ATLAS Forum, SLAC, April 2007

Hadron Collisions Inside and Out

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Sjöstrand, PS : NPB659(2003)243, JHEP03(2004)053, EPJC39(2005)129;
PS, Wicke : hep-ph/0703081;
Plehn, Rainwater, PS : PLB645(2007)217 + hep-ph/0511306

Overview

► Introduction

- QCD & Event Generators

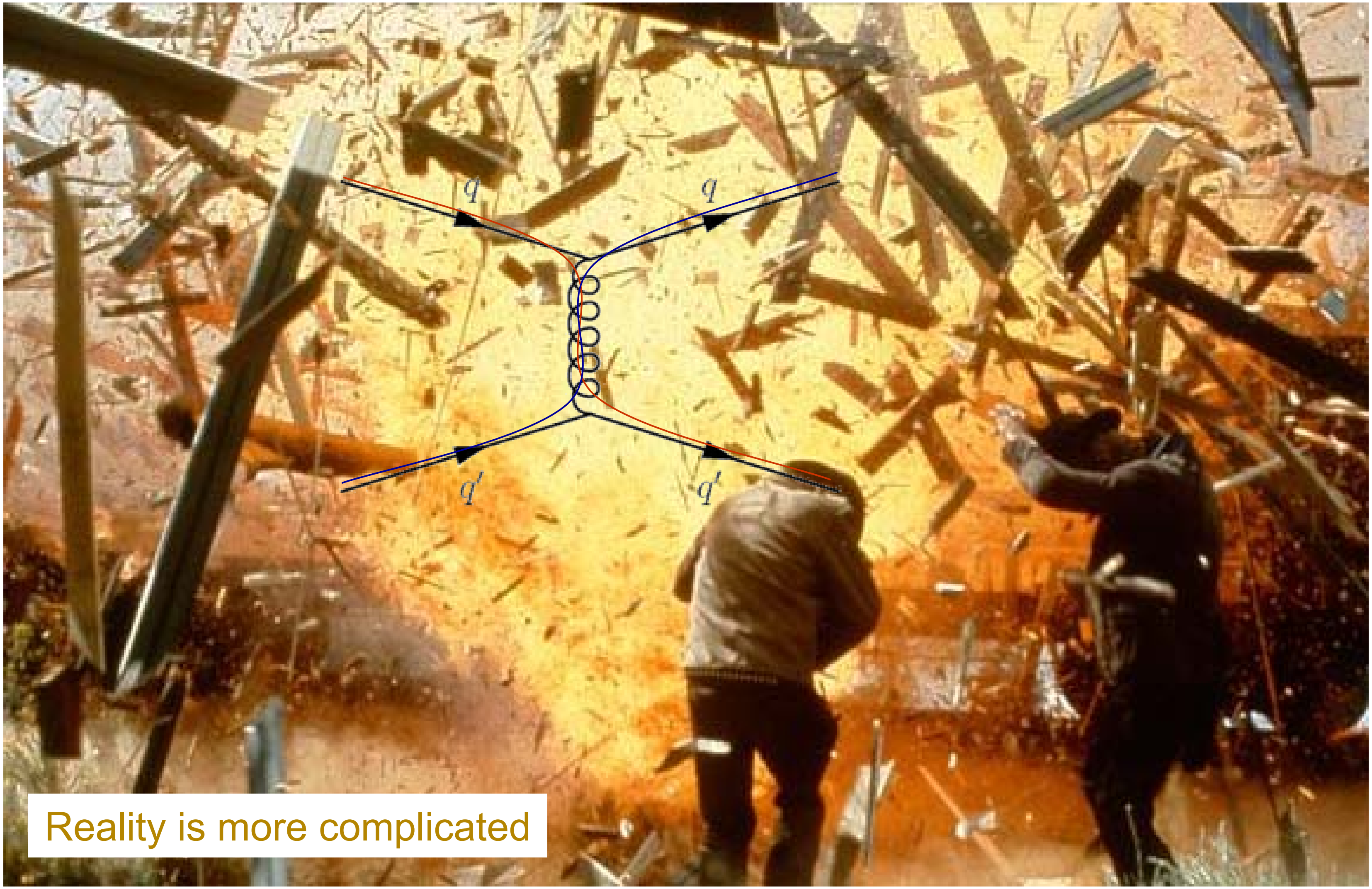
► Towards Improved Event Generators

- Parton Showers
- Combining Matrix Elements and Parton Showers (1)
  - Second part in theory seminar tomorrow
- Minimum Bias and the ‘Underlying Event’

► The Event Generator Outlook

- The move to C++

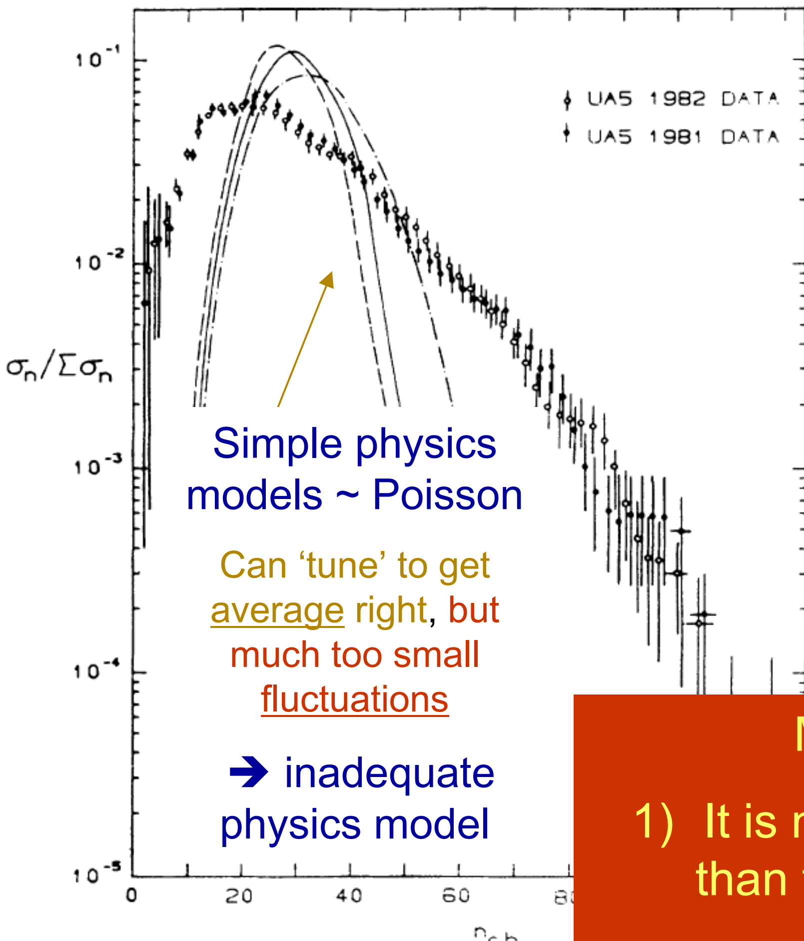
Quantum Chromo Dynamics



Reality is more complicated

Classic Example: Number of tracks

UA5 @ 540 GeV, single pp, charged multiplicity in minimum-bias events

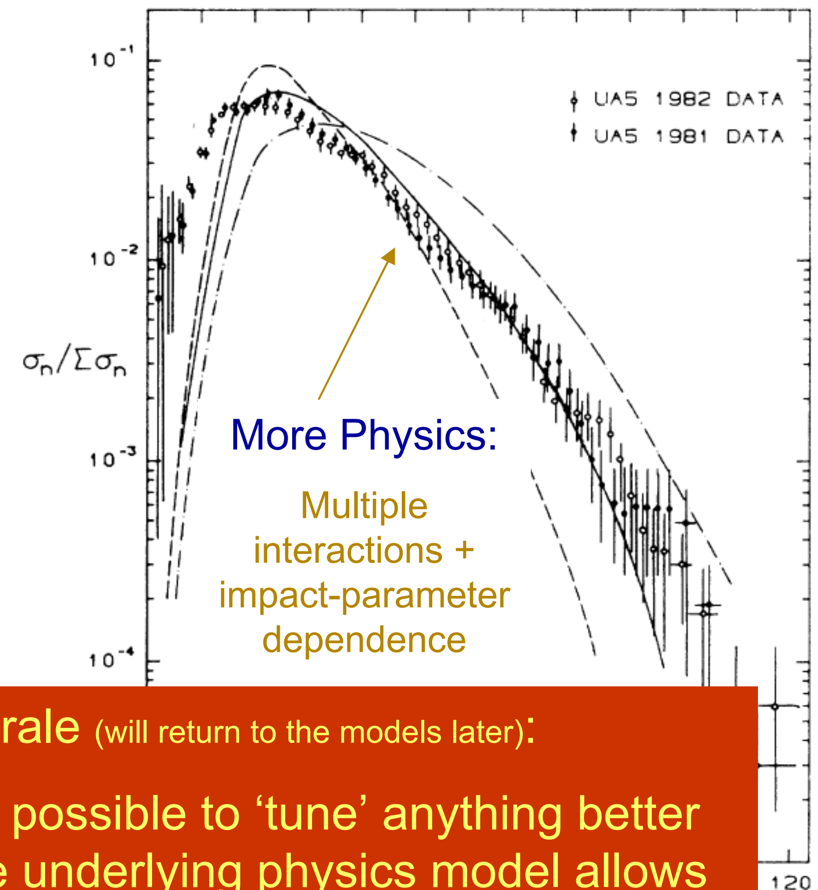


Simple physics models ~ Poisson

Can 'tune' to get average right, but much too small fluctuations

➔ inadequate physics model

FIG. 3. Charged-multiplicity distributio
results (Ref. 32) vs simple models: dashed l
cluding hard scatterings, dash-dotted also i
final-state radiation.



More Physics:

Multiple interactions + impact-parameter dependence

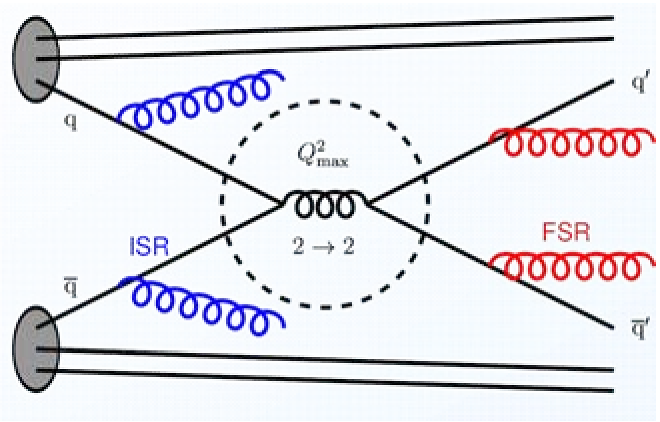
UA5
ltiple-
line,
$p_{T\min} = 1.6$ GeV; dashed-dotted line, $p_{T\min} = 1.2$ GeV.

