From partons to new physics at the CERN Large Hadron Collider

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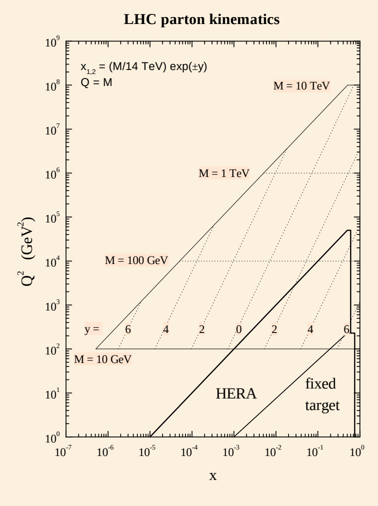
Preparing for a discovery of unseen dimensions

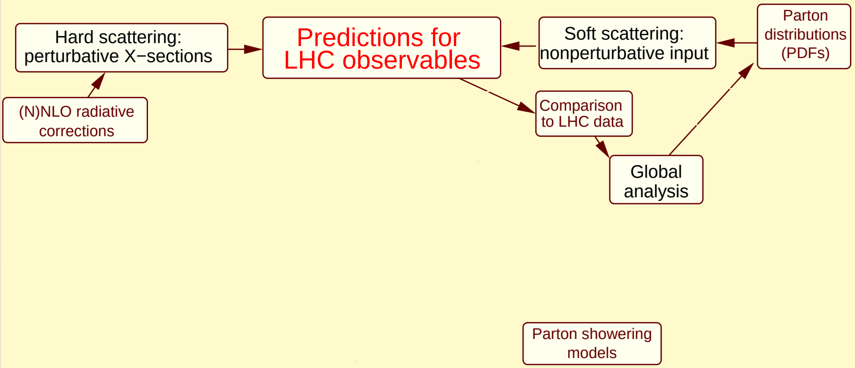
- New phenomena occurring at Terascale energies provide insights about the nature of fundamental symmetries, structure of space and time
- LHC is an experiment of extraordinary scope and sophistication that will look for these phenomena amidst abundant "known" Standard Model processes
- Its potential for success depends on the ability to understand hadronic dynamics in the new energy regime and implement this dynamics in new physics searches

LHC: unprecedented richness of hadronic theory

- dominance of sea parton scattering
- small typical momentum fractions x in several key searches (Higgs, lighter superpartners, ...)
- large QCD backgrounds
- complicated event signatures; reliance on differential distributions
- unique low-energy dynamics (underlying event, multiple interactions...)

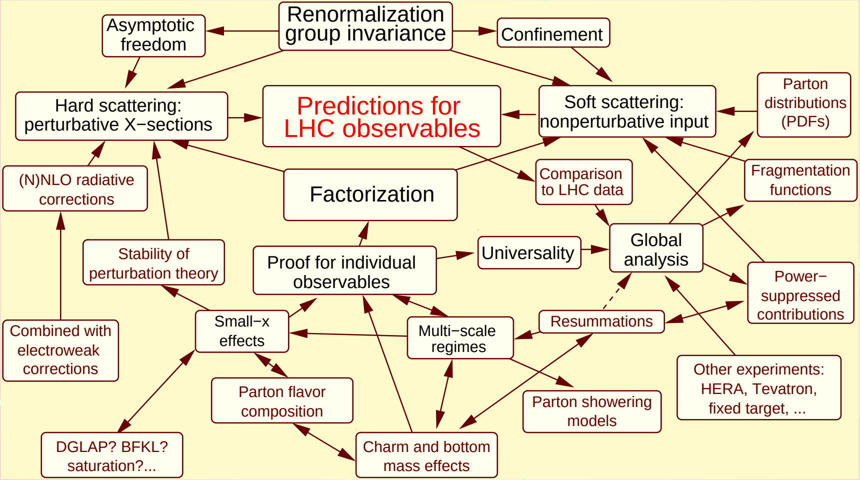


Perturbative QCD computations



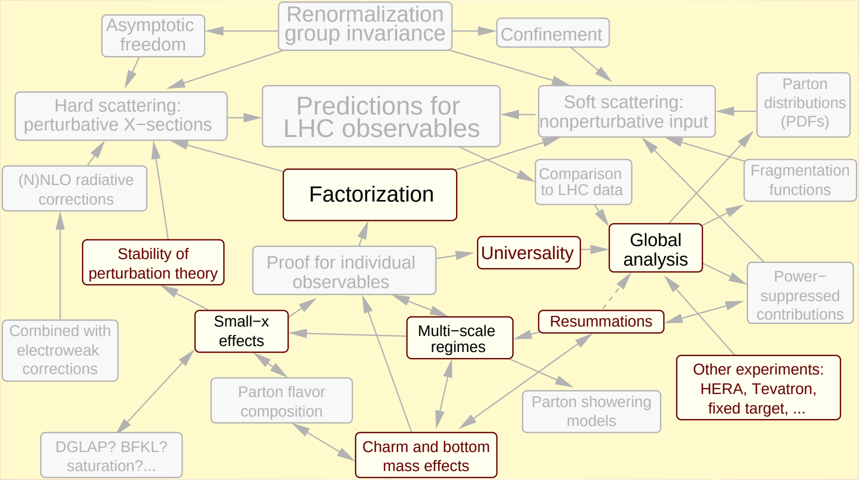
A relevant, yet incomplete, picture

Perturbative QCD computations



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

Perturbative QCD computations



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

Examples of global connections

- Correlations between collider cross sections through shared parton distribution functions

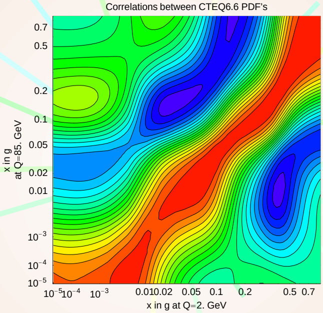
  based on

  Implications of CTEQ6.6 global analysis for collider observables

  with Cao, Huston, Lai, Pumplin, Stump, Tung, Yuan; arXiv:0802.0007

- Constraints on Higgs boson sector from direct searches and precision measurements
  - QCD backgrounds for Higgs $\to \gamma\gamma$ *(with Balazs, Berger, Yuan)*
  - W boson mass at the Tevatron and LHC *(with Berge, Konychev, Olness, Tung, Yuan, and others)*

PDF-induced correlations in hadron scattering



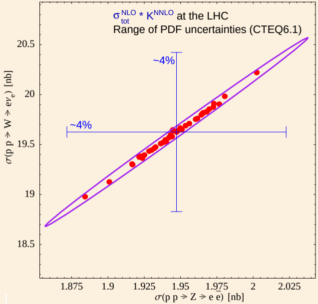
PDF-induced correlations in hadron scattering

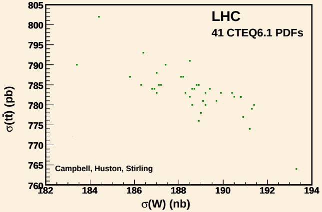
- Dependence on the PDF's is strongly correlated for some pairs of cross sections and anti-correlated for other pairs

- I will discuss the origin of the correlations, especially for $W, Z, t\bar{t}$ cross sections

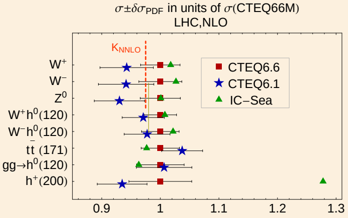
$\Rightarrow$ implications for the monitoring of parton and collider luminosities, determination of new physics parameters

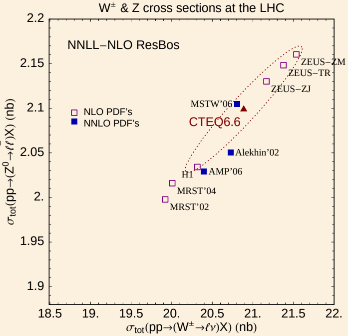
Noteworthy correlations





Theoretical uncertainties on $\sigma_W, \sigma_Z, \sigma_{t\bar{t}}$





$\sigma_{W,Z}$

- NNLO PQCD: (Hamberg et al; Harlander, Kilgore; Anastasiou et al.): $\sigma_{NNLO} - \sigma_{NLO} = -2\%$
- PDF dependence: $\gtrsim 3\%$ at $\approx 90\%$ c.l.

