Experimental Particle Physics

Abstract

I’ll review a few important results established over the 4 past decades mainly from Experiments at Particle Colliders.

- First lecture: past discoveries of, then, new particles
- Second lecture: precision measurements and indirect constraints
- Third lecture: direct searches for new particles

Outline

I. Introduction

- Lecture Reading Grid
- Trigger
- Lepton versus Hadron Colliders

II. Direct production of new particles – Part 1: past discoveries: « how we established our Mendeleev's table »

- Electroweak Vector Bosons: W, Z
- Heavy quarks: c, b

III. Precision measurements: « how we test our models and constrain new physics through virtual effects »

- W mass at LEPII & D0 Run IIA
- Top mass at the TEVATRON Run II
- Indirect constraints on the mass of the SM Higgs boson

IV. Direct production of new particles – Part 2: possible future discoveries: or « how we could enlarge our Mendeleev's table »

- Search for the SM Higgs boson (LEP II, TEVATRON Run II)
- Search for RPC SUSY (LHC)

V. Conclusions and Prospects

I. Introduction

1. Lecture Reading Grid

A. ***The theoretical context***
  - ***What is known at the time of the experiment?***
  - ***What are the stakes of the experiment?***

B. ***The experimental setup***
  - ***Particle accelerator***
  - ***Particle detectors***

C. ***The Data Analysis***
  - ***Trigger***
  - ***Offline selection***
  - ***Uncertainties***
  - ***Results***

D. ***Conclusions:***
  - ***Back to A. or what we learnt from the experiment?***

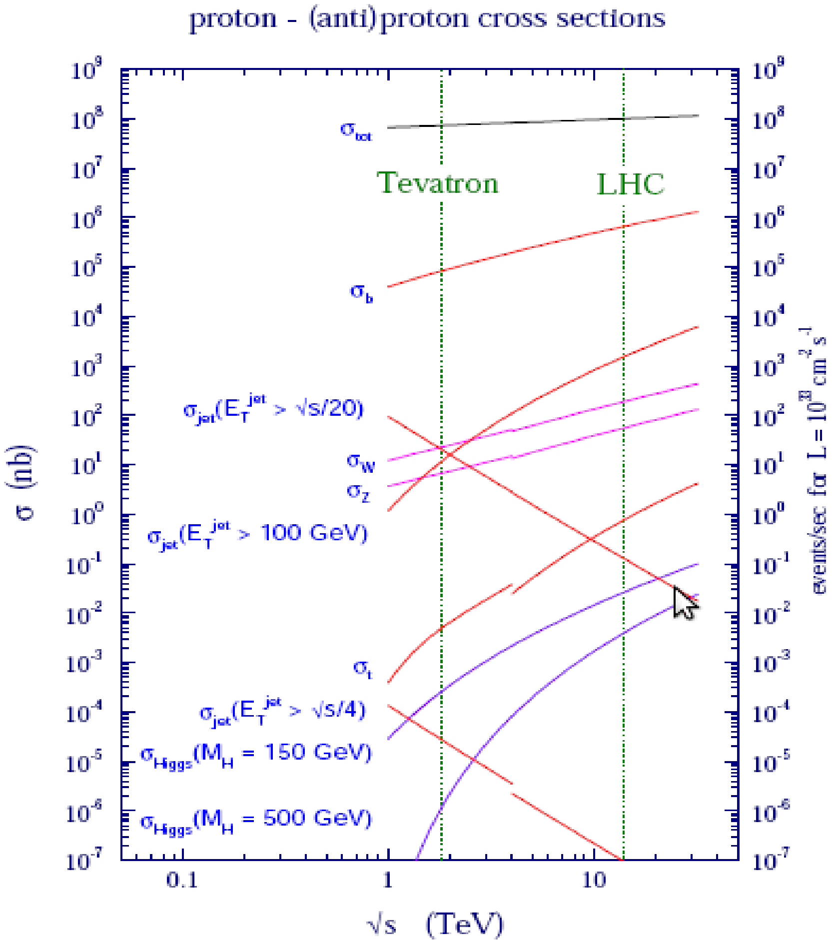
NB: All units in $\hbar = c = 1$

2. Trigger

- ***Problem***:
  - evts from processes collected w/ their unbiased cross sections would lead to a saturation of the DAQ capabilities for collecting uniteresting bkgd evts
  - the DAQ capabilities are limited anyway. In nominal LHC conditions p+p collisions occur at 40 MHz and only 0(200 Hz) are actually written to tape. Even wo/ DAQ limitations, writting 40 MHz would yield unmanageably huge datasets

- ***Solution***:
  - impose online cuts to reject bkgd evts in real time and to write only filtered evts to tape

« Find a needle in a haystack »



Lepton vs Hadron Colliders

- In general e^+e^- colliders are thought of as precision measurements machines whereas hadron colliders as discovery machines
- In a less diplomatic way some evoke e+e- colliders as clean machines in opposition to

1. **Beam Remnants**
2. **Event Kinematics**
3. **Trigger**
4. **Jet Energy Calibration**

Lepton vs Hadron Colliders

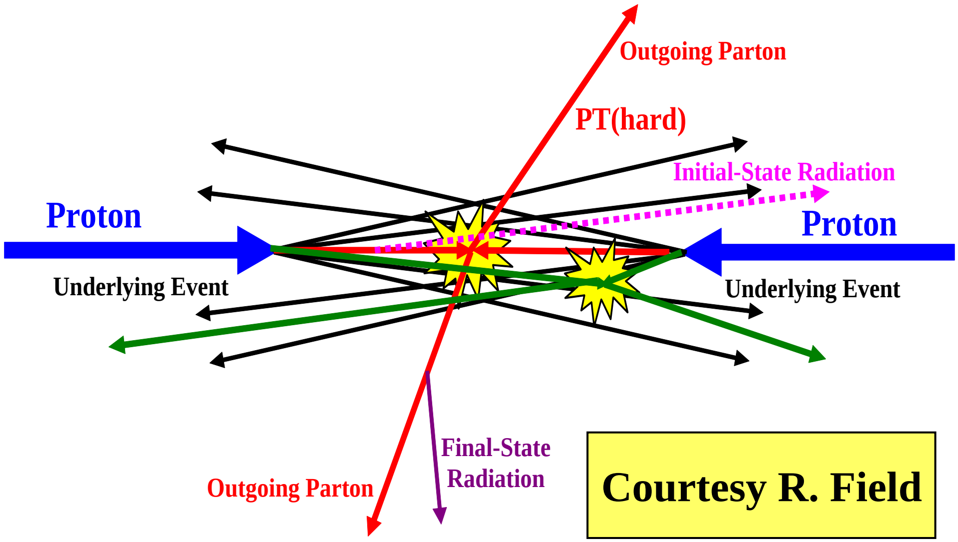
1. Beam Remnants

e^+e^- Colliders

- None: direct collisions of elementary particles

p+p/pbar Colliders

- Spectator partons are not involved in the hard scattering (nor in a 2^{dary} scattering) they constitute the beam remnants
- Beam remnants are part of the underlying event (UE)



Courtesy R. Field

Lepton vs Hadron Colliders
2. Event Kinematics (1)

e^+e^- Colliders

- Full initial state (IS) infos known:
  - Known center-of-mass energy of the e^+e^- collision: $\sqrt{s}$ (on top of the 3 $\vec{p}$ components)
- => More constraints applicable on the final state (FS) using the full $(E, \vec{p})$ conservation laws
- Usual kinematical variables: E, θ, ϕ

p+p/pbar Colliders

- Full IS infos of the 2 colliding hadrons are known,… BUT
- One misses the IS p_z, therefore one also misses the center-of-mass energy of the partons hard scattering: $\sqrt{\hat{s}}$
- => can only exploit the momentum conservation in the transverse plane (p_x,p_y)
- Usual kinematical variables: p_T, η, ϕ

where pseudo-rapidity is defined as

$$\eta \approx -Log(\theta/2)$$

Lepton vs Hadron Colliders
2. Event Kinematics (2)

e^+e^- Colliders

- Missing energy: $E_{miss} = \sqrt{s} - E_{meas}$
- Missing momentum:
  - IS: $p_x^{tot} \approx p_y^{tot} \approx 0$

    $p_z^{tot} = 0$
    - where:

    $$p_z^1 = -p_z^2 = E_{beam} = \frac{\sqrt{s}}{2}$$
  - FS: $p_x^{tot} \approx p_y^{tot} \approx 0$

    $p_z^{tot} = 0$

p+p/pbar Colliders

- Transverse Missing Momentum:
  - improperly called Transverse Missing Energy, denoted: $\not{E}_T$
  - actually calculated as:

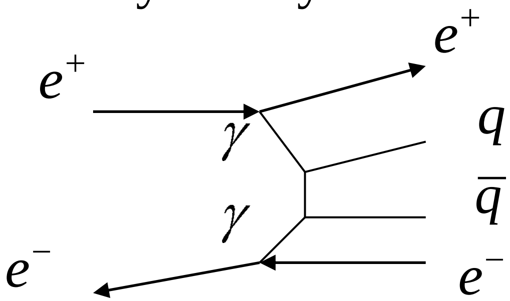
$$\vec{\not{p}}_T = \begin{pmatrix} \not{p}_x = -\sum_{i=1}^{N_{visible}} p_x^i \\ \not{p}_y = -\sum_{i=1}^{N_{visible}} p_y^i \end{pmatrix}$$

Lepton vs Hadron Colliders

3. Trigger

e^+e^- Colliders

- Except for γγ physics, most of the high pT physics analyses rely on the « Energy Trigger »



- Definition: event is kept and copied to tape is the total energy in the calorimeter is larger than a given threshold
- For high p_T physics this trigger:
  - has a relatively fast turn-on
  - is very simple and efficient

p+p/pbar Colliders

- QCD background σ is larger than that of interesting process:
  - Example of SM process:

$\sigma_{QCD} > 10^6 \text{ x } \sigma_{ttbar}$

  - Example of NP process:

$\sigma_{QCD} > 10^9 \text{ x } \sigma_{H(150)}$

- Online selection based on features differing from that of bulk QCD:
  - charged leptons, photons, large mET,…
  - special topologies
  - Examples: mu4j20 or j70_xE70

Lepton vs Hadron Colliders
4. Jet Energy Calibration (1)

e^+e^- Colliders

- EM Scale:

Z→ee

- JES:

Use the Z→qqbar mass peak to correct the jet energies so as to retrieve the dijet invariant mass MPV at the previously well measured Z mass: 91.18 GeV

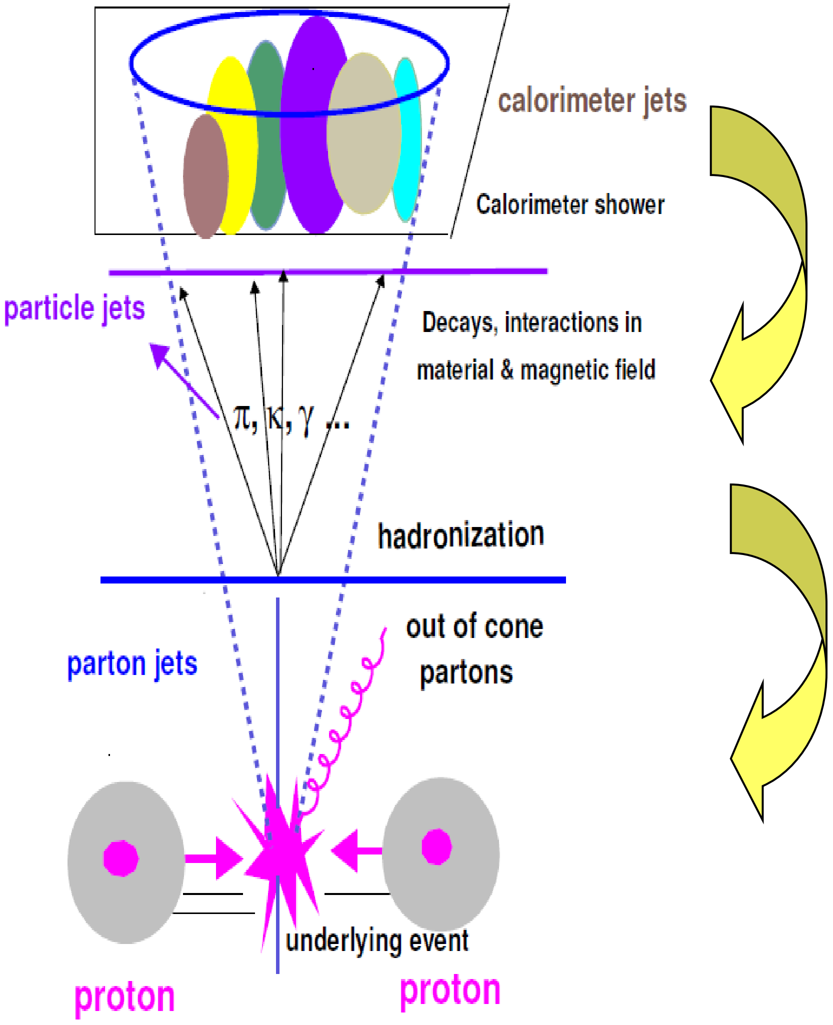
p+p/pbar Colliders

- EM Scale: Z→ee
  - $\mathbf{E_{meas} = E_{true} .(1+\alpha_i)}$
  - $\mathbf{M_{ij}^{meas} \sim M_{ij}^{true}.[1+(\alpha_i+\alpha_j)/2]}$

- JES:

Use γ+jets events to transport the EM scale to the jets by imposing the p_T balance between the EM object and the recoiling hadronic system (in general, reduce this system to a single jet <= $\Delta\phi$ cut)

Lepton vs Hadron Colliders
4. Jet Energy Calibration (2)
p+p/pbar Colliders



Master formula:

$$E_{jet}^{cor} = \frac{(E_{jet}^{calo} - O)}{F_{\eta} \cdot R_{jet} \cdot S}$$

- F_{η}: response η uniformization
- O: jet energy offset
- R_{jet}: jet response
- S: out-of-cone showering
  - Note: S=1 for k_T-type algos

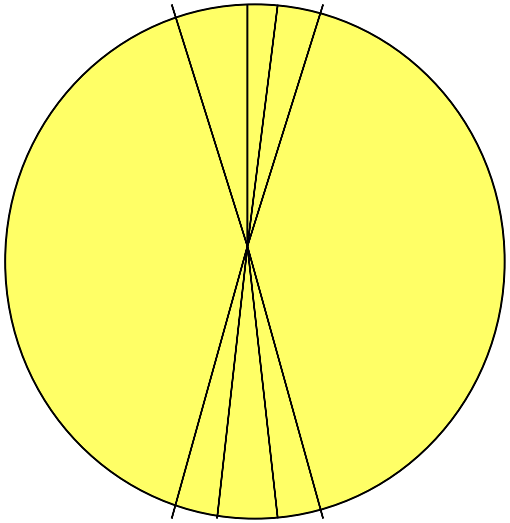
Lepton vs Hadron Colliders

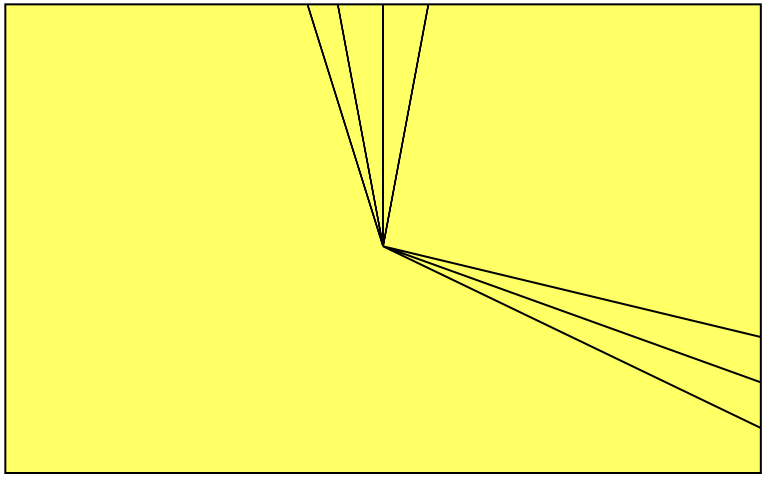
4. Jet Energy Calibration (3)

p+p/pbar Colliders

F_η:

- Select dijets events:
    - well balanced in p_T
    - but that lie in different parts of the calorimeters
- Equalize the jets response





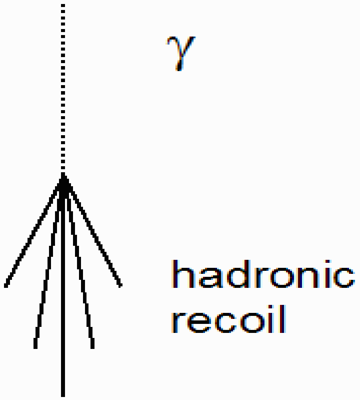
Lepton vs Hadron Colliders

4. Jet Energy Calibration (4)

p+p/pbar Colliders

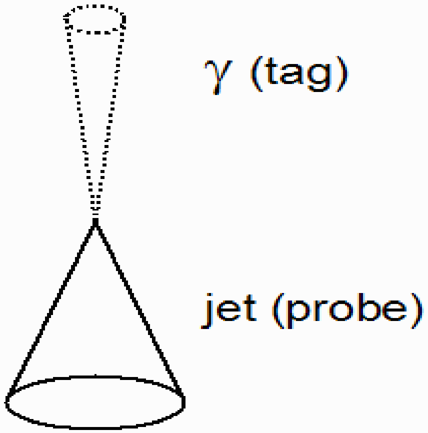
Missing E_T Projection Fraction Method: γ+jet

Particle Level



$$\vec{p}_{T,\gamma} + \vec{p}_{T,had} = \vec{0}$$

Detector Level



$$\vec{p}_{T,\gamma} + R_{had}\vec{p}_{T,had} = -\vec{\not{E}}_T$$

$$R_{had} = 1 + \frac{\vec{\not{E}}_T \cdot \vec{p}_{T,\gamma}}{\vec{p}_{T,\gamma}^{\,2}}$$

For back-to-back events : $R_{jet} \approx R_{had}$

II. Direct Production of New Particles
- Part 1: Past Discoveries -

or « How we established our Mendeleev's table »

Discovery of the Electroweak Vector Bosons: W and Z

Discovery of the Electroweak Vector Bosons: W and Z (1)

- We are in 1983 at the UA1 and UA2 experiments of the CERN SPS collider

A. The theoretical context

- SM is already in place
  - reminder: $SU(2)_L \times U(1)_Y$ gauge group structure proposed to (partly) unify EM and weak interactions (γ plus 3 new bosons: W^+, W^-, Z^0)
    - **S.L. Glashow, Nucl. Phys. 22 (1961) 579**
    - **A. Salam, Proc. 8th Nobel Symposium (ed. N. Svartholm) (Almqvist and Wiksell, Stockholm, 1968), p. 367**
    - **S. Weinberg, Phys. Rev. Lett. 29 (1967) 1264**

- This theoretical model was really taken seriously essentially because of the:
  - proof of the renormalizability of spontaneously broken gauge theories by G. t'Hooft and M. Veltman

    't Hooft, G., Nuclear Physics B 33, 173 and B 35 (1971) 167
  - discovery of the EW neutral currents in the Gargamelle bubble chamber experiment at CERN

    Hasert, F. J., et al., Physics Letters 46B (1973) 138

Discovery of the Electroweak Vector Bosons: W and Z (2)

- Indirect hints of the W and Z masses:
  - $\nu+e \rightarrow \nu+e$ scattering in the Fermi 4-fermions interactions

  has a bad UV behaviour that requires a NP to fix it at some high E

  Refs: E. Fermi, Nuovo Cim.11 (1934) 1-19 and Z. Phys. 88(1934) 161-177

  - Early 1980's, at PETRA e^+e^- collisions at $\sqrt{s}$ ~30-40 GeV:
    - in ν scatterings, charged and neutral currents interpreted in Glashow-Weinberg-Salam model
      => $\sin^2\theta_W \sim 0.23$ => $M_W \sim 77.8$ GeV and $M_Z \sim 88.7$ GeV
    - In the late 1970s and early 1980s the forward-backward angular asymmetry, due to γ^*/Z interference, in $e^+e^- \rightarrow \mu^+\mu^-$ also indicated $m_z < 100$ GeV

- The stakes of this experiment were huge: discovering the W and Z would have been a magistral proof of the EW theory

Discovery of the Electroweak Vector Bosons: W and Z (3)

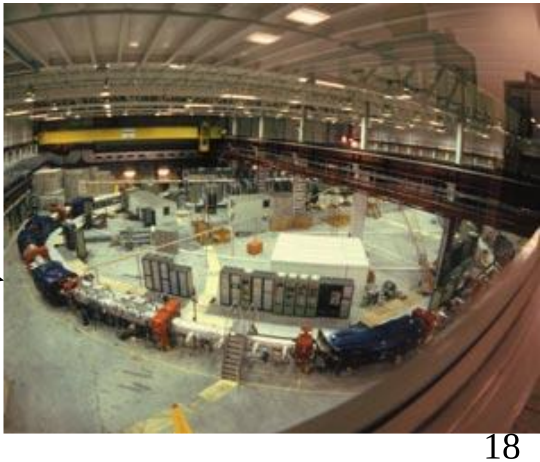
B. The experimental setup

- Accelerator:
  - the CERN SPS accelerator:
    - launched in 1976
    - 7 km in circumference
    - 1317 conventional (room t°) magnets, including 744 dipoles
    - Used the PS (26 GeV) as an injector
    - Initially p beam of up to 400 GeV sent onto a fixed target
    - Other beams: e^+, e^-, pbar, S, or O nuclei

Discovery of the Electroweak Vector Bosons: W and Z (4)

2. The experimental setup

- Accelerator:
  - Happy mariage between 2 key features:
    - Proposal to run SPS in p+pbar collider mode by C. Rubbia, P. McIntyre and D. Cline in 1976
      This alone could provide sufficient CoM E to produce W/Z, yet one needed a sufficient intensity in the pbar beam
    - Intense p and pbar beams had been developed in the meantime
      Especially the Antiproton Accumulator (AA) by F. Bonaudi, S. Van der Meer and B. Pope
    - First p+pbar collision in 1981, at $\mathscr{L}=10^{25}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
    - $\mathscr{L}$ raised to $\sim 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ over the next year



Discovery of the Electroweak Vector Bosons: W and Z (5)

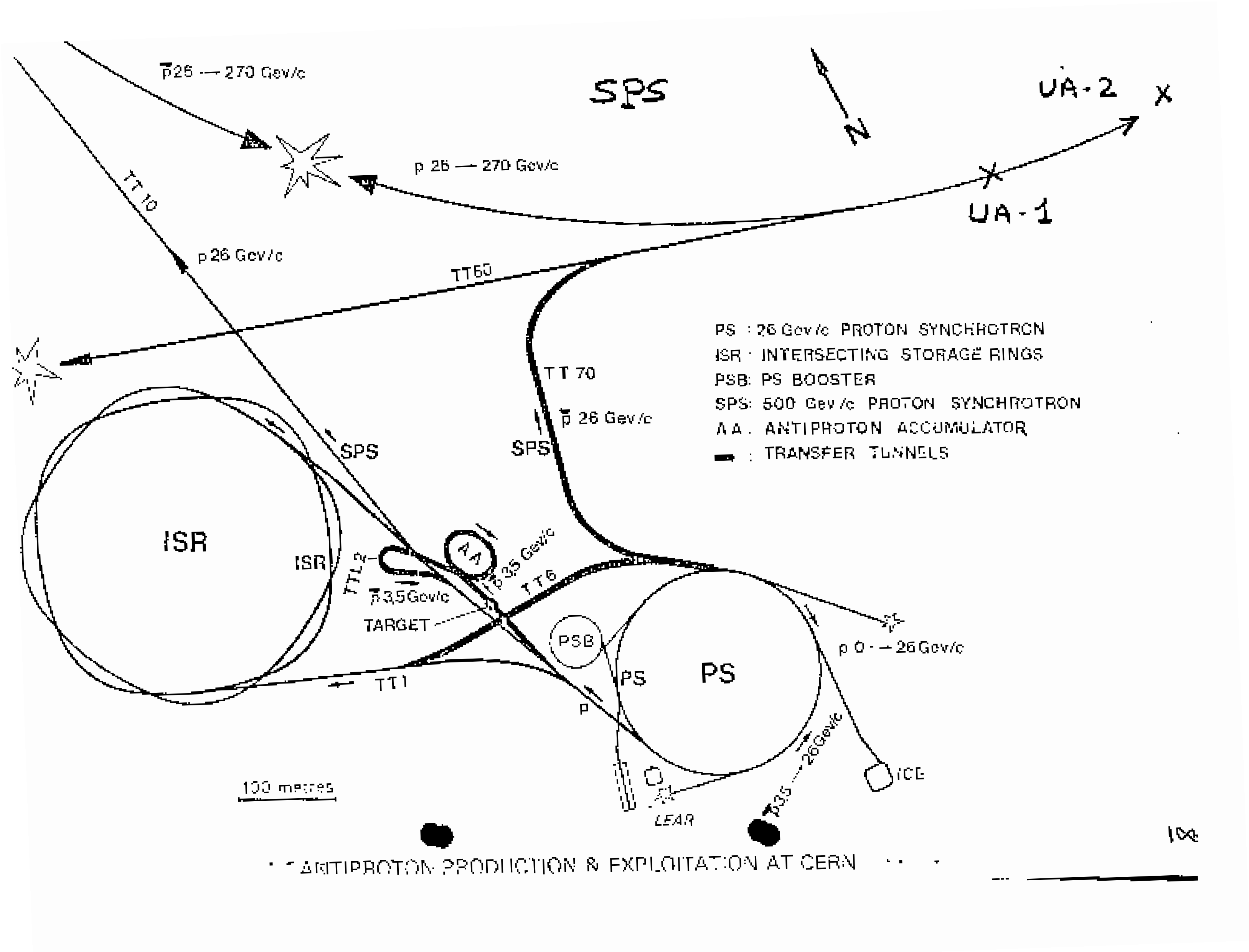
SPS as a collider:

- Large unknown: beam-beam effects
- 1st ppbar collisions: july 9th 1981, ~3 years after the project approval!
- CoM Energy: 540/630 GeV
- $\mathscr{L}=10^{25\text{-}28}$ cm^{-2}s^{-1}
- Exp int. $\mathscr{L}$ by end 1981: ~100 nb^{-1}

Remember:

$$\sqrt{s} = \sqrt{2mE_B} \longrightarrow \sqrt{s} = 2E_B$$

Discovery of the Electroweak Vector Bosons: W and Z (6)



ANTIPROTON PRODUCTION & EXPLOITATION AT CERN

Discovery of the Electroweak Vector Bosons: W and Z (7)

2 Big Detectors: UA1 & UA2

- these are not symmetry groups, but rather prototypes of large scale multipurpose detectors

UA1

- **Spokesman: C. Rubbia**
- **Collaboration @ start-up:**
  - **~130 Persons**
  - **12 Institutes**
- **R&D and construction: 1978-1981**
- **Dim & weight: ~10m x 6m x 6m, ~2000T**
- **Most complex detector at the time:**

« 1st Electronic Bubble Chamber »

- **Cost: 30 M CHF (10% for ECAL)**

UA2

- **Spokesman: P. Darriulat**
- **Collaboration @ start-up:**
  - **60 Persons**
  - **6 Institutes**
- **Cost: 10 M CHF**

Discovery of the Electroweak Vector Bosons: W and Z (8)

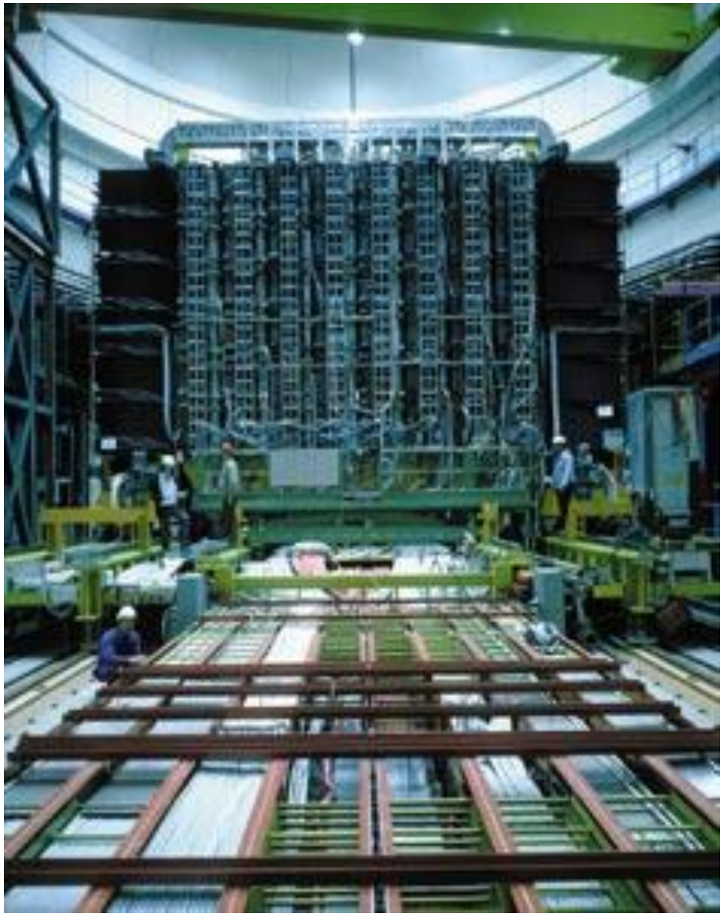
UA1

- **Central tracker:**
    - L x D = 5.3m x 2.8m
    - drift chbers w/ 6176 wires vert. & horiz.
    - $\sigma_{r\text{-}\phi}$=100-300 μm
    - B-field: 7kG = 0.7 T (_|_ to the beam)
- **Calorimeters:**
    - EM: 27 X_0 , Pb/Fe + scintillators
    - HAD: 4.5 λ_I
    - θ_{min}= 0.2°
- **Muon Spectrometer:**
    - 800m^2 of drift chambers
    - σ=300 μm

UA2

- **General features:** only central rapidities covered, simplified design optimized for electron detection
- **Central tracker:**
    - drift and proportional chambers + PS
    - B-field:
        - central: none => no charged particle q measurement (expect for W→eν at max. W asymmetry)
        - forward: toroids
- **Calorimeters:**
    - Fe/Pb + scintillators
    - $\Delta\theta$ x $\Delta\phi$ = 10° x 15°
    - Depths: 3 (central: 40°-140°) and 2 (forward: 20°-40° + Cplt)
    - θ_{min} =20°
- **Muon Spectrometer:** none!

Discovery of the Electroweak Vector Bosons: W and Z (9)



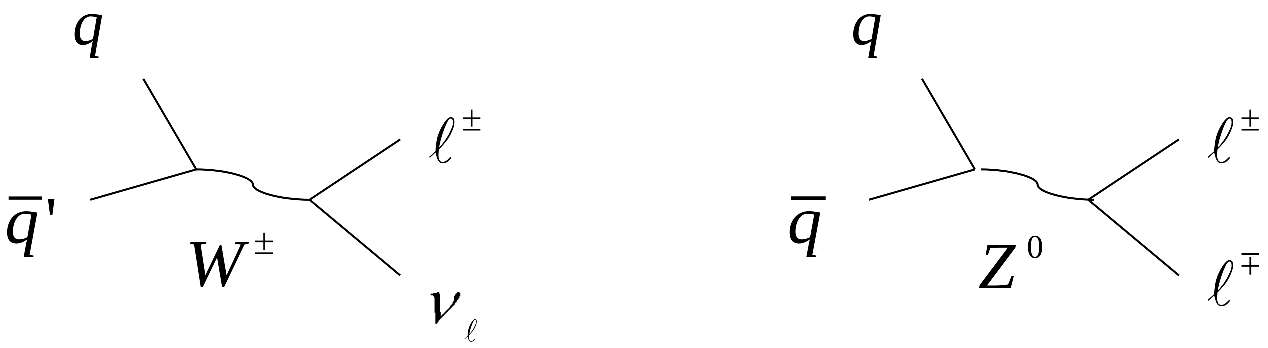
UA1 Detector

UA2 Detector

Discovery of the Electroweak Vector Bosons: W and Z (10)

Production Mechanisms

W and Z are produced through the Drell-Yan process
i.e.: EW hadroproduction of lepton pairs



Ref: S. D. Drell and T. M. Yan, Phys. Rev. Letters 25, 316 (1970)

Higher order QCD corrections may produce additional jets

Discovery of the Electroweak Vector Bosons: W and Z (11)

Event Selection

- Trigger: aka « Online Selection » -

UA1, W→eν_e
Analysis 1984

- Require an EM cluster w/:
    - $\theta > 5°$
    - $p_T > 10$ GeV

$$\int \mathscr{L} dt = 0.136\ pb^{-1}$$

- Offline Selection (1) -

- Preselection cut:
    - Require an electron candidate w/:
        - $p_T > 15$ GeV
    - yield: 1.5×10^{6} events

Discovery of the Electroweak Vector Bosons: W and Z (12)

Event Selection

- Offline Selection (2) -

- Selection cuts: *Electron ID*
  - Require a matching track w/:
  - p_T > 7 GeV (central)
  - yield: ~10^4 events

  - E_{HCAL} (e candidate) < 0.6 GeV
  - yield: 346 events

Event Selection
- Offline Selection (3) -

- Selection cuts: *Dijet Rejection*
  - Reject event if:
    - 1 jet lies within $|\Delta\phi|<30°$ wrt electron candidate
  - yield: 55 events

  - mE_T > 15 GeV
  - yield: 52 events

  - well contained EM showers
  - yield: 46 events

Discovery of the Electroweak Vector Bosons: W and Z (14)

Event Selection

- Offline Selection (4) -

- Expected remaining background:
  - less than 0.5 events from $W \rightarrow \tau(\rightarrow \pi^{+/-}+(\pi^0)+\nu_\tau)+\nu_\tau$
  - 2 events from $W \rightarrow \tau(\rightarrow e^{+/-}+\nu_e+\nu_\tau)+\nu_\tau$

- Systematic uncertainties:
  - ECAL intercalibration:
    - 4% dispersion
    - finally a negliglible impact on m_W
  - absolute EM scale ($Z \rightarrow e^+e^-$):
    - 3%
  - integrated luminosity:
    - 15%

Discovery of the Electroweak Vector Bosons: W and Z (15)

Results

- Mass:
  - from $p_T(e)$ fit: $M_W = 80.5 +/- 0.5$ GeV
  - from $m_T(e,\nu_e)$ fit: $M_W = 80.3 + 0.4 -1.3$ GeV
  - comparison with very first mass measurements:

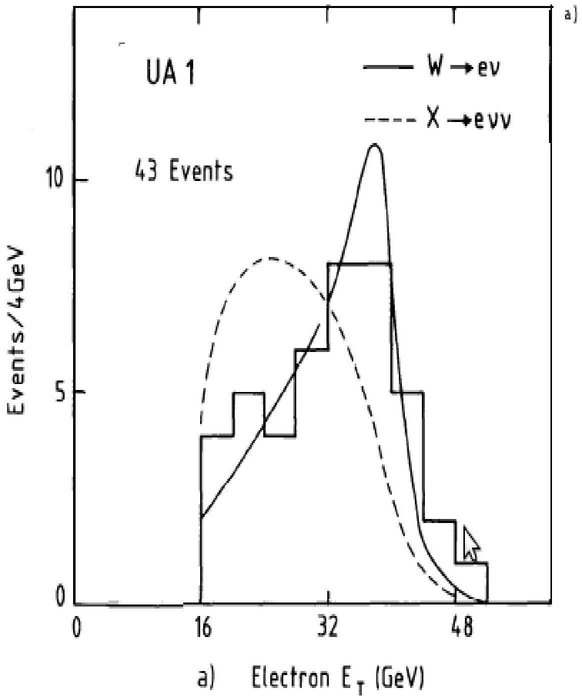
$$\begin{cases} \text{UA1}: & M_W = 80 \pm 5\,\text{GeV} \\ \text{UA2}: & M_W = 80^{+10}_{-6}\,\text{GeV} \end{cases}$$

(see Refs 1983a)

- Cross Section:
  - $\sigma \times BR(W \rightarrow e\nu_e) = 0.53 +/- 0.08\ (\text{stat}) +/- 0.09\ (\text{syst})$ nb
  - theory: 0.39 nb (ISAJET)

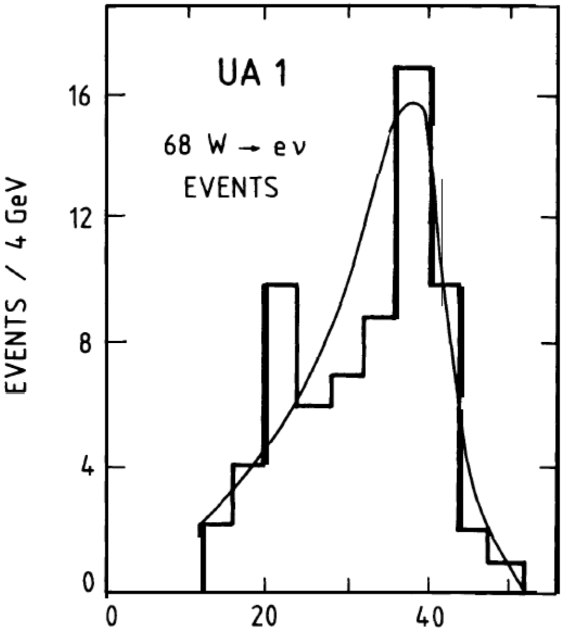
Discovery of the Electroweak Vector Bosons: W and Z (16)

$p_T(e)$



- Selection cuts:
  - All cuts

mET

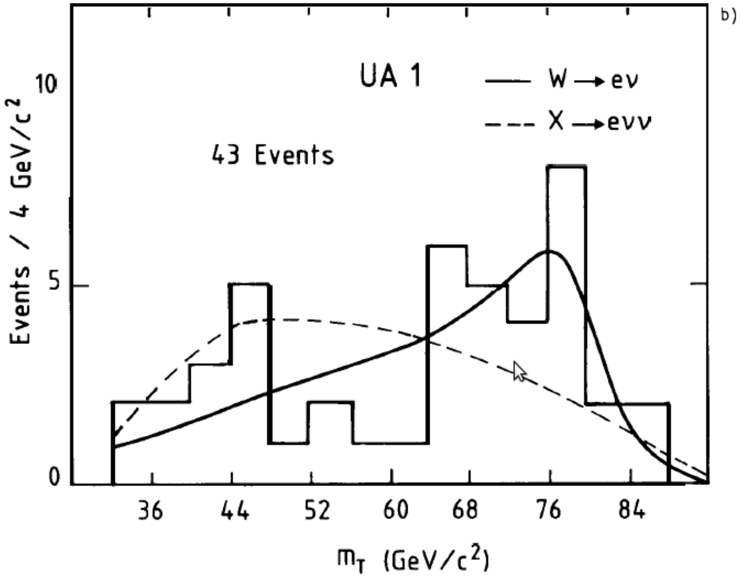


- Selection cuts:
  - Require an electron candidate w/:
    - $p_T > 15$ GeV
  - Dijet rejection

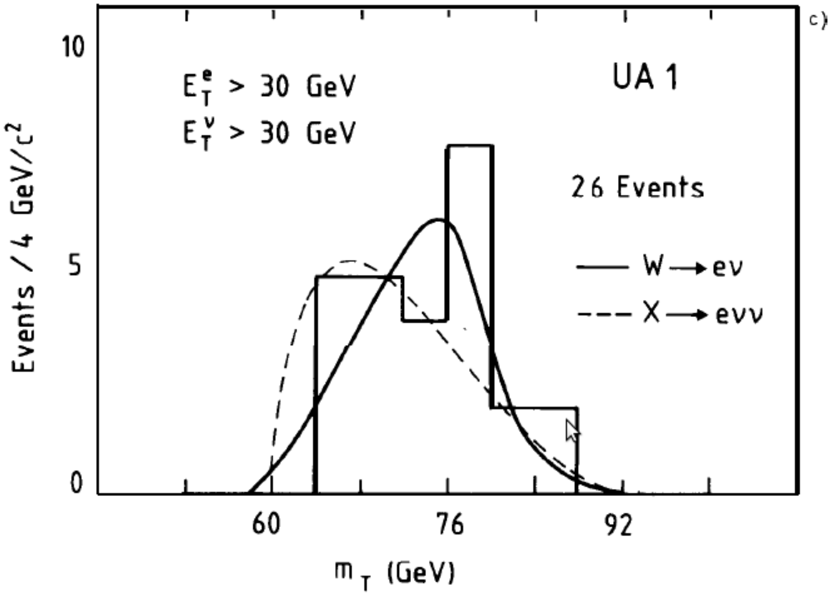
Discovery of the Electroweak Vector Bosons: W and Z (17)

m_T

- Selection cuts:
  - All cuts



$$m_T = \sqrt{2 \cdot p_T(e) \cdot \not{E}_T \cdot (1 - \cos\Delta\varphi)}$$



- Selection cuts:
  - All cuts
  - Tighter pT's

How do we know it's a S=1 particle?

