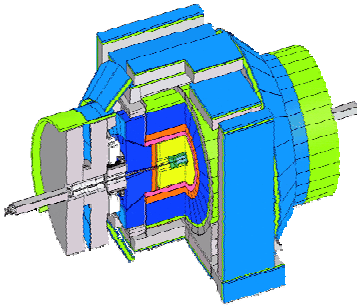
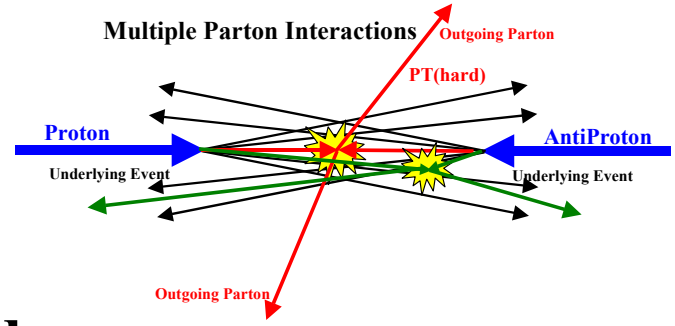
XIII International Workshop on Deep Inelastic Scattering

Hadronic Final States Working Group



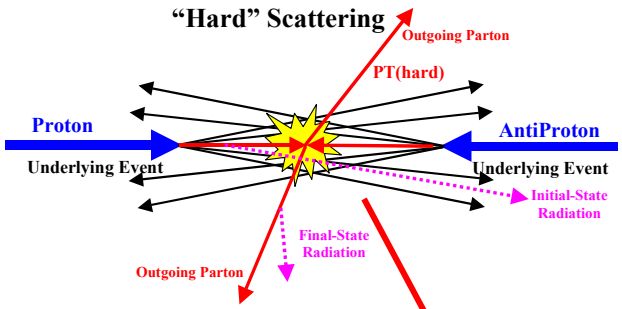


Rick Field

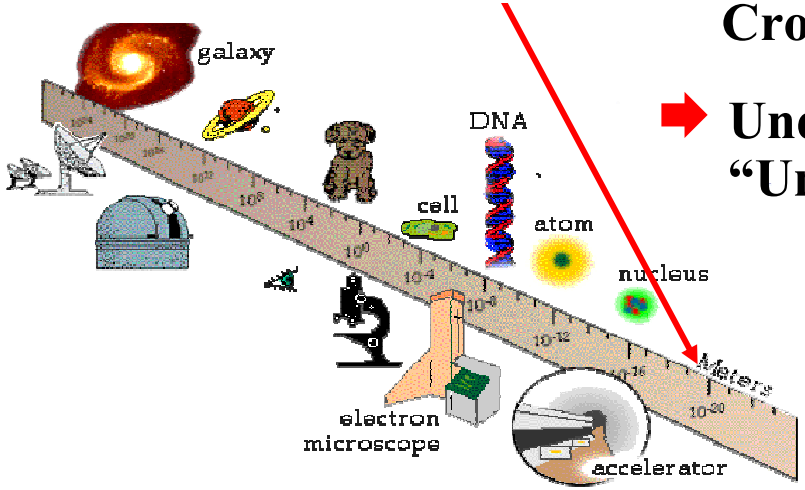
University of Florida

(*for the CDF Collaboration*)

Jet Physics in Run 2 at CDF

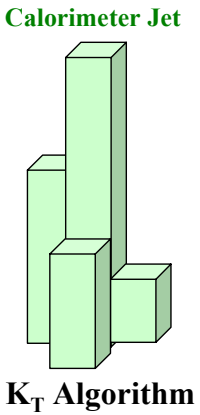


High P_T "jets" probe short distances!

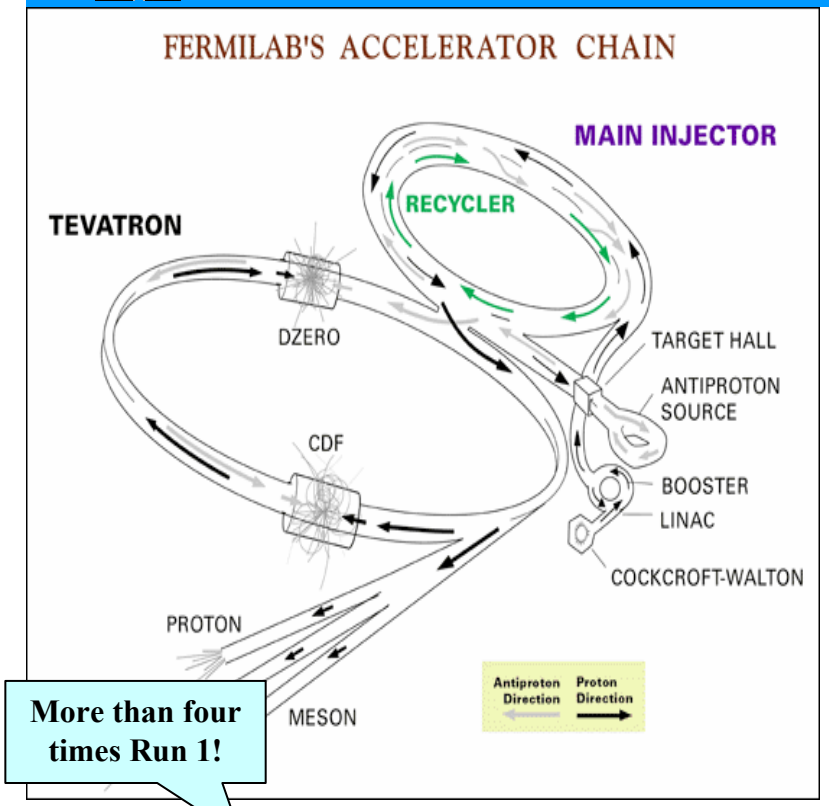


Outline of Talk

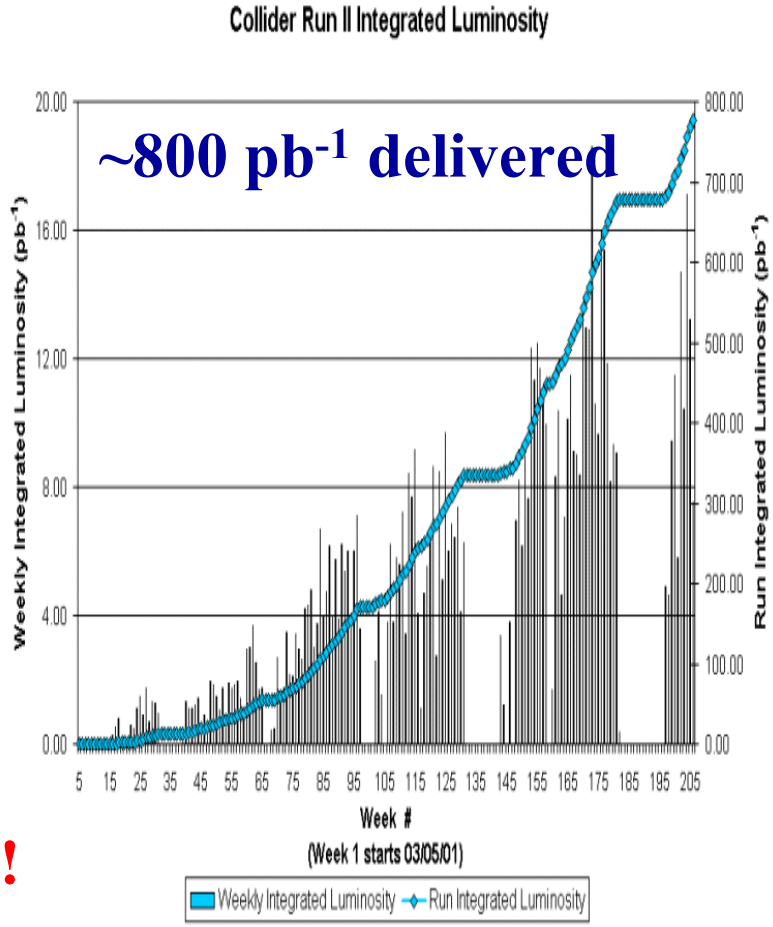
- Constructing Jets in Run 2 at CDF (MidPoint and K_T Algorithms).
- New from CDF: The K_T-Jet Inclusive Cross Section.
- New from CDF: The b-Jet Inclusive Cross Section.
- Understanding and Modeling the "Underlying Event" in Run 2 at CDF.



The TeVatron



More than four times Run 1!



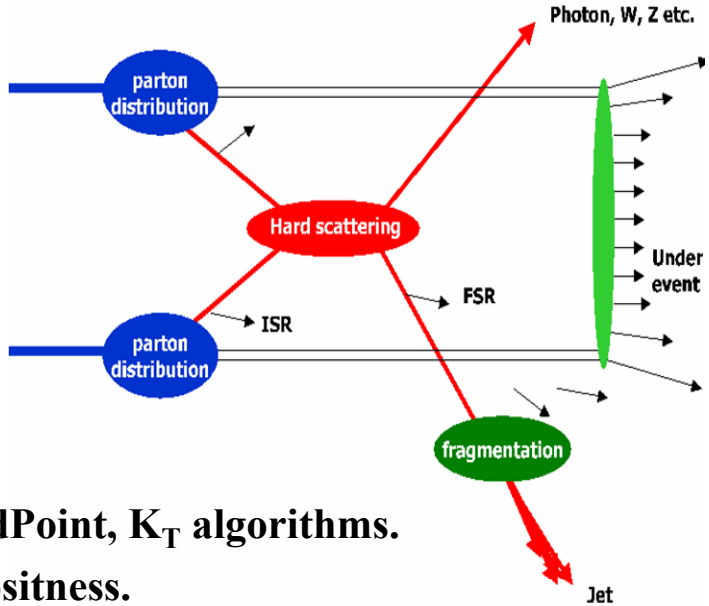
CDF has ~600 pb^{-1} on tape!

