Where We Are Going In Experimental Particle Physics?

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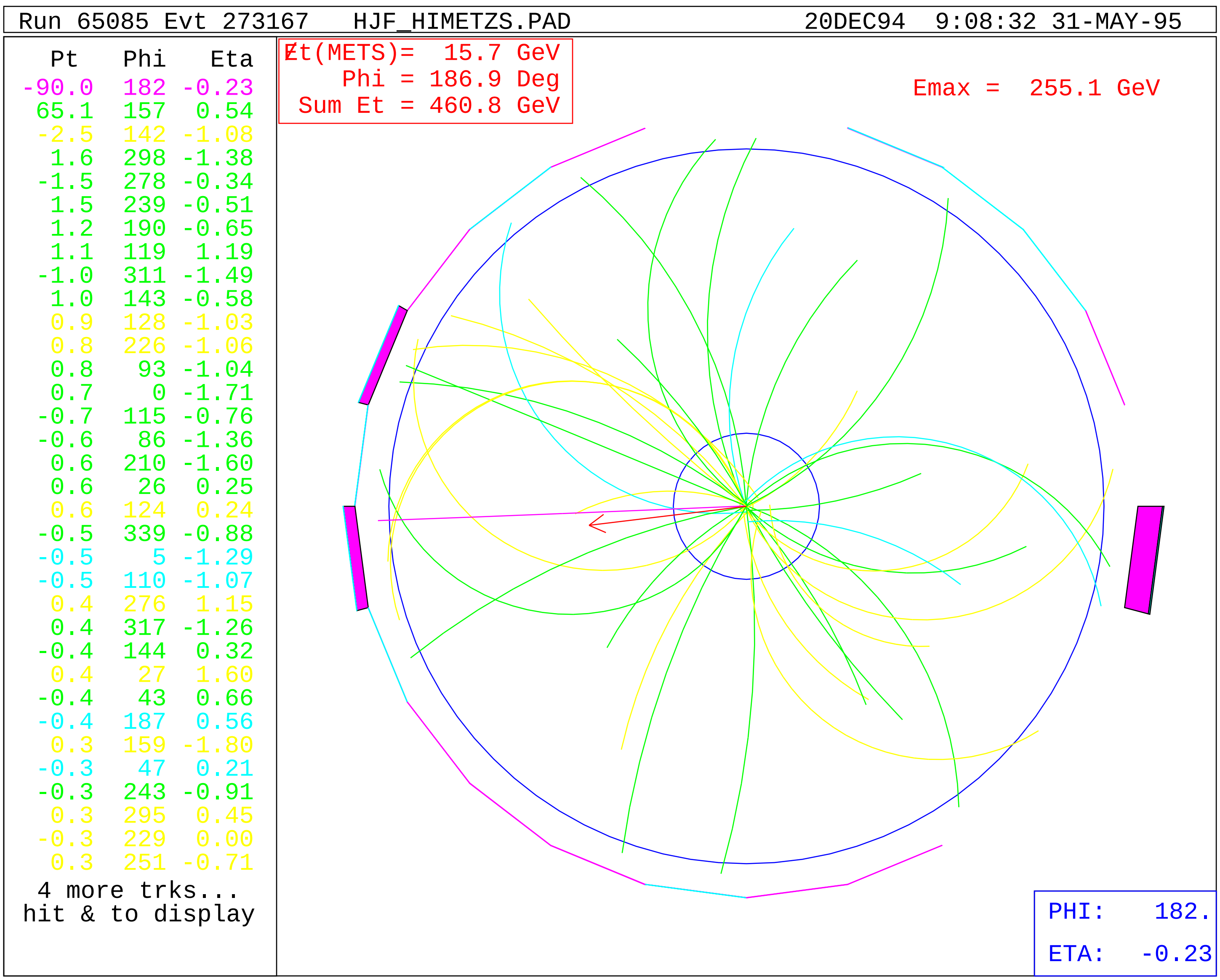


Figure 1:

Where We Are Going In Experimental Particle Physics?

