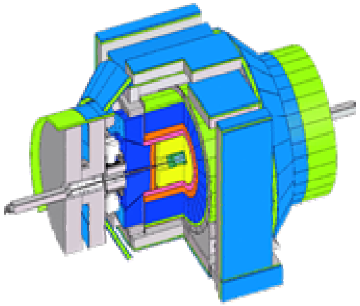
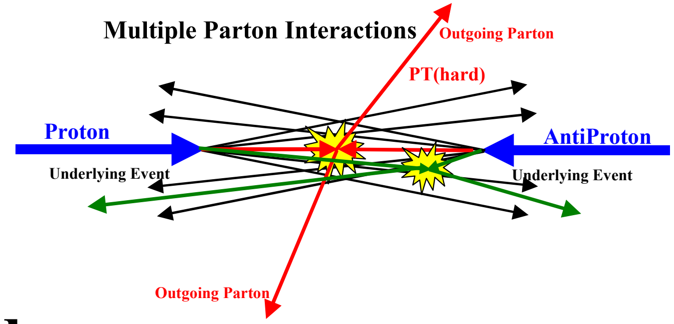
XIII International Workshop on Deep Inelastic Scattering

Hadronic Final States Working Group

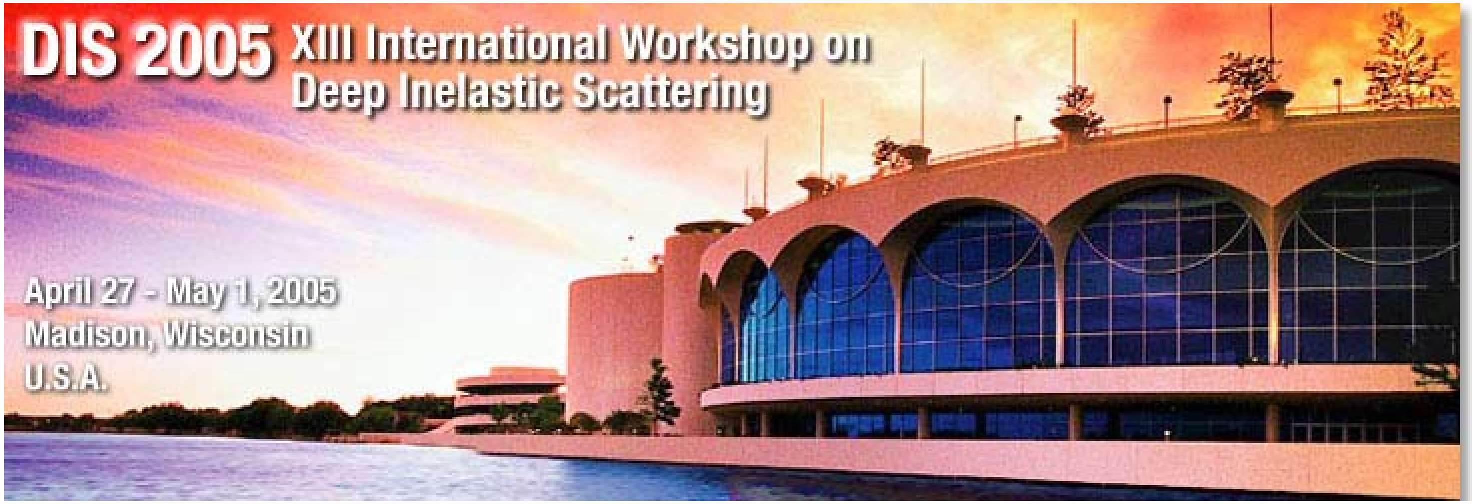




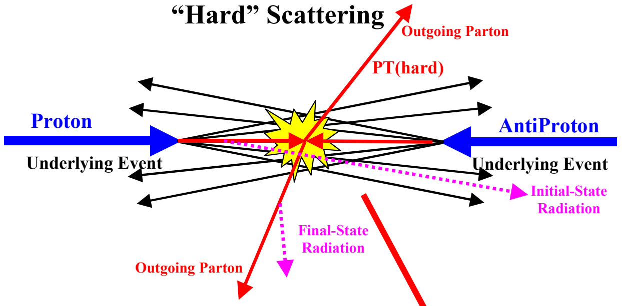
Rick Field

University of Florida

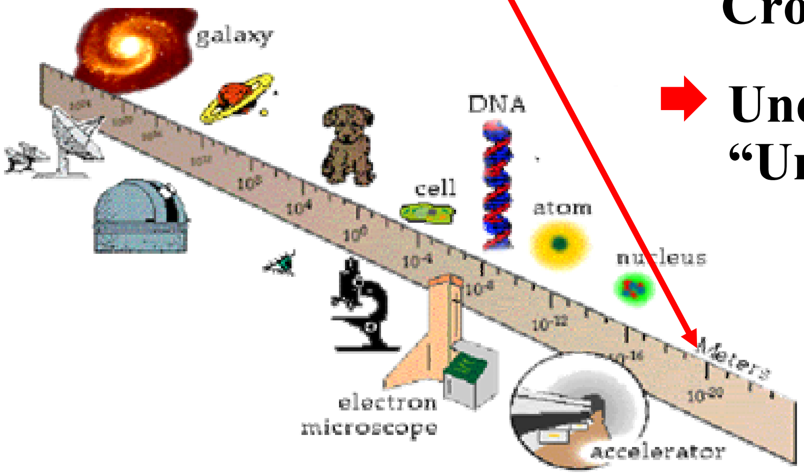
(*for the CDF Collaboration*)



Jet Physics in Run 2 at CDF



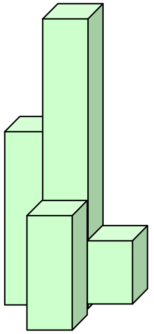
High P_T "jets" probe short distances!



Outline of Talk

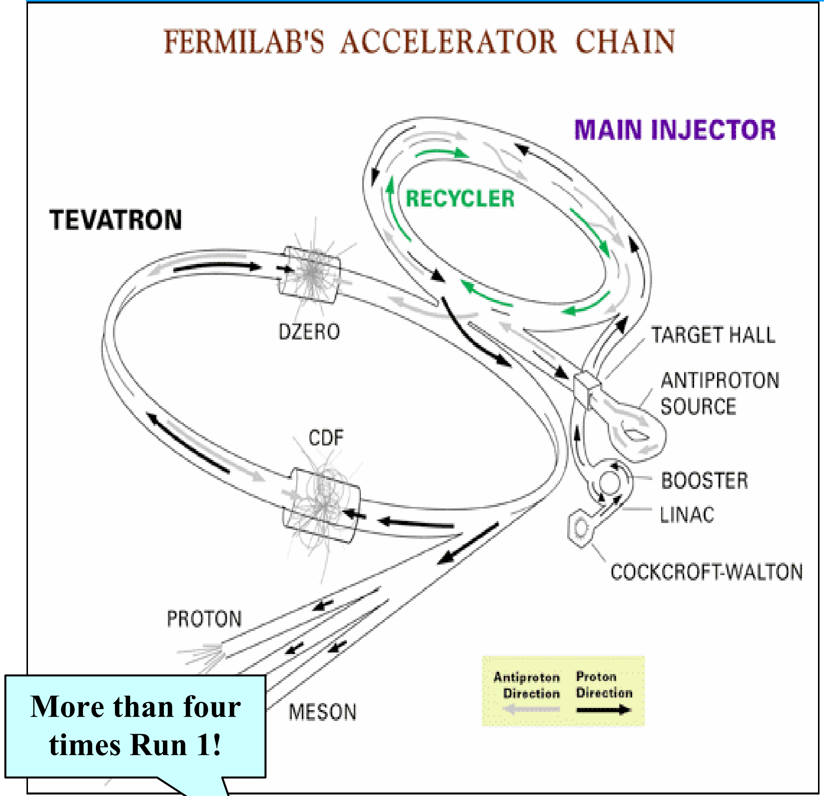
- Constructing Jets in Run 2 at CDF (MidPoint and K_T Algorithms).
- **New from CDF:** The K_T-Jet Inclusive Cross Section.
- **New from CDF:** The b-Jet Inclusive Cross Section.
- Understanding and Modeling the "Underlying Event" in Run 2 at CDF.

Calorimeter Jet

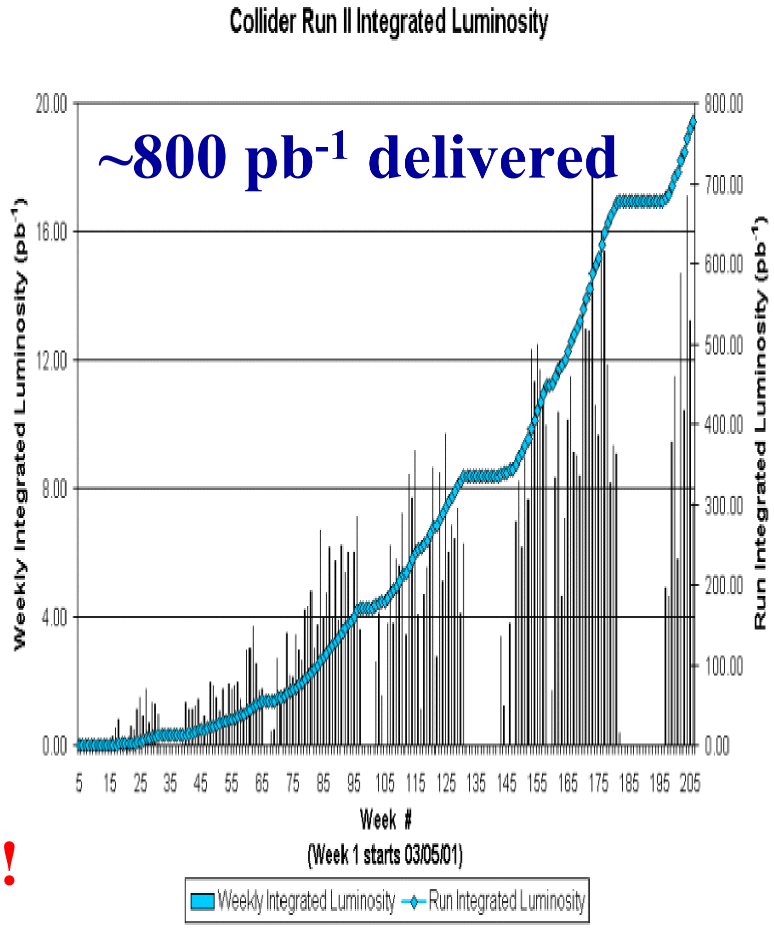


K_T Algorithm

The TeVatron



More than four times Run 1!



