QCD Hard Scattering
and
Massive Hadron Pair Production

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1. Introduction

2. QCD hard scattering

   - Basic formalism

   - Problems and some proposed solutions

3. Next-to-leading-order Monte Carlo calculations

4. Comparison to hadron pair production data

5. Conclusions

Introduction

- Single particle inclusive cross section
  - early test of QCD
  - preceded tests with jet production
  - early evidence for the role of gluons

- Collider Era
  - emphasis shifted to jet production
  - no serious problems noted initially

- However, with increased experimental precision problems appeared in ...
  - B production
  - γ and π^0 production
  - jet production

Some suggested solutions

- Enhance gluon distribution at high-p_T (helps jet problems)

- Uncertainties in fragmentation functions (helps B and π^0 problems)

- Improved theoretical treatment via resummation techniques

Underlying QCD formalism not questioned. But, could there be another hard scattering hadron-hadron process where QCD could be studied?

Hard Scattering in QCD

Basic form for producing some final state from collisions of hadrons A and B

$$\sigma \sim \sum_{a,b} \int dx_a\, dx_b\, G_{a/A}(x_a,\mu_f^2) G_{b/B}(x_b,\mu_f^2) \sigma_{ab}(x_a,x_b,\mu_f^2,s,\theta,...)$$

where

$$\sigma_{ab} = \alpha_s^n \sigma_0 + \alpha_s^{n+1} \sigma_1 + ...$$

- Parton distribution functions from global fits - usually to next-to-leading-logarithm accuracy

- Hard scattering cross section calculated through next-to-leading-order

- For a specific final state hadron, one also needs parton fragmentation functions

Many questions

- Is the hard scattering formalism basically correct?

- Are there large corrections to fragmentation processes?

- Are there large initial state radiation corrections?

- How good is our knowledge of fragmentation functions?

Massive Hadron Pair Production

Process such as $pp \to h_1 + h_2 + X$

$$\sigma \sim \sum_{abcd} \int dx_a \, dx_b \, dz_1 \, dz_2 \, G_{a/A}(x_a, \mu_f^2) G_{b/B}(x_b, \mu_f^2)$$
$$D_{h_1/c}(z_1, M_f^2) D_{h_2/d}(z_2, M_f^2) \sigma_{ab \to cd}(x_a, x_b, \mu_f^2, s, \theta, ...)$$

- High mass $\Rightarrow h_1, h_2$ come from fragmenting partons on opposite sides of the event
- Involves two fragmentation functions, both with high momentum fraction
- Symmetric - no advantage provided by an initial state k_T kick
- Sensitive to same region of fragmentation functions as single particle cross section
- Can test if fragmentation functions are adequate and if large corrections are needed
- Can test underlying hard scattering picture

Next-to-Leading-Order Calculations

- Ingredients
  - $2 \to 2$ $\mathcal{O}(\alpha_s^2)$ subprocesses, e.g. $qq \to qq, qg \to qg$, and $gg \to gg$
  - $\mathcal{O}(\alpha_s^3)$ one-loop corrections to $2 \to 2$ subprocesses
  - $2 \to 3$ subprocesses such as $qq \to qqg$, etc
- $\mathcal{O}(\alpha_s^3)$ terms have singular regions corresponding to soft gluons and/or collinear partons
- Need a method to handle such singularities
- Observables involve many kinematic variables since there are now two hadrons
- Jacobians from parton variables to hadron variables are complex
- Suggests using a Monte Carlo approach, but one which allows the singularities to be properly treated

Phase Space Slicing Monte Carlo

- See B. Harris and J.F. Owens hep-ph/0102128

- Work in n=4-2ϵ dimensions using dimensional regularization

- Notation:

  - At the parton level: $p_1+p_2 \rightarrow p_3+p_4+p_5$

  - Let $s_{ij} = (p_i + p_j)^2$ and $t_{ij} = (p_i - p_j)^2$

- Partition $2 \rightarrow 3$ phase space into three regions

1. Soft: gluon energy $E_g < \delta_s \sqrt{s_{12}}/2$

2. Collinear: s_{ij} or $|t_{ij}| < \delta_c s_{12}$

3. Finite: everything else

- In soft region use the soft gluon approximation to generate a simple expression for the squared matrix element which can be integrated by hand

- In the collinear region use the leading pole approximation to generate a simple expression which can be integrated by hand.

- Resulting expressions have explicit poles from soft and collinear singularities

- Factorize initial and final state mass singularities and absorb into the fragmentation and distribution functions

- Add soft and collinear integrated results to the $2 \to 2$ contributions – singularities cancel

- generate finite region contributions in 4 dimensions using usual Monte Carlo techniques

- End results is a set of two-body weights and a set of three-body weights.

- Both are finite and both depend on the cutoffs δ_s and δ_c

- Cutoff dependence cancels for sufficiently small cutoffs when the two sets of weights are added at the histogramming stage

