Effects of color reconnection on the top mass

Spyros Argyropoulos

work in collaboration with Torbjörn Sjöstrand

JHEP 11(2014)043 (arXiv:1407.6653)

Why I am giving this talk

CR has become one of the dominant systematics in top mass measurements

Experiment	m_{top} [GeV]	Error due to CR	Reference
World comb.	173.34±0.76	310 MeV (**40%**)	arXiv:1403.4427
CMS	172.22±0.73	150 MeV (**20%**)	CMS-PAS-TOP-14-001
D0	174.98±0.76	100 MeV (**13%**)	arXiv:1405.1756

Goals of the talk:

- give you some insight into **what color reconnection is** and **how it affects the top mass**
- discuss **how the top mass uncertainties can be reduced**
- discuss **how/what we can learn about hadronization**

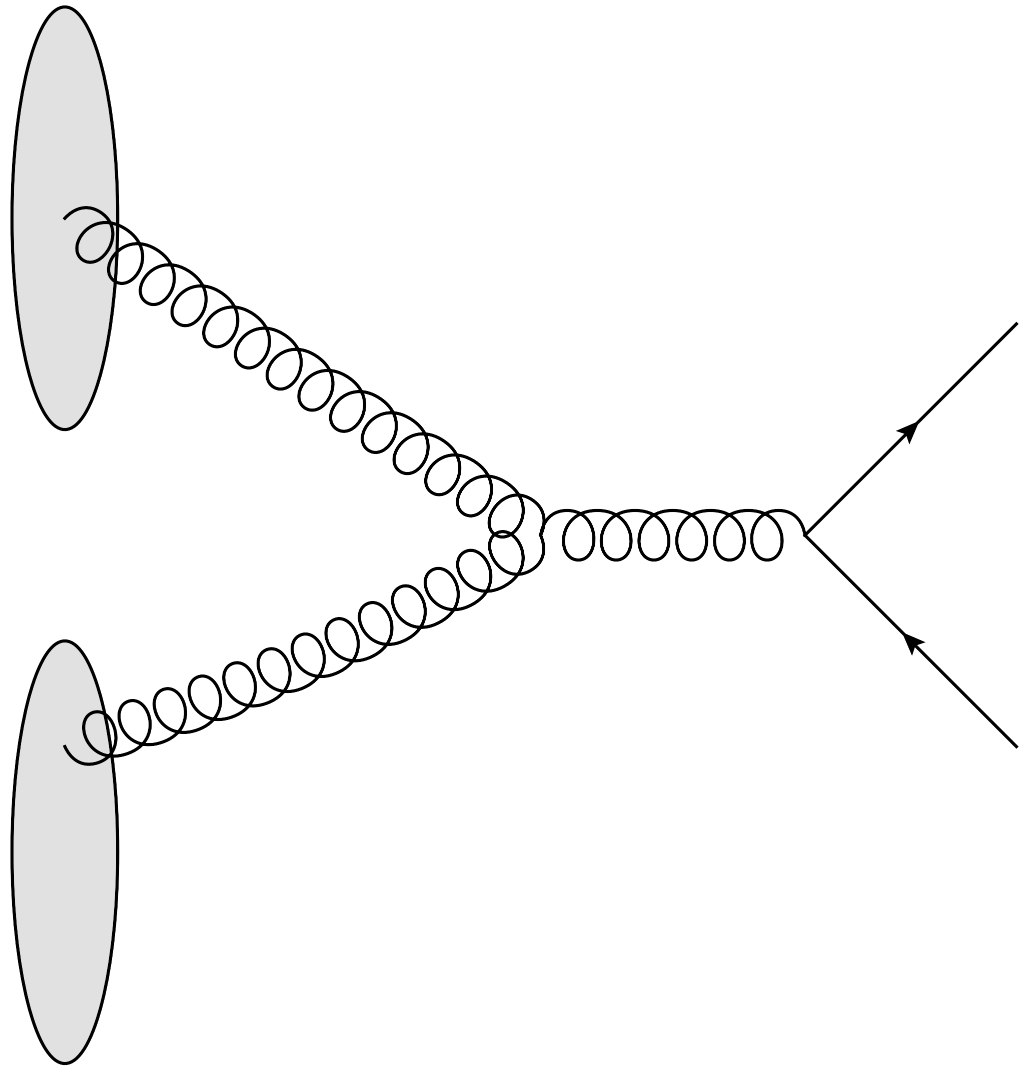
Outline

1. Introduction
   - Parton showers and hadronization
   - Color reconnection: what it is and how it looks like
   - Color reconnection and the top mass

2. The situation so far
   - existing models of CR
   - how the top mass uncertainty is determined

3. Looking ahead
   - new models for CR
   - a new look at the top mass uncertainty
   - what to do in the future

A typical pp event in an event generator



1. Start with the **hard subprocess** (Matrix Element calculation)
2. Add Parton Showers
3. Make colorless combinations of partons (stings)
4. Let the strings decay into hadrons

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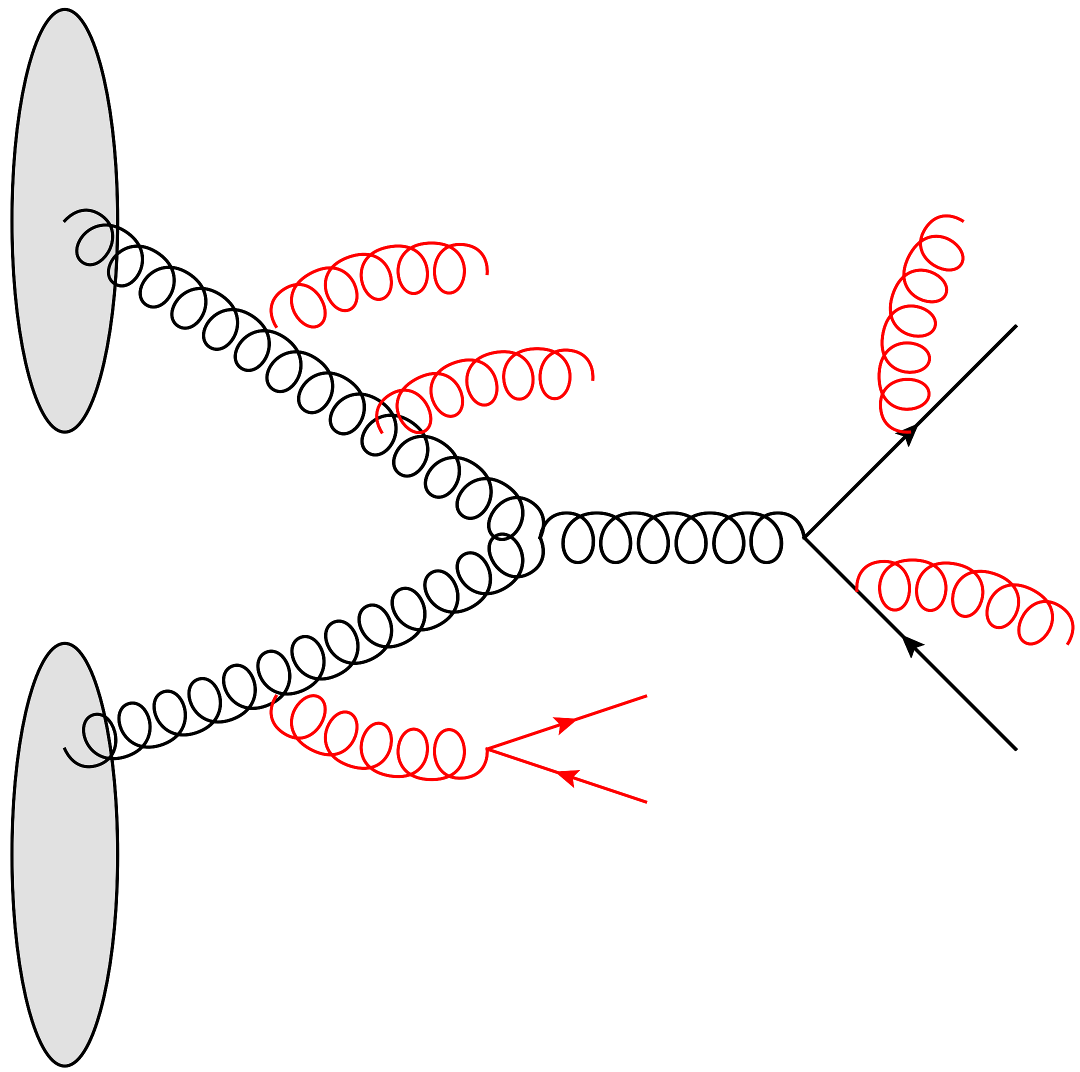

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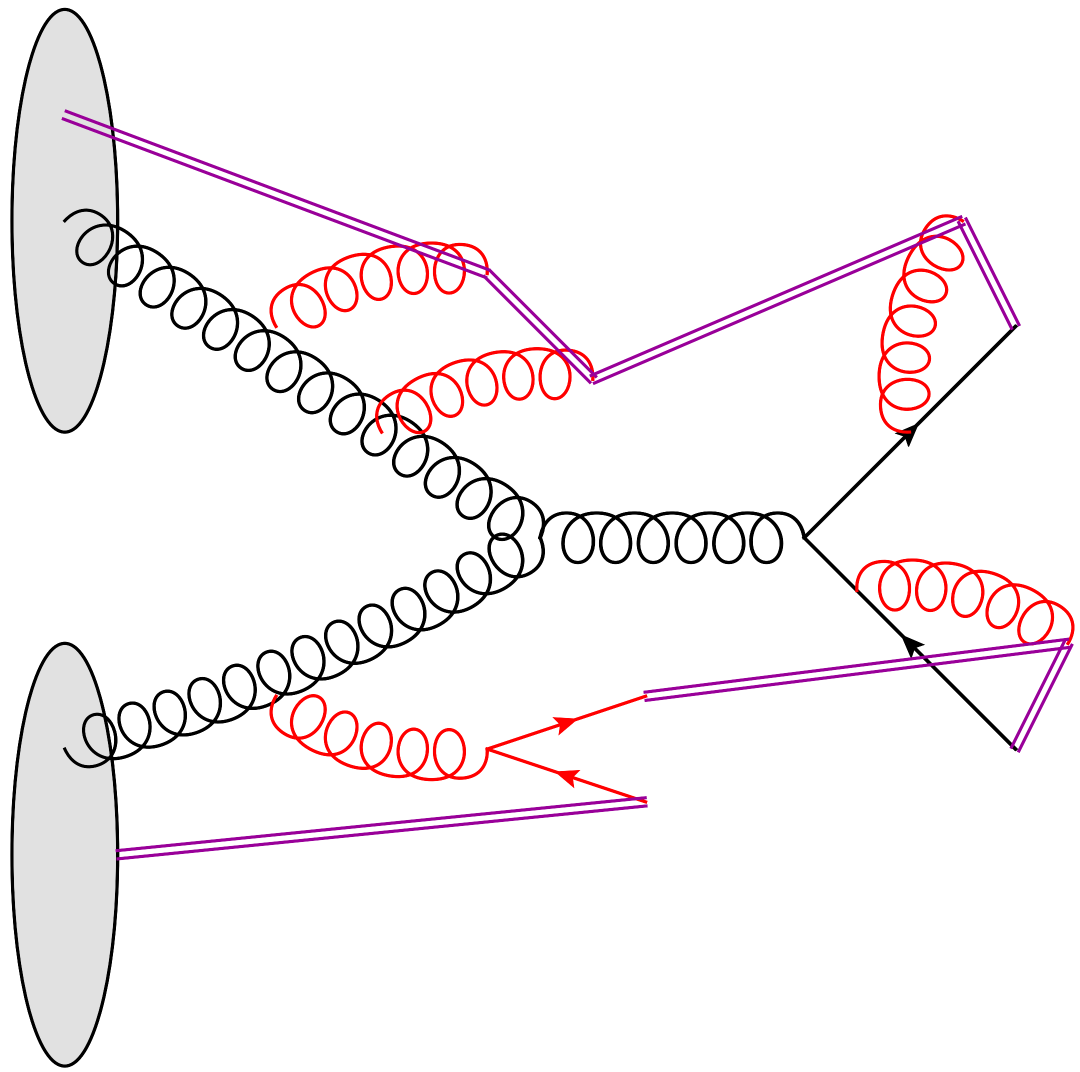

