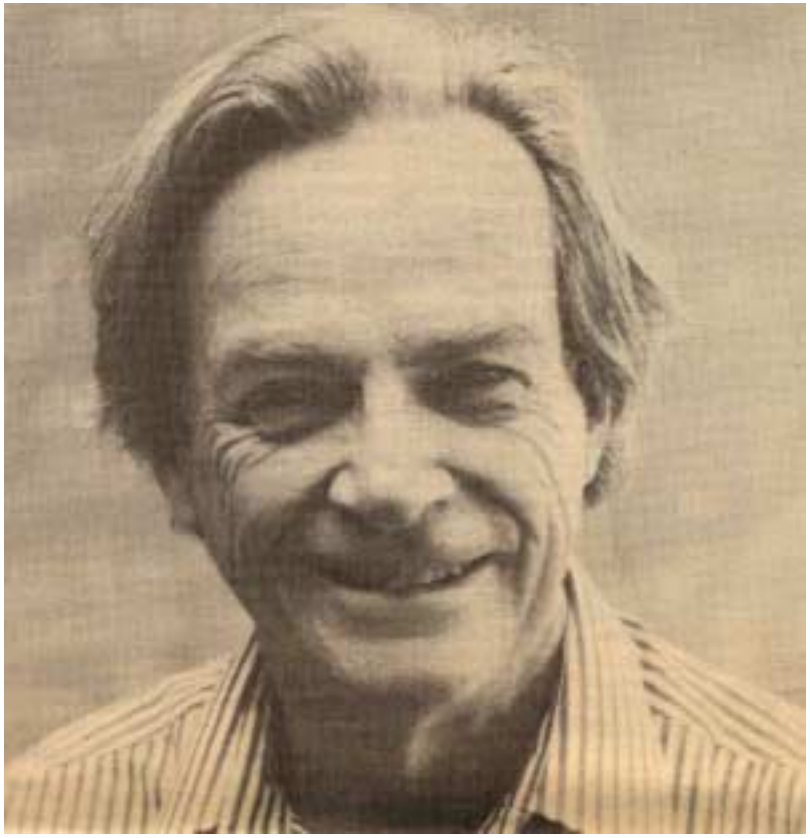
# Toward an Understanding of Hadron-Hadron Collisions

## Outline of Talk

- **The Past:** Feynman-Field Fenomenology (1973-1980).

**7 GeV $\pi^0$'s**
**to**
**400 GeV "jets"**

- **The Present:** Studying "Min-Bias" and the "Underlying Event" at CDF.



# Feynman-Field Fenomenology

## 1973-1980

"Feynman-Field Jet Model"

- FF1: "Quark Elastic Scattering as a Source of High Transverse Momentum Mesons", R. D. Field and R. P. Feynman, Phys. Rev. D15, 2590-2616 (1977).
- FFF1: "Correlations Among Particles and Jets Produced with Large Transverse Momenta", R. P. Feynman, R. D. Field and G. C. Fox, Nucl. Phys. B128, 1-65 (1977).
- FF2: "A Parameterization of the properties of Quark Jets", R. D. Field and R. P. Feynman, Nucl. Phys. B136, 1-76 (1978).
- F1: "Can Existing High Transverse Momentum Hadron Experiments be Interpreted by Contemporary Quantum Chromodynamics Ideas?", R. D. Field, Phys. Rev. Letters 40, 997-1000 (1978).
- FFF2: "A Quantum Chromodynamic Approach for the Large Transverse Momentum Production of Particles and Jets", R. P. Feynman, R. D. Field and G. C. Fox, Phys. Rev. D18, 3320-3343 (1978).
- FW1: "A QCD Model for $e^+e^-$ Annihilation", R. D. Field and S. Wolfram, Nucl. Phys. B213, 65-84 (1983).

My 1st graduate student!

# Feynman-Field Fenomenology

**1973-1980**

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- **FF2: "A Parametrization ... R. D. Field and R. P. Feynman, Nucl. Phys. ...**
- **F1: "Can Existing High Energy Data be Interpreted by Constituent Ideas?", R. D. Field, Phys. Rev. Letters 40, 997-1...**
- **FFF2: "A Quantum Chromodynamic Approach for the High Transverse Momentum Production of Particle Jets", R. P. Feynman, R. D. Field and G. C. Fox, Phys. Rev. D18, 3320-3343 (1978).**
- **FW1: "A QCD Model for $e^+e^-$ Annihilation", R. D. Field and S. Wolfram, Nucl. Phys. B213, 65-84 (1983).**

**Many people have contributed to our understanding of hadron-hadron collisions! I will say a few words about Feynman's influence on the field.**

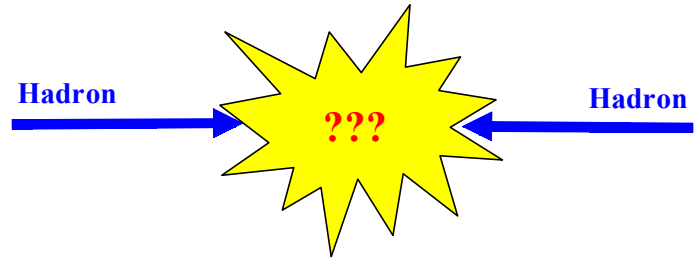
**My 1st graduate student!**

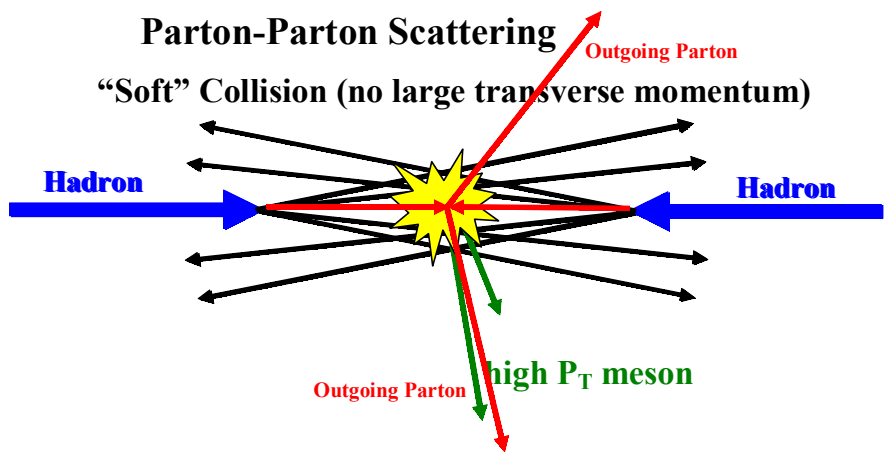
# Hadron-Hadron Collisions

## FF1 1977 (preQCD)

- What happens when two hadrons collide at high energy?
- Most of the time the hadrons ooze through each other and fall apart (*i.e.* no hard scattering). The outgoing particles continue in roughly the same direction as initial proton and antiproton.
- Occasionally there will be a large transverse momentum meson. Question: Where did it come from?
- We assumed it came from quark-quark elastic scattering, but we did not know how to calculate it!

"Black-Box Model"



# Hadron-Hadron Collisions

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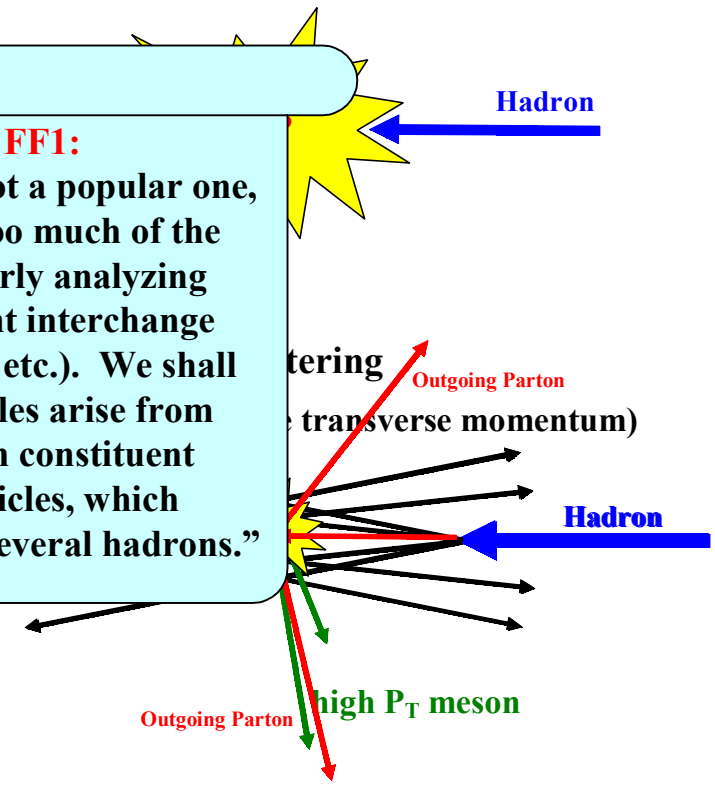
**Feynman quote from FF1:**
"The model we shall choose is not a popular one, so that we will not duplicate too much of the work of others who are similarly analyzing various models (*e.g.* constituent interchange model, multiperipheral models, etc.). We shall assume that the high $P_T$ particles arise from direct hard collisions between constituent quarks in the incoming particles, which fragment or cascade down into several hadrons."



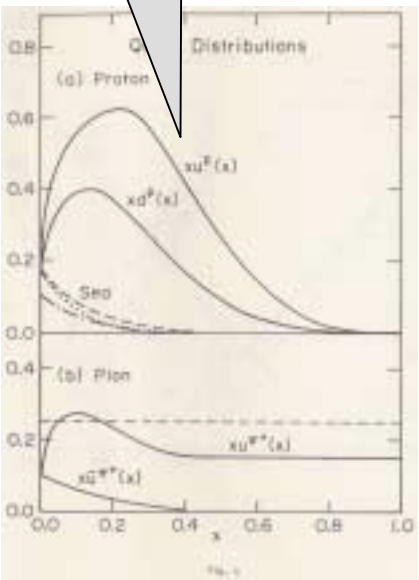

"Black-Box Model"

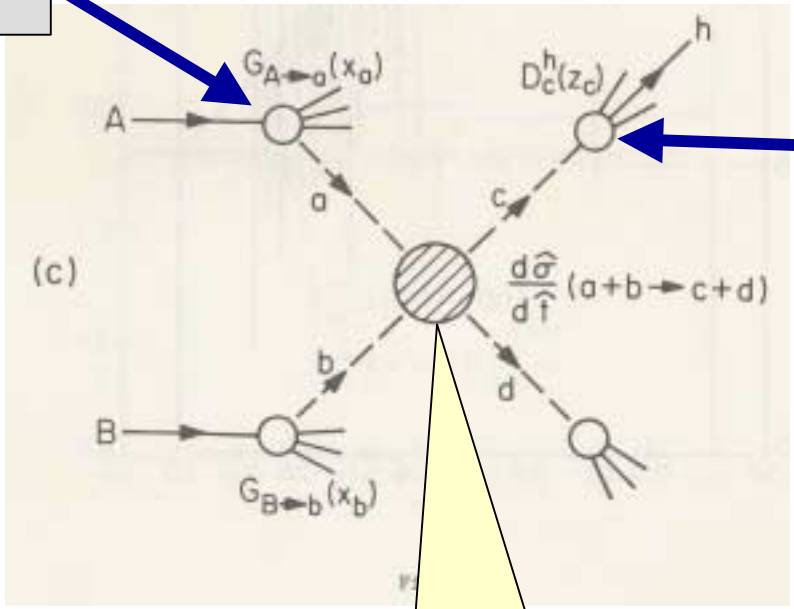
# Quark-Quark Black-Box Model

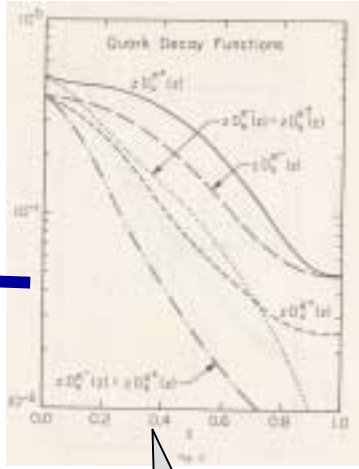
**FF1 1977 (preQCD)**

No gluons!

**Quark Distribution Functions**
**determined from deep-inelastic lepton-hadron collisions**




**Quark-Quark Cross-Section**
**Unknown! Deteremined from hadron-hadron collisions.**

**Quark Fragmentation Functions**
**determined from $e^+e^-$ annihilations**

# Quark-Quark Black-Box Model

No gluons!

## FF1 1977 (preQCD)

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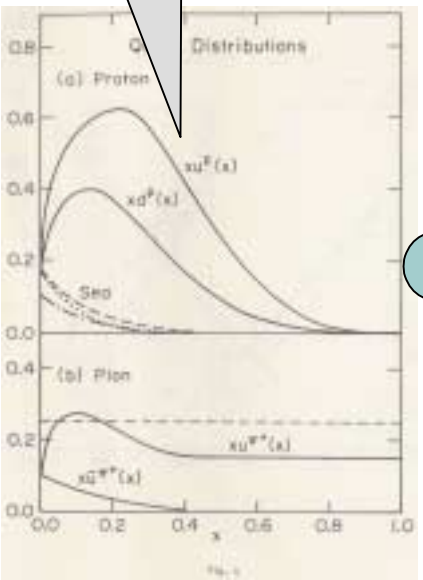
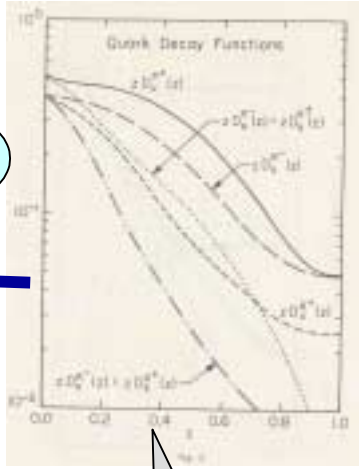



**Feynman quote from FF1:**
"Because of the incomplete knowledge of our functions some things can be predicted with more certainty than others. Those experimental results that are not well predicted can be "used up" to determine these functions in greater detail to permit better predictions of further experiments. Our papers will be a bit long because we wish to discuss this interplay in detail."

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**Quark Fragmentation Functions**
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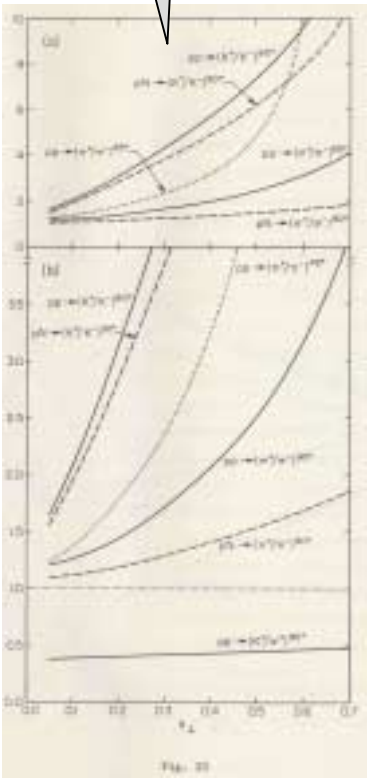
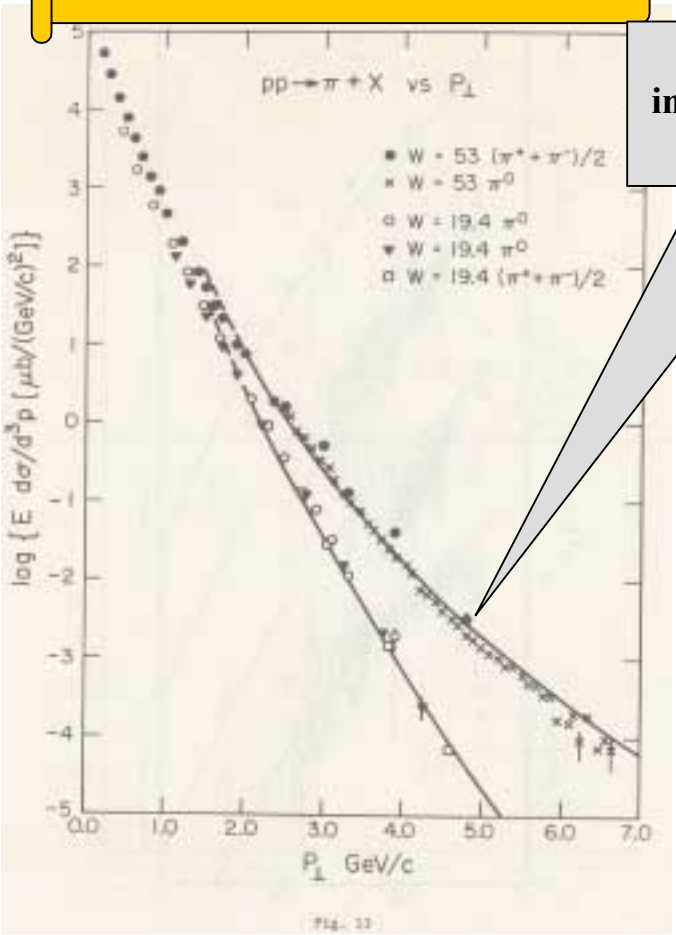
# Quark-Quark Black-Box Model

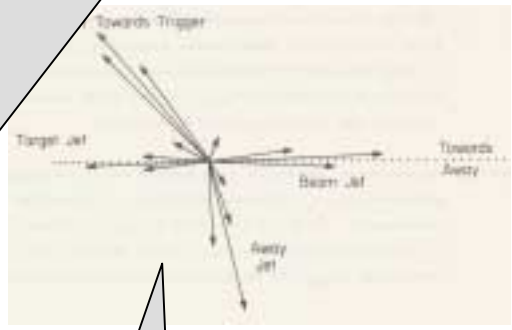
**FF1 1977 (preQCD)**

**Predict**
**particle ratios**






**Predict**
**increase with increasing CM energy W**




**Predict**
**overall event topology (FFF1 paper 1977)**

# Telagram from Feynman

**July 1976**

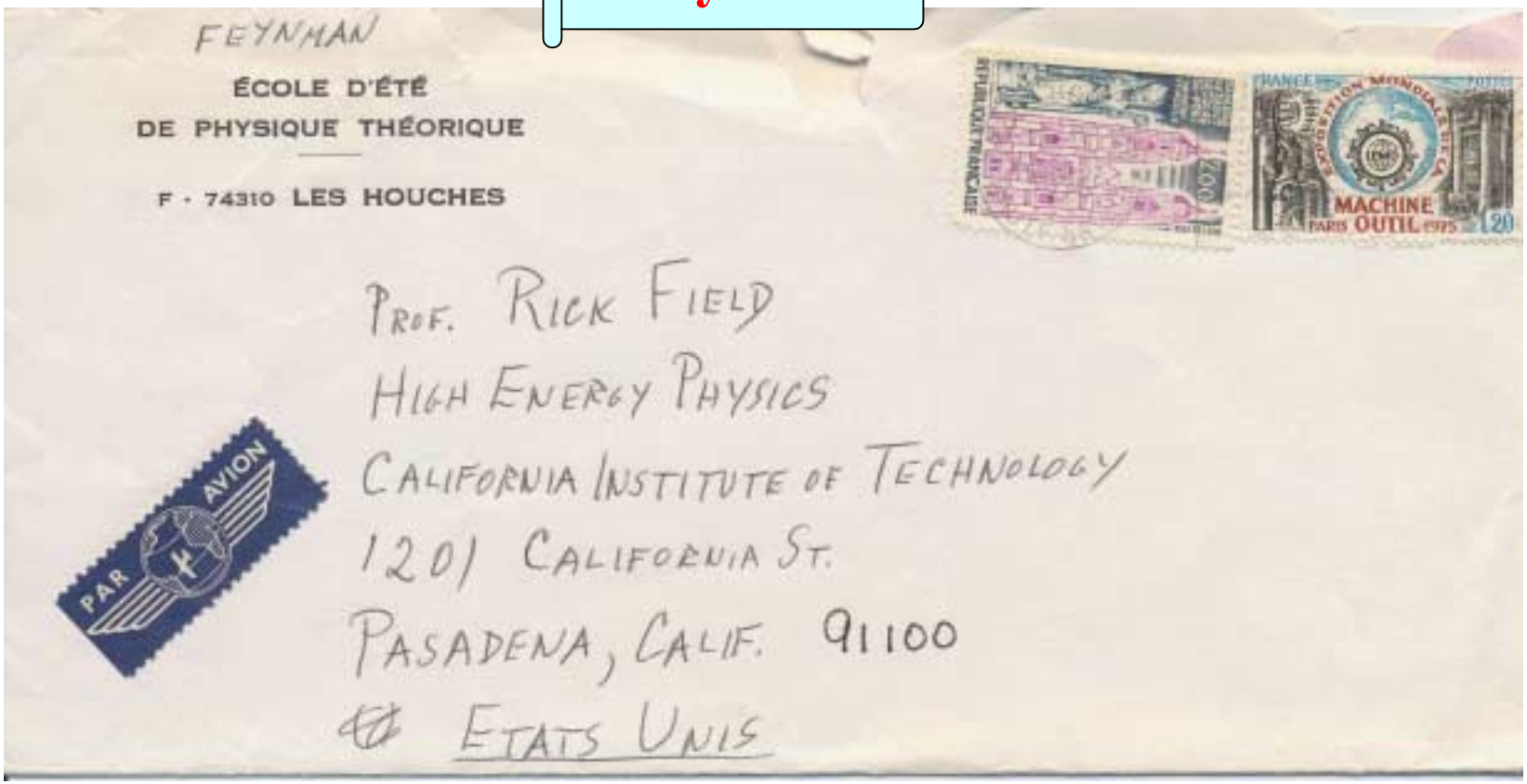
western union — Telefax

ICS IPMIINA IISS
IISS FK WUI 19 0249
PMS PASADENA CA
UWA1871 PSX553 3103B4W 7290
UWNX CO FRXX 015
CHAMONIXMONTBLANC
RICK FIELD CALTECH
PASADENA/CALIF
SAW CRONIN AM NOW CONVINCED WERE RIGHT TRACK QUICK WRITE
FEY
NSAH