Morale (will return to the models later):

1) It is not possible to 'tune' anything better than the underlying physics model allows

2) Failure of a physically motivated model usually points to more, interesting physics

Traditional Event Generators



- Basic aim: improve lowest order perturbation theory by including leading corrections → exclusive event samples
  1. **sequential resonance decays**
  2. **bremsstrahlung**
  3. **underlying event**
  4. **hadronization**
  5. **hadron (and τ) decays**

E.g. PYTHIA

2006: first publication of PYTHIA manual
JHEP **0605:026,2006**
(FERMILAB-PUB-06-052-CD-T)

The Monte Carlo Method

► Want to generate events in as much detail as Mother Nature

➔ Get average *and* fluctuations right

➔ Make random choices, ~ as in nature

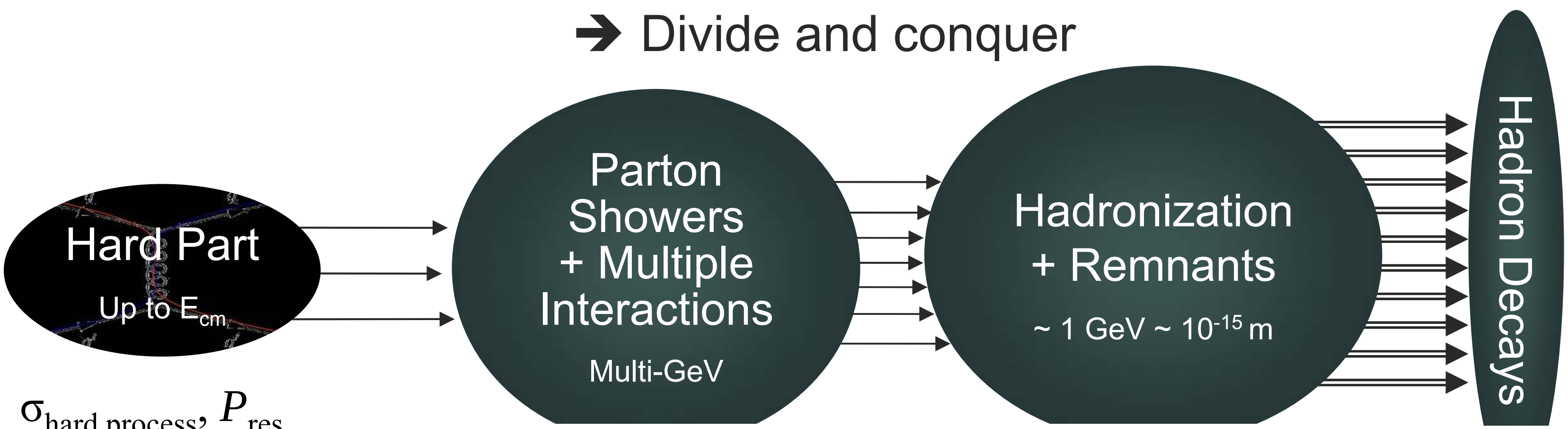
$$\sigma_{\text{final state}} = \sigma_{\text{hard process}}\, P_{\text{tot, hard process} \rightarrow \text{final state}}$$

(appropriately summed & integrated over non-distinguished final states)

where $P_{\text{tot}} = P_{\text{res}}\, P_{\text{ISR}}\, P_{\text{FSR}}\, P_{\text{MI}}\, P_{\text{Remnants}}\, P_{\text{Hadronization}}\, P_{\text{decays}}$

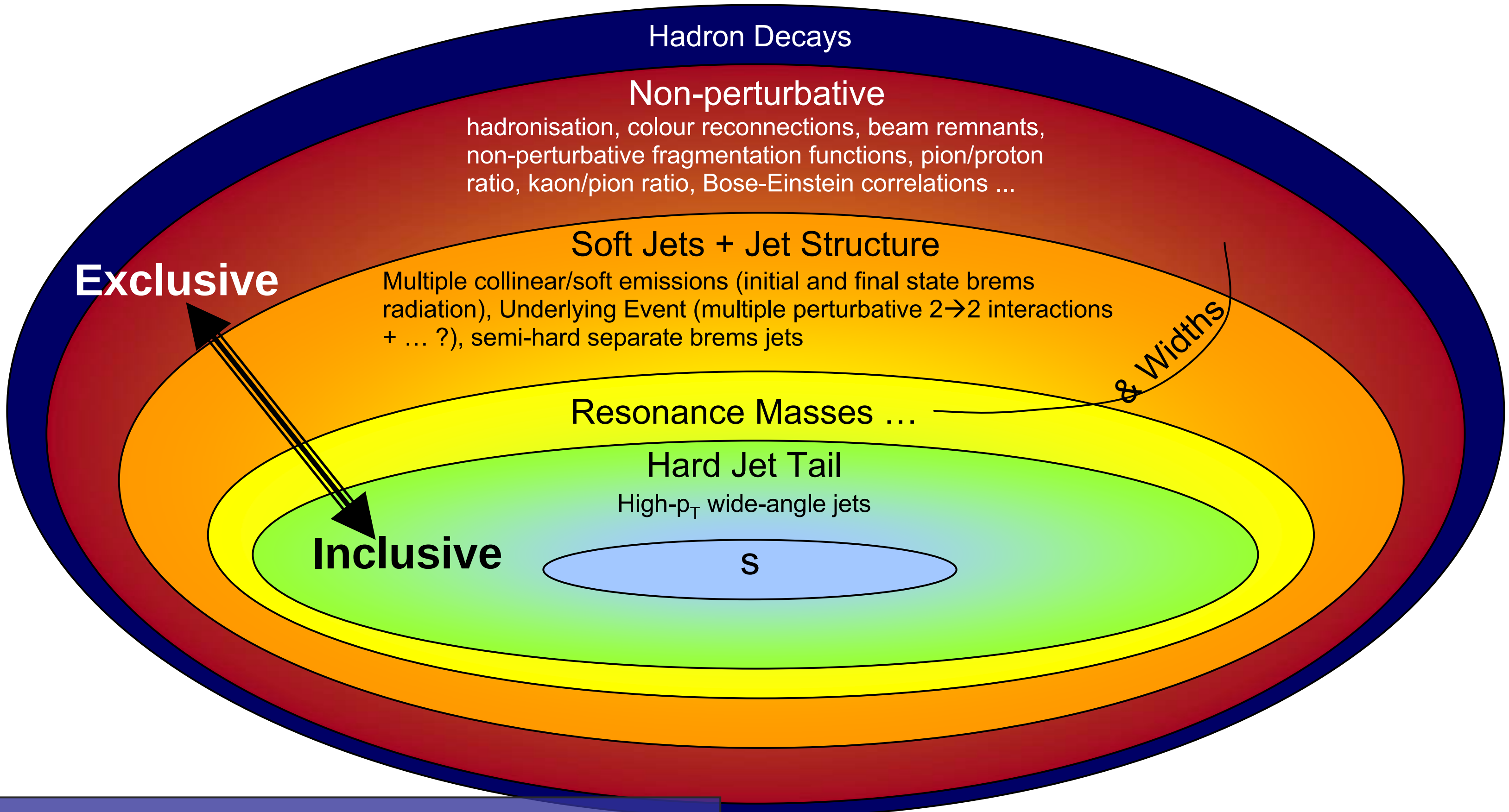
With $P_i = \Pi_j P_{ij} = \Pi_j \Pi_k P_{ijk} = \ldots$in its turn

➔ Divide and conquer



$\sigma_{\text{hard process}}, P_{\text{res}}$ | $P_{\text{ISR}}, P_{\text{FSR}}, P_{\text{MI}}$ | $P_{\text{remnants}}, P_{\text{hadronization}}$ | P_{decays}

Collider Energy Scales



+ "UNPHYSICAL" SCALES:

- Q_F , Q_R : Factorisation(s) & Renormalisation(s)

The Bottom Line

FO DGLAP HQET

The S matrix is expressible as a series in g_i, g_i^n/t^m, g_i^n/x^m, g_i^n/m^m, g_i^n/f_π^m, …

BFKL χPT

To do precision physics:

<u>Solve more of QCD</u>

Combine approximations which work in different regions: matching

<u>Control it</u>

Good to have comprehensive understanding of uncertainties

Even better to have a way to systematically improve

<u>Non-perturbative effects</u>

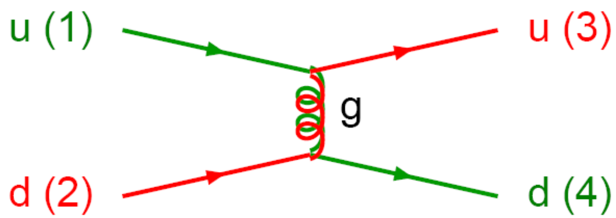
don't care whether we know how to calculate them

QCD-based Event Generators

Parton Showers & Matching

Cross Sections and Kinematics

- Starting point 2→n hard scattering perturbative matrix element



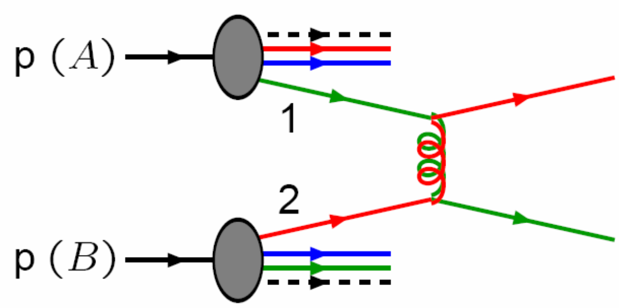
$$\hat{s} = (p_1 + p_2)^2$$

$$\hat{t} = (p_1 - p_3)^2 = -\hat{s}(1 - \cos\hat{\theta})/2$$

$$\hat{u} = (p_1 - p_4)^2 = -\hat{s}(1 + \cos\hat{\theta})/2$$

$$\mathrm{qq'} \to \mathrm{qq'} \quad : \quad \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}} = \frac{\pi}{\hat{s}^2}\frac{4}{9}\alpha_s^2\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} \qquad (\sim \text{Rutherford})$$

