Precision Measurements, Small Crosssections, and Non-Standard Signatures: The Learning Curve at a Hadron Collider

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Lecture 1: Introduction to Collider Physics

Lecture 2: Tevatron Jets; W,Z,γ; Top, Bottom

Lecture 3:
1) Searching for the Higgs
2) Searching for Not-SM events
3) The Learning Curve at a Collider
4) Unsolved Problems

Acknowledgements

- Thanks to many CDF and D0 colleagues whose work I'll show… Also SM MC generator folks (these are the heros- we need more of them!)
- Apologies to D0- I tend to show much more CDF than D0 as I know it much better (happy for help on this).
- Opinions, errors, and some of the plots are my own, and do not represent any official anything.

Note-These lectures are frankly pedagogical- apologies to the experts in advance..

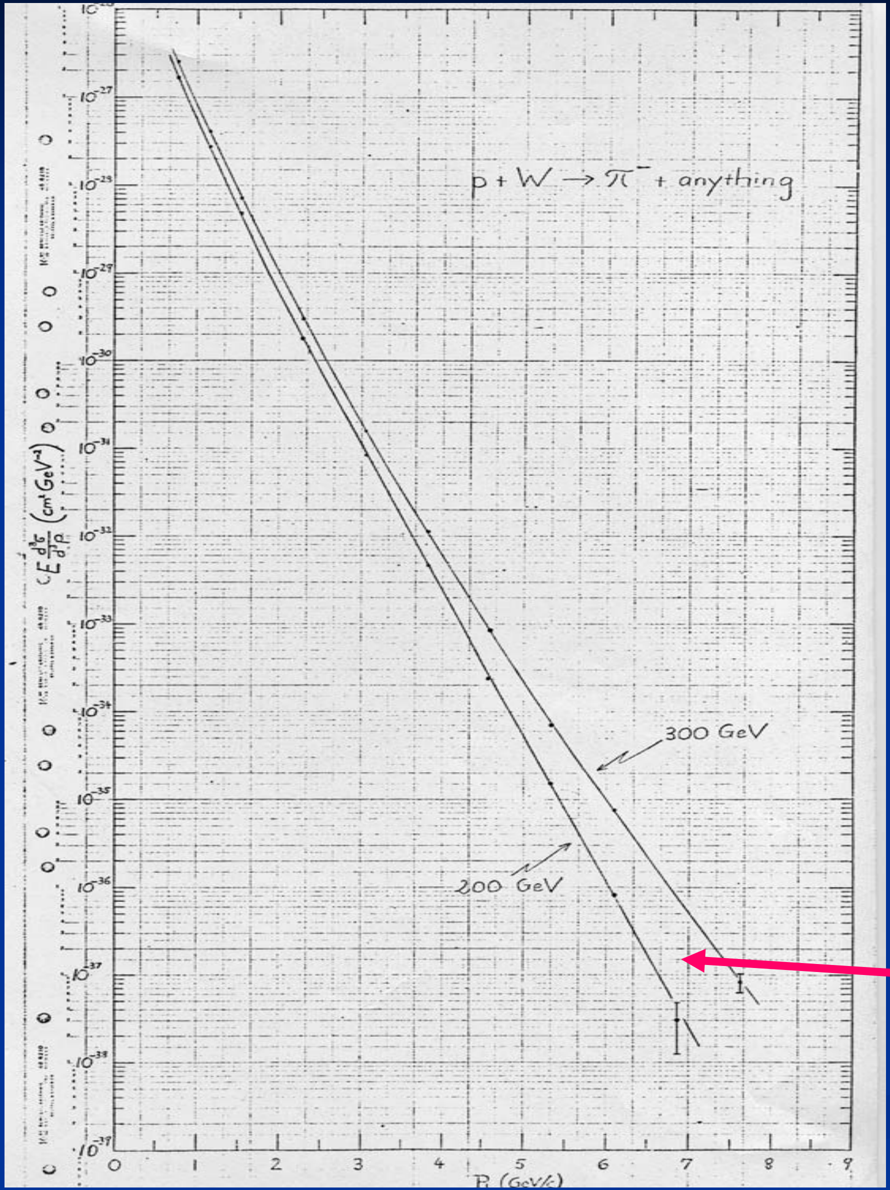
Some topics woven in the lectures: (part of the hadron collider culture)

1. ‘Objects’ and their limitations (e.g. em clusters)
2. Fake rates and efficiencies (z=1 limit and I-spin)
3. The rationale for signature-based searches
4. The problem of communicating experimental results in a model-independent way
5. The problem of Njets in W and Z production
6. Systematics-limiting variables
7. The doubling time: luminosity vs learning
8. The role of hardware in attracting/keeping young folks..

Some Basics- Partons, Luminosity,..

- Before 1970, folk-wisdom was that dsigma-dPt fell like e^{-6pt} – no interest in exploring pt axis of the Peyrou plot. Changed with ISR and Fermilab high Pt pion production..
- Parton model was new- not clear what was source of high-Pt pions- hard-scattering, CIM,..
- Jets and fragmentation - `fans’, or `pencils’?
- We know so much more now, but shouldn’t forget the lessons we learned along the way…

E100 at Fermilab: 1970-77



First Results- 1972- see power-law behavior and energy dependence at large Pt

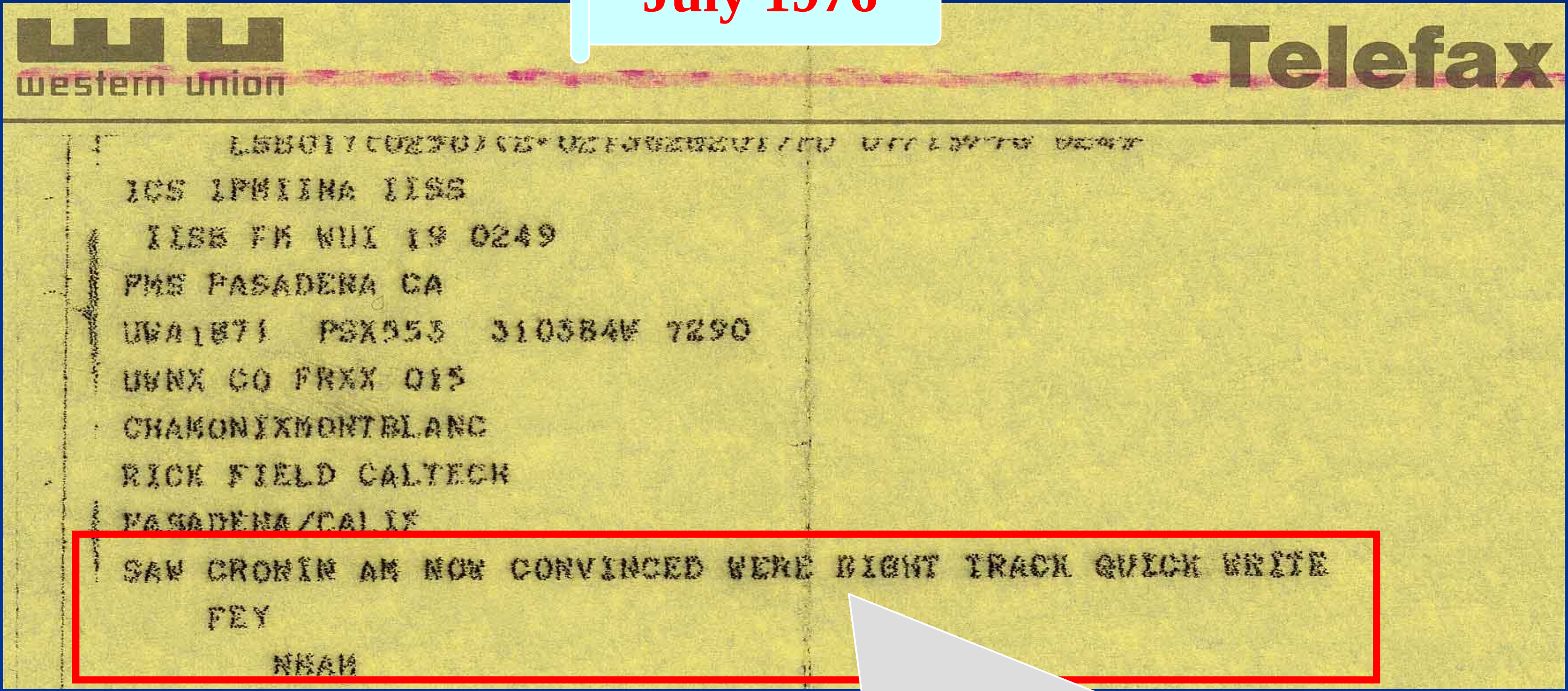
BUT- ISR beat us to punch line (sadly, and barely)

Note energy-dependence at high Pt- evidence of hard scatters

From Rick Field's Lectures at UC, July 2006

Telagram (sic) from Feynman

July 1976



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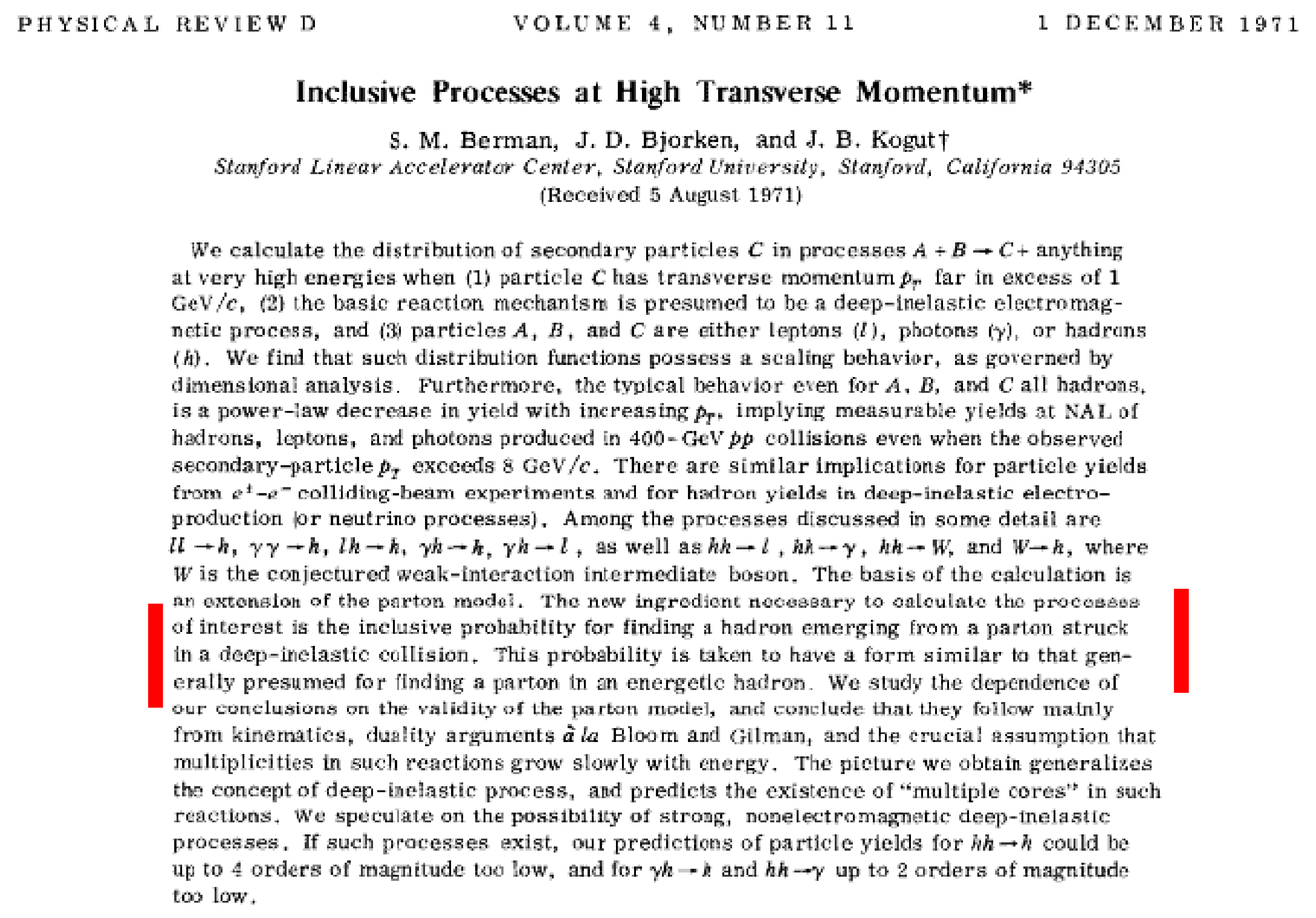
1971 Berman, Bjorken, and Kogut



PHYSICAL REVIEW D VOLUME 4, NUMBER 11 1 DECEMBER 1971

Inclusive Processes at High Transverse Momentum*

S. M. Berman, J. D. Bjorken, and J. B. Kogut†
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 5 August 1971)

We calculate the distribution of secondary particles C in processes $A+B \rightarrow C+$ anything at very high energies when (1) particle C has transverse momentum p_T far in excess of 1 GeV/c, (2) the basic reaction mechanism is presumed to be a deep-inelastic electromagnetic process, and (3) particles A, B, and C are either leptons (l), photons (γ), or hadrons (h). We find that such distribution functions possess a scaling behavior, as governed by dimensional analysis. Furthermore, the typical behavior even for A, B, and C all hadrons, is a power-law decrease in yield with increasing p_T, implying measurable yields at NAL of hadrons, leptons, and photons produced in 400-GeV pp collisions even when the observed secondary-particle p_T exceeds 8 GeV/c. There are similar implications for particle yields from e^+-e^- colliding-beam experiments and for hadron yields in deep-inelastic electroproduction (or neutrino processes). Among the processes discussed in some detail are $ll \rightarrow h$, $\gamma\gamma \rightarrow h$, $lh \rightarrow h$, $\gamma h \rightarrow h$, $\gamma h \rightarrow l$, as well as $hh \rightarrow l$, $hh \rightarrow \gamma$, $hh \rightarrow W$, and $W \rightarrow h$, where W is the conjectured weak-interaction intermediate boson. The basis of the calculation is an extension of the parton model. The new ingredient necessary to calculate the processes of interest is the inclusive probability for finding a hadron emerging from a parton struck in a deep-inelastic collision. This probability is taken to have a form similar to that generally presumed for finding a parton in an energetic hadron. We study the dependence of our conclusions on the validity of the parton model, and conclude that they follow mainly from kinematics, duality arguments *à la* Bloom and Gilman, and the crucial assumption that multiplicities in such reactions grow slowly with energy. The picture we obtain generalizes the concept of deep-inelastic process, and predicts the existence of "multiple cores" in such reactions. We speculate on the possibility of strong, nonelectromagnetic deep-inelastic processes. If such processes exist, our predictions of particle yields for $hh \rightarrow h$ could be up to 4 orders of magnitude too low, and for $\gamma h \rightarrow h$ and $hh \rightarrow \gamma$ up to 2 orders of magnitude too low.

Seminal Paper on Hadron Collider Physics- early days of the parton model

1971 Berman, Bjorken, and Kogut

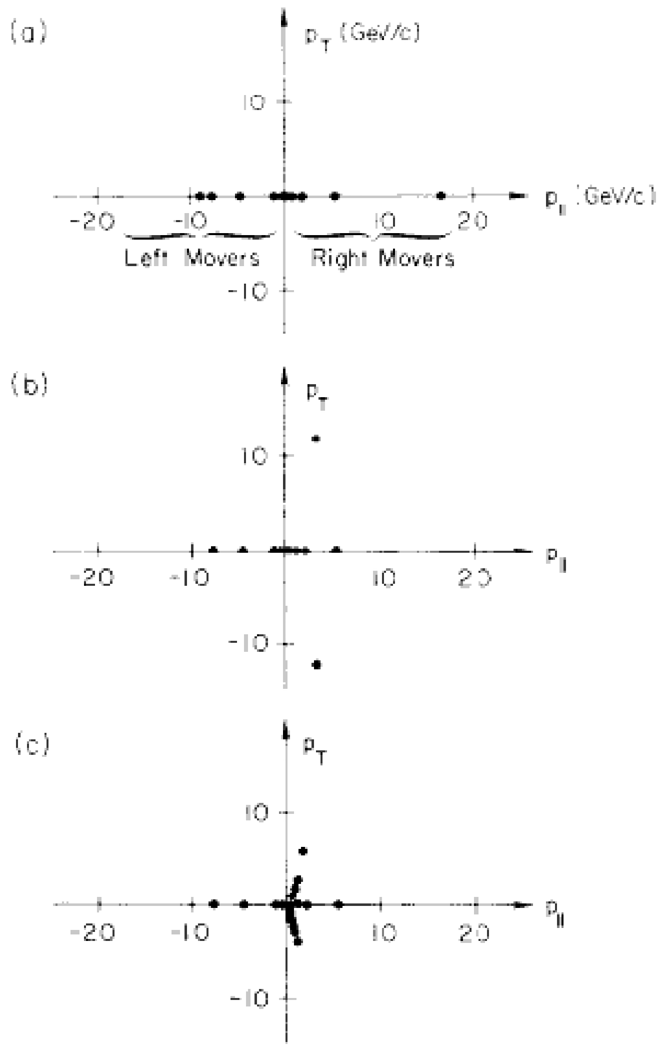


FIG. 4. A momentum-space visualization of hadron-hadron deep-inelastic scattering occurring in three steps.

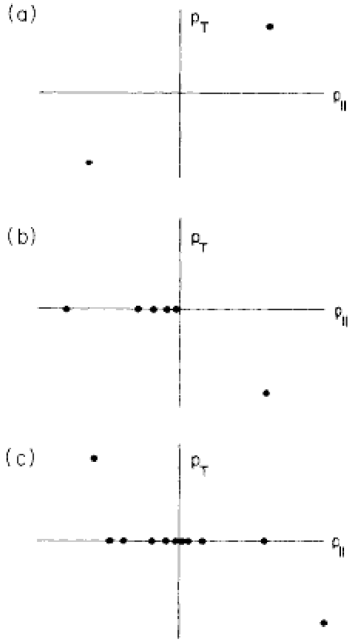


FIG. 37. Configuration of partons in phase space immediately after deep-inelastic interaction for (a) $e^+e^- \rightarrow$ hadrons, (b) $ep \rightarrow e +$ hadrons, (c) $pp \rightarrow$ hadrons.

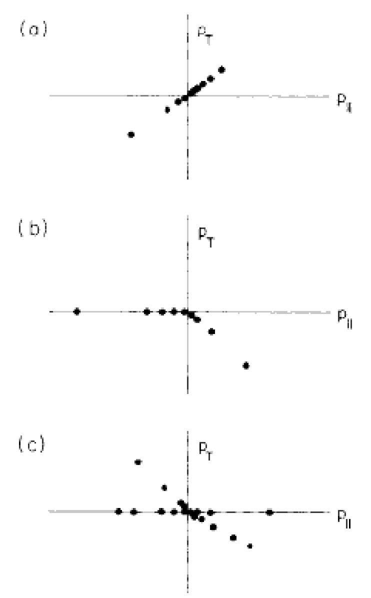
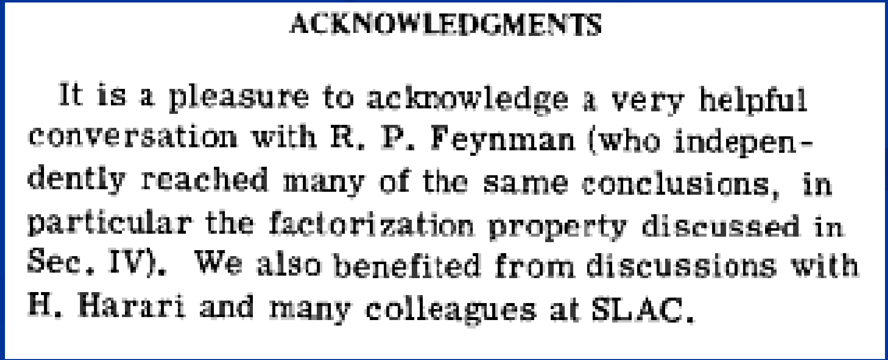


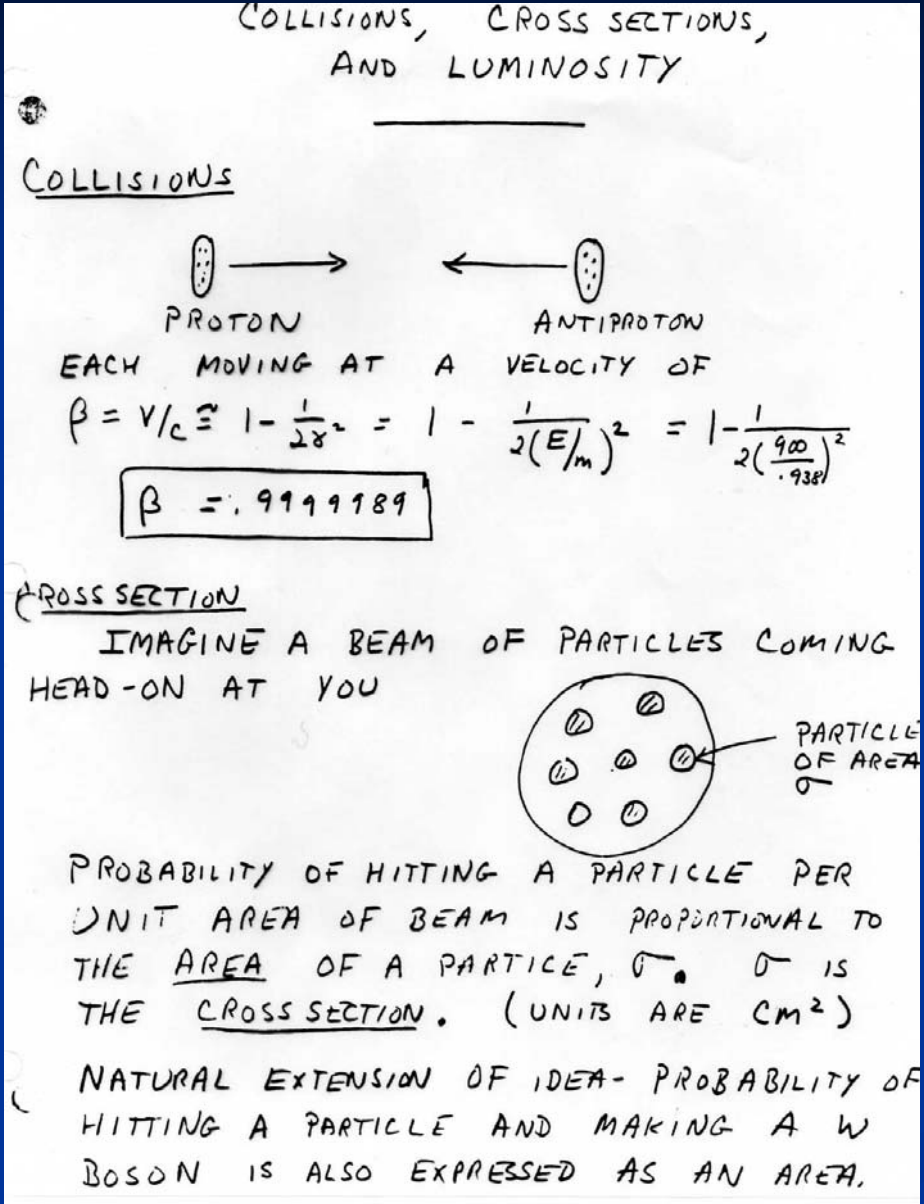
FIG. 38. Configuration of partons in phase space long after deep-inelastic interaction for (a) $e^+e^- \rightarrow$ hadrons, (b) $ep \rightarrow e +$ hadrons, (c) $pp \rightarrow$ hadrons.



ACKNOWLEDGMENTS

It is a pleasure to acknowledge a very helpful conversation with R. P. Feynman (who independently reached many of the same conclusions, in particular the factorization property discussed in Sec. IV). We also benefited from discussions with H. Harari and many colleagues at SLAC.

Crossection and Luminosity



COLLISIONS, CROSS SECTIONS,
AND LUMINOSITY

COLLISIONS

PROTON → ← ANTIPROTON

EACH MOVING AT A VELOCITY OF

$$\beta = v/c \cong 1 - \frac{1}{2\gamma^2} = 1 - \frac{1}{2(E/m)^2} = 1 - \frac{1}{2\left(\frac{900}{.938}\right)^2}$$

$$\boxed{\beta = .9999989}$$

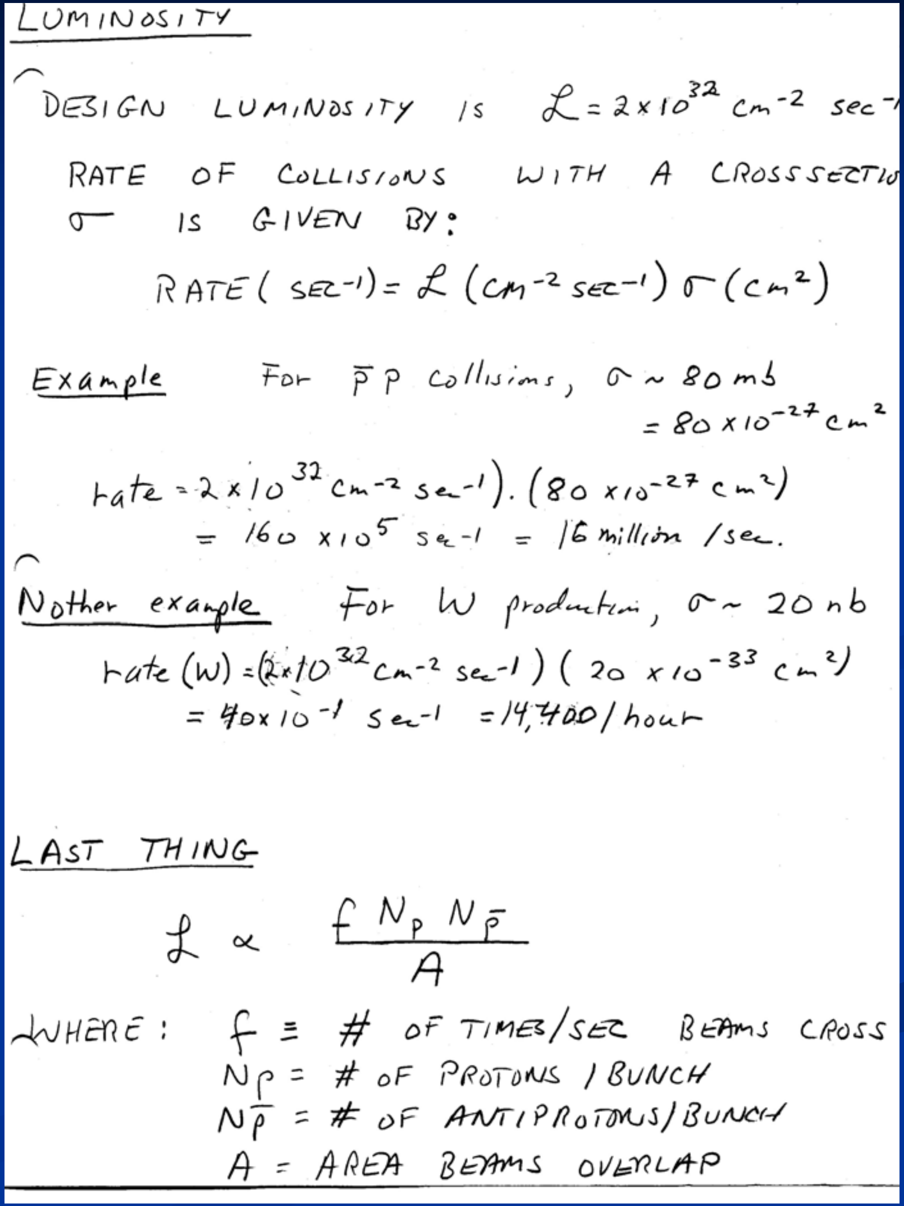
CROSS SECTION

IMAGINE A BEAM OF PARTICLES COMING HEAD-ON AT YOU

PARTICLE OF AREA σ

PROBABILITY OF HITTING A PARTICLE PER UNIT AREA OF BEAM IS PROPORTIONAL TO THE AREA OF A PARTICLE, σ. σ IS THE CROSS SECTION. (UNITS ARE cm^2)

NATURAL EXTENSION OF IDEA- PROBABILITY OF HITTING A PARTICLE AND MAKING A W BOSON IS ALSO EXPRESSED AS AN AREA.



