Color reconnection in $t\bar{t}$ final states

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work in collaboration with Torbjörn Sjöstrand

JHEP 11(2014)043 (arXiv:1407.6653)

Why bother about color reconnection?

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

CR is one of the dominant systematics in top mass measurements

➡ **reduce the error on the top mass**

➡ **learn about the soft component of $t\bar{t}$ events**

Our goal

produce a range of different CR models in Pythia 8 to
study how big an effect color reconnection could have on m_{top}

This talk

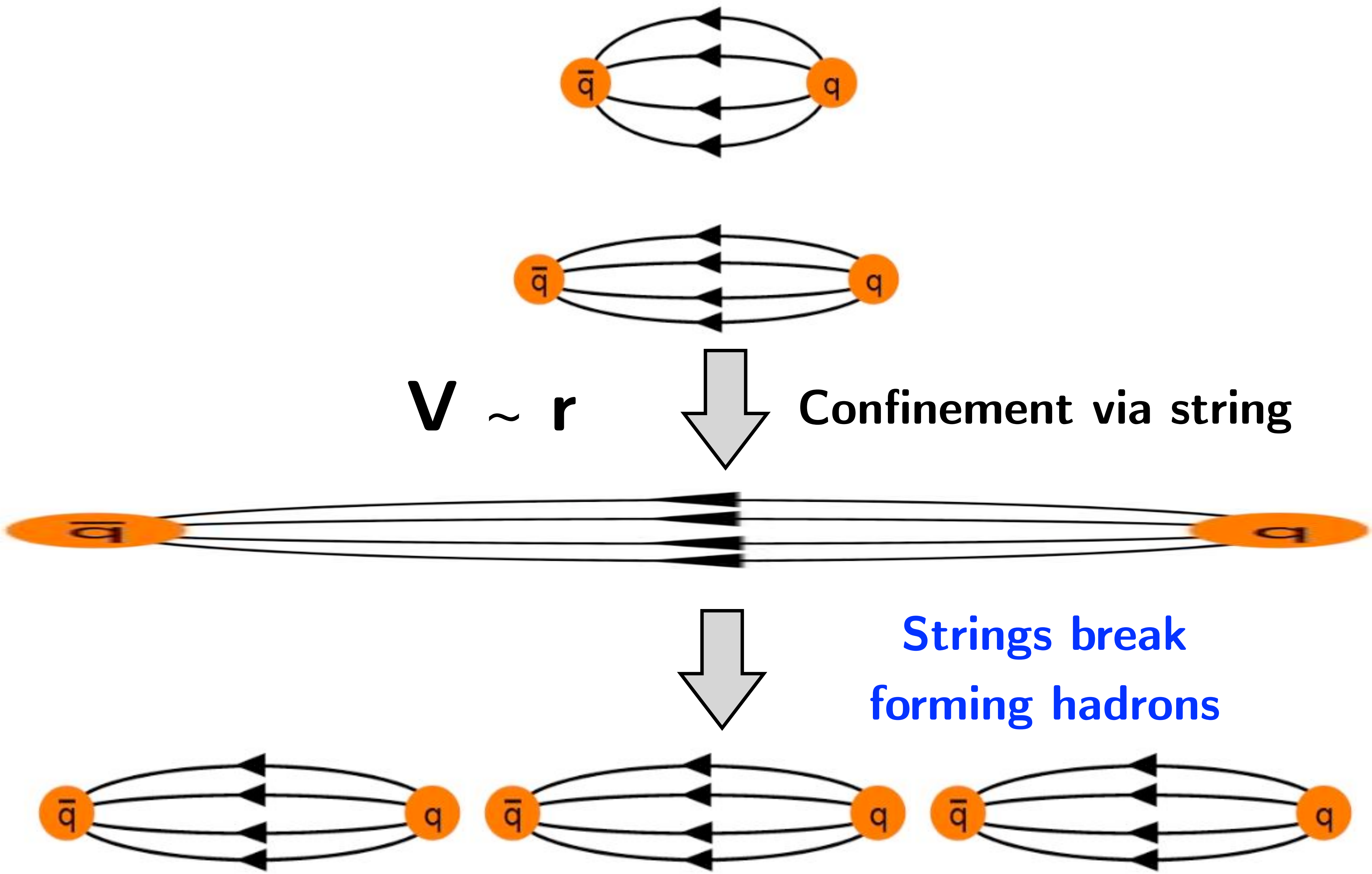
1. **What CR is and how it affects $t\bar{t}$ final states**

2. **How the CR uncertainty is determined**

3. **What we did to improve it**
    a. **new models**
    b. **their effect on the top mass**
    c. **estimate** for the **CR uncertainty**
    d. **how to reduce the uncertainty**