~800 pb^{-1} delivered

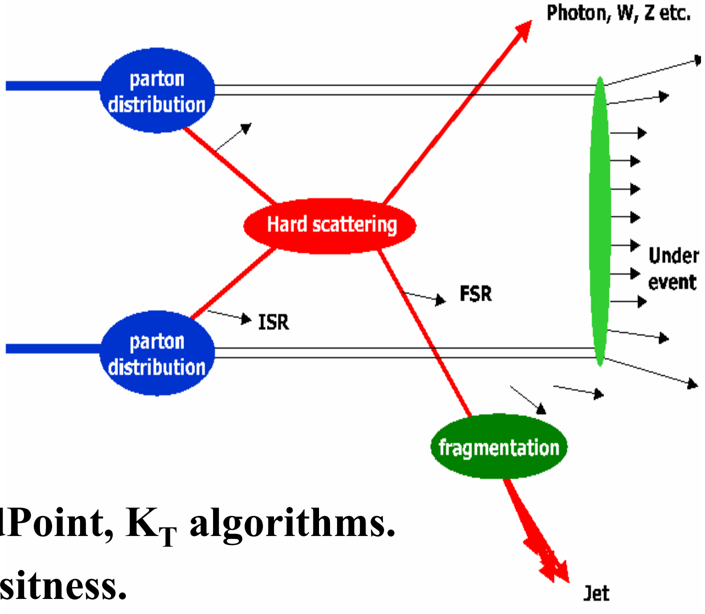
CDF has ~600 pb^{-1} on tape!

The TeVatron delivered more than 350 pb^{-1} in 2004!

CDF-QCD Group

CDF-QCD Group

Learn more about how nature works. Compare with theory and work to provide information that will lead to improved Monte-Carlo models and structure functions. Our contributions will benefit to the colliders of the future!



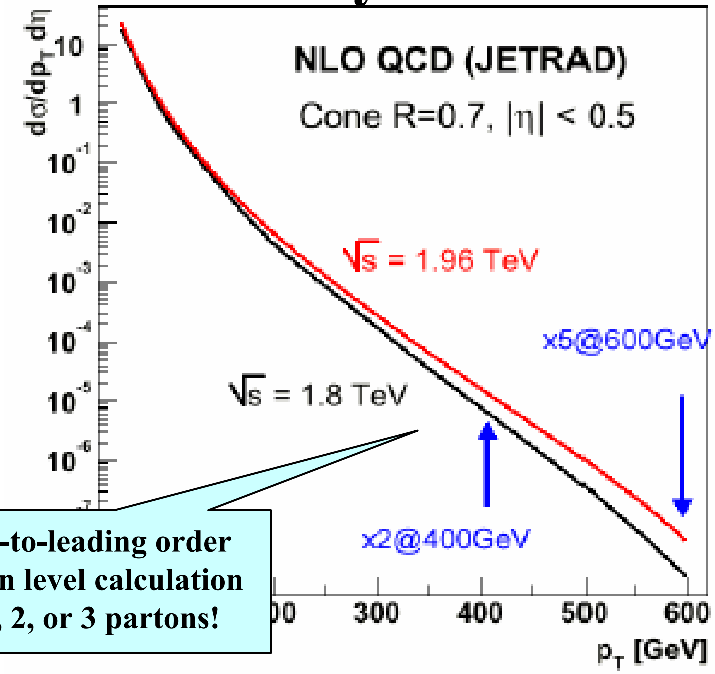
Some CDF-QCD Group Analyses!

- **Jet Cross Sections and Correlations:** Jet Clu, MidPoint, K_T algorithms.
- **DiJet Mass Distributions:** Δϕ distribution, compositness.
- **Heavy Flavor Jets:** b-jet and b-bbar jet cross sections and correlations.
- **Z and W Bosons plus Jets:** including b-jets.
- **Jets Fragmentation:** jet shapes, momentum distributions, two-particle correlations.
- **Underlying Event Studies:** charged particles and energy for jet, jet+jet, γ+jet, Z+jet.
- **Pile-Up Studies:** modeling of pile-up.

Important for the LHC!

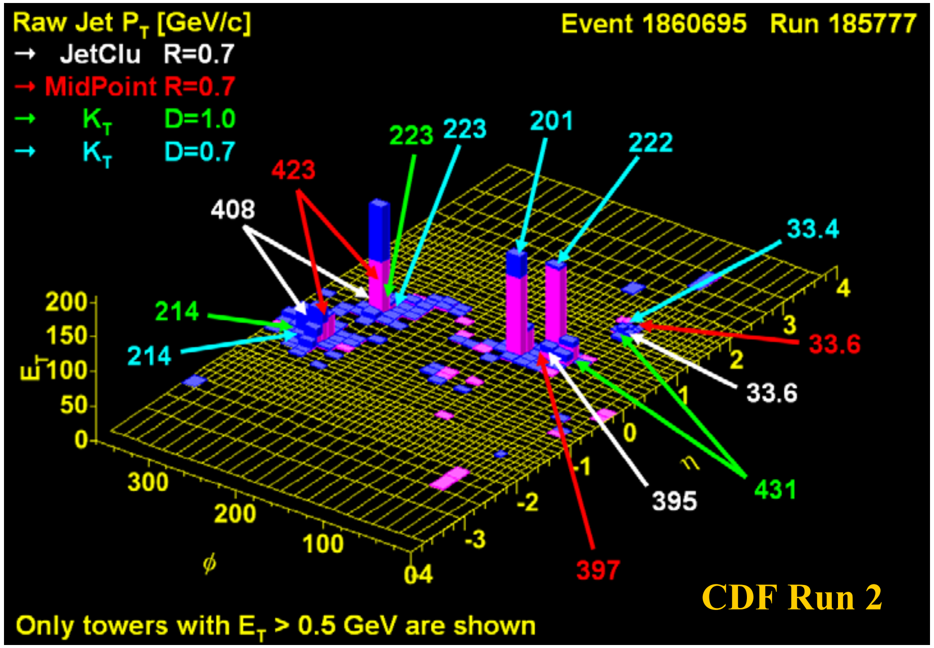
Jets at 1.96 TeV

“Theory Jets”



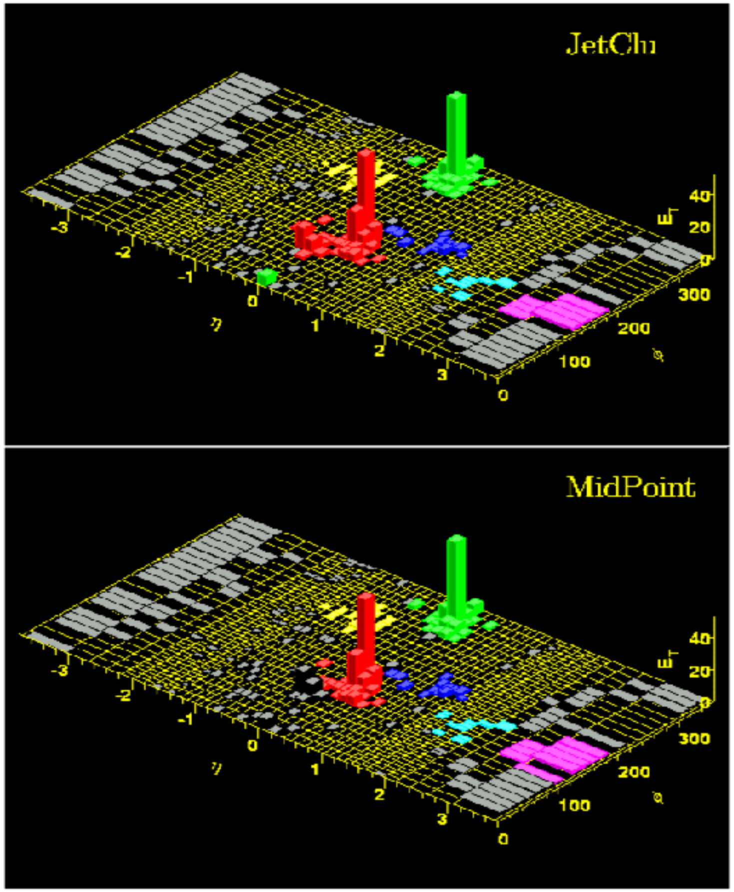
Next-to-leading order parton level calculation 0, 1, 2, or 3 partons!

“Real Jets”



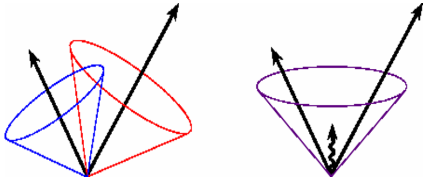
- **Experimental Jets:** The study of “real” jets requires a “jet algorithm” and the different algorithms correspond to different observables and give different results!
- **Experimental Jets:** The study of “real” jets requires a good understanding of the calorimeter response!
- **Experimental Jets:** To compare with NLO parton level (and measure structure functions) requires a good understanding of the “underlying event”!

Cone Algorithms



CDF JetClu Cone Algorithm:

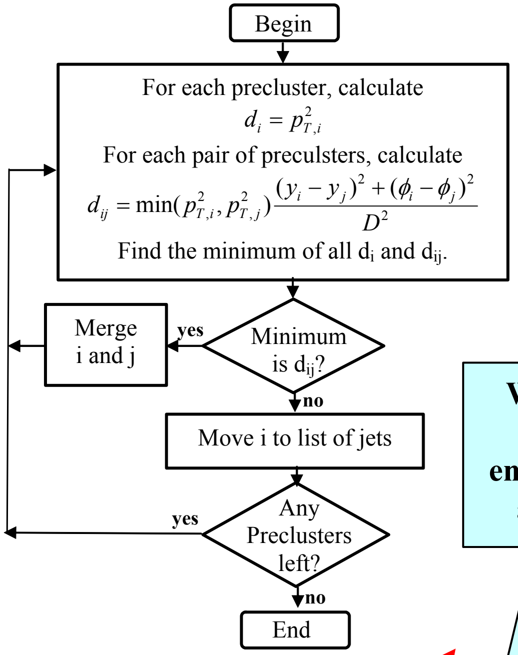
- Detector dependent algorithm (CDF Run 1 legacy)!
- Cluster together calorimeter towers by their "angular" proximity in (η, ϕ) space.
- Merged if common E_T is more than 75% of smallest jet.
- Not infrared safe at the parton level.
- To compare with NLO at the parton level one must introduce and ad hoc parameter R_{sep} ($R'=R_{sep}\times R$).



MidPoint Cone Algorithm:

- Define a list of seeds using CAL towers with $E_T > 1$ GeV.
- Also put seed in a the midpoint (η-ϕ) for each pair of proto-jets separated by less than 2R and iterate for stable jets.
- Merging/Splitting (f_{merge} = 50%, 70%).
- Results in improved infrared stability and can be compared with NLO parton-level calculations, but still needs the ad hoc R_{sep} parameter.
- Not all towers end up in a "jet".
- Use two R values (R/2 for finding stable cones, R for calculating jet properties).

K_T Algorithm



Begin

For each precluster, calculate

$$d_i = p_{T,i}^2$$

For each pair of preclusters, calculate

$$d_{ij} = \min(p_{T,i}^2, p_{T,j}^2)\frac{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}{D^2}$$

Find the minimum of all d_i and d_{ij}.

Minimum is d_{ij}?

yes: Merge i and j

no: Move i to list of jets

Any Preclusters left?

