Color reconnection in $t\bar{t}$ final states at the LHC

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work in collaboration with Torbjörn Sjöstrand

arXiv:1407.6653 (to appear in JHEP)

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A puzzle about m_{top}

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

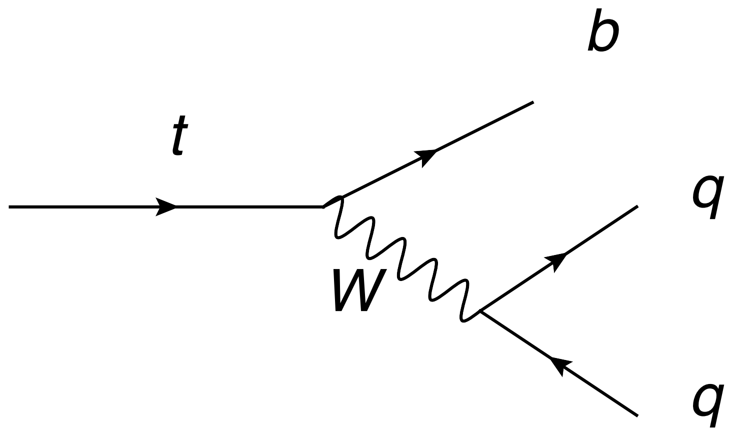
1. **Great job in reducing the errors**

2. **CR is one of the dominant systematics**

3. **Why is the CR uncertainty going down** when there are
   - no advances on the theoretical understanding
   - no measurements to constrain it

Measuring m_{top}

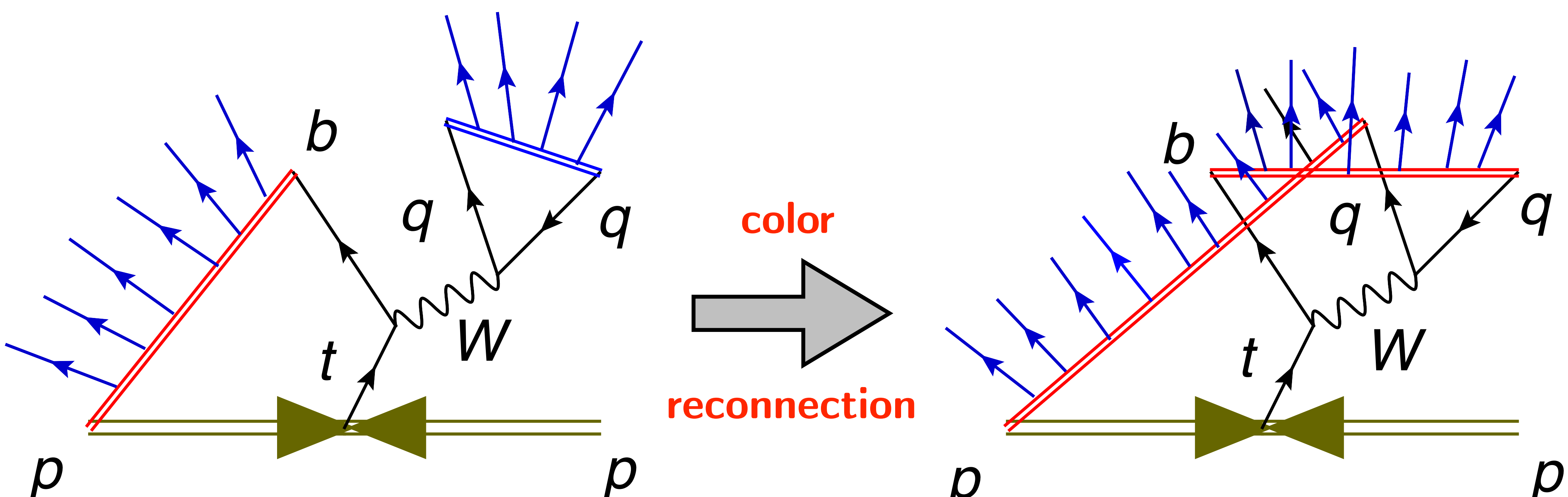
Direct m_{top} measurement



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

Many effects complicate the procedure: showers, hadronization, jet reconstruction

We focus on color topology...



This talk

1. **how is the CR uncertainty determined?**

2. what we did to improve it

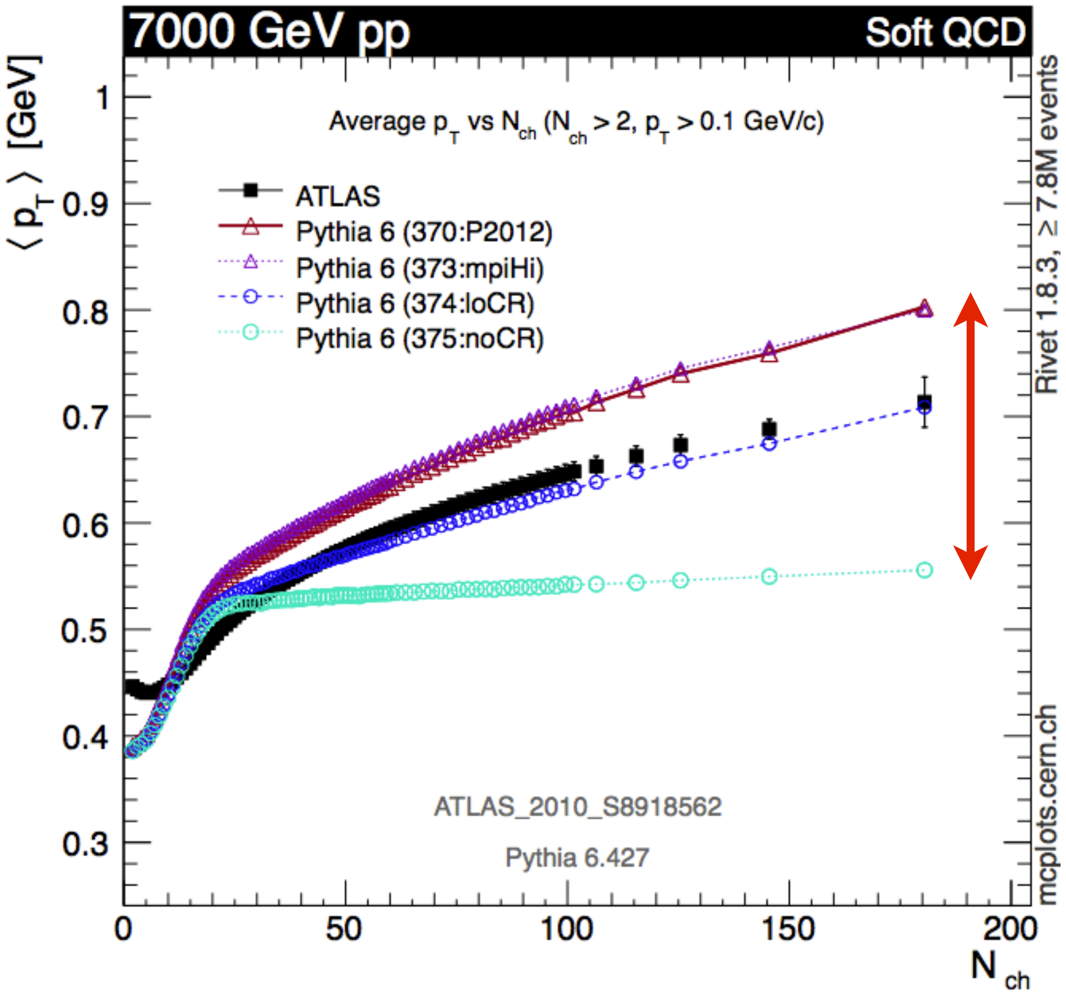
- **new models** in Pythia 8
- **realistic estimates** of the **CR uncertainty**
- **how we can reduce the uncertainty** with data

