Jet-jet angular distributions and search for quark substructure in p-$\bar{p}$ collisions at 1.96 TeV

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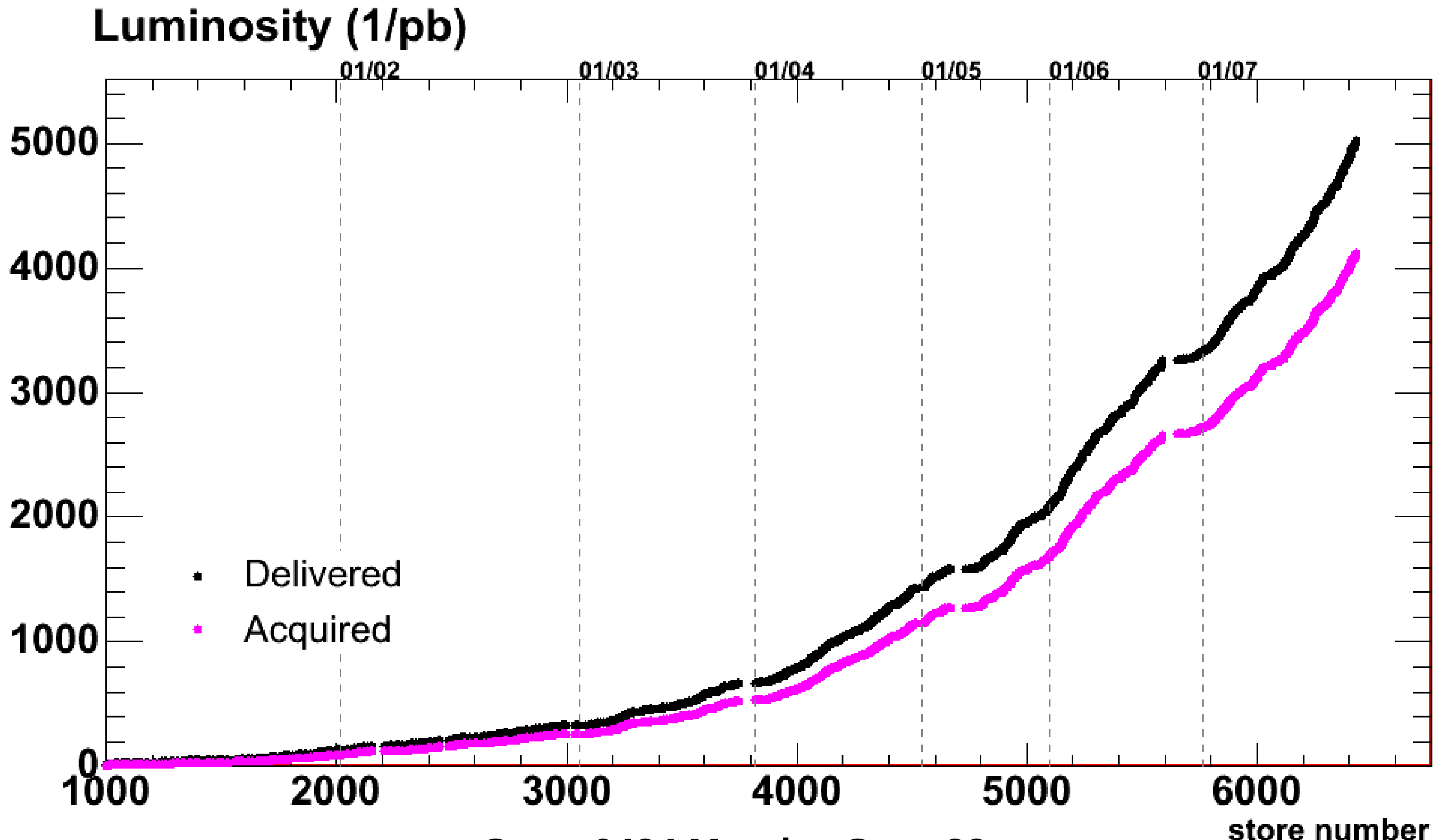
Tevatron Run2 Collider operations

- About 5 fb^{-1} delivered, and 4 fb^{-1} recorded each by CDF and D0.
- About 2 fb^{-1} delivered in calendar 2008.
- Instantaneous luminosity record 315 E30.
- Initial pbars 3E12 at 980 GeV.
- Run to last one or two more years.

Tevatron collider operations



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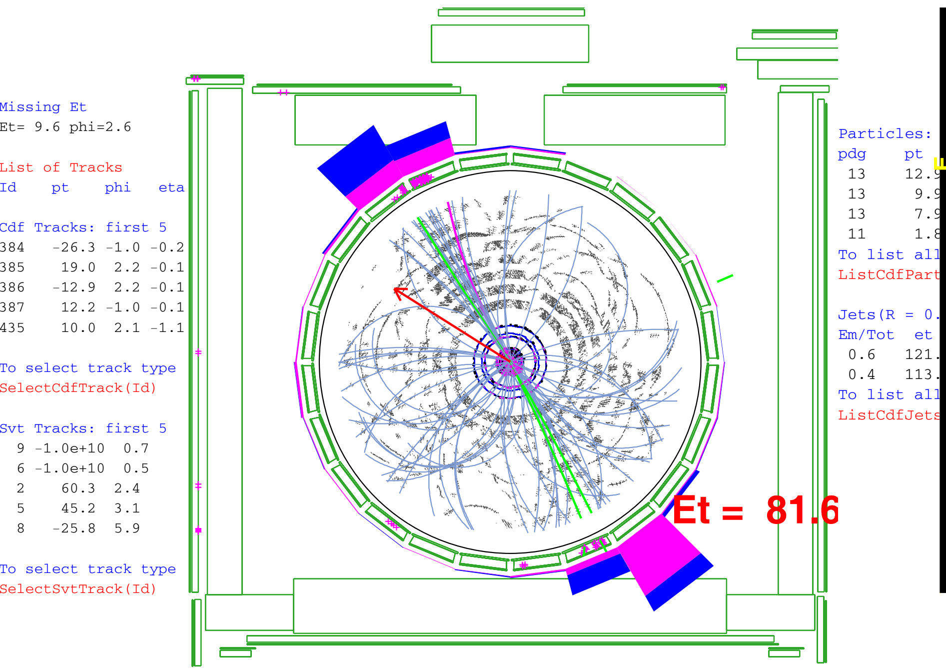
Data Sample

