Towards a Theory of Everything
Phenomenology
The present state of phenomenology

- Heavily based on semi-classical approximations
  - Leading Order, Leading Log, Leading Color, semi-classical string models
- Sufficient to reach $O(10\%)$ accuracy (with hard work)
  - $\rightarrow$ sufficient to get overall picture during first few years of LHC running
- So no immediate danger from not having a P.O.E.T.

However

- Purely experimental precision will reach much better than 10%
- Next machine is a long way off

The task of phenomenology in the LHC era

- Gain a complete understanding of ‘known’ physics $\rightarrow$ P.O.E.T., such that Questions can be asked, measurements performed, with little or no limitations imposed by theoretical accuracy

The more immediate danger

- Is caused by the paradigm implied by being accustomed to events that both look like data and have an underlying (semi-)classical picture
“Another change that I find disturbing is the rising tyranny of Carlo. No, I don’t mean that fellow who runs CERN, but the other one, with first name Monte.

The simultaneous increase in detector complexity and in computation power has made simulation techniques an essential feature of contemporary experimentation. The Monte Carlo simulation has become the major means of visualization of not only detector performance but also of physics phenomena. So far so good. But it often happens that the physics simulations provided by the Monte Carlo generators carry the authority of data itself. They look like data and feel like data, and if one is not careful they are accepted as if they were data. All Monte Carlo codes come with a GIGO (garbage in, garbage out) warning label. But the GIGO warning label is just as easy for a physicist to ignore as that little message on a packet of cigarettes is for a chain smoker to ignore. I see nowadays experimental papers that claim agreement with QCD (translation: someone’s simulation labeled QCD) and/or disagreement (translation: an unrealistic simulation), without much evidence of the inputs into those simulations.”
The Problem of Measurement

- It is tempting to correct measurements for “annoying” effects
  - Measurements are performed on long-lived / macroscopic objects which are almost classical

**Correspondence:** Large quantum numbers $\rightarrow$ classical

- Theory (MC): In Resonant, Singular, and Non-Perturbative limits, quantum $\rightarrow$ semi-classical “MC truth”
  - There either was or wasn’t a H / W / t / … in this event
  - Bremsstrahlung either was off *this* parton or off *that* parton
  - A string goes from *this* parton to *that* parton
  - *This* pion went over here, *that* pion went over there

$\Rightarrow$ hadron-level $\rightarrow$ parton-level corrections, imagining an “LO” matrix element (with asymptotic incoming and outgoing partons) sitting in the middle of a bunch of gook, etc.

**Complementarity:** The wave function is subjective, and it is all you’re going to get - The “underlying classical truth” does not exist (no hidden variables)
We need to listen to Niels! The semi-classical nature of current descriptions is formally correct, but nonetheless deceptive

- Multi-slit experiments. Signal and background will interfere, at some level

Quantum Interference Effects

- Resonant: interference between resonance and background.
  - An event-by-event truth does not exist.
  - That is why SHERPA does not put a Z in the event record for Z(\rightarrow hadrons)+jets.

- Bremsstrahlung: 1st-order interference treated semi-classically (angular ordering), but assignment of radiation to this or that parton still arbitrary.
  - That is why VINCIA does not assign a unique mother for each radiated gluon

- Non-perturbative: interference between different string/cluster topologies
  - Not accounted for in current descriptions
  - And: Color neutralization \rightarrow Impossible to associate a given hadron with a given parton

- Hadron-level: the momentum of each pion is affected by all other pions in the event (identical bosons, Bose-Einstein correlations).
  - There is no universal process-independent correction that would be infinitely precise
  - And: how long do you wait before you observe the leptons and hadrons?
Do we really need to calculate all of this?

- **Non-perturbative** hadronisation, color reconnections, beam remnants, strings, non-perturbative fragmentation functions, charged/neutral ratio, baryons, strangeness...

- **Soft Jets and Jet Structure**
  - Bremsstrahlung, underlying event (multiple perturbative parton interactions + more?), semi-hard brems jets, jet broadening, ...

