Calorimetry at Hadron Colliders: DØ

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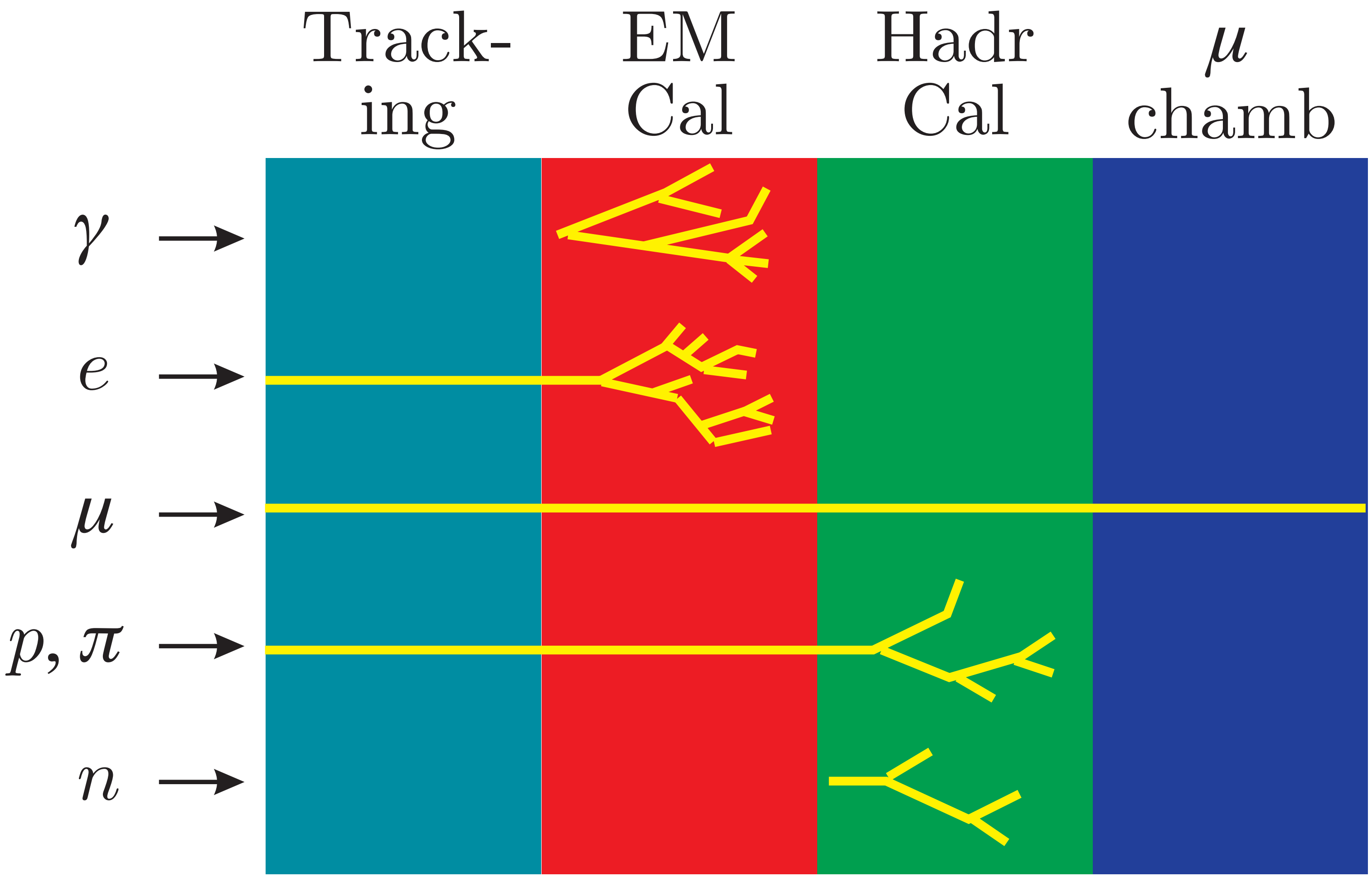
1. Introduction
2. Why Calorimeters
3. Sampling Calorimeter
   (a) How to
   (b) Compensation
   (c) Noise
   (d) Pile-up
4. DØ
5. W and Z
6. Top

Particle Detector



Hadronic jets $\approx$ partons.

ν by $\not{E}_\perp$ 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.

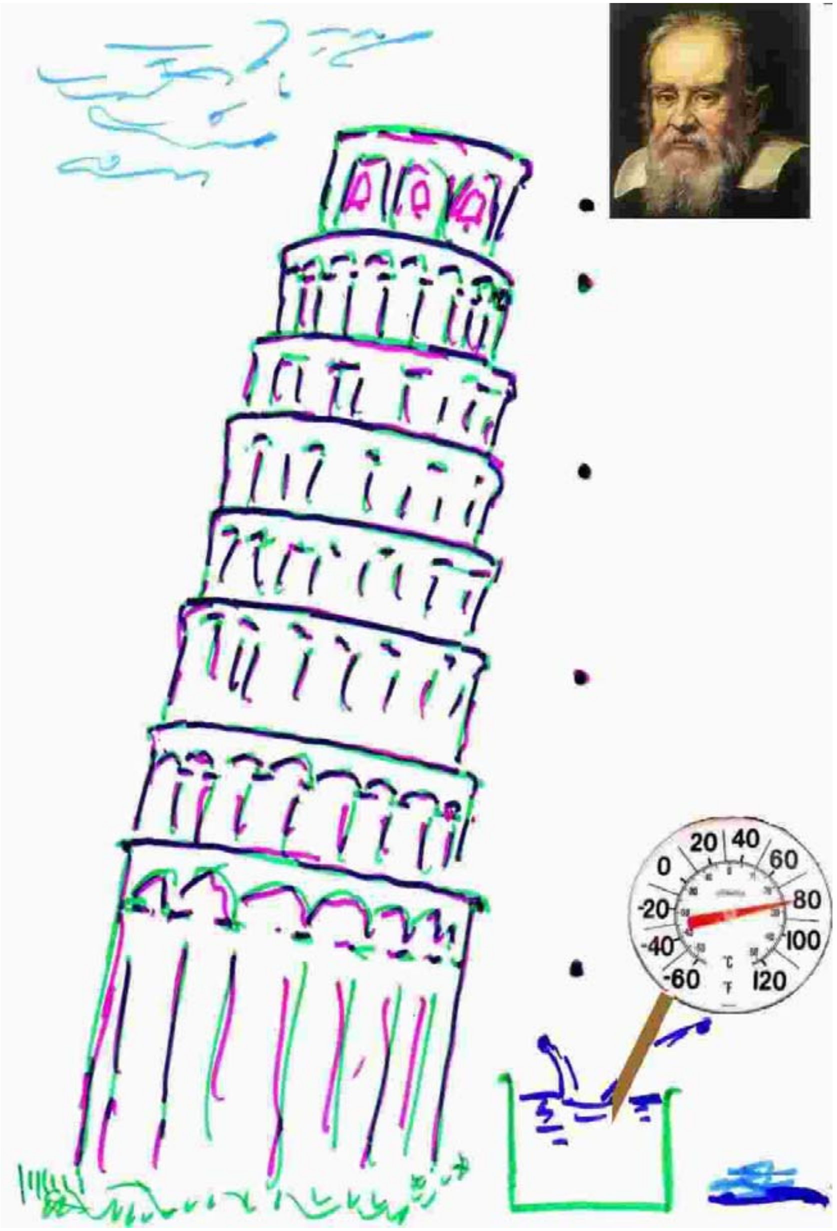
Each energy deposit is measured with an rms accuracy δE_i and, for a perfect calorimeter, the correlation between fluctuations, $G_{ij} = \overline{(E_i - \overline{E}_i)(E_j - \overline{E}_j)} = 0 \ (i \neq j)$.

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 δs=150 μm, $\delta p/p$~4%. For p=1000 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: $h+(Z,A) \rightarrow \pi+N+$nucl. frag. Need $\sim$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×8, fast, heat, cost
Xe	3.7	no gain, cost

Sampling fraction

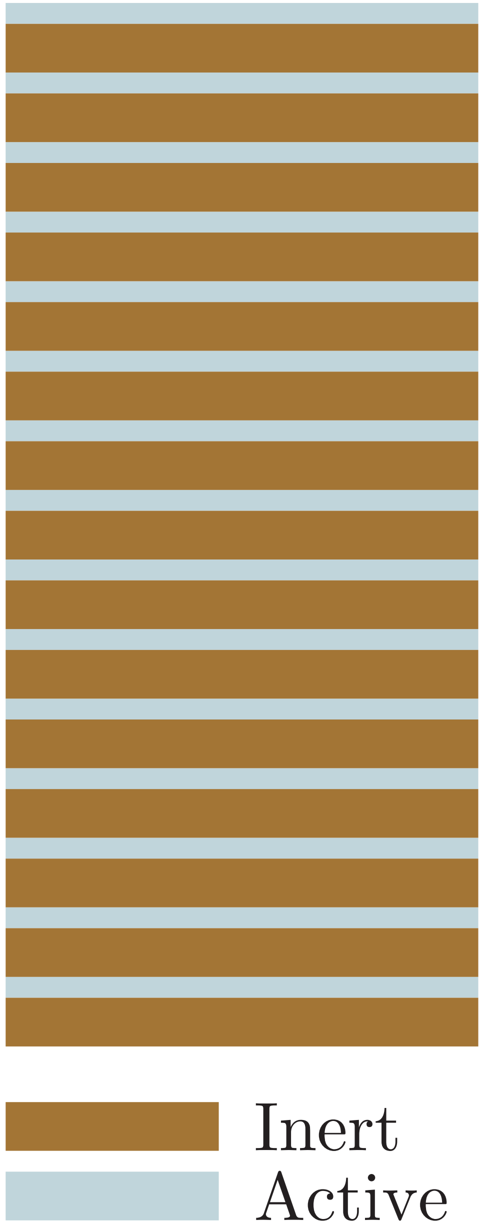
$$S_m = \frac{(\mathrm{d}E/\mathrm{d}x)_A \Delta x_A}{(\mathrm{d}E/\mathrm{d}x)_A \Delta x_A + (\mathrm{d}E/\mathrm{d}x)_I \Delta x_I}$$

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.



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 μm. 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/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, $y \to y' = y - \tanh^{-1}\beta$, *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 $\cos\theta = p_z/p$,

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

.

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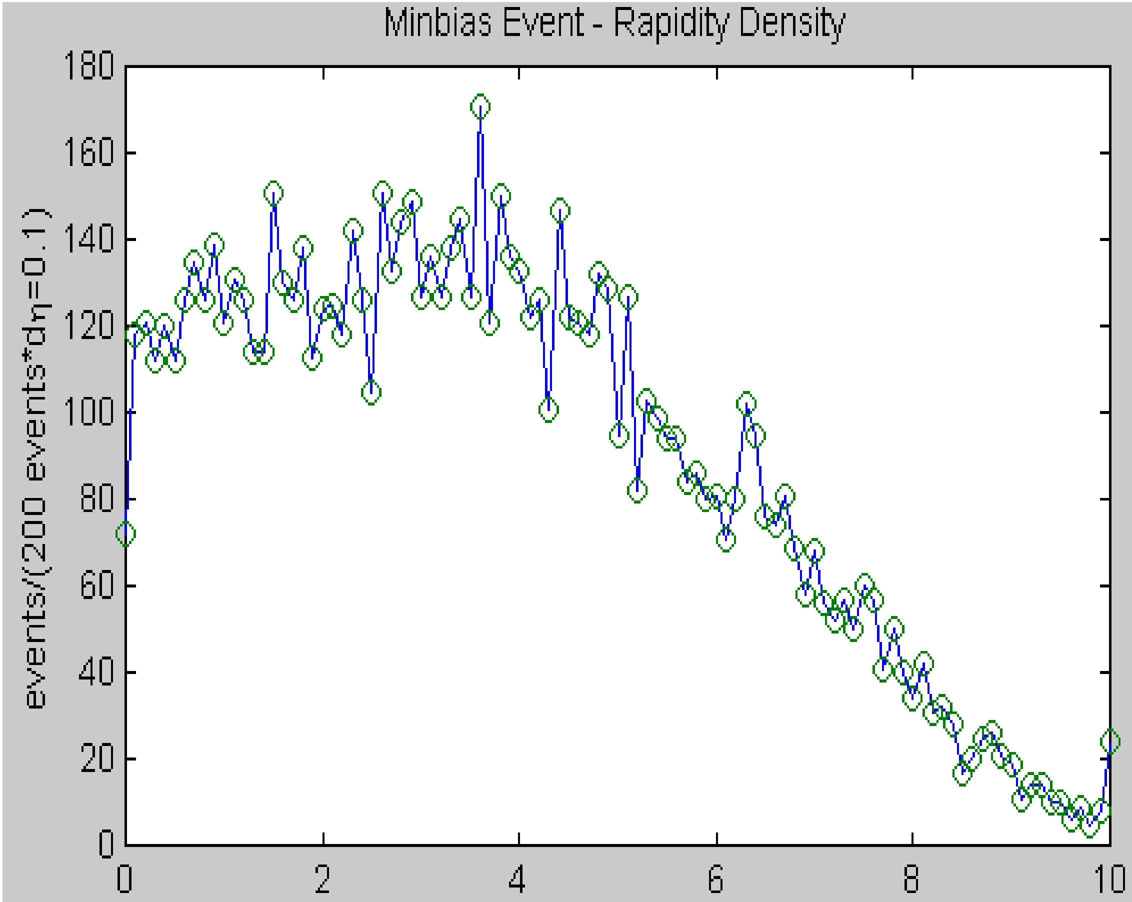
A collider detector should be segmented in slices of equal $\Delta\phi$ and $\Delta\eta$. $\eta_{\text{Max}} - \eta_{\text{min}}$ varies slowly with energy: ~19 at 1+1 TeV, ~24 at 20 TeV. Also, σ is large (plateau) only for $-2 < \eta < 2$ (high mass) or $-5 < \eta < 5$ (low mass).



