Hidden Valleys: From Theory to Experiment via Simulation

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- in preparation
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Hidden Valleys – Preview

Hidden Valleys – Preview

Theoretical Motivation

- Many beyond-the-standard-model theories contain ***new sectors***.

  - Top-down constructions (esp. string theory)
  - Bottom-up constructions (twin Higgs, folded SUSY)
  - Could be home of dark matter
  - Could be related to SUSY breaking, flavor, CP violation, etc.
  - Could affect electroweak phase transition (Espinosa and Quiros 06)
  - Could affect fine-tuning issues

- New sectors may decouple from our own at low energy
  - SUSY breaking scale?
  - TeV scale?

- "Hidden Valley" sectors
  - Coupling not-too-weakly to our sector
  - Containing not-too-heavy particles

  may be observable at Tev/LHC

Experimental Motivation

- We are at a crucial moment for both the Tevatron and the LHC:
- **Tevatron:**
  - 2 more years at forefront
  - Few deviations from standard model at 2 sigma at 1 inv. fb.
  - ***But many searches have not been carried out yet***
  - Large data set: what's hiding?
- **LHC:**
  - Few months left to adjust systems, software
  - Opportunity to optimize before flooded with data
- Both: wise to consider models with unusual phenomenology
- Hidden valleys often do not look like SUSY, Little Higgs, Extra Dimensions

Hidden Valleys – Preview

- *Standard phenomenology may be drastically altered:*
  - Discover Higgs in decays to long-lived particles
  - Lose SUSY MET signal in several soft jets

- *Making phenomenological predictions generally requires*
  - Subtle theoretical analysis of strong dynamics (and I really mean *dynamics*)
  - New event generation software

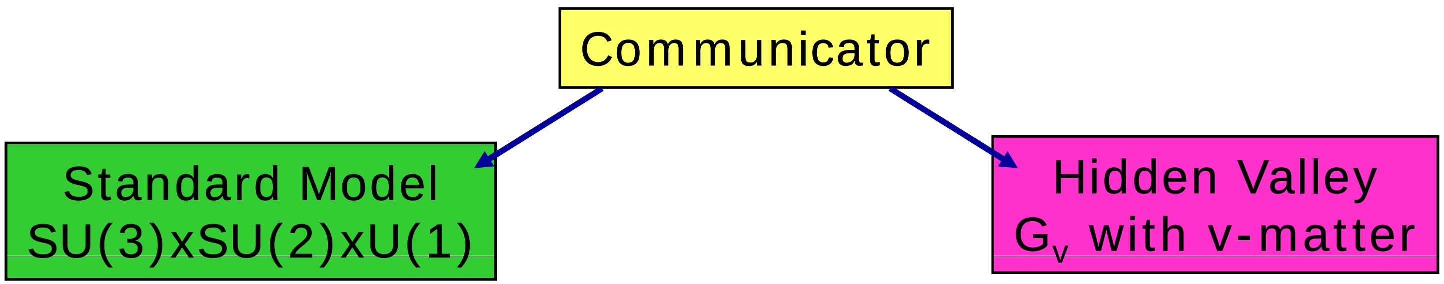
- *Phenomenology of strongly-coupled new sectors may not lend itself to*
  - Object-oriented analysis
  - PGS
  - Vista/BARD
  - OSET

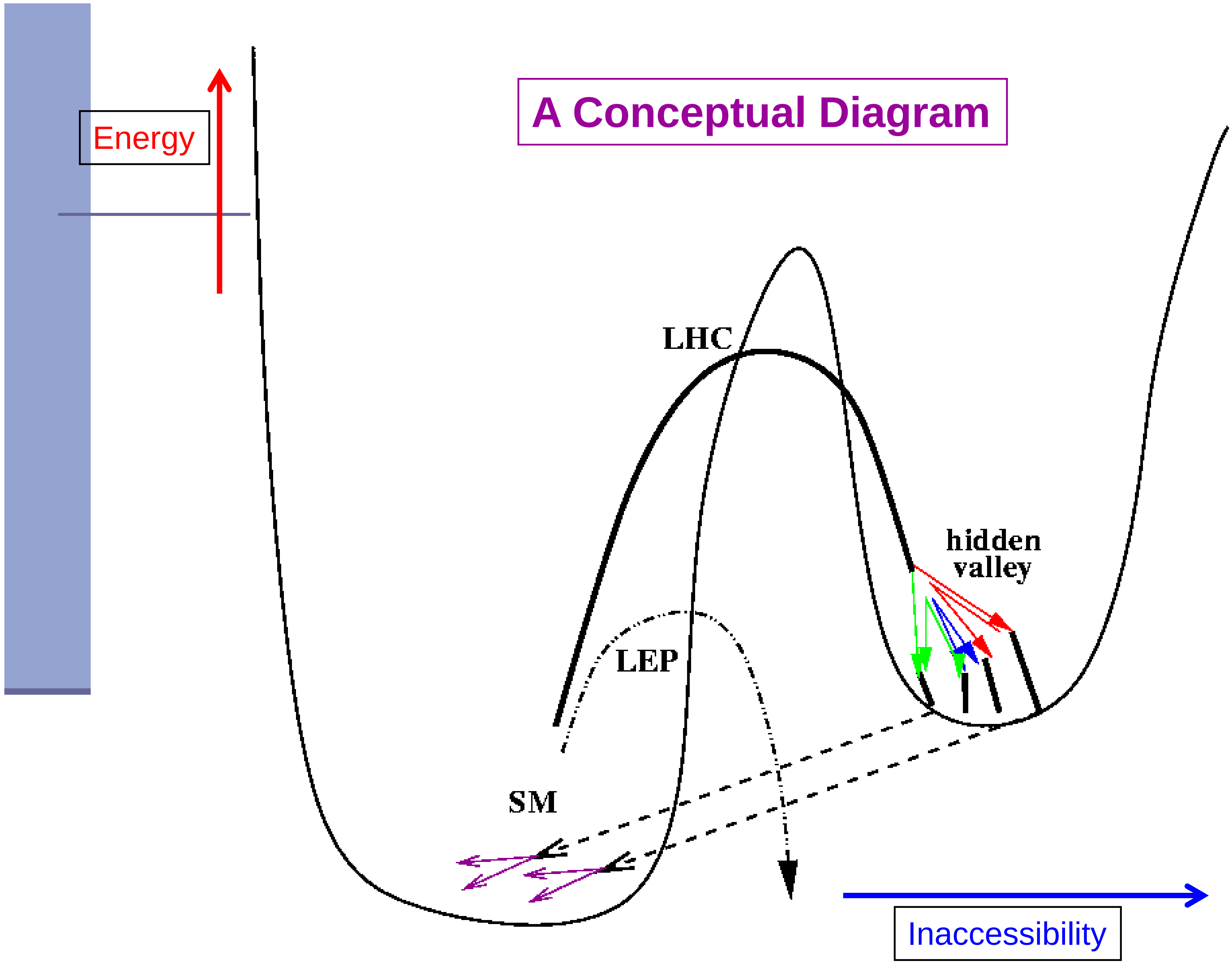
- *Experimental issues including triggering and reconstruction can be tricky*

Hidden Valley Models (w/ K. Zurek)

April 06

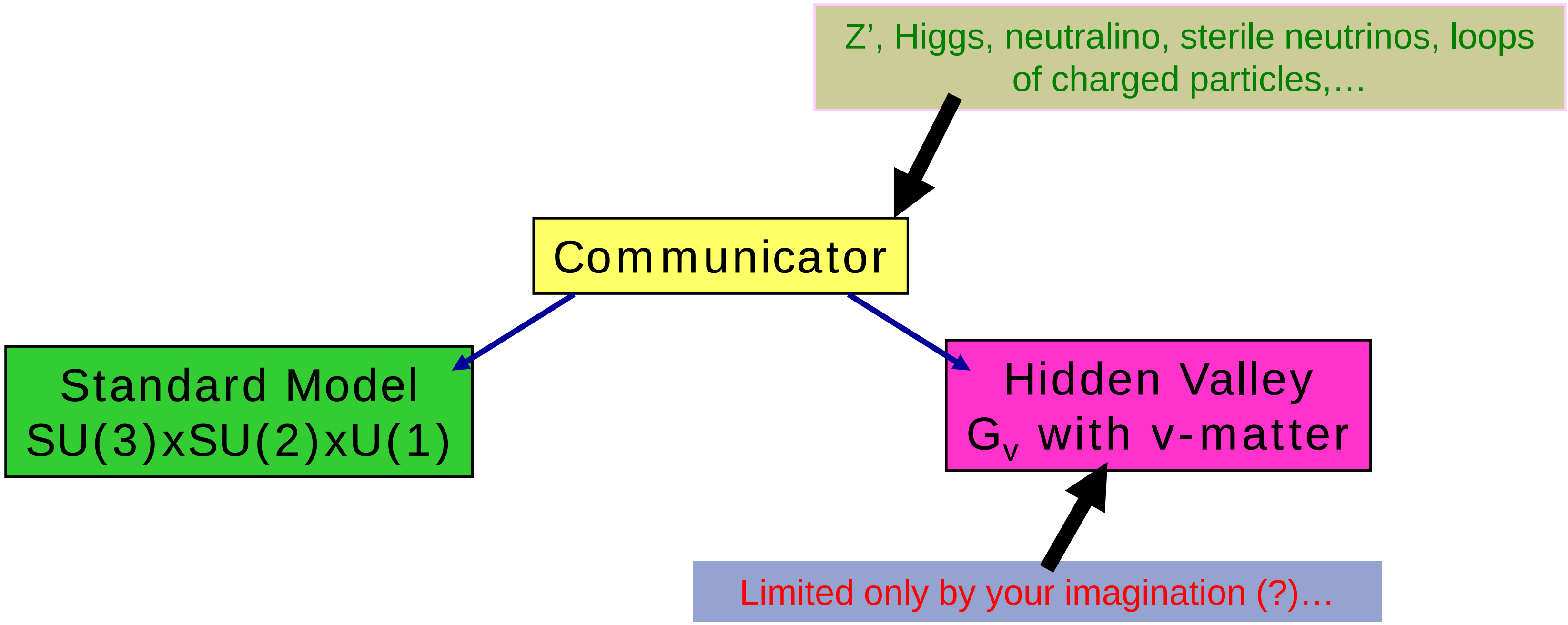
- Basic minimal structure




A Conceptual Diagram
Energy
LHC
hidden
valley
LEP
SM
Inaccessibility

Hidden Valley Models (w/ K. Zurek)

- Basic minimal structure

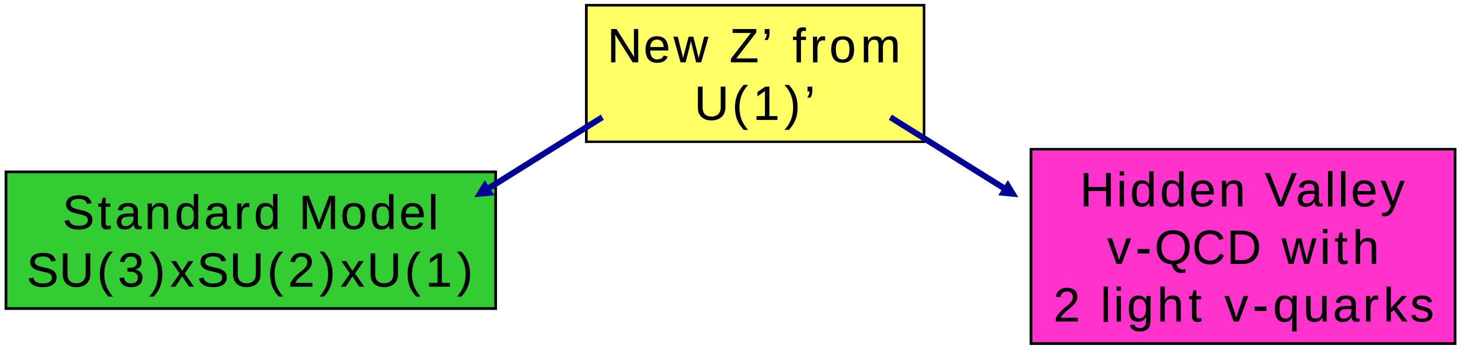


Many Models, Few Constraints

- Number of possibilities is ***huge***! (Even bigger than SUSY.)
- Constraints (LEP direct, indirect; Tevatron direct; cosmology) are limited
- In general, complexities too extreme for purely analytic calculation
  - ***Event Generation Software Needed***
- Reasonable strategy:
  - Identify large class of models with similar experimental signatures
    - Ignore if SUSY-like signatures
  - Otherwise, select a typical subset of this class
    - Compute properties
    - Write event generation software
  - Explore experimental challenges within this subset
  - Infer lessons valid for entire class, and beyond
  - Repeat until all major new phenomenological challenges have been identified

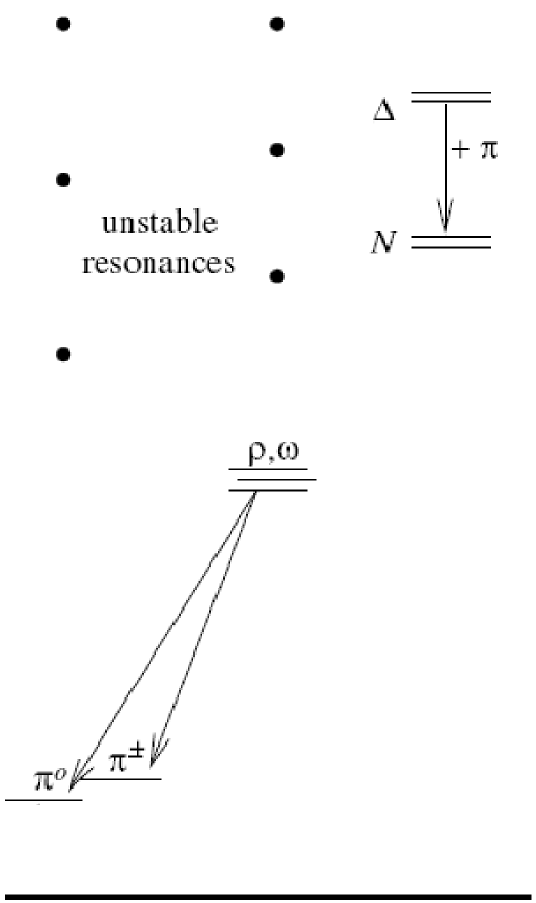
Simplest Class of Models

- Easy subset of models
  - to understand
  - to find experimentally
  - to simulate
  - to allow exploration of a wide range of phenomena
- This subset is part of a wide class of QCD-like theories



Two-flavor scaled-up (v)QCD

- N colors and two light v-quarks
- Becomes strong at a scale Λ_v
- All v-hadrons decay immediately to v-pions and v-nucleons.
- *All v-hadrons are electric and color neutral, since v-quarks are electric and color-neutral*



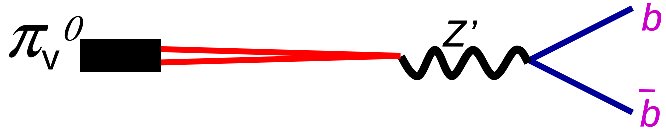
Two-flavor scaled-up (v)QCD

- Two of the three v-pions often cannot decay -- invisible
- *But the third one usually can!*
  - ***may*** have *<u>long lifetime</u>*

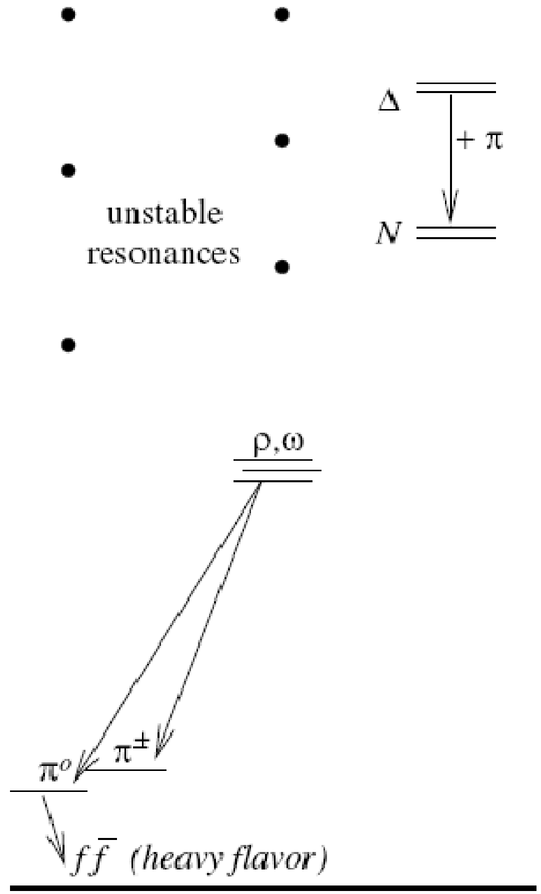
$\pi_v^+ \sim Q_1\bar{Q}_2 \sim$ *stable*