Abstract:

This amounts to a counter-culture view as a complement (not an alternative) to the 'roadmap' laid out in the Bagger-Barish panel report. This will consequently be idiosyncratic and provocative. I strongly believe that in the next 5-10 years we will make major unexpected discoveries beyond the SM. At the LHC we will be extending our reach in energy by an order of magnitude, and in other new or upgraded accelerators making more top, bottom, charm, taus, and neutrinos than ever before. The revolution in FPGAs, fast serial lines, and silicon detectors opens major opportunities at hadron colliders. We will also increasingly be using the Antarctic ice, the Moon, and the Earth as targets for ultra-high energy cosmic rays. The far future depends on providing attractive opportunities for the most talented and creative present young folks; the physics opportunities will be there.

The Decade of Opportunity

(the following isn't a transparency- was an informal intro.- these are my notes to myself...)

Look, I'm a simple-minded experimentalist, so this will be very close to the ground. I've been thinking hard about 'the vision thing' since Paul and Michael's invitation, but slowly, so this'll also be short. In particular, rather than try to envision all the possibilities for new physics and new experimenting, or to make the political case for new facilities, I have tried to focus on what I think will be most important to the field of experimental particle physics in the next 10-15 years.

Although it may seem both obvious and mundane (particular to theorists) to you, I'm a little surprised myself by the details of what I've concluded. The vision is largely taking maximum advantage of our present opportunities with the same flair and creativity that is so well represented by the many talks at this conference.. This will mean developing new detector capabilities and perhaps a different way of working. There are major opportunities in the fields of neutrino physics, dark-matter searches, very high energy cosmic rays, and so forth; however I expect the physics of the coming 10 years to be dominated by discoveries at the LHC, which will substantially determine where we go beyond that. I (partially) apologize in advance for those who find this vision not sexy enough; I tend to be hard-nosed on opportunities lost by solely focusing on distant goals: even the pros drop the ball when they start running downfield before catching it.

A couple of disclaimers:

1. **I'm not on any LHC collaboration (I say this because my conclusions seem very LHC-centric, but that's really because the LHC is the 800-pound gorilla in this game). I apologize to all experimenters doing other things- but I predict that the LHC is going to be the dominant player in where the physics goes...**

2. **I like doing small sweet experiments, and that's where my experimental heart is... Would like to be able to do them wherever the opportunities for new physics are greatest.**

3. **I'm very low-tech in the art of presentation- I work in PowderPoint, by Attosoft...**

WHAT WILL HAPPEN IN THE NEXT 10 YEARS?

One often needs to predict how fast a student, group,or oneself will get a job done. A theorem (Taylor/MacLauren):

The amount that will be done in a future time interval Δt is best estimated by how much was done in the recent past interval - Δt.

So, what have we (a broad we- if it tests reductively one of the fundamental forces it's done by we- one of the wonderful side effects of unification) done lately?

Take Δt= ten years: LAST TEN YEARS:

1. Discovered the breaking of electron number(!);
2. Made first measurements of the lepton mixing and mass matrices;
3. Discovered a fundamental fermion heavier than the EWK scale (top) (Who ordered THAT?);
4. Discovered direct CP violation in the kaon and CP violation in the b systems;
5. Tested the SM with precision measurements to within an inch of its life (the inch on the Higgs mass axis);
6. Made first precision measurements pointing to the unification of the coupling constants.

$\Delta t = -$ 10 years -p2

Another list is:

1. Built at least three new accelerators, are building the largest accelerator ever built, and upgraded two? more (with detectors).
2. Have set record luminosities in e^+e^-, ep, and $\bar{p}p$ collisions.
3. Are building the largest and most sophisticated accelerator-based detectors ever (LHC).
4. Are using Antarctic ice, the rim of the moon, and thousands of square kilometers of the atmosphere as targets for ultra-high energy cosmic rays.
5. Are exploring gravity at short distances and high precision.
6. Have increased the sensitivity (size) of searches for proton decay, dark matter, solar and atmospheric neutrinos by orders of magnitude.
7. Are doing serious R&D and planning for the next accelerator after the next one.