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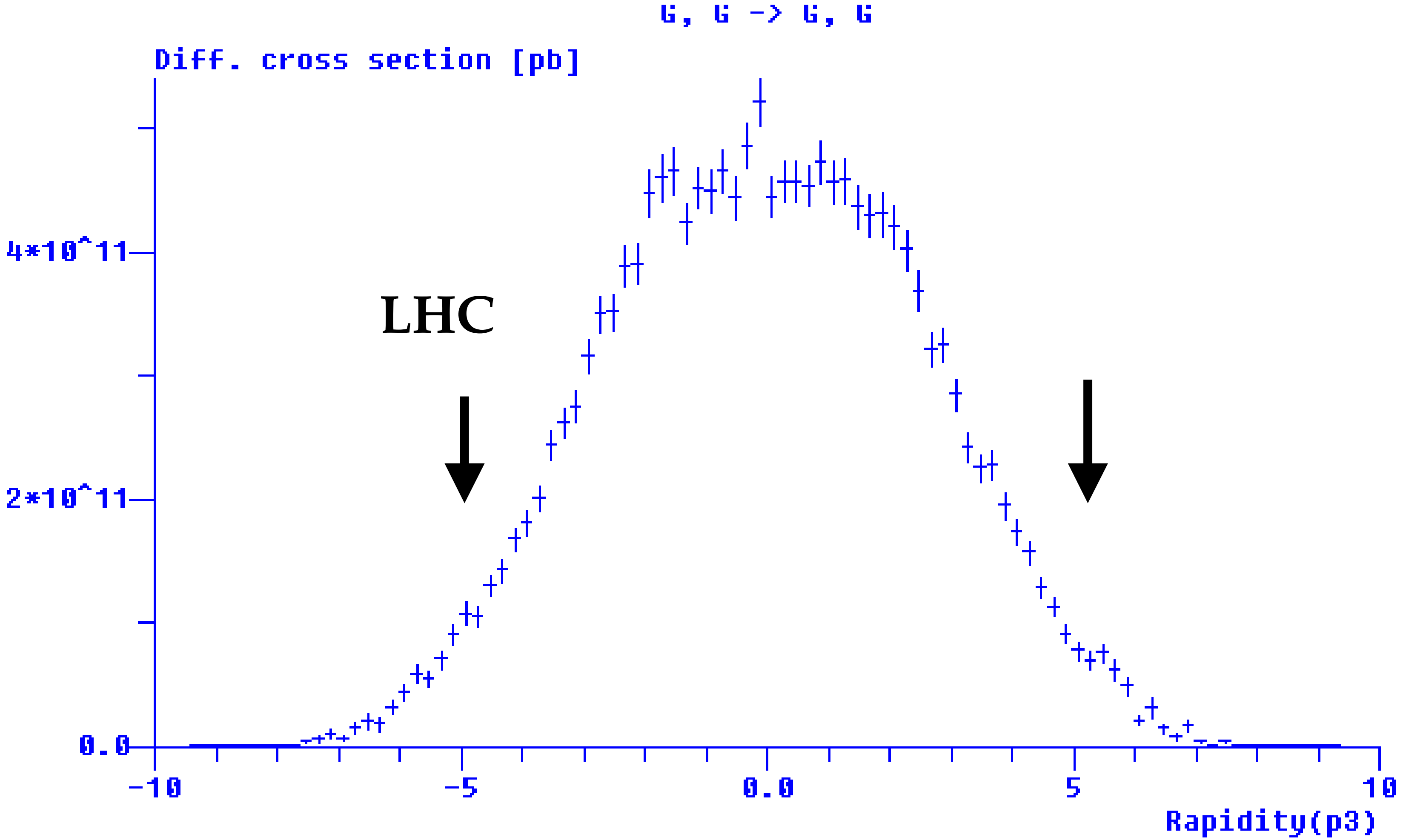
Hard gluons at LHC



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.

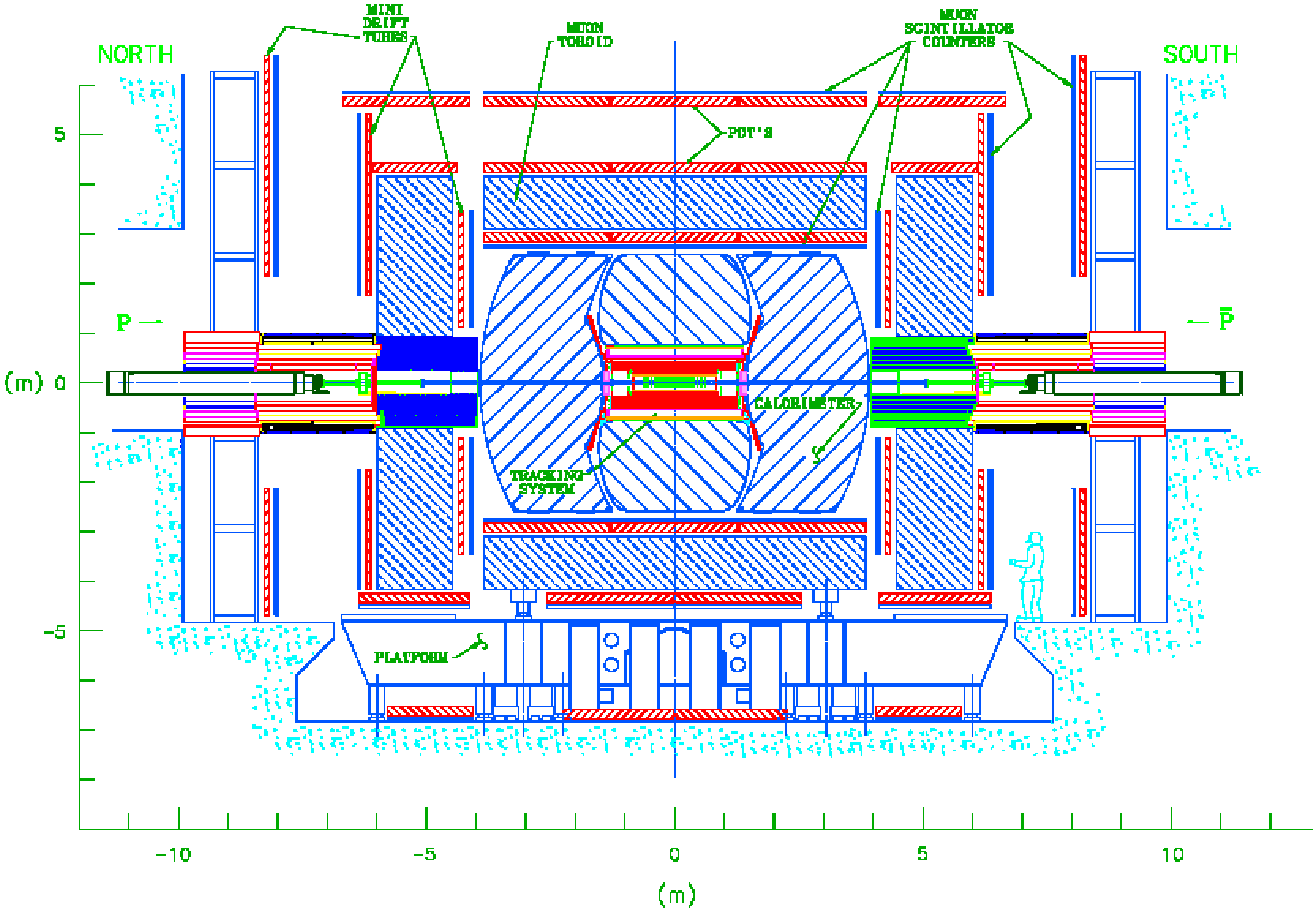
Final resolution in Ar will be strongly affected by:
Total argon traversed depth, gap size
Quality of electronics, thermal noise is important
ϕ, η segmentation to control confusion – pile-up
Noise above the thermal minimum - *i.e.* "coherent"

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$10,000 towers 0.1$\times$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



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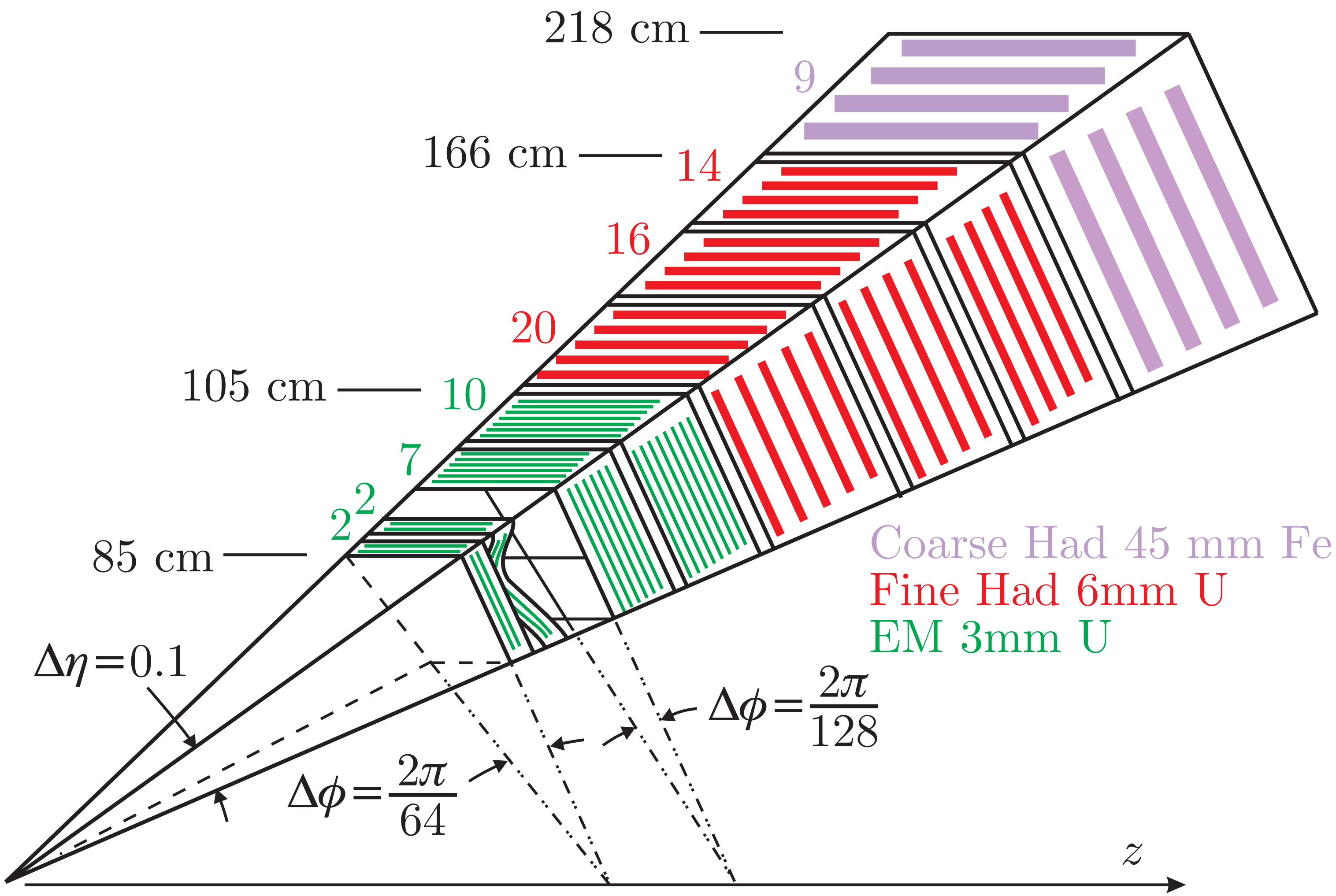


800 ton of U (+Fe)

