# Standard Model Candles, Theory Uncertainties and PDFs 1

Robert Thorne

January 10th, 2011

University College London

Will consider the production of vector bosons, i.e. $W^+, W^-, Z$ and the Standard Model Higgs boson.

Will concentrate on inclusive cross-sections, but also on more differential distributions, i.e. rapidity $y$ or transverse momentum $p_T$ in some cases.

Some of the above are particles which interact via the electromagnetic and/or weak force, but for all the details of the production rates are influenced by both the electroweak sector of the Standard Model and the strongly interacting part.

In fact in most cases the dominant theoretical uncertainties are associated with the strong interaction, both due to corrections to the final state production cross-section, and also that the final state is always created from the initial state quarks and gluons within the proton.

Hence first consider QCD.

**Quantum ChromoDynamics** QCD is the theory of the strong interaction.

Quarks (fermions) interact via the exchange of gluons (vector bosons) with the physics described by the $SU(3)$ gauge theory with Lagrangian

$$\mathcal{L}_{\mathrm{QCD}} = -1/4 F^{\mu\nu}{}_a F_{\mu\nu a} + \sum_{f=1}^{n_f} \bar{q}_f \big( i\gamma^\mu D_\mu - m_f \big) q_f ,$$

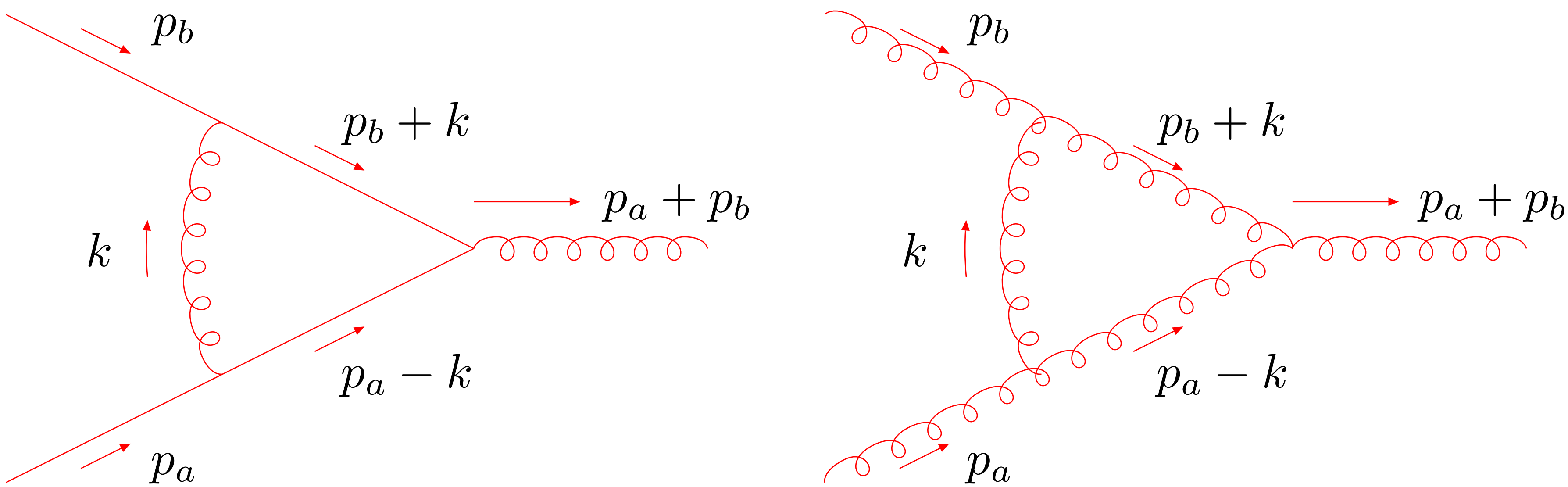
where the covariant derivative is defined by

$$D_\mu q_f = \partial_\mu q_f + i g_s A_{\mu a} 1/2 \lambda_a q_f$$

and $q_f$ represent the fermionic quark fields and $A_{\mu,a}$ the vector boson gluon fields. (Very similar for the electroweak sector.) The sum over $f$ is for the different quark flavours, up. down, strange, charm, bottom and top, each with different masses.

Can formulate Feynman rules to calculate particle interactions as a perturbation series in $\alpha_S = g_s^2/(4\pi)$

At first non-classical order obtain corrections to quark-gluon or gluon-gluon coupling of form




This results in integrals of the form

$$\mathcal{V} \sim \int \frac{d^4k}{(2\pi)^4} \frac{k\ k}{k^2(p_b+k)^2(p_a-k)^2} \to \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^4} \sim \int \frac{dk}{(2\pi)} \frac{1}{k}$$

when we consider the limit $k \to \infty$ in the loop. Leads to *ultraviolet* divergence.

In order to obtain a well-defined result must implement some *ultraviolet cutoff* $\Lambda_0$ above which QCD is no longer a reliable theory (e.g. $\Lambda_0$ is the scale of new physics).

Also introduce a physical *renormalization scale* $\mu_R$ – choose to be similar to scale of physics.

Subtract divergences like $\ln(\Lambda_0^2/\mu_R^2)$ and absorb into definition of **bare** parameters, leaving behind finite predictions in terms of physical **renormalised** parameters.

$$g_s^0 = g_s + g_s^3 C \ln(\Lambda_0^2/\mu_R^2) \qquad\qquad \sigma(\{p\}, g_s^0, \Lambda_0) \equiv \sigma(\{p\}, g_s)$$

Process known as renormalization. Long been proved that it can be applied successfully to all orders in QCD and rest of the Standard Model.

However, we have introduced artificial renormalization scale $\mu_R$ on which renormalised couplings, masses, *etc* depend, though dependence disappears (at all orders in physical quantities), e.g.

$$\frac{d}{d\ln\mu_R^2}\left(\alpha_S(\mu_R^2)\sigma_1(\{p\},\mu_R) + \alpha_S^2(\mu_R^2)\sigma_2(\{p\},\mu_R)\right) = \mathcal{O}(\alpha_S^3(\mu_R^2)).$$

By calculating previous diagrams representing coupling find that coupling satisfies evolution equation

$$\frac{d\alpha_S}{d\ln\mu_R^2} = -\beta_0\alpha_S^2 - \beta_1\alpha_S^3 + \cdots, \qquad \beta_0 = \frac{(11 - 2/3N_f)}{4\pi}$$

Negative $\beta$-function means strong at low scales but weaker at higher scales. Opposite sign for electromagnetic coupling.

Ignoring the $\mathrm{O}(\alpha_s^3)$ corrections this may be solved

$$-\int_{\mu_0^2}^{\mu_R^2} d\,\ln\tilde{\mu}_R^2 = \frac{1}{\beta_0}\int_{\alpha_s(\mu_0^2)}^{\alpha_s(\mu_R^2)} \frac{d\,\tilde{\alpha}_s}{\tilde{\alpha}_s^2},$$

where $\mu_0$ is some fixed scale, or defining a scale $\Lambda_{QCD}$ by

$$\ln(\mu_0^2) - \frac{1}{\beta_0\alpha_s(\mu_0^2)} = \ln(\Lambda_{QCD}^2),$$

i.e. $\Lambda_{QCD}$ is the value of $\mu_0^2$ for $\alpha_s(\mu_0^2) \to \infty$

$$\alpha_s(\mu_R^2) \approx \frac{4\pi}{(11 - 2/3N_f)\ln(\mu_R^2/\Lambda_{QCD}^2)}$$

Binds partons into hadrons at scales $\sim \Lambda_{QCD}$, but can do perturbative calculations at higher scales. Easier to solve evolution numerically beyond LO, but the same features.

## General form of Perturbative Expansion

Suppose we calculate a total cross-section with one variable, e.g. centre of mass energy $\sqrt{s}$. Since the coupling depends on the renormalization scale $\mu$ the cross-section is scale-dependent. At LO in $\alpha_S$

$$\sigma(s) = A\alpha_S(\mu_R^2).$$

This automatically leads to

$$\frac{d\sigma(s)}{d\ln\mu_R^2} = -A\beta_0\alpha_S^2(\mu_R^2).$$

At NLO in $\alpha_S$ renormalisation leads to explicit scale dependence

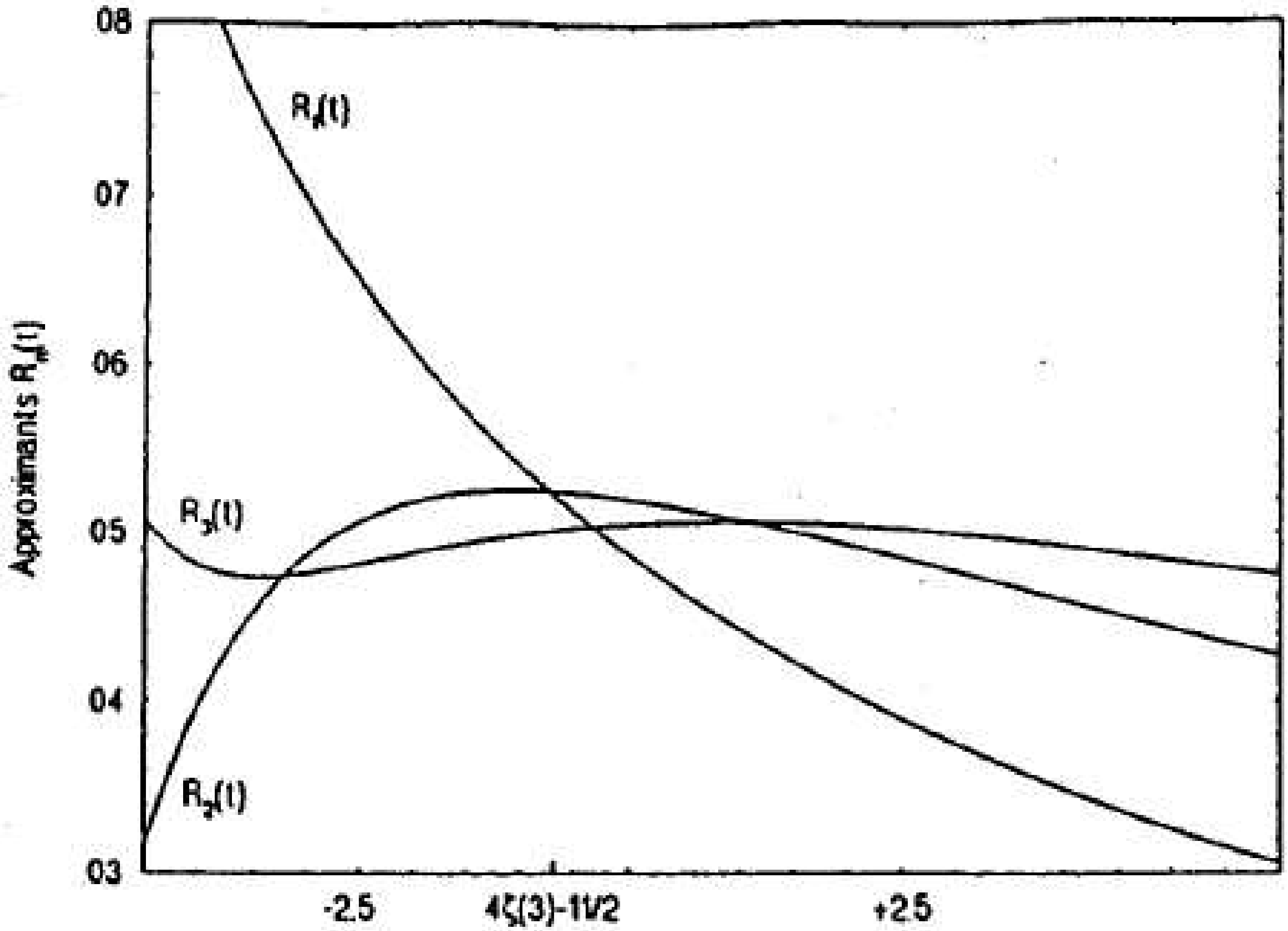
$$\sigma(s) = A\alpha_S(\mu_R^2) + \alpha_S^2(\mu_R^2)(B + b\ln(\mu_R^2/s)).$$

In general the scale dependence is

$$\frac{d\sigma(s)}{d\ln\mu_R^2} = -A\beta_0\alpha_S^2(\mu_R^2) + b\alpha_S^2(\mu_R^2) + \mathcal{O}(\alpha_S^3).$$

The scale dependence must decrease as we go to higher orders.

Achieved if $b = A\beta_0$, i.e. scale dependent part of NLO correction determined by lower orders and running of the coupling. Constant $B$ has to be calculated explicitly.




Renormalisation scheme dependence at LO, NLO and NNLO, for ratio of $e^+ + e^- \rightarrow \mathrm{hadrons/leptons}$ (Samuel and Surguladze).

## Initial State - Parton Distribution Functions (PDFs)

Another complication at the LHC and Tevatron is that the colliding particles are not fundamental.

Hadrons are bound together by the strong force, described QCD.

As seen the strong coupling constant $\alpha_S(\mu^2)$ runs with the energy scale $\mu^2$ of a process, decreasing as $\mu^2$ increases (**asymptotic freedom**), i.e. $\alpha_s(\mu^2)$ is very large if $\mu^2 \sim \Lambda^2_{\mathrm{QCD}}$ $(\sim 0.3\mathrm{GeV})$, the scale of nonperturbative physics, but $\alpha_s(\mu^2) \ll 1$ if $\mu^2 \gg \Lambda^2_{\mathrm{QCD}}$, and perturbation theory can be used.