$\sigma_{t\bar{t}}$

- NLO scale dependence: 11% (to be reduced at NNLO soon)
- m_t dependence: $2-3\%$ for $m_t = 172\pm1$ GeV
- PDF dependence: 3%

“Standard candle” processes: $W, Z, t\bar{t}$ production

- Event rates for $pp \to W^{\pm}X$, $pp \to Z^0 X$ at the LHC can be measured with accuracy $\delta\sigma/\sigma \sim 1\%$ (tens of millions of events even at low luminosity)

- These measurements will be employed to tightly constrain PDF’s and monitor the LHC luminosity $\mathcal{L}$ in real time

  (Dittmar, Pauss, Zurcher; Khoze, Martin, Orava, Ryskin; Giele, Keller’;...)

  - other methods will initially give $\delta\mathcal{L} = 10 - 20\%$

- $t\bar{t}$ event rate can be potentially measured with accuracy $\approx 5\%$

Tevatron: the accuracy of luminosity monitoring in $p\bar{p}$ elastic scattering is of order 5%

Cross section ratios

- LHC collaborations will normalize many cross sections σ to the "standard candle" cross sections σ_{sc} (i.e., measure $r = \sigma/\sigma_{sc}$)
  - dependence on $\mathcal{L}$ and other systematics may cancel in r
  - PDF uncertainties cancel in r for strongly correlated cross sections; add up in anticorrelated cross sections
- Similar cancellations may occur in $S/\sqrt{B}$, asymmetries, etc.

It helps to find a correlated "standard candle" cross section for each interesting LHC cross section

For example, it is better to normalize σ_{Higgs} to σ_Z ($\sigma_{t\bar{t}}$) if σ_{Higgs} is correlated (anticorrelated) with σ_Z

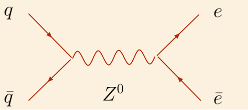
A mini-poll: Z production at the LHC

Choose all that apply and select the x range

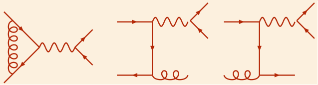
The PDF uncertainty in σ_Z is mostly due to...

1. $u, d, \bar{u}, \bar{d}$ PDF's
   at $x < 10^{-2}$ ($x > 10^{-2}$)
2. gluon PDF
   at $x < 10^{-2}$ ($x > 10^{-2}$)
3. s, c, b PDF's
   at $x < 10^{-2}$ ($x > 10^{-2}$)

Leading order



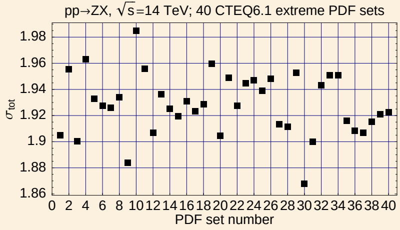
Next-to-leading order



An inefficient application of the error analysis

☺ Compute σ_Z for 40 (now 44) extreme PDF eigensets

☺ Find eigenparameter(s) producing largest variation(s), such as #9, 10, 30



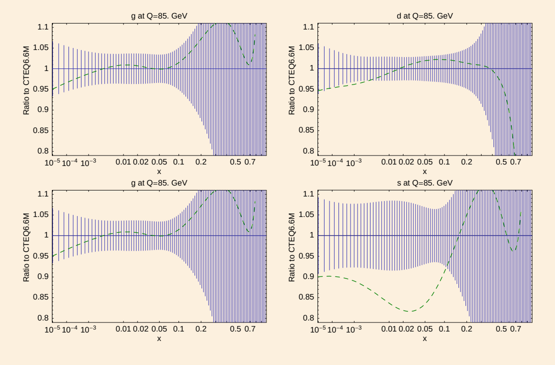
☹ It is not obvious how to relate abstract eigenparameters to physical PDF's $u(x)$, $d(x)$, etc.

CTEQ6.6 theoretical framework

(Michigan State/Taiwan/Washington)

- A full NLO analysis (NNLO is nearly completed)
- 2700 data points from 35 experiments on DIS, Drell-Yan process, jet production
- Recent improvements in treatment of heavy quark masses in DIS, etc. (CTEQ6.5), with important impact on W, Z cross sections
  - a general-mass factorization scheme with full dependence on $m_{c,b}$
  - free parametrization for strange quarks (constrained by CCFR, NuTeV charged-current DIS data)

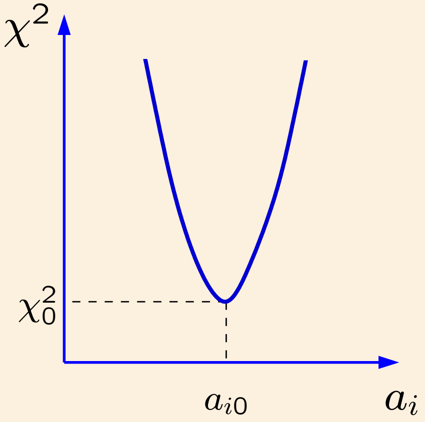
CTEQ6.6 PDF's



dashes: CTEQ6.1M

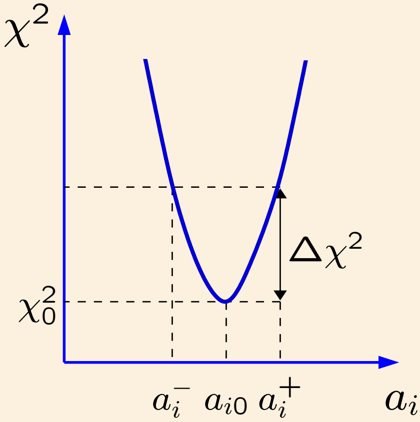
- CTEQ6.6 $u,\ d$ are above CTEQ6.1 by 2-4%
  - The result of suppressed charm contribution to $F_2(x,Q)$ at HERA in the general-mass scheme
- very different strange PDF's

Multi-dimensional PDF error analysis



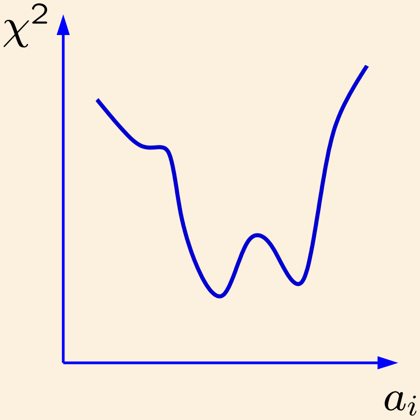
- Minimization of a likelihood function (χ^2) with respect to ~ 30 theoretical (mostly PDF) parameters $\{a_i\}$ and > 100 experimental systematical parameters
  - partly analytical and partly numerical

Multi-dimensional PDF error analysis



- Establish a confidence region for $\{a_i\}$ for a given tolerated increase in χ^2

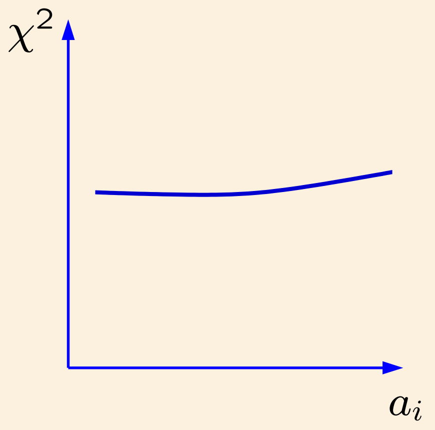
Multi-dimensional PDF error analysis



Pitfalls to avoid

- "Landscape"
  - disagreements between the experiments

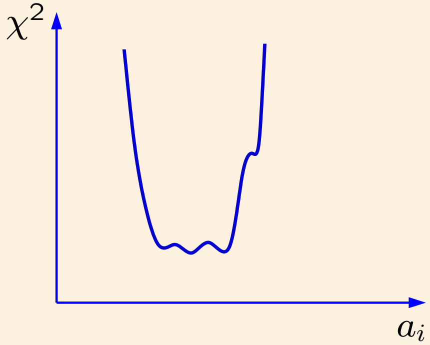
Multi-dimensional PDF error analysis



Pitfalls to avoid

- Flat directions
  - unconstrained combinations of PDF parameters
  - dependence on the PDF parametrization, free theoretical parameters (factorization scale, etc.)