Now the Future: $\Delta t = +\ 10$ years

Theorists have been busy and have revolutionized our perceptions of the opportunities for experimentalists. It's a completely different landscape: (experimentalists knew they'd come around...)

1. Gravity and the Planck Scale could be within reach of accelerators (my dream is to do quantum gravity experiments);
2. Much richer range of possibilities of new physics- KK towers of excited particles, SUSY partners, technithingees, new gauge bosons, new scales for breaking lepton flavor,...
3. The heavy top quark means that in SUSY could have a light stop;
4. The SUSY Higgs sector may be much richer and more complicated than we (I) thought...
5. Have built a much closer connection to Astronomy and the precision experiment community through the Quarks $\rightarrow$ Cosmos connection (note the direction of the arrow!).

Hadron Machines As Flavor Factories

One of the surprises at the Tevatron has been precision flavor physics. Hadron colliders are flavor factories:

- Copious production of s, c, b, t; e, μ, τ
- Surprising ability to do exclusive final states (B's, D's, etc.)
- Can hence do precision studies of flavor (e.g. b, rare decays, b_s, mixing, top, top rare decays, ..
- Large control samples for identifying flavor in decays of new heavy particles, e.g. $\tilde{t} \rightarrow c\tilde{\chi}^+$, $h \rightarrow \tau^+\tau^-$,...)

We will consequently want large samples of all the flavors, quarkonic and leptonic.

Hadron Machines as Flavor Factories- Continued

- At the Tevatron we are on the learning curve of flavor ID- nursery school for LHC and beyond
- Now identify charm, bottom, top, neutral strange (Λ, K_0). We find π^0's (and η's and ρ's). Always have done e's and μ's. Now τ's are coming onto an equal footing.
- (Not just flavor as ingredients- also γ's, W's, and Z's..)
- So one ingredient of the vision is to develop and use flavor identification to a much higher degree.
- The revolutions in the silicon industry and in communications can provide the essential capabilities in this. The present collider detectors are using decade-old (at least) technology in many places; the LHC detectors will be in the same situation when they come on-line.

Question: HOW FAR CAN WE GO?

Detectors

- Think of Bruno Rossi's setups in the 1930's of a few Geiger counters, bulky amplifiers, and coincidence circuits.
- Now have multiwire proportional systems with approximately 10^5 wires, silicon detectors with $> 10^6$ amplifier channels,...
- With silicon detectors spatial resolutions of $< 10\mu$m is typical.

So, invoking our $\pm\Delta T$ Theorem, what detector capabilities do we want most to develop?

Detectors Continued

My choice for development is time-of-flight (!?). Precise measurement of the 3-vector, the point of origin, and the particle type gives *all the information possible about each particle*.

If we could measure with $\sigma = 1$ psec (yes) in a path length of 1.5m (e.g. CDF), get 1 σ $\pi - K$ separation at $p_T = 25$ GeV.

Is this crazy?

- There exist GaAs Schottky photodiodes with $\sigma \sim 1$ psec, so no law of nature precludes it.
- Need a fast source of light- e.g. Cherenkov radiation.
- Light cannot bounce- has to go straight in.
- Need spatial resolution $< 300\mu$m for $\delta t = 1$ psec.
- Find the collision 'start' time by measuring the time of tracks relative to each other.
- Have to calibrate entire volume *in situ*- need lots of π, K, p,...

So, could we build an outer layer for a central (solenoidal) detector with good spatial resolution and segmentation such that **for every track with $p_T < 25$ GeV we measure not only p_x, p_y, p_z, but also its flavor content?**

The Revolution in Pattern Recognition Hardware and Silicon Tracking and the Next Machine (LHC)

This is provocative, but we historically we have underestimated the experimental opportunities at hadron colliders. What happens at the LHC will have a big impact on the future. Hard to make changes in the big hardware, but electronics and data acquisition can make big differences in the physics, and can be upgraded on a much faster time scale.

