Towards a ~~Model~~ ~~Theory~~ Phenomenology of Everything

Peter Skands
Theoretical Physics, Fermilab

A Phenomenology of Every Thing

► 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)
  - → 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 → 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

The Tyranny of Carlo

"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 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 with an alternative piece of physics (translation: an unrealistic simulation), without much evidence of the inputs into those simulations."

Green: not rather than the GIGO label? Theoretical Uncertainties:
What is in/relevant? What checks should be performed?

► **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 → classical

Niels Bohr (1885-1962)

- Theory (MC): In Resonant, Singular, and Non-Perturbative limits, quantum → 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

✂ ➔ hadron-level → 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)

Niels Bohr (1885-1962)

A (change of) Paradigm

► **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 <u>will</u> 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 <u>no universal process-independent correction</u> that would be infinintely precise
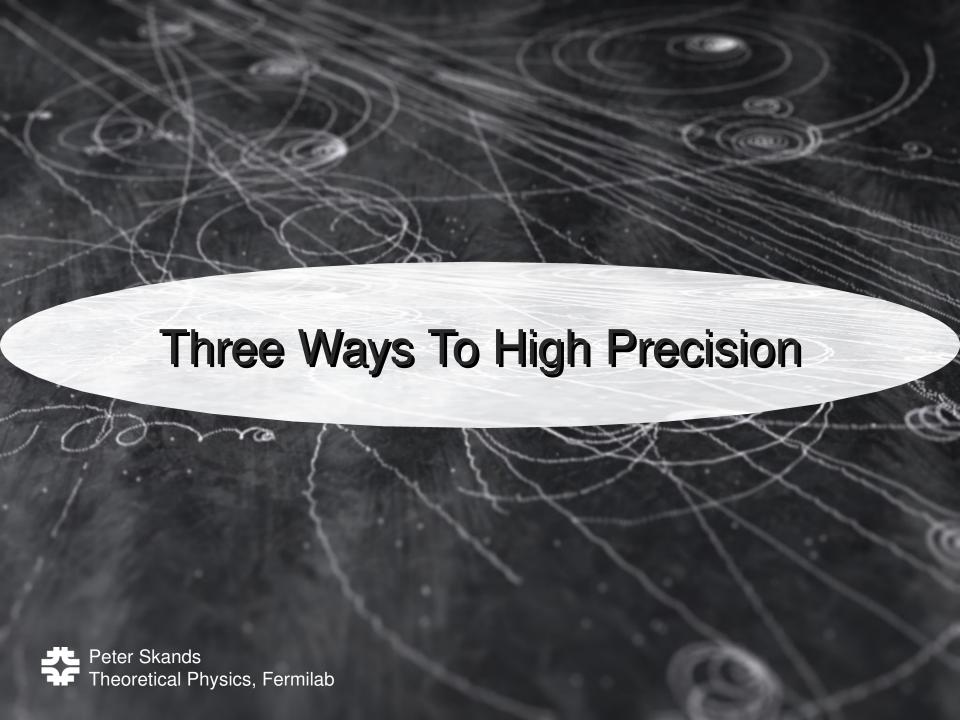   - And: how long do you wait before you observe the leptons and hadrons?

► Do we really need to calculate all of this?

Hadron Decays

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

Exclusive

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

My Resonance Mass…

Mass & Width

Hard Jet Tail
High-p_T jets at large angles

Inclusive

s

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(fragmentation) = 1, …)

+ Un-Physical Scales:
• Q_F , Q_R : Factorization(s) & Renormalization(s)
• Q_E : Evolution(s)

Three Ways To High Precision

Peter Skands
Theoretical Physics, Fermilab

The Way of the Chicken

► **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**

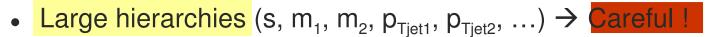- Put all its eggs in one basket and didn't solve QCD

