Pythia and Vincia

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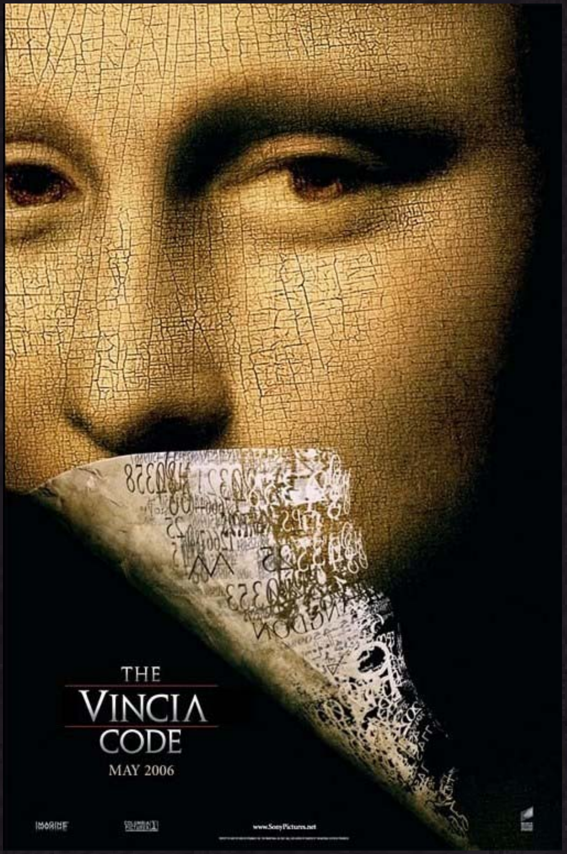


Overview

- The VINCIA code
  - Matching with QCD Antennae
  - Parton showers with error bars

- PYTHIA
  - A p_T-ordered parton shower
  - The underlying event and color
    - Color Annealing – a toy model of color reconnections

Matching – the state of the art

See e.g. hep-ph/0507129

X=Anything (e.g. ttbar)
PS=Parton Shower

Hard & Soft

Marriage Desireable!

- Several different ceremonies:

1) **Merging** (correcting first jet in X+PS to X+jet matrix element)
   - PYTHIA: many ee →X + jet, pp → (h,V) + jet and most top, EW & MSSM decays
   - HERWIG: many ee →X + jet (incl VV), DIS, pp → (V,h) + jet, top decay

2) **LO Matching** (combining LO X, X+jet, X+2jets, ... with PS)
   - SHERPA: "CKKW" matching for e+e- → n jets, pp → (V,VV) + jets
   - PATRIOT: Pre-prepared ME/PS matched samples (using MADGRAPH with PYTHIA, stored in MCFIO format) for (W, Z) + jets (≤ 4) , for Tevatron
   - ARIADNE: Vetoed Shower matching (interface to MADGRAPH) for e+e- → n jets and pp → W + jets (DIS underway)

3) **NLO Matching** (matching NLO matrix elements with PS)
   - MC@NLO: NLO + HERWIG for: pp → (h,V,VV,QQ,ll) + jets new: single top

[+ MCFM: NLO (no PS) for pp → (V,h)+jets, VV,Vh, WBF, single top]

[+ FEHiP: NNLO (no PS) for pp→ $h_{h\to\gamma\gamma}$ + jets]

New Approaches – Why Bother?

- MC@NLO:
  - Used to think it was impossible! Giant step towards precision QCD ☺
  - But complicated → tough to implement new processes ☹
  - "Only" gets first jet right (rest is PS) ☹
  - Hardwired to HERWIG ☹

- CKKW & MLM:
  - Best approach when multiple hard jets important.
  - Relatively straightforward (but still very time-consuming)
  - Retains LO normalization ☹
  - Dependence on matching scale ☹

- "CKKW@NLO": Nagy & Soper ...
- MC with SCET: Bauer & Schwartz ...

• Not easy to control theoretical error on exponentiated part (also goes for ARIADNE, HERWIG, PYTHIA, ...) ☹

VINCIA – Basic Sketch

- Perturbative expansion for some observable J,

  $$d\sigma = \Sigma_{m=0} d\sigma_m \quad ; \qquad d\sigma_m = d\Pi_m |M|^2 \delta(J - J(k_1, k_2, \ldots, k_m))$$

- Assume
  - We calculate some Matrix Elements $d\sigma_0$, $d\sigma_1$, … $d\sigma_n$ (w or w/o loops)
  - And we have some approximation $d\sigma_{n+1} \sim T_{n \to n+1} d\sigma_n$ (~ parton shower)

- A 'best guess' cross section for J is then:

  $$d\sigma \sim d\sigma_0 + d\sigma_1 + \ldots + d\sigma_n (1 + T_{n \to n+1} + T_{n \to n+1} T_{n+1 \to n+2} + \ldots)$$

  ➔ $$d\sigma \sim d\sigma_0 + d\sigma_1 + \ldots + d\sigma_n S_n \qquad ; S_n = 1 + T_{n \to n+1} S_{n+1}$$

- The $T_{n \to n+1}$ have to at least contain the correct singularities (in order to correctly sum up all logarithmically enhanced terms), but they are otherwise arbitrary.

- Now reorder this series in a useful way …

Reordering Example: "H" → gluons

- Assume we know $H \to gg$ and $H \to ggg$. Then reorder:

Use $1 = S_n - T_{n \to n+1} S_{n+1}$

- $d\sigma \sim d\sigma_{gg} + d\sigma_{ggg}\, S_{ggg}$

$= S_{gg} d\sigma_{gg} + S_{ggg}\,(d\sigma_{ggg} - T_{gg \to ggg} d\sigma_{gg})$

$= S_{gg} d\sigma_{gg} + S_{ggg}\, d\chi_{ggg}$ (generalises to n gluons)

- I.e shower off gg and subtracted ggg matrix element.

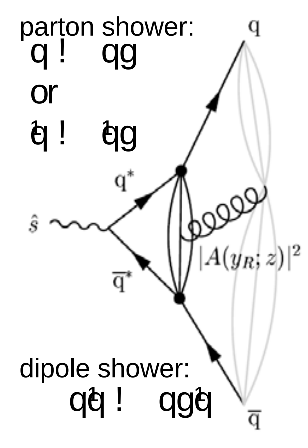
Double counting avoided since singularities (shower) subtracted in $d\chi_{ggg}$.

- The shower kernels, T_{gg}, are precisely the singular subtraction terms used in HO perturbative calculations. As a basis we use Gehrman-Glover antennae:

Gehrmann-De Ridder, Gehrmann, Glover PLB612(2005)49

Parton Showers: the basics

Essentially: a simple approximation → infinite perturbative orders



- Today, basically 2 (dual) approaches:
  - Parton Showers (1→2, e.g. HERWIG, PYTHIA)
  - and Dipole Showers (2→3, e.g. ARIADNE, VINCIA)

- Basic Formalism: Sudakov Exponentiation:

$$\mathrm{d}\mathcal{P}_a = \frac{\mathrm{d}X^2}{X^2}\,\frac{\alpha_s(X^2)}{2\pi}\,P_{a\to bc}(z)\,\mathrm{d}z\;\exp\left(-\int_X^{X_{\max}}\cdots\right)$$

Sudakov Form Factor = 'no-branching' probability

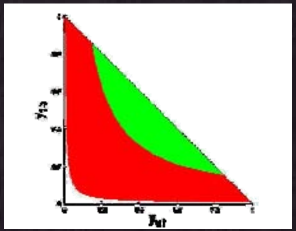
  - **"Evolution" in X =** measure of hardness (p^2, p_T^2, …)
    - z: energy-sharing
    - n partons → n+1. Cut off at some low scale → natural match to hadronisation models

–**Formally correct in** collinear **limit $p_{T(i)} << p_{T(i-1)}$,** but approximate for hard emissions → need matching.

The VINCIA code

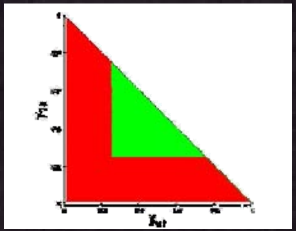
VIrtual **N**umerical **C**ollider with **I**nterfering **A**ntennae

- C++ code running: gluon cascade
- Dipole shower with 4 different ordering variables:



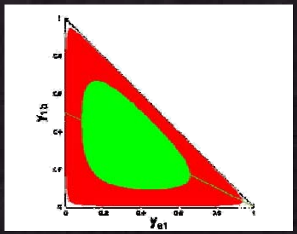
$R^{I}(m_{12},m_{23}) = 4\, s_{12}s_{23}/s$

