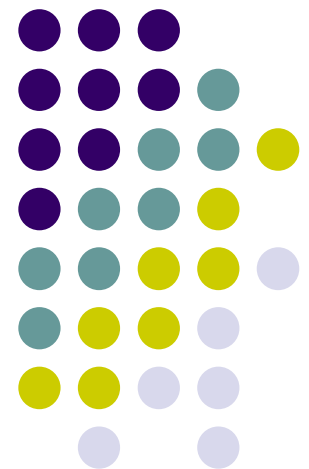


Testing the PFA algorithm

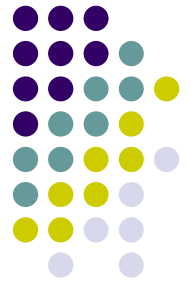
Adam Para, Fermilab

March 13, 2006

LCWS 06, Bangalore, India



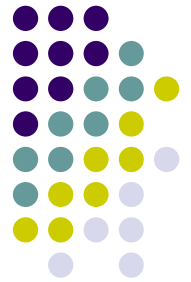
The ILC Calorimetry Challenge



- Multi (di-) jet spectroscopy, W/Z separation requires jet energy resolution of the order $30\%/\sqrt{E}$
- Such a resolution is thought to be beyond the reach of 'traditional' hadron calorimeters
- Possible solution: PFA algorithm

The PFA mantra: one can achieve excellent jet energy resolution if one can replace calorimetric energy measurement of all charged hadrons by the momentum measured in the tracker.

The PFA Challenges



- Tracking efficiency?

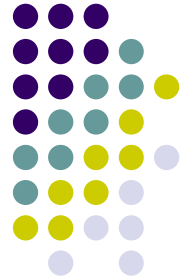
Not really. If some tracks are not reconstructed the corresponding energy will be measured with the resolution of the hadron calorimeter. Not a serious obstacle to reach the '30%' challenge if the tracking efficiency $\geq 90\%$

- Subtraction 'quality':

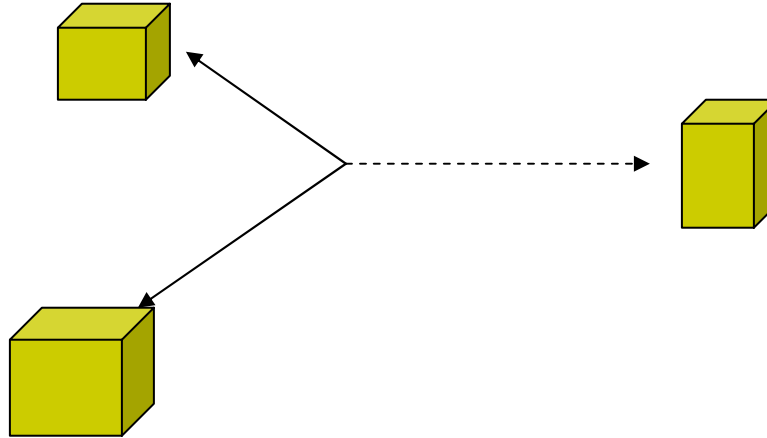
- Some of the energy deposited by neutral hadrons can be mistakenly removed \Rightarrow reduce the jet energy
- Some of the energy deposits of charged particles may not be properly subtracted and identified as neutral particles.
Double counting \Rightarrow increase the jet energy