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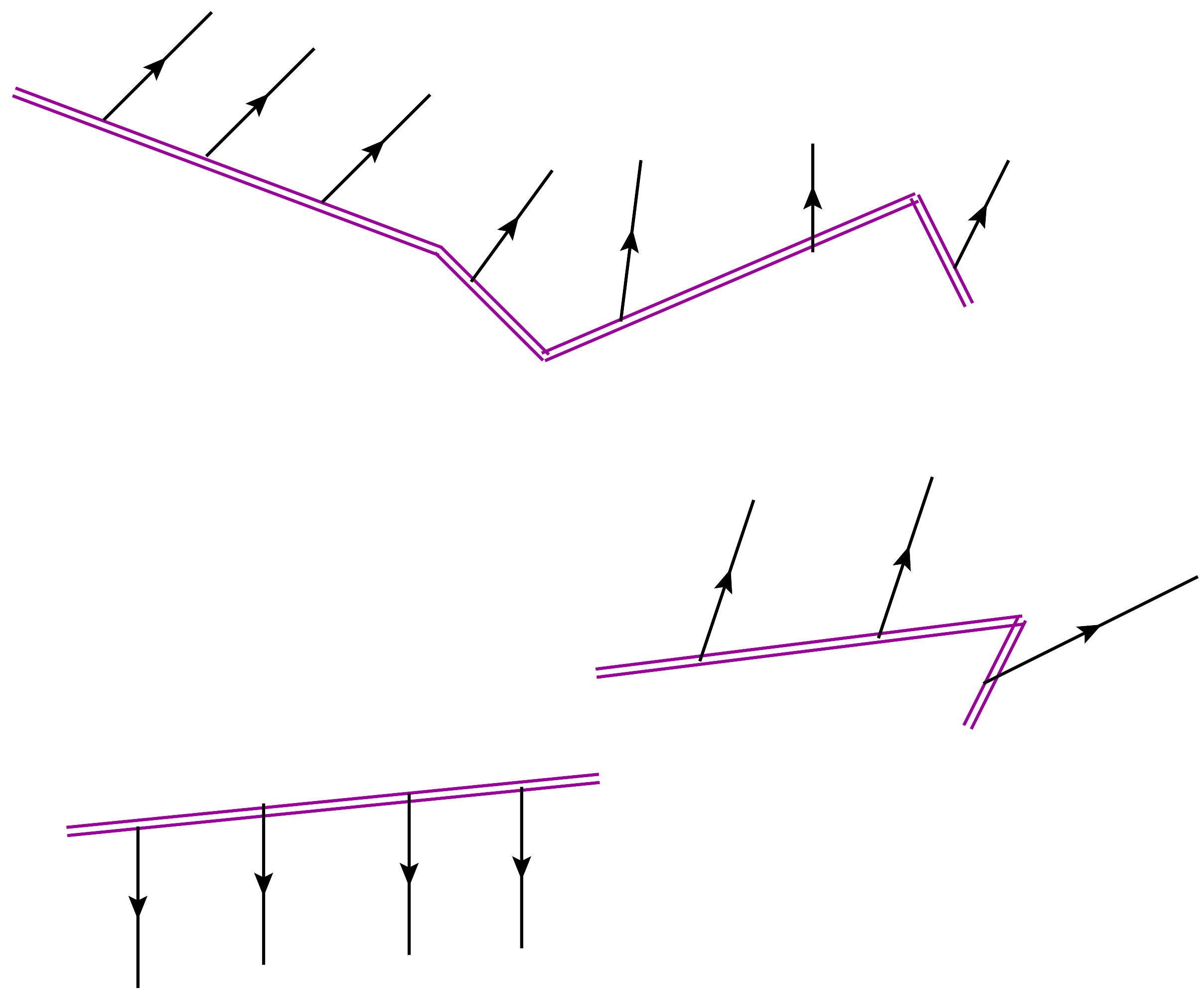

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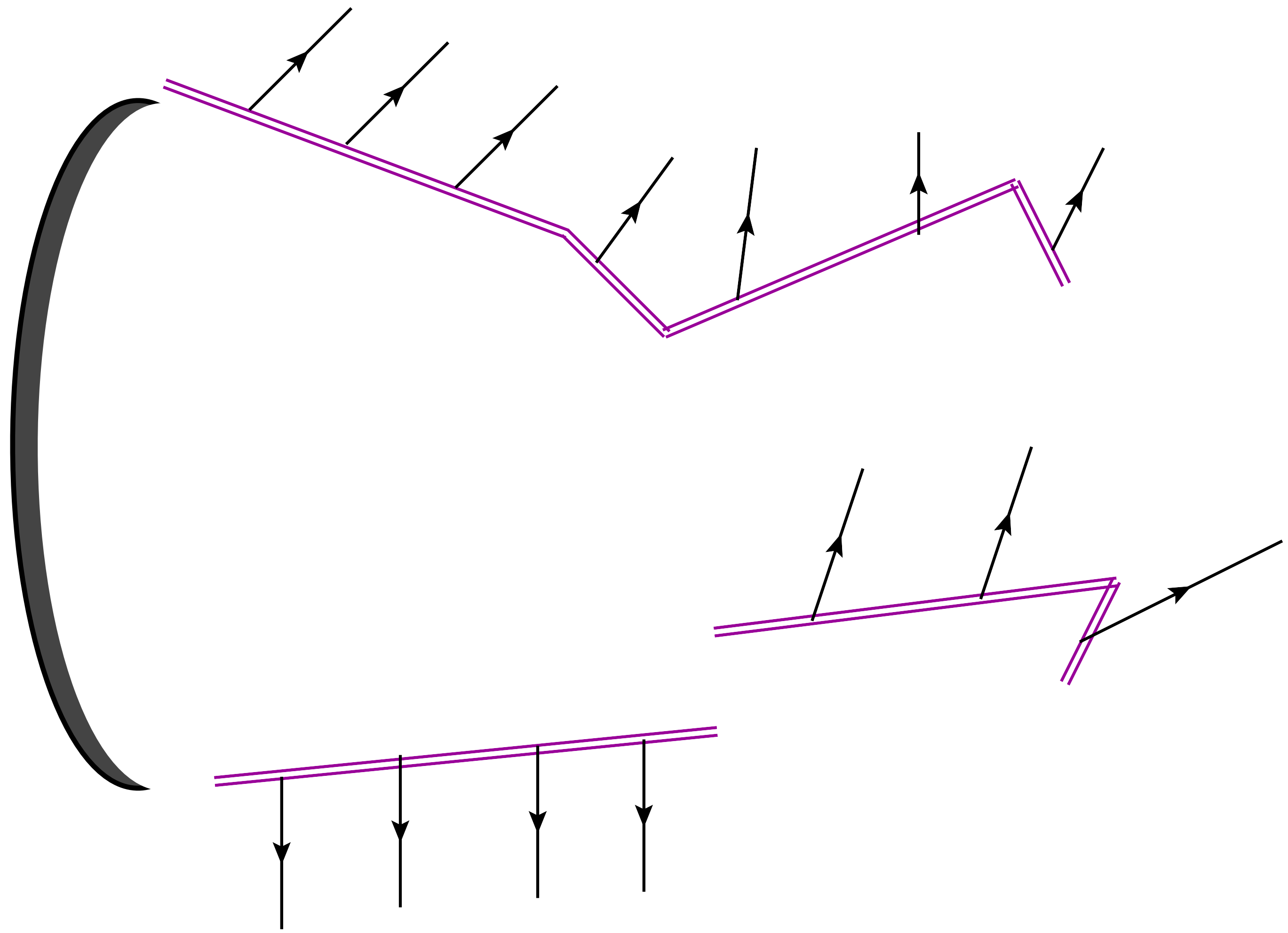
A typical pp event in an event generator

Deficit of hadrons expected in regions not spanned by any strings



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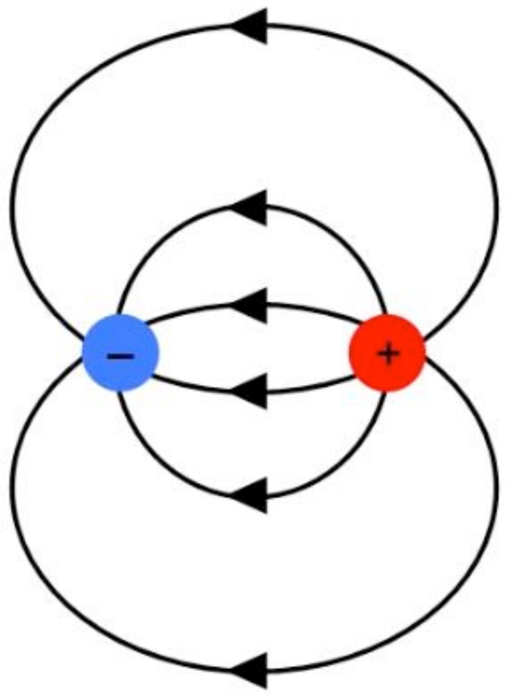
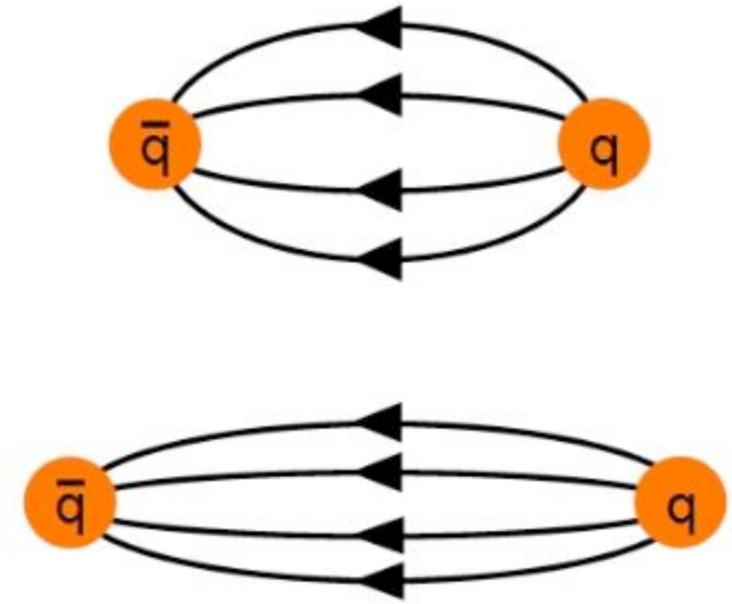
A stringy picture of confinement

