PDFs and Top Physics at Tevatron and LHC

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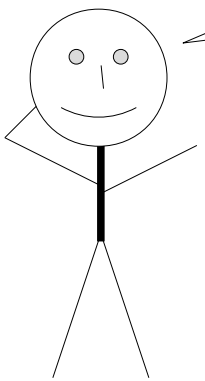
LPSC

Top Workshop: From D0 to ATLAS

Grenoble, 10/10/06

Scope

" What do/will we know about PDF's and the possible constraints relevant to top physics at the Tevatron and LHC? "



Outline

I. PDFs: Status

II. PDF Uncertainties: Implications for Top Physics

III. Top Physics: Constraints for PDFs
(just two remarks due to lack of time)

IV. Conclusions

I. PDFs: Status

- Factorization (defines PDFs)
- Global Analyses
  - Many old or semi-global analyses
  - Updated fully global analyses by two groups (only): CTEQ, MRST
- PDF Uncertainties
- Lines of Improvement

Web-Resources:

Durham PDF server: http://durpdg.dur.ac.uk/hepdata/pdf.html

LHAPDF: http://hepforge.cedar.ac.uk/lhapdf/

CTEQ: http://www.phys.psu.edu/~cteq/ --> Schools: 2006, A.M. Cooper-Sarkar

Les Houches 2005, SM Benchmarks/PDF Uncertainties Webpage:

http://www.pa.msu.edu/~huston/Les_Houches_2005/Les_Houches_SM.html

Factorization

QCD --> QCD factorization --> PDFs

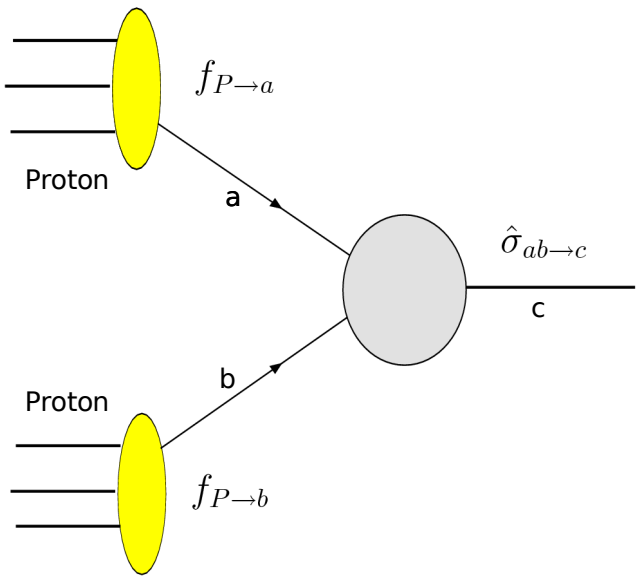
PDFs only meaningful in this context!

Predictions for observables and their uncertainties

within this standard framework!

There might be breaking of QCD factorization, deviations from DGLAP evolution, or ...

Factorization



$$\sigma = f_{P\to a} \otimes f_{P\to b} \otimes \hat{\sigma}_{ab\to c}$$

From experiment

Calculable from theoretical model

Parton Distribution Functions (PDFs)

$$f_{P\to a,b}(x,\mu^2)$$

- Universal
- Describe the structure of hadrons
- The key to calculations involving hadrons in the initial state!!!

The hard part $\hat{\sigma}_{ab\to c}(\mu^2)$

- Free of short distance scales
- Calculable in perturbation theory
- Depends on the process

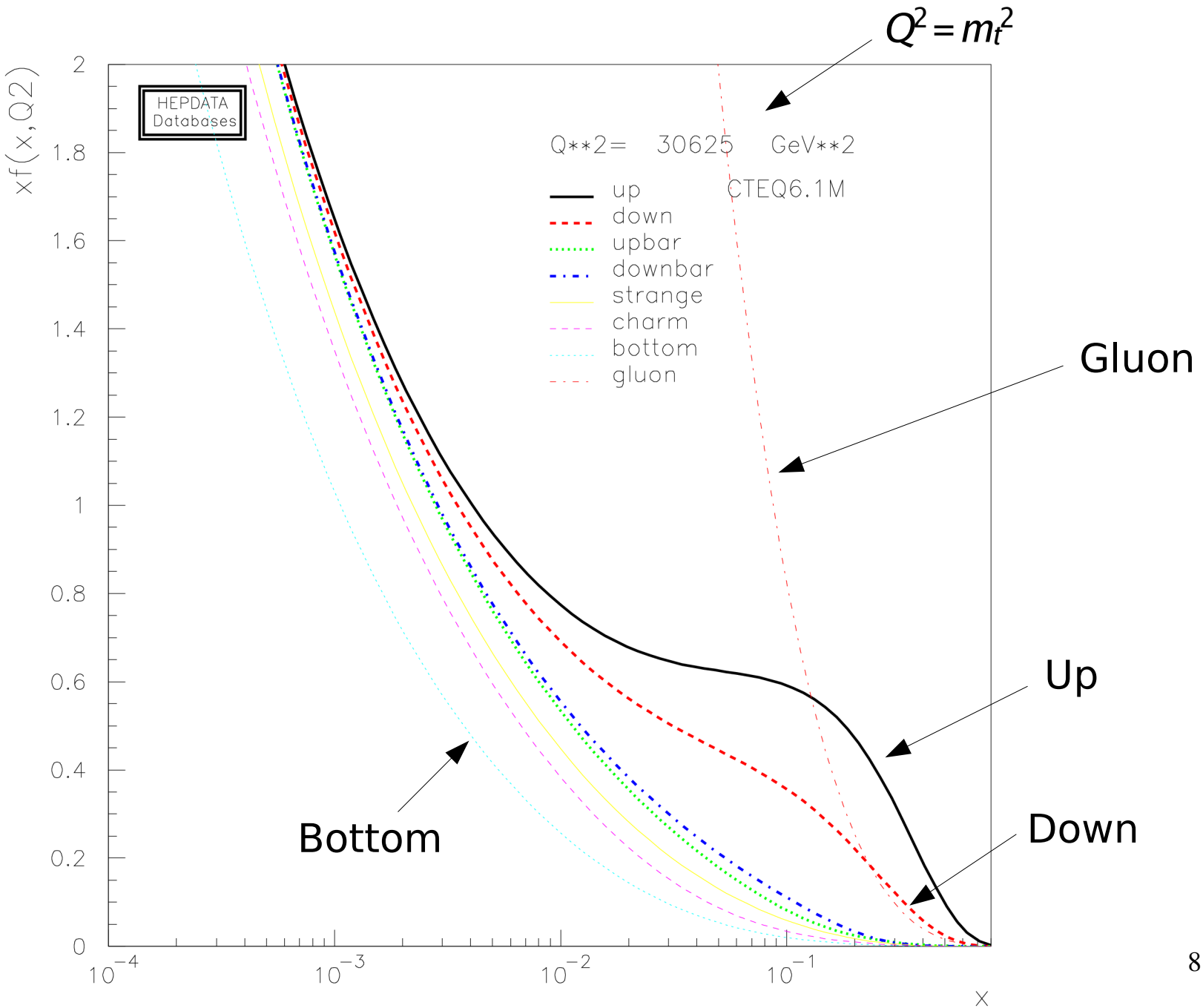
The different Parton Distributions:

$u_v(x,Q^2), d_v(x,Q^2)$	quark model, carry 50% of proton mom.
$\bar{\mathrm{u}}(\mathrm{x},\mathbf{Q^2}), \bar{\mathrm{d}}(\mathrm{x},\mathbf{Q^2})$	light sea, E866: $\bar{\mathrm{u}} \neq \bar{\mathrm{d}}$
$g(x,Q^2)$	gluon, carries 30% of momentum
$\mathrm{s}(\mathrm{x},\mathbf{Q^2}), \bar{\mathrm{s}}(\mathrm{x},\mathbf{Q^2})$	strange sea, NuTeV: $\mathrm{s} \neq \bar{\mathrm{s}}$ ->Fred Olness
$c(x,Q^2), b(x,Q^2)$	heavy quark PDFs, perturbatively generated
	possible intrinsic contribution at large-x
$\gamma(x,Q^2)$	Photon PDF in proton <-> QED radiation

Small isospin violation: $u^p(x,Q^2) \neq d^n(x,Q^2)$

(already due to QED radiation)

CTEQ6.1M PDFs



Global Analyses

1.) Parameterize x-dependence of PDFs at input scale Q_0:

$$f(x,Q_0)=A_0 x^{A_1}(1-x)^{A_2} P(x;A_3,...);\ f=u_v,d_v,g,\bar{u},\bar{d},s,\bar{s}$$

2.) Evolve from Q_0 -->Q by solving the DGLAP evolution equations

--> f(x,Q)

3.) Define suitable Chi^2 function and minimize w.r.t. fit parameters

$$\chi^2_{global}[A_i]=\sum_n w_n \chi^2_n;\ \chi^2_n=\sum_I \left(\frac{D_{nI}-T_{nI}}{\sigma_{nI}}\right)^2$$

Sum over experiments

weights, default=1

Sum over data points

The fine art of fitting

Note: Not at all straight forward and easy!