- **My Resonance Mass…**

- **Hard Jet Tail**
  - High-$p_T$ jets at large angles

- **Inclusive**

- **Exclusive**

- **Hadron Decays**

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**These Things Are Your Friends**

- **IR Safety**: guarantees non-perturbative (NP) corrections suppressed by powers of NP scale

- **Factorization**: allows you to sum inclusively over junk you don’t know how to calculate

- **Unitarity**: allows you to estimate things you don’t know from things you know (e.g., loop singularities = - tree ones; $P(\text{fragmentation}) = 1, \ldots$)

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**+ Un-Physical Scales:**

- $Q_F, Q_R$ : Factorization(s) & Renormalization(s)
- $Q_E$ : Evolution(s)
Three Ways To High Precision
Who needs QCD? I’ll use leptons

- Sum inclusively over all QCD
  - Leptons *almost* IR safe by definition
  - WIMP-type DM, Z’, EWSB → may get some leptons
- Beams = hadrons for next decade (RHIC / Tevatron / LHC)
  - At least need *well-understood* PDFs
  - High precision = *higher orders* → enter QCD (and more QED)
- Isolation → indirect sensitivity to QCD
- Fakes → indirect sensitivity to QCD
- Not everything gives leptons
  - Need to be a lucky chicken …

The unlucky chicken

- Put all its eggs in one basket and didn’t solve QCD
I’ll use semi-inclusive observables

- Sum inclusively over the worst parts of QCD
  - IR safety $\rightarrow$ N.P. corrs suppressed by $Q_{\text{had}}$
  - $\rightarrow$ IR safe jet algs (e.g., FASTJET)

- Beams = hadrons for next decade (RHIC / Tevatron / LHC)
  - Still need well-understood PDFs
  - High precision $\Rightarrow$ more higher orders $\rightarrow$ more QCD

- Large hierarchies $(s, m_1, m_2, p_{T\text{jet}1}, p_{T\text{jet}2}, \ldots) \rightarrow$ Careful!
  - Huge jet rate enhancements: perturbative series “blows up”
  - $\rightarrow$ cannot truncate at any fixed order
    - For 600 GeV particles, a 100 GeV jet can be “soft”
  - Use infinite-order approximations $=$ parton showers
    - Only “LL” $\rightarrow$ not highly precise + only good when everything is hierarchical
    - Need to combine with explicit matrix elements $\rightarrow$ matching (more later)
    - Still, non-factorizable + non-pert corrections set an ultimate limit
Now Hadronize This

Simulation from
D. B. Leinweber, hep-lat/0004025
gluon action density: 2.4 x 2.4 x 3.6 fm

Need a POET!
“Solving QCD” Part 1: Bremsstrahlung
Towards a Phenomenology of Everything

Beyond Fixed Order

Interpretation: the structure evolves

This is an approximation to infinite-order tree-level cross sections

This includes both real and virtual corrections

"DLA" $\alpha_s s_{ab} \frac{\sigma}{s_{ai} s_{ib}}$

$d\sigma_X = \ldots$

$d\sigma_{X+1} \sim 2g^2 d\sigma_X \frac{ds_{a1}}{s_{a1}} \frac{ds_{1b}}{s_{1b}}$

$d\sigma_{X+2} \sim 2g^2 d\sigma_{X+1} \frac{ds_{a2}}{s_{a2}} \frac{ds_{2b}}{s_{2b}}$

$d\sigma_{X+3} \sim 2g^2 d\sigma_{X+2} \frac{ds_{a3}}{s_{a3}} \frac{ds_{3b}}{s_{3b}}$

But something's not right…

Unitarization

Given a jet definition

- An even has either 0, 1, 2, … jets

$\sigma_{X;\text{excl}} = \sigma_X - \sigma_{X+1}$

$= \sigma_X - \sigma_{X+1;\text{excl}} - \sigma_{X+2;\text{excl}} - \ldots$
In these calculations, there are many dependencies on things not traditionally found in matrix-element calculations:

- The choice of shower evolution “time”
- The splitting functions (finite terms not fixed)
- The phase space map (“recoils”, $d\Phi_{n+1}/d\Phi_n$)
- The renormalization scheme (vertex-by-vertex argument of $\alpha_s$)
- The infrared cutoff contour (hadronization cutoff)
- + Matching prescription and “matching scales”

Variations ➔ Comprehensive uncertainty estimates (showers with uncertainty bands)

Matching to MEs (& $N^nLL$?) ➔ Reduced Dependence (systematic reduction of uncertainty)
“Matching”? 

► A (Complete Idiot’s) Solution – Combine

- \([X]_{ME} +\) showering
- \([X + 1\ \text{jet}]_{ME} +\) showering
- ...

