Monte Carlo Generators for the LHC

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1. (Monday) Introduction and Overview; Matrix Elements
2. (Tuesday) Parton Showers; Matching Issues
3. (today) Multiple Interactions and Beam Remnants
4. (Thursday) Hadronization and Decays; Summary and Outlook
Event Physics Overview

Repetition: from the “simple” to the “complex”,
or from “calculable” at large virtualities to “modelled” at small

Matrix elements (ME):

1) Hard subprocess:
\(|\mathcal{M}|^2\), Breit-Wigners, parton densities.

\[ \bar{q} \rightarrow Z^0 \rightarrow \bar{h}^0 \]
\[ q \rightarrow Z^0 \rightarrow h^0 \]

2) Resonance decays:
includes correlations.

\[ Z^0 \rightarrow W^+ \rightarrow c \bar{s} \]
\[ W^- \rightarrow \tau^- \rightarrow \nu_\tau \]

Parton Showers (PS):

3) Final-state parton showers.

\[ q \rightarrow qg \]
\[ g \rightarrow gg \]
\[ q \rightarrow q\bar{q} \]
\[ q \rightarrow q\gamma \]

4) Initial-state parton showers.

\[ q \rightarrow Z^0 \]
\[ g \rightarrow Z^0 \]

\[ g \rightarrow Z^0 \]
5) Multiple parton–parton interactions.

6) Beam remnants, with colour connections.

5) + 6) = Underlying Event

7) Hadronization

8) Ordinary decays: hadronic, $\tau$, charm, …
What is multiple interactions?

Cross section for $2 \to 2$ interactions is dominated by $t$-channel gluon exchange, so diverges like $d\sigma/dp_{\perp}^2 \approx 1/p_{\perp}^4$ for $p_{\perp} \to 0$.

Integrate QCD $2 \to 2$

$qq' \to qq'$
$q\bar{q} \to q'\bar{q}'$
$q\bar{q} \to gg$
$qg \to qg$
$gg \to gg$
$gg \to q\bar{q}$

with CTEQ 5L PDF's

Integrated cross section above $p_{\text{Tmin}}$ for pp at 14 TeV
So $\sigma_{\text{int}}(p_{\perp \text{min}}) > \sigma_{\text{tot}}$ for $p_{\perp \text{min}} \gtrsim 5$ GeV

Half a solution: many interactions per event

$$\sigma_{\text{tot}} = \sum_{n=0}^{\infty} \sigma_n$$

$$\sigma_{\text{int}} = \sum_{n=0}^{\infty} n \sigma_n$$

$$\sigma_{\text{int}} > \sigma_{\text{tot}} \iff \langle n \rangle > 1$$

If interactions occur independently then Poissonian statistics

$$P_n = \frac{\langle n \rangle^n}{n!} e^{-\langle n \rangle}$$

but energy–momentum conservation $\Rightarrow$ large $n$ suppressed
Other half of solution: perturbative QCD not valid at small $p_\perp$ since $q, g$ not asymptotic states (confinement!).

Naively breakdown at

$$p_{\perp \text{min}} \approx \frac{\hbar}{r_p} \approx \frac{0.2 \text{ GeV} \cdot \text{fm}}{0.7 \text{ fm}} \approx 0.3 \text{ GeV} \approx \Lambda_{\text{QCD}}$$

...but better replace $r_p$ by (unknown) colour screening length $d$ in hadron

\[ \lambda \sim \frac{1}{p_\perp} \]
so modify

\[
\frac{d\hat{\sigma}}{dp_{\perp}^2} \propto \frac{\alpha_s^2(p_{\perp}^2)}{p_{\perp}^4} \rightarrow \frac{\alpha_s^2(p_{\perp}^2)}{p_{\perp}^4} \theta(p_{\perp} - p_{\perp \text{min}}) \quad \text{(simpler)}
\]

or \[
\frac{\alpha_s^2(p_{\perp 0}^2 + p_{\perp}^2)}{(p_{\perp 0}^2 + p_{\perp}^2)^2} \quad \text{(more physical)}
\]

where \( p_{\perp \text{min}} \) or \( p_{\perp 0} \) are free parameters, empirically of order 2 GeV

