QCD Models

A) Start from pQCD. Extend towards Infrared.
   HERWIG/JIMMY, PYTHIA, SHERPA, EPOS

Elastic & Diffractive
Treated as separate class
No predictivity

Color Screening
Regularization of pQCD
Hadronization

Unitarity
Showers (ISR+FSR)
Multiple 2→2 (MPI)

Hard Process
Perturbative 2→2 (ME)
Resonance Decays

PYTHIA uses **string fragmentation**, HERWIG & SHERPA use **cluster fragmentation**

Elastic

Min-Bias

Dijets/WZ/Top/…

0  \Lambda_{QCD}  5 GeV  \infty

B) Start from Hadrons & Optical Theorem. Extend towards Ultraviolet.
   PHOJET, DPMJET, QGSJET, SIBYLL, …

Hadrons
Optical Theorem
pp→pp

Pomerons: Diffraction
Cut Pomerons: Non-diffractive (soft)

Hard Pomeron?

Note: PHOJET & DPMJET use **string fragmentation** (from PYTHIA) → some overlap

P. Skands
A) Start from pQCD. Extend towards Infrared. HERWIG/JIMMY, PYTHIA, SHERPA, EPOS

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Treated as separate class
No predictivity

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Fixed-Order Matrix Elements

LO vs K×LO vs NLO vs ...
PDF set (& uncertainties & LO vs LO* vs NLO vs ...)
Factorization scale
Renormalization scale(s) (& other RGE-improved couplings)

Note: LO* may not be optimal compromise between LO and NLO. Alternatives under investigation.

Talk by F. Siegert

Keep in Mind:
LO×LL is doing very well
if it gets within 10% of an IR safe quantity
Multi-Scale Problems

Start from pQCD. Extend towards Infrared. HERWIG/JIMMY, PYTHIA, SHERPA, EPOS

A) Elastic & Diffractive
   Treated as separate class
   No predictivity

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PYTHIA uses string fragmentation, HERWIG & SHERPA use cluster fragmentation

Multi-Scale Problems (in fixed-order context)

Scale hierarchies (jet scales, particle masses) \(\rightarrow\) conformal enhancements

Renormalization scale(s)

Resonance Decays (finite widths, spin correlations,…)

Mass Effects

Resummation Effects & Matching to Parton Showers

Large Rapidities (forward jets \(\rightarrow\) high-energy limit)

WARNINGS and common pitfalls:
Too low ME cutoffs, “NLO” \(\rightarrow\) LO, zero widths, weird \(\mu_R\) choices, inconsistent parameters when combining codes

Talk by F. Siegert
Bremsstrahlung

A) Start from pQCD. Extend towards Infrared. HERWIG/JIMMY, PYTHIA, SHERPA, EPOS

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No predictivity

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Hadronization

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FSR+ISR

Size of Phase Space (matching onto ME scales)
Coherence (e.g., angular ordering vs p_T-ordering vs …)
Renormalization Scale(s)
Momentum Recoils
Initial-Final connections (e.g., FSR broadening of an ISR jet…)
Radiation Kernels (e.g., DGLAP vs Dipoles/Antennae vs …)
Polarization Effects

Modern parton showers approximate NLL, but still large uncertainties. At least vary/tune \( \mu_R \) to reflect ambiguities

Keep in Mind:
LO×LL is doing very well
if it gets within 10% of an IR safe quantity

P. Skands
Underlying Event

A) Start from pQCD. Extend towards Infrared. HERWIG/JIMMY, PYTHIA, SHERPA, EPOS

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Multiple Parton Interactions

Multi-Parton PDFs & Correlations (e.g., in x and impact parameter)

Perturbative vs Non-Perturbative Dynamics

Hard Scatterings ~ Rutherford with unknown K-factor

Soft Scatterings ~ Cut Pomerons?

