Search for a New Hadronic Resonance Using Jet Ensembles at CDF

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with
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Has there been a blind spot in new physics searches?

- Most new physics searches require either
  - leptons (e, μ)
  - missing momentum (ie, MET) from ν, lightest neutralino, extra dimensions…
  - Photons
- What if new physics has color (*q*- *or g*-like)?
  - Not produced at e^+e^- colliders
  - Could be pair produced at hadron colliders
  - Of course, **massive** QCD backgrounds
  - *Important exception: Ongoing dijet bump hunt at Tevatron/LHC. Not as sensitive to multiple jet final states.*

New or Excited Fermions

Search
t' in Lepton + Jets + Missing E_T
Right-Handed Quarks in Dileptons + X
Long-Lived b' Quarks in the Z + X Channel

SUSY

Search
Squark and/or Gluino Production
Stop → c + neutralino in Jets + Missing E_T
Stop → b + l + sneutrino in Dilepton + Jet + Missing E_T
Chargino + Neutralino Production
Unified Trilepton and Dilepton + Track
Gaugino Pair Production in Z + W + Missing E_T
Low p_T ee + Track
R-parity Violation
Sneutrino in eμ, eτ, μτ channels

High Mass Resonances

Search
RS Graviton to ee (+diphotons)
W' search
3-jet resonances
μμ Channel
ZZ Channel (Graviton)
tt Channel (Massive Gluon)

Signature-based

Search
Photon + Jet (+ Missing E_T)
Lepton+Photon+MET+Bjet (and top-antitop+photon production cross section
Photon + Jet (+ Missing E_T)
Z Boson Production at High p_T^Z
Photon + Heavy Quark (b, c)

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Searches for new physics without e, μ, γ, or missing energy signatures are rare.

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μμ Channel
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Photon + Heavy Quark (b, c)

New Physics with Color

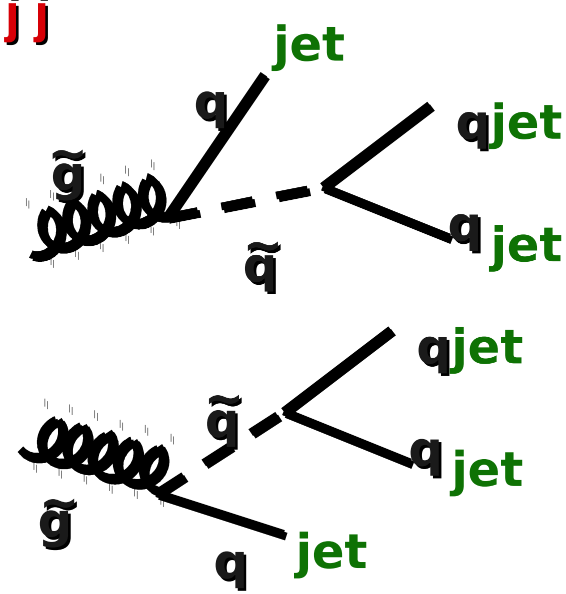
pp → QQ

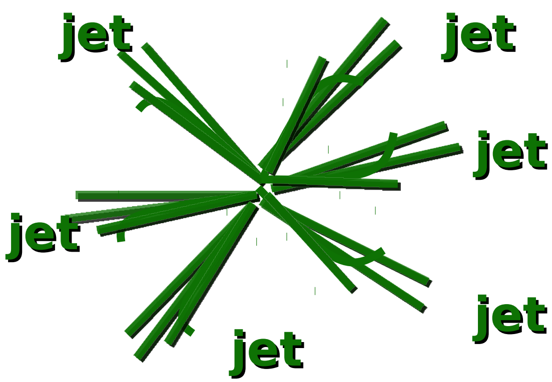
j j j

j j j

Q= g̃

- **Q= *g̃*** = SU(3)$_C$ Adjoint Majorana Fermion





No leptons, No MET,
No W resonance, No b

Some questions before we start

- Is this even possible?
- Test: Can you find the top quark?
  - **Cons**: Top really heavy, our analysis is geared to lighter objects, produced with some boost.
  - **Pros:** Know top is there...
- How will you handle backgrounds?
  - Has to be data-driven..

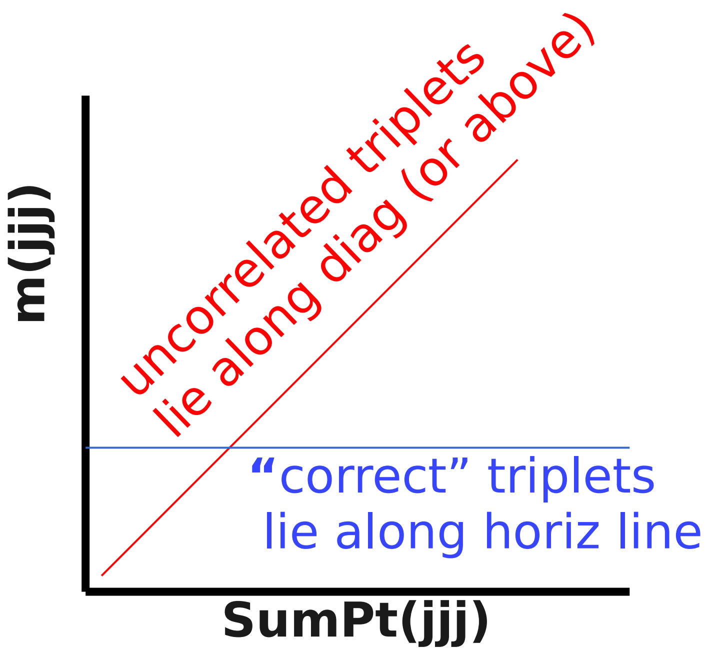
Usual tricks do not work

- Picking the correct 3 jets in a multiple-jet event is difficult.
  - In a 6-jet event, there are 6-choose-3=20 different triplets.
  - Some hard jets are from initial- and final-state radiation (not part of signal)
- Techniques like *min[M(a,b,c) – M(d,e,f)]* just don't work.
- NN etc are good only if you are very sure of your model’s kinematics.
- QCD 6-jet cross-section, kinematics not known well (*except that it's huge*).

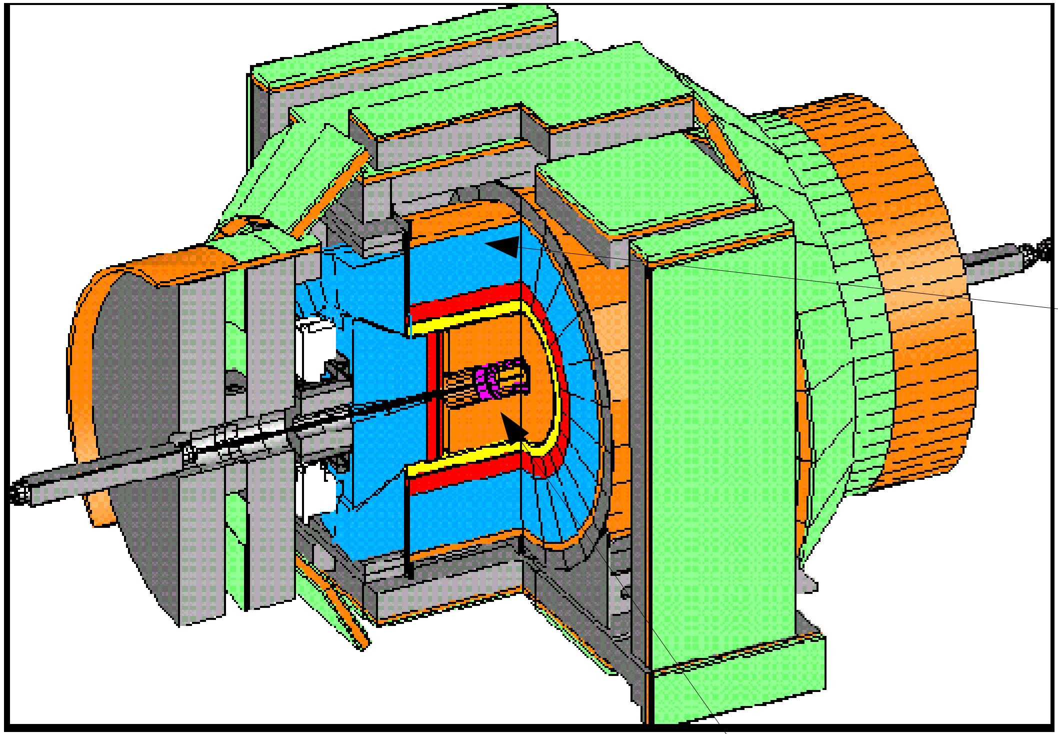
Our technique: Look at them all

- *Ensemble* method
- There are several jet triplets in a multi-jet event.
- Plot the invariant mass

  m_{jjj} vs ΣPt_{jjj}
- We look at them all (multiple entry plot).



The CDF Detector



Calorimeter

EM Energy Resolution:

sigma(E)/E = 13.5% / sqrt(E * sin(theta)) + 2%

HAD Energy Resolution:

sigma(E)/E = 0.5 / sqrt(E) [GeV]

Slightly worse for the PLUG (endcaps)

Tracker:

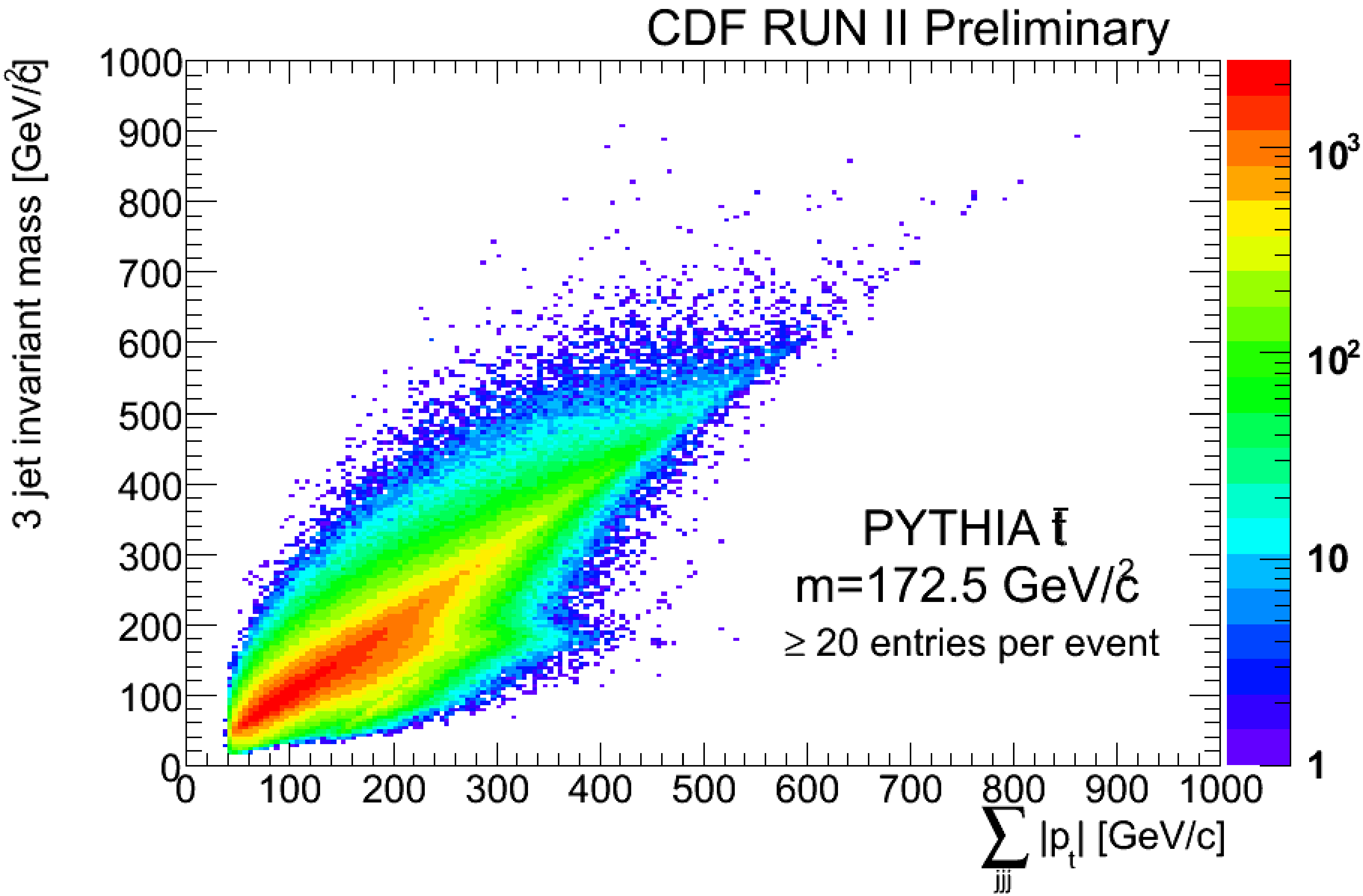
Momentum Resolution: σ(pT) / pT

COT alone : 0.15% pT [GeV/c]-1

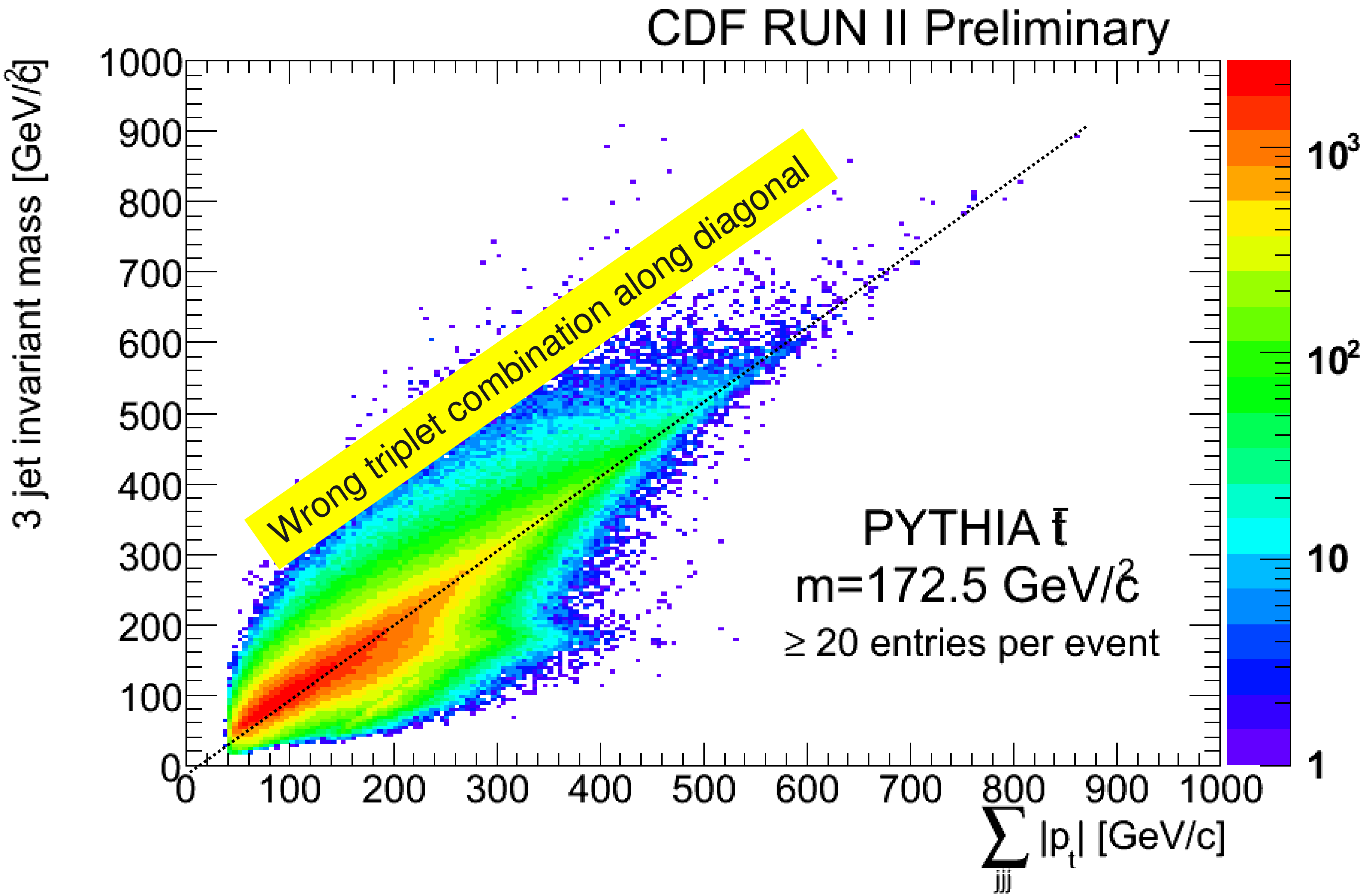
COT + SVX + ISL: 0.07% pT [GeV/c]-1

COT beam constrained: 0.05% pT [GeV/c]-1

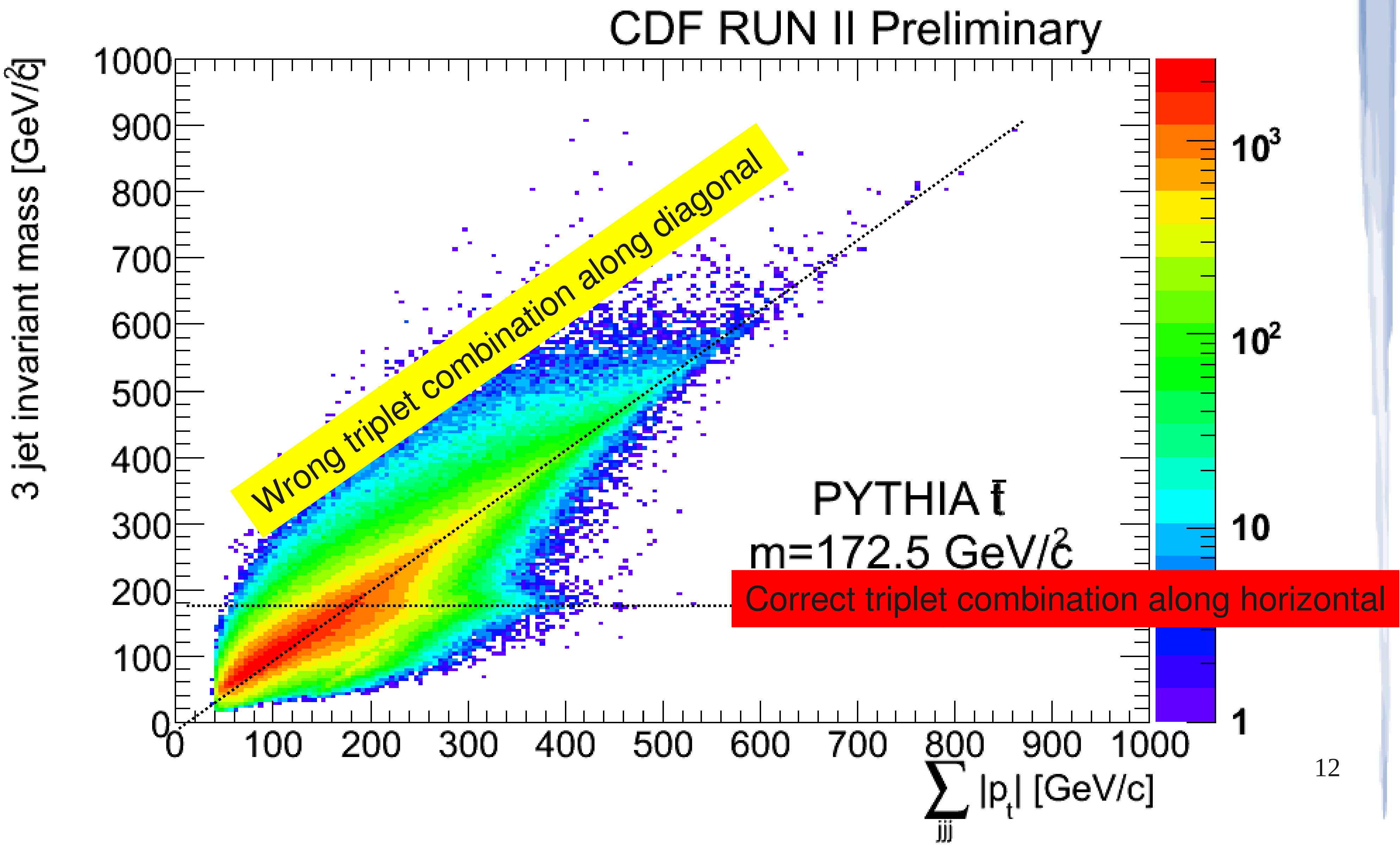
CDF Monte Carlo: ttbar



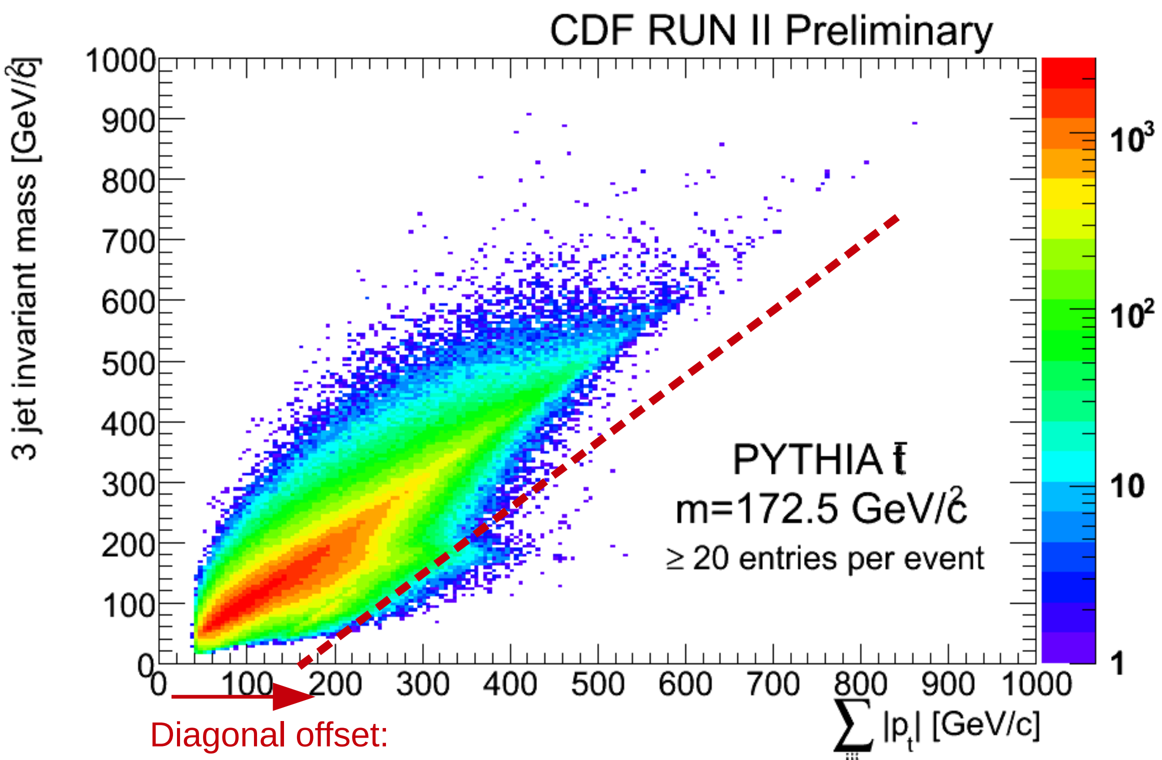
CDF Monte Carlo: ttbar

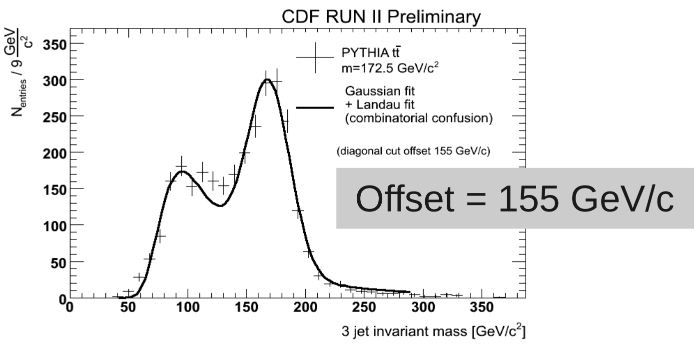


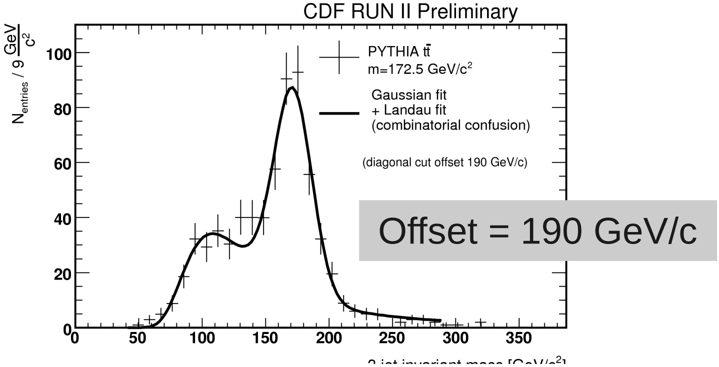
CDF Monte Carlo: ttbar

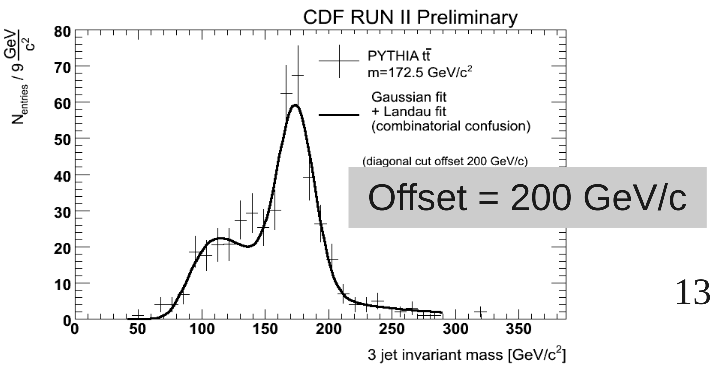


The diagonal offset cut







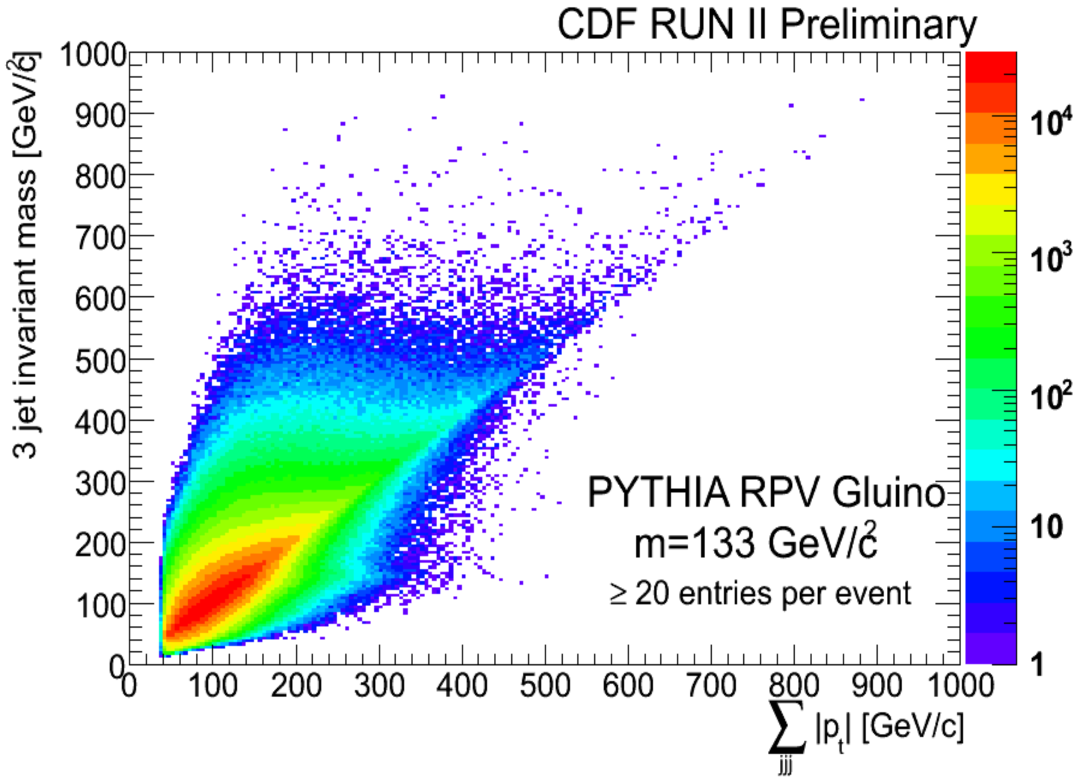


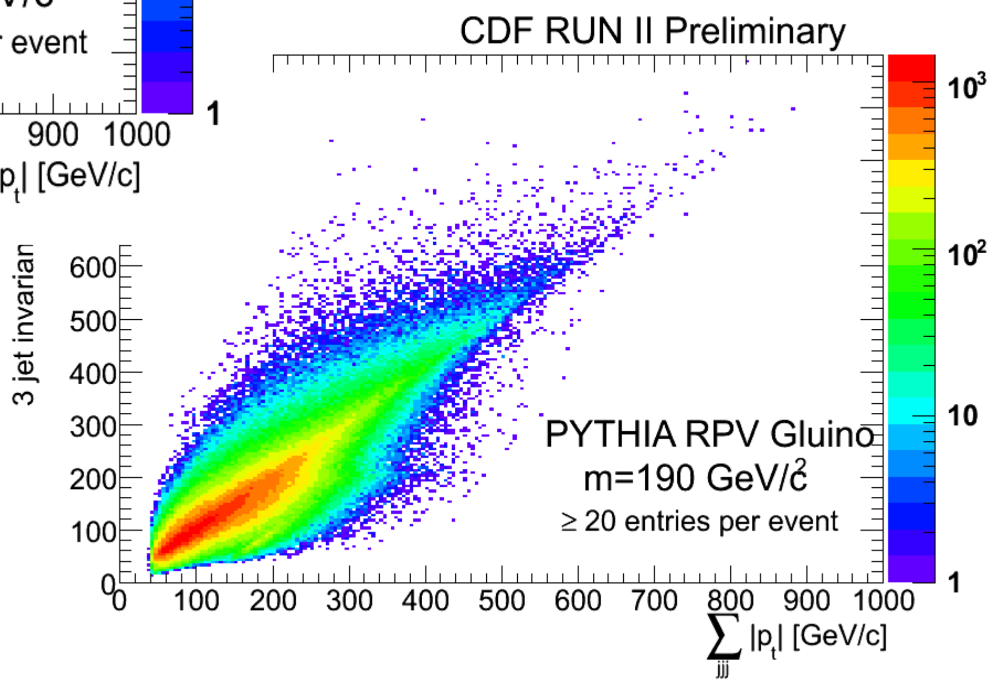
For ANY triplet of jets require:

$M_{jjj} < \sum|p_{T,jjj}|$ - **diagonal-offset**

- where M_{jjj} is the invariant mass of the 3 jets
- $\sum|p_{T,jjj}|$ is the scalar sum $|p_T|$ of the 3 jets

R-Parity Violating Gluino MC





Notes on the technique

- We look for just one 3-jet mass resonance in a multi-jet environment.
  - No attempt to fully reconstruct both decays.
  - Nothing model dependent: no b-quarks, no internal resonances, no requirements on geometry (hemisphere, ΔR, etc.)
- New physics with strong couplings will have large cross sections.
  - Recall ttbar production is ~7 pb.
  - RPV gluinos are similar, ~10 pb at m_{top}, rising to ~200 pb at 90 GeV/c^2 (LO, higher with NLO).
  - The power of this technique is in the focus on (slightly) boosted decays. Reduces QCD and combinatoric backgrounds.

Trigger

- CDF has an interesting *Quad-Jet* trigger
  - Designed for top and Higgs (all hadronic) modes
  - Constructs calorimeter clusters at trigger Level 2 (raw, *energy not corrected*).
  - Thresholds changed as luminosity went up (total L2 rate ~300 Hz).
- Triggers on 4 jets @L2 (15 GeV raw each) and SumEt >175 GeV raw.
  - This is ideal for our search.

Basic Event Selection

- MET < 50   (get rid of beam splash)
- Vertex: between 1 and 4
- Jets: between 6 and 8
- Σ pt of top 6 jets > 250 GeV

Multiple interactions could be a large background:

- Two 3-jet (or three di-jet) events may be more likely than 6-jet events.

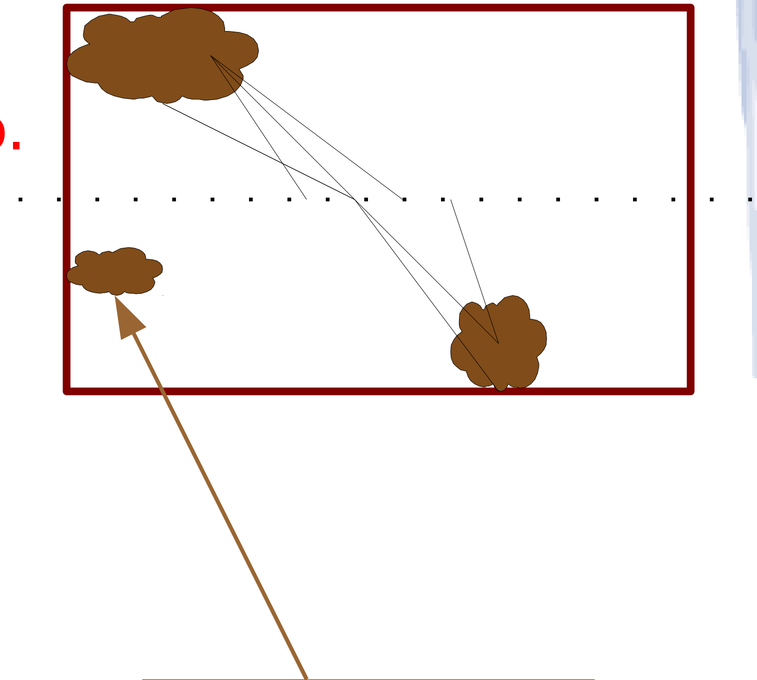
Jet Z Requirement

- CDF Beamline is z-coordinate
  - Event with multiple interactions will typically be a multiple vertex event.
  - Cannot simply cut on Nvertex

- Calorimeter jets do not come with Z info.
- Need to create.
  - Loop over tracks (pt >1 Gev)
  - Associate w/ jet (cone 0.4)

- Take mean z of tracks as Jet-z.
- If RMS_z > 4cm, treat as no Z info.

- Event must have >3 jets w/ Z info
- “Good” triplet must have at lest 2 jets w/ Z info.



This lowers our acceptance for forward clusters

Summary of jet Z

- Define $\bar{z}_j = \frac{\sum_{\text{tracks}} z_0}{N_{tracks}}.$ (mean position of all the tracks within a jet)
- Error on z_{jet}: $\delta(z_j) = \sqrt{\frac{\bar{z_j^2} - \bar{z}_j{}^2}{N_{tracks}}}.$
- Define z_{rms} $z_{\text{rms}} = \sqrt{\frac{(\sum_{\text{jets}} \bar{z}_j{}^2)/N_{\text{jets}} - \left(\sum_{\text{jets}} \bar{z}_j/N_{\text{jets}}\right)^2}{N_{\text{jets}}}}$ $z_{rms} < 0.5$

- Within a triplet,
  - $\delta(z_{jet})$ for any jet in triplet <2.5
    - Event level cut was < 4
  - number of jets without z info <= 1
    - These tend to be high eta jets w/out tracks
  - $|\bar{z}_{jet}$ - VTX-z$|$ < 10 cm for all jets in triplet

Summary of jet Z

- Define $\bar{z}_j = \frac{\sum_{\text{tracks}} z_0}{N_{tracks}}$. (mean position of all the tracks within a jet)

Make sure tracks pointing to cluster come from same point on the beamline

- Error on z_{jet}: $\delta(z_j) = \sqrt{\frac{\bar{z_j^2} - \bar{z}_j^{\,2}}{N_{tracks}}}$.

- Define z_{rms} $z_{\text{rms}} = \sqrt{\frac{(\sum_{\text{jets}} \bar{z}_j^{\,2})/N_{\text{jets}} - \left(\sum_{\text{jets}} \bar{z}_j/N_{\text{jets}}\right)^2}{N_{\text{jets}}}}$ $z_{rms} < 0.5$

Make sure *(almost)* all jets come from same point on the beamline.

