Standard Model at Hadron Colliders

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Lecture 1:

- Hadron collider basics

Lecture 2:

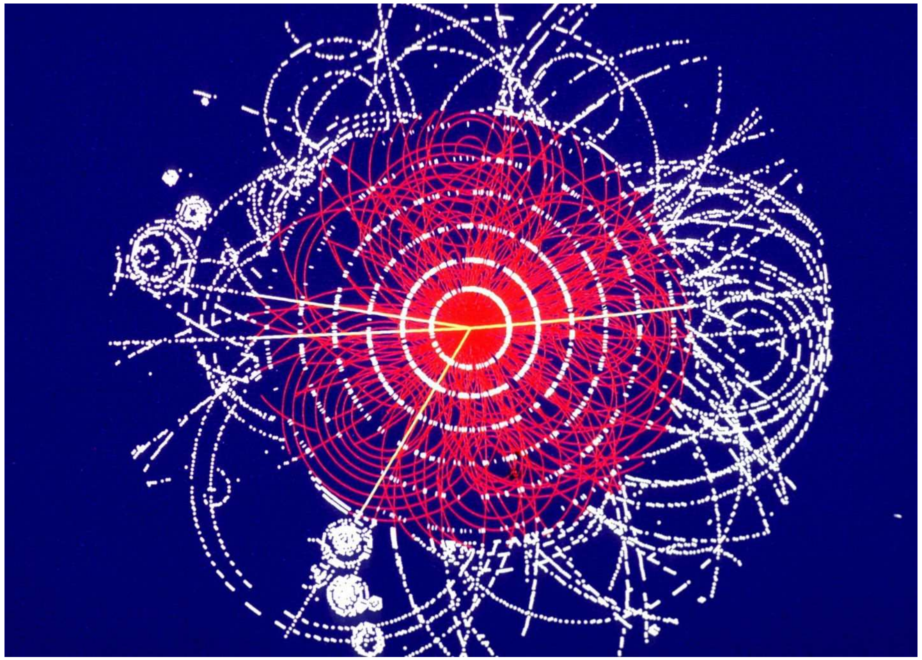
- Jets and W, Z production

Lecture 3:

- Event generation;
  top quarks

Lecture 4:

- Higgs production



Hadron Collider basics

Existing: Tevatron, $p\bar{p}$ collisions at

$\sqrt{s} = 1.96$ TeV $\qquad \mathcal{L} \approx 10^{32}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1} \leftrightarrow 1\mathrm{fb}^{-1}/\mathrm{year}$

ready in 2007: LHC, pp collisions at

$\sqrt{s} = 14$ TeV $\qquad \mathcal{L} \approx 10^{33}$–$10^{34}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1} \leftrightarrow 10$–$100\mathrm{fb}^{-1}/\mathrm{year}$

Advantage: available energy is much larger than at e^+e^- colliders

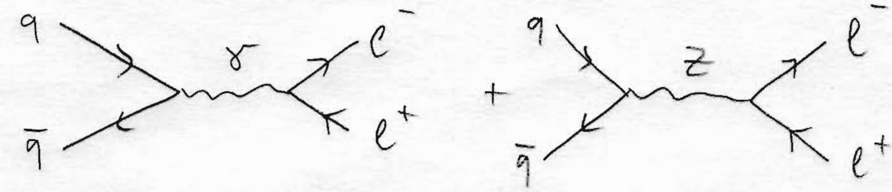
- $t\bar{t}$ pairs could not be produced at LEP...

Disadvantage: protons are composite $\Longrightarrow$

- hard scattering is between
  partons = quarks, anti-quarks, gluons
- proton-(anti)proton cross section is large
  $\sigma_{tot}(p\bar{p}) \approx 100$ mb $\geq 10^{11}$ times new physics cross sections
  $\Longrightarrow$ Must understand patterns of SM and new physics processes to identify something new
- useful energy = $\sqrt{\hat{s}}$ of partons $<< \sqrt{s}$

Example hard scattering processes

Drell-Yan: e^+e^- (γ, Z) or $\ell^\pm\nu$ $(W^\pm)$ production



$q = u, d, s, c, b$

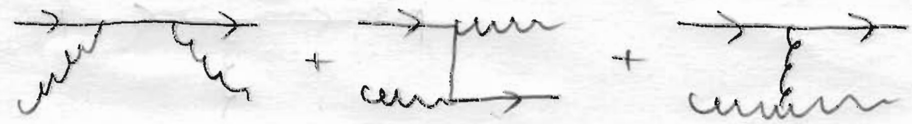
$$\frac{d\hat{\sigma}}{d\Omega^*} = \frac{\alpha^2}{4\hat{s}}\, e_q^2\, (1+\cos^2\theta^*) + \cdots$$

$e_u = +\frac{2}{3}$

$e_d = -\frac{1}{3}$

dijets = hadronization products of hard scattered quarks and gluons

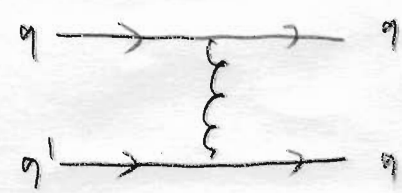
$qg \rightarrow qg$



$$\frac{d\hat{\sigma}}{d\Omega^*} = \frac{\alpha_s^2}{4\hat{s}}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2} - \frac{4}{9}\,\frac{\hat{s}^2+\hat{u}^2}{\hat{u}\hat{s}}\right)$$