Hadron Pair Production

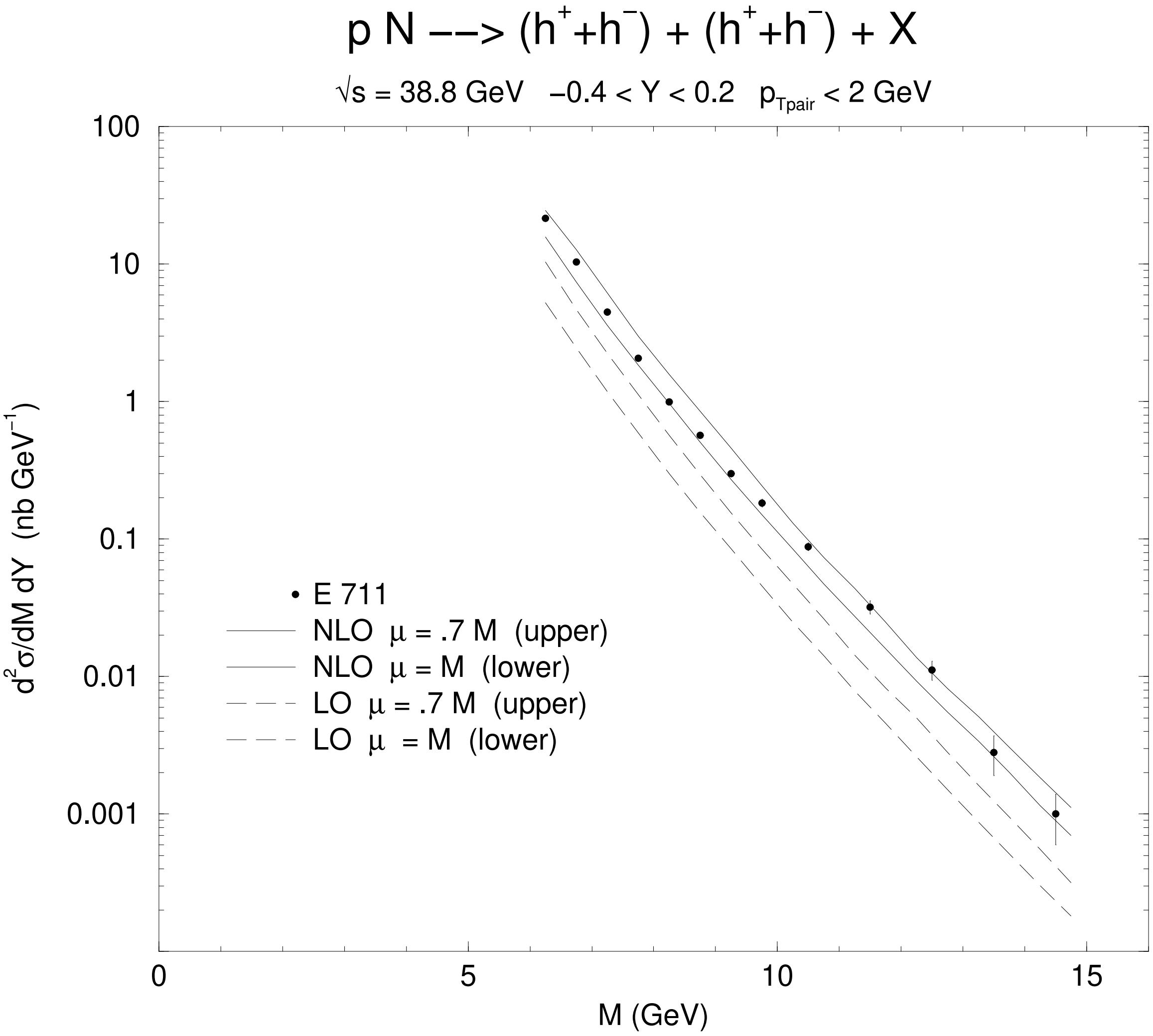
- Kinematic variables for the dihadron system
  - Mass of the dihadron system M
  - Rapidity of the hadron pair Y
  - Cosine of the scattering angle in the parton-parton system $\cos\theta^*$
  - Transverse momentum of the dihadron system $p_{T pair}$
  - Event sample may also involve cuts being placed on the transverse momenta and rapidities of the individual hadrons

- High statistics, large acceptance experiments
  1. NA-24: $pp \to \pi^0\pi^0 + X, \sqrt{s} = 23.7$ GeV
  2. E-706: $pN \to \pi^0\pi^0 + X, \sqrt{s} = 31.6, 38.8$ GeV
  3. CCOR: $pp \to \pi^0\pi^0 + X, \sqrt{s} = 44.8, 62.4$ GeV
  4. E-711: $pN \to (h^+ + h^-)(h^+ + h^-) + X, \sqrt{s} = 38.8$ GeV