$\pi_v^- \sim Q_2\bar{Q}_1 \sim$ *stable*

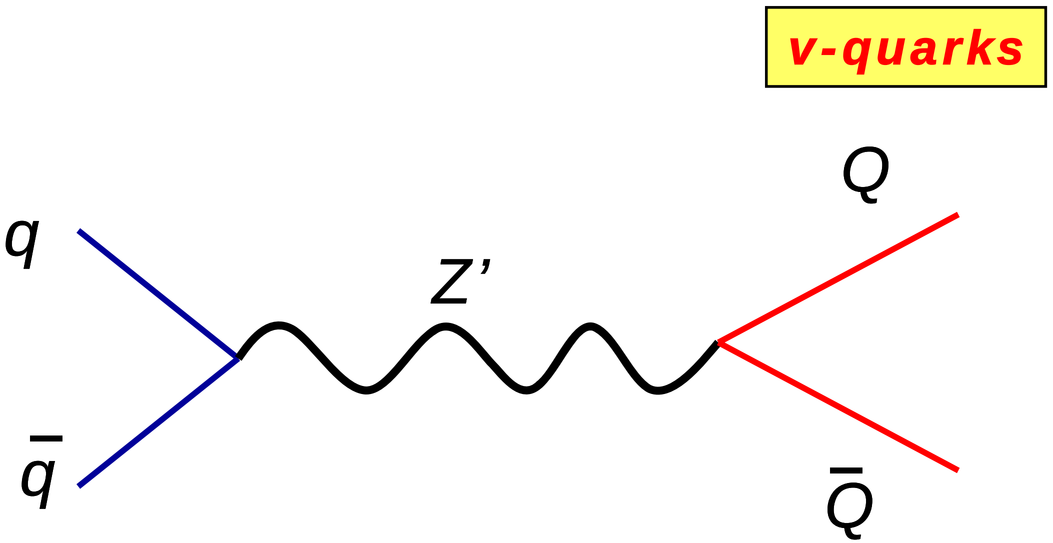
$\pi_v^0 \sim Q_1\bar{Q}_1 - Q_2\bar{Q}_2 \rightarrow (Z')^* \rightarrow f\bar{f}$



Pseudoscalars: their decays require a helicity flip; branching fractions proportional to fermion masses m_f^2