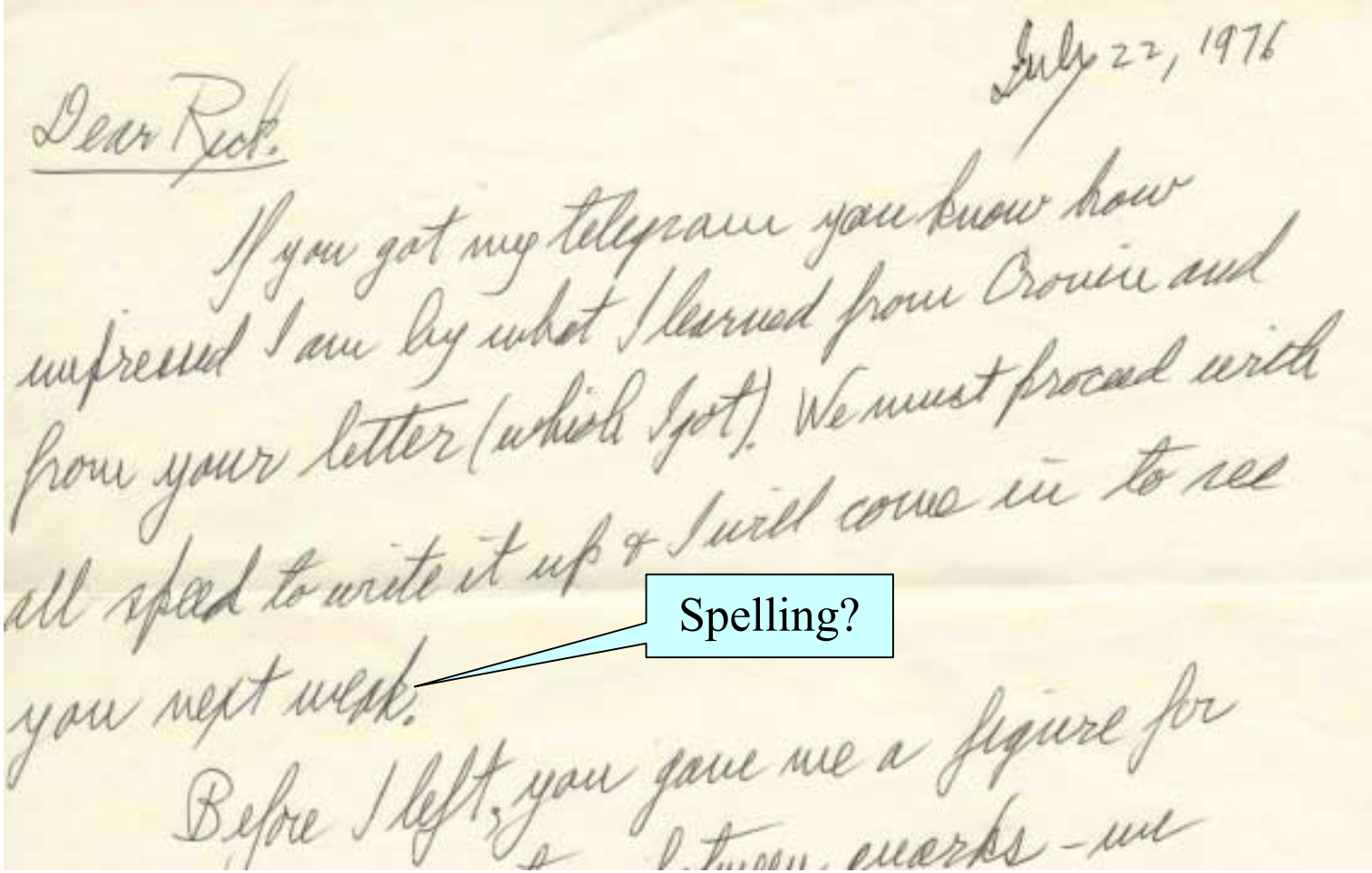
**SAW CRONIN AM NOW CONVINCED WERE RIGHT TRACK QUICK WRITE FEYNMAN**

# Letter from Feynman

**July 1976**



# Letter from Feynman: page 1



July 22, 1976

Dear Rick.

If you got my telegram you know how impressed I am by what I learned from Cronin and from your letter (which I got). We must proceed with all speed to write it up & I will come in to see you next week.

Spelling?

Before I left, you gave me a figure for [illegible] between quarks - me

# Letter from Feynman: page 3

It is fun!

It is fun.
Because mail here is slow, intermittent and balled up in France, try a telegram. ~~Cable address~~ ECOLE D'ETE DE PHYSIC
F-74310 LES HOUCHES

just send the number for A in $d^2\sigma/dt = A/s^2 t$. If instead it is for $B/s^2 t^2$ say "B is 2700 mb" or whatever. Just a few words.

Onward!

Onward,
Dick Feynman.

# Napkin from Feynman

F approximates f if z is not near

$$\int_0^1 \frac{dz}{1-z} \ln f(z) = \int_0^1 \frac{dz}{1-z} \ln \frac{f(z)}{F(z)} + \int_0^1 \frac{dz}{1-z} \ln F(z)$$

approx

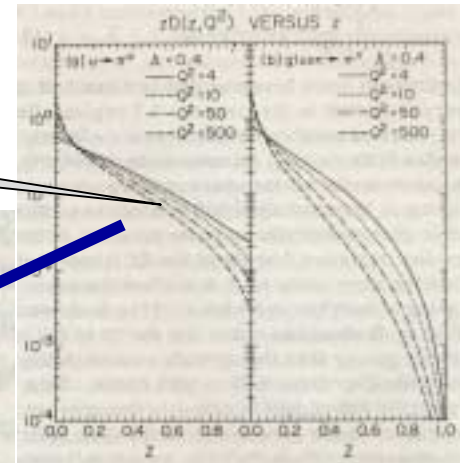
easier

$$\int_0^\infty \frac{dx}{x} \ln \frac{f(1-x)}{F(1-x)}$$

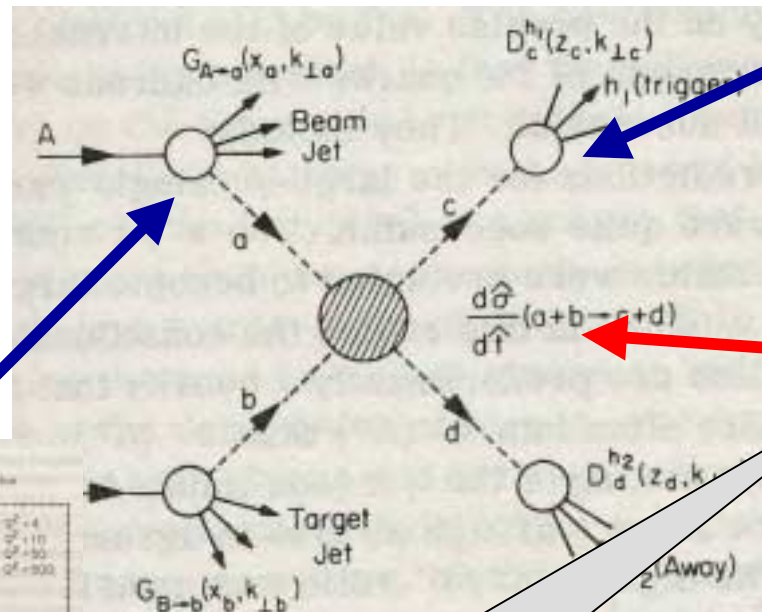
# QCD Approach
# Quarks & Gluons

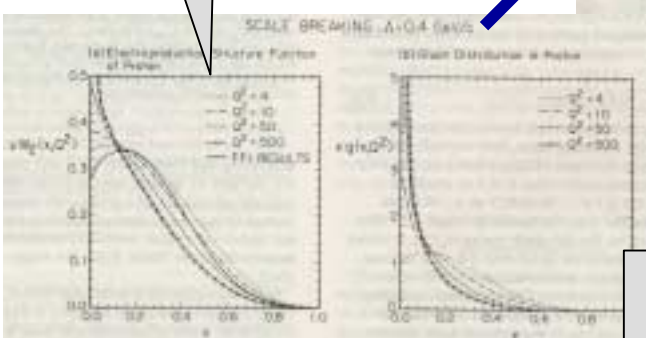
**Quark & Gluon Fragmentation Functions**
**$Q^2$ dependence predicted from QCD**

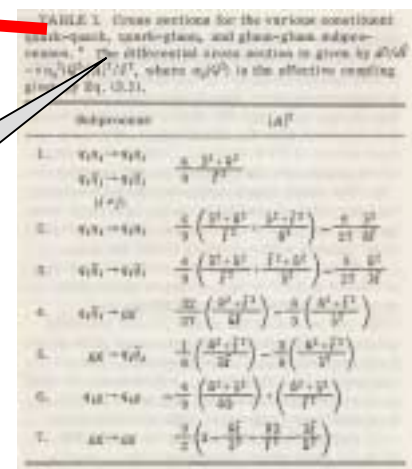
**FFF2 1978**



**Parton Distribution Functions**
**$Q^2$ dependence predicted from QCD**





**Quark & Gluon Cross-Sections**
**Calculated from QCD**

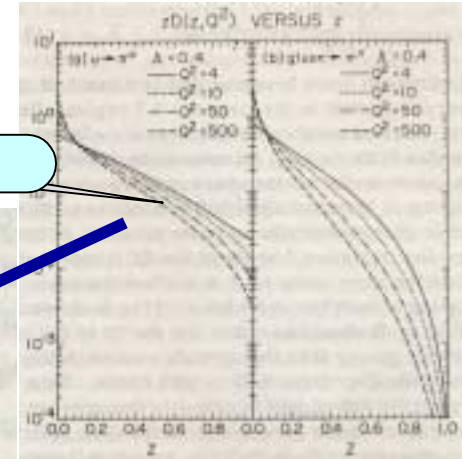
# QCD Approach
# Quarks & Gluons

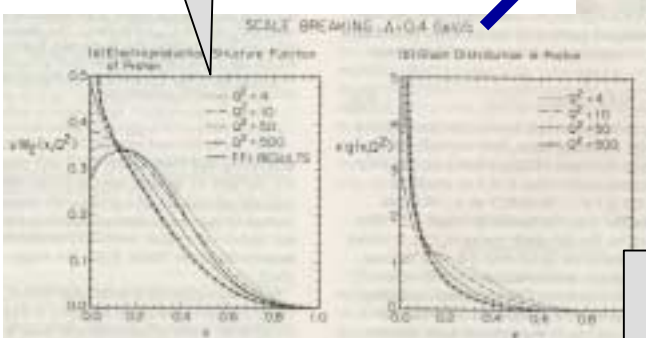
**Quark & Gluon Fragmentation Functions**
**$Q^2$ dependence predicted from QCD**

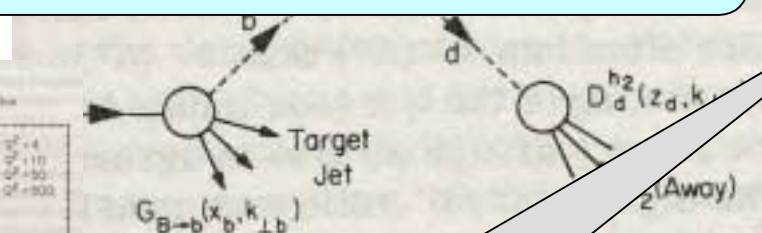
**FFF2 1978**

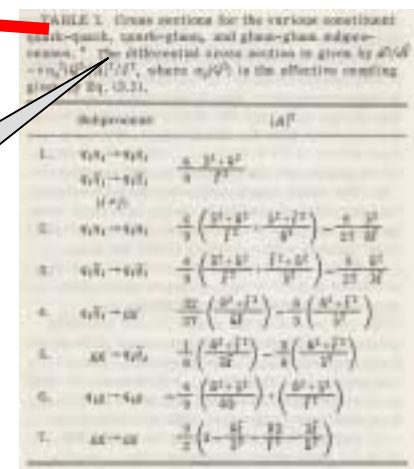
**Parton Distribution Functions**
**$Q^2$ dependence predicted from QCD**

**Feynman quote from FFF2:**
**"We investigate whether the present experimental behavior of mesons with large transverse momentum in hadron-hadron collisions is consistent with the theory of quantum-chromodynamics (QCD) with asymptotic freedom, at least as the theory is now partially understood."**







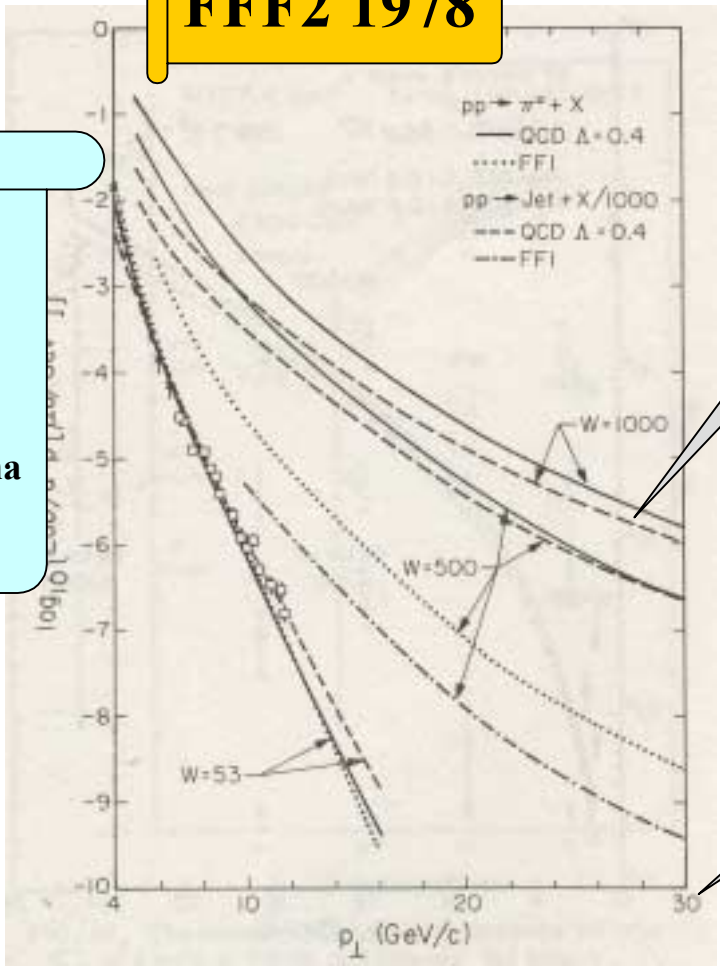



**Quark & Gluon Cross-Sections**
**Calculated from QCD**

# QCD Approach
# Quarks & Gluons

**FFF2 1978**

**Feynman quote from FFF2:**
**"At the time of this writing, there is still no sharp quantitative test of QCD. An important test will come in connection with the phenomena of high $P_T$ discussed here."**



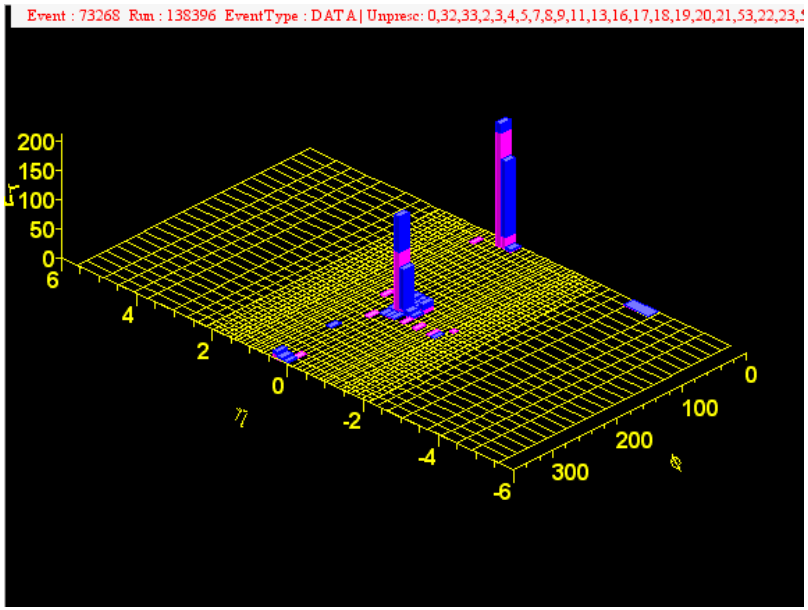

**Predict**
**large "jet" cross-section**

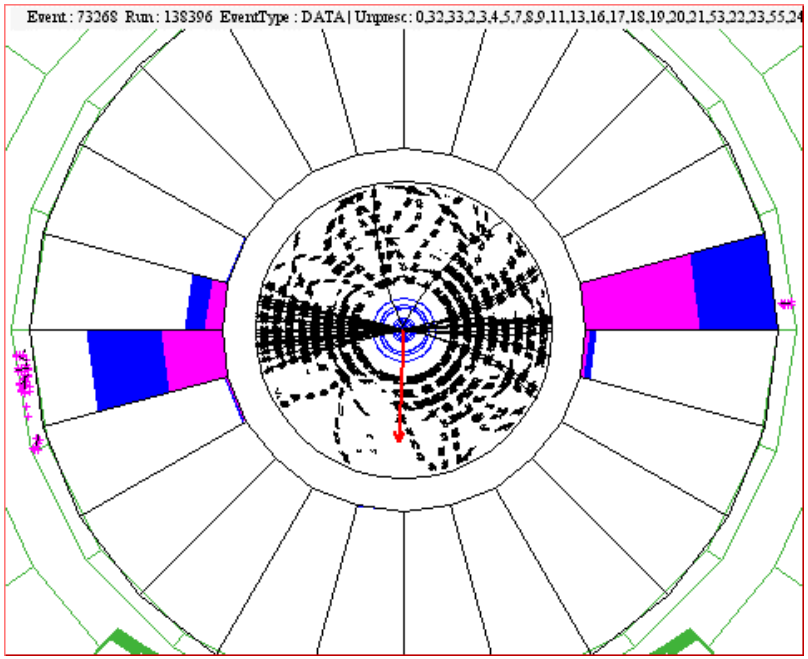
**30 GeV!**

# CDF Run II DiJet Event
# July 2002

$E_T^{jet1}$ = 403 GeV
$E_T^{jet2}$ = 322 GeV

**Raw $E_T$ values!!**



# Monte-Carlo Simulation of Hadron-Hadron Collisions

**FF1-FFF1 (1977)**
"Black-Box" Model

**F1-FFF2 (1978)**
QCD Approach

**FF2 (1978)**
Monte-Carlo simulation of "jets"

**FFFW "FieldJet" (1980)**
QCD "leading-log order" simulation of hadron-hadron collisions

"FF" or "FW" Fragmentation

the past

today

**ISAJET**
("FF" Fragmentation)

**HERWIG**
("FW" Fragmentation)

**PYTHIA**

# Monte-Carlo Simulation of Hadron-Hadron Collisions

**FF1-FFF1 (1977)**
"Black-Box" Model

**F1-FFF2 (1978)**
QCD Approach

**FF2 (1978)**
Monte-Carlo
ulation of "jets"

**Feynman quote from FF2:**
"The predictions of the model are reasonable enough physically that we expect it may be close enough to reality to be useful in designing future experiments and to serve as a reasonable approximation to compare to data. We do not think of the model as a sound physical theory, ...."

"FF" or "FW" Fragmentation

the past

today

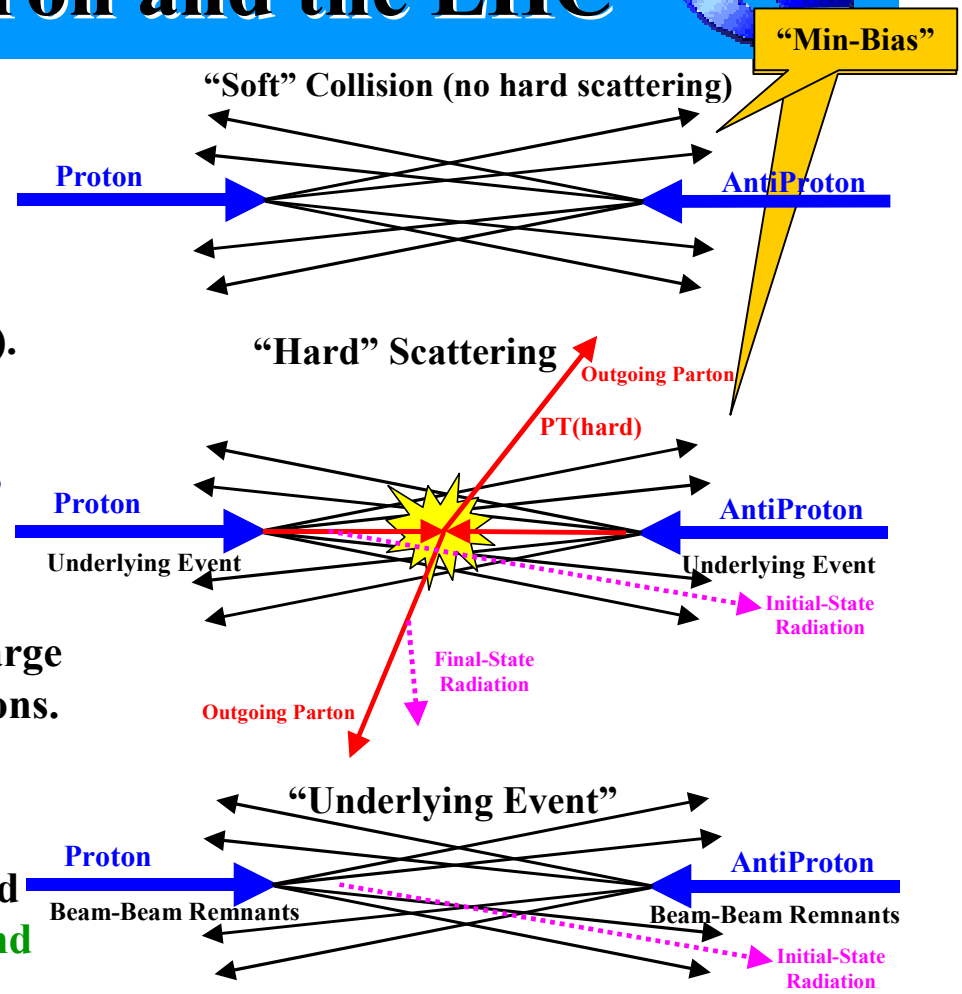
**ISAJET**
("FF" Fragmentation)

**HERWIG**
("FW" Fragmentation)

**PYTHIA**

# "Min-Bias" & "Underlying Event" at the Tevatron and the LHC

- What happens when a high energy proton and an antiproton collide?
- Most of the time the proton and antiproton ooze through each other and fall apart (*i.e.* no hard scattering). The outgoing particles continue in roughly the same direction as initial proton and antiproton. A "Min-Bias" collision.
- Occasionally there will be a "hard" parton-parton collision resulting in large transverse momentum outgoing partons. Also a "Min-Bias" collision.
- The "underlying event" is everything except the two outgoing hard scattered "jets". It is an unavoidable background to many collider observables.