$= p^2_{T;ARIADNE}$



$R^{II}(m_{12},m_{23}) = 2\min(s_{12},s_{23})$

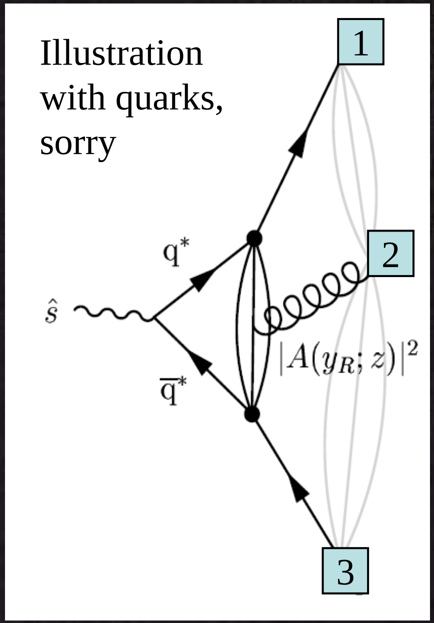
$\sim m^2_{PYTHIA}$

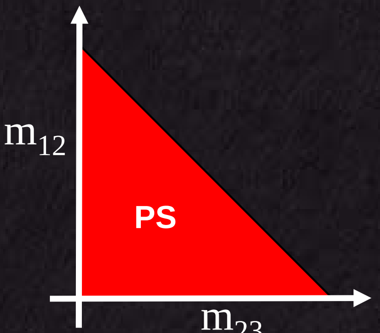


$R^{III}(m_{12},m_{23}) = 27\, s_{12}s_{23}s_{31}/s^2$

$\sim p^2_{T;PYTHIA}$

$R^{IV}(m_{12},m_{23}) = 2\min(s_{12},\min(s_{23},s_{31}))$

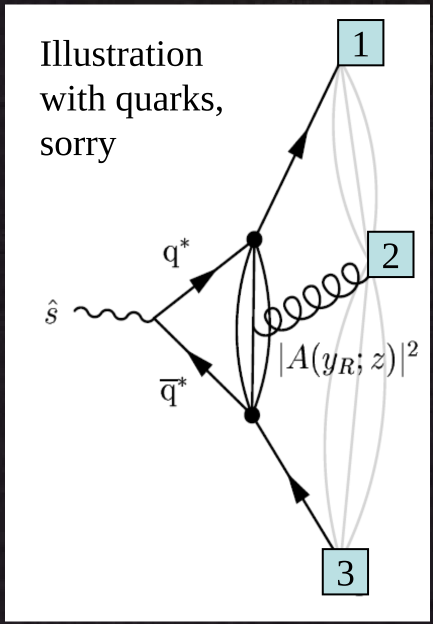




The VINCIA code

VIrtual **N**umerical **C**ollider with **I**nterfering **A**ntennae

- For each evolution variable:
  - an infinite family of antenna functions, all with correct collinear and soft behaviour:
  - Using rescaled invariants: $y_{ij} = s_{ij}/s$
  - Our antenna function (a.k.a. radiation function, a.k.a. subtraction function) is:



$$a(y_{12}; y_{23}) = (1 - y_{12} - y_{23}) \left(\frac{1}{y_{12} y_{23}} + \frac{y_{12}}{2 y_{23}} + \frac{y_{23}}{2 y_{12}} + 1 \right) + \sum_{m,n=0} C_{mn} \, y_{12}^n y_{23}^m$$

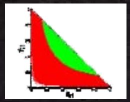
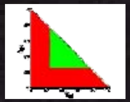
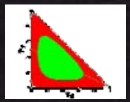
- Changes to Gehrman-Glover:
  - → ordinary DGLAP limit

$$\lim_{y_{ar} \to 0} \left(a(y_{a-1,a}; y_{ar}) + a(y_{ar}; y_{rb}) \right) = \frac{1}{y_{ar}^C} P_{g \to gg}(z)$$

  - → First parton shower with systematic possibility for variation (+ note: variation absorbed by matching!)

The VINCIA code

VIrtual **N**umerical **C**ollider with **I**nterfering **A**ntennae

- Sudakov Factor contains integral over PS:

$$\Delta_{13}(Q_R) = \exp\left(-\frac{2g^2N_c}{\hat{s}_{13}}\int d\,\mathrm{PS}_R(p_1;p_2;p_3)\,\Theta\left(s_{123}R(y_{12};y_{23}) - Q_R^2\right)\,a(y_{12};y_{23})\right)$$

- Compact analytical solutions for types I and II (here without C_{mn} pieces)

$$D_{ab}^{(I)} = \frac{32}{9} + \frac{4}{9}w_-(2w_+^2 - w_+ - 16) + \frac{1}{6}(w_+ - w_-)(1 + 8w_+w_-)$$
$$+ \left(\frac{11}{6} + w_+w_-\right)\log\left(\frac{w_-}{w_+}\right) + \frac{1}{2}\log^2(w_-) - \frac{1}{2}\log^2(w_+) + \mathrm{Li}_2(w_-) - \mathrm{Li}_2(w_+)$$

$; w_\pm = \frac{1}{2}\left(1 \pm \sqrt{1 - R}\right)$

$$D_{ab}^{(II)} = \log^2(w) - \log(w)\log(1-w) + \frac{1}{6}(1-w)(2w^2 - w + 11)\log\left(\frac{w}{1-w}\right)$$
$$+ \mathrm{Li}_2(w) - \mathrm{Li}_2(1-w) + \frac{1}{36}(1-2w)(16w^2 + 2w + 61) + \frac{1}{6}(1-2w)^3$$

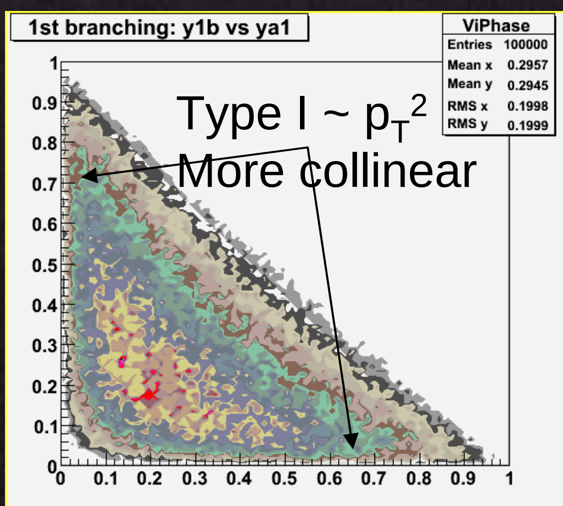
$; w = \frac{1}{2}R$

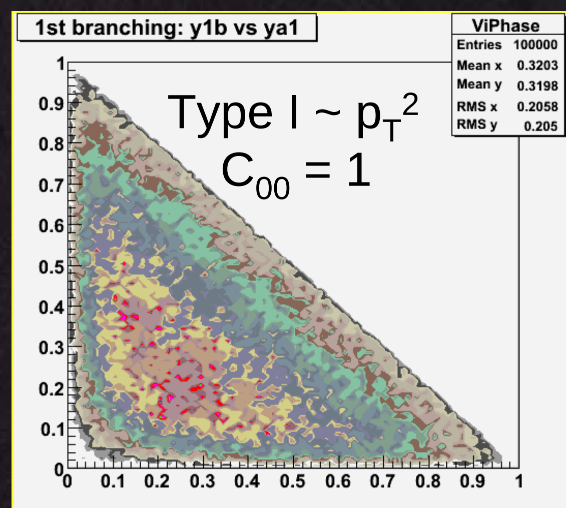
- Types III and IV solved numerically (+ num. options for I and II as well)
→Splines, so only need to evaluate once → fast.

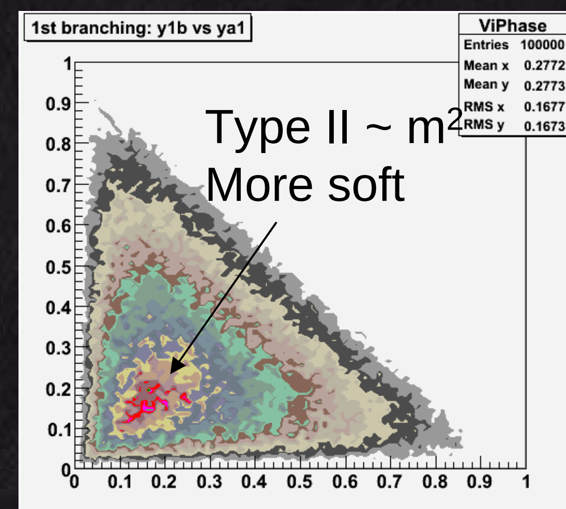
- Successive branchings found with Metropolis algorithm according to 2D ordered branching probability: $P(y_{12},y_{23}) = a(y_{12},y_{23})\,\Delta(y_R(y_{12},y_{23});1)$

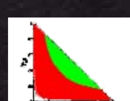
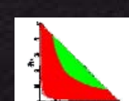
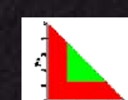
VINCIA – First Branching

- Starting scale Q = 20 GeV
- Stopping scale Q_{had} = 1 GeV
- ~ 1st order expansion in perturbation theory
- Axes: $y_{ab} = m^2_{ab} / m^2_{dipole}$







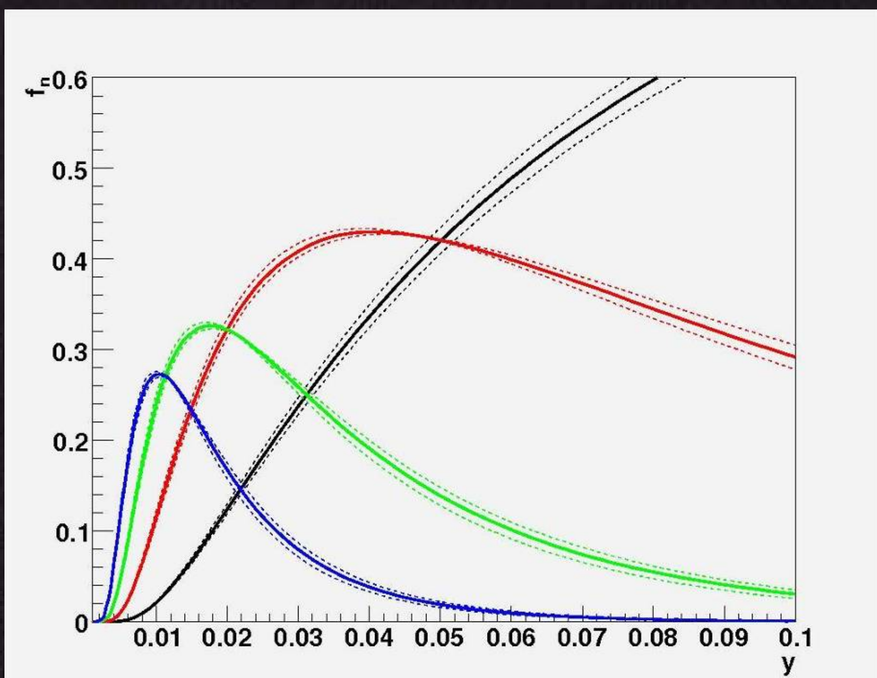
VINCIA – Matching – k_T jet rates

- Type I Sudakov (~ p_T evolution) with C_{00} = -1,0,1

$$a(y_{12};y_{23}) = (1 - y_{12} - y_{23})\left(\frac{1}{y_{12}y_{23}} + \frac{y_{12}}{2y_{23}} + \frac{y_{23}}{2y_{12}} + 1\right) + \sum_{m;n=0} C_{mn}\, y_{12}^n y_{23}^m$$