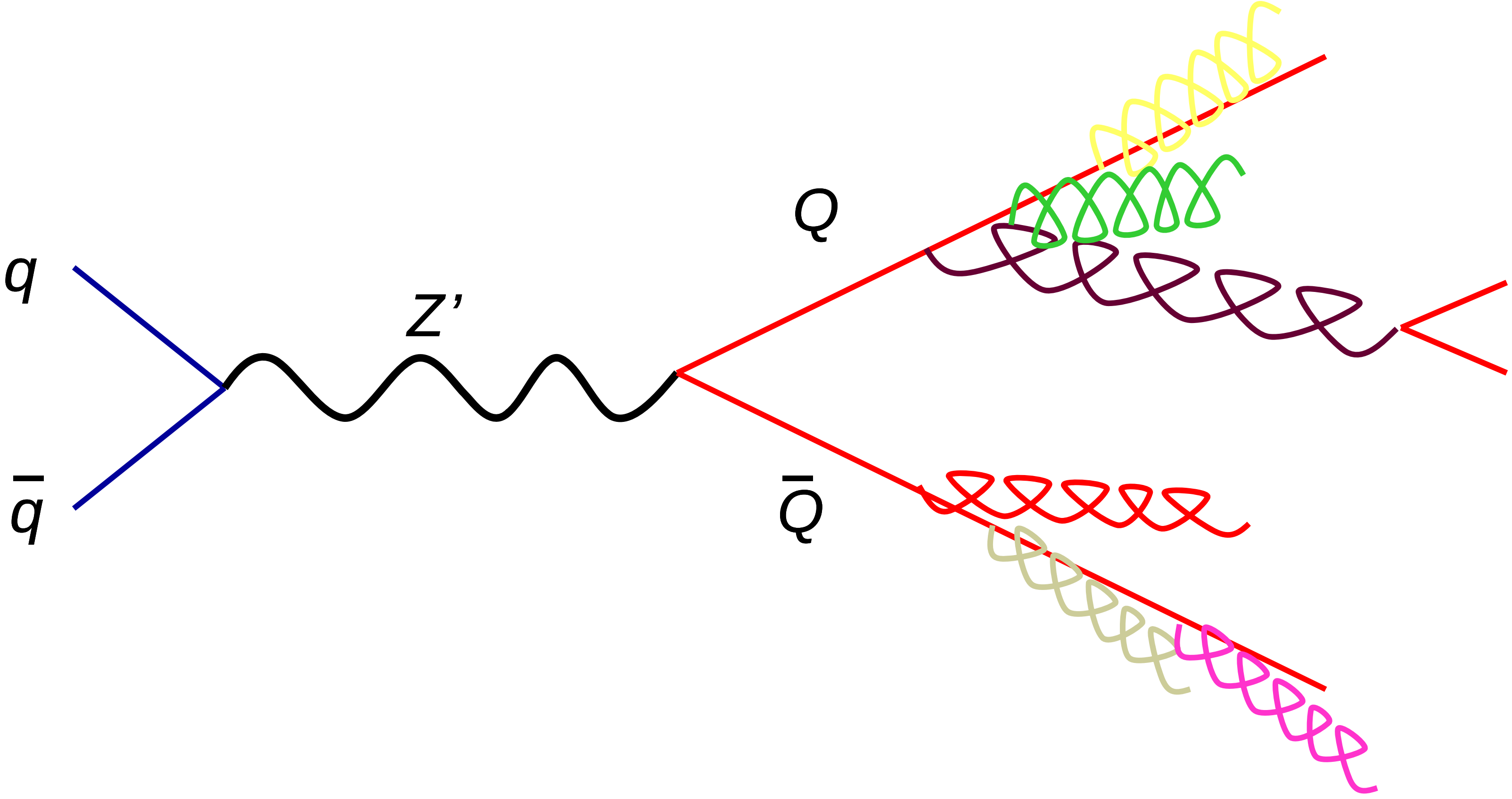


$q\,\bar{q} \rightarrow Q\,\bar{Q}$: v-quark production

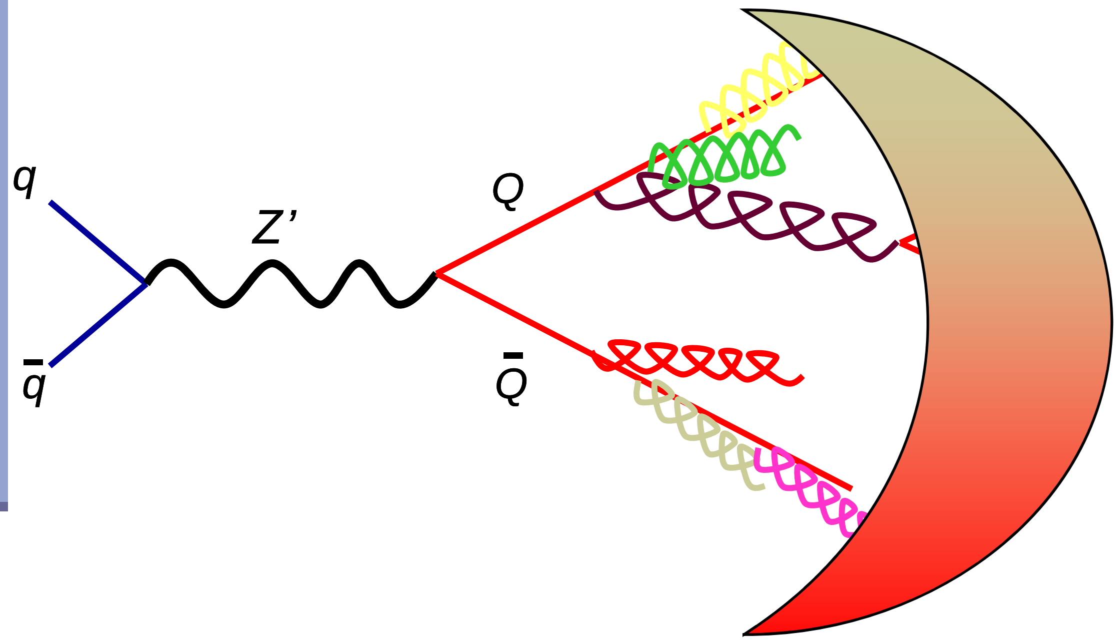


$q\bar{q} \rightarrow Q\bar{Q}$

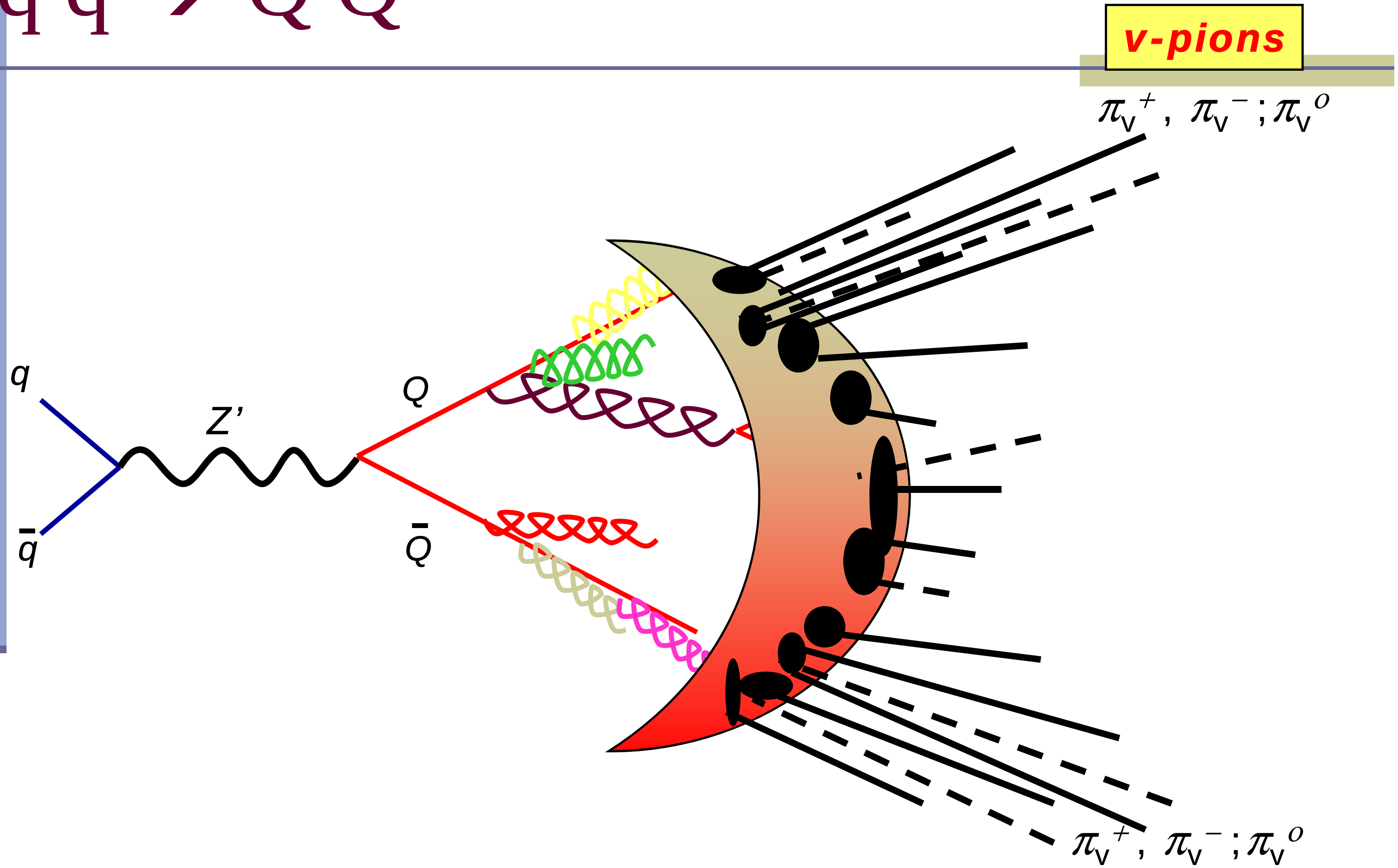
v-gluons



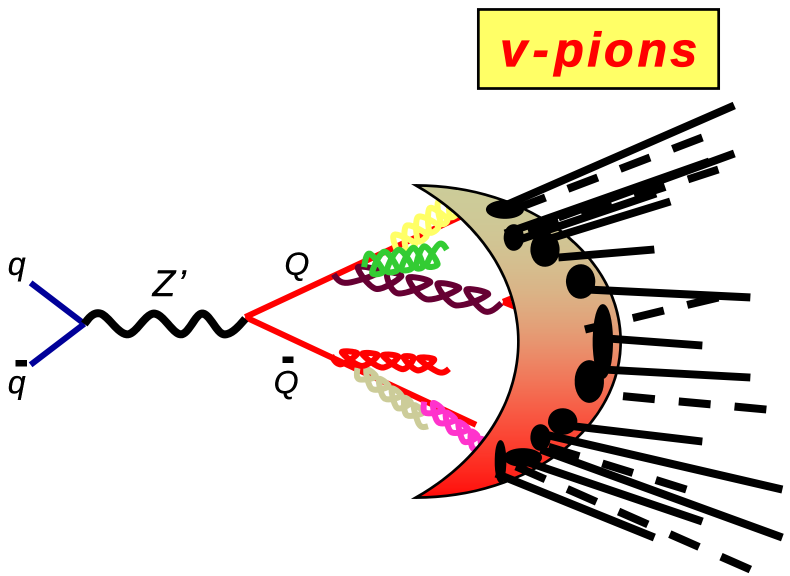
$q\bar{q} \rightarrow Q\bar{Q}$



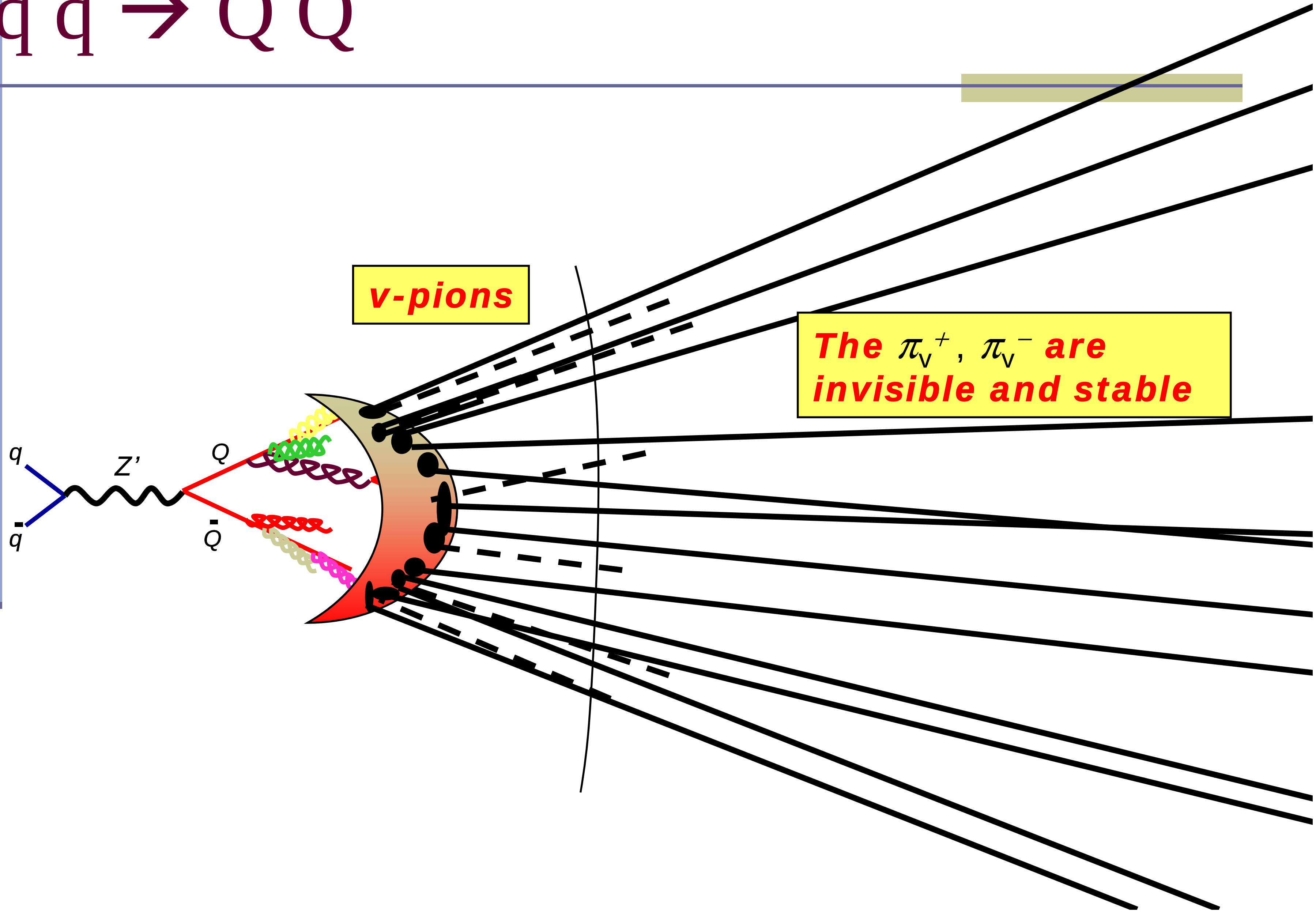
$q\bar{q} \rightarrow Q\bar{Q}$



$q \bar{q} \rightarrow Q \bar{Q}$



$q\,\bar{q} \rightarrow Q\,\bar{Q}$



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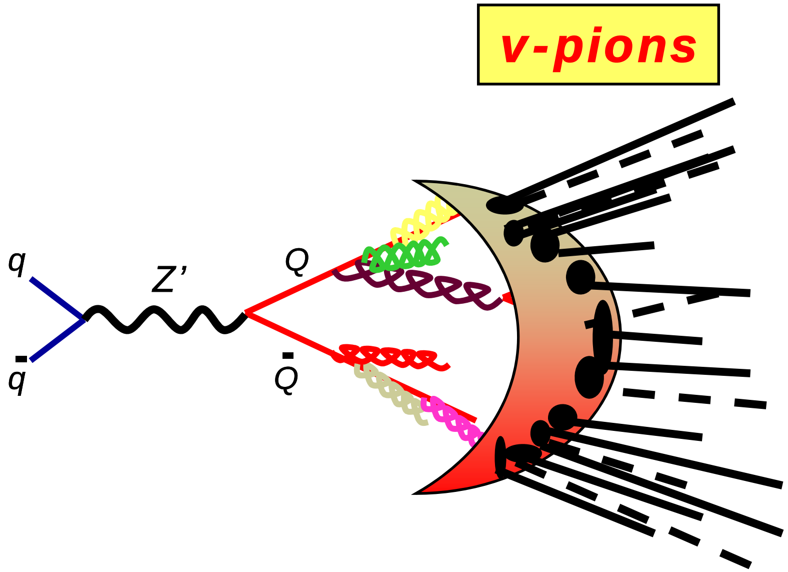
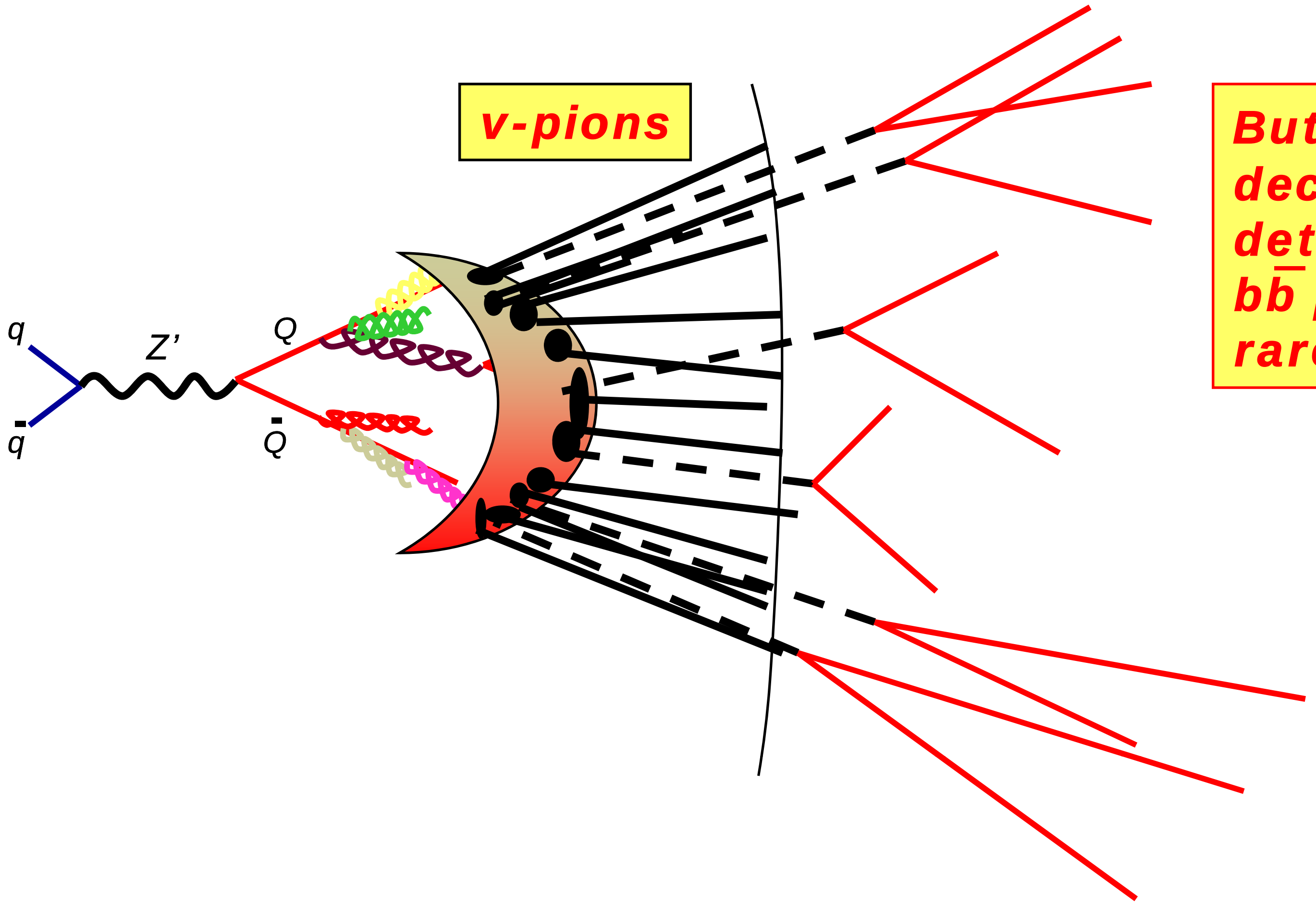
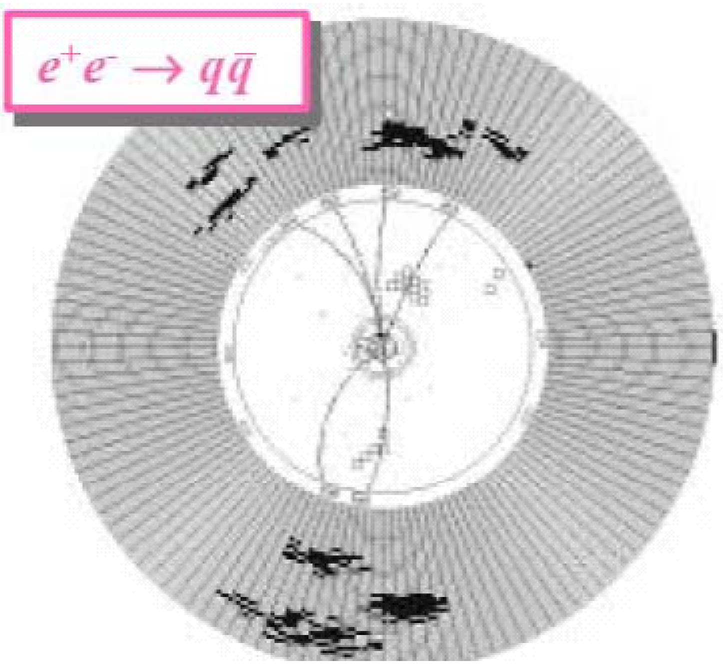