Because of the strong force it is difficult to perform analytic calculations of scattering processes involving hadronic particles from first principles. However, the weakening of $\alpha_S(\mu^2)$ at higher scales $\longrightarrow$ the **Factorization Theorem** – separates processes into nonperturbative **parton distributions** which describe the composition of the proton and can be determined from experiment, and perturbative **coefficient functions** associated with higher scales which are calculated as a power-series in $\alpha_S(\mu_R^2)$.

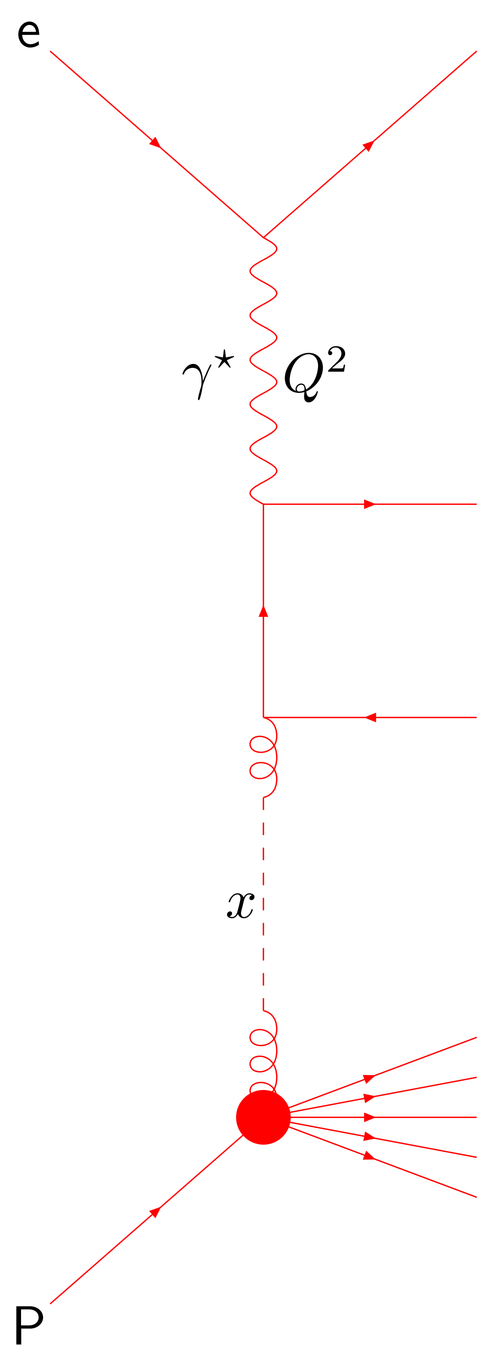
Hadron scattering with an electron factorizes.

$Q^2$ – Scale of scattering

$x = \frac{Q^2}{2P\cdot q}$ – Momentum fraction of parton.

In proton rest frame $P \cdot q = M_P \nu$ where $\nu$ =energy transfer.

$\mu_F$ – factorisation scale, i.e. scale at which PDF and hard cross-section separated (terms of $\ln(\mu_F^2/m_g^2)$ – infrared divergences).




perturbative
calculable
coefficient function
$C_i^P(x, Q^2/\mu_F^2, \alpha_s(\mu_R^2))$

nonperturbative
incalculable
parton distribution
$f_i(x, \mu_F^2, \alpha_s(\mu_F^2))$

The cross-section for this process can be written in the factorised form

$$\sigma(ep \to eX) = \sum_i C_i^P(Q^2/\mu_F^2, \alpha_s(\mu_R^2)) \otimes f_i(\mu_F^2, \alpha_s(\mu_R^2)) \equiv \sum_i \int_x^1 \frac{dz}{z} C_i^P(x/z) f_i(z)$$

where $f_i(x, \mu_F^2, \alpha_s(\mu_R^2))$ represent the probability to find a parton of type $i$ carrying a fraction $x$ of the momentum of the hadron.

Corrections to above formula of size $\Lambda_{\mathrm{QCD}}^2/Q^2$.

The partons are intrinsically nonperturbative. However, once $\mu_F^2$ is large enough they do evolve with $\mu_F^2$ in a perturbative manner.

$$\frac{df_i(x, \mu_F^2, \alpha_s(\mu_R^2))}{d \ln \mu_F^2} = \sum_j P_{ij}(x, \alpha_s(\mu_R^2)) \otimes f_j(x, \mu_F^2, \alpha_s(\mu_R^2))$$

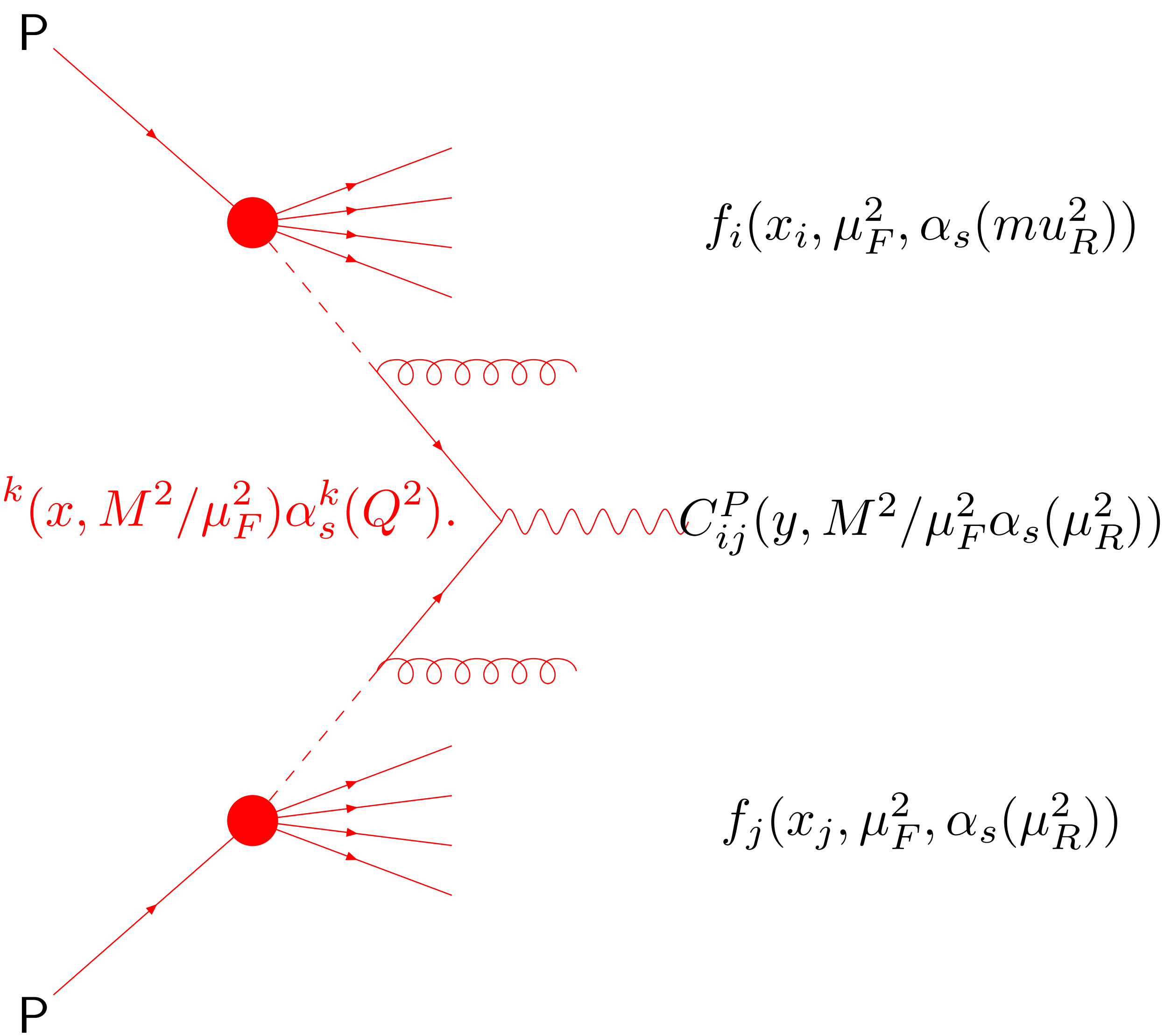
where the splitting functions $P_{ij}(x, \alpha_s(\mu_R^2))$ describing how a parton splits into more partons are calculable order by order in perturbation theory, beginning at $\mathcal{O}(\alpha_s)$.

Partons parameterized at one low scale $Q_0^2$, evolved to higher $\mu_F^2 \sim Q^2$.

The coefficient functions $C_i^P(x, M^2/\mu_F^2, \alpha_s(\mu_R^2))$ are process dependent (new physics) but are calculable as a power-series in $\alpha_s(\mu_R^2)$.

$$C_i^P(x, M^2/\mu_F^2, \alpha_s(\mu_R^2)) = \sum_k C_i^{P,k}(x, M^2/\mu_F^2)\alpha_s^k(Q^2).$$

Since the parton distributions $f_i(x, \mu_F^2, \alpha_s(\mu_R^2))$ are process-independent, i.e. **universal**, once they have been measured at one experiment, one can predict many other scattering processes.




However, $\mu_F$ is a new source of uncertainty at finite order.

## Form of Perturbative Expansion

Consider production of a vector boson of mass $M$ at rapidity $y$ at LO, i.e. zeroth order in $\alpha_s$.

$$\sigma(M^2, y) \propto \sum_{i,j} f_i(x_i, \mu_F^2) f_j(x_j, \mu_F^2),$$

where $x_i x_j s = M^2$ and $x_{i(j)} = M/\sqrt{s}\,\exp(+(-)y)$.

This automatically leads to

$$\frac{d\sigma(M^2, y)}{d\ln\mu_F^2} = \sum_{i,j,k} \alpha_S \big(P^0_{ik} \otimes f_i(x_k, \mu_F^2) f_j(\mu_F^2) + f_i(x_i, \mu_F^2) P^0_{jk} \otimes f_k(\mu_F^2),$$

where $\alpha_s P^0_{jk}$ is the LO splitting function, i.e. the factorisation scale dependence is related to the evolution of the parton distributions.

Would expect $\mu_F^2 \sim M^2$.

At NLO, ignoring renormalisation scale dependence

$$\sigma(M^2, y) \propto \sum_{i,j} f_i(x_i, \mu_F^2) f_j(x_j, \mu_F^2) + \alpha_S \Bigg( c_{ij}^1 \otimes f_i(\mu_F^2) \otimes f_j(\mu_F^2)$$

$$+ \ln(M^2/\mu_F^2) \sum_k (\tilde{c}_{ik}^1 \otimes f_i(\mu_F^2)\, f_j(x_j, \mu_F^2) + \tilde{c}_{jk}^1 \otimes f_k(\mu_F^2)\, f_i(x_i, \mu_F^2)) \Bigg),$$

This leads to

$$\frac{d\sigma(M^2, y)}{d \ln \mu_F^2} = \sum_{i,j,k} \alpha_S \big( P_{ik}^0 \otimes f_i(x_k, \mu_F^2) f_j(\mu_F^2) + f_i(x_i, \mu_F^2) P_{jk}^0 \otimes f_k(\mu_F^2),$$

$$- \sum_{i,j,k} (\tilde{c}_{ik}^1 \otimes f_i(\mu_F^2)\, f_j(x_j, \mu_F^2) + \tilde{c}_{jk}^1 \otimes f_k(\mu_F^2)\, f_i(x_i \mu_F^2)) + \mathcal{O}(\alpha_s^2).$$

and to cancel the LO factorisation scale dependence the $\tilde{c}_{ik}^1$ must be identical to $P_{ik}^0$, while the $c_{ij}^1$ must be determined explicitly.

With this definition the factorisation scale dependence at NLO becomes $O(\alpha_S^2)$, due both to NLO evolution and the NLO term.

This movement of scale dependence to one higher order extends to higher orders.

Since both renormalisation scale and factorisation scale dependence diminishes at higher orders, scale variation at fixed order used to $estimate$ the $theoretical$ uncertainty.