► Doesn’t work

- \([X] +\) shower is inclusive
- \([X+1] +\) shower is also inclusive

What you get

\[X\ \text{inclusive}
\]

\[X+1\ \text{inclusive}
\]

\[X+2\ \text{inclusive}
\]

Overlapping “bins”

\[\neq\]

What you want

\[X\ \text{exclusive}
\]

\[X+1\ \text{exclusive}
\]

\[X+2\ \text{inclusive}
\]

One sample

Run generator for \(X\) (+ shower)
Run generator for \(X+1\) (+ shower)
Run generator for … (+ shower)
Combine everything into one sample
[X]_{ME} + shower already contains sing { [X + n jet]_{ME} }

- So we really just missed the non-LL bits, not the entire ME!
- Adding full [X + n jet]_{ME} is overkill ➞ LL singular terms are double-counted

Solution 1: work out the difference and correct by that amount

[ X + n jet ]_{ME} ➞ add “shower-subtracted” matrix elements

- Correction events with weights: \( w_n = [X + n jet]_{ME} - \text{Shower}\{w_{n-1,2,3,...}\} \)
- I call these matching approaches “additive”
  - Herwig, CKKW, MLM, ARIADNE + MC@NLO

Solution 2: work out the ratio between PS and ME

[ X + n jet ]_{ME} \times \text{Shower}\{(X+n-1 jet)_{ME}\} ➞ multiply shower kernels by that ratio (1 if shower is an overestimate)

- Correction factor on n’th emission \( P_n = \frac{[X + n jet]_{ME}}{\text{Shower}\{(X+n-1 jet)_{ME}\}} \)
- I call these matching approaches “multiplicative”
  - Pythia, POWHEG, VINCIA
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**First Order Shower expansion**

\[
\int d\Phi_2 \, |M_2^{(0)}|^2 \int_{Q_{\text{had}}^2}^s \frac{d\Phi_3}{d\Phi_2} A_{q\bar{q}}(\ldots) \delta (O - O(\{p\}^3))
\]

Unitarity of shower \(\Rightarrow\) 3-parton real = \(\div\) 2-parton “virtual”

**3-parton real correction** \((A_3 = |M_3|^2/|M_2|^2 + \text{finite terms; } \alpha, \beta)\)

\[
w_3^{(R)} = |M_3^{(0)}|^2 - \left( A_3^{0}(\ldots) + \frac{4\pi \alpha_s \hat{C}_F}{s} \left( \alpha + \beta \frac{s_{ar} + s_{rb}}{s} \right) \right) |M_2^{(0)}|^2
\]

\[
= - \frac{4\pi \alpha_s \hat{C}_F}{s} \left( \alpha + \beta \frac{s_{ar} + s_{rb}}{s} \right) |M_2^{(0)}|^2
\]

\[
\Rightarrow \text{Finite terms cancel in 3-parton } O
\]

**2-parton virtual correction** (same example)

\[
w_2^{(V)} = 2 \text{Re} \left[ M_2^{(1)} M_2^{(0)*} \right] + |M_2^{(0)}|^2 \int_0^s \frac{d\Phi_3}{d\Phi_2} A_{q\bar{q}}(\ldots) + \int_{Q_{\text{had}}^2}^s \frac{d\Phi_3}{d\Phi_2} w_3^{(R)}
\]

\[
= \frac{\alpha_s \hat{C}_F}{2\pi} \left( 2I_{qq}^{(1)}(\epsilon, s) - 4 - 2I_{q\bar{q}}^{(1)}(\epsilon, s) + \frac{19 + \alpha + \frac{2}{3} \beta}{4} \right) |M_2^{(0)}|^2
\]

\[
= \frac{\alpha_s}{\pi} \left( 1 + \frac{1}{3} \left( \alpha + \frac{2}{3} \beta \right) \right) |M_2^{(0)}|^2
\]

\[
\Rightarrow \text{Finite terms cancel in 2-parton } O \text{ (normalization)}
\]
Based on Dipole-Antennae

- Shower off color-connected pairs of partons
- Plug-in to PYTHIA 8 (C++)

So far:

- **Choice of evolution time:**
  - $p_T$-ordering
  - Dipole-mass-ordering
  - Energy-Ordering

- **Splitting functions**
  - QCD singular terms + arbitrary finite terms (Taylor series)

- **Phase space map**
  - Antenna-like or Parton-shower-like

- **Renormalization scheme** ($\mu_R = \{\text{evolution scale, } s_{\text{ant}}, \text{ fixed}\}$)

- **Infrared cutoff contour (hadronization cutoff)**
  - Same options as for evolution time (except E), but independent of time $\rightarrow$ universal choice
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Ordering

Phase Space for $2 \to 3$

\[ y_{jk} = \frac{s_{jk}}{s} \]

\[ y_{23} \]

\[ y_{12} \]

collinear

\[ Q_1^2(p_a, p_r, p_b) = 4 \frac{s_{ar} s_{rb}}{s_{arb}} = 4 p_\perp^2 \]

\[ Q_\perp^2(p_a, p_r, p_b) = 2 \min(s_{ar}, s_{rb}) \]

\[ \text{VINCIA, ARIADNE & JAN} \]

\[ \text{VINCIA} \]

\[ p_T^2 - \text{Ordering} \]

\[ m_{\text{Am}}^2 - \text{Ordering} \]

\[ VINCIA, ARIADNE \& JAN \]

\[ VINCIA \]

Jetset & Fortran Pythia

Pythia 6.3+ & Pythia 8.