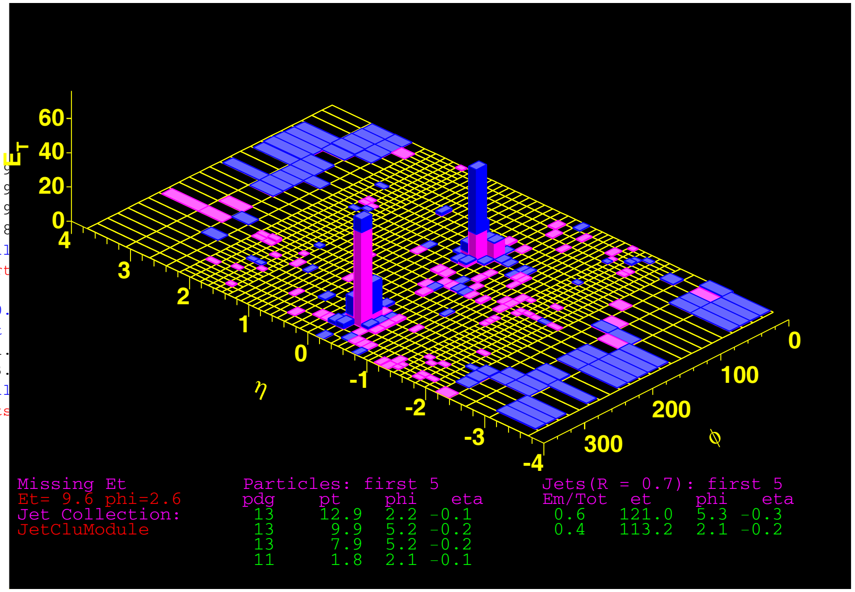
- 1.1 fb^{-1} integrated luminosity
- 12 million jet100 triggers
- 10 nb constant trigger cross section

Minimal cuts

- $|\eta|<2$
- $|Z_{vertex}|<60$ cm
- Missing ET significance < 5 $\sqrt{GeV}$

Typical dijet event display





QCD 2$\rightarrow$2 angular distributions

- The formulas of Combridge for q+q$\rightarrow$q+q, q+qbar$\rightarrow$q+qbar, q+qbar$\rightarrow$g+g, q+g$\rightarrow$q+g, g+g$\rightarrow$g+g, and g+g$\rightarrow$q+qbar give angular distributions which resemble Rutherford's formula $d\sigma/d\Omega \sim 1/\sin^4(\theta^*/2)$.

Rutherford's formula is flat in $\chi = \exp(|\eta_1 - \eta_2|)$

Where η's refer to the two leading jets

Jet-jet angular distribution and quark substructure

- Quark substructure effective contact color singlet Lagrangian of Eichten, et al is:
- $L = \pm(g^2/2\Lambda^2(\bar{\Psi}_L\gamma_\mu\bar{\Psi}_L)(\bar{\Psi}_L\gamma^\mu\Psi_L))$
- Looks just like muon decay. Affects only the u and d quarks. Color singlet means that some diagrams have no interference term.
- $g^2/4\pi = 1$; strength of the interaction $\sim(\hat{s}/\Lambda^2)^2$
- This measurement is not sensitive to the interference term.

Effect of quark substructure

- The quark substructure Lagrangian is basically isotropic, so the angular distribution near $\theta^*=\pi/2$, or $\chi=1$ is most sensitive to Λ.
- The E_T distribution also depends on Λ, but is more sensitive to the jet energy scale than the angular distribution in a given mass bin.

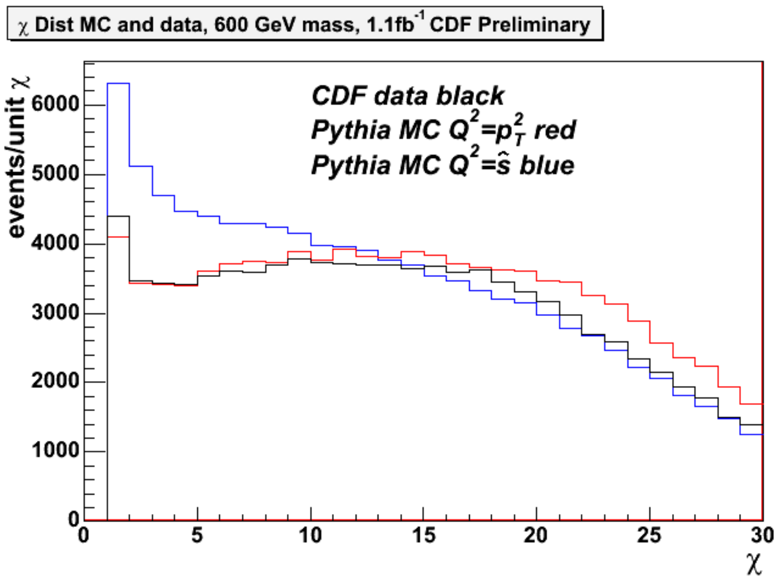
treatment of the data

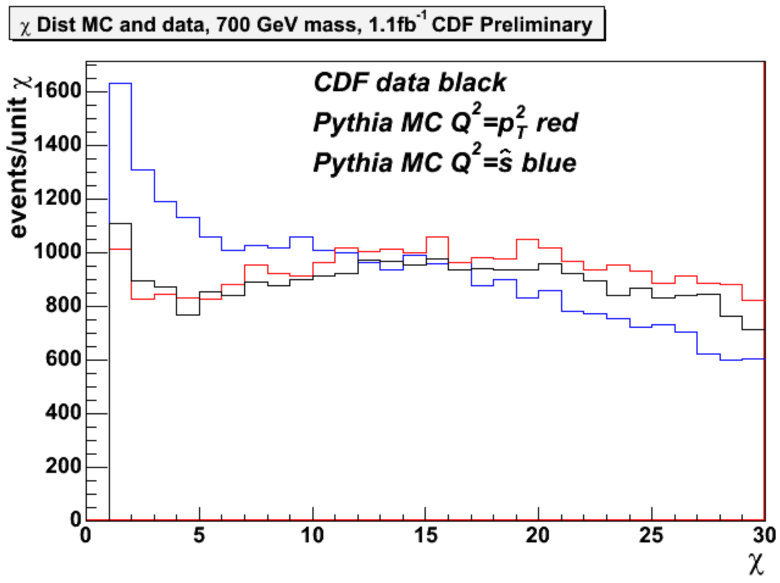
- Divide the data into four bins in jet-jet invariant mass, using the two highest E_T jets in the event. Do not look for third jets.
- Each bin is 100 GeV wide, starting at 550-650 GeV, and ending at 850-950 GeV.

Monte Carlo predicts the expected QCD distributions, and the effects of quark substructure

- The MC program used is Pythia.
- Pythia generates the QCD event at the ‘hadron level’, without the CDF detector simulation, via a multistep process involving ISR, 2→2,FSR, and parton fragmentation.
- Hadron level events are then subject to the full CDF detector simulation, and analyzed with the same code as data.

