Effect of New Gauge Sectors on Tevatron and LHC Phenomenology

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- hep-ph/0607160
- in preparation

Prologue

- ***What does string theory predict?***

- Minimal models are elegant and attractive – esp. to theorists
  - Verlinde, Ovrut, Faraggi, Ratz, Raby…
- But string theory does not really *suggest* minimal models
- Many new sectors of SM-neutral particles are common
  - Schellekens…
- Standard Model + … + … + … + … + … + … + … + … + …

- Is there any chance that some of this extra stuff is visible at the Tevatron or LHC?
- Have we considered carefully how it would appear?
- Are we sure we can find it if it is there?

Theoretical Motivation

- String theory easily accommodates, often predicts, ***new sectors***;
- New sectors may decouple from our own at relatively low energy
- Decoupling could naturally occur at SUSY-breaking scale and/or TeV scale
- Such sectors could be responsible for, have influence on, or provide insight into SUSY-breaking and/or flavor
- *Learning about these sectors, which may contain many particles, could open up an entirely new view of nature.*

Theoretical Motivation

- Remnants of these sectors may be observable at Tevatron/LHC; may alter phenomenology of superpartners and/or Higgs bosons.
- But cross-sections may be low, and phenomena produced may be subtle.
- Missing these sectors experimentally at the Tevatron/LHC could set back our efforts to understand nature by a couple of decades.
- Therefore, we should make sure we understand their phenomenology.
- Also, the dynamics of these new sectors, and its manifestation in Tevatron/LHC phenomena, is theoretically interesting in its own right

Experimental Motivation

- We are at a crucial moment for both the Tevatron and the LHC:

- **Tevatron**:
  - 2 years more at forefront
  - Few 2σ deviations at 1 fb^{-1} ; cannot expect 5σ at 8 fb^{-1}
  - ***But many searches have not been carried out***
  - Large data set: *What's hiding in it?*
  - Need to carry out high-stakes high-risk analyses

- "Hidden valley": an example of something likely to have evaded current Tevatron analyses

- **LHC**:
  - 1 year left to adjust basic systems, software tools
  - Any last suggestions on how to optimize the detectors are needed *NOW!*
  - Wise to consider many models with radical phenomenology to ensure all bases covered

LHC

- **Hardware of the detectors is largely finished, but not the software.**
  - Time-sensitive hard-to-change parts of the software are:
    - Trigger [partly hardware]
    - First-pass Reconstruction
    - Tracking Algorithms
- **Detectors designed for *high-energy isolated jets, moderate-energy isolated leptons and photons emerging from the interaction point***
  - Works for standard SUSY, standard Higgs, standard little Higgs…
  - Experimentalists confident they can get the detectors ready for such physics
  - Any new model predicting similar signatures is not crucial right now

LHC

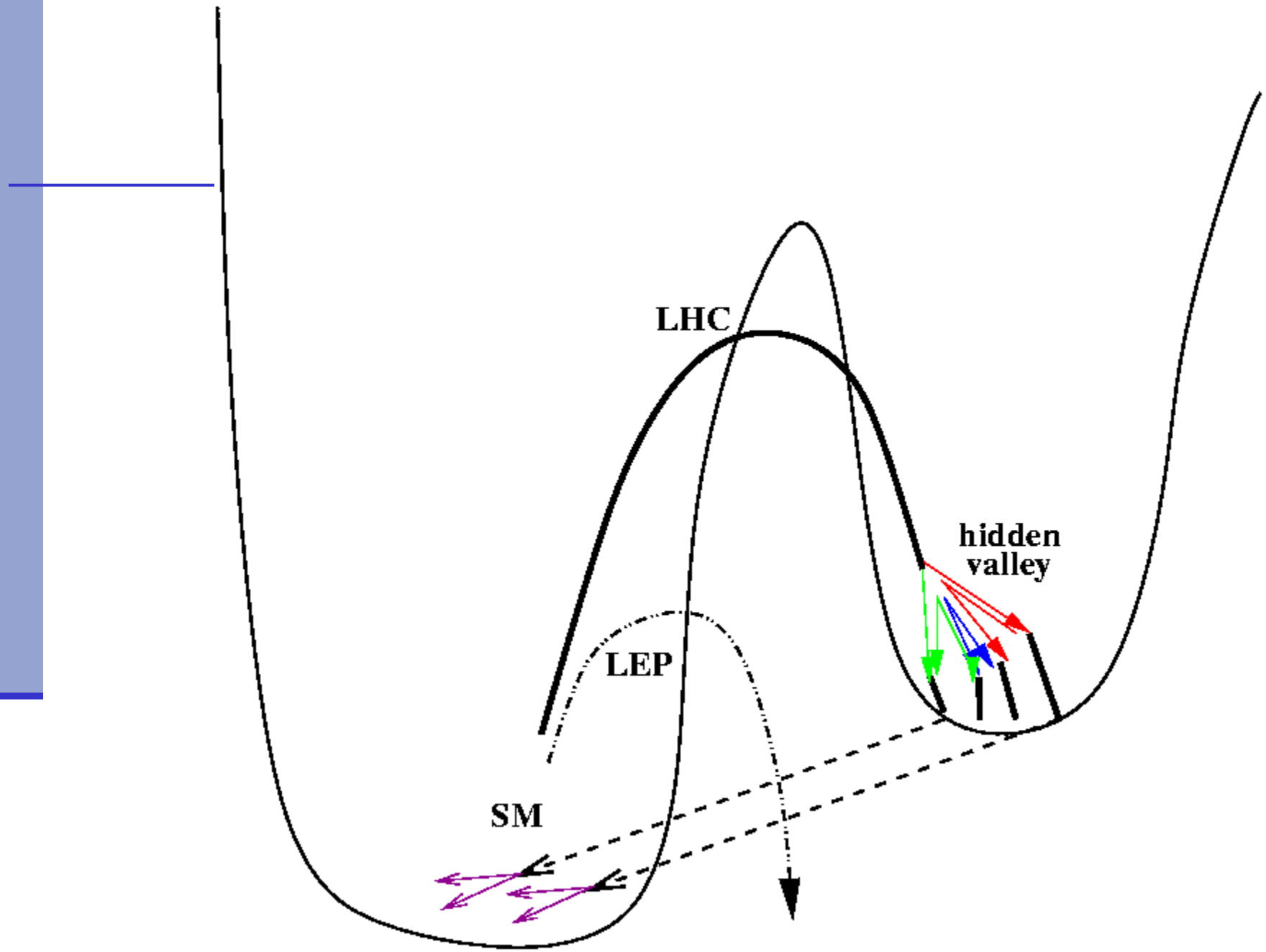
- ***But what if the new physics isn't of this form?!***
  - Many moderate-energy non-isolated jets?
  - Low-energy non-isolated leptons?
  - Long-lived particles appearing in middle of the detector?
  - Monopoles?
- Need to ensure that non-standard physics makes it past the trigger, is spotted in the initial reconstruction
- *Often this requires adjusting the tracking software at the trigger and reconstruction levels*

- **Important to investigate models that pose a severe but not impossible challenge**
- Indeed, other than standard model backgrounds, most frequent request of theorists by experimentalists;

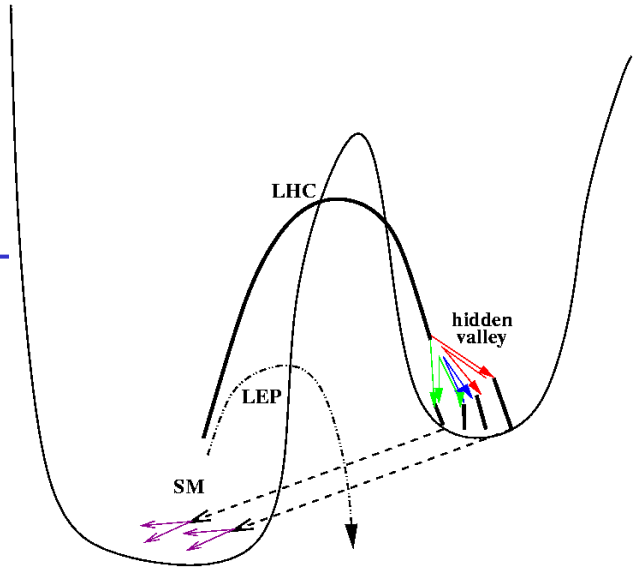
- ***We have only a few months left for this kind of work***

New Non-Abelian Sectors

- Much work on Abelian gauge sectors coupled to the SM: Z' physics
- *Little work on non-Abelian gauge sectors not coupling to SM particles*.
  - The reason: traditionally assumed that such particles are invisible
  - However, this is not true: some new states may decay entirely or partly via SM particles
  - The likelihood of such a phenomenon is greatly enhanced by strong coupling, confinement, a mass gap, etc. in new sector
- We will see that such "hidden valleys" can have remarkable effects at Tevatron/LHC


LHC
hidden
valley
LEP
SM

The “v-sector”

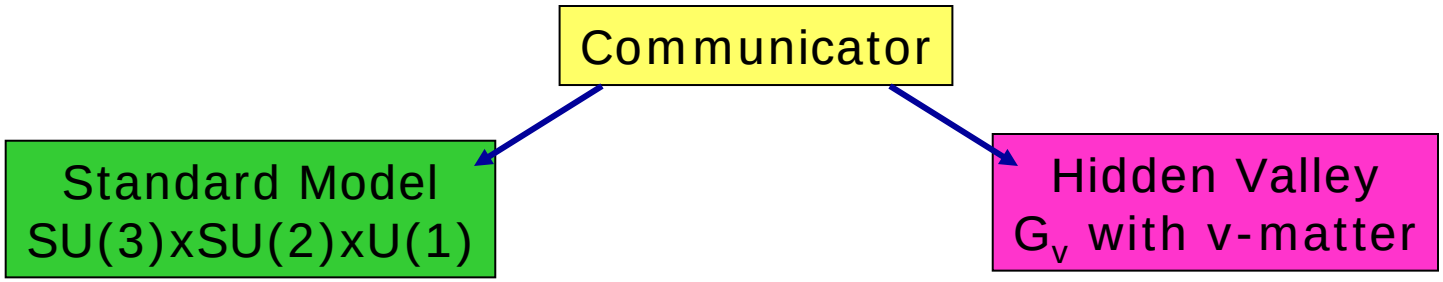


“Hidden Valley” not hidden for much longer!

- Could be
  - a nearby throat
  - nearby D-branes
  - a nearby singularity
  - non-geometric in origin
- Separated from us by a “mountain”: ultra-weak interaction(s)
- Valley floor allows for decays via tunneling, by the same interaction(s)
- Ultra-weak interaction between sectors could be induced by
  - a loop of new massive particles, or
  - any neutral particle: Higgs, Z’, neutralinos, neutrinos
- Physics in the valley is poorly constrained
  - LEP: at best rare production, sometimes with backgrounds
  - Precision experiments: new sector contributes at two loops
  - Cosmology: few constraints
    - strong interactions → efficient mixing of v-hadron species
    - If one light v-hadron decays well before 1 sec, entire sector annihilates efficiently before BBN

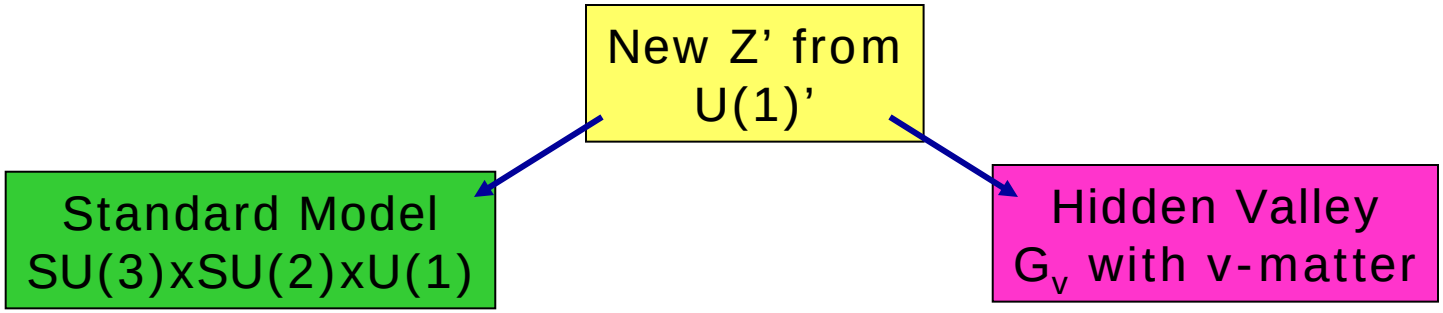
Models

- Many Models to Consider



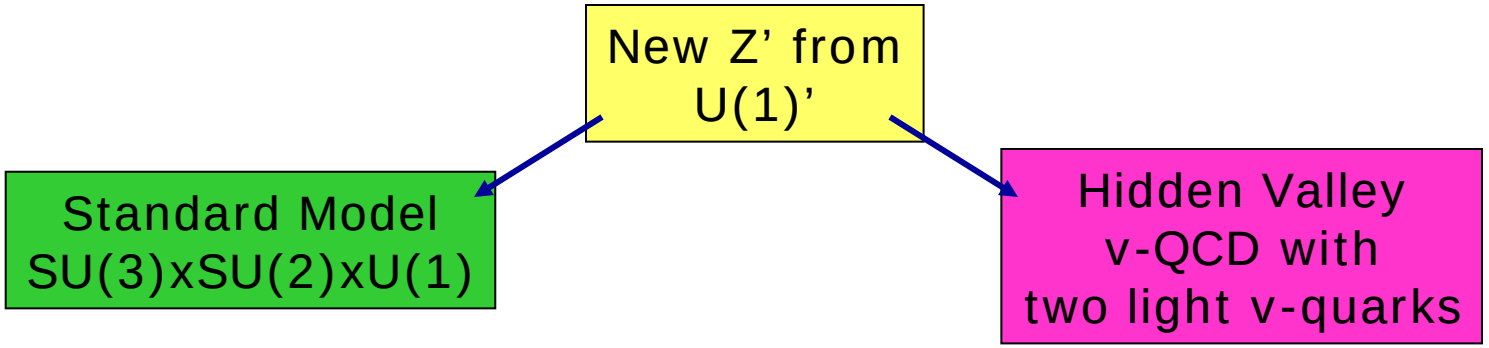
Simplest Class of Models

- Easy model to understand:

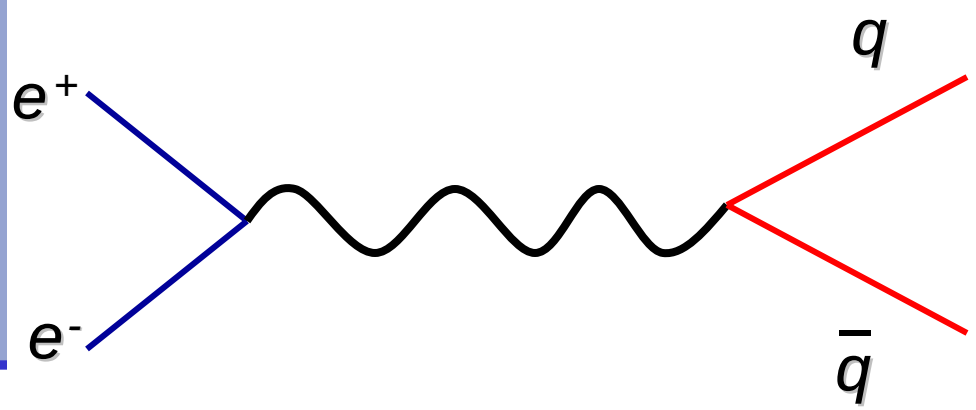


Simplest Class of Models

- Easiest model to understand ***and*** simulate:



$e^+e^- \rightarrow q\,\bar{q}$



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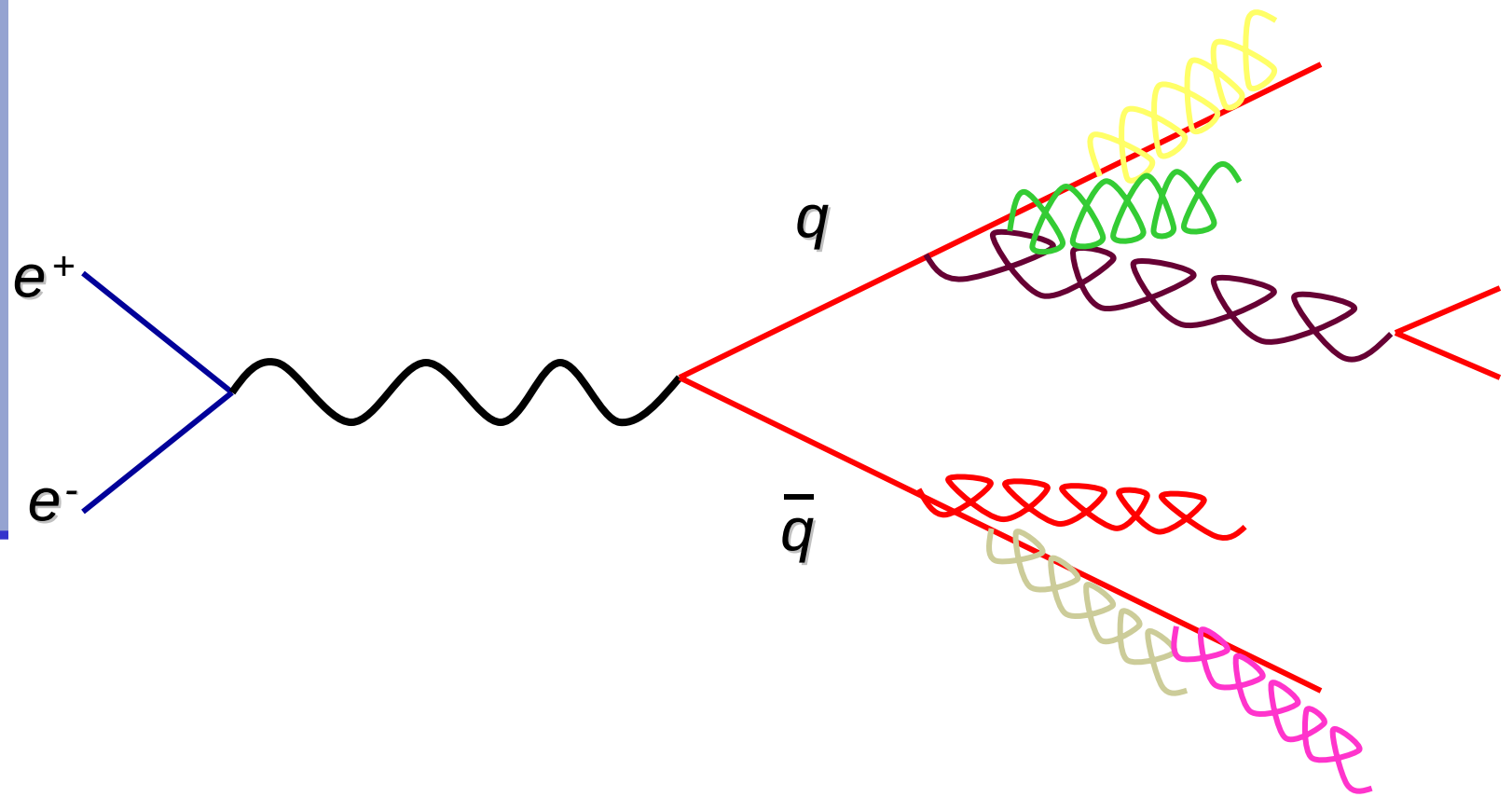

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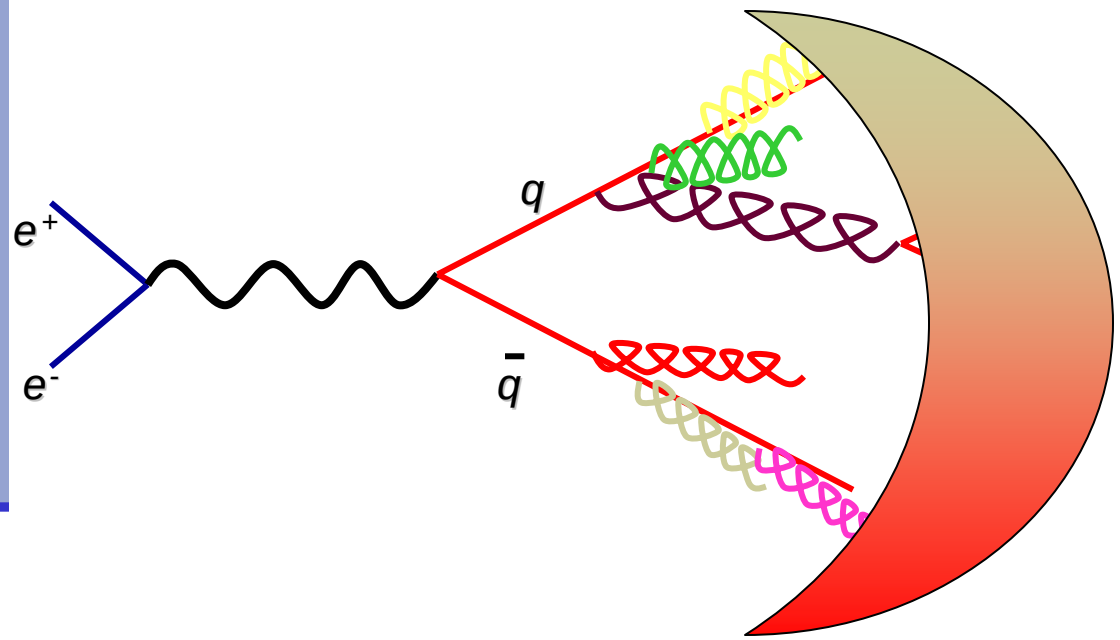