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!



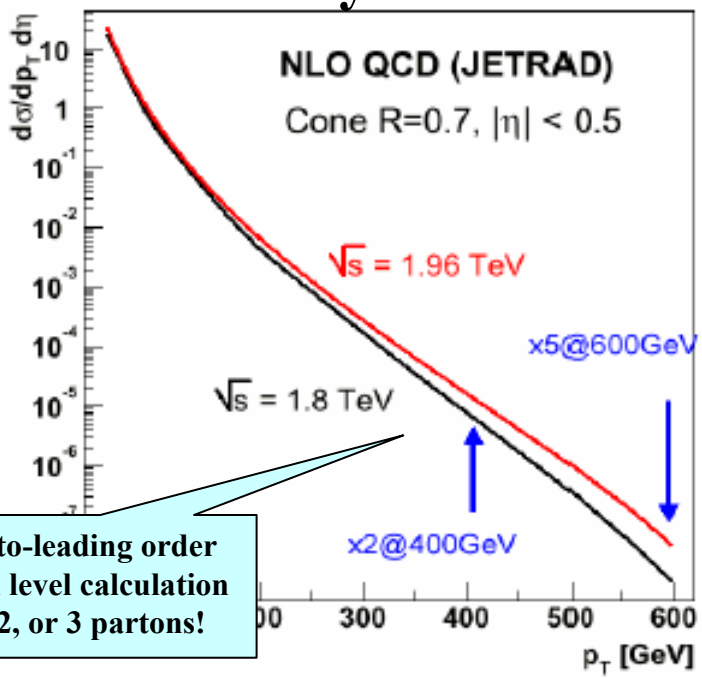
Some CDF-QCD Group Analyses!

- **Jet Cross Sections and Correlations:** Jet Clu, MidPoint, K_T algorithms.
- **DiJet Mass Distributions:** $\Delta\phi$ 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!

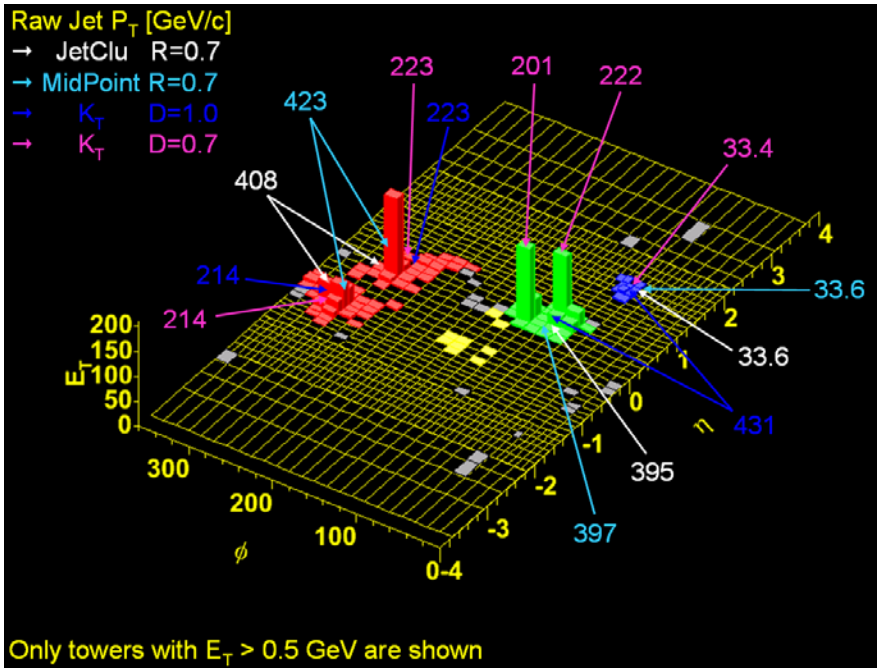
Jets at 1.96 TeV

"Theory Jets"



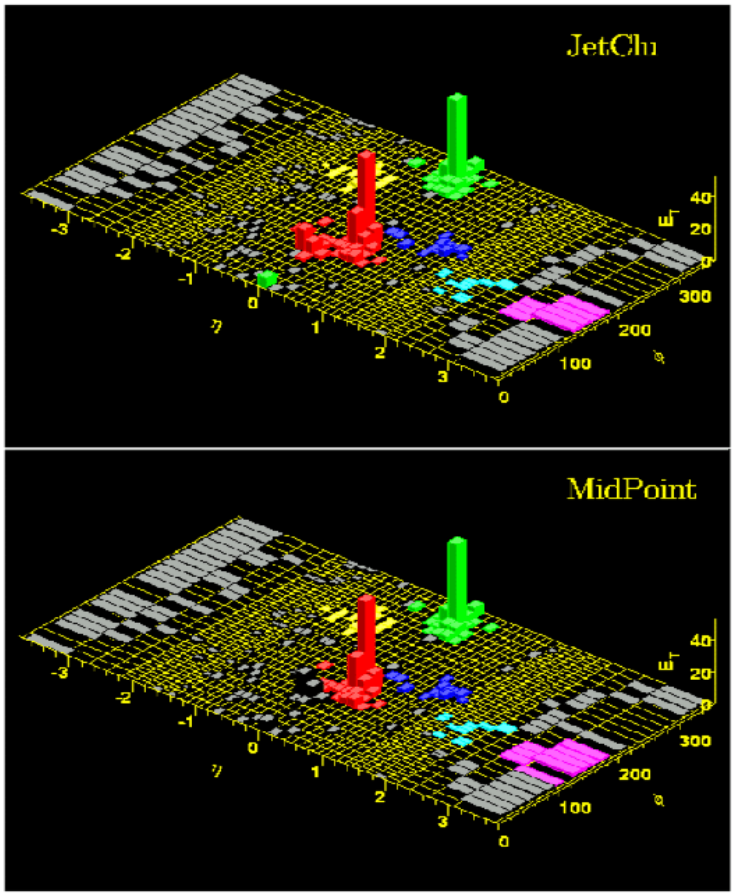
Next-to-leading order parton level calculation 0, 1, 2, or 3 partons!

"Real Jets"

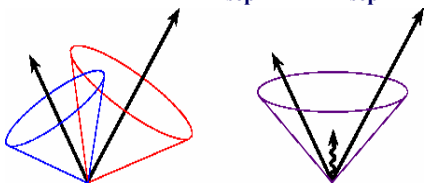


- **Experimental Jets:** The study of "real" jets requires a "jet algorithm" and the different algorithms correspond to different observables and give different results!
- **Experimental Jets:** The study of "real" jets requires a good understanding of the calorimeter response!
- **Experimental Jets:**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

Cone Algorithms

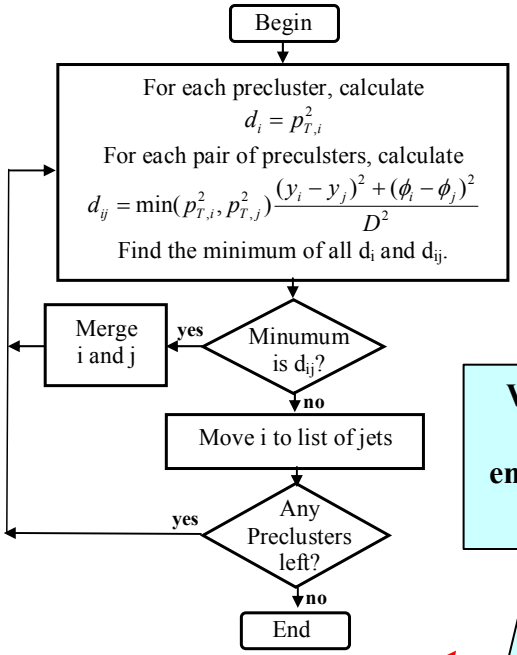


- **CDF JetClu Cone Algorithm:**
  - Detector dependent algorithm (CDF Run 1 legacy)!
  - Cluster together calorimeter towers by their "angular" proximity in (η, ϕ) space.
  - Merged if common E_T is more than 75% of smallest jet.
  - Not infrared safe at the parton level.
  - To compare with NLO at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



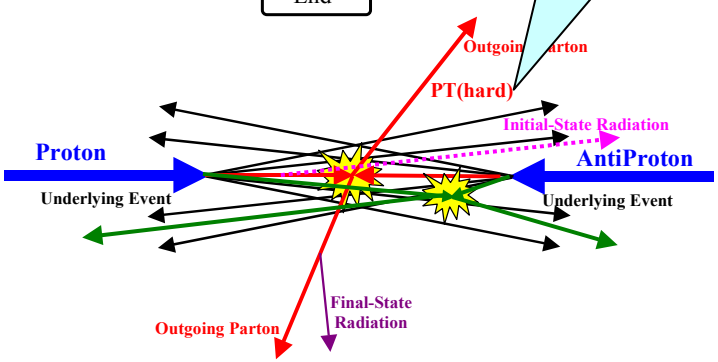
- **MidPoint Cone Algorithm:**
  - Define a list of seeds using CAL towers with $E_T > 1$ GeV.
  - Also put seed in a the midpoint (η-ϕ) for each pair of proto-jets separated by less than 2R and iterate for stable jets.
  - Merging/Splitting (f_{merge} = 50%, 70%).
  - Results in improved infrared stability 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).

