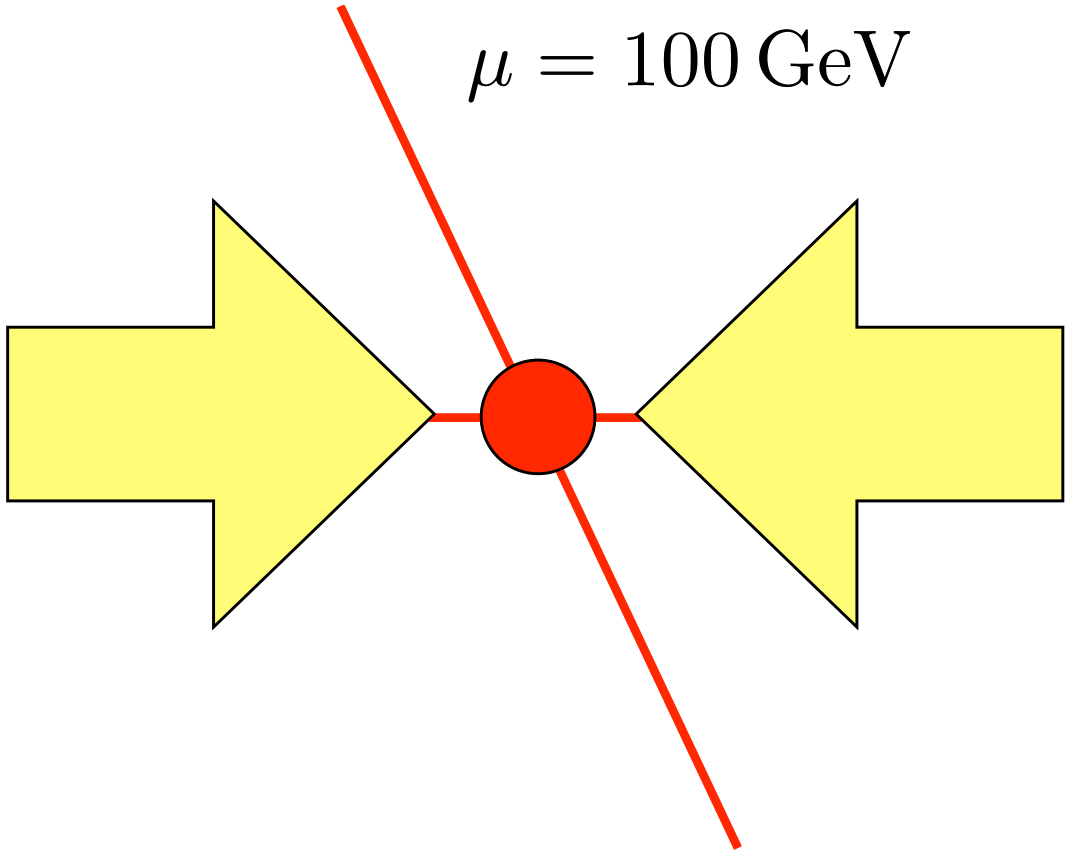
This operator dresses up the physical state with one real and virtual radiations that *is softer or more collinear than the hard state*. Thus the emissions are ordered. Now we can use this to build up physical states by considering all the possible way to go from t to t'.

$$\begin{aligned}\big|\rho(t')\big) = {} & \big|\rho(t)\big) \\ & + \int_t^{t'} d\tau \, [\mathcal{H}_I(\tau) - \mathcal{V}_I(\tau)] \big|\rho(t)\big) \\ & + \int_t^{t'} d\tau_2 \, [\mathcal{H}_I(\tau_2) - \mathcal{V}_I(\tau_2)] \int_t^{\tau_2} d\tau_1 \, [\mathcal{H}_I(\tau_1) - \mathcal{V}_I(\tau_1)] \big|\rho(t)\big) \\ & + \cdots \\ = {} & \underbrace{\mathbb{T} \exp \left\{ \int_t^{t'} d\tau \, [\mathcal{H}_I(\tau) - \mathcal{V}_I(\tau)] \right\}}_{\mathcal{U}(t',t) \ \textit{shower evolution operator}} \big|\rho(t)\big)\end{aligned}$$

$$\Rightarrow \quad \big|\rho(t')\big) = \mathcal{U}(t',t) \big|\rho(t)\big)$$

Multiple Interaction

Let us see how it looks at hadron collider



In hadron-hadron collision the parton distribution function also absorbs the contribution of the multiple interactions, correlations and rescattering.

Our strategy:

- Identify factorazible singular contributions systematically.
- Sum up the strongly ordered radiations.
- Minimize the number of the ad-hoc assumptions and tuning parameters.

Now, one can try to define the evolution operator in the following form

$$\mathcal{U}(t,t') = \mathbb{T}\exp\left\{\int_t^{t'} d\tau \left[\underbrace{\mathcal{H}_I(\tau) - \mathcal{V}_I(\tau)}_{\text{Single radiations}} + \underbrace{\sum_{\beta=\mathrm{MI,\,C,\,RC}} \{\mathcal{H}_\beta(\tau) - \mathcal{V}_\beta(\tau)\}}_{\text{Everything else}}\right]\right\}$$

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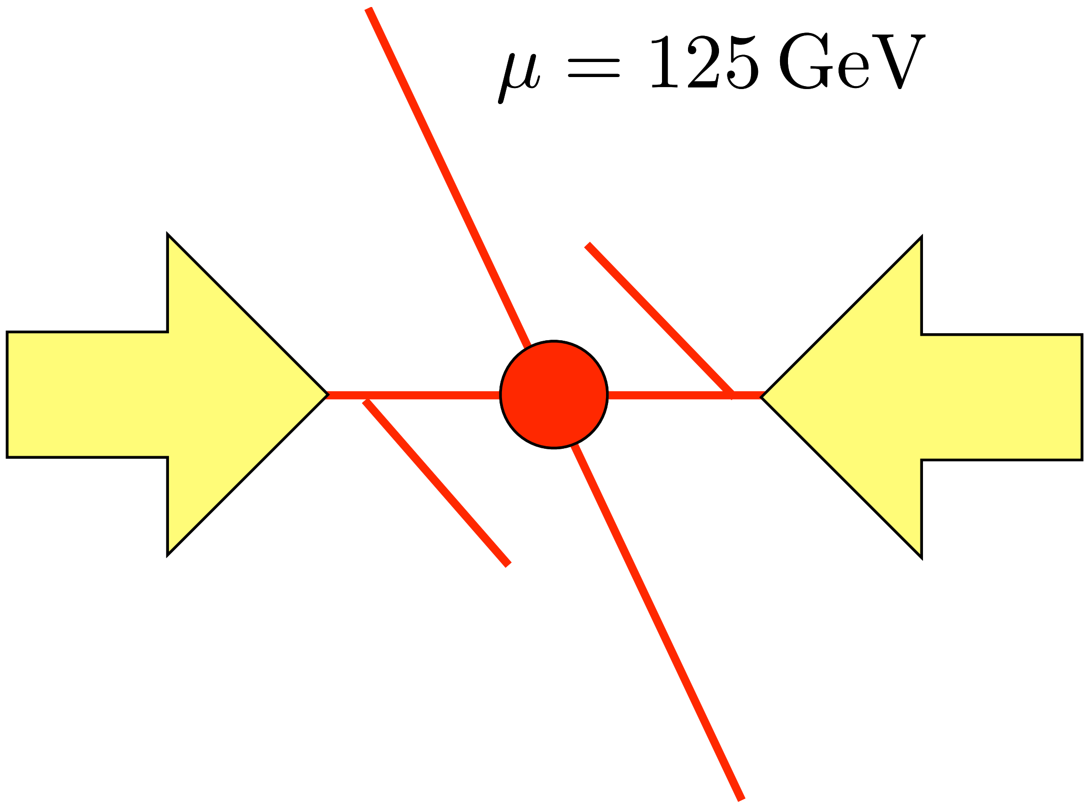