- **Jacob's formula:**

$$\langle \cos\theta^{*} \rangle = \frac{\langle hel_{ini} \rangle \langle hel_{fin} \rangle}{S(S+1)}$$

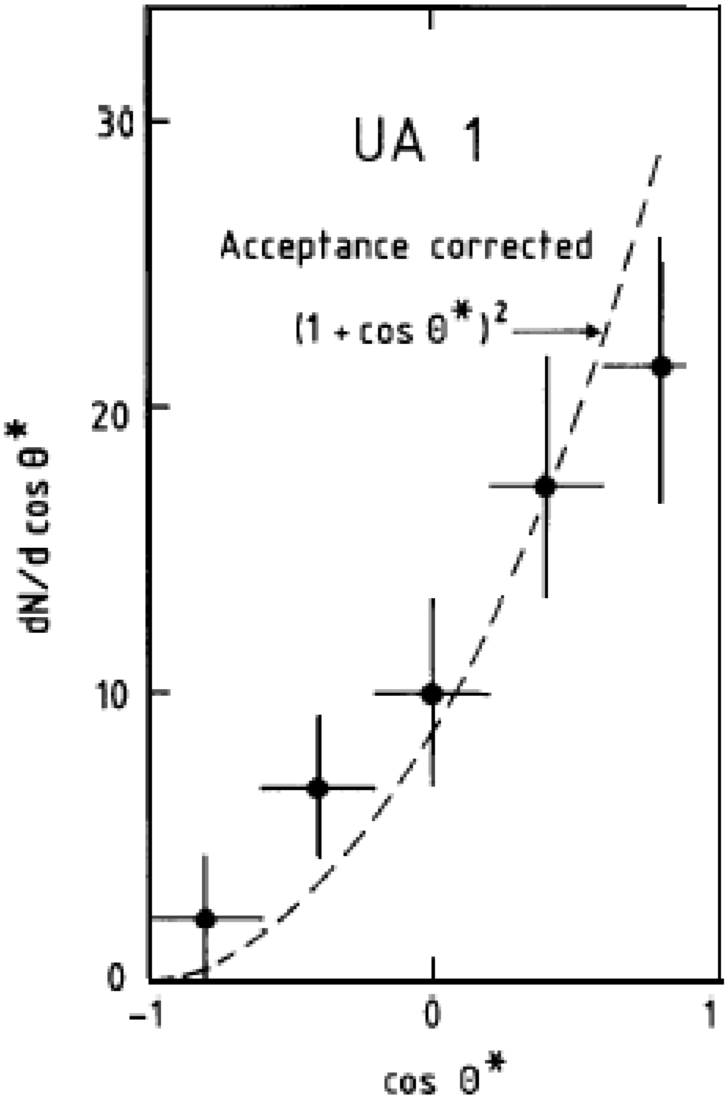
Ref: M. Jacob, Nuovo Cimento 9 (1958) 826

- **θ*: decay angle of the electron in the W rest frame, for example**
- **<hel$_{ini}$>: helicity of the IS: (u+dbar) system**
- **<hel$_{fin}$>: helicity of the FS: (e+ν_e) system**

- **for V-A couplings: <hel$_{ini}$> = <hel$_{fin}$> = -1**
- **and if vector bosons have S=1**
  - **one expects: <cosθ^{*}> = 0.5**
  - **UA1 measurement: <cosθ*> = 0.5+/-0.1**
- **for S=0 particles, one would have expected: <cosθ*> = 0**
- **for S>1 particles, one would have expected: <cosθ*> <=1/6**

Discovery of the Electroweak Vector Bosons: W and Z (18)

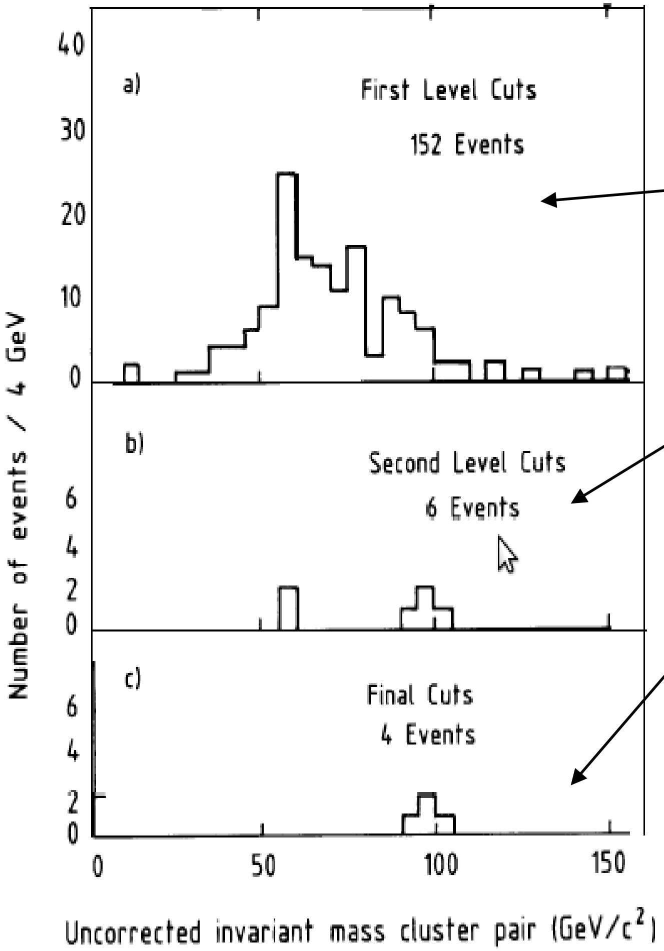
How do we know it's S=1 particle with V-A couplings?



- Selection cuts:
  - Require an electron candidate w/:
    - $p_T > 15$ GeV
  - Dijet rejection

Discovery of the Electroweak Vector Bosons: W and Z (19)

UA1: Z→e^+e^-



- Selection cuts:

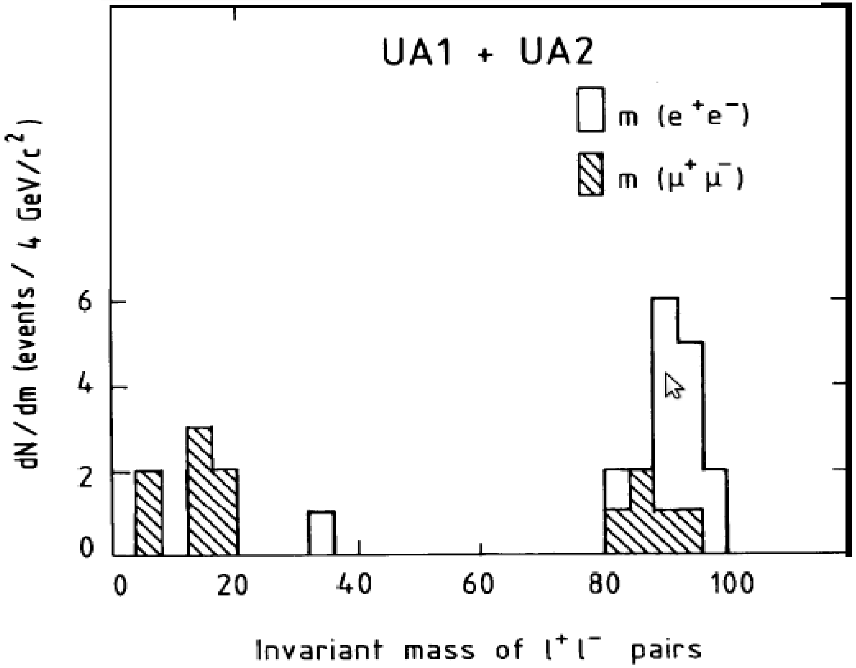
a) Require 2 electron candidates w/:

  - $p_T > 25$ GeV

b) 1 matching tracks w/ pT > 7 GeV
low HCAL leakage < 0.8 GeV

c) 2nd matching track w/ pT > 7 GeV

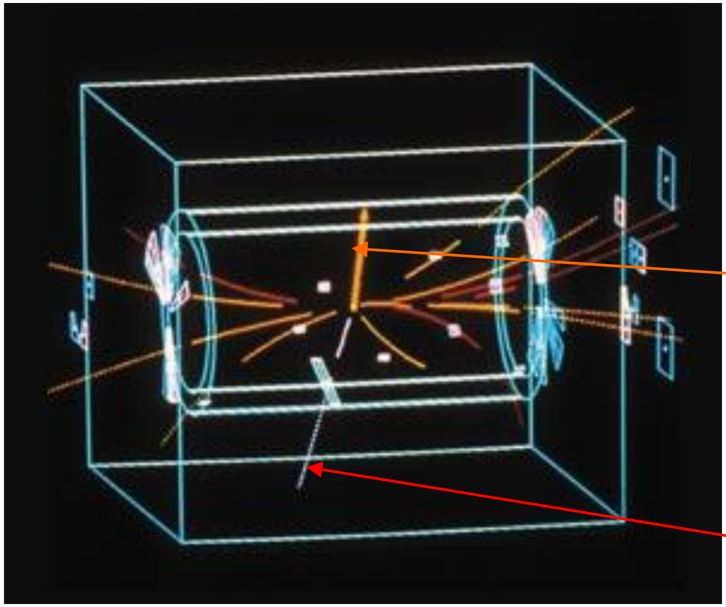
UA1+UA2: Z→e^+e^- & $\mu^+\mu^-$



First UA1 mass measurement:
MZ = 95.5 +/- 2.5 GeV

(see Ref 1983b)

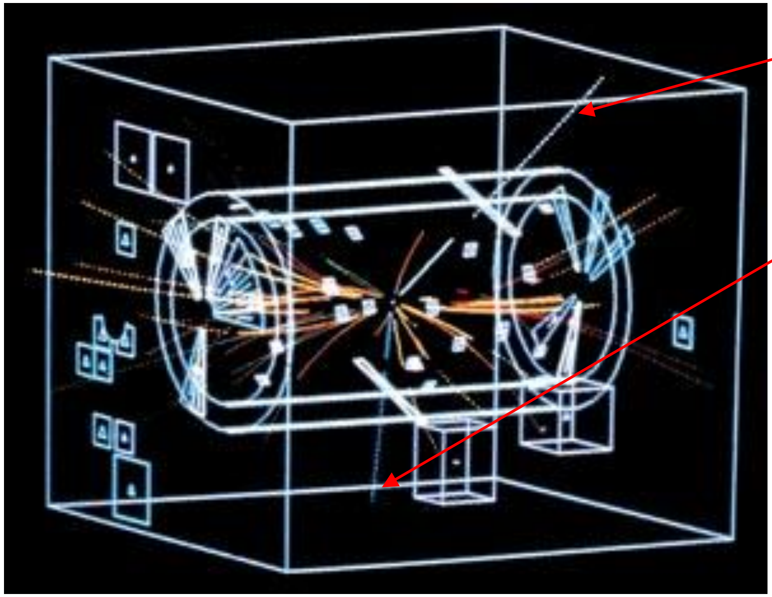
Discovery of the Electroweak Vector Bosons: W and Z (20)



UA1: $W \rightarrow e\nu$ candidate

mET

electrons



UA1: $Z \rightarrow e^{+}e^{-}$ candidate

References

- UA1 collaboration 1981, G. Arnison *et al. Phys. Lett.* 107B 320
- UA1 collaboration 1983a, G. Arnison *et al. Phys. Lett.* 122B 103
- UA1 collaboration 1983b, G. Arnison *et al. Phys. Lett.* 126B 398
- UA2 collaboration 1983a, M. Banner *et al. Phys. Lett.* 122B 476
- UA2 collaboration 1983b, P. Bagnaia *et al. Phys. Lett.* 129B 130

C. Rubbia and S. Van der Meer shared the 1984 Physics Nobel Prize

End note:

« Adage »: Some particles discovered in the past later become « Standard Candles »

- **Nowadays the EW vector bosons are the main calibration processes:**
  - **ie: $Z\rightarrow e^+e^-$, $Z\rightarrow qq$, $Z\rightarrow bb$ used to set the absolute EM scale, the JES and to calibrate the b-tagging at e^+e^- colliders**
  - **ie: $Z\rightarrow e^+e^-$ used to set the absolute EM scale at hadron colliders**

Discovery of the charm quark

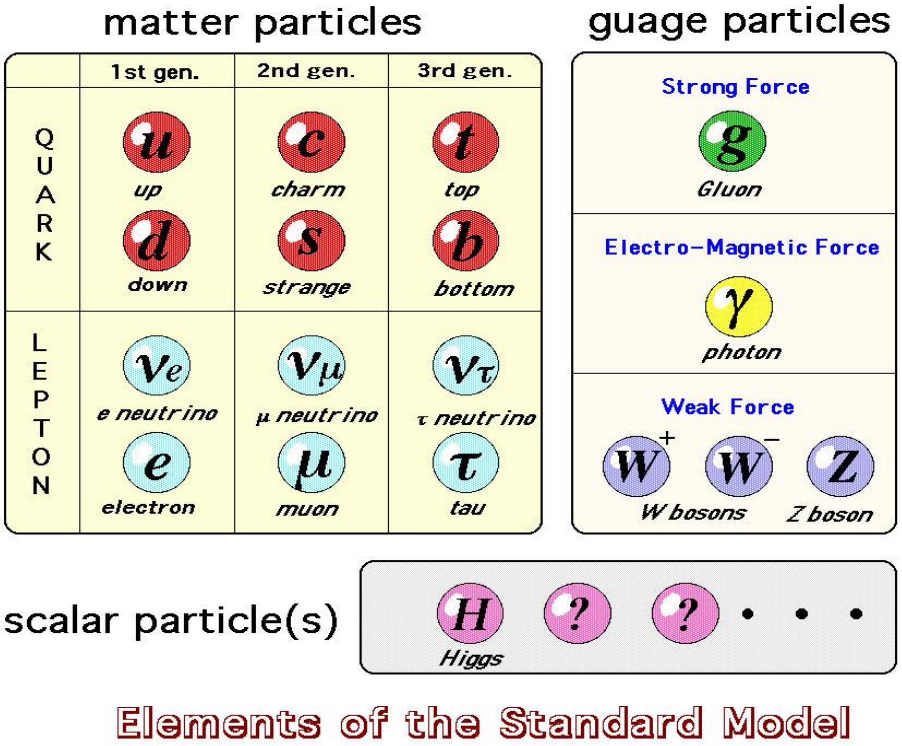
Theoretical Context:

GIM mechanism:

- Mechanism to suppress FCNC at tree level:
  - Strong hypothesis: postulates the existence of a 4th quark (not observed at the time)
  - Explains the rarity of certain decay processes:

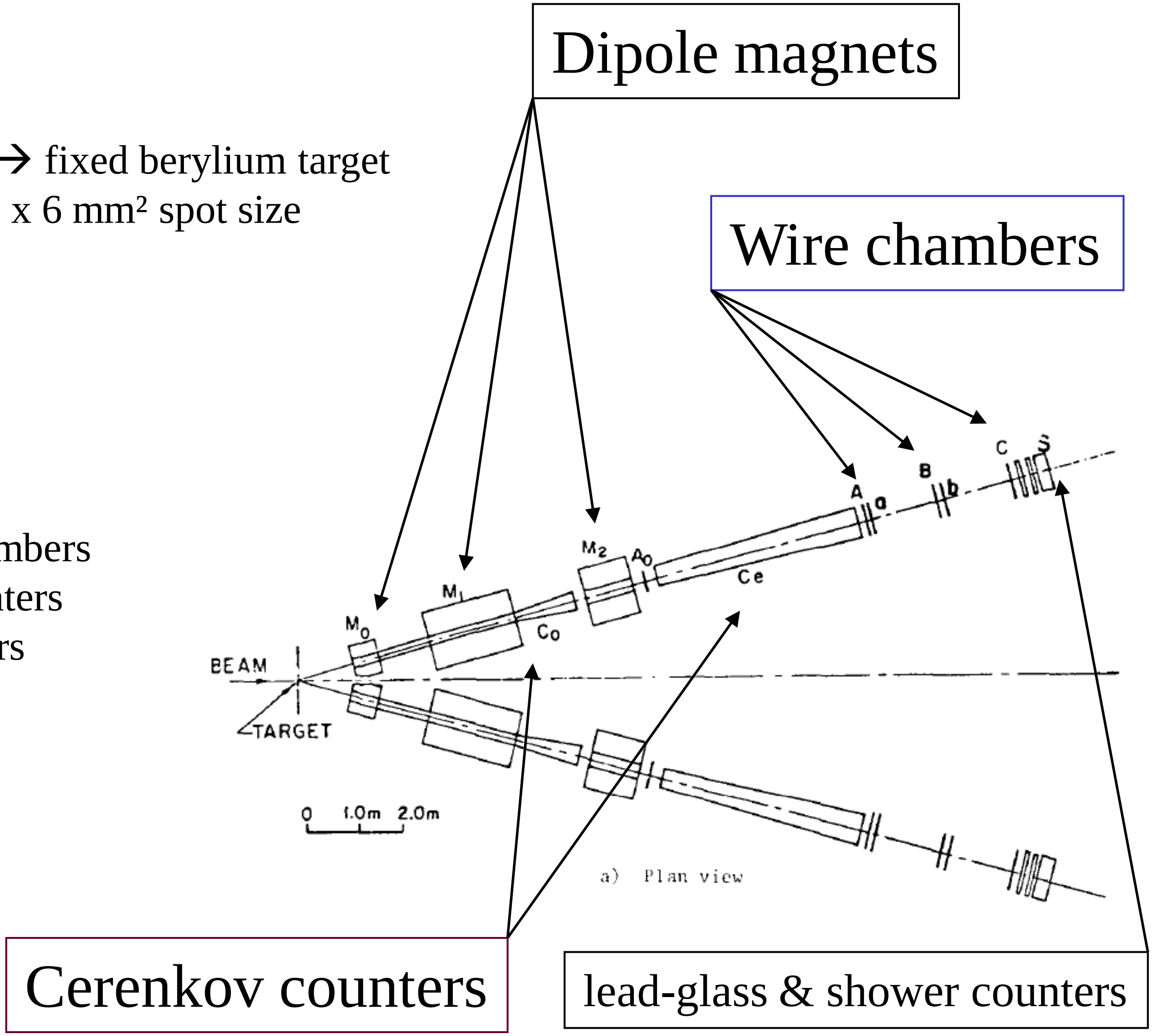
$$\frac{BR(K^0 \to \mu^+\mu^-)}{BR(K^+ \to \mu^+\nu_\mu)} = \frac{7\times 10^{-9}}{0.64} \approx 10^{-8}$$

- **Ref: S. L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D 2, 1285 (1970)**



Accelerator:
- BNL:
  - 30 GeV proton beam from AGS → fixed berylium target
  - 2 x 10^{12} p / pulse, focused onto 3 x 6 mm² spot size

Detector:
- BNL:
  - double arm spectrometer:
    - scintillators
    - multiwire proportional chambers
    - lead-glass and shower counters
    - hydrogen Cerenkov counters


Dipole magnets

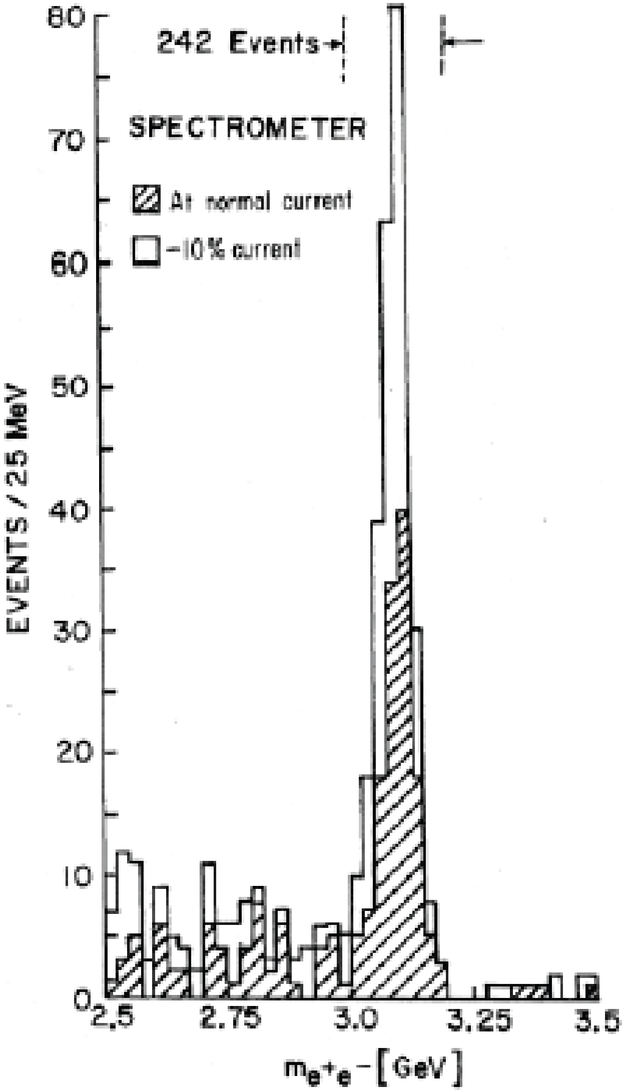
Wire chambers

Cerenkov counters

lead-glass & shower counters

Analysis:

- needed rejection factor against hadron pairs > 10^8



Accelerator:

- SLAC:
  - e+e- Energy Scan
  - e+e- collisions from SPEAR
  - 2.6 < sqrt(s) < 8 GeV
  - spot size: (0.1 x 0.01 x 5) cm^3

Interpretation:

- **J/Ψ is a resonance made from a bound state of c+cbar, called charmonium**

Sam C.C. Ting and Burton Richter shared the 1976 Physics Nobel Prize

- **BNL: J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, Sau Lan Wu, Phys. Rev. Lett. 33 (1974) 1404**

- **SLAC: J.-E. Augustin et al., Phys. Rev. Lett. 33 (1974) 1406**

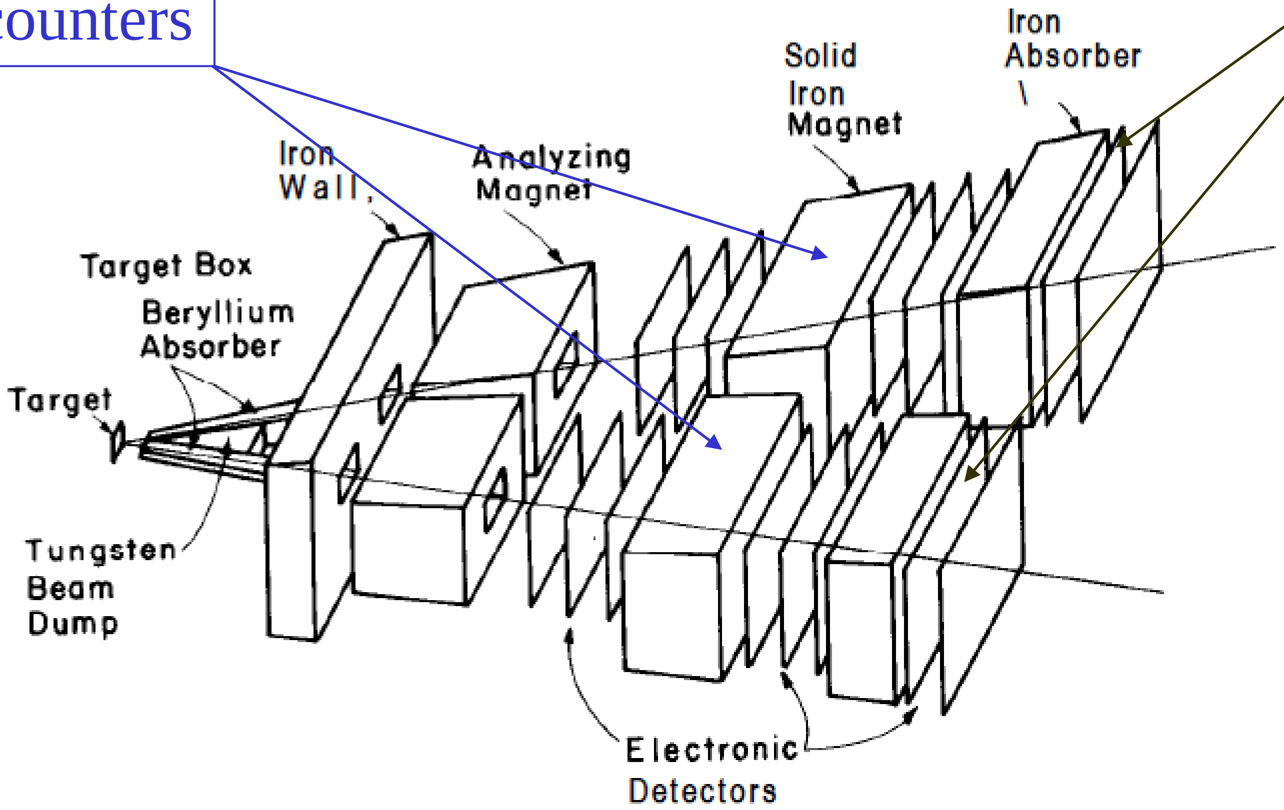
Discovery of the bottom quark

Accelerator:

- At FNAL (aka « FERMILAB »), 1977
- sqrt(s)=400 GeV p+N collisions

Detector:

- scintillator-based trigger
- shield against hadron using 30 feet of Be
- multiwire proportional chambers, scintillators, gas-filled Cerenkov counters

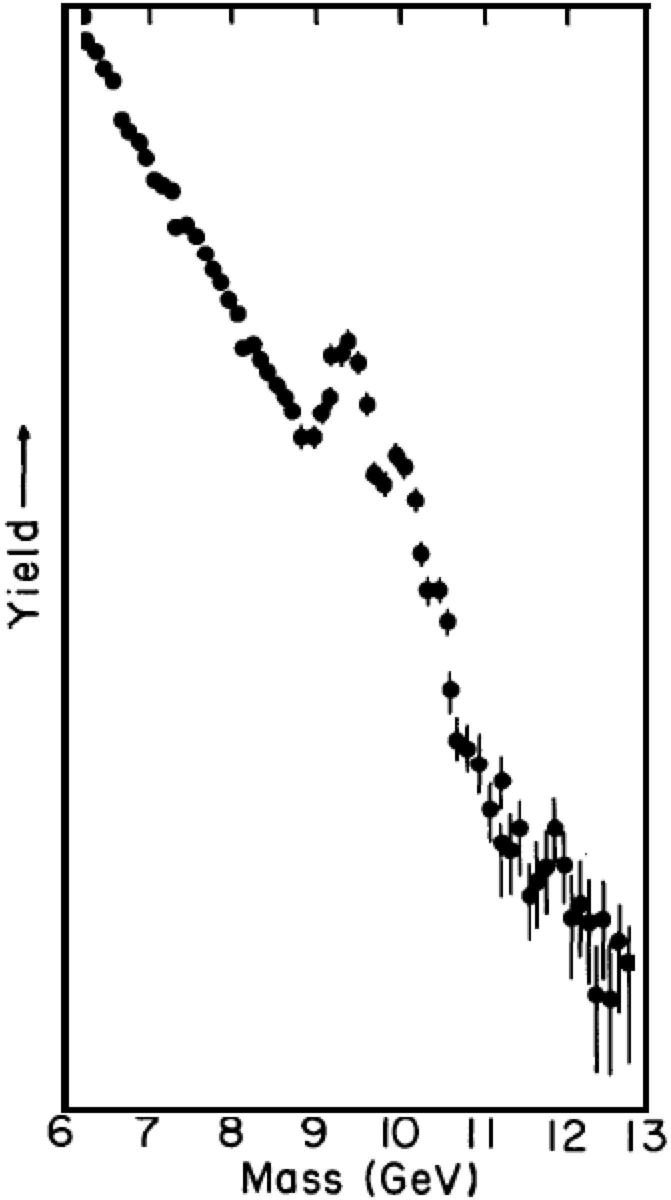


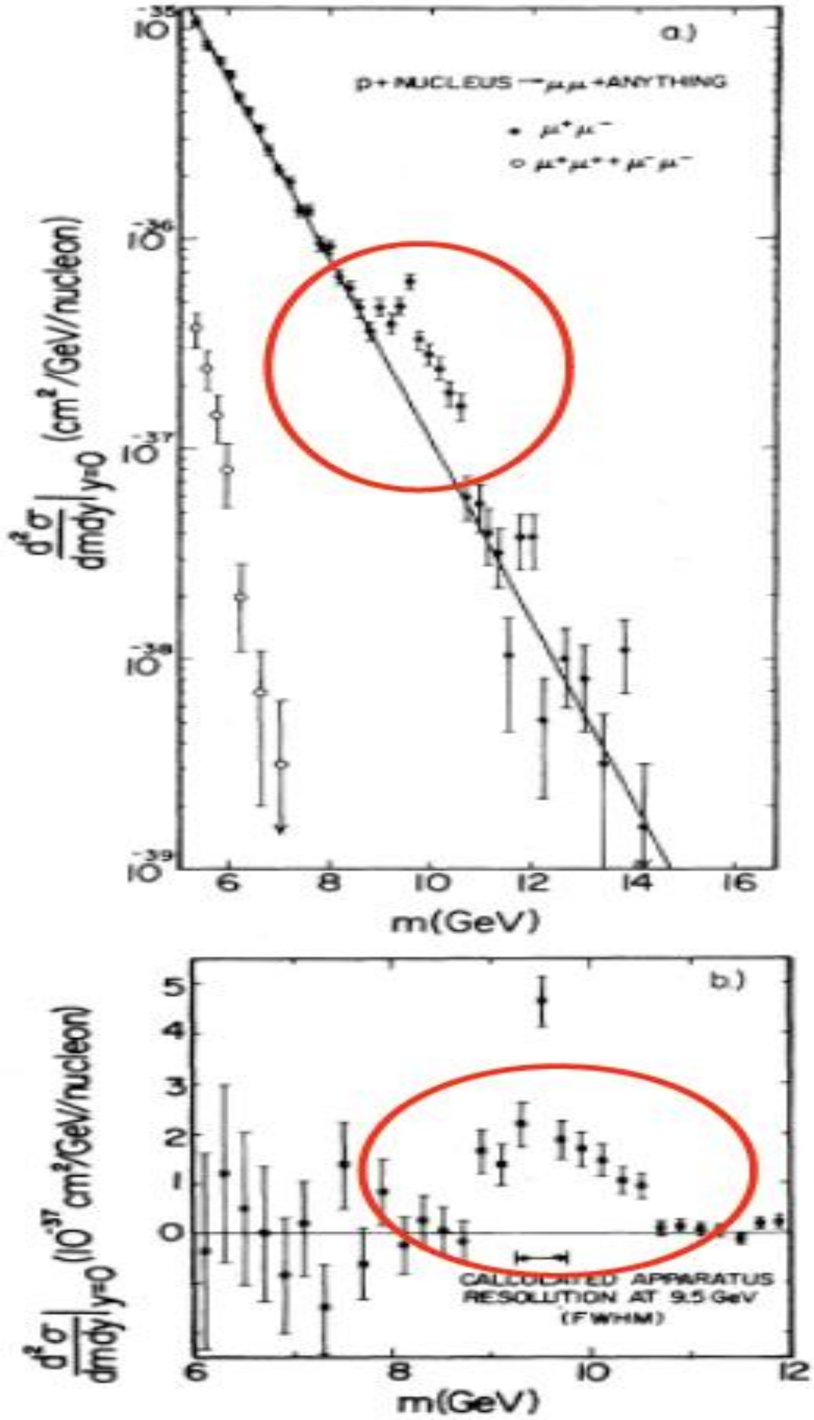
Drift chambers

Cerenkov counters

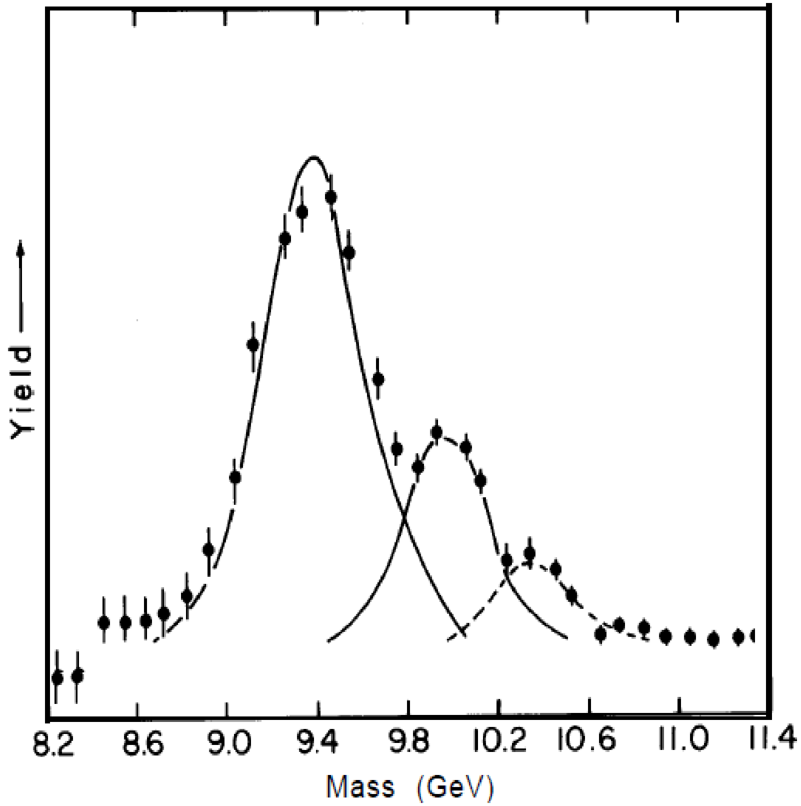
Analysis

- Trigger:
  - di-muon events
- Offline:
  - 1 month of data taking
  - dataset: 7000 events w/ $M_{\mu+\mu-}$ > 4 GeV
  - about 800 events on top of a D-Y continuum
  - negliglible background





- Increased statistics (30k evts) enabled to resolve the bump into 3 separate peaks: Y, Y’, Y”
- Interpretation: 1S, 2S and 3S of a b+bbar bound states, called bottomium



L. Lederman shared the 1988 Physics Nobel Prize with M. Scwartz and J. Steinberger for their discovery of the ν_μ

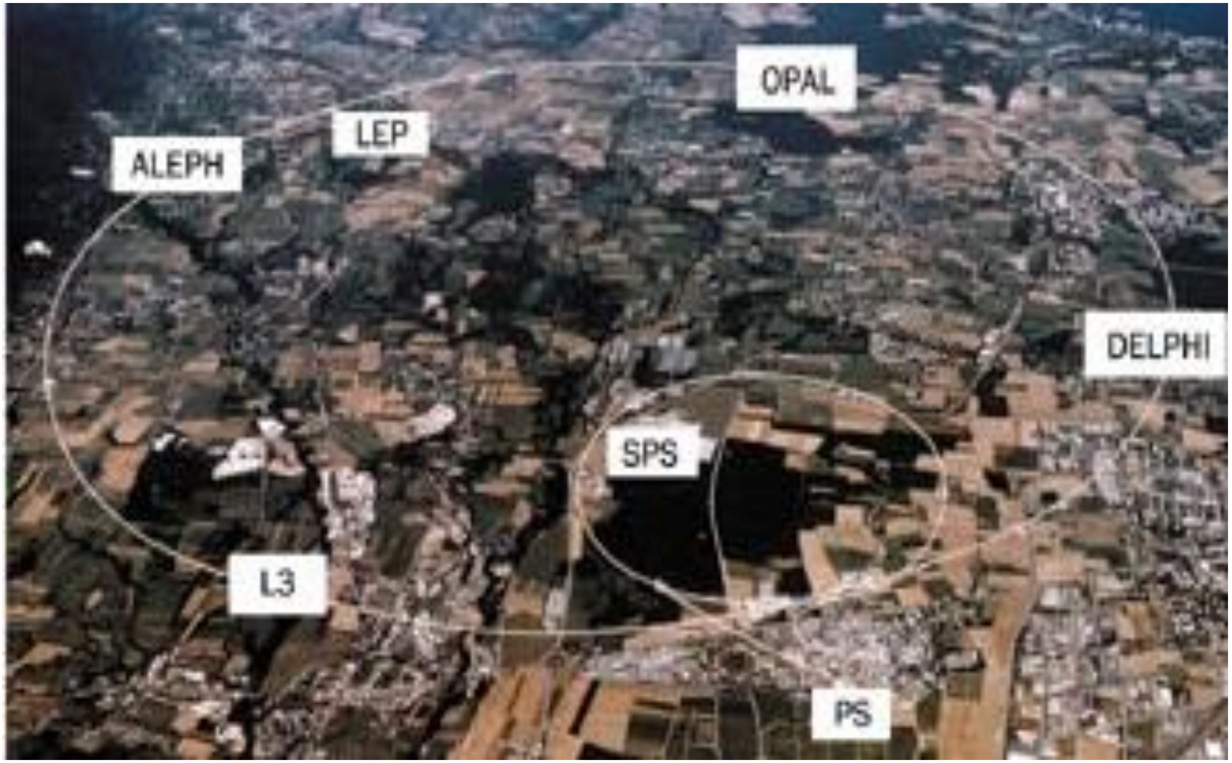
III. Precision Measurements

or « how we test our models and constrain NP through virtual effects »