Herwig++

DM, ANA & VINCIA

Virtuality-Ordering: side a

\[ V_n = \frac{s_{ar}}{s_{arb}} = 1 - x_b \]

\[ 0.25 \]

\[ 0.5 \]

\[ 0.75 \]

\[ p_T^2_{\text{eval}} - \text{Ordering: side a} \]

\[ V_n = \frac{s_{ar}}{s_{arb}} = 1 - x_b \]

\[ 0.25 \]

\[ 0.5 \]

\[ 0.75 \]

\[ \text{Angular Ordering} \]

\[ \text{Energy-Ordering} \]

\[ y_{ar} = \frac{s_{ar}}{s_{arb}} = 1 - x_b \]

\[ 0.25 \]

\[ 0.5 \]

\[ 0.75 \]
Second Order

Second Order Shower expansion for 4 partons (assuming first already matched)

\[
\int d\Phi_3 |M_3^{(0)}|^2 \int_{Q_{had}^2}^{Q_{Z}^2} \frac{d\Phi_3}{d\Phi_2} (A_{qg} + A_{g\bar{q}}) \delta (\mathcal{O} - \mathcal{O}([p]_4))
\]

Problem 1: dependence on evolution variable

- Shower is ordered \( t_4 \) integration only up to \( t_3 \)
- \( \rightarrow 2, 1, \) or \( 0 \) allowed “paths”
- \( 0 = \) Dead Zone: not good for reweighting

Largest/Smallest no of paths: Ev=1 Kin=1

AR \( p_T \) + AR recoil

max # of paths

min # of paths

4pT2(1,2,3)

4pT2(0,1,2)
Second Order Shower expansion for 4 partons (assuming first already matched)

\[ \int \Phi_3 |M_3(0)|^2 \int_{Q_{\text{had}}^2} \frac{d\Phi_3}{d\Phi_2} (A_{qq} + A_{g\bar{q}}) \delta (\mathcal{O} - \mathcal{O}(|p\rangle_4)) \]

Define over/under-counting ratio: PS_{tree} / ME_{tree}

\[ R_4^E = \frac{\Theta(Q_{A3} - Q_{A4}) A_{qq}(1, 2, 3) + \Theta(Q_{B3} - Q_{B4}) A_{g\bar{q}}(1, 2, 3, 4)}{A_4(1, 2, 3, 4)} \]

NB: EXTREMA of R_4\_distribution (100M points)

\[ A_{4LC} = \frac{|M_{4LC}(p_1, p_2, p_3, p_4)|^2}{|M_{\mathcal{A}}(s)|^2} \]
Current Vincia without matching, but with “improved” antenna functions (including suppressed unordered branchings)

**Improved antenna functions**

- Removes dead zone + still better approx than virt-ordered
  - (Good initial guess $\rightarrow$ better reweighting efficiency)

**Problem 2: leftover Subleading Logs after matching**

- There are still unsubtracted subleading divergences in the ME
At Pure LL,

- Can definitely see a non-perturbative correction, but hard to precisely constrain it.
- Can see ‘hard corrections’ too, which are not under control.

VINCIA in Action – LEP Event Shapes

After 1st Order Matching

- ~ MC@NLO


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VINCIA in Action – LEP Event Shapes

After 2nd order matching

- 2nd order Logs (NLL): ➔ Non-perturbative part can be precisely constrained
- 2nd order ME: ➔ Hard rad can be precisely constrained

Starting point: Matrix Elements + Parton Showers

- Hard parton-parton scattering
  - Normally $2 \rightarrow 2$ at LO or NLO

- + bremsstrahlung associated with it
  - $\Rightarrow 2 \rightarrow n$ in (improved) LL approximation
  - $\Rightarrow 2 \rightarrow n$ at LO up to matched order

But hadrons are not elementary

+ QCD diverges at low $p_T$

$\Rightarrow$ multiple perturbative parton-parton collisions
  - e.g. $4 \rightarrow 4$, $3 \rightarrow 3$, $3 \rightarrow 2$

