PHYSICS AT THE TERA SCALE

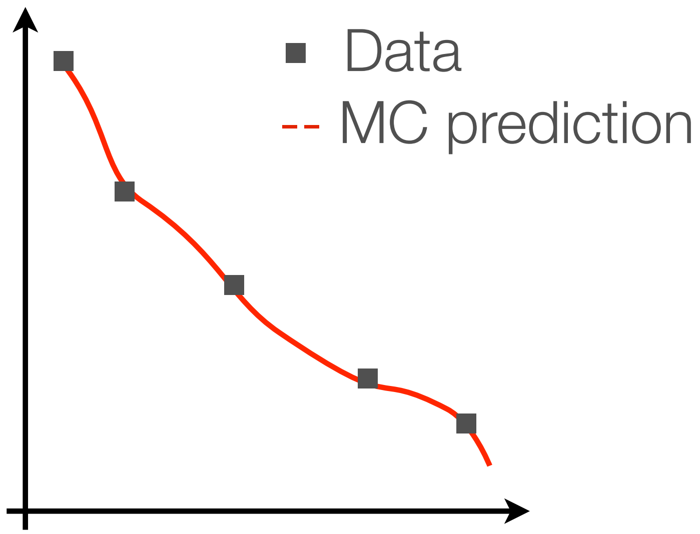
Helmholtz Alliance

Is MC Development Important?

Zoltán Nagy

DESY

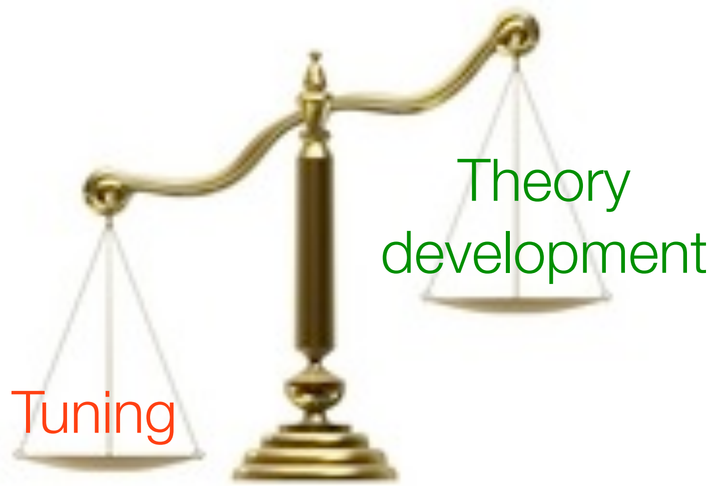
Experimentalists' Good MC



Experimentalists like only the "good" MC program. That describes everything perfectly. I heard many times:

- ✗ We need just a "blackbox"...
- ✗ We need something that "describes" the data...
- ✗ We need just something to unfold the data ...
- ✗ ... anyway we don't need theory predictions, we can get everything from data ....
- ✗ OK, just to make sure we use PYTHIA....

Experimentalists focus on tuning



It should be the other way around

MC Programs

- The technology is about 30 years old.
- In the last 10 years we didn’t have ground shaking new developments
  - Matching at Born level (CKKW)
  - Matching at NLO level (MC@NLO, POWHEG)
  - These are the first steps (pleasing experimentalists) but it would be nice to have active theoretical development.
- I think there are many thing to understand to be able to control LHC experiments in the next decade.
  - Color correlations (CMS ridge,...)
  - Coulomb gluon effect (diffraction, super leading logs,...)
  - Variables like Jade algorithm where the analytic resummation is not available
  - Multi Parton Interaction (beyond the empirical models,...)
  - Matching at quantum level
  - Validating MC programs against known QCD results (This is not tuning!!!)

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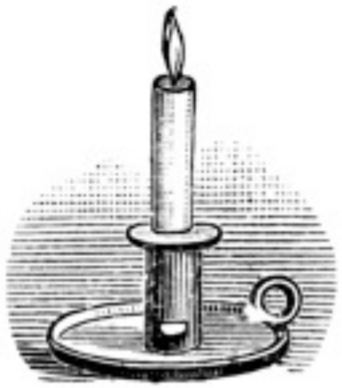

