Jet Energy Scale at CDF

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The Rockefeller University
Hadron Collider Physics Symposium
July 4-9 2005
Les Diablerets, Switzerland

Introduction
Procedure to determine Jet Scale
Systematic Uncertainties
Cross Checks and Current limitations
DiJet Resonances
Inclusive Jet Cross Section
Conclusions

Jets at Hadron Colliders

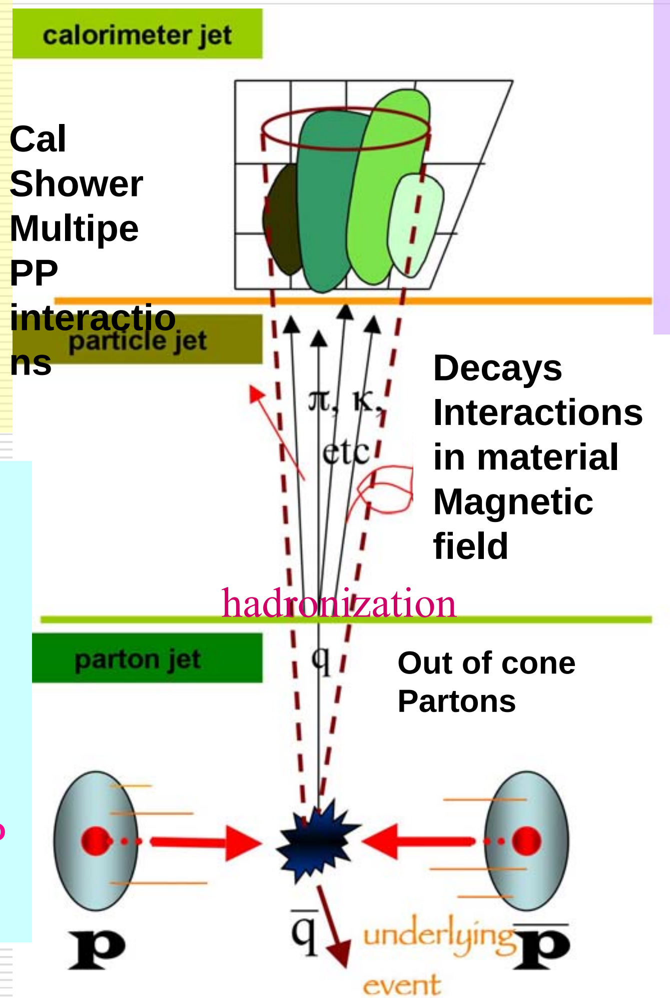
Jets are complex objects, defined by an algorithm and measured with a calorimeter.

Complex detector properties

- non-linear response hadron
- different response to electrons and hadrons
- non-instrumented regions
- larger fluctuations in deposited energy
- some of the particles do not reach calorimeter

Complex physics

- spectator interaction energy
- partons radiate initial and final state gluons
- energy from different ppbar interactions
- different parent partons: light quarks, gluons, b/ c
- large fluctuations in neutral to charged particles
- fluctuations in OOC energy



Clustering Algorithms (cone, cone-midpoint, KT)

- stable with various jet fragmentation/shapes (infra red safe
- reproducible in theory calculations
- able to separate two close-by jets
- boost invariant
- capture reasonable amount of jet energy

Need to correct for detector, (algorithm?) and physics effects to obtain the "true" energy of the jet/parton:

Different criteria for mass measurement, resonance searches, cross section measurement.

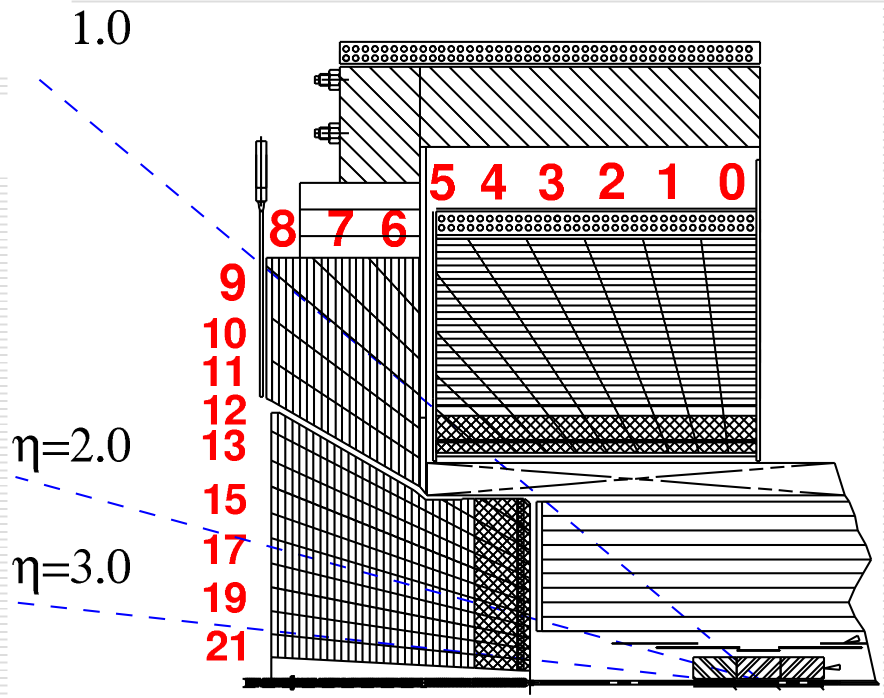
Steps in Jet Energy Correction

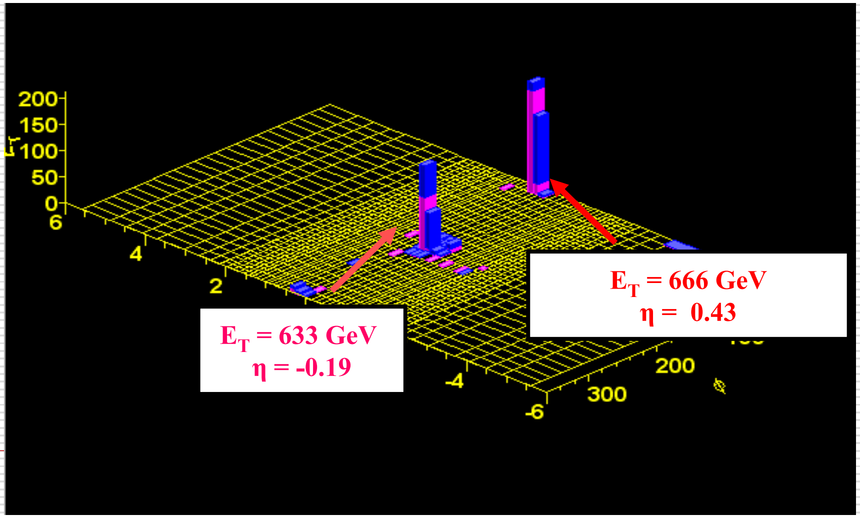
$$P_T(R) = \left[P_T^{raw}(R) \times f_{rel} - UEM(R)\right] \times f_{abs}(R) - UE(R) + OOC(R)$$

- **(f_{rel}) Relative Corrections**
  - Make response uniform in η
- **(*UEM*) Multiple Interactions**
  - Energy from different ppbar interaction increases jet energy
- **(f_{abs}) Absolute (Calorimeter-to-Particle) Corrections (central region)**
  - Calorimeter is non-linear and non-compensating
- **(*UE*) Underlying Event**
  - Energy associated with the spectator partons in a hard collision
- **(*OOC*) Out-of-Cone (Particle-to-Parton)**
  - It is an attempt to determine "parent parton energy"
    (Most analyses determine it in their environment/definitions)
- **Systematic uncertainties at each step:**
  - Differences between Monte Carlo and data: since we use Monte Carlo (generators, CDF simulation) we need to treat jets in data and in Monte Carlo on equal footing
  - Uncertainties from the method used to obtain the corrections.

CDF Calorimeters

- Scintillating tile with lead/iron absorbers $|\eta|<3.6$:
- CEM(18 X0) CHA (4.7 λ)
- PEM(21 X0) PHA (7 λ)
- Projective Towers $\Delta\eta\sim0.11, \Delta\varphi=2\pi/24$ (central)
  Variable in plug calorimeter
- Non-linear response to hadrons
- Linear response to electrons
- Coarse granularity (R=0.7 jet covers 53 towers in central region). Hadron shower mostly in 3x3 towers in central region.
- Very low noise: 1/1248 towers per event has Et>50 MeV.





Electrons: $\sigma_E / E = 13.5\% / \sqrt{E}$ **(central)**

$\sigma_E / E = 16\% / \sqrt{E}$ **(plug)**

Charged Pions $\sigma_E / E \sim 80\% / \sqrt{E}$

Jet Scale Determination

- Measure energy observed in calorimeter for a known momentum particle in situ and/or in test beam
- Calibrate/tune the simulation to reproduce the calorimeter response.
- Use a fragmentation model (Pythia Tune A) which reasonable describes Pt spectrum of particles within a jet.
- Use simulated dijet events to derive calorimeter → particle jet corrections.

Use di-jet events to make jet energy scale uniform in η using Pt balancing.
(Scale all non-central jets such that they can be treated as the same as central.)

Pile up is measured from MinBias data, consistent with Jets/W-boson Data
~ 1GeV per interaction (extra vertex) for R=0.7

•The "parton" energy correction is derived using Shower Monte Carlo.
•Underlying event: We use Pythia Tune A which is tuned to CDF DiJet data.

Cross check the energy scale using photon-jet and Z-jet data.

Calorimeter Simulation

CDF Run II simulation is based on GEANT 3 but calorimeter simulation uses parameterized response (Gflash from H1). GEANT propagate particles up to the first inelastic interaction in the calorimeter. After first interaction Gflash simulates the shower.

- For longitudinal shower, use Γ distribution

  Photon and electrons one distribution

  Hadron: Longitudinal shape is described by 3 shower profiles

  a) Purely hadronic shower (depends on λ)

  b) PiZero produced in first interaction (depends on X0)

  c) PiZero produced in subsequent interactions (λ)

$$\mathbf{f(z)} = \frac{(\beta \mathbf{z})^{\alpha-1} \mathbf{e}^{-\beta \mathbf{z}}}{\Gamma(\alpha)}$$

- Transverse shape is given by:

$$\mathbf{g(r)} = \frac{2\mathbf{r}\mathbf{R}_0^2}{\mathbf{r}^2 + \mathbf{R}_0^2} \qquad \int_0^\infty \mathbf{g(r)dr} = 1$$

$$\langle \mathbf{R}_0(\mathbf{E}, \mathbf{z}) \rangle = [\mathbf{R}_1 + (\mathbf{R}_2 - \mathbf{R}_3 \log \mathbf{E})\mathbf{z}]^{\mathbf{n}} \qquad n = 1, 2$$

  Free parameter R_0 depends on shower energy E and the depth z.

- The parameters (not all) are tuned to CDF isolated tracks and test beam data.
- Energy deposition depends on hadron-type (π,K,p,pbar ..).
- Gflash simulate “energy spots” in 3 dimensions. Spots are summed according CDF tower structure.

Special treatment for tower boundaries, based on ppbar /test beam measurements.