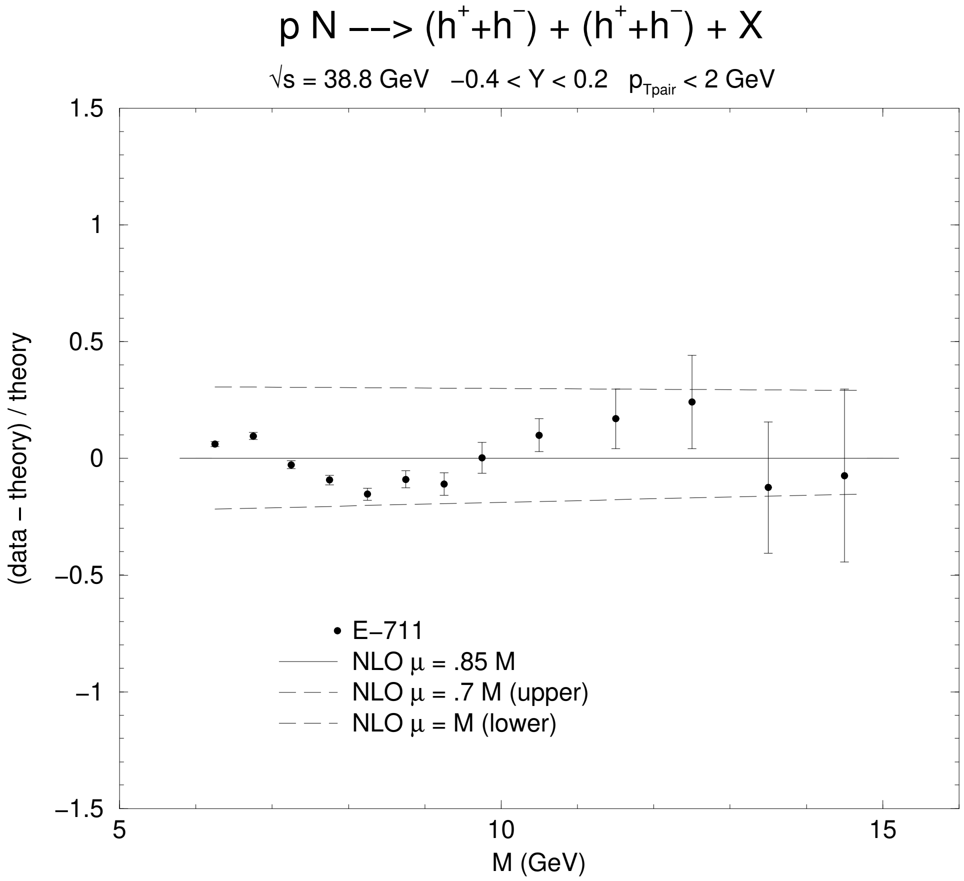
- For details, see hep-ph/0110036

- Use CTEQ5M parton distributions as standard

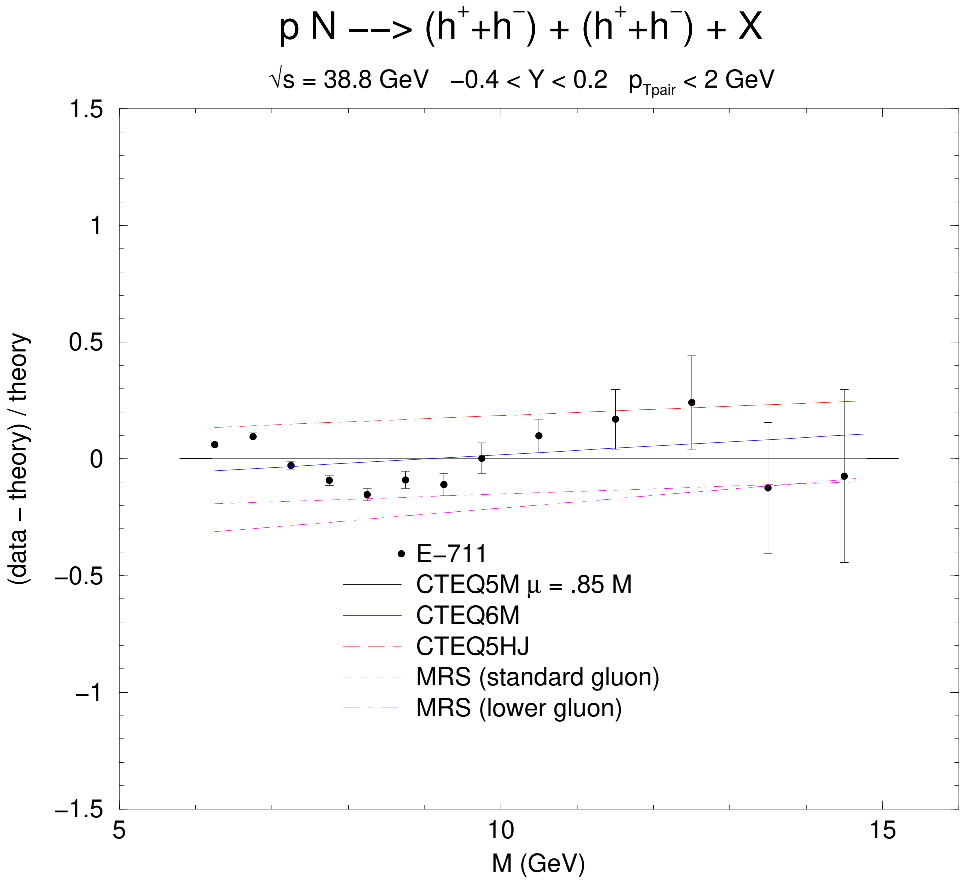
- Two sets of parton fragmentation functions fit to high statistics LEP data
  - Kniehl, Kramer, and Pötter (use as standard)
  - Bourhis, Fontannaz, Guillet, and Werlen



- NLO results significantly higher than LO results
- Still have significant scale dependence
  - Two scale dependent fragmentation function
  - Two scale dependent distribution functions
  - Two powers of α_s at lowest order



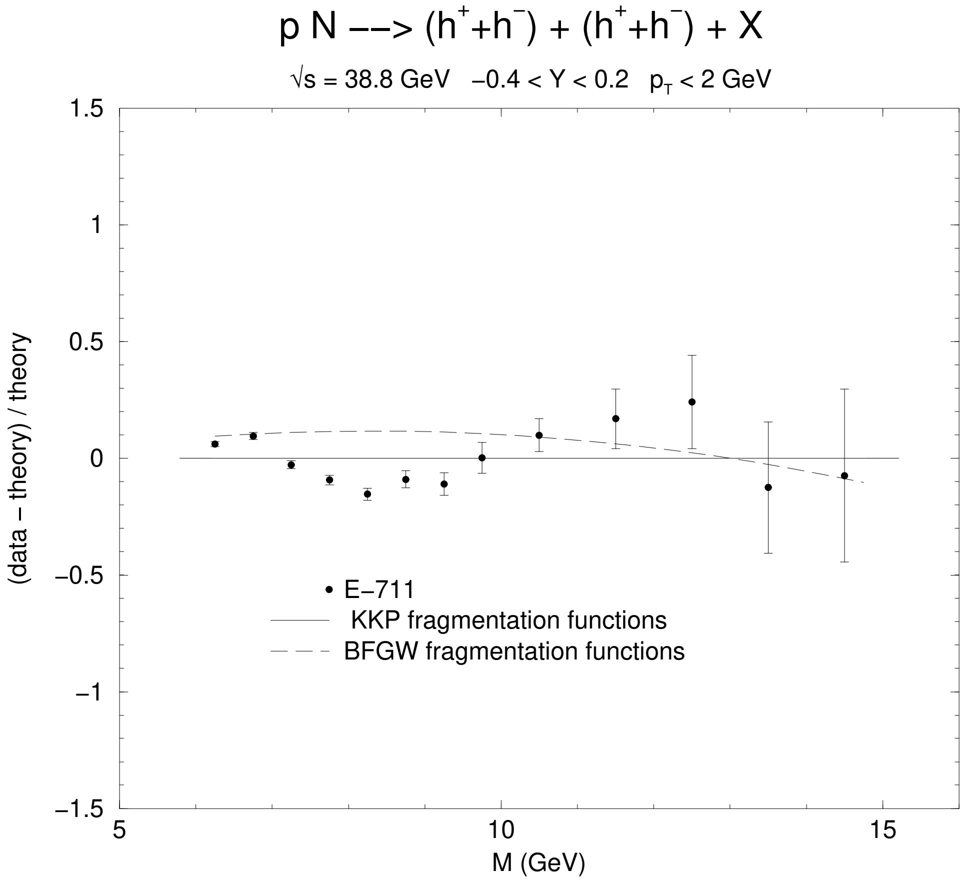
Expanded linear scale shown in (data-theory)/theory format