Need to include many (~15) data sets to constrain PDFs; >2000 points

Data not perfect

- Data individually acceptable?
- Data from different experiments compatible?;

Cuts, Data selection, include correlated erros

Theory not perfect!

Assumptions about unconstrained PDFs

Data:

• Deep inelastic scattering data	Backbone: 10^-5 < x < 0.1
• H1 ,ZEUS (ep)	up > down, evolution of F2 -> gluon
• BCDMS,NMC (μp,μd)	
• CCFR (υ-Fe)	
• p+pbar -> jet +X : D0, CDF	large-x gluon: 0.01 < x <0.5 dominated by systematics
• DY pp: E605	$q\bar{q} \to \mu^+\mu^-$ info on sea
• DY pd/pp: NA51, E866 (updated)	Asymmetry: info on $\bar{d}/\bar{u}$
• W-lepton asymmetry: CDF	*d/u* at large-x $(u\bar{d} \to W^+ \, , \, d\bar{u} \to W^-)$
• υ-DIS dimuon data: Nutev	$s \, , \bar{s}$

PDF Uncertainties

Three ways to estimate uncertainties due to PDFs:

1.) Compare different PDF sets (only method until ~5 yrs. ago)

2.) 'Hessian method' --> Eigenvector PDF sets

--> PDFs and Parton-Parton luminosity functions with errors
--> **Any observable with (1-σ) errors**

3.) 'Lagrange multiplier method' (most general method)

--> Uncertainty analysis using constrained fits
--> Requires dedicated analysis for each observable

Hessian method:

Assume only one fit parameter a --> Expand $\chi^2(a)$ around Minimum a_0

$$\chi^2(a)=\chi^2(a_0)+\frac{1}{2}\chi^{2''}(a_0)(a-a_0)^2+\ldots$$

Eigenvalue of Hessian 'matrix'

Determine Tolerance T <--> 1-sigma uncertainty: $T=\Delta\chi^2$

--> 1-σ uncertainty range for parameter a such that:

$$\chi^2(a\pm\Delta a)=\chi^2(a_0)+\Delta\chi^2\Rightarrow\Delta a=T\sqrt{2/\chi^{2''}(a_0)}$$

--> best fit PDF: a_0, two 'Eigenvector' PDFs: $a_0+\Delta a, a_0-\Delta a$

1-σ uncertainty for Observable X:

$$\Delta X=\frac{X(PDF[a_0+\Delta a])-X(PDF[a_0-\Delta a])}{2}\propto\Delta a\propto T$$

Lagrange multiplier method:

Find best PDFs under the constraint that an Observable X takes a particular value. No quadratic approximation (but time-consuming).

No constraint --> Best fit: $\chi_0^2, X = X_0$

Constraint by adding Lagrange multiplier term: $\chi^2 \Rightarrow \chi^2 + \lambda(X - X_c)$

Minimize → $\chi^2[X]$

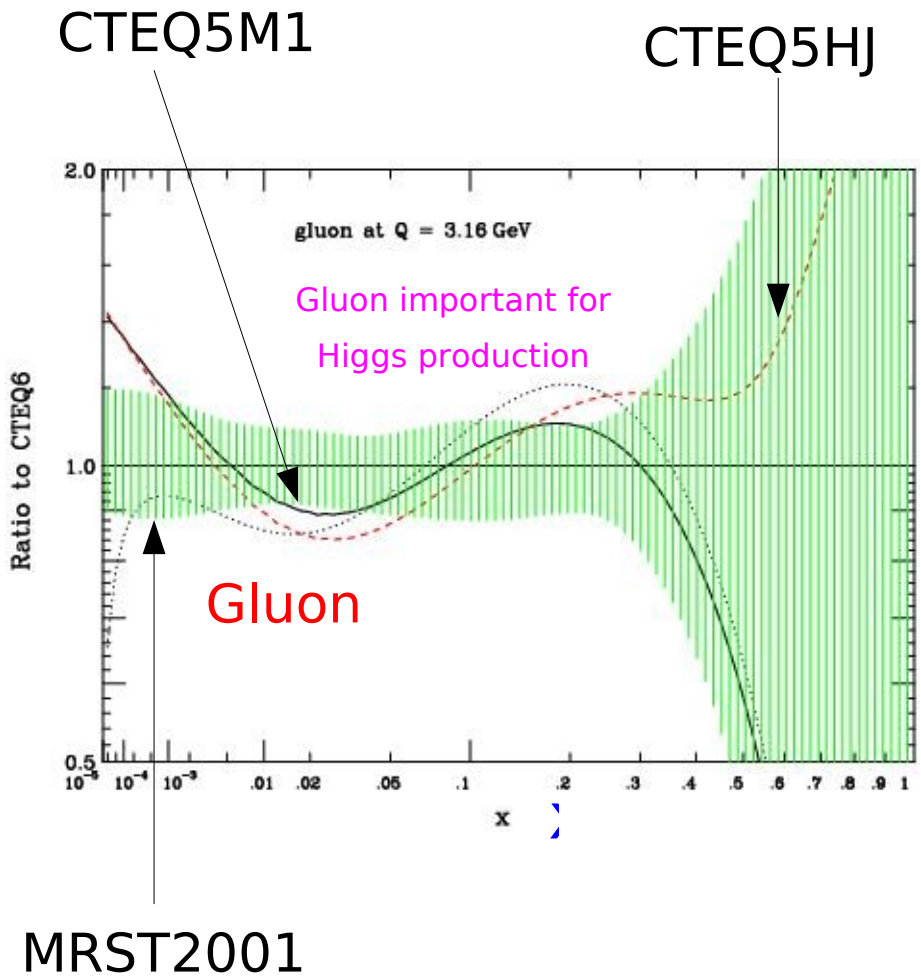
Demand → $\chi^2[X \pm \Delta X] = \chi_0^2 + \Delta\chi^2$ determines ΔX

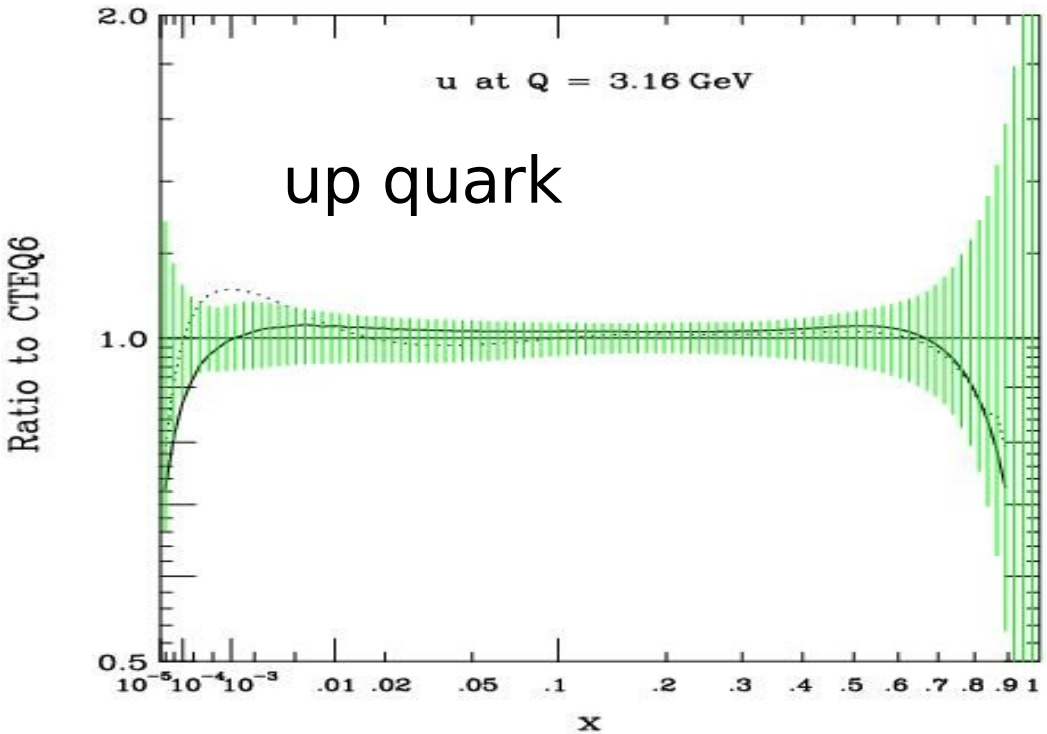
→ 1-σ uncertainty range ΔX

dedicated max./min. PDFs for Observable X

Uncertainty Bands (w.r.t. CTEQ6M)