Showers & MPI (Interleaving, showers off MPI, intertwining, rescattering, …)

Note: crazy to require agreement between current MPI-based models and data at 5%-level or better …
Confinement

A) Start from pQCD. Extend towards Infrared. HERWIG/JIMMY, PYTHIA, SHERPA, EPOS

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Partonic Confinement

FSR Cutoff (~ scale of hadronization)
ISR Cutoff (~ starting scale for DGLAP ISR evolution)
MPI Cutoff (~ starting scale for perturbative MPI evolution)
Color Space (formation of color-singlet hadronizing systems)
Hadronization Modeling (clusters vs strings, fragmentation functions)

IR Physics.
Uncertainties guaranteed to be >> LO

Expect worse agreement for rare phenomena (e.g., Ω). Order-of-magnitude may have to be accepted.
Parton/Hadron Dynamics

A) Start from pQCD. Extend towards Infrared.
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No predictivity

Color Screening
Regularization of pQCD
Hadronization

Unitarity
Showers (ISR+FSR)
Multiple 2→2 (MPI)

Hard Process
Perturbative 2→2 (ME)
Resonance Decays

PYTHIA uses string fragmentation, HERWIG & SHERPA use cluster fragmentation

Parton/Hadron Interplay

Hard Diffraction (→ diffractive jets + UE in high-mass diffraction?)

Soft Non-Diffractive Scattering (incl soft diffraction)

Color Reconnections (String/Cluster reinteractions)

Note: expect larger uncertainties on very soft phenomena, rapidity gaps, …

IR Physics.
Uncertainties guaranteed to be >> LO
Soft QCD

A) Start from pQCD. Extend towards Infrared.
HERWIG/JIMMY, PYTHIA, SHERPA, EPOS

Elastic & Diffractive
Treated as separate class
No predictivity

Color Screening
Regularization of pQCD
Hadronization

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Showers (ISR+FSR)
Multiple 2→2 (MPI)

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Long-Distance Physics

Hadron and τ Decay Modeling
Bose-Einstein Correlations
Elastic Scattering
Soft Diffractive Scattering
Hadronic Re-interactions? (Boltzmann gas vs hydro … ?)

IR Physics.
Uncertainties guaranteed to be >> LO
A) Start from pQCD. Extend towards Infrared.
HERWIG/JIMMY, PYTHIA, SHERPA, EPOS

- Elastic & Diffractive
  - Treated as separate class
  - No predictivity

- Color Screening
  - Regularization of pQCD
  - Hadronization

- Unitarity
  - Showers (ISR+FSR)
  - Multiple 2→2 (MPI)

- Hard Process
  - Perturbative 2→2 (ME)
  - Resonance Decays

PYTHIA uses **string fragmentation**, HERWIG & SHERPA use **cluster fragmentation**

\[
\sigma_{\text{INEL}}(s) : \text{Donnachie-Landshof} \ (\sigma_{\text{tot}}(s) - \sigma_{\text{el}}(s))
\]

**PYTHIA:**

\[
\sigma_{SD,DD}(s) : \text{Parametrization} \sim \frac{dM^2}{M^2} \ (\text{See next slides})
\]

\[
\sigma_{\text{NON-DIFF}}(s) = \sigma_{\text{tot}} - \sigma_{\text{el}} - \sigma_{SD} - \sigma_{DD}
\]

This is defined by what you choose for the others

\[
\downarrow \quad \downarrow \quad \downarrow \quad \downarrow \quad \downarrow
\]

You can adjust these, individually, if you don’t like PYTHIA’s def
Color Space
Color Connections

Some ideas:
- Hydro? (EPOS)
- E-dependent string parameters? (DPMJET)
- “Color Ropes”?

N_C \rightarrow \infty

Multiplicity \propto N_{\text{MPI}}

Rapidity
Color Reconnections?

Do the systems really form and hadronize independently?

Can Gaps be Created?