NB: "improve" doesn't always mean to reduce the uncertainties but to show if and how it can be done

Estimating the CR uncertainty

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

Currently this is done with **Pythia 6**, where multiple CR models are available.



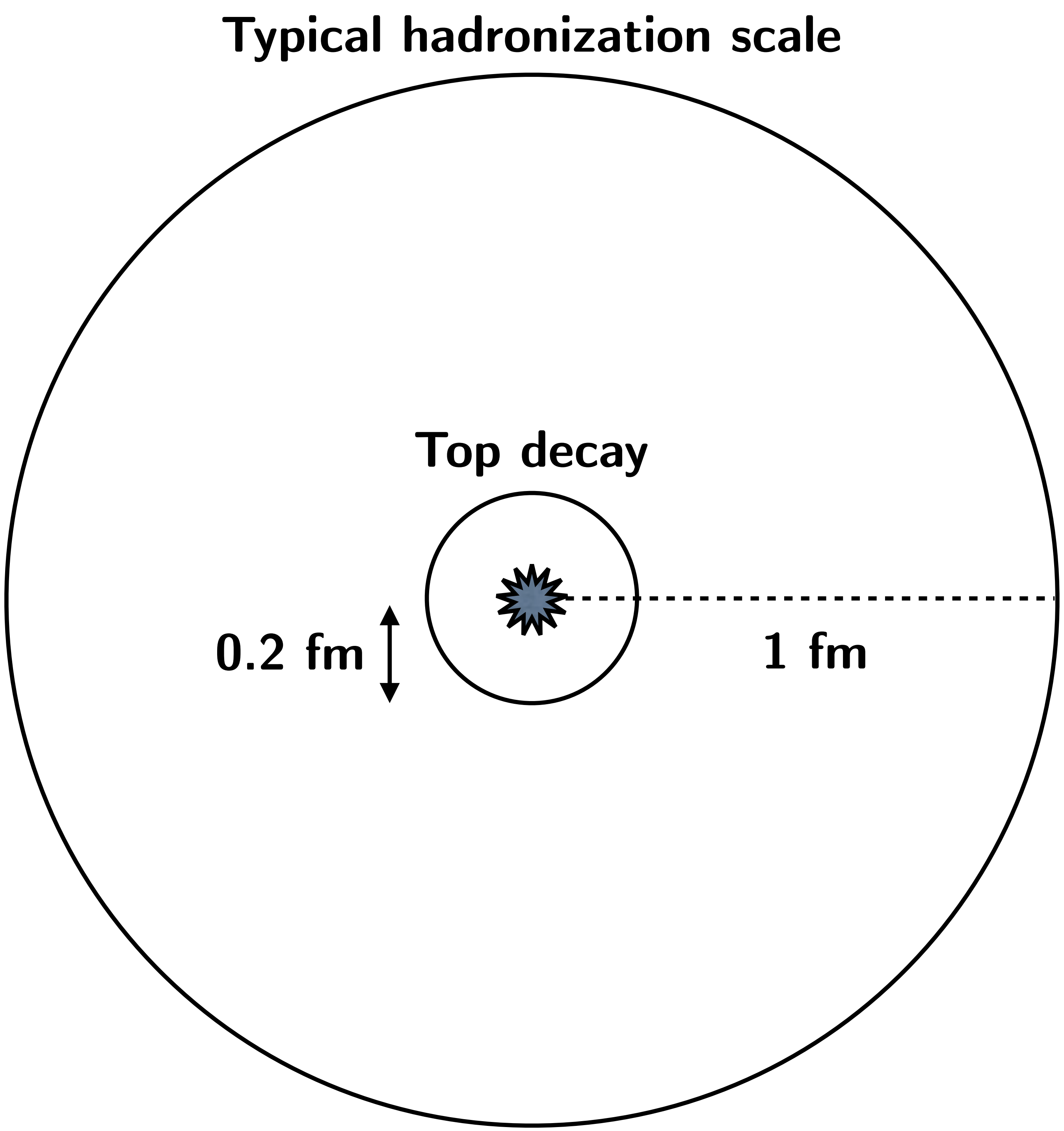
The problem

- **'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 => uncertainty band**
- a **way to kill them**

Time scales



Big time difference between top decay and hadronization:

CR in top can be modeled differently than CR in Min Bias

Two extreme options:

- **late resonance decay**
  top decays after CR has taken place

- **early resonance decay**
  CR happens after top decay (e.g. W can reconnect with b/MPI)

The models

Existing

default

default ERD

New

Toy

only top events - default CR afterburner

forced random
forced nearest
forced farthest
forced smallest $\Delta\lambda$
smallest $\Delta\lambda$

More sophisticated

all events

swap
move
swap + flip
move + flip

To become available in Pythia 8.2

Models differ in...