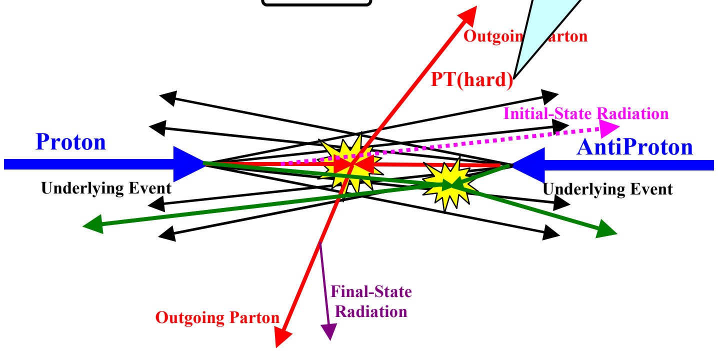
yes

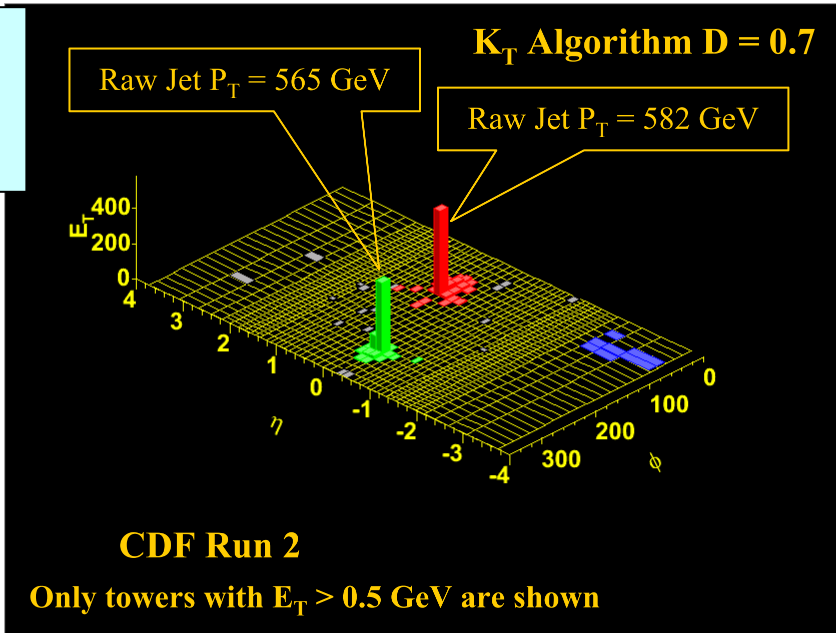
no: End

k_T Algorithm:

- Cluster together calorimeter towers by their k_T proximity.
- Infrared and collinear safe at all orders of pQCD.
- No splitting and merging.
- No ad hoc R_{sep} parameter necessary to compare with parton level.
- Every parton, particle, or tower is assigned to a “jet”.
- No biases from seed towers.
- Favored algorithm in ep and e^+e^- annihilations!

Will the K_T algorithm be effective in the collider environment where there is an “underlying event”?





K_T Algorithm D = 0.7

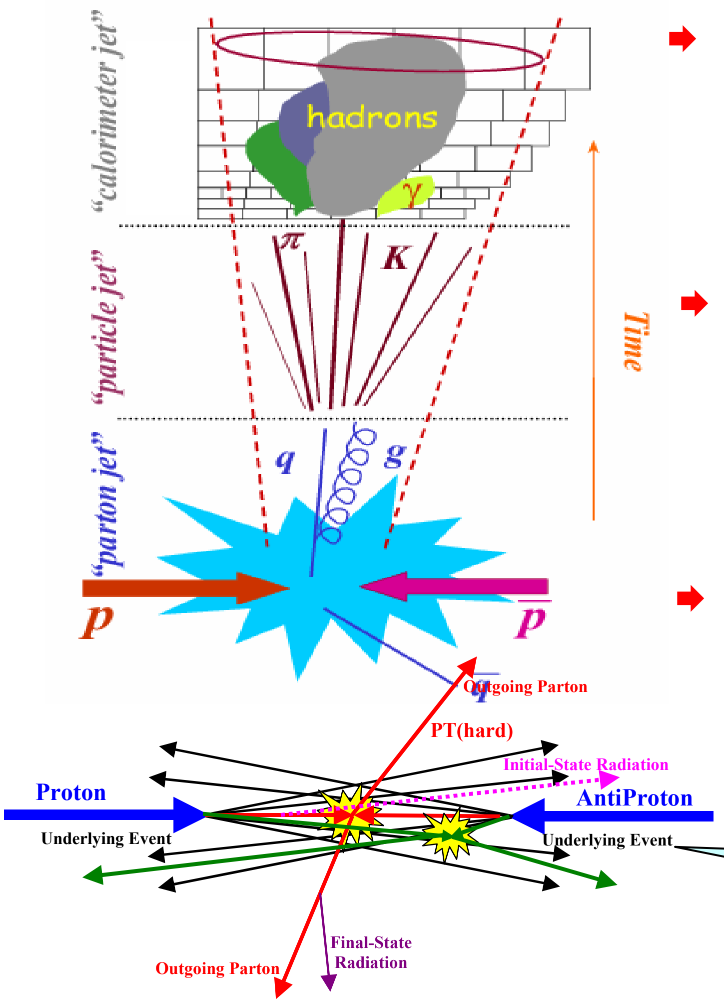
Raw Jet P_T = 565 GeV

Raw Jet P_T = 582 GeV

CDF Run 2

Only towers with E_T > 0.5 GeV are shown

Jet Corrections

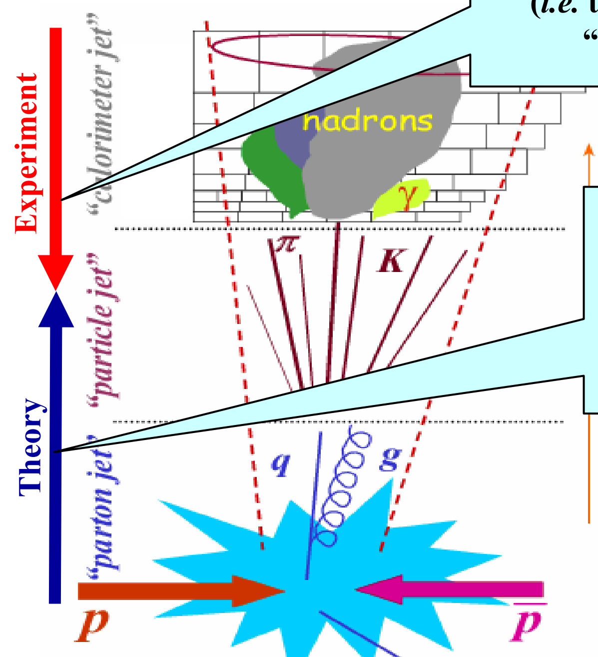


- **Calorimeter Jets:**
  - We measure "jets" at the "hadron level" in the calorimeter.
  - We certainly want to correct the "jets" for the detector resolution and effieciency.
  - Also, we must correct the "jets" for "pile-up".
  - Must correct what we measure back to the true "particle level" jets!
- **Particle Level Jets:**
  - Do we want to make further model dependent corrections?
  - Do we want to try and subtract the "underlying event" from the "particle level" jets.
  - This cannot really be done, but if you trust the Monte-Carlo models modeling of the "underlying event" you can try and do it by using the Monte-Carlo models.
- **Parton Level Jets:**
  - Do we want to use our data to try and extrapolate back to the parton level? Necessary if one wants to measure structure functions by comparint with NLO parton level!
  - This also cannot really be done, but again if you trust the Monte-Carlo models you can try and do it by using the Monte-Carlo models.

The "underlying event" consists of hard initial & final-state radiation plus the "beam-beam remnants" and possible multiple parton interactions.

Jet Corrections

I believe we should correct the data back to what we measure (*i.e.* the hadron level with an "underlying event")!



I believe we should correct (or calculate) the theory for what we measure (*i.e.* the hadron level with an "underlying event")!
We need MC@NLO!

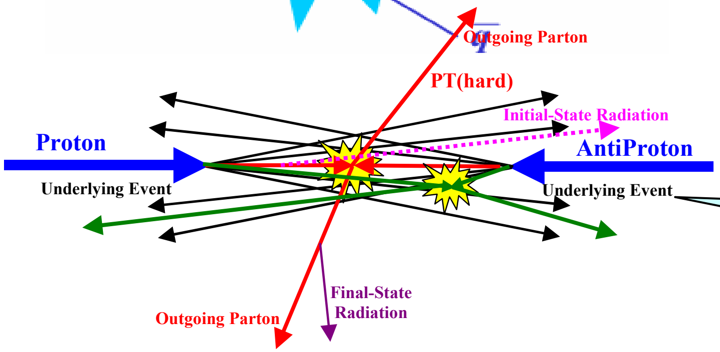
ts:

- We measure "jets" at the "hadron level" in the calorimeter.
- We certainly want to correct the "jets" for the detector resolution and effieciency.
- ct the "jets" for "pile-up".
- e measure back to the true "particle level" jets!

- e further model dependent corrections?
- nd subtract the "underlying event" from the "particle level" jets.
- This cannot really be done, but if you trust the Monte-Carlo models modeling of the "underlying event" you can try and do it by using the Monte-Carlo models.

Parton Level Jets:

- Do we want to use our data to try and extrapolate back to the parton level? Necessary if one wants to measure structure functions by comparint with NLO parton level!
- This also cannot really be done, but again if you trust the Monte-Carlo models you can try and do it by using the Monte-Carlo models.

