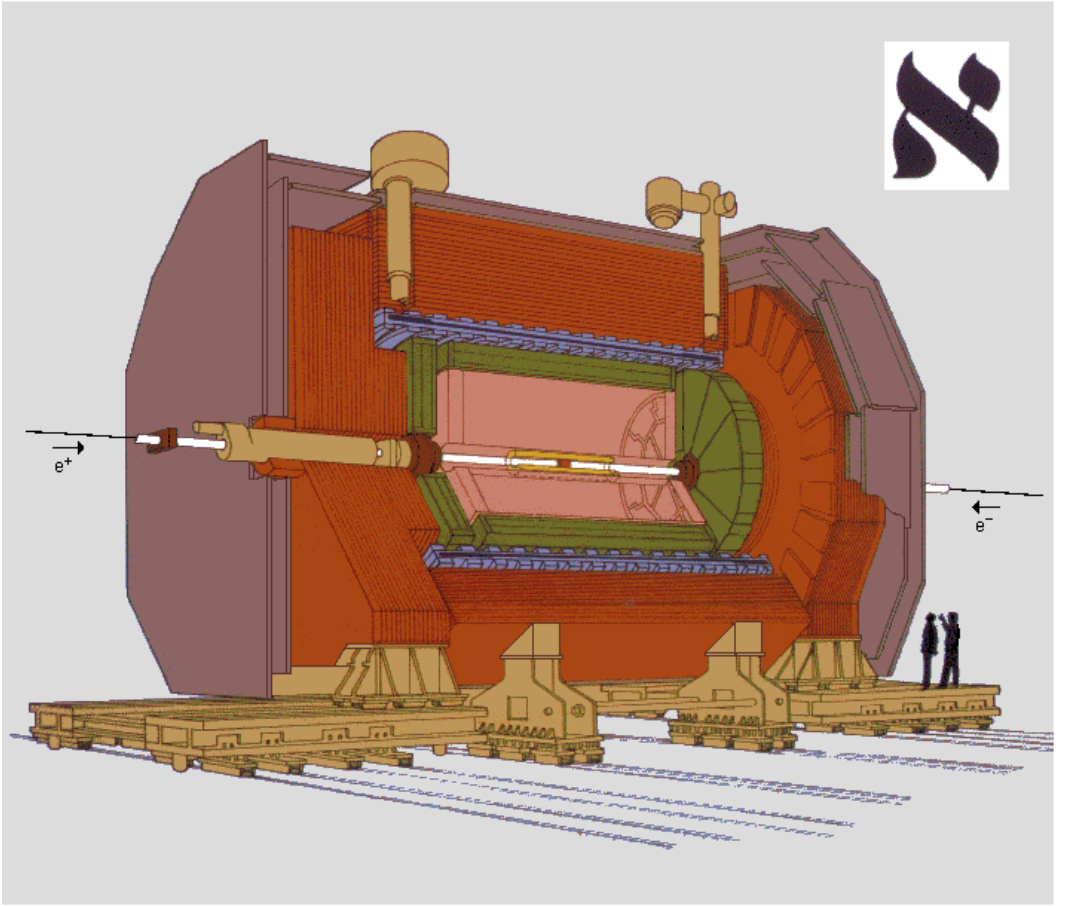
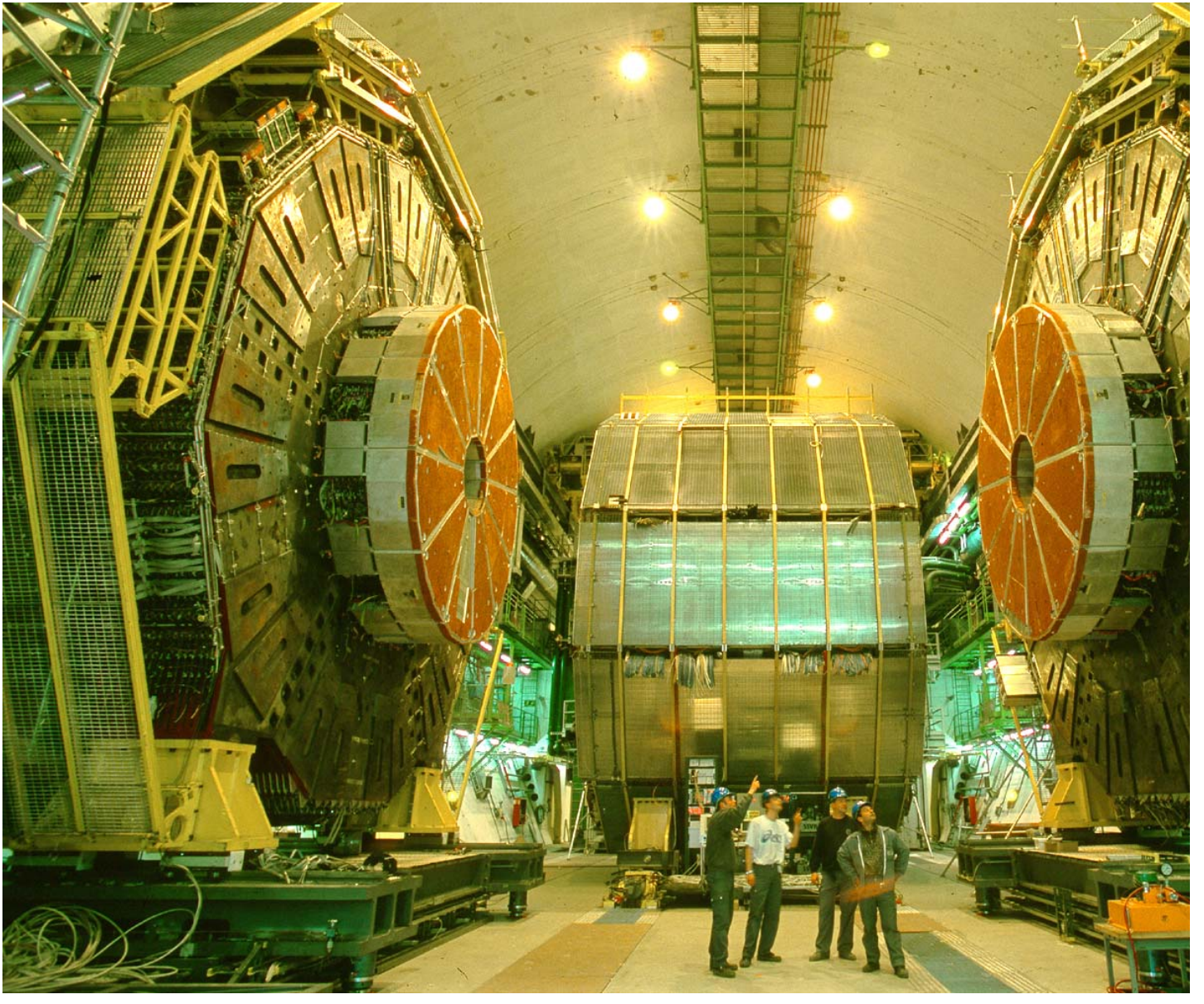
Accelerator	Location	Process	CM Energy	Dates	Some Expts.	Major results
SPEAR	SLAC	e^-e^+	3-6 GeV	72-90	Mark I, Crystal Ball	Charm, τ, jets
Petra	DESY	e^-e^+	14-46 GeV	78-86	JADE, Tasso, Argus ...	gluon jets, b mixing
PEP	SLAC	e^-e^+	29 GeV	80-90	Mark II, TPC, MAC, ASP	b-lifetime
Sp$\overline{p}$S	CERN	$p\overline{p}$	540 GeV	81-90	UA1, UA2, UA5	W/Z
Tristan	KEK	e^-e^+	50-64 GeV	87-95	Amy, Topaz, Venus	top has very high mass
SLC	SLAC	e^-e^+	91 GeV	90's	SLC	polarized Z prod. (A_{LR})
LEP	CERN	e^-e^+	91 GeV	89-96	Aleph, Opal, L3, Delphi	high statistics EW
Hera	DESY	ep	30GeV on 900 GeV	92-now	H1, Zeus, Hermes, HeraB	Proton structure, diffraction
Tevatron I	Fermilab	$p\overline{p}$	900 GeV	87-96	CDF, D0	top and W mass
LEP II	CERN	e^-e^+	91-210 GeV	96-00	Aleph, Opal, L3, Delphi	WW production, W mass
Tevatron II	Fermilab	$p\overline{p}$	980 GeV	01 - 09?	CDF, D0	Higgs? Supersymmetry?
LHC	CERN	pp	14 TeV	late 00's	Atlas, CMS, LHCb	Higgs? Supersymmetry?
ILC	??	e^-e^+	500 GeV	late 10's	??	Higgs ? Supersymmetry?

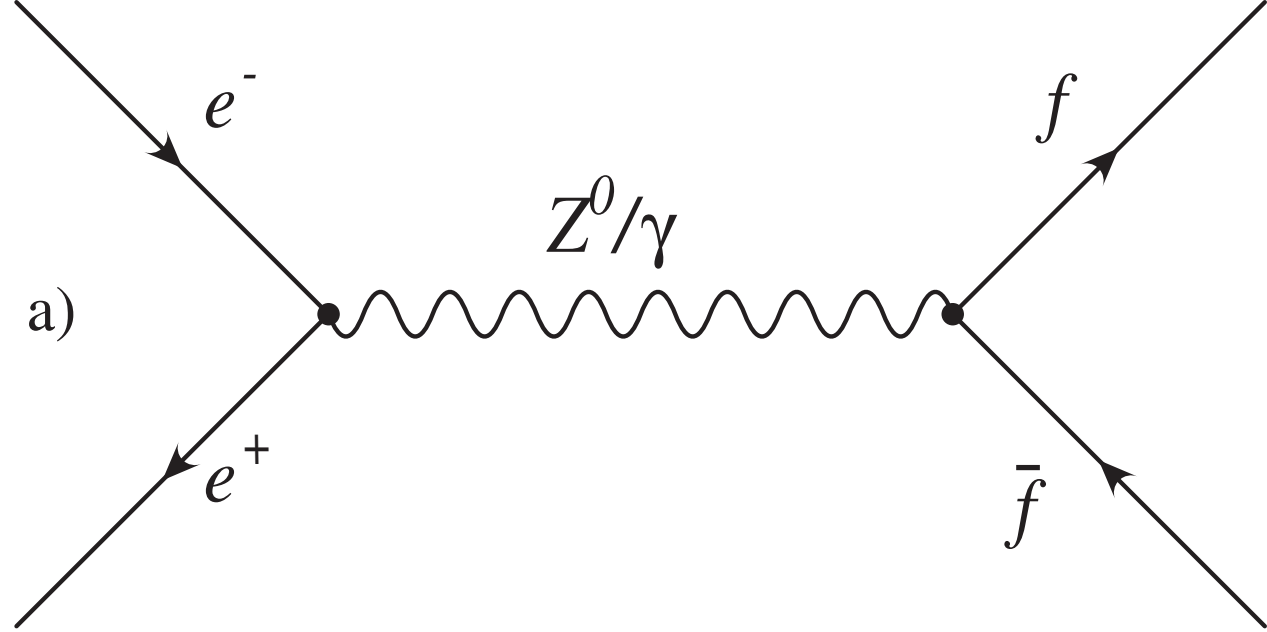
Table 1: Collider experiments at the energy frontier (DORIS, CESR, BES, Belle, Pep II not included

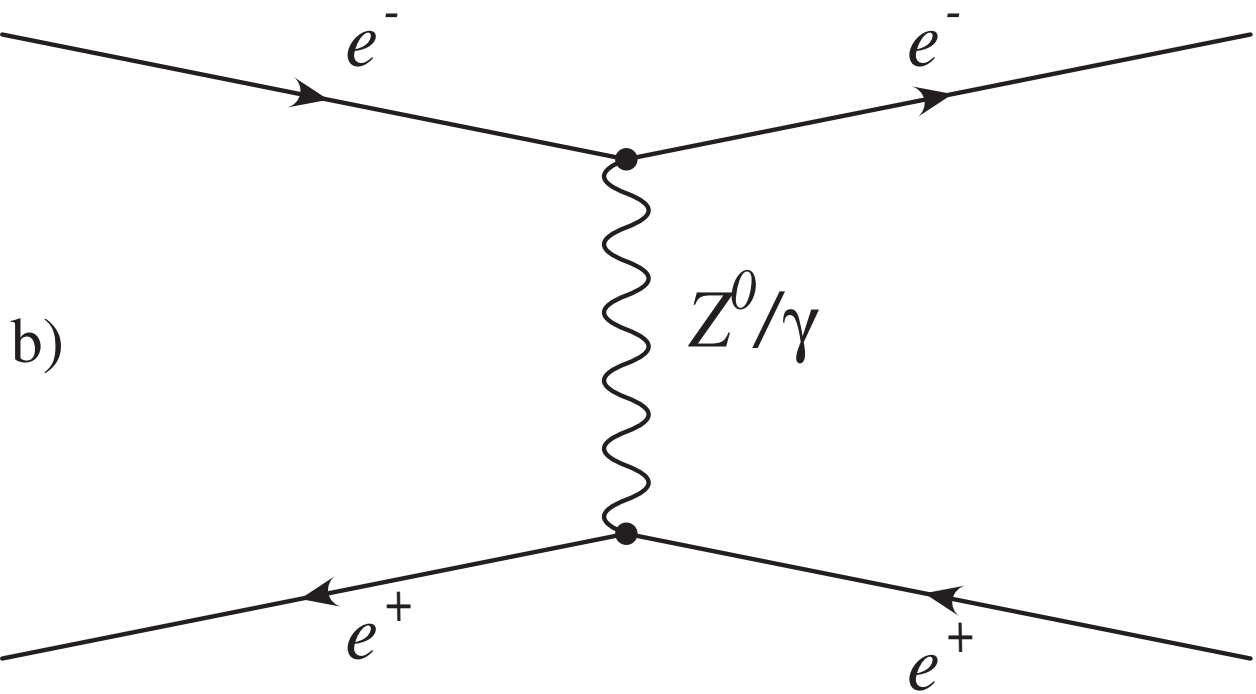


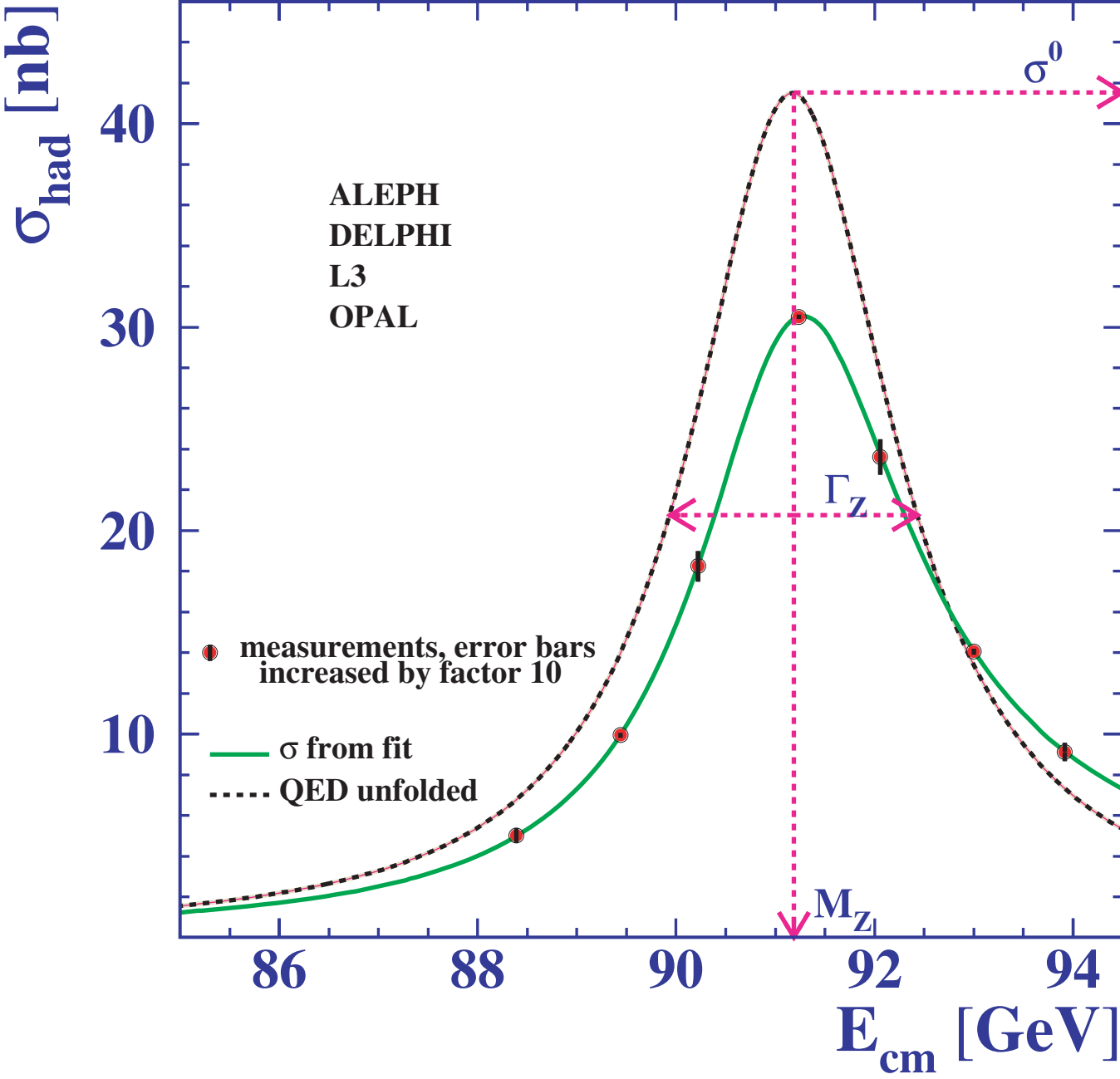
- Vertex Detector
- Inner Tracking Chamber
- Time Projection Chamber
- Electromagnetic Calorimeter
- Superconducting Magnet Coil
- Hadron Calorimeter
- Muon Chambers
- Luminosity Monitors