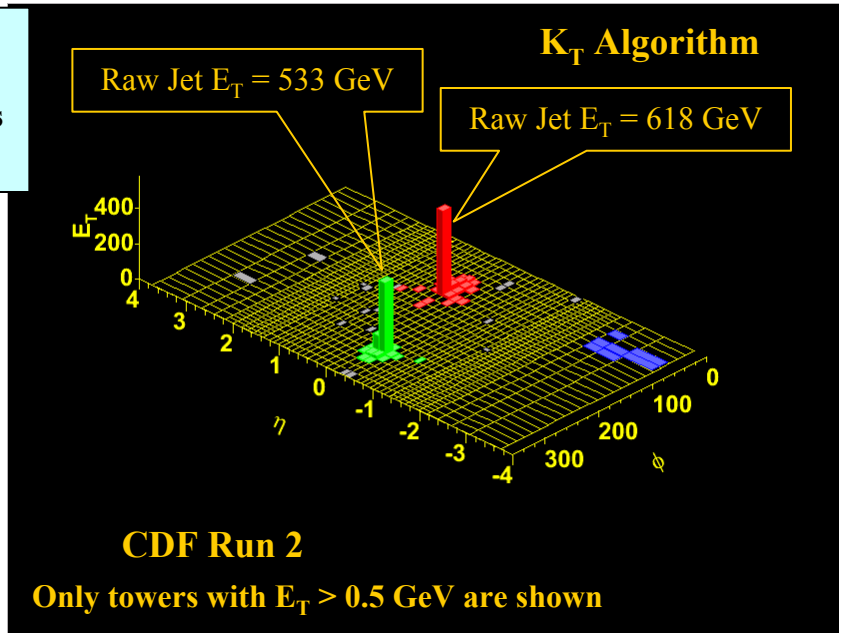
K_T Algorithm



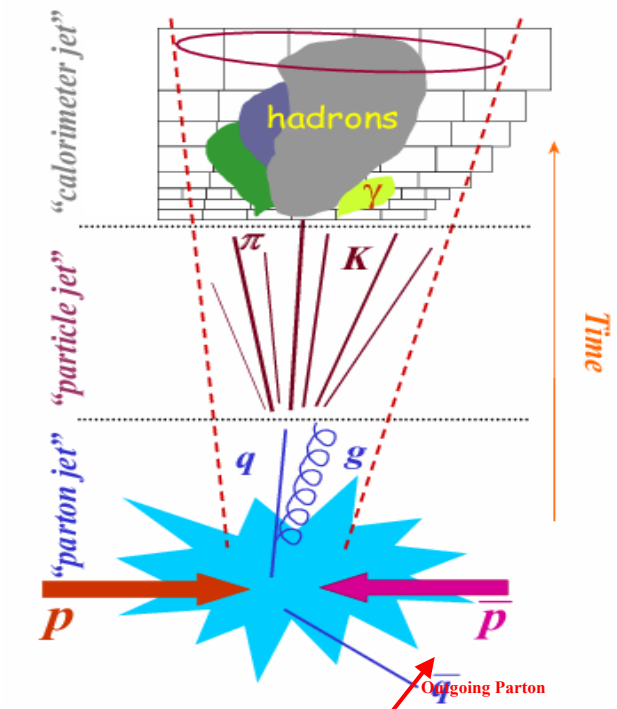
- **k_T Algorithm:**
  - **Cluster together calorimeter towers by their k_T proximity.**
  - **Infrared and collinear safe at all orders of pQCD.**
  - **No splitting and merging.**
  - **No ad hoc R_{sep} parameter necessary to compare with parton level.**
  - **Every parton, particle, or tower is assigned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

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

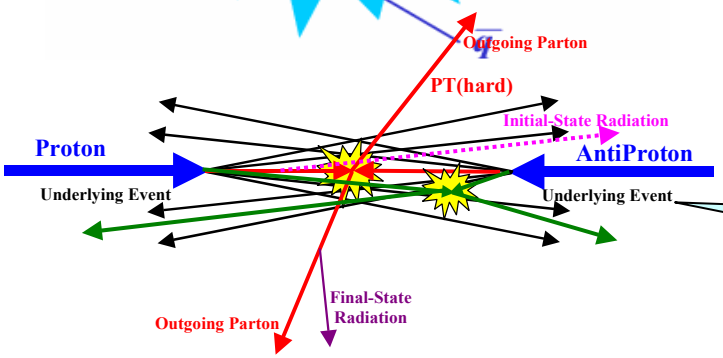




Jet Corrections



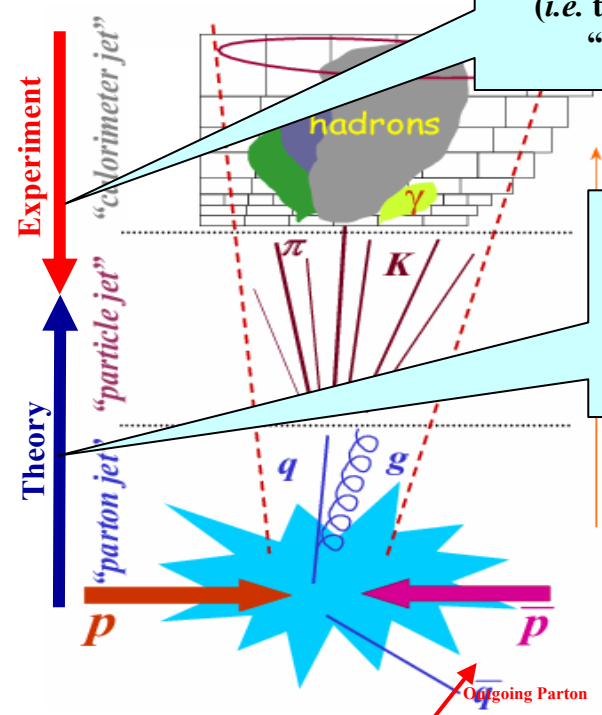
- **Calorimeter Jets:**
  - We measure "jets" at the "hadron level" in the calorimeter.
  - We certainly want to correct the "jets" for the detector resolution and effieciency.
  - Also, we must correct the "jets" for "pile-up".
  - Must correct what we measure back to the true "particle level" jets!
- **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?
  - 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.

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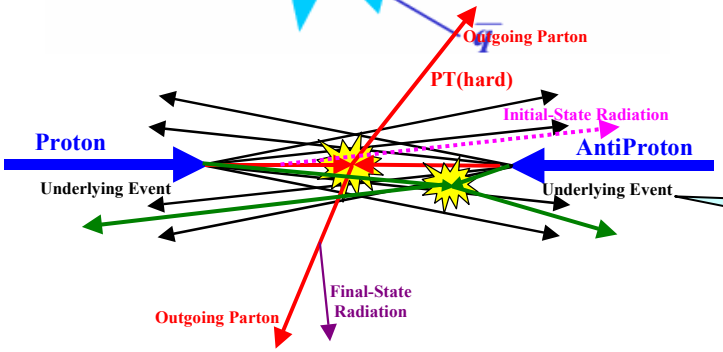
- This cannot really be done, but if you trust the Monte-Carlo models modeling of the "underlying event" you can try and do it by using the Monte-Carlo models.

➡ **Parton Level Jets:**

- Do we want to use our data to try and extrapolate back to the parton level?
- 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.

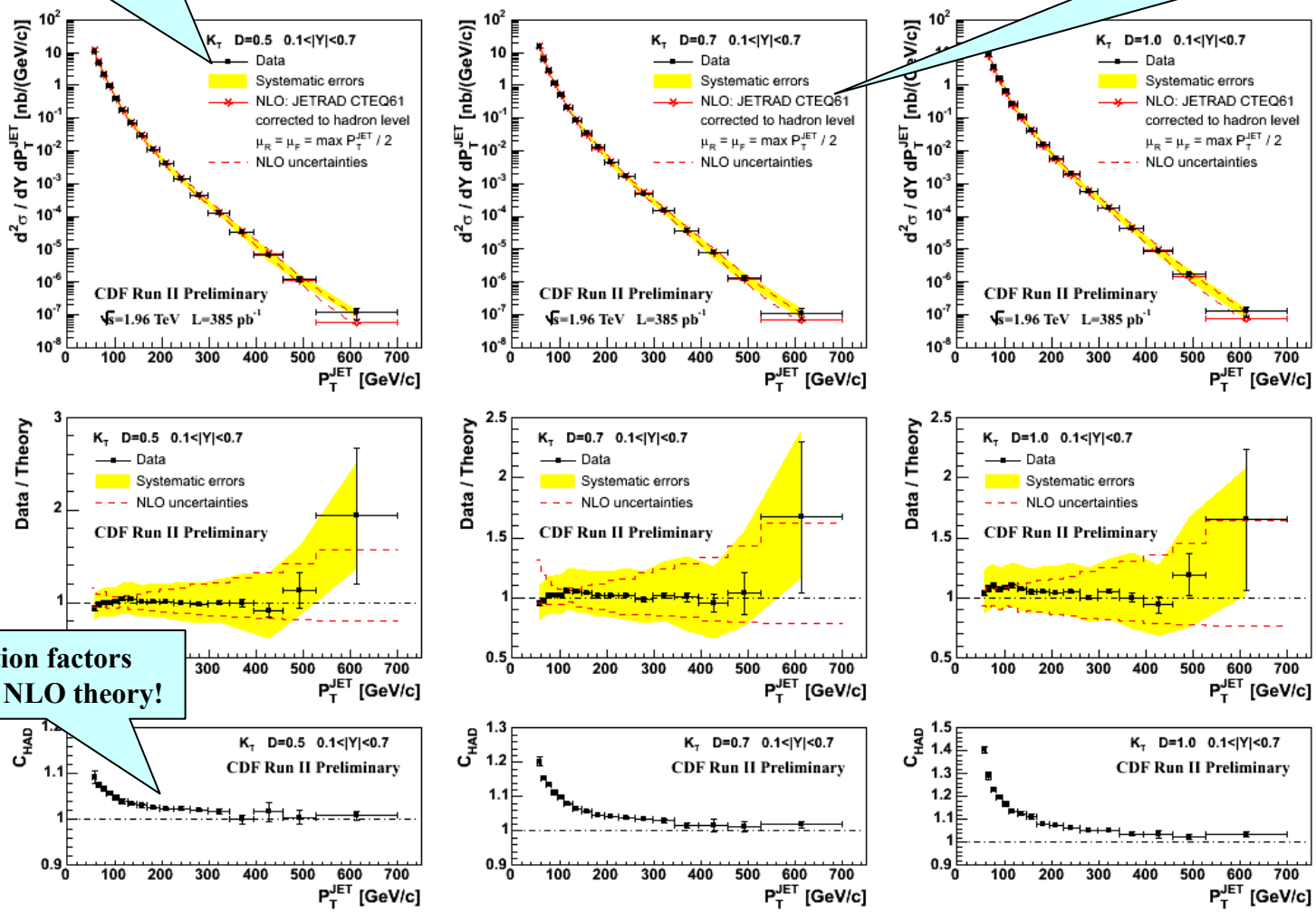


The "underlying event" consists of hard initial & final-state radiation plus the "beam-beam remnants" and possible multiple parton interactions.