CTEQ6,JHEP07(2002)012





However, uncertainty shrinks at larger scales

Bottom PDF

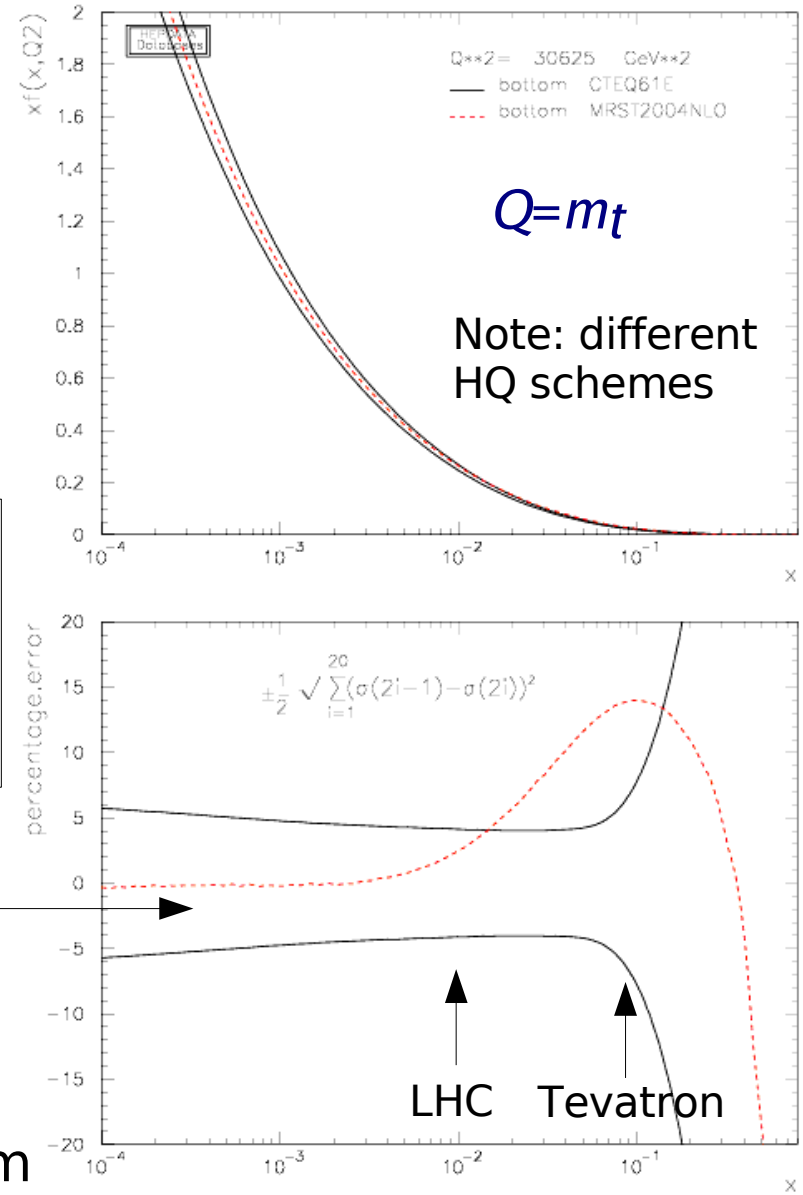
Bottom PDF important for (t-channel) single top production and several new physics processes

The uncertainty band can greatly underestimate the true uncertainty, if assumptions have been made, like:

$$s(x, Q_0) = \bar{s}(x, Q_0) = \kappa \frac{\bar{u} + \bar{d}}{2} \qquad \text{(CTEQ6)}$$

Assumption here: Heavy quark PDFs are dynamically generated,i.e., by perturbative boundary conditions and evolution!

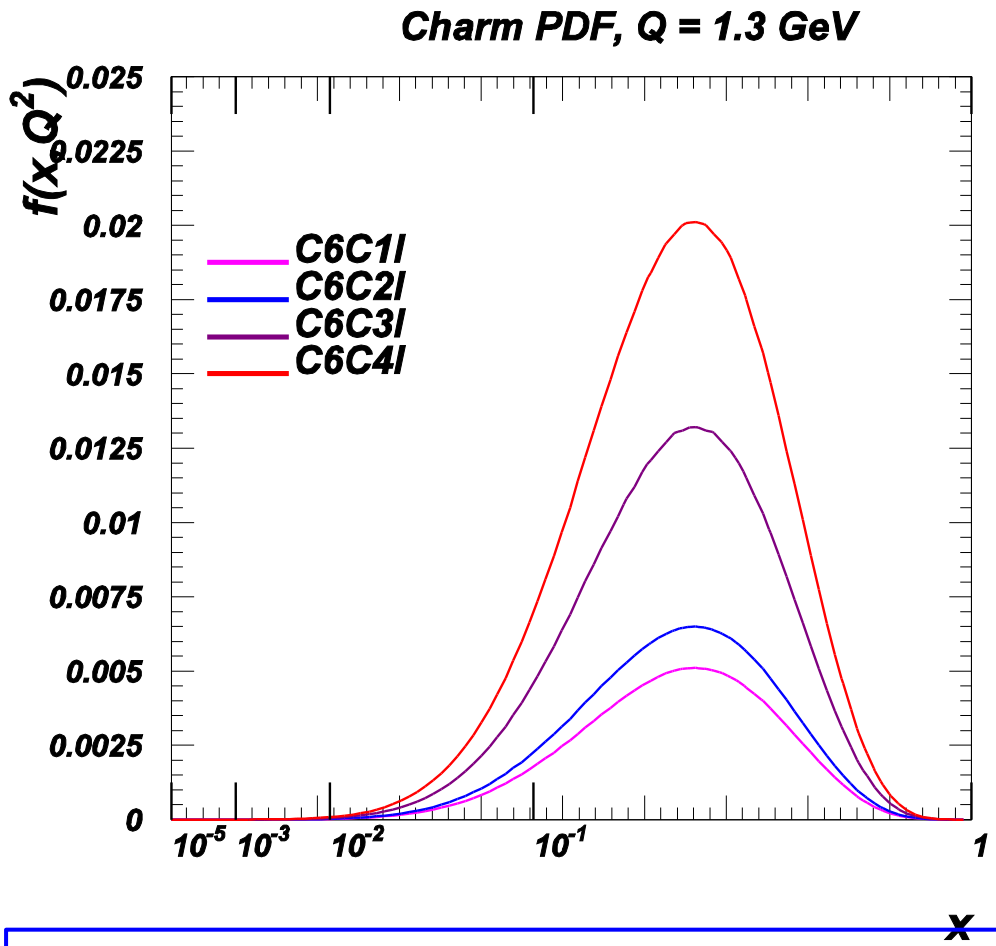
Is this small error realistic?

