

Calorimetry at Hadron Colliders: DØ

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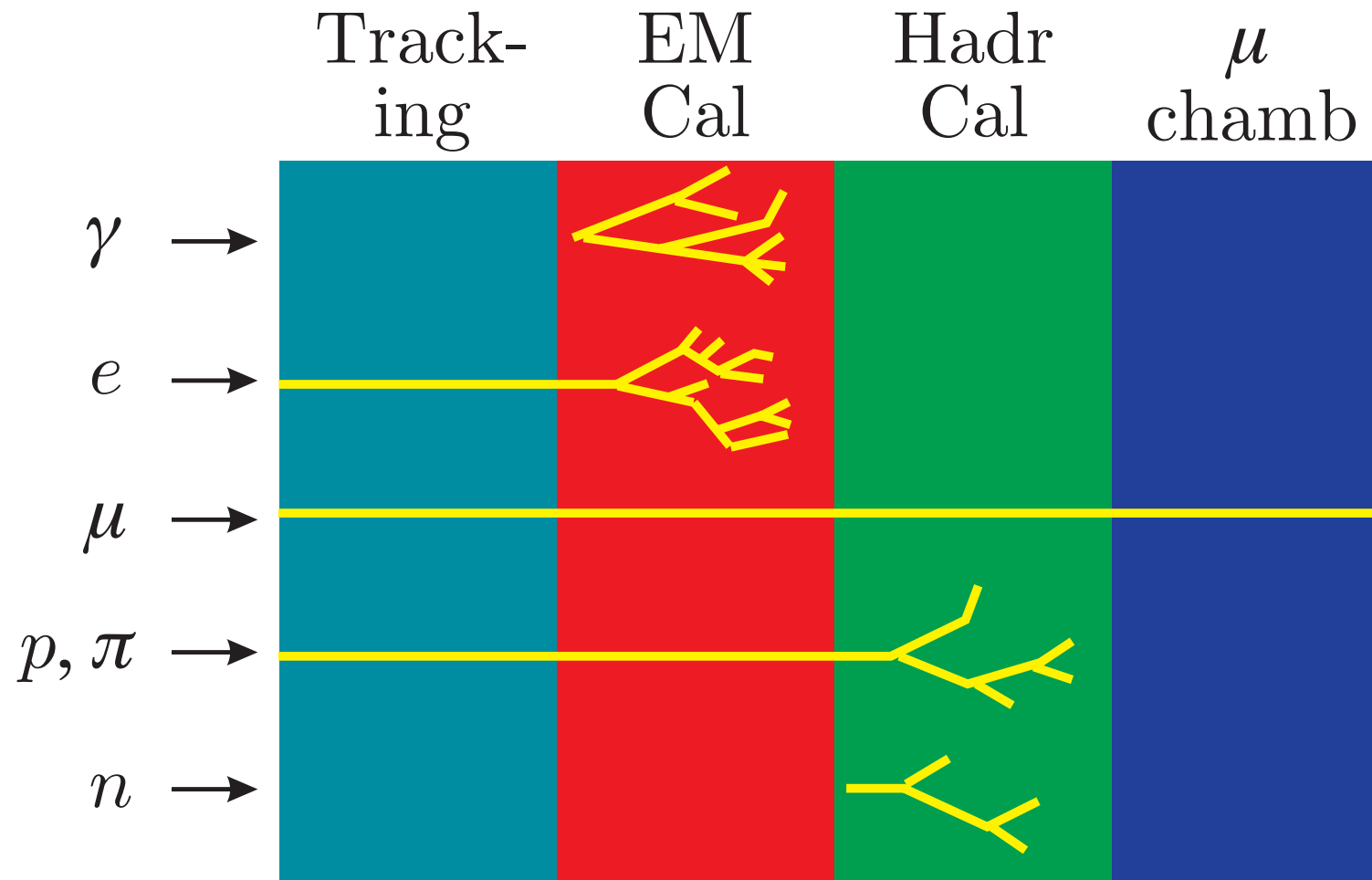
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 - (a) How to
 - (b) Compensation
 - (c) Noise
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4. $D\emptyset$
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Particle Detector



Hadronic jets \approx partons.

ν by \cancel{E}_\perp or missing E_\perp (Kin closure only for one ν)

Calorimetry in HEP

A calorimeter is a device which responds to the total absorbed energy. In order to measure a particle energy, all of its energy must be transferred to a medium which produces a signal proportional to the particle energy.

We do not measure $\Delta Temp$. This was in done in early electron accelerator days, absorbing the beam in Hg and measuring ΔT . It is also done in WIMP searches etc. We get our signal from ionization due to charged particles and the signal is charge or light.

For a perfect calorimeter, into which N energy deposits E_i are delivered, the output signal is $S = R_E \sum E_i$. In transducer's theory, R_E is called responsivity, in our case measured in C/MeV or other appropriate units.

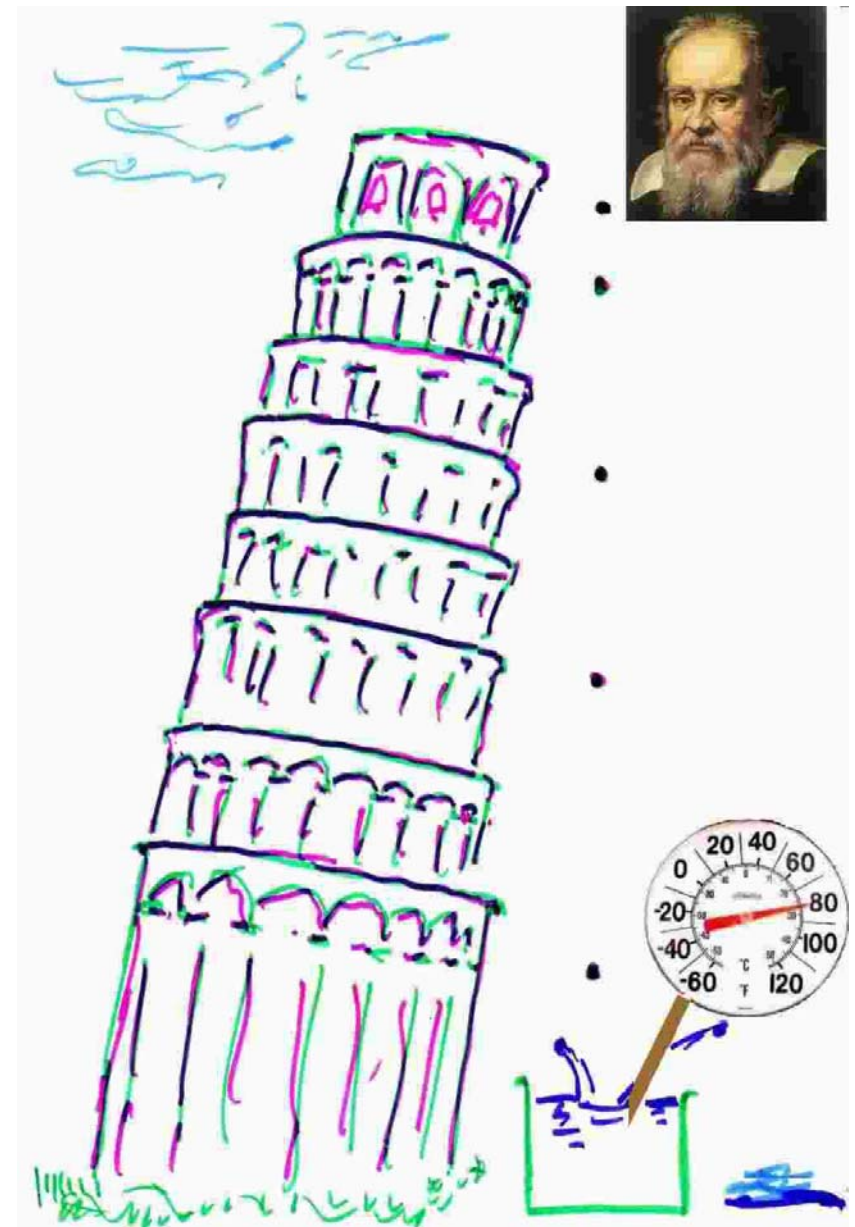
Each energy deposit is measured with an rms accuracy δE_i and, for a perfect calorimeter, the correlation between fluctuations, $G_{ij} = \overline{(E_i - \bar{E}_i)(E_j - \bar{E}_j)} = 0$ ($i \neq j$).

It follows that the rms fluctuation of the measurement of $\sum E_i$ is given by $\sqrt{\sum(\delta E_i)^2}$, therefore

$$\sigma_E = \kappa \times \sqrt{E} \text{ or } \frac{\sigma_E}{E} = \frac{\kappa}{\sqrt{E}}.$$

A calorimeter thus allows us to perform measurements whose fractional accuracy increases with energy.

Compare to a 10 GeV/c particle in a 1 T field. For 1 m track and $\delta s = 150 \mu\text{m}$, $\delta p/p \sim 4\%$. For $p = 1000 \text{ GeV/c}$, to maintain accuracy, need $l \times 100$ or $B \times 100$ or $(l, B) \times 10$. ($\delta p/p \propto E$.)



Early use of calorimeters at linear accelerators.

How do they work

Only charged particles are detectable but $e, \gamma \Rightarrow$ em showers, as we saw. Need $\gtrsim 20X_0$

Hadrons \Rightarrow hadronic cascades: $h + (Z, A) \rightarrow \pi + N + \text{nucl. frag.}$
Need ~ 5 nuclear int. lengths, λ_I .

Mat.	X_0 cm	λ_I cm	dE/dx MeV/cm	density g/cm ³
Al	8.9	39	4.4	2.7
Fe, Cu	1.8, 1.4	17, 15	11.5, 12.5	8, 9
Pb	0.6	17.1	12.7	11.4
U	0.3	10.5	20.5	19.0

$$L(\text{U}):L(\text{Pb}):L(\text{Cu}):L(\text{Al}) = 1:2:5:30 \Big|_{\text{em}} = 1:1.5:1.5:4 \Big|_{\text{hadr}}$$

Sampling calorimeter

In practice homogeneous calorimeters are not affordable at high energy and mostly not necessary, especially for hadrons which typically require 4-8 times the thickness.

One resorts to sampling, *i.e.* the calorimeter is built of many **layers of inert material** in which the shower or cascade develops, alternating with **active layers** where a signal is produced, ideally proportional to the local energy loss.

Shower position is found from segmented sampling layers:

scintillator tiles

charge collecting pads, etc.

Shower development information is easily available in sampling calorimeters.

Sampling materials

Mat.	dE/dx MeV/cm	Comments
Pl. scint	2	pm gain large, unstable
Ar	2.1	no gain, electronics noise
Si	3.9	no gain, $Q \times 8$, fast, heat, cost
Xe	3.7	no gain, cost

Sampling fraction

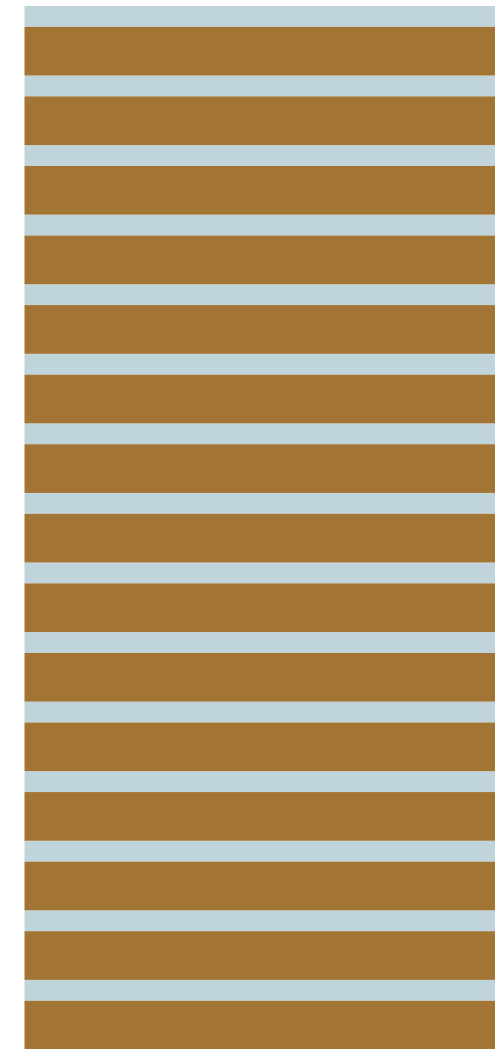
$$S_m = \frac{(dE/dx)_A \Delta x_A}{(dE/dx)_A \Delta x_A + (dE/dx)_I \Delta x_I}$$

With reasonable but realistic assumptions ($N \gg 1$, etc.) we find

$$\frac{\sigma_E}{E} = \frac{\kappa' \sqrt{S_m}}{\sqrt{E}}.$$

In general $S_{\text{true}} < 2 \times S_m$. A 10% sampling calorimeter has a resolution $\gtrsim 3 \times$ poorer than a homogeneous calorimeter.

The structure must be repeated many times over the shower development.



 Inert
 Active

Early calorimeters, using Fe or Cu, observed $em/hadr \sim 2$. This is well explained by the energy lost to breaking-up nuclei and to neutrinos from weak decays. The problem is π^0 's. They decay into γ 's with higher response. Since $N(\pi^0)$ is small, its fractional fluctuation is large, especially at low energy, degrading the hadronic response.

It should be noted that already in the late 70s-early 80s it was realized that in a segmented calorimeter it is easy to correct the problem (CDHS).

Still in the 80's many people made a living exaggerating the problem and creating a big confusion about it. (thermal neutrons, hydrogen, gap tuning, compensating layers, timing...)

Compensation: $e/h=1$

There is more confusion on the subject than at Babel's Tower time. It was suggested U would, by fission, increase hadron response. Measurements "proved" the effect! But it is clearly nonsense since fission fragments have a range in U of $1 \mu\text{m}$. U calorimeters are however "compensated" because the em response is approximately halved. In U there is strong self absorption of the low energy debris of the em shower, Pb is almost as good. The photoelectric effect $\propto Z^3$



Dore's Babel Tower



Brueghel's Babel

Mr. W. insists that the only comp. calorimeter is in Zeuss ($\sim 1 e/\text{GeV}$). The DØ U-Ar calorimeter has an em/had response ratio of 1.02 at 150 GeV. And that's very good, especially for jets which begin as a parton shower, *i.e.* many hadrons and not a single high energy hadron.