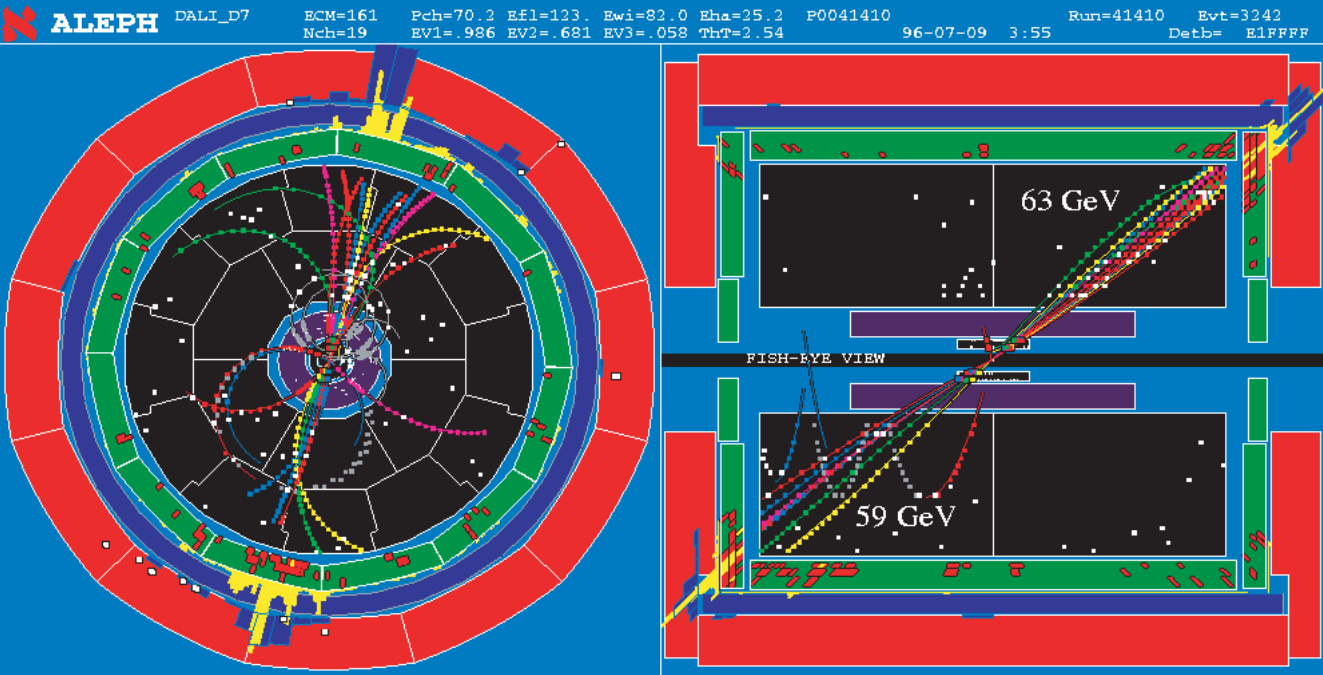
The ALEPH Detector

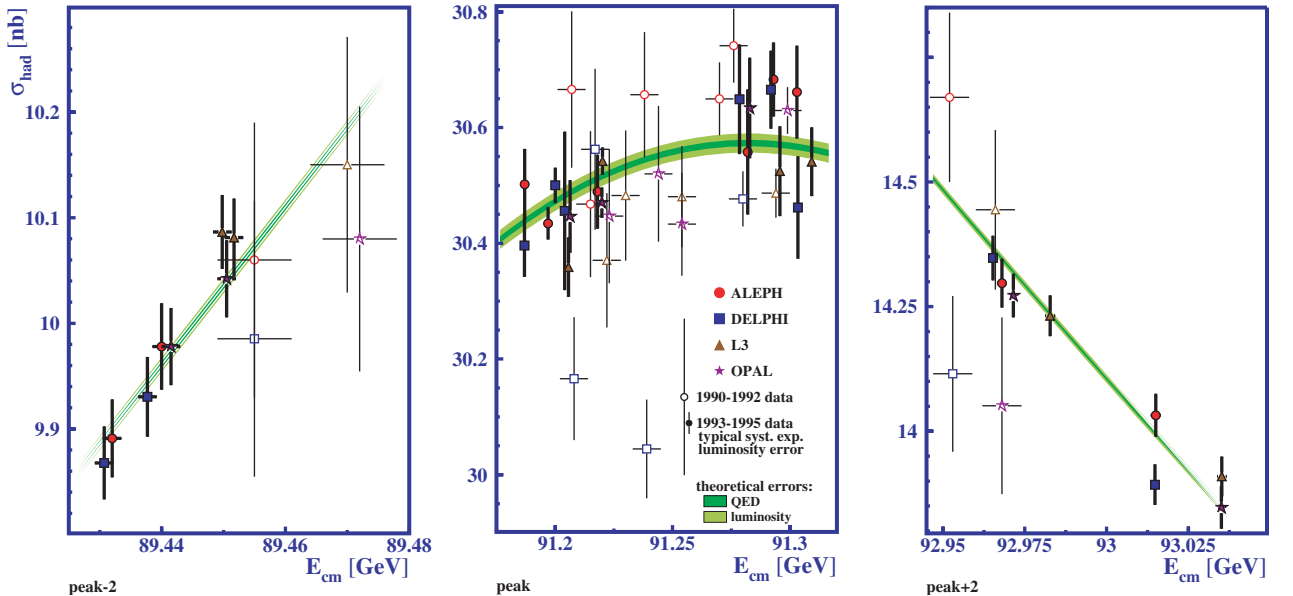


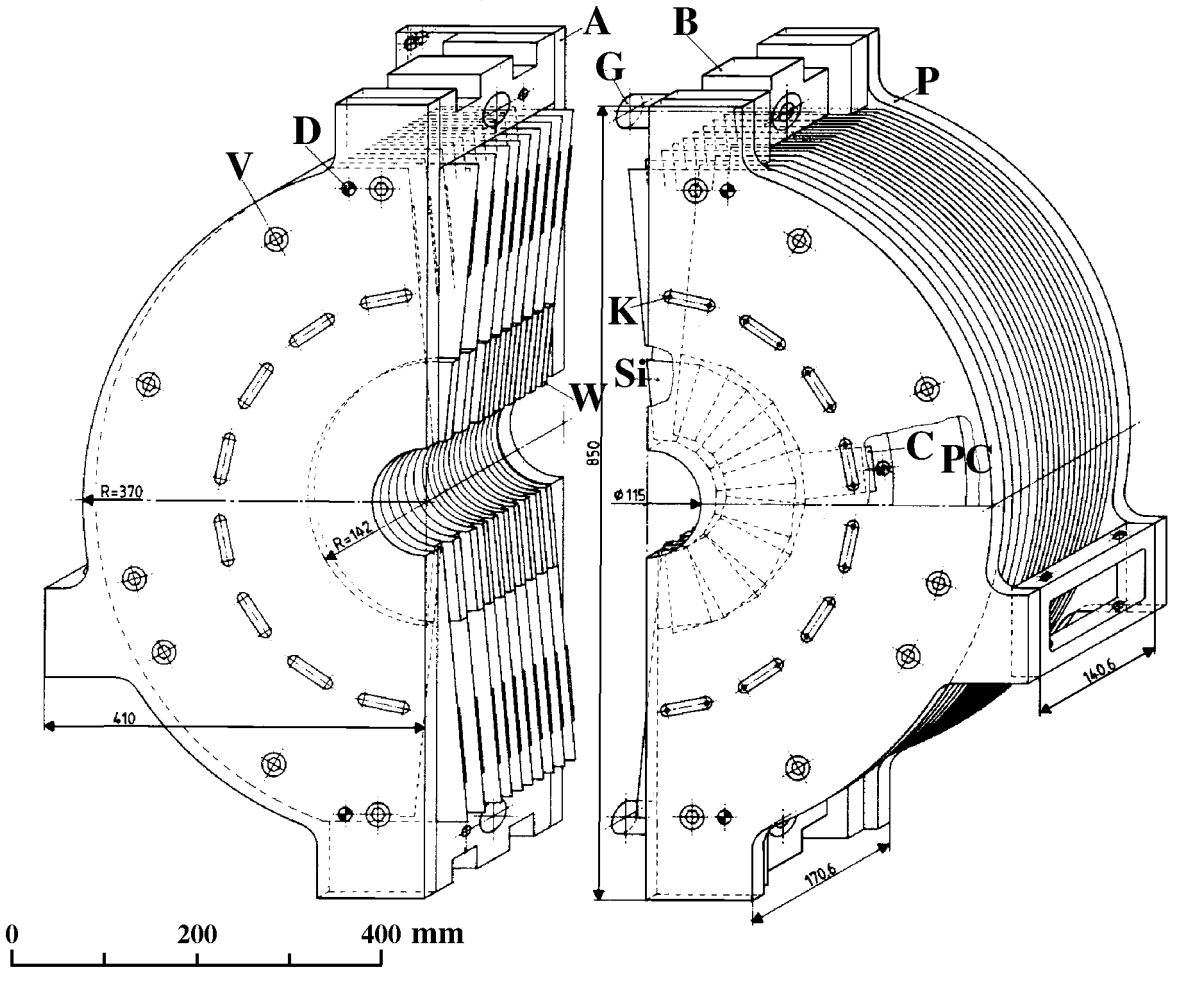

a)
e^-
e^+
Z^0/γ
f
$\bar{f}$

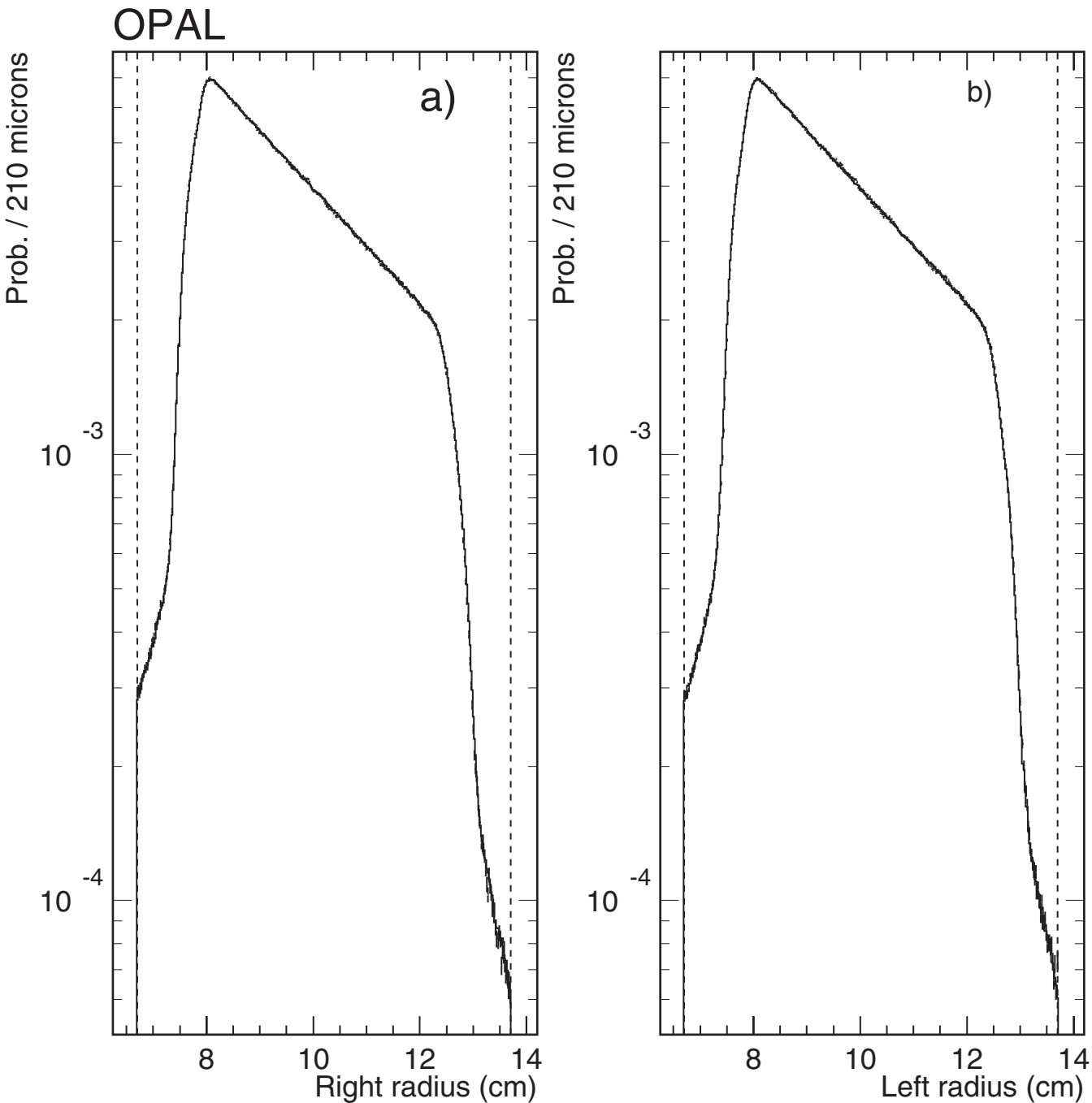

b)
e^-
e^-
Z^0/γ
e^+
e^+

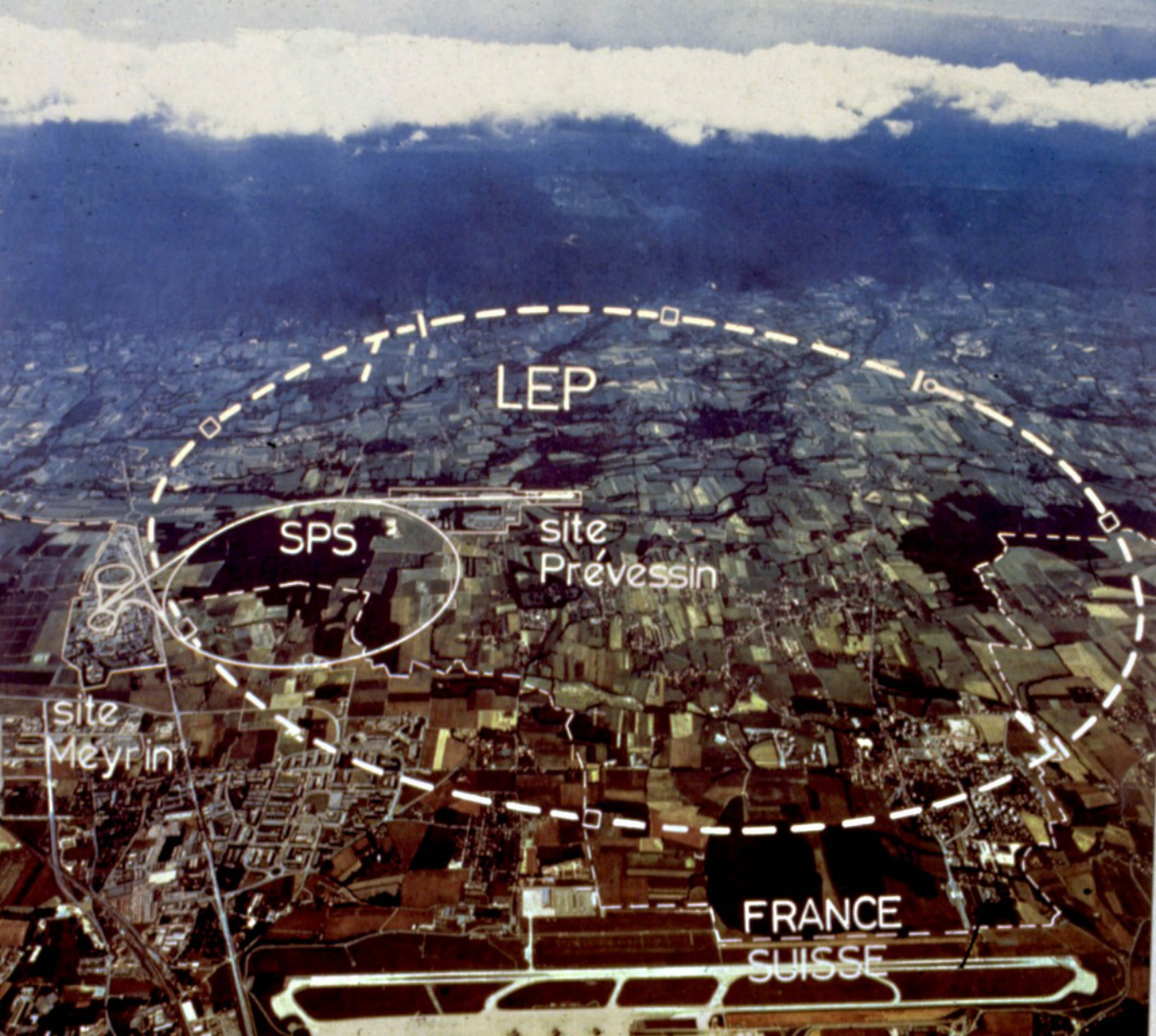

σ_{had} [nb]
40
30
20
10
86
88
90
92
94
E_{cm} [GeV]
ALEPH
DELPHI
L3
OPAL
σ^0
Γ_Z
M_Z
measurements, error bars increased by factor 10
σ from fit
QED unfolded

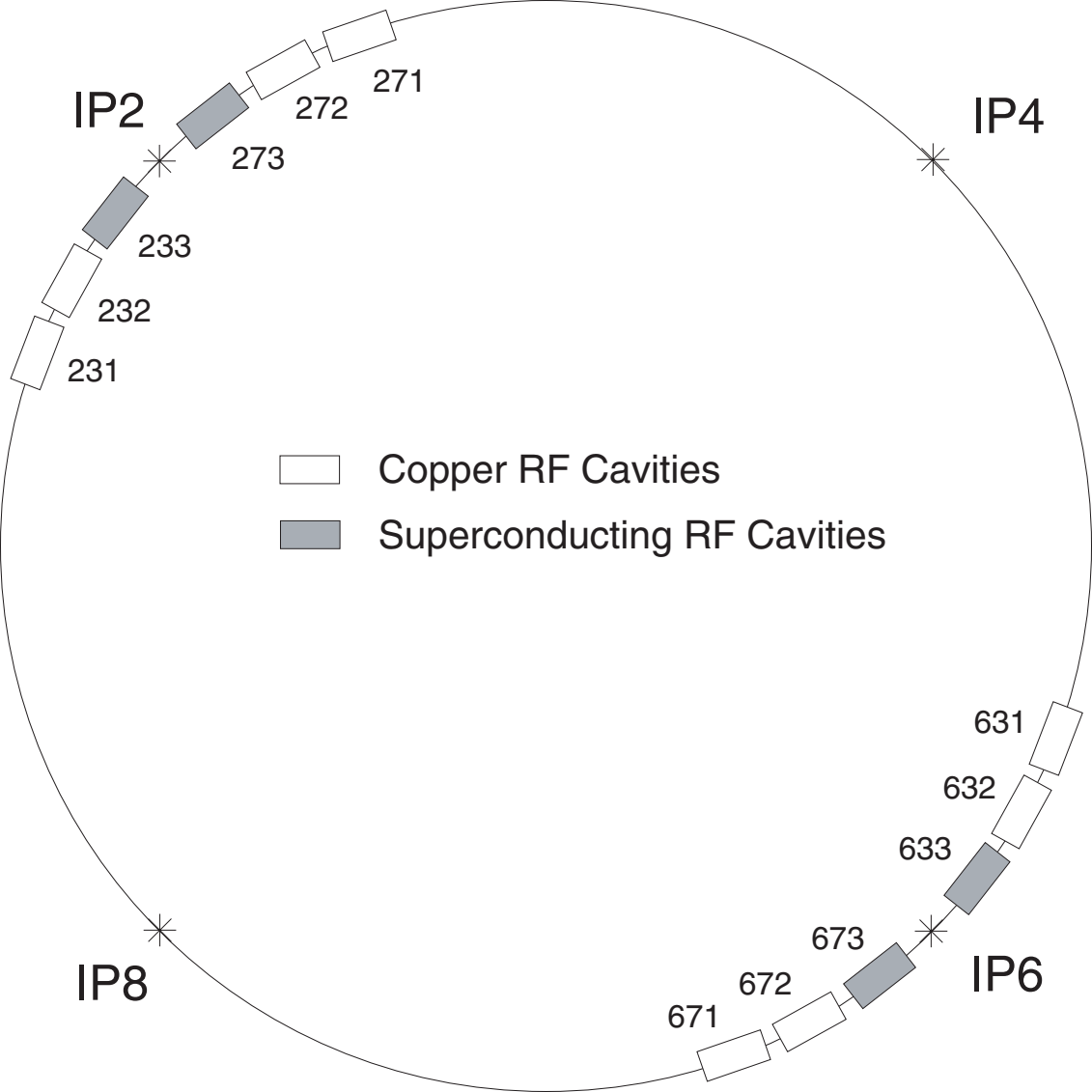

ALEPH
DALI_D7
ECM=161 Pch=70.2 Ef1=123. Ewi=82.0 Eha=25.2 P0041410
Nch=19 EV1=.986 EV2=.681 EV3=.058 ThT=2.54
96-07-09 3:55
Run=41410 Evt=3242
Detb= ElFFFF
63 GeV
FISH-EYE VIEW
59 GeV

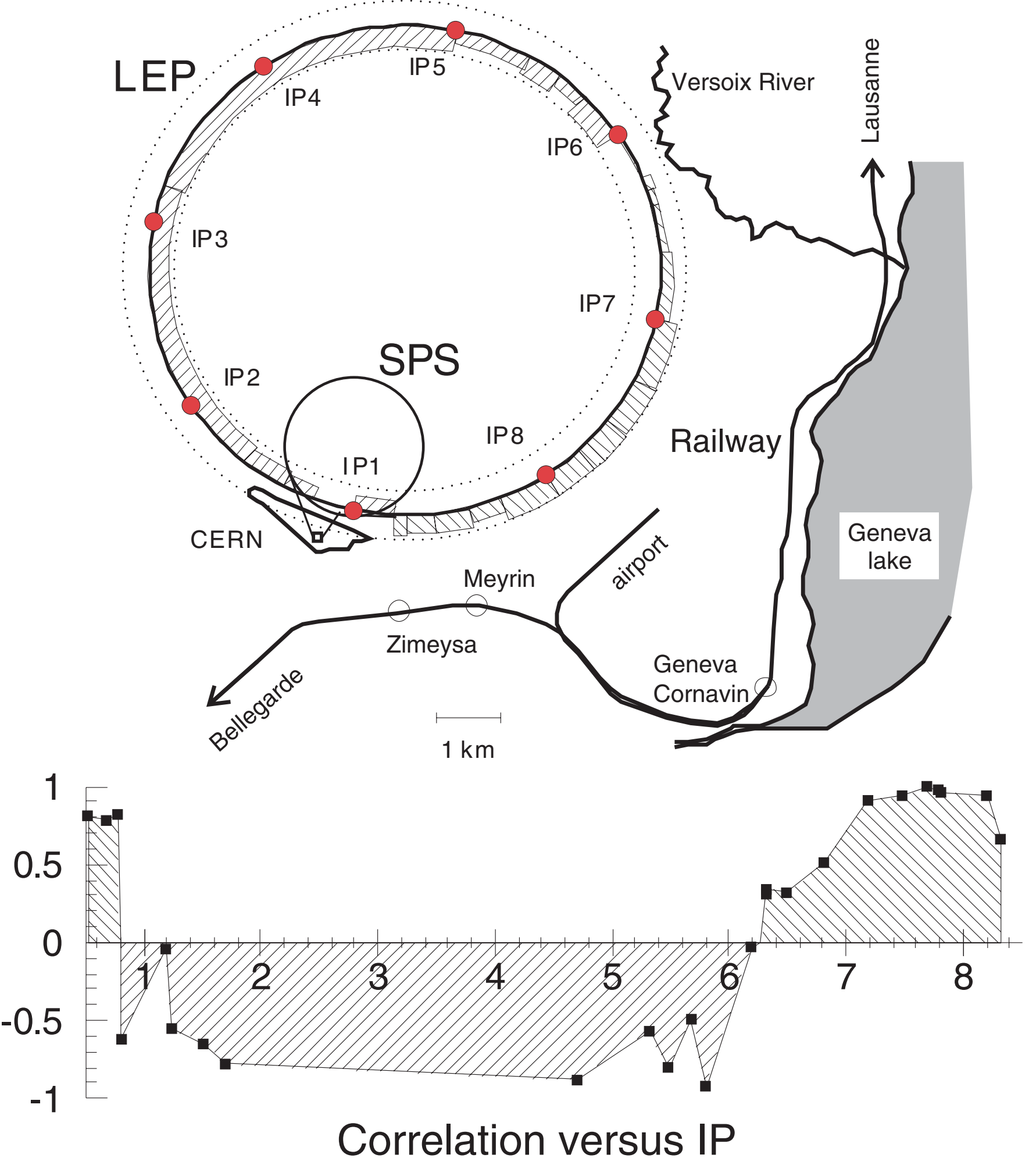

σ_{had} [nb]
10.2
10.1
10
9.9
89.44
89.46
89.48
E_{cm} [GeV]
peak-2
30.8
30.6
30.4
30.2
30
91.2
91.25
91.3
E_{cm} [GeV]
peak
ALEPH
DELPHI
L3
OPAL
1990-1992 data
1993-1995 data
typical syst. exp.
luminosity error
theoretical errors:
QED
luminosity
14.5
14.25
14
92.95
92.975
93
93.025
E_{cm} [GeV]
peak+2

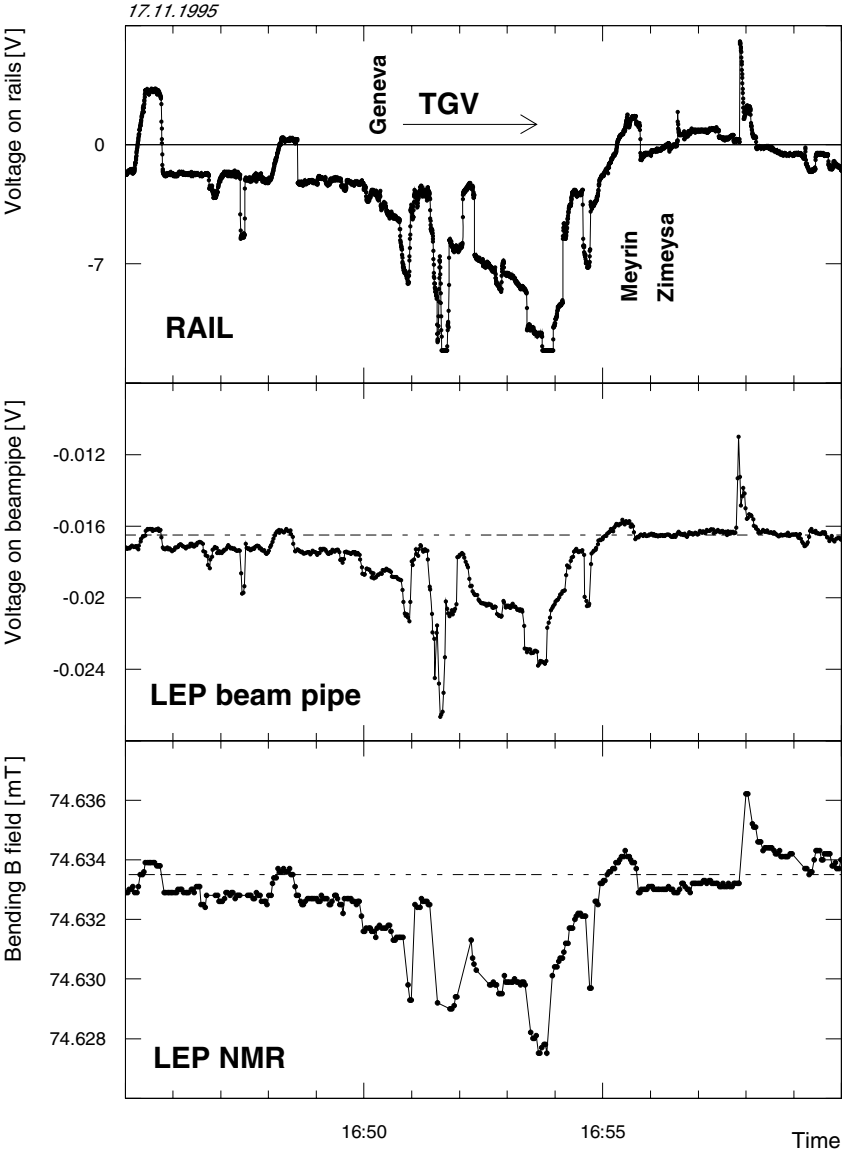

A
B
G
P
D
V
K
Si
W
C
PC
R=370
R=142
850
ϕ115
410
140.6
170.6
0
200
400 mm

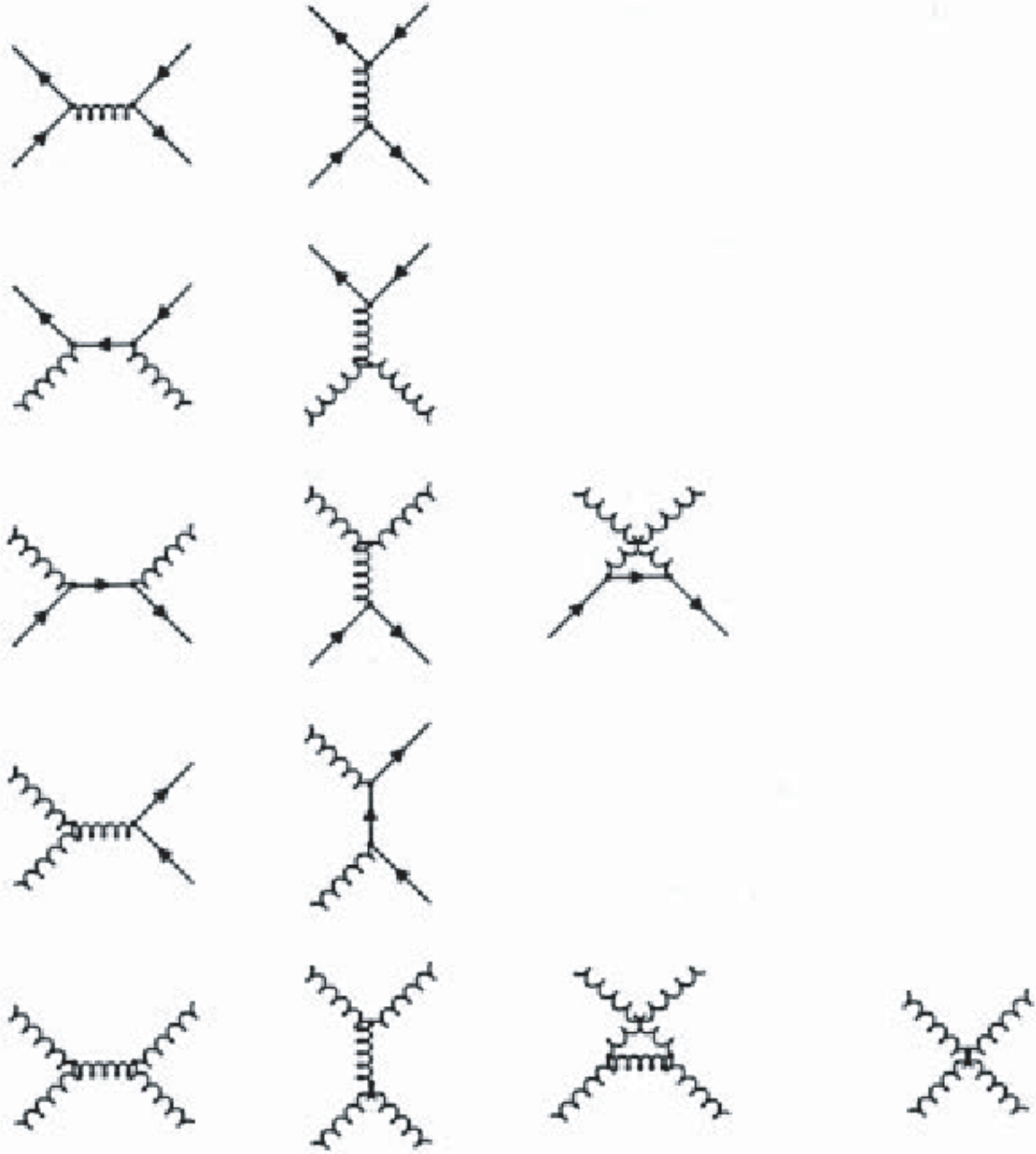

OPAL
a)
b)
Prob. / 210 microns
Prob. / 210 microns
10^{-3}
10^{-4}
10^{-3}
10^{-4}
8
10
12
14
8
10
12
14
Right radius (cm)
Left radius (cm)

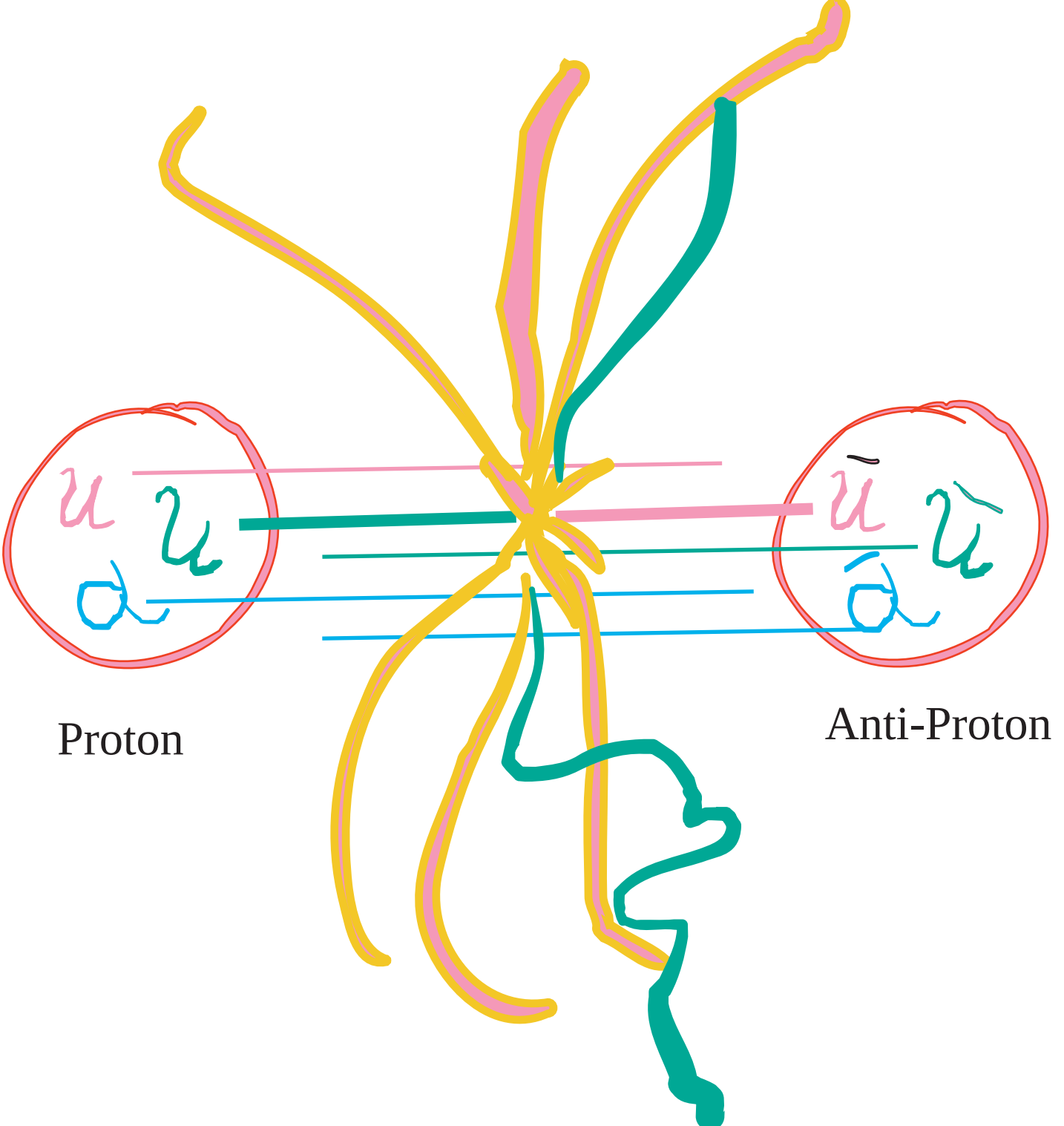

LEP
SPS
site
Prévessin
site
Meyrin
FRANCE
SUISSE

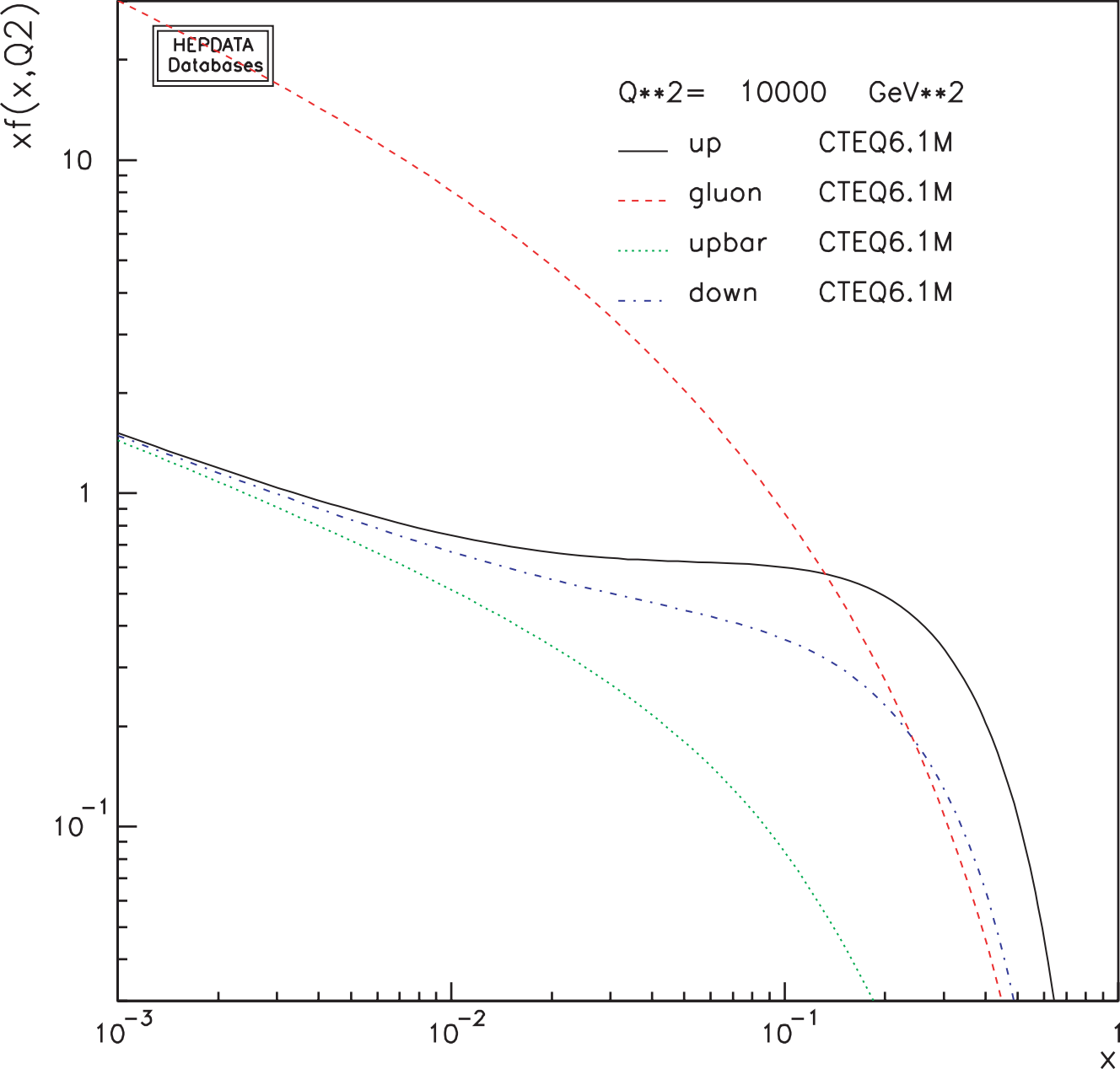

IP2
IP4
IP6
IP8
271
272
273
233
232
231
631
632
633
673
672
671
Copper RF Cavities
Superconducting RF Cavities

