The Tevatron as a Probe of the Fundamental Particles and their Interactions in our Universe

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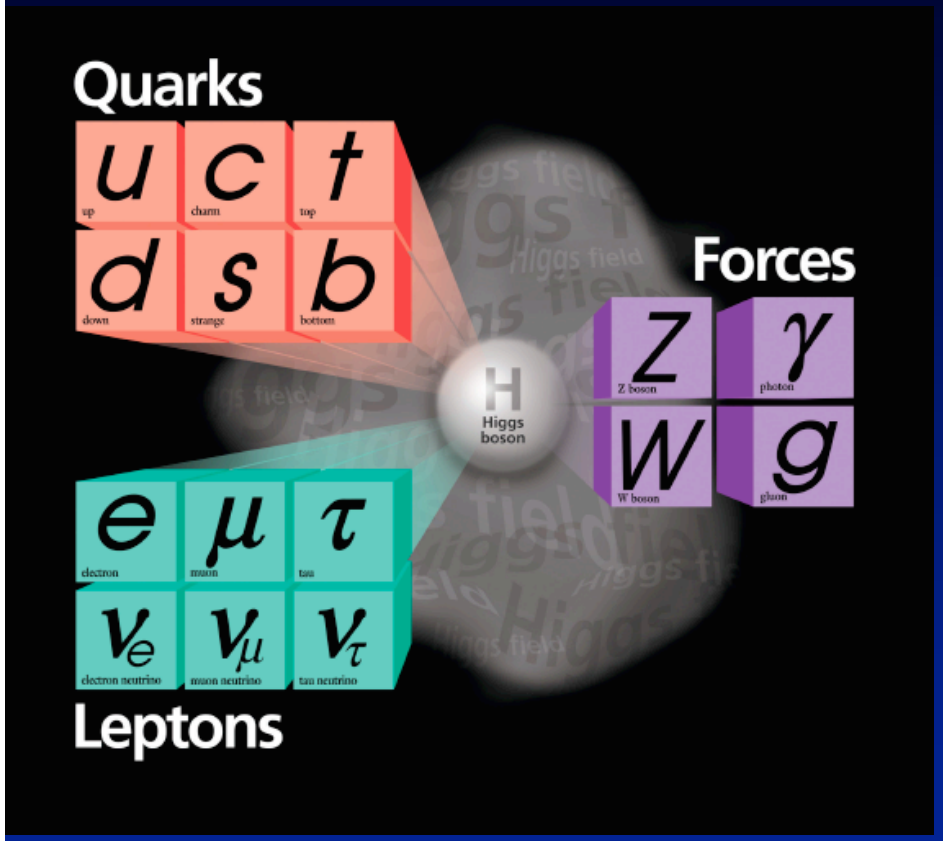
Outline

- The Standard Model of particle physics and it's problems
- The Tevatron, CDF and DØ
- Precision measurements of the Standard Model
- Searches for the Unknown
- Outlook and Conclusions

Fundamental Particles and Forces



- **Matter**
  - is made out of fermions
- **Forces**
  - are mediated by bosons
- **Higgs boson**
  - breaks the electroweak symmetry and gives mass to fermions and weak gauge bosons

Amazingly successful in describing precisely data from all collider experiments

The Standard Model Lagrangian

$$\begin{aligned}\mathcal{L} \;=\; & -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} \;+\; i\,\bar{\psi}D\psi \\ & +\,\psi_i\lambda_{ij}\psi_j h \;+\; \text{h.c.} \\ & +\,|D_\mu h|^2 - V(h) \\ & +\,\frac{1}{M}L_i\lambda^\nu_{ij}L_j h^2 \text{ or } L_i\lambda^\nu_{ij}N_j\end{aligned}$$

gauge sector ✓

flavour sector ✓

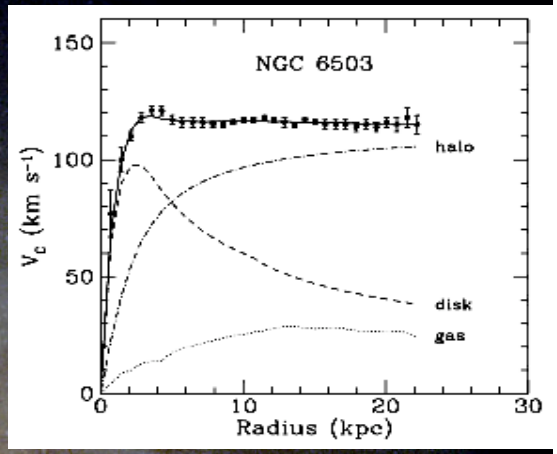
EWSB sector ✓

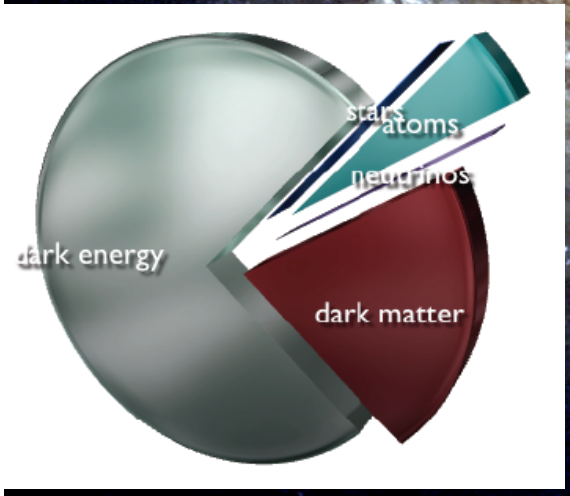
ν mass sector

… and beyond?

supersymmetry (many variants)
extra spacetime dimensions
compositeness
strong electroweak symmetry breaking
…
something new?! ✓

Problem I:
What is the Dark Matter?

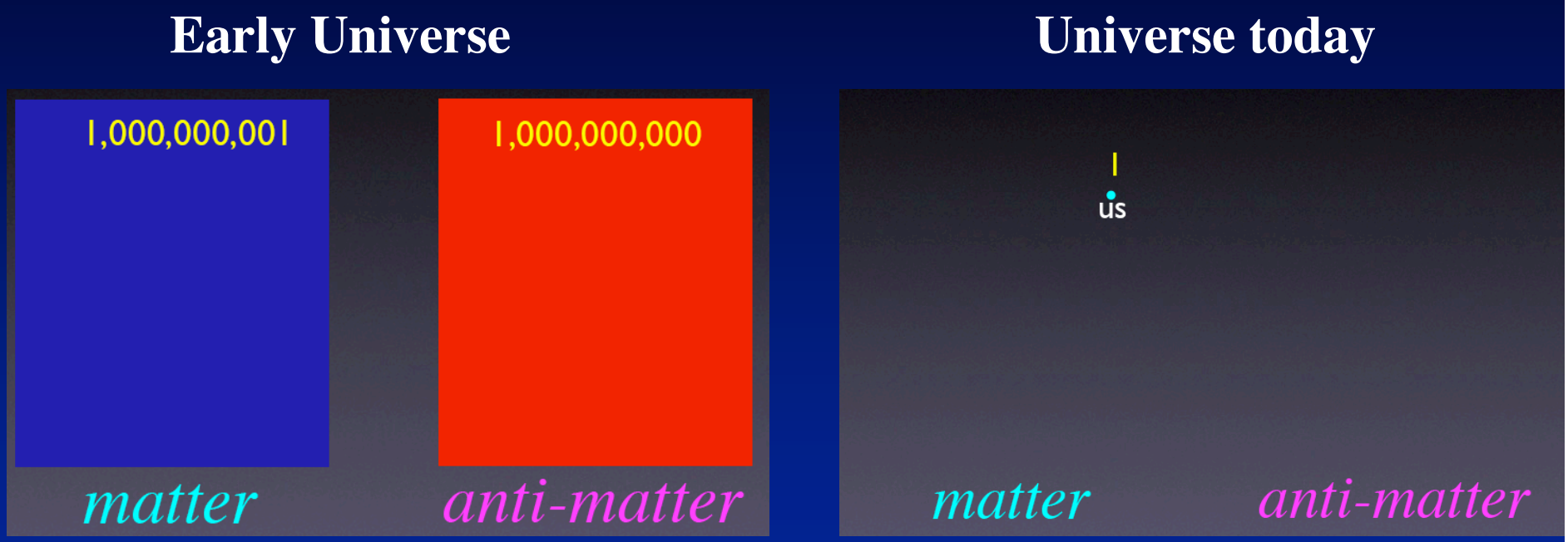




Standard Model only accounts for 20% of the matter of the Universe

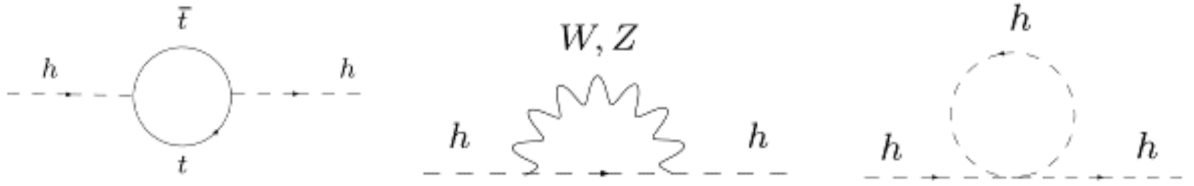
$$\frac{\text{matter}}{\text{all atoms}} = 5.70^{+0.39}_{-0.61}$$

Problem II:
Where did all the Antimatter go?



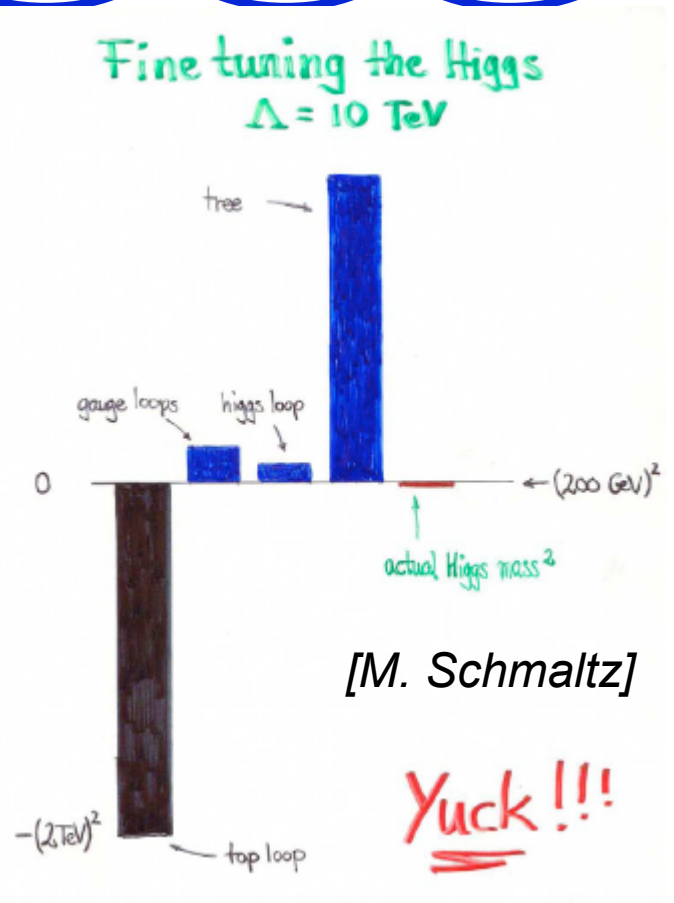
- **Not explained by Standard Model**

Problem III: Hierarchy Problem



$$m^2_H \approx (200\ \text{GeV})^2 = m^2_H{}^{\text{tree}} + \delta m^2_H{}^{\text{top}} + \delta m^2_H{}^{\text{gauge}} + \delta m^2_H{}^{\text{higgs}}$$

- **Why is gravity so weak?**
  - M_W/M_{Planck} ~10^{16} or G_F/G_N~10^{32}!
  - Free parameter $m^2_H{}^{tree}$ needs to be "finetuned" to cancel huge corrections
- Can be solved by presence of **new particles at M ~1 TeV**
  - Already really bad for M~10 TeV

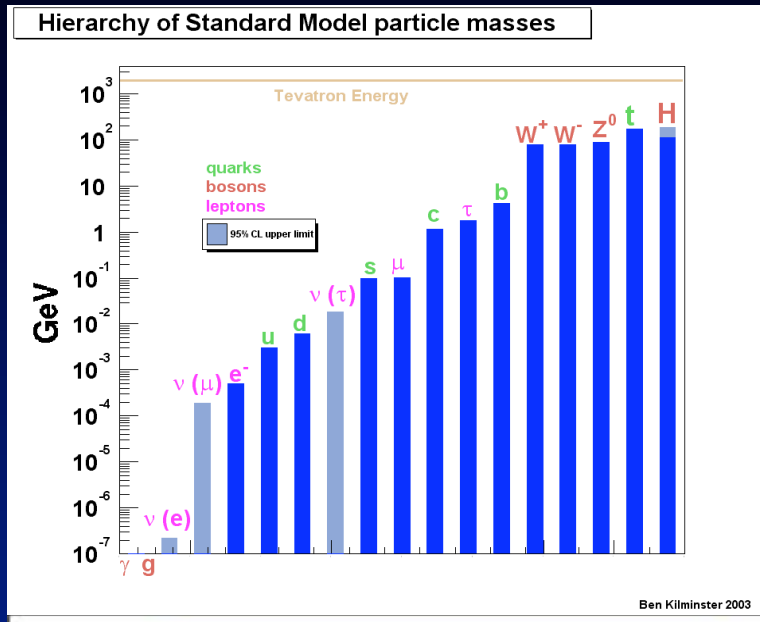


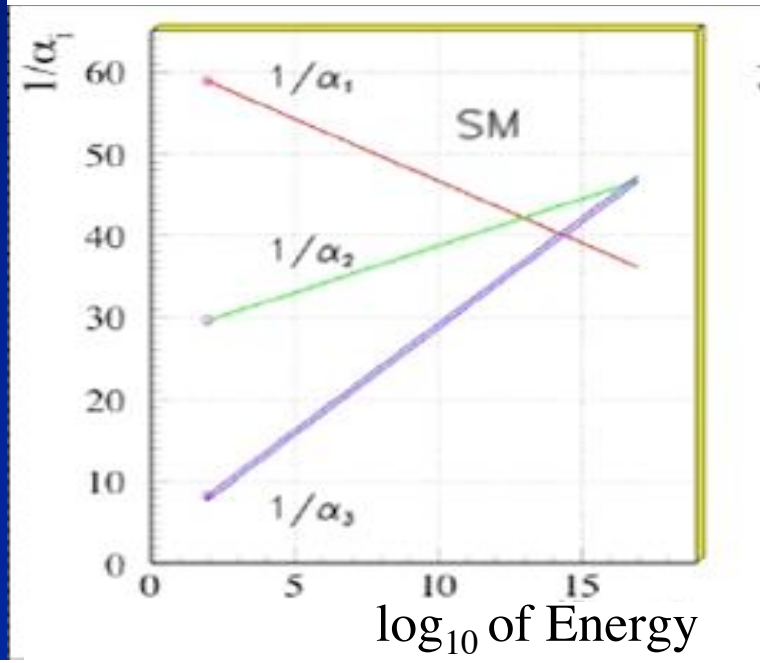
[M. Schmaltz]

(Some) More Problems …

- **Matter:**
  - SM cannot explain **number of fermion generations**
  - or their **large mass hierarchy**
    - m_{top}/m_{up}~100,000
- **Gauge forces:**
  - electroweak and strong **interactions do not unify** in SM
  - SM has no concept of **gravity**
- **Higgs boson:**
  - Has not yet been found: m_H=?
- **What is Dark Energy?**

Supersymmetry (SUSY) can solve some of these problems

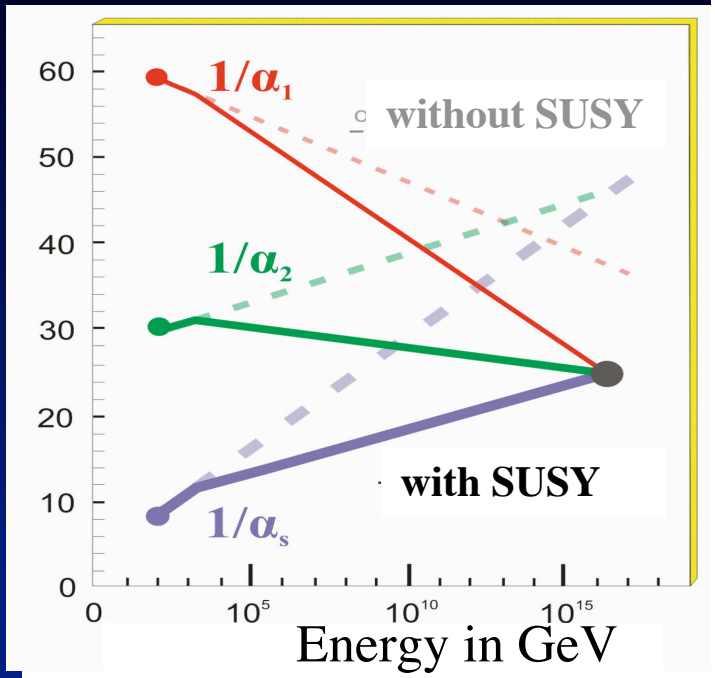


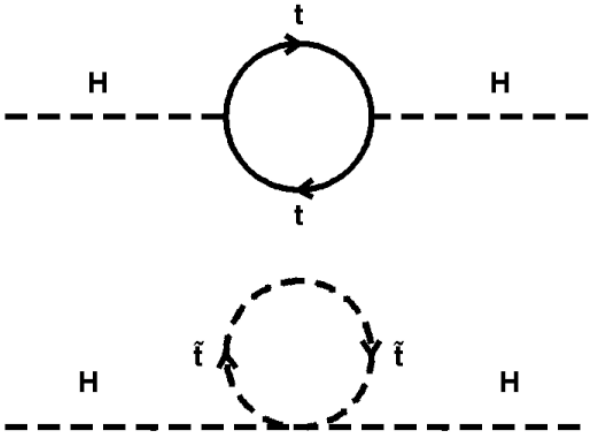


SUSY can solve some problems

- Supersymmetry (SUSY)
  - Each SM particle gets a partner differing in spin by 1/2
- Unifications of forces possible
  - SUSY changes running of couplings
- Dark matter candidate exists:
  - The lightest neutral partner of the gauge bosons
- No (or little) fine-tuning required
  - Radiative corrections to Higgs acquire SUSY corrections
    - Cancellation of fermion and sfermion loops

Mass of supersymmetric particles must not be too high (~TeV)





Already happened in History!

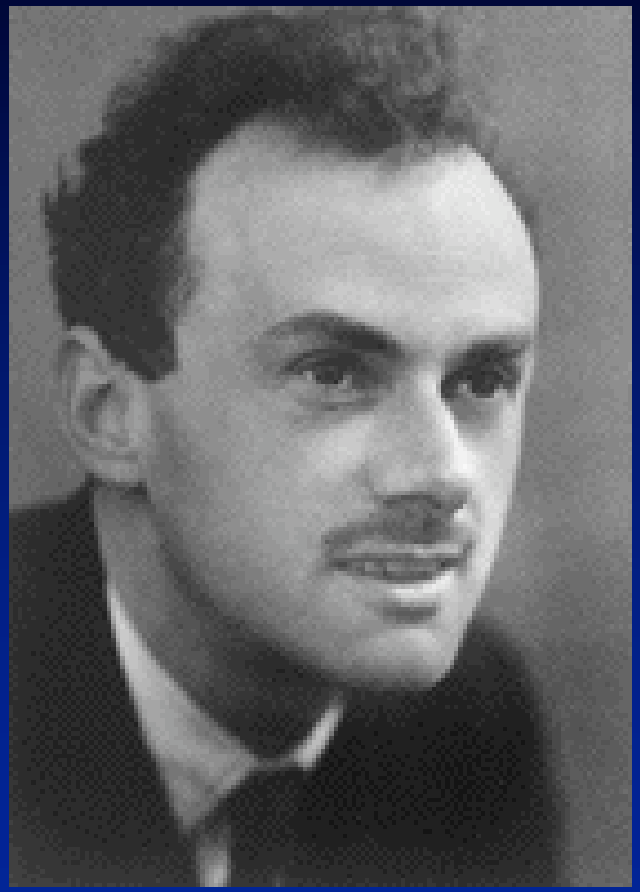
- Analogy in electromagnetism: *[H. Murayama]*
  - Free electron has Coulomb field: $\Delta E_{\text{Coulomb}} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_e}.$
  - Mass receives corrections due to Coulomb field:
    - $(m_e c^2)_{obs} = (m_e c^2)_{bare} + \Delta E_{\text{Coulomb}}.$
    - With r_e<10^{-17} cm: $0.000511 = (-3.141082 + 3.141593)\ \text{GeV}.$
  - Solution: the positron!

$$\Delta E = \Delta E_{\text{Coulomb}} + \Delta E_{\text{pair}} = \frac{3\alpha}{4\pi} m_e c^2 \log\frac{\hbar}{m_e c r_e}\ .$$

<<$m_e c^2$

Problem was not as bad as today's but solved by new particles: anti-matter

Paul Dirac's View of History



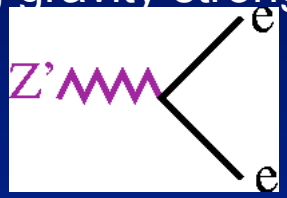
When I first thought of the idea I thought that this particle would have to have the same mass as the electron, because of the symmetry between positive and negative masses and energies which occurs all the way through this theory. But at that time the only elementary particles that were known were the electron and the proton. I didn't dare to postulate a new particle. The whole climate of opinion in those days was against postulating new particles, quite different from what it is now. So I published my work as a theory of electrons and protons, hoping that in some unexplained way the Coulomb interaction between the particles would lead to the big difference in mass between the electron and the proton.