- Within a triplet,
  - $\delta(z_{jet})$ for any jet in triplet <2.5
    - Event level cut was < 4
  - number of jets without z info <= 1
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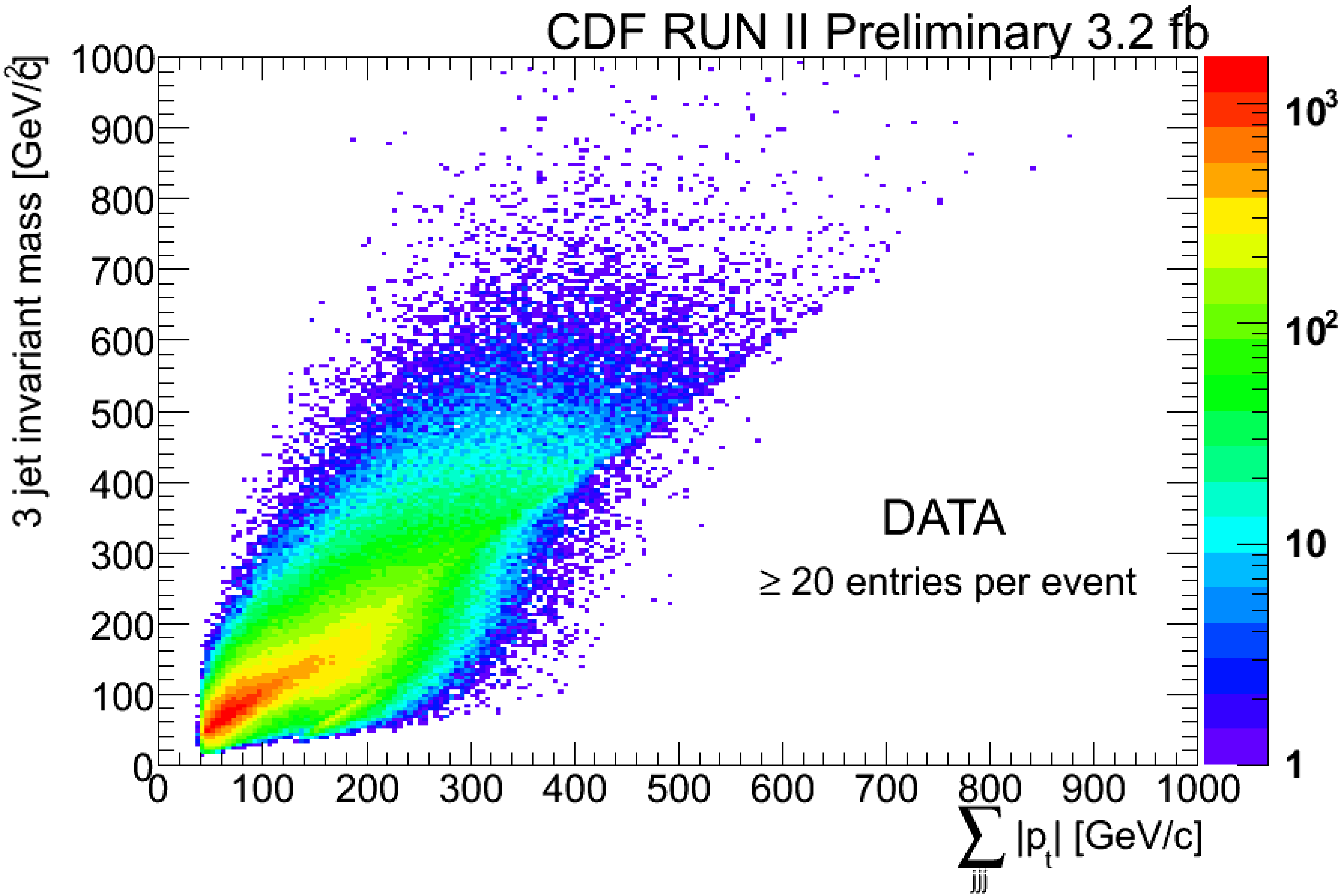
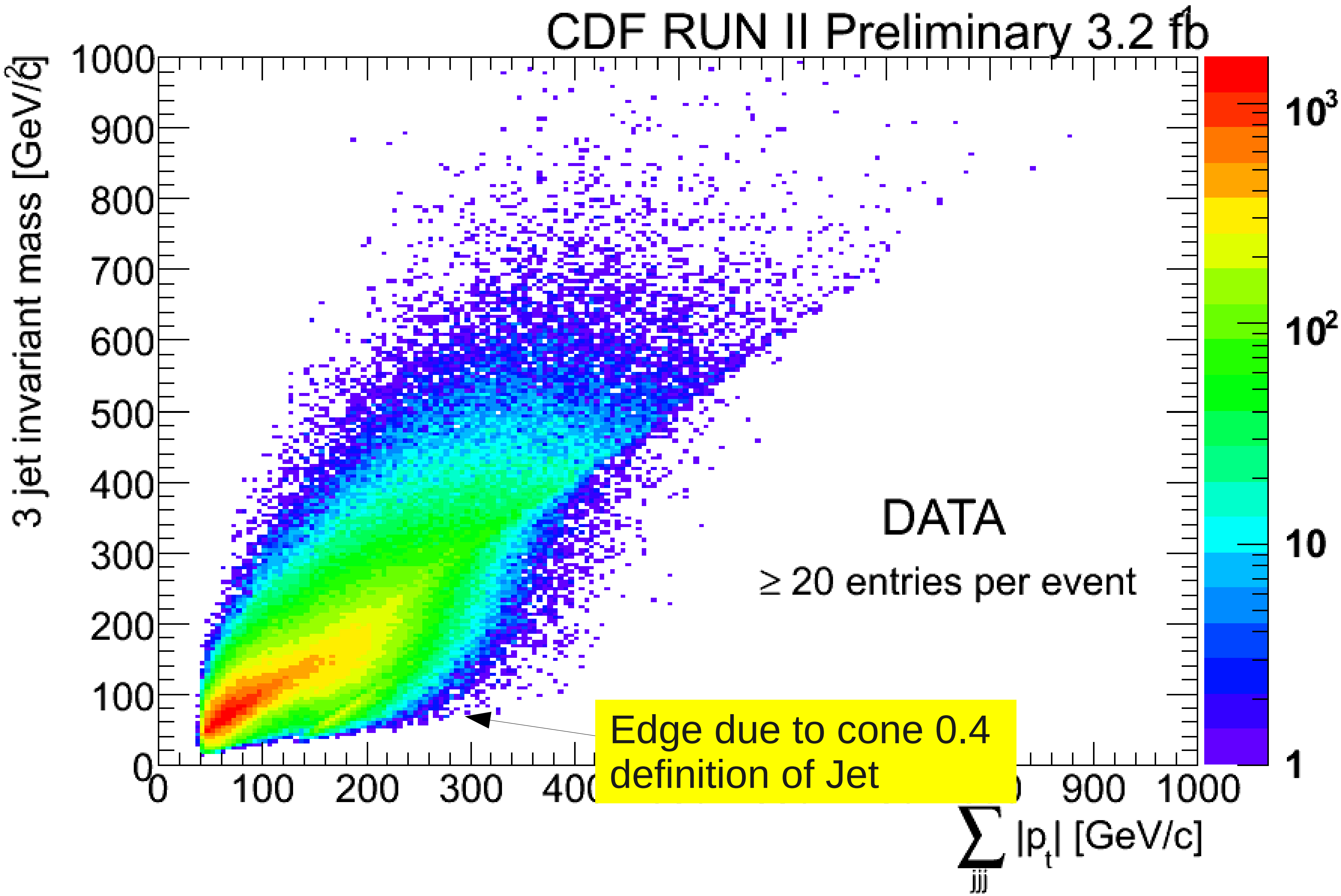
CDF Data



CDF RUN II Preliminary 3.2 fb⁻¹
3 jet invariant mass [GeV/c²]
DATA
≥ 20 entries per event
∑jjj |pt| [GeV/c]
0
100
200
300
400
500
600
700
800
900
1000
1
10
10²
10³

CDF Data



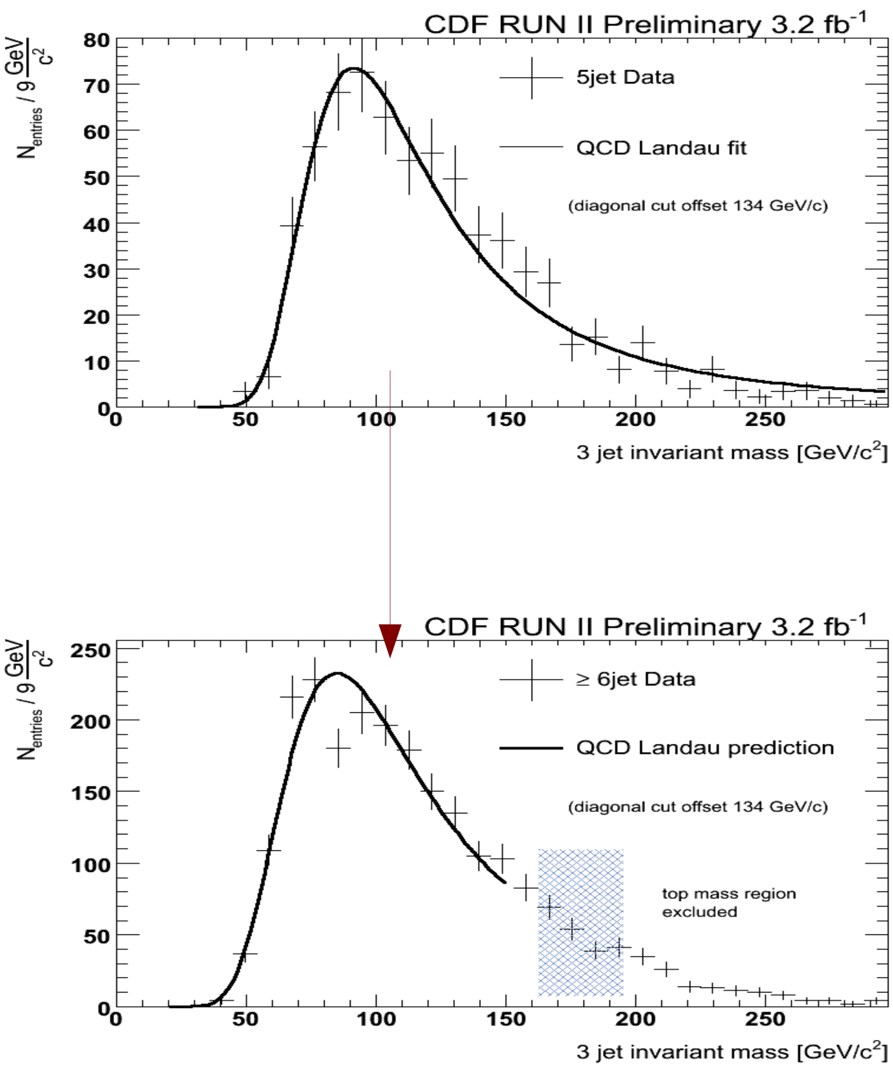
CDF RUN II Preliminary 3.2 fb^{-1}
3 jet invariant mass [GeV/c^2]
1000
900
800
700
600
500
400
300
200
100
0
0
100
200
300
400
900
1000
$\sum_{jjj} |p_t|$ [GeV/c]
10^3
10^2
10
1
DATA
≥ 20 entries per event
Edge due to cone 0.4
definition of Jet

Backgrounds

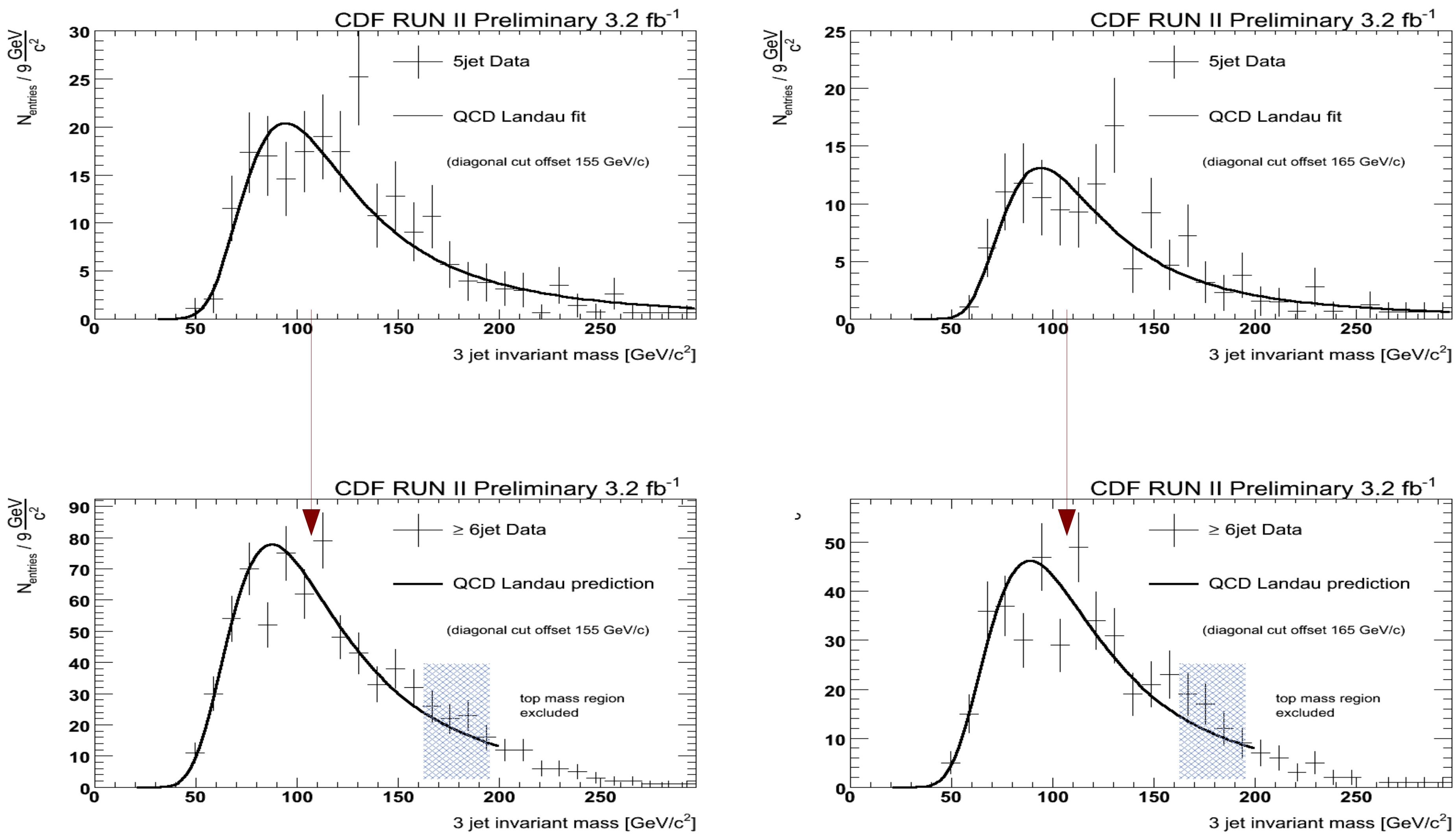
- QCD and combinatoric (both have Landau shape)
- Also need to optimize diagonal offset cut
- Need parametrized background function.
  - Why not just fit the data with Landau+Gaussian and let Minuit handle it?
  - Minuit will chase fluctuations, we need an *independent* background estimate.

Background Procedure

- Get 5-jet sample and make triplets.
  - Statistically independent
- Create ratio of triplet Σpt
  - (6-jet/5-jet)
- Correct the 5-jet mass distribution by this weight.
- Fit the scaled 5-jet mass dist with Landau
  - Extract MPV, width..
- Use parameters from scaled 5-jet fit on the 6+-jet data



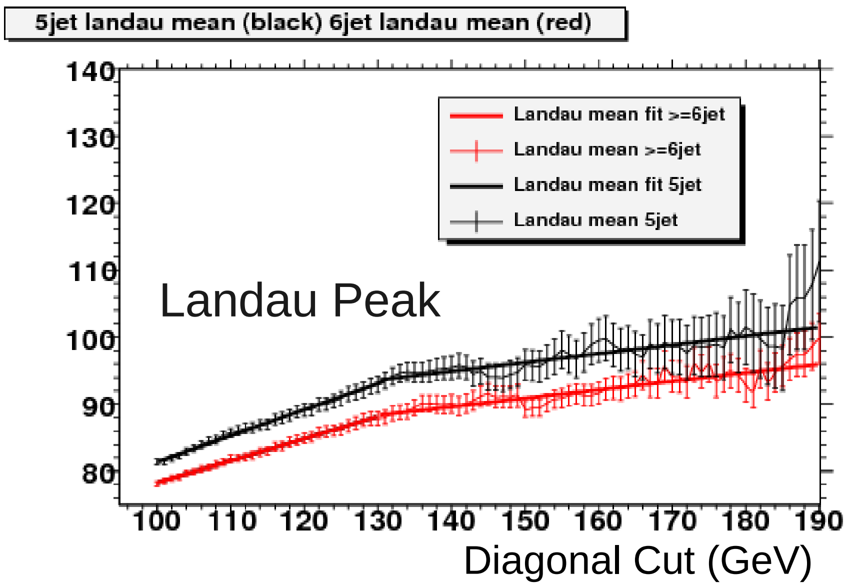
Background Procedure

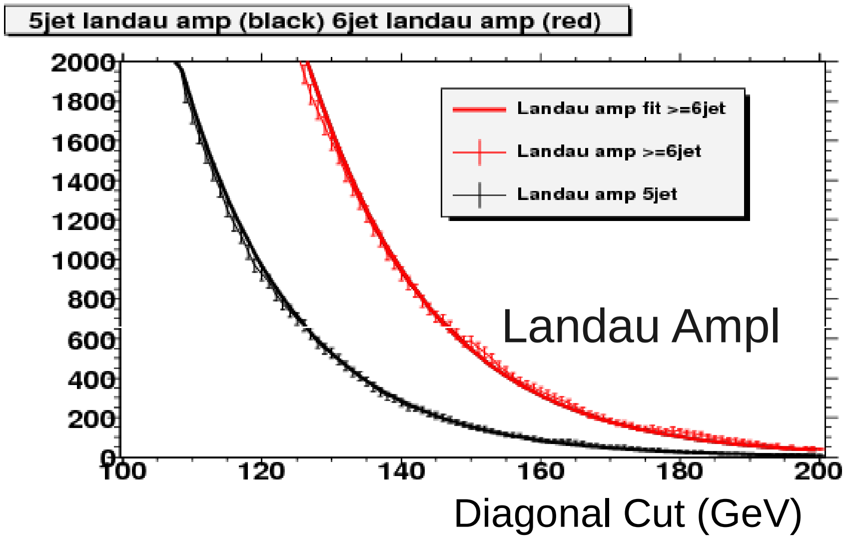


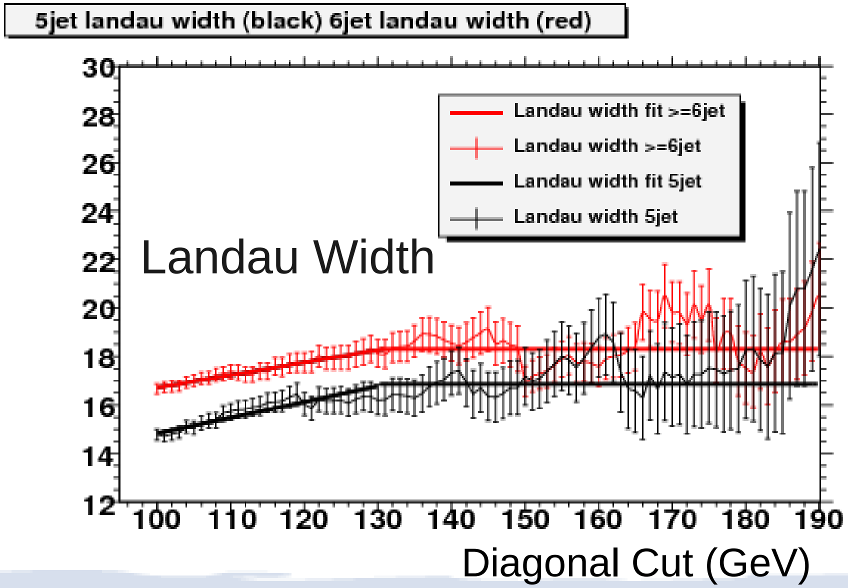
Comment on Background Procedure

- The 6-jet triplets have a softer Σpt distribution than the 5-jet
  - The main difference between a QCD 5-jet and QCD 6-jet is a soft gluon emission.
- We use the pt (non-invariant) ratio to correct the mass (invariant).
  - Note that for signal, pt and mass are not correlated
- What if there is signal in the 5-jet?
  - Tough problem when doing data-driven backgrounds. But we note that Landau parameters are smooth functions of diagonal offset cut.
  - σ(QCD 5-jet) is ~10x σ(QCD 6-jet).