K_T Jet Cross-Section

Data at the "hadron level"!

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

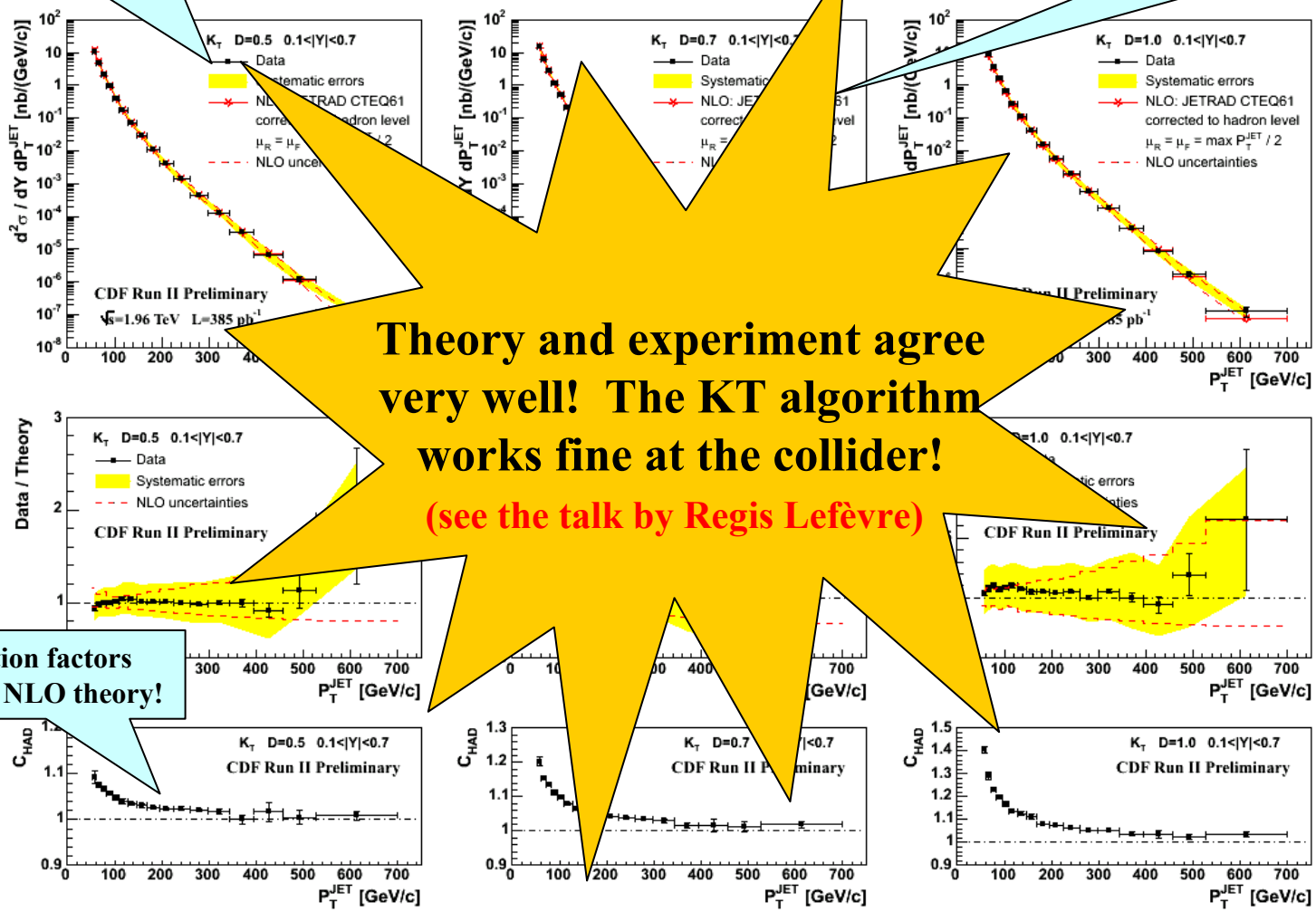


Correction factors applied to NLO theory!

K_T Jet Cross-Section

Data at the "hadron level"!

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



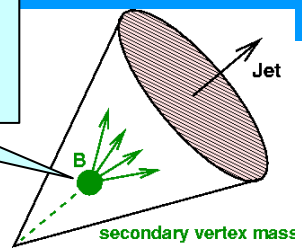
Theory and experiment agree very well! The KT algorithm works fine at the collider!

(see the talk by Regis Lefèvre)

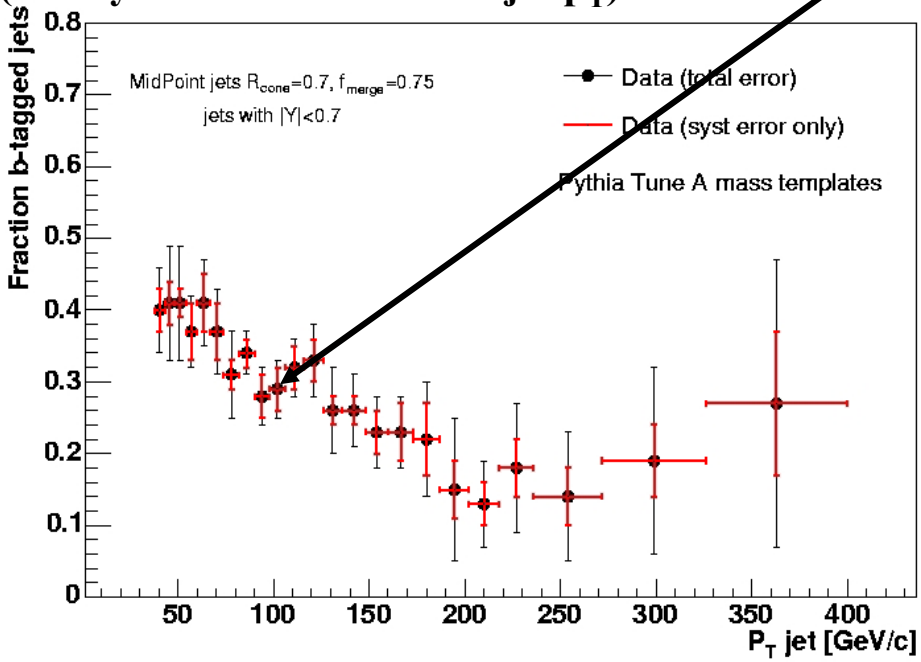
Correction factors applied to NLO theory!

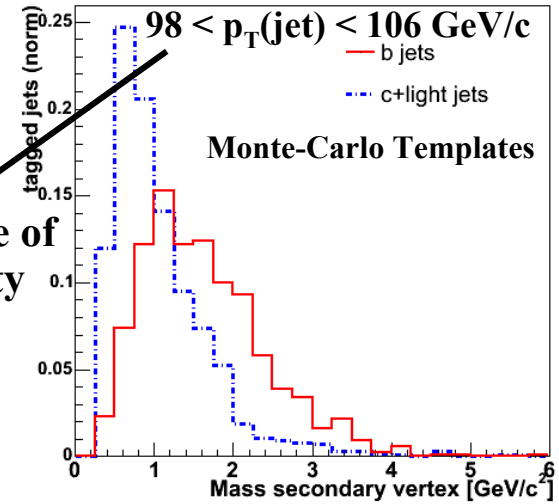
The b-Jet Cross-Section

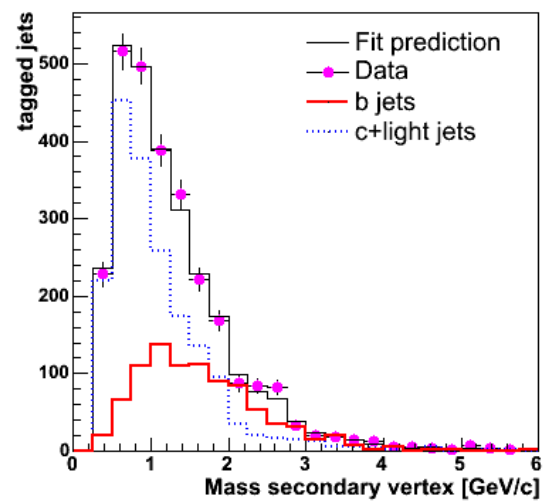
Construct the invariant mass of particles pointing back to the secondary vertex!



