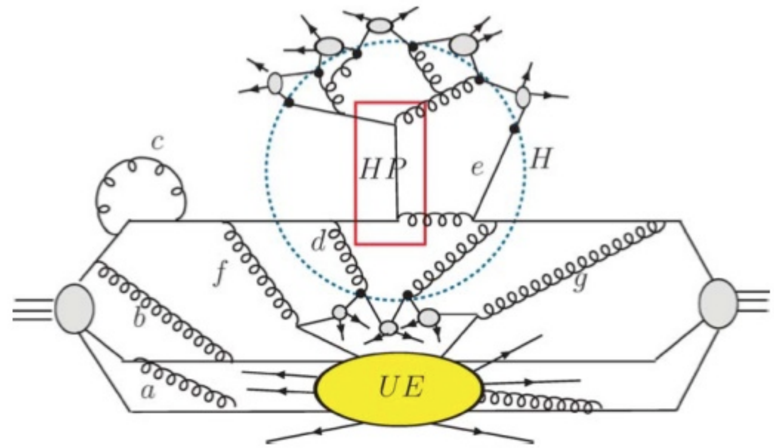
Hard Scattering in Hadron-Hadron Collisions: Physics and Anatomy

Section 3: Underlying Events, ISR and FSR

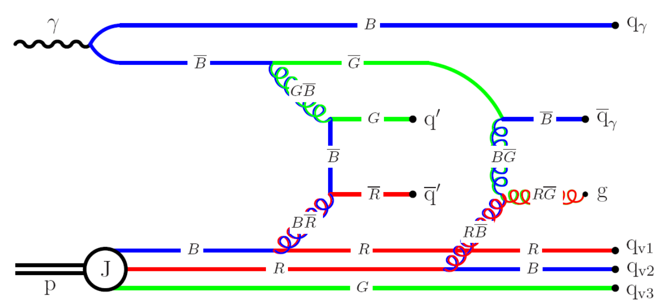
1. Minimum Bias and Underlying Event
2. Initial and Final State Radiation
3. Example: ISR/FSR at CDF
4. Modelling of UE
5. Example: Colour Connections at Tevatron
6. Multiple Interactions and Pileup
7. Example: Calorimetry Pileup

1. Underlying Event

- **A number ways to understand what happens when two hadrons collide**
  - **The "free parton" model only applies to some accuracy**
  - **At a level of O(1 GeV), everything is being torn apart**
    - Complete disruption of the two hadrons
    - Non-perturbative effects dominate
  - **No clean theoretical model that connects all the scales**
    - Yet there is a connection!



Mangano & Stelzer, ARNPS 55, 555 (2005)



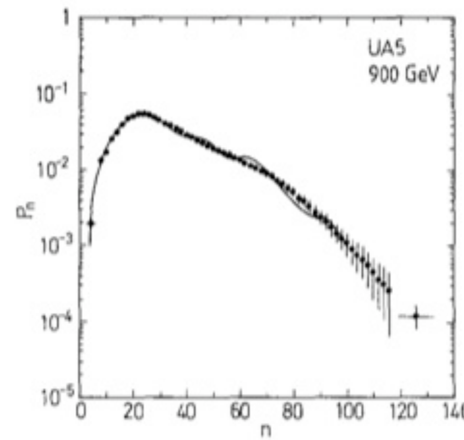
T. Sjöstrand and P.Z. Skands, JHEP 0403:053 (2004)

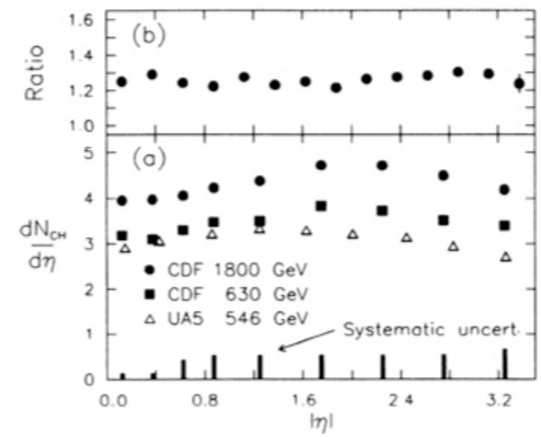
Definitional Issues

- What is the Underlying Event?
  - Several definitions
    1. Everything except "leading order" process
       - Was a traditional '80s view
       - Separate treatment of ISR/FSR
    2. Everything except the hard-scattering process
       - What about ISR/FSR effects?
    3. Everything not included in ME
- Modern convention is to adopt the last approach
  - Only one that is theoretically consistent
  - Reflects the reality that everything is connected
  - Helps to avoid missing or double-counting
- The strategy is to separate out high and low-momentum scales
  - This is ultimately an approximation
  - We will, for example, be trying to understand ISR/FSR effects, although difficult to separate from UE
- First, we need to understand what the UE really looks like
  - So start with some observations about Min-Bias events
  - See how UE differs
  - Then look at models

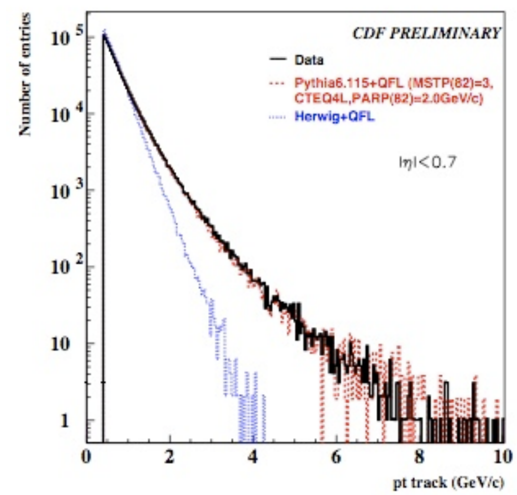
What is a Min-Bias Event?

- "Minimum-Bias" (MB) events are really inelastic, non-diffractive collisions:
  - Large number of "soft" particles
    - $<n_{ch}> \sim 40$ (at Tevatron)
    - $<P_T> \sim 0.5$ GeV/c
    - Uniform in rapidity (and η)
  - At first glance, looks like "underlying event" (UE)
    - In detail, relationship breaks down
- MB events studied in detail:
  - Taken with random triggers or special runs
  - UA5 measurements at SppS
  - CDF in early Run 0/1 days





R.E. Ansorge et al. (UA5), Z. Phys. C 43, 357 (1989)
F. Abe et al. (CDF), Phys. Rev. D 41:2330 (1990).