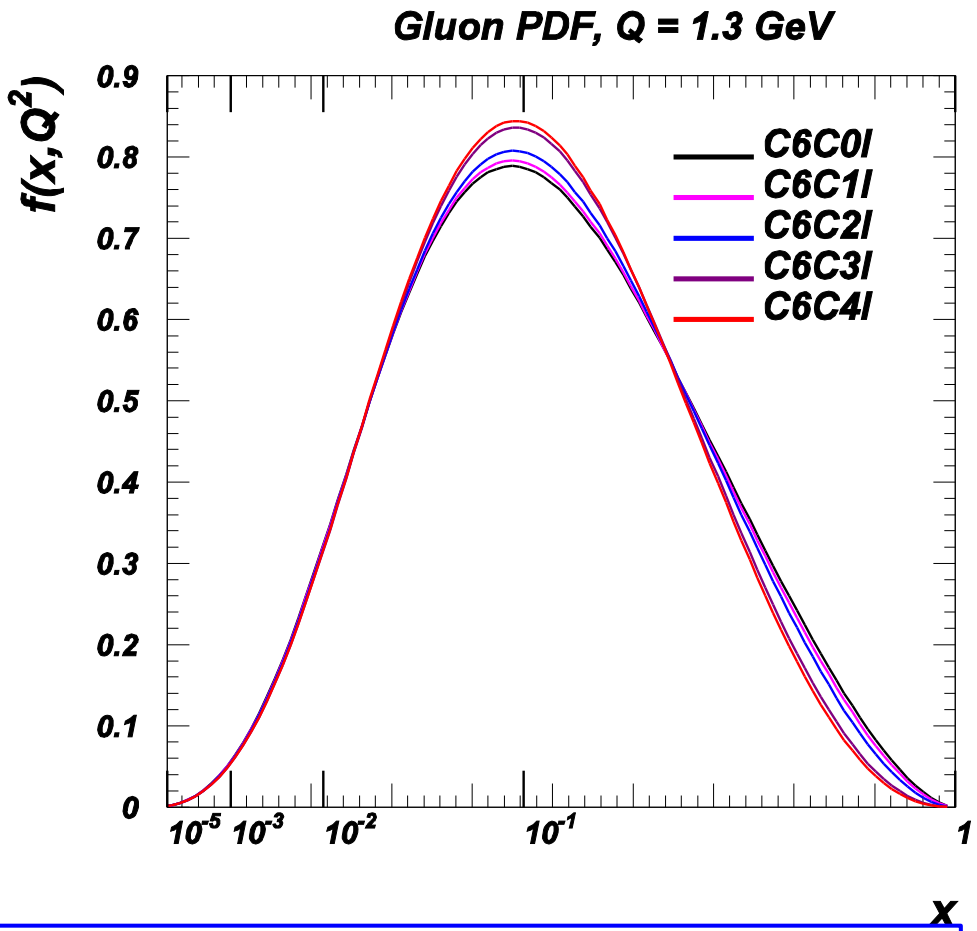


See talk by Wu-Ki Tung at DIS'06 about allowed amount of intrinsic charm

Charm and Gluon Distributions at Q = 1.3 GeV

Varying amounts of input lightcone charm components
(à la Brodsky etal.) : Momentum frac. at Q_0 = 0 — 0.02.



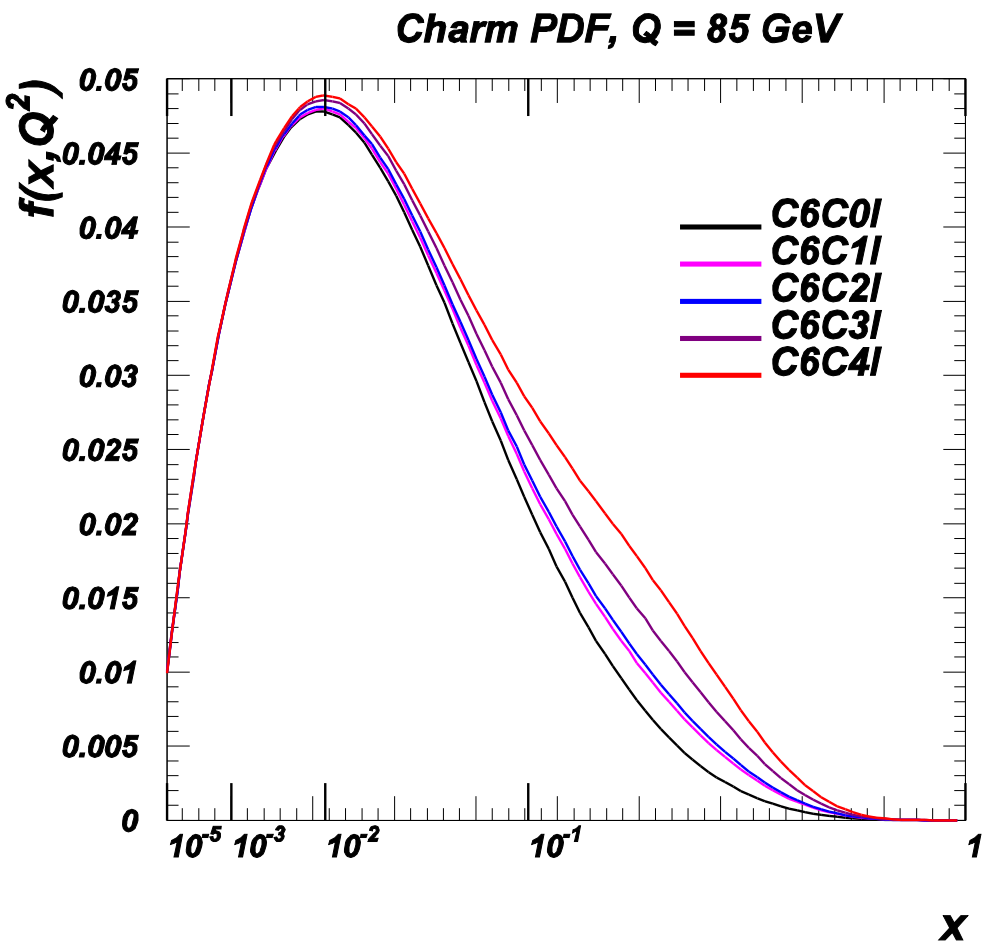


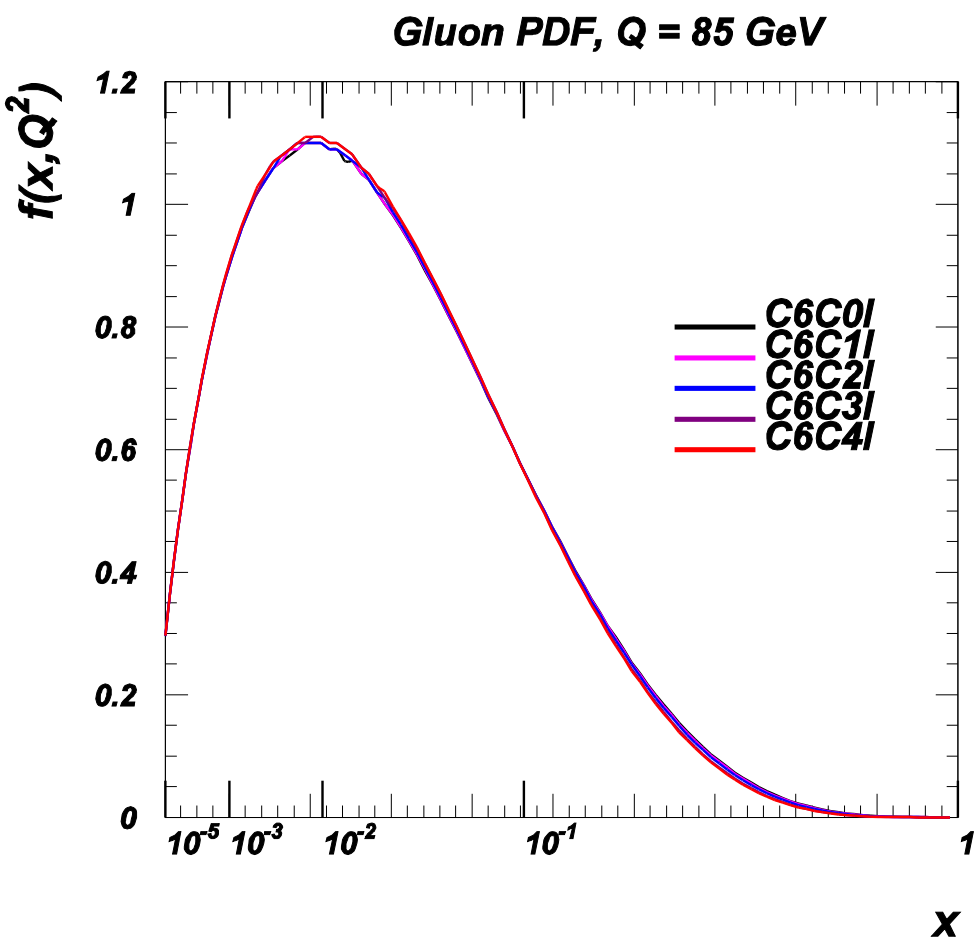
Horizontal axis is scaled in $x^{1/3}$—inbetween linear and log— in order to exhibit the behavior at both large and small x.

Wu-Ki Tung, DIS'06

Charm and Gluon Distributions at $Q^2 = (85\ \text{GeV})^2$

Varying amounts of input lightcone charm components (à la Brodsky etal.) : Momentum frac. at Q0 = 0 — 0.02.





* Very substantial amount of charm, over the radiatively generated component (C6C0I), still persists at this very large scale ➔ there can be interesting phenomenological consequences even at LHC.

