What is Tuning?

Theory

Experiment

Adjust this to agree with this
What is Tuning?

Adjust this to agree with this

→ Science
In Practice

“Virtual Colliders” = Simulation Codes

Particle Physics Models, Simplifications, Algorithms, ...

→ Simulated Particle Collisions

Real Universe → Experiments & Data

Particle Accelerators, Detectors, Statistical Analyses, Calibrations

→ Published Measurements

Events

Histograms
**Data Preservation:** [HEPDATA]
Online database of experimental results
Please make sure published results make it there

**Analysis Preservation:** [RIVET]
Large library of encoded analyses + data comparisons
Main analysis & constraint package for event generators
All your analysis are belong to RIVET

**Updated validation plots:** [MCPLOTS.CERN.CH]
Online plots made from Rivet analyses
Want to help? Connect to Test4Theory (LHC@home 2.0)

**Reproducible tuning:** [PROFESSOR]
Automated tuning (& more)
The LHC@home 2.0 project Test4Theory allows users to participate in running simulations of high-energy particle physics using their home computers.

The results are submitted to a database which is used as a common resource by both experimental and theoretical scientists working on the Large Hadron Collider at CERN.
Explicit tables of data & MC points
Run cards for each generator
Link to experimental reference paper
Steering file for plotting program
(Will also add link to RIVET analysis)
**Manual Tunes**

Tuning done by hand/eye (few parameters and observables at a time)
Common sense (and experience) → subjective judgement of importance of each observable, and tails vs averages
Theoretically motivated uncertainty variations can be included
Current Methods

Manual Tunes

Tuning done by hand/eye (few parameters and observables at a time)
Common sense (and experience) → subjective judgement of importance of each observable, and tails vs averages
Theoretically motivated uncertainty variations can be included

Automated Tunes (Professor, Profit?)

Sense and experience encoded as elaborate sets of weights + “sensible” parameter ranges → faster & “easier” than manual

Does not relieve you from critical judgement

Are/were ranges, weights, and observables included indeed “sensible”? Are tuning interpolations looking stable and convergent? Are there strong correlations / flat directions? Do some parameters end up at the end of their physical ranges?

“Data-driven” uncertainty variations do not reflect intrinsic theory uncertainties (cf PDF “errors”!) → Systematic mis-tuning?
Not only central tunes

Your experimental (and other user-end) colleagues are relying on you for **serious** uncertainty estimates.

Modeling uncertainties are intrinsically non-universal. Including data uncertainties only → **lower bound** (cf PDFs).

A **serious** uncertainty estimate includes some modeling variation (irrespectively of, and in addition to, what data allows).

*) This is intended as a cultural reference, not a religious one.
Quo Vadis?

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Not only global tunes

Your theoretical (MC author) colleagues are relying on you for stringent tests of the underlying physics models, not just ‘best fits’ (which may obscure “tensions”).

Tuning can be done to several complementary data sets.

All give same parameters $\rightarrow$ universality ok $\rightarrow$ model ok
Some give different parameters $\rightarrow$ universality is breaking down $\rightarrow$ can point to where $\rightarrow$ feedback to authors $\rightarrow$ improved models.

*) This is intended as a cultural reference, not a religious one.
Example: $\alpha_s$

Theory: default is factor 2 $\mu_R$ variation

→ lots/less of FSR! Use this to define a theory uncertainty associated with $\alpha_s$ (e.g., done in Perugia tunes)

Data-driven (expect smaller?): define variations by $\sim 2$-sigma consistent with 3-jet observables

Use as cross check on theory uncertainty. How much variation does data actually allow (for the included observables)?

Decide (if you dare) to reduce nominal factor 2, keeping in mind that a larger theory uncertainty is still needed to evaluate uncertainty on extrapolating to other observables/processes.

Bonus! Can re-use the data-driven ones ...

Retune string parameters, using the data-driven large/small $\alpha_s$

→ hadronization variations for use with central $\alpha_s$

→ can add more systematic “mistunings” to explore uncertainty envelope better
Global Tunes vs Model Tests

Do independent tunes for several complementary “windows” on same physics

Similar observables at different CM energies
Similar observables, ee vs pp
Same collider, different observable ranges

E.g., for different pTjet, different Q^2, different cuts, ...

Example: 3-parameter tuning at 630, 900, 1800, and 7000 GeV

pT0 for MPI
Impact-parameter profile
CR Strength

Schulz, Skands, arXiv:1103.3649
What is Tuning?