- Variations in parton distributions comparable to variations due to changes of scale

- Can not decide between CTEQ5HJ and other data sets

- Good news is that no large variations in scale are needed in order to describe data

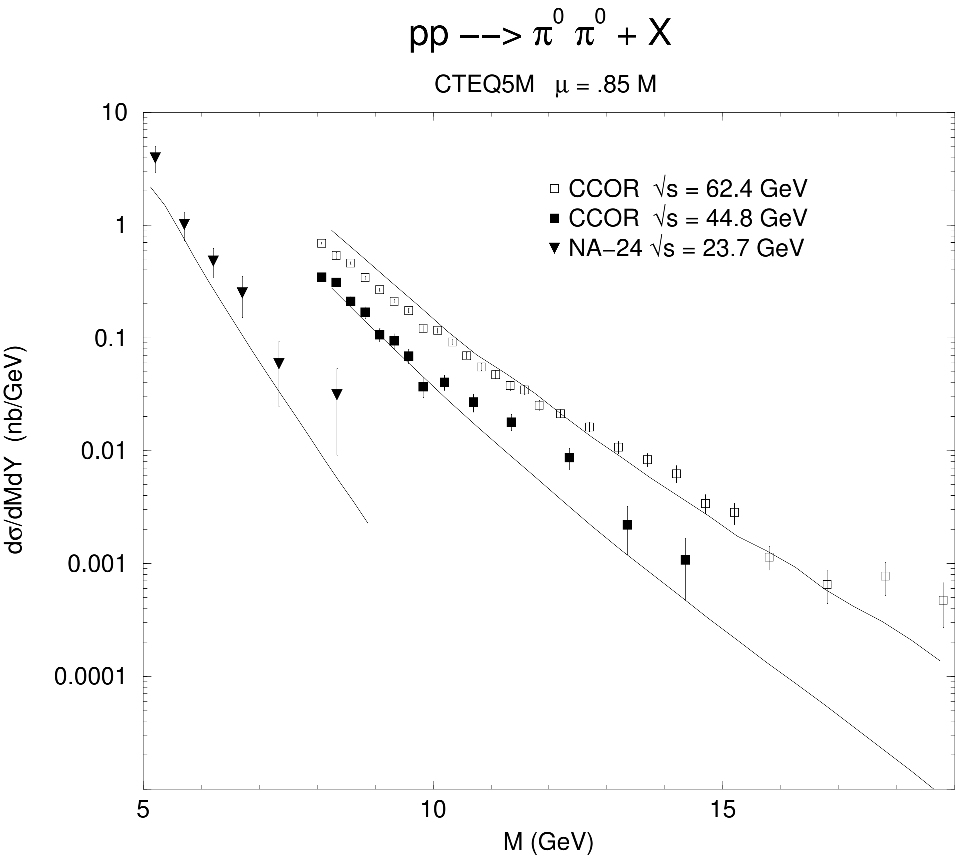


Variations due to fragmentation functions are within about 10 %

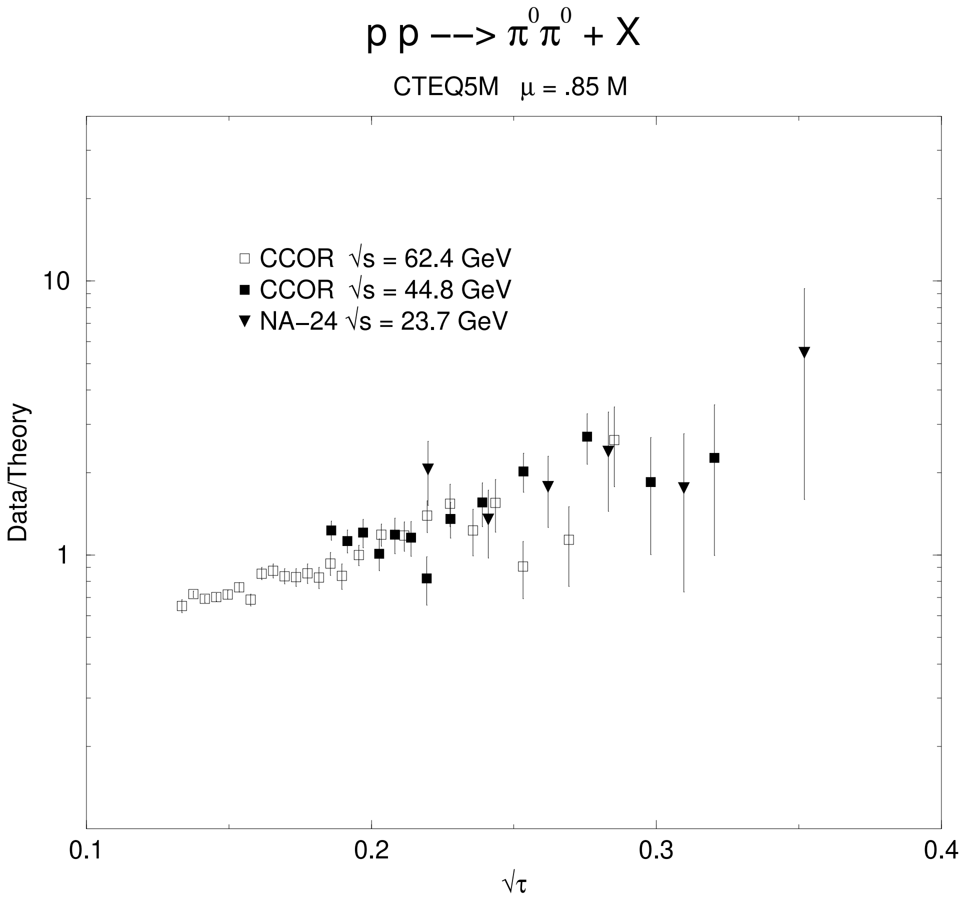
$$pp \to \pi^0\pi^0 + X$$

- NA-24 and CCOR experiments used the same sets of cuts to analyze their data