LUMINOSITY

DESIGN LUMINOSITY IS $\mathcal{L} = 2\times10^{32}\ cm^{-2}\ sec^{-1}$

RATE OF COLLISIONS WITH A CROSSSECTIO
σ IS GIVEN BY:

$$\text{RATE}(sec^{-1}) = \mathcal{L}\,(cm^{-2}\,sec^{-1})\,\sigma\,(cm^2)$$

Example For $\bar{p}p$ collisions, $\sigma \sim 80\,mb$
$= 80\times10^{-27}\,cm^2$

$$\text{rate} = 2\times10^{32}\,cm^{-2}\,sec^{-1}).(80\times10^{-27}\,cm^2)$$
$$= 160\times10^{5}\,sec^{-1} = 16 \text{ million}/sec.$$

Nother example For W production, $\sigma \sim 20\,nb$

$$\text{rate}(W) = (2\times10^{32}\,cm^{-2}\,sec^{-1})(20\times10^{-33}\,cm^2)$$
$$= 40\times10^{-1}\,sec^{-1} = 14{,}400/\text{hour}$$

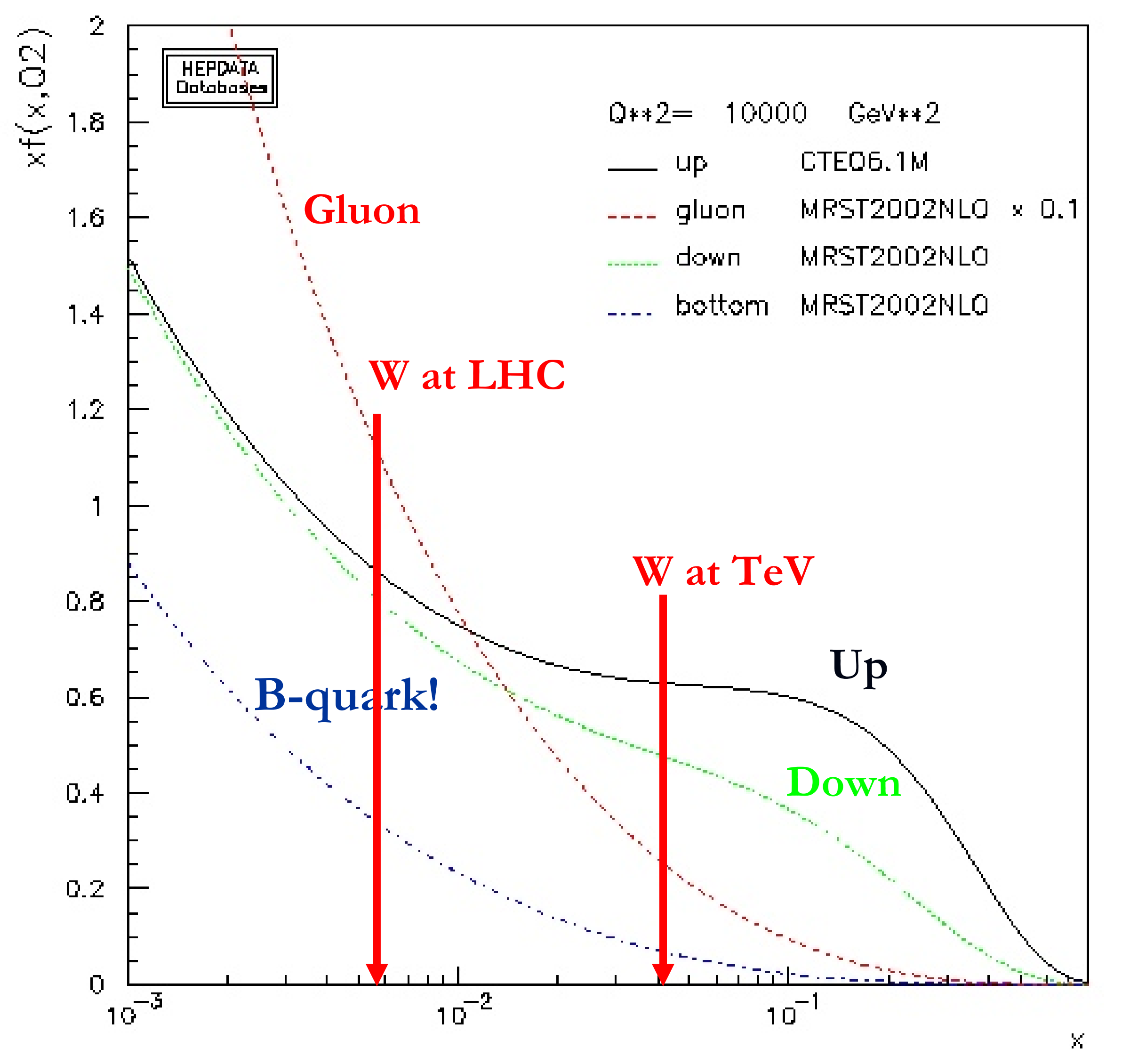
LAST THING

$$\mathcal{L} \propto \frac{f\,N_p\,N_{\bar{p}}}{A}$$

WHERE:
f ≡ # OF TIMES/SEC BEAMS CROSS
N_p = # OF PROTONS / BUNCH
$N_{\bar{p}}$ = # OF ANTIPROTONS/BUNCH
A = AREA BEAMS OVERLAP

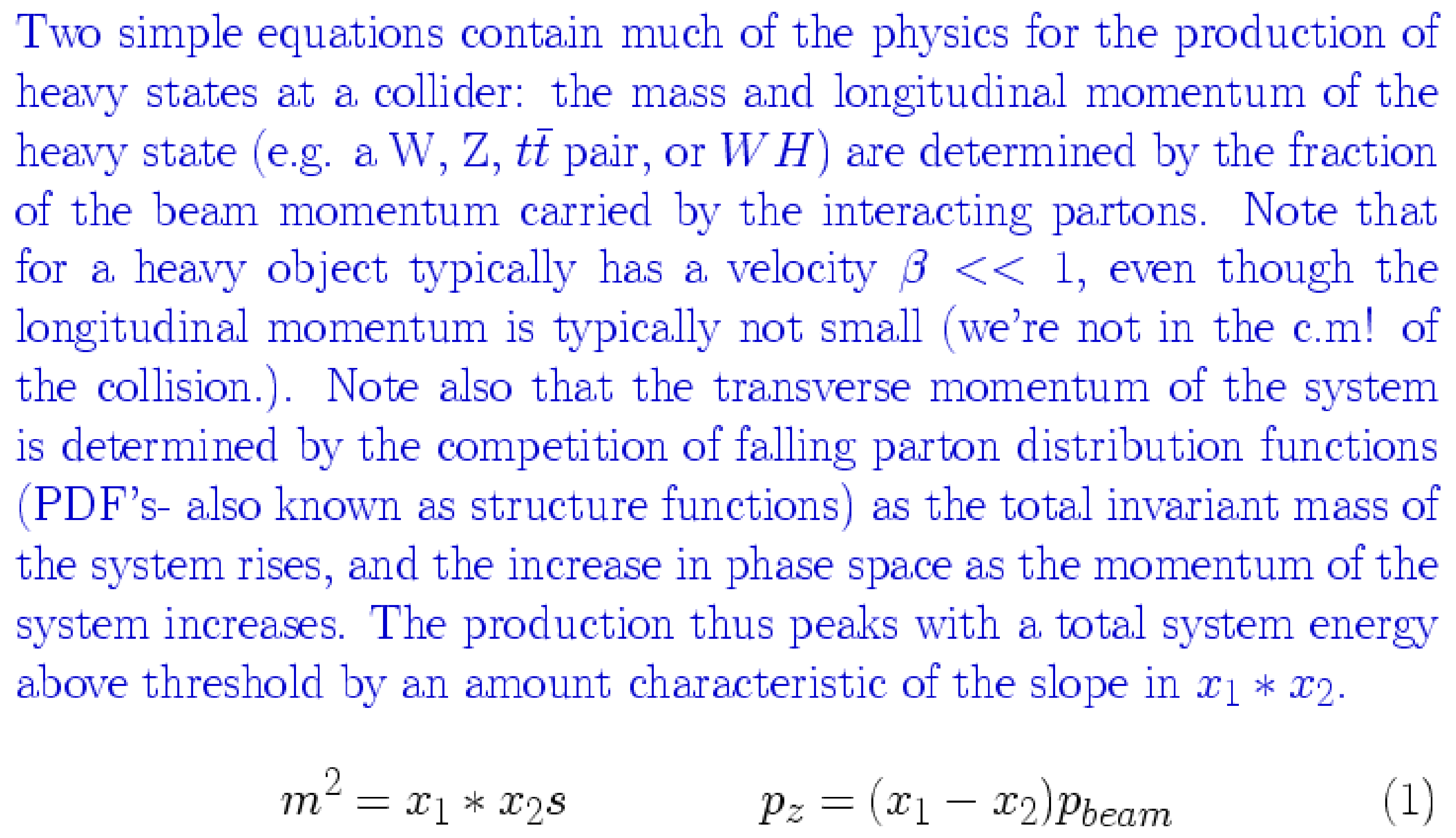
(This slide for string theorists- apologies to others)

Parton Distribution Functions



Thanks to Joey Huston

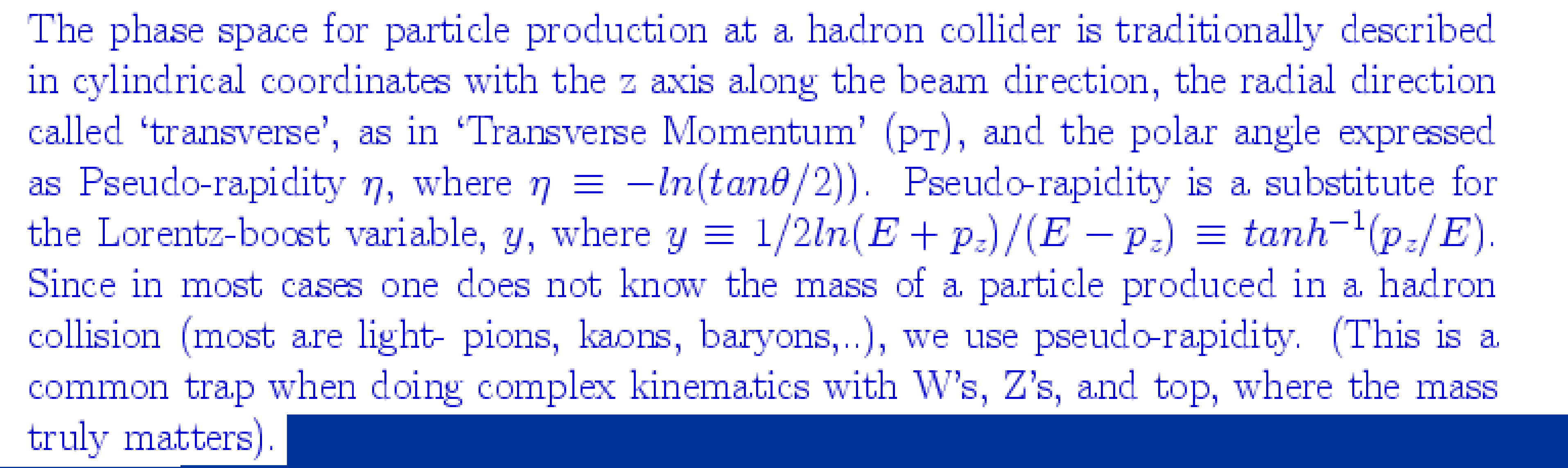
Parton-parton Collisions

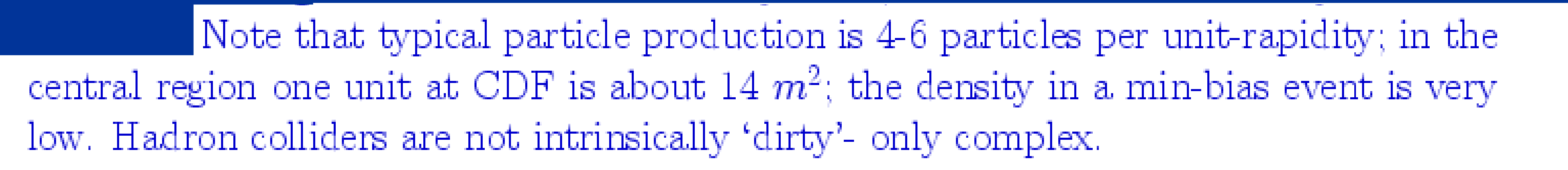


Two simple equations contain much of the physics for the production of heavy states at a collider: the mass and longitudinal momentum of the heavy state (e.g. a W, Z, $t\bar{t}$ pair, or WH) are determined by the fraction of the beam momentum carried by the interacting partons. Note that for a heavy object typically has a velocity $\beta << 1$, even though the longitudinal momentum is typically not small (we're not in the c.m! of the collision.). Note also that the transverse momentum of the system is determined by the competition of falling parton distribution functions (PDF's- also known as structure functions) as the total invariant mass of the system rises, and the increase in phase space as the momentum of the system increases. The production thus peaks with a total system energy above threshold by an amount characteristic of the slope in $x_1 * x_2$.

$$m^2 = x_1 * x_2 s \qquad\qquad p_z = (x_1 - x_2) p_{beam} \tag{1}$$

The Peyrou Plot: Pt vs Plong; Rapidity, Pseudo-rapidity

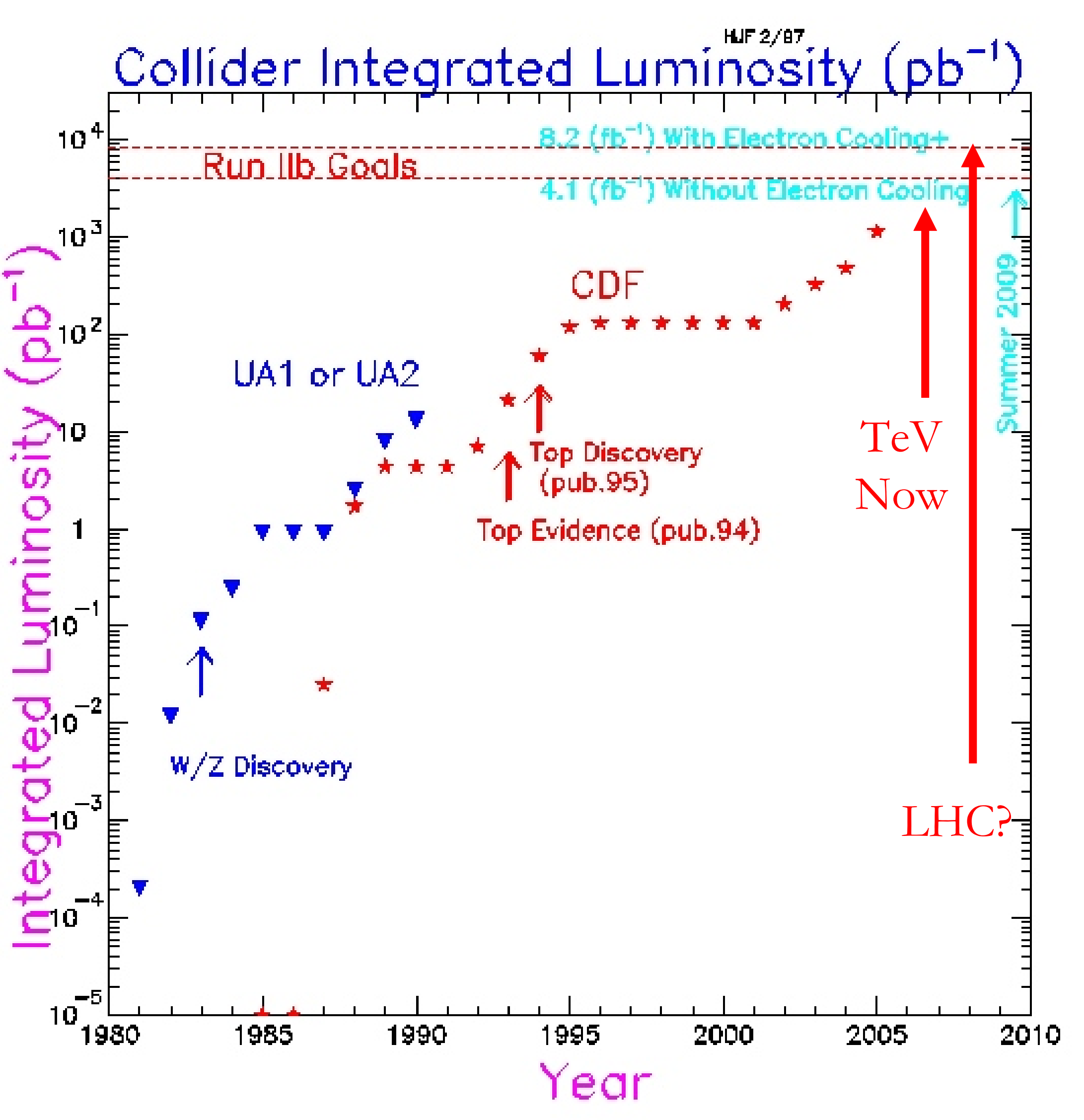

The phase space for particle production at a hadron collider is traditionally described in cylindrical coordinates with the z axis along the beam direction, the radial direction called 'transverse', as in 'Transverse Momentum' (p_T), and the polar angle expressed as Pseudo-rapidity η, where $\eta \equiv -ln(tan\theta/2)$). Pseudo-rapidity is a substitute for the Lorentz-boost variable, y, where $y \equiv 1/2ln(E+p_z)/(E-p_z) \equiv tanh^{-1}(p_z/E)$. Since in most cases one does not know the mass of a particle produced in a hadron collision (most are light- pions, kaons, baryons,..), we use pseudo-rapidity. (This is a common trap when doing complex kinematics with W's, Z's, and top, where the mass truly matters).


Note that typical particle production is 4-6 particles per unit-rapidity; in the central region one unit at CDF is about 14 m^2; the density in a min-bias event is very low. Hadron colliders are not intrinsically 'dirty'- only complex.

Orders of Magnitude in Lum vs time

Race of SppS and Tevatron for the W and Z; then for top; now with LHC for ….?

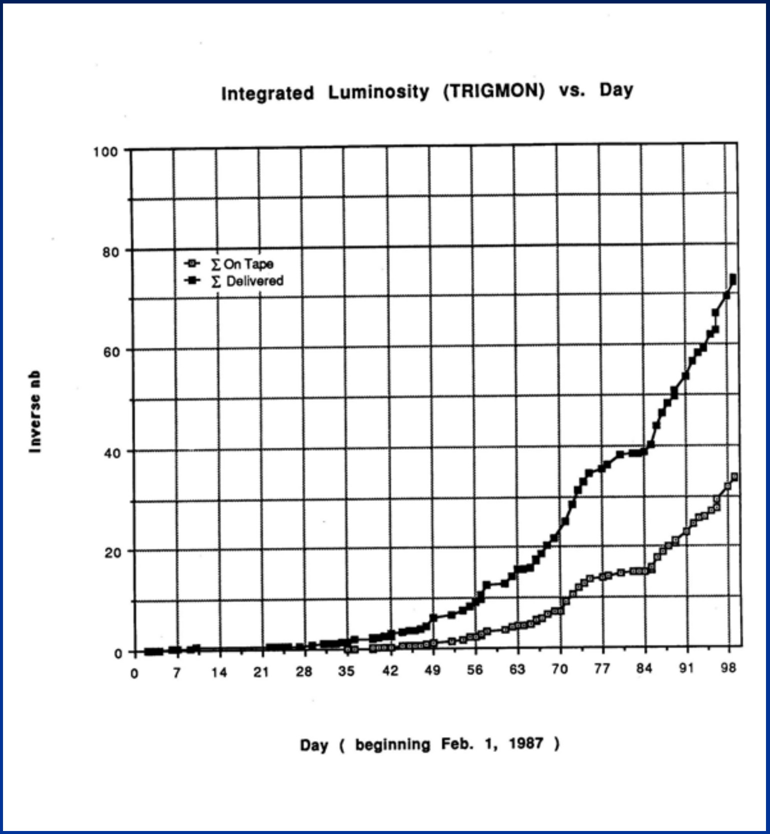
(note date on slide-1997- 10 yrs ago)

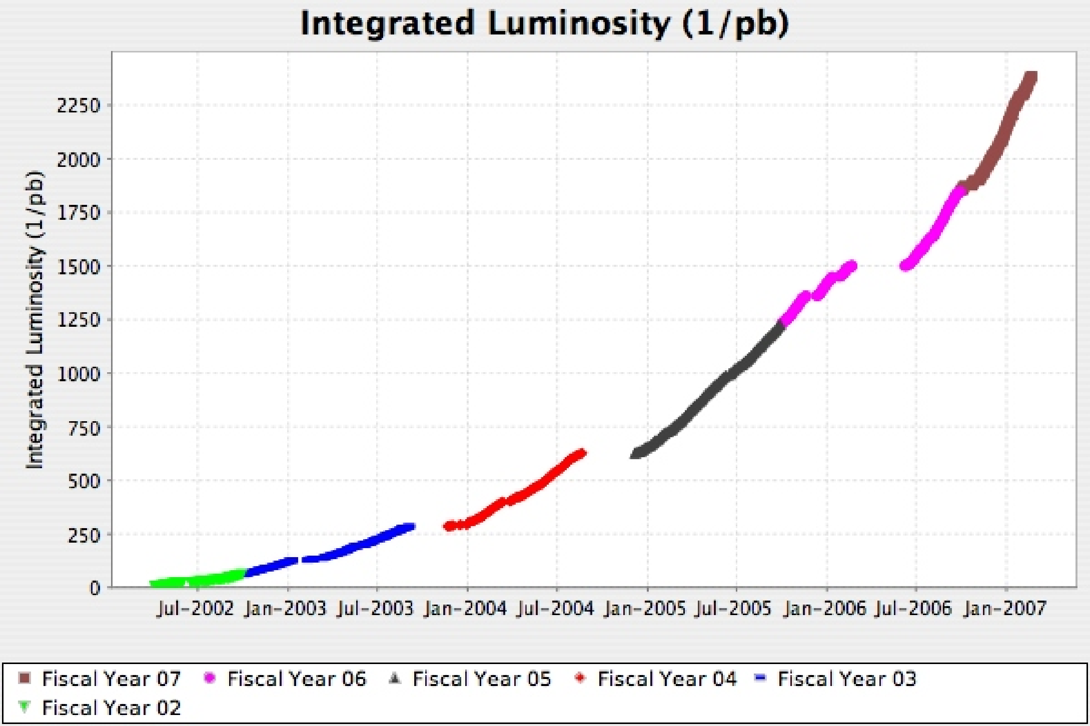


Fermilab (40 miles west of Chicago)

Tevatron Startups: 1987 & 2007

(Recent interest wrt LHC- may or may not be relevant to LHC startup)





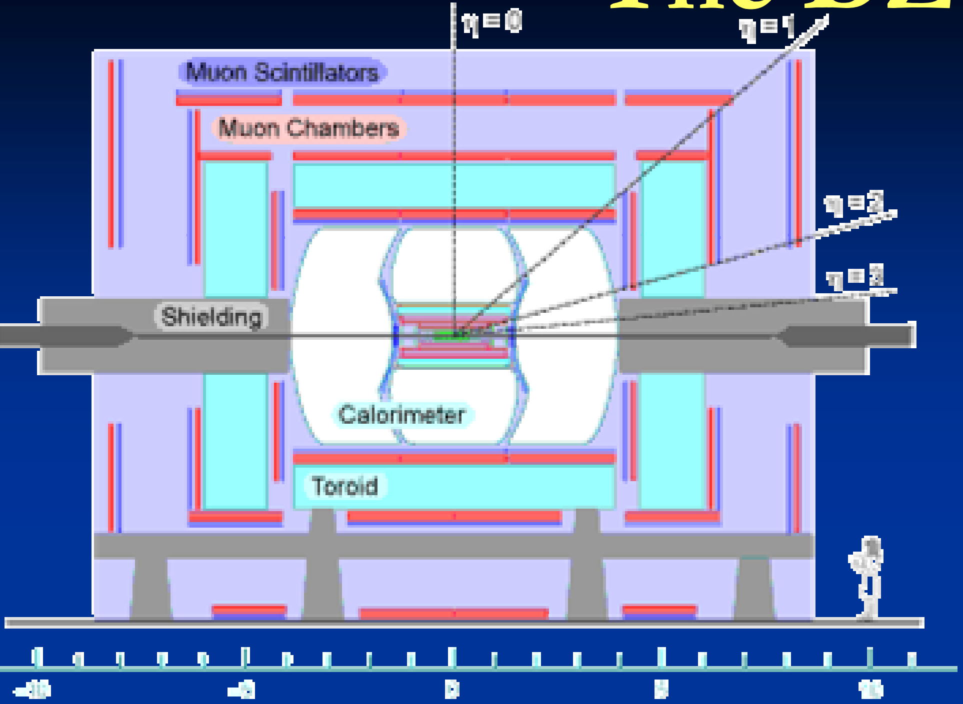
2007: In picobarns

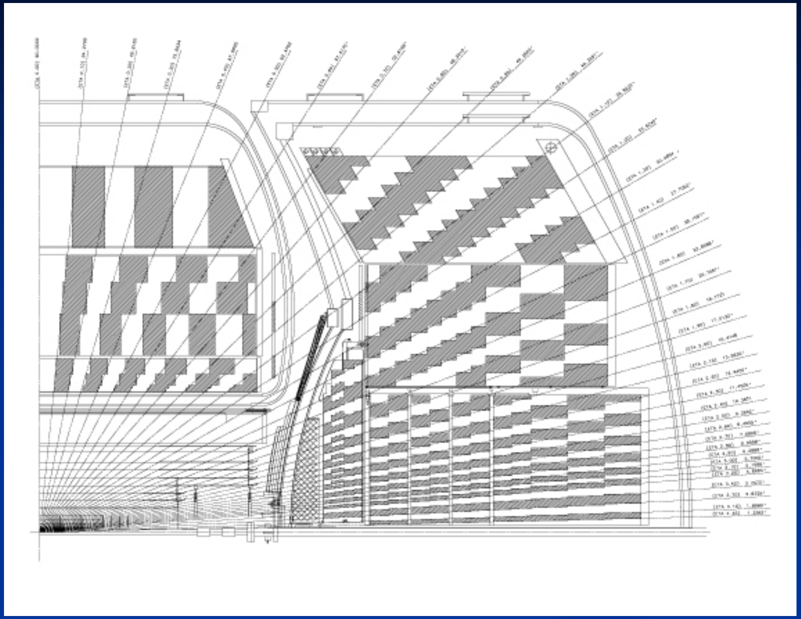
1987: In nanobarns

LHC is a different beast, but the positive 2nd derivative vs time is deeply fundamental