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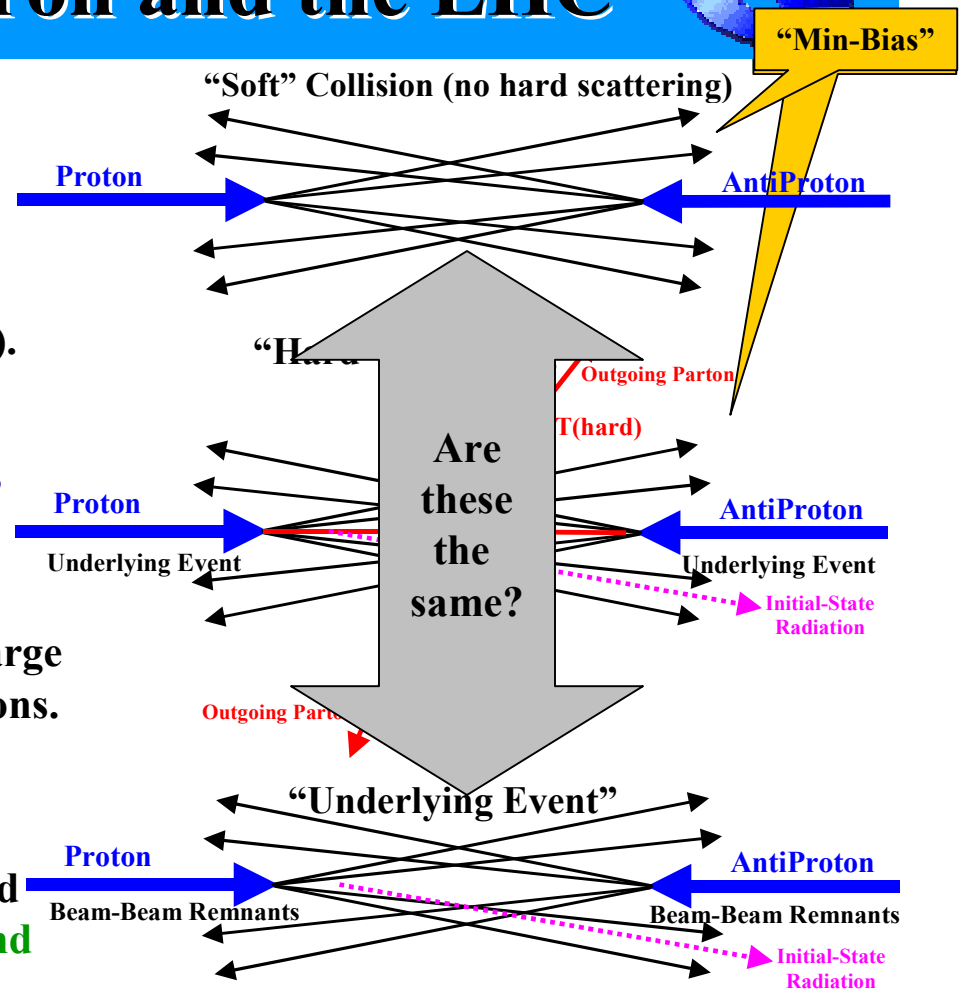
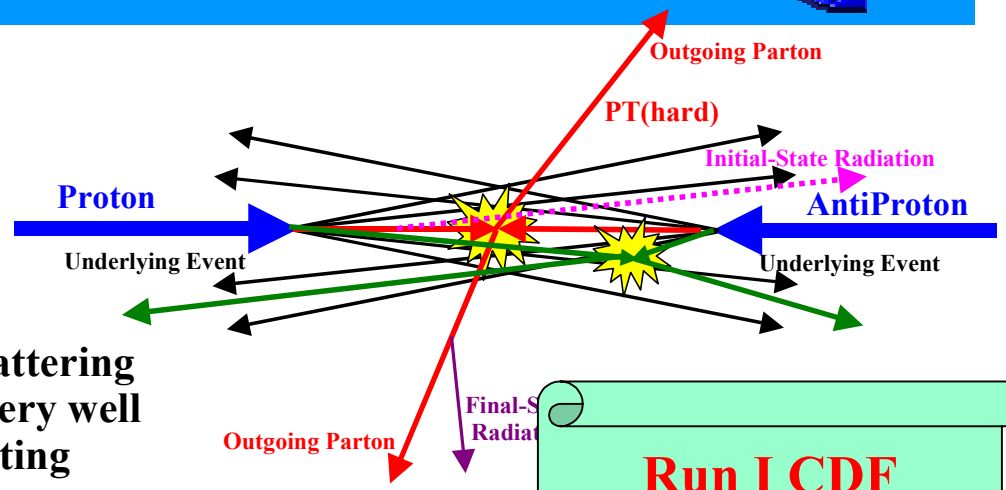


# Studying the "Underlying Event" at CDF

**The Underlying Event:**
**beam-beam remnants**
**initial-state radiation**
**multiple-parton interactions**



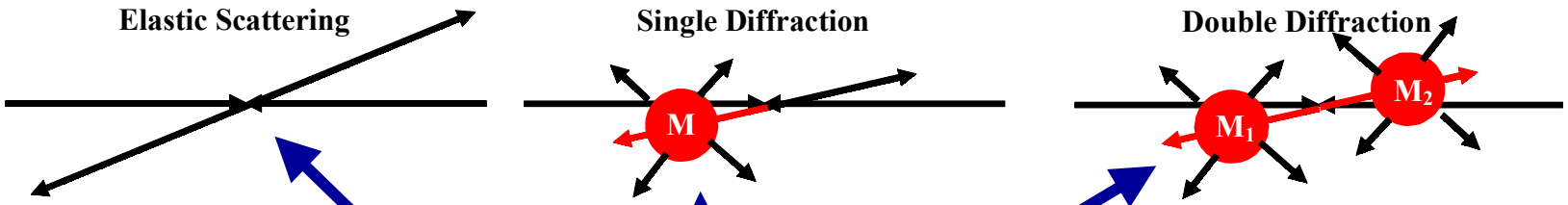

- The underlying event in a hard scattering process is a complicated and not very well understood object. It is an interesting region since it probes the interface between perturbative and non-perturbative physics.
- There are three CDF analyses which quantitatively study the underlying event and compare with the QCD Monte-Carlo models (2 Run I and 1 Run II).
- It is important to model this region well since it is an unavoidable background to all collider observables. Also, we need a good model of "min-bias" collisions.

**Run I CDF**
"Evolution of Charged Jets"
Rick Field
David Stuart
Rich Haas

**Run I CDF**
"Cone Analysis"
Valeria Tano
Eve Kovacs
Joey Huston
Anwar Bhatti

**Run II CDF**
"Jet Shapes & Energy Flow"
Mario Martinez

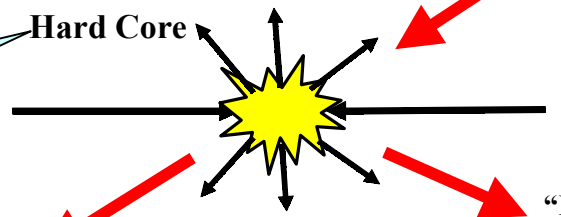
# The Proton-Antiproton Total Cross-Section

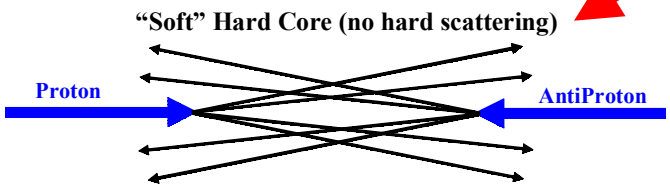


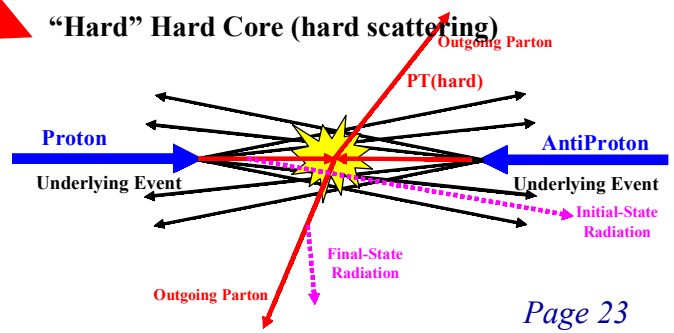

$$\sigma_{tot} = \sigma_{EL} + \sigma_{SD} + \sigma_{DD} + \sigma_{HC}$$

**1.8 TeV: 78mb = 18mb + 9mb + (4-7)mb + (47-44)mb**

The "hard core" component contains both "hard" and "soft" collisions.



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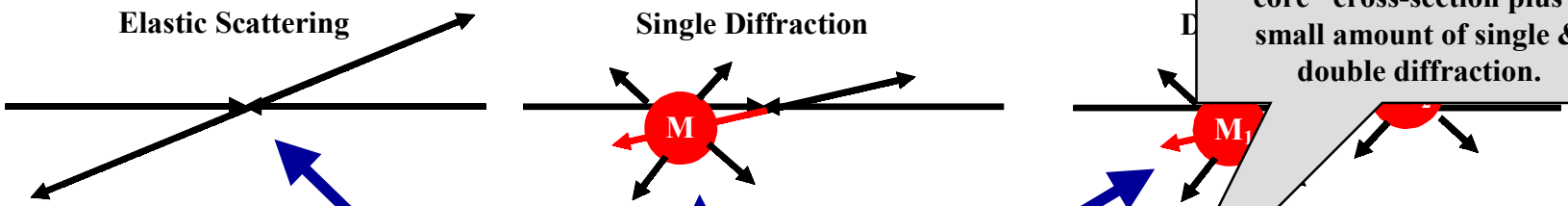


The CDF "Min-Bias" trigger picks up most of the "hard core" cross-section plus a small amount of single & double diffraction.

$$\sigma_{tot} = \sigma_{EL} + \sigma_{SD} + \sigma_{DD} + \sigma_{HC}$$

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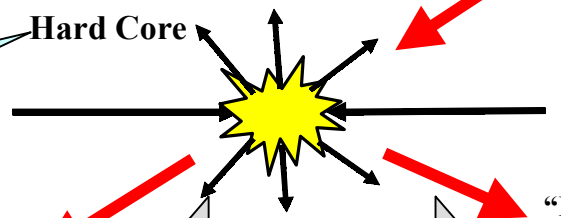
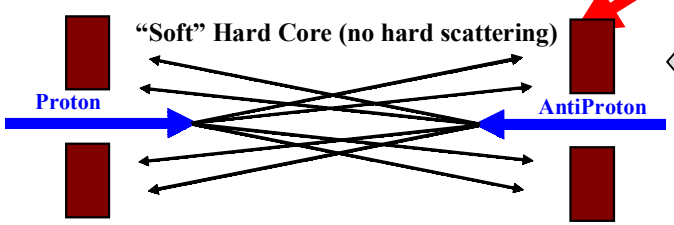
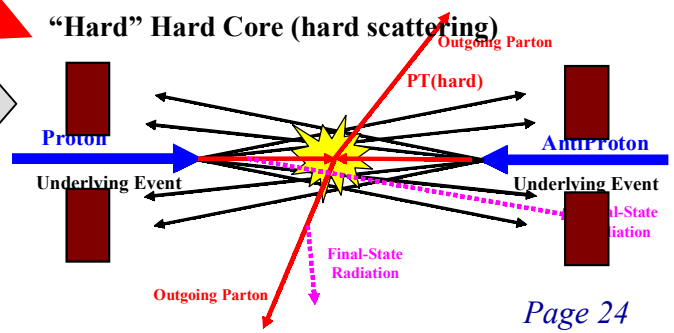



**CDF "Min-Bias" trigger**
1 charged particle in forward BBC
AND
1 charged particle in backward BBC

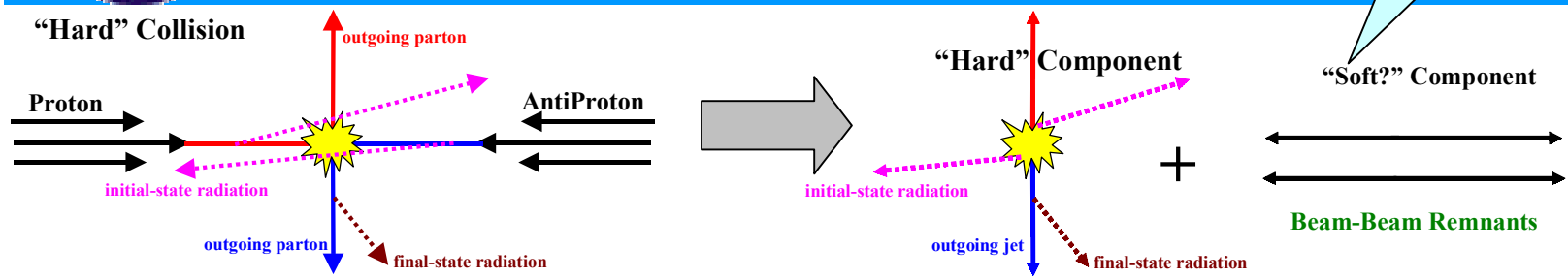



Beam-Beam Counters
$3.2 < |\eta| < 5.9$

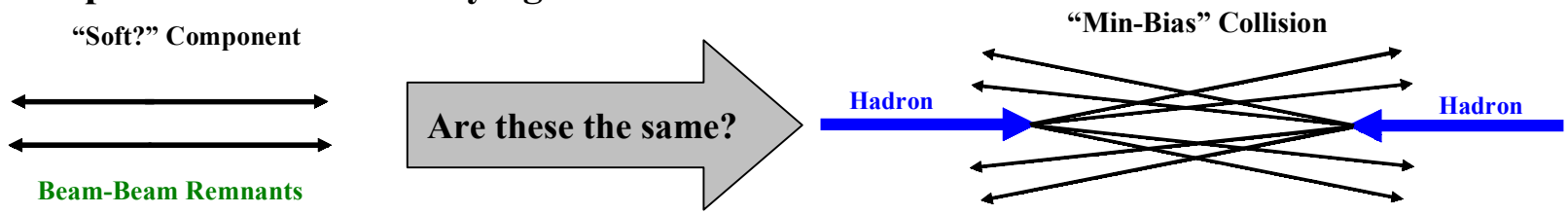


# Beam-Beam Remnants

Maybe not all "soft"!

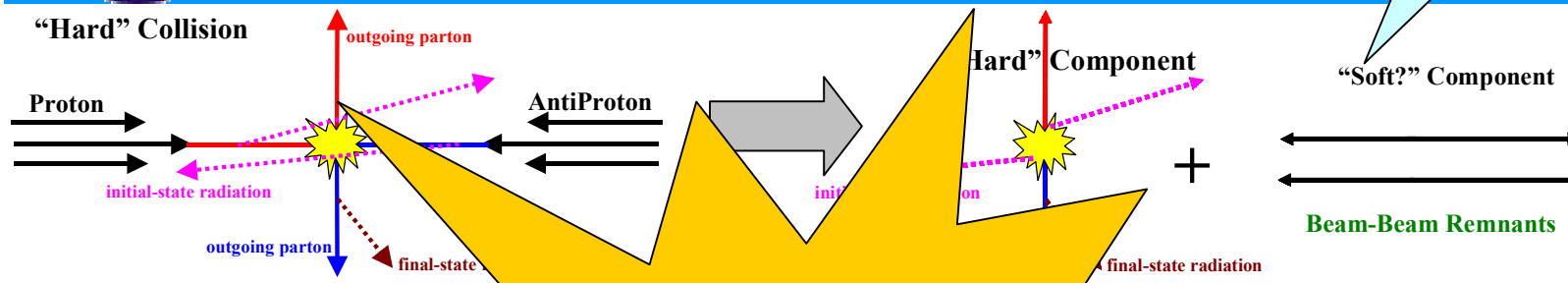



- The underlying event in a hard scattering process has a "hard" component (particles that arise from initial & final-state radiation and from the outgoing hard scattered partons) and a "soft?" component ("beam-beam remnants").
- Clearly? the "underlying event" in a hard scattering process should not look like a "Min-Bias" event because of the "hard" component (*i.e.* initial & final-state radiation).
- However, perhaps "Min-Bias" collisions are a good model for the "beam-beam remnant" component of the "underlying event".



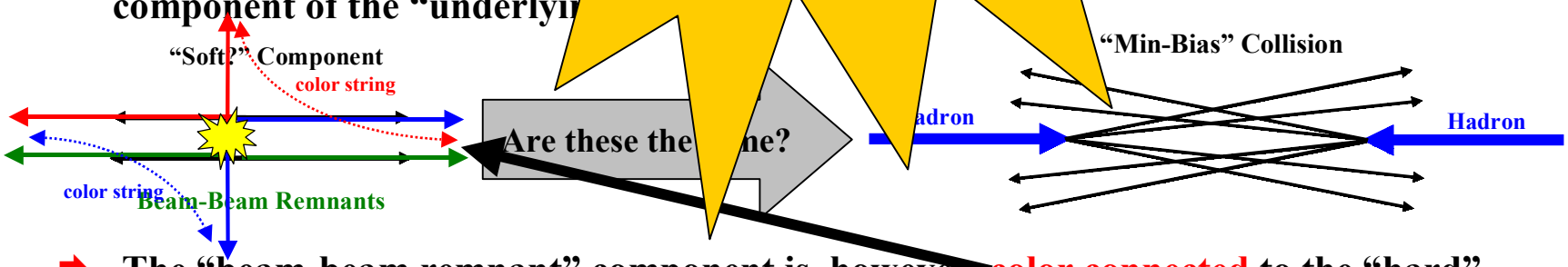
# Beam-Beam Remnants

Maybe not all "soft"!



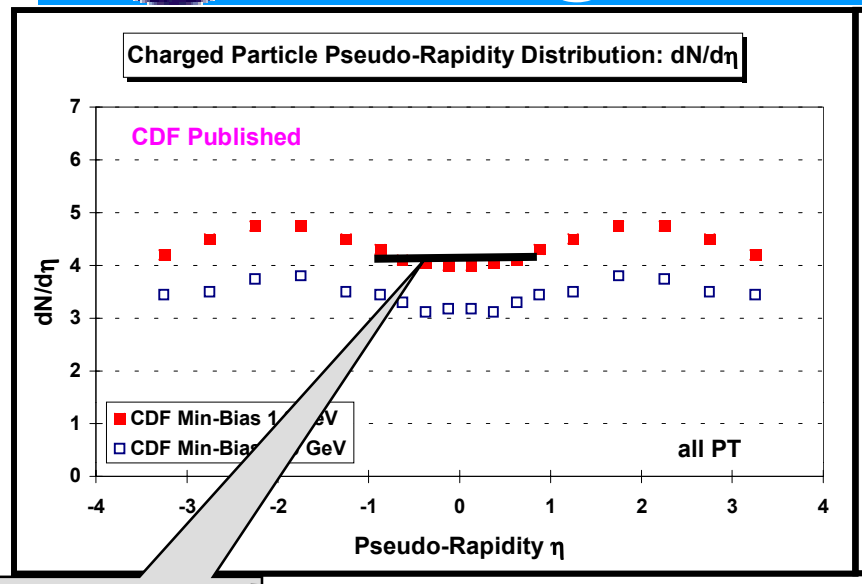

- The underlying event in a hard" component (particles that arise from initial-s rd scattered partons) and a "soft?" comp
- Clearly? the "underlyin hould not look like a "Min-Bias" event because of ate radiation).
- However, perhap Min-Bias for the "beam-beam remnant" component of the "underlyin

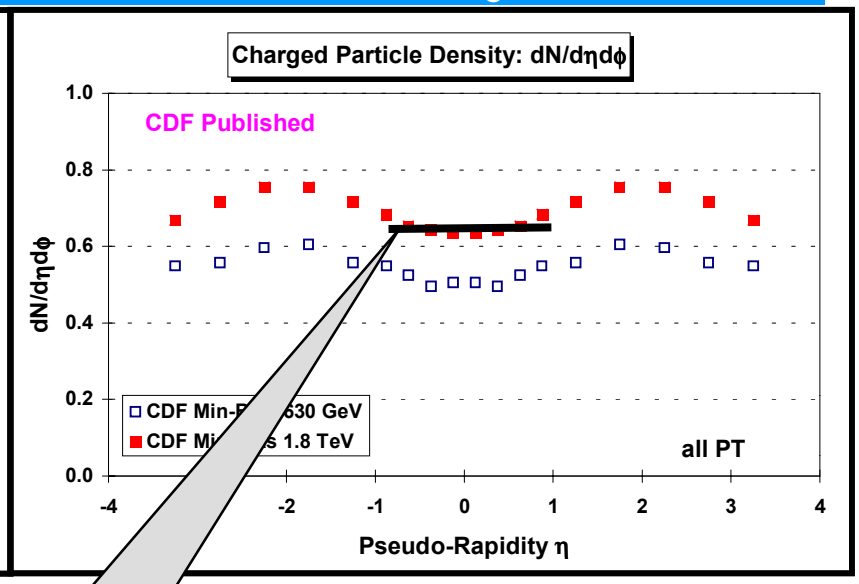
If we are going to look at "Min-Bias" collisions as a guide to understanding the "beam-beam remnants", then we better study carefully the "Min-Bias" data!




- The "beam-beam remnant" component is, however, color connected to the "hard" component so this comparison is (at best) an approximation.

