

# PARTICLE THEORY AT SMU

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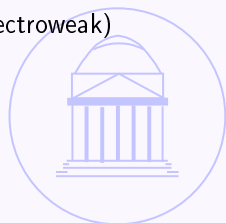
Southern Methodist University

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# SMU group of particle phenomenology

- Phenomenology = particle theory applied to collider experiments
  - ▶ A highly demanded topic in the era of the Large Hadron Collider
- Members of our group include Guzzi, Dalley, Nadolsky, Olness, Park
  - ▶ funding for graduate students will be available starting in 2011
- Research topics cover
  - ▶ theory of high-energy hadronic (both strong and electroweak) interactions
  - ▶ factorization in quantum chromodynamics (QCD)
  - ▶ all-order summation of perturbative theory
  - ▶ computer simulations for collider experiments



# Standard Model: a successful effective theory of elementary particles

LEPTONS		QUARKS	
<b>Electron</b> Responsible for electricity and chemical reactions. It has a charge of $-1$ . Its anti-particle, the positron, has a charge of $+1$ .	<b>Electron Neutrino</b> Particle with no electric charge, and tiny mass. Billions fly through your body every second.	<b>Up</b> It has an electric charge of $+2/3$ . Protons contain 2, neutrons contain 1.	<b>Down</b> It has an electric charge of $-1/3$ . Protons contain 1, neutrons contain 2.
<b>Muon</b> It is heavier than the electron. It lives for two millionths of a second. It has a charge of $\pm 1$ .	<b>Muon Neutrino</b> Created along with muons when some particles decay. It has no electric charge.	<b>Charm</b> Discovered in 1974. It is heavier than the Up. It has a charge of $+2/3$ .	<b>Strange</b> Discovered in 1963. It is heavier than the Down. It has a charge of $-1/3$ .
<b>Tau</b> Heavier still; it is extremely unstable. It was discovered in 1975. It has a charge of $\pm 1$ .	<b>Tau Neutrino</b> Discovered in 2000. It has no electric charge.	<b>Top</b> Heavier still. Discovered in 1995. Electric charge $+2/3$ .	<b>Bottom</b> Heavier still; measuring bottom quarks is an important test of electroweak theory. Discovered in 1977. Electric charge $-1/3$ .

**Mass Particles**

All ordinary particles belong to this group

These particles only existed just after the Big Bang. Now they are found in cosmic rays or produced in scientific laboratories such as CERN.

**Force Particles**

These particles transmit the four fundamental forces of nature. Gravitons have so far not been discovered.

**Gluons**  
 Carriers of the strong force between quarks.  
 Felt by: quarks and gluons  
 The explosive release of nuclear

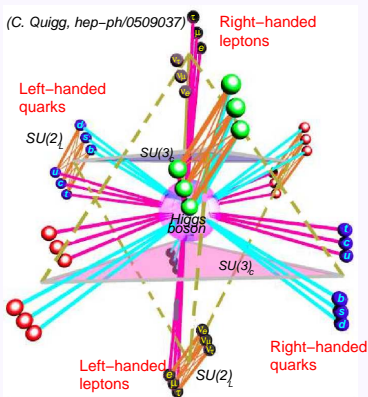
**Photons**  
 Particles that make up light. They carry the electromagnetic force.  
 Felt by: charged particles  
 Electricity, magnetism and

**Intermediate vector bosons**  
 Carriers of the weak force.  
 Felt by: quarks and leptons  
 Some forms of radio-activity

**Gravitons**  
 Carriers of gravity.  
 Felt by: all particles with mass  
 All the weight we experience

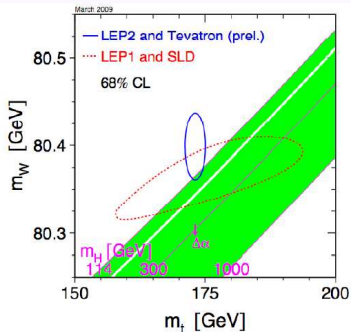
**ANTIMATTER:** Each particle also has an antimatter counterpart... sort of a mirror image.