Electric field



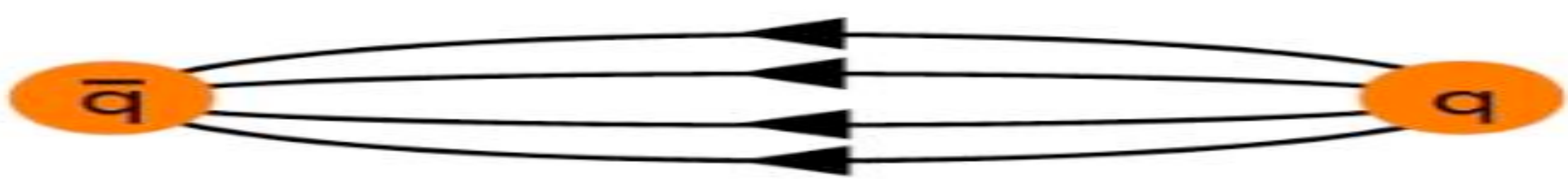
$V \sim r^{-1}$

Color field



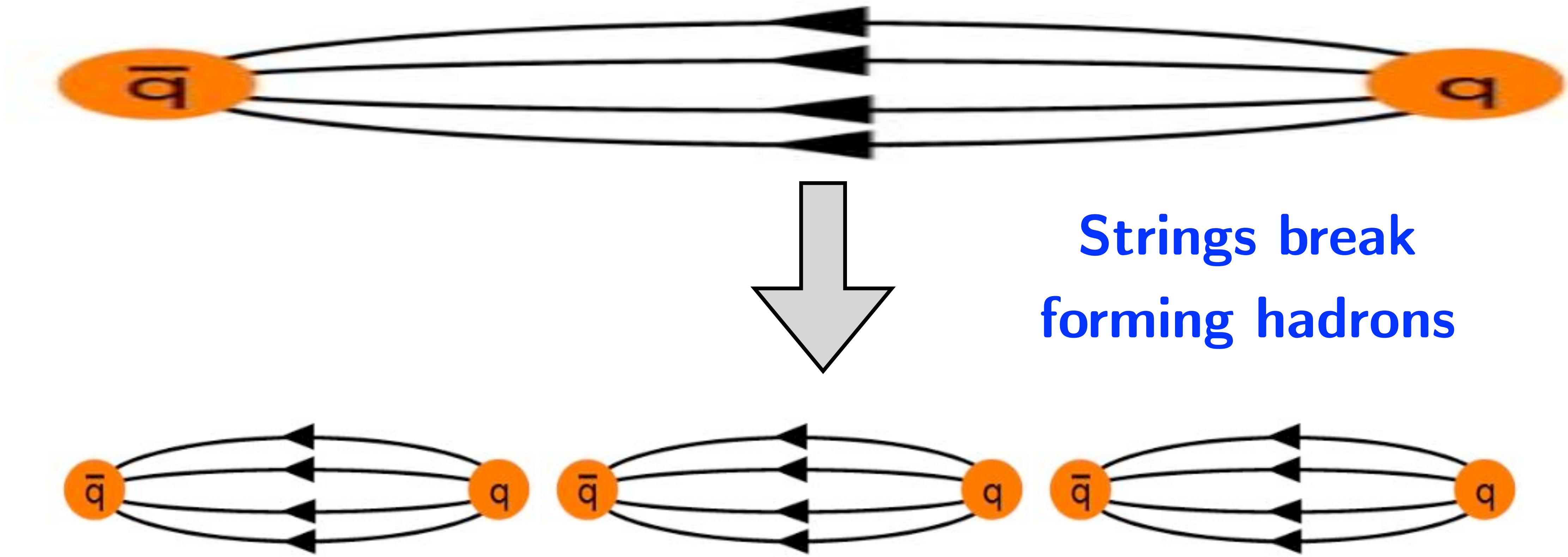
$V \sim r$

Confinement via **string**



$q\bar{q}$ system = massless relativistic string

Hadrons from strings



Strings break forming hadrons

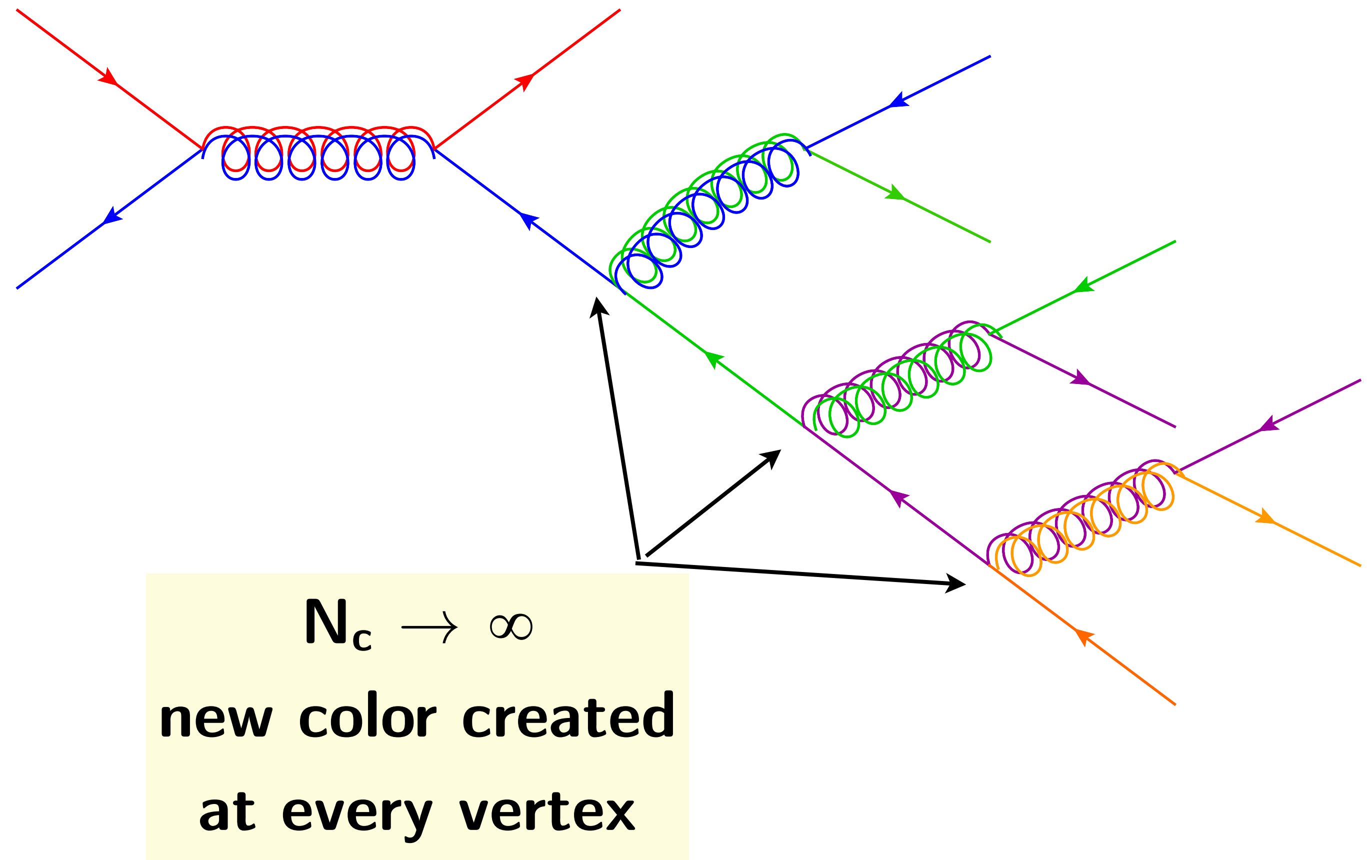
'Longer' strings $\Rightarrow$ more hadrons

length measured in $\lambda = \ln\left(1 + \frac{m_{ij}^2}{m_0^2}\right)$

Remark #1: the $N_c \to \infty$ approximation

The question that arises is

how one should draw the strings?



The planar approximation ($N_c \to \infty$) used in the parton showers provides a unique answer

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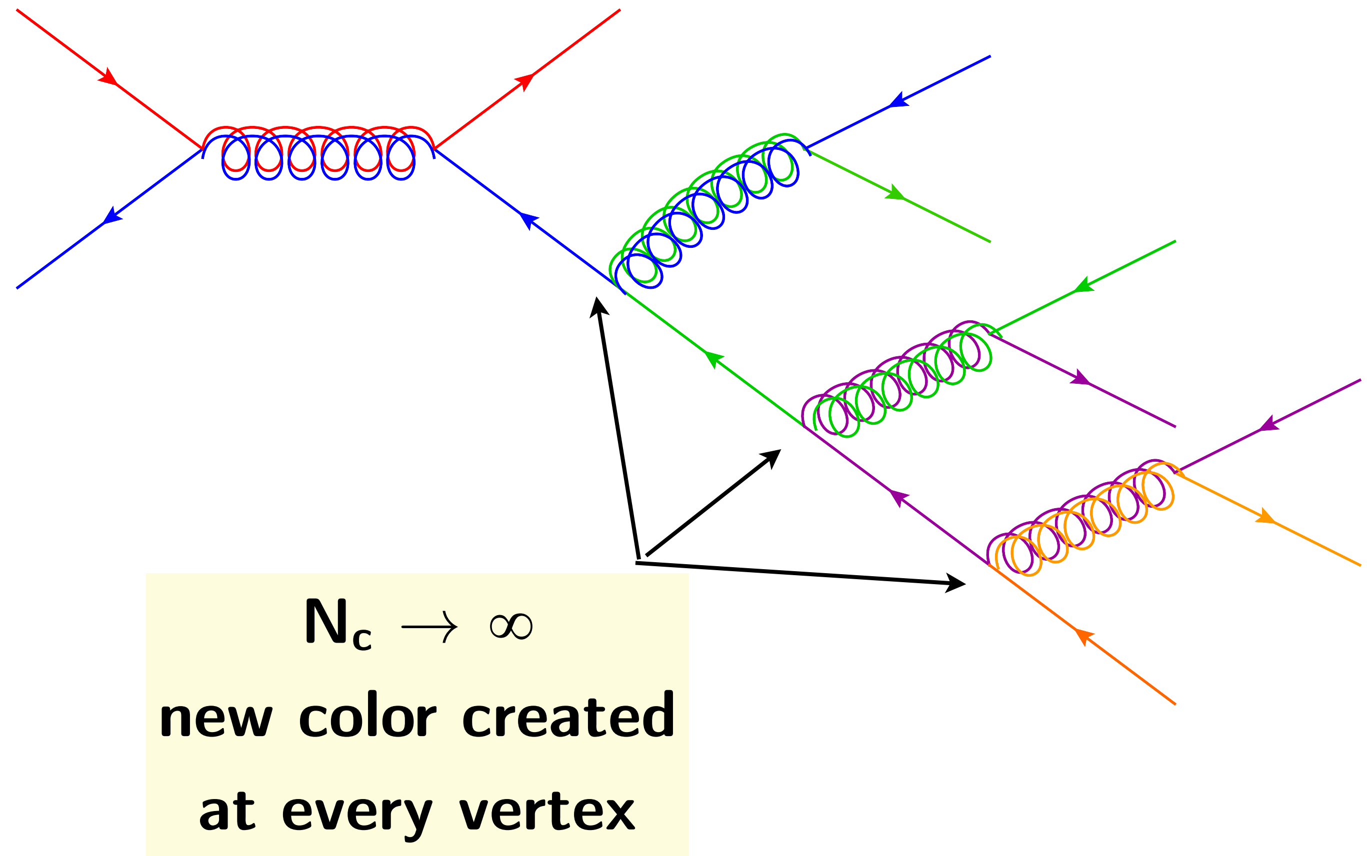

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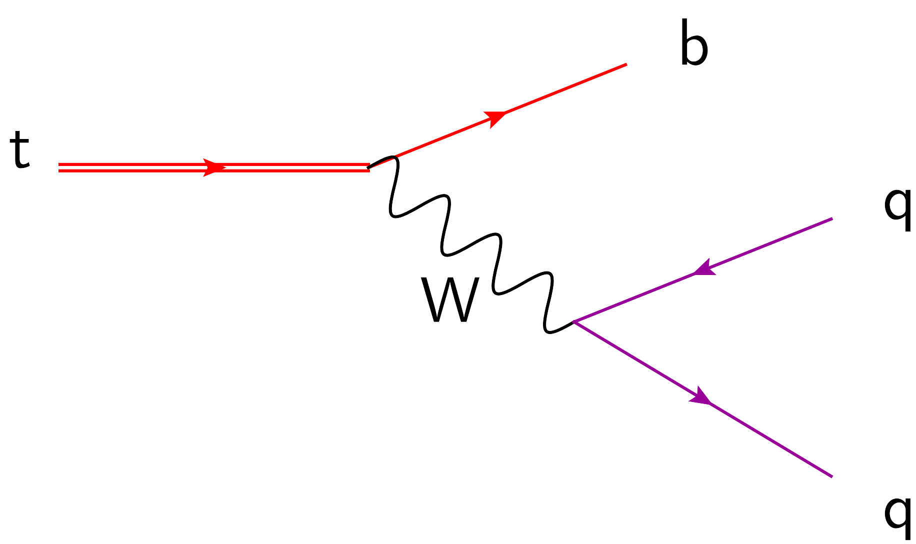
Consequences for top decay