# CDF "Min-Bias" Data
# Charged Particle Density



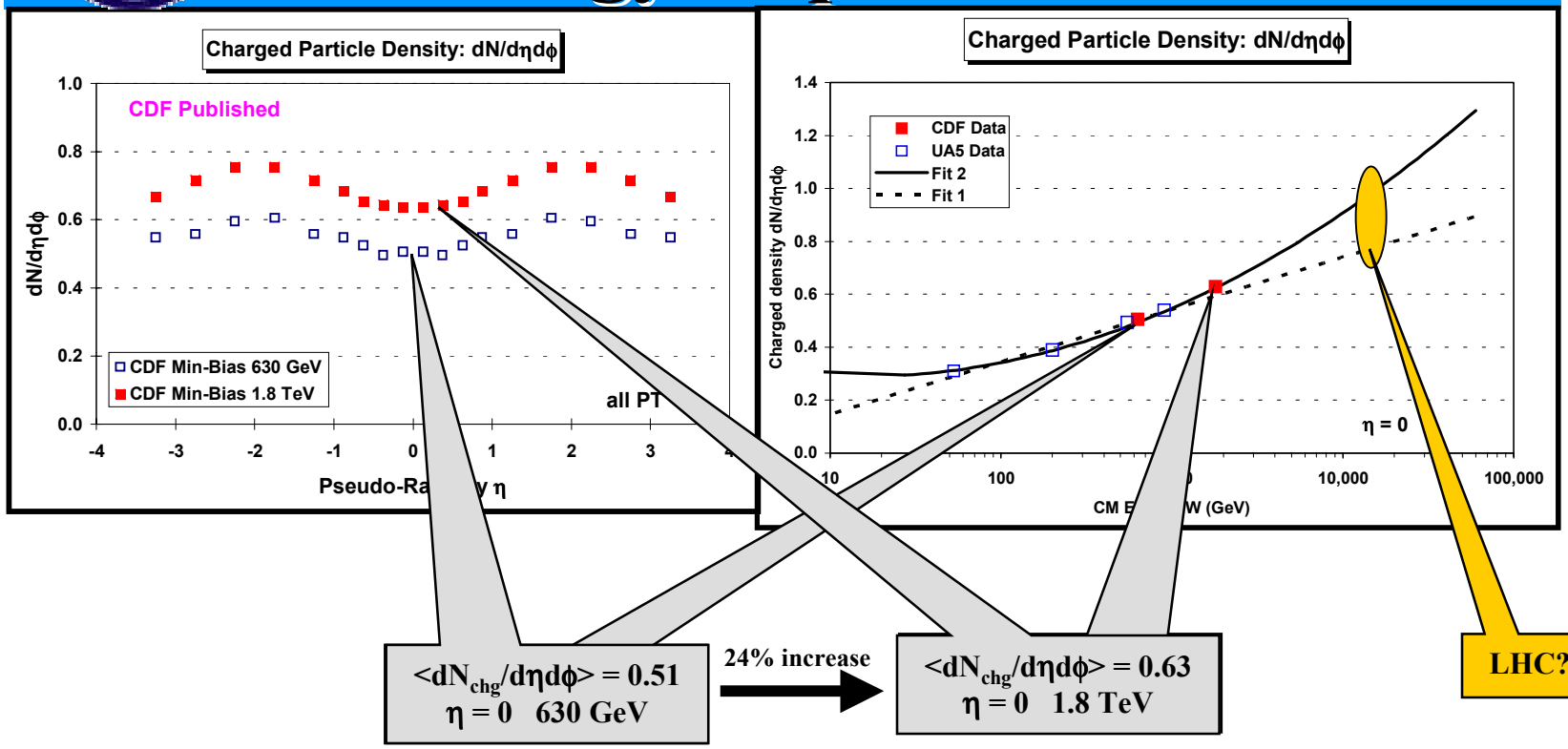




$\langle dN_{chg}/d\eta \rangle = 4.2$

$\langle dN_{chg}/d\eta d\phi \rangle = 0.67$

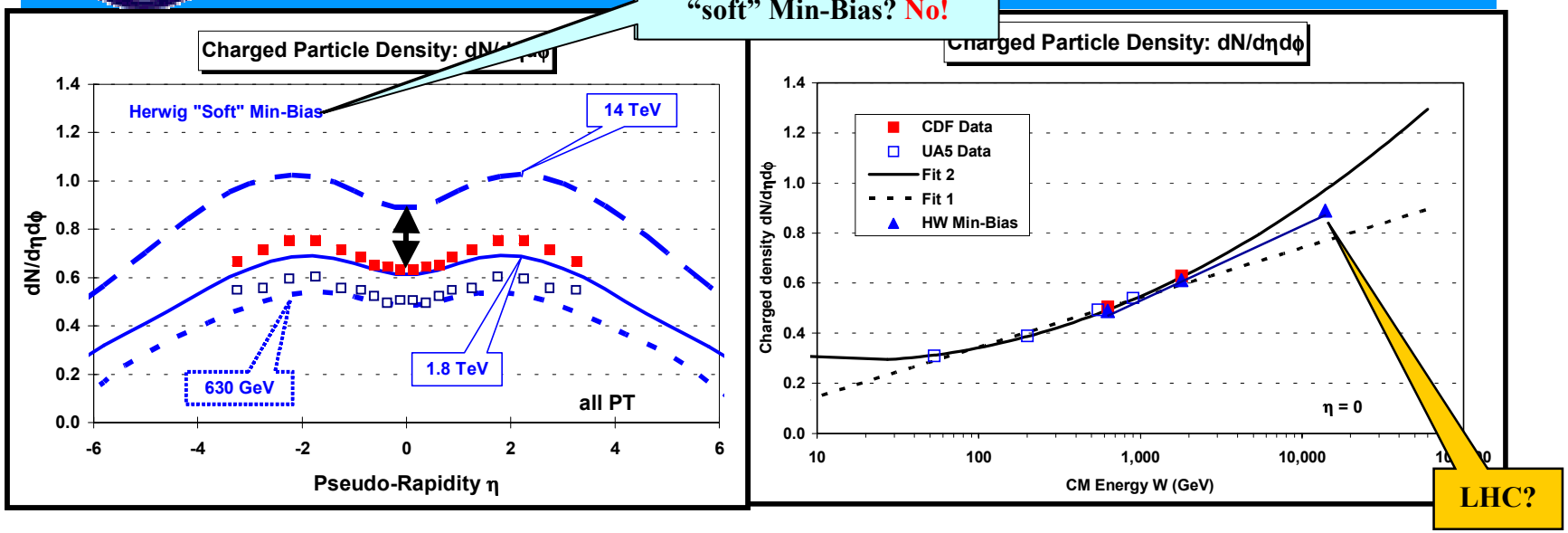
- Shows CDF "Min-Bias" data on the number of charged particles per unit pseudo-rapidity at 630 and 1,800 GeV. There are about 4.2 charged particles per unit η in "Min-Bias" collisions at 1.8 TeV ($|\eta| < 1$, all $P_T$).
- Convert to charged particle density, $dN_{chg}/d\eta d\phi$, by dividing by $2\pi$. There are about 0.67 charged particles per unit η-ϕ in "Min-Bias" collisions at 1.8 TeV ($|\eta| < 1$, all $P_T$).

# CDF "Min-Bias" Data Energy Dependence



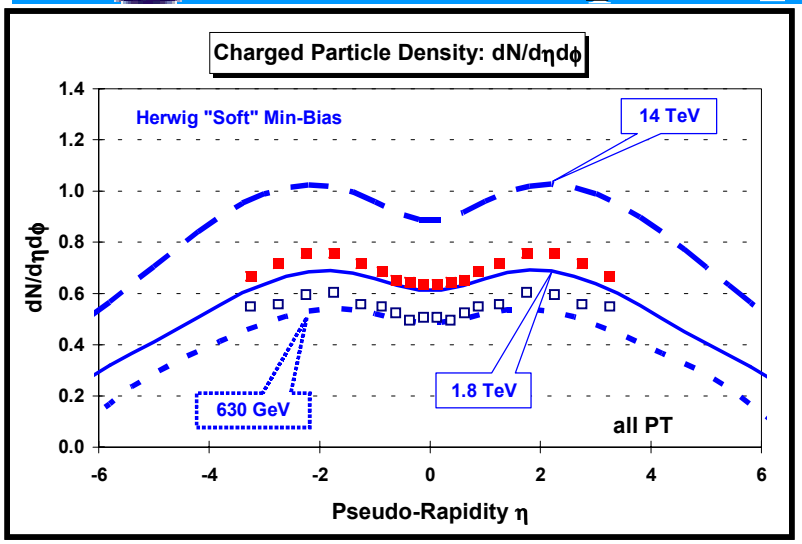

- **Shows the center-of-mass energy dependence of the charged particle density, $dN_{chg}/d\eta d\phi$, for "Min-Bias" collisions at $\eta = 0$. Also show a log fit (Fit 1) and a $(\log)^2$ fit (Fit 2) to the CDF plus UA5 data.**
- **What should we expect for the LHC?**

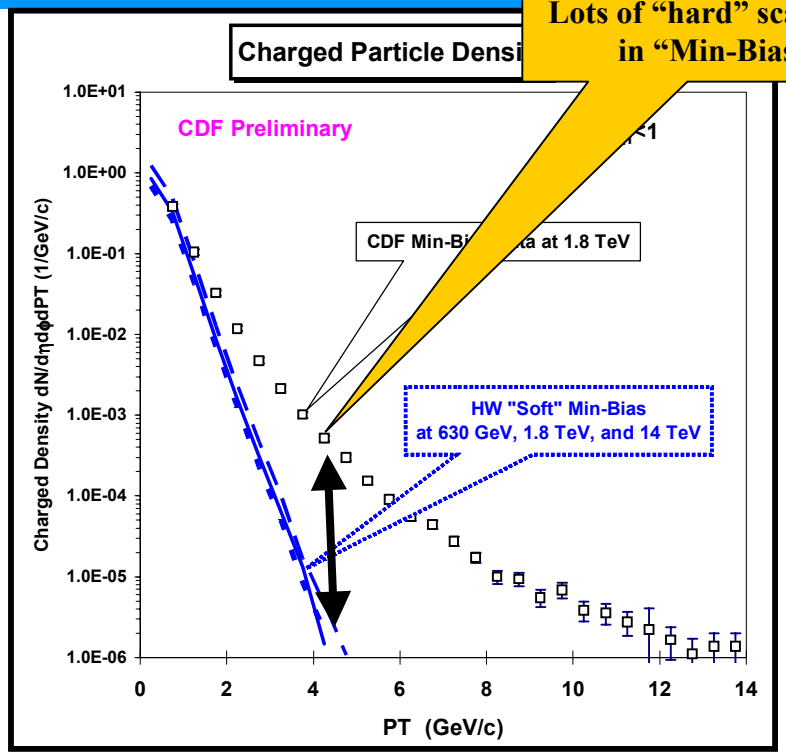
# Herwig "Soft" Min-Bias




- Shows the center-of-mass energy dependence of the charged particle density, $dN_{chg}/d\eta d\phi$, for "Min-Bias" collisions compared with the HERWIG "Soft" Min-Bias Monte-Carlo model. Note: there is no "hard" scattering in HERWIG "Soft" Min-Bias.
- HERWIG "Soft" Min-Bias contains no hard parton-parton interactions and describes fairly well the charged particle density, $dN_{chg}/d\eta d\phi$, in "Min-Bias" collisions.
- HERWIG "Soft" Min-Bias predicts a 45% rise in $dN_{chg}/d\eta d\phi$ at $\eta = 0$ in going from the Tevatron (1.8 TeV) to the LHC (14 TeV). 4 charged particles per unit $\eta$ becomes 6.

# CDF "Min-Bias" Data $P_T$ Dependence

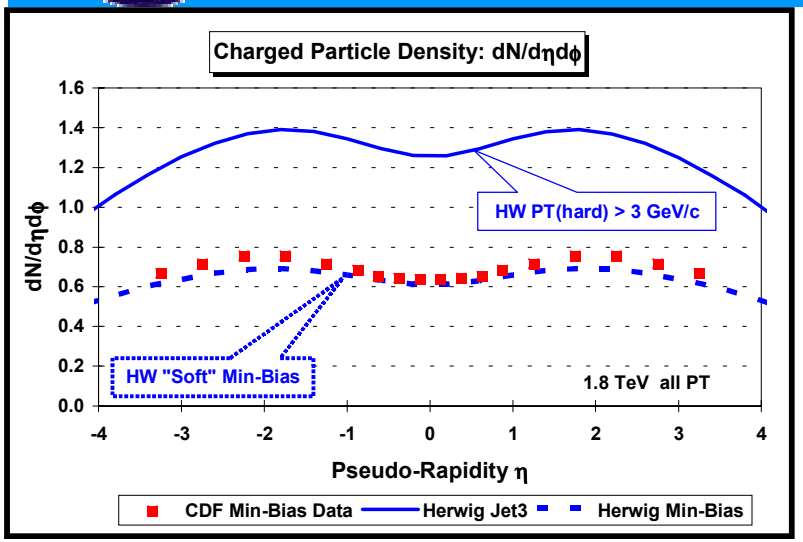


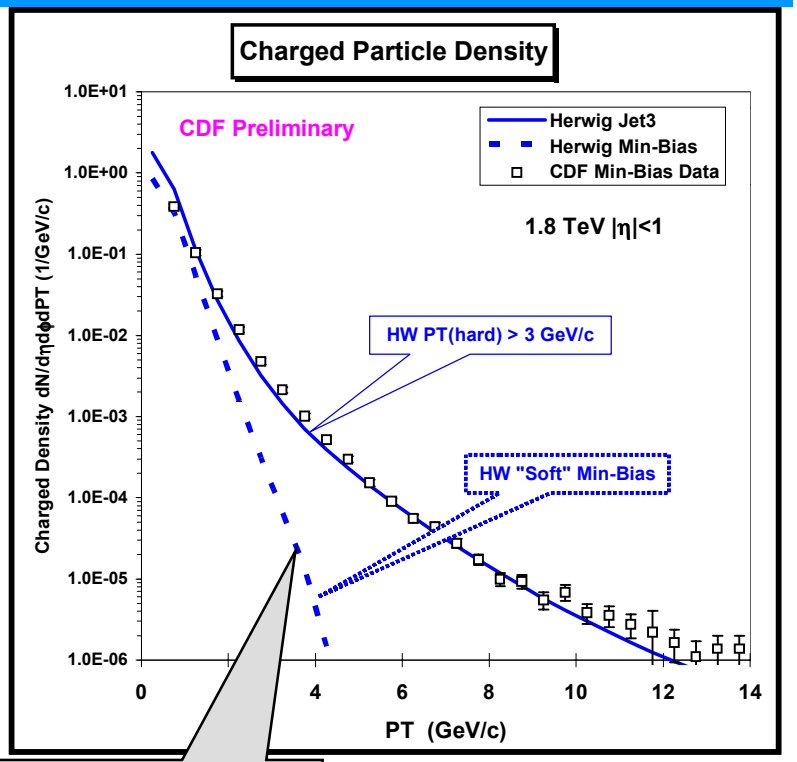




Lots of "hard" scattering in "Min-Bias"!

- Shows the energy dependence of the charged particle density, $dN_{chg}/d\eta d\phi$, for "Min-Bias" collisions compared with HERWIG "Soft" Min-Bias.
- Shows the $P_T$ dependence of the charged particle density, $dN_{chg}/d\eta d\phi dP_T$, for "Min-Bias" collisions at 1.8 TeV collisions compared with HERWIG "Soft" Min-Bias.
- HERWIG "Soft" Min-Bias does not describe the "Min-Bias" data! The "Min-Bias" data contains a lot of "hard" parton-parton collisions which results in many more particles at large $P_T$ than are produces by any "soft" model.

# Min-Bias: Combining "Hard" and "Soft" Collisions



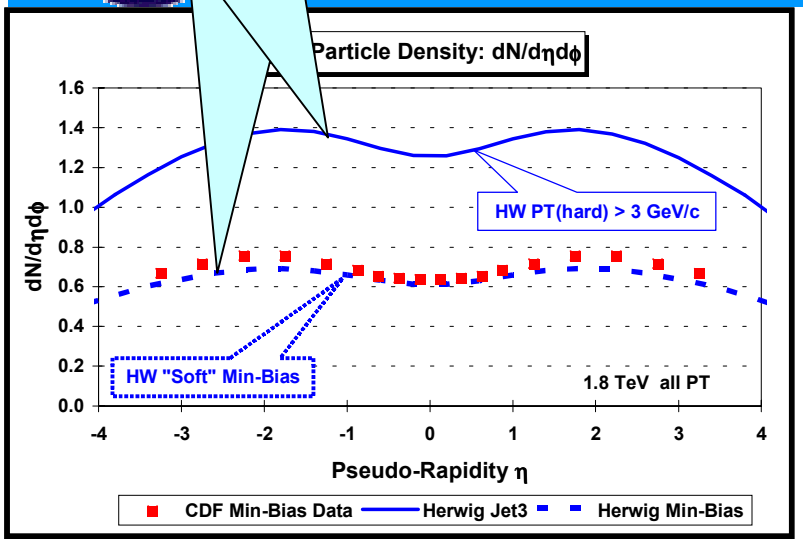

- **HERWIG "hard" QCD with $P_T$(hard) > 3 GeV/c describes well the high $P_T$ tail but produces too many charged particles overall. Not all of the "Min-Bias" collisions have a hard scattering with $P_T$(hard) > 3 GeV/c!**

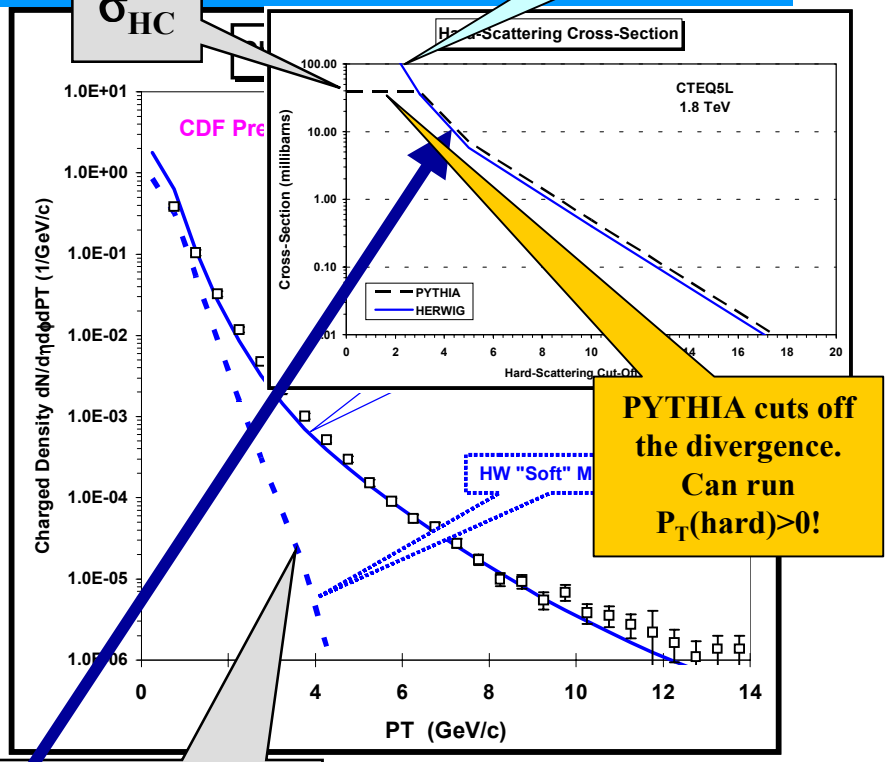
**HERWIG "soft" Min-Bias does not fit the "Min-Bias" data!**

# Min-Bias: Combining "Hard" and "Soft" Collisions

No easy way to "mix" HERWIG "hard" with HERWIG "soft".

HERWIG diverges!



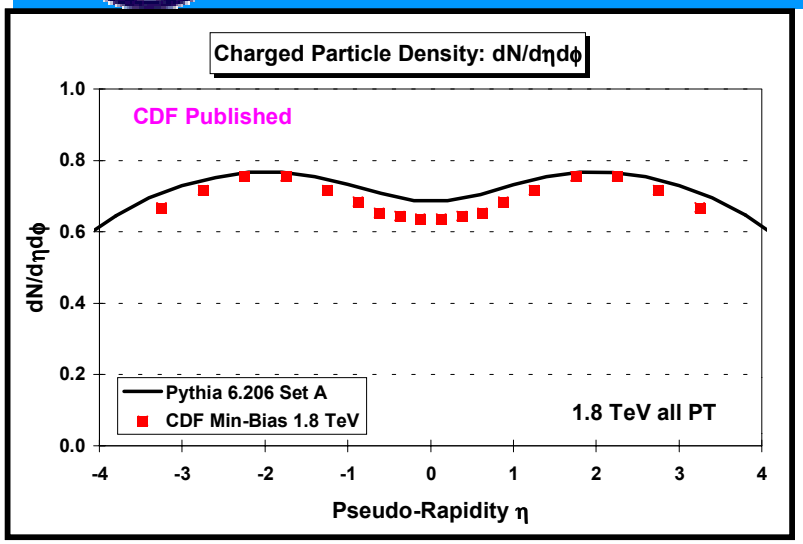

PYTHIA cuts off the divergence. Can run $P_T$(hard)>0!

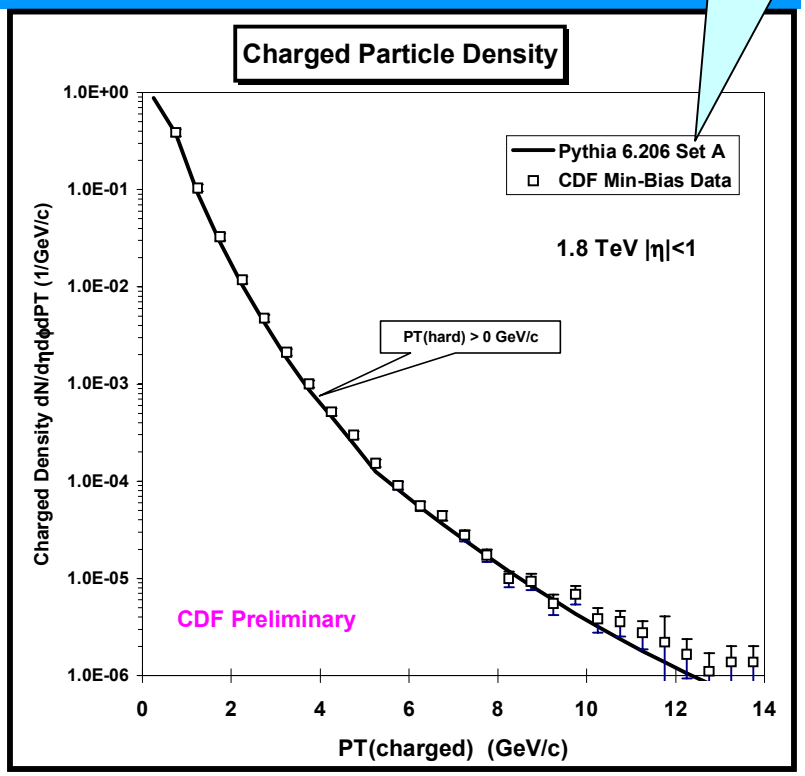
HERWIG "soft" Min-Bias does not fit the "Min-Bias" data!

- **HERWIG "hard" QCD with $P_T$(hard) > 3 GeV/c describes well the high $P_T$ tail but produces too many charged particles overall. Not all of the "Min-Bias" collisions have a hard scattering with $P_T$(hard) > 3 GeV/c!**
- **One cannot run the HERWIG "hard" QCD Monte-Carlo with $P_T$(hard) < 3 GeV/c because the perturbative 2-to-2 cross-sections diverge like $1/P_T(\text{hard})^4$?**

# PYTHIA Min-Bias "Soft" + "Hard"

Tuned to fit the "underlying event"!