Fluctuations of the above effects will likely dominate the energy resolution

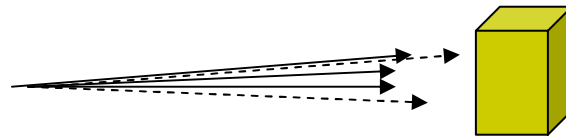
PFA: the extreme cases



- 'trivial': low energy/low multiplicity

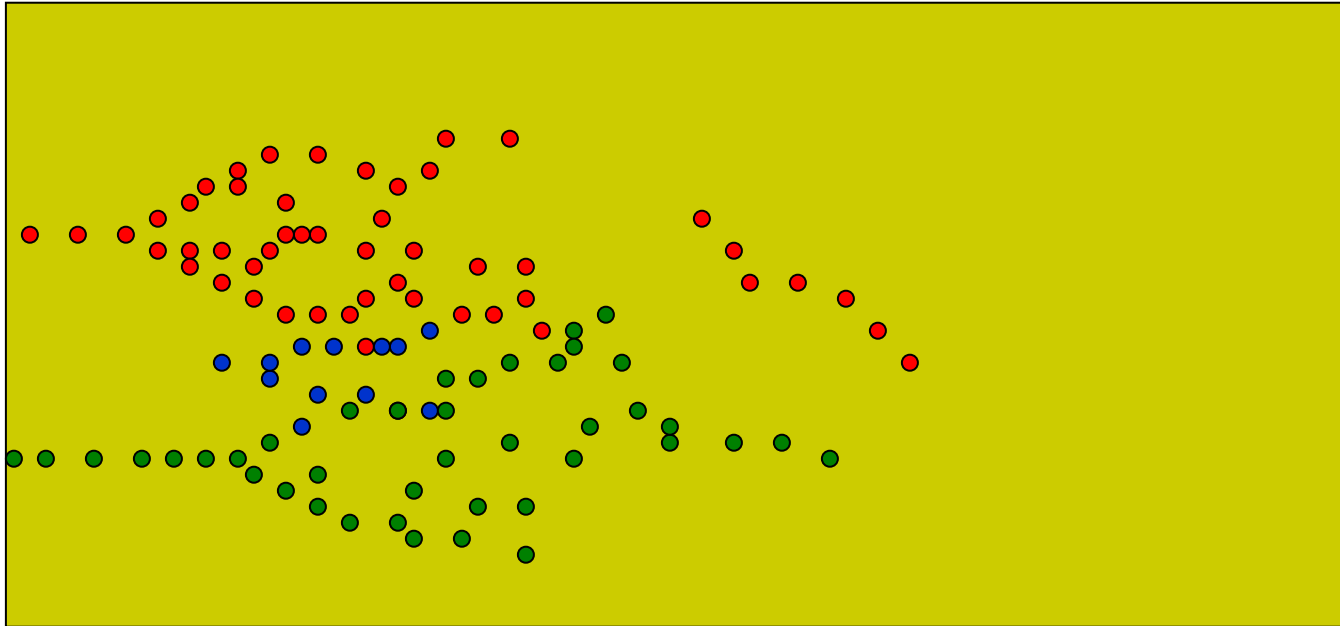


- 'impossible': very high energy/multiplicity



- Where are we at the ILC?

PFA: what do we want?



PFA Challenge:

- identify and discard all red/green points
- Identify and count all blue points

Chief (?) difficulties:

- identify 'blue' cluster in the midst of the red/green one
- Properly identify the disconnected red cluster (a.k.a. 'fragment')

PFA: is it obviously impossible?



Yes?

- Hadrons impact the calorimeter at ~ 10 cm distance
- Hadronic shower has transverse dimension of $\Phi \sim 40\text{-}50$ cm
- Hadronic showers are extremely irregular, they do not follow 'shower profile'

No?

- Hadronic showers are extremely irregular, they do not follow 'shower profile'
- Shower develops in 3 dimensions. ALL displays are projections on 2D plane and they convey unnecessarily pessimistic picture
- Although to contain the shower energy one needs a 'cylinder' $\Phi \sim 40\text{-}50$ cm, $L=100$ cm for any particular hadron shower this cylinder is very sparsely occupied. Example: such a cylinder contains $\sim 8,000$ readout cells, $1 \times 1 \text{ cm}^2$. Only ~ 1000 of them are hit. Occupancy is $\sim 12\%$

Distance scales relevant to PFA



- EM transverse shower size $\sim 3\text{-}5\text{ cm}$
- Hadron shower 'core' $D \sim 10\text{ cm}$
- Hadron shower tails $D \sim 70\text{-}100\text{ cm}$
- Distance between hadrons $D = \Delta\alpha \times R$
 $R \sim 150\text{ cm}$

Error rates (hence contribution to the jet energy resolution) depends on the **particle density**. It is primarily determined by the angular correlation function at the vertex. Magnetic field will move particles around but it will not significantly alter the distances between particles.