These points are presented quite incorrectly in accepted textbooks.

In the design of the LHC calorimeters, e/h has been, correctly, ignored.

High energy hadron collision kinematics

Rapidity

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$$

Invariant x-section

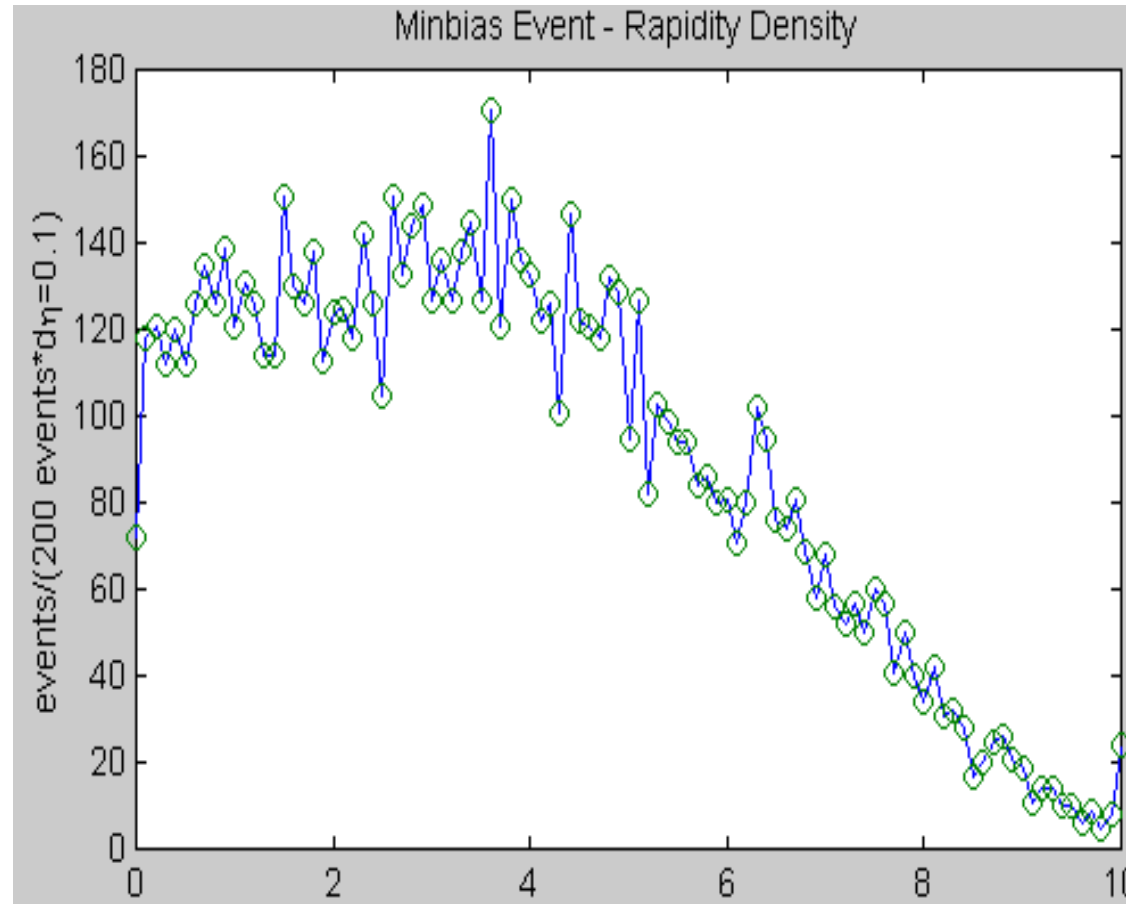
$$E \frac{d^3\sigma}{d^3p} = \frac{d^3\sigma}{d\phi dy p_\perp dp_\perp}$$

Under a boost along z , to a frame with velocity β , $y \rightarrow y' = y - \tanh^{-1} \beta$, i.e. $dy = dy'$ and the shape of dN/dy is invariant. In high energy hadron collisions, the single particle cross section $d\sigma/d\phi dy$ is approximately constant in y , because p_\perp is limited, and ϕ – unpolarized beams.

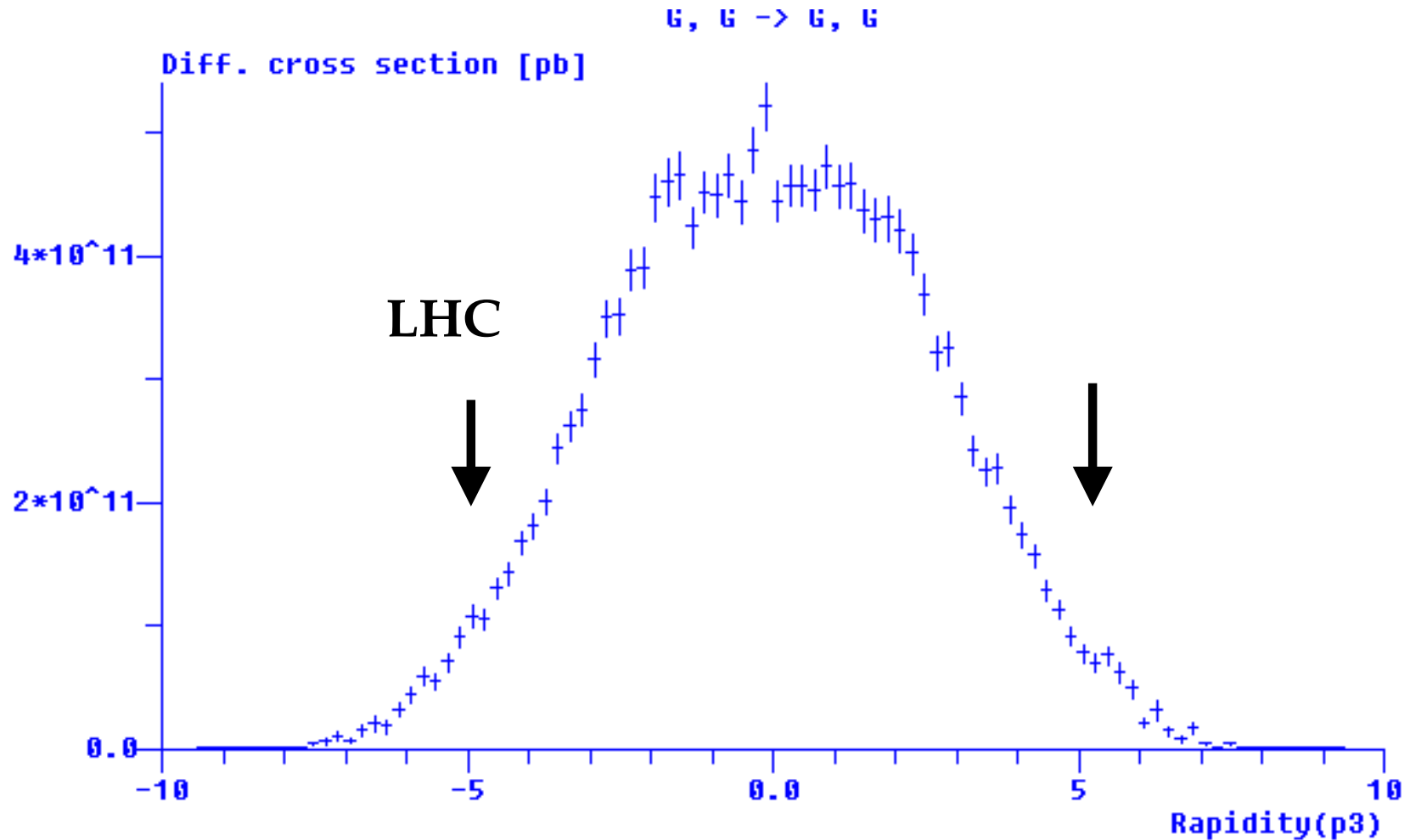
For $p \gg m$ and $\theta \gg 1/\gamma$, with $\cos \theta = p_z/p$,

$$y \sim -\ln \tan(\theta/2) \equiv \eta$$

A collider detector should be segmented in slices of equal $\Delta\phi$ and $\Delta\eta$. $\eta_{\text{Max}} - \eta_{\text{min}}$ varies slowly with energy: ~ 19 at $1+1$ TeV, ~ 24 at 20 TeV. Also, σ is large (plateau) only for $-2 < \eta < 2$ (high mass) or $-5 < \eta < 5$ (low mass).



Hard gluons at LHC



Practical things

Calorimeters have been used in: ν , LEP, TeV-I, HERA and LHC. . . . They are complex devices and their usage is still evolving. We can list the essentials:

1. Energy resolution
2. Spatial resolution: for kinematics and **non-isolated e or μ inside jet cone**. Define $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$. Then **jet $\equiv \Delta R < 0.3 - 0.7$**
3. Depth segmentation: **particle id**

But also: occupancy, pile-up, noise. . . and **COST!**

The signal must be measurable and fast. The advantage of liquid Ar is that the response is determined by one number: C/MeV. At worst, change the argon. Otherwise it's just mechanical tolerances, even only in average.

Final resolution in Ar will be strongly affected by:

Total argon traversed depth, gap size

Quality of electronics, thermal noise is important

ϕ , η segmentation to control confusion – pile-up

Noise above the thermal minimum - *i.e.* "coherent"

Rather than go to it by first principles let me use DØ, for which I'm largely responsible, as an example.

U is chosen for dimensions and cost rather than for compensation, even if desirable. Ar, for the absolute response.

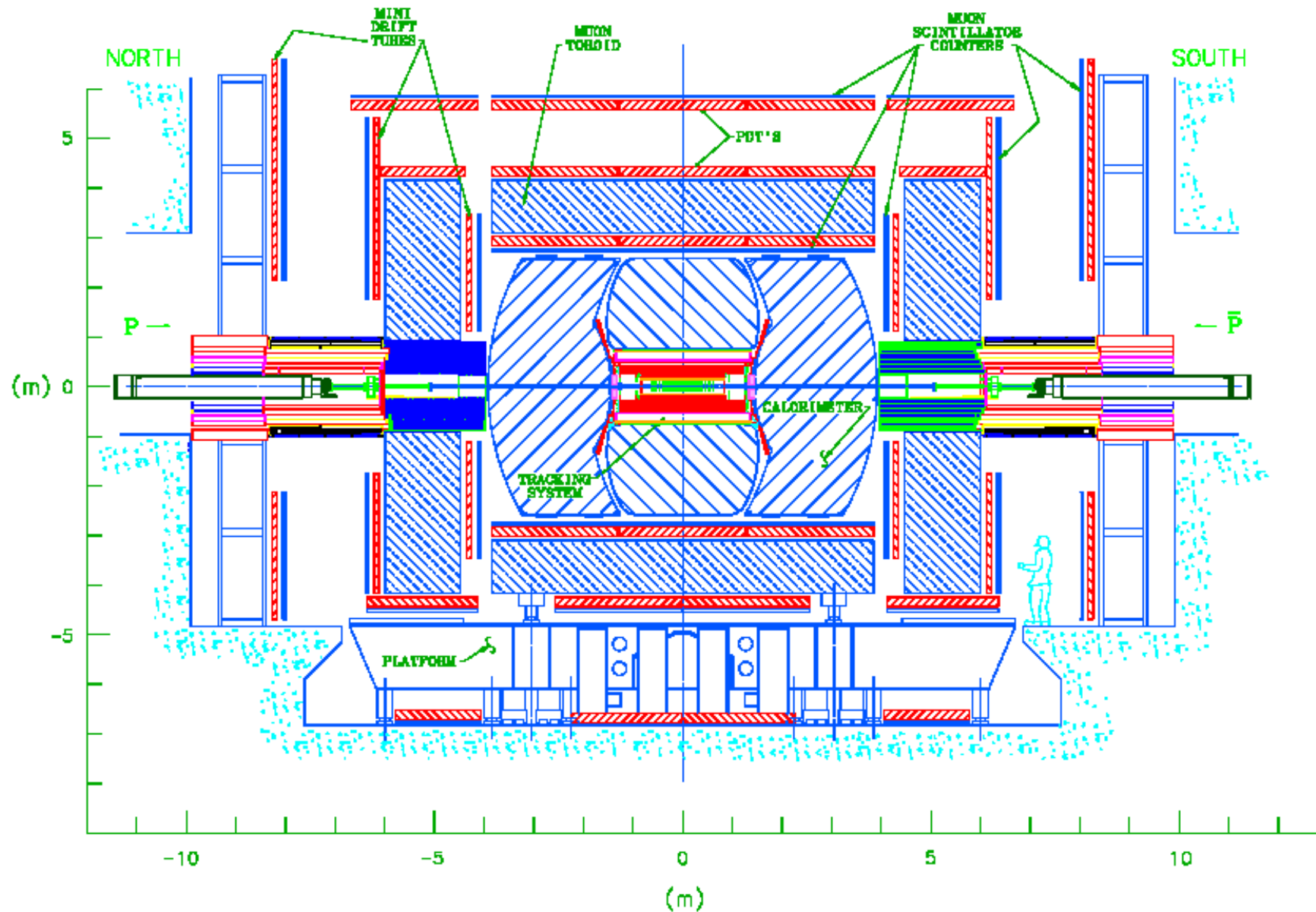
The basic parameters for the calorimeters are:

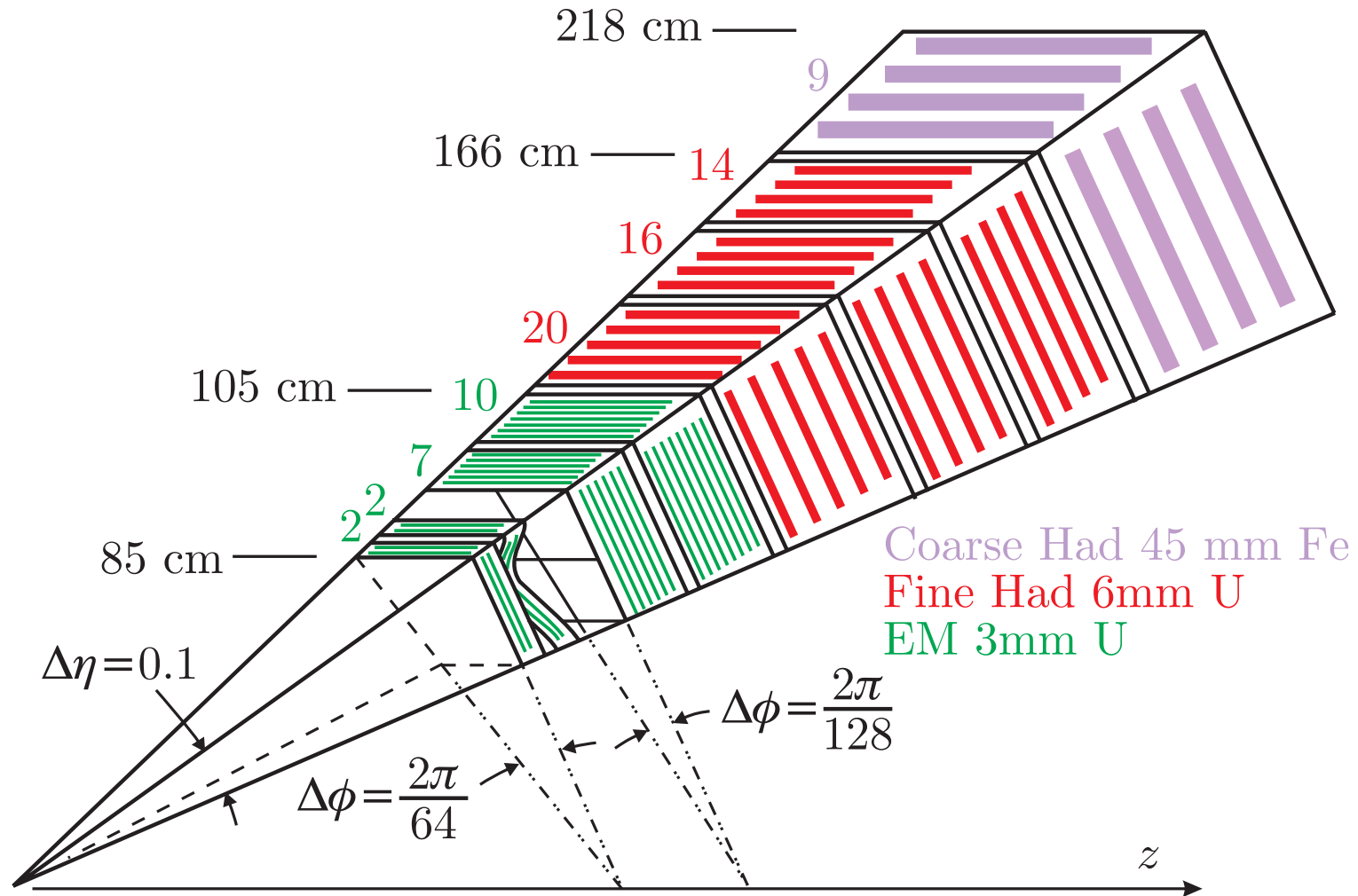
EM: 3mm U, 4mm Ar, 21 gaps, 22 X_0 , 4 depth segments, $\sim 10,000$ towers 0.1×0.1 , $\times 4$ at shower maximum

Hadr: 6mm U, 4mm Ar, 50 gaps, 30cm U, $(1+3)\lambda_I$, 3 seg.

Hadr., tail catcher: 4.5 cm Fe, 9 gaps, $\sim 2\lambda_I$

DØ Detector





800 ton of U (+Fe)
 45,000 l of Ar

DØ calorimeter

$-5 < \eta < 5, \Delta\eta = 0.1$

$\Delta\phi = 2\pi/64(128)$

Tot. towers 6400

Tower seg. 4(5)+4

Tot. signals 64,000

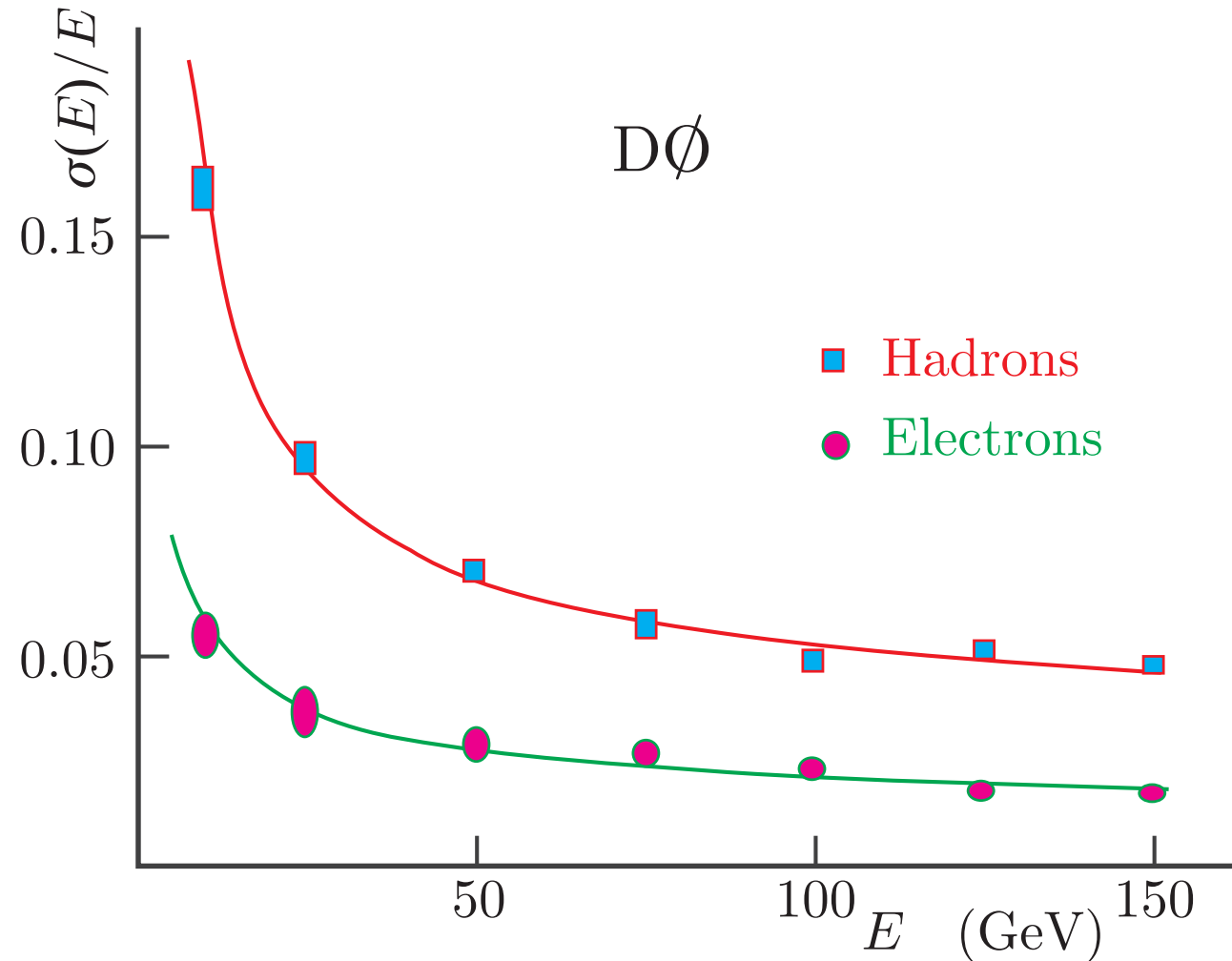
EM $\sigma(E)/E=2\%$,

Had $\sigma(E)/E=6\%$

@ 100 GeV

$\delta x, \delta y < 2$ mm, em sh'r

$e/\pi \sim 1000/1$



Read-out and response

1 ADC count=3600 'e'=3.1 MeV of em energy deposited

Preamp noise, 1 em cell, $\sim 1\text{nF}$: 5000 e

Contributions to resolution:

Sampling fluctuations \mathcal{S}

Preamp noise \mathcal{N} : thermal, (3×3 em towers)

Constant term \mathcal{C} : calibration, response non-uniformities

$$\frac{\sigma(E)}{E} = \frac{\mathcal{S}}{\sqrt{E}} \oplus \frac{\mathcal{N}}{E} \oplus \mathcal{C}, \quad E \text{ in GeV}$$

$\mathcal{S}, \mathcal{N}, \mathcal{C}$ in % for DØ*

section	\mathcal{S}	\mathcal{N}	\mathcal{C}
em	16	16	0.3
hadr	49	40	2

*9 em towers or 1 jet cone

NOISE

The thermal electronics noise is effectively proportional to the shunt capacitance. Dividing the detector into N read-out segments, reduces the single channel noise by $\times(1/N)$ and the total noise by $\times(1/\sqrt{N})$. This is a way to make the noise acceptable. We must avoid adding **empty channels**, which only increases noise. We can however run into a problem in **systems with additional, correlated**, noise.

Let $S_{\text{tot}} = \sum S_i$ and \mathbf{G} the matrix of the signal fluctuations:

$$\mathbf{G} = \begin{pmatrix} \overline{\delta_1 \delta_1} & \overline{\delta_1 \delta_2} & \dots & \overline{\delta_1 \delta_n} \\ \overline{\delta_2 \delta_1} & \overline{\delta_2 \delta_2} & \dots & \overline{\delta_2 \delta_n} \\ \vdots & \vdots & \ddots & \vdots \\ \overline{\delta_n \delta_1} & \overline{\delta_n \delta_2} & \dots & \overline{\delta_n \delta_n} \end{pmatrix}$$

with $\overline{\delta_i \delta_j} = \langle (S_i - \bar{S}_i)(S_j - \bar{S}_j) \rangle$. Then the mean square fluctuation on the sum is

$$(\delta S_{\text{tot}})^2 = \left(\frac{\partial \sum S_i}{\partial S_i} \right)^T \mathbf{G} \left(\frac{\partial \sum S_i}{\partial S_i} \right) = \sum_{ij} G_{ij}$$

For $\overline{\delta_i \delta_i} = \sigma^2$ and $\overline{\delta_i \delta_j} = \alpha^2 \sigma^2$

$$\mathbf{G} = \begin{pmatrix} \sigma^2 & \dots & \alpha^2 \sigma^2 \\ \vdots & \ddots & \vdots \\ \alpha^2 \sigma^2 & \dots & \sigma^2 \end{pmatrix}$$

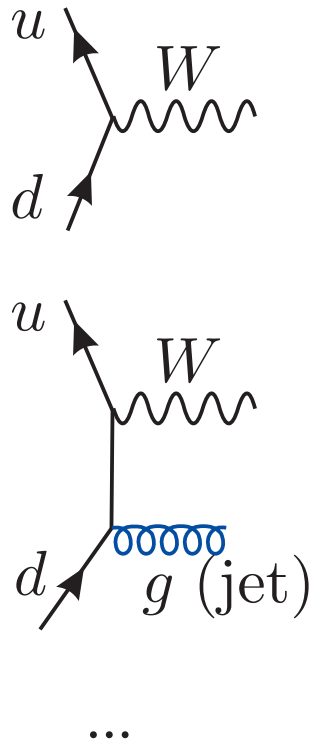
and $\delta S_{\text{tot}} = \sigma \sqrt{n} + \alpha \sigma \sqrt{n(n-1)} \sim \sigma \sqrt{n} + \sigma n \alpha$. Unless $\alpha < 1/\sqrt{n}$, the accuracy of the measurement is degraded.

Example: $n=10,000$, $\alpha = 0.1$. $\delta S_{\text{tot}} = 1000 \times \sigma$, instead of $100 \times \sigma$.

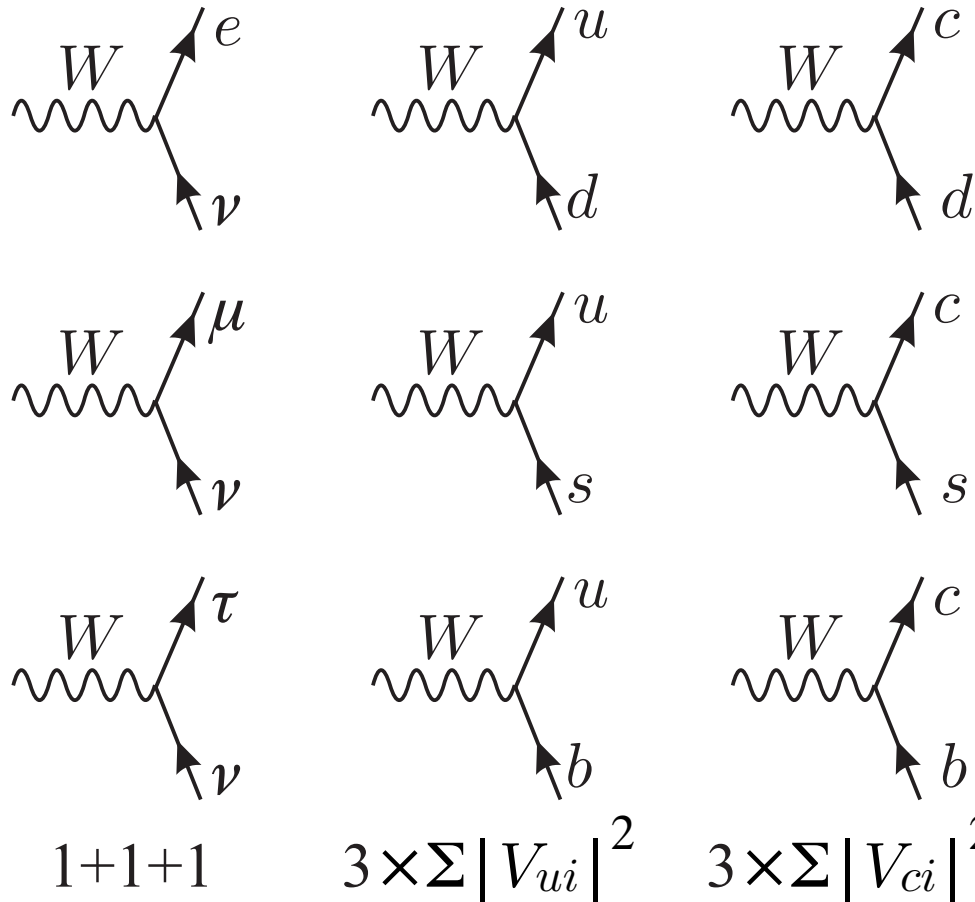
In $D\emptyset$ $\alpha \sim 0.01$, can add 10,000 channels.