The Way of the Fox
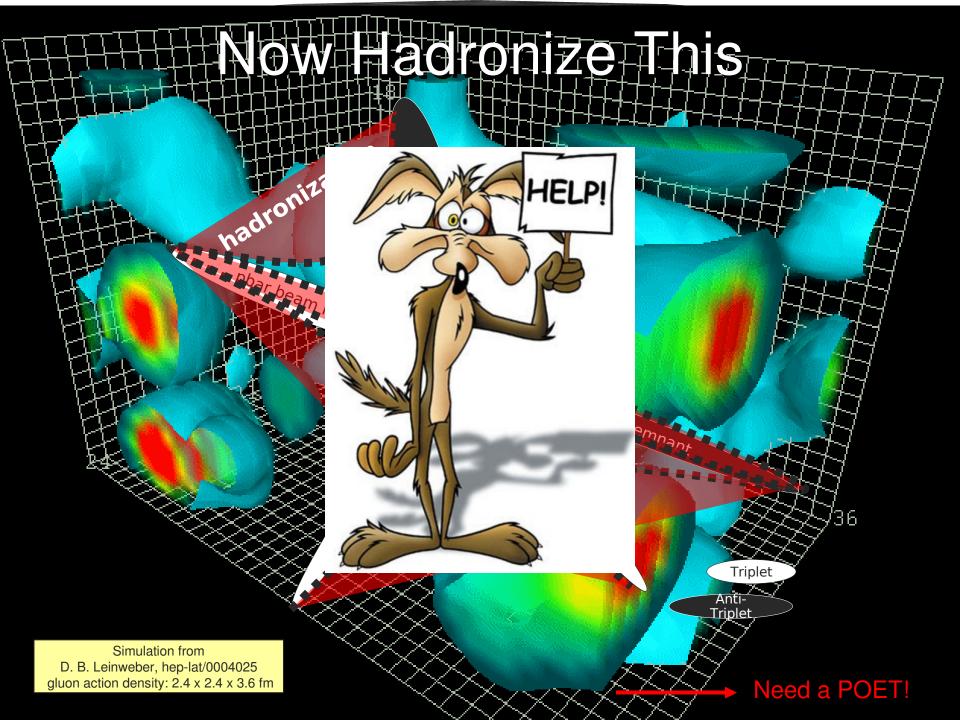
► **I'll use semi-inclusive observables**

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

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

- Large hierarchies (s, m_1, m_2, p_{Tjet1}, p_{Tjet2}, …) → Careful !
  - **Huge jet rate enhancements :** perturbative series "blows up"
  - → 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" → not highly precise + only good when **everything** is hierarchical
    - Need to combine with explicit matrix elements → **matching** (more later)
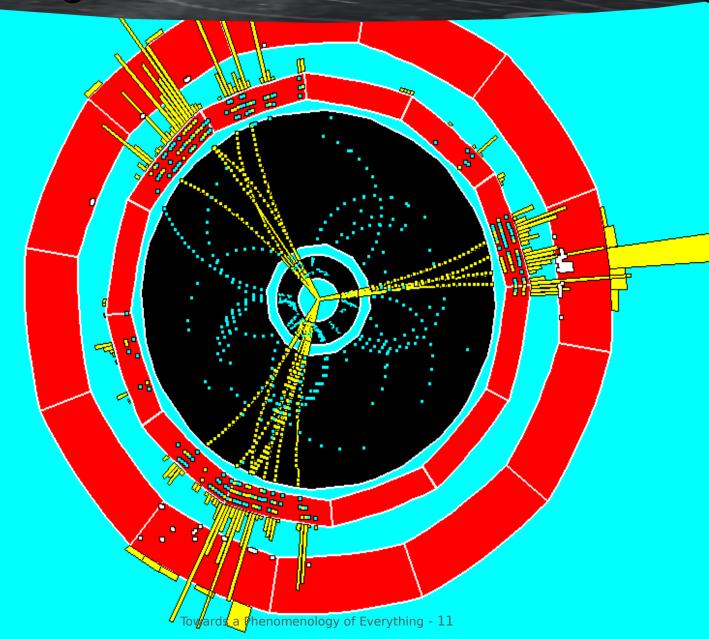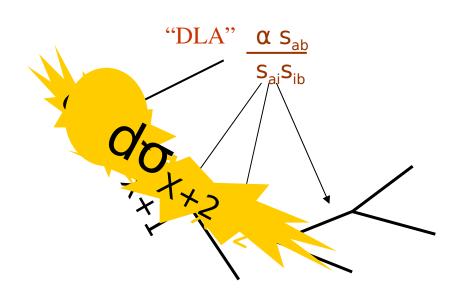   - Still, non-factorizable + non-pert corrections set an **ultimate** limit

Now Hadronize This

hadroniza

pbar beam

remnant

HELP!

