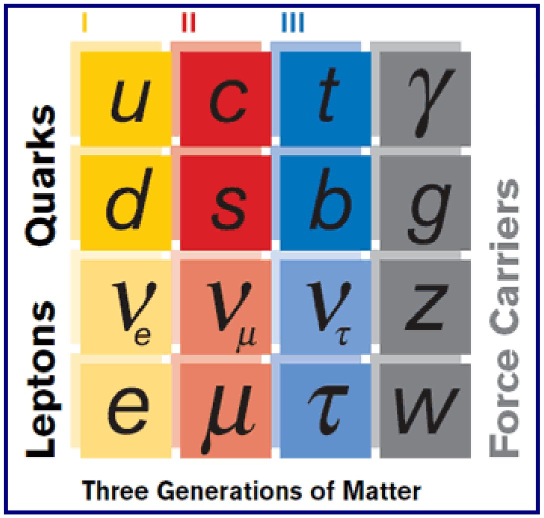
Standard Model – Part II

Eckhard von Törne
Universität Bonn, Kansas State University

14./15. Februar 2006

Overview

1. Theory Overview
2. Experimental Verification of QCD
   except QCD@LHC
3. Experimental Verification of Electroweak Sector
4. Higgs Search Strategies at the LHC
5. Experimental Evidence for Physics beyond the Standard Model
6. Exam

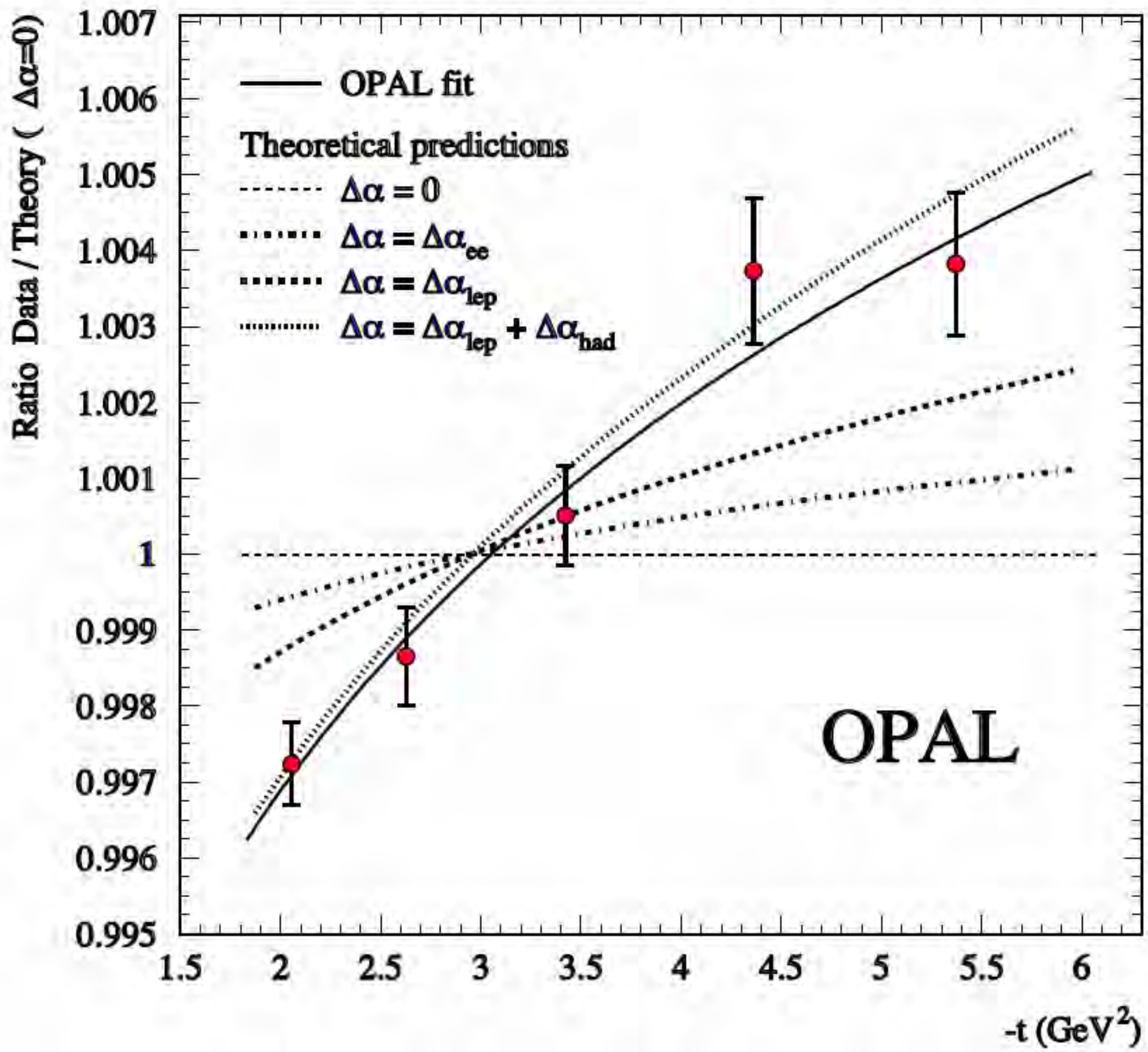


Section 3

Experimental Verification of the Electroweak Sector

- 3.1 α_{QED}
- 3.2 Electroweak I.A.
- 3.3 Z^0 Properties
- 3.4 W Properties
- 3.5 Gauge Boson Production at the Tevatron
- 3.6 Electroweak Precision Fits

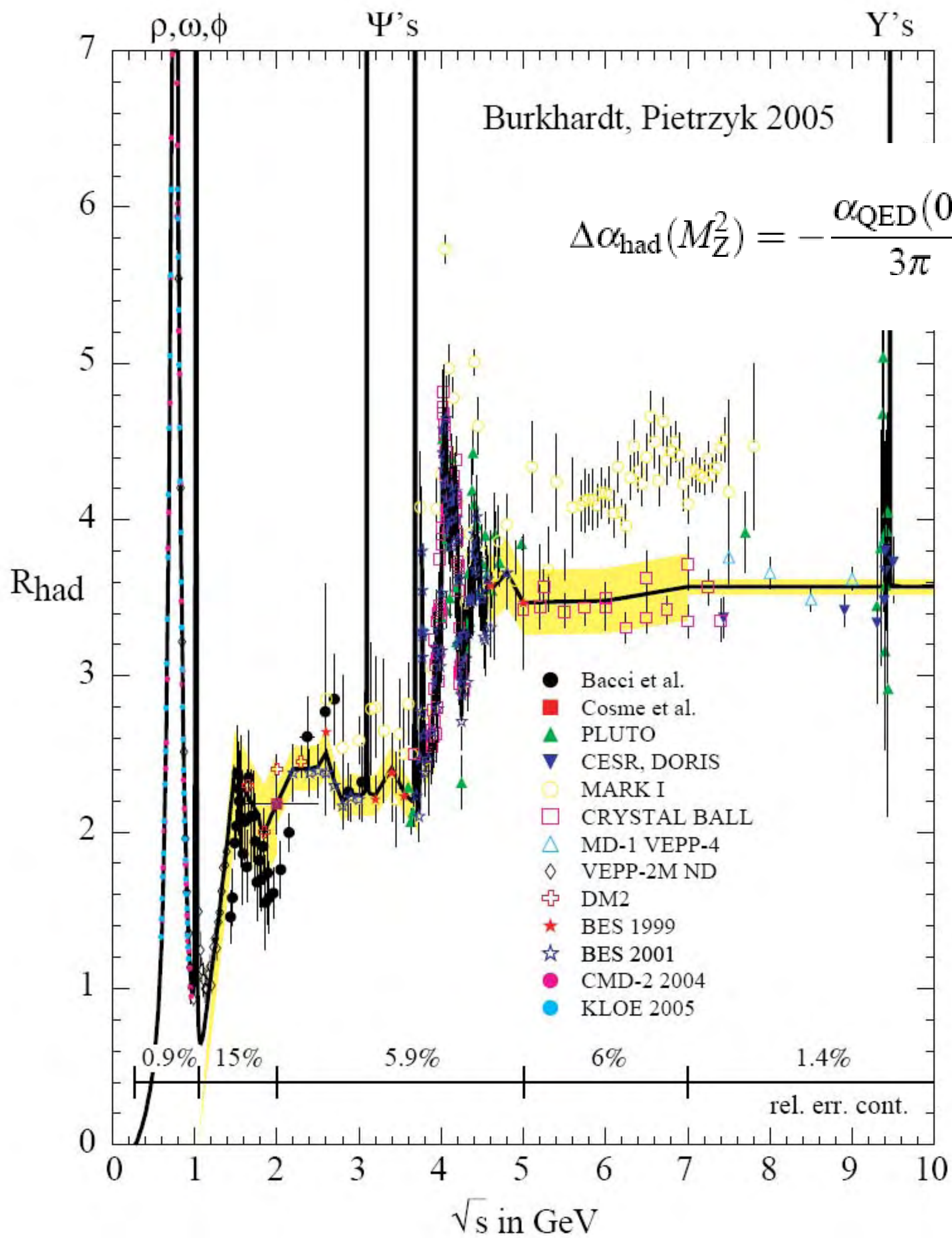
3.1 α_{QED}



t-channel small-angle elastic e+e- scattering

Measurement uses SiW Luminosity Monitor

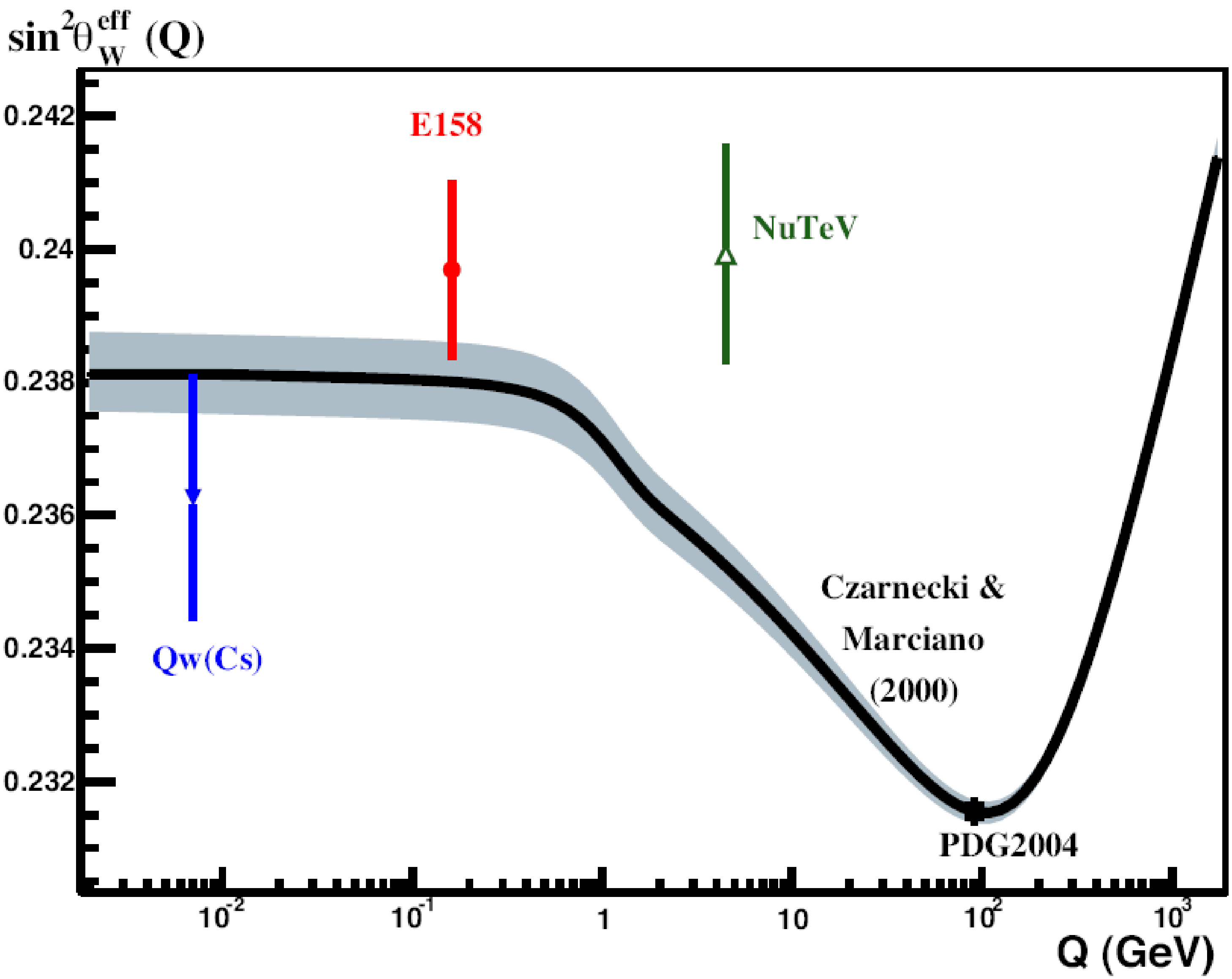
$$\alpha^{-1}_{\text{QED}}(Q^2) = \alpha^{-1}_{\text{QED}}(0)\left(1 - \Delta\alpha_{\text{lep}}(Q^2) - \Delta\alpha_{\text{had}}(Q^2)\right)$$



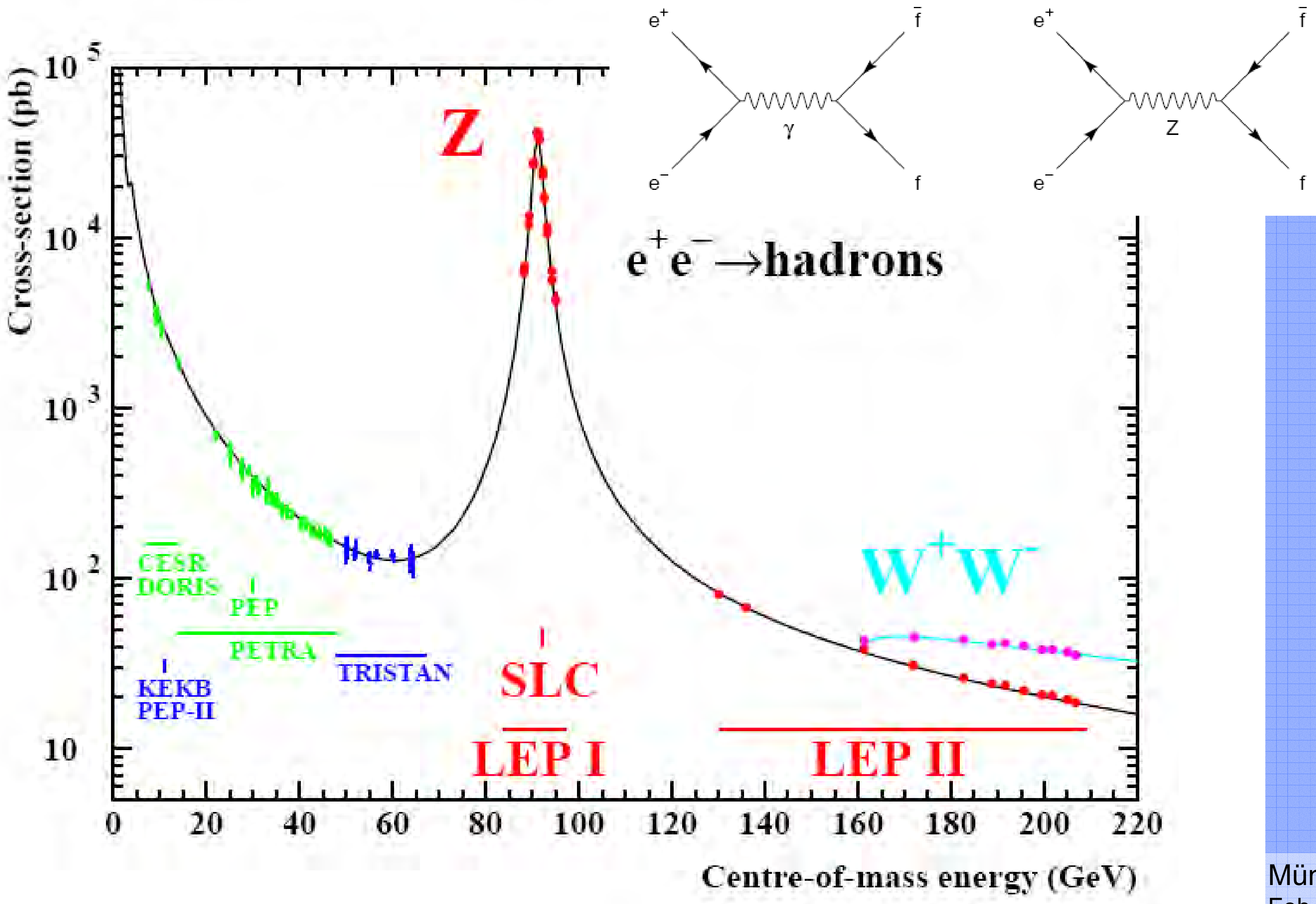
$$\Delta\alpha_{\rm had}(M_Z^2) = -\frac{\alpha_{\rm QED}(0)\,s}{3\pi}\int_{s'=4m_\pi^2}^{\infty}\frac{R_{\rm had}(s')}{s'(s'-M_Z^2)}\mathrm{d}s' + \Delta\alpha_{\rm top}(M_Z^2),$$