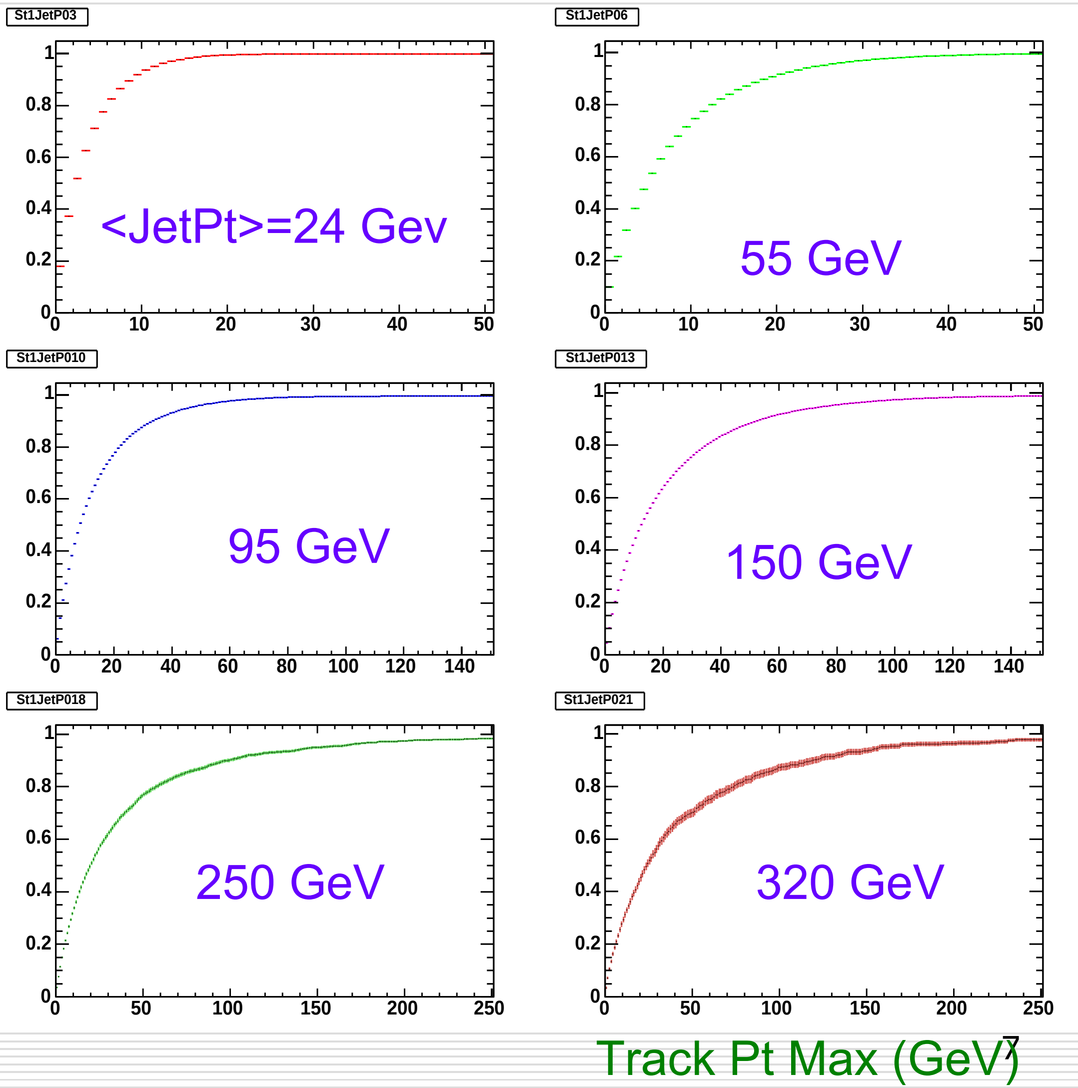
Fraction of Jet Pt in particles with Pt<PtMax

How high in Pt we need to tune simulations?

ΣPt (Pt<PtMax)/ΣPt(all)

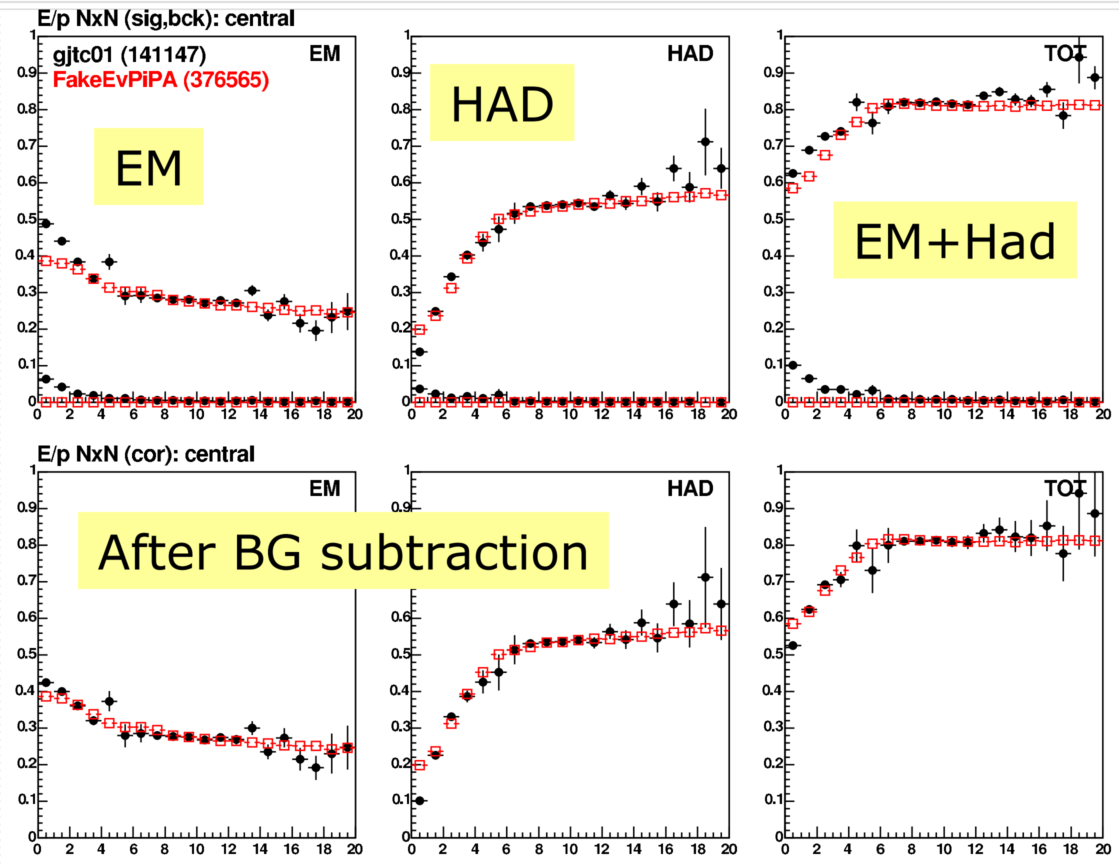
Use reconstructed tracks in CDF Jet data in cone R=0.7 around calorimeter jet axis. No tracking efficiency corrections used for this plot. (tracking eff. in jets ~97%)

For 95 GeV jet ~80% of energy is in charged particles with Pt<20 GeV or in neutral pions/photons.



Charged Pion E/p Measurement

- MinBias or isolated track trigger
- Select good tracks within 81% of tower.
- No extra track within 7x7 towers, no ShowerMax cluster.
- Signal: 4 em+9 had towers
- Measure E/p in data
- Tune Gflash params.
- Difference in data and simulation is taken as uncertainty.

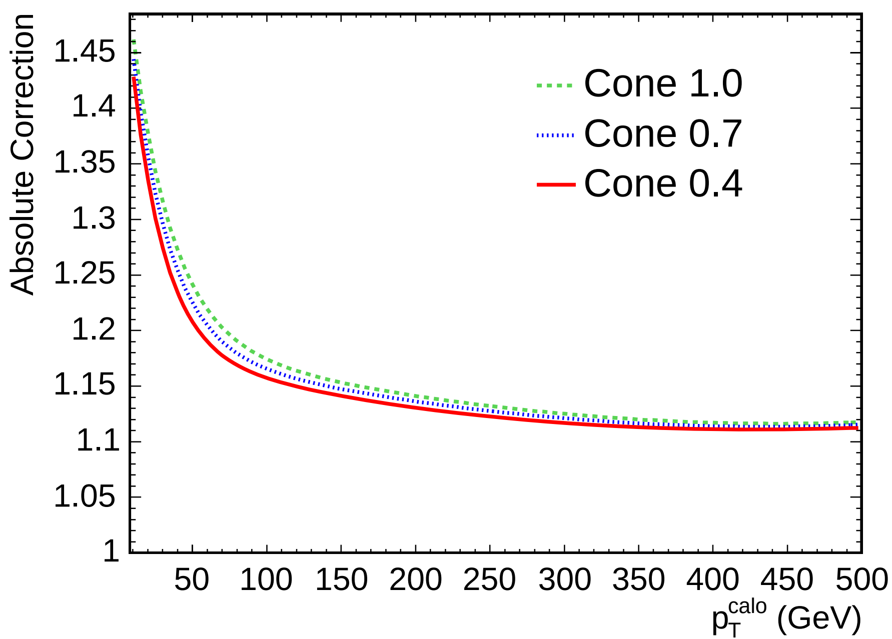


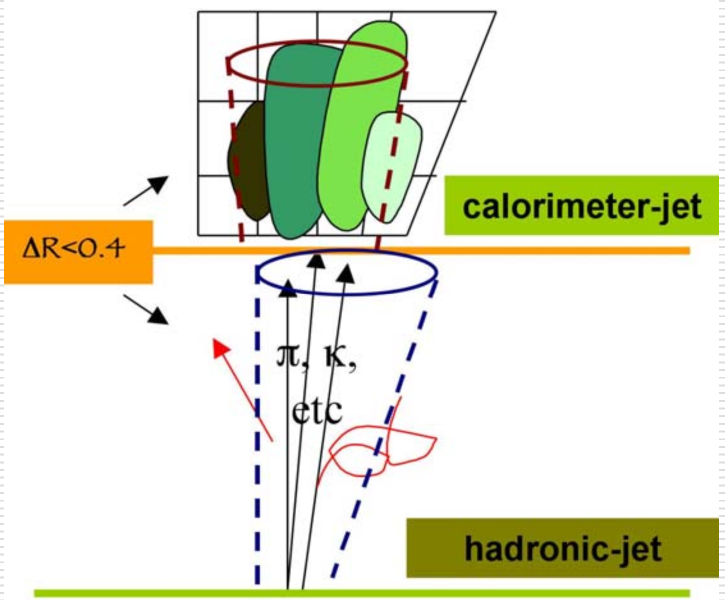
For Pt>20 GeV, we still use Test Beam (1985/90) calibration data.

We are working on extending the Pt range of in-situ calibration

Hadron-level Corrections (Absolute)

- The corrections are calculated using two leading jets in PYTHIA dijet events (0 - 800 GeV).
- Map the calorimeter jet P_T to the particle jet P_T and obtain the probability of observing P_T^{Cal} when P_T^{Had} was produced. Use Most Probable Value as the correction.



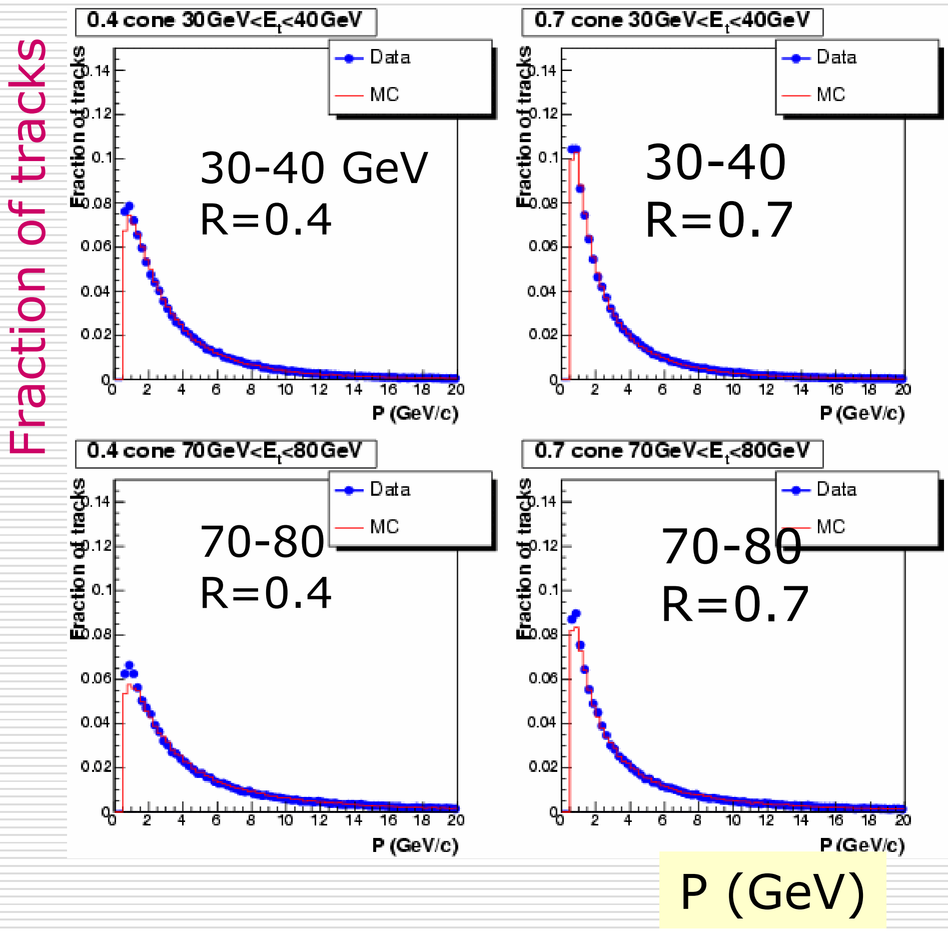


Corrections for FLAT input spectrum.
Addition correction needed to unsnear.

After this correction, jets are independent of the detector.

Jet Fragmentation

- If E/p was flat, uncertainty in Pt spectrum of particles in the jet will not lead to any uncertainty in energy scale.
- Momentum distribution of charged tracks distribution in data and Pythia MC agree except at low momenta.
- However, for same measured jet , total energy carried by charged tracks is different in data and Pythia (~a few %).
- Pythia/Data scale differ by <1% for 20-220 GeV jets. Take as systematic uncertainty.
- HERWIG and Pythia agree to better than 1%.