1.a. W Mass at LEP II

LEP: Large Electron Positron (Collider) at CERN

- LEP I:
  - 1989-1993
  - Z Physics: sqrt(s) scanning around M_Z
  - Statistics: 18M Z→f+fbar events produced
- LEP II:
  - 1996-2000
  - Bi-boson and searches: $161 < \sqrt{s} < 209$ GeV
  - 80k W^+W^- events produced



4 Multipurpose Experiments: ADLO

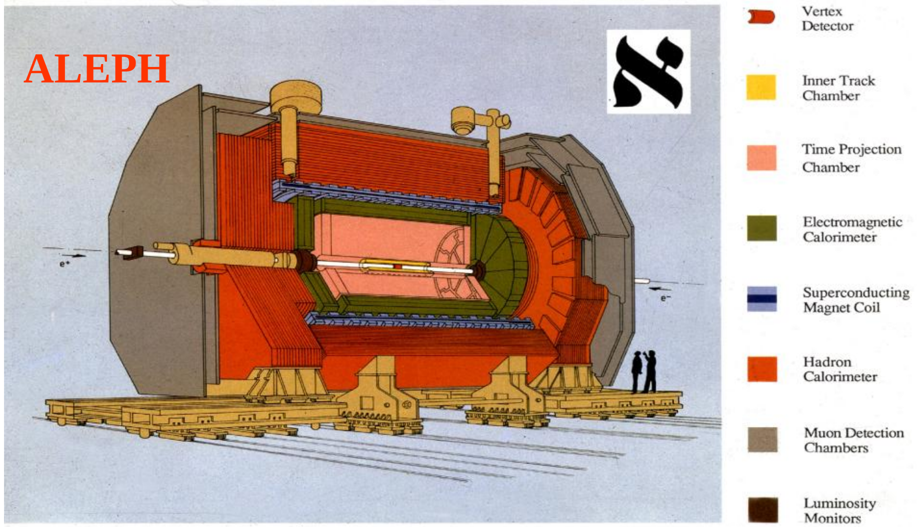
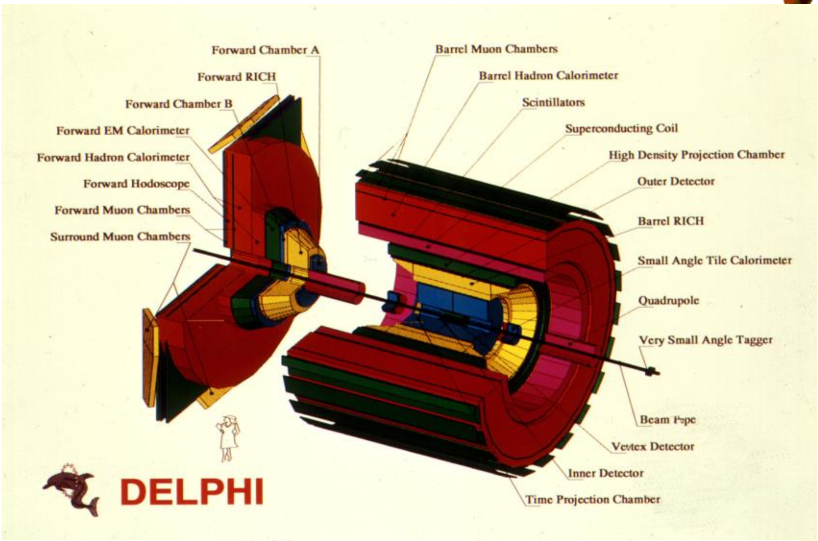
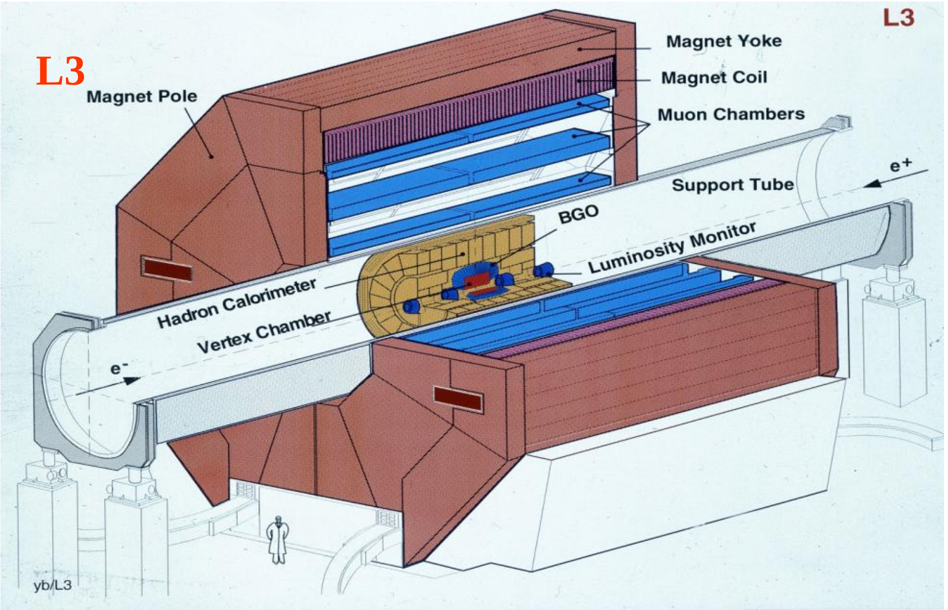
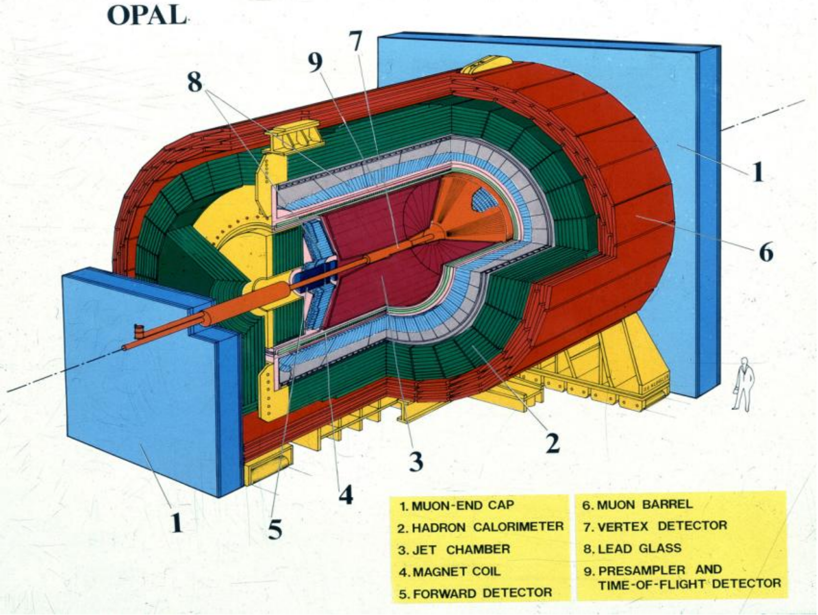


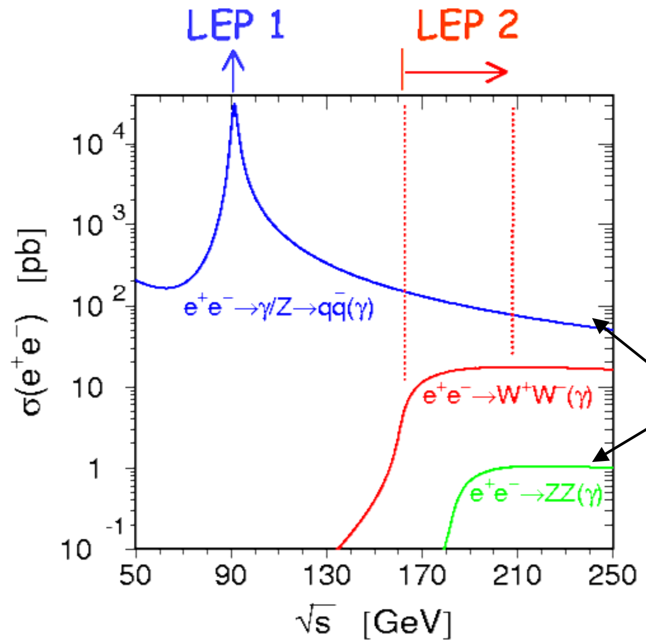
Fig. 1 - The ALEPH Detector



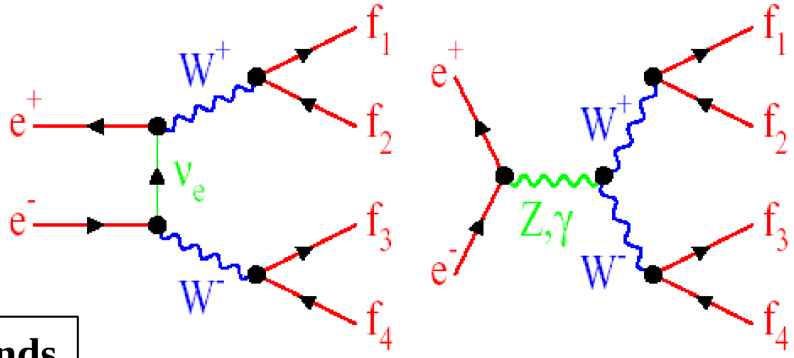




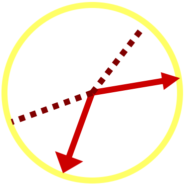
W pairs production and decay at LEP



Backgrounds

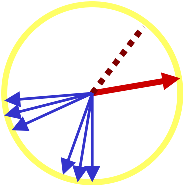


WW→ lνlν



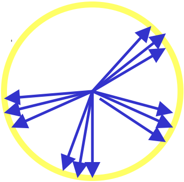
BR ~ 10%

WW→ qqlν



BR ~ 44%

WW→ qqqq



BR ~ 46%

	Efficiency	Purity
lν lν	70%	90%
qqlν	85%	90%
qqqq	85%	80%

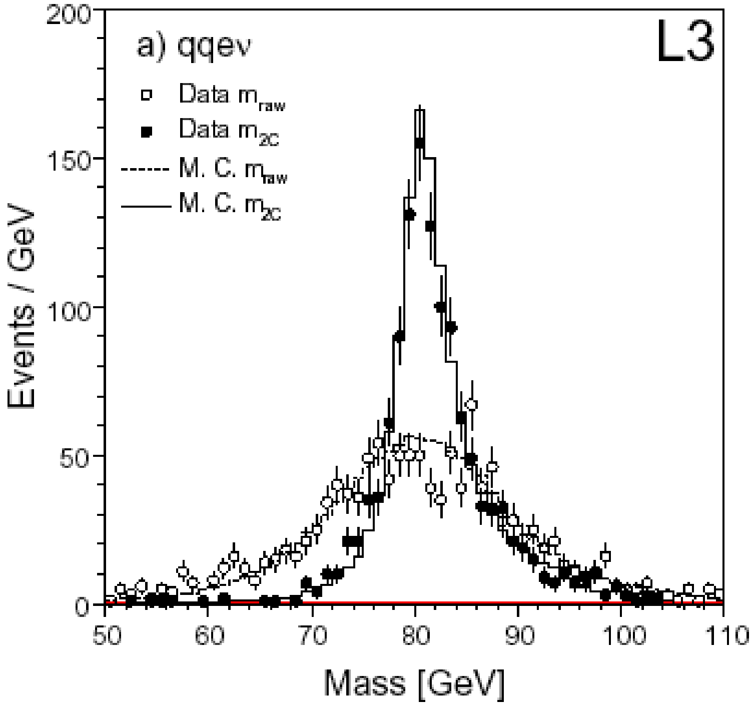
Methodology

Two main steps in measuring W mass:

1. Reconstruct event-by-event mass of W's
2. Fit mass distribution ⇒ extract M_W

But, limited resolutions for jet energy measurements ($\sigma_E/E \sim 12\%$), neutrinos unobserved,…

⇒ **Use kinematic fits**



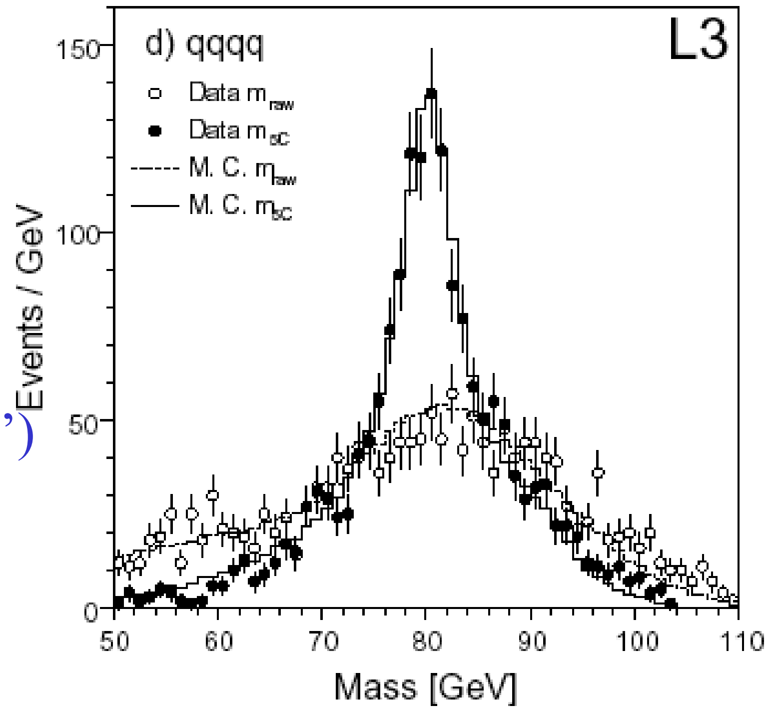
Mass Reconstruction:

- Kinematic fitting:
  - $E_{tot} = \sqrt{s}$
  - $\vec{p}_{tot} = \vec{0}$
  - $M_{W^+} = M_{W^-}$

=> significant improvement of the resolution

Caveat:

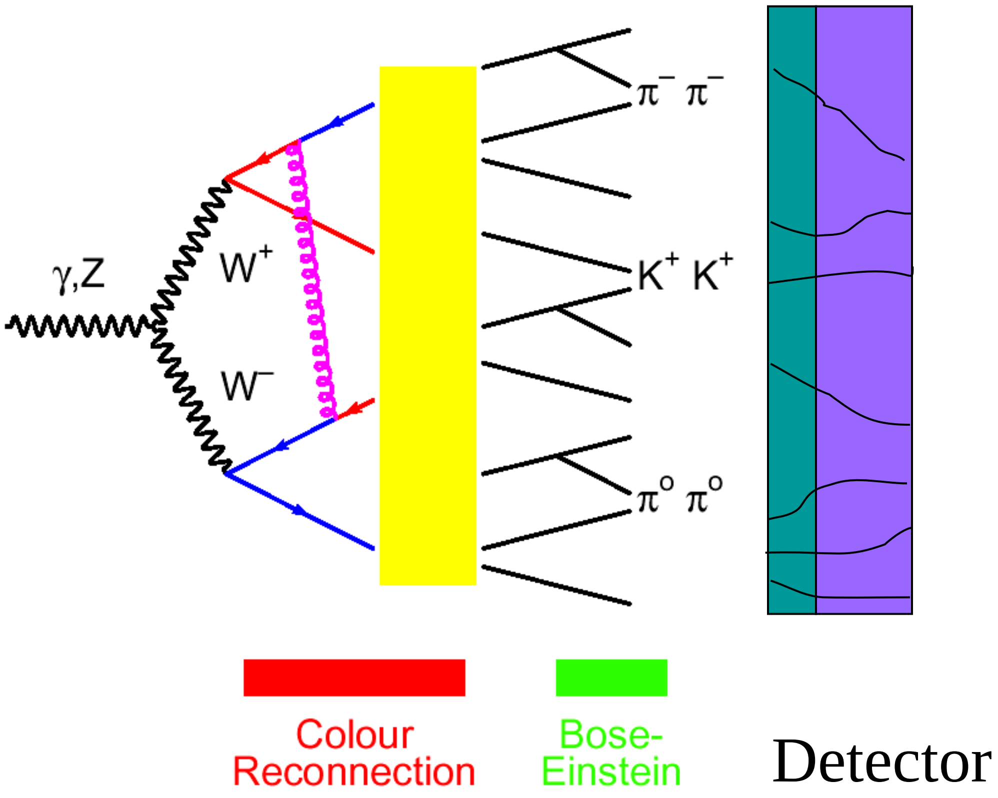
- IS γ radiation will change sqrt(s) to sqrt(s')
- theoretical modeling: ~0.5%



Systematic Uncertainties

Main Sources:

- QED/EW radiative effects
- Detector Modeling
- Hadronisation Modeling
- Background Modeling
- Final State Interaction



Data modeled using MC;

Disagreements ⇒ Systematic error

Combined LEP W Mass

Combined Preliminary LEP W mass:

$M_W = 80.376 \pm 0.025\ (\mathrm{stat}) \pm 0.022\ (\mathrm{syst})\ \mathrm{GeV}$

$M_W = 80.376 \pm 0.033\ \mathrm{GeV}$

Systematics on W mass:

Source	$qql\nu$	qqqq	combined
Hadronisation	13	19	14
QED(ISR/FSR)	8	5	7
Detector	10	8	10
Colour Reconnection	0	35	9
Bose-Einstein Correlation	0	7	2
LEP Beam Energy	9	9	10
Other	3	11	4
Total Systematics	21	44	22
Statistical	30	40	25
Total	36	59	33

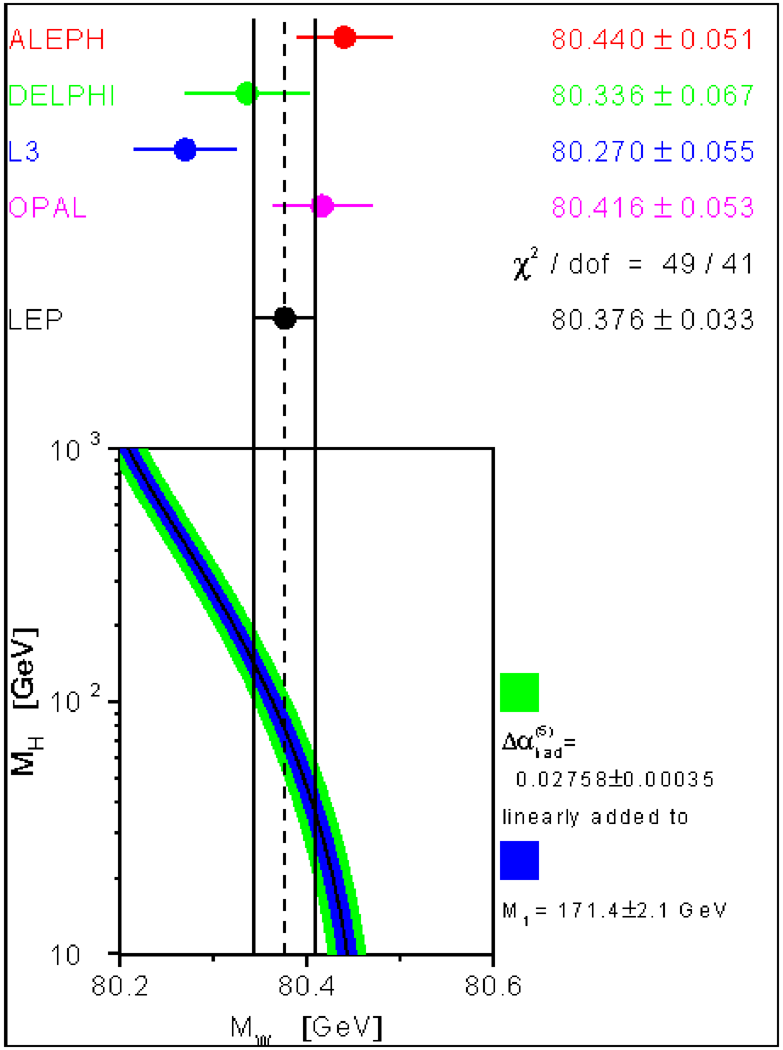
(MeV)

Channel wght

qqlv : 76%
qqqq : 22%
xs : 2%

Combined LEP W Mass

M_W (ADLO) = 80.376   0.033 GeV



NB: It took about five years after LEP shut down to get final W mass results from all the four experiments

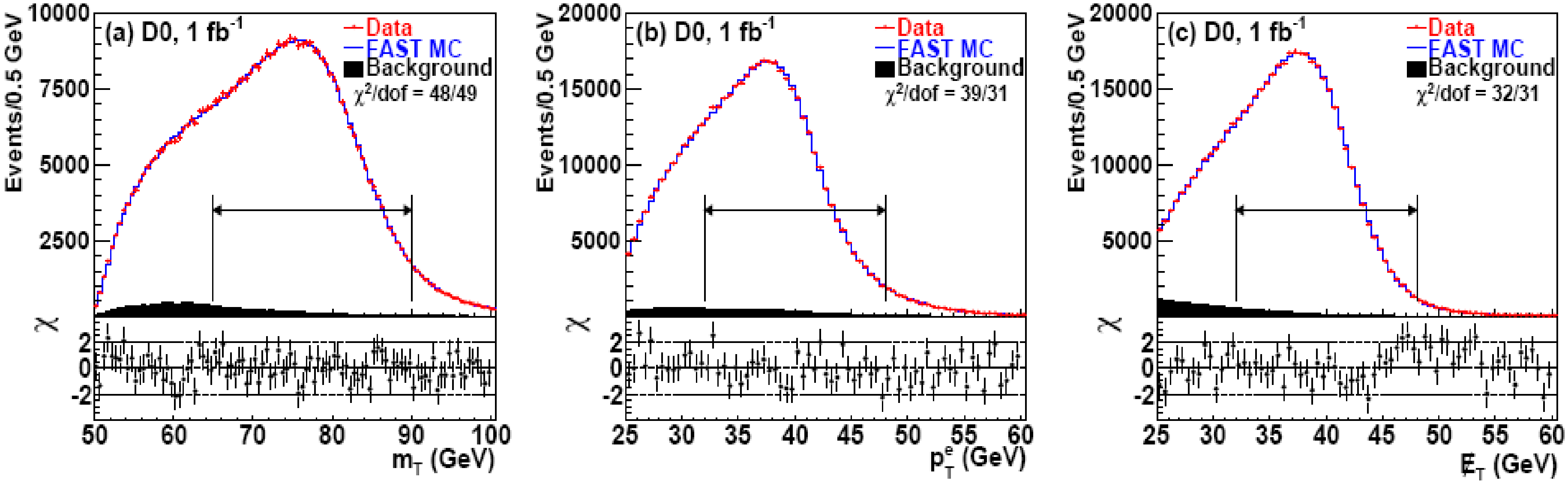
1.b. W Mass at TEVATRON Run II

D0 Run IIa analysis

- Dataset:
  - 2002-2006, $\boxed{\int \mathcal{L} dt = 1\ fb^{-1}}$
  - 500k W→eν_e events produced
  - 18.7k Z→ee events used to set EM scale (70<M_{ee}<110 GeV)

- Analysis:
  - Single EM triggers
  - Offline event selection:
    - $p_T(e) > 25 GeV$
    - $|\eta(e)| < 1.05$
    - Isolation
    - EMF>80%
    - 1 matching track
    - $\|\vec{u}_T\| < 15 GeV$
  - Background:
    - W→τ(→e$\nu_e\nu_\tau$)ν_τ (1.6%); QCD (1.5%); Z→ee (0.9%)

Fit the 3 following distributions using MC templates



Correlations:

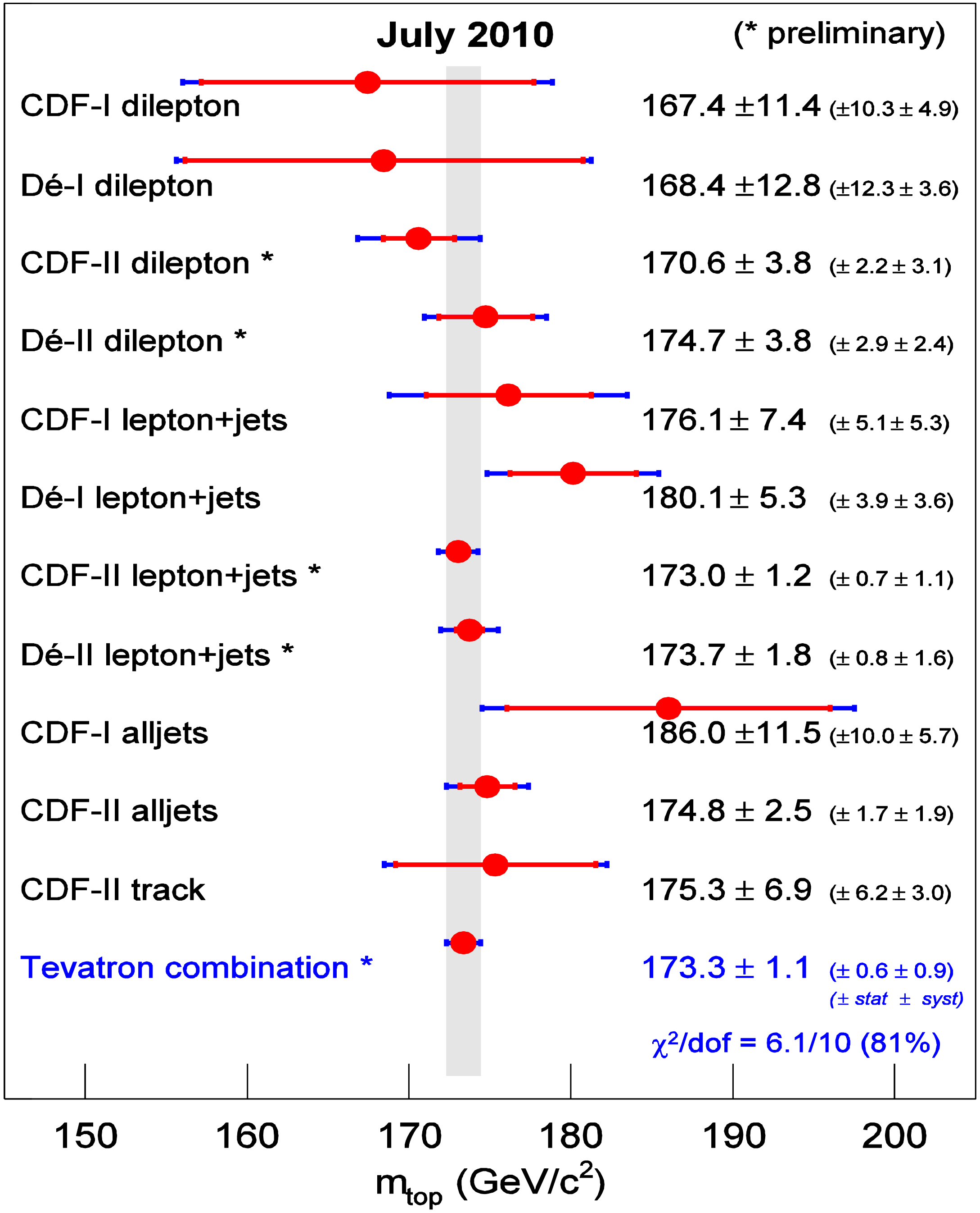
- 83% a) & b); 82% a) & c); 68% b) & c)

$$M_W = 80.401 \pm 0.021(stat) \pm 0.038(syst)\, GeV$$

$$M_W = 80.401 \pm 0.043\, GeV$$

Ref: V.M. Abazov *et al.*, D0 Collaboration, Phys. Rev. Lett. 103, 141801 (2009), **arXiv.org:0908.0766**

Mass of the Top Quark



Indirect Constraints on H Mass

- Standard Model predicts relation between the parameters: W boson mass(M_W) and Fermi constant(G_F), fine structure constant(α), Z boson mass (M_Z)

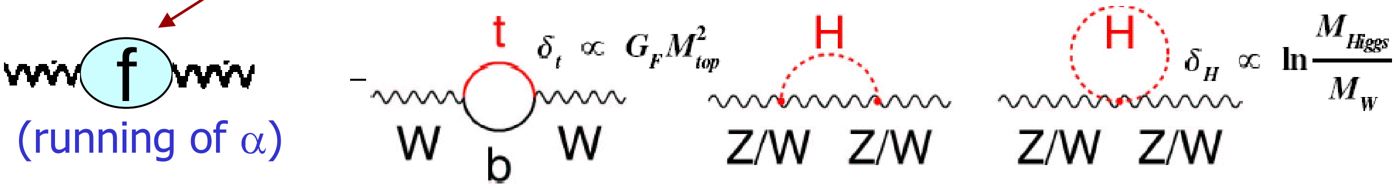
$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{G_F\sqrt{2}}(1-\Delta r)$$

α : electron g-2 0.004 ppm

G_F : muon life-time 9 ppm

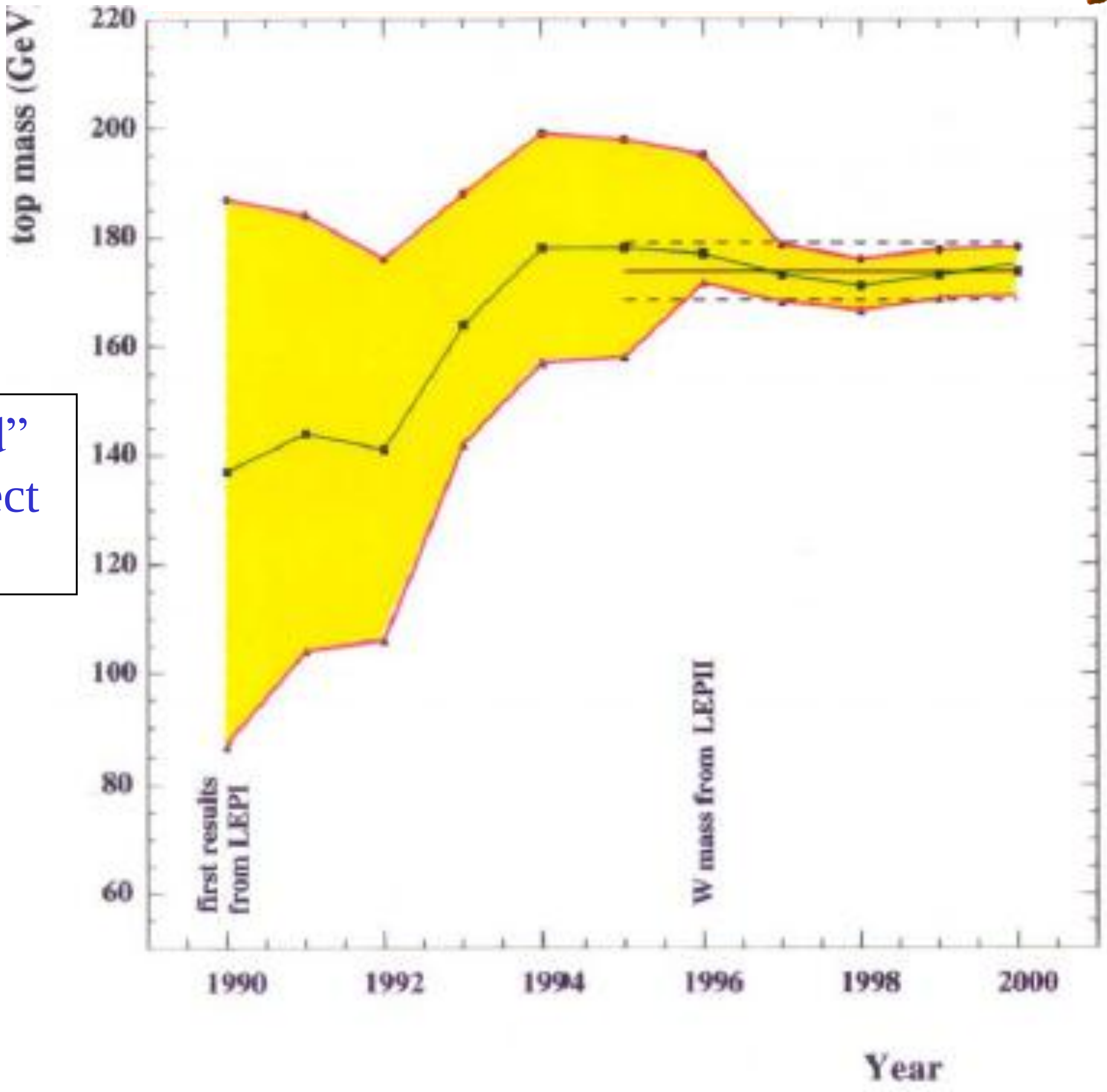
M_Z : LEP 1 lineshape 23 ppm

$$\Delta \mathbf{r} \equiv -\Delta\alpha + \Delta \mathbf{r}_{\mathbf{weak}}$$

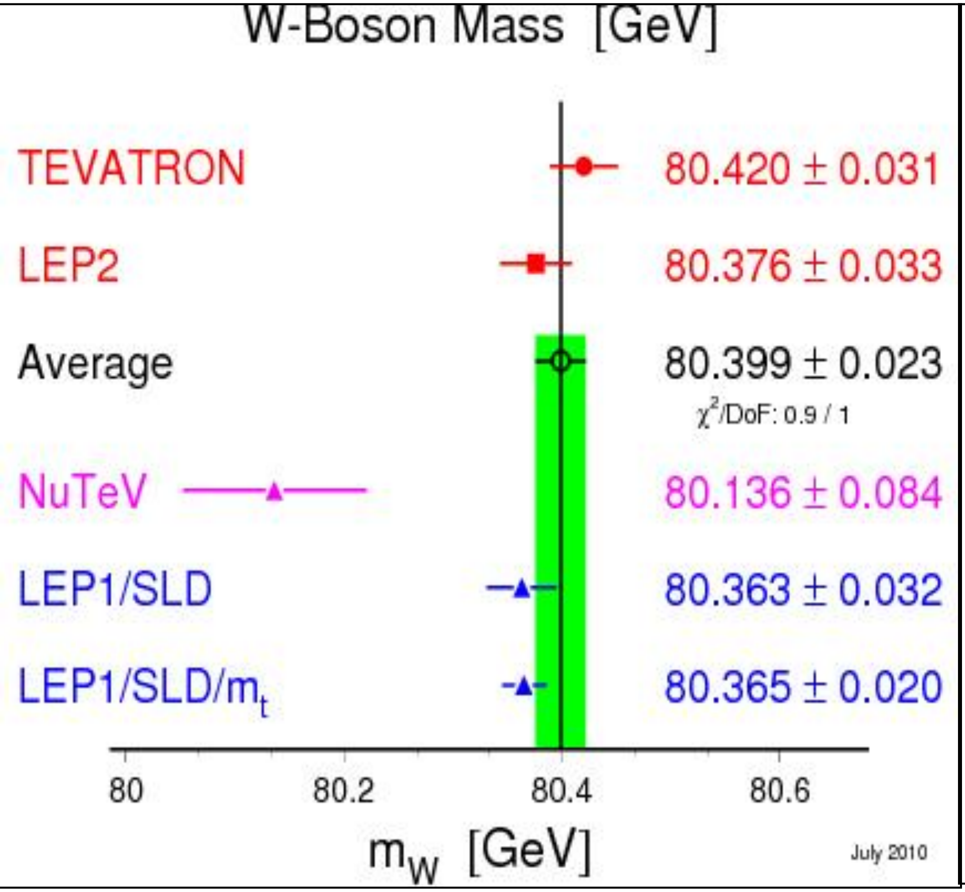


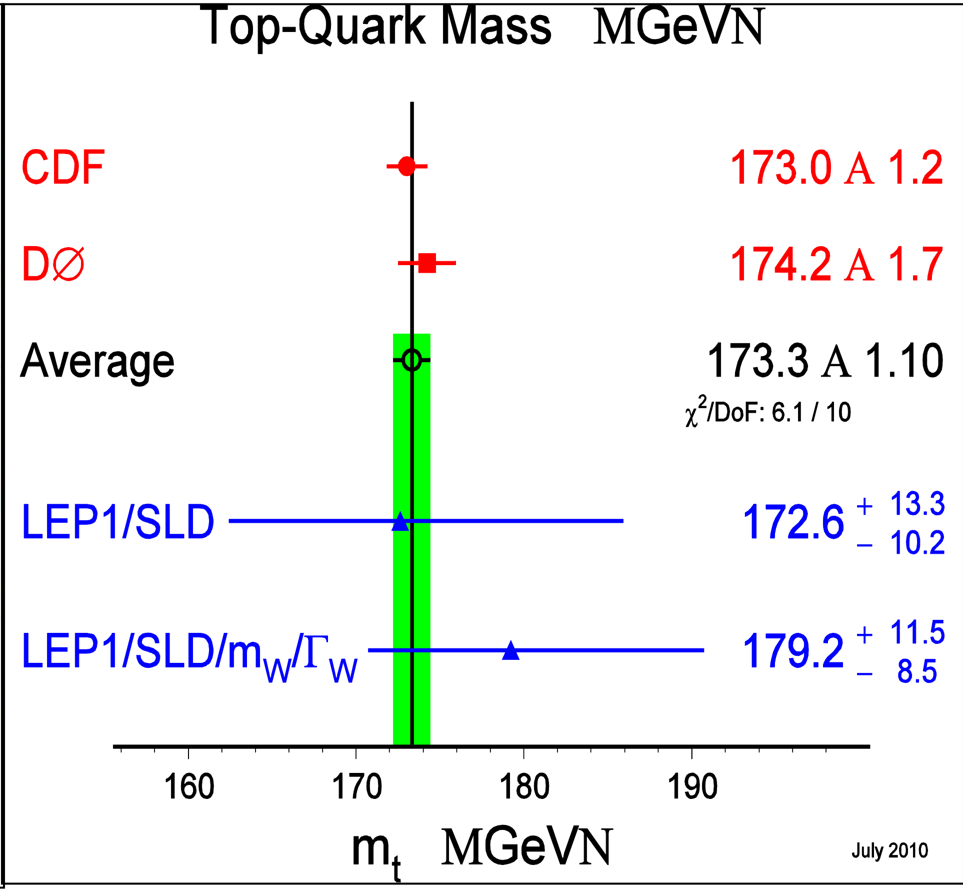
- Precision measurements require higher order terms in the theory and help constraint the unknown pieces