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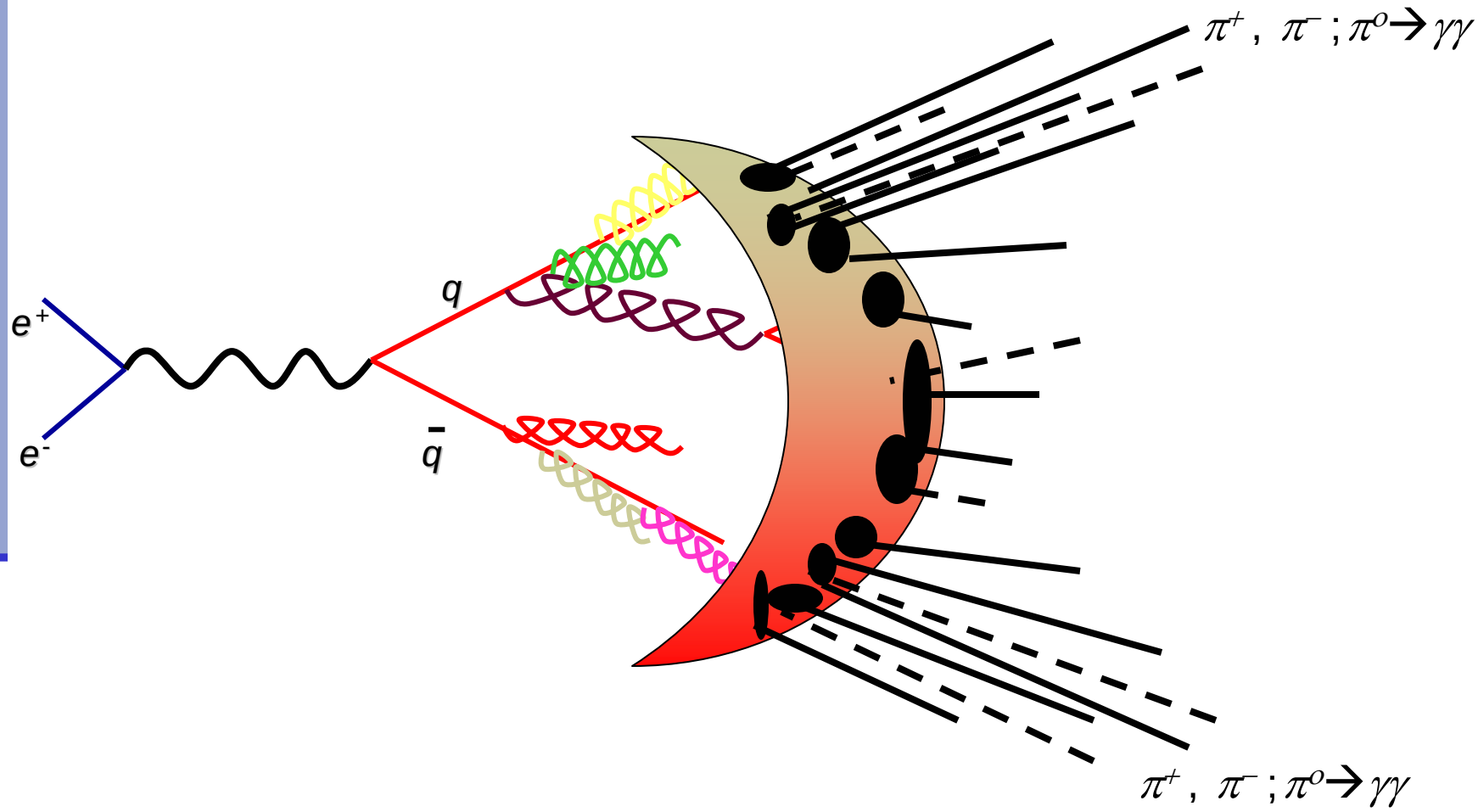
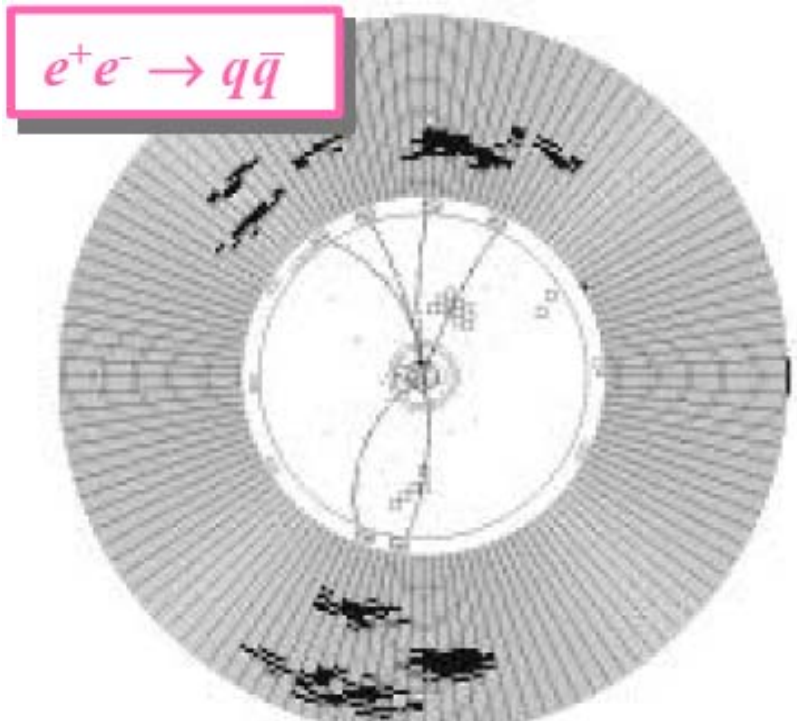
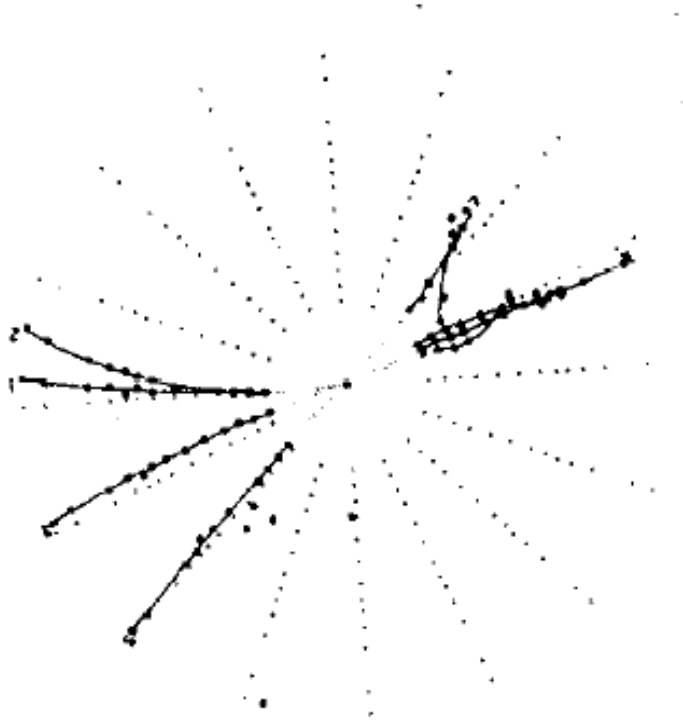


What does it look like?





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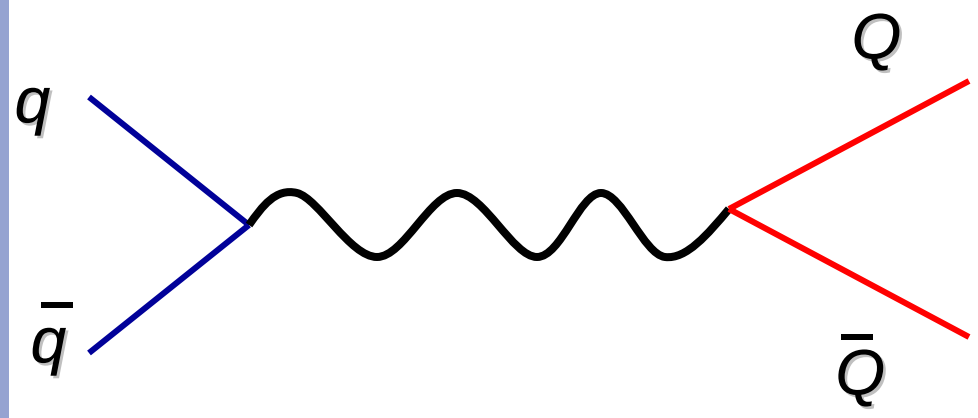

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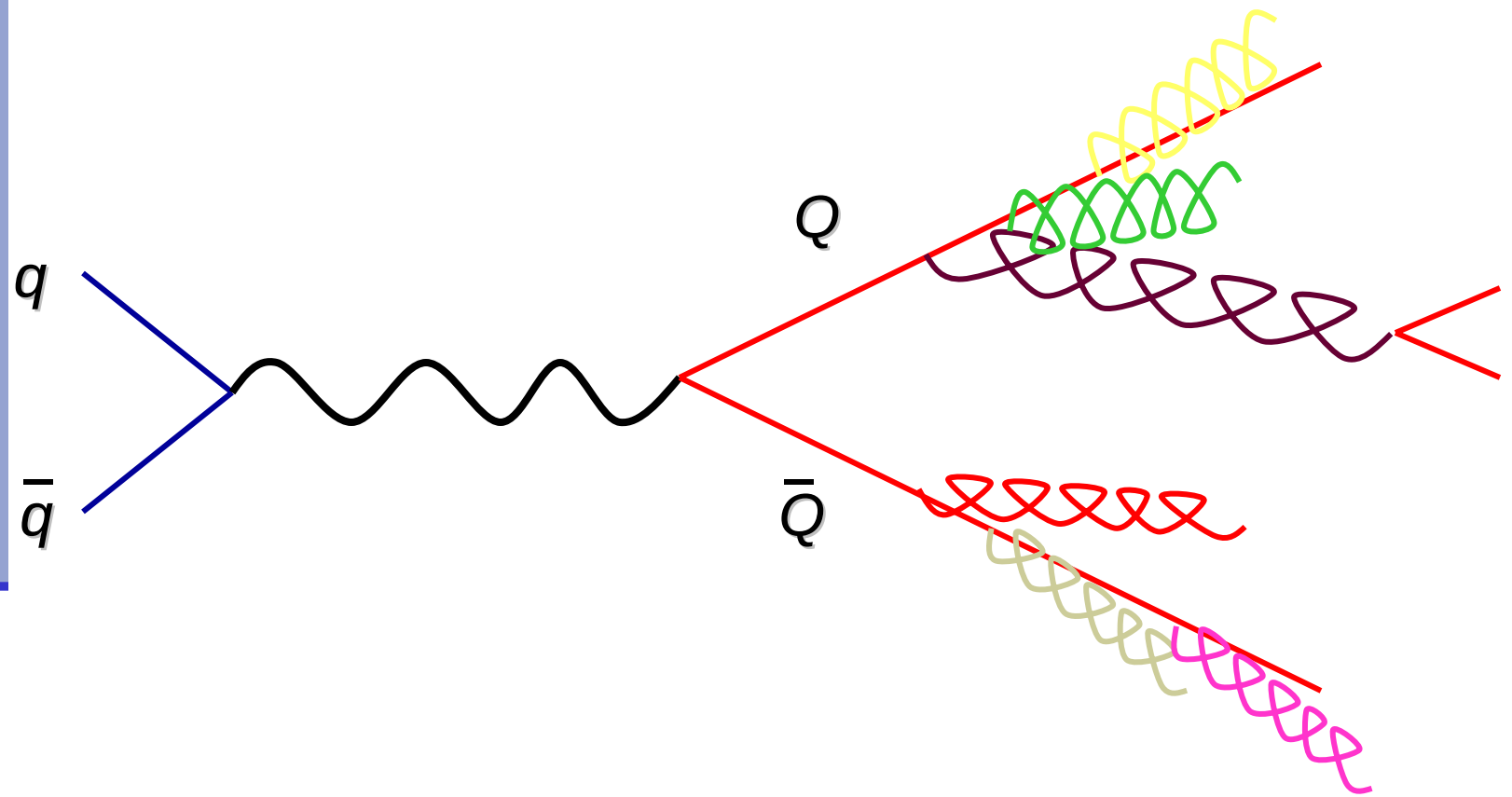

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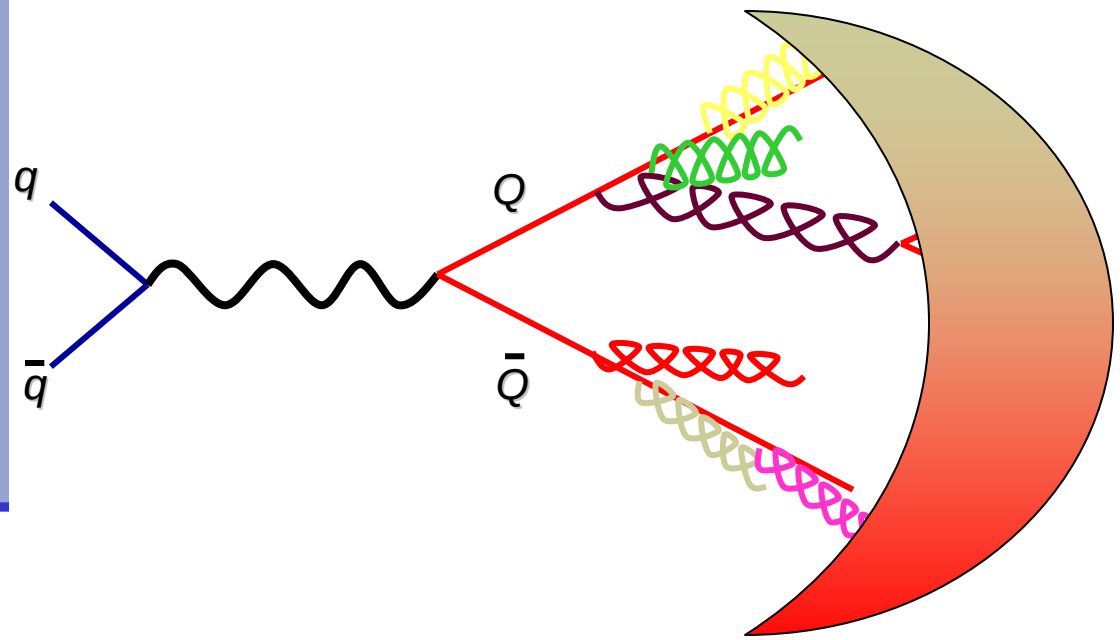

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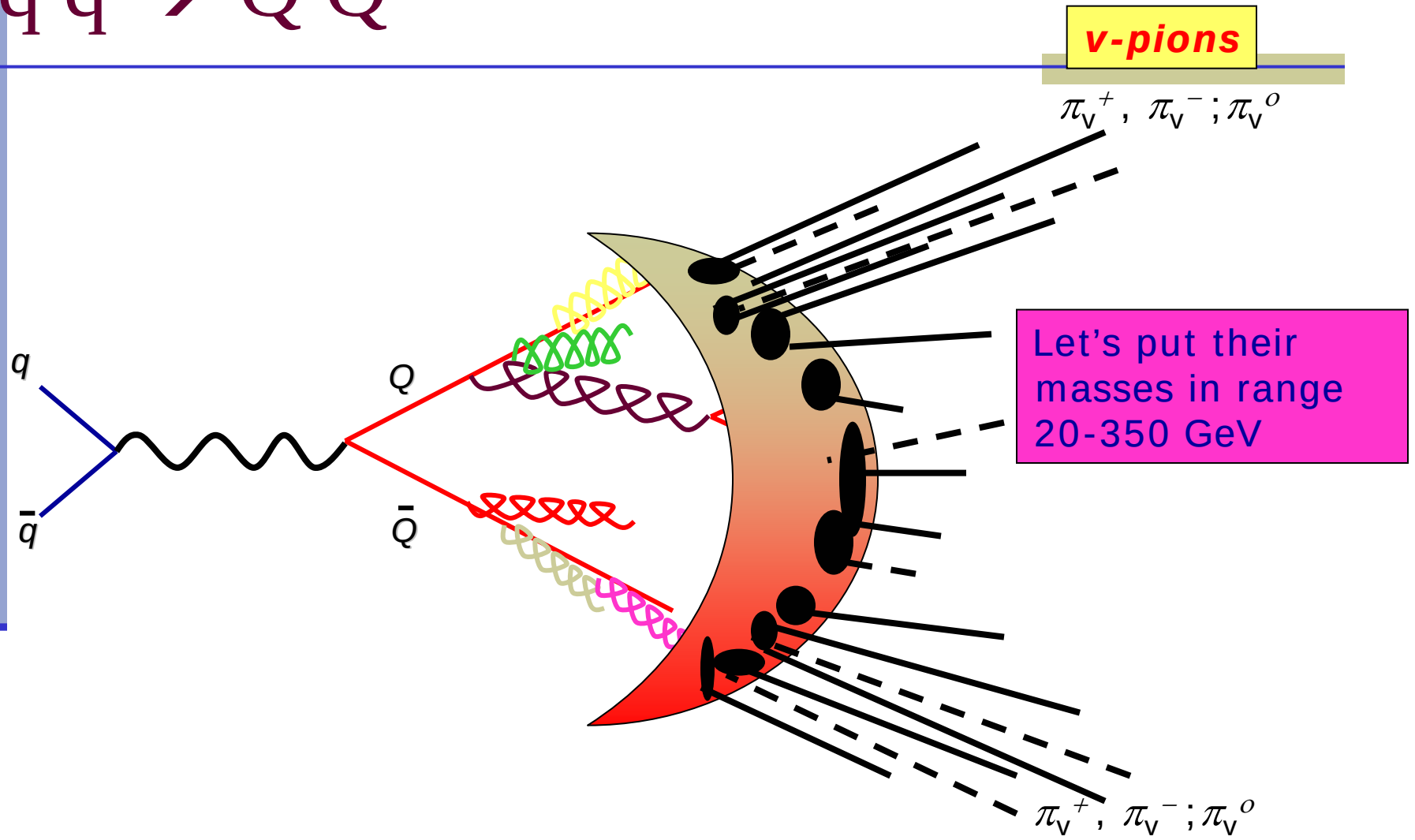

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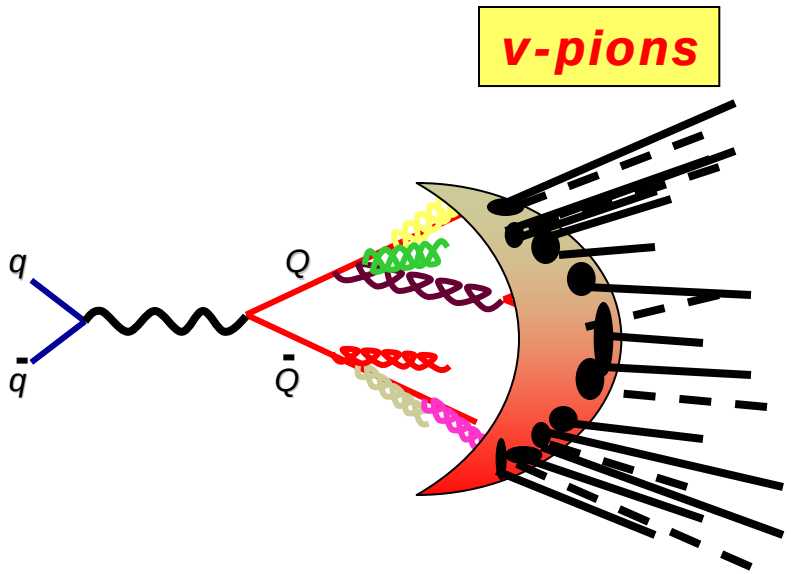
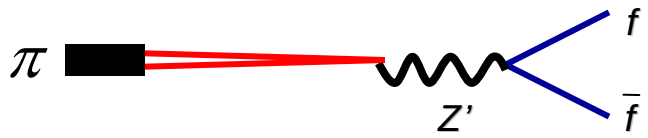


The Easiest Model

- With two light flavors, v-QCD is similar to real QCD
- The Z' can decay to a pair of v-quarks
- All v-hadrons decay immediately to v-pions and the lightest v-baryons
- Two of the three v-pions cannot decay via a Z'
- *But the third one can!*

$$\pi_v^+ \sim Q_1\bar{Q}_2 \sim \textit{stable}$$
$$\pi_v^- \sim Q_2\bar{Q}_1 \sim \textit{stable}$$

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



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

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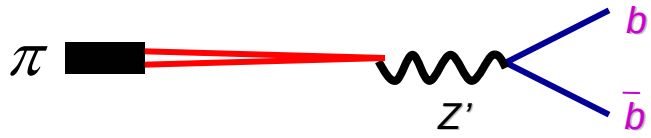
Pseudoscalars: their decays require a helicity flip; branching fractions proportional to fermion masses m_f^2

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



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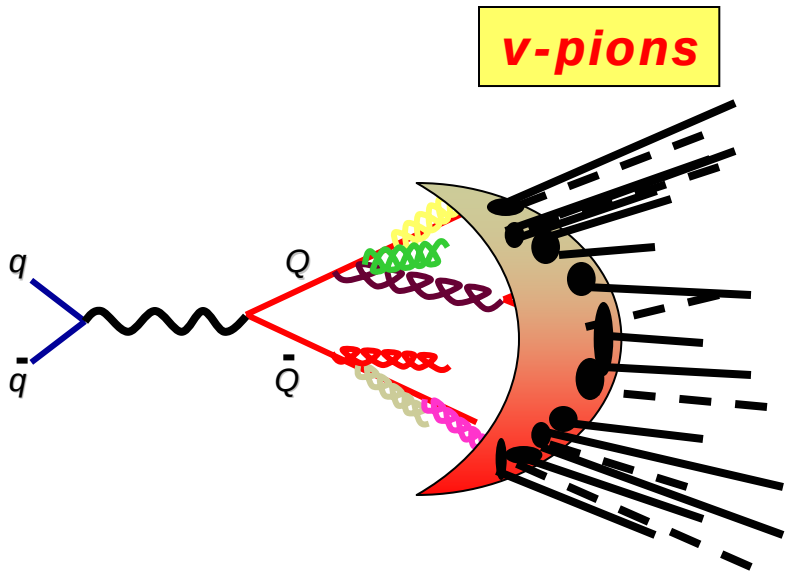