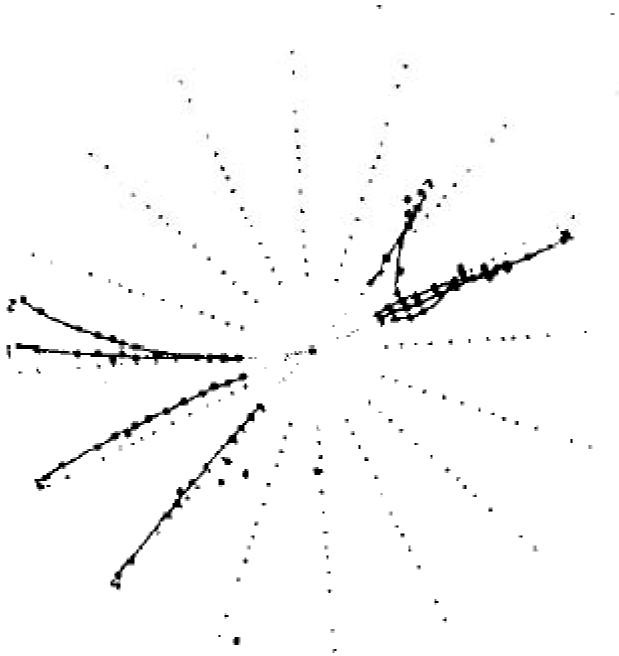
$q\,\bar{q} \rightarrow Q\,\bar{Q}$



But the $\pi_v{}^o$s decay in the detector to $b\bar{b}$ pairs, or rarely taus

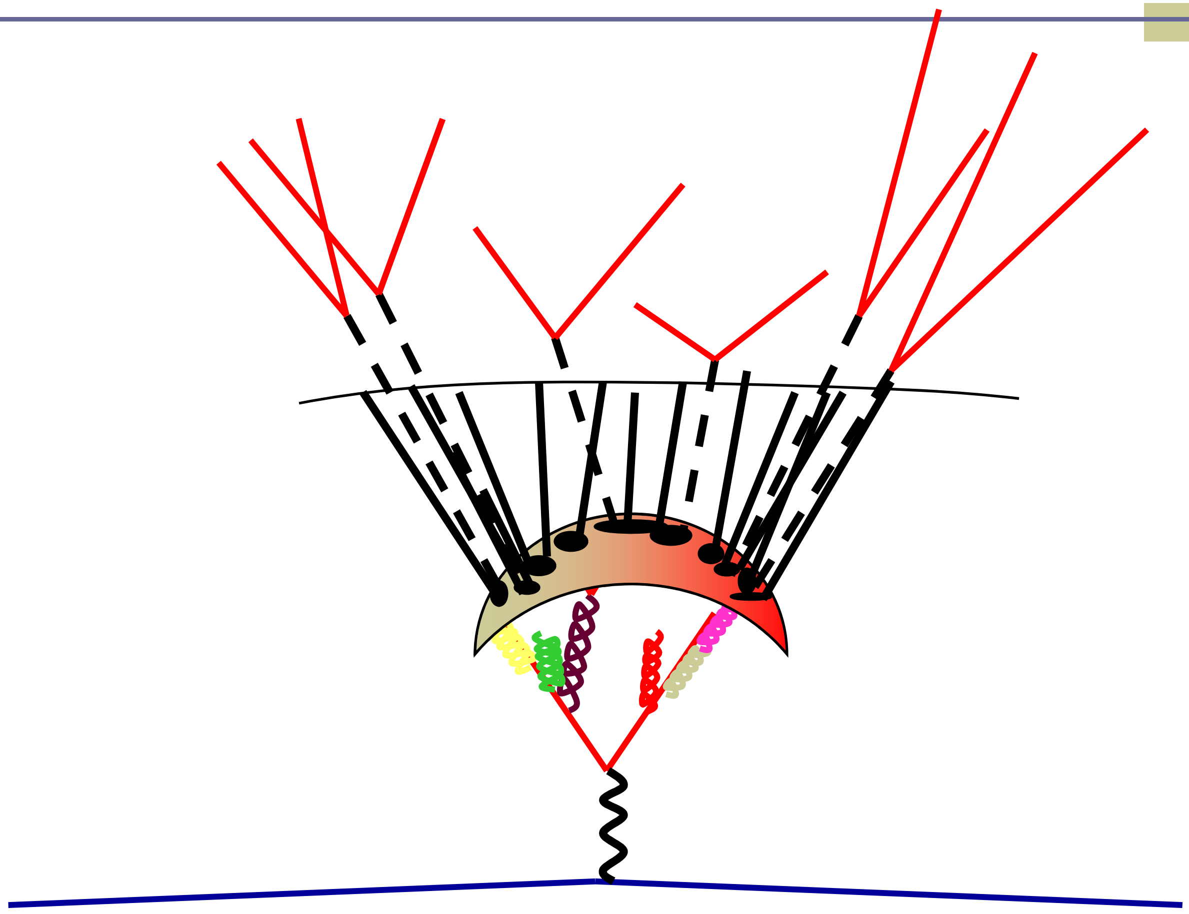
How to simulate? Analogy…



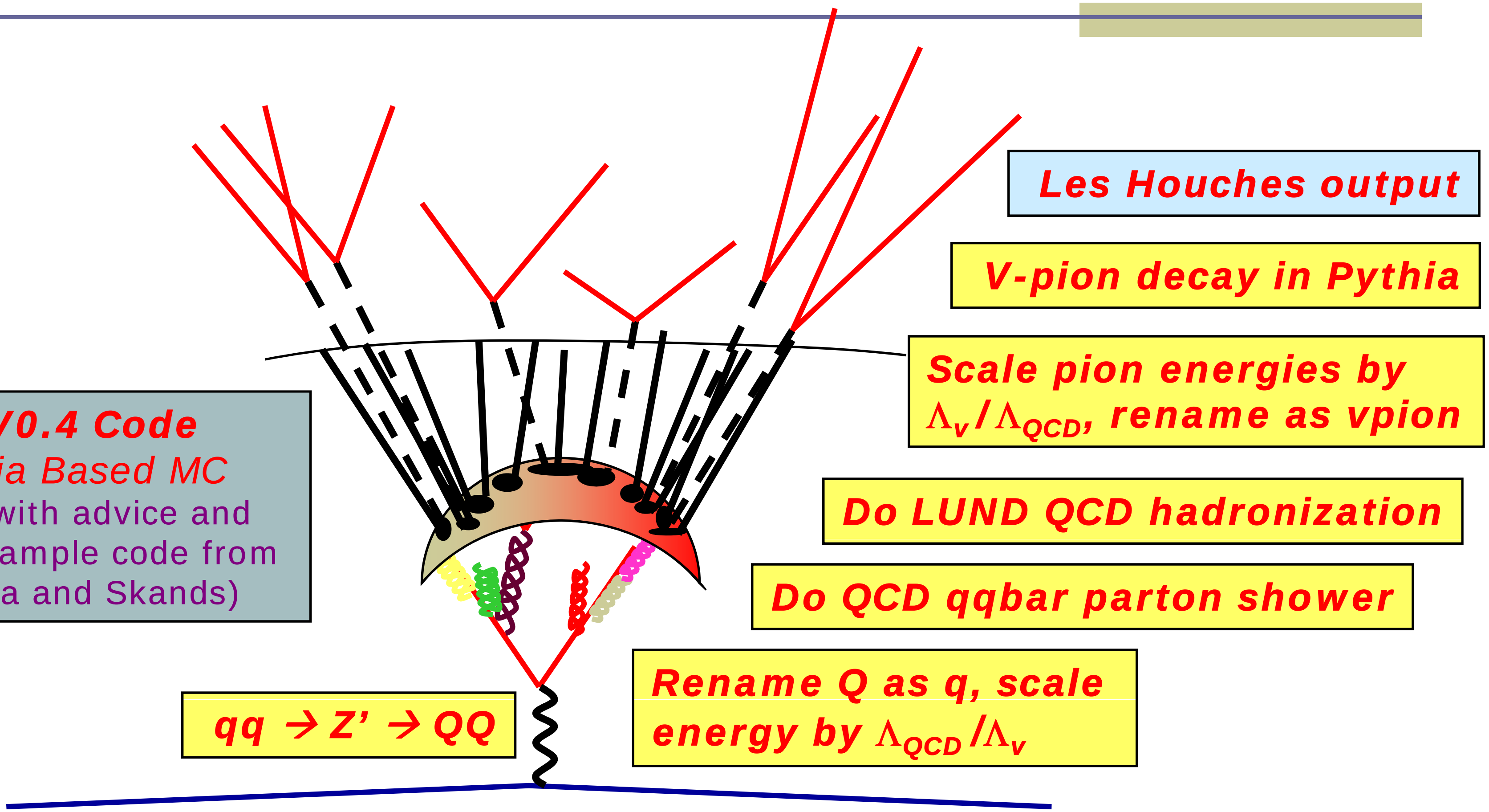


Pythia is designed to reproduce data from 70's/80's

$q\,\bar{q} \rightarrow Q\,\bar{Q}$



$q\bar{q} \rightarrow Q\bar{Q}$

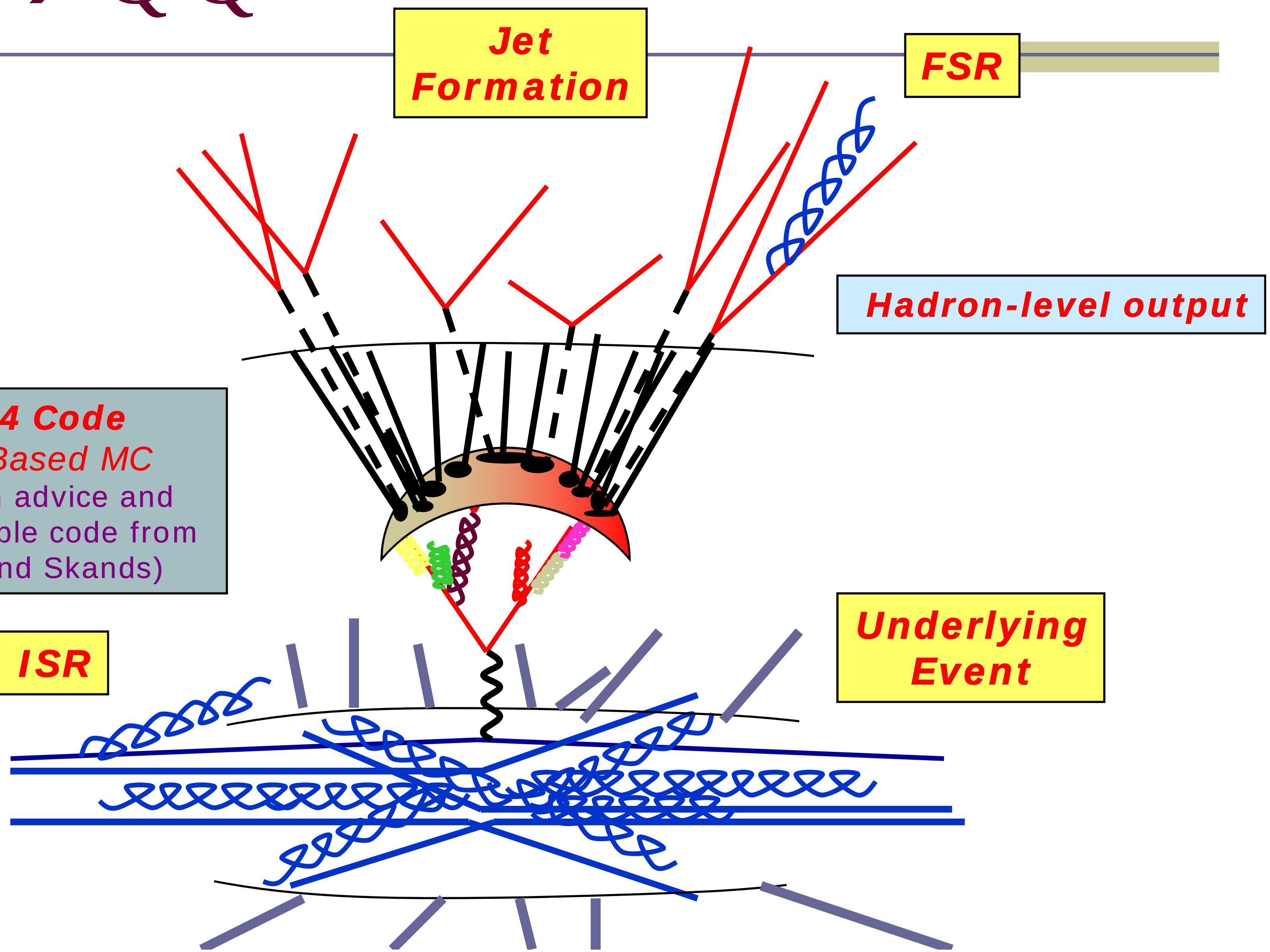


HV0.4 Code

Pythia Based MC

(MJS, with advice and some example code from Mrenna and Skands)

$q\bar{q} \rightarrow Q\bar{Q}$



HV0.4 Code

Pythia Based MC

(MJS, with advice and some example code from Mrenna and Skands)

3 TeV Z' decays to 30 GeV v-pions

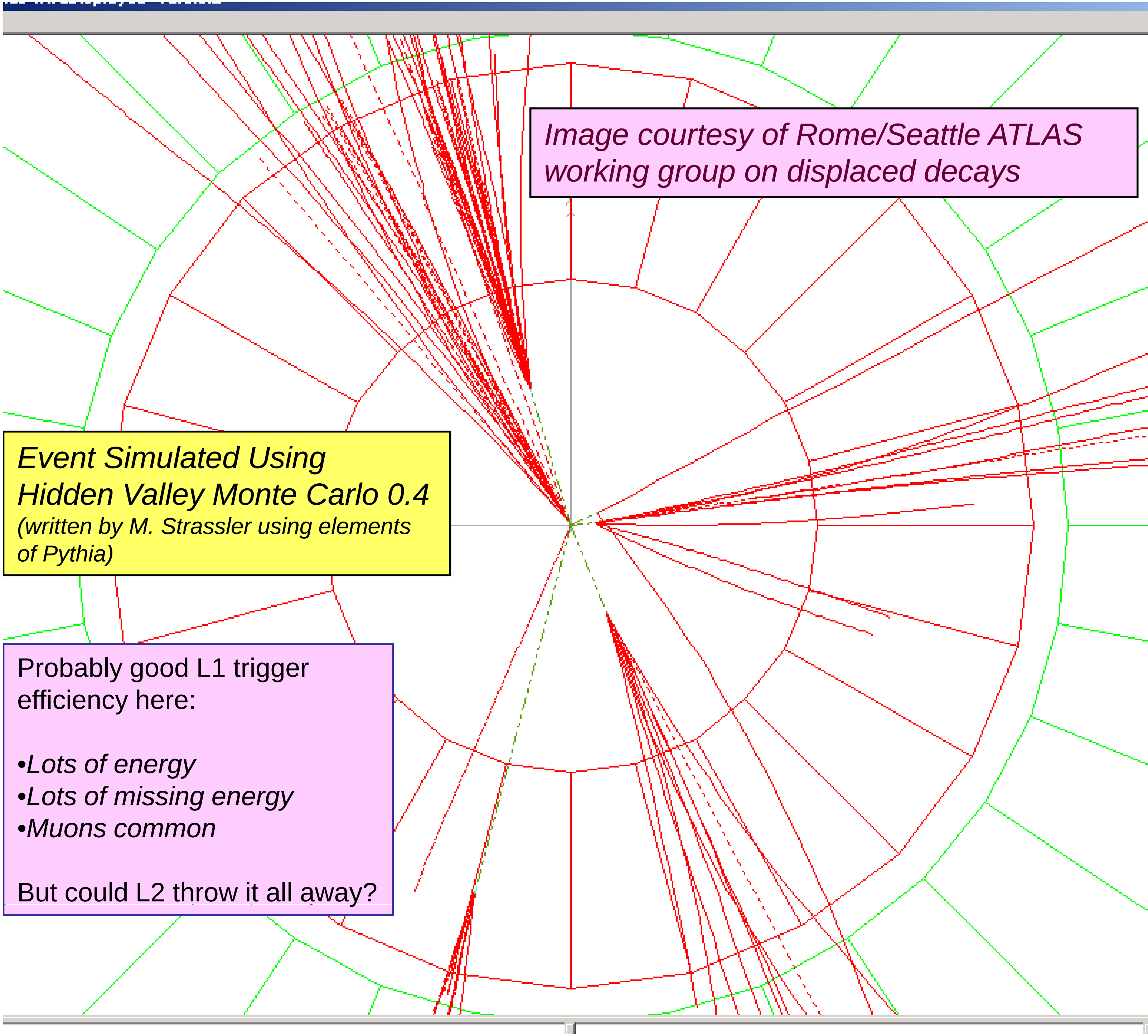


Image courtesy of Rome/Seattle ATLAS working group on displaced decays

Event Simulated Using Hidden Valley Monte Carlo 0.4
(written by M. Strassler using elements of Pythia)

Probably good L1 trigger efficiency here:

- *Lots of energy*
- *Lots of missing energy*
- *Muons common*

But could L2 throw it all away?

EM Calorimeter: green

TRT: red

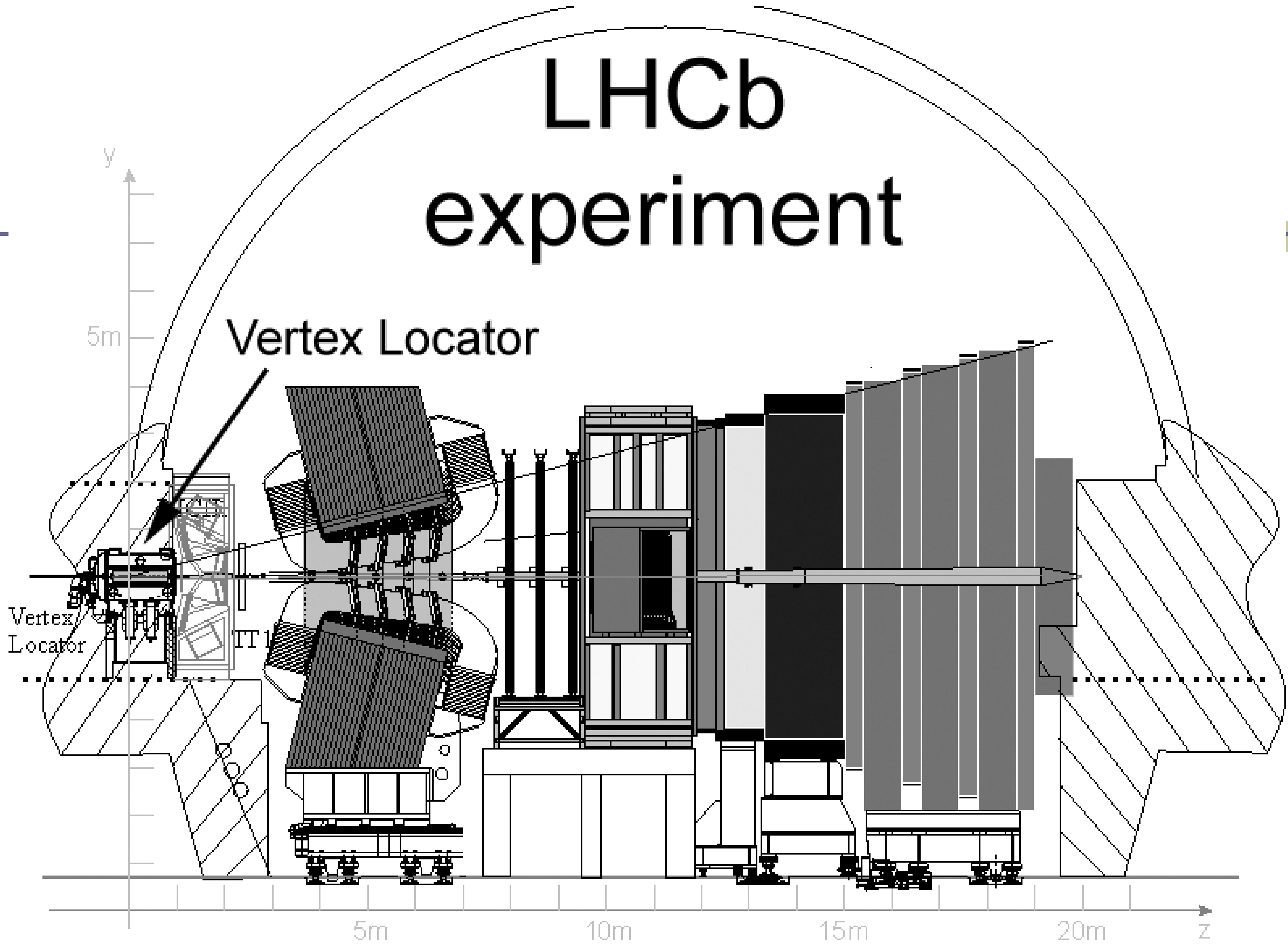
Silicon/Pixels: not shown

V-pions: green dot-dash lines

Charged hadrons: solid lines

Neutral hadrons: dashed lines

LHCb experiment



Can’t reconstruct entire events, but can find vertices, resonances!

Overlooked Discovery Mode for Higgs?

