Expectations from the early LHC data

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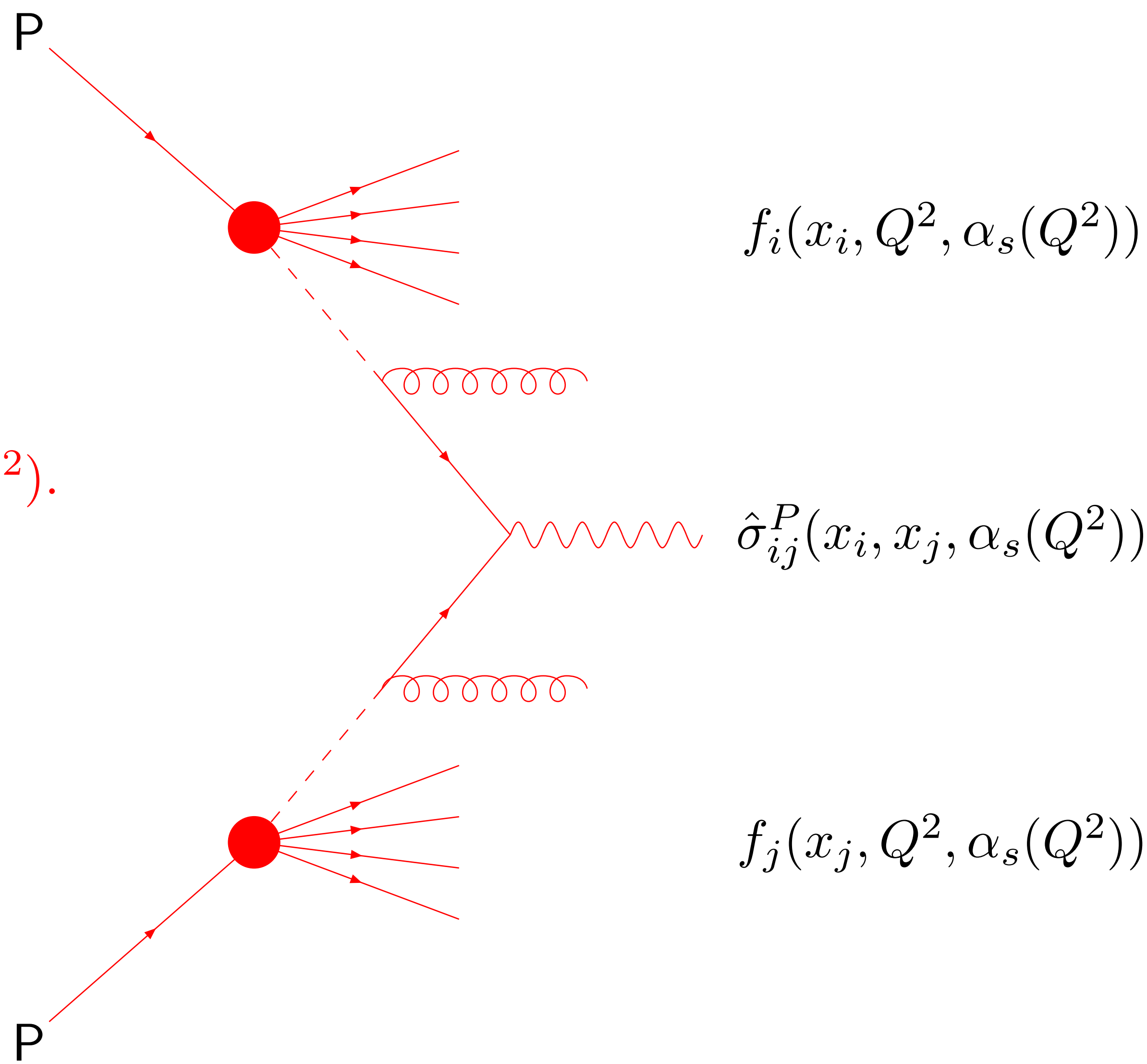
The weakening of $\alpha_S(\mu^2)$ at higher scales $\longrightarrow$ the **Factorization Theorem**.