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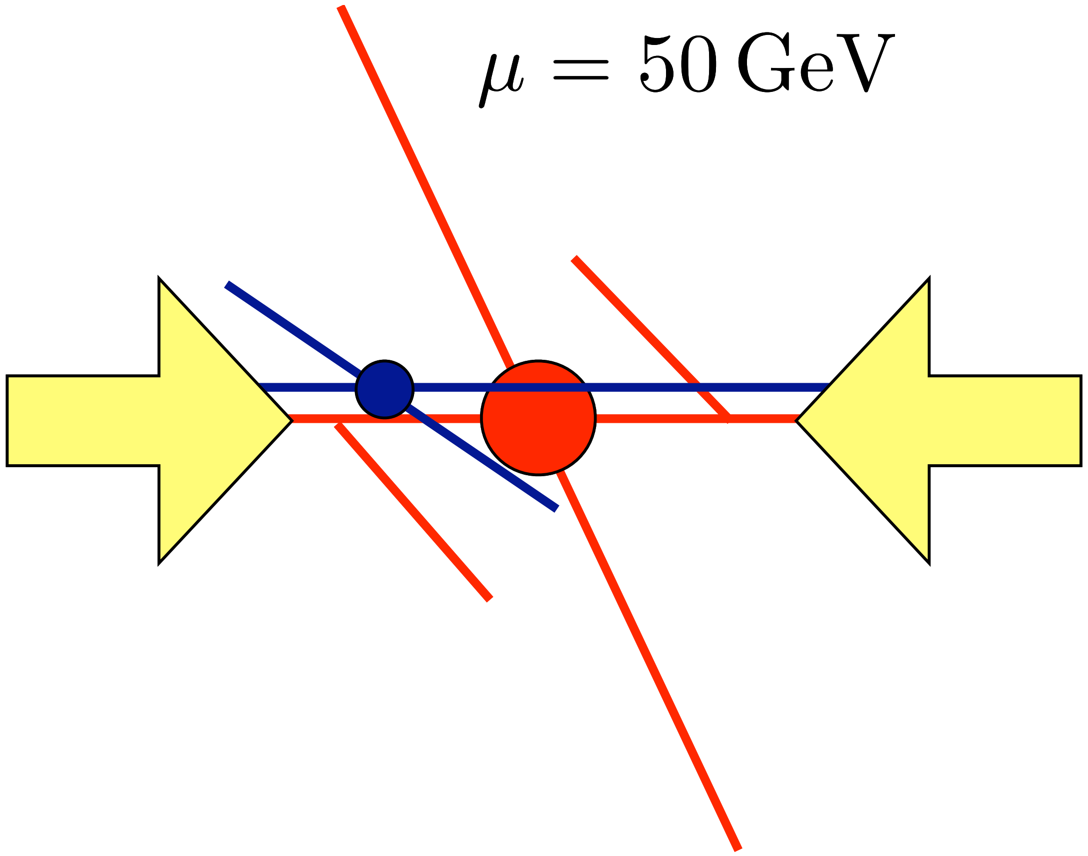

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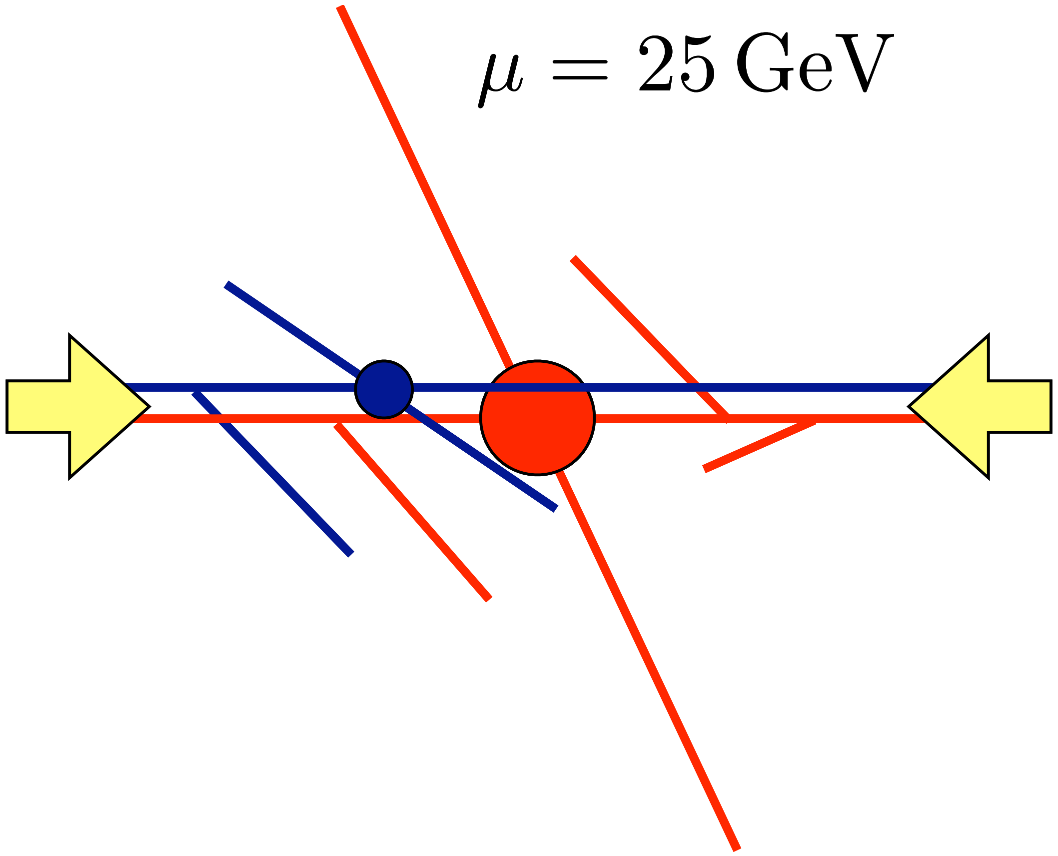

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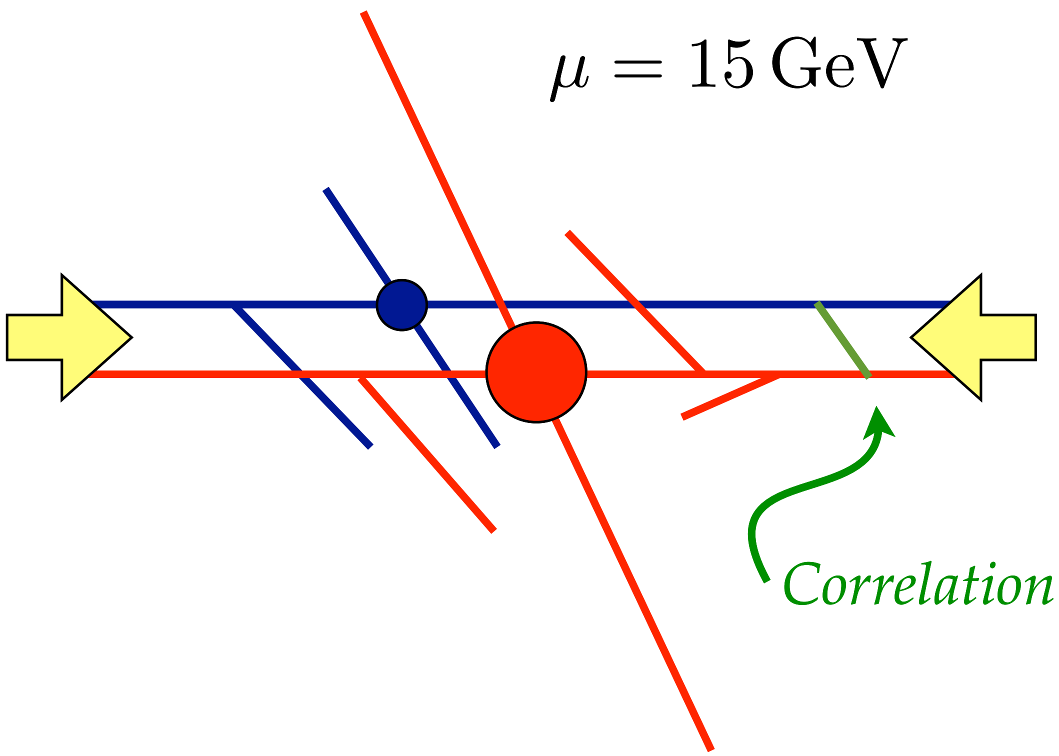