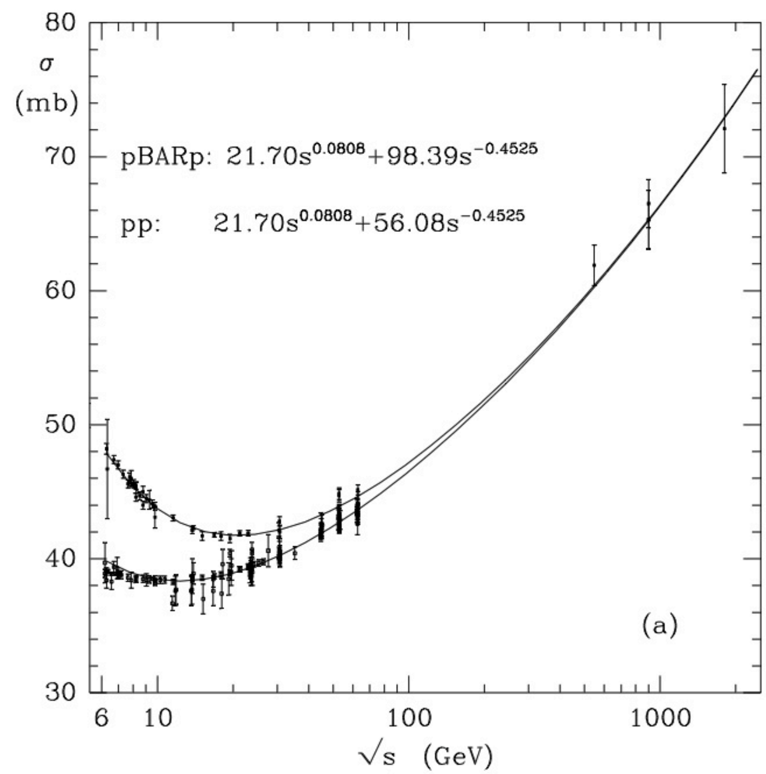


Cross Section for MB

- **Inelastic, non-diffractive cross section (σ_{in})**
  - **Needed for most luminosity measurements**
  - **Proportional to # of collisions**
    - Drives rate of multiple interactions
- **Surprisingly (perhaps), σ_{in} is not well understood**
  - **Only phenomenological models to describe the process**

$$\sigma_{tot} = 24.22 \times s^{0.0667} + 0.0139 \times s^{0.452} \text{ mb}$$

  - **Extrapolations to LHC energies range from 90 to 160 mb for σ_{tot}**
    - So generally have to assume one needs to measure it
      - **Dedicated experiment designed for this task - TOTEM**
    - Elastic+diffractive ~25%



A. Donnachie & P. V. Landshoff, Phys. Lett. B296, 227 (1992)
M. Bauer, J. Butterworth & M. Seymour, JHEP 0901:065 (2009).

Cross Section at LHC

Nature Comm. 2 (2011) 463. and CMS-PAS-FWD-11-001 (2011).

- **Inelastic, non-diffractive cross section (σ_{in})**
  - **Previous formula gave 120.5 mb for total cross section**
  - **Inelastic part now measured by ATLAS and CMS**
    - Drives rate of multiple interactions

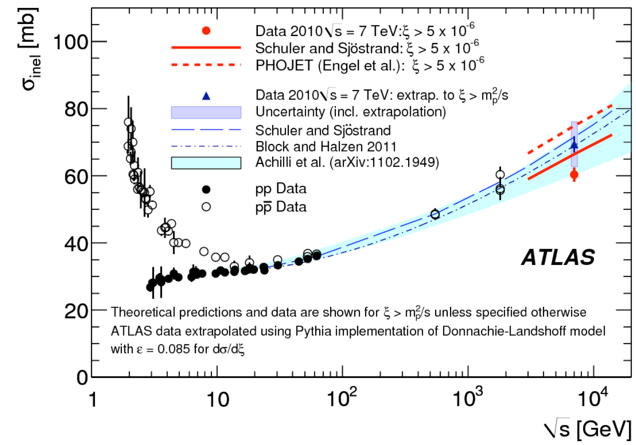
$$\sigma_{tot} = 60.3 \pm 2.3 \text{ mb (ATLAS)}$$

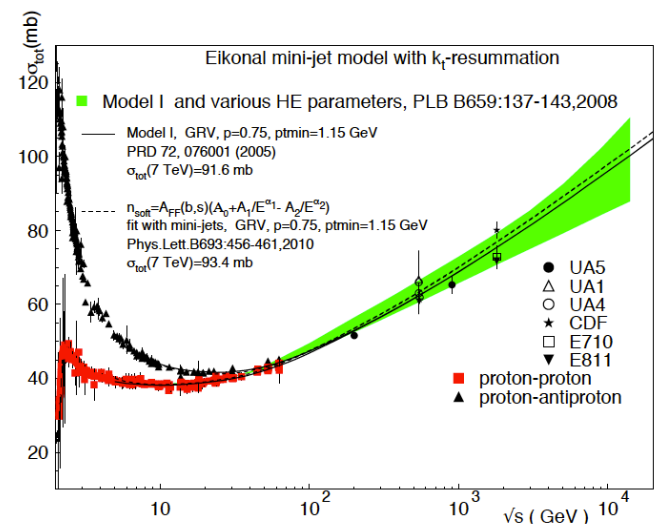
$$\text{for } M_X^2 / s > 5\text{x}10^{-6}$$

$$\sigma_{tot} = 58.7 \pm 3.5 \text{ mb (CMS)}$$

$$\text{for } M_X^2 / s > 6\text{x}10^{-5}$$

- **The elastic cross section, σ_{el}, is not yet measured**
  - **Its expected to be around 30 mb**
  - **Total cross section is then ~90 mb**

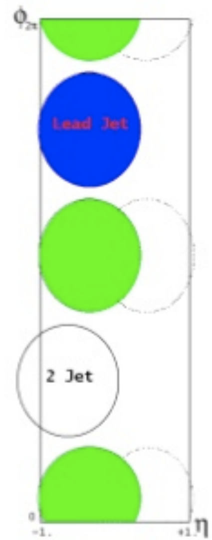


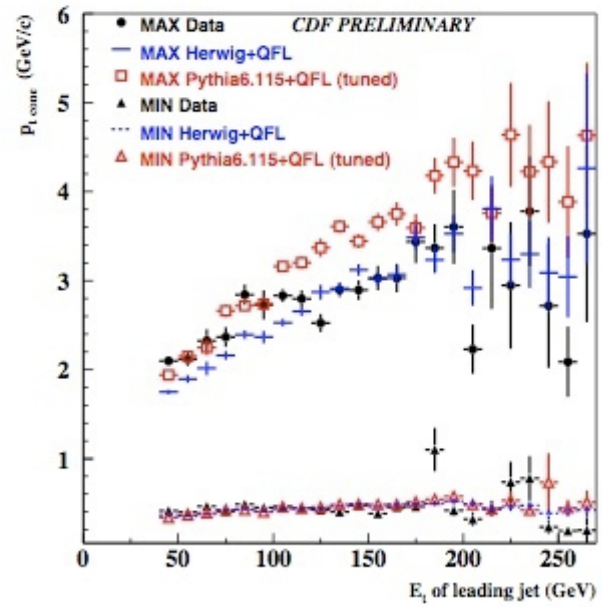


A. Achilli et al., arXiv:1102.1949

UE & Min-Bias Event Differences

- **There are significant differences between UE and MB**
  - **Good example is energy flow in jet events**
    - Need to model to get jet energy corrections right
  - **UE adds additional stochastic uncertainty in measurement of jets**
  - **UE particles readily confused with the softer products of jet hadronization**
- **Studied charged track P_T in "cones"**
  - **Look at "dijet" events where one has clear "axis"**
  - **Define 2 cones 90^o from leading jet**
    - "Max" cone one with largest P_T, "Min" cone the other