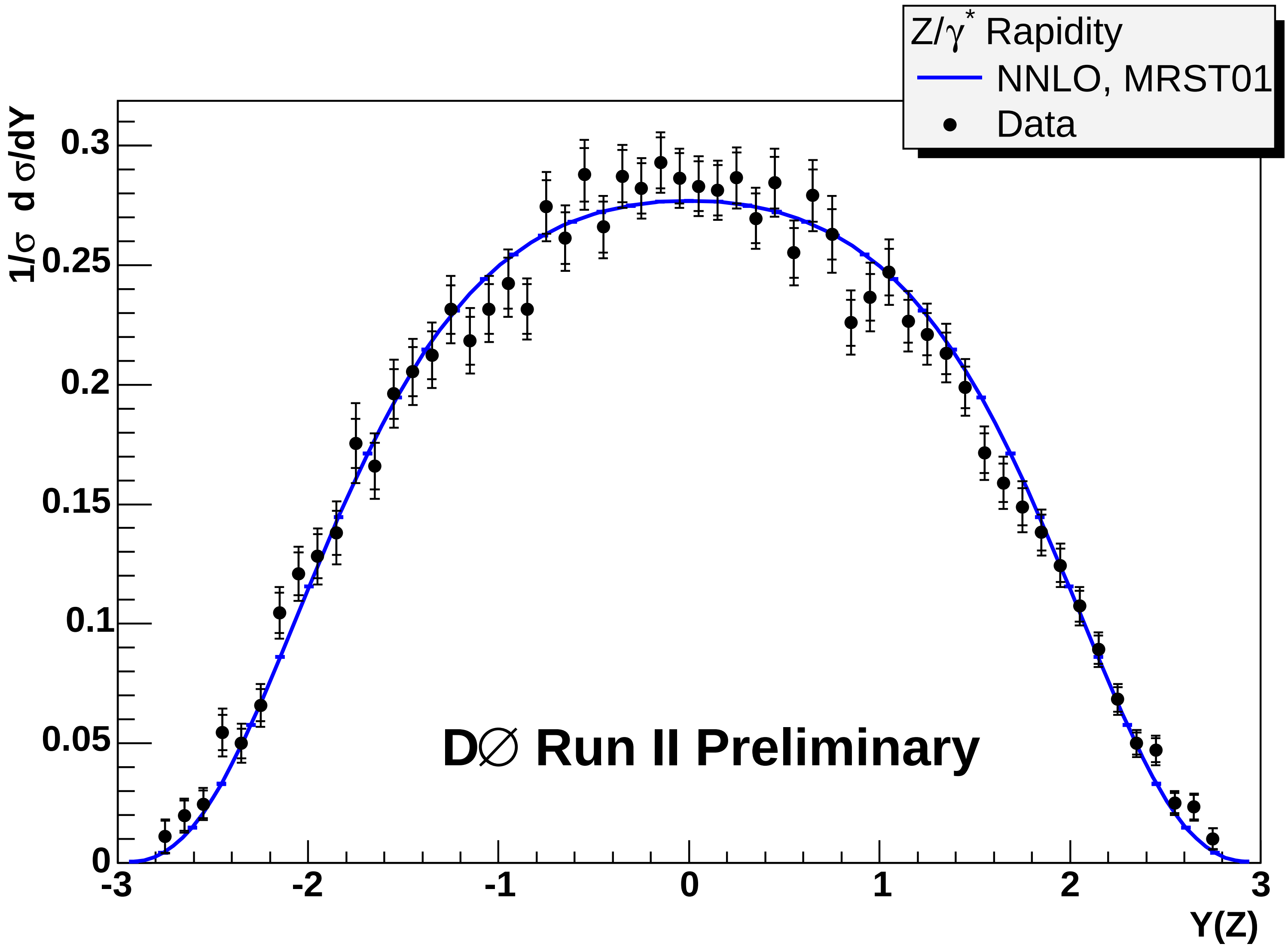
The partonic hard cross-sections $\hat{\sigma}_i^P(x, \alpha_s(Q^2))$ are process dependent (new physics) but are calculable as a power-series in $\alpha_s(Q^2)$.

$$\hat{\sigma}_i^P(x, \alpha_s(Q^2)) = \sum_k \hat{\sigma}_i^{P,k}(x)\alpha_s^k(Q^2).$$

The nonperturbative parton distributions $f_i(x, Q^2, \alpha_s(Q^2))$ are process-independent, i.e. **universal**, once they have been measured at one experiment, and evolved using perturbation theory, one can predict many other scattering processes.



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



Interplay of LHC and theory

Make predictions for all processes, both SM and BSM, as accurately as possible given current experimental input and theoretical accuracy. More potential problems at the LHC than Tevatron.

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 .....

Early running at the LHC unlikely to spot obvious deviations from SM predictions.

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

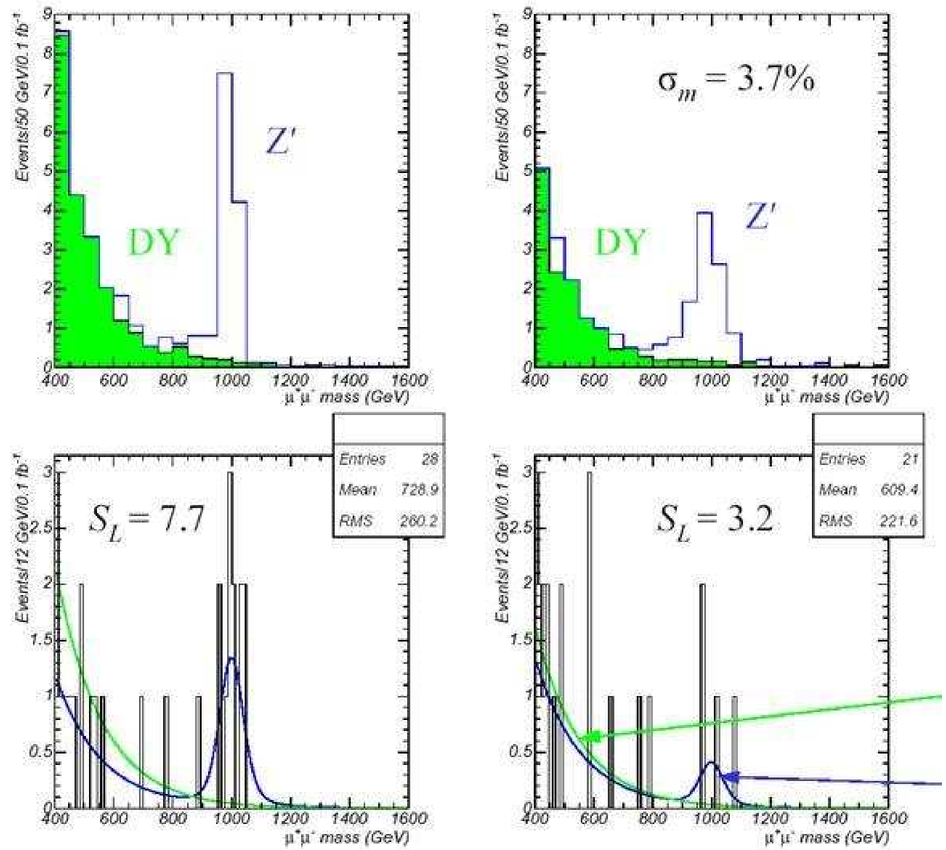
Make improved predictions for both background and signals with improved partons and surrounding theory.