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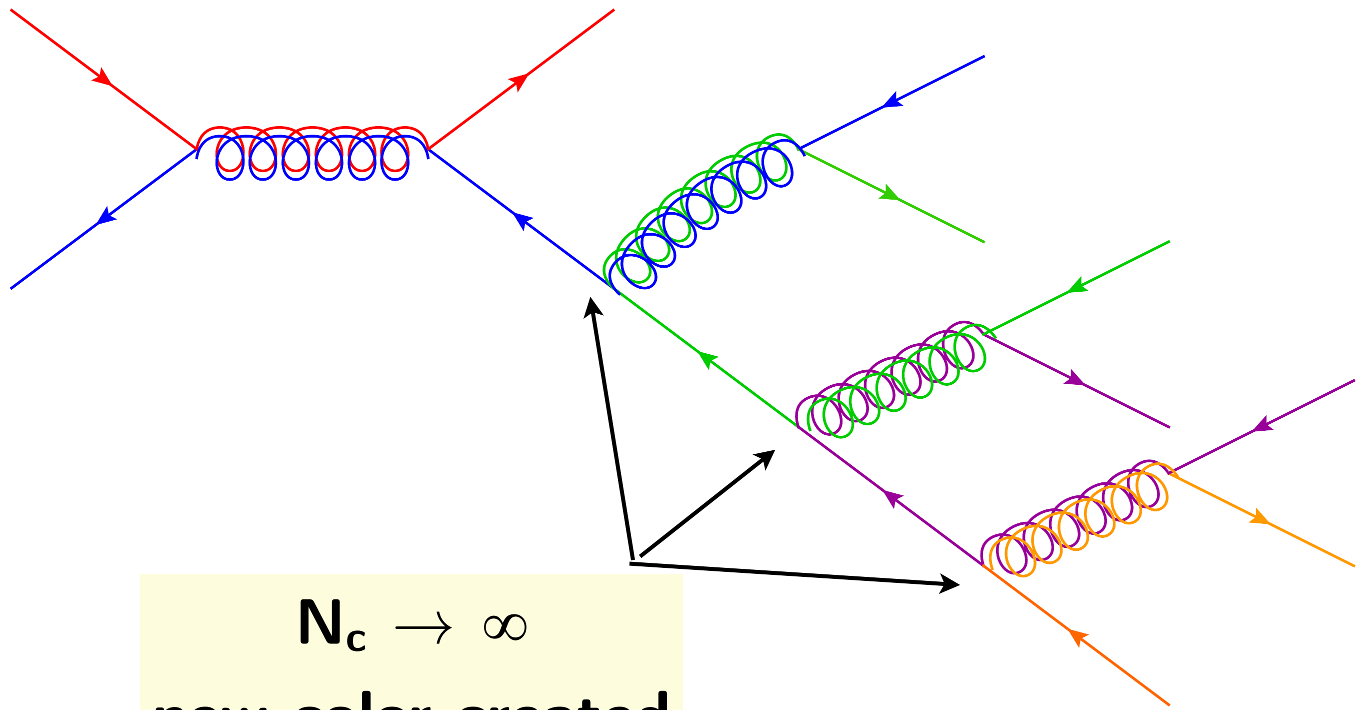
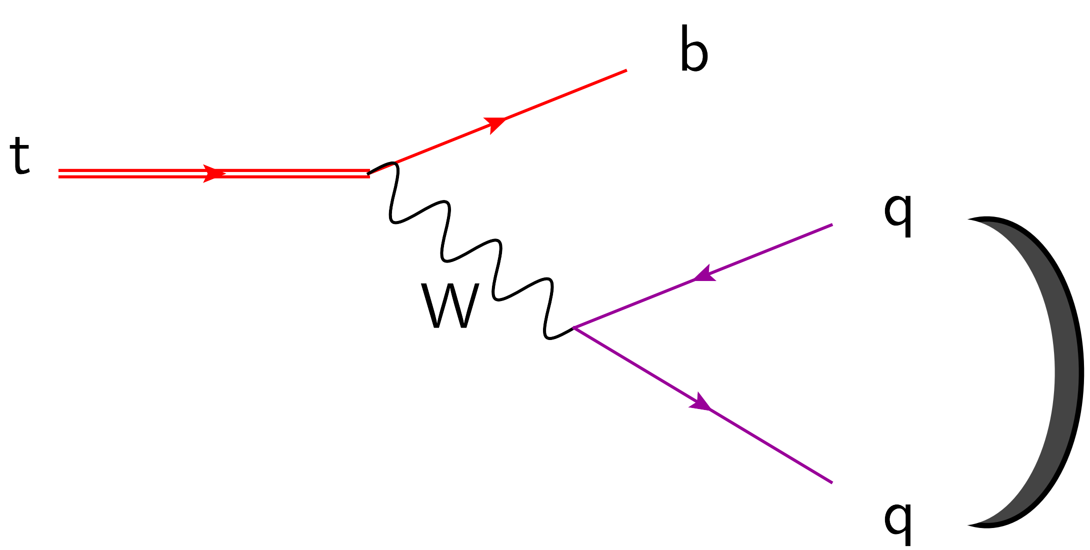


The planar approximation ($N_c \to \infty$) used in the parton showers provides a unique answer

$N_c \to \infty$
new color created
at every vertex

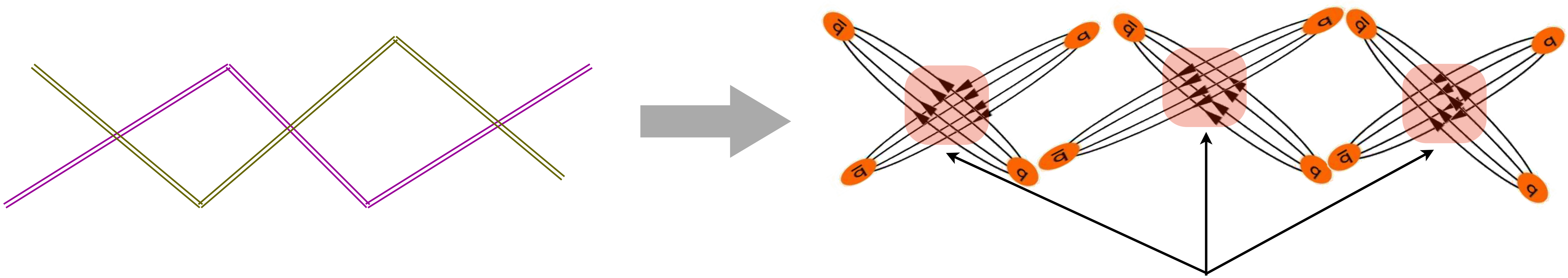
Consequences for top decay



In the planar approximation
the W decay products
are always color connected

Remark #2: non-perturbative interactions

Many MPIs ⇒ overlapping strings



String overlap: multiple soft gluon exchanges in all possible color states

Another question:

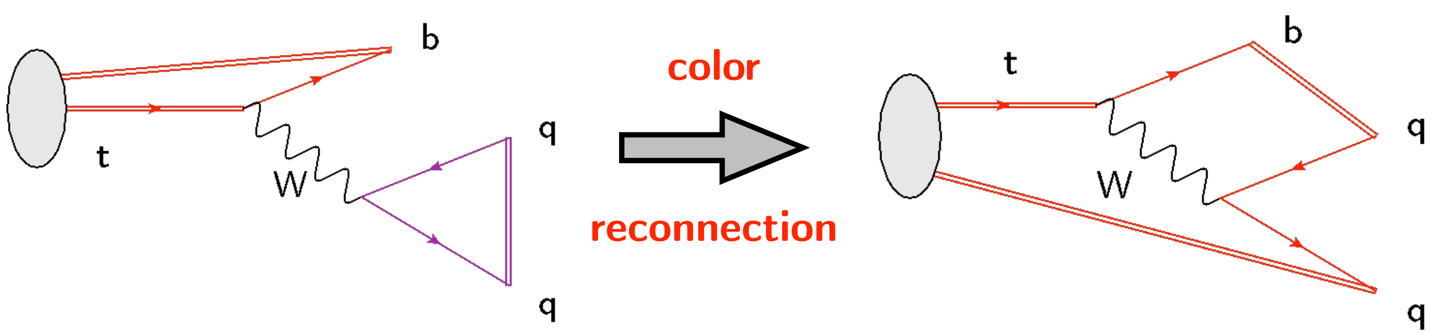
- what happens when the **strings overlap?**
- **can the strings** (drawn based on the planar color flow) **be rearranged by the non-perturbative dynamics?**

See e.g.
Sjöstrand, Khoze hep-ph/9310242
Biro, Nielsen, Knoll NPB 245 (1984) 449
Bierlich, Gustafson, Lönnblad, Tarasov 1412.6259
Werner 0704.1270

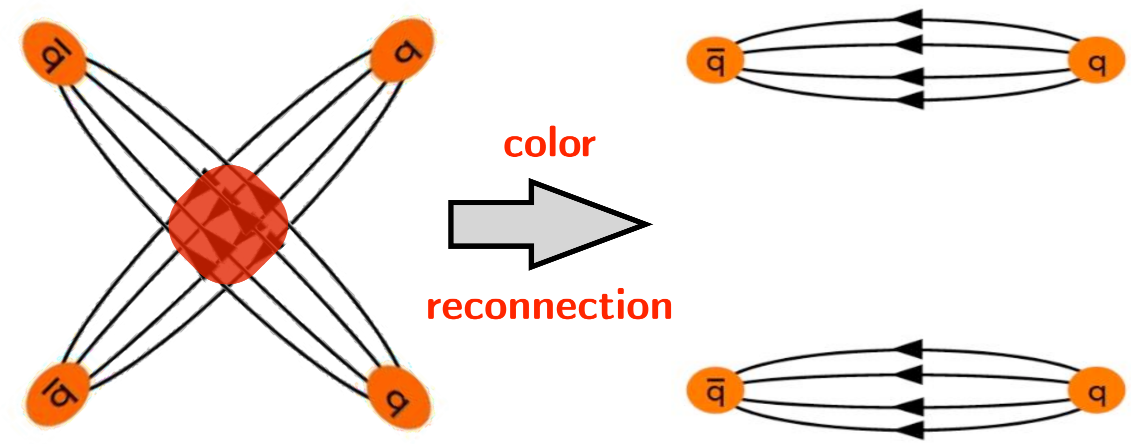
Color reconnection

An ad-hoc mechanism to describe:
- **sub-leading color effects in the perturbative part of the calculation**
- **interactions between color fields during the hadronization transition**

Static effects



Dynamic effects



➡ **Static effects associated to the color algebra**

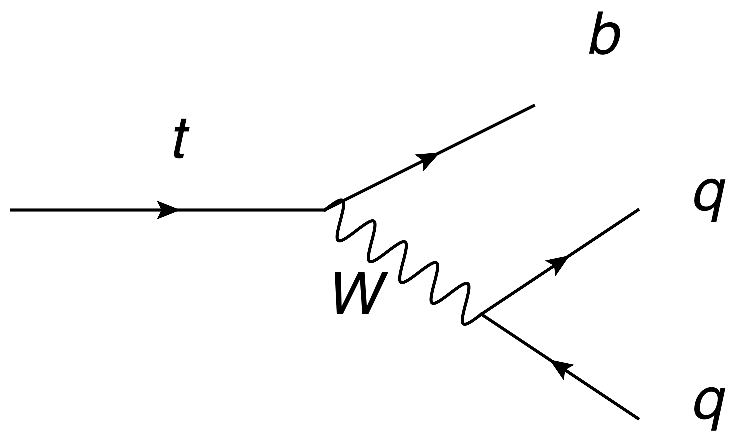
Probability for reconnection dictated by the SU(3) multiplet structure

➡ **Dynamic effects associated to string-string interactions**

In the following: no complete treatment of either the multiplet structure or the dynamics.
Underlying dynamical mechanisms allow reconnection probability to go up to 1.

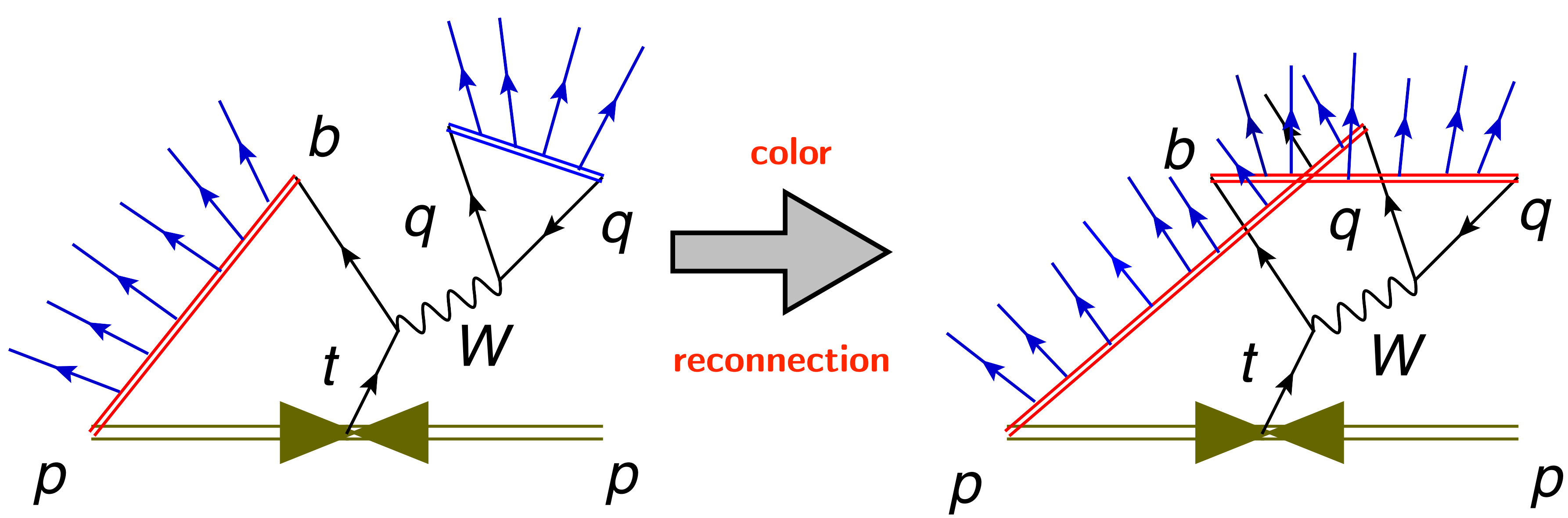
Effect of CR on m_{top}

Direct m_{top} measurement (lepton+jets channel)



$$\widehat{m}_{\mathrm{top}}^2 = (p_{\mathrm{b}} + p_{\mathrm{j1}} + p_{\mathrm{j2}})^2$$

Color reconnection affects the reconstruction of the top system



Ambiguity in the definition of the top mass: $m_{\mathrm{top}}^2 \neq (p_{\mathrm{b}} + p_{\mathrm{j1}} + p_{\mathrm{j2}})^2$

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The default CR model in Pythia 8

When

1. Starting from lowest p_T interaction calculate **reconnection probability**

$$P_{\rm rec}(p_T) = \frac{(R_{\rm rec} p_{T0})^2}{(R_{\rm rec} p_{T0})^2 + p_T^2}$$