Rapidity

My view:
Universality is ok \((a \text{ string is a string})\)
Problem is \(3 \neq \infty\)

Multiplicity \(\not\propto N_{\text{MPI}}\)

More ideas:
Coherent string formation?
Color reconnections?
String dynamics?
Diffraction (in PYTHIA 8)

Navin, arXiv:1005.3894
Diffraction (in PYTHIA 8)

Navin, arXiv:1005.3894

Diffractive Cross Section Formulae:

\[
\frac{d\sigma_{sd(AX)}(s)}{dt \, dM^2} = \frac{g_{3p}^2}{16\pi} \beta_{AIP}^2 \beta_{BIP}^2 \frac{1}{M^2} \exp(B_{sd(AX)}t) F_{sd},
\]

\[
\frac{d\sigma_{dd}(s)}{dt \, dM_1^2 \, dM_2^2} = \frac{g_{3p}^2}{16\pi} \beta_{AIP}^2 \beta_{BIP}^2 \frac{1}{M_1^2 M_2^2} \exp(B_{dd}t) F_{dd}.
\]

Partonic Substructure in Pomeron:

Follows the Ingelman-Schlein approach of Pompyt

- \( M_X \leq 10\text{GeV} \): original longitudinal string description used
- \( M_X > 10\text{GeV} \): new perturbative description used

Choice between 5 Pomeron PDFs. Free parameter \( \sigma_{PP} \) needed to fix \( \langle n_{\text{interactions}} \rangle = \sigma_{\text{jet}}/\sigma_{PP} \).

Framework needs testing and tuning, e.g. of \( \sigma_{PP} \).
**Framework needs testing and tuning**

E.g., interplay between non-diffractive and diffractive components

+ LEP tuning used directly for diffractive modeling

*Hadronization preceded by shower at LEP, but not in diffraction → dedicated diffraction tuning of fragmentation pars?*

**+ Little experience with new PYTHIA 8 MPI component in high-mass diffractive events**

→ This component especially needs testing and tuning

E.g., look at $n_{\text{ch}}$ and $p_T$ spectra in high-mass (>10GeV) diffraction

(Not important for UE as such, but can be important if using PYTHIA to simulate pile-up!)

\[
\sigma_{\text{IP}} \text{ determines level of UE in high-mass diffraction through } \langle n_{\text{MPI}} \rangle = \sigma_{\text{jet}} / \sigma_{\text{IP}}. \text{ (Larger } \sigma_{\text{IP}} \text{ → smaller UE)}
\]
Consequences

Harder Spectrum in High-M Diffraction

More $p_T$ generated in high-mass diffractive events
+ High-mass diffraction is likely to throw something into the observable region of calorimeters etc (bias)

+ new MPI-based UE in high-M Diffraction

High-Mass diffraction now has a “pedestal” relative to low-mass diffraction, similar to the case of UE in jets vs Min-Bias → further increases amount of activity (and dissipated energy) in high-mass diffractive events.

Little experience with new PYTHIA 8 MPI component in high-M diffractive events

→ This component especially needs testing and tuning (e.g., look at $n_{ch}$ and $p_T$ spectra in high-mass (>10GeV) diffraction). Constrain size of “pedestal” in high-M diffraction.

Can be important if using PYTHIA to simulate pile-up!
Summary

For most perturbative physics

We are still at LO×(N)LL
(Lots of theoretical activity towards improving this, e.g., VINCIA)
For the time being, uncertainties ~ 10% or greater (with tuning)
Multi-scale problems → fixed order breaks down → larger uncertainties

For UE in central region

Amazing agreement with MPI-based models → right direction
Formal accuracy still lower than for hard interaction

For non-perturbative and forward UE physics

Single chain ~ well understood (LEP); baryons + rare phenomena (J/ψ, Ω, etc) tough.
Need more studies (and data) on breakup of beam remnant
Coherence not well understood for multiple chains. Need more studies (and data) on role of color reconnections, and on properties of (high-mass) diffraction.
New models developed in all MCs, need constraints. You have an active role to play.
Scales: $\mu_R = p_T$ and $\Lambda_{CMW}$

Compute $e^+e^\rightarrow 3$ jets, for arbitrary choice of $\mu_R$ (e.g., $\mu_R = m_Z$)

One-loop correction $2\text{Re}[M^0M^{1*}]$ includes a universal $O(\alpha_s^2)$ term from integrating quark loops over all of phase space

$$n_f A^0_3 \left( \ln \left( \frac{s_{23}}{\mu_R^2} \right) + \ln \left( \frac{s_{13}}{\mu_R^2} \right) \right) + \text{gluon loops}$$

Proportional to the $\beta$ function ($b_0$).