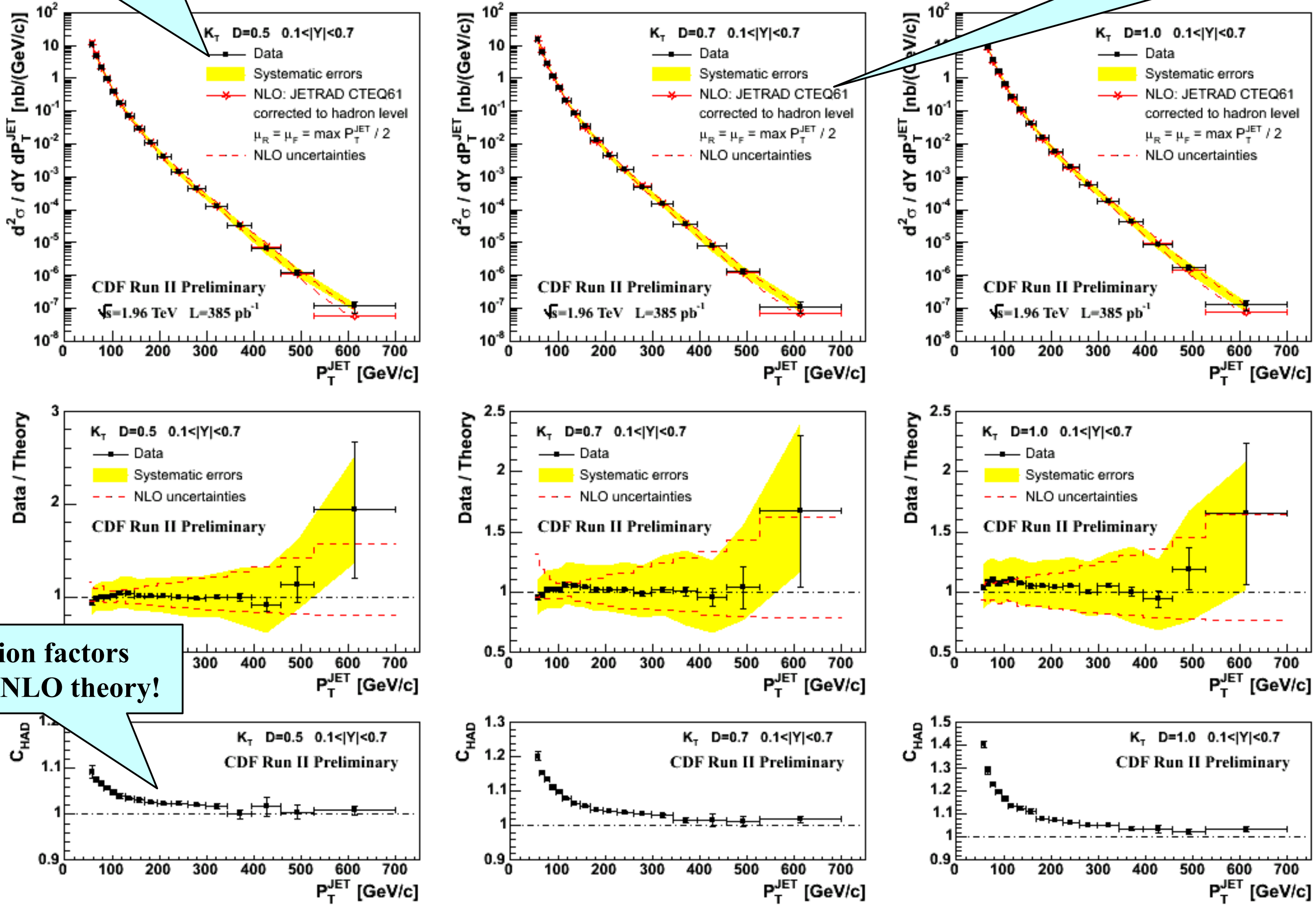


The "underlying event" consists of hard initial & final-state radiation plus the "beam-beam remnants" and possible multiple parton interactions.

K_T Jet Cross-Section

Data at the "hadron level"!

NLO parton level theory corrected to the "hadron level"!



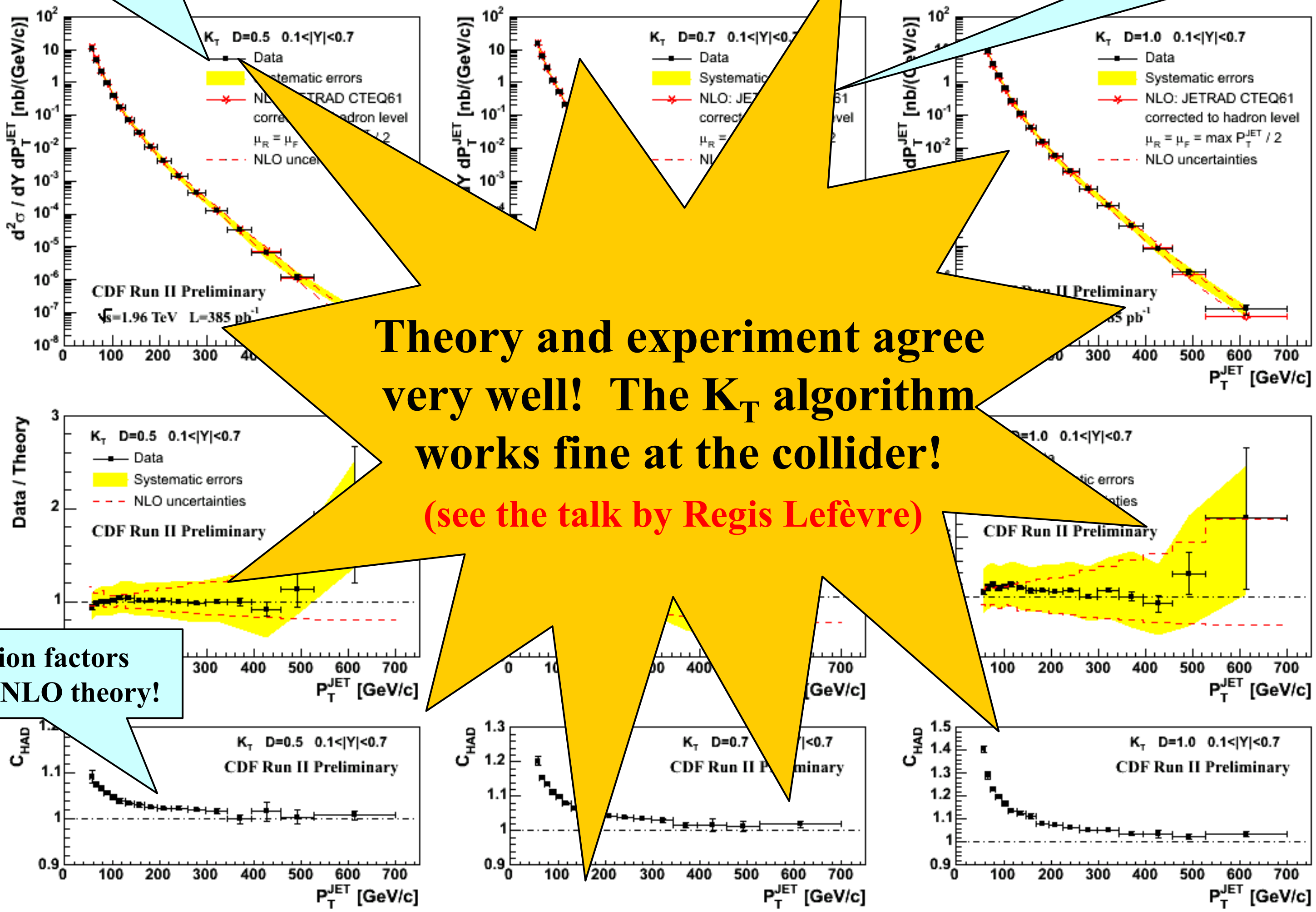
Correction factors applied to NLO theory!

K$_T$ Jet Cross-Section

Data at the “hadron level”!

NLO parton level theory corrected to the “hadron level”!

Correction factors applied to NLO theory!

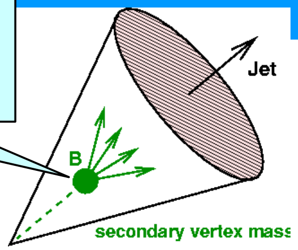


Theory and experiment agree very well! The K$_T$ algorithm works fine at the collider!

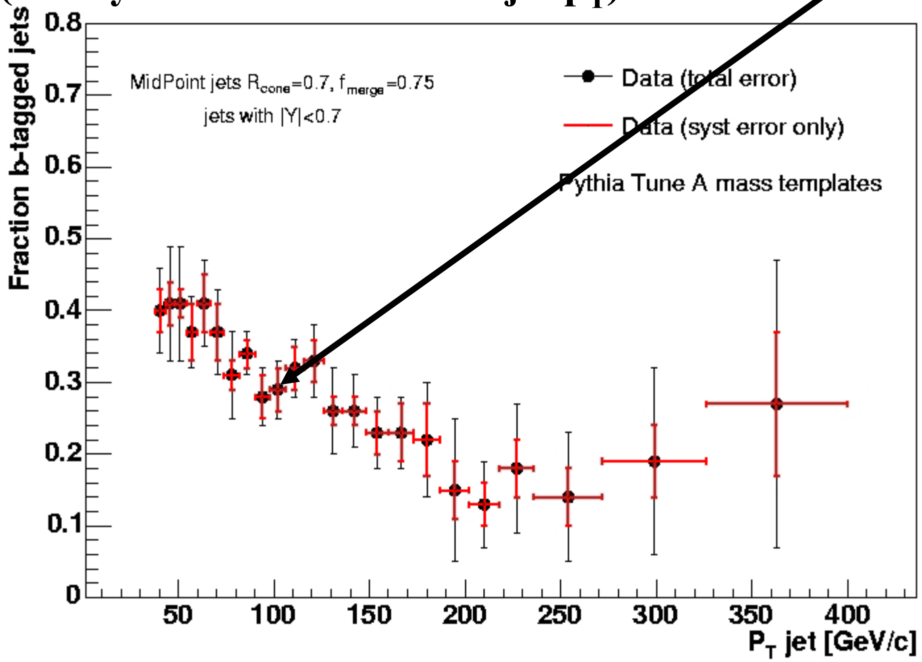
(see the talk by Regis Lefèvre)

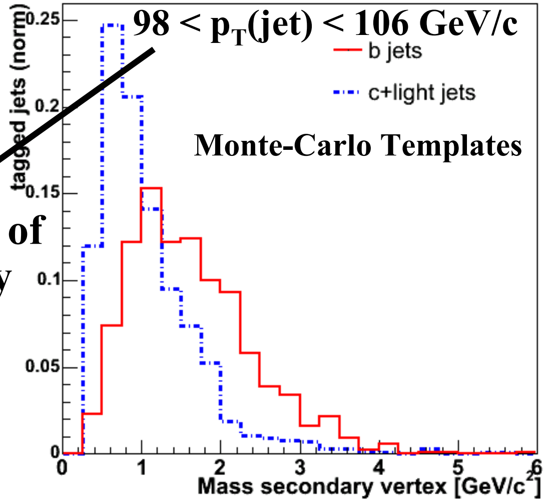
The b-Jet Cross-Section

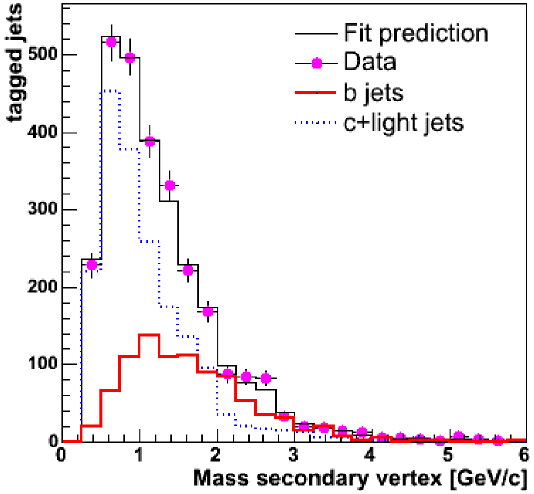
Construct the invariant mass of particles pointing back to the secondary vertex!