- One the big experiment is mature, treat it more like a lab or facility. Encourage (formal) proposals for new capabilities, measurements, from small collaborations, both inside and outside.
- Multiple opportunities for creative science for young people.
- One example: the advent of big FPGA's allows smart pattern recognition in tracking in hardware: do primitives analysis in hardware.
- Fast (2 Gigabit/sec) serial lines revolutionize the cable plant and physical constraints on trigger hardware; much more powerful processing is possible.
- Silicon systems allow exclusive state reconstruction, impact parameter on b's, charm, tau's, etc.

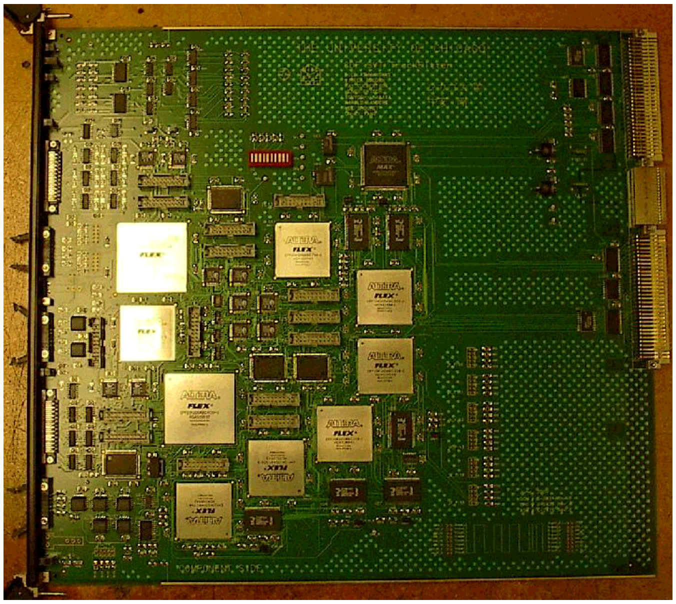
Being More Specific:
Hadronic B Factories

- A big detector like CDF or D0 is in some ways two experiments superposed: the searches and precision measurements in high-Et physics (top, W,Z, WW, SUSY, LED,...).
- High Et wants large live-time;
- high-cross section physics such as B-physics wants bandwidth.
- The (LO(MadGraph)) cross section for b production is $\sim 6.4\ \mu$b for $p_T^b > 5$ GeV, $|\eta| < 2.0$;
- At 2E32 this is 1000 b's per second (10^{10} b's/year) produced.

Could one write them many more of them 'to tape'?

Idea: Preprocess tracks in hardware- reduce datasize but not precision (by keeping residuals)

(Note: At LHC factor of >14 in cross-section, 50? in lum $\Rightarrow 10^{13}$ b's/year, but...))



SVT: > 100 VME Boards

New thing: The Silicon Vertex Tracker/Trigger reconstructs all central tracks with $p_T > 2$ in about 15 μ sec with a resolution of $0.3\% p_T$(GeV) and an impact resolution of about 35 μm.

This allows CDF to trigger on hadronic b-decays.