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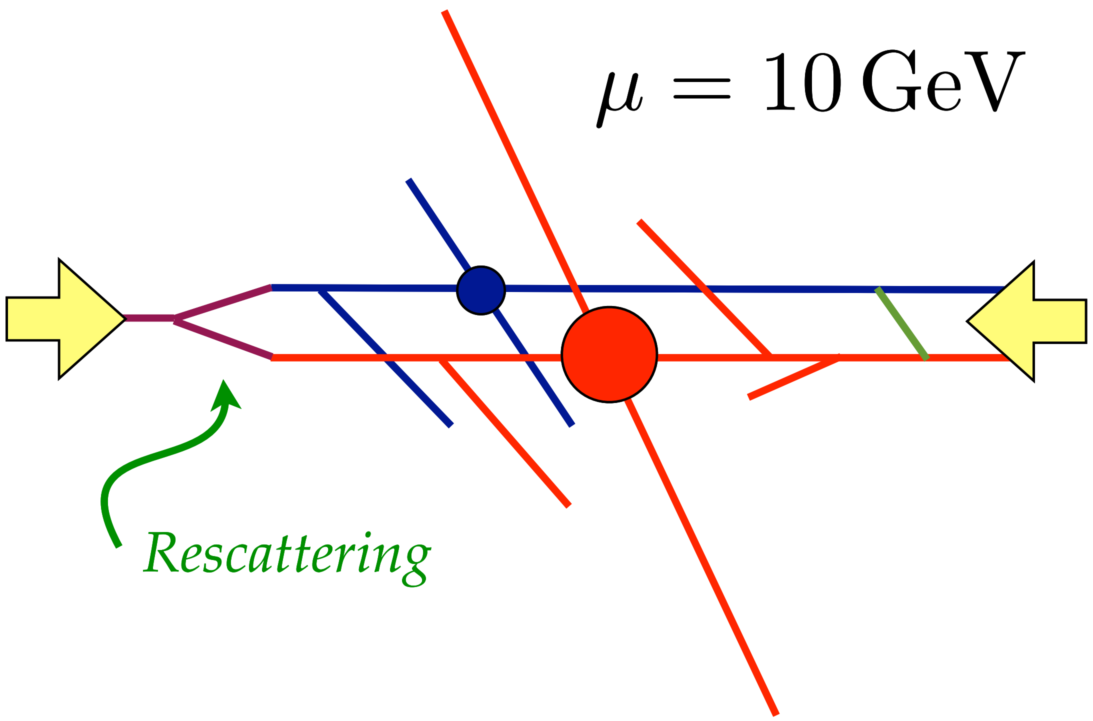

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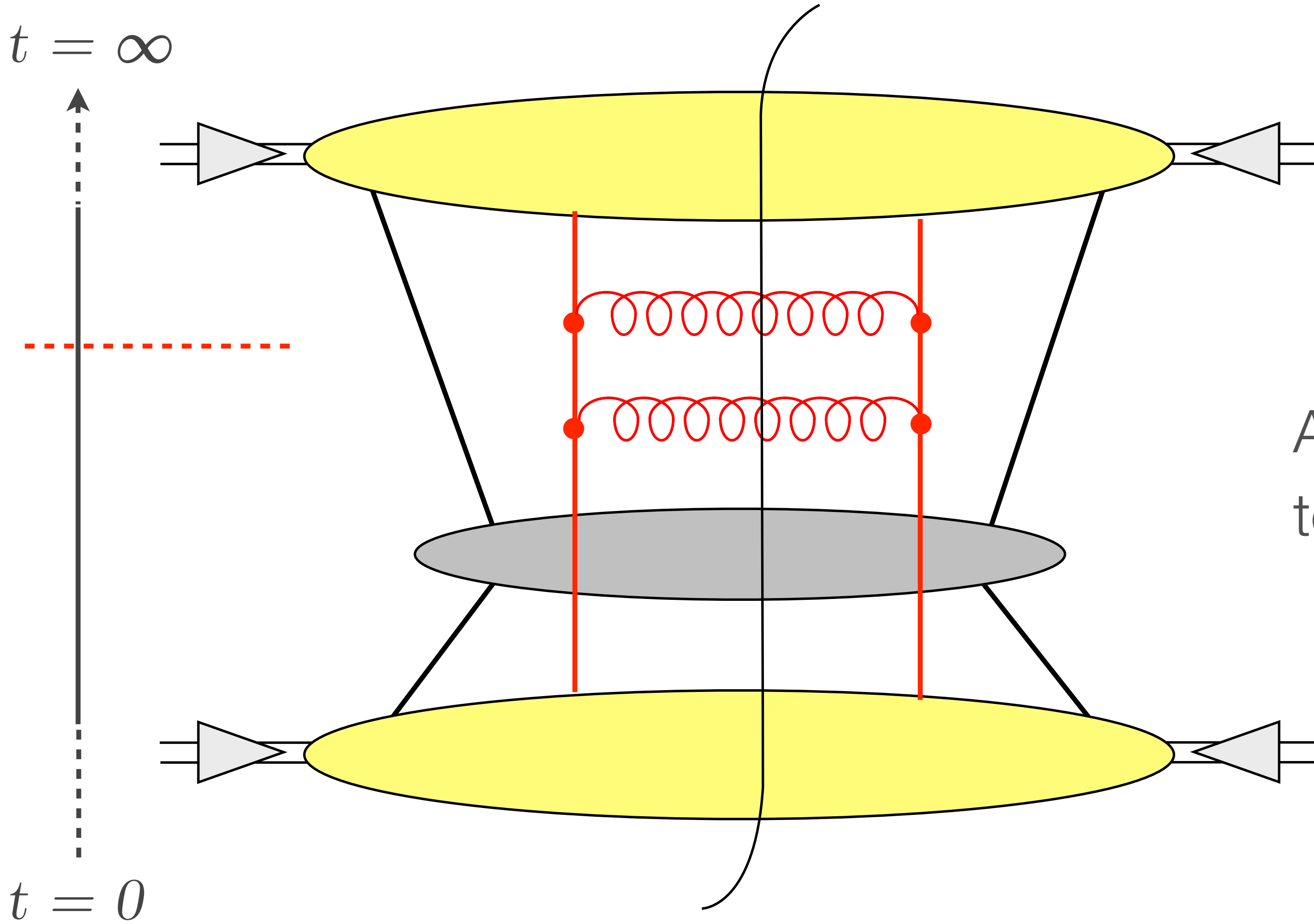


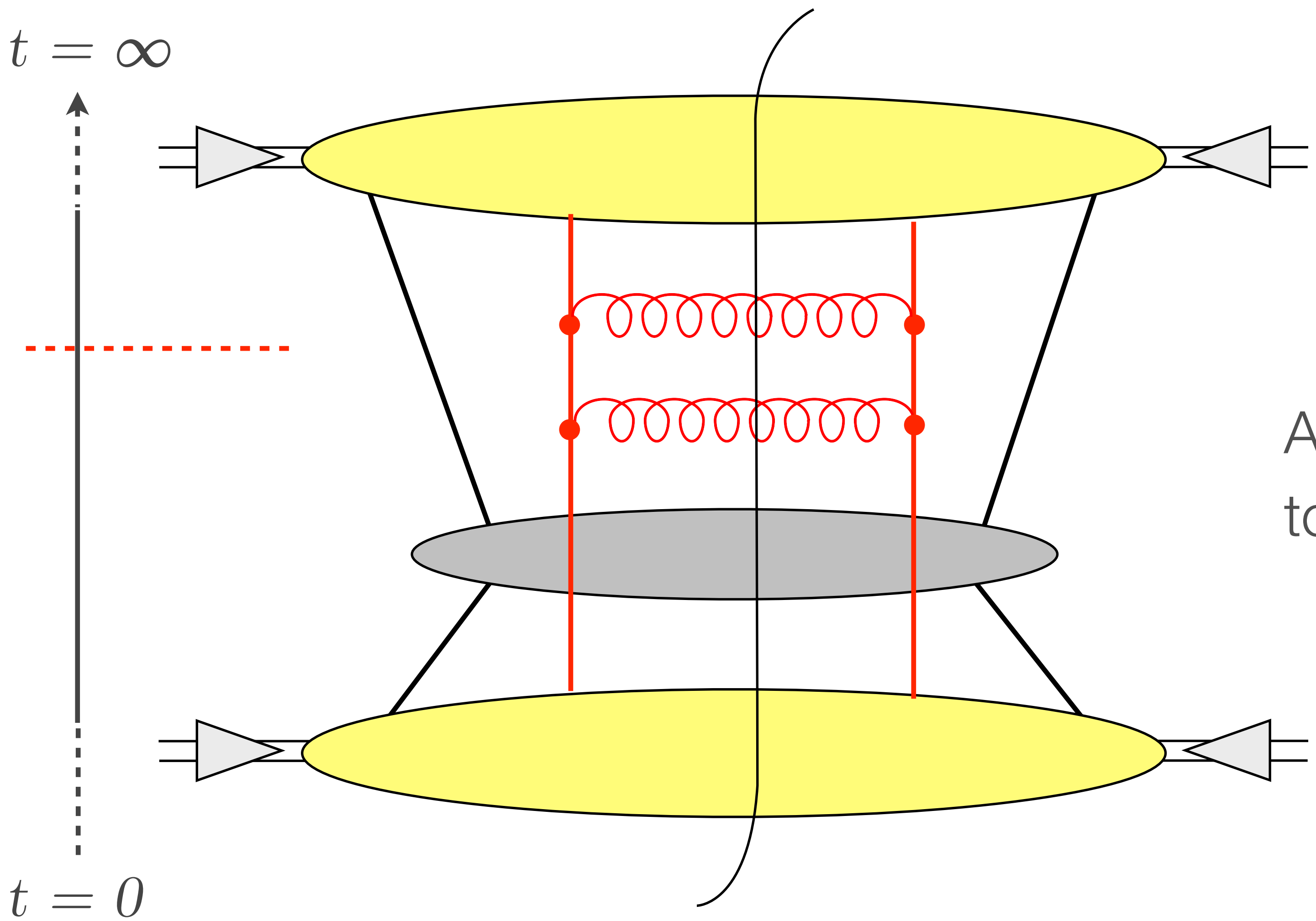
$$\mathcal{H}_{\rm MI}(t) = \left(\frac{\alpha_{\rm s}}{2\pi}\right)^2 \mathcal{O}(e^t)$$