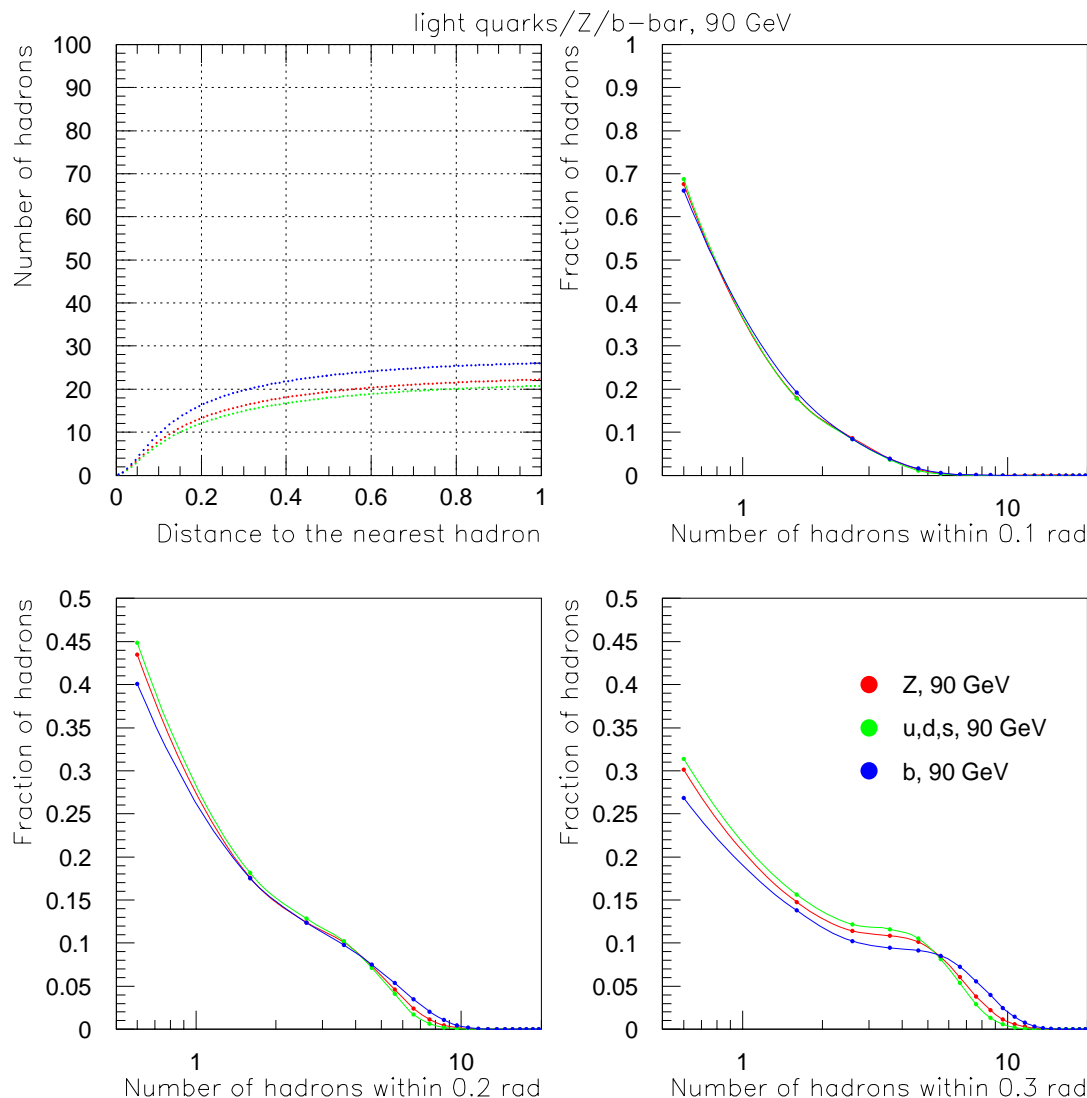
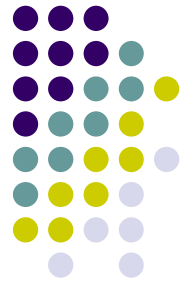
Usual 'test'/'proof' of the PFA: total energy for uds jets at the Z0 pole



It begs several questions:

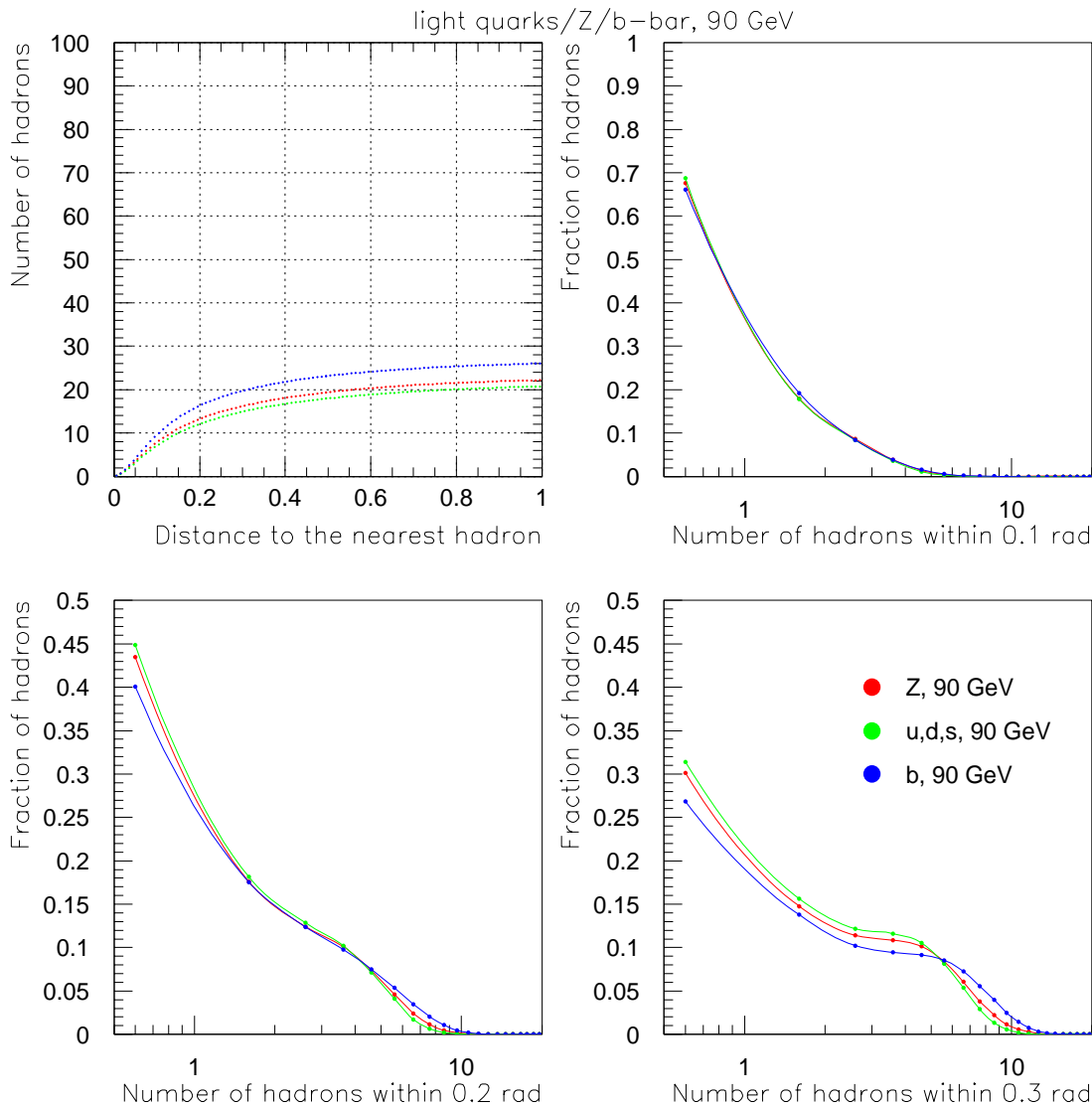
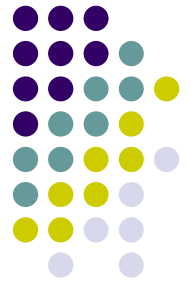
- Why total energy and not individual jet energies: to sidestep jet finding. OK
- Why uds? To avoid fluctuations of missing energy due to neutrinos. OK? Are these jets 'representative'? Bias?
- Is the performance of PFA representative for the higher energies?
- Is the performance of the PFA for uds jets representative for other processes? ZH ? Ttbar?
- What is the right measure of the energy resolution? RMS, gaussian, several gaussians?
- What is the energy dependence of the resulting energy resolution?? $1/\sqrt{E}$? Constant? \sqrt{E} ??