Wu-Ki Tung, DIS'06

Lines of Improvement

- New data sets (HERA-II, Tevatron Run-II)
  - υ-DIS dimuon data --> strange quark PDF
  - DIS cross section data (in contrast to F_{123} data)
  - combined H1, ZEUS data for F_2 ; data for F_2^c
  - HERA jet data --> **reduce gluon uncertainty!**
  - HERA-II CC cross section data: improve large-x d(x)/u(x)
- Correlated errors
- Improved theory
  - TMC, Nuclear corrections --> E.g. Nutev υ-Fe data
  - Heavy flavour schemes (ACOT,...) --> quark mass effects
  - Intrinsic charm/bottom
  - Resummations, NNLO
  - Light SUSY degrees of freedom
- Reduce tolerance T! Note linear dependence on T

II. PDF Uncertainties: Implications for Top Physics

- Parton Kinematics
- Luminosity functions
  (--> quick estimate of cross sections. and PDF uncertainties)
- Uncertainties of Observables due to PDFs
  (all calculations should come with uncertainty bands)
  - Example: $t\bar{t}$-production

- Don't discuss implications for backgrounds to top physics

Parton Kinematics

$$x_{1,2} = \frac{M}{\sqrt{S}} \exp(\pm y)$$

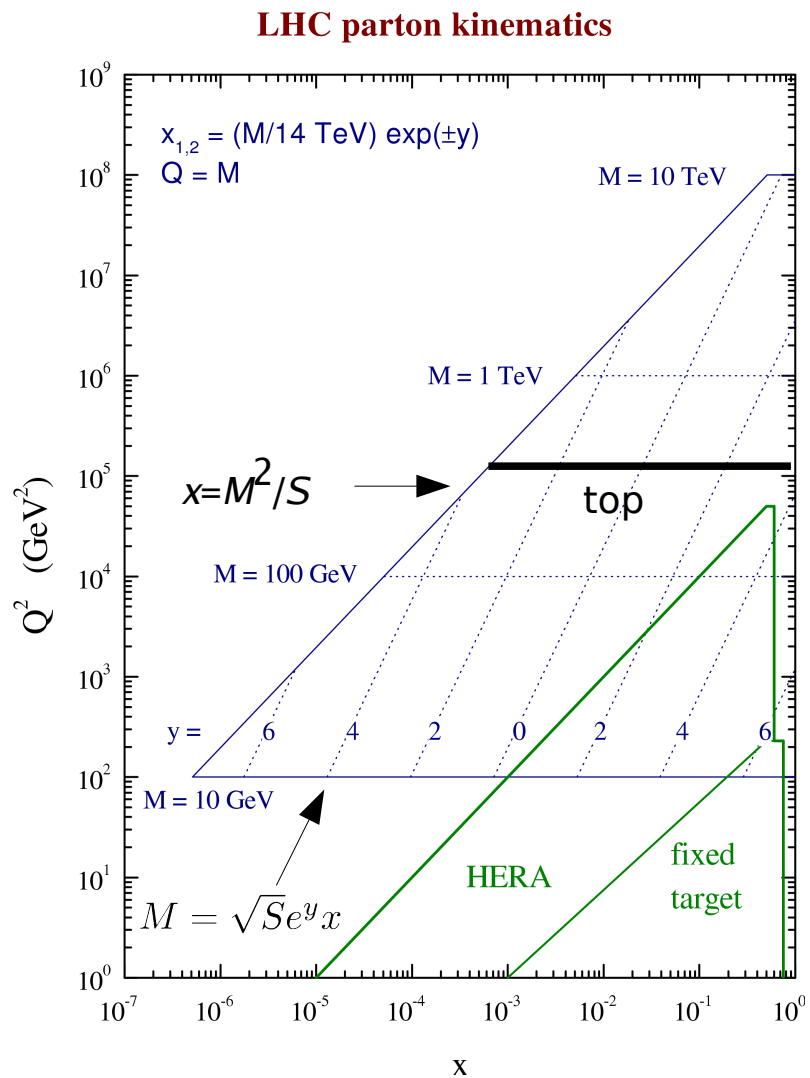
Estimates:

$y=0, M=2m_t=350\,GeV$

$$\sqrt{S} = 2\,TeV\,(Tevatron),\ 14\,TeV\,(LHC)$$

x ~= 0.175 (Tevatron)

x ~= 0.025 (LHC)



R. Thorne, et al., hep-ph/0507015

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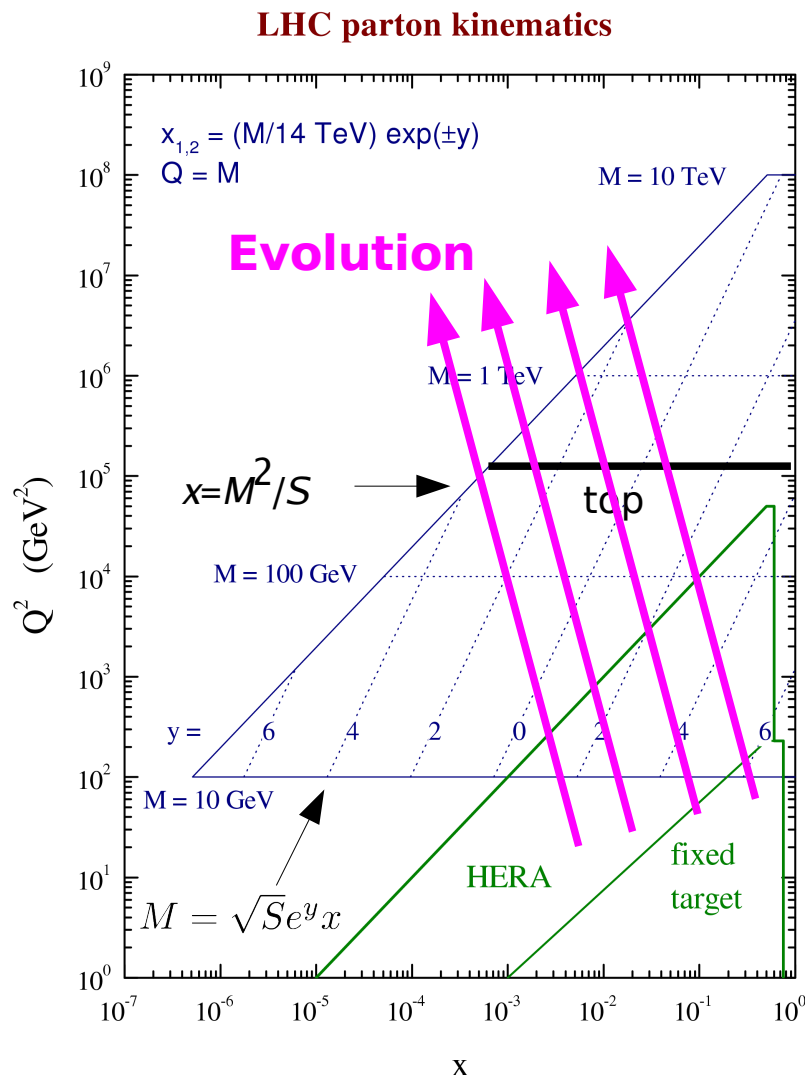


R. Thorne, et al., hep-ph/0507015

Luminosity functions

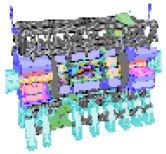
$$\frac{d\sigma}{d\hat{s}} = \int dx_1 dx_2 f_i(x_1) f_j(x_2) \hat{\sigma}_{ij} \delta(x_1 x_2 S - \hat{s})$$

$$\frac{d\sigma}{d\hat{s}} \simeq \hat{\sigma}_{ij}[x_1 = x_2 = \hat{s}/S] \boxed{\int dx_1 dx_2 f_i(x_1) f_j(x_2) \delta(x_1 x_2 S - \hat{s})}$$

(*y*=0)

$$\frac{dL_{ij}}{d\hat{s}}$$ Luminosity function

Talk by Joey Huston, ATLAS top meeting



gg luminosity uncertainties

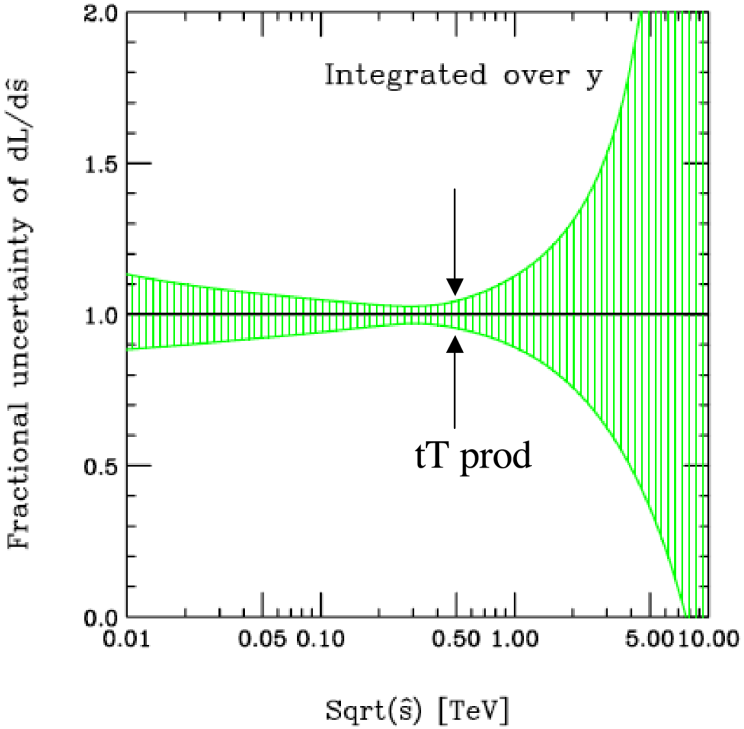


Fig. 4: Fractional uncertainty of gg luminosity integrated over y.