Uncertainty on Absolute Jet Energy Scale

- CALORIMETER SIMULATION

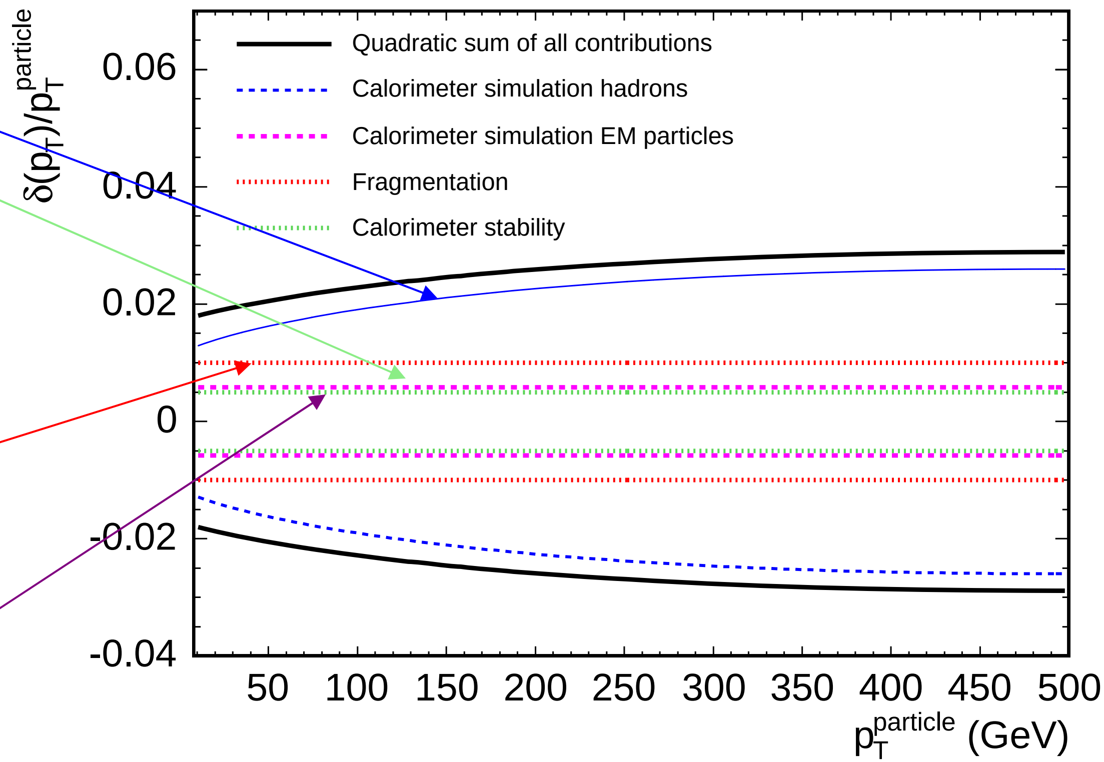
  Is the response of the calorimeter to single particles (pions, protons, neutrons, etc) simulated correctly?

- FRAGMENTATION(1%)

  Does the Monte Carlo describe the particle spectra and densities at all Jet E_T

- STABILITY (0.5%)

  Calorimeter scale variation with time

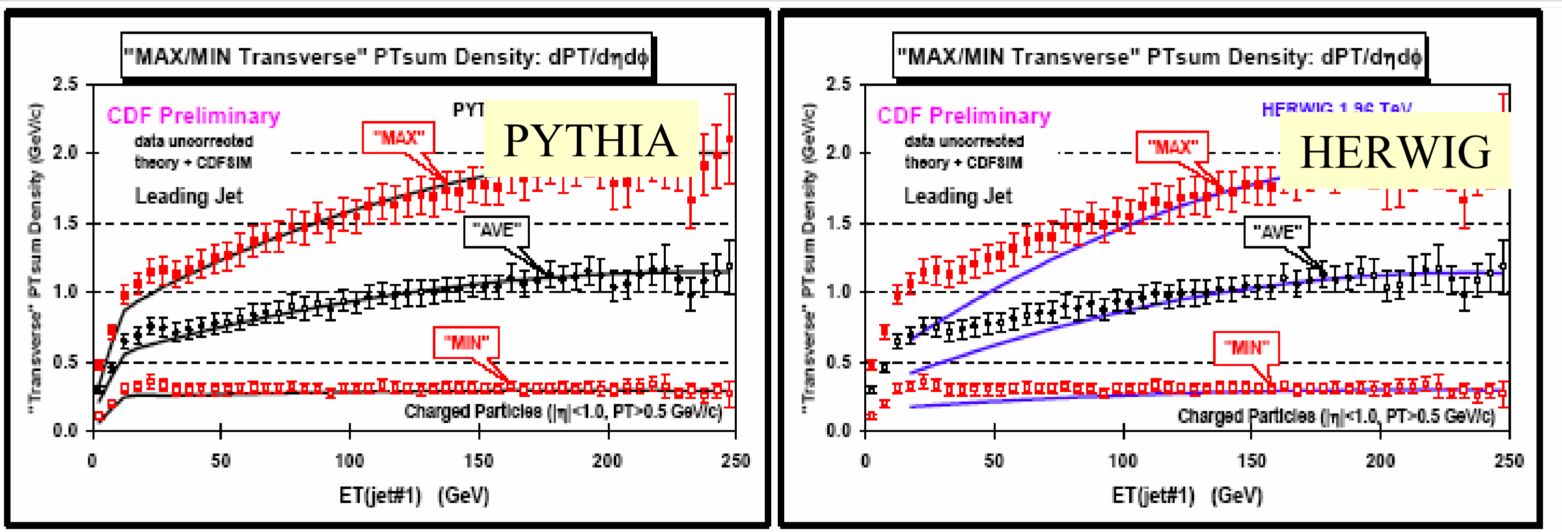


Using test beam data P_T regions (relatively large uncertainty), important for high P_T jets

Correcting for physics effects

Remove energy not associated with the hard interaction

- Subtract the energy from underlying event and multiple ppbar interactions
  - Measure energy in a cone of R in minimum bias data
  - Subtract mean value of the distribution.
  - Multiple ppbar correction is based on number of reconstructed vertices.
- Pythia UE has been tuned to data. Herwig UE seems too small. Currently, we (Rick Field) are tuning Jimmy (Herwig ad-on UE model) to CDF data.



PTsum density for "leading jet" events versus E_T(jet#1) for PYTHIA Tune A and HERWIG.

Alison Lister's talk

Parton-level Corrections (Out of Cone)

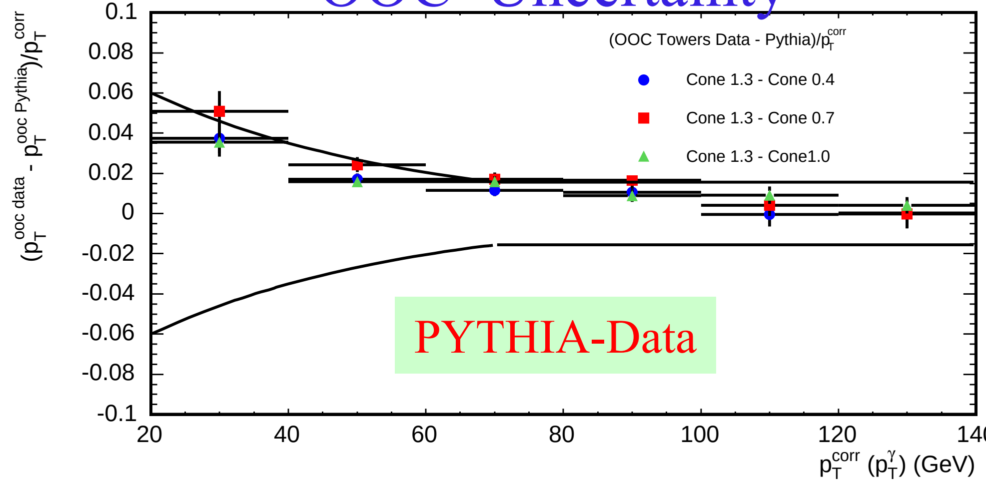
Add energy from particles/partons outside the jet.

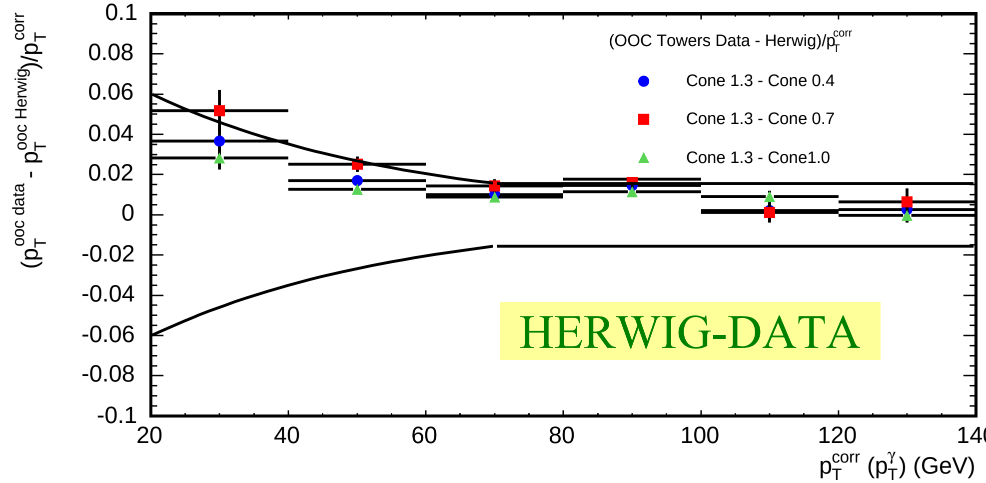
- Correction obtained by matching particle-jet with the parton in Pythia DiJet event.
- Applied only in some physics analysis. Many analyses determine corrections from their samples.
- The uncertainty is the difference in energy outside jet cone(R→1.3) between data and MC in photon+jet events.

Need to improve MC generators /simulation

OOC Uncertainty

Photon-jet

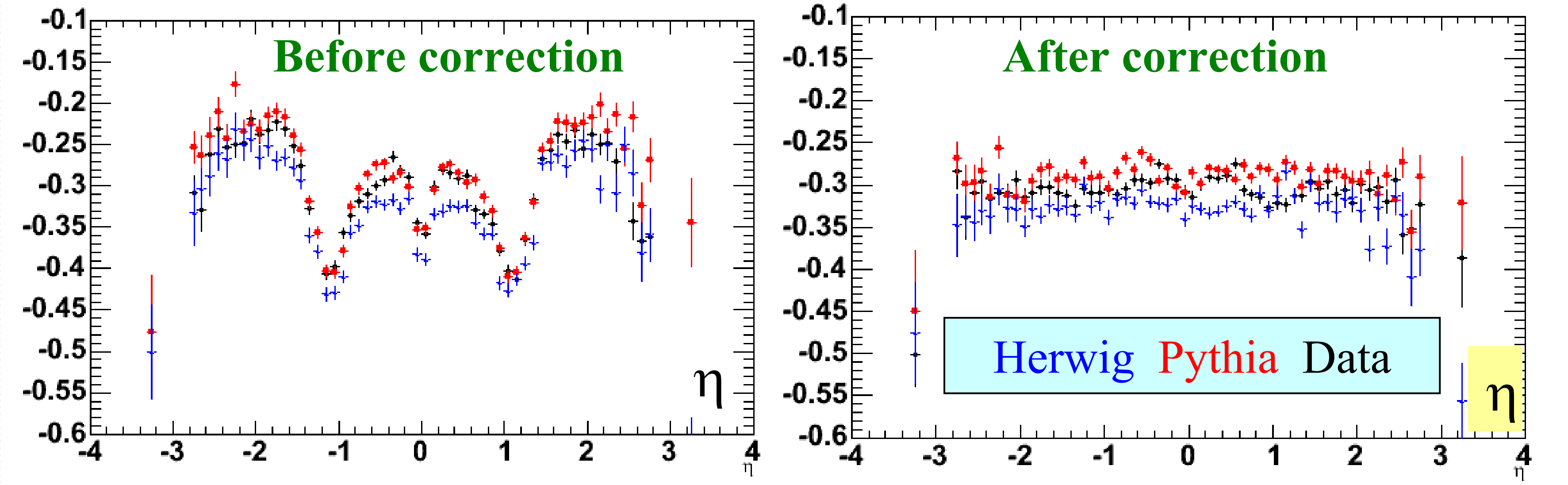




Non-central Jets

- Pt-balance in DiJet events to scale the response of jets outside 0.2<|η|< 0.6 to jets to well understood jets within.
- This method corrects for non-uniformity of calorimeter response, shower leakage outside the clustering cone and η dependence of OOC, if any.
- Two corrections: one for data and another for MC (based on PYTHIA)

Photon+jet balance P_T^{jet}/P_T^{γ} -1 as a function of η



After this correction, non-central jets are treated just like central jets.