See also:

Limit of model mentioned in **hep-ph/0511250, Naturalness and Higgs decays in the MSSM with a singlet.** Chang, Fox and Weiner

hep-ph/0607204 : **Reduced fine-tuning in supersymmetry with R-parity violation.** Carpenter, Kaplan and Rhee

Higgs Decay to Two Long-Lived Particles

M. Strassler & K. Zurek 5/2006

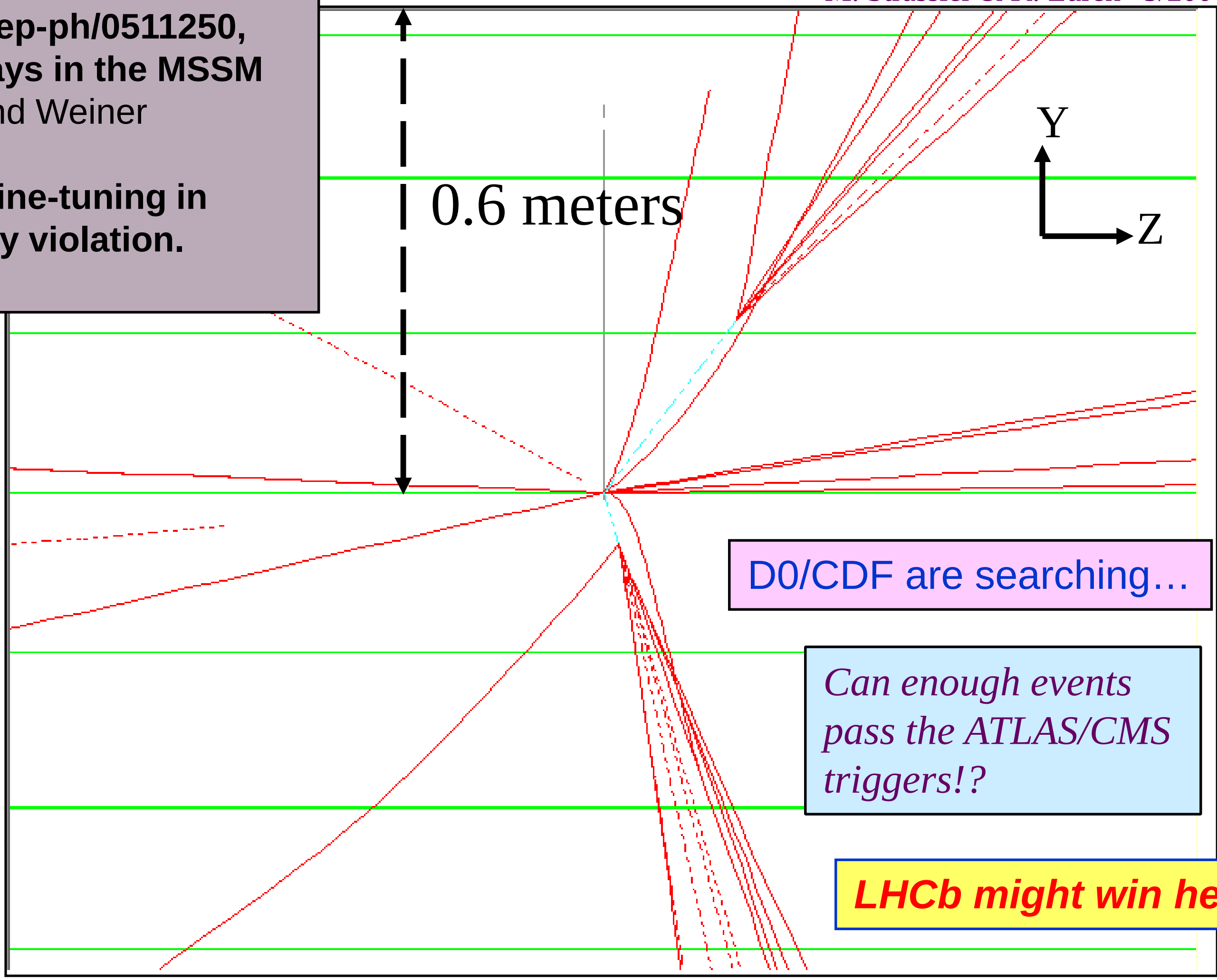


Image provided by ATLAS Rome-Seattle working group:

Guido Ciapetti
Carlo Dionisi
Stefano Giagu
Daniele DePedis
Giuseppe Salamanna
Marco Rescigno
Lucia Zanello
Barbara Mele*
Henry Lubatti
Matt Strassler*
Dan Ventura
Laura Bodine

D0/CDF are searching…

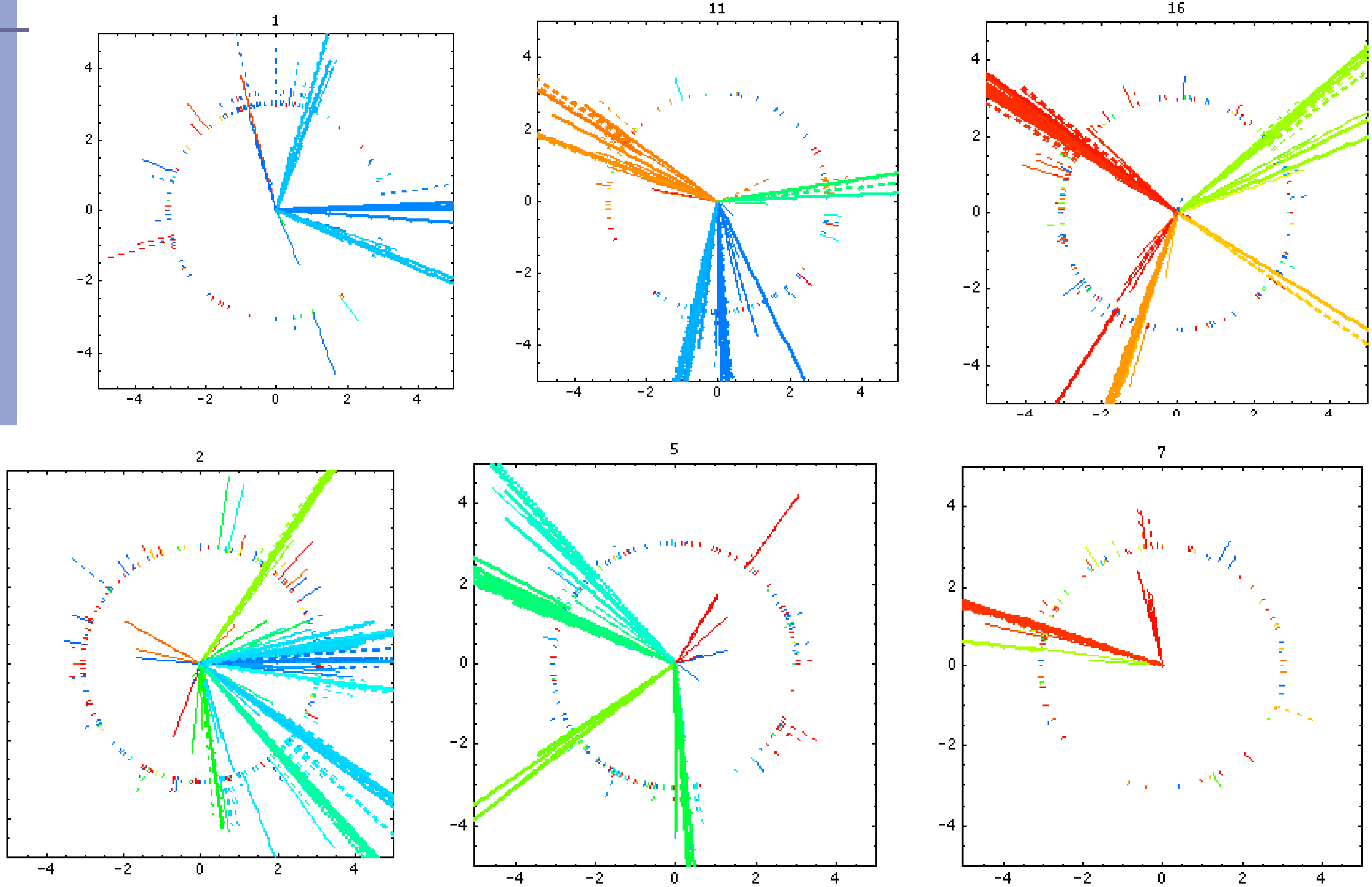
Can enough events pass the ATLAS/CMS triggers!?

LHCb might win here!

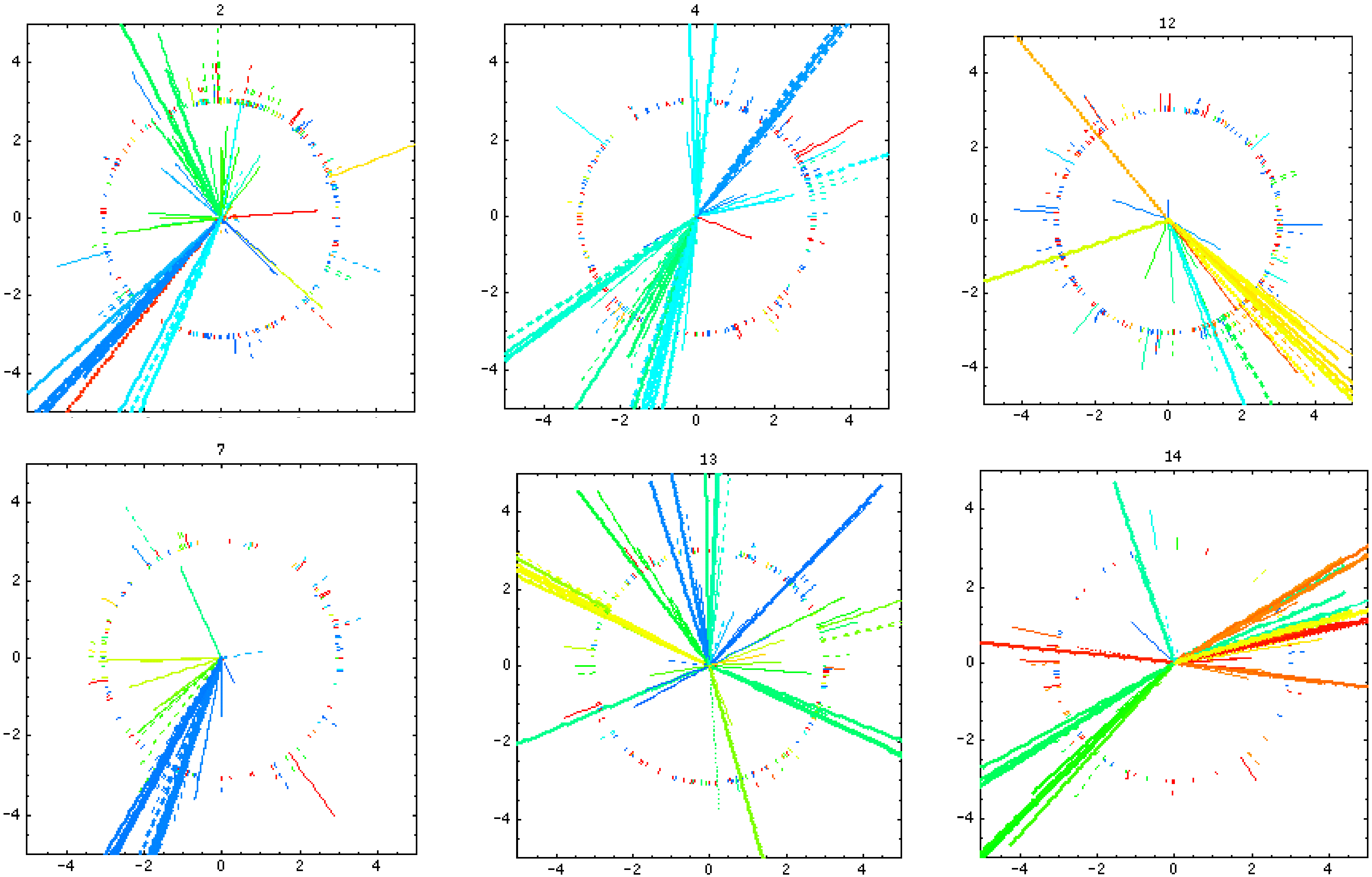
Harder Case – All decays prompt

- If the decays are very late, this is an experimentalist's problem;
  - No backgrounds to calculate
  - The analysis does not require help from theorists
  - Tricky detector issues
- If not, it's a theorist's challenge: get events with
  - Multiple jets
  - Some b-tags
  - Possibly taus
  - Some missing energy from invisible v-hadrons
  - Backgrounds? What are they? Not obviously computable…
  - *What clues may assist with identifying this signal?*
- **An in-progress Case Study, with some lessons.**

150 GeV v-pions



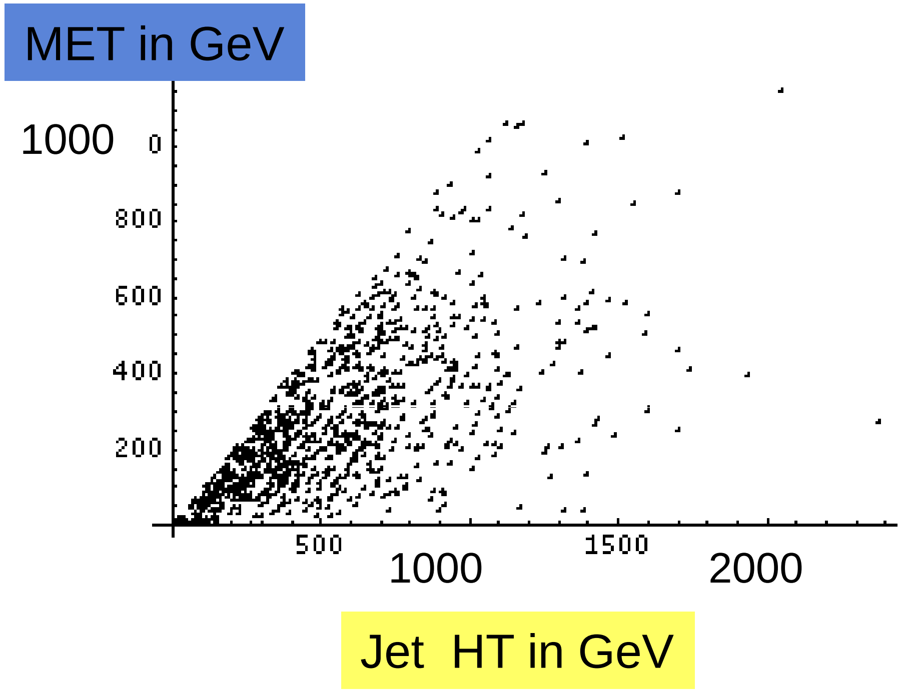
60 GeV v-pions



Triggering

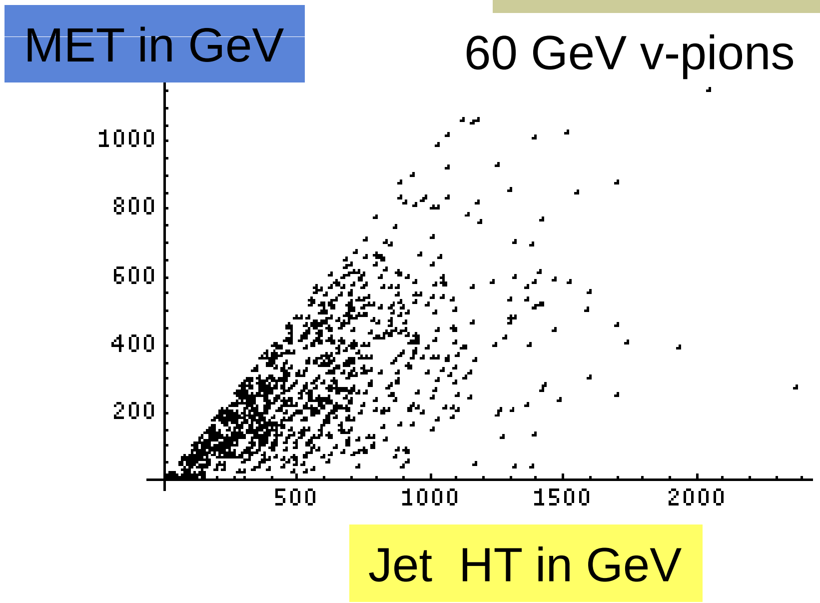
60 GeV v-pions

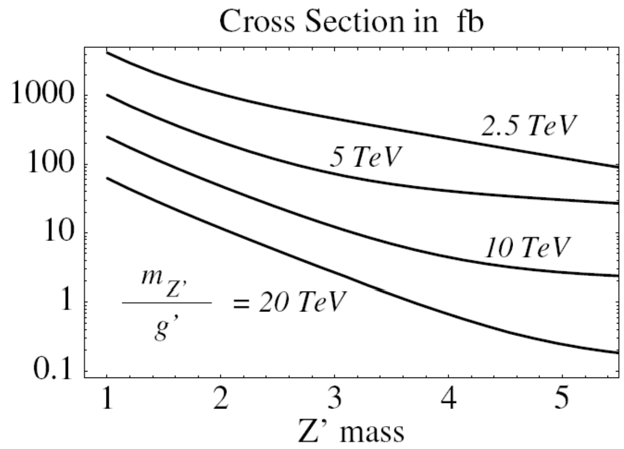
- Should not be a problem in this model
- Will assume here that we can ignore for the most part
- Needs to be checked!
- Need to study correlation between triggering and number of jets, etc.



Backgrounds … ??