Pythia Angular distributions compared to CDF data





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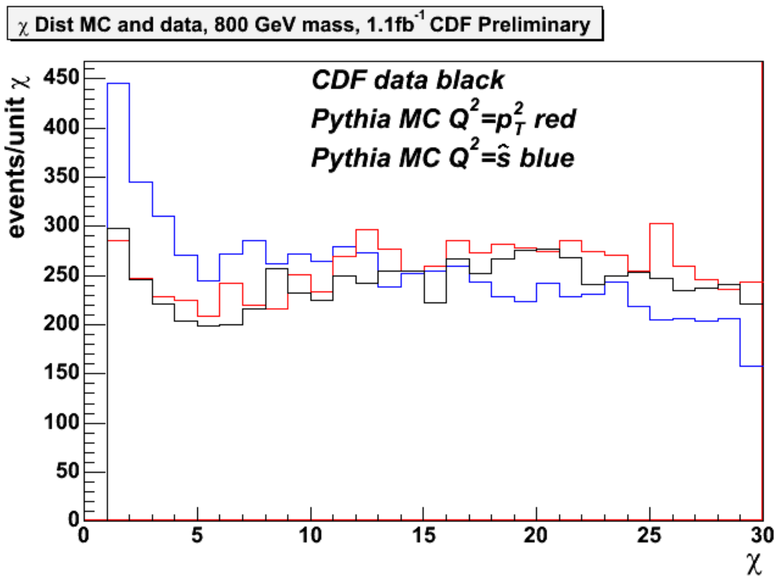
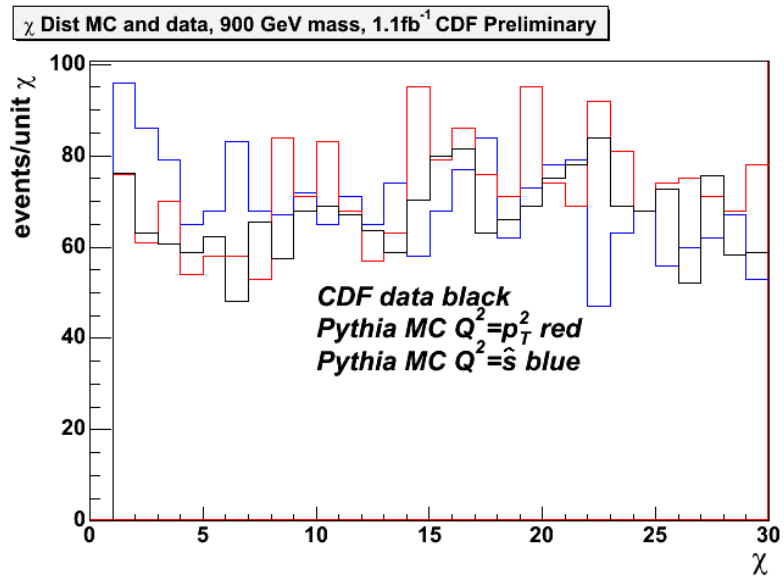
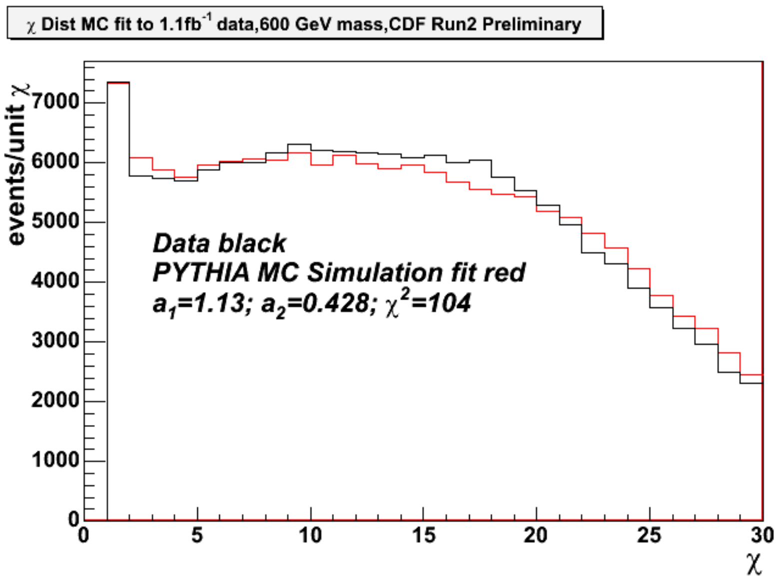
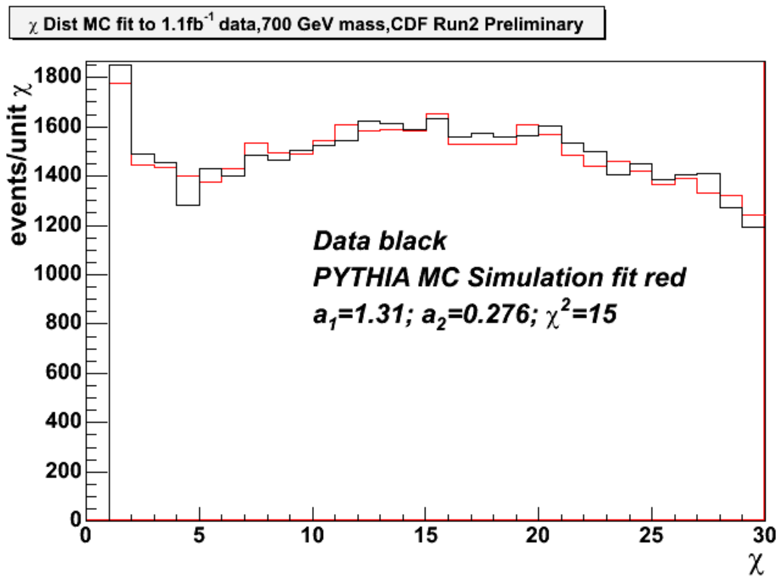