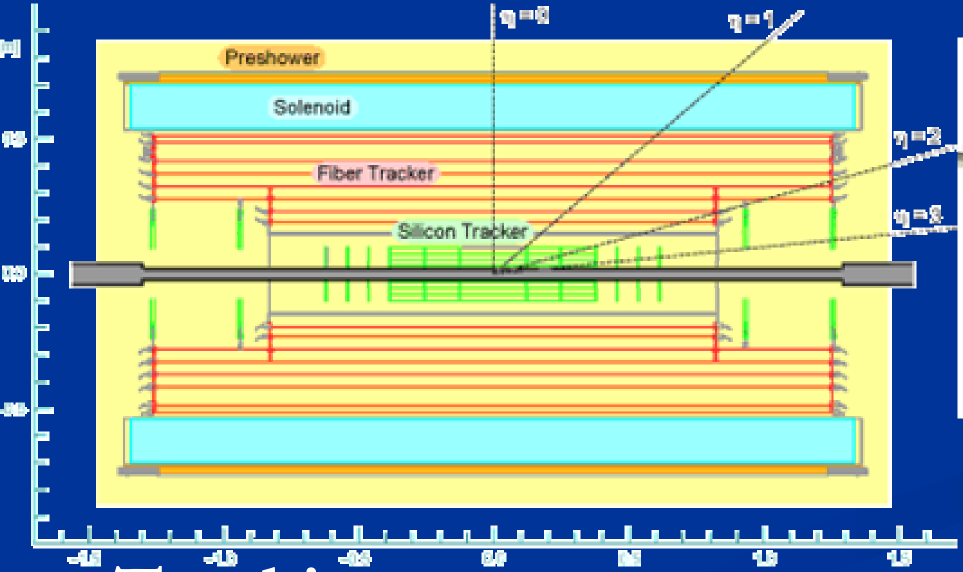
The accelerator guys continue learning and improving- lum grows faster and faster…

The DZero Detector

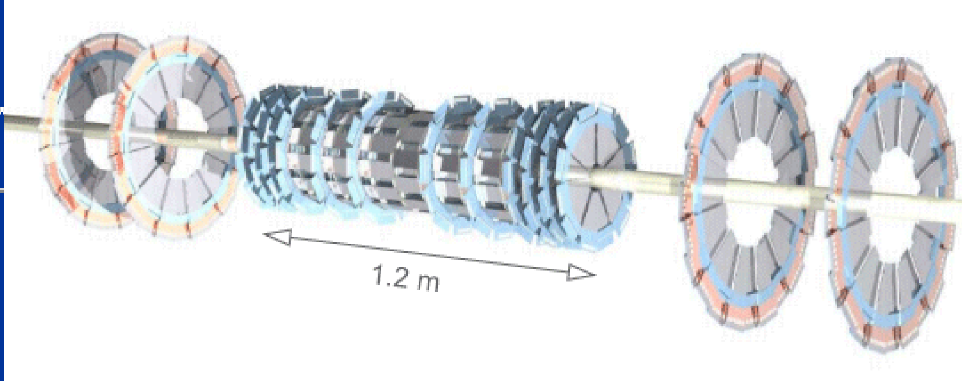




Calorimeter

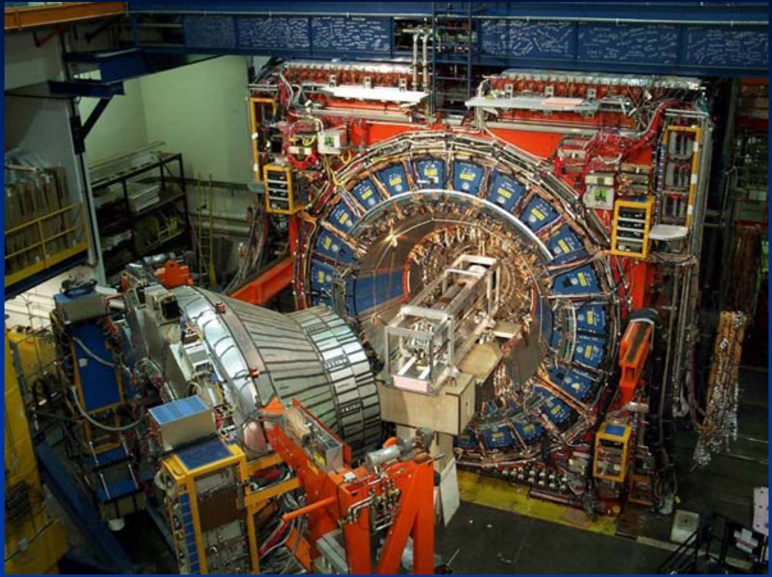


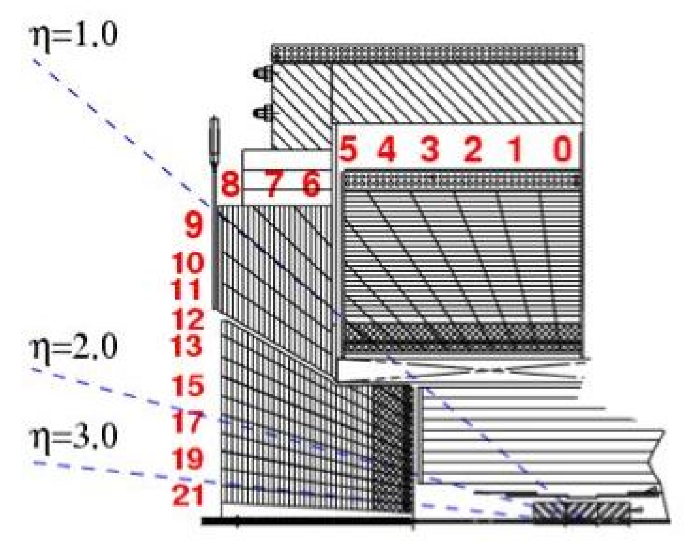
Tracking



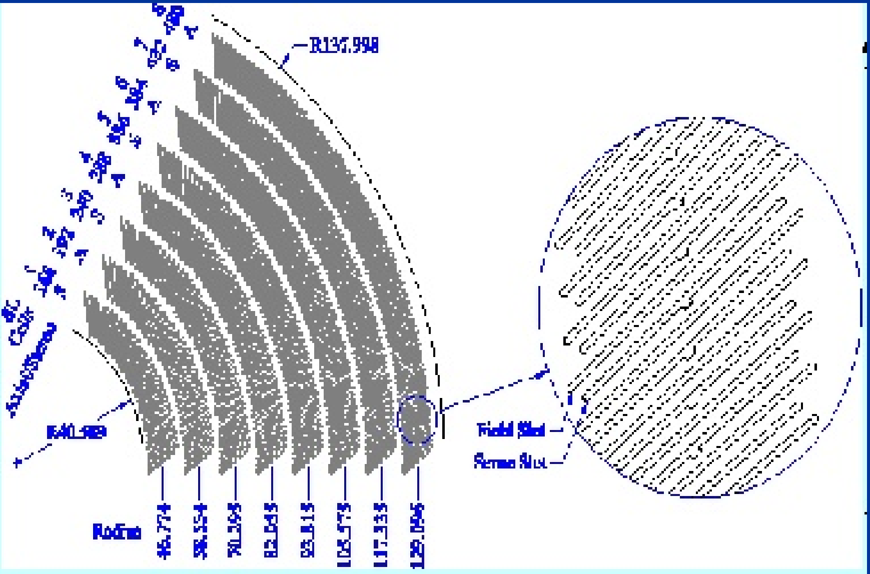
Silicon

CDF Detector (5000 Tons)

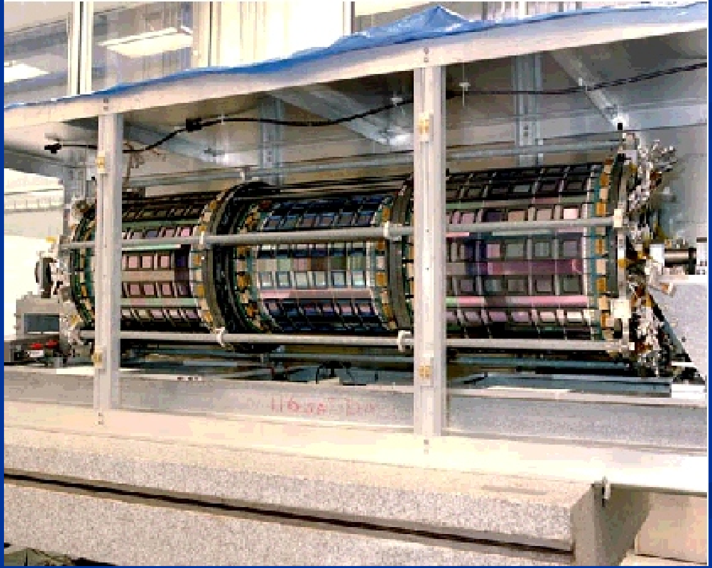




EM, Had, with embedded 1 plane of MWCP at $6X_0$



Tracking: 8 Layers of 12 sense wires



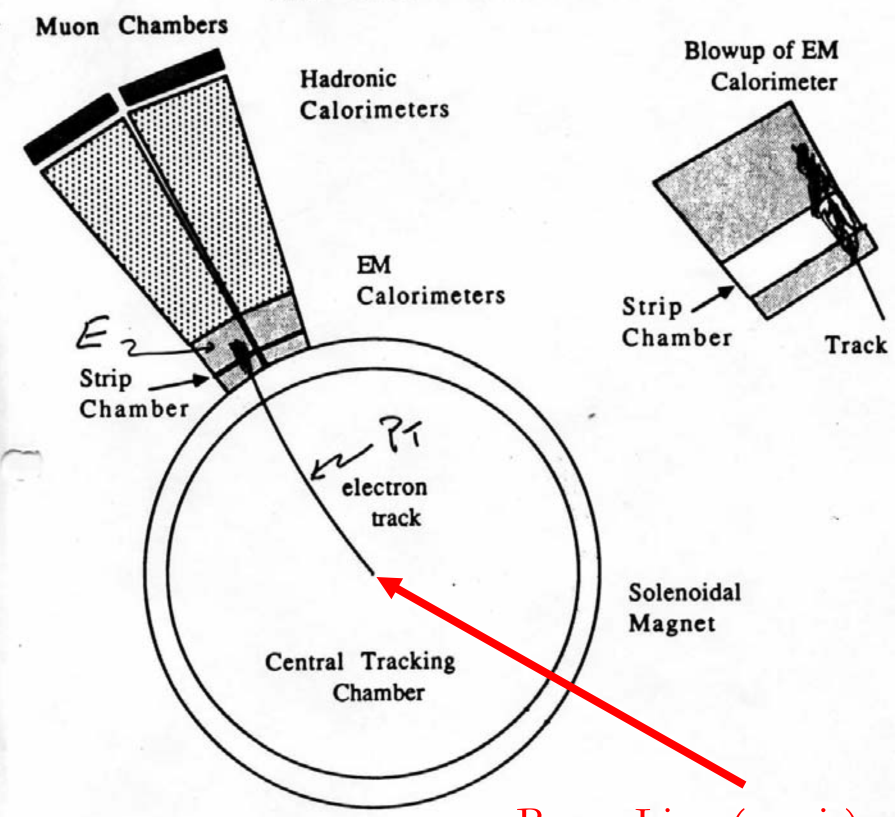
Silicon: L00,5SVX,2ISL layers

Particle Identification

- Charged Leptons- particularly the e and μ are how we trigger on the W and Z- and hence the top (t->Wb), SUSY (charginos, neutralinos), ..
- Neutral leptons- neutrinos- partially ID's by MET
- Heavy flavor- charm, bottom, is identificable by lifetime- CDF can trigger on displaced vertices
- Photons identified by no em cluster, no track
- Taus identified surprisingly well
- At low Pt can separate pi, K, p by TOF and dE/dx
- All else lumped into `jets' or hadrons

Electron Identification

Schematic View of an Electron in the CDF Central Calorimeter



CDF Central Electron Variables:

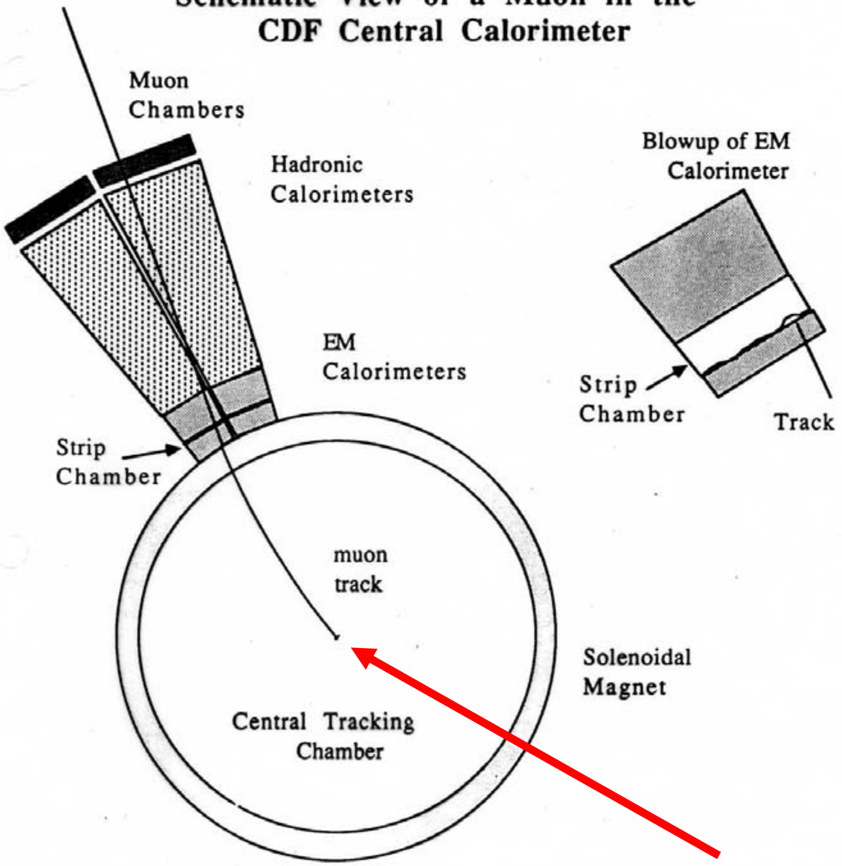
- E_T
- Had/EM
- Lateral Sharing (LSHR)
- Strip χ^2
- Strip-Track Match (δx, δz)
- E/P
- Isolation/Border Tower Energy

Identification variables-

Muon Identification

Credit: Sacha Kopp, undergrad

Schematic View of a Muon in the CDF Central Calorimeter

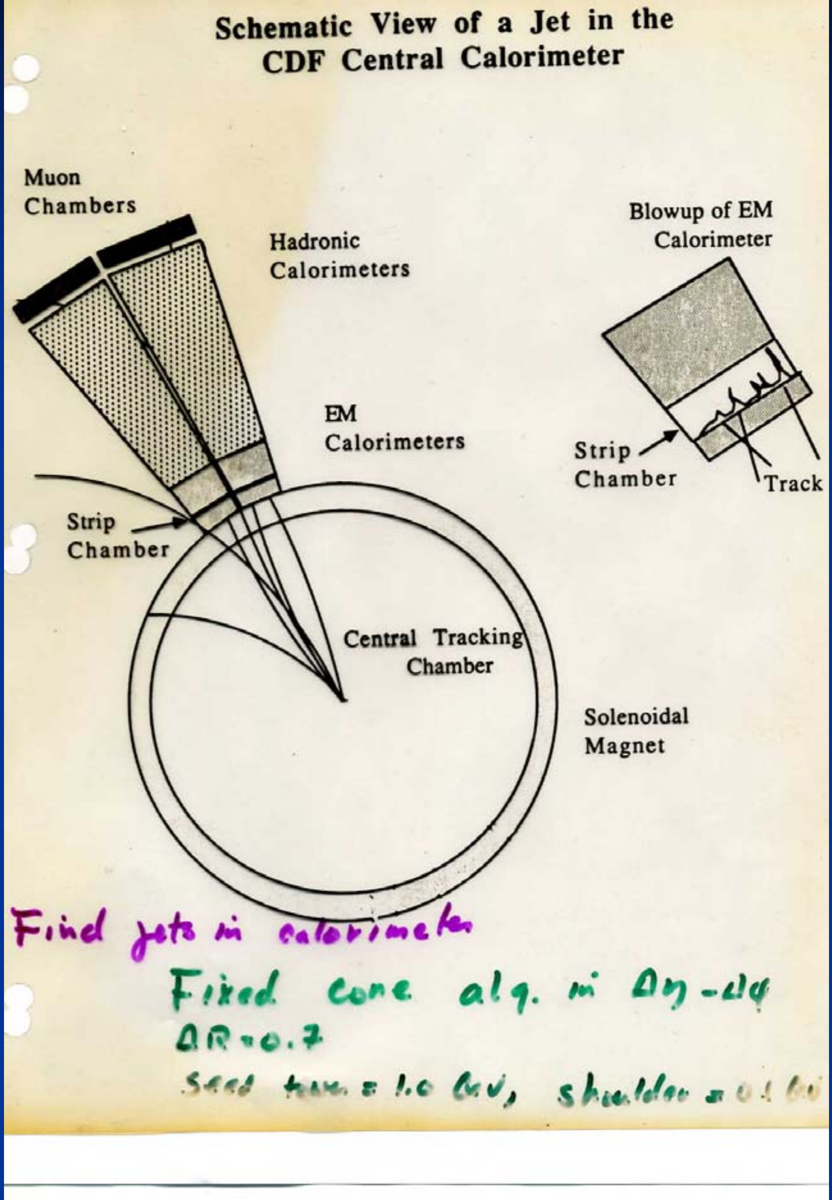


CDF Central Muon Variables:

- P_T
- EM
- Had
- Muon Chamber-Track Match(δx, δz)
- Slope Match
- Isolation

widely-used jargon

Jet Identification



Schematic View of a Jet in the CDF Central Calorimeter

Find jets in calorimeter

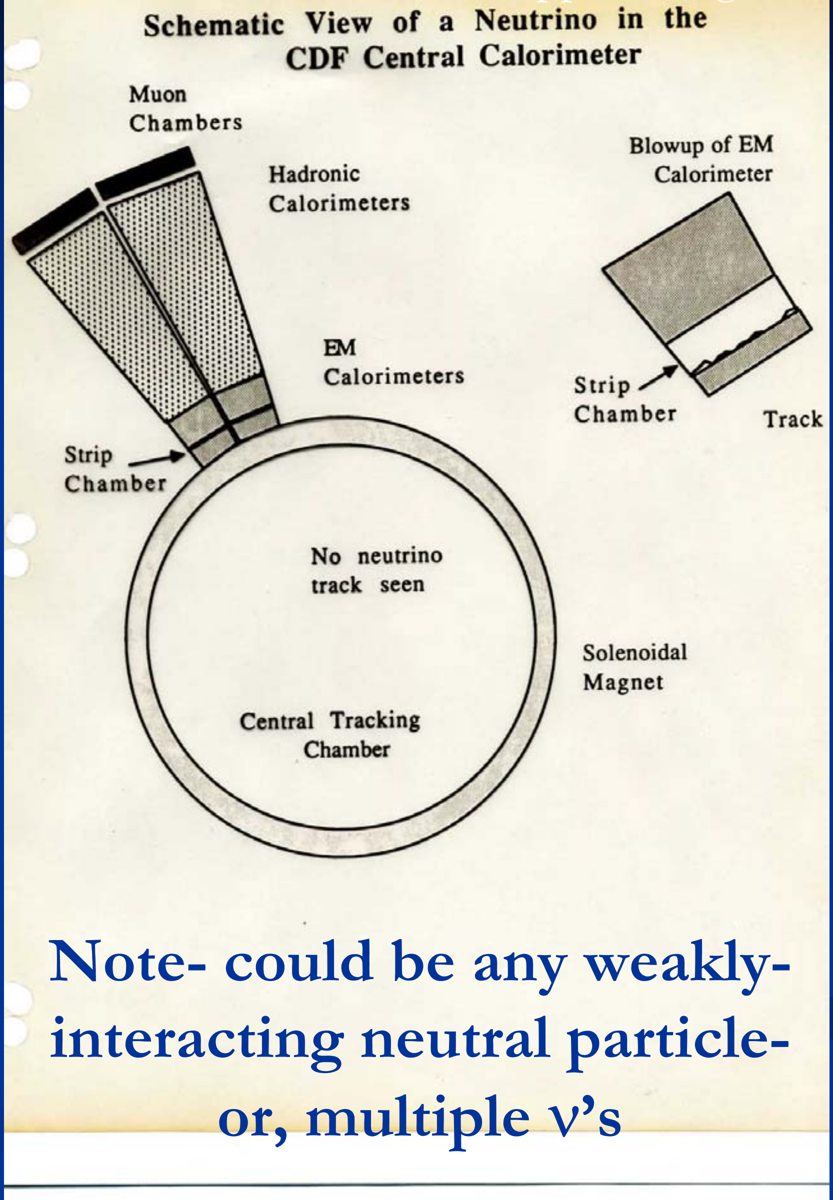
Fixed cone alg. in Δη-Δφ

ΔR=0.7

Seed tow. = 1.0 GeV, shoulder = 0.1 GeV

Neutrino Identification

Credit: Sacha Kopp, undergrad

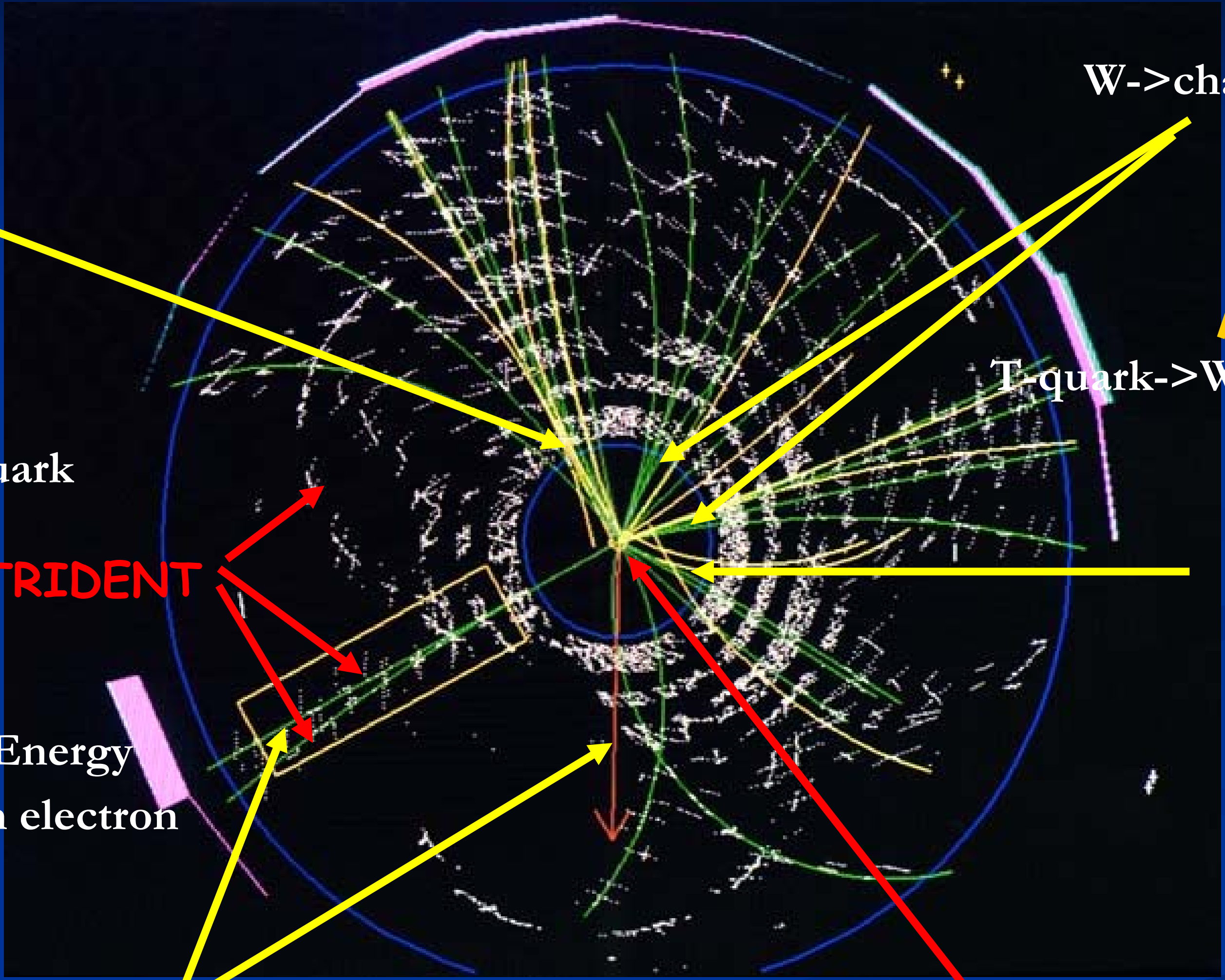


Schematic View of a Neutrino in the CDF Central Calorimeter

Note- could be any weakly-interacting neutral particle- or, multiple ν's

A real CDF Top Quark Event

T-Tbar -> W^+bW^-bbar



W->charm sbar

B-quark

T-quark->W+bquark

T-quark->W+bquark

TRIDENT

B-quark

Cal. Energy
From electron

W->electron+neutrino

Beam (not at 0,0!)

