# Monte Carlo tuning at the LHC

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Hadron-Hadron & Cosmic-Ray Interactions at multi-TeV Energies
November 30, 2010
Trento

[1]on behalf of the Professor and the Rivet collaborations

# Introduction

- LHC is a QCD-machine in a new energy regime
- QCD well known where perturbation theory applies
- 'Soft effects' (Underlying event (UE), hadronisation. . . ) need to be modelled
- Use Monte-Carlo generators to do that
- Models often phenomenological ⇒ tuneable parameters (a priori unknown)
- MC predictions used to
  - estimate experimental efficiencies, uncertainties
  - test theories
- ⇒ generator tuning essential to simulate events that look like real data

# Typical tuneables

- **Intrinsic $k_T$:** a dirty little MC secret, important for first 5 GeV of boson $p_\perp$ (peak)
- **(FSR):** assume universality $\rightarrow$ tune to $e^+e^-$ data (eventshapes). Parameters: $\alpha_s$, cutoff, starting scale fudge factors; different shower evolutions $(Q^2, p_\perp, \dots) \rightarrow$ different tunings
- **Hadronisation:** model dependent! String or cluster constants, many parameters, separate heavy quark fragmentation. Tune to $(e^+e^-)$ identified particle spectra
- **(ISR):** similar to FSR, tune to hadron collider data. Inter-jet data e.g. $Z$ $p_\perp$ and dijet angular decorrelation – but jet shapes now considered important. For PYTHIA, fitting jet shapes means more semi-dirty tricks: vary $\alpha_s$ in FSR of ISR particles! (Perugia 2010)
- **Underlying Event (UE):** Tune to hadron collider data, sensitive to PDF choice. Parameters: beam particle matter distribution, cutoff for Multiple Parton Interactions (MPI)

# Tuning through the ages (and at LHC)

- Manual tunes: lots of time and manpower or tuning experience of a life-time
- Brute-force grid-scans: tough in higher dimensions of parameter space
- Genetic algorithm (GAMPI, Sami Kama): burns a LOT of CPU
- systematically:
  - Bin-wise interpolation of MC generator response and $\chi^2$ minimization (DELPHI 1995, Hamacher et al.)
  - $2^{nd}$ order polynomials account for parameter correlations

but:

- Code (`fortran`) not sufficiently flexible
- Restricted to $2^{nd}$ order polynomial for bin-wise interpolation

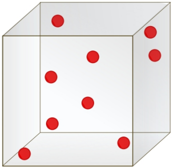
Professor (arXiv:0907.2973, arXiv:0906.0075, arXiv:0902.4403)

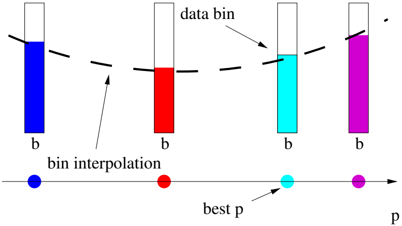
## "PROcedure For EStimating Systematic errORrs"

- Pick up DELPHI idea, much more functionality
- Implemented as a Python package and set of scripts:
- Actively being developed

# Tuning procedure in Professor (1D, 1Bin)

1. Random sampling: $N$ parameter points in $n$-dimensional space
2. Run generator and fill histograms
3. For each bin: use $N$ points to fit interpolation ($2^{nd}$ or $3^{rd}$ order polynomial)
4. Construct overall (now trivial) $\chi^2 \approx \sum_{bins} \frac{(interpolation - data)^2}{error^2}$
5. and Numerically *minimize* `pyMinuit, SciPy`





# Professor news


- Version 1.0.0 just released, version 1.0.1 out soon
- Focus on usability, user friendliness
- Have setup scripts now
- Extensive documentation (SPHINX)
- Command lines unified, simplified
- Can assign weights bin-wise now
- More exploitation of covariance matrices ("Eigentunes")
- Readily available on AFS
  `/afs/cern.ch/sw/lcg/external/MCGenerators/professor/1.0.0`
- Started a YouTube channel for screencasts
  `http://www.youtube.com/user/ProfessorRivet`

