Tuning Herwig 7 with Lund String Model

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in collaboration with

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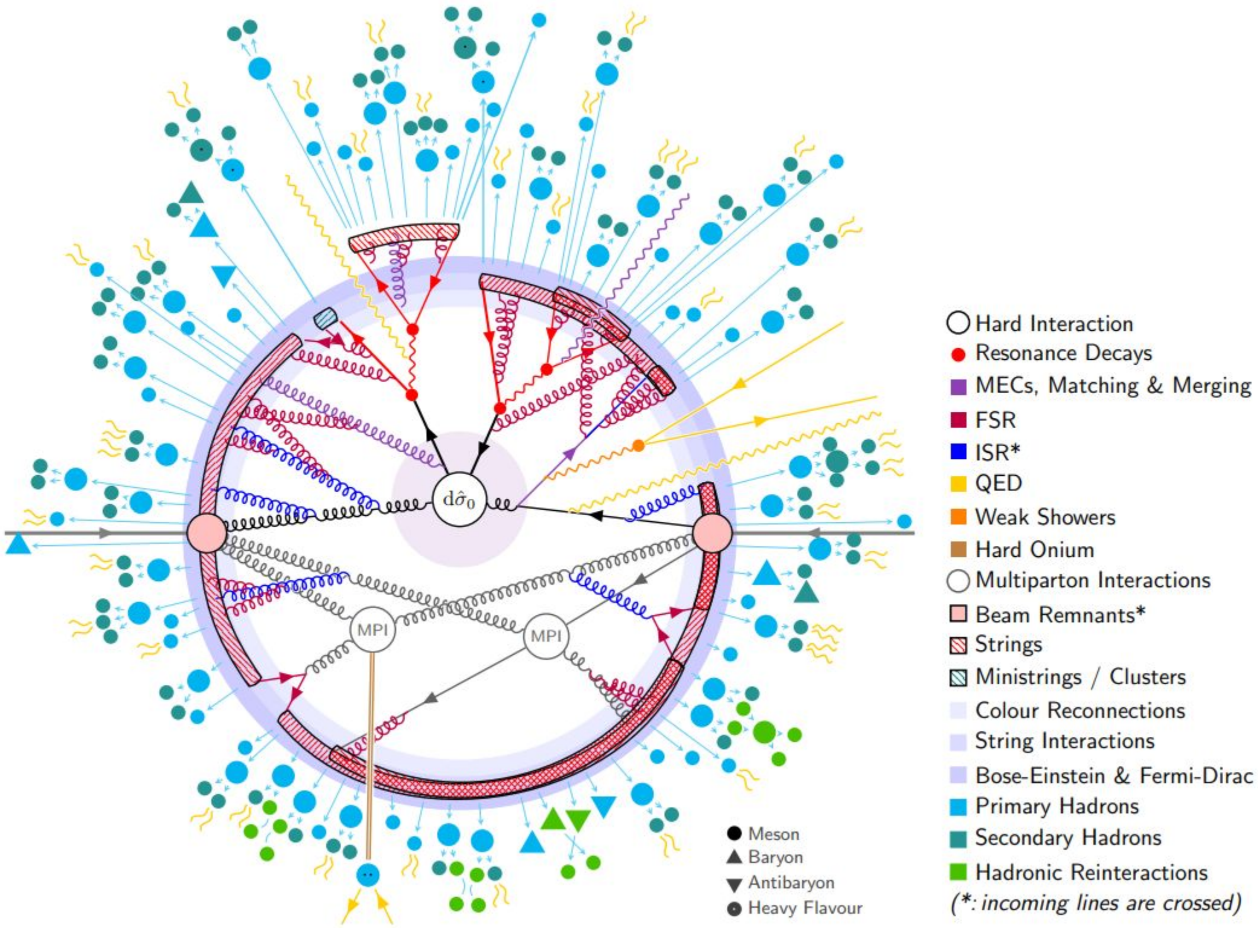
Introduction

- **Monte Carlo generators** are tools that can simulate collisions and bridges the **gap** between theory and experiment. An event generation simulation with the different stages looks like:



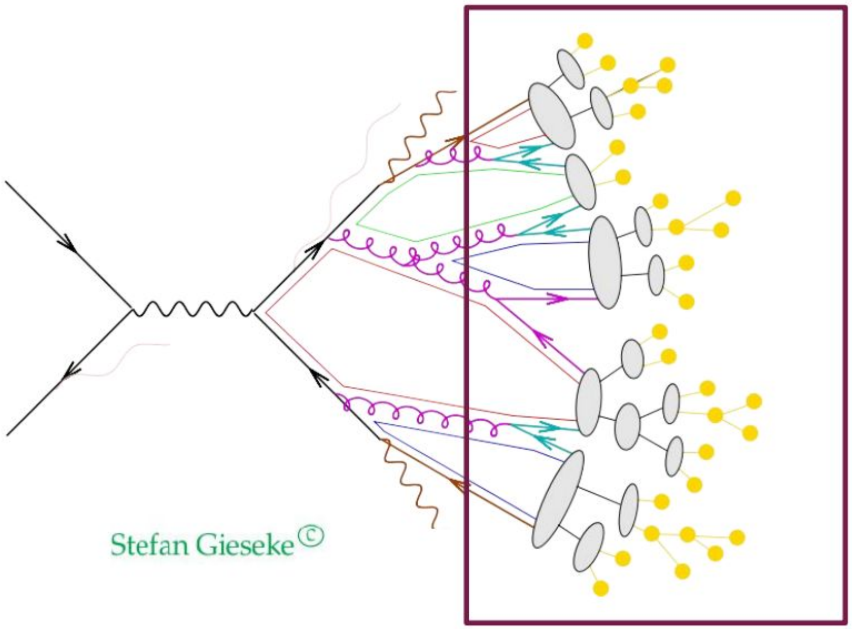
Introduction

High Energy

- **perturbative QCD**
- **in theory we know what to do**
- **in practice very difficult**

Low Energy

- **non-perturbative QCD**
- **we don't know what to do**
- **phenomenological models (with many free parameters)**



Hadronization:
one of the least understood region of MCEG

Motivation

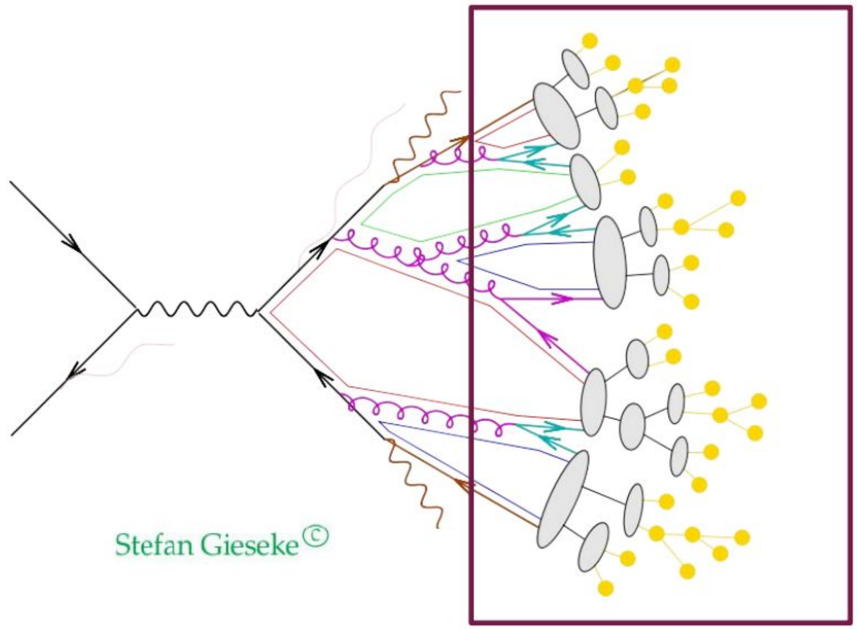
High Energy

- **Increased control of perturbative corrections**

Low Energy

- **more often LHC measurements limited by non-perturbative components (e.g hadronization)**

- W mass measurement using a new method [Freytsis at al. JHEP 1902 (2019) 003]
- Extraction of the strong coupling [M. Johnson, D. Maître, Phys.Rev. D97 (2018) no.5]
- Top mass [S. Argyropoulos, T. Sjöstrand, JHEP 1411 (2014) 043]
- and more...



Hadronization:
one of the least understood region of MCEG

High Energy

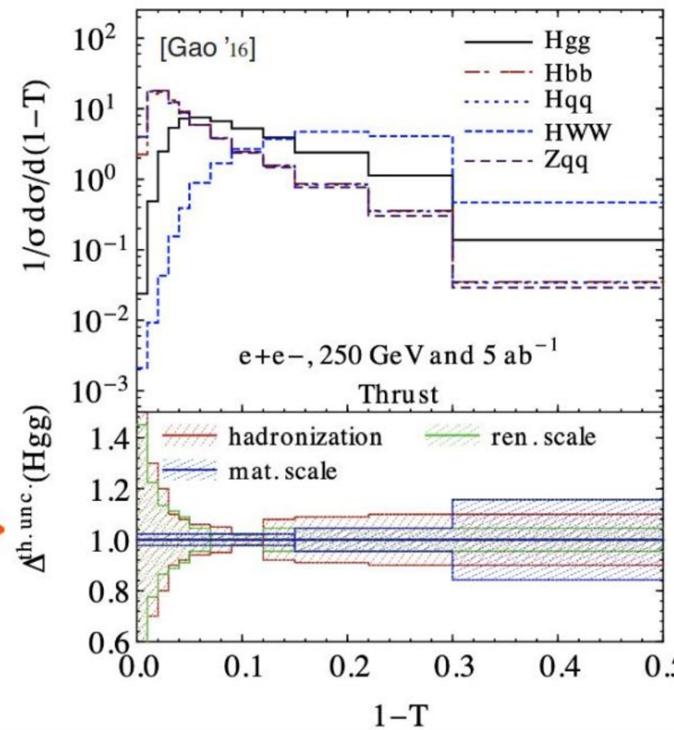
- **Increased control of perturbative corrections**

$\Rightarrow$

Low Energy

- **more often LHC measurements limited by non-perturbative components (e.g hadronization)**

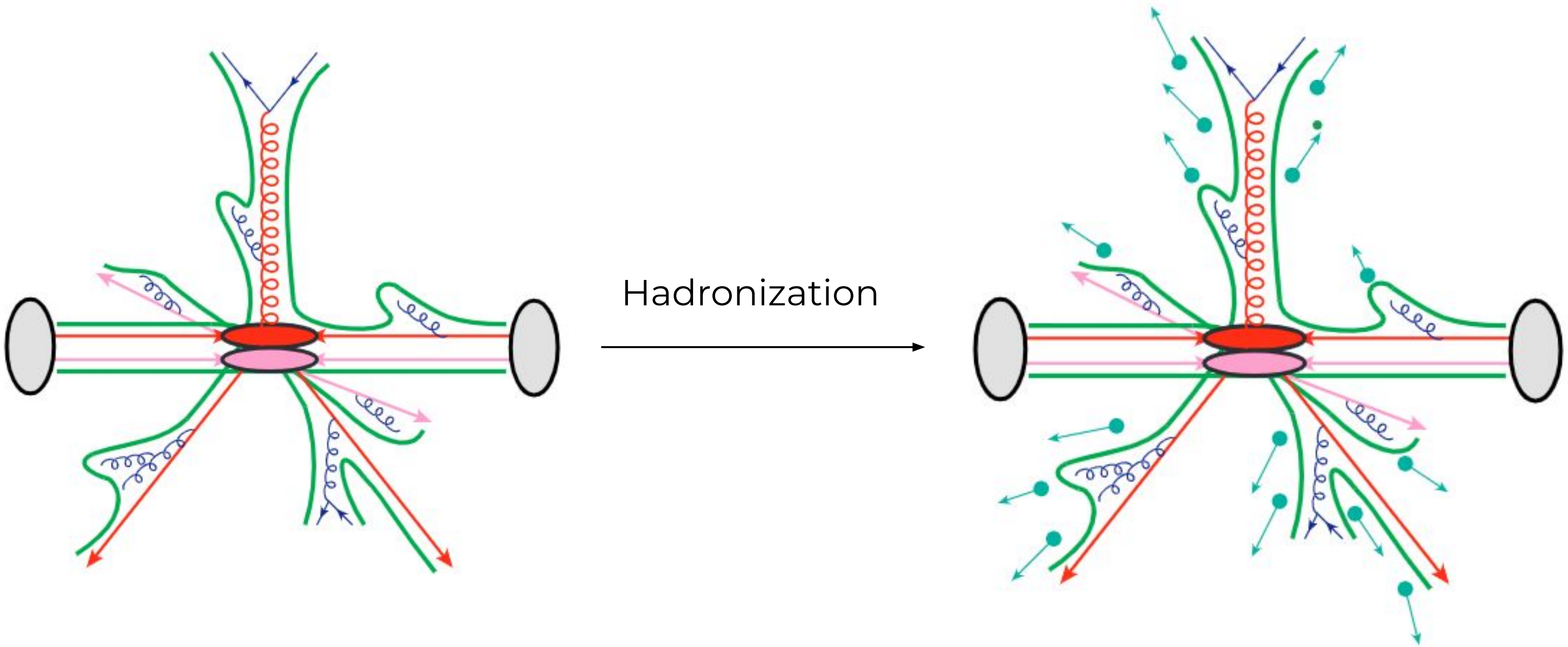
- However, hadronisation remains the main bottleneck
  - e.g. thrust in Higgs decays (MC variation in plot)
- Increase in energy insufficient for suppression ($Q \sim m_H$)
- Runs at lower energies are essential for a robust tuning of NP models in MCs
- Also crucial for training of ML algorithms for jet tagging, instrumental in extraction of Higgs couplings



Pier Moni's talk at FCC Physics Workshop 2023

Motivation

- **Hadronization** - two most commonly used models are **String Model** in Pythia and **Cluster Model** in Herwig and Sherpa



- These models generally contain several free parameters that cannot be inferred from first principles and require **tuning** to experimental data.