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

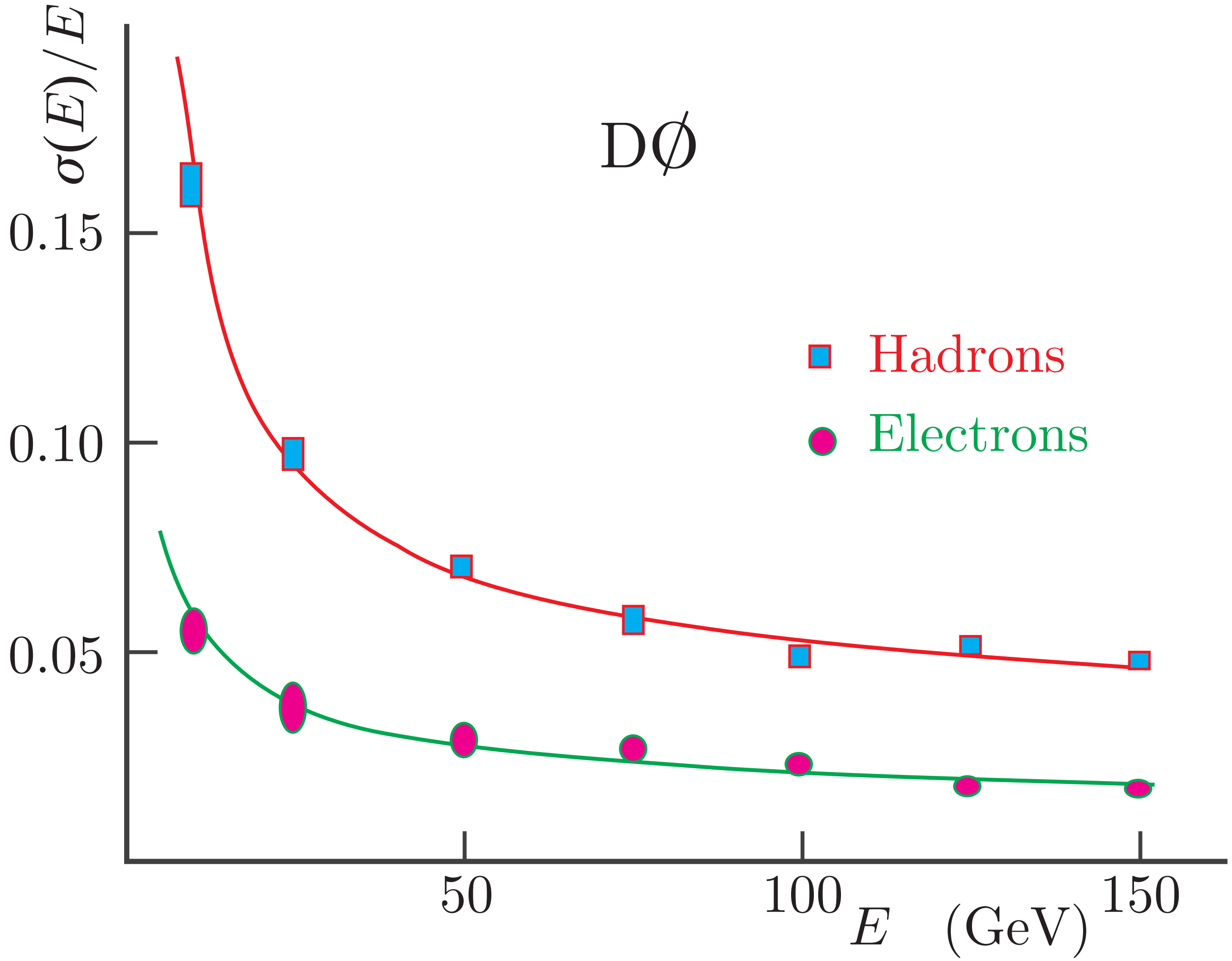
EM σ(E)/E=2%,

Had σ(E)/E=6%

@ 100 GeV

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

e/π~1000/1



Read-out and response

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

Preamp noise, 1 em cell, ~1nF: 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:

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

with $\overline{\delta_i \delta_j} = \langle (S_i - \overline{S}_i)(S_j - \overline{S}_j) \rangle$. 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 $\overline{\delta_i \delta_j} = \alpha^2 \sigma^2$

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

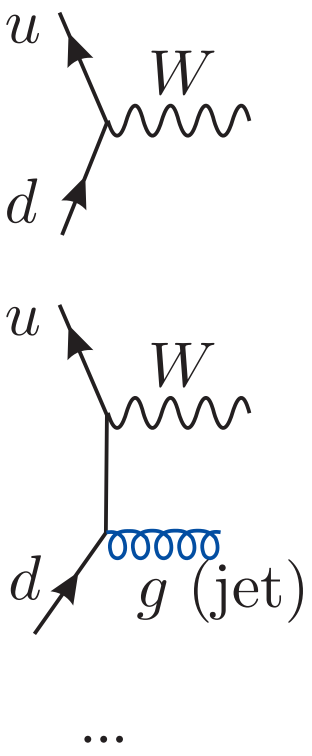
and $\delta S_{\text{tot}} = \sigma\sqrt{n} + \alpha\sigma\sqrt{n(n-1)} \sim \sigma\sqrt{n} + \sigma n \alpha$. Unless $\alpha < 1/\sqrt{n}$, the accuracy of the measurement is degraded.

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

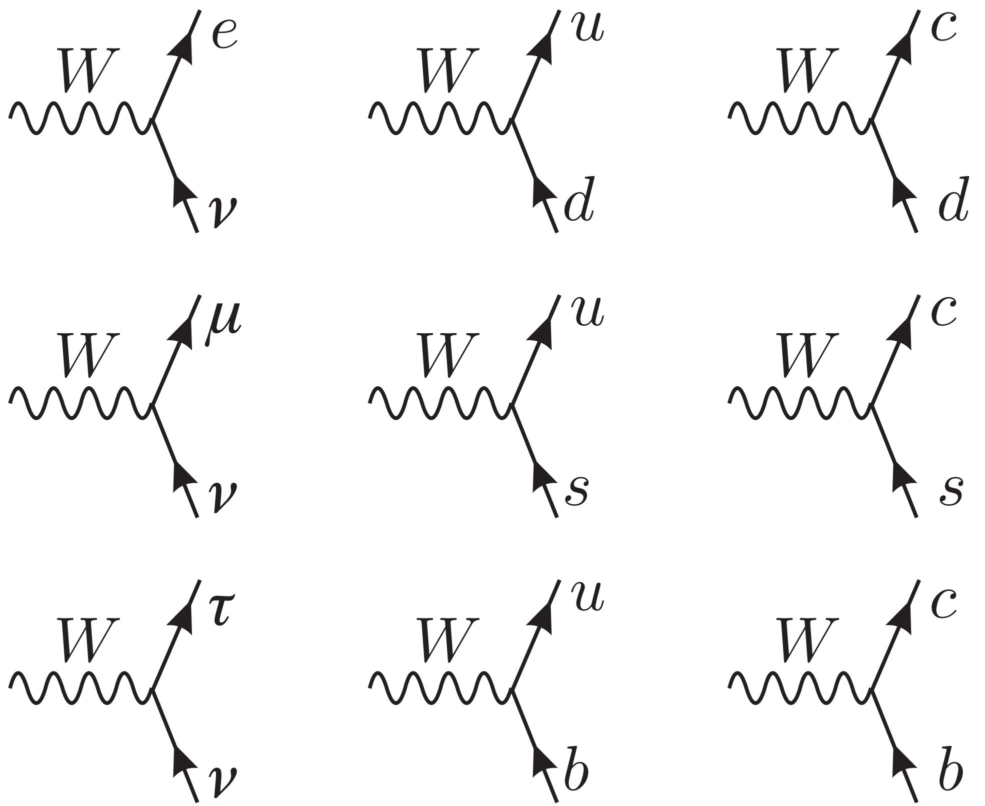
In DØ $\alpha \sim 0.01$, can add 10,000 channels.

The W boson mass

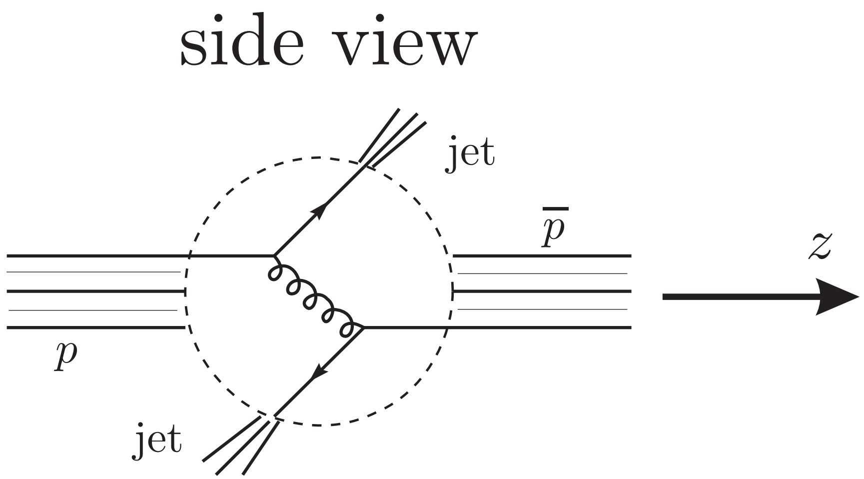
Production

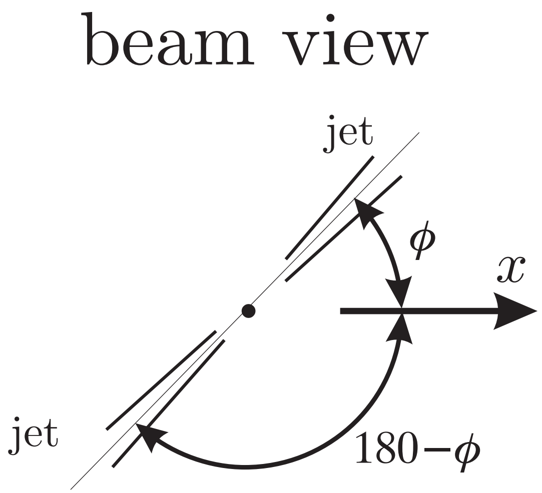


Decay



$1+1+1$ $\quad 3\times\Sigma|V_{ui}|^2$ $\quad 3\times\Sigma|V_{ci}|^2$





p_z unknown, $p_\perp \sim e^{-p/p_0}$

$d\sigma/d\eta \sim$ const

$q\bar{q}$ SCATTERING

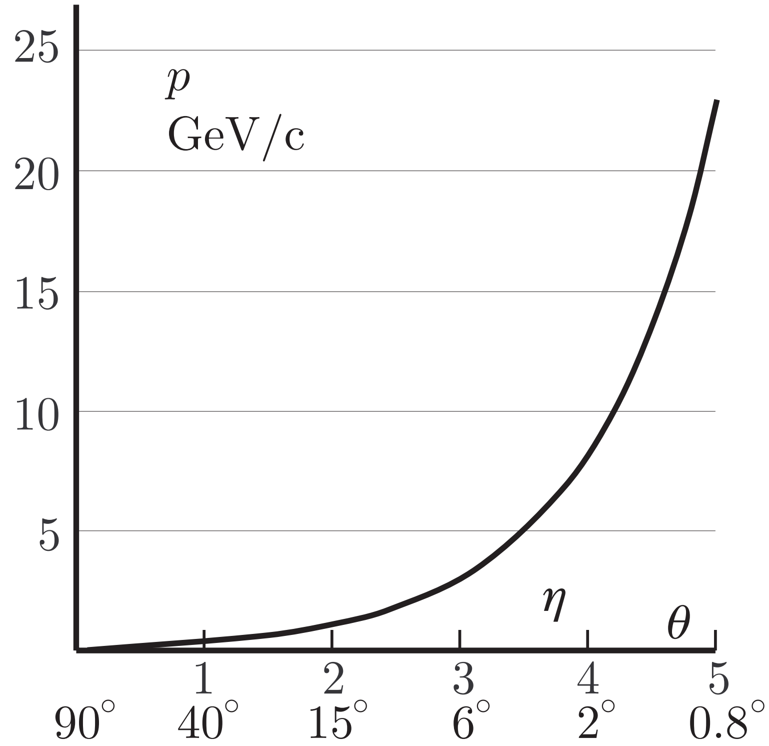
$\langle p_\perp^{\text{in}}\rangle \sim 300$ MeV/c ~ 0