Typically 2 – 3 interactions/event at the Tevatron, 4 – 5 at the LHC, but may be more in “interesting” high-\( p_{\perp} \) ones.
Modelling multiple interactions

T. Sjöstrand, M. van Zijl, PRD36 (1987) 2019: first model(s) for event properties based on perturbative multiple interactions

(1) Simple scenario:

- Sharp cut-off at $p_{\perp \text{min}}$ main free parameter
- Is only a model for nondiffractive events, i.e. for $\sigma_{\text{nd}} \simeq (2/3)\sigma_{\text{tot}}$
- Average number of interactions is $\langle n \rangle = \sigma_{\text{int}}(p_{\perp \text{min}})/\sigma_{\text{nd}}$
- Interactions occur almost independently, i.e.
  
  Poissonian statistics $P_n = \langle n \rangle^n e^{-\langle n \rangle}/n!$
  
  with fraction $P_0 = e^{-\langle n \rangle}$ pure low-$p_{\perp}$ events
- Interactions generated in ordered sequence $p_{\perp 1} > p_{\perp 2} > p_{\perp 3} > \ldots$
  
  by “Sudakov” trick (what happens “first”?)

\[
\frac{dP}{dp_{\perp i}} = \frac{1}{\sigma_{\text{nd}} d\sigma_{\perp}} \exp \left[ - \int_{p_{\perp i-1}}^{p_{\perp i-1}} \frac{1}{\sigma_{\text{nd}} d\sigma_{p_{\perp}^{'}}} dp_{\perp}^{'}, \right] \]

- Momentum conservation in PDF’s $\Rightarrow P_n$ narrower than Poissonian
- Simplify after first interaction: only $gg$ or $q\bar{q}$ outgoing, no showers, \ldots
(2) More sophisticated scenario:

- Smooth turn-off at $p_{\perp0}$ scale
- Require $\geq 1$ interaction in an event
- Hadrons are extended,
  e.g. double Gaussian (“hot spots”):

$$\rho_{\text{matter}}(r) = N_1 \exp\left(-\frac{r^2}{r_1^2}\right) + N_2 \exp\left(-\frac{r^2}{r_2^2}\right)$$

where $r_2 \neq r_1$ represents “hot spots”

- Events are distributed in impact parameter $b$
- Overlap of hadrons during collision

$$\mathcal{O}(b) = \int d^3x \, dt \, \rho_{1,\text{matter}}^{\text{boosted}}(x, t) \rho_{2,\text{matter}}^{\text{boosted}}(x, t)$$

- Average activity at $b$ proportional to $\mathcal{O}(b)$
  $\Rightarrow$ central collisions normally more active
  $\Rightarrow \mathcal{P}_n$ broader than Poissonian
- More time-consuming $(b, p_{\perp})$ generation
- Need for simplifications remains
(3) HERWIG
Soft Underlying Event (SUE), based on UA5 Monte Carlo

- Distribute a (∼ negative binomial) number of clusters independently in rapidity and transverse momentum according to parametrization/extrapolation of data
- modify for overall energy/momentum/flavour conservation
- no minijets; correlations only by cluster decays

(4) Jimmy (HERWIG add-on)
- similar to PYTHIA (2) above; but details different
- matter profile by electromagnetic form factor
- no $p_{\perp}$-ordering of emissions, no rescaling of PDF: abrupt stop when (if) run out of energy

(5) Phojet/DTUjet
- comes from “historical” tradition of soft physics of “cut Pomerons” $\approx p_{\perp} \rightarrow 0$ limit of multiple interactions
- extended also to “hard” interactions similarly to PYTHIA
FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low $p_T$ only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

FIG. 4. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs simple models; the latter models with notation as in Fig. 3.

without multiple interactions
FIG. 5. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs impact-parameter-independent multiple-interaction model: dashed line, $p_{T\text{min}}=2.0$ GeV; solid line, $p_{T\text{min}}=1.6$ GeV; dashed-dotted line, $p_{T\text{min}}=1.2$ GeV.