Fake Rates

- In addition to the efficiency for identifying an `object', need to know how often you get it wrong (`fake rate')- depends on definition of the object.
- Examples-
  - an isolated pizero in a jet (z=1) can fake a photon
  - A low momentum (~5 GeV) K+ can decay K->$\mu\nu$, and the kaon track segment and the muon track segment can reconstruct to a straight line, giving a high-Pt μ.
  - A jet can fake an electron
  - A jet can fake a tau
  - A tau can fake a photon… etc.

‘Understanding Objects’ and their limitations

Example- electro-magnetic (em) cluster

Identify an em cluster as one of 3 objects: (CDF)

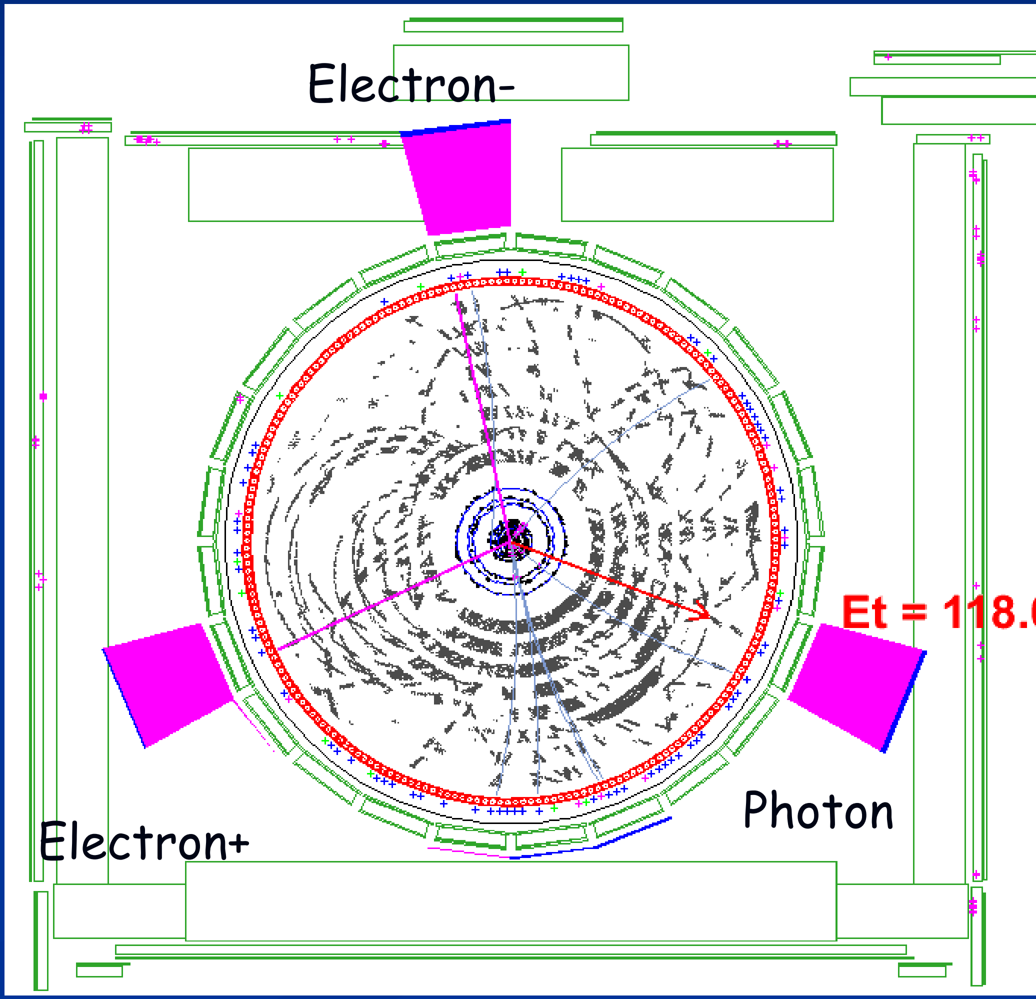
E/p < 2: Electron

E/p> 2: Jet

P <1: Photon

Where p is from track, E is from cal

E/p measures bremstrahlung fraction



Recent ‘typical’ zoo event (only an example)

'Understanding Objects' and their limitations

Example- Muons becomingElectrons

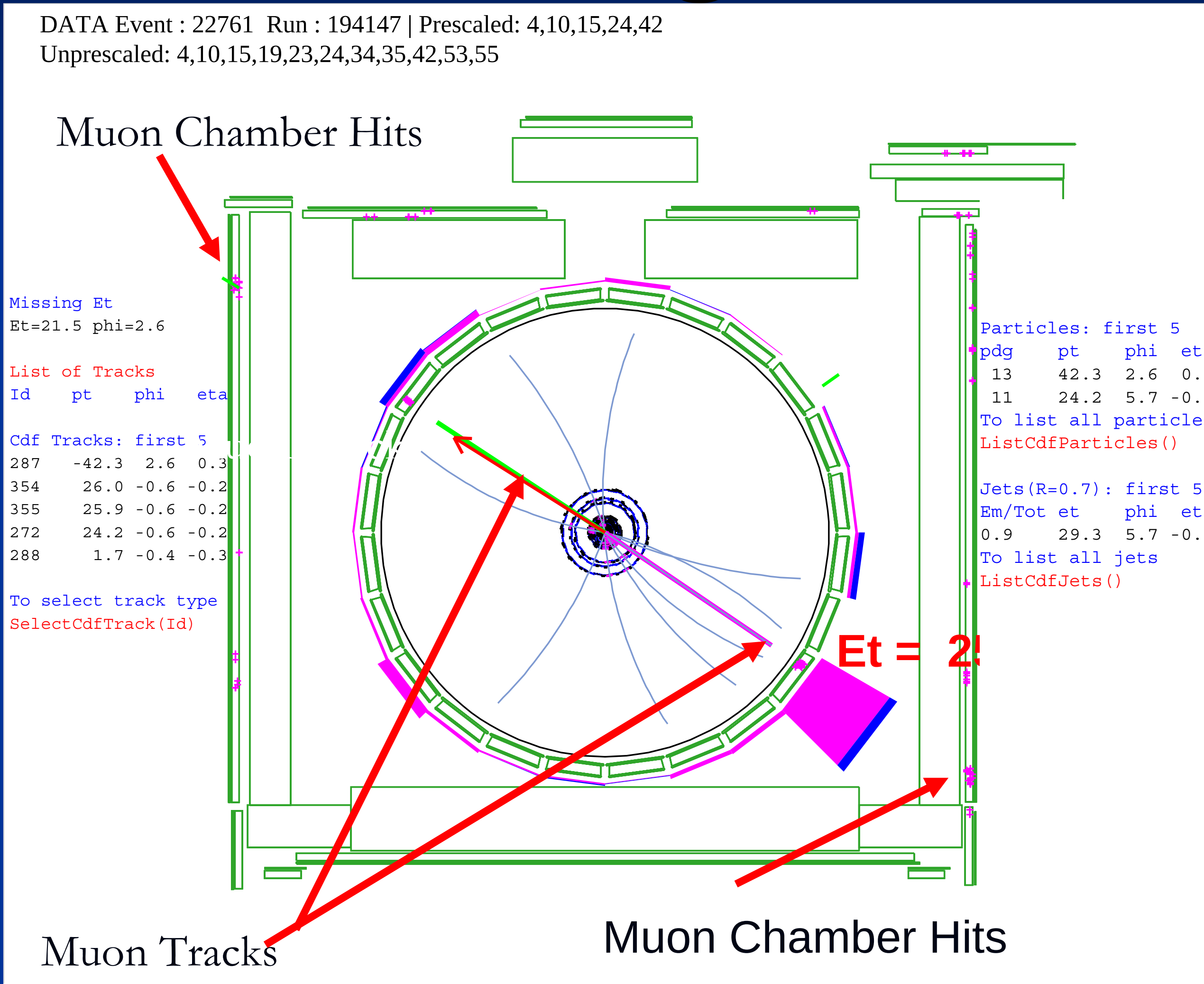
CDF has a cut on EM energy for muons- not more than ~2 GeV (minI

E< ~2 GeV: Muon

E> 12, E/p<2: Electron

E<12, or E/p>2 Jet

p is from track, E is from calorimeter



DATA Event : 22761 Run : 194147 | Prescaled: 4,10,15,24,42
Unprescaled: 4,10,15,19,23,24,34,35,42,53,55

```
Missing Et
Et=21.5 phi=2.6

List of Tracks
Id    pt    phi    eta

Cdf Tracks: first 5
287   -42.3  2.6  0.3
354    26.0 -0.6 -0.2
355    25.9 -0.6 -0.2
272    24.2 -0.6 -0.2
288     1.7 -0.4 -0.3

To select track type
SelectCdfTrack(Id)
```

```
Particles: first 5
pdg    pt    phi  et
 13    42.3  2.6  0.
 11    24.2  5.7 -0.
To list all particle
ListCdfParticles()

Jets(R=0.7): first 5
Em/Tot et    phi  et
0.9    29.3  5.7 -0.
To list all jets
ListCdfJets()
```

Muon Chamber Hits

Et = 2

Muon Tracks

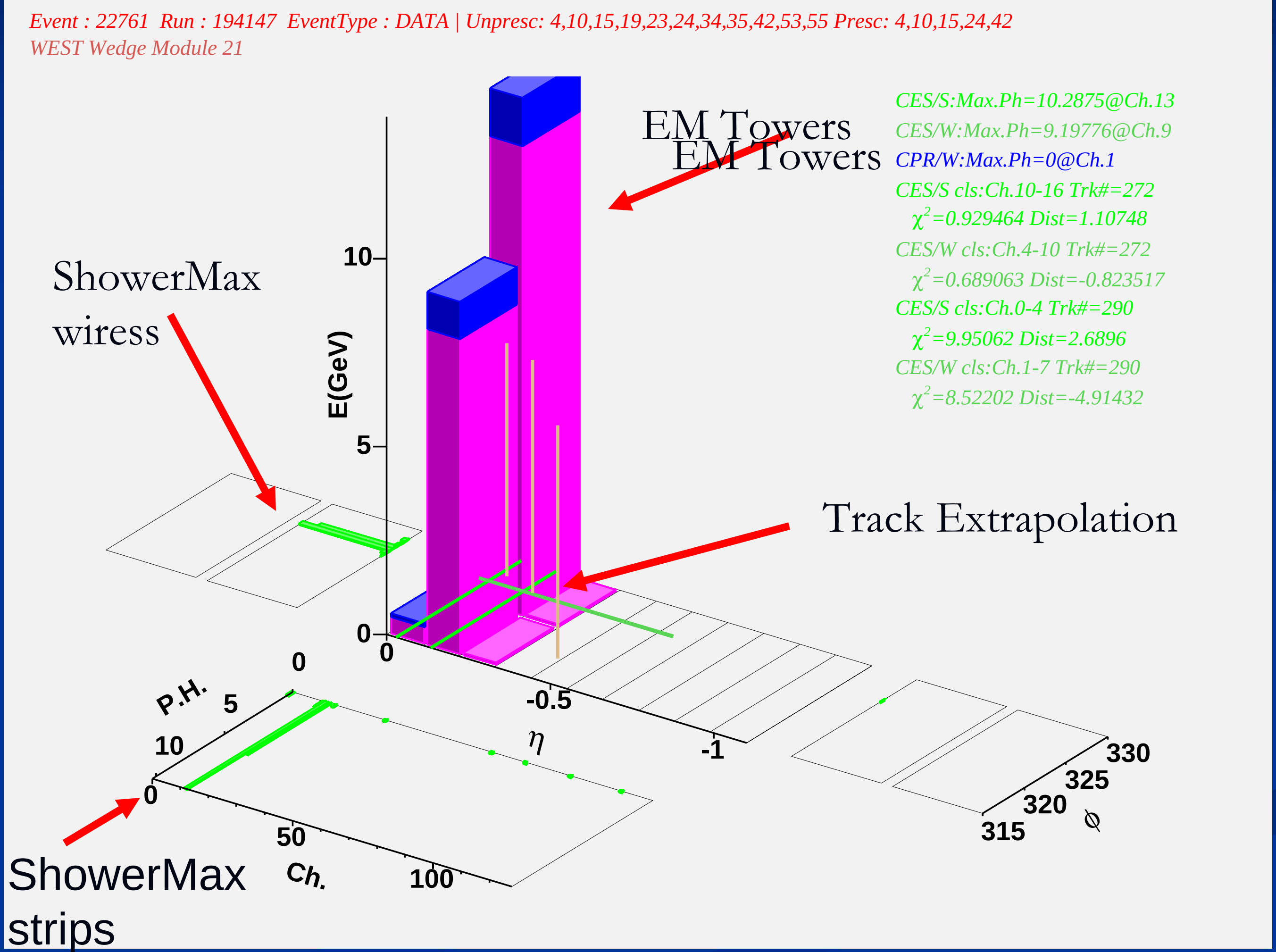
Muon Chamber Hits

This is a ``Z->eμ' event: $M_{e\mu}$(2trks+cluster)=91.4 GeV

'Understanding Objects' and their limitations

Example- Muons becomingElectrons

Look inside \`wedge' at calorimeter towers- see a 25 GeV colinear brem off of muon track



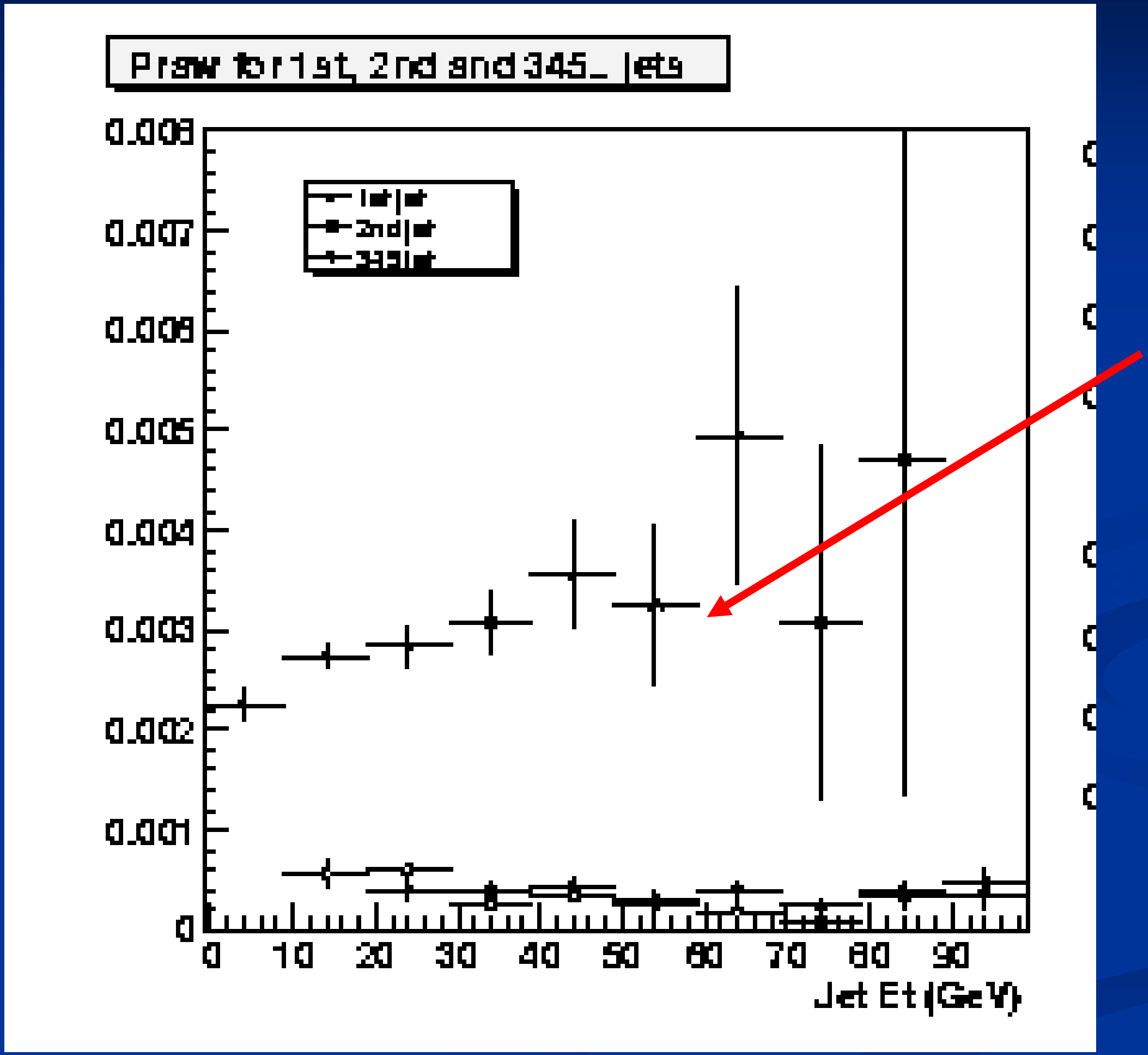
Event : 22761 Run : 194147 EventType : DATA | Unpresc: 4,10,15,19,23,24,34,35,42,53,55 Presc: 4,10,15,24,42
WEST Wedge Module 21

CES/S:Max.Ph=10.2875@Ch.13
CES/W:Max.Ph=9.19776@Ch.9
CPR/W:Max.Ph=0@Ch.1
CES/S cls:Ch.10-16 Trk#=272
χ^2=0.929464 Dist=1.10748
CES/W cls:Ch.4-10 Trk#=272
χ^2=0.689063 Dist=-0.823517
CES/S cls:Ch.0-4 Trk#=290
χ^2=9.95062 Dist=2.6896
CES/W cls:Ch.1-7 Trk#=290
χ^2=8.52202 Dist=-4.91432

This is a \`\`Z->eμ' event: $M_{e\mu}$=91.4 GeV

It's not just partons inside hadrons- we need hadrons inside partons!

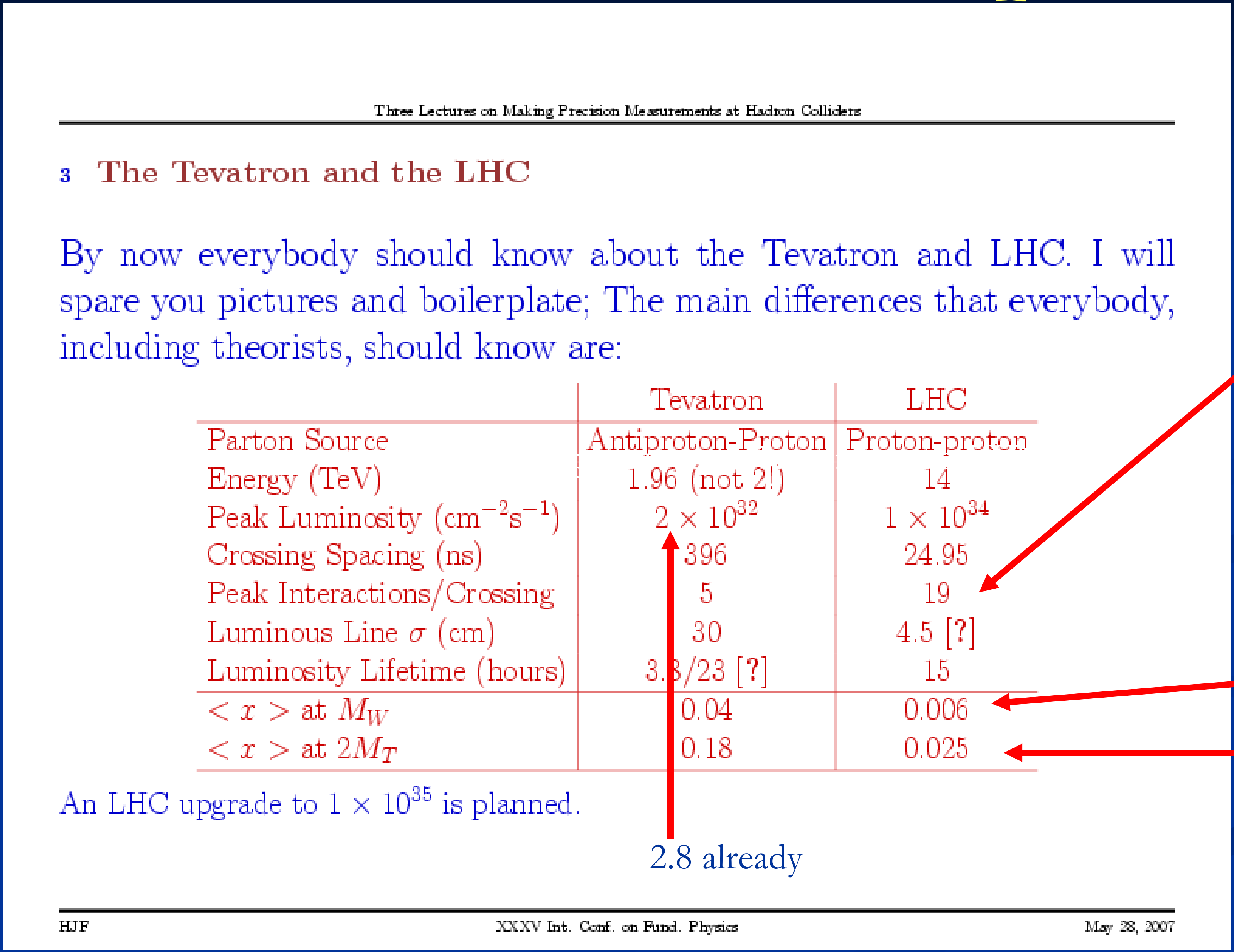
'Raw Fake' rate for a jet faking a photon- jets are ordered in Et



Highest Pt jet fakes photon much more often…

Z=1 limit of jet fragmentation determines fake rates for isolated photons- really different for q,g,b,c,…!

Tevatron LHC comparisons



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3 The Tevatron and the LHC

By now everybody should know about the Tevatron and LHC. I will spare you pictures and boilerplate; The main differences that everybody, including theorists, should know are:

	Tevatron	LHC
Parton Source	Antiproton-Proton	Proton-proton
Energy (TeV)	1.96 (not 2!)	14
Peak Luminosity ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	2×10^{32}	1×10^{34}
Crossing Spacing (ns)	396	24.95
Peak Interactions/Crossing	5	19
Luminous Line σ (cm)	30	4.5 [?]
Luminosity Lifetime (hours)	3.3/23 [?]	15
$< x >$ at M_W	0.04	0.006
$< x >$ at $2M_T$	0.18	0.025

An LHC upgrade to 1×10^{35} is planned.

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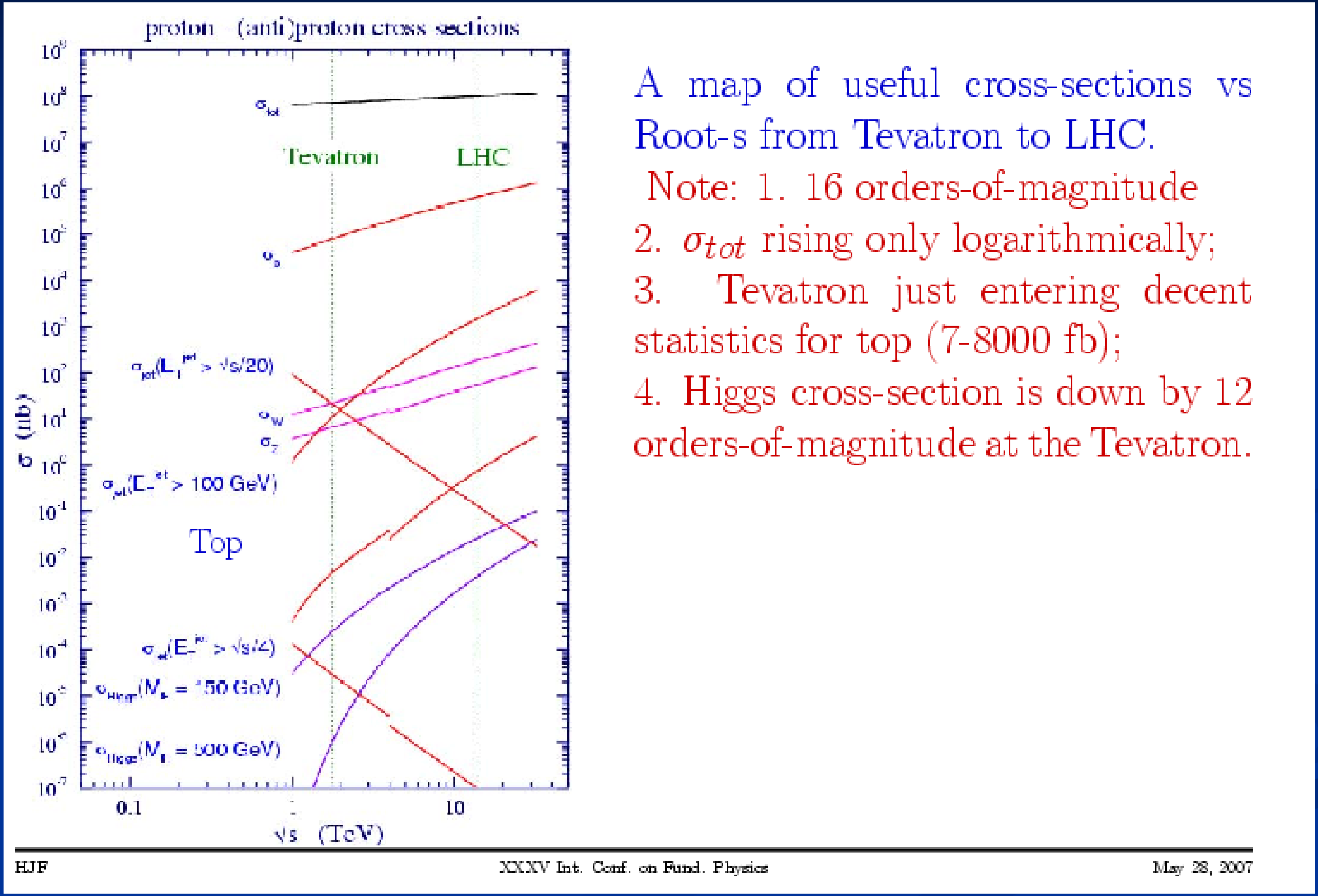
2.8 already

Mention Trigger Bias

Bad

Good

Tevatron LHC comparisons



A map of useful cross-sections vs Root-s from Tevatron to LHC.