Triplet

Anti-Triplet

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

"DLA" $\dfrac{\alpha\, s_{ab}}{s_{ai} s_{ib}}$

$\mathrm{d}\sigma_X$

$\mathrm{d}\sigma_{X+1}$

$\mathrm{d}\sigma_{X+2}$

$$\mathrm{d}\sigma_X = ...$$

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

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

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

Interpretation: the structure evolves

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

$$\sigma_{X+1}(Q) = \sigma_{X,\mathrm{incl}} - \sigma_{X,\mathrm{excl}}(Q)$$

This includes both real and virtual corrections

But some Unitarization t…

► Given a jet definition

- An even has *either* 0, 1, 2, … jets

$$\sigma_{X;\mathrm{excl}} = \sigma_X - \sigma_{X+1}$$
$$= \sigma_X - \sigma_{X+1;\mathrm{excl}} - \sigma_{X+2;\mathrm{excl}} - \cdots$$

Controlling the Calculation

► In these calculations, there are many dependencies on things not traditionally found in matrix-element calculations:

► The final answer will depend on:

- 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 α_s)

- The infrared cutoff contour (hadronization cutoff)

- + Matching prescription and "matching scales"

Variations →	Matching to MEs (& N^nLL?) →
Comprehensive uncertainty estimates	**Reduced Dependence**
(showers with uncertainty bands)	(systematic reduction of uncertainty)

"Matching"?
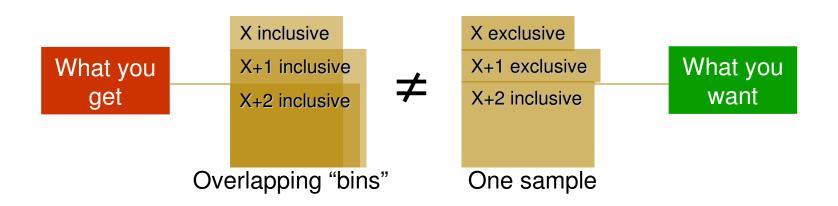
► A (Complete Idiot's) Solution – Combine

- $[X]_{ME}$ + showering
- $[X + 1\ jet]_{ME}$ + showering
- …

Run generator for X (+ shower)

Run generator for X+1 (+ shower)

Run generator for … (+ shower)

Combine everything into one sample

► Doesn't work

- [X] + shower is inclusive
- [X+1] + shower is also inclusive

What you get	X inclusive			≠	X exclusive			What you want
	X+1 inclusive				X+1 exclusive			
	X+2 inclusive				X+2 inclusive			

Overlapping "bins"   One sample

The Matching Game

- ► $[X]_{ME}$ + shower **already** contains $\mathrm{sing}\{$ $[X + n\ jet]_{ME}$ $\}$

  - 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 <u>double-counted</u>

- ► Solution 1: work out the <u>difference</u> and correct by *that amount*

  Seymour, CPC90(1995)95
  + many more recent …

  - ✂ ➔ add "shower-subtracted" matrix elements

  - Correction events with weights : $w_n = [X + n\ jet]_{ME} -$ Shower$\{w_{n-1,2,3,..}\}$

  - I call these matching approaches **"additive"**
    - **Herwig, CKKW, MLM, ARIADNE + MC@NLO**

  Sjöstrand, Bengtsson : NPB289(1987)810; PLB185(1987)435
  + one or two more recent …

- ► Solution 2: work out the <u>ratio</u> between PS and ME

  - ✂ ➔ multiply shower kernels by that ratio (< 1 if shower is an overestimate)

  - Correction **factor** on n'th emission $P_n = [X + n\ jet]_{ME}$ / Shower$\{[X+n-1\ jet]_{ME}\}$

  - I call these matching approaches **"multiplicative"**
    - **Pythia, POWHEG, VINCIA**
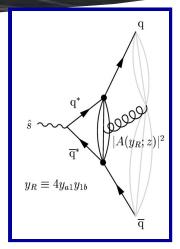
NLO with Addition

► **First Order Shower expansion**

PS

$$\int \mathrm{d}\Phi_2 \, |M_2^{(0)}|^2 \int_{Q_{\mathrm{had}}^2}^{s} \frac{\mathrm{d}\Phi_3}{\mathrm{d}\Phi_2} A_{q\bar{q}}(...)\delta\left(\mathcal{O} - \mathcal{O}(\{p\}_3)\right)$$

Unitarity of shower ➔ 3-parton real = ÷ 2-parton "virtual"

