Theory Lessons from the First LHC Runs at O(1 TeV)

Peter Skands (CERN PH-TH)
Disclaimer

• Impossible to cover everything

• *Focus* on important outstanding questions which could be settled by early LHC measurements at 900 and 2360 GeV

• Note that, for most of them, this is our *only* chance to settle these questions

• The answers are crucial to improving our physics models
Monte Carlos and Precision

• A Good Physics Model gives you
  • Reliable calibrations for both signal and background (e.g., jet energy scales)
  • Reliable corrections (e.g., track finding efficiencies)
  • Background estimates with as small uncertainty as possible (fct of both theoretical accuracy and available experimental constraints)
  • Reliable discriminators with maximal sensitivity to New Physics
Count what is Countable
Measure what is Measurable
(and keep working on the beam)

Theory

Feedback Loop

Experiment

Amplitudes
Monte Carlo
Resummation
Strings
...

Theory worked out to Hadron Level with acceptance cuts (~ detector-independent)

Measurements corrected to Hadron Level with acceptance cuts (~ model-independent)

If not worked out to hadron level: data must be unfolded with someone else’s hadron-level theory

Unfolding beyond hadron level dilutes precision of raw data (Worst case: data unfolded to ill-defined ‘MC Truth’ or ‘parton level’)

Thursday, January 28, 2010
Constraining Models

- A wealth of data available at lower energies
- Used for constraining (‘tuning’) theoretical models (E.g., Monte Carlo Event Generators)
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But wait ... which gaps?
Charged Multiplicity

• One of the most fundamental quantities to measure
  • But fundamental does not imply easy
Charged Multiplicity

• One of the most fundamental quantities to measure
  • But fundamental does not imply easy
  • Complications: Corrections for Trigger Bias, Diffraction, Zero Bin, Long-Lived particles, Extrapolations from raw measurement to: hadron-level (with acceptance cuts) and/or to: hadron-level (full phase space), ...
Dissecting Minimum-Bias

Physics requirements: basics

The MC description of LHC events is tremendously complex

Hadronisation and decay

Final state radiation

Hard interaction: \( qq, q\bar{q}, qg, gg \)

PDF, proton structure

Initial state radiation

Beam remnants

Secondary interactions

Hadronisation and decay

This is a schematization to be able to cut down the problem in pieces and model them in a different way. The "pieces" are correlated!

(slide from F. Cossutti (CMS), 7th MCnet Annual Meeting, January 2010)
Dissecting Minimum-Bias

Inelastic, Non-Diffractive

Zero Bias

Low Multiplicity

Elastic

DPI

Beam Remnants (BR)

Multiple Parton Interactions (MPI)

Double Diffraction

Inelastic, Non-Diffractive

Hard Trigger Events

High-Multiplicity Tail

Minijets

High Multiplicity

NSD
Measured Results

• How to Compare to Older Measurements?
  • Bubble chambers etc extrapolated to full phase space
  • More model-dependent at Tevatron and LHC experiments
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• **How to Compare to Older Measurements?**
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• **How to Compare to Theory?**
  • Inelastic > ‘NSD’ > Inelastic Non-Diffractive, ...
  • For all: Define *event set in terms of hadron-level cuts*
  • Today’s theorists not interested in filling up unmeasured region with some model (especially if it is some other guy’s model) - *Keep main measured result as close to raw acceptance as possible. Extrapolate only to do comparisons (inflates uncertainties)*

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Issues at Low Multiplicity

- Inelastic, Non-Diffractive
  - Hard Trigger Events
  - Minijets
  - High-Multiplicity Tail
- Single Diffraction
- Zero Bias
- Low Multiplicity
  - Elastic
  - Double Diffraction
  - DPI
  - Beam Remnants (BR)
- Multiple Parton Interactions (MPI)
- High Multiplicity

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Low Multiplicities: Correcting for Diffraction

- Diffractive processes
  - Large part of total cross section
  - Populate the low-multiplicity bins: lower $<N_{ch}>$
  - Characteristic rapidity spectrum with large rapidity gaps: affect $dN_{ch}/d\eta$
  - Impossible to interpret min-bias spectra without knowing precisely how diffraction was treated
Low Multiplicities:
Correcting for Diffraction

- CDF Run-I Data
  - Corrected to $p_T > 0.4$ GeV instead of full PS: less model dependence
  - First few bins corrected for diffraction (also affects average $N_{ch}$ and $dN/d\eta$)

Data from CDF Collaboration, PRD65(2002)072005
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What about the 630 GeV data?