When a CR is made

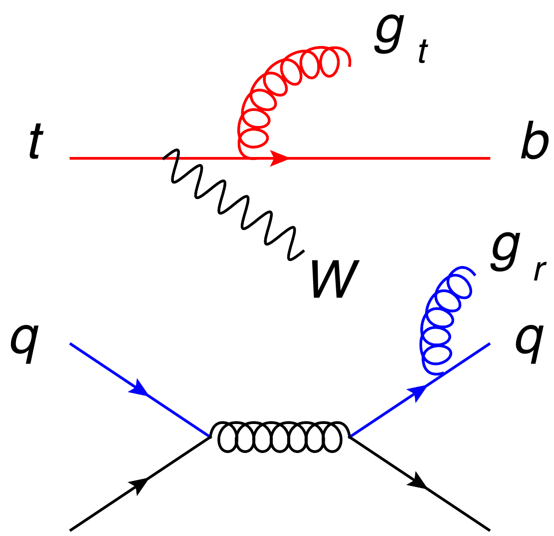
1. stochastic
2. forced
3. minimization

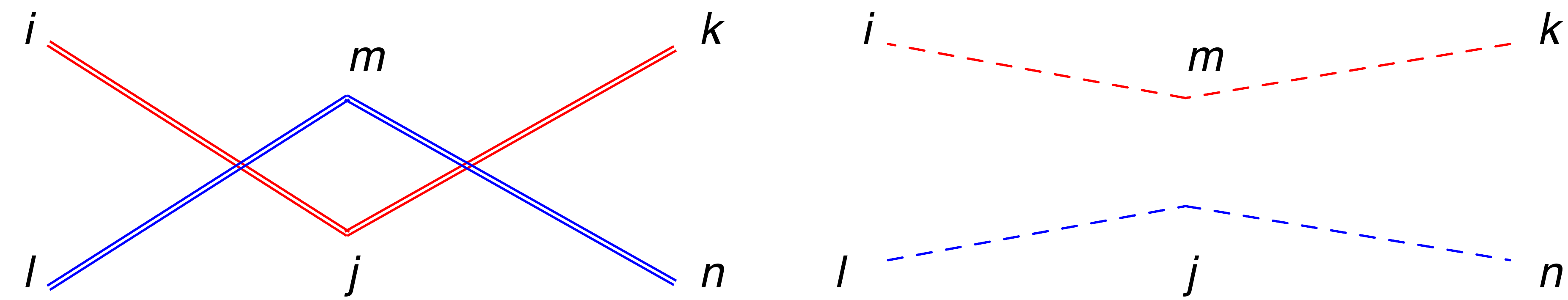
How a CR is made

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

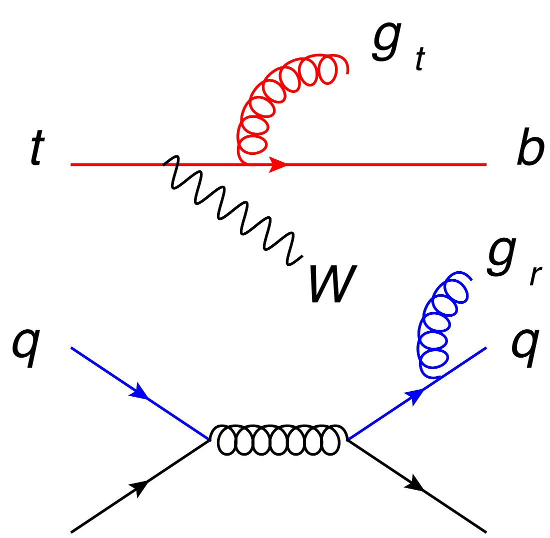
Ways to perform a reconnection

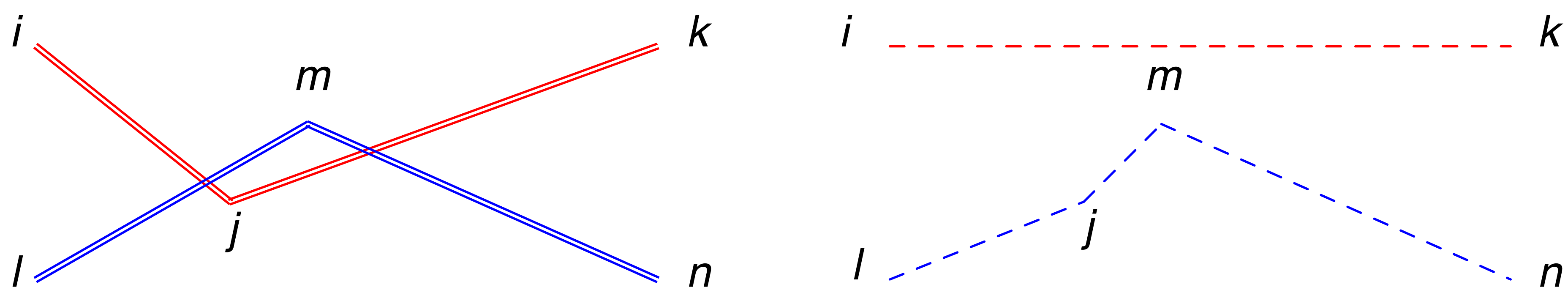
Color exchange



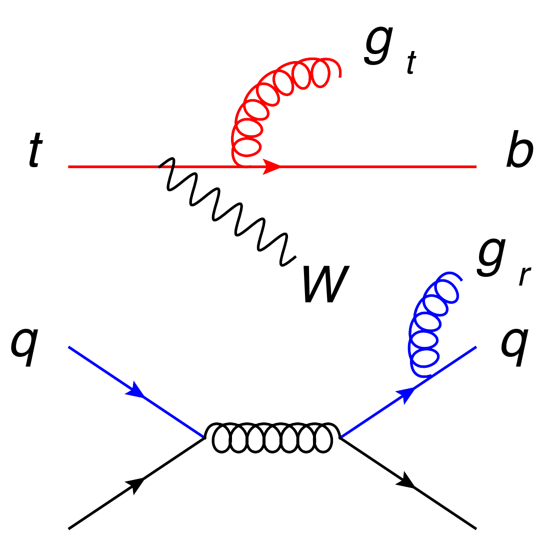


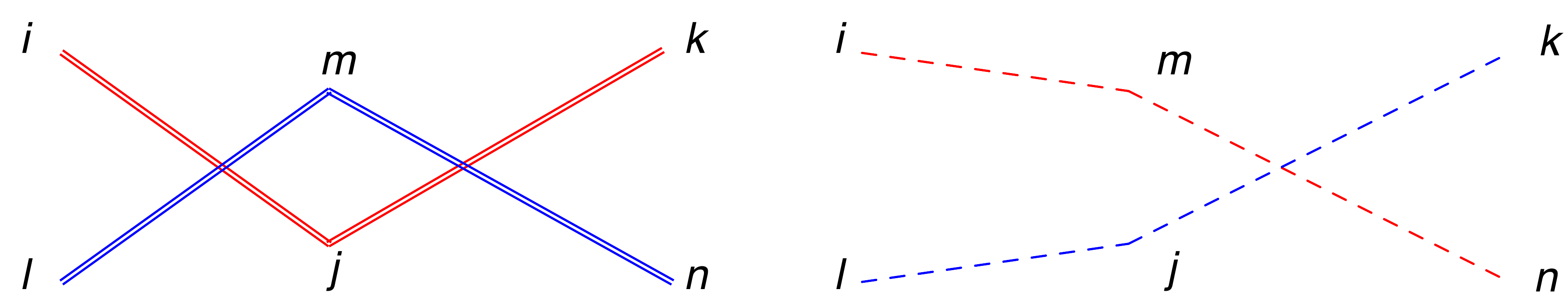
Gluon move





Flip





CR in the default model