Note: 1. 16 orders-of-magnitude

2. σ_{tot} rising only logarithmically;

3. Tevatron just entering decent statistics for top (7-8000 fb);

4. Higgs cross-section is down by 12 orders-of-magnitude at the Tevatron.

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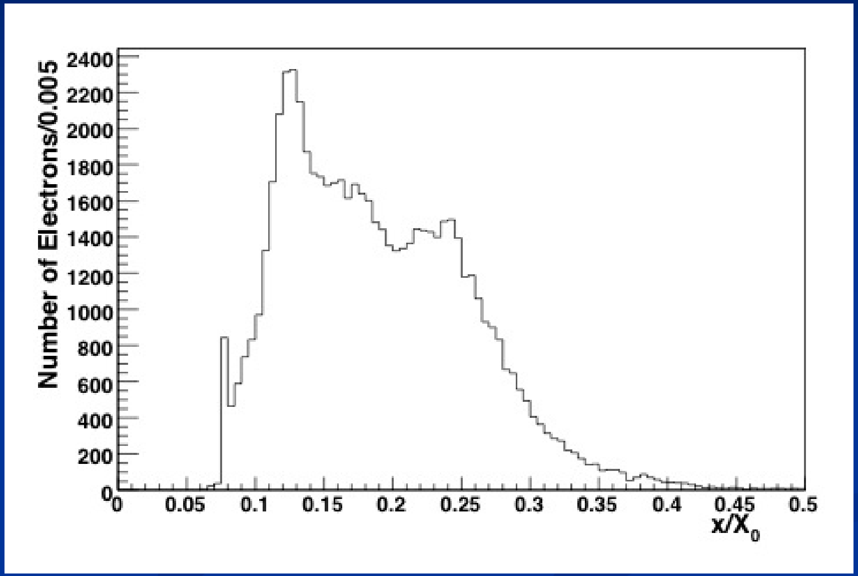
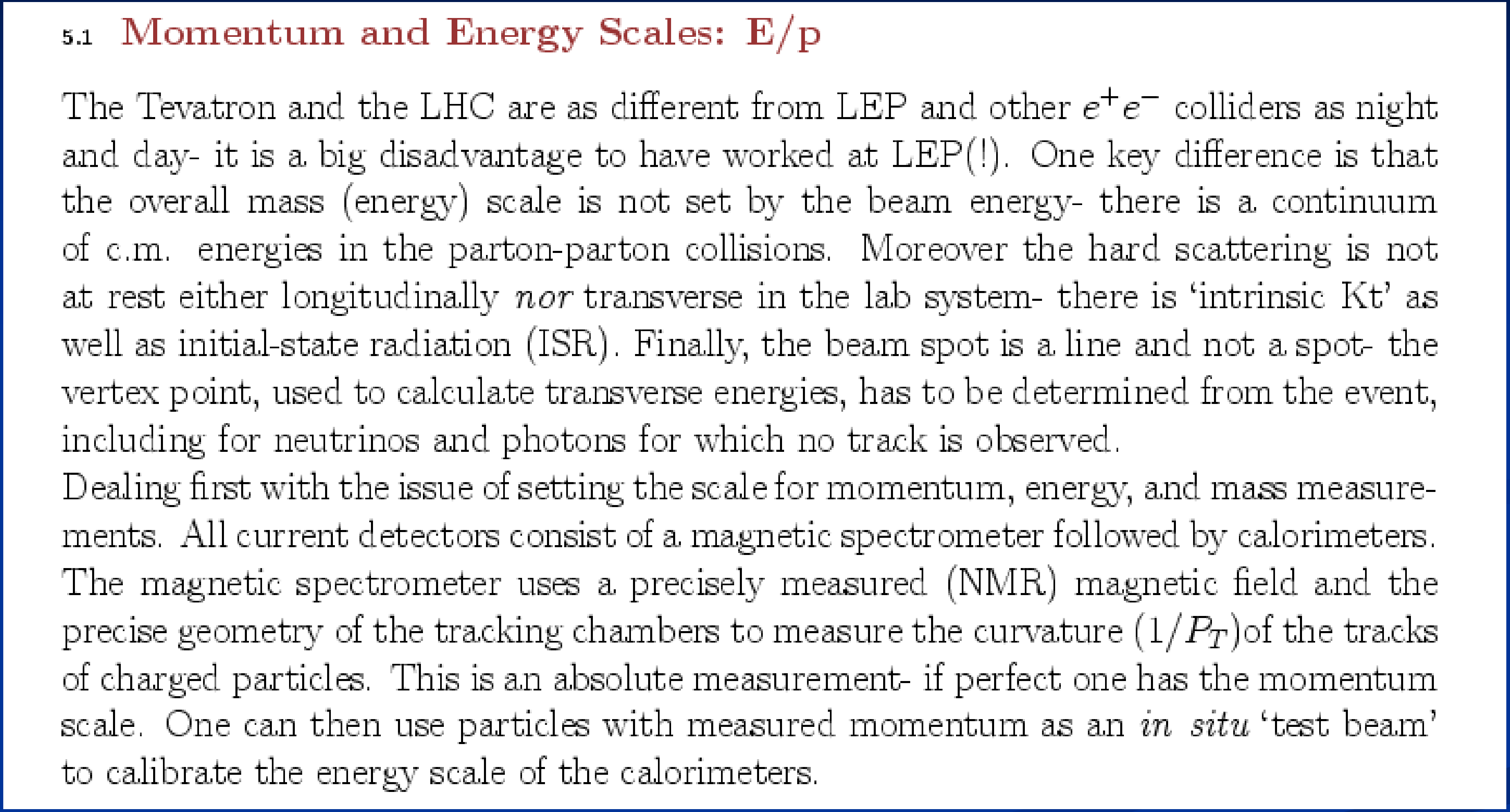
Tevatron strengths compared to LHC

- Obvious ones (pbar-p,..)
- Electron, photon, tau ID has much less material- ultimate M_W, H->taus,?
- Tau-ID; photon/pizero separation (shower max)
- Triggering at met~20GeV
- Triggering on b, c quarks (SVT)- also (?) hyperons,…



Fraction of a radiation length traversed by leptons from W decay (CDF Wmass analysis)- << 1 X_0

Calibration Techniques

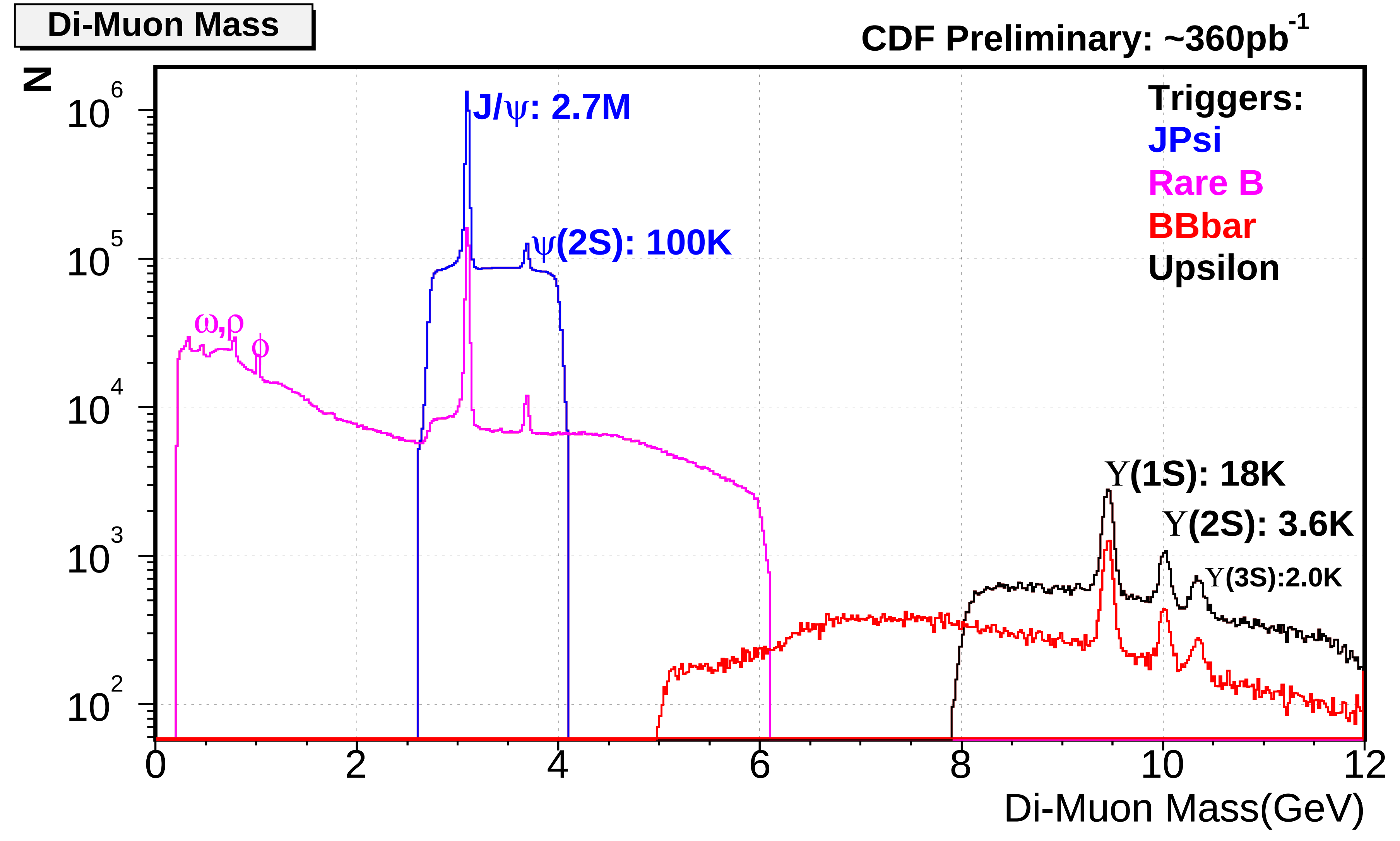


5.1 Momentum and Energy Scales: E/p

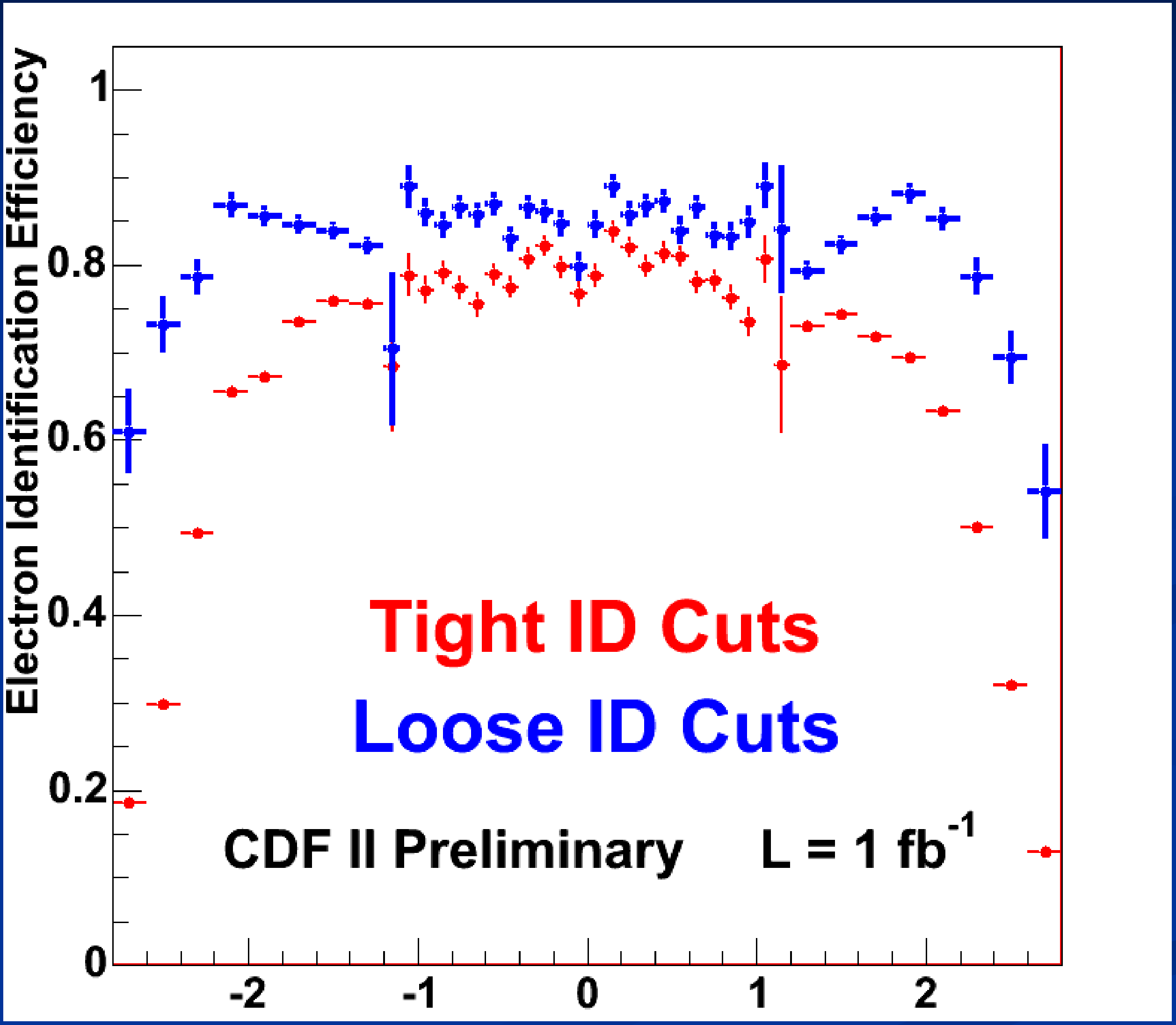
The Tevatron and the LHC are as different from LEP and other e^+e^- colliders as night and day- it is a big disadvantage to have worked at LEP(!). One key difference is that the overall mass (energy) scale is not set by the beam energy- there is a continuum of c.m. energies in the parton-parton collisions. Moreover the hard scattering is not at rest either longitudinally *nor* transverse in the lab system- there is 'intrinsic Kt' as well as initial-state radiation (ISR). Finally, the beam spot is a line and not a spot- the vertex point, used to calculate transverse energies, has to be determined from the event, including for neutrinos and photons for which no track is observed.

Dealing first with the issue of setting the scale for momentum, energy, and mass measurements. All current detectors consist of a magnetic spectrometer followed by calorimeters. The magnetic spectrometer uses a precisely measured (NMR) magnetic field and the precise geometry of the tracking chambers to measure the curvature ($1/P_T$)of the tracks of charged particles. This is an absolute measurement- if perfect one has the momentum scale. One can then use particles with measured momentum as an *in situ* 'test beam' to calibrate the energy scale of the calorimeters.

Triggering on Low Mass Dimuon Bumps- SVT



Muon Efficiency vs η in CDF

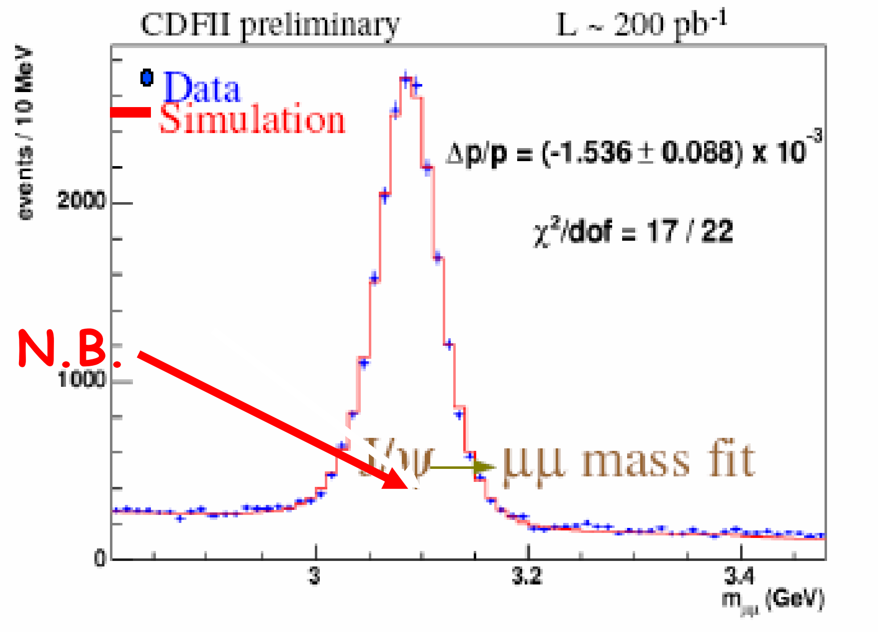


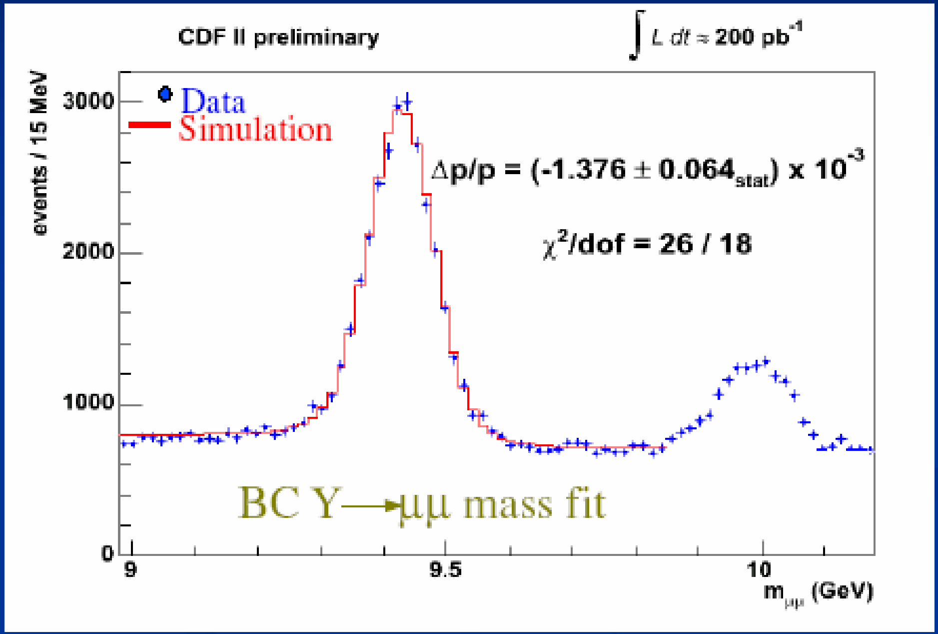
η

Calibrating the momentum scale

CDF Data from Feb. 02-Sept 03

218 pb^{-1} for e; 191 pb^{-1} for μ

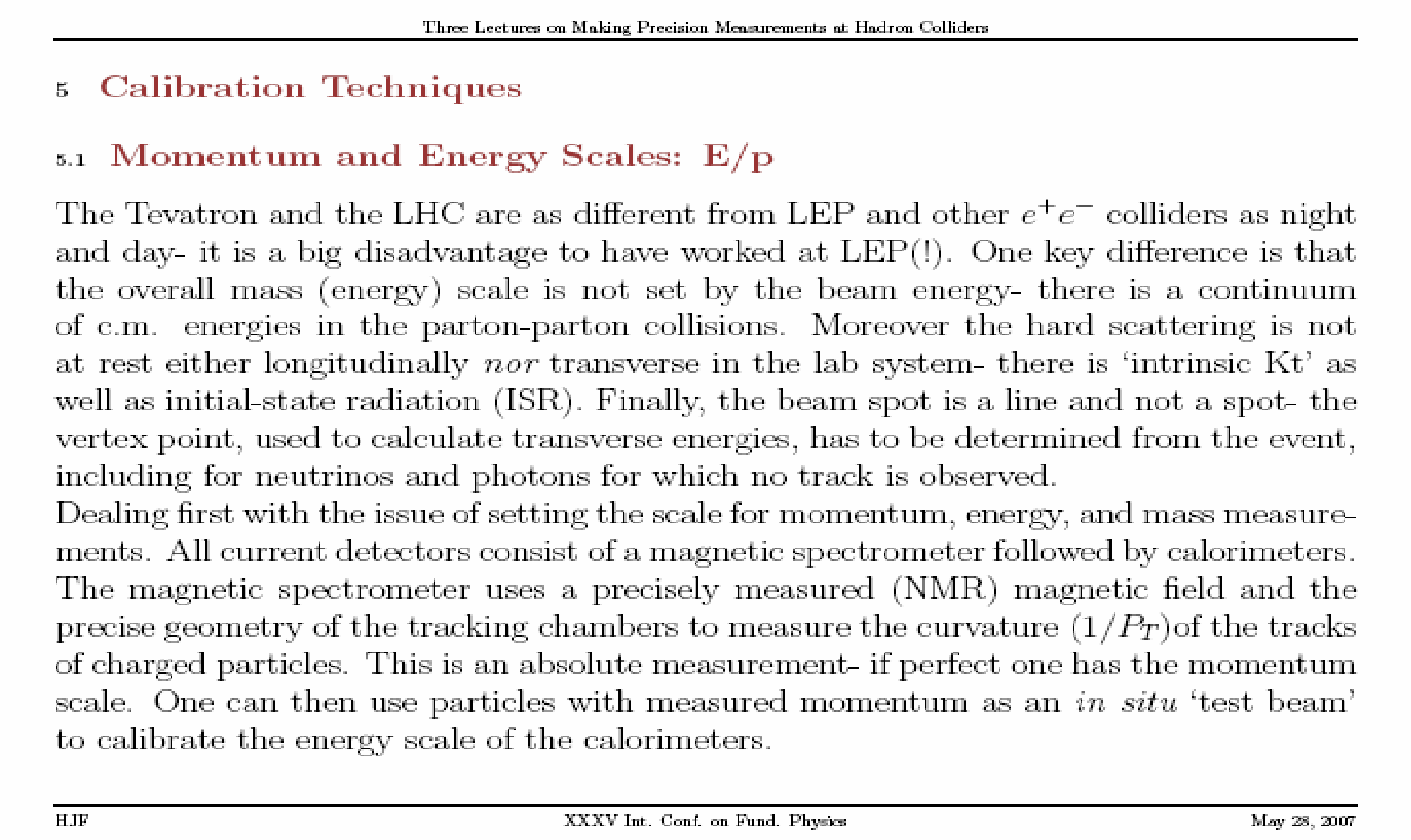




First, Calibrate the spectrometer momentum scale on the J/Psi and Upsilon-

Material traversed by muons really matters in calibration (e.g. for Wmass measurement.)