- **Extract fraction of b-tagged jets from data using the shape of the mass of the secondary vertex as discriminating quantity (bin-by-bin as a function of jet p_T).**

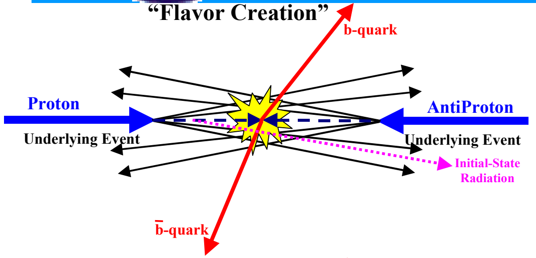




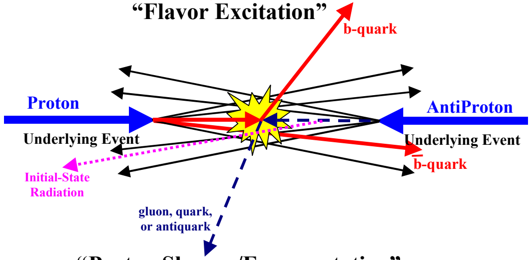


The b-Jet Cross-Section

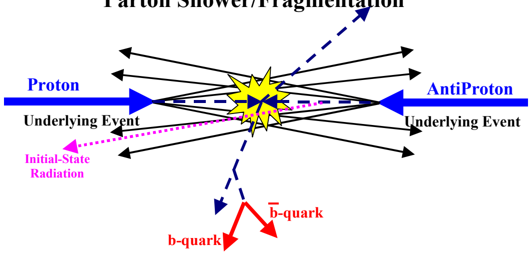
“Flavor Creation”

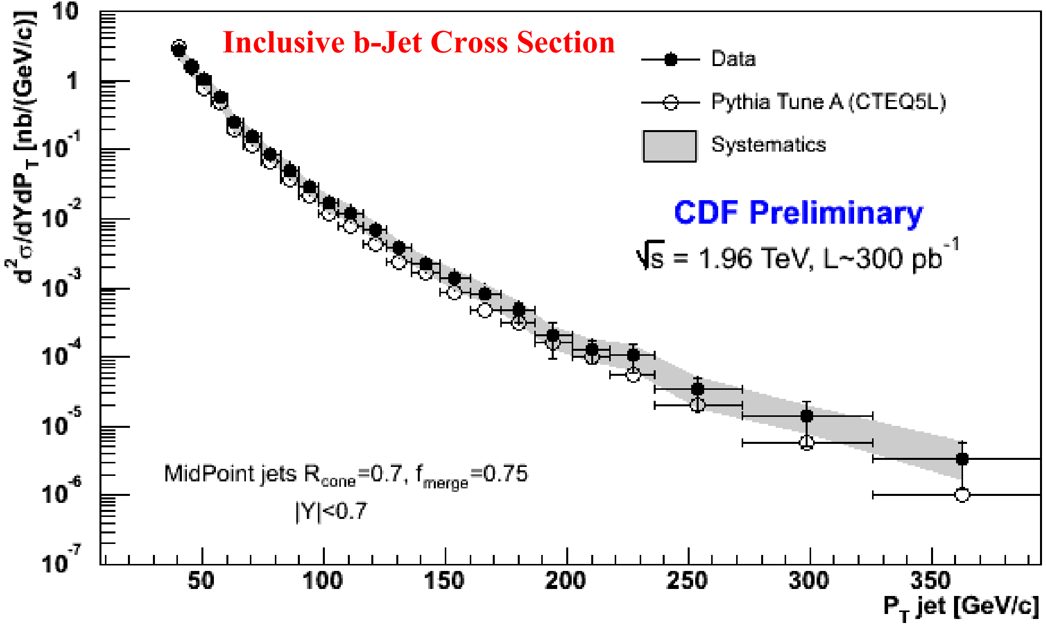


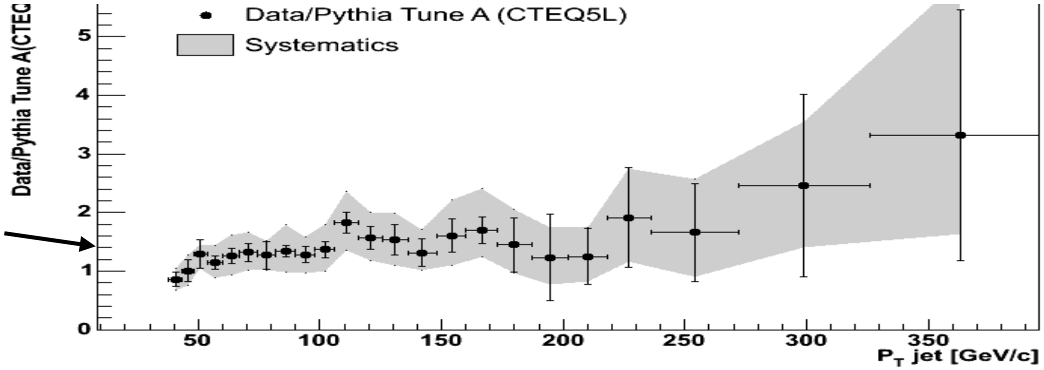
“Flavor Excitation”



“Parton Shower/Fragmentation”

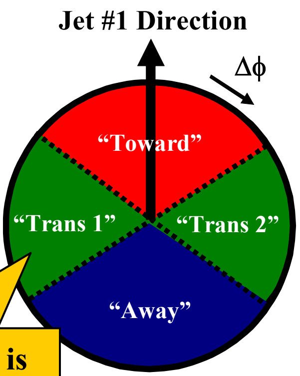






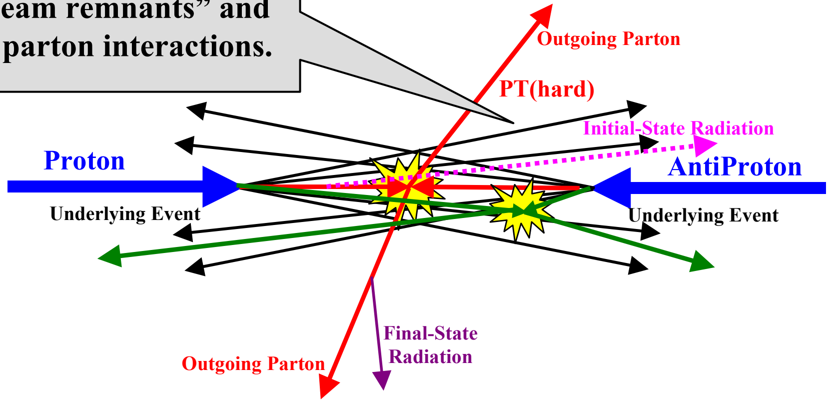
- The data are compared with PYTHIA (tune A)! Data/PYA ~ 1.4
- Comparison with MC@NLO coming soon!

The "Underlying Event" in Run 2 at CDF



"Transverse" region is very sensitive to the "underlying event"!

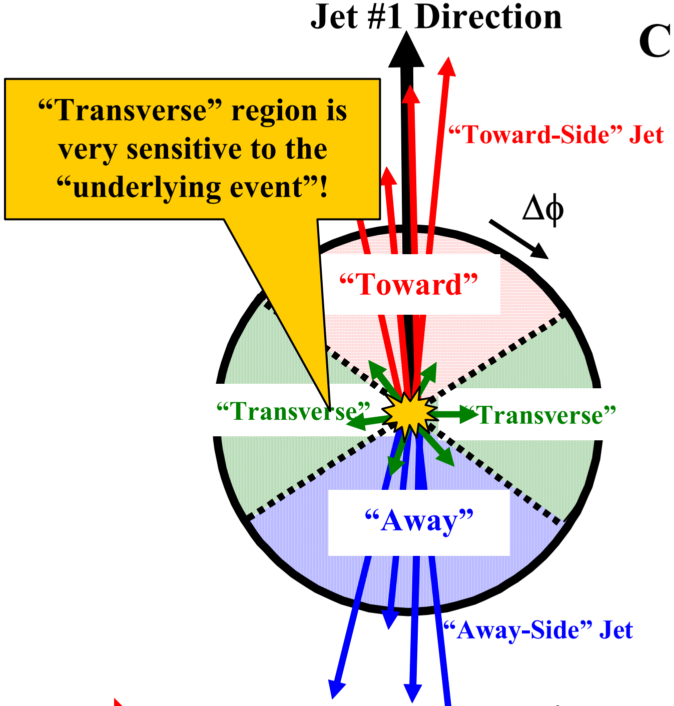
The "underlying event" consists of hard initial & final-state radiation plus the "beam-beam remnants" and possible multiple parton interactions.



CDF Run 2 results

- **Two Classes of Events:** "Leading Jet" and "Back-to-Back".
- **Two "Transverse" regions:** "transMAX", "transMIN", "transDIF".
- **PTmax** and **PTmaxT** distributions and averages.
- **Δφ Distributions:** "Density" and "Associated Density".
- **$<p_T>$ versus charged multiplicity:** "min-bias" and the "transverse" region.
- **Correlations between the two "transverse" regions:** "trans1" vs "trans2".

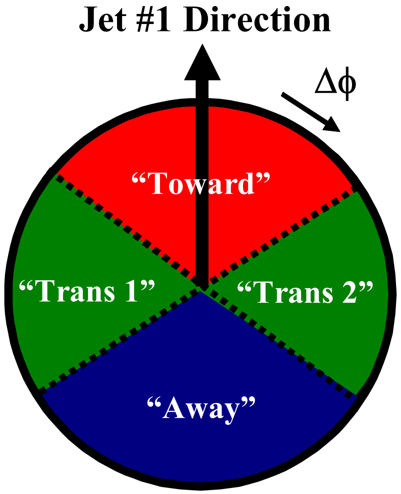
The “Transverse” Regions
as defined by the Leading Jet

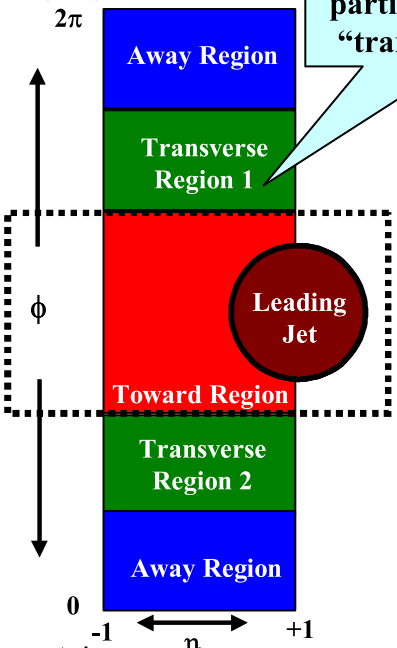


“Transverse” region is very sensitive to the “underlying event”!