# Observables and Weights

- This is what Professor minimises: $\chi^2(\vec{p}) = \sum_{\mathcal{O}} \sum_{b \in \mathcal{O}} w_b \frac{(f^{(b)}(\vec{p}) - \mathcal{R}_b)^2}{\Delta_b^2}$
- Slightly more art than science
- Garbage in, garbage out
- Use weights $w_b$ to:
  - emphasize certain observables
  - emphasize certain bins of an observable
  - switch off single bins (e.g. MinBias region for Jimmy Herwig)

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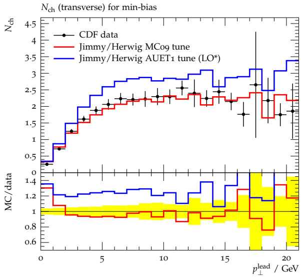
- No MinBias physics in Jimmy Herwig
- Cannot get first 3 bins or so right
- Transition from MinBias to UE type physics
- ⇒ Exclude these bins from Professor minimisation



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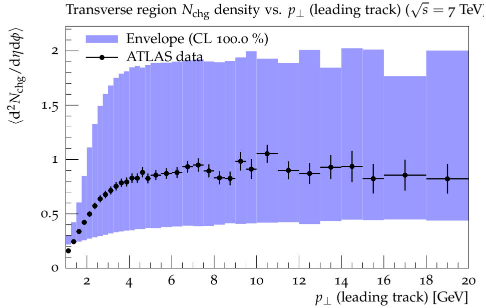

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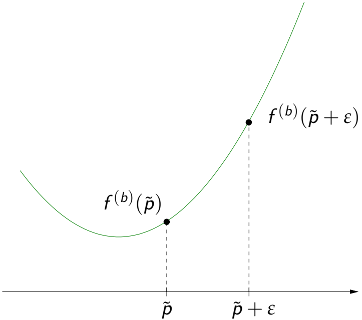

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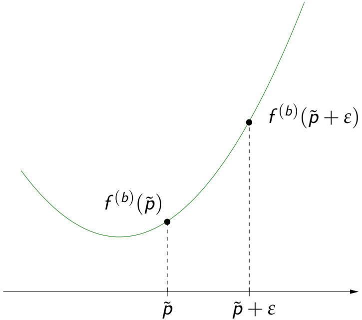


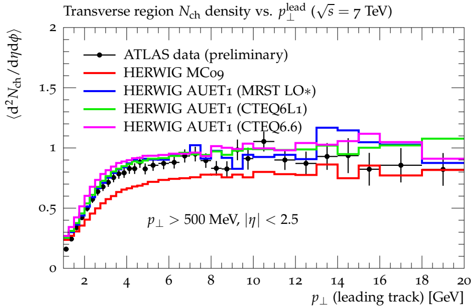

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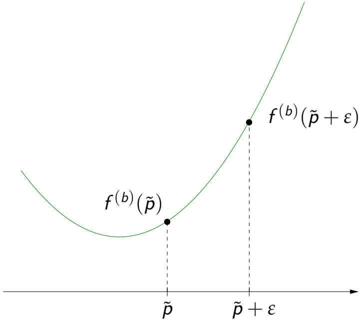
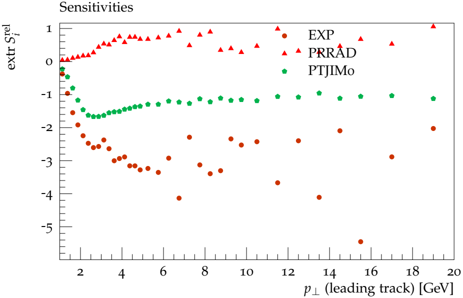
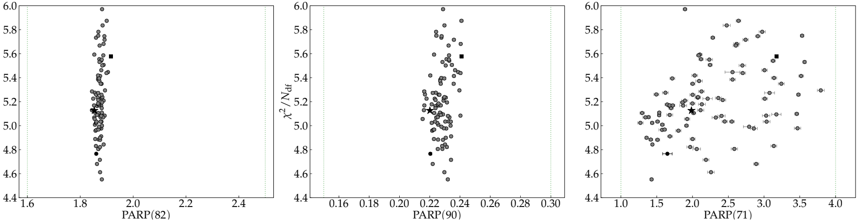