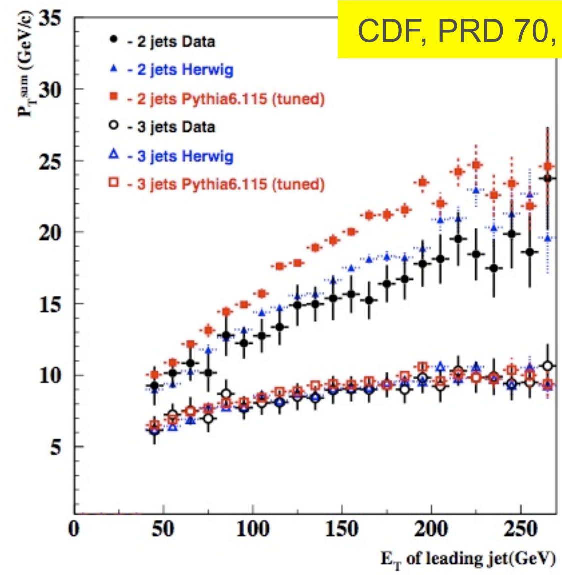


CDF, PRD 70, 07002 (2004)

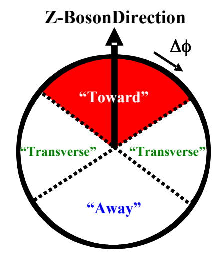
- **Data show:**
  - **"Max" cone energy rises with leading jet ET**
    - Consistent with extra jets from NLO processes
  - **"Min" cone about constant**
    - $P_T \sim 0.4$ GeV/c

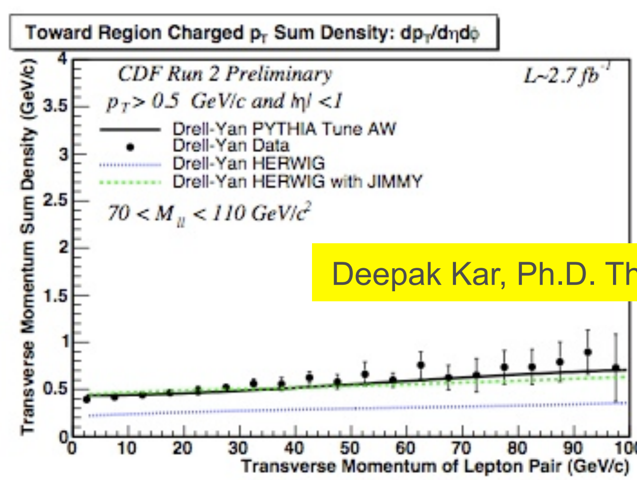
Other UE & Min-Bias Studies

- Another way of looking at jet data is by "Swiss cheese"
  - Sum P_T of tracks in |η|<1 that are at least R=0.7 away from highest E_T jets
    - Reduces the effect of NLO contributions
  - Average "momentum density", when subtracting 2&3 jets
    - $P_T/\Delta\phi\Delta\eta = 0.52 \pm 0.05$ GeV/c/rad
  - Compare with Min-bias events
    - $P_T/\Delta\phi\Delta\eta = 0.34 \pm 0.03$ GeV/c/rad
    - Multijet data has 50% higher momentum density
- Similar effect in Drell-Yan events
  - Not quite as large a difference as for dijet events



CDF, PRD 70, 07002 (2004)



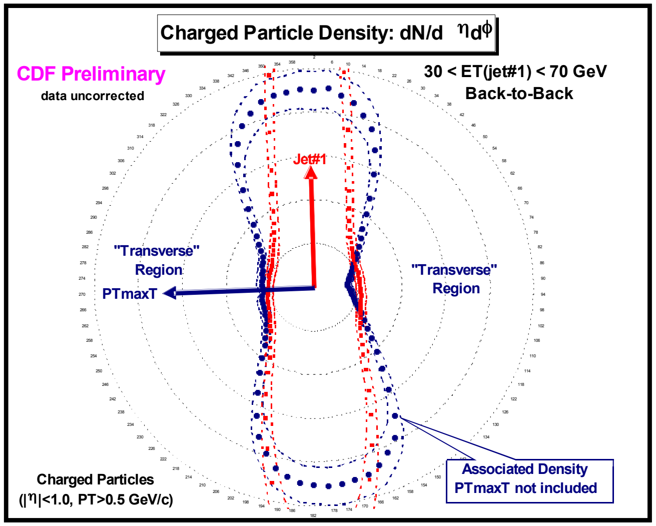


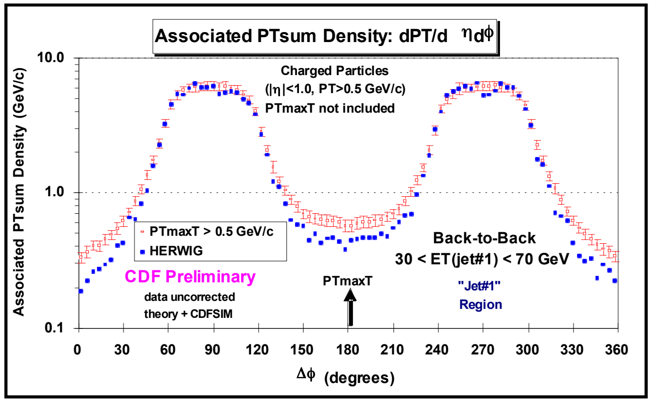
Deepak Kar, Ph.D. Thesis (2008)

2. Initial & Final State Radiation

- **When we talk about UE, need to consider ISR/FSR effects**
  - **"Hard" radiation from partons**
    - Characterized by P_T scales O(2-5) GeV/c and higher
    - Include (at least in part) in ME calculation?
      - **Where does ME end and UE begin?**
  - **"Soft" radiation coming from QCD showering of partons**
    - **Most parton "shower" models incorporate effects**
- **"Merging/matching will be discussed a little more in Section 4 on Jets (see also Section 2)!**

- **These effects have been studied in dijet events**

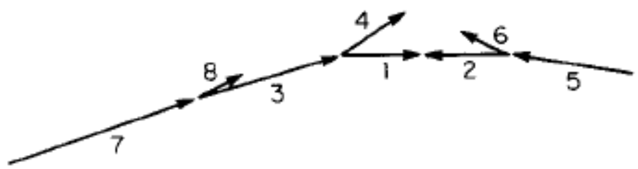




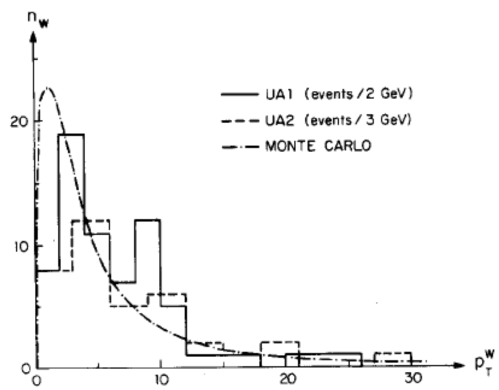
R. Field, Oregon Terascale Workshop, Feb 2009

Models for ISR/FSR

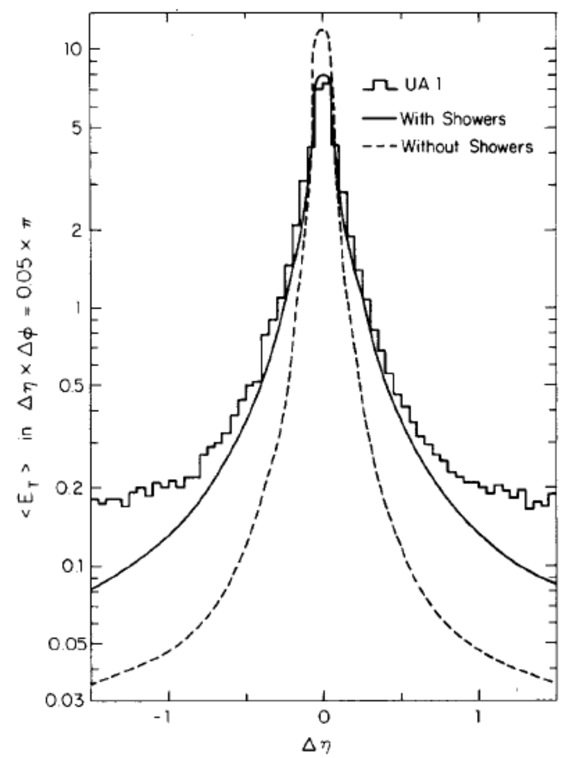
- **The standard model for "ISR"**
  - **Altarelli-Parisi evolution backwards of initial state partons**
  - **Developed by Sjostrand in 1985**