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  - First few bins

What about the 630 GeV data?

LHC Measurements at 900 and 2360 GeV, with a well-defined, agreed-upon, definition of diffraction can kill this issue
The most problematic is the zero bin: the event was triggered, but no fiducial tracks

E.g., was it a diffractive event with no tracks, or an inelastic non-diffractive event, with no tracks? Or ...?
The Zero Bin

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<table>
<thead>
<tr>
<th>Predictions for Mean Densities of Charged Tracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \langle N_{\text{ch}} \rangle</td>
</tr>
<tr>
<td>LHC 10 TeV</td>
</tr>
<tr>
<td>LHC 14 TeV</td>
</tr>
</tbody>
</table>


Redefine the event sample to include at least one fiducial track?
Issues at High Multiplicity

- Inelastic, Non-Diffractive
- Single Diffraction
- Double Diffraction
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- DPI
- Beam Remnants (BR)
- Multiple Parton Interactions (MPI)
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High Multiplicities: An Unresolved Question

- UA5 at 200, 546, and 900 GeV
- E735 at 300, 546, 1000, and 1800 GeV
- Mutually Inconsistent over Entire Range
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Without even knowing how many tracks to tune to, how could we hope to constrain non-perturbative models (i.e., Monte Carlos)?
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T. Alexopoulos et al., PLB435(1998)453

Important to ‘see’ low-\(p_T\) tracks: the lower, the better to settle this.
(eta cuts ~ ok, since UA5 gives data in eta bins)
Fragmentation

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  - Fragmentation and Flavour parameters constrained at LEP, then used in pp/ppbar (Jet Universality)
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• Check fragmentation \textit{in situ} at hadron colliders

  • $N$ and $p_T$ spectra (and $x$ spectra normalized to ‘jet’/minijet energy?)
  \textbf{Identified particles} highly important to dissect fragmentation
The Kaon Problem

Too many Kaons in MC?
(even though tuned at LEP)

But Lambdas look OK

http://home.fnal.gov/~skands/leshouches-plots

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Identified Particle Spectra Not Checked in Run II

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• Check fragmentation *in situ* at hadron colliders
  • $N$ and $p_T$ spectra (and $x$ spectra normalized to ‘jet’/minijet energy?)
    **Identified particles** highly important to dissect fragmentation
  • (How) do the spectra change with (pseudo-)rapidity? (different dominating production/fragmentation mechanisms as fct of rapidity? E.g., compare LHCb with central?)
  • How do they change with event activity? (cf. heavy-ion ~ central vs peripheral collisions)
Change with Event Activity

- One (important) example: $<p_T>(N_{ch})$

The $p_T$ spectrum becomes harder as we increase $N_{ch}$.

Important tuning reference (highly non-trivial to describe correctly)

(Color reconnections, string interactions, rescattering, collective flow in $pp$, ...)
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• Check extrapolation to forward region

• Subir’s Synergy with Cosmic Ray Fragmentation

• ‘New’ Physics: collective effects, multiple scatterings, low-x evolution, BFKL, ..., but central region remains important testing ground
Particle-Particle Correlations probe fragmentation beyond single-particle level. E.g.,:

- A baryon here, where’s the closest antibaryon?
  - + Is the Baryon number of the beam carried into the detector?

- A Kaon here, where’s the closest strange particle?
  - + Multi-Strange particles. Over how big a distance is the strangeness ‘neutralized’?

- Charge correlations. Special case: is the charge of the beam carried into the detector?
Baryon Transport

- Models disagree wildly.
  - Don’t listen to them
  - (Still, can be used to gauge possible size of effect)

900 GeV p+p Inelastic, Non-Diffractive

$\frac{N(\Lambda^0_{\mathrm{bar}})}{N(\Lambda^0)}$ Distribution (generator-level)

- Perugia 0
- Perugia HARD
- Perugia SOFT
- Perugia NOCR
- DW

Pythia 6.422

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Radiation vs MPI

• What is producing the tracks?
  • Is it **Radiation**? (tends to produce partons close in phase space)
  • Or is it **MPI**? (partons going out in opposite directions)
  • Or is it soft production between the **remnants**?

• Probing long- vs short-distance correlations can tell us!
  • E.g., forward-backward correlation, $b$
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![Different MPI models have different shapes](image-url)
Summary

• The Low-Energy LHC runs offer a unique possibility to settle important business

• These are questions faced by every person (within or outside experiments) trying to constrain (‘tune’) physics models

• In a broader context, they concern our knowledge of nature