with multiple interactions

FIG. 6. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs impact-parameter-independent multiple-interaction model; the latter with notation as in Fig. 5.
Evidence for multiple interactions

- **Width of multiplicity distribution: UA5, E735**
  (previous slides)

- **Forward–backward correlations: UA5**
  (previous slides)

- **Minijet rates: UA1**

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<th>simple</th>
<th>double Gaussian</th>
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<td>0.07</td>
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</table>
Direct observation: AFS, (UA2,) CDF

Order 4 jets \( p_{\perp 1} > p_{\perp 2} > p_{\perp 3} > p_{\perp 4} \) and define \( \varphi \) as angle between \( p_{\perp 1} - p_{\perp 2} \) and \( p_{\perp 3} - p_{\perp 4} \)

**Double Parton Scattering**

\[
|p_{\perp 1} + p_{\perp 2}| \approx 0 \\
|p_{\perp 3} + p_{\perp 4}| \approx 0
\]

\[d\sigma/d\varphi \text{ flat}\]

**Double Bremsstrahlung**

\[
|p_{\perp 1} + p_{\perp 2}| \gg 0 \\
|p_{\perp 3} + p_{\perp 4}| \gg 0
\]

\[d\sigma/d\varphi \text{ peaked at } \varphi \approx 0\]

AFS 4-jet analysis (pp at 63 GeV);

double bremsstrahlung subtracted:

- observed 6 in arbitrary units
- no MI 0
- simple MI 1
- double Gaussian 3.7
CDF 3-jet + prompt photon analysis

Yellow region = double parton scattering (DPS)

The rest = PYTHIA showers

\[
\sigma_{\text{DPS}} = \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}} \quad \text{for } A \neq B \quad \implies \sigma_{\text{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3} \text{ mb}
\]

Strong enhancement relative to naive expectations!
Jet pedestal effect: UA1, H1, CDF

Events with hard scale (jet, W/Z, ...) have more underlying activity!

Events with \( n \) interactions have \( n \) chances that one of them is hard,
so "trigger bias": hard scale \( \Rightarrow \) central collision
\( \Rightarrow \) more interactions \( \Rightarrow \) larger underlying activity.

Centrality effect saturates at \( p_{\text{hard}} \sim 10 \text{ GeV} \).

Studied in detail by Rick Field, comparing with CDF data:

"MAX/MIN Transverse" Densities

Define the MAX and MIN "transverse" regions on an event-by-event basis with
MAX (MIN) having the largest (smallest) density.
Plot shows the “Transverse” $<\text{Nchg}>$ versus $P_T(\text{chgjet#1})$ compared to the QCD hard scattering predictions of Herwig 5.9, Isajet 7.32, and Pythia 6.115 (default parameters with $P_T(\text{hard})>3\text{ GeV/c}$).

Only charged particles with $|\eta| < 1$ and $P_T > 0.5\text{ GeV}$ are included and the QCD Monte-Carlo predictions have been corrected for efficiency.
Plot shows the “Transverse” charged particle density versus $P_T(chgjet#1)$ compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and PYTHIA 6.206 (Set A) PARP(67)=4)).
Compares the average “transverse” charge particle density ($|\eta|<1$, $P_T>0.5$ GeV) versus $P_T$ (charged jet#1) and the $P_T$ distribution of the “transverse” density, $dN_{\text{chg}}/d\eta d\phi dP_T$ with the QCD Monte-Carlo predictions of two tuned versions of PYTHIA 6.206 ($P_T$(hard) > 0, CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).
Charged particle density and PTsum density for “leading jet” events versus $E_{T}(\text{jet#1})$ for PYTHIA Tune A and HERWIG.
Shows the average charged particle density, \( \frac{dN_{\text{ch}}}{d\eta d\phi} \), in the "transverse" region (\( p_T > 0.5 \text{ GeV}/c \), \(|\eta| < 1\)) versus \( E_T(jet\#1) \) for "Leading Jet" and "Back-to-Back" events.