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+ *R&D*

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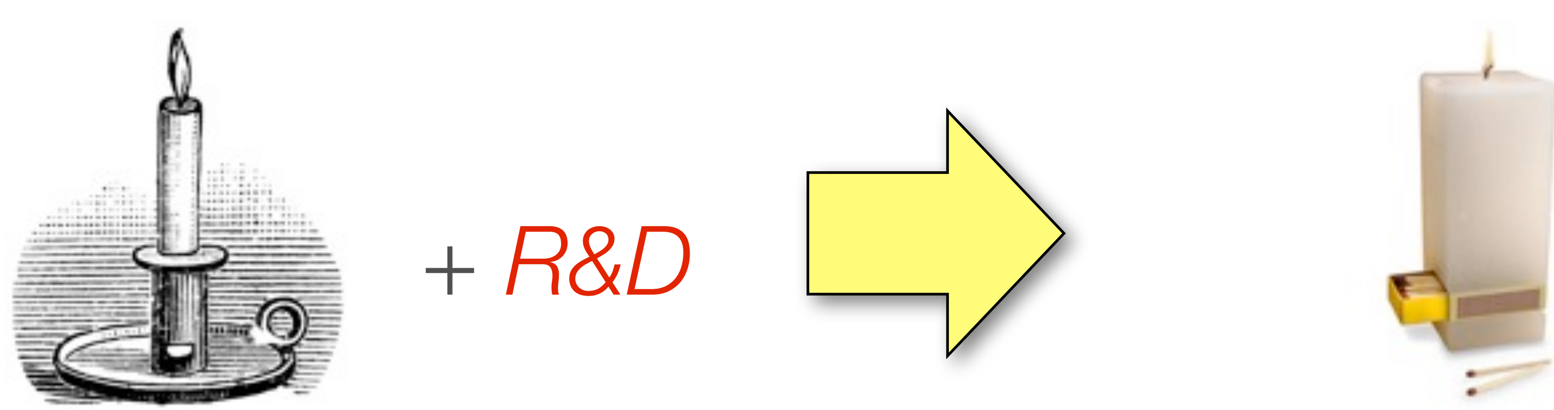

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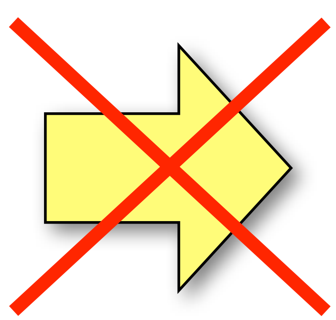


Do we need subleading color?

Matrix element square is

$$|\mathcal{M}(\{p,f\}_m)|^2 = N_c^n \sum_{\{c\}_m} |A(\{p,f,c\}_m)|^2 + \mathcal{O}\left(\frac{1}{N_c^2}\right)$$

where $A(\{p,f,c\}_m)$ is the color subamplitudes of the color configuration $\{c\}_m$

Cross sections at $\sqrt{s} = 1960$ GeV, with structure functions, in nanobarns,
$p_T > 10\,\mathrm{GeV}$ $|\eta| < 2.0$.

Process	σ_0 : Normal	σ_1 : Large Nc component	$\frac{\sigma_1 - \sigma_0}{\sigma_0}$
ud→W+g	0.1029(5)D+01	0.1158(5)D+01	13%
ud→W+gg	0.1018(8)D+00	0.1283(10)D+00	26%
ud→W+ggg	0.1119(17)D-01	0.1564(22)D-01	40%
ud→W+gggg	0.1339(36)D-02	0.2838(71)D-02	120%

Results were calculated by HELAC

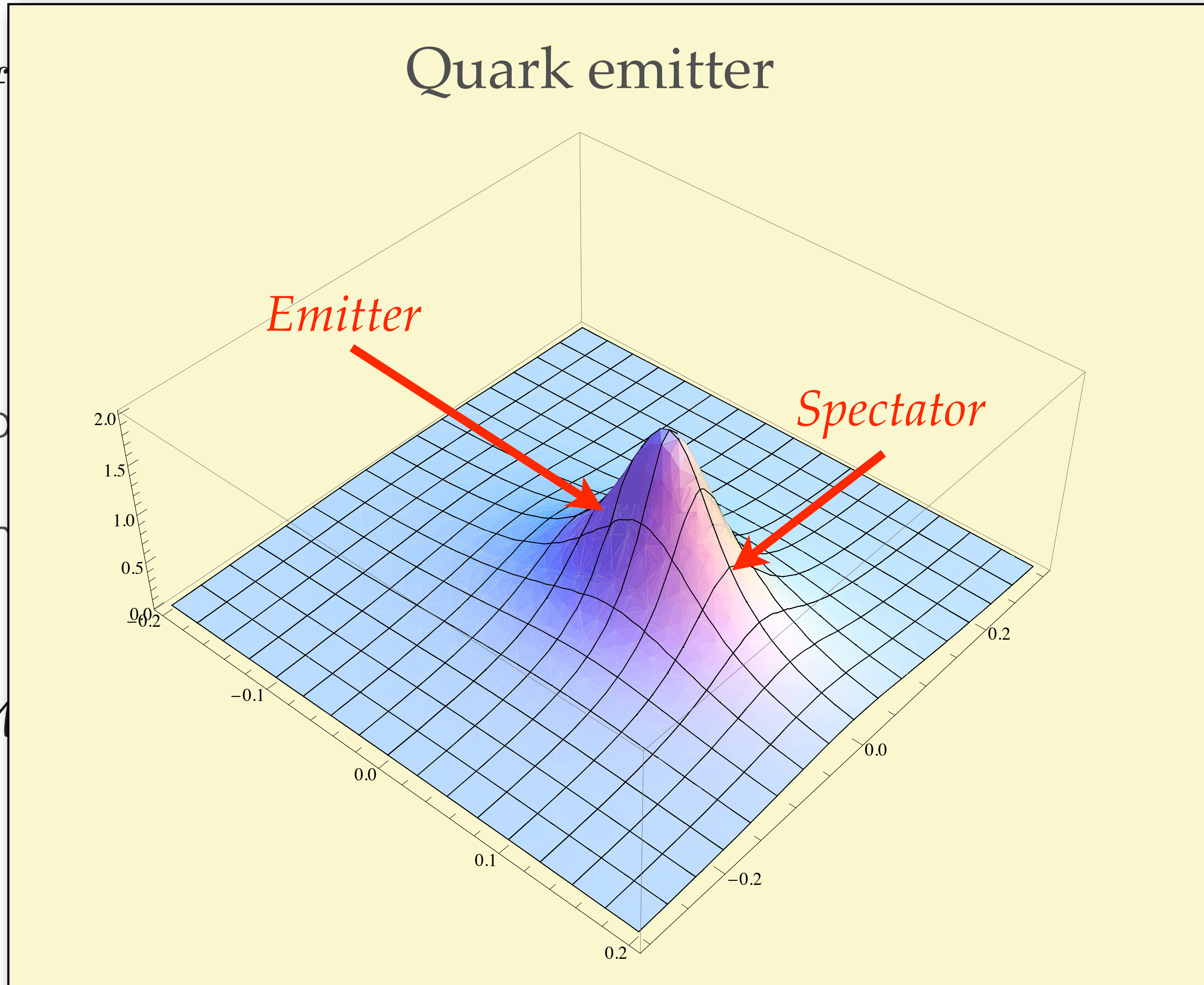
Do we need subleading color?