- Fold with parton distribution functions → pp cross section



$$s = (p_A + p_B)^2$$

$$x_1 \approx E_1/E_A$$

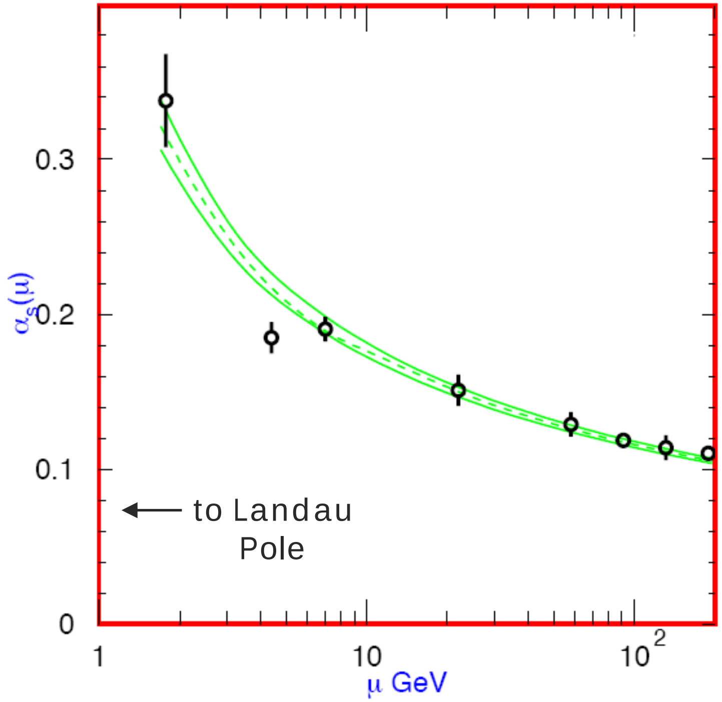
$$x_2 \approx E_2/E_B$$

$$\hat{s} = x_1 x_2 s$$

$$\sigma = \sum_{i,j} \iiint \mathrm{d}x_1\, \mathrm{d}x_2\, \mathrm{d}\hat{t}\, f_i^{(A)}(x_1, Q^2)\, f_j^{(B)}(x_2, Q^2)\, \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}\hat{t}}$$

$\mathbf{Q}$uantum $\mathbf{C}$hromo $\mathbf{D}$ynamics

► To connect this with 'real' final states, 2 fundamental problems:



Problem 1: QCD becomes non-perturbative at scales below ~ 1 GeV

$e^+e^- \rightarrow$ 3 jets

$$\frac{1}{\sigma}\frac{d^2\sigma}{dx_1 dx_2} = \frac{2\alpha_s}{3\pi}\frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}$$

$$x_i = \frac{2E_i}{\sqrt{s}}$$

Problem 2: bremsstrahlung corrections singular for soft and collinear configurations

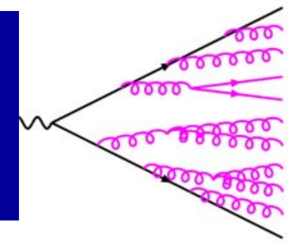
Bremsstrahlung: Parton Showers

- Starting observation: forward singularity of bremsstrahlung is universal
  - ➔ Leading contributions to all radiation processes (QED & QCD can be worked out to <u>all orders</u> once and for all
  - → exponentiated (Altarelli-Parisi) integration kernels

Schematic: Forward (collinear) factorization of QCD amplitudes ➔ exponentiation

$$d\sigma_{n+1} = d\sigma_n \, d\Pi_{n\rightarrow n+1} \, P_{n\rightarrow n+1}$$

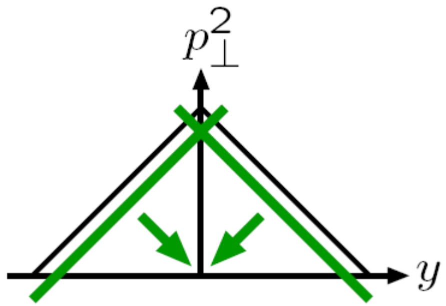
$$\Rightarrow d\sigma_{n+2} = d\sigma_n \, (d\Pi_{n\rightarrow n+1} \, P_{n\rightarrow n+1})^2 \quad \text{and so on} \ldots \rightarrow \exp[]$$



- Iterative (Markov chain) formulation = <u>parton shower</u>
  - Generates the leading "collinear" parts of QED and QCD corrections to any process, to infinite order in the coupling
  - The chain is ordered in an "evolution variable": parton virtuality, jet-jet angle, transverse momentum, …
  - → a series of successive factorizations the lower end of which can be matched to a hadronization description at some fixed low hadronization scale ~ 1 GeV

Ordering Variables

PYTHIA: $Q^2 = m^2$



large mass first

$\Rightarrow$ "hardness" ordered

coherence brute force

covers phase space

ME merging simple

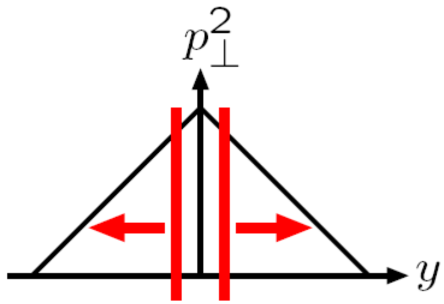
g $\rightarrow$ q$\overline{\text{q}}$ simple

not Lorentz invariant

no stop/restart

ISR: $m^2 \rightarrow -m^2$

HERWIG: $Q^2 \sim E^2\theta^2$



large angle first

$\Rightarrow$ **hardness not ordered**

coherence inherent

gaps in coverage

ME merging messy

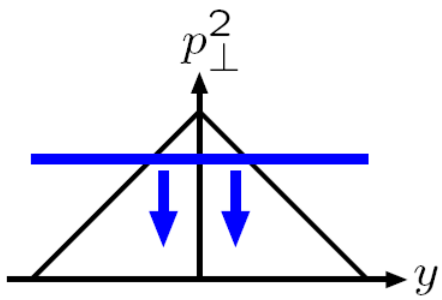
g $\rightarrow$ q$\overline{\text{q}}$ simple

not Lorentz invariant

no stop/restart

ISR: $\theta \rightarrow \theta$

ARIADNE: $Q^2 = p_\perp^2$



large $p_\perp$ first

$\Rightarrow$ "hardness" ordered

coherence inherent

covers phase space

ME merging simple

g $\rightarrow$ q$\overline{\text{q}}$ **messy**

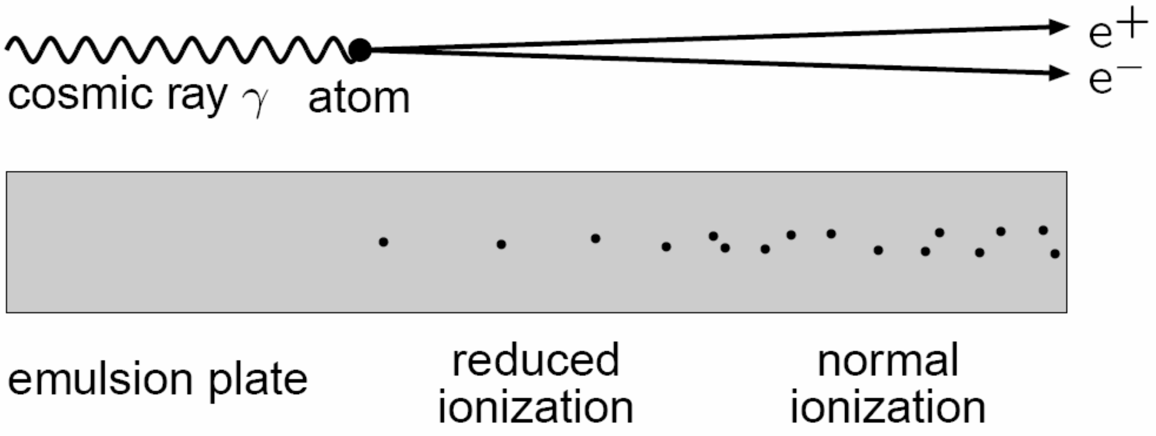
Lorentz invariant

can stop/restart

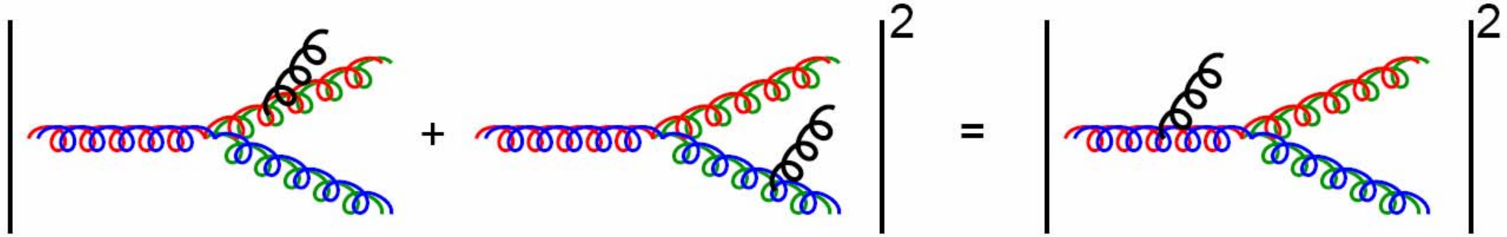
ISR: more messy

Coherence

QED: Chudakov effect (mid-fifties)



QCD: colour coherence for **soft** gluon emission



solved by • requiring emission angles to be decreasing

or • requiring transverse momenta to be decreasing

A Problem

► The best of both worlds? We want:

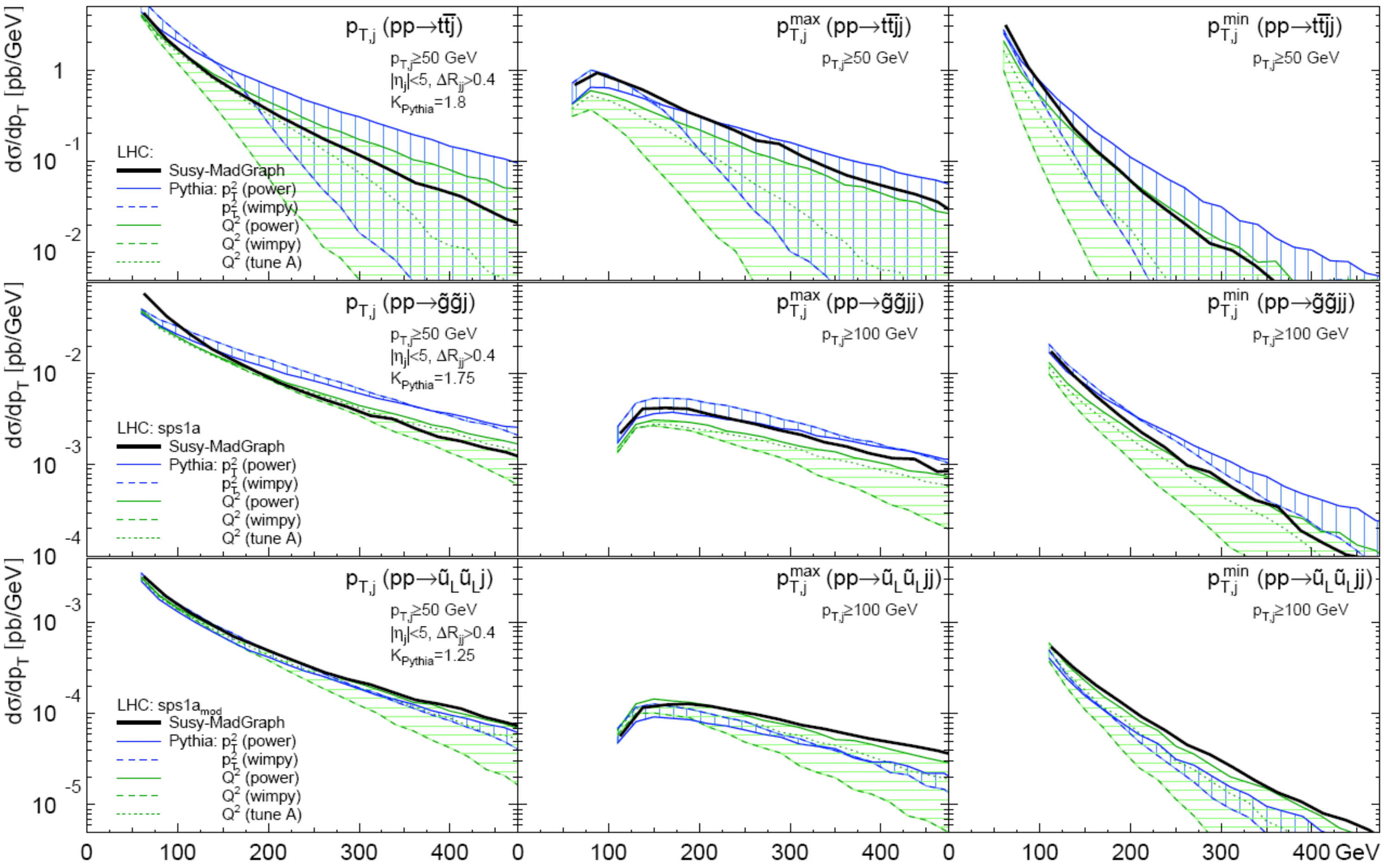
- A description which accurately predicts hard additional jets
- + jet structure and the effects of multiple soft emissions

► How to do it?

- Compute emission rates by parton showering?
  - Misses relevant terms for hard jets, rates only correct for strongly ordered emissions $p_{T1} \gg p_{T2} \gg p_{T3}$ ...
  - (common misconception that showers are soft, but that need not be the case. They can err on *either side* of the right answer.)
- Compute emission rates with matrix elements?
  - Misses relevant terms for soft/collinear emissions, rates only correct for well-separated individual partons
  - Quickly becomes intractable beyond one loop and a handfull of legs

Example: tops, gluinos, and squarks plus jets

$p_\perp$(1 jet) $p_\perp^{\max}$(2 jets) $p_\perp^{\min}$(2 jets)



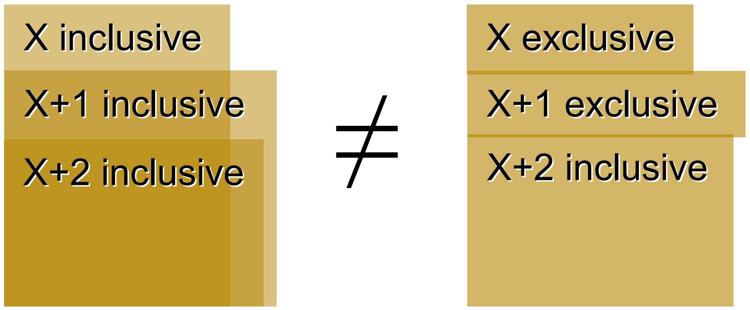
power: $Q^2_{\max} = s$; wimpy: $Q^2_{\max} = m^2_\perp$; tune A: $Q^2_{\max} = 4m^2_\perp$

$m_{\mathrm{t}} = 175$ GeV, $m_{\tilde{\mathrm{g}}} = 608$ GeV, $m_{\tilde{\mathrm{u}}_L} = 567$ GeV

T. Plehn, D. Rainwater, PS -PLB645(2007)217 + hep-ph/0511306

Double Counting

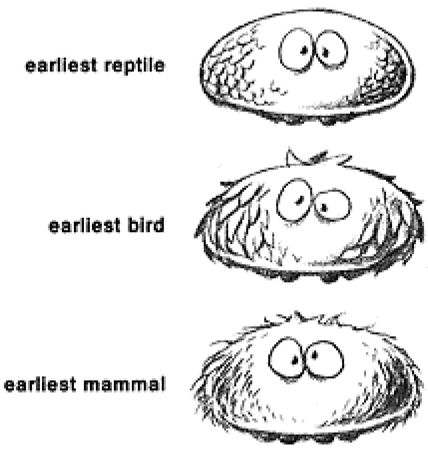
- Combine different multiplicites ➔ *inclusive* sample?
- In practice – Combine
  1. $[X]_{ME}$ + showering
  2. $[X + 1\ \mathrm{jet}]_{ME}$ + showering
  3. …



- ➔ Double Counting:
  - $[X]_{ME}$ + showering produces some X + jet configurations
    - The result is X + jet in the shower approximation
  - If we now add the *complete* $[X + \mathrm{jet}]_{ME}$ *as well*
    - the total rate of X+jet is now approximate + exact ~ double !!
    - some configurations are generated *twice*.
    - and the total inclusive cross section is also not well defined ☹
- When going to X, X+j, X+2j, X+3j, etc, this problem gets worse

Matching

- ► Matching of up to one hard additional jet (since long)
  - PYTHIA-style (reweight shower)
  - HERWIG-style (add separate events from ME: weight = ME-PS)
  - MC@NLO-style (ME-PS subtraction similar to HERWIG, but NLO)
- ► Matching of generic (multijet) topologies (since a few years)
  - ALPGEN-style (MLM)
  - SHERPA-style (CKKW)
  - ARIADNE-style (Lönnblad-CKKW)
  - PATRIOT-style (Mrenna & Richardson)
- ► Brand new approaches (still in the oven)
  - Refinements of MC@NLO (Nason)
  - CKKW-style at NLO (Nagy, Soper)
  - SCET approach (based on SCET – Bauer, Schwarz)
  - VINCIA (based on QCD antennae – Giele, Kosower, PS)



Evolution

If you want to know more about matching, ask Johan Alwall, and/or come to the theory seminar tomorrow

The Underlying Event

Towards a complete picture of hadron collisions

Additional Sources of Particle Production

- Domain of fixed order and parton shower calculations: hard partonic scattering, and bremsstrahlung associated with it.

- But hadrons are not elementary
- + QCD diverges at low p_T
- → multiple perturbative parton-parton collisions should occur

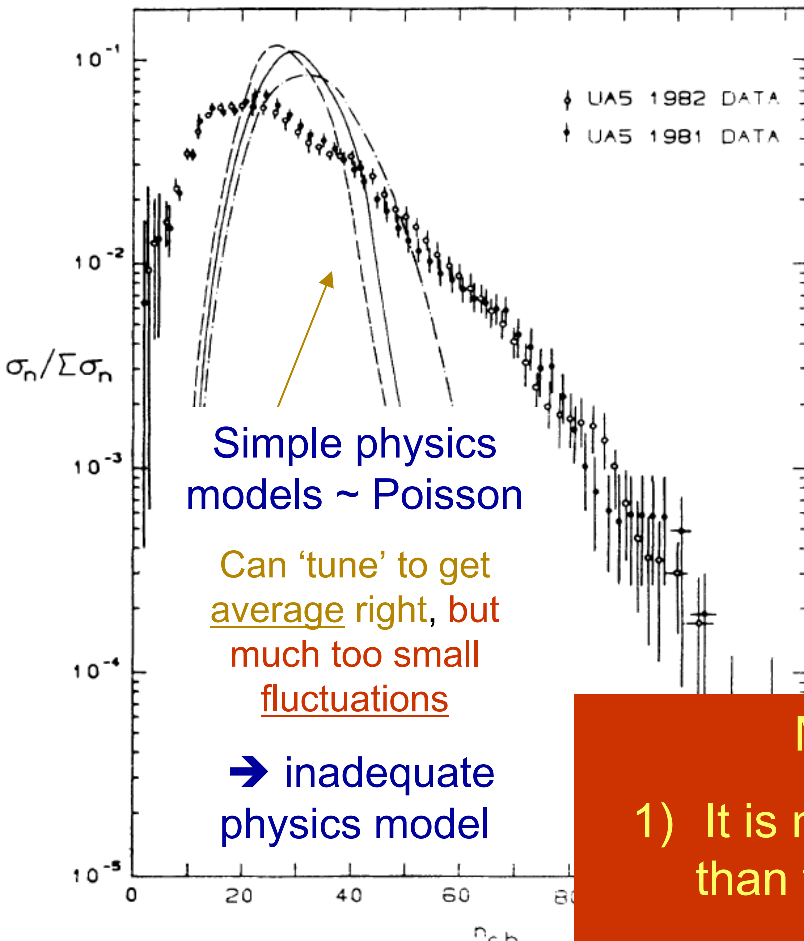
  e.g. 4→4, 3→ 3, 3→2

- Normally omitted in explicit perturbative expansions

- + Remnants from the incoming beams
- + additional (non-perturbative / collective) phenomena?
  - Bose-Einstein Correlations
  - Non-perturbative gluon exchanges / colour reconnections ?
  - String-string interactions / collective multi-string effects ?
  - Interactions with “background” vacuum / with remnants / with active medium?