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

Possible very early signals?

A very heavy vector boson, e.g. a Z' with mass $1\mathrm{TeV}$ would stand out clearly with little data above far off mass shell Drell-Yan production.

Not a particularly likely scenario in my opinion.

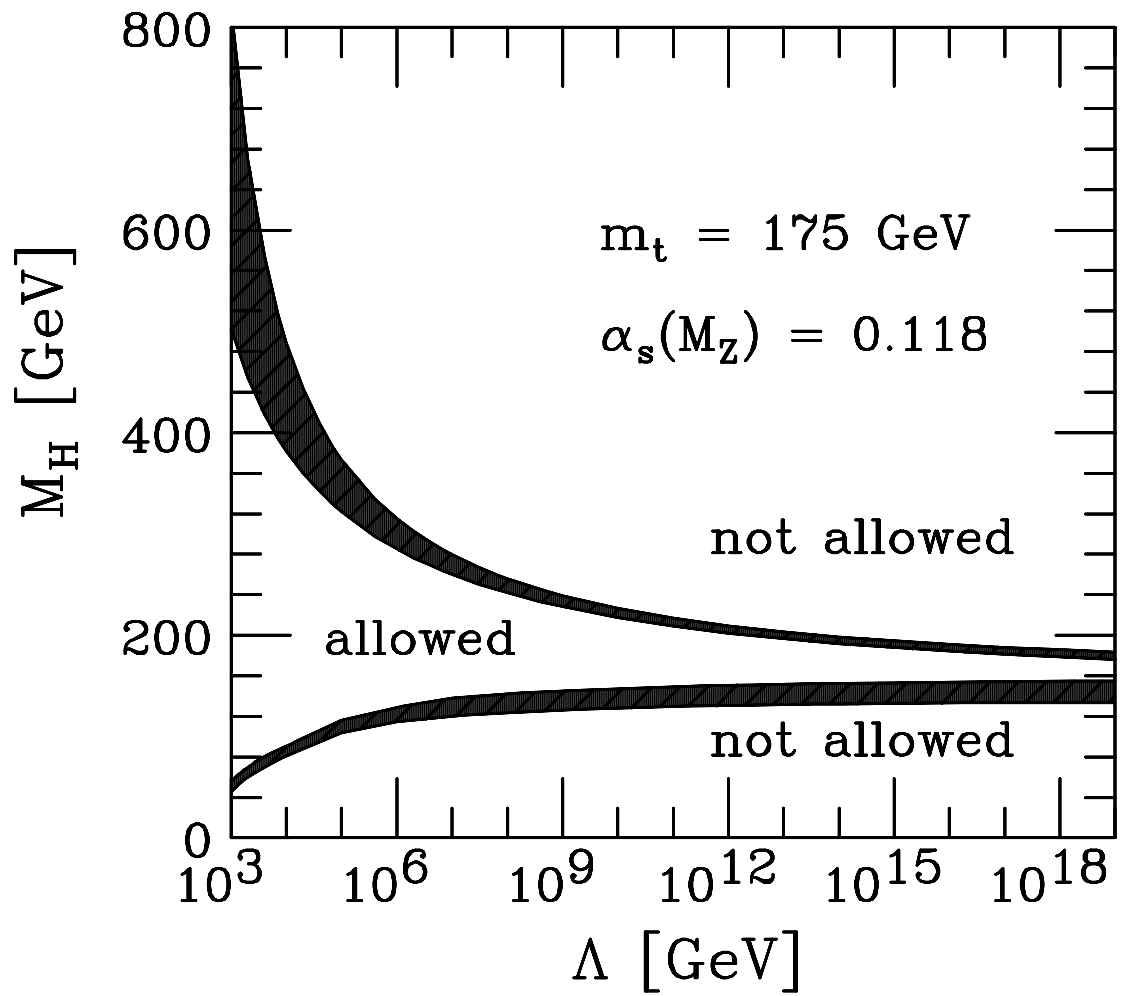


What might we indeed find at the LHC? Perhaps only the Higgs?

Upper limit from non-perturbative existence of scalar theory (not perturbative unitarity).

Lower limit on stability of vacuum. Problem if $g_t \gg \lambda$.

$m_H = 170 \pm 15\mathrm{GeV}$ consistent with no further physics until M_{Planck}.



Hambye and Riesselmann

At least such a Higgs signal would be amongst the easiest to see.