$p_T \downarrow \quad \Longrightarrow \quad P_{\rm rec} \uparrow$

softer systems easier to reconnect

soft = extended wavefunction

2. Iterate (1) for all interactions ; if $\mathbf{P_{rec}} > \boldsymbol{\alpha} \in \mathbf{[0,1]}$ do reconnection $\longrightarrow$ **stochasticity**

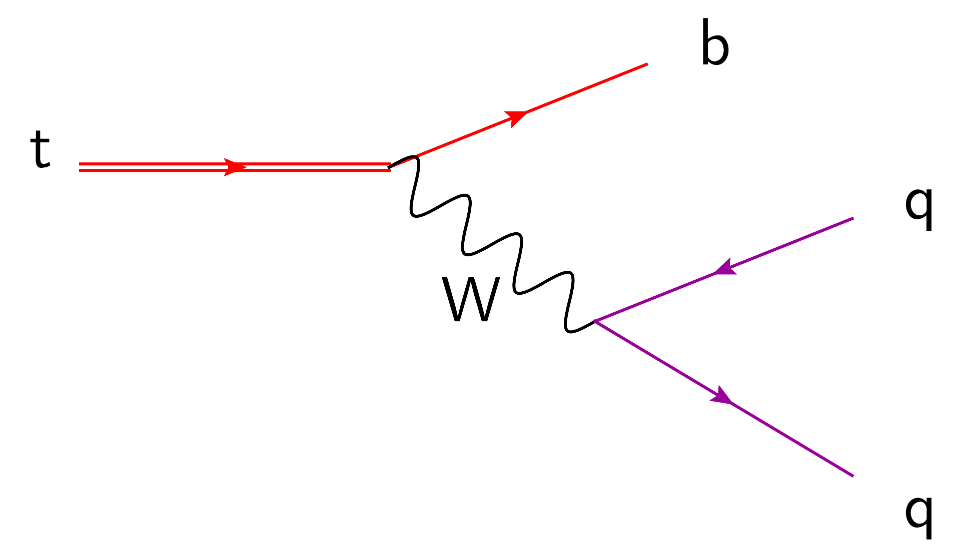
How

1. Sort interactions that where CR will happen in **decreasing p_T** $\longrightarrow$ **minimally affect the perturbative color flow!**
2. Starting from the **hardest interaction** find color dipoles (i,j)
3. **Move gluons** {k} from softer interactions **to dipole** (i,j) **that minimizes the increase in 'string length'**

$$\Delta\lambda = \lambda_{ik} + \lambda_{jk} - \lambda_{ij} = \ln \frac{(p_i \cdot p_k)(p_j \cdot p_k)}{(p_i \cdot p_j) m_0^2}$$

Remarks on the default model

1. By default the **only the top quark takes part in the CR machinery - not its decay products**



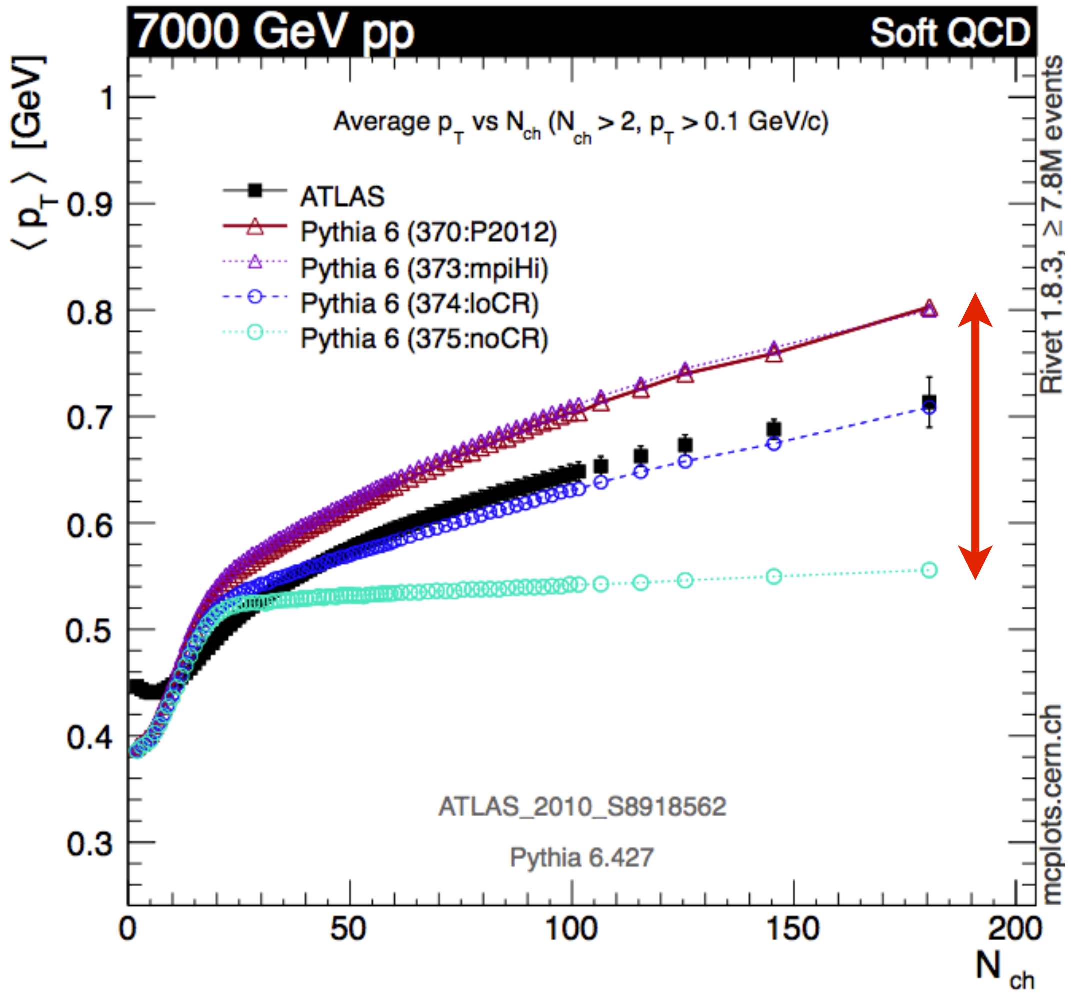
2. Default model is designed so as to **minimally affect the perturbative color flow**
   String endpoints are held fixed - at most gluon kinks are inserted

We don’t expect the default model to provide a bound on the effects of CR on the top mass

Estimating the CR uncertainty

$$\Delta m_{top} = m_{top}(\text{default CR}) - m_{top}(\text{no CR})$$

Until now this was done with **Pythia 6**, where multiple CR models are available.



The problem

- **'no CR' is unphysical** (uncertainty overestimated?)
- m_{top}(no CR) might not provide a bound for Δm_{top} (**uncertainty underestimated?**)
- **limited range of modeling options** in Pythia 8

We want:

- **range of** (new) CR **models**
- models (even extreme scenarios) that will **envelop the data** $\Rightarrow$ **uncertainty band**
- a **way to kill them**

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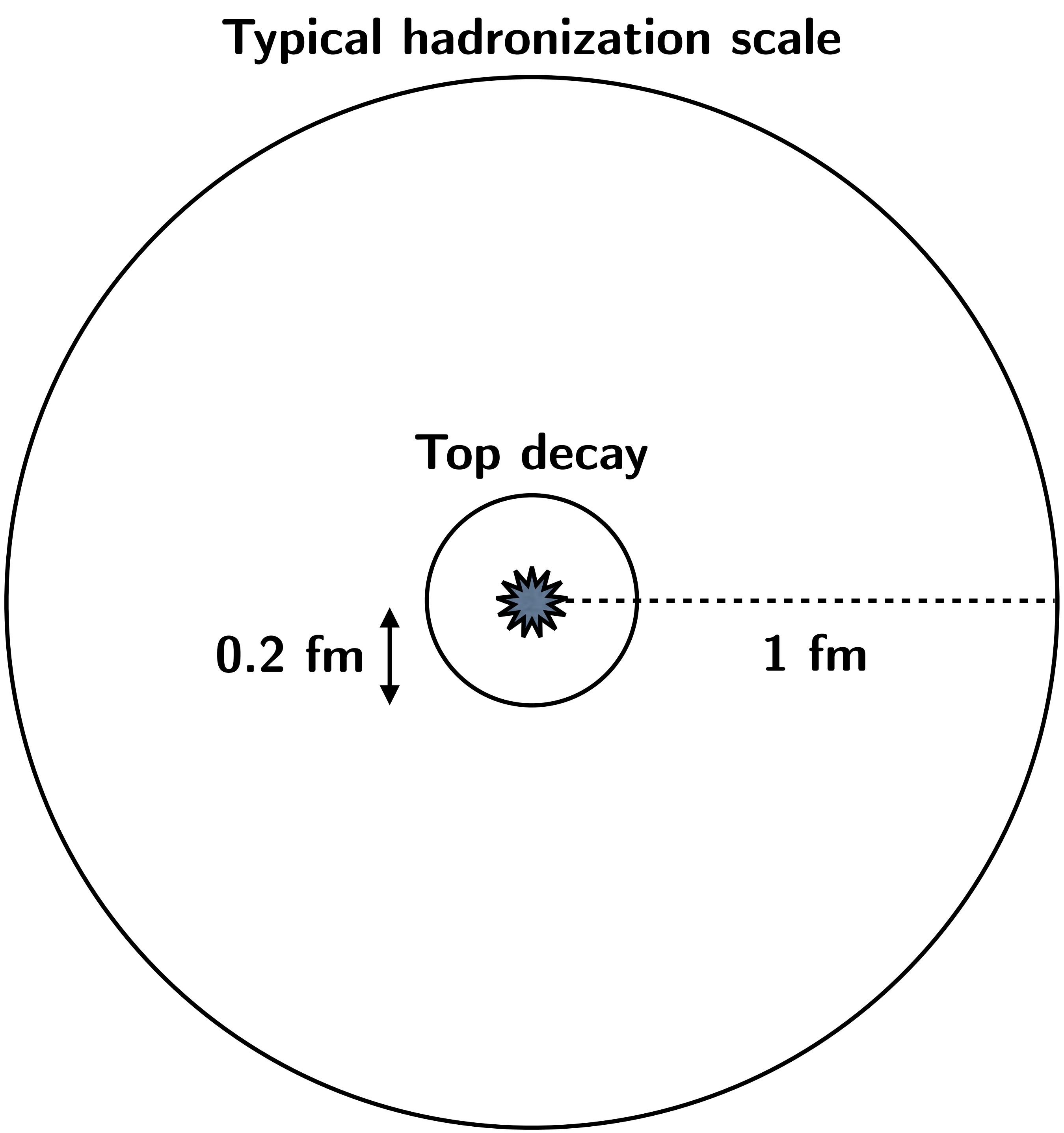
A word on time scales



$$\ell = \frac{\gamma\beta c\hbar}{\Gamma_{\mathrm{top}}} \simeq 0.2 \text{ fm}$$

CR in top can be different than CR in Min Bias

Two extreme options:

- **late resonance decay**
  top decay products cannot reconnect
- **early resonance decay**
  top decay products can reconnect

The models

Old
- default
- default ERD

New (toy models)
- forced random
- forced nearest
- forced farthest
- forced smallest $\Delta\lambda$
- smallest $\Delta\lambda$

only top events
default CR afterburner

New (more sophisticated)
- swap
- move
- swap + flip
- move + flip

all events

All models available in **Pythia 8.2** - examples/main29.cc

Models differ in...