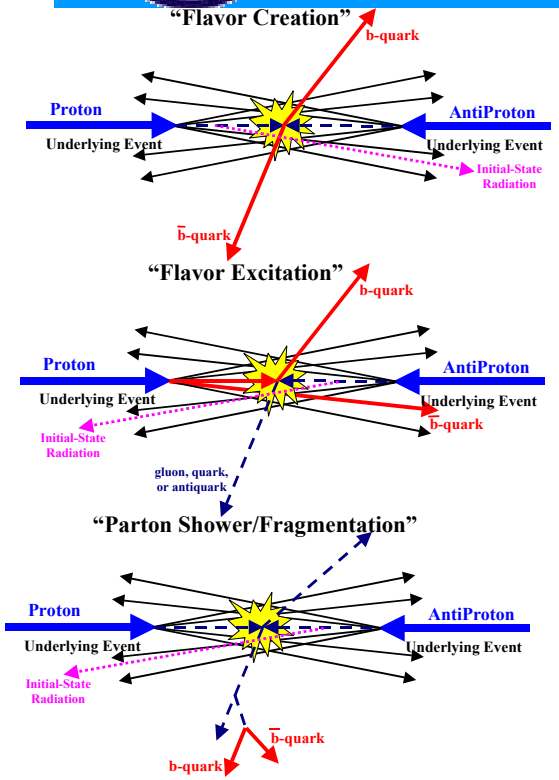
- Extract fraction of b-tagged jets from data using the shape of the mass of the secondary vertex as discriminating quantity (bin-by-bin as a function of jet p_T).

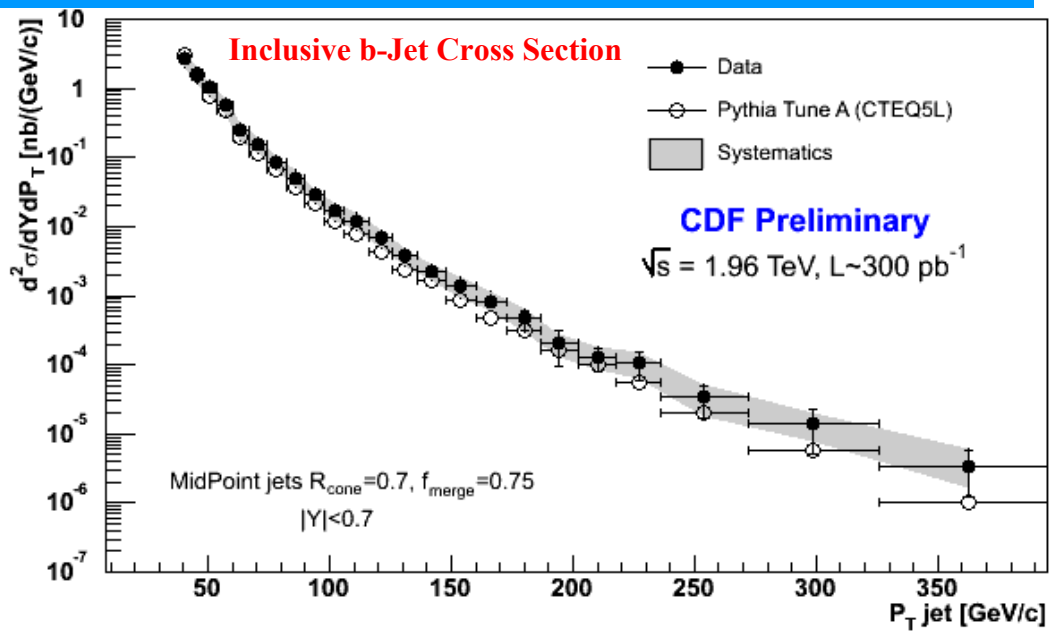


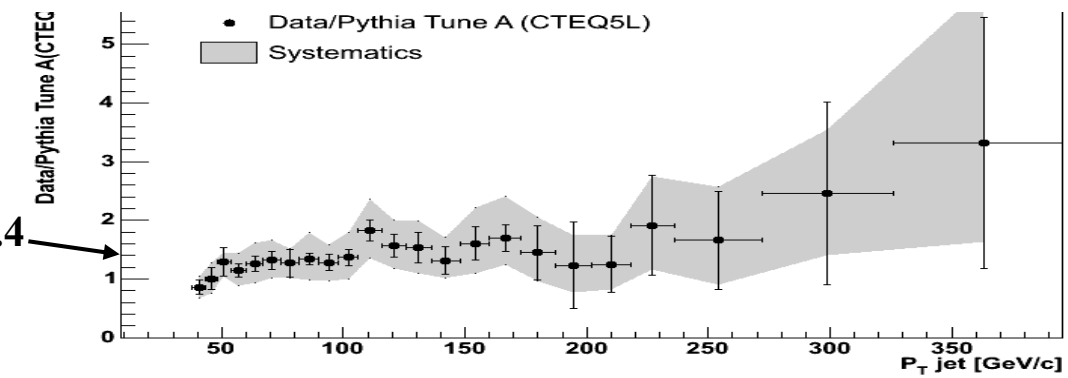




The b-Jet Cross-Section



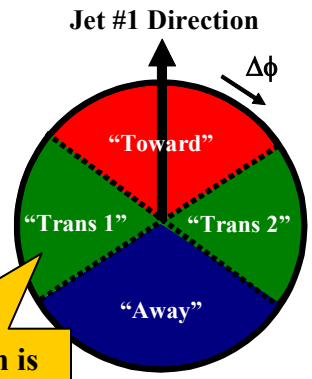




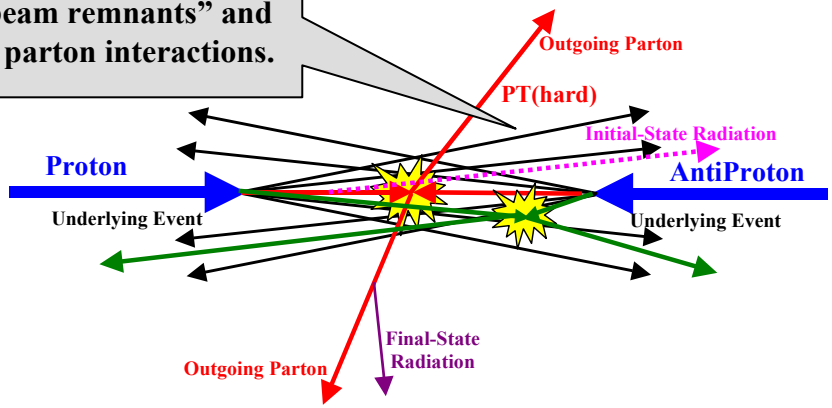
- **The data are compared with PYTHIA (tune A)! Data/PYA ~ 1.4**
- **Comparison with MC@NLO coming soon!**

The "Underlying Event" in Run 2 at CDF

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



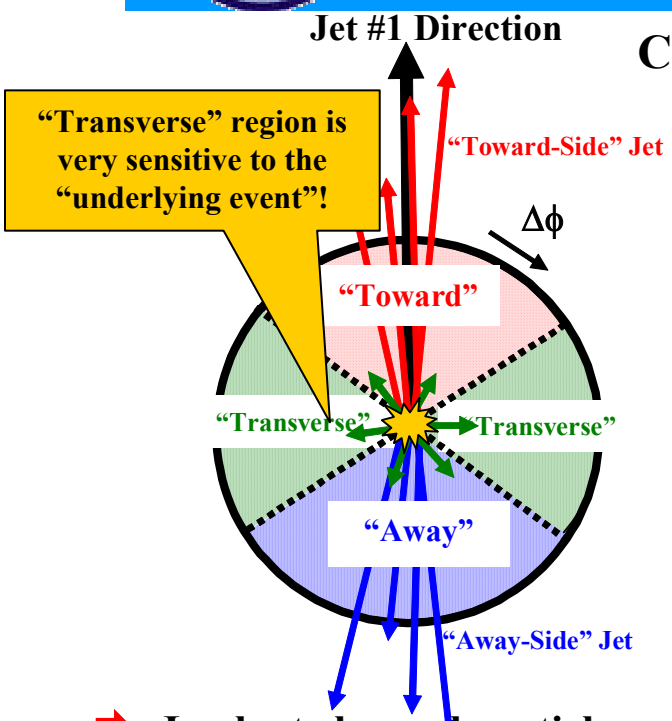
"Transverse" region is very sensitive to the "underlying event"!



CDF Run 2 results

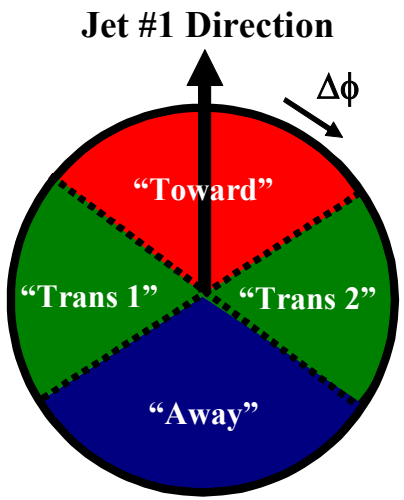
- **Two Classes of Events:** "Leading Jet" and "Back-to-Back".
- **Two "Transverse" regions:** "transMAX", "transMIN", "transDIF".
- **PTmax** and **PTmaxT** distributions and averages.
- **Δϕ Distributions:** "Density" and "Associated Density".
- **$<p_T>$ versus charged multiplicity:** "min-bias" and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

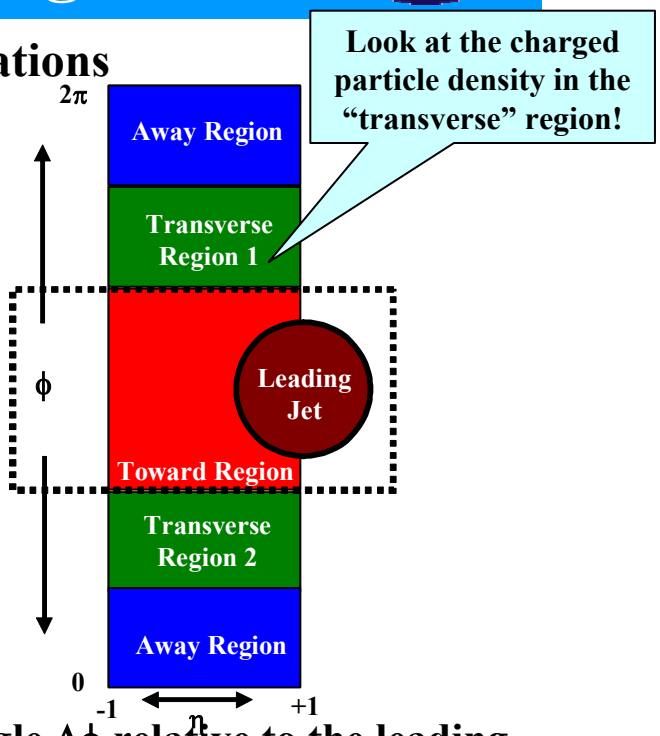
The "Transverse" Regions
as defined by the Leading Jet



Charged Particle Δϕ Correlations

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





- Look at charged particle correlations in the azimuthal angle Δϕ relative to the leading calorimeter jet (JetClu R = 0.7, $|\eta| < 2$).
- Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < -\Delta\phi < 120^o$ and $60^o < \Delta\phi < 120^o$ as "Transverse 1" and "Transverse 2", and $|\Delta\phi| > 120^o$ as "Away". Each of the two "transverse" regions have area $\Delta\eta\Delta\phi = 2x60^o = 4\pi/6$. The overall "transverse" region is the sum of the two transverse regions ($\Delta\eta\Delta\phi = 2x120^o = 4\pi/3$).