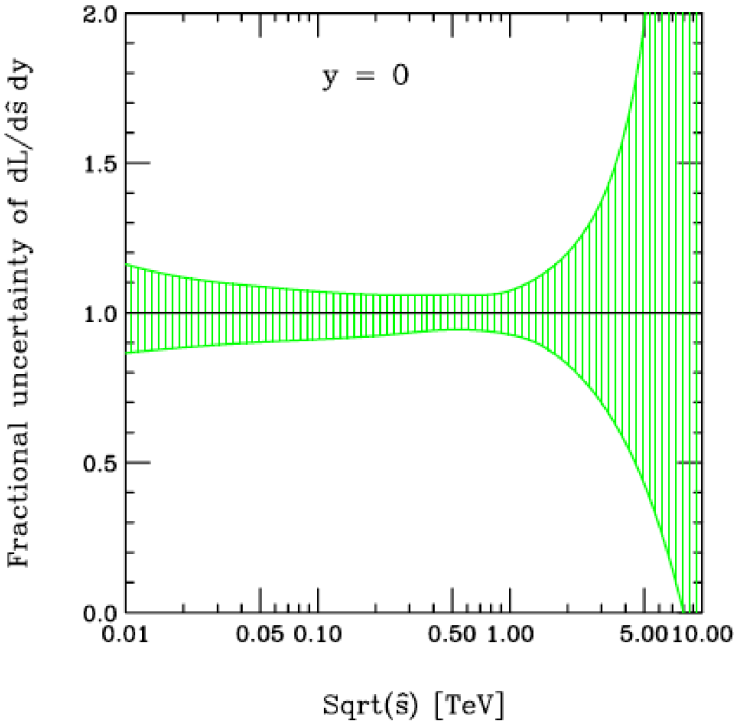
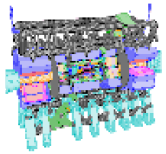


Fig. 5: Fractional uncertainty of gg luminosity at $y = 0$.

Dominant uncertainty well under control

Talk by Joey Huston, ATLAS top meeting



gq luminosity uncertainties

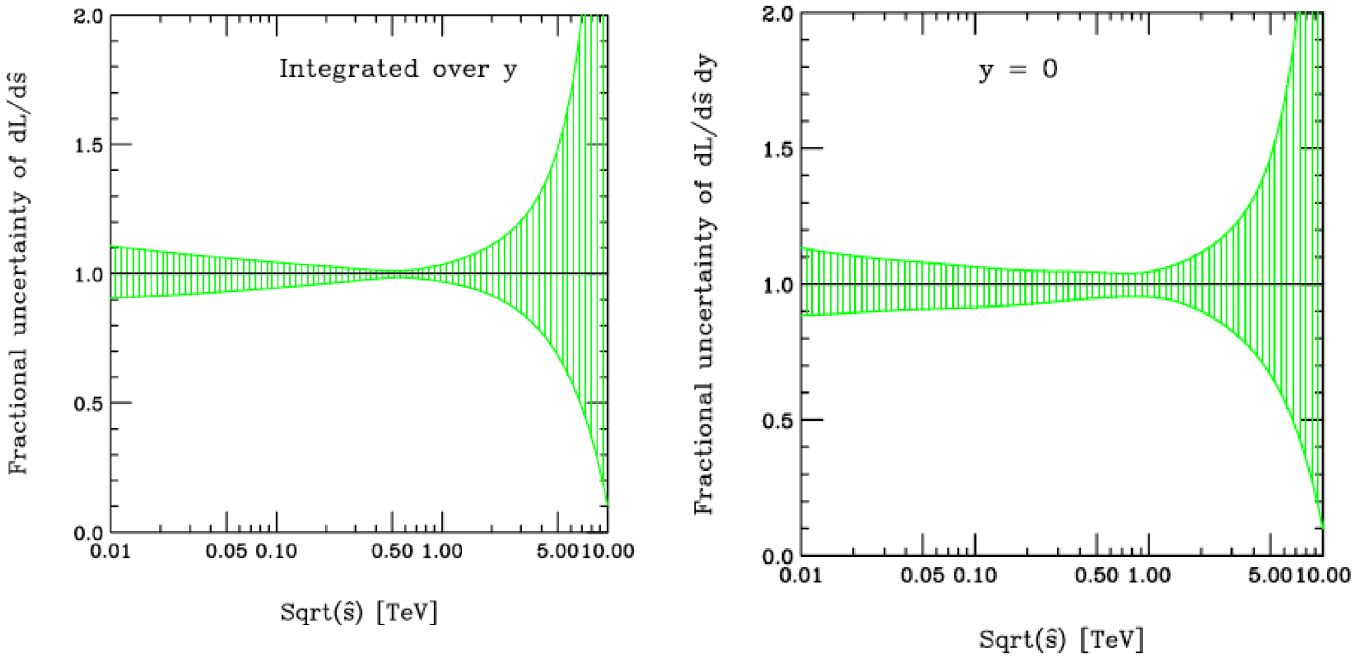


Fig. 6: Fractional uncertainty for Luminosity integrated over y for $g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$,

Talk by Joey Huston, ATLAS top meeting

qQ luminosity uncertainties

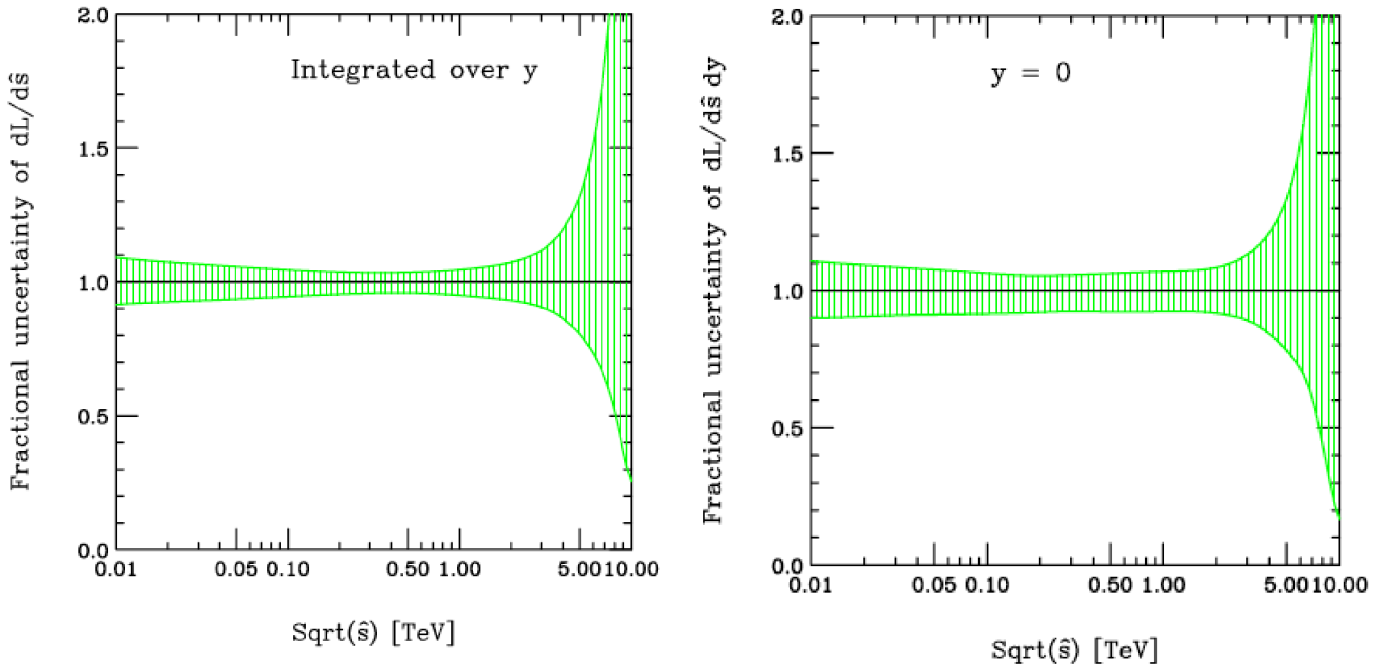


Fig. 7: Fractional uncertainty for Luminosity integrated over y for $d\bar{d} + u\bar{u} + s\bar{s} + c\bar{c} + b\bar{b} + \bar{d}d + \bar{u}u + \bar{s}s + \bar{c}c + \bar{b}b$.