When a CR is made
1. random
2. forced
3. minimization

How a CR is made

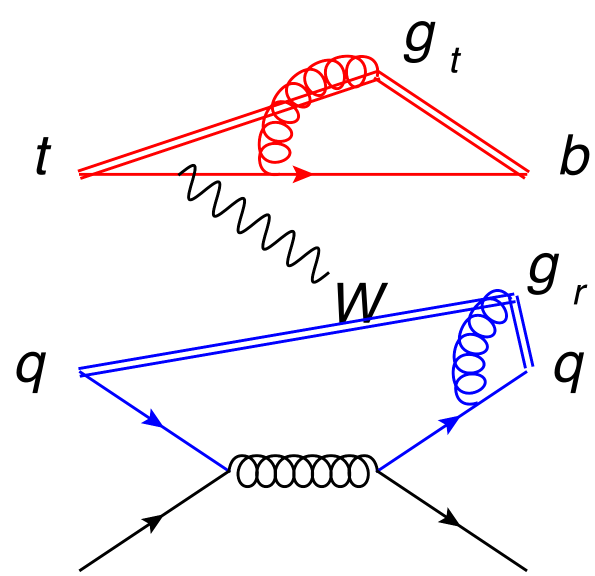
A. gluon move

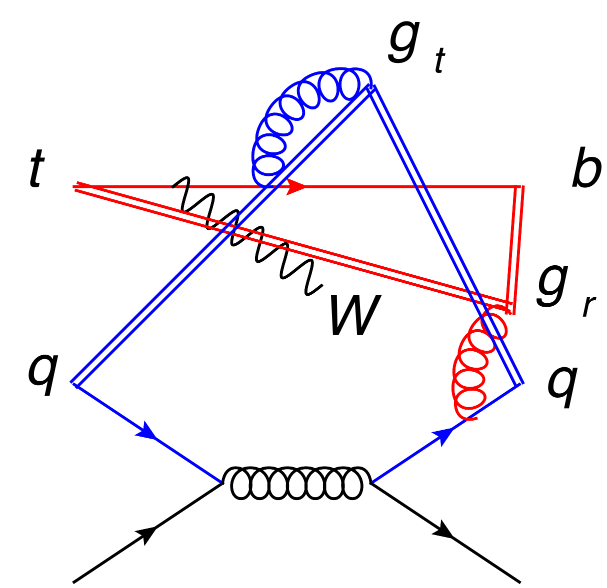
B. color swap (both indices)

C. color flip (single index)

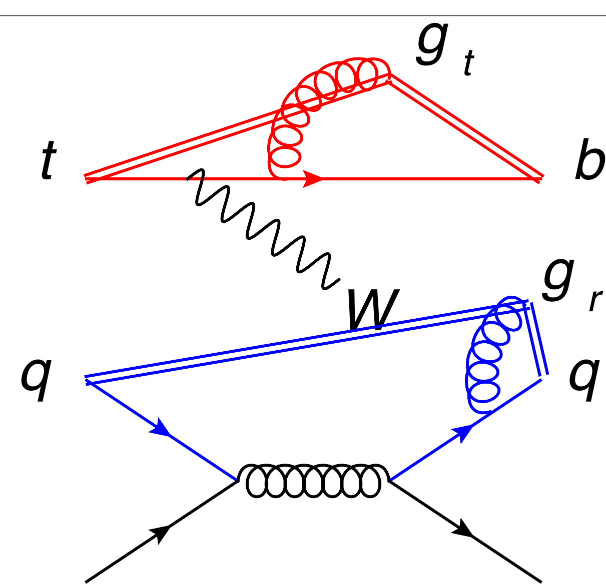
How a CR is made

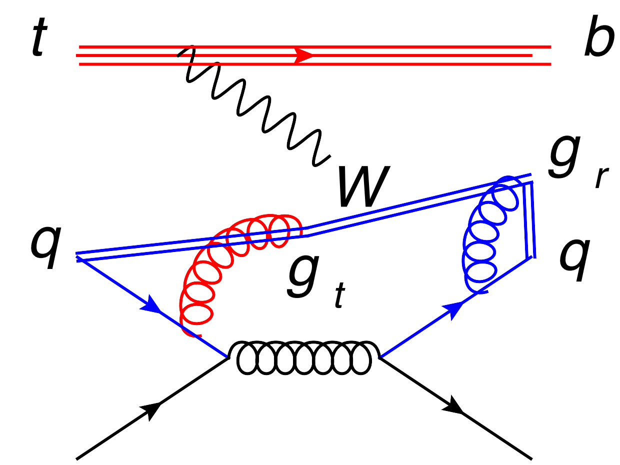
Color swap



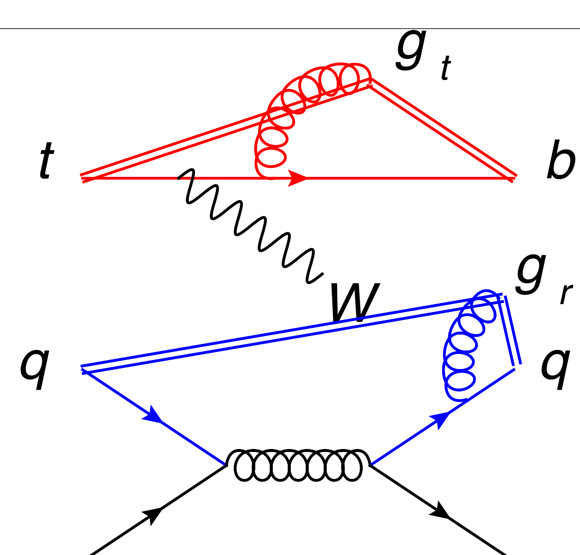


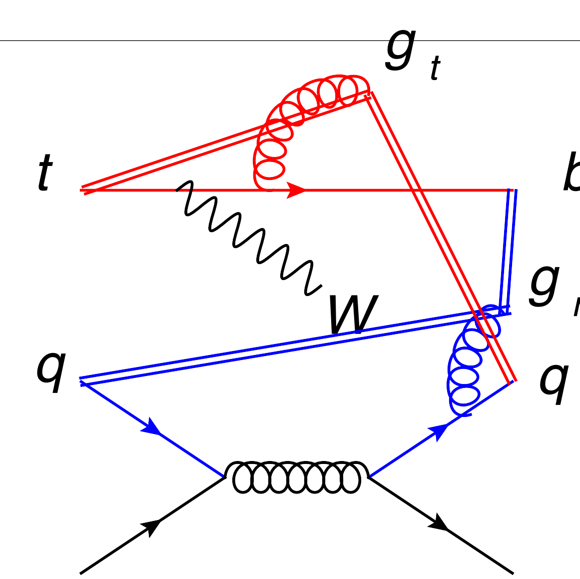
Gluon move



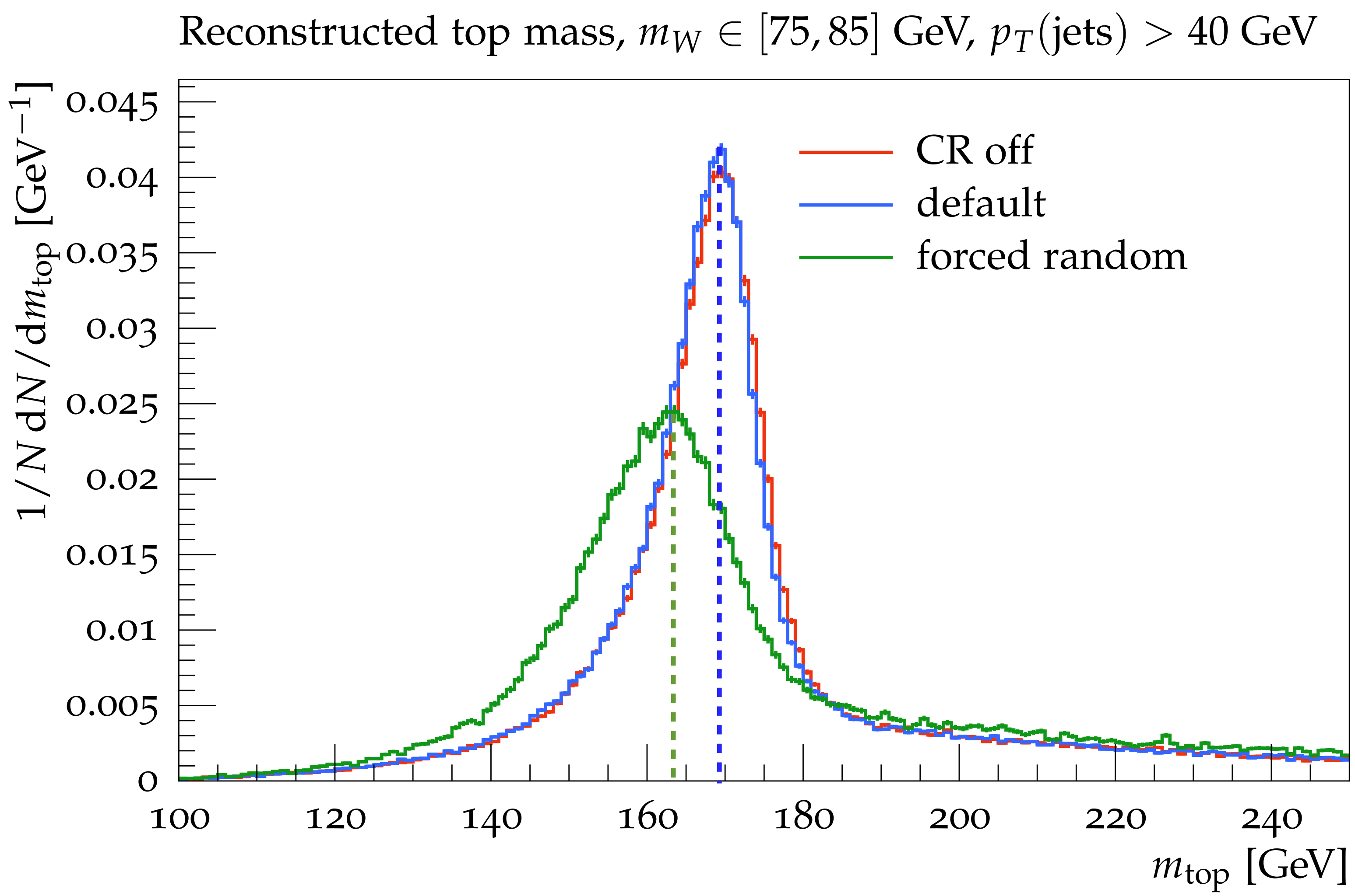


Color flip





Effect on m_{top} (before tuning)