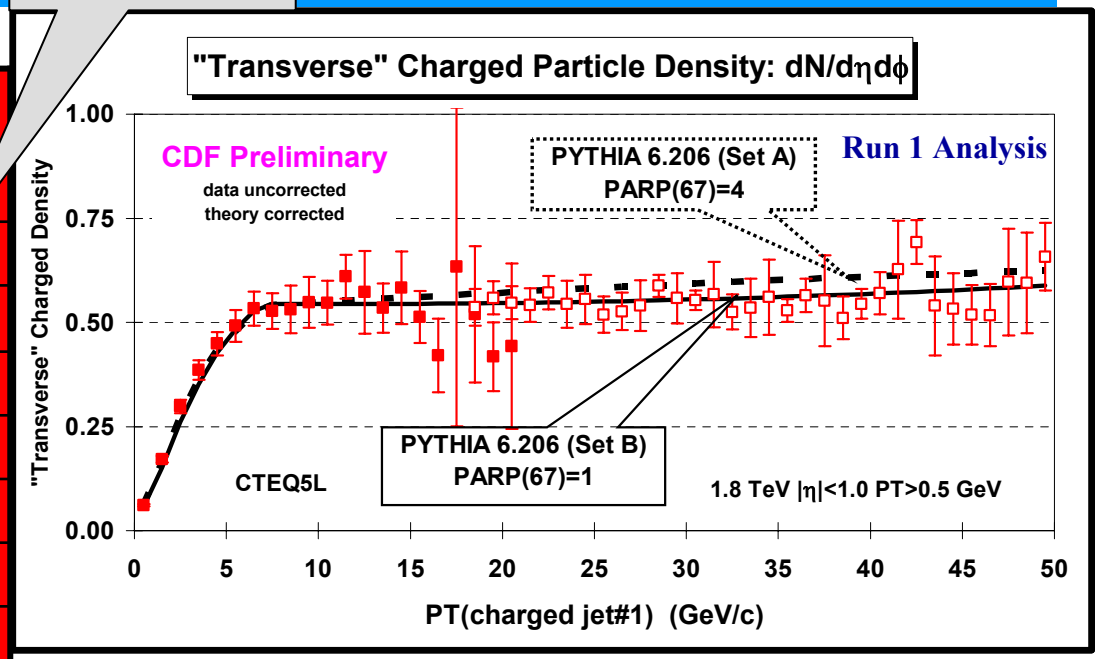
Tuned PYTHIA 6.206

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

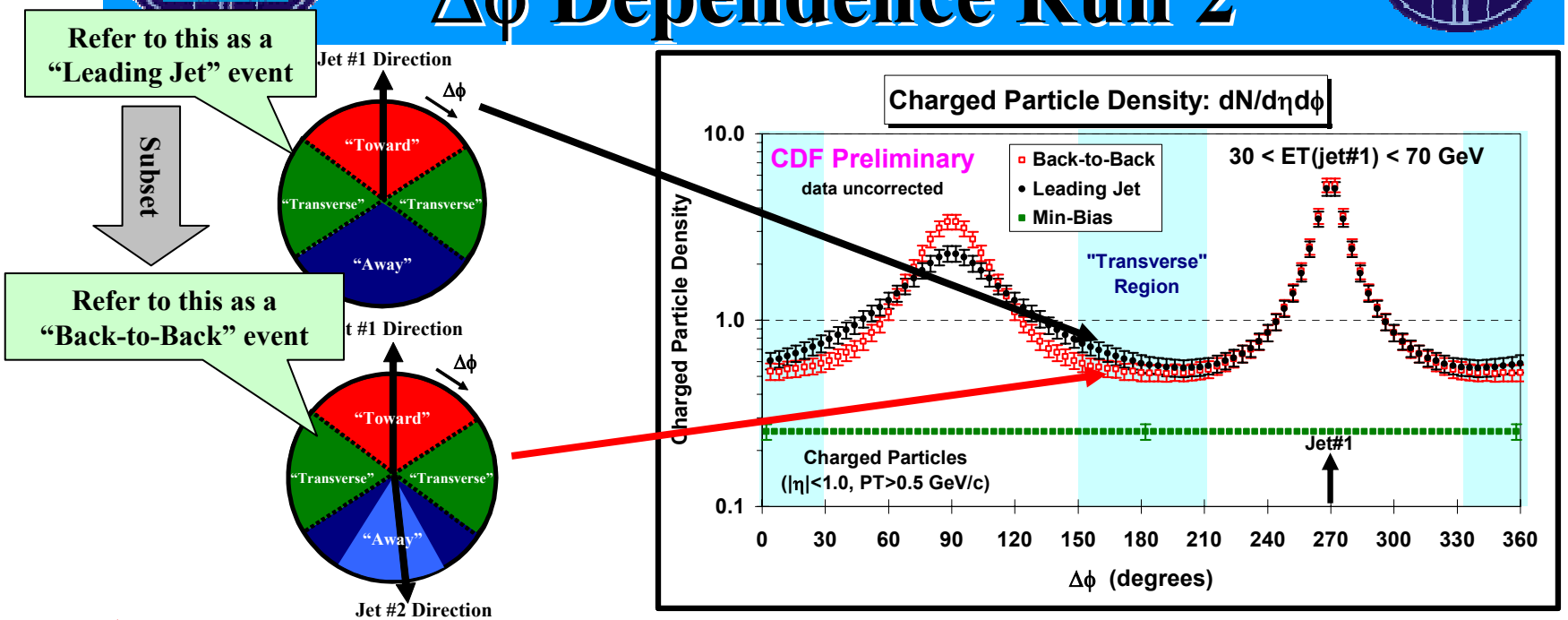
Double Gaussian

CDF Run 2 default



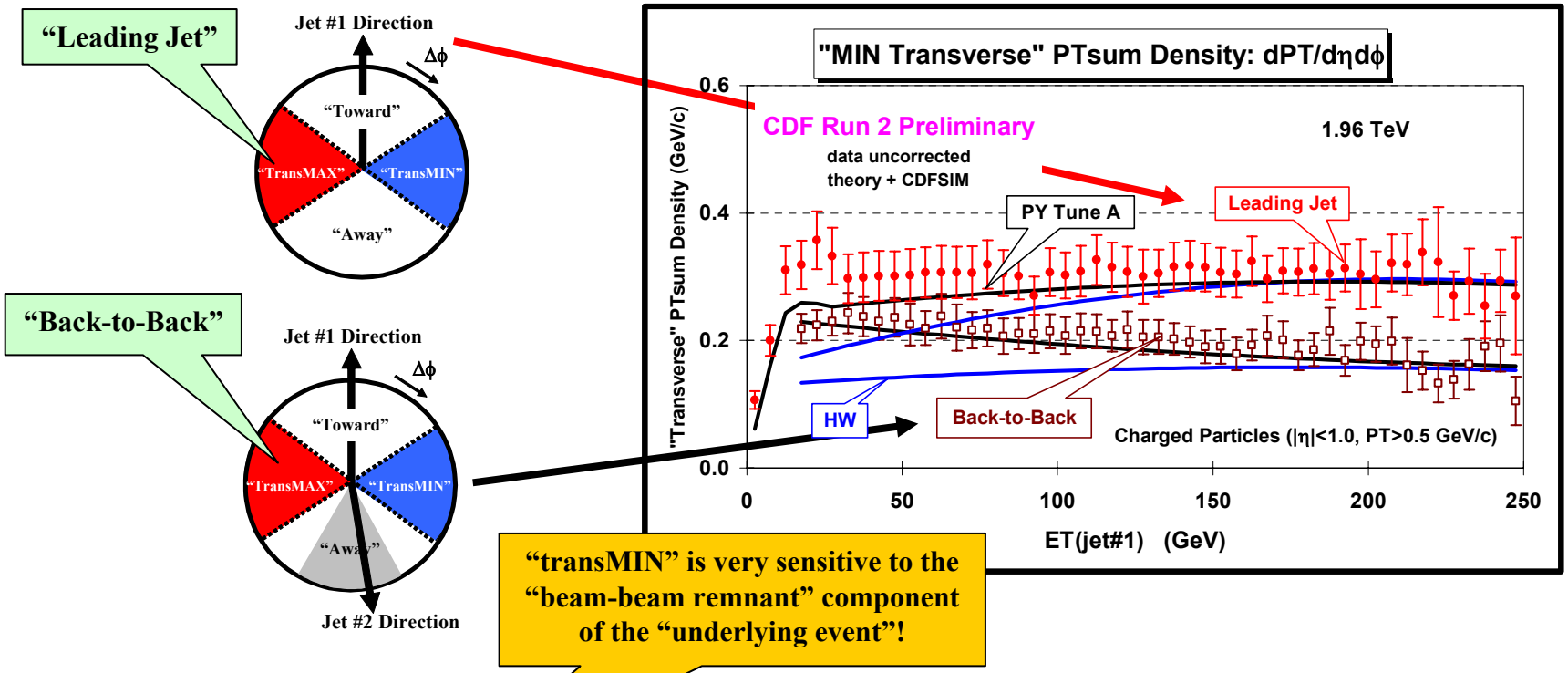
➡ **Plot shows the "Transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).**

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



- Look at the "transverse" region as defined by the leading jet (JetClu R = 0.7, $|\eta| < 2$) or by the leading two jets (JetClu R = 0.7, $|\eta| < 2$). "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 $|\eta| < 1$ relative to jet#1 (rotated to 270°) for 30 < E_T(jet#1) < 70 GeV for "Leading Jet" and "Back-to-Back" events.