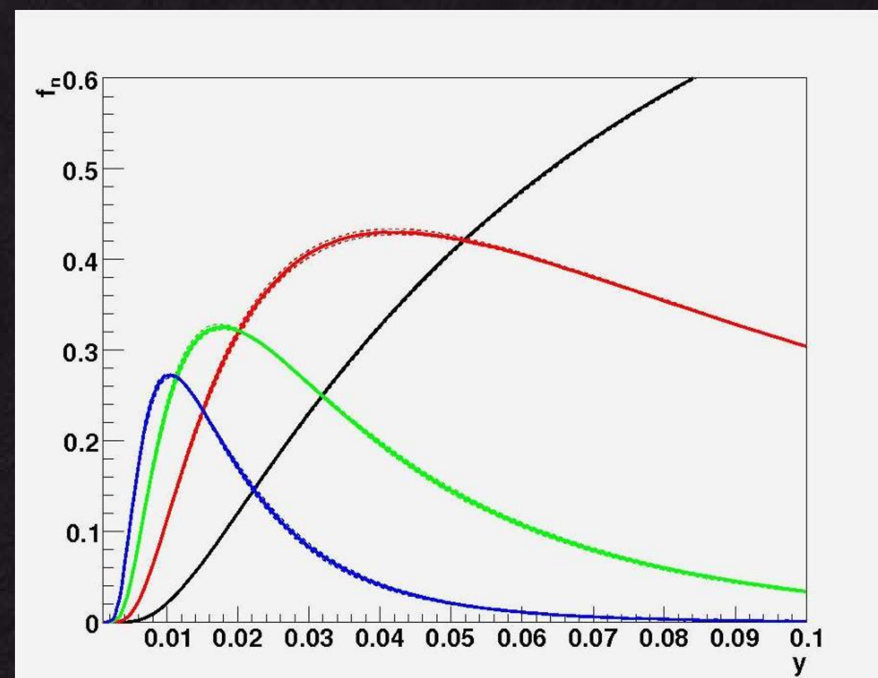
<u>2-jet only – no matching</u>

~ standard Parton Shower



<u>Matched: 2-jet + 3-jet ME</u> + PS

~ matched Parton Shower



Outlook – VINCIA

- Construction of VINCIA shower MC
  - gluon shower MC

    Giele, Kosower, PS ; writeup in progress…

    - based on LO done!
    - based on NLO 'trivial' so far → total **width** meaningful. Remains to demonstrate technique for **σ**
    - Can vary both Sudakov ordering and radiation function → systematic exploration of uncertainty
    - Can do matching to improve uncertainty (no δ_{sep} dependence)
    - Number of hard legs can be as many as you can calculate
    - Computations so far uncomplicated
  - Hadron collider shower MC
    - Including initial-state radiation …
    - Including quarks …
  - Higher orders: NNLO, NLL ?

Overview

- The VINCIA code
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  - Parton showers with error bars
- PYTHIA
  - A p_T-ordered parton shower
  - The underlying event and color
    - Color Annealing – a toy model of color reconnections

New Parton Shower – Why Bother?

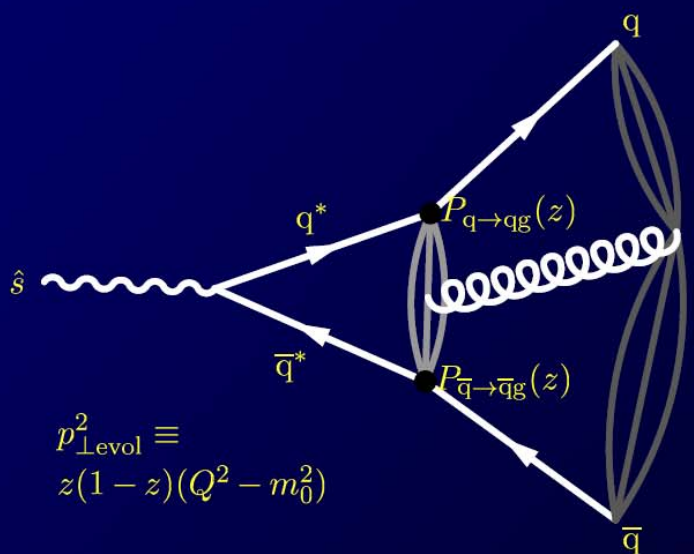
- Pros and cons of existing showers, e.g.:
  - In PYTHIA, ME merging is easy, and emissions are ordered in some measure of (Lorentz invariant) hardness, but angular ordering has to be imposed by hand, and kinematics are somewhat messy. Matching not straightforward.
  - HERWIG has inherent angular ordering, but also has the 'dead zone' problem, is not Lorentz invariant and has somewhat messy kinematics. Matching not straightforward.
  - ARIADNE has inherent angular ordering, simple kinematics, and is ordered in a (Lorentz Invariant) measure of hardness, matching is straightfroward, but is primarily a tool for e^+e^-, and g→qq is 'artificial' in dipole formalism.
- These all describe LEP data well, but none are perfect (ARIADNE probably slightly the better)

➔ Try combining the virtues of each of these while avoiding the vices?

p_T-ordered showers

Merged with X + 1 jet Matrix Elements (by reweighting) for:
h/γ/Z/W production, and for most EW, top, and MSSM decays!

Exclusive *kinematics* constructed inside dipoles based on Q^2 and z, assuming yet unbranched partons on-shell



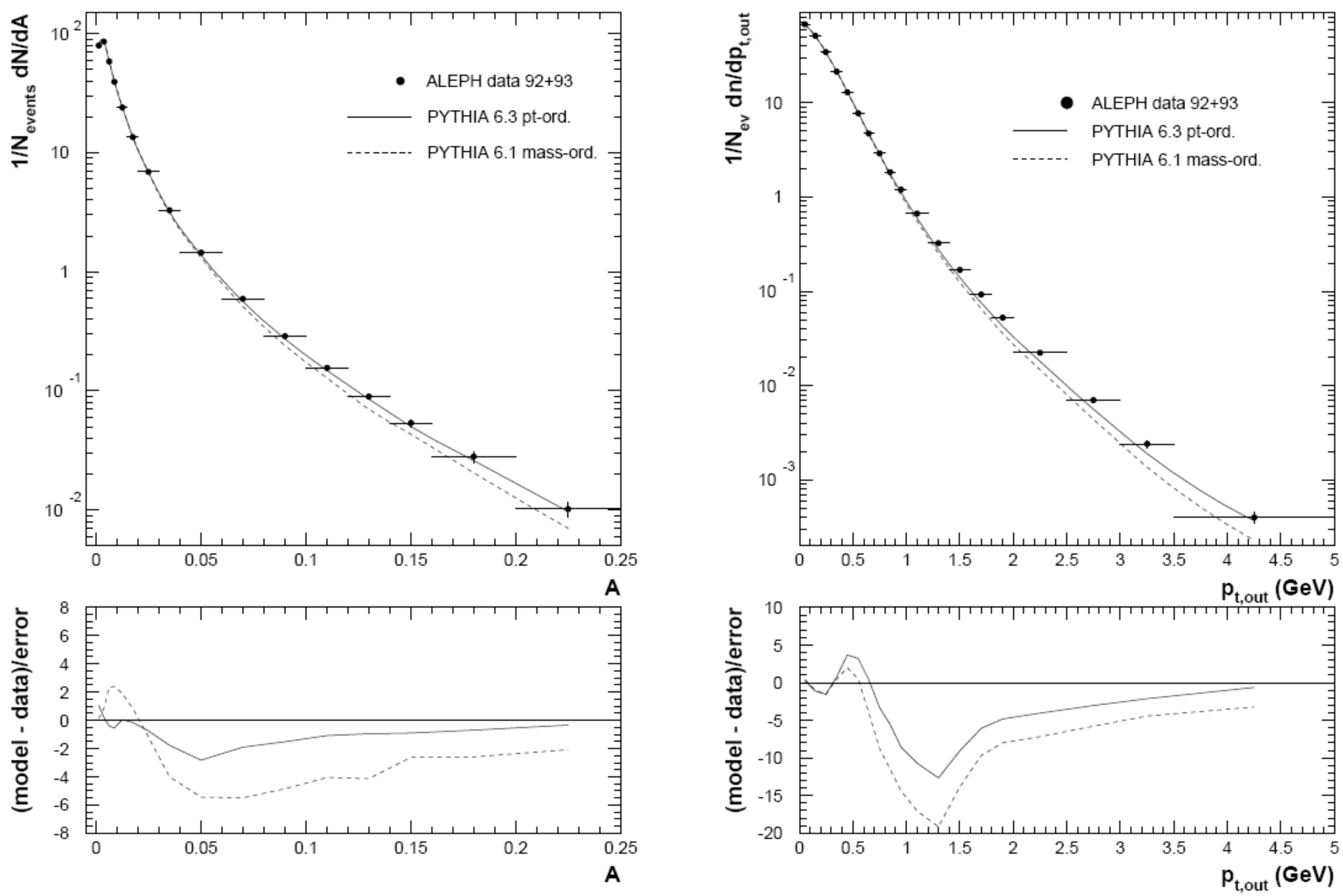
Iterative application of Sudakov factors...