Images taken from S.Prestel

Motivation

- Several tunes have been performed to LHC data over the years for event generators Pythia and Herwig

- It has been seen, the **Lund String** model in Pythia does better describing data sensitive to hadronization process and the **Angular Ordered (AOPS)** shower in Herwig7 does better in regions sensitive to perturbative calculations

- A first attempt was made to tune Herwig7 with Lund String in a new framework named AutoTunes [J.Bellm, L.Gellersen, EPJC 2020]

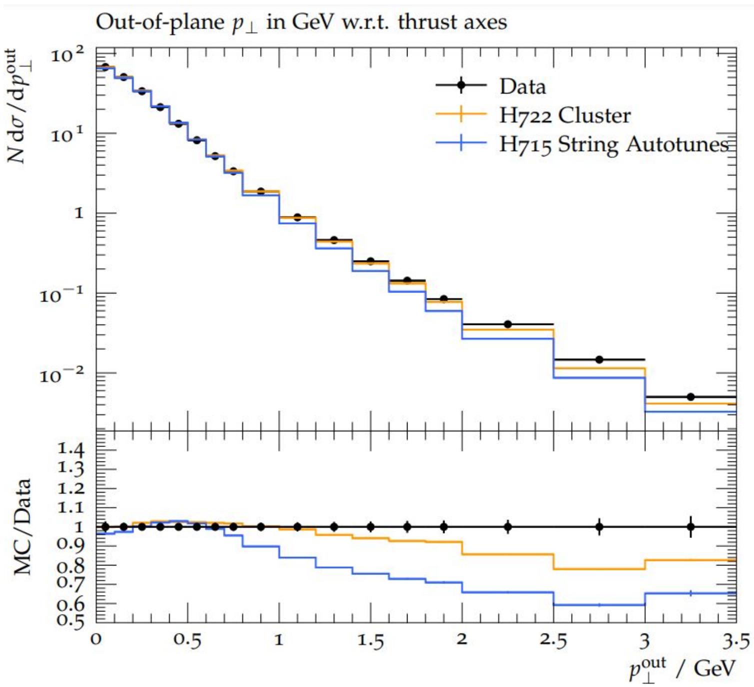
- **TheP8I**, written by L. Lonnblad allowed the internal use of Pythia 8 strings with Herwig 7 events

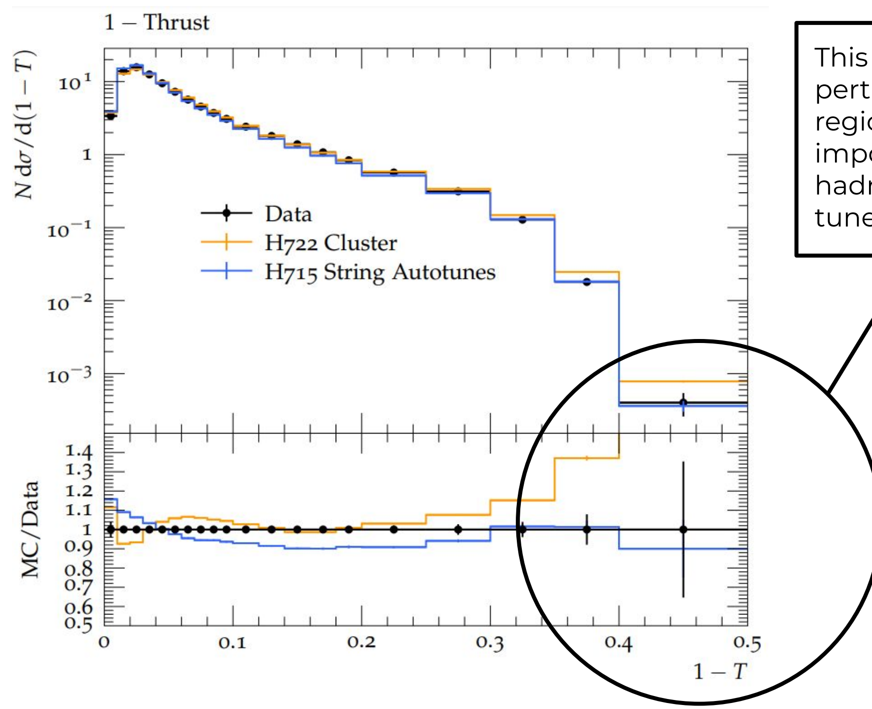
Motivation

- However, the AutoTunes paper focused more on a new automatized tuning procedure than getting the best tune.

- Thus, we reproduced the results based on their tuned parameters
  [there were no plots comparing the tune to the data in the paper]

- The results didn’t show much improvement and it also performed **worse** in many regions when compared to the default Herwig7 + cluster tune. This could be due to AutoTunes not taking correlations into account.

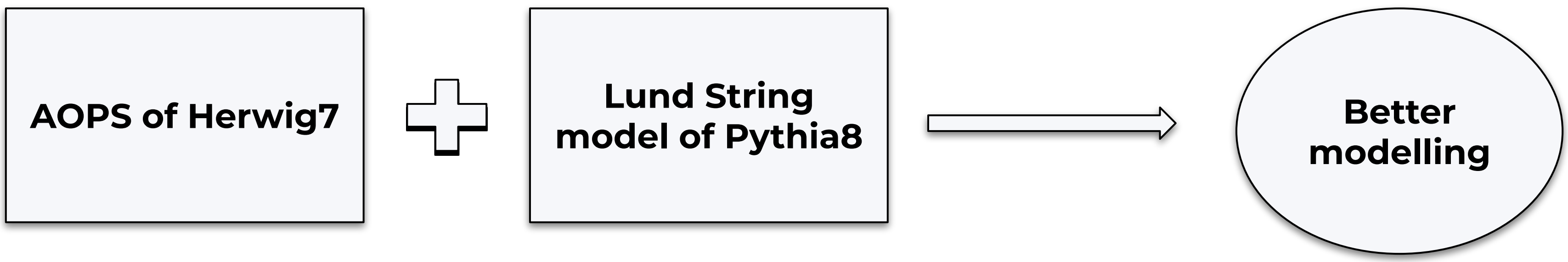




This is perturbative region not important for hadronization tune.

Motivation

- We would naively expect:



- Therefore we want to understand if the gap between our expectation and previous results are due to the tuning setup or physics understanding of the NP* region.

- A successfully combined model would also provide a setup for a dedicated study of the systematics of NP effects.

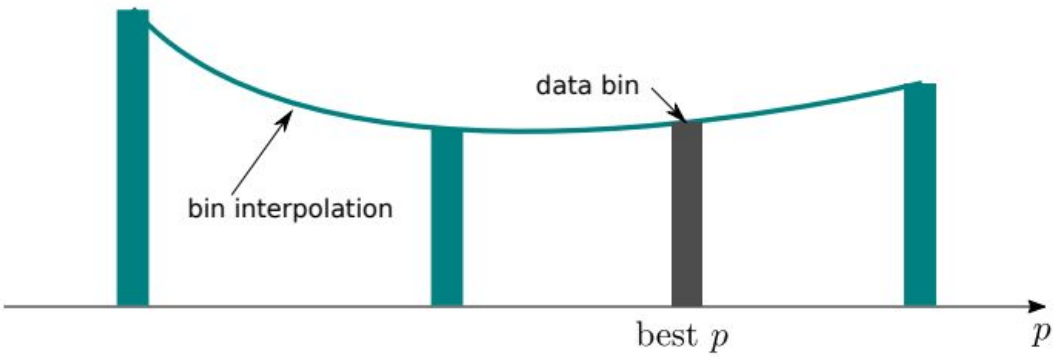
*NP - Non-Perturbative

Tuning to LEP data

Herwig 7.2.2 + Lund String Model

Tuning strategy

- We follow the PROFESSOR approach (as done in Pythia 6 tune) to tune the AOPS of Herwig7 + Lund String model to **LEP data** [A.Buckley et al, EPJC 2010].
  Two stages of tuning:
  - Fragmentation parameters and
  - Flavour parameters



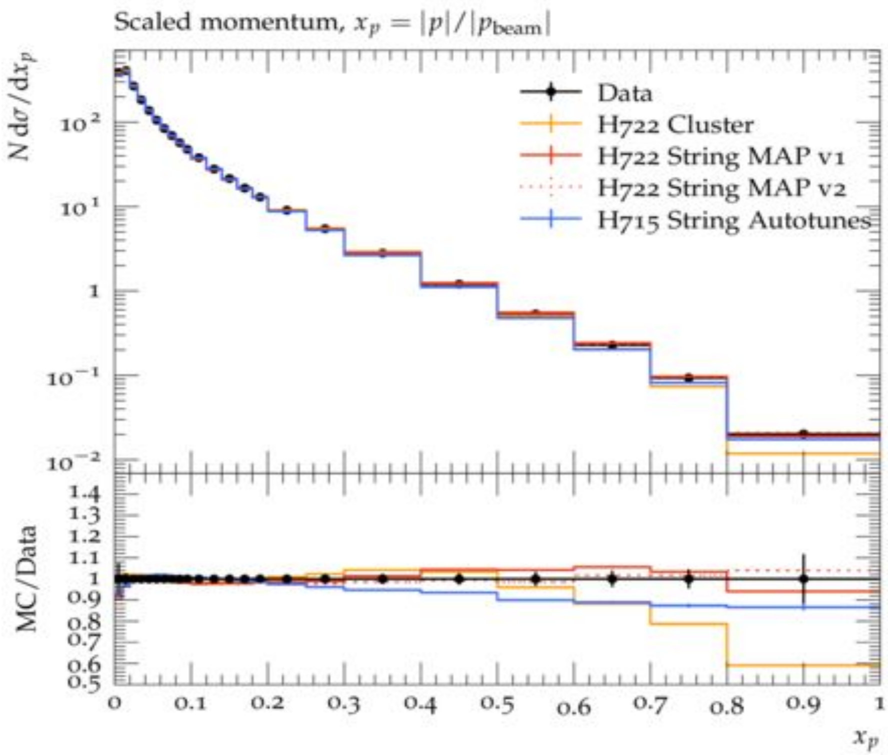
- The **PROFESSOR** framework parameterizes the generator response to a n-order polynomial and minimizes a Goodness-of-Fit function (χ^2) to get the set of best parameter values.

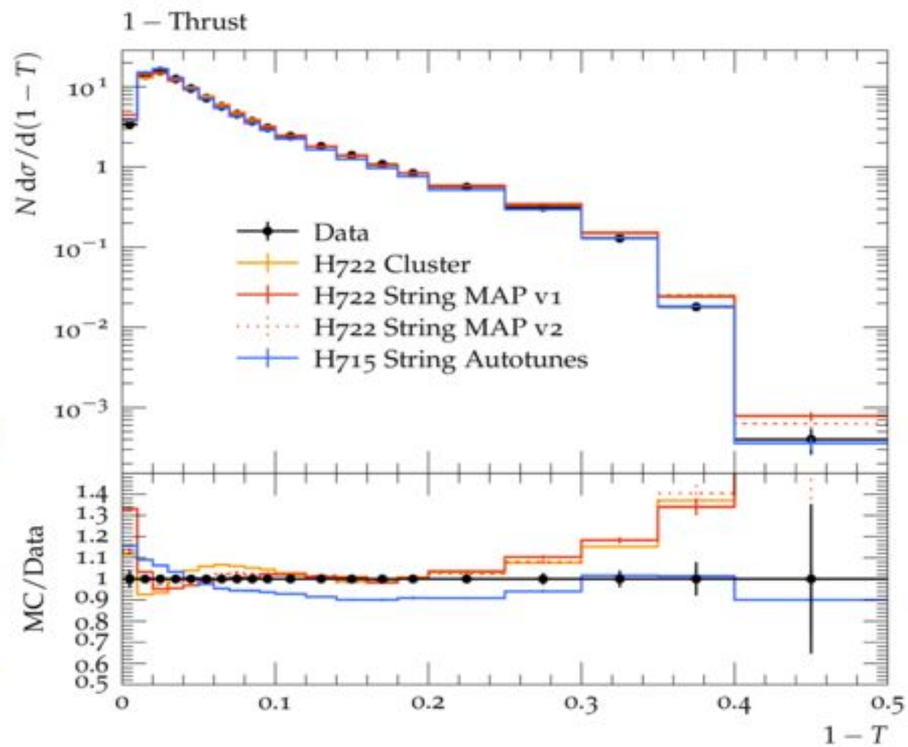
- Two different sets of tuning weights were used to obtain two versions of our **MAP** (Mira, Andrzej, Pratixan) tune **v1** and **v2** and compared them with the default Herwig7.2.2 + cluster tune and the AutoTunes tune.