Classic Example: Number of tracks

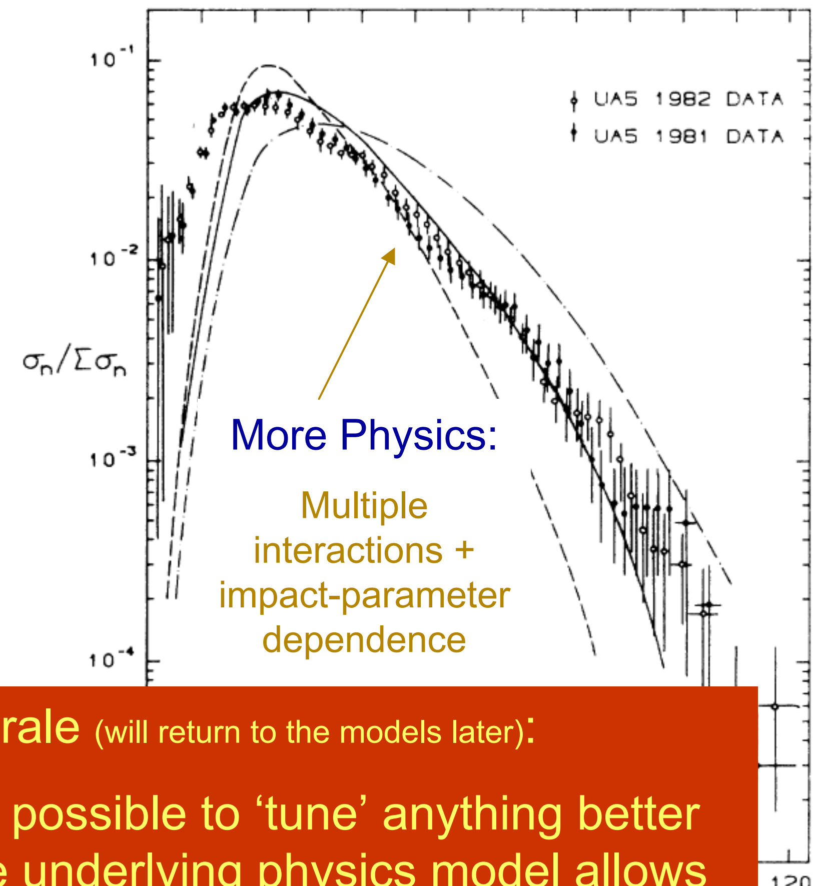
UA5 @ 540 GeV, single pp, charged multiplicity in minimum-bias events



Simple physics models ~ Poisson

Can 'tune' to get average right, but much too small fluctuations

➔ inadequate physics model



More Physics:

Multiple interactions + impact-parameter dependence

Morale (will return to the models later):

1) It is not possible to 'tune' anything better than the underlying physics model allows

2) Failure of a physically motivated model usually points to more physics

FIG. 3. Charged-multiplicity distributio[…] results (Ref. 32) vs simple models: dashed […] cluding hard scatterings, dash-dotted also i[…] final-state radiation.

[…] UA5 […]ltiple- […] line, $p_{T\min} = 1.6$ GeV; dashed-dotted line, $p_{T\min} = 1.2$ GeV.

Multiple Interactions → Balancing Minijets

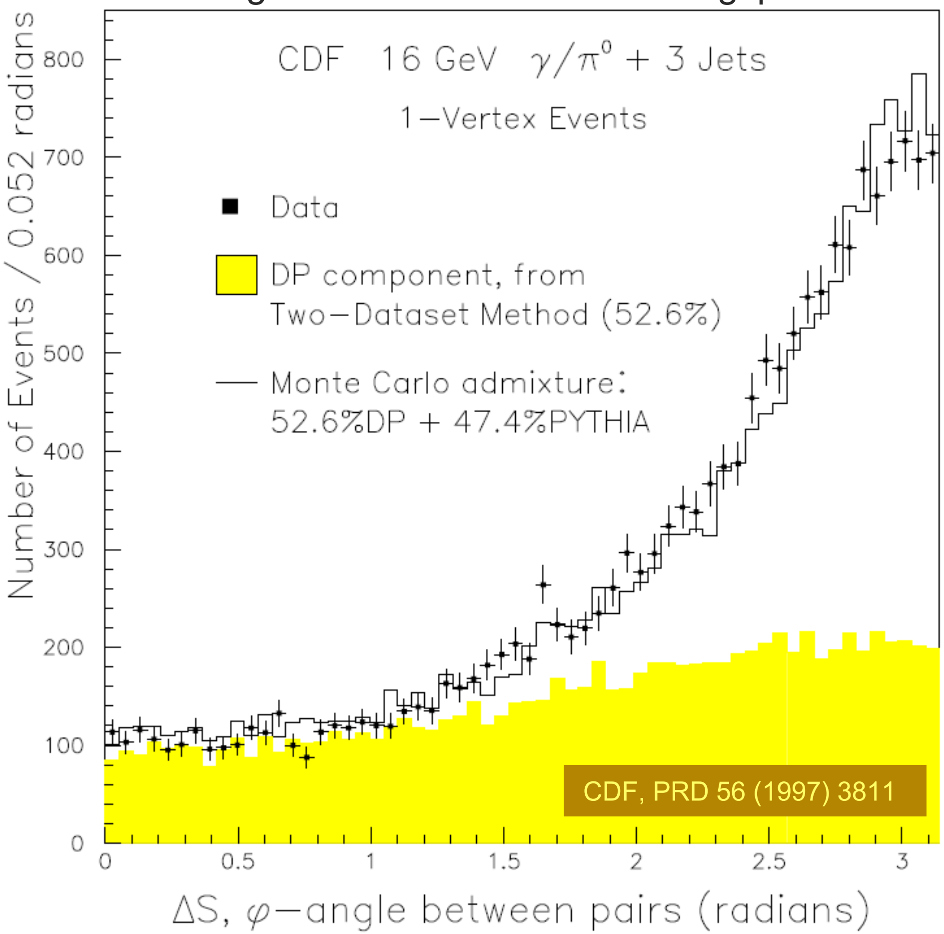
- Look for additional balancing jet pairs “under” the hard interaction.
- Several studies performed, most recently by Rick Field at CDF → ‘lumpiness’ in the underlying event.

(Run I)

CDF: Extraction by comparing double parton scattering (DPS) to a mix of two separate scatterings. Sample: 14000 $\gamma/\pi^0 + 3j$ events.

Strong signal observed, 53% DPS

angle between 2 ‘best-balancing’ pairs



Basic Physics

- Sjöstrand and van Zijl (1987):
  - First serious model for the underlying event
  - Based on resummation of <u>perturbative</u> QCD 2→2 scatterings at successively smaller scales → multiple parton-parton interactions
  - Dependence on impact parameter crucial to explain N_{ch} distributions.
    - Peripheral collisions → little matter overlap → few interactions. Central collisions → many
    - N_{ch} Poissonian for each impact parameter ⊗ convolution with impact parameter profile → wider than Poissonian!
  - Colour correlations also essential
    - Determine between which partons hadronizing strings form (each string → log(m_{string}) hadrons)
    - Important ambiguity: what determines how strings form *between* the different interactions?

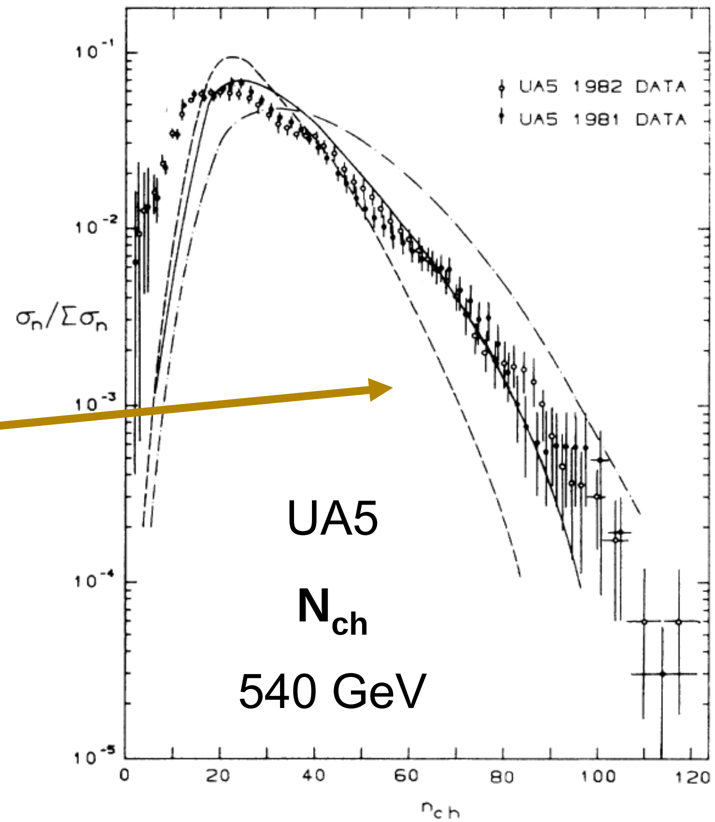
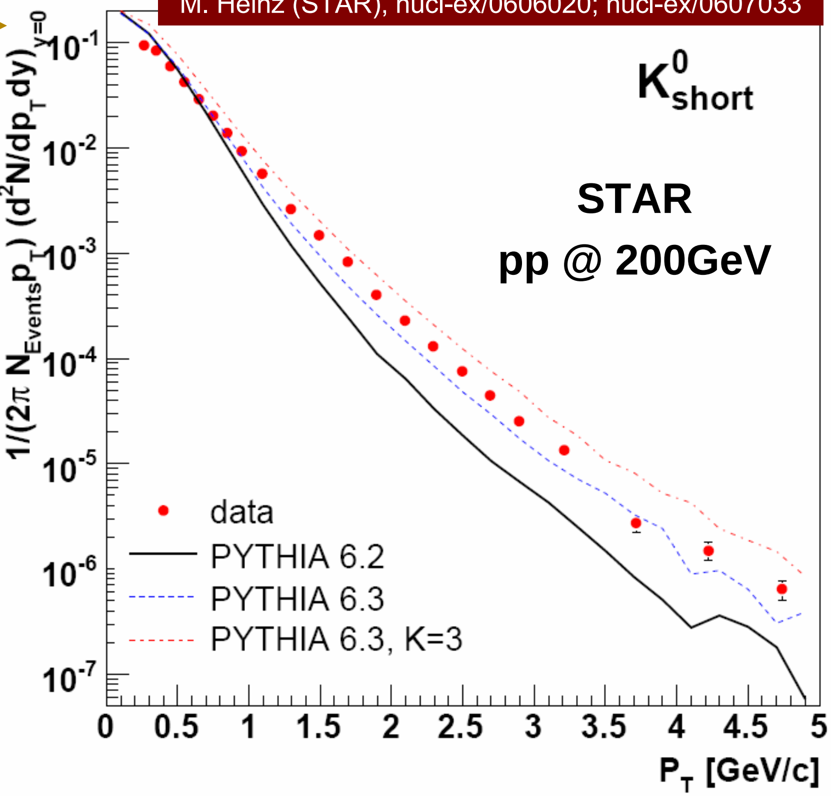


FIG. 5. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs impact-parameter-independent multiple-interaction model: dashed line, $p_{T\min} = 2.0$ GeV; solid line, $p_{T\min} = 1.6$ GeV; dashed-dotted line, $p_{T\min} = 1.2$ GeV.