Particles densities: figure of merit?



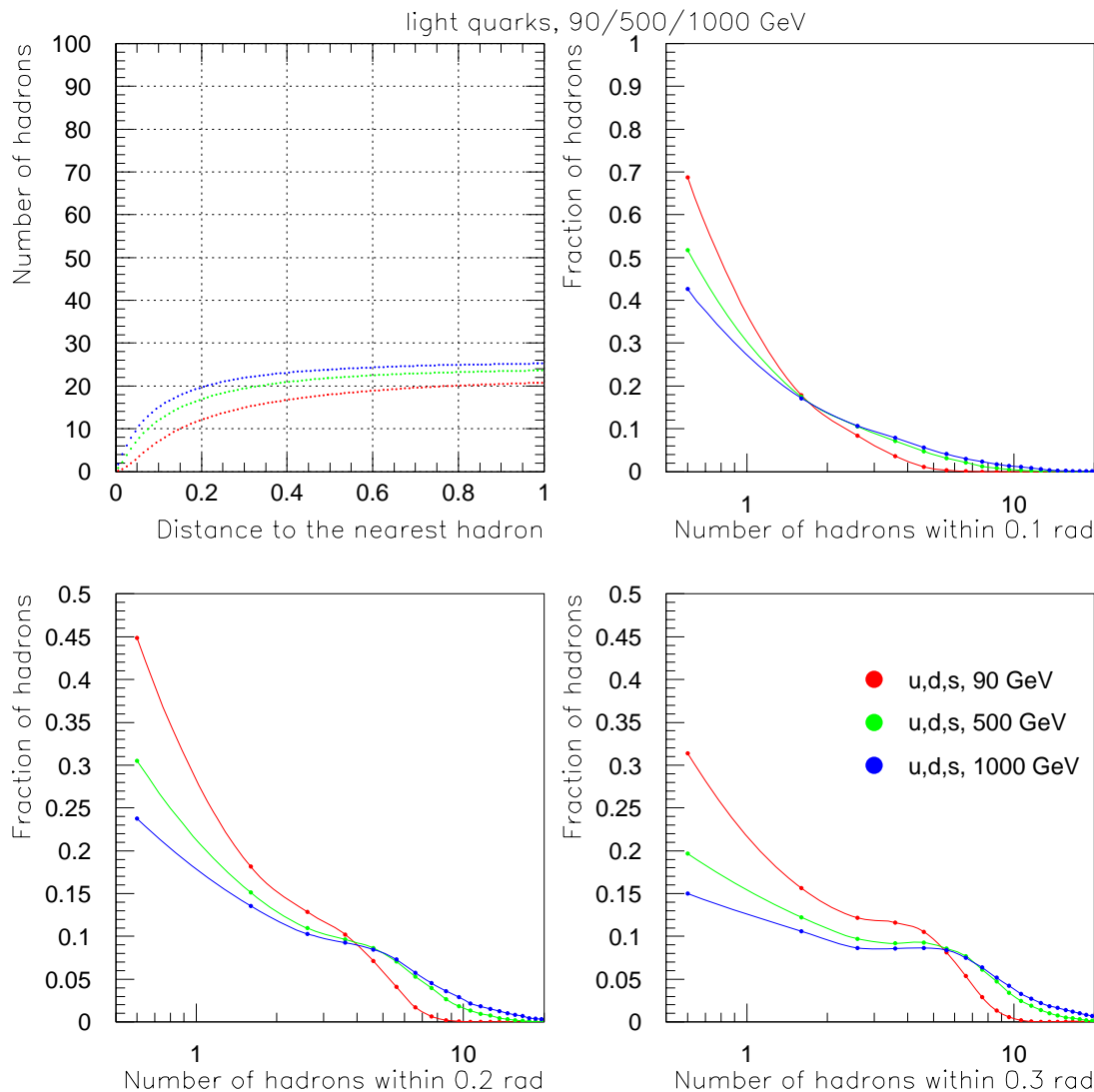
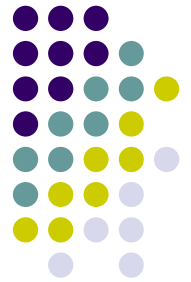
- PFA performance depends on particle densities == relative production angles at the vertex
- Number of particles which have another hadron closer then $\Delta\alpha$
 - Number of hadrons in a cone with half-opening angle of 0.1, 0.2, 0.3 rad