Of course I was quite wrong there and the mathematicians soon pointed out that it was impossible to have such a dissymmetry between the positive and negative energy states. It was Weyl who first published a categorical statement that the new particle would have to have the same mass as the electron. The theory with equal masses was confirmed a little later by observation when the positron was discovered by Anderson.

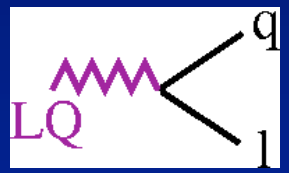
Beyond Supersymmetry

- **Strong theoretical prejudices for SUSY being true**
  - But so far there is a lack of SUSY observation….

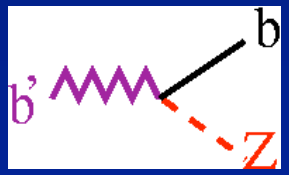
- **Need to keep an open eye for e.g.:**
  - **Extra spatial dimensions:**
    - Addresses hierarchy problem by making gravity strong at TeV scale
  - **Extra gauge groups: Z', W'**
    - Occur naturally in GUT scale theories



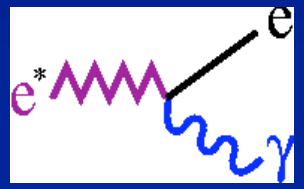
  - **Leptoquarks:**
    - Would combine naturally the quark and lepton sector



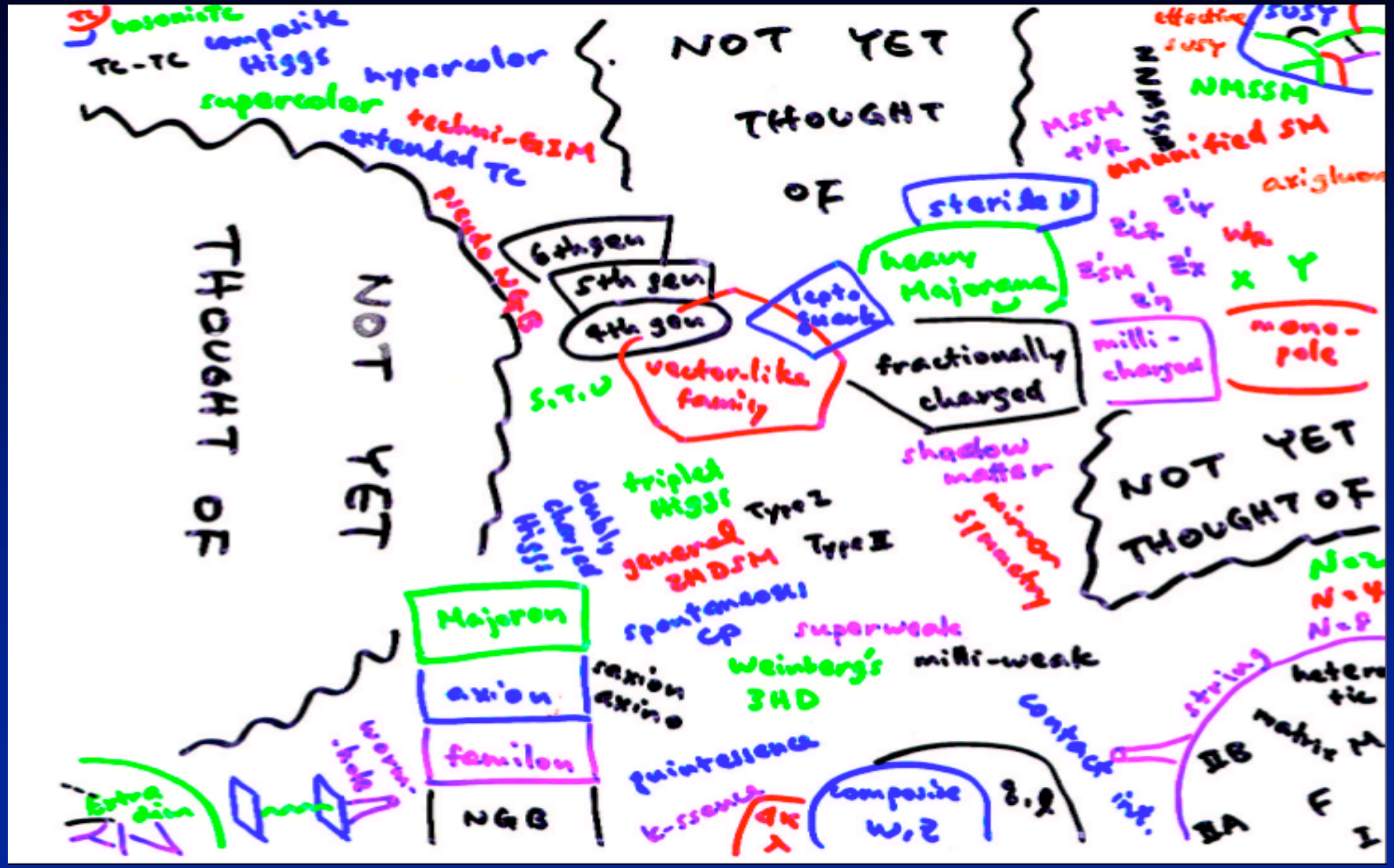
  - **New/excited fermions**
    - More generations? Compositeness?



  - **Preons:**
    - atom⇒nucleus ⇒ proton/neutron ⇒ quarks ⇒ preons?
  - **… ????:** something nobody has thought of yet

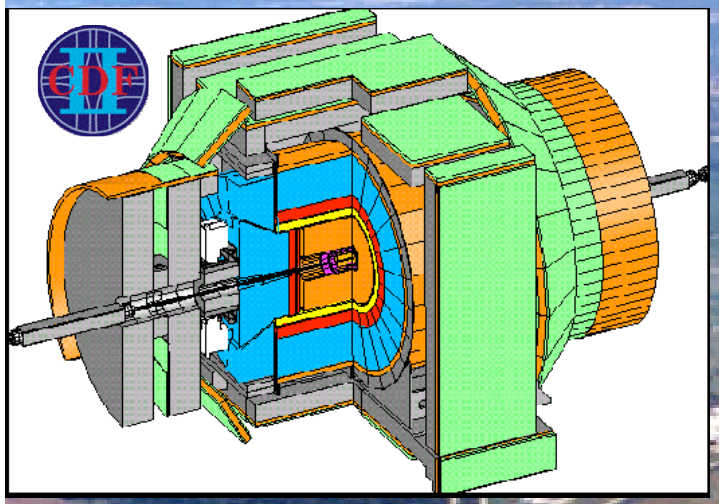


Confusion among Theorists?



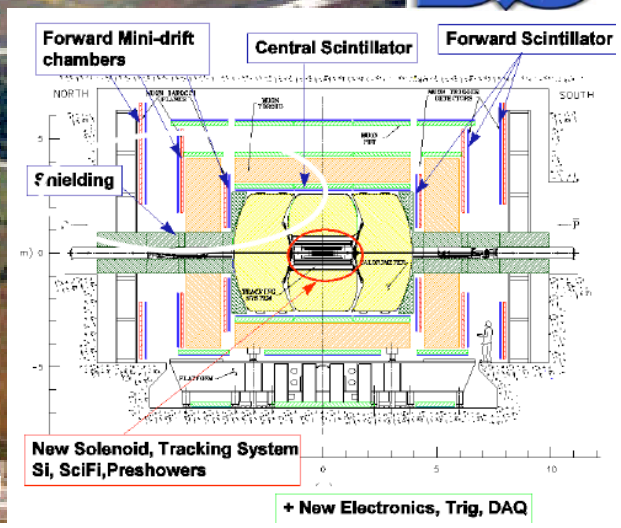
[Hitoshi Murayama]

Tevatron Run II

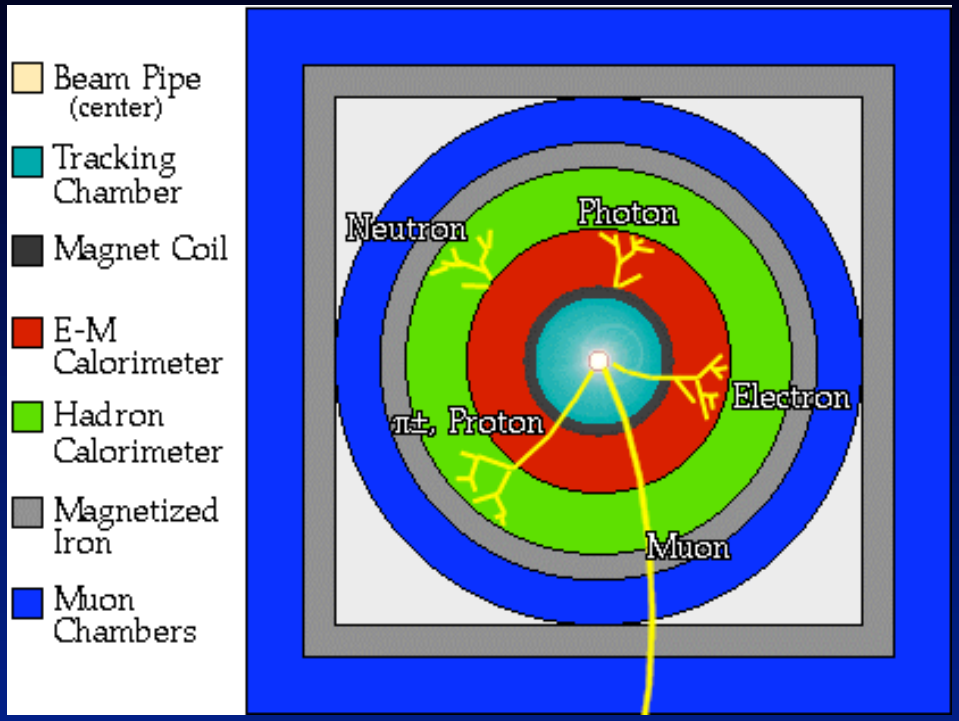


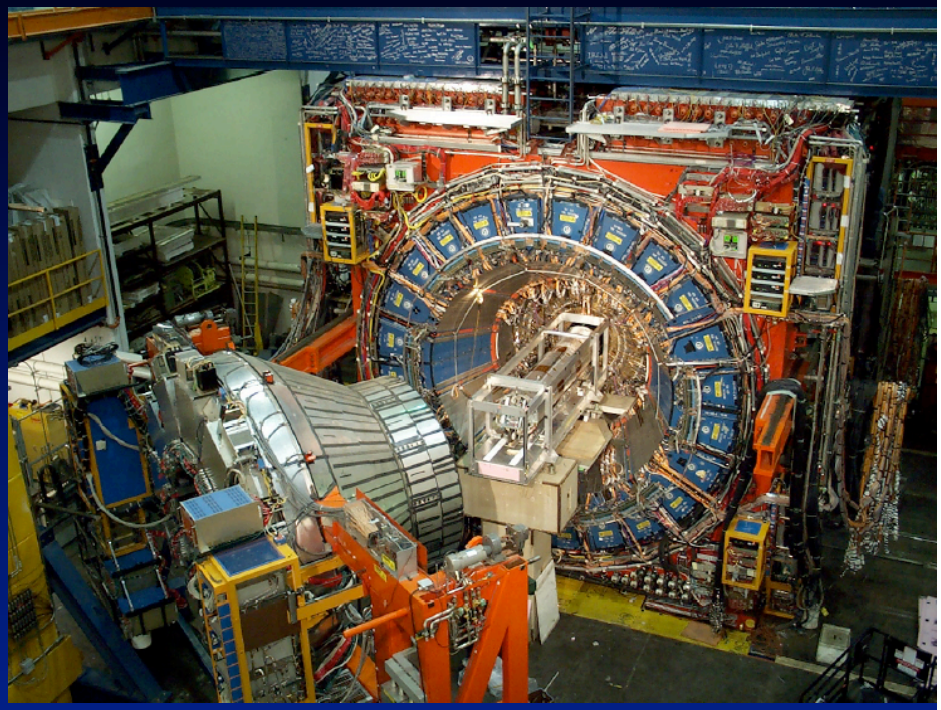
$\sqrt{s}$=1.96 TeV

p $\bar{p}$



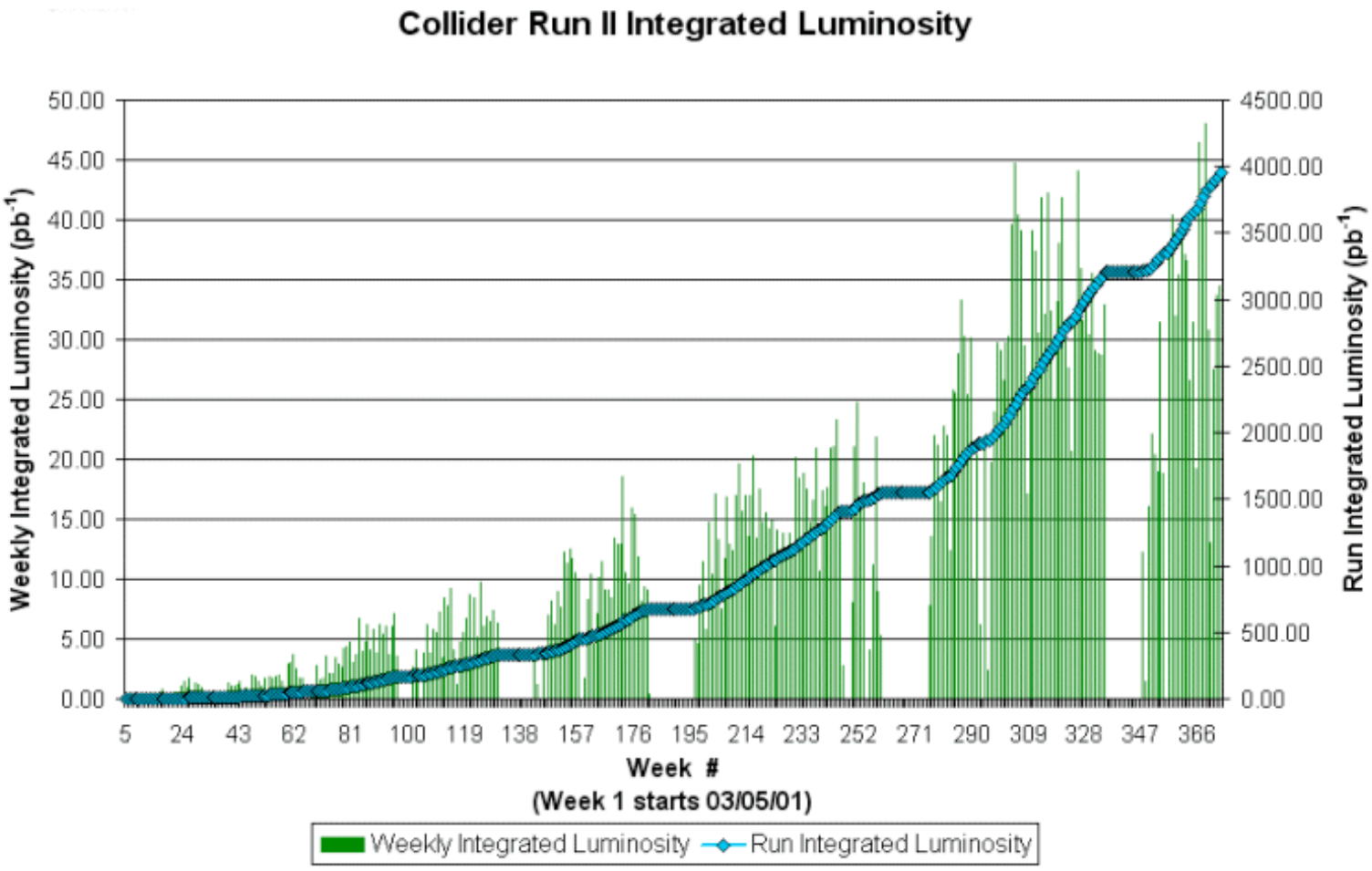
CDF and DØ Detectors





- **Multi-purpose detectors arranged like an onion around collision:**
  - Tracking system inside magnetic field:
    - measure momenta and charge of charged particles
  - Electromagnetic and hadronic calorimeters
    - Energies of electrons, photons and jets (quarks)
  - Muon detector
    - Identification (and momentum measurement) of muons
- **About 1 million separate readout channels per detector**

Tevatron Luminosity

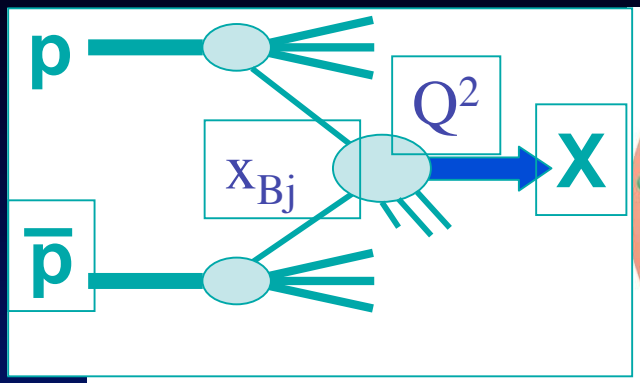


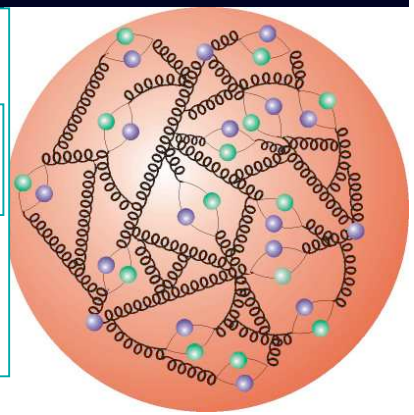
Results shown today: $\int Ldt$=1-2.5 fb^{-1}