Underlying Event and Colour

- In PYTHIA (up to 6.2), some “theoretically sensible” default values for the colour correlation parameters had been chosen
  - Rick Field (CDF) noted that the default model produced too soft charged-particle spectra.
  - (The same is seen at RHIC:) →
  - For ‘Tune A’ etc, Rick noted that $\langle p_T \rangle$ increased when he increased the colour correlation parameters
  - Virtually all ‘tunes’ now used by the Tevatron and LHC experiments employ these more ‘extreme’ correlations
  - Tune A, and hence its more extreme colour correlations are now the default in PYTHIA (will return to this …)

M. Heinz (STAR), nucl-ex/0606020; nucl-ex/0607033



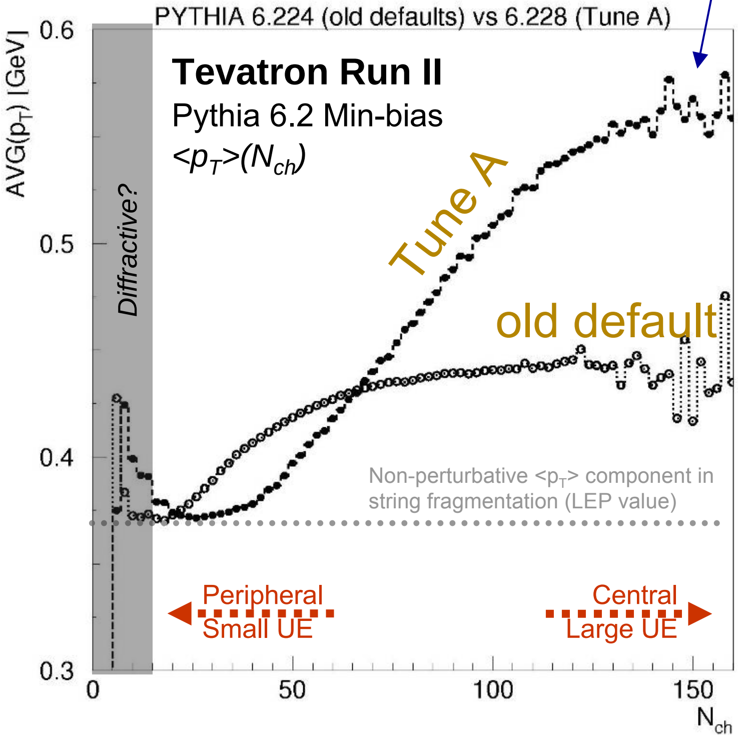
Correlation: $\langle p_T \rangle$ vs N_{ch}

- Both RHIC and Rick find the average hadron is harder in high-multiplicity events than in low-multiplicity ones

- If high multiplicity is interpreted as ~ large UE, this raises the question:

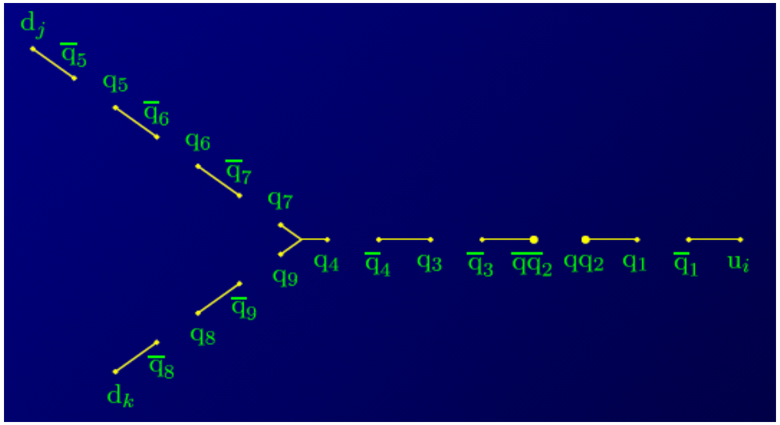
- Why do 'active' collisions produce harder hadrons?
  - If I just stack independent collisions on top of each other, the prediciton would be ~ flat
  - How do the hadrons from a central collision 'know' it was central? Do they talk to each other?
  - What do they talk about? And how?

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



The ‘Intermediate’ Model

- Meanwhile in Lund: Sjöstrand and PS (2003):
  - Further developments on the multiple-interactions idea
  - First serious attempt at constructing multi-parton densitities
    - If sea quark kicked out, “companion” antiquark introduced in remnant (distribution derived from gluon PDF and gluon splitting kernel)
    - If valence quark kicked out, remaining valence content reduced
  - Introduction of “string junctions” to represent beam baryon number
    - Detailed hadronization model for junction fragmentation → can address baryon number flow separately from valence quarks

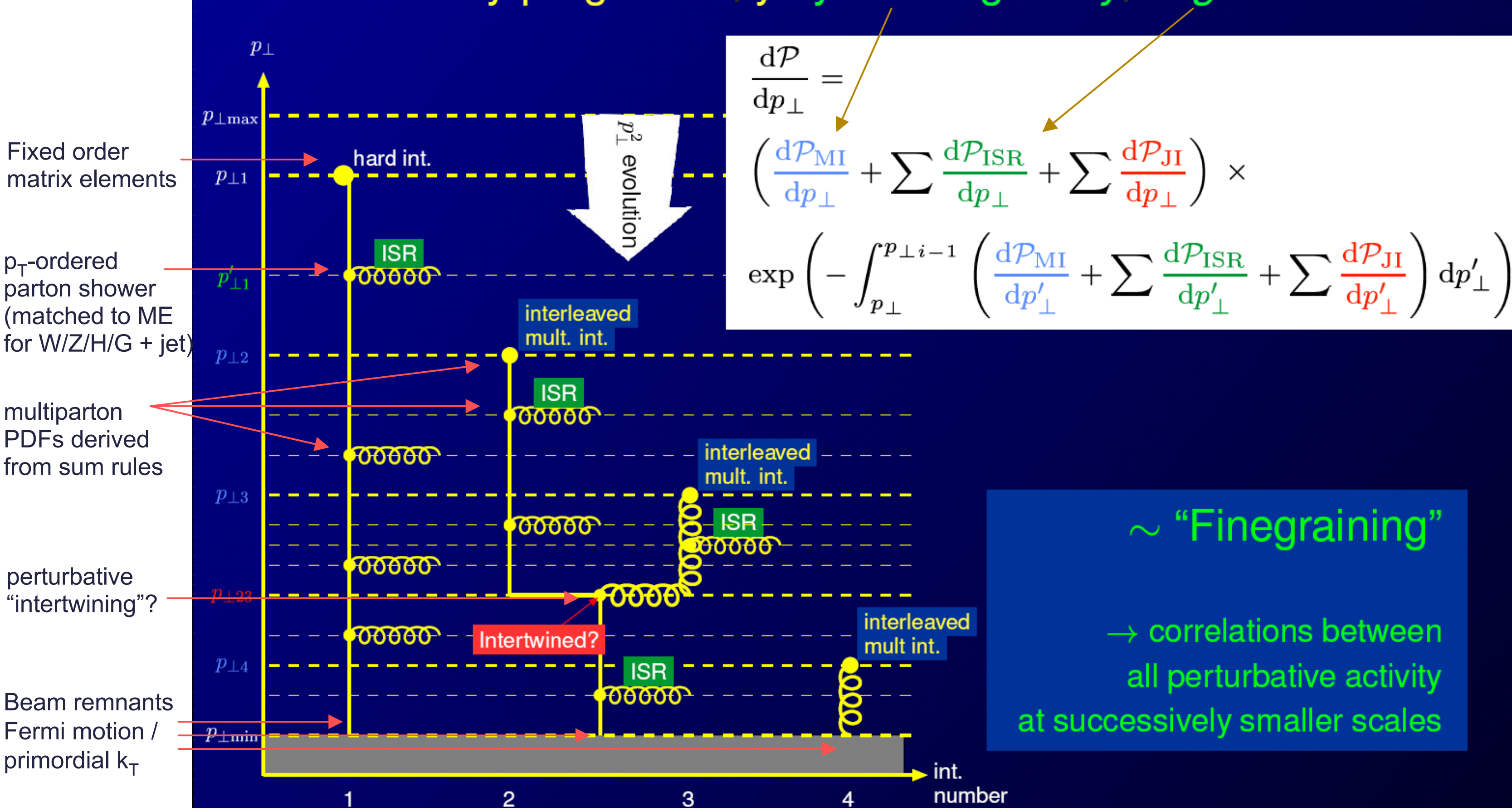


Sjöstrand & PS : Nucl.Phys.B659(2003)243, JHEP03(2004)053

The 'New' Model

NB: Tune A still default since more thoroughly tested.
To use new models, see e.g. PYTUNE (Pythia6.408+)

- Sjöstrand and PS (2005): The new picture: star
  - 'In Add exclusivity progressively by evolving *everything* downwards.