  - **Showed that you can do a MC using backward AP efficiently**



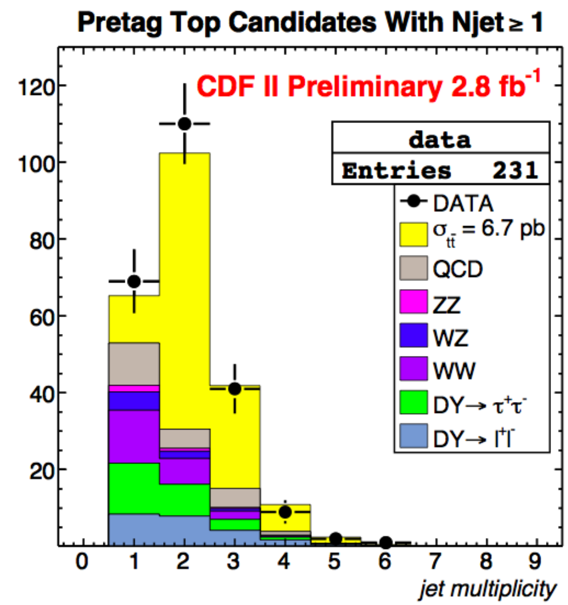
- **FSR simply uses AP as a means of calculating probability of emission**
  - **Test with energy flow near a jet**
  - **Data: UA1 with E_T>35 GeV jets**



T. Sjostrand, Phys. Lett. 157B, 321 (1985)

3. Example: ISR/FSR at CDF

- **Good example: CDF dilepton events**
  - **Two high P_T leptons and MET**
  - **Require jets with**
    - E_T>15 GeV & |η|<2.5
- **Have required at least one jet**
  - **Expect two jets from b**
  - **With N_{Jet}>1, have 162 events with**
    - ~110 expected tt signal events
      - **80 with 2 jets**
      - **25 with 3 jets**
      - **5 with 4 jets**
      - **2 with 5 jets & 1 with 6 jets**
    - N.B. PYTHIA gets DY N_{Jet} distribution wrong by 5-10%
      - **So measure using Z decays and corrected DY prediction, assuming independent of dilepton invariant mass**

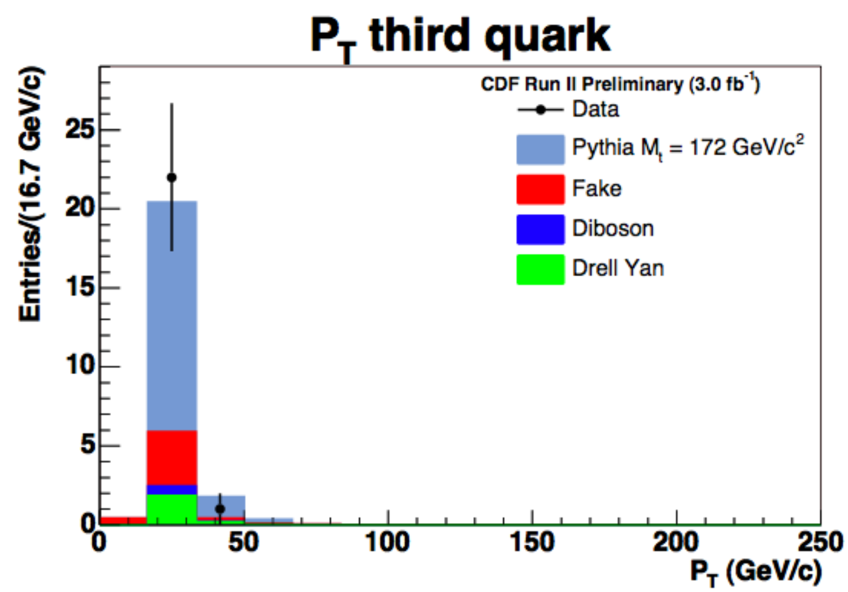


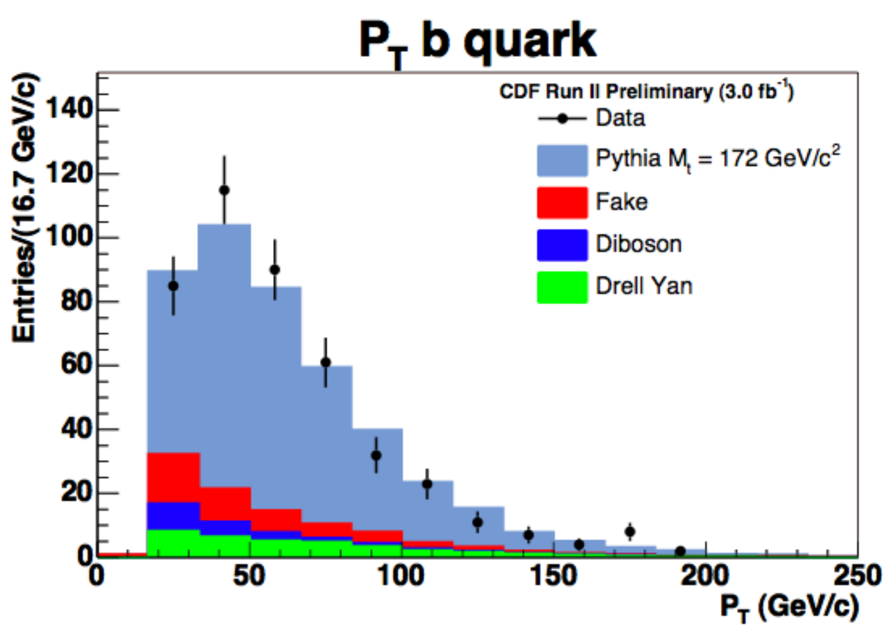
CDF Public Note 9647 (2008)

- **About 30% of events have at least one extra jet**
  - **Could be "ISR" or "FSR"**
  - **Logically, can also think of this as "tt+X"**

Top Dilepton Jet Spectra

- Latest plots of E_T spectrum of jets in dilepton sample
  - B jet is quite hard (as expected)
  - Third jet E_T is relatively soft
    - But 1 event with $E_T > 33$ GeV