Parton shower starts from the tree level exact matrix elements

$$|\mathcal{M}(\{p, f$$

$$, c'\}_m)^* \Big\}$$

How to assign co ... ence contributions? *In* ... get the normalization righ



$$|\mathcal{M}$$

$$n)|^2$$

Note this is just the standard K-factor trick.

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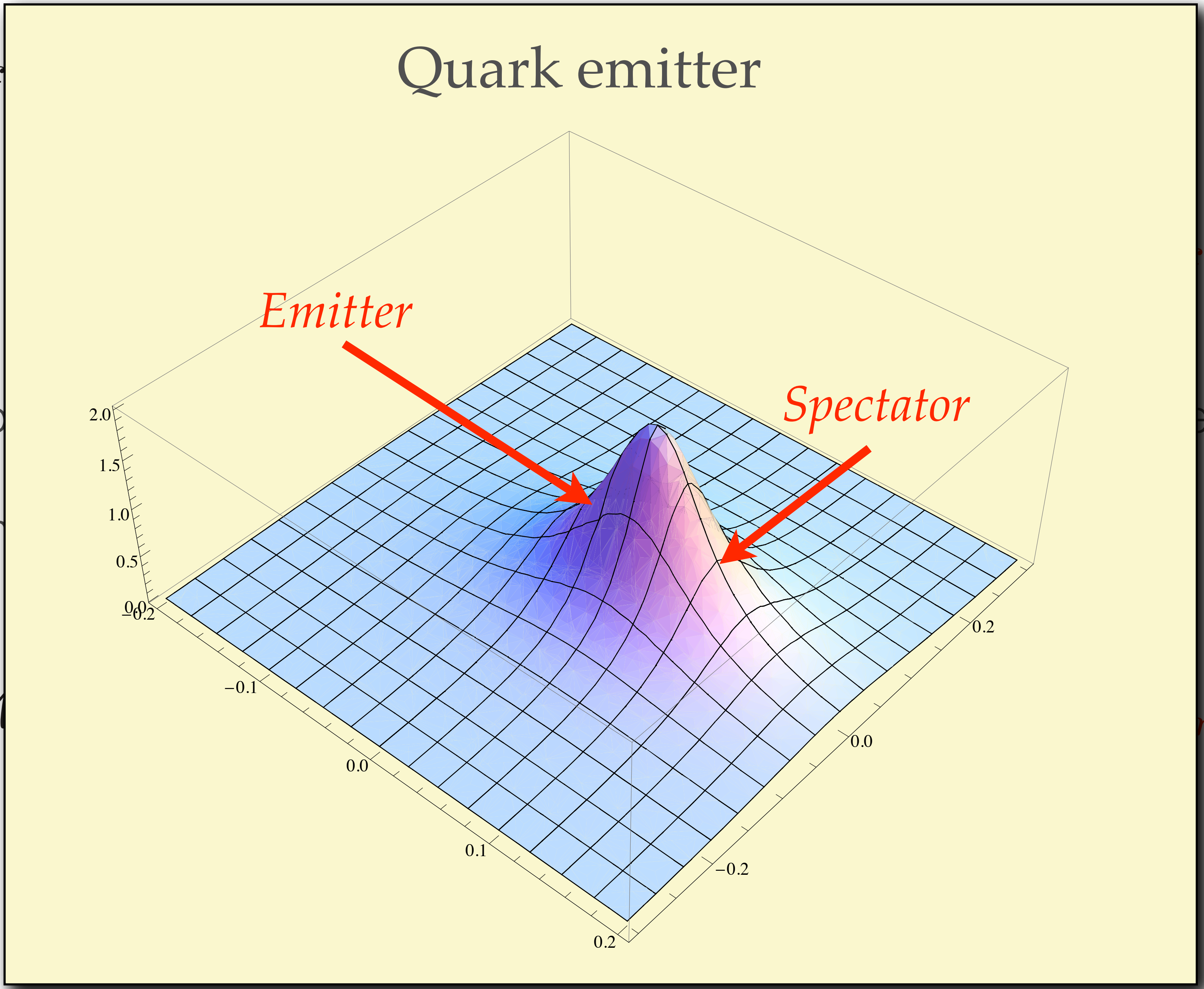