# Symmetries of standard model



- Forces between SM particles emerge from the local  $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$  symmetry of SM Lagrangian
- Mass terms relate left- and right-handed fermions; arise as a result of the  $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{EM}$  symmetry breaking, induced by the existence of Higgs scalar field doublet(s)
  - ▶ Nature of the electroweak breaking mechanism is still uncertain

# Higgs sector in SM and minimal supersymmetry



Green band:  $114 \leq M_H \leq 1000$  GeV

SM: 1 Higgs doublet, one boson  $H$

■ Direct search:

$m_H > 114$  GeV at 95% c.l.

■ indirect:  $M_H = 80_{-28}^{+39}$  GeV at 68% c.l.

MSSM: 2 Higgs doublets;  $h^0, H^0, A^0, H^\pm$

$m_h \leq m_Z |\cos 2\beta| + \text{rad. corr.} \lesssim 135$  GeV

- In these models, expect one or more Higgs bosons with mass below 140 GeV
- Many other possibilities for EW symmetry breaking exist!

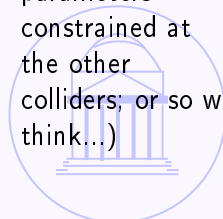


# Large Hadron Collider at CERN

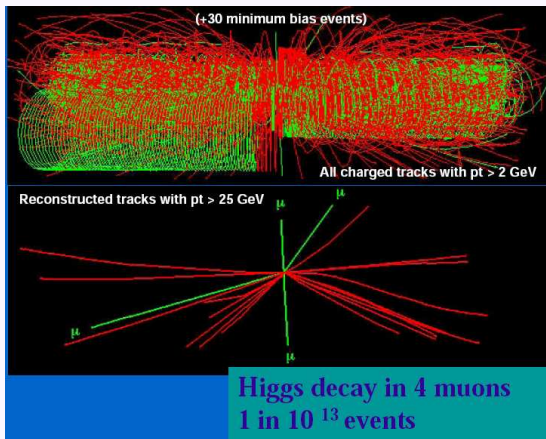
( $pp$  collision energy 10-14 TeV)



- is quickly ramping up
- search for new physics! (SM parameters constrained at the other colliders; or so we think...)



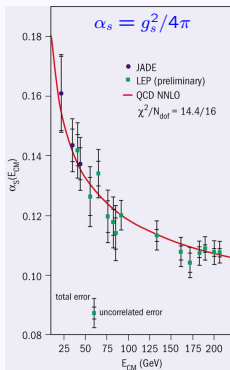
# A typical Higgs production event at the LHC



Production of high-energy particles can be systematically described in perturbation theory, in contrast to messy production of low-energy particles

# Asymptotic freedom of strong interactions

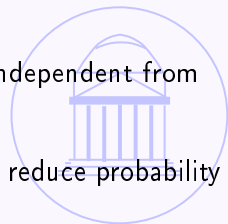
- Strong interactions are extremely intensive at small energies; weaken at large energies



- At  $E > 1\text{GeV}$ , the proton is a loosely bound system of partons (quarks and gluons)



- hard scatterings of partons are independent from one another
- emission of each additional parton tends to strongly reduce probability of the scattering (suppression by  $g_s$ )





# PDFs and QCD factorization

According to QCD factorization theorems, typical cross sections (e.g., for vector boson production  $p(k_1)p(k_2) \rightarrow [V(q) \rightarrow \ell(k_3)\bar{\ell}(k_4)] X$ ) take the form

$$\sigma_{pp \rightarrow \ell\bar{\ell}X} = \sum_{a,b=q,\bar{q},g} \int_0^1 d\xi_1 \int_0^1 d\xi_2 \hat{\sigma}_{ab \rightarrow V \rightarrow \ell\bar{\ell}} \left( \frac{x_1}{\xi_1}, \frac{x_2}{\xi_2}; \frac{Q}{\mu} \right) f_{a/p}(\xi_1, \mu) f_{b/p}(\xi_2, \mu) + \mathcal{O}(\Lambda_{QCD}^2/Q^2)$$