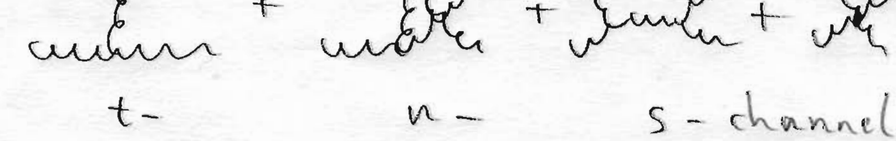
$qq' \rightarrow qq'$

$q \neq q'$



$$\frac{d\hat{\sigma}}{d\Omega^*} = \frac{\alpha_s^2}{9\hat{s}}\,\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$$

$gg \rightarrow gg$



t- u- s-channel

dijets cont'd

$q\bar{q} \to gg \quad , \quad gg \to q\bar{q} \qquad (q = u, d, s, c, b)$

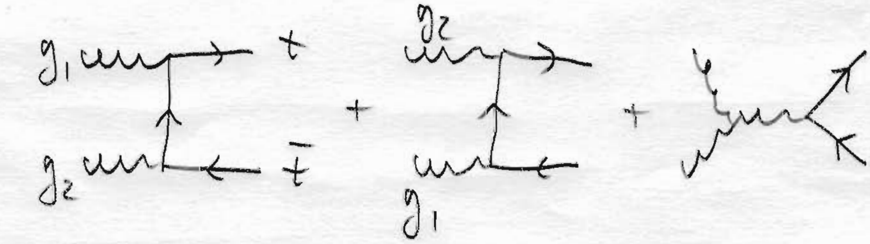
$q\bar{q} \to q'\bar{q}' \quad , \quad q\bar{q} \to q\bar{q} \quad , \quad qq \to qq$

$\bar{q}\bar{q} \to \bar{q}\bar{q} \quad , \quad \bar{q}\bar{q}' \to \bar{q}\bar{q}' \quad , \quad q\bar{q}' \to q\bar{q}'$

Most signatures get contributions from many different subprocesses!

<u>top</u> pair production

$gg \to t\bar{t}$

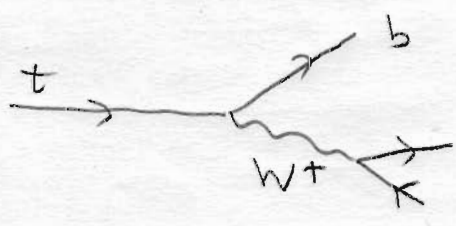


(dominant at LHC)

$q\bar{q} \to t\bar{t}$

(dominant at Tevatron)

top is special: decays weakly before it hadronizes $(m_t = 174\,\text{GeV} > m_W = 80.4\,\text{GeV})$

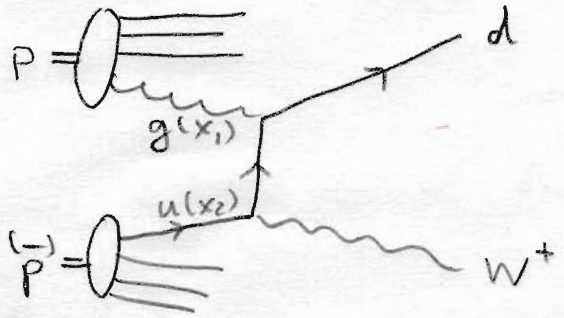


$\Gamma \approx 1.4\,\text{GeV}$

Probability for scattering two partons

$a, b \in \{q, \bar{q}, g\}$, $q = u, d, s, c, b$

is given by parton distribution functions (pdf)



$$p_g = x_1 \frac{\sqrt{s}}{2}(1,0,0,1)$$

$$p_u = x_2 \frac{\sqrt{s}}{2}(1,0,0,-1)$$

available energy^2: $\hat{s} = (p_g + p_u)^2 = 2 p_g \cdot p_u = x_1 x_2 s$

pdf: $f_{a/p}(x)$ = probability density to find parton a of momentum fraction x in proton p

$$\Rightarrow \sigma(p\bar{p} \to X) = \sum_{\substack{\text{subproc.} \\ ab \to \hat{X}}} \int_0^1 dx_1\, dx_2\, f_{a/p}(x_1)\, f_{b/\bar{p}}(x_2)$$

$$\cdot \frac{1}{2\hat{s}} \overline{\sum_{\substack{\text{color} \\ \text{spin}}}} |\mathcal{M}|^2(ab \to \hat{x})\, d\phi_n(ab \to \hat{x})\, \Theta(\text{cuts})$$

$\mathcal{M}$ = matrix element from Feynman rules

$$d\phi_n = (2\pi)^4 \delta\left(p_a + p_b - \sum_{i=1}^n p_i\right) \prod_{i=1}^n \frac{d^3\vec{p}_i}{(2\pi)^3 2p_i^0} = \begin{array}{l}\text{Lorentz} \\ \text{invariant} \\ \text{phase space} \\ \text{measure}\end{array}$$

$\Theta = \begin{cases} 0 \\ 1 \end{cases}$ depending on whether final state $\hat{x}$ satisfies "cuts"

Parton Distribution Functions (pdf's)

Factorization Theorem for infrared and collinear safe observable i.e. observables which are insensitive to soft gluon emission or collinear splitting