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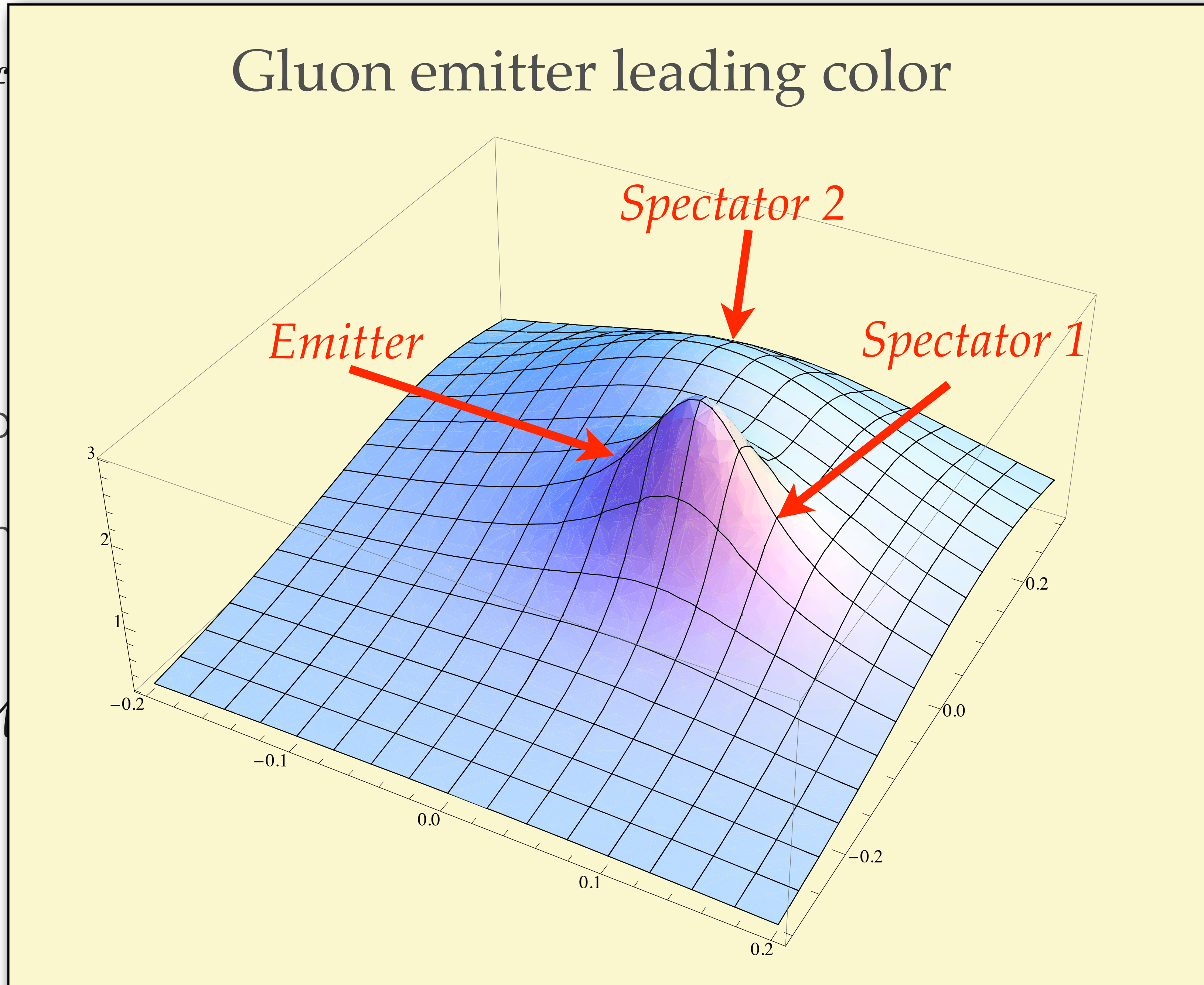