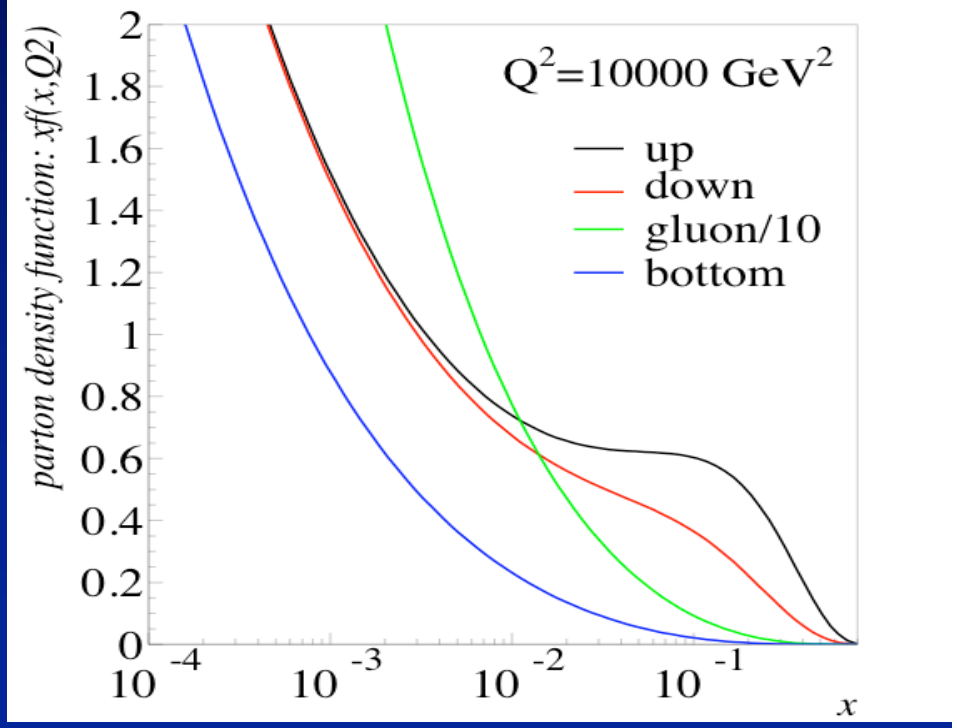
The Proton

- It's complicated:
  - Valence quarks
  - Gluons
  - Sea quarks
- Exact mixture depends on:
  - Q^2: ~$(M^2+p_T^2)$
  - x_{Bj}: fractional momentum carried by parton
- Hard scatter process:

$$\hat{s} = x_p \cdot x_{\bar{p}} \cdot s$$

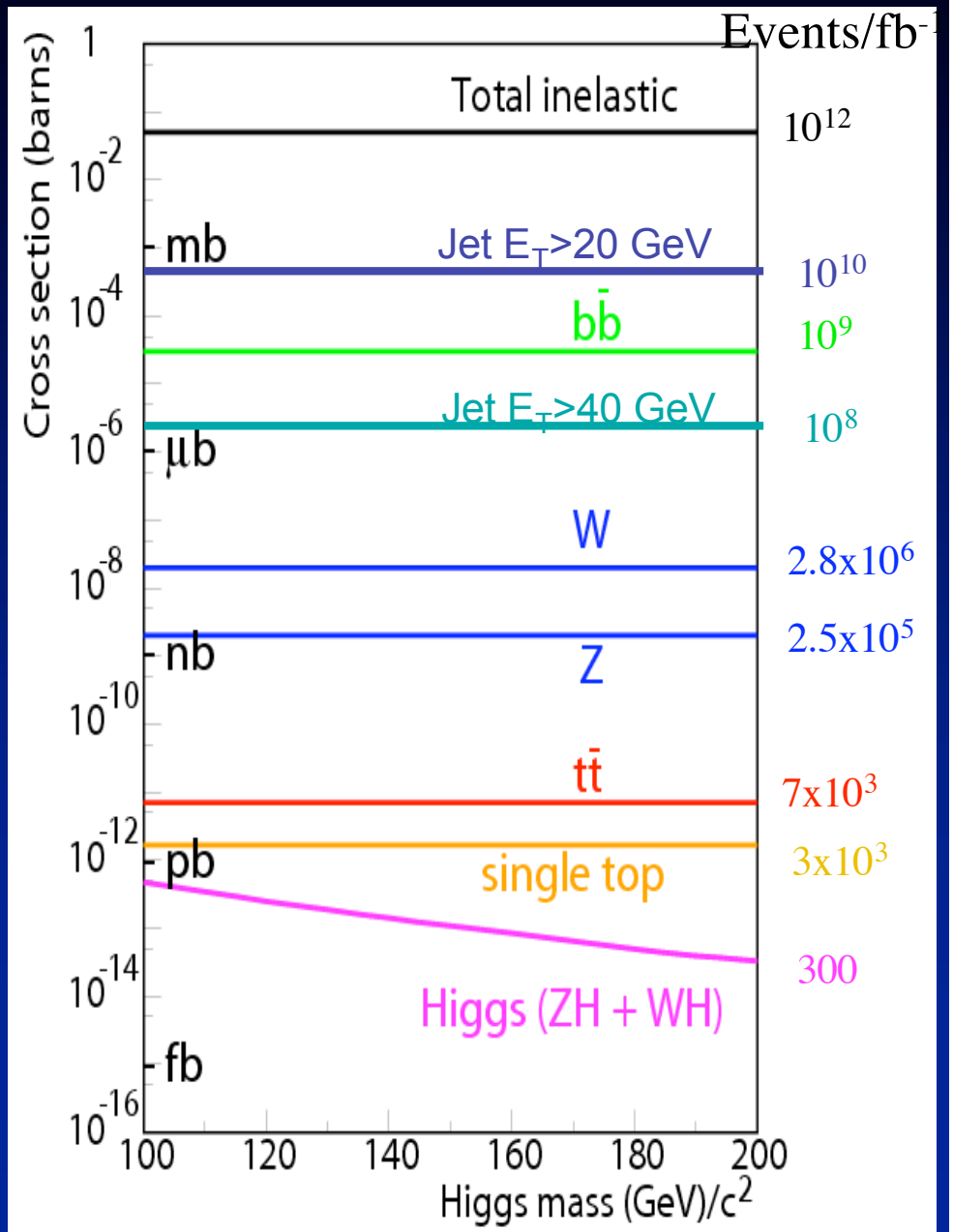




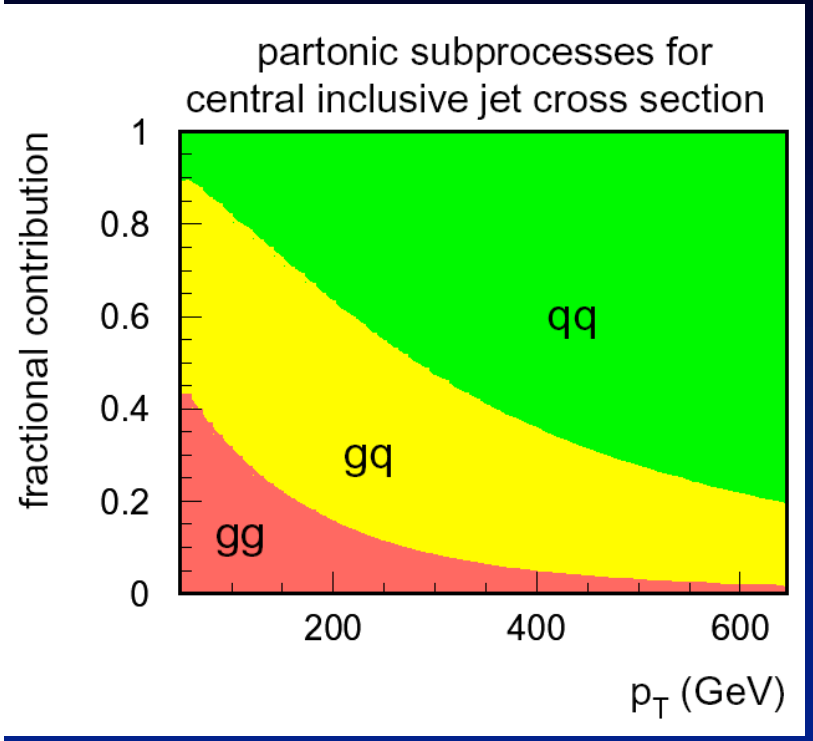


Processes and Cross Sections

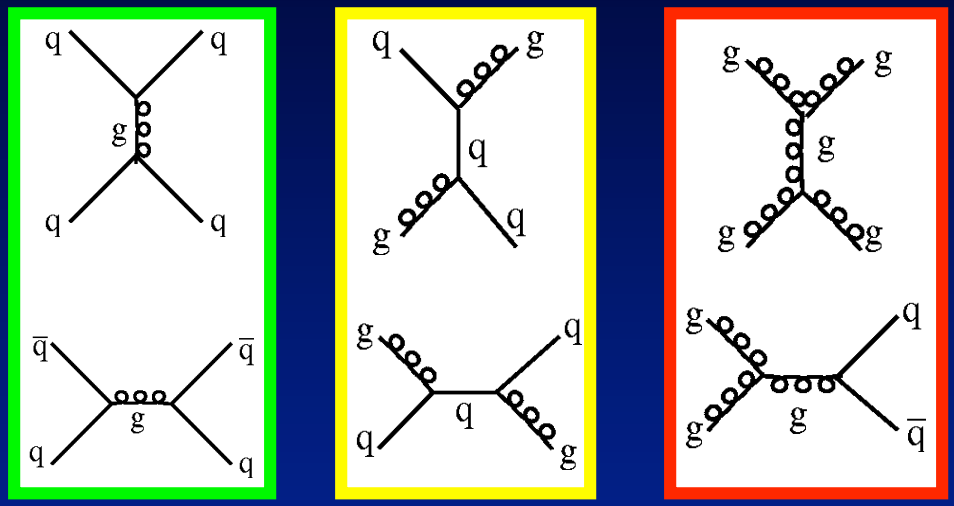
- Cross section:
  - Total inelastic cross section is huge
    - Used to measure luminosity
- Rates at e.g. $L=1x10^{32}$ $cm^{-2}s^{-1}$
  - Total inelastic: 70 MHz
  - bb: 42 kHz
  - Jets with E_T>40 GeV: 300 Hz
  - W: 3 Hz
  - Top: 25/hour
- Tricky to select the interesting events
  - Mostly fighting generic jets!



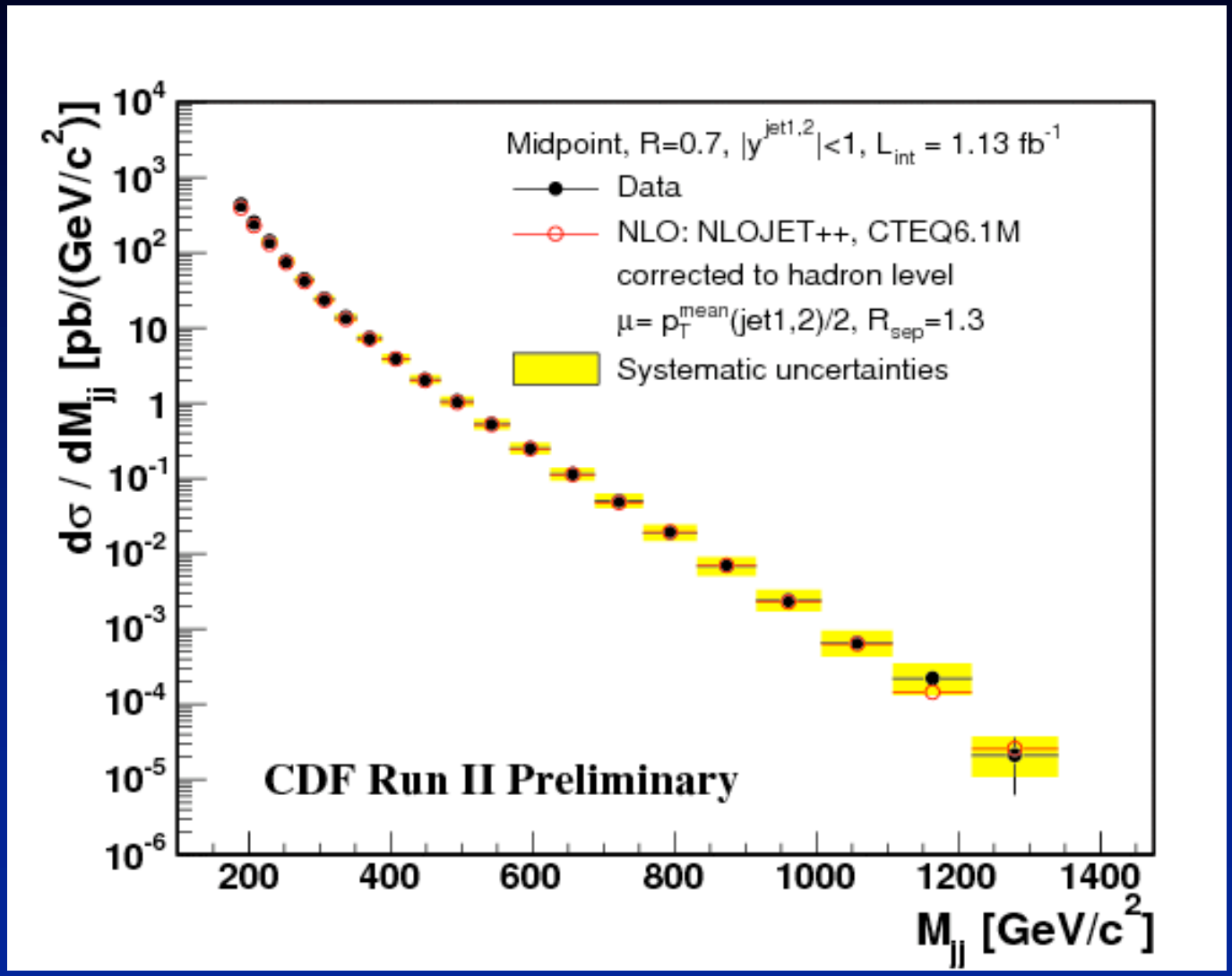
Jet Cross Sections



Inclusive jets:
processes qq, qg, gg

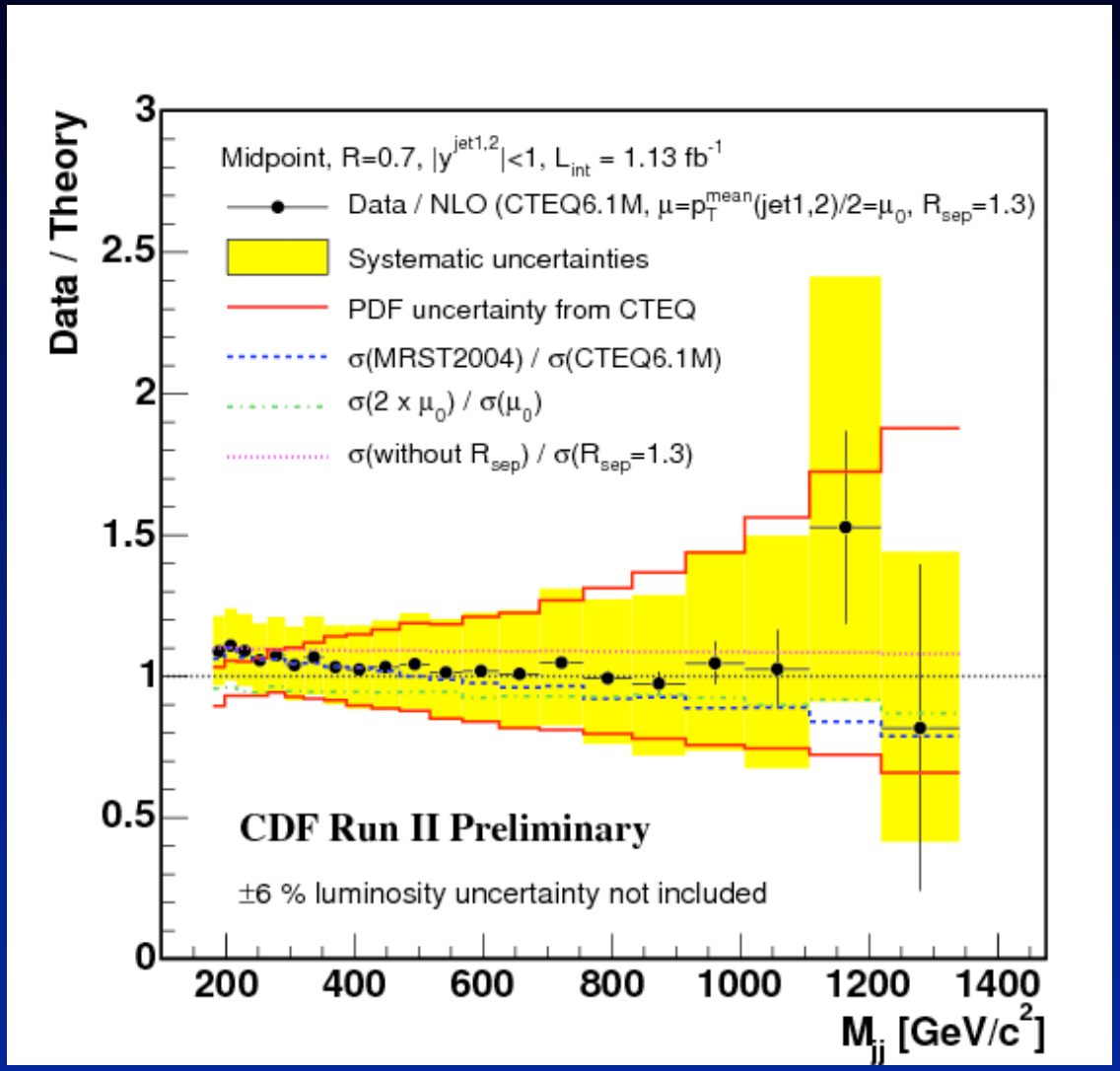


Di-Jet Cross Section



Probe $Q^2 \sim 10^6$ GeV^2 ⇔ distances of 10^{-18} m

Di-Jet Cross Section



Agreement with theory over full mass range

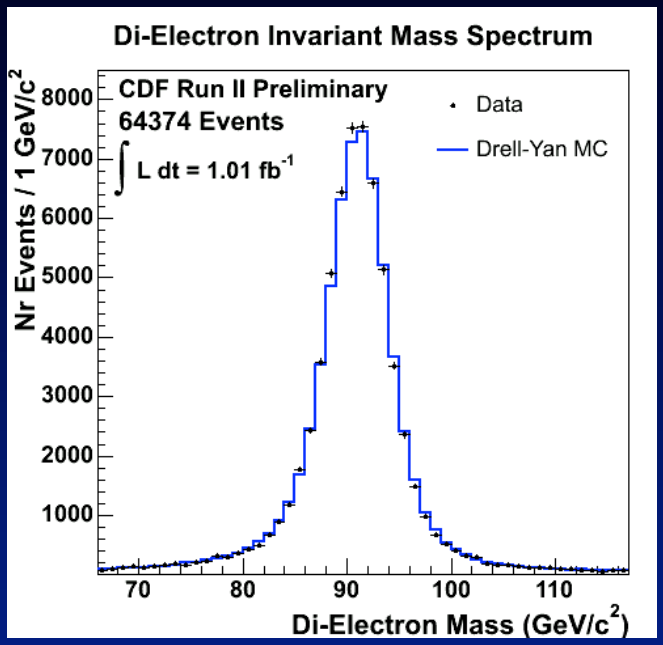
W's and Z's

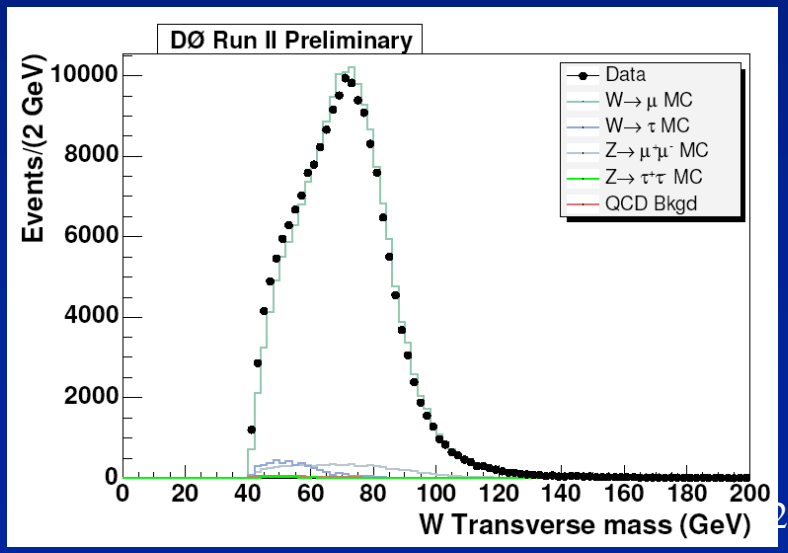
- Z mass reconstruction
  - Invariant mass of two leptons

$$m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

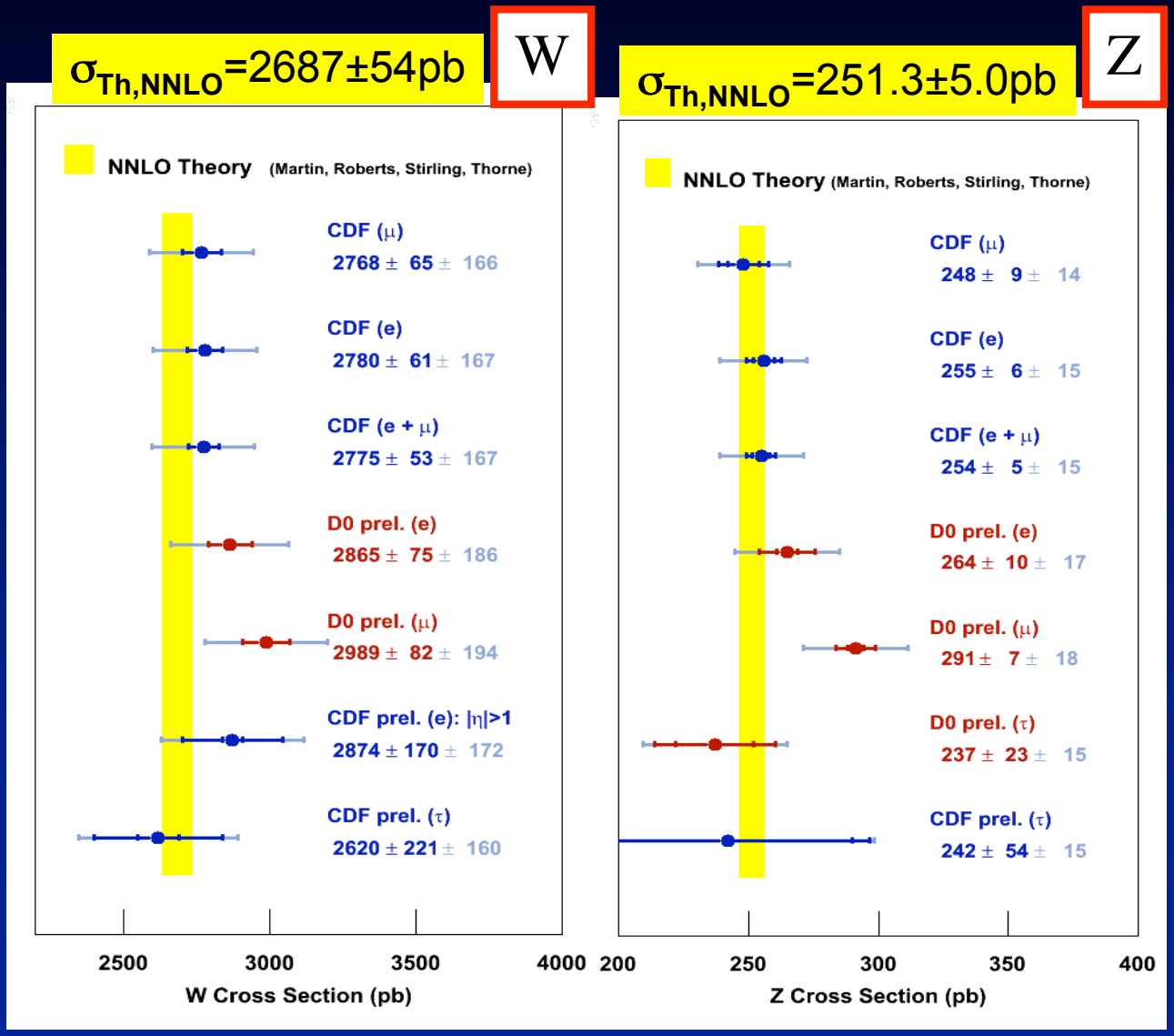
- W mass reconstruction
  - Do not know neutrino p_z
  - No full mass resonstruction possible
  - Transverse mass:

$$m_T = \sqrt{|p_T^\ell|^2 + |p_T^\nu|^2 - (\vec{p}_T^{\,\ell} + \vec{p}_T^{\,\nu})^2}$$