Light quarks/bbar/all jets



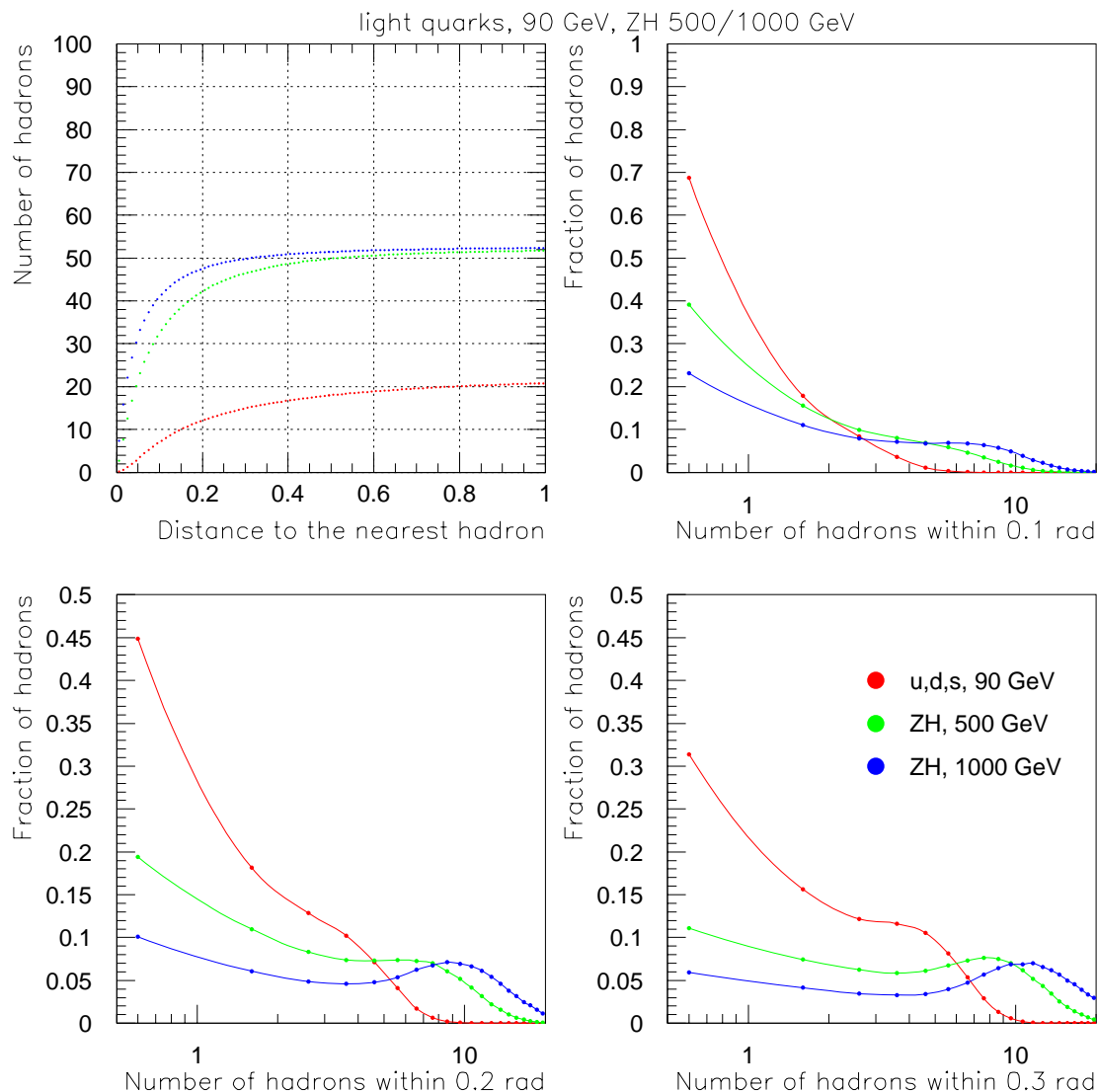
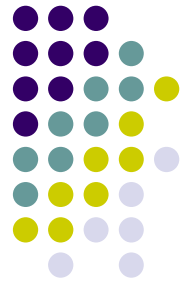
- Bbar jets have slightly higher multiplicity
- Hadron density is very similar
- It's not a problem to use uds quark jets only to assess PFA performance for di-jet events