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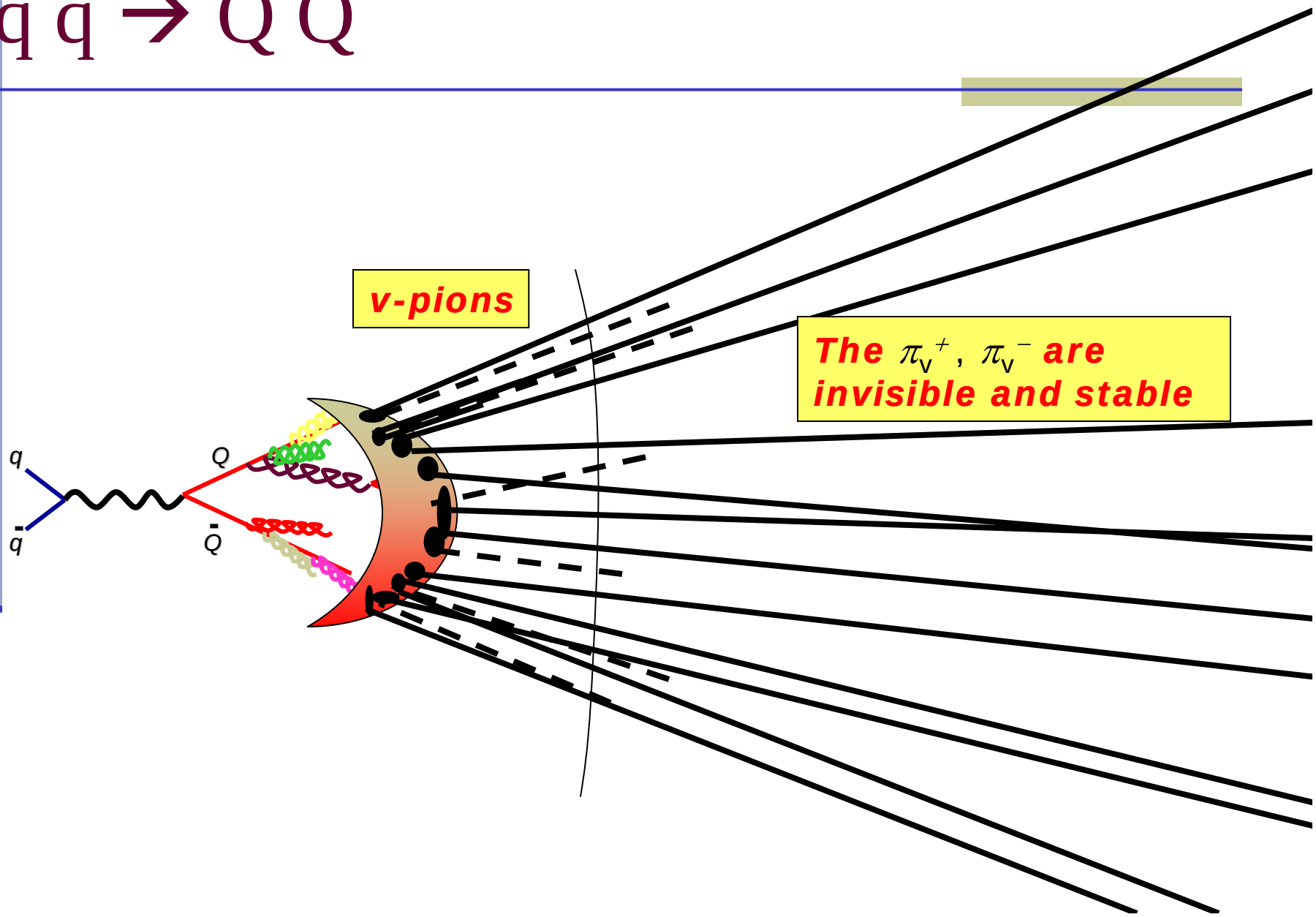

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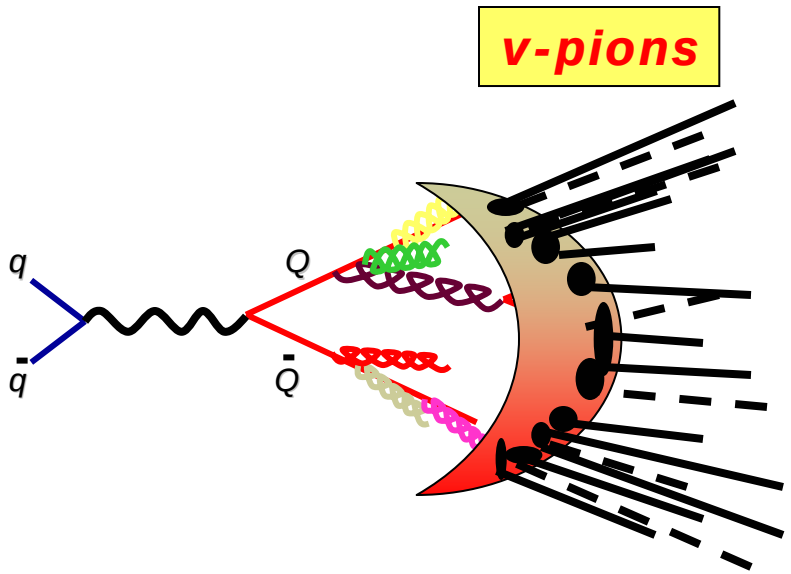

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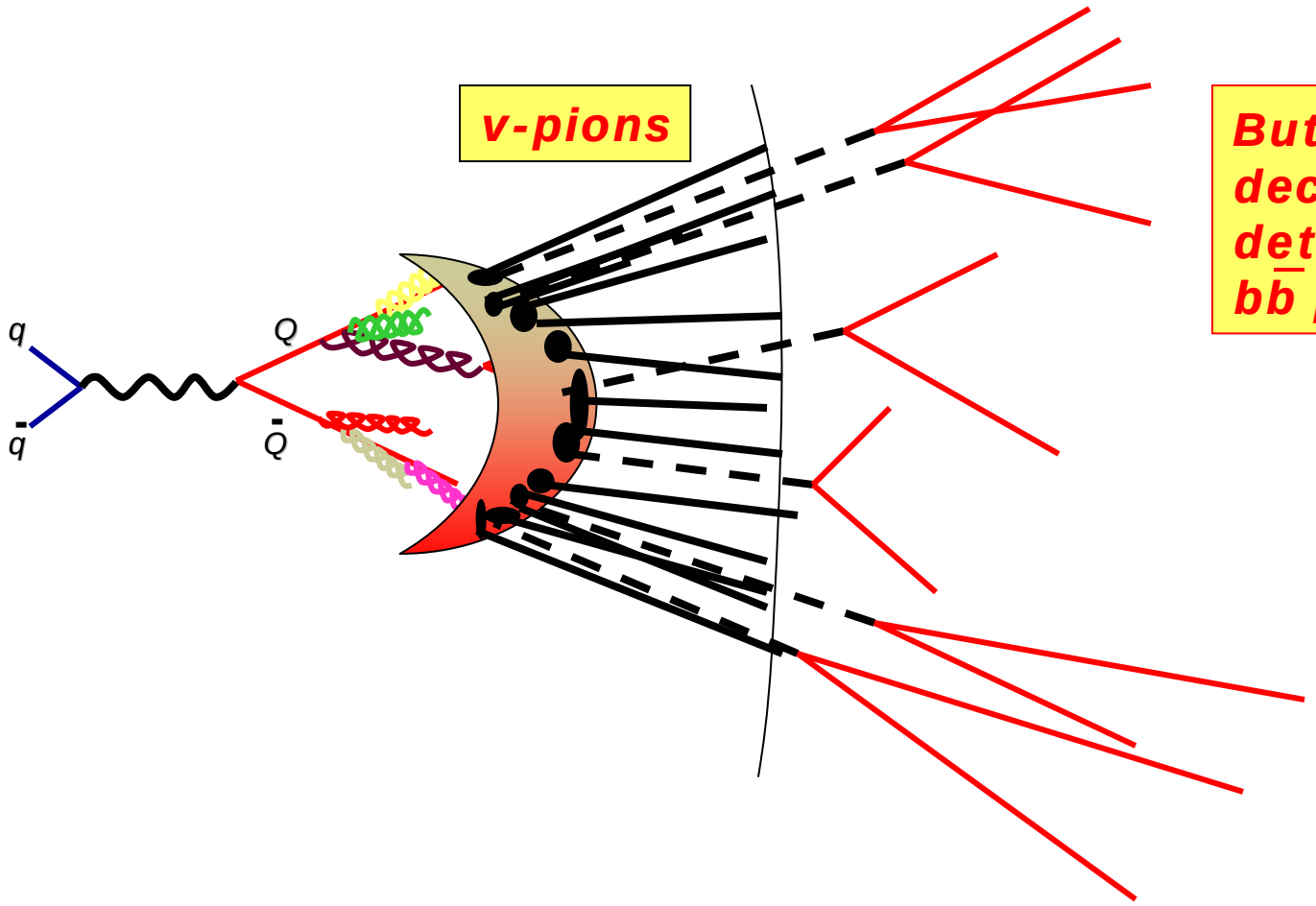
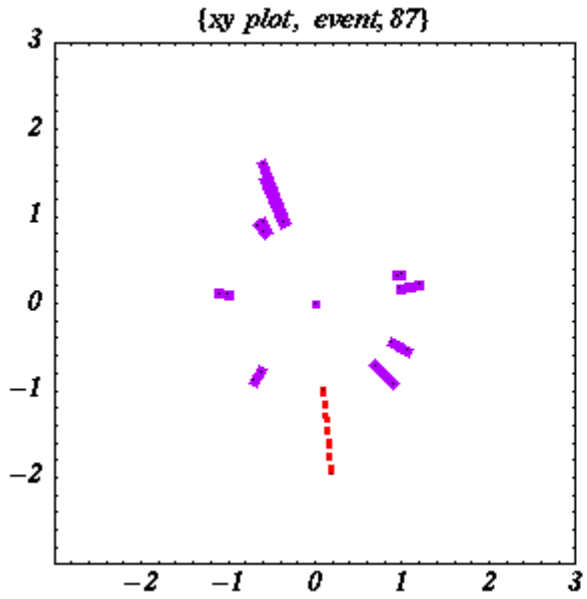
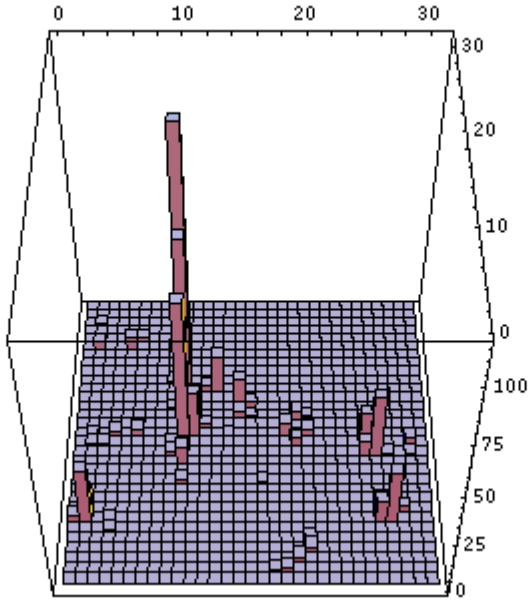
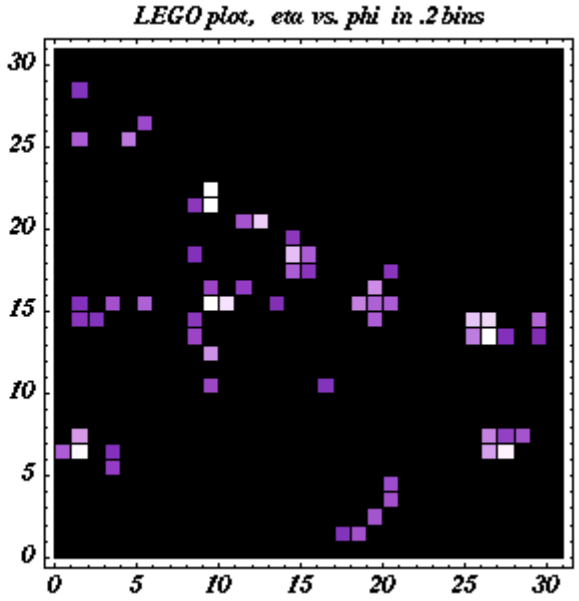


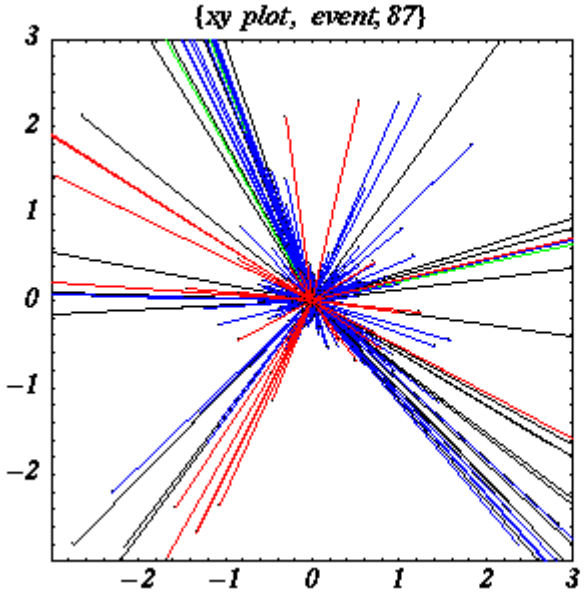
But the π_v^os decay in the detector to $b\bar{b}$ pairs

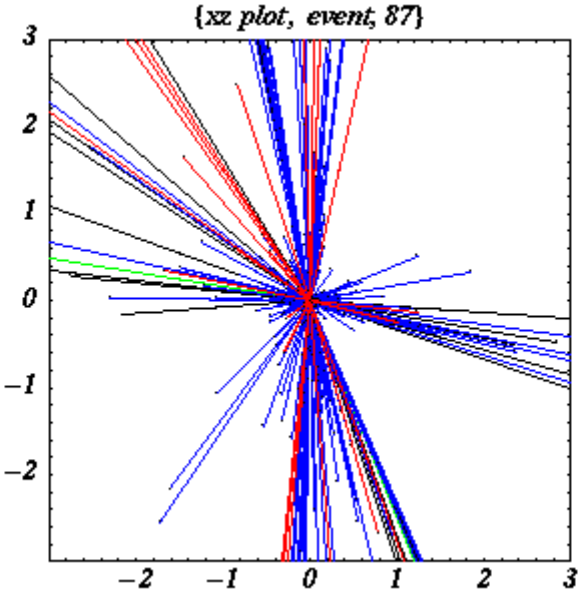
3 TeV Z' → many v-hadrons including 5 π_v^0's *(mass 42 GeV)* → 10 b quarks

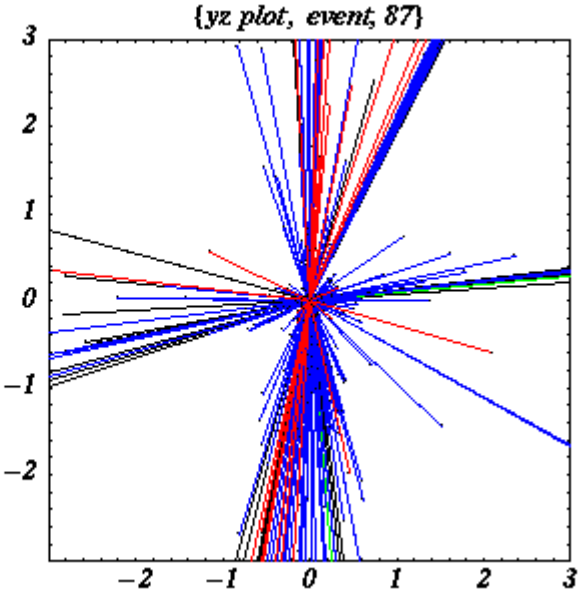












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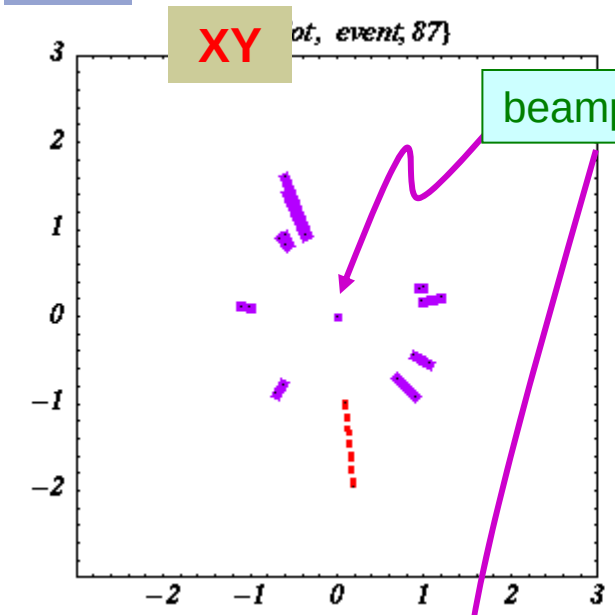
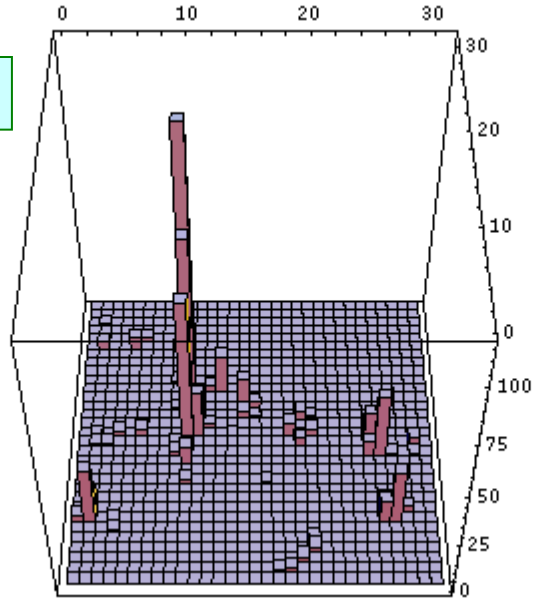
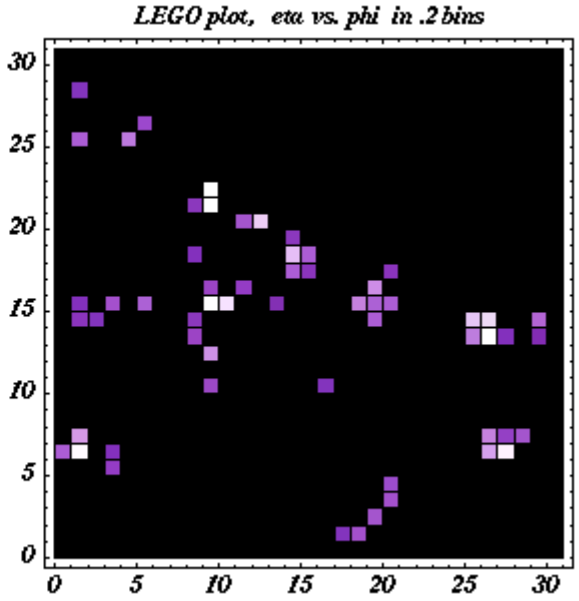
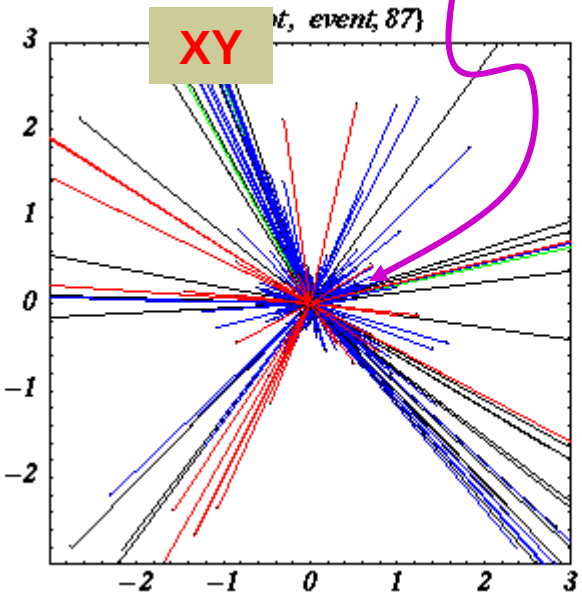
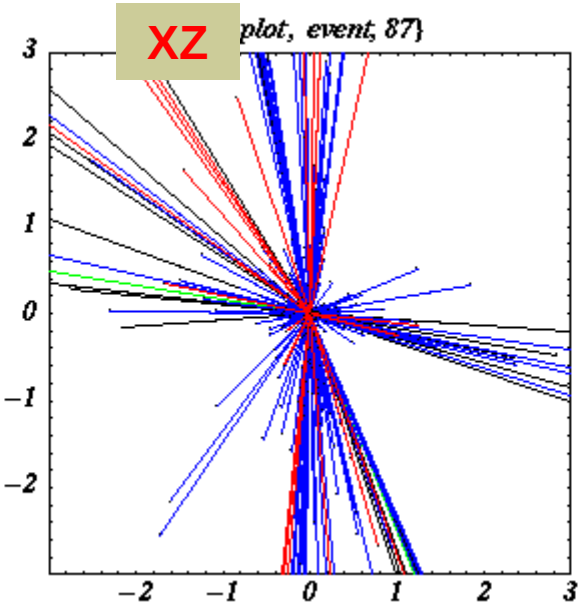
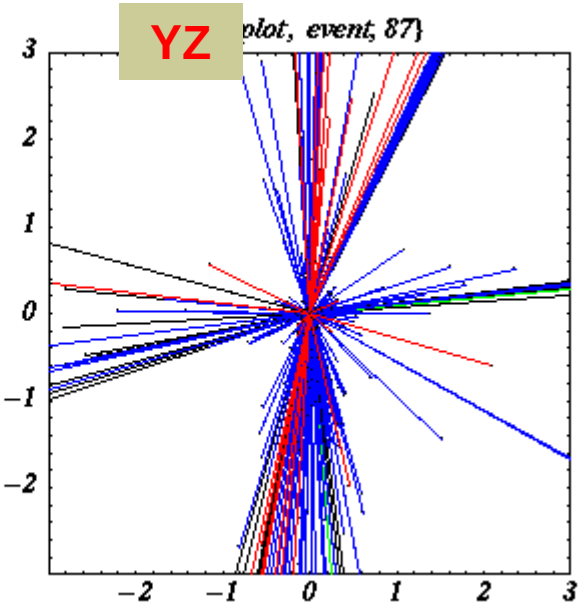