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 $\mathbf{P_{rec}} > \boldsymbol{\alpha} \in [0,1]$ do reconnection

stochasticity

How

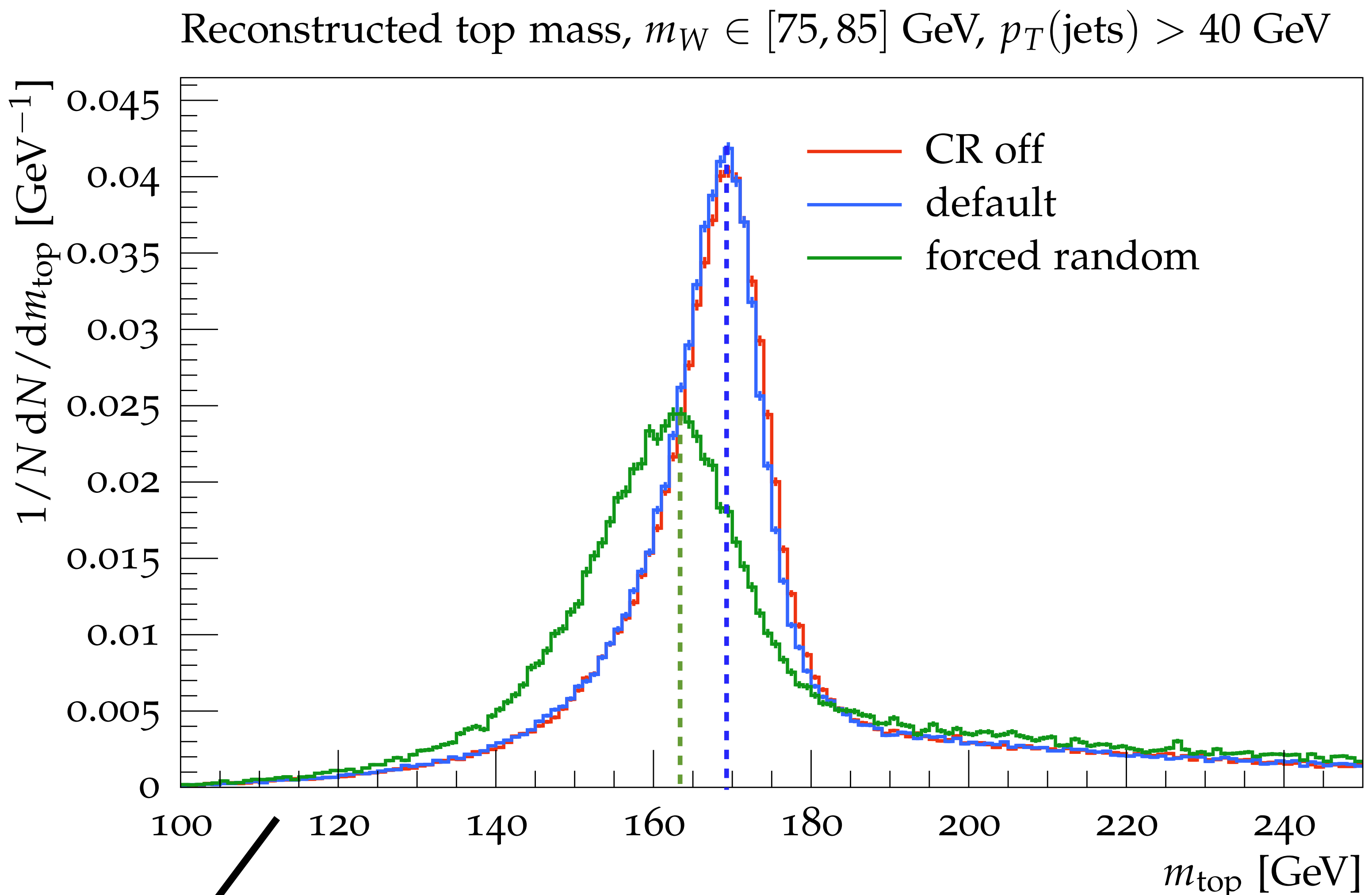
1. Sort interactions that where CR will happen in **decreasing p_T**
2. Starting from the **hardest interaction** find color dipoles (i,j)
3. **Move gluons** {k} from softer interactions **to dipole** (i,j) **that minimizes the increase in 'string length'**

minimally affect the perturbative color flow!