$y_R \equiv 4y_{a1}y_{1b}$

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

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

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

Finite terms cancel in 3-parton O

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

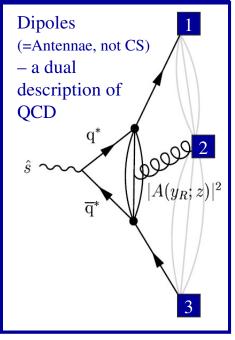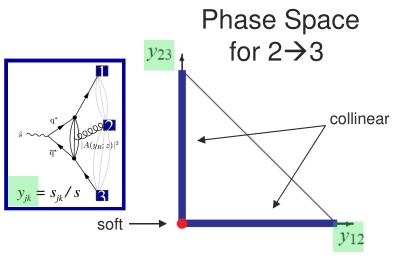$$w_2^{(V)} = 2\mathrm{Re}\left[M_2^{(1)}M_2^{(0)*}\right] + |M_2^{(0)}|^2 \int_0^s \frac{\mathrm{d}\Phi_3}{\mathrm{d}\Phi_2} A_{q\bar{q}}(...) + \int_0^{Q_{\mathrm{had}}^2} \frac{\mathrm{d}\Phi_3}{\mathrm{d}\Phi_2} w_3^{(R)}$$

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

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

Finite terms cancel in 2-parton O (normalization)

VINCIA

Gustafson, PLB175(1986)453; Lönnblad (ARIADNE), CPC71(1992)15.
Azimov, Dokshitzer, Khoze, Troyan, PLB165B(1985)147
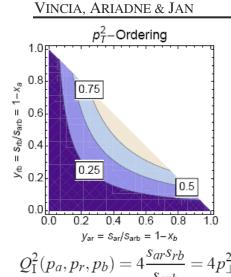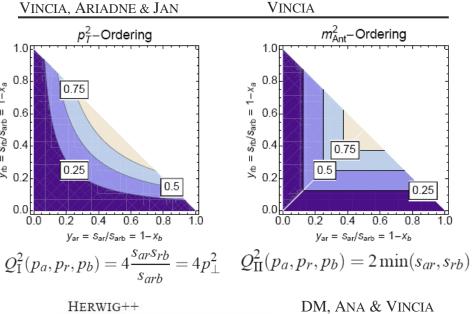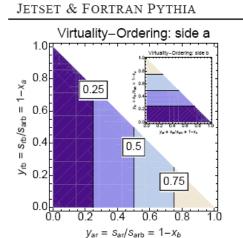Kosower PRD57(1998)5410; Campbell,Cullen,Glover EPJC9(1999)245

► **Based on Dipole-Antennae**

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

► So far: Giele, Kosower, PS : hep-ph/0707.3652 + Les Houches 2007

- Choice of evolution time:
  - pT-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 (μ_R = {evolution scale, s_{ant}, fixed})

- Infrared cutoff contour (hadronization cutoff)
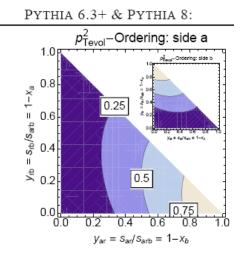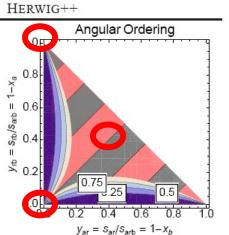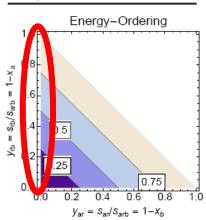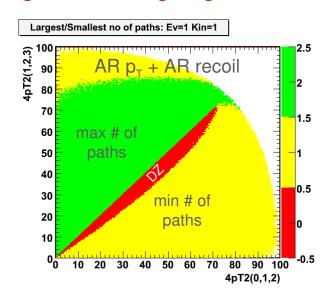 - Same options as for evolution time (except E), but independent of time → universal choice

Dipoles
(=Antennae, not CS)
– a dual
description of
QCD

$|A(y_R; z)|^2$

Ordering

Phase Space for 2→3

$$y_{jk} = s_{jk} / s$$

y_{23}

y_{12}

collinear

soft

p_T^2−Ordering

m_{Ant}^2−Ordering

$y_{rb} = s_{rb}/s_{arb} = 1 - x_a$

$y_{ar} = s_{ar}/s_{arb} = 1 - x_b$

0.75

0.25

0.5

0.75

0.5

0.25

$$Q_I^2(p_a, p_r, p_b) = 4\frac{s_{ar}s_{rb}}{s_{arb}} = 4p_\perp^2 \qquad Q_{II}^2(p_a, p_r, p_b) = 2\min(s_{ar}, s_{rb})$$