Image taken from L.Gellersen

Event Shape Observables

- Plots from the analysis DELPHI_1996_S3430090

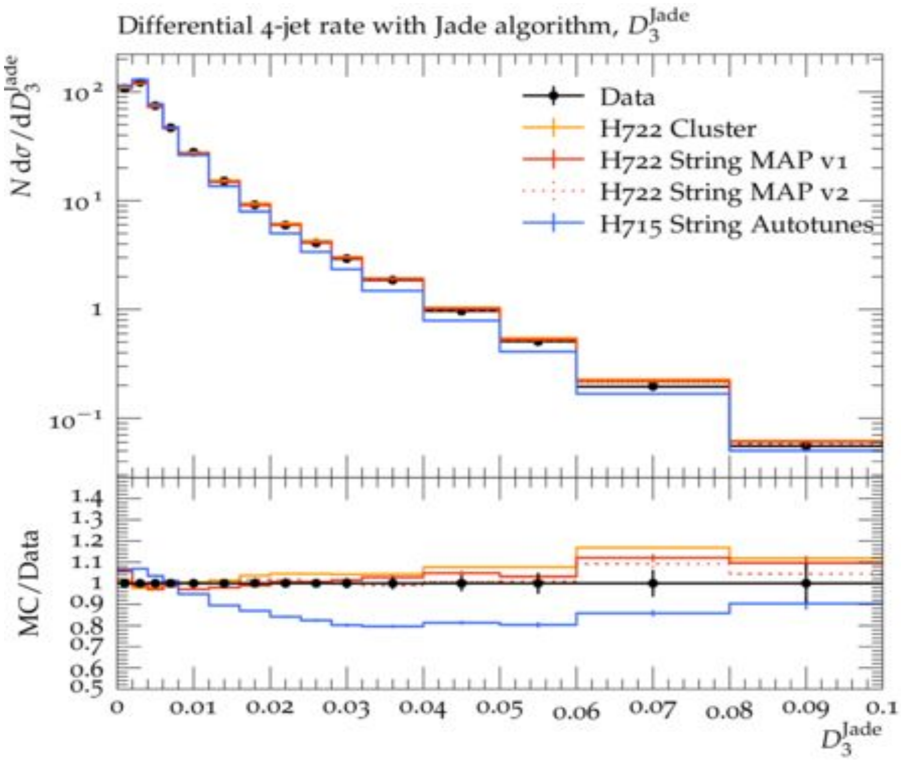


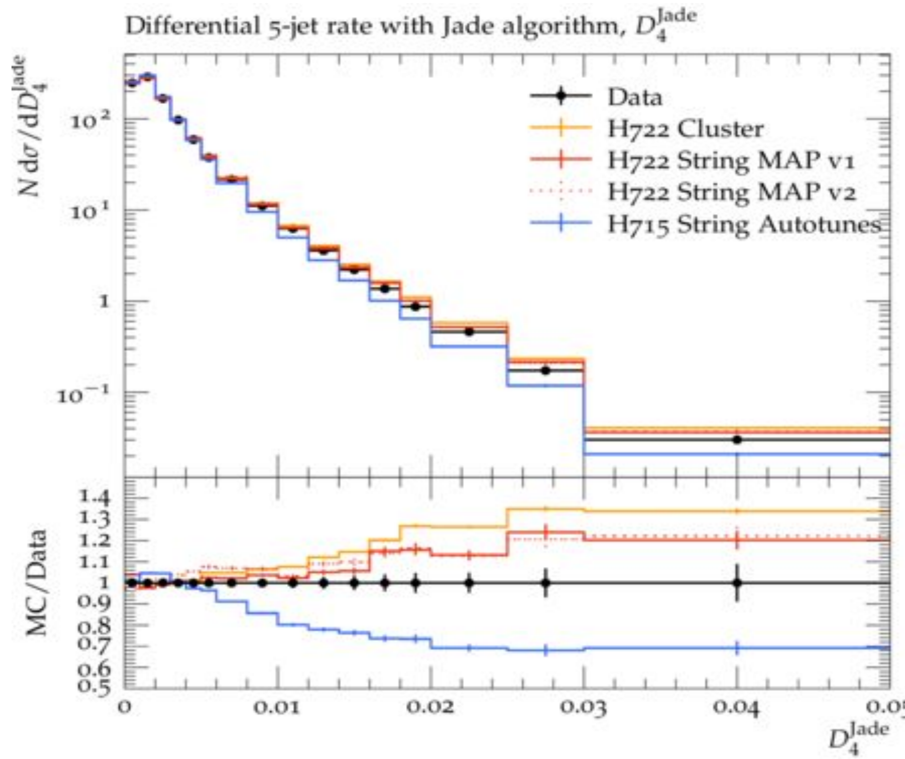


- Both these distributions were used in tune.

- Regions of the distribution sensitive to non-perturbative region are significantly better modelled by MAP tune.
- for x_p distribution, string model does better than the cluster

- Plots from the analysis DELPHI_1996_S3430090



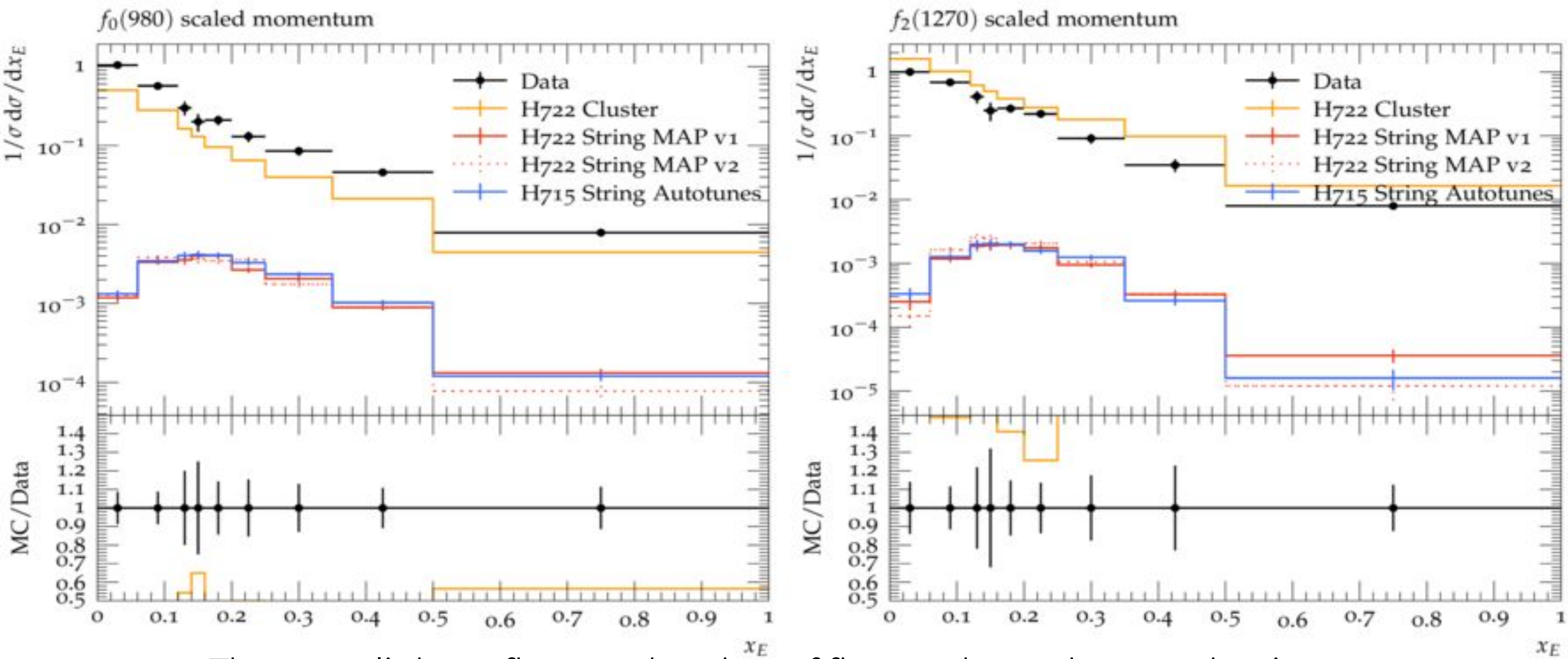


- Both these distributions were **not** used in the tune.

- MAP tune again does better even though jet observable distributions were not weighted in the tuning.

Flavour sensitive Observables

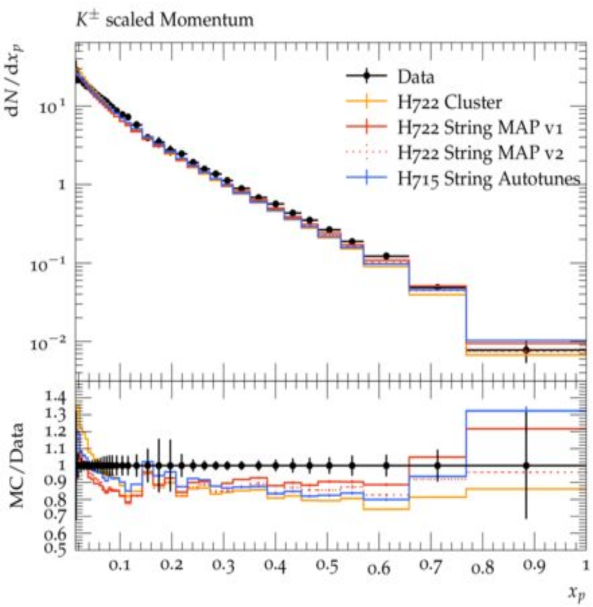
- Plots from the analysis OPAL_1998_S3702294

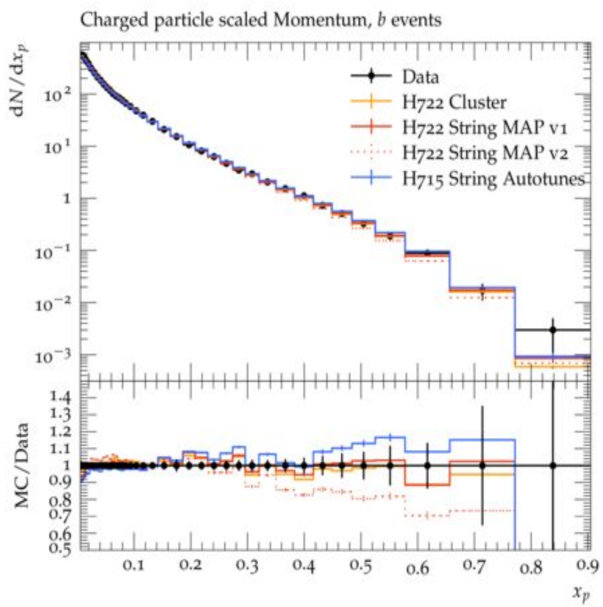


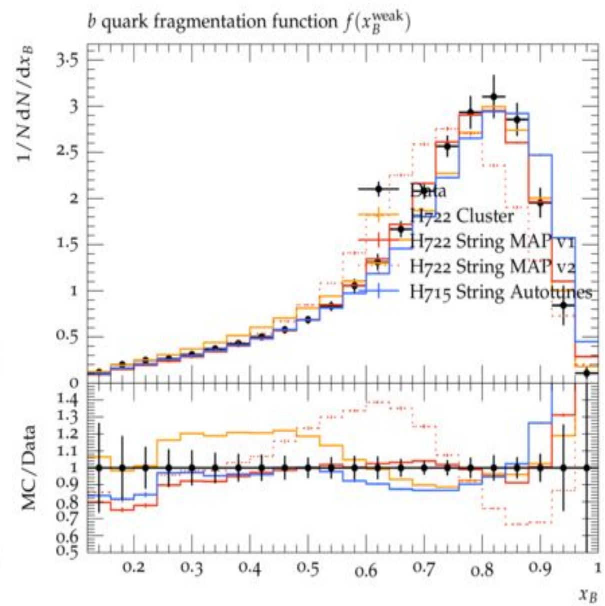
- These are light unflavoured probes of flavour dependent production.
- These distributions were **not** used in the tune
- It would also be interesting to see how Pythia does for the observables.
- The cluster model could be insensitive to the flavour as it does reasonably well in these distributions.

Flavour sensitive Observables

- Plots from the analysis SLD_2004_S5693039 (left and center) and SLD_2002_S4869273 (right).







- MAP tune does much better in these distributions than in previous flavour sensitive distributions

- MAP tune v1 and v2 shows much differences with v1 performing better over a wider range

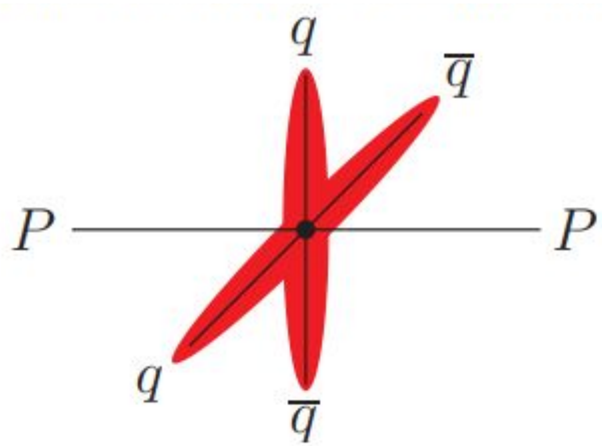
Tuning to LHC data

Herwig 7.2.2 + Lund String Model
with Colour Reconnection

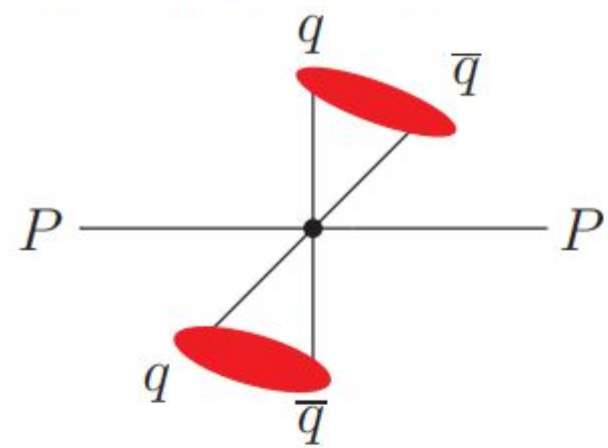
Colour Reconnection

- **Colour Reconnection (CR)** reshuffles the colours just prior to hadronization such that strings form between favourable partons
- This is needed to explain the rise of **$\langle p_T \rangle$** with multiplicity as observed experimentally
- We implemented **CR** in the **P8I** interface and switched it on when tuning to LHC data which is particularly sensitive to it due to large partonic activity in the final state