■  $\hat{\sigma}_{ab \rightarrow V \rightarrow \ell\bar{\ell}}$  is the **hard-scattering cross section**

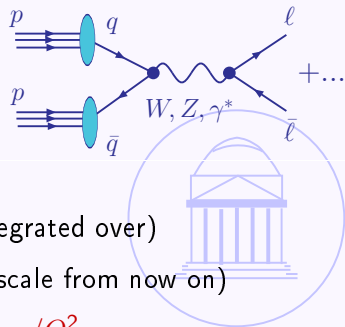
■  $f_{a/p}(\xi, \mu)$  are the **PDFs**

■  $Q^2 = (k_3 + k_4)^2$ ,  $x_{1,2} = (Q/\sqrt{s}) e^{\pm y_V}$  — measurable quantities

■  $\xi_1, \xi_2$  are partonic momentum fractions (integrated over)

■  $\mu$  is a factorization scale (=renormalization scale from now on)

■ Factorization holds up to terms of order  $\Lambda_{QCD}^2/Q^2$



# PDFs and QCD factorization

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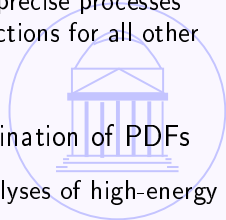
## Purpose of this arrangement:

- Subtract large collinear logarithms  $\alpha_s^n \ln^k(Q^2/m_q^2)$  from  $\hat{\sigma}$
- Resum them in  $f_{a/p}(\xi, \mu)$  to all orders of  $\alpha_s$



# How our group contributes

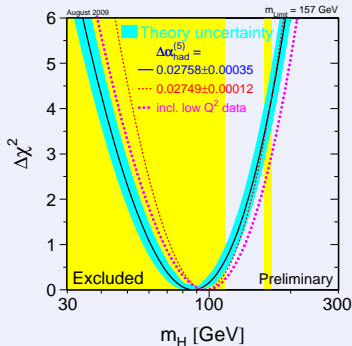
- **Perturbative** calculations for collider scattering processes
  - ▶  $W$ ,  $Z$ , and Higgs boson production
  - ▶ Scattering of heavy quarks ( $c$  and  $b$ )
  - ▶ All-order summation of perturbative contributions
- Determination of CTEQ **nonperturbative** parton distributions
  - ▶ The energy ( $\mu$ ) dependence of  $f_{a/p}(x, \mu)$  is known;
  - ▶  $f_a(x, \mu)$  can be “measured” (constrained) in a few precise processes (DIS, lepton pair production,...) and used for predictions for all other processes
- Our group is among the world leaders in the determination of PDFs
  - ▶ has an important impact on most experimental analyses of high-energy hadronic scattering



## Key Tevatron/LHC measurements require trustworthy QCD calculations

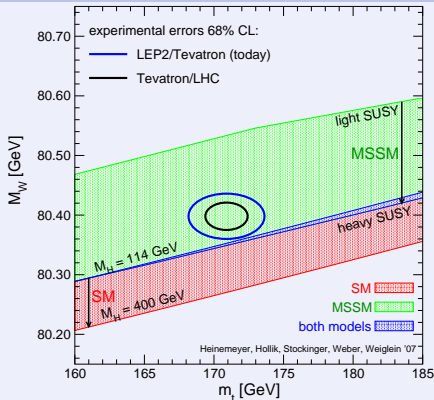
For example, leading syst. uncertainties in tests of electroweak symmetry breaking are due to uncertainties in QCD inputs