# Some tune param spreads

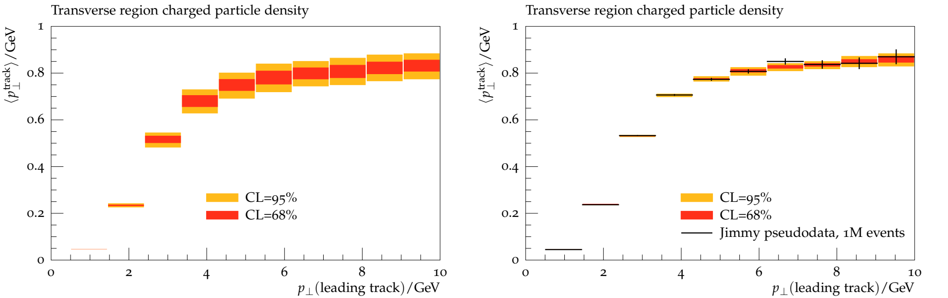
Oversampling required, but if we *really* oversample, then can make many combinations of input MC runs:




- *informal* picture of how well-constrained a parameter is
- We are happy if it looks like a vertical line
- Spread used for tuning-uncertainty estimates

# Statistically-driven tune error bands

## Errors from run-combination sampling

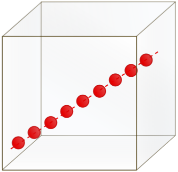


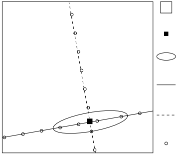

$\Rightarrow$ turned parameter spread into uncertainty belts

Most complete procedure for full systematics in Les Houches proceedings (arXiv:1003.1643). Full treatment requires asymmetric covariance sampling.

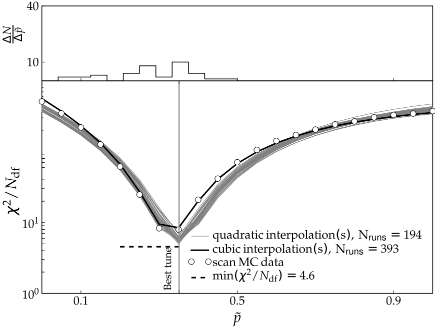
# Checking parameterisation: line-scans

- Sample params from straight hyperline through $\chi^2$ valley





- Calculate and compare $\chi^2$ of parameterisation with "true" MC response



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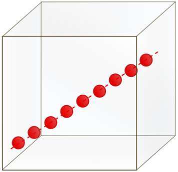

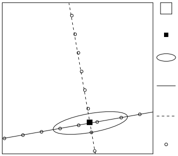

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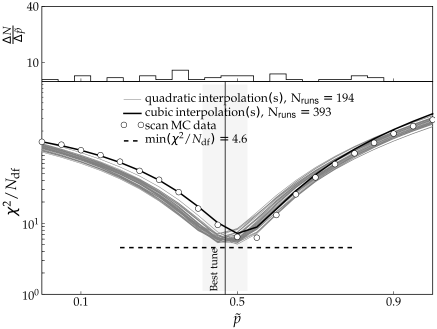


# Interactivity

Key feature of Professor:

1. we are parameterising a very expensive function
2. input to that parameterisation can be trivially parallelised