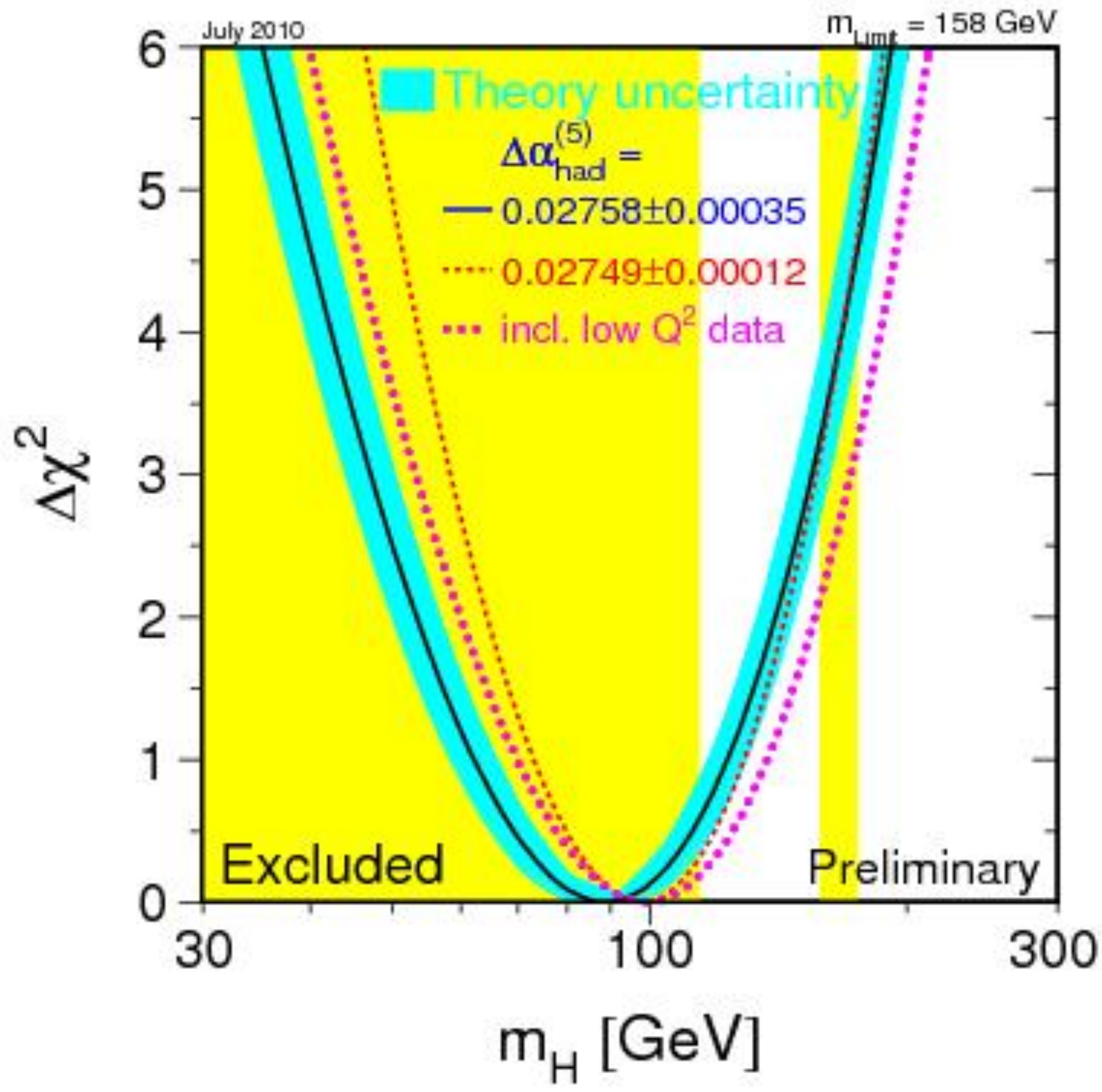
Precision EW



Top quark mass was "predicted" by EW corrections prior to direct discovery


W-Boson Mass [GeV]
TEVATRON
80.420 ± 0.031
LEP2
80.376 ± 0.033
Average
80.399 ± 0.023
χ^2/DoF: 0.9 / 1
NuTeV
80.136 ± 0.084
LEP1/SLD
80.363 ± 0.032
LEP1/SLD/m_t
80.365 ± 0.020
80
80.2
80.4
80.6
m_W [GeV]
July 2010


Top-Quark Mass MGeVN
CDF
173.0 A 1.2
DØ
174.2 A 1.7
Average
173.3 A 1.10
χ^2/DoF: 6.1 / 10
LEP1/SLD
$172.6^{+13.3}_{-10.2}$
LEP1/SLD/m_W/Γ_W
$179.2^{+11.5}_{-8.5}$
160
170
180
190
m_t MGeVN
July 2010


July 2010
m_{Limit} = 158 GeV
Theory uncertainty
$\Delta\alpha_{had}^{(5)}$ =
0.02758±0.00035
0.02749±0.00012
incl. low Q^2 data
Excluded
Preliminary
$\Delta\chi^2$
0
1
2
3
4
5
6
30
100
300
m_H [GeV]

IV. Direct Production of New Particles

1. **SM Higgs Search at LEP II**
2. **Latest Result from TEVATRON Run II**

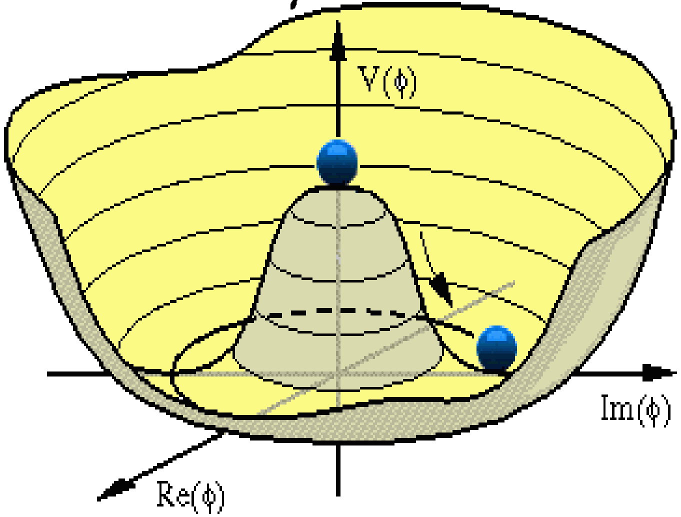
Theoretical Aspects

Higgs Mechanism in SM

$$\Phi = \begin{pmatrix} \varphi^{+} \\ \varphi^{0} \end{pmatrix} \quad \Rightarrow 1\, scalar\ neutral\ particle\ H$$

$$V(\Phi) = \mu^2 \,|\Phi^\dagger\Phi| + \lambda\, |\Phi^\dagger\Phi|^2$$

$$\lambda > 0 \ and\ \mu^2 < 0$$



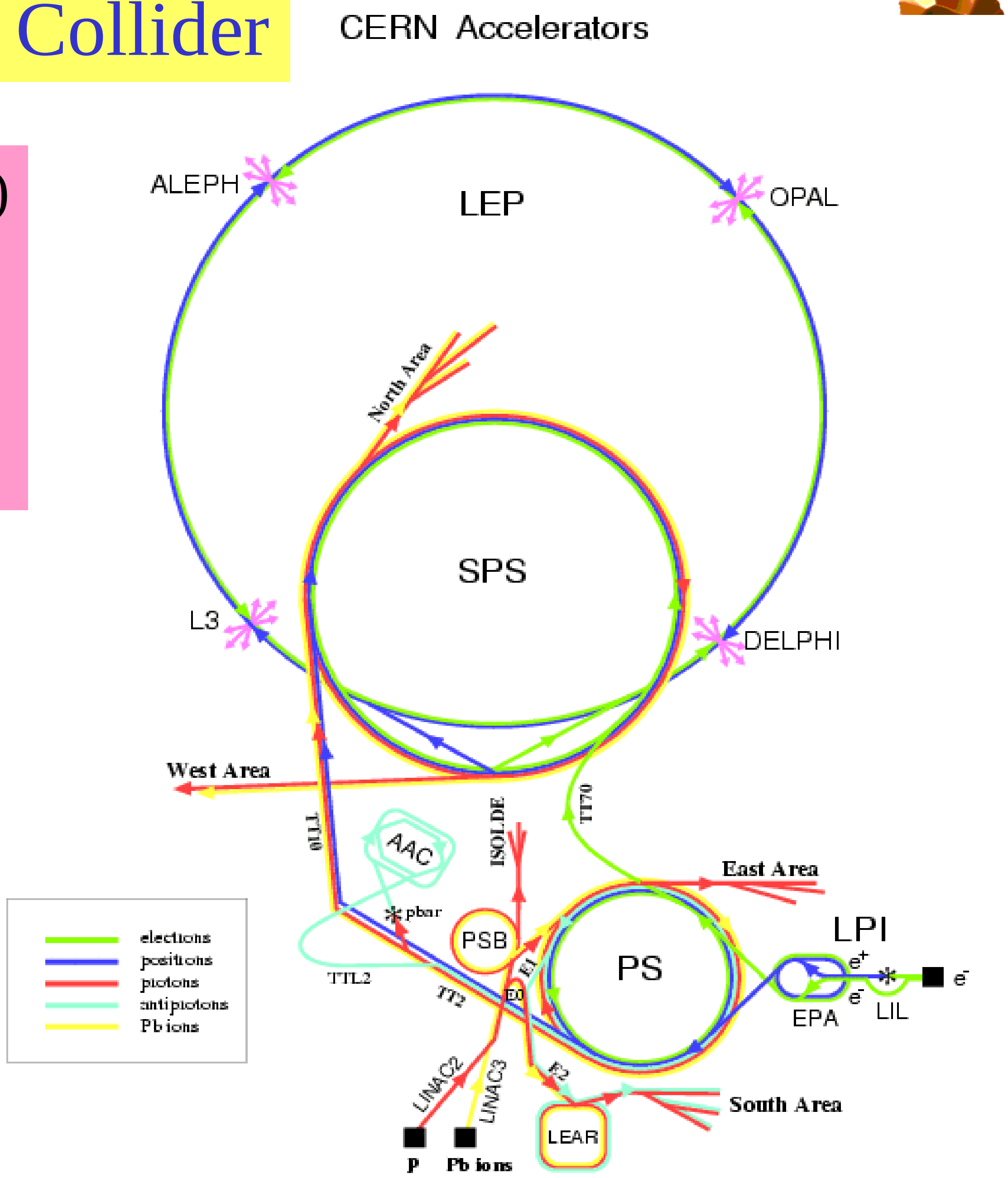
$$\mathrm{v} = \sqrt{\frac{-\mu^2}{\lambda}} \approx 246\ GeV$$

Mass Generation

- Gauge Bosons:
  - $m_W = \dfrac{g \cdot \mathrm{v}}{2}$
  - $m_Z = \dfrac{g \cdot \mathrm{v}}{2\cos\theta_W}$
  - $m_\gamma = 0$
- Charged Fermions:
  - $m_f = \dfrac{\lambda_f \mathrm{v}}{\sqrt{2}}$
- Higgs Boson:
  - $m_H = \sqrt{2\lambda}\,\mathrm{v}$

LEP II Collider

Located at CERN (R=4.2 km)
4 Experiments: ALEPH,
DELPHI,
L3,
OPAL



- LIL: 600 MeV
- EPA
- PS: 3.5 GeV
- SPS: 22 GeV
- LEP

LEP II Collider

Collided e^+e^-
LEP I (1989-1995)
LEP II (1996-2000)

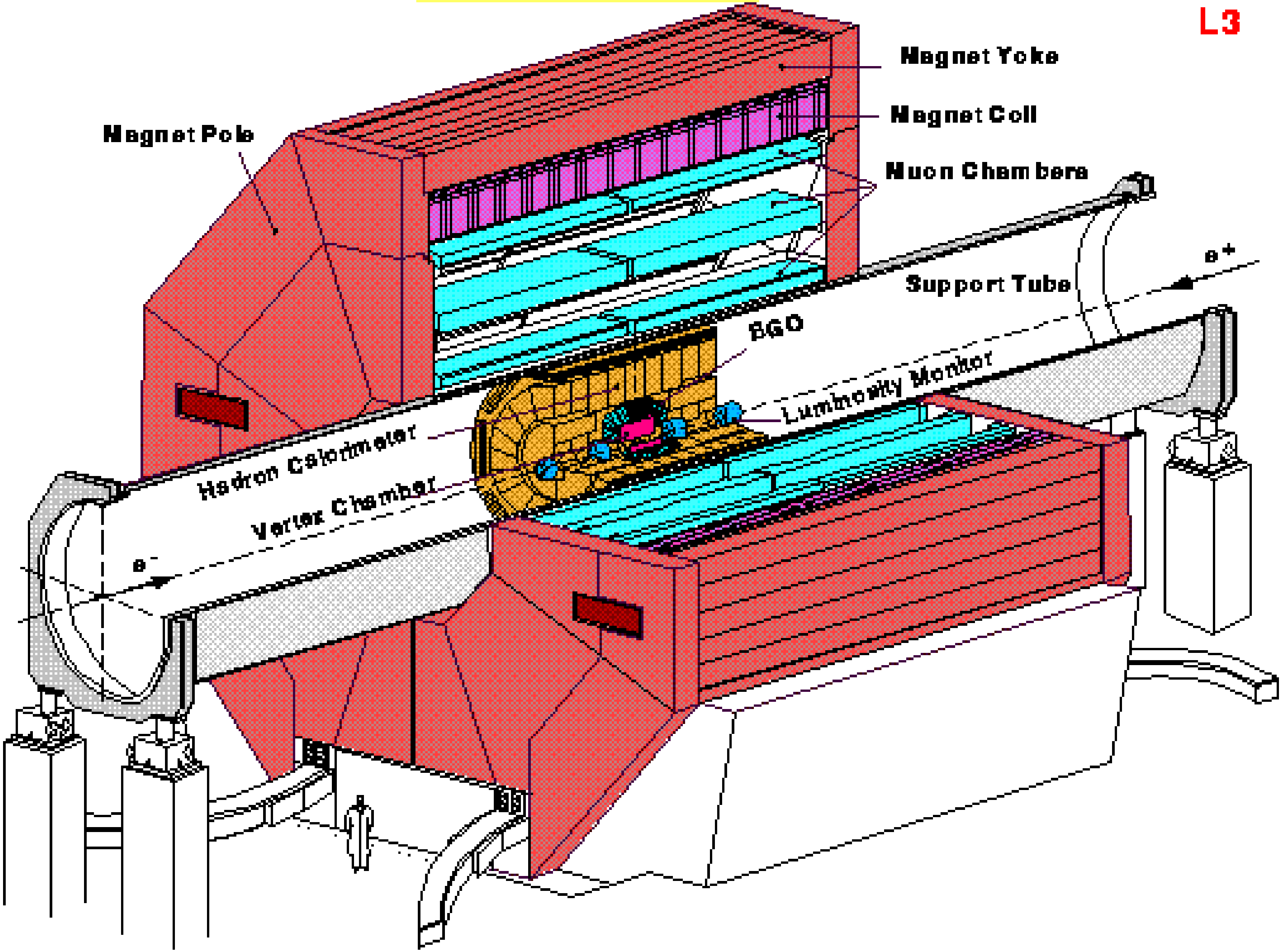
$$\Delta t_X = 22\ \mu s$$

$$\begin{cases} \int L dt = 2.465\ \ fb^{-1} \\ \sqrt{s} > 189\ GeV\ _{(ADLO)} \end{cases}$$

L3 Integrated Luminosity

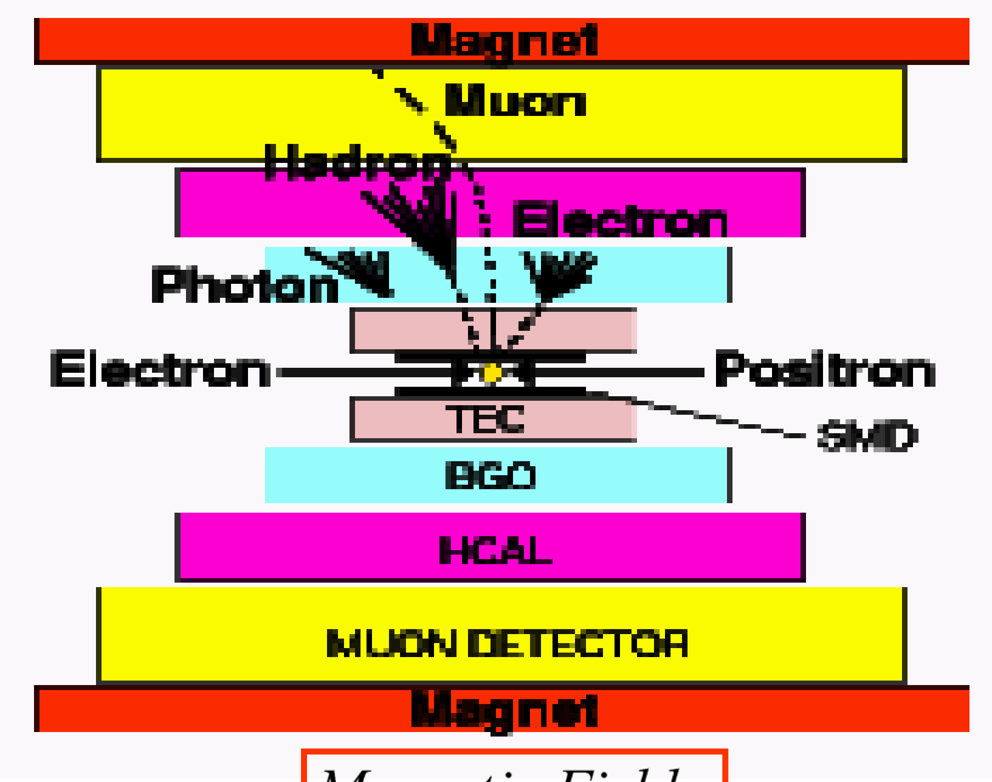
$\sqrt{s}\ (GeV)$	$\int L dt\ (pb^{-1})$
130	**6.1**
136	**5.8**
161	**10.8**
172	**10.2**
183	**55.5**
189	**176.4**
192	**29.8**
196	**84.1**
200	**83.3**
202	**37.1**
202-206	**145.3**
206-209	**72.0**

L3 Detector


L3
Magnet Yoke
Magnet Coil
Magnet Pole
Muon Chambers
Support Tube
e+
BGO
Luminosity Monitor
Hadron Calorimeter
Vertex Chamber
e-

L3 Detector

Particle/Object ID



Magnetic Field :

$$B = 0.51T\ (SOL)$$

$$B = 1.20T\ (TOR)$$

Muon :

$$\frac{\Delta p}{p} = 2.5\%, \quad 5-25\%, \quad 35\%$$

$(Central, EndCap, Forward)$

Calorimeter :

$$\frac{\sigma_{EM}}{E} = \frac{2.8\%}{\sqrt{E}} \oplus 0.4\% \oplus \frac{0.0008}{E}$$

$$\frac{\sigma_{Jet}}{E} = \frac{55\%}{\sqrt{E}} \oplus 0.05$$

Tracking :

$$\sigma(r\varphi) = 7/50\ \mu m\ (SMD/TEC)$$

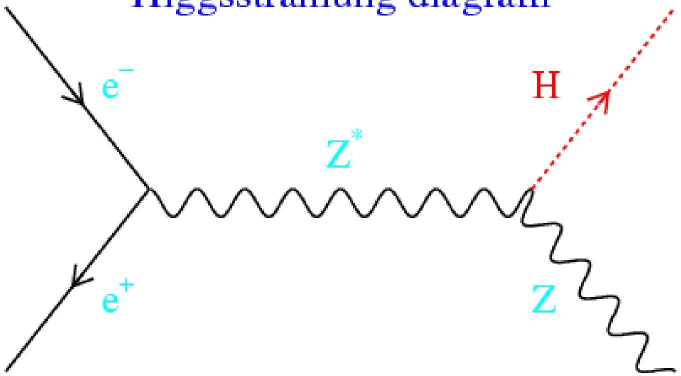
$$\sigma(sz) = 14/320\ \mu m\ (SMD/TEC)$$

$$\frac{\Delta p_T}{p_T} = 0.02\ (TEC)$$

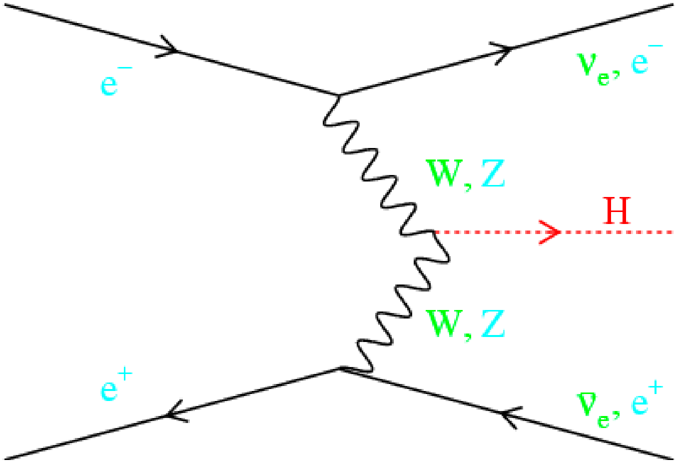
Analyses: Higgs Boson Production

Production Mechanisms

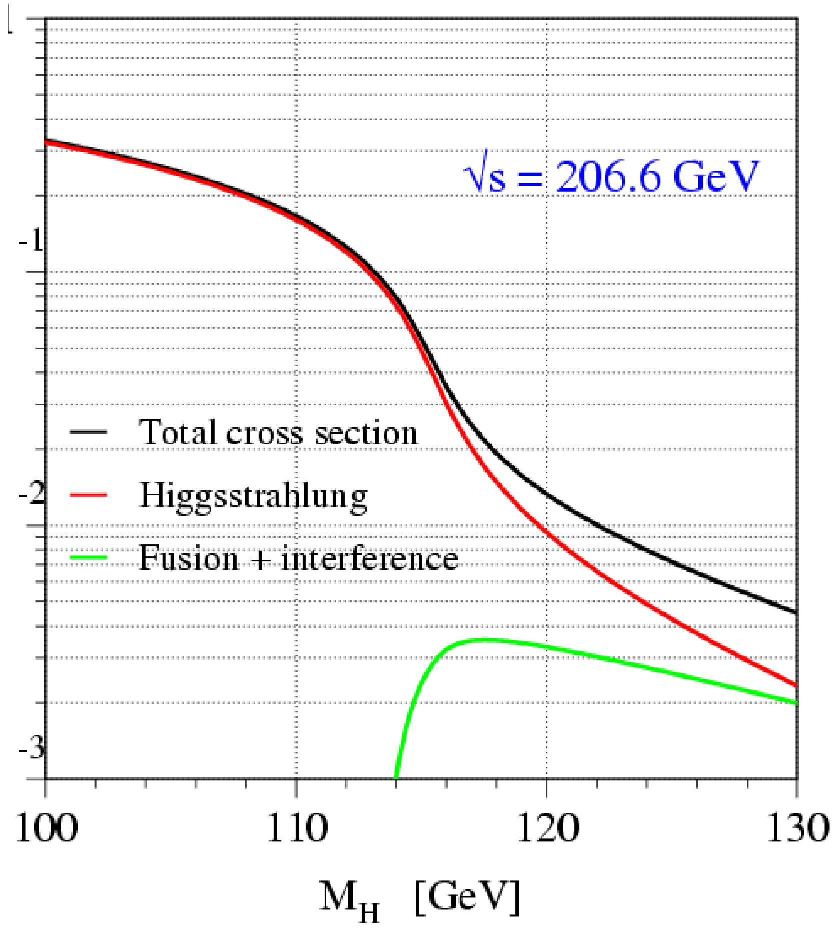
Higgsstrahlung diagram



Fusion diagram



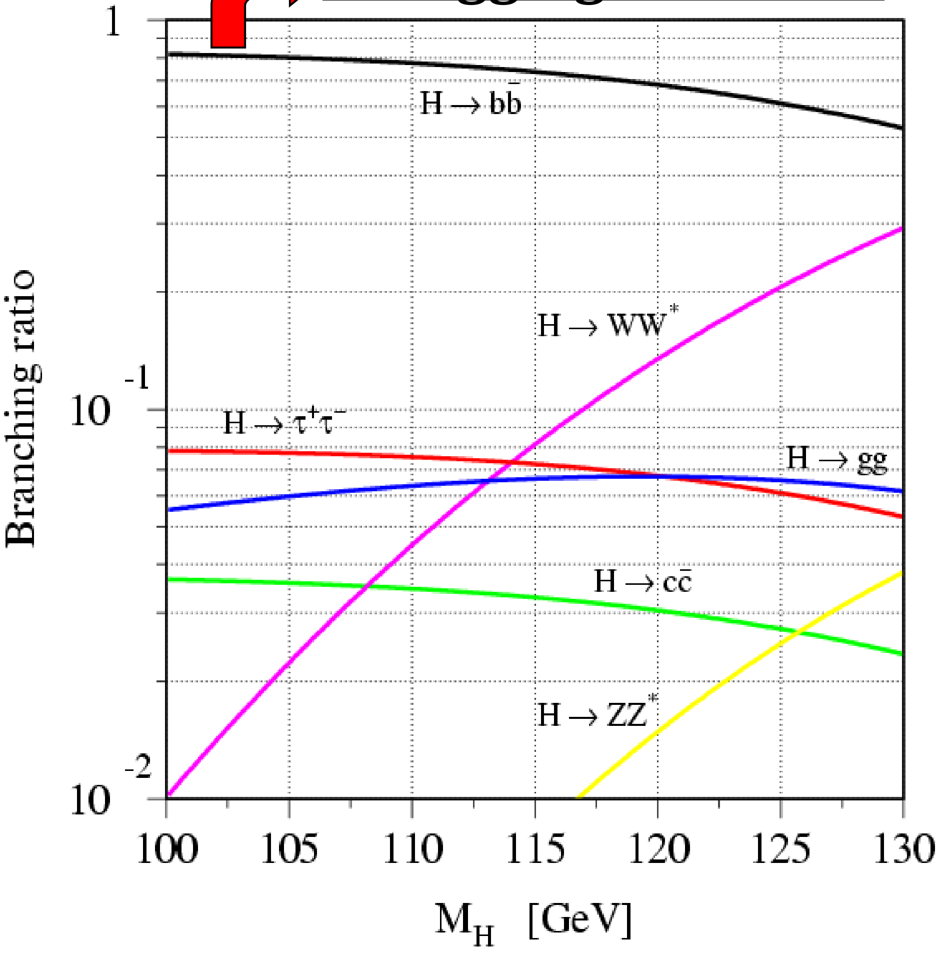
Signal Cross Section



Analyses: Higgs Boson Decays

Higgs Boson Branching Fractions

B-tagging is crucial



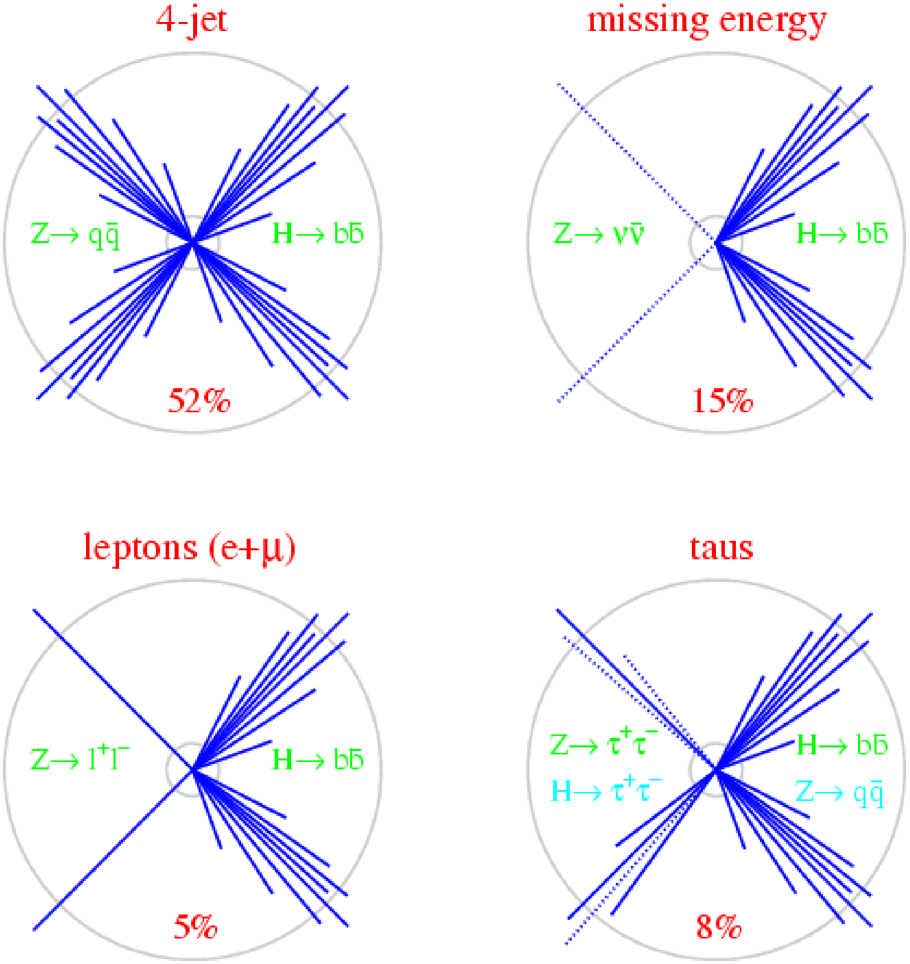
Z Boson Branching Fractions

$$\left\{ \begin{array}{l} BR(Z \to q\bar{q}) = 69.9\% \\ BR(Z \to \nu\bar{\nu}) = 20.0\% \\ BR(Z \to \ell^+ \ell^-) = 10.1\% \end{array} \right.$$

Analyses: Higgs Boson Decays

Signal Topologies (82%)

$$(m_H = 115\ GeV)$$

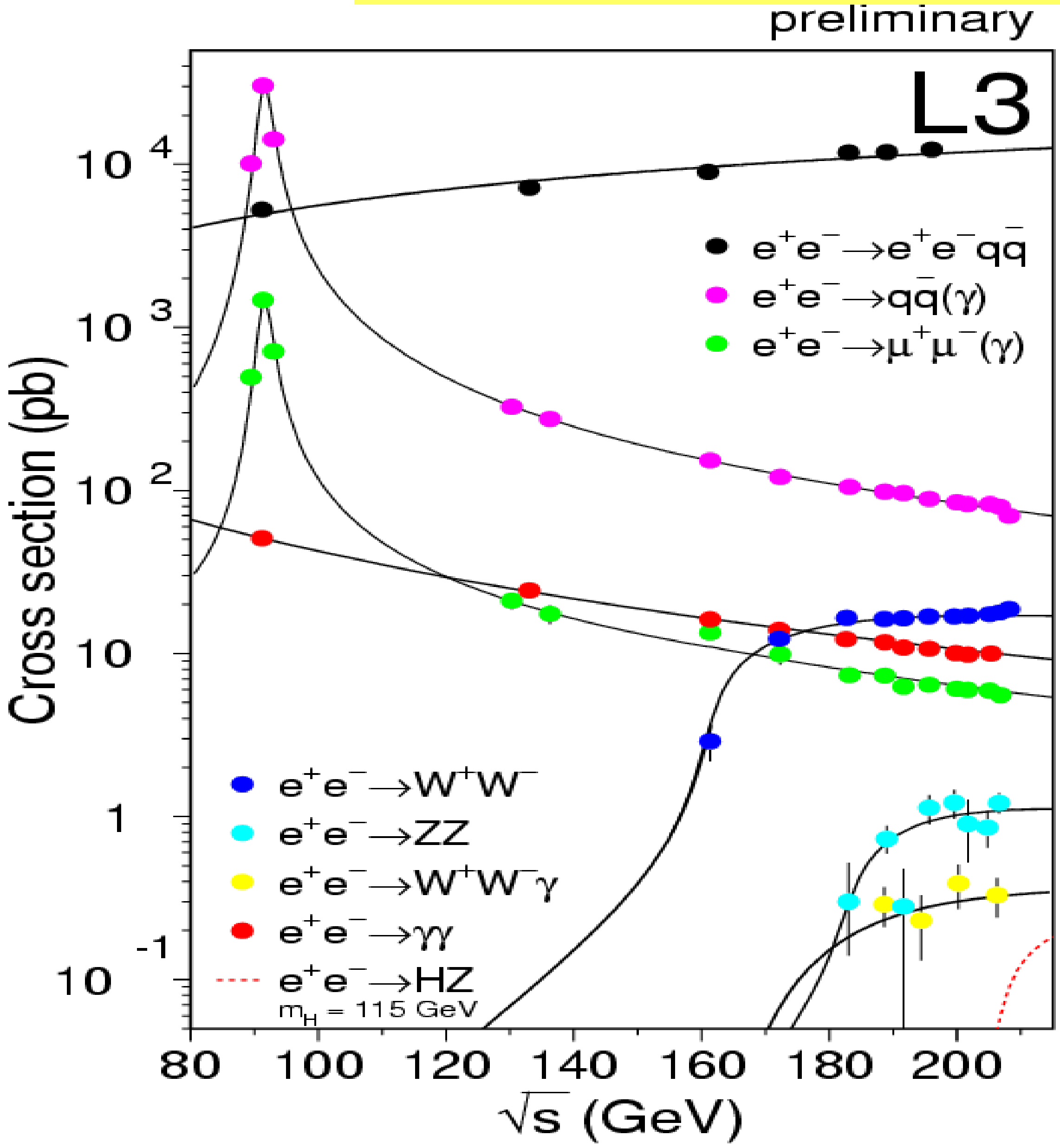


Analyses: Higgs Boson Decays

$200 \le \sqrt{s} \le 209\,GeV$	$N_{exp}(m_H=115\text{ GeV})$		
Channel	DATA	B	S
$Hq\bar{q}$	12	9.4	1.8
$H\nu\bar{\nu}$	5	3.3	0.66
He^+e^-	0	0.38	0.14
$H\mu^+\mu^-$	0	0.26	0.11
$H\tau^+\tau^-$	1	0.14	0.03
$\tau^+\tau^-q\bar{q}$	0	0.84	0.15
Total	18	14.3	2.9

$$\frac{S}{B} > 0.05$$

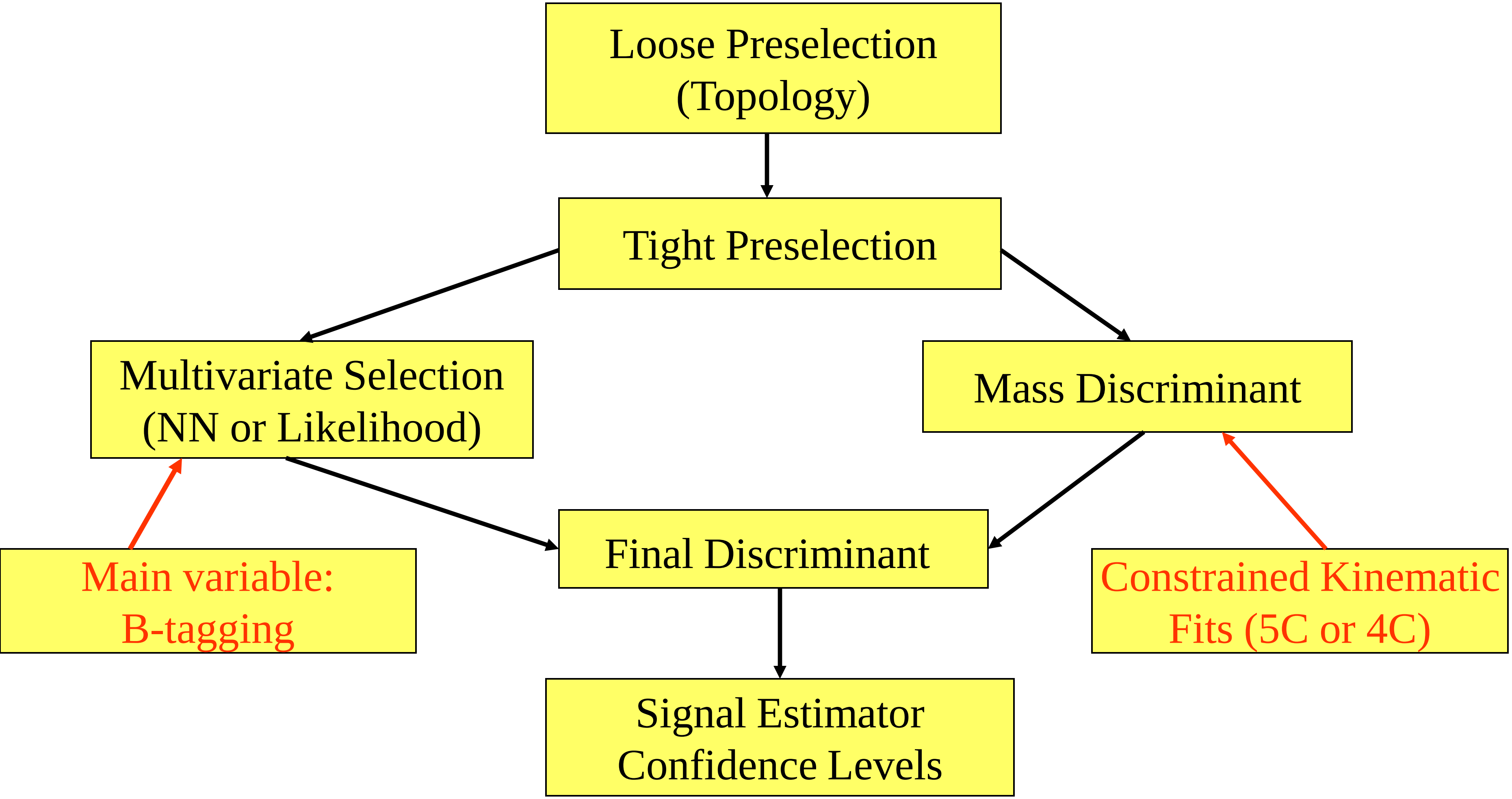
Analyses: SM Backgrounds



Main Backgrounds

$$\begin{cases} e^+e^- \to W^+W^- \\ e^+e^- \to ZZ \\ e^+e^- \to q\bar{q}(\gamma) \end{cases}$$