Actually the real scaling is weaker due to the *power suppression*:

$$e^{t-t_0} \sim \frac{\Lambda^2_{\rm QCD}}{p_\perp^2}$$

- This is important in the very small pT regions and negligible in the large pT regions but it is hard to tell how import in the intermediate region. The cumulative effect could be sizable.
- Important to note that this is an NLO contributions. Thus, compared to the standard shower this is also suppressed by an extra power of α_s.
- Requires multi parton PDF (mPDF).
- Implemented in HERWIG & PYTHIA. (No "proper" mPDF implemented.)

Multiple Interaction



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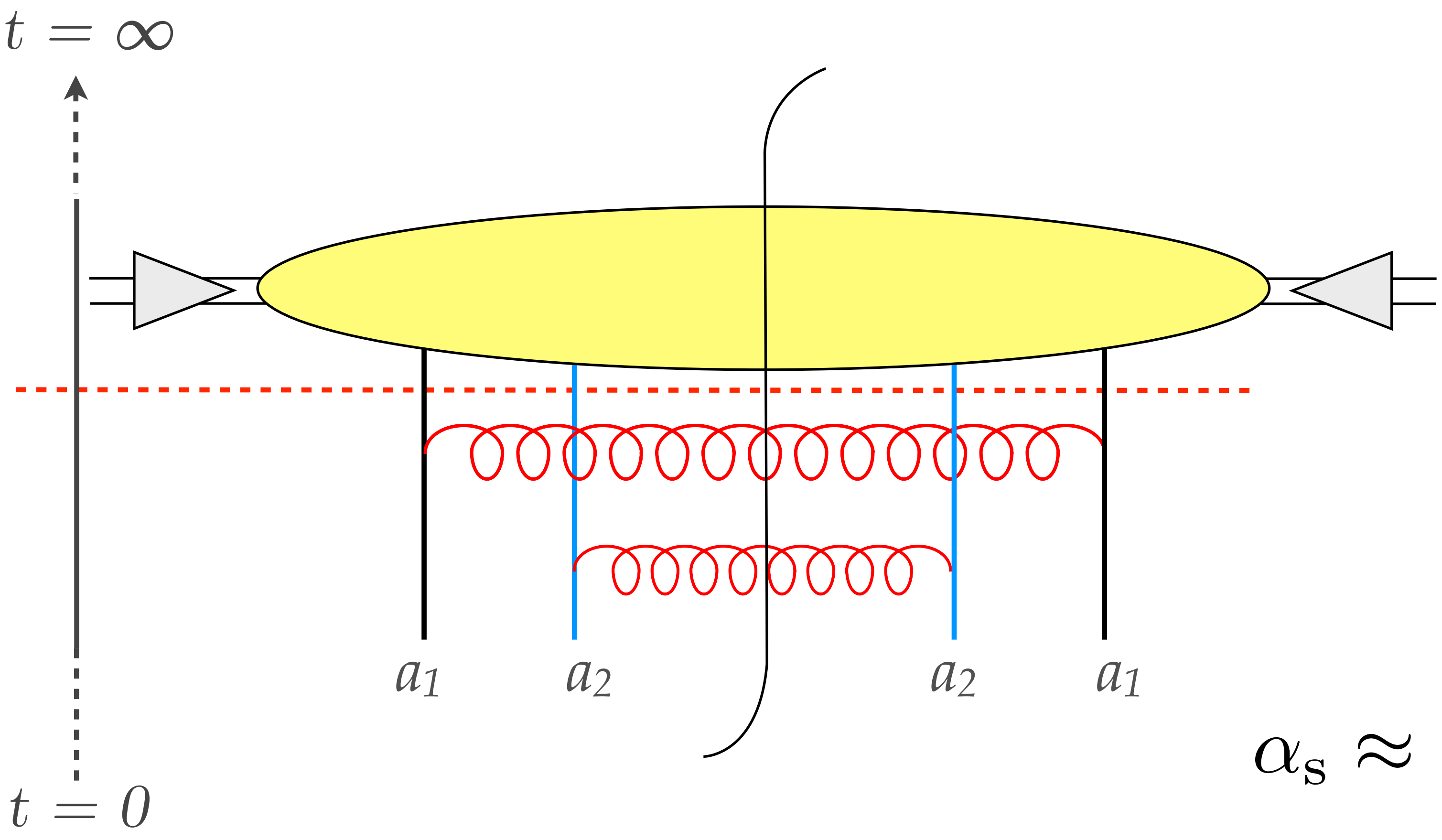
Standard Initial State Radiations



$$\mathcal{H}_{\mathrm{I}}(t) = \frac{\alpha_s}{2\pi}\mathcal{O}(t^2) + \frac{\alpha_s}{2\pi}\frac{1}{N_c^2}\mathcal{O}(t) + \left(\frac{\alpha_s}{2\pi}\right)^2\mathcal{O}(t^3)$$

$$\alpha_s \approx \frac{1}{N_c^2} \approx 0.1$$

- This is the standard shower evolution. Adds LL and NLL contributions. Not power suppressed.
- Since the MPI kernel is NLO contribution we should consider the standard shower at NLO level as well. (Just to be systematic.)
- If we consider NLO terms then we need subleading color contributions, too.
- Adds correction to the primary interaction as well as to the MPI contributions.
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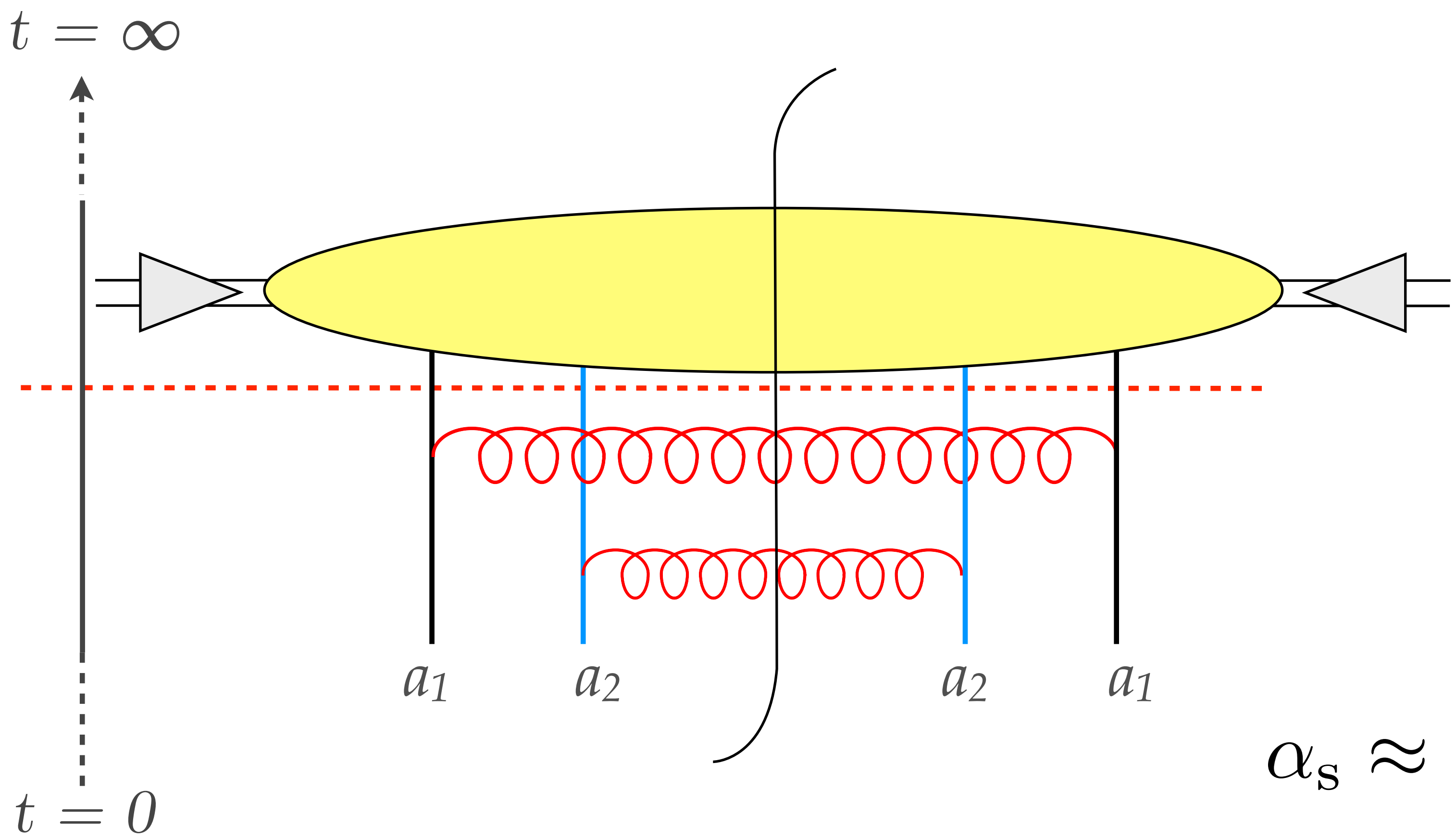