Pythia simulation fits to data
$a_1 \times p_T^2 + a_2 \times \hat{s}$





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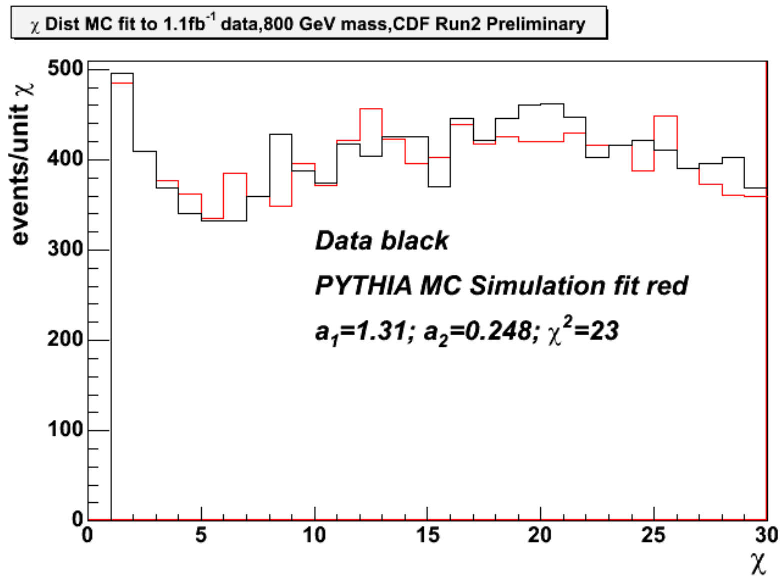
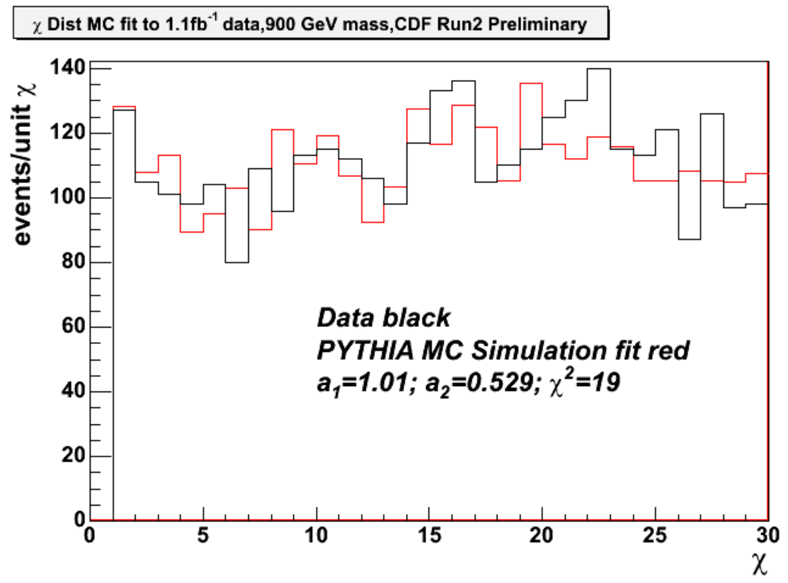
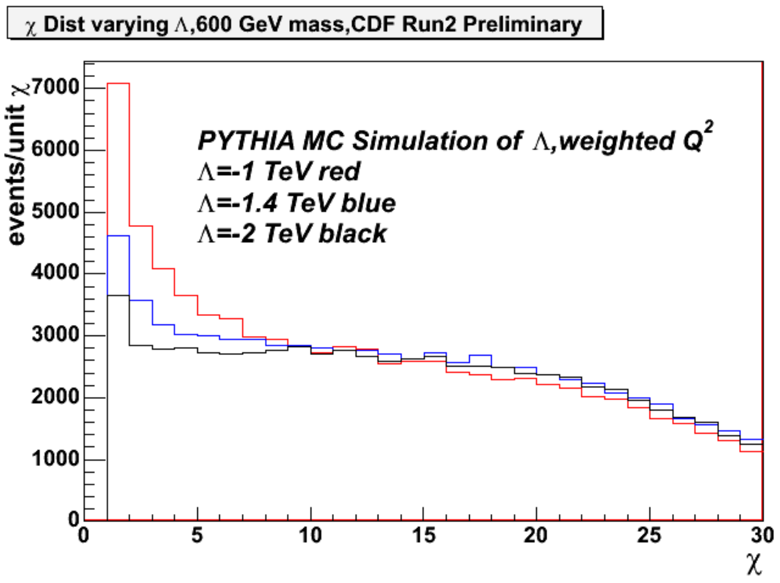
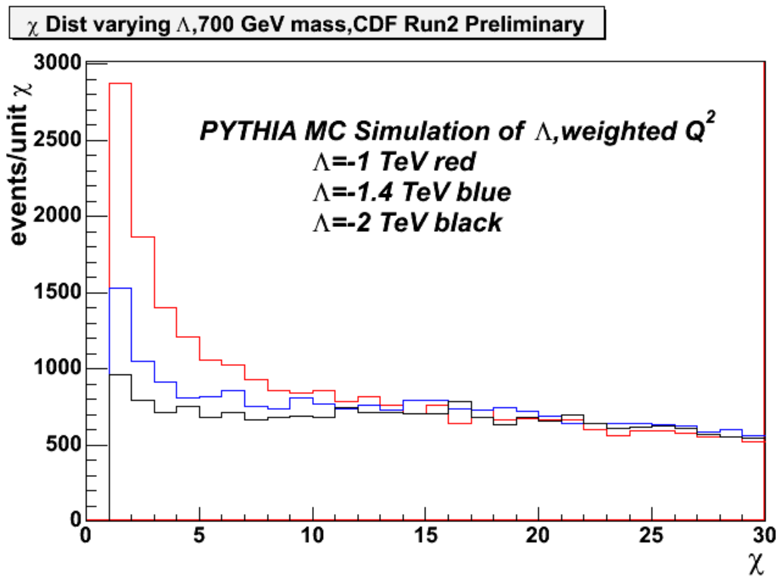