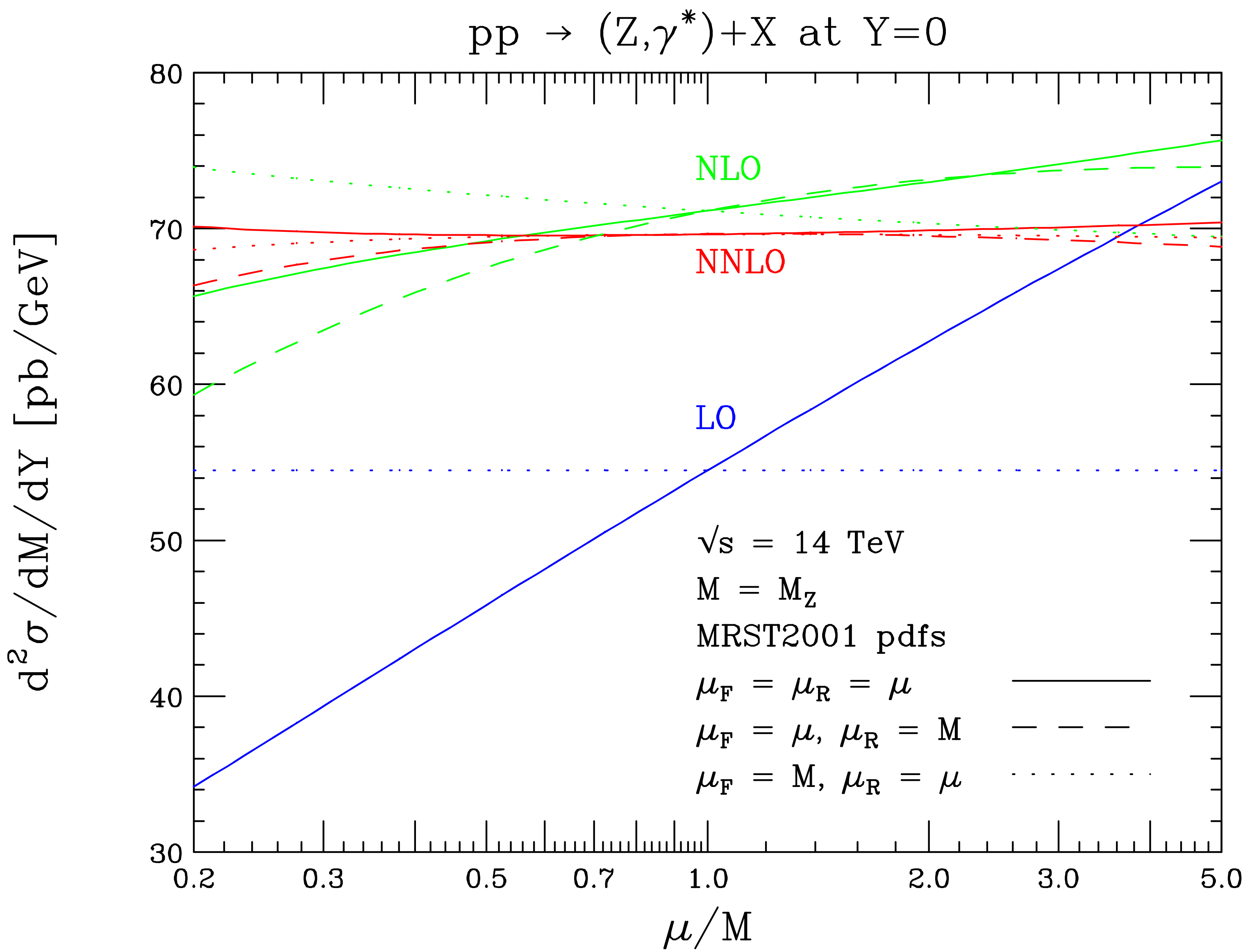
It is seen as a measure of how much allowed variation there is before the unknown higher-order corrections are added.

Usually reasonable, but must be treated with some caution.

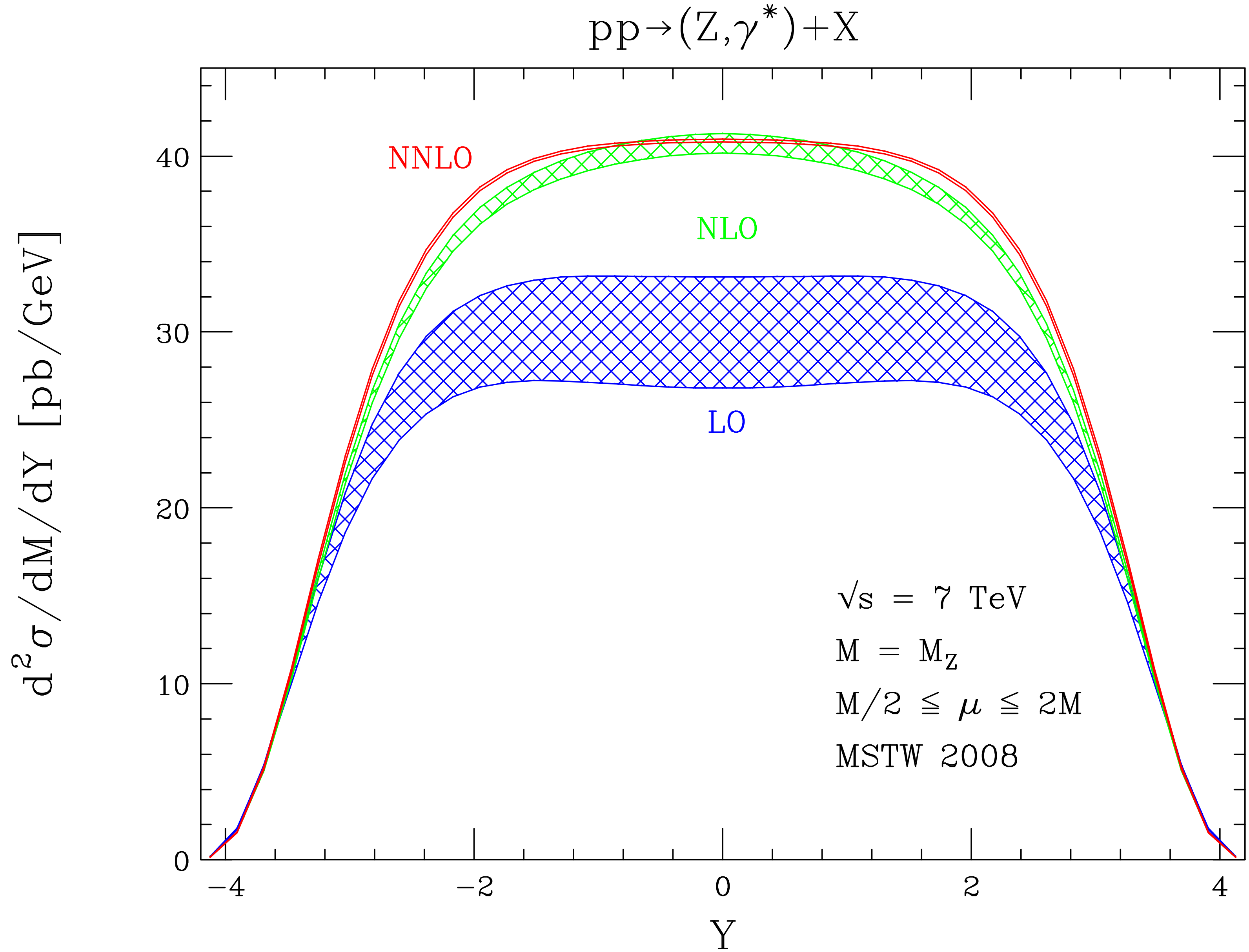
If something fundamentally new appears at higher orders, e.g. a new dependence on energy, scale variation knows nothing of this.

Will see some examples later.

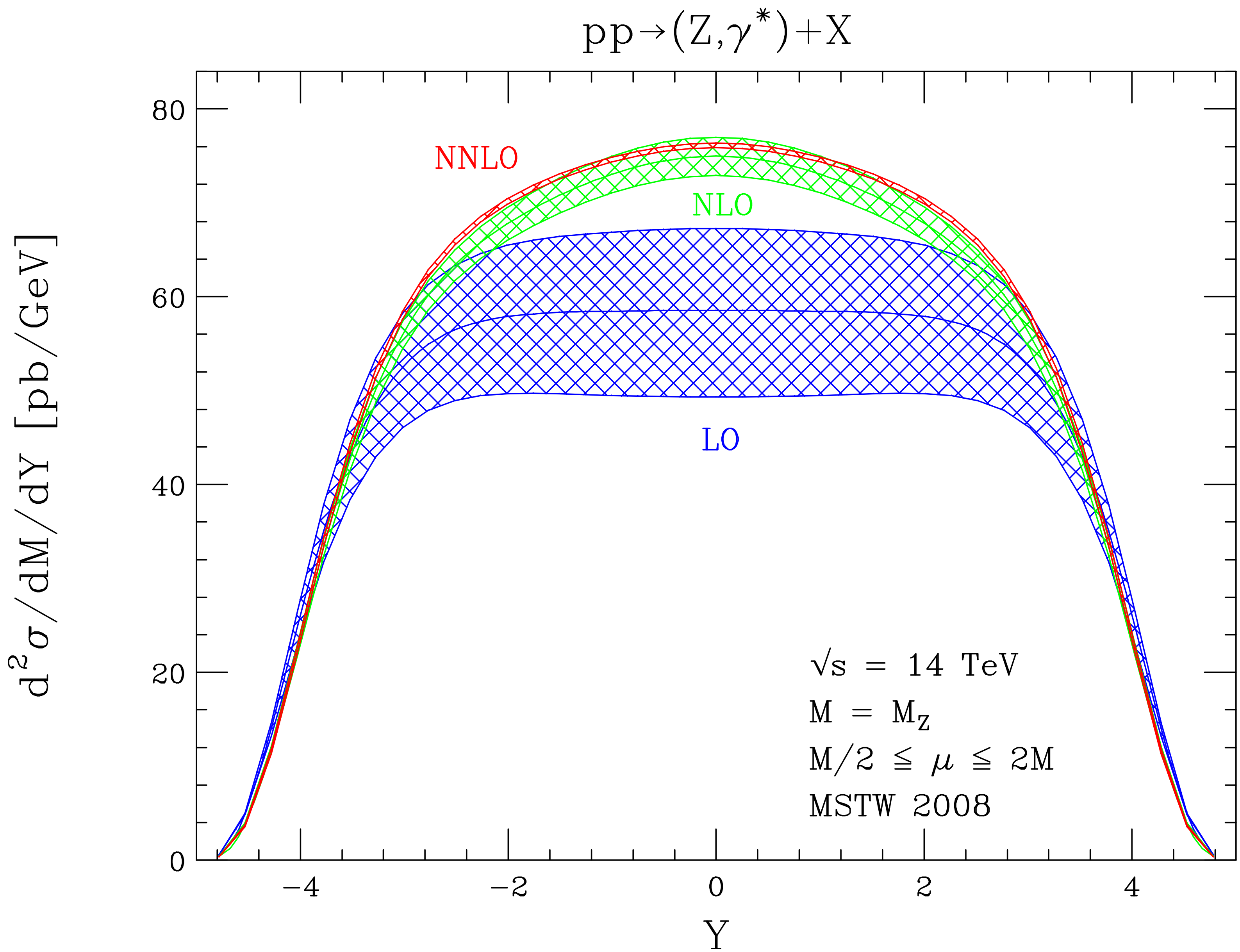
Scale variations of $Z$ production (Anastasiou *et al.*).




With a NNLO correction the scale dependence is postponed to $\mathcal{O}(\alpha_S^4)$.




Based on (Anastasiou *et al.*), from Lance Dixon.




Based on (Anastasiou *et al.*), from Lance Dixon.

## Obtaining PDF sets.

However, the PDF sets themselves must be determined, and have a distinct set of uncertainties unrelated to that due to use of fixed order perturbative QCD.

General procedure for extraction – start parton evolution at low scale $Q_0^2 \sim 1\mathrm{GeV}^2$. In principle 11 different partons to consider.

$$u, \bar{u}, \quad d, \bar{d}, \quad s, \bar{s}, \quad c, \bar{c}, \quad b, \bar{b}, \quad g$$

$m_c, m_b \gg \Lambda_{\mathrm{QCD}}$ so heavy parton distributions determined perturbatively. Leaves 7 independent combinations, or 6 if we assume $s = \bar{s}$ (just started not to).

$$u_V = u - \bar{u}, \quad d_V = d - \bar{d}, \quad \mathrm{sea} = 2 * (\bar{u} + \bar{d} + \bar{s}), \quad s + \bar{s} \quad \bar{d} - \bar{u}, \quad g.$$

Input partons parameterised as, e.g. MSTW, – much more general form for NNPDF, but same limits as $x \rightarrow, 0, 1$.

$$xf(x, Q_0^2) = (1-x)^\eta (1 + \epsilon x^{0.5} + \gamma x) x^\delta.$$

Evolve partons upwards using LO, NLO (or NNLO) DGLAP equations.

Fit data for scales above $2-5\mathrm{GeV}^2$. Need many different types for full determination.

- Lepton-proton collider HERA – (DIS) $\rightarrow$ small-$x$ quarks (best below $x \sim 0.05$). Also gluons from evolution (same $x$), and now $F_L(x,Q^2)$. Also, jets $\rightarrow$ moderate-$x$ gluon.Charged current data some limited info on flavour separation. Heavy flavour structure functions – gluon and charm, bottom distributions and masses.

- Fixed target DIS – higher $x$ – leptons (BCDMS, NMC, ...) $\rightarrow$ up quark (proton) or down quark (deuterium) and neutrinos (CHORUS, NuTeV, CCFR) $\rightarrow$ valence or singlet combinations.