Analyses: Search Strategy



Loose Preselection
(Topology)

Tight Preselection

Multivariate Selection
(NN or Likelihood)

Mass Discriminant

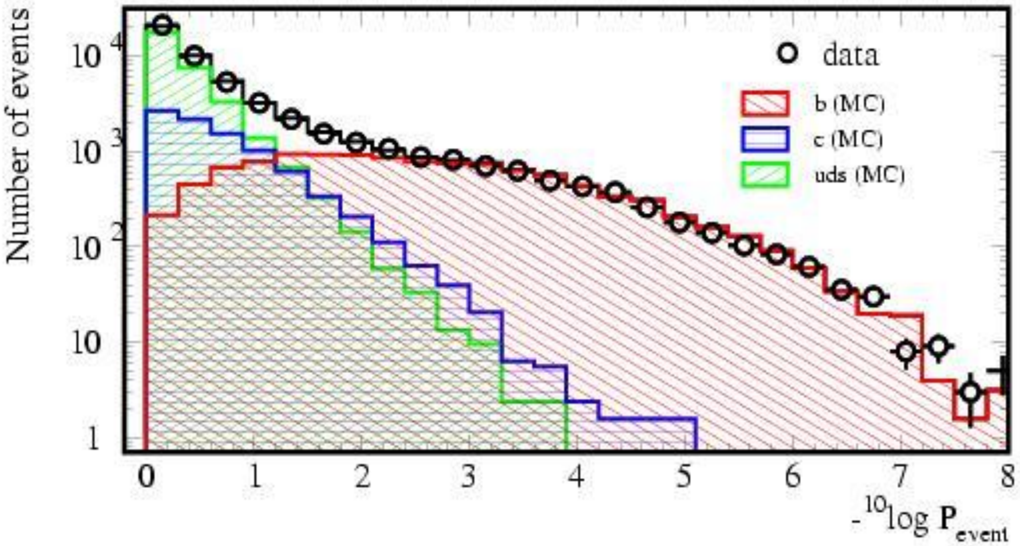
Main variable:
B-tagging

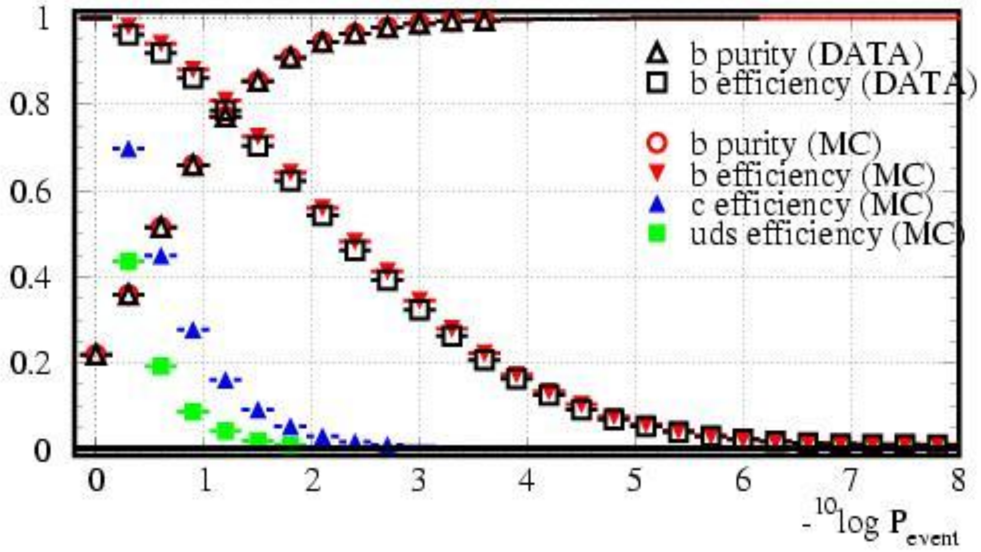
Final Discriminant

Constrained Kinematic
Fits (5C or 4C)

Signal Estimator
Confidence Levels

Analyses: B-Tagging





L3 Implementation

NN combination of:

•Non-isolated muon tagging,

•Non-isolated electron tagging,

•Decay length (high IP tracks),

•Explicit 2^{ndary} vertex reco.,…

Analyses: Higgs Boson Mass Reconstruction

Use kinematic fits

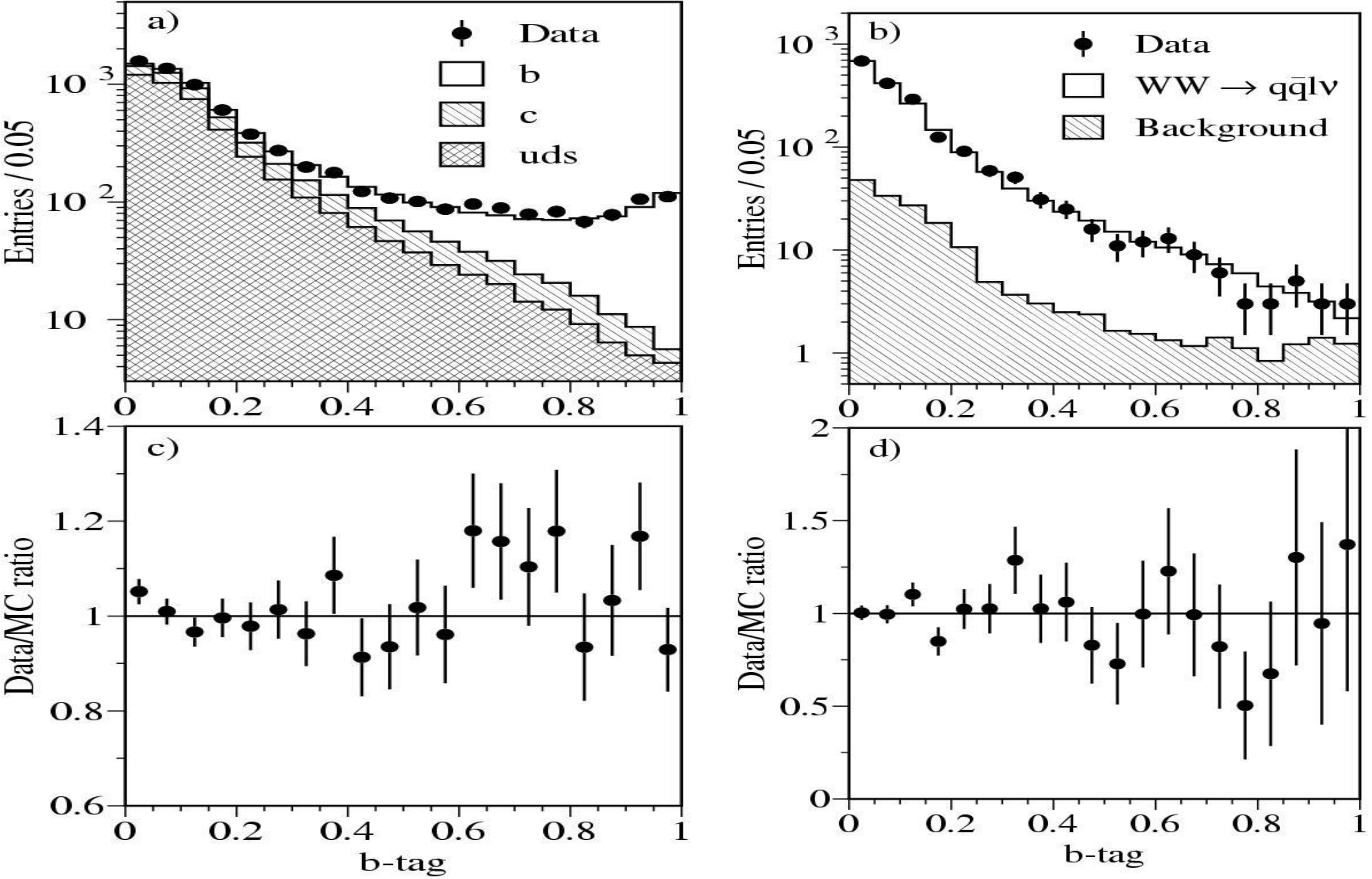
- Aim: Improve the mass resolution
- Method: do the HZ kinematic hypothesis
- Take advantage of:
  - Momentum conservation (3C)
  - Energy conservation (1C)
  - Mass constraint (1C)

$$e^+e^- \to HZ$$

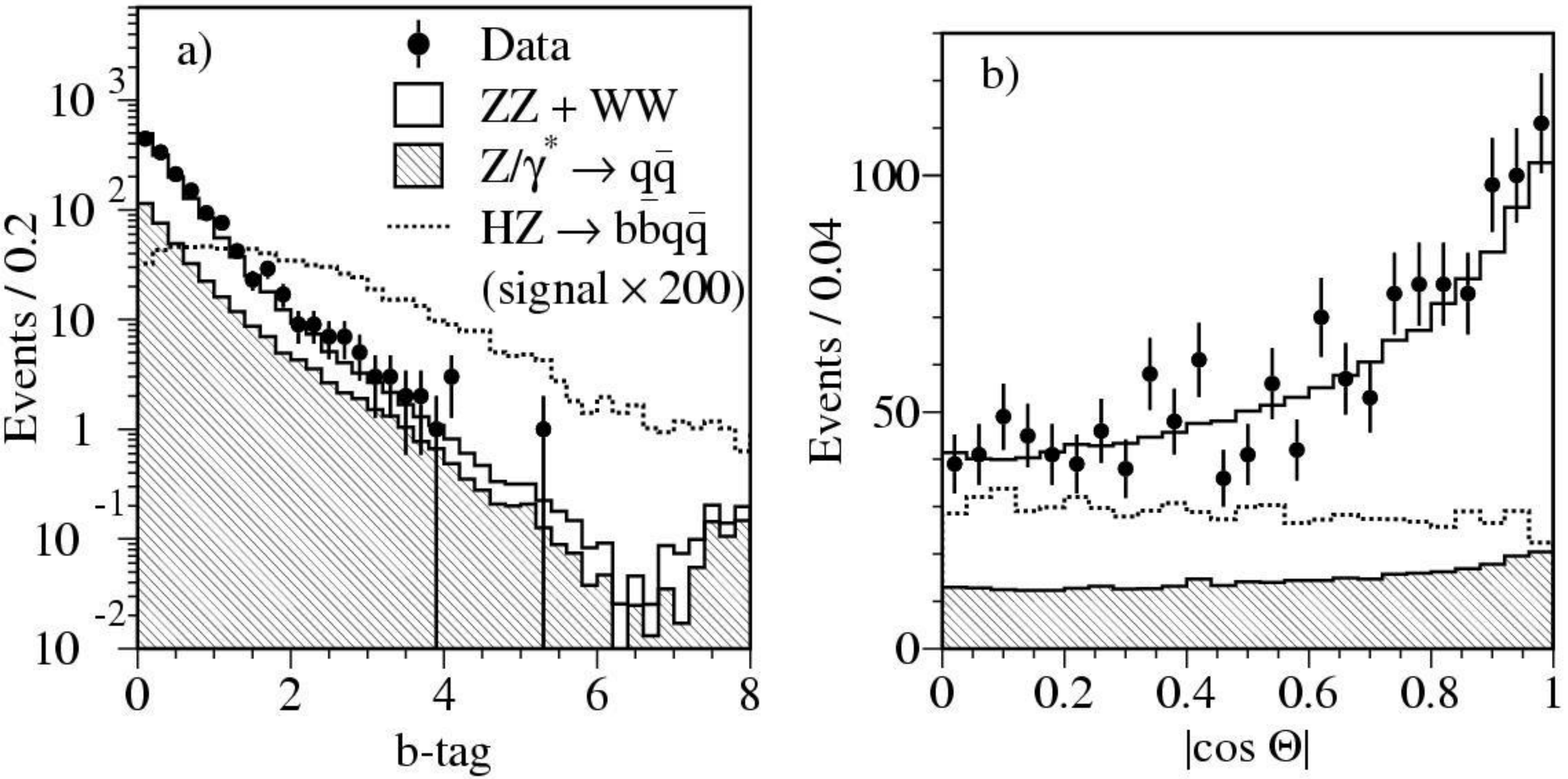
$$\Downarrow$$

$$\begin{cases} H \to b\bar{b}\ (\tau^+\tau^-) \\ Z \to \mathrm{f}\bar{\mathrm{f}} \end{cases} \Longrightarrow \begin{cases} \mathrm{m}_H = \mathrm{m}_{b\bar{b}} \ or\ \mathrm{m}_{\tau^+\tau^-} \\ \mathrm{m}_\mathrm{Z} = \mathrm{m}_{\mathrm{f}\bar{\mathrm{f}}} \end{cases}$$

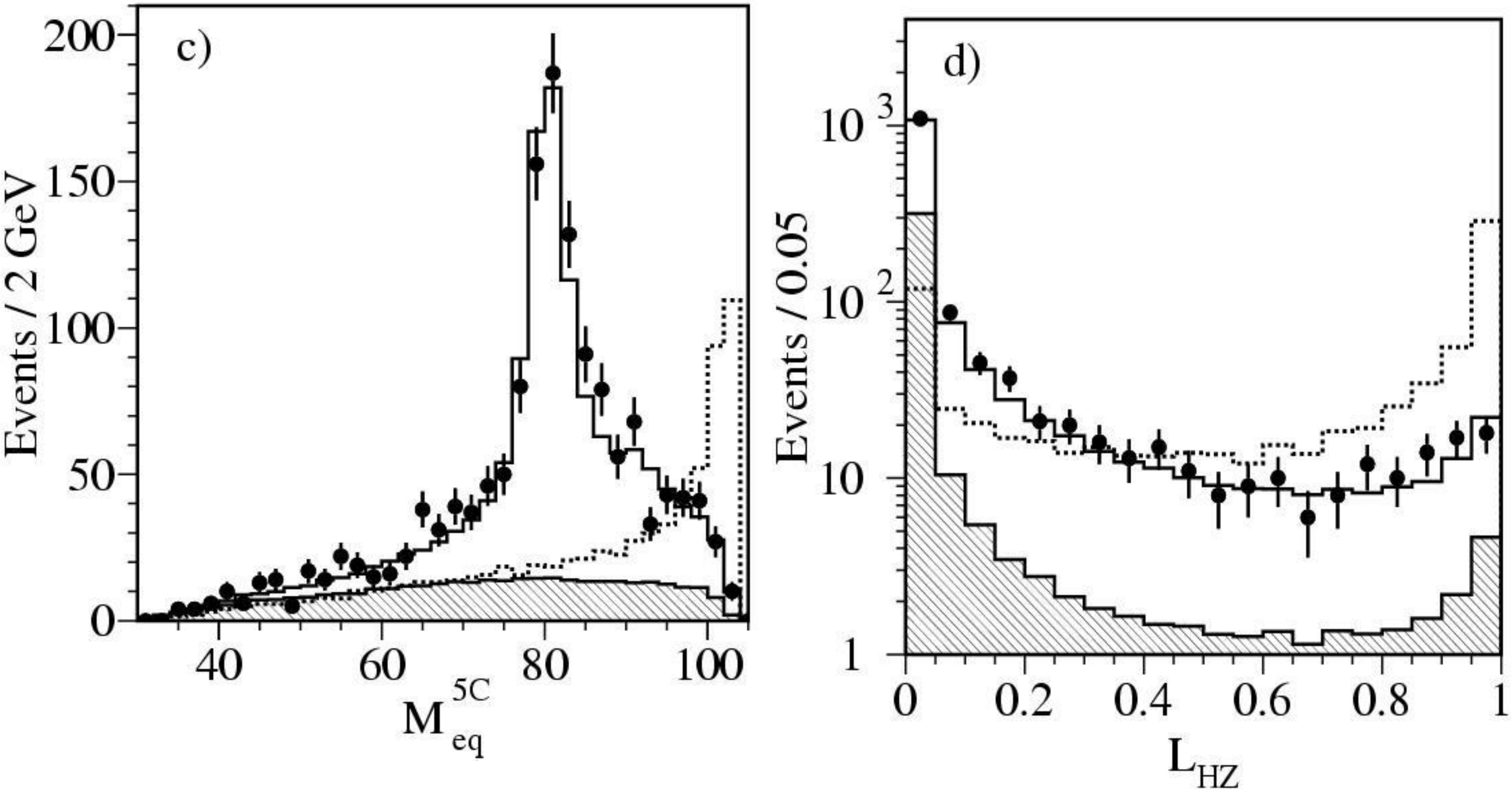
Analyses: 4j Channel



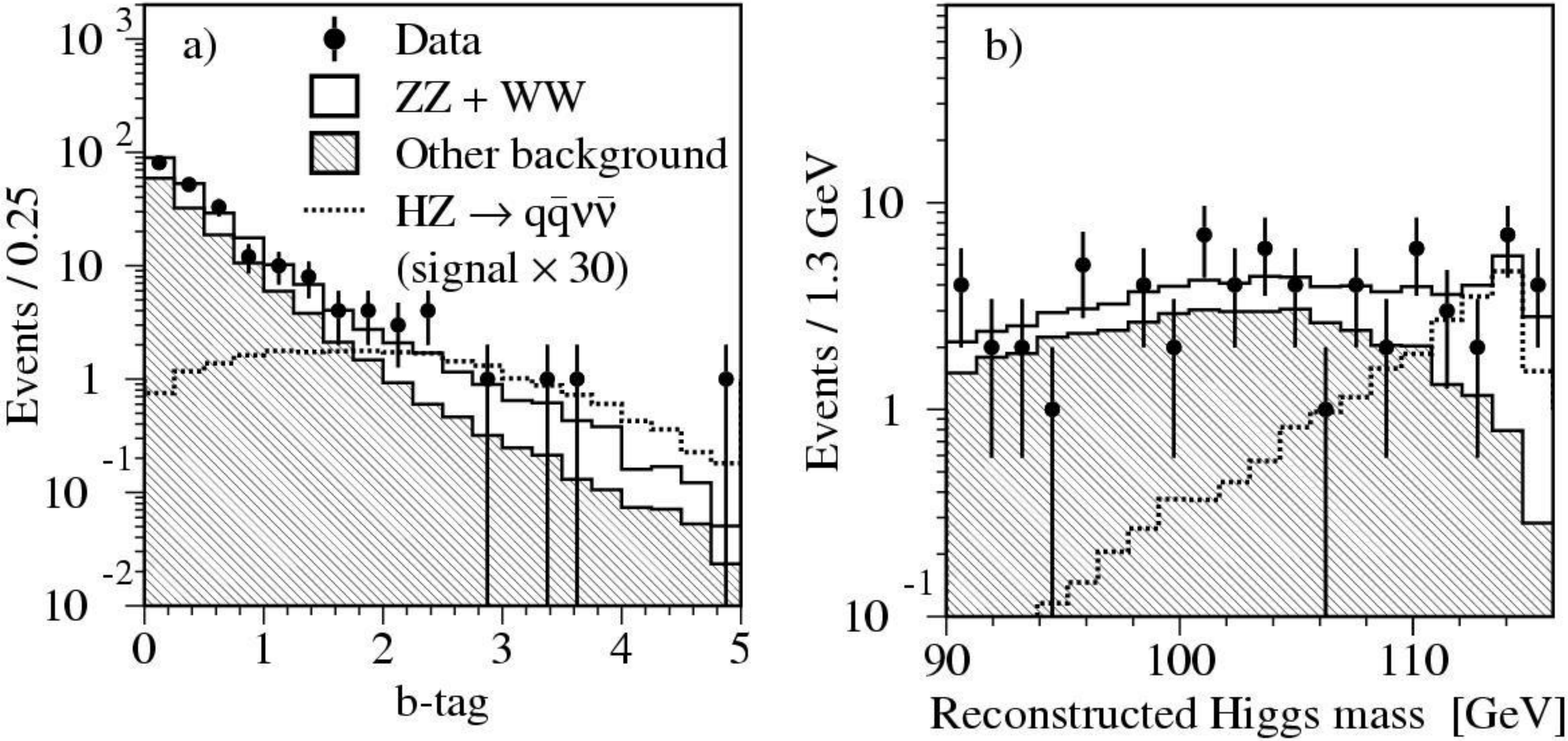
Analyses: 4j Channel



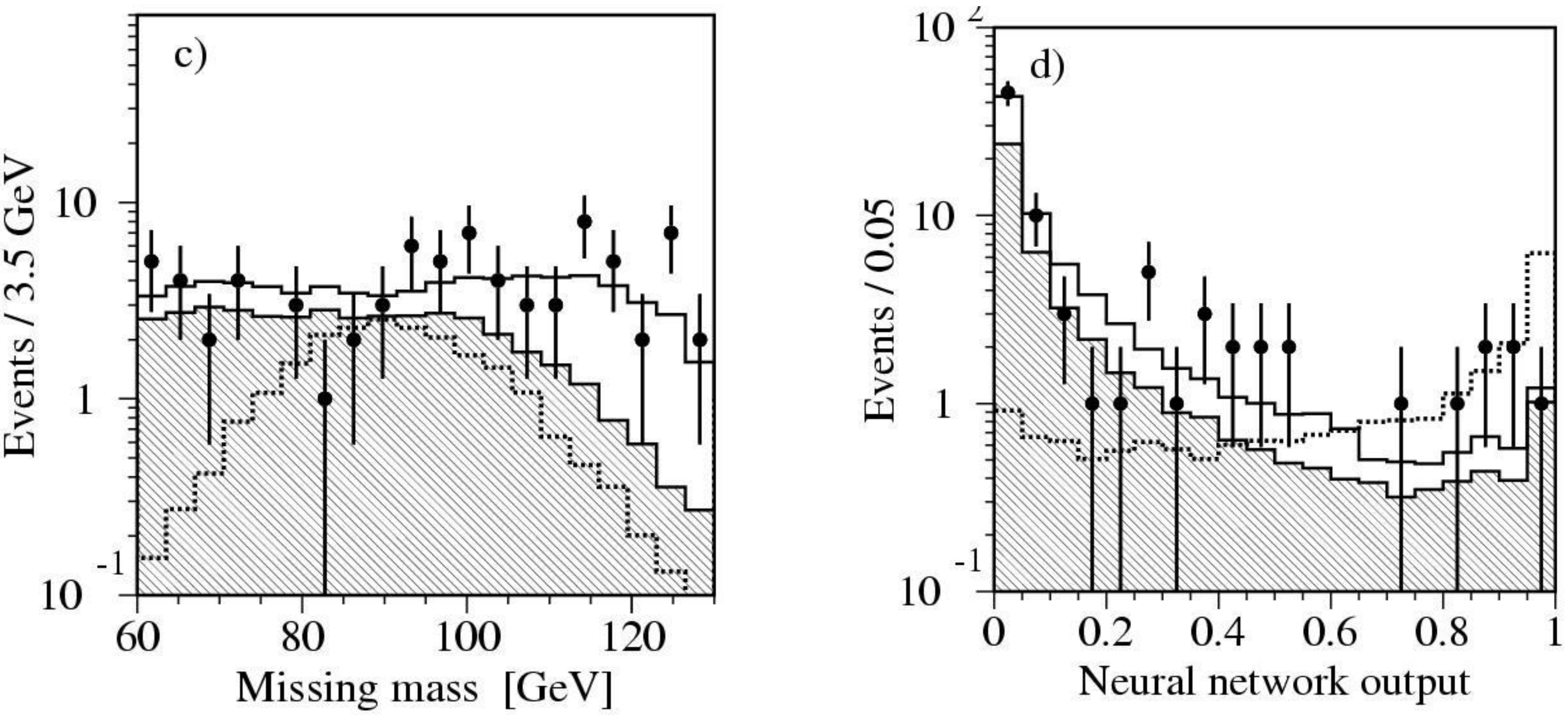
Analyses: 4j Channel



Analyses: 2j+E_{miss} Channel



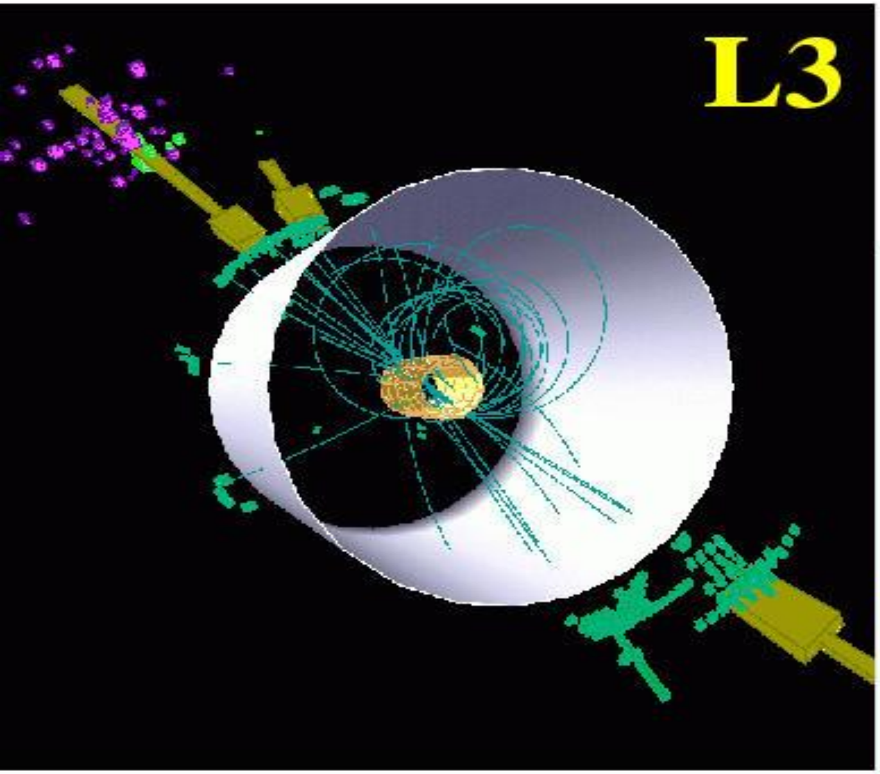
Analyses: 2j+E_{miss} Channel



Analyses: 2j+E_{miss} Channel

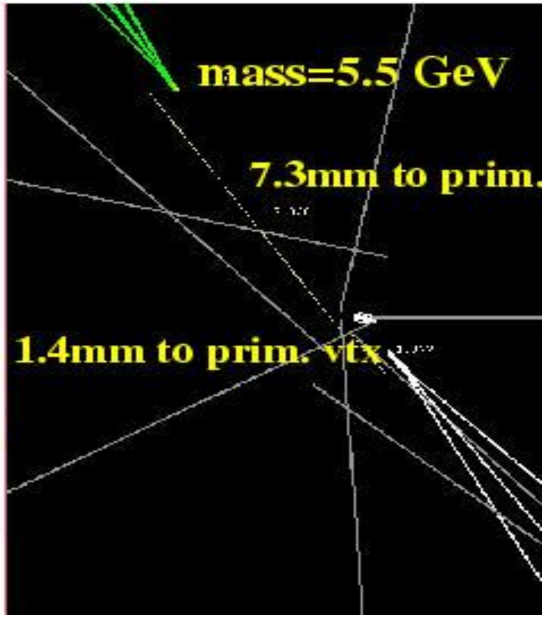
$$\begin{cases} m_{mis} = 99.4\,GeV \\ m_{vis} = 106.6\,GeV \\ m_H^{rec} = 115.0\,GeV \\ \text{btag(jet}_1) = 0.61 \\ \text{btag(jet}_2) = 0.95 \end{cases}$$