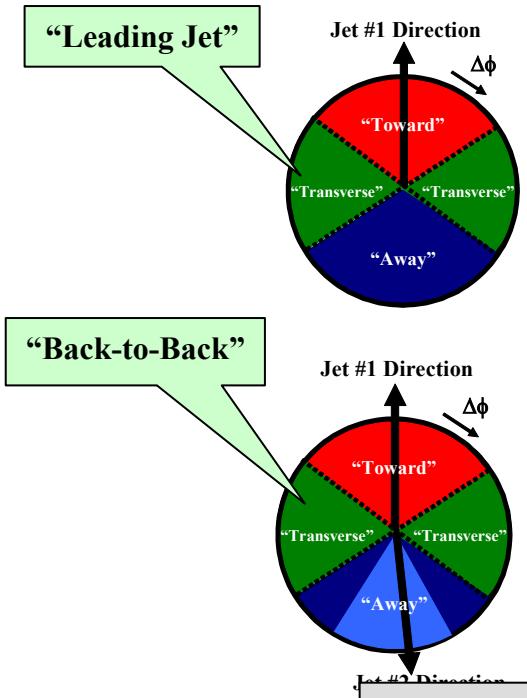
"TransMIN" PTsum Density versus E_T(jet#1)

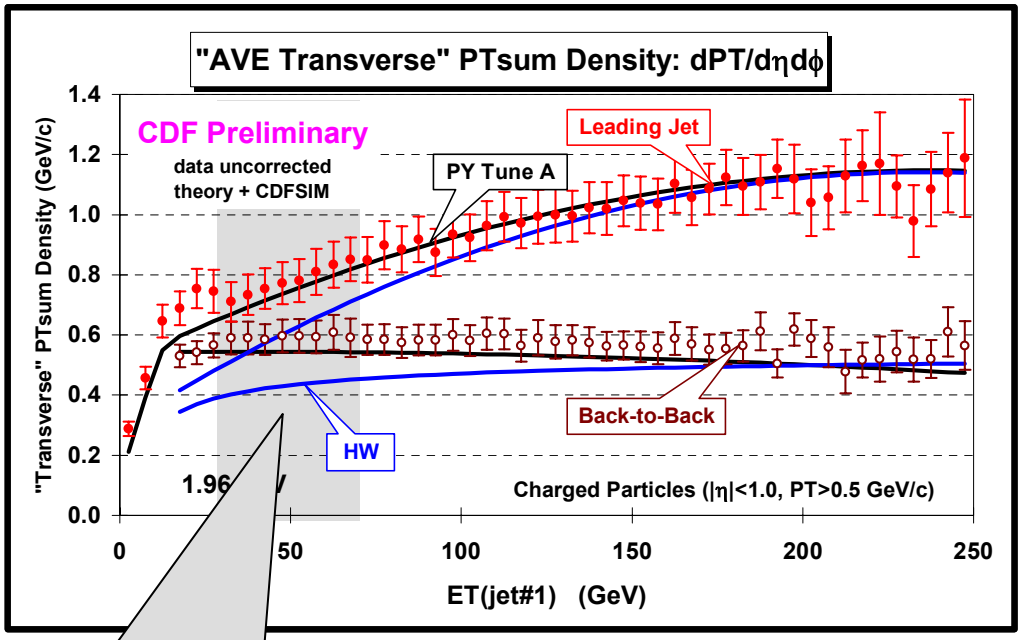


"transMIN" is very sensitive to the "beam-beam remnant" component of the "underlying event"!

- Use the leading jet to define 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



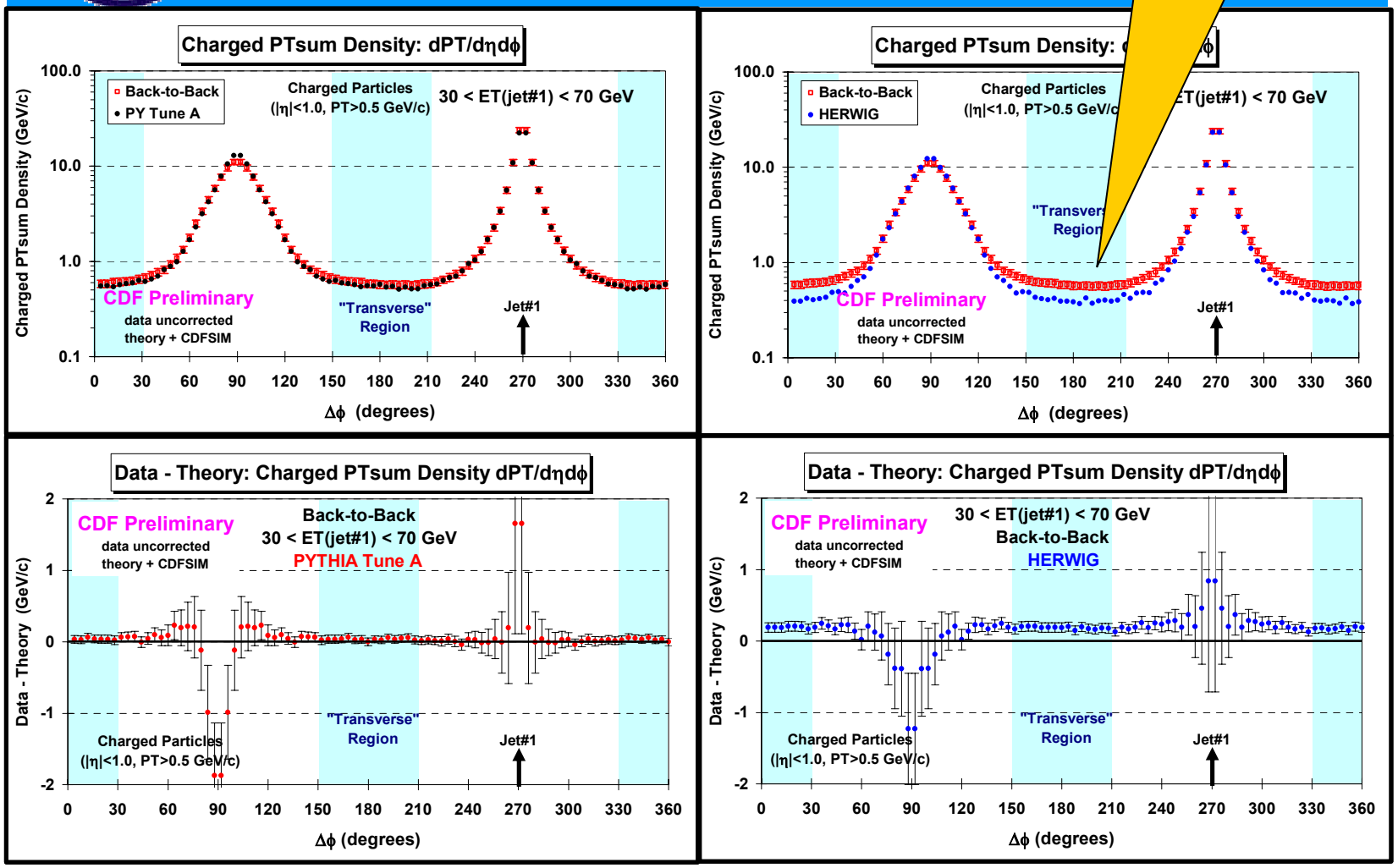


Now look in detail at "back-to-back" events in the region $30 < E_T(\text{jet\#1}) < 70$ GeV!

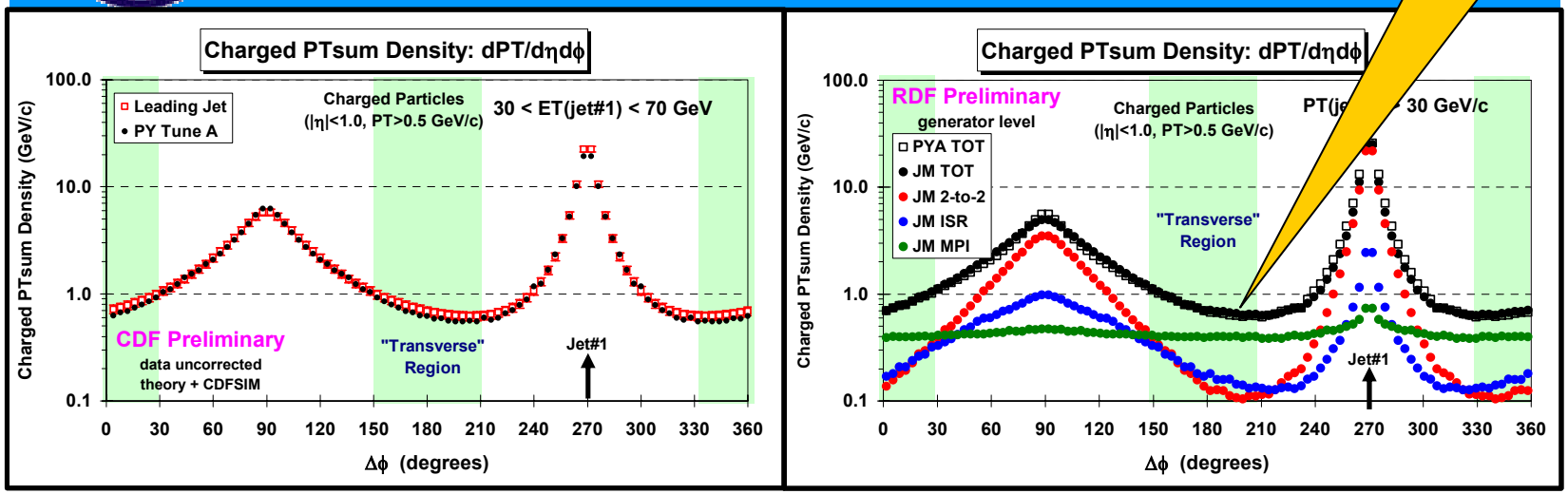
- Shows the average charged PTsum density, $dPT_{sum}/d\eta d\phi$, in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus E_T(jet#1) for "Leading Jet" and "Back-to-Back" events.
- Compares the (*uncorrected*) data with PYTHIA Tune A and HERWIG after CDFSIM.

