PARTICLE
THEORY
AT
SMU

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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
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

(C. Quigg, hep-ph/0509037)
Higgs sector in SM and minimal supersymmetry

**SM: 1 Higgs doublet, one boson \( H \)**
- Direct search: \( m_H > 114 \text{ GeV} \) at 95\% c.l.
- Indirect: \( M_H = 80^{+39}_{-28} \text{ GeV} \) at 68\% c.l.

**MSSM: 2 Higgs doublets; \( h^0, H^0, A^0, H^\pm \)**
\[ m_h \leq m_Z \left| \cos 2\beta \right| + \text{rad. corr.} \lesssim 135 \text{ GeV} \]

- 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...)

Pavel Nadolsky (SMU)  SMU HEP seminar  January 25, 2010
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

\[ \alpha_s = \frac{g_s^2}{4\pi} \]

- 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

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

$$+ \mathcal{O} \left( \frac{\Lambda_{QCD}^2}{Q^2} \right)
$$

- $\hat{\sigma}_{ab\rightarrow V\rightarrow \ell\bar{\ell}}$ 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 (i.e., renormalization scale from now on)
- Factorization holds up to terms of order $\Lambda_{QCD}^2/Q^2$
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$$\sigma_{pp\rightarrow \ell\bar{\ell}X} = \sum_{a,b=q,\bar{q},g} \int_0^1 d\xi_1 \int_0^1 d\xi_2 \hat{\sigma}_{ab\rightarrow V\rightarrow \ell\bar{\ell}} \left( \frac{x_1}{\xi_1}, \frac{x_2}{\xi_2}; \frac{Q}{\mu} \right) f_{a/p}(\xi_1, \mu) f_{b/p}(\xi_2, \mu) + \mathcal{O} \left( \Lambda_{QCD}^2 / Q^2 \right)$$

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**

![Graph showing EW precision fits](image)

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

**EW fits + direct Higgs searches**

![Graph showing EW fits and direct Higgs searches](image)

SM band: $114 \leq M_H \leq 400$ GeV

SUSY band: random scan
Global picture of QCD factorization at the LHC

- Hard scattering: perturbative X-sections
- Predictions for LHC observables
  - (N)NLO radiative corrections
- Soft scattering: nonperturbative input
  - Comparison to LHC data
- Parton distributions (PDFs)
- Global analysis
- Parton showering models
- Perturbative X-sections
- Nonperturbative input
- LHC observables
- Perturbative corrections
- Nonperturbative corrections

Other experiments:
- HERA, Tevatron, fixed target...
- Mass effects
- Charm and bottom
- Stability of perturbation theory
- Composition
- Parton flavor
- Multi-scale regimes
- Resummations
- Saturation?...
- DGLAP? BFKL?
- Combined with electroweak corrections
Global picture of QCD factorization at the LHC

Hard scattering: perturbative X-sections

Predictions for LHC observables

Soft scattering: nonperturbative input

Parton distributions (PDFs)

(N)NLO radiative corrections

Comparison to LHC data

Global analysis

Parton showering models

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