Compares the (uncorrected) data with PYTHIA Tune A and HERWIG after CDFSIM.
"Back-to-Back" "Associated" Charged Particle Densities

Shows the $\Delta \phi$ dependence of the "associated" charged particle density, $dN_{\text{chg}}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, $PT_{\text{maxT}} > 2.0$ GeV/c (not including $PT_{\text{maxT}}$) relative to $PT_{\text{maxT}}$ (rotated to 180°) and the charged particle density, $dN_{\text{chg}}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, relative to jet#1 (rotated to 270°) for "back-to-back events" with $30 < E_T(\text{jet#1}) < 70$ GeV.
For PT$_{\text{maxT}}$ > 2.0 GeV both PYTHIA and HERWIG produce slightly too many “associated” particles in the direction of PT$_{\text{maxT}}$!

But HERWIG (without multiple parton interactions) produces too few particles in the direction opposite of PT$_{\text{maxT}}$!
"Transverse 1" Region vs "Transverse 2" Region

CDF Run 2 Preliminary
Leading Jet
30 < ET(jet#1) < 70 GeV
1.96 TeV
Charged Particles (|η|<1.0, PT>0.5 GeV/c)

CDF Run 2 Preliminary
Back-to-Back
30 < ET(jet#1) < 70 GeV
1.96 TeV
Charged Particles (|η|<1.0, PT>0.5 GeV/c)
PYTHIA Tune A vs JIMMY: “Transverse Region”

- **(left)** Run 2 data for charged scalar PTsum density ($|\eta|<1$, $p_T>0.5$ GeV/c) in the MAX/MIN/AVE “transverse” region versus $P_T(jet#1)$ compared with PYTHIA Tune A (after CDFSIM).

- **(right)** Shows the generator level predictions of PYTHIA Tune A (*dashed*) and JIMMY ($P_T\text{min}=1.8$ GeV/c) for charged scalar PTsum density ($|\eta|<1$, $p_T>0.5$ GeV/c) in the MAX/MIN/AVE “transverse” region versus $P_T(jet#1)$.

- The tuned JIMMY now agrees with PYTHIA for $P_T(jet#1) < 100$ GeV but produces much more activity than PYTHIA Tune A (and the data?) in the “transverse” region for $P_T(jet#1) > 100$ GeV!
Colour correlations

\( \langle p_\perp \rangle (n_{\text{ch}}) \) is very sensitive to colour flow

long strings to remnants \( \Rightarrow \) much \( n_{\text{ch}}/\text{interaction} \) \( \Rightarrow \) \( \langle p_\perp \rangle (n_{\text{ch}}) \sim \) flat

short strings (more central) \( \Rightarrow \) less \( n_{\text{ch}}/\text{interaction} \) \( \Rightarrow \) \( \langle p_\perp \rangle (n_{\text{ch}}) \) rising

FIG. 27. Average transverse momentum of charged particles in \( |\eta| < 2.5 \) as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming \( q\bar{q} \) scatterings only; dotted line, \( gg \) scatterings with “maximal” string length; solid line \( gg \) scatterings with “minimal” string length.
"Transverse" \( <p_T> \) versus "Transverse" \( N_{\text{chg}} \)

- Look at the \( <p_T> \) of particles in the "transverse" region (\( p_T > 0.5 \) GeV/c, \( |\eta| < 1 \)) versus the number of particles in the "transverse" region: \( <p_T> \) vs \( N_{\text{chg}} \).

- Shows \( <p_T> \) versus \( N_{\text{chg}} \) in the "transverse" region (\( p_T > 0.5 \) GeV/c, \( |\eta| < 1 \)) for "Leading Jet" and "Back-to-Back" events with \( 30 < E_T(jet#1) < 70 \) GeV compared with "min-bias" collisions.
Energy dependence of $p_{\perp \min}$ and $p_{\perp 0}$

Larger collision energy
⇒ probe parton ($\approx$ gluon) density at smaller $x$
⇒ smaller colour screening length $d$
⇒ larger $p_{\perp \min}$ or $p_{\perp 0}$