$\Rightarrow$ One combined sequence $p_{\perp max} > p_{\perp 1} > p_{\perp 2} > \ldots > p_{\perp min}$

Sjöstrand & PS : Eur.Phys.J.C39(2005)129; Plehn, Rainwater & PS: hep-ph/0510144 & hep-ph/0511306

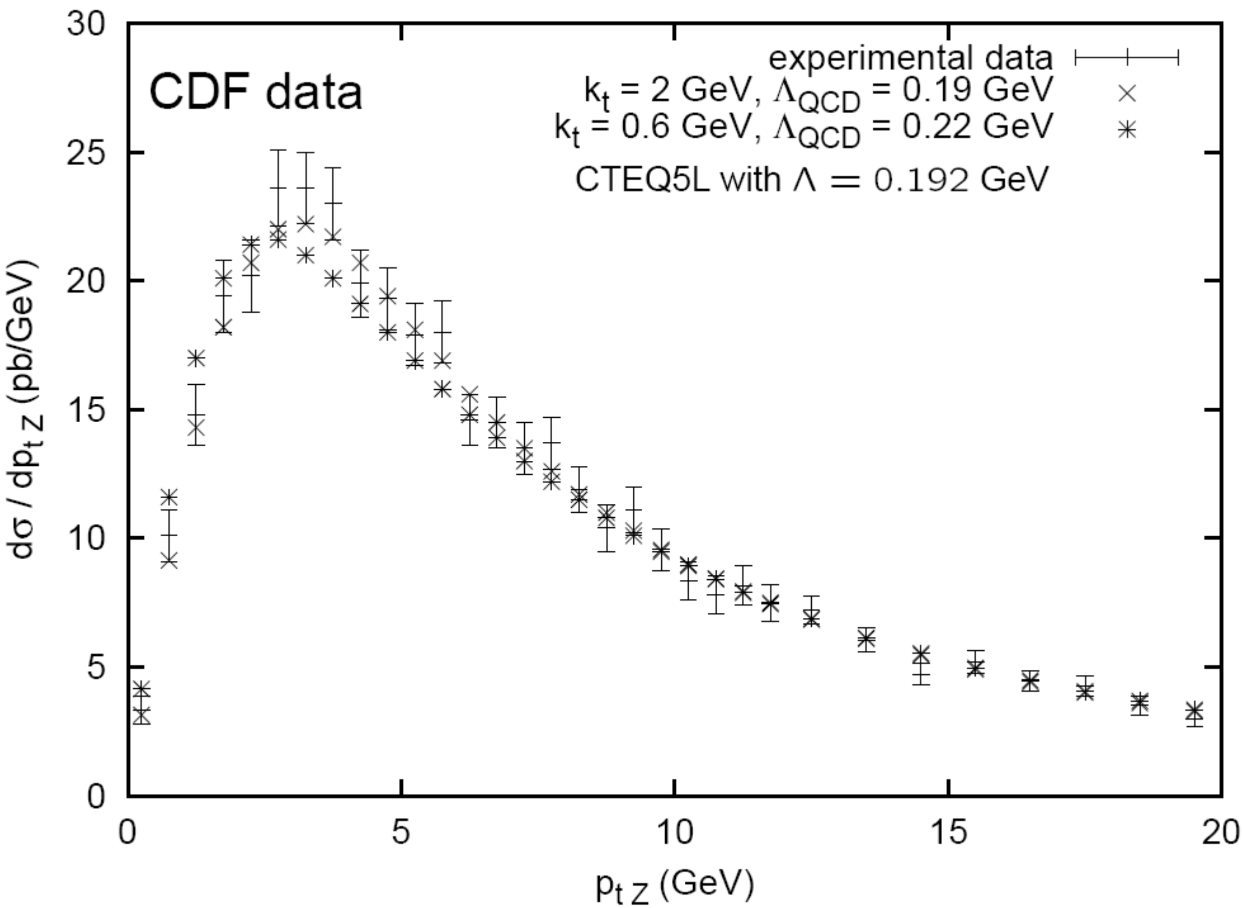
Testing the FSR algorithm

Tune performed by Gerald Rudolph (Innsbruck)
based on ALEPH 1992+93 data:



Testing the ISR algorithm

Still only begun. . .

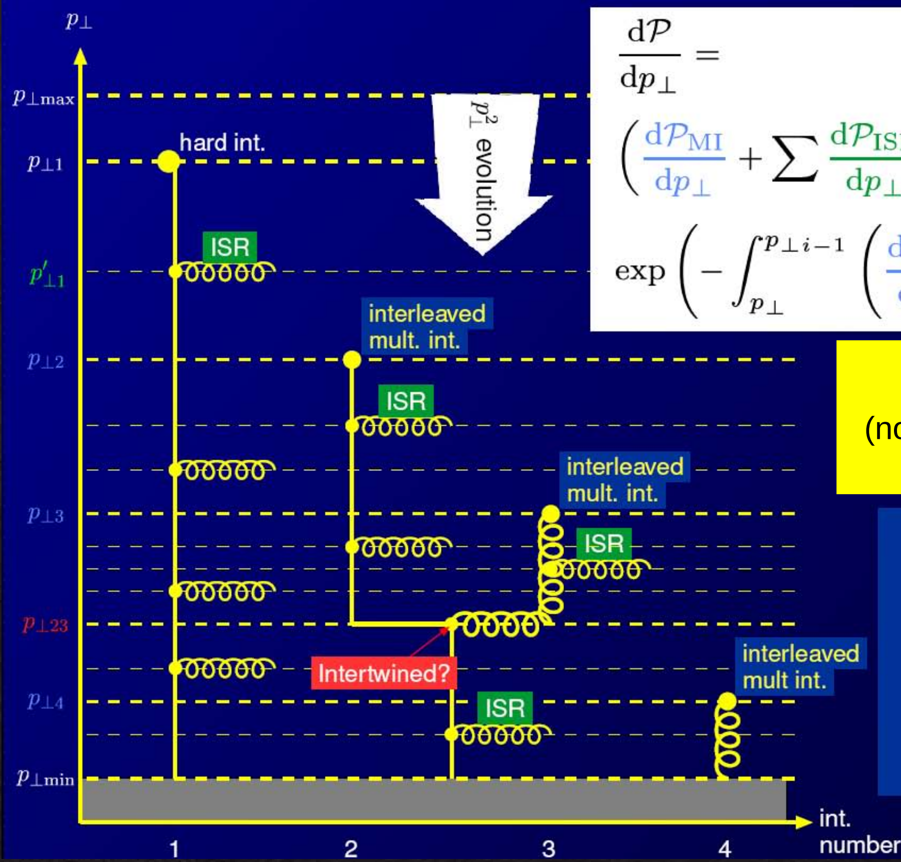


. . . but so far no showstoppers

‘Interleaved evolution’ with Multiple Parton Interactions

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

Add exclusivity progressively by evolving *everything* downwards.



Pythia 6.3

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

→ Underlying Event

(note: interactions correllated in colour: hadronization not independent)

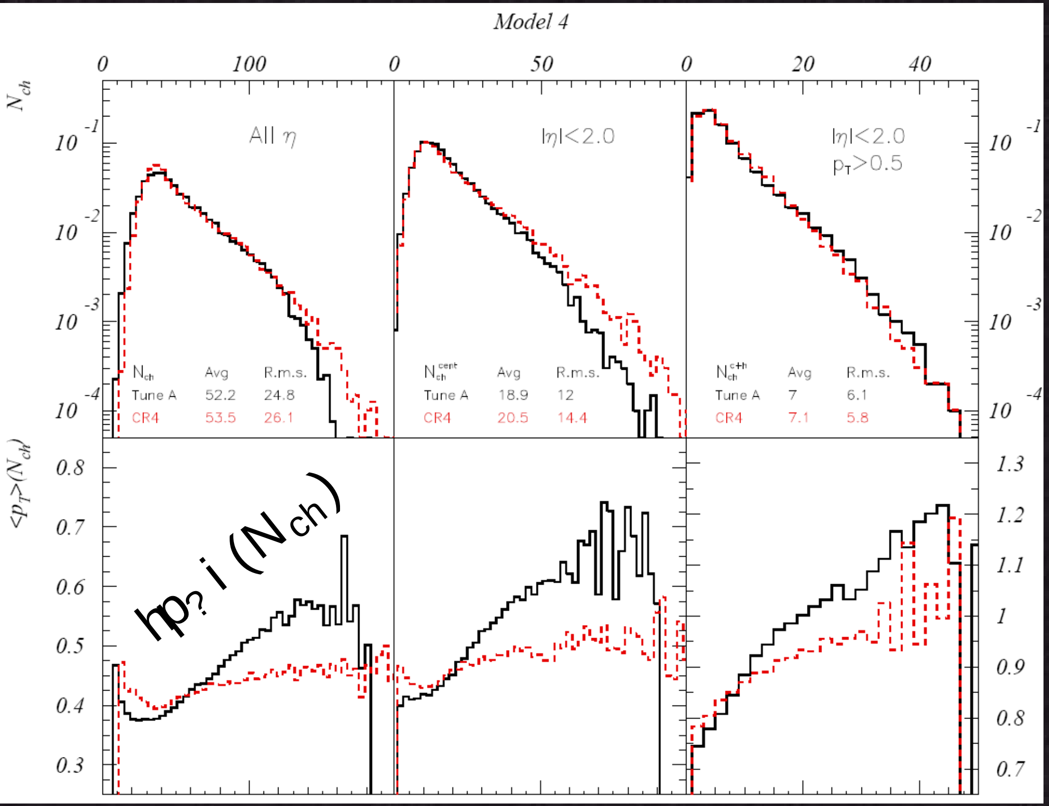
∼ “Finegraining”