The W boson mass

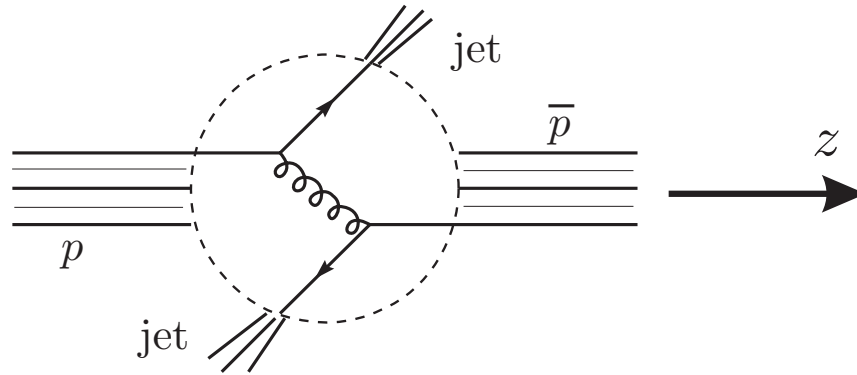
Production



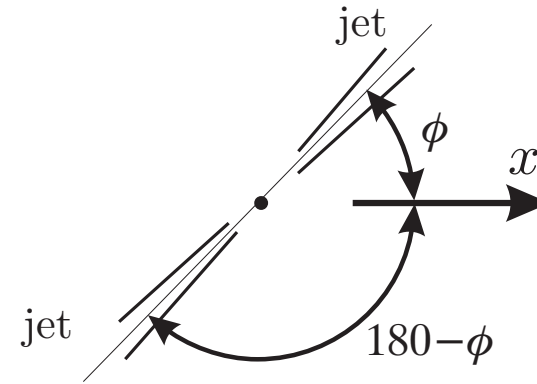
Decay



side view



beam view



p_z unknown, $p_{\perp} \sim e^{-p/p_0}$
 $d\sigma/d\eta \sim \text{const}$

$q\bar{q}$ SCATTERING

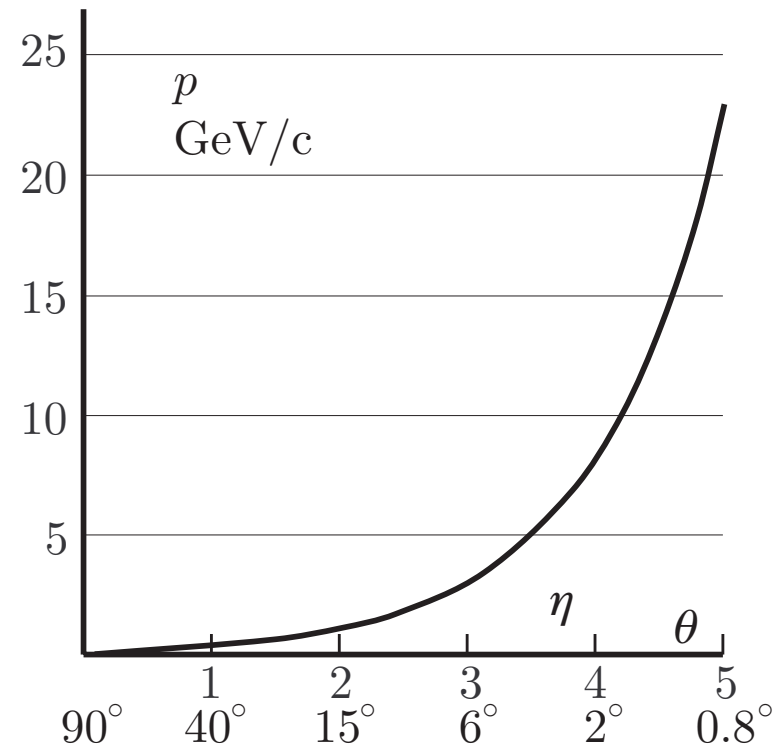
$\langle p_{\perp}^{\text{in}} \rangle \sim 300 \text{ MeV}/c \sim 0$

Large angle: low p

Small angle: high p

W PRODUCTION

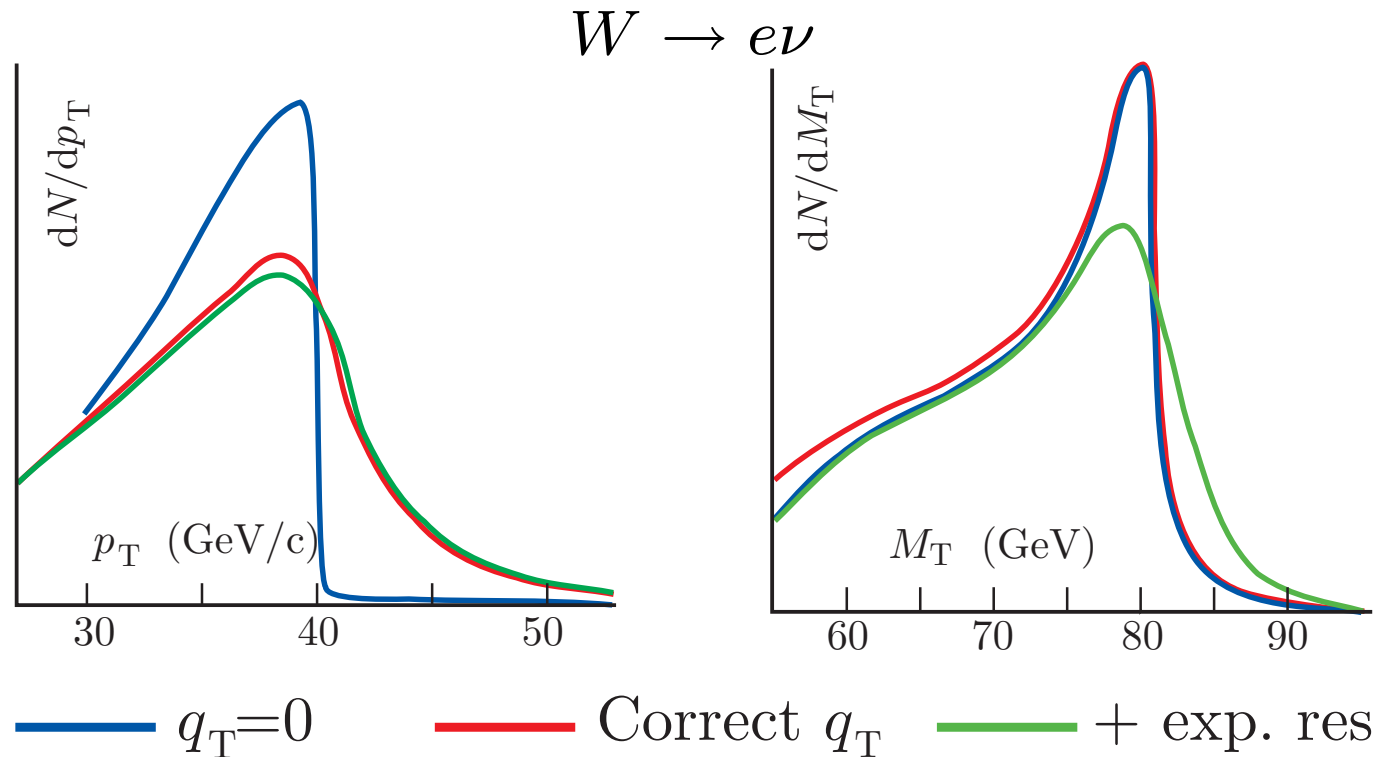
$\langle p_{\perp}(e, \nu) \rangle \sim M_W/2, \sum p_{\perp} \sim 0$



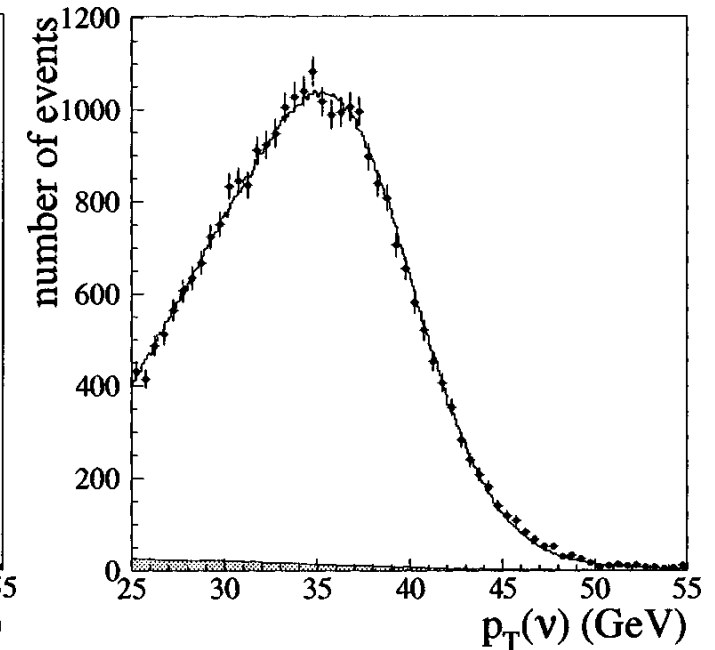
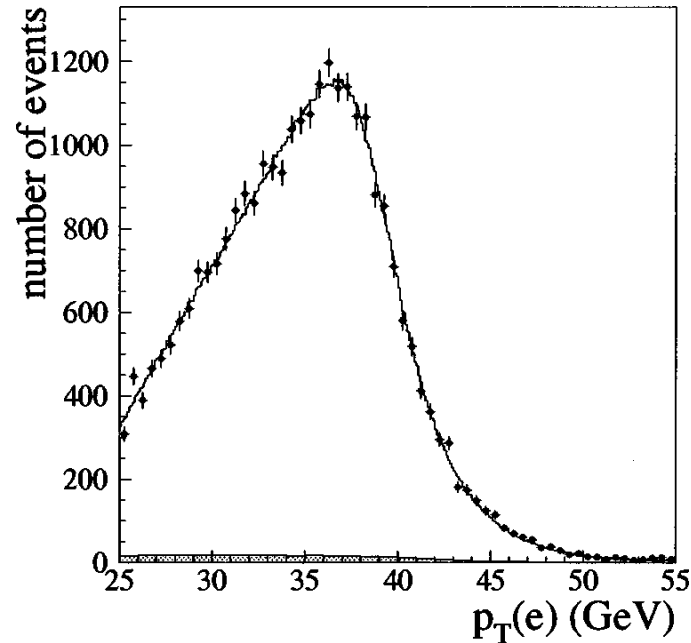
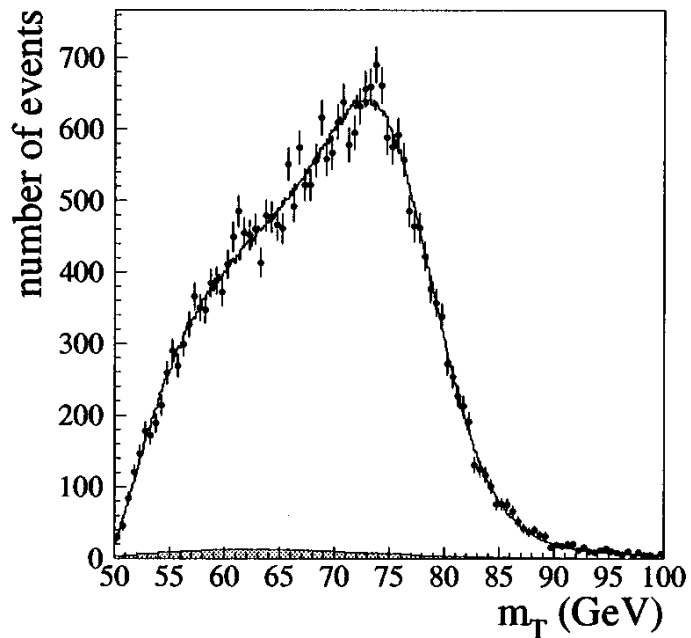
Hard processes in $p\bar{p}(p)$ collisions

$pp \rightarrow W (q\bar{q} \rightarrow W + \text{radiation}), s(q\bar{q}) > (80 \text{ GeV})^2$

How good is it to assume $P_{\perp} = 0$?



M_{\perp} is better than p_{\perp} . $M_{\perp} = \sqrt{p_{\perp,e}^2 p_{\perp,\nu}^2 (1 - \cos(\phi_e - \phi_{\nu}))}$.