$R_{had} = \sigma(had)/\sigma(QED)$

3.2 Electroweak Interactions

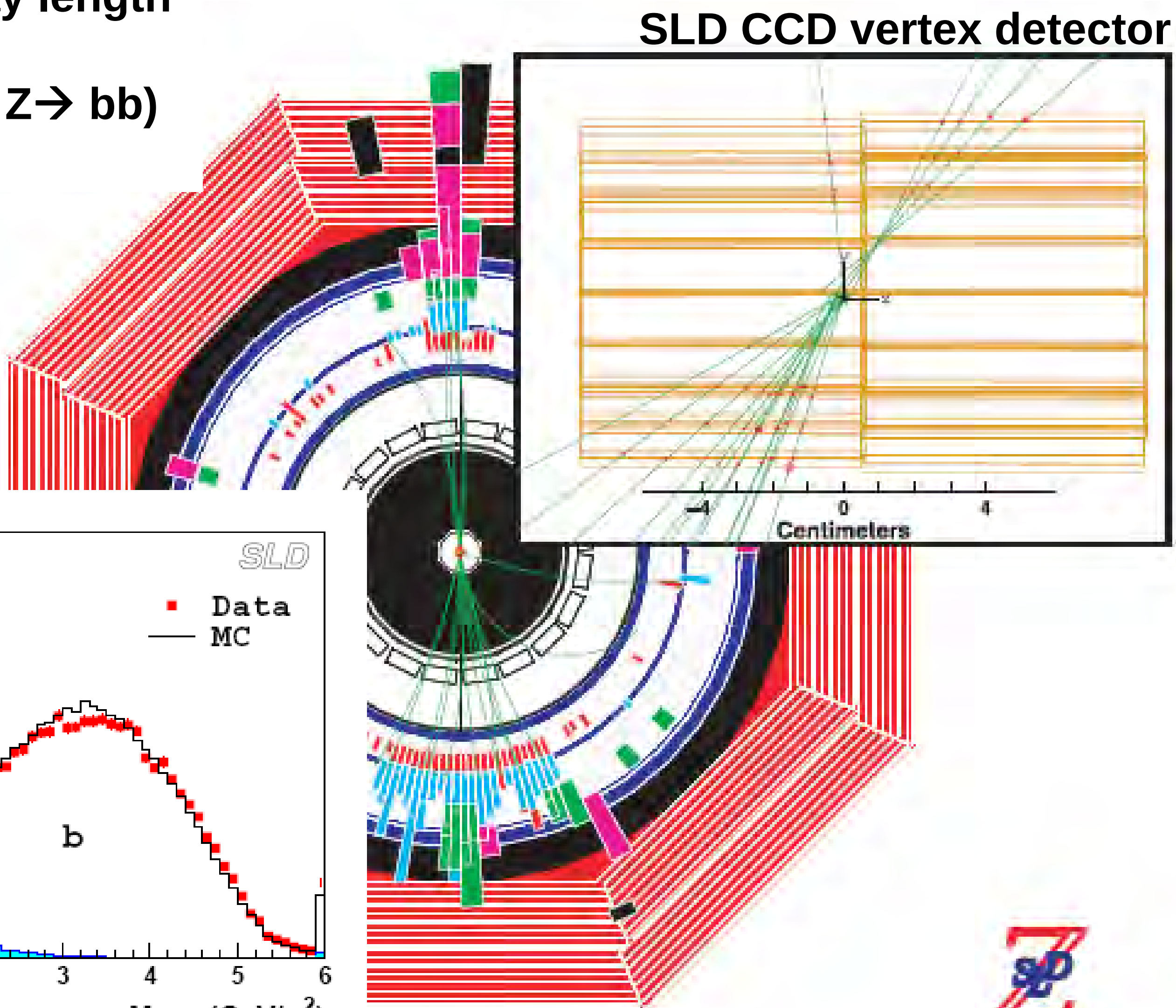


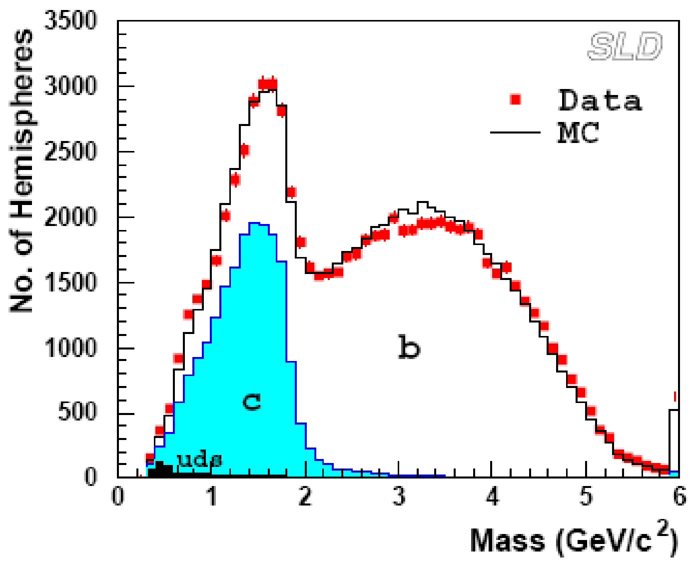
3.3 Z^0 Properties



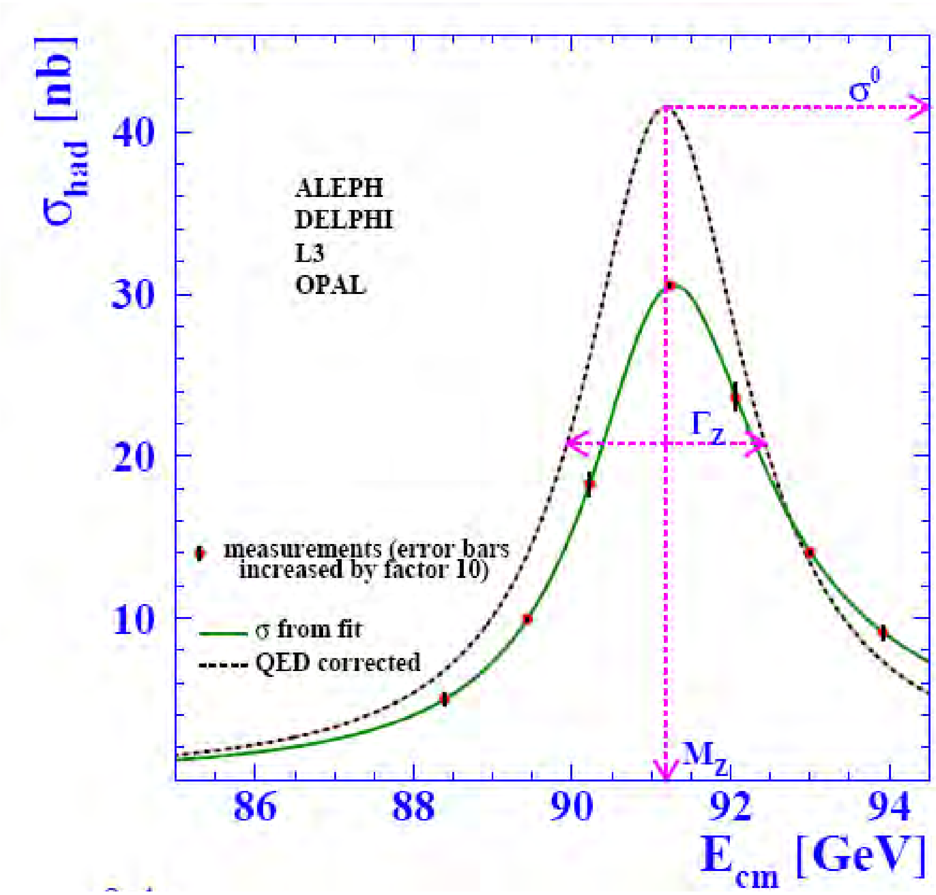
Z → bb-bar

- Excellent Decay length resolution
- (large boost in Z→ bb)
- Vertex Mass

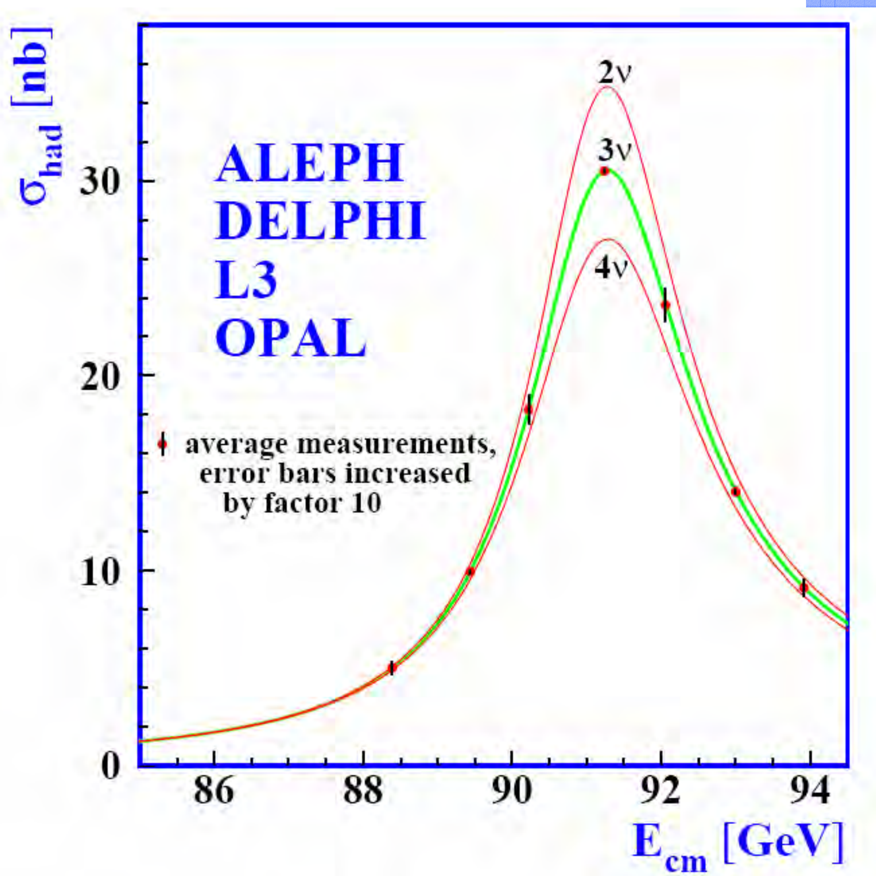




Z lineshape



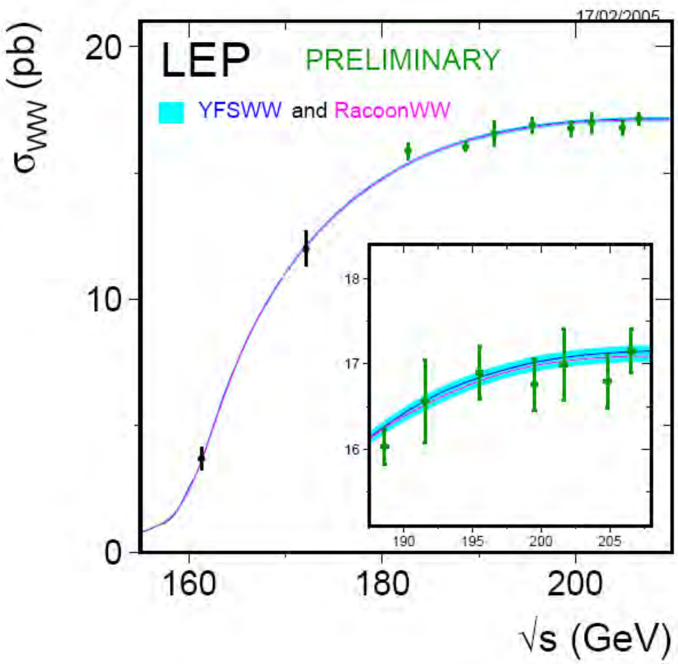
σ_{had} [nb]
ALEPH
DELPHI
L3
OPAL
σ^0
Γ_Z
M_Z
measurements (error bars increased by factor 10)
σ from fit
QED corrected
40
30
20
10
86
88
90
92
94
E_{cm} [GeV]

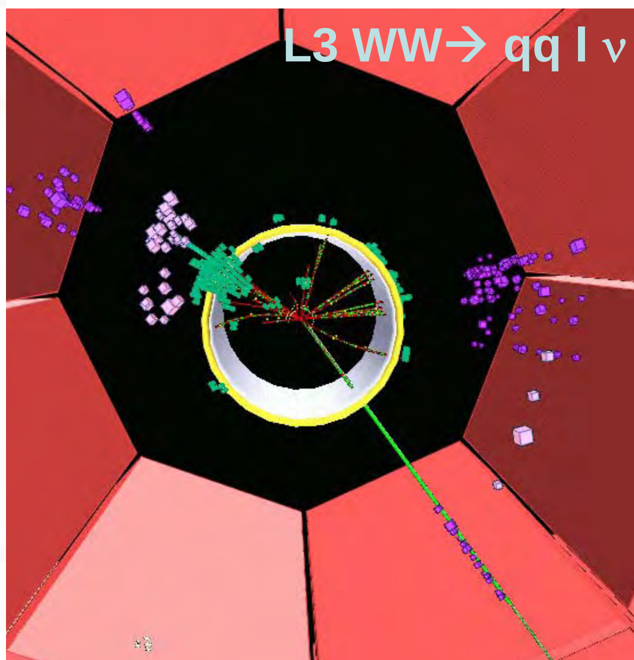


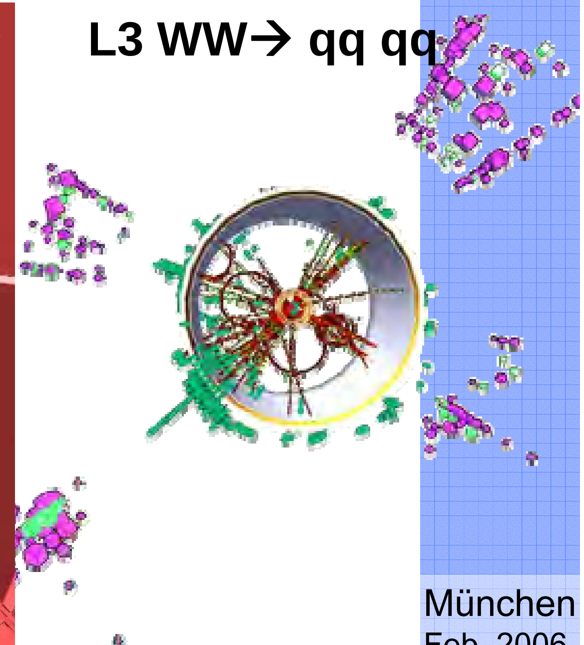
σ_{had} [nb]
ALEPH
DELPHI
L3
OPAL
2ν
3ν
4ν
average measurements, error bars increased by factor 10
30
20
10
0
86
88
90
92
94
E_{cm} [GeV]

3.4 W Properties

- W Mass — ΔM (MeV)
  - W W Threshold scan in e+e- ~400
  - $WW \rightarrow qq\, l\nu$ ~80
  - $WW \rightarrow qqqq$ ~120
  - $W \rightarrow l\, \nu$ @ Tevatron ~90