Charged Particle Δϕ Correlations

$p_T > 0.5$ GeV/c $|\eta| < 1$

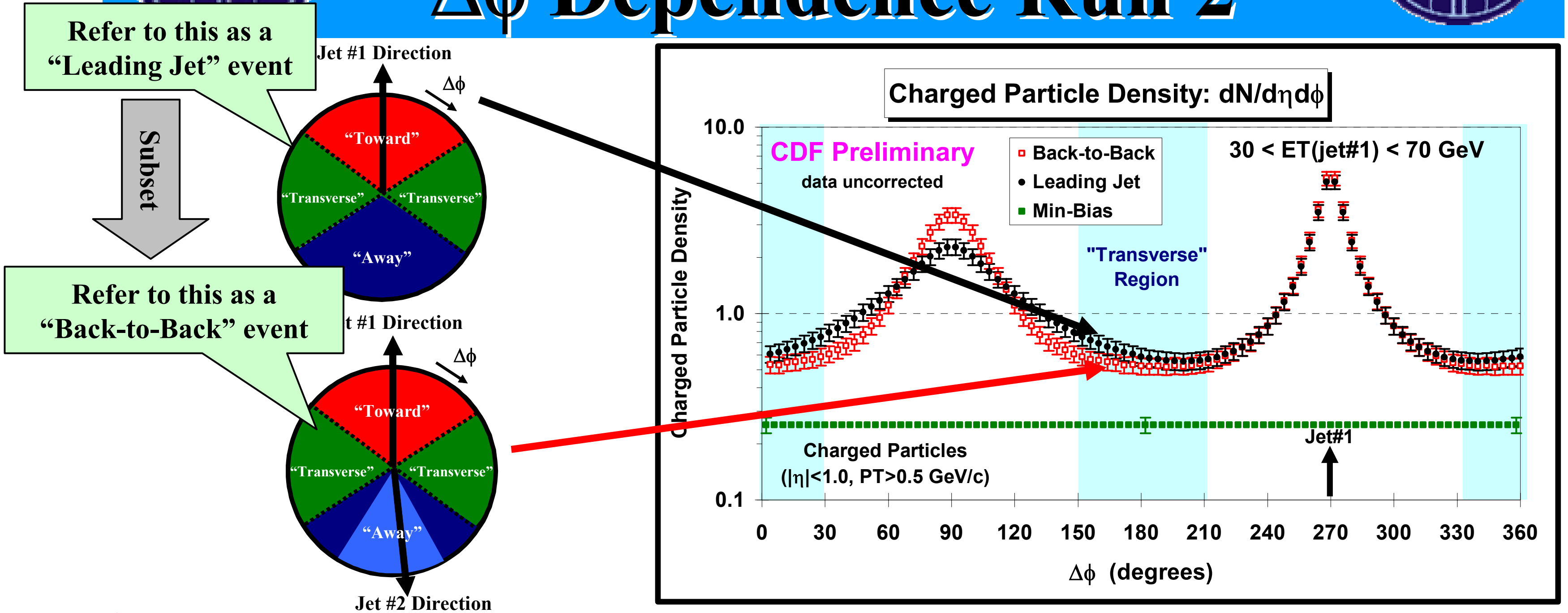




Look at the charged particle density in the “transverse” region!

- Look at charged particle correlations in the azimuthal angle Δϕ relative to the leading calorimeter jet (JetClu R = 0.7, |η| < 2).
- Define |Δϕ| < 60° as “Toward”, 60° < -Δϕ < 120° and 60° < Δϕ < 120° as “Transverse 1” and “Transverse 2”, and |Δϕ| > 120° as “Away”. Each of the two “transverse” regions have area ΔηΔϕ = 2x60° = 4π/6. The overall “transverse” region is the sum of the two transverse regions (ΔηΔϕ = 2x120° = 4π/3).

Charged Particle Density $\Delta\phi$ Dependence Run 2



Refer to this as a "Leading Jet" event

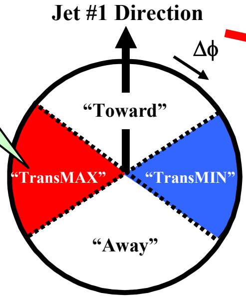
Subset

Refer to this as a "Back-to-Back" event

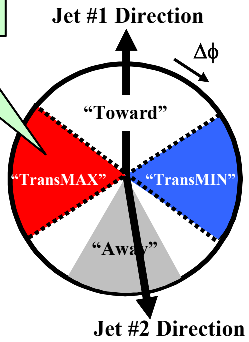
- Look at the "transverse" region as defined by the leading jet (JetClu R = 0.7, |η| < 2) or by the leading two jets (JetClu R = 0.7, |η| < 2). "Back-to-Back" events are selected to have at least two jets with Jet#1 and Jet#2 nearly "back-to-back" ($\Delta\phi_{12} > 150^o$) with almost equal transverse energies (E_T(jet#2)/E_T(jet#1) > 0.8) and E_T(jet#3) < 15 GeV.
- Shows the $\Delta\phi$ dependence of the charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles in the range $p_T > 0.5$ GeV/c and |η| < 1 relative to jet#1 (rotated to 270°) for 30 < E_T(jet#1) < 70 GeV for "Leading Jet" and "Back-to-Back" events.

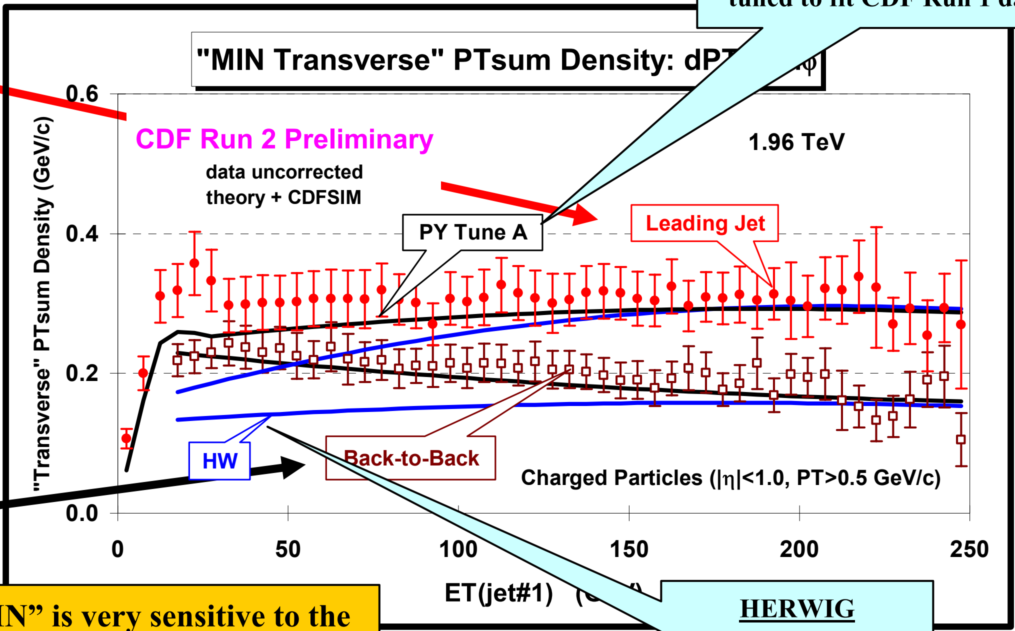
“TransMIN” PTsum Density versus E_T(jet#1)

“Leading Jet”



“Back-to-Back”





PYTHIA Tune A
Multiple parton interactions tuned to fit CDF Run 1 data!

HERWIG
No multiple parton interactions!

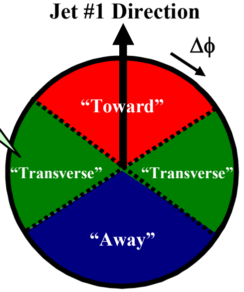
“transMIN” is very sensitive to the “beam-beam remnant” component of the “underlying event”!

- Use the leading jet to defin MAX and MIN “transverse” regions on an event-by-event basis with MAX (MIN) having the largest (smallest) charged PTsum density.
- Shows the “transMIN” charged PTsum density, $dPT_{sum}/d\eta d\phi$, for $p_T > 0.5$ GeV/c, $|\eta| < 1$ versus E_T(jet#1) for “Leading Jet” and “Back-to-Back” events.

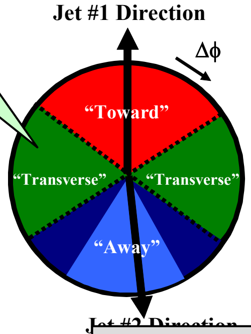
“Transverse” PTsum Density
PYTHIA Tune A vs HERWIG

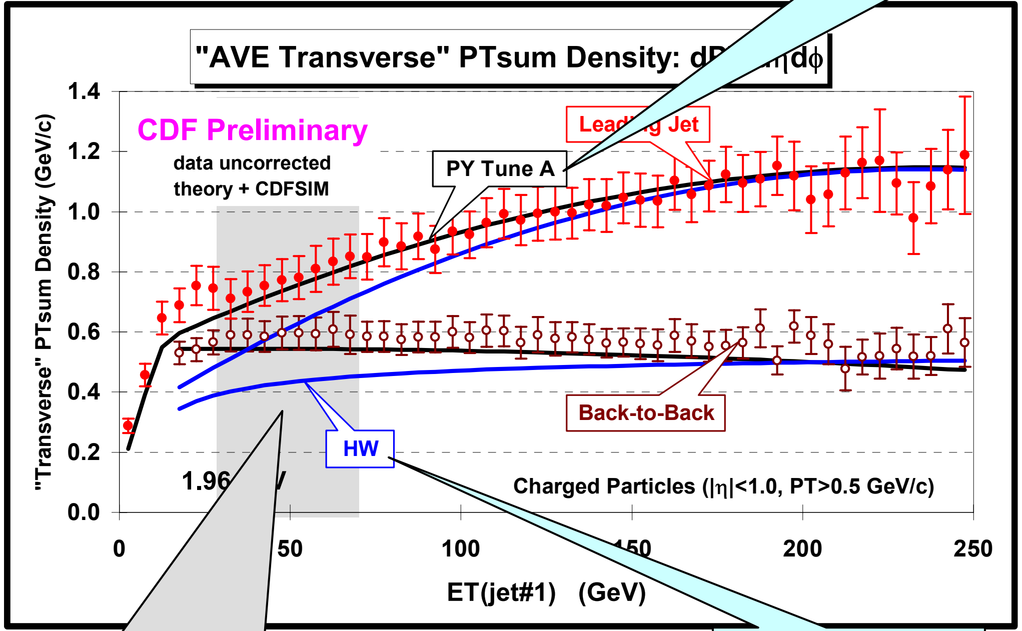
PYTHIA Tune A
Multiple parton interactions tuned to fit CDF Run 1 data!

“Leading Jet”



“Back-to-Back”





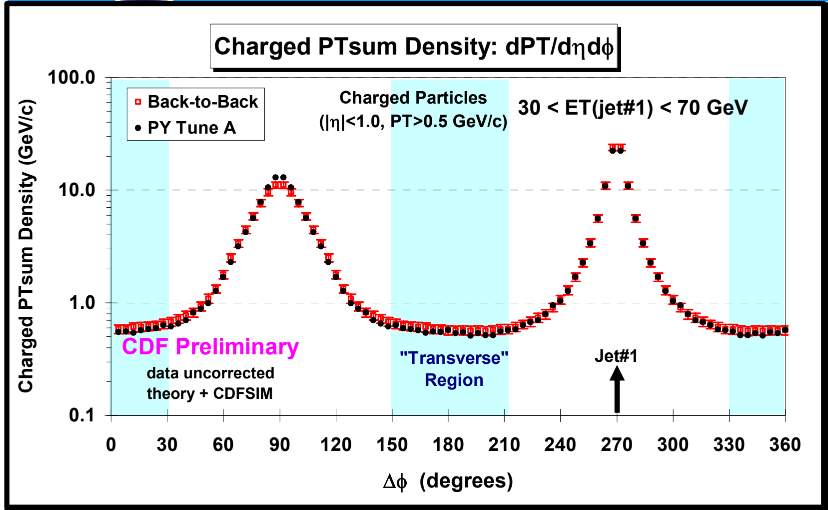
Now look in detail at “back-to-back” events in the region 30 < E_T(jet#1) < 70 GeV!