Di-jets at 90/500/1000 GeV



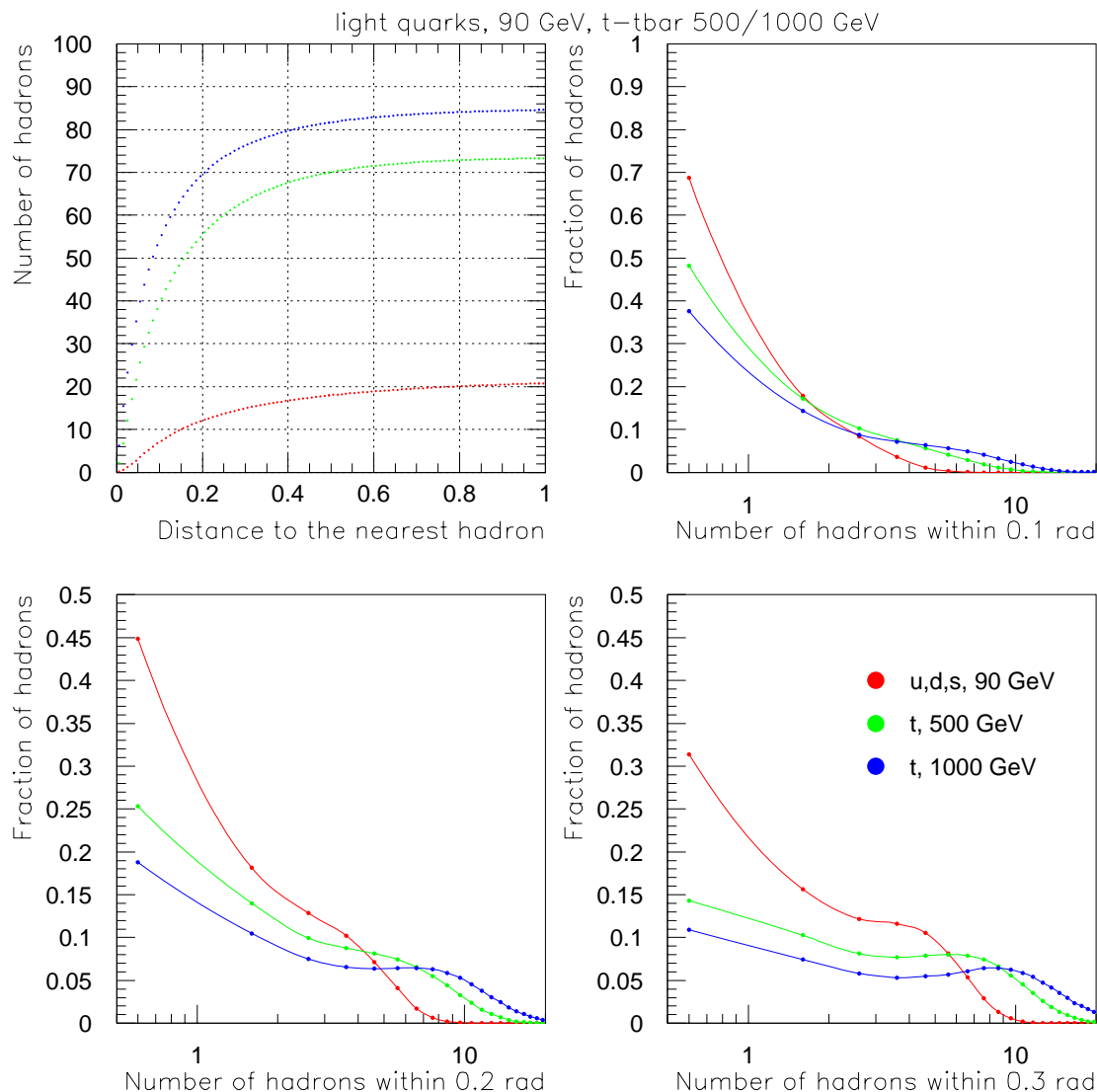
- Overall particle multiplicity rises somewhat ($\sim 25\%$)
- Number of isolated hadrons drops by $\sim 50\%$
- Probability of having multiple hadrons within 0.1 rad cone rises appreciably

Uds at Z0 pole vs ZH at 500/1000 GeV?



- Event multiplicity higher by a factor ~ 3
- Number of isolated hadrons drops very significantly
- High probability, $\sim 50\%$, of having several (>5) hadrons in a very tight cone of 0.1 rad
- Particle density/isolation changes significantly for ZH events between 500 and 1000 GeV, although the overall multiplicity the same (jet colimation?)