- $|Y| < 0.35$, $p_{T\,pair} < 1$ GeV, and $|\cos\theta^*| < 0.4$

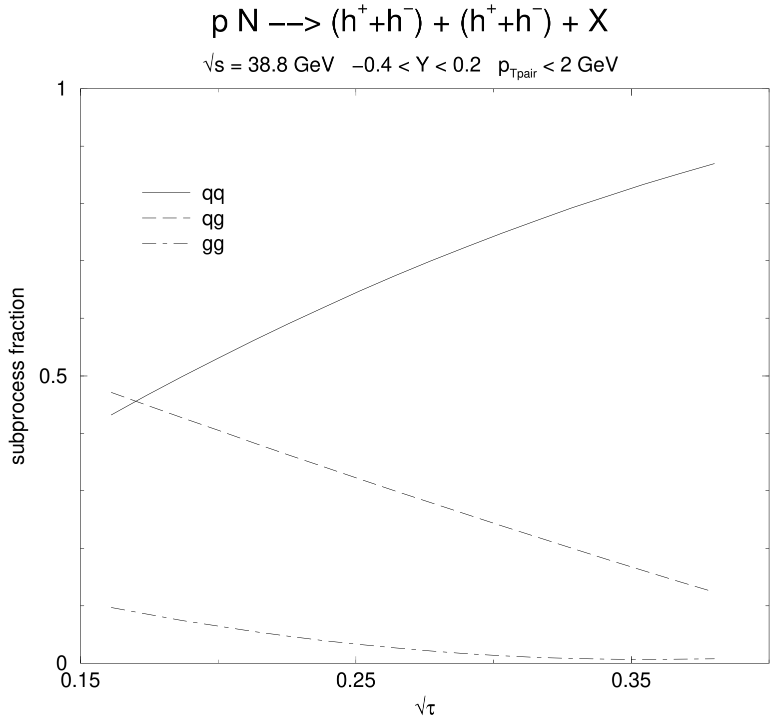


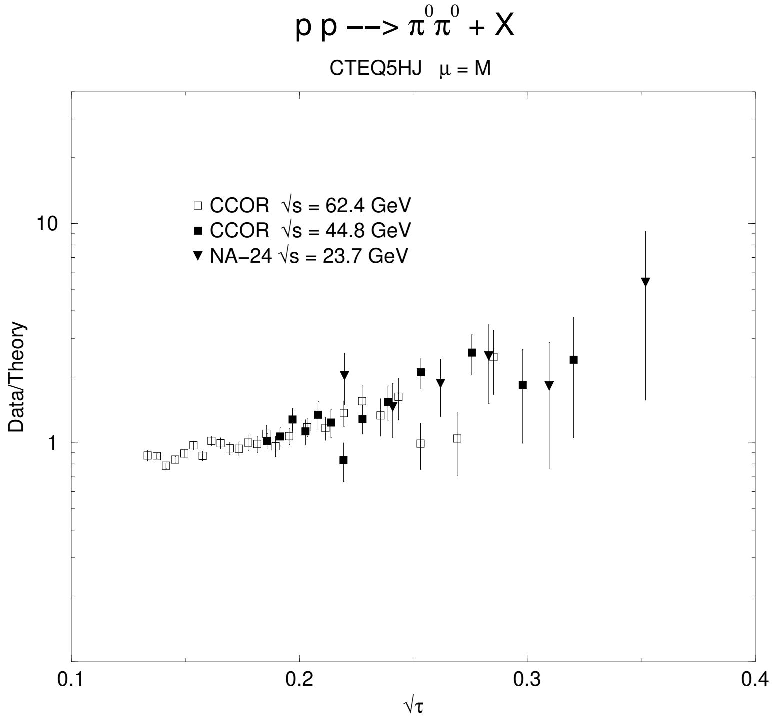
Plot same data in a data/theory format versus $\sqrt{\tau} = M/\sqrt{s}$



Upward slope suggests that CTEQ5HJ might improve the agreement with the data

Need to examine what subprocesses contribute to the data at different masses





Some effect, but not enough...