1. CR and its effect on the top mass

Hadrons from strings

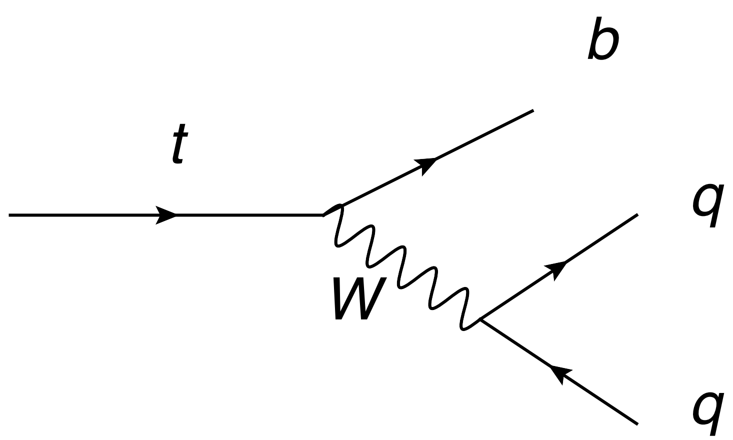


‘Longer’ strings $\Rightarrow$ more hadrons

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

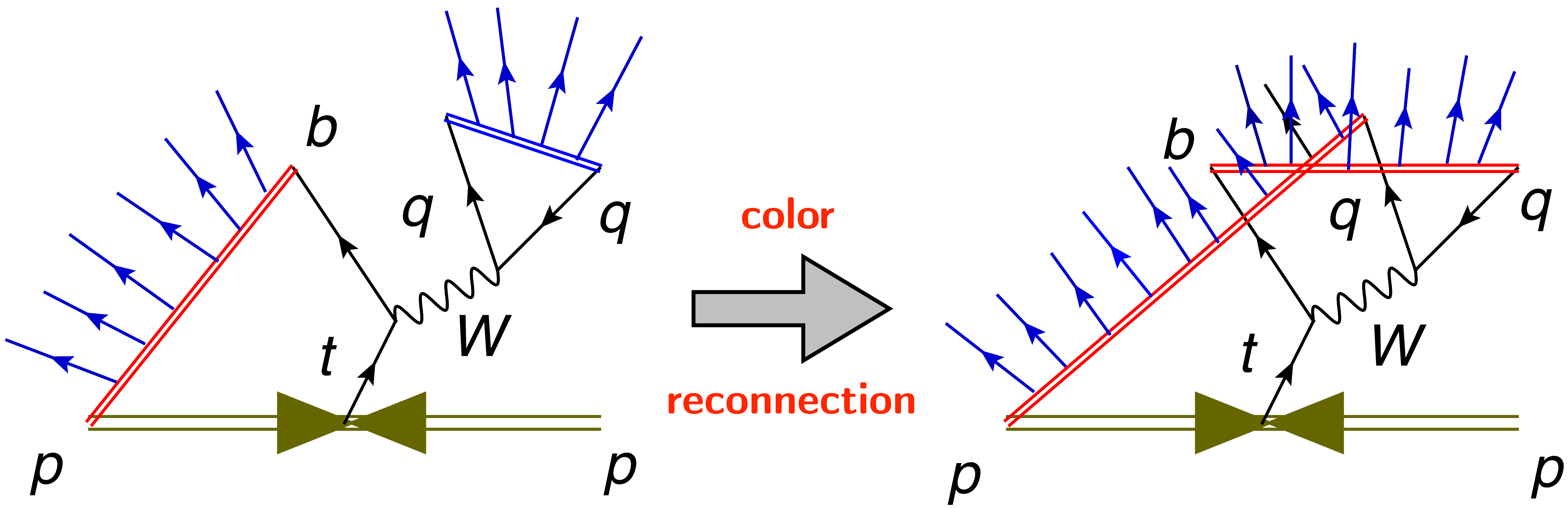
Effect of CR on m_{top}

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

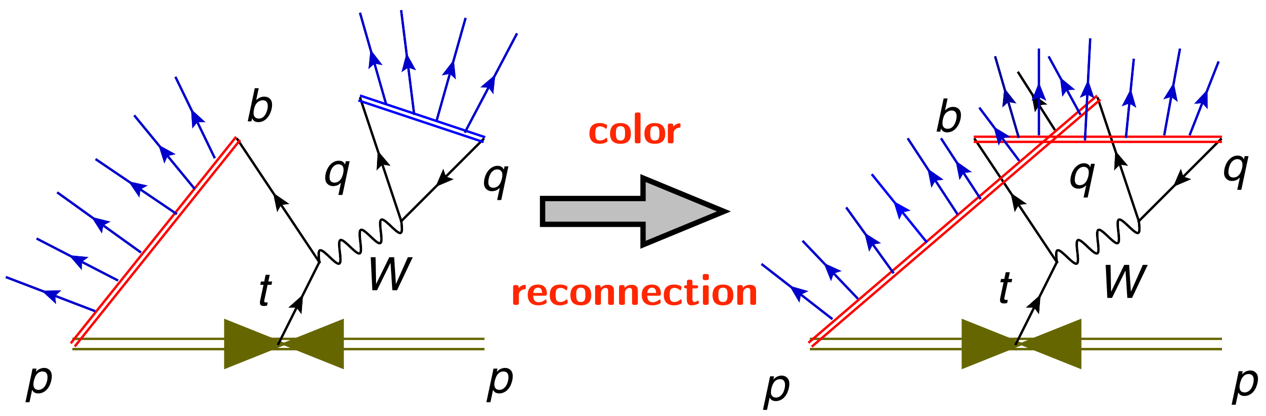


$$m_{\rm top}^2 = (p_{\rm b} + p_{\rm j1} + p_{\rm j2})^2$$

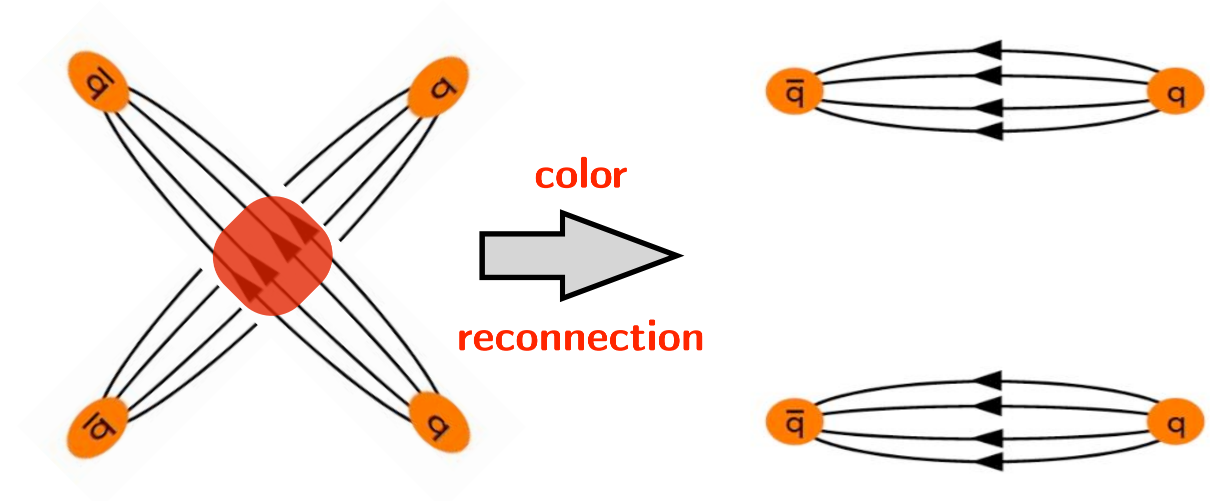
We are interested in the color topology...



Some remarks on CR



(i)



(ii)

i. **Perturbative part: Parton showers** (generally) **use $N_c \to \infty$**

this means in particular that quarks from W will always have a different color than the top

➡ **Color reconnection probes sub-leading $(1/N_c)$ effects**

ii. **Non-perturbative part:** in busy events strings can overlap ⇒ many soft gluon exchanges impossible to handle perturbatively