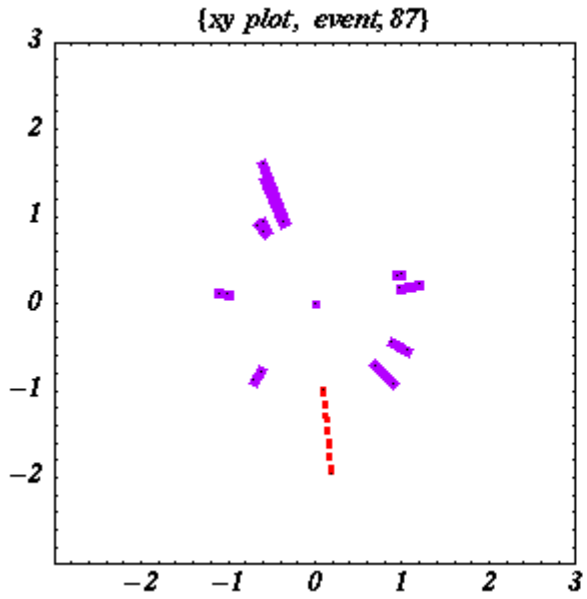


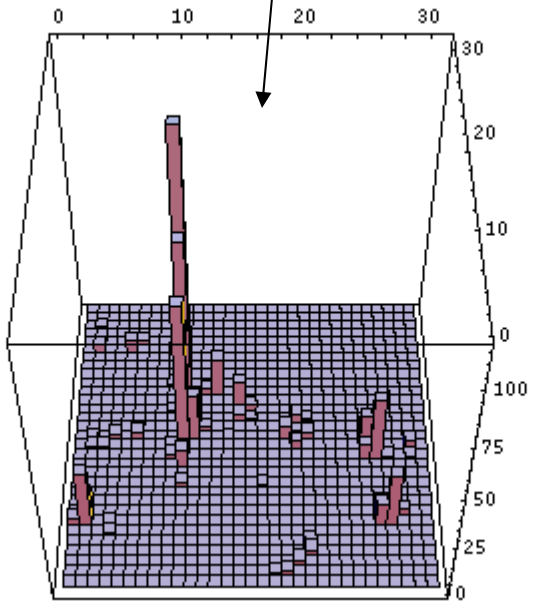


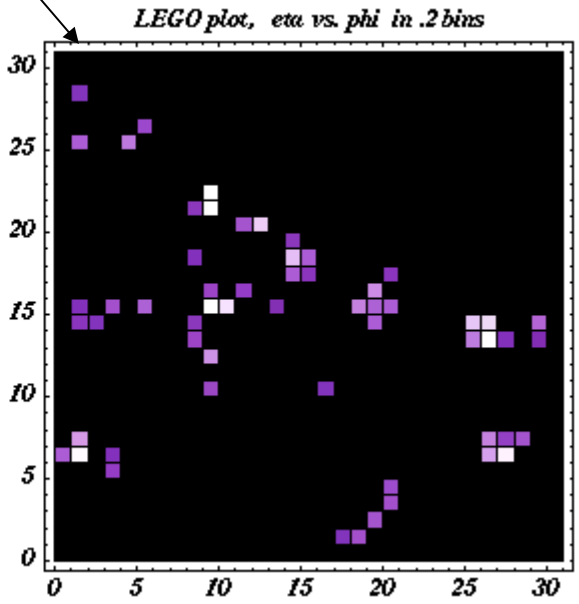


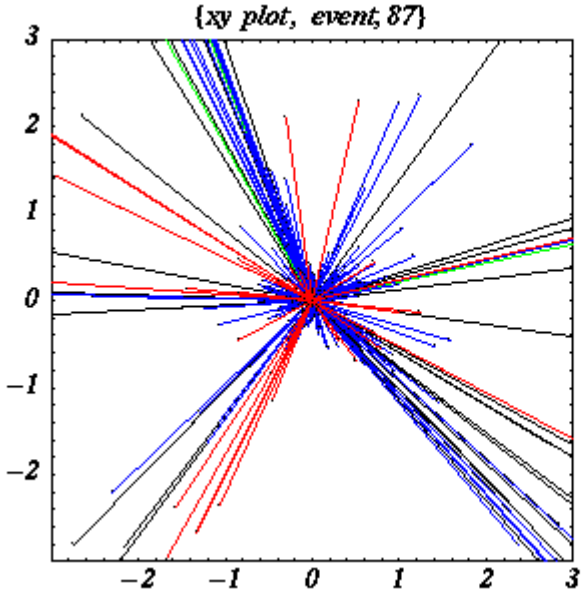
3 TeV Z' → many v-ha

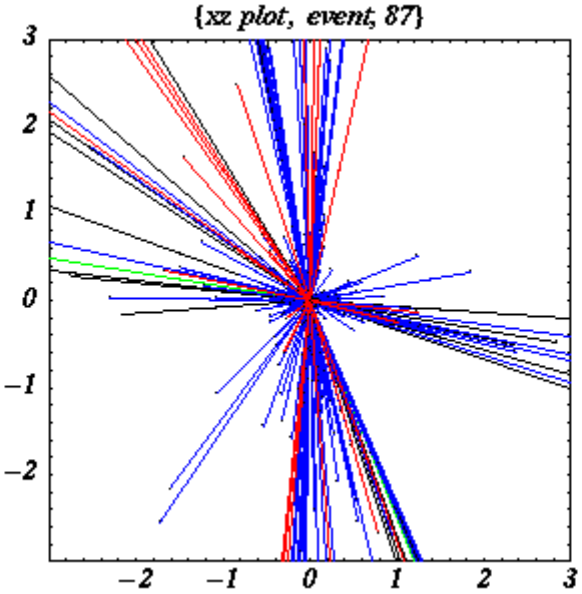
Energy Deposition on "Unwrapped Detector"

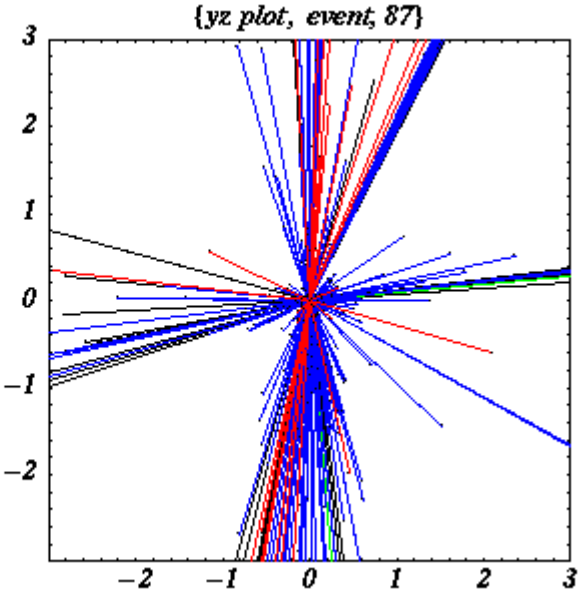








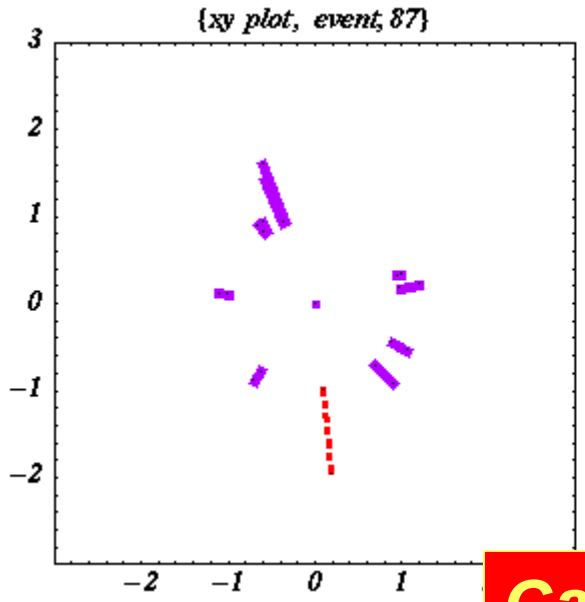


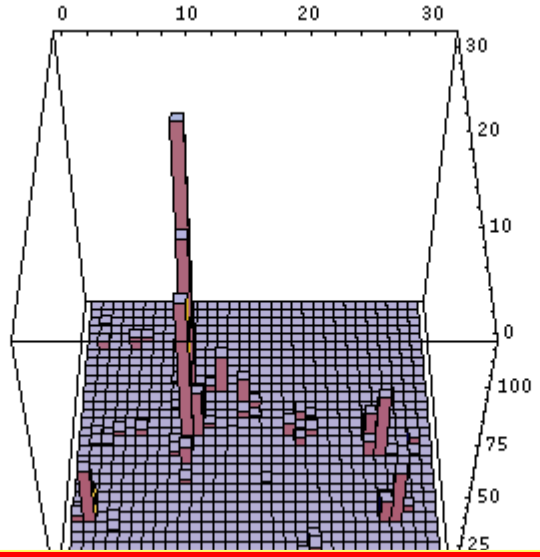


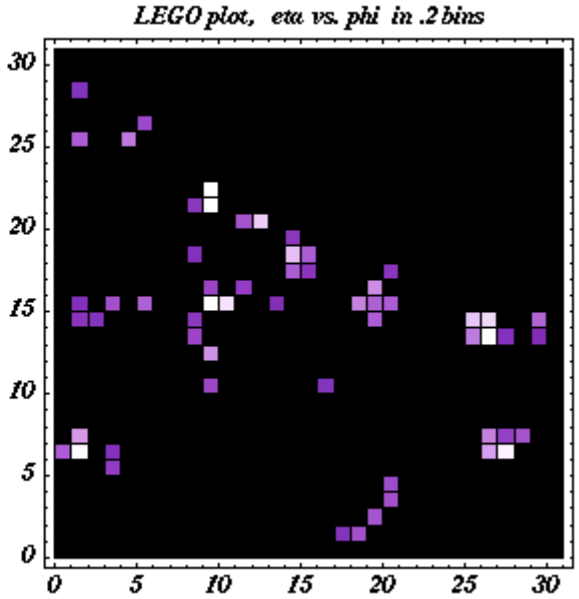
An Event!

- ***An event with many jets, plus possibly large missing energy***
  - A 10-b-plus-missing-energy event! no SM background – *in principle* –
  - But:
    - The event is very complicated, a challenge for tracking and b-tagging
    - The jets tend to overlap, a challenge for jet algorithms
    - It is unlikely that the ten jets of hadrons will be reconstructed
    - It is unlikely that most of the jets will be identified as b-quark jets
  - So it is not clear what “bin” this event will be stored in and what the backgrounds in that bin will be

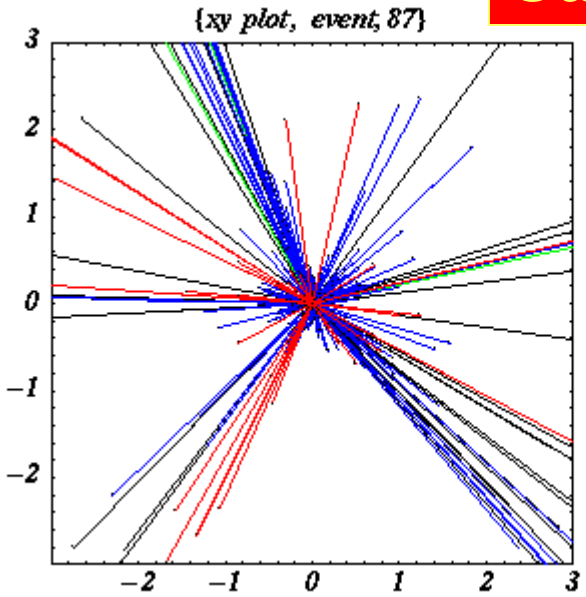
Z' → many v-hadrons including 5 π_v^0's →10 b quarks

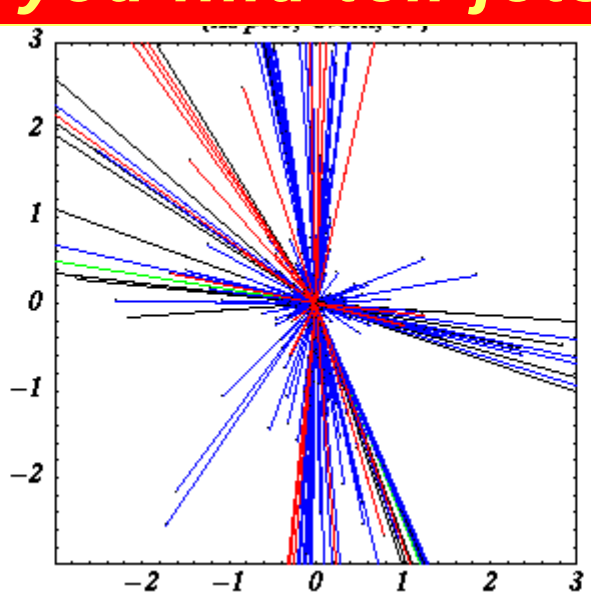


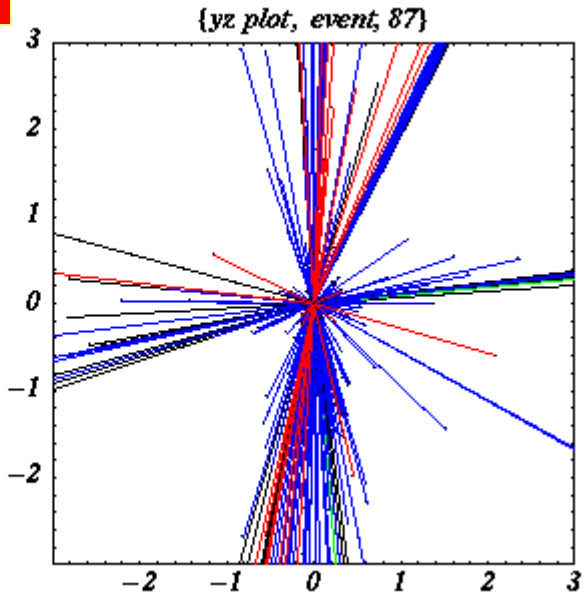




Can you find ten jets?







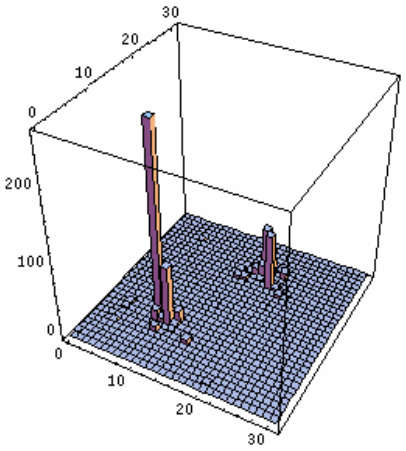
Many Events!

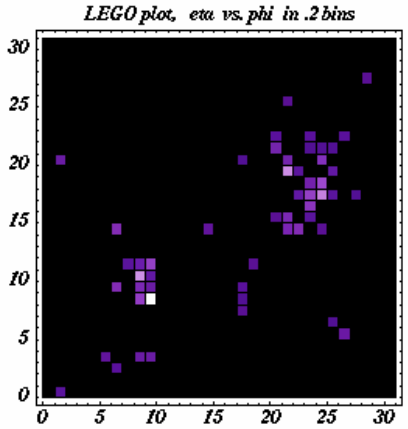
- *But that's not the big problem…*
- **These Z' decays fluctuate wildly**
  - The multiplicity of v-hadrons varies event to event
  - The momentum distribution of the v-hadrons varies
  - The number of π_v^0's versus π_v^+ and π_v^- varies
  - The decay angles of the π_v^0's vary
  - The b-jets also vary in their QCD-pion multiplicity
  - Occasional τ pairs, c-jets
- So events will be stored in many different bins:
  hard to reassemble into a signal, remove background, interpret

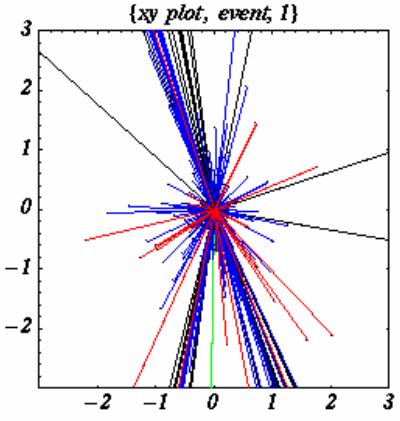
Many Events!

- Let's see these fluctuations in action:
  - use a well-understood computer program (PYTHIA) to simulate e^+e^- → hadrons
  - rescale the energies to simulate $q\ q$ → v-hadrons
  - let the π_v^0's decay to b quark pairs, and
  - let the b quark pairs form jets

- ***Remember:* every event below is a *Z' decay to v-quarks***

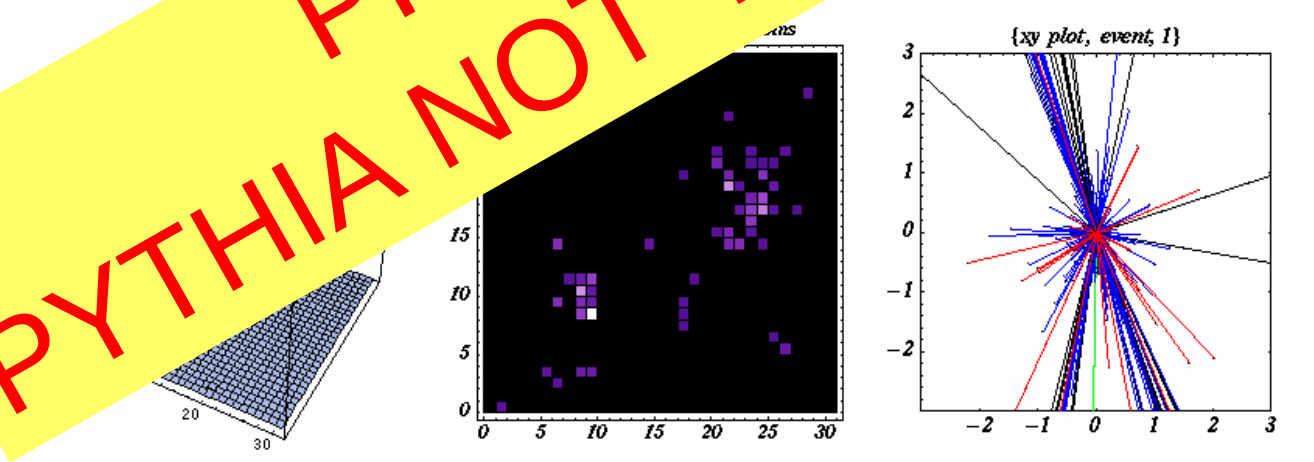




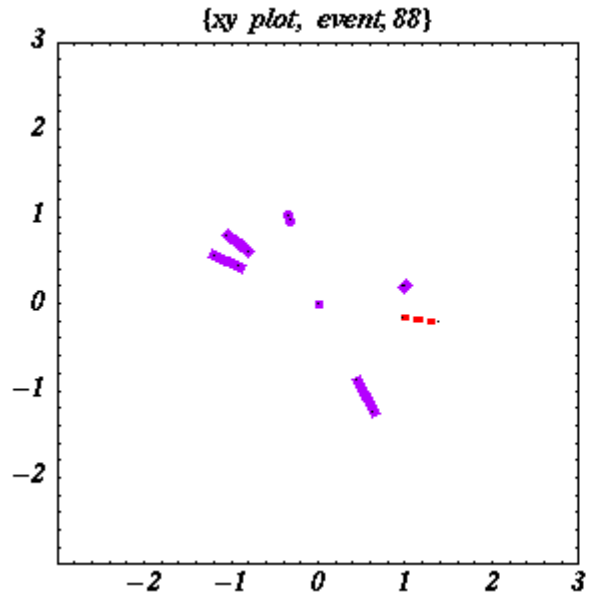


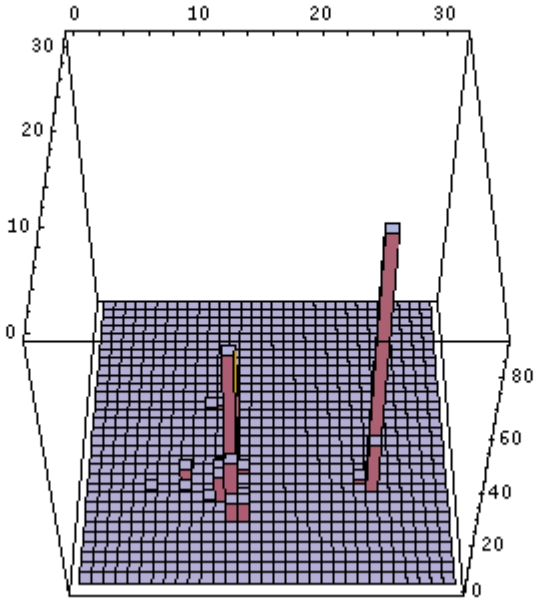
Many Events!