Post-HERA PDF fits steeper at small $x$
⇒ stronger energy dependence

Current PYTHIA default (Tune A, old model), tied to CTEQ 5L, is

$$p_{\perp \min}(s) = 2.0 \text{ GeV} \left( \frac{s}{(1.8 \text{ TeV})^2} \right)^{0.08}$$
Extrapolation of $P_{T\_min}$ I

Fitting to: $P_{T\_min}(\sqrt{s}) = P_{T\_min}^{LHC} \left( \frac{\sqrt{s}}{14 \text{ TeV}} \right)^{2\epsilon}$

$P_{T\_Min} = 3.34 \pm 0.13$

$\epsilon = 0.079 \pm 0.006$

These values give:

$<dN_{ch}/d\eta>_{\eta=0}^{LHC} = 6.45 \pm 0.25$

in Single-Diffractive Events

Compared to the phenomenological extrapolation of:

$<dN_{ch}/d\eta>_{\eta=0}^{LHC} = 6.27 \pm 0.50$

→ Compatible
Comparison of the dijet and the Z-boson data on the average number of charged particles ($P_T > 0.5$ GeV, $|\eta| < 1$) for the “transverse” region.

The plot shows the QCD Monte-Carlo predictions of PYTHIA 6.115 (default parameters with $P_T$(hard)$>3$ GeV/c) for dijet (dashed) and “Z-jet” (solid) production.
Initiators and Remnants

- PDF after preceding MI/ISR activity:
  0) Squeeze range $0 < x < 1$ into $0 < x < 1 - \sum x_i$ (ISR: $i \neq i_{\text{current}}$)
  1) Valence quarks: scale down by number already kicked out
  2) Introduce companion quark $q/\bar{q}$ to each kicked-out sea quark $\bar{q}/q$, with $x$ based on assumed $g \rightarrow q\bar{q}$ splitting
  3) Gluon and other sea: rescale for total momentum conservation

- Need to assign:
  - correlated flavours
  - correlated $x_i = p_{zi}/p_{z\text{tot}}$
  - correlated primordial $k_{\perp i}$
  - correlated colours
  - correlated showers
Beam remnant physics

Colour flow connects hard scattering to beam remnants. Can have consequences, e.g. in $\pi^- p$

$$A(x_F) = \frac{\#D^- - \#D^+}{\#D^- + \#D^+}$$

(Also B asymmetries at LHC, but small)

If low-mass string e.g.:
- $\bar{c}d$: $D^-, D^{*-}$
- $cud$: $\Lambda_c^+, \Sigma_c^+, \Sigma_c^{*-}$

$\Rightarrow$ flavour asymmetries

Can give $D$ ‘drag’ to larger $x_F$ than $c$ quark for any string mass
Interleaved Multiple Interactions

$p_\perp$

$p_\perp_{\text{max}}$

$p_\perp_1$

$p_\perp_{\text{ISR}}$

$p_\perp_2$

$p_\perp_{\text{ISR}}$

$p_\perp_3$

$p_\perp_{\text{ISR}}$

$p_\perp_{\text{ISR}}$

$p_\perp_{123}$

$p_\perp_4$

$p_\perp_{\text{min}}$

hard int.

ISR

mult. int.

interaction number
Competition

“Evolution” equation, only Multiple Interactions:

\[
\frac{d\mathcal{P}}{dp_\perp} = \frac{d\mathcal{P}_{\text{MI}}}{dp_\perp} \exp \left( - \int_{p_\perp}^{p_{\perp i-1}} \frac{d\mathcal{P}_{\text{MI}}}{dp'_\perp} dp'_\perp \right)
\]

Evolution equation, only Initial State Radiation:

\[
\frac{d\mathcal{P}}{dp_\perp} = \frac{d\mathcal{P}_{\text{ISR}}}{dp_\perp} \exp \left( - \int_{p_\perp}^{p_{\perp i-1}} \frac{d\mathcal{P}_{\text{ISR}}}{dp'_\perp} dp'_\perp \right)
\]