Large angle: low p

Small angle: high p

W PRODUCTION

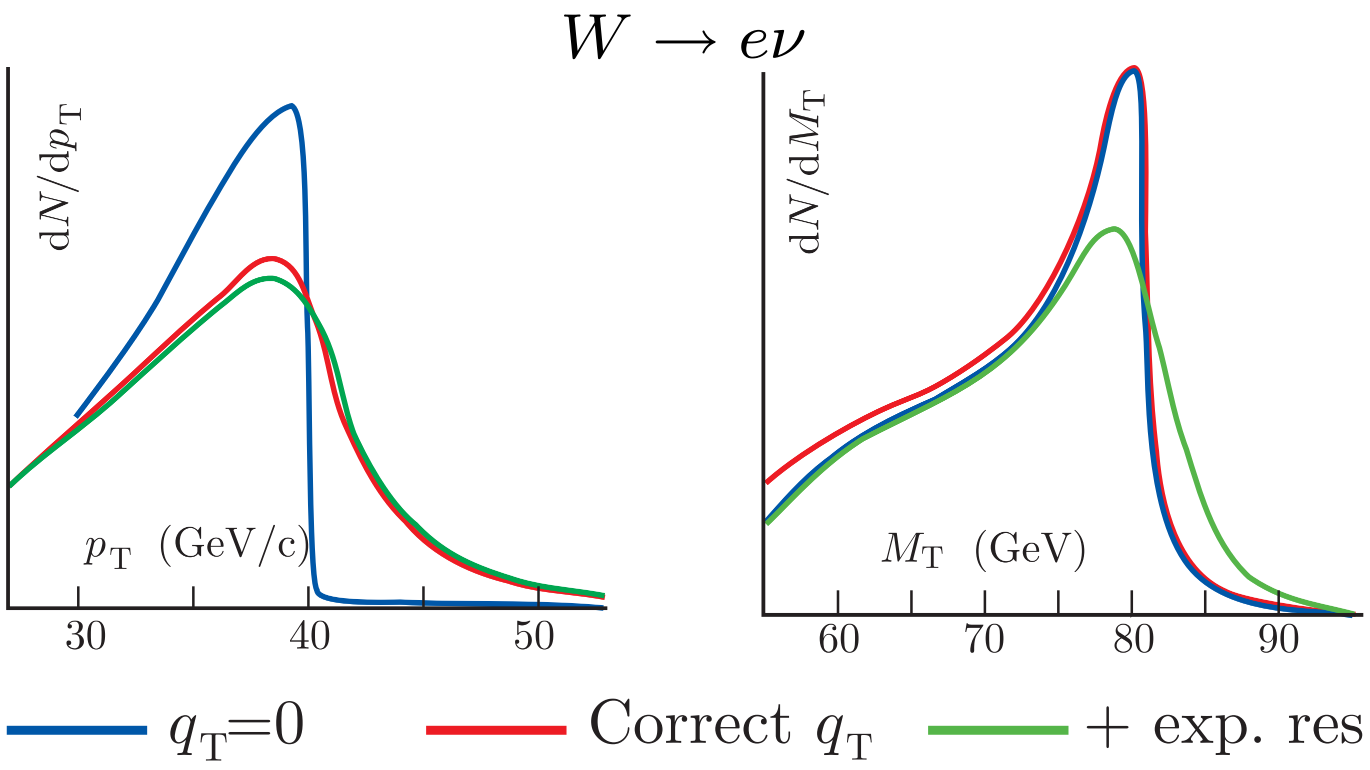
$\langle p_\perp(e,\nu)\rangle \sim M_W/2$, $\sum p_\perp \sim 0$



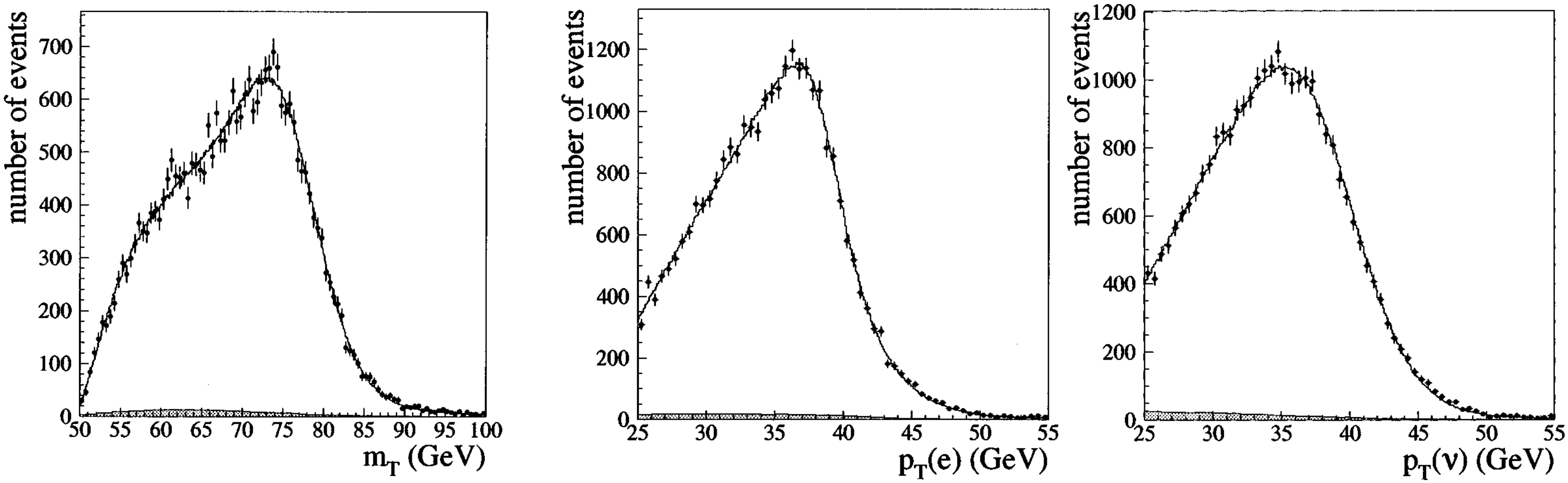
Hard processes in $p\bar{p}(p)$ collisions

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

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



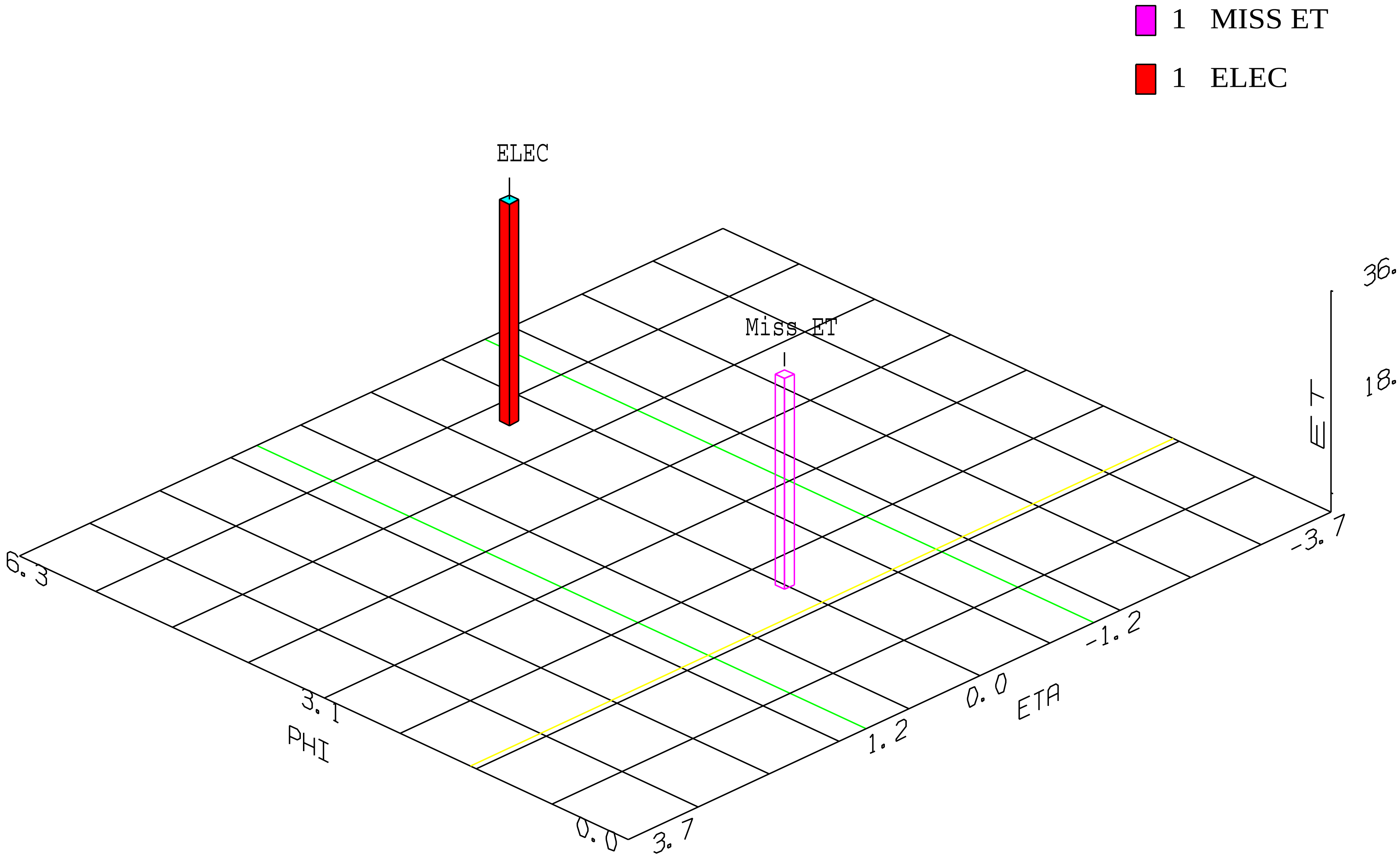
$M_\perp$ is better than $p_\perp$. $M_\perp = \sqrt{p^2_{\perp,e} p^2_{\perp,\nu}(1 - \cos(\phi_e - \phi_\nu))}$.

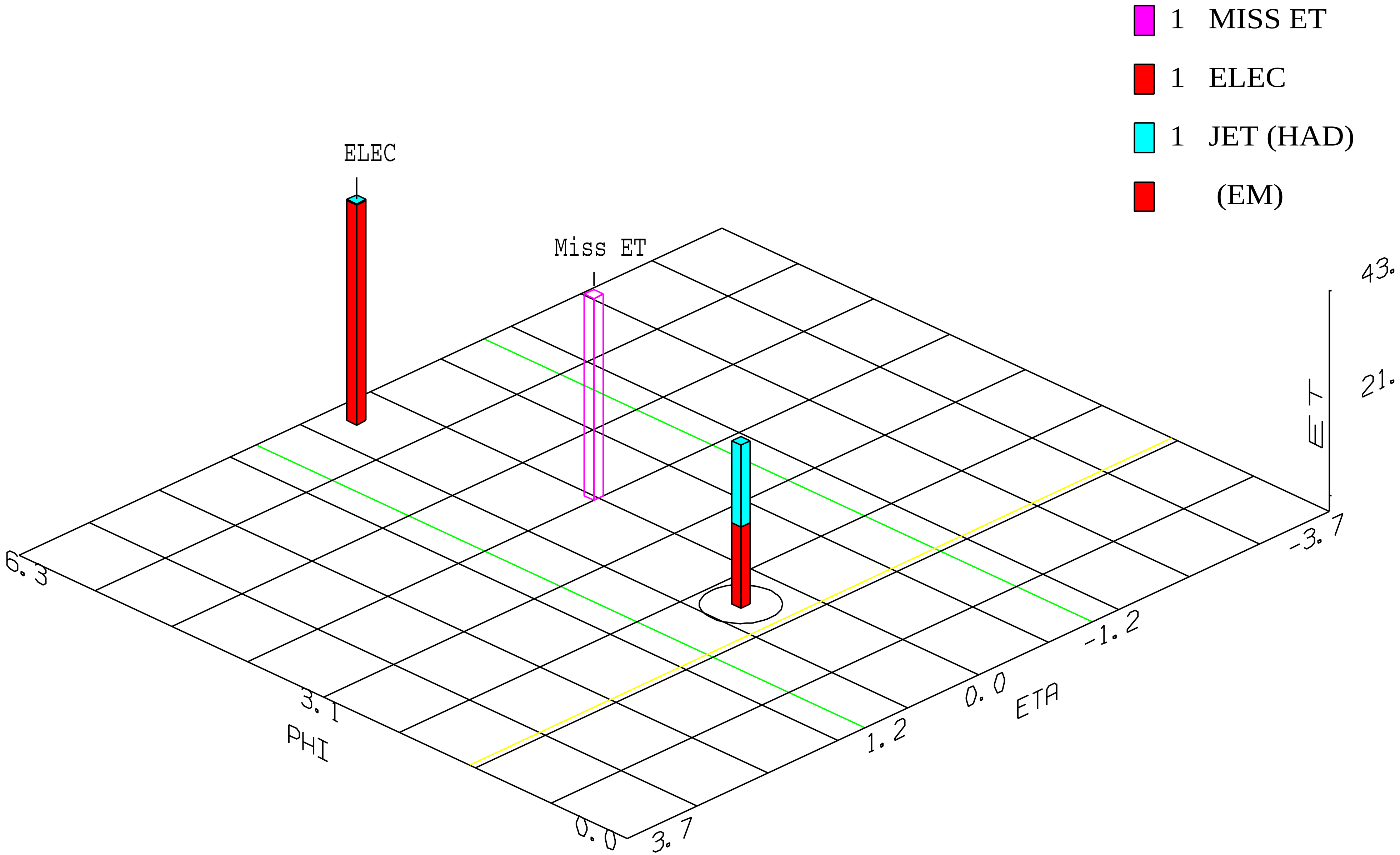


All three distributions, $M_\perp$, $p_\perp(e)$ and $p_\perp(\nu)$ are shown. They are not independent. $p_\perp(\nu)$ is measured as $\not{E}_\perp = -\sum E_{i,\perp}$.