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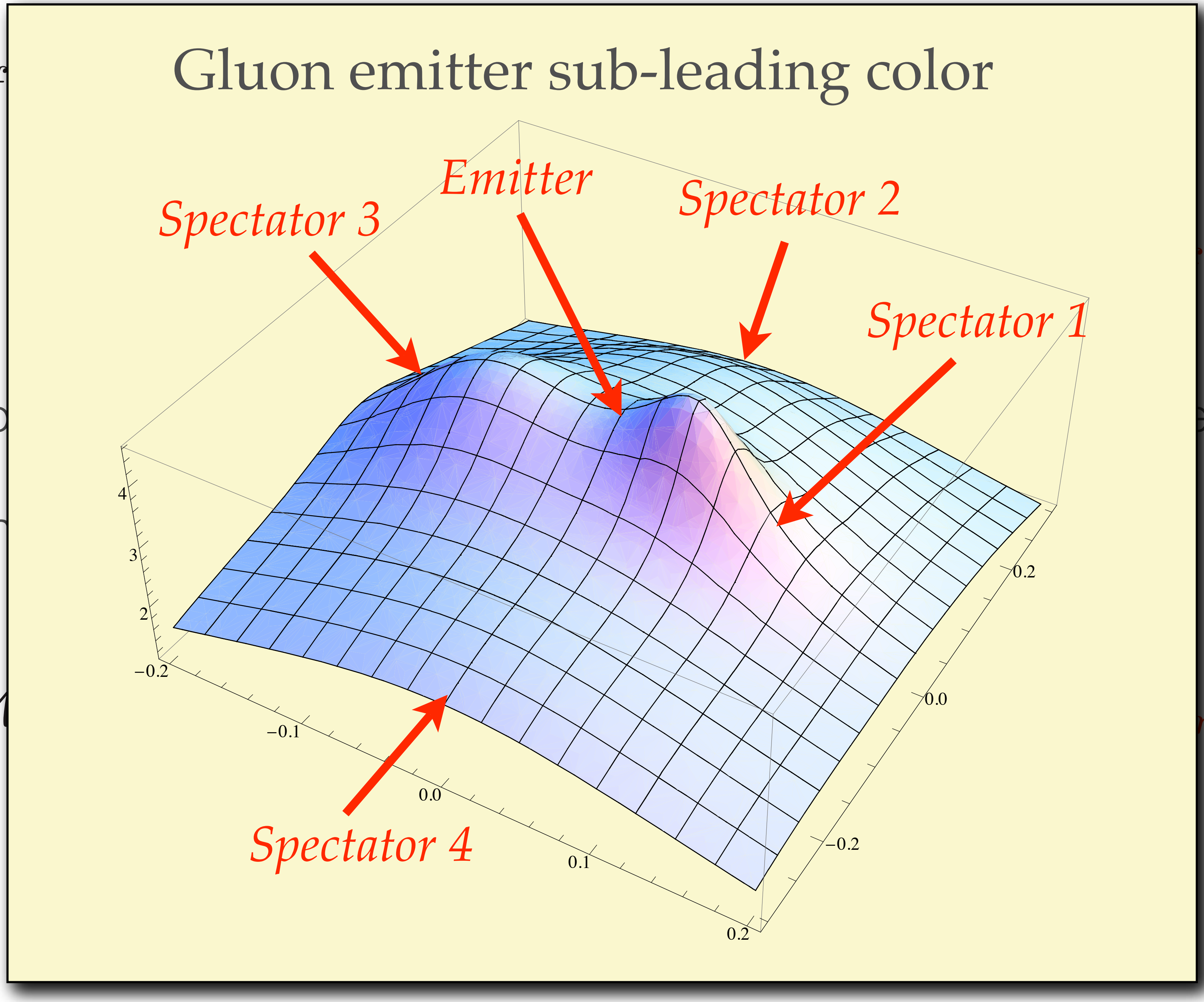

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Do we need subleading color?

One can think about to go beyond the LO shower or include multi parton interaction (MI). It is clear that there is no way to go higher order with leading color approximation.

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

There are two perturbative parameters. The *formal expansion* of the splitting operator is

$$\begin{aligned}\mathcal{H}_{\mathrm{I}} = \frac{\alpha_{\mathrm{s}}}{2\pi}\mathcal{H}_{\mathrm{I}}^{(0,0)} + \frac{\alpha_{\mathrm{s}}}{2\pi}\frac{1}{N_c^2}\mathcal{H}_{\mathrm{I}}^{(0,1)} &+ \left(\frac{\alpha_{\mathrm{s}}}{2\pi}\right)^2 \mathcal{H}_{\mathrm{I}}^{(1,0)} \\ &+ \left(\frac{\alpha_{\mathrm{s}}}{2\pi}\right)^2 \mathcal{H}_{\mathrm{MI}}^{(0,0)} \\ &+ \cdots\end{aligned}$$

Furthermore we *need two color indices* to represent a partonic states (interference terms).