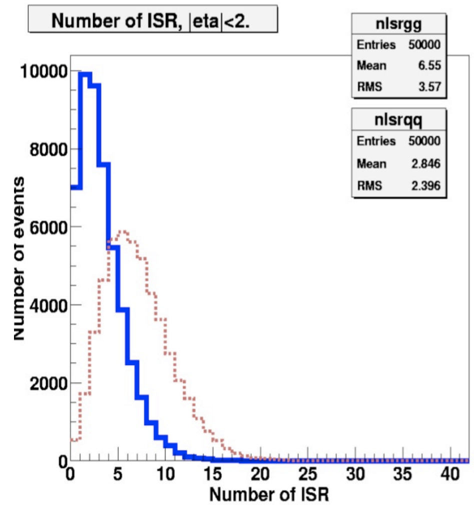


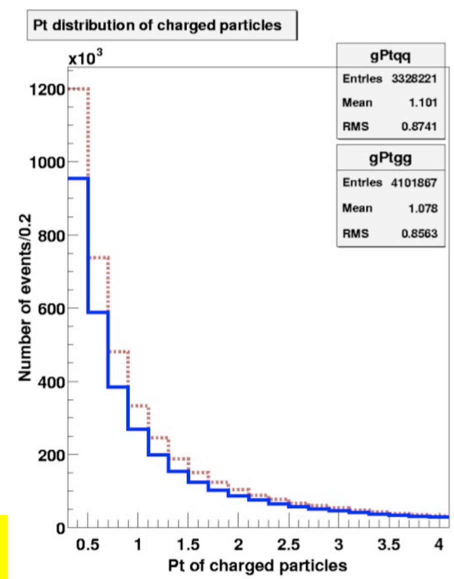


- About 30% of events have at least one extra jet
  - These jets have rapidly falling spectrum
  - "Harder" jets do cause problems in event reconstruction

"Soft" ISR/FSR

- Soft ISR/FSR are typically modelled as QCD shower of incoming partons
  - Use Altarelli-Parisi evolution "backward"
  - Add to the UE, so difficult to sort out ISR from other underlying event effects
- Example: PYTHIA creating ISR in ttbar events
  - Looked at ISR with |η|<2
    - Low P_T typical of MB events
    - Typical multiplicities are relatively small at parton level
      - Produces significantly large # of hadrons
  - See difference between quarks & gluons
    - Confirmed in W+jet and dijet studies
  - Actual rate has very large uncertainties
    - Difficult to tune in MC with any accuracy

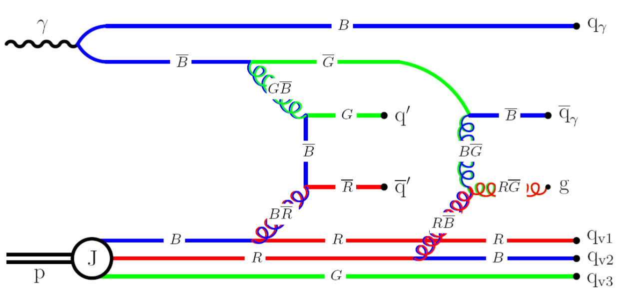




S. Pashapour, Ph.D. Thesis, CDF Public Note 9693, 2008.
(CDF Collab), Phys. Rev. D **78**, 111101 (2008).

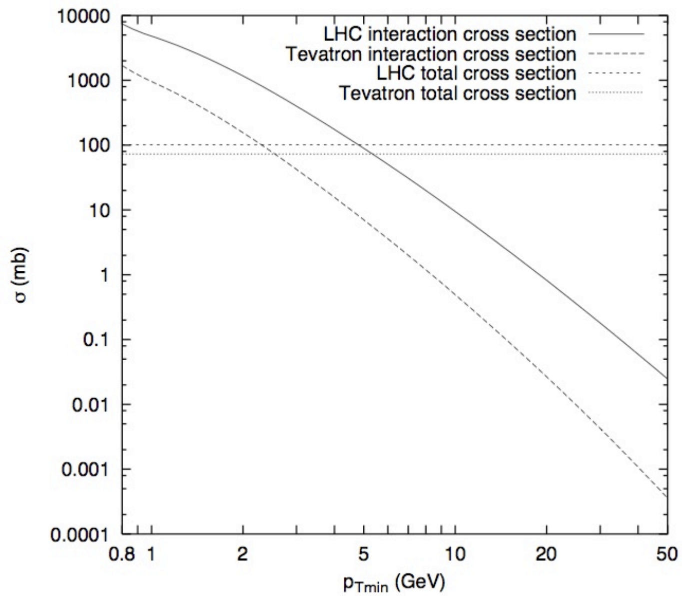
4. Modelling of UE

- **So the UE contains**
  - **Showering from incoming and outgoing partons in ME**
  - **Some part of "hard scattering" process**
  - **"Break-up" of incoming hadrons**
- **Various UE models developed**
  - **"Soft" bulk scattering**
    - Model UA5 data
    - HERWIG has good example of this
      - **OK, but doesn't reproduce energy flow accurately**
      - **Also fails to account for relatively rare, higher P_T particle production**
  - **Eikonal model**
    - Multiple 2-to-2 scatterings are basis of model
    - PYTHIA and JIMMY employ this as an underlying premise
- **Lately, emphasis has been on models that incorporate "Multiple Parton Interactions" (MPI)**
  - **Recognize that QCD still drives interactions at some low scale P_{Tmin}**
  - **Allow for MPI, taking into account**
    - Colour effects
    - Energy sharing
    - Other "screening" effects that reasonably affect the # of interactions
  - **PYTHIA authors have been taking this approach**



MPI In Action

- **Introduce an MPI cross section**
  - **Function of P_{Tmin}**
  - **"Regularize" at low P_T to get # of 2-to-2 scatters about right**
  - **Build up a complete model**
    - Verify against data



T. Sjöstrand and P.Z. Skands, JHEP 0403:053 (2004)

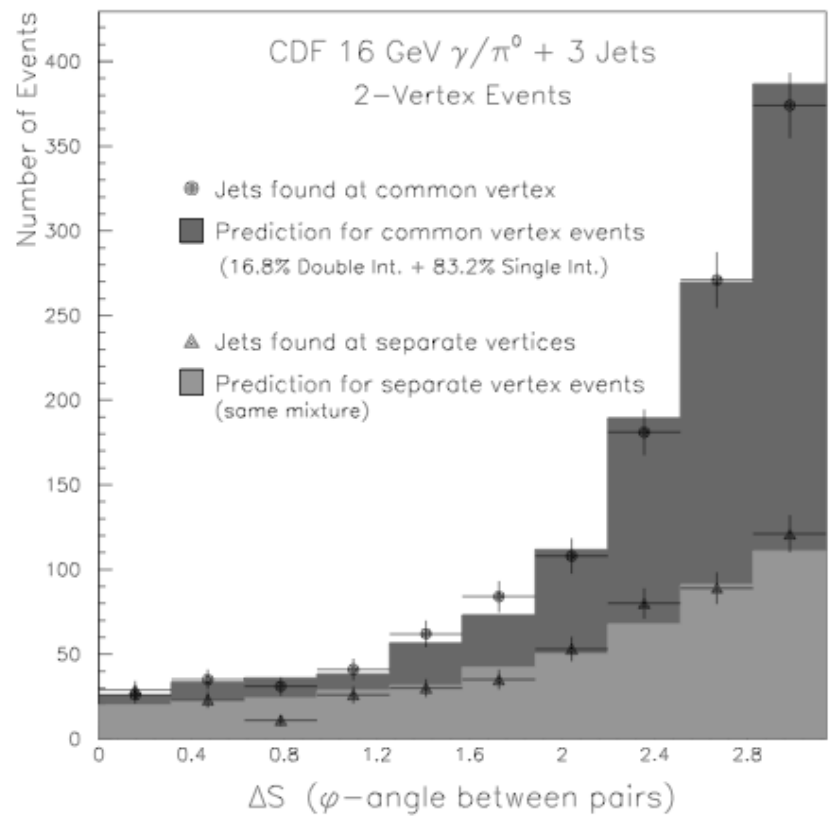
- **Real challenge is that it still requires "tuning"**
  - **This makes extrapolations to LHC energies very uncertain**
  - **Immediate LHC issue will be "tuning" of this or any other model**
- **Reasonable question:**
  - **Is one set up to do this sort of study?**
    - Energy flow and isolation?
    - Charged particle densities?
  - **How significant a problem will this be?**
    - Answer will depend on instantaneous luminosity