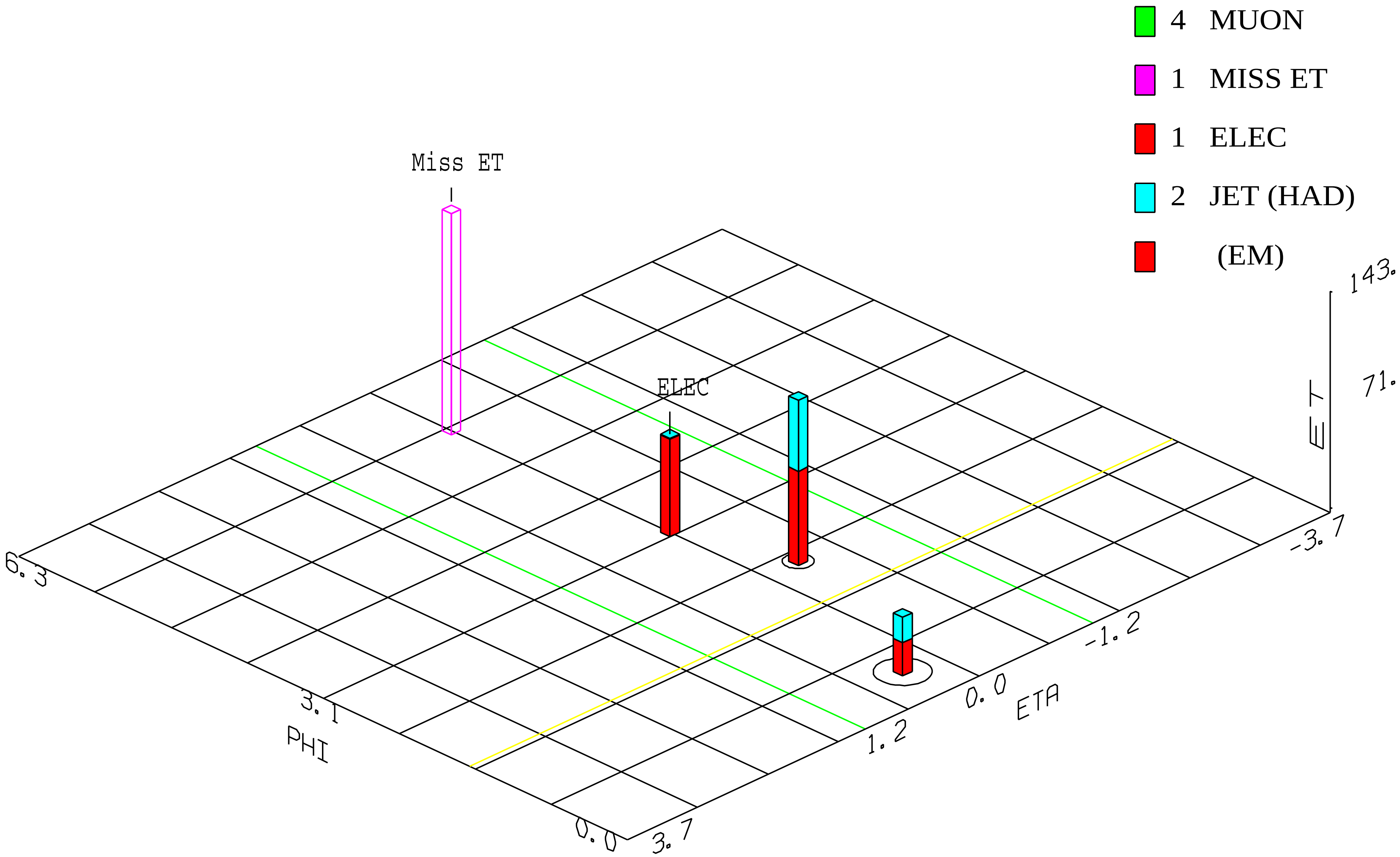
Note the very small background, which vanishes toward the end of the spectra.

(This made finding the W "easy".)


1 MISS ET
1 ELEC
ELEC
Miss ET
ET
36.
18.
6.3
3.1
PHI
0.0
3.7
1.2
0.0
ETA
-1.2
-3.7



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


4 MUON
1 MISS ET
1 ELEC
2 JET (HAD)
(EM)
Miss ET
ELEC
143.
71.
ET
6.3
3.1
PHI
0.0
3.7
1.2
0.0
ETA
-1.2
-3.7

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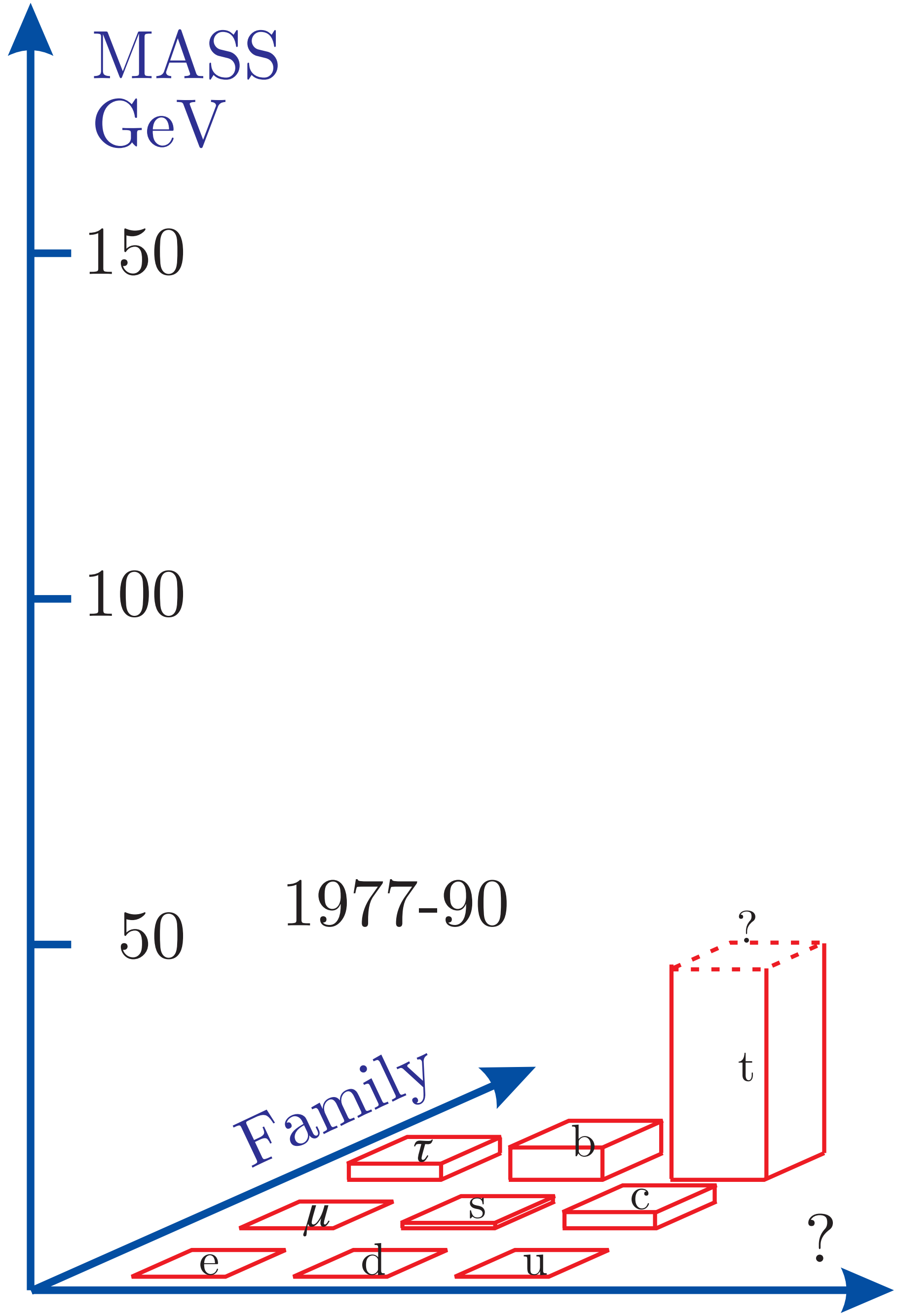
$M(W)$ results

$$M_W = 80.482 \pm 0.091 \text{ GeV, DØ}$$
$$\sigma(W) * BR(e\nu) = 2.7 \text{ nb, DØ}$$
$$M_W = 80.423 \pm 0.039 \text{ GeV, DØ+CDF+4×LEP}$$

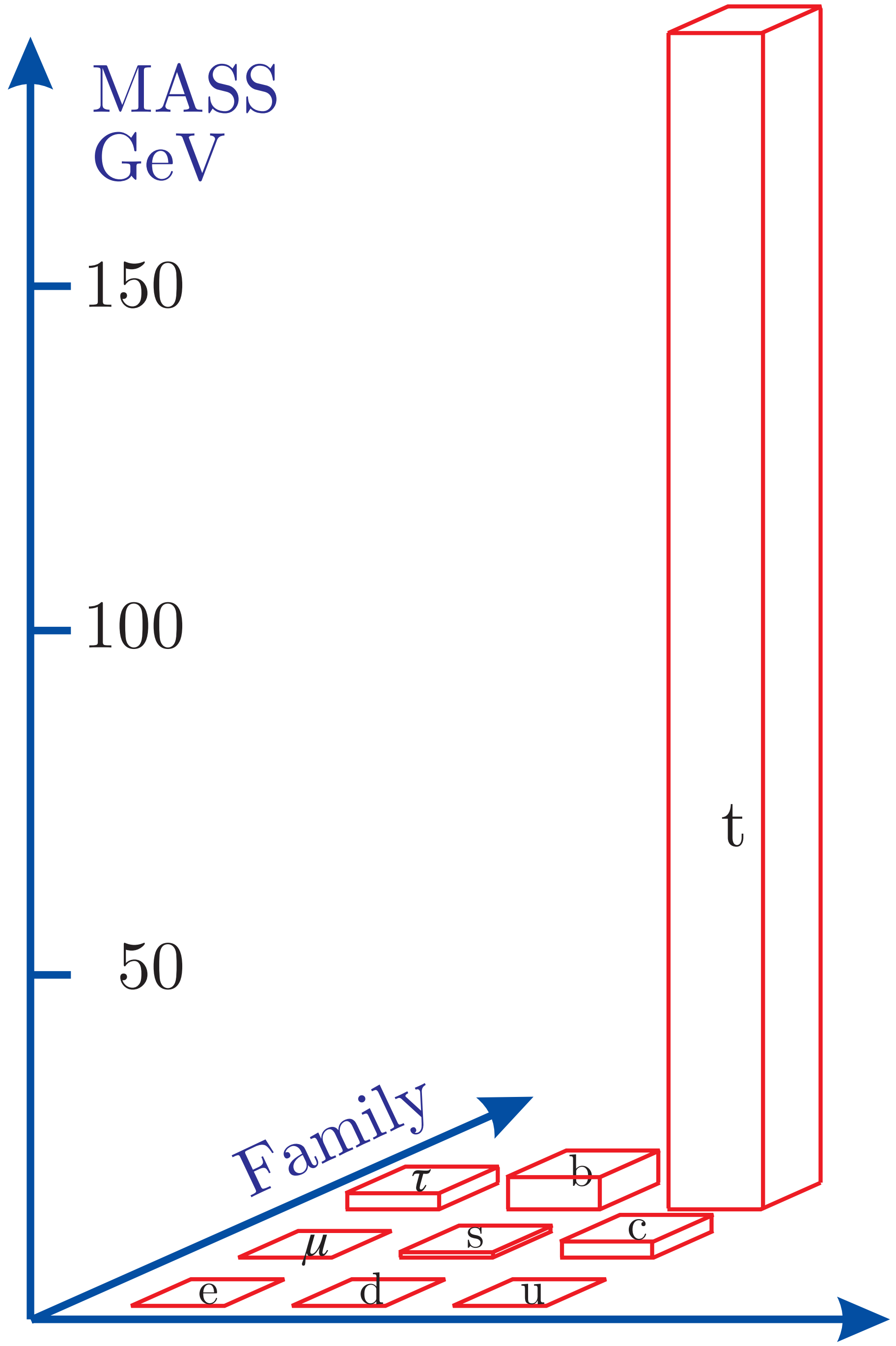
A measurement of the W mass to this accuracy, requires a knowledge of the em calorimeter response to an accuracy of 0.1%, over a long time. The absolute scale comes from the M_{Z^0} values from CERN based on the calibration of LEP with the $g-2$ depolarizing resonances.