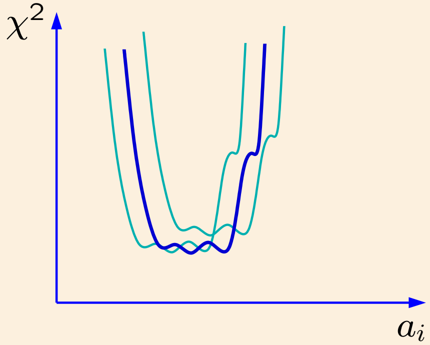
Multi-dimensional PDF error analysis



The actual χ^2 function shows

- a well pronounced global minimum χ_0^2
- weak tensions between data sets in the vicinity of χ_0^2 (mini-landscape)
- some dependence on assumptions about flat directions

Multi-dimensional PDF error analysis



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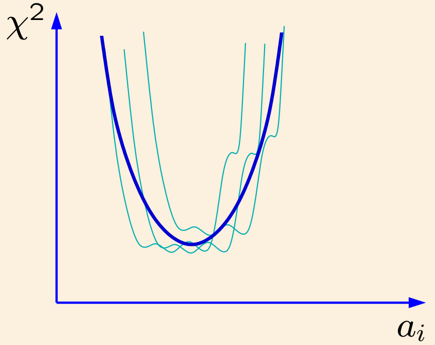

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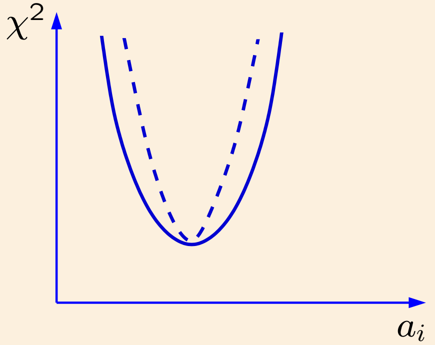
The likelihood is approximately described by a quadratic χ^2 with a revised tolerance condition $\Delta\chi^2 \leq T^2$

Multi-dimensional PDF error analysis



The actual χ^2 function shows

- a well pronounced global minimum χ^2_0
- weak tensions between data sets in the vicinity of χ^2_0 (mini-landscape)
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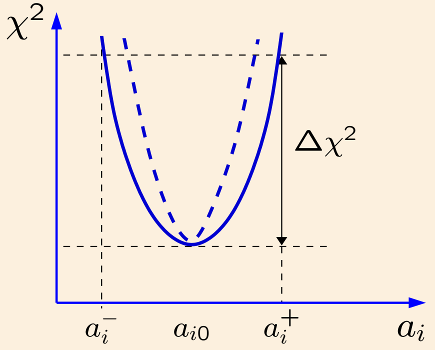
Multi-dimensional PDF error analysis



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Correlation analysis for collider observables

(J. Pumplin et al., PRD 65, 014013 (2002); P.N. and Z. Sullivan, hep-ph/0110378)

A technique based on the Hessian method to relate the PDF uncertainty in physical cross sections to PDF's of specific flavors at known (x, μ)

For $2N$ PDF eigensets and two cross sections X and Y:

$$\Delta X = \frac{1}{2}\sqrt{\sum_{i=1}^{N}\left(X_i^{(+)} - X_i^{(-)}\right)^2}$$

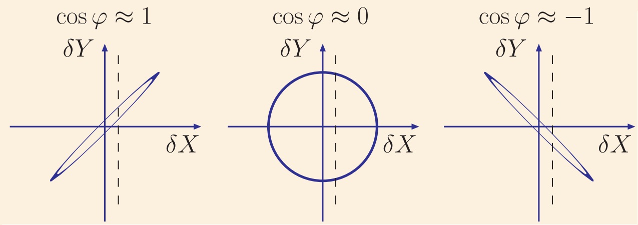
$$\cos\varphi = \frac{1}{4\Delta X\,\Delta Y}\sum_{i=1}^{N}\left(X_i^{(+)} - X_i^{(-)}\right)\left(Y_i^{(+)} - Y_i^{(-)}\right)$$

$X_i^{(\pm)}$ are maximal (minimal) values of X_i tolerated along the i-th PDF eigenvector direction; $N = 22$ for the CTEQ6.6 set

Correlation angle φ

Determines the parametric form of the $X-Y$ correlation ellipse

$$\begin{aligned} X &= X_0 + \Delta X \cos\theta \\ Y &= Y_0 + \Delta Y \cos(\theta+\varphi) \end{aligned}$$



X_0, Y_0: best-fit values

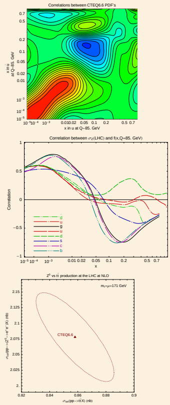
$\Delta X, \Delta Y$: PDF errors

$\cos\varphi \approx \pm 1$: Measurement of X imposes tight constraints on Y
$\cos\varphi \approx 0$: Measurement of X imposes loose constraints on Y

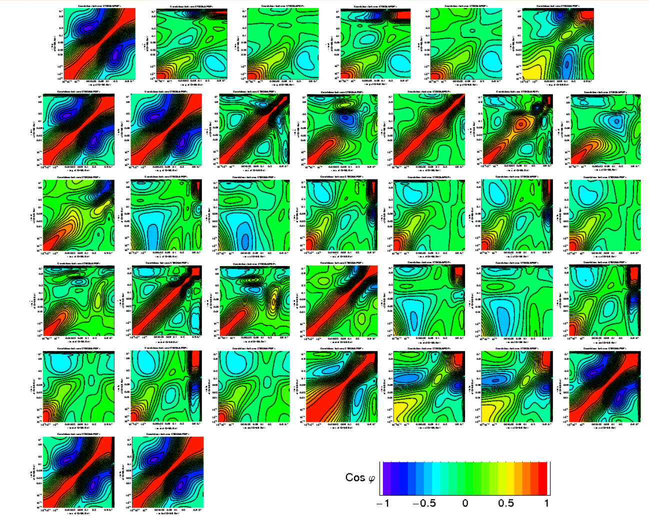
Types of correlations

X and Y can be

- two PDFs $f_1(x_1, Q_1)$ and $f_2(x_2, Q_2)$ (plotted as $\cos\varphi$ vs x_1 & x_2)
- a physical cross section σ and PDF $f(x, Q)$ (plotted as $\cos\varphi$ vs x)
- two cross sections σ_1 and σ_2



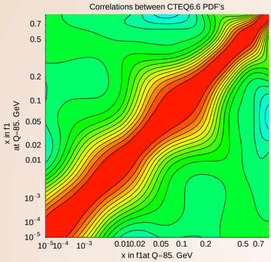
Correlations between $f_1(x_1, Q)$ and $f_2(x_2, Q)$ at $Q = 85$ GeV



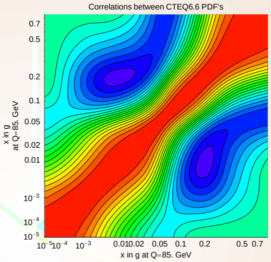
Figures from http://hep.pa.msu.edu/cteq/public/6.6/pdfcorrs/

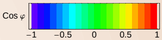
Correlations between $f(x_1, Q)$ and $f(x_2, Q)$ at $Q = 85$ GeV

$u(x_1, Q)$ vs. $u(x_2, Q)$



$g(x_1, Q)$ vs. $g(x_2, Q)$

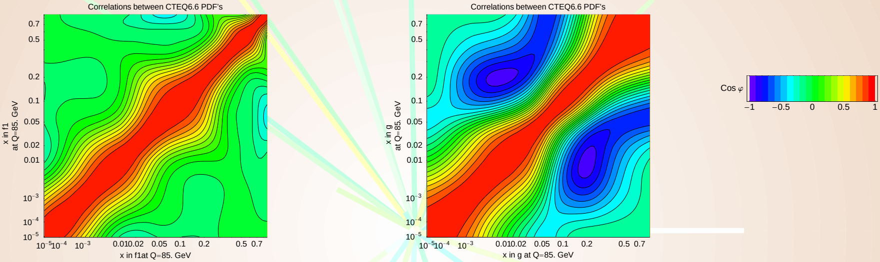




Can you explain why the gluon correlation pattern looks so different?