Systematic Checks

- γ-Jet:
  - highest statistics
  - systematically limited (kt-kick, BG contributions: π^0)
  - Not available for E_T<25 GeV (trigger), currently up to 140 GeV
- Z-Jet:
  - Usable at lower E_T values than γ-Jet
  - lower statistics than γ-Jet at high P_T
- Z→bb: (working on it)
  - Nice to have calibration peak
  - Only for b-jets and difficult to trigger
  - Small signal on large background
- W→jj in b-tagged top events:
  - Expect 250 double-b-tagged top events in 2/fb ➔ 1-2 % precision? ☺

But none of them can test jets with E_T>150 GeV to 2%

Current limitations

- Not enough isolated tracks at high enough momentum. We are implementing a better trigger with higher bandwidth. We are working on improving calorimeter simulation.

- Physics simulation of photon-jet data. Data, Herwig and Pythia disagree to 2-3% in photon-jet balancing. This discrepancy may dominate the systematic uncertainty in future. Photon-jet balancing depends on second jet cut differently for three samples.

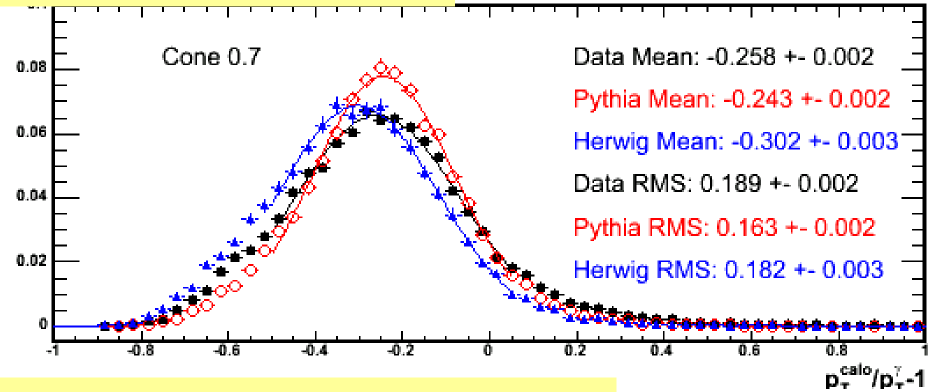
- Current Out-of-cone systematic comes from data/Pythia/Herwig difference. Again improved physics generator/simulation will help.

Photon-Jet Balancing

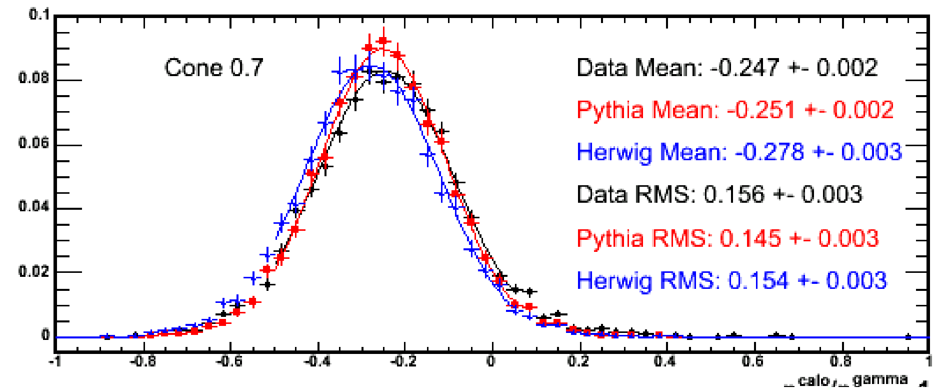
- Good sample to test as photon energy is well measured and simulated.
- However, the results depend on the event selection cuts e.g. second jet P_T and opening angle.
- With tight selection cuts data, Pythia, HERWIG and data agree to ~1-2%.
- Based on jet fragmentation studies, we expect ~1% difference. Rest is probably due to radiation.

Herwig	Pythia	Data
-0.302	-0.243	-0.258

Δφ> 3, No 2nd jet cut



Δφ>3 , second Jet Pt<3 GeV



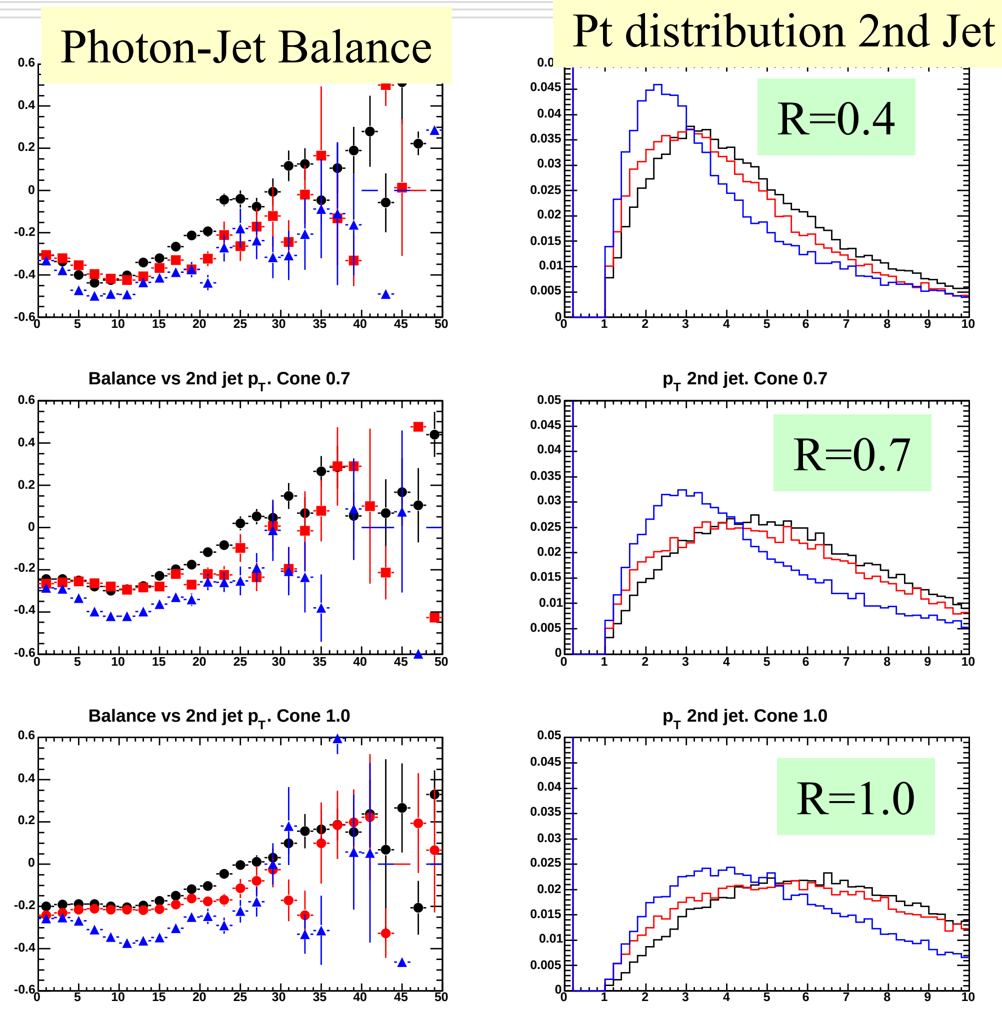
Herwig	Pythia	Data
-0.278	-0.251	-0.247

$$P_T \text{ balance} = \frac{P_T^{jet}}{P_T^{\gamma}} - 1$$

Second Jet Activity in γ-Jet

Herwig Pythia Data

- Herwig, Pyhtia and data have very different second jet activity.
- Photon-jet balancing depends on the second jet cut.
- Need to understand better which generator is better.
- The difference may not be universal but we do see some differences in DiJet sample also.



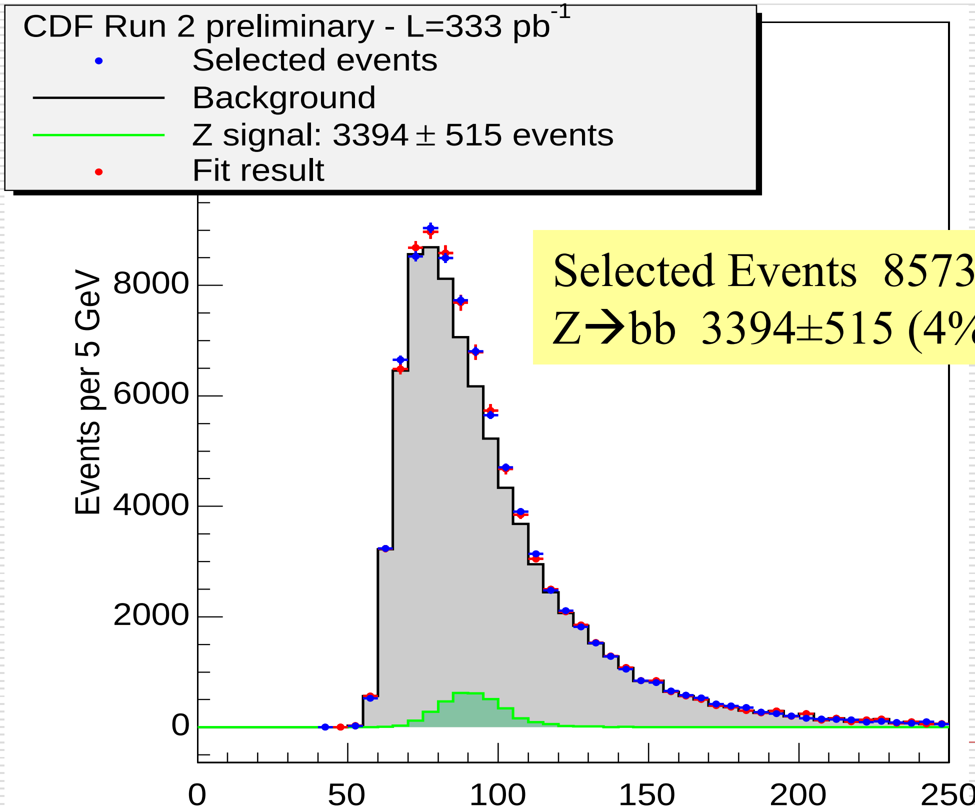
Pt of Second Jet

Comments on CDF Procedure

- CDF procedure demands a very accurate simulation of calorimeter showers and good understanding of underlying physics. It requires a detailed understanding of material in tracking volume, calorimeter response to single particles as well as particle Pt spectrum in jets (good knowledge of track reconstruction efficiency in high multiplicity environment). It is a lot of work but at the end we are confident about energy scale.
- Ensuring good simulation implies that simulated data can be directly compared with real data in the variable of one's choice (e.g. size of τ Jet).
- Easy to build upon to improve jet resolution.
- Same procedure valid for all Pt Jets, even at 500 GeV jets.
- The procedure depends only on jet/calorimeter simulation and is independent of extra radiation in the event.
- Various stages of corrections allow users to do analysis at calorimeter-level, particle-level, particle-level after UE subtraction, parton-level, depending on physics question.