nost significant Hνν candidate

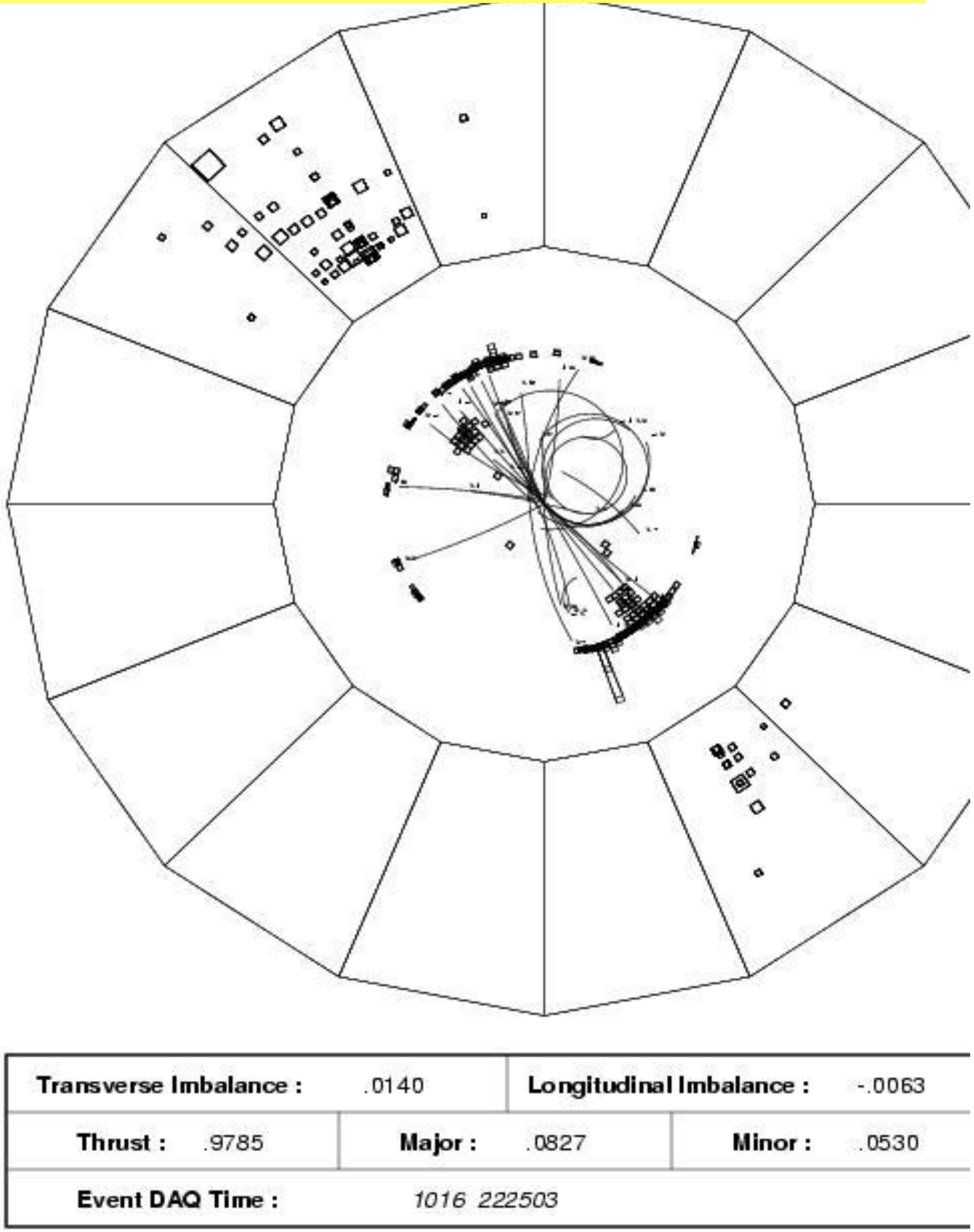


measured H mass=114 GeV

Secondary vtx's



Analyses: 2j+E_{miss} Channel

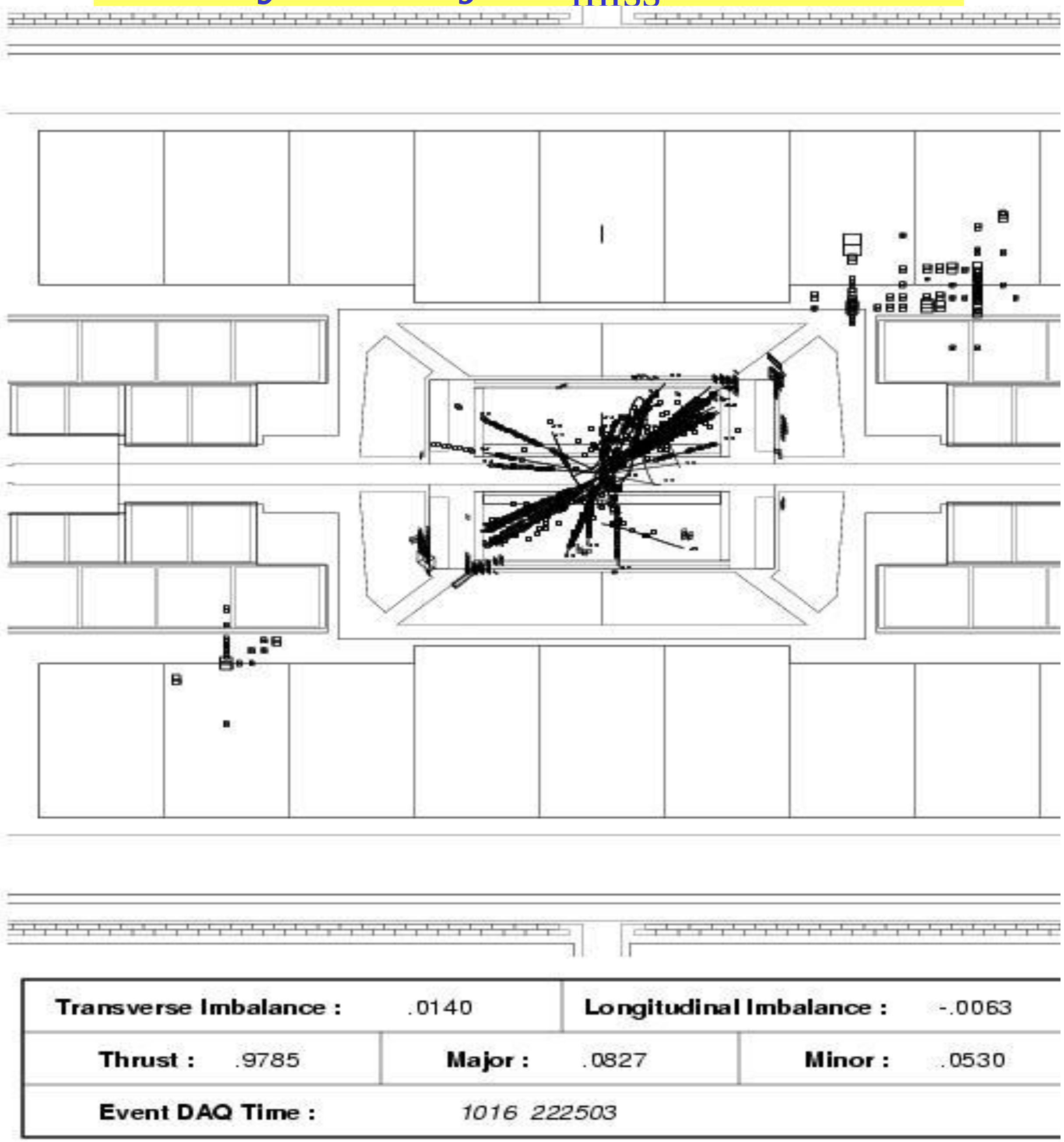


Transverse Imbalance : .0140 **Longitudinal Imbalance :** -.0063

Thrust : .9785 **Major :** .0827 **Minor :** .0530

Event DAQ Time : *1016 222503*

Analyses: 2j+E_{miss} Channel



Transverse Imbalance : .0140

Longitudinal Imbalance : -.0063

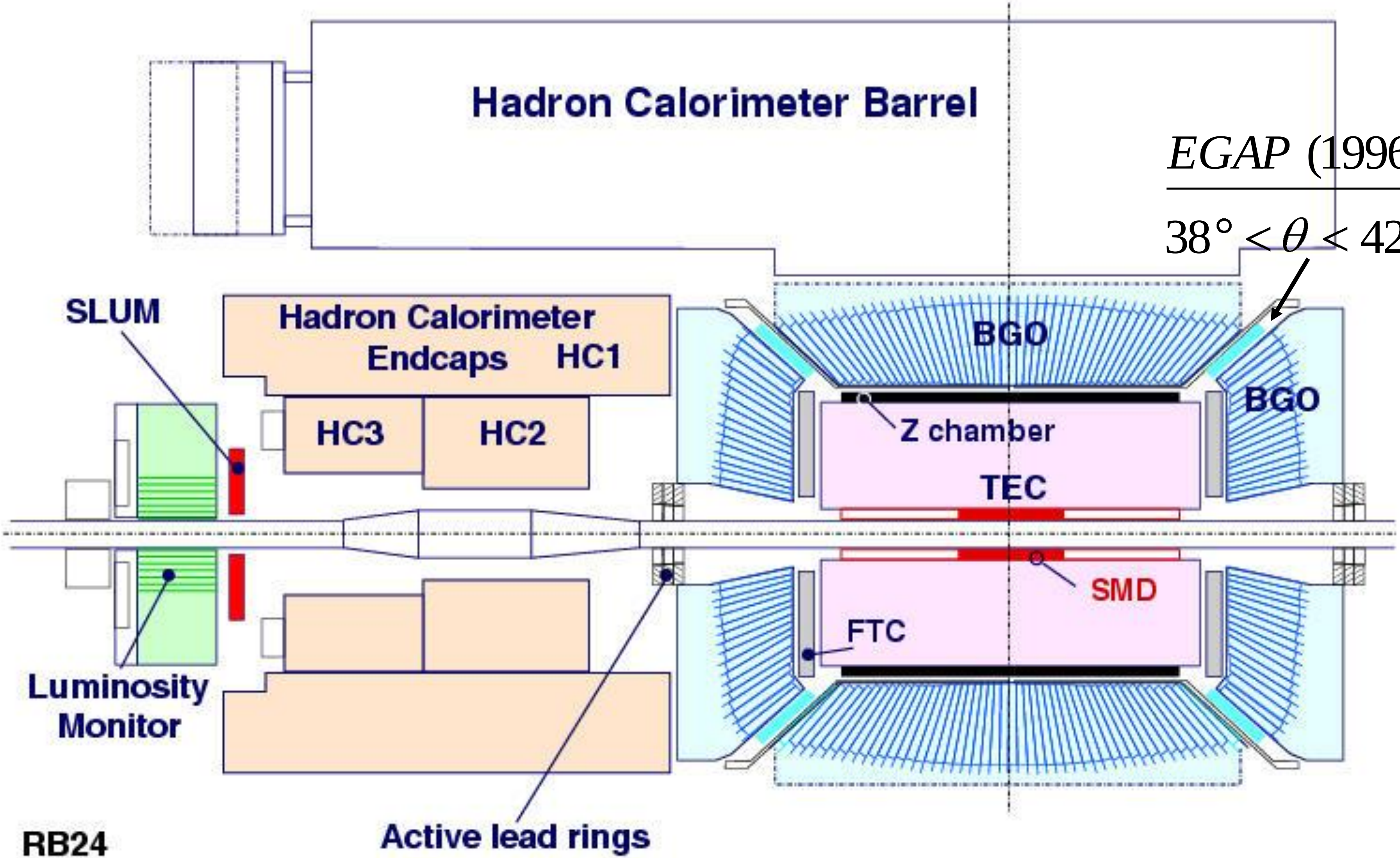
Thrust : .9785

Major : .0827

Minor : .0530

Event DAQ Time : *1016 222503*

L3 Detector

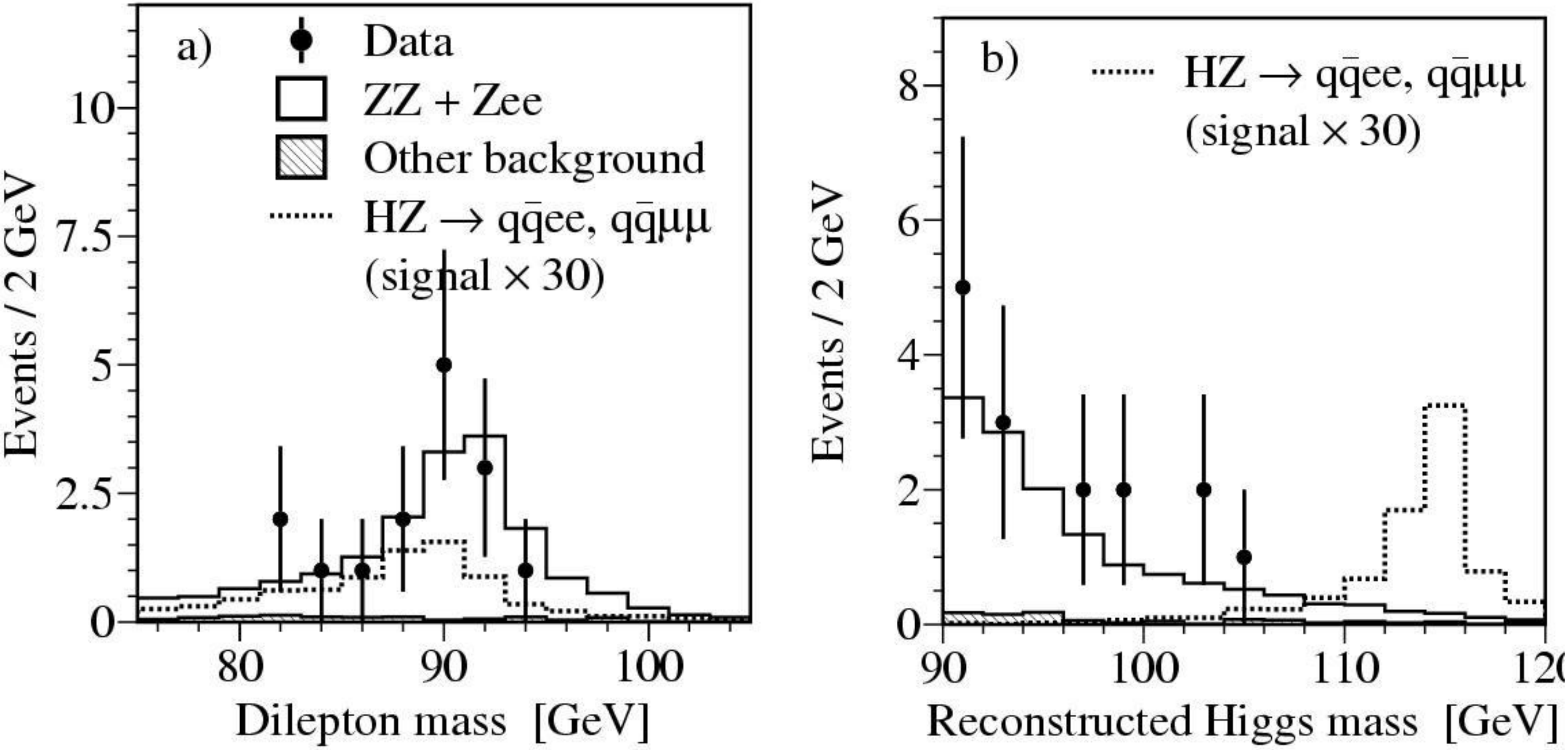


$\frac{EGAP\ (1996)}{38° < \theta < 42°}$

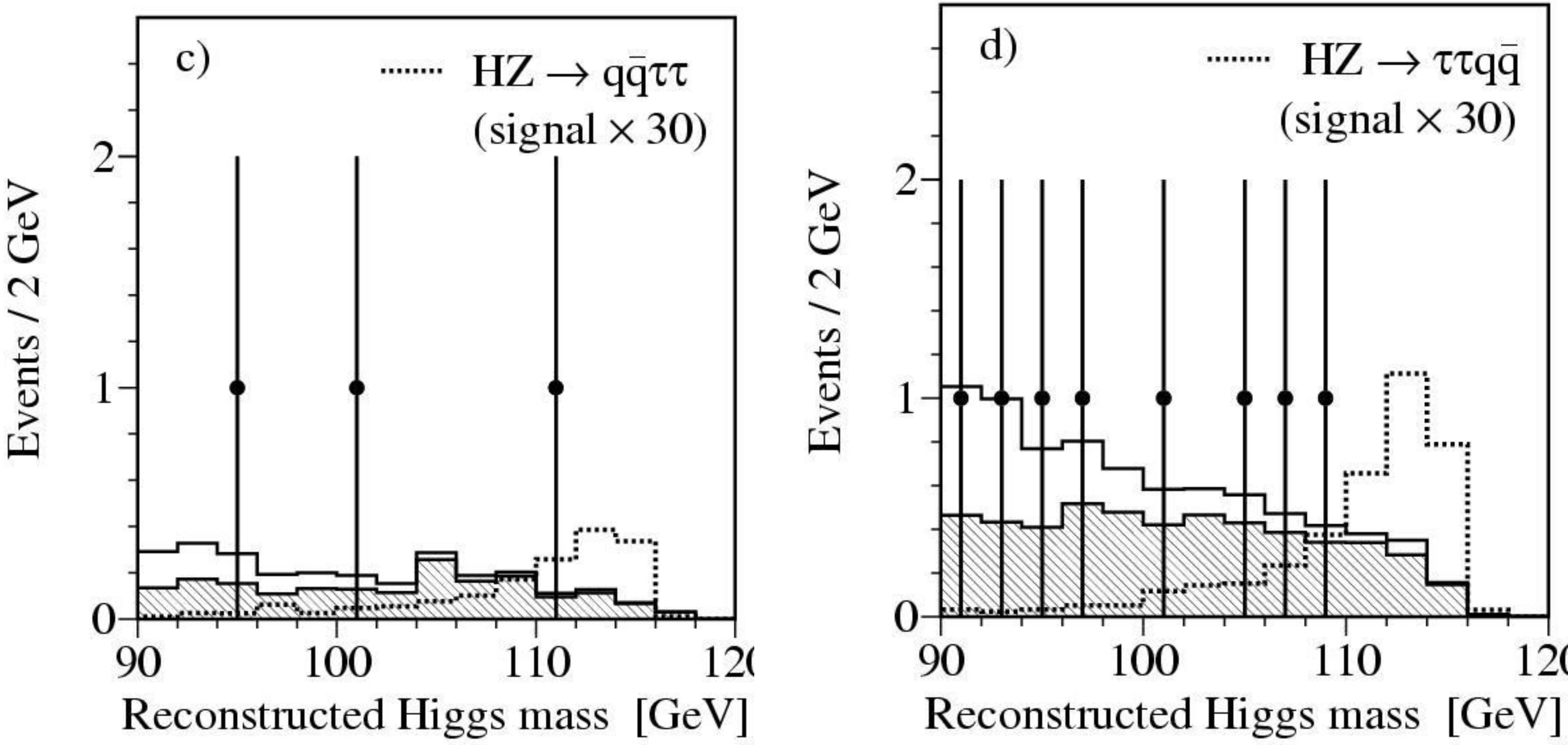
$3.9° < \theta < 9°$

Lead – Scintillating Fibers

Analyses: ¨Lepton¨ Channel



Analyses: ¨Lepton¨ Channel



Analyses: Limits Derivation

Statistical Estimator

$$-2 \cdot Ln\,Q = -2 \cdot Ln \frac{\ell(data \mid S+B)}{\ell(data \mid B)}$$

$$(\ell : product\ \ of\ \ Poisson\ \ probabilities)$$

$$Ln\,Q = -s_{tot} + \sum_{i=1}^{N_{bins}} n_i \cdot Ln(1+\frac{s_i}{b_i})$$

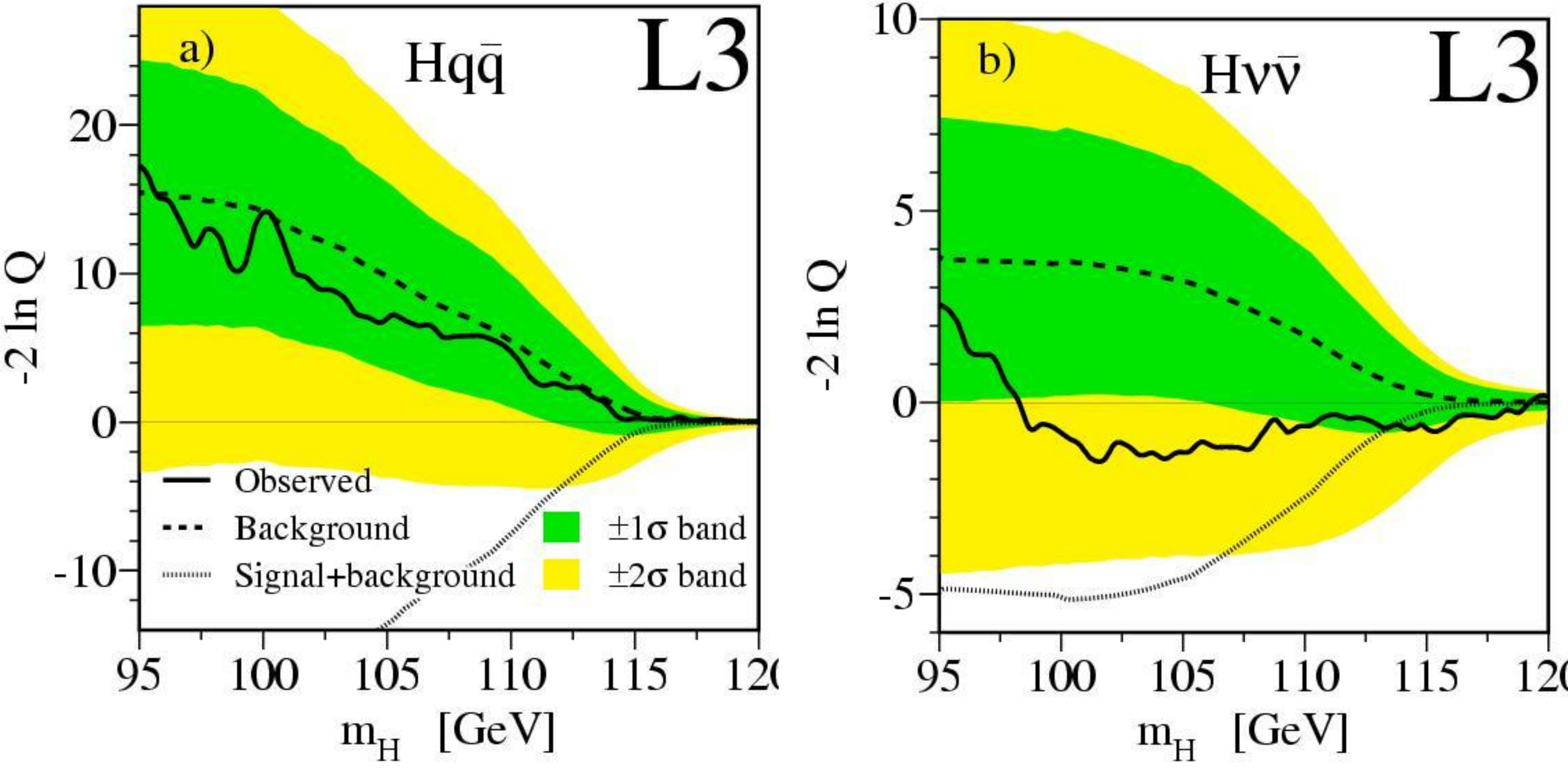
$-s_{tot}$: directly related to the signal (integrated) cross section

$\Rightarrow$ the highest it is the more observed candadites one needs

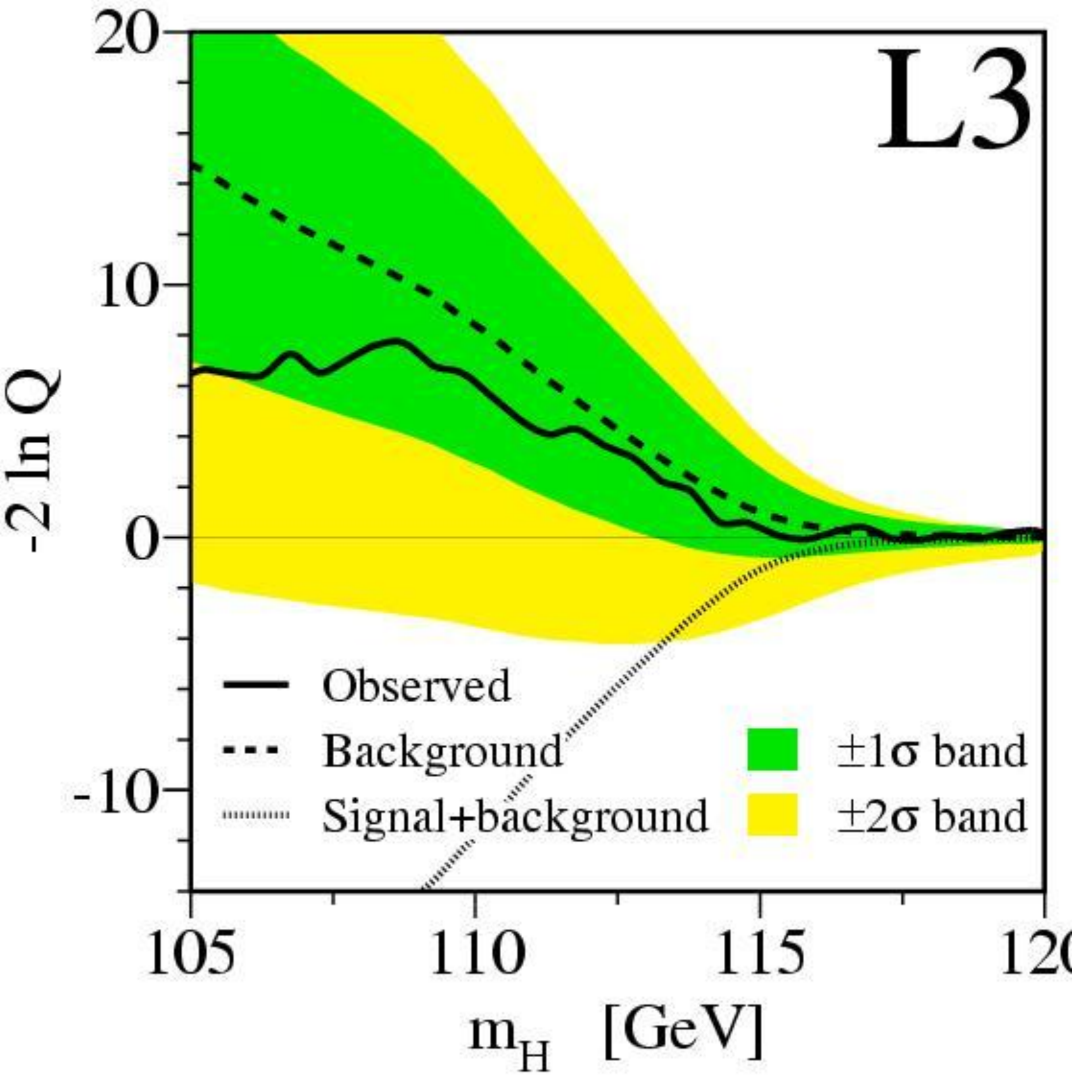
$w_i = Ln(1+\frac{s_i}{b_i})$: related to the (local) $\frac{\mathrm{S}}{\mathrm{B}}$ ratio

$\Rightarrow$ the highest it is the more "signal-like" is the candidate

Analyses: L3 Search Results



Analyses: L3 Search Results

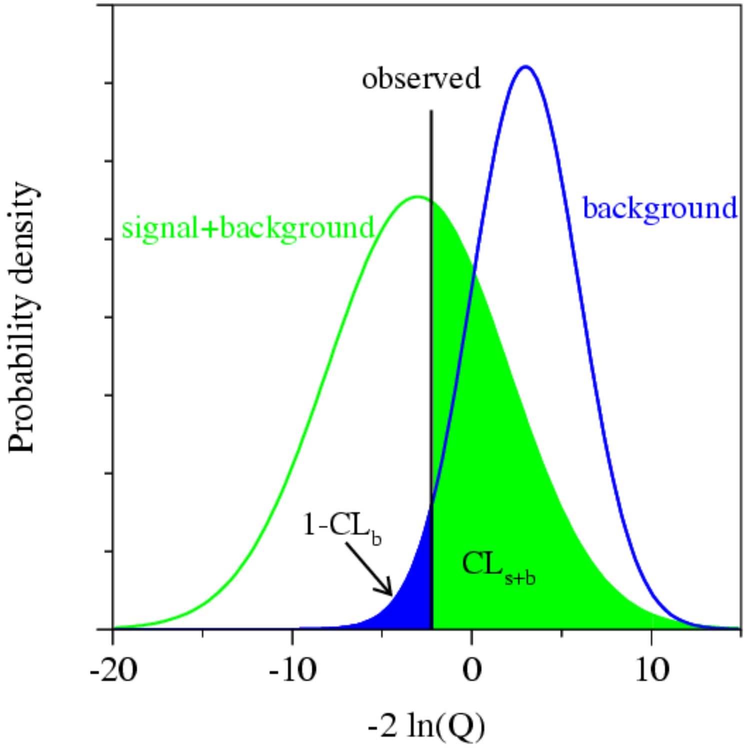


Analyses: Limits Derivation

Confidence Levels

Systematics uncertainties are accounted for by varying (gaussian distr.) S and B in the MC trials

CL_s ($1-CL_B$) : measures resp. the incompatibility between the observed events and the S (B) hypothesis (resp. exclusion / discovery CL)



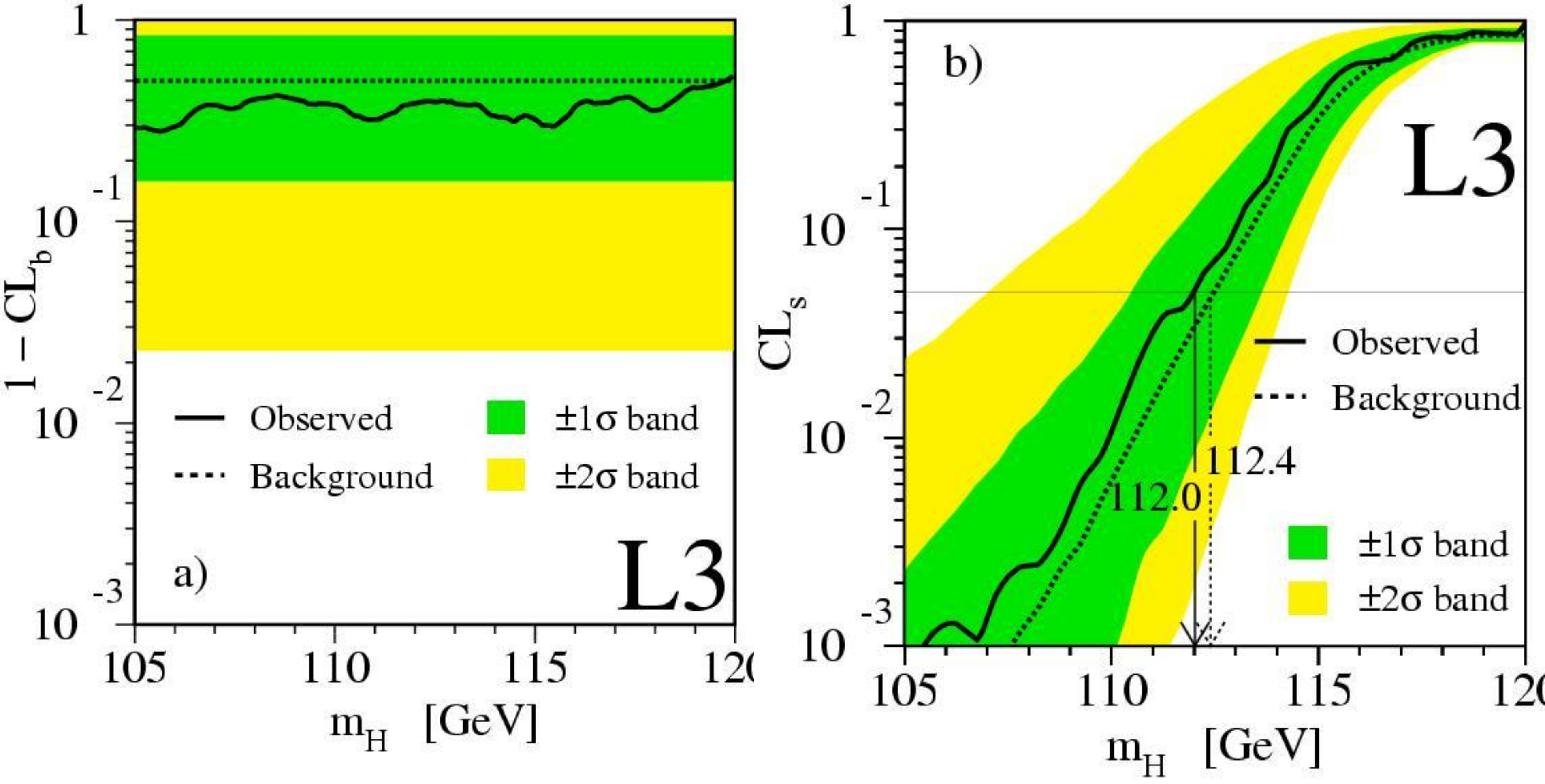
Exclusion: $CL_S = CL_{S+B} / CL_B$

$CL_S < 5\%$ (S hypothesis excluded at 95% CL)

Discovery: $1-CL_B < 2.7\times10^{-3}$ (3σ: signal ¨hint¨)

$1-CL_B < 5.7\times10^{-7}$ (<u>5σ: actual signal discovery</u>)

Analyses: L3 Search Results



Analyses: L3 Search Results

Systematic Uncertainties

Theory

$\Delta\sigma/\sigma$=O(1%)

LEP

ΔE_{CM}=30 MeV

Lumi: 1%

Analyses

Topological cuts: O(1%)

B–tagging: 3-5%

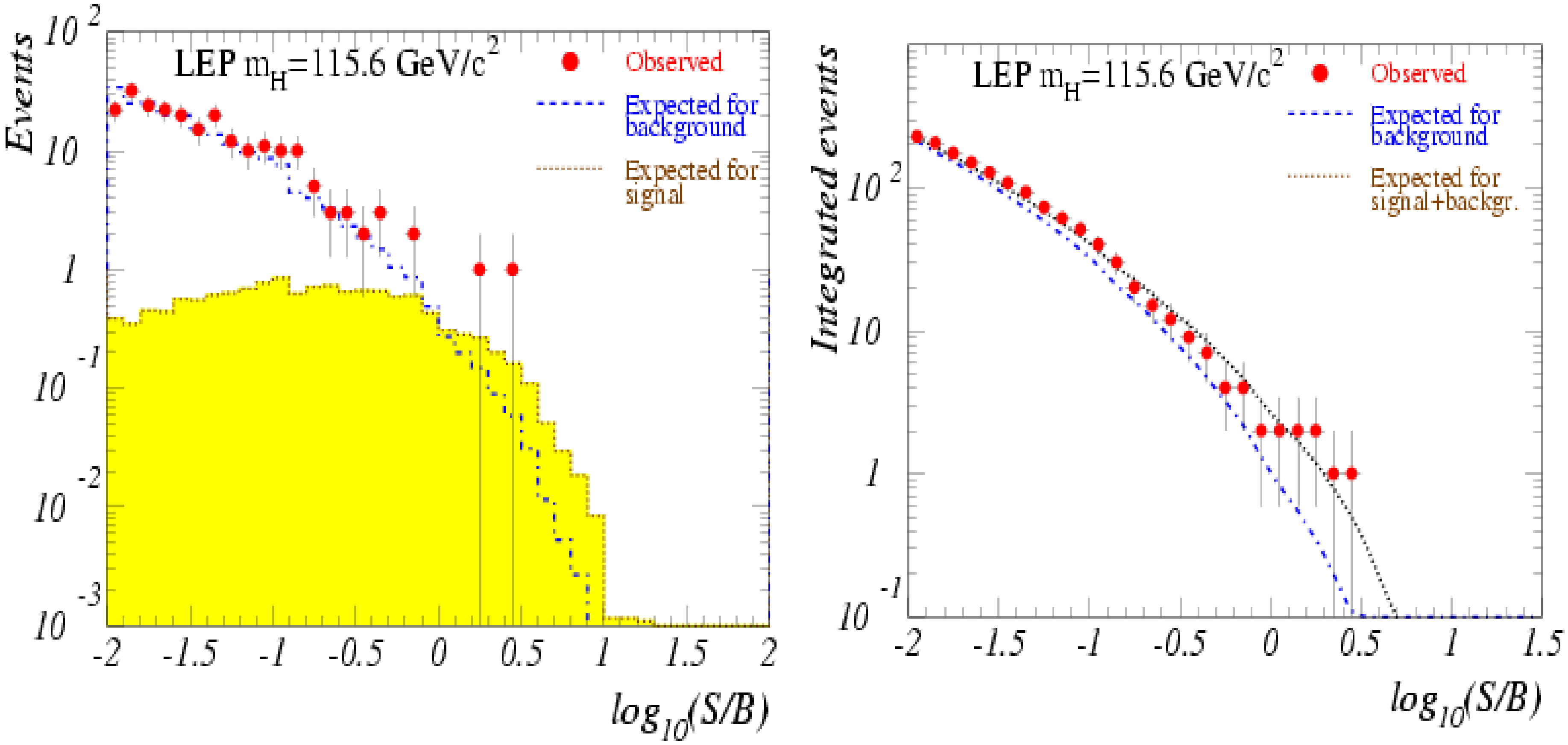
MC Stat.: 2% (S)

8% (B)

- Overall systematics:
  - Signal: 4%
  - Background: 8-10%
- + qq background (populates the high mass region for 4j and 2j+E_{miss} channels)
- Uncertainty on Nexp(background): 6-15%
- Uncertainty on Nexp(signal): 3-6%

(Both for m_H close or beyond HZ kinematic limit)

Analyses: LEP Search Results

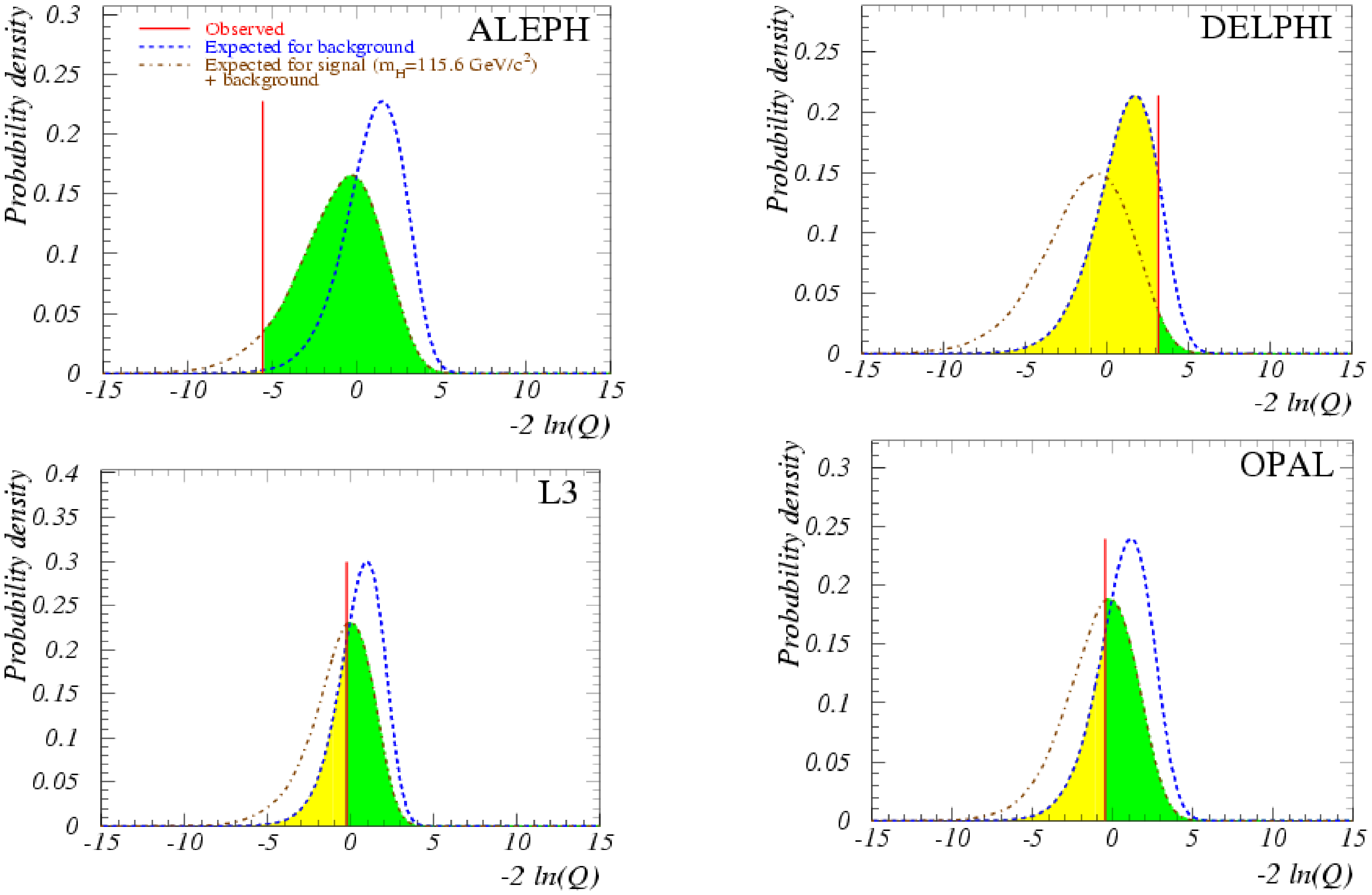


Analyses: LEP Search Results

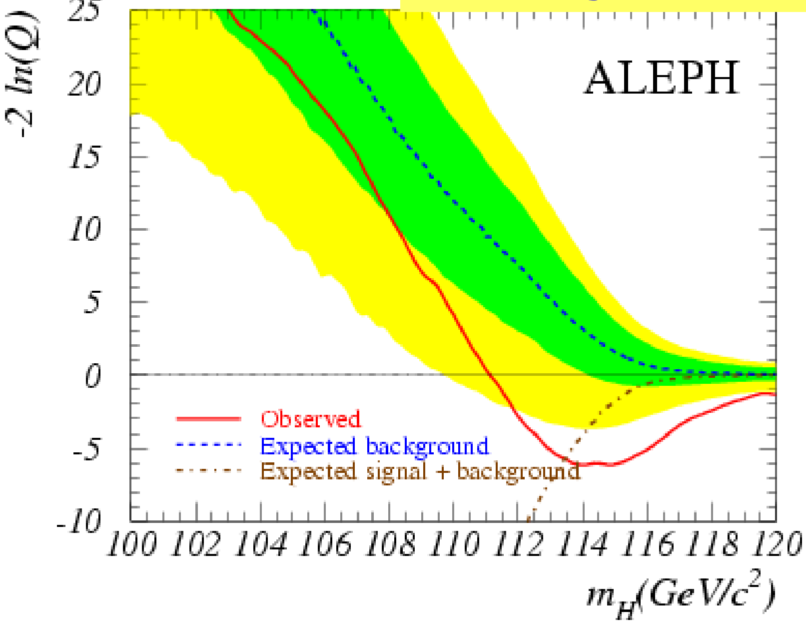
Most Significant Candidates

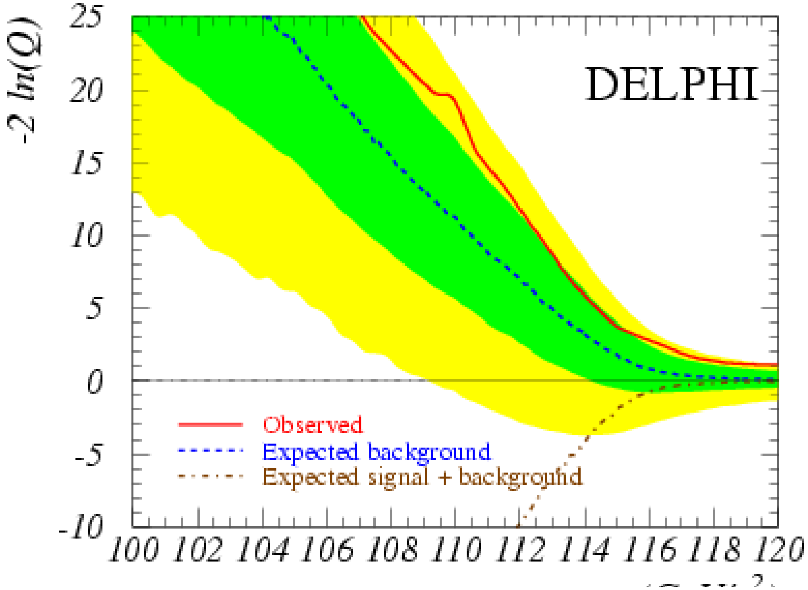
Rank	**Expt**	**E_{CM}**	**Channel**	$m_H^{rec}\ (GeV)$	**Weight @115 GeV**
1	ALEPH	206.7	4j	114.3	1.73
2	ALEPH	206.7	4j	112.9	1.21
3	ALEPH	206.5	4j	110.0	0.64
4	L3	206.4	$2j+E_{miss}$	115.0	0.53
5	OPAL	206.6	4j	110.7	0.53
6	DELPHI	206.7	4j	114.3	0.49