Correlations between $f(x_1, Q)$ and $f(x_2, Q)$ at $Q = 85$ GeV

$u(x_1, Q)$ vs. $u(x_2, Q)$ $\qquad$ $g(x_1, Q)$ vs. $g(x_2, Q)$

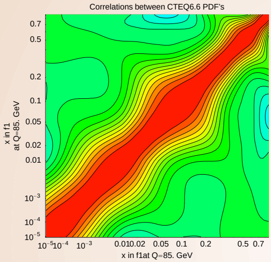


- Momentum sum rule:

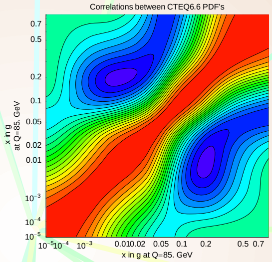
$$\int_0^1 xg(x)dx + \sum_{i=1}^{N_f} \int_0^1 x\left[q_i(x) + \bar{q}_i(x)\right] dx = 1$$

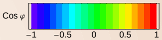
Correlations between $f(x_1, Q)$ and $f(x_2, Q)$ at $Q = 85$ GeV

$u(x_1, Q)$ vs. $u(x_2, Q)$



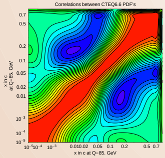
$g(x_1, Q)$ vs. $g(x_2, Q)$



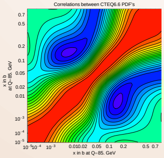


Correlation patterns look similar for g, c, b PDF's
(no intrinsic charm here!)

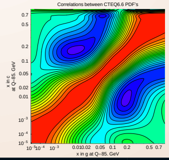
c vs. c



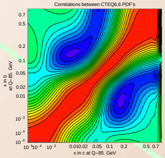
b vs. b



c vs. g

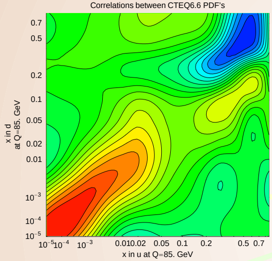


b vs. c

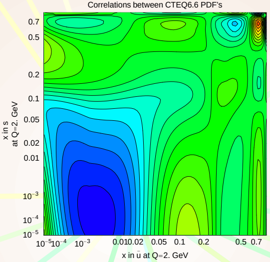


Correlations between $f_1(x_1, Q)$ and $f_2(x_2, Q)$ at $Q = 85$ GeV

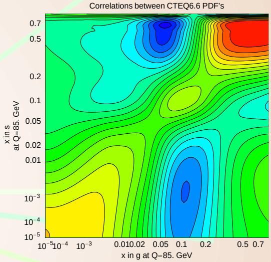
d vs u

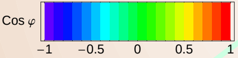


s vs $\bar{u}$ at Q=2 GeV



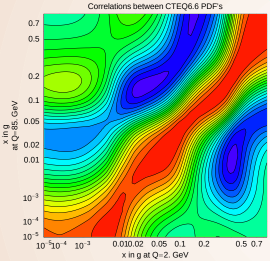
s vs. g





Sometimes there is a clear physics reason behind the correlation (e.g., sum rules, assumed Regge behavior, data constraints); sometimes not

Correlations between $g(x_1, 2\text{ GeV})$ and $g(x_2,\ 85\text{ GeV})$

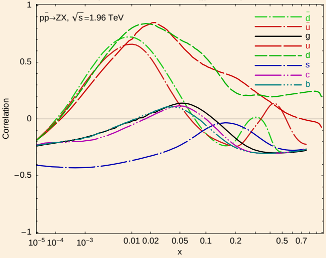


Gluons at $Q = 85$ GeV are correlated with gluons at $Q = 2$ GeV and larger x because of DGLAP evolution

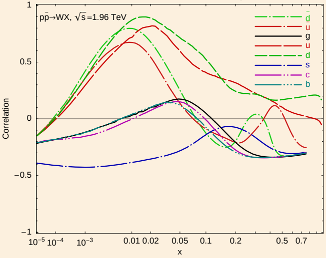
Correlations between W, Z cross sections and PDF's

Tevatron Run-2

CTEQ6.6: correlation between σ_{tot} and f(x,Q=85. GeV)

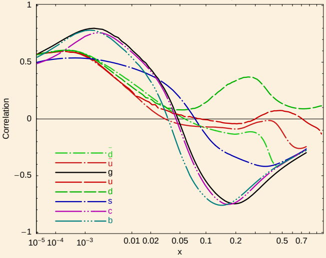


CTEQ6.6: correlation between σ_{tot} and f(x,Q=85. GeV)

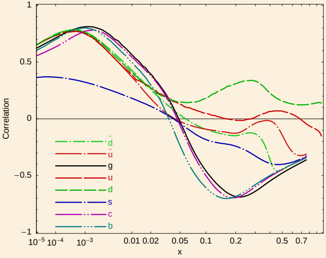


LHC

Correlation between σ_Z(LHC) and f(x,Q=85. GeV)



Correlation between $\sigma_{W^\pm}$(LHC) and f(x,Q=85. GeV)

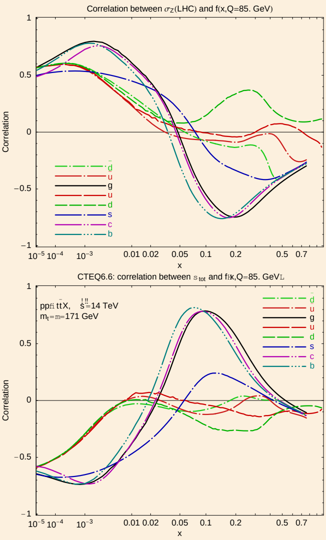


Correlations of Z and $t\bar{t}$ cross sections with PDF's

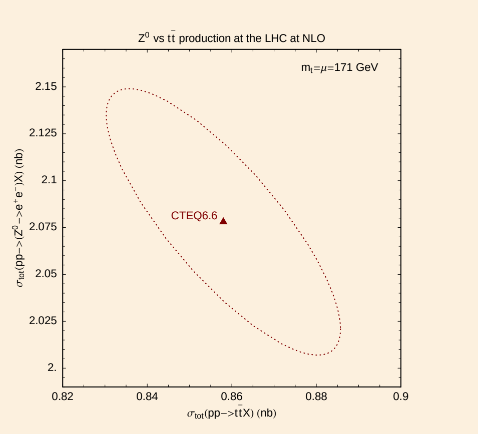
LHC Z, W cross sections are strongly correlated with $g(x)$, $c(x)$, $b(x)$ at $x \sim 0.005$

$\therefore$ they are strongly anticorrelated with processes sensitive to $g(x)$ at $x \sim 0.1$

($t\bar{t}$, $gg \to H$ for $M_H > 300$ GeV)