JETSET & FORTRAN PYTHIA

Virtuality−Ordering: side a

Virtuality−Ordering: side b

0.25

0.5

0.75

PYTHIA 6.3+ & PYTHIA 8:

p_{Tevol}^2−Ordering: side a

p_{Tevol}^2−Ordering: side b

0.25

0.5

0.75

HERWIG++

Angular Ordering

0.75

0.25

0.5

DM, ANA & VINCIA

Energy−Ordering

0.5

0.25

0.75

$y_{rb} = s_{rb}/s_{arb} = 1 - x_a$
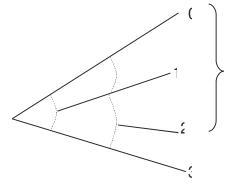
$y_{ar} = s_{ar}/s_{arb} = 1 - x_b$

Second Order

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

$$\int d\Phi_3 \, |M_3^{(0)}|^2 \int_{Q_{\text{had}}^2}^{Q_{E3}^2} \frac{d\Phi_3}{d\Phi_2} \, (A_{qg} + A_{g\bar{q}}) \, \delta\left(\mathcal{O} - \mathcal{O}(\{p\}_4)\right)$$

► Problem 1: dependence on evolution variable

- Shower is ordered ➔ t_4 integration only up to t_3

- ➔ 2, **1**, or **0** allowed "paths"
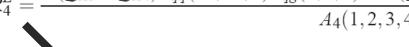
- **0** = Dead Zone : not good for reweighting

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

AR p_T + AR recoil

max # of paths

DZ

min # of paths

4pT2(1,2,3)

4pT2(0,1,2)

► **Second Order Shower expansion for 4 partons** (assuming first already matched)
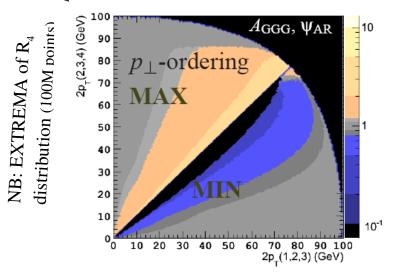
$$\int d\Phi_3 \, |M_3^{(0)}|^2 \int_{Q_{had}^2}^{Q_{E3}^2} \frac{d\Phi_3}{d\Phi_2} \, (A_{qg} + A_{g\bar{q}}) \, \delta \left(\mathcal{O} - \mathcal{O}(\{p\}_4) \right)$$
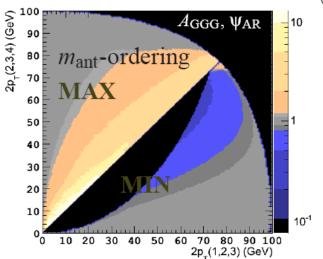
Define over/under-counting ratio: $\text{PS}_{tree} / \text{ME}_{tree}$

$$R_4^E = \frac{\Theta(Q_{A3} - Q_{A4}) A_{q\bar{q}}(\hat{12}, \hat{23}, 4) A_{qg}(1,2,3) + \Theta(Q_{B3} - Q_{B4}) A_{q\bar{q}}(1, \hat{23}, \hat{34}) A_{g\bar{q}}(2,3,4)}{A_4(1,2,3,4)}$$

$$A_{4LC} = \frac{|M_{4LC}(p_1, p_2, p_3, p_4)|^2}{|M_{\wedge}(s)|^2}$$

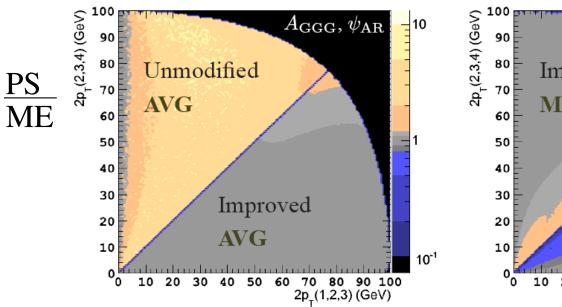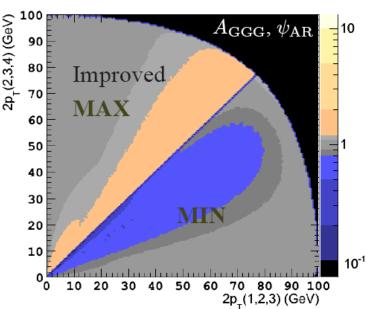NB: EXTREMA of R_4 distribution (100M points)

The Right Choice

► Current Vincia without matching, but with "improved" antenna functions (including suppressed unordered branchings)