Before Colour Reconnection



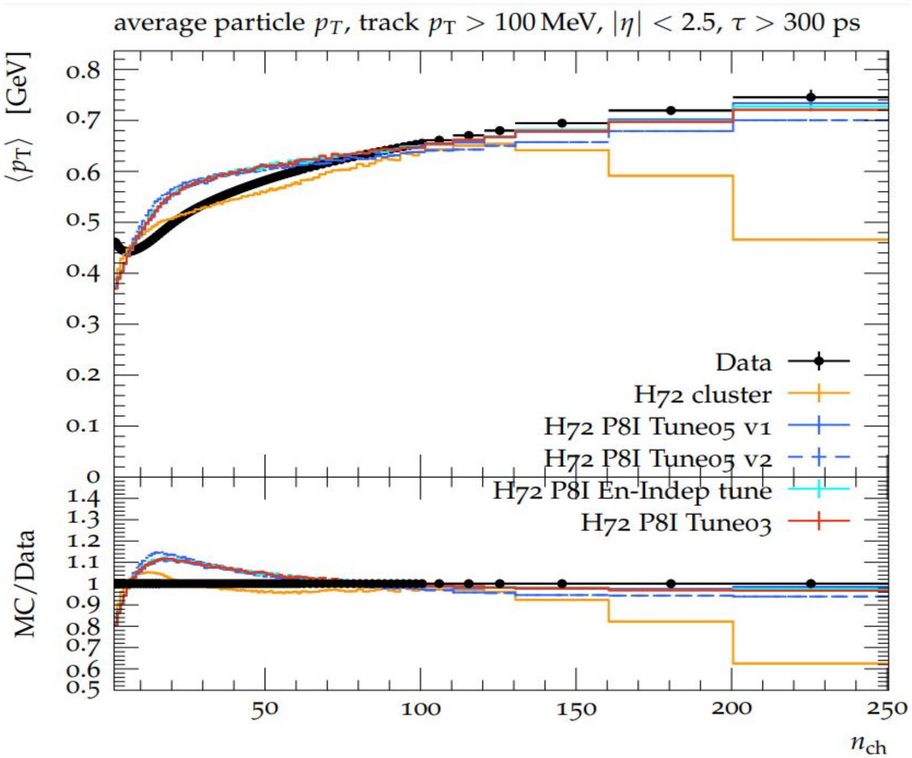
After Colour Reconnection

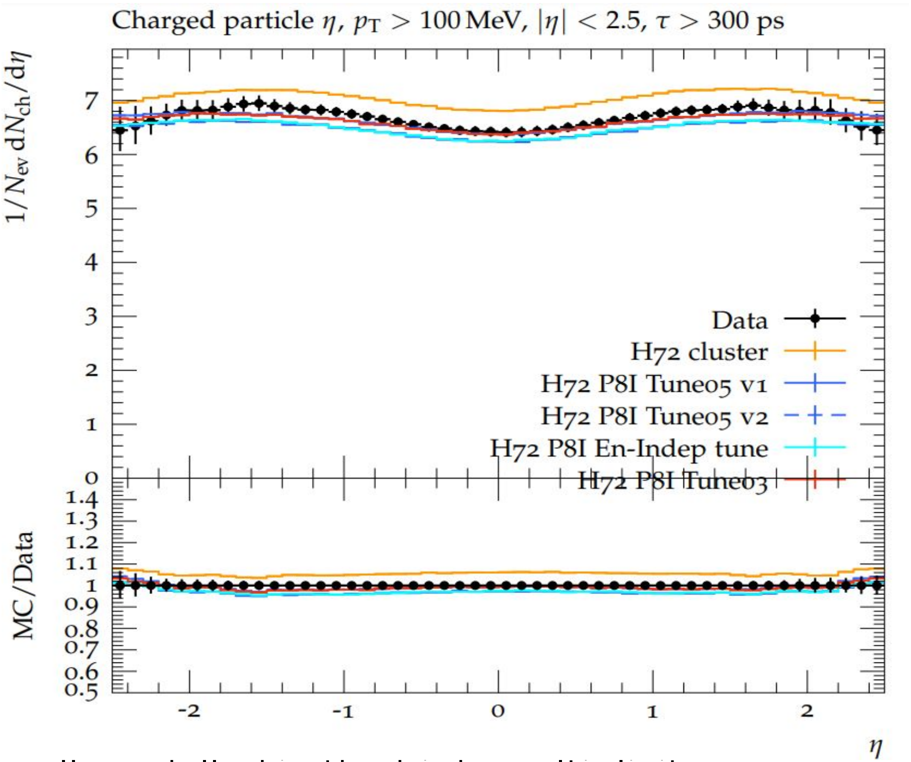


Images taken from J.R. Christiansen

Tuning to LHC Data (at 13 TeV)

- Plots from the analysis ATLAS_2016_I1467230 (Track based minimum biased events)

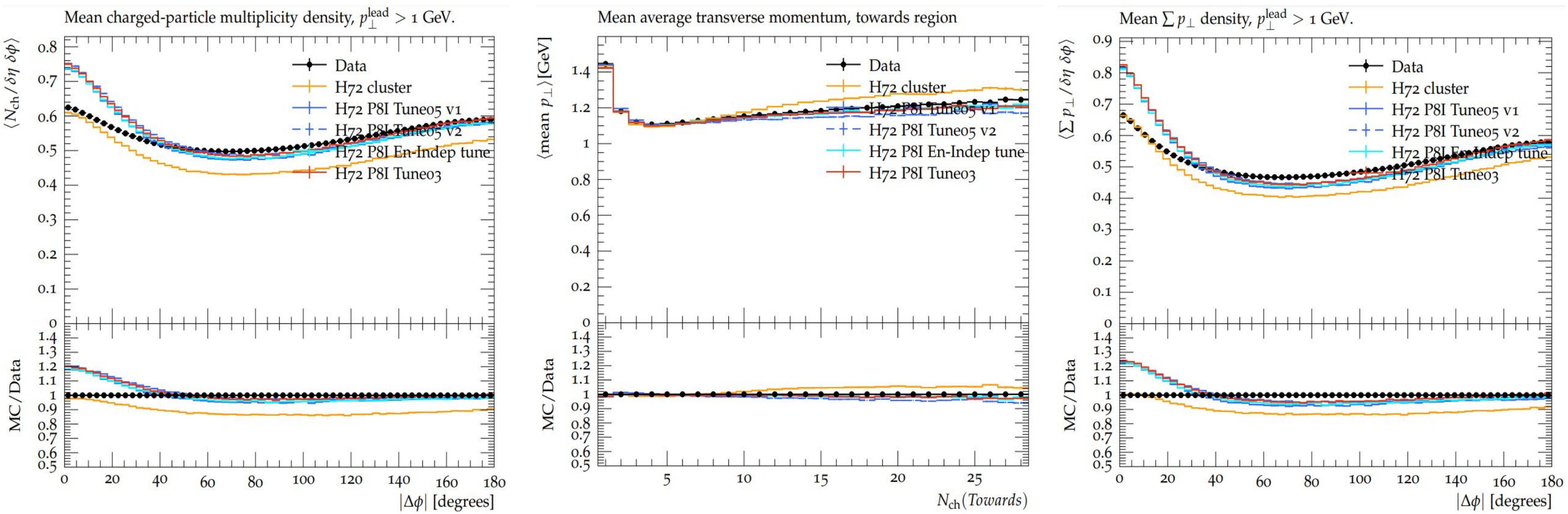




- Average particle pT distribution (left) well modelled in the high multiplicity region by our tune compared to default cluster tune
- Better modelling of charged particle pseudorapidity as well (right)

Tuning to LHC Data (at 13 TeV)

- Plots from the analysis ATLAS_2017_I1509919 (Track based underlying events)



- More examples of observables well modelled by MAP tune over large regions in multiplicity and mean transverse momenta distributions
- LHC data at different energies (900 GeV, 1.8 TeV, 7 TeV, 13 TeV) were tuned on independently as well as combined obtaining similar results

Tuning to LEP data

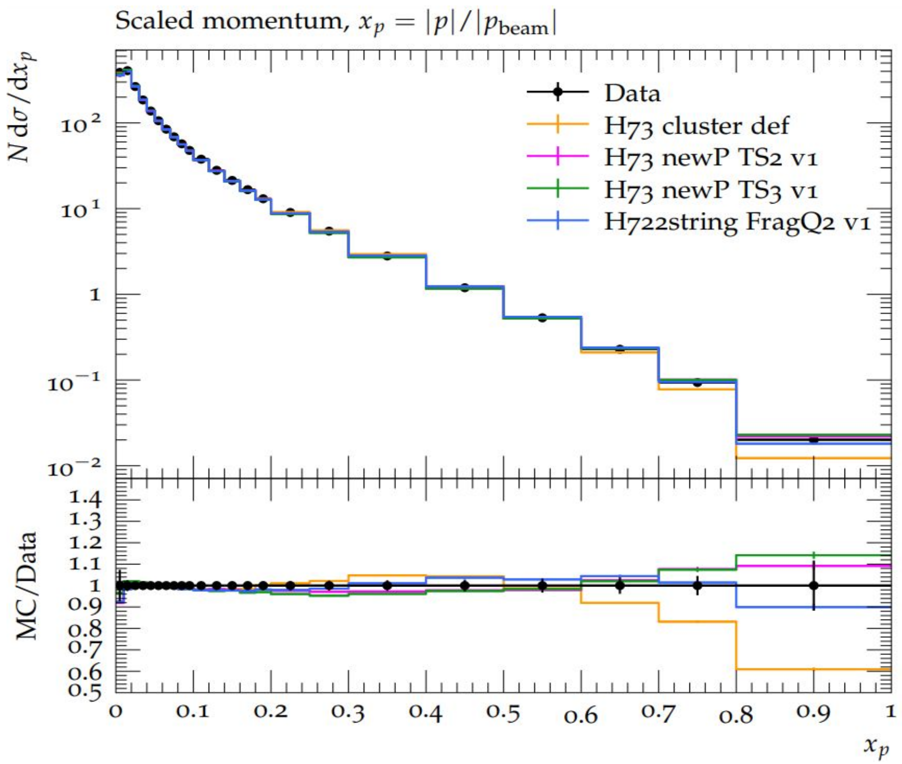
Herwig 7.3 + Lund String Model
with Regularized GOF

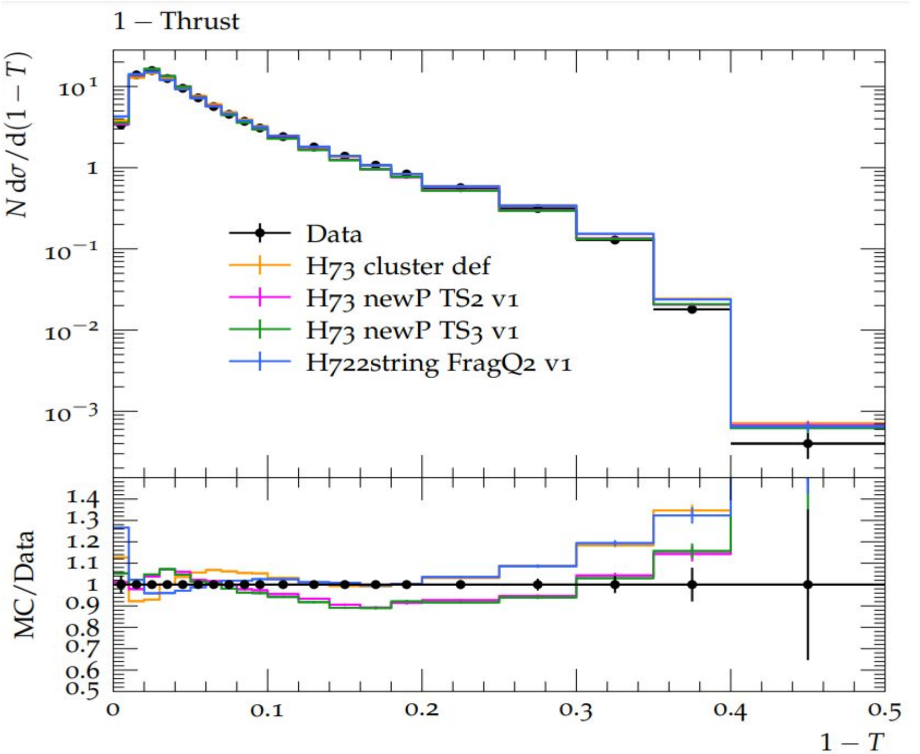
Regularized GOF

- Having obtained robust tunes for Herwig 7.2.2, we performed the tuning procedure on Herwig 7.3 similarly.
- The GOF used to tune Herwig 7.3 is a **regularized χ^2** function of the form $\chi^2/(1 + \chi^2)$ or $\tanh(\chi^2)$ [Implemented in Professor 2.4.2 by S. Kiebacher]. This in principle allows for a better global tune.
- However the tune obtained showed much difference to MAP tunes on the previous version of Herwig (likely due to changes in Shower)
- While charged multiplicities and hadronic scaled momenta distributions look better, event shape distributions are worse.
- Different tuning strategies were followed labelled **TS1 to TS3** corresponding to different subsets of parameters fixed while tuning. Parameters corresponding to minimum and next to minimum GOF were also checked which are labelled as **v1** and **v2** respectively. (*only v1 plots will be shown here since v2 plots are worse in general)