Background Parameters





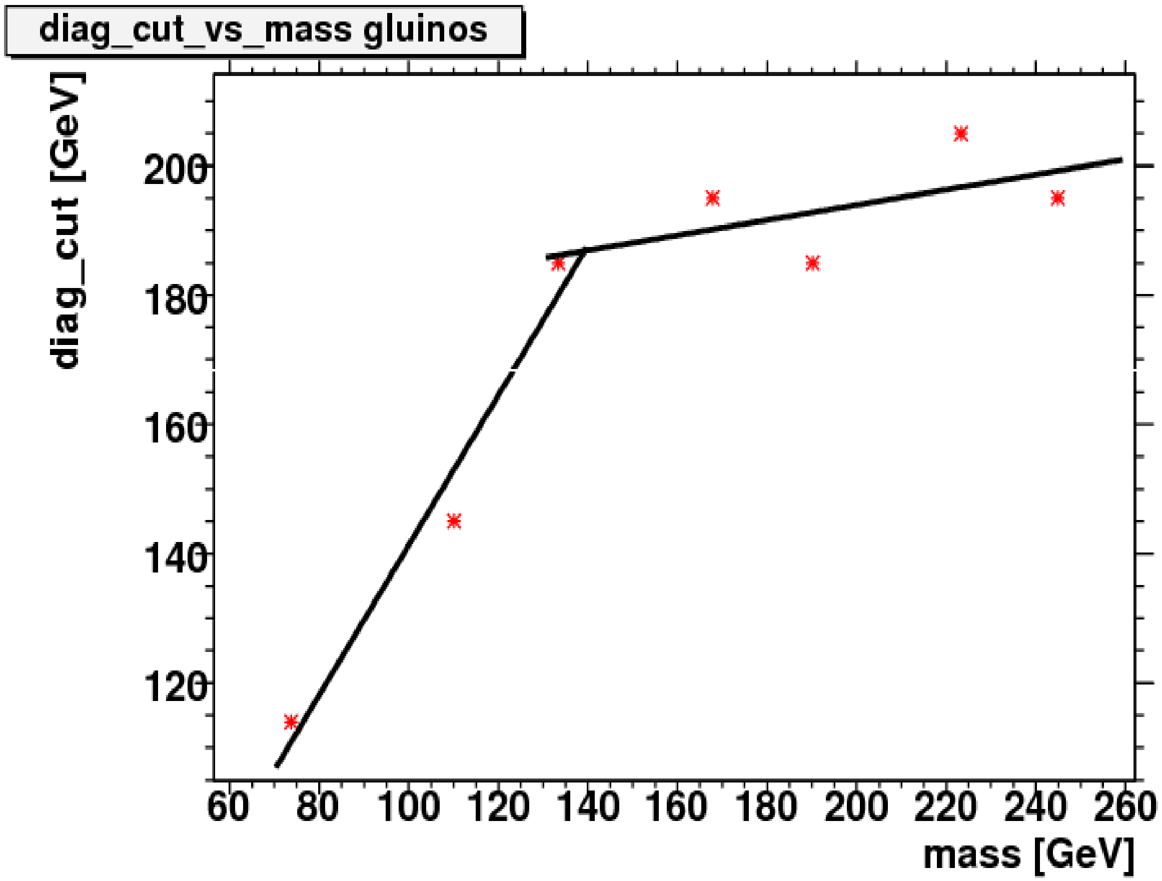


- **5jet scaled** and **6jet w/ top window blind** MPV, Width nearly agree
- Amplitude curves obviously different.
- When we fit for signal we **FIX background params.**

Optimizing the diagonal cut

- What is the best diagonal cut for a given m_{gluino}?
  - Cannot avoid signal MC
- Use signal/background as metric
  - We have a (*data-driven*) background estimate as function of diagonal cut.
  - Make pseudoexpts by adding signal MC
  - Vary diagonal cut, fit. Extract optimal diagonal cut.
- Note: fitting background & optimizing cuts in same step with data *does not work.*

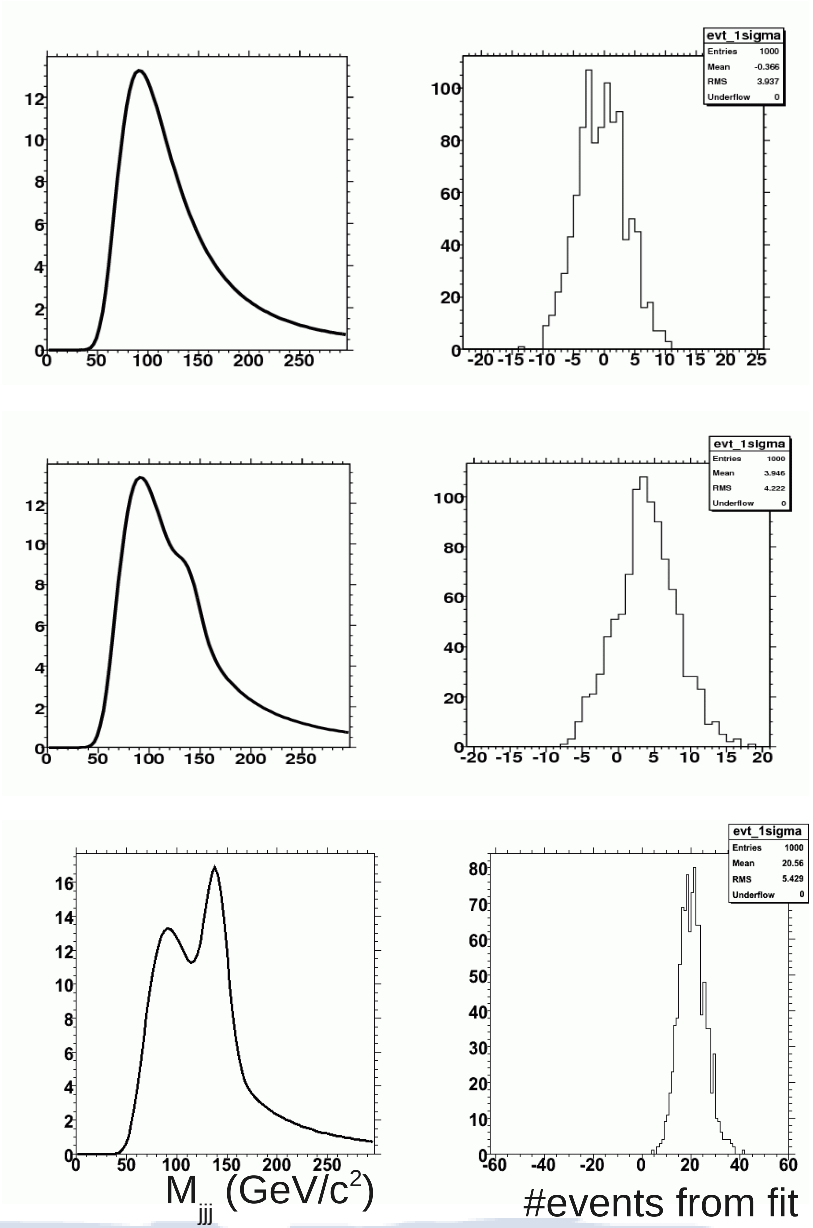
Optimized diagonal cut



Pole mass	Optimal diagonal cut
110.1	145
133.5	180
167.9	185
190.3	195
223.3	205
245.0	195
ttop25	190

What do we expect to see?

- We need to quantify our expectation before we can claim we see anything.
- Get background shape (Landau) and signal (Gaussian)
- Use as parent distribution to throw pseudoexperiments.
- Recover #events (signal and background) and calculate σ_{95}
- Systematic uncertainties incorporated as jitter in parent Landau parameters
  - Adding systematics does not change the mean # events found, but raises the $\sigma_{95.}$



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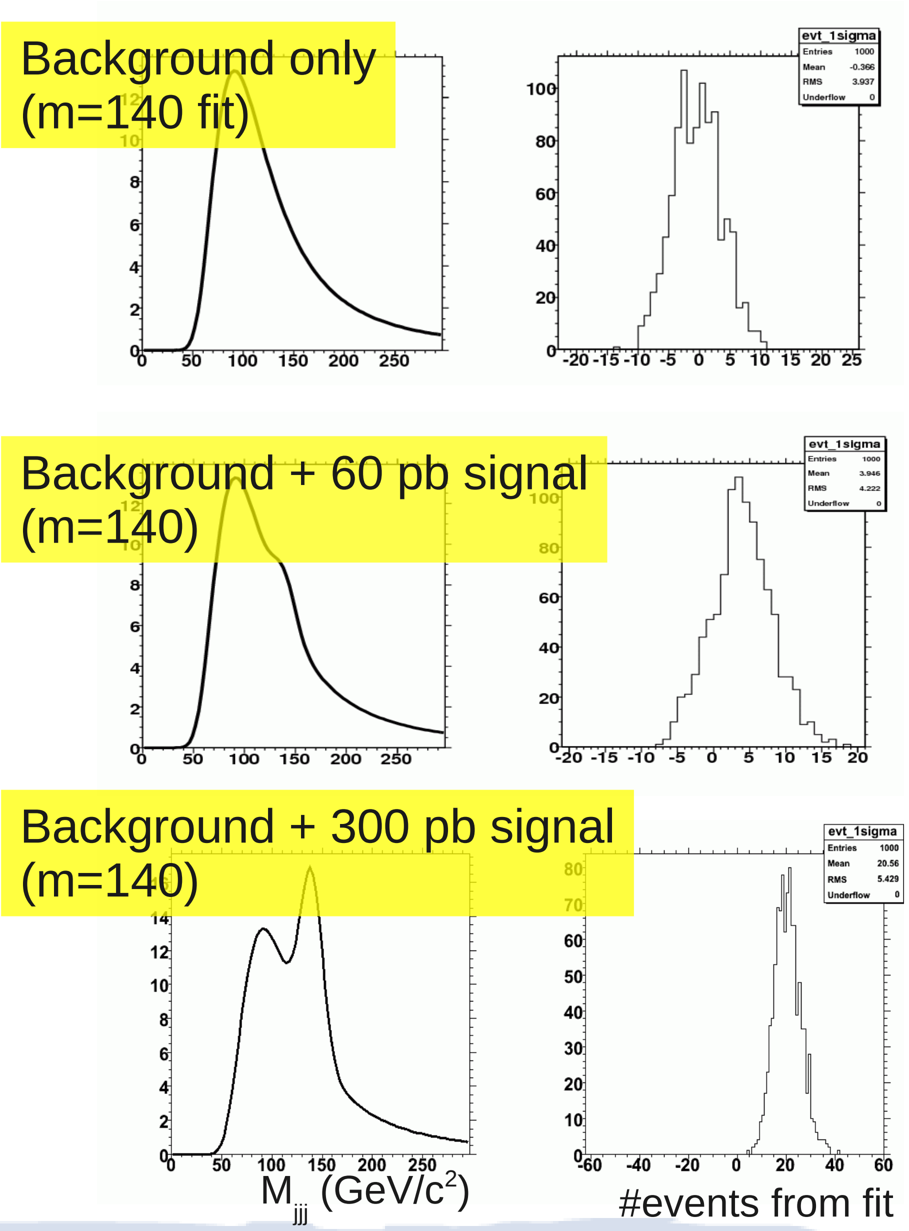
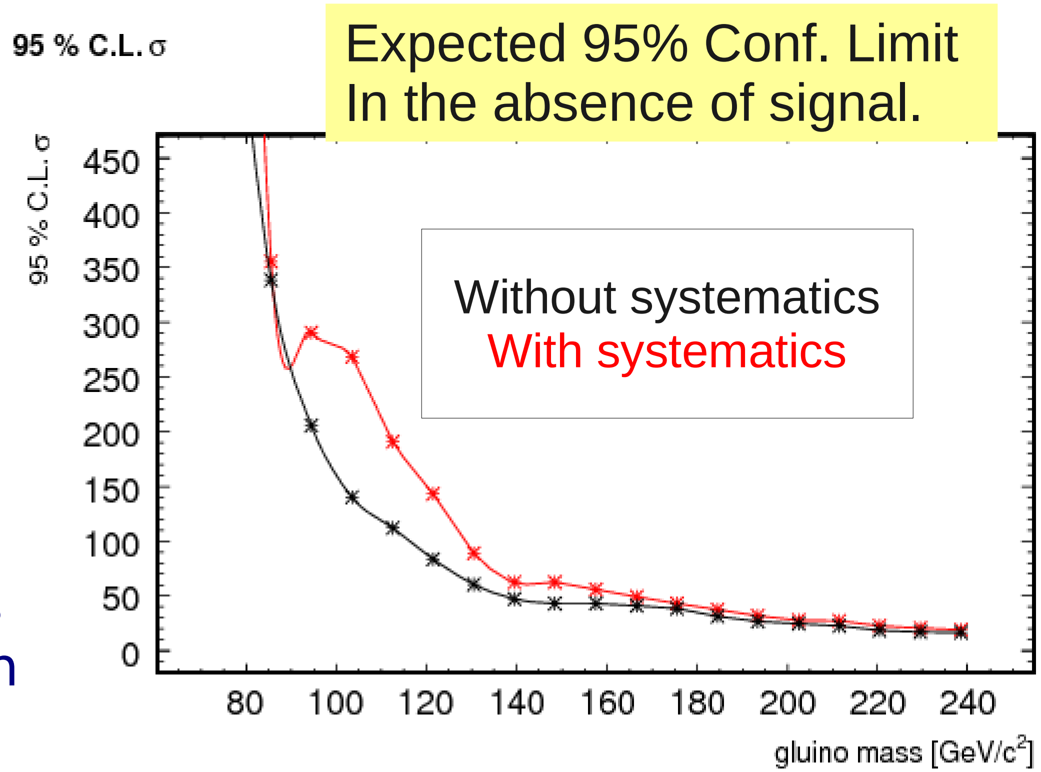
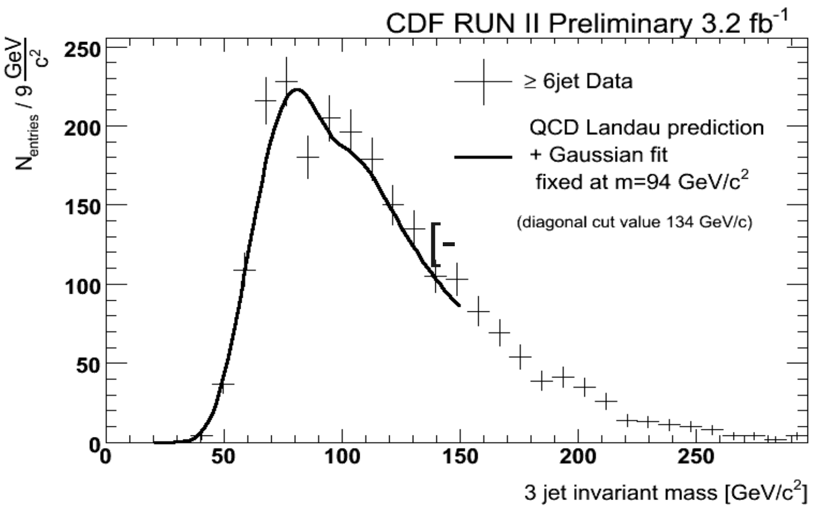


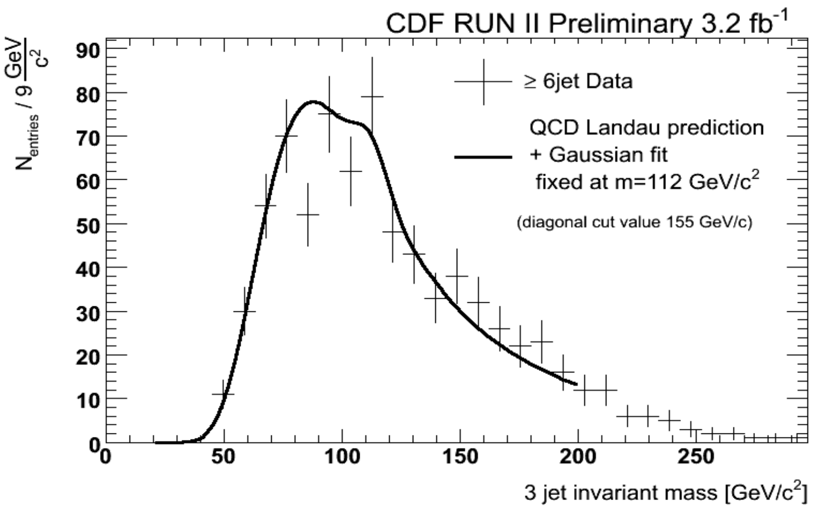
Expected Limits

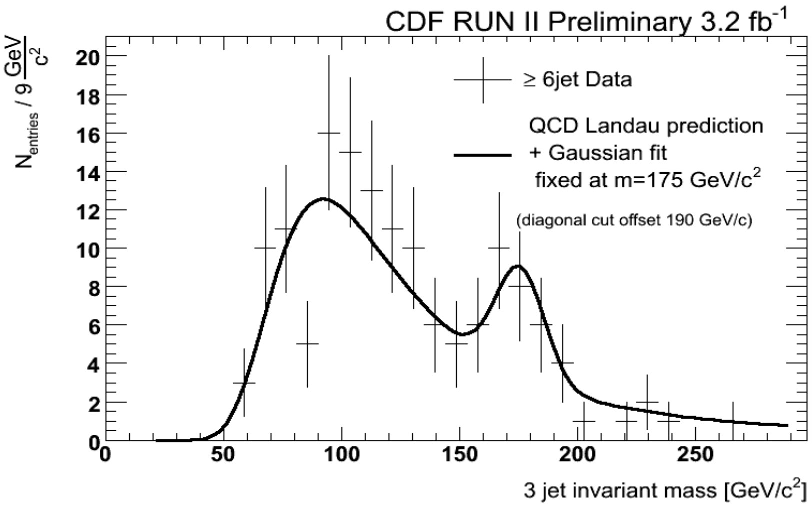
- Gluino acceptance is (4.9 +- 1.1) e-5.
- Systematic uncertainties:
  - Jet Energy Scale: 38%
  - ISR/FSR: 20%
  - PDF: 10%
- Systematics incorporated as jitter of parent distribution Landau params in the pseudoexperiments.
  - For signal extraction we **fix** background params at nominal values.