Any infrared and collinear safe observable (depending on hard internal momenta Q) in the scattering of two hadrons h_1 and h_2 can be expressed as a convolution of parton distribution functions $f_{a/h}(x, \mu_f)$ with hard scattering kernels H_{ab}

$$
\begin{aligned}
H &= \sum_{a,b} \int_0^1 dx_1 dx_2\, f_{a/h_1}(x_1, \mu_f)\, H_{ab}(Q; Q^2/\mu^2, \mu_f/\mu, \alpha_s(\mu))\, f_{b/h_2}(x_2, \mu_f) \\
&+ \text{terms of order} \frac{\Lambda^2_{QCD}}{Q^2}
\end{aligned}
$$

- The hard scattering kernel is calculable in perturbation theory and is independent of long distance effects, in particular it does not depend on the nature of the hadrons h_1 and h_2. Trick: consider the special case with $h_i =$ external partons
- The pdf's are universal in that they only depend on the nature of the hadron h_1, h_2 and the extracted parton a, b, but not on the details of the hard process.

pdf's cont'd

The physical observable H is independent of the factorization scale μ_f. Using the perturbative μ_f dependence of the H_{ab} one obtains evolution equations for the pdf's, the DGLAP equation

$$\mu \frac{d}{d\mu} f_{a/h}(x,\mu) = \sum_{j=q,\bar{q},g} \int_x^1 \frac{d\xi}{\xi} P_{ij}\left(\frac{x}{\xi}, \alpha_s(\mu)\right) f_{j/h}(\xi,\mu)$$

where the P_{ij} are exactly the Altarelli-Parisi evolution kernels

By combining information from many experiments, the pdf's are extracted from data