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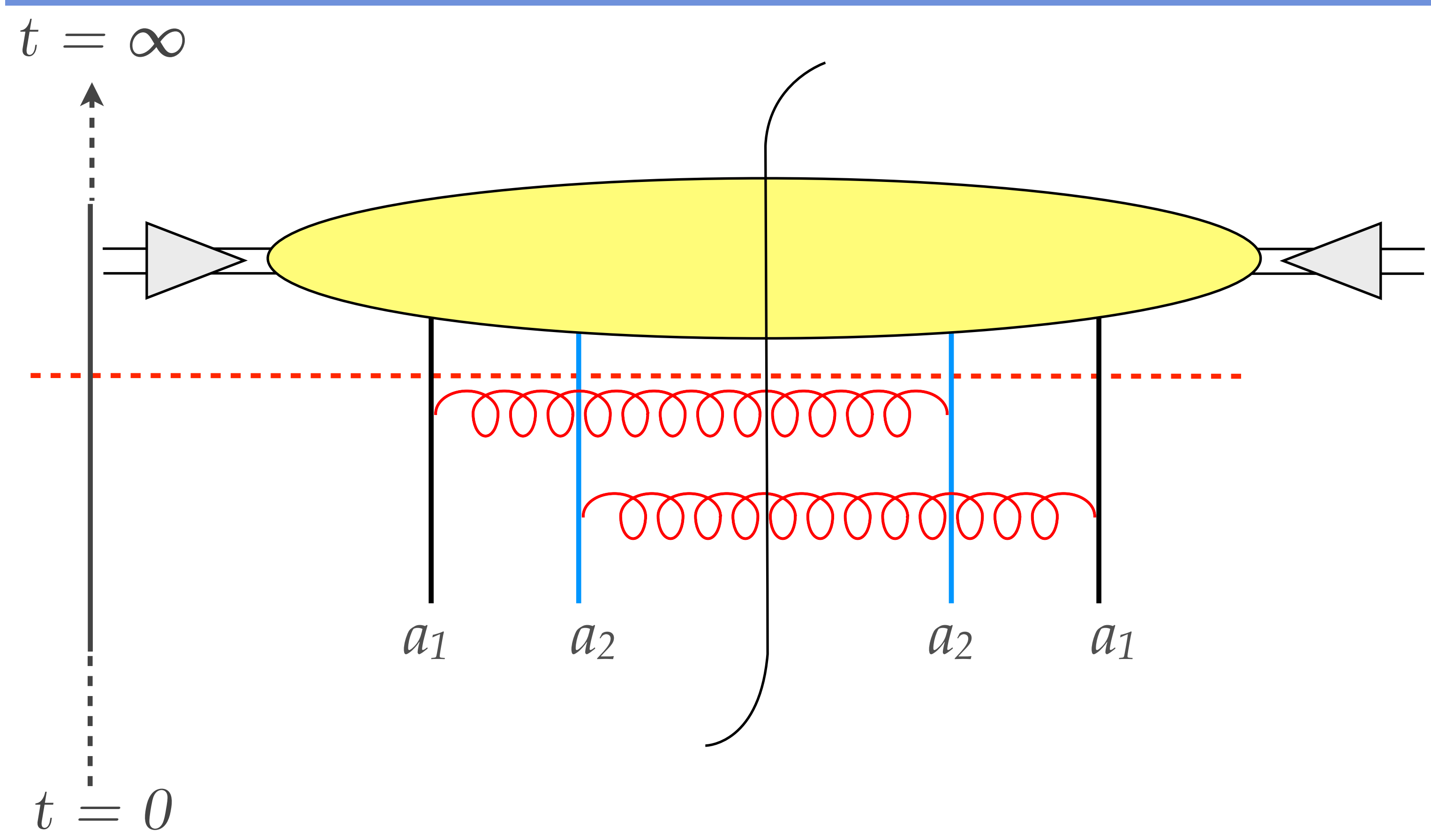
Correlations



$$\mathcal{H}_{\mathrm{C}}(t) = \frac{\alpha_{\mathrm{s}}}{2\pi}\mathcal{O}(t^2) + \frac{\alpha_{\mathrm{s}}}{2\pi}\frac{1}{N_c^2}\mathcal{O}(t) + \left(\frac{\alpha_{\mathrm{s}}}{2\pi}\right)^2\mathcal{O}(t^3)$$

- This operator can be applied on states with at least two chains. (They are already power suppressed.)
- Since the MPI kernel is NLO contribution we should consider the correlation at NLO level as well. (Just to be systematic.)
- In MPI terms it is as important as the standard shower.
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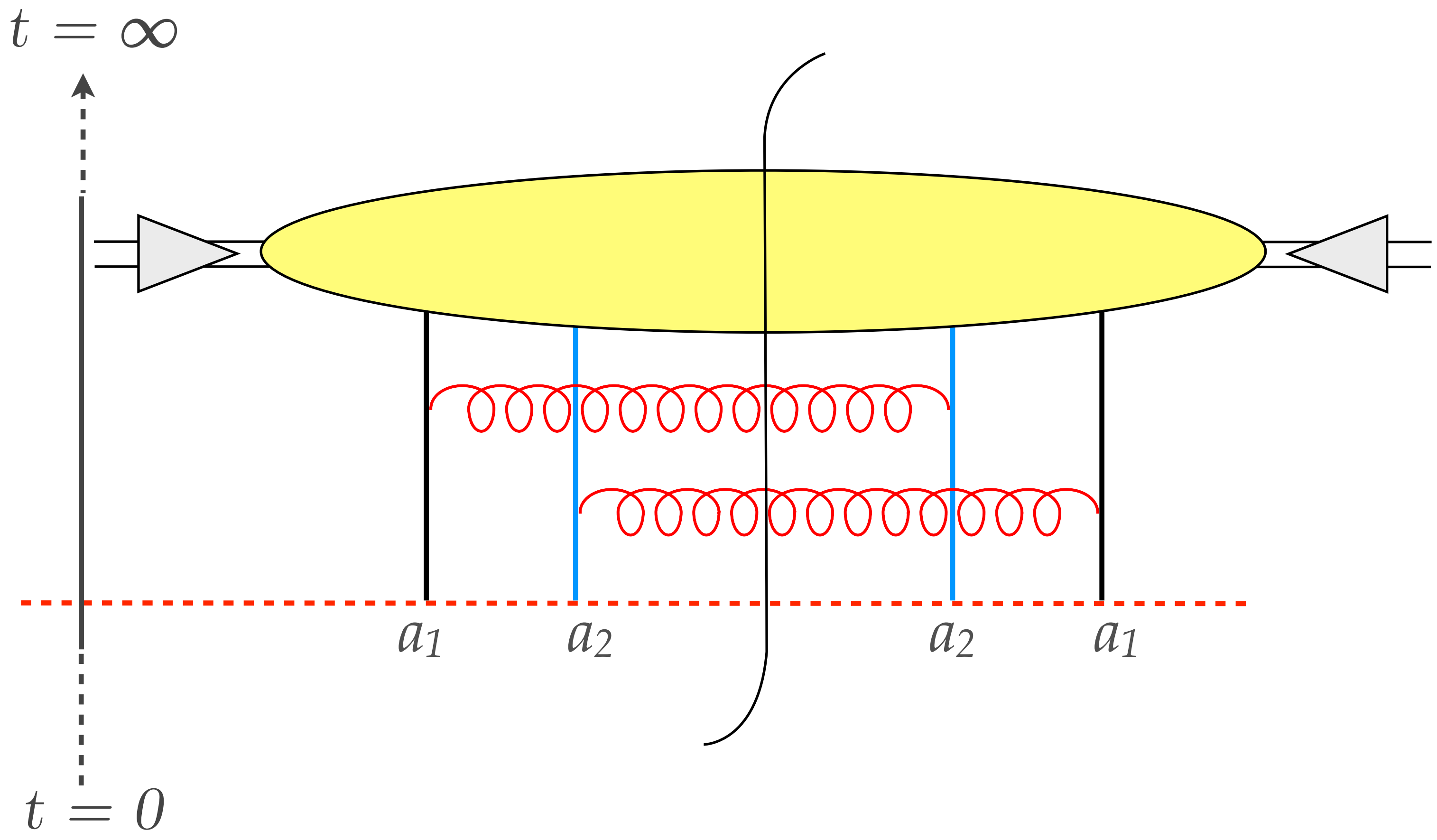
Correlations