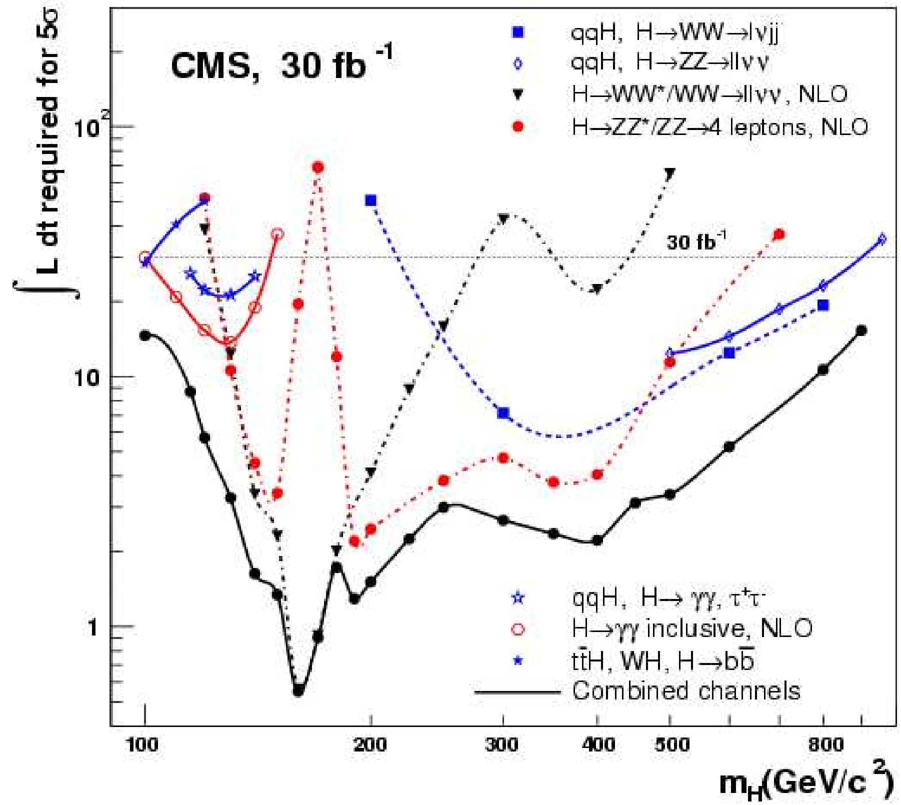
Right in the range for

$H \to WW^* \to ll\nu\nu$

or possibly

$H \to ZZ \to 4l$.

No chance with $m_H < 150\text{GeV}$ with early data. (Possibility with SUSY – see later.)



Probably most likely Beyond Standard Model Physics is supersymmetry.

- Circumstantial evidence from convergence of couplings. Not overwhelming for me.
- Candidate for dark matter. Fairly attractive.
- Predicts light Higgs. Maybe attractive, but not a good reason for believing.
- Consistent with precision constraints? So is no BSM physics.
- As a theorist prefer fact that it protects fundamental scalars from quadratic radiative corrections to masses – $\delta m_H^2 \sim m^2 \ln(\Lambda_{UV}^2/m^2)$ not $\delta m_H^2 \sim \Lambda_{UV}^2$.

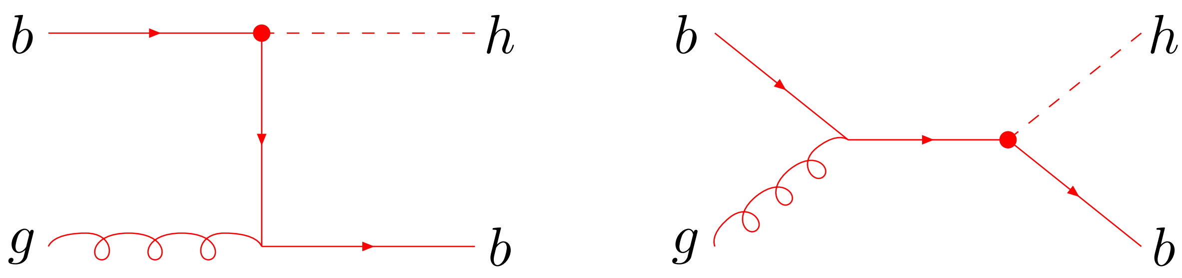
Gauge boson masses kept small by gauge symmetry.

Fermion masses kept small by chiral symmetry, only softly broken.

Scalar masses (if we have fundamental scalars) can be kept light by supersymmetry.

However, parameter space already being squeezed. Good limits from some precision measurements, e.g. $(g-2)_\mu$, $b \to s\gamma$ (relaxation from NNLO corrections? Misiak *et al*), m_H. $\tan\beta$ – ratio of vevs – constrained to be large.

Can enhance Higgs production along with bottom quarks.



In Standard Model tiny since Higgs-bottom coupling $g_{b\bar{b}h} = m_b/v$, (v Higgs vacuum expectation value.) $m_b = 4.5\text{GeV}$, $v = 246\text{GeV}$.

In Minimal Supersymmetric Standard Model two Higgs doublets coupling separately to d-type and u-type quarks. Expectation values v_d and v_u.

Ratio $\tan\beta = v_u/v_d$.

Enhancement of Higgs-bottom coupling

$$g_{b\bar{b}h} \propto \frac{g^{SM}_{b\bar{b}h}}{\cos\beta}.$$

Bounds from LEP, $\tan\beta$ large $\rightarrow \cos\beta$ small. Enhancement of Higgs-bottom coupling.

Can be large signal from $gb \rightarrow H$ and $b\bar{b} \rightarrow H$. Need b-tagging.

One of main goals for LHCb – improved measurement of angles in CKM triangle. Again currently fits very well with Standard Model. Difficult within SUSY unless masses degenerate.

Improvements largely from rare decays. Mainly requires a lot of luminosity. Possibilities with early data of γ measurement from $B^0 \to \pi^+\pi^-$, $B_S \to K^+K^-$.