Angular distributions

- Boost to frame where the two hadron system has zero longitudinal momentum

- Calculate cosine of the angle between each hadron and the beam direction

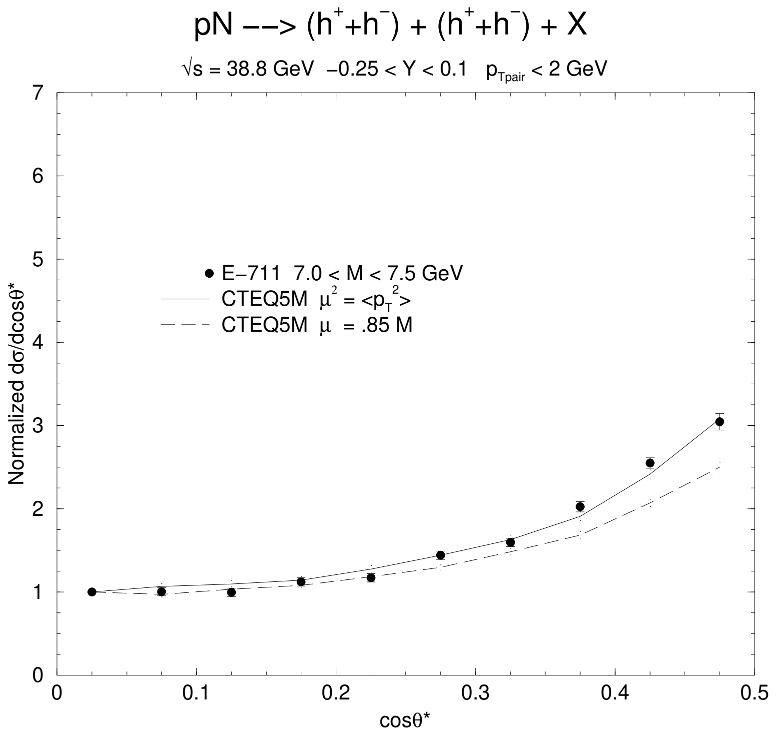
- Won't be the same since the two hadrons aren't exactly back to back (transverse momenta need not be the same in this frame because of fragmentation effects, for example)

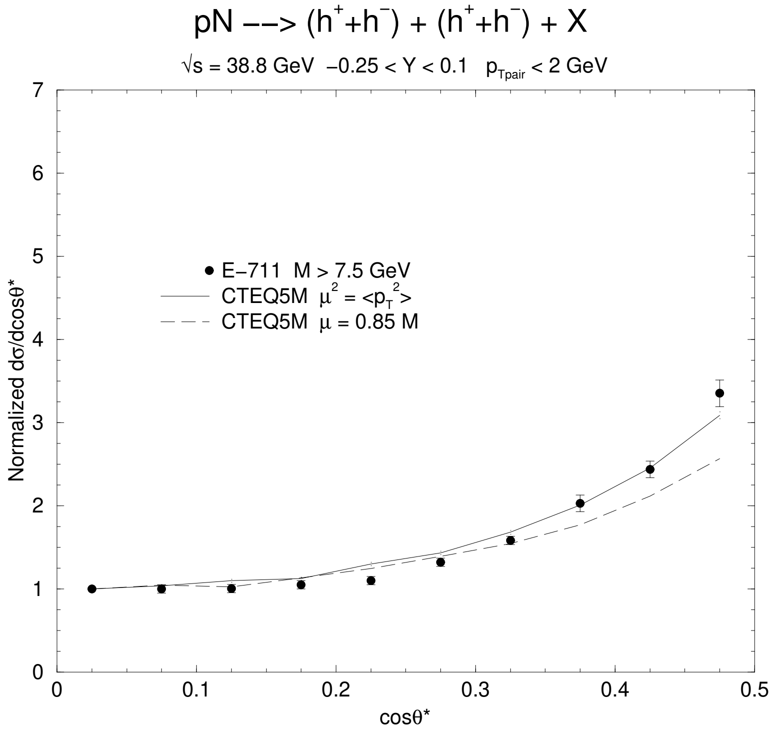
- Use average of the two values

- Scale choice: for $d\sigma/dM$ only have one variable with the dimension of mass to use for the scale - M

- For $d\sigma/d\cos\theta^*$ at fixed M, one could choose M again or something like $M\sin\theta^*$ which is proportional to the transverse momentum of the individual hadrons

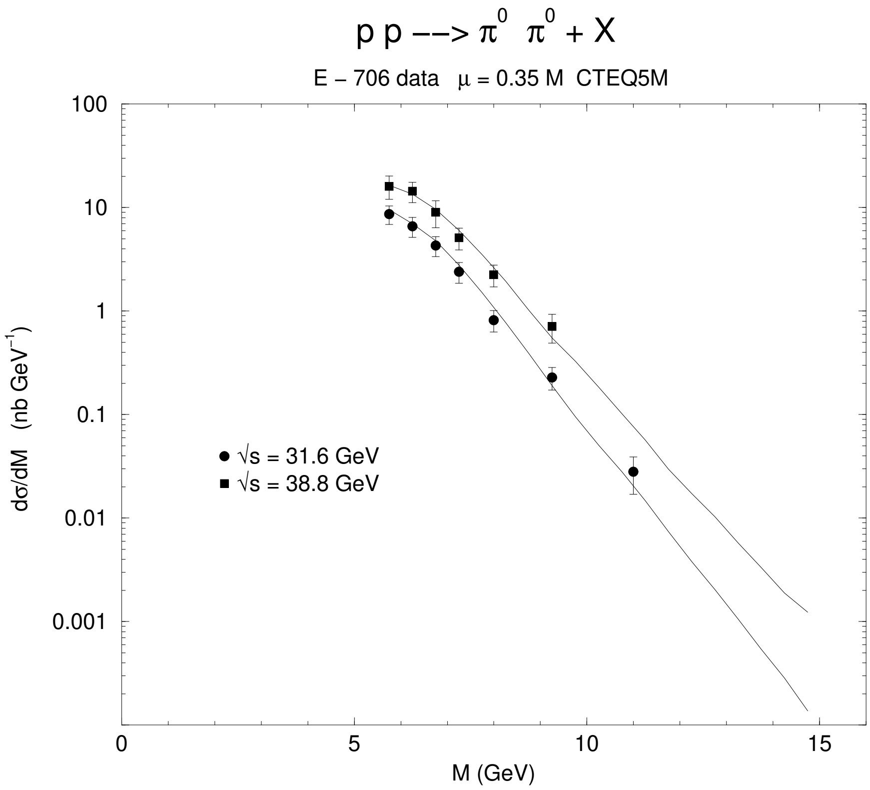
- Use two choices: M and the average of the two squared p_T values