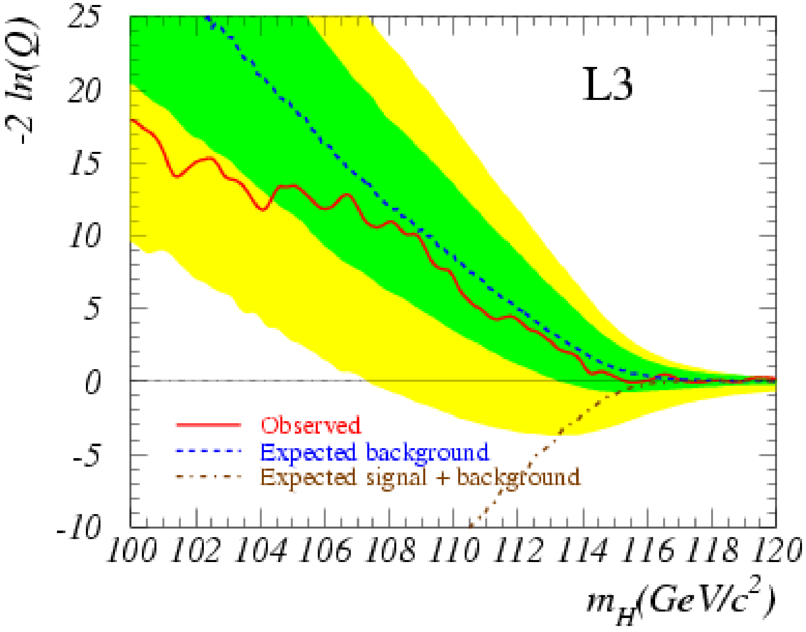
Analyses: LEP Search Results

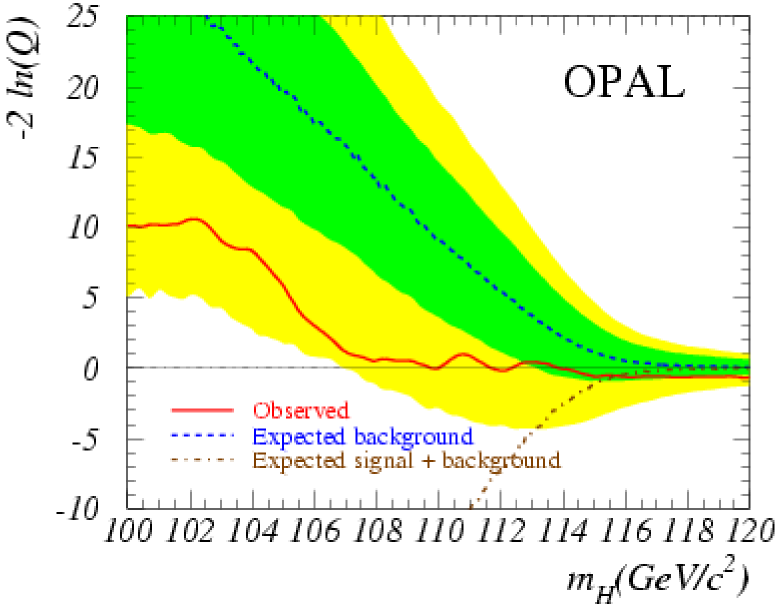


Analyses: LEP Search Results

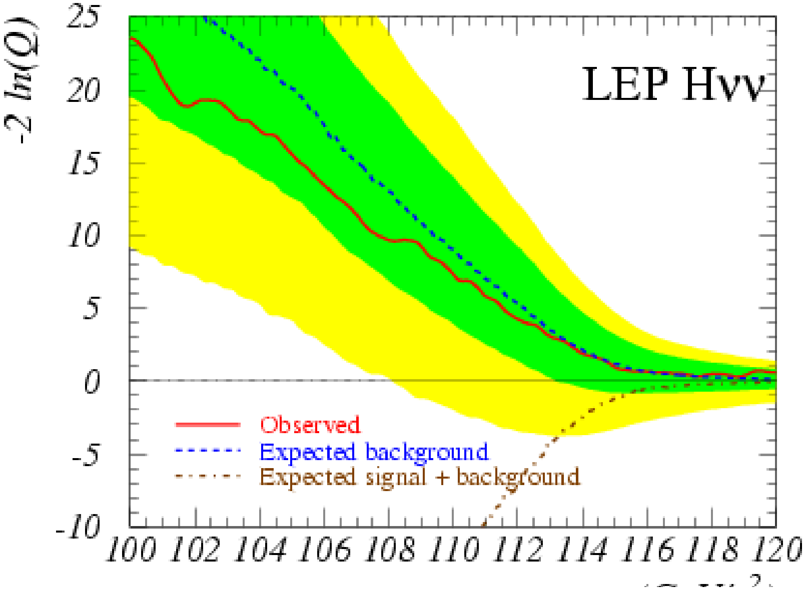


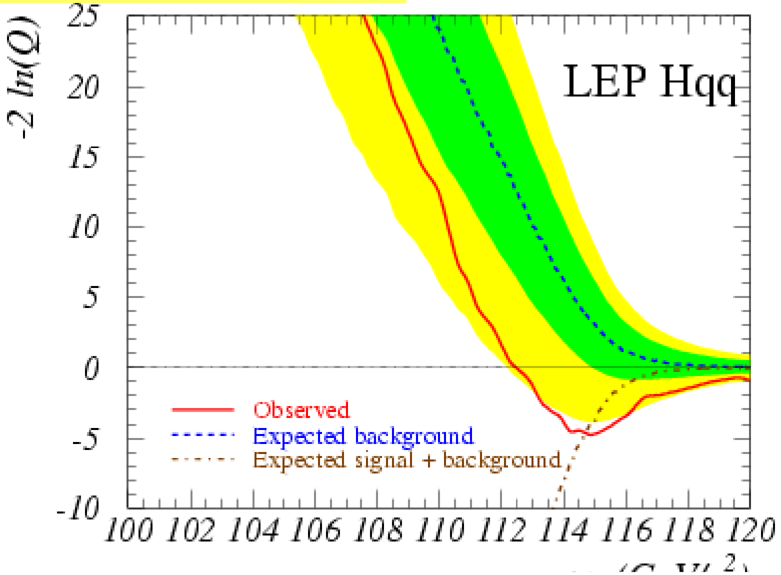


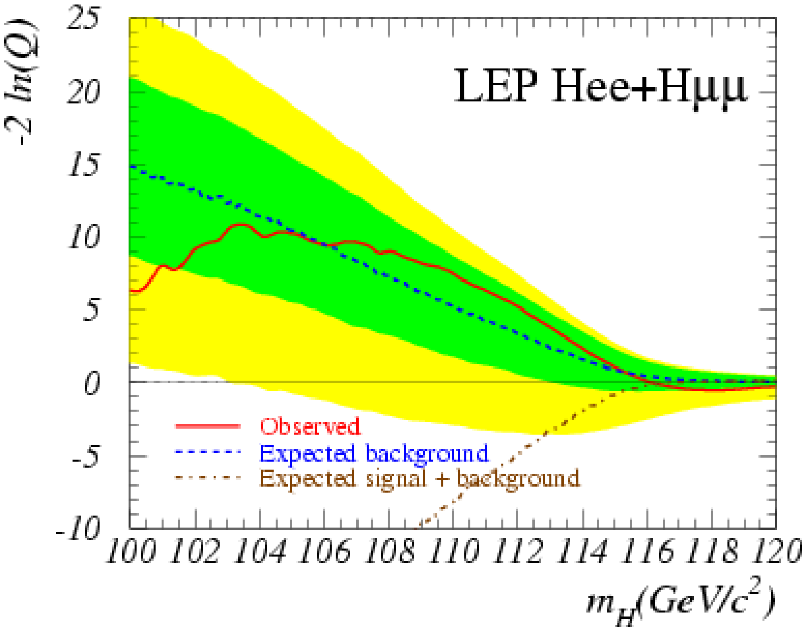


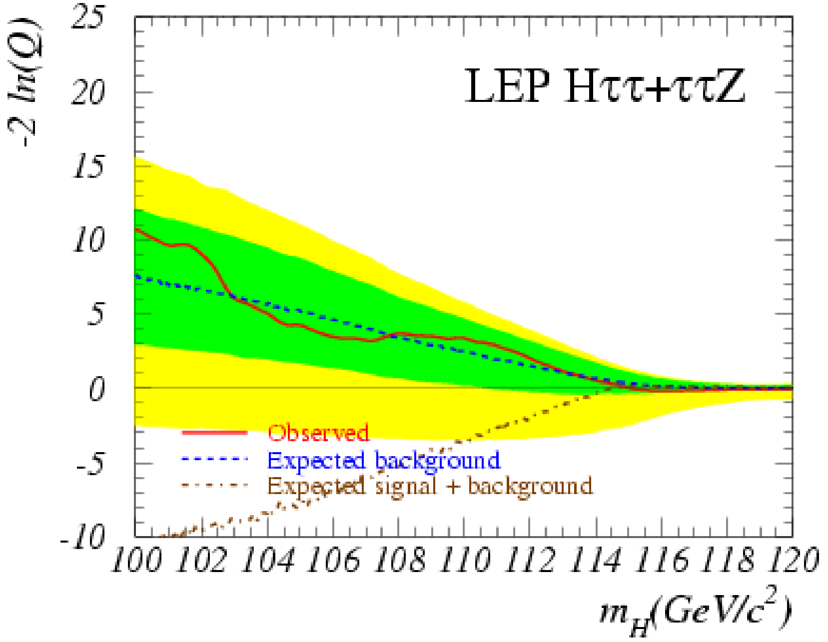


Analyses: LEP Search Results

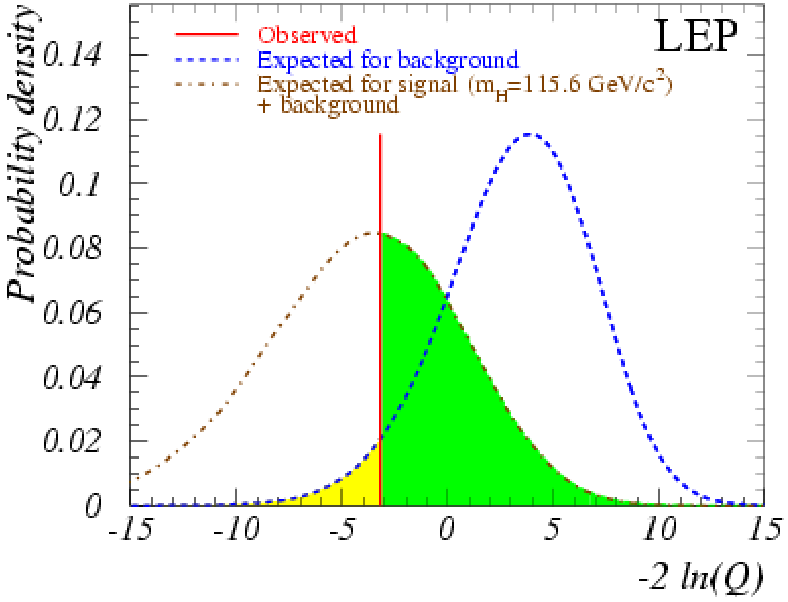


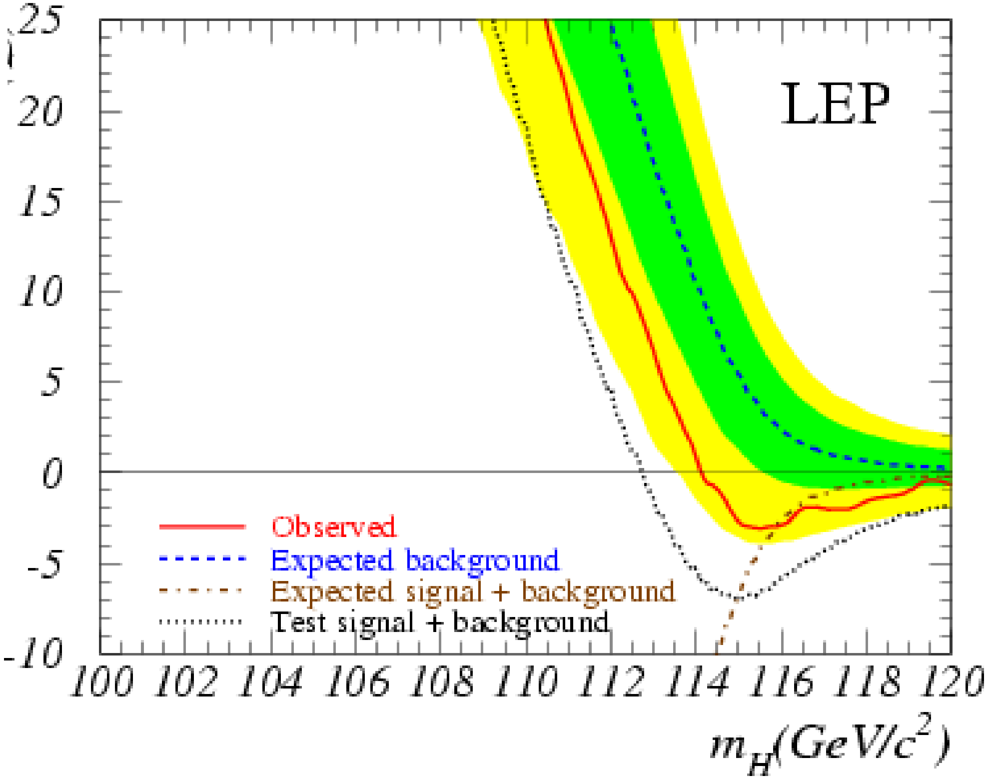




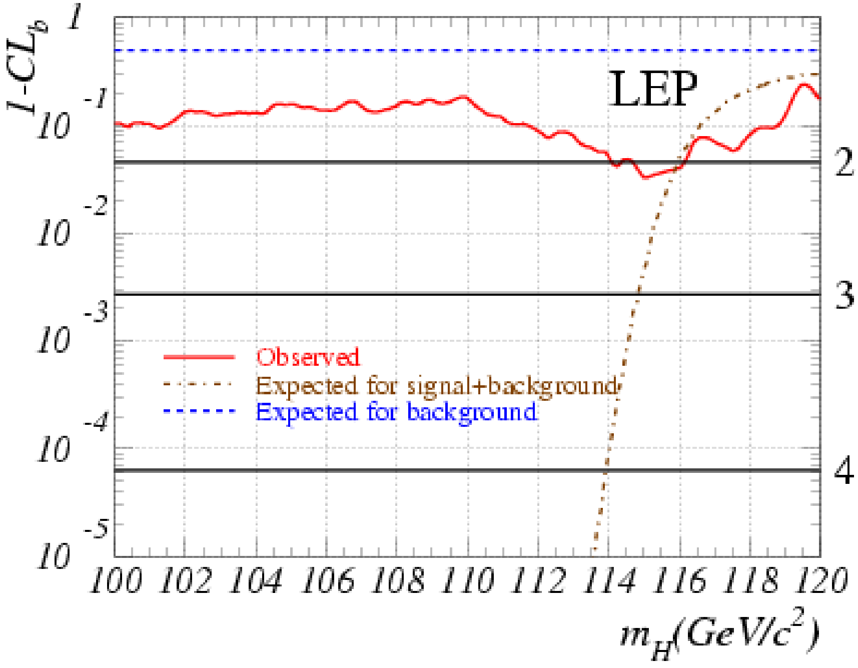


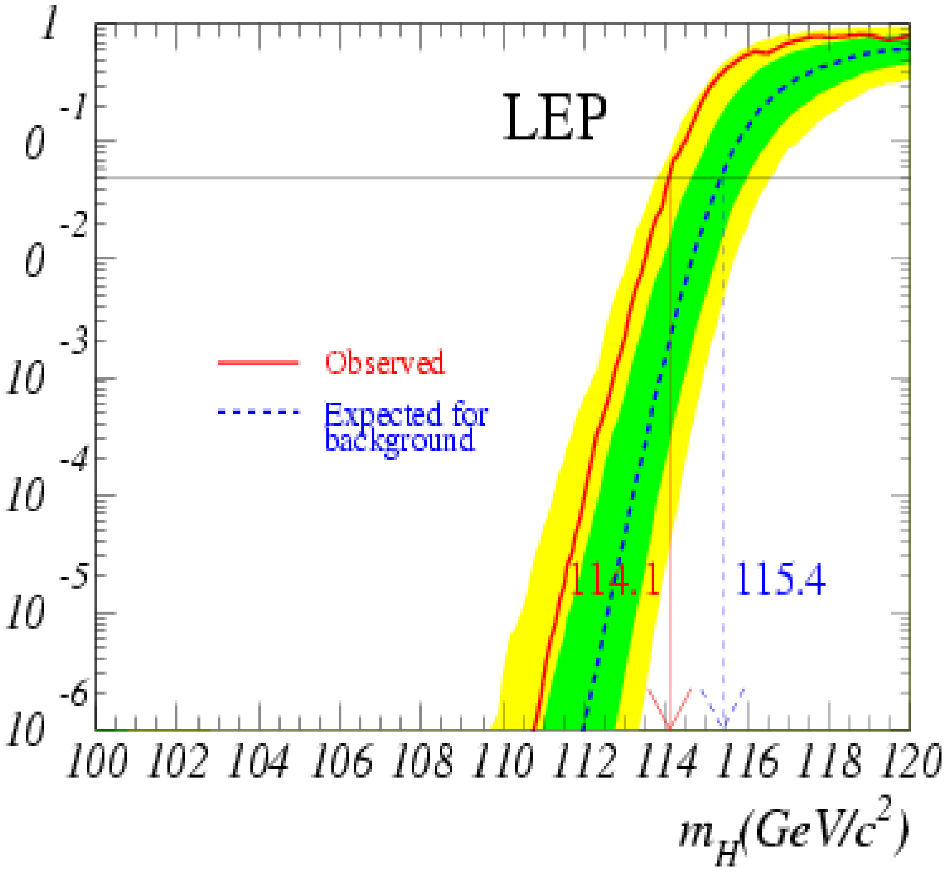
Analyses: LEP Search Results





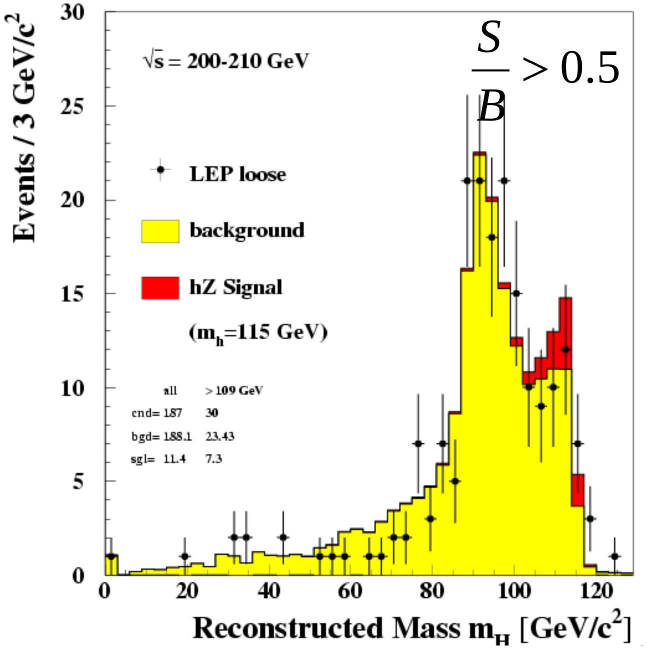
Analyses: LEP Search Results



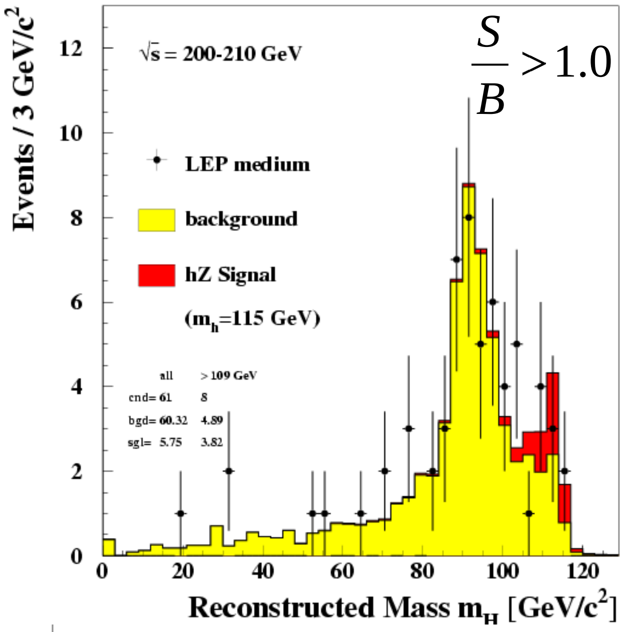


Analyses: LEP Search Results

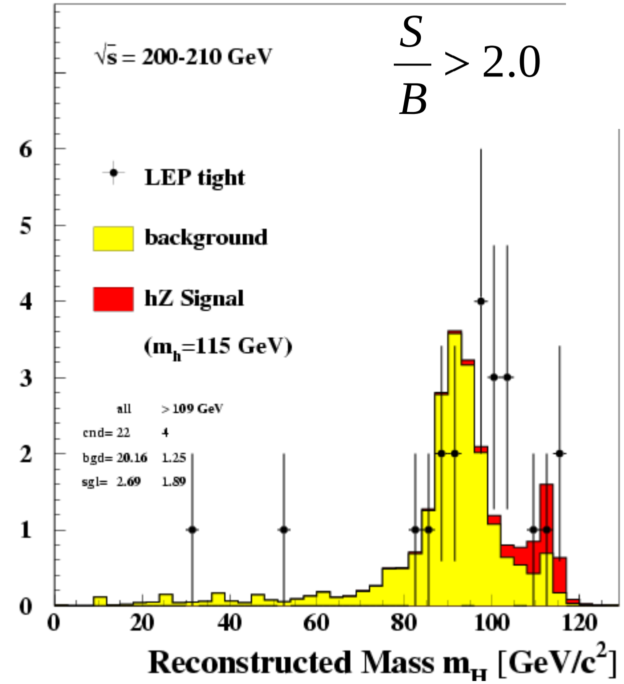
$$m_H^{rec} > 109\ \text{GeV}$$



$$\frac{S}{B} > 0.5$$



$$\frac{S}{B} > 1.0$$

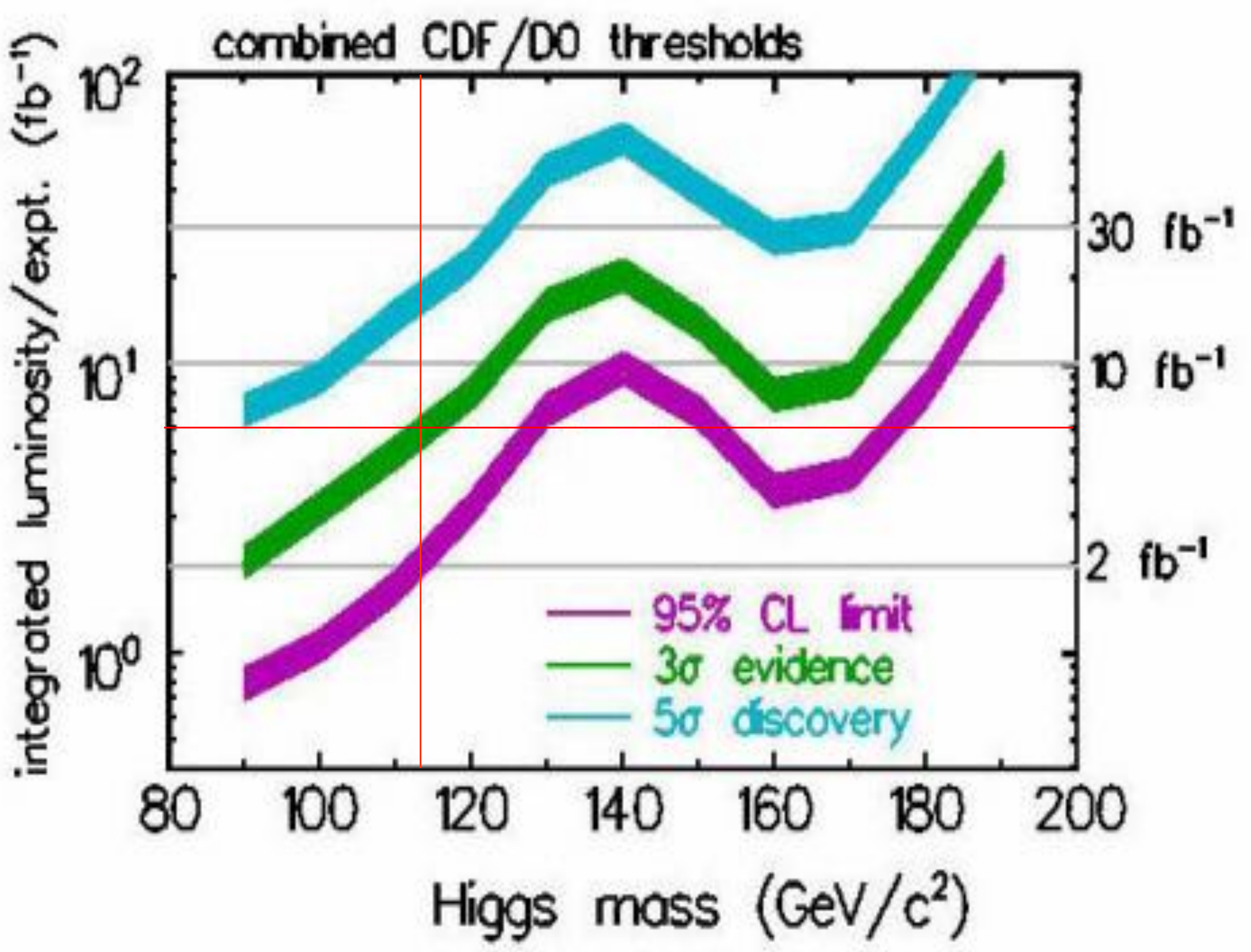


$$\frac{S}{B} > 2.0$$

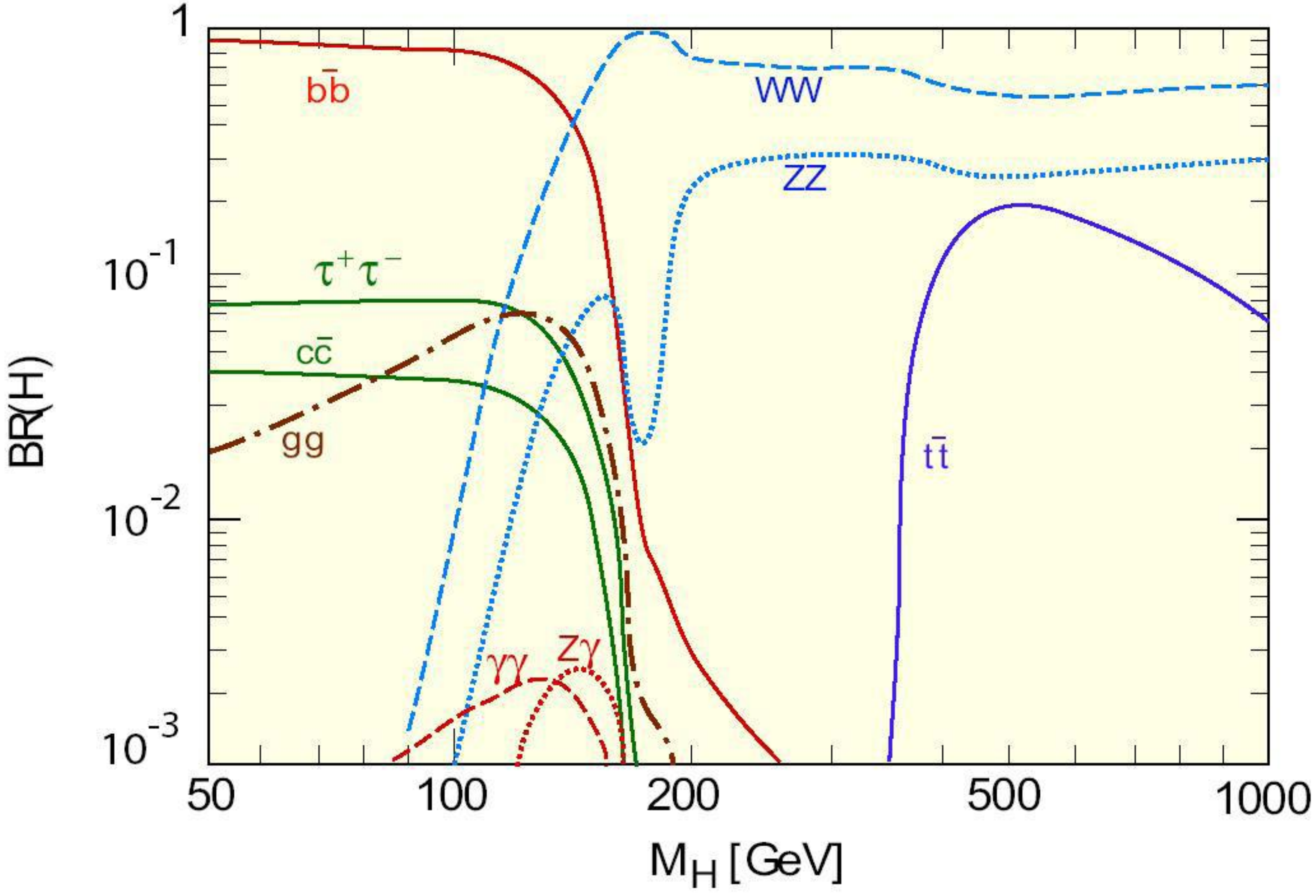
Conclusions

- L3: No signal observed (despite the interesting candidate)
  - Limit: $$\begin{cases} m_H^{obs} > 112.0\,\mathrm{GeV} \\ m_H^{exp} > 112.4\,\mathrm{GeV} \end{cases}$$
- LEP: Interesting excess observed 2.1σ
  - Compatible with a background fluctuation
  - ¨Compatible¨ with a 115 GeV signal
  - The case is still open!!!
  - Limit: $$\begin{cases} m_H^{obs} > 114.1\,\mathrm{GeV} \\ m_H^{exp} > 115.4\,\mathrm{GeV} \end{cases}$$

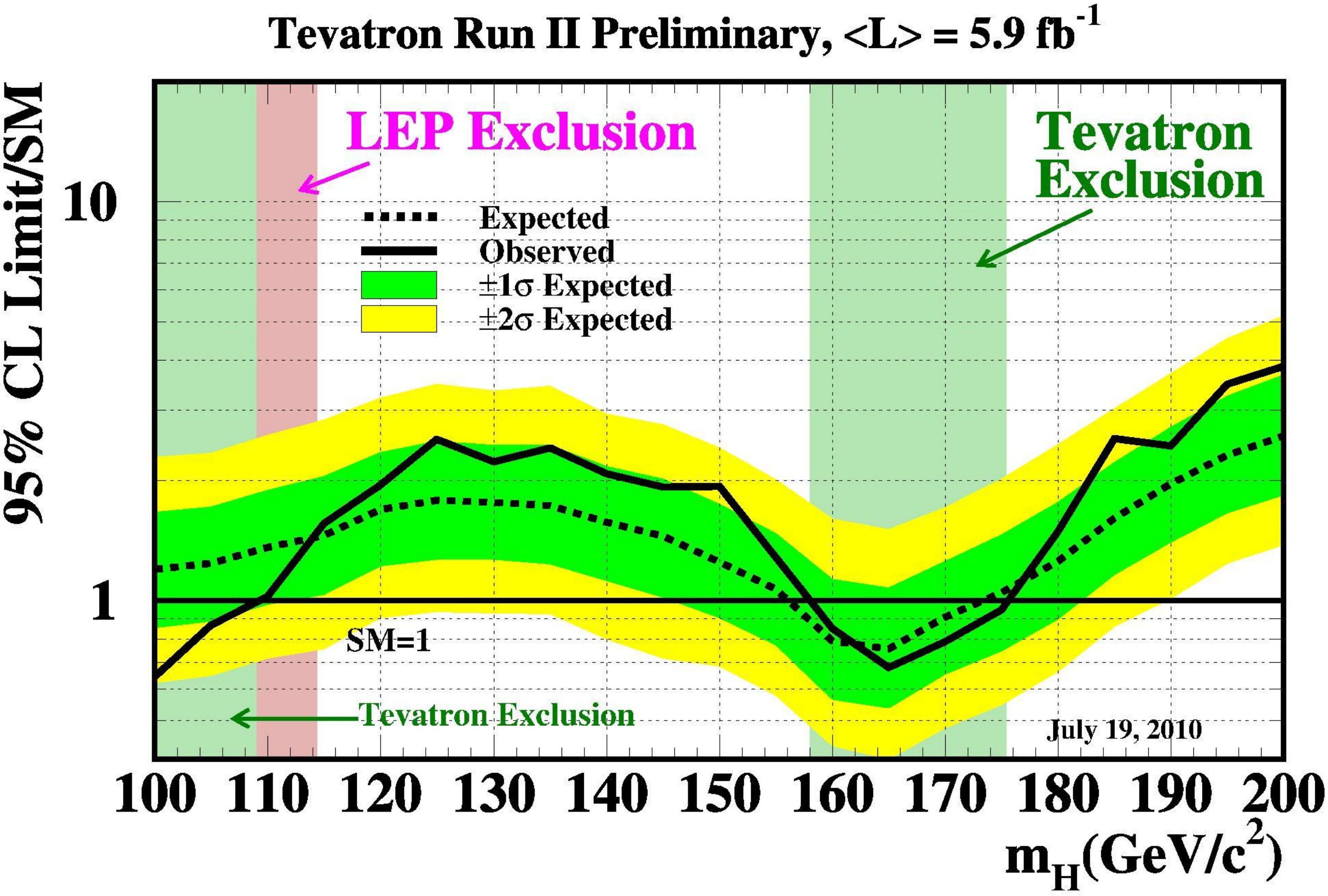
Prospects at TEVATRON Run II



Prospects at TEVATRON Run II



Latest TEVATRON
Run II Combination



3. SUSY Searches

- SUSY Models
- ATLAS Sensitivity
- SUSY Measurements

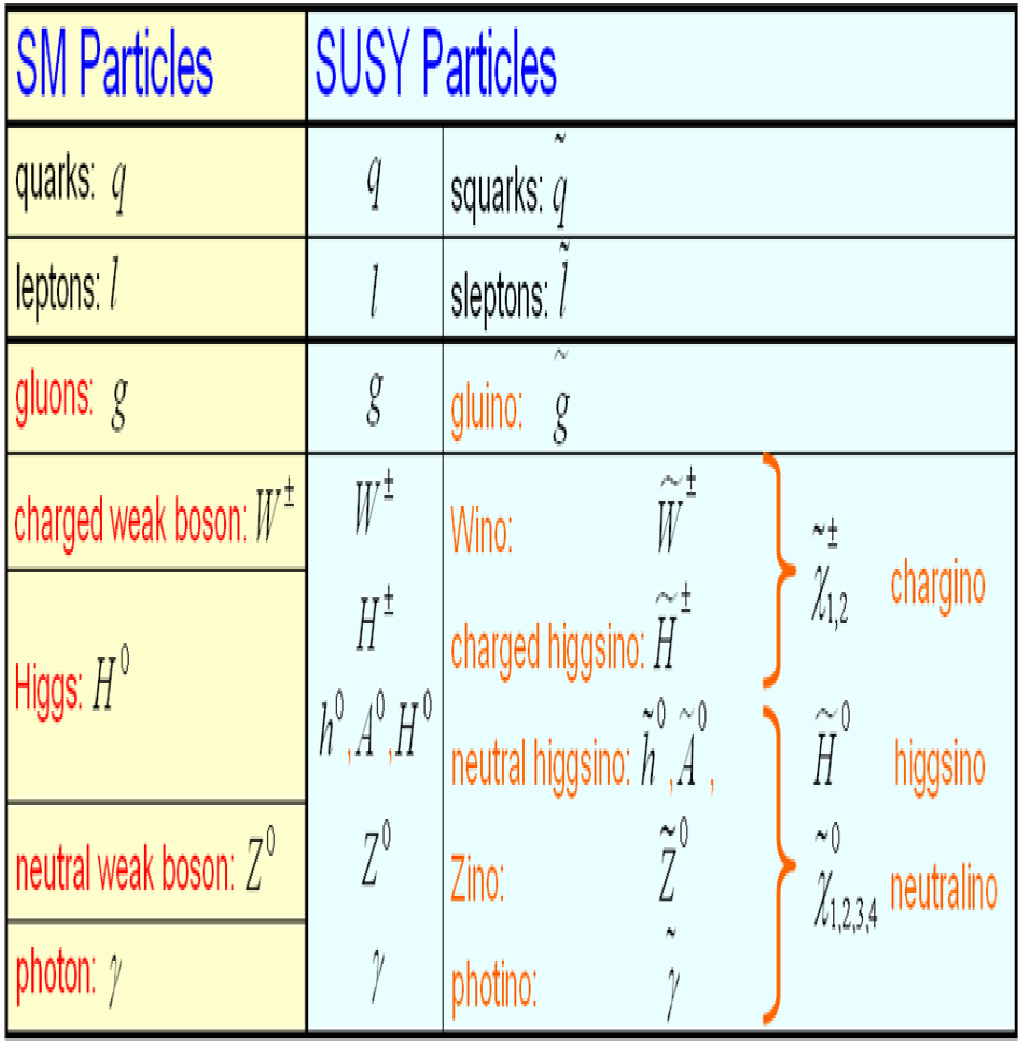
SUSY Models
-Basics of the MSSM-

<u>Minimal SUSY Extension of the SM</u>

- N=1 SUSY
- Minimal field content (2 Higgs doublets)
- Parameters:
  - more than 100 new wo/ specific SUSY breaking mechanism
  - reduced to a few ones by invoking GUT
  - GUT:
    - gauge couplings
    - SUSY soft-breaking terms

<u>R-parity: $R_P=(-1)^{L+2S+3B}$</u>

- **Pair production of SUSY particles**
- **SUSY particles decay to a stable LSP**
- **In general LSP: lightest neutralino**
  - **neutral and weakly interacting**
  - **$\Rightarrow$ Generic mE_T signature**

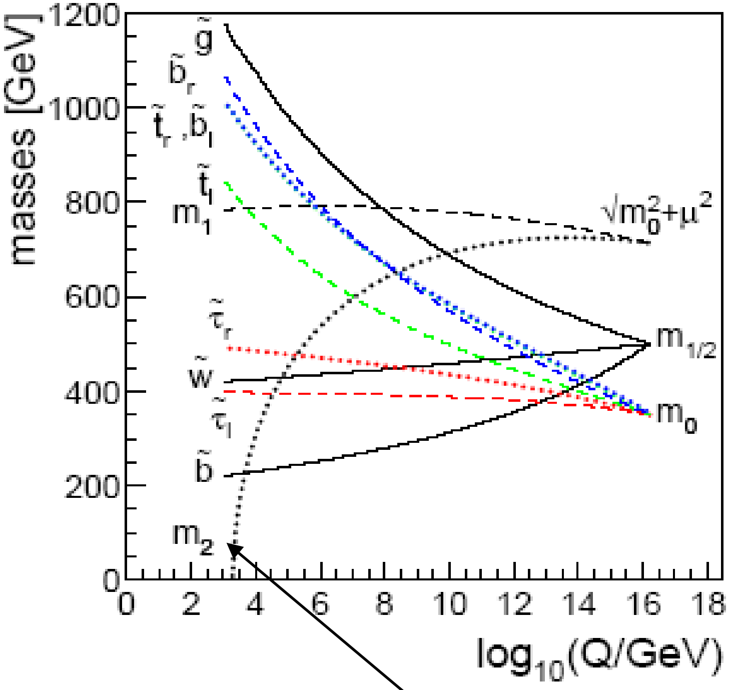


SM Particles	SUSY Particles			
quarks: q	q	squarks: $\tilde{q}$		
leptons: l	l	sleptons: $\tilde{l}$		
gluons: g	g	gluino: $\tilde{g}$		
charged weak boson: $W^{\pm}$	$W^{\pm}$	Wino: $\tilde{W}^{\pm}$	$\tilde{\chi}^{\pm}_{1,2}$	chargino
Higgs: H^0	$H^{\pm}$	charged higgsino: $\tilde{H}^{\pm}$		
	h^0, A^0, H^0	neutral higgsino: $\tilde{h}^0, \tilde{A}^0,$	$\tilde{H}^0$	higgsino
neutral weak boson: Z^0	Z^0	Zino: $\tilde{Z}^0$	$\tilde{\chi}^0_{1,2,3,4}$	neutralino
photon: γ	γ	photino: $\tilde{\gamma}$		

SUSY Models
-Basics of mSUGRA-

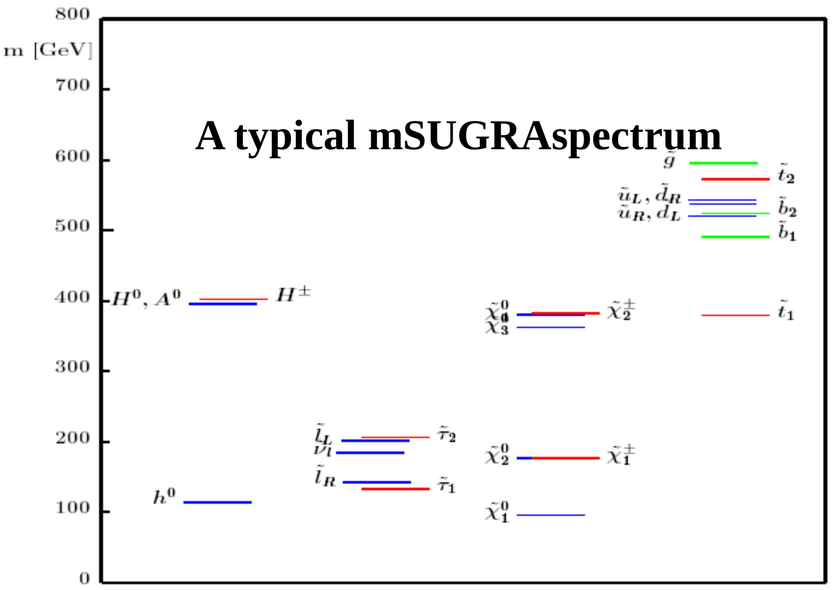
- The most widely studied model is mSUGRA:

m_0:	**common scalar mass at GUT scale**
$m_{1/2}$:	**common gaugino mass at GUT scale**
A_0:	**common trilinear coupling at GUT scale**
sign(μ):	**supersymmetric Higgs mass term ($\mu\Phi_1\Phi_2$)**
tan(β):	**ratio of the vev's of the neutral Higgs fields at the EW scale**