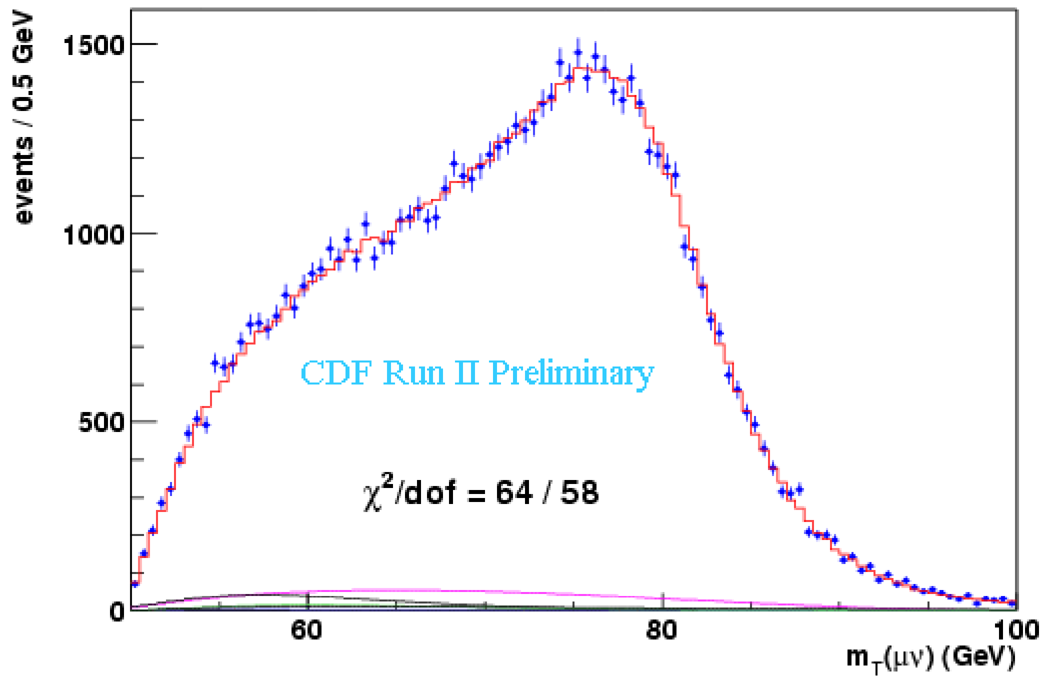


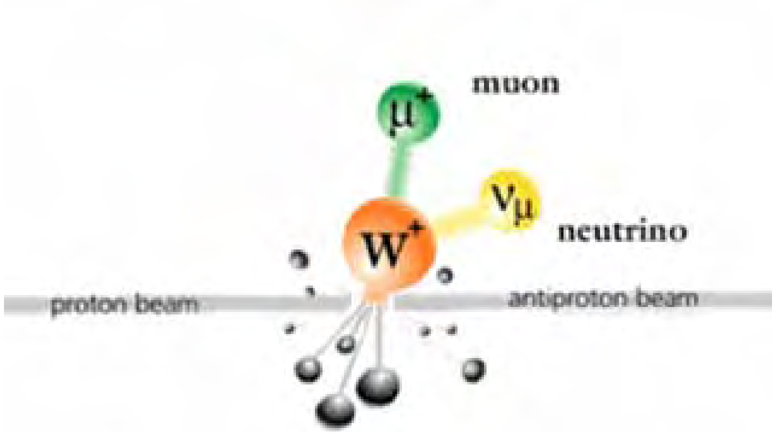


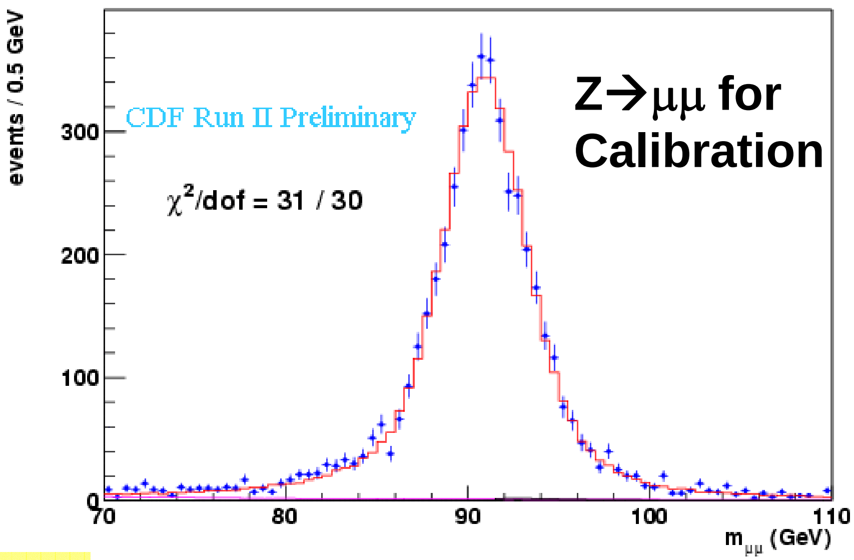


W Mass @ Tevatron

Transverse mass m_T



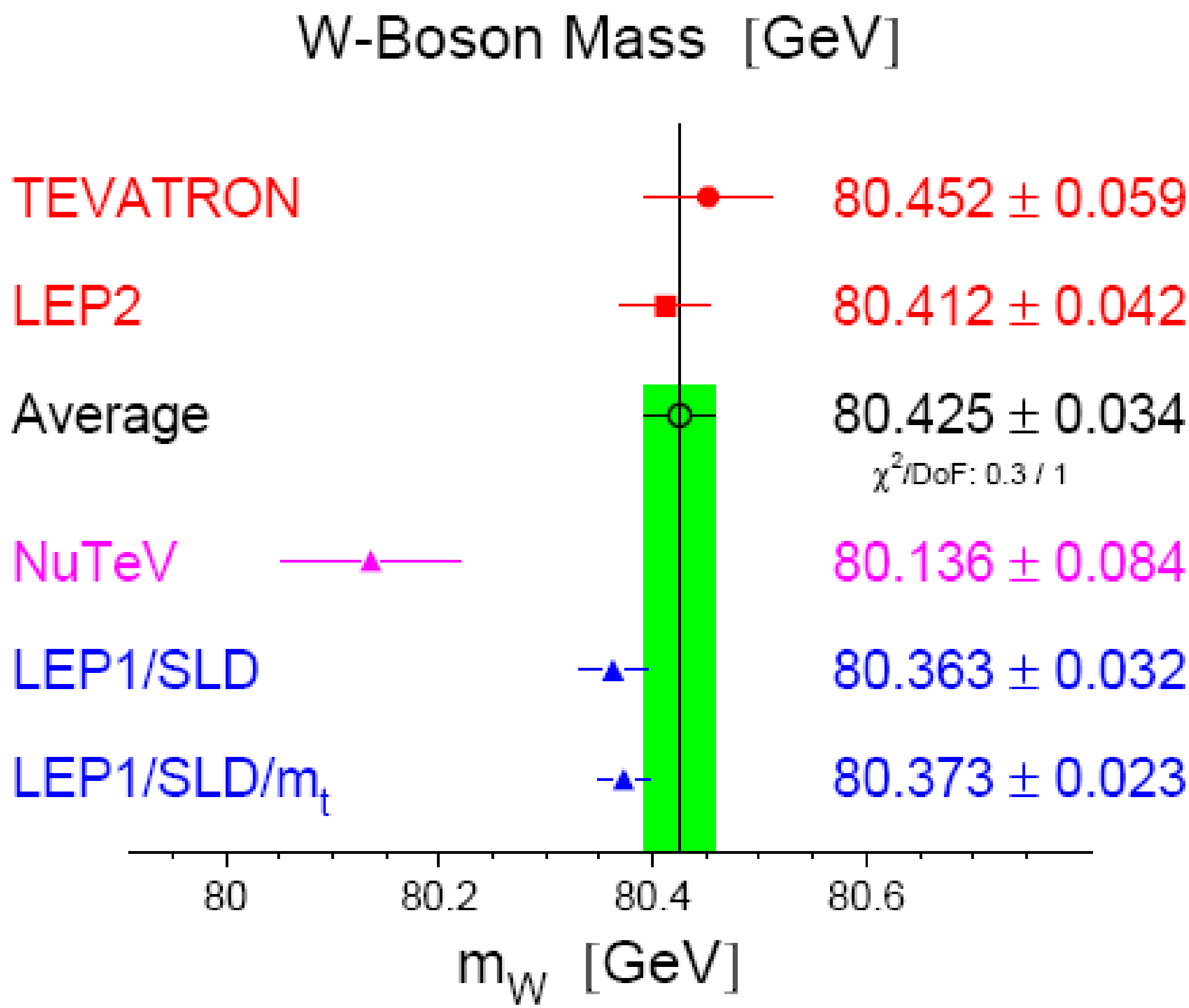




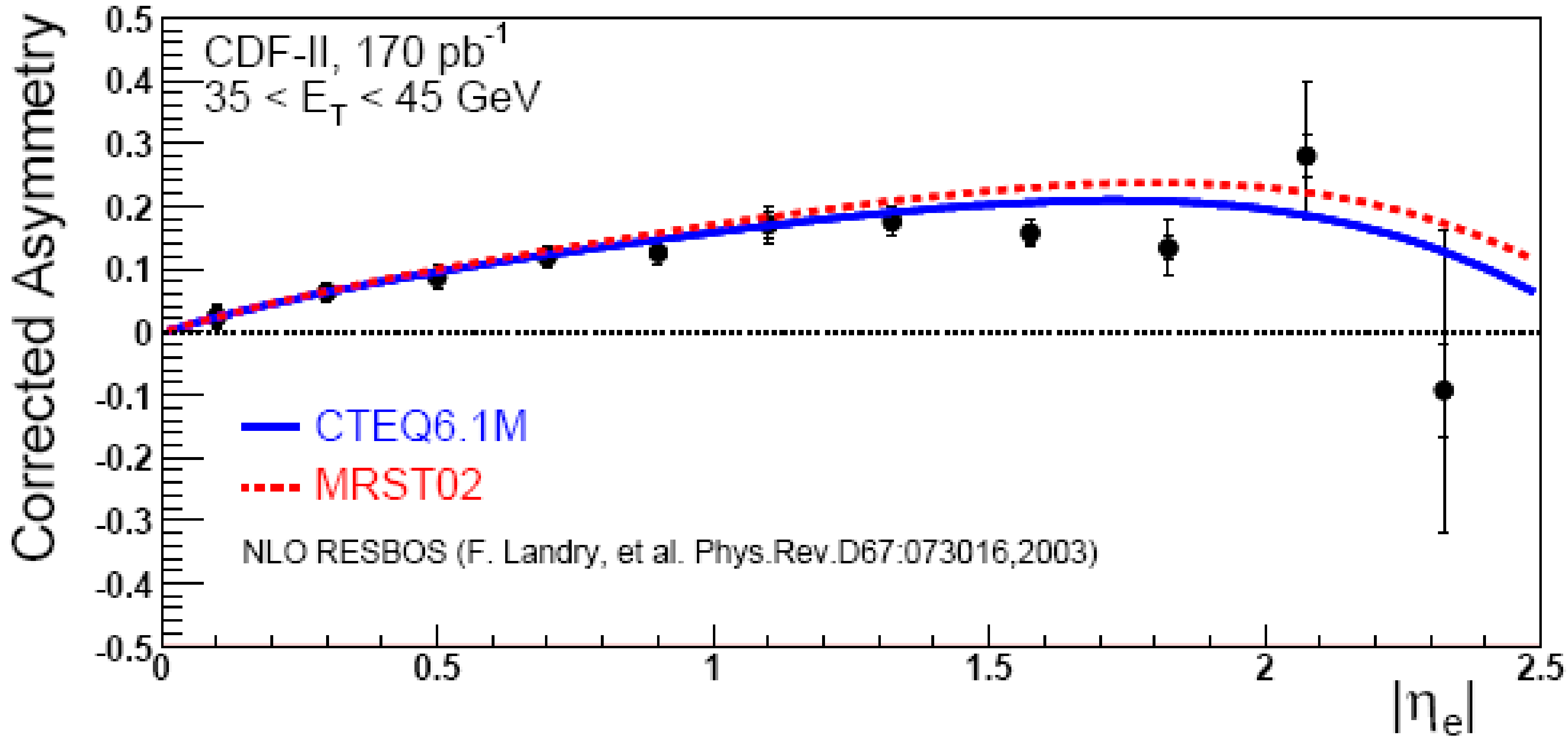
Z→μμ for Calibration

$$m_T^2 = 2\, p_{T,\ell}\, \not{E}_T\, (1 - \cos(\phi_\ell - \phi_{\not{T}}))$$

W Mass Summary

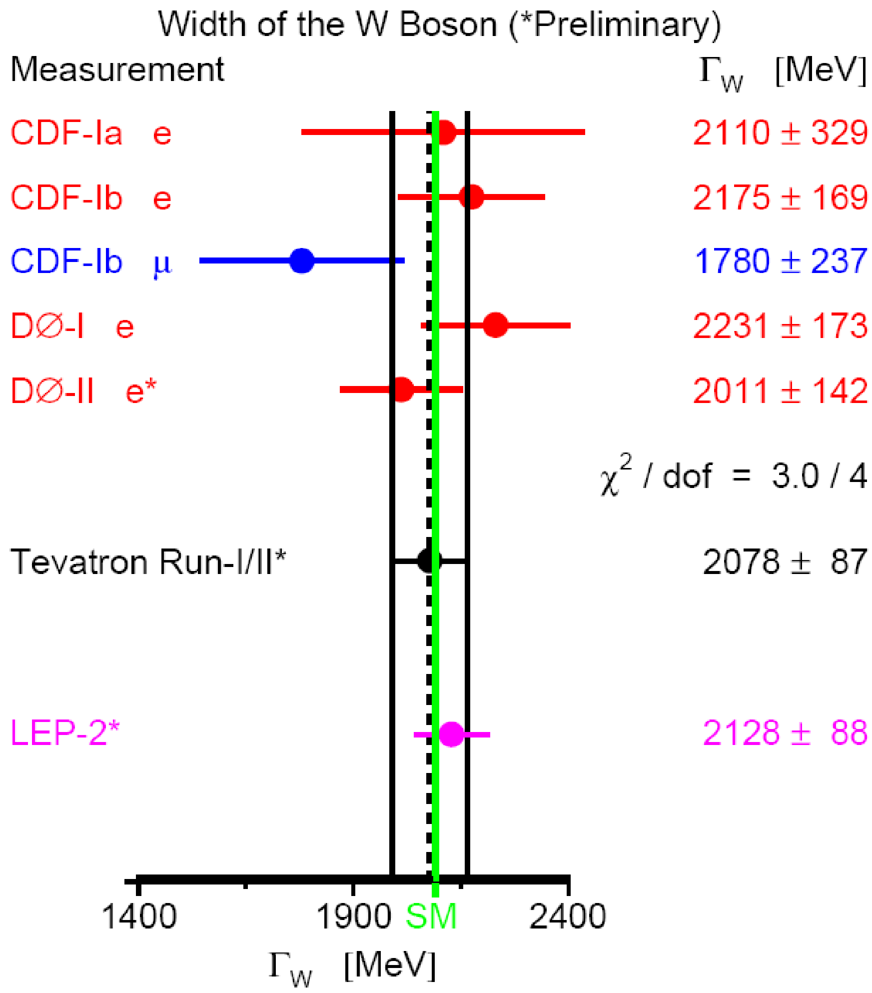


W Charge Asymmetry



$$A(\eta_e) = \frac{d\sigma(e^+)/d\eta_e - d\sigma(e^-)/d\eta_e}{d\sigma(e^+)/d\eta_e + d\sigma(e^-)/d\eta_e}$$

W Width

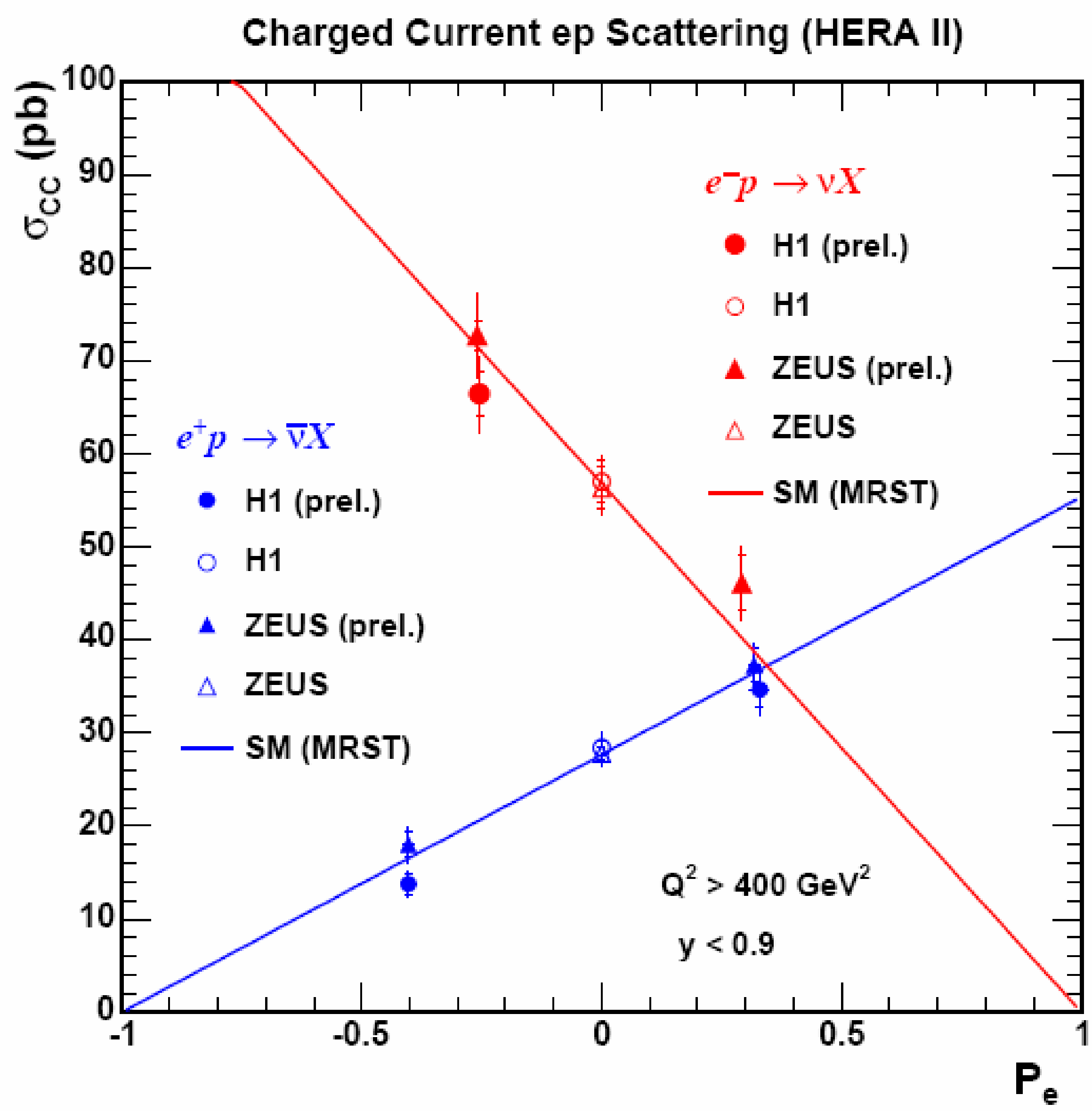


Two methods

- **Tail of M_T distrib.**

- **R(W/Z) production**

$$R = \frac{\sigma(W)\cdot BR(W\to \ell\nu)}{\sigma(Z)\cdot BR(Z\to \ell\ell)} = \frac{\sigma(W)}{\sigma(Z)}\,\frac{1}{BR(Z\to\ell\ell)}\,\frac{\Gamma(W\to\ell\nu)}{\Gamma_W}$$