- DIS = deep inelastic lepton nucleon scattering
- Drell-Yan data at hadron colliders
- di-muon data in ν_μ DIS give information on $s(x)$ via $s \to c$ CC transition and $c \to \mu X$ decay
- Inclusive jet production at the Tevatron as input for $g(x)$
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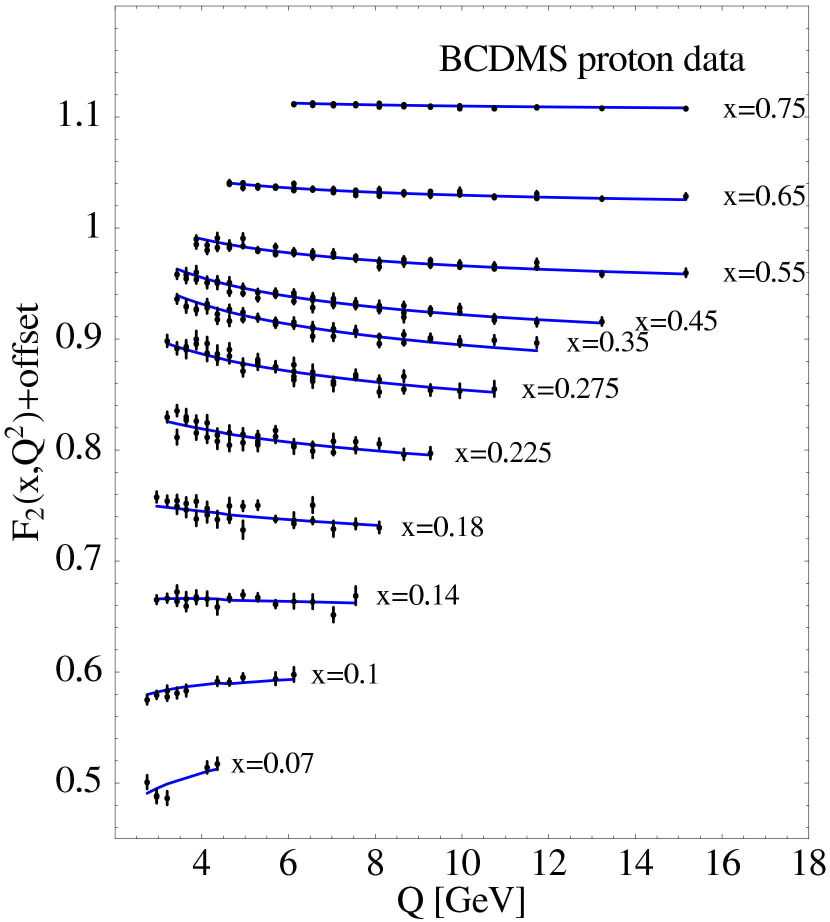
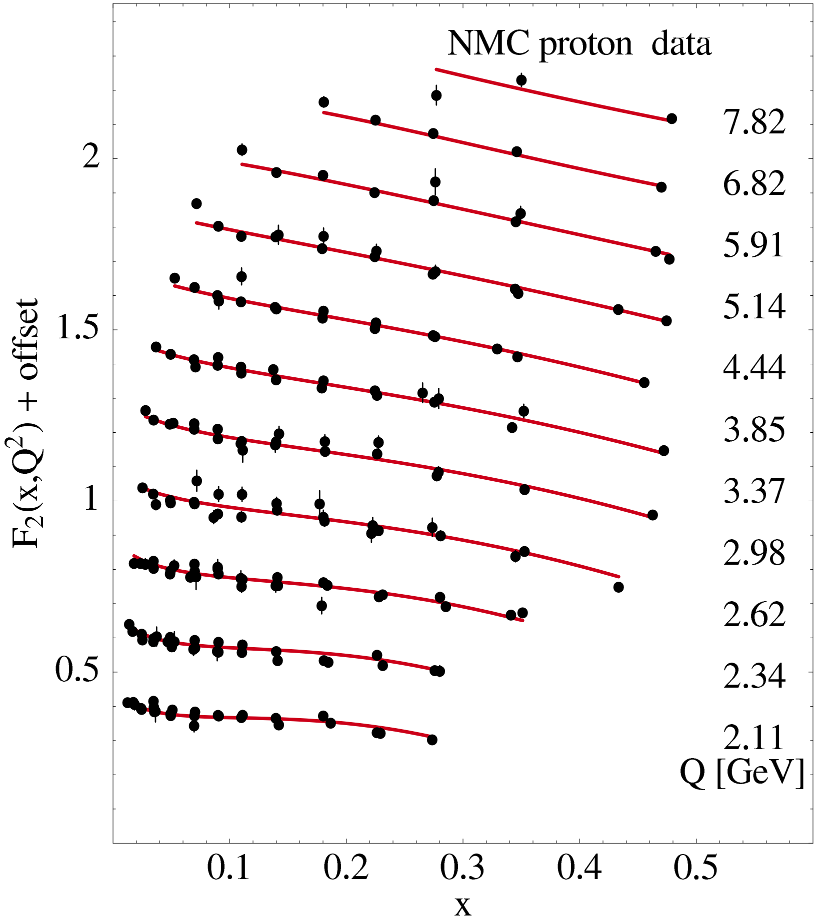
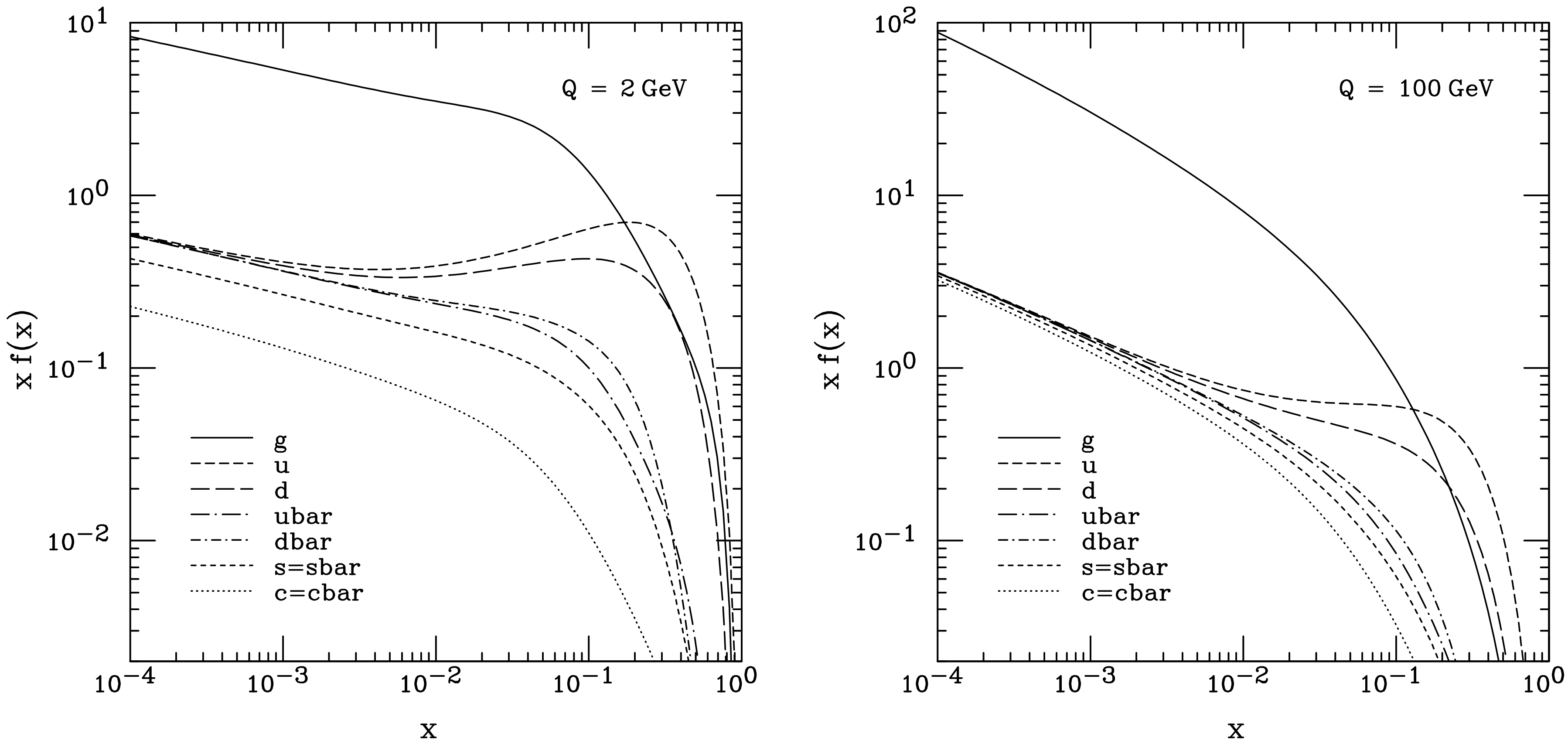
Example DIS input data with CTEQ6 fit





CTEQ and MRS and ... perform global fits to available data...