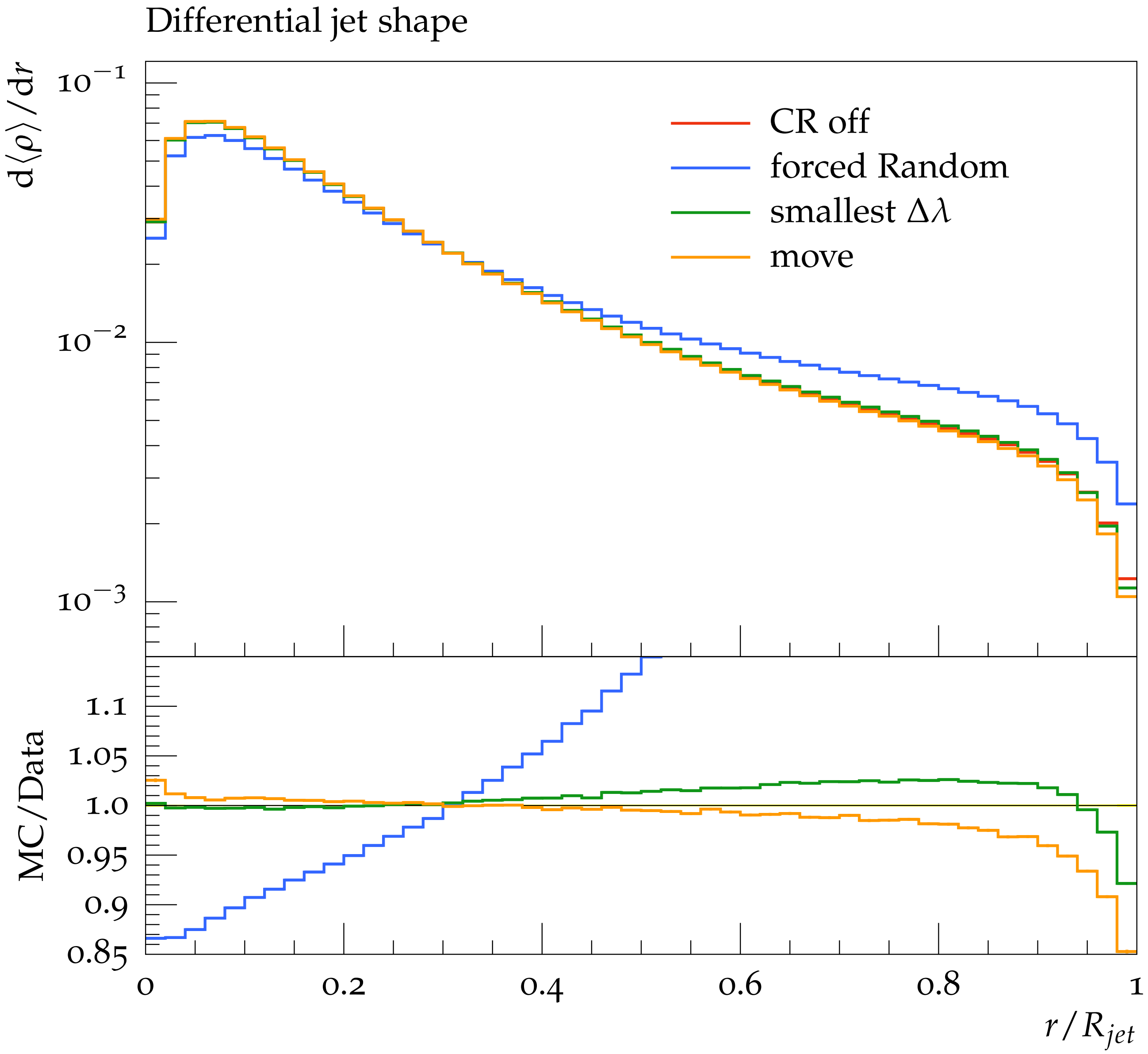


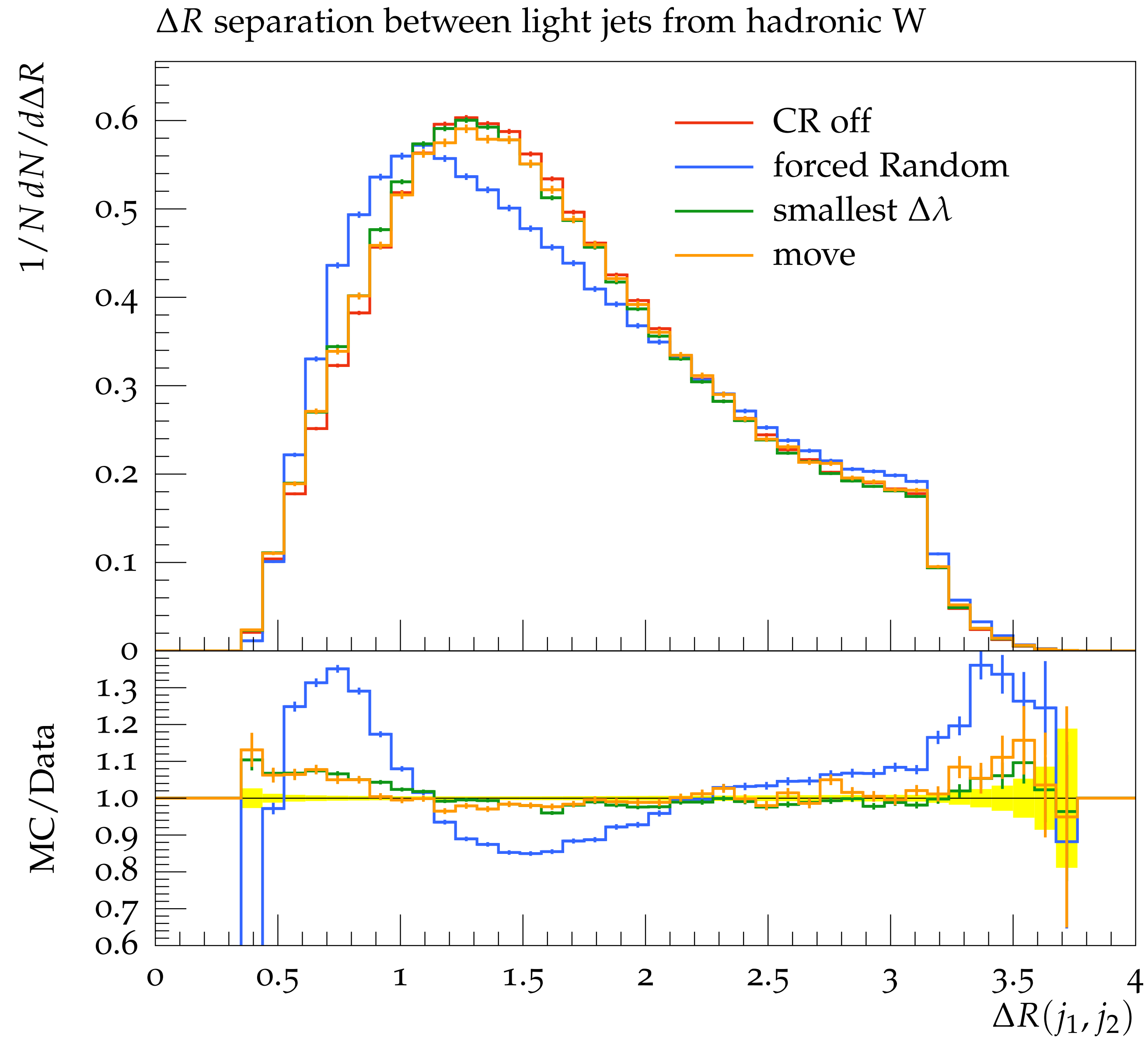
Model	$\Delta m_{top}^{rescaled}$ [GeV]
default	+0.209
default ERD	+0.285
forced random	-6.508

1. **CR can** inherently **have big effects!**
2. Δm_{top} is not bounded by m_{top}(no CR), in other words **m_{top}(CR)-m_{top}(no CR) probably underestimates the uncertainty**
3. **Effects are asymmetric** - negative mass shift easy, positive one hard

Why CR shifts m_{top}

$$\widehat{m}^2_{\mathrm{top}} = (p_{\mathrm{b}} + p_{\mathrm{j1}} + p_{\mathrm{j2}})^2$$



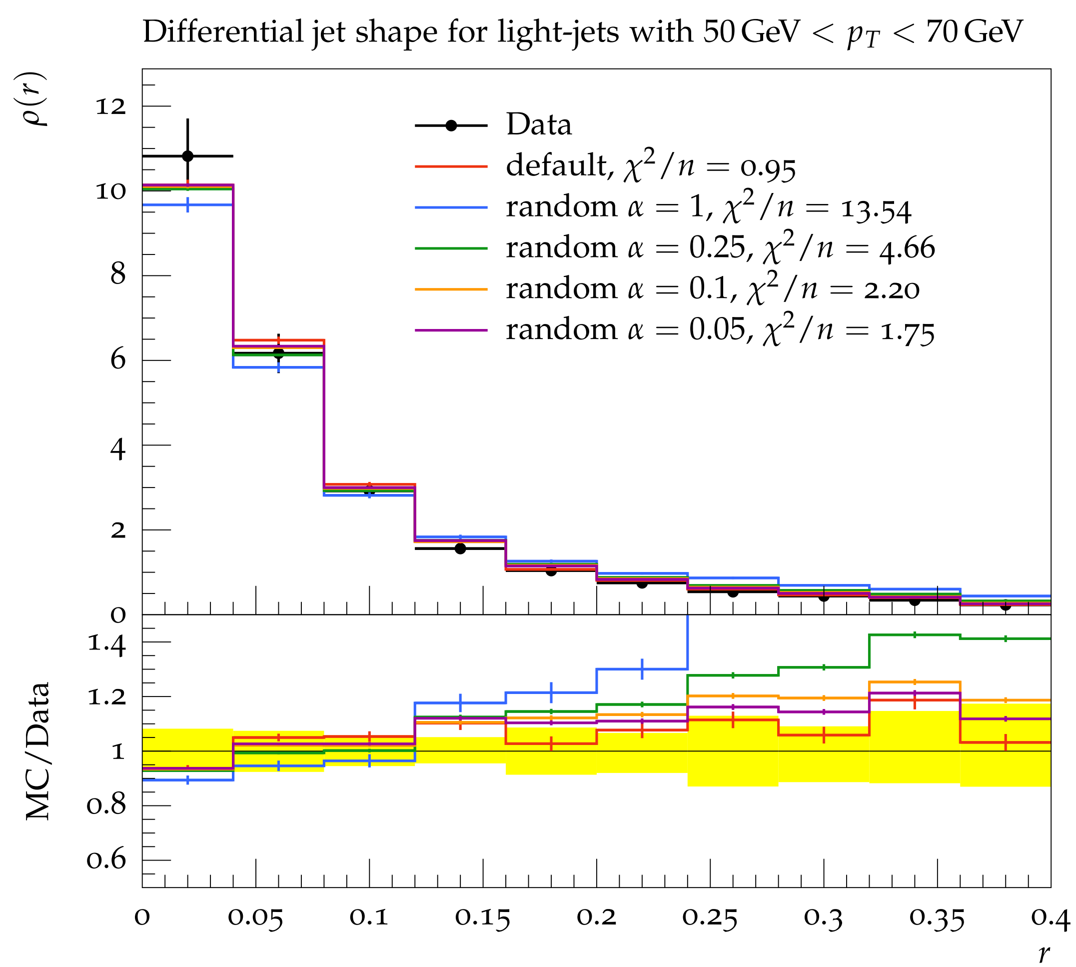


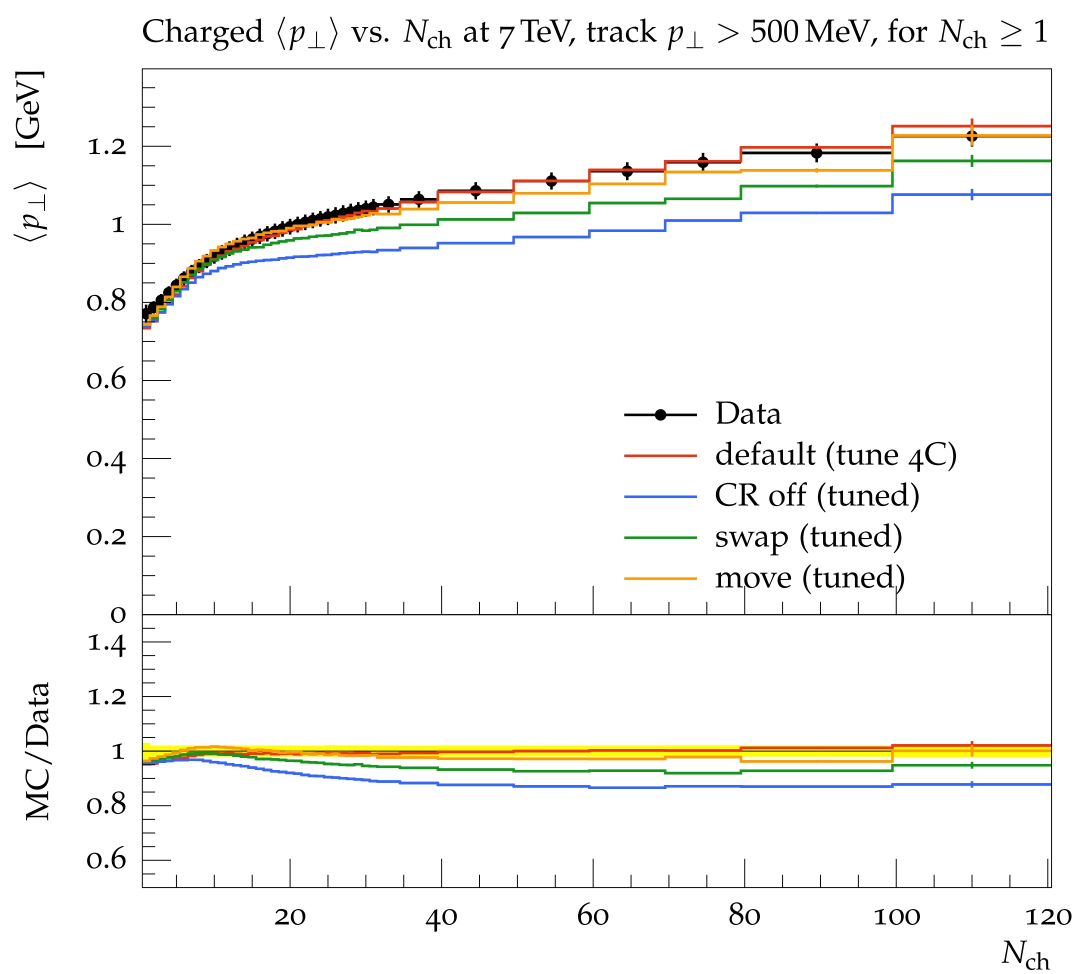
changes in p (**leakage** of hadrons **out of the jet cone**)

changes in $p_{j1}p_{j2} \sim \cos\theta_{j1j2}$

Tuning

- toy models: **jet shapes** in **$t\bar{t}$ events** (CR strength α)
- **MB models**: **minimum bias** data (p_{T0}^{ref}, $\Delta\lambda_{cut}$)





Forced models with high CR strength disfavored

Minimization models require maximal CR strength

- similar features observed with Herwig++ Gieseke, Röhr, Siódmok '12 (arXiv:1206.0041)
- models come pre-tuned - no need to excessively worry about tuning them!