$$\mathcal{H}_{\mathrm{C}}(t) = \frac{\alpha_{\mathrm{s}}}{2\pi}\mathcal{O}(t^2) + \frac{\alpha_{\mathrm{s}}}{2\pi}\frac{1}{N_c^2}\mathcal{O}(t) + \left(\frac{\alpha_{\mathrm{s}}}{2\pi}\right)^2\mathcal{O}(t^3)$$

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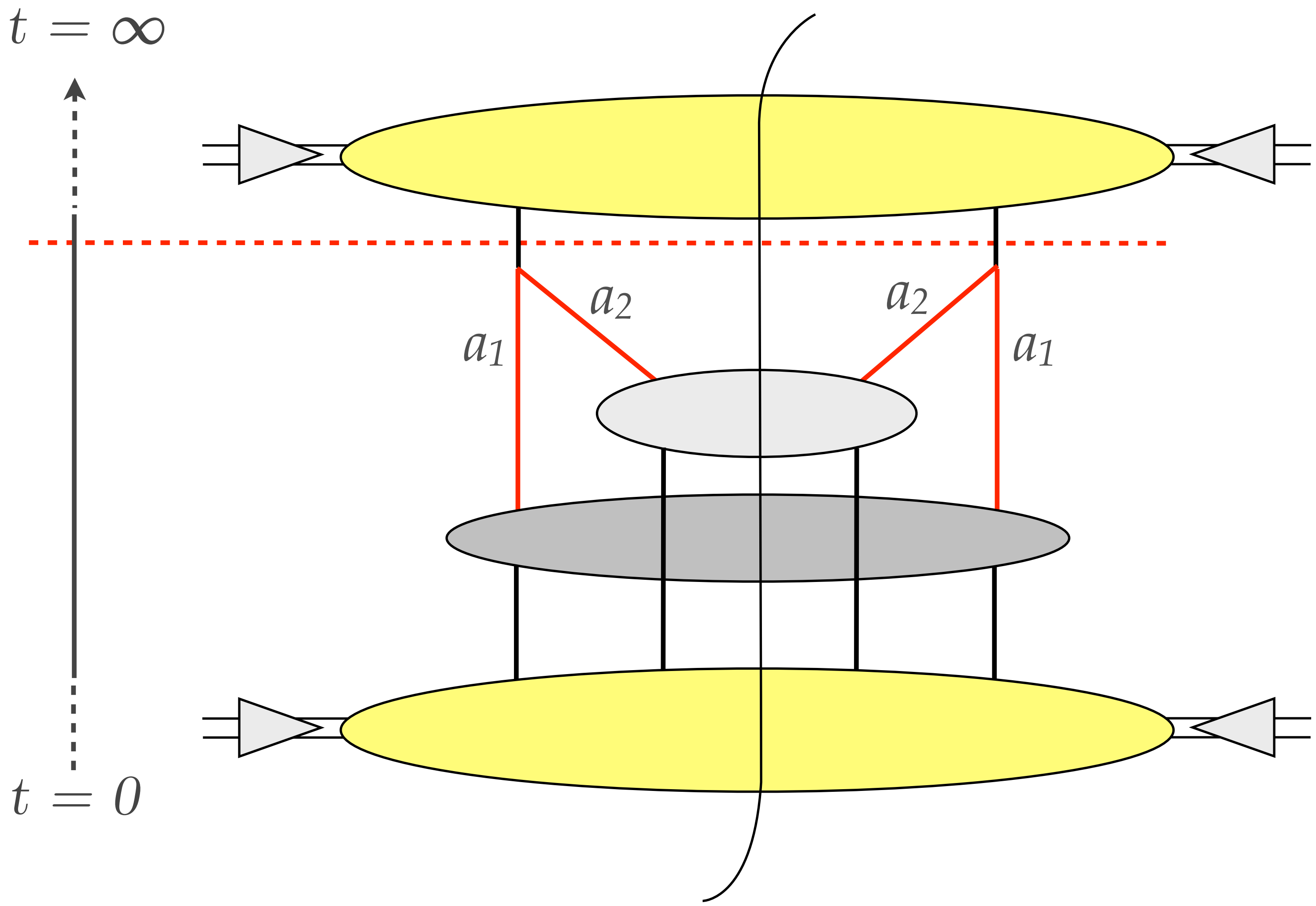
Rescattering



$$\mathcal{H}_{\mathrm{RS}}(t) = \frac{\alpha_s}{2\pi}\mathcal{O}(t) + \left(\frac{\alpha_s}{2\pi}\right)^2 \mathcal{O}(t^2)$$

This is the most problematic contribution

$$\mathcal{V}_{\mathrm{RS}}(t) = 0$$

- This operator can be applied on states with at least two chains. (They are already power suppressed.)
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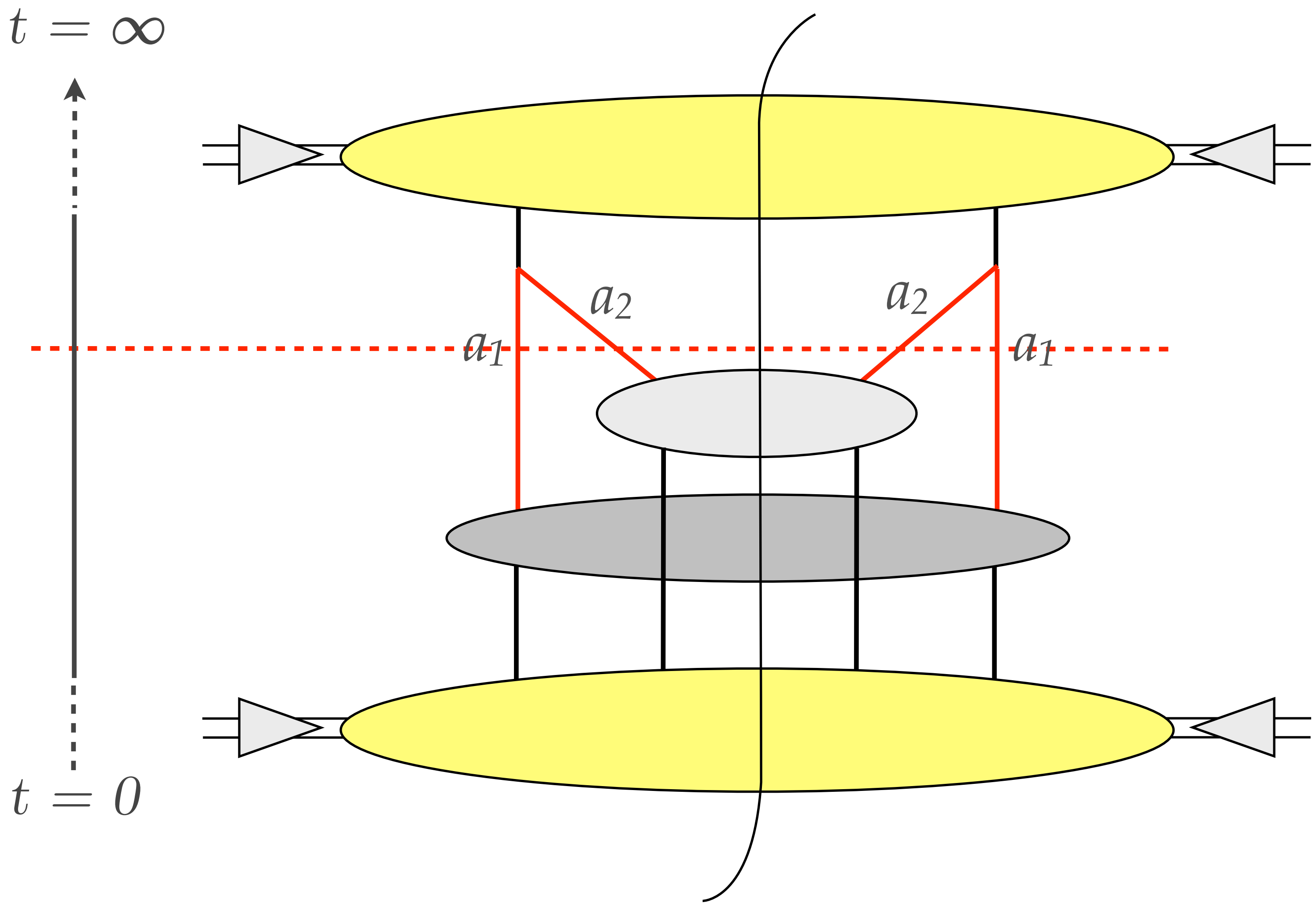