Choice of $< p_T^2 >$ gives a steeper curve, in better agreement with the data. At fixed M larger $\cos\theta^*$ gives a smaller scale which increases the cross section.

E-706 Data



- Agreement is good, but the scale is much smaller than in the previous cases

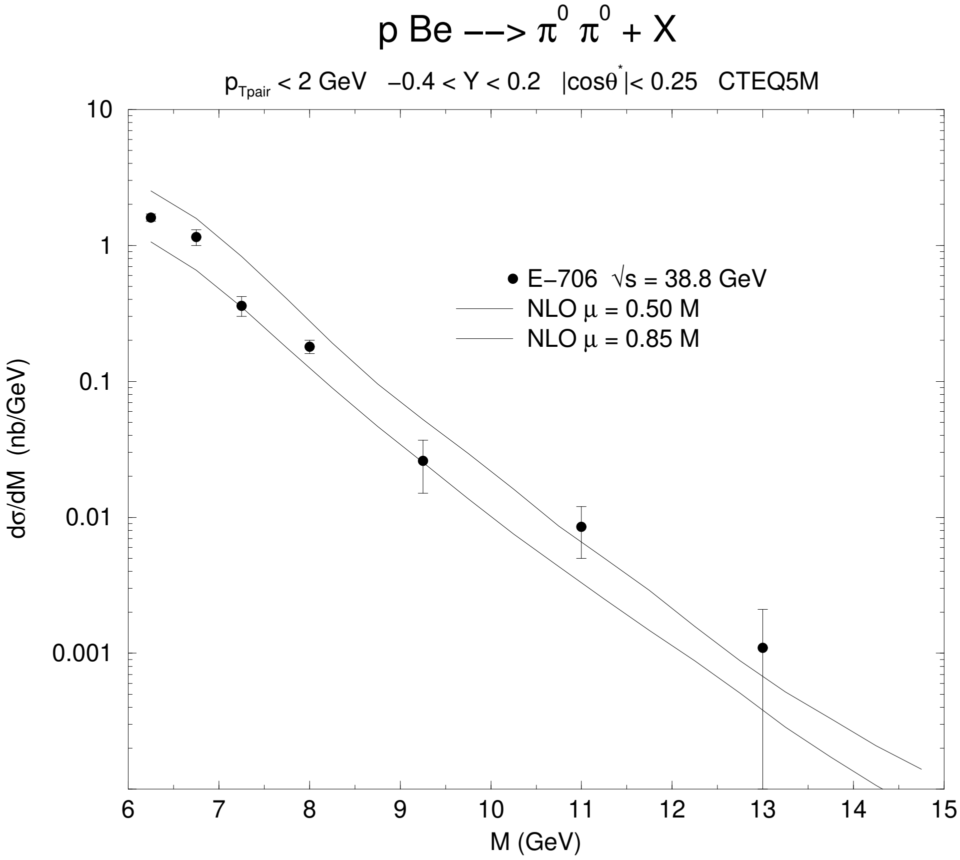
- Cuts used are much different than the other experiments, but they can be duplicated in the calculation

- Require each pion to satisfy $p_T > 2.5$ GeV and $-.8 < y < .8 (-1.05 < y < .55)$ for $\sqrt{s} = 31.6(38.8)$ GeV

- No cuts on p_{Tpair}, wider acceptance in the azimuthal angle between the two pions ($\Delta\phi$)

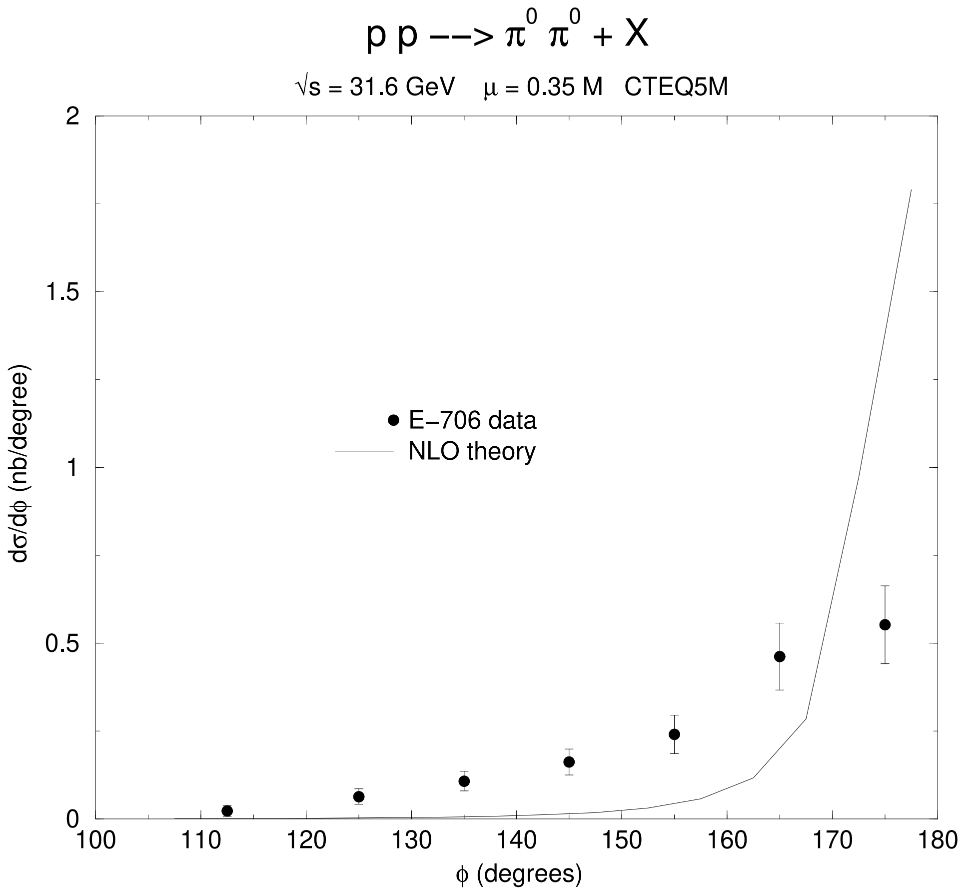
- So what is causing the difference?