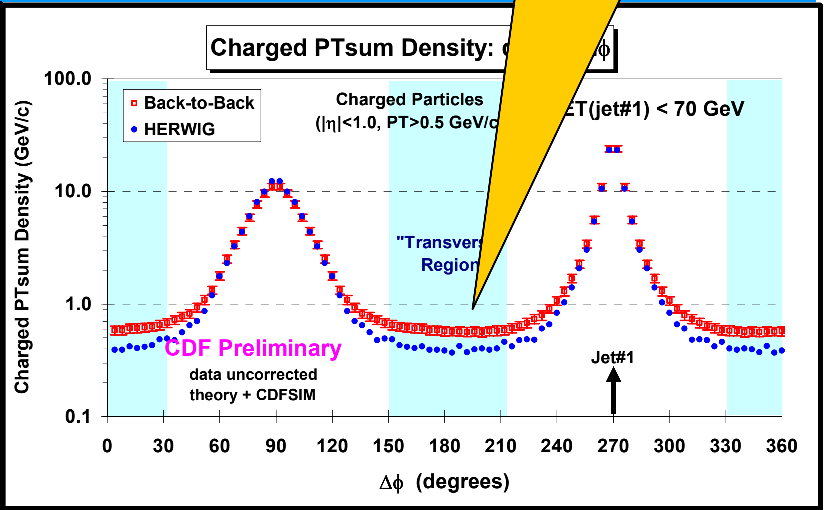
HERWIG
No multiple parton interactions!

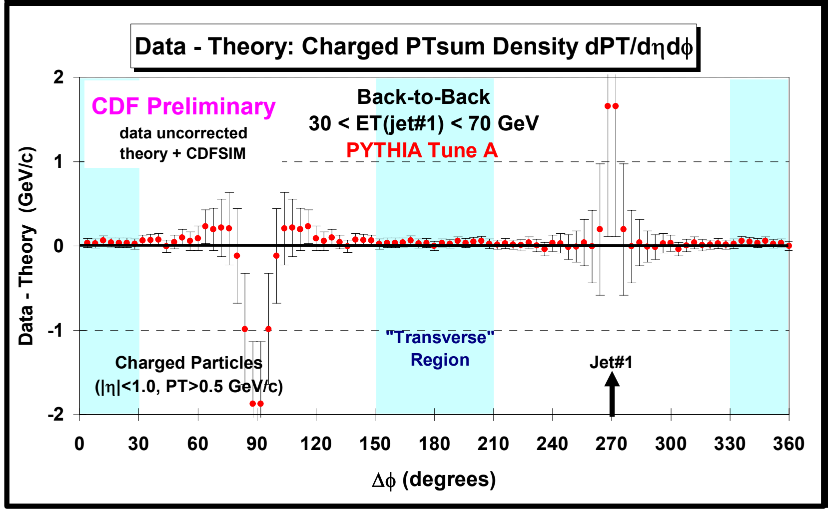
- **Shows the average charged PTsum density, $dPT_{sum}/d\eta d\phi$, in the “transverse” region (p_T > 0.5 GeV/c, $|\eta| < 1$) versus E_T(jet#1) for “Leading Jet” and “Back-to-Back” events.**
- **Compares the (*uncorrected*) data with PYTHIA Tune A and HERWIG after CDFSIM.**

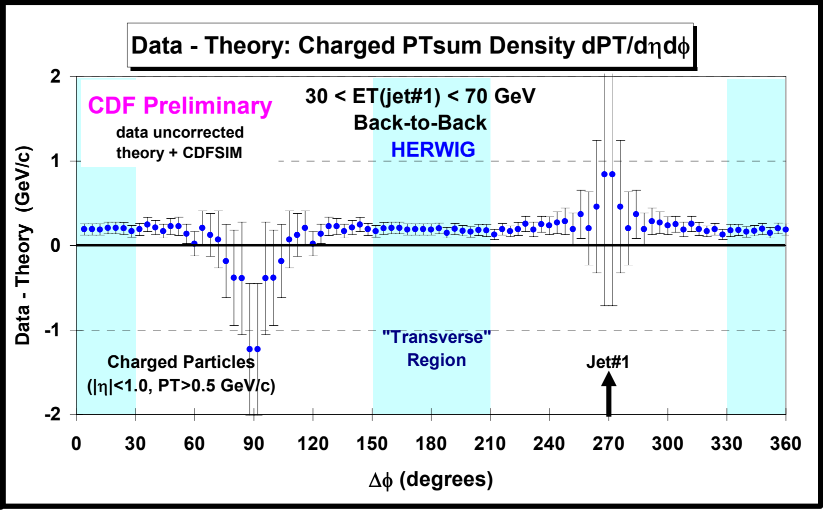
Charged PTsum Density
PYTHIA Tune A vs HERW

HERWIG (*without multiple parton interactions*) does not produces enough PTsum in the “transverse” region for 30 < E_T(jet#1) < 70 GeV!


Charged PTsum Density: dPT/dηdϕ


Charged PTsum Density:


Data - Theory: Charged PTsum Density dPT/dηdϕ

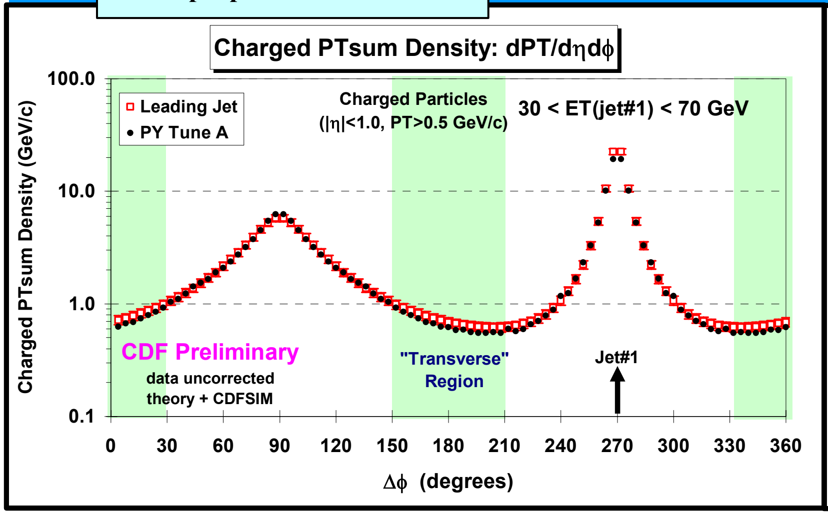

Data - Theory: Charged PTsum Density dPT/dηdϕ

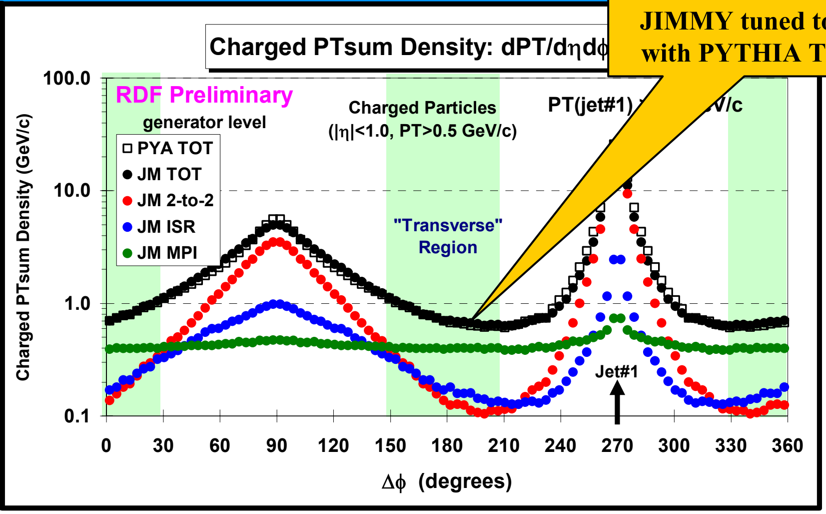
Tuned JIMMY versus PYTHIA Tune A

JIMMY
Runs with HERWIG and adds multiple parton interactions!

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

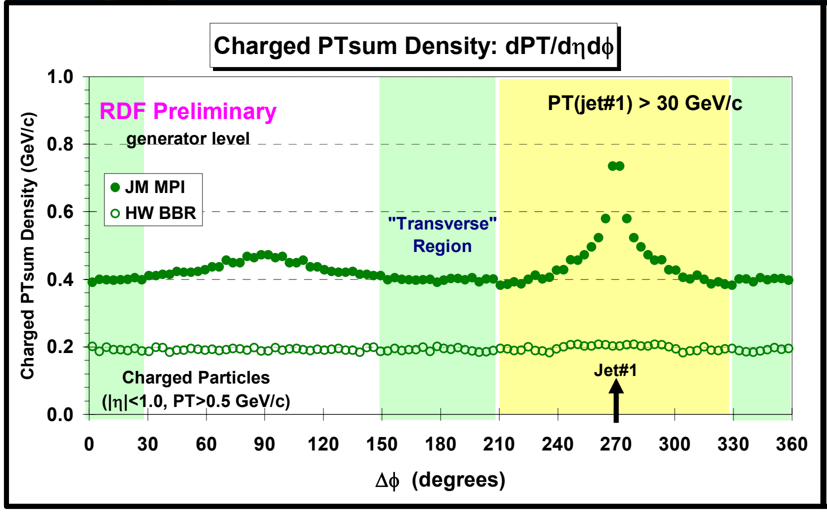
JIMMY tuned to agree with PYTHIA Tune A!

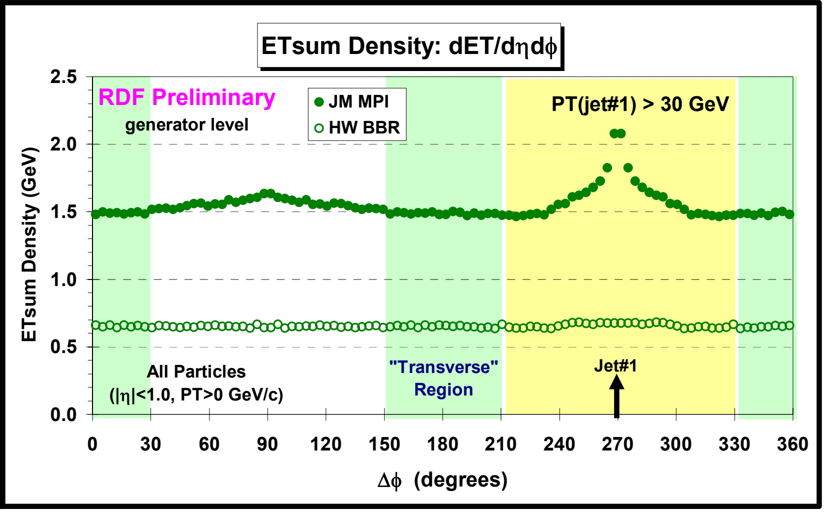




- **(*left*) Shows the Run 2 data on the Δϕ dependence of the charged *scalar* PTsum density (|η|<1, p_T>0.5 GeV/c) relative to the leading jet for 30 < E_T(jet#1) < 70 GeV/c compared with PYTHIA Tune A (*after CDFSIM*).**
- **(*right*) Shows the generator level predictions of PYTHIA Tune A and a tuned version of JIMMY (PT_{min}=1.8 GeV/c) for the Δϕ dependence of the charged *scalar* PTsum density (|η|<1, p_T>0.5 GeV/c) relative to the leading jet for PT(jet#1) > 30 GeV/c. The tuned JIMMY and PYTHIA Tune A agree in the "transverse" region.**
- **(*right*) For JIMMY the contributions from the multiple parton interactions (MPI), initial-state radiation (ISR), and the 2-to-2 hard scattering plus finial-state radiation (2-to-2+FSR) are shown.**