Can be absorbed by using $\mu_R^4 = s_{13} s_{23} = p_T^2 s$. (~"BLM")

In an ordered shower, quark (and gluon) loops restricted by strong-ordering condition $\rightarrow$ modified to

$\mu_R = p_T$ (but depends on ordering variable? Anyway, we're using $p_T$ here)

Additional logs induced by gluon loops can be absorbed by replacing $\Lambda_{\text{MS}}$ by $\Lambda_{\text{MC}} \sim 1.5 \Lambda_{\text{MS}}$ (with mild dependence on number of flavors)

Catani, Marchesini, Webber, NPB349 (1991) 635

Note: CMW not automatic in PYTHIA, has to be done by hand, by choosing effective $\Lambda$ or $\alpha_s(M_Z)$ values instead of $\overline{\text{MS}}$ ones
Note 2: There are obviously still order 2 uncertainties on $\mu_R$, but this is the background for the central choice made in showers
Interfaces to External MEs (POWHEG/SCALUP)

Standard Les Houches interface (LHA, LHEF) specifies startup scale SCALUP for showers, so “trivial” to interface any external program, including POWHEG. Problem: for ISR

\[ p_\perp^2 = p_\perp^{2\text{evol}} - \frac{p_\perp^{4\text{evol}}}{p_\perp^{2\text{evol,max}}} \]

i.e. \( p_\perp \) decreases for \( \theta^* > 90^\circ \) but \( p_\perp^{\text{evol}} \) monotonously increasing.

Solution: run “power” shower but kill emissions above the hardest one, by POWHEG’s definition.

Available for ISR-dominated, coming for QCD jets with FSR issues.

in PYTHIA 8

Note: Other things that may differ in comparisons: PDFs (NLO vs LO), Scale Choices
Interfaces to External MEs (MLM)

B. Cooper et al., arXiv:1109.5295 [hep-ph]

If using one code for MEs and another for showering

Tree-level corrections use $\alpha_s$ from Matrix-element Generator

Virtual corrections use $\alpha_s$ from Shower Generator (Sudakov)

Mismatch if the two do not use same $\Lambda_{QCD}$ or $\alpha_s(m_Z)$

$$\alpha_s^2 b_0 \ln \left( \frac{\Lambda_{MG}^2}{\Lambda_{SG}^2} \right) \frac{dQ^2}{Q^2} \sum_i P_i(z) |M_F|^2.$$ note: running order also has a (subleading) effect

AlpGen: can set $xlclu = \Lambda_{QCD}$ since v.2.14 (default remains to inherit from PDF)

Pythia 6: set common PARP(61)=PARP(72)=PARP(81) = $\Lambda_{QCD}$ in Perugia 2011 tunes

Pythia 8: use TimeShower:alphaSvalue and SpaceShower:alphaSvalue
Lönnblad Matching in PYTHIA 8

Get the state $S_{+n}$ (with all partons above a cut $t_{MS}$) from a matrix element generator

Find all possible shower histories $(S_{+0}, \rho_0), \ldots, (S_{+n}, \rho_n)$

Pick one according to the probability with which the shower would have produced it

Generate the Sudakov factor by trial showering

Reweight with $\alpha_s$ factors and PDF factors

Start shower from last reconstructed scale

If $n$ is the highest multiplicity, continue;
Else veto events with shower splittings above $t_{MS}$

Combine histograms for all MEs

→ distributions with ME+PS merging.

Now automated in PYTHIA 8 (needs ME events in LHEF format)
L. Lönnblad & S. Prestel, arXiv:1109.4829
In total, ten tune variations are included in the "Perugia 2011" set. The starting point was in all cases Perugia 2010, with modifications as documented in the tables below.