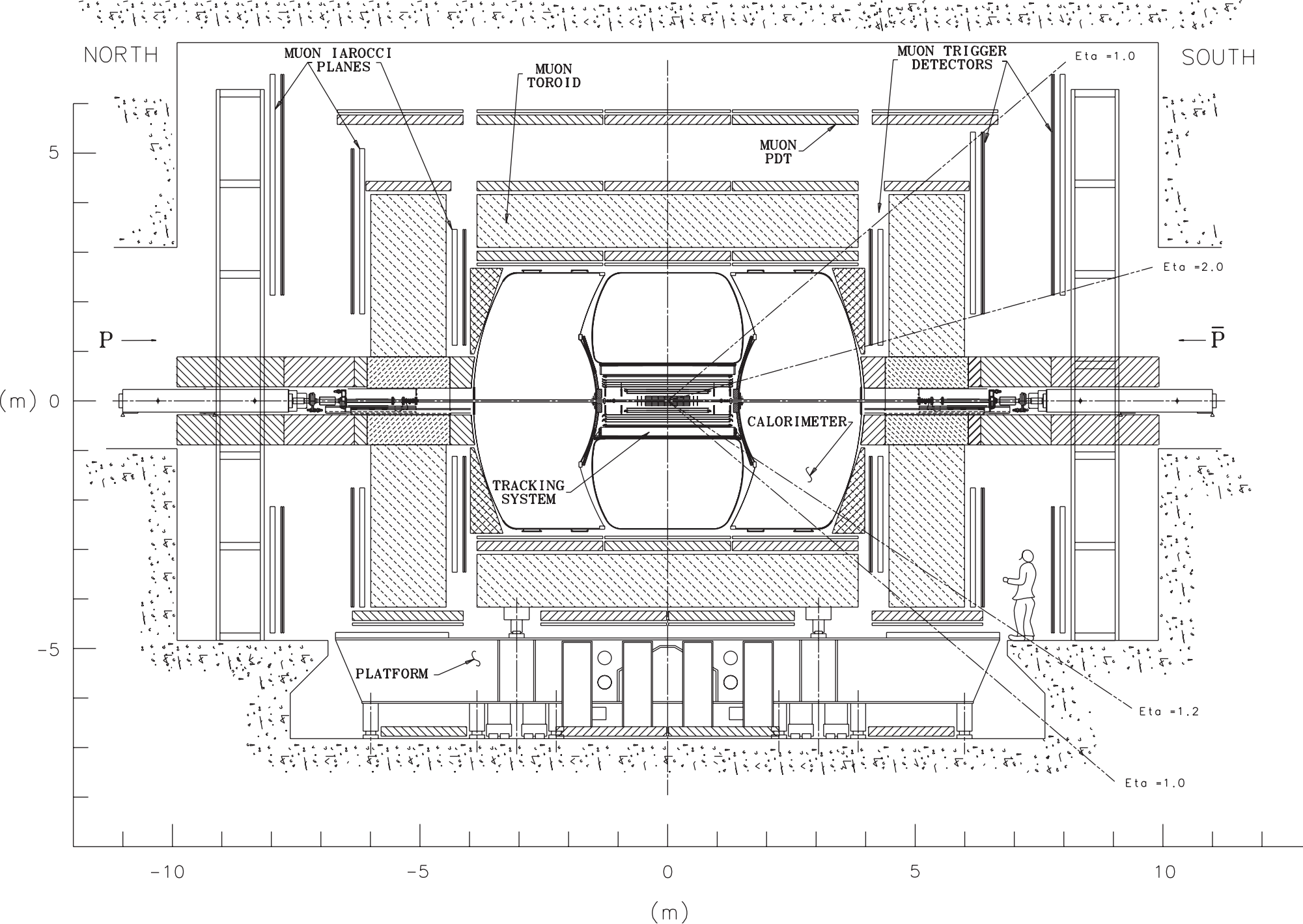

LEP
IP1
IP2
IP3
IP4
IP5
IP6
IP7
IP8
SPS
CERN
Versoix River
Lausanne
Railway
Geneva
lake
airport
Meyrin
Zimeysa
Geneva
Cornavin
Bellegarde
1 km
1
0.5
0
-0.5
-1
1
2
3
4
5
6
7
8
Correlation versus IP

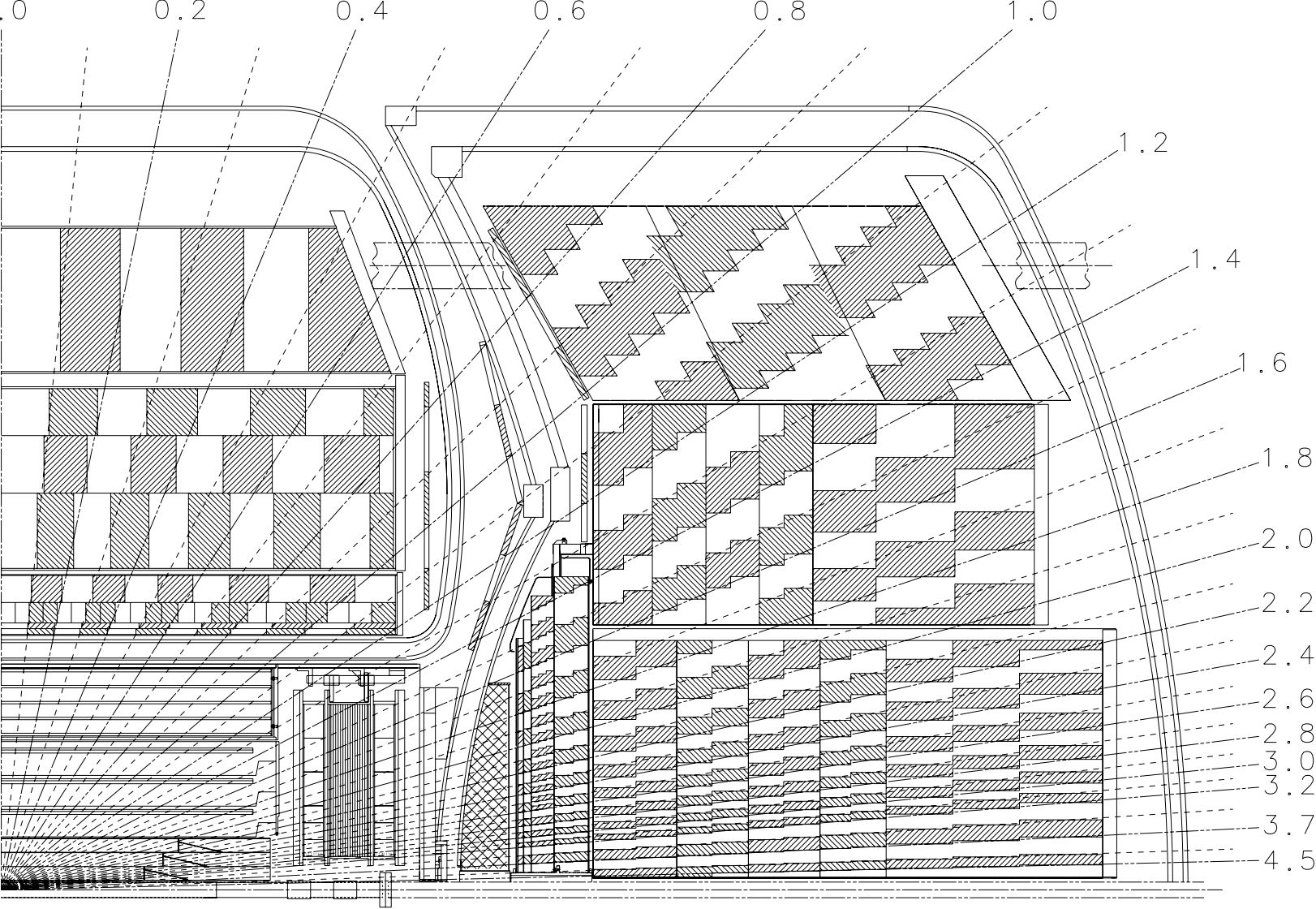

17.11.1995
Voltage on rails [V]
0
-7
Geneva
TGV
Meyrin
Zimeysa
RAIL
Voltage on beampipe [V]
-0.012
-0.016
-0.02
-0.024
LEP beam pipe
Bending B field [mT]
74.636
74.634
74.632
74.630
74.628
LEP NMR
16:50
16:55
Time

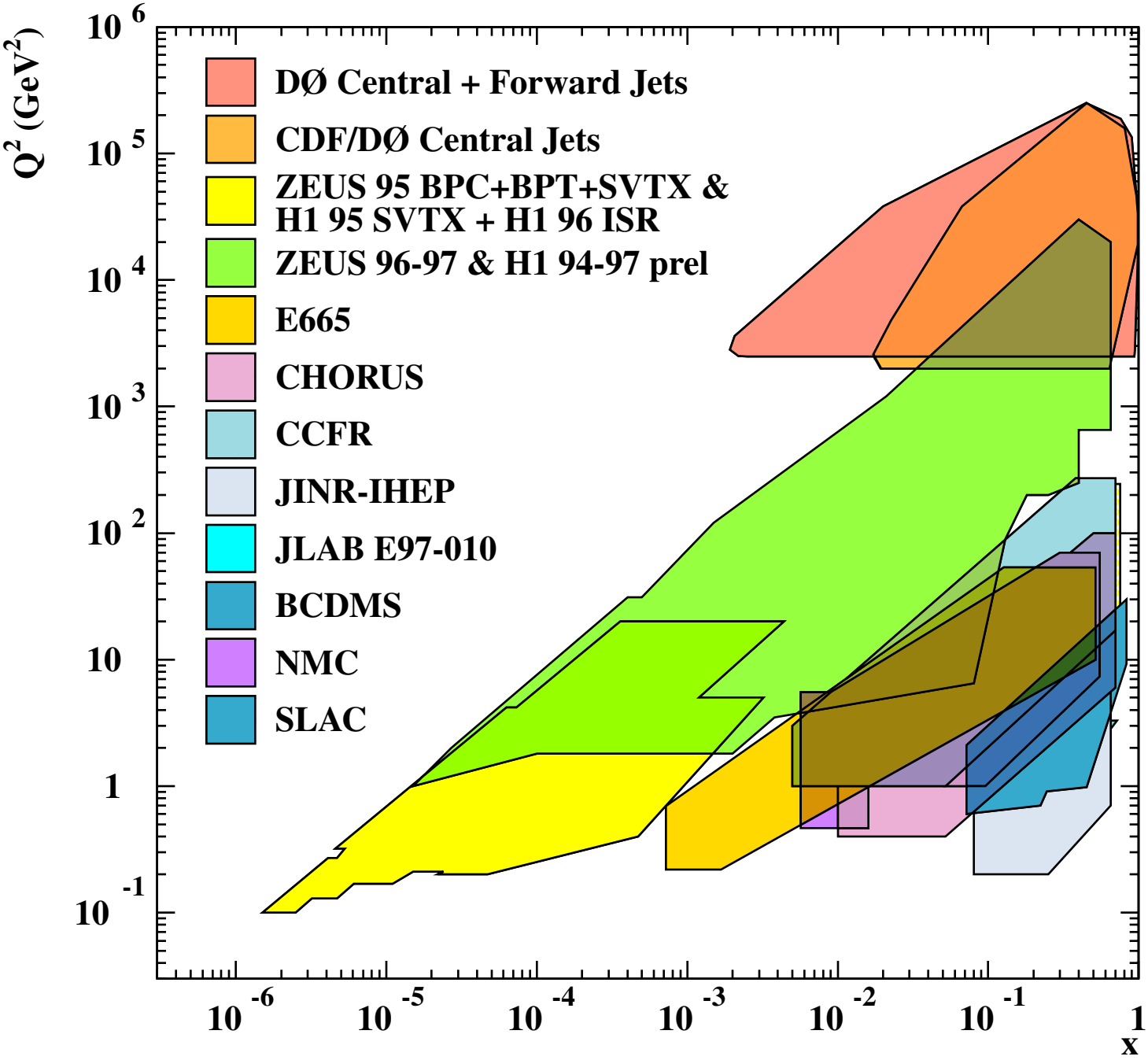


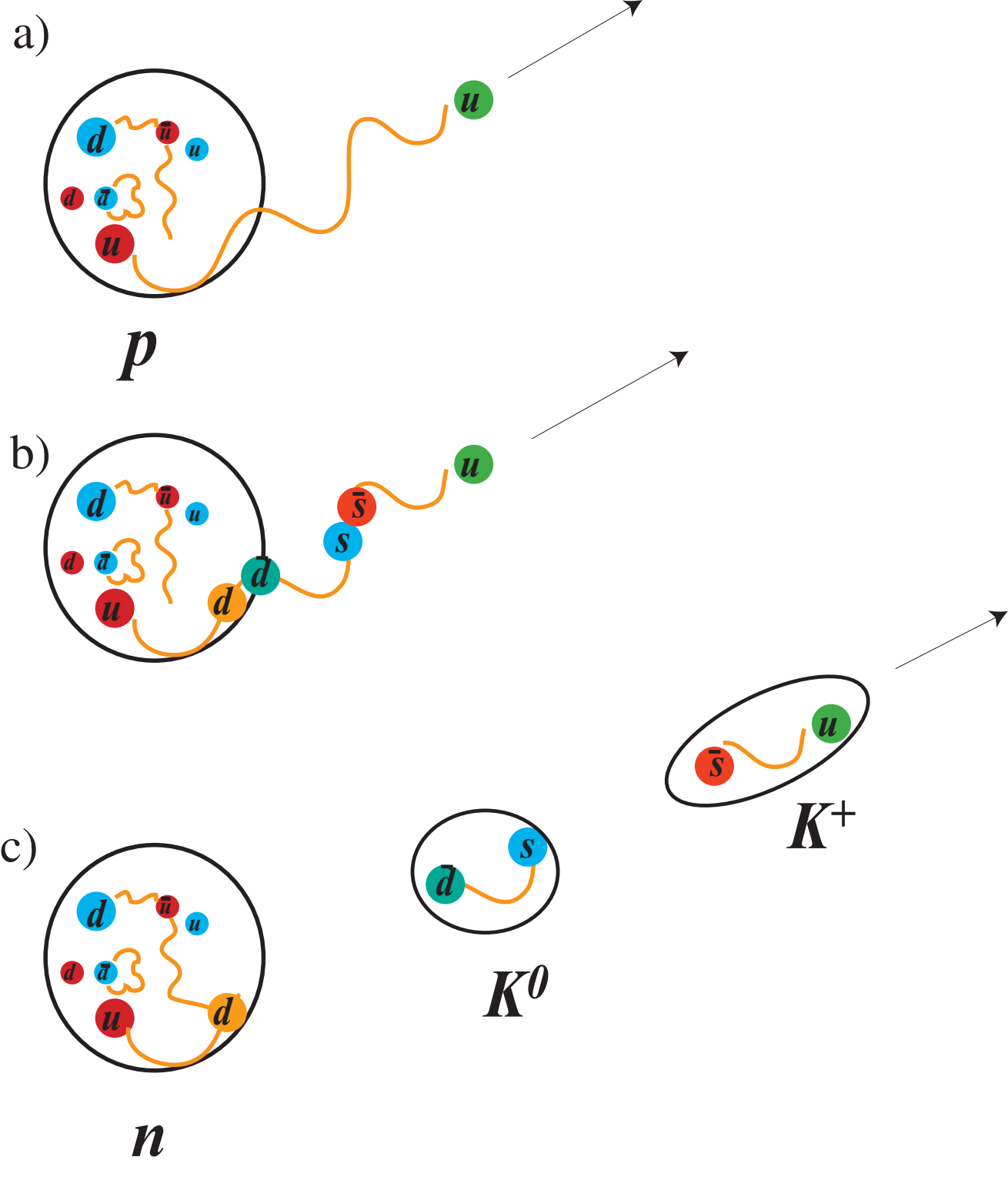

u
u
d
ū
ū
d̄
Proton
Anti-Proton


HEPDATA
Databases
Q**2= 10000 GeV**2
up CTEQ6.1M
gluon CTEQ6.1M
upbar CTEQ6.1M
down CTEQ6.1M
xf(x,Q2)
10
1
10^-1
10^-3
10^-2
10^-1
1
x


NORTH
SOUTH
MUON IAROCCI PLANES
MUON TOROID
MUON TRIGGER DETECTORS
Eta =1.0
MUON PDT
Eta =2.0
P
$\bar{P}$
CALORIMETER
TRACKING SYSTEM
PLATFORM
Eta =1.2
Eta =1.0
5
(m) 0
-5
-10
-5
0
5
10
(m)

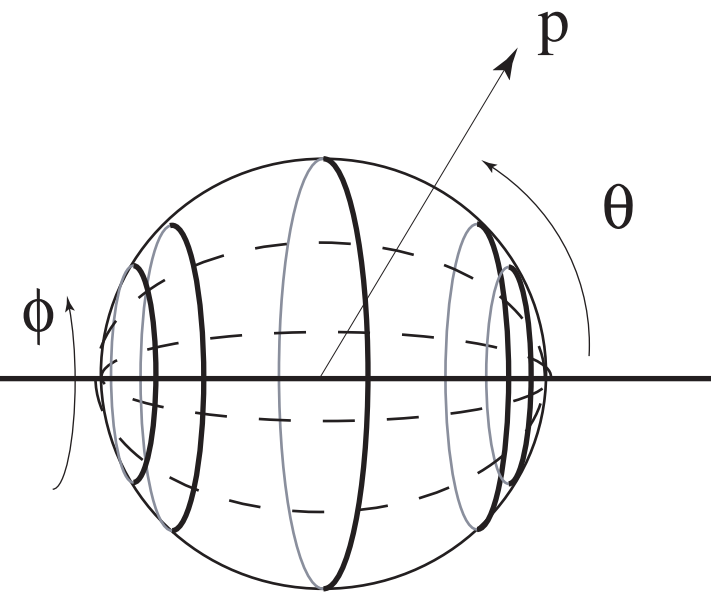

.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.7
4.5

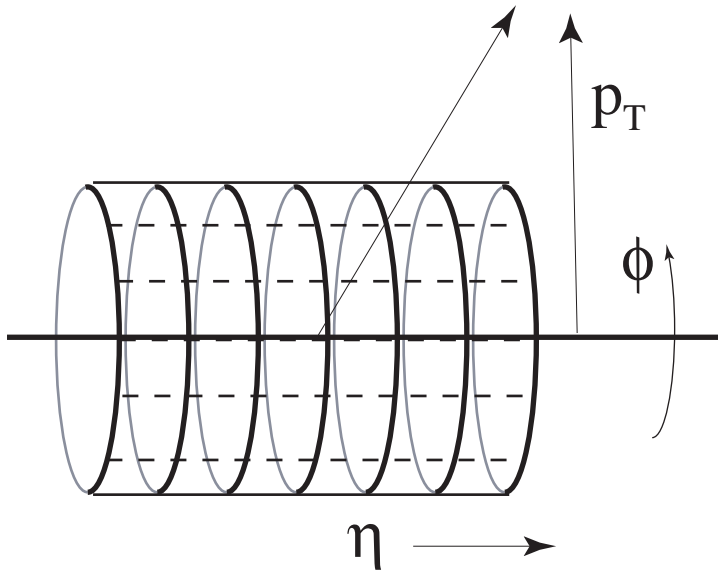

DØ Central + Forward Jets
CDF/DØ Central Jets
ZEUS 95 BPC+BPT+SVTX &
H1 95 SVTX + H1 96 ISR
ZEUS 96-97 & H1 94-97 prel
E665
CHORUS
CCFR
JINR-IHEP
JLAB E97-010
BCDMS
NMC
SLAC
Q^2 (GeV^2)
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x


a)
d
ū
u
d
d̄
u
u
p
b)
d
ū
u
d
d̄
u
d̄
d
s̄
s
u
s̄
u
K+
c)
d
ū
u
d
d̄
u
d
n
s
d̄
K0