No factorization theorem

Herwig++, Pythia, Sherpa: MPI models

Underlying Event has perturbative part!
**Towards a Phenomenology of Everything**

**MC Models: Non-Perturbative Part**

- **Need-to-know issues for IR sensitive quantities (e.g., $N_{ch}$)**

- $Q_F >> \Lambda_{QCD}$
  - $Q_F$ + perturbative MPI

- $Q_F \sim \Lambda_{QCD}$
  - + Stuff at
  - Hadronization
  - Remnants from the incoming beams
  - Additional (non-perturbative / collective) phenomena?
    - Bose-Einstein Correlations
    - Non-perturbative gluon exchanges / color reconnections?
    - String-string interactions / collective multi-string effects?
    - “Plasma” effects?
    - Interactions with “background” vacuum, remnants, or active medium?
Many nomenclatures being used.

- Not without ambiguity. I use:

- \( Q_{cut} \)
- \( IS \) → \( R \) 2→2
- Primary Interaction (~ trigger)

Inelastic, non-diffractive

Some freedom in how much particle production is ascribed to each: “hard” vs “soft” models

Multiple Parton Interactions

Underlying Event

Beam Remnants

Note: each is colored ➔ Not possible to separate clearly at hadron level
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**Analogue:** Resummation of multiple bremsstrahlung emissions

- Divergent $\sigma$ for one emission ($X + \text{jet}$, fixed-order)
- Finite $\sigma$ for divergent number of jets ($X + \text{jets}$, infinite-order)
  - $N(\text{jets})$ rendered finite by finite perturbative resolution = parton shower cutoff

**(Resummation of) Multiple Perturbative Interactions**

- Divergent $\sigma$ for one interaction (fixed-order)
- Finite $\sigma$ for divergent number of interactions (infinite-order)
  - $N(\text{jets})$ rendered finite by finite perturbative resolution = color-screening cutoff
    - ($E_{\text{cm}}$-dependent, but large uncert)

![Graph showing the resummation of multiple interactions](Bahr, Butterworth, Seymour: arXiv:0806.2949 [hep-ph])

- $\sigma [\text{mb}]$
  - MRST2007 LO
  - CTEQ6L
  - MRST2001 int.

- $p_{T,\text{min}} [\text{GeV}]$
  - QQ' $\rightarrow$ QQ'
  - QQ $\rightarrow$ p'Q'
  - QQ $\rightarrow$ gg
  - qq $\rightarrow$ gg
  - QQ $\rightarrow$ qq
  - $p_{T,\text{min}}$ with CTEQ 5L PDFs

- Integrate QCD $2 \rightarrow 2$
The new picture: start at the most inclusive level, \(2 \rightarrow 2\). Add exclusivity progressively by evolving everything downwards.

The Interleaved Idea

Fixed order matrix elements

Parton Showers (matched to further Matrix Elements)

multiparton PDFs derived from sum rules

perturbative “intertwining”?

Beam remnants
Fermi motion / primordial \(k_T\)

Underlying Event
(note: interactions correlated in colour: hadronization not independent)

→ correlations between all perturbative activity at successively smaller scales

New” Pythia model

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

∼ “Finegraining”

▶ Min-bias data at Tevatron showed a surprise

- Charged particle $p_T$ spectra were highly correlated with event multiplicity: **not expected**
- For his ‘Tune A’, Rick Field noted that a high correlation in color space between the different interaction chains could account for the behavior
- But needed ~ 100% correlation. So far not explained
- Virtually all ‘tunes’ now employ these more ‘extreme’ correlations
  - But existing models too crude to access detailed physics
- What is their origin? Why are they needed?

Successful models: string interactions (area law)


Solving QCD Part 3: Hadronization
Conclusions

► A perturbative Poet would allow us
  • To forget about the perturbative uncertainties
    ▪ (although we should still remember to evaluate them carefully)
  • To become reconciled with Niels and BJ
  • Extract really high precision from inclusive measurements
    ▪ High-energy frontier difficult to access → go for high-precision frontier
    ▪ Extract higher-energy information from high-precision lower-energy measurements
  • and focus on the really hard stuff …

► For which fundamentally new ideas may be needed
  • Non-factorizable perturbative dynamics. Is there a factorization theorem? Is there a no-go theorem? In any case, sensitive experimental tests needed to study detailed properties.
  • Non-perturbative dynamics so far only accessed by the lattice and phenomenological models.
    ▪ Input from heavy-ion limit (hydrodynamics, collective phenomena)?
    ▪ Input from AdS/QCD? (low-energy QCD ~ frozen coupling ~ conformal?)