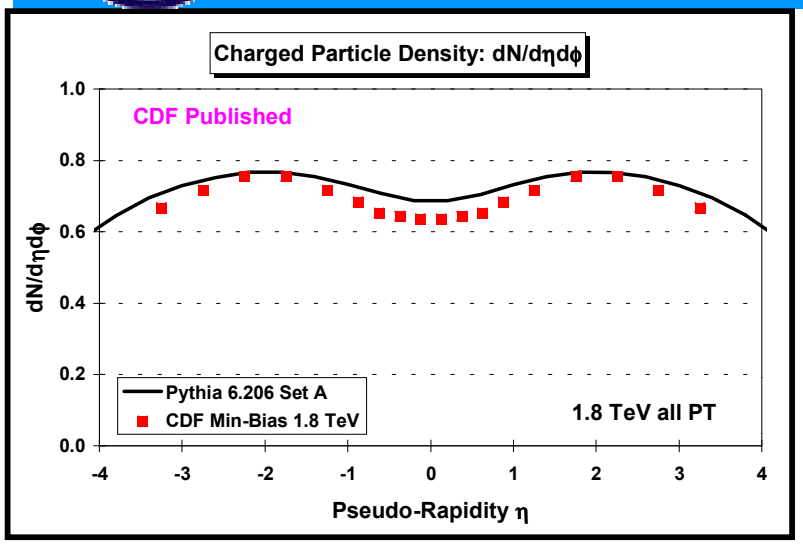


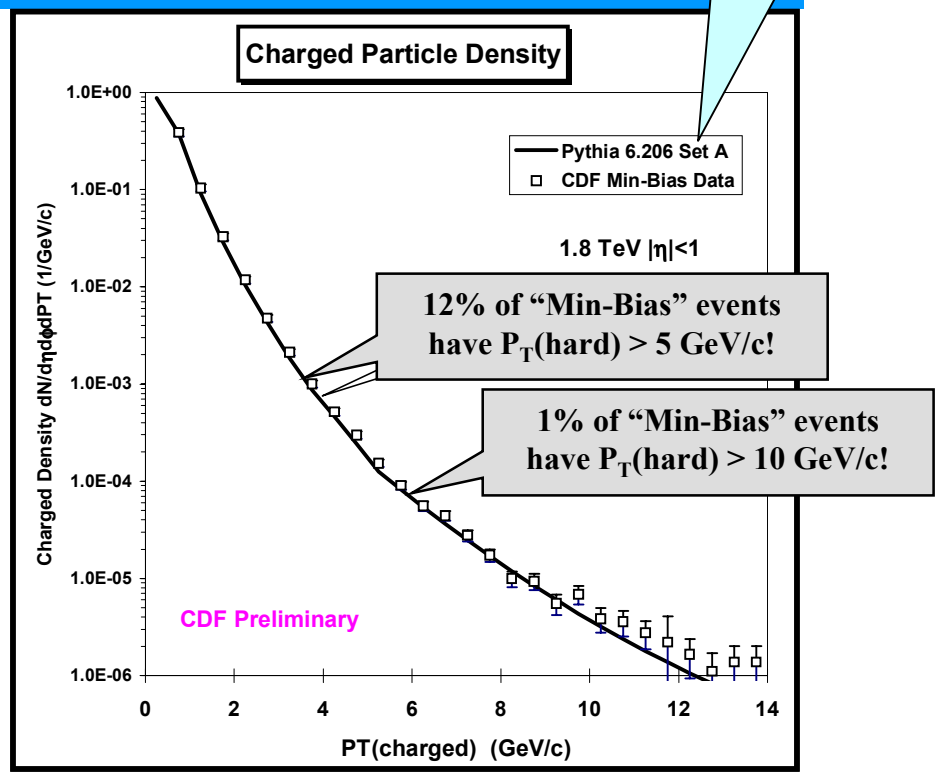




- PYTHIA regulates the perturbative 2-to-2 parton-parton cross sections with cut-off parameters which allows one to run with $P_T$(hard) > 0. One can simulate both "hard" and "soft" collisions in one program.
- The relative amount of "hard" versus "soft" depends of the cut-off and can be tuned.
- This PYTHIA fit predicts that 12% of all "Min-Bias" events are a result of a hard 2-to-2 parton-parton scattering with $P_T$(hard) > 5 GeV/c (1% with $P_T$(hard) > 10 GeV/c)!

# PYTHIA Min-Bias
# "Soft" + "Hard"

Tuned to fit the "underlying event"!

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Lots of "hard" scattering in "Min-Bias"!

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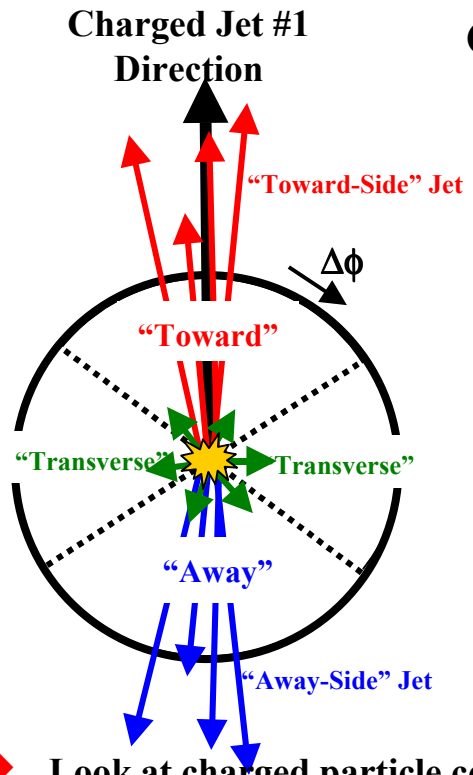
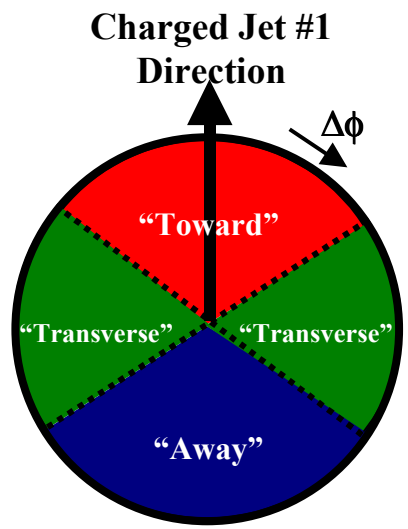
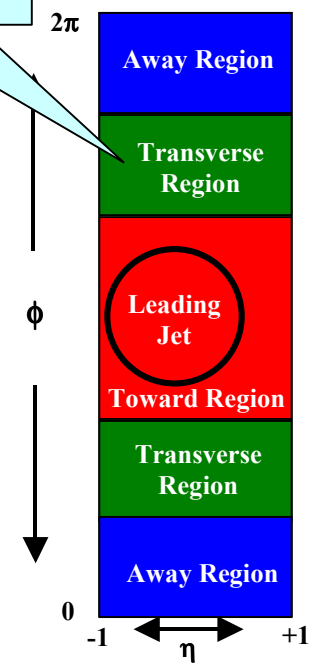
# Evolution of Charged Jets "Underlying Event"

Charged Particle Δϕ
$P_T > 0.5$ GeV/c $|\eta| < 1$

Look at the charged particle density in the "transverse" region!

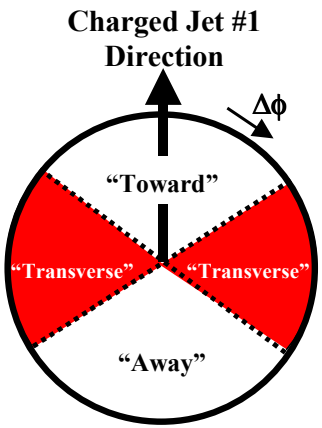


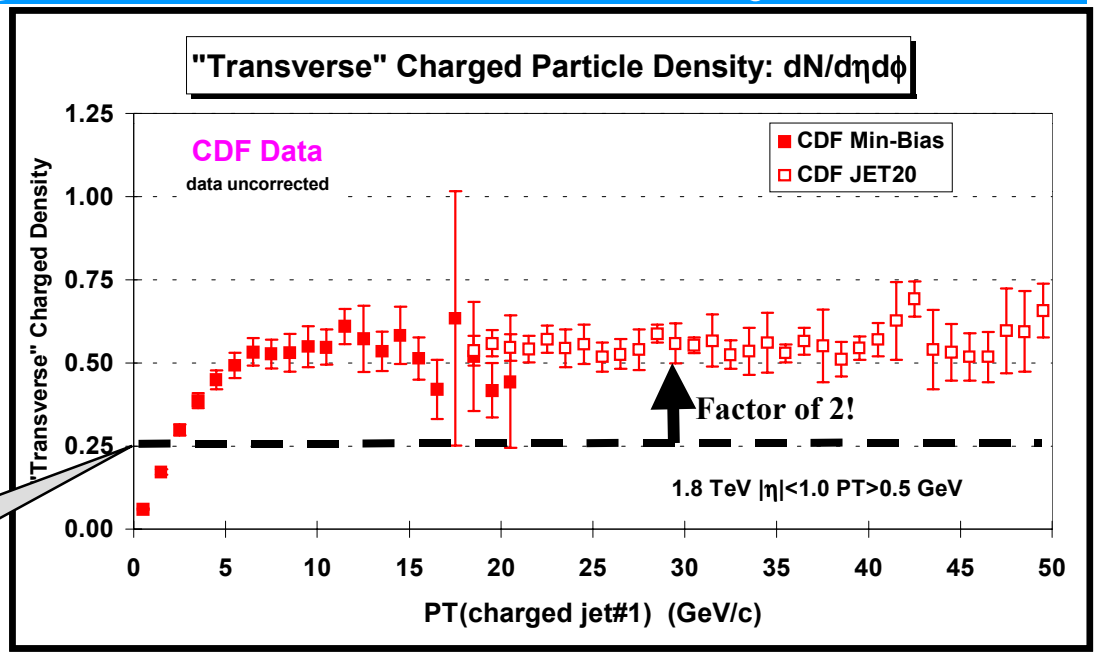




- Look at charged particle correlations in the azimuthal angle Δϕ relative to the leading charged particle jet.
- Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < |\Delta\phi| < 120^o$ as "Transverse", and $|\Delta\phi| > 120^o$ as "Away".
- All three regions have the same size in η-ϕ space, $\Delta\eta x \Delta\phi = 2x120^o = 4\pi/3$.

# "Transverse" Charged Particle Density

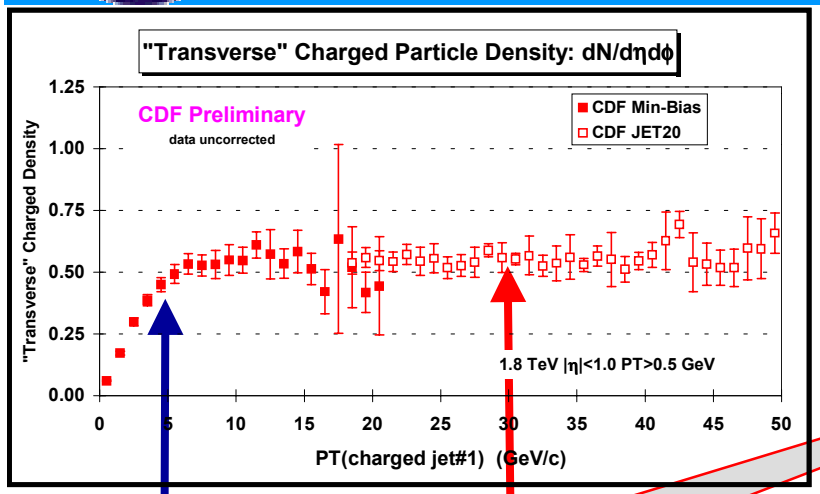


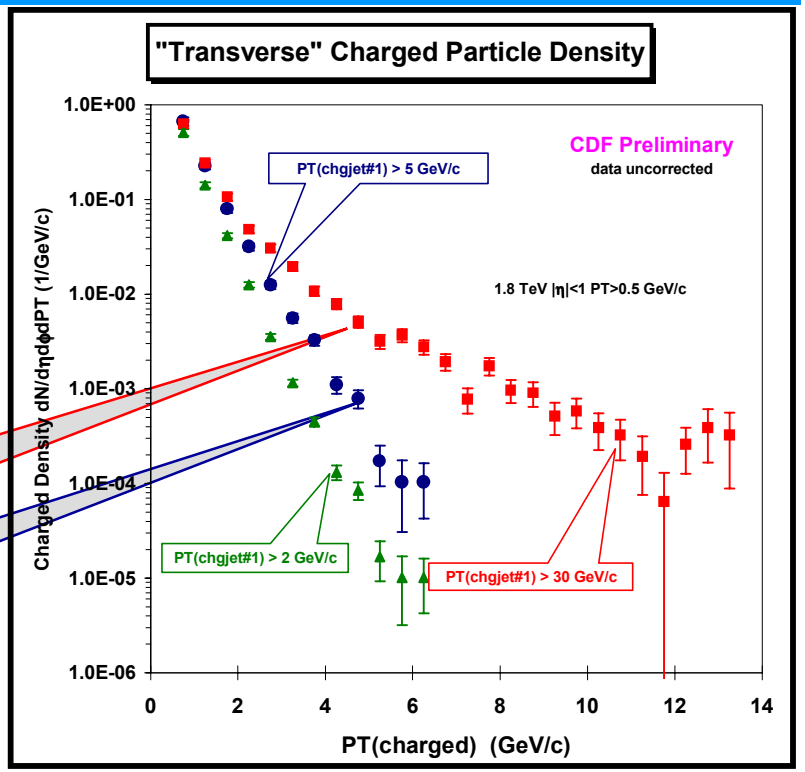

CDF "Min-Bias" data
($|\eta|<1$, $P_T>0.5$ GeV)
$\langle dN_{chg}/d\eta d\phi \rangle = 0.25$




- **Data on the average charge particle density ($P_T > 0.5$ GeV, $|\eta| < 1$) in the "transverse" ($60<|\Delta\phi|<120^o$) region as a function of the transverse momentum of the leading charged particle jet. Each point corresponds to the $\langle dN_{chg}/d\eta d\phi \rangle$ in a 1 GeV bin. The solid (open) points are the Min-Bias (JET20) data. The errors on the (*uncorrected*) data include both statistical and correlated systematic uncertainties.**

# Charged Particle Density
# "Transverse" $P_T$ Distribution



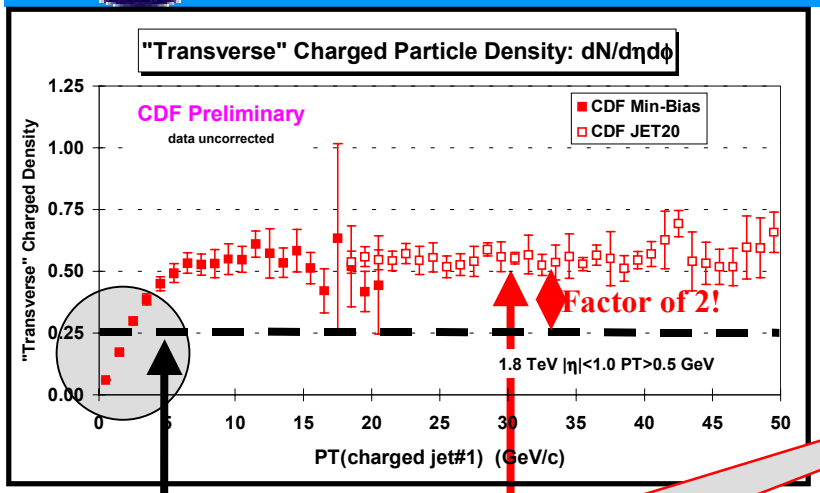



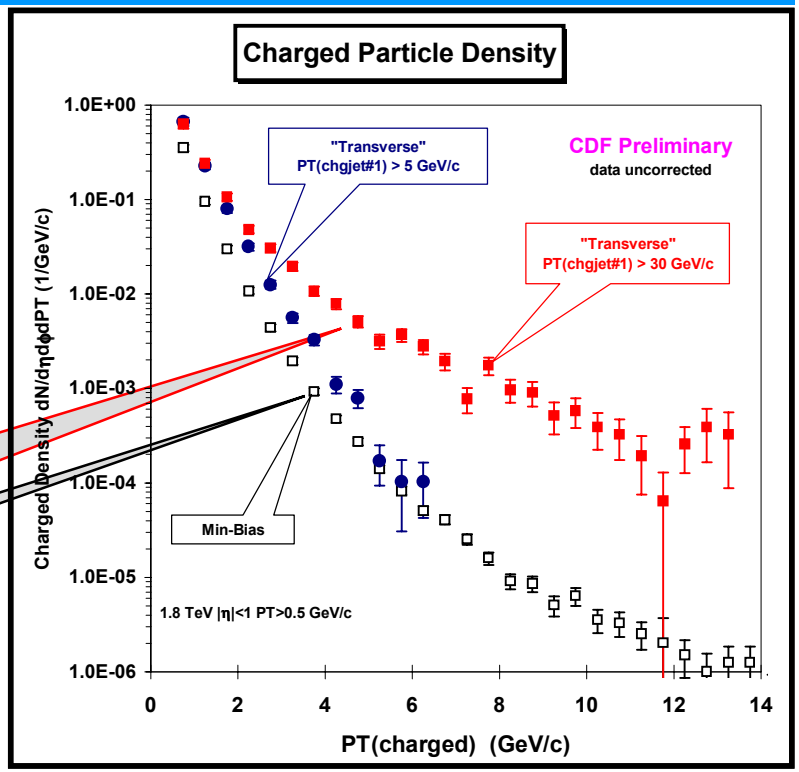

$P_T$(charged jet#1) > 30 GeV/c
"Transverse" $\langle dN_{chg}/d\eta d\phi \rangle = 0.56$

$P_T$(charged jet#1) > 5 GeV/c
"Transverse" $\langle dN_{chg}/d\eta d\phi \rangle = 0.52$

- **Compares the average "transverse" charge particle density ($|\eta|<1$, $P_T>0.5$ GeV) versus $P_T$(charged jet#1) with the $P_T$ distribution of the "transverse" density, $dN_{chg}/d\eta d\phi dP_T$. Shows how the "transverse" charge particle density is distributed in $P_T$.**

# Charged Particle Density $P_T$ Distribution



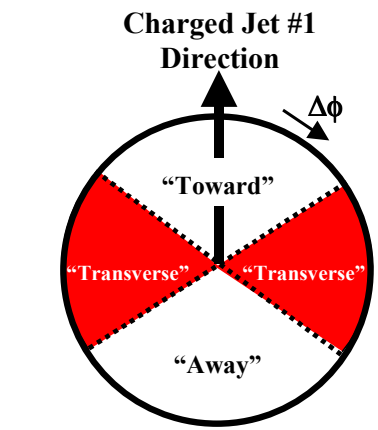




$P_T$(charged jet#1) > 30 GeV/c
"Transverse" $\langle dN_{chg}/d\eta d\phi \rangle = 0.56$

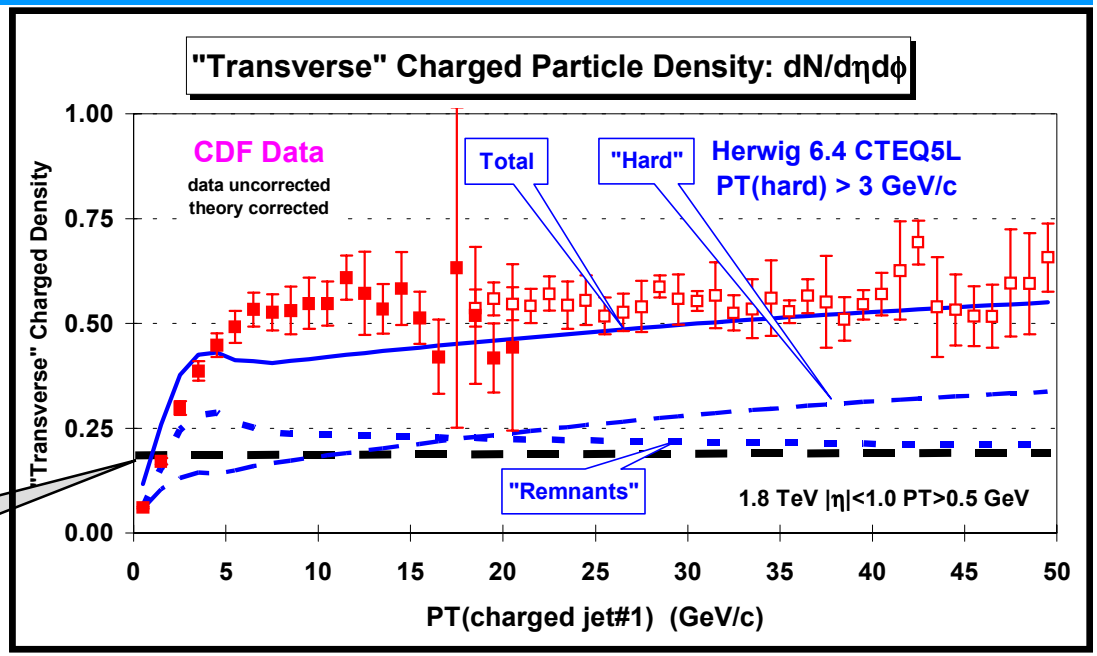
Min-Bias
$\langle dN_{chg}/d\eta d\phi \rangle = 0.25$

- **Compares the average "transverse" charge particle density with the average "Min-Bias" charge particle density ($|\eta|<1$, $P_T>0.5$ GeV). Shows how the "transverse" charge particle density and the Min-Bias charge particle density is distributed in $P_T$.**

# HERWIG 6.4 ($P_T$(hard) > 3 GeV/c)
## "Transverse" Charged Particle Density

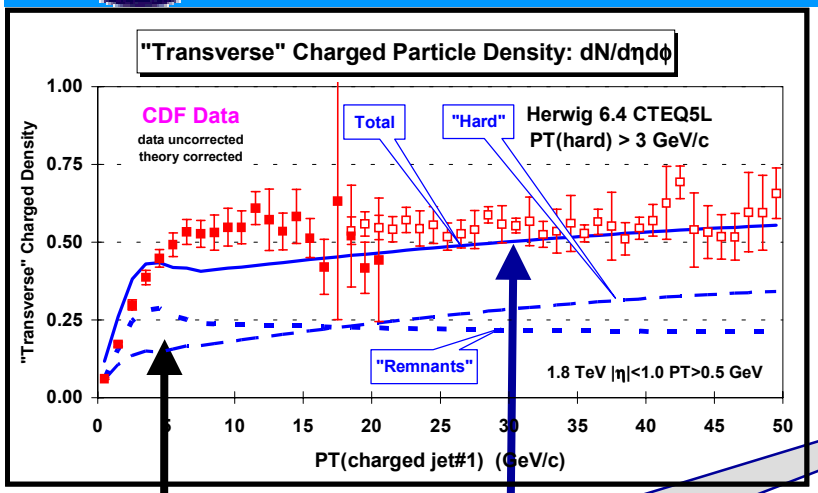


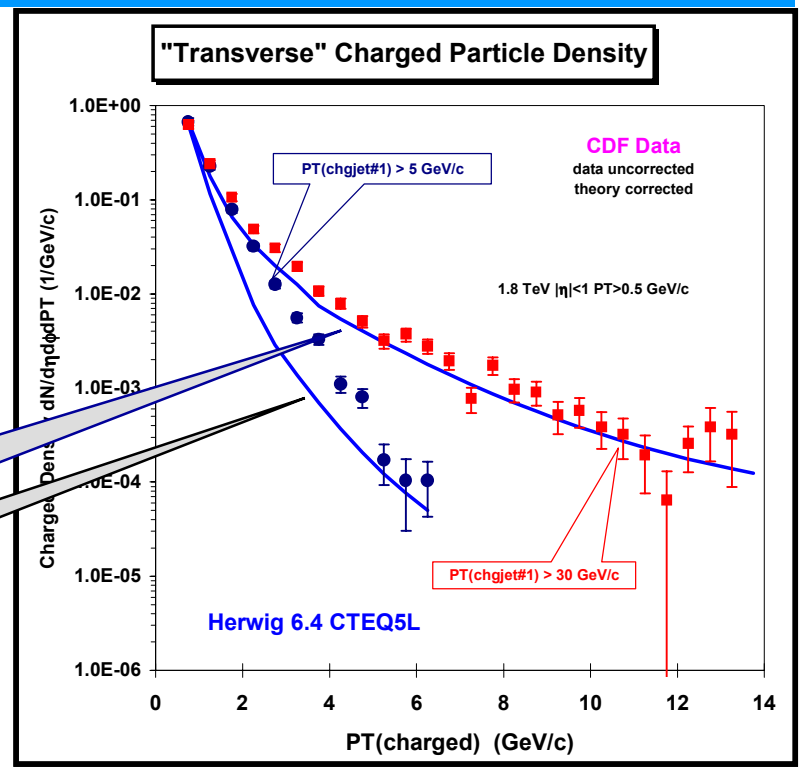

Herwig "Soft" Min-Bias
($|\eta|<1$, $P_T>0.5$ GeV)
$\langle dN_{chg}/d\eta d\phi \rangle = 0.18$




- Plot shows the "transverse" charged particle density vs $P_T$(chgjet#1) compared to the QCD hard scattering predictions of HERWIG 6.4 (default parameters with $P_T$(hard)>3 GeV/c).
- The predictions of HERWIG are divided into two categories: charged particles that arise from the break-up of the beam and target ("beam-beam remnants"); and charged particles that arise from the outgoing jet plus initial and final-state radiation ("hard scattering component").