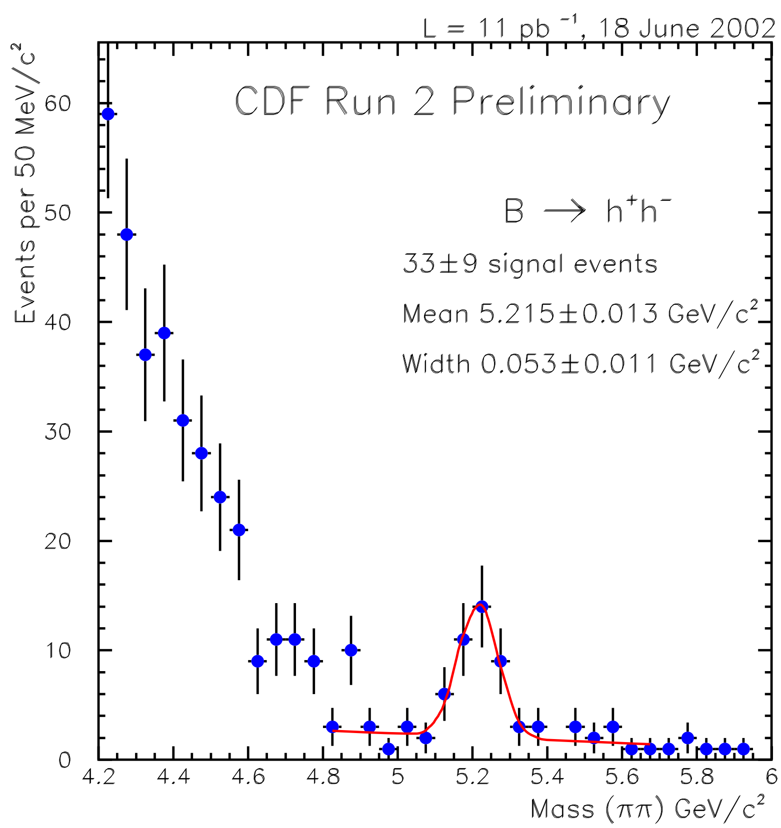


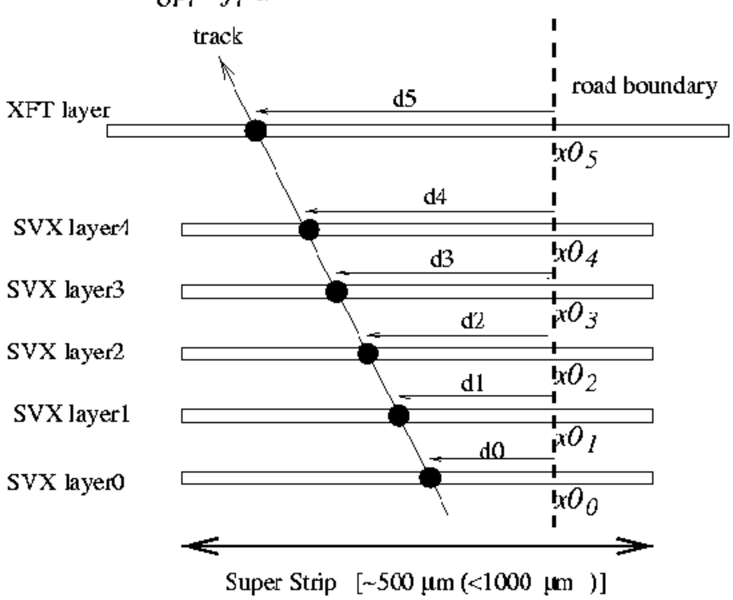
Figure 2: SVT-triggered Run II CDF data

SVT is a first example of where we can go in the electronics frontier:

- Input is 200 Gigabits/sec (but it's idle 90% of the time!)
- Does energy-weighted clustering of strips, precision like offline (has full data).
- Present SVT limited to tracks with $p_T > 1.5$ GeV by older chip sizes; new chips much larger.
- Goal would be to process silicon tracks and save full precision on hits on tracks.
- Similar preprocessing in the outer tracker puts processing power in front of readout, data handling (and software performance).

$$p_i = \vec{f}_i \cdot \vec{x} + q_i$$
$$p0_i + \delta p_i = f_i \cdot (\vec{x0} + \vec{d}) + q_i$$

$$p0_i = \vec{f}_i \cdot \vec{x0} + q_i \quad \textbf{(Precalculable)}$$
$$\delta p_i = \vec{f}_i \cdot \vec{d}$$



Exploiting the Electronics Frontier- cont.