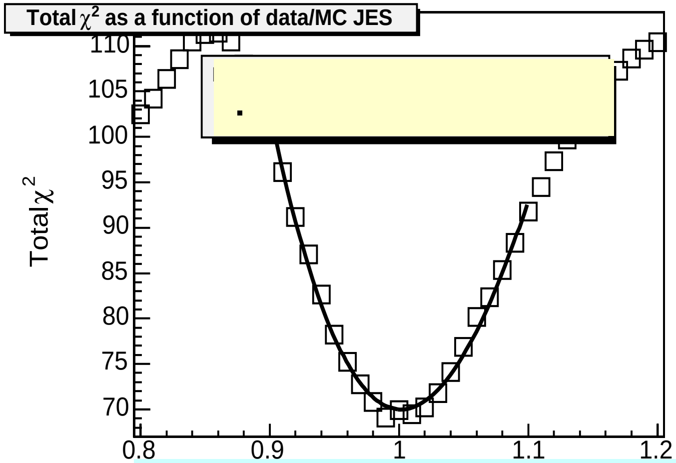
Extraction of $Z \rightarrow b\bar{b}$ signal

- b-jet energy scale, tools to extract DiJet mass resonances (H→bb)
- Good signal to study/improve/confirm jet resolution
- Trigger on two displaced tracks+ two 10 GeV jets $\mathcal{L} = 333\ pb^{-1}$, **21.5 M events**
- DisplacedVertex tag, SecondryVertex Mass to select b-jets, kinematic cuts to improve S/B
- **Fit signal and background (direct QCD production) templates**, for varying JES



DiJet Invariant mass GeV

Selected Events 85730
Z→bb 3394±515 (4%)



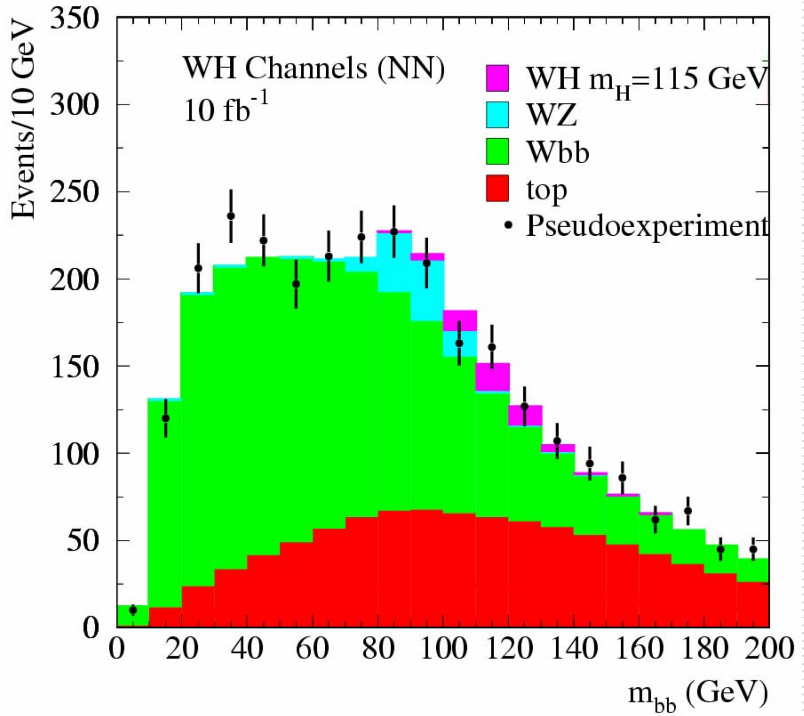
Data/MC Relative b-jet-scale

Further Studies:
Evaluate systematic biases, if any
Improve Z→bb modeling
Aim 1% b-jet energy scale (10k Z→bb)

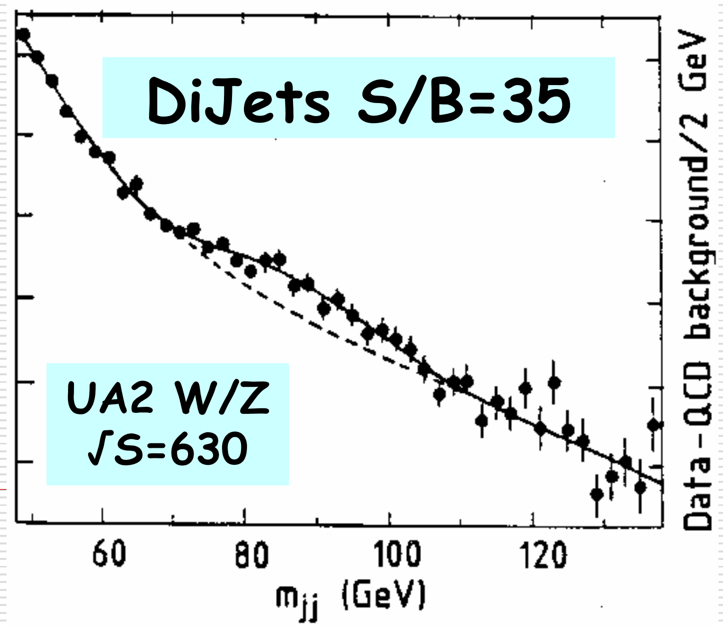
Why Hadronic γ+W/Z

Want to reconstruct hadronic mass peak

- Techniques/tool to extract dijet resonance signal
- Jet energy resolution and jet energy scale studies
- S/√B in inclusive DiJet sample too small at √1960 GeV.
- Use W/Z (→qq) +Photon



Photon+SumEt Trigger to cover low mass part of spectrum, important to parameterize background.



Dijet Resonances are one of the top priority for Jet Corrections CDF

γ+W/Z Signal

Neutral Net to improve $S/\sqrt{B}$

Kinematics:

Et, ΣEt, Σ Et^{jets}, H_T,

Topology:

$\Delta\varphi(i,j)$, $\Delta\eta(i,j)$ i,j = j1, j2, γ

$\Delta\varphi max(\gamma,jet)$, $\Delta\varphi min(\gamma,jet)$

Radiation in φ region between jets

Jet Properties:

Quark/Gluon Jet Separation,

Aplanarity, Sphericity

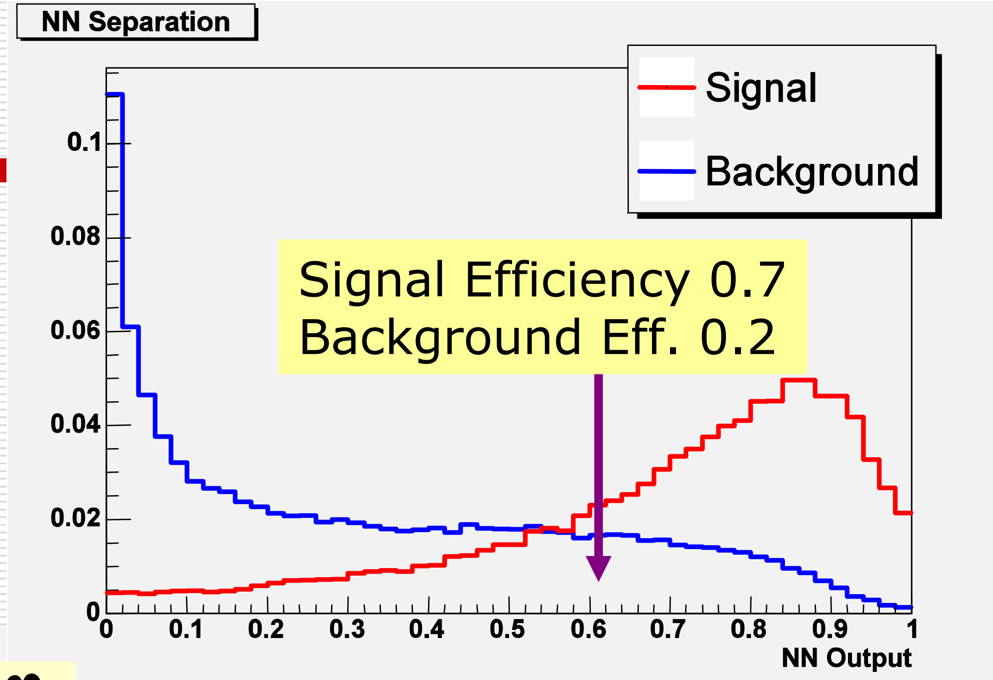
Mass Window 72-110 GeV

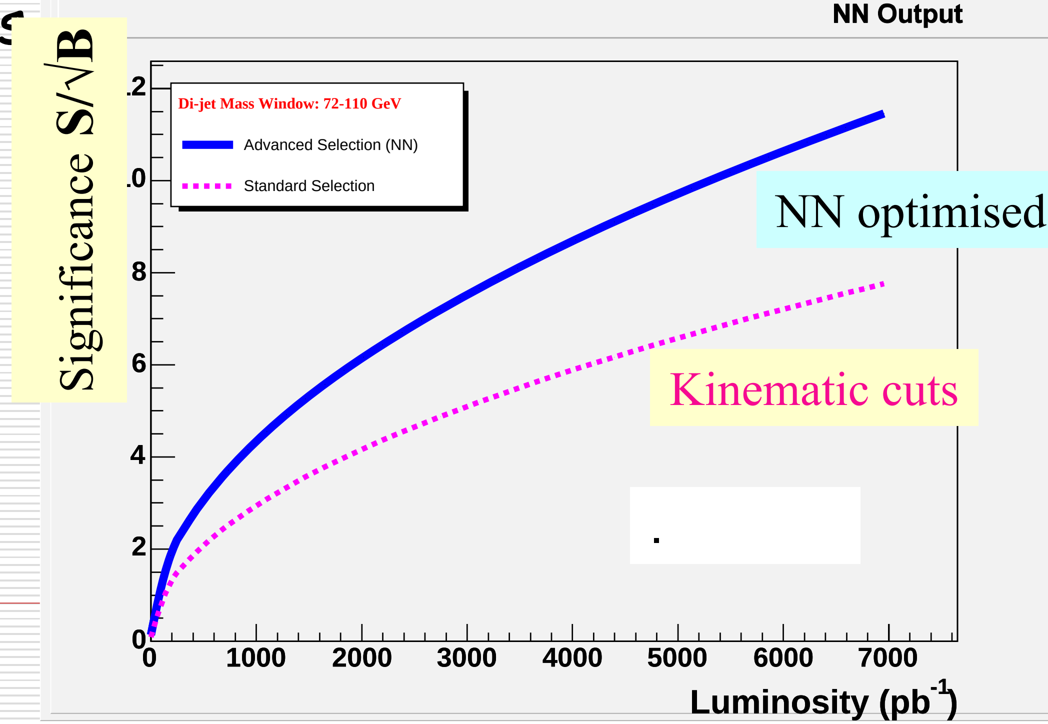
We picked 10 variables.

S/B

Simple kinematic 1/342

NN optimized 1/41





Conclusions on Jet Energy Scale

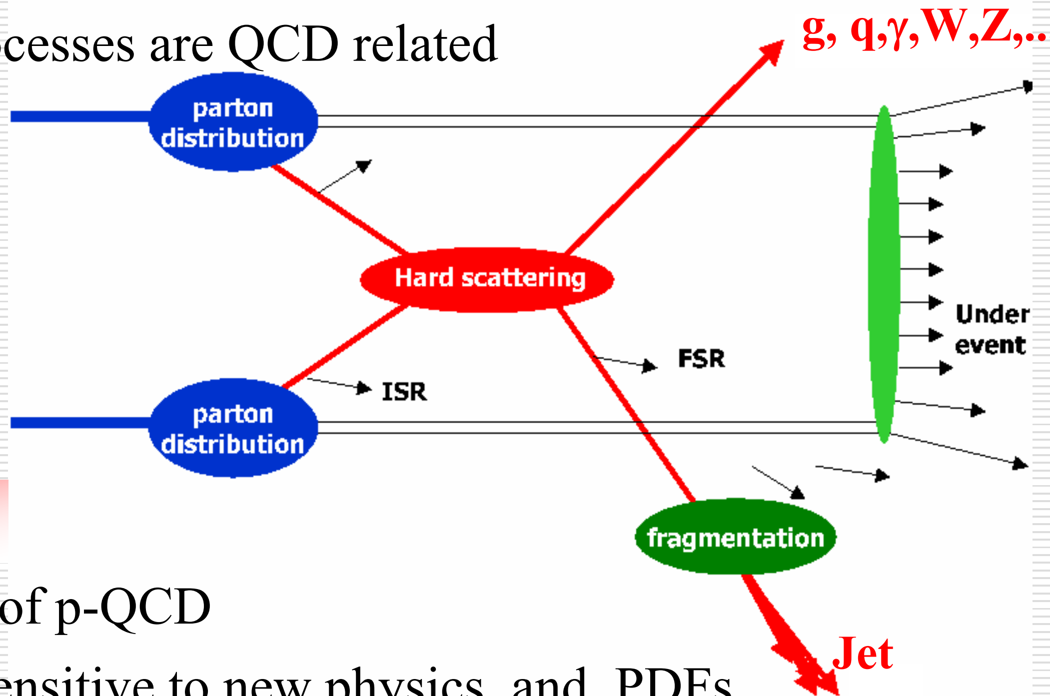
- We have determined the jet energy scale at CDF from first principles, using calorimeter response to single particles and particle Pt spectrum and density in jets.
- The current uncertainty on particle jets ranges from 1.8% at 20 GeV to 2.9% at 300 GeV.
- The Out-Cone-Energy uncertainty ranges from 6% (20 GeV) to 0.8% at 140 GeV.
- The current energy scale is supported by photon-jet, Z+jet and hadronic W mass in top events.
- This improvement has lead to single best top mass measurement in the world.

We are working to improve calorimeter simulation.

Improved γ-jet Pythia and Herwig simulation will help.