"Radiative EWSB"

~



A typical mSUGRAspectrum

$M(\chi+) \sim M(\chi^0_2) \sim 2M(\chi^0_1)$

$M(g) \sim 3M(\chi+)$

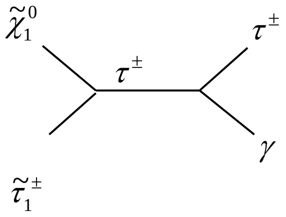
A light Higgs

A neutralino LSP

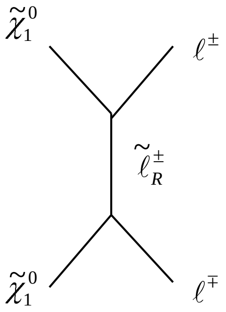
Isajet 7.71, m(top)=175 GeV

Large tanβ, μ>0

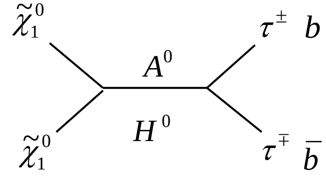
SUSY Models
-of Cosmological Interest-



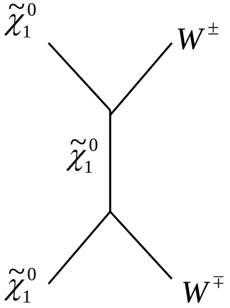
- light $\tilde{\tau}_1^\pm$
- in equilibrium w/ LSP
- heavy bino LSP



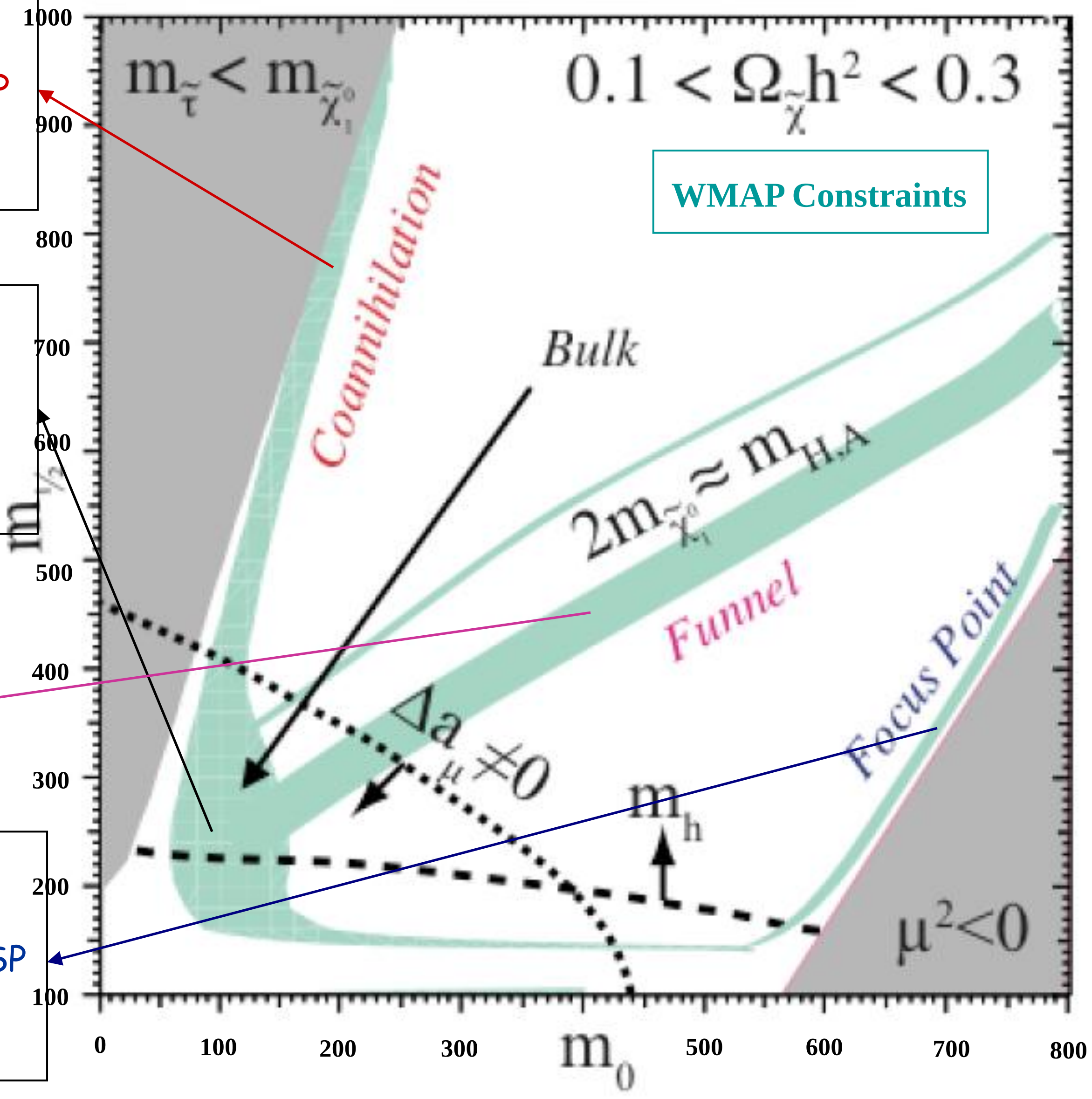
- bino LSP
- light $\tilde{\ell}_R^\pm$
- (g-2) ok, FCNC risky



- H, A poles
- large tanβ
- heavy bino LSP



- small μ
- higgsino light LSP
- heavy $\tilde{\ell}_R^\pm$



Aug 11th 2010

SUSY Models
- ATLAS Benchmarks -

Point	m_0 (GeV)	$m_{1/2}$ (GeV)	A_0 (GeV)	$\tan\beta$	SIGN(μ)	σ_{NLO} / σ_{LO} (pb)
Coannihilation (SU1)	70	350	0	10	+1	10.86 / 8.15
Focus Point (SU2)	3550	300	0	10	+1	7.18 / 5.17
Bulk (SU3)	100	300	-300	6	+1	27.68 / 20.85
Low Mass (SU4)	200	160	-400	10	+1	402.19 / 294.46
Funnel (SU6)	320	375	0	50	+1	6.07 / 4.47
Coannihilation (SU8.1)	210	360	0	40	+1	8.70 / 6.48
Bulk (SU9)	300	425	20	20	+1	3.28 / 2.46

$b \rightarrow s\gamma$: favours m>0 (in mSUGRA)

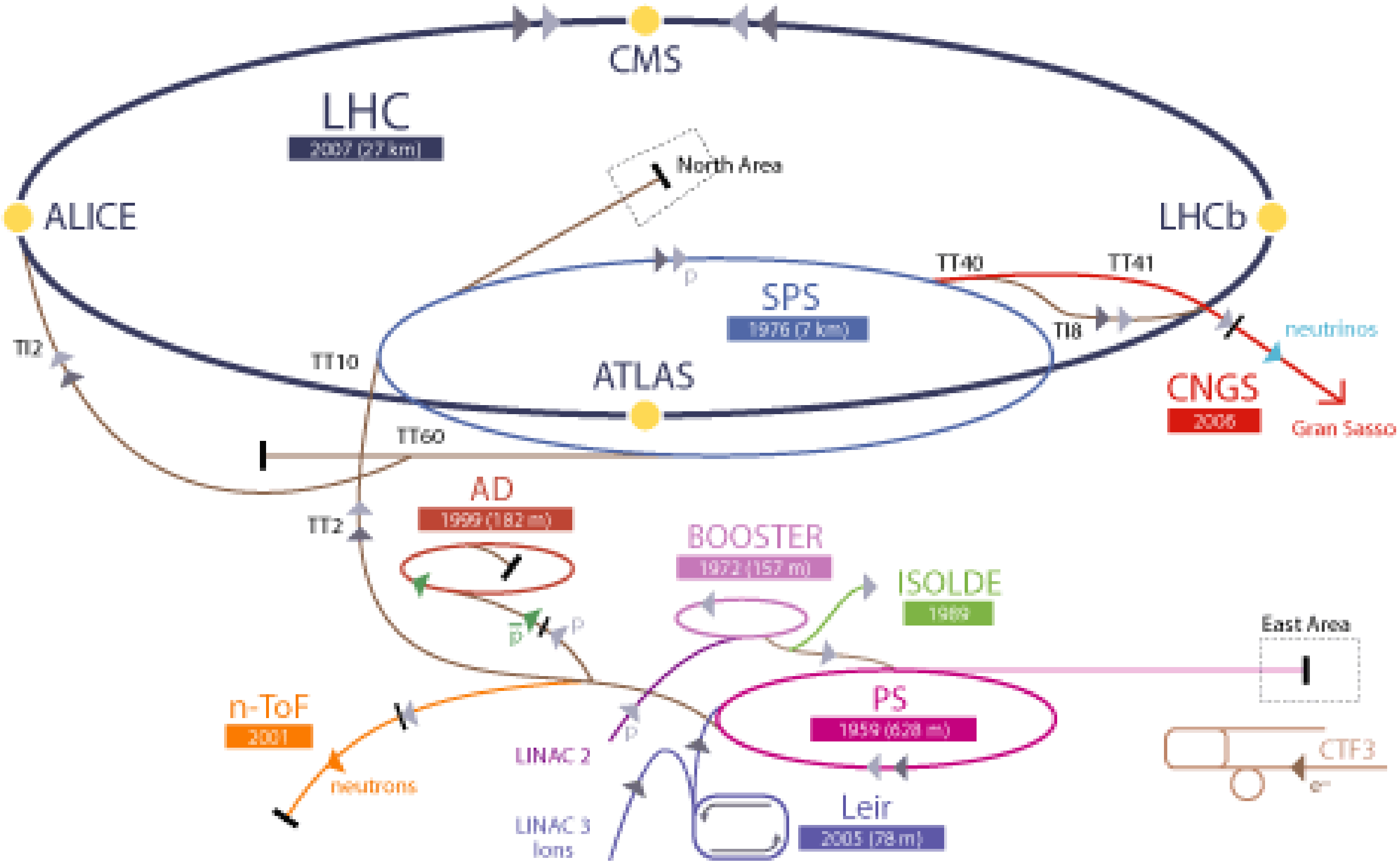
Cross sections:

- $s^{1/2}$ = 14 TeV
- CTE6M/CTEQ6L1

SUSY Models
- ATLAS Benchmarks -

Particle	SU1	SU2	SU3	SU4	SU6	SU8.1	SU9
$\langle\tilde{q}_L\rangle$	762.7	3563.7	633.9	416.0	868.8	799.1	954.3
$\langle\tilde{q}_R\rangle$	734.5	3575.2	611.3	405.6	841.2	772.8	922.2
$\tilde{t}_1$	573.0	2131.1	424.1	206.0	641.6	603.7	725.0
$\tilde{b}_1$	697.9	2924.8	575.2	358.5	716.8	690.3	868.1
$\tilde{e}_L$	255.1	3547.5	230.5	231.9	411.9	325.4	417.2
$\tilde{e}_R$	154.1	3547.5	155.5	212.9	351.1	253.4	340.9
$\tilde{\nu}_e$	238.3	3546.3	217.0	217.9	401.9	315.3	407.9
$\tilde{\tau}_1^+$	146.5	3519.6	150.0	200.5	181.3	151.9	320.2
$\tilde{\nu}_\tau$	237.6	3532.3	216.3	215.5	358.3	297.0	401.1
$\tilde{g}$	832.3	856.6	717.5	413.4	894.7	856.5	999.3
$\tilde{\chi}_1^+$	262.1	149.2	218.3	113.2	288.3	274.3	326.0
$\tilde{\chi}_2^0$	263.6	160.4	218.6	113.5	288.0	274.0	325.4
$\tilde{\chi}_1^0$	137.0	103.4	117.9	59.8	149.6	142.5	173.3
t	175.0	175.0	175.0	175.0	175.0	175.0	175.0
h^0	115.8	119.0	114.8	114.0	116.9	116.7	114.5
H^0	516.0	3529.7	512.9	370.5	388.9	430.5	632.8
A^0	512.4	3506.6	511.3	368.2	386.5	427.7	628.6
H^+	521.9	3530.6	518.2	378.9	401.2	440.2	638.9

CERN Accelerator Complex



▸ p (proton) ▸ ion ▸ neutrons ▸ p̄ (antiproton) ▸ neutrinos ▸ electron

→→ proton/antiproton conversion

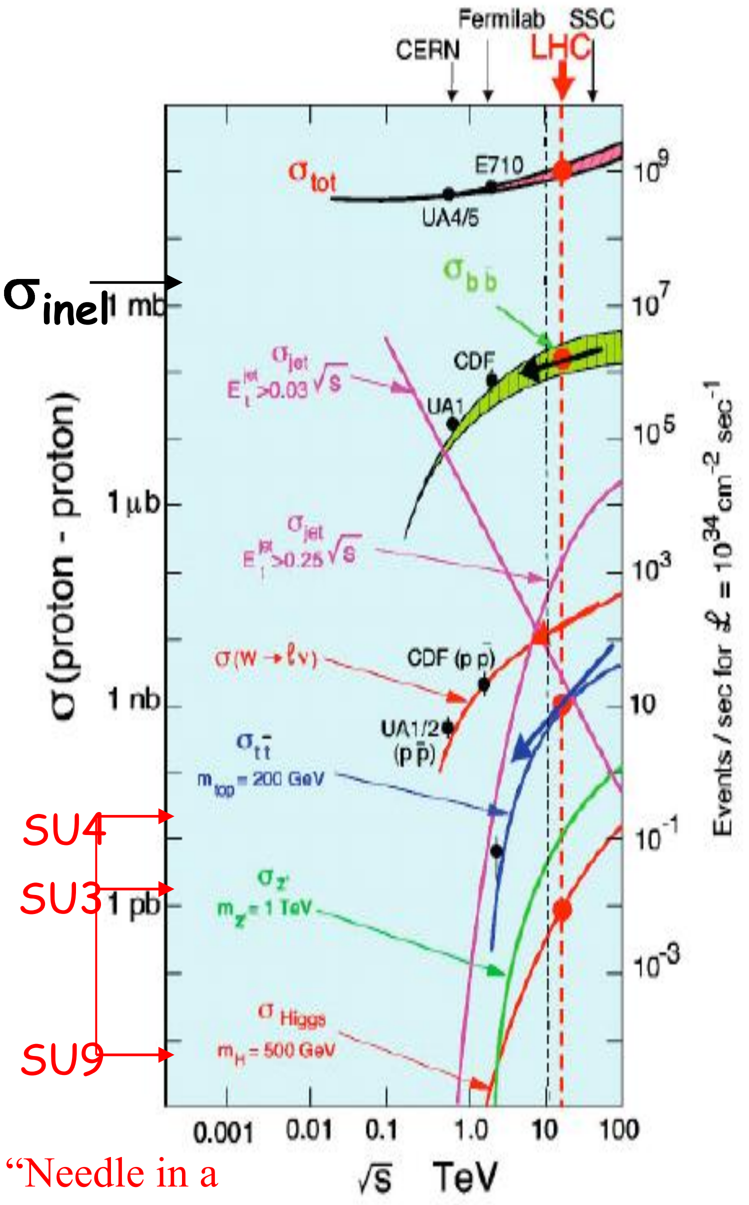
LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron
AD Antiproton Decelerator CTF3 Clic Test Facility
CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

ATLAS Sensitivity
- Events Online Selection -

Common fetaures

- Trigger efficiencies ($\mathcal{L}$=2x10^{33} $cm^{-2}s^{-1}$)
- Full detector simulation (GEANT 4)
- Detector misalignment
- NO: Multiple p-p interactions + pile-up
- Improved BKGD estimations:
  - « data-driven » methods

ATLAS Sensitivity
- Events Online Selection -



"Needle in a Haystack"

Search Topologies

- $0l+4j+mE_T$
- $0l+(2/3)j+mE_T$
- $1l+jets+mE_T$
- $2l+jets+mE_T$ (OS, SS)
- $3l+jets+mE_T$
- $3l+mE_T$
- t+X
- b+X

Triggers for point SU3

- j70_xE70:
    - 1j w/ $p_T > 70$ GeV AND
    - $mE_T > 70$ GeV
- 1LEP:
    - 1 μ w/ $p_T > 20$ GeV OR
    - 1 isol. e w/ $p_T > 20$ GeV
- 2 LEP:
    - 2μ w/ $p_T > 10$ GeV OR
    - 2 isol. e w/ $p_T > 15$ GeV

ATLAS Sensitivity
- Events Offline Selection -

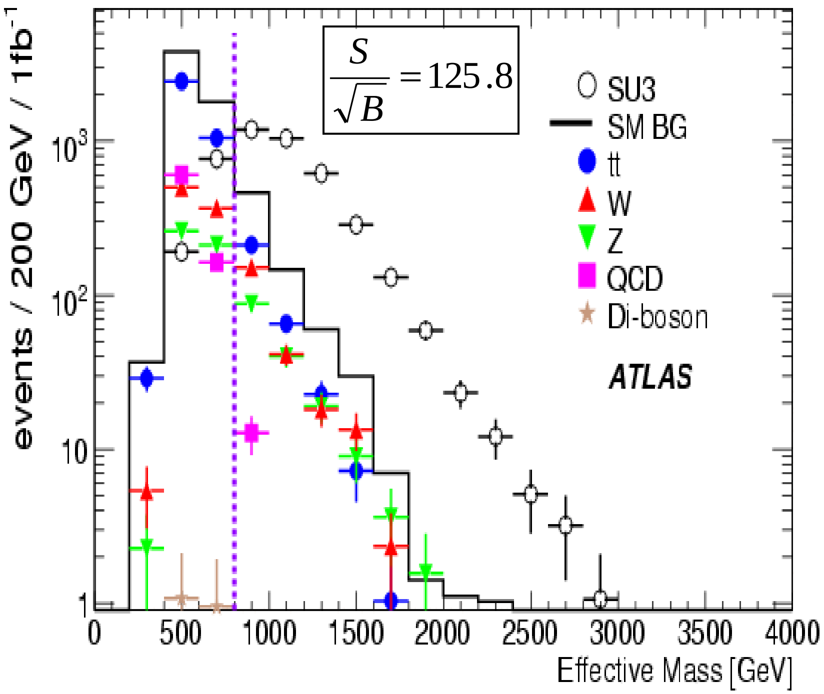
Topology: 4j+mET incl.

Cuts:

- **Jets:**
  - **$N_j > 3$**
  - **$p_T(j_1) > 100$ GeV**
  - **$p_T(j_4) > 50$ GeV**
- **Missing Transverse Energy & Effective Mass:**
  - **$mE_T > 100$ GeV**
  - **$mE_T/M_{eff} > 20\%$ ($M_{eff} = H_T + mE_T$)**
  - **$M_{eff} > 800$ GeV**
- **Topological cuts:**
  - **Transverse sphericity > 0.2**
  - **$\Delta\phi(j_{1,2,3}, mE_T) > 0.2$ rad**
- **Veto on isolated e/μ**

Event yields for 1 fb^{-1}

Process	N_{exp}	ε(%)
SU3	3349	12.3
Bkgd	708	-



BKGD systematics

- QCD multijet: 50%
- ttbar, V+jets, VV: 20%

ATLAS Sensitivity
- Events Offline Selection -

Cuts:

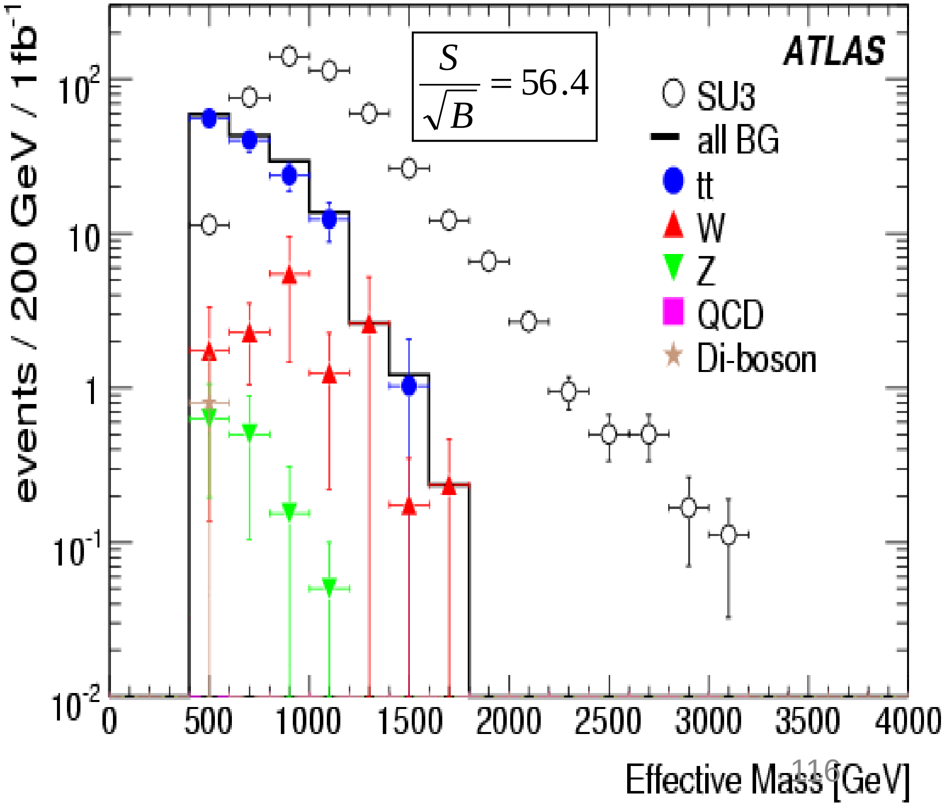
- **Isolated Leptons:**
  - $N_{lep} > 0$
  - $p_T(lep) > 20$ GeV
  - reject add'l leptons w/ $p_T > 10$ GeV
- **Jets:**
  - $N_j > 3$
  - $p_T(j_1) > 100$ GeV
  - $p_T(j_4) > 50$ GeV
- **Missing Transverse Energy & Effective Mass:**
  - $mE_T > 100$ GeV
  - $mE_T/M_{eff} > 20\%$ ($M_{eff} = H_T + mE_T$)
  - $M_{eff} > 800$ GeV
  - $m_T(l, mE_T) > 100$ GeV
- **Topological cuts:**
  - Transverse sphericity > 0.2

Topology: 1lep+4j+mE_T incl.

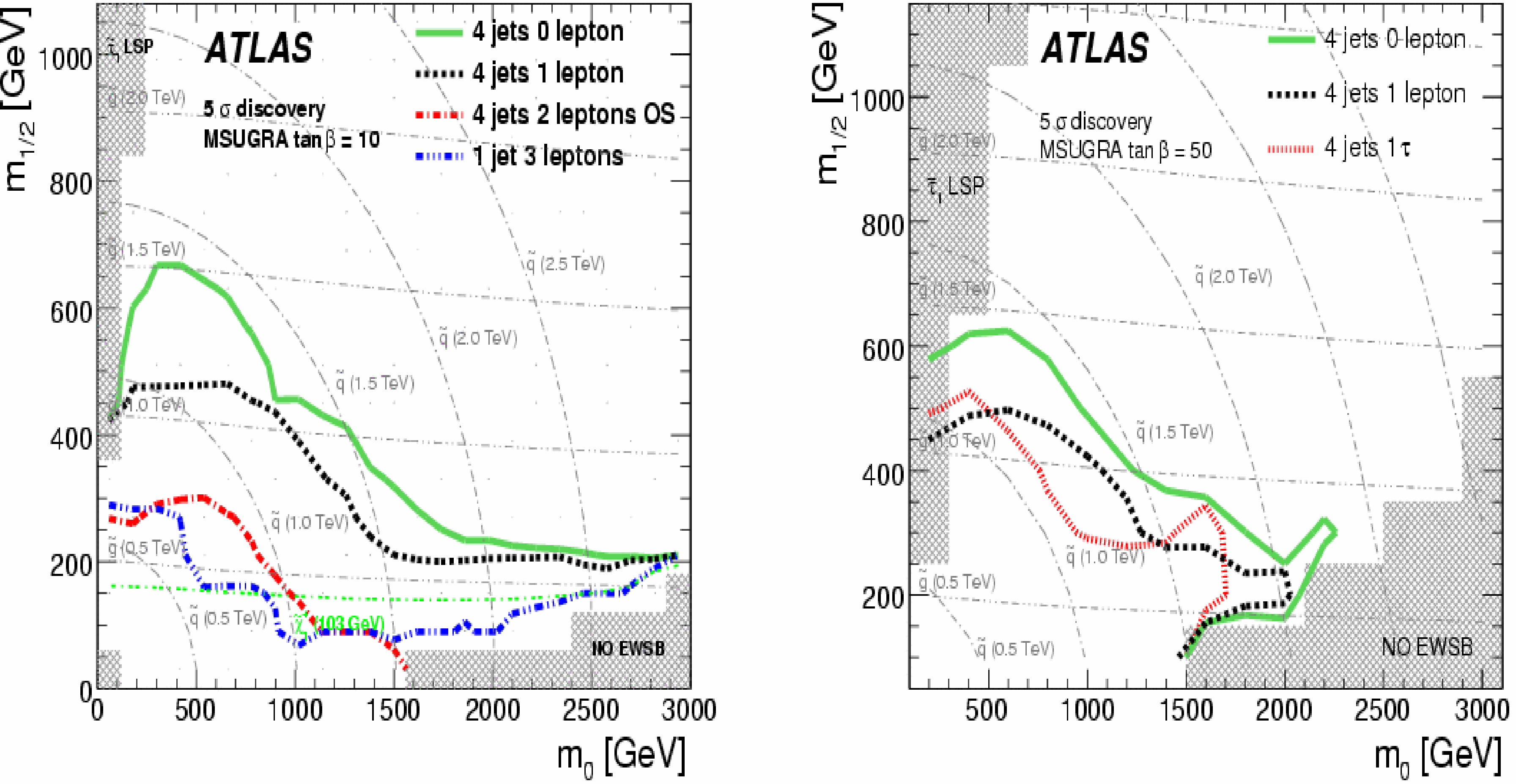
lep=e or μ

Event yields for 1 fb^{-1}

Process	N_{exp}	ε(%)
SU3	363.6	1.3
Bkgd	41.6	-

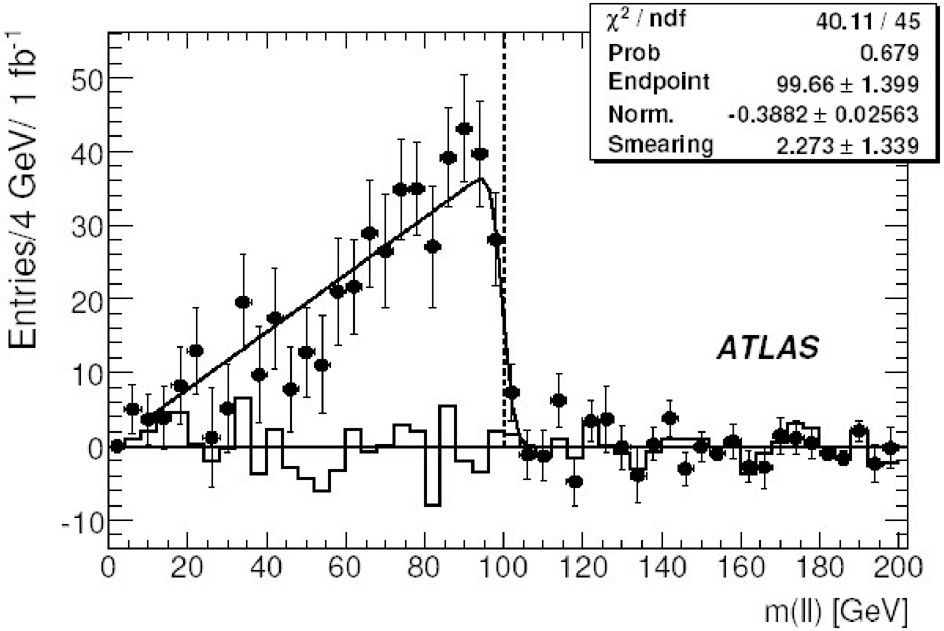


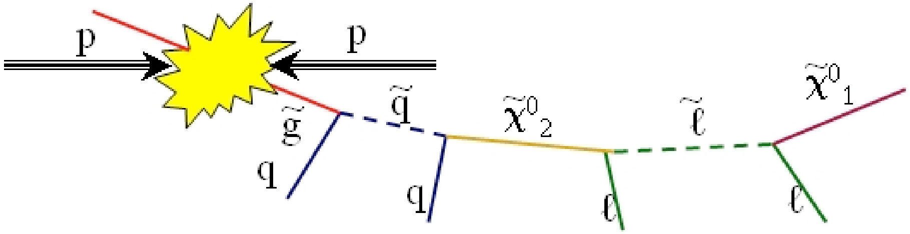
ATLAS Sensitivity
- Reach in mSUGRA Parameter Space -



SUSY Measurements
- Kinematical Edges &Thresholds -

- Possible observables:
    - mass differences (edges),
    - σ,
    - BR,
    - spin,…
- Here:
    - Choose some exclusive decay chains and ONLY infer mass differences





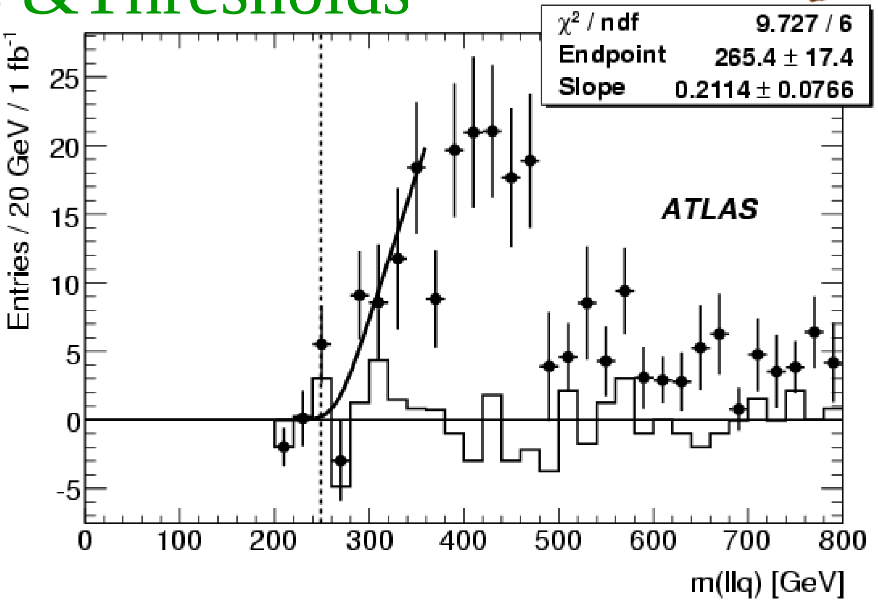
$$\tilde{q}_L \to \tilde{\chi}_2^0 q(\to \tilde{\ell}^{\pm}\ell^{\mp}q) \to \tilde{\chi}_1^0\ell^+\ell^- q$$

$$m_{\ell^+\ell^-}^{\max} = m_{\tilde{\chi}_2^0}\sqrt{1-\frac{m_{\tilde{\ell}}^2}{m_{\tilde{\chi}_2^0}^2}}\sqrt{1-\frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\ell}}^2}}$$

Meas.: m_{ll}^{max}=99.7 +/- 1.4(stat) +/- 0.3(syst) GeV

MC truth: m_{ll}^{max}=100.2 GeV

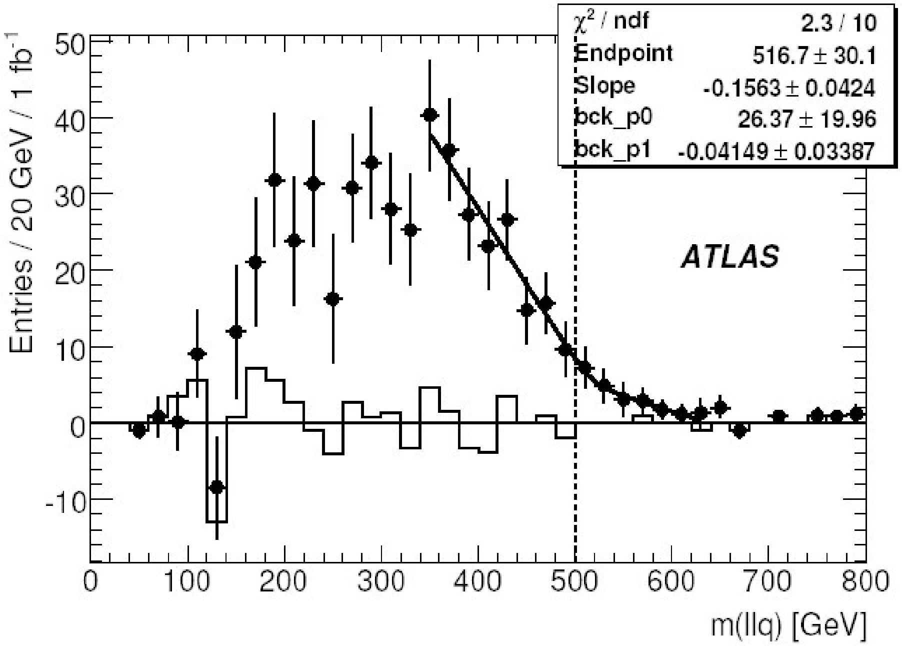
SUSY Measurements
- Kinematical Edges &Thresholds -



Threshold: m(llq)_min

Meas.: 265 +/- 17(stat) +/- 15(syst) +/- 7(JES) GeV

MC Truth: 249 GeV



Edge: m(llq)_max

Meas.: 517 +/- 30(stat) +/- 10(syst) +/- 13(JES) GeV

MC Truth: 501 GeV

SUSY Measurements
- Fitting mSUGRA -

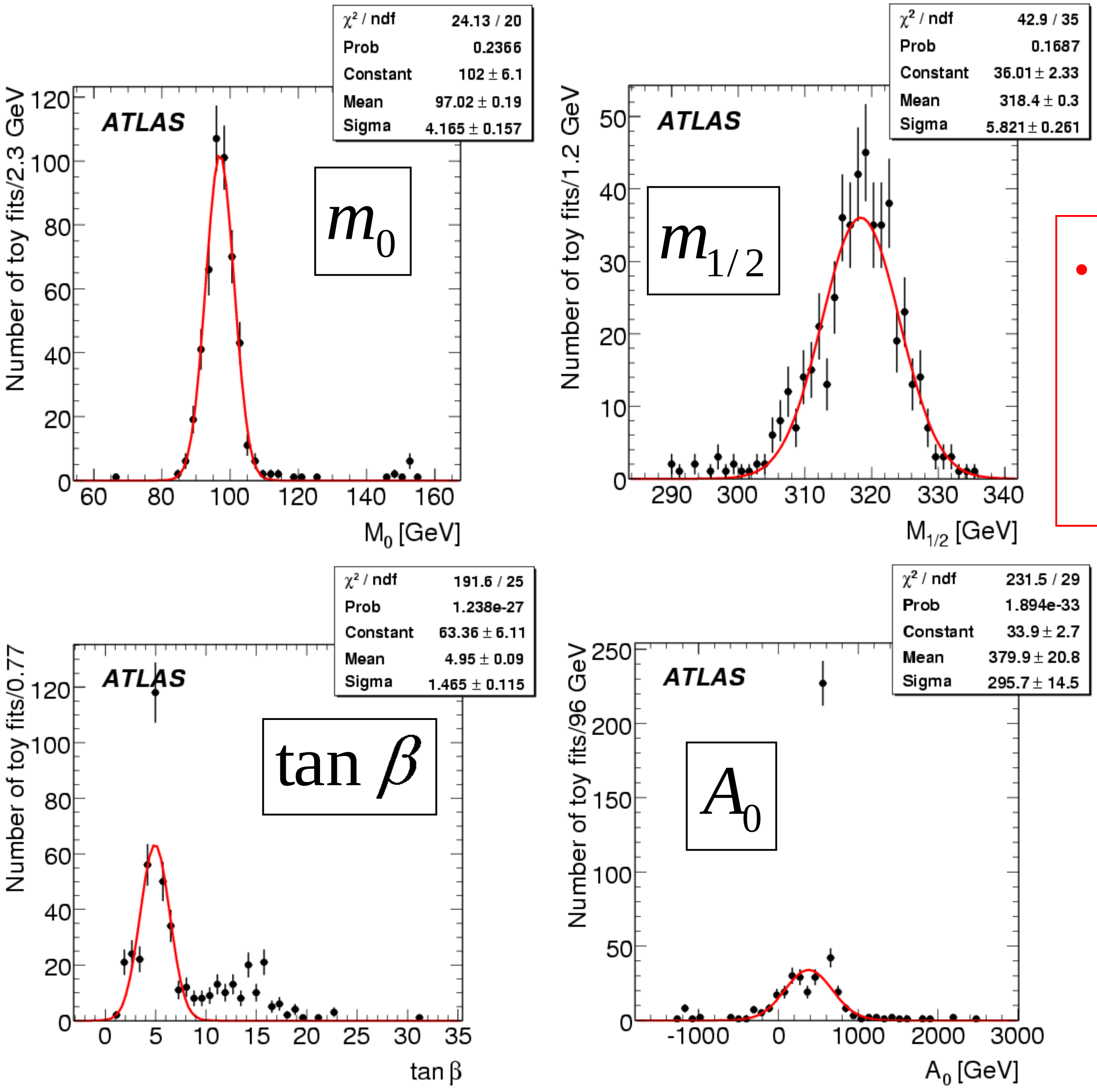
- Fitting SUSY Particles Mass from edges/thresholds measurements

$$\chi^2 = \sum_{i=1}^{n} \frac{[meas_i^{\max} - theory_i^{\max}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\ell}_R^\pm}, m_{\tilde{q}_L})]^2}{\sigma_i^2}$$

- n: nber of measured endpoints
- meas: endpoint fit value
- σ_i: endpoint fit uncertainty
- theory$_i$: endpoint theoretical value

Observable	measure^t	MC truth
$m_{\tilde{\chi}_1^0}$	88 +/- 60 +/- 2	118
$m_{\tilde{\chi}_2^0}$	189 +/- 60 +/- 2	219
$m_{\tilde{q}}$	614 +/- 91 +/- 11	634
$m_{\tilde{\ell}^\pm}$	122 +/- 61 +/- 2	155

SUSY Measurements
- Fitting mSUGRA -



- Tools:
    - Fittino (interfaced to Spheno)
    - MINUIT