Fits to Data

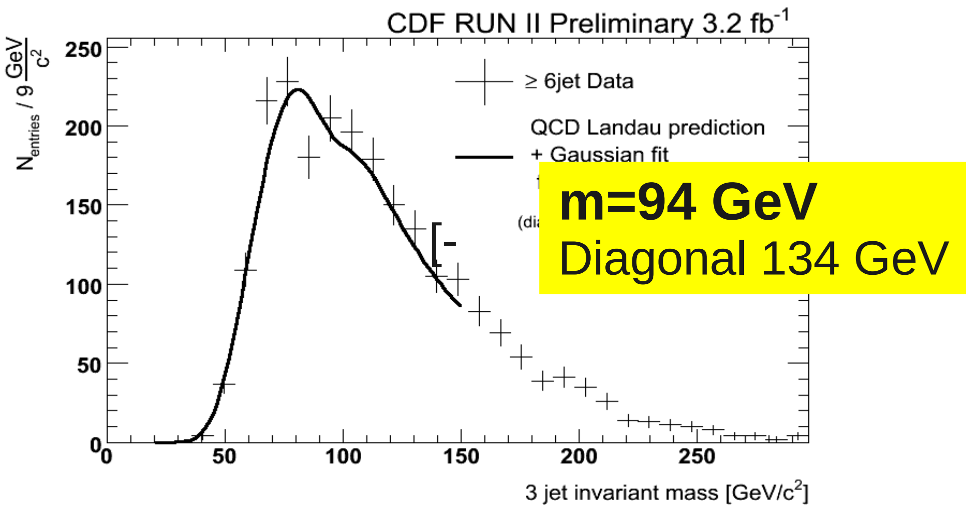


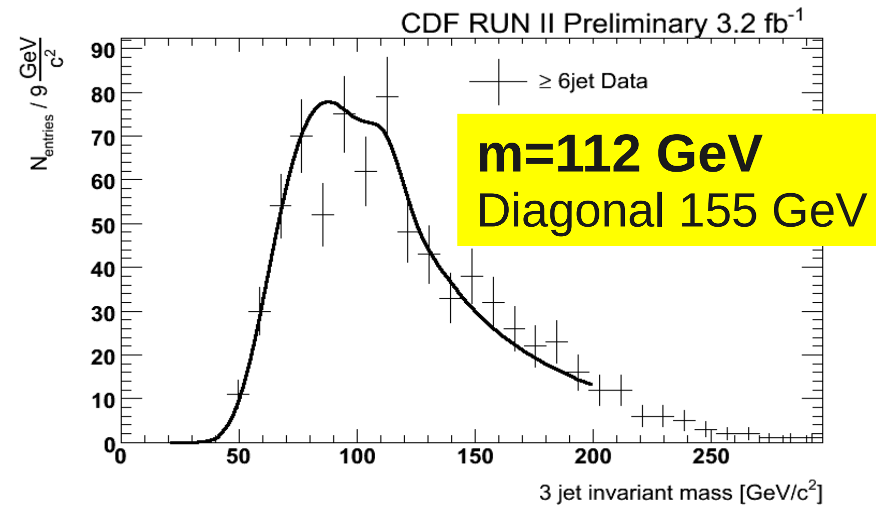


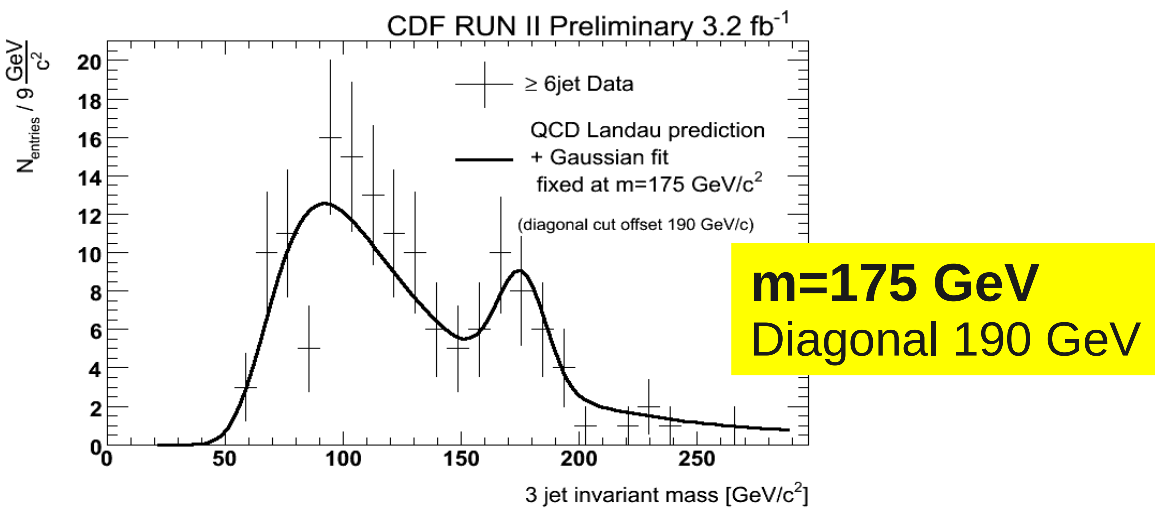


We fit data the same way:
- **Fix** background params
- Float Gaussian amplitude
- Extract #events (sig,bckg)

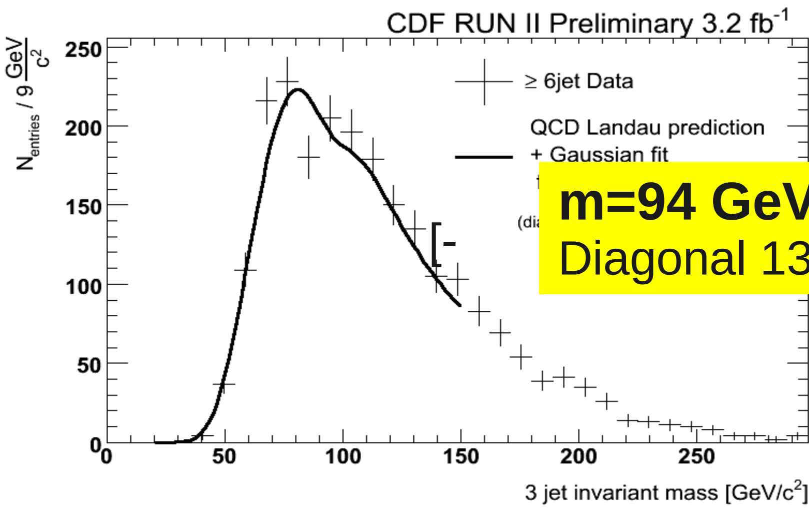
Fits to Data


CDF RUN II Preliminary 3.2 fb^{-1}
$N_{entries}$ / 9 $\frac{GeV}{c^2}$
≥ 6jet Data
QCD Landau prediction
+ Gaussian fit
3 jet invariant mass [GeV/c^2]
m=94 GeV
Diagonal 134 GeV

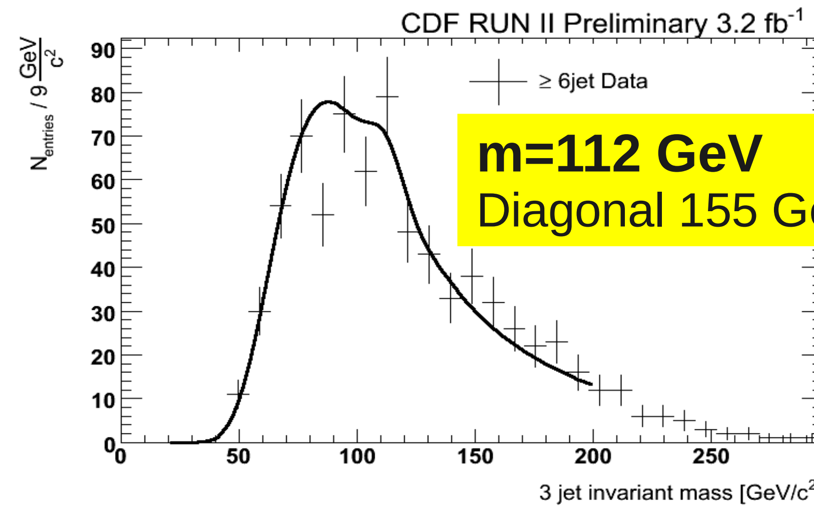

CDF RUN II Preliminary 3.2 fb^{-1}
$N_{entries}$ / 9 $\frac{GeV}{c^2}$
≥ 6jet Data
3 jet invariant mass [GeV/c^2]
m=112 GeV
Diagonal 155 GeV


CDF RUN II Preliminary 3.2 fb^{-1}
$N_{entries}$ / 9 $\frac{GeV}{c^2}$
≥ 6jet Data
QCD Landau prediction
+ Gaussian fit
fixed at m=175 GeV/c^2
(diagonal cut offset 190 GeV/c)
3 jet invariant mass [GeV/c^2]
m=175 GeV
Diagonal 190 GeV

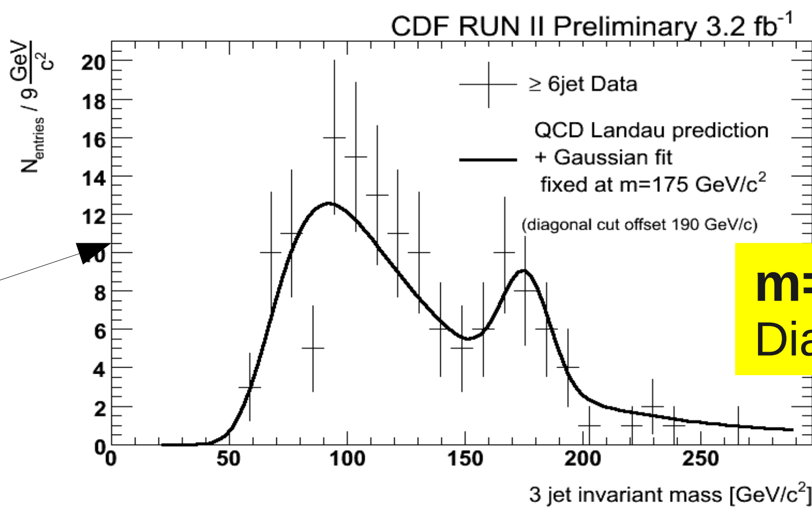
Fits to Data



m=94 GeV
Diagonal 134 GeV



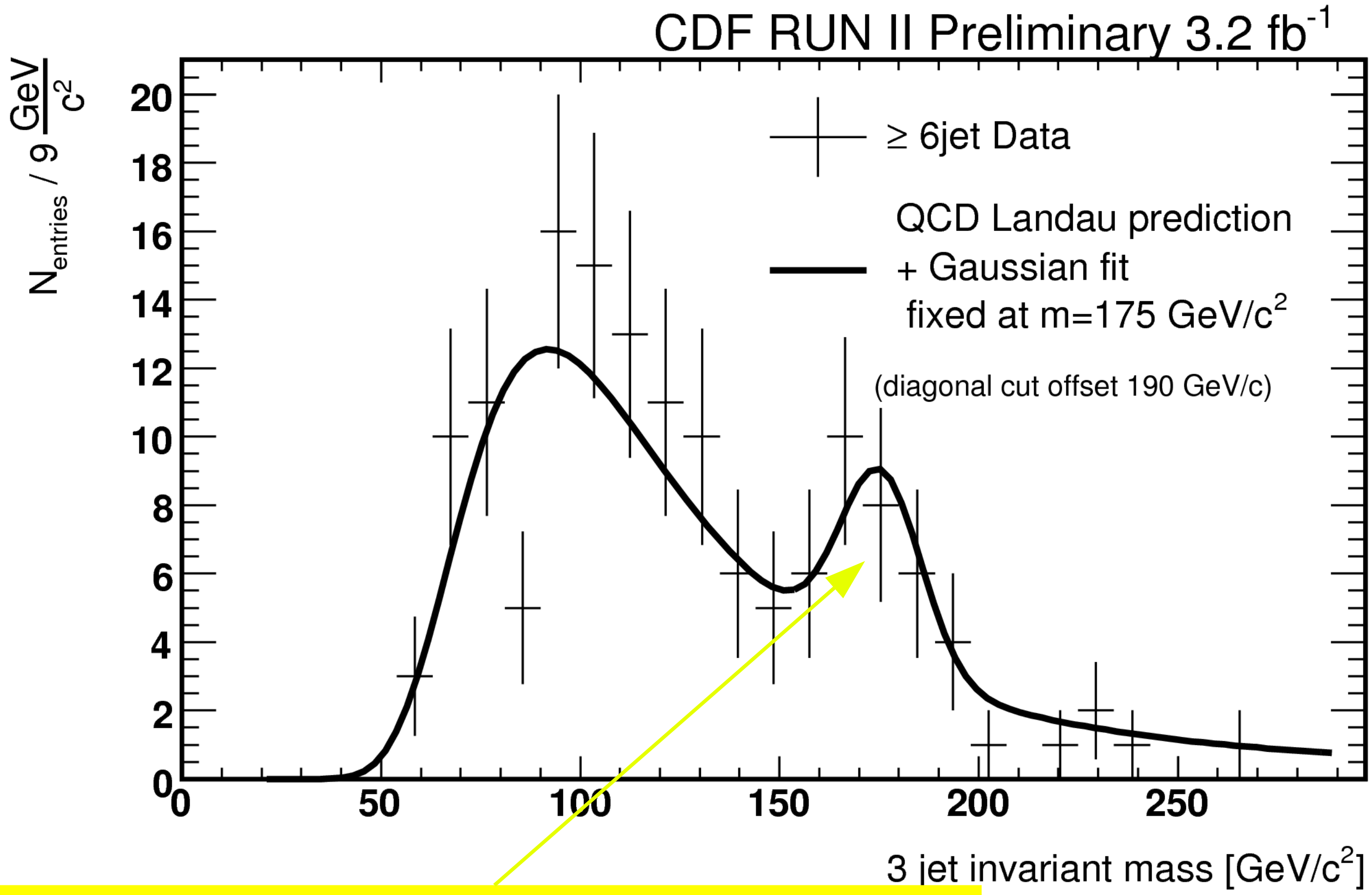
m=112 GeV
Diagonal 155 GeV



m=175 GeV
Diagonal 190 GeV

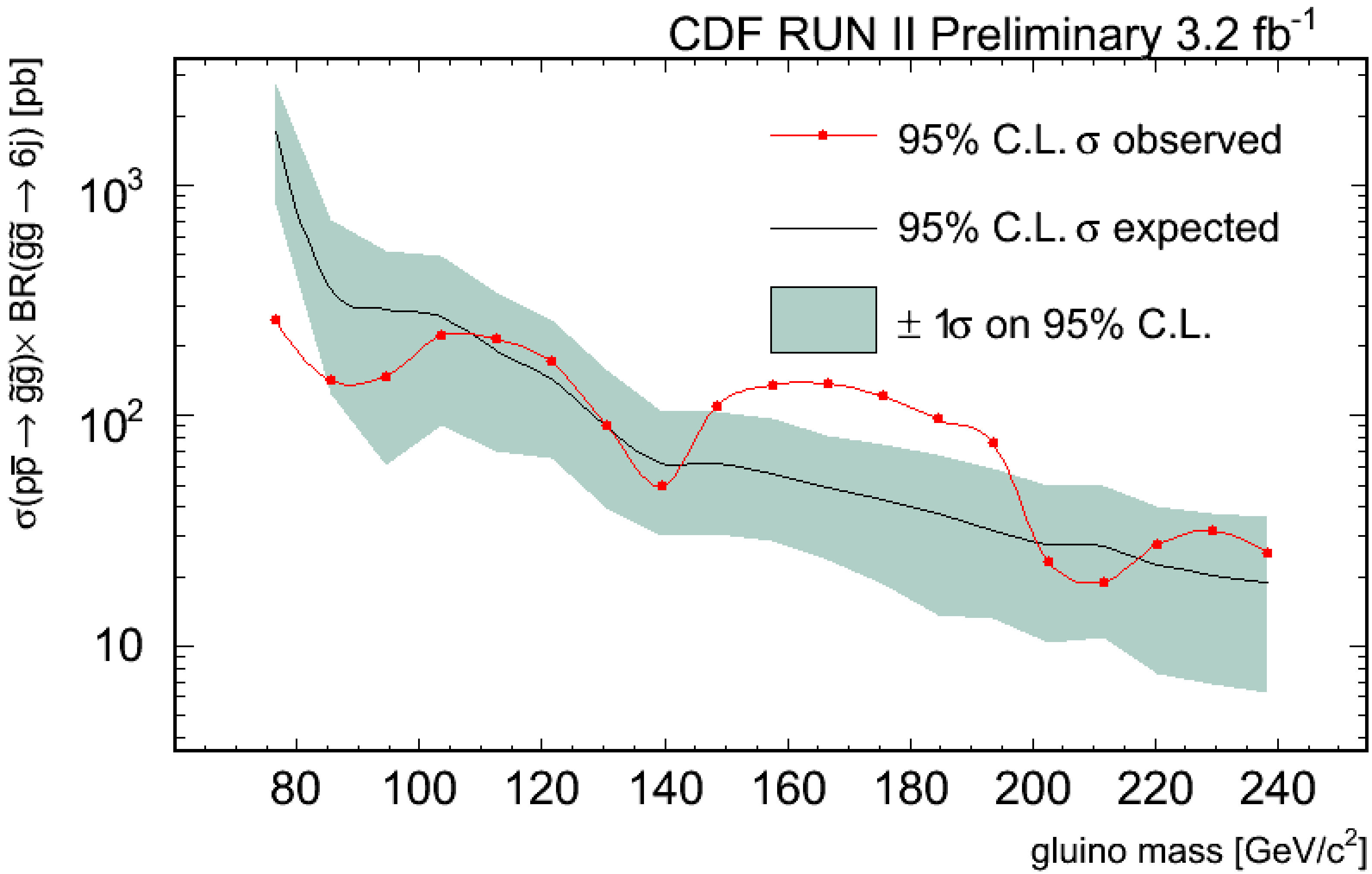
See ~2σ excess. More on this fit later...