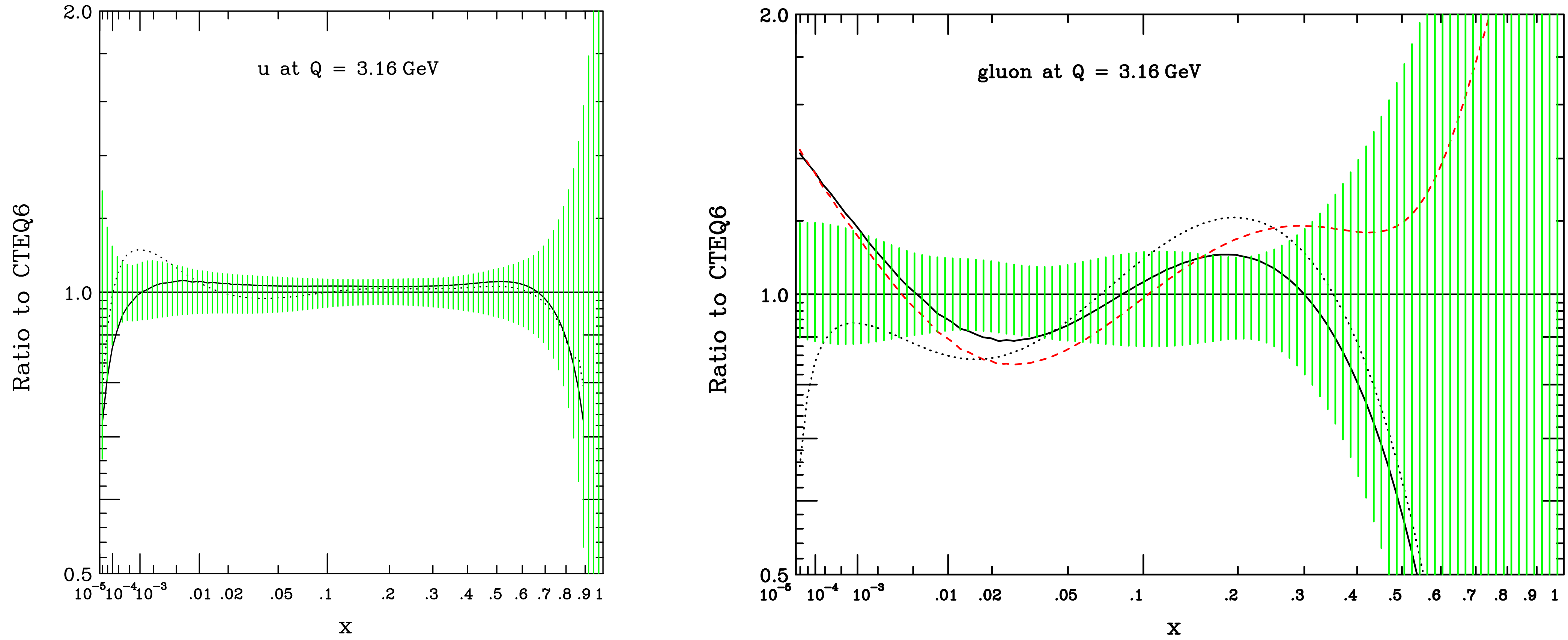
CTEQ6 pdf's at two different scales



- gluons dominate the $xf_{i/p}(x, Q)$
- large valence u and d quark contributions at $x > 0.01$
- pronounced scale ($Q = \mu_f$) dependence of pdf's

Uncertainties of pdf determinations

relative errors on: $u(x,Q)$ at $Q^2 = 10\ \mathrm{GeV}^2$ $g(x,Q)$ at $Q^2 = 10\ \mathrm{GeV}^2$



Uncertainties cont'd

Modern pdf parameterizations provide information on uncertainties which arise from

- experimental errors: statistical and systematic
- theory errors, e.g. missing higher orders in cross section calculations

Note: limitations of ansatz for functional form of pdf's cannot be included in error estimates

Typical uncertainties are in the 5–10% range, but much larger at $x \gtrsim 0.3$ for gluons, $x \gtrsim 0.5$ for valence quarks. Note that these ranges are factorization scale dependent!