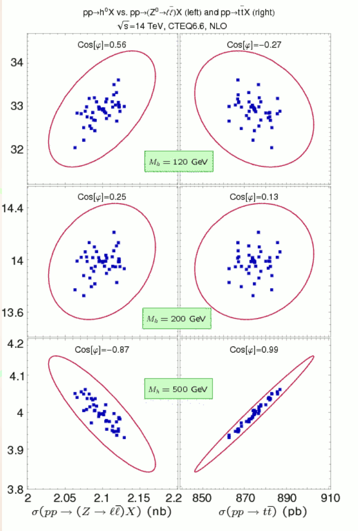


$t\bar{t}$ vs Z cross sections at the LHC



Measurements of $\sigma_{t\bar{t}}$ and σ_Z probe the same (gluon) PDF degrees of freedom at different x values

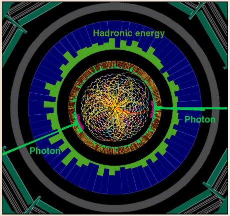
Correlations between $\sigma(gg \to H^0)$, σ_Z, $\sigma_{t\bar{t}}$

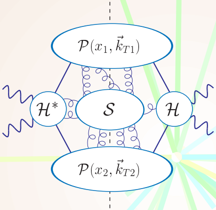


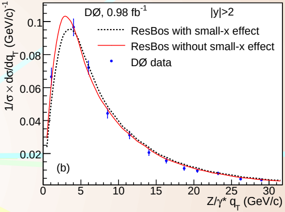
Other topics explored in the CTEQ6.6 paper

- Strong sensitivity of σ_Z/σ_W to the strangeness PDF and $\sigma_{W^+}/\sigma_{W^-}$ to $u_V - d_V$
- Potential role of $\sigma_{t\bar{t}}$ as a standard candle observable
- Origin of PDF uncertainties in single-top production
- Correlation cosines for various Higgs production channels in SM and MSSM

LHC studies of electroweak symmetry breaking





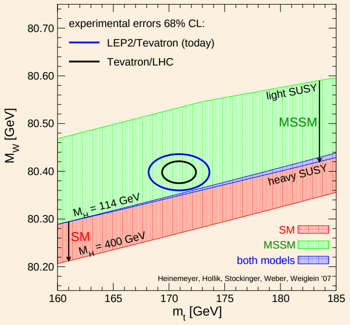


- A new aspect: multi-scale factorization (resummation)

Higgs sector in SM and MSSM

- *Standard Model: 1 Higgs doublet, one scalar field* H
  - Direct search: $m_H > 114$ GeV at 95% c.l.
  - indirect: $M_H = 80^{+39}_{-28}$ GeV at 68% c.l.
- Minimal Supersymmetric Standard Model:
  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!

Higgs sector in SM and MSSM



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

- the goal of direct and indirect measurements is to over-constrain the Higgs sector in SM, greatly constrain SUSY
- indirect constraints strongly depend on M_W, m_t values, hence require accurate QCD predictions for W and t production

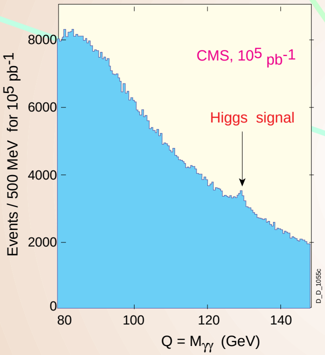
For example, in SM

$$M_W = 80.3827 - 0.0579 \ln\left(\frac{M_H}{100\text{ GeV}}\right) - 0.008 \ln^2\left(\frac{M_H}{100\text{ GeV}}\right)$$

$$+0.543\left(\left(\frac{m_t}{175\text{ GeV}}\right)^2 - 1\right) - 0.517\left(\frac{\Delta\alpha^{(5)}_{had}(M_Z)}{0.0280} - 1\right) - 0.085\left(\frac{\alpha_s(M_Z)}{0.118} - 1\right)$$

$pp \to (H \to \gamma\gamma)X$: resummation for signal and background

with Balazs, Berger, Yuan; PLB 635, 235 (2006); PRD 76, 013008 & 013009 (2007)

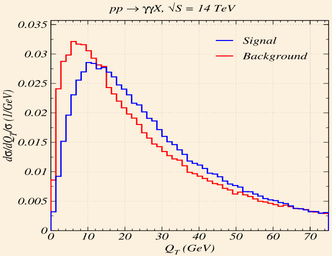


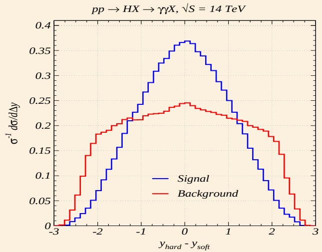
Signal and background in $H \to \gamma\gamma$

- To find the narrow Higgs resonance, it is useful to understand differences between fully **differential distributions** of the Higgs signal and large QCD background
- **resummation is needed for logarithmic corrections** of several types from all orders in α_s
  - e.g., $\alpha_s^n \ln^k(Q_T/Q)$ at $Q_T \ll Q$

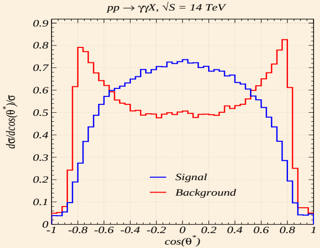
NNLL/NLO distributions for Higgs $\to \gamma\gamma$ signal and background (ResBos, normalized; $M_H = 130$ GeV, $128 < Q < 132$ GeV)

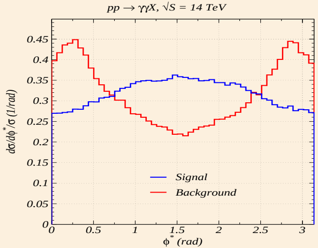
Q_T and $y_{\gamma 1} - y_{\gamma 2}$ in the lab frame





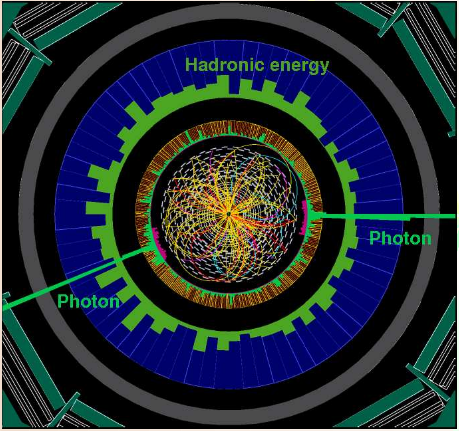
Decay angles θ_*, φ_* in the $\gamma\gamma$ rest frame





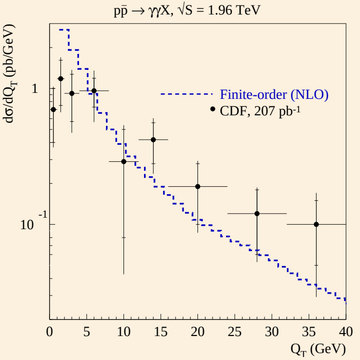
no singularities, in contrast to the fixed-order rate

Transverse energy distribution in $H \to \gamma\gamma$

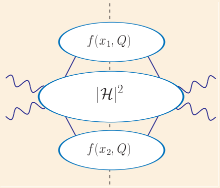


- A typical $\gamma\gamma$ pair recoils against many mini-jets with small $\vec{k}_{Ti}$, rather than against a few jets with large $\vec{k}_{Ti}$
- leading mini-jet contributions must be summed to all orders in α_s to obtain reliable predictions