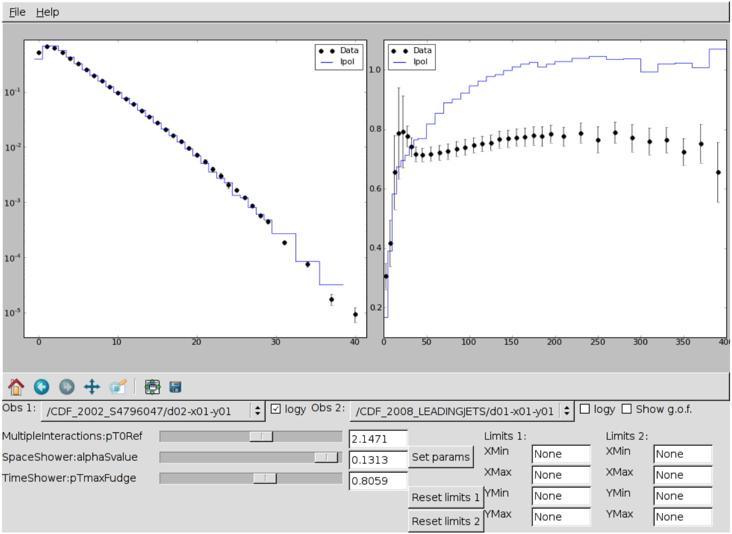
- Can parallelise parameterisation (for many run combinations)
- Optimisation, too

Parameterisation produces a fast, analytic "pseudo-generator"

- $\Rightarrow$ Can get a good approximation of what a generator will do when run for many hours/days with particular params, in $< 1$ second!

Why not make an interactive MC simulator?

# PROF-I


File Help
Data
Ipol
Obs 1: /CDF_2002_S4796047/d02-x01-y01
logy
Obs 2: /CDF_2008_LEADINGJETS/d01-x01-y01
logy
Show g.o.f.
MultipleInteractions:pT0Ref
2.1471
SpaceShower:alphaSvalue
0.1313
TimeShower:pTmaxFudge
0.8059
Set params
Reset limits 1
Reset limits 2
Limits 1:
XMin None
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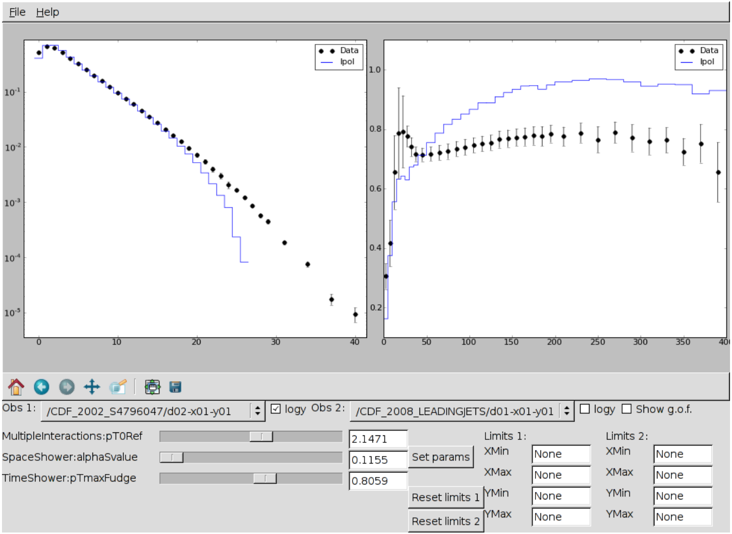
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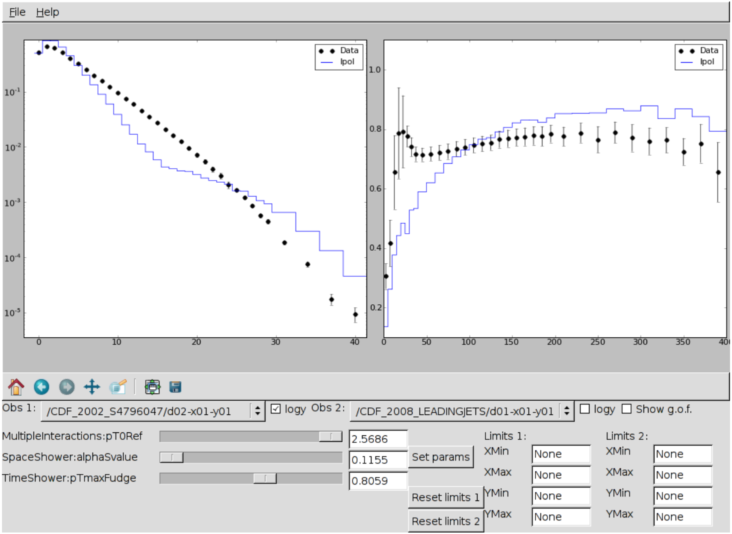