**FSR pQCD Parameters**

- \( \alpha_s(m_Z) \)
- \( \alpha_s \) Running
- Matching
- Subleading Logs

The value of the strong coupling at the Z pole

Governed overall amount of radiation

Renormalization Scheme and Scale for \( \alpha_s \)

1- vs 2-loop running, MSbar / CMW scheme, \( \mu_R \sim p_T^2 \)
What is Tuning?

**FSR pQCD Parameters**

- $\alpha_s(m_Z)$: The value of the strong coupling at the Z pole. Governs overall amount of radiation.
- $\alpha_s$ Running: Renormalization Scheme and Scale for $\alpha_s$.
  - 1- vs 2-loop running, MSbar / CMW scheme, $\mu_R \sim p_T^2$
- Matching: Additional Matrix Elements included?
  - At tree level / one-loop level? Using what matching scheme?
- Subleading Logs
What is Tuning?

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1- vs 2-loop running, MSbar / CMW scheme, \( \mu_R \sim p_T^2 \)

**Additional Matrix Elements included?**

At tree level / one-loop level? Using what matching scheme?

**Ordering variable, coherence treatment, effective**

1→3 (or 2→4), recoil strategy, ...

**Branching Kinematics (z definitions, local vs global momentum conservation), hard parton starting scales / phase-space cutoffs, masses, non-singular terms, ...**
PYTHIA 8 (hadronization on) vs LEP: Thrust

\[ T = \max \left( \sum_{i} \frac{|\vec{p}_i \cdot \vec{n}|}{\sum_{i} |\vec{p}_i|} \right) \]

1 - T \rightarrow 0

Note: Value of Strong coupling is

\[ \alpha_s(M_Z) = 0.12 \]
three-jet to two-jet final states in the Durham jet algorithm
and total jet broadenings in great detail: the thrust
other variables were constructed such that they require at l
require three particles (and are thus closely related to thr
These variables can be categorised into two classes, accord
(b) Heavy hemisphere mass,
(a) Thrust,

Among the event shapes requiring three-particle final state
In the two-particle limit
The thrust variable for a hadronic final state in
The larger of the two hemisphere invariant masses yields the
thrust axis.
The associated light hemisphere mass,

At lowest order, the heavy jet mass and the (1
particles. The unit vector
\( \vec{P} \times \vec{n} \)
denotes the three-momentum of particle
\( E \) is the total energy visible in the event. In the original defin

\[ T = \max \left( \frac{\sum_i |p_i \cdot \vec{n}|}{\sum_i |p_i|} \right) \]

\[ 1 - T \to 0 \]

Note: Value of Strong coupling is
\( \alpha_s(M_Z) = 0.14 \)
Wait ... is this Crazy?

Best tuning result (and default in PYTHIA)

Obtained with $\alpha_s(M_Z) \approx 0.14$

≠ World Average = 0.1176 ± 0.0020
Best tuning result (and default in PYTHIA)

Obtained with $\alpha_s(M_Z) \approx 0.14$

$\neq$ World Average $= 0.1176 \pm 0.0020$

Value of $\alpha_s$ depends on the order and scheme

MC $\approx$ Leading Order + LL resummation
Other LO extractions of $\alpha_s \approx 0.13 - 0.14$
Effective scheme interpreted as “CMW” $\rightarrow 0.13$;
2-loop running $\rightarrow 0.127$; NLO $\rightarrow 0.12$?
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Not so crazy

Tune/measure even pQCD parameters with the actual generator.
Sanity check = consistency with other determinations at a
similar formal order, within the uncertainty at that order
(including a CMW-like scheme redefinition to go to ‘MC scheme’)
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Tune/measure even pQCD parameters with the actual generator.
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Improve → Matching at LO and NLO
Sneak Preview:

VINCIA: Multijet NLO Corrections

First LEP tune with NLO 3-jet corrections

LO tune: $\alpha_s(M_Z) = 0.139$ (1-loop running, MSbar)

NLO tune: $\alpha_s(M_Z) = 0.122$ (2-loop running, CMW)

Data from Phys.Rept. 399 (2004) 71
**Sneak Preview:**

**VINCIA: Multijet NLO Corrections**

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---

The three main event-shape variables that were used to determine the value of $\tau = (M_Z^{-1})$ are shown in figure 15, with upper panes showing the distributions themselves (data and MC) and lower panes showing the ratios of MC/data, with one- and two-sigma uncertainties on the data shown by darker (green) and lighter (yellow) shaded bands, respectively. The Thrust (left) and $C$-parameter (middle) distributions both have perturbative expansions that start at $O(\tau)$ and hence they are both explicitly sensitive to the corrections considered in this paper. The expansion of the $D$ parameter (right) begins at $O(\tau^2)$. It is sensitive to the NLO 3-jet corrections mainly via unitarity, since all 4-jet events begin their lives as 3-jet events in our framework. It also represents an important cross-check on the value extracted from the other two variables.