First small step example: (use CDF Run2 numbers- can scale up):

- Present rate of 50 Hz limited by: a) readout time, b) bandwidth to tape
- Bandwidth to tape is 50 Hz of 400 Kbyte events
- Would be 2 KHz of 10 Kbyte events with no changes.
- SVT reads out in 20 microseconds.
- Outer tracker to do pattern recognition in front-end cards- ship up track segments and 1byte hit offsets
- Looks very possible with new FPGA's at TDC level?
- 40 tracks $\times$ 100 hits/track + rest fits in 10Kbytes.
- 'Vernier' scheme- N% of events are read-out fully as well as compressed- monitor the heck out of them, and change N as appropriate.

Hadron Colliders As Precision Instruments

Premise: the LHC will dominate the HEP landscape at some point (not to diminish the importance of anything else, but it will be the energy frontier).

QUESTION: **Can we sharpen the comparison with the SM predictions by by canceling out uncertainties inherent in the hadron collisions?**

Example: W+Jets and Z+Jets Channels:

Much interest in the W+jets and Z+ jets channels for measurements of the top quark ($t\bar{t}$ and $t\bar{b}$), charginos, neutralinos, Z-primes, W-primes, LED's, leptoquarks,....

Hard to measure though- W+3 jets gets mixed up with W+4 jets (theoretically AND experimentally),...

Suggest that experimentalists pick quantities that they can measure well (think ϵ'/ϵ) and measure those- let theorists 'deal'. (Like a change of basis).

Conclusion- for searches, top physics, forget (!) the W+Jets cross sections– measure ratios such as (W+Njets)/(Z+Njets).

New Measurables- page 1

For example, look at the experimental uncertainties on $\sigma(W + jets)$ as published by CDF:

N(Jets)	Et_J Scale	Und Ev	QCD Bkgd	Mult Int	η_J	Acc	Oblit	Top
≥ 1	6.8%	5.8%	5.2%	3.2%	1.9%	0.8%	0.2%	0.05%
≥ 2	11%	9.8%	5.4%	7.2%	3.7%	1.0%	0.3%	0.3%
≥ 3	17%	16%	9.1%	9.8%	4.8%	1.8%	0.6%	1.3%
≥ 4	23%	21%	15.8%	14%	5.5%	3.5%	1.3%	0.5%

Looking at the uncertainties in turn and rating cancellation in the W/Z ratio (this is to first order- $\exists$ 2nd order effects):

1. Jet Energy Scale: Cancels in Ratio
2. Underlying Event: Cancels in Ratio
3. QCD Background- different in W and Z
4. Multiple Interactions- Cancels in Ratio
5. Finite jet η resolution- Cancels in Ratio, but small effect due to different jet η distributions in W and Z events.
6. Acceptance- Partial cancellation in Ratio
7. Obliteration of electron by Jets- Partial Cancellation
8. Top. No cancellation.

New Measurables- page 2

For example, look at the theoretical uncertainties as seen by an experimentalist running LO MC (MCFM) due to Q^2: $\sigma(W + jets)$ changes by more than 15%; ratio $\sigma(W + jets)/\sigma(W + jets)$ changes by less than 2%.