JIMMY (MPI) versus HERWIG (BBR)





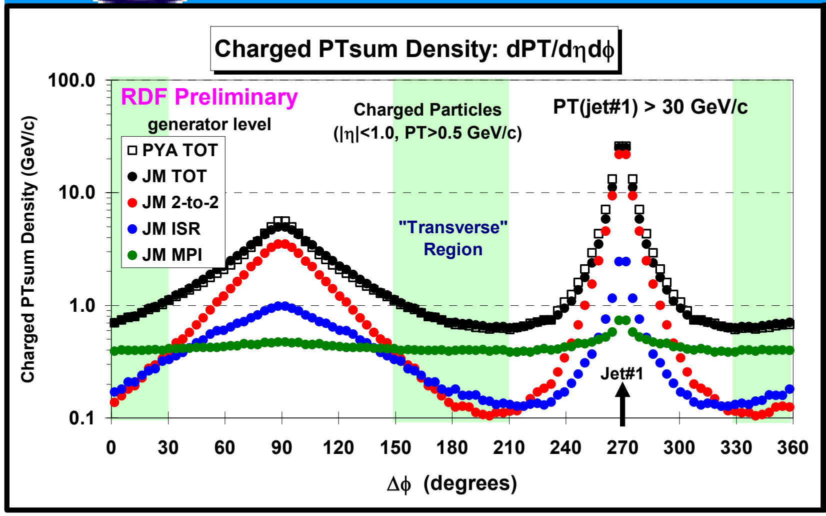
- **(*left*) Shows the generator level predictions of JIMMY (MPI, PT_{min}=1.8 GeV/c) and HERWIG (BBR) for the Δϕ dependence of the charged *scalar* PTsum density ($|\eta|<1$, $p_T>0.5$ GeV/c) relative to the leading jet for P_T(jet#1) > 30 GeV/c.**

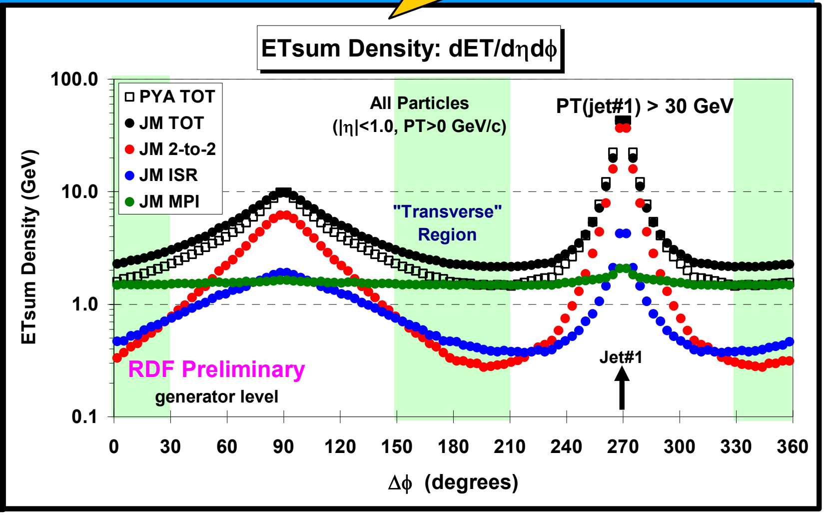
- **(*right*) Shows the generator level predictions of JIMMY (MPI, PT_{min}=1.8 GeV/c) and HERWIG (BBR) for the Δϕ dependence of the *scalar* ETsum density ($|\eta|<1$, $p_T>0$ GeV/c) relative to the leading jet for P_T(jet#1) > 30 GeV/c.**

- **The "multiple-parton interaction" (MPI) contribution from JIMMY is about a factor of two larger than the "Beam-Beam Remnant" (BBR) contribution from HERWIG. The JIMMY program replaces the HERWIG BBR is its MPI.**

Tuned JIMMY versus PYTHIA Tune A

Tuned JIMMY produces more ETsum than PYTHIA Tune A!





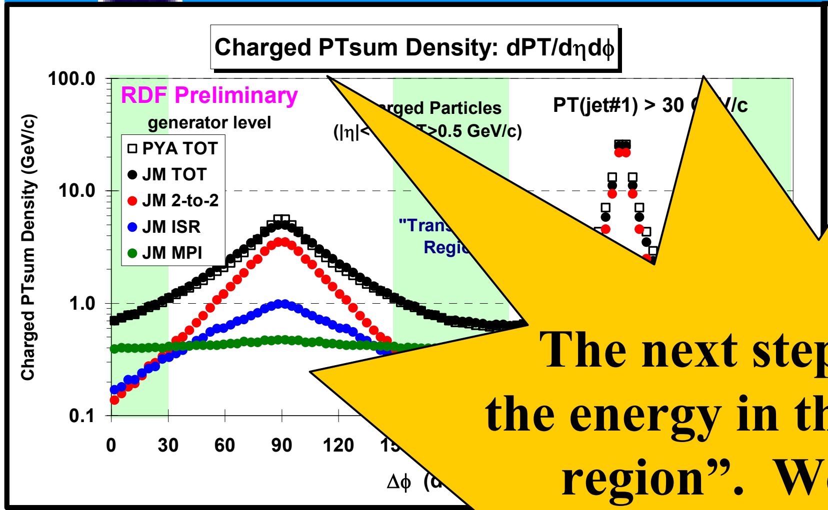
- (*left*) Shows the generator level predictions of PYTHIA Tune A and JIMMY (PT_{min}=1.8 GeV/c) for the $\Delta\phi$ dependence of the charged *scalar* PTsum density ($|\eta|<1$, $p_T>0.5$ GeV/c) relative to the leading jet with P_T(jet#1) > 30 GeV/c. JIMMY and PYTHIA Tune A agree in the “transverse” region..

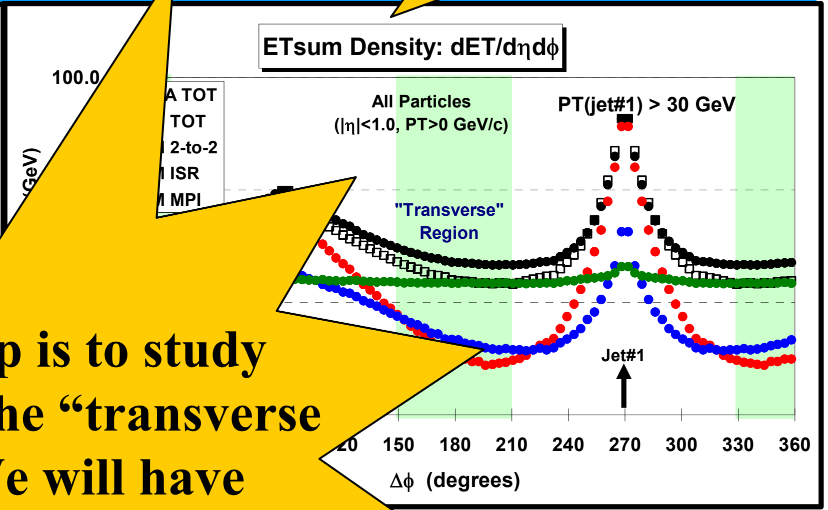
- (*right*) Shows the generator level predictions of PYTHIA Tune A and JIMMY (PT_{min}=1.8 GeV/c) for the $\Delta\phi$ dependence of the *scalar* ETsum density ($|\eta|<1$, $p_T>0$) relative to the leading jet for P_T(jet#1) > 30 GeV/c.

- The tuned JIMMY produces a lot more ETsum ($p_T>0$) in the “transverse” region than does PYTHIA Tune A!

Tuned JIMMY versus PYTHIA Tune A

Tuned JIMMY produces more ETsum than PYTHIA Tune A!



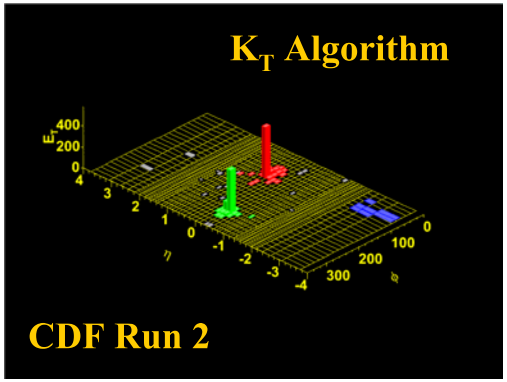


The next step is to study the energy in the “transverse region”. We will have results on this soon!

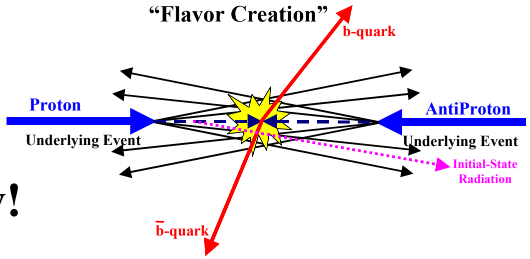
- **(*left*) Shows the generat (PT$_{min}$=1.8 GeV/c) for the Δφ dependence o 0.5 GeV/c) relative to the leading jet with P$_T$(jet#1) > 30 GeV/c. JI in the “transverse” region..**
- **(*right*) Shows the generator leve dic f P Tune A l JIMMY (PT$_{min}$=1.8 GeV/c) for the Δφ dependence of the *scala* ETsum ty (|η| >0) relativ to the leading jet for P$_T$(jet#1) > 30 GeV/c.**
- **The tuned JIMMY produces a lot more Tsum (p$_T$>0) in the “transverse” region than does PYTHIA Tune A!**

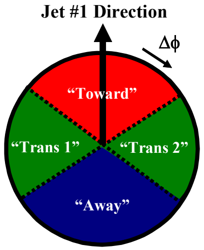
Summary

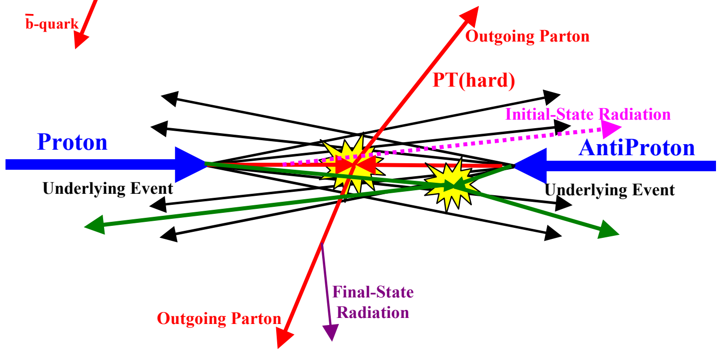
- **The K_T algorithm works fine at the Tevatron and theory/data (CTEQ61M) look flat!**



- **We have measured the inclusive b-jet section and everything is as expected - nothing goofy!**







- **We are making good progress in understanding and modeling the "underlying event". We now have PYTHIA tune A and JIMMY tune A! Energy density in the "transverse region" coming soon!**