For a pedagogical description of the variables, see [63]. Pencil-like 2-jet configurations are to the left (near zero) for all three observables. This region is particularly sensitive to non-perturbative hadronization corrections. More spherical events, with several hard perturbative emissions, are towards the right (near $0.5$ for Thrust and $1.0$ for $C$ and $D$). The maximal $\tau = 1$ for a 3-particle configuration is $\tau = 1/3$ (corresponding to the Mercedes configuration), beyond which only 4-particle (and higher) states can contribute. This causes a noticeable change in slope in the distribution at that point, see the left pane of figure 15. The same thing happens for the $C$ parameter at $C = 3/4$, in the middle pane of figure 15. The $D$ parameter is sensitive to the smallest of the eigenvalues of the sphericity tensor, and is therefore zero for any purely planar event, causing it to be sensitive only to 4- and higher-particle configurations over its entire range.

Both the new NLO tune (solid blue line with filled-dot symbols) and the old LO one (dashed magenta line with open-triangle symbols) reproduce all three event shapes very well. With the NLO corrections switched off (solid red line with open-circle symbols), the new tune produces a somewhat too soft spectrum, consistent with its low value of $\alpha_s(M_Z)$ not being too low.

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**HADRON COLLISIONS**

**LO tune:** $\alpha_s(M_Z) = 0.139$ (1-loop running, MSbar)

**NLO tune:** $\alpha_s(M_Z) = 0.122$ (2-loop running, CMW)

---

**Vincia 1.030 + MadGraph 4.426 + Pythia 8.175**

Data from Phys.Rept. 399 (2004) 71

Hartgring, Laenen, Skands, arXiv:1303.4974
Classic example:
Thrust distribution at LEP

Herwig++ (unmatched) generates too many hard 4-jet events
Can attempt to tune away (if possible)
    Do not sacrifice agreement in logarithmic region for arm-twisting tuning in hard region
Or choose to not use problematic region for Herwig++
    Problematic for universal approach to tuning?
In any case, must be aware, and must make and report a decision
Main String Parameters

Longitudinal FF = f(z)

Lund Symmetric Fragmentation Function
The a and b parameters

Scale of string breaking process
IR cutoff and <p_T> in string breaks

Meson Multiplets

Baryon Multiplets
String Tuning

Main String Parameters

Longitudinal FF = f(z)

Lund Symmetric Fragmentation Function
  The a and b parameters

Scale of string breaking process
  IR cutoff and <p_T> in string breaks

Mesons
  Strangeness suppression, Vector/Pseudoscalar, η, η', ...

P. Skands
Lund Symmetric Fragmentation Function

The a and b parameters

Scale of string breaking process

IR cutoff and \( \langle p_T \rangle \) in string breaks

Mesons

Strangeness suppression, Vector/Pseudoscalar, \( \eta, \eta', \ldots \)

Baryons

Diquarks, Decuplet vs Octet, popcorn, junctions, \ldots ?
String Tuning

Main String Parameters

- Longitudinal FF = f(z)
- Lund Symmetric Fragmentation Function
  - The a and b parameters
- Scale of string breaking process
  - IR cutoff and $<p_T>$ in string breaks
- Mesons
  - Strangeness suppression, Vector/Pseudoscalar, $\eta, \eta', \ldots$
- Baryons
  - Diquarks, Decuplet vs Octet, popcorn, junctions, ...?

(or equivalent parameters for Cluster Model)
**Causality → Left-Right Symmetry**

→ Constrains form of fragmentation function!

→ Lund Symmetric Fragmentation Function

\[
  f(z) \propto \frac{1}{z} (1 - z)^a \exp \left( -\frac{b(m_h^2 + p_{\perp h}^2)}{z} \right)
\]

**Note:** In principle, \(a\) can be flavour-dependent. In practice, we only distinguish between baryons and mesons.
Note: use infrared-unsafe observables - sensitive to hadronization (example)

Multiplicity Distribution of Charged Particles (tracks) at LEP ($Z \rightarrow \text{hadrons}$)

Momentum Distribution of Charged Particles (tracks) at LEP ($Z \rightarrow \text{hadrons}$)