Overview of the resummation procedure



$Q_T^2 \sim Q^2$

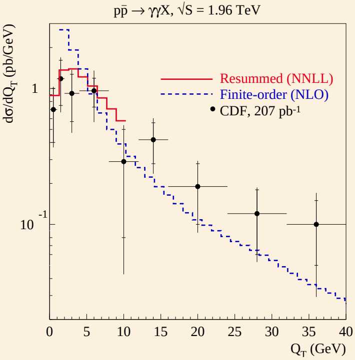


Collinear factorization at NLO; unstable at $Q_T^2 \ll Q^2$

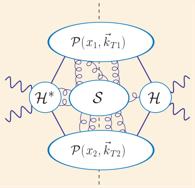
$$\frac{d\sigma}{dQ^2 dy dQ_T^2} = \sum_{partons} \int dx_1 dx_2 f_a(x_1, Q) f_b(x_2, Q) \left|\mathcal{H}(ab \to V)\right|^2$$

$$\left(\frac{d\sigma}{dQ_T^2}\right)_{Q_T^2 \ll Q^2} \approx \sum_{k=0}^{\infty} \alpha_s^k \left[c_k \delta(\vec{Q}_T) + Q_T^{-2} \cdot \sum_{n=0}^{2k-1} d_{nk} \ln^n(Q^2/Q_T^2) \right]$$

Overview of the resummation procedure



$Q_T^2 \ll Q^2$

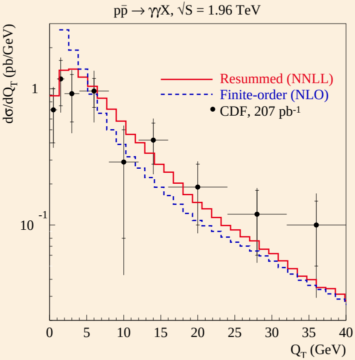


Factorization in terms of a soft factor S, $\vec{k}_T$-dependent PDF's $\mathcal{P}_a$, and LO hard vertex $\mathcal{H}_{ab}^{LO}$

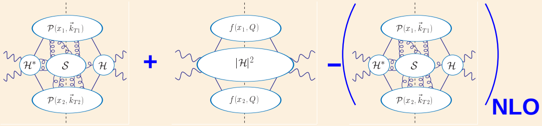
$$\frac{d\sigma}{dQ^2 dy dQ_T^2} = \sum_{partons} \left|\mathcal{H}_{ab}^{LO}\right|^2 \int d\vec{k}_{Ts} d\vec{k}_{T1} d\vec{k}_{T2} \delta\left[\vec{Q}_T - \vec{k}_{Ts} - \vec{k}_{T1} - \vec{k}_{T2}\right]$$

$$\times \quad S(\vec{k}_{Ts}, Q)\mathcal{P}_a(x_1, \vec{k}_{T1})\mathcal{P}_b(x_2, \vec{k}_{T2})$$

Overview of the resummation procedure



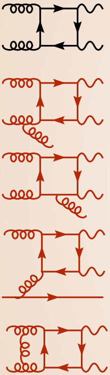
$Q_T^2 \lesssim Q^2$



Add small-Q_T and large-Q_T X-sections, subtract the overlap

We include large-Q_T Xsection at NLO, resummed perturbative coefficients up to three loops (NNLL)

Resummation for $gg + gq \to \gamma\gamma X$ at $\mathcal{O}(\alpha_s^3)$



1-loop $2 \to 3$ diagrams

- obtained in the helicity amplitude formalism

  (Bern, Dixon, Kosower)

- checked against the "sector decomposition" calculation *(Binoth, Guillet, Mahmoudi, 2003)*

- soft and collinear limits derived in the splitting amplitude method *(Bern, Chalmers, Dixon, Dunbar, Kosower;...)*

- resummed to all orders in α_s

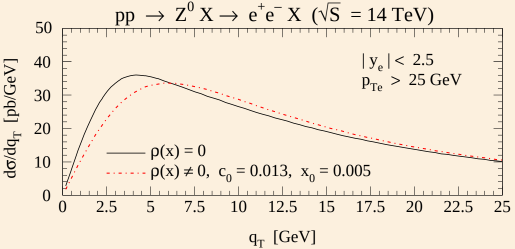
M_W measurement at hadron colliders

- The Tevatron (LHC) collaborations intend to measure M_W with accuracy 15 MeV (5 MeV)
- Several theoretical factors contribute at this level of accuracy
  - NNLO QCD+NLO EW perturbative contributions
  - PDF dependence
    with Lai, Pumplin,Tung
  - small-p_T resummation
    with Brock, Konychev, Landry, Yuan
  - small-x effects
    with Berge, Olness, Yuan
  - dependence on $m_{c,b}$
    with Berge, Olness

Small-x broadening of Q_T distributions

Complicated small-x dynamics may result in harder Q_T distributions at the LHC than predicted by conventional CSS resummation *(Berge, PN, Olness, Yuan, 2004)*

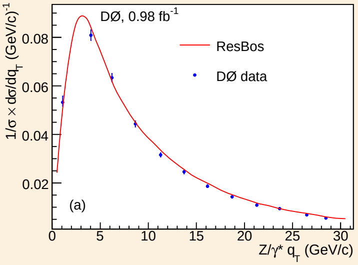
$\Rightarrow$ Consequences for M_W measurement



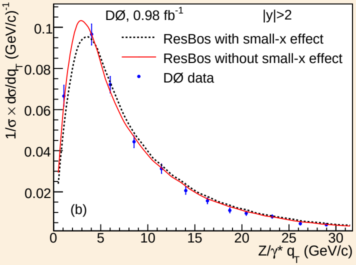
Small-x broadening of Q_T distributions

New D0 measurements in $p\bar{p} \to (\gamma^*, Z)X$ *(arXiv:0712.0803)* provide first constraints on the magnitude of small-x broadening

All Z rapidities

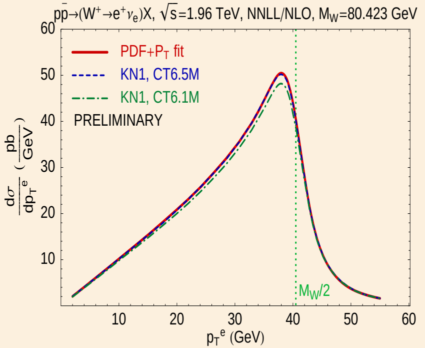


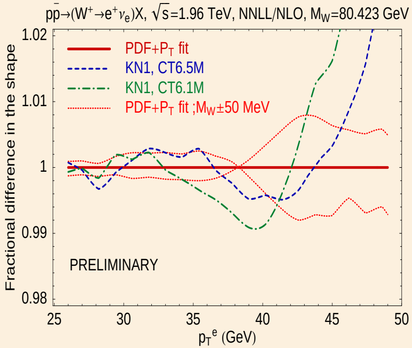
$|y_Z| > 2$



Correlations between PDF's and nonperturbative p_T function *(Lai, P.N., Pumplin, Tung, Yuan, in progress)*

The PDF dependence of the power-suppressed resummed contribution to $d\sigma/dQ_T$ is analyzed in a combined PDF+p_T fit; leads to a somewhat larger M_W value extracted from the data

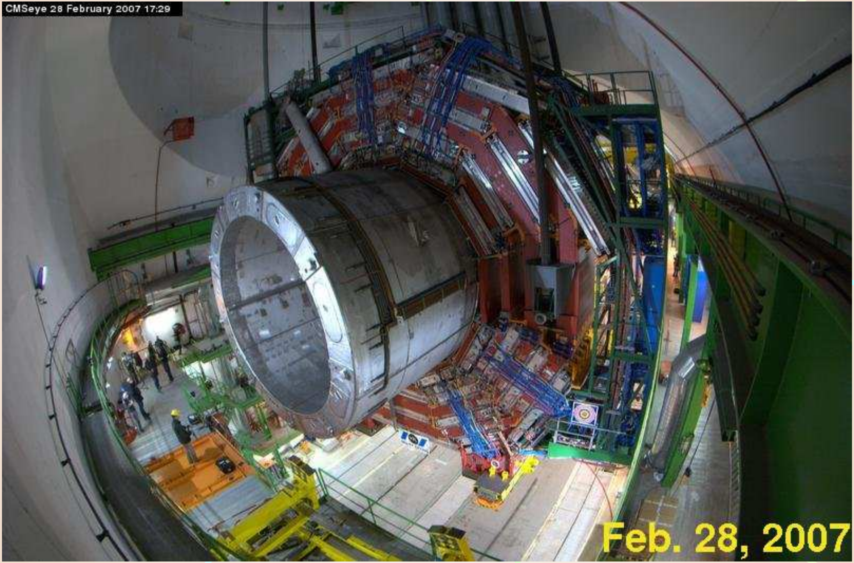




Conclusions

- It is exciting to explore rich global connections between the LHC cross sections and diverse domains of the Standard Model
  - to calibrate the LHC detectors, monitor LHC luminosity
  - to explore new forms of QCD factorization (resummations) and merge them with important EW contributions
  - to precisely test the Standard Model, understand the EWSB mechanism
  - to impose limits on new physics parameters using hadron collider data