Calibration of E and P



5 Calibration Techniques

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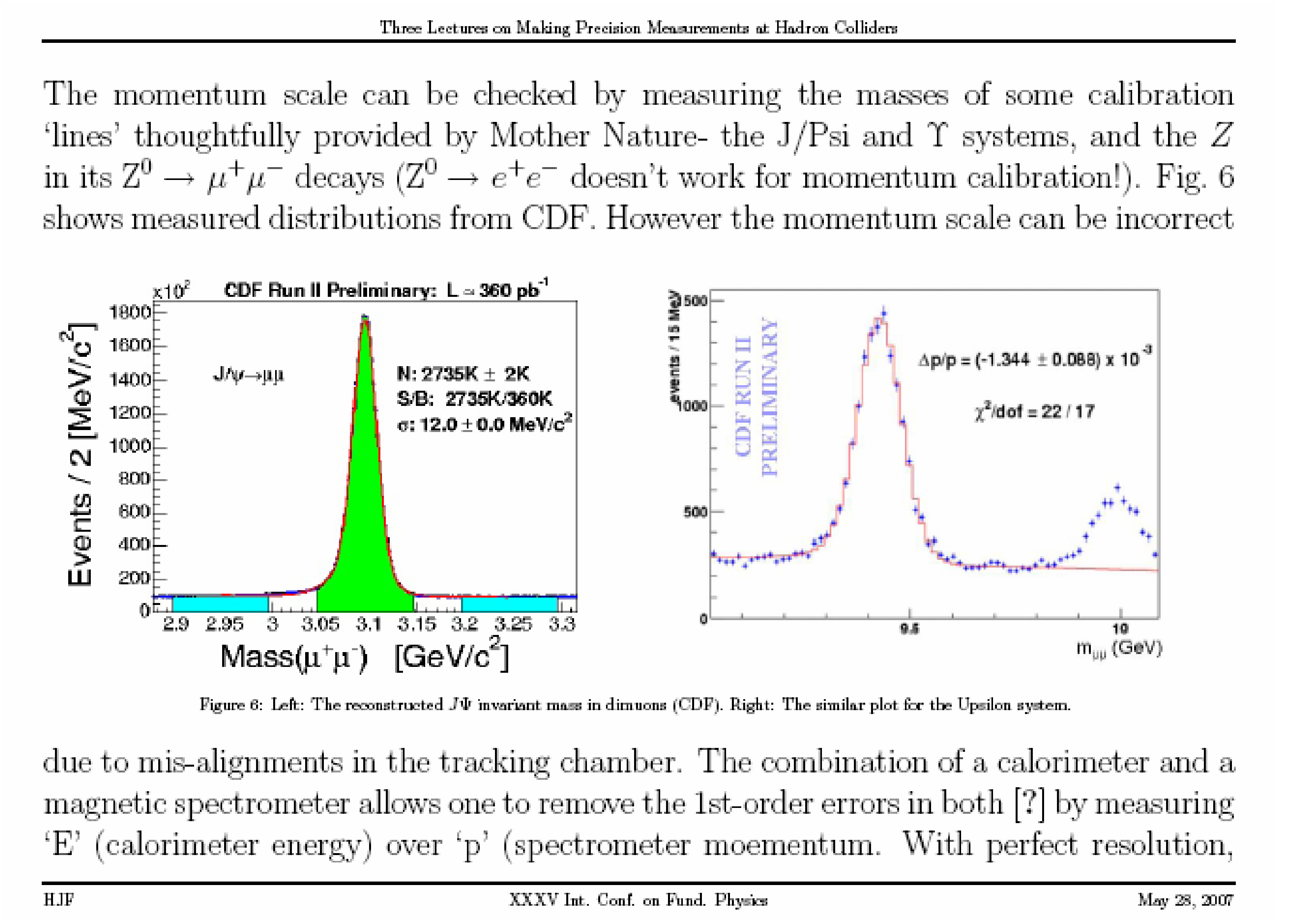
Calibration of E and P



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The momentum scale can be checked by measuring the masses of some calibration 'lines' thoughtfully provided by Mother Nature- the J/Psi and Υ systems, and the Z in its $Z^0 \rightarrow \mu^+\mu^-$ decays ($Z^0 \rightarrow e^+e^-$ doesn't work for momentum calibration!). Fig. 6 shows measured distributions from CDF. However the momentum scale can be incorrect

Figure 6: Left: The reconstructed $J\Psi$ invariant mass in dimuons (CDF). Right: The similar plot for the Upsilon system.

due to mis-alignments in the tracking chamber. The combination of a calorimeter and a magnetic spectrometer allows one to remove the 1st-order errors in both [?] by measuring 'E' (calorimeter energy) over 'p' (spectrometer moementum. With perfect resolution,

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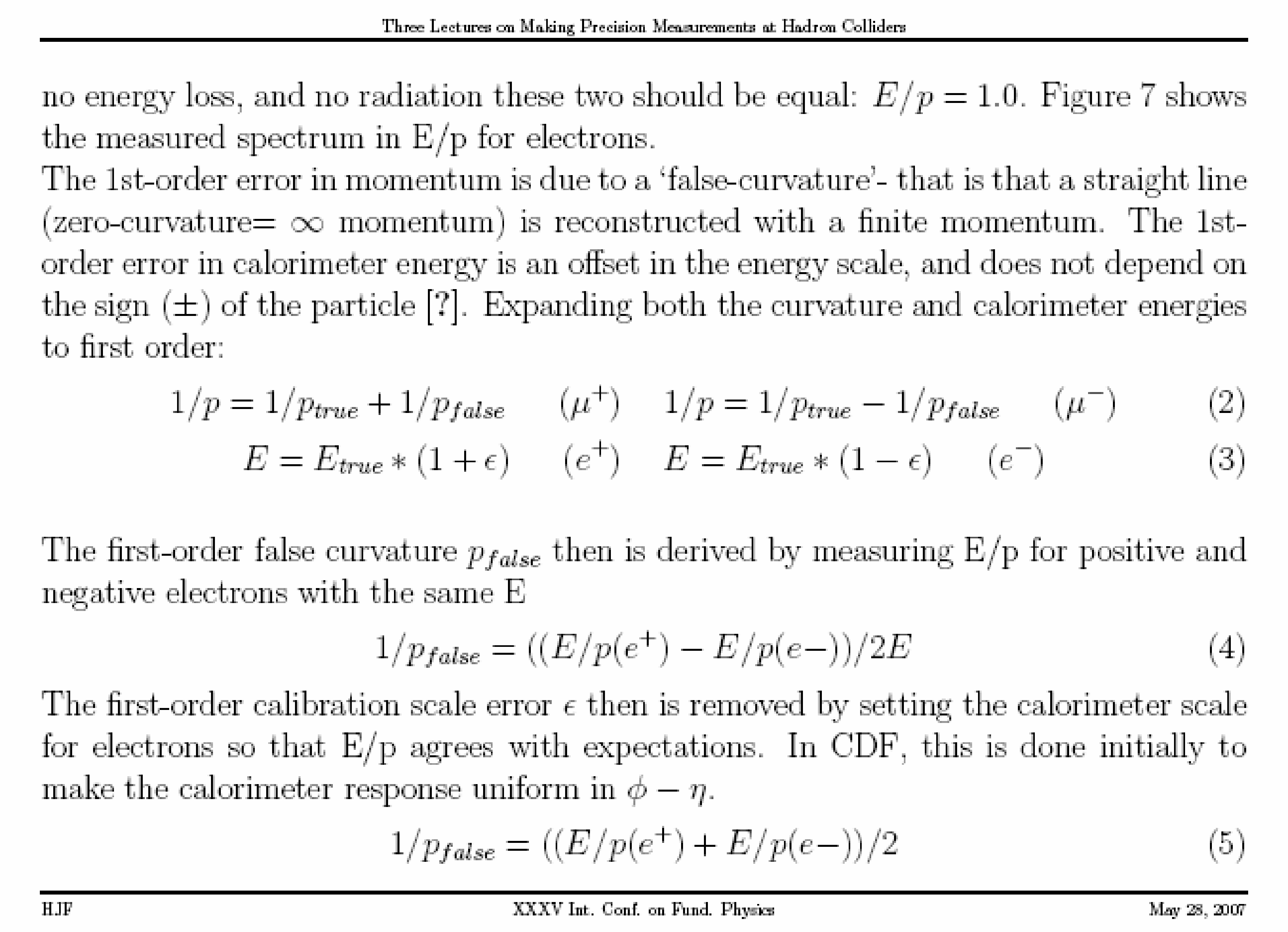
Calibration of E and P



no energy loss, and no radiation these two should be equal: $E/p = 1.0$. Figure 7 shows the measured spectrum in E/p for electrons.
The 1st-order error in momentum is due to a 'false-curvature'- that is that a straight line (zero-curvature= ∞ momentum) is reconstructed with a finite momentum. The 1st-order error in calorimeter energy is an offset in the energy scale, and does not depend on the sign (±) of the particle [?]. Expanding both the curvature and calorimeter energies to first order:

$$1/p = 1/p_{true} + 1/p_{false} \quad (\mu^+) \quad 1/p = 1/p_{true} - 1/p_{false} \quad (\mu^-) \tag{2}$$

$$E = E_{true} * (1 + \epsilon) \quad (e^+) \quad E = E_{true} * (1 - \epsilon) \quad (e^-) \tag{3}$$

The first-order false curvature p_{false} then is derived by measuring E/p for positive and negative electrons with the same E

$$1/p_{false} = ((E/p(e^+) - E/p(e-))/2E \tag{4}$$

The first-order calibration scale error ϵ then is removed by setting the calorimeter scale for electrons so that E/p agrees with expectations. In CDF, this is done initially to make the calorimeter response uniform in $\phi - \eta$.

$$1/p_{false} = ((E/p(e^+) + E/p(e-))/2 \tag{5}$$

Calibration of E and P

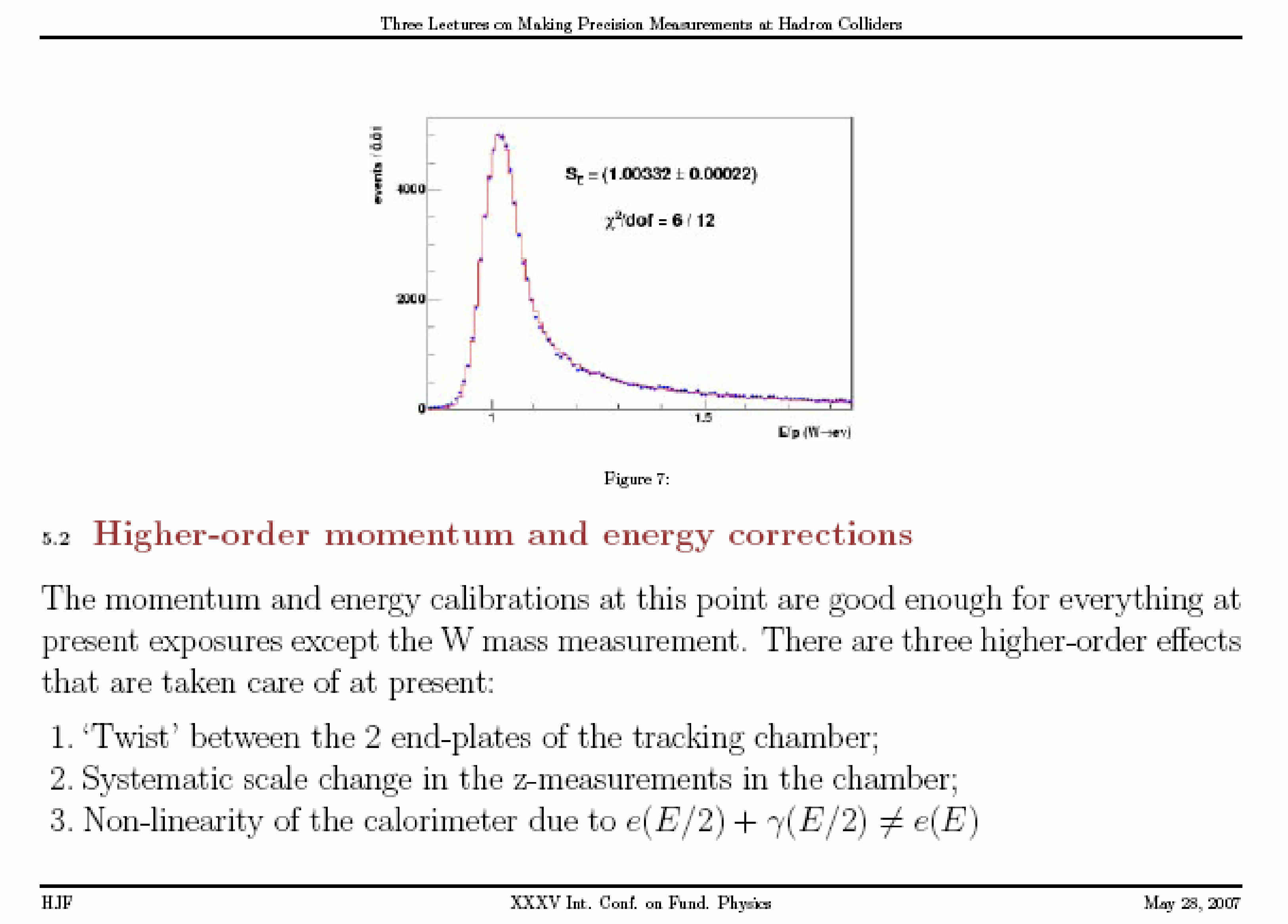


Figure 7:

5.2 Higher-order momentum and energy corrections

The momentum and energy calibrations at this point are good enough for everything at present exposures except the W mass measurement. There are three higher-order effects that are taken care of at present:

1. 'Twist' between the 2 end-plates of the tracking chamber;
2. Systematic scale change in the z-measurements in the chamber;
3. Non-linearity of the calorimeter due to $e(E/2) + \gamma(E/2) \neq e(E)$

Calibration of E and P

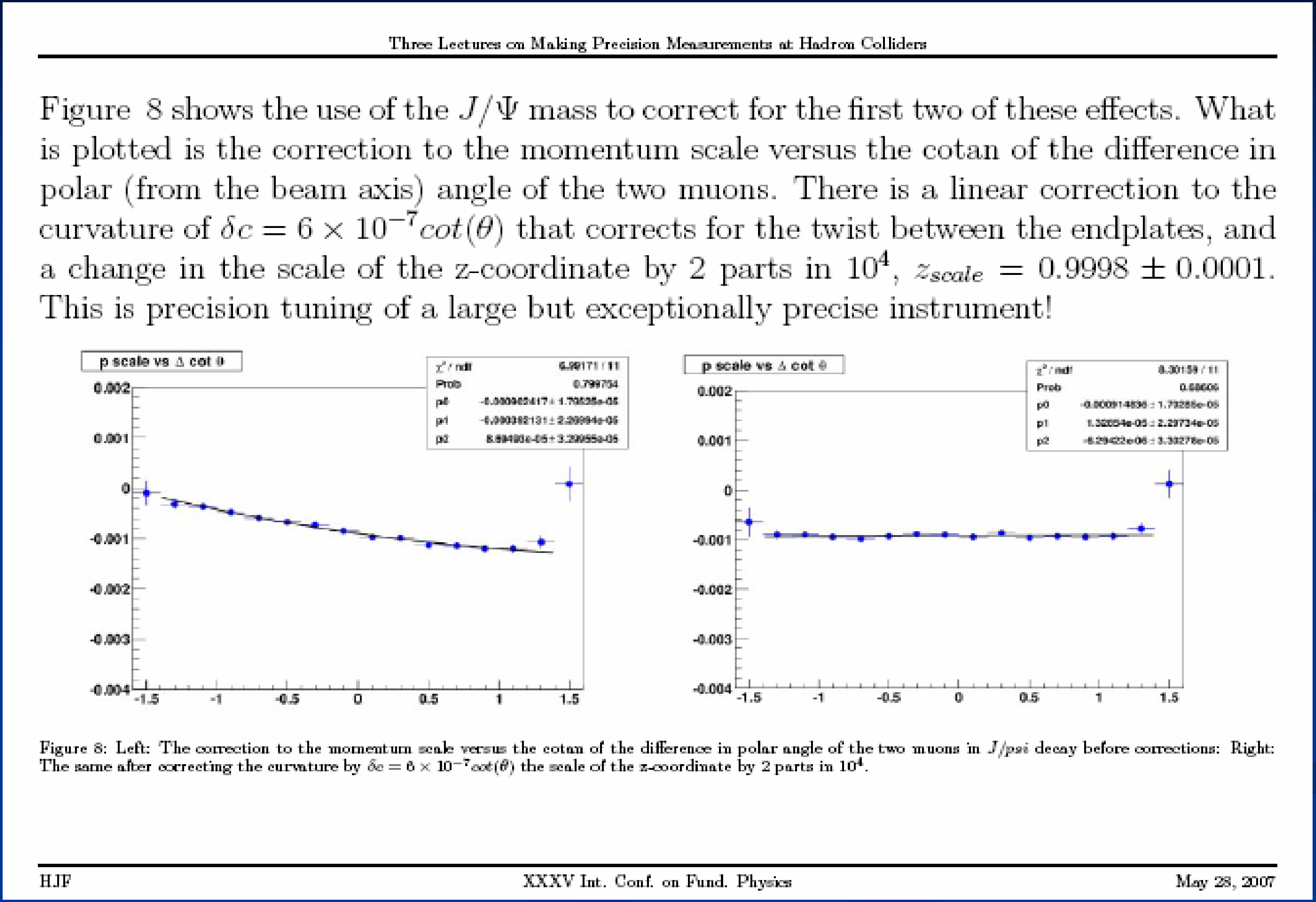


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Figure 8 shows the use of the J/Ψ mass to correct for the first two of these effects. What is plotted is the correction to the momentum scale versus the cotan of the difference in polar (from the beam axis) angle of the two muons. There is a linear correction to the curvature of $\delta c = 6 \times 10^{-7} cot(\theta)$ that corrects for the twist between the endplates, and a change in the scale of the z-coordinate by 2 parts in 10^4, $z_{scale} = 0.9998 \pm 0.0001$. This is precision tuning of a large but exceptionally precise instrument!

Figure 8: Left: The correction to the momentum scale versus the cotan of the difference in polar angle of the two muons in J/psi decay before corrections: Right: The same after correcting the curvature by $\delta c = 6 \times 10^{-7} cot(\theta)$ the scale of the z-coordinate by 2 parts in 10^4.

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Calibration of E and P

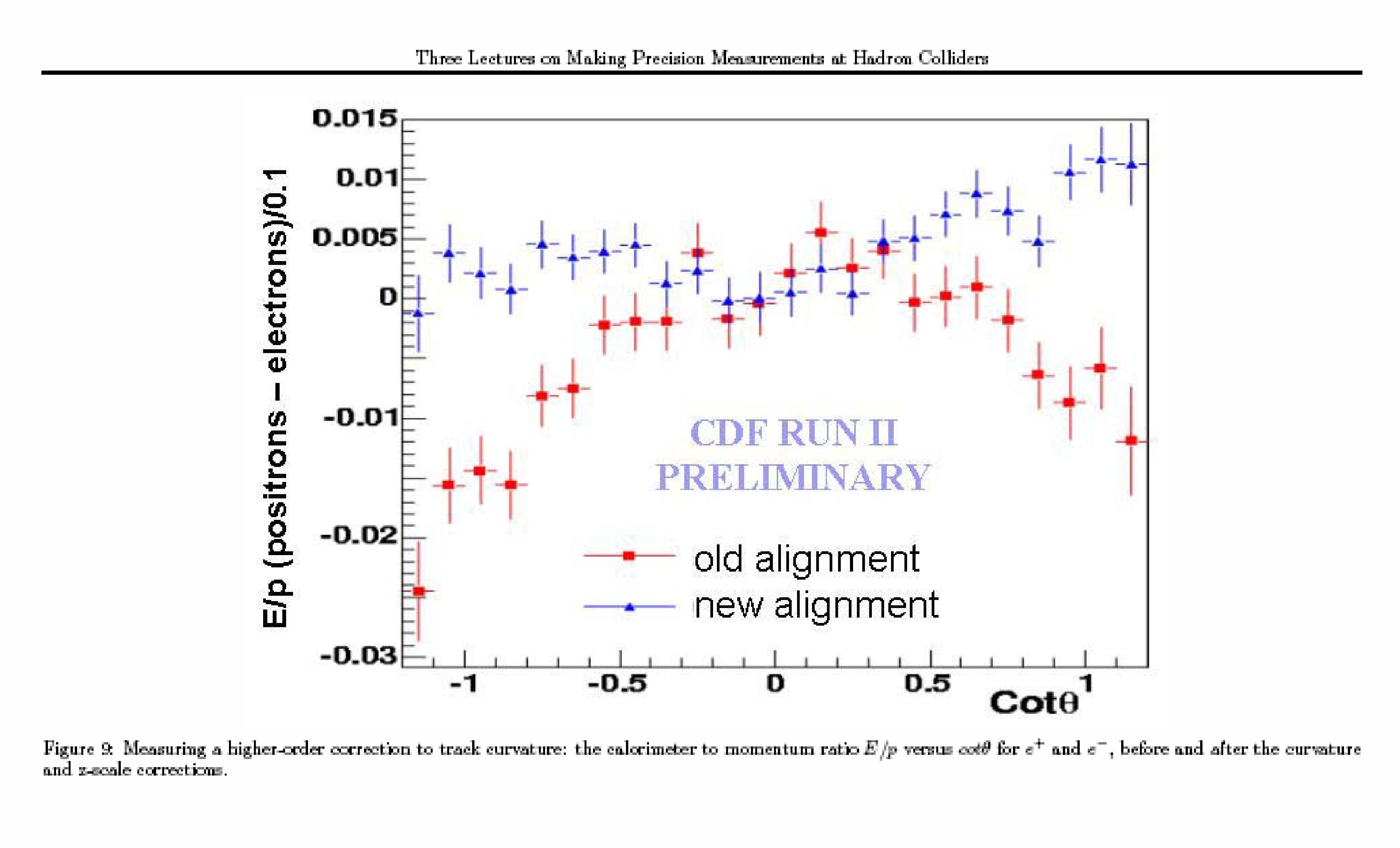

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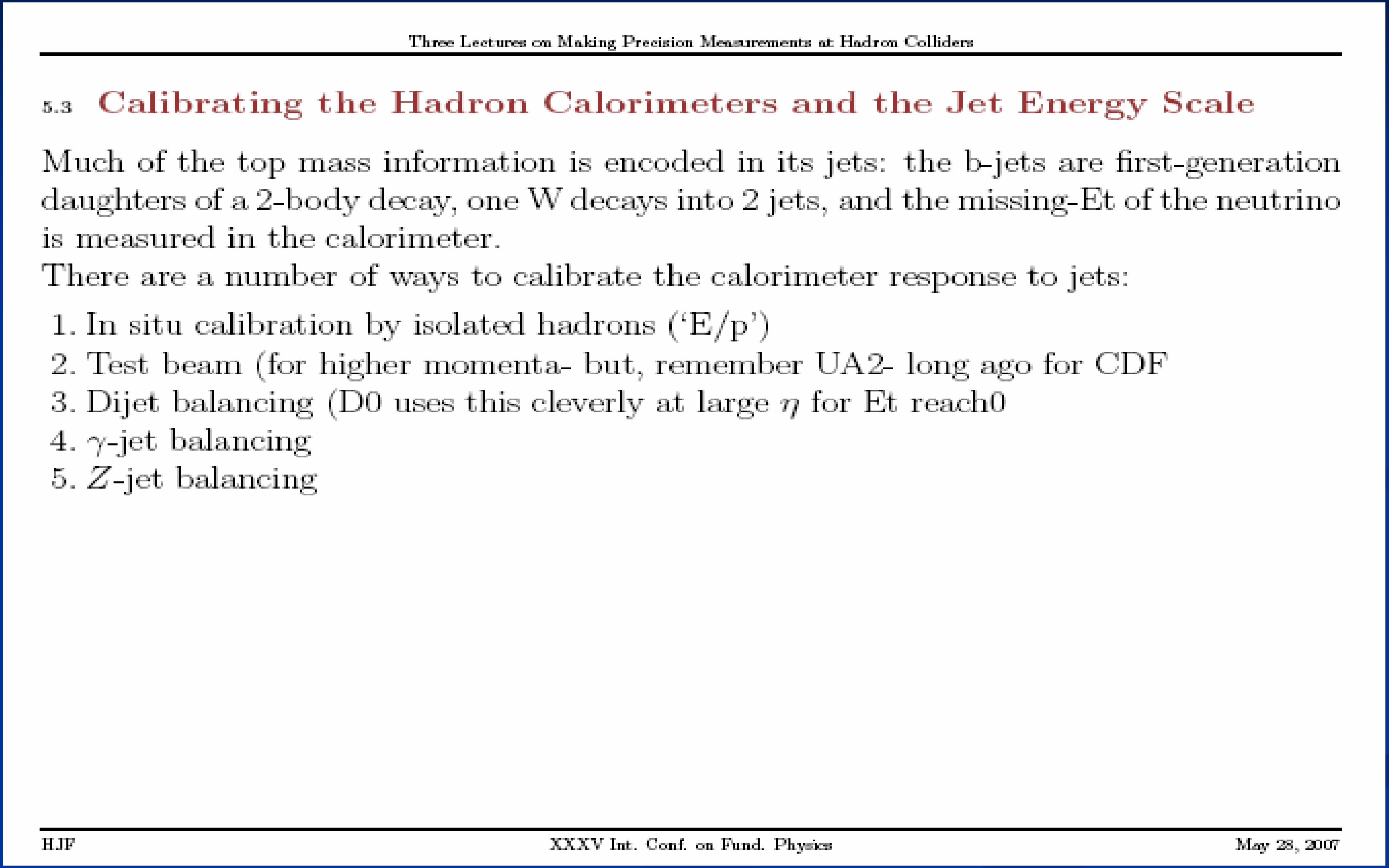
Figure 9: Measuring a higher-order correction to track curvature: the calorimeter to momentum ratio E/p versus $cot\theta$ for e^+ and e^-, before and after the curvature and z-scale corrections.

Calibration of Jet E



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5.3 Calibrating the Hadron Calorimeters and the Jet Energy Scale

Much of the top mass information is encoded in its jets: the b-jets are first-generation daughters of a 2-body decay, one W decays into 2 jets, and the missing-Et of the neutrino is measured in the calorimeter.

There are a number of ways to calibrate the calorimeter response to jets:

1. In situ calibration by isolated hadrons ('E/p')
2. Test beam (for higher momenta- but, remember UA2- long ago for CDF
3. Dijet balancing (D0 uses this cleverly at large η for Et reach0
4. γ-jet balancing
5. Z-jet balancing

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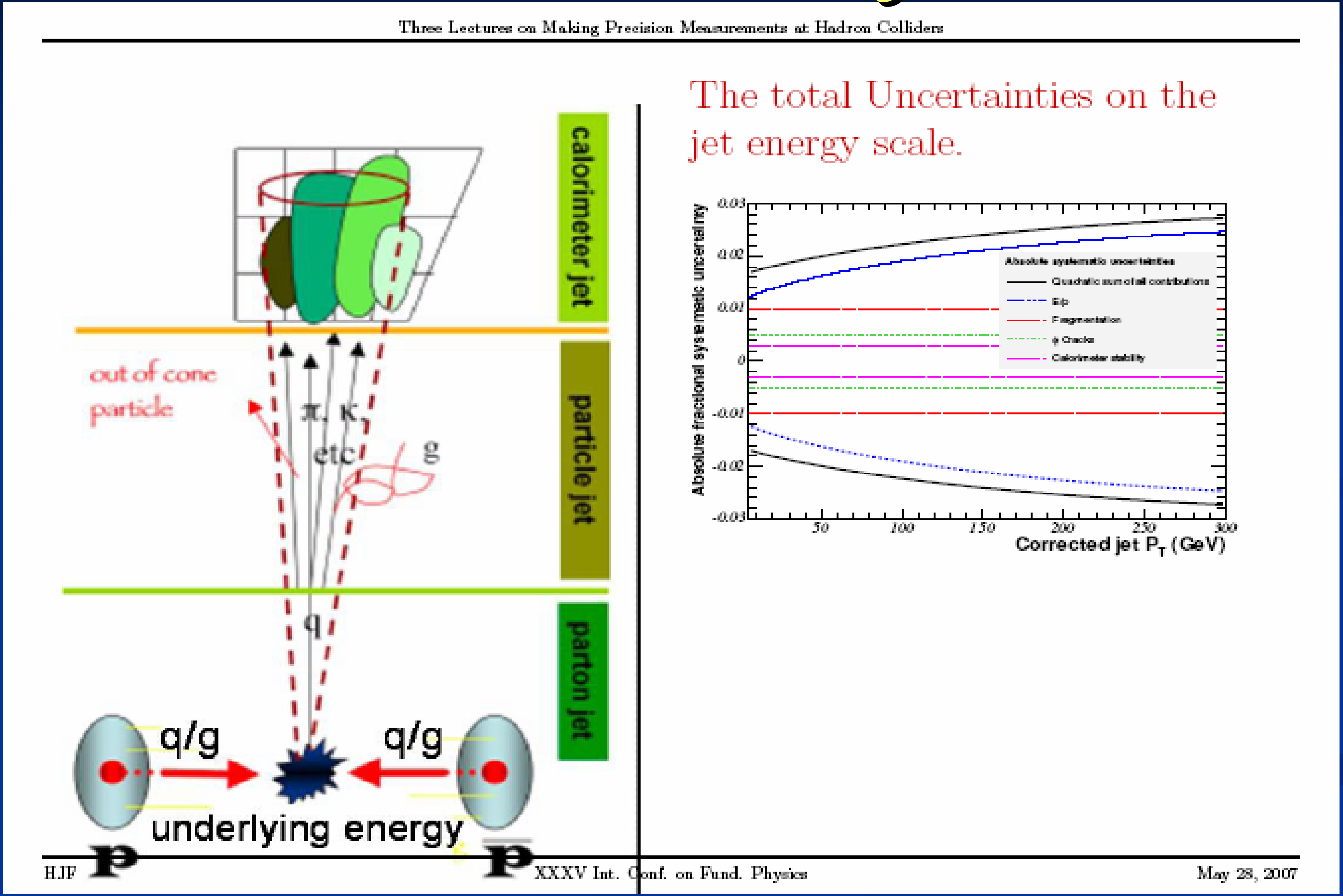
Calibration of Jet E



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The total Uncertainties on the jet energy scale.