Improved antenna functions

$$\frac{\text{PS}}{\text{ME}}$$
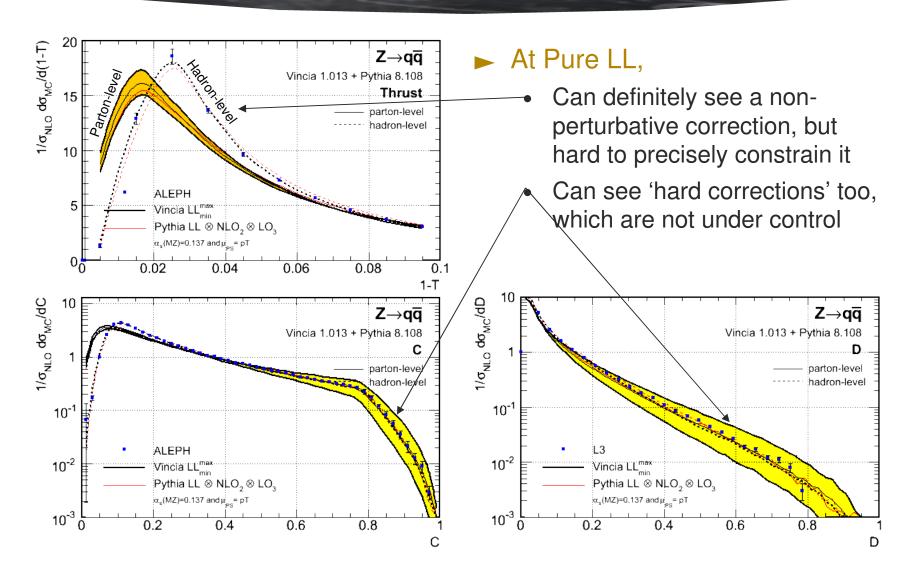
- Removes dead zone + still better approx than virt-ordered
  - (Good initial guess → better reweighting efficiency)

► Problem 2: leftover Subleading Logs after matching

- There are still unsubtractred 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
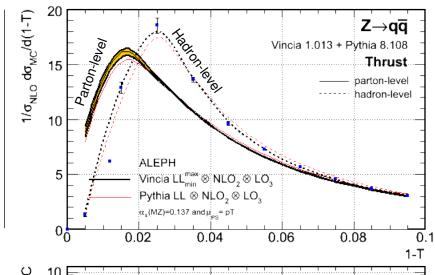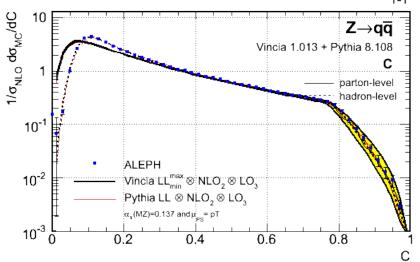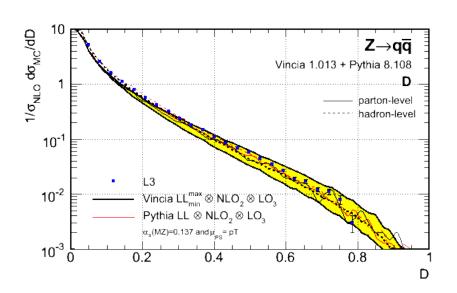
► **After 1st Order Matching**
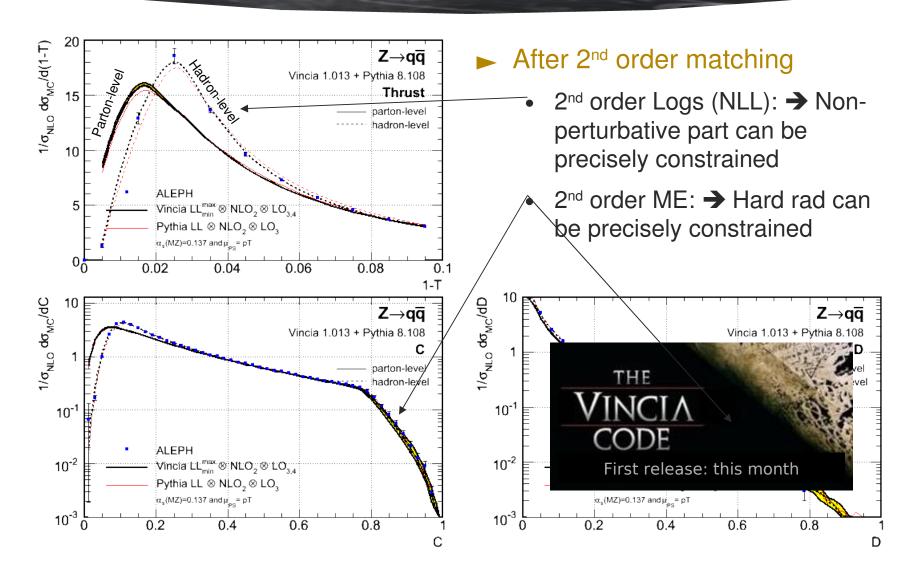
- ~ MC@NLO