QCD at Tevatron

✓All production processes are QCD related



Jet Production

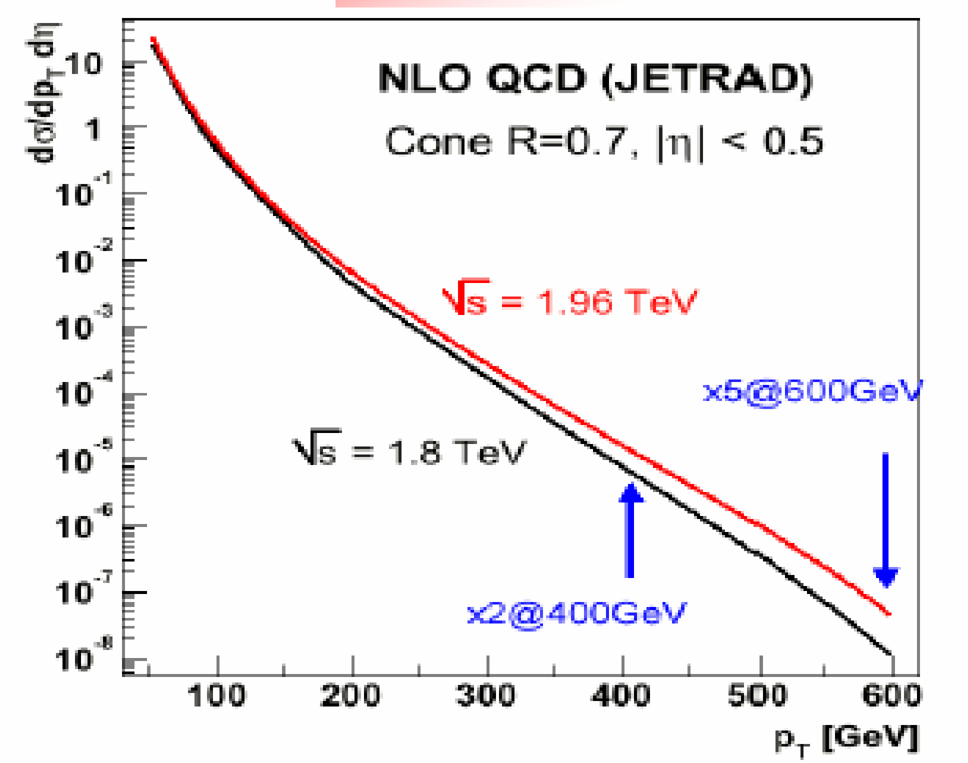
- ✓Stringent test of p-QCD
- ✓High-p_T tail sensitive to new physics and PDFs

Non-perturbative QCD contributions: Underlying event , Jet Fragmentation

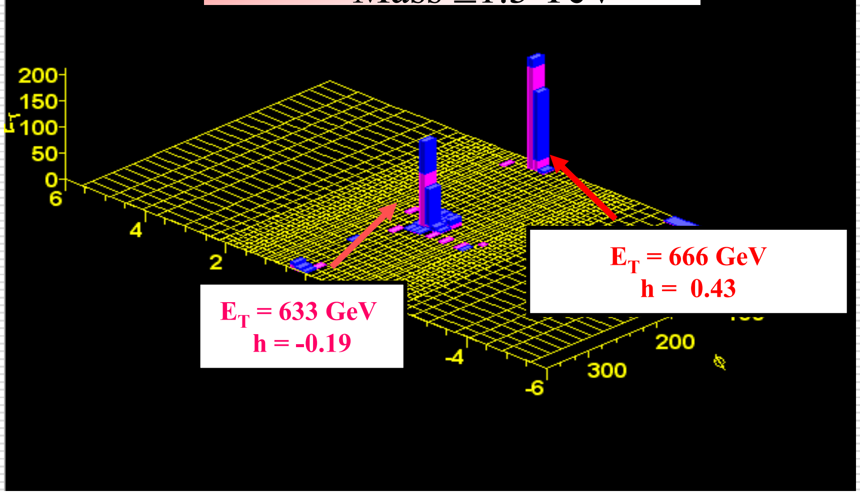
Other studies of interest: W+jets, diphoton, γ + heavy quark, inclusive b-jet production, hadron spectroscopy, diffraction

Jet Physics at Tevatron

Inclusive Jet Cross Section

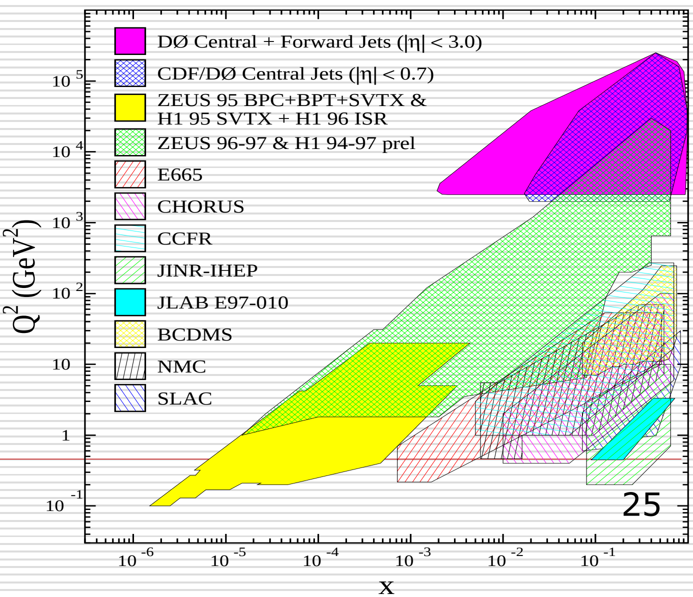


Highest dijet mass so far
Mass ≅1.3 TeV

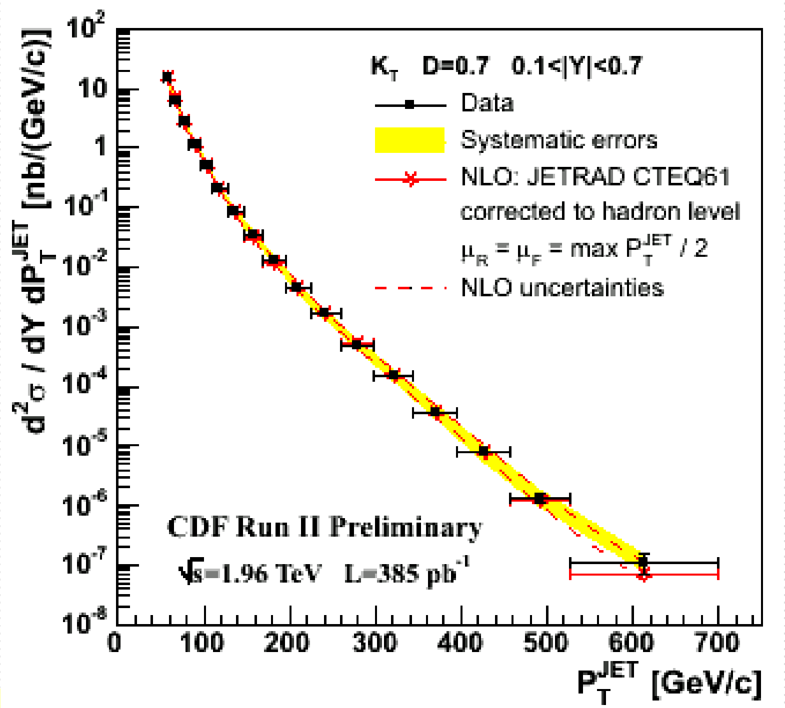


Higher σ_{jet} with respect to RunI

Increase p_T range for jet production



Inclusive Jet Cross Section with K_T



Good data-theory agreement

- Data uncertanties dominated by energy scale (5% energy scale systematic)
- NLO error mainly from PDFs (high x gluon)

No hadronization and Underlying event corrections applied to NLO prediction

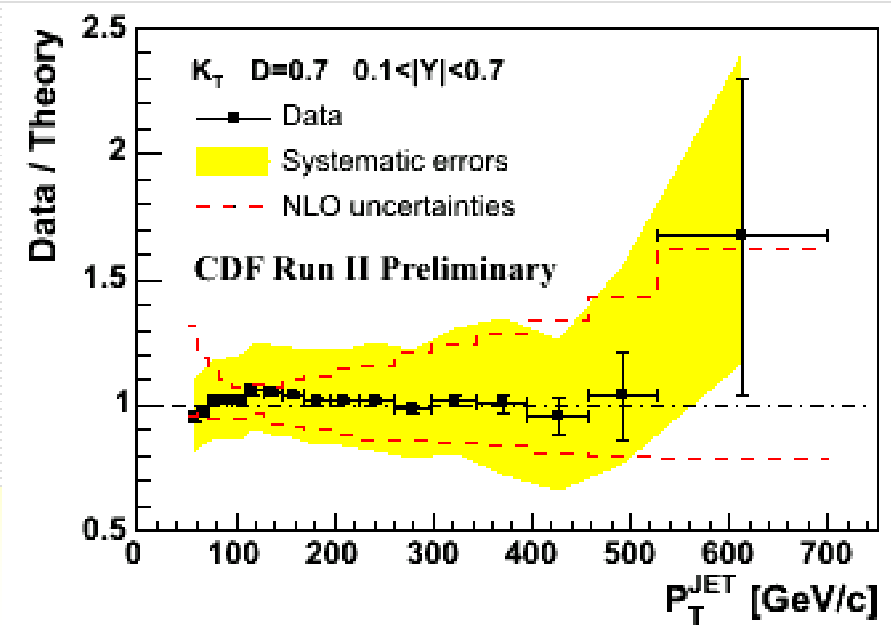
K_T Algorithm

$$d_{ij} = \min(P^2_{T,i}, P^2_{T,j}) \frac{\Delta R^2}{D^2}$$

$$d_i = (P_{T,i})^2$$

✓Infrared and collinear safe to all orders in p-QCD (relevant for NNLO)

✓No merging/splitting parameter



MidPoint-Cone algorithm

Run I Cone algorithm is not infra red safe. Add additional seed at middle two jets close by jets.

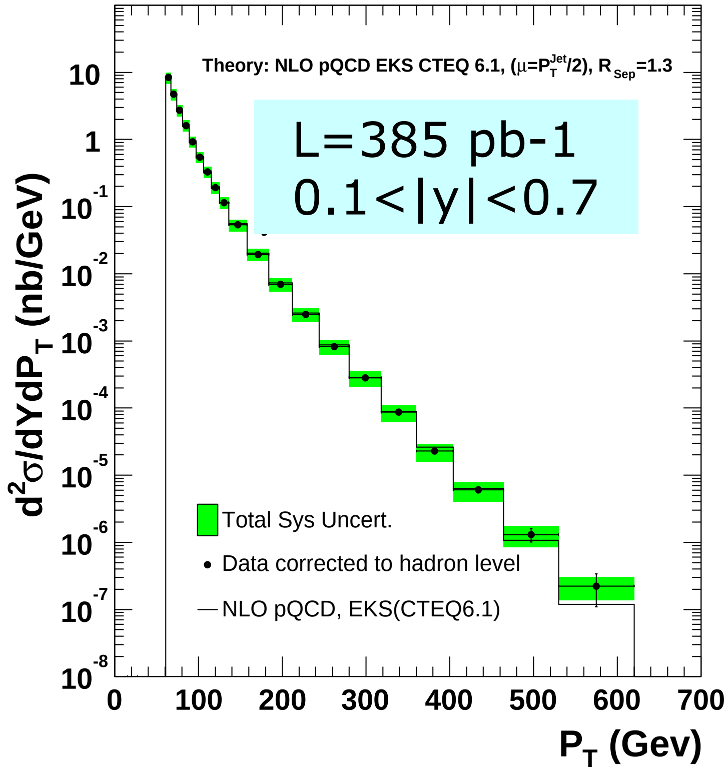
1. Define a E-ordered list of seeds using CAL towers with E > 1 GeV
2. Draw a cone of radius R around each seed and form "proto-jet"

$$E^{Jet} = \sum_k E^k \qquad \bar{P}^{Jet} = \sum_k \bar{P}^k$$

$$\text{Massive jet use} \quad p_T^{Jet}, \text{rapidity} \quad y^{Jet}$$

3. Draw new cones around "proto-jets" and iterate until stable cones
4. Put seed at Midpoint (η-ϕ) for each pair of proto-jets **separated by less than 2R** and iterate for stable jets
5. Merge two jets if overlap energy >75%.

Experimental clustering still not modeled in NLO pQCD calculations. Use Rsep parameter.



Analysis using MidPoint Clustering using new jet energy scale ready for public release soon.

The data are in general agreement with NLO QCD (EKS,CTEQ6.1) predictions.

Summary and Conclusions

RunII at Tevatron will define a new level of precision for QCD studies in hadron-hadron collisions

Jet production studies with the K_T algorithm

- Good agreement between data and NLO

Jet production studies with MidPoint Cone Clustering

- New results with 385 pb-1 soon, expect no surprises.