Event Shape Observables

- Plots from the analysis DELPHI_1996_S3430090

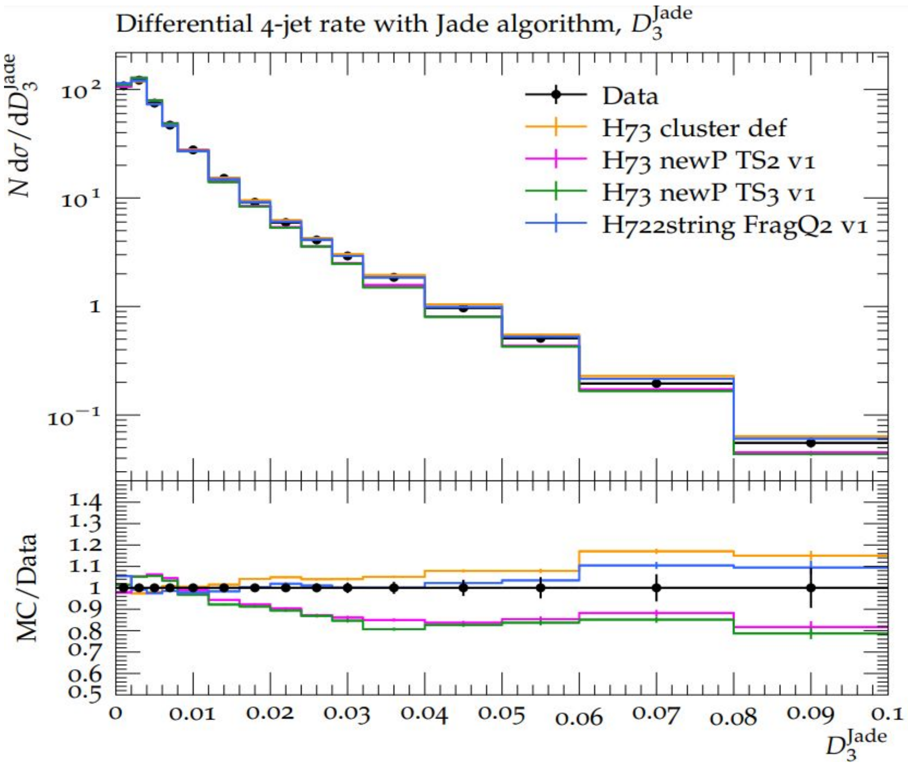


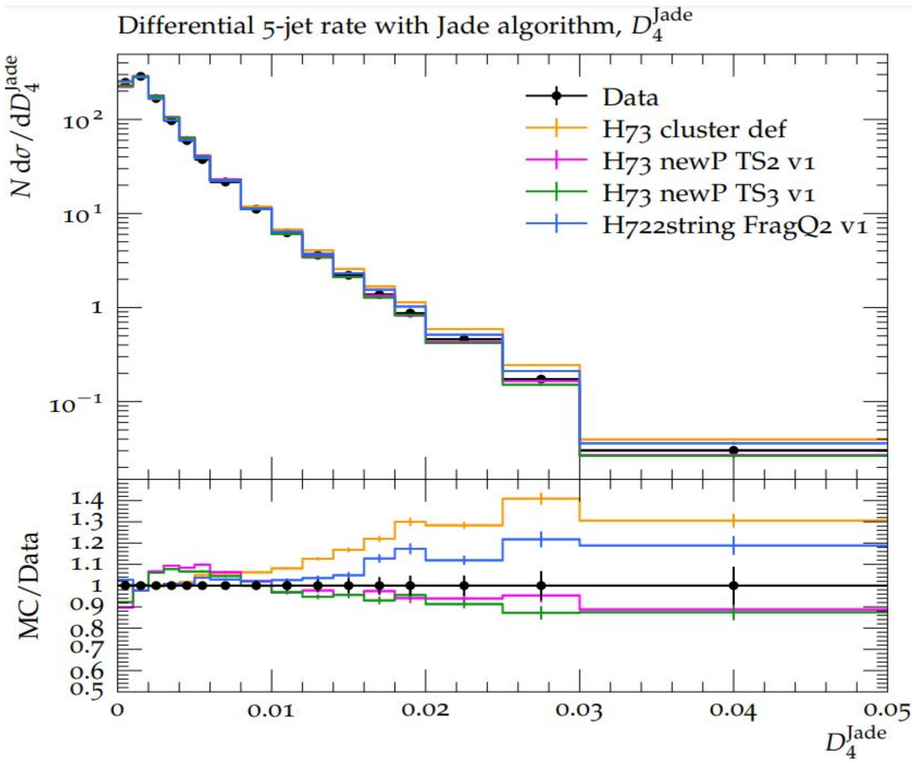


- The new MAP tune does similar to old tune but does significantly better than the default cluster tune for scaled momenta distribution.
- Parts of the thrust distribution is well modeled by the new MAP tune, although the non-perturbative region is largely modelled better by old MAP tune

Jet Observables

- Plots from the analysis DELPHI_1996_S3430090

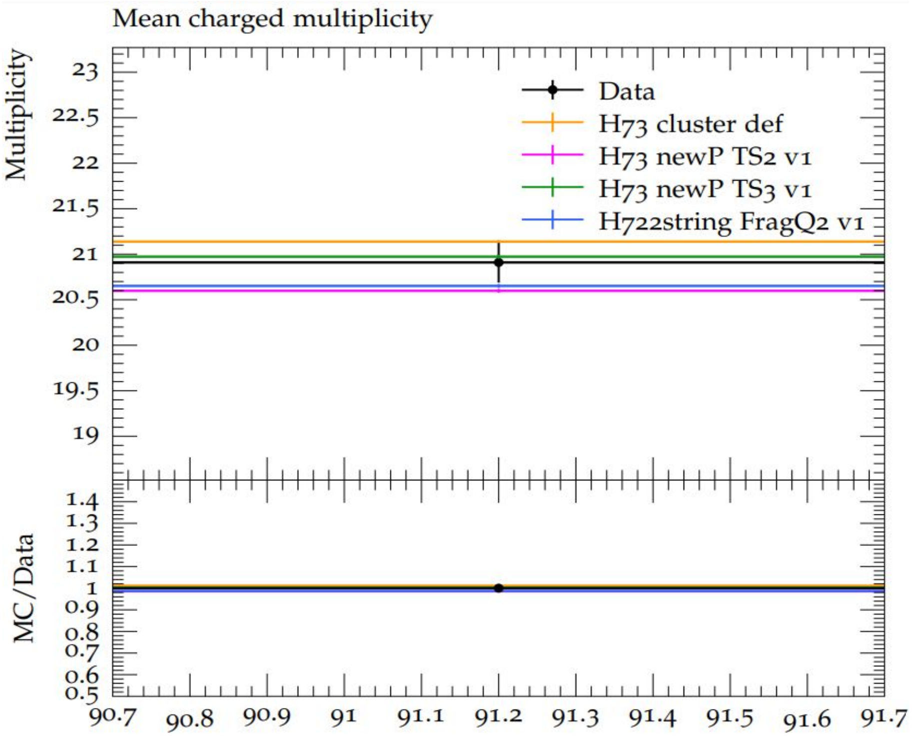


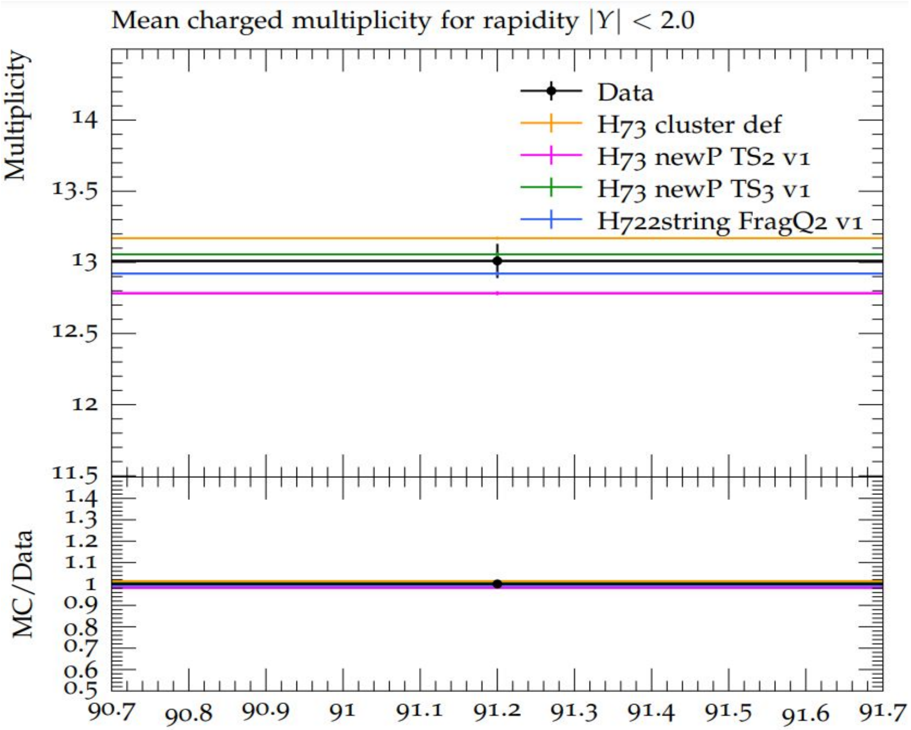


- The D_3^{Jade} distribution (left) is worse for the new MAP tune compared to the old MAP tune and default cluster however it performs better for D_4^{Jade} distribution (right)