### Perugia 2011 Tune Set

<table>
<thead>
<tr>
<th>Tune ID</th>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>Central Perugia 2011 tune (CTEQ5L)</td>
<td>MSTP(5) = 350</td>
</tr>
<tr>
<td>351</td>
<td>Variation using $\alpha_s\left(\frac{1}{2}p_{\perp}\right)$ for ISR and FSR</td>
<td>MSTP(5) = 351</td>
</tr>
<tr>
<td>352</td>
<td>Variation using $\alpha_s\left(2p_{\perp}\right)$ for ISR and FSR</td>
<td>MSTP(5) = 352</td>
</tr>
<tr>
<td>353</td>
<td>Variation using $\Lambda_{QCD} = 0.26\text{ GeV}$ also for MPI</td>
<td>MSTP(5) = …</td>
</tr>
<tr>
<td>354</td>
<td>Variation without color reconnections</td>
<td>Harder radiation</td>
</tr>
<tr>
<td>355</td>
<td>Variation using MRST LO** PDFs</td>
<td>Softer radiation</td>
</tr>
<tr>
<td>356</td>
<td>Variation using CTEQ 6L1 PDFs</td>
<td>UE more “jetty”</td>
</tr>
<tr>
<td>357</td>
<td>Variation using PARP(90)=0.16 scaling away from 7 TeV</td>
<td>Softer hadrons</td>
</tr>
<tr>
<td>358</td>
<td>Variation using PARP(90)=0.32 scaling away from 7 TeV</td>
<td>UE more “jetty”</td>
</tr>
<tr>
<td>359</td>
<td>Variation optimized for Tevatron</td>
<td>Recommended</td>
</tr>
<tr>
<td></td>
<td>~ low at LHC</td>
<td></td>
</tr>
</tbody>
</table>

Note: no variation of hadronization parameters! (sorry, ten was already a lot)

---

**Table 5:** Hadronisation Parameters of the Perugia 2011 tunes compared to Perugia 0 and Perugia 2010.

Parameters that were not explicitly part of the Perugia 0 and Perugia 2010 tuning but were included in Perugia 2011 are highlighted in blue. For more information on each parameter, see [14].

---

Can be obtained in standalone Pythia from 6.4.25+

<table>
<thead>
<tr>
<th>MSTP(5)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>Perugia 2011</td>
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<td>351</td>
<td>Perugia 2011 radHi</td>
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<tr>
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<td>Perugia 2011 radLo</td>
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<tr>
<td>353</td>
<td>Perugia 2011 mpiHi</td>
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<td>354</td>
<td>Perugia 2011 noCR</td>
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<td>355</td>
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<td>Perugia 2011 T16</td>
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<td>358</td>
<td>Perugia 2011 T32</td>
</tr>
<tr>
<td>359</td>
<td>Perugia 2011 Tevatron</td>
</tr>
</tbody>
</table>

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Tunes of PYTHIA 8 : Corke & Sjöstrand - JHEP 03 (2011) 032 & JHEP 05 (2011) 009
A) Start from pQCD. Extend towards Infrared. HERWIG/JIMMY, PYTHIA, SHERPA, EPOS

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$\sigma_{2\to2}(p_T) > \sigma_{\text{tot}}$ for $p_\perp \approx 5$ GeV

→ fixed-order unreliable, but pQCD still ok if resummed (unitarity)

→ Resum dijets? Yes → MPI!

Regularise cross section with $p_{\perp 0}$ as free parameter

$$\frac{d\hat{\sigma}}{dp_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \rightarrow \frac{\alpha_s^2(p_\perp^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2}$$

with energy dependence

$$p_{\perp 0}(E_{\text{CM}}) = p_{\perp 0}^{\text{ref}} \times \left( \frac{E_{\text{CM}}}{E_{\text{CM}}^{\text{ref}}} \right)^\epsilon$$

MultipleInteractions:alphaSvalue 0.135 $\alpha_s(m_Z)$
MultipleInteractions:alphaSorder 1
MultipleInteractions:Kfactor 1.0
MultipleInteractions:bProfile 3
MultipleInteractions:pT0Ref 2.085 Gauss
MultipleInteractions:ecmPow 0.19

IR reg scale at 1.8 TeV
Energy-Scaling power of IR scale

+ see “Multiple Interactions” and “PDF selection”

+ “A Second Hard Process” (can specify 2nd interaction)
(Hadronization)

A) Start from pQCD. Extend towards Infrared.
HERWIG/JIMMY, PYTHIA, SHERPA, EPOS

- Elastic & Difffractive
  Treated as separate class
  No predictivity

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  Hadronization

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  Multiple 2→2 (MPI)