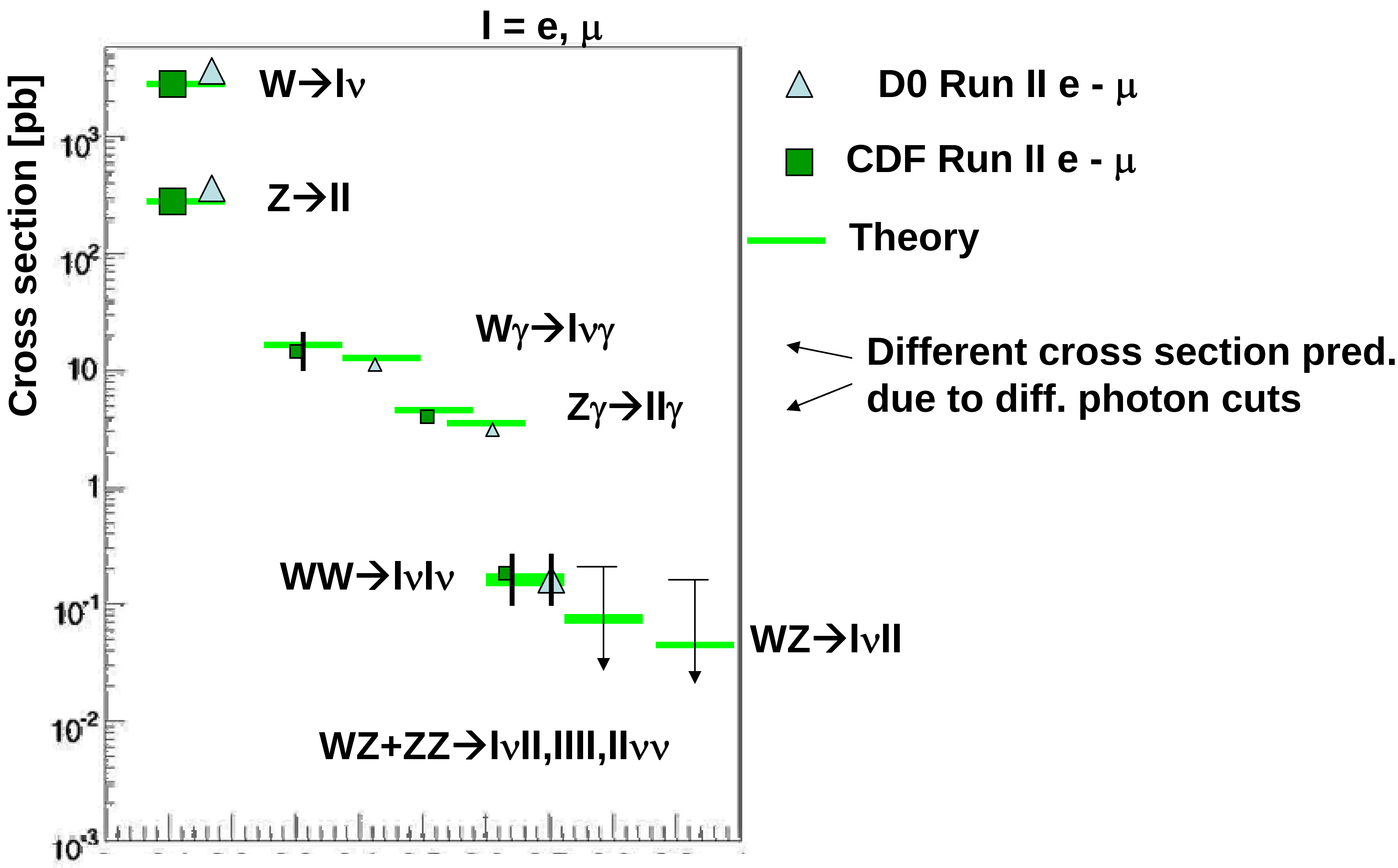
Shows:
W is purely V-A

Transverse electron polarisation due to Sokolov-Ternov effect

Transverse → longitudinal via spin rotators

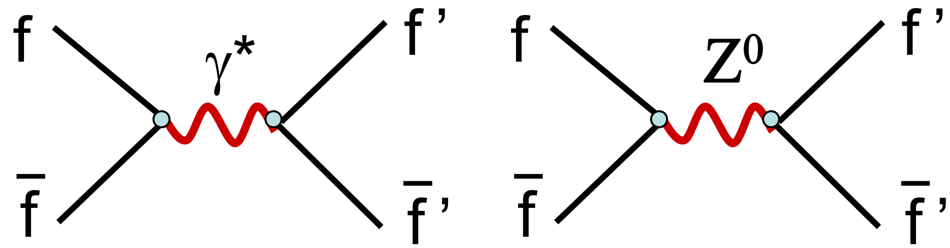
$e^{\pm}$ Beam polarization

3.5 Gauge Boson Production at Tevatron



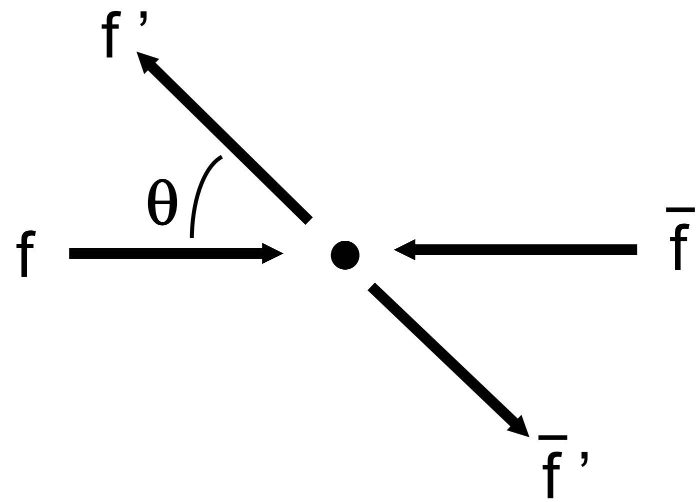
Fermion Gauge Boson Coupling

- Drell-Yan
- A_{FB} in DY
- W-Asymmetry

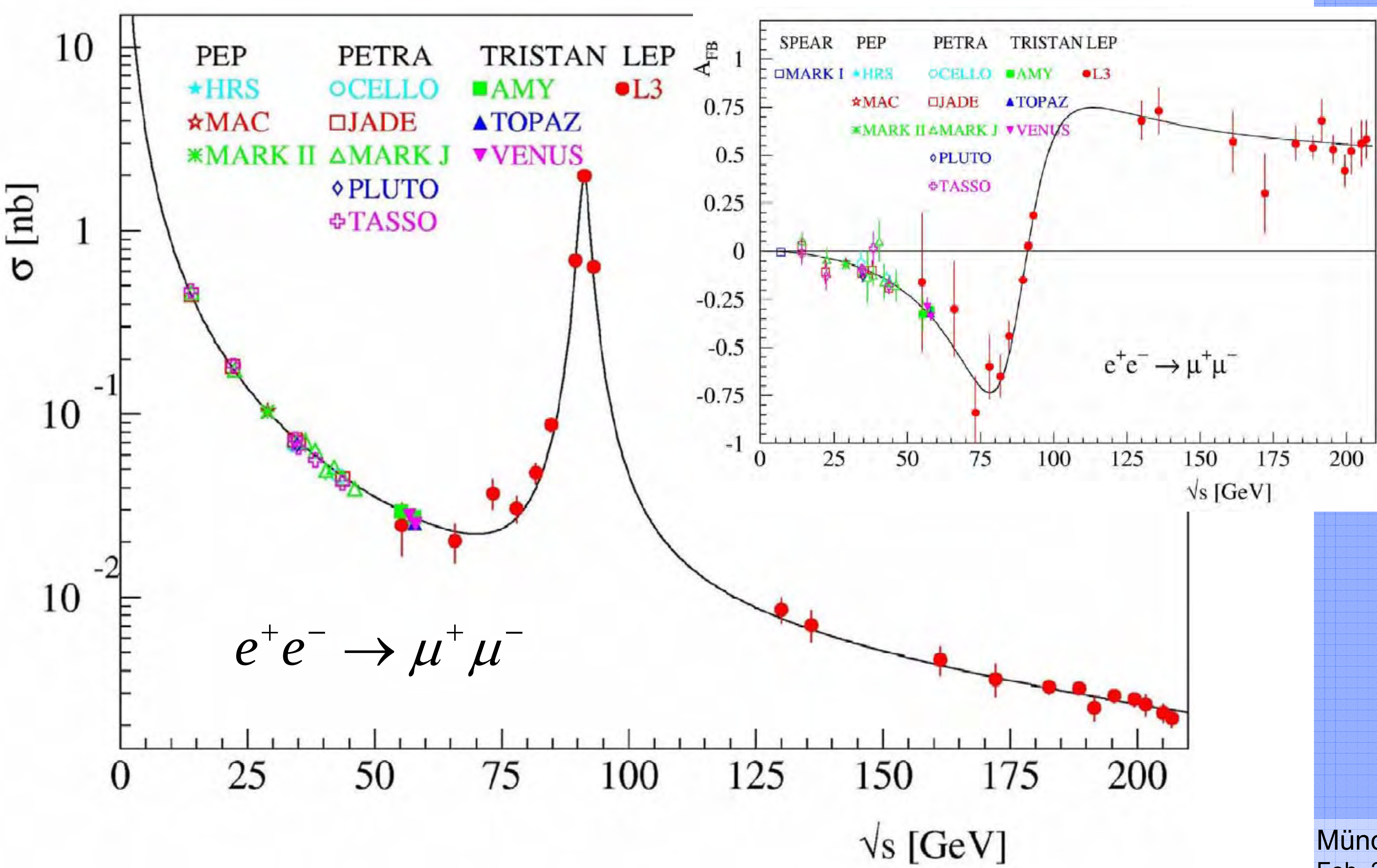


$$A_{FB} = \frac{\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)}{\sigma(\cos\theta > 0) + \sigma(\cos\theta < 0)}$$

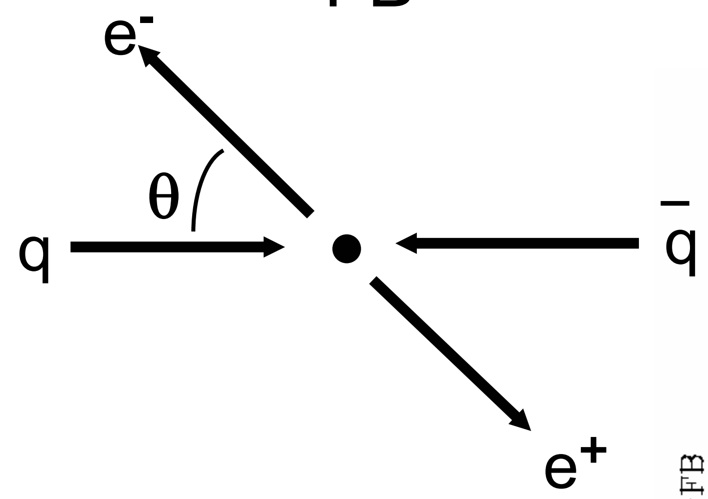
$$\sigma = A(1+\cos^2\theta) + B\cos\theta, \quad A_{FB} = 3B/8A$$