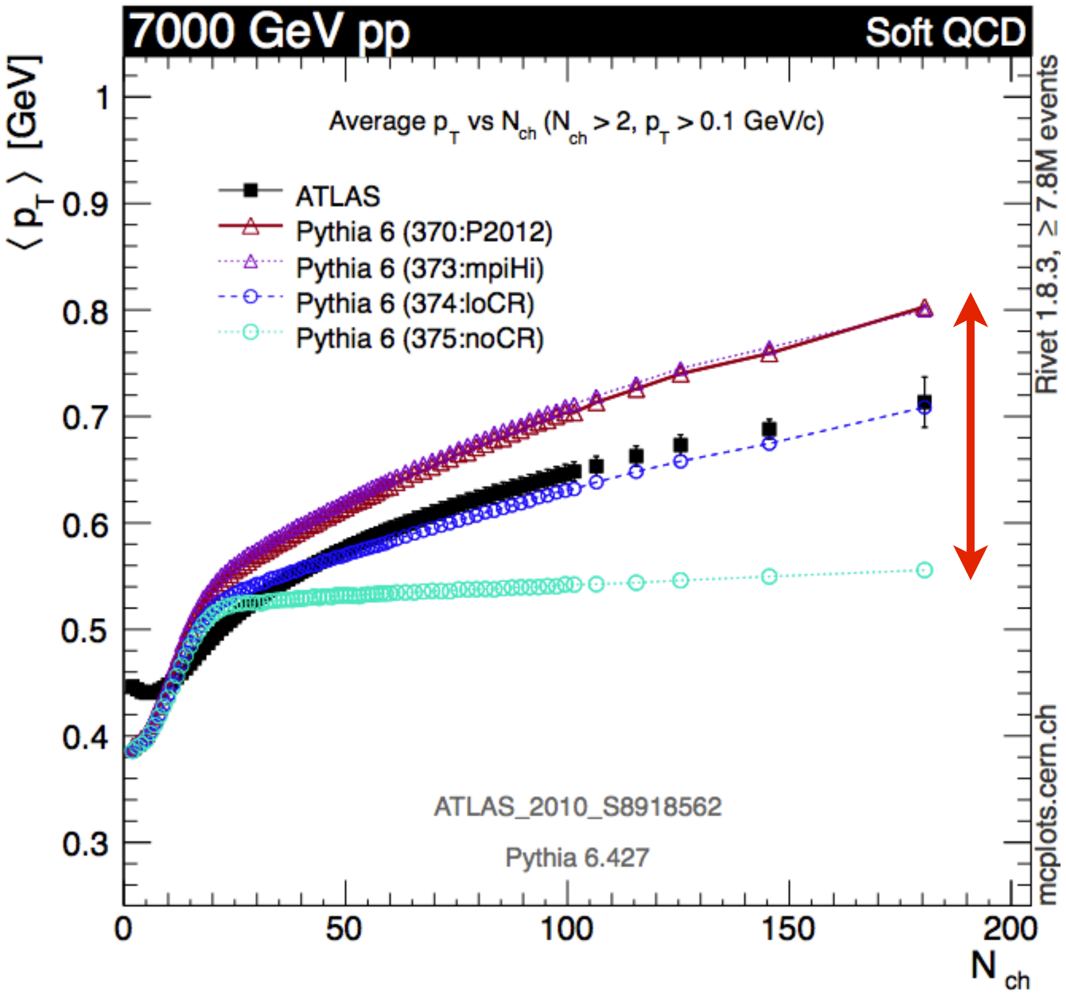
➡ **Color reconnection allows to model non-perturbative interactions between color fields during the hadronization transition**

2. Assigning an uncertainty

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

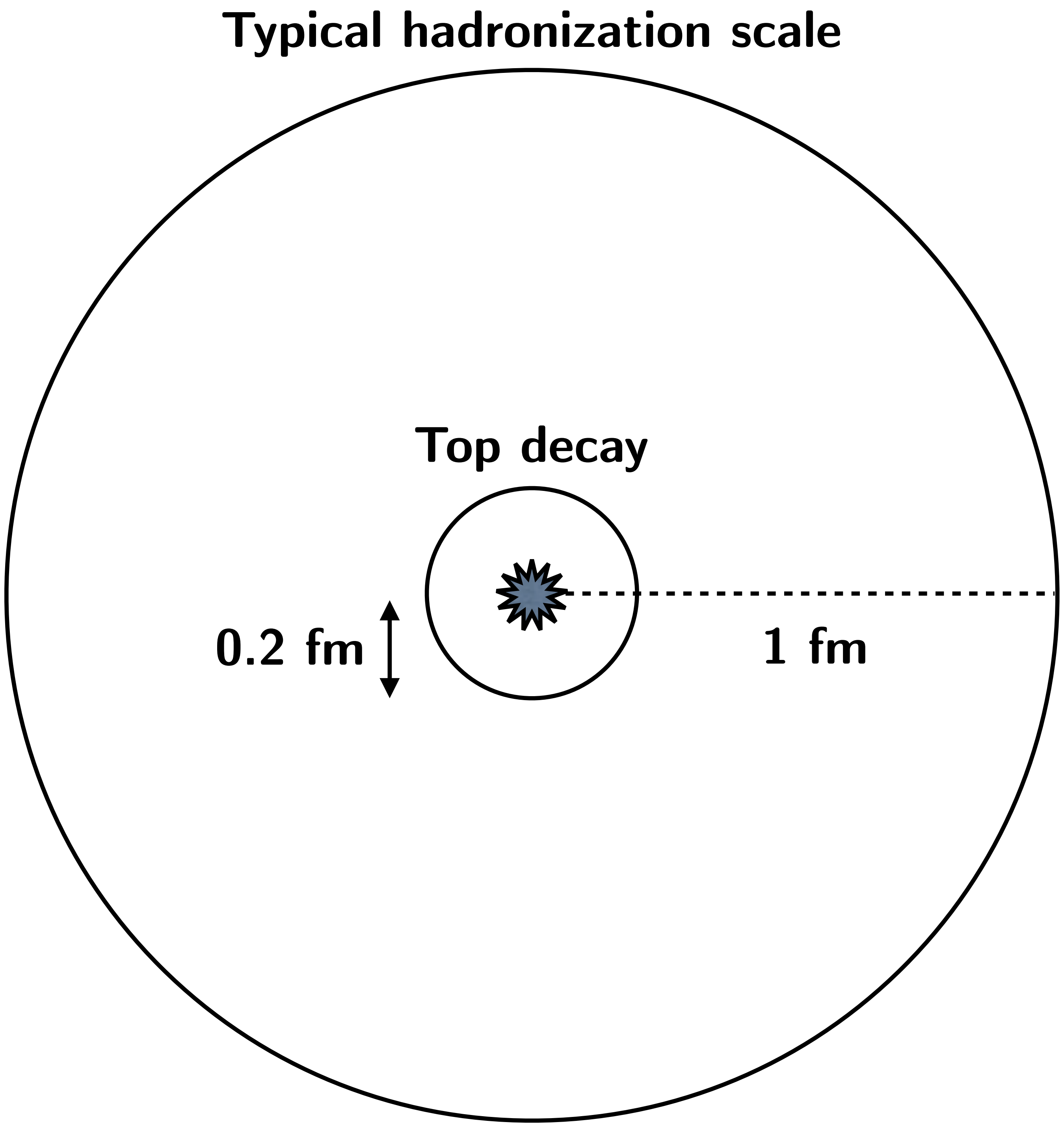
- **'no CR' is unphysical** (uncertainty overestimated?)
- m_{top}(no CR) might not provide a bound for Δm_{top} (**uncertainty underestimated?**)
- **limited range of modeling options** in Pythia 8

We want:

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

3a. The new models

A word on time scales



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

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...