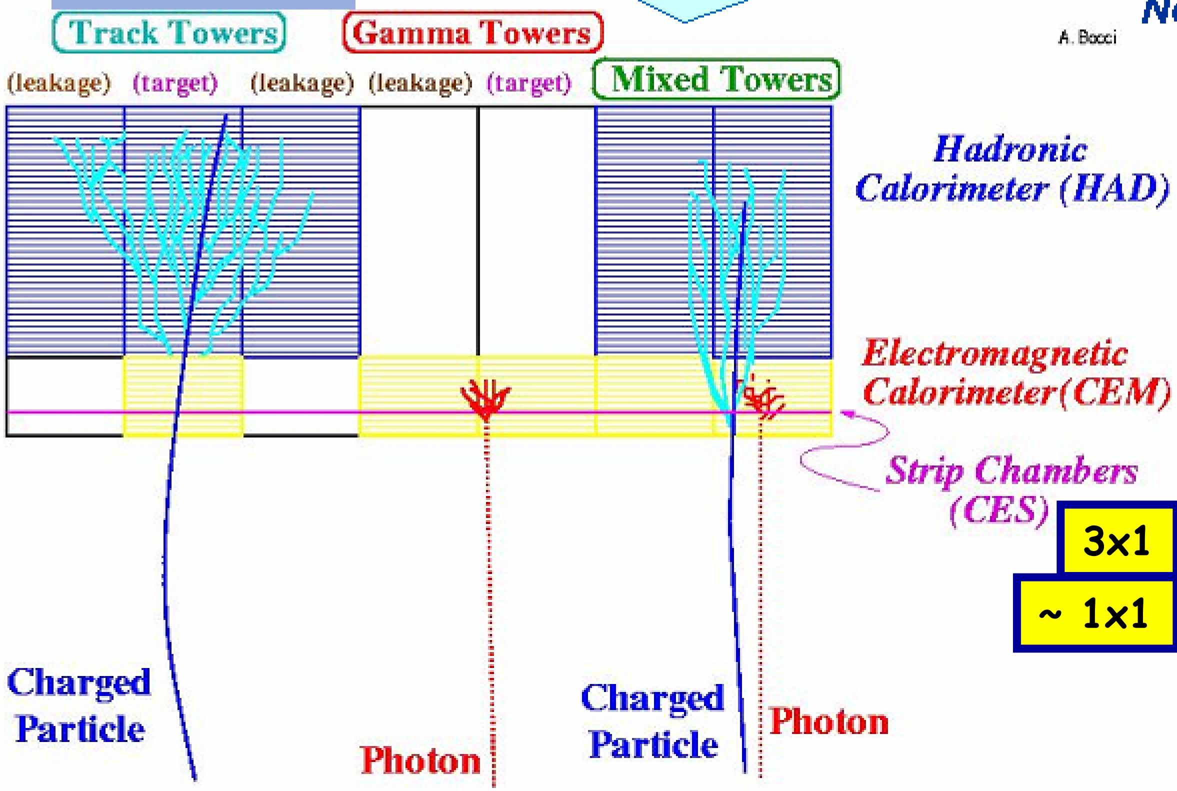
Backup Slides

Jet Energy Resolution

PFA in CDF-I

- *Tower energy including track momenta from CTC (to reduce calo non-linearity) and CES info (to sort out overlapping π^0 - $\pi^+\pi^-$)*

Four tower classes:
Track, Gamma, Mixed, Not Assigned



Track: ΣP_T (target), No energy to leakage towers.
Gamma: CEM energy
Mixed: ΣP_T + CEM – CEM_{trk} + kHAD
Not Assigned: scaled CEM+HAD

$$CEM_{trk} = \alpha \, \Sigma P_T^{tgt} + \beta \, (\Sigma P_T^{tgt+1} + \Sigma P_T^{tgt-1})$$

3x1
~ 1x1

Run 1b γ-jet data

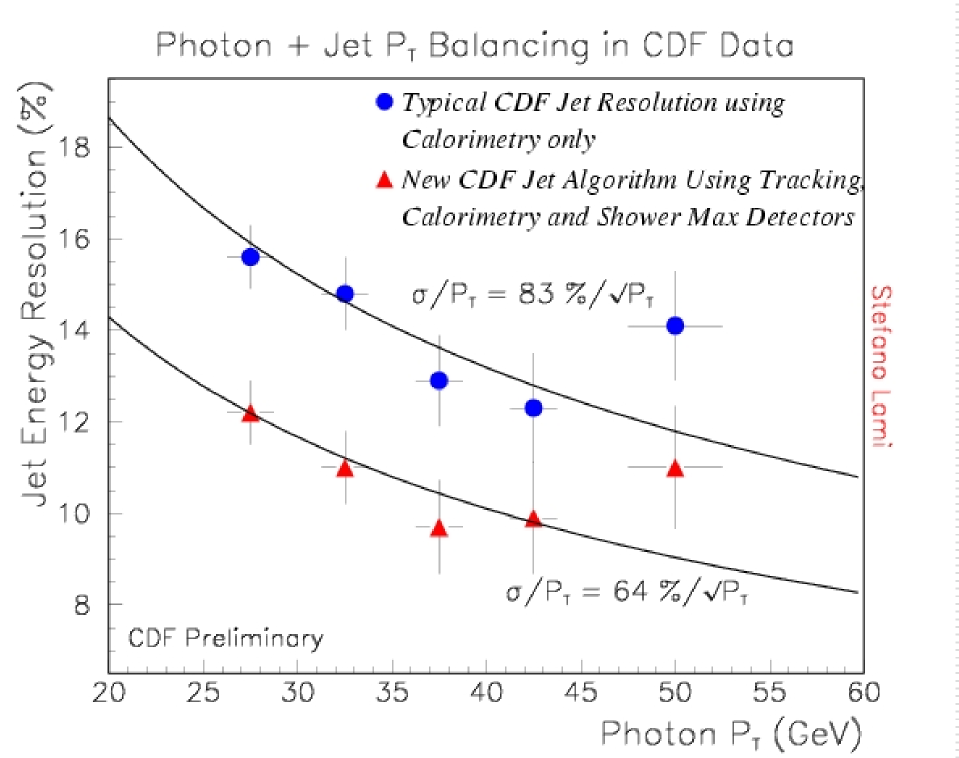
Tower type	Fraction of towers	Fraction of energy
Track	58.6 %	31.0 %
Gamma	8.8 %	7.9 %
Mixed	17.8 %	57.8 %
N.A.	14.8 %	3.4 %

Run I Results using Energy Flow Algorithm

Study limited to central only, no eta dependent corrections

Pt jet reconstructed with cone R=1.0, no OO correction, few % rescale needed

Very low statistics in the last two bins. Never clarified if improvement poorer at high Pt



Nobody has really worked on this algorithm in Run II.

TrackCalorimeter Algorithm (H1)

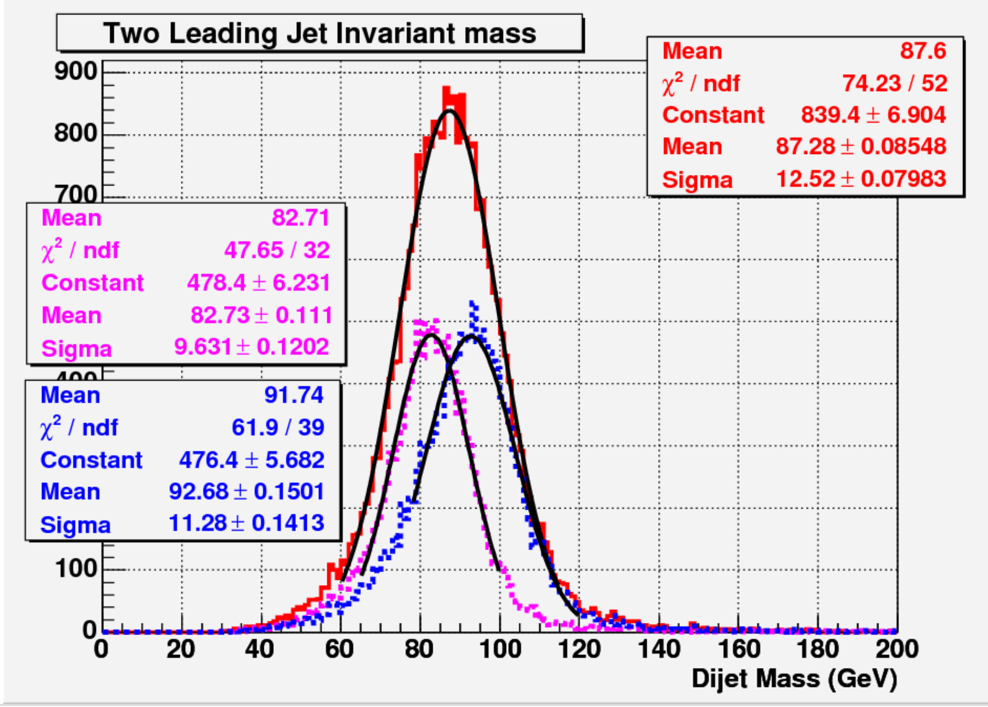
- Apply relative corrections to make response flat in η.
- Use EM+HAD towers
- Use tracks (0.5<Pt<15 GeV, Pt ordered), extrapolate to face of calorimeter
- Select towers within $\Delta\eta$=0.1 and $\Delta\varphi$=0.2. (Central towers are 0.1x0.26.) Take the nearest tower one if none within these limits.
- Order selected towers in distance from the track.
- Remove towers such that corresponding removed energy is always less or equal to the energy of the track. Remove only a fraction of tower energy if needed.
- Energy already removed by a previous track is not considered by subsequent tracks.
- Jet is sum of all quality-selected tracks and remaining towers in the jet.
- Scale the final jet energy to recover correct average.
- Jet Energy Resolution is improved but need more work to optimize the algorithm.

Search for W/Z→DiJet Signal

$$\sigma_{W(Z)\gamma} = \sigma(p\bar{p} \to W\gamma) \times \mathfrak{B}(W \to q\bar{q}) + \sigma(p\bar{p} \to Z\gamma) \times \mathfrak{B}(Z \to q\bar{q})$$

$$= 20.50 \pm 2.53 \quad pb$$

Limit 54 pb at 95%



NN Inputs Selection

Started with 19 NN variables. Use first 10 based on performance.