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

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

Effect on m_{top} (before tuning)

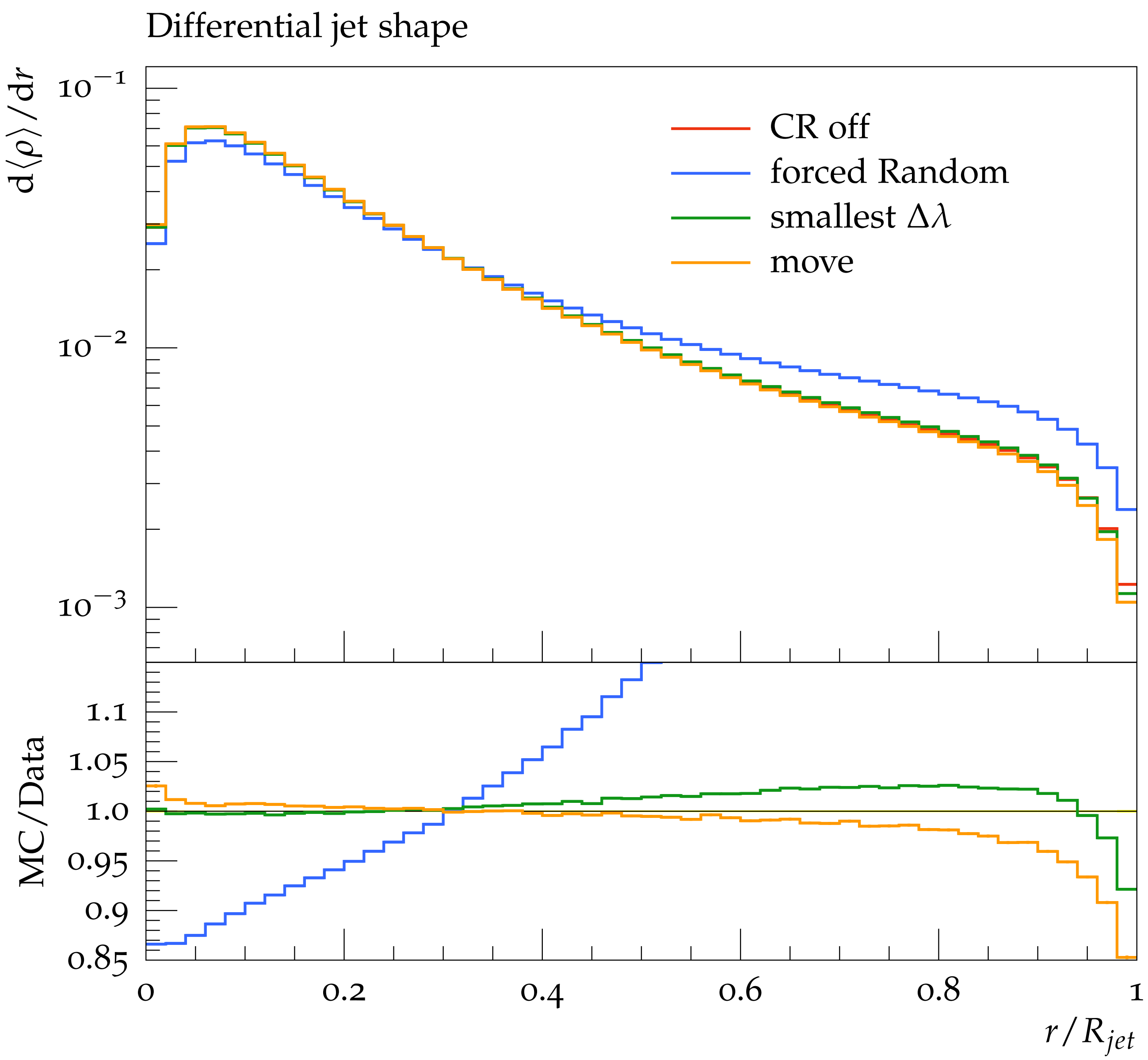


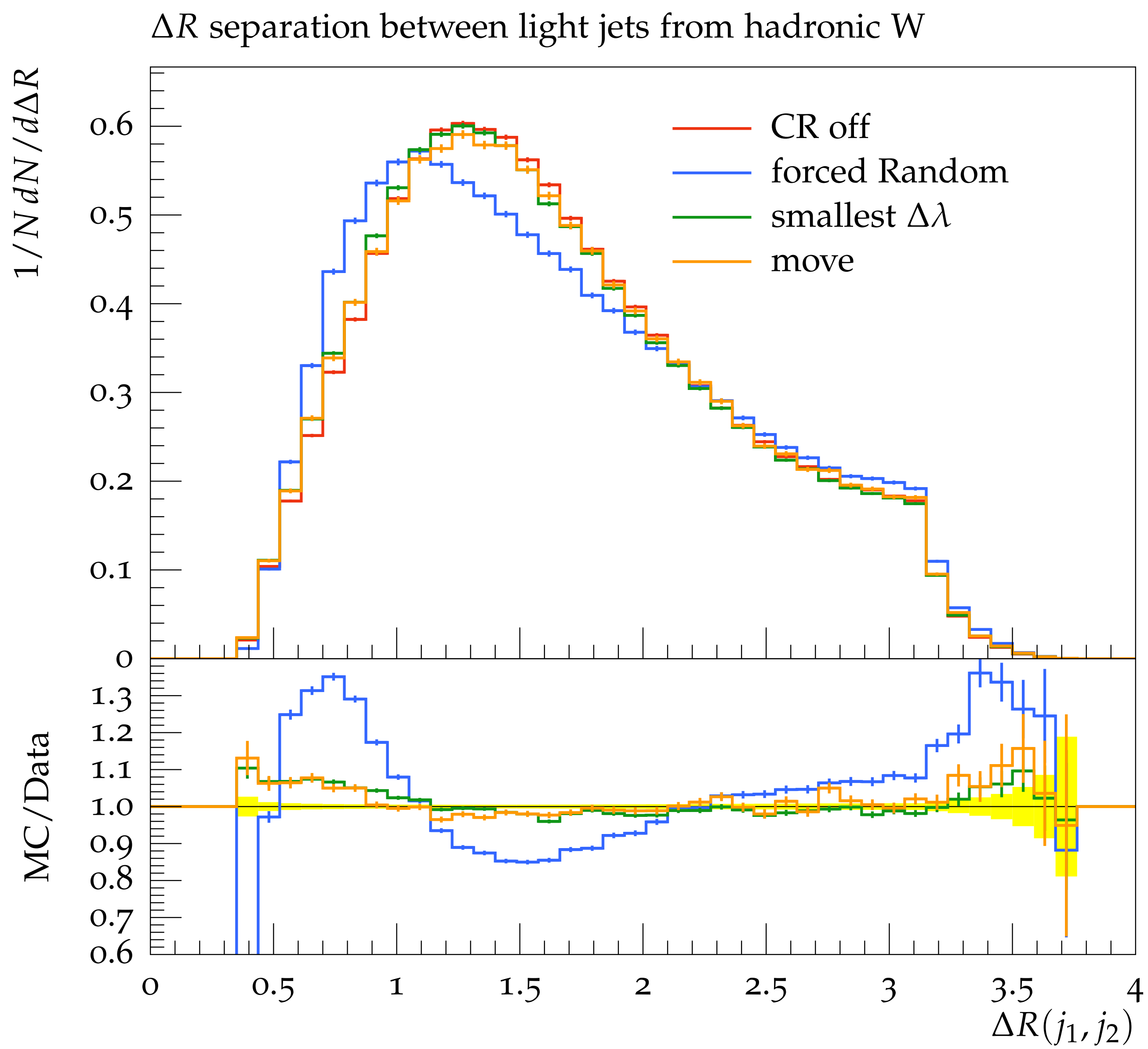
Model	Δm_{top} [GeV]	$\Delta m_{top}^{rescaled}$ [GeV]
default	-0.415	+0.209
default ERD	+0.381	+0.285
forced random	-6.970	-6.508