- The energy and missing energy are large
- But the rates are small
- Therefore standard model backgrounds are not small enough to ignore
- Unfortunately they are all out on tails, with many jets.
- Very difficult to estimate:
- First step: ***Understand Signal***

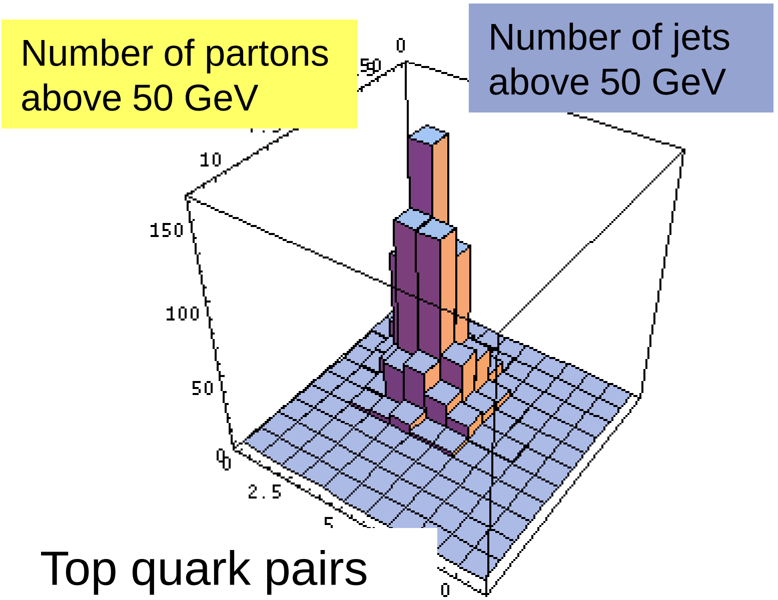




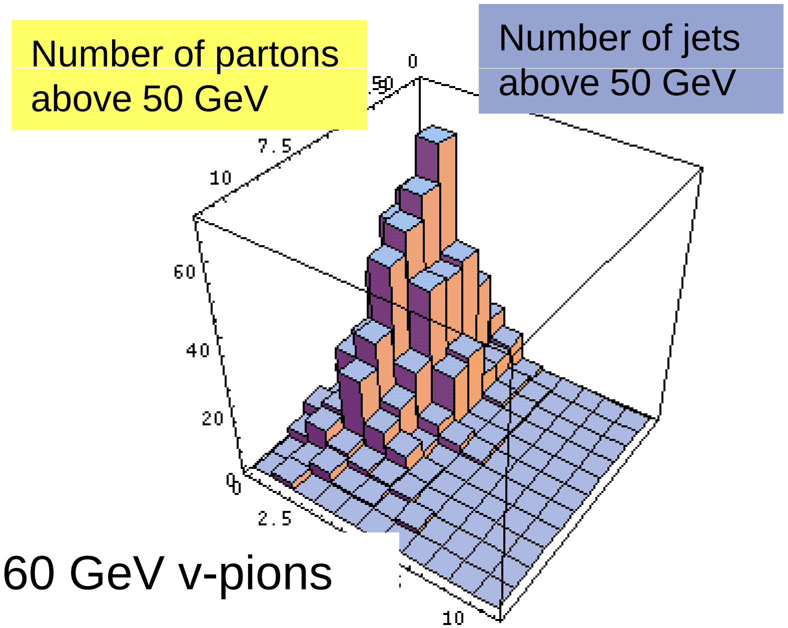
Jet-to-Parton (mis)Matching

- For any setting of cone algorithm, jets *[after showering/hadronization]* not well correlated with short-distance partons *[before showering/hadronization]*

Midpoint Cone 0.7



Top quark pairs



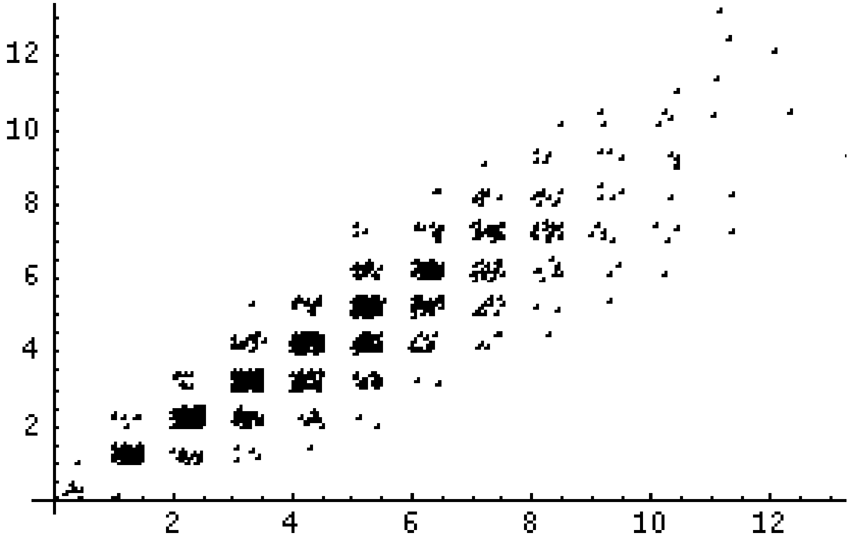
60 GeV v-pions

Parton-to-Hadron **Cluster** matching

- However, the news is good:
  - if one applies the **same algorithm** to the **short-distance** partons as to the hadrons, one gets reasonable agreement –
  - i.e., data and short-distance theory do match, if one constructs jets from both.

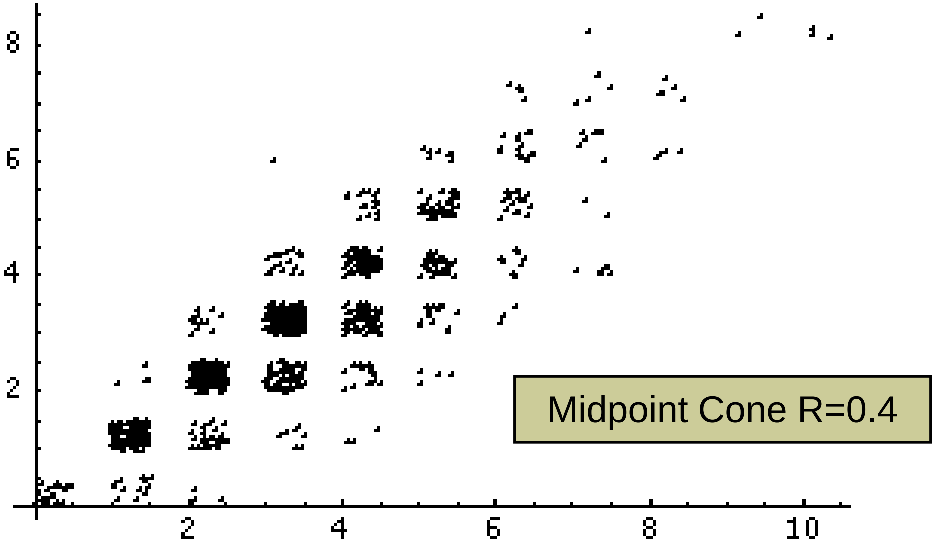
3 TeV Z'
50 GeV v-pions
1000 events

hadronic jets w/ pt > 25 GeV



partonic jets w/ pt > 25 GeV

hadronic jets w/ pt > 50 GeV

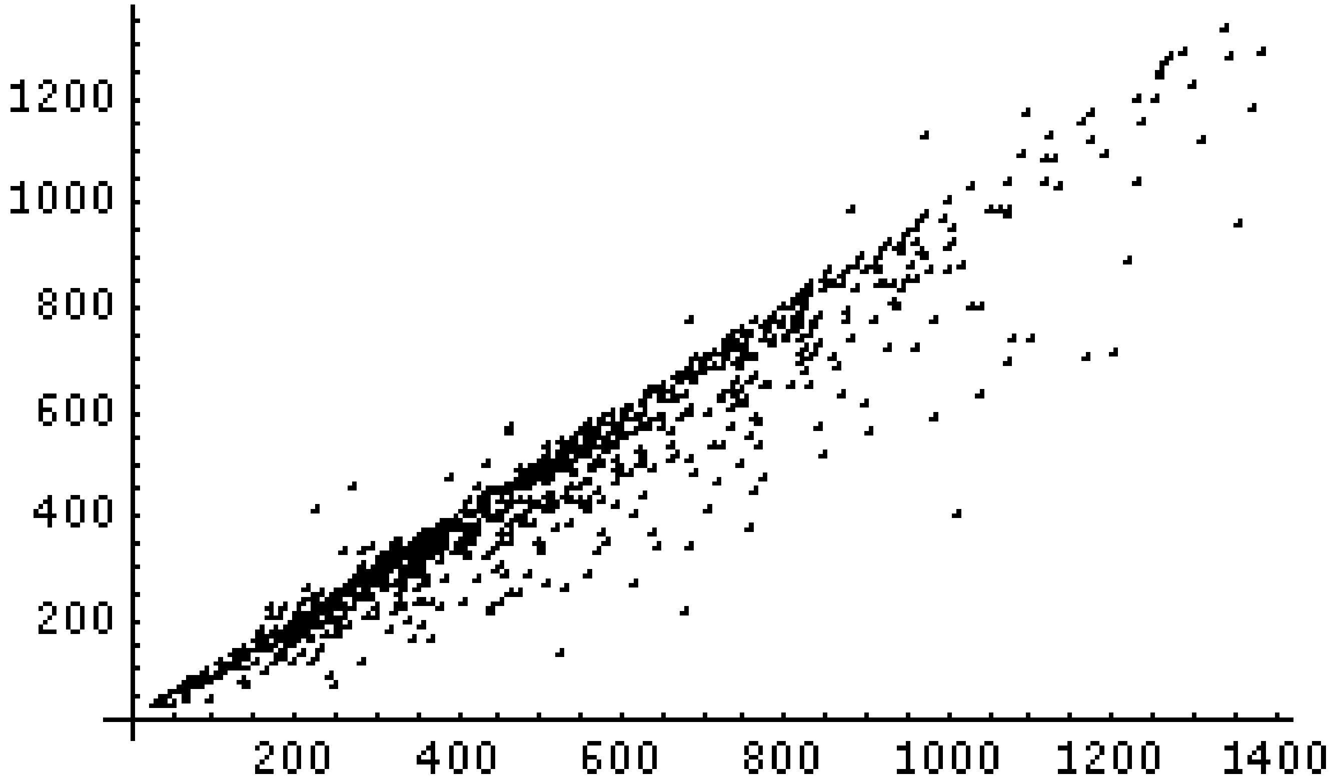


partonic jets w/ pt > 50 GeV

Parton-to-Hadron **Cluster** matching

Pt of hardest hadronic jet

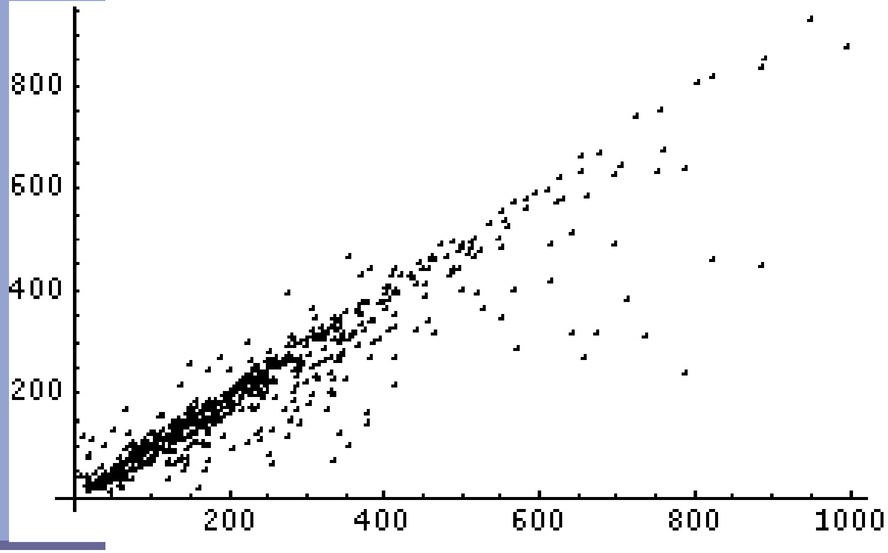
FastJet kT D=0.52



Pt of hardest short-distance partonic jet

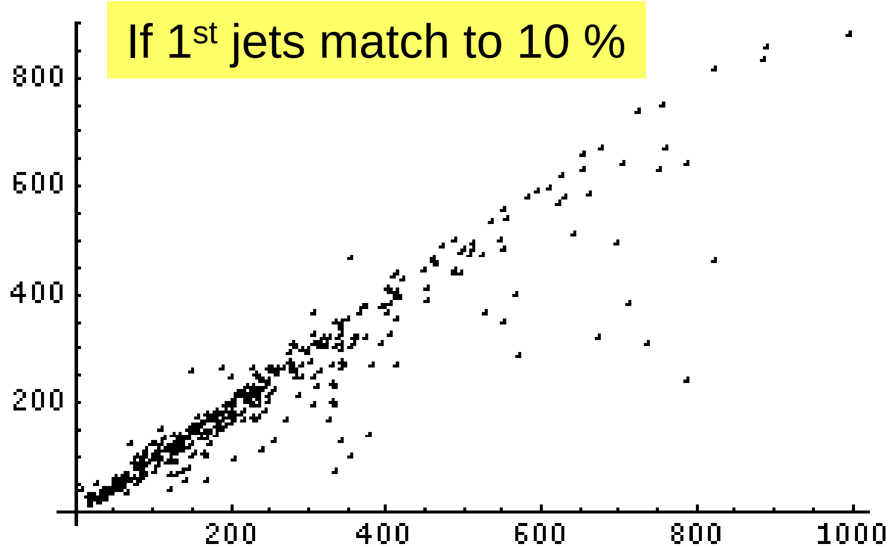
Parton-to-Hadron **Cluster** matching

Pt of 2nd hardest hadronic jet



Pt of 2nd hardest partonic jet

Pt of 2nd hardest hadronic jet



Pt of 2nd hardest partonic jet

FastJet kT D=0.52

This is Useful:

- All results shown
  - using Pythia hadron-level output;
  - *no detector resolution effects!*
  - use multi-algorithm software compiled by Joey Huston and student Kurtis Geerlin;
    - kT uses FastJet (Cacciari and Salam)

- We see short-distance-partonic and final-state-hadronic jets largely match,

- Let me now show you what is in the hadronic jets, with pretty good accuracy, by showing you what is in the partonic jets:

- *All results for 1000 Events, Z' of mass 3 TeV, v-pions of mass 50 GeV.*

- All results Preliminary!! Do not quote me yet.