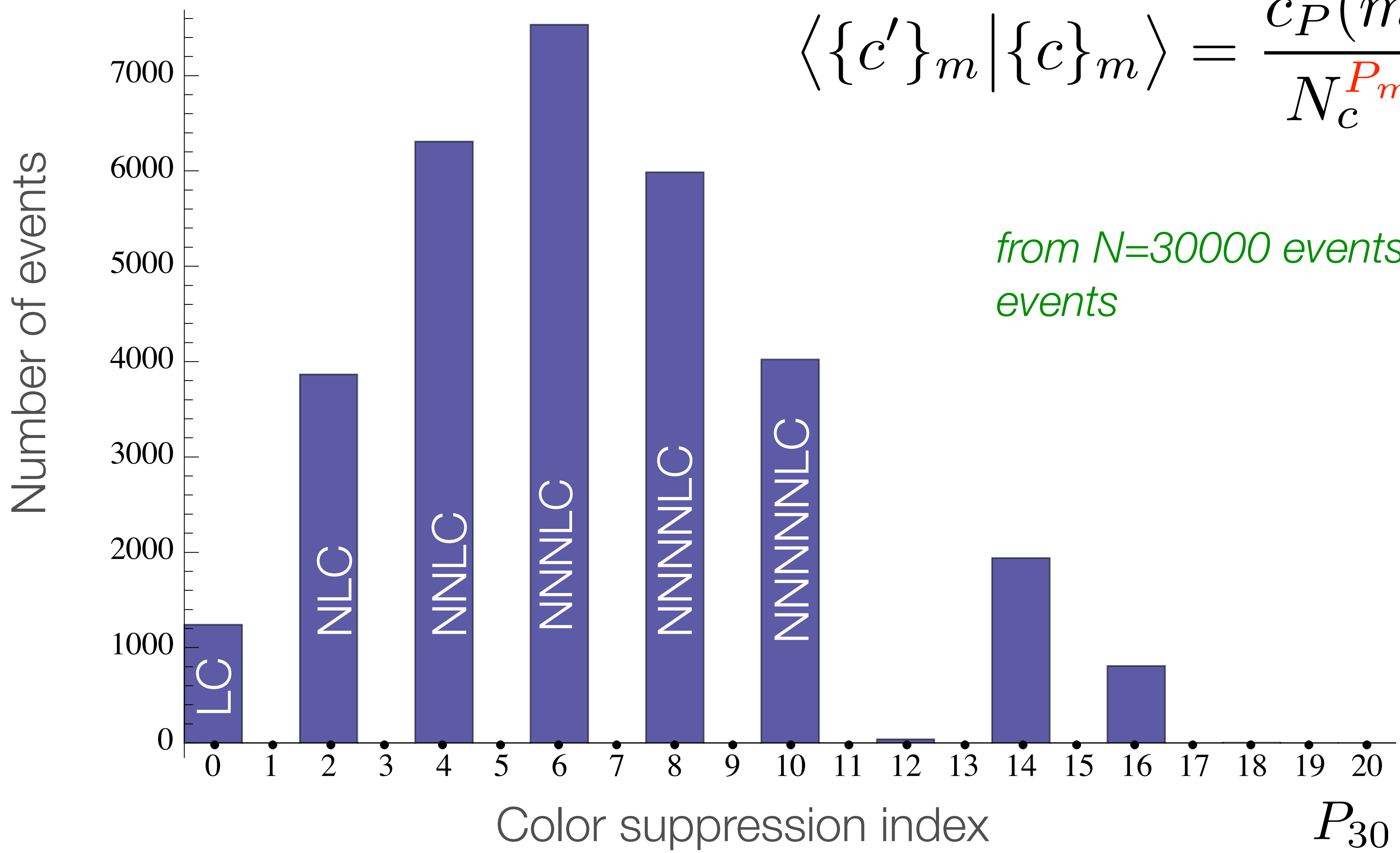
Note that $\mathcal{H}_I$ is an operator and it is impossible to do this expansion in practice.

Numerical Efficiency

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

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

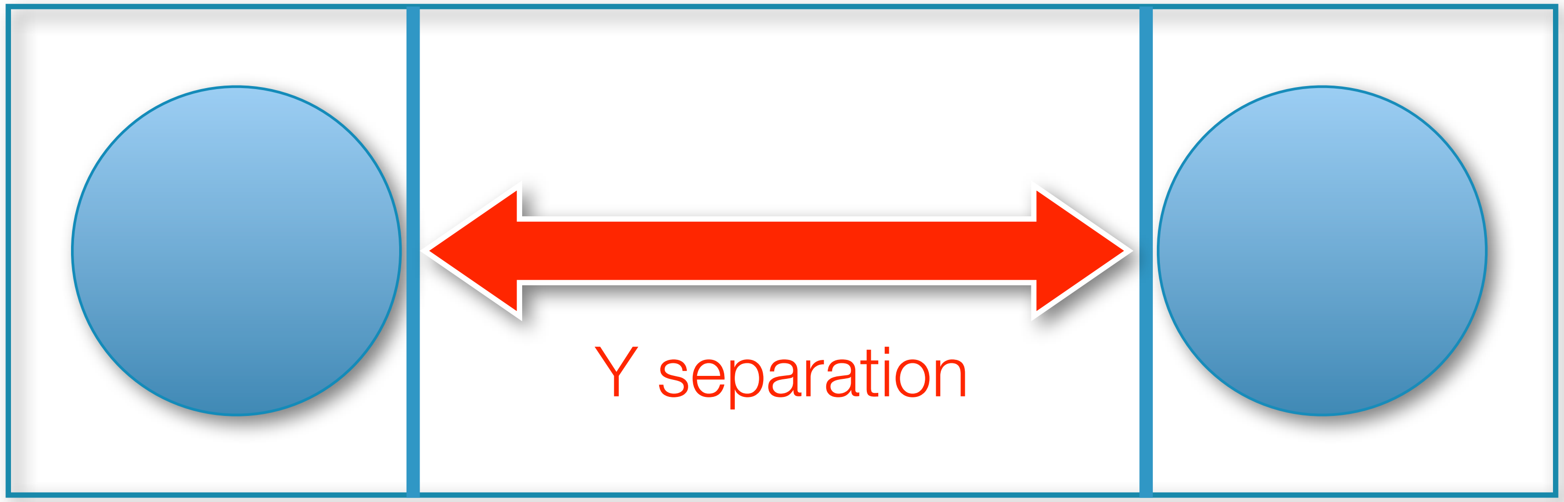
$$\left\langle \{c'\}_m \middle| \{c\}_m \right\rangle = \frac{c_P(m)}{N_c^{P_m}} \left\{ 1 + \mathcal{O}\left(\frac{1}{N_c^2}\right) \right\}$$