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

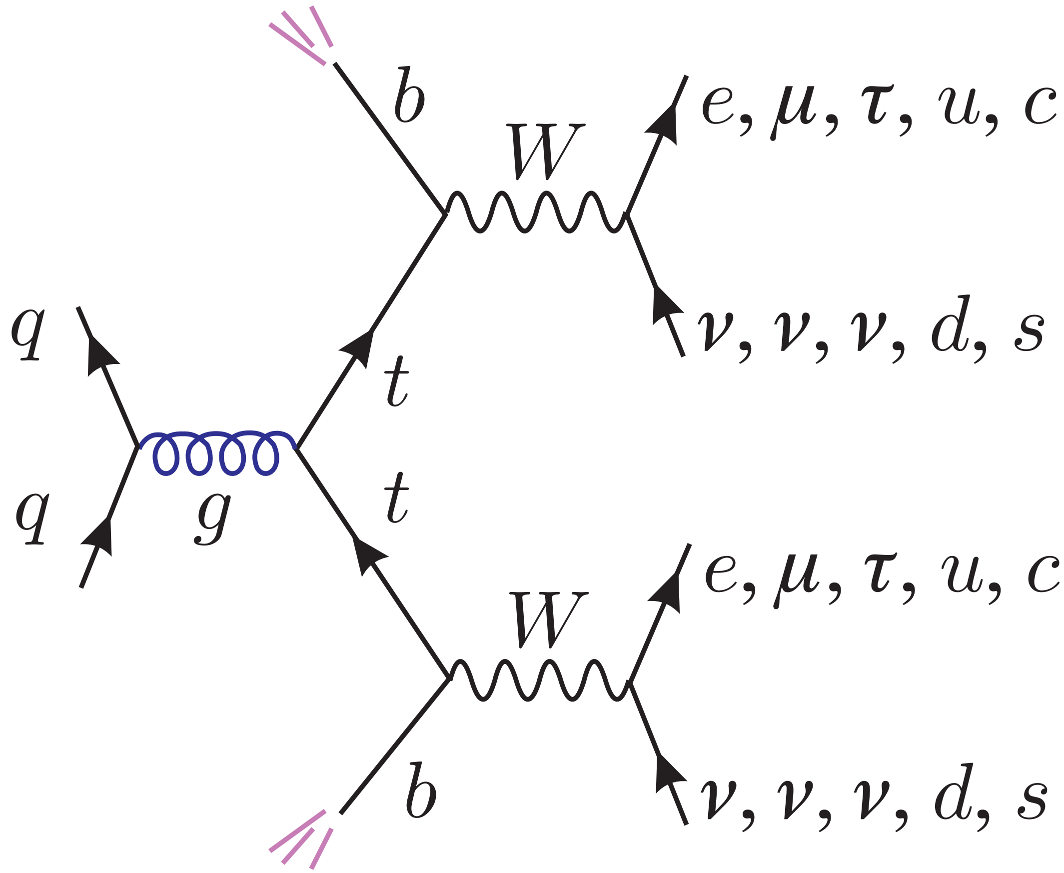
The top



1995



The top mass is harder

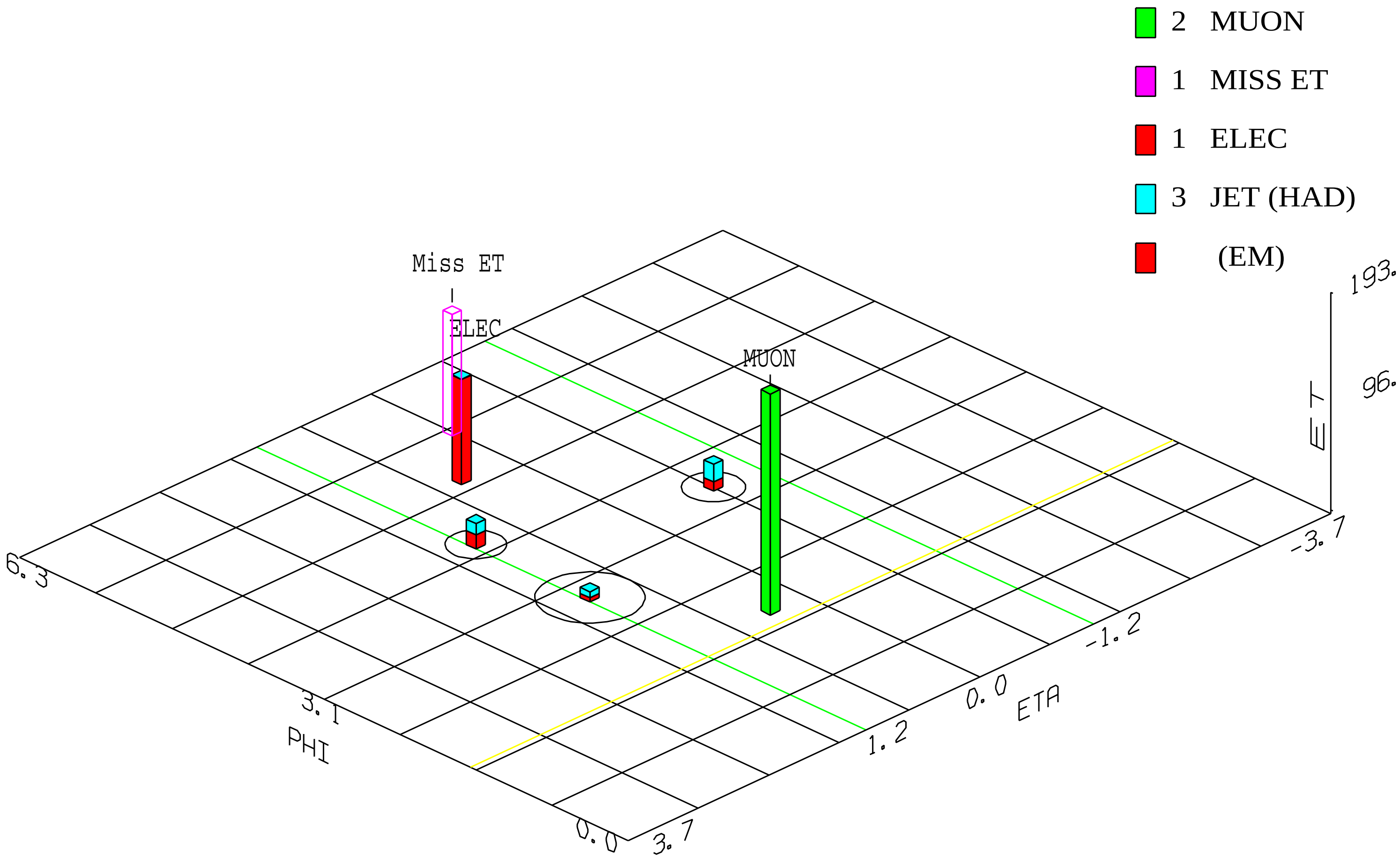


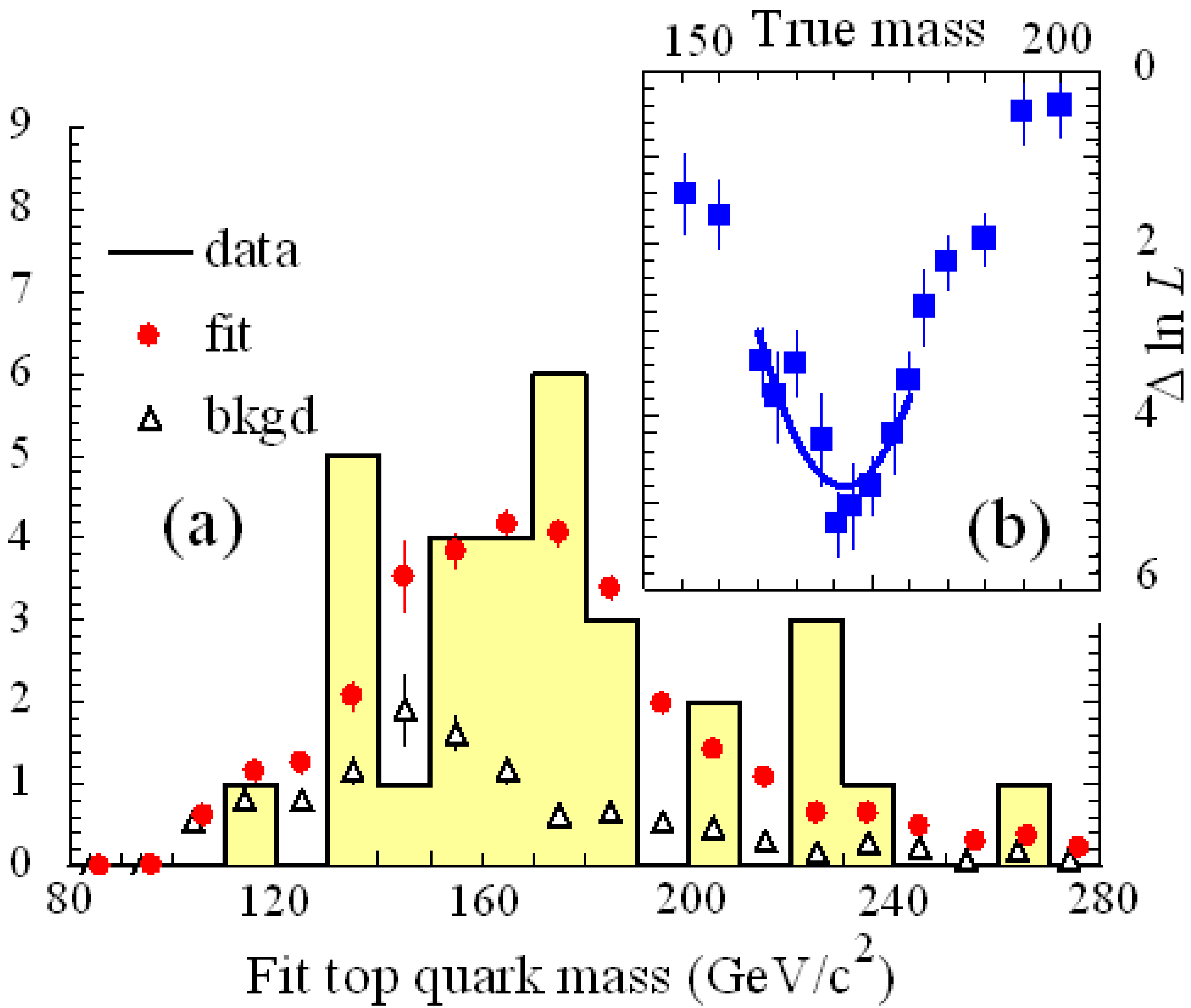
$t\bar{t} \rightarrow e^{+}e^{-}\ \nu\bar{\nu}\ \ b\bar{b}$ ~1.2% $s(q\bar{q}) >$(350 GeV)^2.

1 lepton + jets + missing $E_{\perp}$ ~30%. . .

up to 8 jets, only kinematically over-constrained channel

Not constrained events: compute P(configuration | M)


2 MUON
1 MISS ET
1 ELEC
3 JET (HAD)
(EM)
Miss ET
ELEC
MUON
193.
96.
E T
6.3
3.1
PHI
0.0
3.7
1.2
0.0
ETA
-1.2
-3.7


150 True mass 200
0
2
4
6
$\Delta \ln L$
9
8
7
6
5
4
3
2
1
0
data
fit
bkgd
(a)
(b)
80
120
160
200
240
280
Fit top quark mass (GeV/c^2)