Pythia Monte Carlo Simulation of quark substructure





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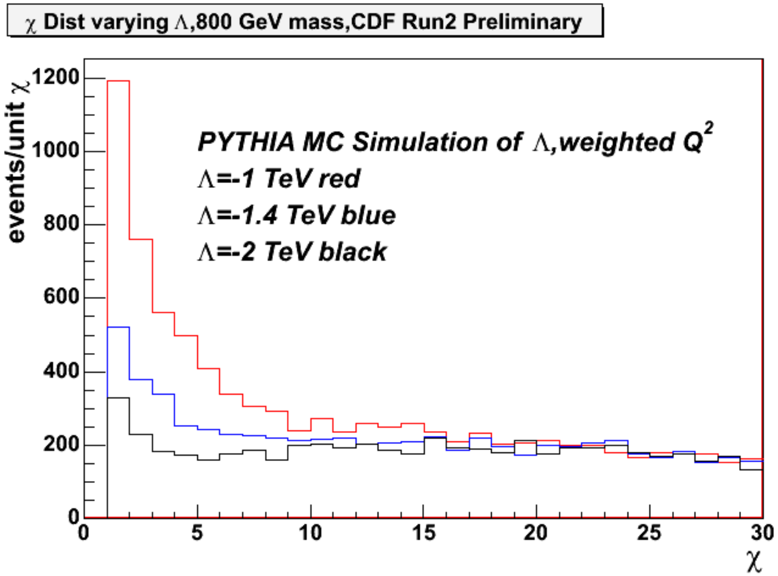
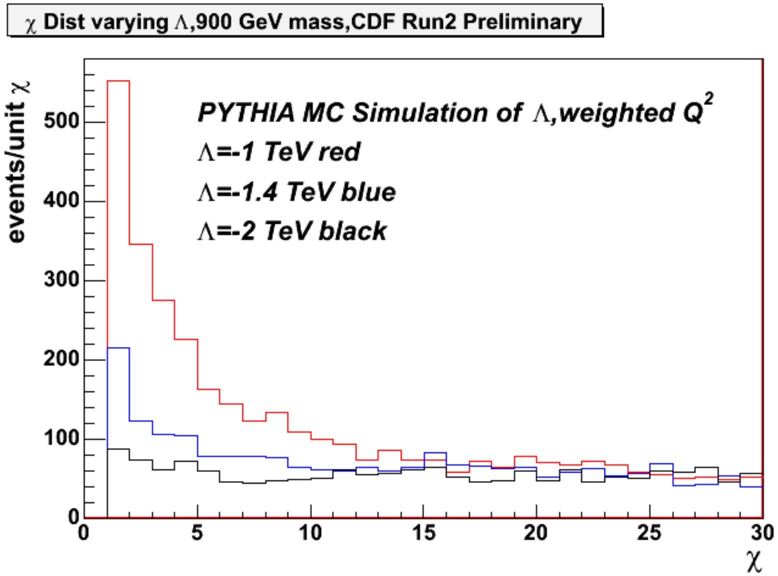
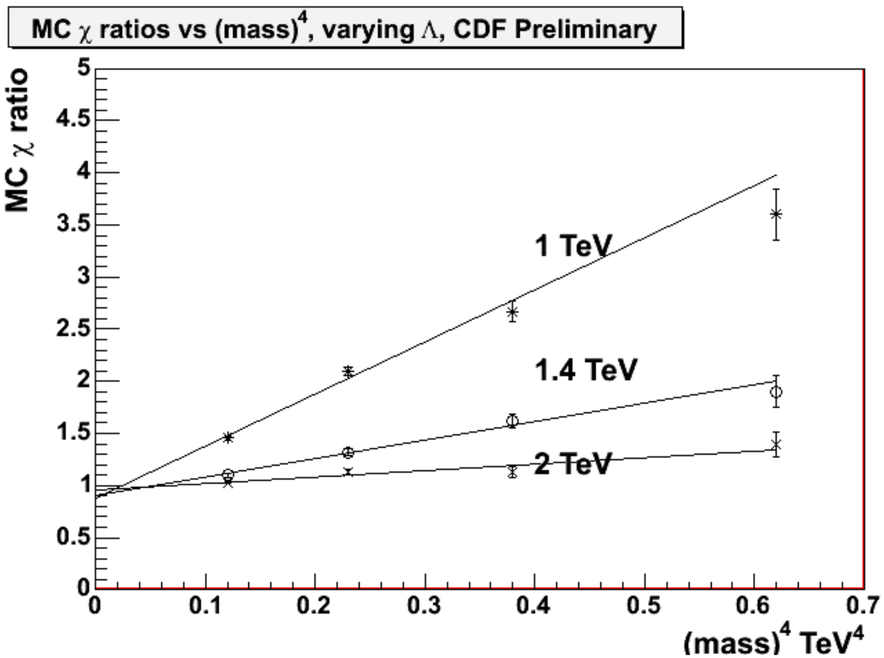


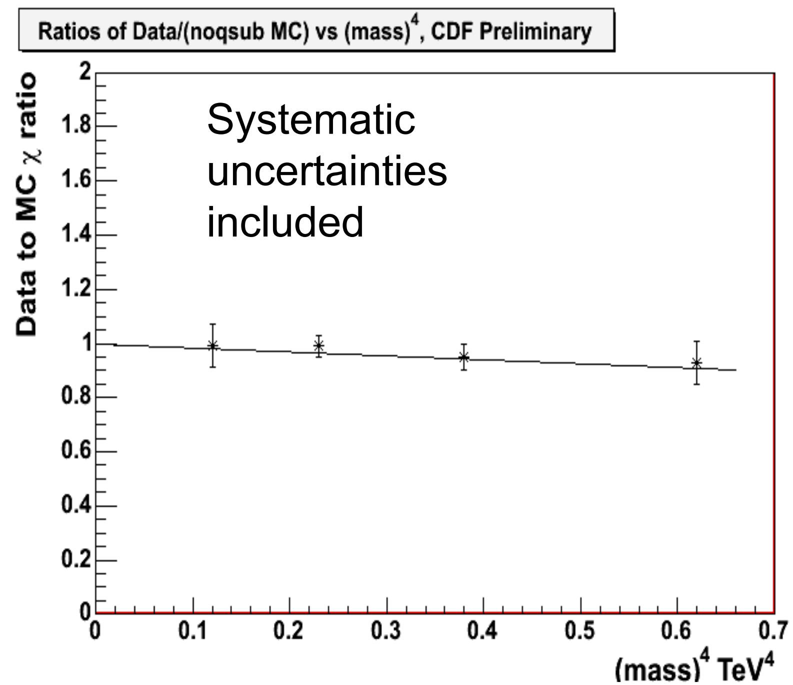


χ Distribution sensitivity to Λ

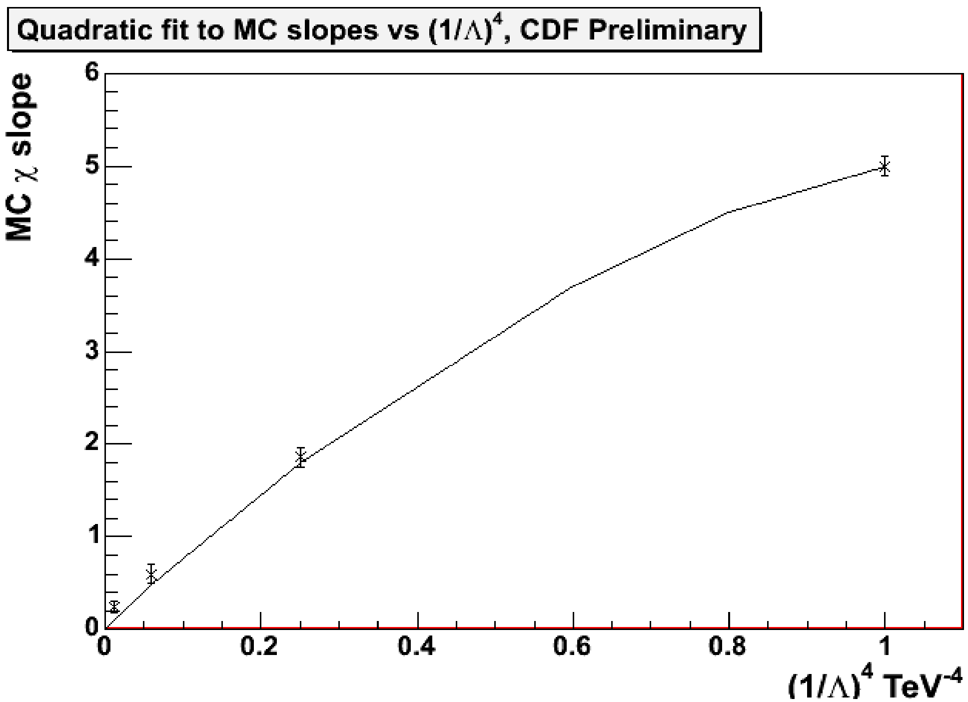
- A ratio method was used to measure the effect of Λ on the angular distribution in a given mass bin.
- Define $R=(1<\chi<10)/(15<\chi<25)$.
- Using Pythia for the Λ dependence, plot $R(\Lambda)/R(\infty)$ versus $(\text{mass})^4$, where $R(\infty)$ means no quark substructure.