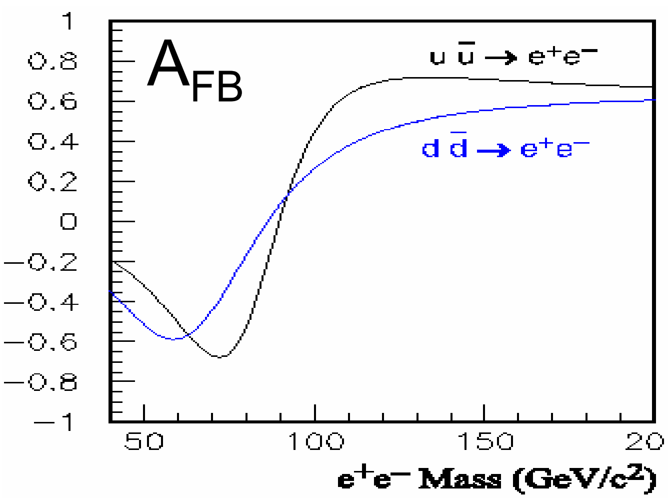


A_{FB} at e^+e^- Colliders

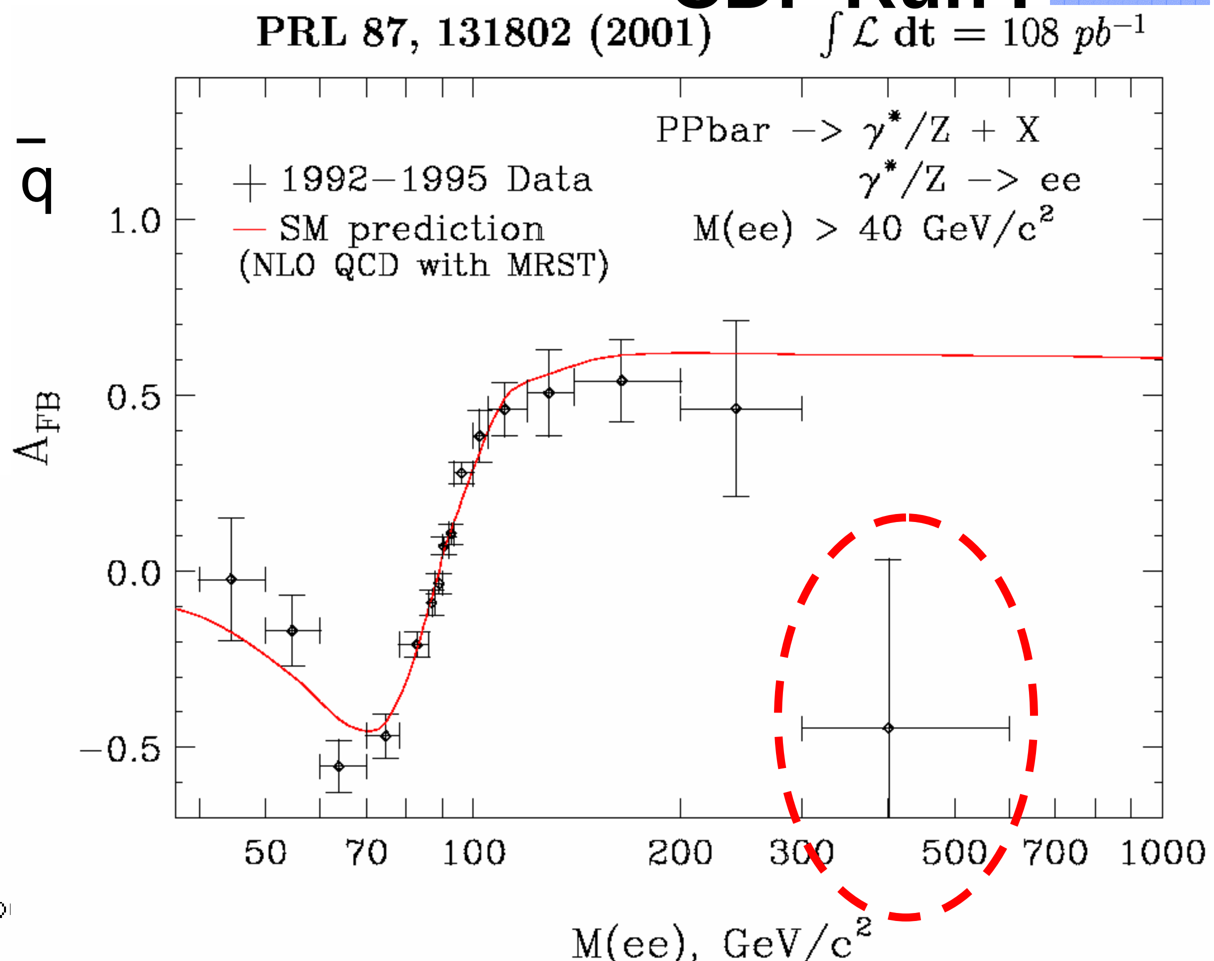


A_{FB} at Hadron Colliders



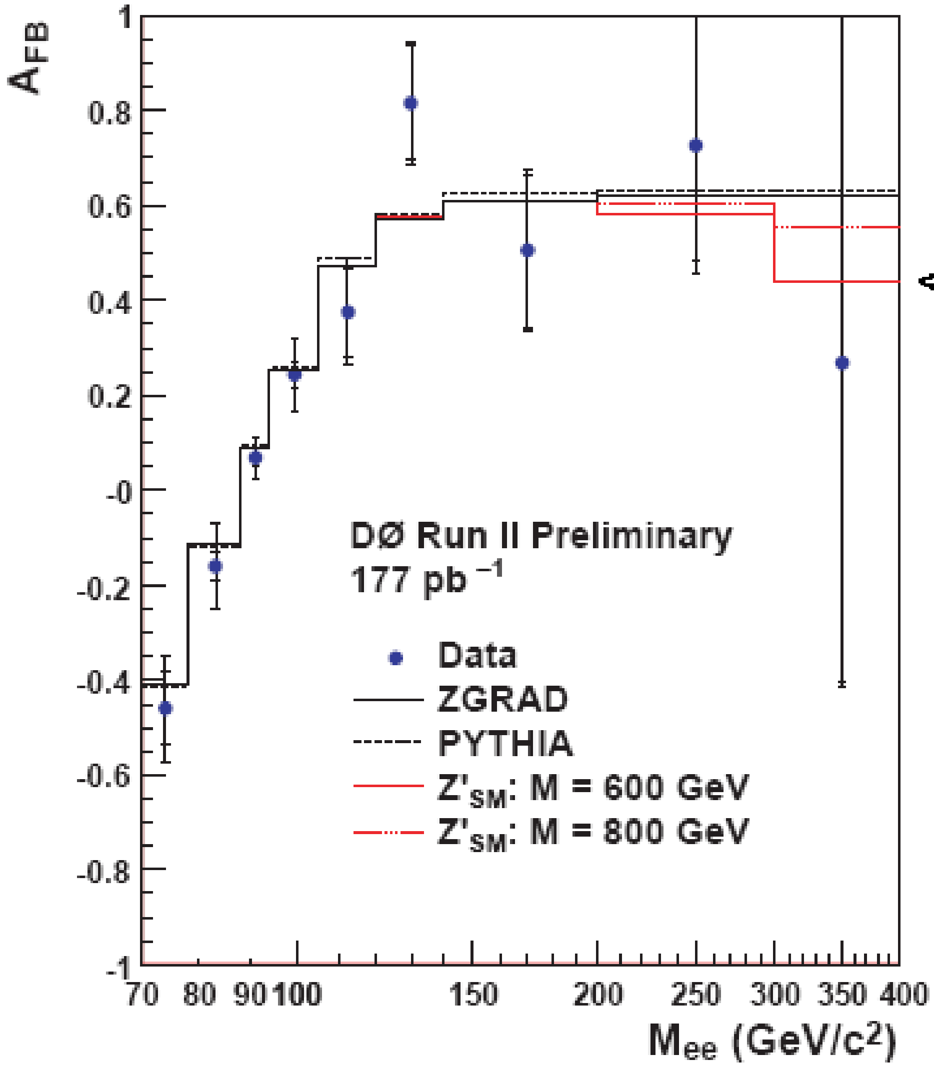


CDF Run I

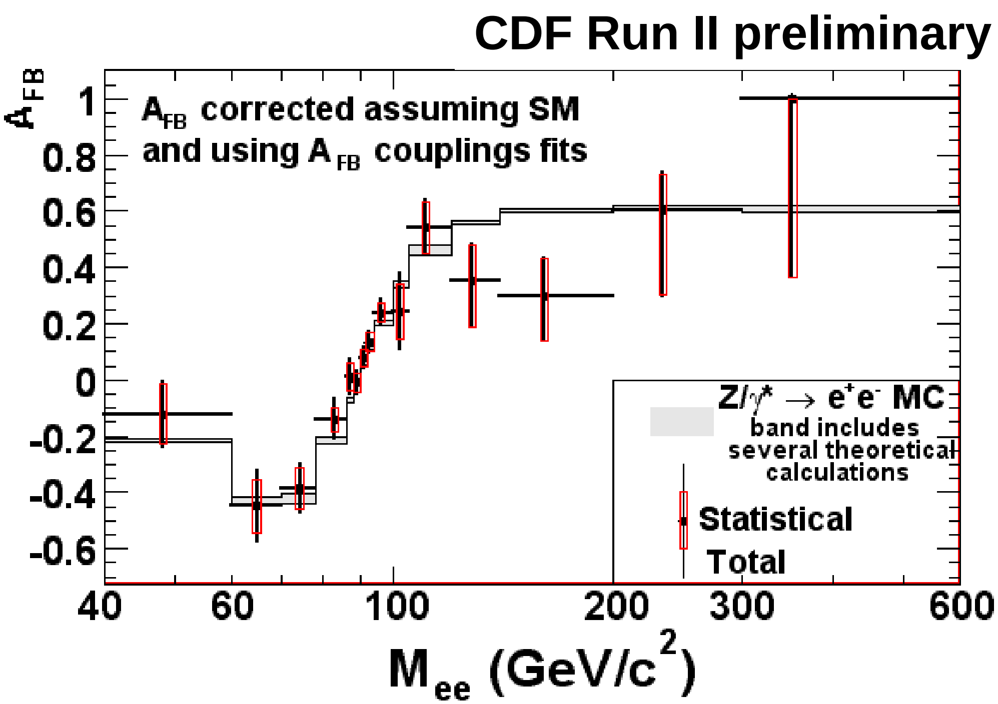


The last data point in a range usually is not very good, because if it was there would be another point further along. (R. Feynman), however…

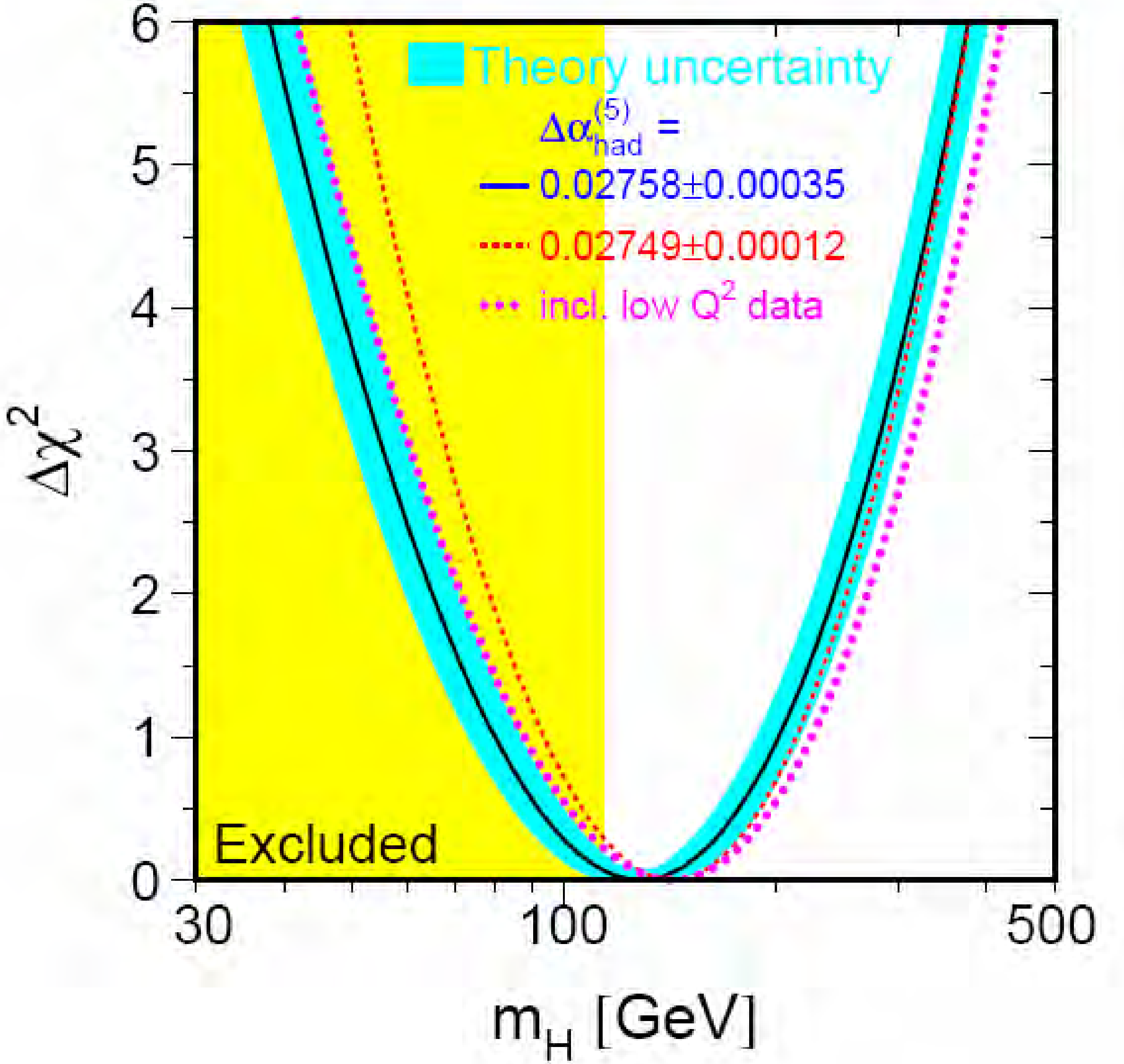
Run II Data



Still very exciting!



3.6 Electroweak Precision Fits



$$\chi^2 / d.o.f. = 18.3/13$$

Input Parameter

14 Z-pole results

$\boldsymbol{\Delta\alpha_{had}^{(5)}}$

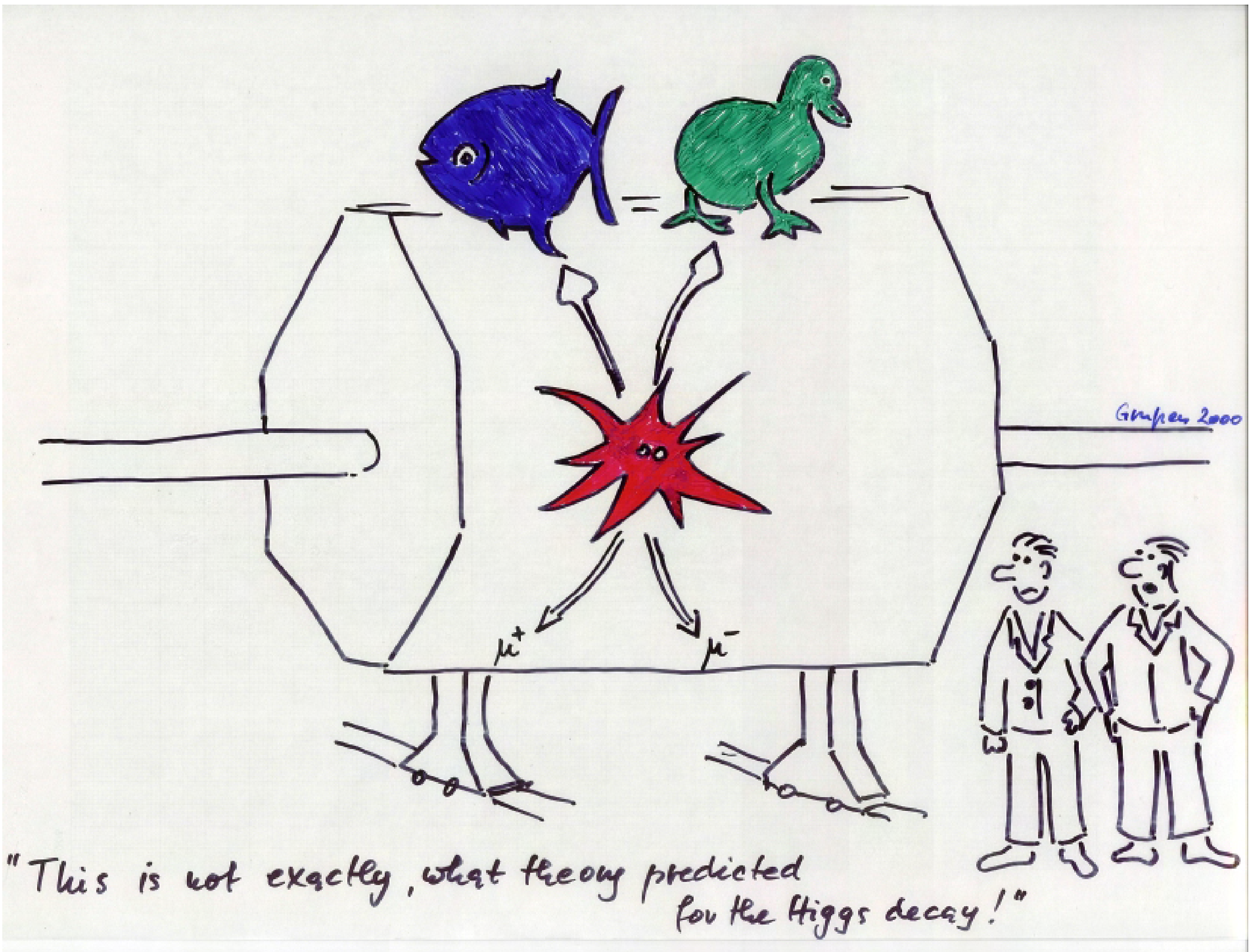
$\boldsymbol{m_W}$

$\boldsymbol{\Gamma_W}$

$\boldsymbol{M_{top}}$

Fitted Parameter: 5

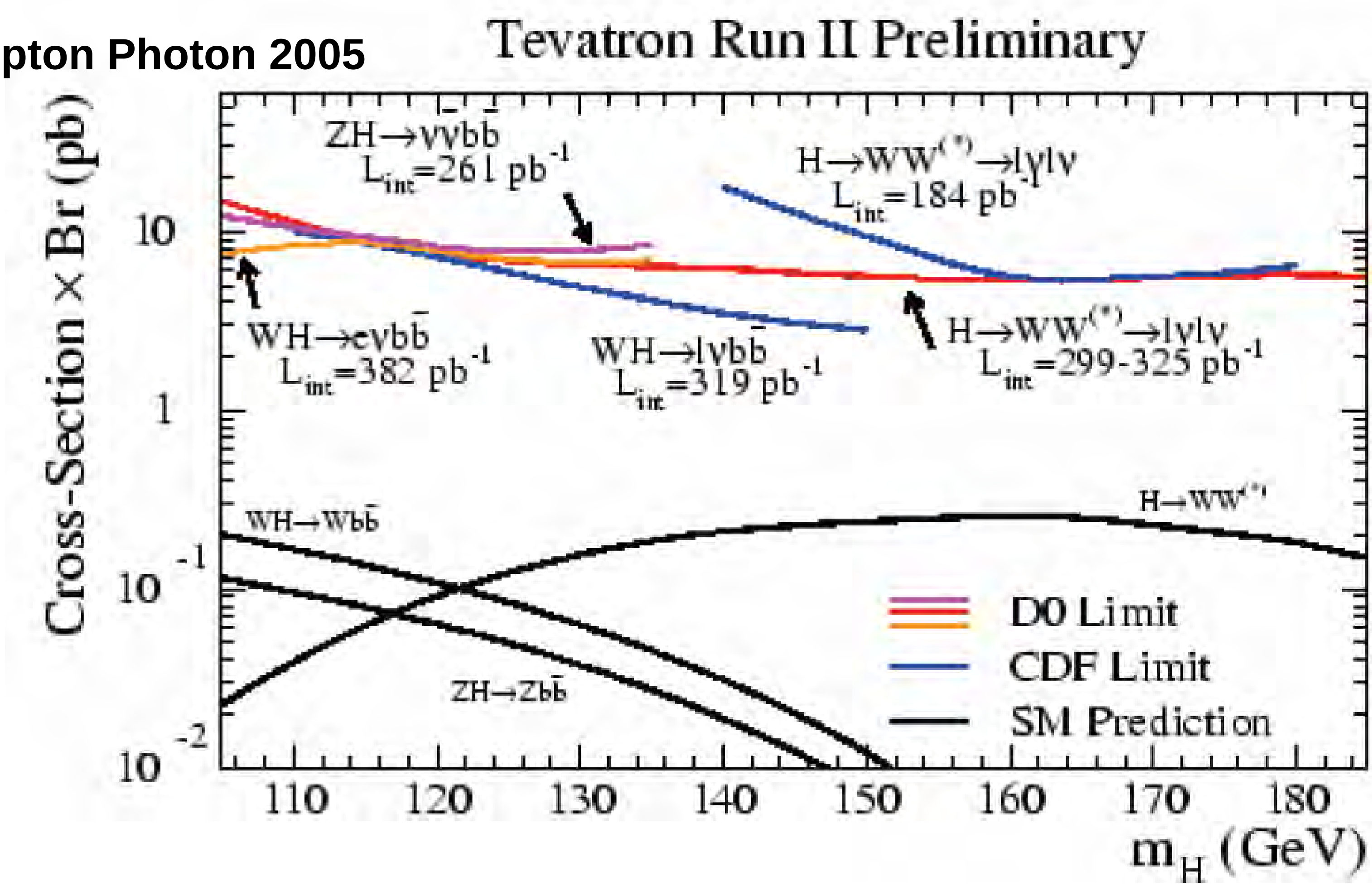
Section 4
SM Higgs Search Strategies at the LHC