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Multi Parton PDF

We need PDF functions with multiple parton. Of course there no factorization proven but one can set up a scheme by trying to follow some kind of *systematic treatment*.

Standard DGLAP part

$$\frac{d}{dt}D_m(\{x,a\}_m,t) = [P\otimes D_m]\,(\{x,a\}_m,t)$$
$$+\,[C\otimes D_m]\,(\{x,a\}_m,t)$$
$$+\,[R\otimes D_{m-1}]\,(\{x,a\}_m,t)$$

Correlation

I think C = 0

Rescattering

The momentum sum rules are important

$$\sum_{\{a\}_m}\int_0^1 dx_1\cdots\int_0^1 dx_m\,\theta(\sum_i x_i\le 1)\sum_i x_i\,D_m(\{x,a\}_m,t)=1$$

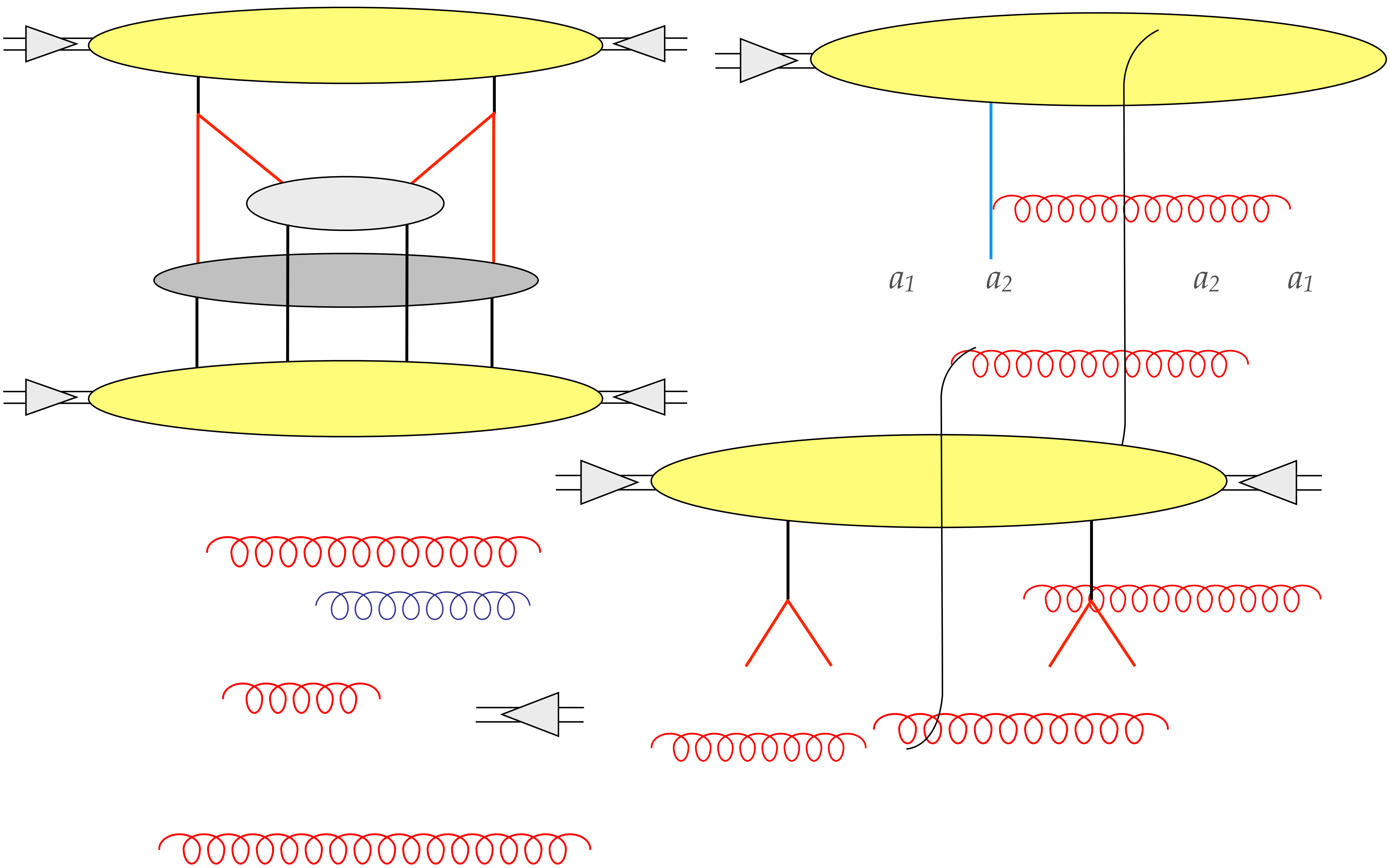
Gaut & Stirling, JHEP **1003:005,2010**

PYTHIA & HERWIG mPDF modeling do not obey the momentum sum rules and their evolution are not synchronized with the shower evolution.