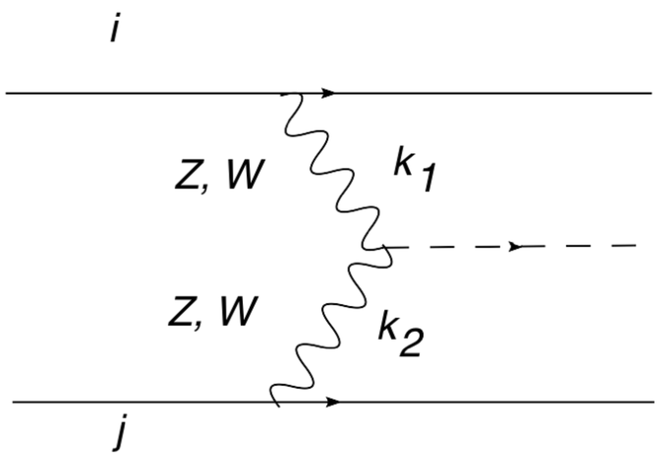
from N=30000 events; m=30 splitting in every events

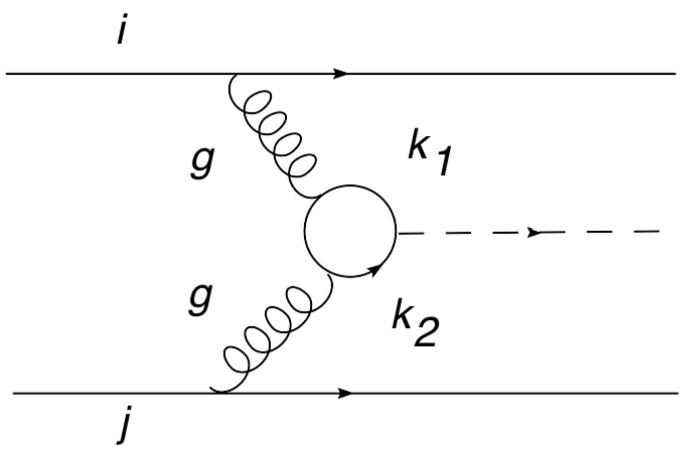
Non-global Observables

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

$$Q_0 < k_T < Q$$

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

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

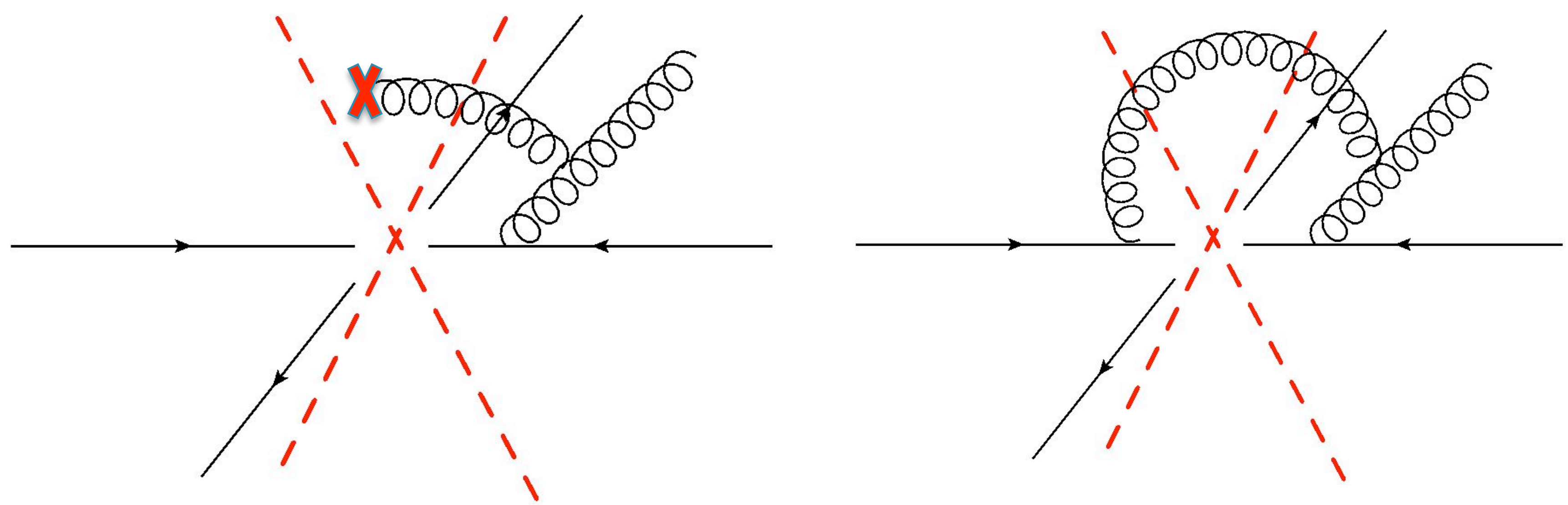
Z.N, D.E.Soper: JHEP 0709:114,2007; JHEP 0803:030,2008; JHEP 0807:025,2008