→ correlations between all perturbative activity at successively smaller scales

Sjöstrand & PS : Eur.Phys.J.C39(2005)129 + JHEP03(2004)053

Motivation

- Min-bias collisions at the Tevatron
  - Well described by Rick Field's "Tune A" of PYTHIA
  - Theoretical framework is from 1987. I made some improvements.
  - Wanted to use "Tune A" as initial reference target
  - But it kept on being different …



Multiplicity distribution OK (plus a lot of other things), but $<p_T>(N_{ch})$ never came out right ➔ <u>something must be wrong or missing?</u>

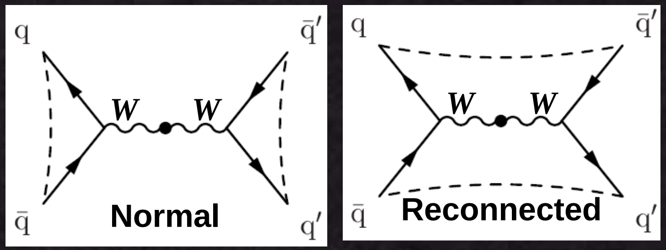
Underlying Event and Color

- Multiplicity in string fragmentation ~ $\log(m_{string})$
  - More strings → more hadrons, but average p_T stays same
  - Flat $\langle p_T \rangle(N_{ch})$ spectrum ~ 'uncorrellated' underlying event
- But if MPI interactions correlated in colour
  - Sjöstrand & v Zijl : Phys.Rev.D36:2019,1987 → "Old" Pythia model
  - each scattering does not produce an independent string,
  - average p_T → not flat
- Central point: multiplicity vs p_T correllation probes color correllations!
- What's so special about Tune A?
  - It and all other realistic 'tunes' made turn out to have to go to the very most extreme end of the parameter range, with 100% color correllation in final state.

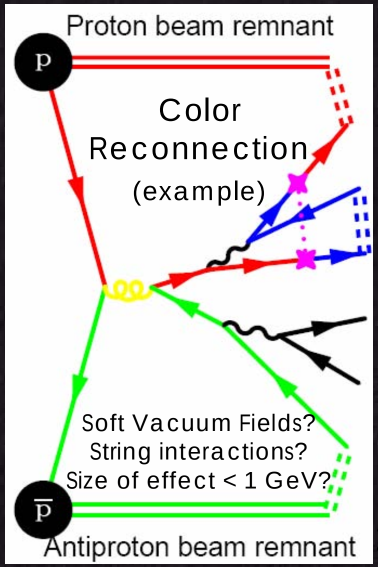
Sjöstrand, Khoze, Phys.Rev.Lett.72(1994)28 & Z. Phys.C62(1994)281 + more …

Color Reconnections

- Searched for at LEP **OPAL**, Phys.Lett.B453(1999)153 & **OPAL**, hep-ex0508062
  - Major source of W mass uncertainty
  - Most aggressive scenarios excluded
  - But effect still largely uncertain ~ 10%



- Prompted by CDF data and Rick Field's 'Tune A' to reconsider. What do we know?
  - More prominent in hadron-hadron collisions?
  - What is $\langle p_T \rangle (N_{ch})$ telling us?
  - Top mass?
  - Implications for LHC?



- Problem: existing models only for $e^+e^- \rightarrow WW$

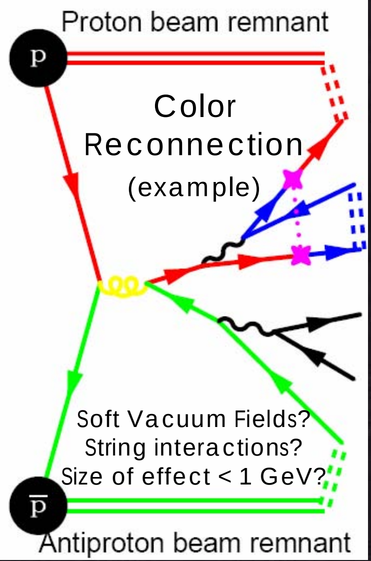
Color Annealing

- 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:

$$P_{reconnect} = 1 - (1-^{3})^{n_{int}}$$

^{3}: Strength parameter
n_{int}: Number of parton-parton interactions

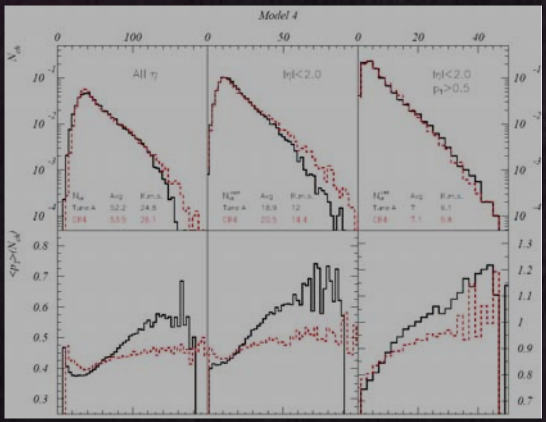
  - String formation for interacting string pieces determined by annealing-like minimization of ‘Lambda measure’ (~string length~log(m)~N)

