Unique LHCb Observables to constrain MC models

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(From October: Monash University, Melbourne)
Collider Physics

Dominated by QCD

More than just a perturbative expansion in $\alpha_s$

Emergent phenomena:

**Jets** (the QCD fractal) $\leftrightarrow$ amplitude structures $\leftrightarrow$ fundamental quantum field theory. Precision jet (structure) studies, jet vetoes

**Strings** (strong gluon fields) $\leftrightarrow$ quantum-classical correspondence. String physics. Dynamics of hadronization phase transition. Colour neutralization

**Hadrons** $\leftrightarrow$ Spectroscopy (incl excited and exotic states), lattice QCD, (rare) decays, mixing. Identified particles: rates, spectra (FFs), correlations. Hadron beams $\rightarrow$ PDFs, MPI, diffraction, ...

See eg TASI lectures, e-Print: [arXiv:1207.2389](https://arxiv.org/abs/1207.2389)
**MC: Divide and Conquer**

**Factorization** → Split the problem into many (nested) pieces
+ **Quantum mechanics** → Probabilities → Random Numbers (MC)

\[
P_{\text{event}} = P_{\text{hard}} \otimes P_{\text{dec}} \otimes P_{\text{ISR}} \otimes P_{\text{FSR}} \otimes P_{\text{MPI}} \otimes P_{\text{Had}} \otimes \ldots
\]

**Hard Process & Decays:**
Use (N)LO matrix elements

**Initial- & Final-State Radiation (ISR & FSR):**
DGLAP or antenna-dipole showers down to ~ 1 GeV

**MPI (Multi-Parton Interactions)**
Additional (soft) parton-parton interactions: LO matrix elements
→ Additional (soft) “Underlying-Event” activity
Dominated by low-x gluons (especially in FWD region)

**Hadronization**
The process of colour neutralization
Non-perturbative model for parton systems → hadrons
**Example of Color Flow in a Parton Cascade**

Coherence of pQCD cascades → not much “overlap” between singlet subsystems → Leading-colour approximation pretty good

**Note**: (much) more color getting kicked around in hadron collisions
MPI and Colour

Better theory models needed

$N_C \to \infty$

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

Rapidity
Color Reconnections?

E.g.,

Better theory models needed

Do the systems really form and hadronize independently?

Rapidity

Multiplicity grows much slower than $N_{\text{MPI}}$
The Effects of CR

Fewer particles ... with higher pT
The Effects of CR

Fewer particles ... with higher pT

Strong dependence on Nch
Without Colour Reconnections
Each MPI hadronizes independently of all others

See also Ortiz et al., Phys.Rev.Lett. 111 (2013) 4, 042001
... from boosted strings?

With Colour Reconnections
MPI hadronize collectively

Highly important theory question now
Is there collective flow in pp? Or not?
Is it stringy, or hydrodynamic? (or ...?)

LHCb
How do the MPI ‘hook up’
with the beam remnant?

See also Ortiz et al., Phys.Rev.Lett. 111 (2013) 4, 042001
Central vs Forward

Take an extremely simple case of just 2 MPI

**Add Final-state Radiation**

Small overlaps between different jets:
- main CR questions are inter-jet and jet-beam
- boosted strings etc.

**Add Initial-state Radiation**

All the ISR radiation overlaps!
- (each MPI scattering centre must reside within one proton radius of all others)
- expect significant ‘colour confusion’
- intra-jet CR (unlike central and LEP)
- Strong effects in FWD region
The distributions shown so far were all measured in the central region.

Within a given model, FWD region is essentially fixed by the parameters chosen to tune the central one: but there are discrepancies (hence it also makes sense that LHCb pursue their own tuning efforts).

There might be much more physics going on in the forward region, not accessed by the central measurements.

Only LHCb sees this region clearly (with PID, etc).

+ Feedback to central experiments since their pileup modeling depends on FWD modeling.
Examples: Nch and E Flow

4C and Monash 13 ~ same in central region

7000 GeV

$\langle \frac{dE}{d\eta} \rangle$ (n$_{ch}$ > 1, $p_T$ > 0.04, 5.3 < $\eta$ < 6.5)

- TOTEM
- PY8 (Monash 13) $\chi^2_{\text{exp}} / N_{\text{bins}}$ = 0.2 ± 0.0
- PY8 (4C) $\chi^2_{\text{exp}} / N_{\text{bins}}$ = 2.6 ± 0.0
- PY8 (2C) $\chi^2_{\text{exp}} / N_{\text{bins}}$ = 6.1 ± 0.0

Data from Europhys. Lett. 98 (2012) 31002
Pythia 8.181

Different in FWD region
(But TOTEM doesn't have PID)

7000 GeV

MB Fwd E Flow (n$_{ch}$ ≥ 1 in both 3.23 < $\eta$ < 4.65)

- CMS
- PY8 (Monash 13) $\chi^2_{\text{exp}} / N_{\text{bins}}$ = 0.2 ± 0.0
- PY8 (4C) $\chi^2_{\text{exp}} / N_{\text{bins}}$ = 0.4 ± 0.0
- PY8 (2C) $\chi^2_{\text{exp}} / N_{\text{bins}}$ = 2.2 ± 0.0

Data from JHEP 11 (2011) 148
Pythia 8.181

Depends on low-x gluon PDF and on CR/remnant modeling $\rightarrow$ constraints!
1. Baryon Number Transport

How much does the **beam remnant** ‘break up’?