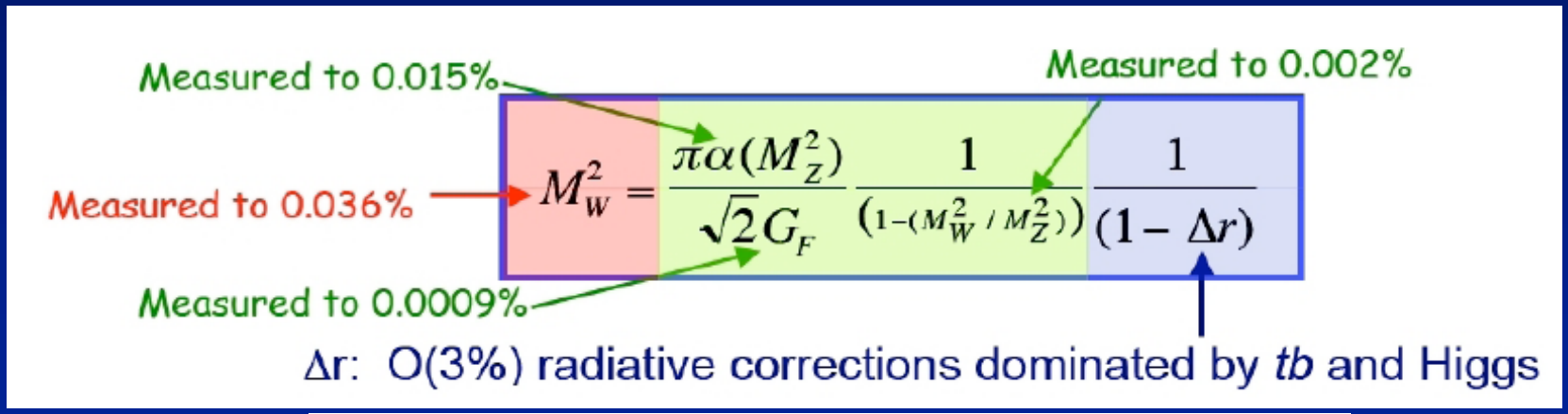
W and Z Cross Section Results

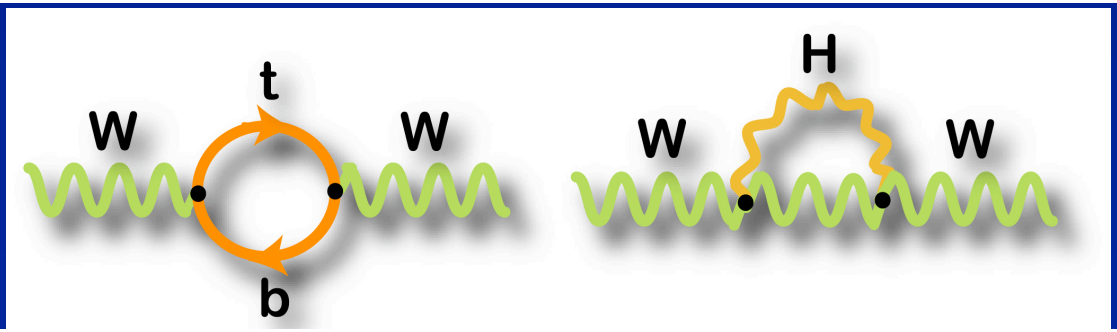


Data agree with theory to 2% precision

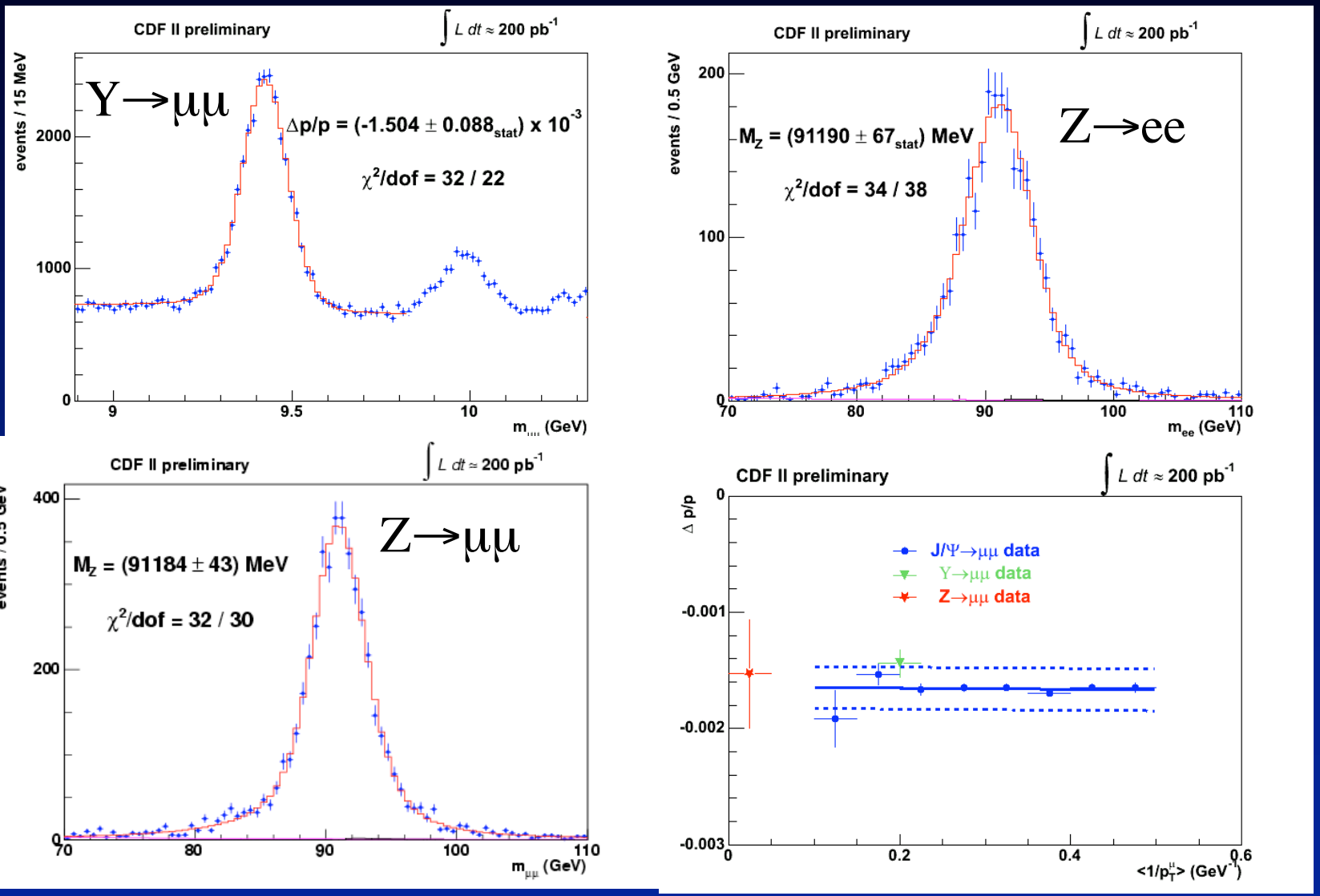
The Electroweak Precision Data

- **Precision measurements of**
  - muon decay constant (G_F) and fine structure constant (α)
  - Z boson mass and properties (LEP,SLD)
  - W boson mass (LEP+Tevatron)
  - Top quark mass (Tevatron)