- **CR can** inherently **have big effects**
- Δm_{top} is not bounded by m_{top}(no CR), in other words **m_{top}(CR)-m_{top}(no CR) probably underestimates the uncertainty**

Why CR shifts m_{top}

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



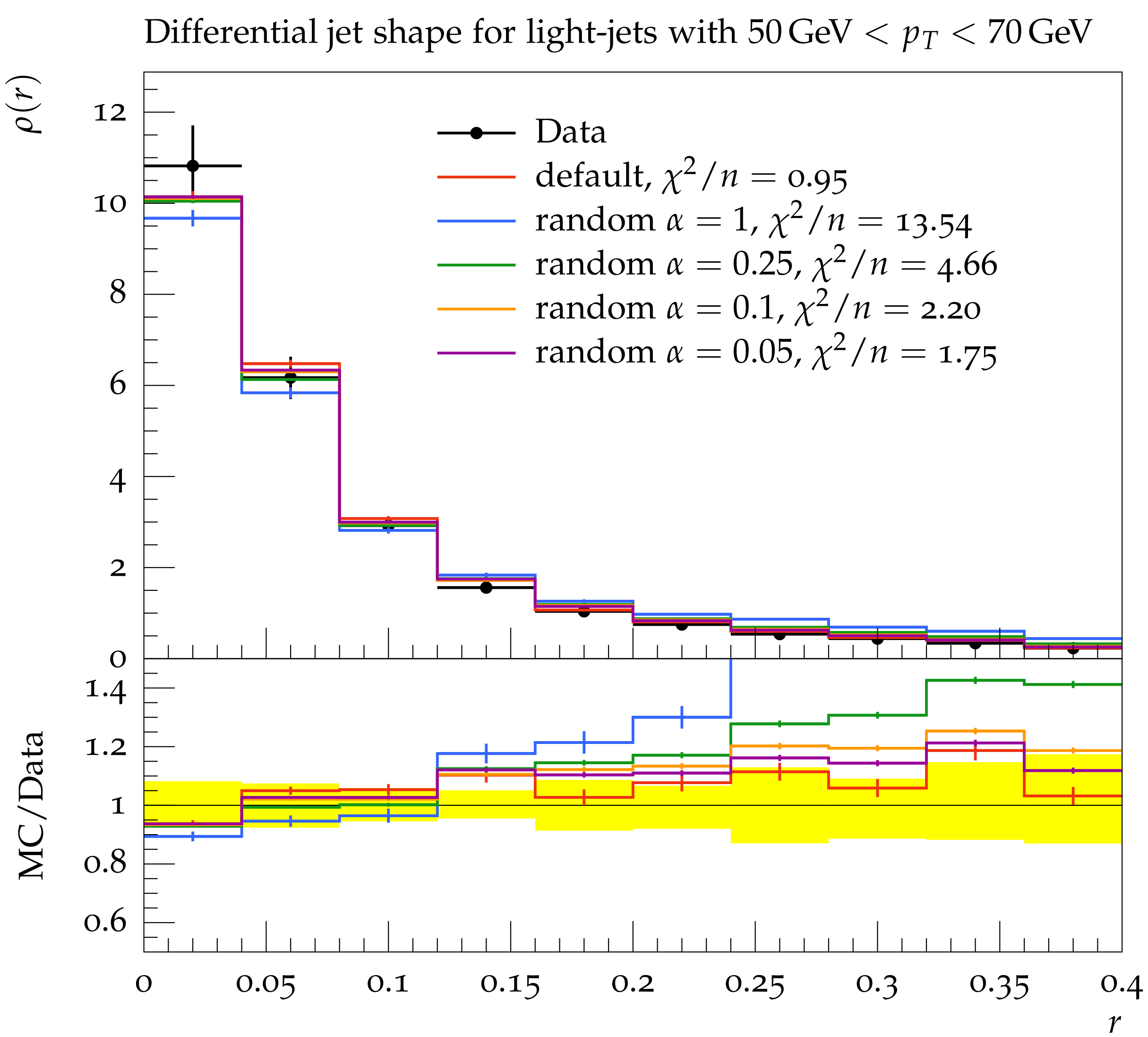


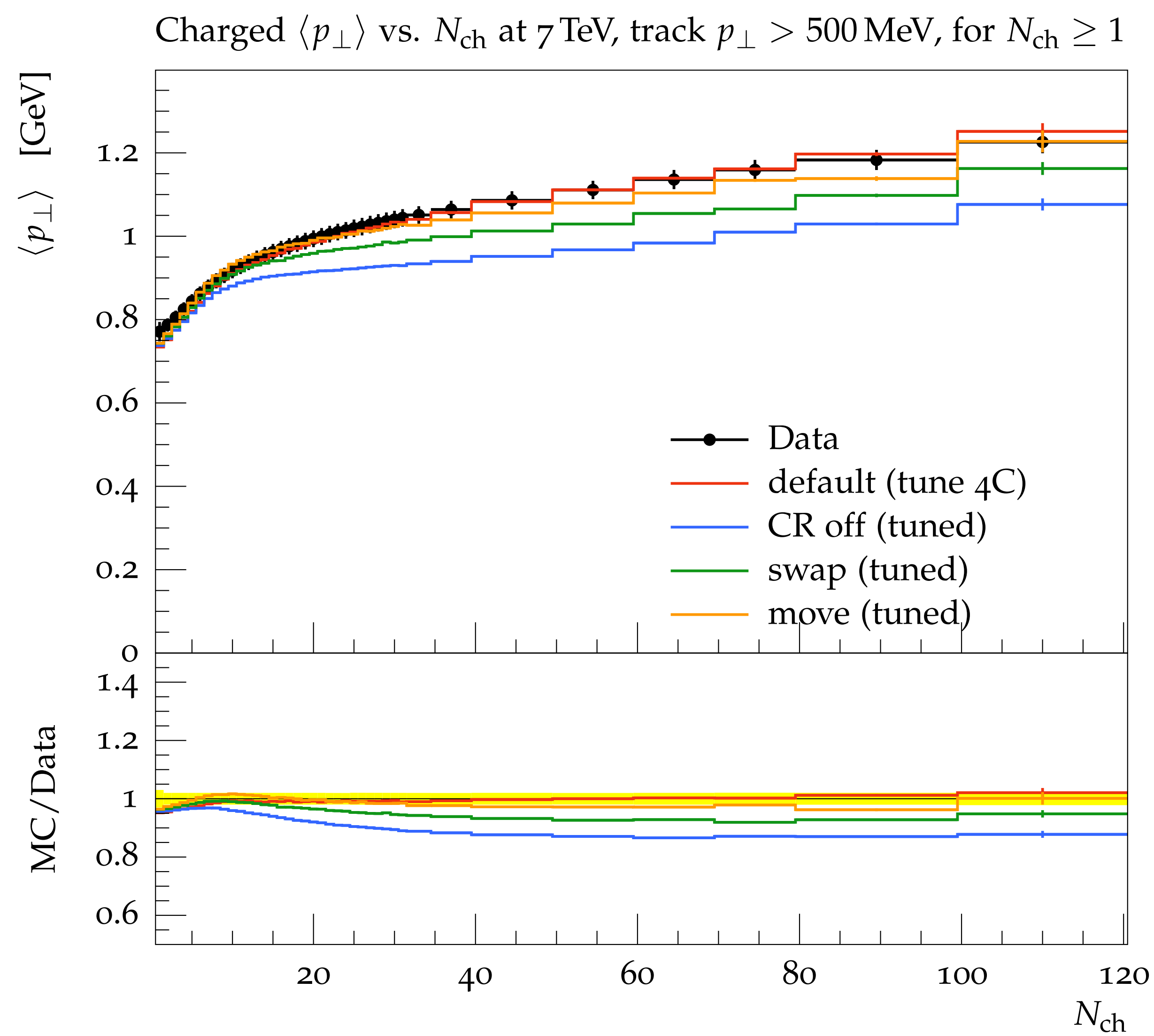
changes in p (**leakage** of hadrons **out of the jet cone**)

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