The m=175 fit

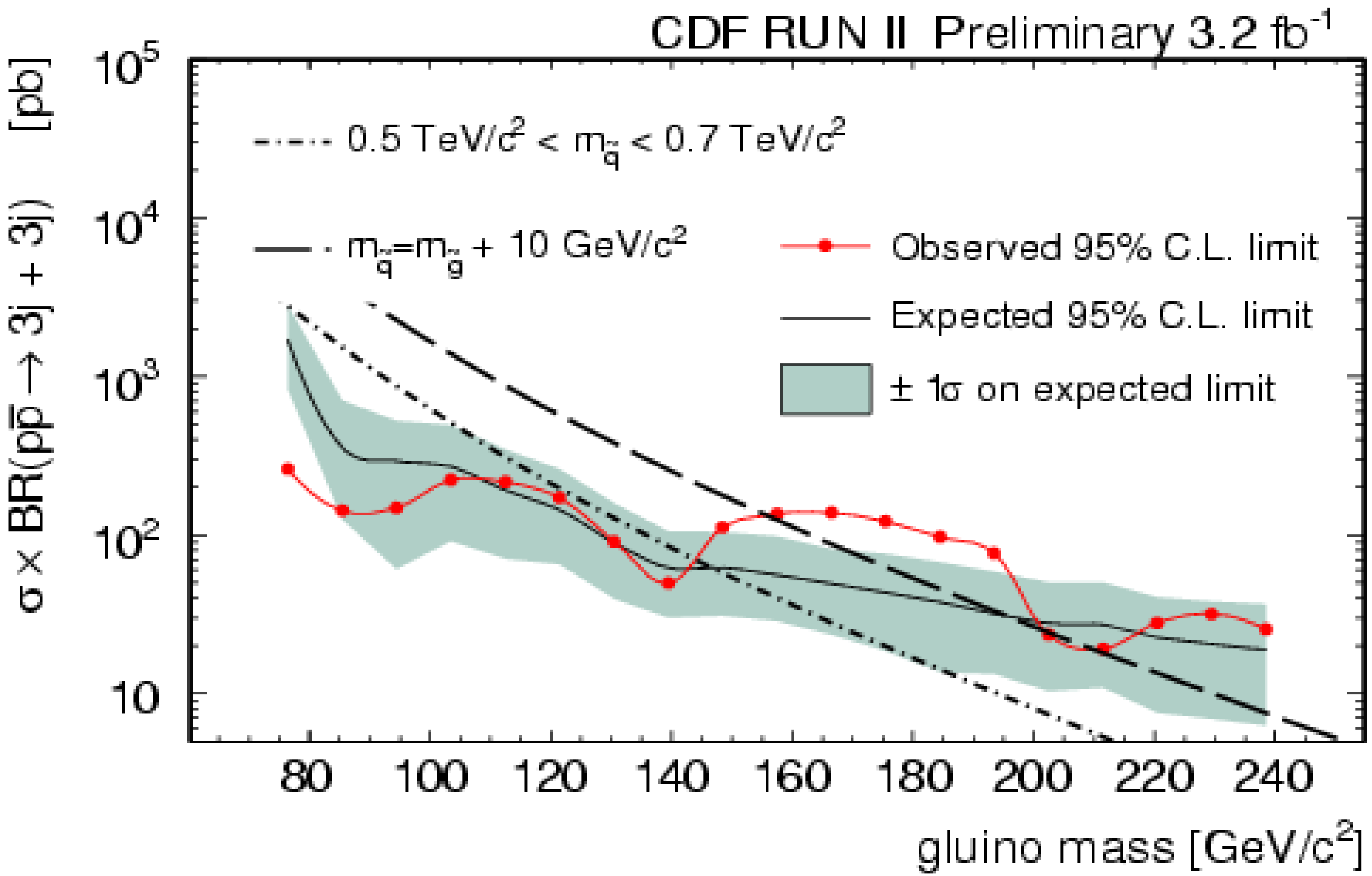


At the top mass, we expect ~1 event,
But see 11 events (+-1 σ integral of Gaussian)

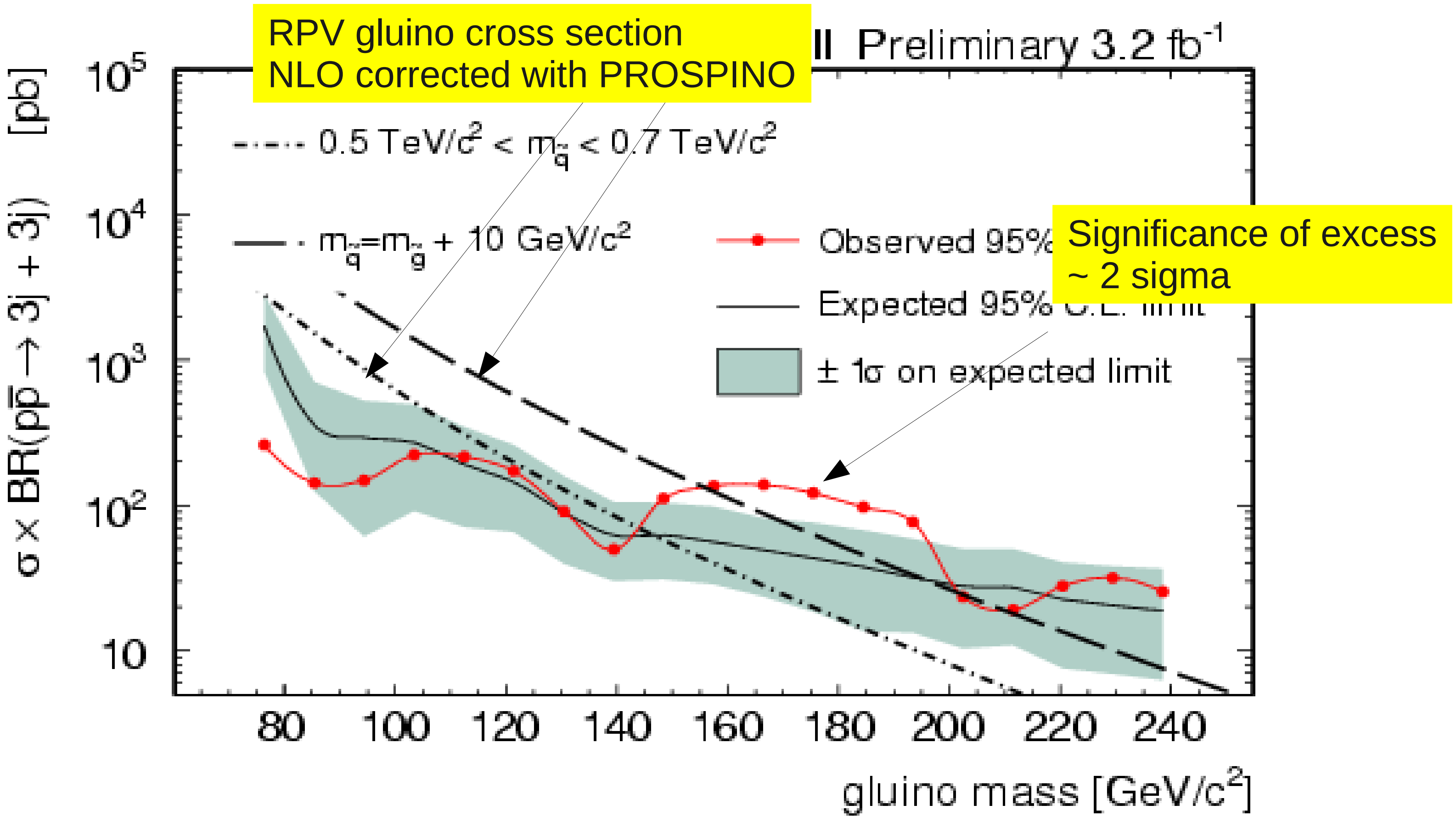
Limits


CDF RUN II Preliminary 3.2 fb^{-1}
$\sigma(p\bar{p} \to \tilde{g}\tilde{g}) \times BR(\tilde{g}\tilde{g} \to 6j)$ [pb]
10^3
10^2
10
80
100
120
140
160
180
200
220
240
gluino mass [GeV/c^2]
95% C.L. σ observed
95% C.L. σ expected
± 1σ on 95% C.L.

Limits


CDF RUN II Preliminary 3.2 fb^{-1}
0.5 TeV/c^2 < $m_{\tilde{q}}$ < 0.7 TeV/c^2
$m_{\tilde{q}}$=$m_{\tilde{g}}$ + 10 GeV/c^2
Observed 95% C.L. limit
Expected 95% C.L. limit
± 1σ on expected limit
σ × BR(p$\bar{p}$ → 3j + 3j) [pb]
10^5
10^4
10^3
10^2
10
80
100
120
140
160
180
200
220
240
gluino mass [GeV/c^2]

Limits



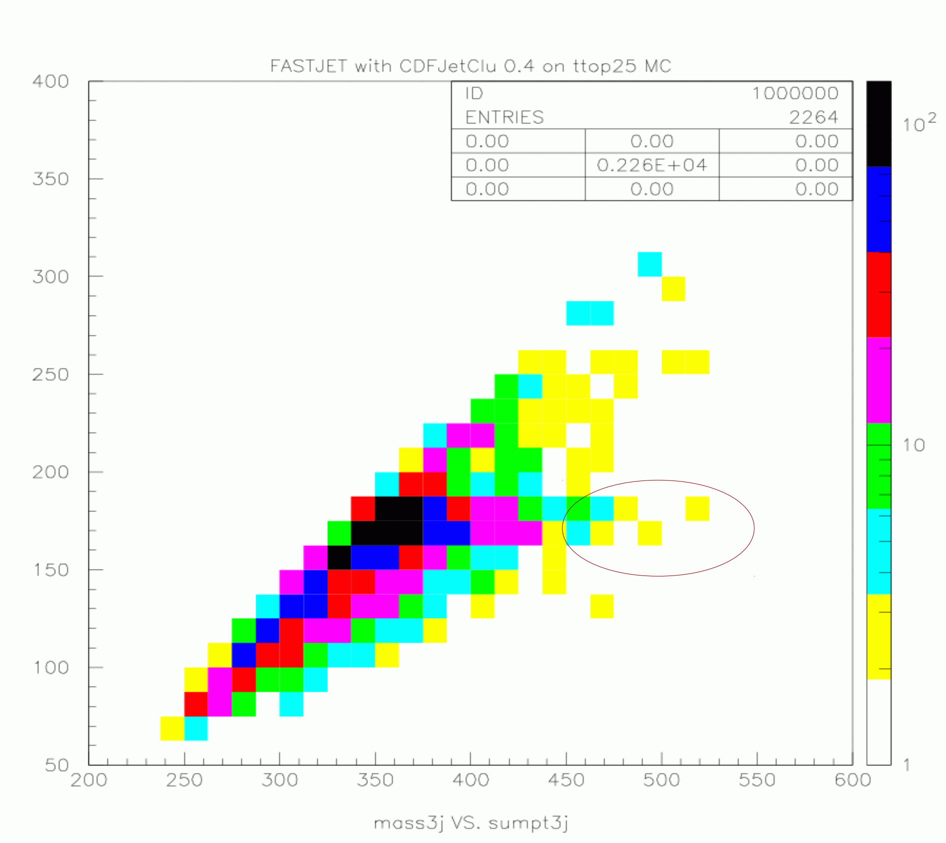
RPV gluino cross section
NLO corrected with PROSPINO
II Preliminary 3.2 fb-1
0.5 TeV/c2 < mq̃ < 0.7 TeV/c2
mq̃=mg̃ + 10 GeV/c2
Observed 95%
Significance of excess
~ 2 sigma
Expected 95% C.L. limit
± 1σ on expected limit
σ × BR(pp̄ → 3j + 3j) [pb]
10
10²
10³
10⁴
10⁵
80
100
120
140
160
180
200
220
240
gluino mass [GeV/c²]

Examine top acceptance

- We looked at various top MC
  - PYTHIA (various mtop)
  - CTEQ and MRST PDFs
  - more/less ISR and FSR
  - ALPGEN → PYTHIA
  - MC@NLO
- All predict 0.75 – 1.5 events after diagonal cut of 190 GeV.
- Excess is robust wrt sliding pt, diagonal cut around nominal.
- These are 3.2 fb-1 plots. We also looked at
  - 6 fb-1 of data
  - JET100 trigger (not good for m=90, but fine for m>150)
  - Semileptonic top (in lepton+4jet events)
- Bottom line: excess is real, there is a discrepancy with MC

Toy top study

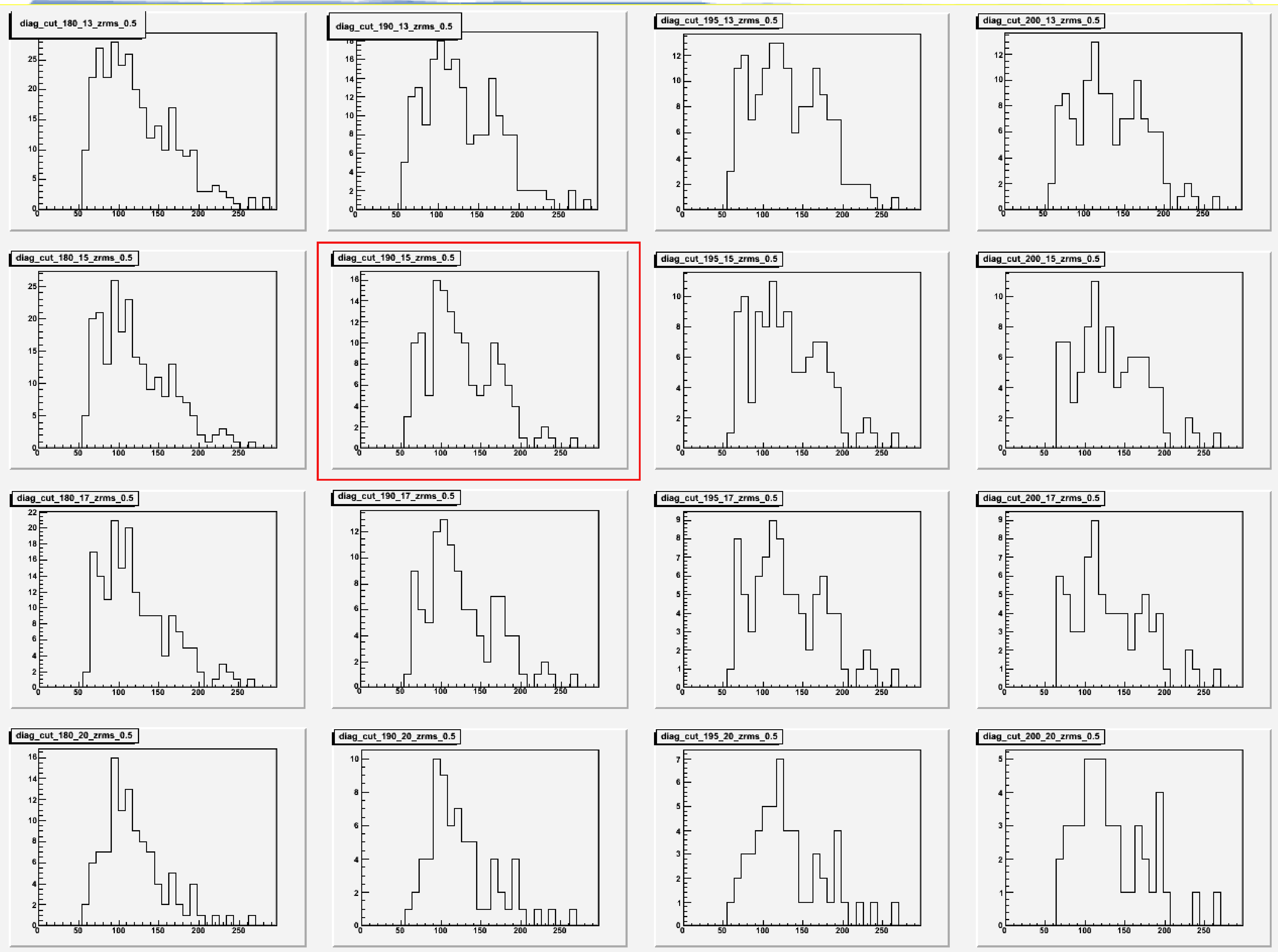
- Generator-level study
- PYTHIA → FastJet
  - Perfect detector output.
- After just eta, pt, diagonal cuts:
  - Expect 5.5 events.
- Note that jet_z, detector ineff. not taken into account at all.
- MC simply *not producing* enough top with high pt.