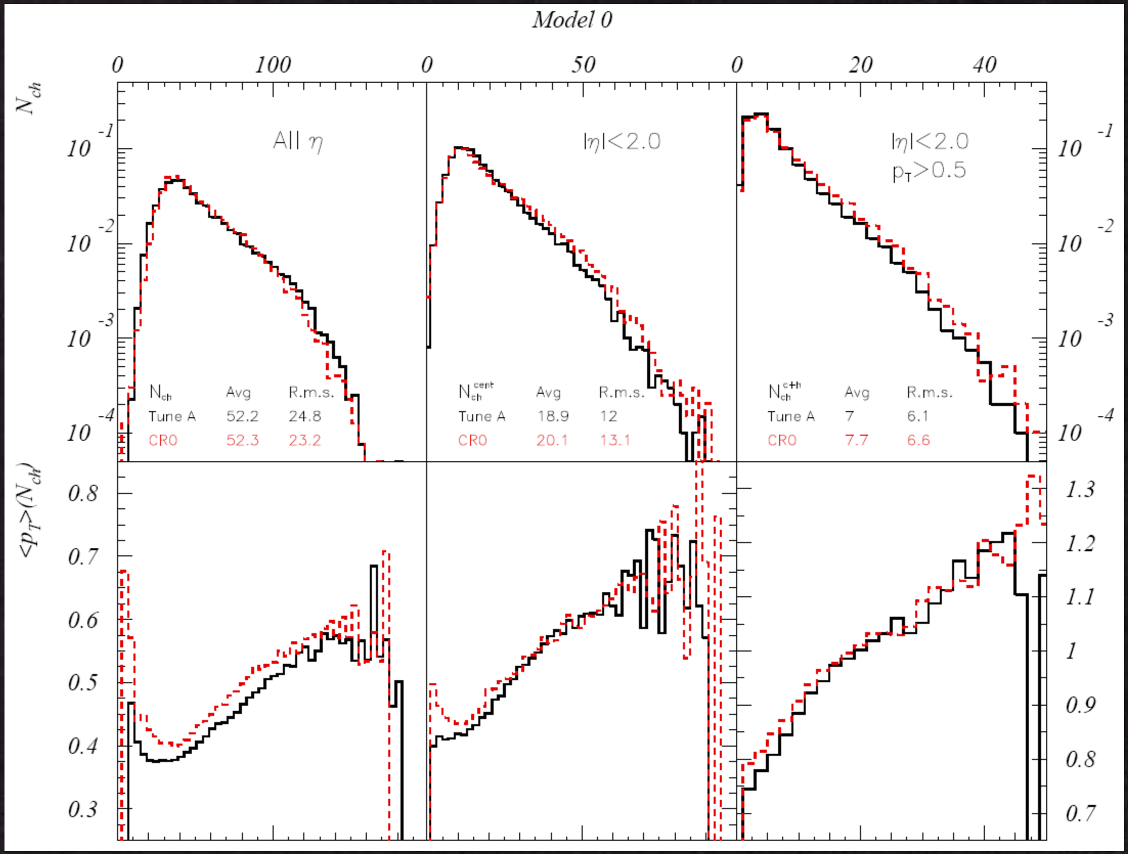


- → good enough for order-of-magnitude

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

First Results





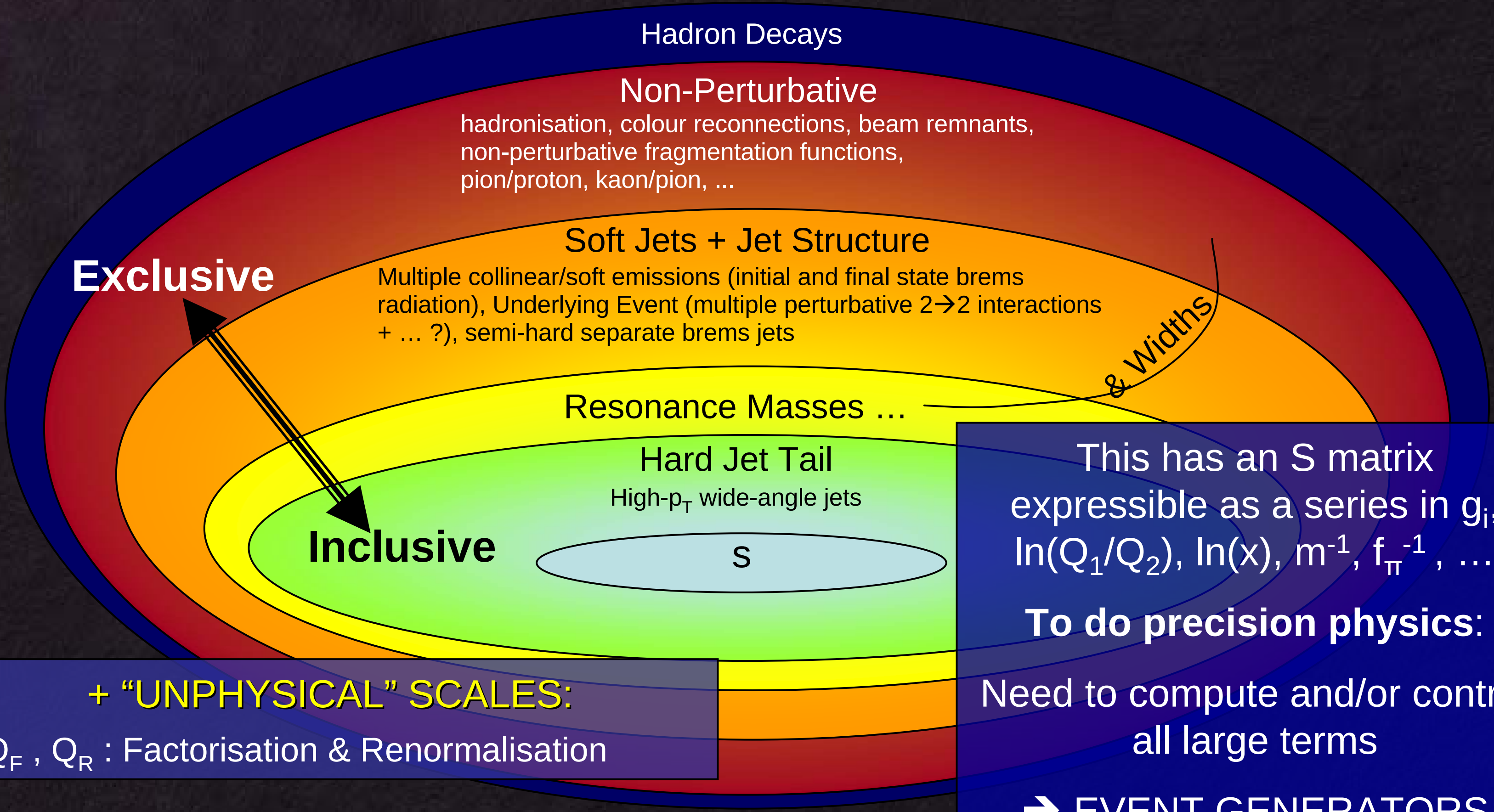
- Improved Description of Min-Bias
- Effect <u>Still</u> largely uncertain
- Worthwhile to look at top etc

- Investigating effect on DØ top mass with D. Wicke (U. Wuppertal)

Conclusions – Underlying Event

- Ever-present yet poorly understood part of QCD. How ‘good’ are current physical models/parametrizations?
- What’s the relation between min-bias and underlying events? Are there color reconnections? Are they more prolific in hadron collisions? Are there other collective phenomena? Does this influence top mass etc?
- Physics Impact
  - Calibration (e.g. 3.6M min-bias events → 1% calibration of CMS ECAL)
  - Lepton isolation, photon isolation
  - Jet energy scale
  - Tails → Fakes! (Enormous rate) x (small probability) = still large
  - Min-bias → underlying event
- New generation of models address more detailed questions: correllations, baryon flow, … more?
- Energy Extrapolation largest uncertainty for LHC!
  - RHIC pp collisions vital? → energy scaling
  - Can be measured in situ, but more interesting to predict than postdict

Collider Energy Scales



+ "UNPHYSICAL" SCALES:

- Q_F , Q_R : Factorisation & Renormalisation

This has an S matrix expressible as a series in g_i, $\ln(Q_1/Q_2)$, $\ln(x)$, m^{-1}, f_π^{-1} , …

To do precision physics:

Need to compute and/or control all large terms

➔ EVENT GENERATORS

The Monte Carlo method

Want to generate events in as much detail as Mother Nature

$\Longrightarrow$ get average *and* fluctutations right

$\Longrightarrow$ make random choices, $\sim$ as in nature

$$\sigma_{\text{final state}} = \sigma_{\text{hard process}} \mathcal{P}_{\text{tot,hard process}\to\text{final state}}$$

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

where $\mathcal{P}_{\text{tot}} = \mathcal{P}_{\text{res}} \mathcal{P}_{\text{ISR}} \mathcal{P}_{\text{FSR}} \mathcal{P}_{\text{MI}} \mathcal{P}_{\text{remnants}} \mathcal{P}_{\text{hadronization}} \mathcal{P}_{\text{decays}}$

with $\mathcal{P}_i = \prod_j \mathcal{P}_{ij} = \prod_j \prod_k \mathcal{P}_{ijk} = \ldots$ in its turn

$\Longrightarrow$ **divide and conquer**

an event with n particles involves $\mathcal{O}(10n)$ random choices,

(flavour, mass, momentum, spin, production vertex, lifetime, ...)

LHC: ~ 100 charged and ~ 200 neutral (+ intermediate stages)

$\Longrightarrow$ several thousand choices

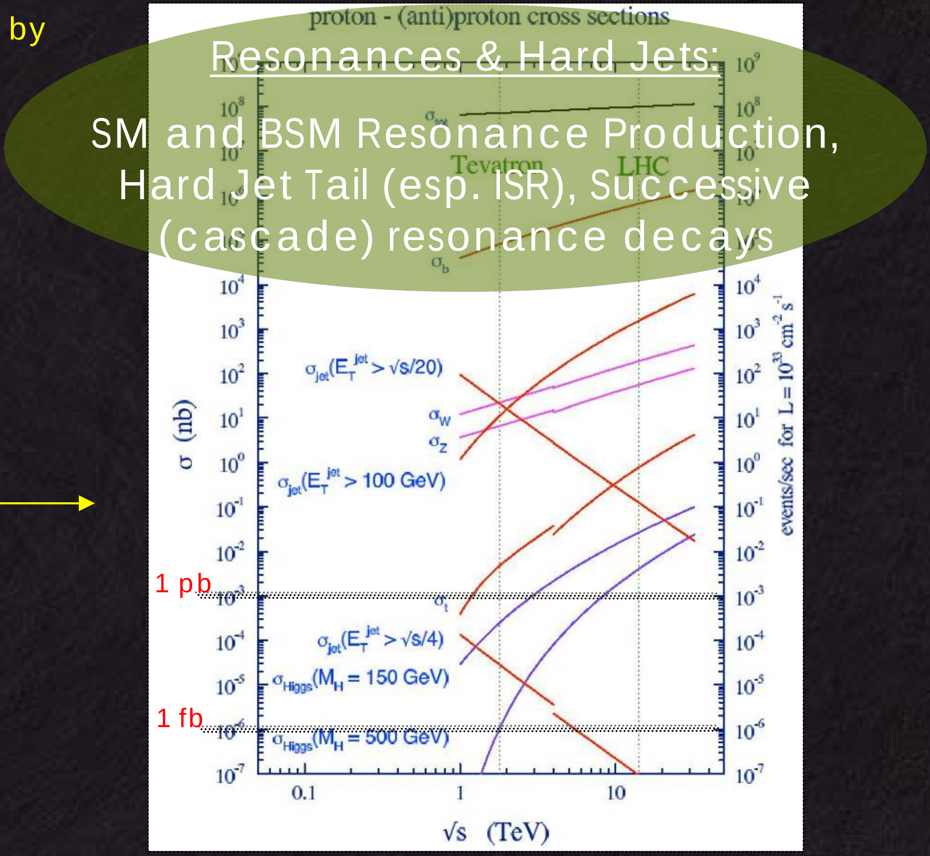
(of $\mathcal{O}(100)$ different kinds)

from T. Sjöstrand

High-p_T phenomenology

- The signal
  - Large cross sections for coloured BSM resonances
  - E.g. monojet signature for ED relies on hard QCD radiation
  - Cascade decays → Many-body final states
- Backgrounds
  - Also large cross sections for top, nZ/W, *other* resonances (?), …
  - With jets
- Theory:
  - Fixed-order perturbation theory
  - Asymptotic freedom → improved convergence at high p_T
  - Phase space increases

e.g. talk by Lillie



Problem 1: Many legs is hard → E.g. successive factorization of res. decays

Problem 2: Many loops is hard → Get a personal physician for Frank

Problem 3: Only good for inclusive observables → Match to resummation

Medium-p_T phenomenology

- Extra Jets
  - In signal
    - = extra noise / confusion
    - Combinatorics, vetos
  - In backgrounds
    - Irreducible backgrounds
    - Some fraction → <u>fakes</u>!
- Heavy flavour
- Jet energy scale
  - Jet broadening
  - Underlying activity
- Theory
  - Fixed Order with explicit jets
  - Parton Showers / Resummation
  - Models of Underlying Event

e.g. talk by Sullivan

e.g. talk by Gupta

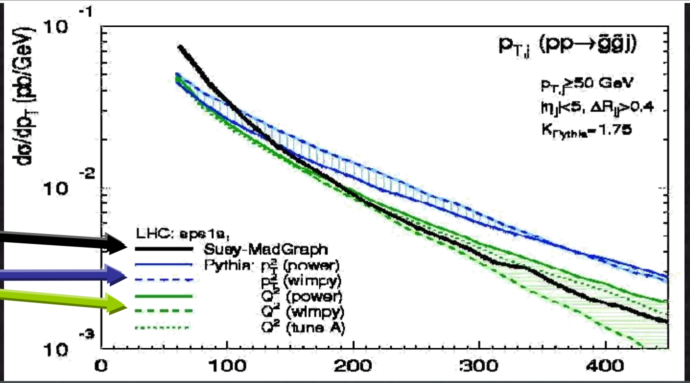
e.g. talk by Lecomte

<u>Minijets & Jet Structure:</u>

Semi-hard separate brems jets (esp. ISR), jet broadening (FSR), g→cc/bb, multiple perturbative 2→2 interactions (underlying event), ... ?