Claus Grupen 2000

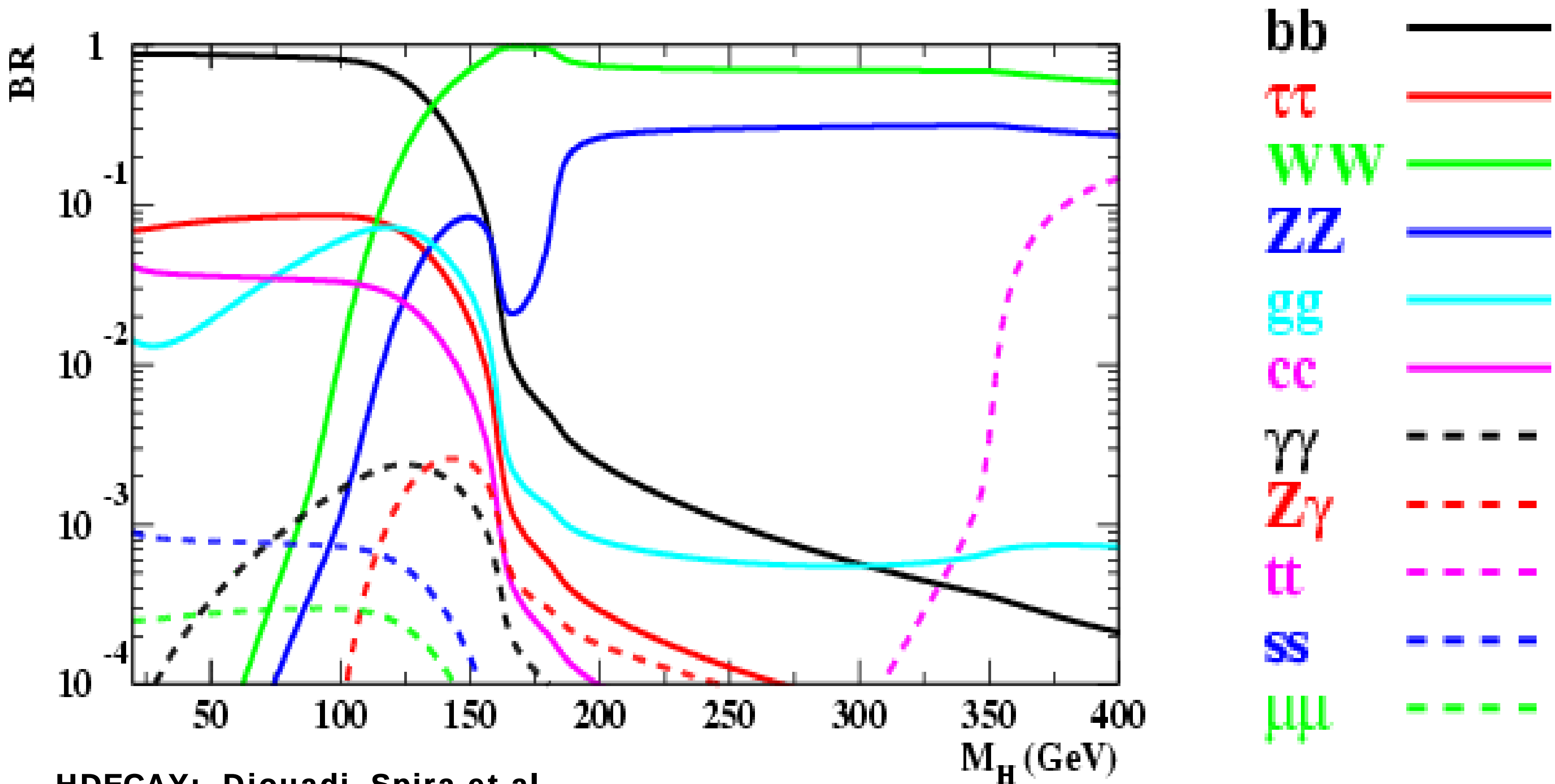
Higgs Search Status Tevatron

Lepton Photon 2005



Current sensitivity: Cross section limits ~ 10 x SM cross section

Higgs Boson Decays in SM

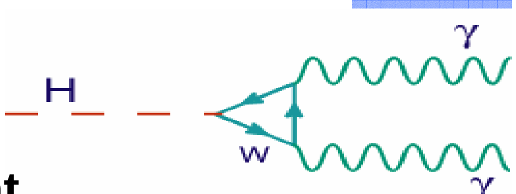


HDECAY: Djouadi, Spira et al.

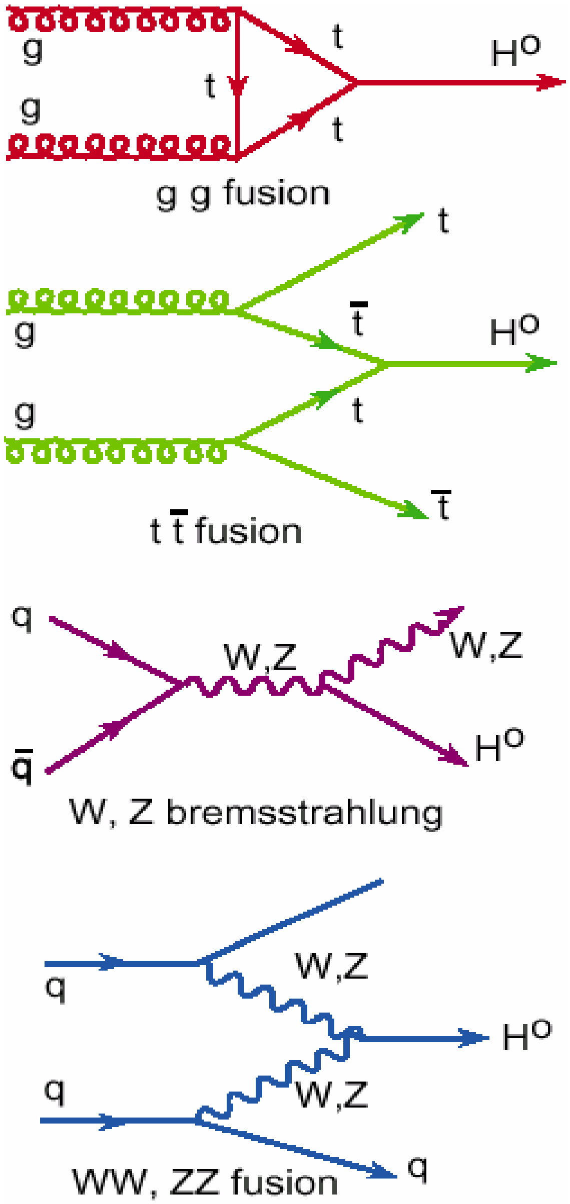
for M<135 GeV: H → bb, tt dominant

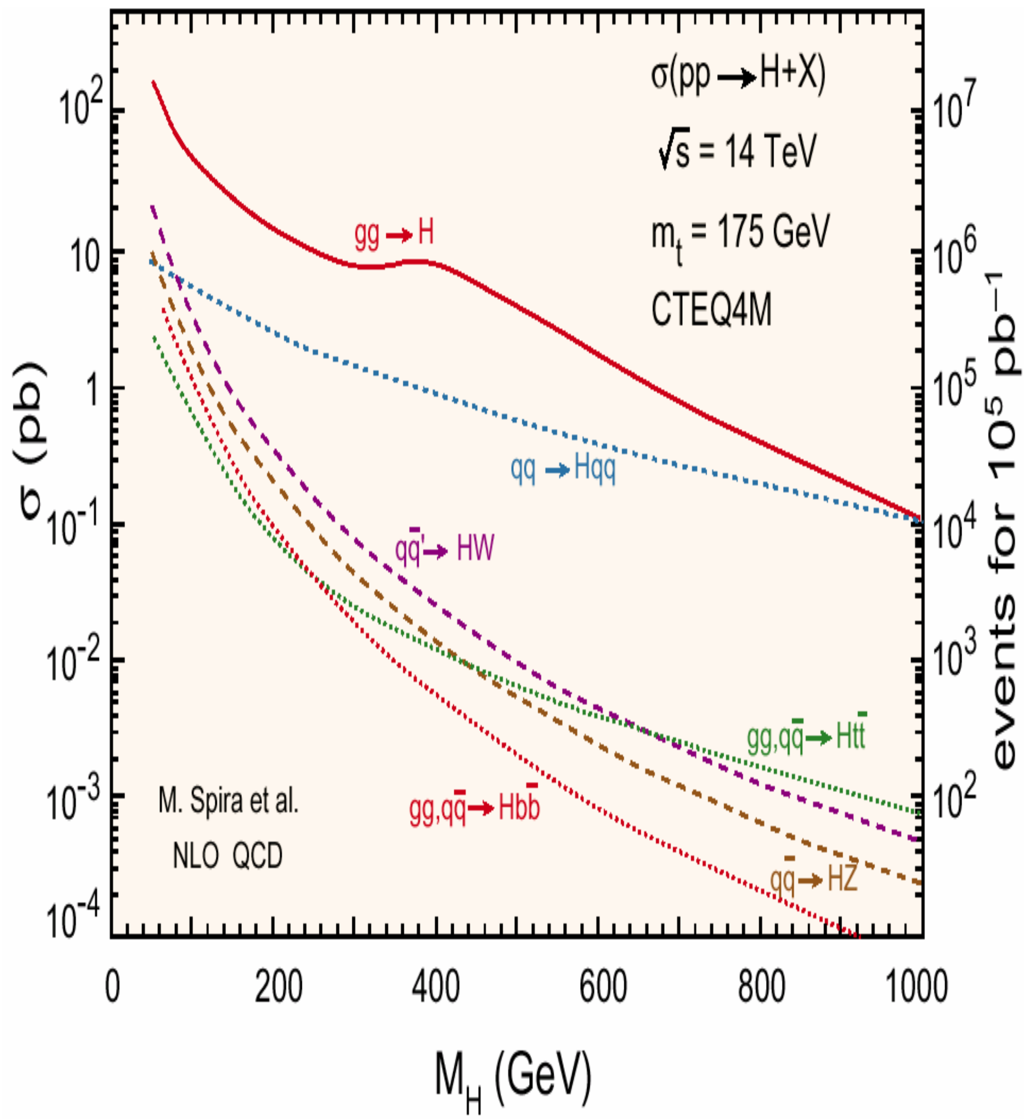
for M>135 GeV: H → WW, ZZ dominant

H → $\gamma\gamma$ tiny BR, but also important

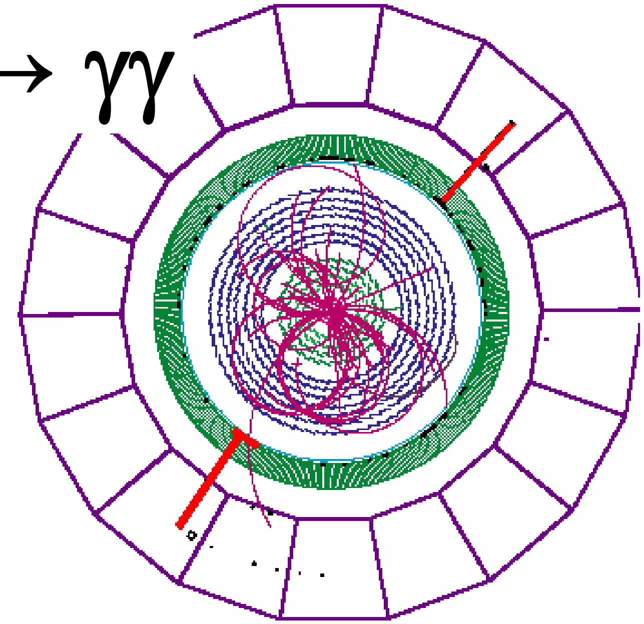


Production of the SM Higgs Boson

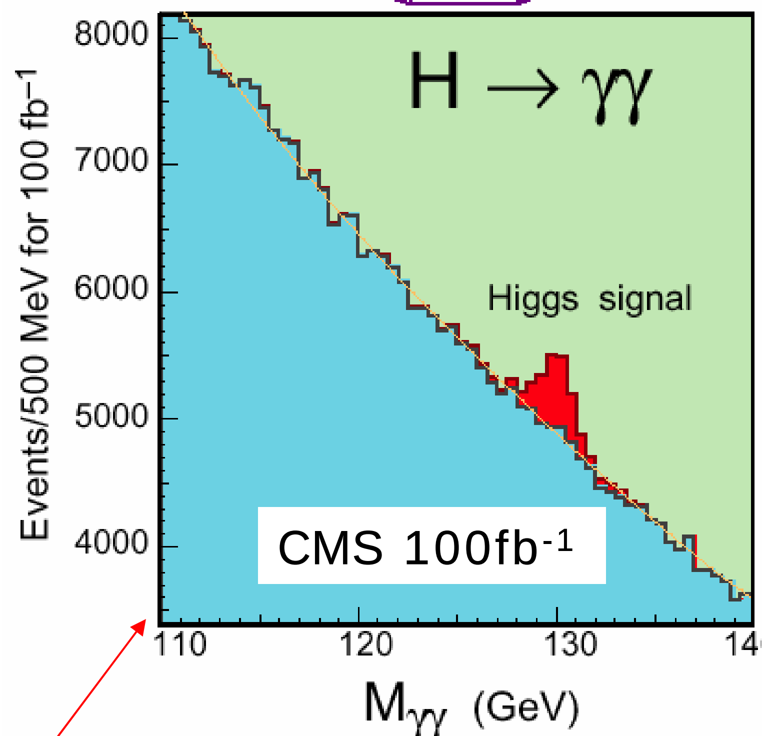




5.2 Low-Mass Higgs: $H \rightarrow \gamma\gamma$

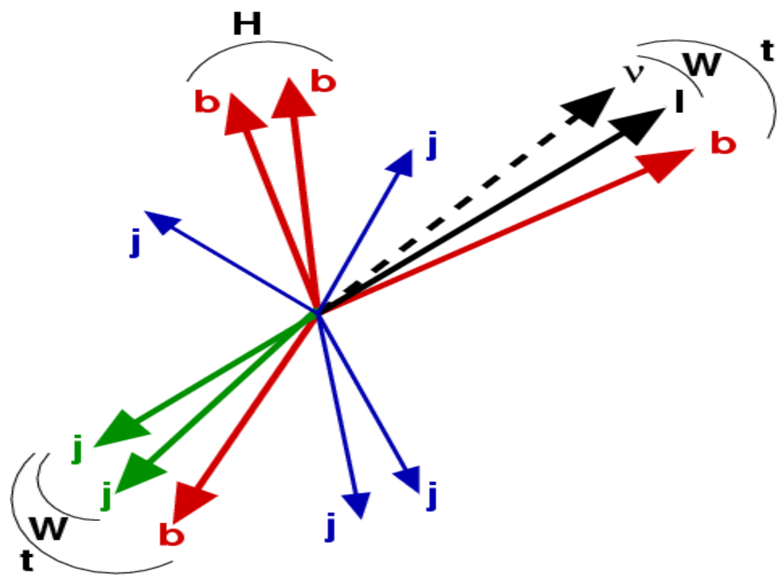


- ❑ Good trigger available no associate prod. required.
- ❑ Background
  - ➢ reducible:
    - ✓ non-photon bg
    - ✓ Drell Yang (e+e-) with lost tracks
  - ➢ irreducible:
    - ✓ Hard process $pp \rightarrow \gamma\gamma + X$
    - ✓ ISR/FSR off jets
- ❑ $\gamma\gamma$ mass resolution < 1%
  - ➢ requires PV z-position