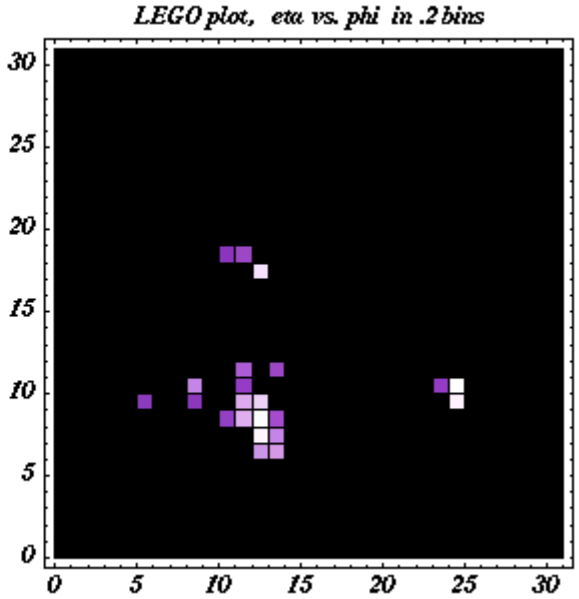
- Let's see these fluctuations in action:
  - use a well-understood computer program (P
  - rescale the energies to simulate $q\,q$ →
  - let the π_v^0's decay to b quark pair
  - let the b quark pairs form jet
- ***Remember:* every ev** ***KS***

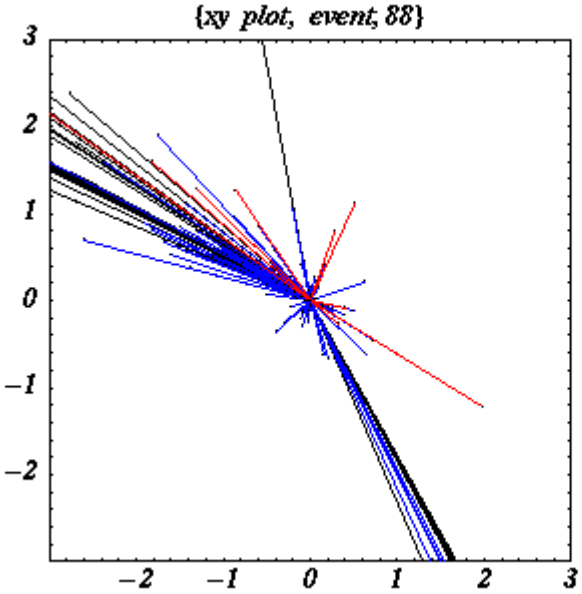


6 b quarks


{xy plot, event, 88}




LEGO plot, eta vs. phi in .2 bins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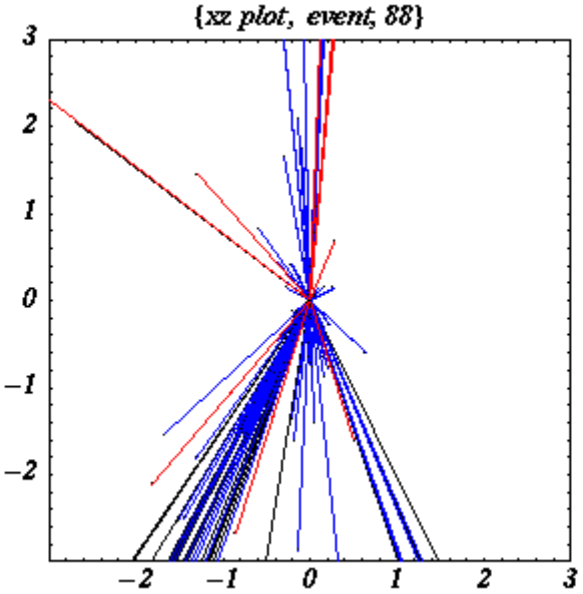
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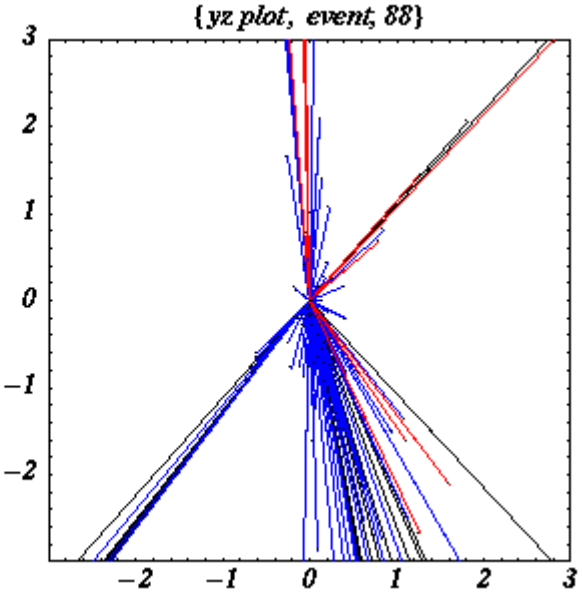
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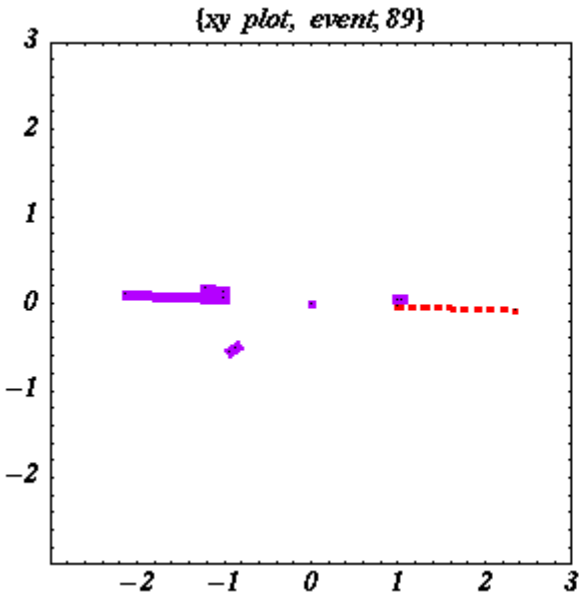
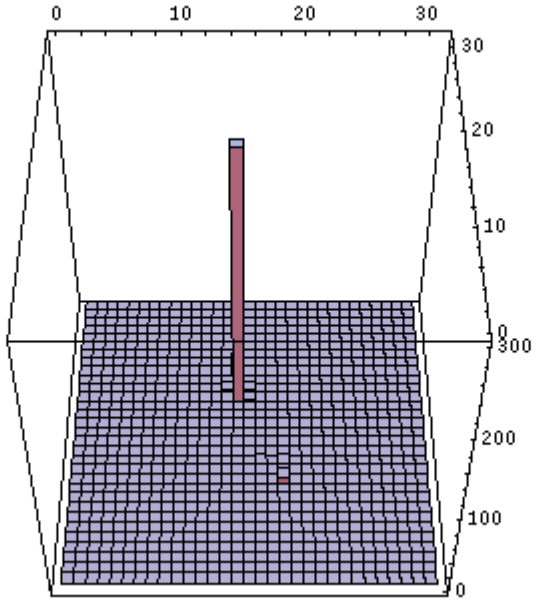
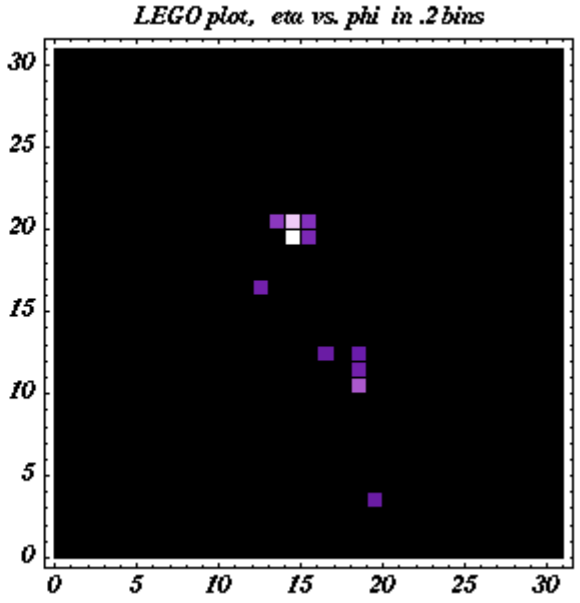
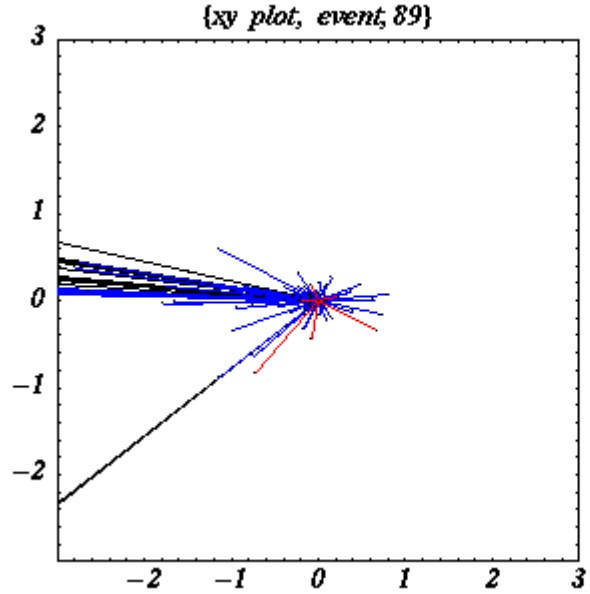
4 b quarks


{xy plot, event, 89}




LEGO plot, eta vs. phi in .2 bins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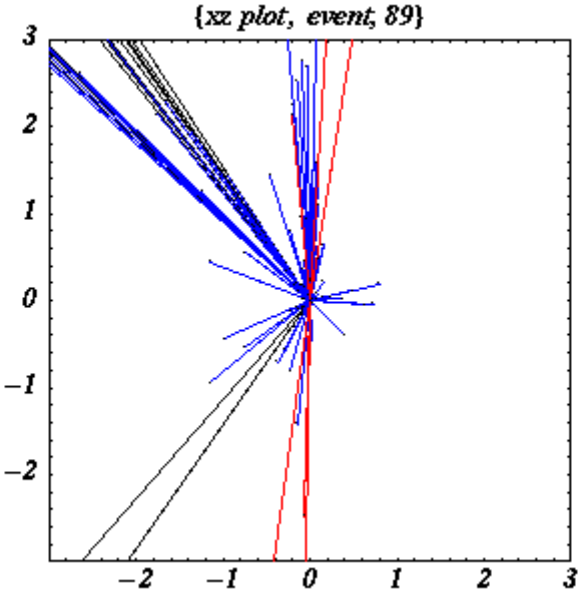
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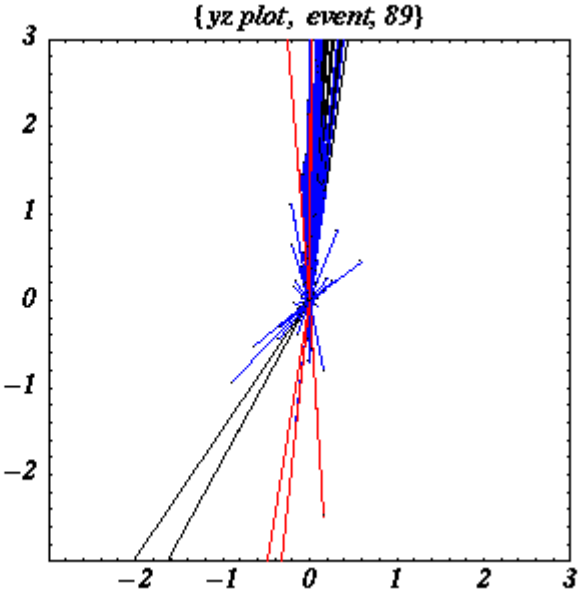
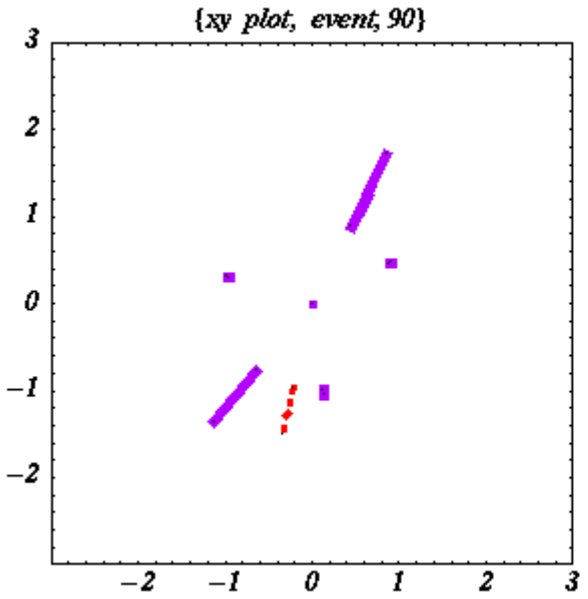

{yz plot, event, 89}

6 b quarks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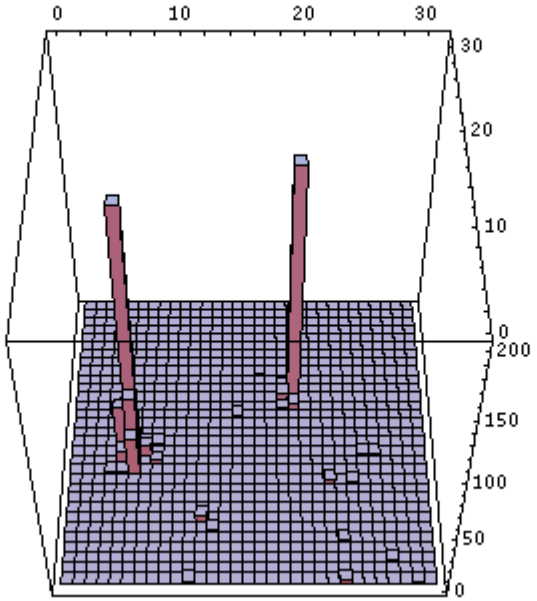
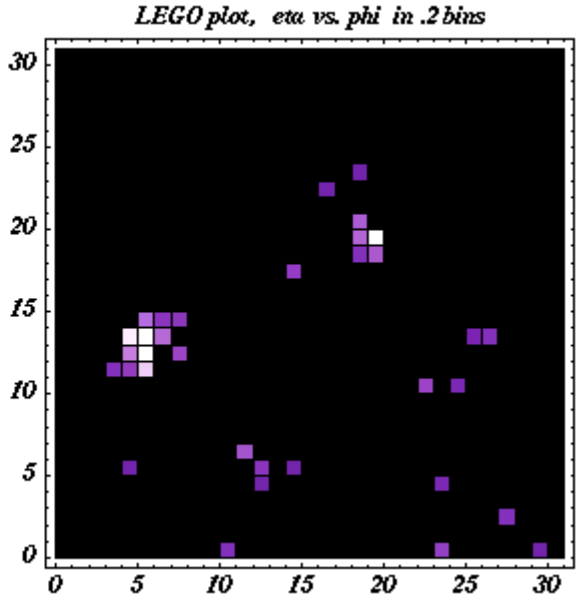
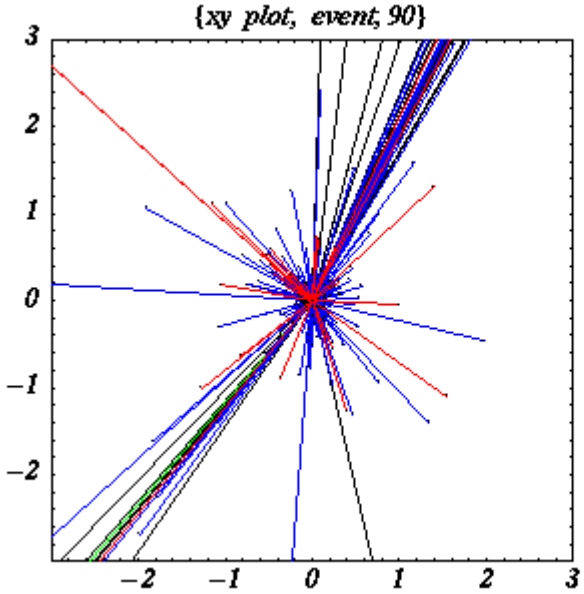



LEGO plot, eta vs. phi in .2 bins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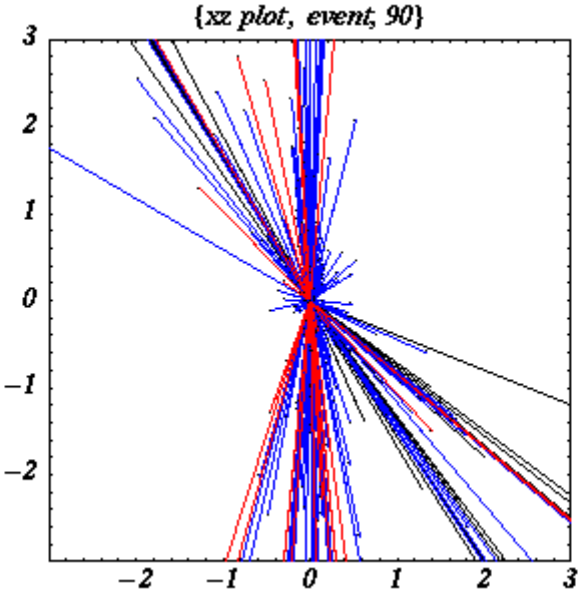
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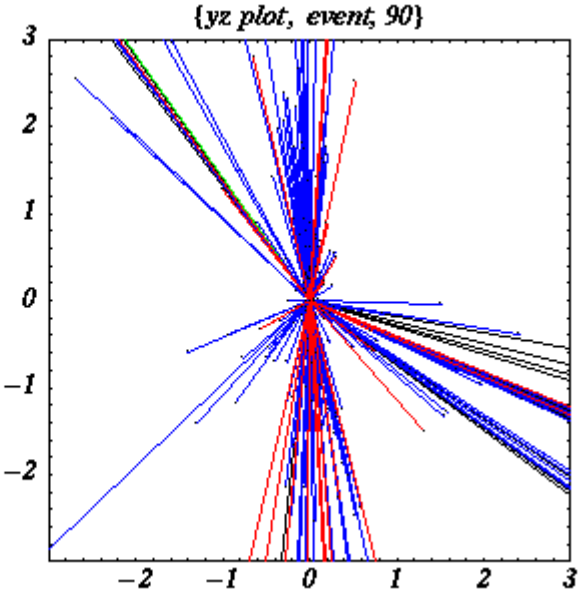
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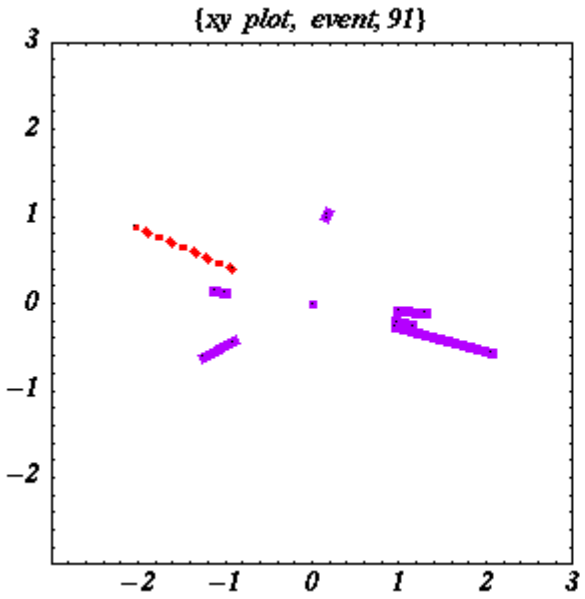
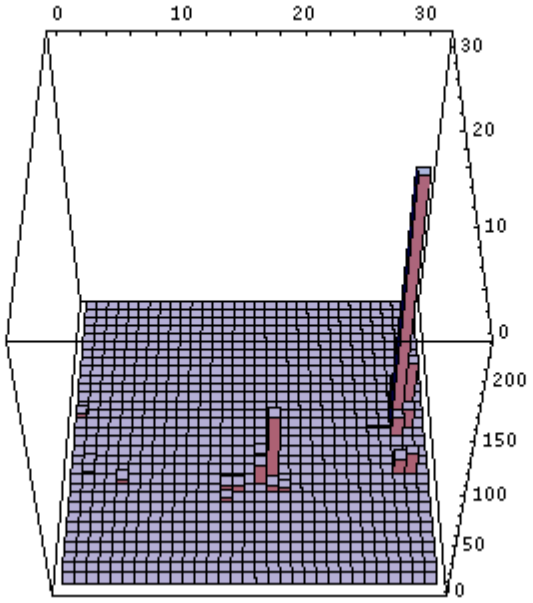
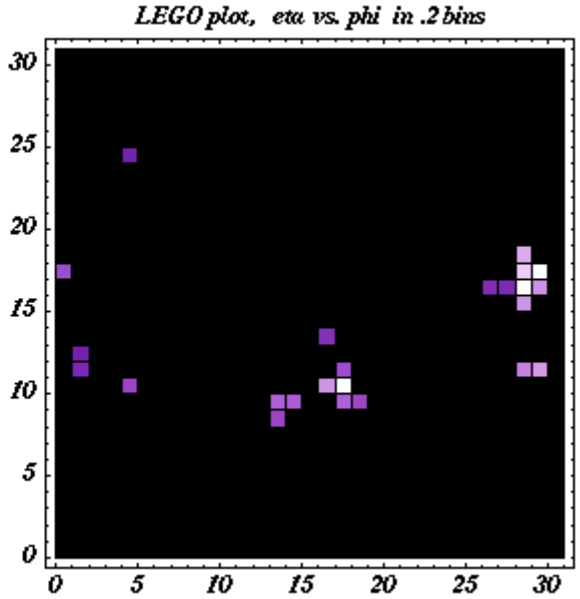
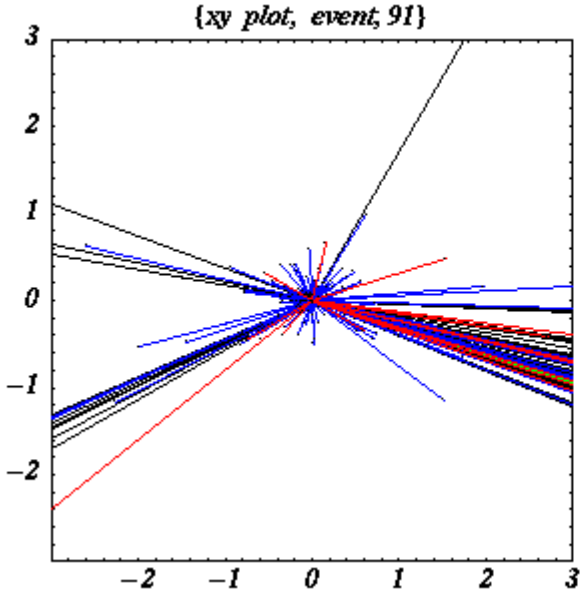
6 b quarks