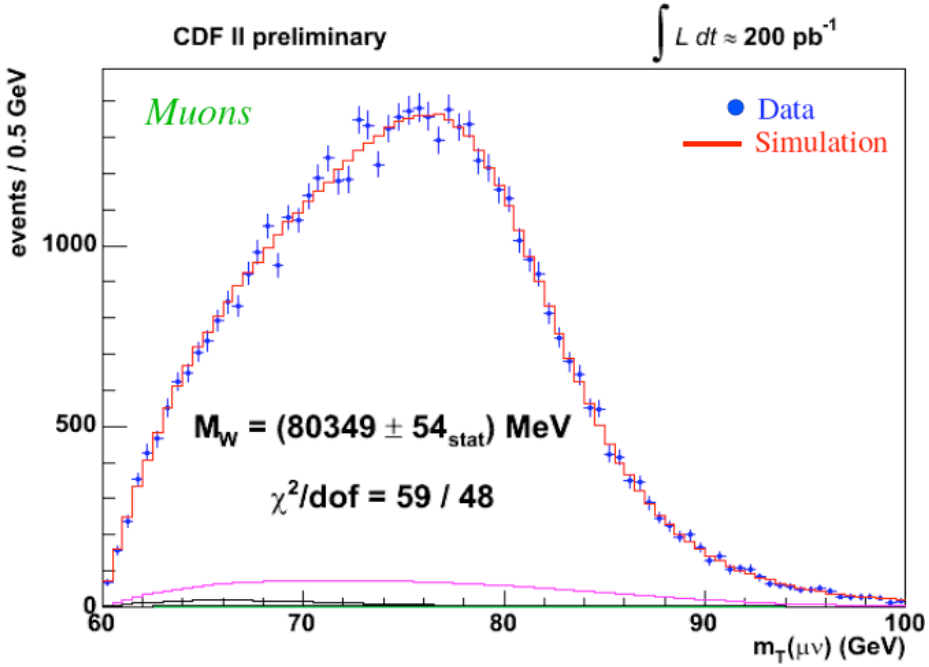


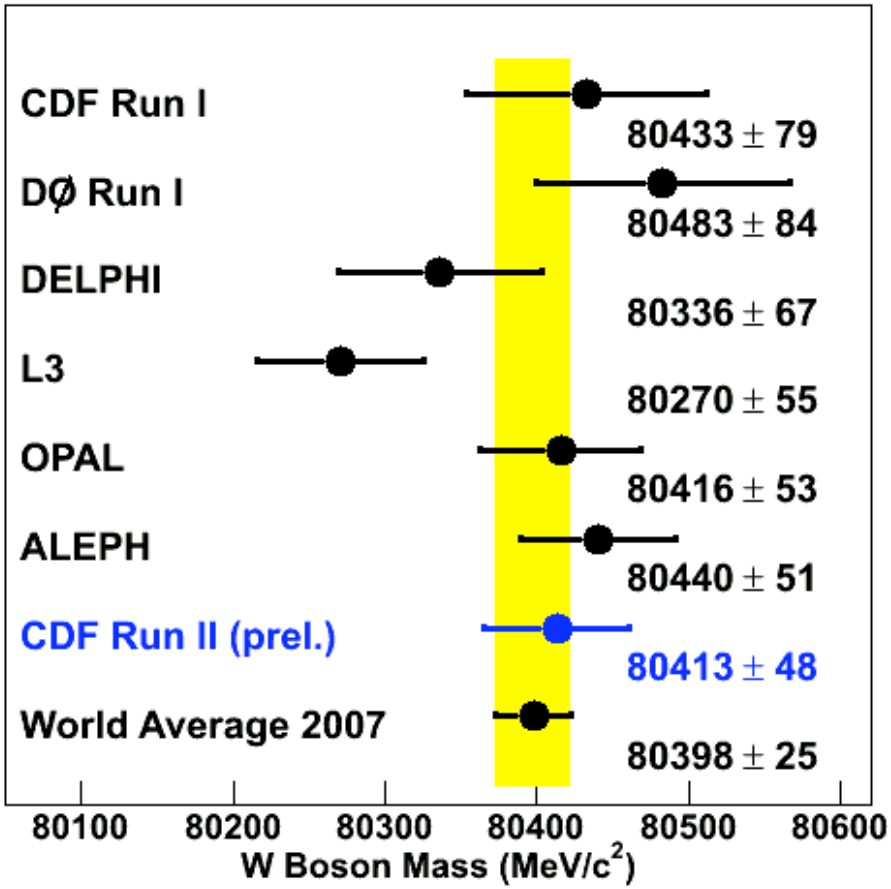
Lepton Energy Scale and Resolution



Systematic uncertainty on momentum scale: 0.04%

W Boson Mass



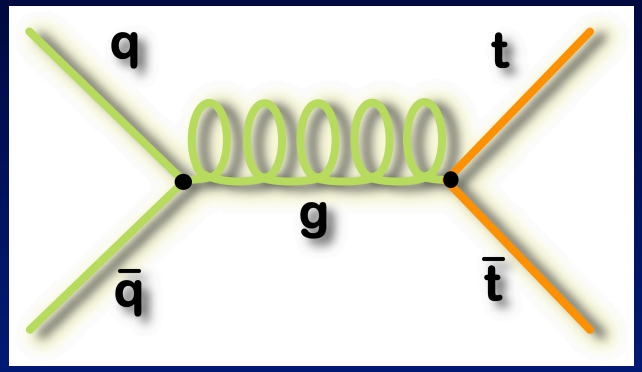


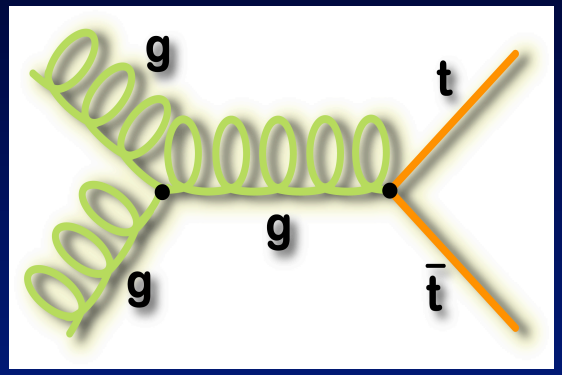
M_W=80398 ± 25 MeV

Top Quark

- **Mainly produced in pairs via the strong interaction**

85%

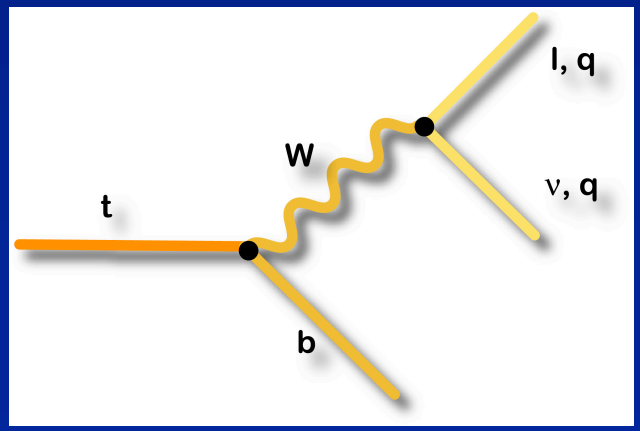




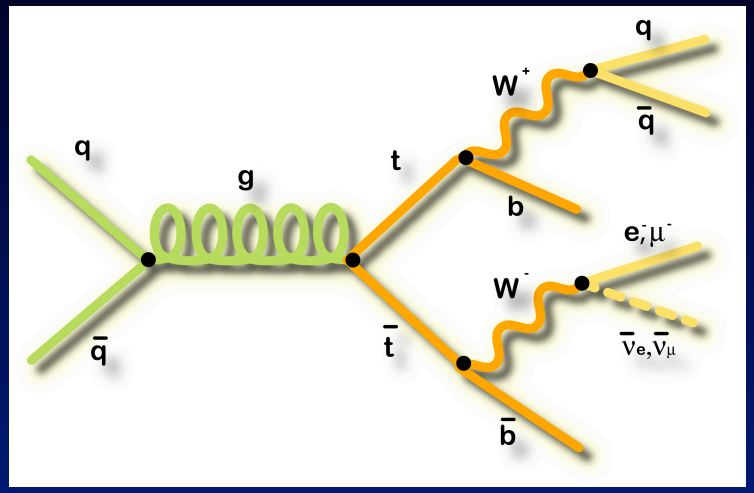
15%

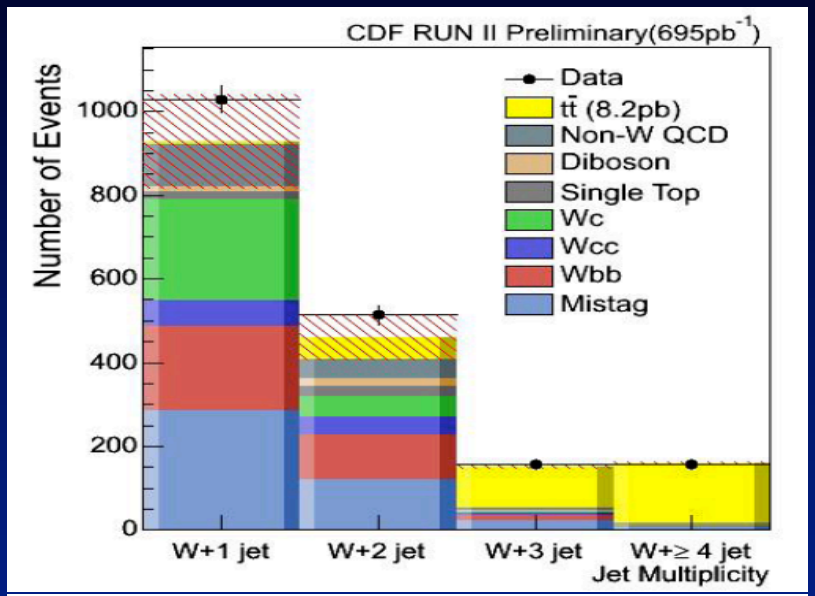
- **Decay via weak interaction**

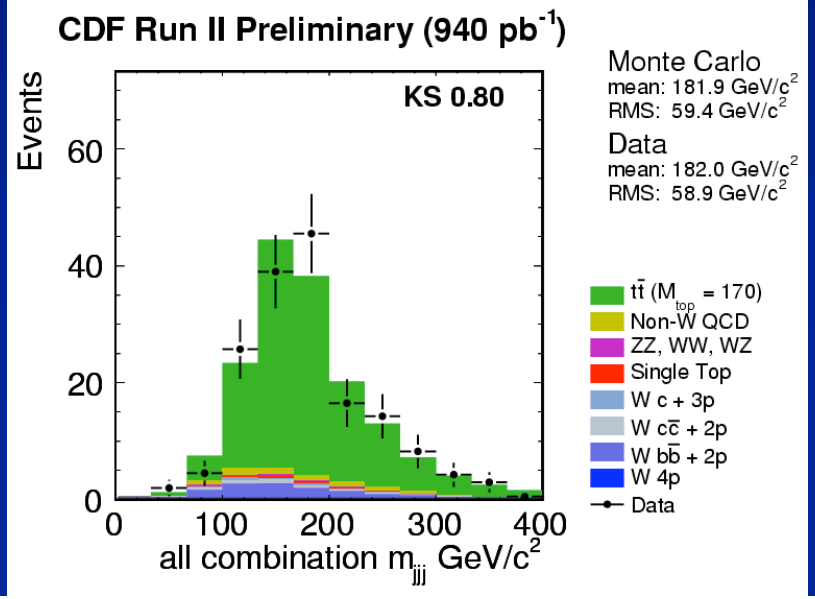
Br(t →Wb) ~ 100%



Top Quark Mass

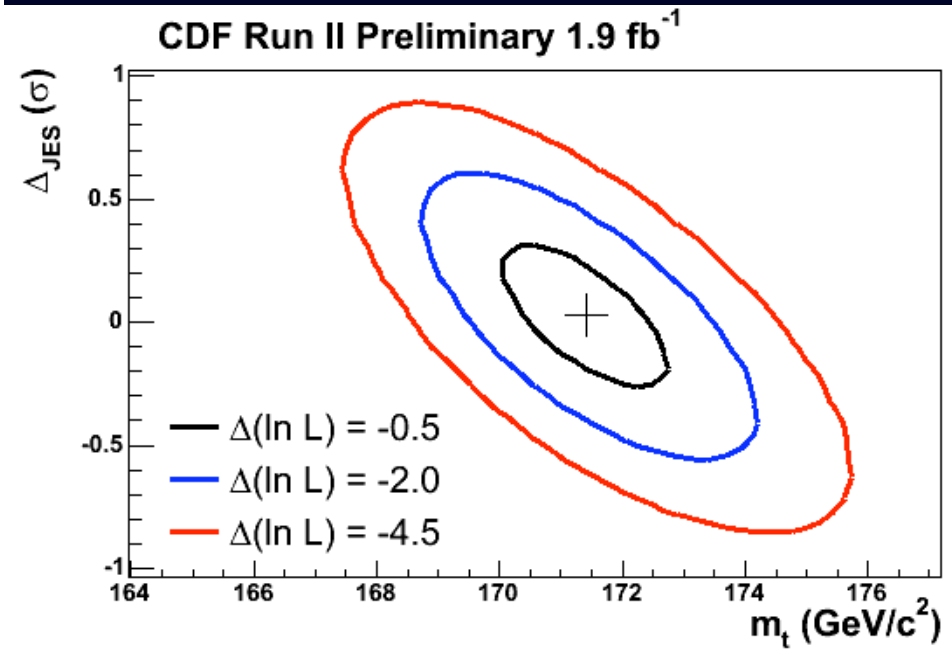


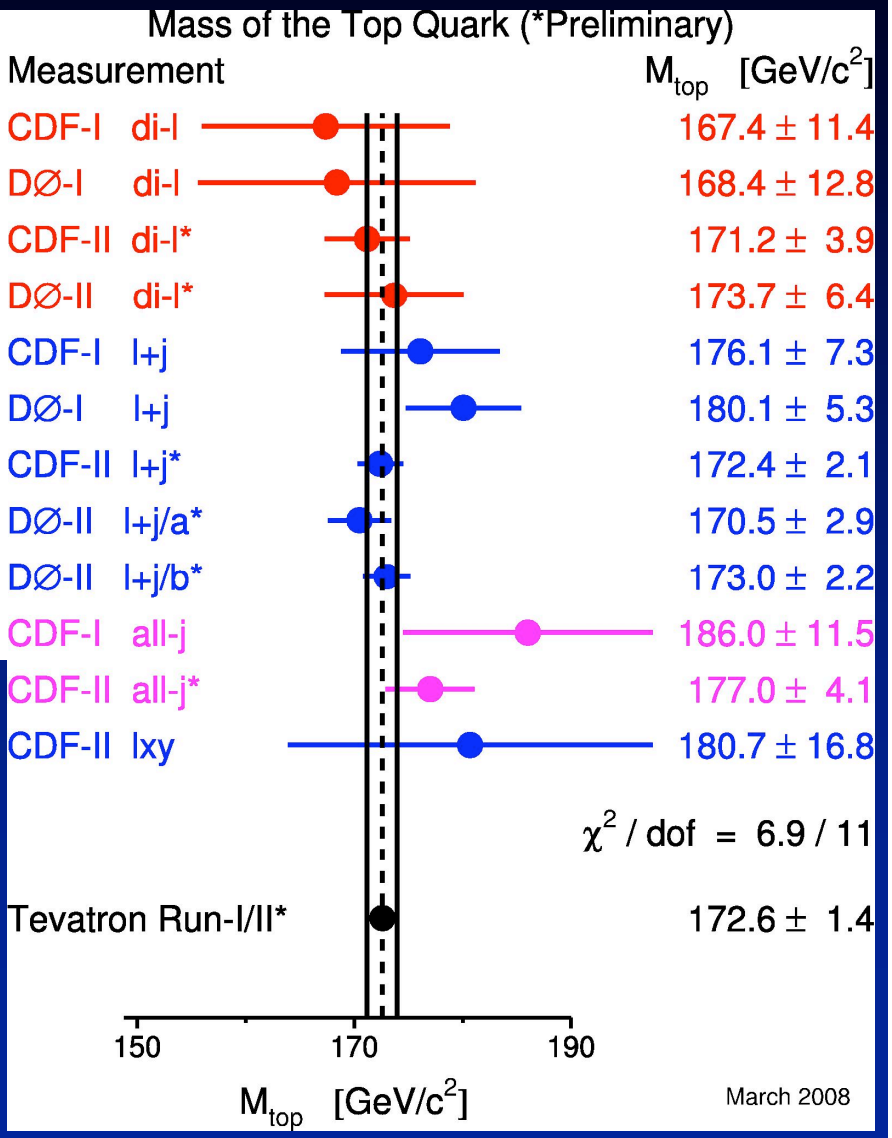




- Rather large pure samples available:
  - 371 events: S:B=5:1
- Perform simultaneous fit for
  - Top quark mass
  - Jet energy scale (M_W=M_{jj})
    - dominant systematic uncertainty

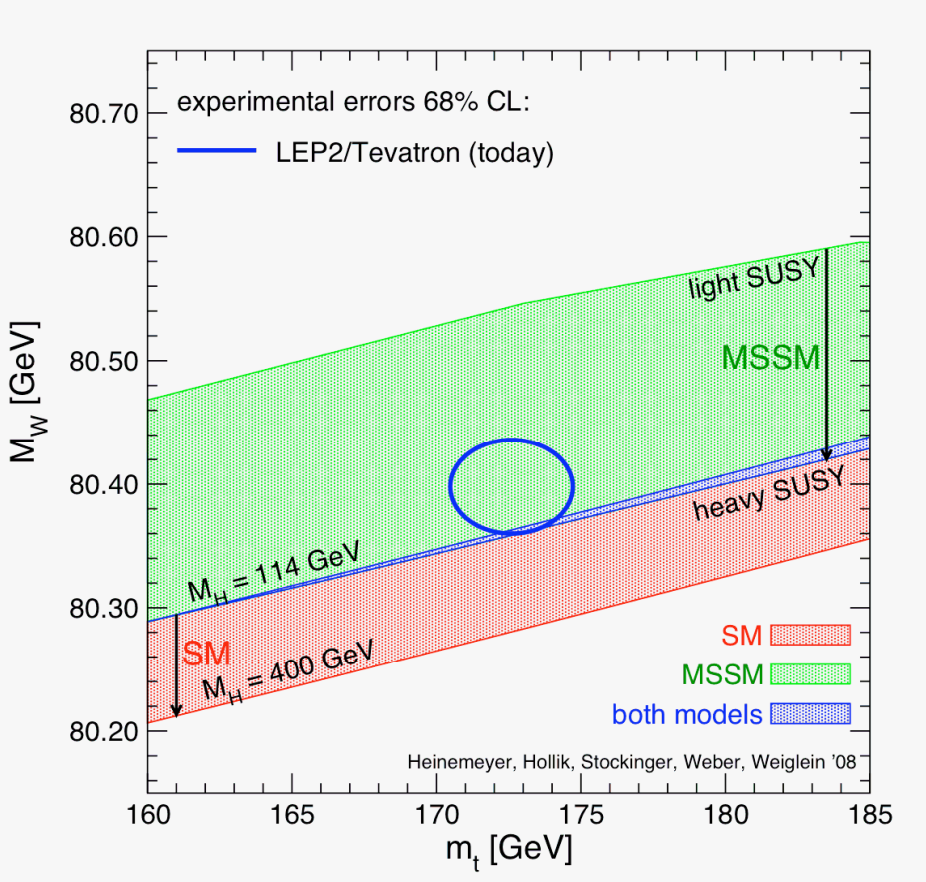
Mass of the Top Quark

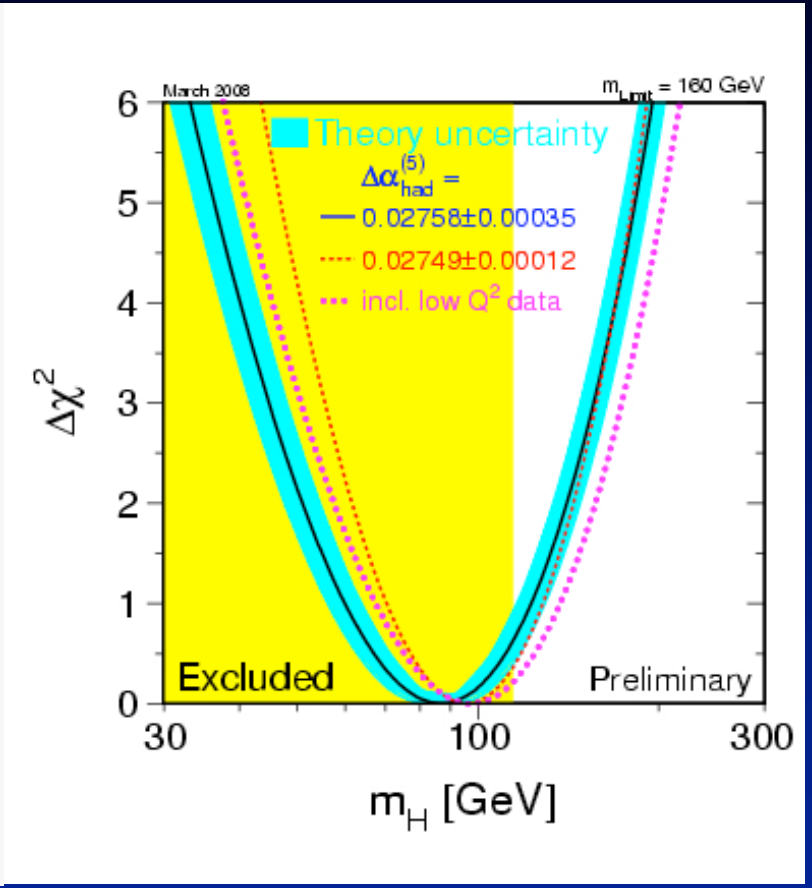




M_{top} = 172.6 +/- 1.4 GeV/c^2

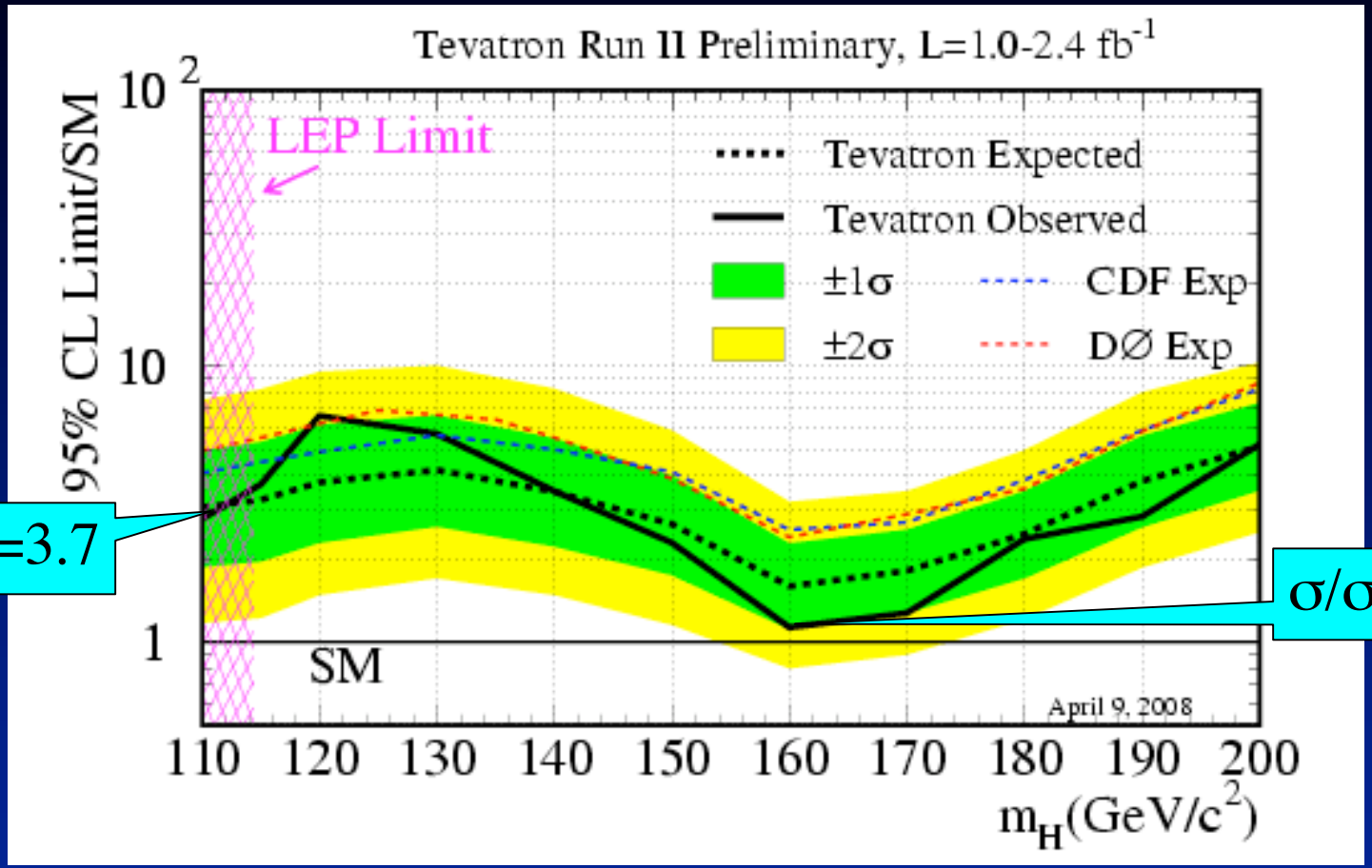
m_W, m_{top} and m_{Higgs}





- **Indirectly: m_H<160 GeV @ 95% CL**
  - **$m_H=87^{+36}_{-27}$ GeV**
- **Directly (LEP): m_H>114 GeV @ 95%CL**

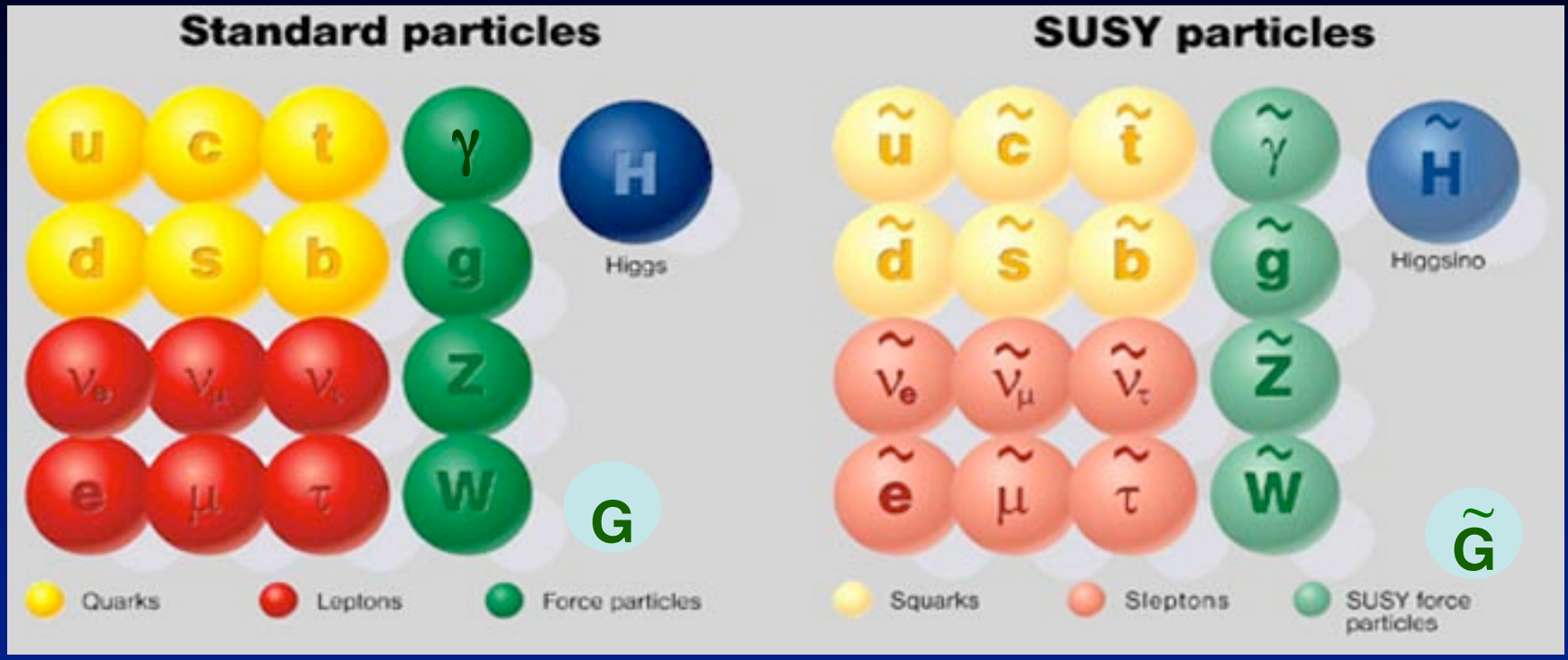
Direct Higgs Cross Section Limit



- **Ratio of limit to SM about 3.7 (1.1) for m_H=115 (160) GeV/c^2**
  - more data coming and experimental improvements ongoing
- **Can the Tevatron say anything before the LHC?**
  - Maybe this summer at high mass!

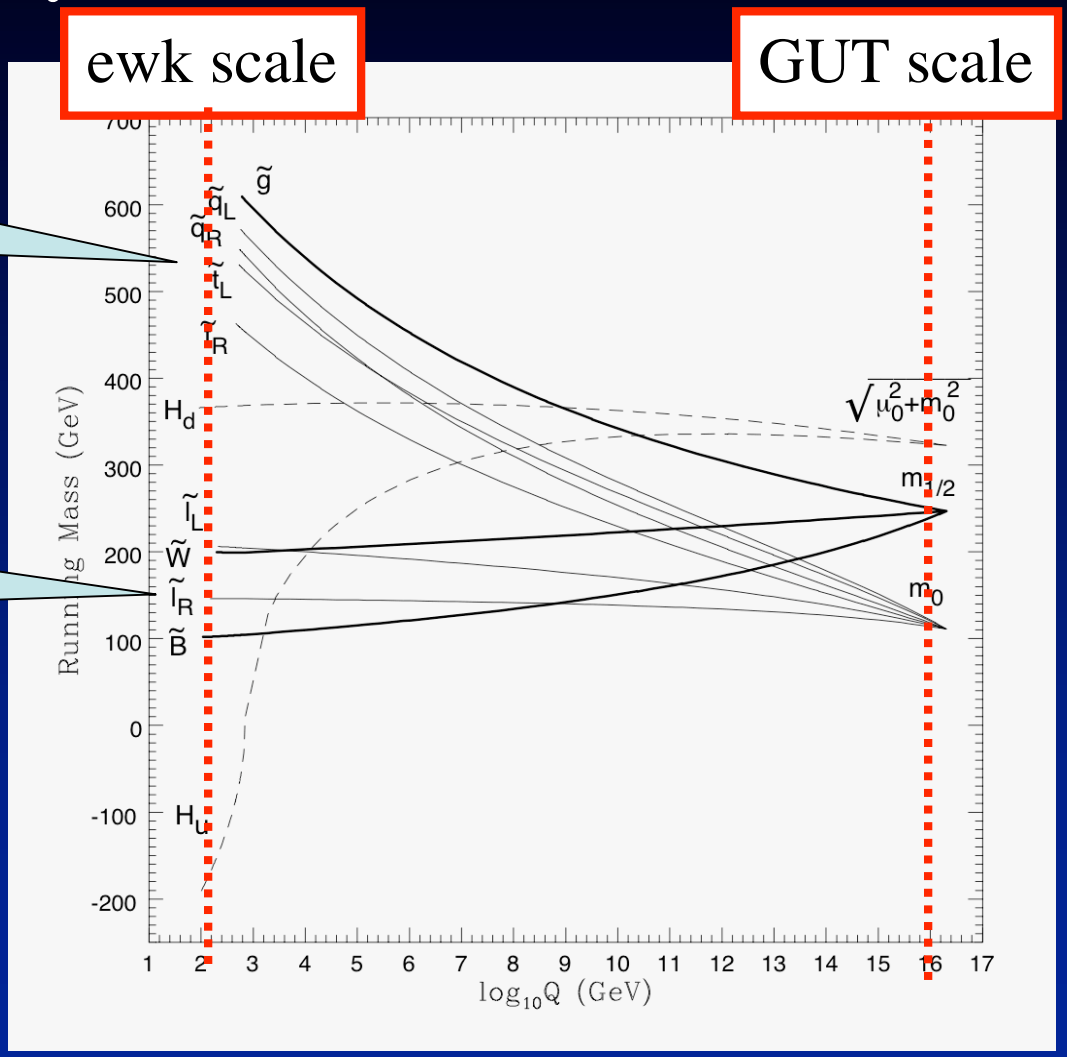
Searches for the Unknown

Supersymmetry (SUSY)