- Hard Process
  Perturbative 2→2 (ME)
  Resonance Decays

PYTHIA uses **string fragmentation**, HERWIG & SHERPA use **cluster fragmentation**

**ISR and FSR cutoffs**

+ String-Fragmentation Parameters


**Important** task: evaluate whether LEP/LHC universality holds

  E.g., use universality-testing technique proposed in Schulz & PS, EPJ C71 (2011) 1644

For percent-level $m_{top}$, must also consider non-perturbative uncertainties

  E.g., Central vs NOCR, etc, discussed in PS & Wicke, EPJ C52 (2007) 133
PYTHIA Models

Note: tunes differ significantly in which data sets they include
- LEP fragmentation parameters
- Level of Underlying Event & Minimum-bias Tails
- Soft part of Drell-Yan $p_T$ spectrum
## PYTHIA Models

### Main Data Sets included in each Tune (no guarantee that all subsets ok)

<table>
<thead>
<tr>
<th>A</th>
<th>DW, D6, ...</th>
<th>S0, S0A</th>
<th>MC09(c)</th>
<th>Pro-..., Perugia 0, Tune 1, 2C, 2M</th>
<th>AMBT1</th>
<th>Perugia 2010</th>
<th>Perugia 2011</th>
<th>Z1, Z2</th>
<th>4C, 4Cx</th>
<th>AMBT2B, A2, AU2</th>
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<tr>
<td>LEP</td>
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<td>✔</td>
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</tbody>
</table>

### Models

- **pt-ordered PYTHIA 6**
  - Tune S0
  - Tune S0A
  - S-...-Pro

- **Q-ordered PYTHIA 6**
  - Tune A (default)
  - DW(T)
  - D6(T)
  - D-...-Pro
  - Pro-Q2O

- **pt-ordered PYTHIA 8**
  - 2C
  - 2M

### Data Sets

- **LHC data**
  - AMBT1
  - Z1, Z2
  - Perugia 2010 (+ Variations)
  - AUET2B?
  - Perugia 2011 (+ Variations)
  - Q2-LHC?

### Additional Details

- **LEP** ✔
- **TeV MB** ✔
- **TeV UE** ✔
- **TeV DY** ✔
- **LHC MB** ✔
- **LHC UE** ✔

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This table provides an overview of the main data sets included in each tune, indicating where the data is available under the conditions specified.
What Works*

*) if you use an up-to-date tune. Here comparing to PY6 default (~Tune A) to show changes.

Underlying Event & Jet Shapes

PS: yes, we should update the PYTHIA 6 defaults ...
What Works*  
* ) if you use an up-to-date tune. Here comparing to PY6 default (~ Tune A) to show changes.

**Drell-Yan \( p_T \) (Normalized to Unity)**

- \( d\sigma \) (no K-factor)
- \( d\sigma/\sigma \) (norm to unity)

\( \varphi^* \) (norm to unity)

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**PS:** yes, we **should** update the PYTHIA 6 defaults ...
**What Kind of Works**

*) if you use an up-to-date tune. Here comparing to PY6 default (~Tune A) to show changes.

Minimum-Bias Multiplicities

(here showing as inclusive as possible)

Charged Multiplicity Distribution

η distribution

Forward-Backward Correlation (UA5)
Hoping for LHC measurements soon
See Wraight + PS, EPJC71(2011)1628

Central LHC Detectors
ALICE FMD

PS: yes, we **should** update the PYTHIA 6 defaults ...
pT Spectra / Mass Dependence

STAR measurement
Average pT versus particle mass
Model predict **too hard** Pions and **too soft** massive particles

Massive particles can only be made **softer!**

So: tuning problem? or physics problem? Will return on Friday
Strangeness and Baryons

Tried to learn from early data, but still not there …

Again, quite difficult to adjust flavor parameters while remaining within LEP bounds …
Very Soft Structure

Minimum-Bias too lumpy?

Underlying Event ok?

\( p_{T\text{Lead}} > 1 \)

\( p_{T\text{Lead}} > 5 \)

Plots from mcplots.cern.ch