Charged Multiplicities

- Plots from the analysis ALEPH_1996_S3486095

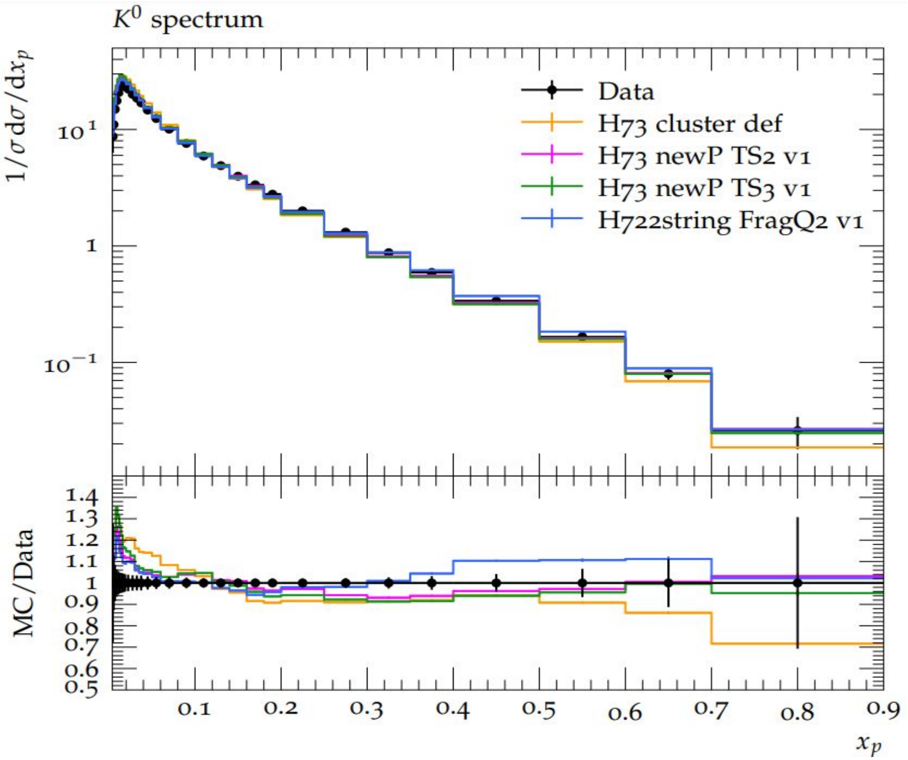


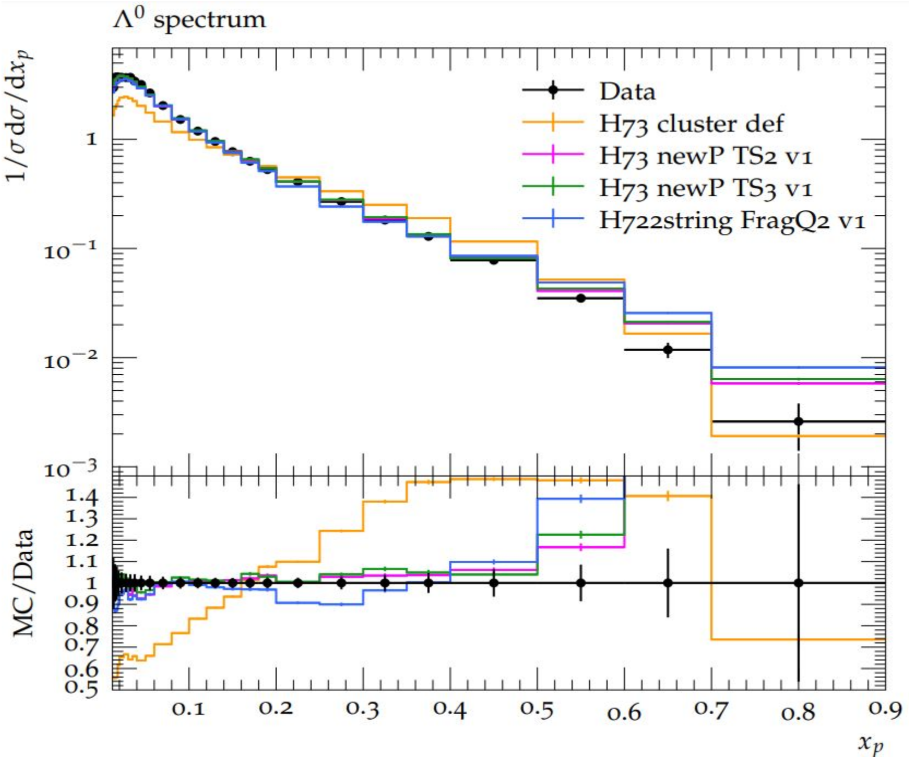


- Charged multiplicities are well modelled with the new MAP tune

Particle Spectra

- Plots from the analysis ALEPH_1996_S3486095

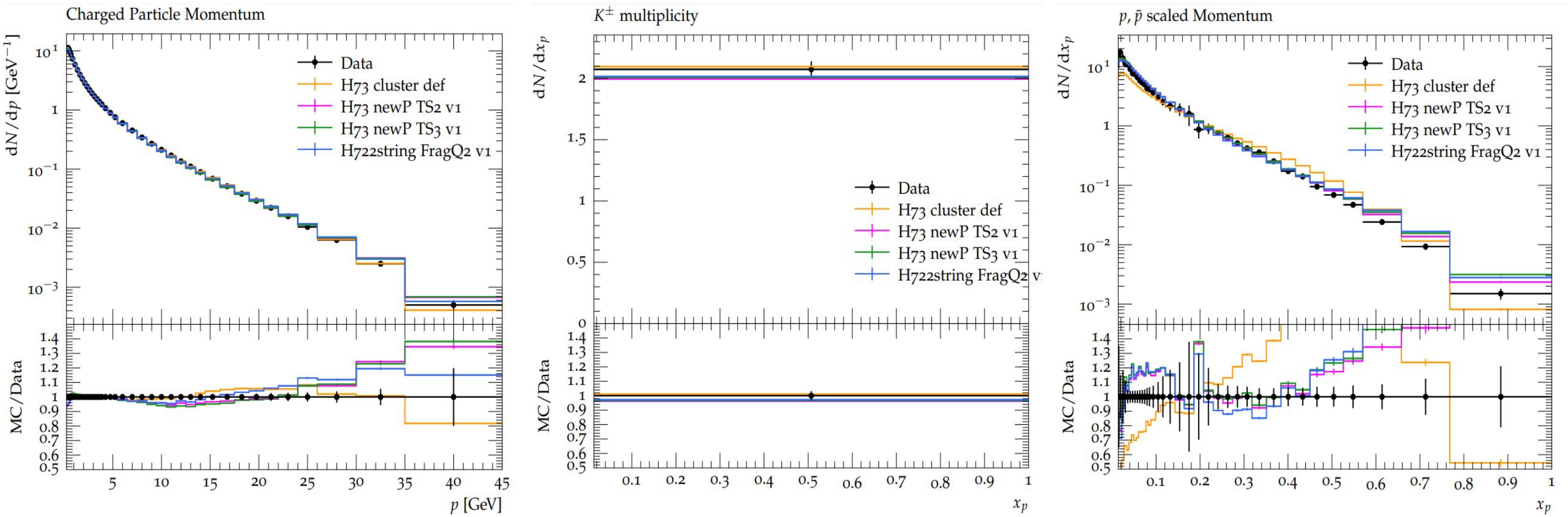




- Identified particle spectra for K^0 and Λ^0 are very well modelled by the new MAP tune compared to previous tune and default cluster tune which behaves poorly.

More Observables...

- Plots from the analysis SLD_2004_S5693039



- Some more observables including identified particle multiplicities and charged particle momenta where new MAP tune does quite well.

Summary

- MAP Tune for Herwig 7.2.2 does much better than AutoTunes over a large set of observables. It does better than the default cluster tune for event shape and jet observables.
- MAP tune for Herwig 7.3 with a regularized GOF shows tension with the previous tune. Due to possible changes in shower, further investigation needed.
- While old MAP tune does well for event shape and jet observables, new MAP tune does well for multiplicities and flavour sensitive observables. Change in tuning weights might be needed to address the tension.
- New MAP tune for LHC data is in progress.
- Overall we have a robust setup to use both strings and cluster for systematics studies of NP effects for e+e- and hadron colliders.

Thank you!

Backup Slides

Parameter Values (old MAP Tune v1)

Pythia8 parameters:

Fragmentation related Parameters

StringZ_aLund	0.750043
StringZ_bLund	0.898493
StringZ_sigma	0.309940
StringZ_aExtraSQuark	0.175699
StringZ_bExtraDiquark	0.053576
StringZ_rFactC	0.680046
StringZ_rFactB	1.265325

Herwig7 parameters:

/Herwig/Shower/AlphaQCD:AlphaIn	0.125772
/Herwig/Shower/NLOAlphaS:input_alpha_s	0.125772
/Herwig/Shower/PTCutOff:pTmin	1.027660

Flavour related Parameters

StringFlav_probStoUD	0.190037
StringFlav_probQQtoQ	0.079770
StringFlav_probSQtoQQ	0.998577
StringFlav_probQQ1toQQ0	0.022243
StringFlav_etaSup	0.512356
StringFlav_etaPrimeSup	0.184657
StringFlav_popcornRate	0.734028
StringFlav_mesonUDvector	0.329842
StringFlav_mesonSvector	0.676458
StringFlav_mesonCvector	1.065635
StringFlav_mesonBvector	1.849178

Parameter Values (old MAP Tune v2)

Pythia8 parameters:

Fragmentation related Parameters

StringZ_aLund	0.394348
StringZ_bLund	0.688822
StringZ_sigma	0.308203
StringZ_aExtraSQuark	0.863354
StringZ_bExtraDiquark	1.901871
StringZ_rFactC	0.522541
StringZ_rFactB	1.577757

Flavour related Parameters

StringFlav_probStoUD	0.185213
StringFlav_probQQtoQ	0.076194
StringFlav_probSQtoQQ	0.998577
StringFlav_probQQ1toQQ0	0.063338
StringFlav_etaSup	0.537677
StringFlav_etaPrimeSup	0.135651
StringFlav_popcornRate	0.002145
StringFlav_mesonUDvector	0.330021
StringFlav_mesonSvector	0.688189
StringFlav_mesonCvector	1.151696
StringFlav_mesonBvector	2.257771

Herwig7 parameters:

/Herwig/Shower/AlphaQCD:AlphaIn	0.124523
/Herwig/Shower/NLOAlphaS:input_alpha_s	0.124523
/Herwig/Shower/PTCutOff:pTmin	0.894570

Parameter Values (new MAP Tune)

Pythia8 parameters:

Fragmentation related Parameters

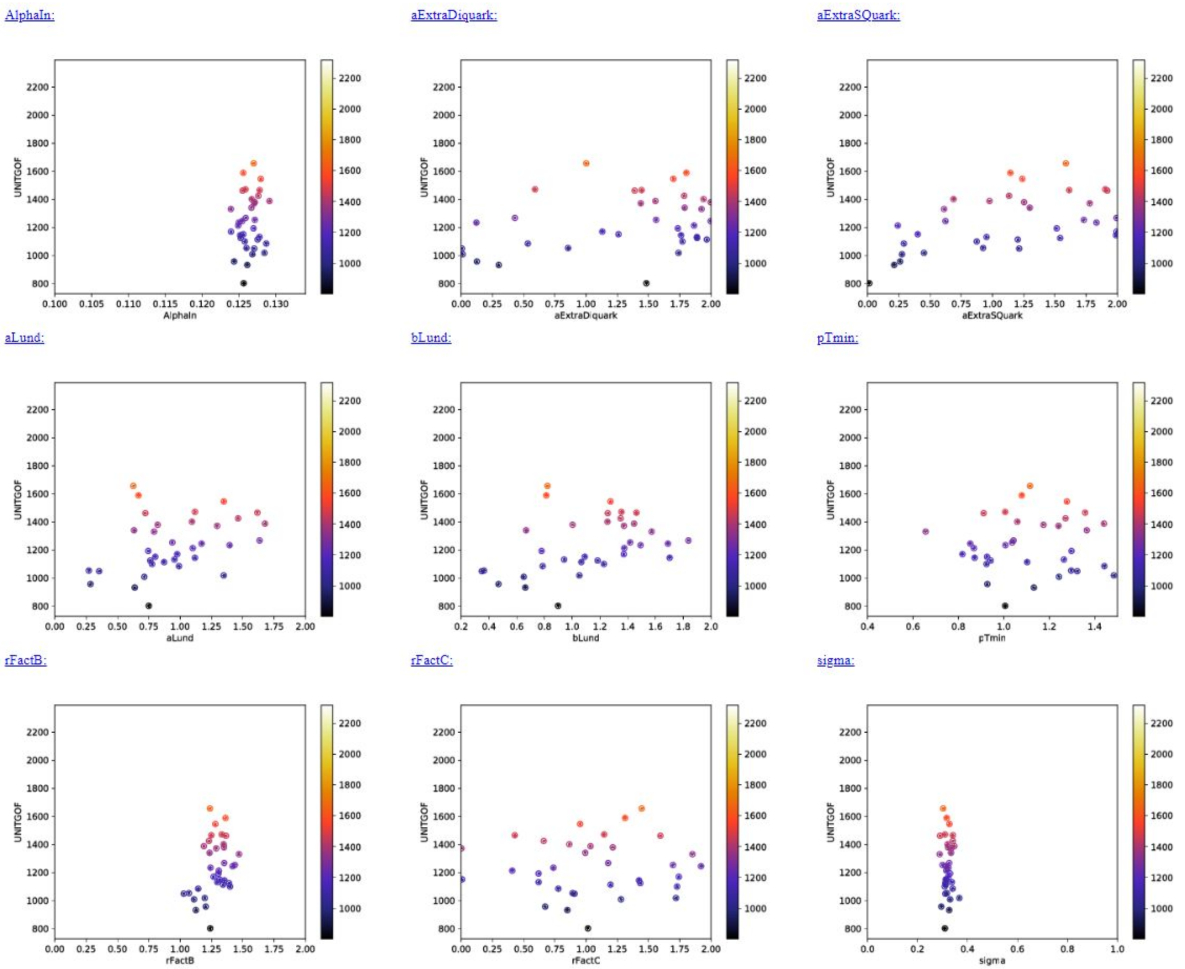
StringZ_aLund	0.678793
StringZ_bLund	0.406674
StringZ_sigma	0.343670
StringZ_aExtraSQuark	0.446032
StringZ_bExtraDiquark	0.037296
StringZ_rFactC	1.997171
StringZ_rFactB	1.505399

Herwig7 parameters:

/Herwig/Shower/AlphaQCD:AlphaIn	0.116677
/Herwig/Shower/NLOAlphaS:input_alpha_s	0.116677
/Herwig/Shower/PTCutOff:pTmin	1.259054

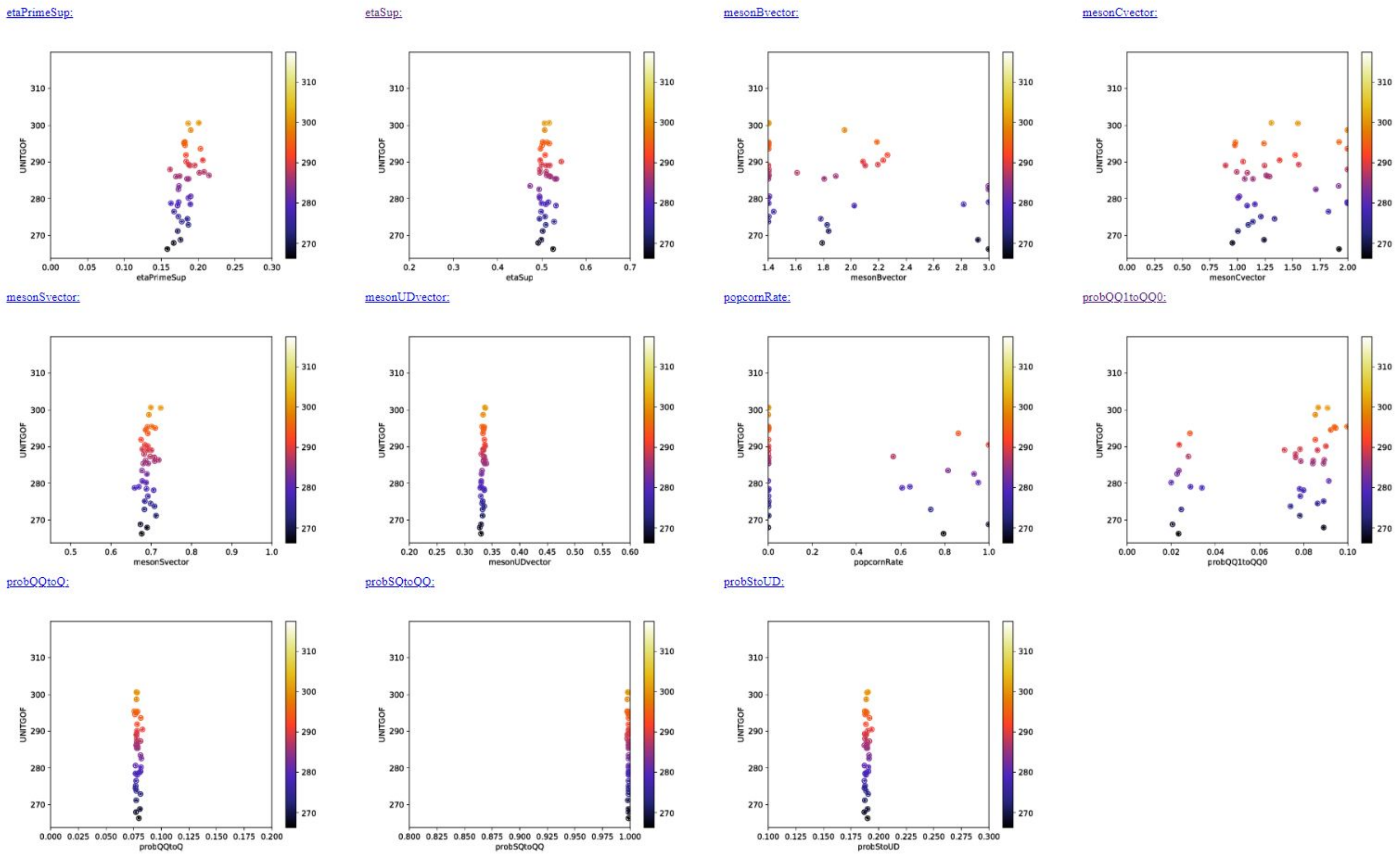
Note. Flavour related Parameters not tuned yet for new MAP tune

Scatter plots (Fragmentation parameters)



- Parameters which are constrained in a narrow range are fixed and the tune is run again until maximum number of parameters are fixed.
- This reduces the number of parameters to be tuned after each step.