- **SM particles have supersymmetric partners:**
  - **Differ by 1/2 unit in spin**
    - **Sfermions (squarks, selectron, smuon, ...): spin 0**
    - **gauginos (chargino, neutralino, gluino,…): spin 1/2**
- **No SUSY particles found as yet:**
  - **SUSY must be broken: breaking mechanism determines phenomenology**
  - **More than 100 parameters even in "minimal" models!**

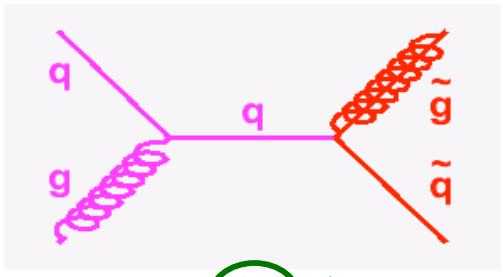
Mass Spectrum and Unification

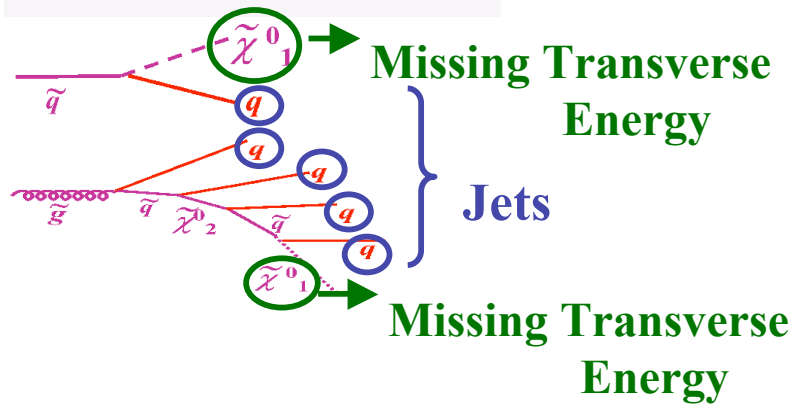


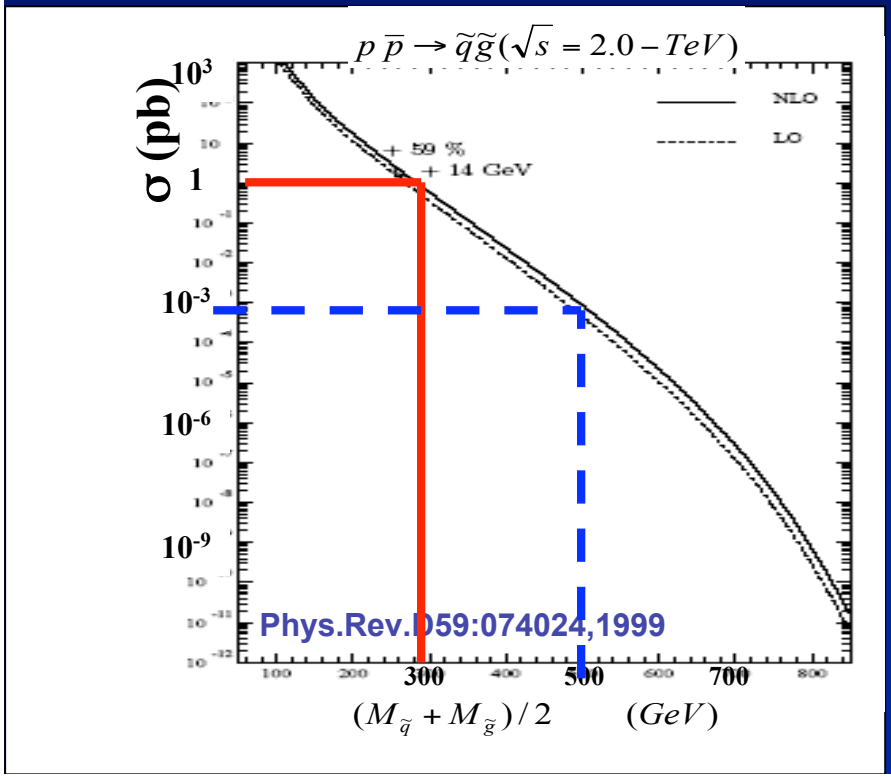
- Lightest SUSY particle ($\tilde{\chi}_1^0$) is Dark Matter candidate (if stable)
- Models predict mass relations: $M(\tilde{g}) \approx 3M(\tilde{\chi}_1^{\pm}) \approx 6M(\tilde{\chi}_1^0)$

Generic Squarks and Gluinos

- **Squark and Gluino production:**
  - Signature: jets and $\not{E}_t$



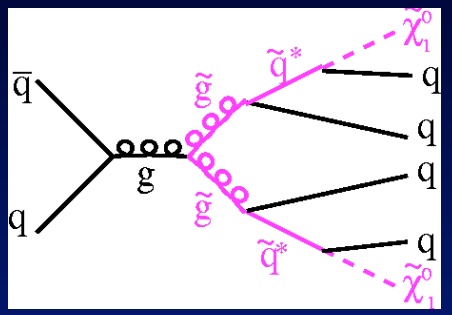


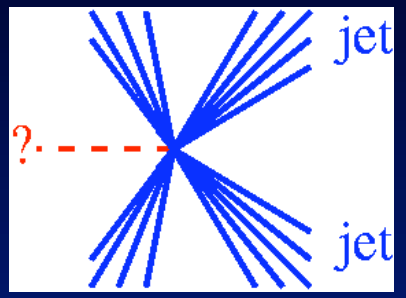


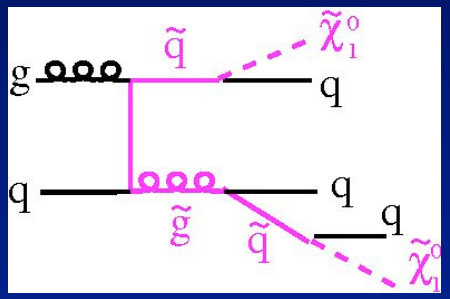
- **Strong interaction => large production cross section**
  - **for M(g̃) ≈ 300 GeV/c²:**
    - **1000 event produced/ fb⁻¹**
  - **for M(g̃) ≈ 500 GeV/c²:**
    - **1 event produced/ fb⁻¹**

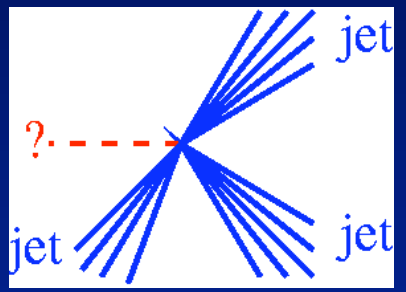
Signature depends on q and g Masses

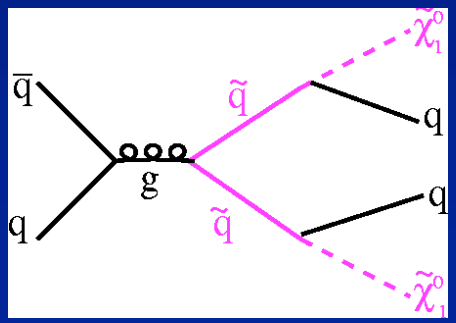
- Consider 3 cases:
  1. $m(\tilde{g})<m(\tilde{q})$
  2. $m(\tilde{g})\approx m(\tilde{q})$
  3. $m(\tilde{g})>m(\tilde{q})$

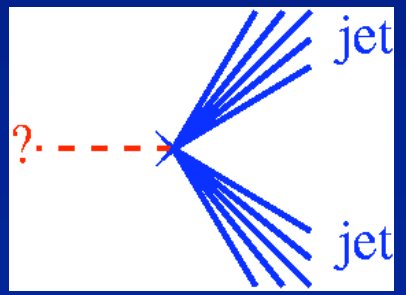






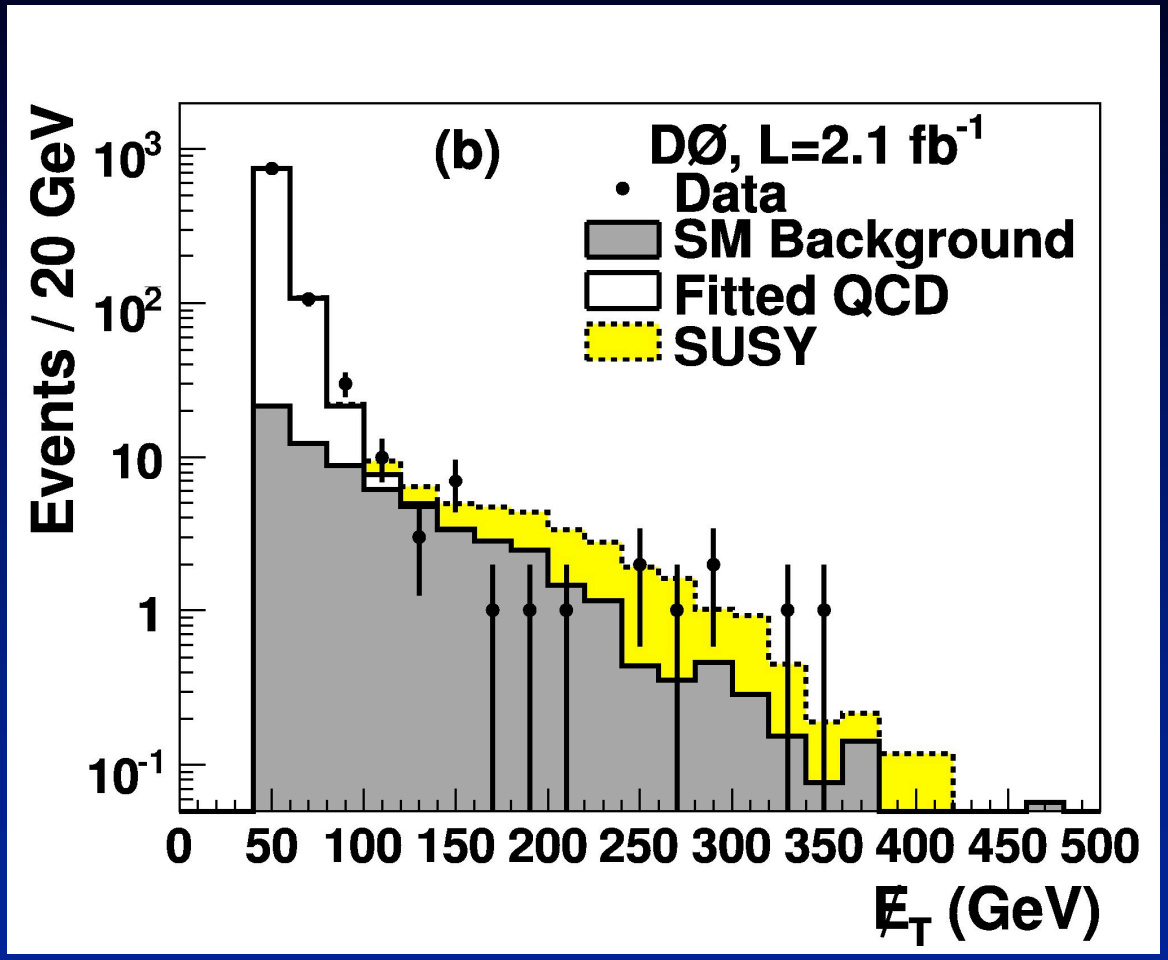






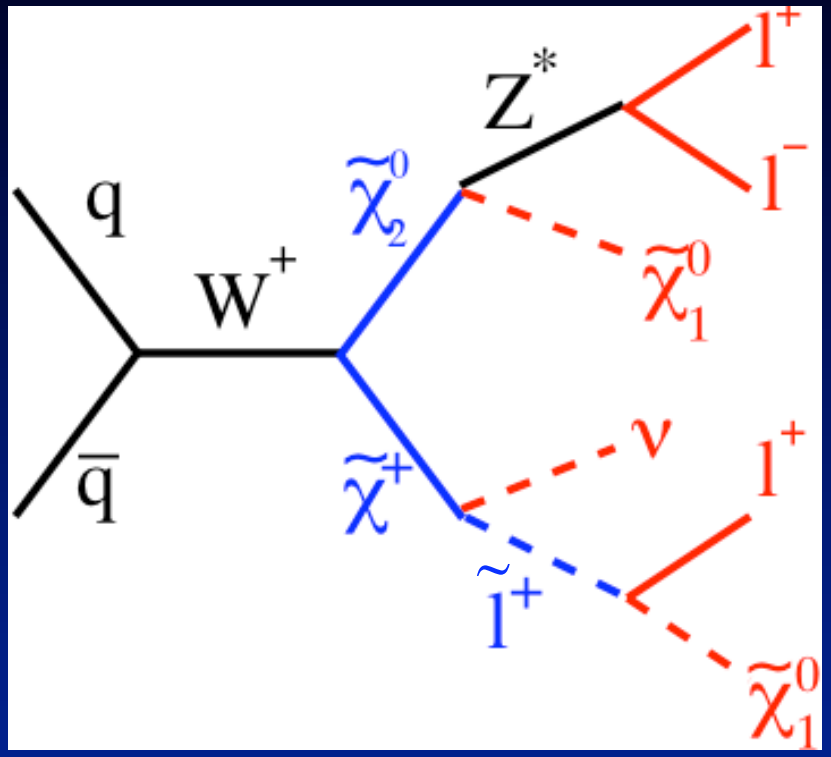
Optimize for different signatures in different scenarios

The Jets + Missing E_T Data

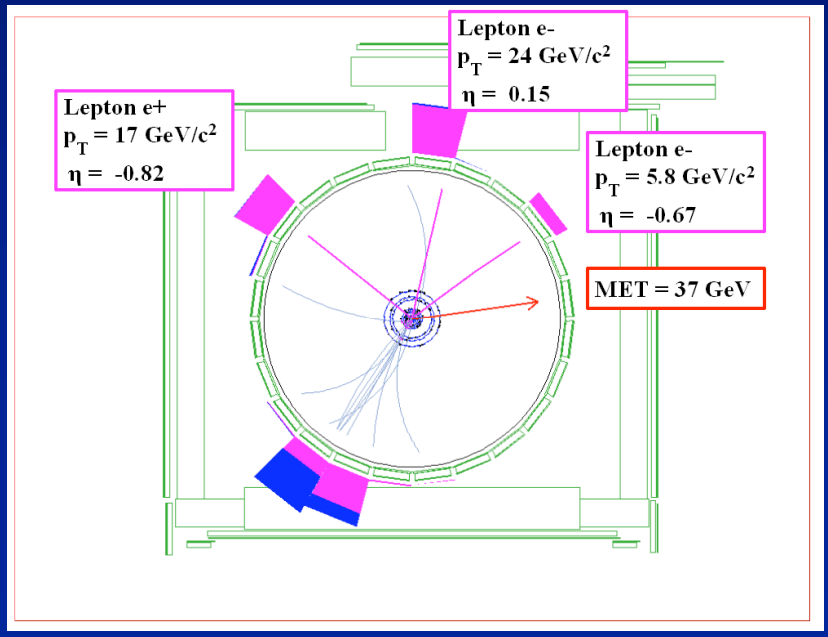


Data in agreement with Background Expectation
=> M(gluino)>308 GeV/c^2, M(squark)>379 GeV/c^2

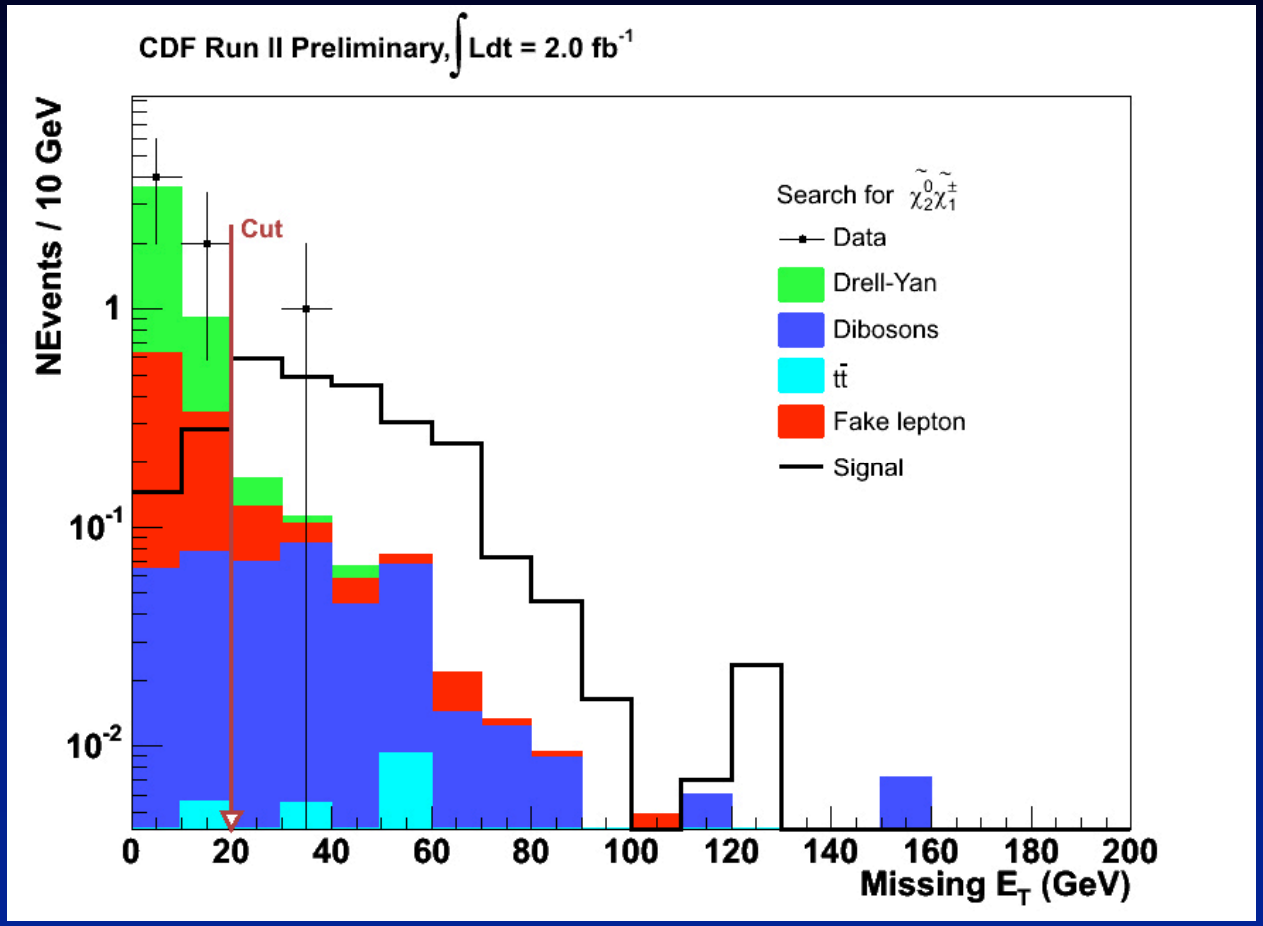
Trileptons: Another Look for SUSY



- Search for partners of W and Z boson
  - Decaying via leptons
- Signal:
  - 3 leptons and missing E_T



The Trilepton Data



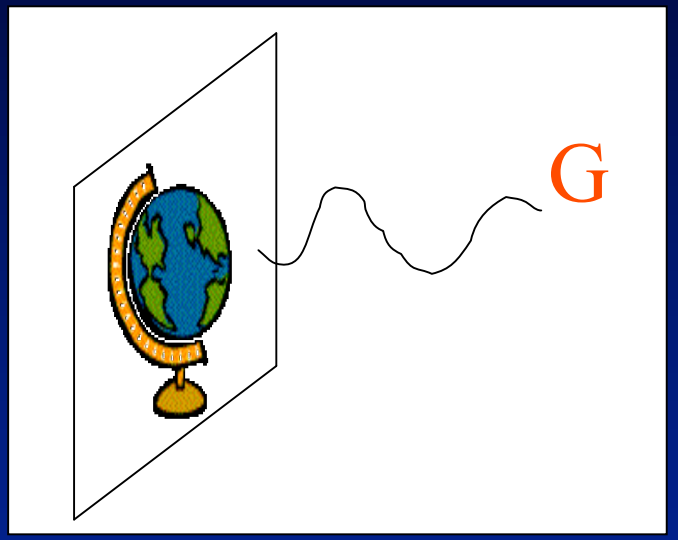
- Also consistent with background expectations
  - M(chargino)>140 GeV/c^2 at 95% confidence level
  - rather model-dependent though