The t-tbar cross section at the Tevatron

Detailed Study of Systematics due to PDFs and Scale Dependence

Cacciari et al.

hep-h/0303085

small increase of x-sec, reduced scale uncert.

- NLO QCD + resummed NLL soft logs
- global PDFs with 1-σ uncertainties
- Scale uncertainty: $(m_t/2 < \mu_R = \mu_F < 2m_t)$
  - ~ ±10% : NLO
  - **~ ±5% : NLO + NLL**
- PDF uncertainty: **~ ±6-7%** (eigenvector sets CTEQ,MRST)
- Strong dependence on m_t

PDF Uncertainty 6-7% dominated by gluon uncertainty!

At Tevatron:

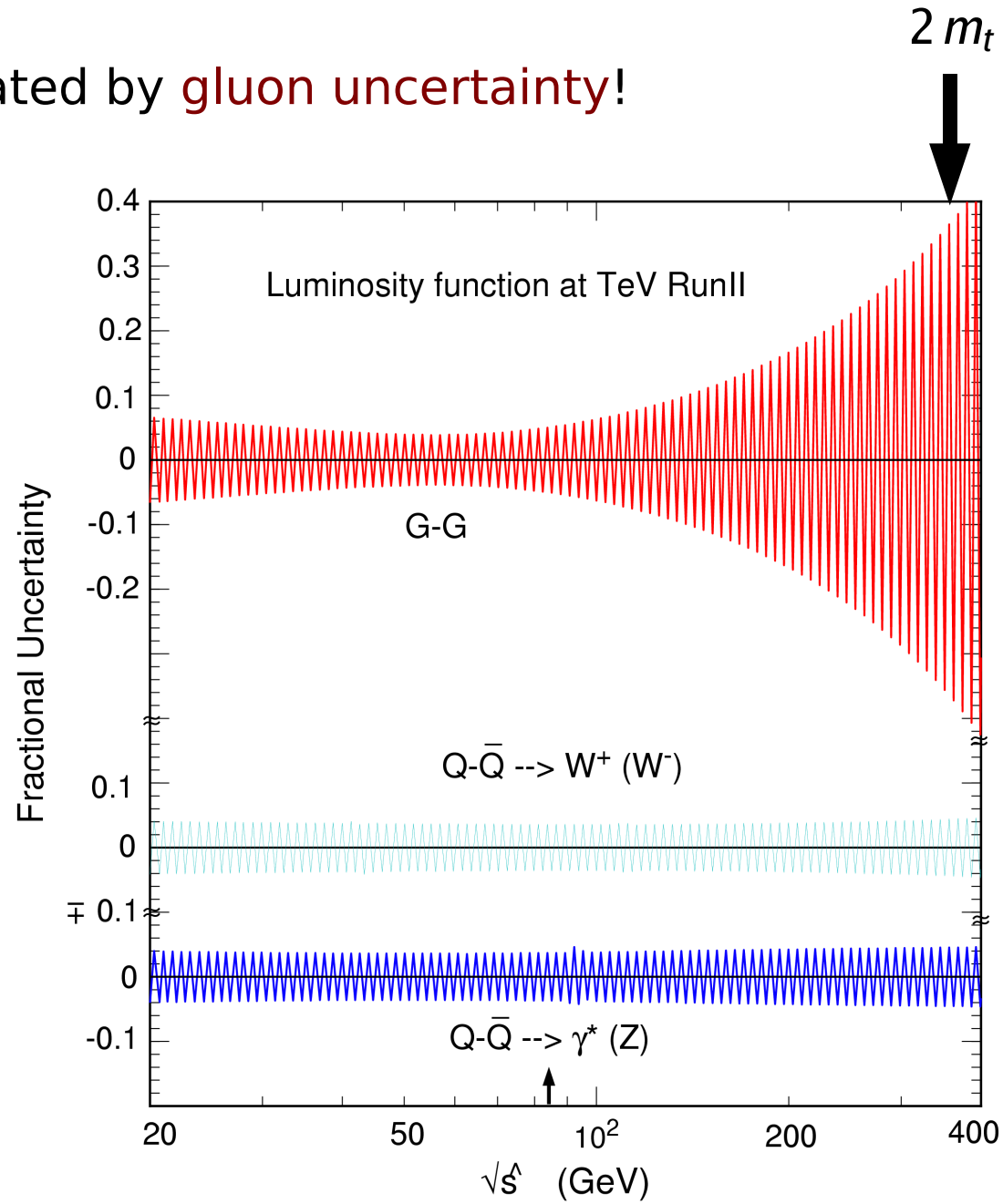
1.) $x \simeq 0.2$ and larger, since contributions from $y \neq 0$

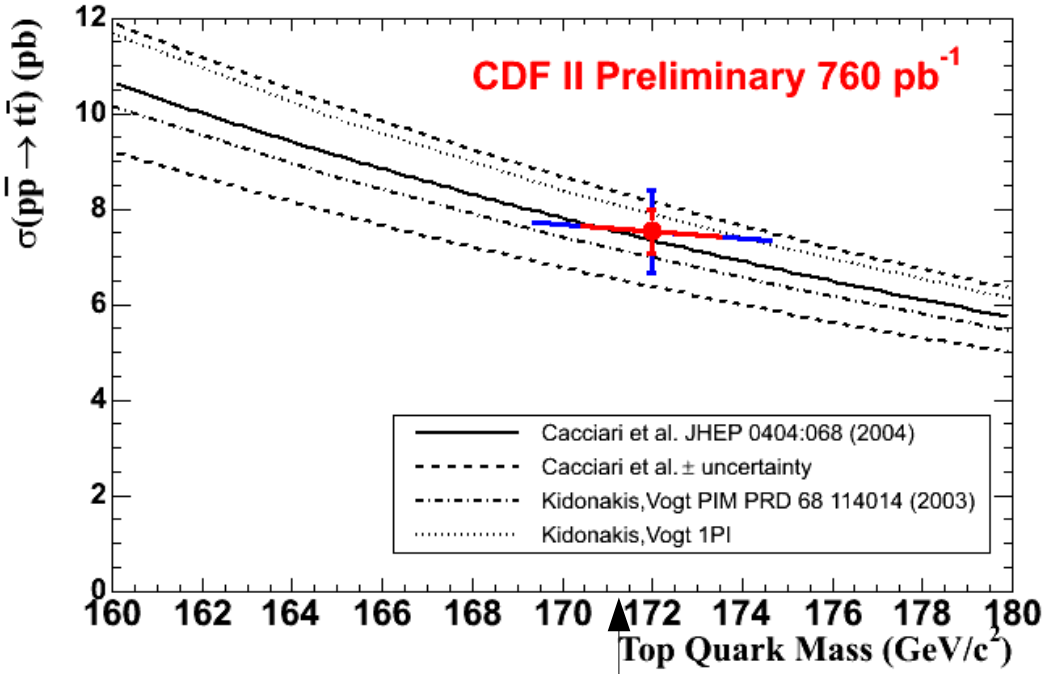
2.) $q\bar{q}$ -channel dominates! 80-90%

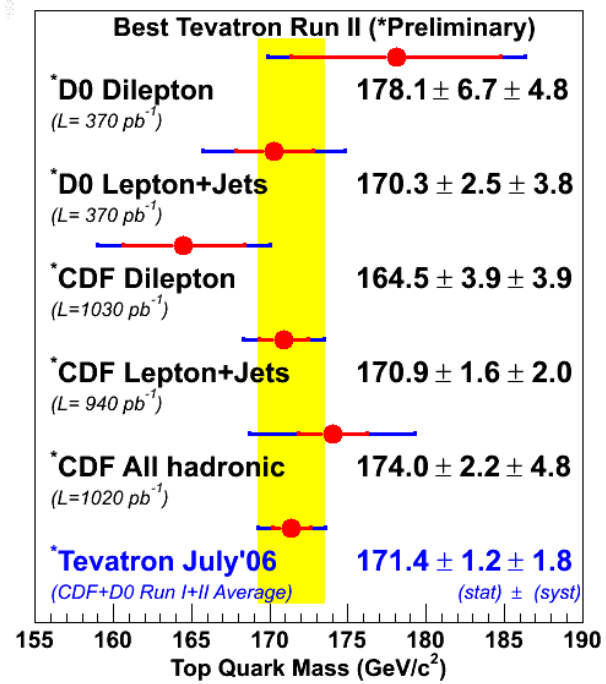
3.) Large uncertainty for large-x gluon

parton-parton luminosity:

$$\int dx_1 dx_2 f_1(x_1) f_2(x_2) \delta(x_1 x_2 S - \hat{s})$$







$$m_t = 171.4 \pm 2.1\text{GeV}$$

The t-tbar cross section at the LHC?