# HERWIG 6.4
## "Transverse" $P_T$ Distribution



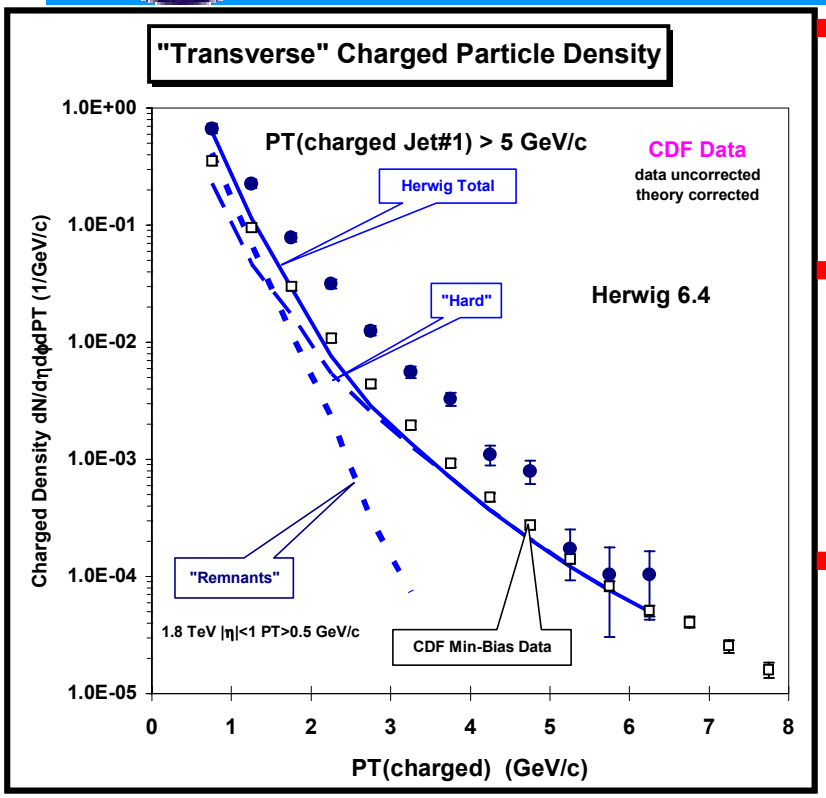




**Herwig $P_T$(chgjet#1) > 30 GeV/c**
**"Transverse" $\langle dN_{chg}/d\eta d\phi \rangle = 0.51$**

**Herwig $P_T$(chgjet#1) > 5 GeV/c**
**$\langle dN_{chg}/d\eta d\phi \rangle = 0.40$**

- **Compares the average "transverse" charge particle density ($|\eta|<1$, $P_T>0.5$ GeV) versus $P_T$(charged jet#1) and the $P_T$ distribution of the "transverse" density, $dN_{chg}/d\eta d\phi dP_T$ with the QCD hard scattering predictions of HERWIG 6.4 (default parameters with $P_T$(hard)>3 GeV/c. Shows how the "transverse" charge particle density is distributed in $P_T$.**

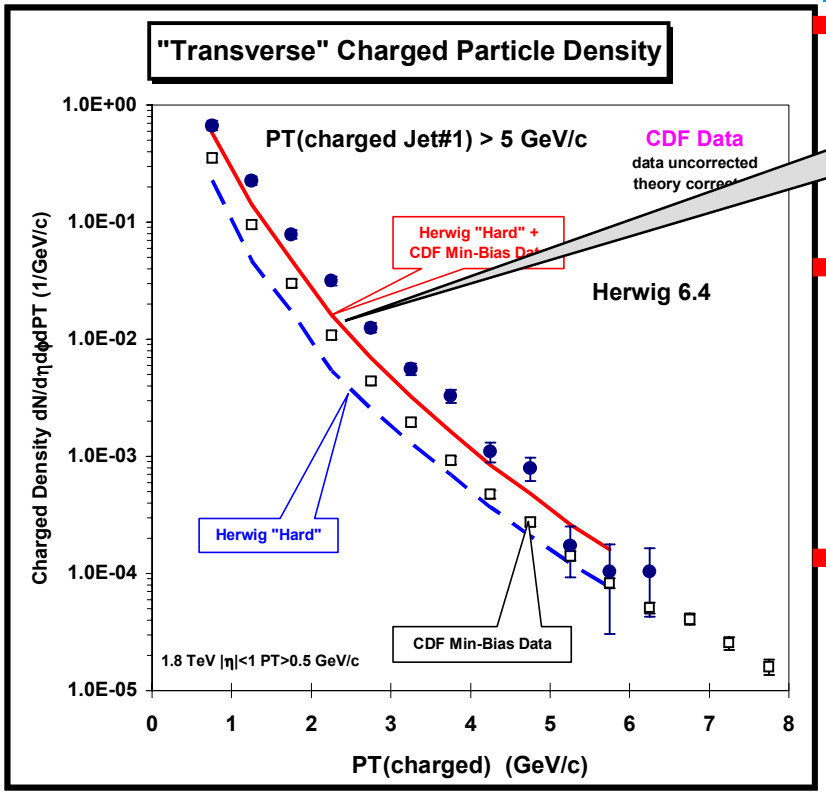
# HERWIG 6.4
# "Transverse" $P_T$ Distribution




- Plot shows the $P_T$ dependence of the "transverse" charged particle density compared to the QCD hard scattering predictions of HERWIG 6.4 (default parameters with $P_T$(hard)>3 GeV/c).
- The predictions of HERWIG are divided into two categories: charged particles that arise from the break-up of the beam and target ("beam-beam remnants"); and charged particles that arise from the outgoing jet plus initial and final-state radiation ("hard scattering component").
- Both HERWIG's "soft" Min-Bias model and HERWIG's model for the "beam-beam remnants" do not produce enough high $P_T$ hadrons (*i.e.* they are both too "soft").

# HERWIG 6.4

## "Transverse" $P_T$ Distribution




HERWIG "hard" component (*i.e.* initial & final state radiation) + CDF "Min-Bias" data.

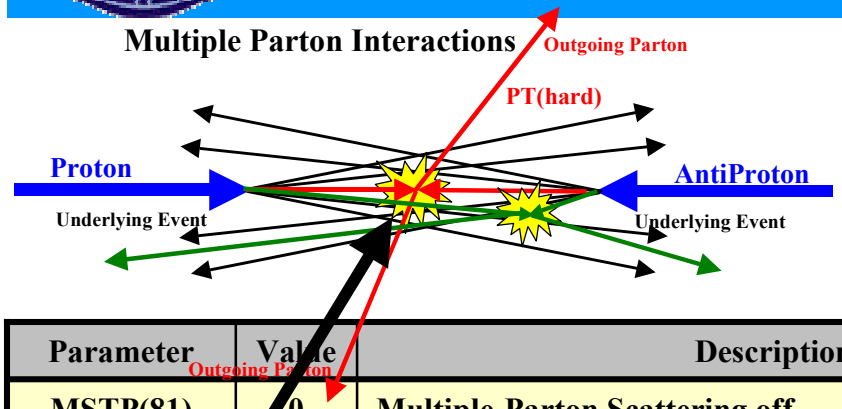
- P e of the " e density compared t CD hard scattering predictions of HERW 6.4 (default parameters with $P_T$(hard GeV/c).
- The pred ns of HERWIG are divided into two categ charged particles that arise from the break he beam and target ("beam-beam rem and charged particles that arise nd final-state onent").
- Both el and HERWIG's model for the "beam-beam remnants" do not produce enough high $P_T$ hadrons (*i.e.* they are both too "soft").

Adding the two assumes no correlations, but if there is one hard scattering in the event then maybe it is more probable that there is a second one!

- The CDF "Min-Bias" data describe the "beam-beam" remnants better than HERWIG! But the CDF "Min-Bias" data contain a hard scattering component and hence maybe the "beam-beam remnants" have a hard scattering component (*i.e.* multiple parton interactions).

# PYTHIA: Multiple Parton Interaction Parameters

Multiple Parton Interactions




Pythia uses multiple parton interactions to enhance the underlying event.

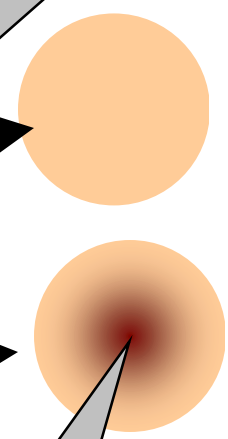
and now HERWIG!

Jimmy: MPI
J. M. Butterworth
J. R. Forshaw
M. H. Seymour

| Parameter | Value | Description |
|---|---|---|
| MSTP(81) | 0 | Multiple-Parton Scattering off |
| | 1 | Multiple-Parton Scattering on |
| MSTP(82) | 1 | Multiple interactions assuming the same probability, with an abrupt cut-off $P_T$min=PARP(81) |
| | 3 | Multiple interactions assuming a varying impact parameter and a hadronic matter overlap consistent with a single Gaussian matter distribution, with a smooth turn-off $P_{T0}$=PARP(82) |
| | 4 | Multiple interactions assuming a varying impact parameter and a hadronic matter overlap consistent with a double Gaussian matter distribution (governed by PARP(83) and PARP(84)), with a smooth turn-off $P_{T0}$=PARP(82) |

Same parameter that cuts-off the hard 2-to-2 parton cross sections!

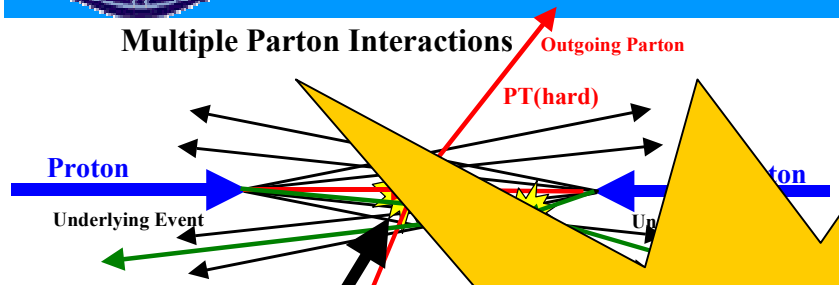
Multiple parton interaction more likely in a hard (central) collision!



Hard Core

# PYTHIA: Multiple Parton Interaction Parameters

Multiple Parton Interactions




ia uses multiple parton teractions to enhance ng event.

and now HERWIG!

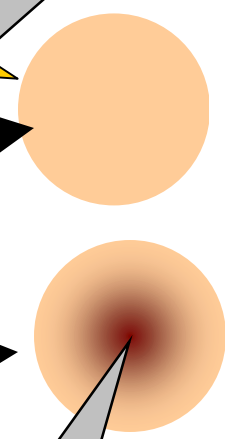
Jimmy: MPI
J. M. Butterworth
J. R. Forshaw
M. H. Seymour

Note that since the same cut-off parameters govern both the primary hard scattering and the secondary MPI interaction, changing the amount of MPI also changes the amount of hard primary scattering in PYTHIA Min-Bias events!

| Parameter | Value | |
|---|---|---|
| MSTP(81) | 0 | |
| | 1 | M |
| MSTP(82) | 1 | Multi a |
| | 3 | Multiple inte pa parameter a ter onsist a single Ga mat buti a smooth off $P_{T0}$=PARP(82) |
| | 4 | Multiple interactions a ing a varyi mpact parameter and a hadro matter overla consistent with a double Gaussian matt distribution (governed by PARP(83) and PARP(84)), with a smooth turn-off $P_{T0}$=PARP(82) |

Multiple parton interaction more likely in a hard (central) collision!

Same parameter that cuts-off the hard 2-to-2 parton cross sections!



Hard Core

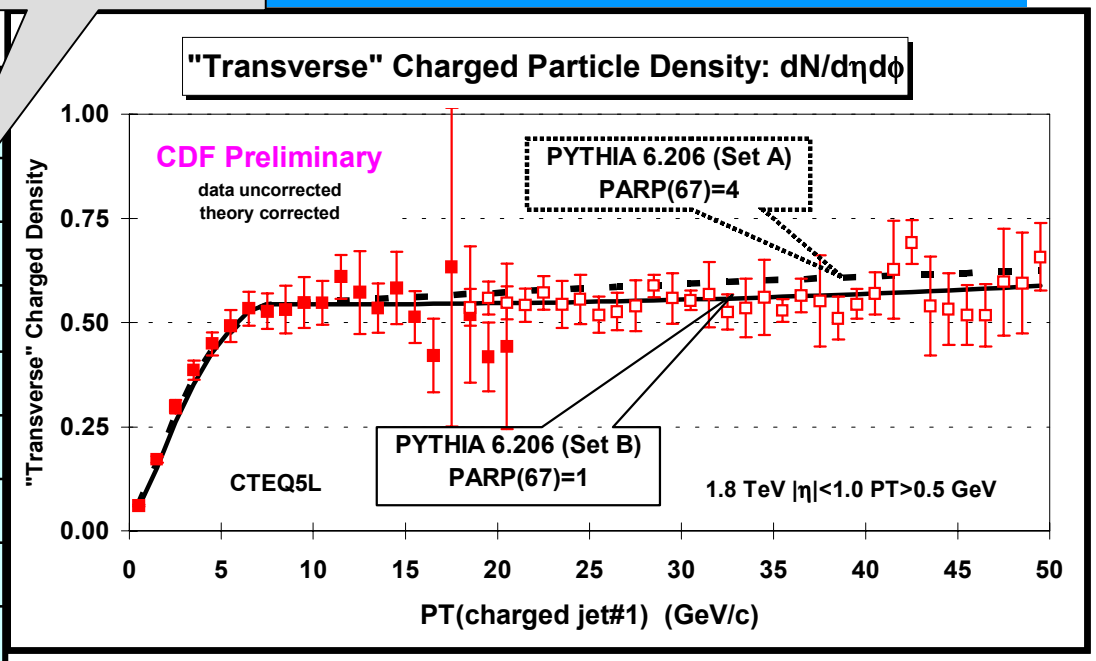
# Tuned PYTHIA 6.206

**PYTHIA 6.206 CTEQ5L**

| Parameter | Tune B | Tune A |
|---|---|---|
| MSTP(81) | 1 | 1 |
| MSTP(82) | 4 | 4 |
| PARP(82) | 1.9 GeV | 2.0 GeV |
| PARP(83) | 0.5 | 0.5 |
| PARP(84) | 0.4 | 0.4 |
| PARP(85) | 1.0 | 0.9 |
| PARP(86) | 1.0 | 0.95 |
| PARP(89) | 1.8 TeV | 1.8 TeV |
| PARP(90) | 0.25 | 0.25 |
| PARP(67) | 1.0 | 4.0 |

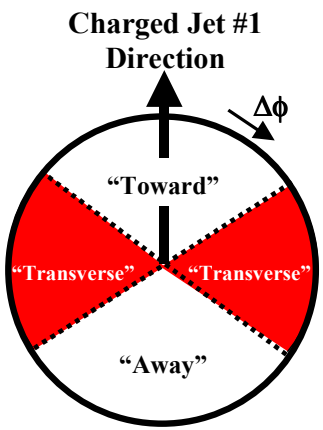
Corrected 11/4/02

Double Gaussian



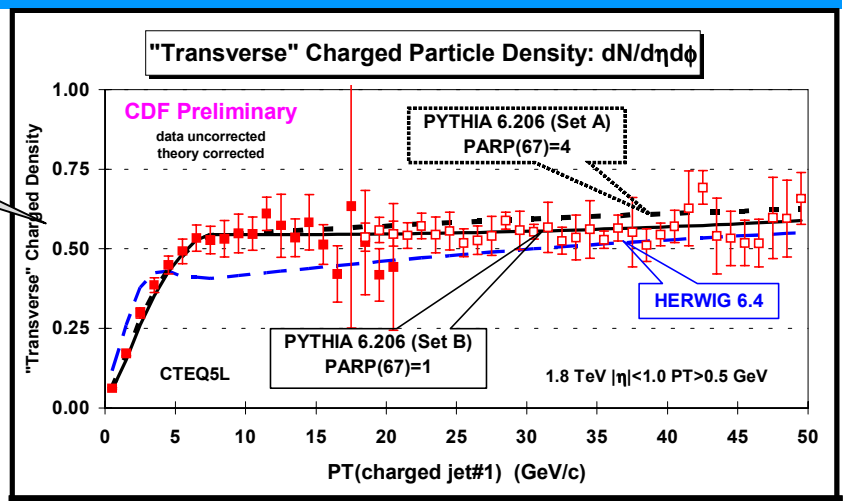

➡ Plot shows the "Transverse" charged particle density versus $P_T$(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).

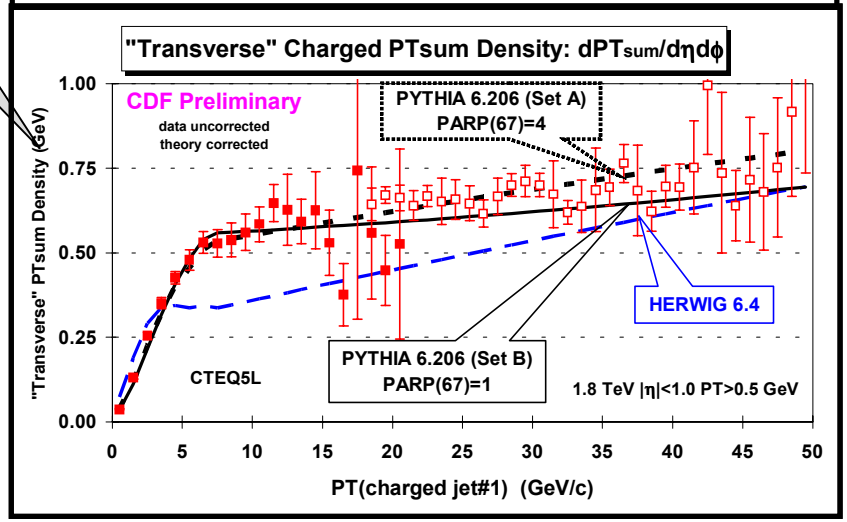
# Tuned PYTHIA 6.206 vs HERWIG 6.4
# "Transverse" Densities




Charged Particle Density

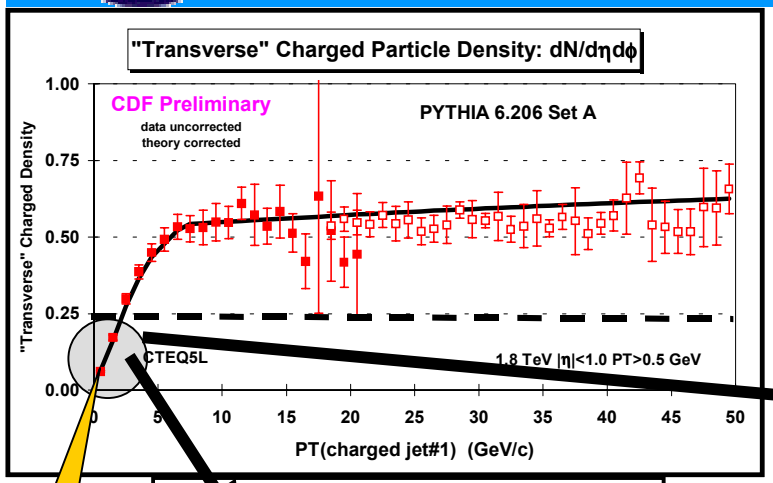
Charged $PT_{sum}$ Density

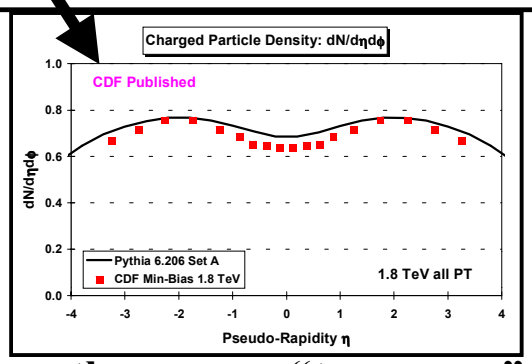


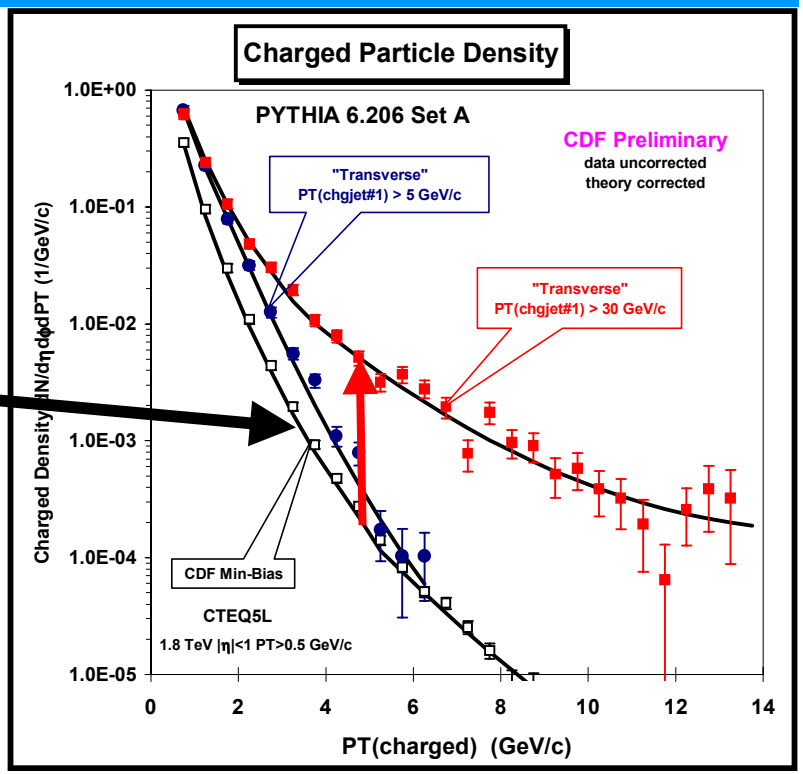

- Plots shows CDF data on the charge particle density and the charged $PT_{sum}$ density in the "transverse" region.
- The data are compared with the QCD Monte-Carlo predictions of HERWIG 6.4 (CTEQ5L, $P_T$(hard) > 3 GeV/c) and two tuned versions of PYTHIA 6.206 ($P_T$(hard) > 0).