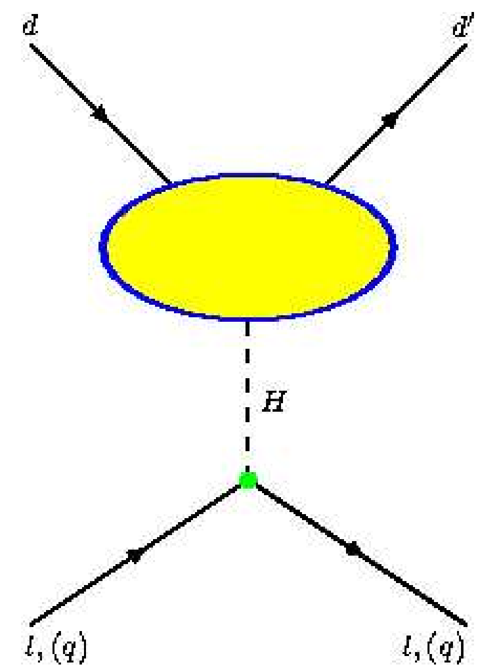
Possible early result improved bound on decay $B_s \to \mu^+\mu^-$. (Later ATLAS, CMS.)

Branching ratio 3.5×10^{-9} in Standard Model. Current limit 8×10^{-8} from CDF.

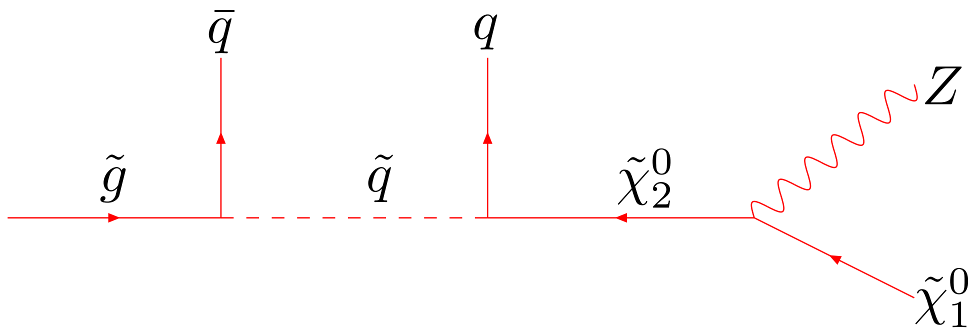
$= 5 \times 10^{-7} (\frac{\tan\beta}{50})^6 (\frac{220}{M_{H_3}})^4 + 8 \times 10^{-9}$

in MSSM (Dedes) due to Higgs penguins.

Can be significantly enhanced or give bound on heaviest Higgs.



More direct – some SUSY signals would have rather distinctive signatures.

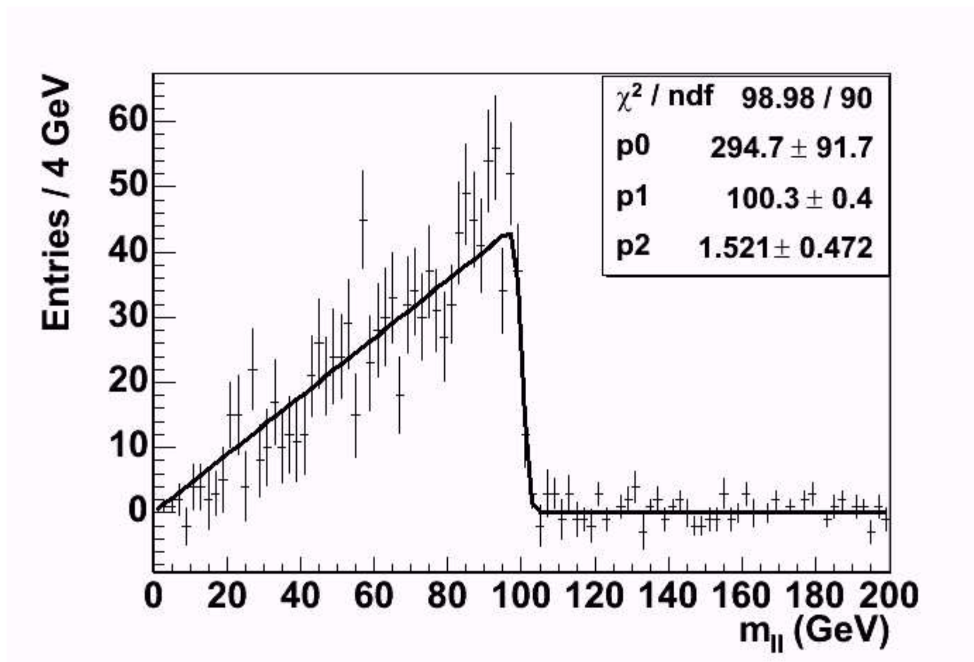


Where the $\tilde{\chi}^0_1$ is the lightest SUSY particle and carries away missing E_T. (Not the case if R-parity – $(-1)^{3(B-L)+2S}$ – is violated. Couplings in this case very small – $\lambda < 0.001$. Good reason why?)

Decays involving leptons can lead to clear indications of mass differences in invariant masses.