Spherical Coordinates

Collider Coordinates

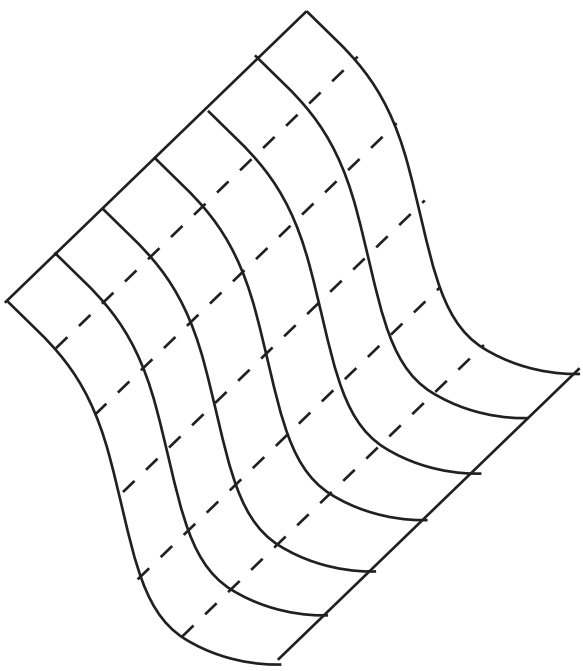


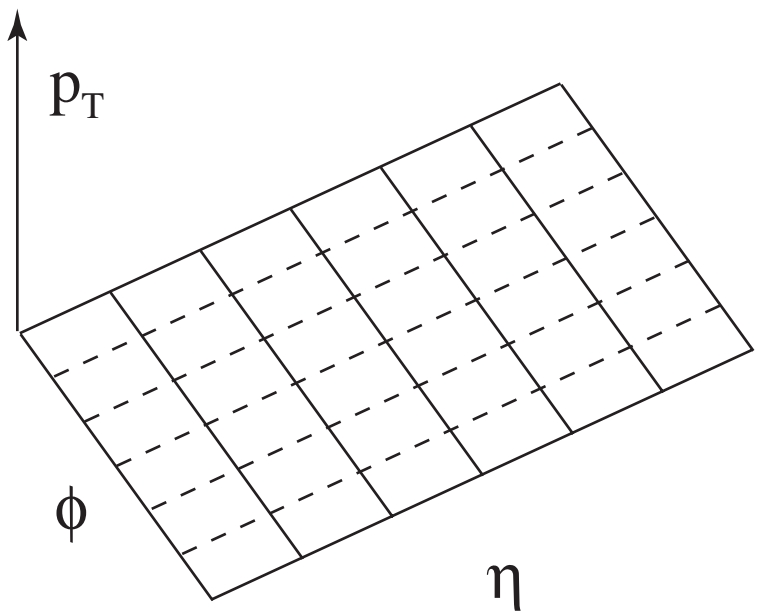


$p\ \theta\ \phi$

$\eta = \ln \tan \theta/2$

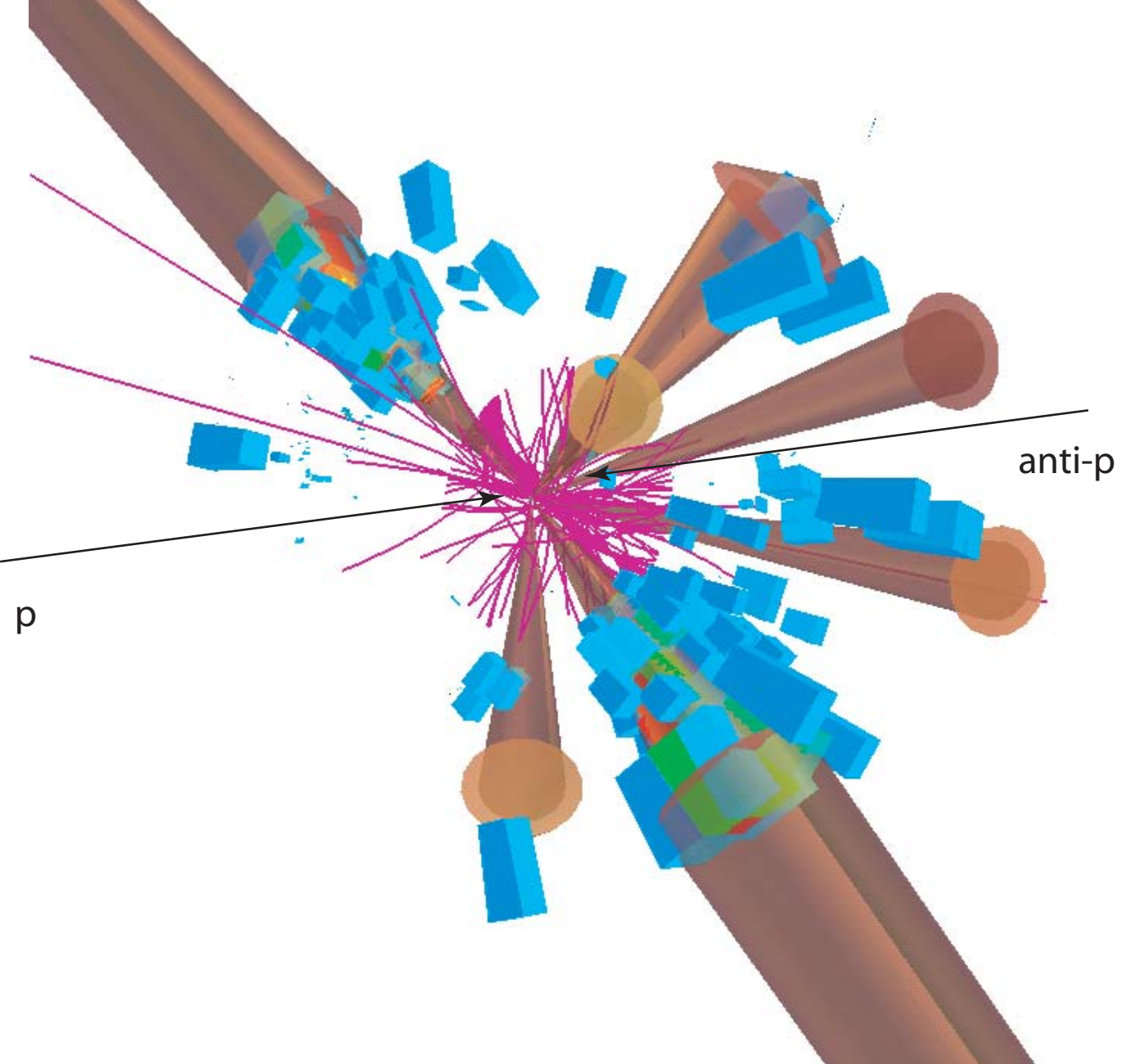
$p_T\ \eta\ \phi$

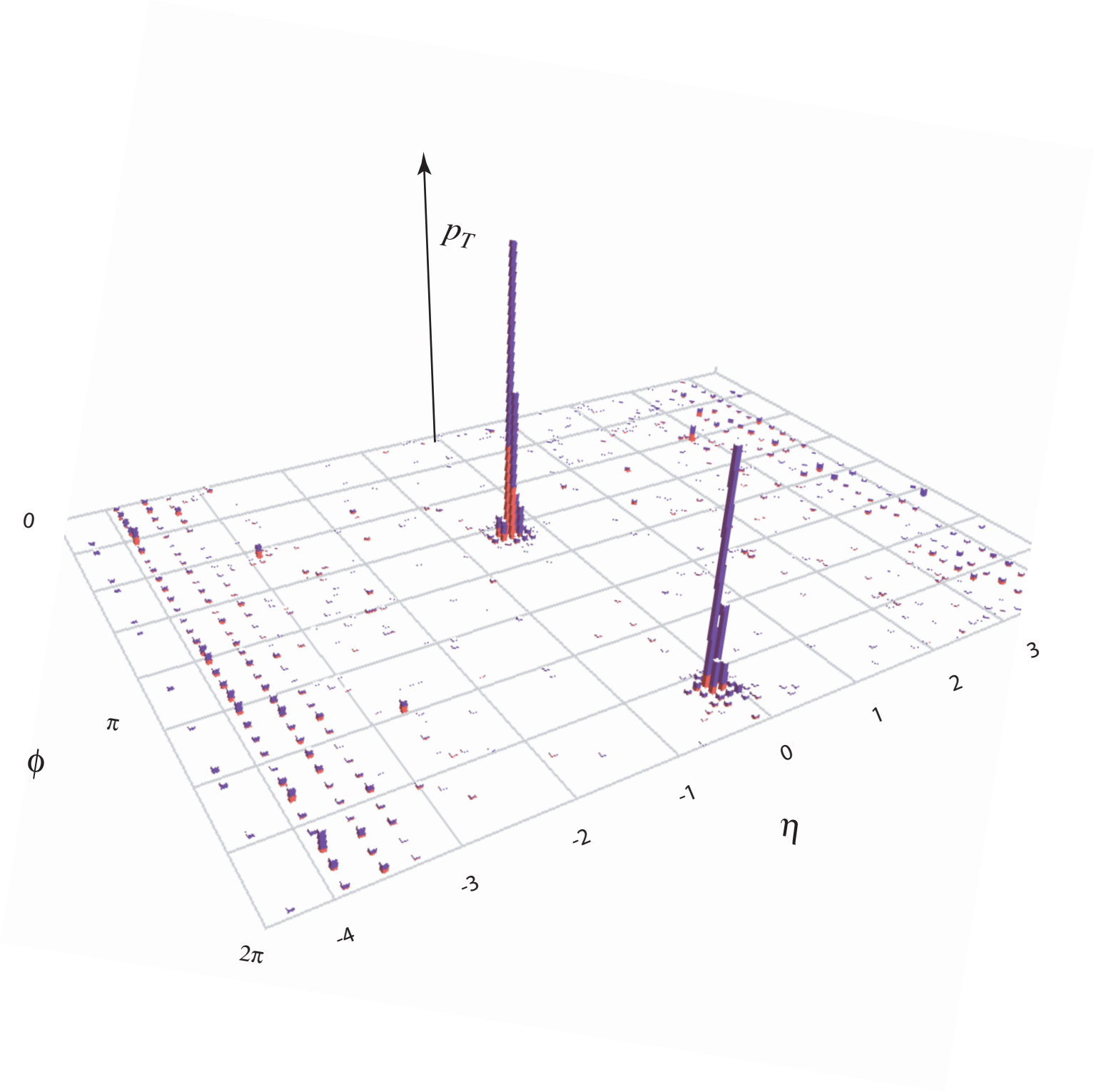




Unroll in ϕ

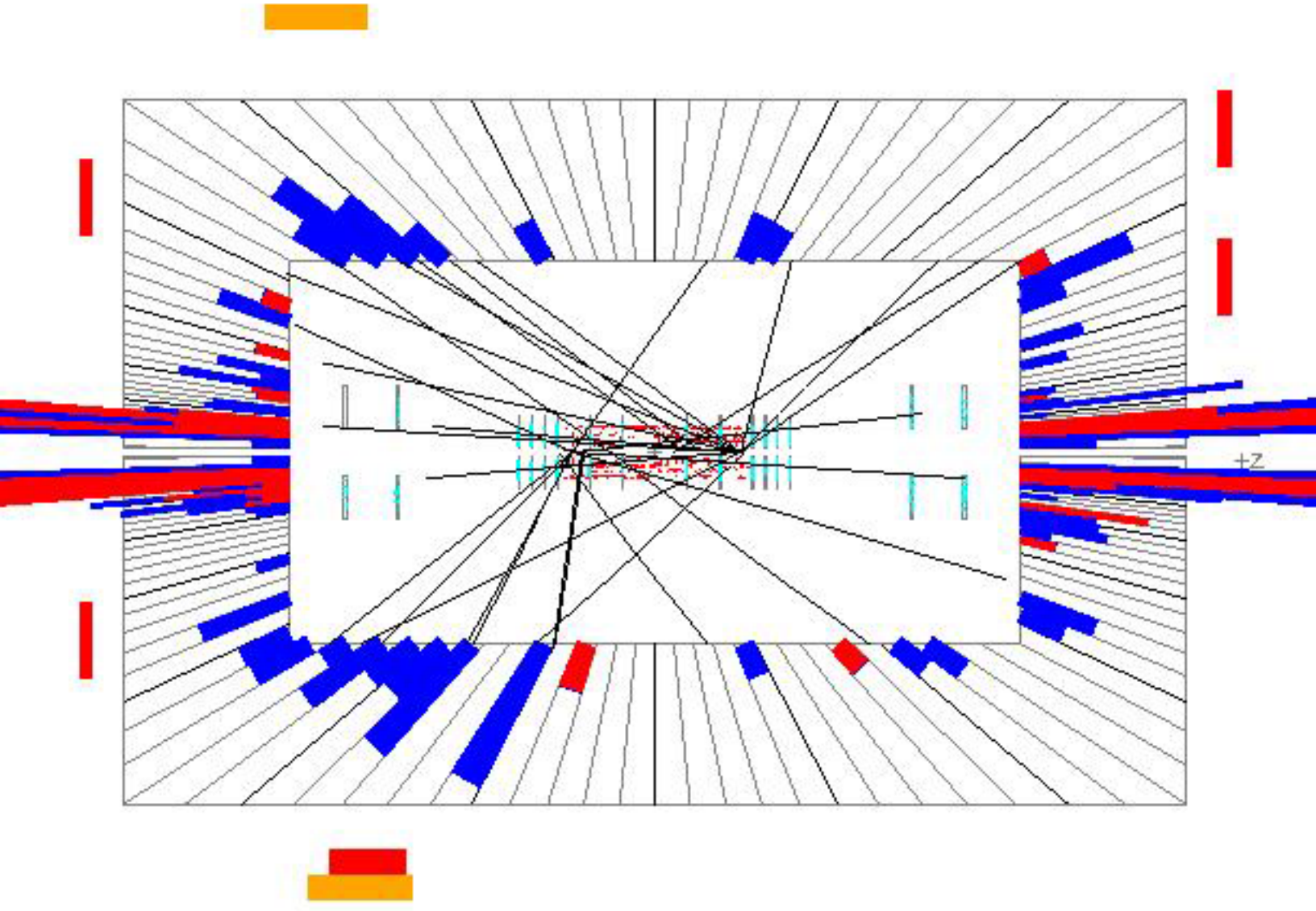
Lego Plot


anti-p
p

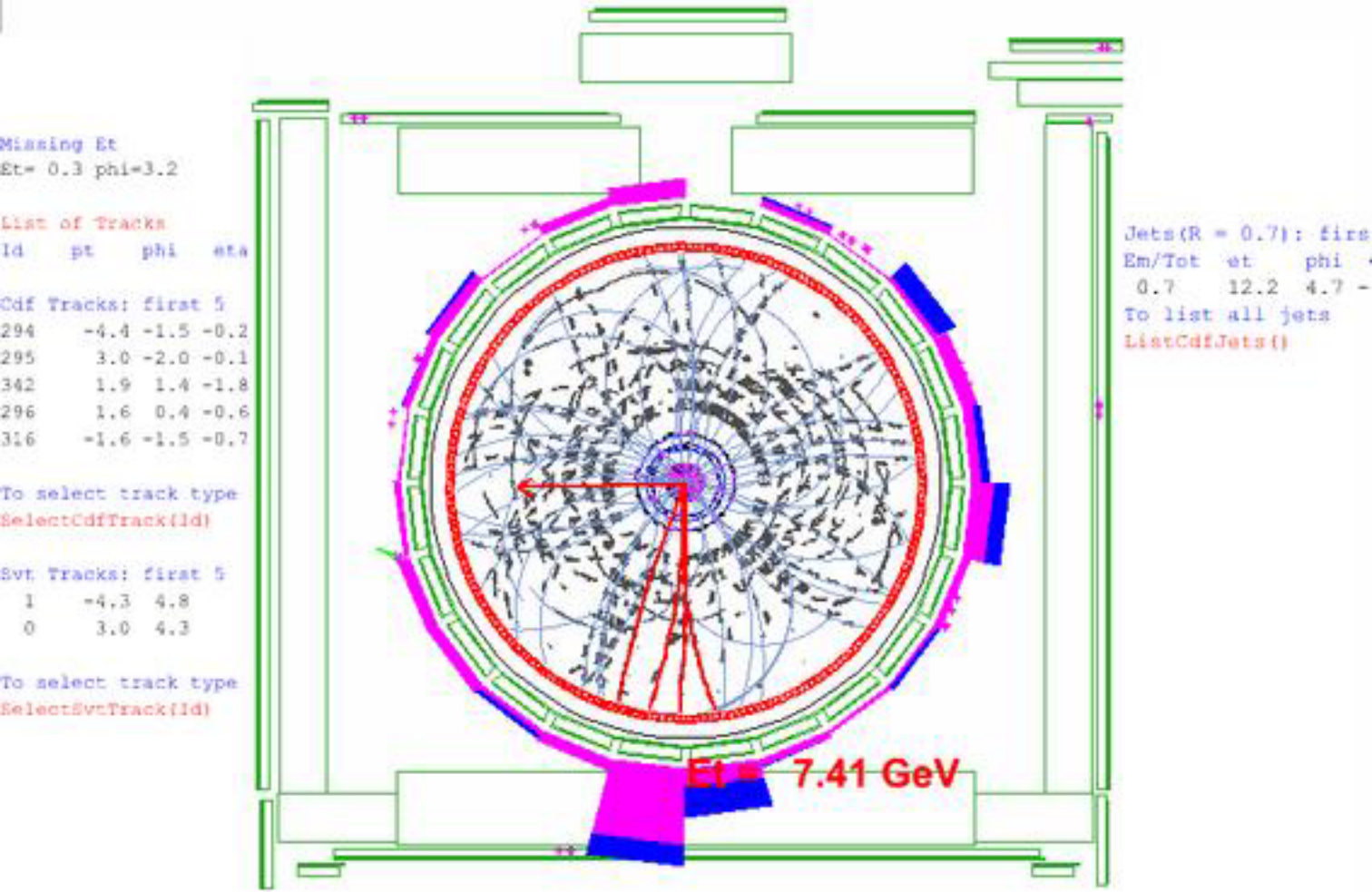

p_T
0
π
ϕ
2π
-4
-3
-2
-1
0
1
2
3
η

Run 208433 Evt 45794747 Tue Jul 19 06:10:39 2005

E scale: 3 GeV



Event : 10198473 Run : 201133 EventType : DATA | Unpresc: 32,33,37,53,23,55,60,62 Presc: 33,60,62

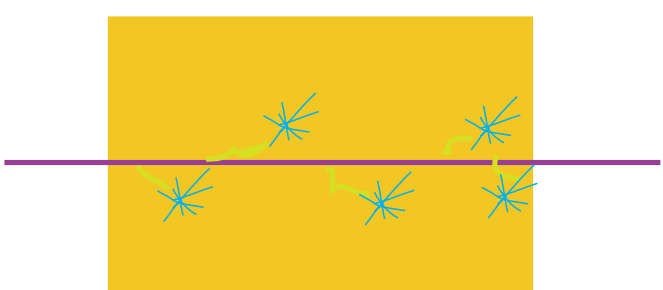


Detection of charged particles

When a relativistic charged particle passes through matter, it knocks electron out of atoms as it passes by. This is what we call 'Energy Loss' and it is reasonably independent of the particle or material type.

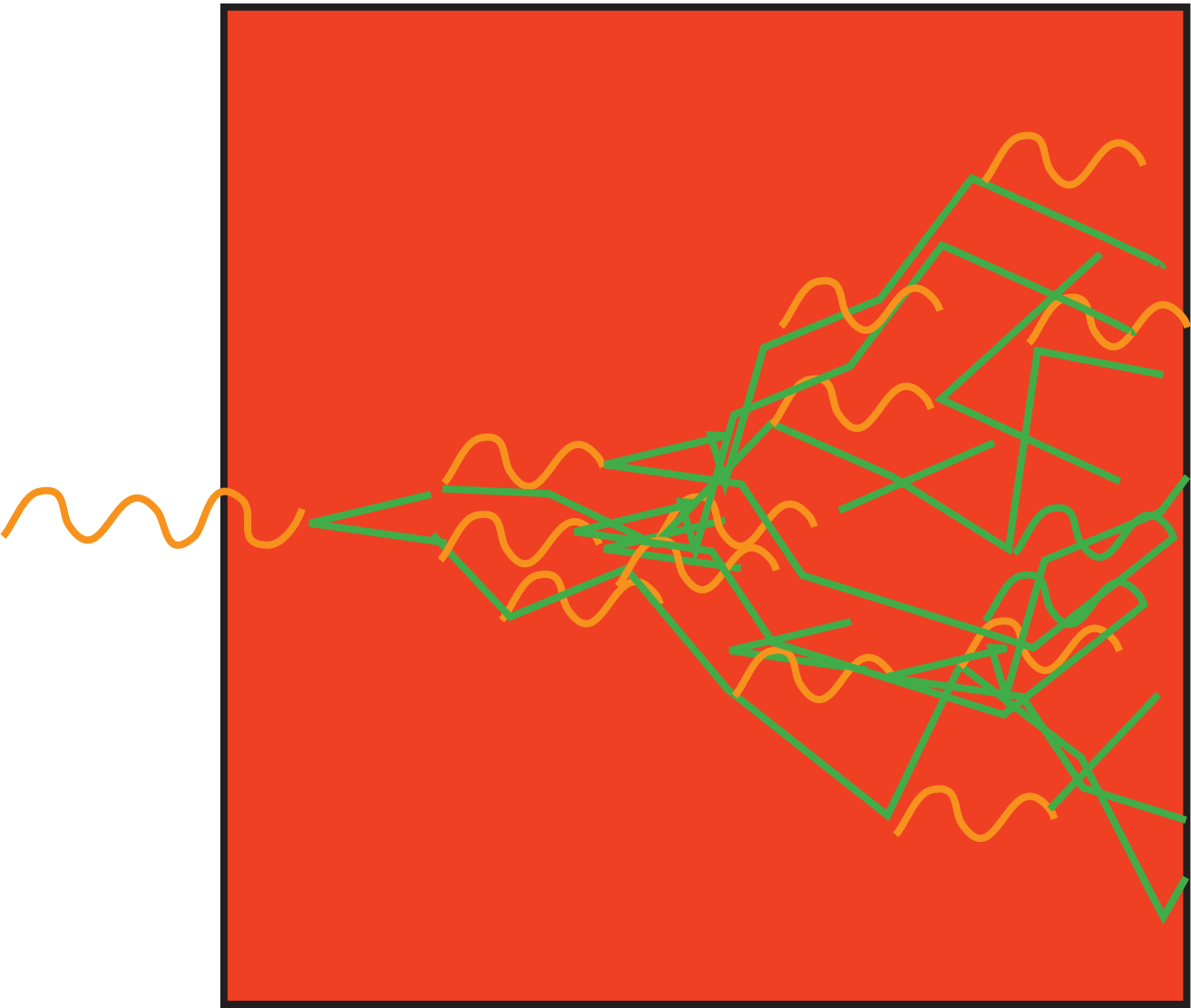
$$dE/dx \sim 2\ \mathrm{MeV/cm} \times \rho\ [\mathrm{gr/cm^3}]$$

this energy shows up as low energy electrons and photons and can be detected optically or electronically.



Scintillator

Electromagnetic showers



6.0.1 Basics of electromagnetic calorimetery

High energy photons and electrons interact two ways in high Z materials.

- Electrons can scatter from atomic electrons and ionize the material - we can detect this ionization but the electron energy does not change much. This is an incoherent process and scales as Z/atom or Z/A/gram of material.
- Both Electrons and photons can scatter off of the atomic nucleus. This a coherent scatter and scales as Z^2/atom or Z^2/A atom. The electron scatter is bremsstrahlung and the photon is pair-production of an e^-e^+ pair. The cross section for these interaction is approximately approximately independent of energy once the energy of the particles is $\gg m_e c^2$.

The mean free path for both processes is

$$X_0 \sim \frac{1}{4\alpha r_e^2 Z^2 \frac{N_A}{A}} \tag{21}$$

What happens when a high energy photon or electron hits some high Z material is illustrated in Figure

After the first interaction 1 particle becomes 2, after the next, 2 particles become 4 etc. asymptotically there are slightly more electrons than photons.

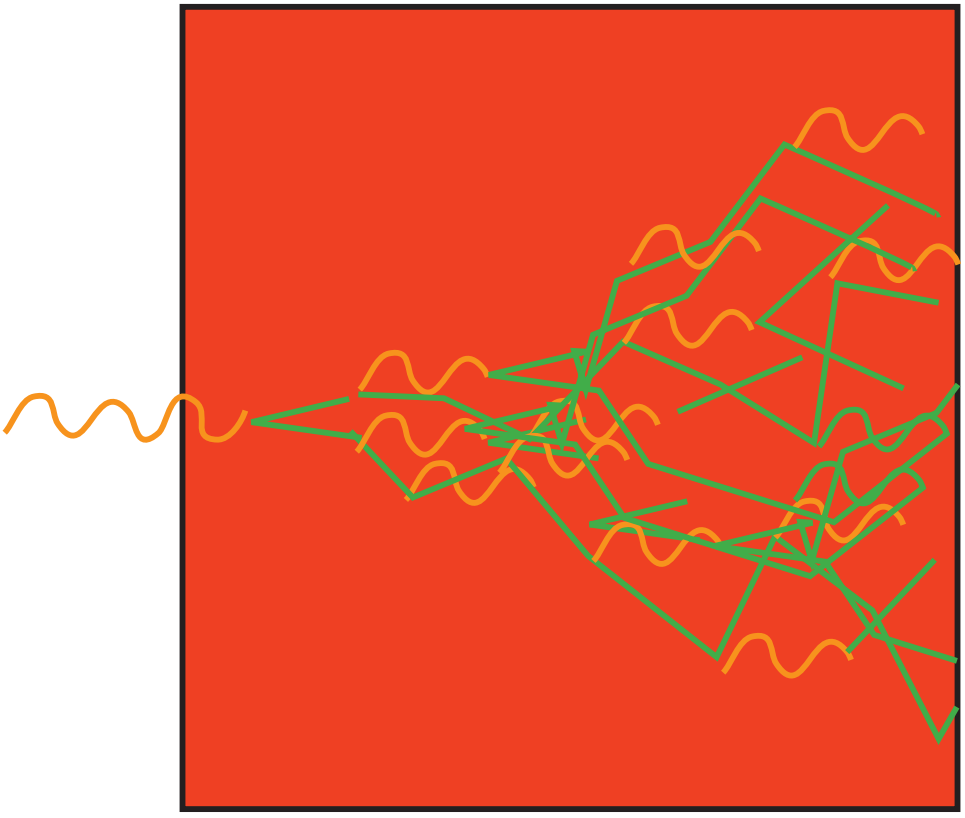


Figure 19: A photon showers in material. One can expect a hard interaction (bremsstrahlung or pair production) every X_0.

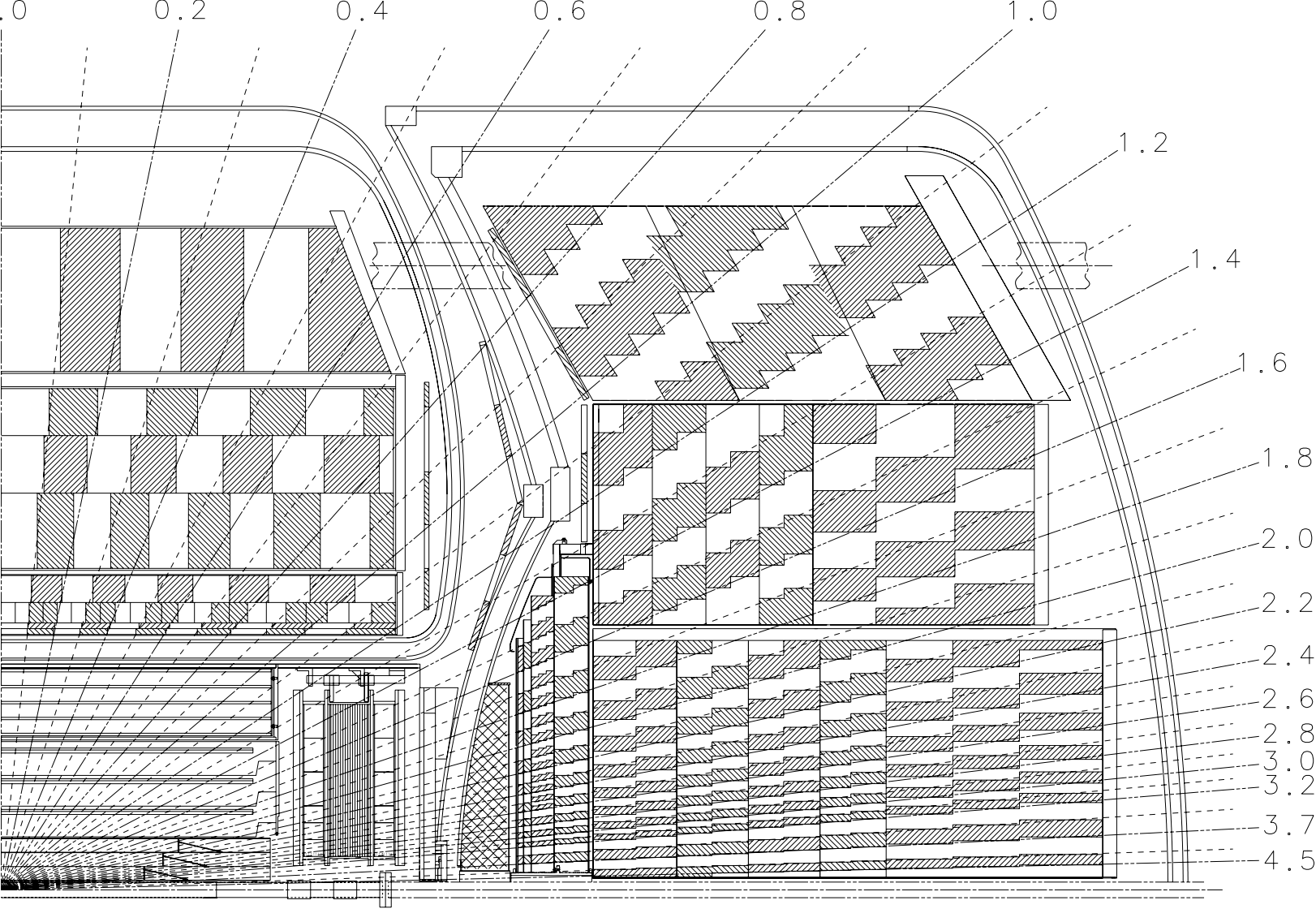
The number of particles/layer grows as 2^i where i is the number of X_0 you have traversed and the energy/particle drops by a factor of 2 each layer. At some point the energy/particle ($E_0/2^i$) becomes close to $m_e c^2$ and the hard scatters stop. The critical energy is called E_c and is actually more like 10 MeV. You can use this to solve for the maximum number of radiation lengths N.

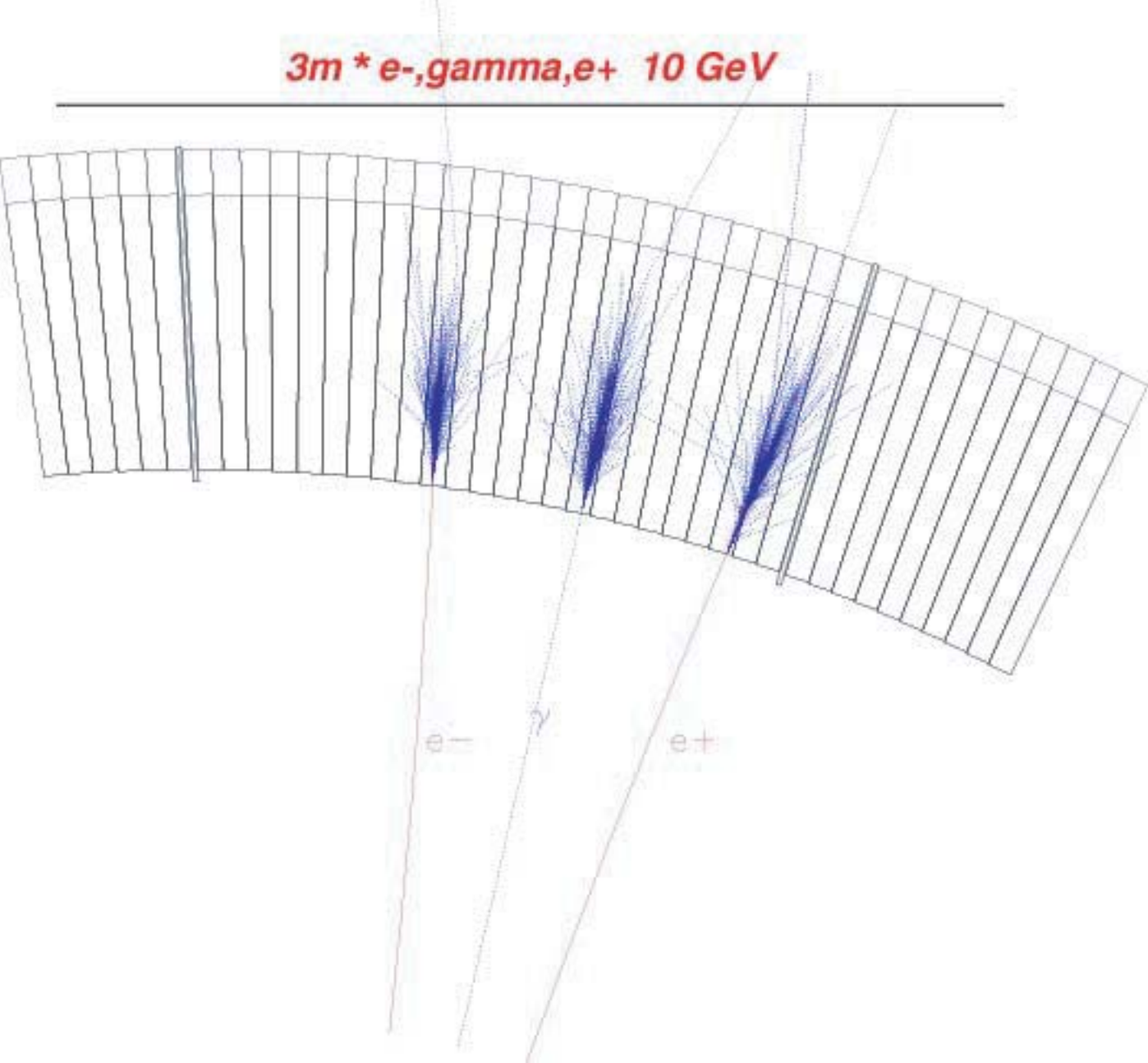
$$2^N = E_0/E_c \tag{22}$$

What we detect is the ionization caused by the particles, which is proportional to the total path length.

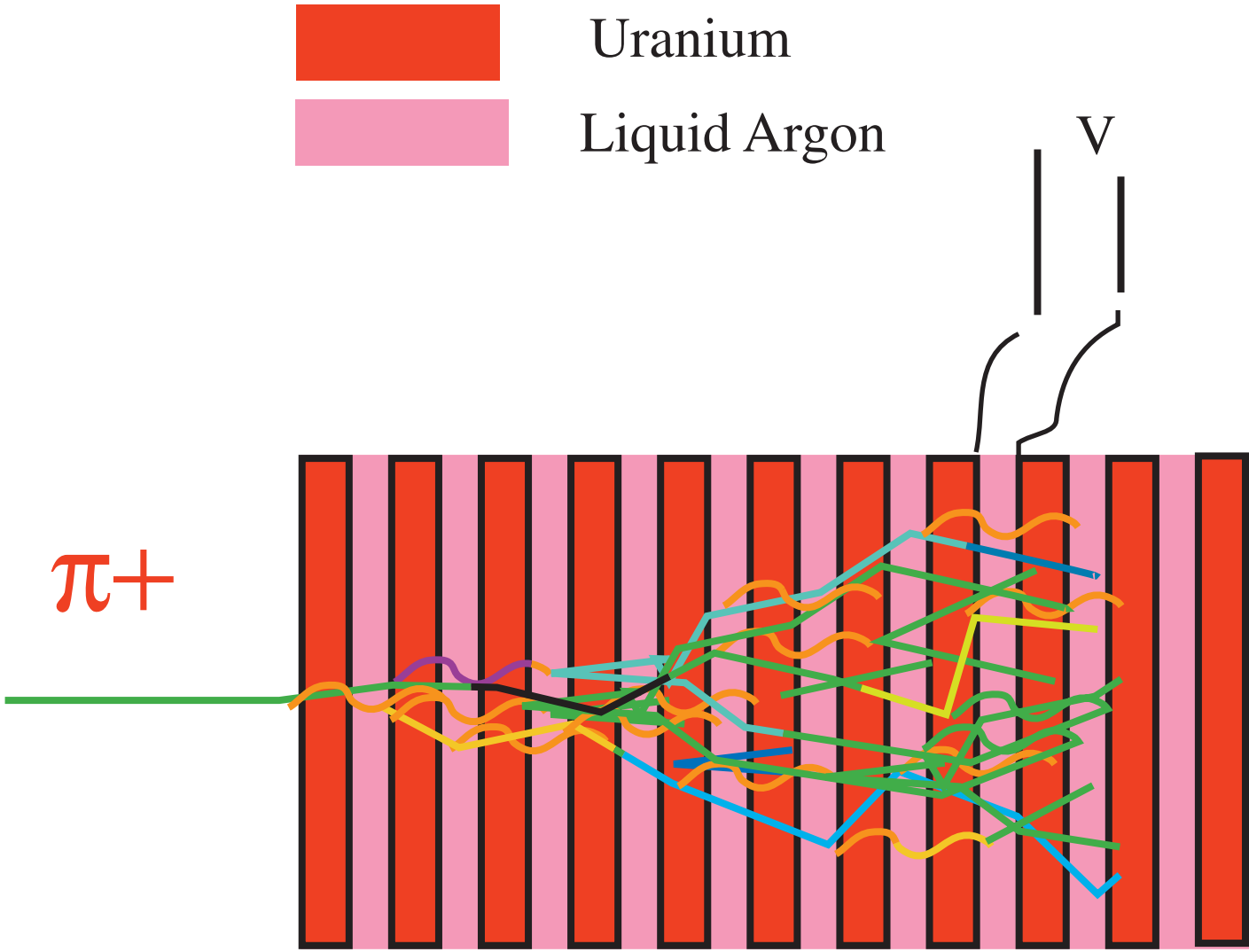
$$L = \sum_{i=1}^{N} (2^i f_e X_0) = f_e X_0 (2^N - 1) \sim f_e X_0 E_0/E_c \tag{23}$$

where f_e is the electron fraction in the shower $\sim 5/8$. So the ionization observed is proportional to the incident energy. This is a nice linear detector.