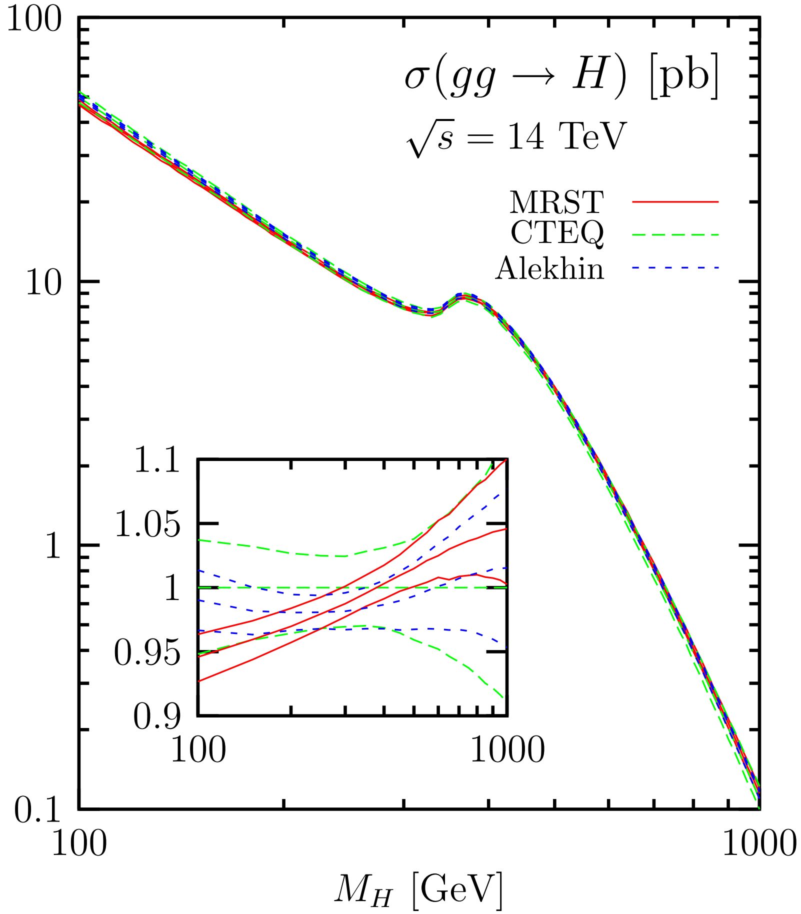
MRS and CTEQ pdf's available as FORTRAN packages

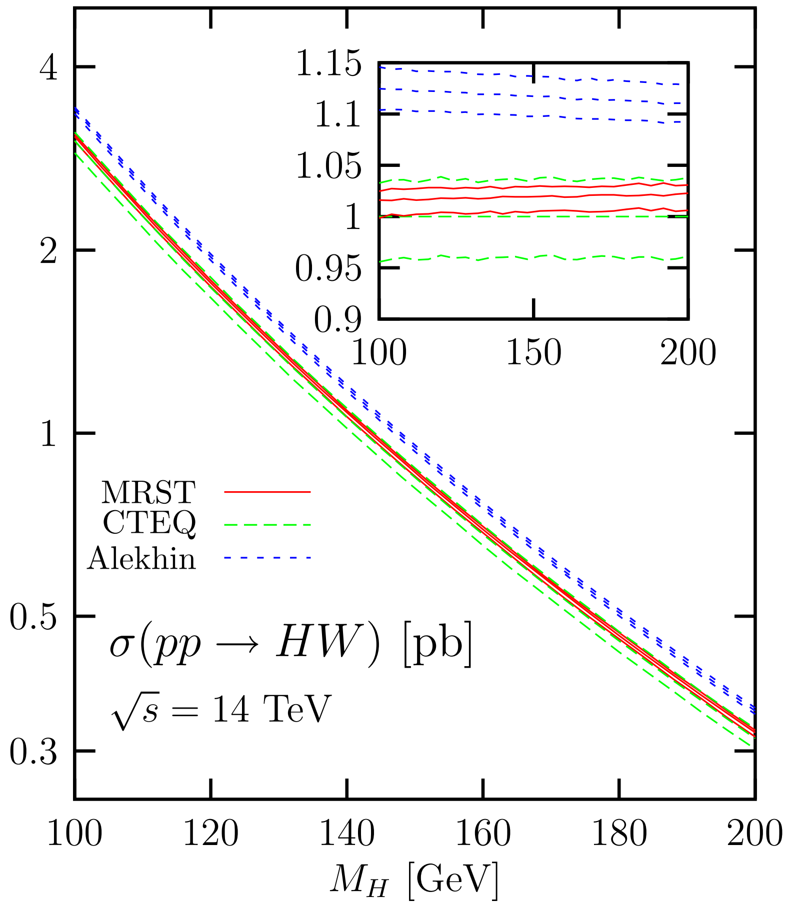
(google cteq or mrst)