JIMMY Model for UE

- **JIMMY developed to model UE**
  - **Mean # of scatters N**

$$N \propto \sigma_{2\to 2} / 2\sigma_{tot}$$

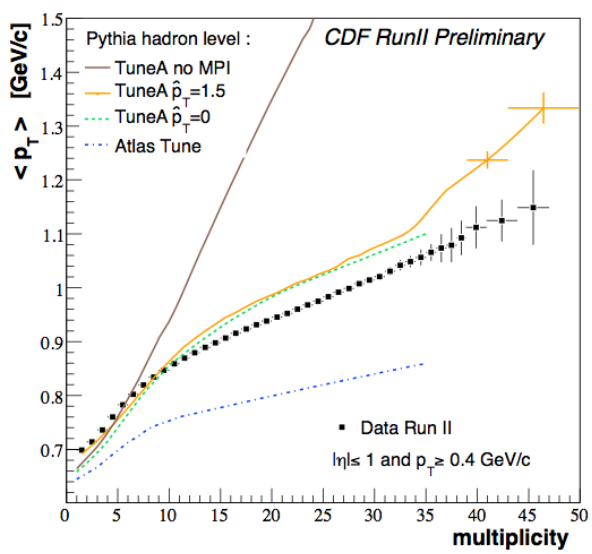
  - **Suggests effective 🅧 of 10-20 mb**
  - **Have to get each scatter approximately right**
- **Adherents believe that we' ve already seen MPI at Tevatron**
  - **Photon + 3 jet data**
    - Argue for two independent 2-to-2 scatters
  - **I' m skeptical, at least in detail….**

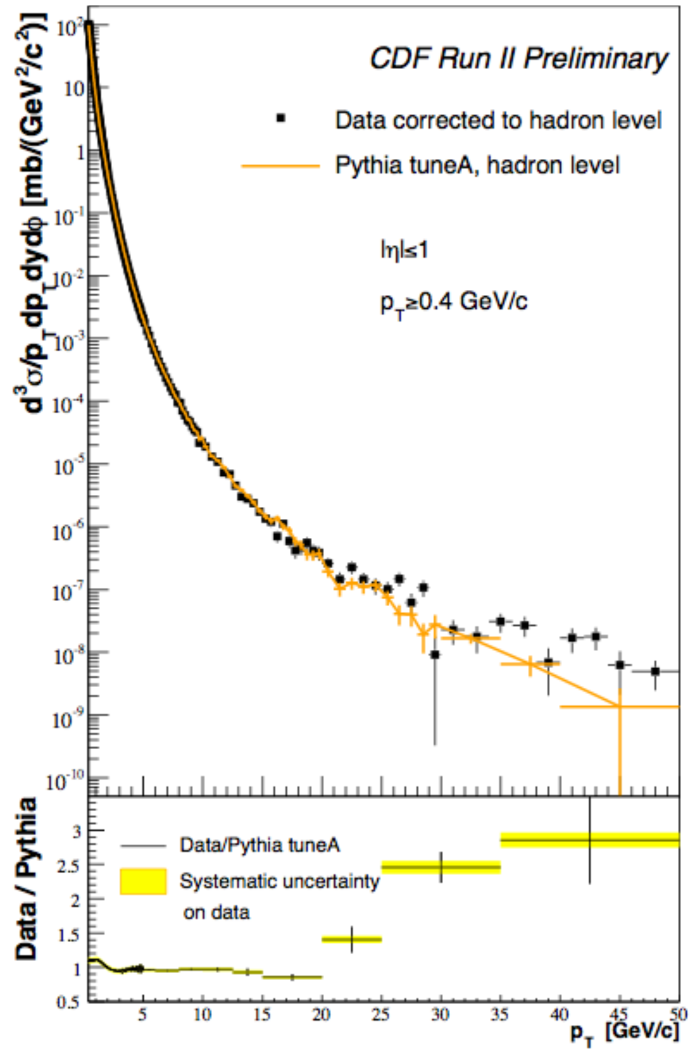


CDF, Phys. Rev. D 56, 3811 (1997).

Latest CDF Results on MB

- **Latest results on Min-bias data illustrates the uncertainties**
  - **Select min-bias events**
    - Dynamically pre-scaled to <1 Hz
  - **Plot the charged particle multiplicity & spectrum**
  - **Compare with various models**
    - Note the variation in $<P_T>$
    - Also the lack of agreement at high P_T

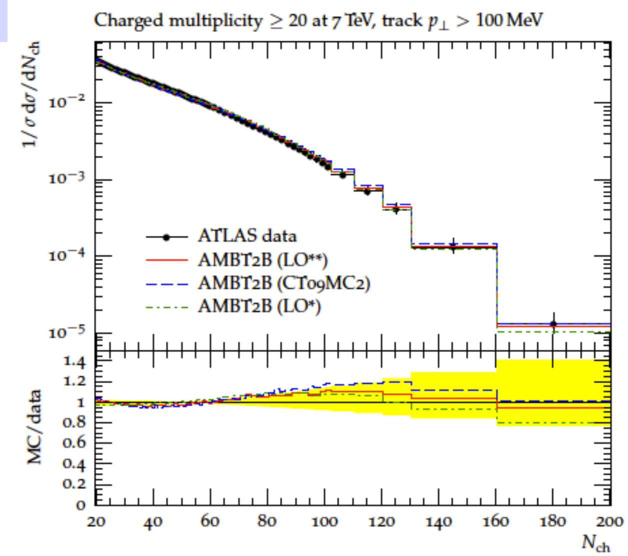


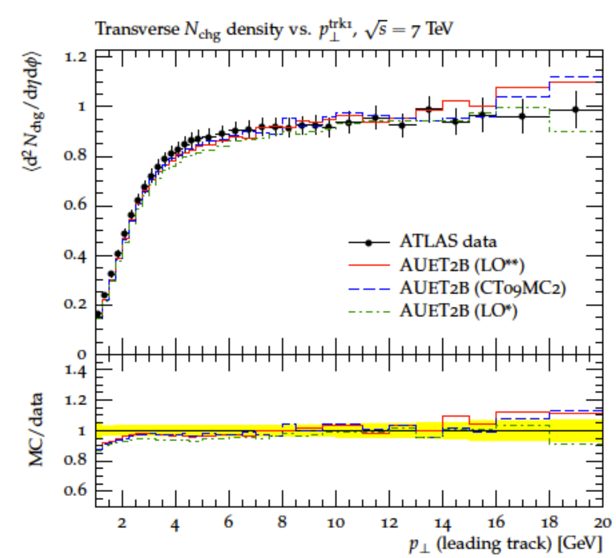


CDF, Public Note 9337 (2008)