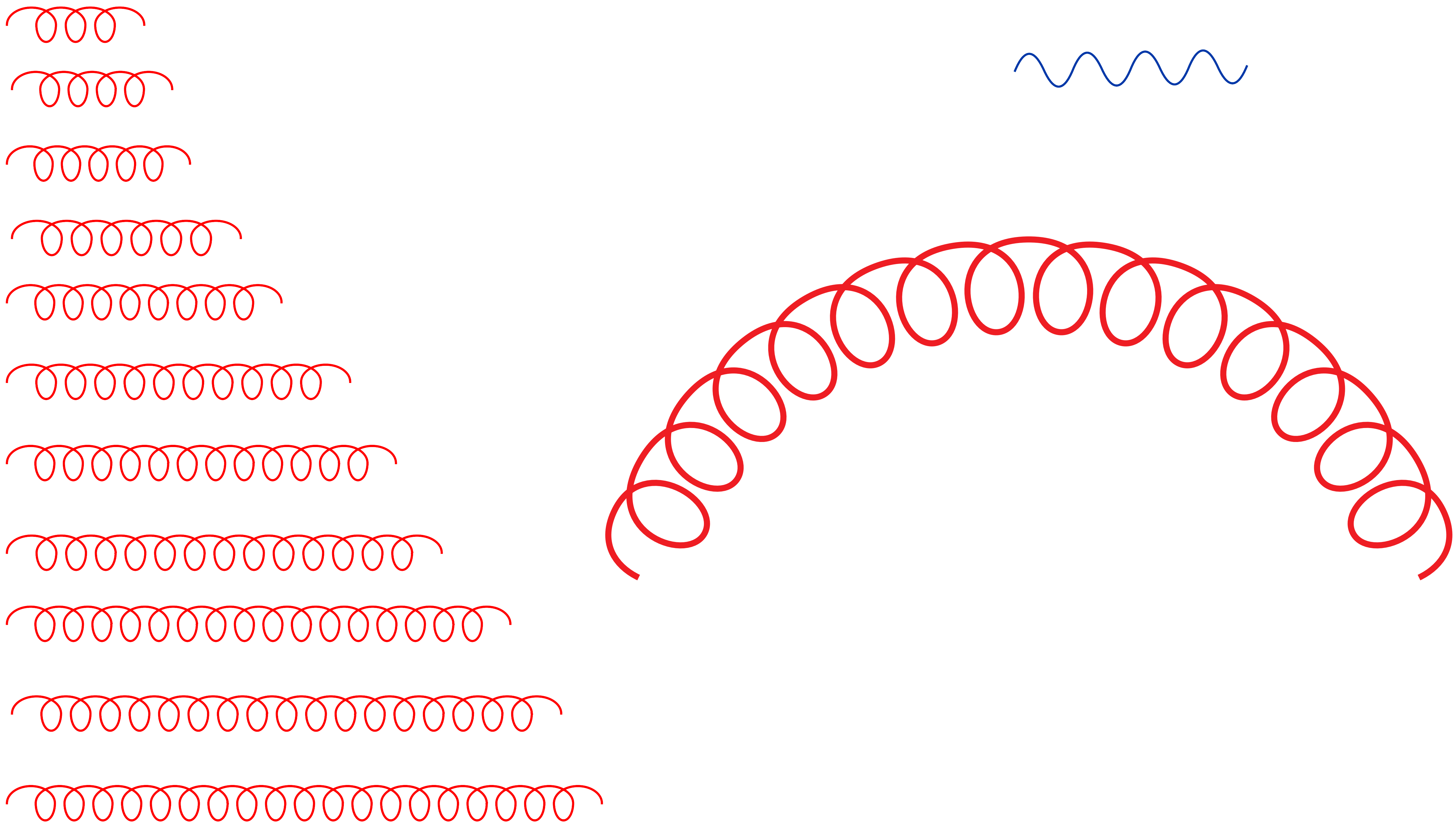
Conclusion

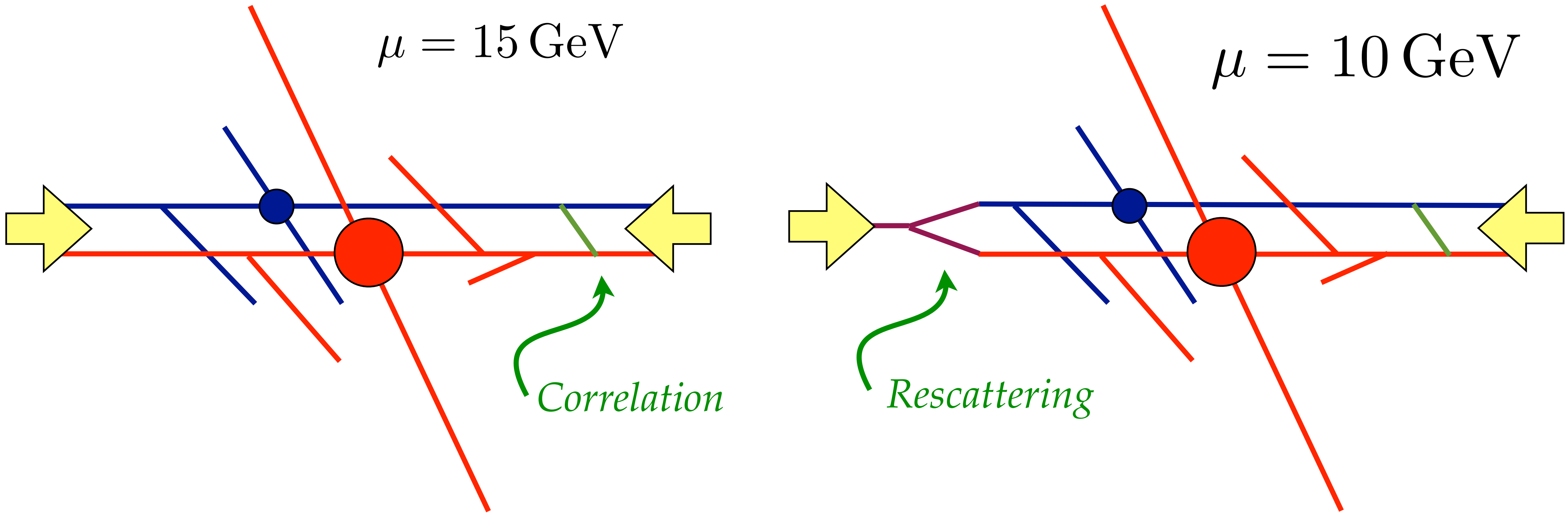
.... I hope we are doing better than Rodney ....

Wizard of **ID**

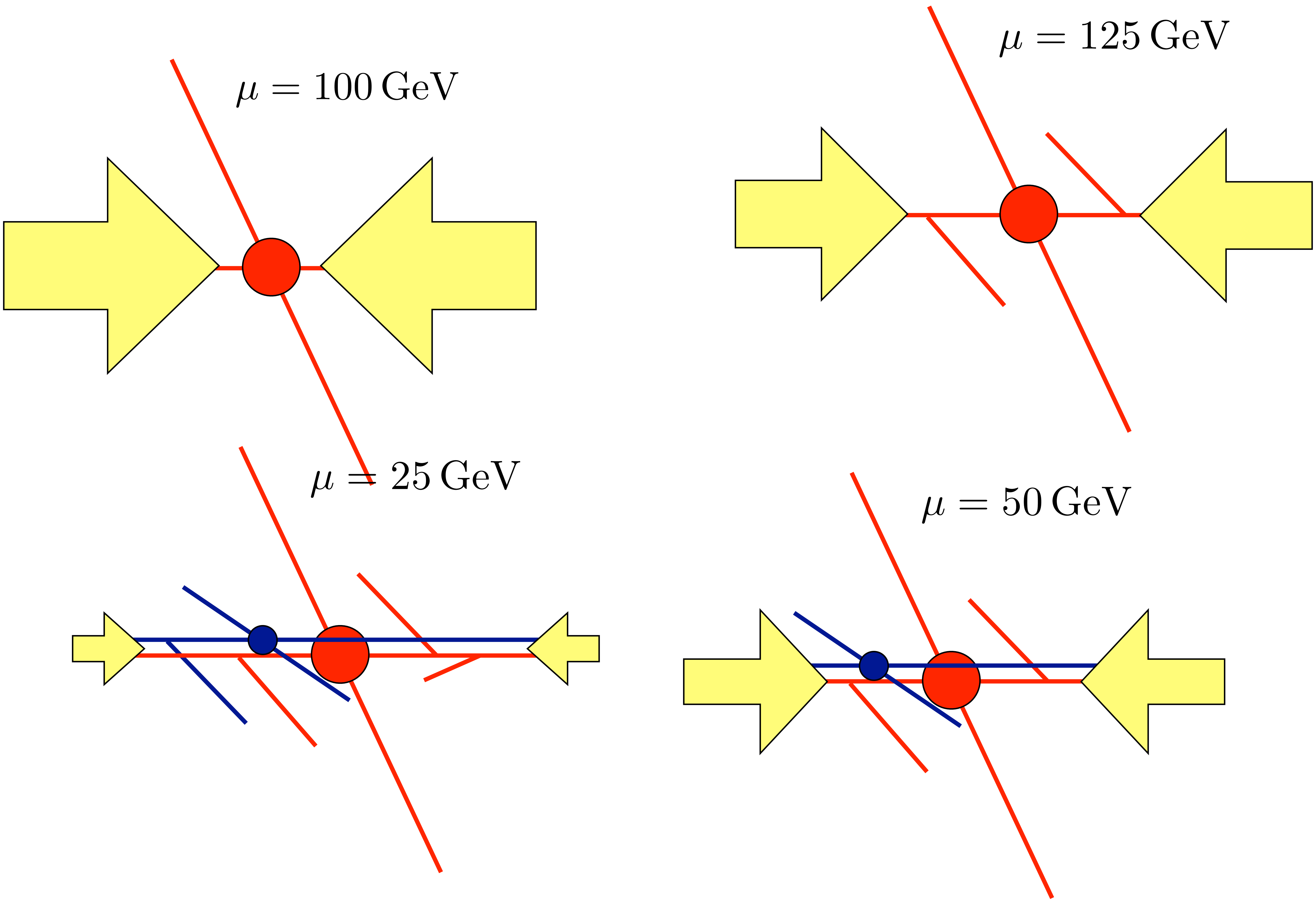


a_1
a_2
a_2
a_1





$\mu = 15\,\mathrm{GeV}$
Correlation
$\mu = 10\,\mathrm{GeV}$
Rescattering


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