LHC - sps1a - m~600 GeV   Plehn, Rainwater, PS (2005)

FIXED ORDER pQCD	σ_{tot} [pb]	$\tilde{g}\tilde{g}$	$\tilde{u}_L\tilde{g}$	$\tilde{u}_L\tilde{u}_L^*$	$\tilde{u}_L\tilde{u}_L$	TT
$p_{T,j} >$ 100 GeV	σ_{0j}	4.83	5.65	0.286	0.502	1.30
inclusive **X + 1 "jet"** →	σ_{1j}	2.89	2.74	0.136	0.145	0.73
inclusive **X + 2 "jets"** →	σ_{2j}	1.09	0.85	0.049	0.039	0.26



Problem 1: Need to get both soft and hard emissions "right" → ME/PS Matching

Problem 2: Underlying Event not well understood → what does it look like at LHC?

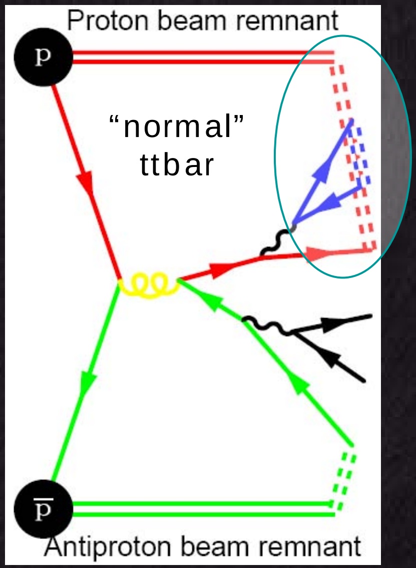
Low-p_T phenomenology

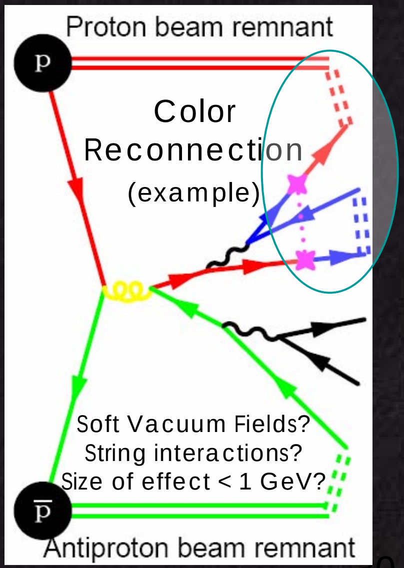
- Measurements at LEP →
  - Fragmentation models (HERWIG, PYTHIA) "tuned"
  - Strangeness and baryon production rates well measured
  - Colour reconnections ruled out in WW (to ~ 10%)
- Measurements at hadron colliders
  - Different vacuum, colour in initial state → "colour promiscuity"?
  - Underlying Event and Beam Remnants
  - Intrinsic k_T
  - Lots of min-bias. Fragmentation tails → fakes!

Example Problem:
What is the non-perturbative uncertainty on the top mass?

Non-Perturbative:

hadronisation, beam remnants, fragmentation functions, intrinsic k_T, colour reconnections, pion/proton ratios, kaon/pion ratios, Bose-Einstein, diffraction, elastic, ...





What is the Difference?

CKKW (& friends) in a nutshell:

1. Generate a n-jet Final State from n-jet (singular) ME
2. Construct a "fake" PS history
3. Apply Sudakov weights on each "line" in history → from inclusive n-jet ME to exclusive n-jet (i.e. probability that n-jet **remains** n-jet above cutoff) → gets rid of double counting when mixed with other ME's.
4. Apply PS with no emissions above cutoff

VINCIA in a nutshell:

1. Subtract PS singularities from n-jet ME (antenna subtraction)
2. Generate a n-jet Final State from the subtracted (finite) ME.
3. Apply PS with same antenna function → Leading Logs resummed

+ full NLO: divergent part already there → just include extra finite contribution in $d\sigma = d\sigma_0^{(0)} + d\sigma_1^{(0)} + \text{sing}[d\sigma_0^{(1)}] + F^{(1)} + \ldots$

+ NNLO/NLL possible? Gehrmann-De Ridder, Gehrmann, Glover JHEP09(2005)056

+ Easy to vary shower assumption

→ first parton shower with 'error band'! (novelty in itself)

PYTHIA Process Library

No.	Subprocess
Hard QCD processes:	
11	$f_i f_j \to f_i f_j$
12	$f_i \bar{f}_i \to f_k \bar{f}_k$
13	$f_i \bar{f}_i \to gg$
28	$f_i g \to f_i g$
53	$gg \to f_k \bar{f}_k$
68	$gg \to gg$
Soft QCD processes:	
91	elastic scattering
92	single diffraction (XB)
93	single diffraction (AX)
94	double diffraction
95	low-$p_\perp$ production
Open heavy flavour: (also fourth generation)	
81	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
82	$gg \to Q_k \bar{Q}_k$
83	$q_i f_j \to Q_k f_l$
84	$g\gamma \to Q_k \bar{Q}_k$
85	$\gamma\gamma \to F_k \bar{F}_k$
Closed heavy flavour:	
86	$gg \to J/\psi g$
87	$gg \to \chi_{0c} g$
88	$gg \to \chi_{1c} g$
89	$gg \to \chi_{2c} g$
104	$gg \to \chi_{0c}$
105	$gg \to \chi_{2c}$
106	$gg \to J/\psi \gamma$
107	$g\gamma \to J/\psi g$
108	$\gamma\gamma \to J/\psi \gamma$
W/Z production:	
1	$f_i \bar{f}_i \to \gamma^*/Z^0$
2	$f_i \bar{f}_j \to W^\pm$
22	$f_i \bar{f}_i \to Z^0 Z^0$
23	$f_i \bar{f}_j \to Z^0 W^\pm$
25	$f_i \bar{f}_i \to W^+ W^-$
15	$f_i \bar{f}_i \to g Z^0$
16	$f_i \bar{f}_j \to g W^\pm$
30	$f_i g \to f_i Z^0$
31	$f_i g \to f_k W^\pm$
19	$f_i \bar{f}_i \to \gamma Z^0$
20	$f_i \bar{f}_j \to \gamma W^\pm$
35	$f_i \gamma \to f_i Z^0$

No.	Subprocess
36	$f_i \gamma \to f_k W^\pm$
69	$\gamma\gamma \to W^+ W^-$
70	$\gamma W^\pm \to Z^0 W^\pm$
Prompt photons:	
14	$f_i \bar{f}_i \to g\gamma$
18	$f_i \bar{f}_i \to \gamma\gamma$
29	$f_i g \to f_i \gamma$
114	$gg \to \gamma\gamma$
115	$gg \to g\gamma$
Deeply Inel. Scatt.:	
10	$f_i f_j \to f_k f_l$
99	$\gamma^* q \to q$
Photon-induced:	
33	$f_i \gamma \to f_i g$
34	$f_i \gamma \to f_i \gamma$
54	$g\gamma \to f_k \bar{f}_k$
58	$\gamma\gamma \to f_k \bar{f}_k$
131	$f_i \gamma^*_T \to f_i g$
132	$f_i \gamma^*_L \to f_i g$
133	$f_i \gamma^*_T \to f_i \gamma$
134	$f_i \gamma^*_L \to f_i \gamma$
135	$g\gamma^*_T \to f_i \bar{f}_i$
136	$g\gamma^*_L \to f_i \bar{f}_i$
137	$\gamma^*_T \gamma^*_T \to f_i \bar{f}_i$
138	$\gamma^*_T \gamma^*_L \to f_i \bar{f}_i$
139	$\gamma^*_L \gamma^*_T \to f_i \bar{f}_i$
140	$\gamma^*_L \gamma^*_L \to f_i \bar{f}_i$
80	$q_i \gamma \to q_k \pi^\pm$
Light SM Higgs:	
3	$f_i \bar{f}_i \to h^0$
24	$f_i \bar{f}_i \to Z^0 h^0$
26	$f_i \bar{f}_j \to W^\pm h^0$
32	$f_i g \to f_i h^0$
102	$gg \to h^0$
103	$\gamma\gamma \to h^0$
110	$f_i \bar{f}_i \to \gamma h^0$
111	$f_i \bar{f}_i \to g h^0$
112	$f_i g \to f_i h^0$
113	$gg \to g h^0$
121	$gg \to Q_k \bar{Q}_k h^0$
122	$q_i \bar{q}_i \to Q_k \bar{Q}_k h^0$
123	$f_i f_j \to f_i f_j h^0$
124	$f_i f_j \to f_k f_l h^0$