MC Tunes

- Tevatron and LHC experiments have resorted to "tuning" MCs
  - Tevatron: Tune A, Tune B, etc.
    - Typically adjusted parameters in PYTHIA model of UE
  - LHC: have extended this to include both PYTHIA and HERWIG/JIMMY
    - Further adjust QCD hadronization model
    - Adjust model of MPI
- Two sets of tunes recently validated:
  - AMBT2B (for PYTHIA with LO PDFs)
  - AUET2B (for HERWIG/JIMMY)
- Extensive "industry" working on this

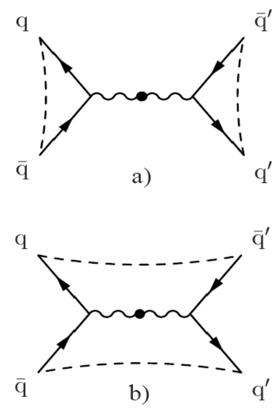




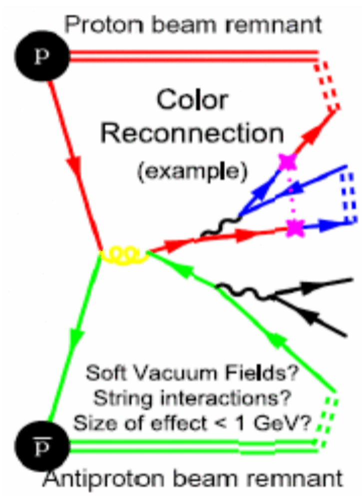
ATLAS-PHYS-PUB-2011-9 (2011)

5. Example: Colour Connection & M_{top}

- With precision of M_{top} measurements ~ 1 GeV/c^2
  - Colour connection effects between beam hadrons & top quarks become important
    - Experiments starting to investigate these
- Strategy is to use PYTHIA to explore these
  - Look at the changes in energy flow as constraints from LEP data on WW production
    - 8 MeV/c^2 uncertainty
  - Use latest UE "tunes"



LEPEWWG, hep-ex/061203



- Recent CDF/D0 work show M_{top} shift of (0.4-0.5) ± 0.3 GeV/c^2
  - Work is ongoing -- shift is large enough to start to explore in more detail

D. Wicke and P. Skands, arXiv:0807.3248V1

6. Multiple Interactions/Pileup

- **With a good understanding of the UE and MB events:**
  - **Can begin to anticipate what the entire event will look like**
- **In particular, we need to add in the multiple interactions**
  - **First look at those in the same beam crossing**

$$P(N \mid \nu = L\sigma_{tot}) = \frac{\nu^N e^{-\nu}}{N!}$$

	Sigma_in (10^-24 cm^2)	L (10^30 cm-2s-1)	Crossing Rate (10^6 s-1)	<N>	P(N>1)	P(N>5)
Tevatron	0.050	200	2.5	4.0	0.98	0.215
LHC	0.080	10	10.0	0.1	0.08	0.000
LHC	0.080	100	40.0	0.2	0.18	0.000
LHC	0.080	3,600	20.0	14.4	1.00	0.996
LHC	0.080	10,000	40.0	20.0	1.00	1.000

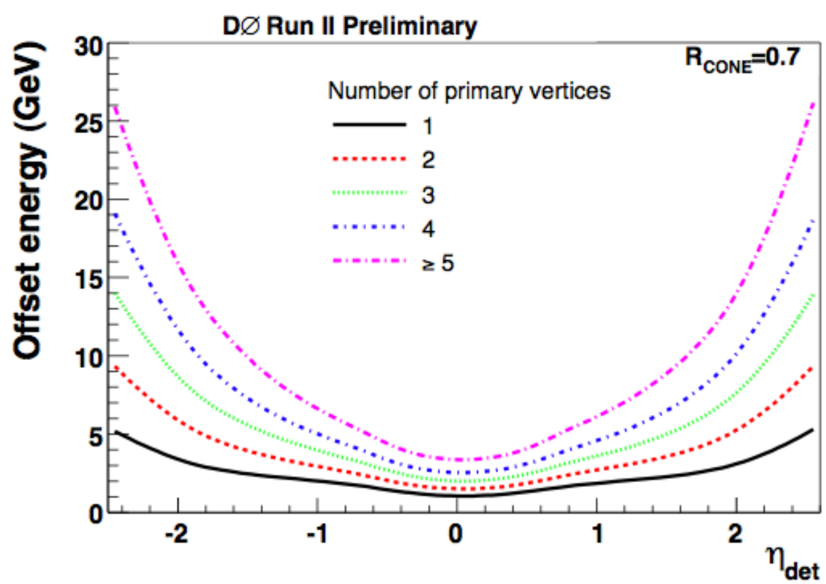
- **Second, look at the effect of out-of-time "pileup"**
  - Only matters for detectors where time resolution, t_R, greater than bunch crossing period
  - Biggest concern is LAr calorimetry in ATLAS
  - In Tevatron experiments, D0 has similar issue
    - **CDF has scintillator calorimetry**
    - **However, CDF Central Outer Tracker vulnerable**

Strategies for Multiple Interactions

- Group strategies into following categories:
  1. Correct for the effects in an average sense
  2. Separate out the hard scattering process, event-by-event
  3. Ignore the additional interactions
- Tevatron data analyses have employed all 3
  - Have demonstrated that MI/ pileup can be accommodated
  - Need to plan and model it, especially detector rate-capability
  - Give examples of all three

D0, http://www-d0.fnal.gov/phys_id/jes/public/plots_v7.1/index.html

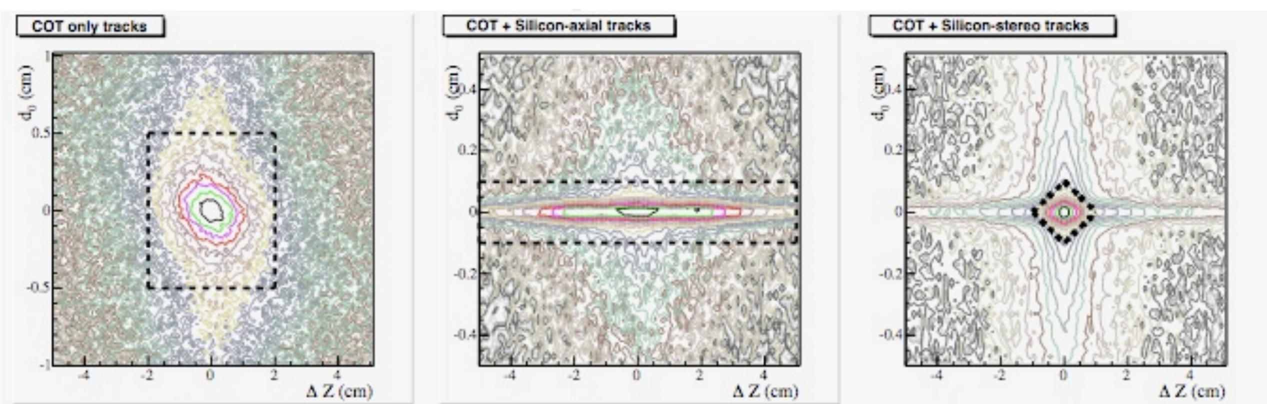
- Technique #1: D0 jet energy calibration
  - Defines an "offset energy"
    - Takes into account both MI and "pileup"
    - Characterize by # of vertices in event
      - But counting vertices, event-by-event, is a challenge