Solving the Hierarchy Problem with Extra Dimensions

- String theory:
  - There are more than 3 spatial dimensions
- Large Extra Dimensions
  (Arkhani-Hamed, Dimopoulos, Dvali)
  - Electroweak and strong interaction live in our dimensions
  - Gravity lives also in extra dimensions

$$M_{Pl}^2 \sim R^n M_{Pl(4+n)}^{(2+n)}$$

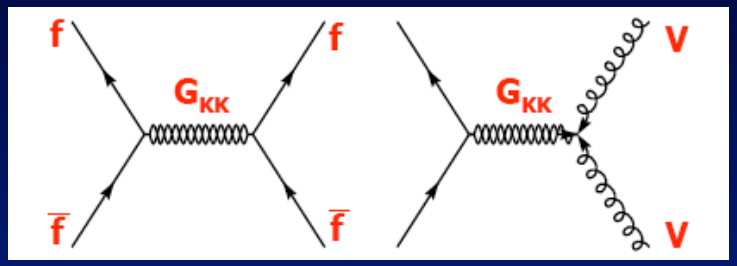
  - R=radius of extra dimensions
    - R=100 μm - 1 fm for n=2-7



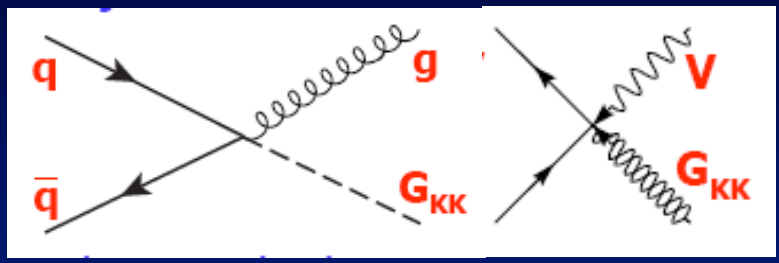
Other models:
e.g. Randall-Sundrum

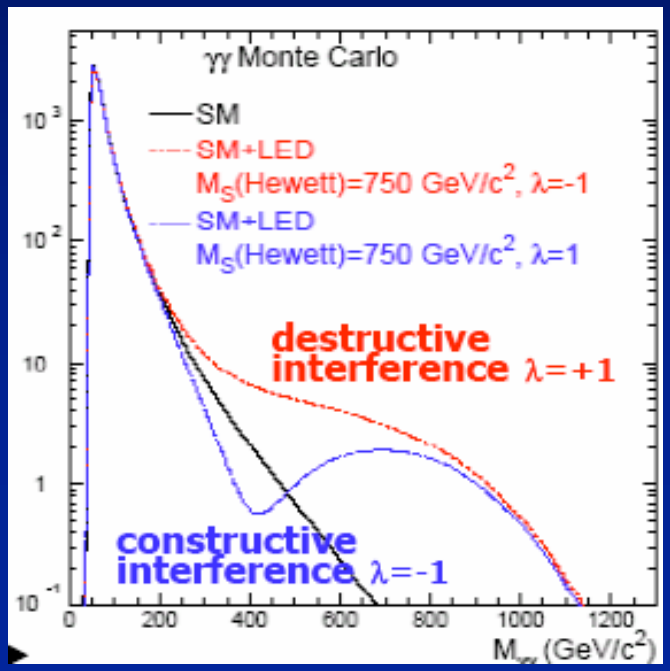
Possible Experimental Signatures

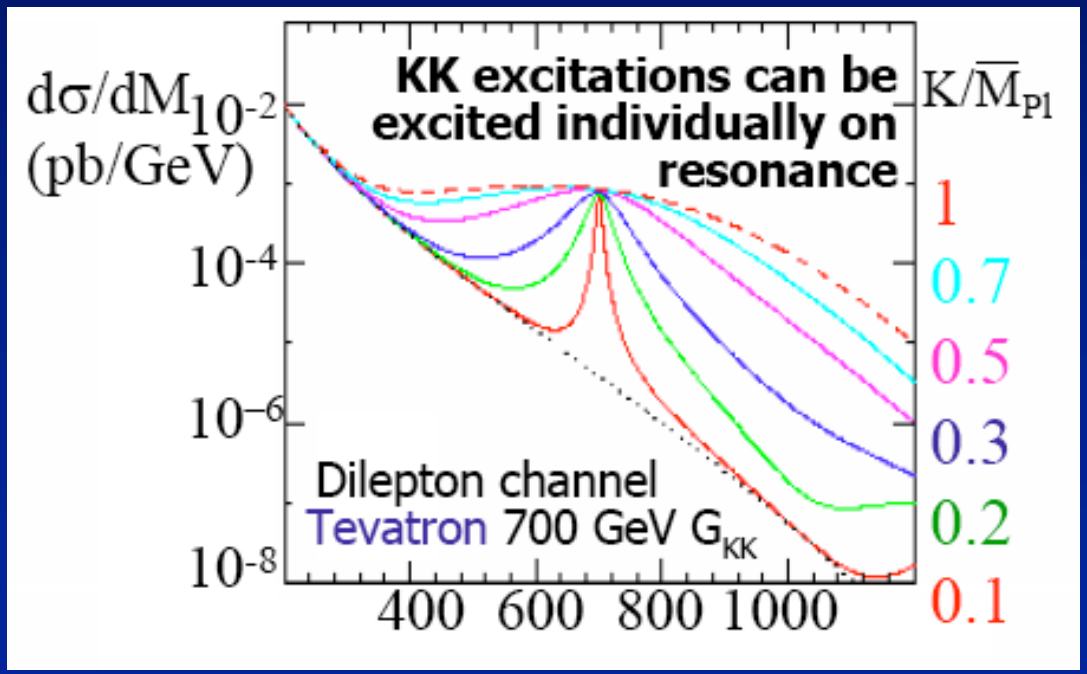
Virtual exchange



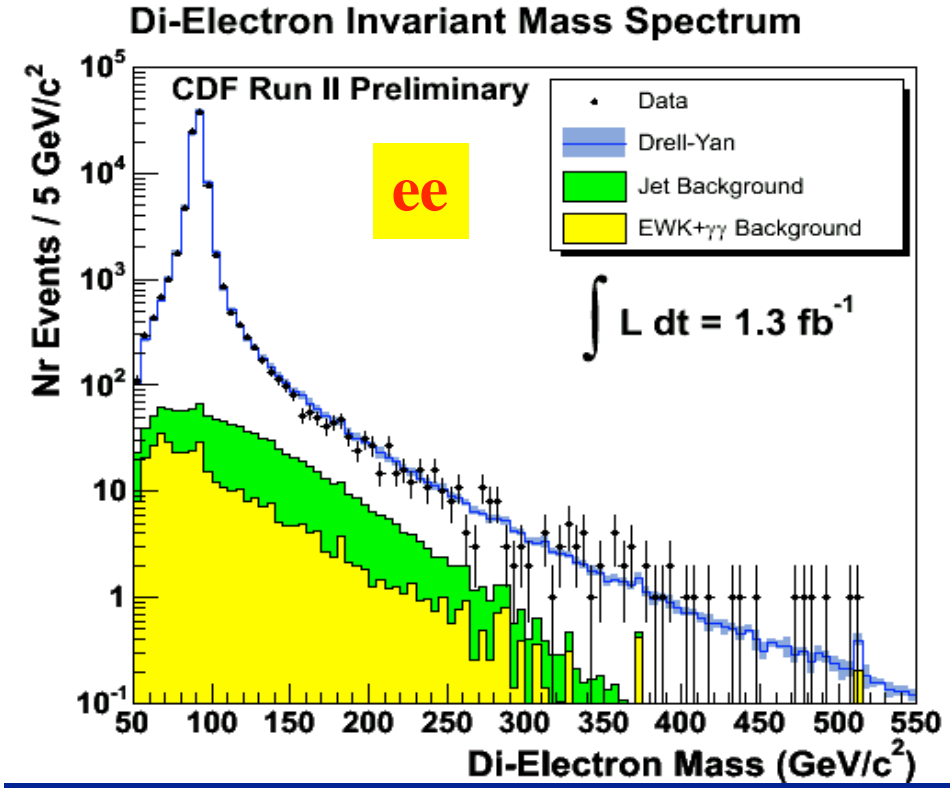
Direct emission

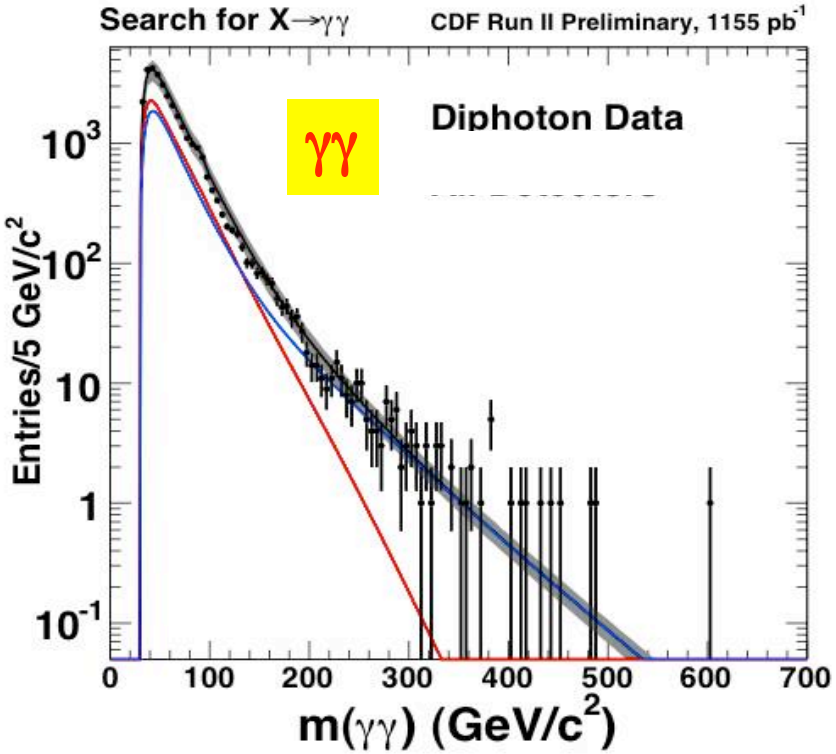






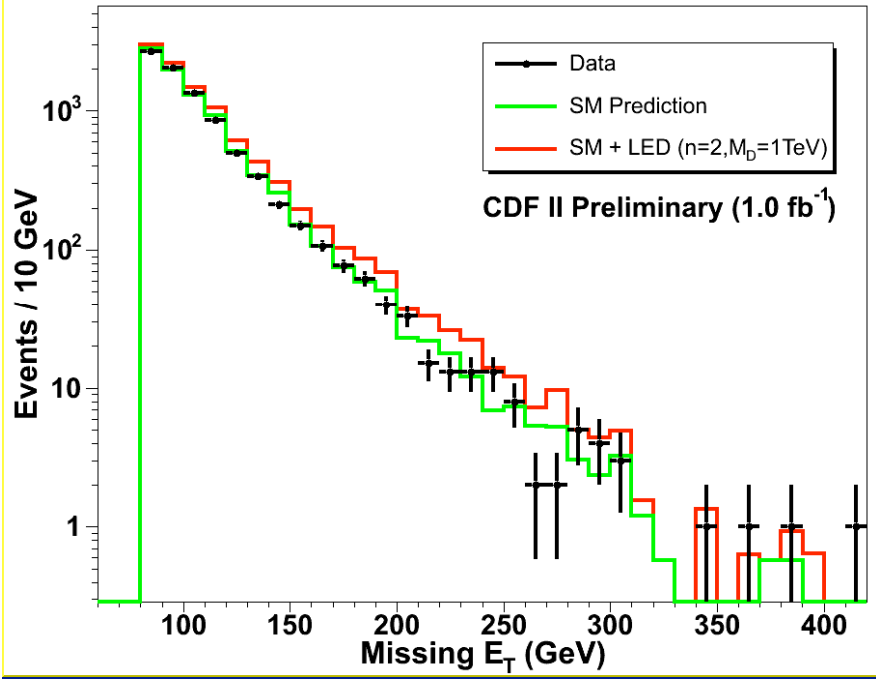
Dielectron and Diphoton Mass Spectra

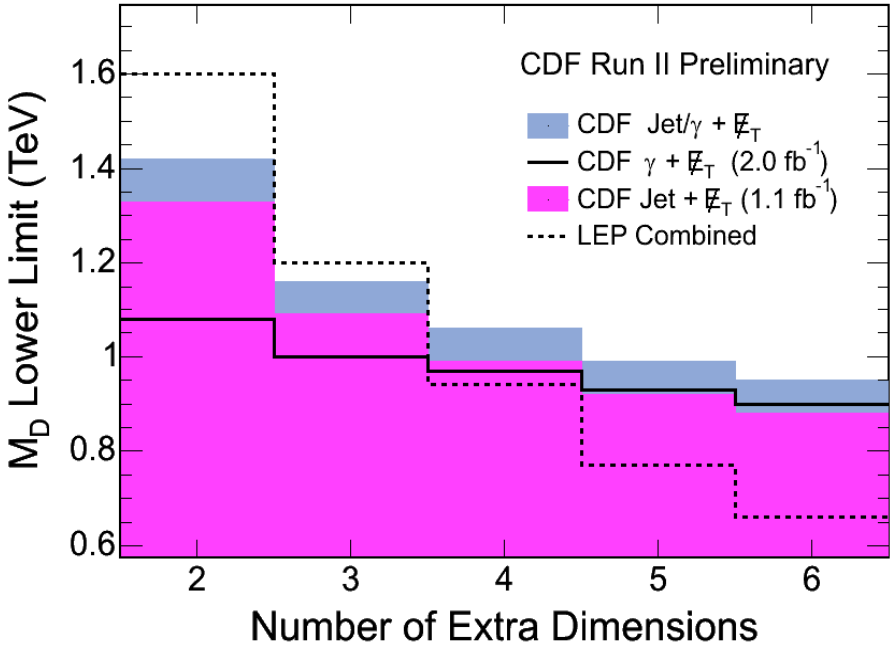




- Data agree with background prediction
  - No evidence for mass peak or deviation in tail
  - M_G>270-890 GeV/c^2 (depending on coupling) in RS model

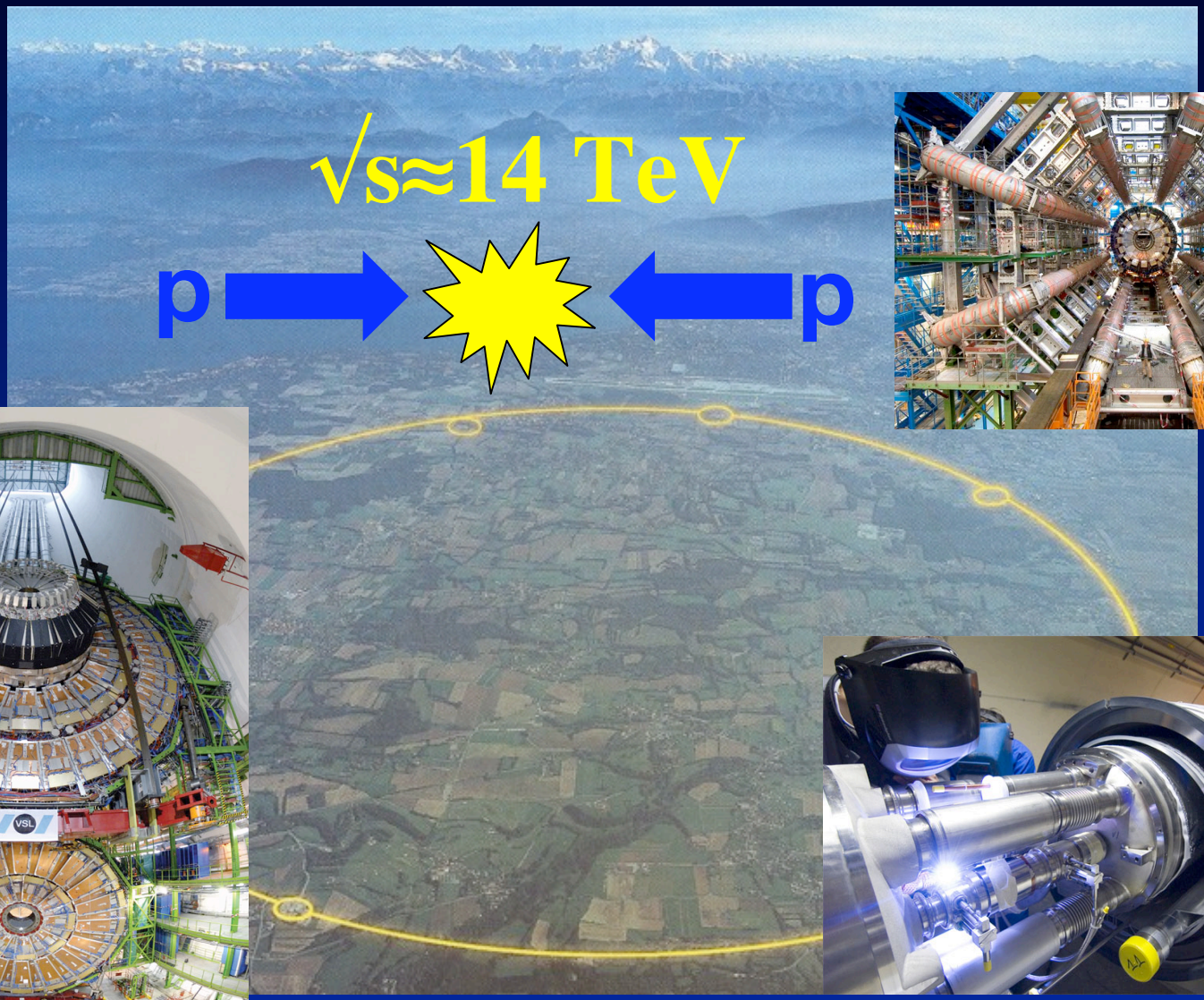
Monojets and Monophotons



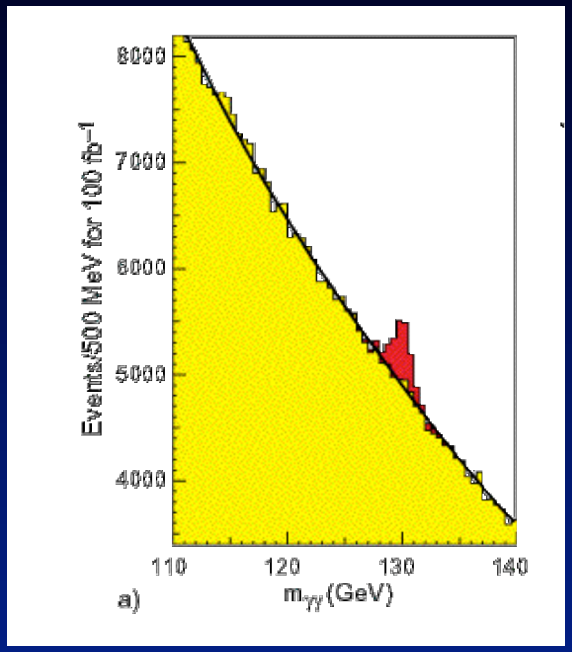


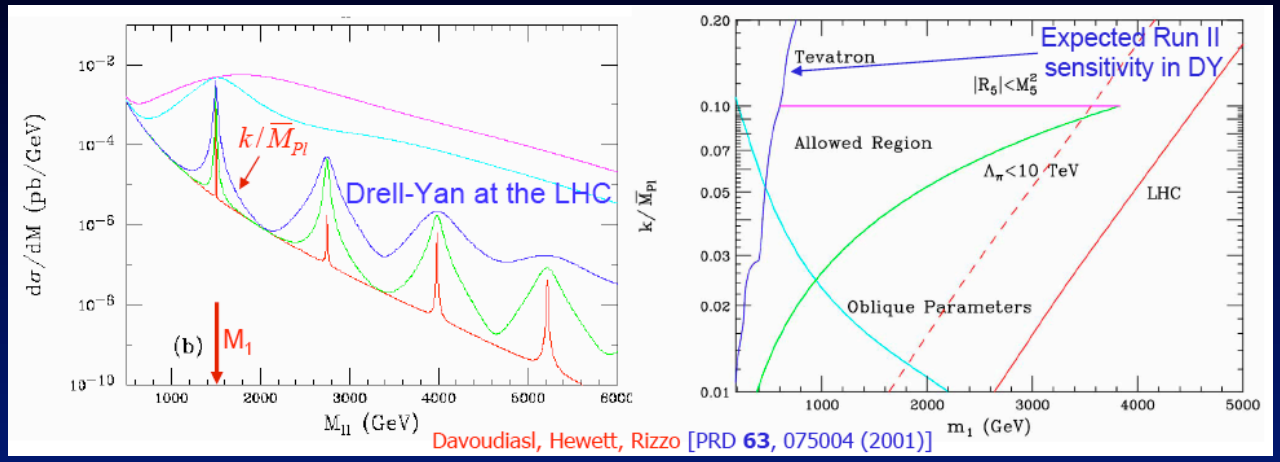
- Data agree with background
  - N=6: M_D> 950 GeV or R < 10,000 fm
  - N=4: M_D>1060 GeV or R < 0.3 fm