Dependence of the χ ratios vs $(\text{mass})^4$ on the parameter Λ





Sensitivity of the slope to the quark substructure parameter Λ



χ slope of data = -0.16 $\pm$ 0.08

Λ > 2.4 TeV 95% confidence

Limit is dominated by systematic uncertaities

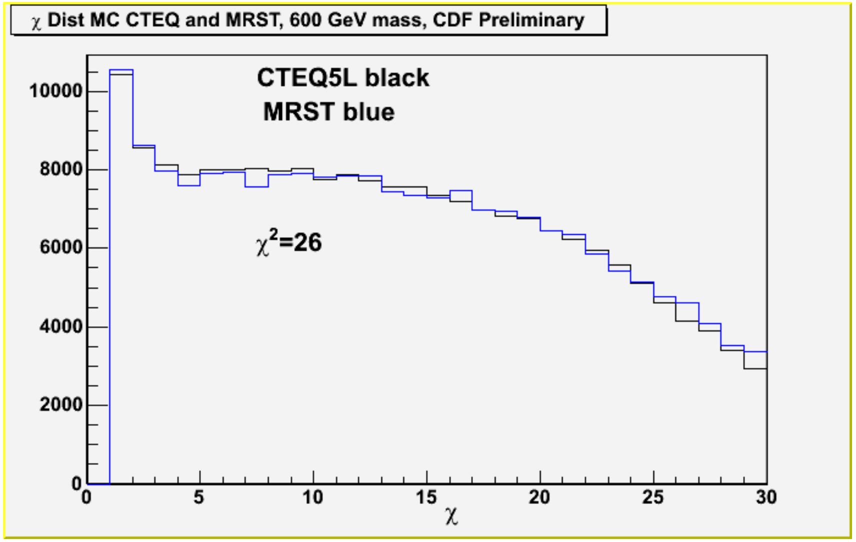
Systematics

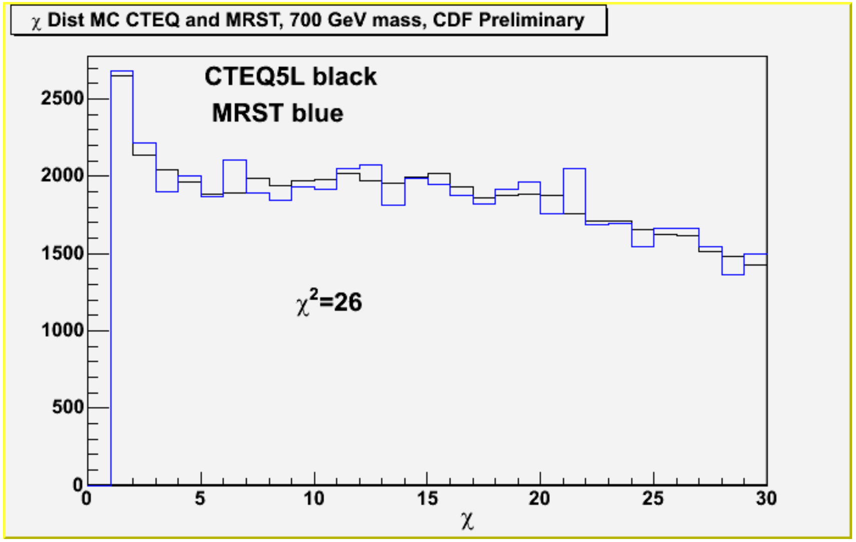
- There are many adjustable parameters in the comparison of data to Monte Carlo simulation.
- Is it possible to adjust the Monte Carlo to mask the presence of new physics in the data?
- The answer is yes. The study of systematics should give the degree of flexibility inherent in the comparison.

To obtain a limit we must understand the systematics

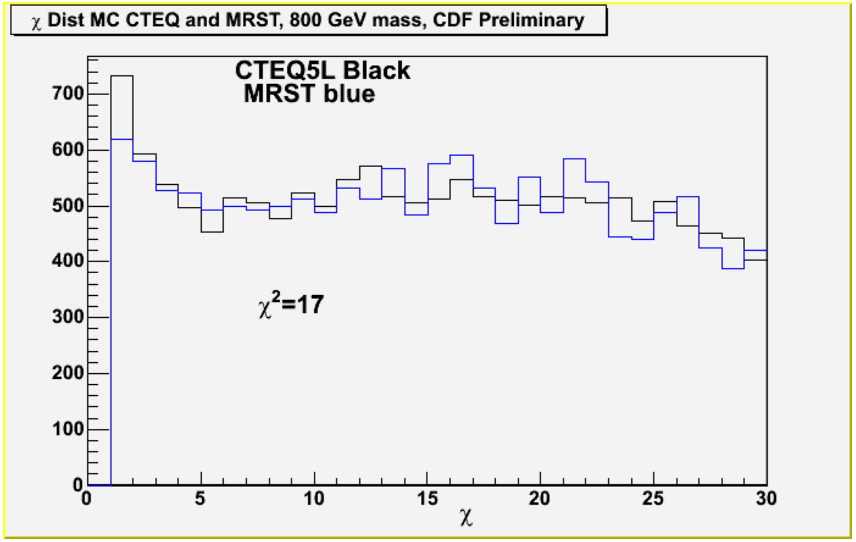
- Sensitivity to the choice of the parton distribution functions. We are looking at high mass dijets, searching for quark substructure, so the most important pdf’s are proton valence $\times$ valence.
- The first study compared CTEQ and MRST.