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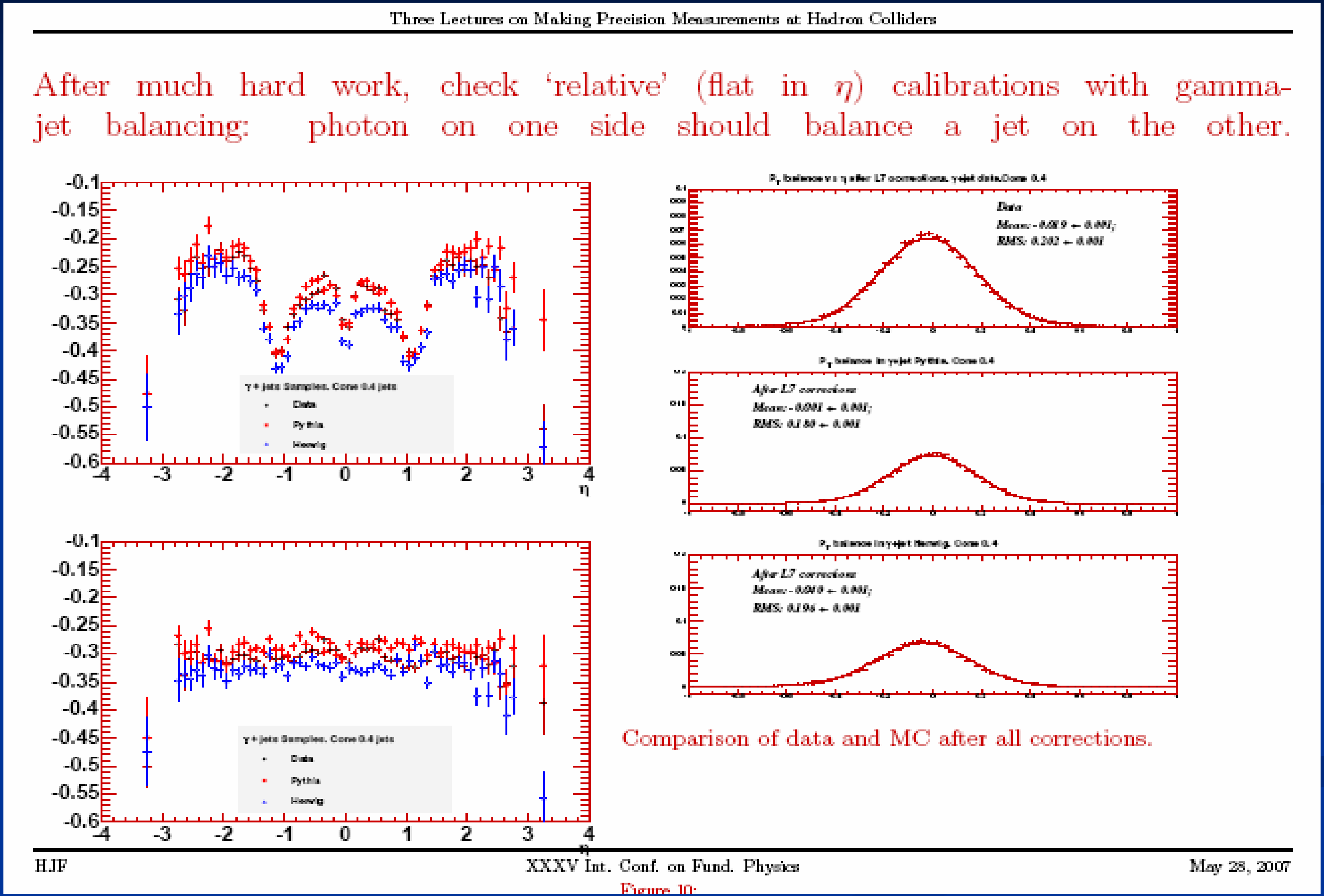
Calibration of Jet E



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After much hard work, check 'relative' (flat in η) calibrations with gamma-jet balancing: photon on one side should balance a jet on the other.

Comparison of data and MC after all corrections.

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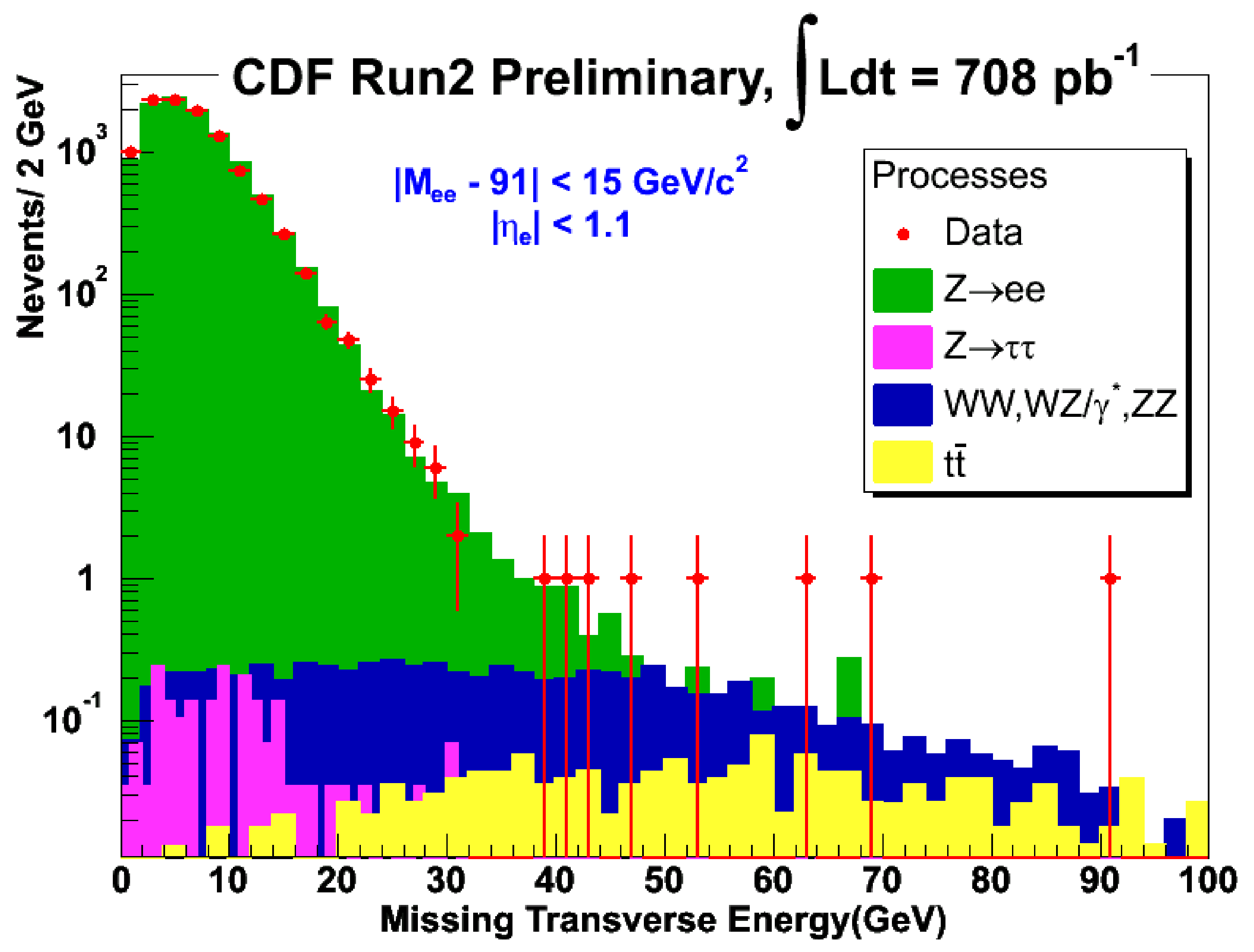
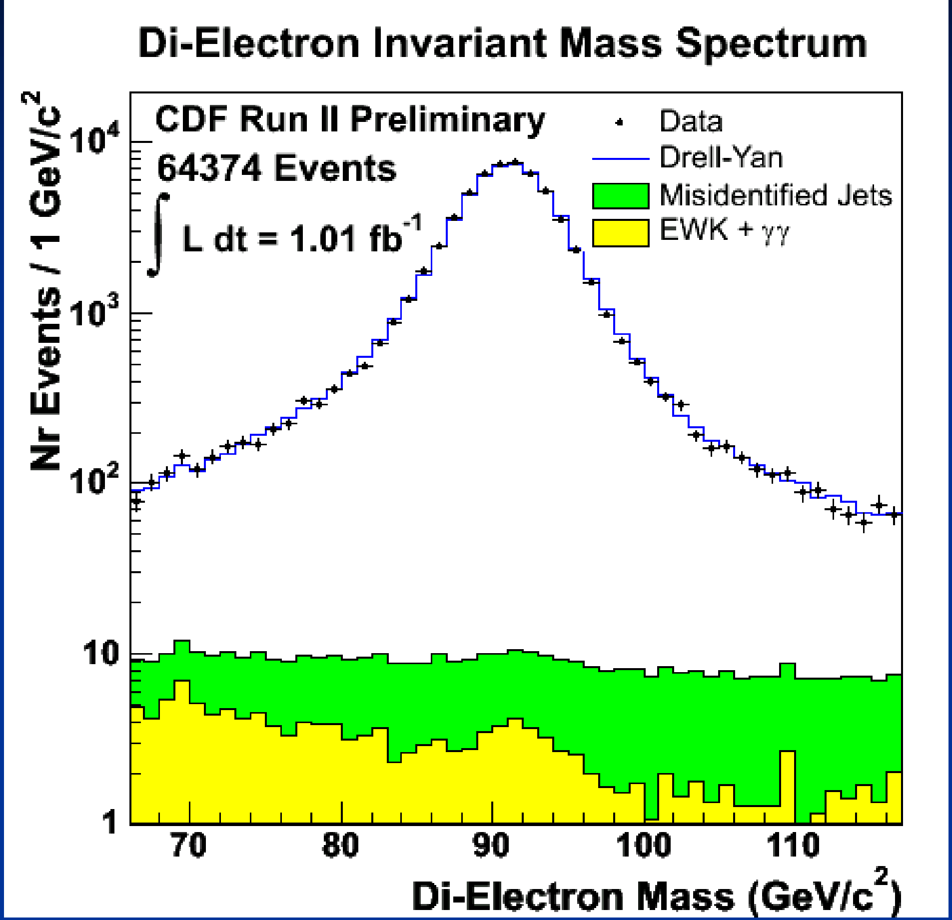
Figure 10:

Z+jet Production- THE Standard Candle

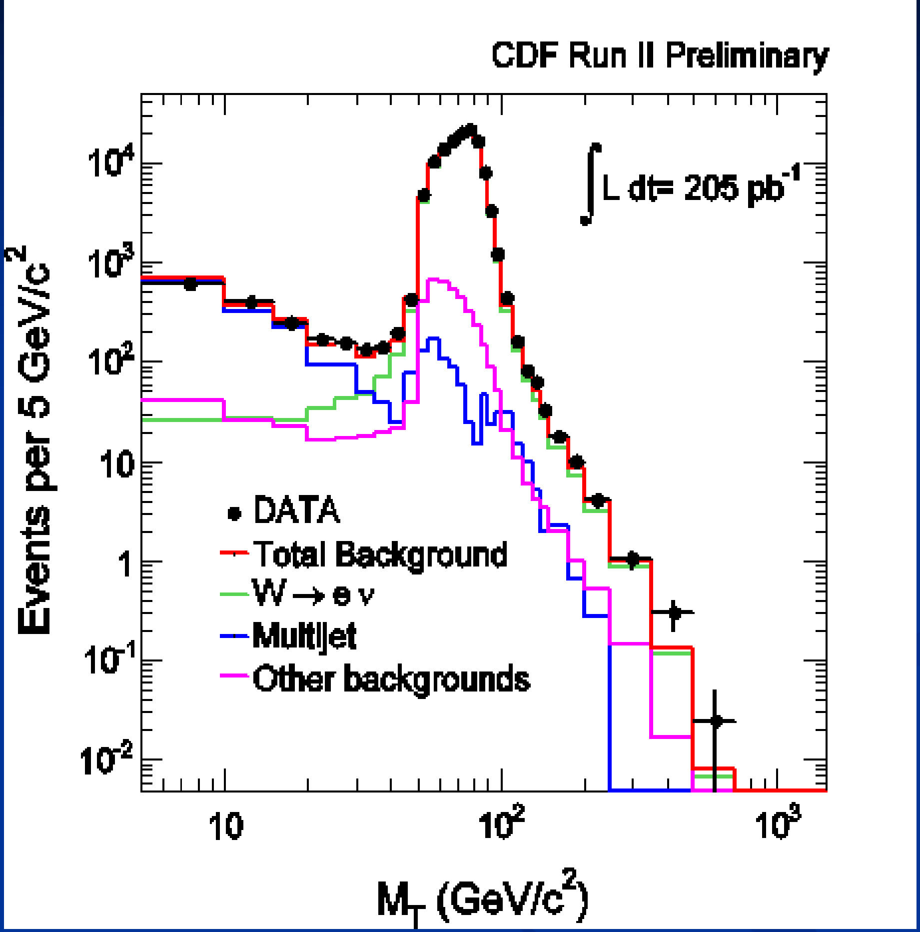


Use Met in Zee events
to measure Met resolution

Z+jet Production- THE Standard Candle



M(e+e-)- note low side is ok



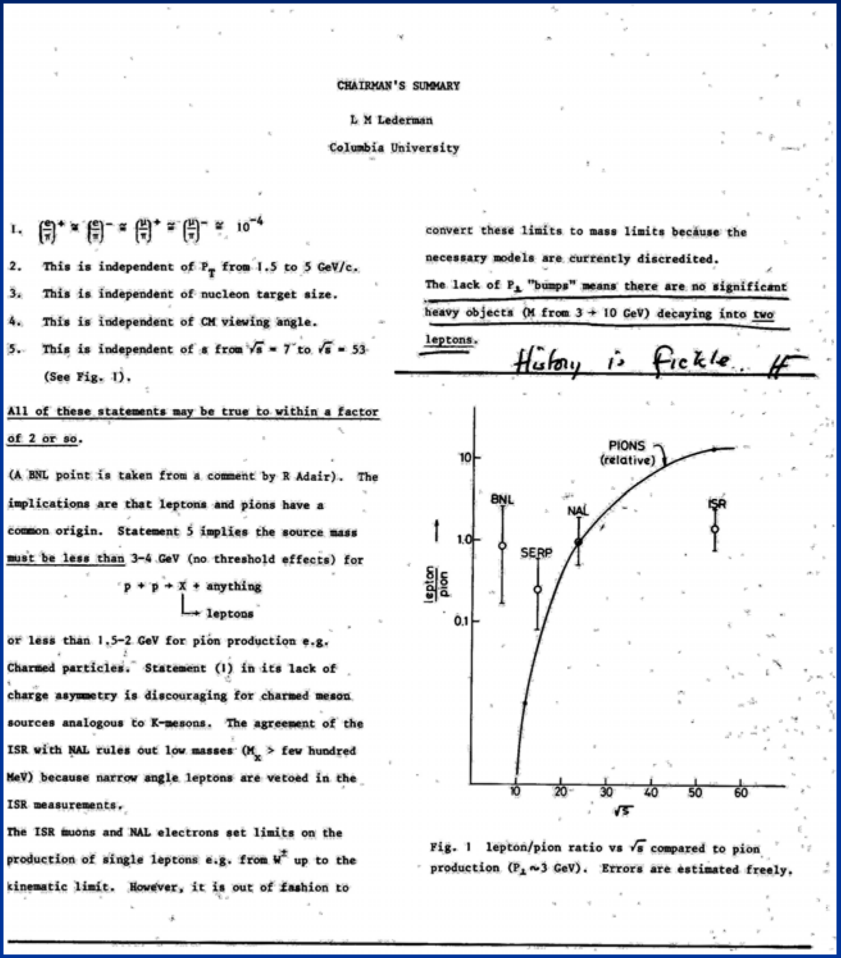
MT(enu)- note low side QCD bkd

The Importance of SM Predictions!

- Next 2 slides show pratfalls due to not knowing what was `old' (SM in these 3 cases charm, W+jets, and Z+jets) physics and hence what was new .
- However, getting it wrong didn't stop these guys: Lederman and Rubbia …

An historical aside: Lederman (Dir, Fermilab), Richter (Dir, SLAC), and Rubbia (Director, CERN)were on a panel at Aspen on the Future of HEP. Richter spoke first about how SLAC would explore the Z with SLC ; Rubbia spoke 2nd on how CERN would explore the Z and beyond with LEP; and for Leon?……………

Two cases of non-understanding of 'What's Beneath'



CHAIRMAN'S SUMMARY

L M Lederman

Columbia University

1. $\left(\frac{e}{\pi}\right)^+ \cong \left(\frac{e}{\pi}\right)^- \cong \left(\frac{\mu}{\pi}\right)^+ \cong \left(\frac{\mu}{\pi}\right)^- \cong 10^{-4}$
2. This is independent of P_T from 1.5 to 5 GeV/c.
3. This is independent of nucleon target size.
4. This is independent of CM viewing angle.
5. This is independent of s from $\sqrt{s}$ = 7 to $\sqrt{s}$ = 53 (See Fig. 1).

All of these statements may be true to within a factor of 2 or so.

(A BNL point is taken from a comment by R Adair). The implications are that leptons and pions have a common origin. Statement 5 implies the source mass must be less than 3-4 GeV (no threshold effects) for

$$p + p \rightarrow X + \text{anything}$$
$$\quad\quad\quad\; \llcorner\!\!\rightarrow \text{leptons}$$

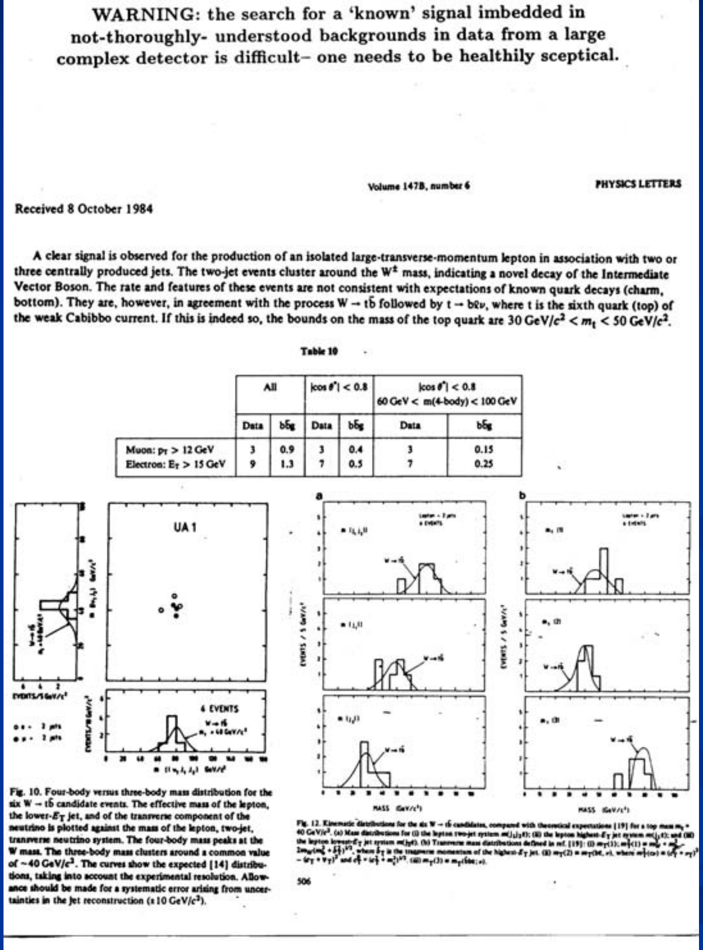
or less than 1.5-2 GeV for pion production e.g. Charmed particles. Statement (1) in its lack of charge asymmetry is discouraging for charmed meson sources analogous to K-mesons. The agreement of the ISR with NAL rules out low masses (M_x > few hundred MeV) because narrow angle leptons are vetoed in the ISR measurements.

The ISR muons and NAL electrons set limits on the production of single leptons e.g. from $W^{\pm}$ up to the kinematic limit. However, it is out of fashion to convert these limits to mass limits because the necessary models are currently discredited.

The lack of $P_\perp$ "bumps" means there are no significant heavy objects (M from 3 → 10 GeV) decaying into two leptons.

History is fickle.. HF

Fig. 1 lepton/pion ratio vs $\sqrt{s}$ compared to pion production ($P_\perp \sim 3$ GeV). Errors are estimated freely.



WARNING: the search for a 'known' signal imbedded in not-thoroughly- understood backgrounds in data from a large complex detector is difficult– one needs to be healthily sceptical.

Volume 147B, number 6 PHYSICS LETTERS

Received 8 October 1984

A clear signal is observed for the production of an isolated large-transverse-momentum lepton in association with two or three centrally produced jets. The two-jet events cluster around the $W^{\pm}$ mass, indicating a novel decay of the Intermediate Vector Boson. The rate and features of these events are not consistent with expectations of known quark decays (charm, bottom). They are, however, in agreement with the process $W \rightarrow t\bar{b}$ followed by $t \rightarrow b\ell\nu$, where t is the sixth quark (top) of the weak Cabibbo current. If this is indeed so, the bounds on the mass of the top quark are $30\ \text{GeV}/c^2 < m_t < 50\ \text{GeV}/c^2$.

Table 10

	All		$\lvert\cos\theta^*\rvert < 0.8$		$\lvert\cos\theta^*\rvert < 0.8$ 60 GeV < m(4-body) < 100 GeV	
	Data	bkg	Data	bkg	Data	bkg
Muon: p_T > 12 GeV	3	0.9	3	0.4	3	0.15
Electron: E_T > 15 GeV	9	1.3	7	0.5	7	0.25

Fig. 10. Four-body versus three-body mass distribution for the six $W \rightarrow t\bar{b}$ candidate events. The effective mass of the lepton, the lower-E_T jet, and of the transverse component of the neutrino is plotted against the mass of the lepton, two-jet, transverse neutrino system. The four-body mass peaks at the W mass. The three-body mass clusters around a common value of ~40 GeV/c^2. The curves show the expected [14] distributions, taking into account the experimental resolution. Allowance should be made for a systematic error arising from uncertainties in the jet reconstruction (±10 GeV/c^2).

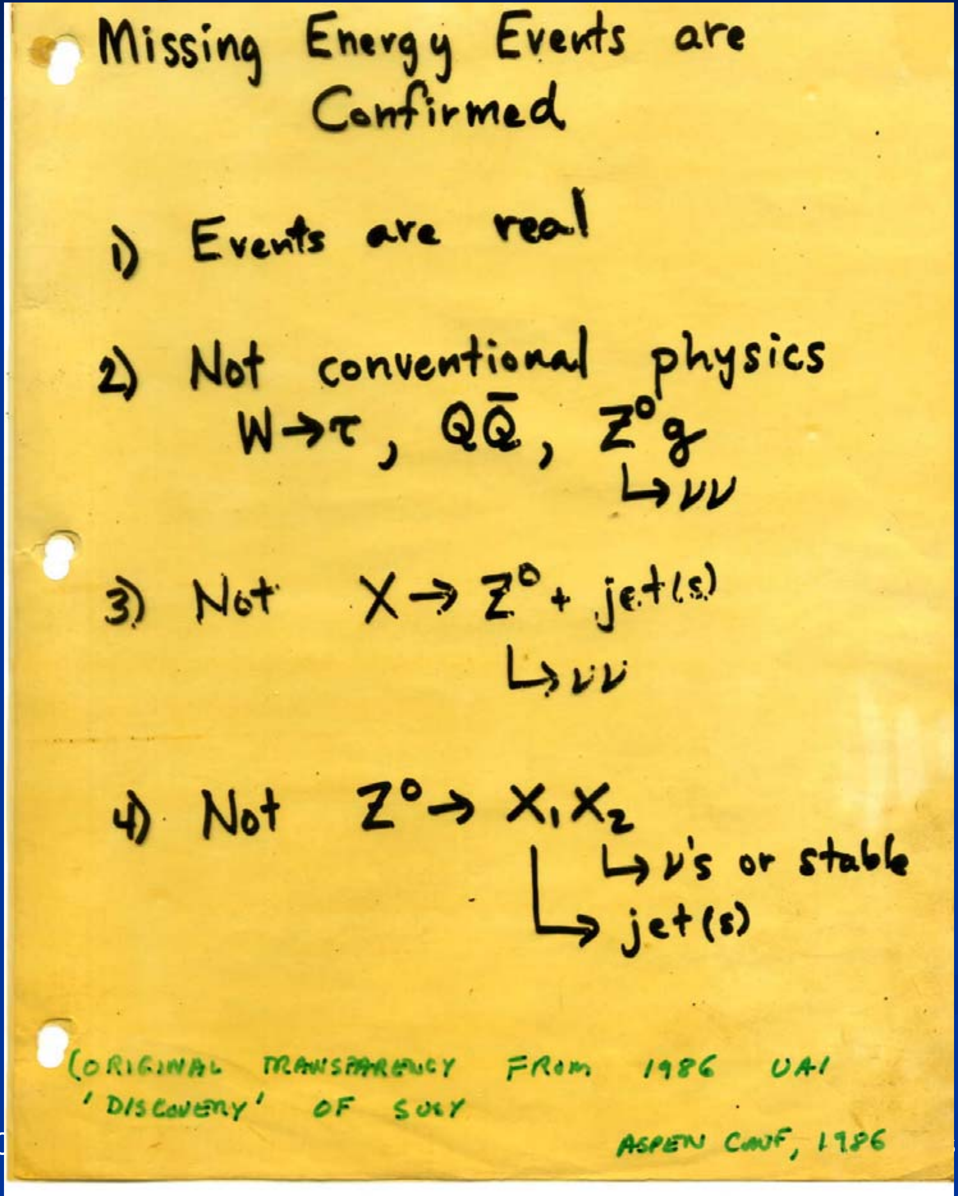
Fig. 12. Kinematic distributions for the six $W \rightarrow t\bar{b}$ candidates, compared with theoretical expectations [19] for a top mass m_t = 40 GeV/c^2. [illegible]

506

Leon Lederman and 1971 J/Psi Non-discovery

Carlo and the 1984 Top 'Discovery'

Classic example of the importance of thorough SM predictions of what you expect



Missing Energy Events are Confirmed

1) Events are real

2) Not conventional physics
$W \to \tau$, $Q\bar{Q}$, $Z^0 g$
$\hookrightarrow \nu\nu$