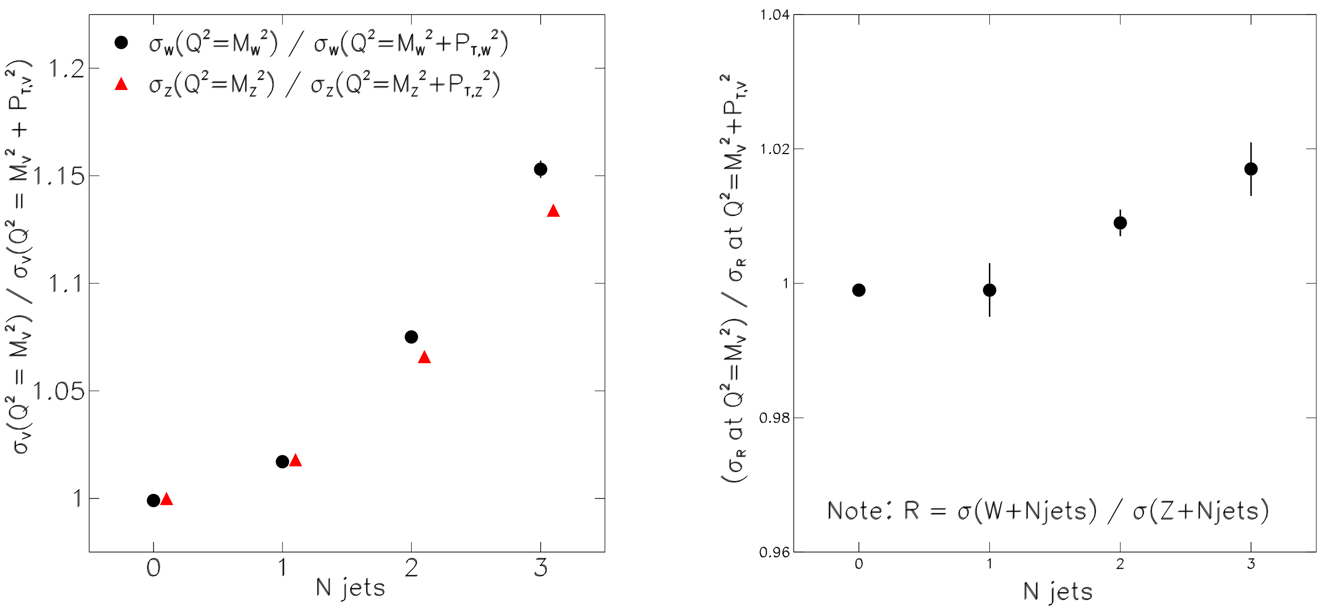


Figure 3:

(Erin Abouzaid- UC)

New Measurables- page 3

As another example, look at uncertainties in cross sections when one changes parton distribution functions:

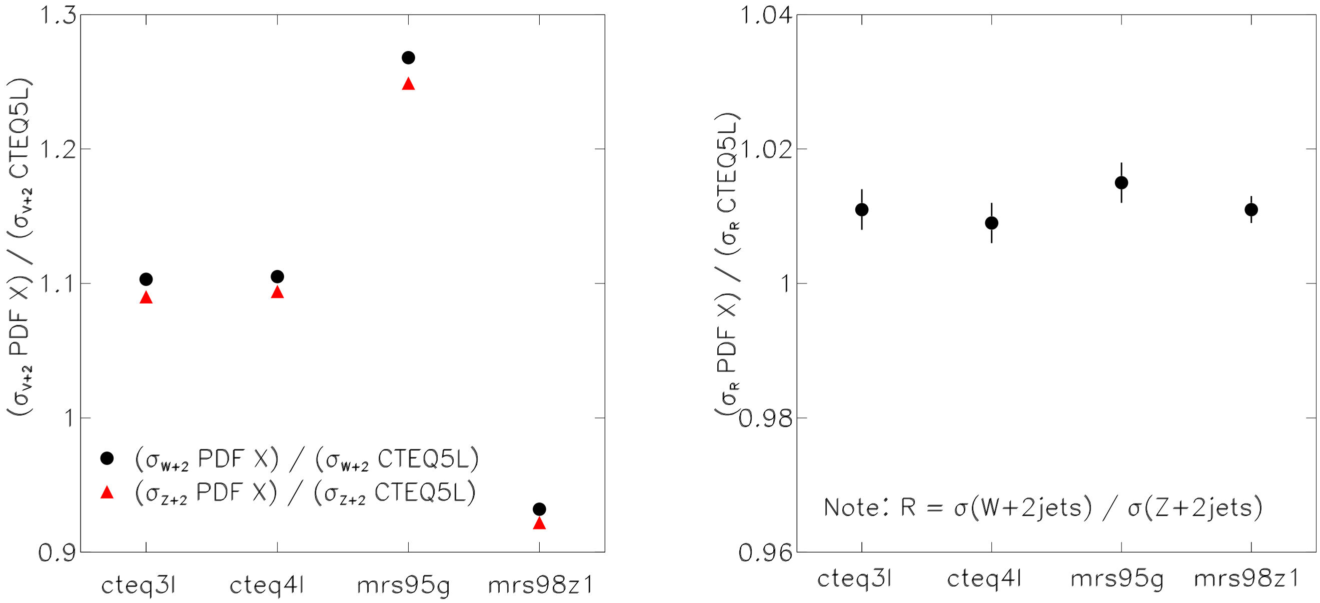


Figure 4:

More than 30% excursion in individual cross sections comes down to less than 2% in the ratios.

(Erin Abouzaid- UC)

Conclusions

This is a great time for experimental particle physics. The last 10 years have been a period of spectacular growth in our knowledge of the particle world. There is every reason to believe that the next 10 years will be as good or better. We are pushing the frontiers in energy and precision on a wider front than ever before. Last, but not least, we thrive on the intellectual excitement we get from the progress of our theoretical friends. It's a tremendous kick to be able to measure these amazing building blocks, whatever they are.

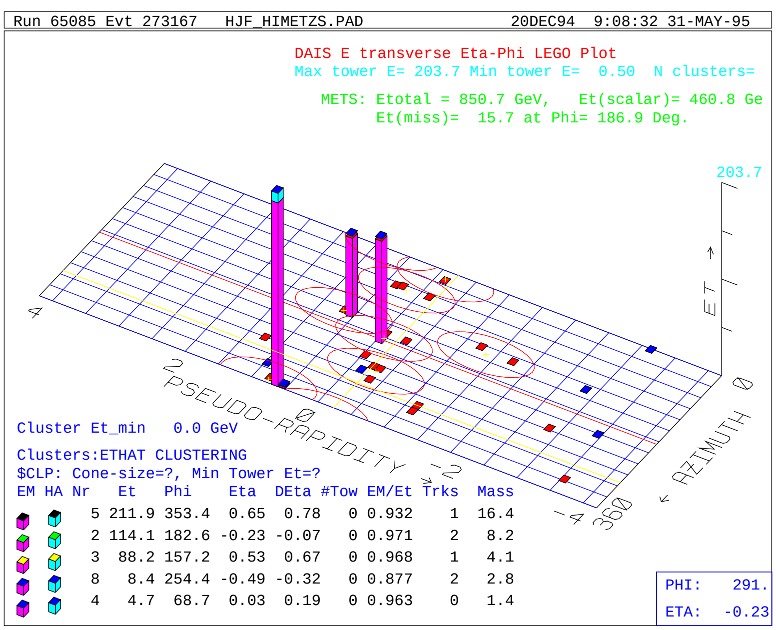


Figure 5:

A Wish List

I conclude with a wish list: (my mom prays for Tevatron luminosity every evening, among other things):

1. **An effective Planck scale of 1 TeV or below;**
2. **At least one light (<400 GeV) squark that decays into Higgsinos/Photinos (so that we can produce weakly coupled things strongly**
3. **L**$\geq 10^{32}R$ **and** $\int \mathcal{L}dt \geq 15$ **fb**$^{-1}$*on tape* **at Fermilab;**
4. **More of the odd photon events and non-top-like top events at Fermilab.**
5. **An affordable TOF detector with 1 psec resolution**

A Serious Comment on the Far-Future

The Far Future is in our young folk. There is wonderful intellectual challenge and creative opportunity in Experimental HEP- I would claim (arguably, of course) unsurpassed by any other field. It's up to us to make sure that the present is such that they will be there in the far future.