Some errors are correlated and cancel in cross section calculations

Effect on calculated/predicted cross sections

Example: Higgs production at the LHC for 3 pdf sets with errors





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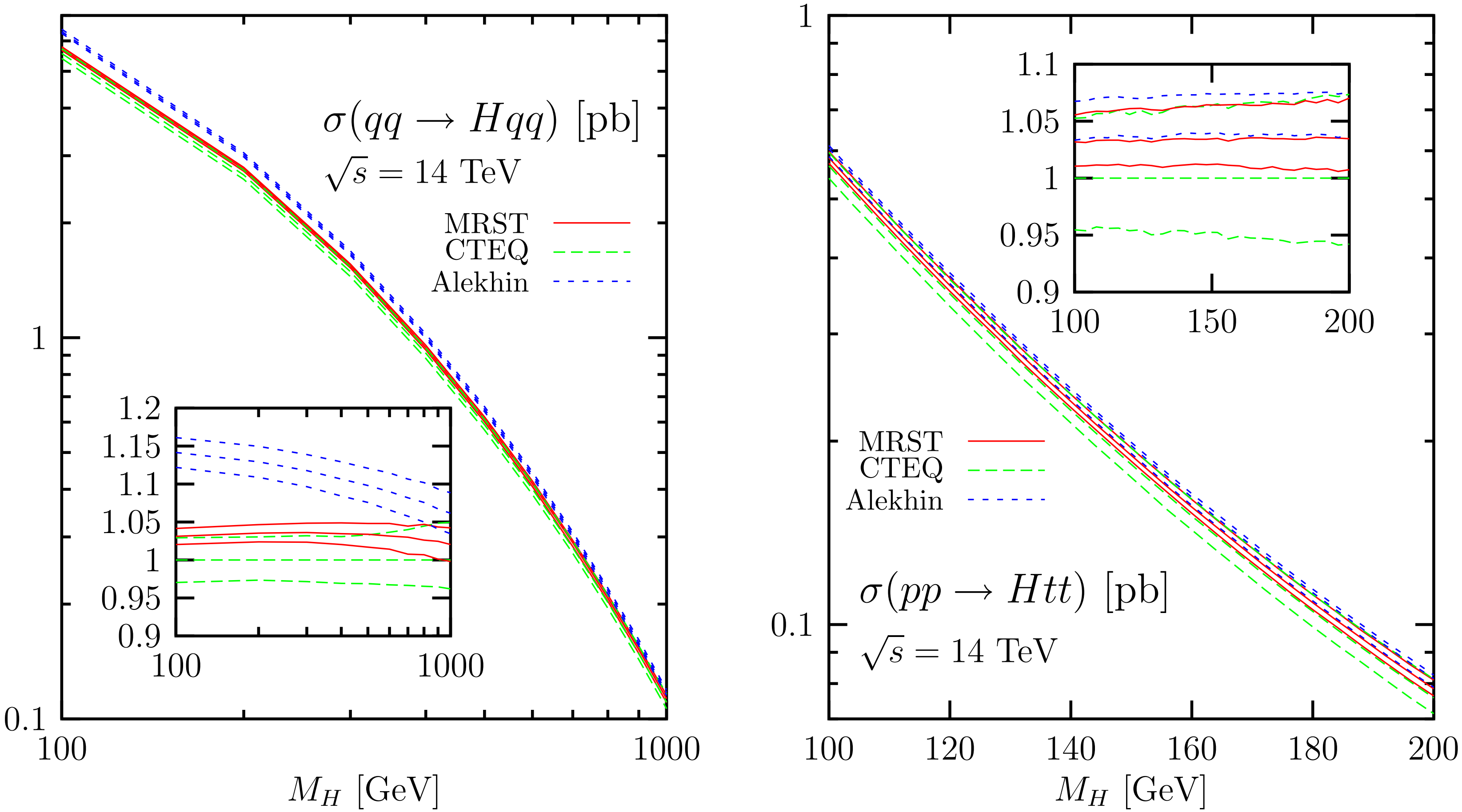
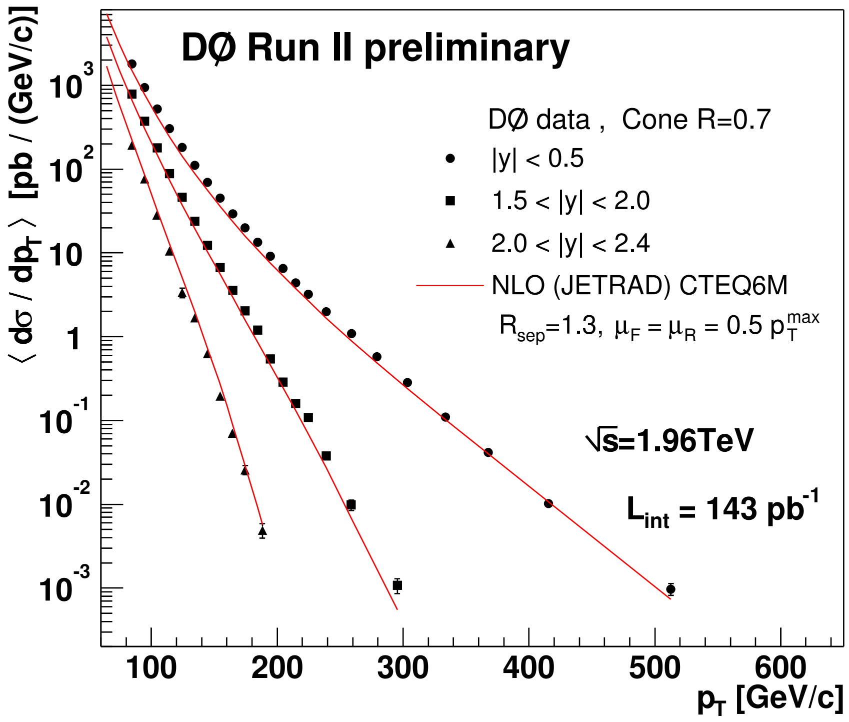
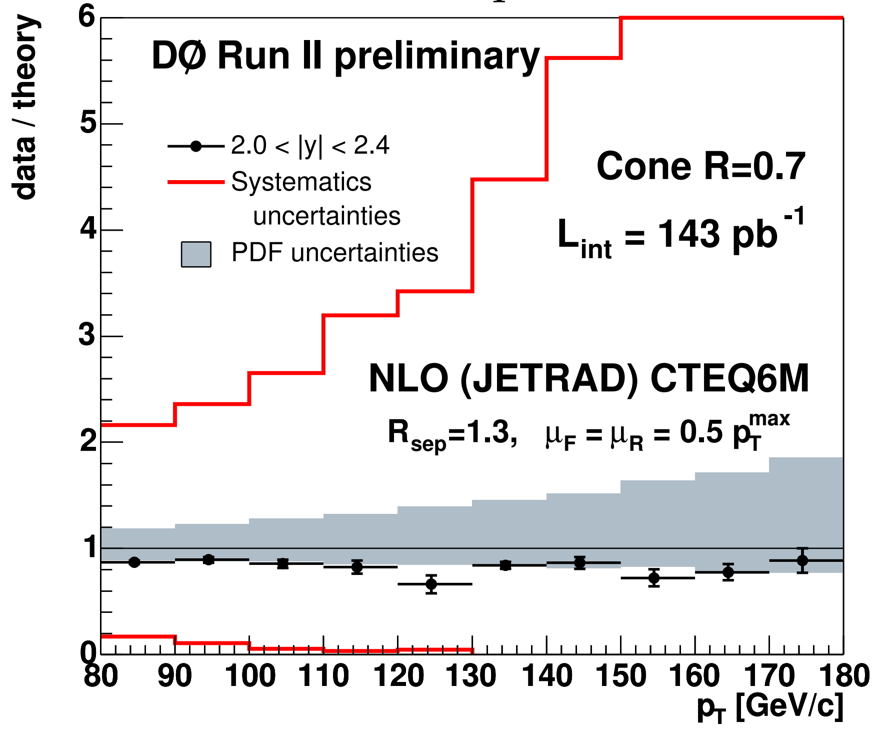