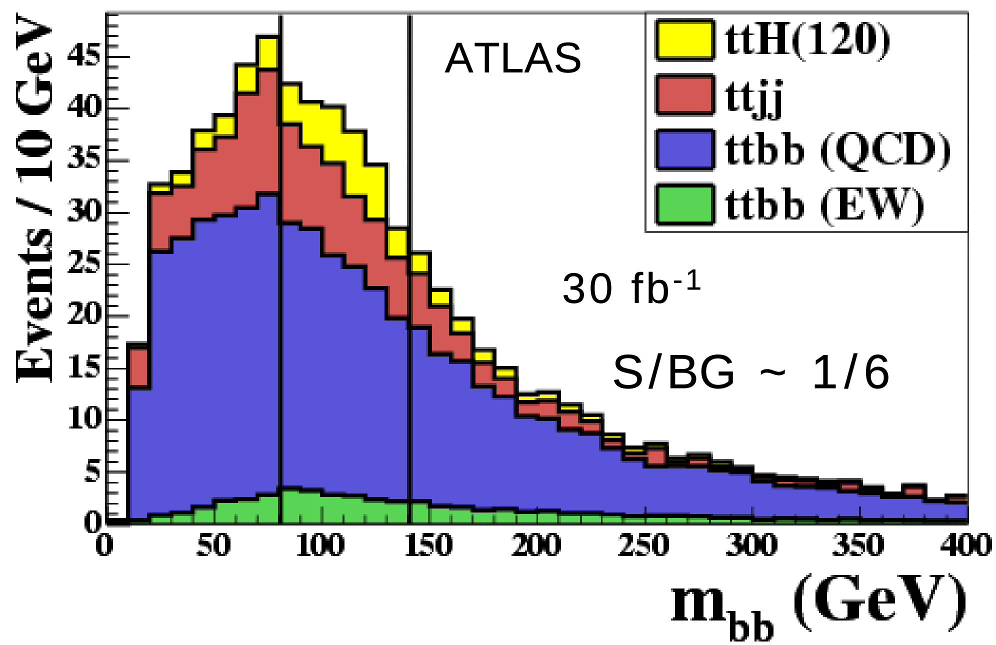
Zero-suppr. y-axis

ttH with H→bb

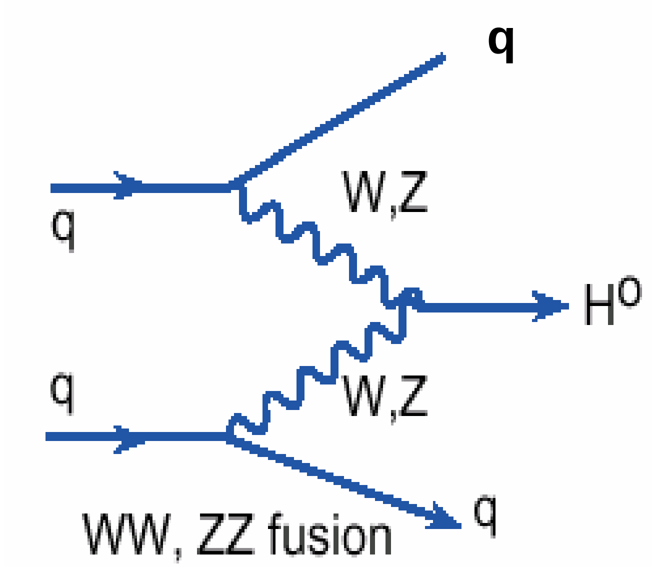


- ❑ Leptonic trigger on lepton from W→ l+ν decay
- ❑ 6 jets minimum in final state → combinatorics!

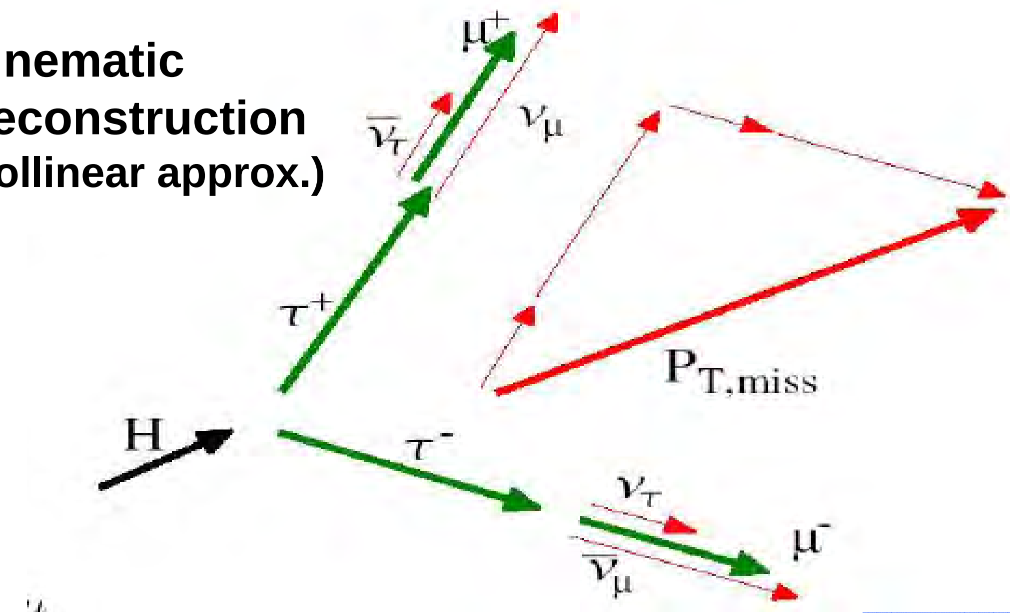
- ❑ Requires good b-tagging
- ❑ ttbb is irreducible BG
- ❑ H->bb mass resolution challenging (15% now)



$H \rightarrow \tau\tau$ in Vector Boson Fusion



Kinematic Reconstruction (collinear approx.)



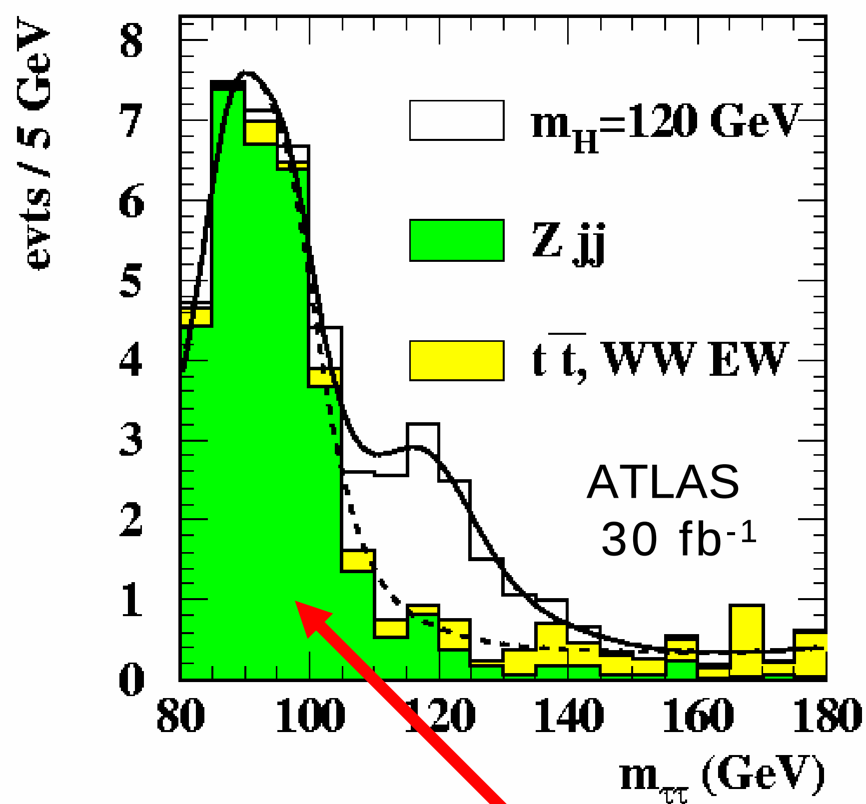
- ❑ Signature: $H \rightarrow \tau\tau$ + two forward jets + rapidity gap

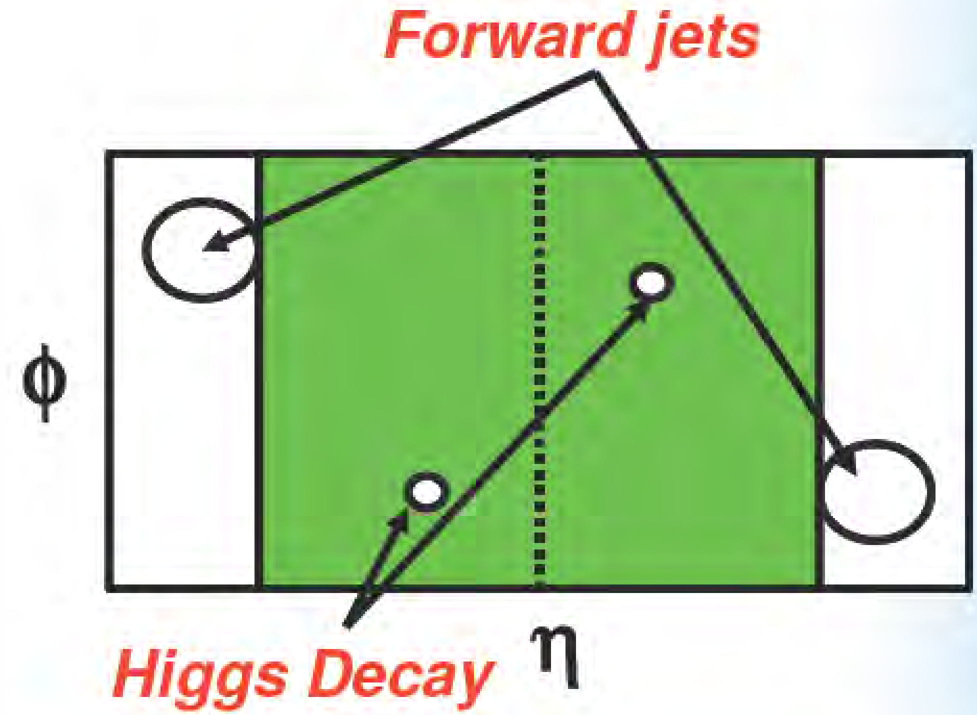
signature weakened by underlying evt + minBias + QCD jets

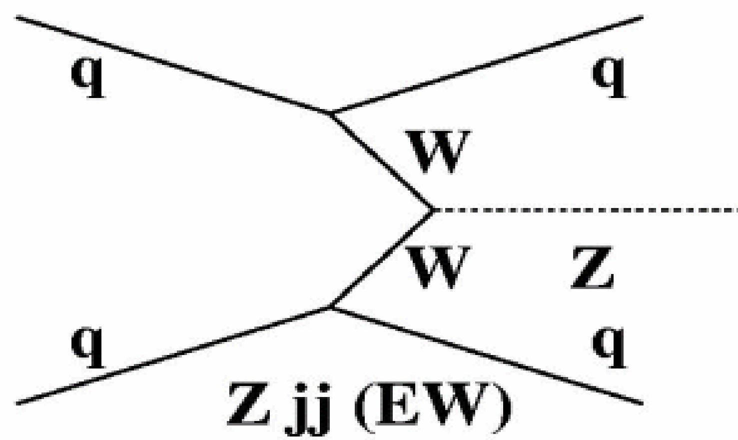
- ❑ Interesting channel under study
- ❑ Open questions: Triggering on Forward jets
  Central jet veto