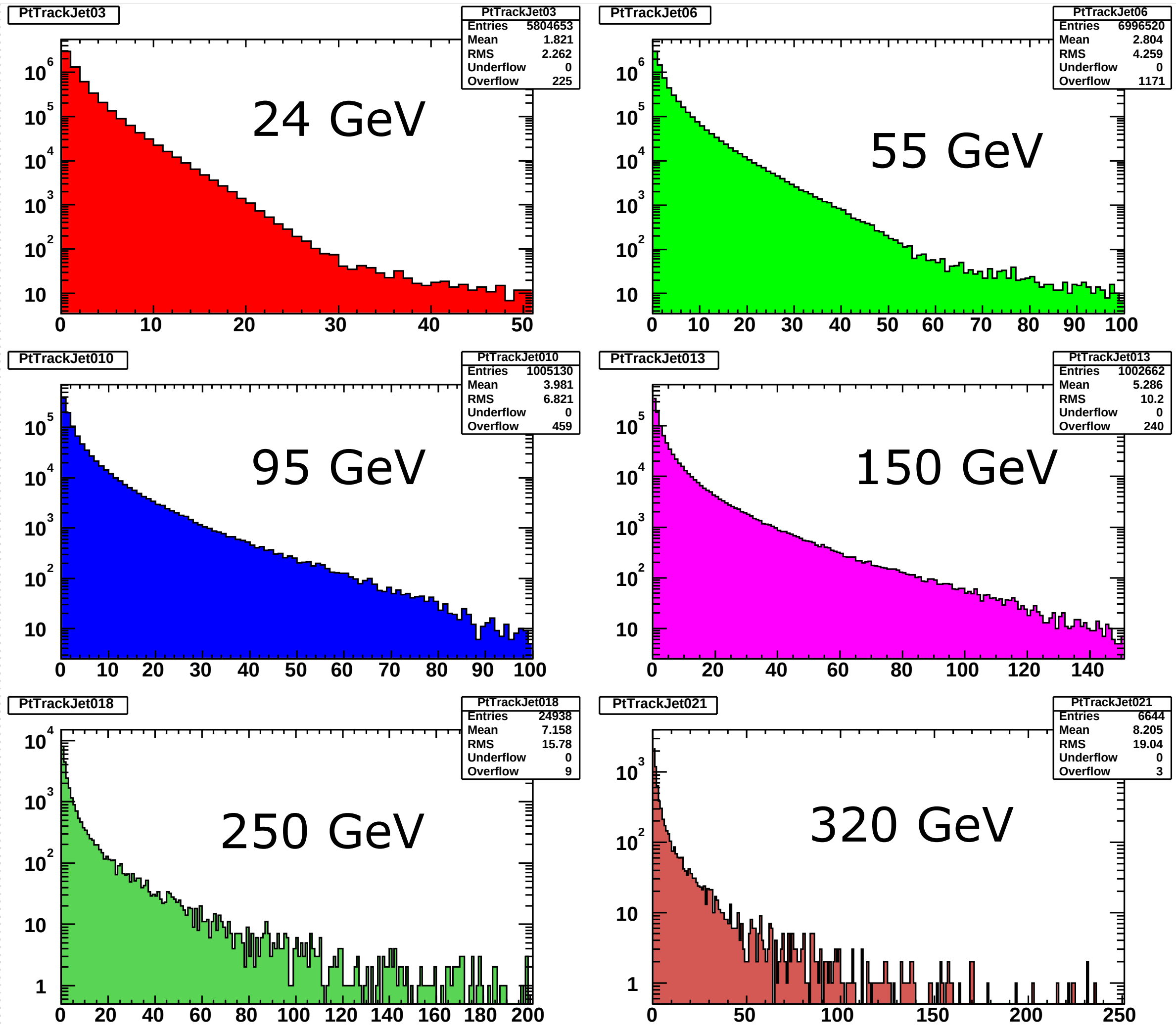
1. $\Delta\eta(J_1, J_2)$;
2. Number of tracks inside a 0.5 cone [12] around the two leading jets;
3. M/E of the second jet ($M = \sqrt{E^2 - P^2}$);
4. Maximum η of the two leading jets;
5. "Intrajet Energy Ω" defined as $\Omega = \left(\sum_T E_T - E_T^{jet1} - E_T^{jet2} - E_T^{\gamma}\right)/\Delta L$ where $\sum_T E_T$ is the E_T scalar sum of the calorimeter towers in the region $(\eta^{DW} - 0.3) < \eta < (\eta^{UP} + 0.3)$ and $\Delta L = \eta^{UP} - \eta^{DW} + 0.6$ with $\eta^{DW} = \min(\eta^{jet1}, \eta^{jet2}, \eta^{\gamma})$ and $\eta^{UP} = \max(\eta^{jet1}, \eta^{jet2}, \eta^{\gamma})$. The energies of the photon and the two jets are *uncorrected*;
6. $(E_T^{jet1} - E_T^{\gamma})/(E_T^{jet1} + E_T^{jet2} + E_T^{\gamma})$;
7. $\Delta\Phi(j_1, j_2)$;
8. $\Delta\Phi(j_{MAX}, \gamma)$ with j_{MAX} the leading jet closet to the photon;
9. $\Delta\Phi(j_{MIN}, \gamma)$ with j_{MIN} the leading jet farthest to the photon;
10. Sphericity [13];
11. $\Delta\eta(j_{MAX}, \gamma)$;
12. $\Delta\eta(j_{MIN}, \gamma)$;
13. $\Delta\Phi(\gamma, W)$ where W is the jet1-jet2 system;
14. η of the second jet;
15. $E_T^{jet1} - E_T^{jet2}$;
16. β of the jet1-jet2 system;
17. Aplanarity[11];
18. $\cos\theta^*(j_1, \gamma)$ where the angle is calculated in the $j_1 - \gamma$ rest frame;

Calorimeter Online Scale

- Z mass is used to set CEM/PEM scale.
- 50 GeV charged pion response measured in Test Beam is used to set CHA scale. Only pions which do not interact in CEM are used.

  The response is lower for pions which interact in CEM.
- Online calibration is changed periodically to keep energy scale constant within 3%.
- Offline calibration done before jet/electron reconstruction using Z, tower occupancy, laser and radio active source (when available). (Jet and electron data are processed twice.) A stability of <1% is achieved.
- Time-dependent DiJet balancing used to remove any remaining change in detector response outside central region.

Pt Spectrum of tracks in a Jet

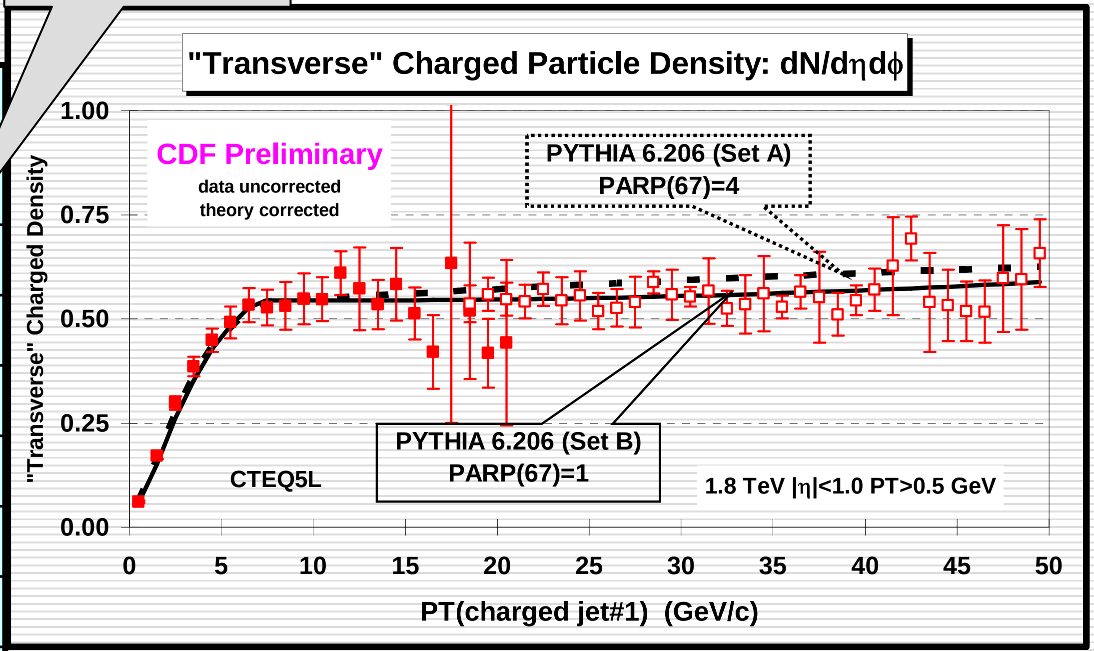


Tuned PYTHIA 6.206

PYTHIA 6.206 CTEQ5L

Parameter	Defaut	Tune A
MSTP(81)	1	1
MSTP(82)	1	4
PARP(82)	1.9 GeV	2.0 GeV
PARP(83)	0.2	0.5
PARP(84)	0.5	0.4
PARP(85)	0.3	0.9
PARP(86)	0.33	0.95
PARP(89)	1.0 TeV	1.8 TeV
PARP(90)	0.16	0.25
PARP(67)	1.0	4.0

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)).

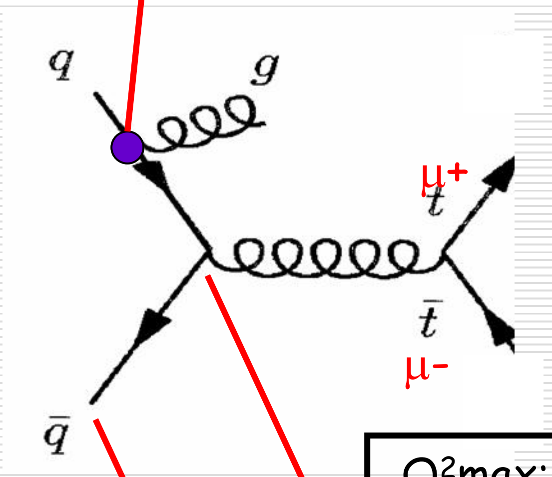
Pythia Underlying Event/ISR Tuning

$Kt^2 = PARP(64)(1-z)Q^2 : \alpha_s$,PDF

$\Lambda_{QCD} = PARP(61) : \alpha_s$

In Jet events, the region transverse to the leading jet is sensitive to underlying event, and initial state radiation.

In Pythia Tune A, beam-remnent - beam- remnant, multiple parton interaction and ISR are tuned.



Q^2max: K PARP(67)

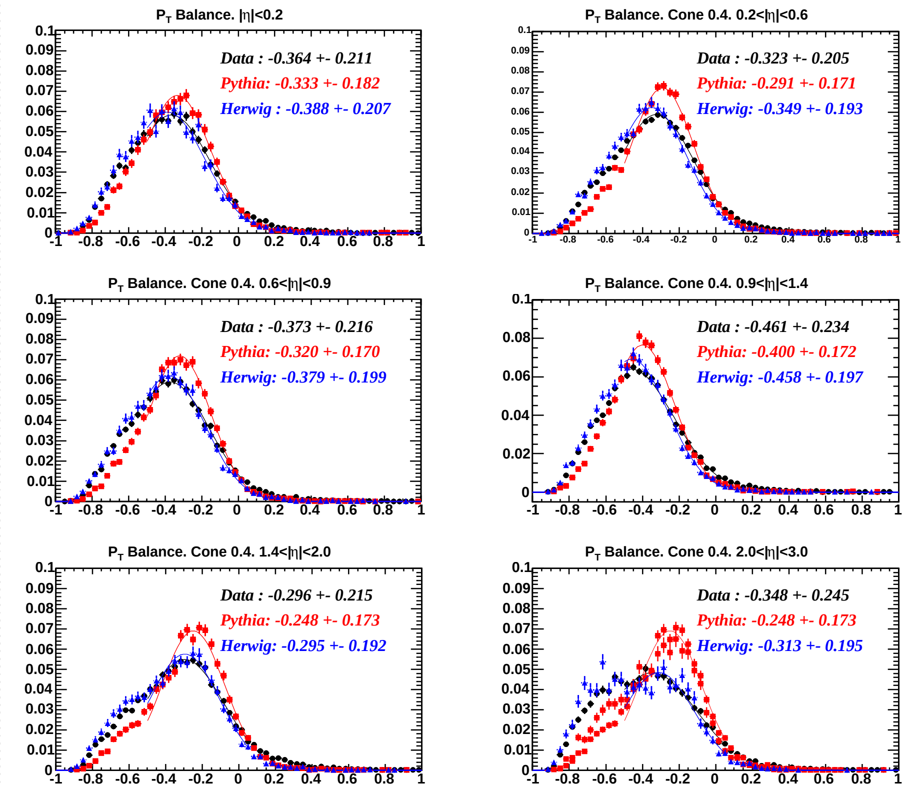
.

Qmin : PARP(62)

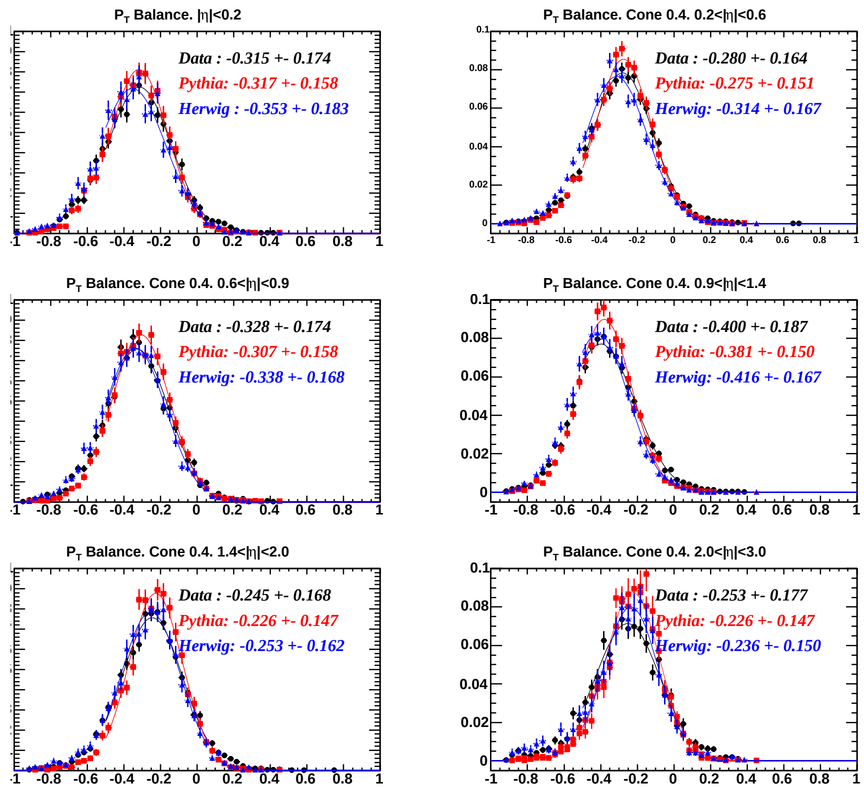
Intrinsic Kt: Gaussian Width: PARP(91)

Photon-Jet Balancing

- β= (PtJet-PtPhoton)/PtPhoton depends on the event selection cuts.
- Data, Pythia and Herwig agree/disagree to within 2-3%.
- It is hard to decide whether Pythia is better or Herwig.



Without second jet cut



Δφ<3.0