### EW precision fits



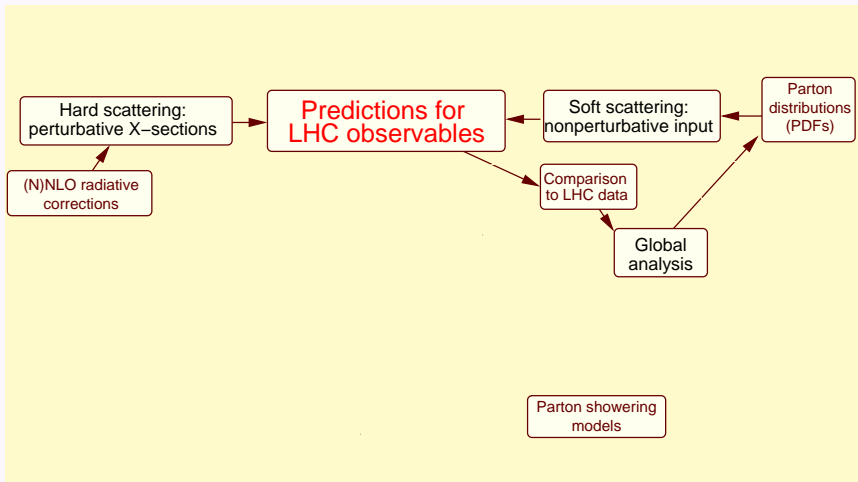
A large part of  $\delta M_H$  arises from  $\delta_{PDF} M_W$

### EW fits + direct Higgs searches

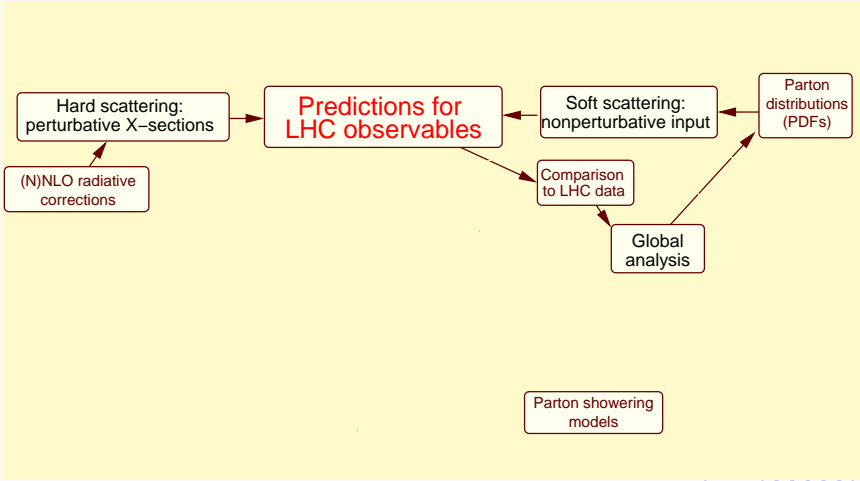


SM band:  $114 \leq M_H \leq 400$  GeV  
 SUSY band: random scan

# Global picture of QCD factorization at the LHC



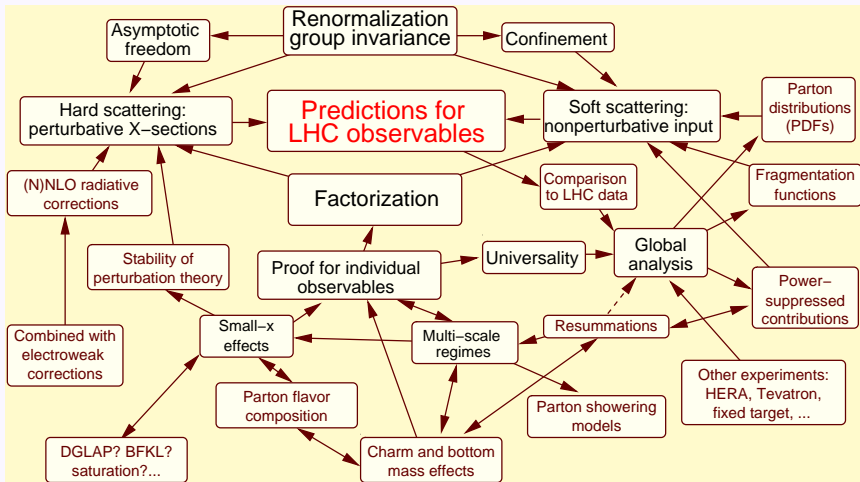
# Global picture of QCD factorization at the LHC



A relevant, yet incomplete, picture



# Global picture of QCD factorization at the LHC



Global interconnections can be as important as (N)NLO perturbative contributions; are different at the LHC and Tevatron