Good tracer: beam **baryon number**. How far does it get transported?

LHCb has already delivered beautiful **measurements** of Baryon Transport signal (Lambdabar/Lambda, & protons)

Λ has one strange quark (so could be beam ud diquark + s). How about multi-strange? Xi, Omega.

+ Spectra? $p_T(\Lambda) - p_T(\bar{\Lambda})$ in bin where asymmetry is large ($\Delta y < 5$), with higher-$\Delta y$ bins as reference? What more can you tell us about these baryons?
2. Baryon-Baryon Correlations

How global/local is baryon formation? (esp in view of the strong possible CR effects expected in the FWD region)

**A** Conventional

- Strong local (anti)correlations in flavor and momentum

**B** Popcorn

- Correlations act over slightly longer distance

**C** Junctions

- Baryon number conservation over arbitrarily long distance

Or pick leading baryon: $\Lambda_{c,b}$

cf eg LHCb arXiv:1405.6842
3. Strangeness

$m_s \sim \Lambda_{QCD}$: Very sensitive to string tension

Right between relativistic and non-relativistic. Non-relativistic velocities good to probe for flow effects

+ correlations: strangeness compensation
(problems: K0S is both s and sbar)
4. Fragmentation around Charm

Can use c (& b) to identify hard string endpoint

Then look for same/opposite-sign Kaons around D⁺ mesons

E.g. M. Kreps pointed to a CDF PUB note (10704) that saw interesting discrepancies

PS: spectra of 2nd rank are interesting too!

(high B_s osc frequency: less clean for B)

E.g. M. Kreps pointed to a CDF PUB note (10704) that saw interesting discrepancies

Same sign Prompt D_{s}^{++}

Opposite sign Prompt D_{s}^{+-}
There are many UE variables. The most important is $\langle \Sigma p_T \rangle$ in the “Transverse Region”

**Leading Track or Jet**  
(more IR safe to use jets, but track-based analyses still useful)

- “TRANSVERSE” REGION
- “TOWARDS” REGION
- “AWAY” REGION

~ Recoil Jet

Sensitive to activity at right angles to the hardest jets

Useful definition of Underlying Event

$\Delta \phi$ with respect to leading track/jet

[Graph showing data for UE and MB, with ATLAS and other models compared]
Jets: scanning the pedestal

For fixed jet $p_T$, study events with LARGE or SMALL transverse $pT_{sum}$ ~ scan over $b$?
Tuning means different things to different people

10% agreement is great for (N)LO + LL

MB/UE/Soft: larger uncertainties since driven by non-factorizable and non-perturbative physics

Complicated dynamics: “If a model is simple, it is wrong” (T. Sjöstrand)
Recent PYTHIA Models/Tunes

Note: I focus on default / author tunes here
(Important complementary efforts undertaken by LHC experiments)

PYTHIA 8.1

Current Default = 4C (from 2010)

Tunes 2C & 4C: e-Print: arXiv:1011.1759

LEP tuning undocumented (from 2009)
LHC tuning only used very early data
based on CTEQ6L1

Aims for the Monash 2013 Tune


• Revise (and document) constraints from $e^+e^-$ measurements
  • In particular in light of possible interplays with LHC measurements

• Test drive the new NNPDF 2.3 LO PDF set (with $\alpha_s(m_Z) = 0.13$) for pp & ppbar
  • Update min-bias and UE tuning + energy scaling → 2013
  • Follow “Perugia” tunes for PYTHIA 6: use same $\alpha_s$ for ISR and FSR
  • Use the PDF value of $\alpha_s$ for both hard processes and MPI

PYTHIA 6.4 (warning: no longer actively developed)

Default: still rather old $Q^2$-ordered tune ~ Tevatron Tune A

Most recent: Perugia 2012 set of $p_T$-ordered tunes (370 - 382) + Innsbruck (IBK) Tunes (G. Rudolph)
Comparisons to Tevatron tunes are not interesting any more ... (Perugia 0, Perugia 2010, A, DW, ...)

(+ 2011 & 2012 updates added as appendices)
10% more strangeness


More forward activity

Sof ter D and B spectra near \( z = 1 \)

Better agreement with ee identified-strange measurements across all energies, and with Kaons at LHC

Ultra-hard tail of c and b fragmentation agrees better with LEP and SLD, including event shapes in b-tagged events

Better agreement with TOTEM \( N_{ch} \) and with forward E and ET flows. Better pileup?
Puzzles (a selection of)

Identified-particles at LHC
- Multi-strange and baryon rates/transport
- $p_T$ Spectra (esp dependence on $N_{ch}$ and particle mass: collectivity?)
- Correlations (local vs global conservation laws)

The physics of Colour Neutralization
- Colour/string (re)connections vs Flow?
- Implications for Top Quark Mass

Forward physics and zero bias (pileup)
- The role and modeling of diffraction from low to high masses
- UE in diffractive jet events & hard diffraction?

Space-time picture of multi-parton interactions (MPI);
interplay with multi-parton PDFs and hadronization

Gluon/Quark discrimination & $G \rightarrow QQ$ splittings in gluon jets