Uds at Z0 vs ttbar at 500/1000 GeV



- Event multiplicity higher by a factor ~ 4
- Number of isolated hadrons drops very significantly
- High probability, $\sim 30\%$, of having several (>5) hadrons in a very tight cone of 0.1 rad
- Hadrons more isolated than those in ZH events. Effect of larger jet isolation from the large Q value?

Conclusions I



- Density of hadrons entering the calorimeter depends very significantly on the event type and energy
- It is likely to lead to a different response and jet energy resolution for different physics processes/beam energies if the PFA algorithm is used
- Performance of the PFA at the Z0 pole is likely to be very poor indication of its performance for events of real interest

Challenge: Case of bottles of (moderately good) wine for a demonstration of $0.3/\sqrt{E}$ resolution for ZH events at $\sqrt{s}=500$ GeV

Unusual Features of PFA Calorimetry



Demonstration heavily dependent on Monte Carlo simulation

Calibration is process dependent, hence dependent on Monte Carlo simulation

Calorimeter used to measure neutral hadrons only

- How to validate the shower simulation?
- What can be learnt from the 1m^3 test beam studies ?
- How can one experimentally demonstrate the performance of the PFA?
- How can we calibrate the 'PFA calorimeter'

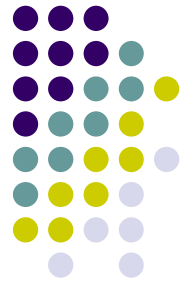
Shower simulation: the PFA angle



- Physics part:
 - Particles multiplicities
 - Charged/neutral fluctuations
 - Correlations (Bose-Einstein?)
- EM showers - EGS, OK
- Hadron showers:
 - Inclusive (momentum distribution) and exclusive (correlations) cross sections for π^0 /charged/neutral hadron production
 - Nuclear effects: resonances, nuclear transparency, nuclear breakup
 - Low energy neutron transport
 - Signal generation in the calorimeter

Reminder: vast majority of the observed signals are generated by very low energy (~ 1 MeV) particles \rightarrow convolution of all the components of the shower simulation.

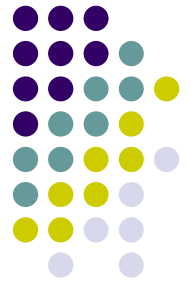
Tests of the shower simulation codes?



- Set up a set of 'test cases' to compare different shower codes?
 - Thin targets to test the hadron interaction modeling
 - Very strong magnetic field to sweep away charged hadrons and compare production of neutral hadrons
 - Gas/scintillator calorimeters to test slow neutron transport

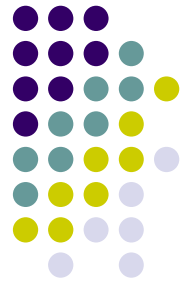
Goal: try to identify which components of the shower simulations agree and which do not

Experimental verification of hadron shower simulation codes?

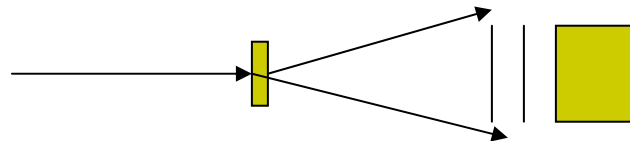


- MIPP Experiment (Fermilab): cross sections and correlations for charged hadron production
 - Incoming particles?
 - Particles energies
 - Target materials?
 - Are the existing MIPP data sets sufficient?
 - What else is necessary?

Neutral hadrons production modeling?

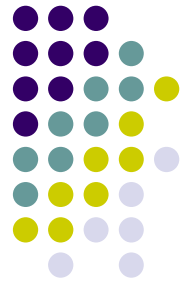


- Probably the most important aspect of hadron shower simulation
- Very scarce experimental information. Need dedicated experiment?
- KO - MIPP/son of MIPP? Acceptance?
- Neutron/antineutron:



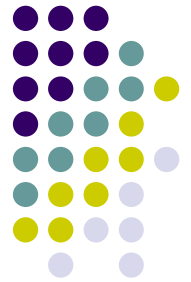
- Isolated neutrals only. Enough for validation?
- Antineutrons?
- MINOS test calorimeter data? (1x1x2 m³ iron-scintillator sandwich) 1-10 GeV . Frequency/ Energy distribution of isolated energy clusters?

1 m³ CALICE prototype: some thoughts



- Stated goal: to provide a test/discriminate between various simulation codes. To provide data to 'tune' the simulation.
- Sceptic's view: no direct test of the ingredients of the shower simulation. Tuned MC may be adequate to simulate the particular detector for which it was tuned but it lacks predictive power for different detectors (geometry/materials/energies)

Some possible tests with the 1 m³ prototype?