► **After 2nd order matching**

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

- 2nd order ME: ➔ Hard rad can be precisely constrained

THE VINCIA CODE

First release: this month

Peter
Skands

STAR
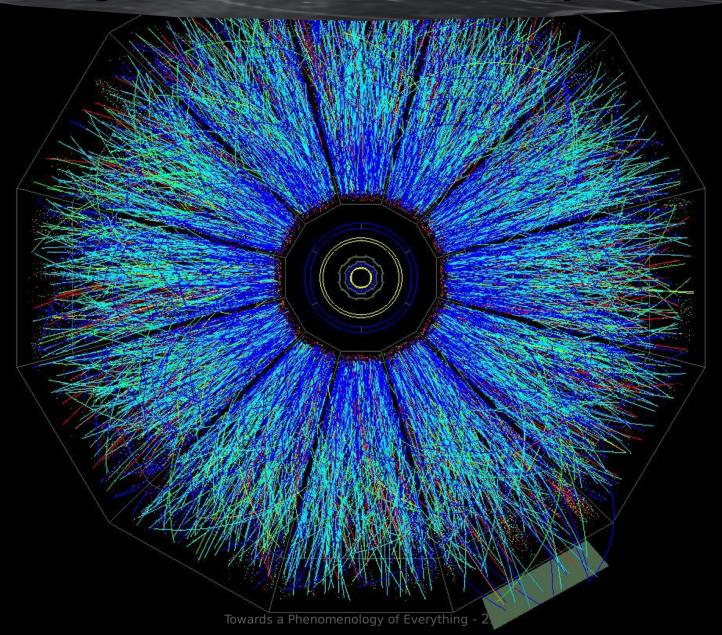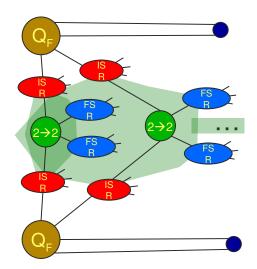
MC Models: Perturbative Part

► **Starting point: Matrix Elements + Parton Showers**

- Hard parton-parton scattering
  - Normally 2→2 at LO or NLO

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

►But hadrons are not elementary

►+ QCD diverges at low p_T

→ multiple <u>perturbative</u> parton-parton collisions e.g. 4→4, 3→ 3, 3→2

►No factorization theorem

→Herwig++, Pythia, Sherpa: MPI models

$Q_F >> \Lambda_{QCD}$
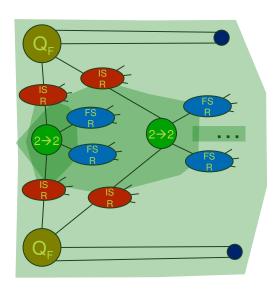
Underlying Event has perturbative part!

$Q_F \gg \Lambda_{QCD}$

ME+ISR/FSR

+ perturbative MPI

+

Stuff at

$Q_F \sim \Lambda_{QCD}$

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

► 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?

Naming Conventions

► **Many nomenclatures being used.**

- Not without ambiguity. I use:

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

Primary Interaction

(~ trigger)

Inelastic, non-diffractive

Multiple Parton Interactions

Beam Remnants

Underlying Event

Note: each is colored ➔ Not possible to separate clearly at hadron level
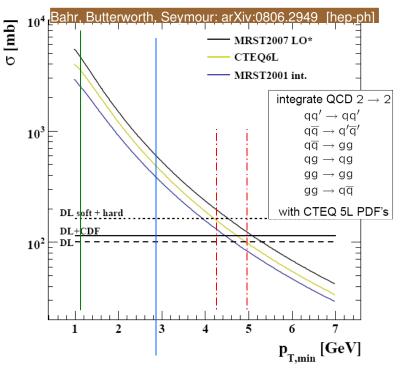
(Why Perturbative MPI?)