✗ 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:

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

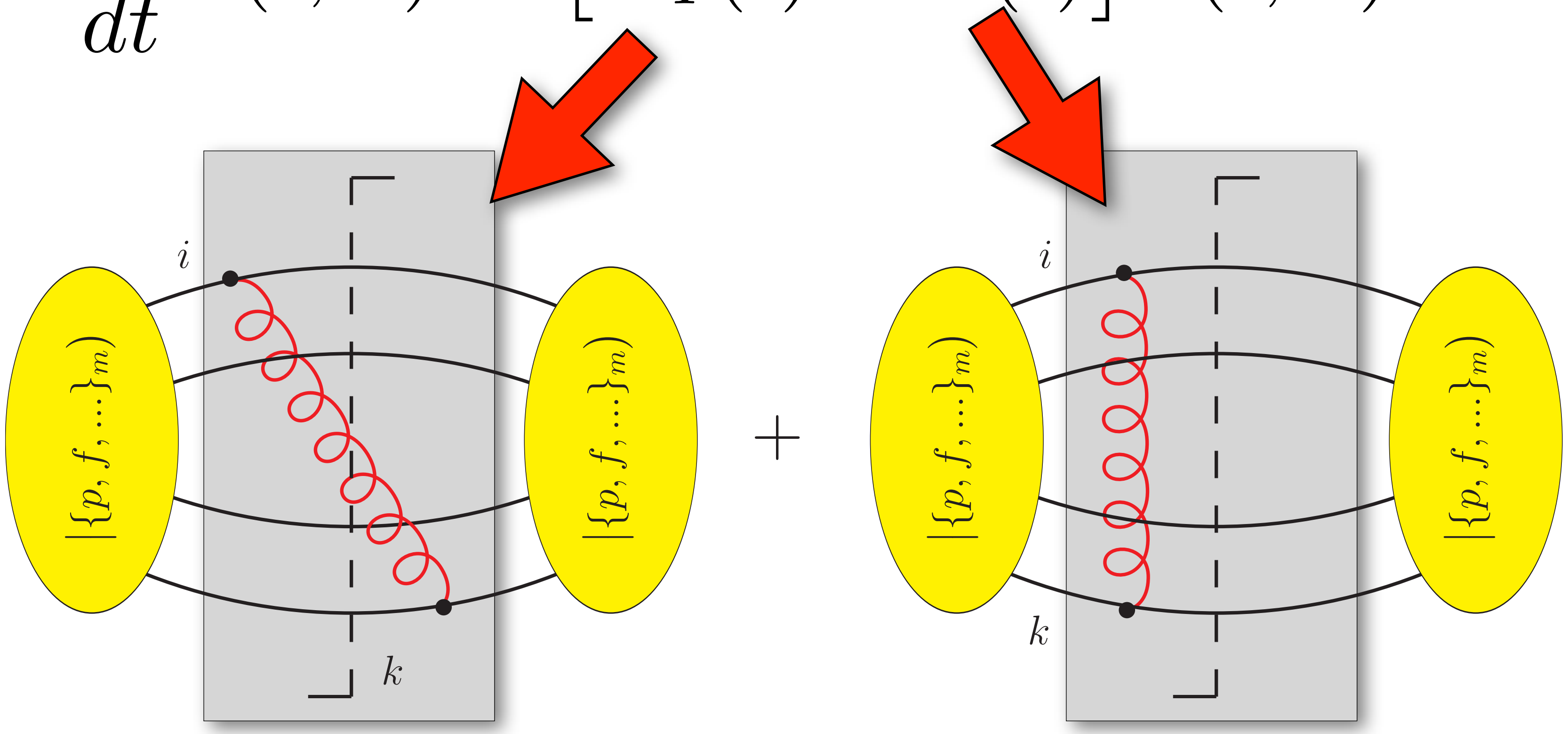
Do the "Quantum Shower" or any other shower know about these logarithms?

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 (w=1)

Quasi-classical probabilities

- still can be organized as a Markovian process
- real weights for color (w ≈ 1)
- complex weights for spins

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

- 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"* ....

Non-global effects

Quantum probabilities

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

Where are we now?

- We are working on the implementation...
- Our default shower will be a virtuality ordered shower.
- We have a promising algorithm that can go beyond the leading color approximation efficiently.
- The finial state radiations are under control; every probabilities are computed both for the massless and massive cases.
- We are computing the initial state probabilities, this is the hardest part if we want to massive partons.
- We want to implement kT and angular ordered shower in the same framework.
- ....

“The proof of the pudding is in the eating”