H→ττ in Vector Boson Fusion

H→ττ→eμ M_H=120 GeV

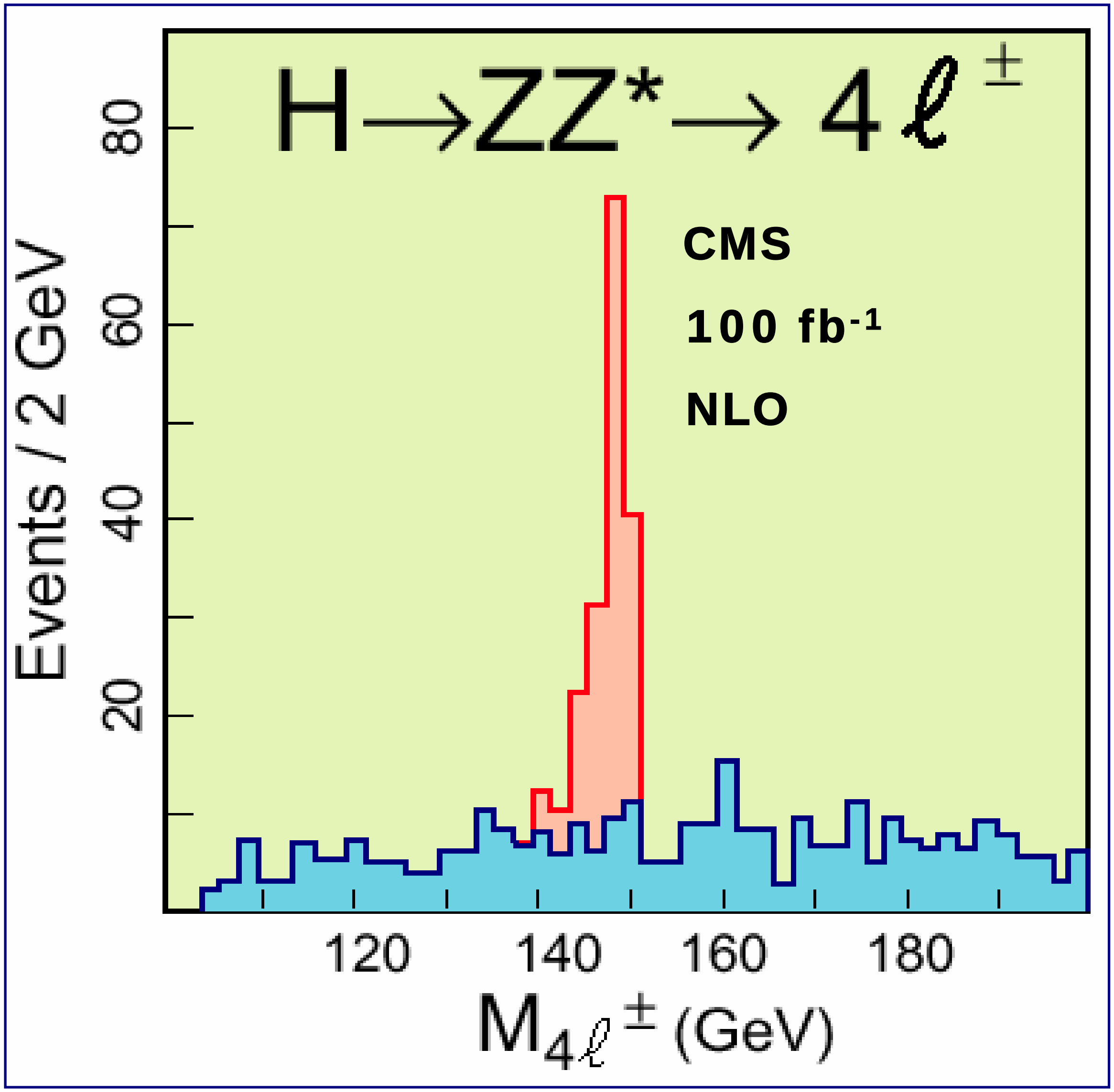


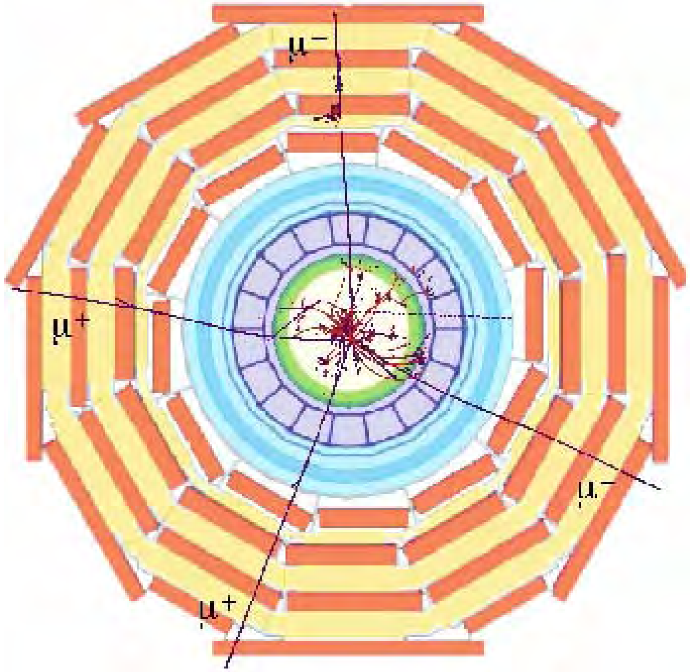




Irreducible BG

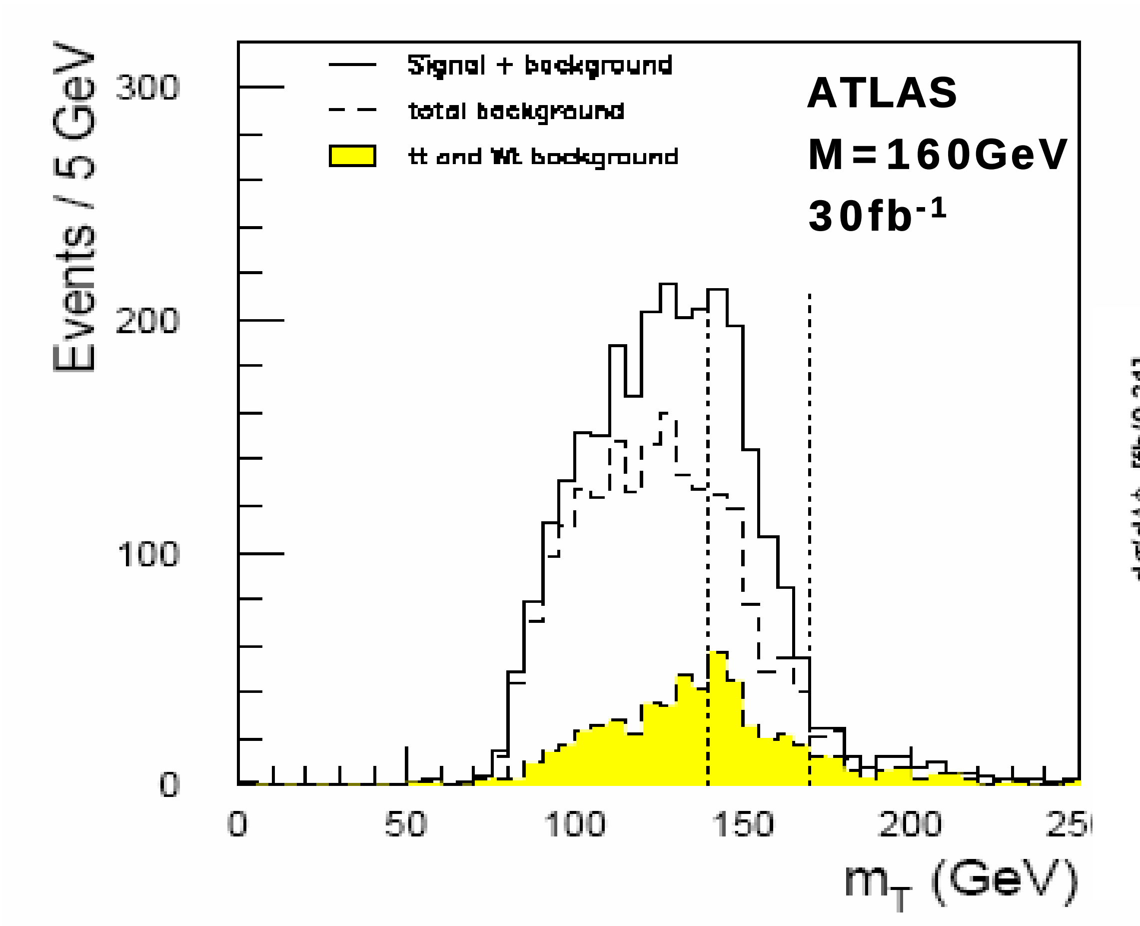
5.2 Higher-Mass Higgs: H→ZZ*



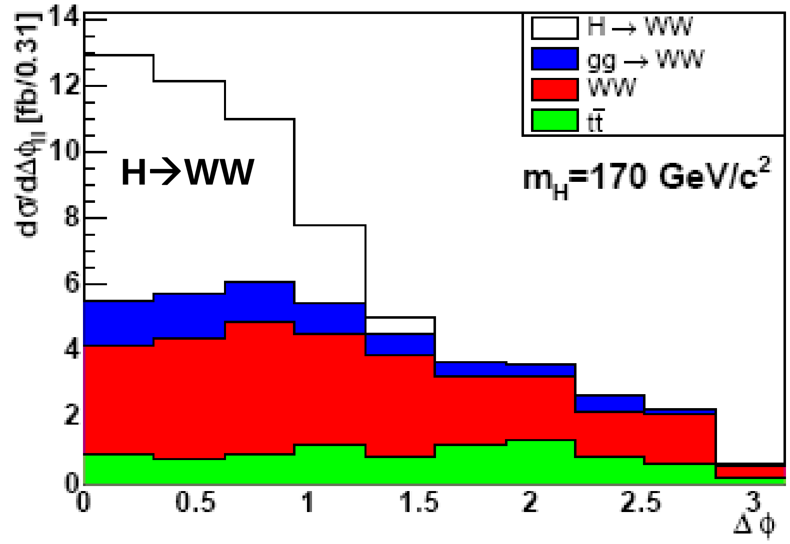


$H \rightarrow W\,W \rightarrow l\nu\; l\nu$

- ❑ Transverse mass $$m_T = \sqrt{2\, P_T^{\ell\ell}\, \not{E}_T\, (1 - \cos\Delta\varphi)}$$

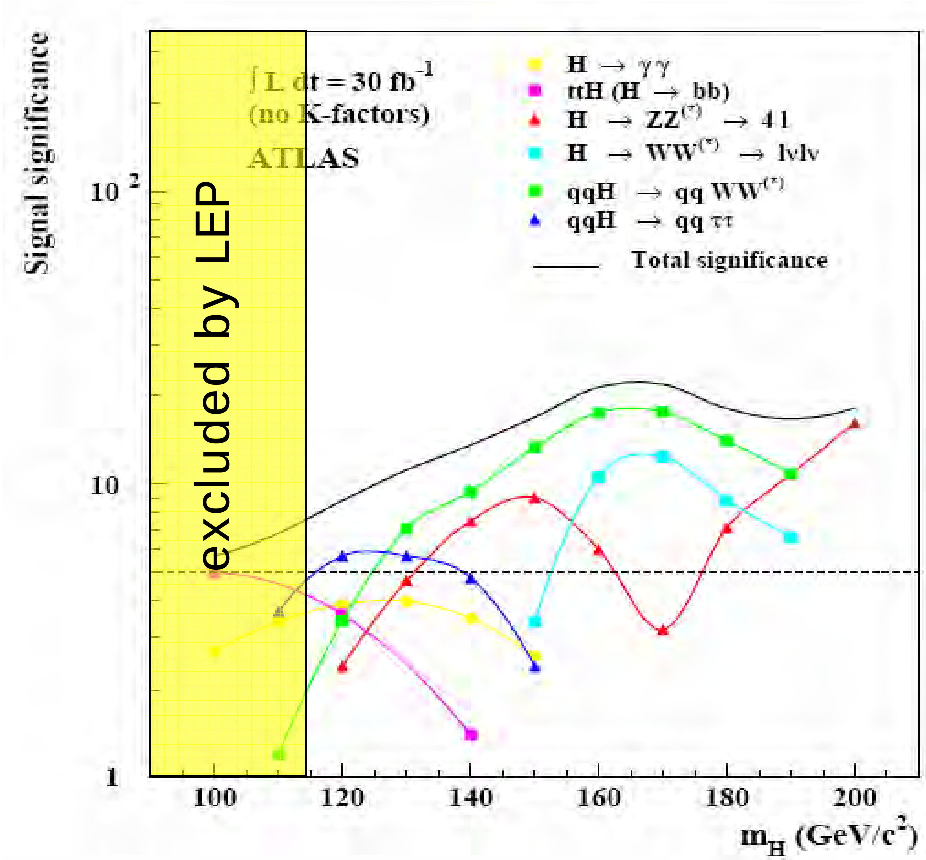


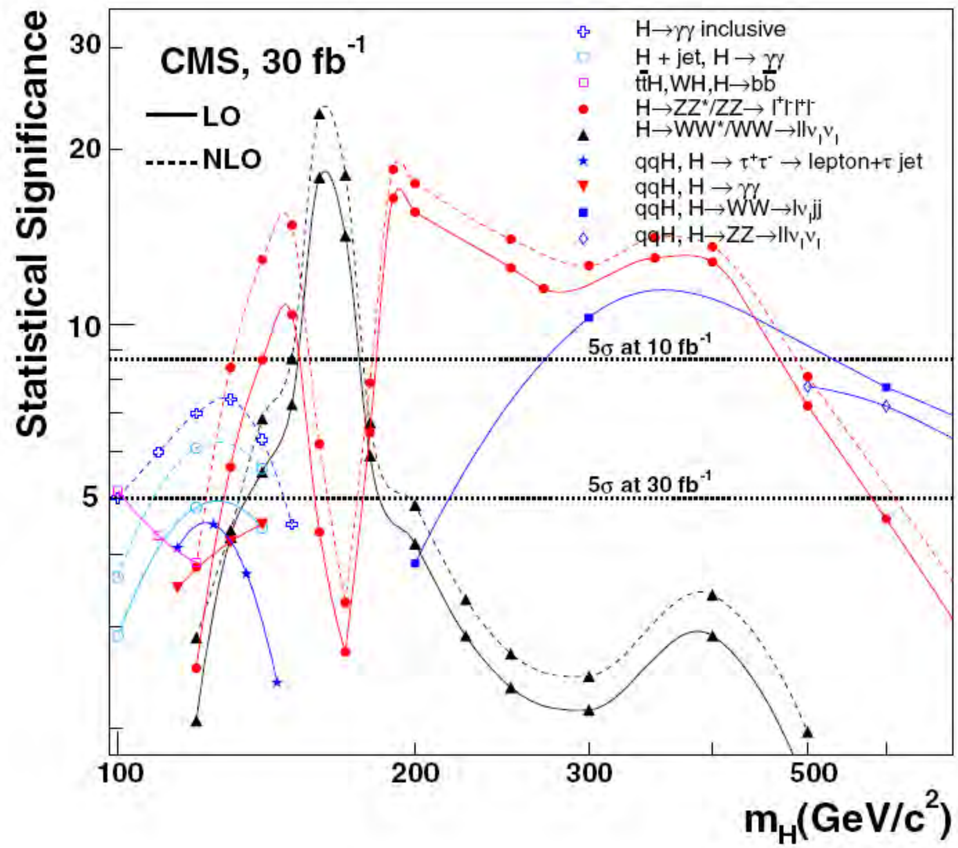
Additional sensitive Variable
Azimuthal Angle diff.



Dührssen et al,
JHEP 0505:064,2005

5.3 Summary Discovery Potential

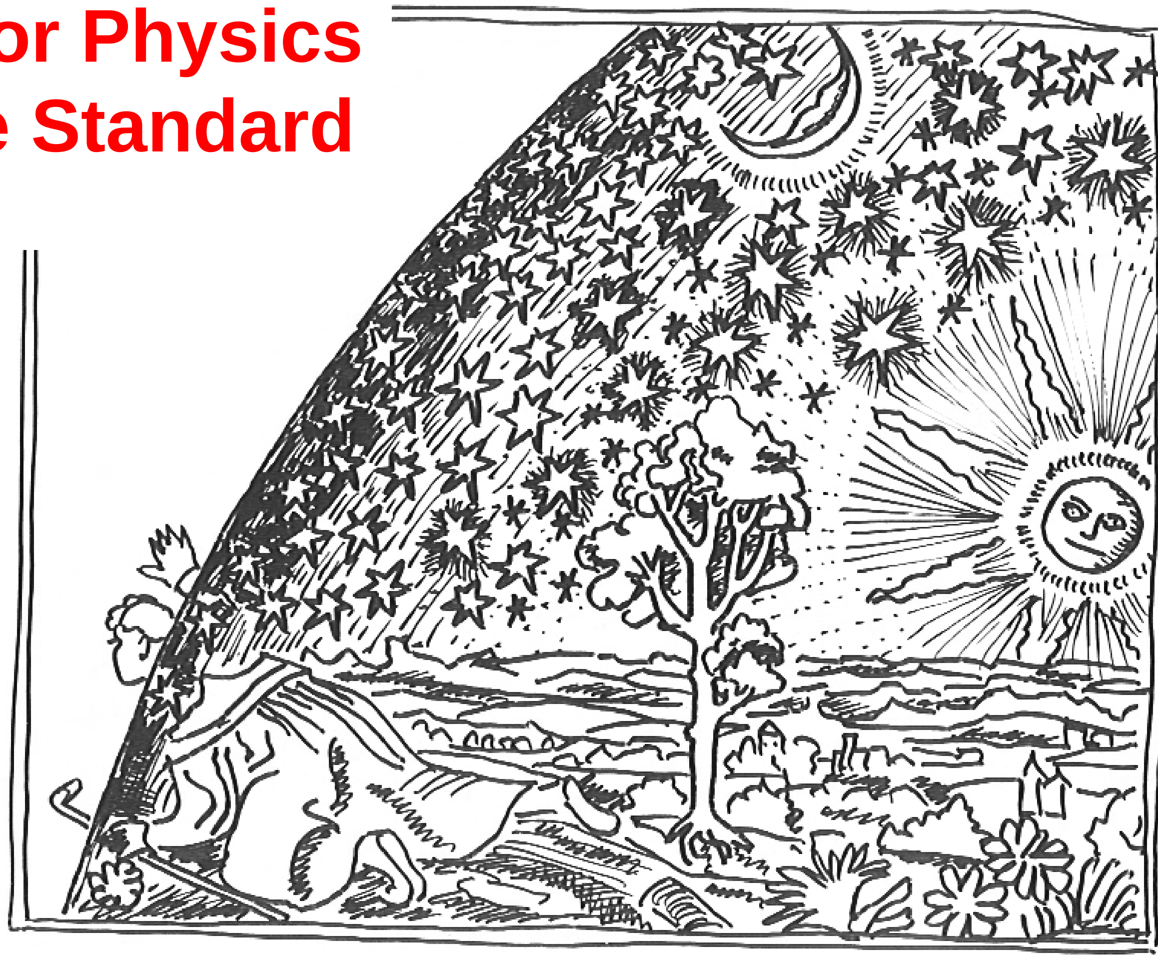




- ❑ Many channels contribute (including some not presented here)
- ❑ LHC has a good chance of observing a SM Higgs

Section 5

Evidence for Physics beyond the Standard Model



Is there anything beyond the Standard Model?

The New Minimal Standard Model

- This section refers to:

  THE NEW MINIMAL STANDARD MODEL, H.Davoudiasl, R. Kitano, T.Li, H. Murayama, Phys.Lett. B609 117 (2005) [hep-ph/0405097]

- Not really a revolutionary paper: but nice review of known effects beyond S.M.,
- Do **not** take the proposed lagrangian too seriously (it is probably not correct)
- Main idea:
  - keep spirit of frugality (therefore no Supersymmetry)
  - New <u>Minimal</u> Standard Model means: try to minimize number of new parameters (19+6)
- Ignore all fine tuning problems (classic SM did same)

Effects beyond the Standard Model

- Dark Matter
- Dark energy
- Measurements from atmospheric, solar and reactor neutrino
  Experiments have established neutrino masses and mixing.
- Baryon asymmetry in the Universe $n_B/n_\gamma = 10^{-10}$
- Necessity to have a mechanism for cosmic inflation to solve horizon problem and the structure of large scale density fluctuations in the universe.

Observations

Most likely scenario: WIMP
minimally: one new stable particle

Cosmological constant: We have not quantized Gravity yet (meanwhile use classical lagrangian)

- Add Neutrino mass matrix:
  Decide on majorana vs. Dirac Type (leave one neutrino massless to minimize parameters).
- $\cancel{CP}$ in neutrino sector might also explain baryogenesis
- Scalar particle with potential term in lagrangian
- Total Count new para.: 6

Hypothesis

Section 6: “EXAM”

- What are the consequences of introducing an additional color charge (purple?) and implementing SU(4) color-symmetry instead of SU(3), but leaving everything else as it is.

- Find a 'natural' explanation for the hypercharge of the quarks. Publish your results on hep-ph. (but check with your supervisor before submission).

- What happens to the CKM matrix if all 6 quarks have the same mass.

  (courtesy of Michael Kobel, Dresden)

- Design and build an experiment to distinguish if neutrinos are of dirac or majorana type.