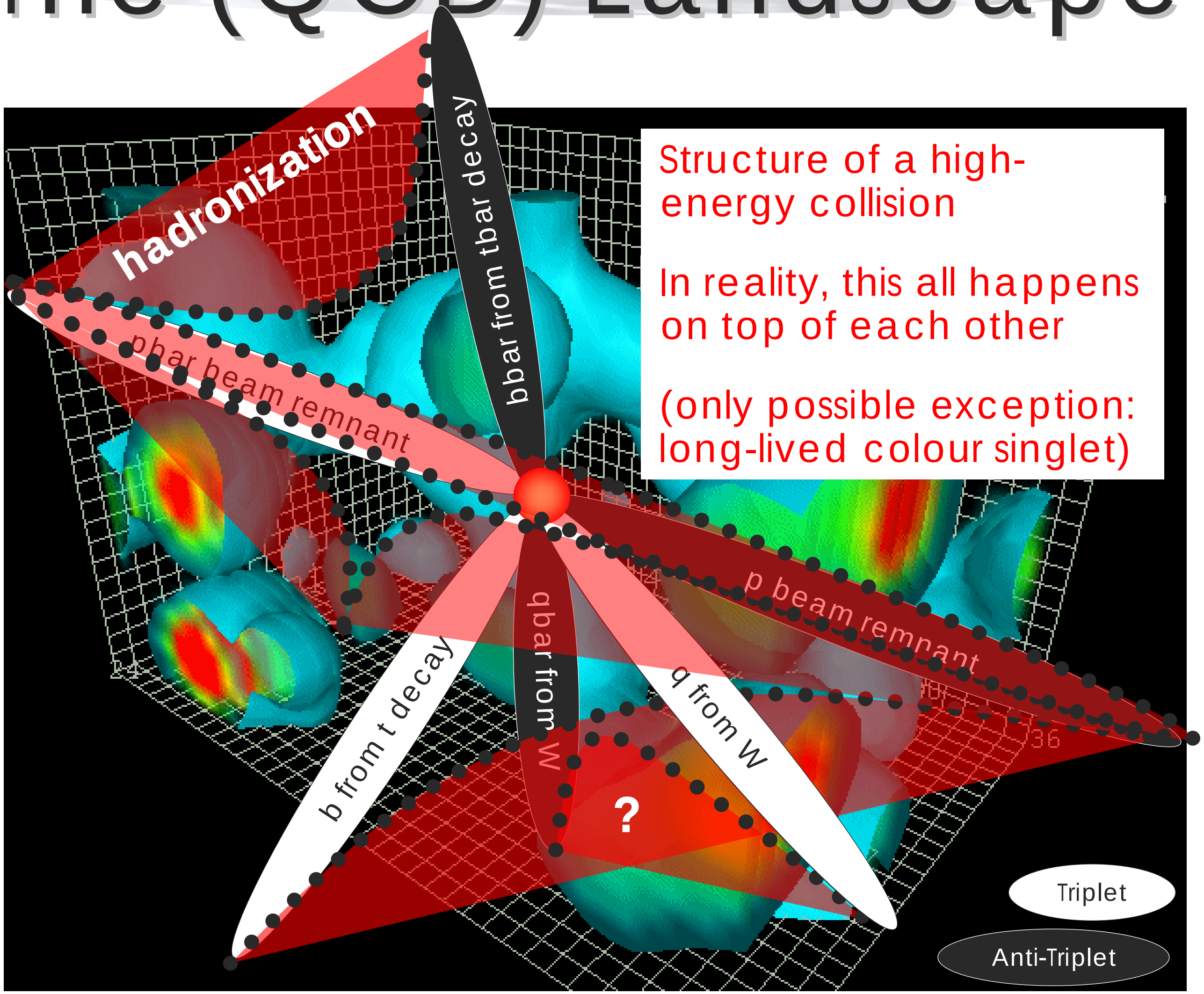


Sjöstrand & PS : JHEP03(2004)053, EPJC39(2005)129

Hooking it Up

- But the old ambiguity remained.
  - How are the interaction initiators (and thereby their final states) correlated in colour?
  - Fundamentally a non-perturbative question, so hard to give definite answers
- Simple-minded guess
  - There are many partons in the proton. Only a few interact → to first approximation their colour correlations should just be random
- But random connections produced the usual flat $\langle p_T \rangle (N_{ch})$ behaviour
  - Clearly, the new model and showers did not change the fact that *some* non-trivial colour correlations appear to be necessary
- We also tried deliberately optimizing the correlations between the initiators to give the most highly correlated final states
  - This did lead to a small rise in the $\langle p_T \rangle (N_{ch})$ distribution, but too little
- One place left to look
  - Could there be some non-trivial physics at work in the final state itself?

The (QCD) Landscape

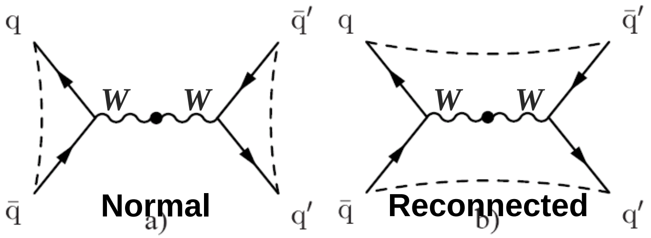


D. B. Leinweber, hep-lat/0004025

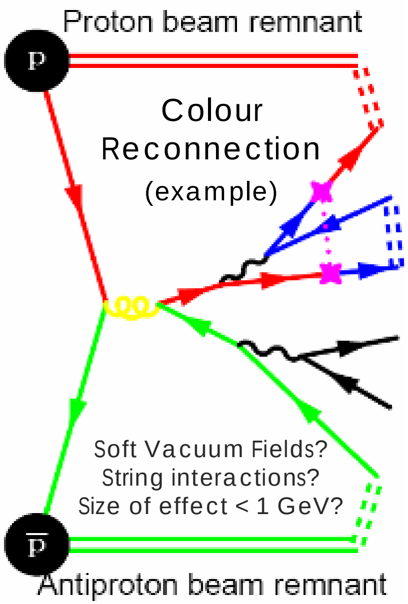
Color Reconnections

Sjöstrand, Khoze, Phys.Rev.Lett.72(1994)28 & Z. Phys.C62(1994)281 + more …
OPAL, Phys.Lett.B453(1999)153 & **OPAL**, hep-ex0508062

- Searched for at LEP
  - Major source of W mass uncertainty
  - Most aggressive scenarios excluded
  - But effect still largely uncertain $P_{reconnect}$ ~ 10%



- Prompted by CDF data and Rick Field's studies to reconsider.
  What do we know?
  - Non-trivial initial QCD vacuum
  - A lot more colour flowing around, not least in the UE
  - String-string interactions? String coalescence?
  - Collective hadronization effects?
  - More prominent in hadron-hadron collisions?
  - What is $<p_T>(N_{ch})$ telling us?
  - What (else) is RHIC, Tevatron telling us?
  - *Implications for Top mass? Implications for LHC?*

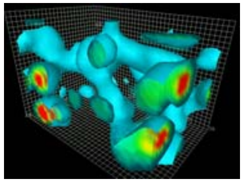


Existing models only for WW ➔ a new toy model for all final states: colour annealing

Sandhoff + PS, in Les Houches '05 SMH Proceedings, hep-ph/0604120

Colour Annealing

- Toy model of (non-perturbative) color reconnections, applicable to any final state
  - at hadronisation time, each string piece has a probability to interact with the vacuum / other strings:



$$P_{reconnect} = 1 - (1-\chi)^n$$

    - χ = strength parameter: fundamental reconnection probability (free parameter)
    - n = # of multiple interactions in current event (~ counts # of possible interactions)

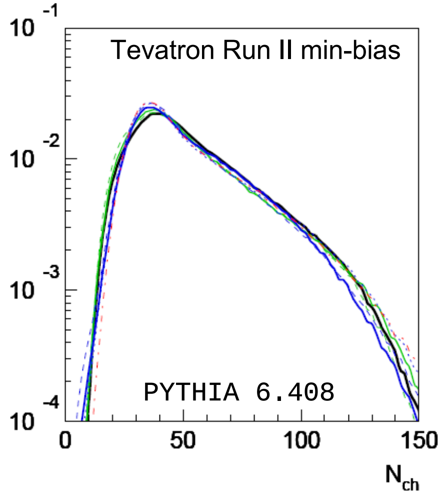
- For the interacting string pieces:
  - New string topology determined by annealing-like minimization of 'Lambda measure'
    - Similar to area law for fundamental strings: Lambda ~ potential energy ~ string length ~ log(m) ~ N

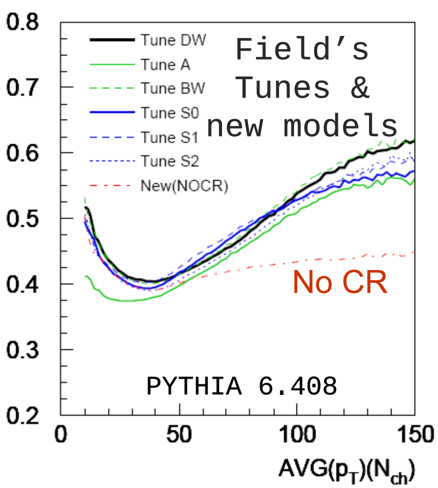
- → good enough for order-of-magnitude

Sandhoff + PS, in Les Houches '05 SMH Proceedings, hep-ph/0604120

A First Study

- Using Tevatron min-bias as constraint
  - Those were the distributions that started it all
  - High-multiplicity tail should be somewhat similar to top → less extrapolation required
  - Why not use LEP? Again, since the extrapolation might not be valid.
    - No UE in ee, no beam remnants, less strings, no ‘bags’ in initial state.
    - The comparison would still be interesting and should be included in a future study
- As a baseline, all models were tuned to describe N_{ch} and $<p_T>(N_{ch})$





- Improved Description of Min-Bias
- Effect Still largely uncertain
- Worthwhile to look at top etc

Top Mass Estimator

D. Wicke (DØ)

Event Generation Selection

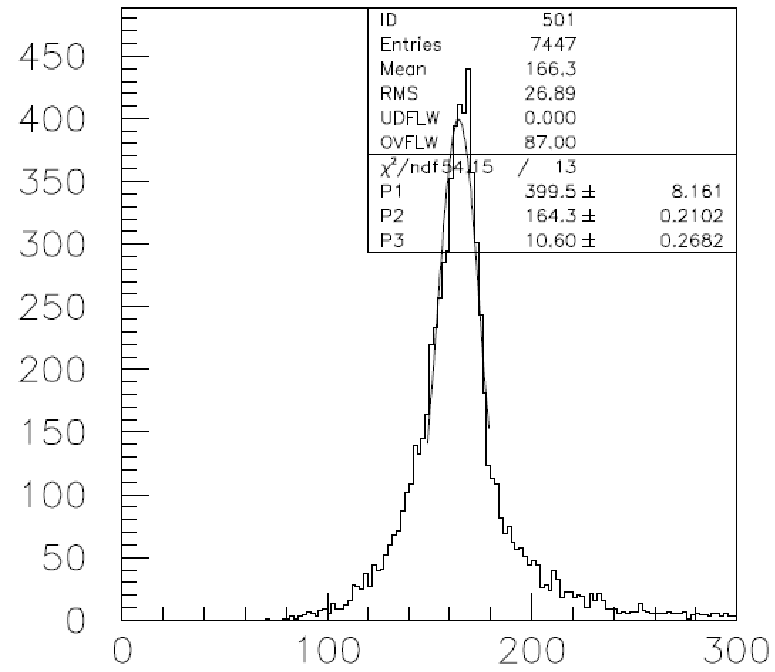
- For each model 100k inclusive events were generated
- Jets are reconstructed using *both*
  - Cone ($\Delta R = 0.5$, $p_T > 15$ GeV) ← Used for paper
  - k_T ($d_{cut} = 150$ GeV^2)
- Exactly 4 reconstructed Jets
- Technical simplifications:
  - Generator semileptonic events.
  - Unique assignment to MC truth by ΔR possible.
- Reconstruct mass on correct assignment only:
  - $m^2 = (p_{\mathrm{bjet}} + p_{qjet} + p_{qbarjet})^2$

Top Mass Estimator

D. Wicke (DØ)

Mass Distribution

- Reconstruct mass on each event.
- Fit distribution with Gaussian.
  Also considered Gaussian + p1, and flat
- Fitrange: ± 15 GeV
  (iterated to avoid bias).
  Also considered +/- 30 GeV
- Obviously suffers from out of cone problems.
- Fit W-mass from light jets.
- Scale m_t with $80.4\,\text{GeV}/m_W$.