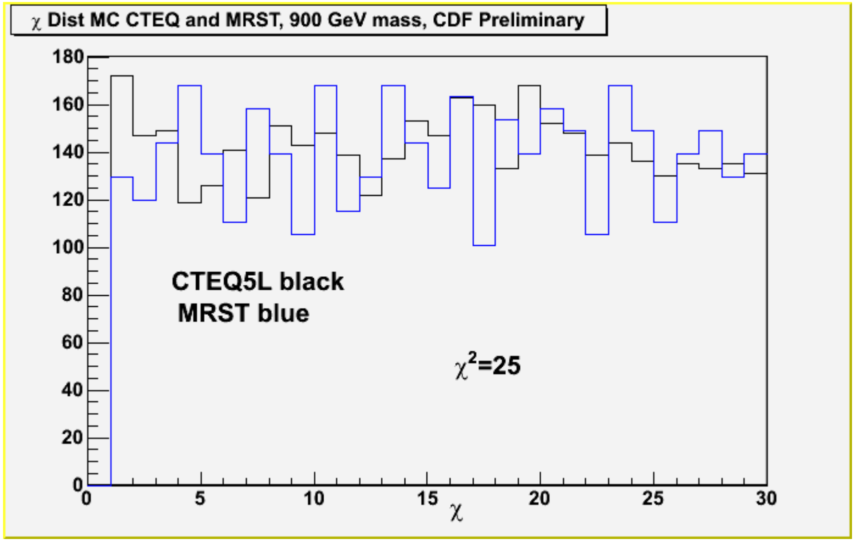
MRST compared to CTEQ





MRST compared to CTEQ





Systematics of the pdf's

- MRSTLO 'high α_s' and CTEQ5L predict the same angular distributions with no quark substructure.
- A new method for evaluating uncertainties from the pdf's, using 'vectors' which represent uncertainties coming from the input experimental data.
- Preliminary studies of the vectors in CTEQ6 indicate small effects on the χ ratios.

Systematic studies continued

- Choice of Q^2. Here the angular distributions differ. Vary the mix of $\hat{s}$ and p_T^2 by $\pm 1\sigma$.
- The jet energy scale. Use the utility to vary the jet energy corrections by $\pm 1\sigma$. The high mass jet-jet cross section depends on the jet energy corrections.

Procedure

- Calculate R for three MC samples: best fit, $+1\sigma$ and -1σ, varying the choice of Q^2.
- Do a simple average $\langle R \rangle = (R_1 + R_2 + R_3)/3$
- Calculate R for three data samples:level7 jetEcorrections, $+1\sigma$ and -1σ.
- Again do a simple average $\langle R_d \rangle = (R_{1d} + R_{2d} + R_{3d})/3$

Systematic uncertainties

- The systematics are included in the uncertainty in each ratio by summing the deviations from the mean: $dR^2 = \Sigma_{i=1,3}(R_i - \langle R \rangle)^2/2$ for the MC, and similarly for dR^2_d.
- Then the final ratios R_d/R are calculated for each mass bin, and plotted vs $(\text{mass})^4$

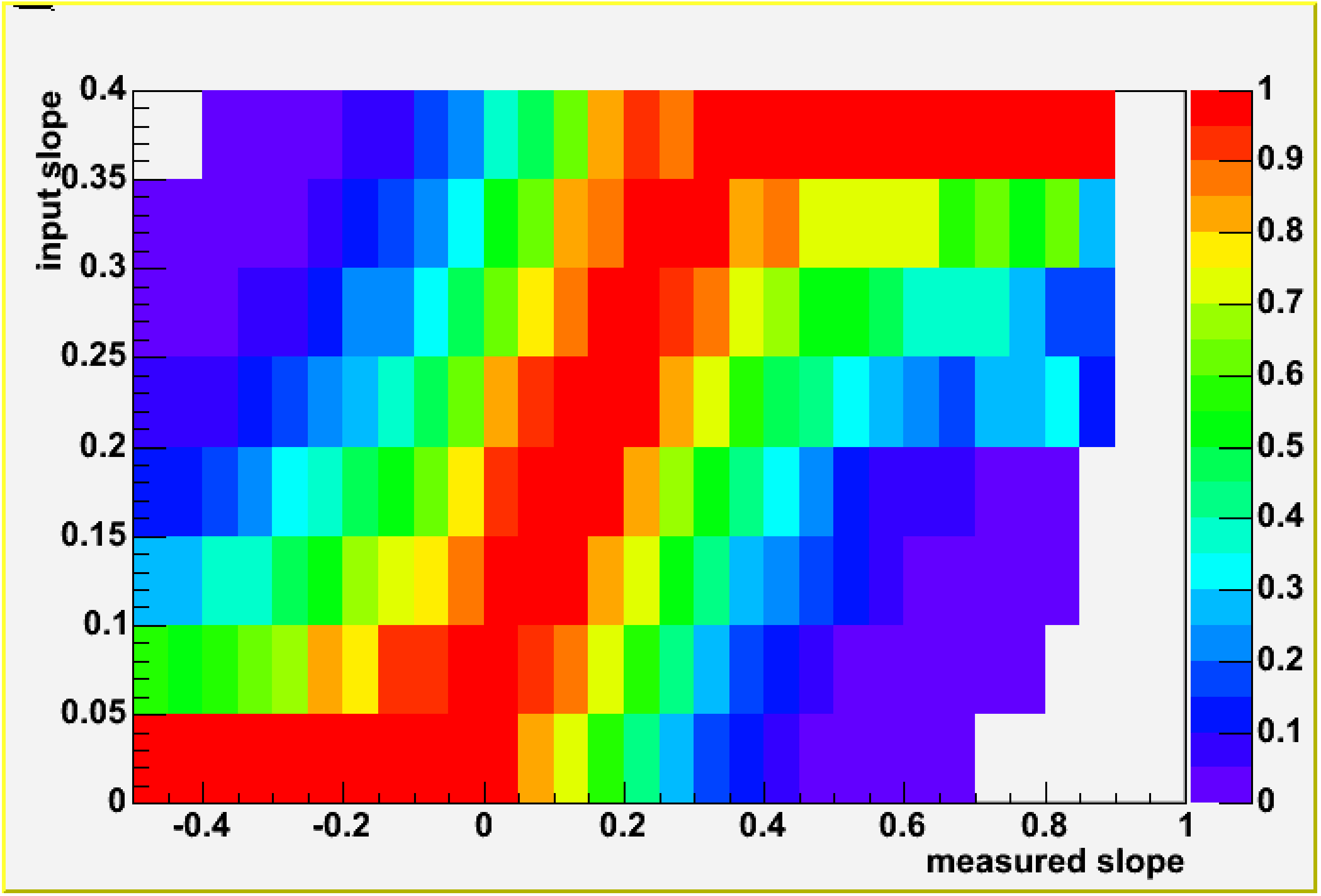
Summary

- The ratio $R=(1\leq\chi\leq10)/(15\leq\chi\leq25)$ shows a linear dependence vs $x=(\mathrm{mass})^4$, with a slope which increases with increasing Λ.
- The data have a slope which is slightly negative: $dR/dx = -0.16\pm0.08$. This result is unphysical.
- To set a limit, we use the Feldman Cousins method (PRD 57,3873 (1998)).

Feldman Cousins method

- The method is based on physically allowed results versus experimental results, which can be unphysical.
- The uncertainties must be known, but not the result.
- For a set of allowed results, generate all possible outcomes, using the uncertainties.