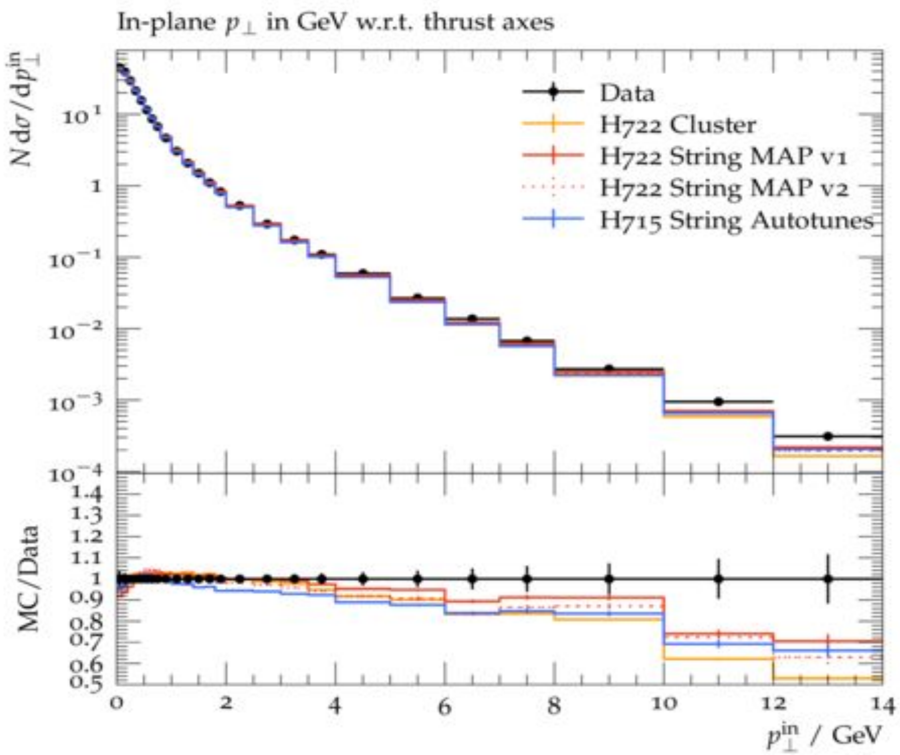
Scatter plots (Flavour Parameters)

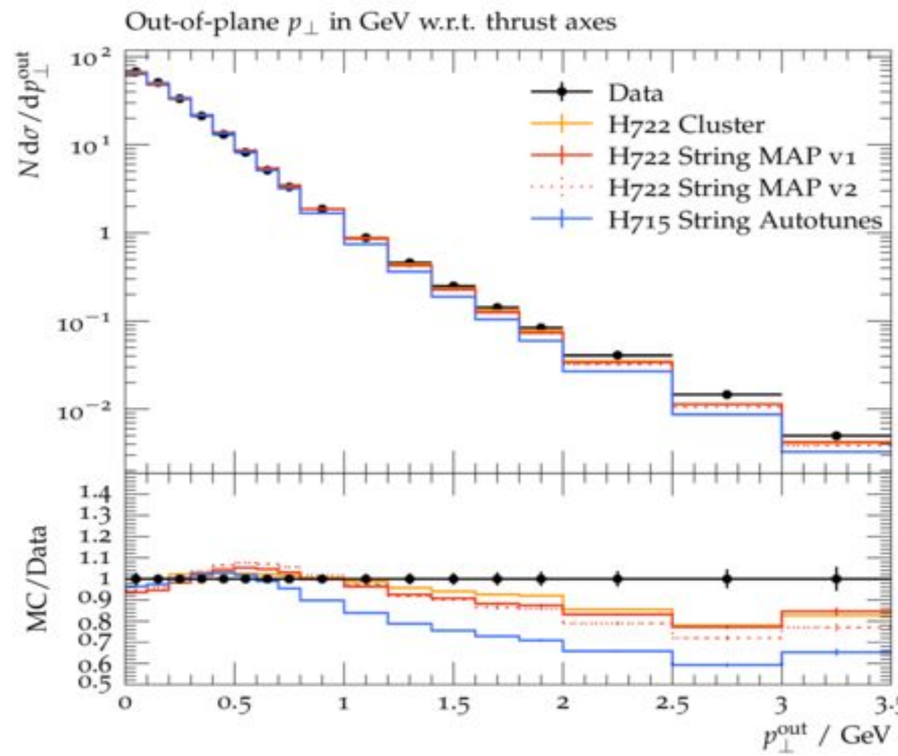


- Many of the flavour parameters are strongly constrained which are fixed and tuned.
- The probQQ1toQQ0 parameter shows interesting constraints near two values, but converges to the lower value for MAP tune v1 and the higher value for MAP tune v2 when other parameters are fixed.

Event Shape Observables (old MAP tunes for Herwig 7.2.2)

- Plots from the analysis DELPHI_1996_S3430090

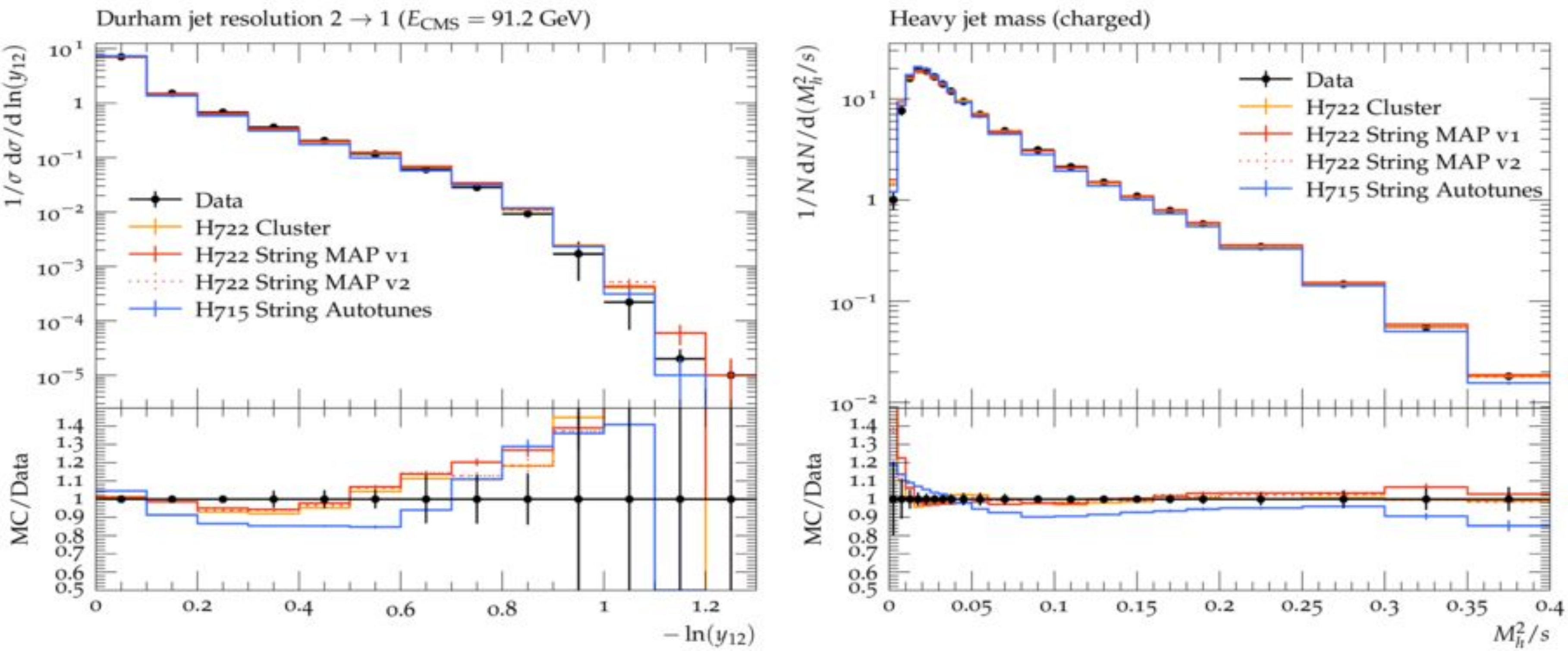




- Both these distributions were used in the tune.
- MAP tune shows small improvement towards the tail of these distributions but is significantly better than AutoTunes tune in the Out-of-plane pT distribution.

Jet Observables (old MAP tunes for Herwig 7.2.2)

- Plots from the analysis ALEPH_2004_S5765862 (left) and ALEPH_1996_S3486095 (right)

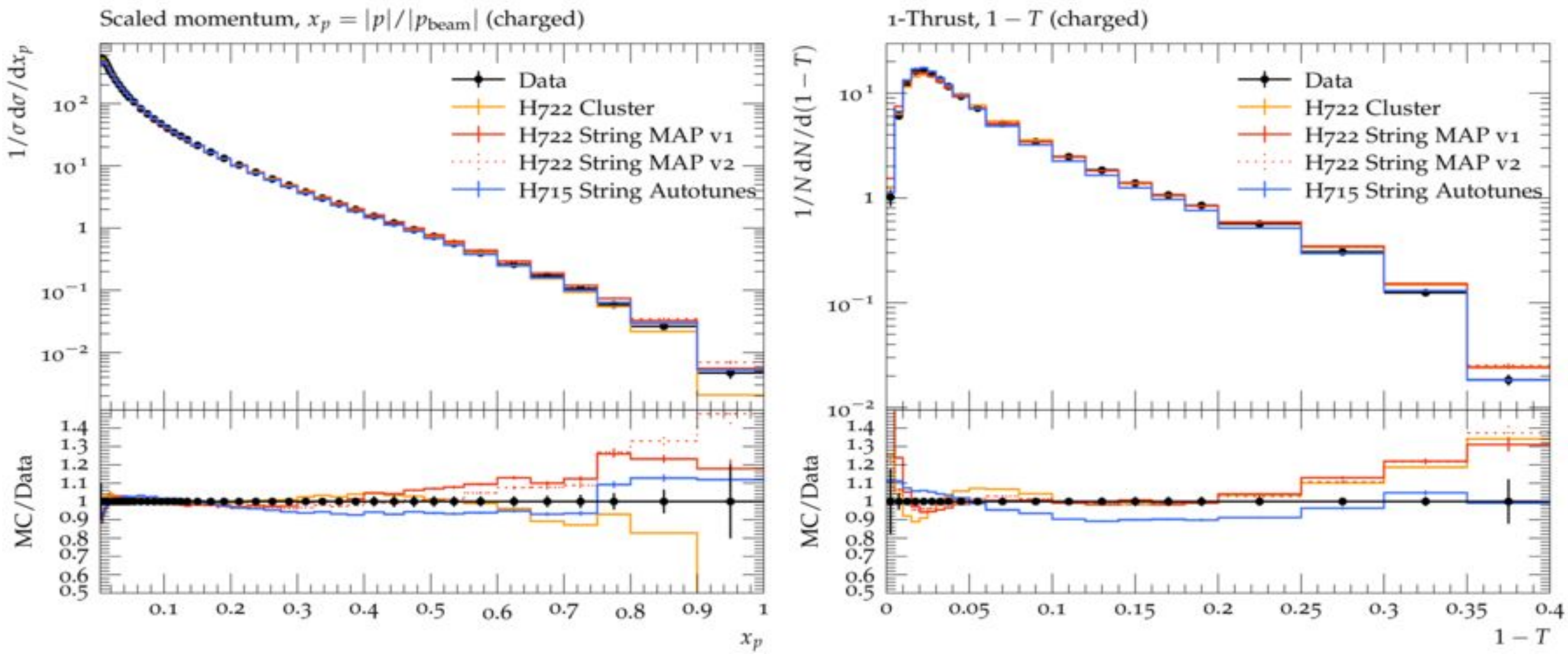


- Both these distributions were **not** used in the tune.

- MAP tune still does better than AutoTunes tune in these distributions and does similar to the default tune - shows robustness of our tune.