$\langle N_{\text{ch}}(M_Z) \rangle \sim 21$

$\xi_\rho = \ln(x_\rho) = \ln(2|p|/E_{\text{CM}})$
PYTHIA 8 (hadronization off) vs LEP: Thrust

\[ T = \max_{\vec{n}} \left( \frac{\sum_i |\vec{p_i} \cdot \vec{n}|}{\sum_i |\vec{p_i}|} \right) \]

For \( T < 0.05 \), Major < 0.15, Minor < 0.2, and for all values of Oblateness

**Significant Effects (>10%)**
three-jet to two-jet final states in the Durham jet algorithm and total jet broadenings in great detail: the thrust four-jet final states). Other variables were constructed such that they require at least three particles (and are thus closely related to the final-state particles required for them to be non-vanishing). These variables can be categorized into two classes, according to the hemisphere that is dominated by a larger number of particles. Among the event shapes requiring three-particle final state is an example of a four-jet observable and vanishes in the thrust axis. In the two-particle limit, the larger of the two hemisphere invariant masses yields the thrust axis. The associated light hemisphere mass, \( \rho \), is an example of a four-jet observable and vanishes in the thrust axis. The unit vector \( \vec{n} \) is varied to find the thrust direction. For a two-particle event, \( 0 \leq T \leq 1 \), while for a three-particle event, \( 0 \leq T < 1 \). In the two-particle limit \( T \to 1 \), \( 1 - T \to 0 \). Significant Effects. For \( T < 0.05, \) Major < 0.15, Minor < 0.2, and for all values of Oblateness + cross checks: different eCM energies (HAD and FSR scale differently).
Identified Particles

\( S_1/S_0, B/M, B_{3/2}/B_{1/2}, \) strange/unstrange, Heavy

Compare with what you see at LHC
Correlate with what you see at LHC
Can variations within uncertainties explain differences? Or not?
Initial-State Radiation

**Main ISR Parameters**

Value and running of the strong coupling
Governs overall amount of radiation (cf FSR)

Starting scale & Initial-Final interference
Relation between $Q_{PS}$ and $Q_F$ (vetoed showers? cf matching)
I-F colour-flow interference effects (cf ttbar asym) & interleaving
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Governs overall amount of radiation (cf FSR)

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Additional Matrix Elements included?
At tree level / one-loop level? What matching scheme?
**Initial-State Radiation**

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  - I-F colour-flow interference effects (cf ttbar asym) & interleaving

- **Additional Matrix Elements included?**
  - At tree level / one-loop level? What matching scheme?

- **“Primordial kT”**
  - A small additional amount of “unresolved” kT
  - Fermi motion + unresolved ISR emissions + low-x effects?
Min-Bias & Underlying Event

Main UE/MB Parameters

- Number of MPI
- Pedestal Rise
- Strings per Interaction
- Beam Remnant
Infrared Regularization scale for the QCD $2 \rightarrow 2$ (Rutherford) scattering used for multiple parton interactions (often called $p_{T0}$) → overall amount of energy in UE
Min-Bias & Underlying Event

Main UE/MB Parameters

Number of MPI

**Infrared Regularization scale** for the QCD 2→2 (Rutherford) scattering used for multiple parton interactions (often called $p_{T0}$) $\rightarrow$ overall amount of energy in UE

Pedestal Rise

**Proton transverse mass distribution** $\rightarrow$ difference between central (active) vs peripheral (less active) collisions. Affects fluctuations & UE/MB ratios.

Strings per Interaction

Beam Remnant
Min-Bias & Underlying Event

Main UE/MB Parameters

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**Strings per Interaction**

**Color correlations** between multiple-parton-interaction systems $\rightarrow$ shorter or longer strings $\rightarrow$ less or more hadrons per interaction $\rightarrow$ can allow more or less MPI

**Beam Remnant**
## Min-Bias & Underlying Event

### Main UE/MB Parameters

<table>
<thead>
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</tr>
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<tbody>
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</table>
Why $dN/d\eta$ is useless (by itself)

Can get $<N>$ right with completely wrong models. Need RMS at least.
Truth is in the eye of the beholder

UE - LHC from 900 to 7000 GeV - ATLAS

"Transverse" Charged Particle Density: $dN/d\eta d\phi$

Track Density (TRANS)

"Transverse" Charged PTsum Density: $dPT/d\eta d\phi$

Sum(pT) Density (TRANS)
Truth is in the eye of the beholder

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Large Non-factorizable Corrections
Prediction off by $\approx 10\%$

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- Large Non-factorizable Corrections
- Prediction off by $< 10\%$
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UE - LHC from 900 to 7000 GeV - ATLAS

"Transverse" Charged Particle Density: $\frac{dN}{d\eta d\phi}$

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- Not Infrared Safe
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"Transverse" Charged PTsum Density: $\frac{dP_T}{d\eta d\phi}$

**Sum(pT) Density (TRANS)**
- (more) Infrared Safe
- Large Non-factorizable Corrections
- Prediction off by $< 10\%$

R. Field: “See, I told you!”
Truth is in the eye of the beholder

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R. Field: “See, I told you!”
Y. Gehrstein: “they have to fudge it again”
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Two beholders:
R. Field: “See, I told you!”
Y. Gehrstein: “they have to fudge it again”
Color Connections

Better theory models needed

$N_C \to \infty$

Rapidity

Multiplicity $\propto N_{\text{MPI}}$
Color Reconnections?