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# Rivet

- Analysis system operating on HepMC events
- Emphasis on not messing with the MC implementation details, reconstruct bosons, jets, don't trace back partons
- Lots of standard analyses built in (mostly driven by tuning needs), try to "mimic" experiments:
  - hadron physics: ATLAS, CDF, D0, E735, SFM, STAR, UA1, UA5
  - $e^+e^-$: ALEPH, BELLE, DELPHI, JADE, OPAL
  - Deep inelastic scattering: H1, ZEUS
  - Pure MC: Jet, W, Z, Photons, SUSY...
- Binning read from data files (check HepData `http://durpdg.dur.ac.uk` for availability)
- Development of new analyses rapid, possible as plug-in (heavily used in ATLAS)
- Most recent version 1.3.0 released a few days ago, patch release 1.3.1 soon
- Recent versions of Sherpa and Herwig++ can be linked against Rivet, Pythia8 will follow soon

# Tuning at the LHC

Most important requirement for tuning: data, corrected for detector effects ⇒ only ATLAS available from LHC in summer
Please correct your data and upload to HepData

## CMS

- UE tunes by Rick Field
- Manual tunings of two Pythia 6 parameters to ATLAS data
- Called "Z1", based on ATLAS AMBT1 tune, available in Pythia6.424

## ALICE, LHCb, LHCf, TOTEM

?

# ATLAS tuning activities – overview

For the moment, concentrated on "work horses" Pythia 6 and Jimmy Herwig 6

- Before we had data, only manual tunes (MC08, MC09)
- Since MinBias data: all tunes done with Professor
- Pythia 6: MC09c, AMBT1 (ATLAS Min Bias Tune 1)
- Jimmy Herwig 6: MC09, AUET1 (ATLAS UE Tune 1)

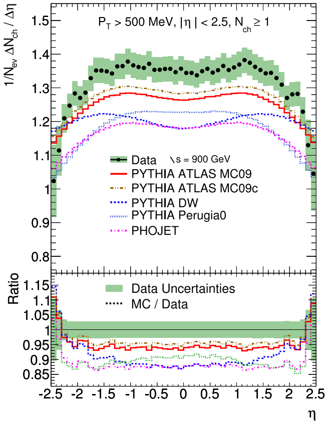
- Jimmy Herwig 6 tune repeated for different PDFs

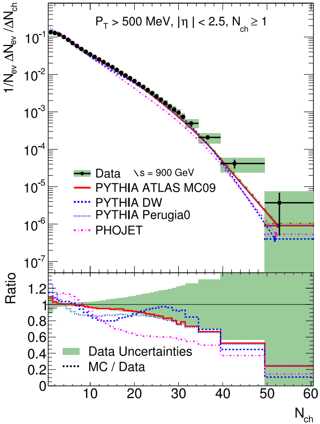
ATLAS now requires that groups provide a Rivet implementation of their analyes. This much more convenient than having to write emails to authors 20 years after publication.