.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.7
4.5


3m * e-,gamma,e+ 10 GeV
e−
γ
e+

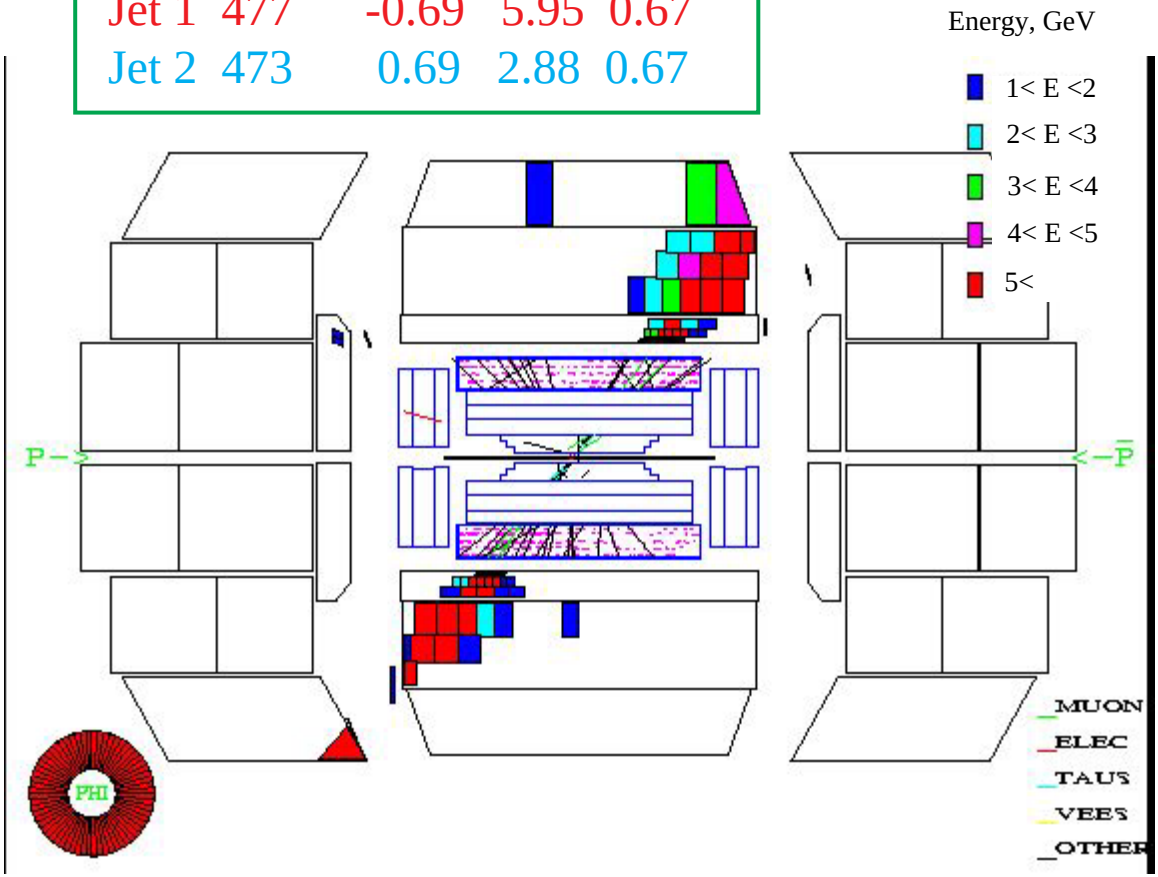
Sampling Calorimeter

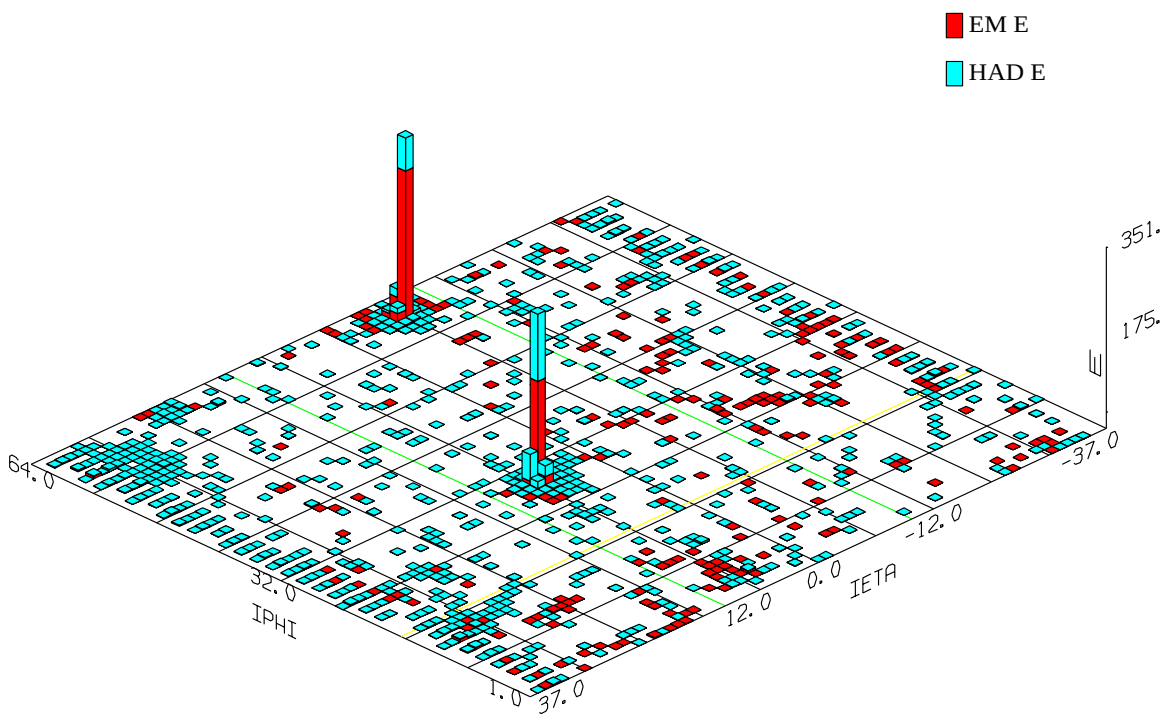


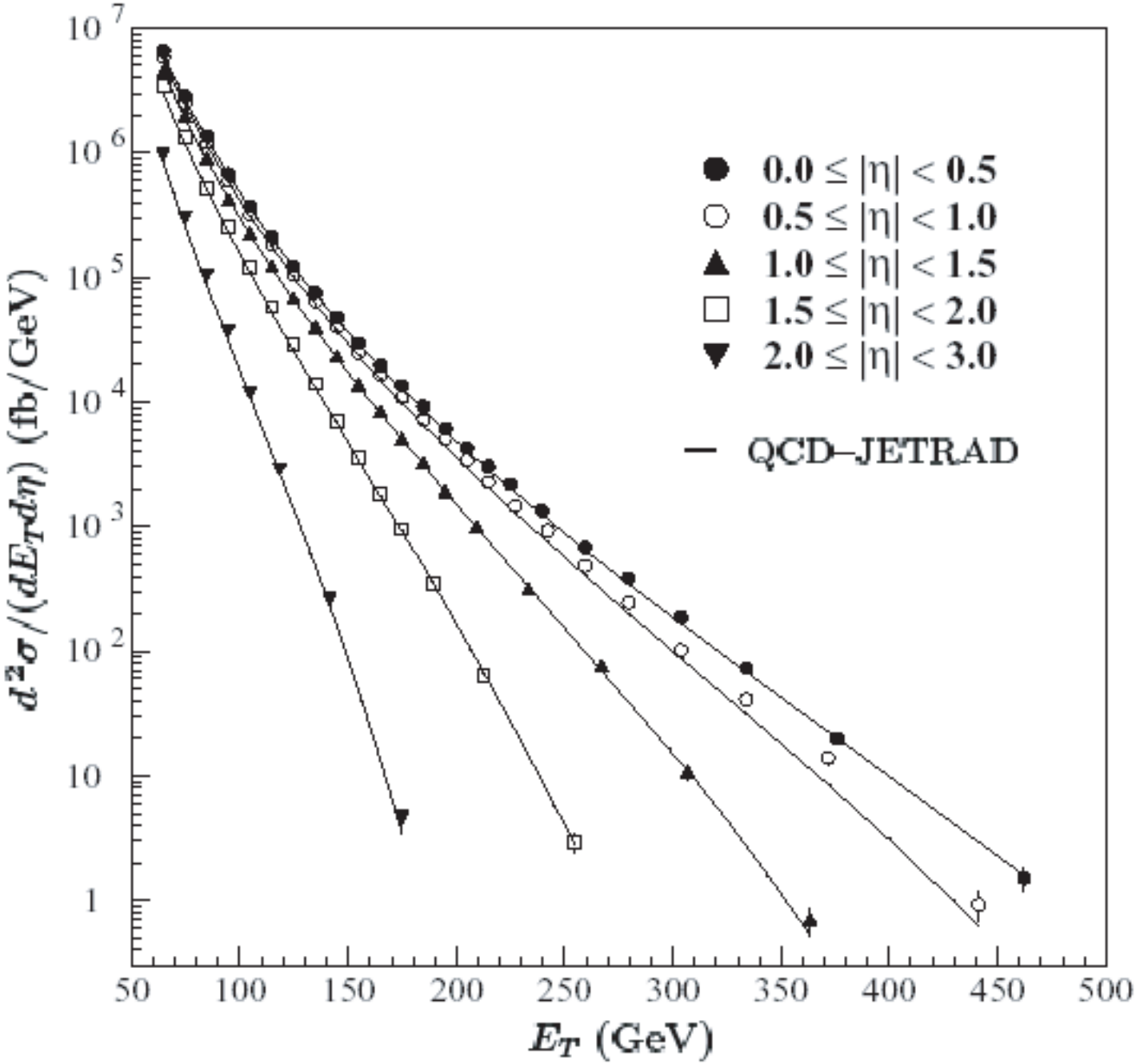
`Typical' Event in the D0 Detector

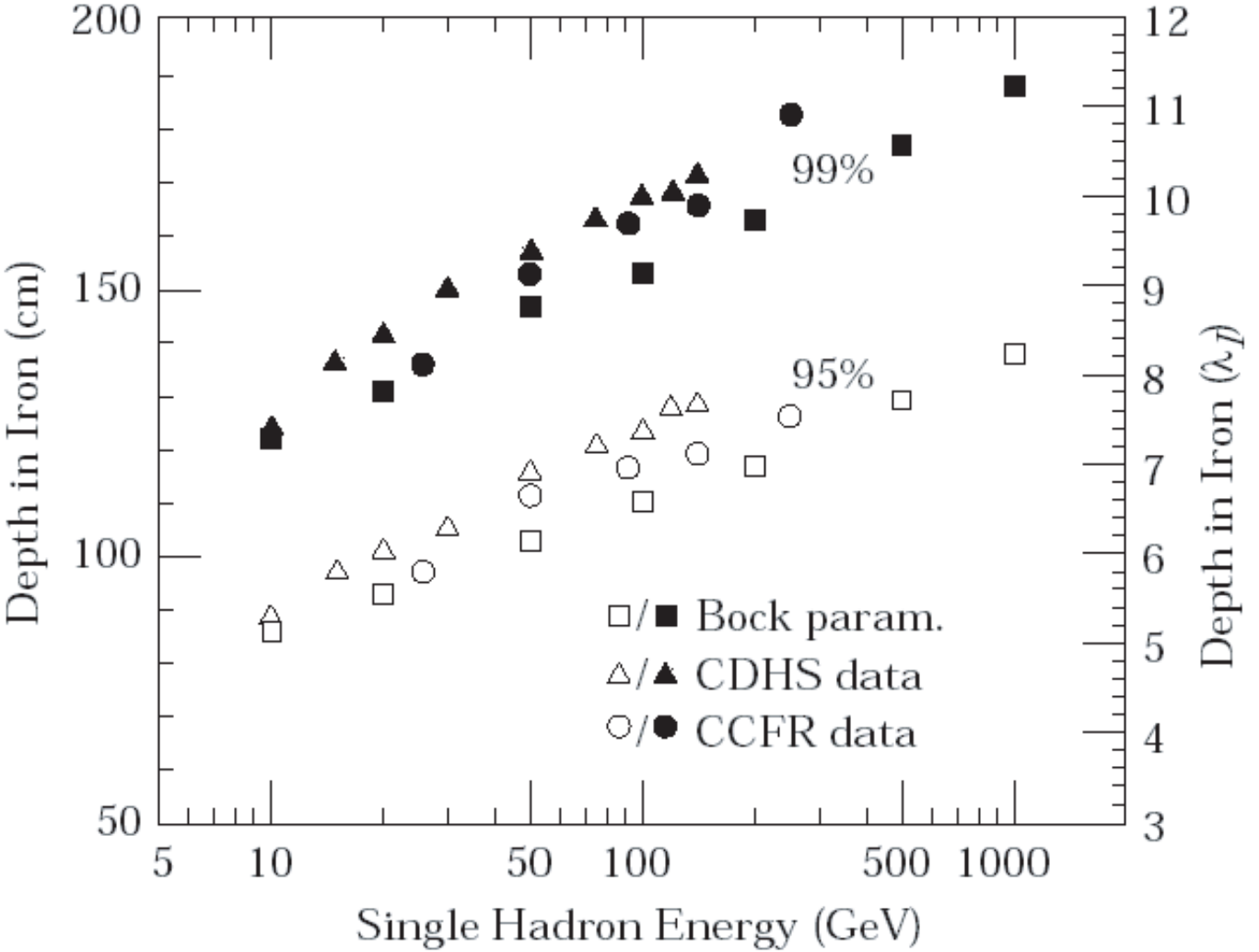
Missing ET 8.4 GeV $\hat{s}$ = 1187 GeV

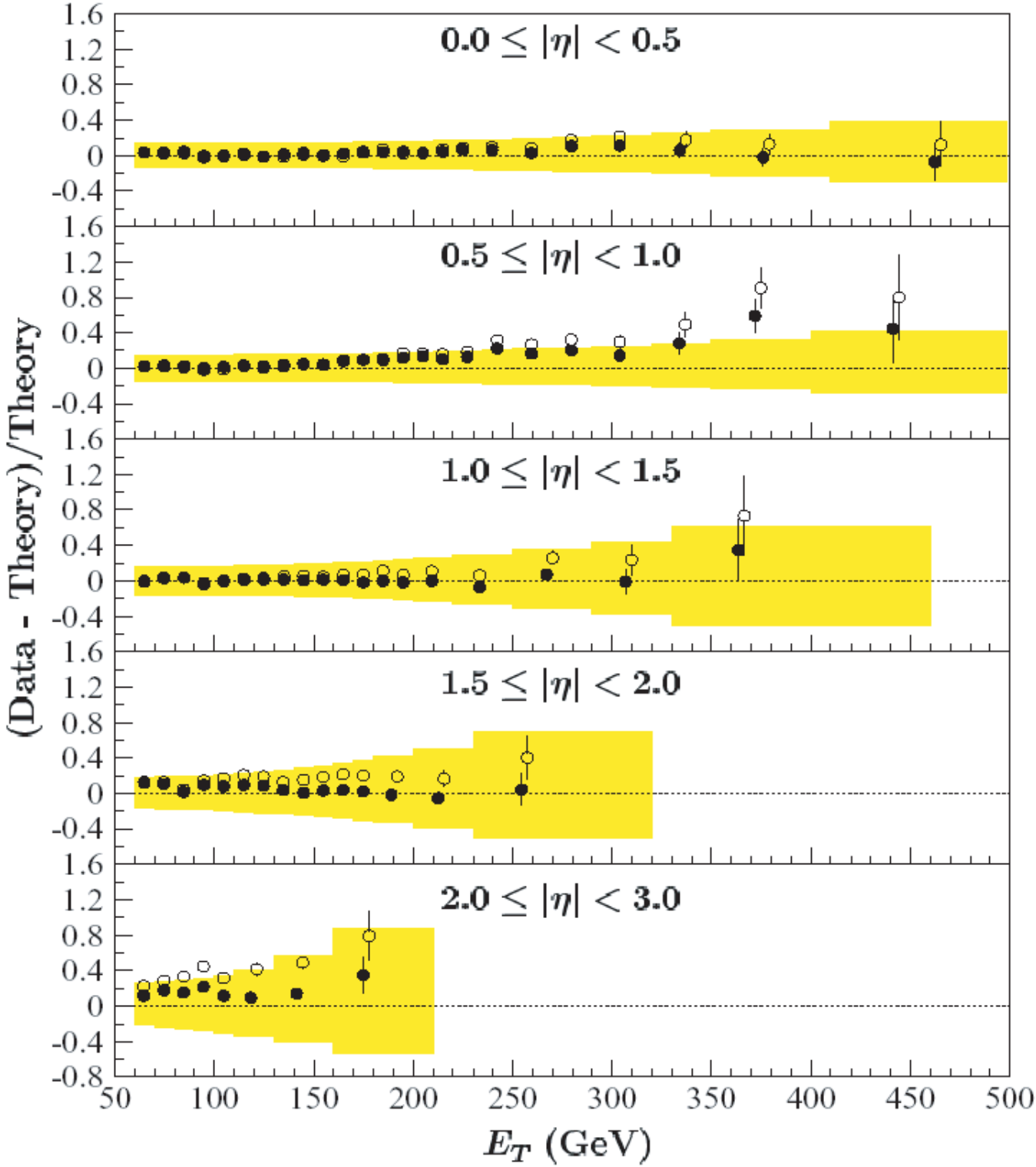
	E_T ,GeV	η	ϕ	x_{parton}
Jet 1	477	-0.69	5.95	0.67
Jet 2	473	0.69	2.88	0.67

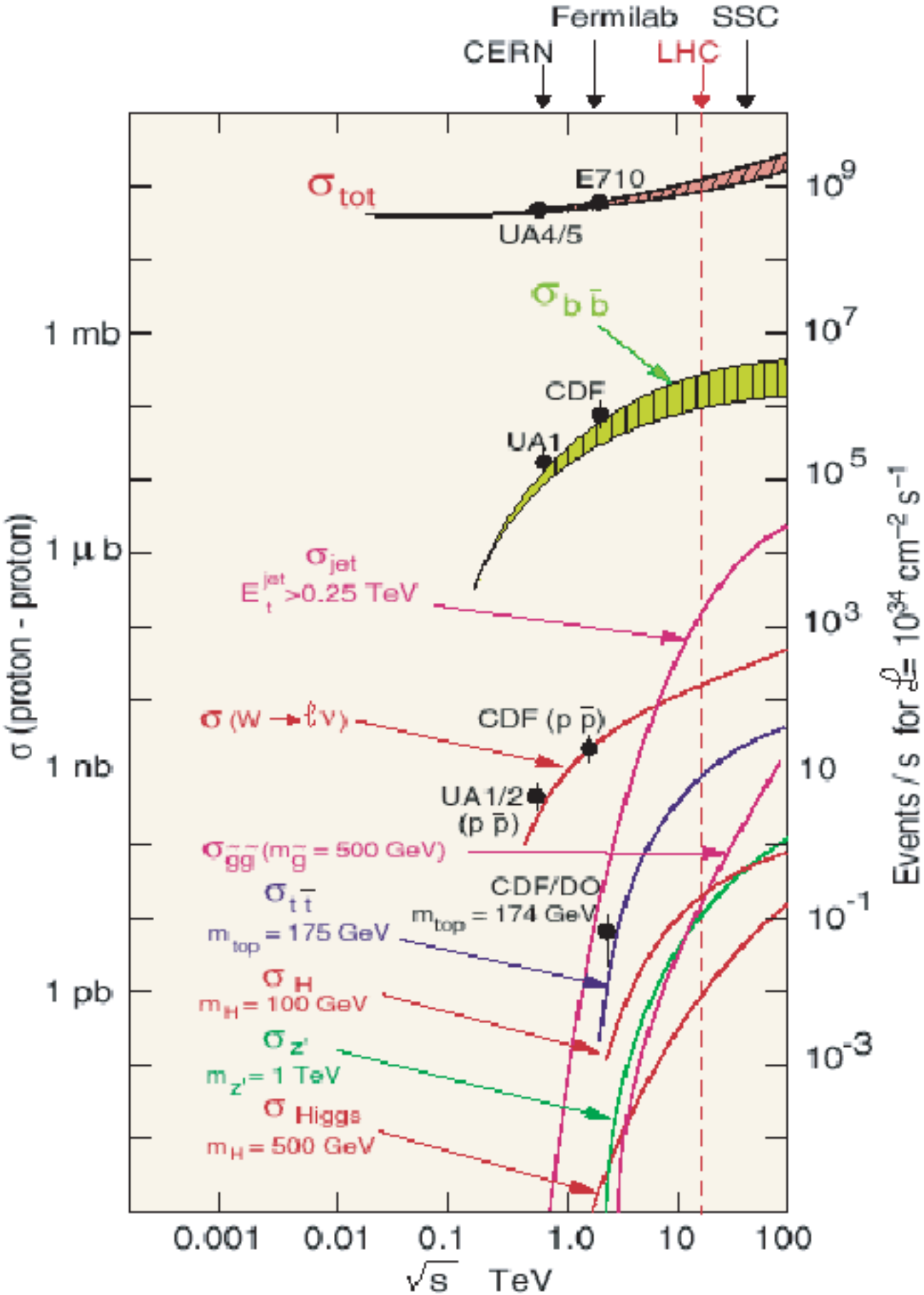



EM E
HAD E
351.
175.
E
64.0
32.0
IPHI
1.0
37.0
12.0
0.0
IETA
-12.0
-37.0


10^7
10^6
10^5
10^4
10^3
10^2
10
1
$d^2\sigma/(dE_T d\eta)$ (fb/GeV)
50
100
150
200
250
300
350
400
450
500
E_T (GeV)
$0.0 \le |\eta| < 0.5$
$0.5 \le |\eta| < 1.0$
$1.0 \le |\eta| < 1.5$
$1.5 \le |\eta| < 2.0$
$2.0 \le |\eta| < 3.0$
QCD–JETRAD

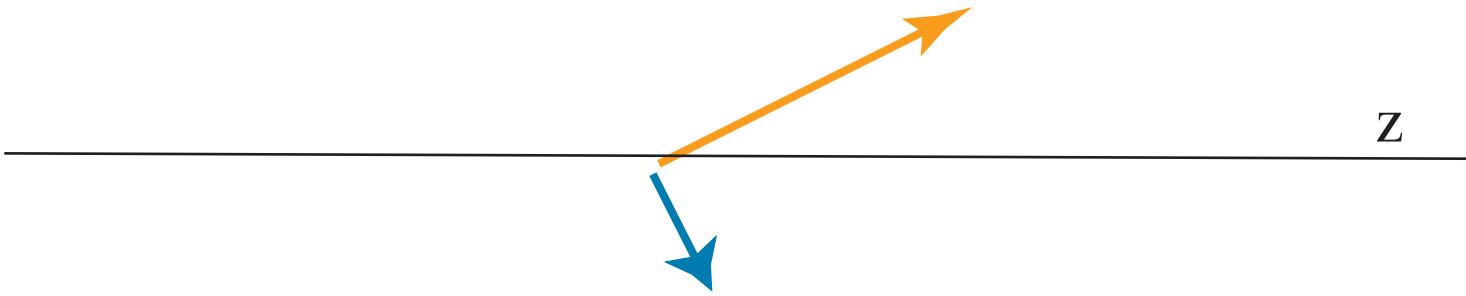

200
150
100
50
12
11
10
9
8
7
6
5
4
3
5
10
50
100
500
1000
Depth in Iron (cm)
Depth in Iron (λ_I)
Single Hadron Energy (GeV)
99%
95%
□/■ Bock param.
△/▲ CDHS data
○/● CCFR data


$0.0 \leq |\eta| < 0.5$
$0.5 \leq |\eta| < 1.0$
$1.0 \leq |\eta| < 1.5$
$1.5 \leq |\eta| < 2.0$
$2.0 \leq |\eta| < 3.0$
(Data - Theory)/Theory
E_T (GeV)
1.6
1.2
0.8
0.4
0
-0.4
-0.8
50
100
150
200
250
300
350
400
450
500

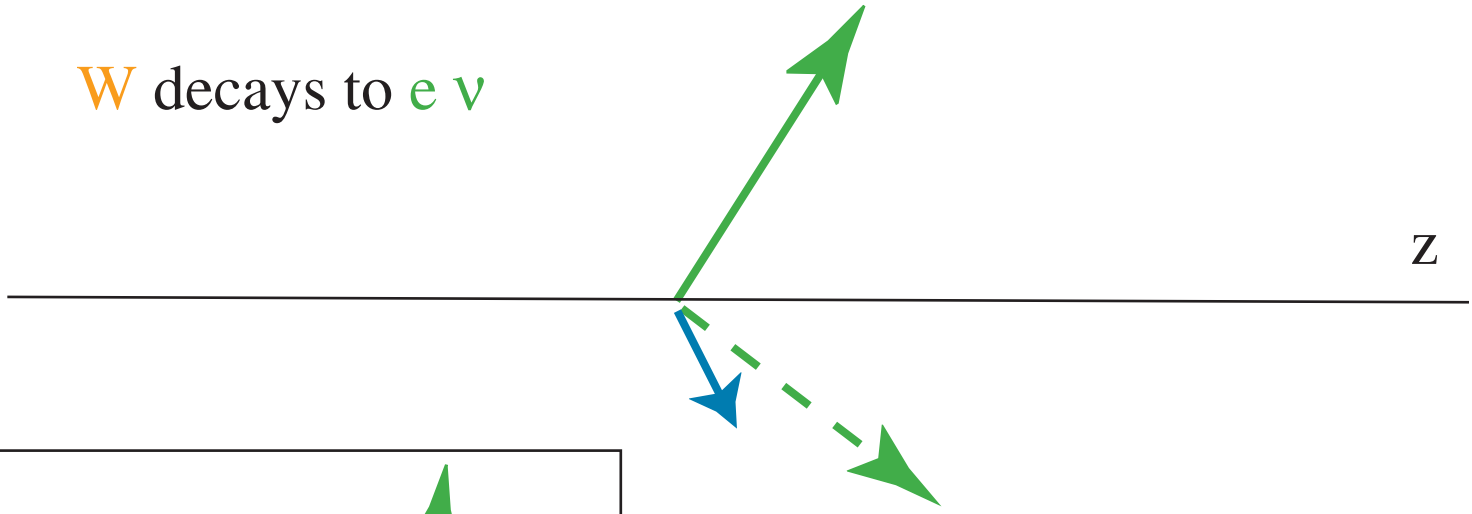

Fermilab
SSC
CERN
LHC
σ tot
E710
UA4/5
σ b b̄
CDF
UA1
σ jet
E t jet >0.25 TeV
σ (W → ℓ ν)
CDF (p p̄)
UA1/2
(p p̄)
σ g̃g̃ (m g̃ = 500 GeV)
σ t t̄
CDF/DO
m top = 174 GeV
m top = 175 GeV
σ H
m H = 100 GeV
σ z'
m z' = 1 TeV
σ Higgs
m H = 500 GeV
1 mb
1 μ b
1 nb
1 pb
σ (proton - proton)
10^9
10^7
10^5
10^3
10
10^-1
10^-3
Events / s for ℒ = 10^34 cm^-2 s^-1
0.001
0.01
0.1
1.0
10
100
√s TeV