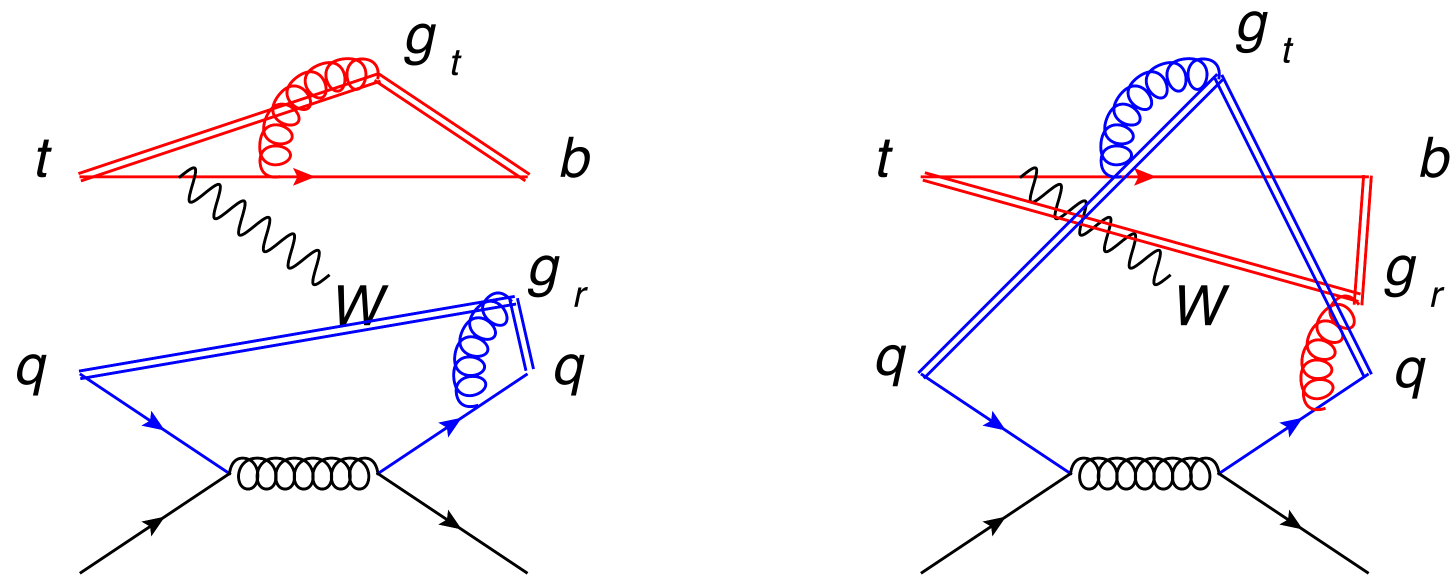
When a CR is made
1. random
2. forced
3. minimization

How a CR is made

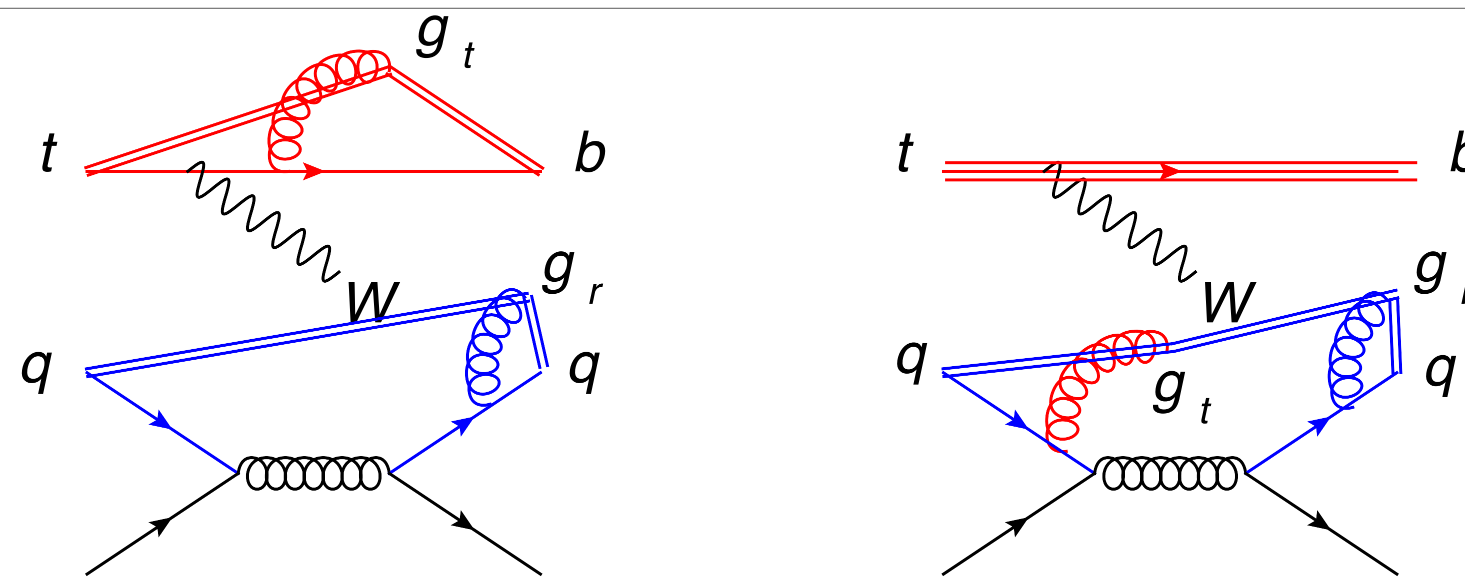
A. gluon move
B. color swap (both indices)
C. color flip (single index)