{xy plot, event, 91}




LEGO plot, eta vs. phi in .2 bins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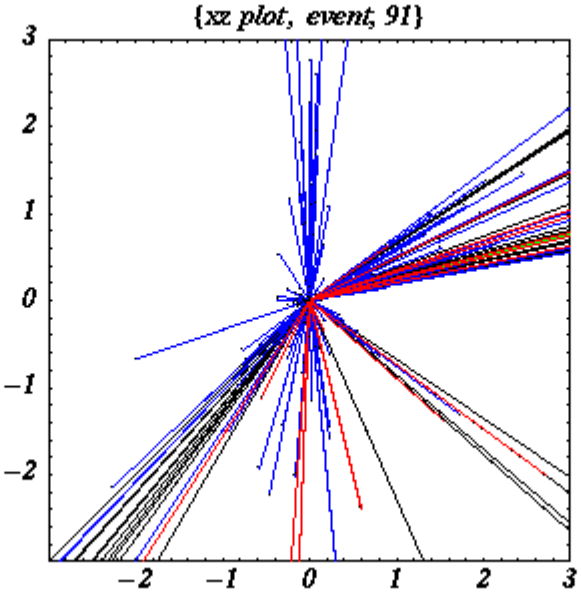
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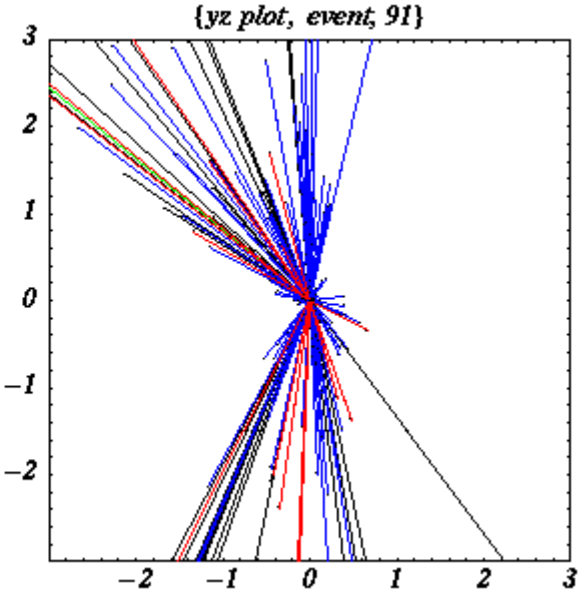
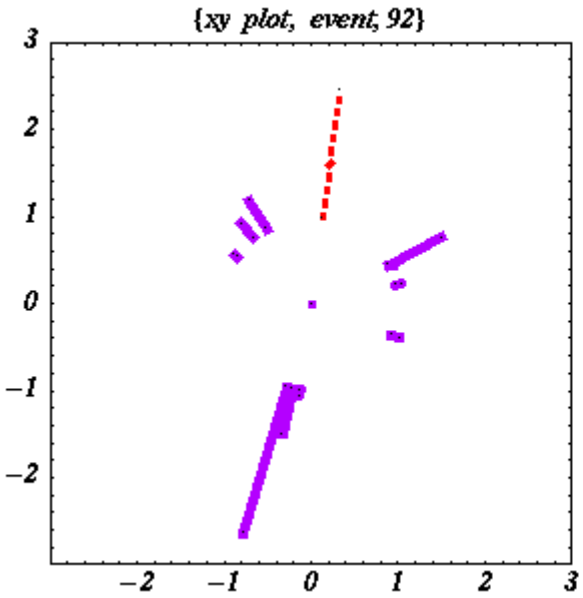

{yz plot, event, 91}

10 b quarks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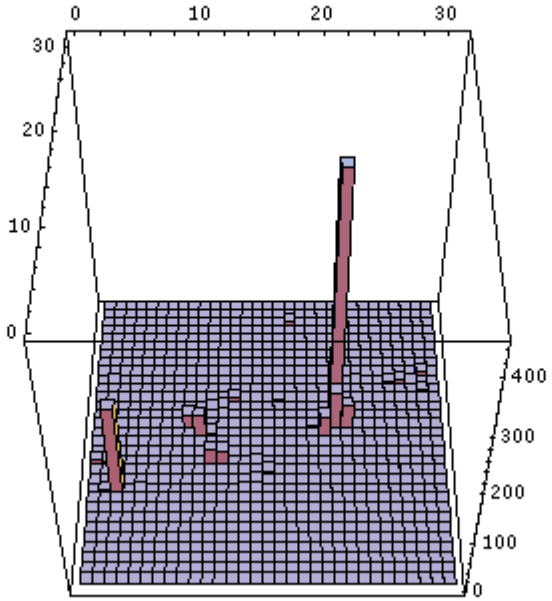
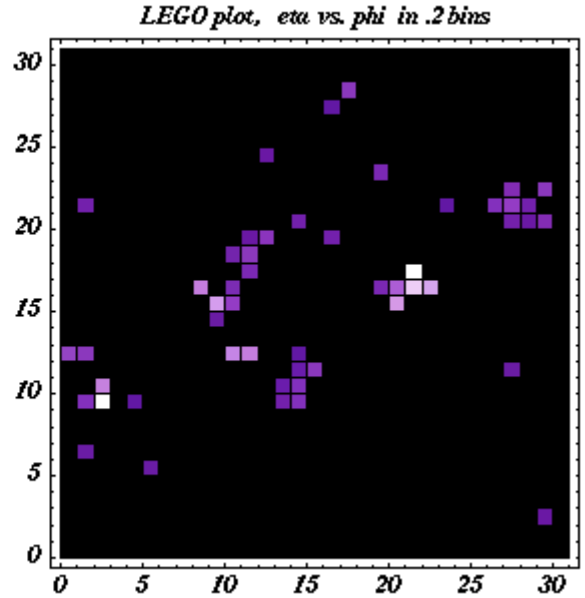
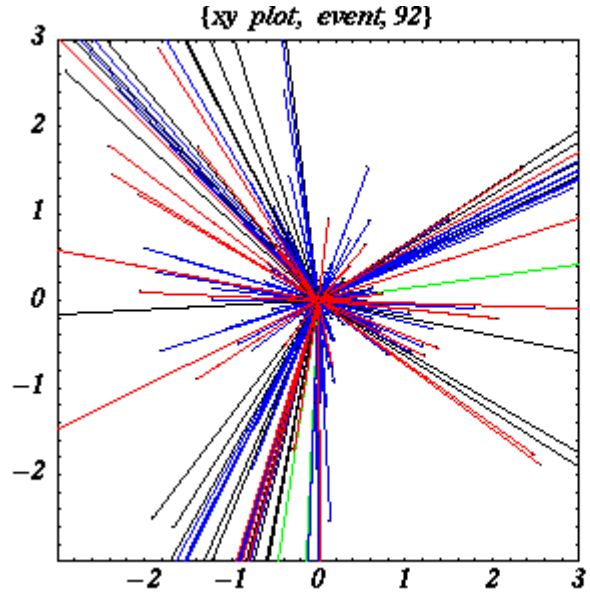



LEGO plot, eta vs. phi in .2 bins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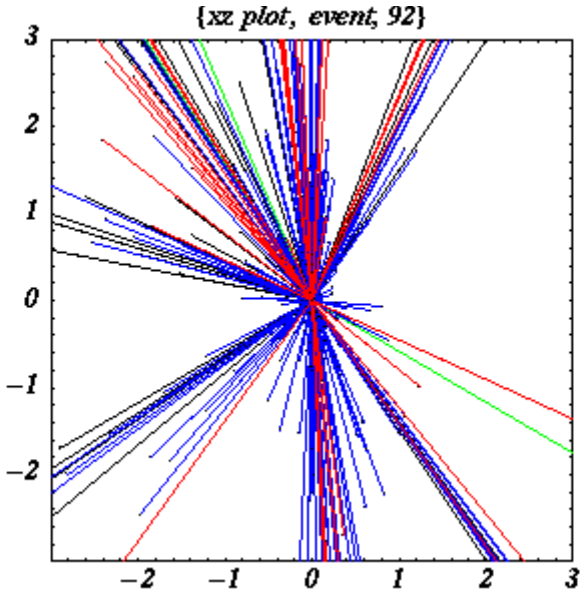
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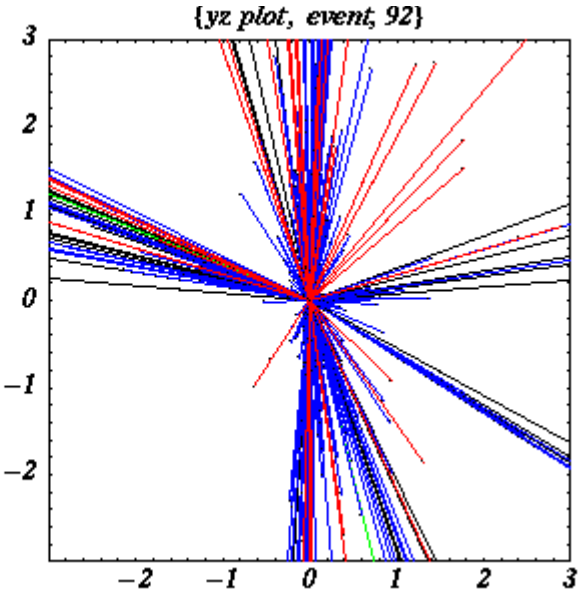
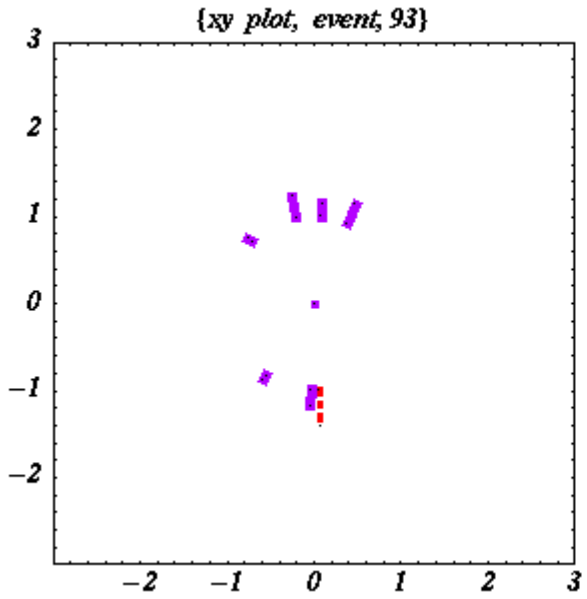
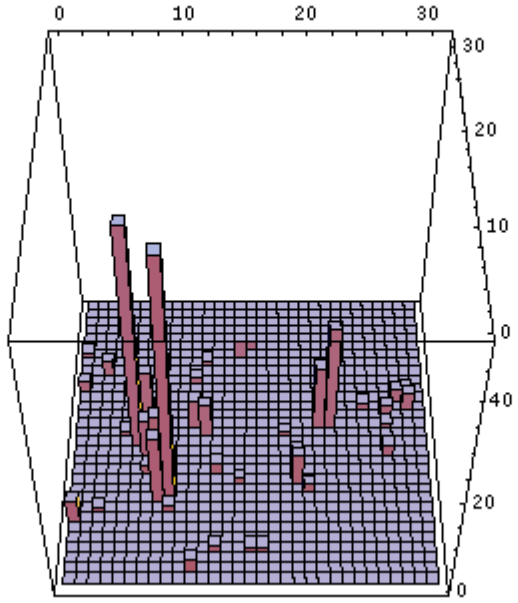
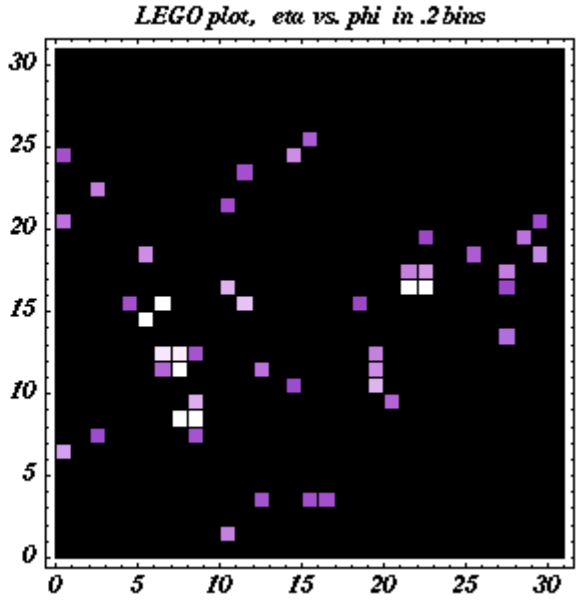
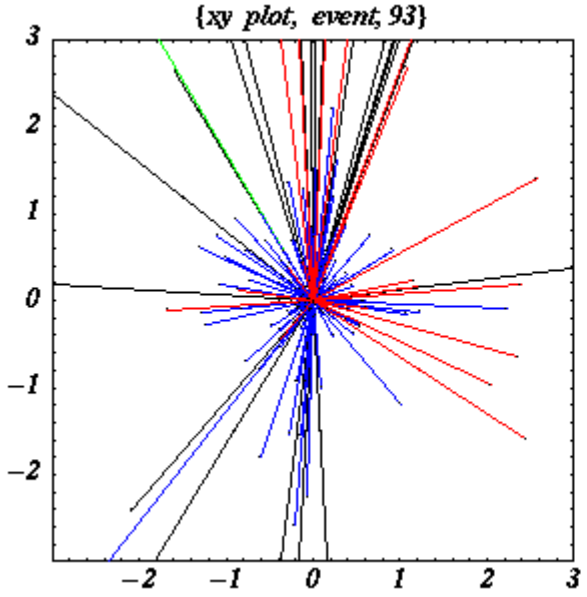

{yz plot, event, 92}

6 b quarks


{xy plot, event, 93}




LEGO plot, eta vs. phi in .2 bins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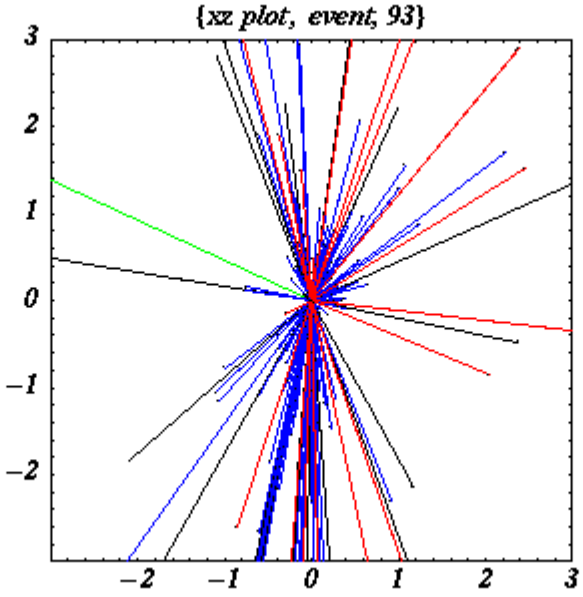
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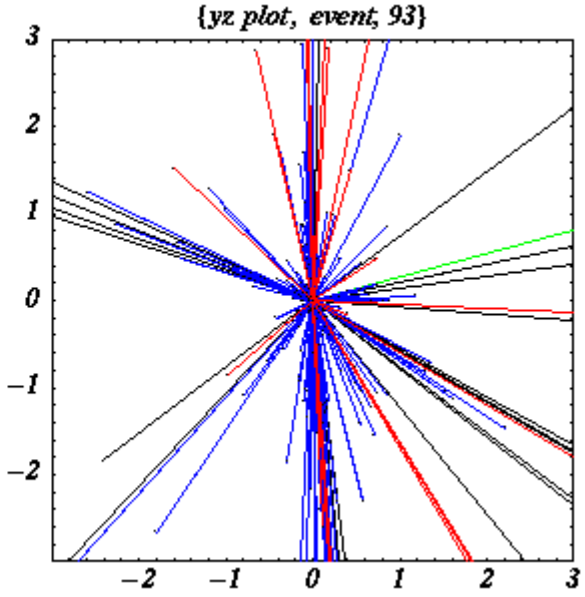
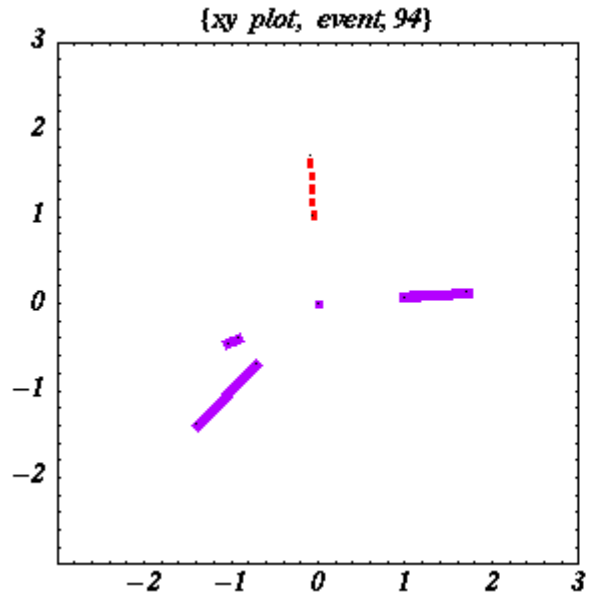

{yz plot, event, 93}

4 b quarks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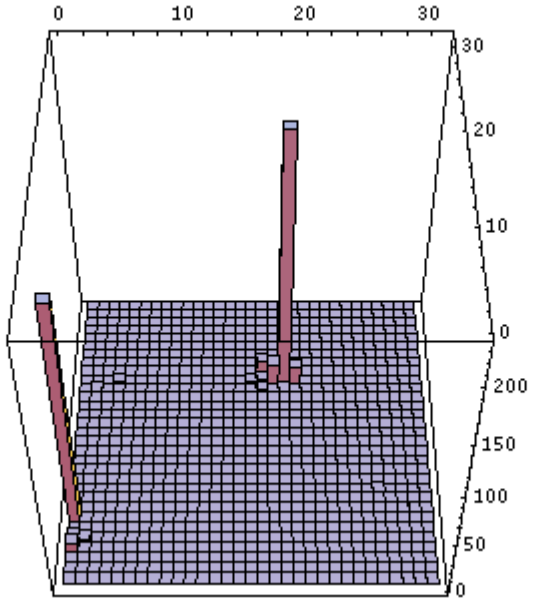
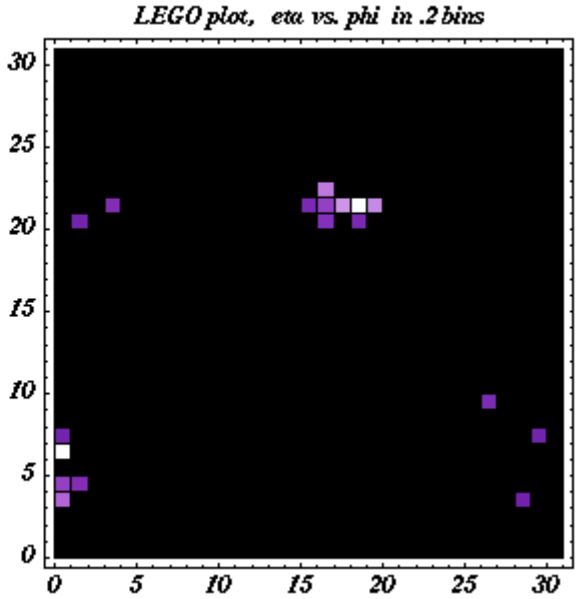
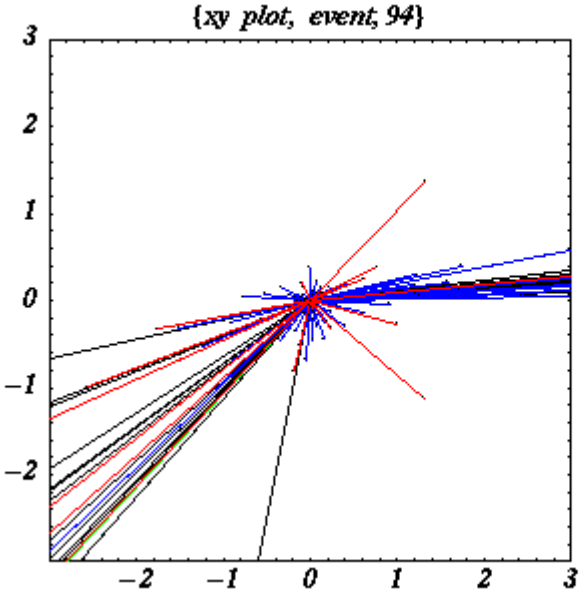