Conclusion

- Developed a new technique (ensemble method) to extract correlated objects in a multi-object background
  - Working closely with theorists pays off big!
    - Rouven Essig (theory GS) thesis on ensemble technique
  - Used it to look at 3jet in multi-jet events
  - Technique will work with other objects.
    - Add leptons, photons, MET?
- Found an excess at top mass. Significance ~2σ
  - Stat. Fluctuation? Boosted tops? PDFs? New physics?
  - Studying this with more data now.
  - Same group doing this analysis on CMS.

Backup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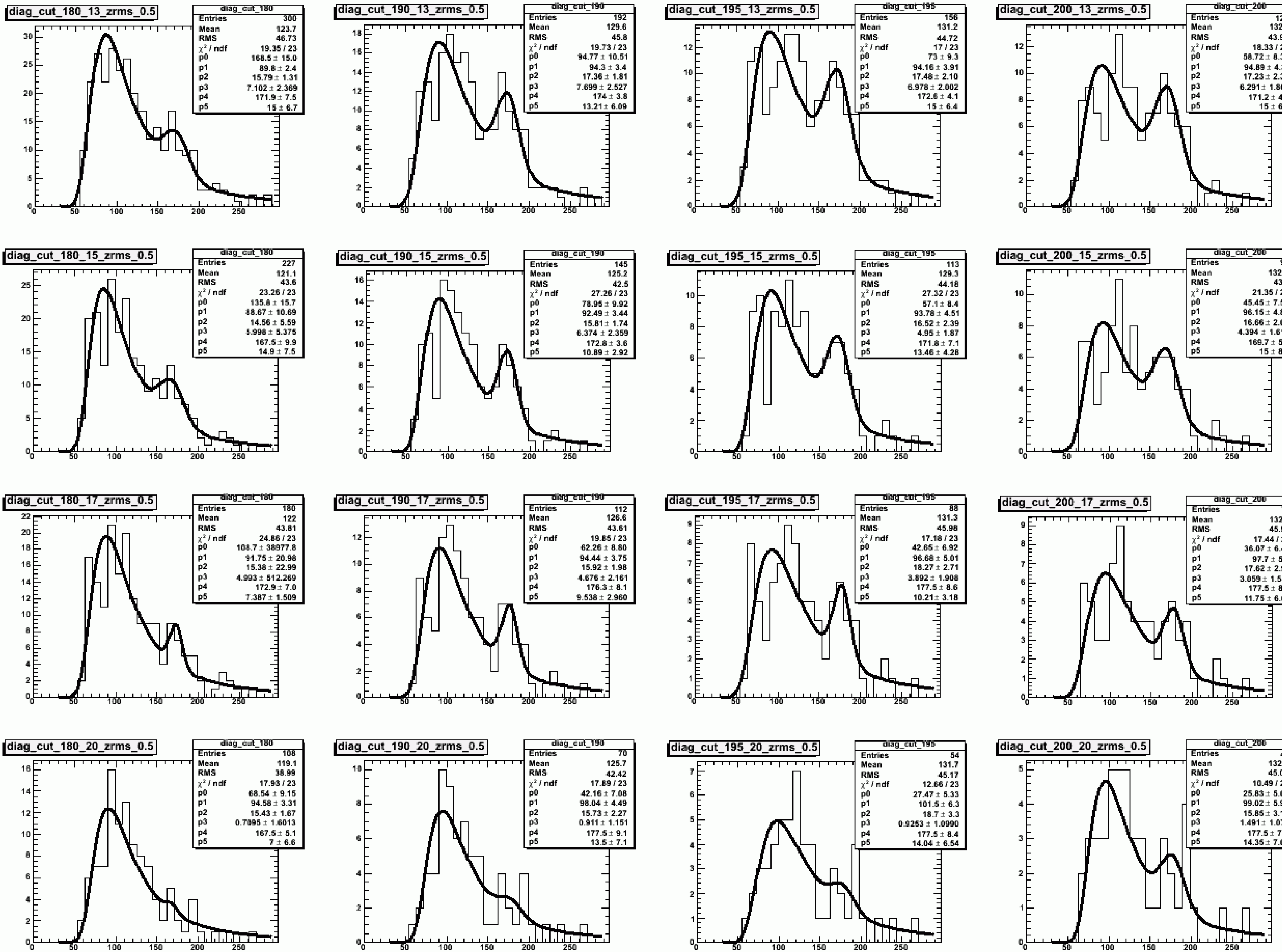
diag_cut_200_20_zrms_0.5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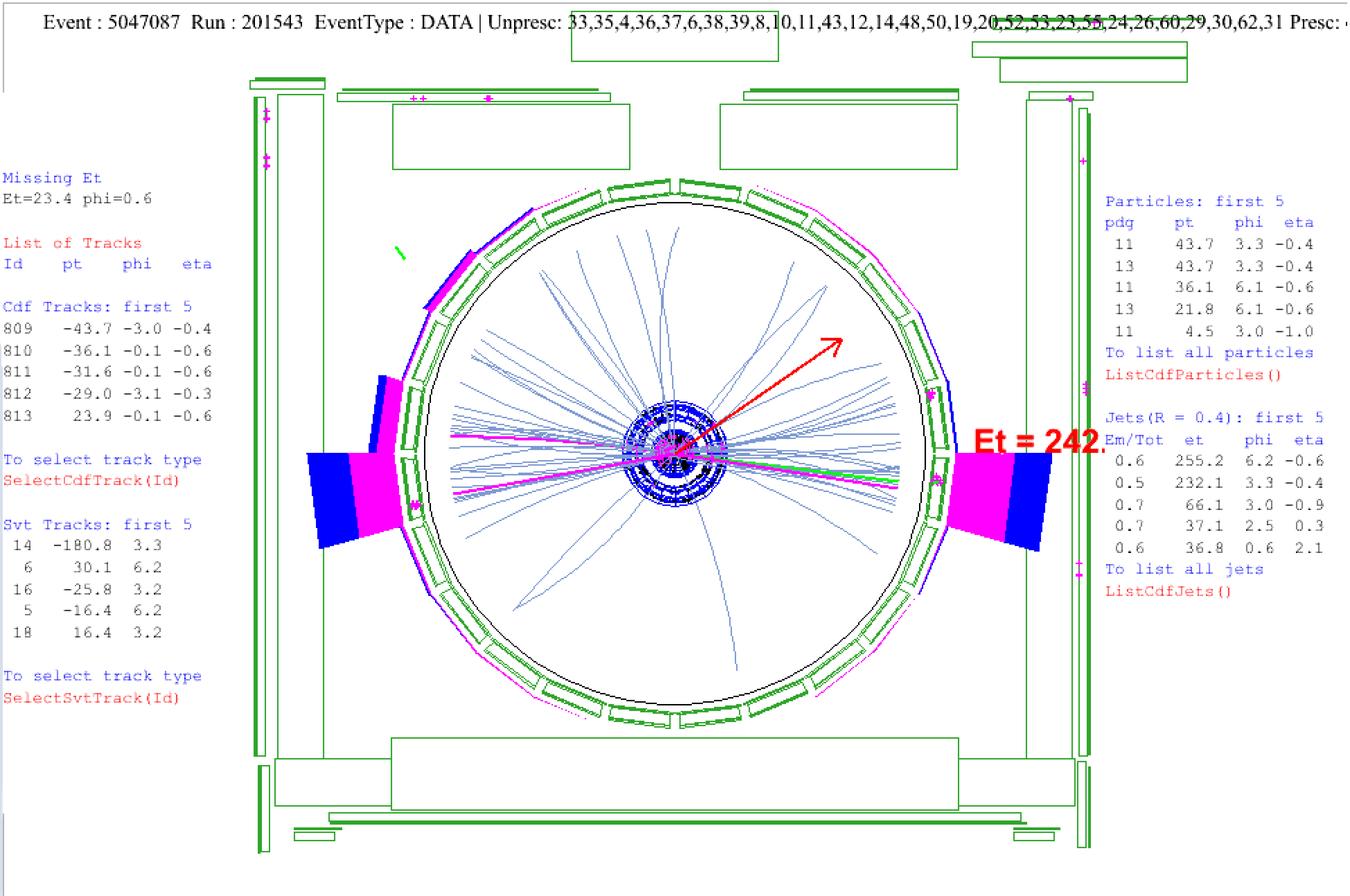
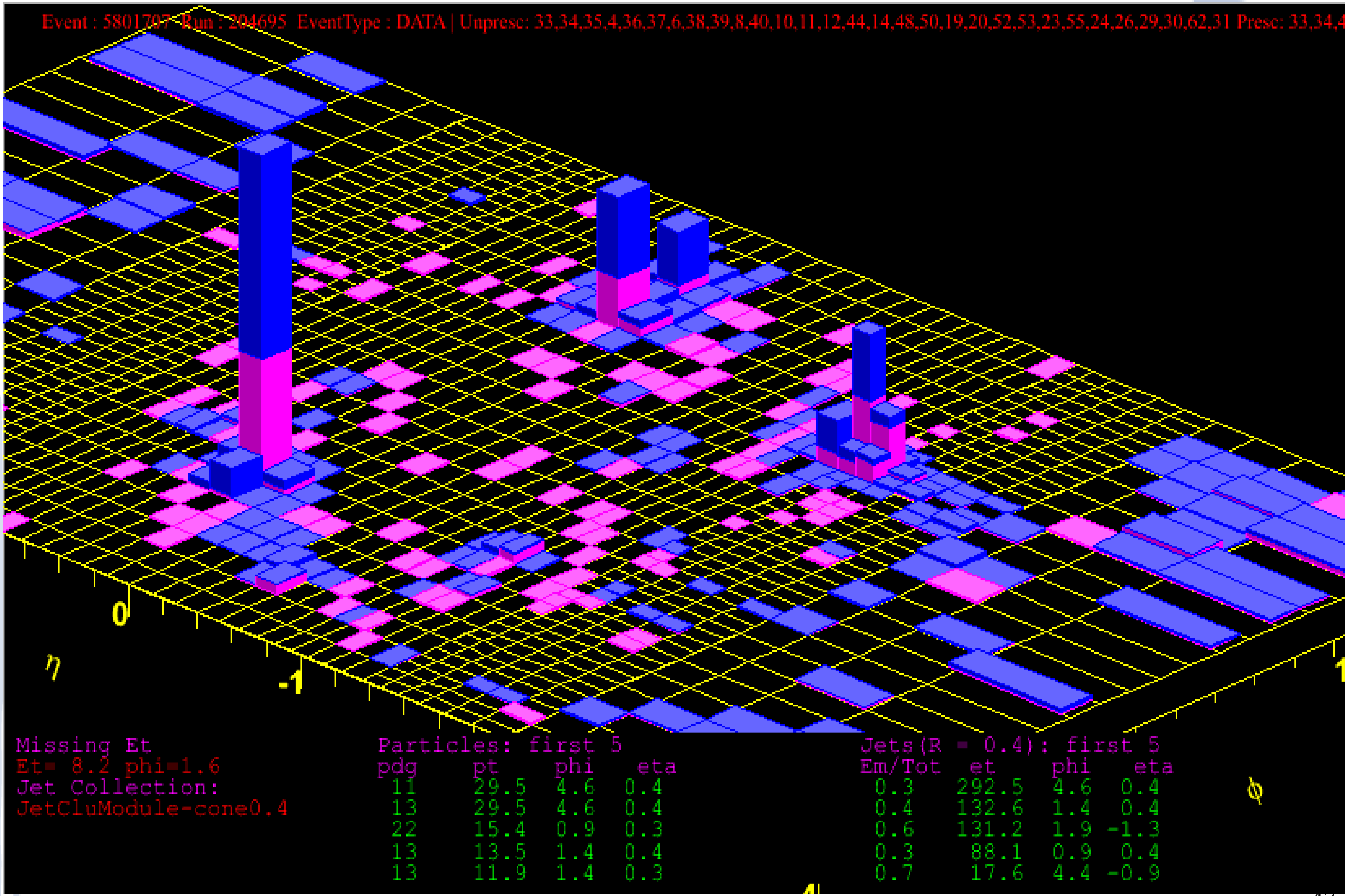
diag_cut_180
Entries 300
Mean 123.7
RMS 46.73
χ² / ndf 19.35 / 23
p0 168.5 ± 15.0
p1 89.8 ± 2.4
p2 15.79 ± 1.31
p3 7.102 ± 2.369
p4 171.9 ± 7.5
p5 15 ± 6.7
diag_cut_190_13_zrms_0.5
diag_cut_190
Entries 192
Mean 129.6
RMS 45.8
χ² / ndf 19.73 / 23
p0 94.77 ± 10.51
p1 94.3 ± 3.4
p2 17.36 ± 1.81
p3 7.699 ± 2.527
p4 174 ± 3.8
p5 13.21 ± 6.09
diag_cut_195_13_zrms_0.5
diag_cut_195
Entries 156
Mean 131.2
RMS 44.72
χ² / ndf 17 / 23
p0 73 ± 9.3
p1 94.16 ± 3.91
p2 17.48 ± 2.10
p3 6.978 ± 2.002
p4 172.6 ± 4.1
p5 15 ± 6.4
diag_cut_200_13_zrms_0.5
diag_cut_200
Entries 127
Mean 132.1
RMS 43.93
χ² / ndf 18.33 / 23
p0 58.72 ± 8.35
p1 94.89 ± 4.31
p2 17.23 ± 2.30
p3 6.291 ± 1.866
p4 171.2 ± 4.1
p5 15 ± 6.8
diag_cut_180_15_zrms_0.5
diag_cut_180
Entries 227
Mean 121.1
RMS 43.6
χ² / ndf 23.26 / 23
p0 135.8 ± 15.7
p1 88.67 ± 10.69
p2 14.56 ± 5.59
p3 5.998 ± 5.375
p4 167.5 ± 9.9
p5 14.9 ± 7.5
diag_cut_190_15_zrms_0.5
diag_cut_190
Entries 145
Mean 125.2
RMS 42.5
χ² / ndf 27.26 / 23
p0 78.95 ± 9.92
p1 92.49 ± 3.44
p2 15.81 ± 1.74
p3 6.374 ± 2.359
p4 172.8 ± 3.6
p5 10.89 ± 2.92
diag_cut_195_15_zrms_0.5
diag_cut_195
Entries 113
Mean 129.3
RMS 44.18
χ² / ndf 27.32 / 23
p0 57.1 ± 8.4
p1 93.78 ± 4.51
p2 16.52 ± 2.39
p3 4.95 ± 1.87
p4 171.8 ± 7.1
p5 13.46 ± 4.28
diag_cut_200_15_zrms_0.5
diag_cut_200
Entries 94
Mean 132.2
RMS 43.6
χ² / ndf 21.35 / 23
p0 45.45 ± 7.52
p1 96.15 ± 4.84
p2 16.66 ± 2.60
p3 4.394 ± 1.613
p4 169.7 ± 5.8
p5 15 ± 8.0
diag_cut_180_17_zrms_0.5
diag_cut_180
Entries 180
Mean 122
RMS 43.81
χ² / ndf 24.86 / 23
p0 108.7 ± 38977.8
p1 91.75 ± 20.96
p2 15.38 ± 22.99
p3 4.993 ± 512.269
p4 172.9 ± 7.0
p5 7.387 ± 1.509
diag_cut_190_17_zrms_0.5
diag_cut_190
Entries 112
Mean 126.6
RMS 43.61
χ² / ndf 19.85 / 23
p0 62.26 ± 8.80
p1 94.44 ± 3.75
p2 15.92 ± 1.98
p3 4.676 ± 2.161
p4 176.3 ± 8.1
p5 9.538 ± 2.960
diag_cut_195_17_zrms_0.5
diag_cut_195
Entries 88
Mean 131.3
RMS 45.98
χ² / ndf 17.18 / 23
p0 42.65 ± 6.92
p1 96.68 ± 5.01
p2 18.27 ± 2.71
p3 3.892 ± 1.908
p4 177.5 ± 8.6
p5 10.21 ± 3.18
diag_cut_200_17_zrms_0.5
diag_cut_200
Entries 73
Mean 132.8
RMS 45.94
χ² / ndf 17.44 / 23
p0 36.07 ± 6.40
p1 97.7 ± 5.4
p2 17.62 ± 2.96
p3 3.059 ± 1.585
p4 177.5 ± 8.6
p5 11.75 ± 6.03
diag_cut_180_20_zrms_0.5
diag_cut_180
Entries 108
Mean 119.1
RMS 38.99
χ² / ndf 17.93 / 23
p0 68.54 ± 9.15
p1 94.58 ± 3.31
p2 15.43 ± 1.67
p3 0.7095 ± 1.6013
p4 167.5 ± 5.1
p5 7 ± 6.6
diag_cut_190_20_zrms_0.5
diag_cut_190
Entries 70
Mean 125.7
RMS 42.42
χ² / ndf 17.89 / 23
p0 42.16 ± 7.08
p1 98.04 ± 4.49
p2 15.73 ± 2.27
p3 0.911 ± 1.151
p4 177.5 ± 9.1
p5 13.5 ± 7.1
diag_cut_195_20_zrms_0.5
diag_cut_195
Entries 54
Mean 131.7
RMS 45.17
χ² / ndf 12.66 / 23
p0 27.47 ± 5.33
p1 101.5 ± 6.3
p2 18.7 ± 3.3
p3 0.9253 ± 1.0990
p4 177.5 ± 8.4
p5 14.04 ± 6.54
diag_cut_200_20_zrms_0.5
diag_cut_200
Entries 47
Mean 132.4
RMS 45.02
χ² / ndf 10.49 / 23
p0 25.83 ± 5.69
p1 99.02 ± 5.95
p2 15.85 ± 3.18
p3 1.491 ± 1.079
p4 177.5 ± 7.5
p5 14.35 ± 7.65