Proton antiProton collision

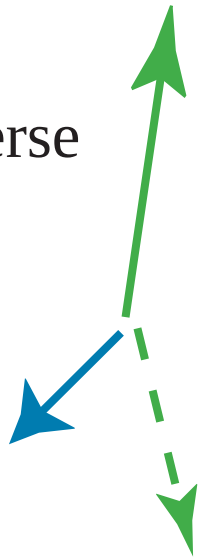
Produces W + recoil



W decays to e ν



Transverse view



Can reconstruct p_T of ν but not $p_{||}$

ν

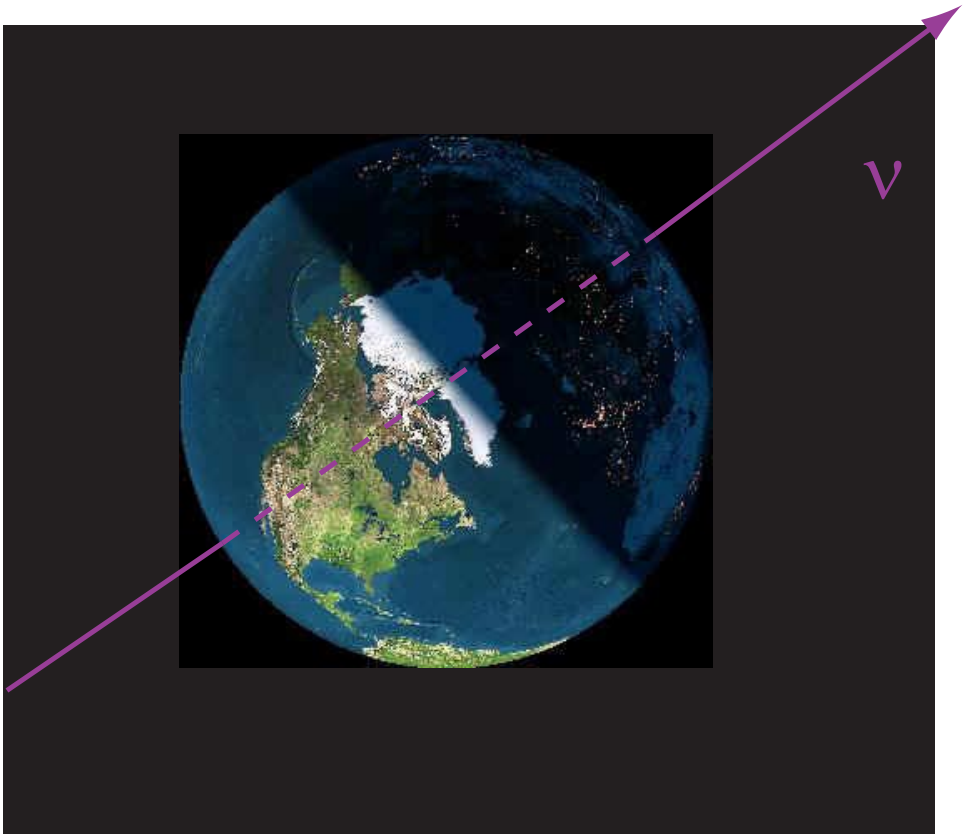
neutrinos

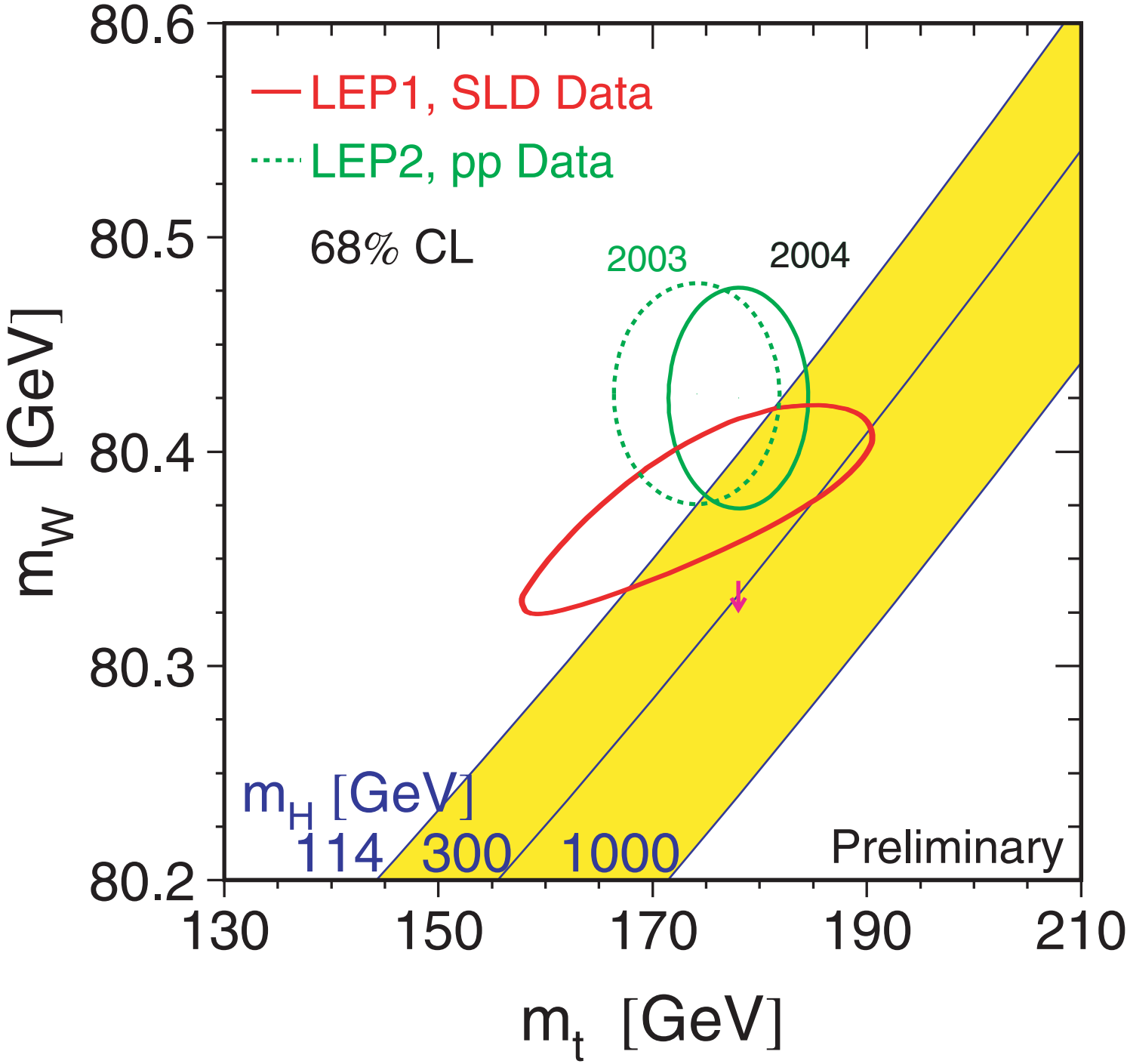
Q = -*0*

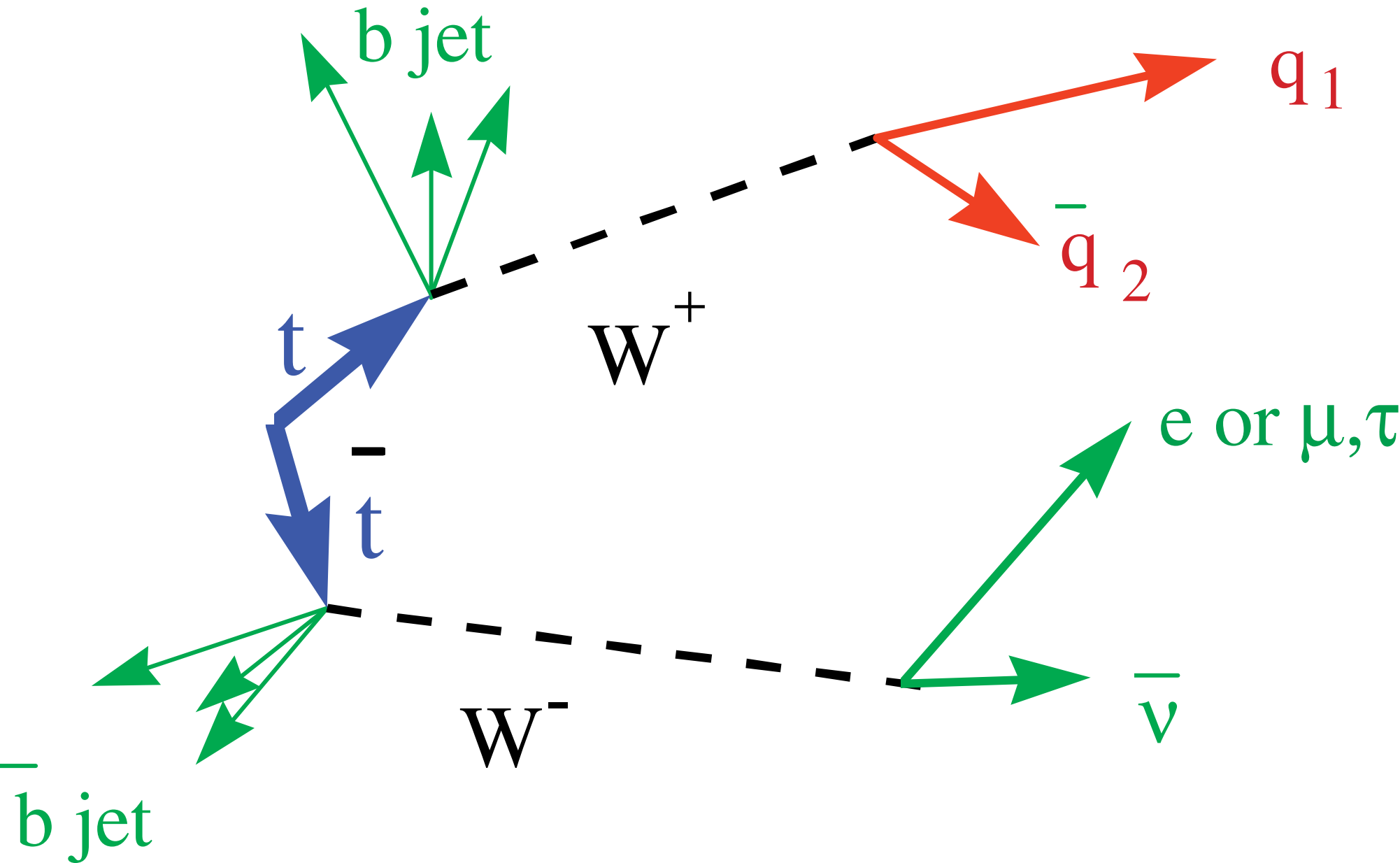
m = 0?

stable

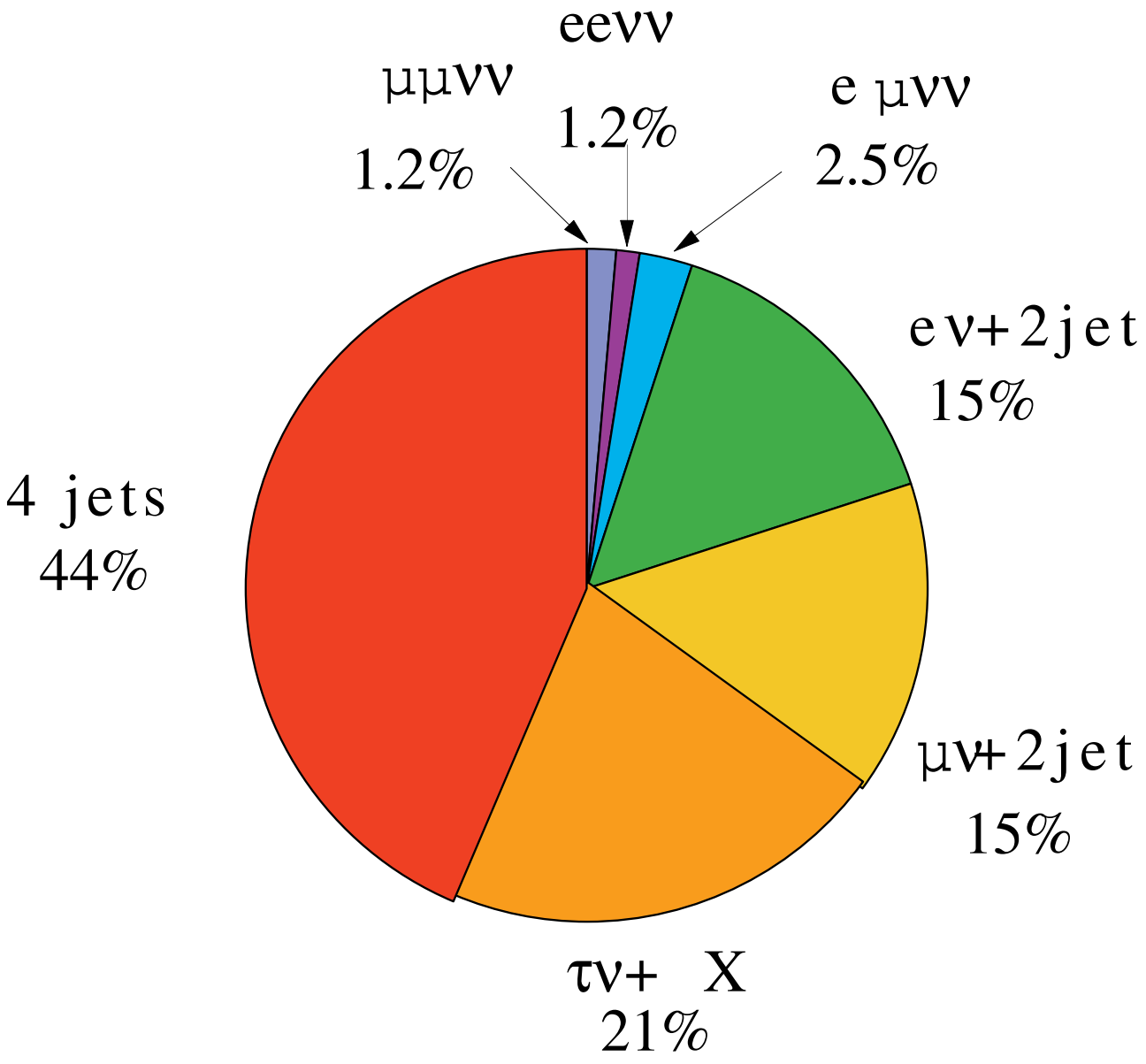
couples to *W*, *Z*

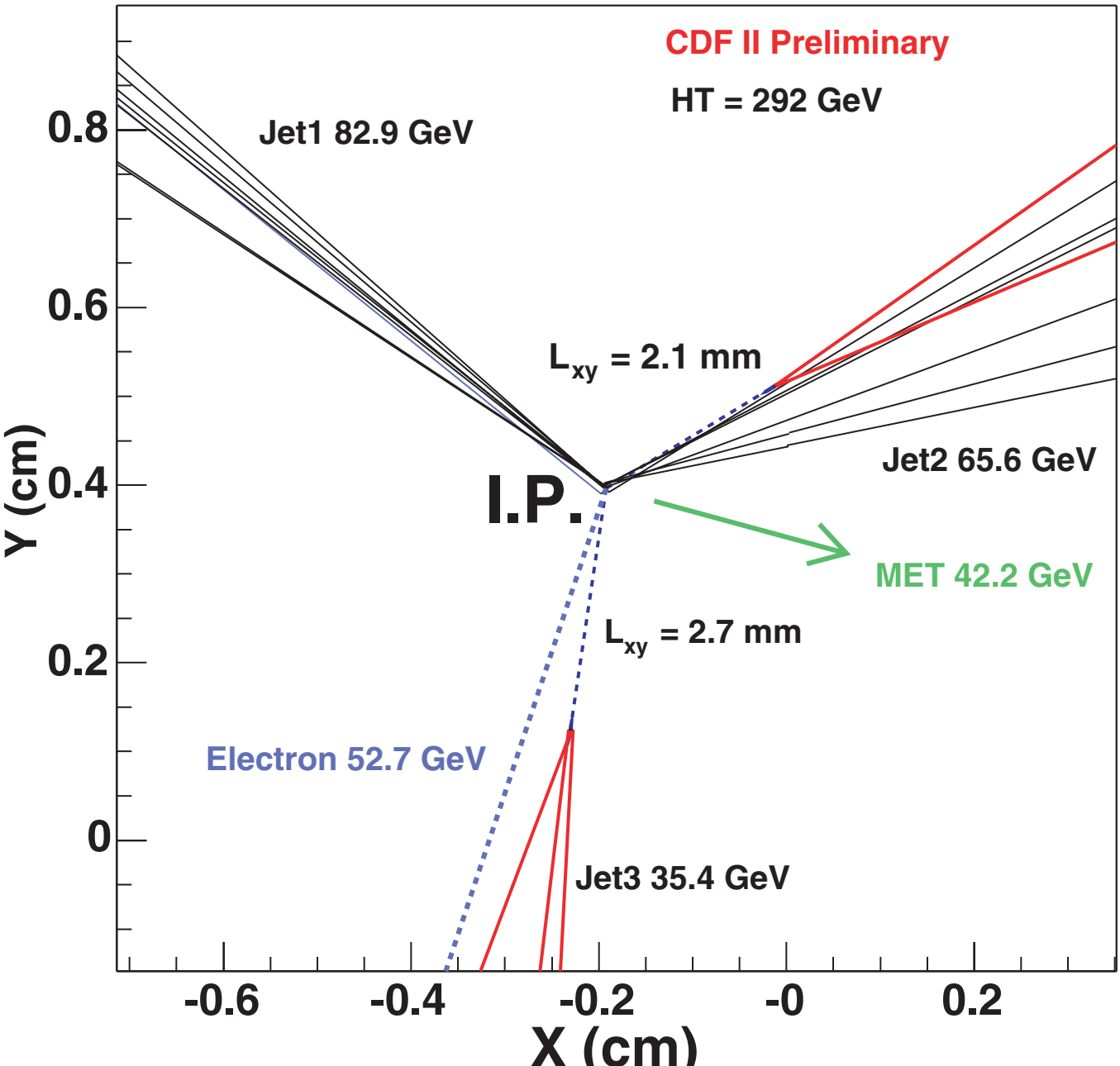


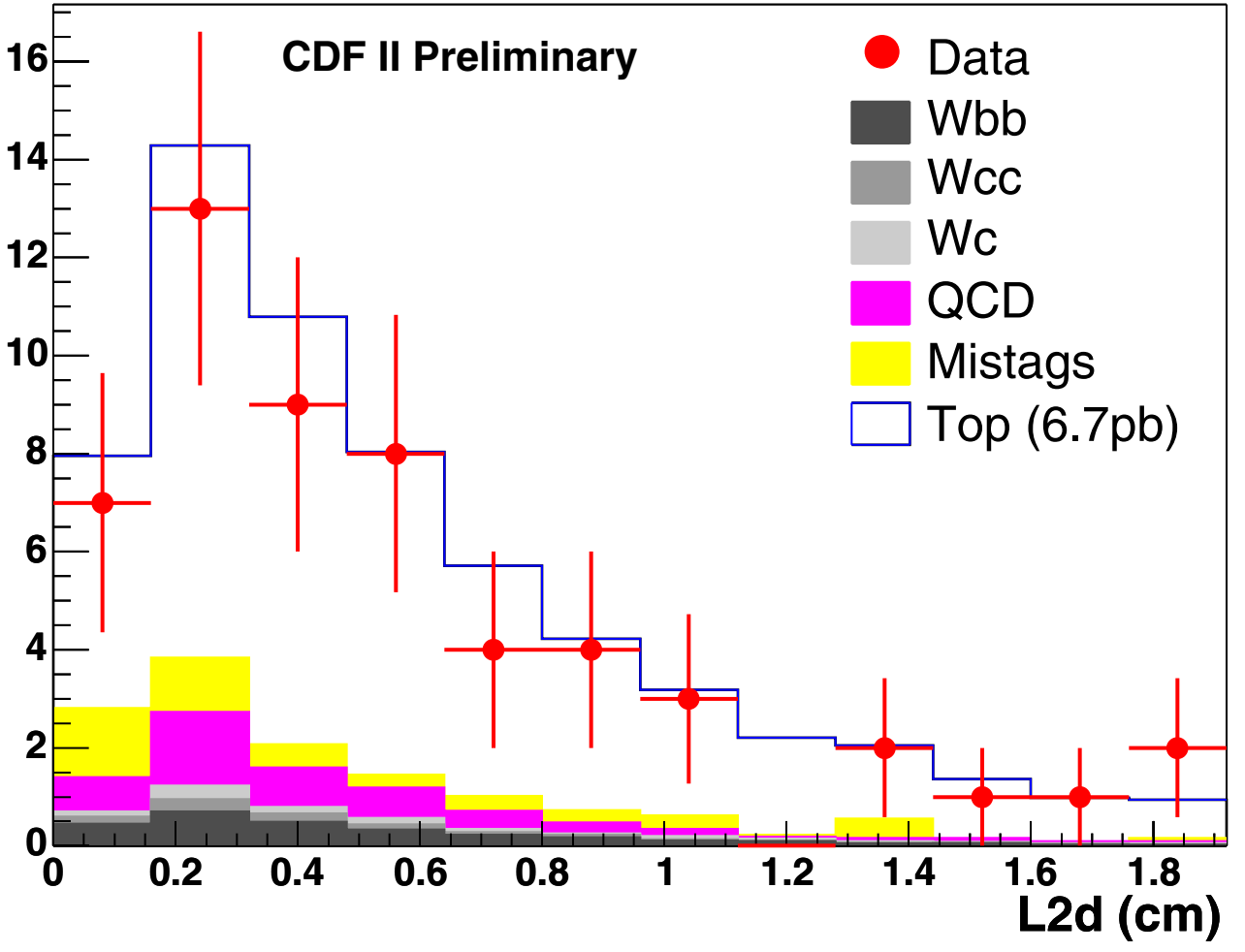

LEP1, SLD Data
LEP2, pp Data
68% CL
2003
2004
m_H [GeV]
114
300
1000
Preliminary
80.6
80.5
80.4
80.3
80.2
130
150
170
190
210
m_W [GeV]
m_t [GeV]

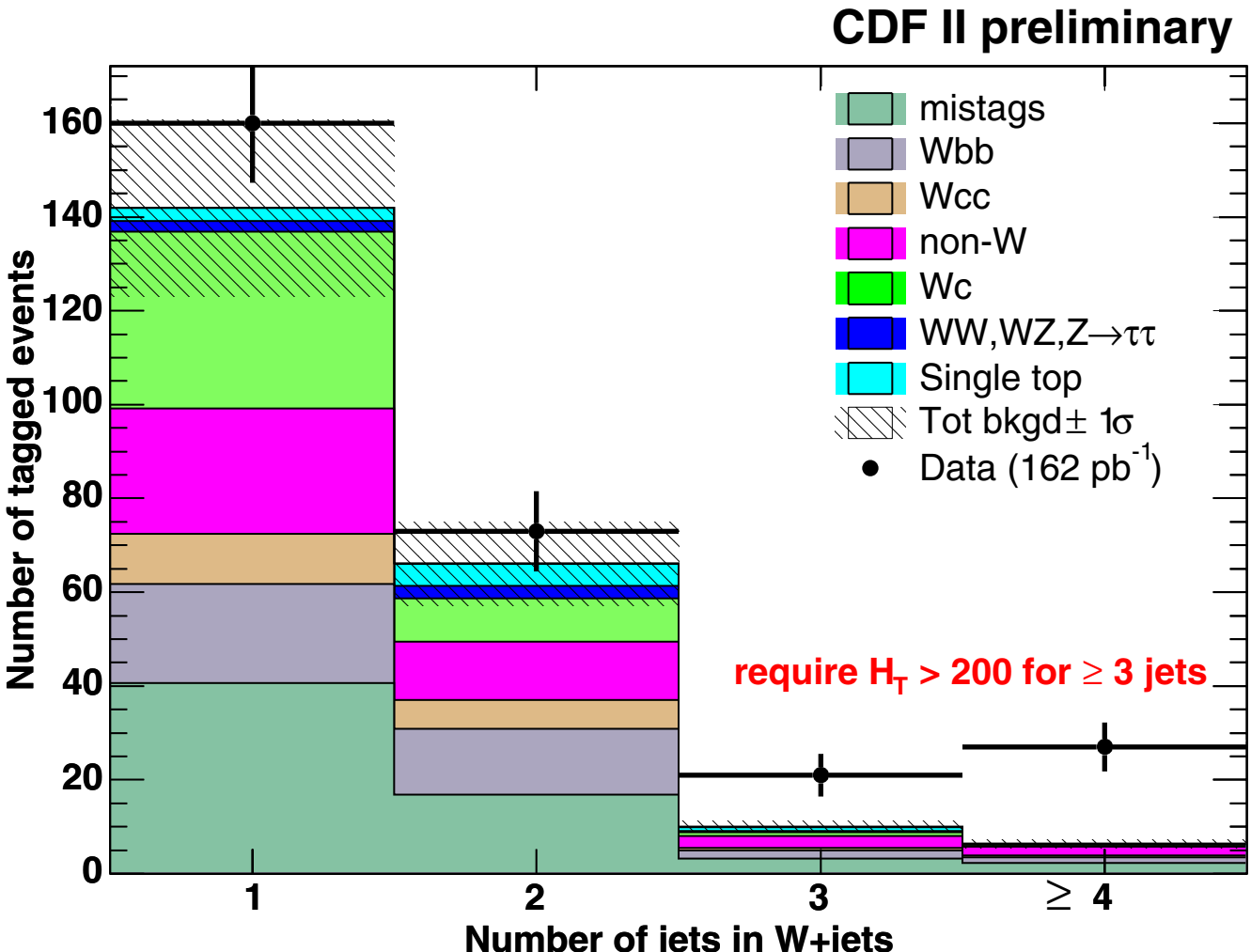

b jet
q 1
q̄ 2
W+
t
t̄
e or μ,τ
W-
ν̄
b̄ jet

W^+W^- decay signatures

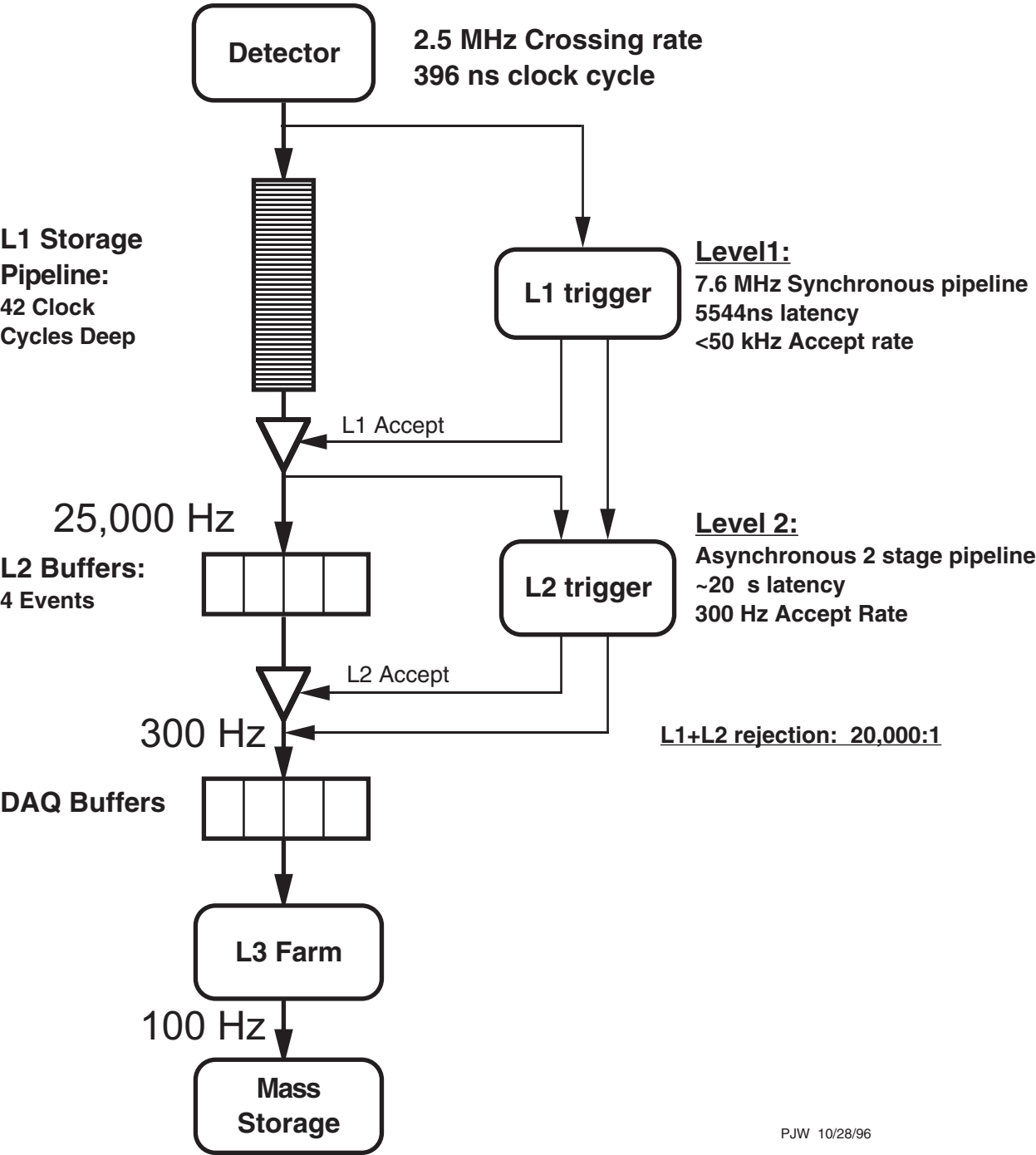



CDF II Preliminary
HT = 292 GeV
Jet1 82.9 GeV
L_{xy} = 2.1 mm
Jet2 65.6 GeV
I.P.
MET 42.2 GeV
L_{xy} = 2.7 mm
Electron 52.7 GeV
Jet3 35.4 GeV
0.8
0.6
0.4
0.2
0
Y (cm)
-0.6
-0.4
-0.2
-0
0.2
X (cm)