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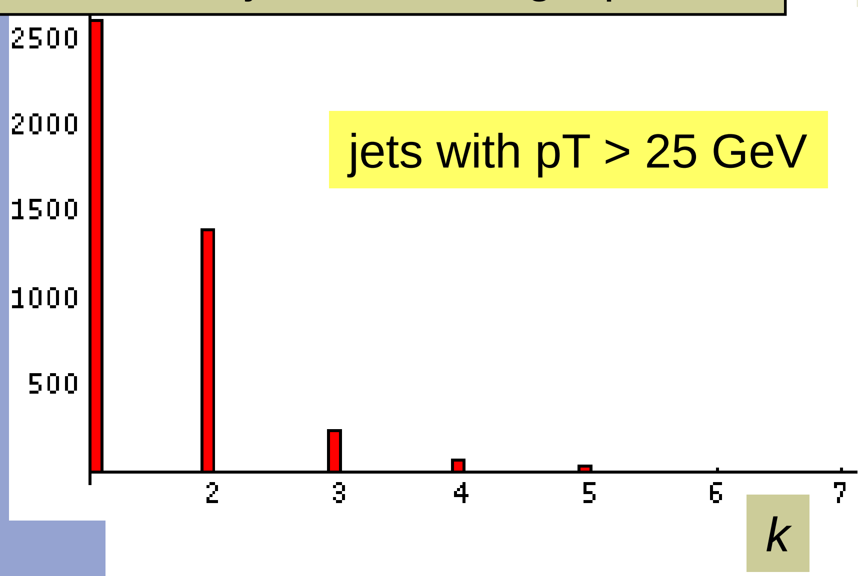
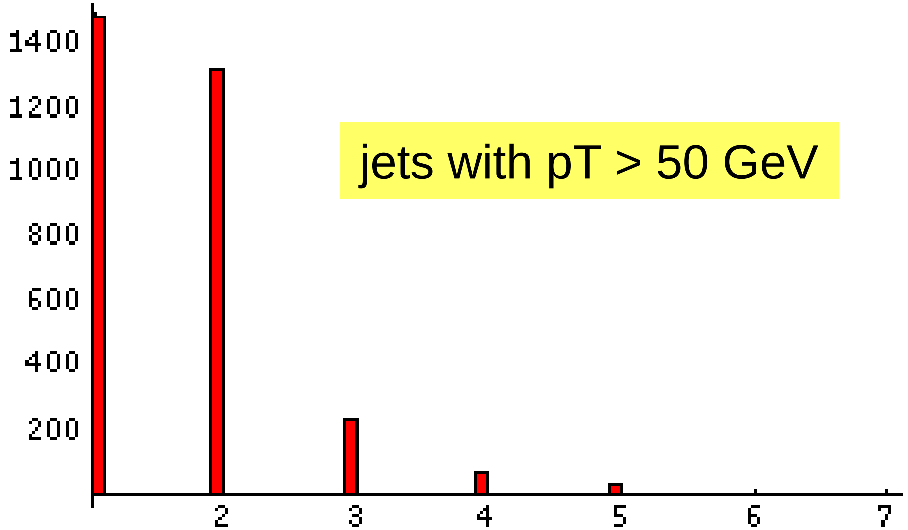
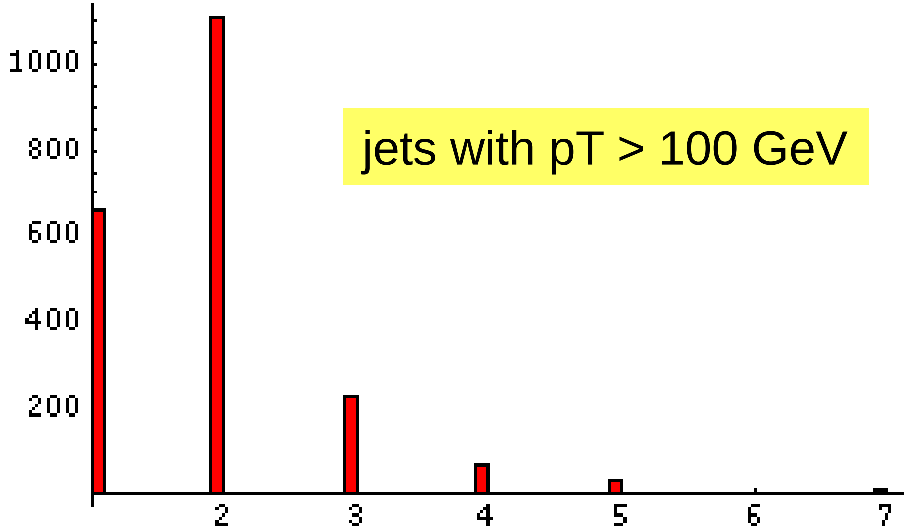
Number of Partons in Partonic Jets

Number of jets containing *k* partons







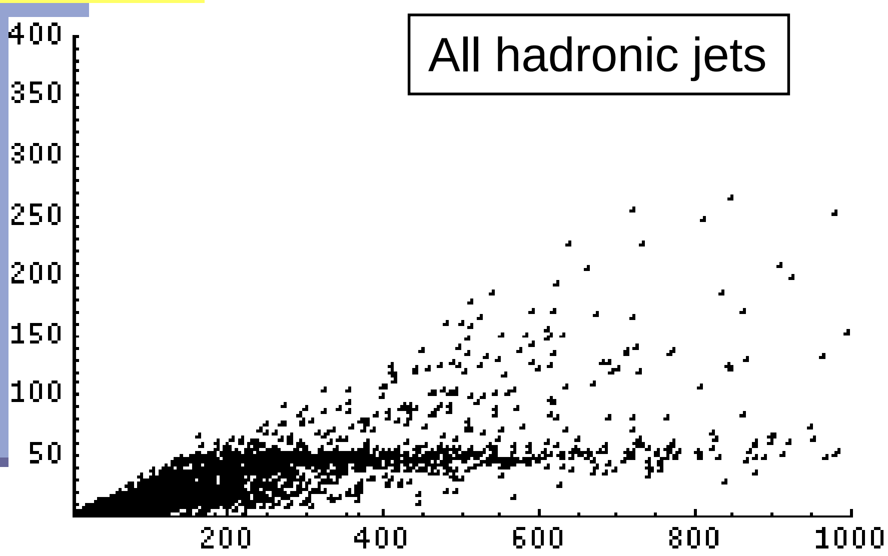
Typical >50 GeV jets are as likely to contain multiple short-distance bottom quarks as one

Most >100 GeV jets contain more than 1, some contain 4,5…

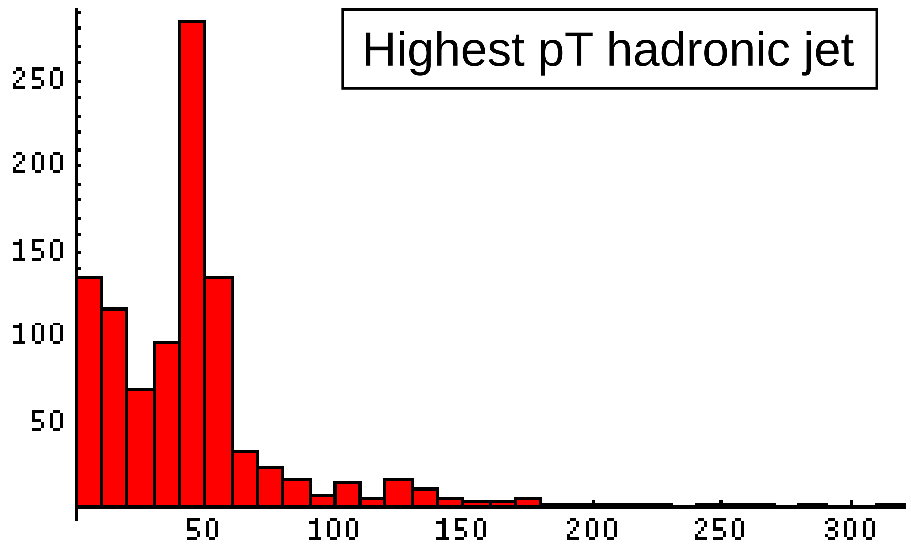
Single Jets may be V-Hadrons

- Opportunity to discover new particles using *jet masses* (invariant mass of the jet itself).

Jet mass



Jet pT



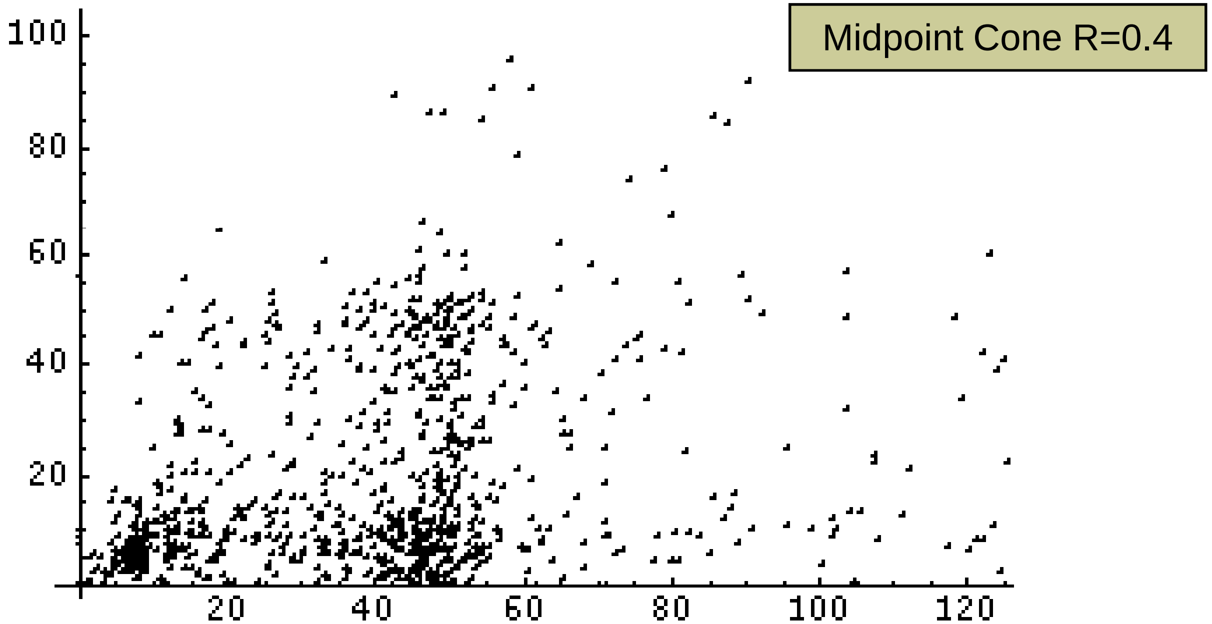
Jet mass

0.1 x 0.1 calorimeter cells
No detector smearing!!

Midpoint Cone R=0.4

Correlations can help

Mass of 2nd Highest-pT hadronic jet

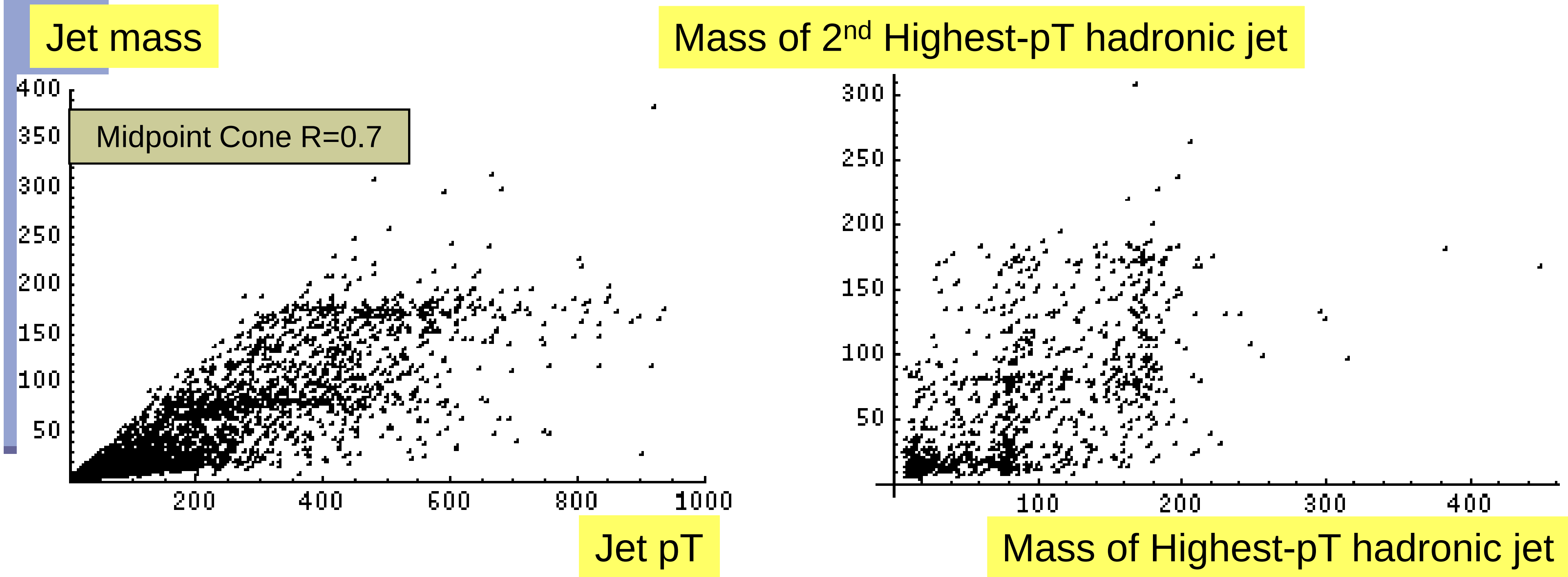


Mass of Highest-pT hadronic jet

All of these facts true with other algorithms, different settings: **robust!**

Compare with High-pT Top Quarks

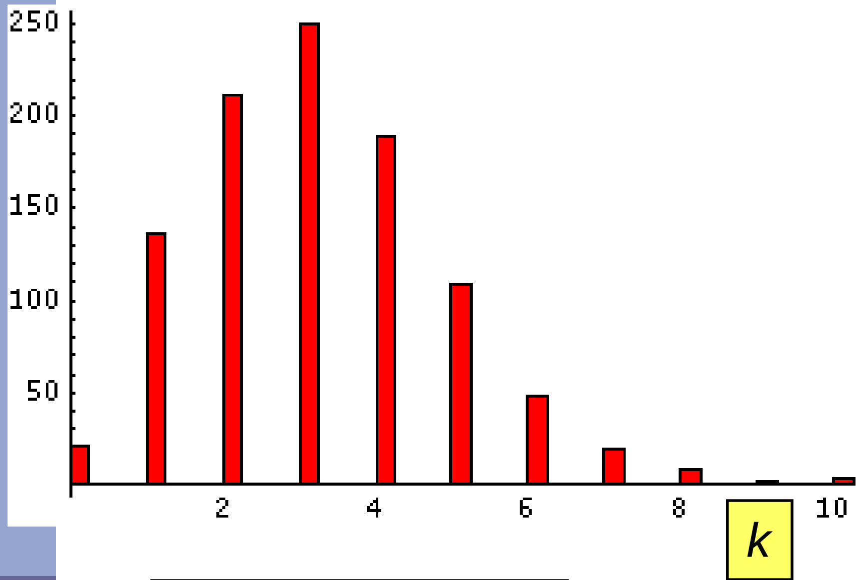
- Take top quark pairs, energy > 1 TeV, all-hadronic decays



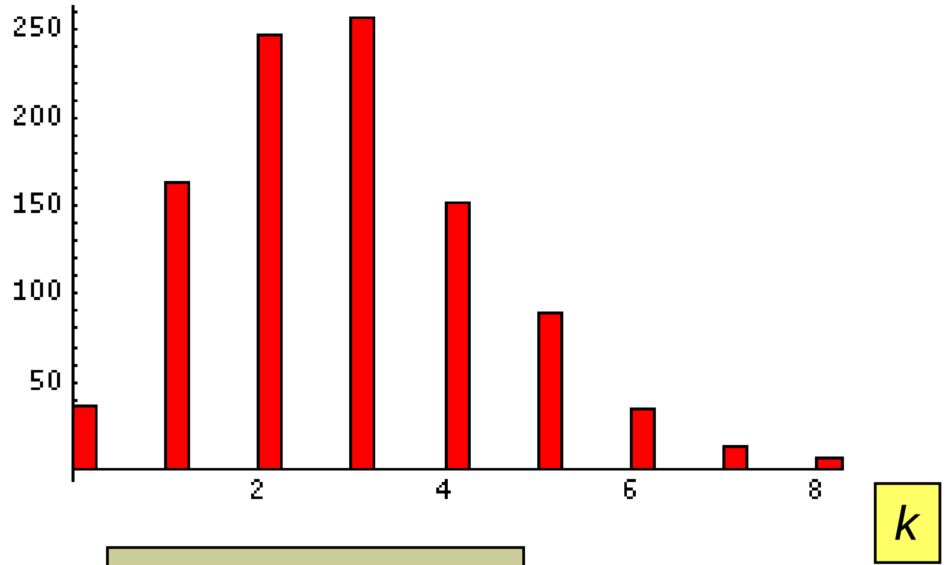
- Jet mass useful for finding new particles produced at high energy , e.g. in decay of heavy particle
- However, the most crucial unknown is the detector resolution on jet mass.