- E706 also analyzed data using the same cuts as for E-711

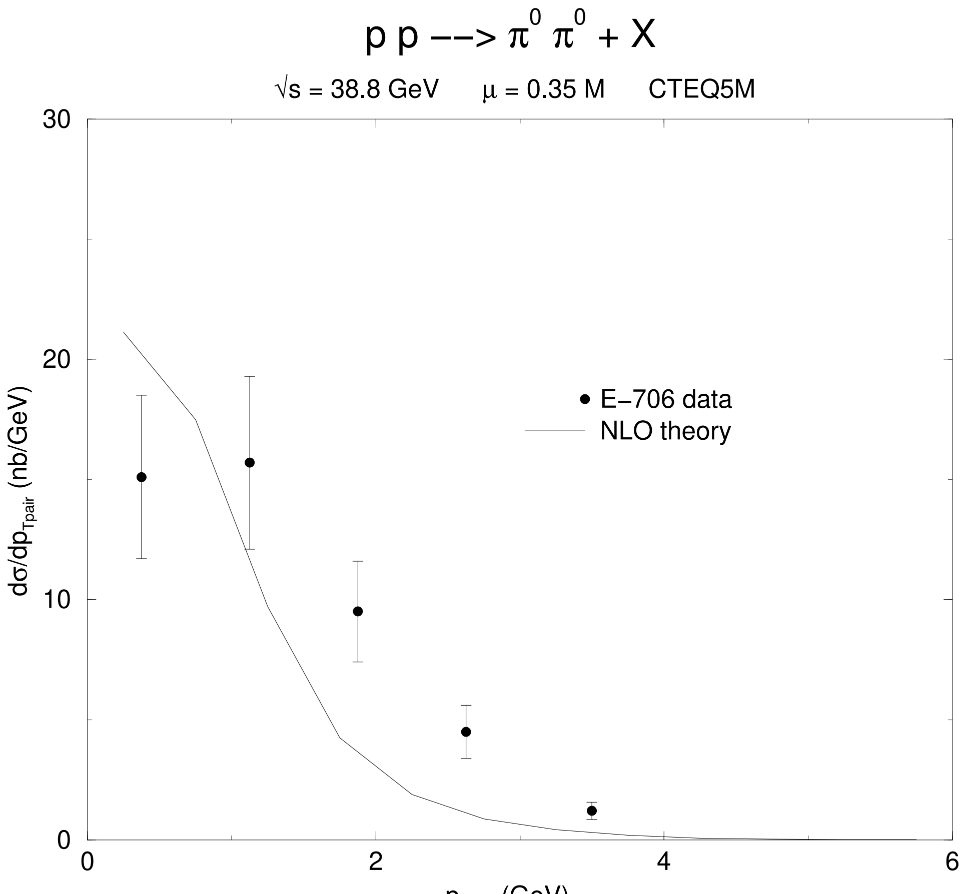


- Agreement is much better with nearly the same scale choice

- Answer to the question lies in the p_{Tpair} and $\Delta\phi$ distributions



p p --> π0 π0 + X
√s = 31.6 GeV μ = 0.35 M CTEQ5M
E−706 data
NLO theory
dσ/dϕ (nb/degree)
ϕ (degrees)
0
0.5
1
1.5
2
100
110
120
130
140
150
160
170
180



p p --> π0 π0 + X
√s = 38.8 GeV μ = 0.35 M CTEQ5M
E−706 data
NLO theory
dσ/dpTpair (nb/GeV)
pTpair (GeV)
0
10
20
30
0
2
4
6

- E-706 has wider acceptance in $p_{T pair}$ and $\Delta\phi$

- Opening up the acceptance region increases the experimental results, but doesn't increase the theoretical result nearly as much

- Results in an apparent normalization shift requiring that the theory be increased (use smaller scale)

- *Not* an experimental problem!

- Both distributions are δ-functions at lowest order

- Correct description requires the use of the appropriate resummation formalism

- Will get misleading results if cuts are placed on a distribution which is not well described by the theory

- Better to integrate over the variable in question if the acceptance of the experiment allows it

Summary and Conclusions

- NLO calculation provides a good description of the mass and angular distributions for the production of high mass hadron pairs

- Distributions which are δ-functions at lowest order are not well described

  - Distributions diverge at the edge of the physical region at this order

  - Resummation techniques required in order to properly treat soft gluon effects

- No apparent problems associated with existing fragmentation functions

- Encouraging evidence that the underlying hard scattering process is correctly described by QCD

- Problems with single photon and single hadron cross sections may be ascribed to a combination of effects due to an incomplete application of the theory and possible inconsistencies amongst data sets