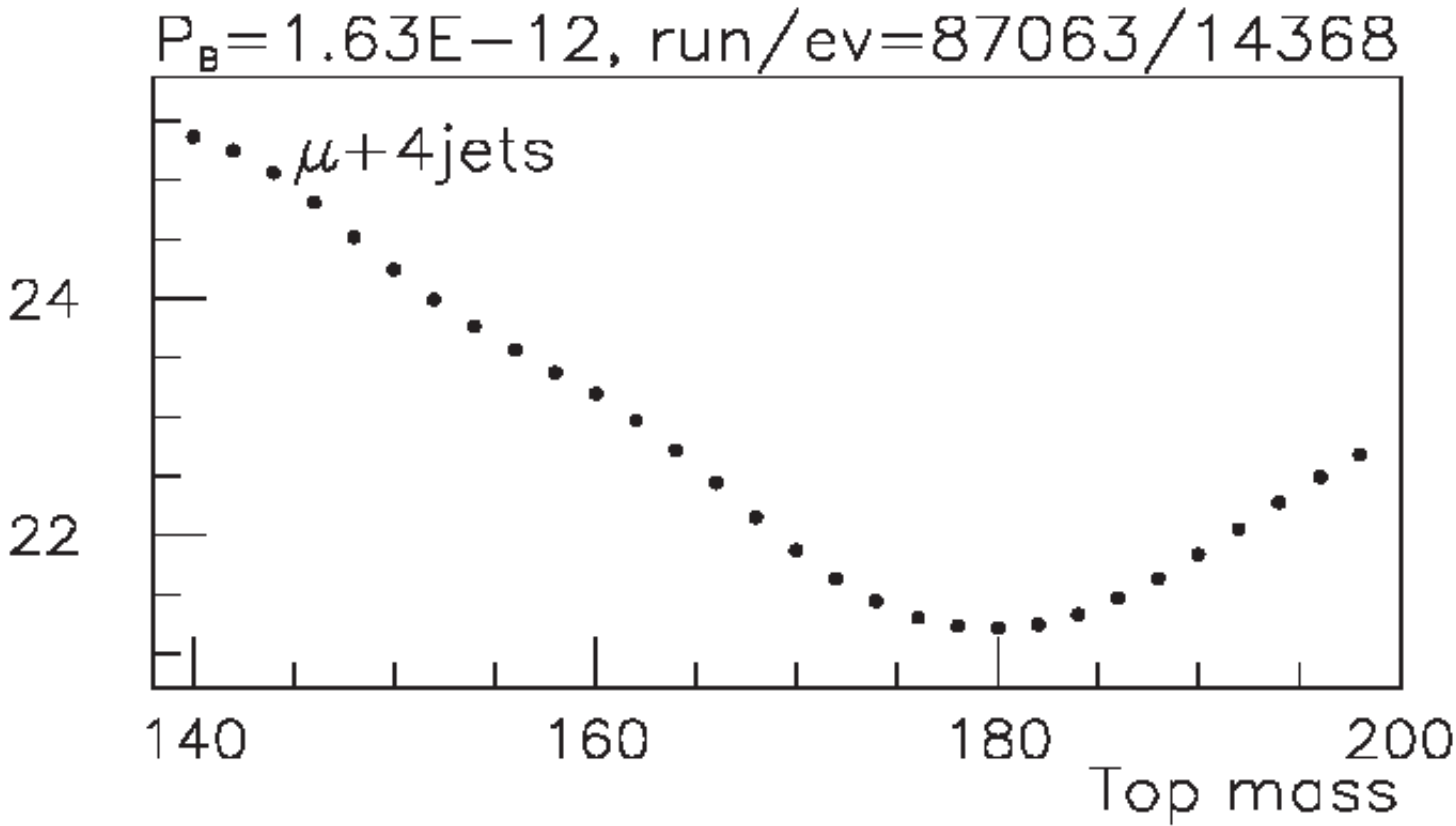

CDF II Preliminary
Data
Wbb
Wcc
Wc
QCD
Mistags
Top (6.7pb)
0
2
4
6
8
10
12
14
16
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
L2d (cm)

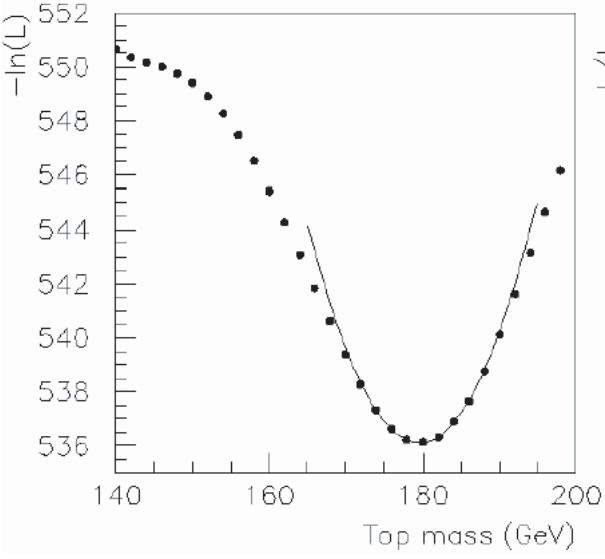

CDF II preliminary
mistags
Wbb
Wcc
non-W
Wc
WW,WZ,Z→ττ
Single top
Tot bkgd± 1σ
Data (162 pb-1)
require HT > 200 for ≥ 3 jets
Number of tagged events
Number of jets in W+jets
0
20
40
60
80
100
120
140
160
1
2
3
≥ 4

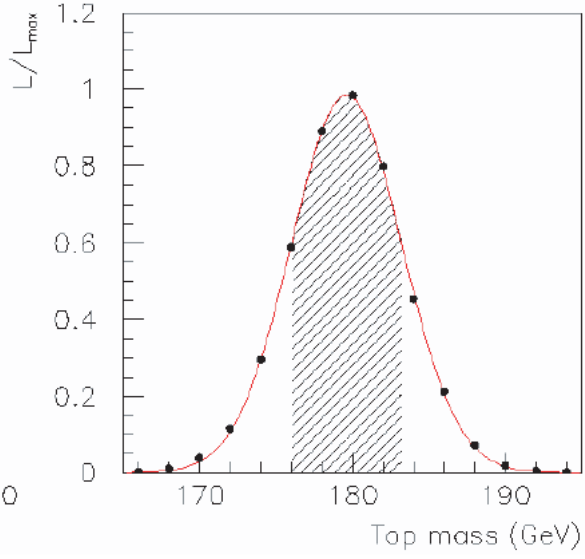
Dataflow of CDF "Deadtimeless" Trigger and DAQ

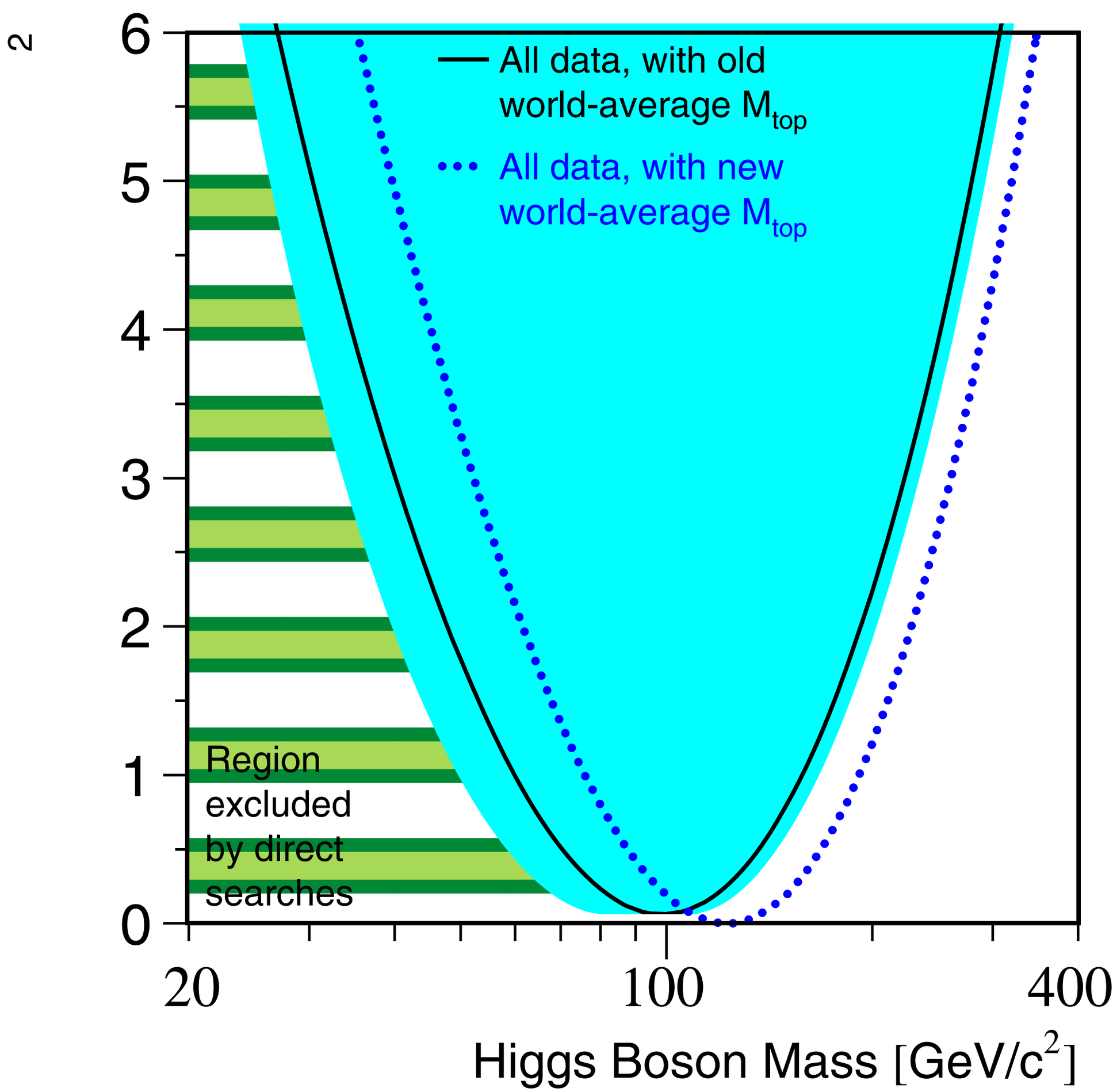


PJW 10/28/96


P_B=1.63E−12, run/ev=87063/14368
μ+4jets
24
22
140
160
180
200
Top mass


−ln(L)
552
550
548
546
544
542
540
538
536
140
160
180
200
Top mass (GeV)

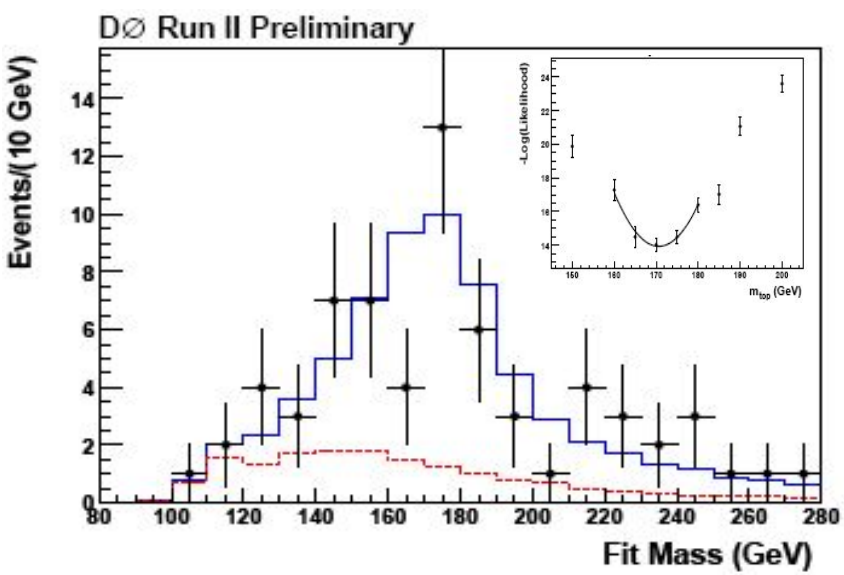

L/L_max
1.2
1
0.8
0.6
0.4
0.2
0
170
180
190
Top mass (GeV)


2
6
5
4
3
2
1
0
All data, with old world-average M_{top}
All data, with new world-average M_{top}
Region excluded by direct searches
20
100
400
Higgs Boson Mass [GeV/c^2]

Lepton+jets: DØ Template Method

- Lepton + jets channel with b-tag using 'SVT' secondary vertex tagger
  - similar selection
  - one or more b-tagged jets
  - ≥ 4 jets with p_T>15 GeV
  - No cut on low bias discriminant D_{LB}
- 60 $t\bar{t}$ candidates selected, S/B ~ 3/1

Systematic Uncertainties	Δmtop (GeV/c2)
Jet Energy Scale	-5.3/+4.7
Gluon Radiation	2 .4
Signal Model	2 .3
Jet Energy Resolution	0.9
Calibration	0.5
Background Model	0.8
b-tagging	0.7
Trigger Bias	0.5
Limited MC Statistics	0.5
Total	**6.0**



$t\bar{t}$+Background
Background
Data

NEW
~230 pb^{-1}

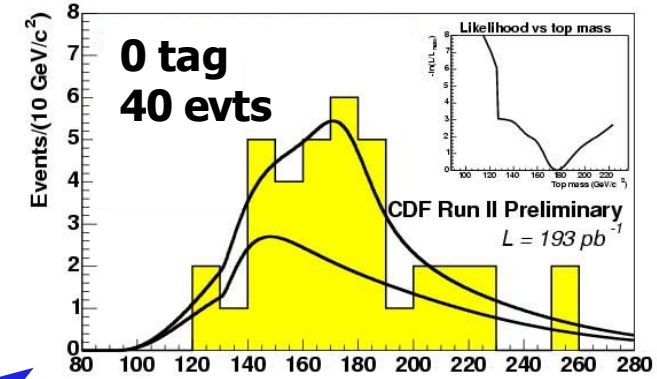
best preliminary RunII top mass result

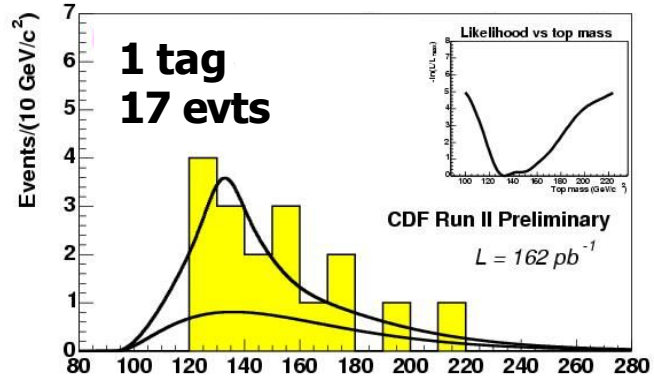
$$M_{top} = 170.6 \pm 4.2(stat) \pm 6.0(sys)\ GeV/c^2$$

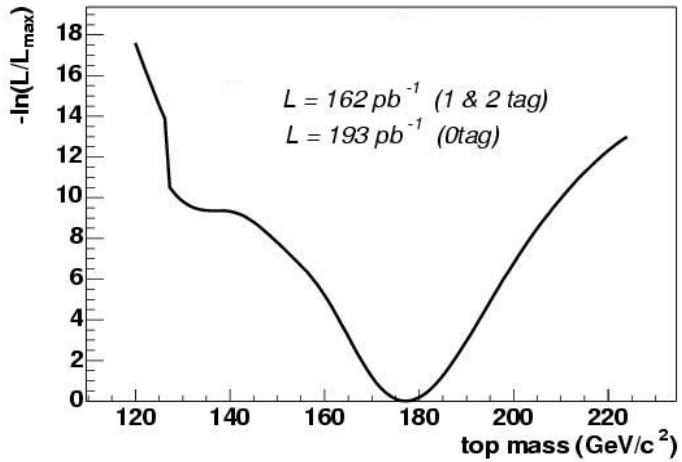
Lepton+jets: CDF Template Method

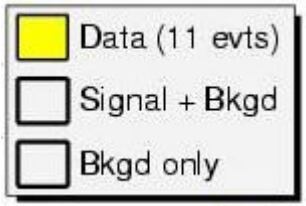
- Lepton +jets selection:
  One e or μ with p_T>20 GeV/c
  3 jets with E_T>15 GeV, 4th jet E_T>8 GeV
  missing E_T>20 GeV
- 0 tag sample: 4th jet E_T > 21 GeV →S/B~2/3
- 1 tag sample: One jet with SVX tag →S/B~3/2
- 2 tag sample: Use more efficient Jet Probability algorithm for 2nd b-tag →S/B~40/1

Kinematic Fit; lowest χ^2 solution compatible with b-tags

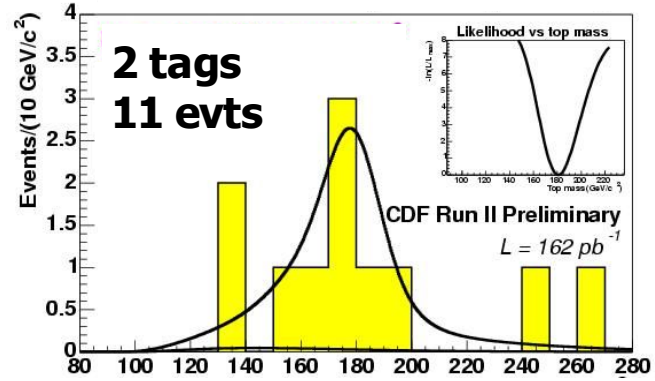






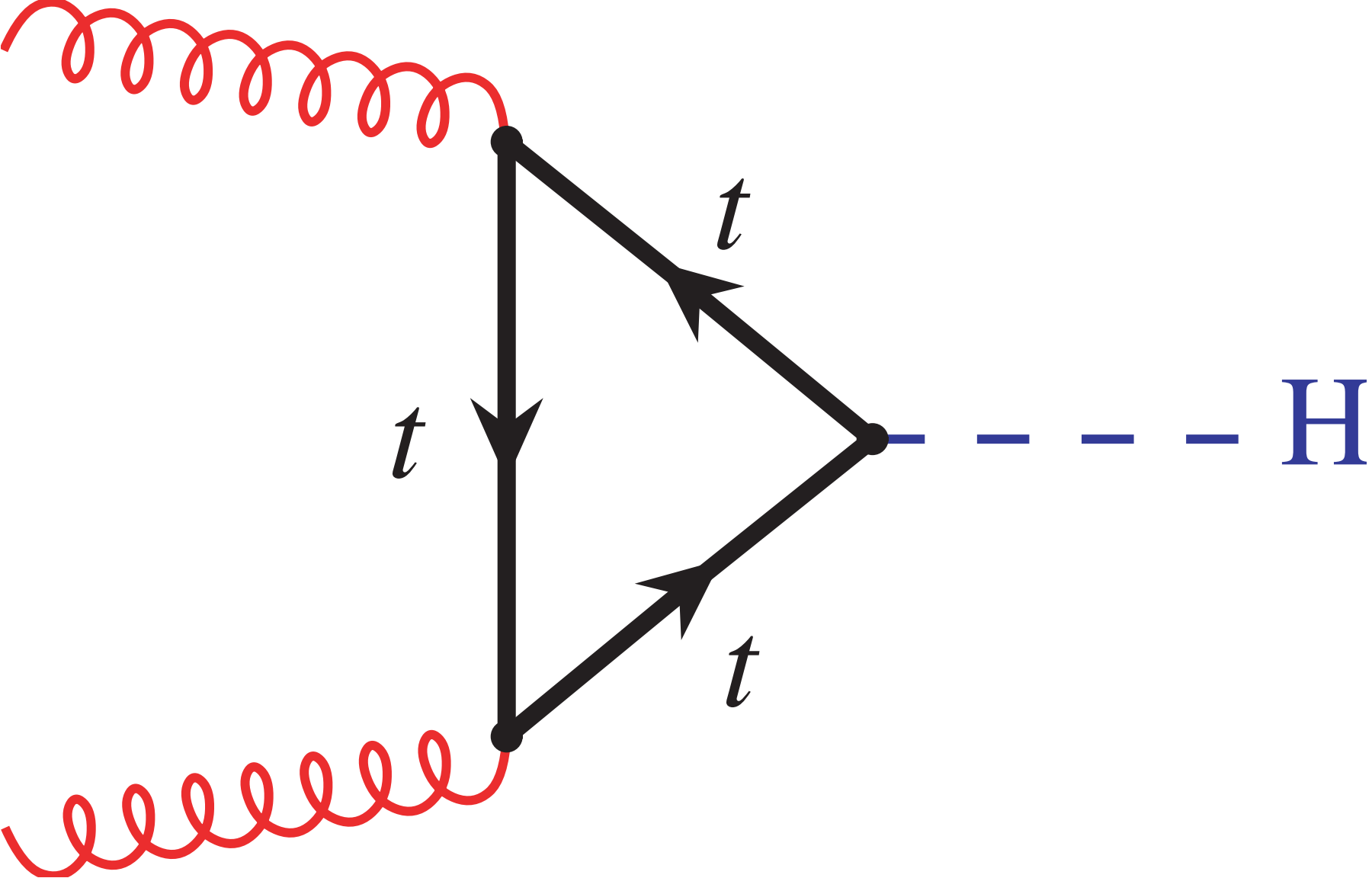


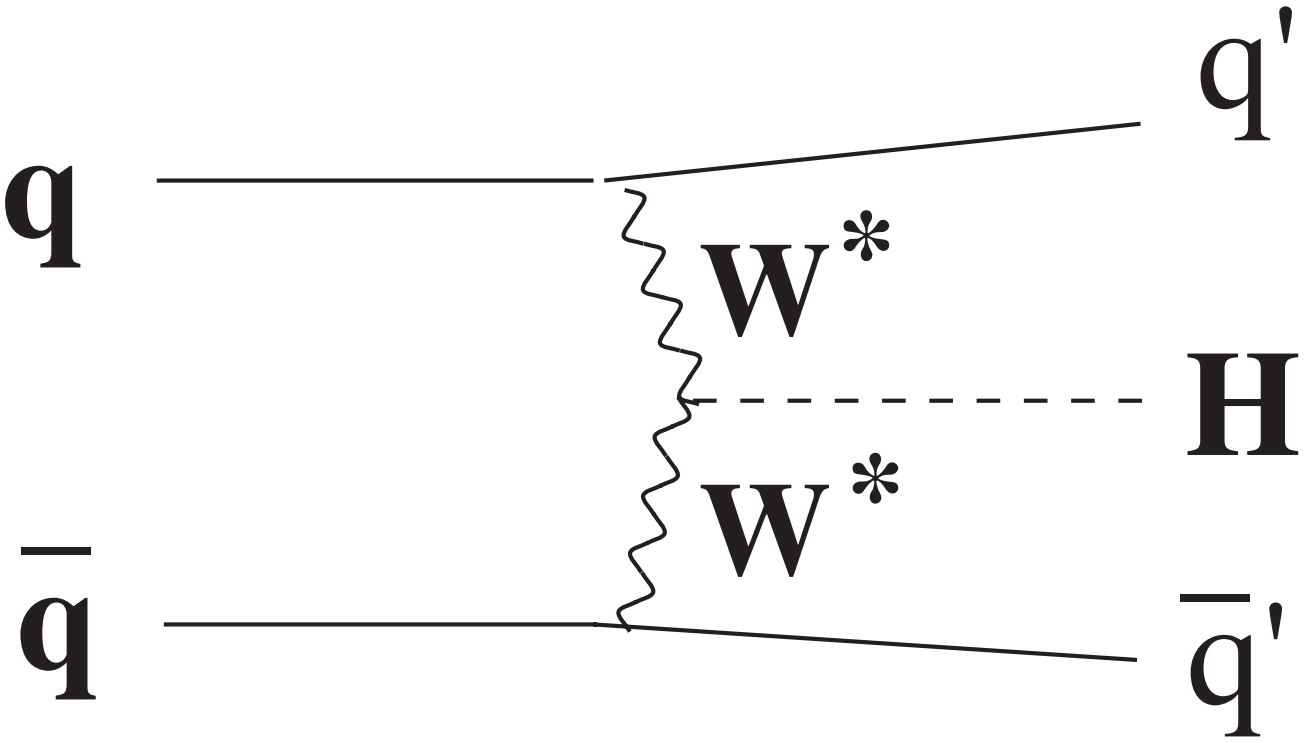
0,1, 2-tag combined

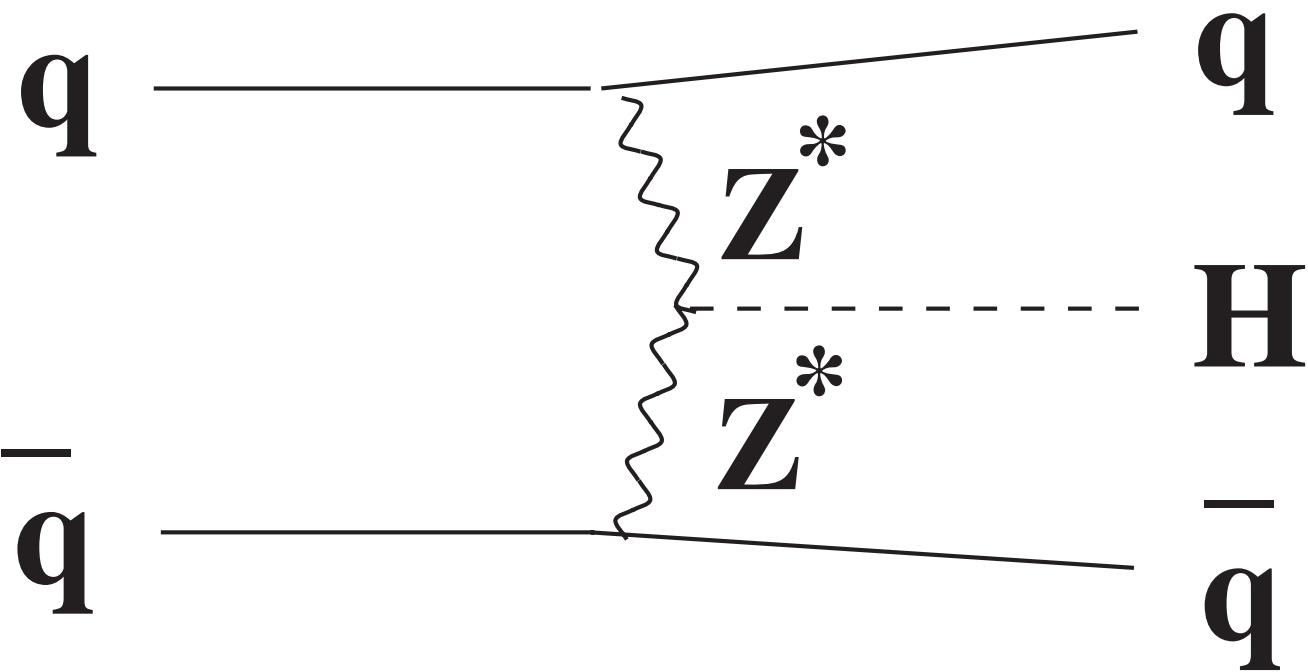


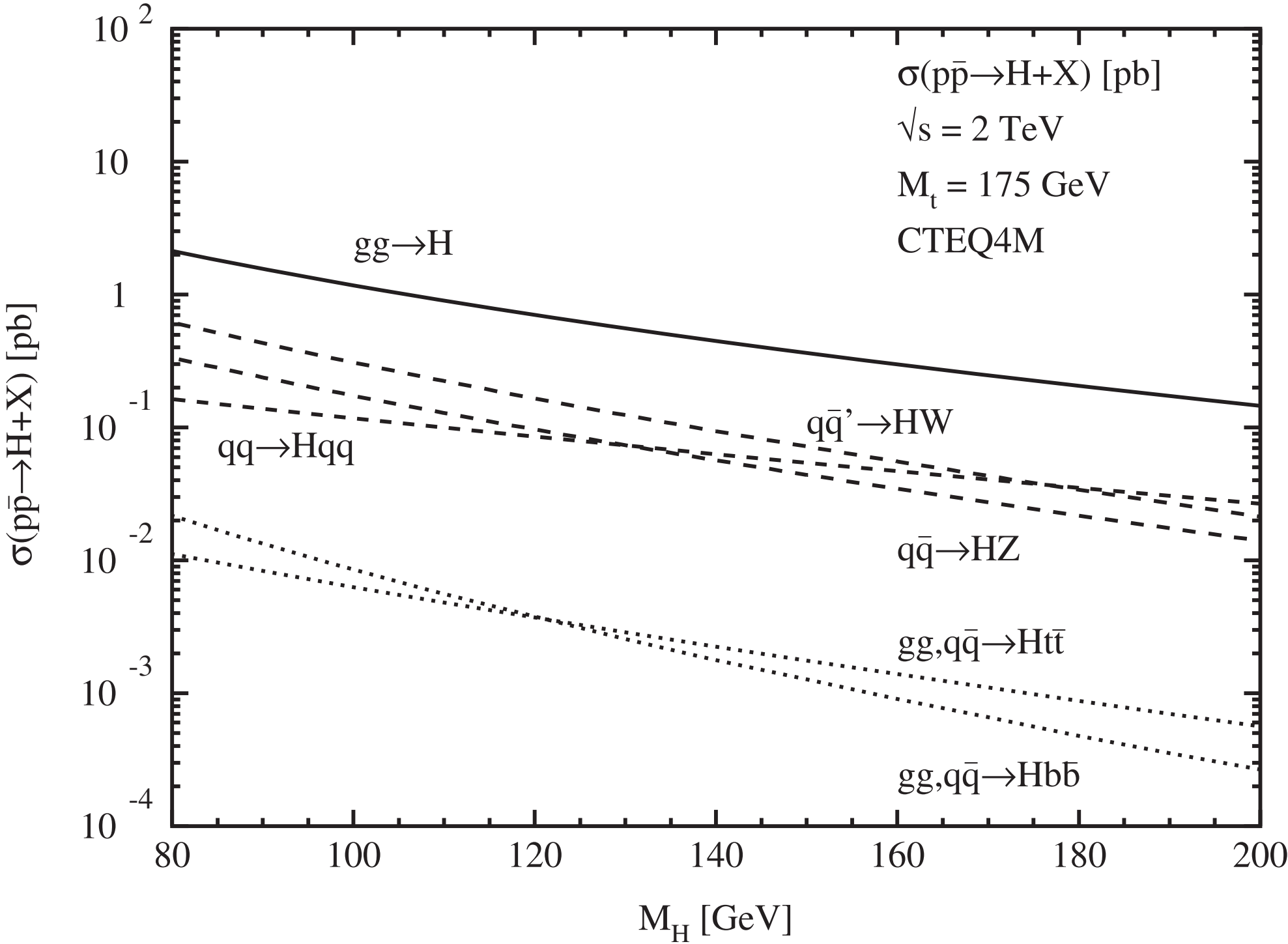
Reconstructed Top Mass (GeV/c²)