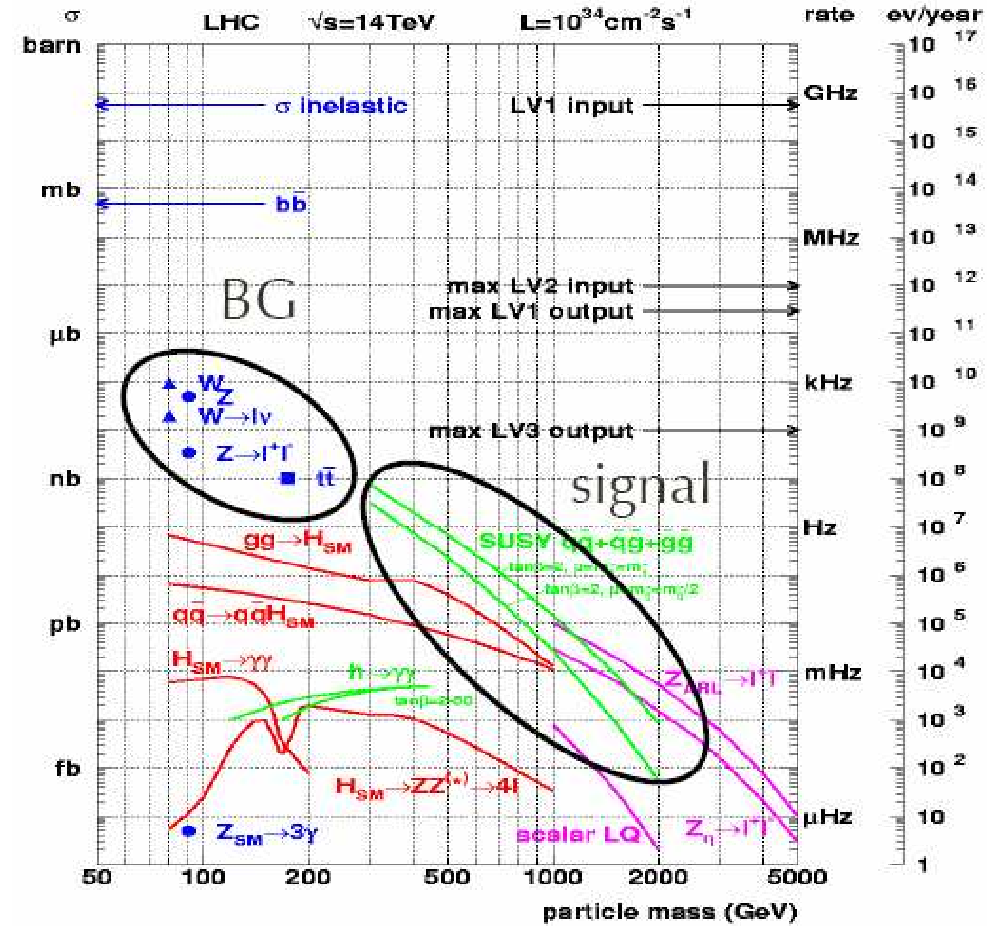
$$(M_{ll}^{max})^2 = \frac{(M^2_{\tilde{\chi}^0_2} - M^2_{\tilde{l}_R})(M^2_{\tilde{l}_R} - M^2_{\tilde{\chi}^0_1})}{M^2_{\tilde{l}_R}}$$

But needs quite a lot of luminosity – $20fb^{-1}$.



Production of squarks and gluinos can be large, if the mass is not too high, due to the interaction via the strong coupling.

Not particularly unlikely scenario.



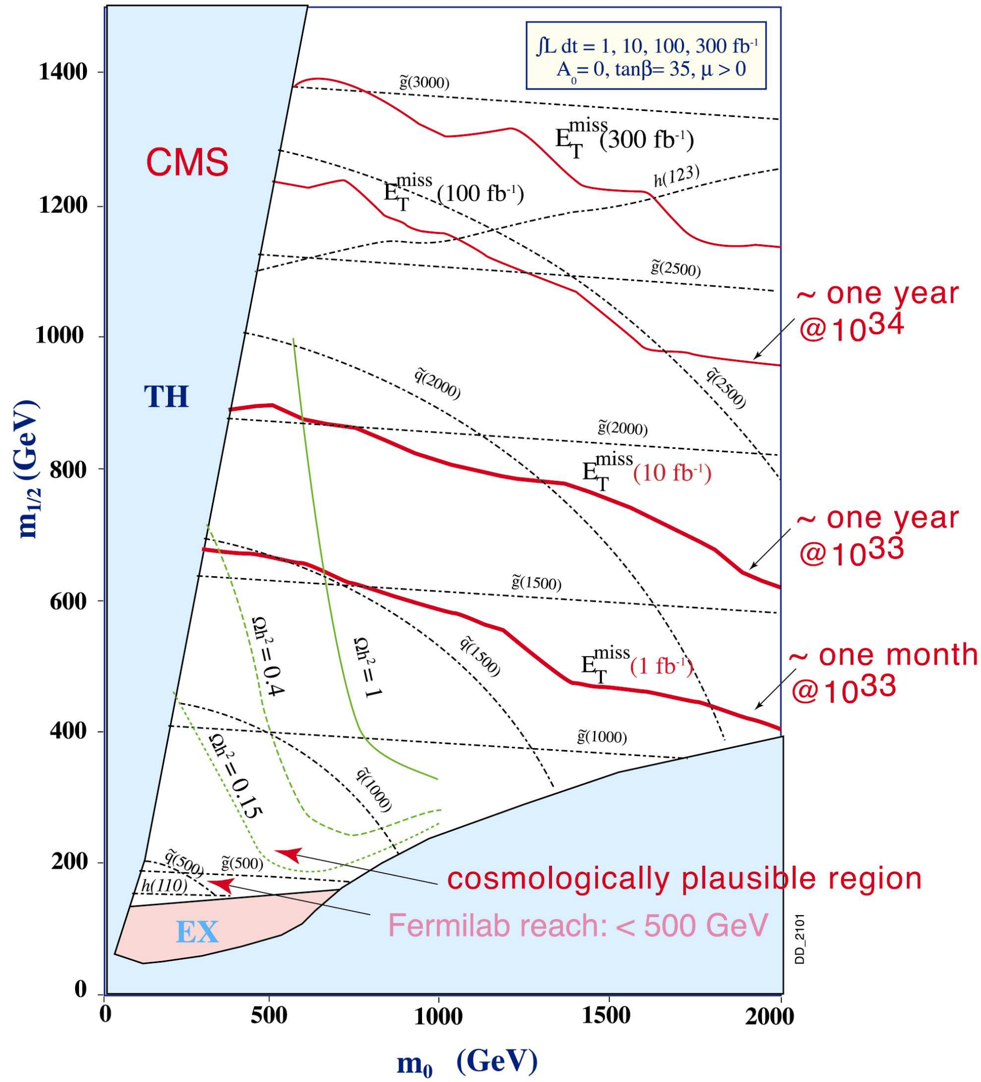
CMS plot

Possible sign with relatively low integrated luminosity.