MI: Correct Event-by-Event

- **Technique #2: Do event-by-event corrections**
  - **CDF uses z location of primary vtx:**
    - Identify "primary vertex" by position along beam
    - Associate lepton candidates, charged particles & jets to this vertex
    - Works because:
      - **Large beam envelope**
      - **Relatively good charged particle tracking**

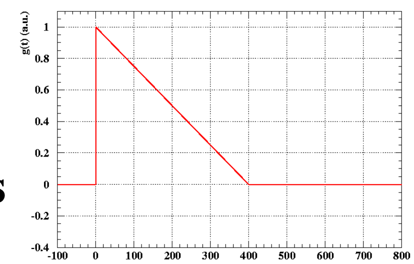
- **Doesn't work particularly well for calorimeter-based analyses**
  - **At least, one is vulnerable to**
    - Inefficiencies due to all-neutral jets
      - **Or jets outside the tracking acceptance**
    - Can't use this for photons
  - **One also needs to understand tracking quite well**
    - Real-life and simulation - difficult to get agreement at necessary level of detail

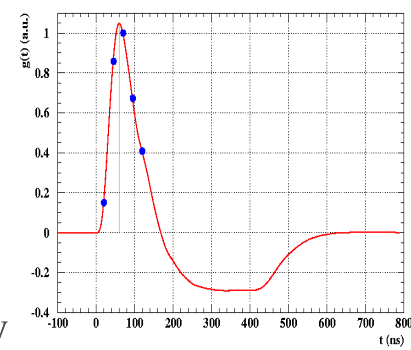


Pileup!

- **Must be clear on definition**
  - **I'm referring to "pileup" as data from "out-of-time" collisions**
  - **At Tevatron, with bunch crossings $\Delta t \sim 360$ ns**
    - Not a big deal-
      - **For CDF, occupancy in COT**
      - **For D0, LAr calorimetry**
    - Manage this OK….
  - **At LHC with $\Delta t \sim 25$-50 ns, it is more of an issue**
    - Most sensitive detector is LAr calorimeters
    - Use it as the example
- **Note that this is a technical and complex issue:**
  - **Will only give a superficial introduction**

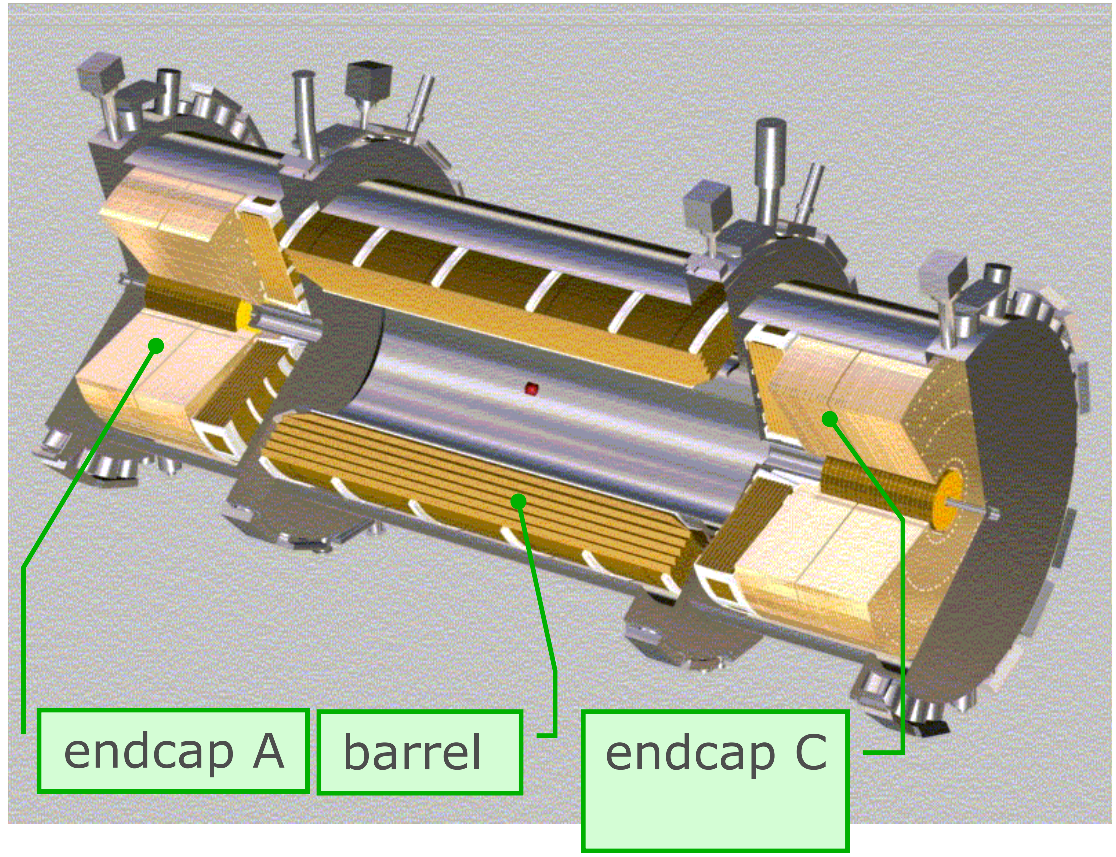
- **For LAr, signal comes in the form of charge collected across a drift gap**
  - **~450 ns drift**
  - **"Shaped by FE CR-RC preamps**
  - **Sampled 5 times and digitized**
  - **Two issues:**
    - A hit within about 200 ns will be see as "+ve" energy
    - A hit within 200-400 ns will be seen as "-ve" energy
  - **In practice, the two could "balance" each other**

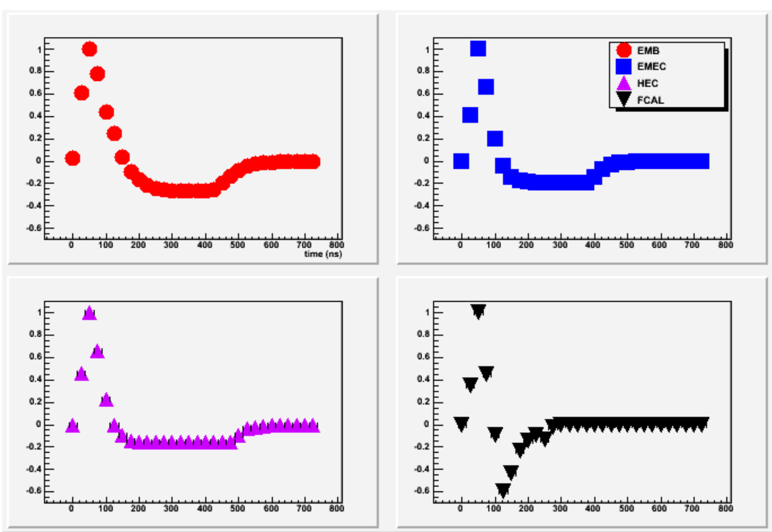




ATLAS LAr Geometry & FE

- **Signal response depends on calorimeter**
  - **This determines average response under high rate**
  - **By appropriate "averaging," can mitigate offset effects**
  - **Still degrades resolution**





- **Keeps this in mind**
  - **Critical for**
    - Jets and MET
    - Lepton isolation

Try out LArResponse.C

7. Example: Jet Energies

- The net effect of pileup is largely on jets and measures of “isolation”
  - Detector simulations have uncertainties
  - Most robust approach is to measure in data
- Compare with what is measured in data with ATLAS
  - Note m is the average number of interactions based on instantaneous luminosity
  - Could be a large or small effect, depending on analysis