No.	Subprocess
New gauge bosons:	
141	$f_i \bar{f}_i \to \gamma/Z^0/Z'^0$
142	$f_i \bar{f}_j \to W'^+$
144	$f_i \bar{f}_j \to R$
Heavy SM Higgs:	
5	$Z^0 Z^0 \to h^0$
8	$W^+ W^- \to h^0$
71	$Z^0_L Z^0_L \to Z^0_L Z^0_L$
72	$Z^0_L Z^0_L \to W^+_L W^-_L$
73	$Z^0_L W^\pm_L \to Z^0_L W^\pm_L$
76	$W^+_L W^-_L \to Z^0_L Z^0_L$
77	$W^\pm_L W^\pm_L \to W^\pm_L W^\pm_L$
BSM Neutral Higgs:	
151	$f_i \bar{f}_i \to H^0$
152	$gg \to H^0$
153	$\gamma\gamma \to H^0$
171	$f_i \bar{f}_i \to Z^0 H^0$
172	$f_i \bar{f}_j \to W^\pm H^0$
173	$f_i f_j \to f_i f_j H^0$
174	$f_i f_j \to f_k f_l H^0$
181	$gg \to Q_k \bar{Q}_k H^0$
182	$q_i \bar{q}_i \to Q_k \bar{Q}_k H^0$
183	$f_i \bar{f}_i \to g H^0$
184	$f_i g \to f_i H^0$
185	$gg \to g H^0$
156	$f_i \bar{f}_i \to A^0$
157	$gg \to A^0$
158	$\gamma\gamma \to A^0$
176	$f_i \bar{f}_i \to Z^0 A^0$
177	$f_i \bar{f}_j \to W^\pm A^0$
178	$f_i f_j \to f_i f_j A^0$
179	$f_i f_j \to f_k f_l A^0$
186	$gg \to Q_k \bar{Q}_k A^0$
187	$q_i \bar{q}_i \to Q_k \bar{Q}_k A^0$
188	$f_i \bar{f}_i \to g A^0$
189	$f_i g \to f_i A^0$
190	$gg \to g A^0$
Charged Higgs:	
143	$f_i \bar{f}_j \to H^+$
161	$f_i g \to f_k H^+$
401	$gg \to \bar{t} b H^+$
402	$q\bar{q} \to \bar{t} b H^+$

No.	Subprocess
Higgs pairs:	
297	$f_i \bar{f}_j \to H^\pm h^0$
298	$f_i \bar{f}_j \to H^\pm H^0$
299	$f_i \bar{f}_i \to A^0 h^0$
300	$f_i \bar{f}_i \to A^0 H^0$
301	$f_i \bar{f}_i \to H^+ H^-$
Leptoquarks:	
145	$q_i \ell_j \to L_Q$
162	$qg \to \ell L_Q$
163	$gg \to L_Q \bar{L}_Q$
164	$q_i \bar{q}_i \to L_Q \bar{L}_Q$
Technicolor:	
149	$gg \to \eta_{tc}$
191	$f_i \bar{f}_i \to \rho^0_{tc}$
192	$f_i \bar{f}_j \to \rho^+_{tc}$
193	$f_i \bar{f}_i \to \omega^0_{tc}$
194	$f_i \bar{f}_i \to f_k \bar{f}_k$
195	$f_i \bar{f}_j \to f_k \bar{f}_l$
361	$f_i \bar{f}_i \to W^+_L W^-_L$
362	$f_i \bar{f}_i \to W^\pm_L \pi^\mp_{tc}$
363	$f_i \bar{f}_i \to \pi^+_{tc} \pi^-_{tc}$
364	$f_i \bar{f}_i \to \gamma \pi^0_{tc}$
365	$f_i \bar{f}_i \to \gamma \pi'^0_{tc}$
366	$f_i \bar{f}_i \to Z^0 \pi^0_{tc}$
367	$f_i \bar{f}_i \to Z^0 \pi'^0_{tc}$
368	$f_i \bar{f}_i \to W^\pm \pi^\mp_{tc}$
370	$f_i \bar{f}_j \to W^\pm_L Z^0_L$
371	$f_i \bar{f}_j \to W^\pm_L \pi^0_{tc}$
372	$f_i \bar{f}_j \to \pi^\pm_{tc} Z^0_L$
373	$f_i \bar{f}_j \to \pi^\pm_{tc} \pi^0_{tc}$
374	$f_i \bar{f}_j \to \gamma \pi^\pm_{tc}$
375	$f_i \bar{f}_j \to Z^0 \pi^\pm_{tc}$
376	$f_i \bar{f}_j \to W^\pm \pi^0_{tc}$
377	$f_i \bar{f}_j \to W^\pm \pi'^0_{tc}$
381	$q_i q_j \to q_i q_j$
382	$q_i \bar{q}_i \to q_k \bar{q}_k$
383	$q_i \bar{q}_i \to gg$
384	$f_i g \to f_i g$
385	$gg \to q_k \bar{q}_k$
386	$gg \to gg$
387	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
388	$gg \to Q_k \bar{Q}_k$

No.	Subprocess
Compositeness:	
146	$e\gamma \to e^*$
147	$dg \to d^*$
148	$ug \to u^*$
167	$q_i q_j \to d^* q_k$
168	$q_i q_j \to u^* q_k$
169	$q_i \bar{q}_i \to e^\pm e^{*\mp}$
165	$f_i \bar{f}_i (\to \gamma^*/Z^0) \to f_k \bar{f}_k$
166	$f_i \bar{f}_j (\to W^\pm) \to f_k \bar{f}_l$
Extra Dimensions:	
391	$f\bar{f} \to G^*$
392	$gg \to G^*$
393	$q\bar{q} \to gG^*$
394	$qg \to qG^*$
395	$gg \to gG^*$
Left–right symmetry:	
341	$\ell_i \ell_j \to H^{\pm\pm}_L$
342	$\ell_i \ell_j \to H^{\pm\pm}_R$
343	$\ell^\pm_i \gamma \to H^{\pm\pm}_L e^\mp$
344	$\ell^\pm_i \gamma \to H^{\pm\pm}_R e^\mp$
345	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \mu^\mp$
346	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \mu^\mp$
347	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \tau^\mp$
348	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \tau^\mp$
349	$f_i \bar{f}_i \to H^{++}_L H^{--}_L$
350	$f_i \bar{f}_i \to H^{++}_R H^{--}_R$
351	$f_i f_j \to f_k f_l H^{\pm\pm}_L$
352	$f_i f_j \to f_k f_l H^{\pm\pm}_R$
353	$f_i \bar{f}_i \to Z^0_R$
354	$f_i \bar{f}_j \to W^\pm_R$
SUSY:	
201	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_L$
202	$f_i \bar{f}_i \to \tilde{e}_R \tilde{e}^*_R$
203	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_R +$
204	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_L$
205	$f_i \bar{f}_i \to \tilde{\mu}_R \tilde{\mu}^*_R$
206	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_R +$
207	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_1$
208	$f_i \bar{f}_i \to \tilde{\tau}_2 \tilde{\tau}^*_2$
209	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_2 +$

No.	Subprocess
210	$f_i \bar{f}_j \to \tilde{\ell}_L \tilde{\nu}^*_\ell +$
211	$f_i \bar{f}_j \to \tilde{\tau}_1 \tilde{\nu}^*_\tau +$
212	$f_i \bar{f}_j \to \tilde{\tau}_2 \tilde{\nu}^*_\tau +$
213	$f_i \bar{f}_i \to \tilde{\nu}_\ell \tilde{\nu}_\ell{}^*$
214	$f_i \bar{f}_i \to \tilde{\nu}_\tau \tilde{\nu}^*_\tau$
216	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_1$
217	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_2$
218	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_3$
219	$f_i \bar{f}_i \to \tilde{\chi}_4 \tilde{\chi}_4$
220	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_2$
221	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_3$
222	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_4$
223	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_3$
224	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_4$
225	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_4$
226	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$
227	$f_i \bar{f}_i \to \tilde{\chi}^\pm_2 \tilde{\chi}^\mp_2$
228	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_2$
229	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_1$
230	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_1$
231	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_1$
232	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_1$
233	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_2$
234	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_2$
235	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_2$
236	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_2$
237	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_1$
238	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_2$
239	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_3$
240	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_4$
241	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_1$
242	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_2$
243	$f_i \bar{f}_i \to \tilde{g} \tilde{g}$
244	$gg \to \tilde{g} \tilde{g}$
246	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_1$
247	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_1$
248	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_2$
249	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_2$

No.	Subprocess
250	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_3$
251	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_3$
252	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_4$
253	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_4$
254	$f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_1$
256	$f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_2$
258	$f_i g \to \tilde{q}_{iL} \tilde{g}$
259	$f_i g \to \tilde{q}_{iR} \tilde{g}$
261	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_1$
262	$f_i \bar{f}_i \to \tilde{t}_2 \tilde{t}^*_2$
263	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_2 +$
264	$gg \to \tilde{t}_1 \tilde{t}^*_1$
265	$gg \to \tilde{t}_2 \tilde{t}^*_2$
271	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jL}$
272	$f_i f_j \to \tilde{q}_{iR} \tilde{q}_{jR}$
273	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jR} +$
274	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jL}$
275	$f_i \bar{f}_j \to \tilde{q}_{iR} \tilde{q}^*_{jR}$
276	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jR} +$
277	$f_i \bar{f}_i \to \tilde{q}_{jL} \tilde{q}^*_{jL}$
278	$f_i \bar{f}_i \to \tilde{q}_{jR} \tilde{q}^*_{jR}$
279	$gg \to \tilde{q}_{iL} \tilde{q}^*_{iL}$
280	$gg \to \tilde{q}_{iR} \tilde{q}^*_{iR}$
281	$bq_i \to \tilde{b}_1 \tilde{q}_{iL}$
282	$bq_i \to \tilde{b}_2 \tilde{q}_{iR}$
283	$bq_i \to \tilde{b}_1 \tilde{q}_{iR} +$
284	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{iL}$
285	$b\bar{q}_i \to \tilde{b}_2 \tilde{q}^*_{iR}$
286	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{iR} +$
287	$f_i \bar{f}_i \to \tilde{b}_1 \tilde{b}^*_1$
288	$f_i \bar{f}_i \to \tilde{b}_2 \tilde{b}^*_2$
289	$gg \to \tilde{b}_1 \tilde{b}^*_1$
290	$gg \to \tilde{b}_2 \tilde{b}^*_2$
291	$bb \to \tilde{b}_1 \tilde{b}_1$
292	$bb \to \tilde{b}_2 \tilde{b}_2$
293	$bb \to \tilde{b}_1 \tilde{b}_2$
294	$bg \to \tilde{b}_1 \tilde{g}$
295	$bg \to \tilde{b}_2 \tilde{g}$
296	$b\bar{b} \to \tilde{b}_1 \tilde{b}^*_2 +$