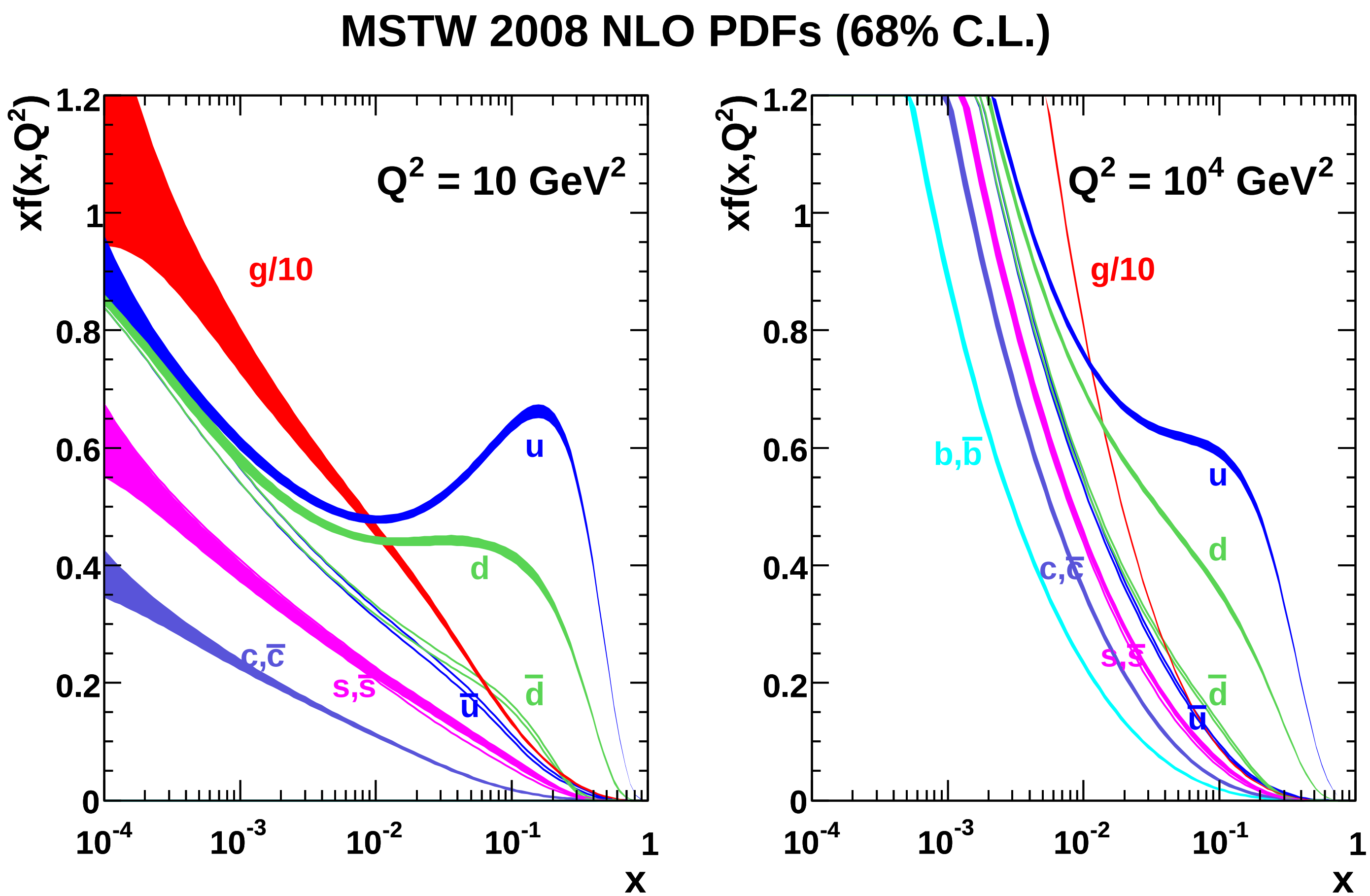
- Di-muon production in neutrino DIS – strange quarks and neutrino-antineutrino comparison $\rightarrow$ asymmetry . Only for $x > 0.01$.

- Drell-Yan production of dileptons – quark-antiquark annihilation (E605, E866) – high-$x$ sea quarks. Deuterium target – $\bar{u}/\bar{d}$ asymmetry.

- High-$p_T$ jets at colliders (Tevatron) – high-$x$ gluon distribution – $x > 0.01$ .

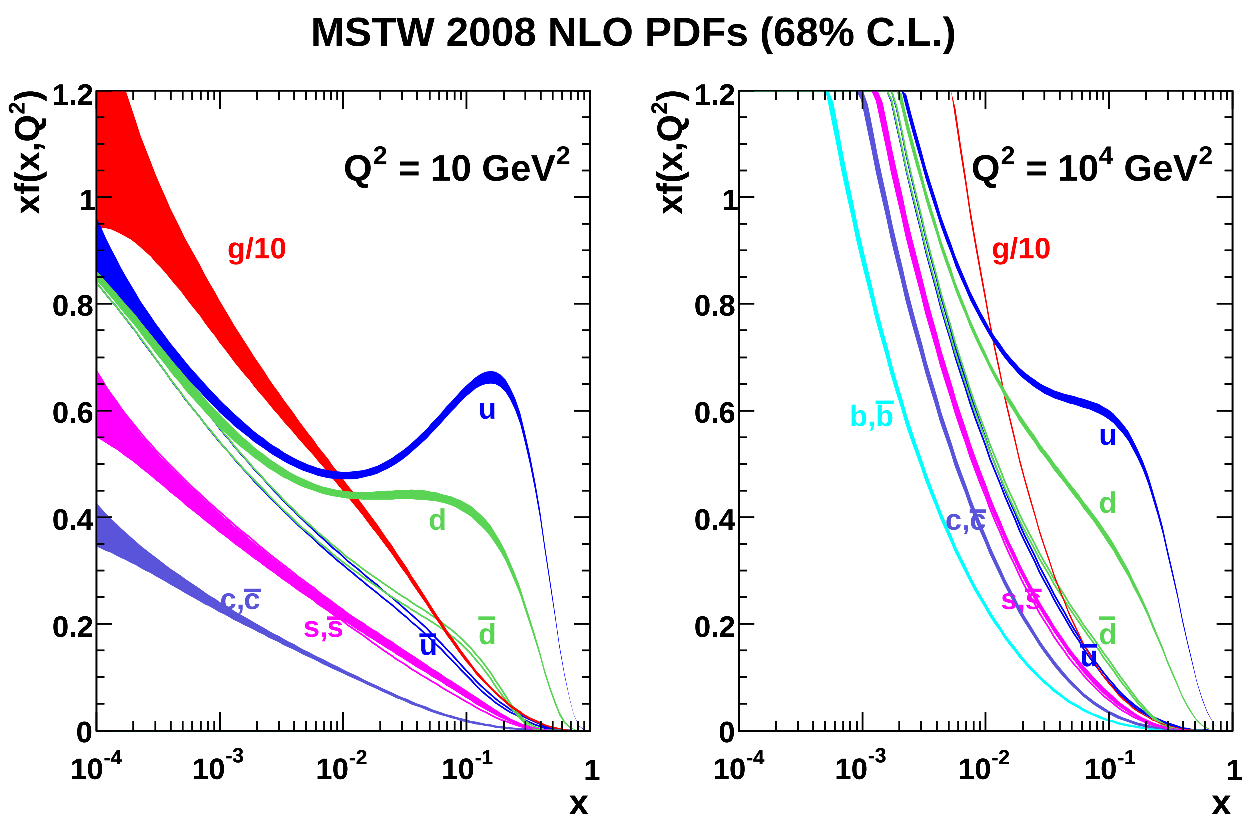
- $W$ and $Z$ production at colliders (Tevatron) – different quark contributions to DIS.

This procedure is generally successful and is part of a large-scale, ongoing project. Results in partons of the form shown.

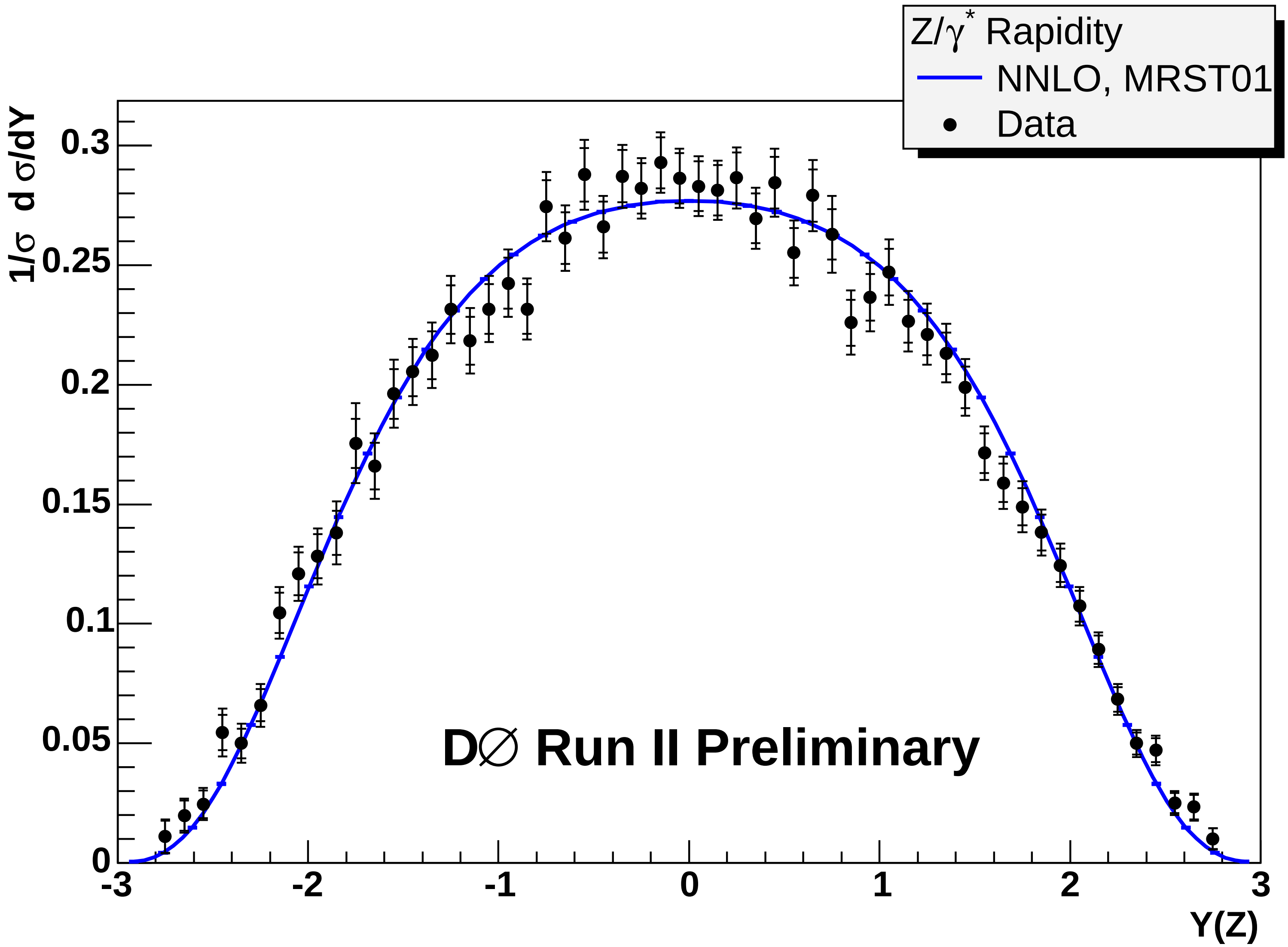



Various choices of PDF – MSTW, CTEQ, NNPDF, Alekhin, HERA, Jimenez-Delgado *et al etc.*. All LHC cross-sections rely on our understanding of these partons.

CMS seem to appreciate the importance of PDFs in their logo. (though their axes are reversed.)



Excellent predictive power – comparison of MRST prediction for $Z$ rapidity distribution with preliminary data.



## Interplay of LHC/Tevatron and pdfs/QCD

Make predictions for all processes, both SM and BSM, as accurately as possible given current experimental input and theoretical accuracy.

Check against well-understood processes, e.g. central rapidity $W, Z$ production (luminosity monitor), lowish-$E_T$ jets, .....

Compare with predictions with more uncertainty and lower confidence, e.g. high-$E_T$ jets, high rapidity bosons or heavy quarks .....

Improve uncertainty on parton distributions by improved constraints, and check understanding of theoretical uncertainties, and determine where NNLO, electroweak corrections, resummations $etc.$ needed.

Make improved predictions for both background and signals with improved partons and Standard Model theory.

Spot new physics from deviations in these predictions. As a nice by-product improve our understanding of the Standard Model considerably.

Remainder of talk describes this process in more detail.

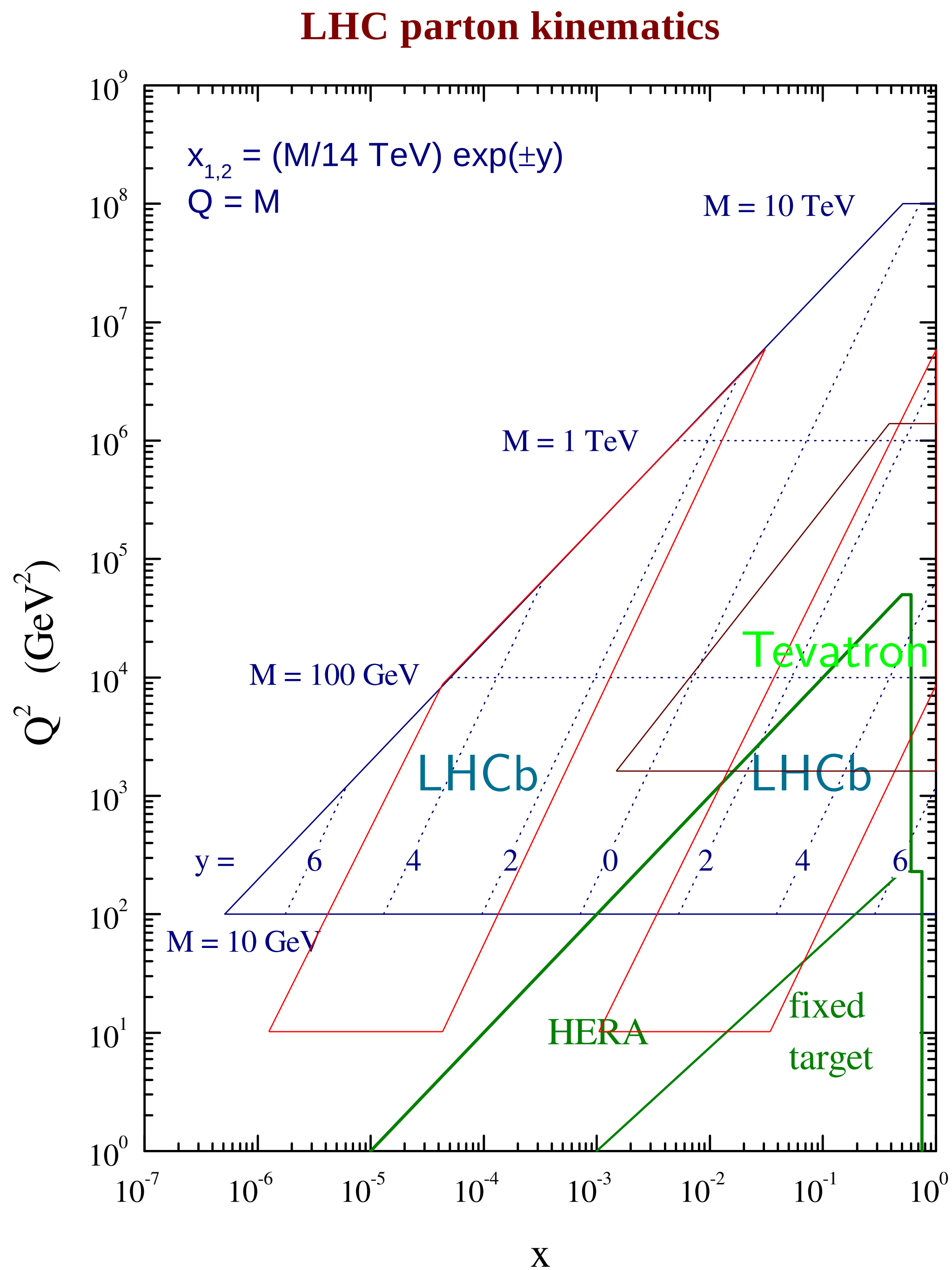
## Predictions at the LHC

New kinematic regime.