# ATLAS tuning of Pythia 6

There was nice teamwork in ATLAS between tuning and MinBias groups:

- Used first MinBias data (arXiv:1003.3124 [hep-ex]) to make tuning MC09c
- Not so great because of bad diffraction modelling in Pythia 6 and data being normalised to number of particles

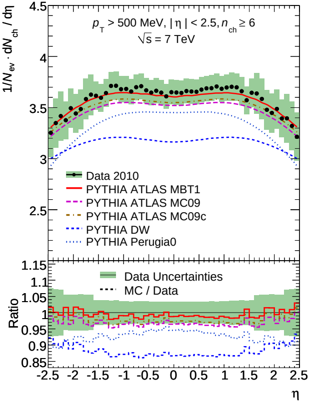


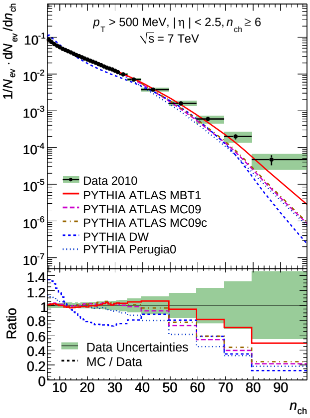



# ATLAS tuning of Pythia 6 (continued)

Asked MinBias guys to redo analysis with additional cut $N_{\text{ch}} \geq 6$

- Used this data (ATLAS-CONF-2010-031) to make tune AMBT1
- We always had close contact with analysis people, therefore implementation of analyses in Rivet was easy



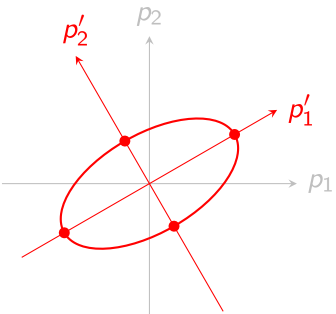



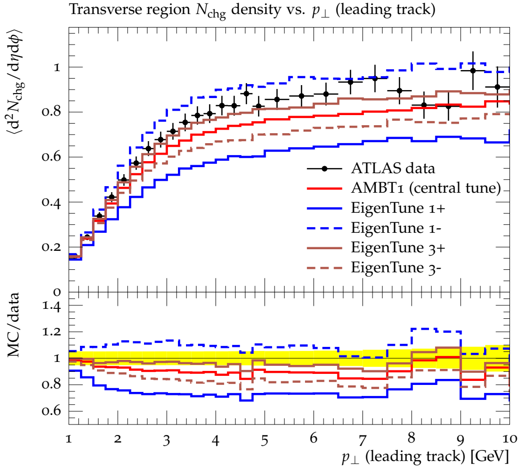
# ATLAS tuning and systematic studies

- For efficiency studies, people need tunings “that have 20% more UE activity”
- How do you do that without breaking model agreement with data too much?
- Pheno. parameters may be higly correlated $\Rightarrow$ varying a single parameter can be a bad idea
- Invented “Eigentunes” in Professor

# Eigentunes

Pick the extremal points of the $\chi^2$ contour hyper-ellipsoid as representative tunes, cf. Hessian PDF errors.
$\Rightarrow$ obtained Eigentunes stay consistent, respect correlations