Reach after a year in the region of $1000\mathrm{GeV}$ if everything is very favourable.

Requires excellent understanding of backgrounds.

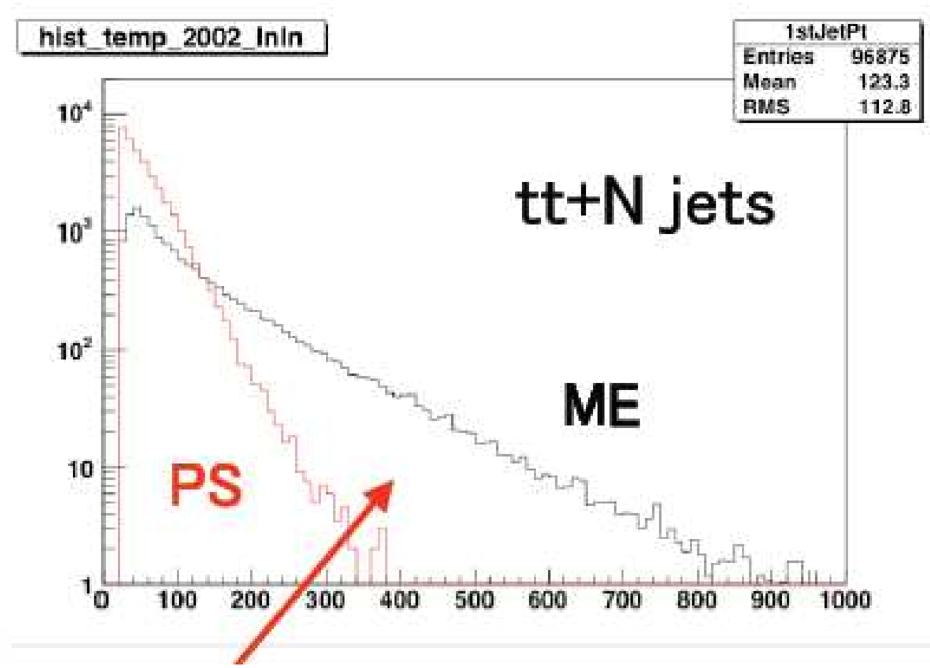
Perhaps a bit more difficult than initially thought.



Must be careful analysing backgrounds to such signals.

Some Monte Carlos only contain jet production from the soft/collinear emission of partons from parton shower.

Miss hard emission of further partons contained in fixed-order calculations which produce largest contribution for largest p_T, E_T in final states.



Hard parton emmision

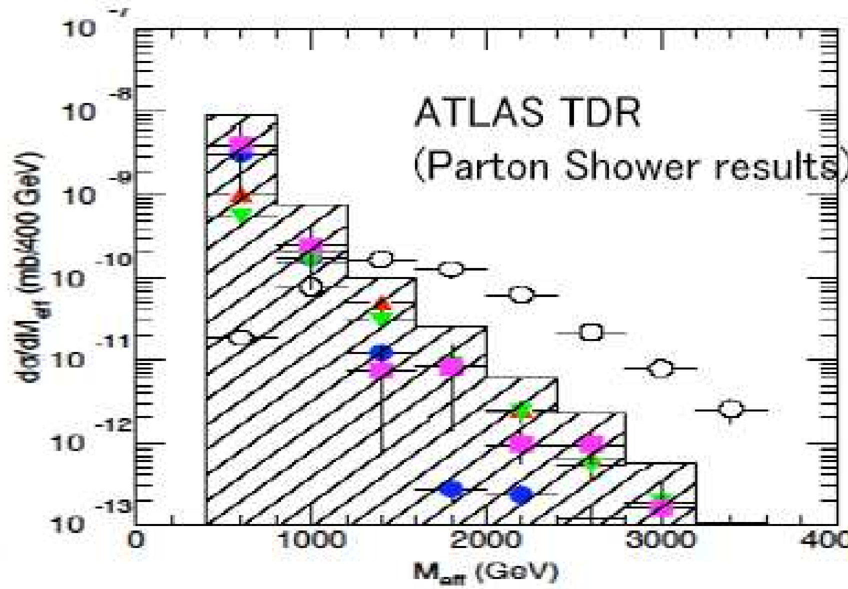
More sophisticated study of backgrounds involving matrix element corrections reduce obvious signs of SUSY.