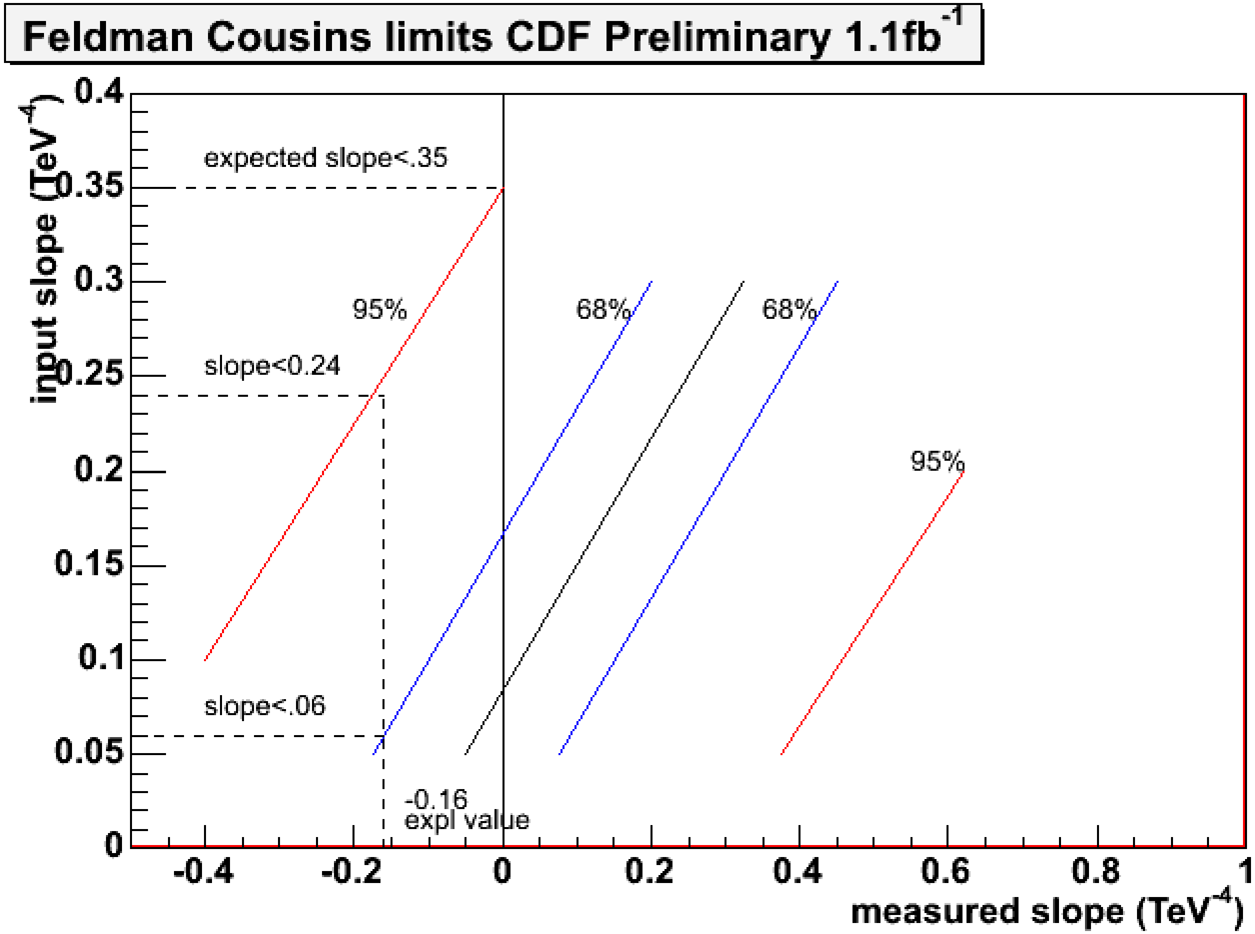
Feldman-Cousins plot



Final limits

- By integration, 95% and 68% confidence contours can be extracted from this plot.

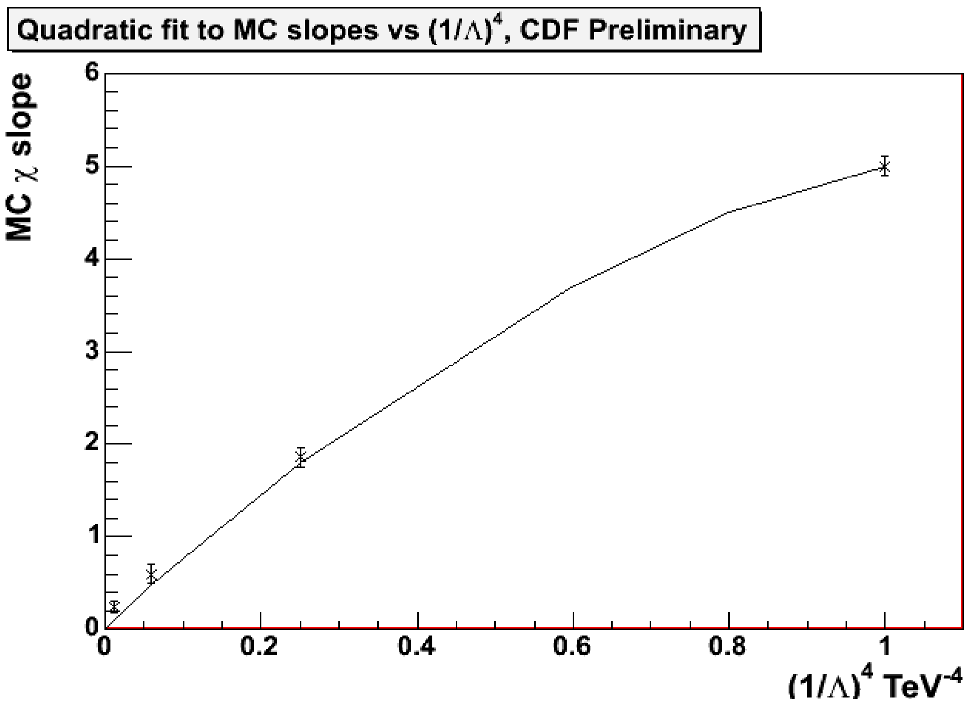
Feldman Cousins limit contours



Limits from the plot

- From the intersection of the measured slope with the confidence level contours, we conclude:
- Slope<0.24 95% confidence
- Slope<0.06 68% confidence
- Expected slope limit for zero slope result (based on these experimental uncertainties) slope<0.35

Sensitivity of the slope to the quark substructure parameter Λ



χ **slope of data = -0.16 $\pm$ 0.08**

Λ **> 2.4 TeV 95% confidence**

Limit is dominated by systematic uncertaities

Conclusions

- To interpret these slopes as lower limits on the quark substructure parameter Λ, we must rely on Pythia Monte Carlo simulation, which gives the sensitivity of the slope of the angular distribution ratio to Λ.
- 95% confidence Λ>2.4 TeV
- 68% confidence Λ>3.5 TeV
- 95% confidence expected result Λ>2.2 TeV