# Tuned PYTHIA 6.206 Set A



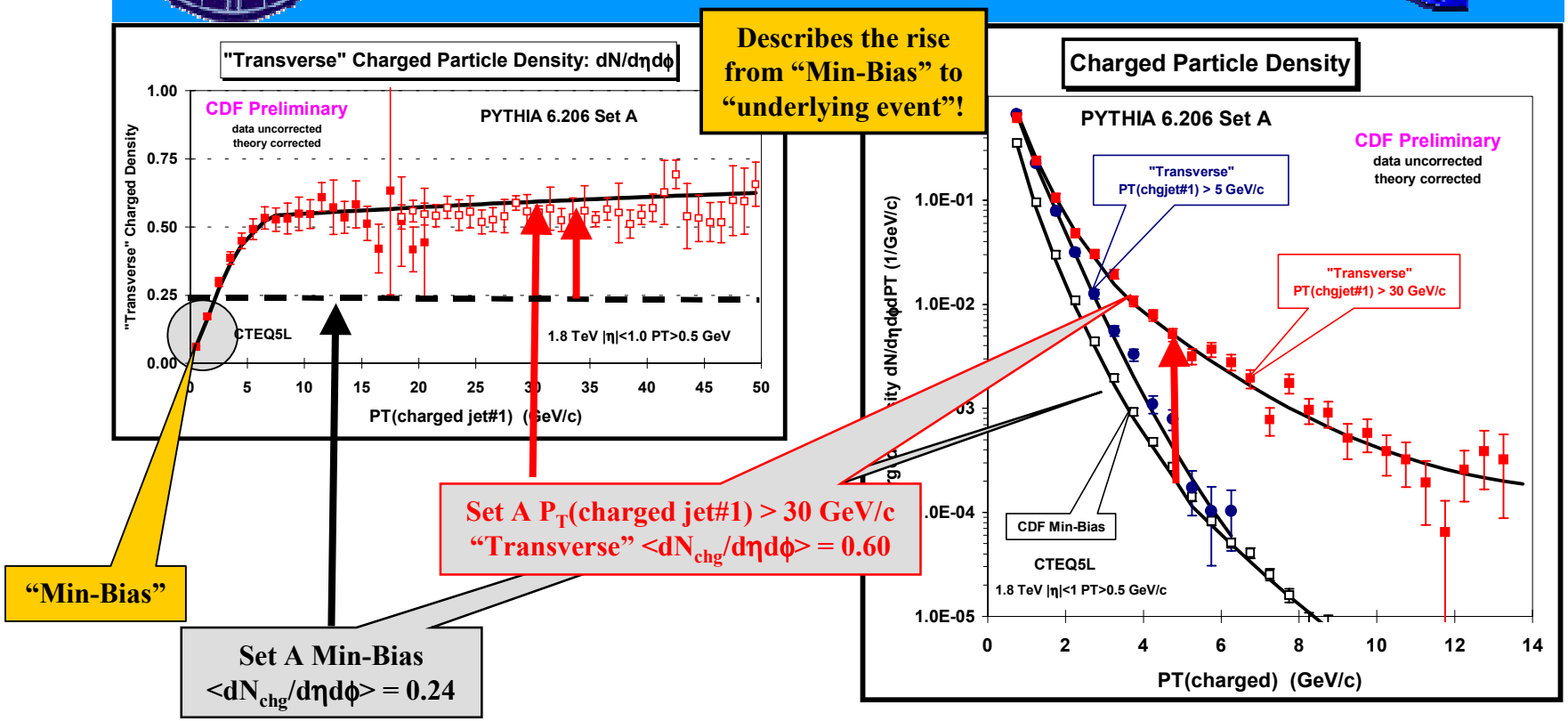




"Min-Bias"



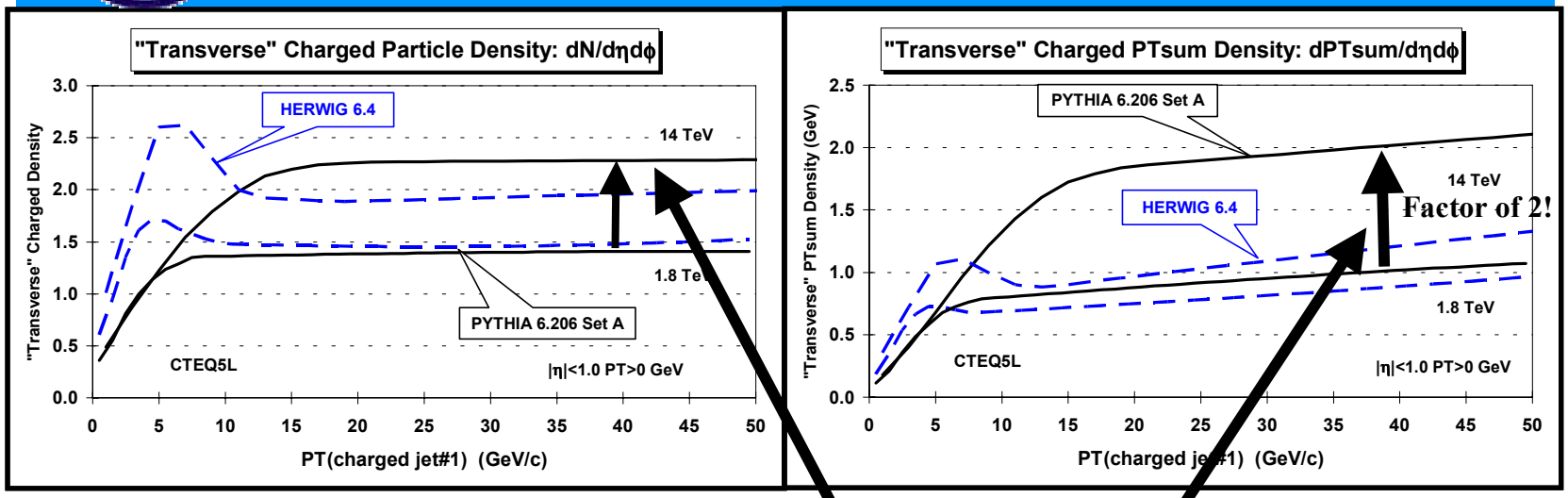

➡ **Compares the average "transverse" charge particle density ($|\eta|<1$, $P_T>0.5$ GeV) versus $P_T$(charged jet#1) and the $P_T$ distribution of the "transverse" and "Min-Bias" densities with the QCD Monte-Carlo predictions of a tuned version of PYTHIA 6.206 ($P_T$(hard) > 0, CTEQ5L, Set A). Describes "Min-Bias" collisions!**

# Tuned PYTHIA 6.206 Set A



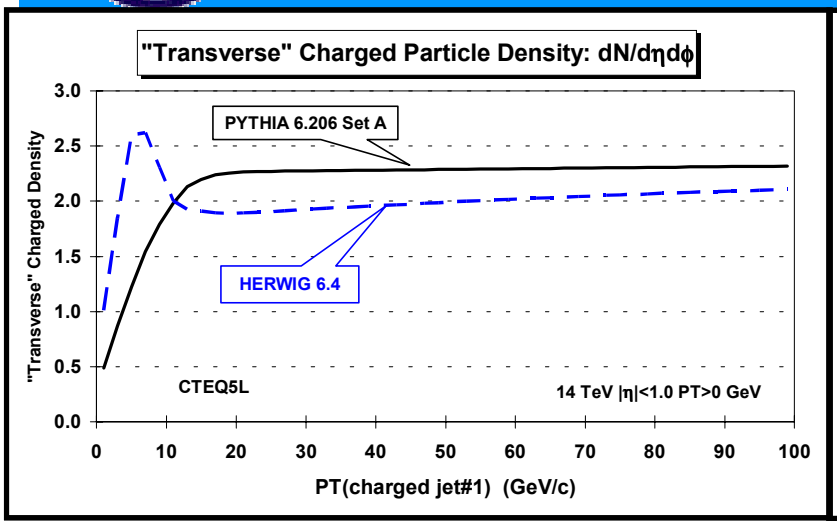

- **Compares the average "transverse" charge particle density ($|\eta|<1$, $P_T>0.5$ GeV) versus $P_T$(charged jet#1) and the $P_T$ distribution of the "transverse" and "Min-Bias" densities with the QCD Monte-Carlo predictions of a tuned version of PYTHIA 6.206 ($P_T$(hard) > 0, CTEQ5L, Set A). Describes "Min-Bias" collisions! Describes the "underlying event"!**

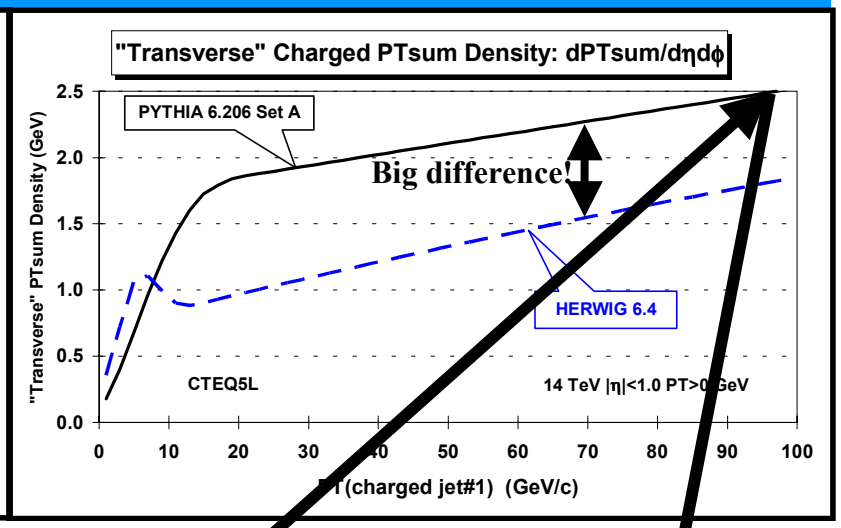
# Tuned PYTHIA (Set A) LHC Predictions




- Shows the average "transverse" charge particle and $PT_{sum}$ density ($|\eta|<1$, $P_T>0$) versus $P_T$(charged jet#1) predicted by HERWIG 6.4 ($P_T$(hard) > 3 GeV/c, CTEQ5L). and a tuned versions of PYTHIA 6.206 ($P_T$(hard) > 0, CTEQ5L, Set A) at 1.8 TeV and 14 TeV.
- At 14 TeV tuned PYTHIA (Set A) predicts roughly 2.3 charged particles per unit η-φ ($P_T > 0$) in the "transverse" region (14 charged particles per unit η) which is larger than the HERWIG prediction.
- At 14 TeV tuned PYTHIA (Set A) predicts roughly 2 GeV/c charged $PT_{sum}$ per unit η-φ ($P_T > 0$) in the "transverse" region at $P_T$(chgjet#1) = 40 GeV/c which is a factor of 2 larger than at 1.8 TeV and much larger than the HERWIG prediction.

# Tuned PYTHIA (Set A) LHC Predictions

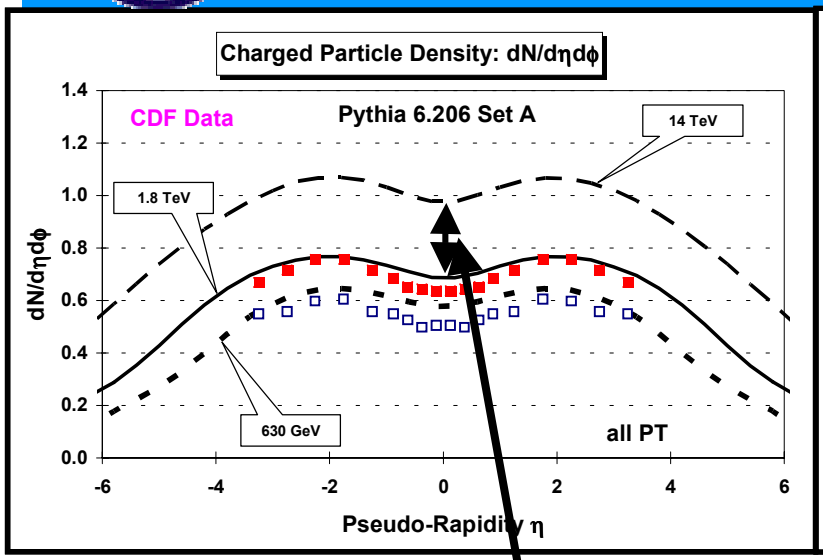


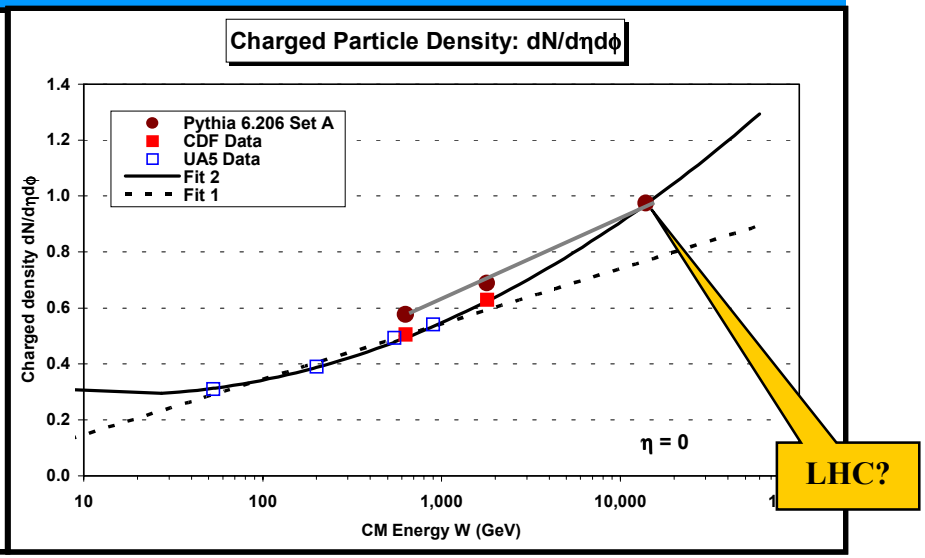




- Shows the average "transverse" charge particle and $PT_{sum}$ density ($|\eta|<1$, $P_T>0$) versus $P_T$(charged jet#1) predicted by HERWIG 6.4 ($P_T$(hard) > 3 GeV/c, CTEQ5L). and a tuned versions of PYTHIA 6.206 ($P_T$(hard) > 0, CTEQ5L, Set A) at 1.8 TeV and 14 TeV. Also shown is the 14 TeV prediction of PYTHIA 6.206 with the default value $\varepsilon = 0.16$.
- Tuned PYTHIA (Set A) predicts roughly 2.5 GeV/c per unit η-ϕ ($P_T > 0$) from charged particles in the "transverse" region for $P_T$(chgjet#1) = 100 GeV/c. Note, however, that the "transverse" charged $PT_{sum}$ density increases rapidly as $P_T$(chgjet#1) increases.

3.8 GeV/c (charged) in cone of radius R=0.7 at 14 TeV

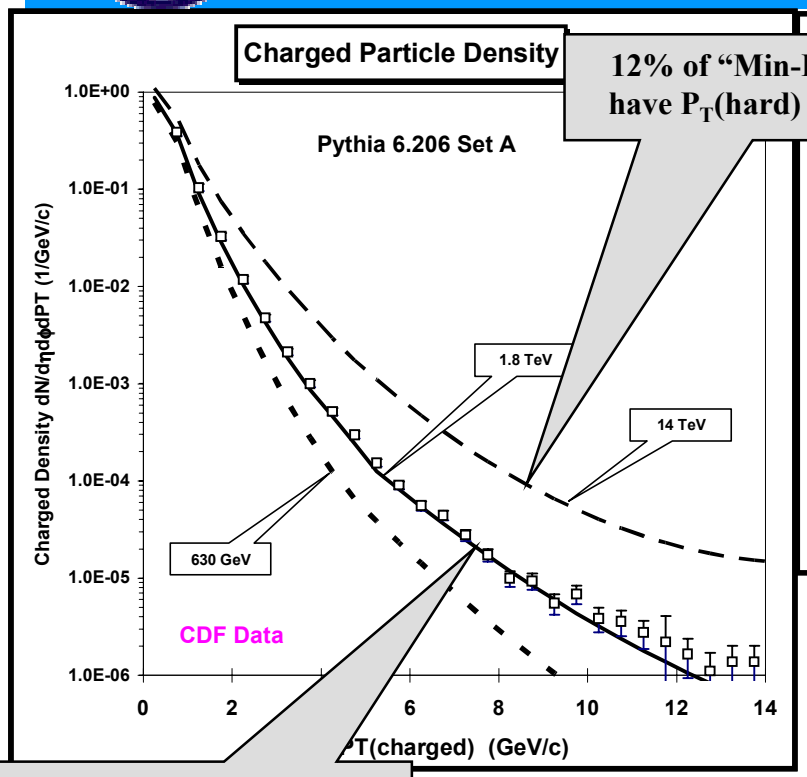
# Tuned PYTHIA (Set A) LHC Predictions



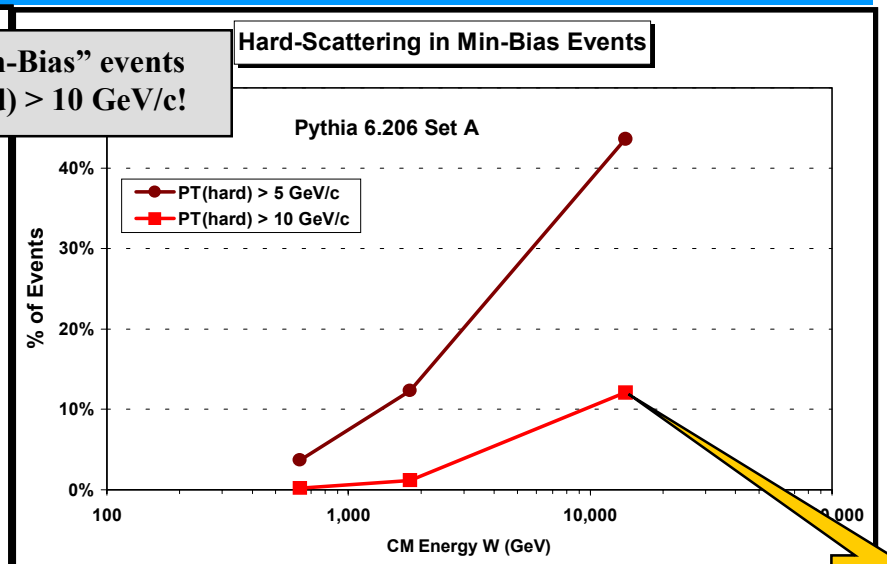

- Shows the center-of-mass energy dependence of the charged particle density, $dN_{chg}/d\eta d\phi$, for "Min-Bias" collisions compared with the a tuned version of PYTHIA 6.206 (Set A) with $P_T(hard) > 0$.
- PYTHIA was tuned to fit the "underlying event" in hard-scattering processes at 1.8 TeV and 630 GeV.
- PYTHIA (Set A) predicts a 42% rise in $dN_{chg}/d\eta d\phi$ at $\eta = 0$ in going from the Tevatron (1.8 TeV) to the LHC (14 TeV).

# Tuned PYTHIA (Set A) LHC Predictions




12% of "Min-Bias" events have $P_T$(hard) > 10 GeV/c!

1% of "Min-Bias" events have $P_T$(hard) > 10 GeV/c!

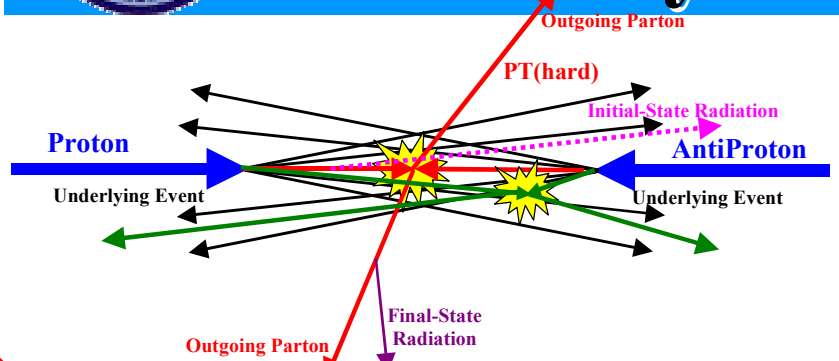



LHC?