The next generation: the Large Hadron Collider

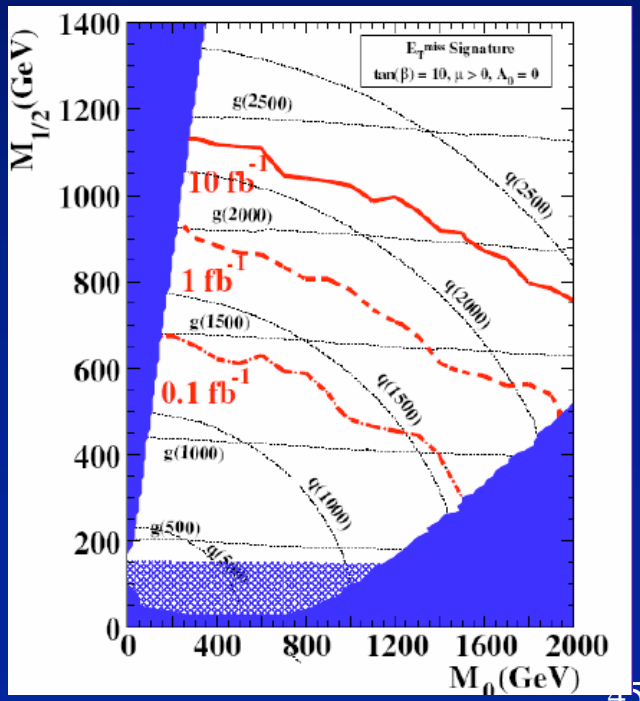


LHC prospects





Davoudiasl, Hewett, Rizzo [PRD **63**, 075004 (2001)]



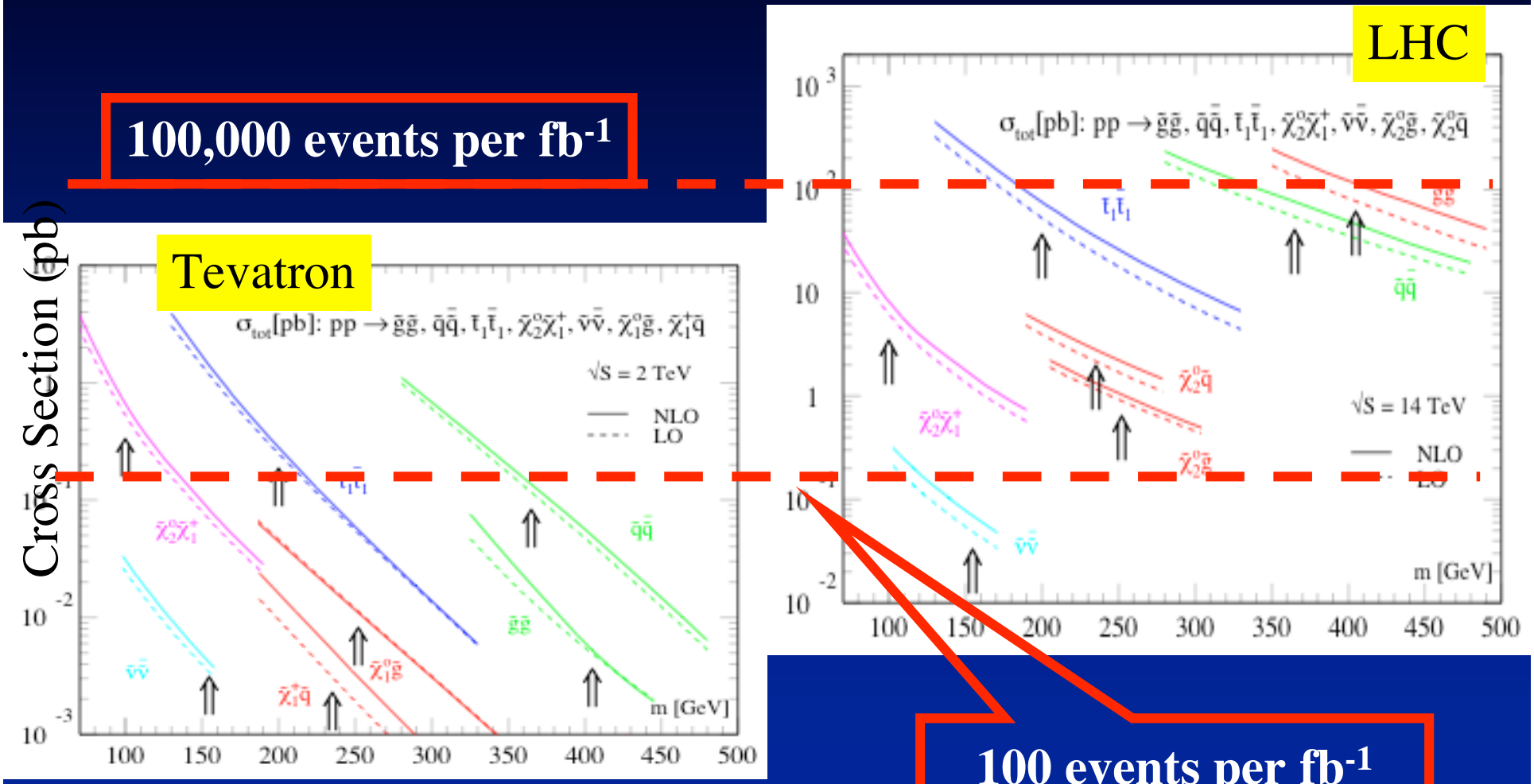
- LHC will (at latest) find out if
  - The Higgs mechanism explain electroweak symmetry breaking
  - The hierarchy problem is solved by new physics at the TeV scale

Conclusions and Outlook

- Tevatron & CDF and DØ experiments operating well
  - 4 fb^{-1} delivered to experiments
- Physics result cover broad range:
  - QCD thoroughly being tested:
    - works very well even in complicated final states!
  - Electroweak precision data getting more and more precise:
    - ♣ $\Delta m_W/m_W$=0.03% , $\Delta m_{top}/m_{top}$=0.8% => m_H<160 GeV/c^2 @95%CL
  - Searches beyond the Standard Model
    - Many searches but no sign of new physics yet
  - Precision test flavor sector
- Anticipate to double data by 2010
  - Vigorous hunt of the Higgs boson
    - And continuing pursuit of new phenomena
  - Continue precision tests of QCD, flavor and electroweak sectors
- LHC will start operation later this year
  - Full exploitation of electroweak energy scale

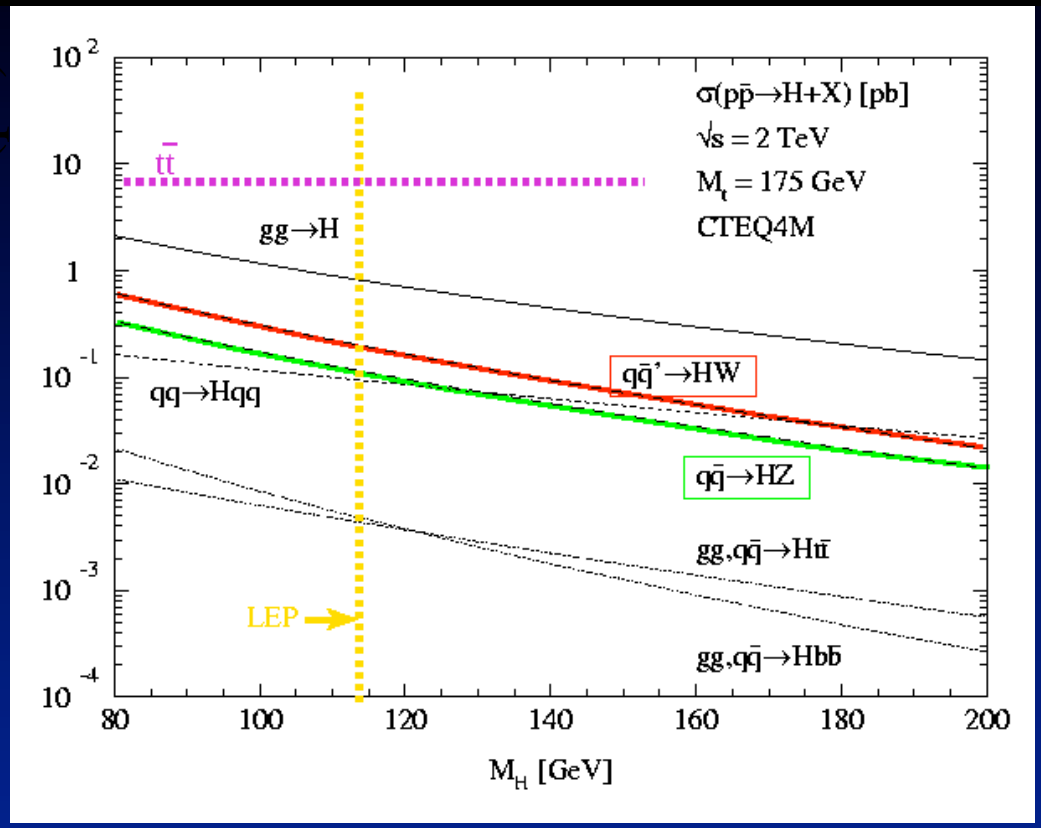
Backup Slides

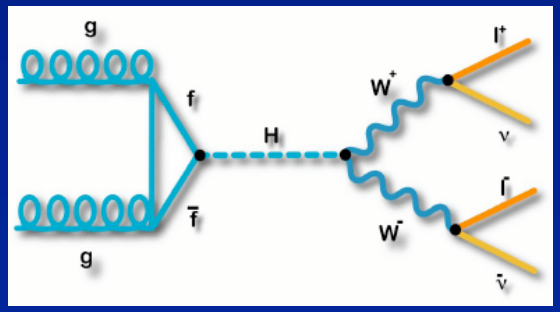
Sparticle Cross Sections

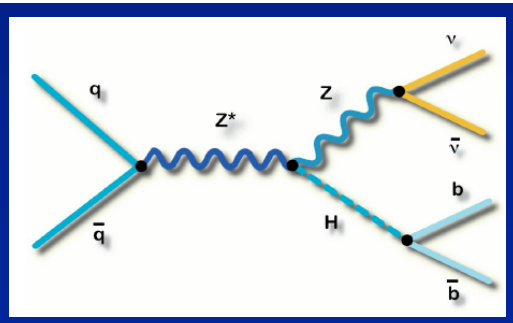


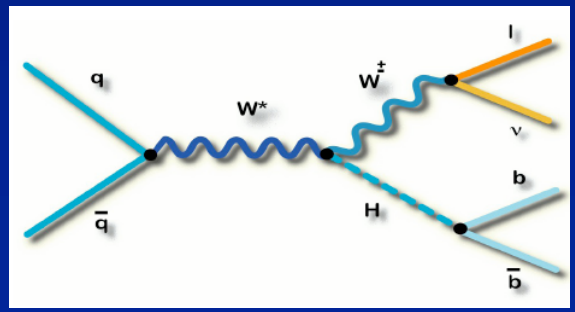
T. Plehn, PROSPINO

Higgs Production at the Tevatron

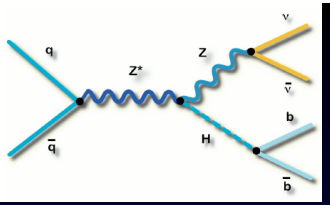




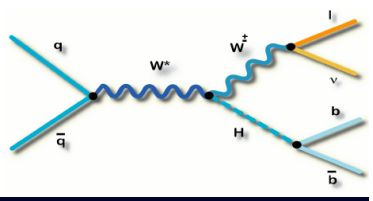


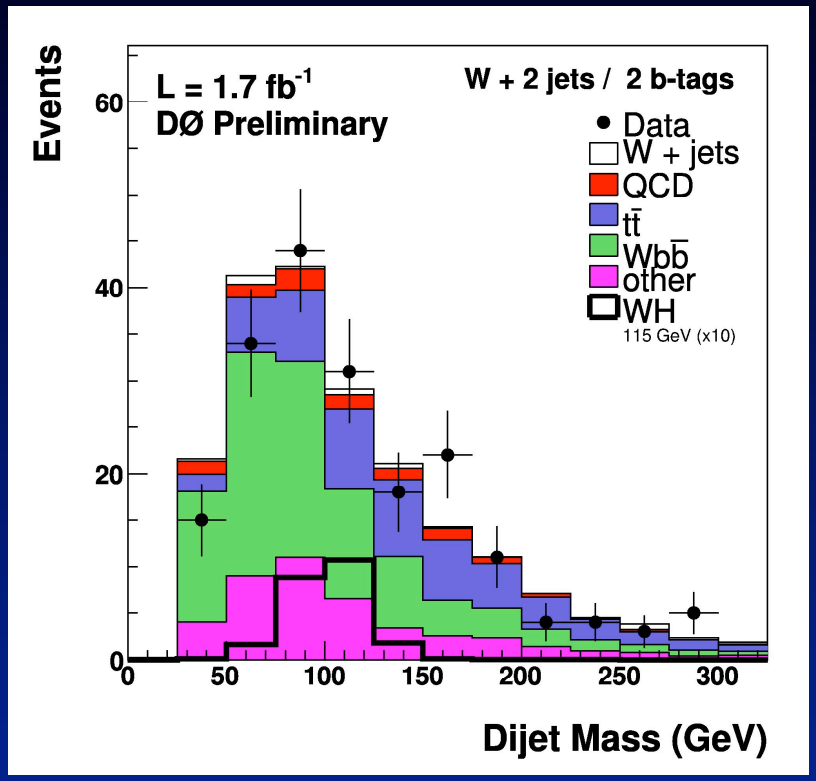


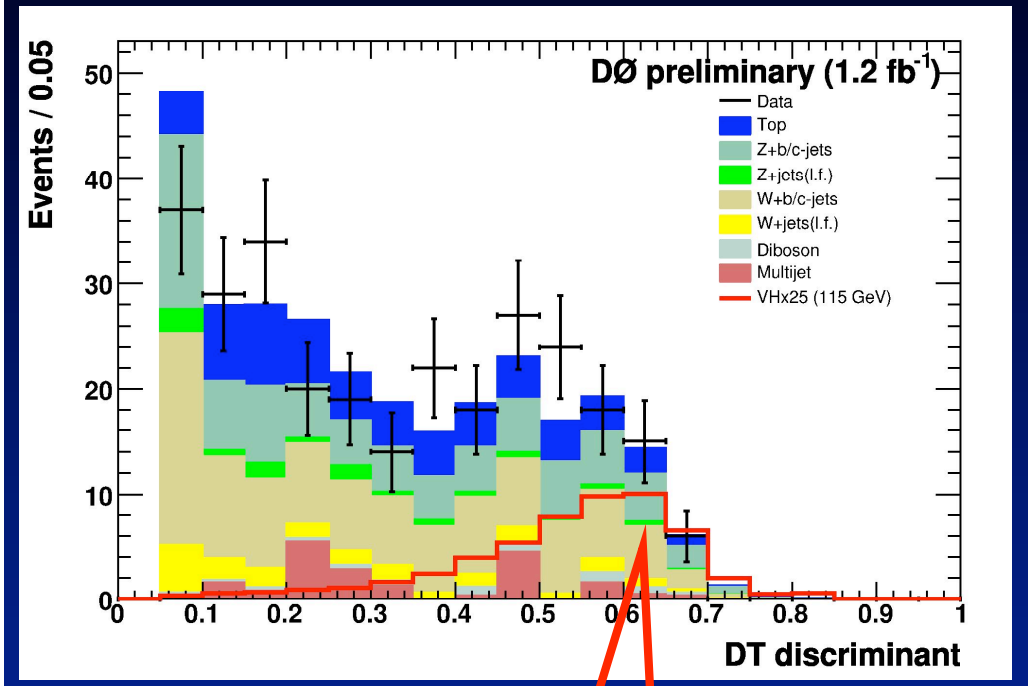
dominant: gg→ H, subdominant: HW, HZ



W/Z+Higgs with H→bb





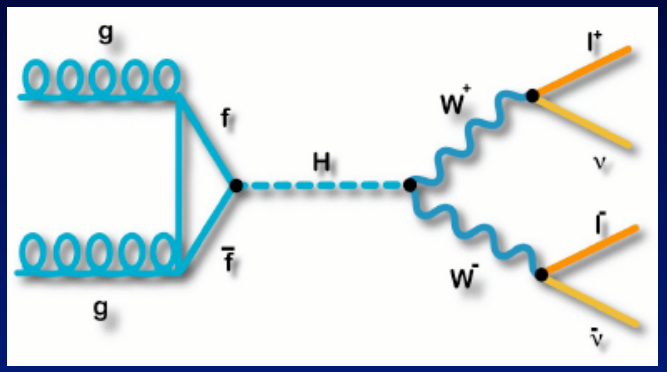


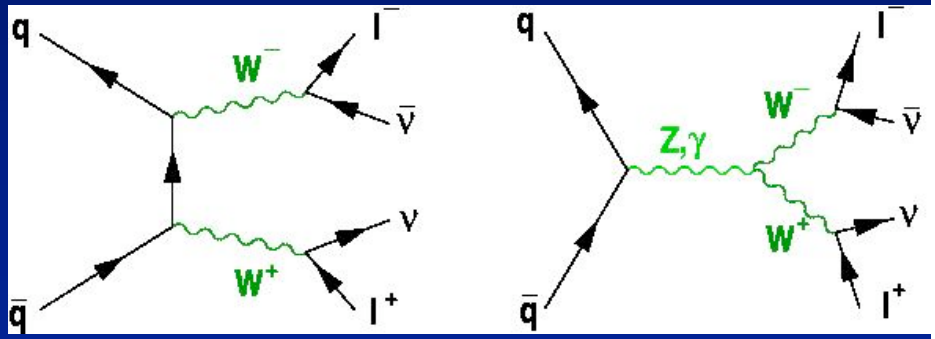
- For m_H<135 GeV/c^2:
  - WH→lνbb, ZH →llbb, ZH →ννbb
- Invariant mass of dijet-system corresponds to Higgs boson mass
  - Additional discrimination using likelihood/neural network techniques

115 GeV Higgs

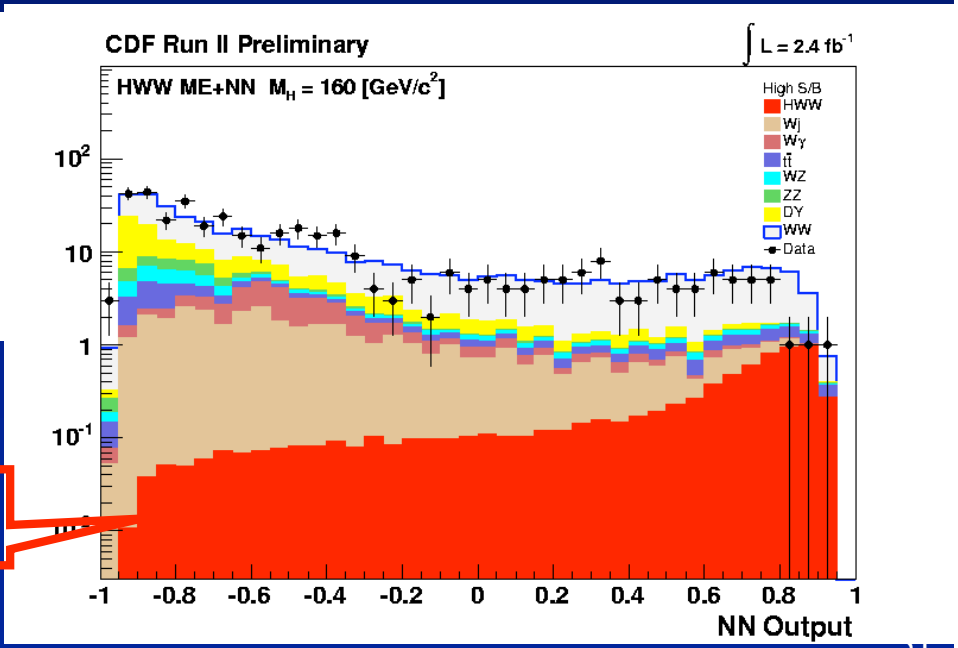
$H \rightarrow WW^{(*)} \rightarrow l^+l^-\nu\nu$

- Higgs mass reconstruction impossible due to two neutrinos in final state
- Make use of spin correlations to suppress WW background:
  - Higgs has spin=0
  - leptons in $H \rightarrow WW^{(*)} \rightarrow l^+l^-\nu\nu$ are collinear
- Main background: WW production





160 GeV Higgs



Supersymmetry Searches