PDFs mainly extrapolated via evolution rather than measured directly.

High scale and small-$x$ parton distributions are vital for understanding processes at the LHC.

More discrepancy at values of $x$ away from this.

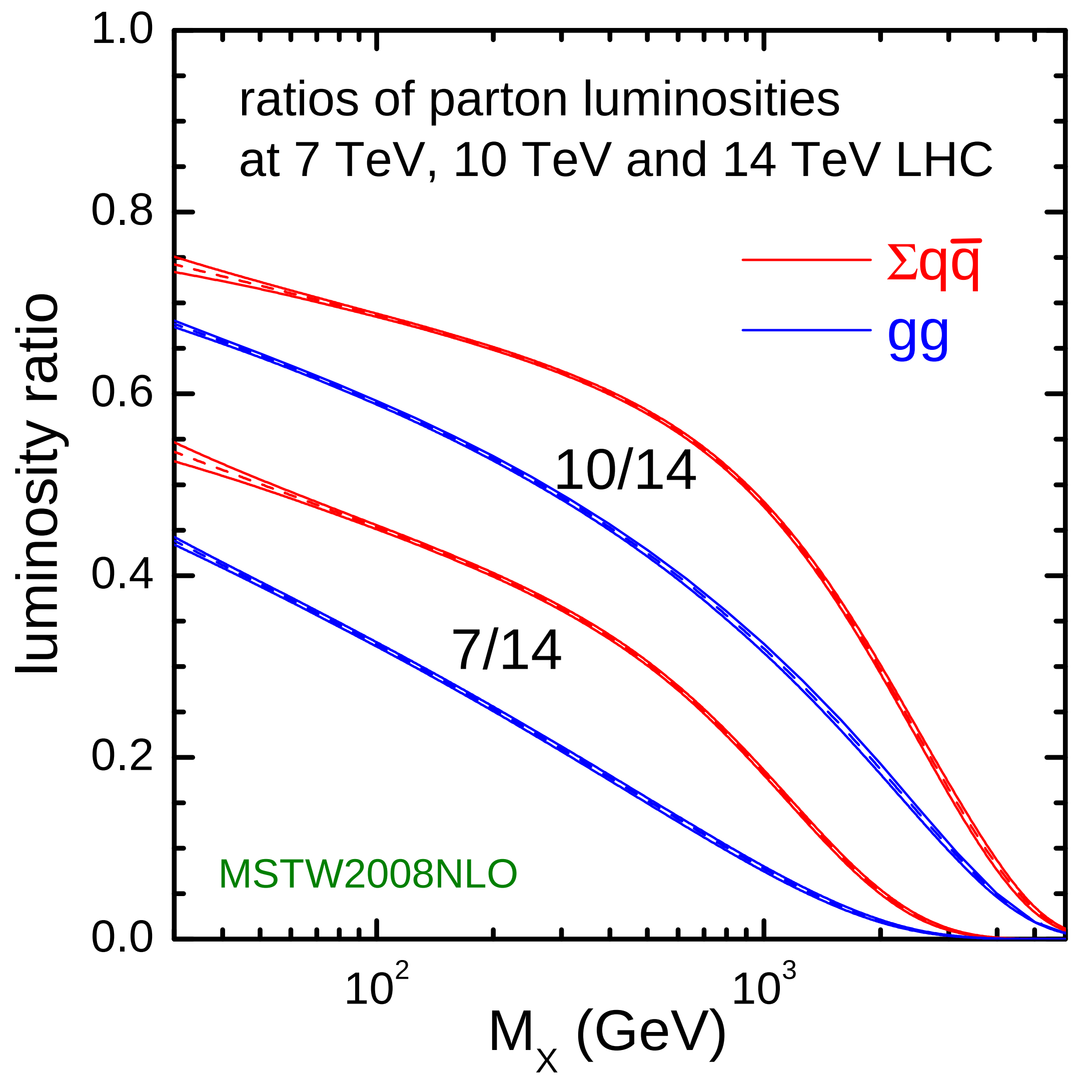


## Initial Running

Of course, the LHC has started running at 7 TeV rather than the full 14 TeV.

Reduces rapidity range by $\ln 2$.

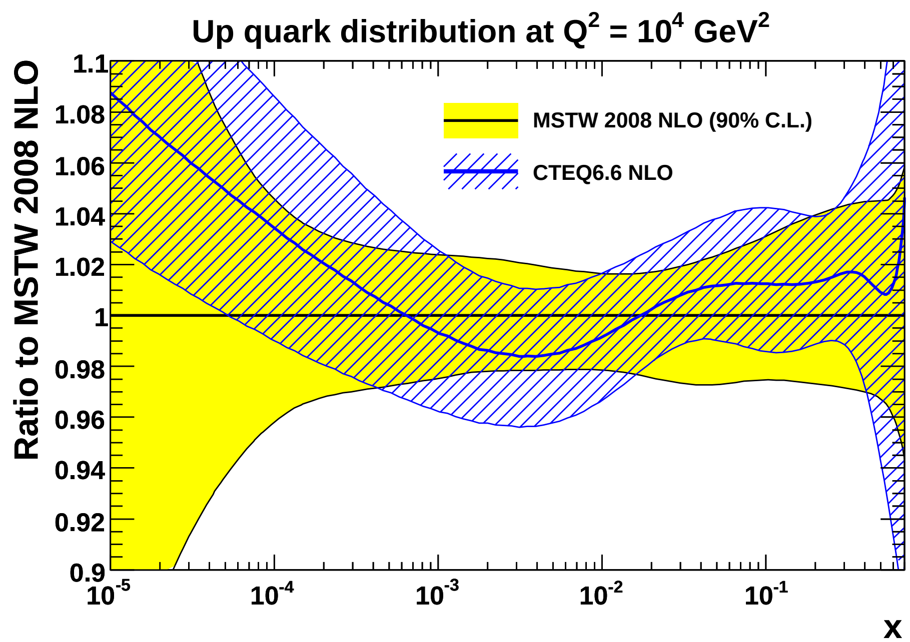
Roughly $30 - 50\%$ the full cross-sections for most standard model (including light Higgs) processes.

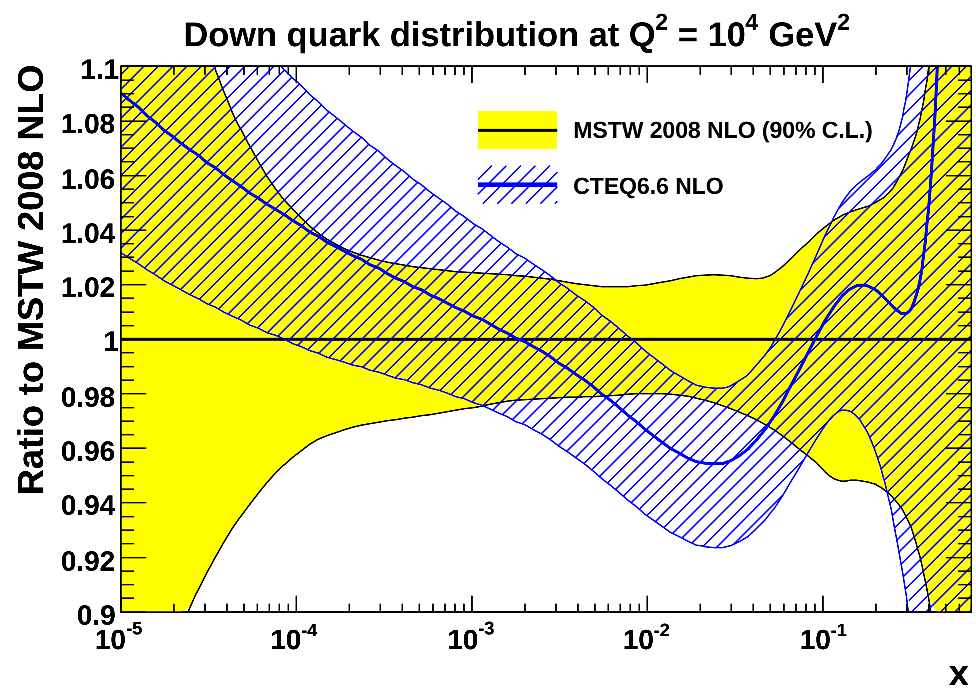


Uncertainty on MSTW $u$ and $d$ distributions, along with CTEQ6.6.

Reasonable agreement between groups.

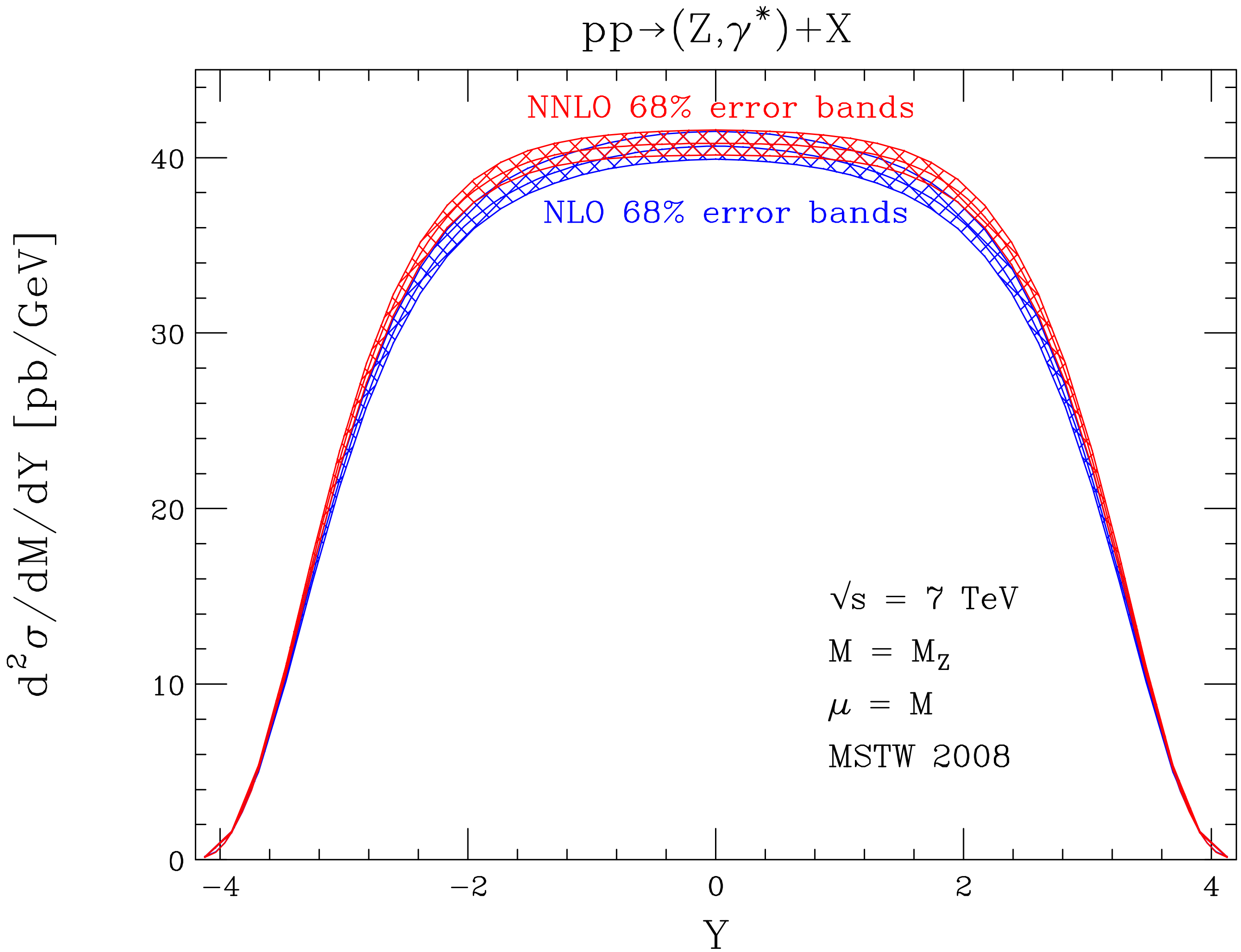
Central rapidity $x = 0.006$ is ideal for uncertainty in $W, Z$ (Higgs?) at the LHC.