Evolution equation, MI + ISR, with competition for PDF and phase space:

\[
\frac{d\mathcal{P}}{dp_\perp} = \left( \frac{d\mathcal{P}_{\text{MI}}}{dp_\perp} + \sum \frac{d\mathcal{P}_{\text{ISR}}}{dp_\perp} \right) \exp \left( - \int_{p_\perp}^{p_{\perp i-1}} \left( \frac{d\mathcal{P}_{\text{MI}}}{dp'_\perp} + \sum \frac{d\mathcal{P}_{\text{ISR}}}{dp'_\perp} \right) dp'_\perp \right)
\]

with ISR sum running over all previous MI

\[ \Rightarrow \text{one interleaved sequence of MI and ISR} \]

FSR: no competition so not required (but nice for ME merging)
Other issues

- **Regularization procedure:**

  \[
  \alpha_s(p^2_\perp) \frac{dp^2_\perp}{p^2_\perp} \rightarrow \alpha_s(p^2_{\perp 0} + p^2_\perp) \frac{dp^2_\perp}{p^2_{\perp 0} + p^2_\perp}
  \]

  common for MI (quadratically) and ISR by colour neutralization

  \[ p_{\perp 0} \approx 2-3 \text{ GeV energy-dependent} \]

- **Intertwined interactions:**

  Not (yet) explicitly included, but estimated; shown not to be critical

- **Where does the baryon number go?**

  Junction “carries” baryon number!

  Motion determined by colour flow attached to it.

  Messy hadronization (but handled with model)
Data comparisons

usually comparable with Tune A (for better or worse), but still in need of good tuning and detailed tests, and 
... \( \langle p_\perp \rangle (n_{ch}) \) problematical (need very short string!)

![](image)

colour correlations not yet understood!
<table>
<thead>
<tr>
<th>Comments</th>
<th>PYTHIA6.2 - Default</th>
<th>ATLAS – TDR (PYTHIA5.7)</th>
<th>CDF – Tune A (PYTHIA6.206)</th>
<th>PYTHIA6.214 - Tuned</th>
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<td>Non-diffractive inelastic (MSEL=1)</td>
<td>Non-diffractive inelastic (MSEL=1)</td>
<td>Non-diffractive inelastic + double diffraction (MSEL=0, ISUB 94 and 95)</td>
<td>Non-diffractive + double diffraction (MSEL=0, ISUB 94 and 95)</td>
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<td>20% of the hadron radius (PARP(84) = 0.2)</td>
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**LHC predictions: pp collisions at $\sqrt{s} = 14$ TeV**

- **PYTHIA** models favour $\ln^2(s)$;
- **PHOJET** suggests a $\ln(s)$ dependence.

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- **Central Region**
  - (min-bias $dN_{\text{chg}}/d\eta \sim 7$)

- **LHC**
  - $dN_{\text{chg}}/d\eta \sim 30$

- **Tevatron**
  - $dN_{\text{chg}}/d\eta \sim 15$

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**A. M. Moraes**

**Minimum-bias and the Underlying Event at the LHC**

5th November 2004
LHC predictions: JIMMY4.1 Tunings A and B vs. PYTHIA6.214 – ATLAS Tuning (DC2)

- JIMMY4.1 - Tuning A
- JIMMY4.1 - Tuning B
- PYTHIA6.214 - ATLAS Tuning
- CDF data

\[ \text{Transverse } N_{\text{chg}} \]
\[ \text{Pt (leading jet in GeV)} \]

x 4  
x 5

x 3

Tevatron  
LHC
Multiple Interactions Outlook

- Multiple interactions concept compelling; it has to exist at some level. ●
  - By now, strong direct evidence, overwhelming indirect evidence ●

- Understanding of multiple interactions crucial for LHC precision physics ●

- Many details uncertain ●
  - $p_{\perp \min}/p_{\perp 0}$ cut-off ●
  - impact parameter picture ●
  - energy dependence ●
  - multiparton densities in incoming hadron ●
  - colour correlations between scatterings ●
  - interferences between showers ●
  - . . . ●

- Above physics aspects must all be present, and more? ●

  [If a model is simple, it is wrong!]

- So stay tuned for even more complicated models in the future. . . . ●