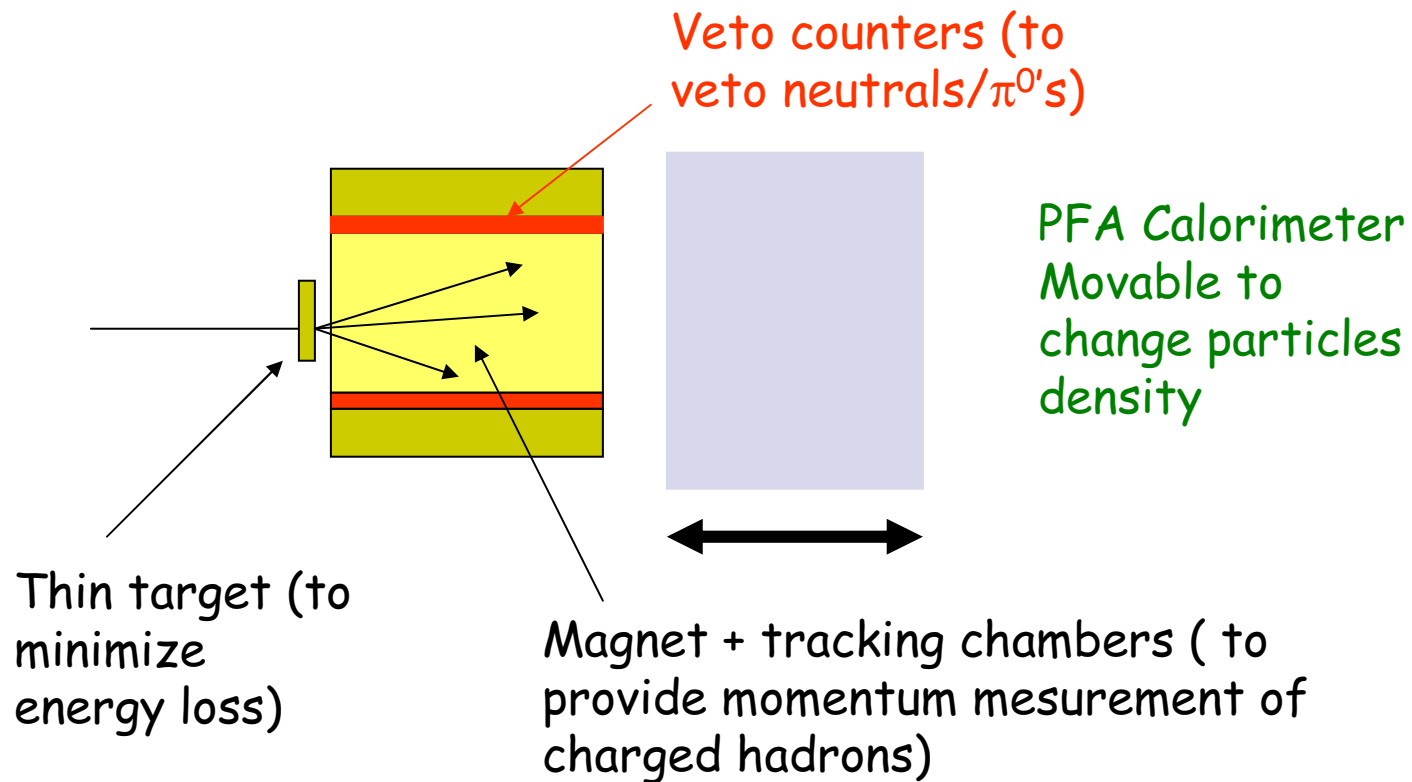
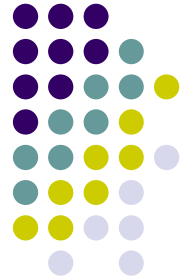
- Place (slow) neutron detectors at different depth and radii to test the production and transport of slow neutrons
- Make the gap between absorber plates wide enough to place BOTH gas and scintillator detector. Compare the shower appearance in these two detectors for the same showers. Provide a convincing test of the difference in the simulation of these two detectors
- Make several absorber planes out of lead glass plates? To provide the experimental test of the π^0 component of the shower?

Experimental demonstration of the PFA



- One day we may have a detector and analysis algorithm which, on paper, will have very good jet energy resolution. It is likely to be very expensive. Can we build it without an experimental demonstration? How can we demonstrate its performance?
- Jet in a calorimeter: a collection of particles with different energies and different distances between them. Calorimeter should be able to separate energy depositions of different particles and use the momentum measurement for charged hadrons

PFA test station ?



PFA Calorimeter Calibration Test Beam



- PFA Calorimeter Function I (topological): separate energy deposits
- PFA Calorimeter Function II: measure energy of neutral hadrons. This is quite a new requirement, it has not been tested before.
- Need known energy neutral beam:
 - Neutrons (from deuterons, stripped, bent protons away)
 - Antineutrons???
 - K⁰'s ???

Conclusion II



- PFA approach to precision calorimetry is very challenging
- A comprehensive set of tests of
 - Algorithms involved
 - Simulation codes
 - Experimental detector performancewill be necessary to demonstrate feasibility and robustness of the PFA detector
- It will be very prudent to build a detector which has very good jet energy resolution when used in a 'traditional' mode even if the PFA is its designed mode of operation.