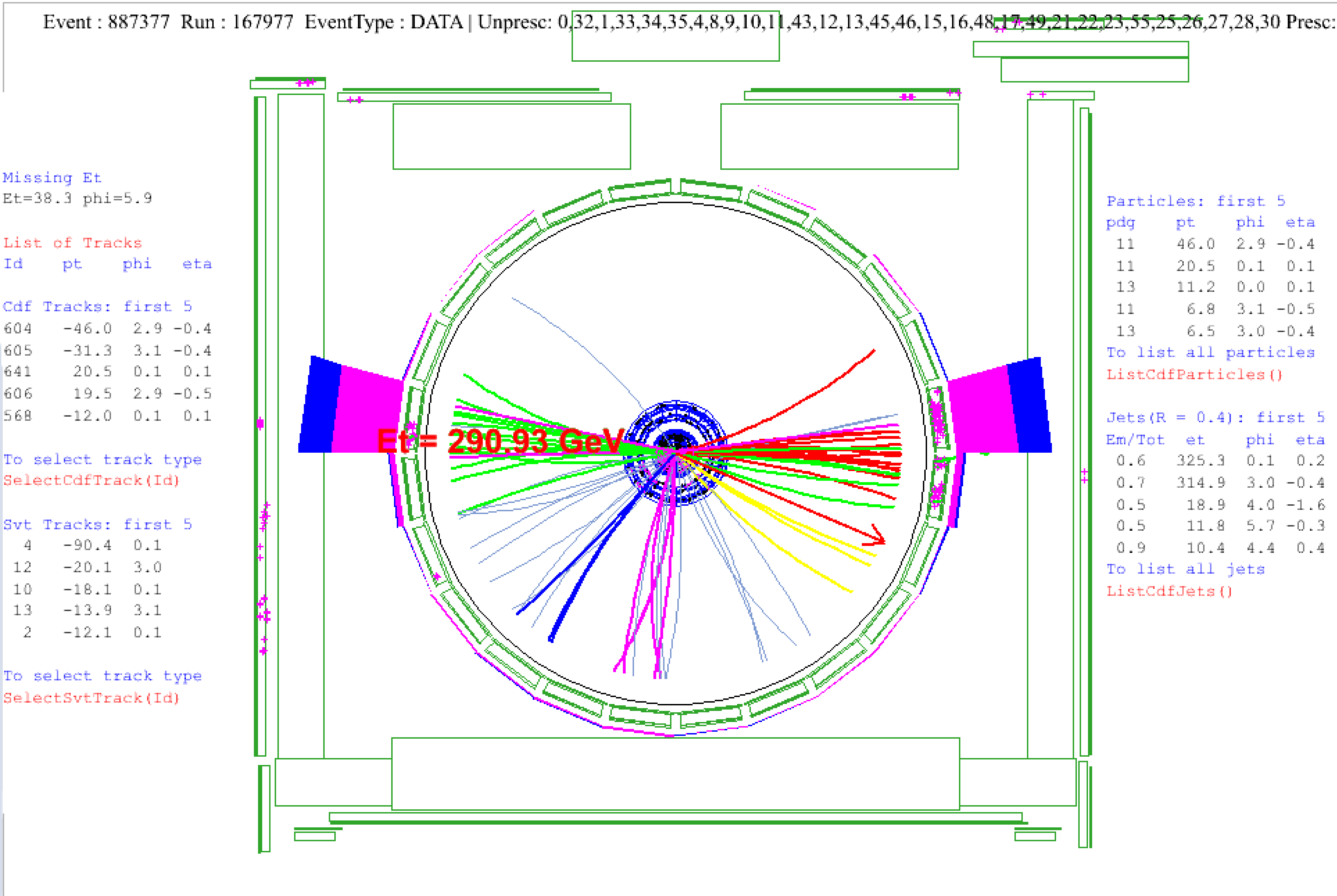
Data event display, in mass window



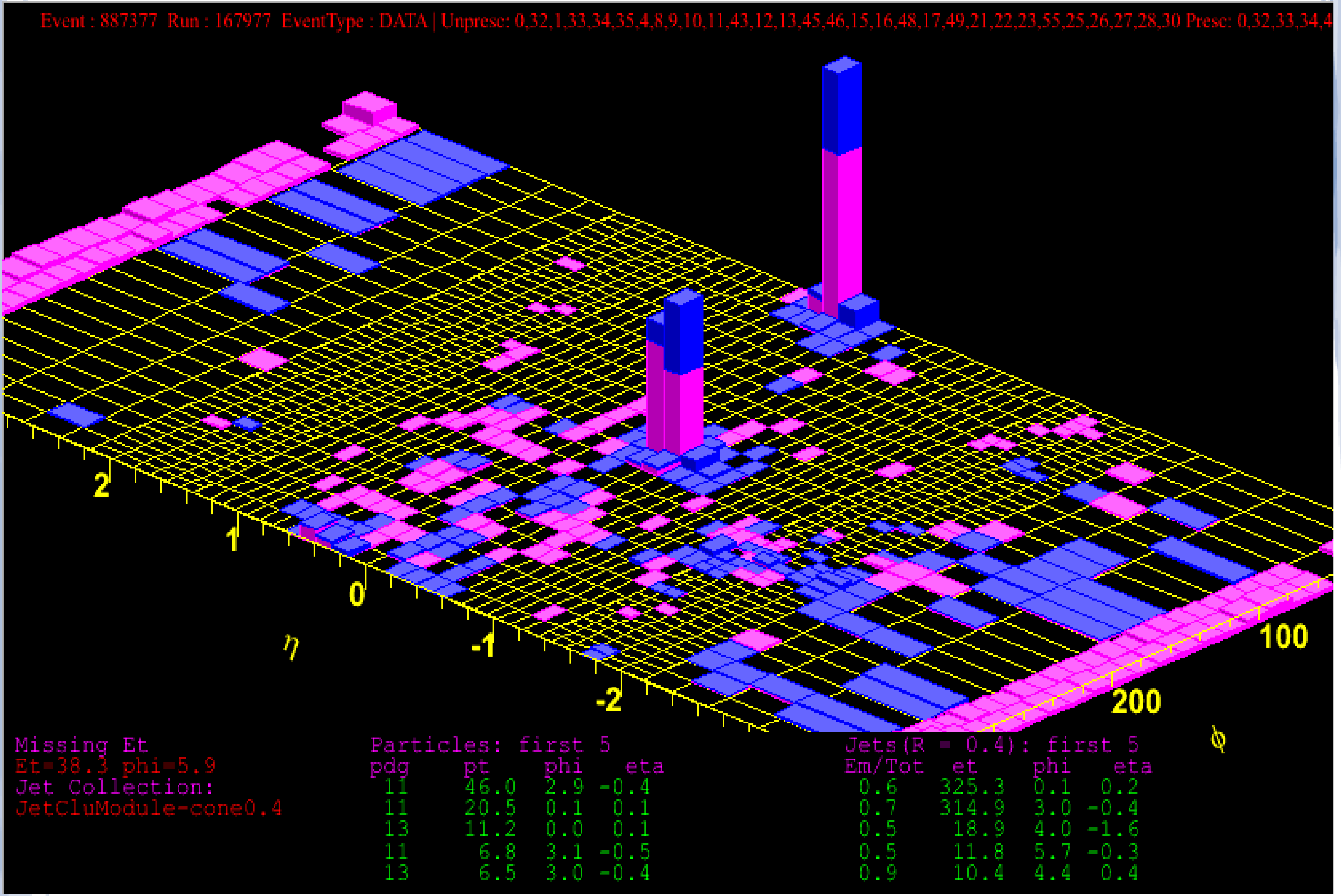
Data event display, in mass window



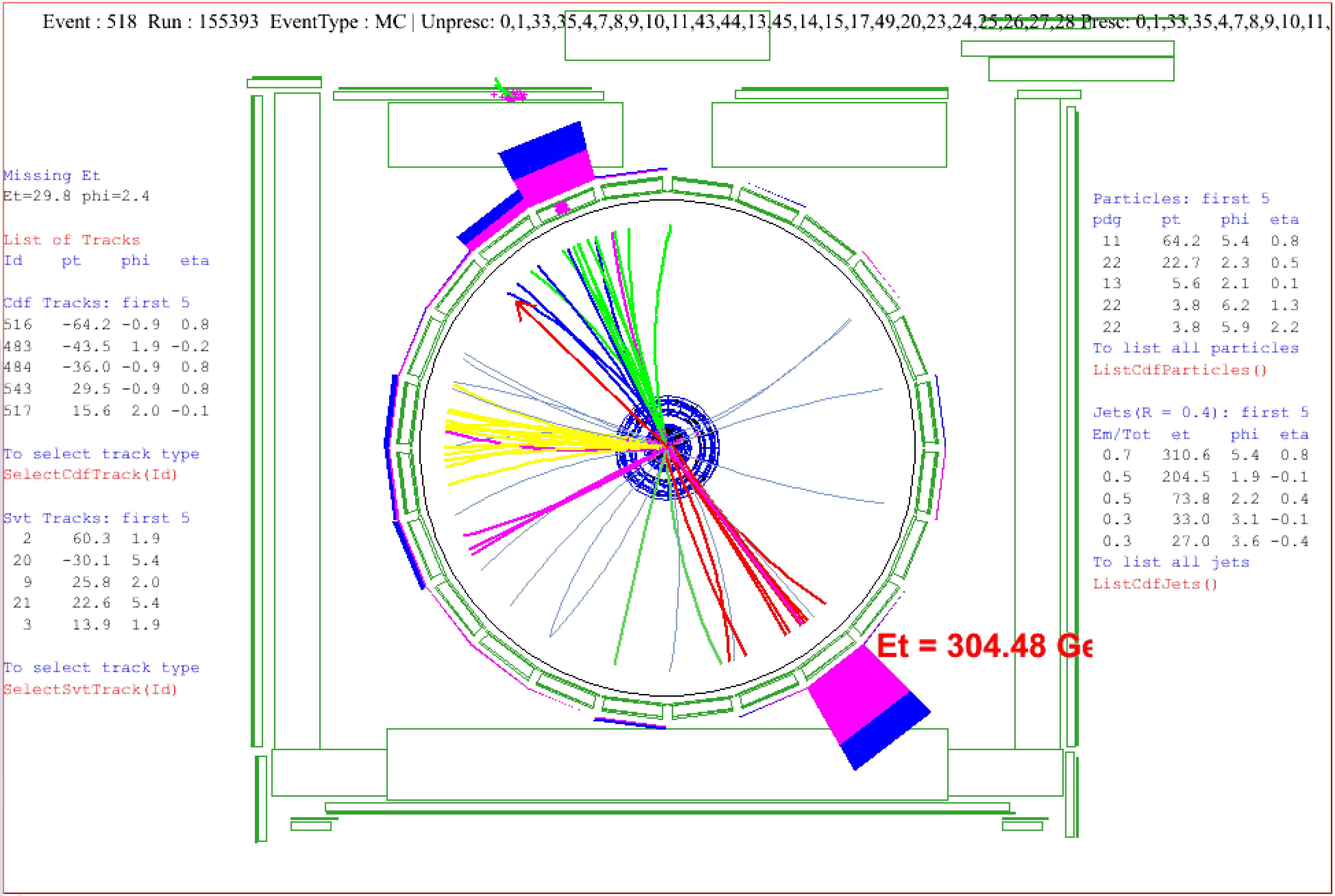
Data event display, in mass window



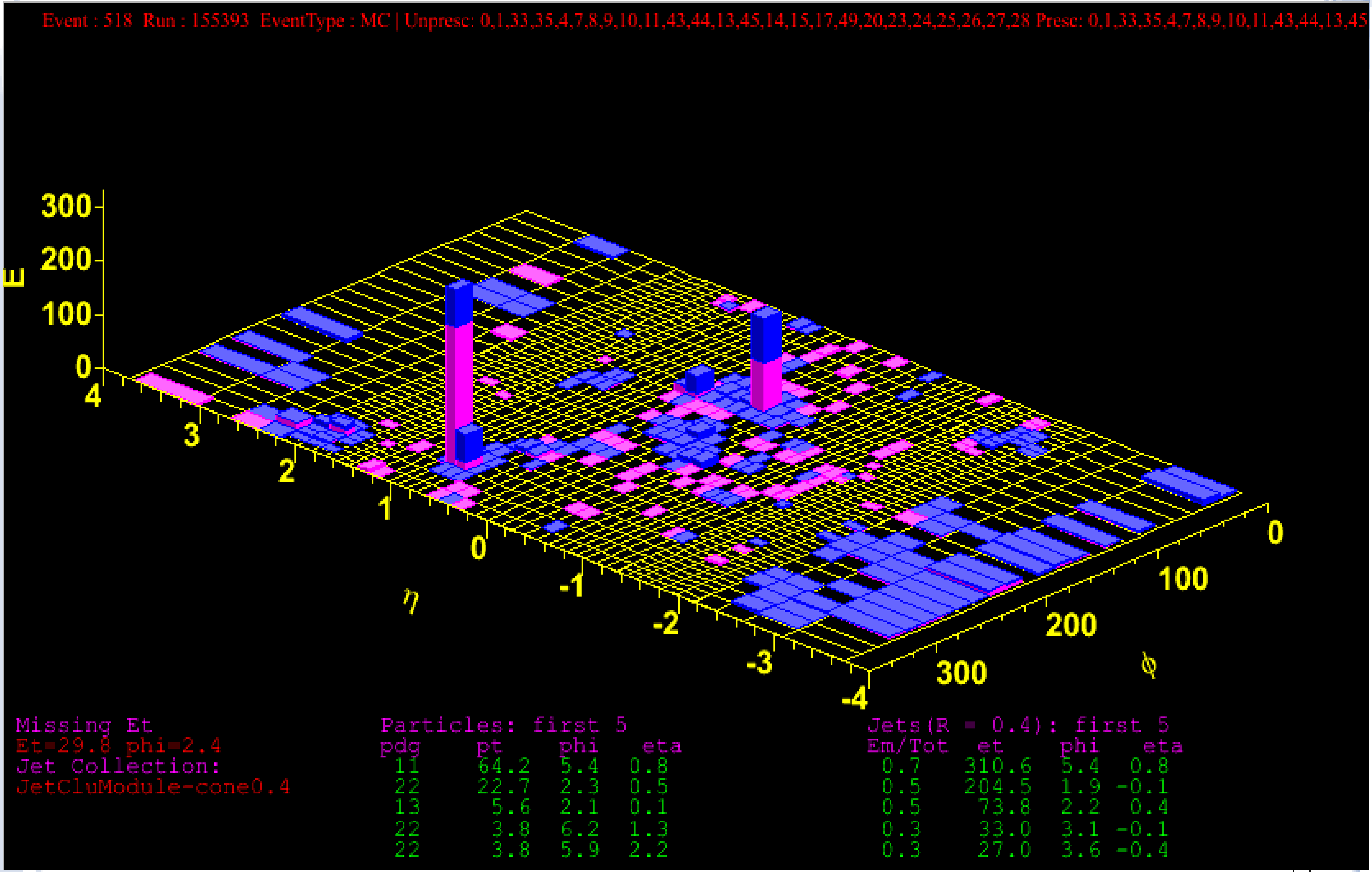
Data event display, in mass window



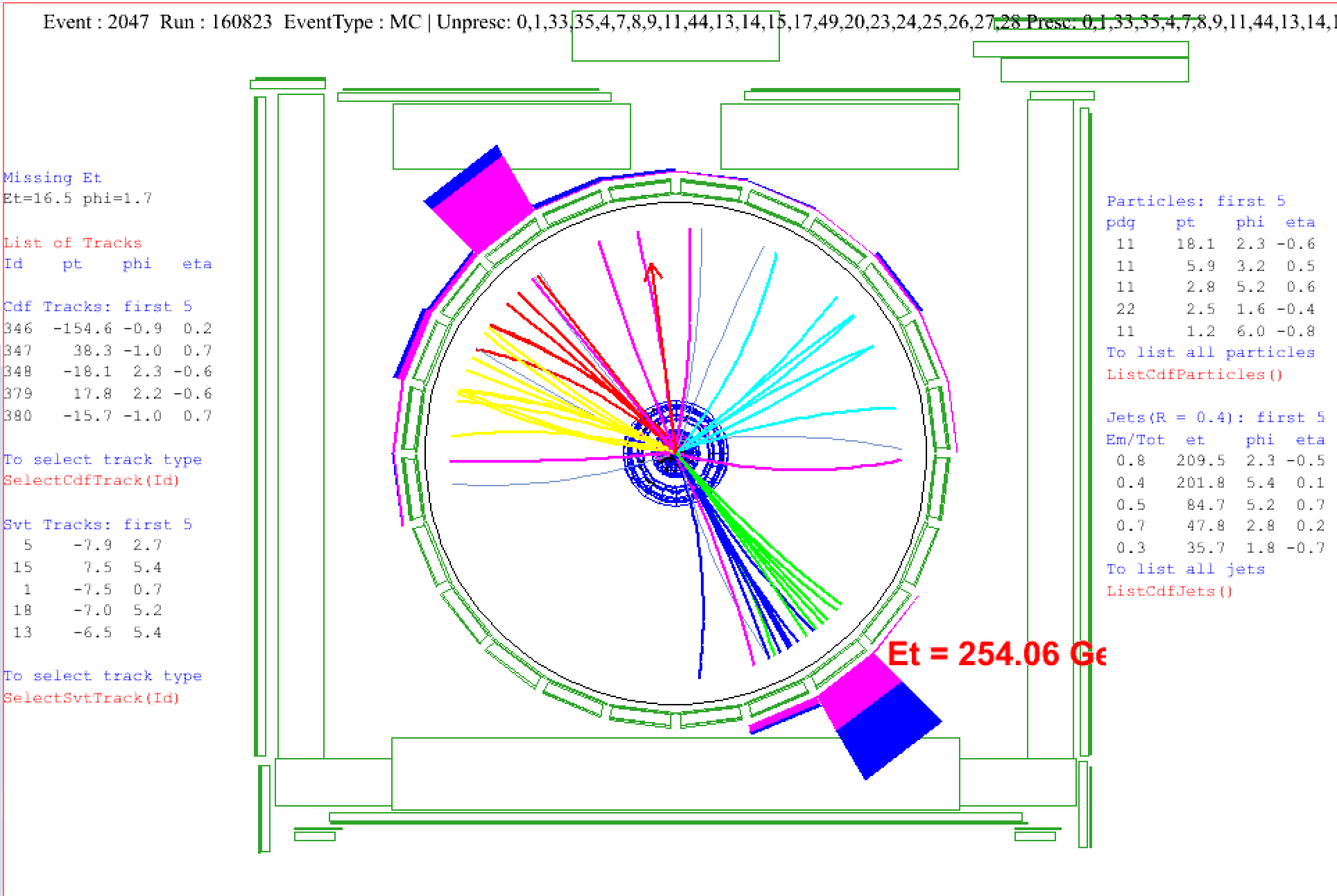
MC ttbar event display, in mass window



MC ttbar event display, in mass window



MC ttbar event display, in mass window



MC ttbar event display, in mass window