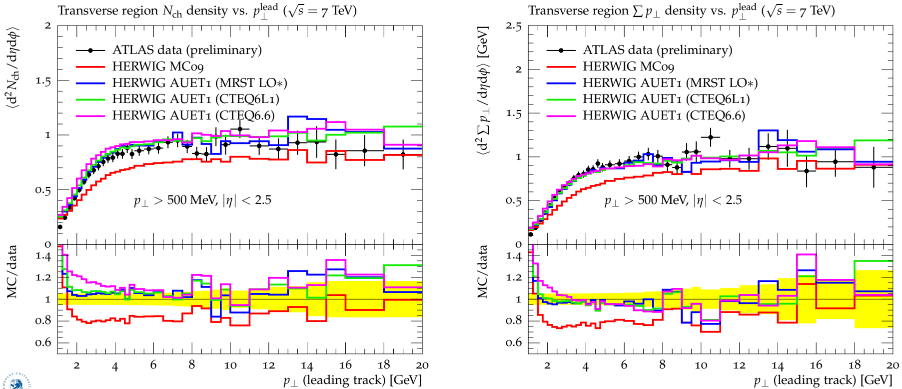


# Retuning for different PDFs

- In ATLAS, different physics groups prefer different PDFs
- Changing the PDF requires retuning of e.g. MPI parameters
- Once tuning successful for one PDF, repetition for others trivial
- Run generator once more with new PDF, tune to same weights
- So far: good observable descriptions achievable independent on PDF choice

Examples for Jimmy Herwig (ATL-PHYS-PUB-2010-014)



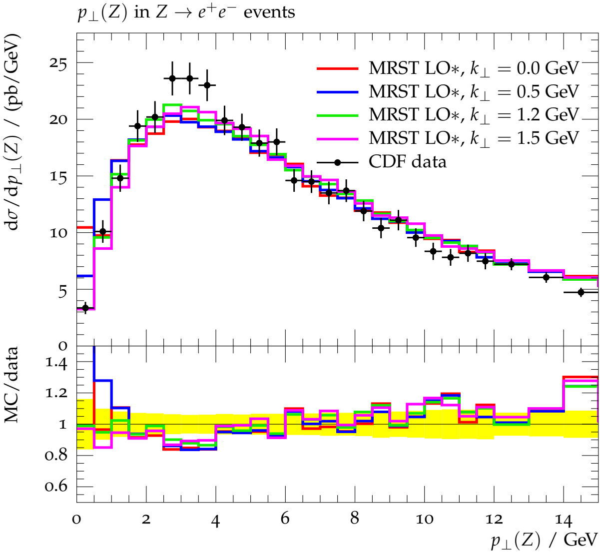
# Summary

- Tuning important for best possible modelling of soft (QCD) physics
- Rivet and Professor have become standard tools to do this systematically
- We need data corrected for detector effects
- Quick turn-around from data-taking at LHC to tuning possible ($\mathcal{O}$(few days))
- Can quantify tuning uncertainties
- Can produce tunings for different purposes (Eigentunes, many PDFs)
- Interactive Explorer (model developers like it)
- More ideas? What about cosmic rays?

Thank you!

# Backup

# INTRINSIC $k_\perp$



# AUET1 PARAMETERS

| Parameter $i$ | | MC09 LO* | $i_{\text{min}}$ | $i_{\text{max}}$ | AUET1 LO* | AUET1 CTEQ6L1 | AUET1 CTEQ6.6 |
|---|---|---|---|---|---|---|---|
| Parameters fixed before numerical tuning | | | | | | | |
| ISPAC | ISR-shower scheme | 0 | 2 | 2 | 2 | | |
| PTRMS | Primordial $k_\perp$ | 0 | 0.5 | 2.0 | 1.2 | 1.2 | 1.2 |
| Tuned cutoff meta-parameters | | | | | | | |
| PTJIM0 | MPI cut-off scale | 3.6 | 1.5 | 5.5 | 2.86 | 2.65 | 2.32 |
| EXP | MPI cut-off evolution | 0.274 | 0.2 | 0.35 | 0.273 | 0.277 | 0.220 |
| Tuned Jimmy parameters | | | | | | | |
| PRRAD | (Anti)proton radius | 2.2 | 1.5 | 2.5 | 1.69 | 1.90 | 1.82 |

## TUNED PARAMETERS

- MPI cut-off:
  naive PTJIM $\longrightarrow \texttt{PTJIM}(\sqrt{s}) = \texttt{PTJIM0} \cdot \left(\frac{\sqrt{s}}{1800\ \text{GeV}}\right)^{\texttt{EXP}}$ (yes, same as in Pythia)
- (Anti-) protonradis PRRAD
- Primordial $k_\perp$-width PTRMS: ATLAS oversight number two, was left at unreasonable default 0, we tuned it manually
- ISR-cut-off scale QSPAC: we tried tuning but observables not sensitive, kept it at MC09 value of 2.5 GeV