## Uncertainty due to PDFs

Greater than NNLO scale dependence.




Based on (Anastasiou *et al.*), from Lance Dixon.

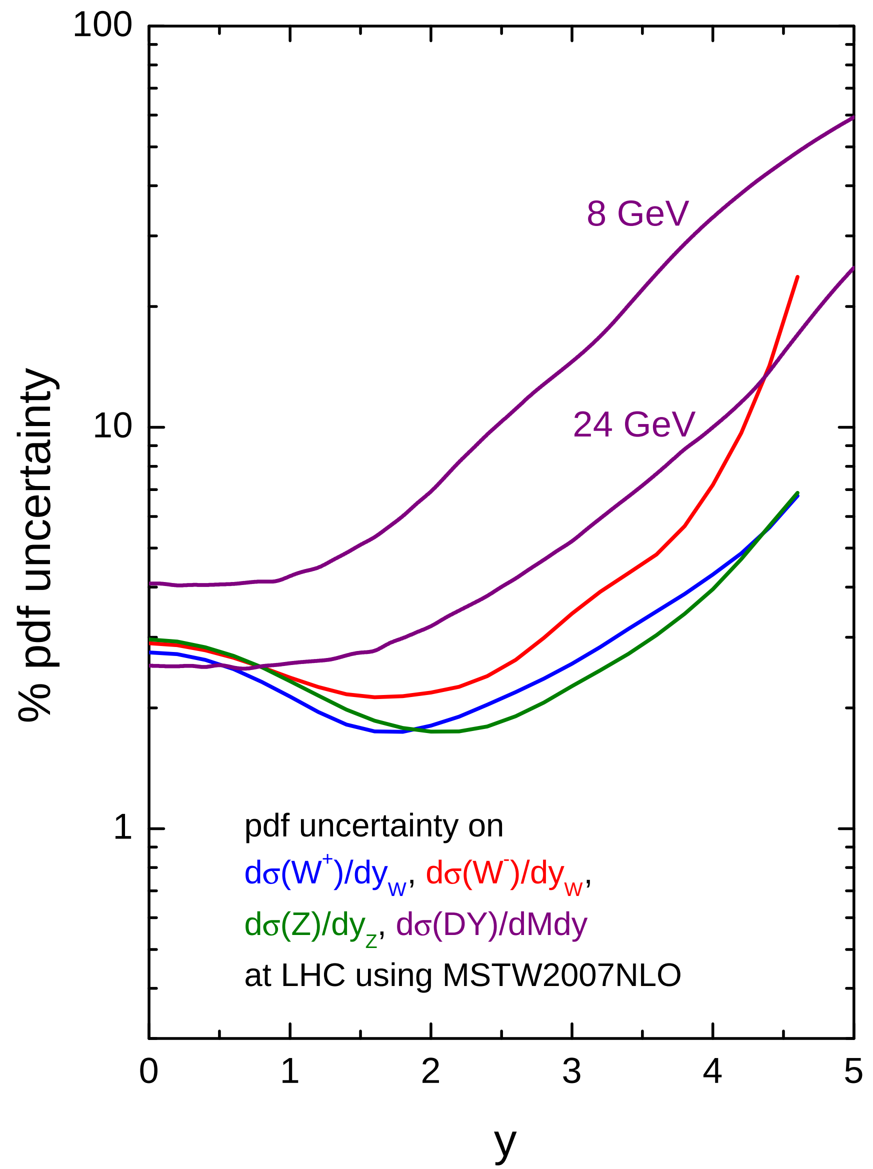
## $W, Z$ uncertainty – more details

Uncertainty on $\sigma(Z)$ and $\sigma(W^+)$ grows at high rapidity.

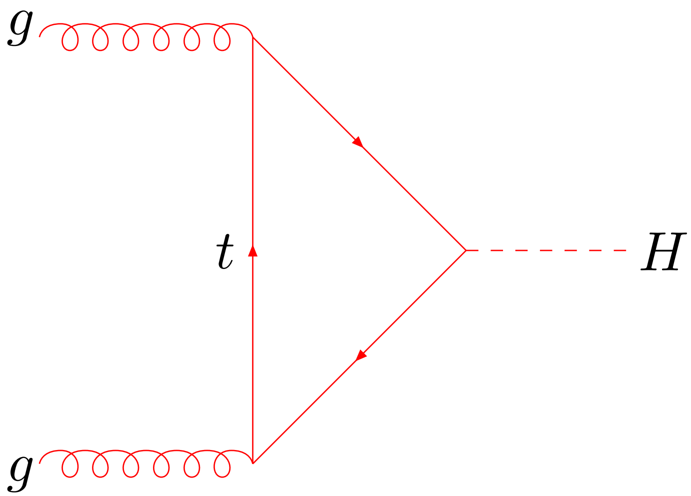
Uncertainty on $\sigma(W^-)$ grows more quickly at very high $y$ – depends on less well-known down quark.

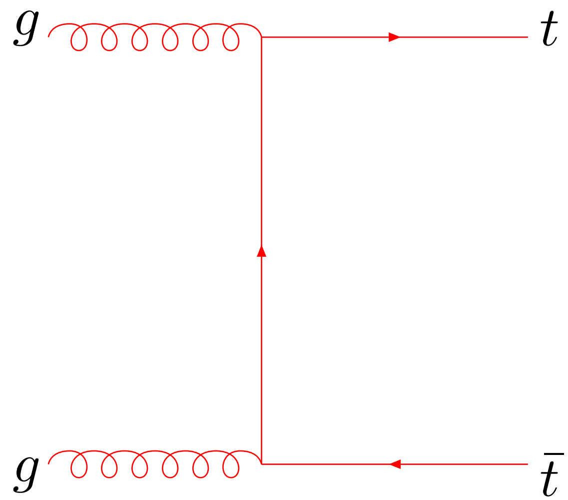
Uncertainty on $\sigma(\gamma^\star)$ is greatest as $y$ increases. Depends on partons at very small $x$.

Lots of interest in LHCb range.

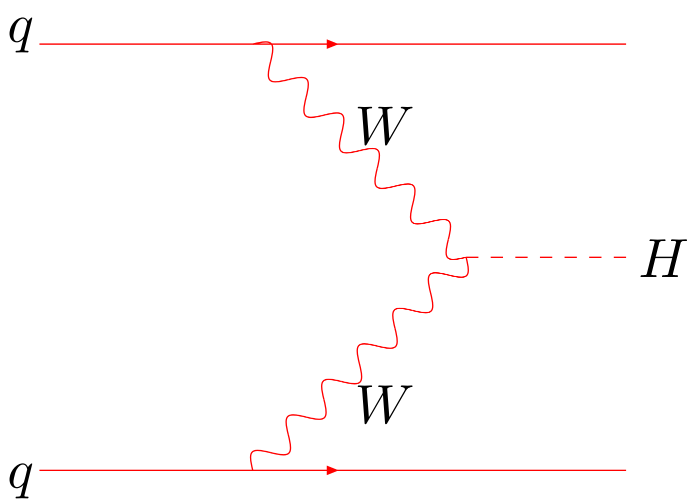


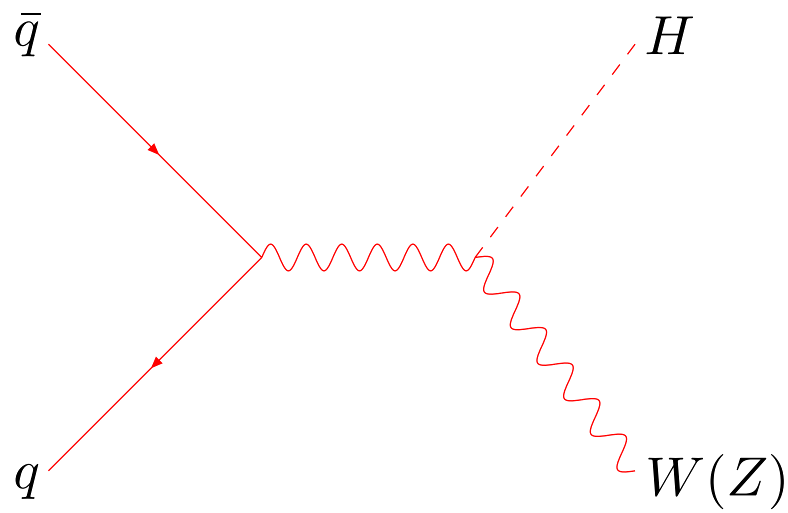
Dominant Higgs production mechanism, gluon-gluon fusion via top quark loop. Very similar to top production (at the LHC)



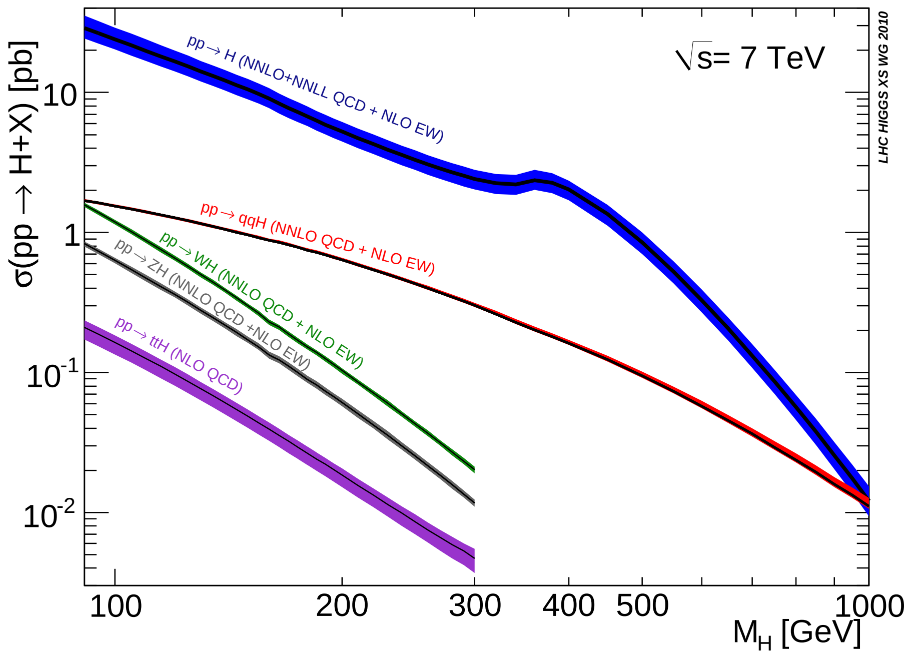

Also large Higgs contributions from vector boson fusion and associated production with $W(Z)$.

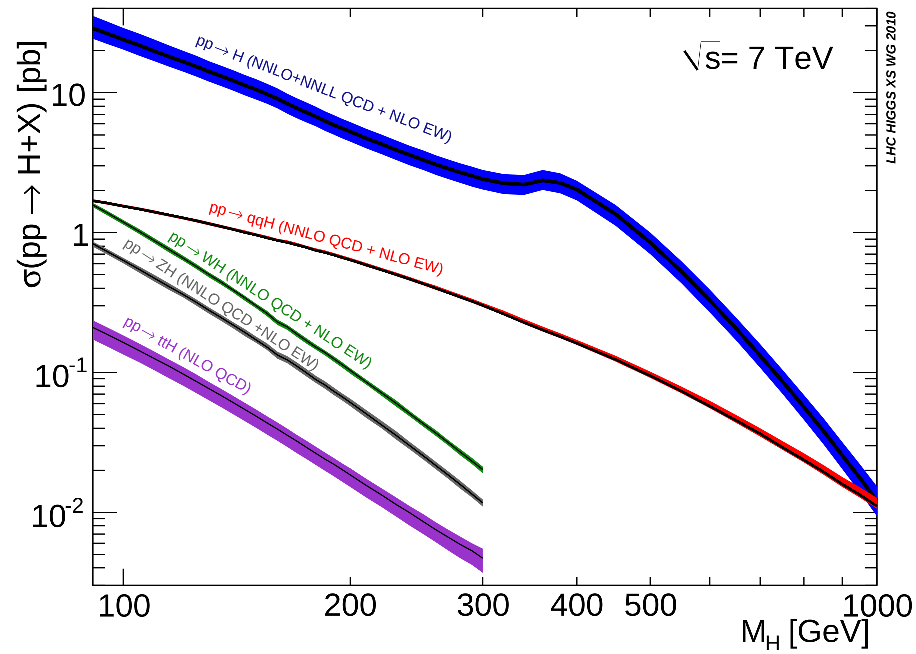


For gluon-gluon fusion cross-section known at NNLO (Harlander, Harlander and Kilgore, Anastasiou and Melnikov, Catani *et al* and Ravindran *et al*) (in large $m_t$ limit). The associated production is known at NNLO (Brein *et al*). There are NLO codes for VBF (VBFNLO – Arnold *et al*, and HAWK – Denner *et al*) and approx. NNLO VBF results are known Bolzoni *et al*).