Do the systems really form and hadronize independently?

Better theory models needed

E.g.,
...

Multiplicity $\propto N_{\text{MPI}}$

Coherence

Rapidity
Do the systems really form and hadronize independently?

E.g.,
...

Better theory models needed

Multiplicity $\propto N_{\text{MPI}}$
Notes on Diffraction

1. Fragmentation in diffraction
   Low mass diffraction modeled as fragmenting string (parameters from LEP)
   
   But LEP starts with FSR \( \rightarrow Q_{\text{had}} \rightarrow \text{string-frag} = f(z,Q_{\text{had}}) \)

   In diffraction, no equivalent definition of \( Q_{\text{had}} \)
   
   Do LEP tunes work for diffraction? At all masses? Depends on \( Q_{\text{had}} \)? Make direct (in situ) checks!

   Observables:
   
   Nch and x spectra, event shapes (e.g., transverse Thrust), ID-paricle ratios (Baryons, s, c, b)

   How high masses can be reached with decent rates? (100k events, 10k, 1k?)
   
   (and what kind of luminosity conditions are required / prohibitive?)

   Outcome: more reliable fragmentation models, tunes for diffraction

2. MPI in diffraction.

   Expected to increase multiplicity in diffractive (jet) events
   
   Pythia 8 incorporates a model, so far largely unconstrained. Main parameter = \( \sigma_{pp} \)

   UE style analyses in diffractive jets (measuring transverse PTsum and Nch, average and rms, wrt diffractive jet pt, etc).

3. Colour reconnections.

   How to separate "genuine" diffraction from accidental gaps created by CR?
N. Bohr:
Only physical observables are quantum mechanically meaningful (it does not make sense to ask which slit the photon went through)
QFT generalization: it does not make sense to ask which quantum path led to the given event

Tevatron example:
Measurement of the pT of the “Z boson” (classified according to “truth” in an MC model.)
Really, observed dimuon system (including some collinear photons)

CMS example:
Measurement of Non-Single Diffractive (NSD) events (in oldest measurements, classified according to MC “truth”)
Really, events with large rapidity gap and one surviving proton

Note: please tell us which of the existing min-bias / NSD CMS analyses in Rivet use the old (unphysical) definition (to be compared with MC with SD switched off) and which use the new observable definition (to be compared to all-inelastic MC, since they include an explicit trigger/cut to single out NSD) - currently we don’t know, so don’t dare use.
Summary

Not only central tunes

* Not only central tunes

Your experimental (and other user-end) colleagues are relying on you for **serious** uncertainty estimates

Must includes some modeling variation

Not only global tunes

* Not only global tunes

Your theoretical (MC author) colleagues are relying on you for stringent tests of the **underlying physics** models, not just ‘best fits’ (which may obscure “tensions”)

Tuning & Matching → Matching & Tuning

* Tuning & Matching → Matching & Tuning

Step 1 (now): tune first, match later. Study change in $\chi^2$ on tuning distributions after matching. Bad? Or not bad?

Step 2: match first, tune later. (Requires tuning a matched generator, so need fast matching strategies.)
MCnet projects:

- PYTHIA (+ VINCIA)
- HERWIG
- SHERPA
- MadGraph
- Ariadne (+ DIPSY)
- Cedar (Rivet/Professor)

Activities include

- summer schools (2014: Manchester?)
- short-term studentships
- graduate students
- postdocs
- meetings (open/closed)

3-6 month fully funded studentships for current PhD students at one of the MCnet nodes. An excellent opportunity to really understand and improve the Monte Carlos you use!

Application rounds every 3 months.

for details go to: www.montecarlonet.org
Come to Australia

Establishing a new group in Melbourne
Working on PYTHIA & VINCIA
NLO Event Generators
Precision LHC phenomenology & soft physics
Support LHC experiments, astro-particle community, and future accelerators
Outreach and Citizen Science

Oct 2014
Monash University
Melbourne, Australia