2nd order polynomial includes lowest-order correlations between parameters

$$MC_b(\vec{p}) \approx f^{(b)}(\vec{p}) = \alpha_0^{(b)} + \sum_i \beta_i^{(b)} p'_i + \sum_{i \le j} \gamma_{ij}^{(b)} p'_i p'_j$$

Now use N generator runs, i.e. N different parameter sets x,y:

$$\underbrace{\begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_N \end{pmatrix}}_{\vec{v}\text{ (N values, i.e. N bin contents)}} = \underbrace{\begin{pmatrix} 1 & x_1 & y_1 & x_1^2 & x_1 y_1 & y_1^2 \\ 1 & x_2 & y_2 & x_2^2 & x_2 y_2 & y_2^2 \\ & & & \vdots & & \\ 1 & x_N & y_N & x_N^2 & x_N y_N & y_N^2 \end{pmatrix}}_{\tilde{\mathbf{P}}\text{ (N sampled parameter sets)}} \underbrace{\begin{pmatrix} \alpha_0 \\ \beta_x \\ \beta_y \\ \gamma_{xx} \\ \gamma_{xy} \\ \gamma_{yy} \end{pmatrix}}_{\vec{c}\text{ (coeffs)}}$$

Therefore: $\boxed{\vec{c}_b = \tilde{\mathcal{I}}[\tilde{\mathbf{P}}]\vec{v}}$ where $\tilde{\mathcal{I}}$ is the pseudoinverse operator.

$$\boxed{\vec{c}_b = \tilde{\mathcal{I}}[\tilde{\mathbf{P}}]\vec{v}}$$

- Use Singular Value Decomposition (SVD), a general diagonalisation for all normal matrices $M$:$M = U\Sigma V^*$
- Method available in SciPy.linalg
- Minimal number of runs = number of coefficients in $\vec{c}_b$:
  $N_{\text{min}}^{(n)} = 1 + n + n(n+1)/2 + \underbrace{(n+1)(n+2)/6}_{\text{cubic only}}$

$\vec{c}_b = \tilde{\mathcal{I}}[\tilde{\mathbf{P}}]\vec{v}$

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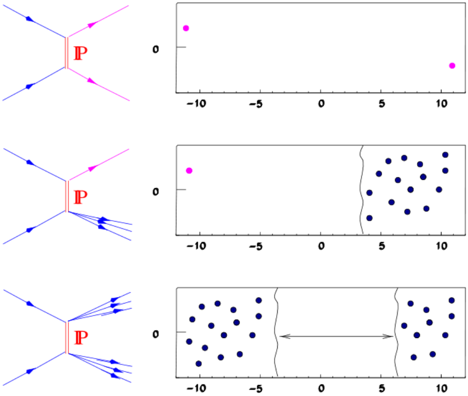
- Oversampling by a factor of three has proven to be much better

| Num params, $P$ | $N_2^{(P)}$ (2nd order) | $N_3^{(P)}$ (3rd order) |
|---|---|---|
| 1 | 3 | 4 |
| 2 | 6 | 10 |
| 4 | 15 | 35 |
| 6 | 28 | 84 |
| 8 | 45 | 165 |
| 9 | 55 | 220 |
| 10 | 66 | 286 |

# Diffractive processes

- Diffractive means exchange of *colourless* object (Pomeron, glueball, no gluon!)
- Leads to "rapidity gap" in detector (e.g. no hits in $|\eta| < 3$)
- Single diffractive (SD) = only one proton dissociates
- Double diffractive (DD) = both protons dissociate
- Contributions to lowest multiplicity bins
- $\rightarrow$ wrong estimate affects $\mathrm{d}N/\mathrm{d}N_{\mathrm{ch}}$!




Mario Deile et al. (arXiv:hep-ex/0602021)