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Top results

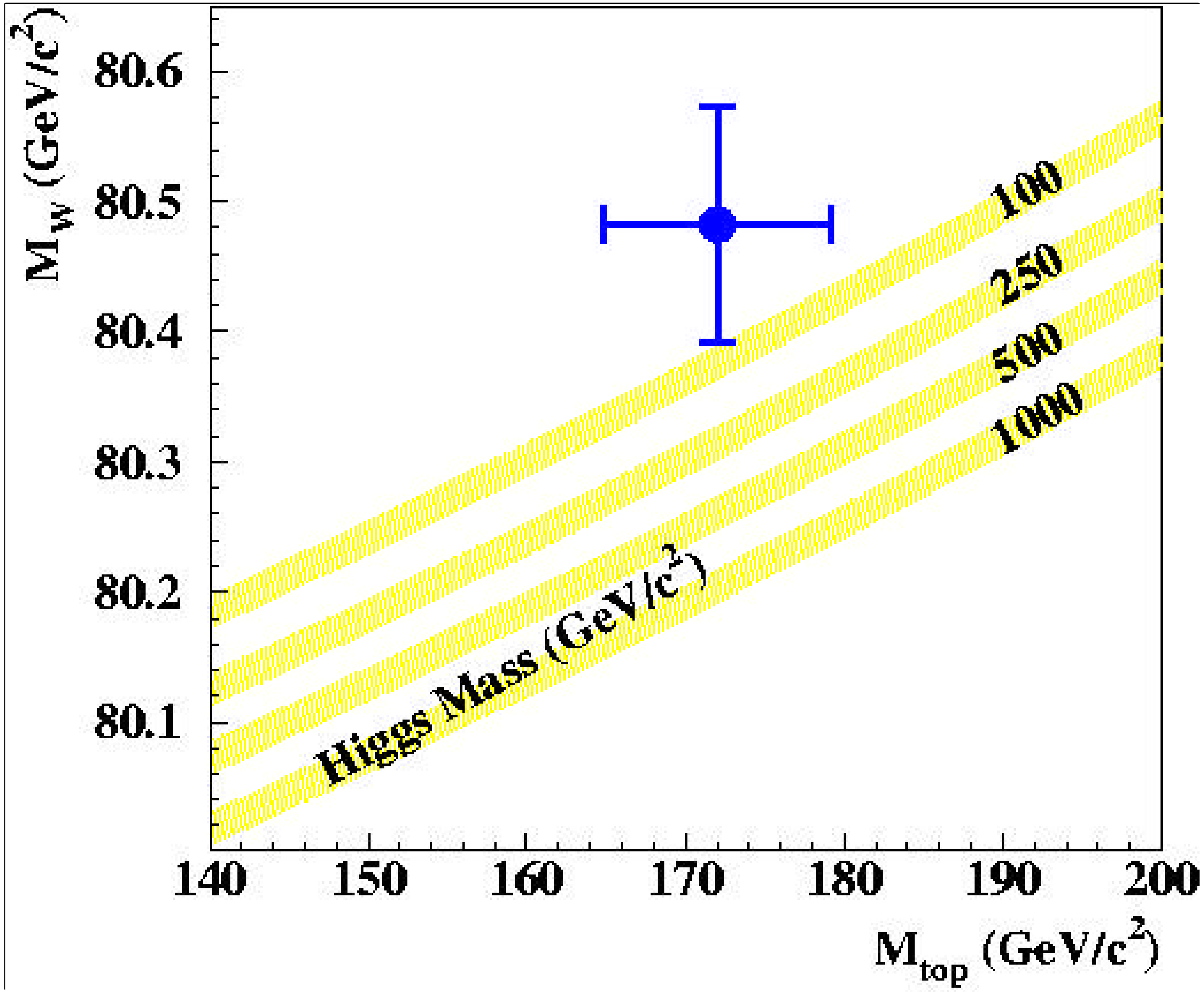
Tot $\mathcal{L}$=128 pb^{-1} - DØ

$\sigma(t\bar{t}) = 5.7 \pm 1.6$ pb - DØ

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

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

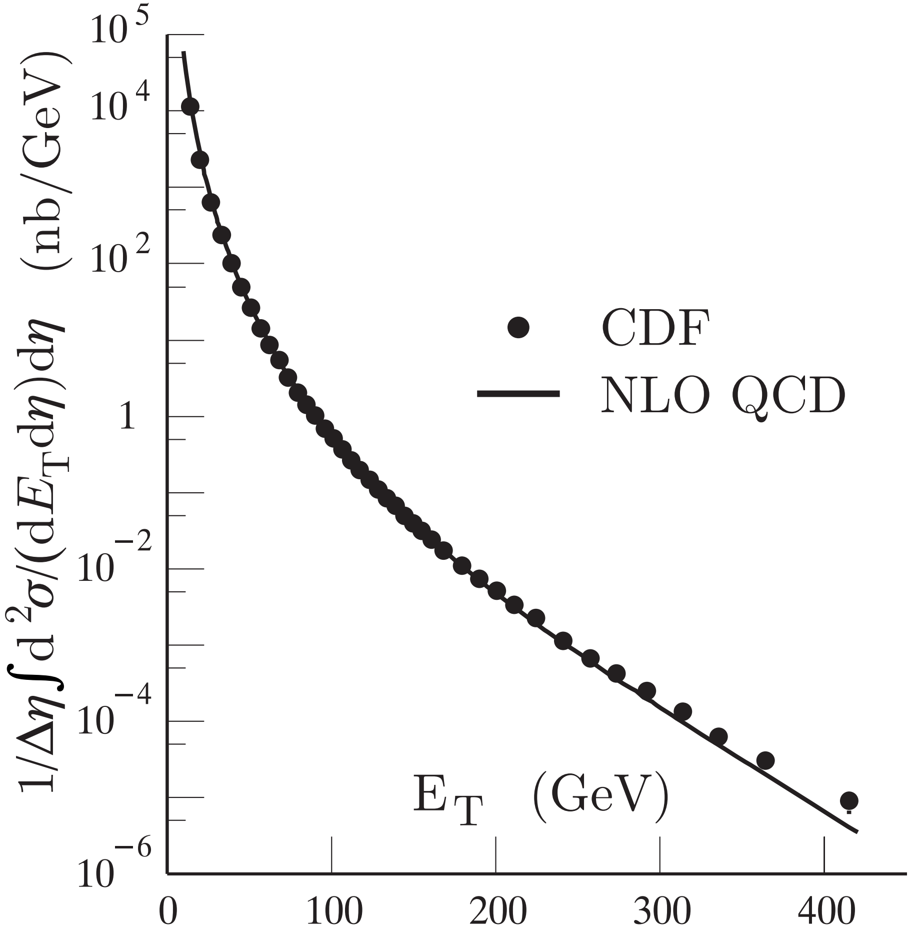
$M_{\text{top}} = 174.3 \pm 3.2 \pm 4.0$ DØ+CDF

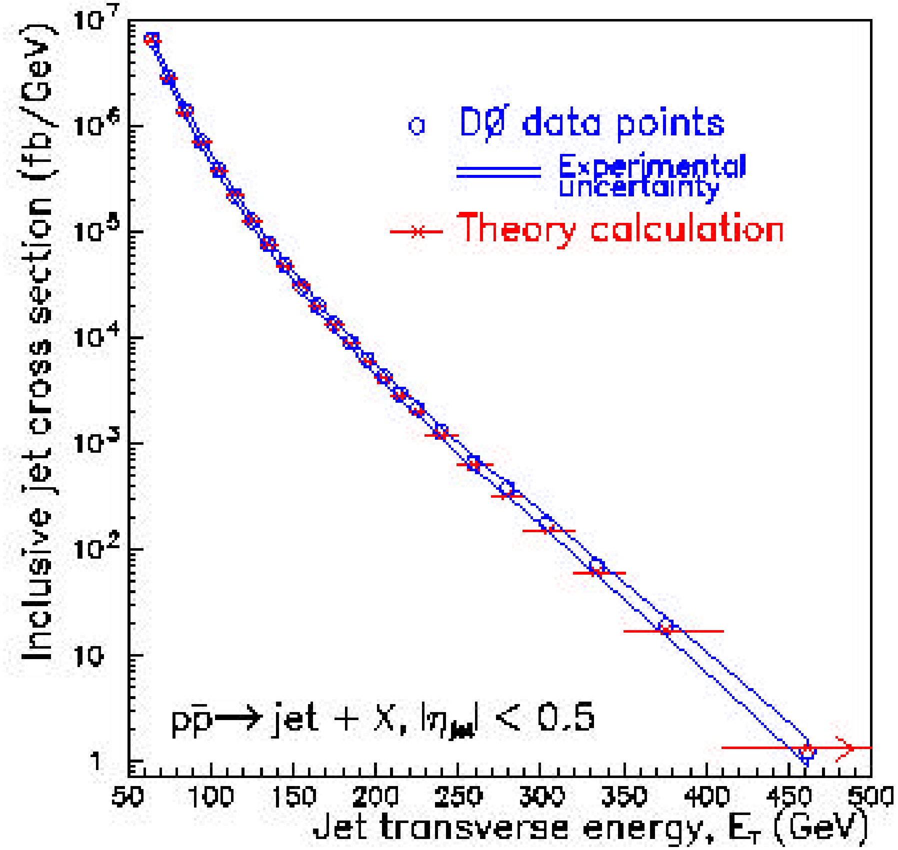


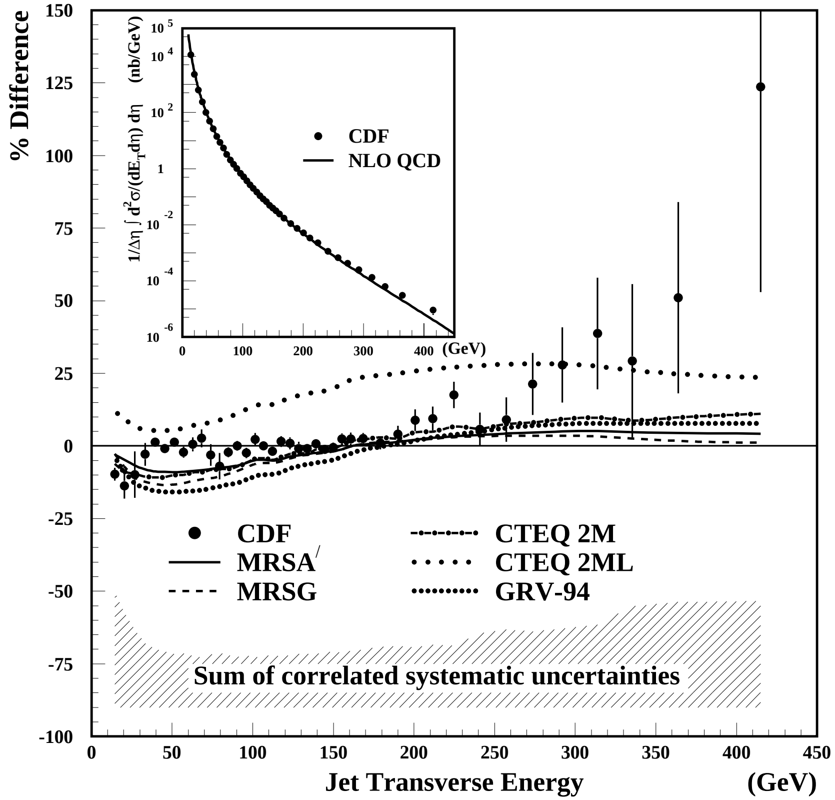
M_W (GeV/c^2)
80.6
80.5
80.4
80.3
80.2
80.1
100
250
500
1000
Higgs Mass (GeV/c^2)
140
150
160
170
180
190
200
M_{top} (GeV/c^2)

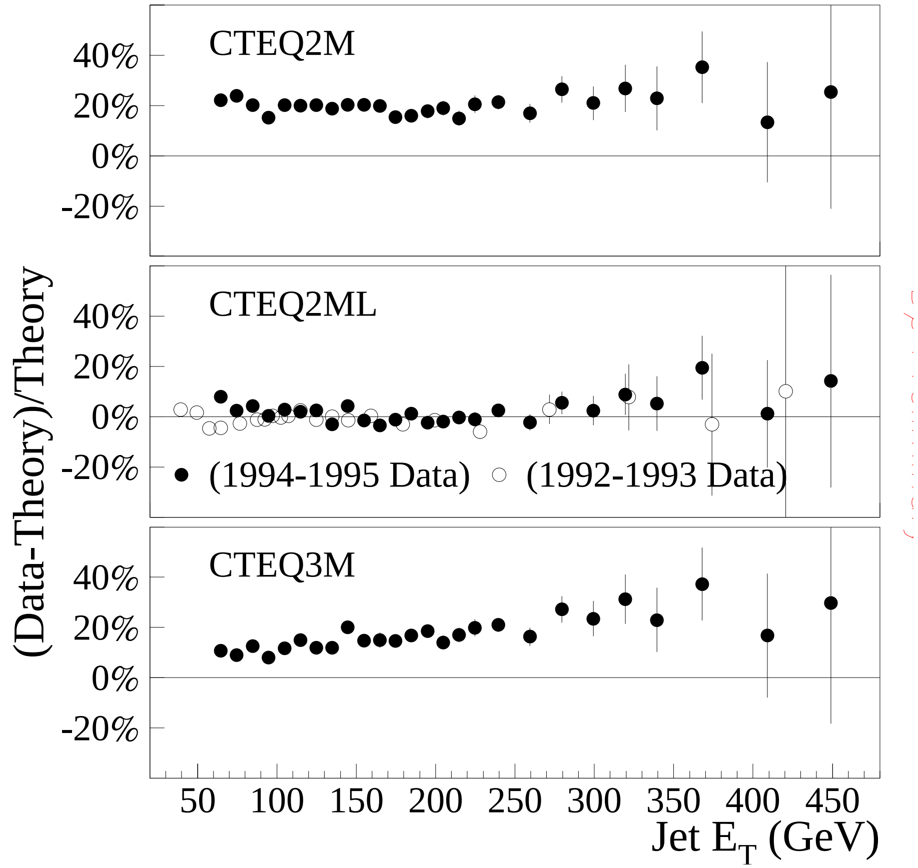
Is the SM OK?

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

...