LEGO plot, eta vs. phi in .2 bins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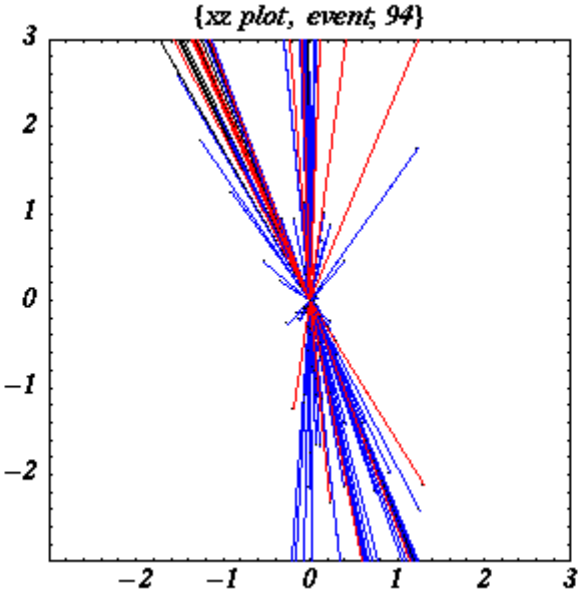
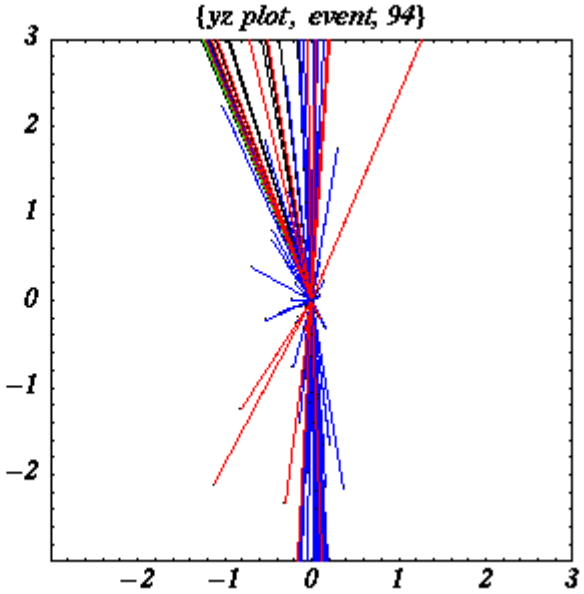
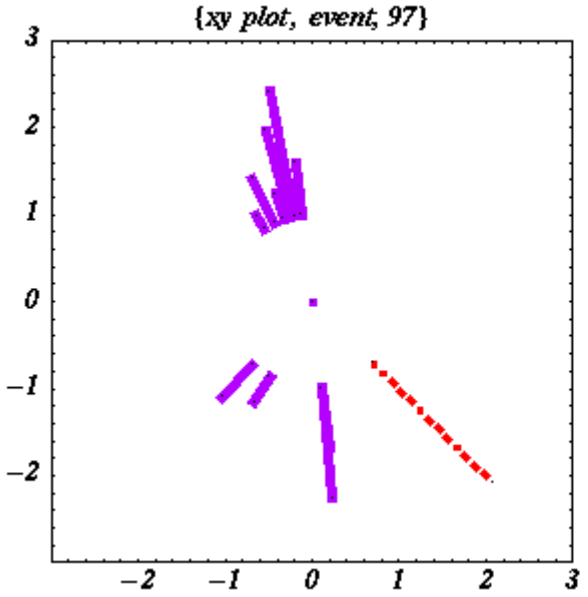

{xz plot, event, 94}


{yz plot, event, 94}

10 b quarks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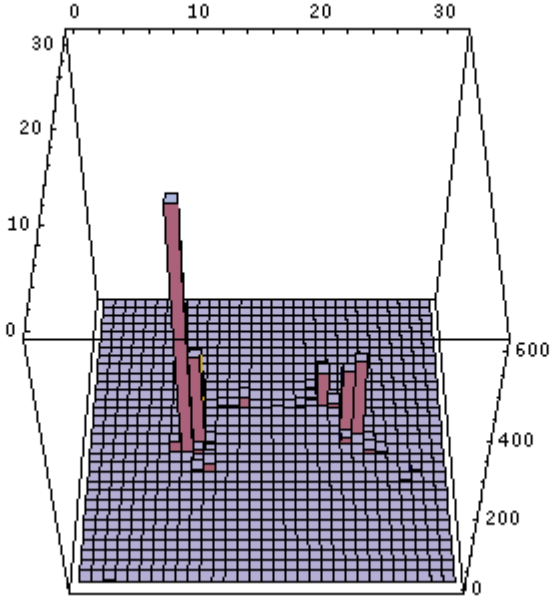
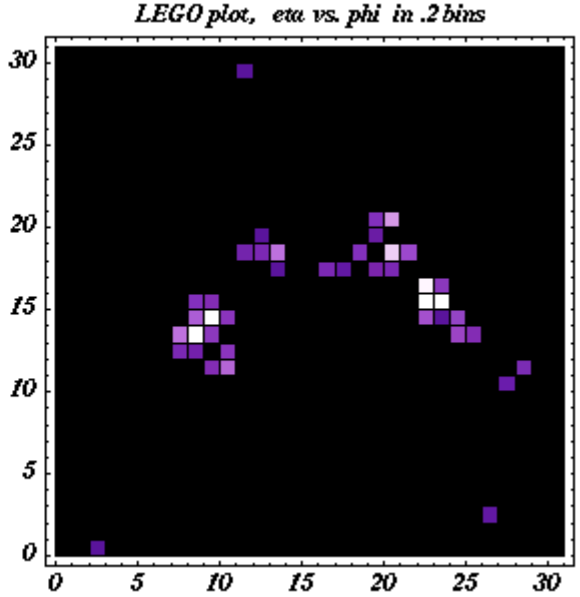
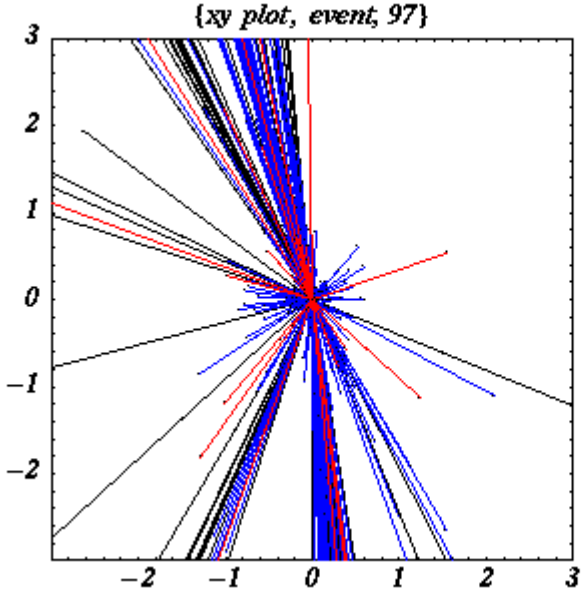



LEGO plot, eta vs. phi in .2 bins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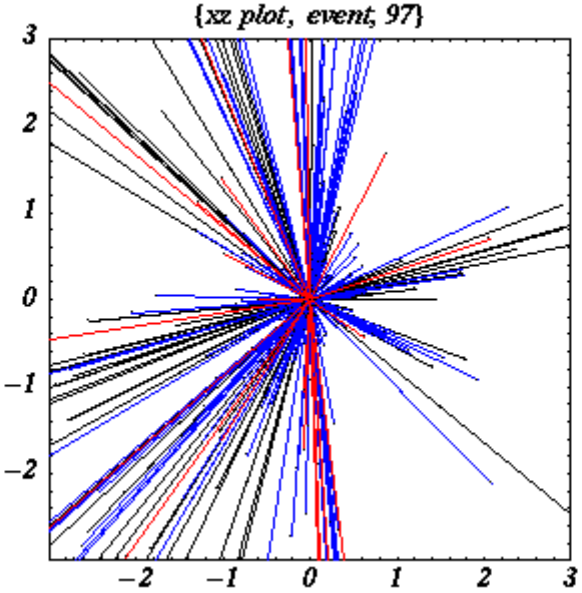
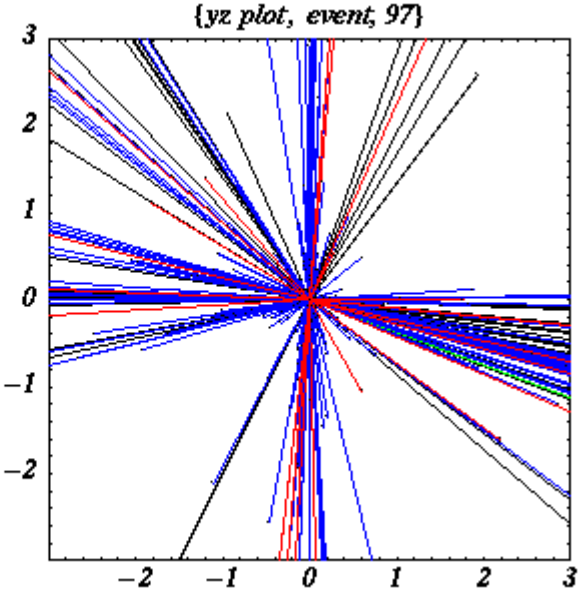
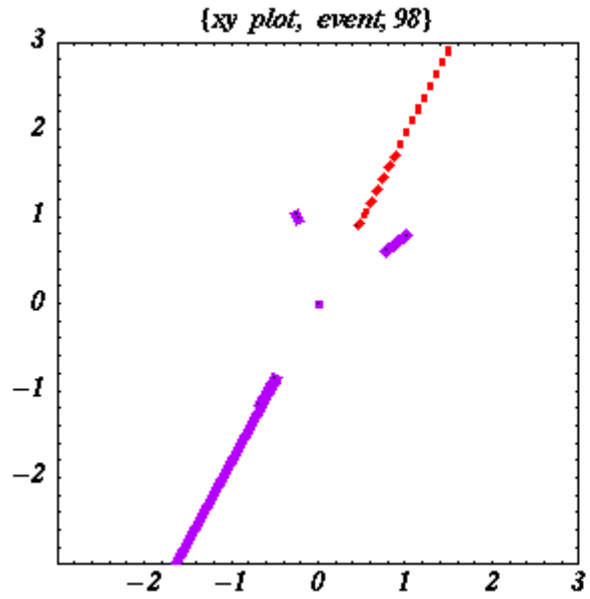
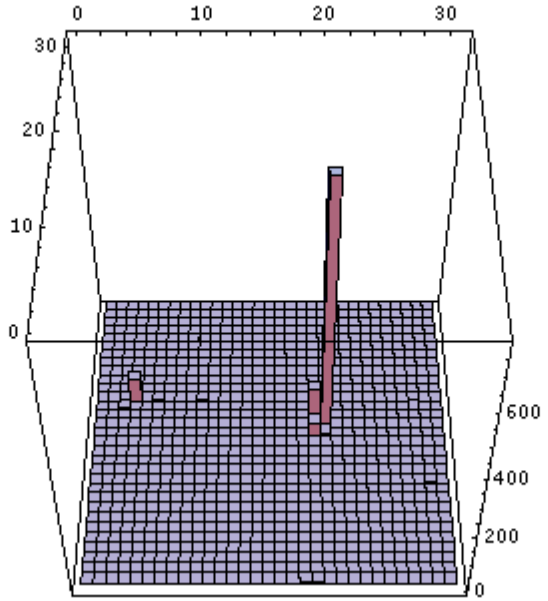
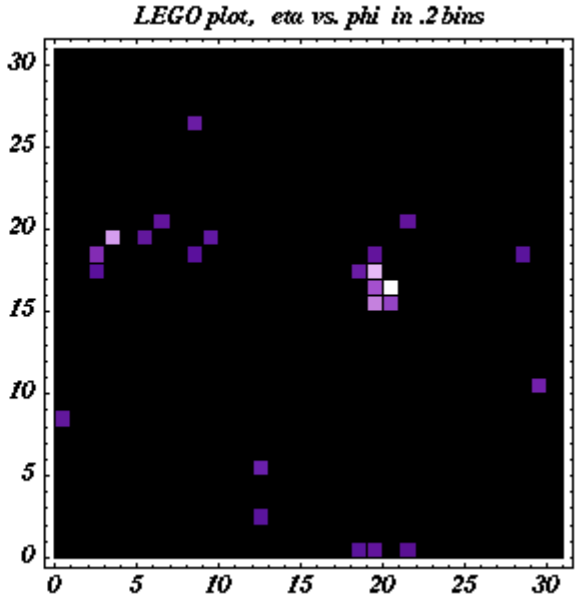

{xz plot, event, 97}

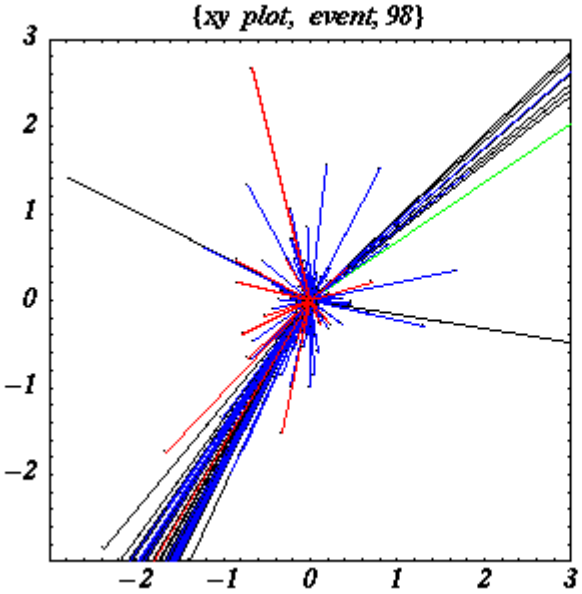

{yz plot, event, 97}

4 b quarks


{xy plot, event, 98}




LEGO plot, eta vs. phi in .2 bins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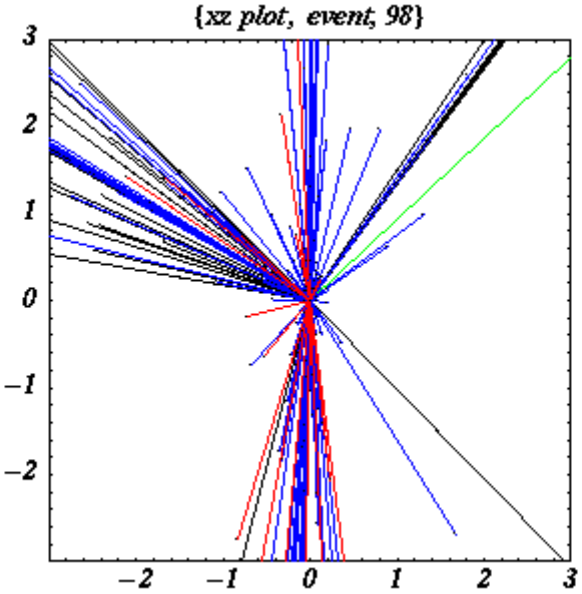
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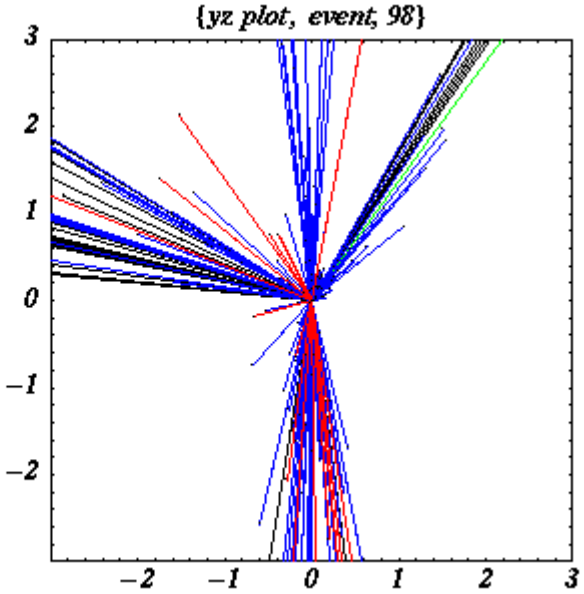
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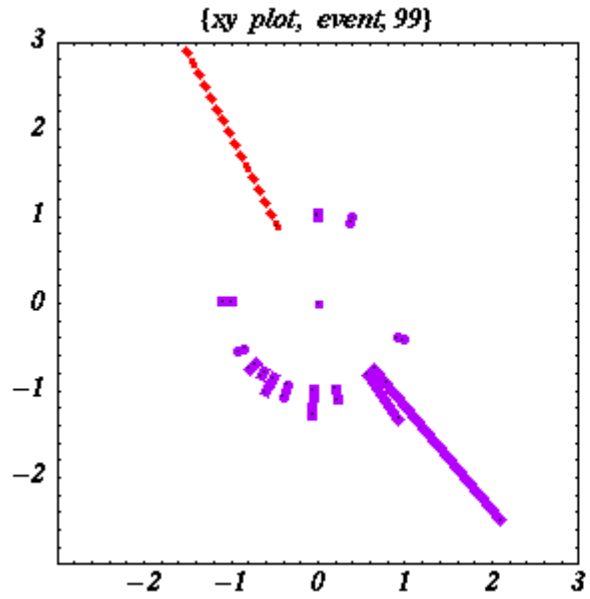
14 b quarks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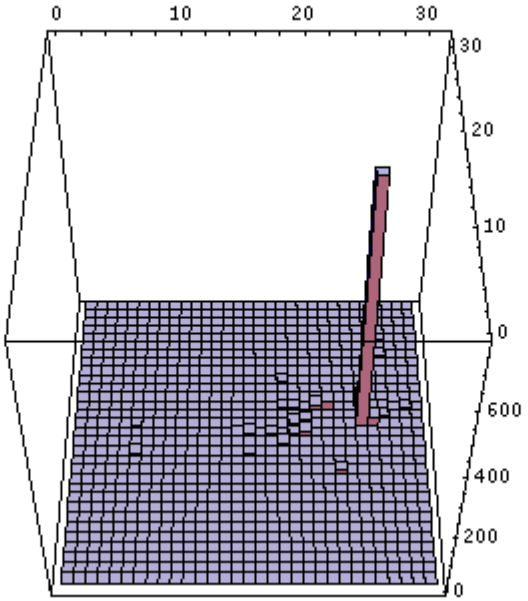
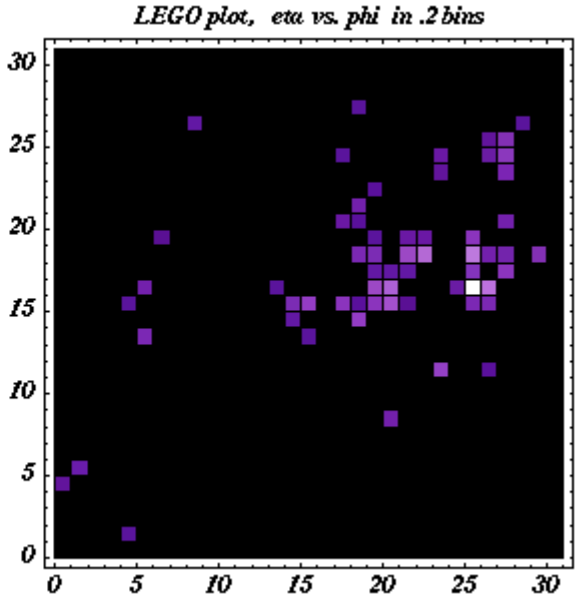
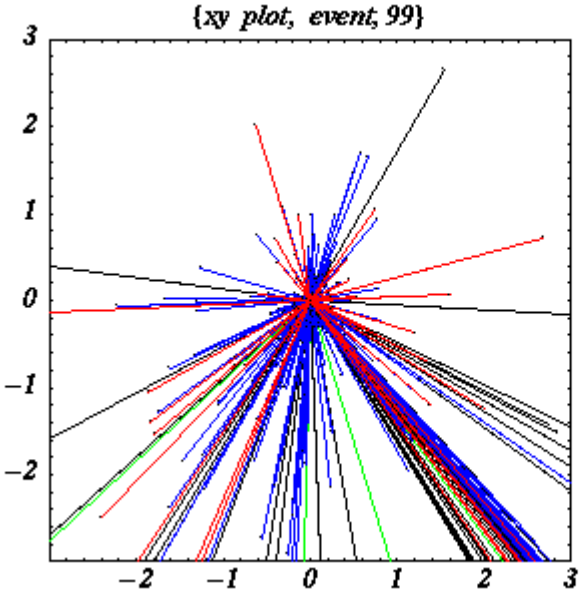



LEGO plot, eta vs. phi in .2 bins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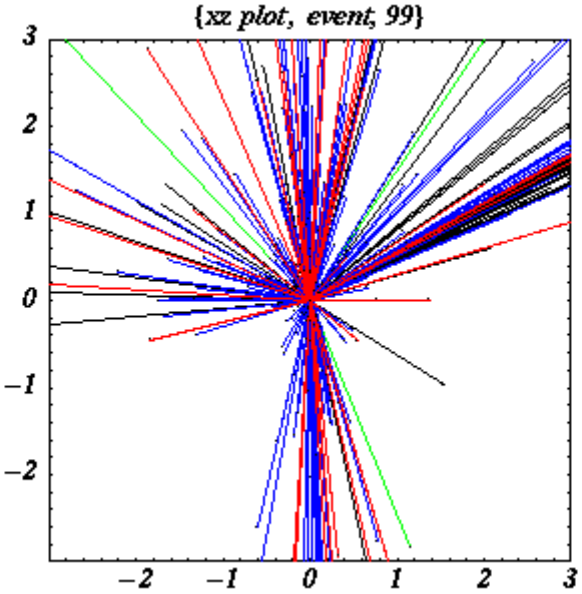
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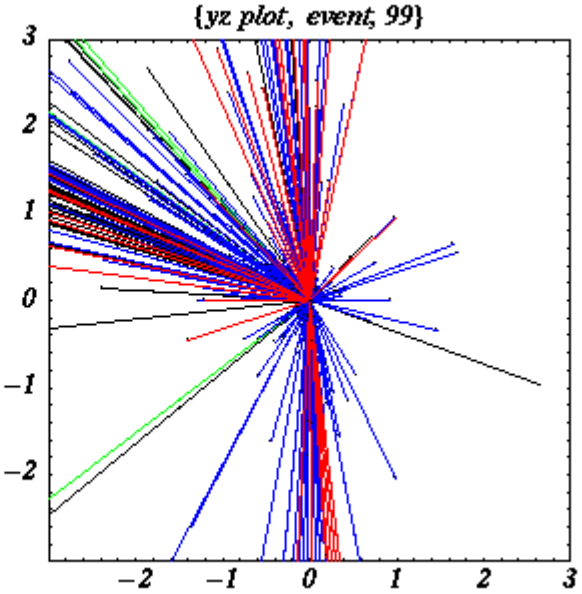

{yz plot, event, 99}

QCD backgrounds

- **Can this signal be identified?**
  - If there were a hundred events of this form [lower energy than simulated] at the Tevatron, would we currently know it?
  - If there are a hundred events per year at the LHC, will we know it?
- Signal is complex, backgrounds are unknown
  - Few-jet backgrounds computable but signal is not straightforward
    - The many jets overlap; how many jets are actually reconstructed?
    - What is the correspondence between jets reconstructed and the b-quarks produced?
    - How much do the answers depend on the algorithm used?
  - Multi-jet backgrounds not computable
    - Can we tell the difference on average between a QCD multi-jet event and a hidden-valley-type multi-jet event?
- **What is the right approach to separating the signal from background?**
- **Ideas exist, but detailed study needed!**

Lifetimes

- The v-hadrons decay to standard model particles by tunneling through the mountain
- *More precisely, a heavy particle mediates their decays*
- **Therefore – no surprise -- these particles have long lifetimes**
- Since
  - There are many v-hadrons, with different lifetimes, in a generic model
  - Many v-hadrons are produced in each event

  there is a significant probability of seeing one or more decays occurring away from the interaction vertex.