How a CR is made

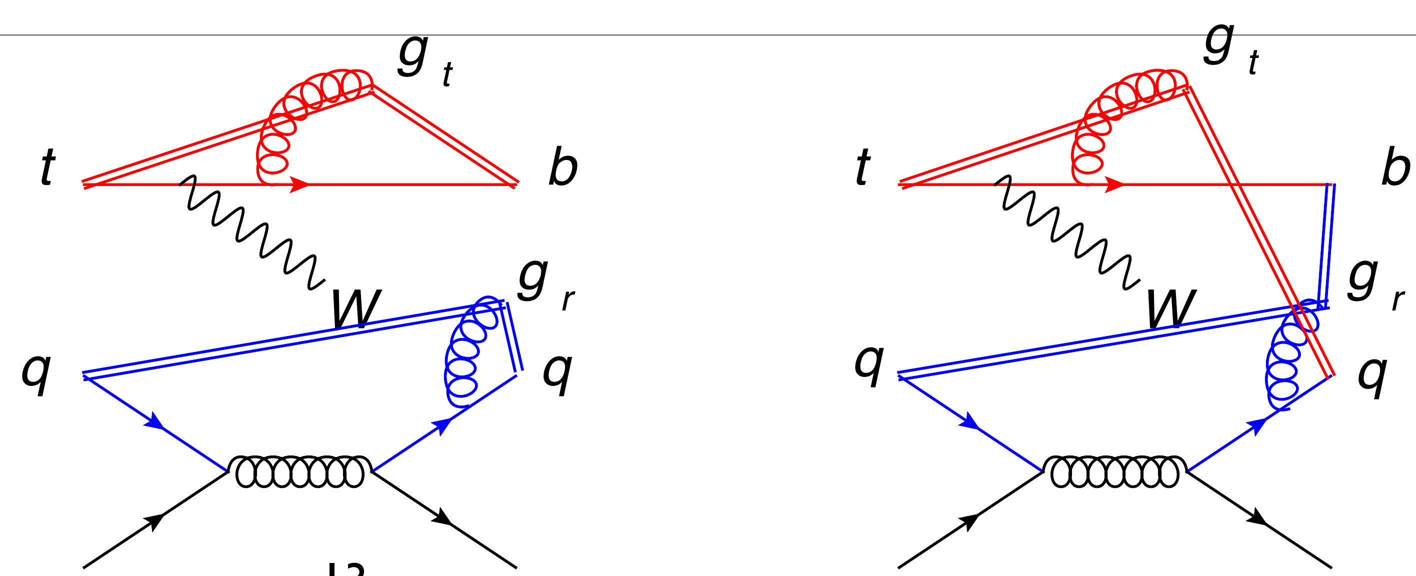
Color swap



Gluon move



Color flip

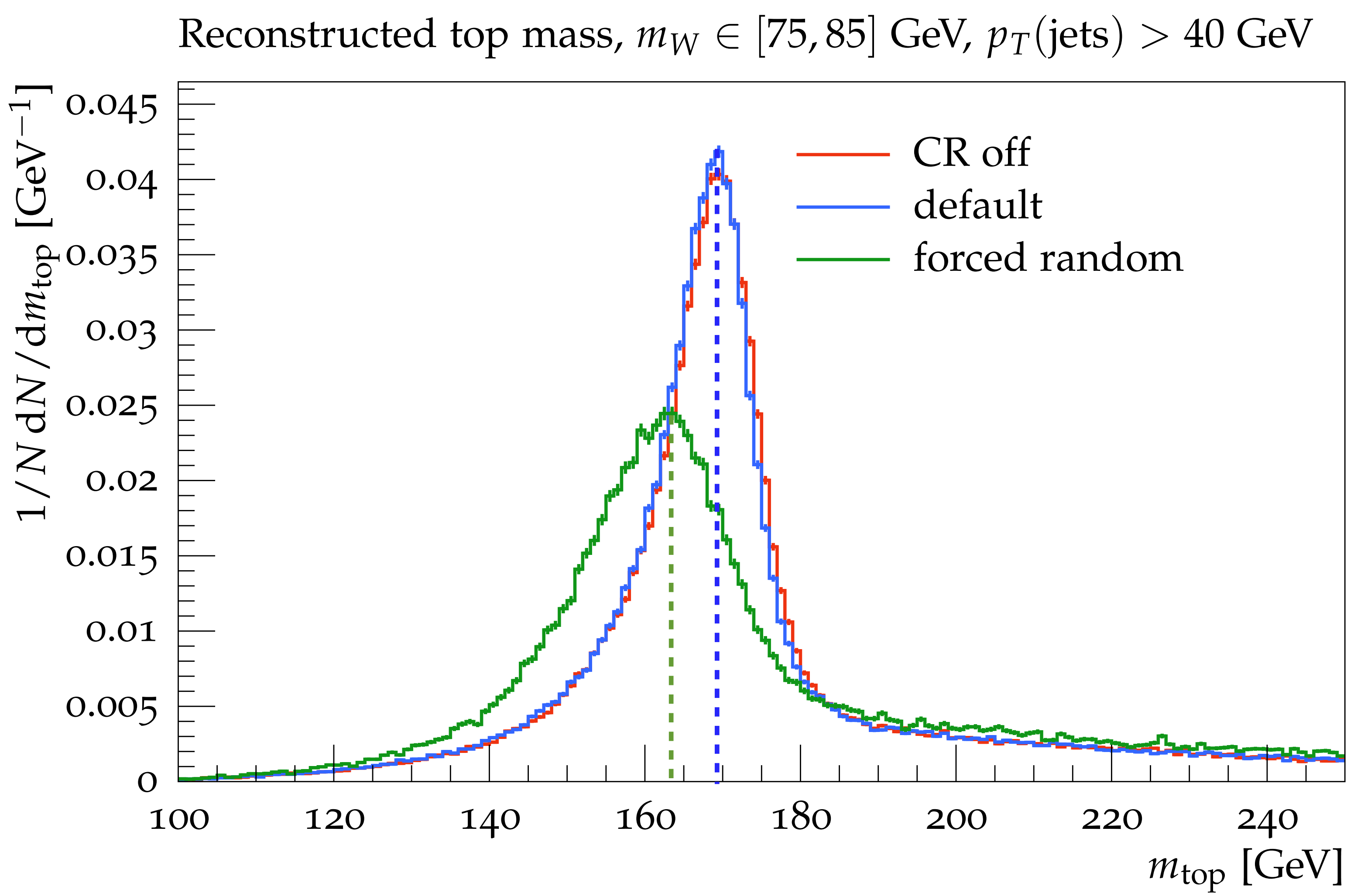


3b. Effect on m_{top}

Disclaimer!

What we do is a **toy top mass measurement**. A real experimental measurement is expected to have different sensitivity to the effects probed herein.

Effect on m_{top} (before tuning)