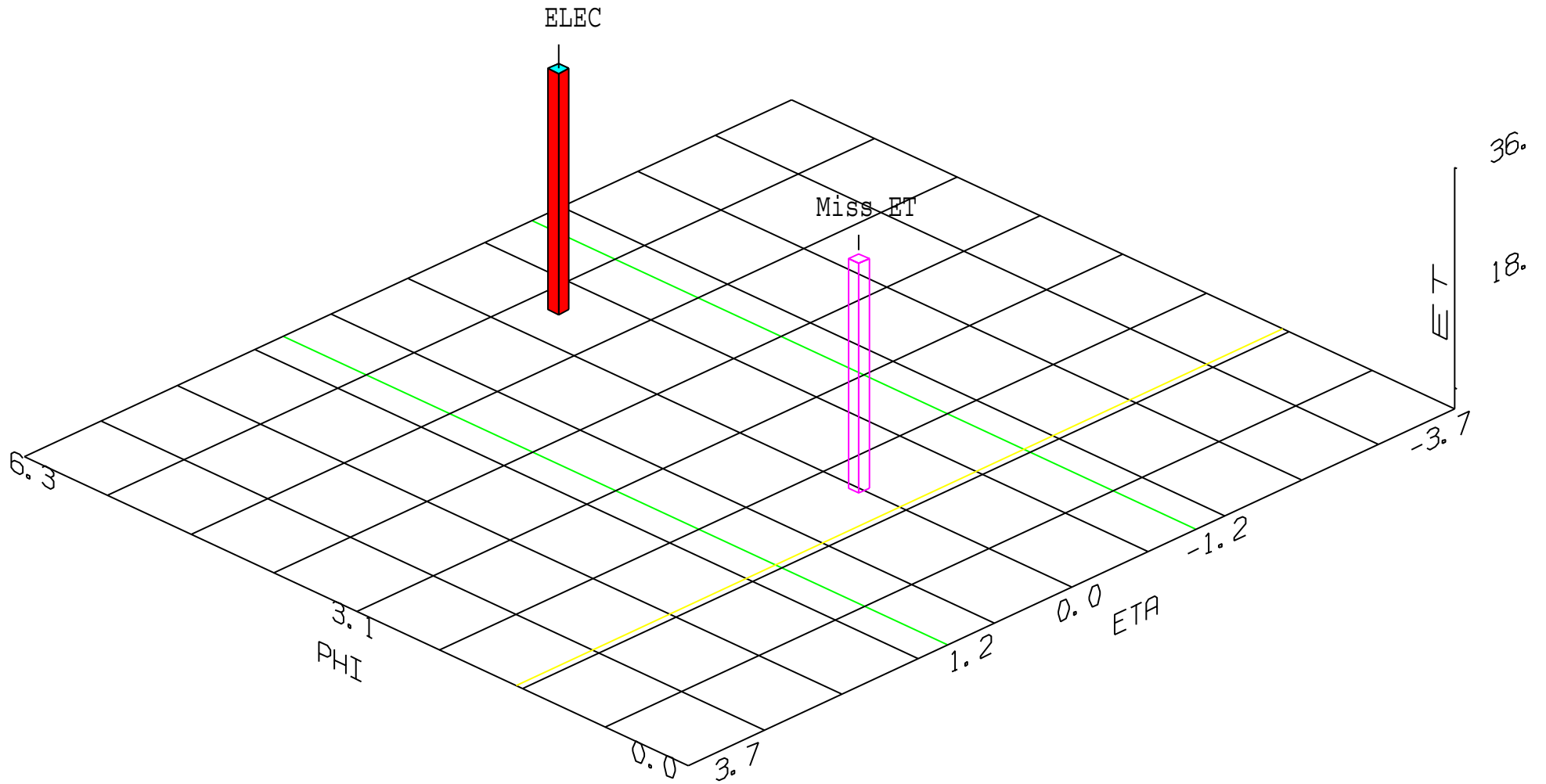


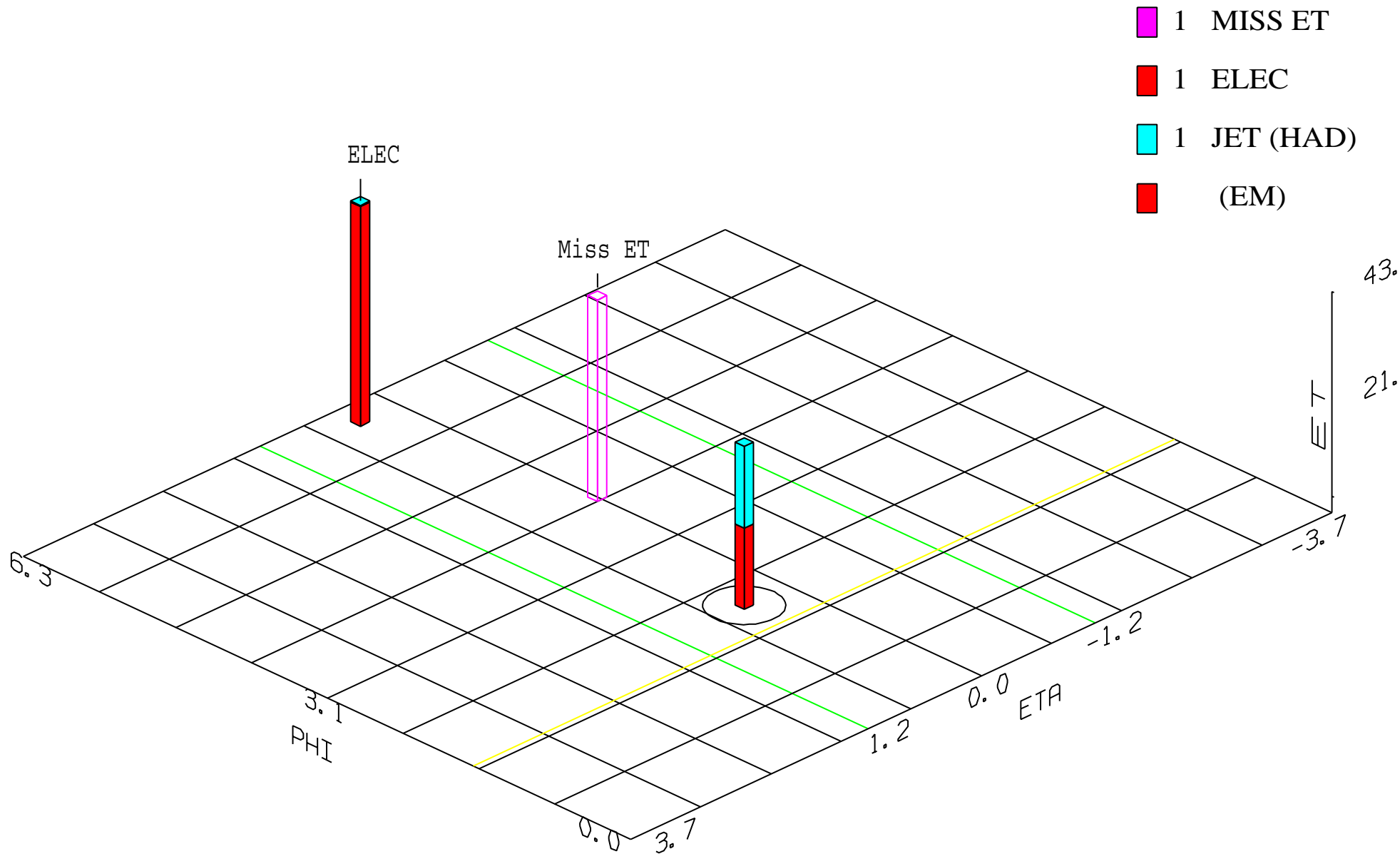
All three distributions, M_{\perp} , $p_{\perp}(e)$ and $p_{\perp}(\nu)$ are shown. They are not independent. $p_{\perp}(\nu)$ is measured as $\cancel{E}_{\perp} = -\sum E_{i,\perp}$.

Note the very small background, which vanishes toward the end of the spectra.

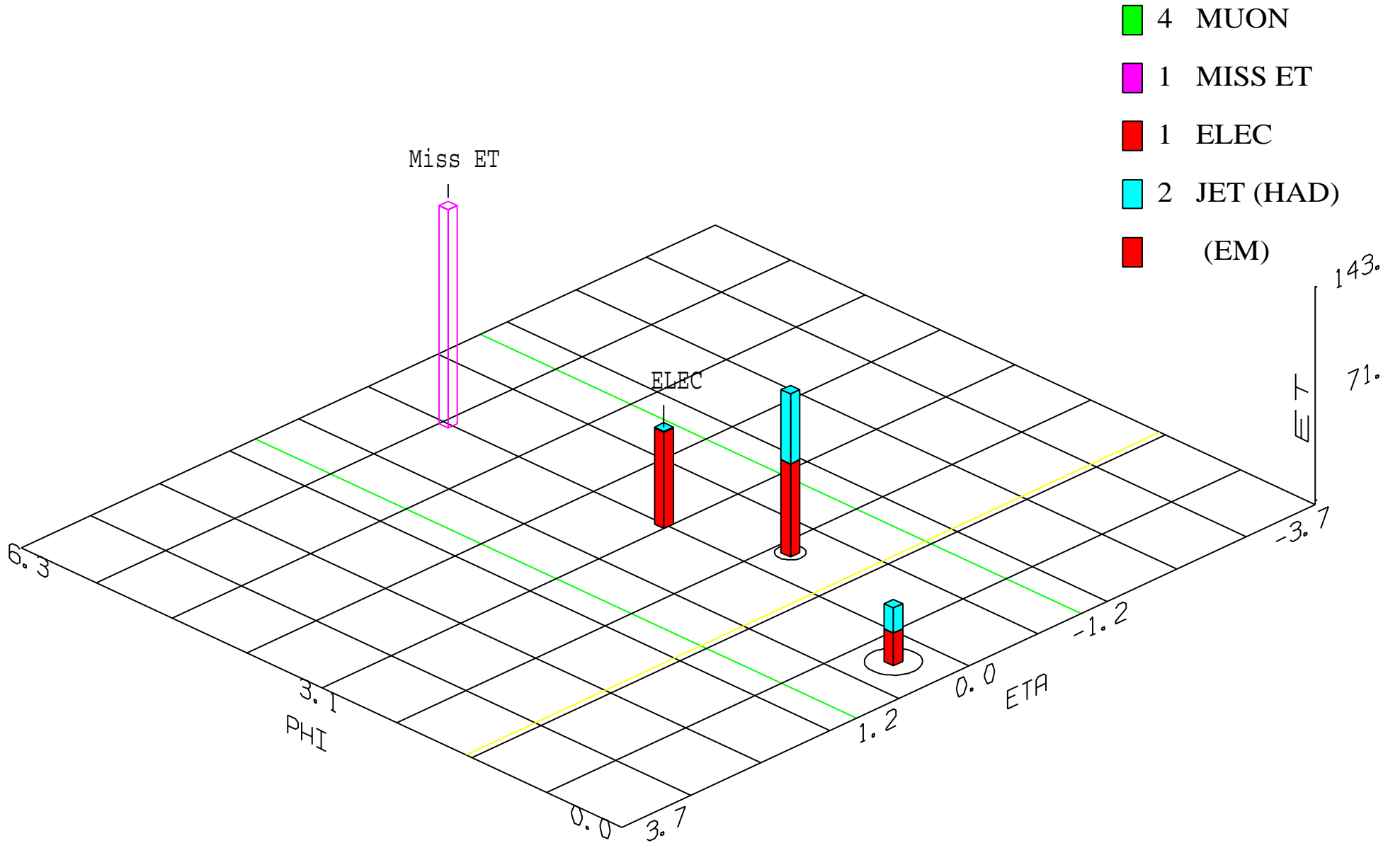
(This made finding the W “easy”.)

- 1 MISS ET
- 1 ELEC





Note jet cone, $\Delta R \approx 0.3$



$M(W)$ results

$$M_W = 80.482 \pm 0.091 \text{ GeV, D}\emptyset$$

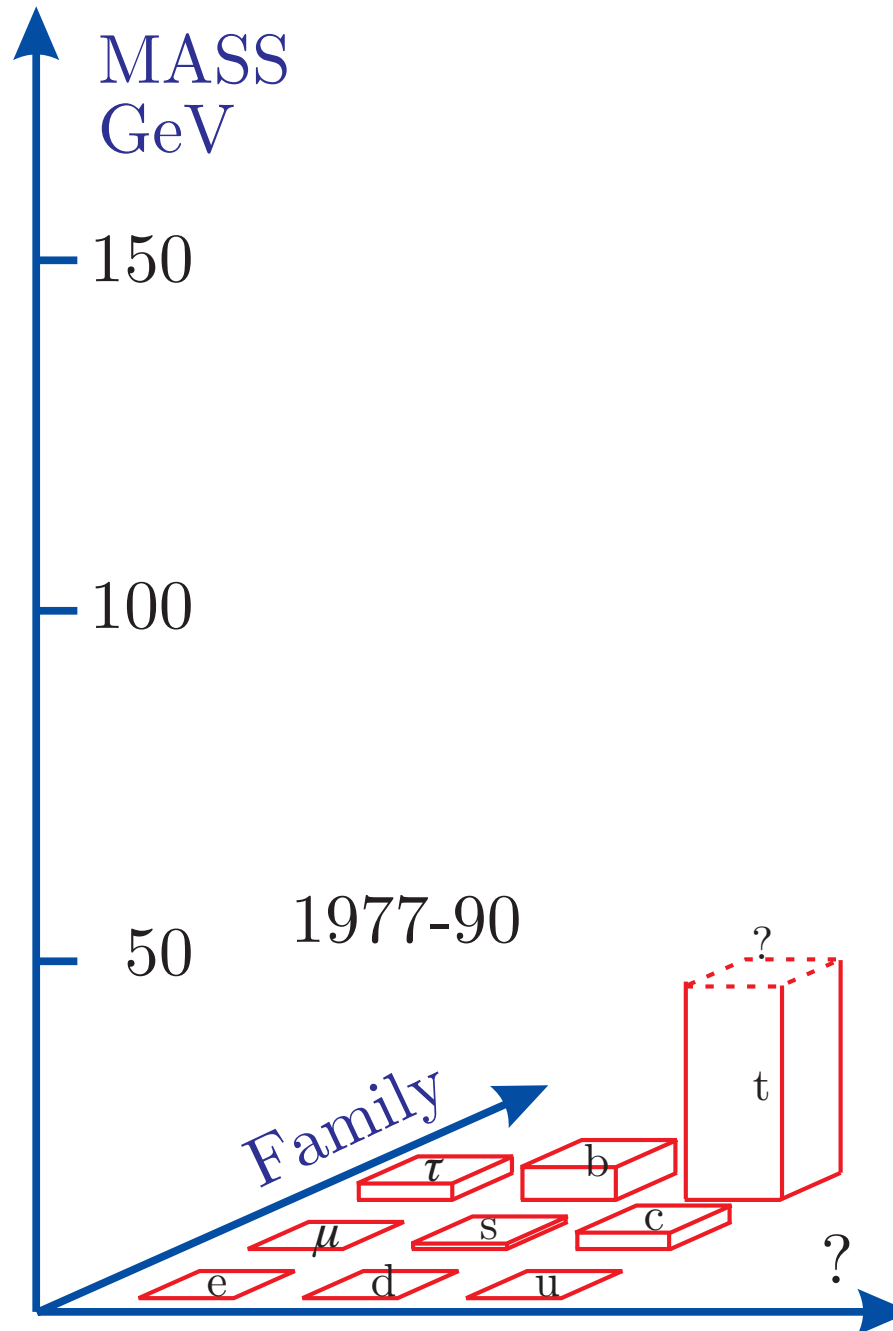
$$\sigma(W) * BR(e\nu) = 2.7 \text{ nb, D}\emptyset$$

$$M_W = 80.423 \pm 0.039 \text{ GeV, D}\emptyset + \text{CDF} + 4 \times \text{LEP}$$