Event Shapes (not used in tuning but doing well for Herwig 7.2.2 tune)

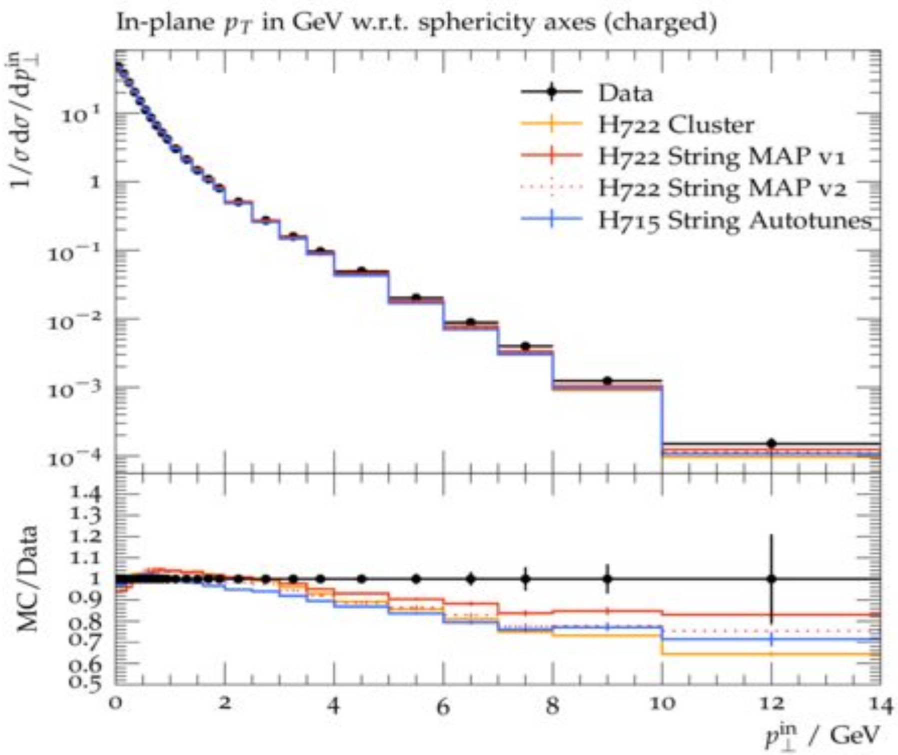
- Plots from the analysis ALEPH_1996_S3486095

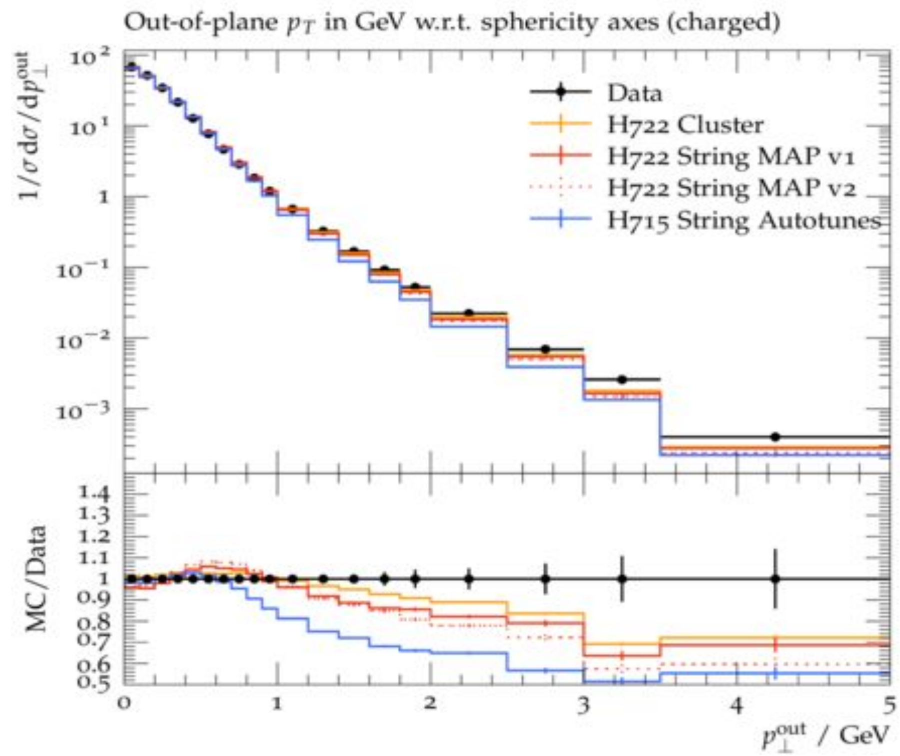


- Both these distributions were **not** used in tune.
- MAP tune does relatively well even though these distributions are no weighted in the tune
- For x_p distribution, MAP tune does better than the default but the AutoTunes is better near the tail.

Event Shapes (not used in tuning but doing well for Herwig 7.2.2 tune)

- Plots from the analysis ALEPH_1996_S3486095



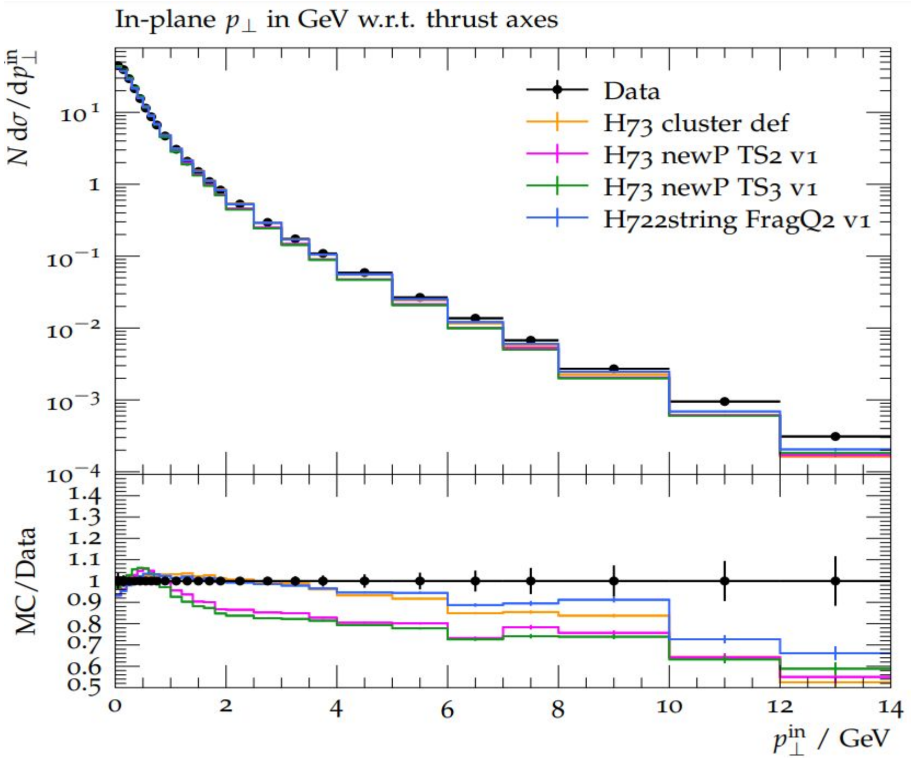


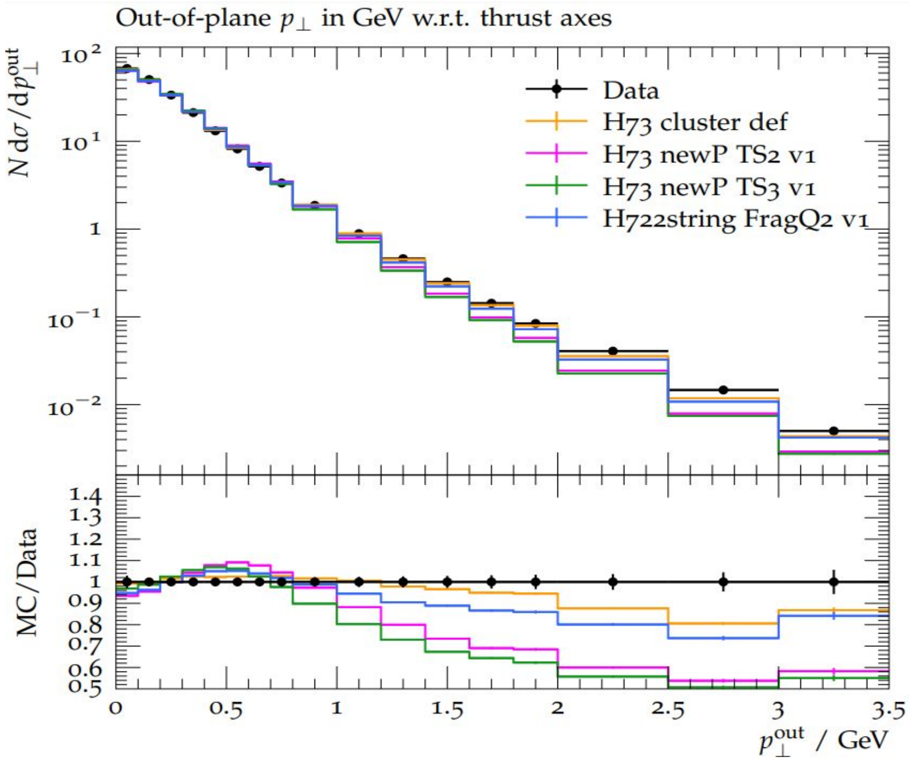
- Both these distributions were **not** used in the tune.

- MAP tune shows small improvement towards the tail of these distributions (similar to distributions from DELPHI experiment in slide 9) even though these are not weighted in the tune.

Event Shape Observables (new MAP tunes for Herwig 7.3)

- Plots from the analysis DELPHI_1996_S3430090

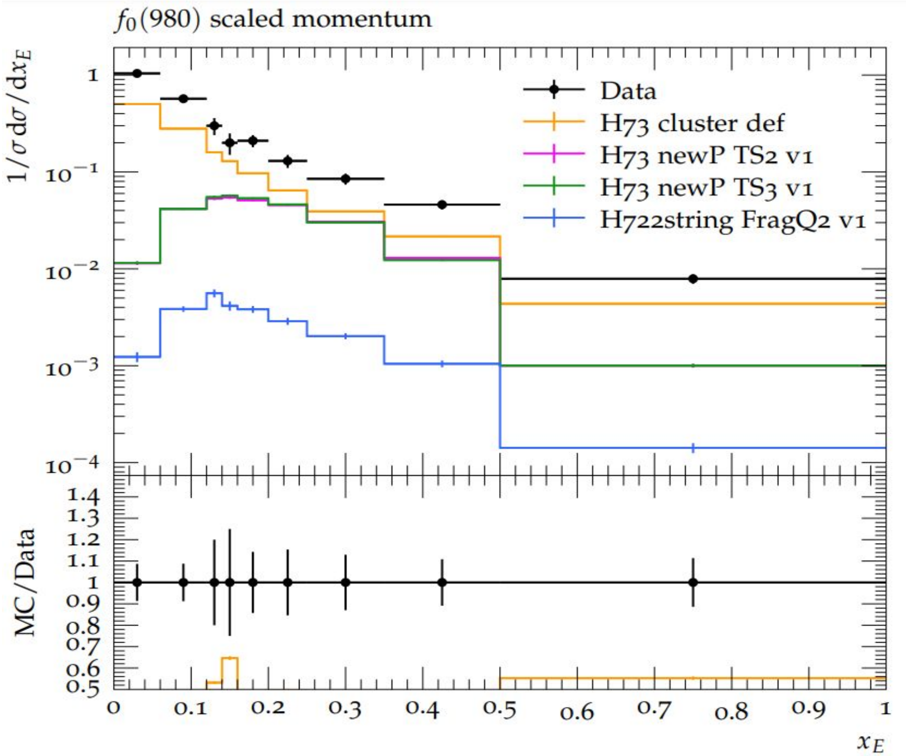


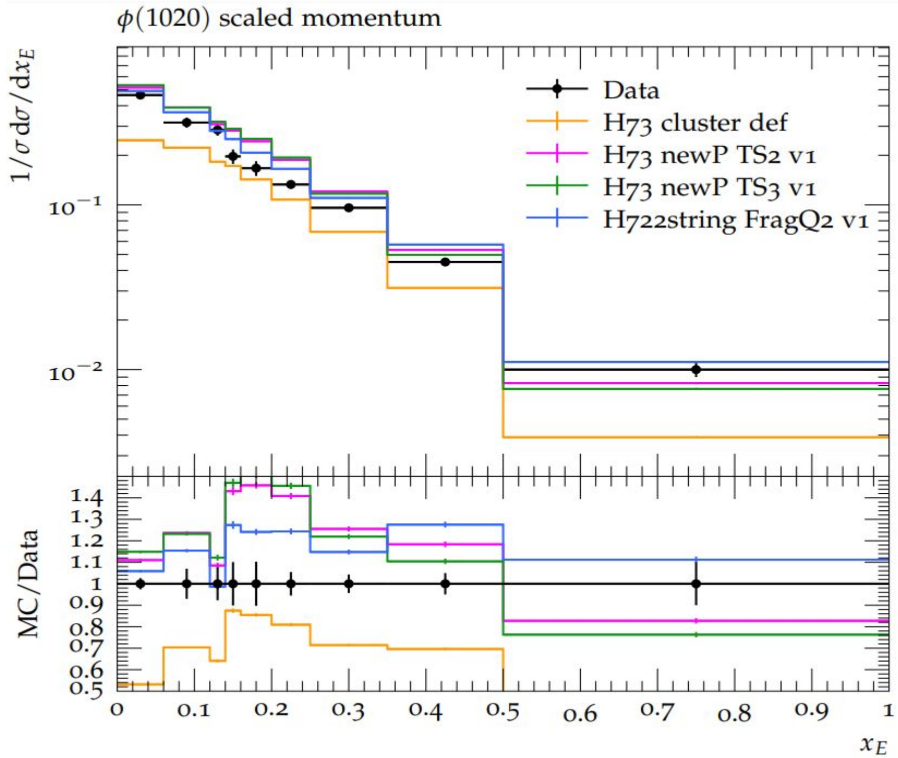


- These distributions are worse for most parts compared to both the previous MAP tune and the default cluster tune.

Flavour sensitive Observables (new MAP tunes for Herwig 7.3)

- Plots from the analysis OPAL_1998_S3702294





- Flavour sensitive observables are actually better modelled by the new MAP tune compared to the old tune. In some regions (right) the new MAP tune even does better than the default cluster.
- These distributions were **not** used in tune weights. Interesting to check if including them improves modelling or need for better models?