Tuning

- No publicly available measurements of UE in top events
- toy models tuned to **jet shapes** in **tt events** measured by ATLAS (CR strength α)
- **MB models** tuned to **minimum bias** data measured by ATLAS (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)

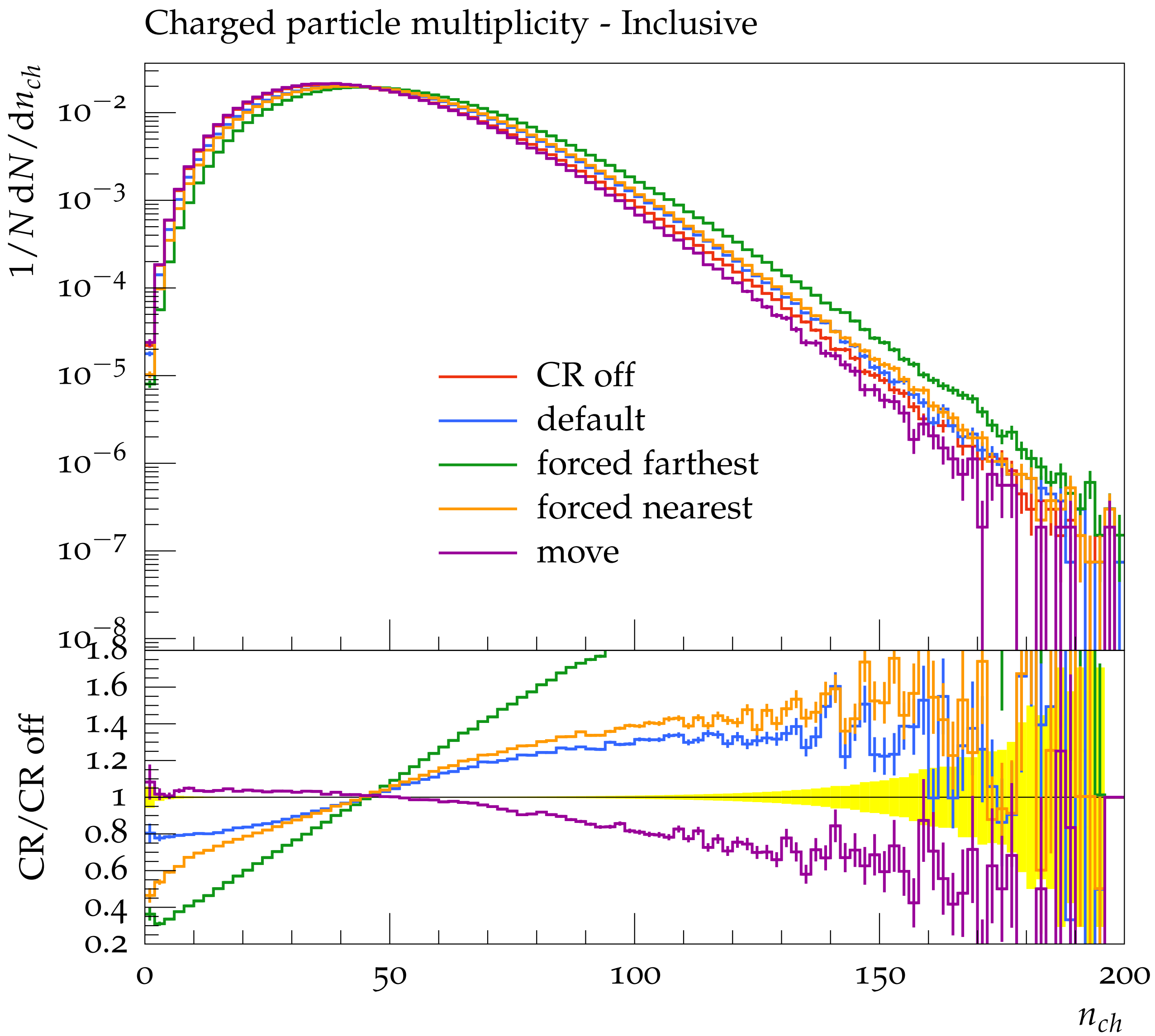
Model	$\Delta m_{top}^{rescaled}$ **[GeV]**
default	+0.239
forced random (min)	-0.524
move	+0.239
swap (max)	+0.273