Detailed Study of Systematics due to
PDFs and Scale Dependence missing!(?)

Estimate of PDF uncertainty:

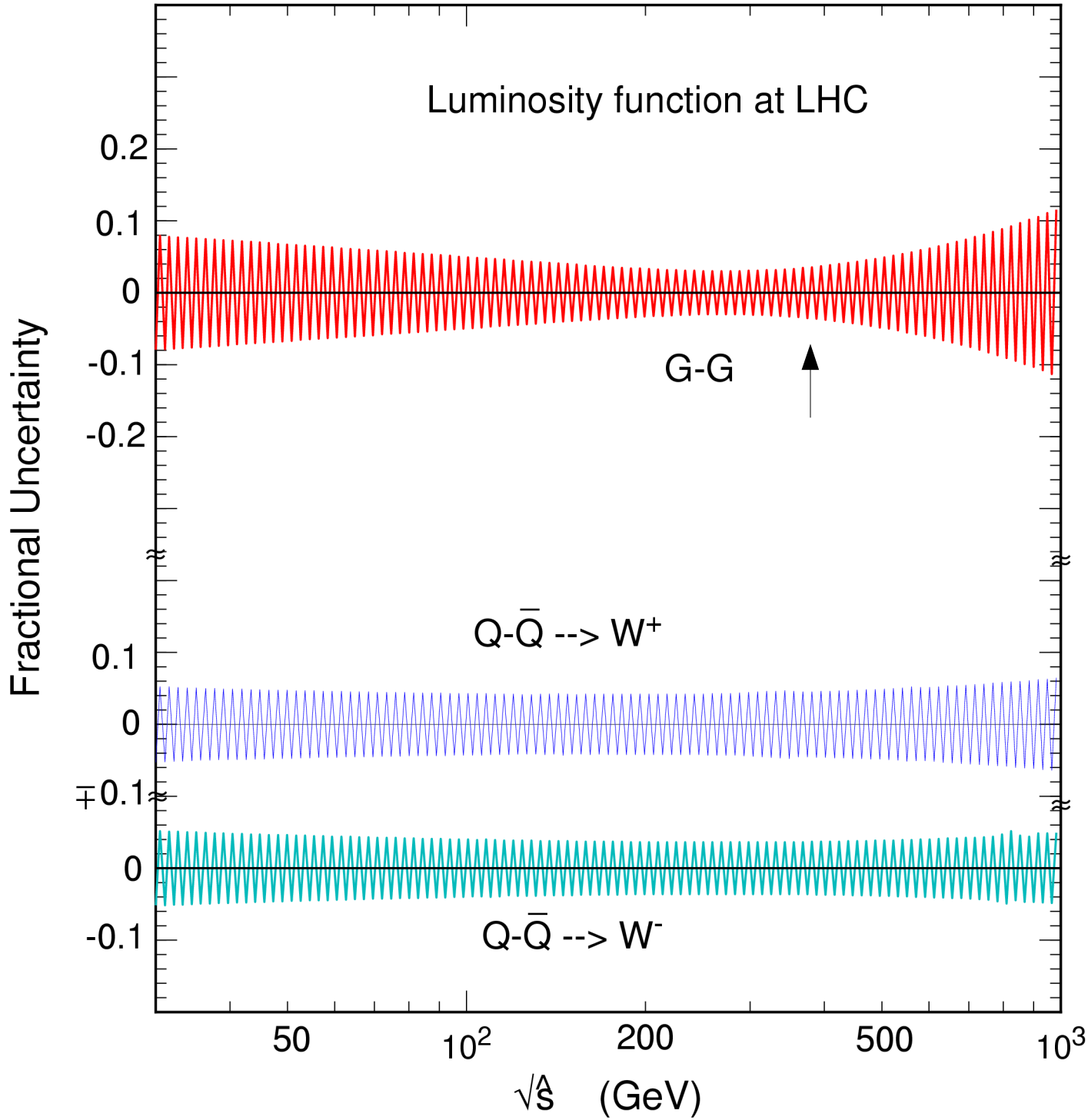
1.) Dominant channel: gg (~90%)

2.) x ~ 0.025 (much smaller than at Tevatron)

--> gluon-gluon luminosity: uncertainty ~ 5%

Note: LHC will be a top factory

--> Measurement of t-tbar x-sec. dominated by systematics


Luminosity function at LHC
Fractional Uncertainty
0.2
0.1
0
-0.1
-0.2
G-G
Q-$\bar{Q}$ --> W^+
0.1
0
∓0.1
0
-0.1
Q-$\bar{Q}$ --> W^-
50
10^2
200
500
10^3
$\sqrt{\hat{s}}$ (GeV)

III. Top Physics: Constraints for PDFs

- Generally, at Tevatron, top production --> large-x PDFs
- Single top production at LHC --> constrain bottom PDF
  - see discussion of bottom uncertainty
    (However, imposing kinematic constraints in the scaling variable a la ACOT-chi probably as important as bottom uncert. itself)
  - unique place!(?)
  - relevant for new physics processes
    for example: $p + p \to b + \bar{b} + h$

IV. Conclusions

- Dominant PDF uncertainty due to gluons well under control for top production
- Further reduction of gluon uncertainty expected due to HERA-II and Tevatron Run II data

  Important: largest theoretical uncertainty of ttbar x-sec. from PDFs

- Global Analyses still improve in many directions

- Didn't discuss impact of PDF uncertainties on background!

Backup Slides

Luminosity Functions

$$\boxed{\frac{dL_{ij}}{dx_1 dx_2} = f_i(x_1,\mu) f_j(x_2,\mu)}$$

(symmetrized in i,j)

$$x_{1,2} = \sqrt{\frac{\hat{s}}{S}} e^{\pm y}\,,\; y = \frac{1}{2}\ln\frac{x_1}{x_2}\,,\; \hat{s} = S x_1 x_2$$

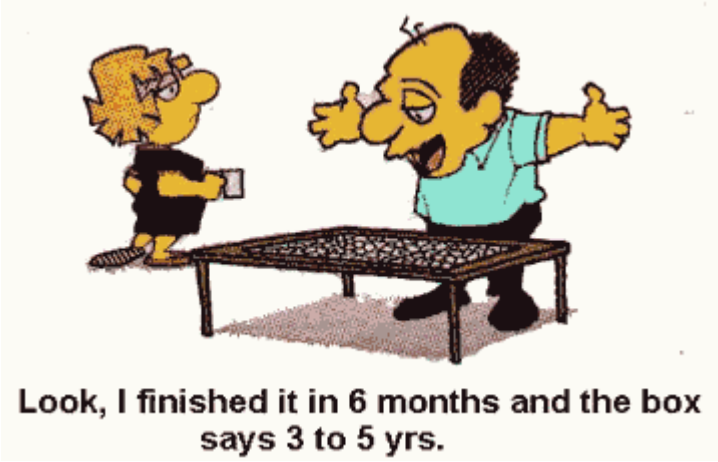
$$\Rightarrow \boxed{\frac{dL_{ij}}{d\hat{s}dy} = \frac{1}{S}\frac{dL_{ij}}{dx_1 dx_2}}$$

$$\sigma = \sum_{i,j}\int_0^1 dx_1 dx_2 f_i(x_1,\mu) f_j(x_2,\mu)\hat{\sigma}_{ij} = \sum_{i,j}\int\left(\frac{d\hat{s}}{\hat{s}}dy\right)\left(\frac{dL_{ij}}{d\hat{s}dy}\right)(\hat{s}\hat{\sigma}_{ij})$$

$$\boxed{\sigma \simeq \frac{\Delta\hat{s}}{\hat{s}}\left(\frac{dL_{ij}}{d\hat{s}}\right)(\hat{s}\hat{\sigma}_{ij})}$$

t-tbar hadroproduction in NNLO?

- NLO computation from 1988
  - Large scale uncertainty --> 10% theoretical error
- NNLO? Would greatly reduce uncertainty!
  - Only the easiest of 4 parts computed (1-loop x 1-loop)
  - Full computation huge effort! Complex + unsolved problems 5-10 years

Koerner
hep-ph/0609048

However, sometimes there are surprises