Tevatron Inclusive Jet p_T Distributions

hep-ex/0409002

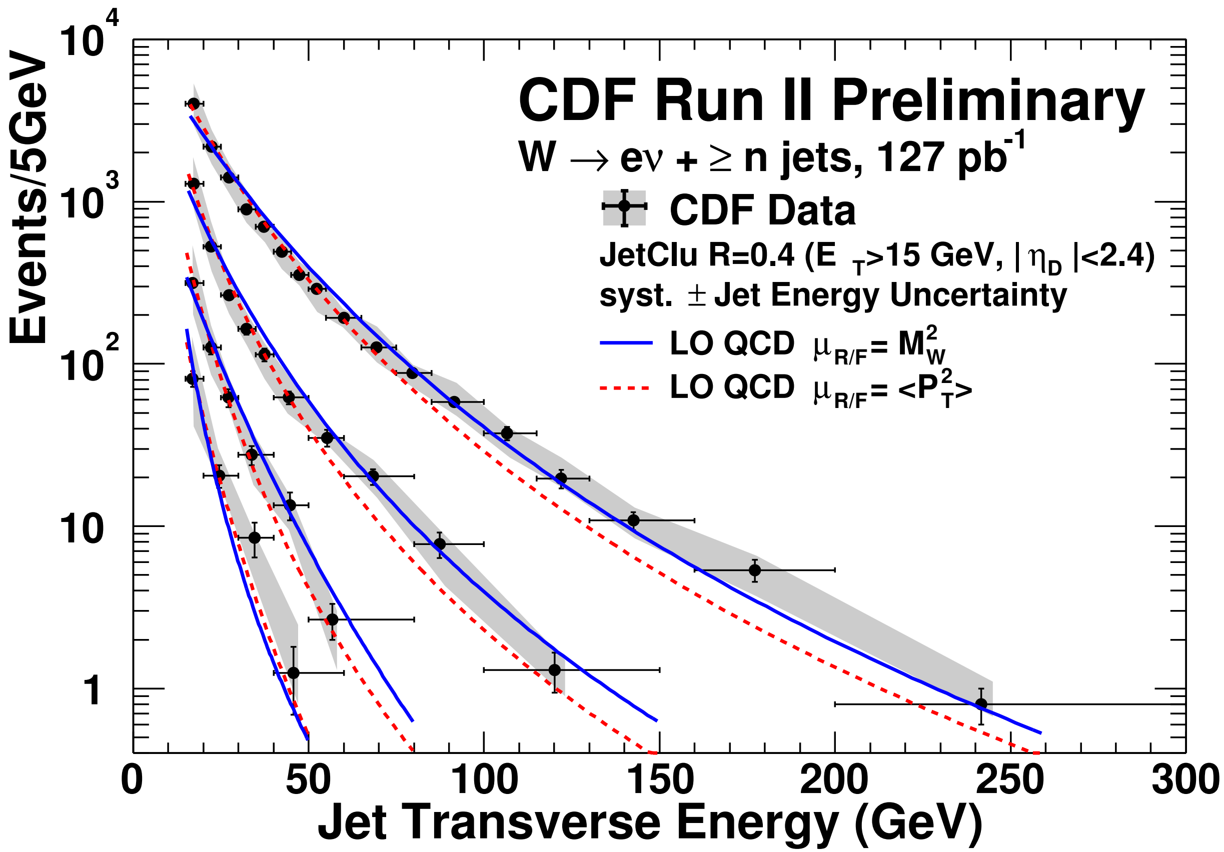




- Agreement with NLO QCD at 10–20% level over more than 6 orders of magnitude
- Steep p_T dependence $\Rightarrow$ jet rates depend totally on applied cuts: no *back-of-the-envelope* estimates

Jet E_T in $W + n$ jet events

E_T distribution of the n-th jet (n=1,2,3,4) in $W + n$ jet events
Jets are E_T ordered in descending order



Perturbative QCD gives good description of distribution of additional jets in W production: important for top quark search