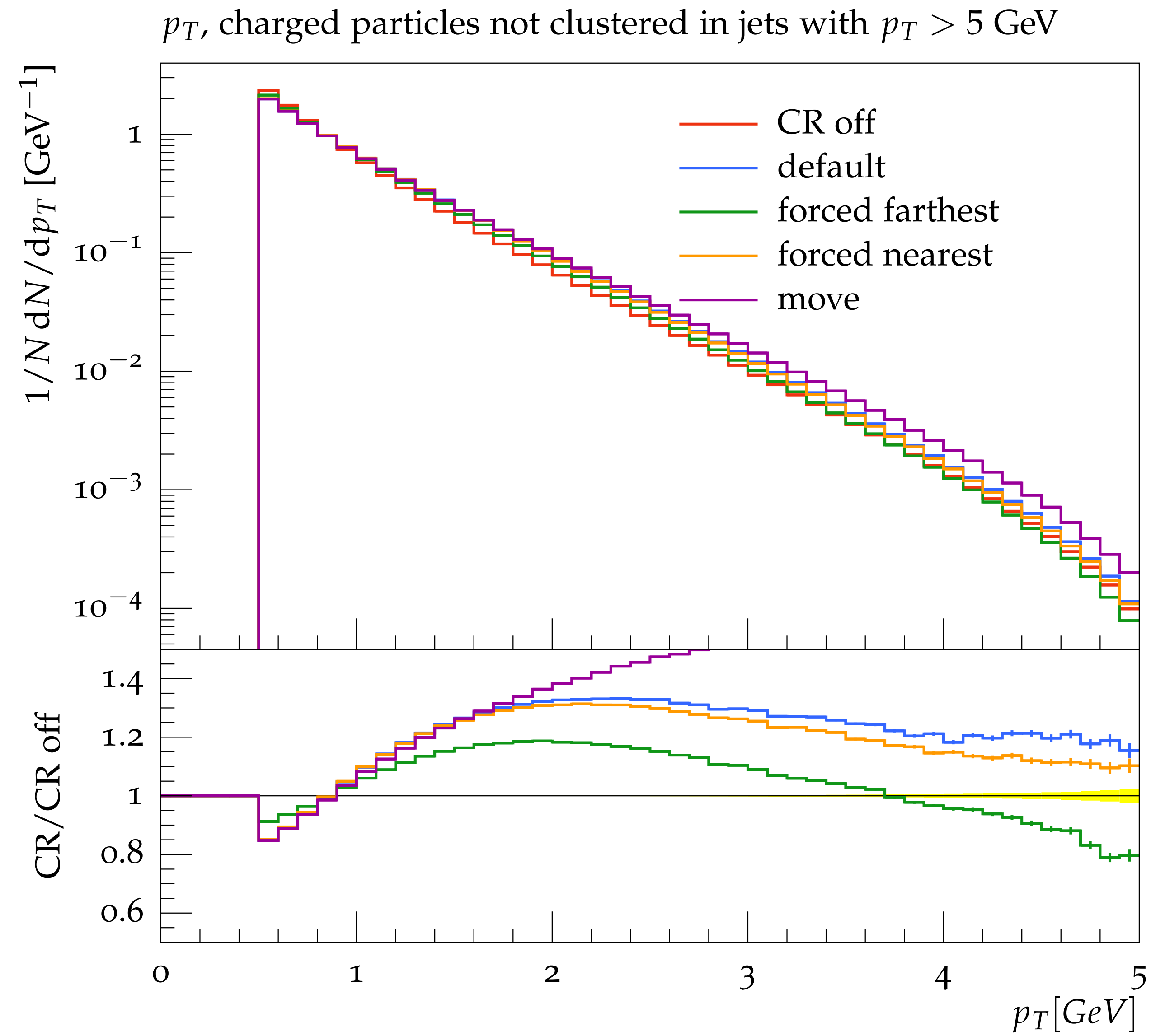
- **Maximum variation**: m_{top}^{max} - m_{top}^{min} $\approx$ **800 MeV**
- considering only the more sophisticated models:

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

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

- charged particle multiplicity, p_T in tt events
- mean p_T density per unit jet area, $<n_{ch}>(\Delta R_{Wb})$
- efforts from both CMS and ATLAS to measure UE in tt events

  ongoing analyses will hopefully incorporate these measurements

Summary

The situation so far...

- **yet no measurements** to constrain CR **in top events**
- **current procedure** to estimate CR uncertainty on top mass probably **underestimates the uncertainty**

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**
- there are **observables that can constrain/exclude** most of these **models** with **existing LHC data**

New model by **J.Christiansen and P.Skands** will allow more tests

Many thanks to Torbjörn, Lund THEP and MCnet