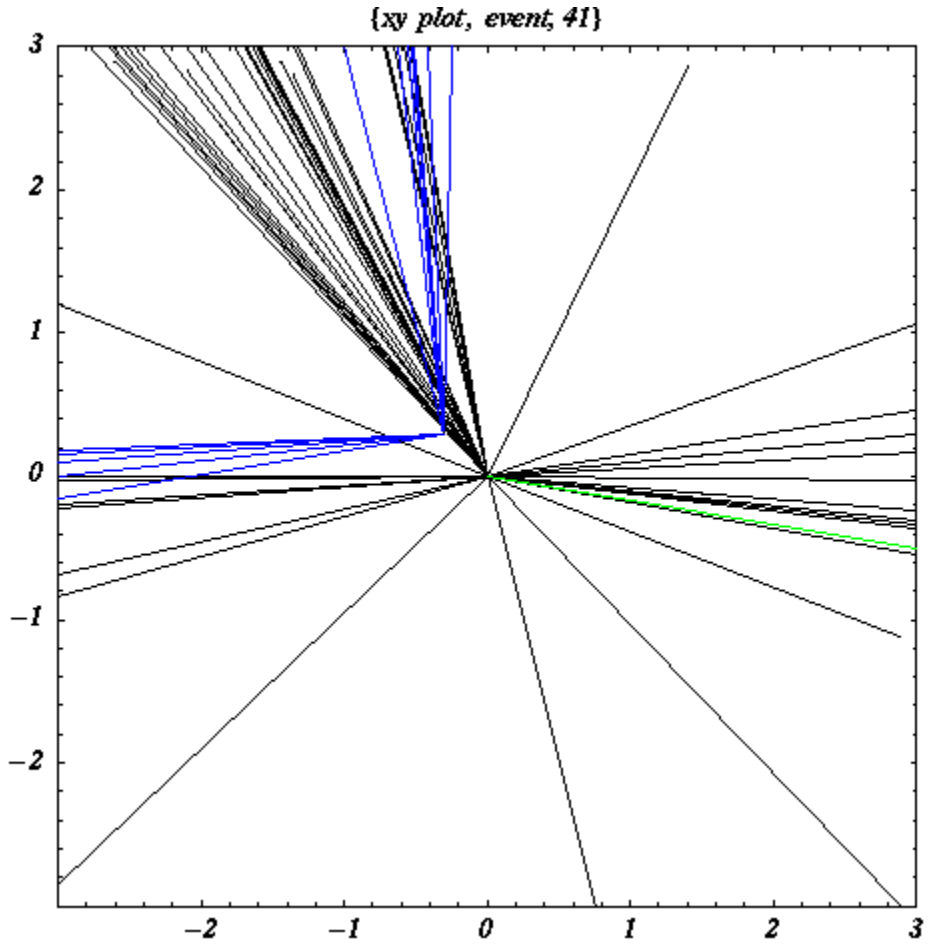
- For example, in the two-flavor v-QCD case,

$$\Gamma_{\pi_v \to b\bar{b}} \sim 6 \times 10^9 \text{ sec}^{-1} \frac{f_{\pi_v}^2 m_{\pi_v}^5}{(20 \text{ GeV})^7} \left(\frac{10 \text{ TeV}}{m_{Z'}/g'} \right)^4$$

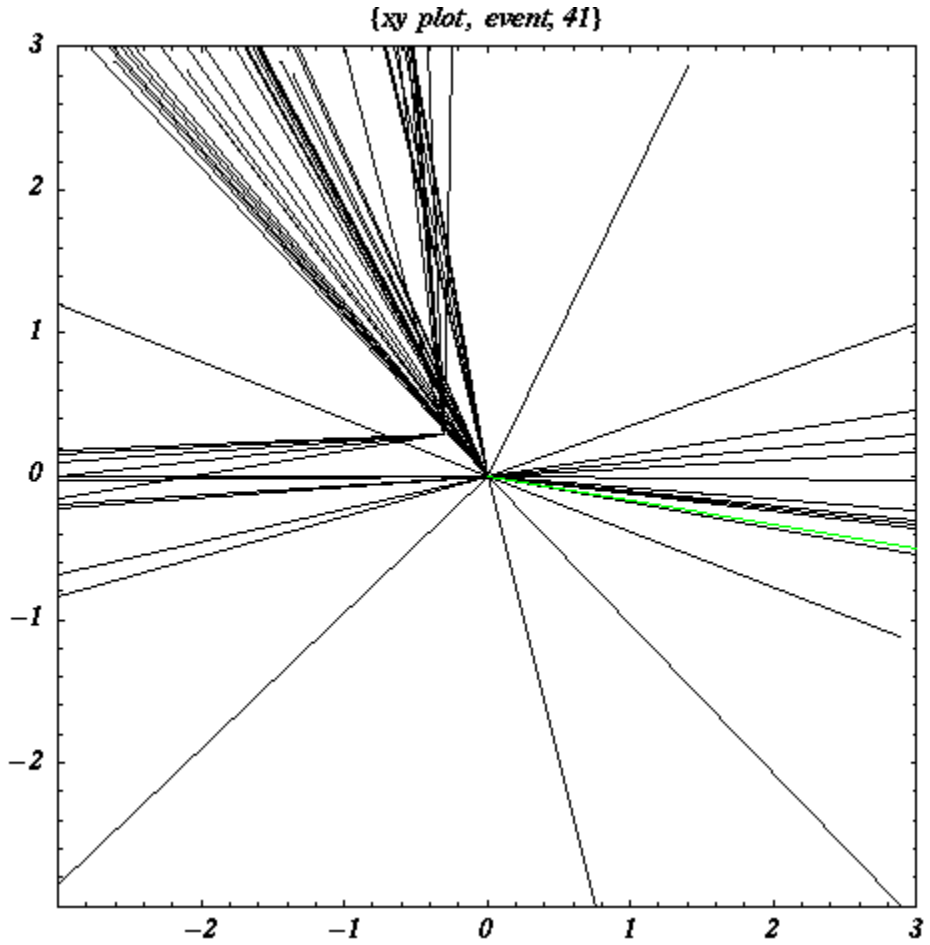
Displaced Decays

- ***Long-lived particles are hardly a new idea***
  - B-tagging based on bottom quark lifetime (where decay occurs inside beampipe)
  - Gauge mediation often predicts long-lived neutralino – two decays per event
- ***But the experimental situation is surprising***
  - Very few searches have been done for the Tevatron experiments
  - Very few cases have been studied for LHC
  - No searches for displaced jet pairs have ever been carried out
- ***Long-lived particles have no standard model background – so why so little study?***

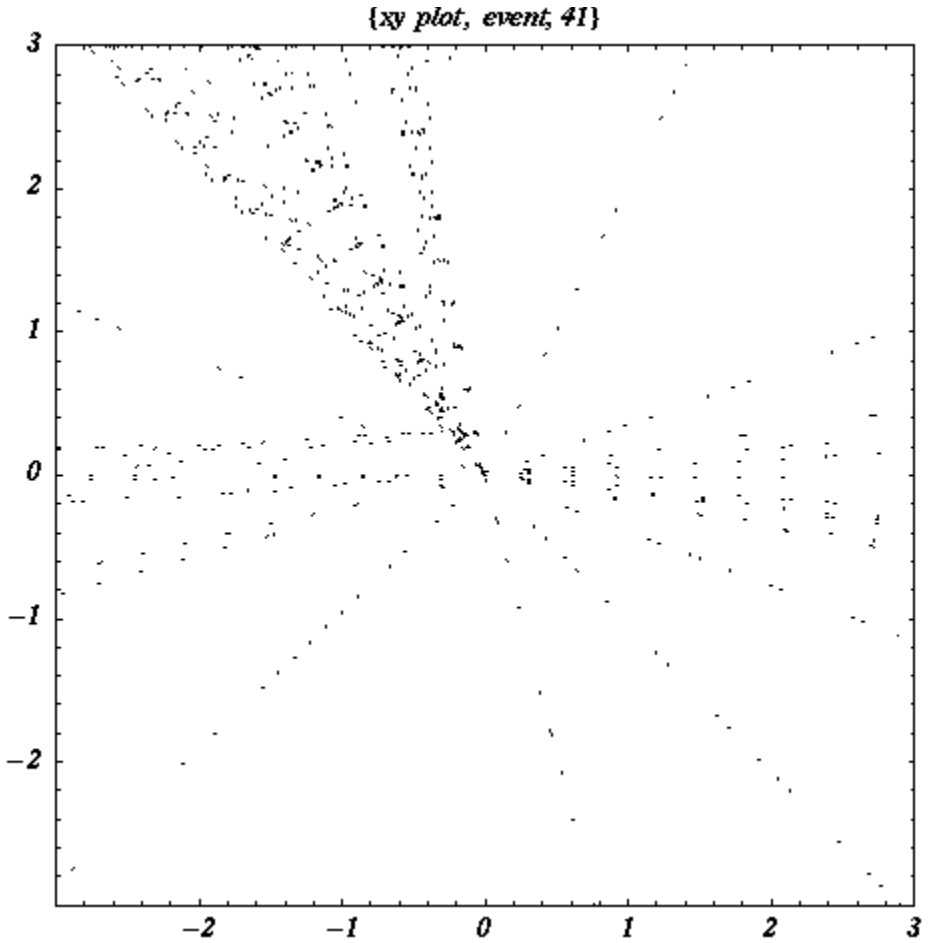
Finding Long-lived Particles



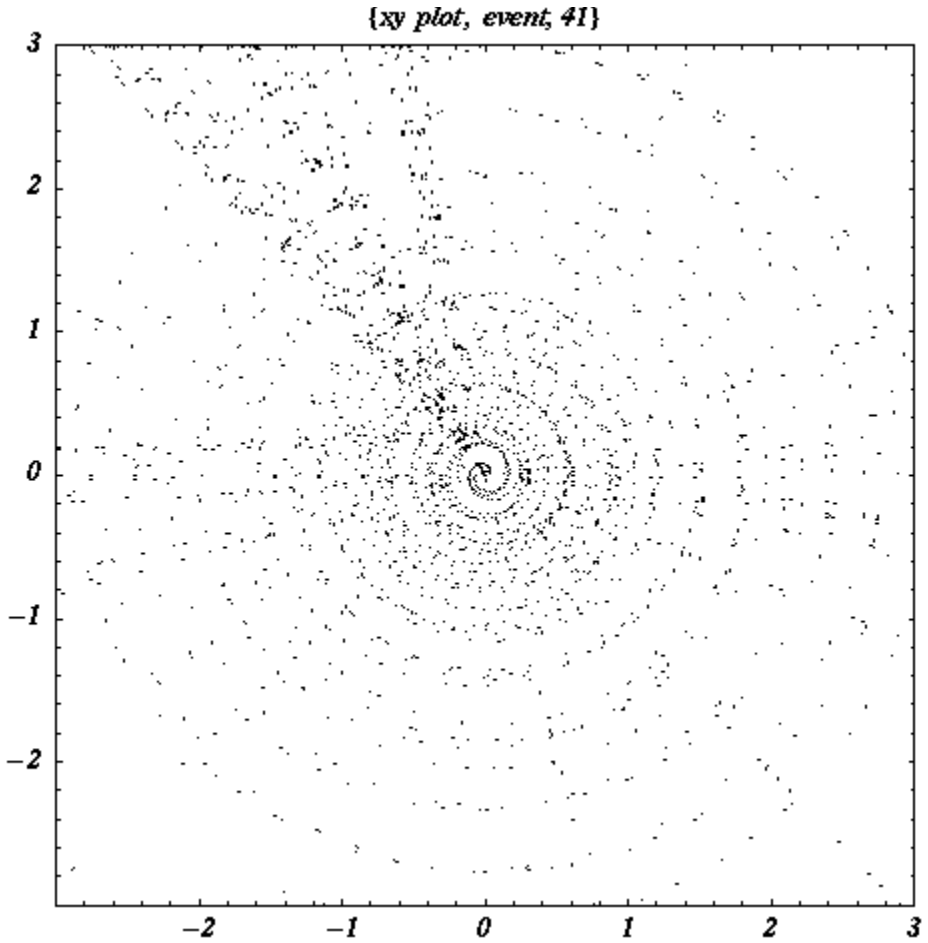
Finding Long-lived Particles



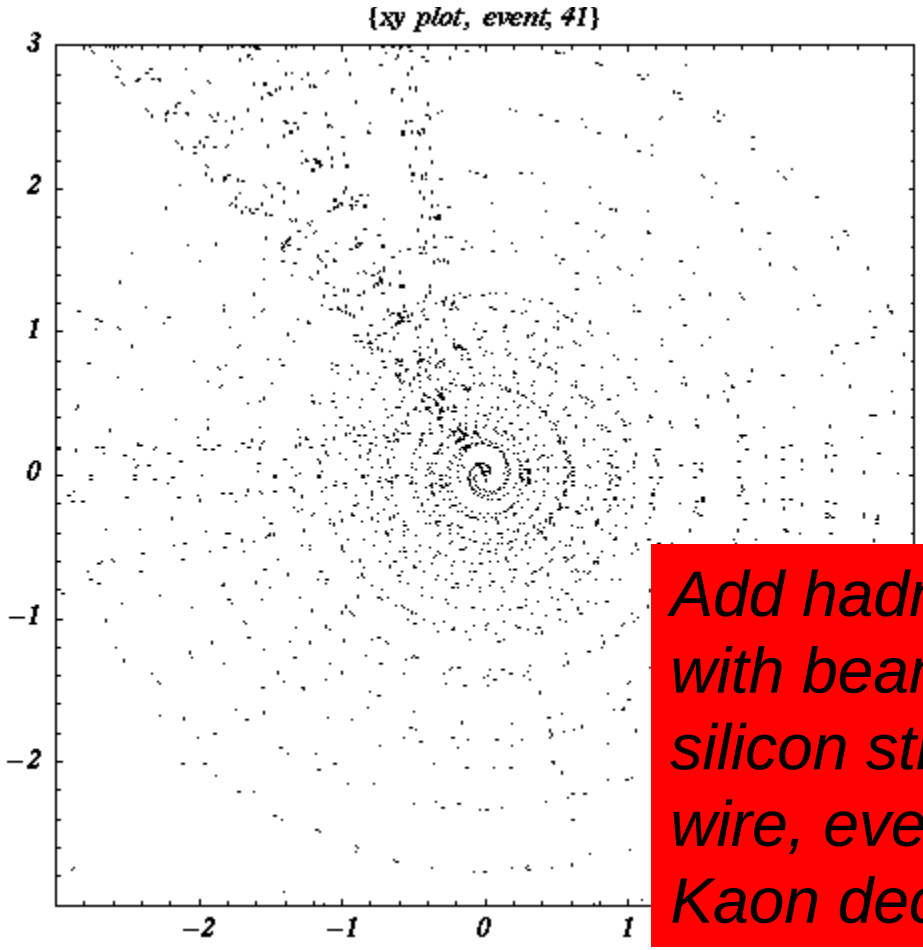
Finding Long-lived Particles



Finding Long-lived Particles



Finding Long-lived Particles



Add hadron collisions with beampipe, silicon strips, copper wire, even air, plus Kaon decays

Why so few searches/studies?

- **It hasn't been done because it is *non-trivial***

- **Displaced isolated leptons easy, displaced jets much harder**
  - **Easy in beampipe,**
  - **Harder in inner tracker due to detector background**
  - **Further out requires reprocessing of all tracks – months!! Which events to reprocess?**
  - **Could be very hard when the event is busy with many jets**

- Need to suggest
  - Search strategies (what triggers, what detector regions) to apply to Tevatron data
  - Strategies to optimize triggering, tracking, reconstruction at the LHC

- Searches at CDF, D0 being undertaken
- General study of long-lived particle detection under discussion at ATLAS
- Interest from CMS

- ***Note: the LHCb experiment should not be underestimated!***
  - *Vertexing! Might find new physics before CMS, ATLAS!*
  - *Studies of long-lived particle detection now being undertaken*

Other Models Suggest Other Issues

Two Other Very Simple Examples:

- One flavor v-QCD, couples to SM by Z' ;
  - η', σ, ω metastable, decay to SM particles
  - Expect ω → leptons sometimes
  - Fewer v-hadrons, little missing transverse momentum
  - Precise decay modes unclear: depend on unknown v-hadron spectrum, v-hadronic matrix elements, etc.
- Pure v-Yang-Mills, couples to SM by loop of heavy particles ;
  - Many glueball resonances with varying lifetimes.
  - Production of heavy particles may be accompanied by glueballs, decaying to b pairs or ordinary jets
  - High-energy jets, stable charged particles, isolated photons, etc. may coexist with v-hadron jet-pairs/triplets
  - Different choices (heavy-particle charges, any light v-quarks) can produce unusual and radically different signals

- Need to classify models by their experimental signatures
- Often requires educated guesswork or new theoretical developments

Summary of signals:

- Most models show at least a few common features
  - Multi-particle production -- **robust**
    - *Missing energy signal possible*
    - *Long-lived particles possible*
  - Many and possibly overlapping jet-pairs -- **robust**
    - Bottom-quark pairs likely
    - *Lepton-pairs possible*
    - *Top-quark pairs, W,Z pairs possible*
    - *(Meta)stable charged particles possible*
  - Large variability event to event -- **robust**
  - Unusual kinematic structure to the events – **robust**

- This is enough info to provide experimentalists with some guidance
- But more theoretical work, more general simulation package [work w/ P. Skands] needed to make searches possible

Other important possibilities

- *In addition to many v-models,* ***there are many possible channels for sector-to-sector communication***
- We have seen how a ***Z'*** can be a direct communicator.
- **Loops of new particles** that bridge the two sectors will induce operators that involve both sectors
- The **Higgs boson** might decay to two or more v-hadrons
  - If v-hadrons long-lived, could actually be a discovery channel for the Higgs boson
- The **lightest supersymmetric particle in our sector** might decay to the v-sector LSP plus either SM particles or v-hadrons
  - Could be the ***dominant*** signature of new physics at the LHC!
  - This can reduce or eliminate the usual missing-energy signals of SUSY
- **Neutrinos** may be messengers – rare W/Z decays, W/Z-mediated production

Conclusions

- New sectors are a generic feature of string models of particle physics
- In lucky but not unreasonable circumstances, these sectors may show up at the Tevatron or LHC
- This physics may
  - coexist with classic Higgs and/or supersymmetric and/or little-Higgs phenomenology
  - drastically alter Higgs and/or supersymmetric and/or little-Higgs phenomenology
- Strong dynamics in these sectors can greatly enhance the visibility and complexity of the resulting signals
- Typically several new neutral resonances are present
- Some may have a long lifetime
- Challenges:
  - Extracting the new resonances inside high-multiplicity events with exceptional variability
  - Long-lived particles, even several per event: possibly hard to find, fantastic signal if seen
  - Triggering, tracking and reconstruction optimization to allow events to be saved, selected
- Efforts to engage the experimental community appear very promising
- Need to study signals, develop search-strategies in well-understood models
- But many v-models have unknown strong dynamics, hadron spectra, decay channels: *an obstruction to Tevatron/LHC predictions*
- **Much theoretical and experimental work lies ahead**