$$M_{top} = 177.2^{+4.9}_{-4.7}(stat) \pm 6.6(sys)\,GeV/c^2$$

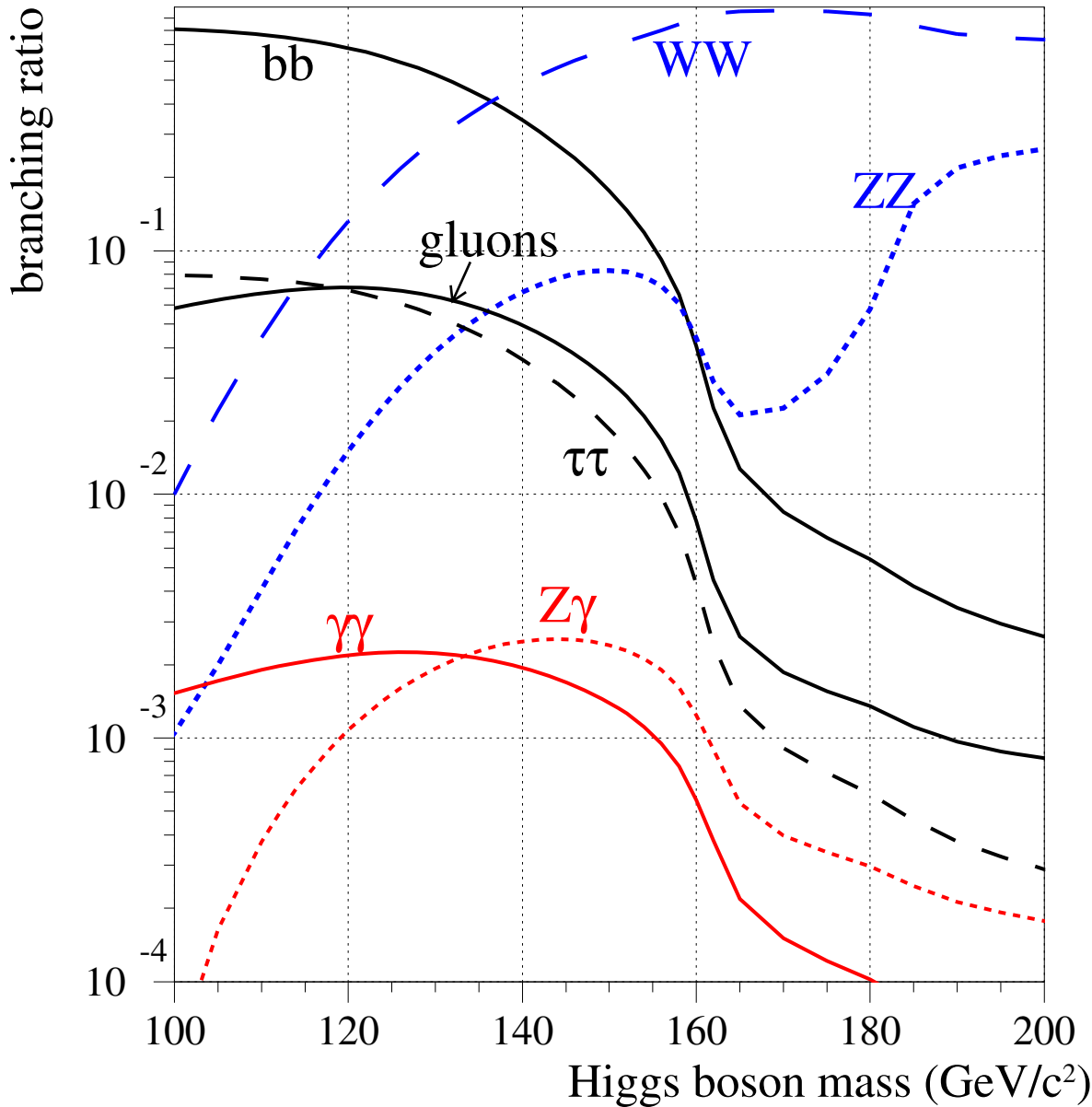

t
t
t
H

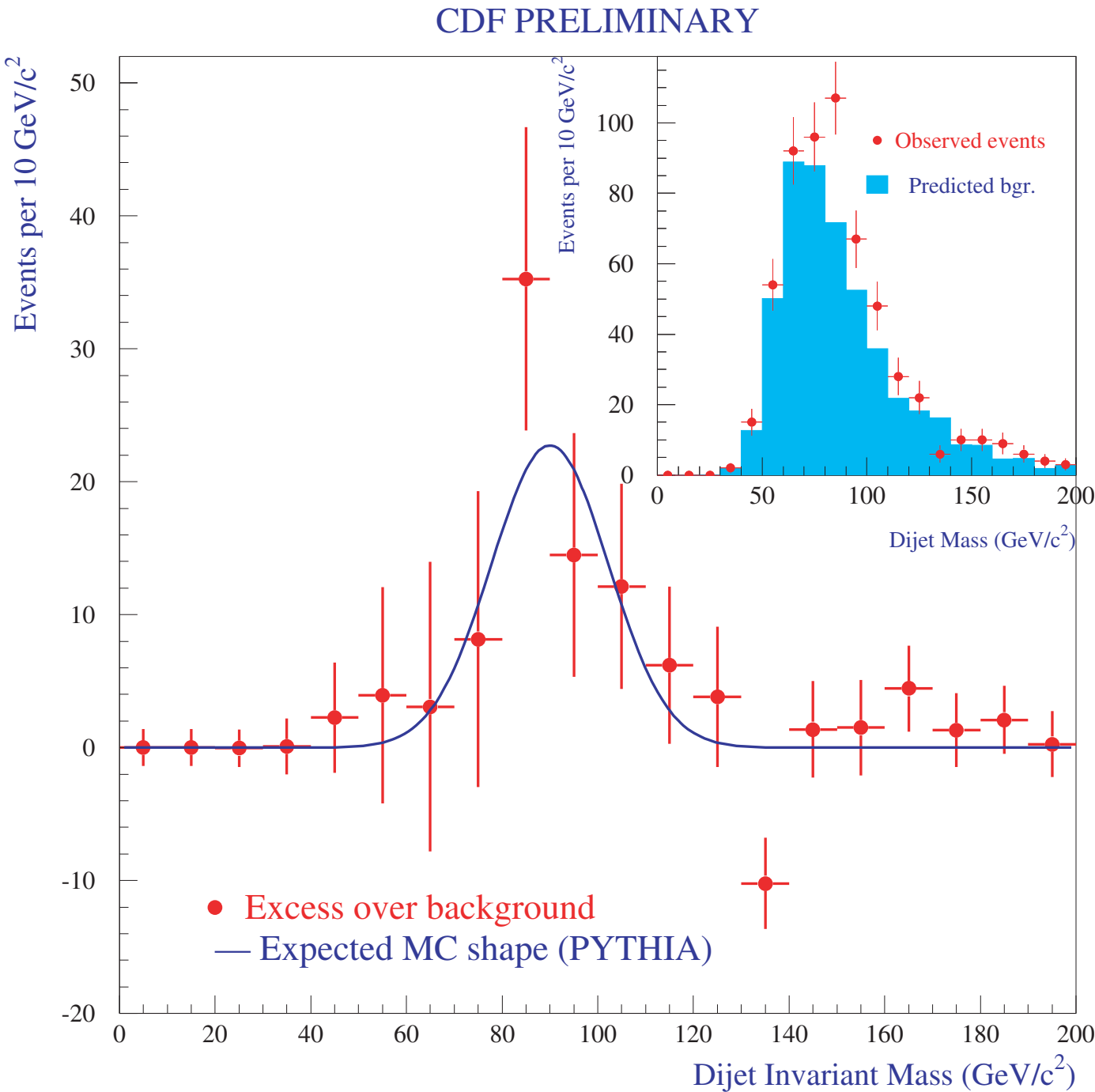

q
q'
W*
H
W*
q̄
q̄'

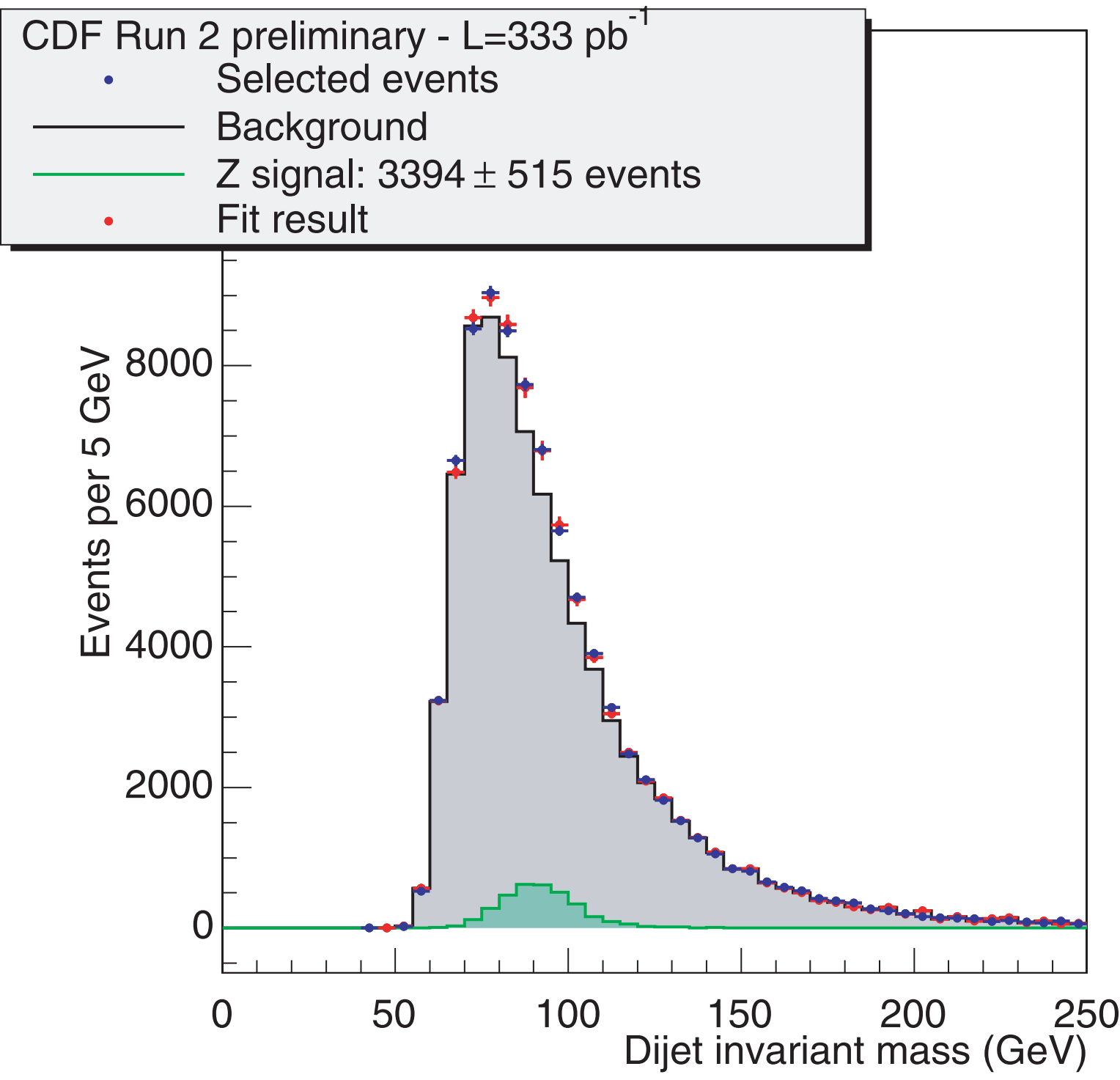

q
q
Z*
H
Z*
q̄
q̄


σ(pp̄→H+X) [pb]
√s = 2 TeV
M_t = 175 GeV
CTEQ4M
gg→H
qq̄'→HW
qq→Hqq
qq̄→HZ
gg,qq̄→Htt̄
gg,qq̄→Hbb̄
σ(pp̄→H+X) [pb]
M_H [GeV]
10^2
10
1
10^-1
10^-2
10^-3
10^-4
80
100
120
140
160
180
200

Higgs Branching Fractions from HDECAY




CDF PRELIMINARY
Events per 10 GeV/c^2
Dijet Invariant Mass (GeV/c^2)
Excess over background
Expected MC shape (PYTHIA)
Observed events
Predicted bgr.
Events per 10 GeV/c^2
Dijet Mass (GeV/c^2)

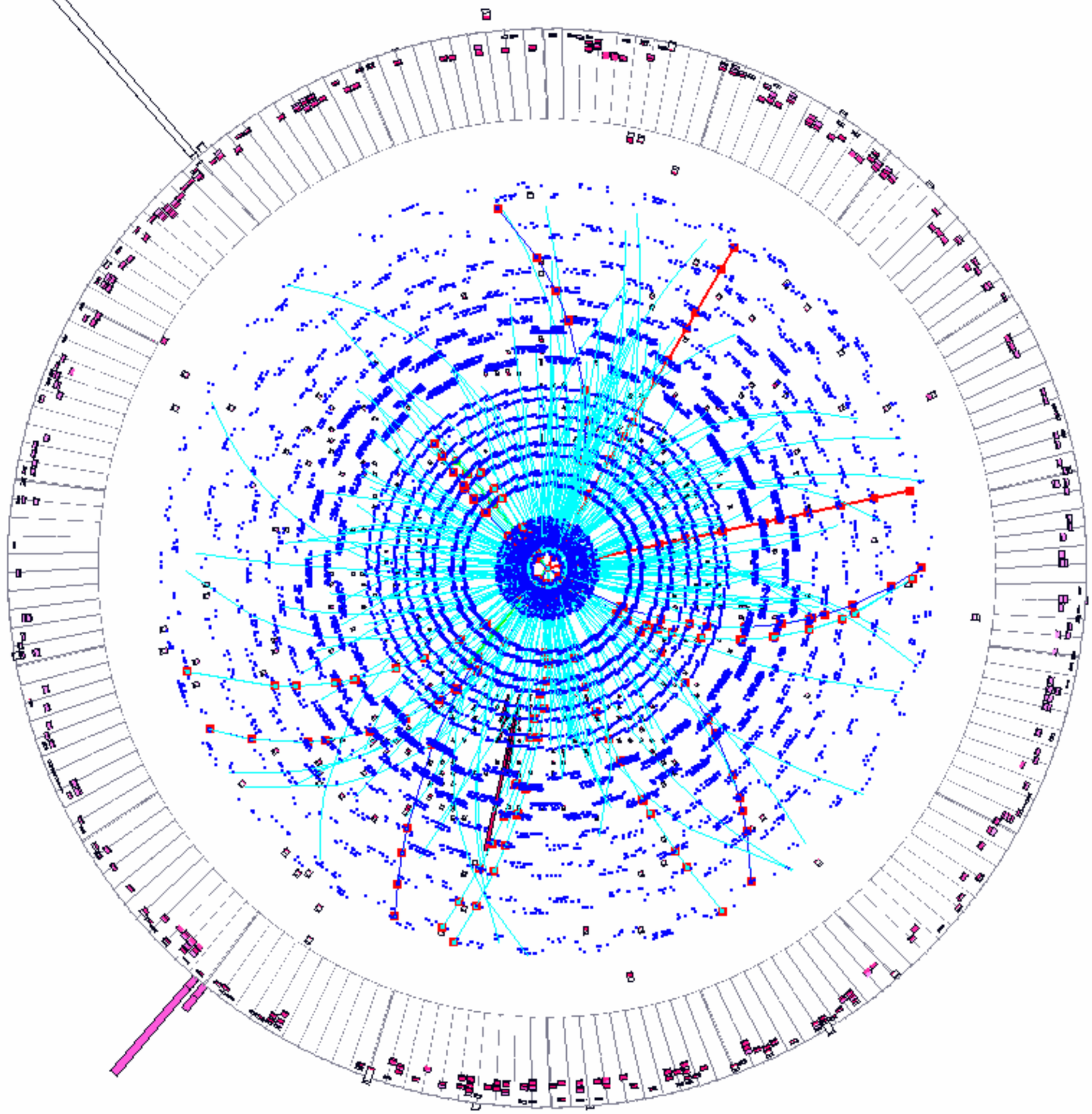

CDF Run 2 preliminary - L=333 pb^{-1}
Selected events
Background
Z signal: 3394 ± 515 events
Fit result
Events per 5 GeV
8000
6000
4000
2000
0
0
50
100
150
200
250
Dijet invariant mass (GeV)

ORCA Rec Application Visualisation - [3D Window #0]

File View Window Config Debug Help

Object | Visi

- Objects
  - Event
    - Containers
    - Calorimetry
      - Ecal Endcap Hits
      - Ecal Barrel Hits
      - Hcal Endcap Hits
      - Hcal Barrel Hits
      - Hcal Forward Hits
      - Preshower Hits
      - Ecal Digis
      - Hcal Digis (color)
      - Hcal Digis
      - Jets
    - Tracker event
      - Sim Hits
      - Sim Hits for Reco
      - Digis
      - Det Units with Hits
      - Sim Tracks
      - Rec tracks
    - CustomTracker
      - TkSelection
        - TrackerSelection
        - Sim Tracks
        - Rec tracks
      - Tk2DMap
        - TrackerMap
  - CMS Detector G3
    - Muon
    - Barrel



0.3/0.0 fps

Run #123, Event #7, Dataset: StW812p3Digis1x1034/h300eemm

ORCA Rec Application Visualisation - [3D Window #0]

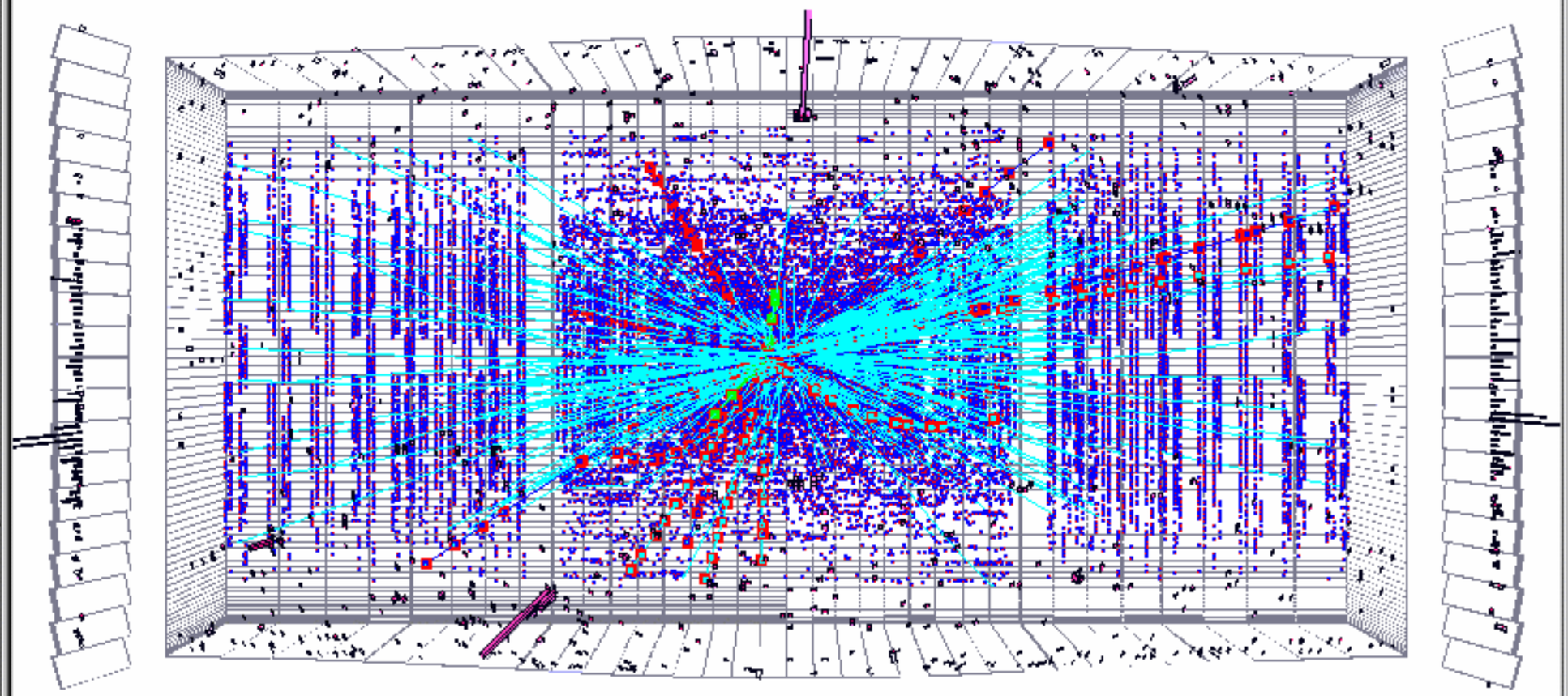
File View Window Config Debug Help

Object | Visibility

- Containers
- Calorimetry
  - Ecal Endcap Hits
  - Ecal Barrel Hits
  - Hcal Endcap Hits
  - Hcal Barrel Hits
  - Hcal Forward Hits
  - Preshower Hits
  - Ecal Digis
  - Hcal Digis (color)
  - Hcal Digis
  - Jets
- Tracker event
  - Sim Hits
  - Sim Hits for Reco
  - Digis
  - Det Units with Hits
  - Sim Tracks
  - Rec tracks
- CustomTracker
  - TkSelection
    - TrackerSelection
    - Sim Tracks
    - Rec tracks
  - Tk2DMap
    - TrackerMap
- CMS Detector G3
  - Muon
    - Barrel

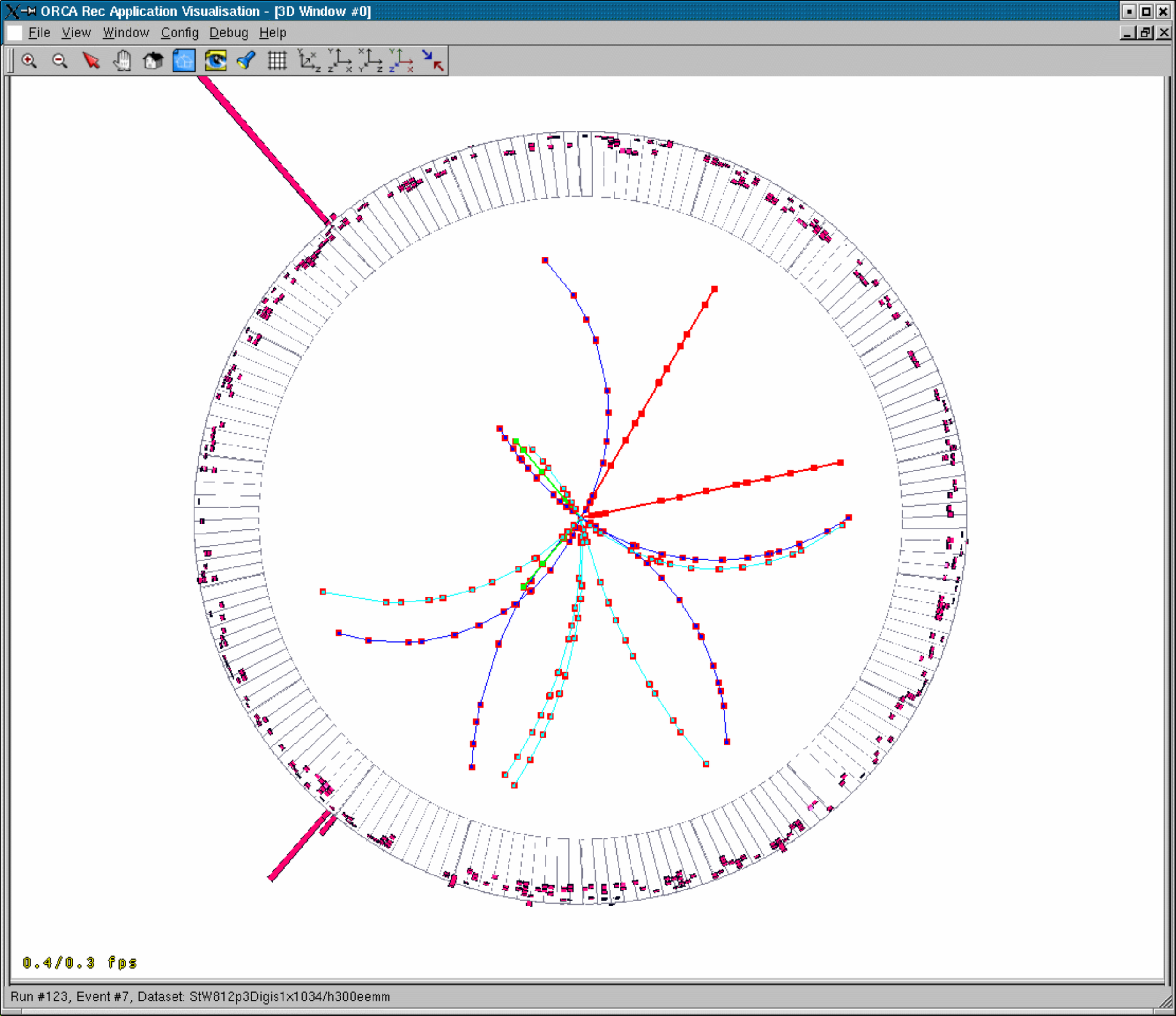
Sim Hits

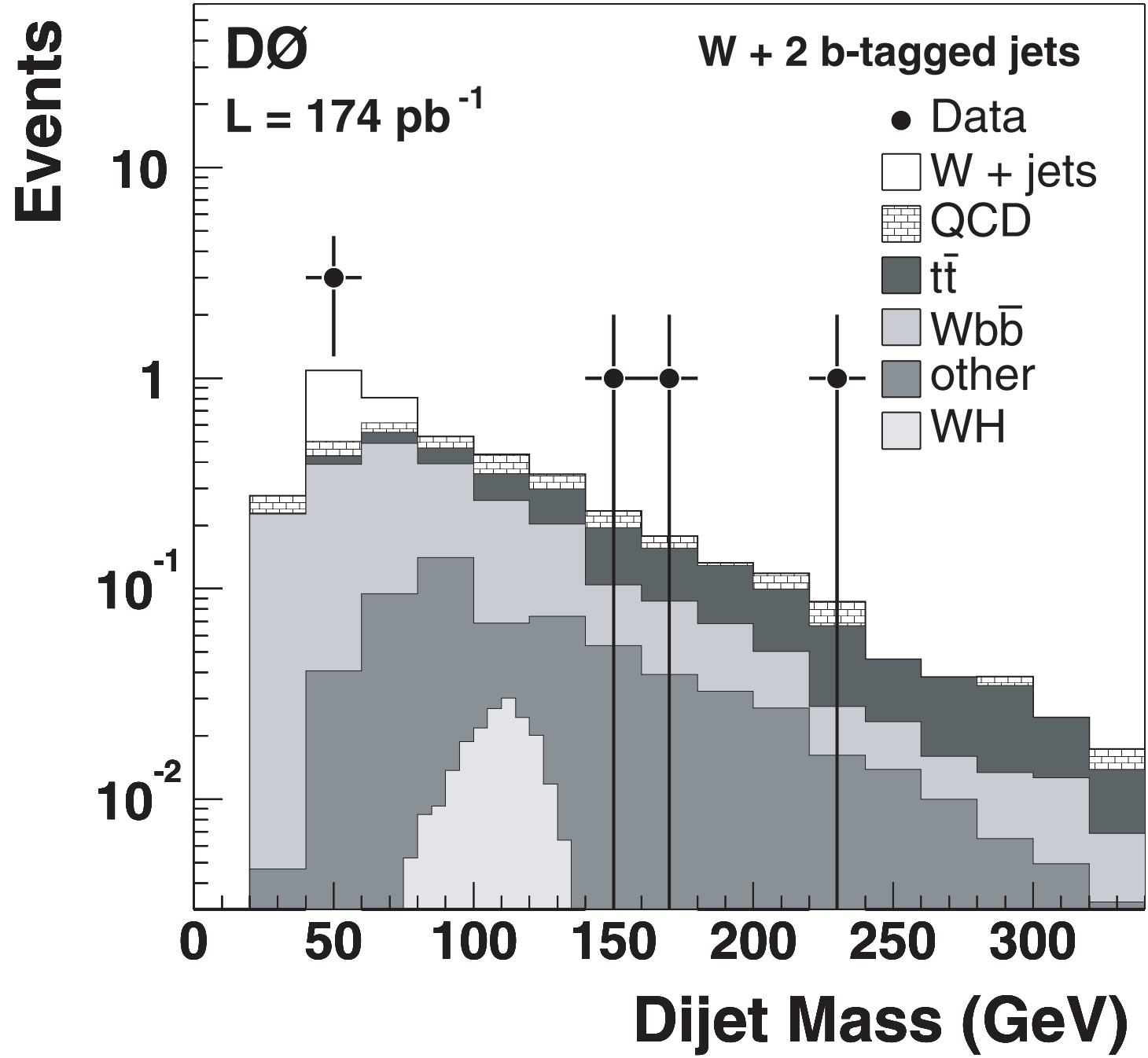
Tracker SimHits: 13434/4153(Pixel barrel/ forward) 46401/62093(Silicon barrel/forward)



0.3/0.2 fps

Run #123, Event #7, Dataset: StW812p3Digis1x1034/h300eemm


ORCA Rec Application Visualisation - [3D Window #0]
File View Window Config Debug Help
0.4/0.3 fps
Run #123, Event #7, Dataset: StW812p3Digis1x1034/h300eemm


DØ
L = 174 pb^{-1}
W + 2 b-tagged jets
Data
W + jets
QCD
$t\bar{t}$
$Wb\bar{b}$
other
WH
Events
10
1
10^{-1}
10^{-2}
0
50
100
150
200
250
300
Dijet Mass (GeV)