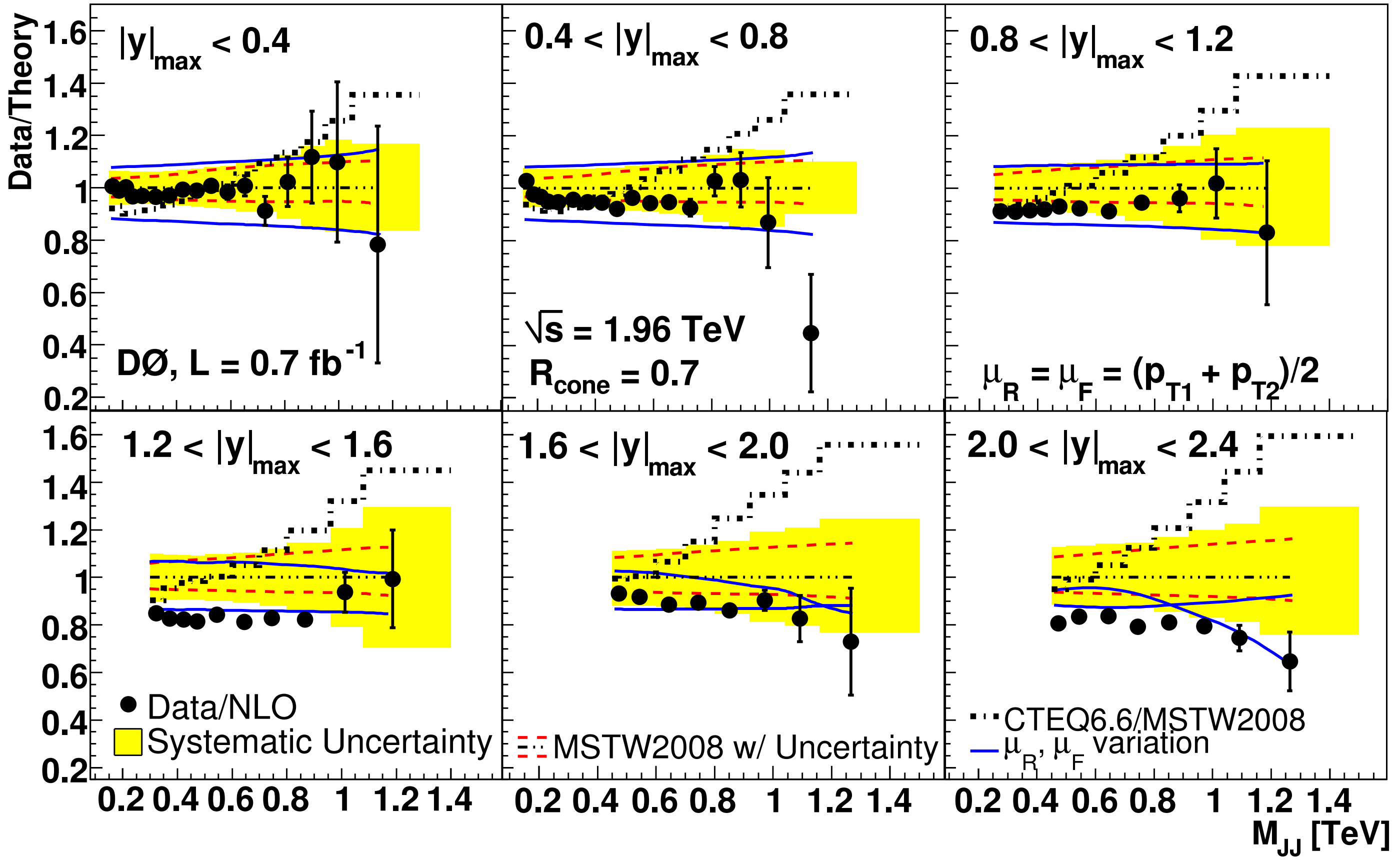
For given PDF set Higgs cross-sections usually dominated by theory (scale) uncertainties (particularly dominant $gg \to H$ mechanism).



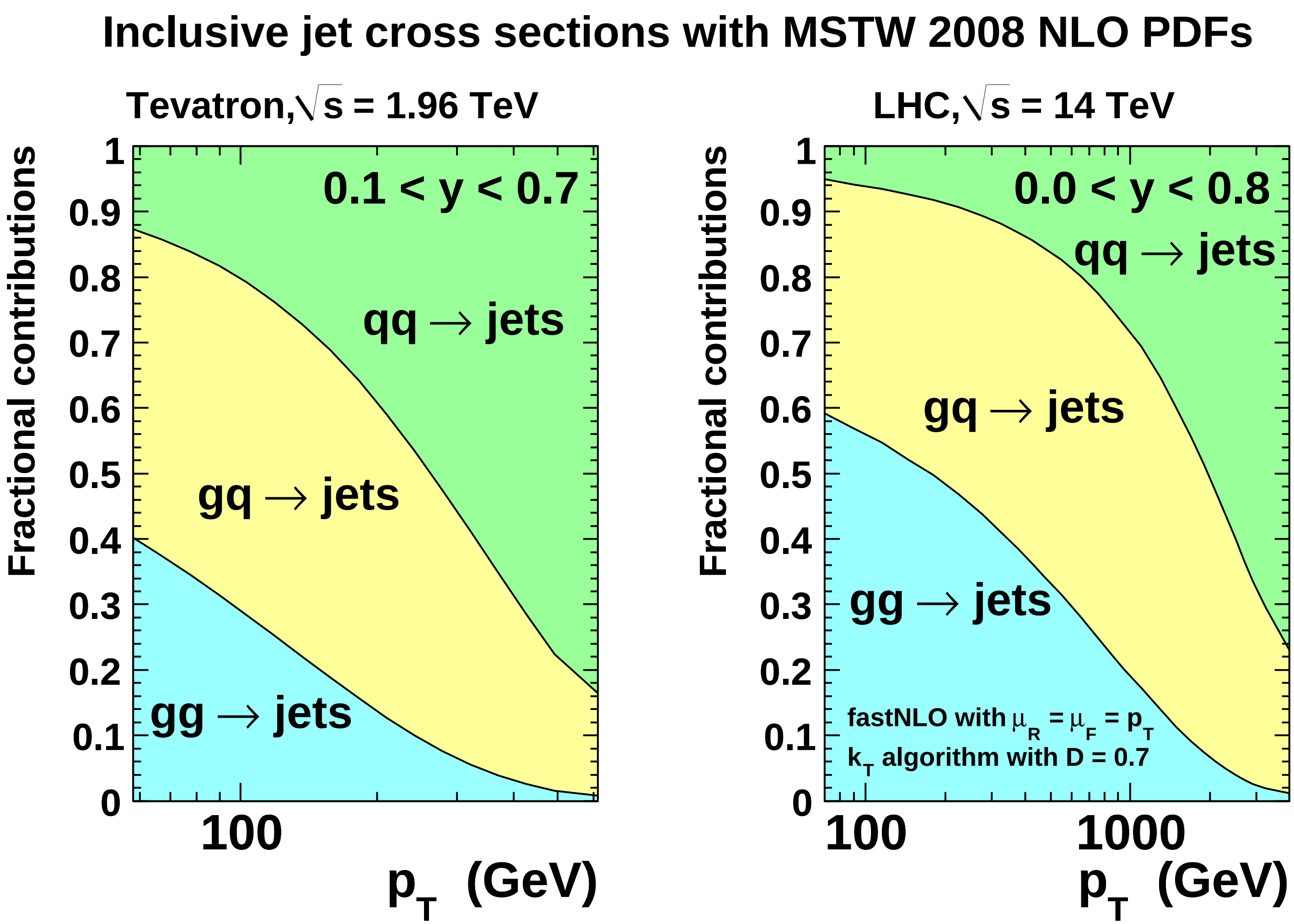

Plots from Handbook of LHC Higgs Cross Sections

For jet production probed at the Tevatron scale and PDF uncertainty similar (and both similar to data *systematic* uncertainty)




Mixture of quark-quark, quark-gluon and gluon gluon induced processes.

Quarks known from DIS so constrains gluon mainly.

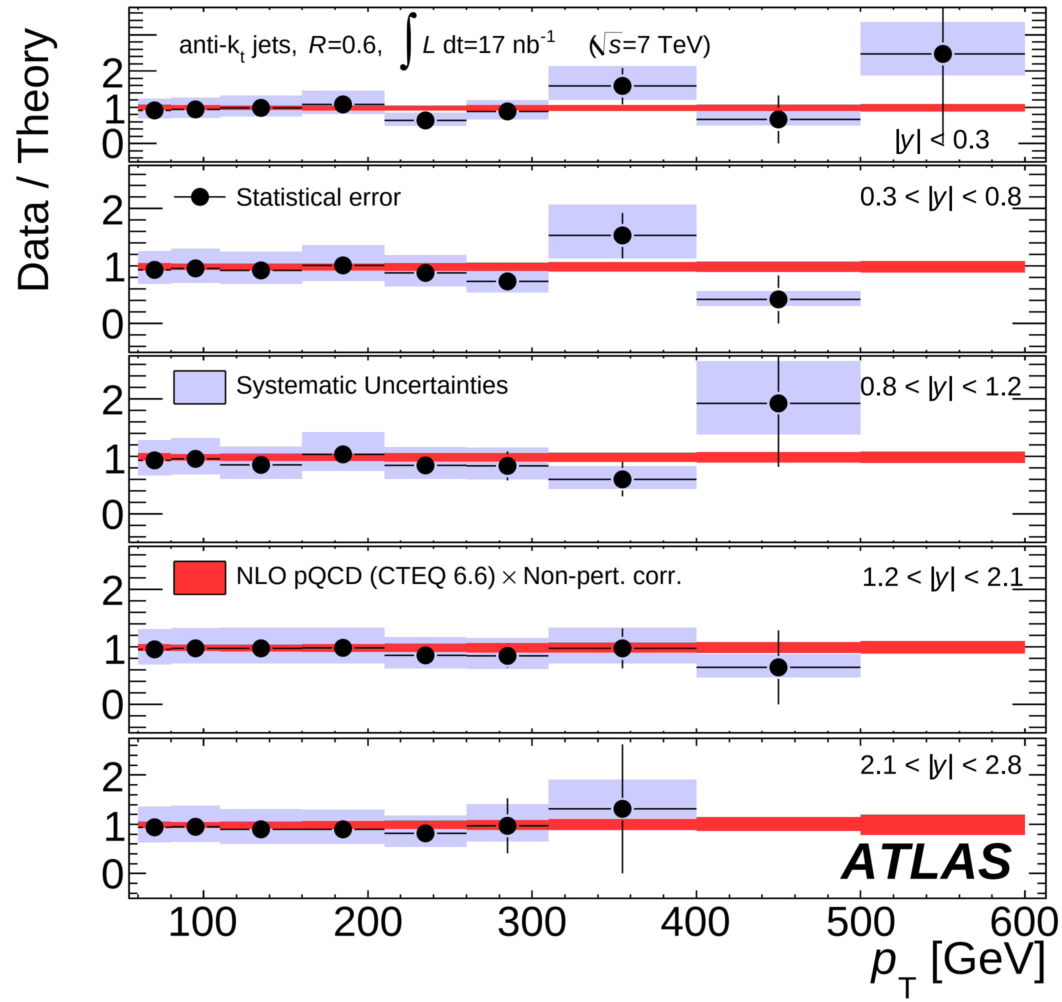



Proton-proton rather than proton-antiproton at LHC leads to more gluon dependence.

Correlated with Higgs production.

In future the LHC jet data will be a good constraint (and test) of the gluon.

At present statistics, and jet energy scale uncertainty not well enough advanced.



## Cross-section ratios

Ratios of vector bosons rates are useful. Cancel many experiment uncertainties, and theory – mainly PDF left. Can use

$$R_{Z/W} = \frac{\sigma(Z)}{\sigma(W^+)+\sigma(W^-)} \simeq \frac{Au(\tilde{x}_1)\bar{u}(\tilde{x}_2) + Bd(\tilde{x}_1)\bar{d}(\tilde{x}_2)}{u(x_1)\bar{d}(x_2) + d(x_1)\bar{u}(x_2)} \simeq \frac{Au(\tilde{x}_1) + Bd(\tilde{x}_1)}{u(x_1)+d(x_1),}$$

Where we have used $\bar{u}(\tilde{x}_2) \approx \bar{d}(\tilde{x}_2)$ and ignored small(ish) strange, charm $etc.$ contributions. This is very precisely predicted, but is equal to $A$ plus small corrections.