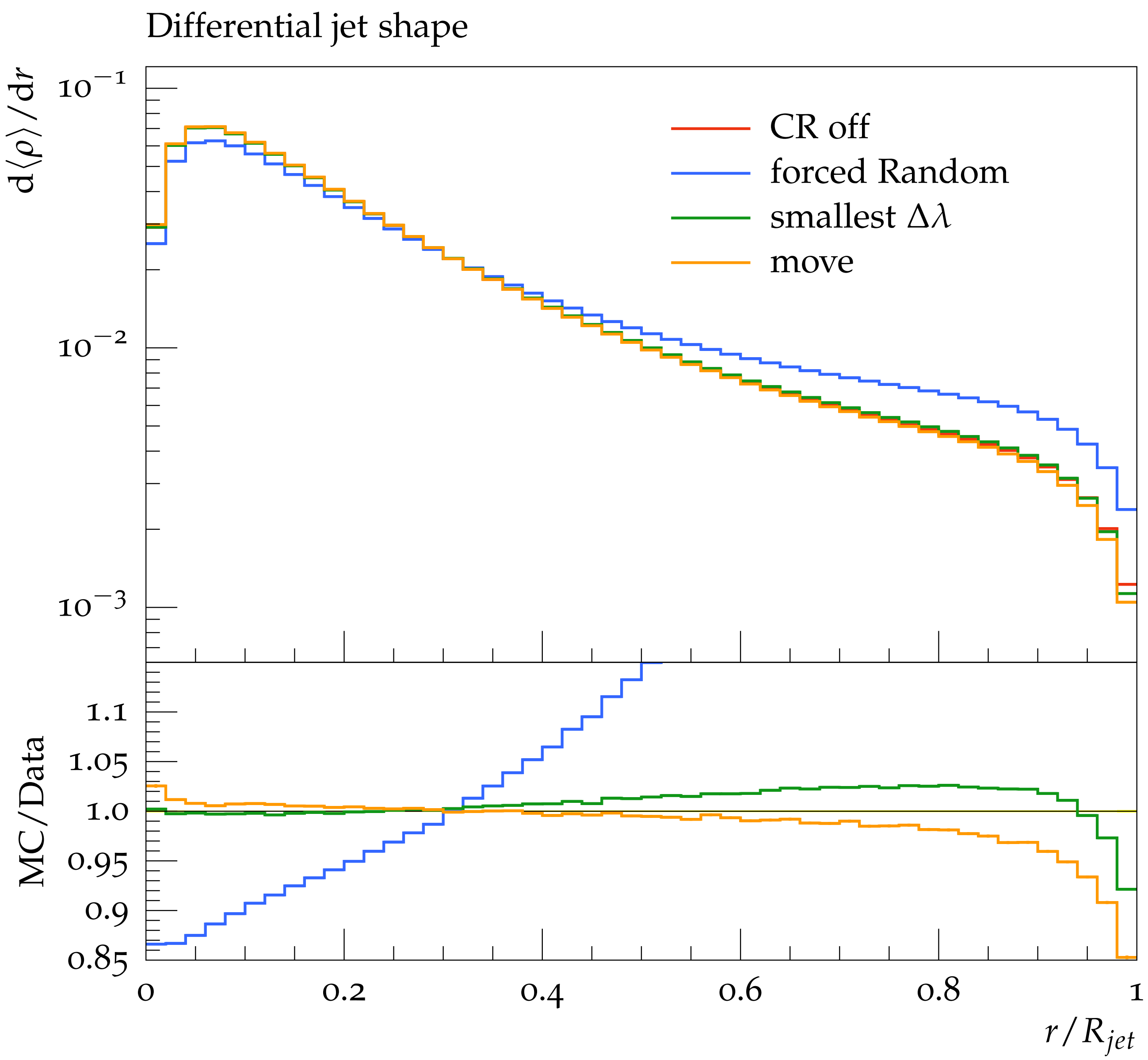


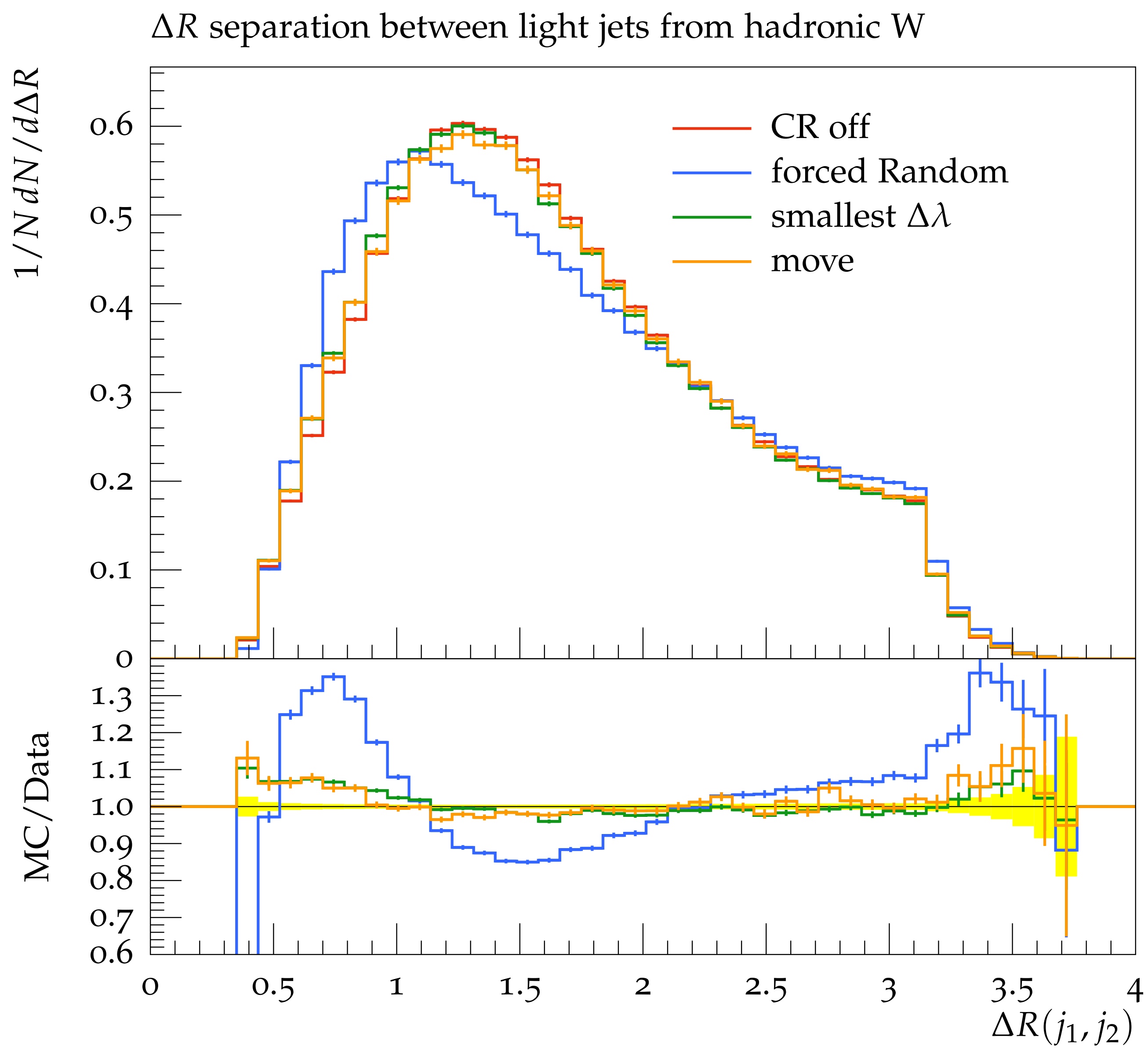
Model	$\Delta m_{top}^{rescaled}$ [GeV]
default	+0.209
default ERD	+0.285
forced random	-6.508