The number of jets is not so large

Number of events with *k* jets, pT>50 GeV



Midpoint Cone R=0.4



Midpoint Cone R=0.7

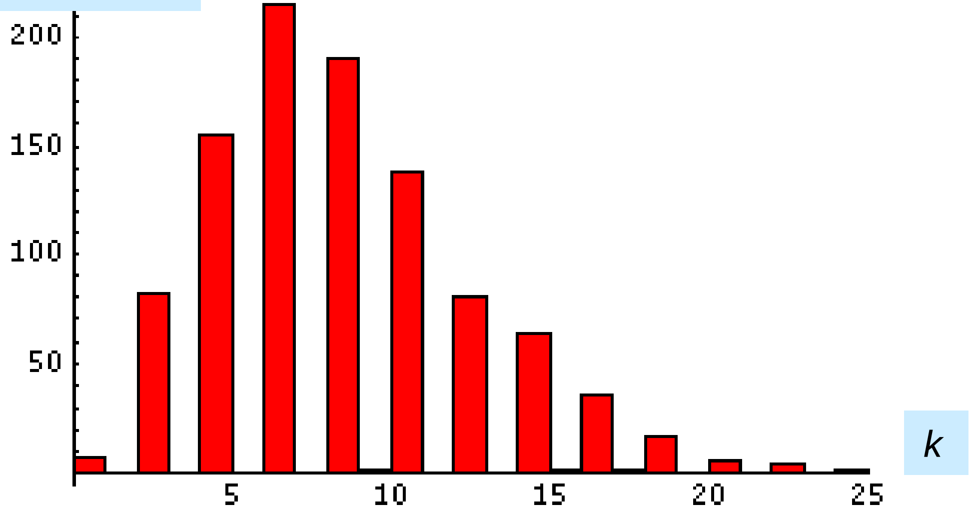
Thus there could be significant backgrounds from
Z + jets, t tbar b bbar, t tbar W, t tbar Z, t tbar h, t tbar t tbar, WWZ, etc.

If we demand 5 jets, we lose most of the events.

The number of b-quarks is very large

Number of events with *k* partons (mostly b quarks)

Only even numbers of course!



Thus the number of B mesons greatly exceeds the number of jets.

But even with 3 b-tagged jets (70 percent tagging, 4 jets → 40 percent eff.)
Z + jets, t tbar b bbar, t tbar W, t tbar Z, t tbar h, t tbar t tbar, are still backgrounds

If we demand 4 jets, 3 b-tagged, we lose many events, still have bckgd.

Object-Oriented Programming

Clearly this is the not an ideal approach.

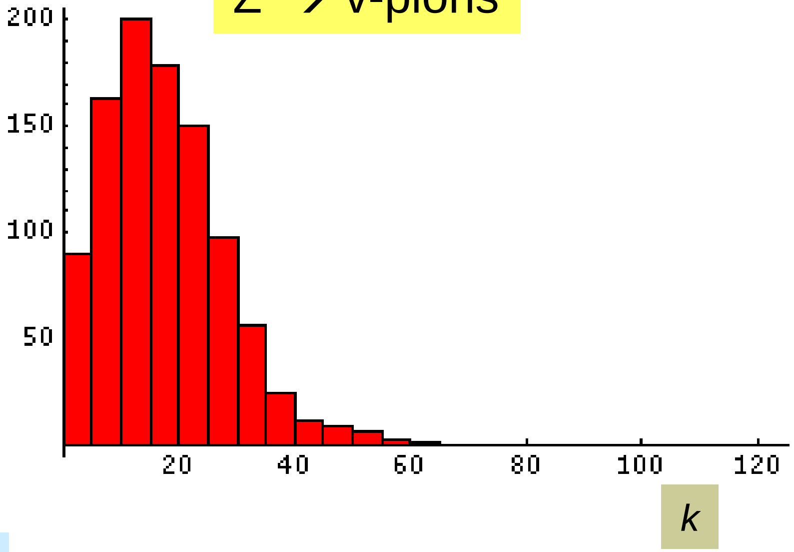
- Jets are often treated together as “objects”….
- If a jet contains a vertex it is “tagged” as containing heavy flavor, or “untagged”
- But …
  - *Jets are really not “Objects”*
  - *Vertices are really not “Objects”*
- The matching between jets and vertices is neither one-to-one nor onto.
  - Find multiple vertices in hard jets (cf. gluons splitting to bottom quarks)
  - Find vertices in soft jets below cuts or in multiple jets
- Characterizing jets as “not b-tagged” or “b-tagged” is not enough at the LHC.
- For this signal, object-oriented methods, BARD, PGS, Marmoset – valuable as they are – eliminate part of what makes these events distinctive.
- A more global approach to these events seems advisable

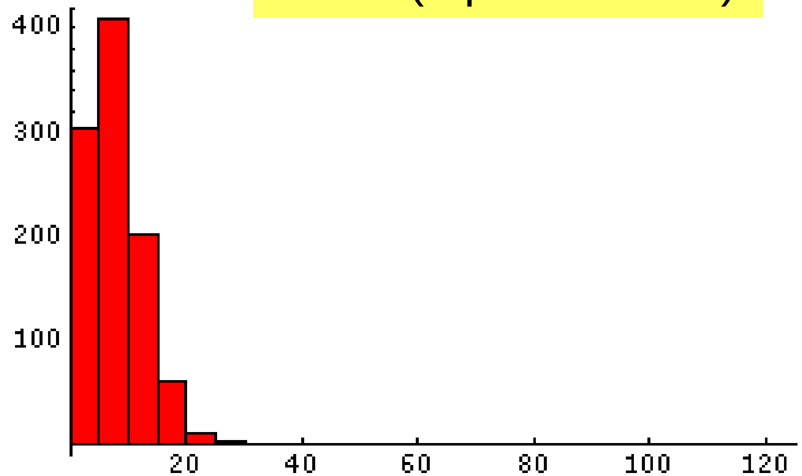
High-Impact-Parameter Tracking

Number of Events with *k* tracks with 3d IP more than 150 microns

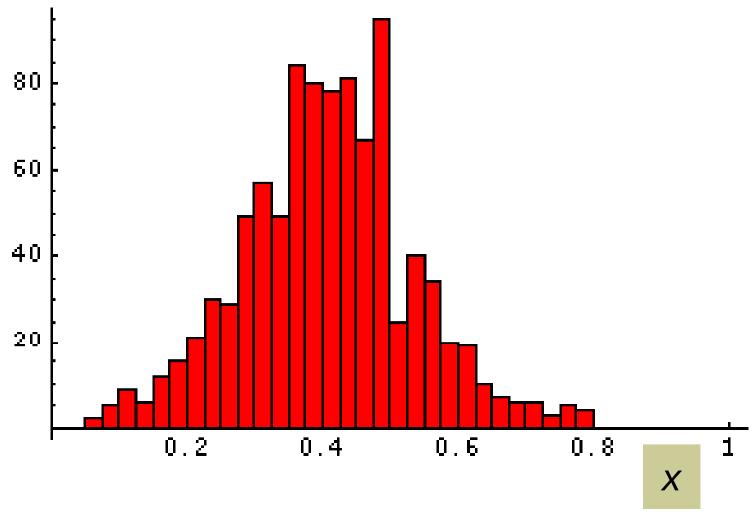
Z' → v-pions

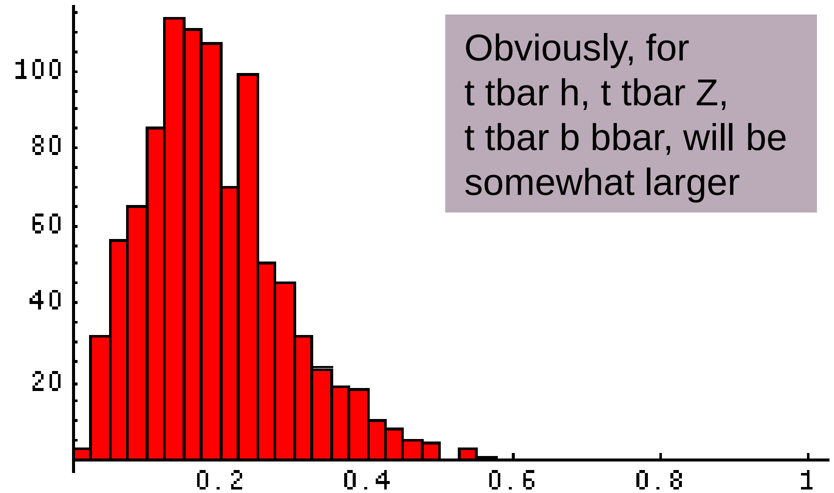
t tbar (sqrt-s > 1 TeV)





Number of Events with fraction *x* of tracks (pT>2 GeV) with 3d IP more than 150 microns





Obviously, for t tbar h, t tbar Z, t tbar b bbar, will be somewhat larger

Backgrounds?! And a concern:

- More work needed even to get a feeling for what the main SM backgrounds actually are:
  - W/Z plus multi-b ?
  - Multiply-produced W/Z/t/h ?
- In any case the backgrounds may well not be calculable
- Will next do a background study…

But even at this stage, there's a lesson:

- *After reconstruction, important not to hide the unique features of these events in compressed data storage*
  - Tagged/untagged jets probably not sufficient to make events stand out
  - Vertices stored, independent of the jets?…
  - Otherwise, backgrounds effectively much larger; more difficult to select a smaller, manageable sample to study

Other Models? HV1.0 Monte Carlo

- More versatile event generator written with Steve Mrenna and Peter Skands
  - Can handle more flavors, non-QCD-like mass spectrum
  - For now uses independent fragmentation;
    - *Maybe return to Lund string fragmentation later, but how?*
  - Will come with crude spectrum generator to assist user
    - *But beware of pitfalls…*

Spectrum generator

SLHA input

Les Houches output

qq → Z' → QQ

Independent Fragmentation

v-hadron decay

Hadron-level output

- Consider 2 flavor QCD as a function of m_u, m_d ,N_c.
  - What is the hadron spectrum?
  - What are the hadron decay branching fractions?
  - How does fragmentation depend upon these parameters?

Test/Guess about $N_f = 2$, N_c small

- Z' mass 3.2 TeV ; V-strong-scale 52 GeV
- **Increase** up/down quark masses

- Guess for reasonable spectrum:
  - Pions: 77 GeV – decays to heavy flavor
  - Rho/Omega: 120 GeV – decays democratically to SM fermions
  - Eta: 138 GeV – decays to heavy flavor
  - Ignore baryons
- Fragmentation probabilities ; should not be not too different from QCD

- **HV1.0$\alpha\alpha\alpha$ Simulation Says:**
  - If only pi0, rho0, eta decay
    - Average of ~6 quarks/leptons per event
    - Average of ~4 b's per event
    - 5-10 percent of events have a mu pair or e pair
    - *Sorry! have not been able to produce nice plots of distributions to show you!*

  - If vFCNCs, so that pi+, rho+ decay, increase multiplicity by ~3 w/ K. Zurek, April 06

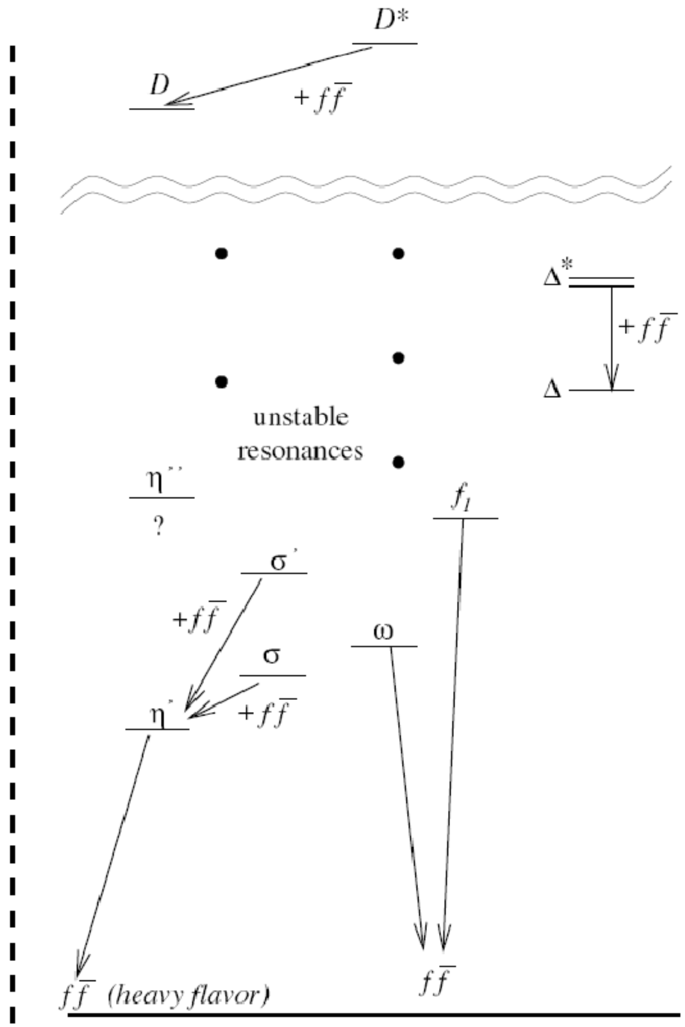
Only one light v-quark?

Previous model is a bit tuned…

but has similar phenomenology to…

vQCD with one light flavor

- If N small, anomaly makes v-omega stable
- The v-omega can decay to any SM fermions
  - dilepton resonance
- Better understanding of spectrum, matrix elements needed also, as input to simulation
- Analytic work and lattice gauge theory needed



Phenomenological Lesson

- Many v-models can give 10-100 resonant lepton pairs per year

- General point: Rare light dilepton resonances are easily obtained
  - In other hidden valley models
  - In many weakly-coupled models

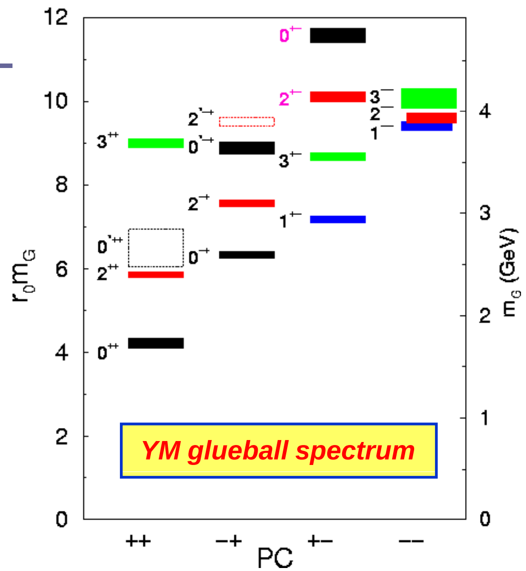
- There are direct constraints from electron-positron colliders and Tevatron
  - *has there been a study integrating all the data?*

- Tevatron/LHC: signal totally lost in Drell-Yan background – unless:
  - Signal events are collected with high efficiency
  - Fairly pure sample of signal events obtained
    - ***Must use other features of the event beyond the lepton pair to purify sample***

  - Tevatron:
    - Inclusive searches for dilepton resonances in all events
    - Restricted searches for dilepton resonances in events with X
  - Lepton isolation cut?

Beyond this stage… HV2.0???

- Lots of b's – *relatively* easy
- Rare lepton pairs – *maybe* relatively easy
- A tougher scenario (MJS and Zurek 06)
  - Communicator: loop of messengers
  - V-sector: pure glue
  - Final state: mostly gluon jets



Morningstar and Peardon 99

- Final states: Need to know decay chains to SM particles
- Signal extraction: Need to focus on unusual patterns of jets
- Kinematic/Flavor distributions: Need to know something about fragmentation!
  - Just try phase space? Intuition from string theory? Tricky problem; experimentally relevant!
- How to simulate? What fragmentation algorithm?!

- Vast array of other scenarios are even more difficult theoretically
  - No good guess for phenomenology yet, so no path to simulation
  - Plenty of subtle questions in Quantum Field Theory and String Theory

Summing up:

- Hidden valley models can give signals that lie outside standard LHC phenomenology
  - Not like SUSY
  - Object-based event reconstruction too limited
- Z' decays to the scaled-up QCD v-sector give events with
  - Many partons – mostly b's, tau's, MET
  - Possibly long-lived neutral particles
- Detecting/analyzing this signal may require non-standard techniques:
  - Jet Mass measurements
  - Vertex/Jet/Soft-lepton combination analysis; loose tagging
  - Displaced vertex searches for long-lived particles
- Other models can have markedly different signatures
  - New dilepton resonances
  - Many more exotic possibilities, but hard to calculate/simulate
- HV1.0 is ready for testing!
  - First exploration of models with non-QCD-like spectrum
  - How to validate a simulation of a non-QCD-like strongly-interacting model?!
- Still just beginning to explore the valleys and their LHC echoes
  - Phenomenology not possible without more theoretical investigation!