$$A_{\pm} = \frac{(\sigma(W^+)-\sigma(W^-))}{(\sigma(W^+)+\sigma(W^-))} \simeq \frac{u(x_1)\bar{d}(x_2) - d(x_1)\bar{u}(x_2) + (\bar{d}(x_1)u(x_2) - \bar{u}(x_1)d(x_2))}{u(x_1)\bar{d}(x_2) + d(x_1)\bar{u}(x_2) + (\bar{d}(x_1)u(x_2) + \bar{u}(x_1)d(x_2))}$$

$$\simeq \frac{u_V(x_1) - d_V(x_1)}{u(x_1)+d(x_1)}$$

so is a good test of valence quarks. Alternatively we have

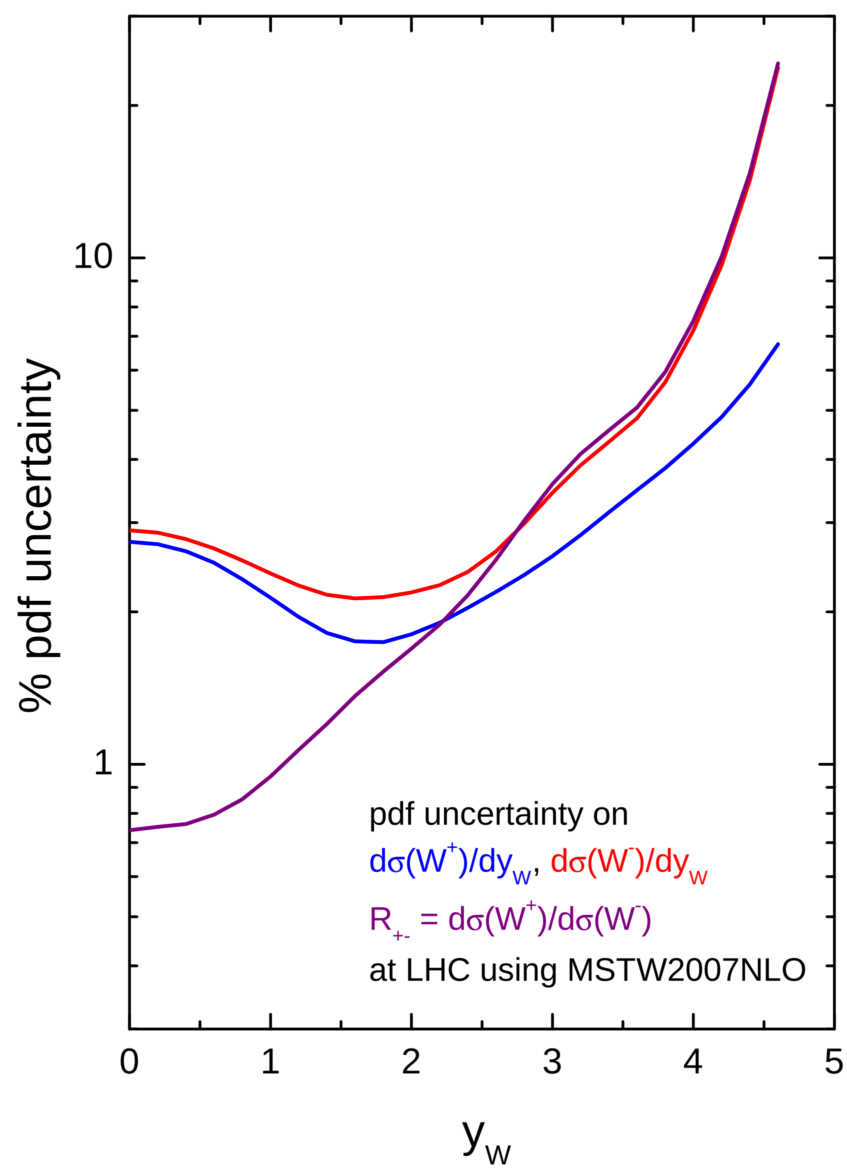
$$R_{\pm} = \frac{\sigma(W^-)}{\sigma(W^+)} \simeq \frac{d(x_1)\bar{d}(x_2)}{u(x_1)\bar{d}(x_2)} \simeq \frac{d(x_1)}{u(x_1)},$$

Uncertainty on $R_{Z/W}$ is very small. Parton combinations highly correlated.

Assumes $\bar{u}(x_2) \approx \bar{d}(x_2)$. Easily checks if this is true.

Uncertainty on $A_{\pm}$ not strongly $y$-dependent.

Uncertainty on $R_{\pm}$ increases strongly at high $y$.



## Lepton Asymmetry

In practice it is leptons seen in final state rather than $W$ and $Z$. For former this causes complications. For $W^{\pm}$ only one charged lepton is seen.

Defining angle of lepton in $W$ rest frame

$$\cos^2\theta^* = 1 - 4p_T^2/M_W^2 \quad \rightarrow \quad y_{lep} = y_W \pm 1/2\log((1+\cos\theta^*)/(1-\cos\theta^*))$$

If $p_T = 30\mathrm{GeV}$ – $\cos\theta^* = 0.66$ and $y_{lep} = y_W \pm 0.8$.

From helicity the decay of the lepton from the boson has distribution

$$(1+\cos\theta^*)^2 \quad \mathrm{or} \quad (1-\cos\theta^*)^2.$$

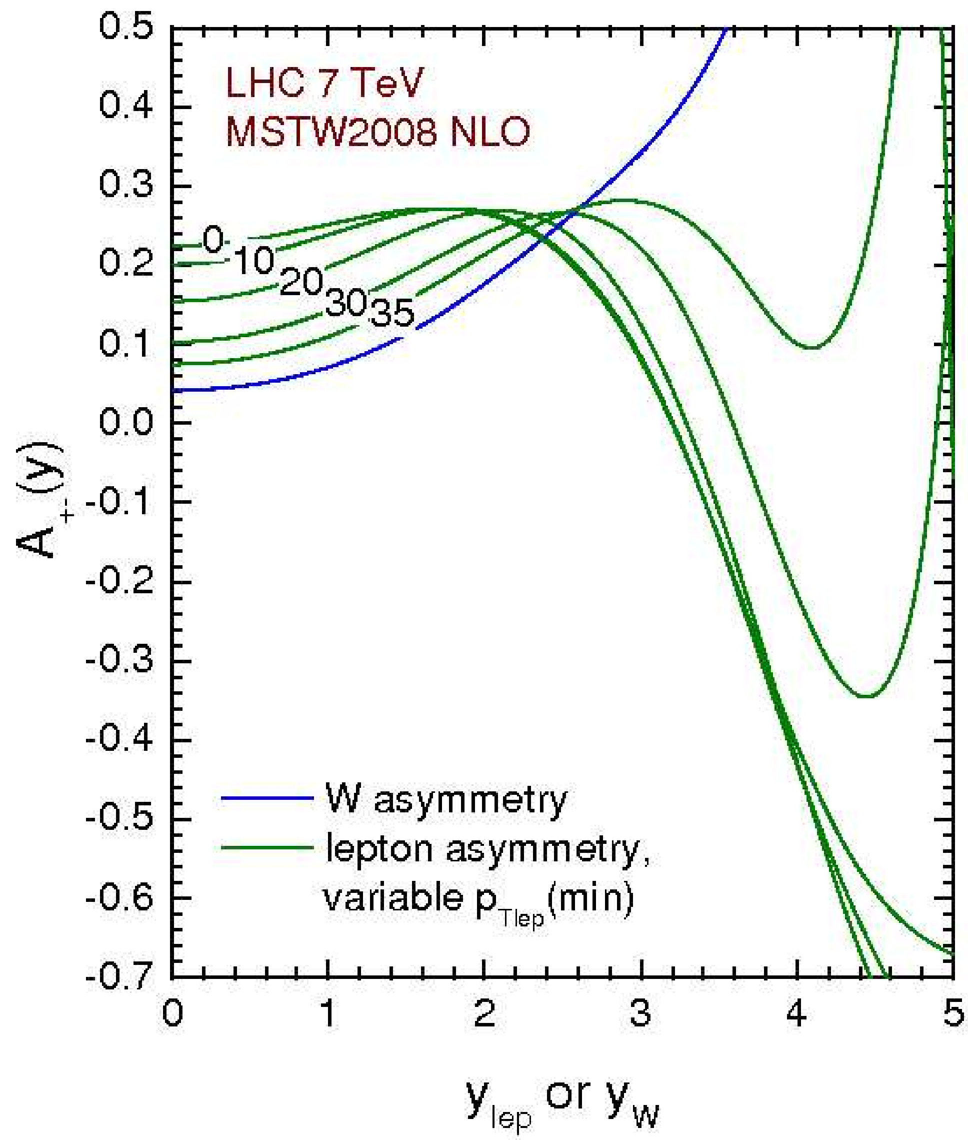
If the former dominates then

$$A_{\pm} = \frac{(\sigma(l^+) - \sigma(l^-))}{(\sigma(l^+) + \sigma(l^-))} \simeq \frac{\bar{d}(x_1)u(x_2) - d(x_1)\bar{u}(x_2)}{\bar{d}(x_1)u(x_2) + d(x_1)\bar{u}(x_2)}$$

which makes no difference for small $y$, i.e. $x_1 \approx x_2$ but for $x_1 \gg x_2$ can change the sign of the asymmetry.

The smaller the $p_{T(\min)}$ the more effect the decay distribution has.

Ultimately at high enough $y$ or $x_1$ the dominance of the $u_V(x_1)$ distribution takes over and $A_\pm \to 1$.



## Other Ratios

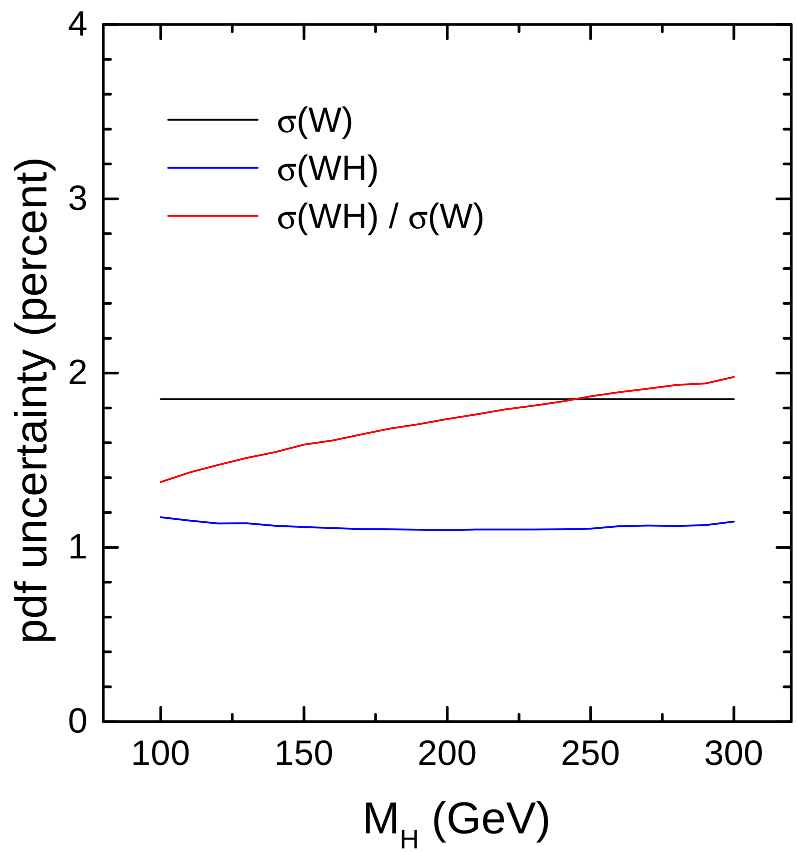
Could $\sigma(W)$ or $\sigma(Z)$ be used to calibrate other cross-sections, e.g. $\sigma(WH)$, $\sigma(Z')$?

$\sigma(WH)$ more precisely predicted because it samples quark pdfs at higher $x$, and scale, than $\sigma(W)$.

However, ratio shows no improvement in uncertainty, and can be worse.

Partons in different regions of $x$ are often anti-correlated rather than correlated, partially due to sum rules.

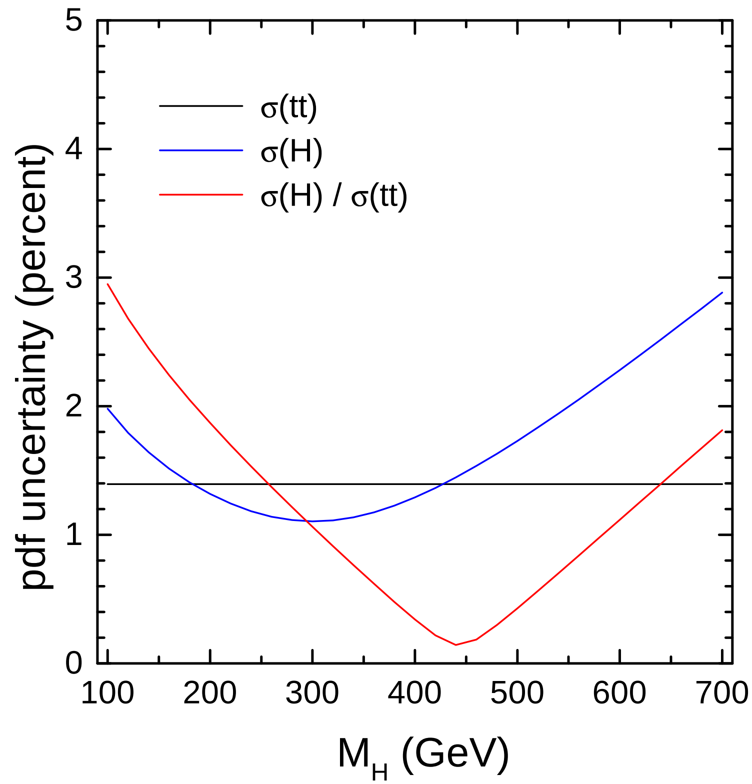
pdf uncertainties on W, WH
cross sections at LHC (MRST2001E)



No obvious advantage in using $\sigma(t\bar{t})$ as a calibration SM cross-section, except maybe for very particular, and rather large, $M_H$.

$\sigma(t\bar{t})$ very similar indeed to $450\mathrm{GeV}$ Higgs.

pdf uncertainties on top, (gg→) H
cross sections at LHC (MRST2001E)



# How straightforward is it in practice?

Predictions (Watt) for W and Z cross-sections for LHC with common NLO QCD and vector boson width effects, and common branching ratios, and at $7\mathrm{TeV}$.

Comparing all groups get significant discrepancies between them even for this benchmark process.

Can understand some of the systematic differences.

Some difference in $W/Z$ ratio.

$W, Z$ total cross-sections best-case scenario.

Leads to second lecture.