Compact Muon Solenoid as seen by BBC



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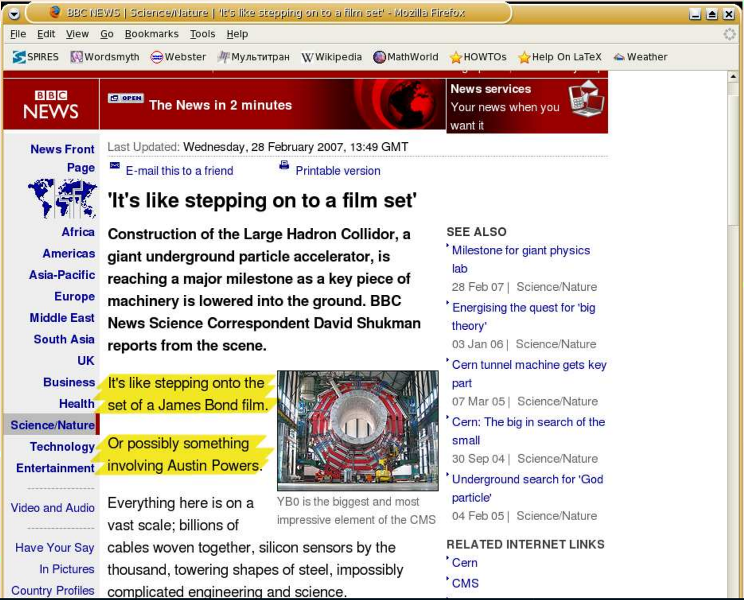

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It's like stepping onto the set of a James Bond film.

Or possibly something involving Austin Powers.

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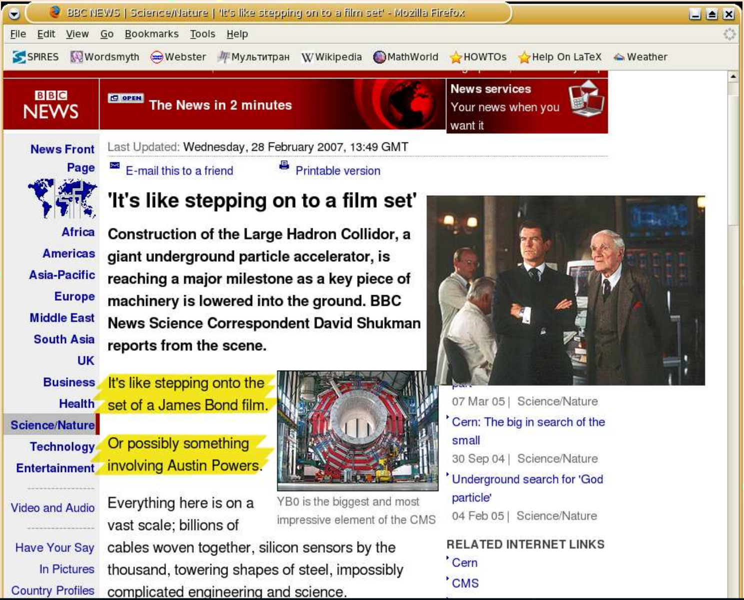

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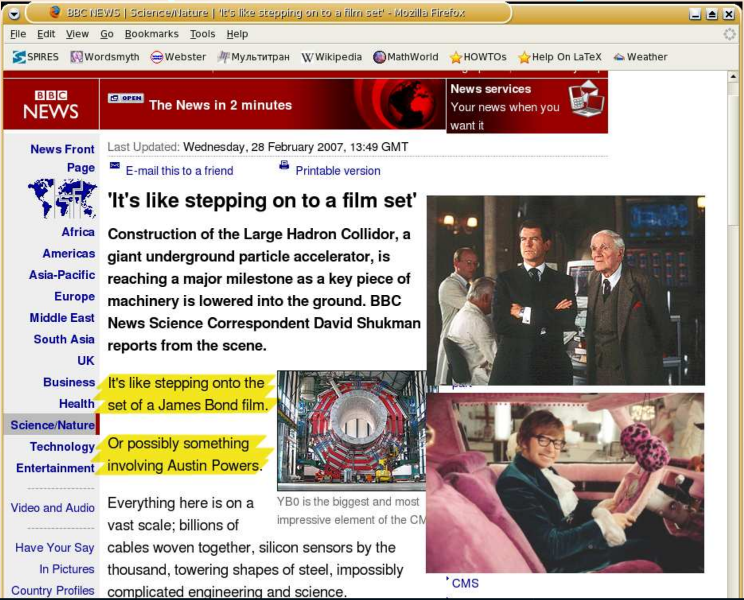
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CMS

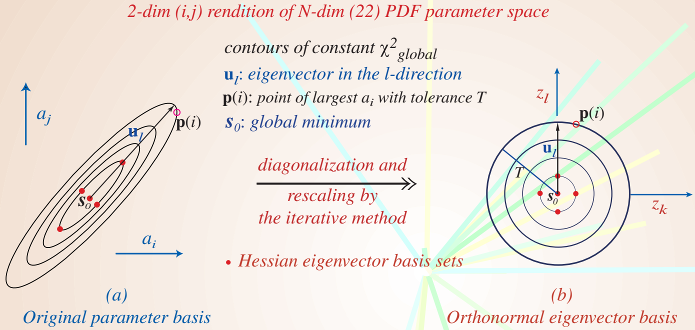
Credibility of LHC discoveries must be supported by dependable numerical tools implementing a realistic theoretical framework

The phenomenological “Q Branch” that develops this framework will be in a high demand for a long time

☺

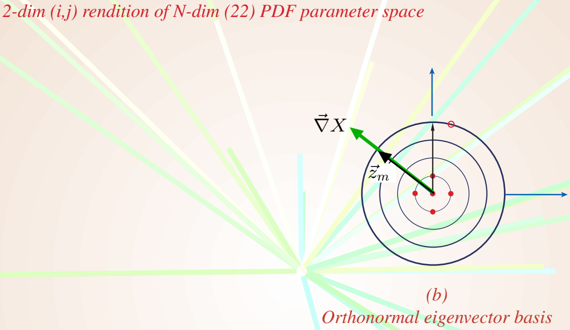
Backup slides

Tolerance hypersphere in the PDF space



A hyperellipse $\Delta\chi^2 \leq T^2$ in space of N physical PDF parameters $\{a_i\}$ is mapped onto a hypersphere of radius T in space of N orthonormal PDF parameters $\{z_i\}$

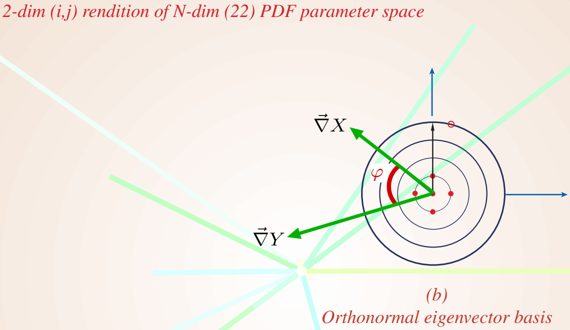
Tolerance hypersphere in the PDF space



PDF error for a physical observable X is given by

$$\Delta X = \vec{\nabla} X \cdot \vec{z}_m = \left| \vec{\nabla} X \right| = \frac{1}{2} \sqrt{\sum_{i=1}^{N} \left(X_i^{(+)} - X_i^{(-)} \right)^2}$$