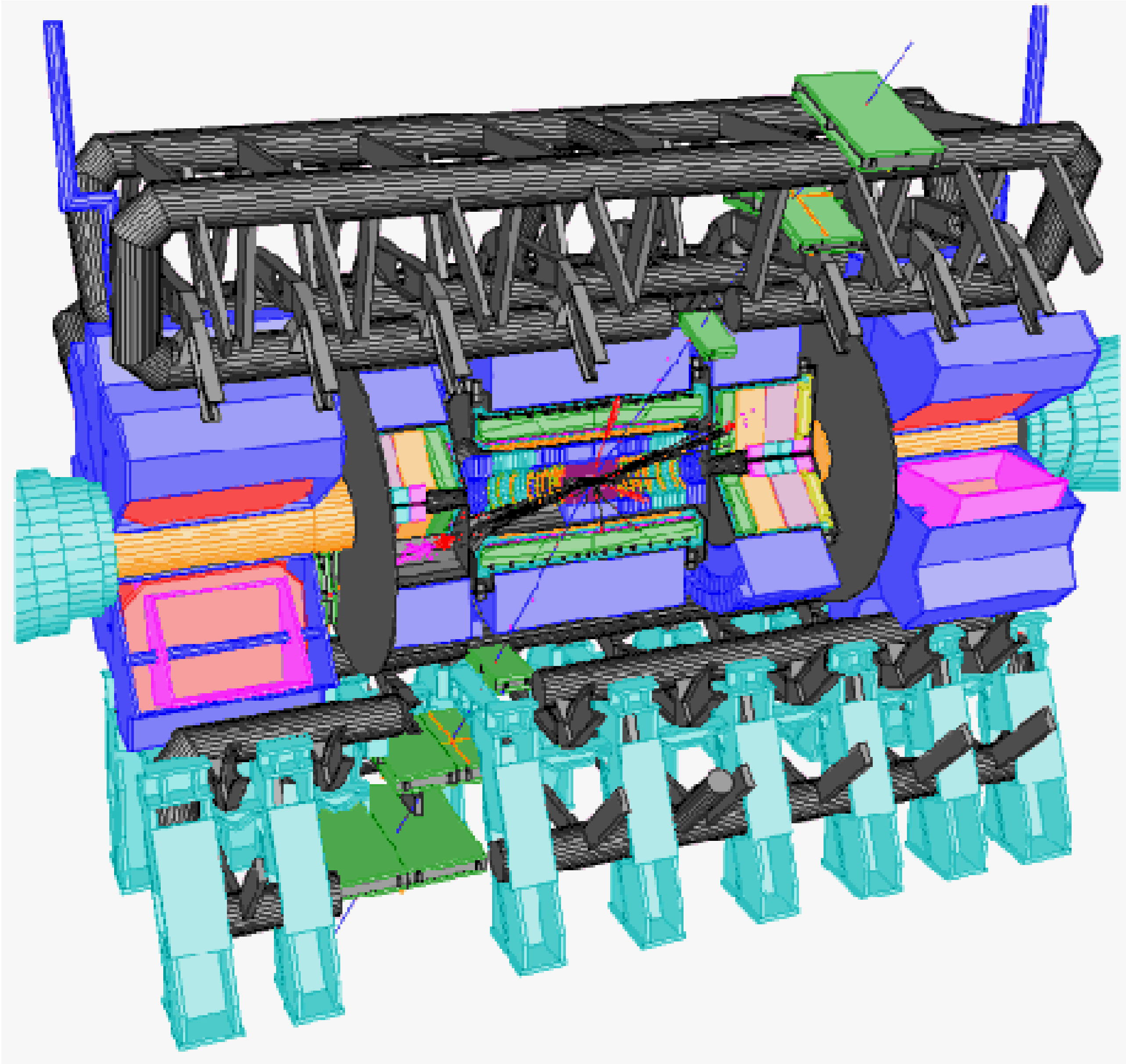
TeV-I, DØ and CDF

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

Will they get the necessary luminosity?

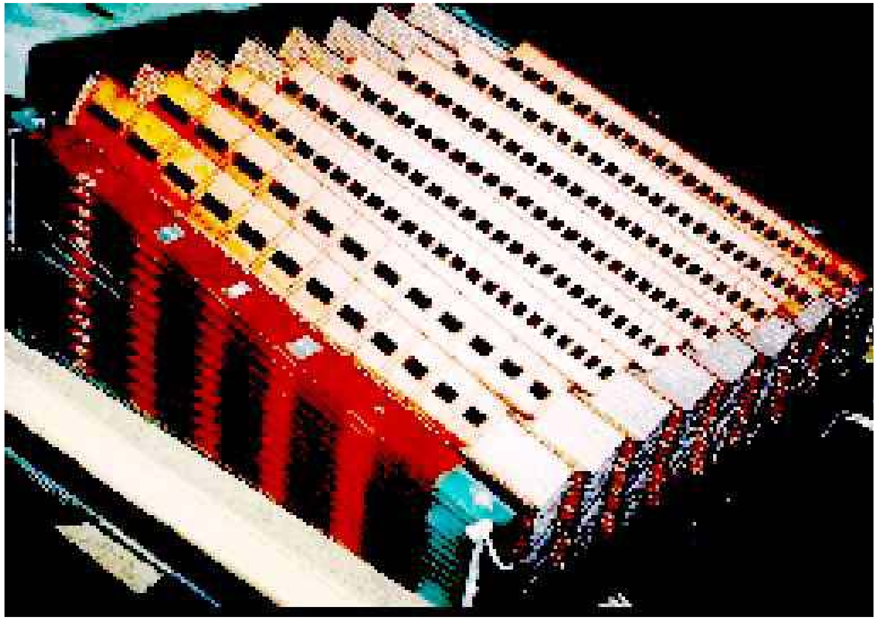
In 200n, $n <$?, LHC will begin. ATLAS and CMS will be equipped with bigger and better calorimeters. And more. . .

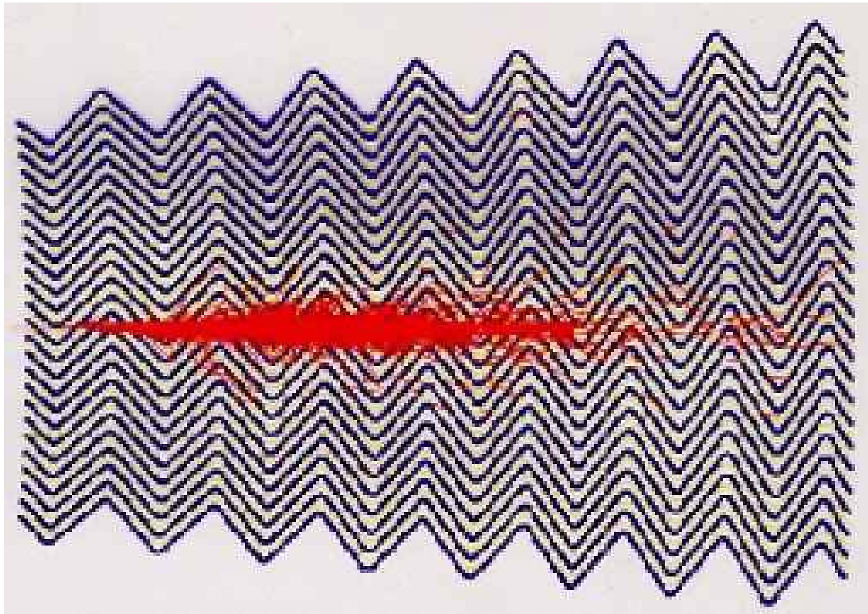
Atlas



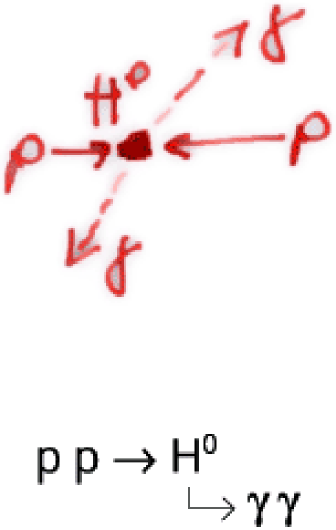
Atlas central em-cal

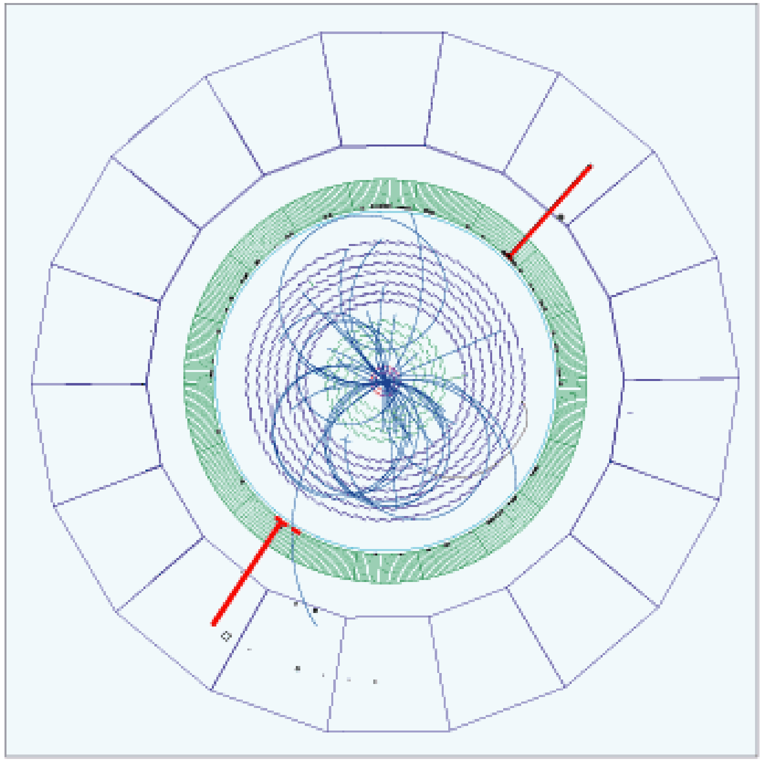
1.5 mm Pb, 4 mm Ar
$\delta E/E \simeq$1.1% at 100 GeV
$\delta E/E \simeq$0.4% at ∞





CMS



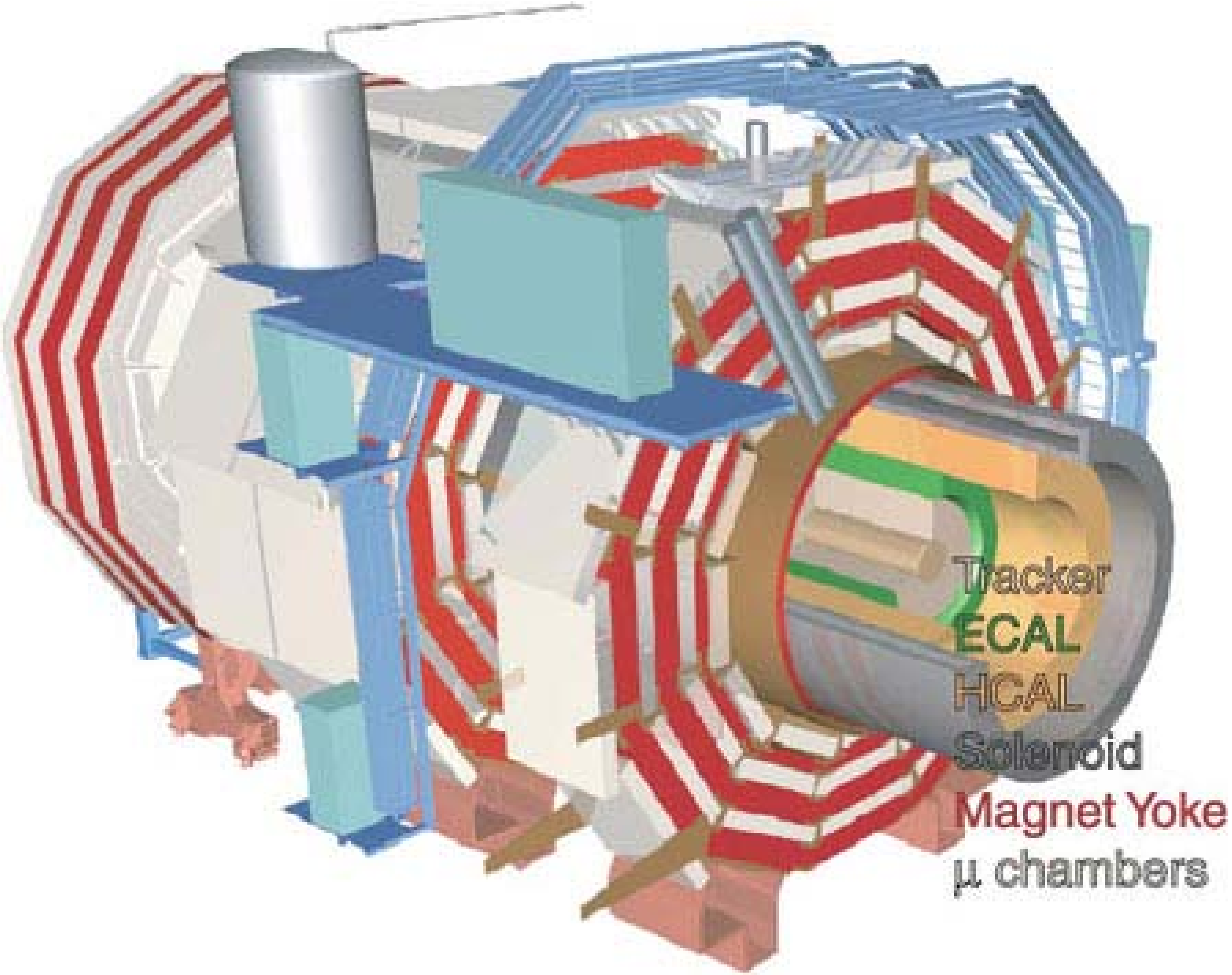


80,000 $PbWO_4$ crystals em-calorimeter,

$\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...