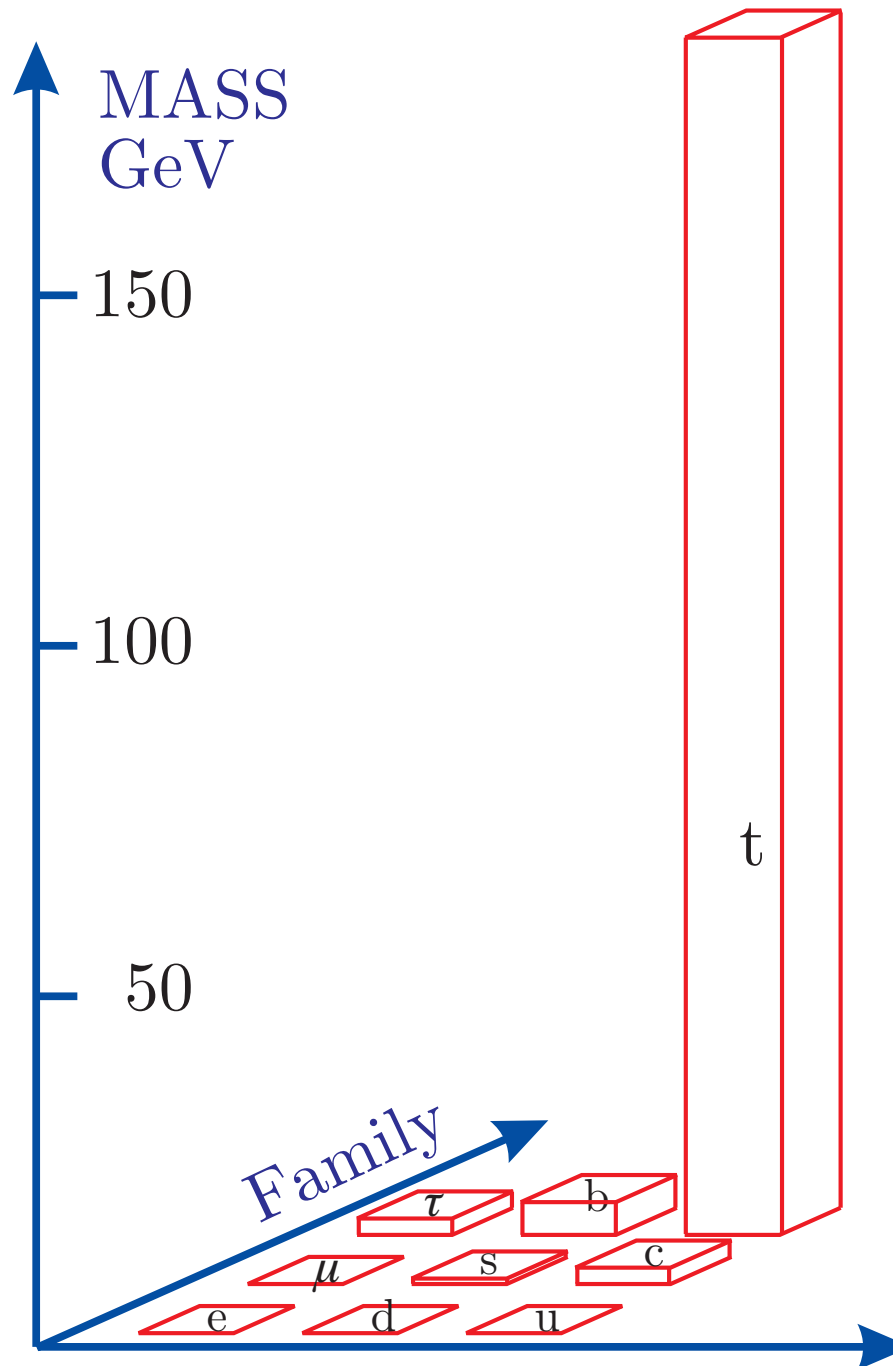
A measurement of the W mass to this accuracy, requires a knowledge of the em calorimeter response to an accuracy of 0.1%, over a long time. The absolute scale comes from the M_{Z^0} values from CERN based on the calibration of LEP with the $g - 2$ depolarizing resonances.

There is no B in D \emptyset . The exceptional qualities and stability of sampling in liquid argon are demonstrated by this result.

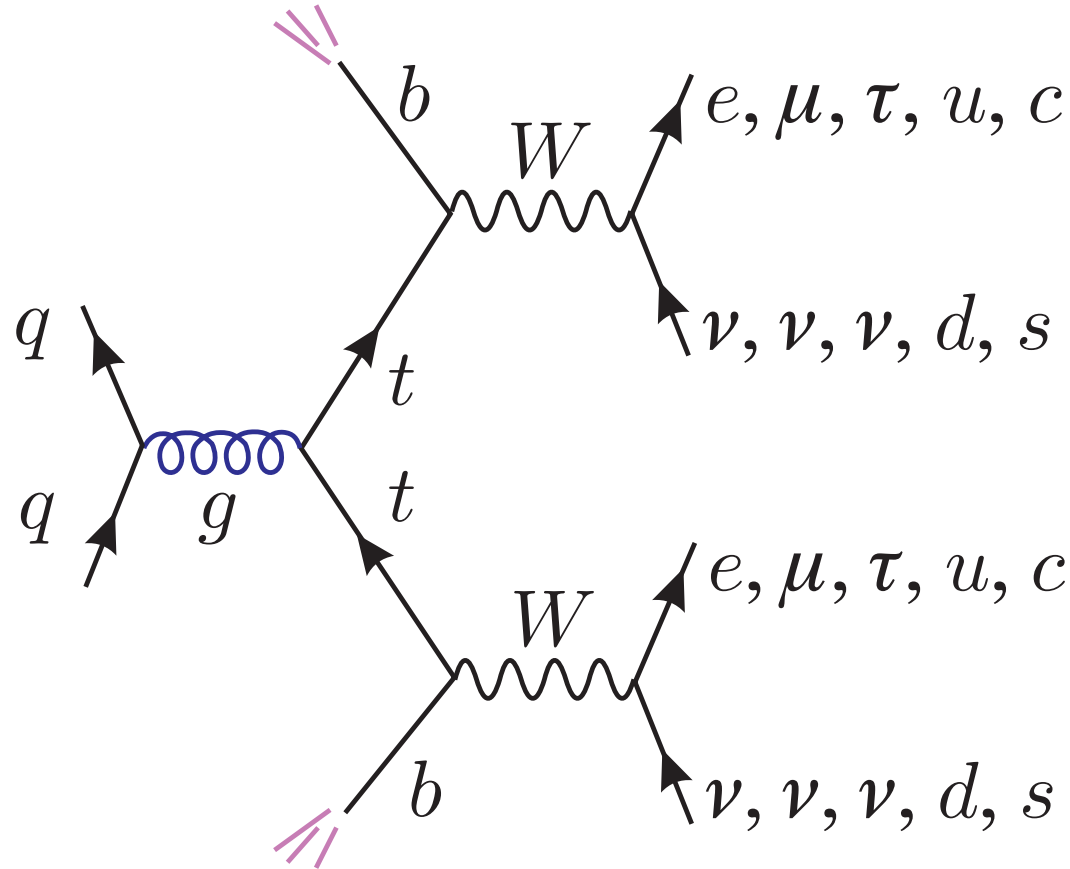
The top



1995



The top mass is harder

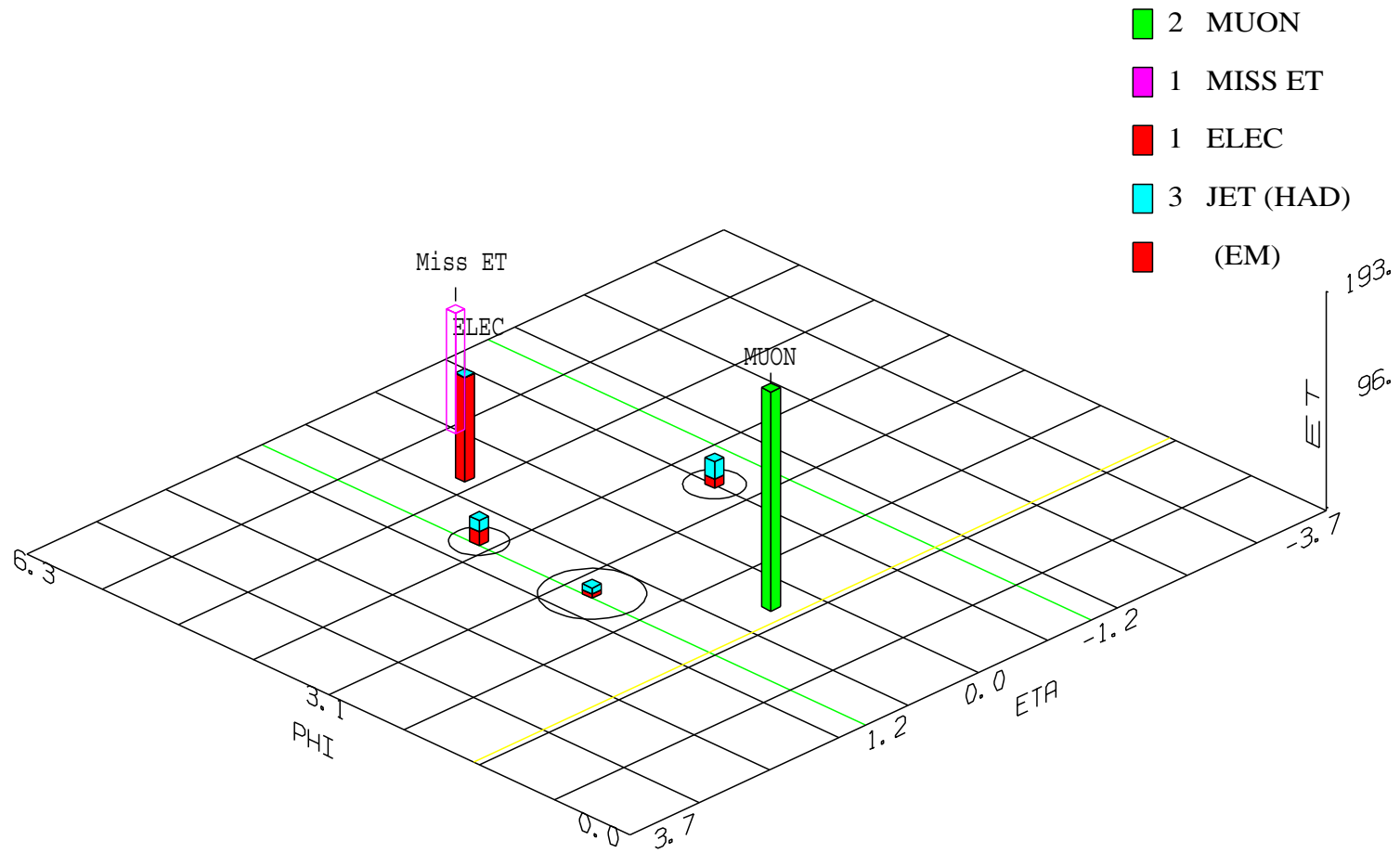


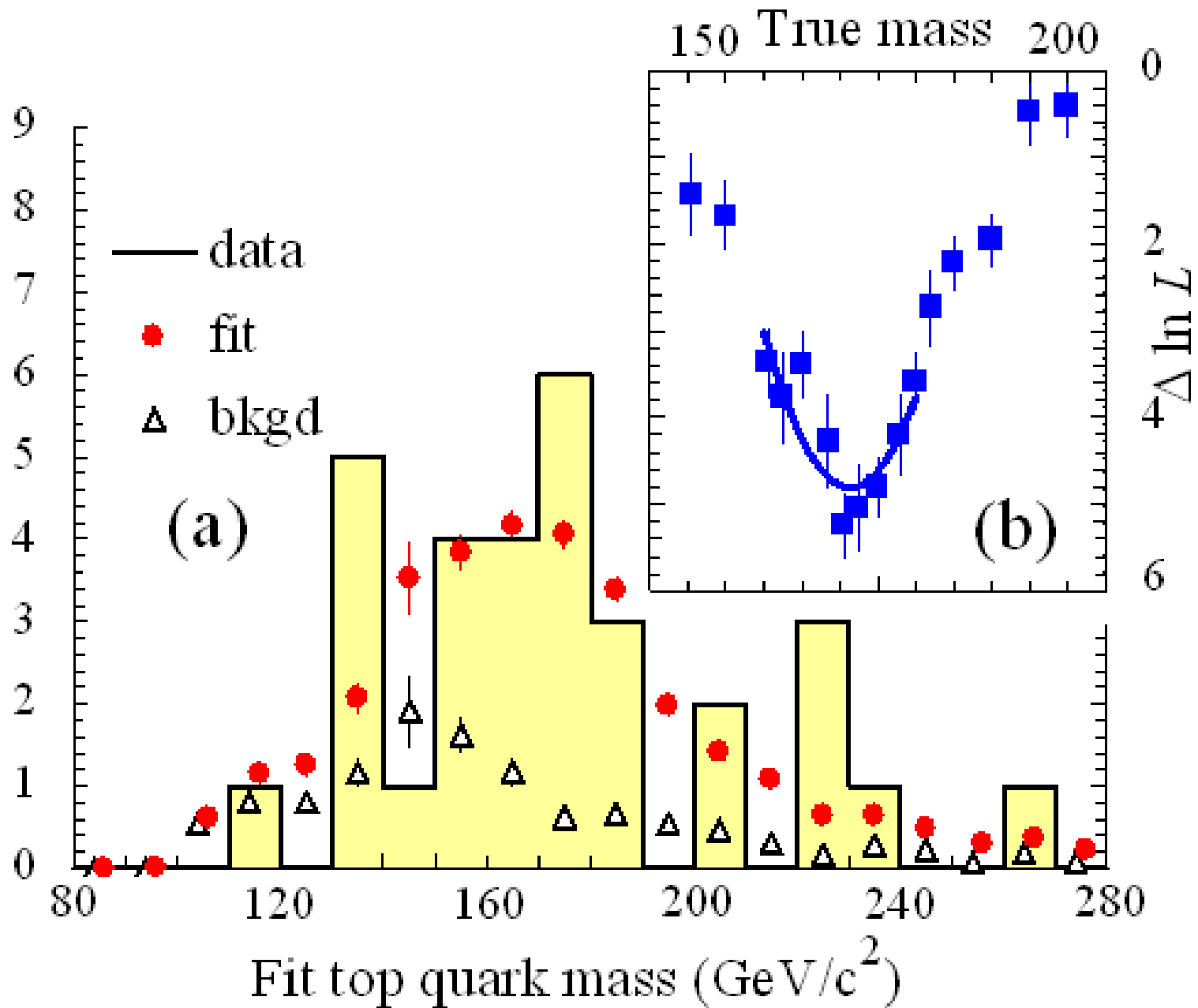
$$t\bar{t} \rightarrow e^+e^- \nu\bar{\nu} b\bar{b} \sim 1.2\% \quad s(q\bar{q}) > (350 \text{ GeV})^2.$$