3) Not $X \to Z^0 + \text{jet(s)}$
$\hookrightarrow \nu\nu$

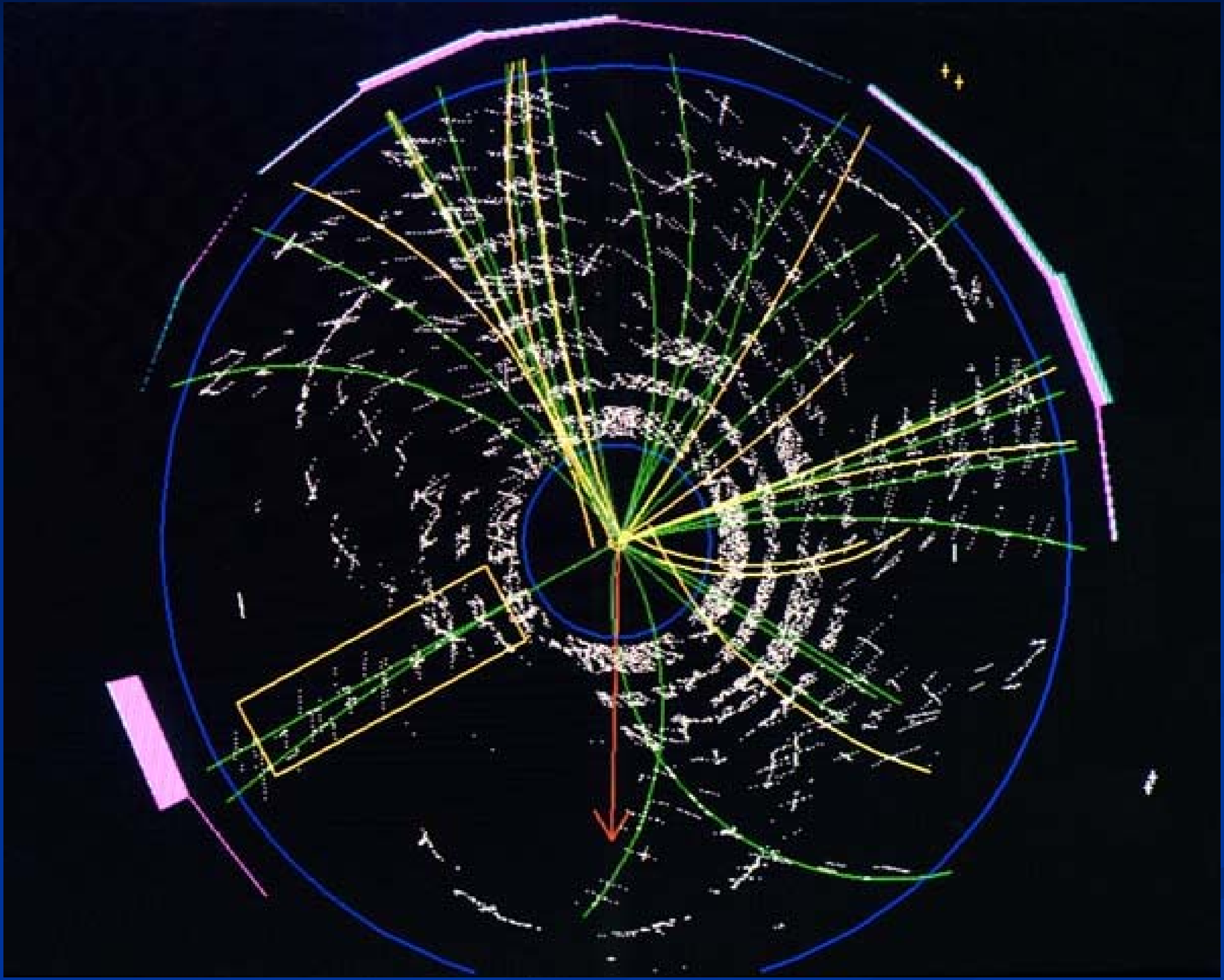
4) Not $Z^0 \to \chi_1 \chi_2$
$\hookrightarrow \nu$'s or stable
$\hookrightarrow$ jet(s)

(ORIGINAL TRANSPARENCY FROM 1986 UA1
'DISCOVERY' OF SUSY

ASPEN CONF, 1986

Original transparency of 1986 UA1 SUSY 'Discovery'! (Steve Ellis showed it was a `cocktail' of SM processes- e.g. Z+jets)

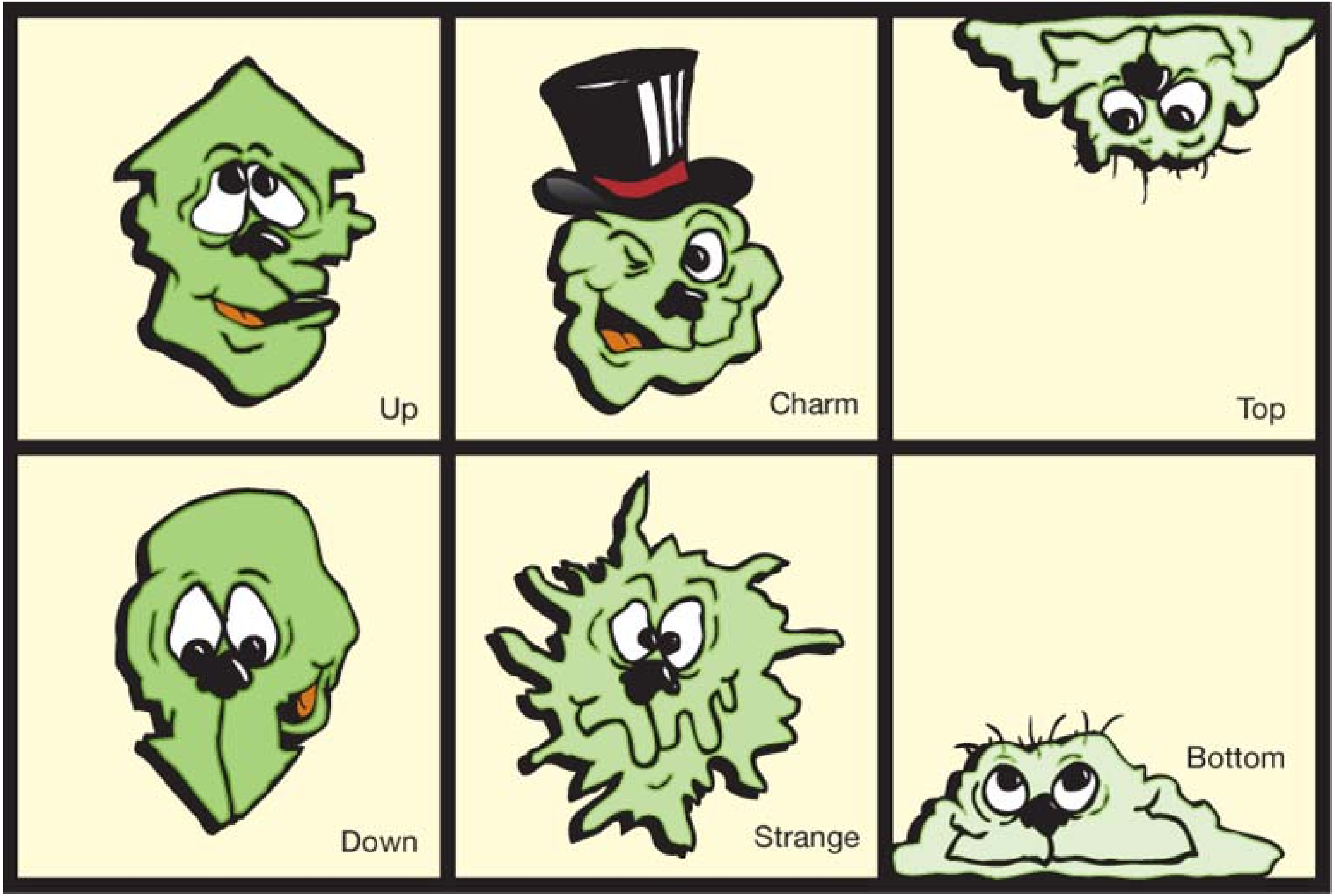
The End of 1st Lecture



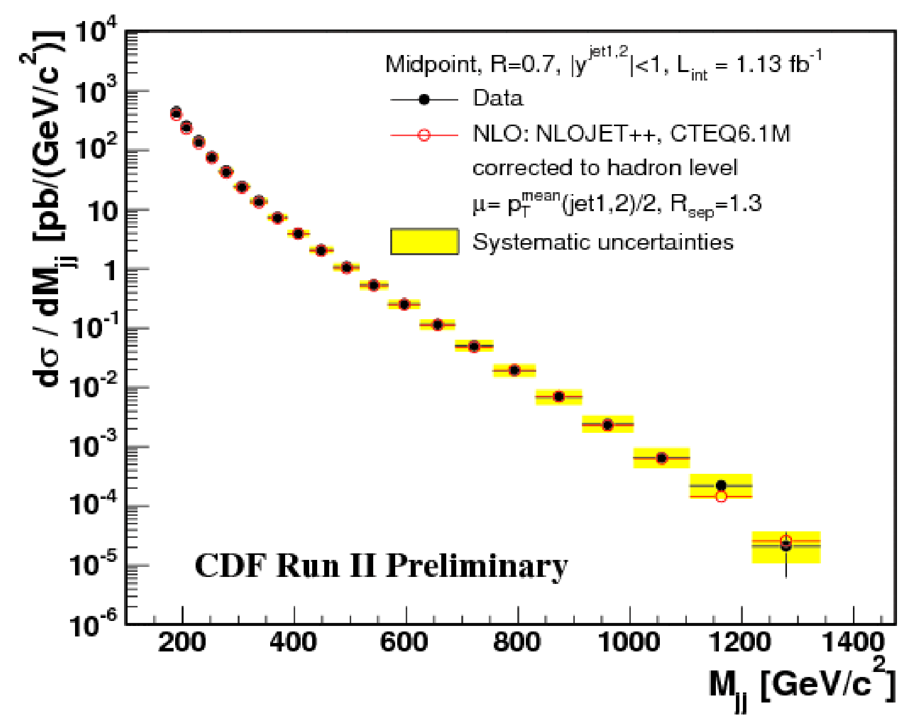
“You could be up to your belly-buttons in (SUSY) and not know it..”- C. Prescott

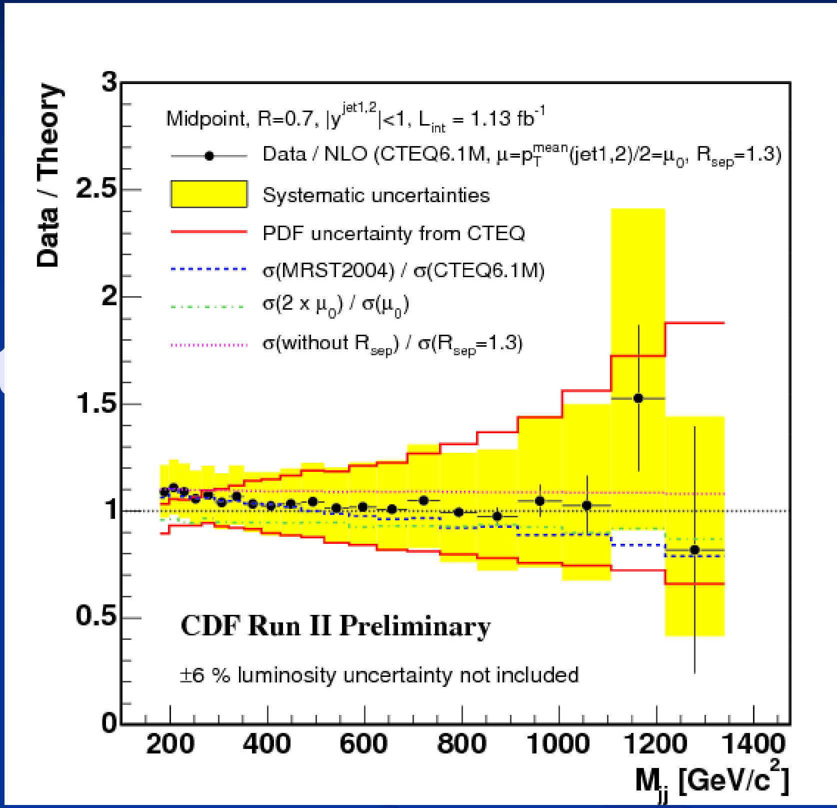
Referemces:

The Quarks



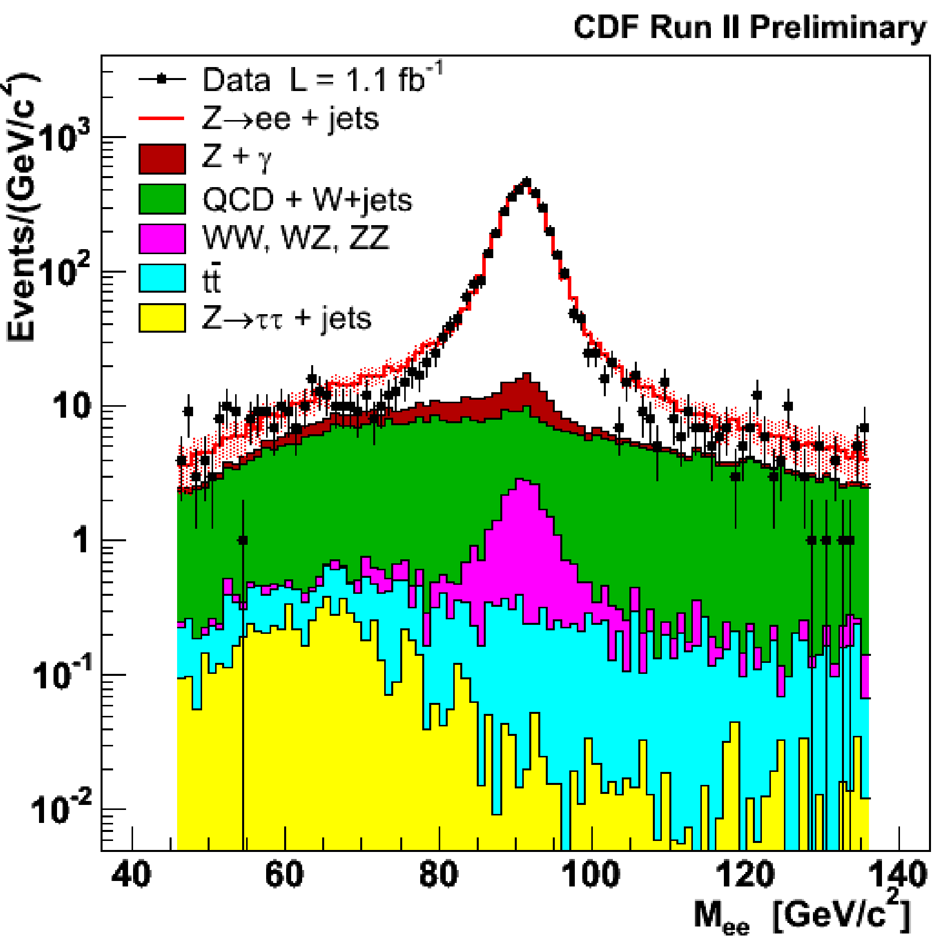
BACKUP SLIDES

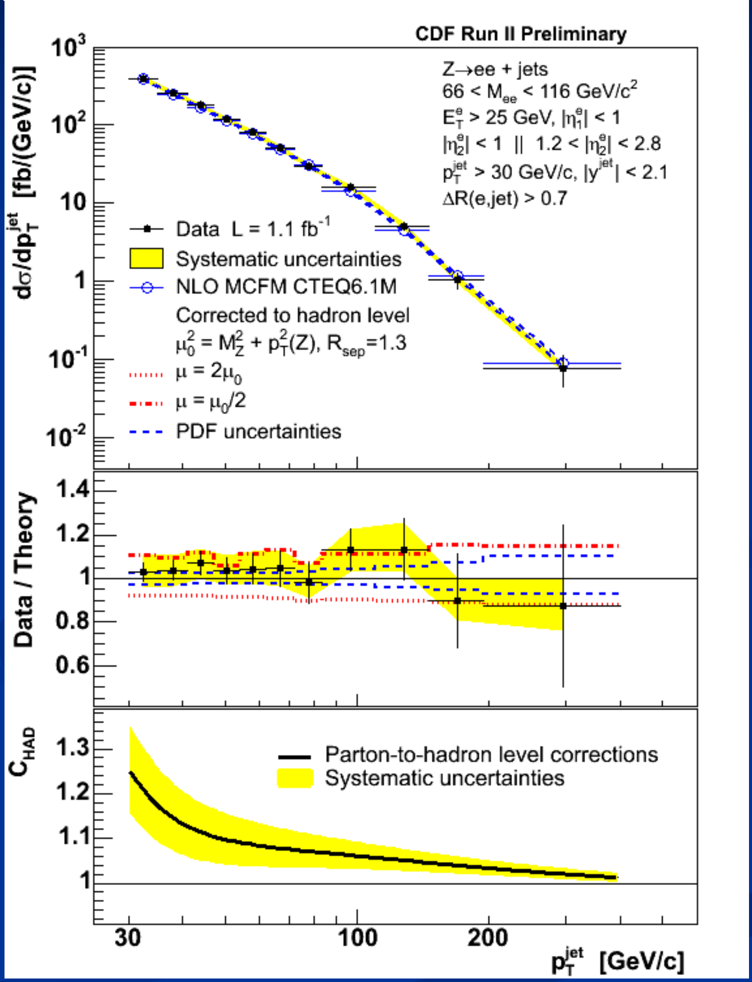




Really remarkable agreement with CTEQ PDF's in Mass (JJ)- note # of decades, systematic uncertainty bands

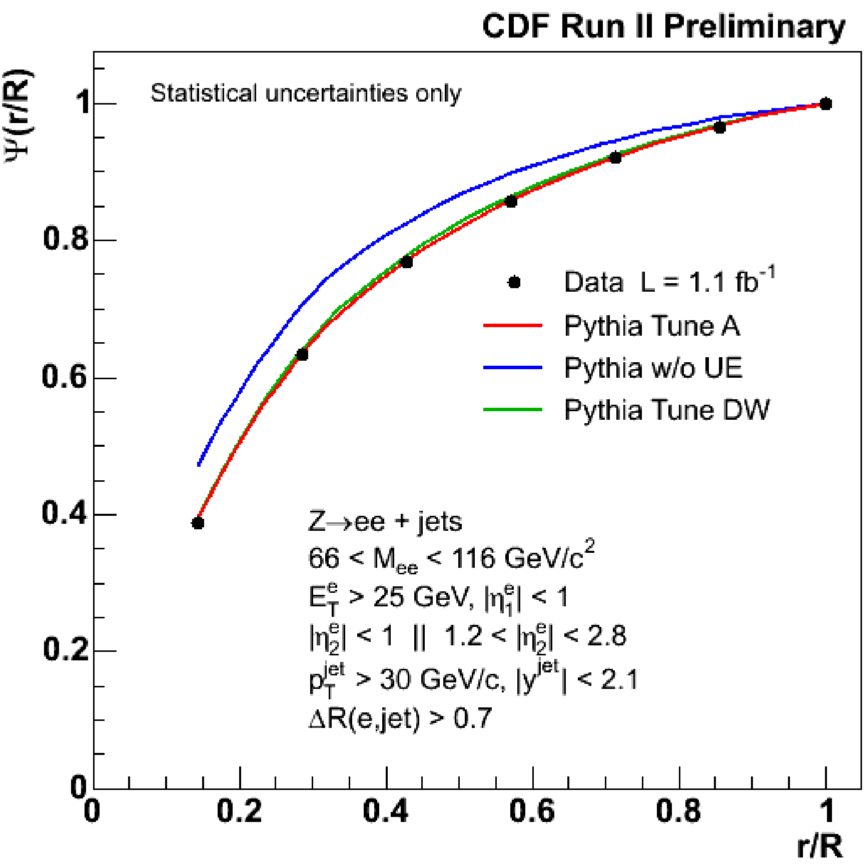
Z+jet Production- THE Standard Candle(SC) and PDF's



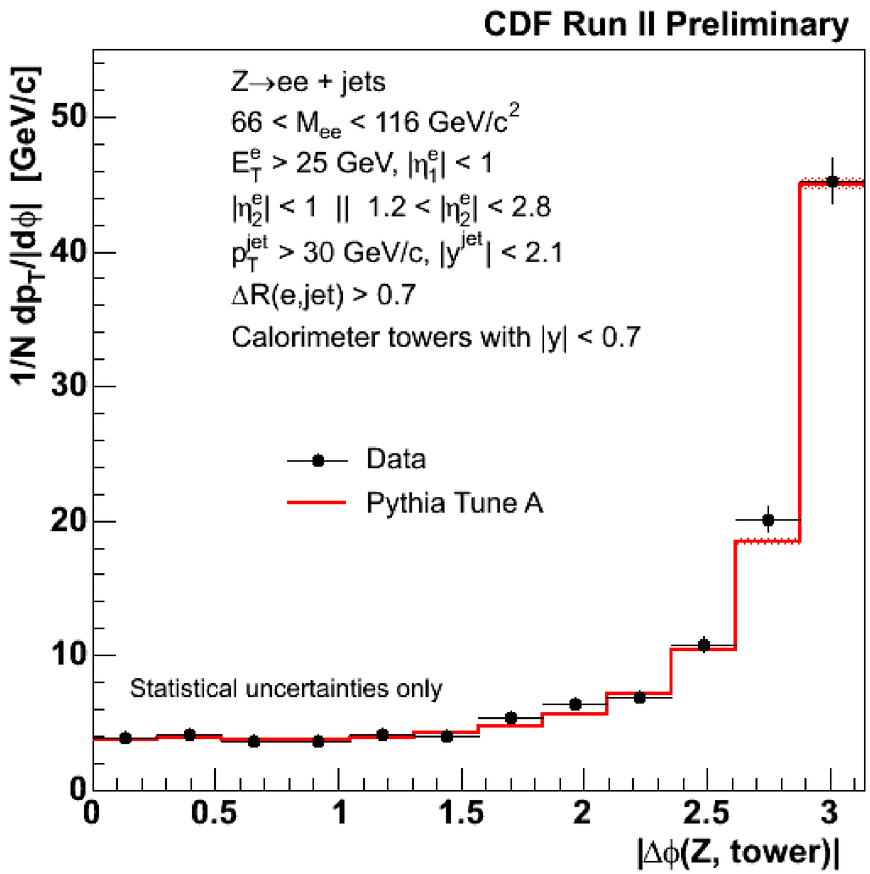


Really remarkable agreement with CTEQ PDF's - note # of decades, systematic uncertainty bands

Z+jet Production- THE Standard Candle (SC) and PDF’s



Jet Shape in eta-phi space (R)

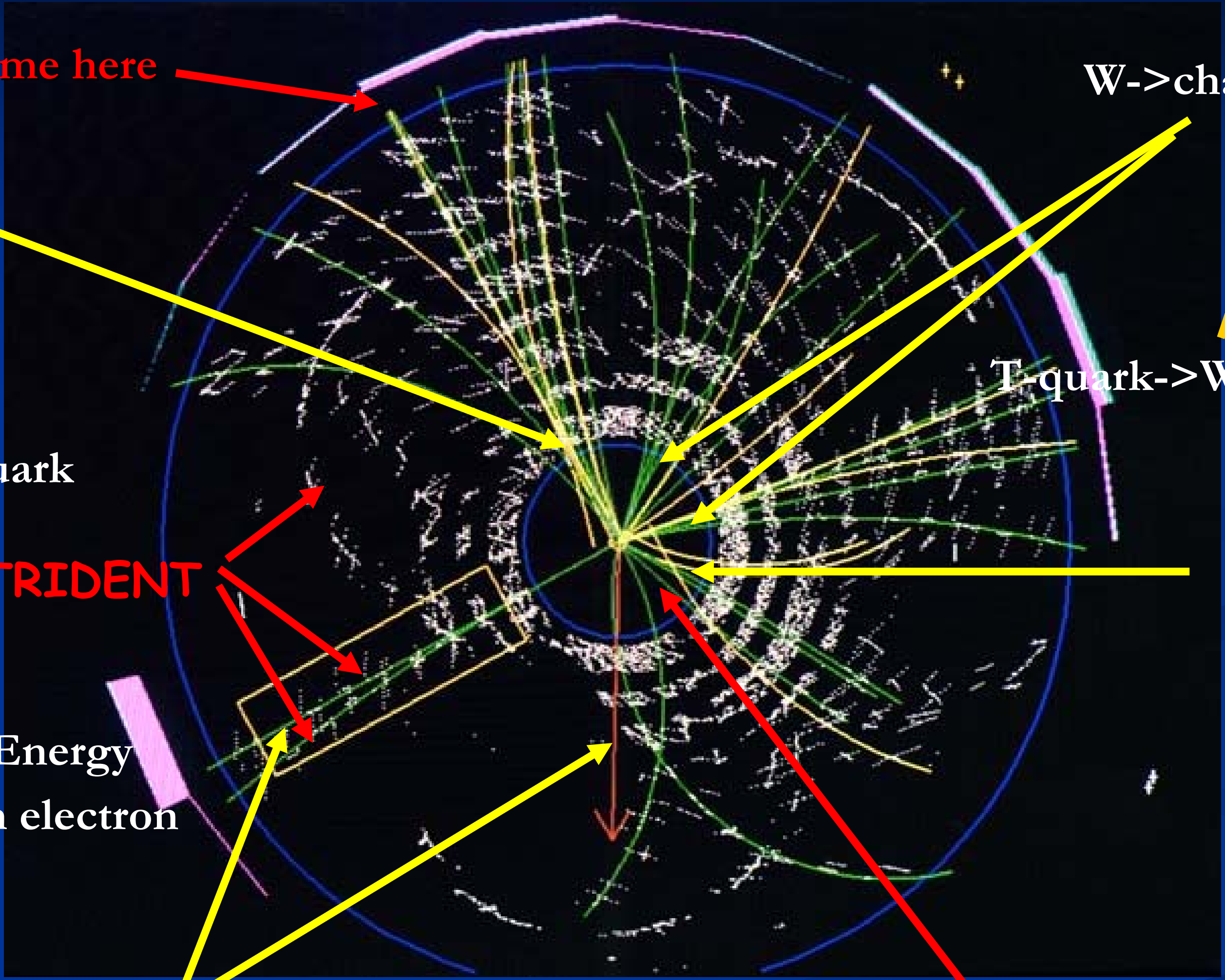


Energy flow in |Delta-y|=0.7

Really remarkable agreement with CTEQ PDF’s - note # of decades, systematic uncertainty bands

A real CDF Top Quark Event

T-Tbar -> W$^+$bW$^-$bbar



Measure transit time here (stop)

W->charm sbar

B-quark

T-quark->W+bquark

T-quark->W+bquark

TRIDENT

B-quark

Cal. Energy
From electron

W->electron+neutrino

Fit t_0 (start) from all tracks

Can we follow the color flow through kaons, charm, bottom? TOF!