► **Analogue**: Resummation of multiple bremsstrahlung emissions

- Divergent σ for one emission (X + jet, fixed-order)

➔ Finite σ for divergent number of jets (X + jets, infinite-order)

  ▪ N(jets) rendered finite by finite perturbative resolution = parton shower cutoff
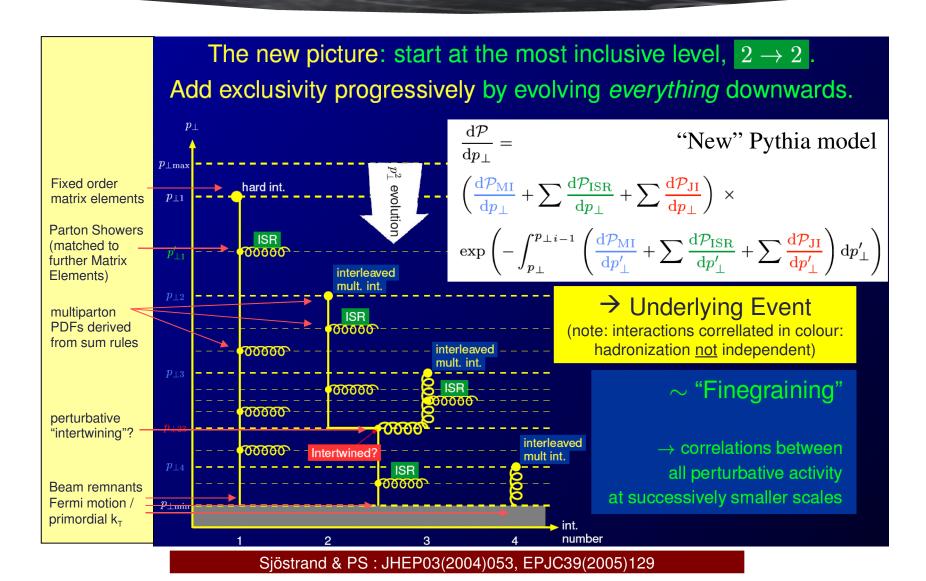
► (Resummation of) **Multiple Perturbative Interactions**

- Divergent σ for one interaction (fixed-order)

➔ Finite σ for divergent number of interactions (infinite-order)

  ▪ N(jets) rendered finite by finite perturbative resolution

  = color-screening cutoff (E_{cm}-dependent, but large uncert)

Bahr, Butterworth, Seymour: arXiv:0806.2949 [hep-ph]

MRST2007 LO*
CTEQ6L
MRST2001 int.

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

DL soft + hard
DL+CDF
DL

σ [mb] vs $p_{T,min}$ [GeV]

The Interleaved Idea

The new picture: start at the most inclusive level, $2 \to 2$.

Add exclusivity progressively by evolving *everything* downwards.

"New" Pythia model

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{JI}}}{\mathrm{d}p_\perp} \right) \times$$

$$\exp \left(- \int_{p_\perp}^{p_{\perp i-1}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{JI}}}{\mathrm{d}p'_\perp} \right) \mathrm{d}p'_\perp \right)$$

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

$p_\perp$

$p_{\perp\mathrm{max}}$

$p_{\perp 1}$ — hard int.

$p'_{\perp 1}$ — ISR

$p_{\perp 2}$ — interleaved mult. int. — ISR

$p_{\perp 3}$ — interleaved mult. int. — ISR

$p_{\perp 23}$ — Intertwined?

$p_{\perp 4}$ — interleaved mult int. — ISR

$p_{\perp\mathrm{min}}$

$p_\perp^2$ evolution

→ Underlying Event
(note: interactions correllated in colour: hadronization <u>not</u> independent)

$\sim$ "Finegraining"

→ correlations between
all perturbative activity
at successively smaller scales

int. number

1   2   3   4

Sjöstrand & PS : JHEP03(2004)053, EPJC39(2005)129

► **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)

PS & D. Wicke : EPJC52(2007)133 ; J. Rathsman : PLB452(1999)364

Not only more (charged particles), but **each one is harder**

PYTHIA 6.224 (old defaults) vs 6.228 (Tune A)

Tevatron Run II
Pythia 6.2 Min-bias
$<p_T>(N_{ch})$

Tune A

old default

Diffractive?

Non-perturbative $<p_T>$ component in string fragmentation (LEP value)

Peripheral Small UE

Central Large UE

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 factoriz… theorem? Is there a no-go theorem? In any case, sensitiv… experimental tests needed to study detailed properties.
- Non-perturbative dynamics so far only accessed by the la… phenomenological models.
  - Input from heavy-ion limit (hydrodynamics, collective phenomena)?
  - Input from AdS/QCD? (low-energy QCD ~ frozen coupling ~ conform…