1 lepton + jets + missing $E_{\perp} \sim 30\% \dots$

up to 8 jets, only kinematically over-constrained channel

Not constrained events: compute $P(\text{configuration} \mid M)$





Top results

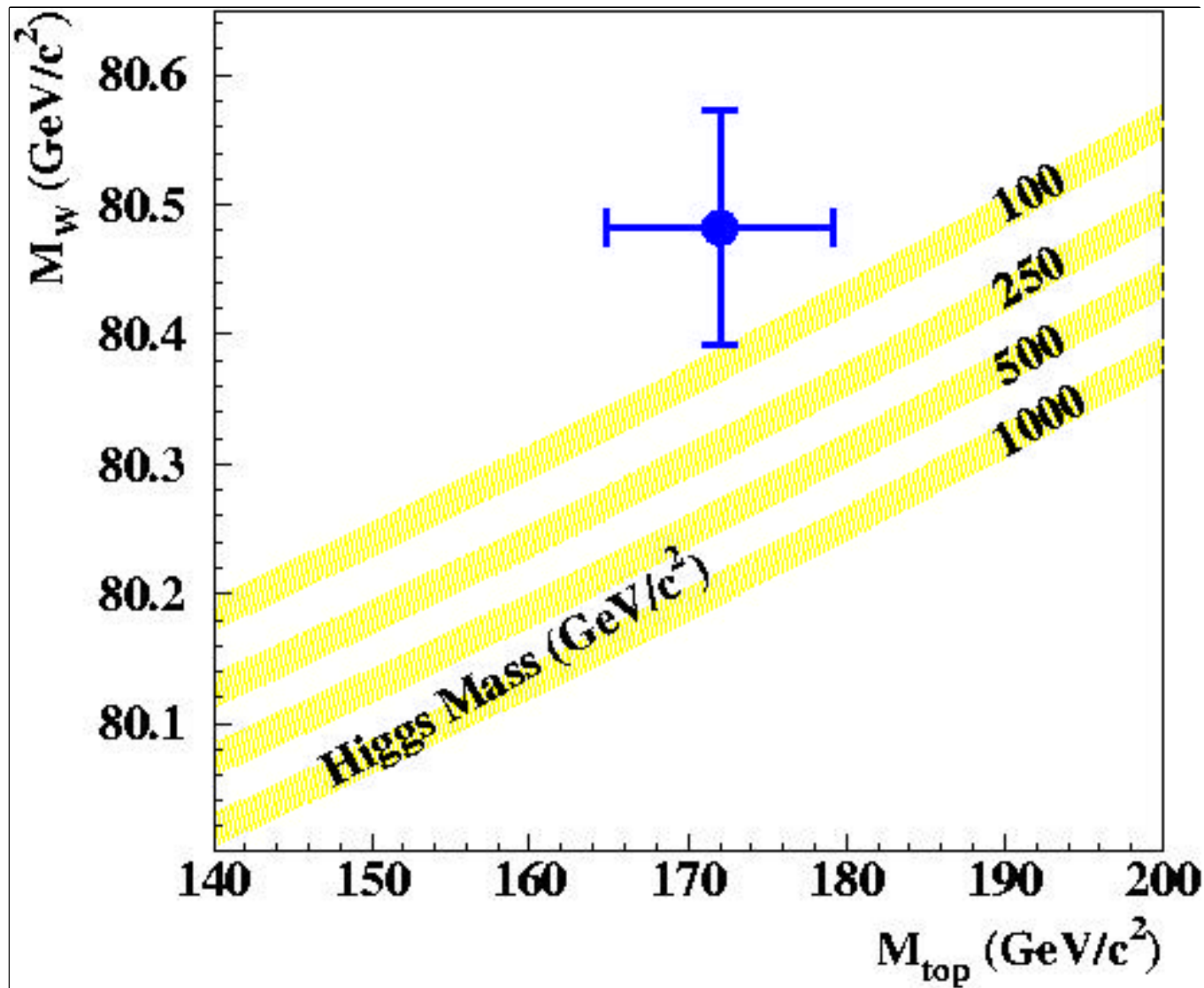
Tot $\mathcal{L}=128 \text{ pb}^{-1}$ - DØ

$\sigma(tt) = 5.7 \pm 1.6 \text{ pb}$ - DØ

$\sigma(tt) = 6.5_{-1.4}^{+1.7} \text{ pb}$, CDF

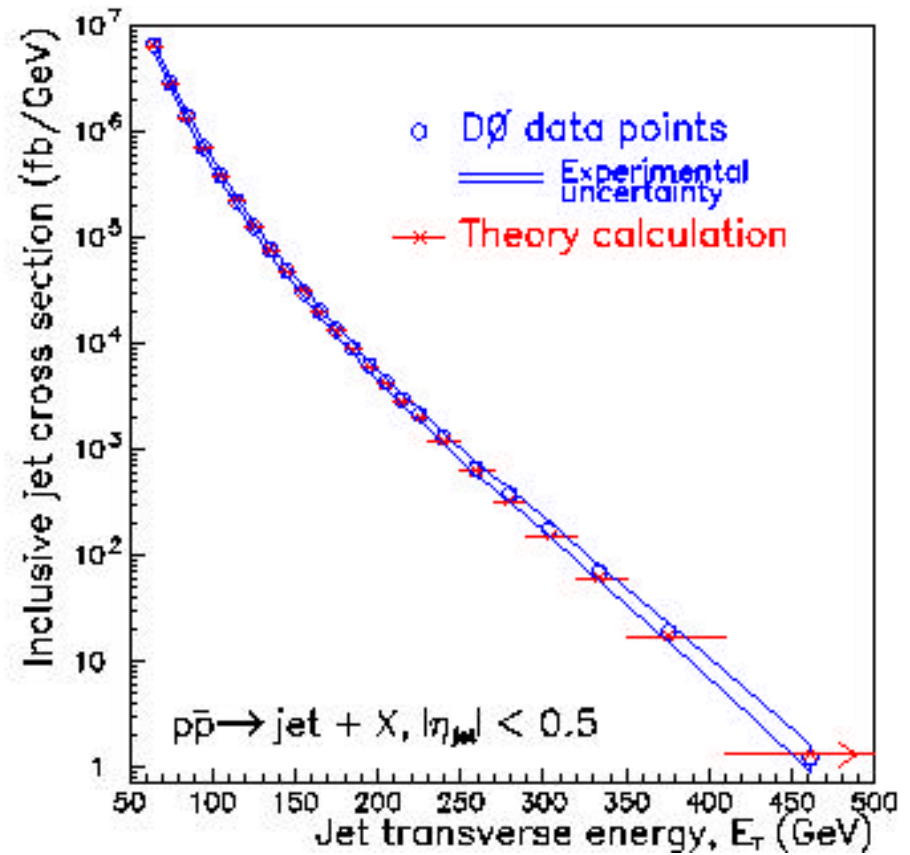
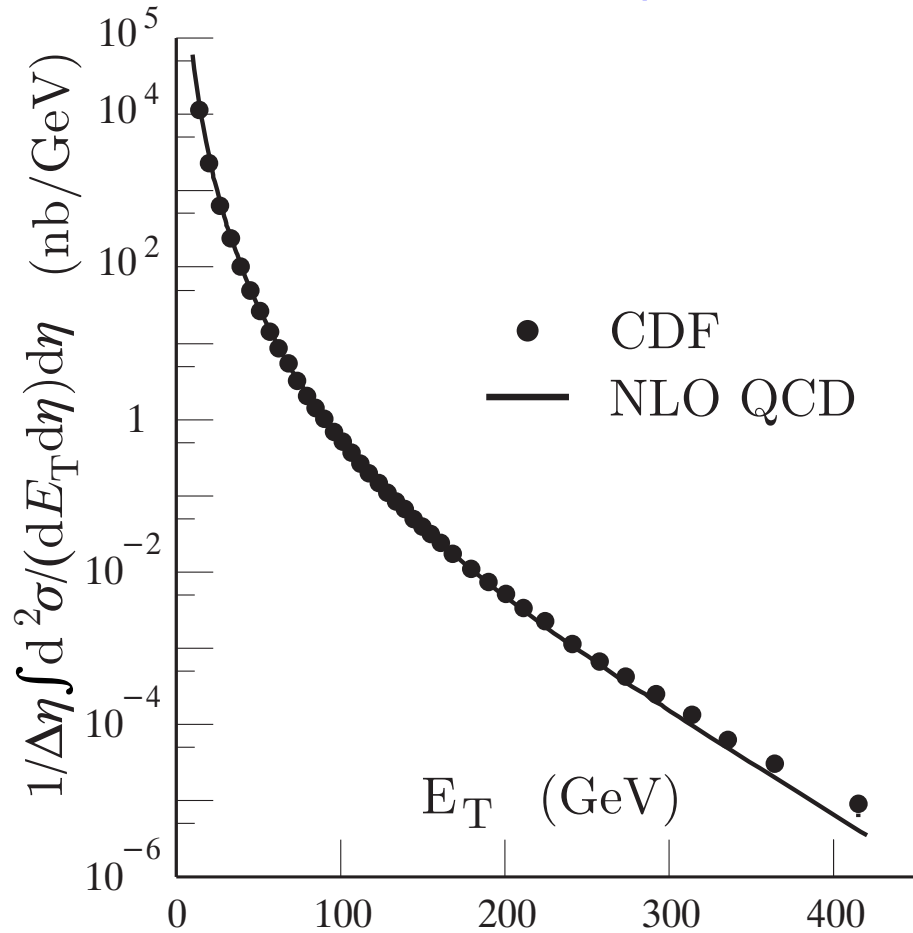
$M_{\text{top}} = 172.1 \pm 5.2 \pm 4.9 \text{ DØ}$

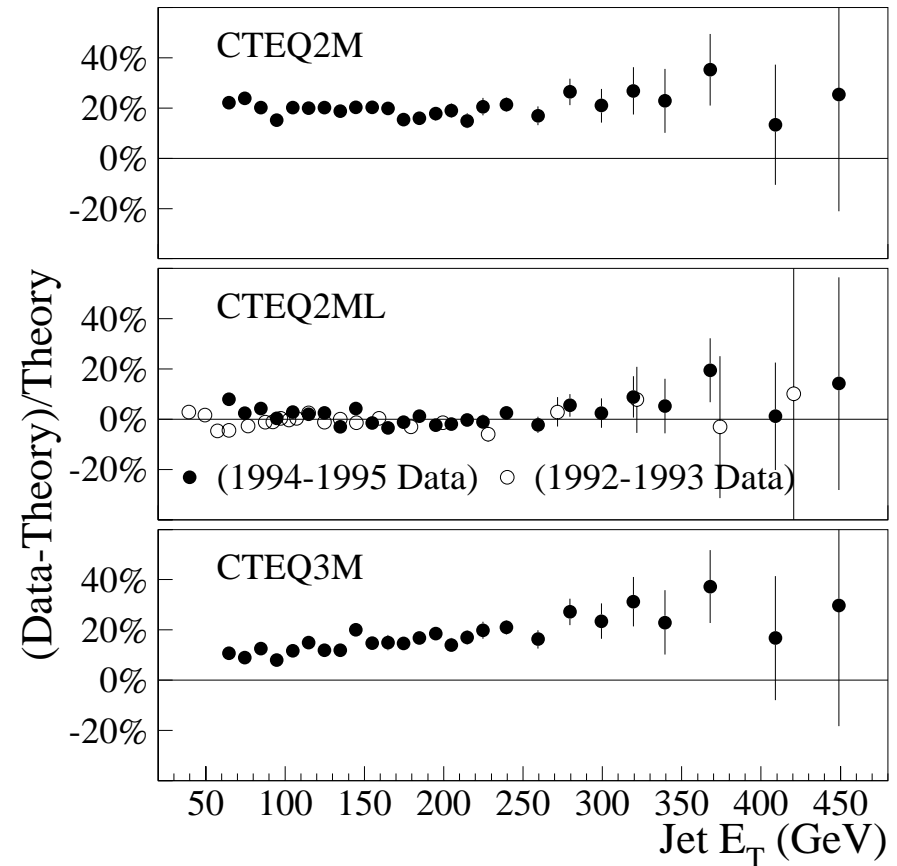
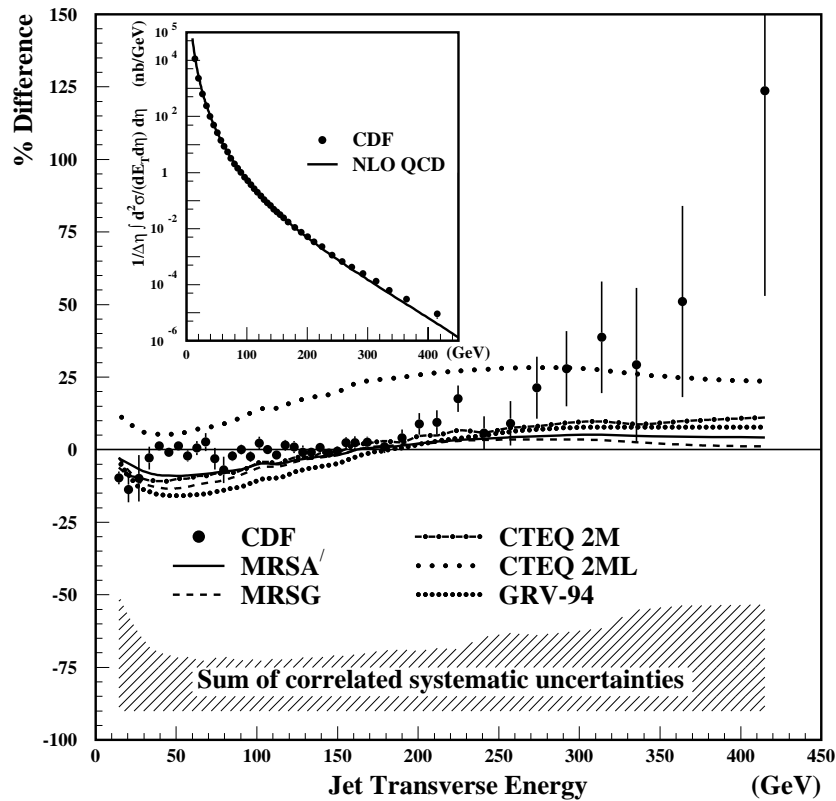
$M_{\text{top}} = 174.3 \pm 3.2 \pm 4.0 \text{ DØ+CDF}$



Is the SM OK?