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!



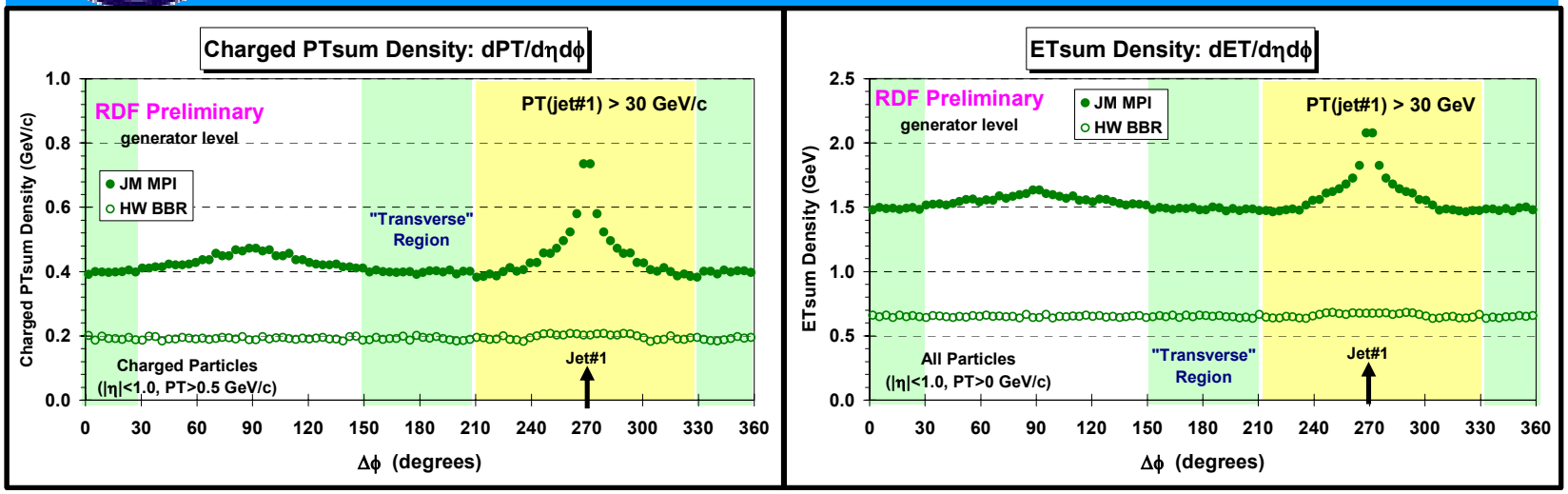
Tuned JIMMY versus PYTHIA Tune A



JIMMY tuned to agree with PYTHIA Tune A!

- (*left*) Shows the Run 2 data on the Δϕ dependence of the charged *scalar* PTsum density ($|\eta|<1$, $p_T>0.5$ GeV/c) relative to the leading jet for $30 < E_T(\text{jet\#1}) < 70$ 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 ($|\eta|<1$, $p_T>0.5$ 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.

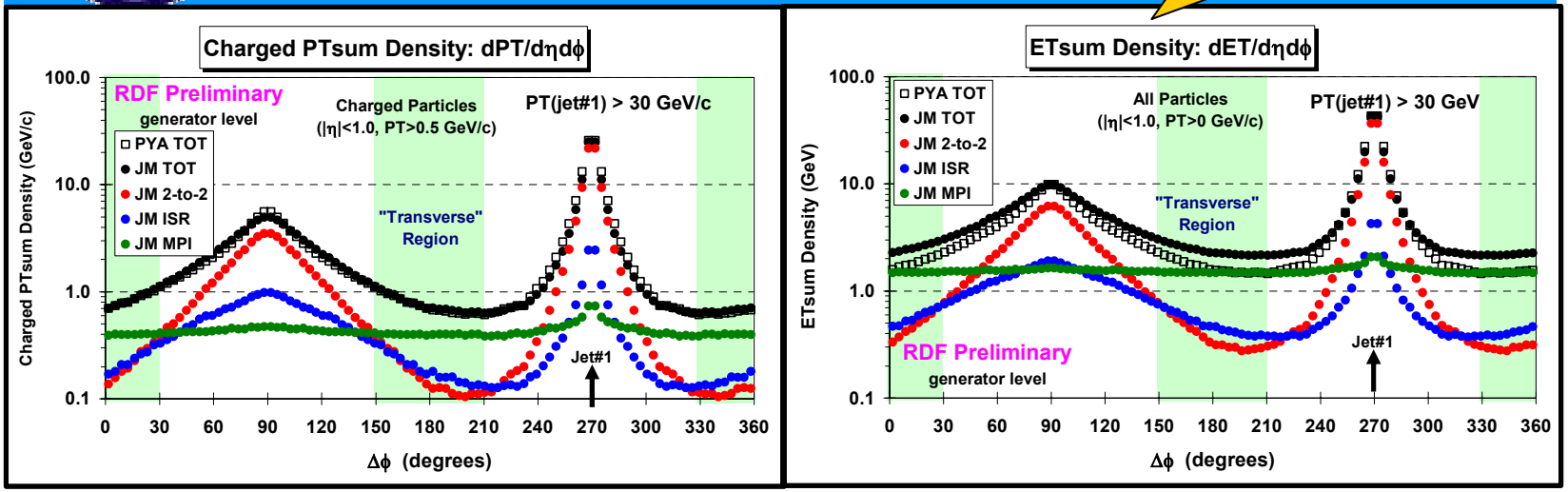
JIMMY (MPI) versus HERWIG (BBR)



- (*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 (|η|<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 (|η|<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

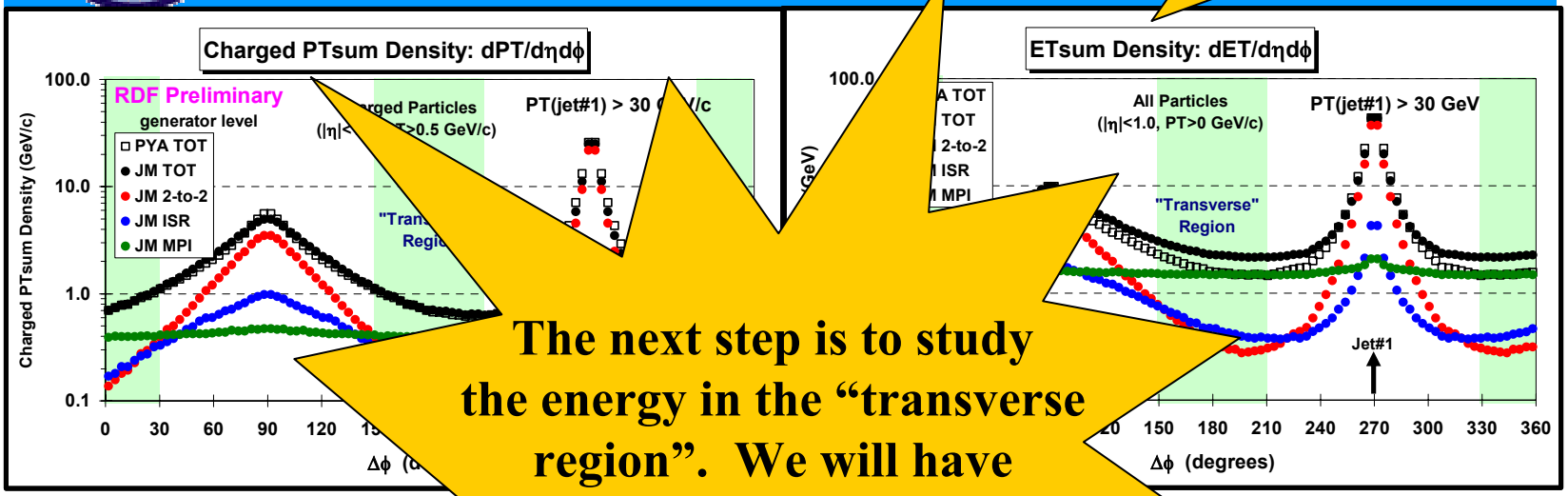
Tuned JIMMY produces more ETsum than PYTHIA Tune A!



- (*left*) Shows the generator level predictions of PYTHIA Tune A and JIMMY (PT_{min}=1.8 GeV/c) for the Δϕ dependence of the charged *scalar* PTsum density (|η|<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 Δϕ dependence of the *scalar* ETsum density (|η|<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 JIMMY (PT_{min}=1.8 GeV/c) for the Δϕ dependence of the *scala* ETsum ty (|η| >0) relati to the leading jet for P_T(jet#1) > 30 GeV/c.
- The tuned JIMMY produces a lot more sum (p_T>0) in the "transverse" region than does PYTHIA Tune A!