Effect on m_{top} (after tuning)

Model	$\Delta m_{top}^{rescaled}$ [GeV]
default	+0.239
forced random (min)	-0.524
move	+0.239
swap (max)	+0.273

- **Maximum variation**: m_{top}^{max} - m_{top}^{min} $\approx$ **800 MeV**
- considering only the more sophisticated models:

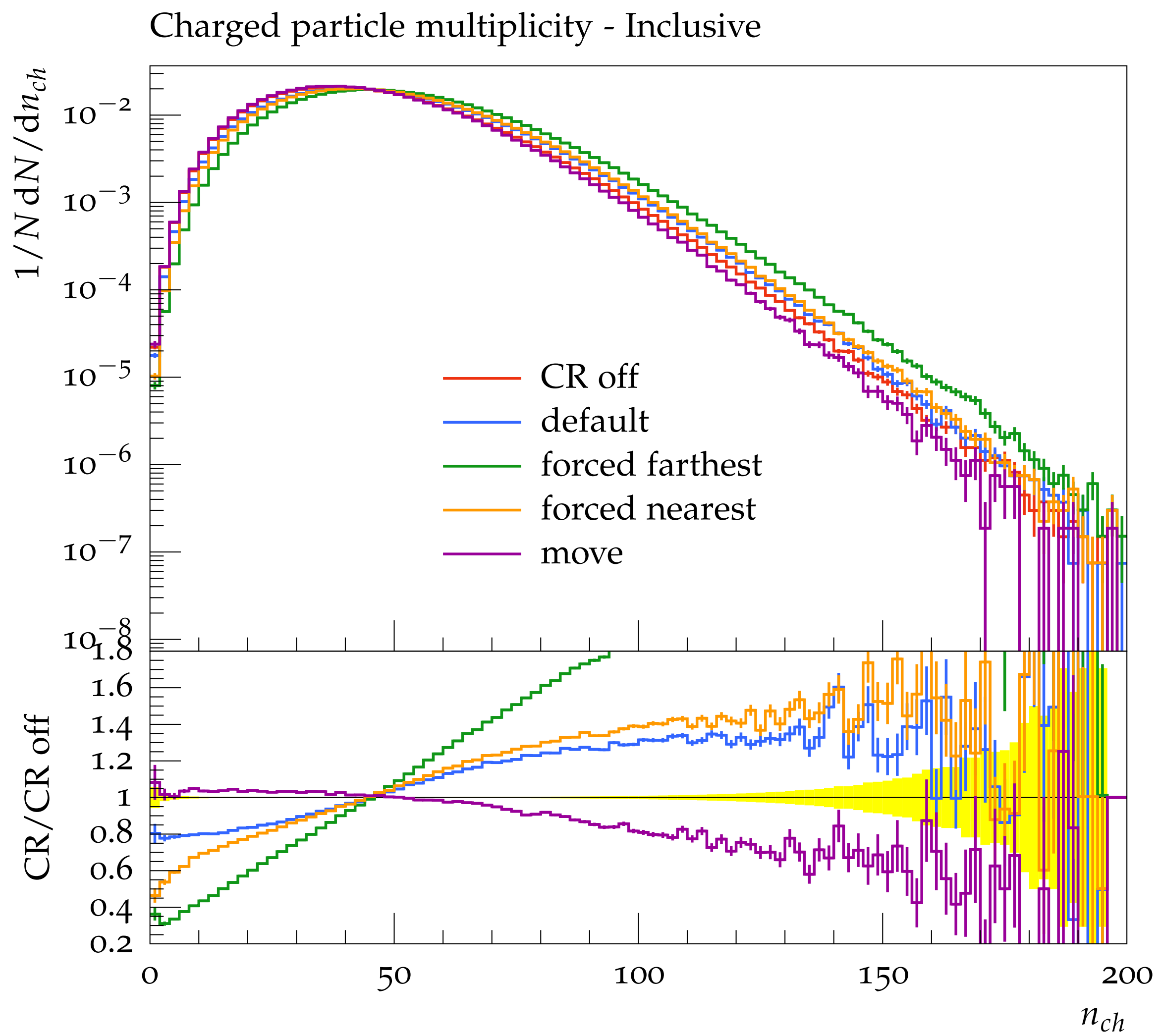
$$\Delta m_{top} \approx 500\ \text{MeV}$$

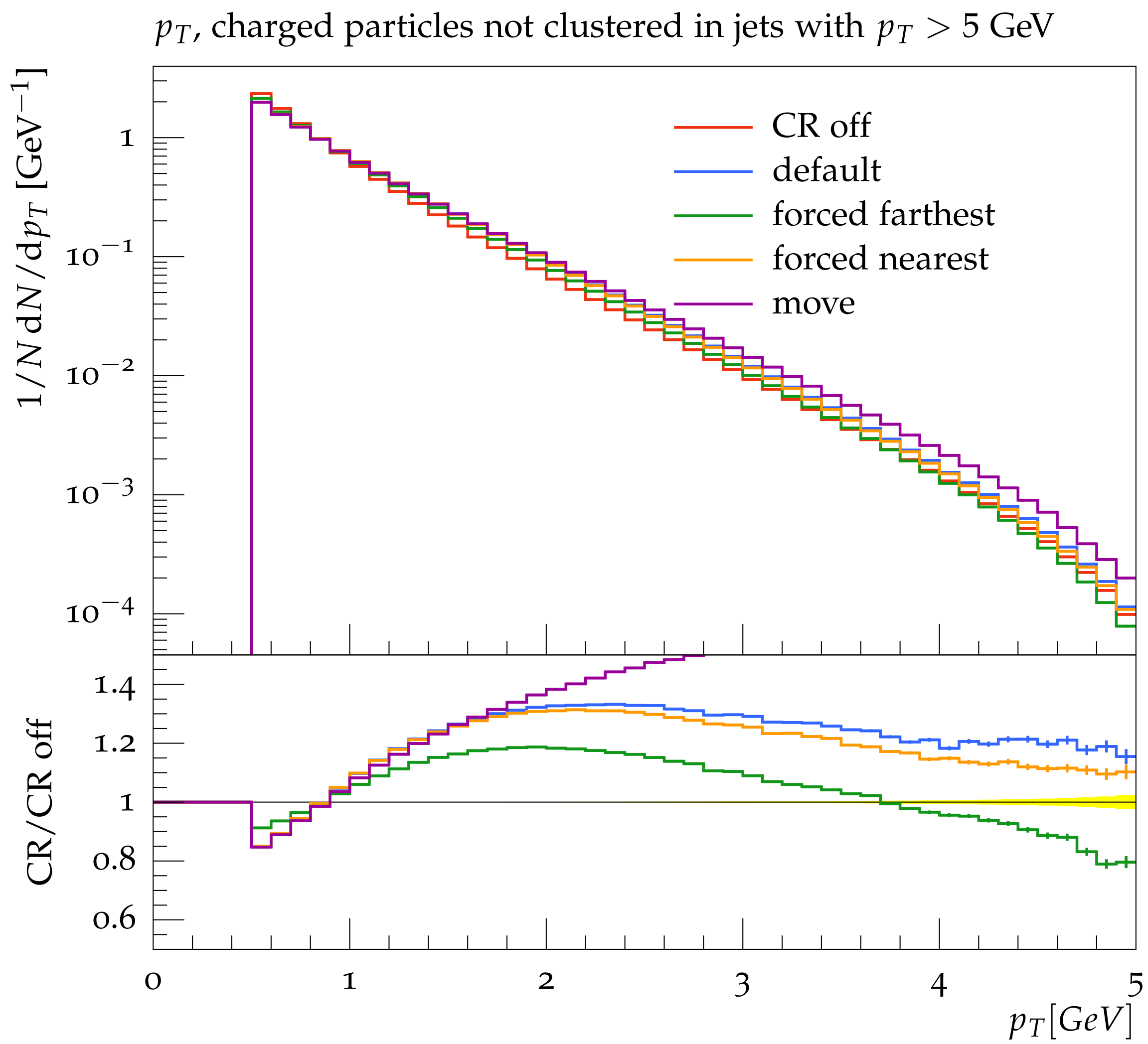
We believe that this is a realistic estimate of the CR uncertainty based on our current understanding of the phenomenon and on the available measurements.

How to reduce CR uncertainty

Make measurements that can constrain the models

- e.g. inclusive ones: **charged particle multiplicity**, **transverse momentum**
- UE type measurements in $t\bar{t}$ events, e.g. charged particle spectra in different regions (as in CMS-PAS-TOP-13-007), $<n_{ch}>(\Delta R_{Wb})$ etc





Ongoing and future analyses will hopefully incorporate these measurements

Summary

The situation so far...

- **until recently very few measurements** to constrain CR **in top events**
- **m_{top}(CR) - m_{top}(no CR)** probably **underestimates the uncertainty**
  (at least when using the default Pythia8 model)

Our work...

- **new CR models** developed and tuned to data
- a **realistic estimate** for the top mass **uncertainty** is of the order of **500 MeV**
- **observables to constrain/exclude** CR **models** with **existing LHC data**

New "QCD-based" model by **J.Christiansen and P.Skands** also introduced in **Pythia 8.2 (arXiv:1410.3012)** - its effects on the top mass are under study

Use the new models and measure observables sensitive to color reconnection.

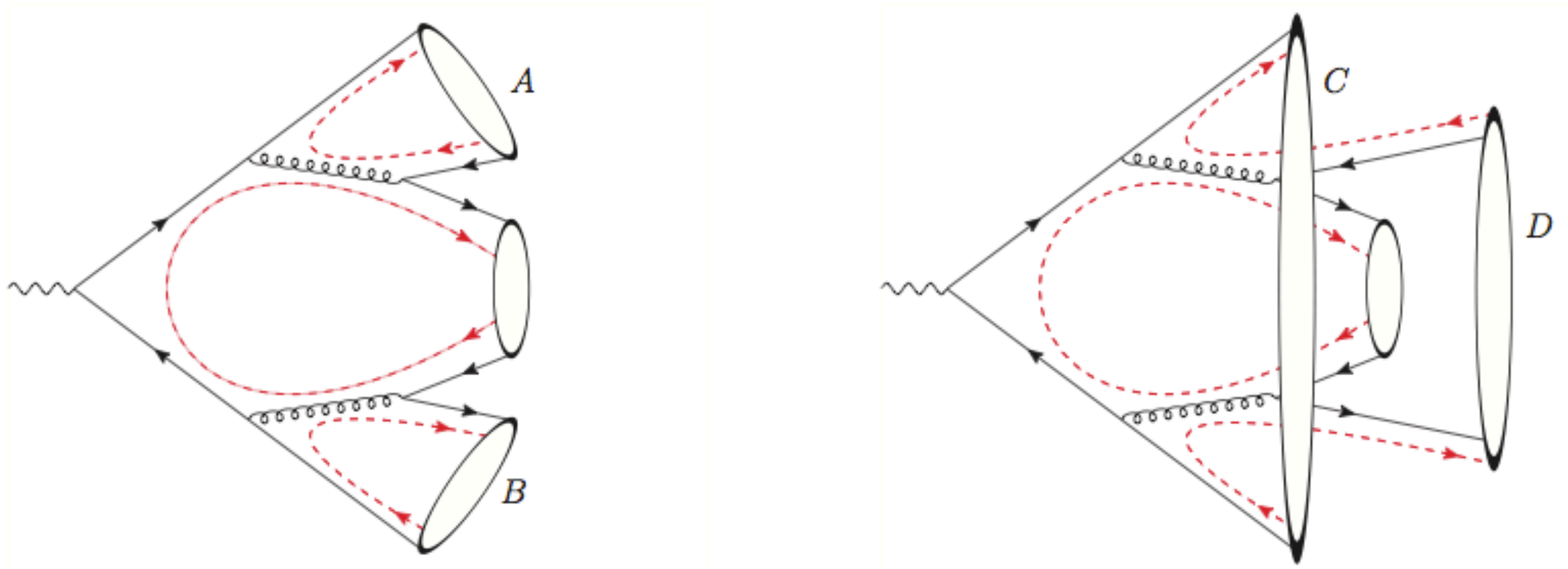
It will not only help to reduce the top mass uncertainty but also help us to better understand hadronization and the related uncertainties which can also affect other measurements!

Thank you for your attention
and the organizers for the invitation!

Additional slides

CR in Herwig++

Gieseke, Röhr, Siódmok '12 (arXiv:1206.0041)



Plain Color Reconnection

- iterating over quarks in all clusters, try reconnection
- Select reconnection which minimizes $m_C + m_D$ iff $\mathbf{m_C + m_D < m_A + m_B}$
- Accept reconnection with probability P_{reco}

Statistical Color Reconnection

- starting from cluster with low "color length": $\lambda \equiv \sum_{\text{cluster}} m^2_{\text{cluster}}$
- Accept all reconnections which reduce λ
- Accept reconnections which increase λ with probability $P = \exp\left(-\frac{\lambda_{\text{after}} - \lambda_{\text{before}}}{T}\right)$
- $T_{\text{in}} = c \cdot \text{median}|\Delta\lambda|$ decreasing after each step by a tunable amount
- Algorithm stops when no reconnections are made or after a tunable number of steps

Herwig 6, Pythia 6 and Sherpa

Herwig 6

- based on space-time structure of event at the end of parton shower
- perform a reconnection (ij)(kl)→(ik)(jl) if $|d_{ik}|^2 + |d_{jl}|^2 < |d_{ij}|^2 + |d_{kl}|^2$
- accept with probability 1/9

Pythia 6

- Color annealing models, very similar to Pythia 8 default
- Generalized Area Law: based on minimizing dipole invariant mass
- Soft Color Interaction: stochastic color exchange between perturbative partons and a background color field

Sherpa

- Model 1: reconnections that minimize "color length"
- Model 2: random assignment of partons into color singlets