Tolerance hypersphere in the PDF space



Correlation cosine for observables X and Y:

$$\cos\varphi = \frac{\vec{\nabla} X \cdot \vec{\nabla} Y}{\Delta X \Delta Y} = \frac{1}{4 \Delta X \, \Delta Y} \sum_{i=1}^{N} \left(X_i^{(+)} - X_i^{(-)} \right) \left(Y_i^{(+)} - Y_i^{(-)} \right)$$

$t\bar{t}$ production as a standard candle process

Uncertainties in $\sigma_{t\bar{t}}$ for $m_t = 171$ GeV

Type	**Current**	**Projected**	**Assumptions**
Scale dependence	11% (NLO)	$\sim 3-5\%?$ (NNLO+resum.)	$m_t/2 \leq \mu \leq 2m_t$
PDF dependence	2%	1%?	1σ c.l.
m_t dependence	5% $\delta m_t = 2$ GeV	$< 3\%$ $\delta m_t = 1$ GeV	
Total (theory)	12%	$\sim 5\%$	
Experiment	8% (CDF)	5%?	

Measurements of $\sigma_{t\bar{t}}$ with accuracy $\sim 5\%$ may be within reach; useful for monitoring of $\mathcal{L}_{LHC}$ in the first years, normalization of cross sections sensitive to large-x glue scattering

Z, W, $t\bar{t}$ cross sections and correlations

Table: Total cross sections σ, PDF-induced errors $\Delta\sigma$, and correlation cosines $\cos\varphi$ for Z^0, $W^\pm$, and $t\bar{t}$ production at the Tevatron Run-2 (Tev2) and LHC, computed with CTEQ6.6 PDFs.

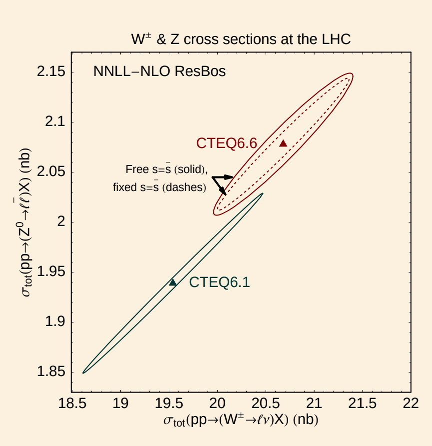
$\sqrt{s}$ (TeV)	Scattering process	σ, $\Delta\sigma$ (pb)	Correlation $\cos\varphi$ with Z^0 (Tev2)	$W^\pm$ (Tev2)	Z^0 (LHC)	$W^\pm$ (LHC)
1.96	$p\bar{p} \to (Z^0 \to \ell^+\ell^-)X$	241(8)	1	**0.987**	0.23	0.33
	$p\bar{p} \to (W^\pm \to \ell\nu_\ell)X$	2560(40)	**0.987**	1	0.27	0.37
	$p\bar{p} \to t\bar{t}X$	7.2(5)	-0.03	-0.09	-0.52	-0.52
14	$pp \to (Z^0 \to \ell^+\ell^-)X$	2080(70)	0.23	0.27	1	**0.956**
	$pp \to (W^\pm \to \ell\nu)X$	20880(740)	0.33	0.37	**0.956**	1
	$pp \to (W^+ \to \ell^+\nu_\ell)X$	12070(410)	0.32	0.36	**0.928**	**0.988**
	$pp \to (W^- \to \ell^-\bar{\nu}_\ell)X$	8810(330)	0.33	0.38	**0.960**	**0.981**
	$pp \to t\bar{t}X$	860(30)	-0.14	-0.13	**-0.80**	**-0.74**

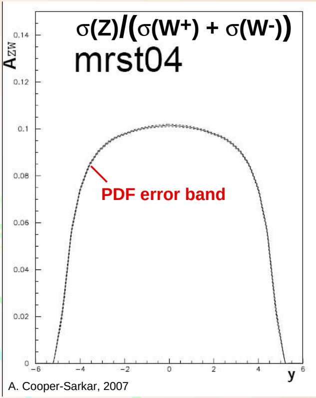
Correlations with single-top cross sections

Table: Correlation cosines $\cos\varphi$ between single-top, W, Z, and $t\bar{t}$ cross sections at the Tevatron Run-2 (Tev2) and LHC, computed with CTEQ6.6 PDFs.

Single-top production channel	Correlation $\cos\varphi$ with					
	Z^0 (Tev2)	$W^{\pm}$(Tev2)	$t\bar{t}$ (Tev2)	Z^0 (LHC)	$W^{\pm}$ (LHC)	$t\bar{t}$ (LHC)
$t-$channel (Tev2)	-0.18	-0.22	**0.81**	**-0.82**	**-0.79**	0.56
$t-$channel (LHC)	0.09	0.14	-0.64	0.56	0.53	-0.42
$s-$channel (Tev2)	**0.83**	**0.79**	0.18	0.22	0.27	-0.3
$s-$channel (LHC)	**0.81**	**0.85**	-0.42	0.6	0.68	-0.33

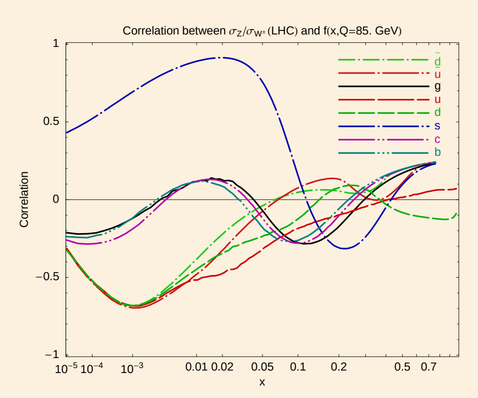
Correlations and ratio of W and Z cross sections





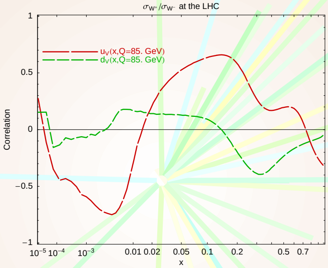
Radiative contributions, PDF dependence have similar structure in W, Z, and alike cross sections; cancel well in Xsection ratios

σ_Z/σ_W at the LHC



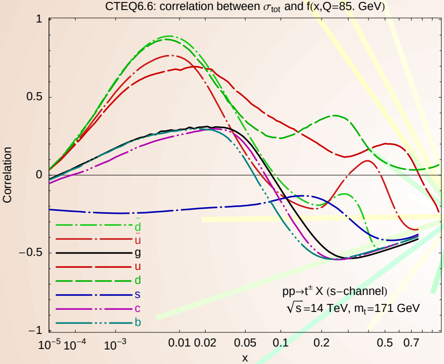
The remaining PDF uncertainty in σ_Z/σ_W is mostly driven by $s(x)$; increases by a factor of 3 compared to CTEQ6.1 as a result of free strangeness in CTEQ6.6

$\sigma(W^+)/\sigma(W^-)$

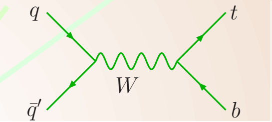


$\sigma(W^+)/\sigma(W^-) = 1.36 + 0.016$ (CTEQ6.6), 1.36 (MSTW'06NNLO), 1.35 (MRST'04NLO)

An example of a small correlation with the gluon



Single-top production (NLO)



- typical $x \sim 0.01$
- mostly correlated with u, d PDF's

PDF uncertainties in W, Z *total* cross sections are irrelevant for some quark scattering processes (single-top, Z', ...)

$\cos\varphi$ for various NLO Higgs production cross sections in SM and MSSM