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}

$$m_{\text{top}}^2 = \left(p(b) + p(j_1) + p(j_2)\right)^2$$



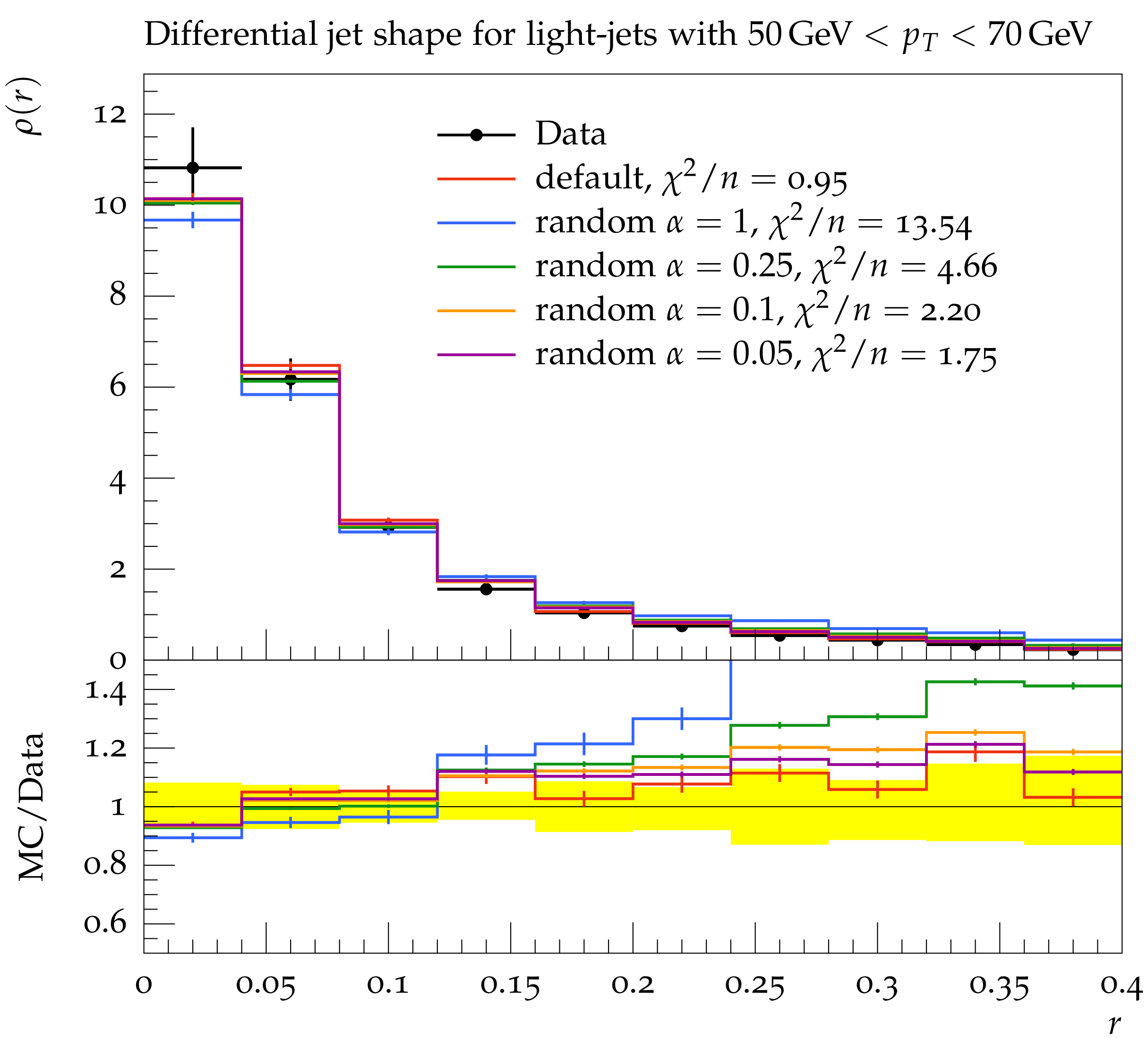


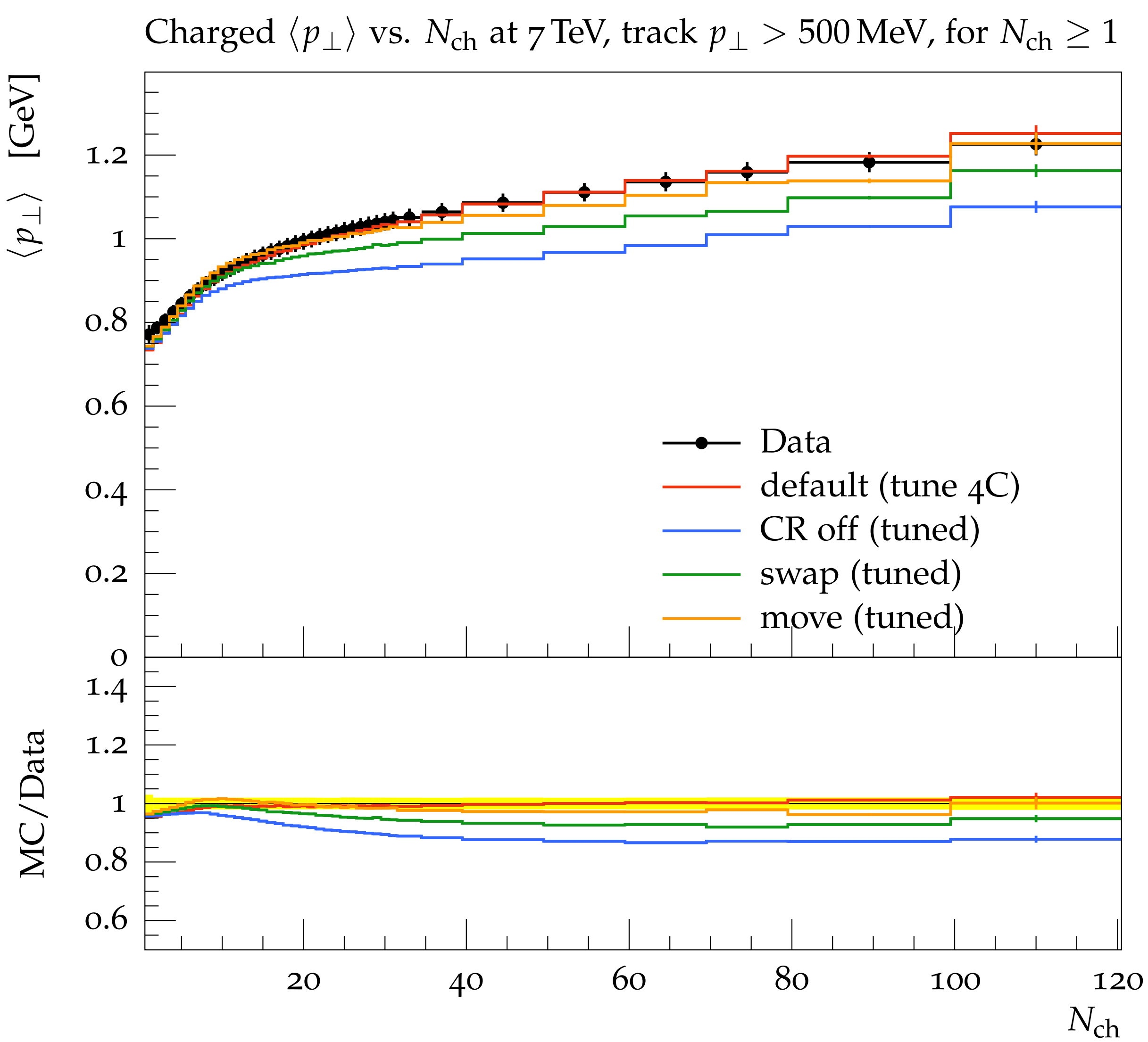
changes in p (**leakage** of hadrons **out of the jet cone**)

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

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:

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

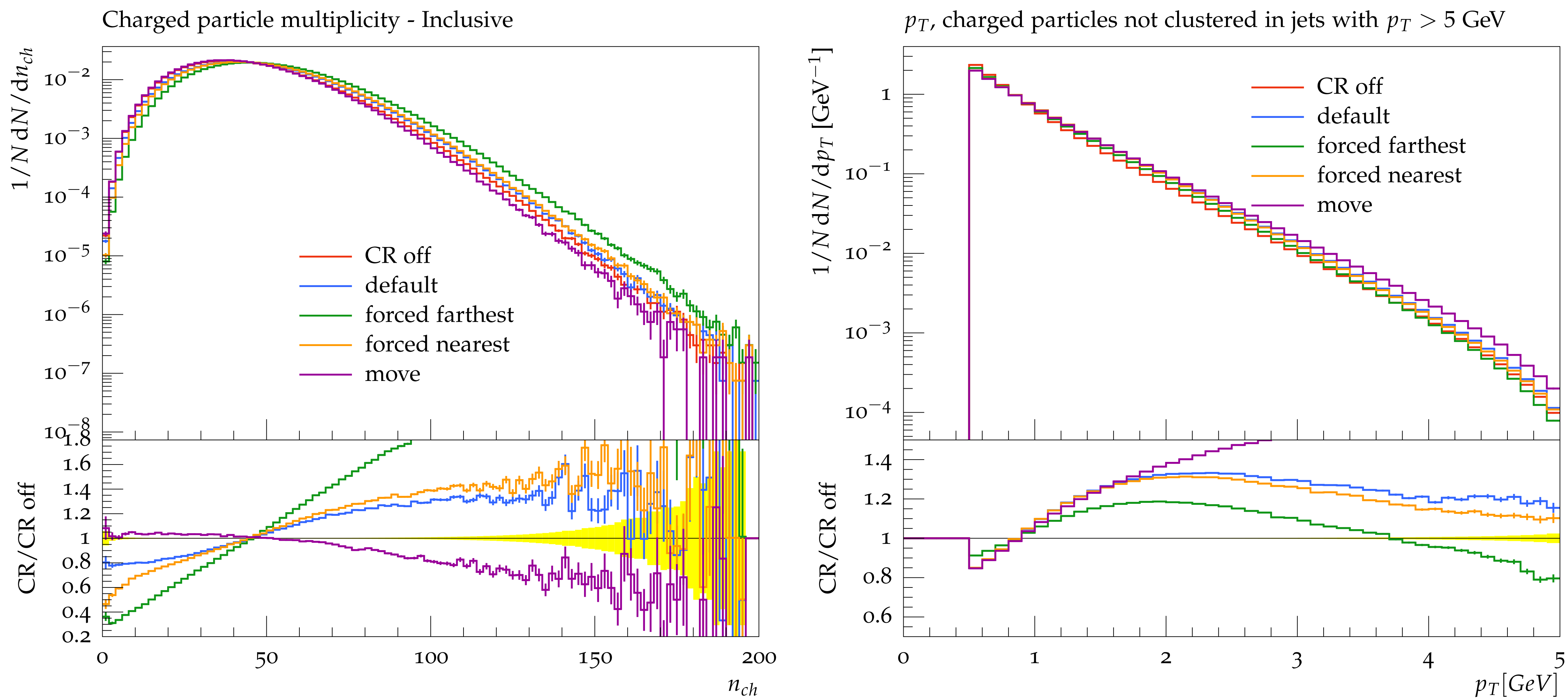
We believe that this is a realistic estimate of the CR uncertainty based on our current understanding of the phenomenon and on the available measurements.

3d. How to reduce the uncertainty

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**
- $\mathbf{m_{top}}$**(CR) - $\mathbf{m_{top}}$(no CR)** probably **underestimates the uncertainty**
  (at least with 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

Thanks for your attention!

CR in the default model

When

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

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

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

softer systems easier to reconnect

soft = extended wavefunction

2. Iterate (1) for all interactions ; if **P_{rec} > α∈[0,1]** do reconnection → **stochasticity**

How

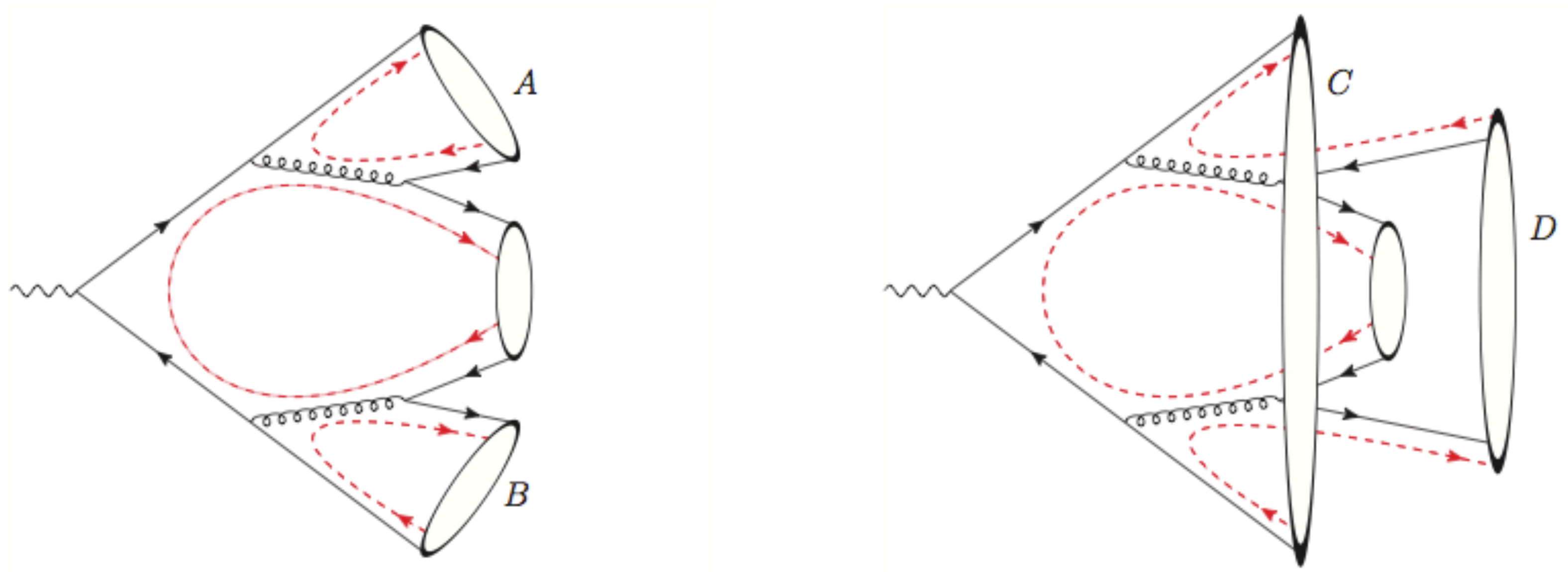
1. Sort interactions that where CR will happen in **decreasing p_T** → **minimally affect the perturbative color flow!**
2. Starting from the **hardest interaction** find color dipoles (i,j)
3. **Move gluons** {k} from softer interactions **to dipole** (i,j) **that minimizes the increase in 'string length'**

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

$$\lambda \sim \Delta y \sim \langle n \rangle$$

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