- Shows the center-of-mass energy dependence of the charged particle density, $dN_{chg}/d\eta d\phi dP_T$, for "Min-Bias" collisions compared with the a tuned version of PYTHIA 6.206 (Set A) with $P_T$(hard) > 0.

- This PYTHIA fit predicts that 1% of all "Min-Bias" events at 1.8 TeV are a result of a hard 2-to-2 parton-parton scattering with $P_T$(hard) > 10 GeV/c which increases to 12% at 14 TeV!

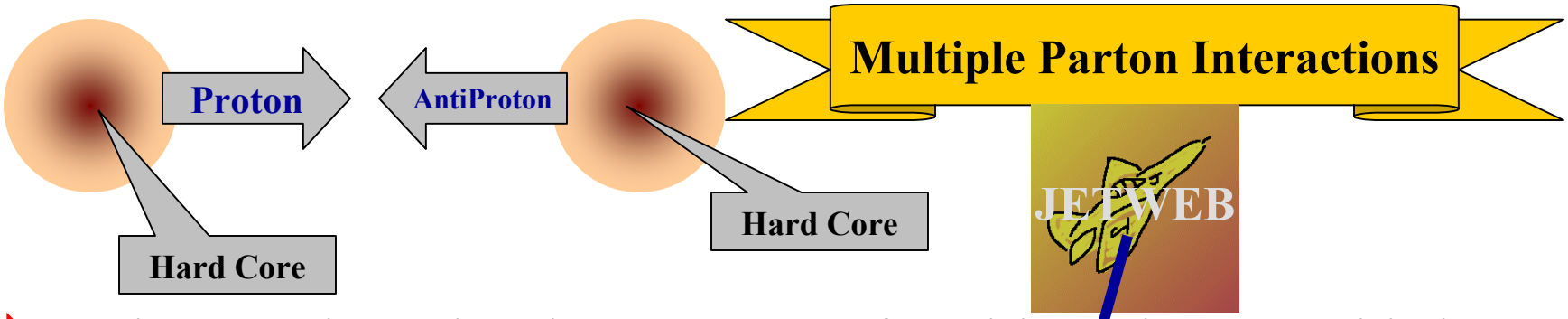
# The "Underlying Event" Summary & Conclusions




**The "Underlying Event"**

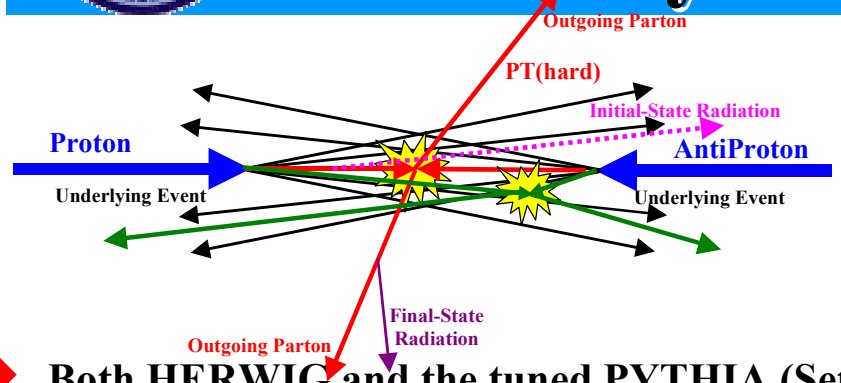
- **ISAJET (with independent fragmentation) produces too many (soft) particles in the "underlying event" with the wrong dependence on $P_T$(jet#1). HERWIG and PYTHIA modify the leading-log picture to include "color coherence effects" which leads to "angle ordering" within the parton shower and do a better job describing the "underlying event".**
- **Both ISAJET and HERWIG have the too steep of a $P_T$ dependence of the "beam-beam remnant" component of the "underlying event" and hence do not have enough beam-beam remnants with $P_T > 0.5$ GeV/c.**
- **The CDF "Min-Bias" data describes the "beam-beam remnants" better than HERWIG does. Adding HERWIG's initial & final state radiation to the CDF "Min-Bias" data comes close to describing the "underlying event", but the CDF "Min-Bias" data contain a lot of "hard" scatterings. Thus, maybe the "beam-beam remnants" also contain "hard" scatterings (*i.e.* multiple parton collisions).**

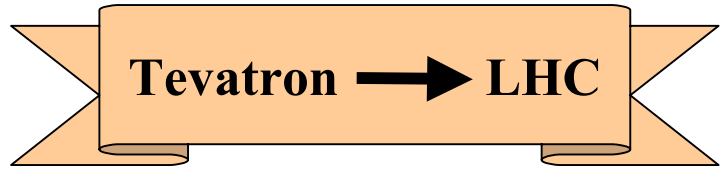
# Multiple Parton Interactions
# Summary & Conclusions




- Multiple parton interactions gives a natural way of explaining the increased activity in the "underlying event" in a hard scattering. A hard scattering is more likely to occur when the hard cores overlap and this is also when the probability of a multiple parton interaction is greatest. For a soft grazing collision the probability of a multiple parton interaction is small.
- PYTHIA (with varying impact parameter) does a good job fitting the "underlying event" data and also describes fairly well the "Min-Bias" data with the same program ($P_T$(hard) > 0).
- A. Moraes, I. Dawson, and C. Buttar (University of Sheffield) have also been working on tuning PYTHIA to fit the underlying event using the CDF data with the goal of extrapolating to the LHC.
- Also check out Jon Butterworth's JETWEB at http://jetweb.hep.ucl.ac.uk/Results/MI/.

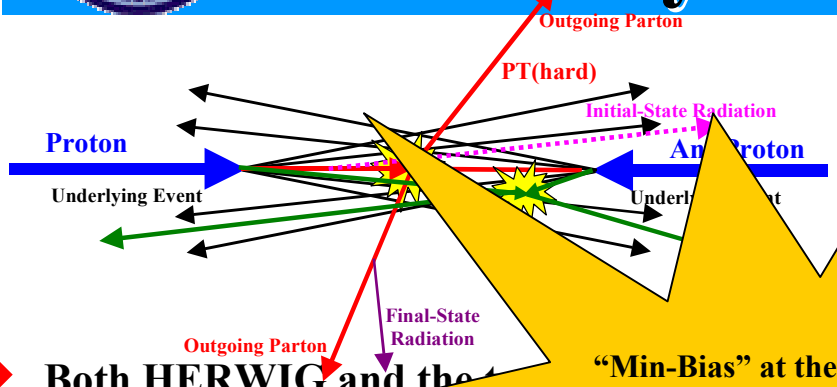
# LHC Predictions
# Summary & Conclusions




- **Both HERWIG and the tuned PYTHIA (Set A) predict a 40-45% rise in $dN_{chg}/d\eta d\phi$ at $\eta = 0$ in going from the Tevatron (1.8 TeV) to the LHC (14 TeV). 4 charged particles per unit $\eta$ at the Tevatron becomes 6 per unit $\eta$ at the LHC.**
- **The tuned PYTHIA (Set A) predicts that 1% of all "Min-Bias" events at the Tevatron (1.8 TeV) are the result of a hard 2-to-2 parton-parton scattering with $P_T$(hard) > 10 GeV/c which increases to 12% at LHC (14 TeV)!**
- **For the "underlying event" in hard scattering processes the predictions of HERWIG and the tuned PYTHIA (Set A) differ greatly (factor of 2!). HERWIG predicts a smaller increase in the activity of the "underlying event" in going from the Tevatron to the LHC.**
- **The tuned PYTHIA (Set A) predicts about a factor of two increase at the LHC in the charged $PT_{sum}$ density of the "underlying event" at the same $P_T$(jet#1) (the "transverse" charged $PT_{sum}$ density increases rapidly as $P_T$(jet#1) increases).**

# LHC Predictions
# Summary & Conclusions




**Tevatron → LHC**

**"Min-Bias" at the LHC contains much more hard collisions than at the Tevatron! At the Tevatron the "underlying event" is a factor of 2 more active than "Tevaron Min-Bias". At the LHC the "underlying event" will be at least a factor of 2 more active than "LHC Min-Bias"!**

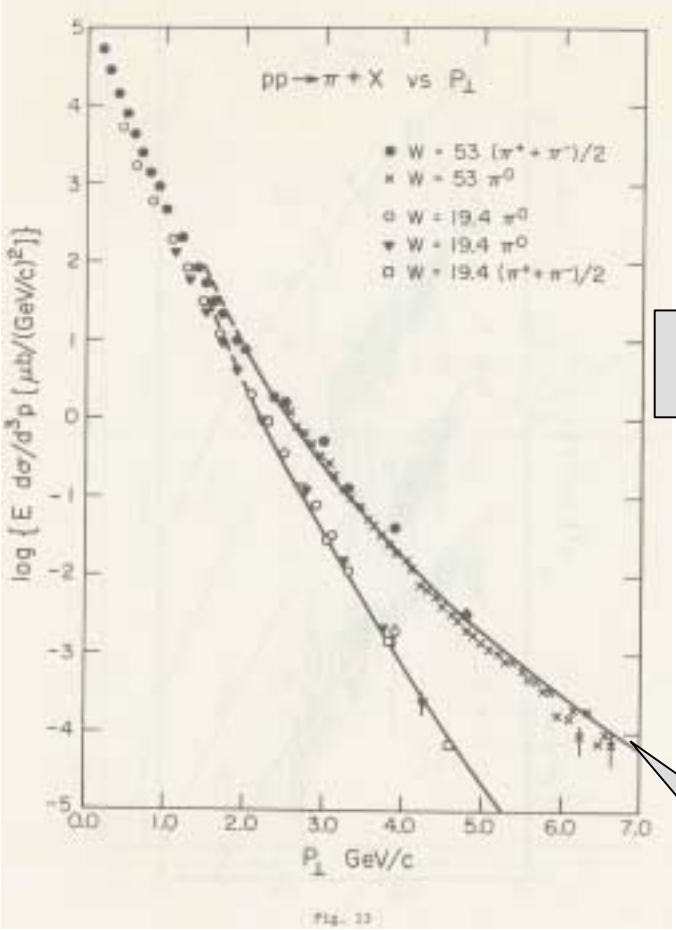
**12 times more likely to find a 10 GeV "jet" in "Min-Bias" at the LHC!**

**Twice as much activity in the "underlying event" at the LHC!**

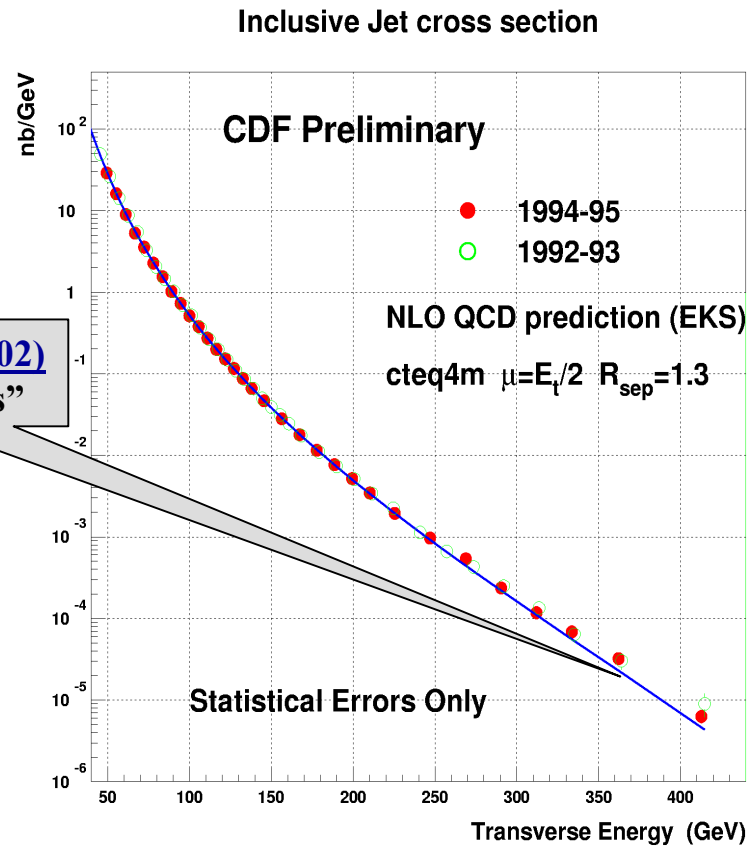
- **Both HERWIG and the [illegible] = 0 in going from [illegible] unit η at the Tevatron [illegible] at η [illegible] per**
- **The tuned PYTHIA (Set [illegible] (1.8 TeV) are the result [illegible] events at th [illegible] with $P_T$([illegible] GeV/c which increa[illegible]**
- **For the "underlying event" in [illegible] predictions of HERWIG and the tuned PYTHIA (Set A) di[illegible] (fa[illegible] f 2!). [illegible]RWIG pr[illegible]cts a smaller increase in the activity of the "unde[illegible]g eve[illegible] in going [illegible]om the Tevatron to the LHC.**
- **The tuned PYTHIA (Set A) predicts [illegible] out a fa[illegible]or of two increase at the LHC in the charged $PT_{sum}$ density of the "under[illegible]ng event" at the same $P_T$(jet#1) (the "transverse" charged $PT_{sum}$ density increases rapi[illegible]ly as $P_T$(jet#1) increases).**

# Collider Phenomenology

## From 7 GeV/c $\pi^0$'s to 400 GeV "Jets"



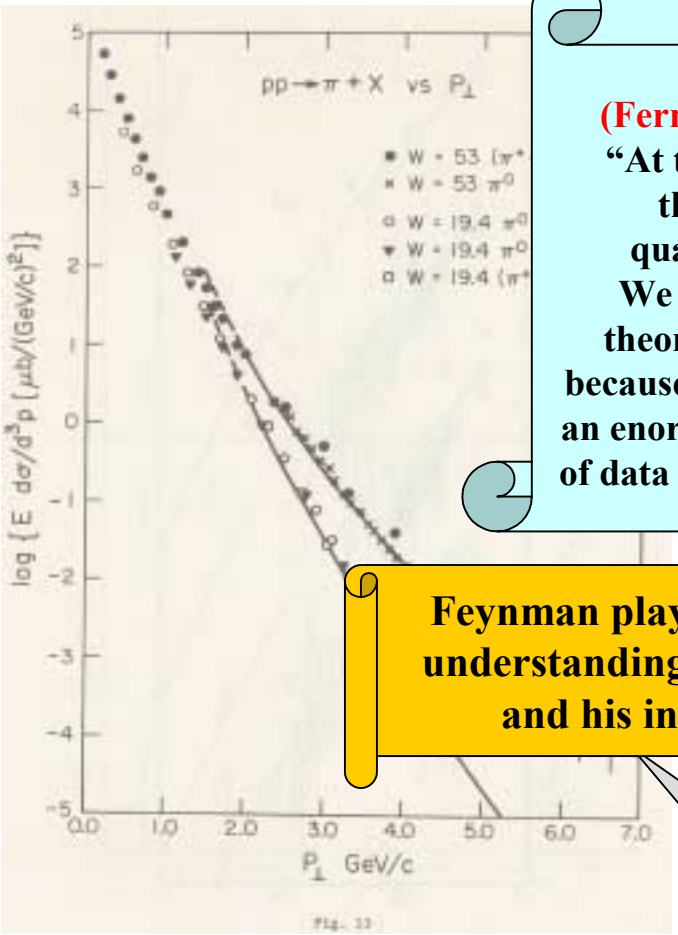

**NLO QCD (2002)**
400 GeV "jets"

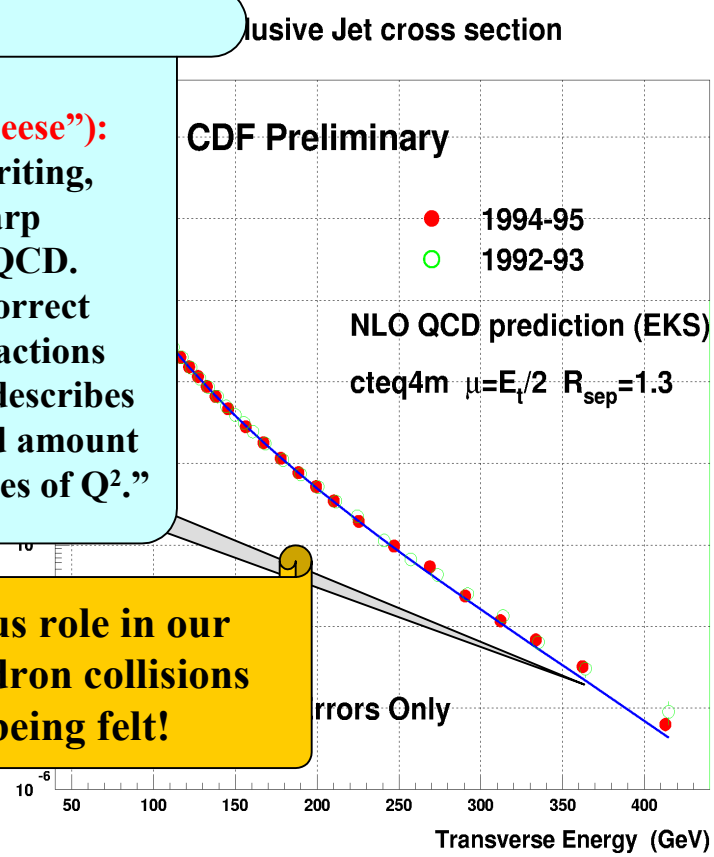



**FF1 (1977)**
7 GeV/c $\pi^0$'s

# Collider Phenomenology

## From 7 GeV/c $\pi^0$'s to 400 GeV "Jets"



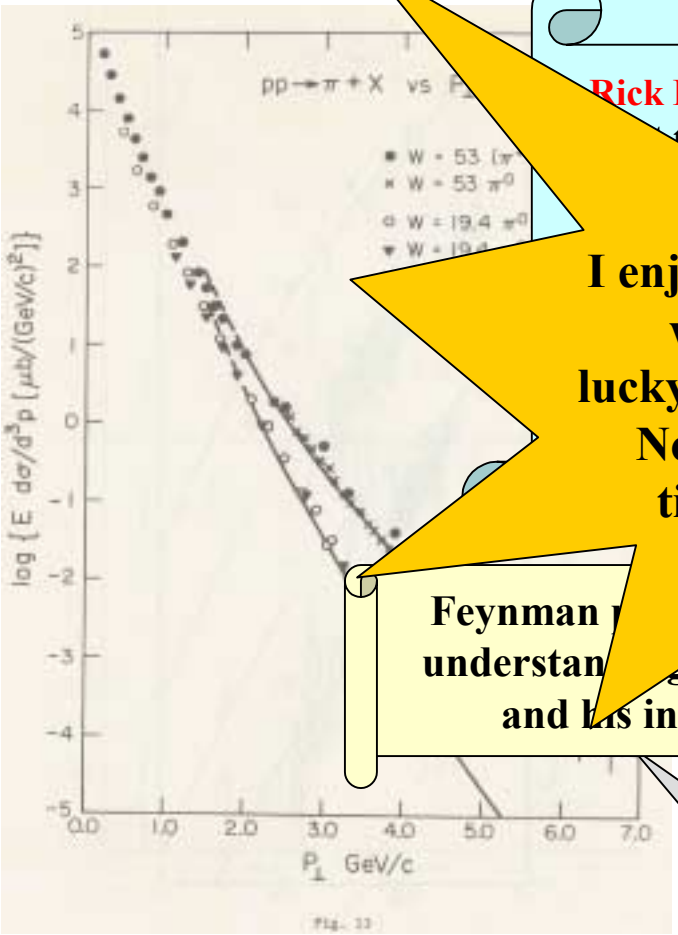

**Rick Field**
**(Fermilab "Wine&Cheese"):**
**"At the time of this writing, there is still no sharp quantitative test of QCD. We believe it is the correct theory of strong interactions because it qualitatively describes an enormous variety and amount of data over many decades of $Q^2$."**

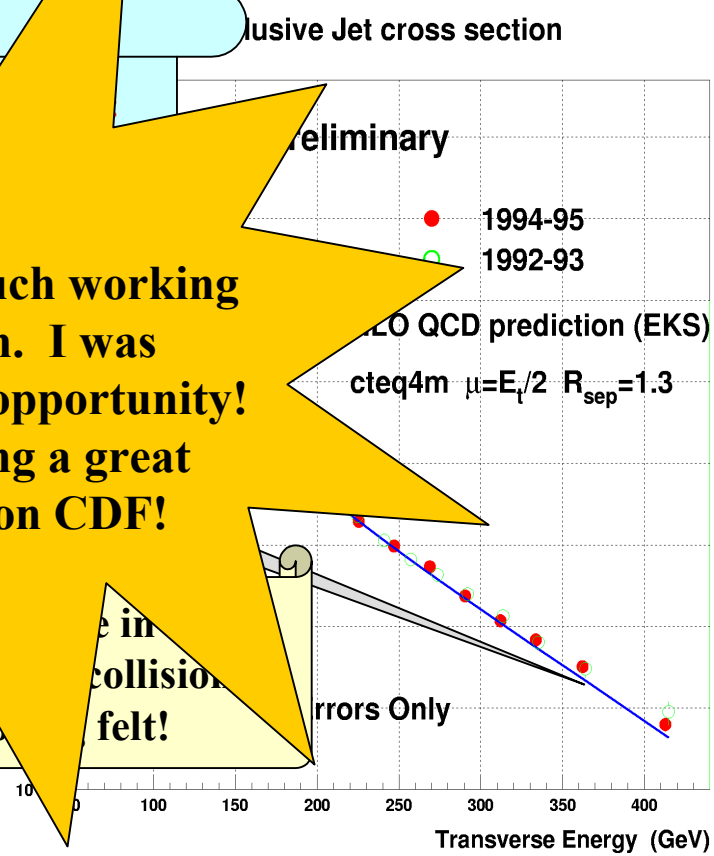
**Feynman played an enormous role in our understanding of hadron-hadron collisions and his influence is still being felt!**

**FF1 (1977)**
**7 GeV/c $\pi^0$'s**

# Collider Phenomenology

## From 7 GeV/c $\pi^0$'s to 400 GeV "Jets"




Rick Fiel ilab
the

I enjoyed very much working with Feynman. I was lucky to have the opportunity! Now I am having a great time working on CDF!

Feynman r e in
understan g of h-ha collisio
and his influe still b felt!

FF (1977)
7 GeV/c $\pi^0$'s