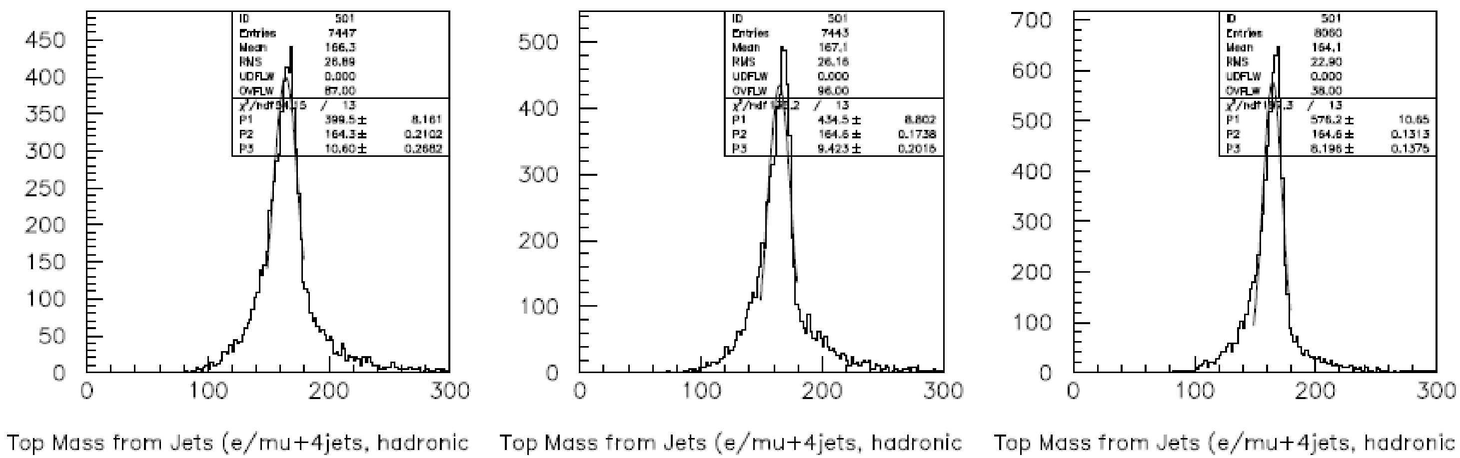
Top Mass from Jets (e/mu+4jets, hadronic

Top Mass Estimator

D. Wicke (DØ)

On Fitting

Different models lead to different shapes



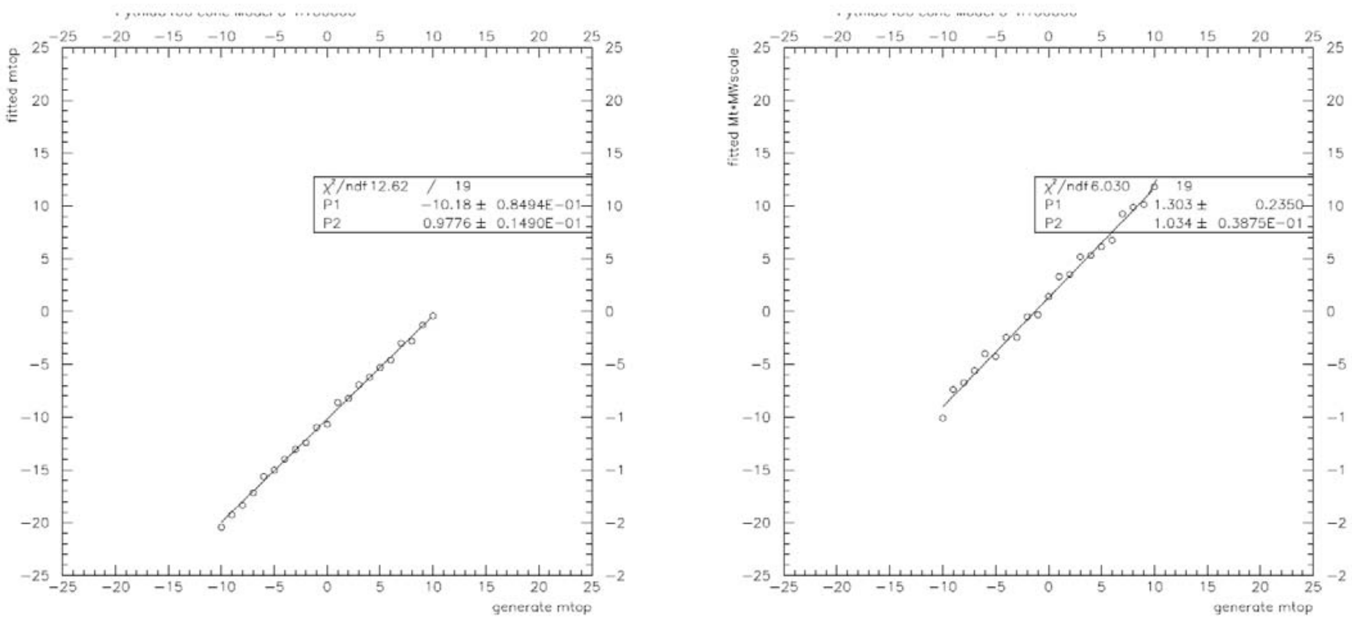
Fit ranges

- Sensitivity depends on fit ranges.
- Thus each mass analysis needs to investigate its own sensitivity.
- Sensitive estimators may be used to restrict models.

Top Mass Estimator

D. Wicke (DØ)

Calibration Curves



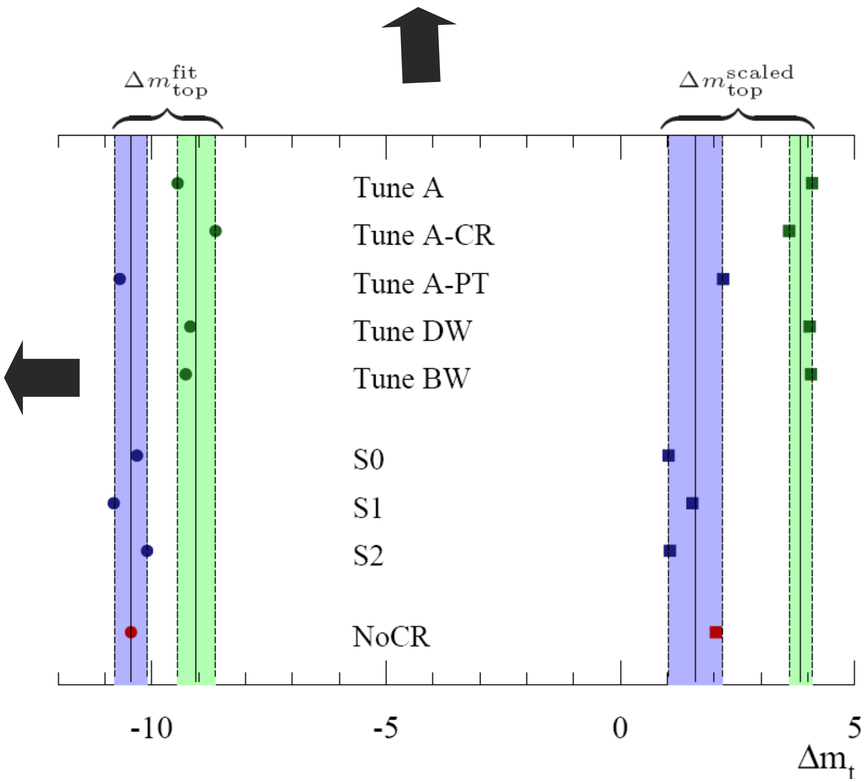
- Calibration curves show reasonably linear behaviour
- Scaling with m_W does the right thing
- Fit straight line to obtain offset at 175 GeV

Procedure has been repeated for a dozen different (tuned) models.

Preliminary Conclusions

- **Delta(mtop) ~ 1 GeV from parton shower**
  - To some extent already accounted for by HERWIG – PYTHIA, should still be investigated
  - Match to hard matrix elements for top + jets + further constrain shower parameters

- **Delta(mtop) ~ 0.5 GeV from infrared effects**
  - Early days. May be under- or overestimated. Models are crude, mostly useful for reconnaissance and order-of-magnitude
  - Pole mass does have infrared sensitivity. Can we figure out some different observable which is more stable?
    - It may be difficult to derive one from first principles, given the complicated environment, but proposals could still be tested on models
  - Infrared physics ~ universal? → use complimentary samples to constrain it. Already used a few min-bias distributions, but more could be included
  - As a last resort, take top production itself and do simultaneous fit?



A few weeks ago: D. Wicke + PS, **hep-ph/0703081**

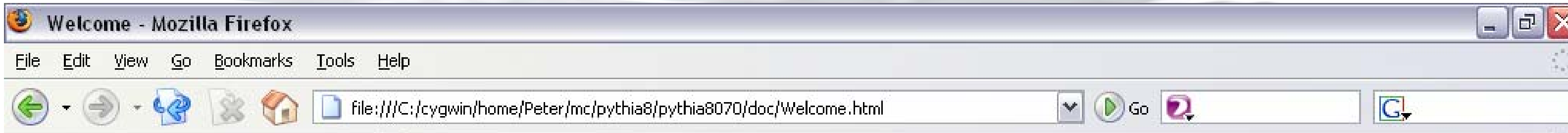
The Generator Outlook

The C++ Monte Carlos

C++ Players

- **HERWIG++: complete reimplementation**
  - Improved parton shower and decay algorithms
  - Eventually to include CKKW-style matching (?)
  - B.R. Webber; S. Gieseke, D. Grellscheid, A. Ribon, P. Richardson, M. Seymour, P. Stephens, . . .
- **SHERPA: complete implementation, has CKKW**
  - ME generator + wrappers to / adaptations of PYTHIA, HERWIG parton showers, underlying event, hadronization
  - F. Krauss; T. Fischer, T. Gleisberg, S. Hoeche, T. Laubrich, A. Schaelicke, S. Schumann, C. Semmling, J. Winter
- **PYTHIA8: selective reimplementation**
  - Improved parton shower and underlying event, limited number of hard subprocesses
  - Many obsolete features not carried over → simpler, less parameters
  - T. Sjöstrand, S. Mrenna, P. Skands
- (+ various more specialized packages)

PYTHIA 8



Basic generator already there

Includes a few processes (+ full Pythia6 library), new p_T-ordered showers, new UE, Les Houches interfaces, and more

You are invited to try it out

Click /future/ on the Pythia homepage, download pythia8080.tgz, follow instructions in readme (./configure, ./make, and have fun)

Still not advised for production runs

If you have suggestions, *now* is the time!

Timeline:

Spring 2007: QED showers, LHAPDF, interleaved FSR, beam remnants, colour reconnections → useful

Fall-Winter 2007: resonance decays, GUI, **official release?**

The Generator Outlook

- Generators in state of continuous development:
- Better & more user-friendly general-purpose matrix element calculators+integrators
- Improved parton showers and improved matching to matrix elements
- Improved models for underlying events / minimum bias
- Upgrades of hadronization and decays
- Moving to C++
- Data needed to constrain models & rule out crazy ideas
  - New methods → could QCD become a precision science?
- Important for virtually all other measurements + can shed light on fundamental & interesting aspects of QCD (e.g. string interactions)