Quark structure?





Checked with jet angular distribution. No deviation from “Rutherford scattering”, $1/\sin^4 \theta/2$.

There are no:

Composite quarks

W', Z', b'

Anomalous couplings

Sparticles

Leptoquarks

Higgs

...

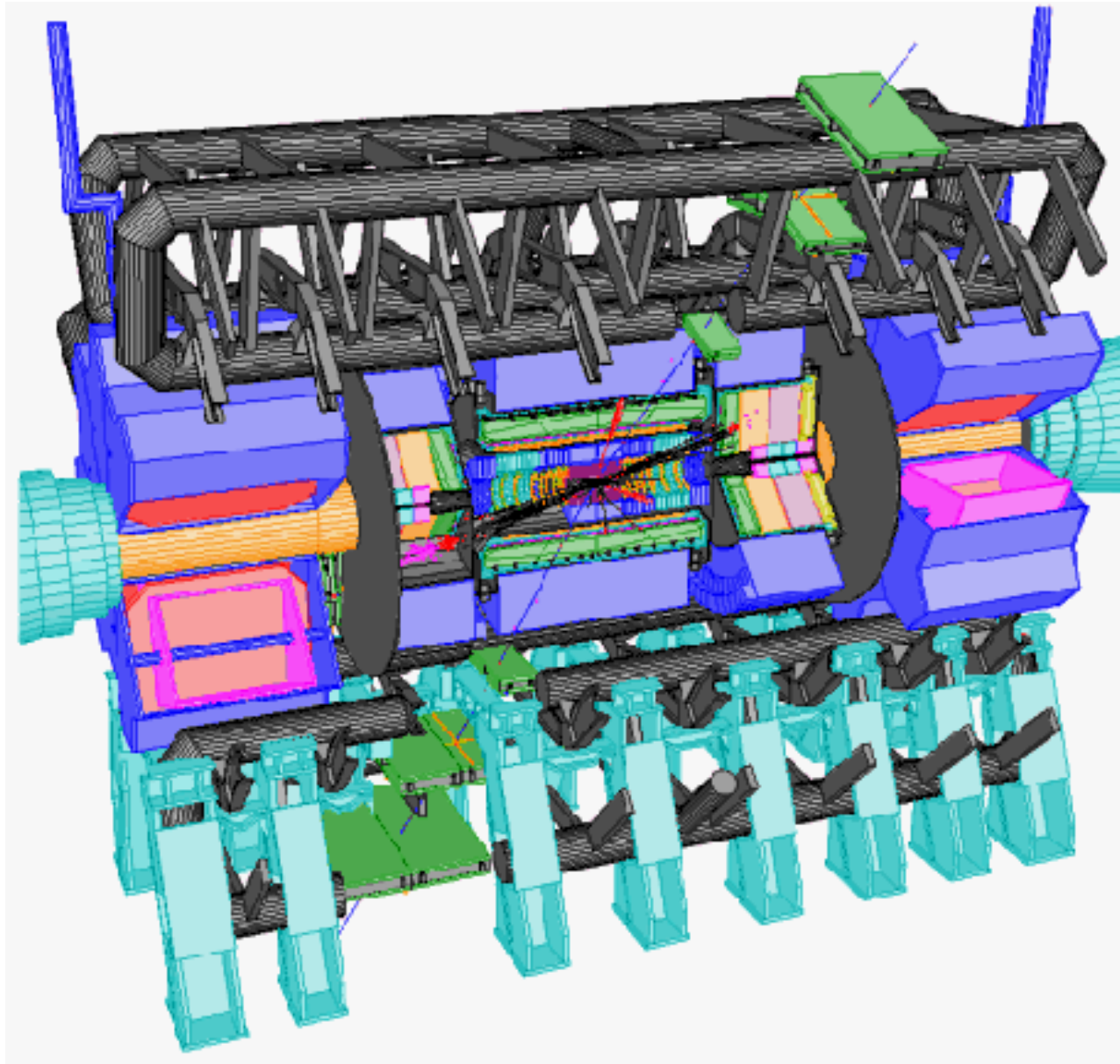
TeV-I, DØ and CDF

Will continue the Higgs search for the next few years, their calorimeters will be their best assets.

Will they get the necessary luminosity?

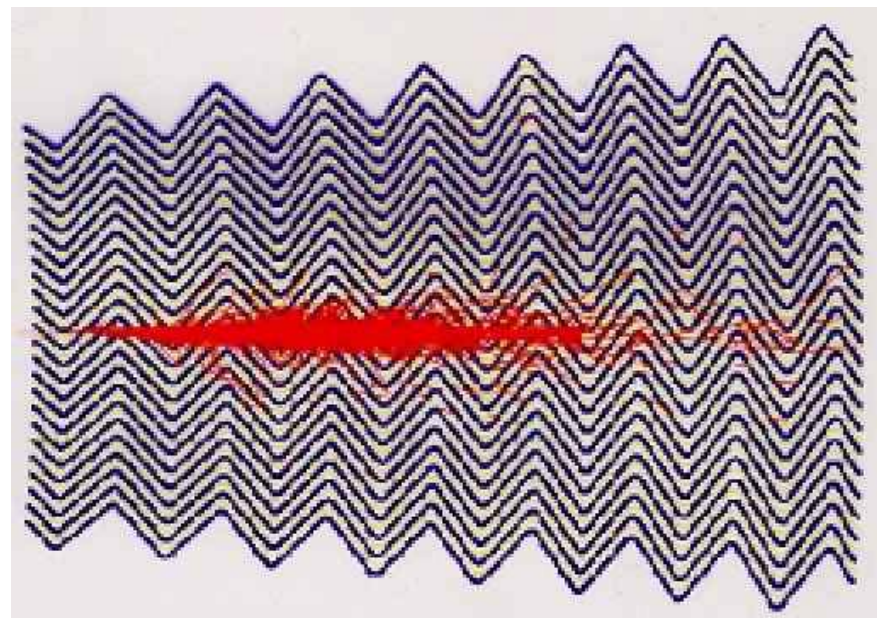
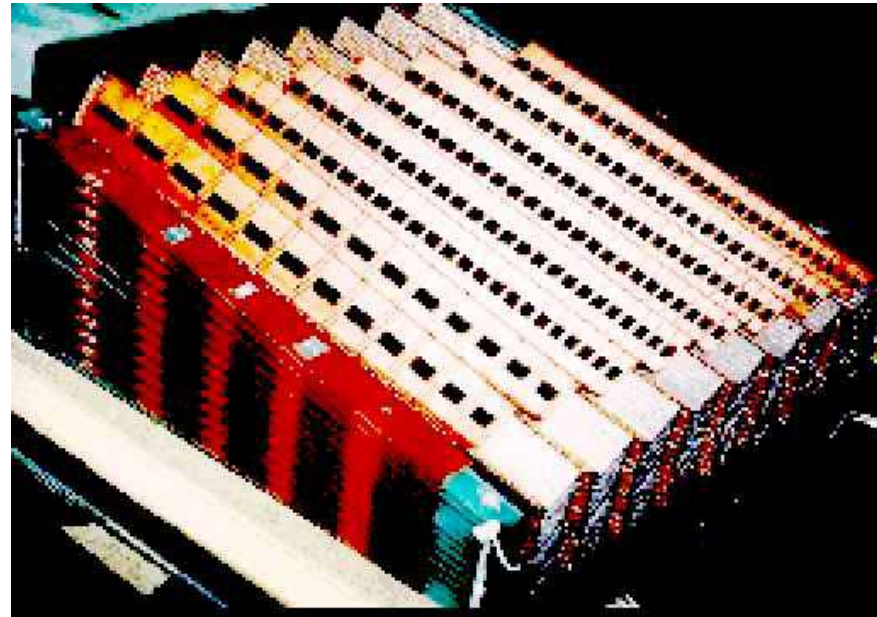
In 200 n , $n < ?$, LHC will begin. ATLAS and CMS will be equipped with bigger and better calorimeters. And more...

Atlas

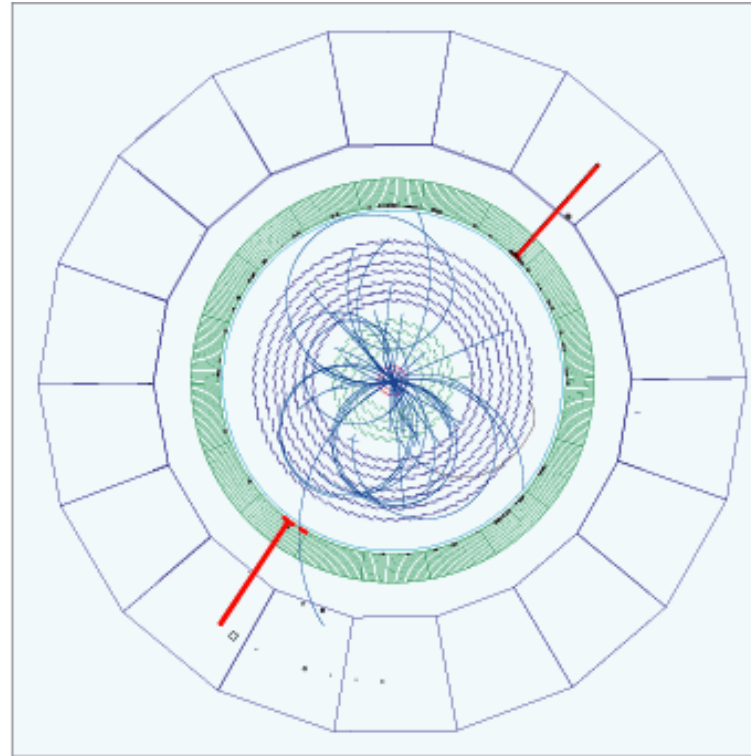
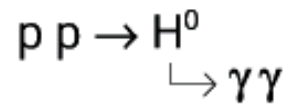


Atlas central em-cal

1.5 mm Pb, 4 mm Ar
 $\delta E/E \simeq 1.1\%$ at 100 GeV
 $\delta E/E \simeq 0.4\%$ at ∞



CMS

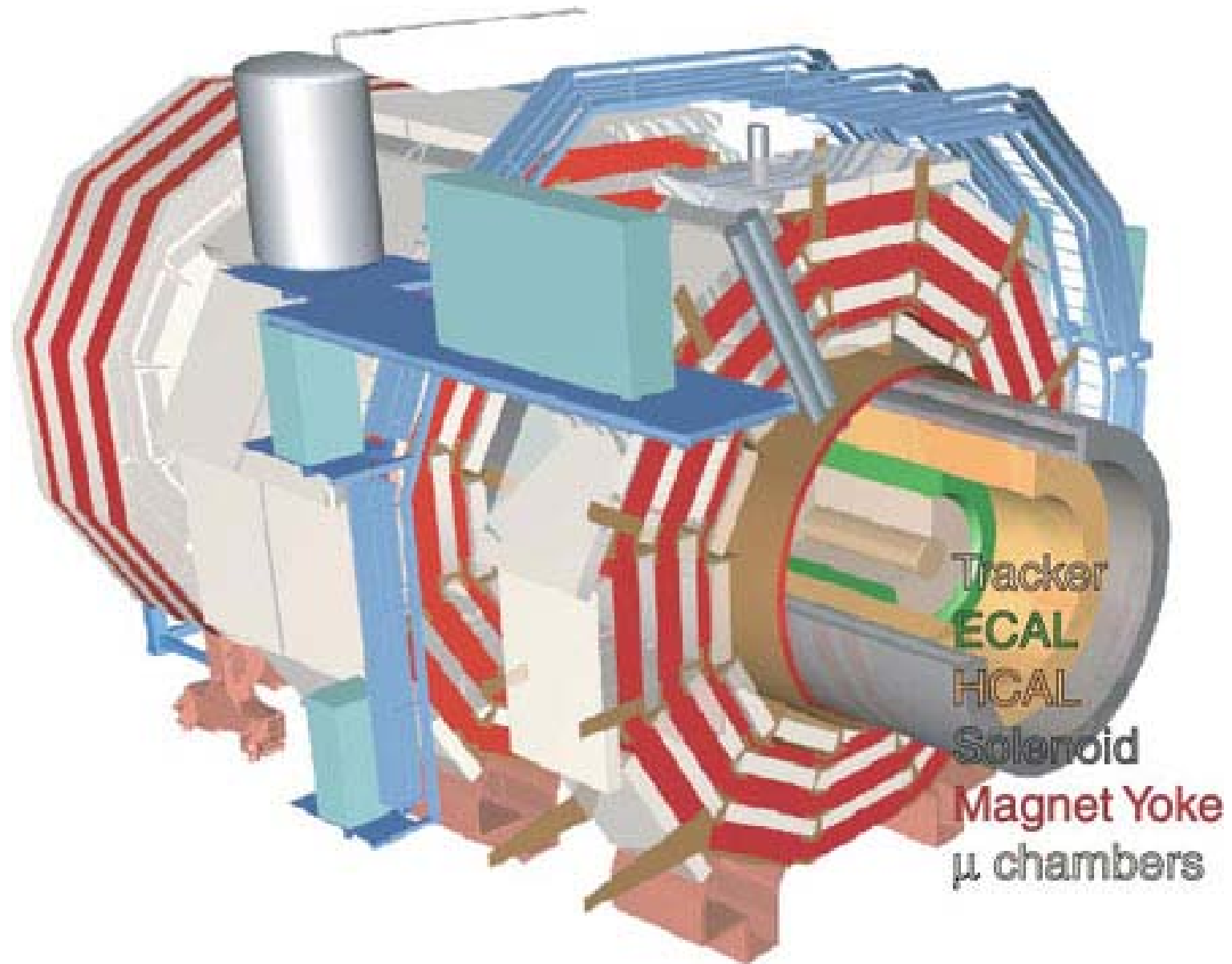


80,000 PbWO₄ crystals em-calorimeter,

$\sigma(E)/E \simeq 0.8\%$ at 50 GeV

A luxury?

CMS



at a future Linear Collider

A W-Si calorimeter?

Very expensive

Fast, space resolution...

Heat removal, how thick Si...