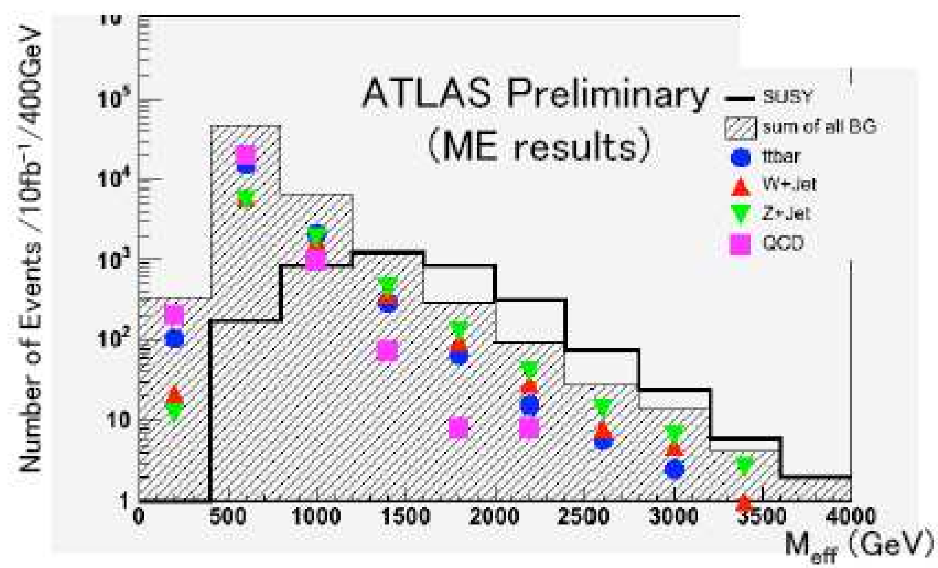
Best available tools at the moment involve combinations of NLO matrix element calculations with parton showers, e.g. MC@NLO – (Frixione, Webber).

Also issue of order of pdfs to use with Monte Carlos, e.g. NLO pdfs with LO Monte Carlos? Not resolved in my opinion.

Some possibility of early "discovery", but details for spin structure from e.g. asymmetries need much more data.

First sign of SUSY could be confused with e.g. extra dimensions (or *vice versa*).





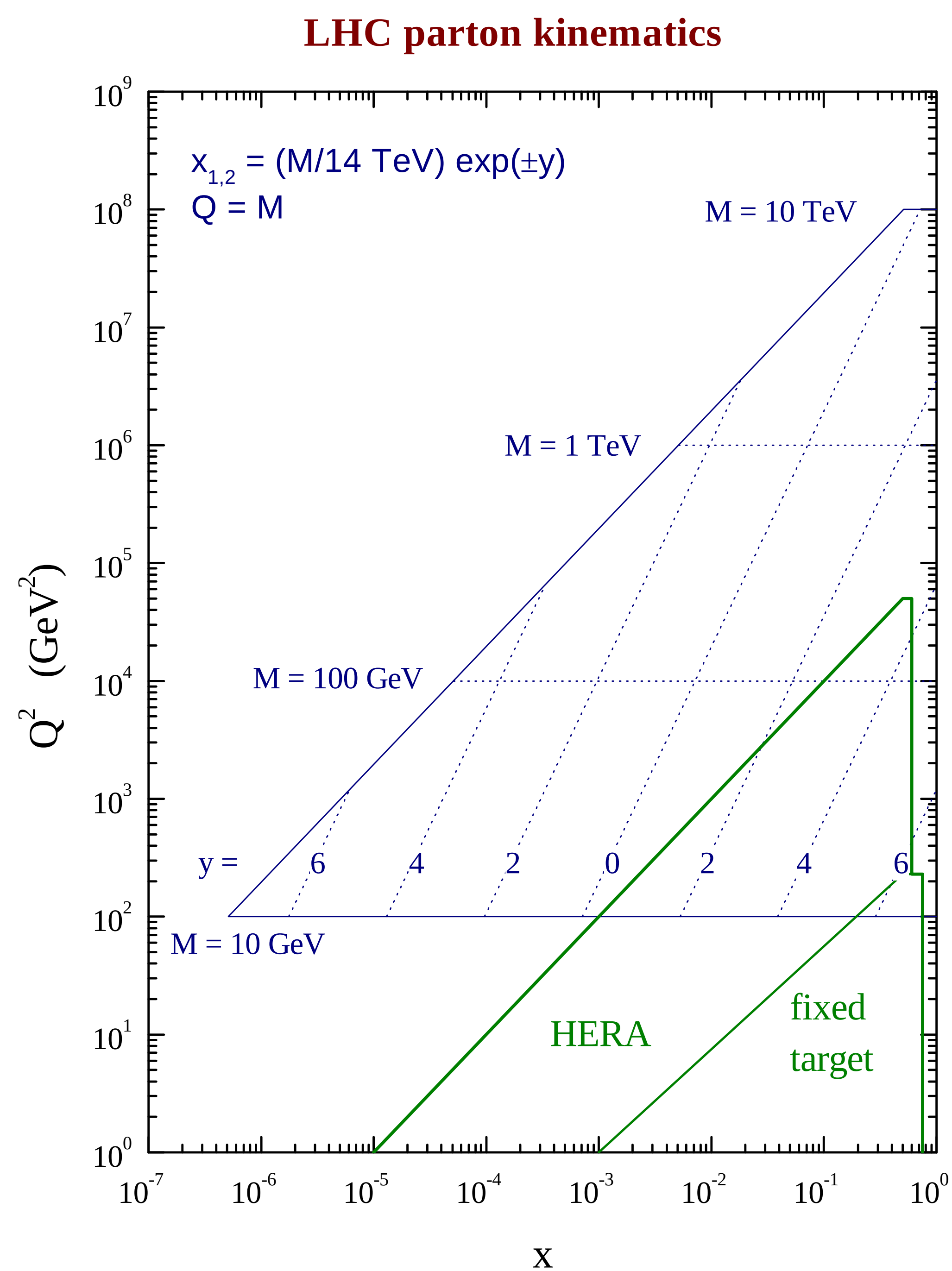
$$M_{eff} = E_T^{miss} + \sum_i P_{T,i}^{jet}$$

LHC **Kinematics**

Other reasons for difficulties with predictions at the LHC – the kinematic range for particle production.

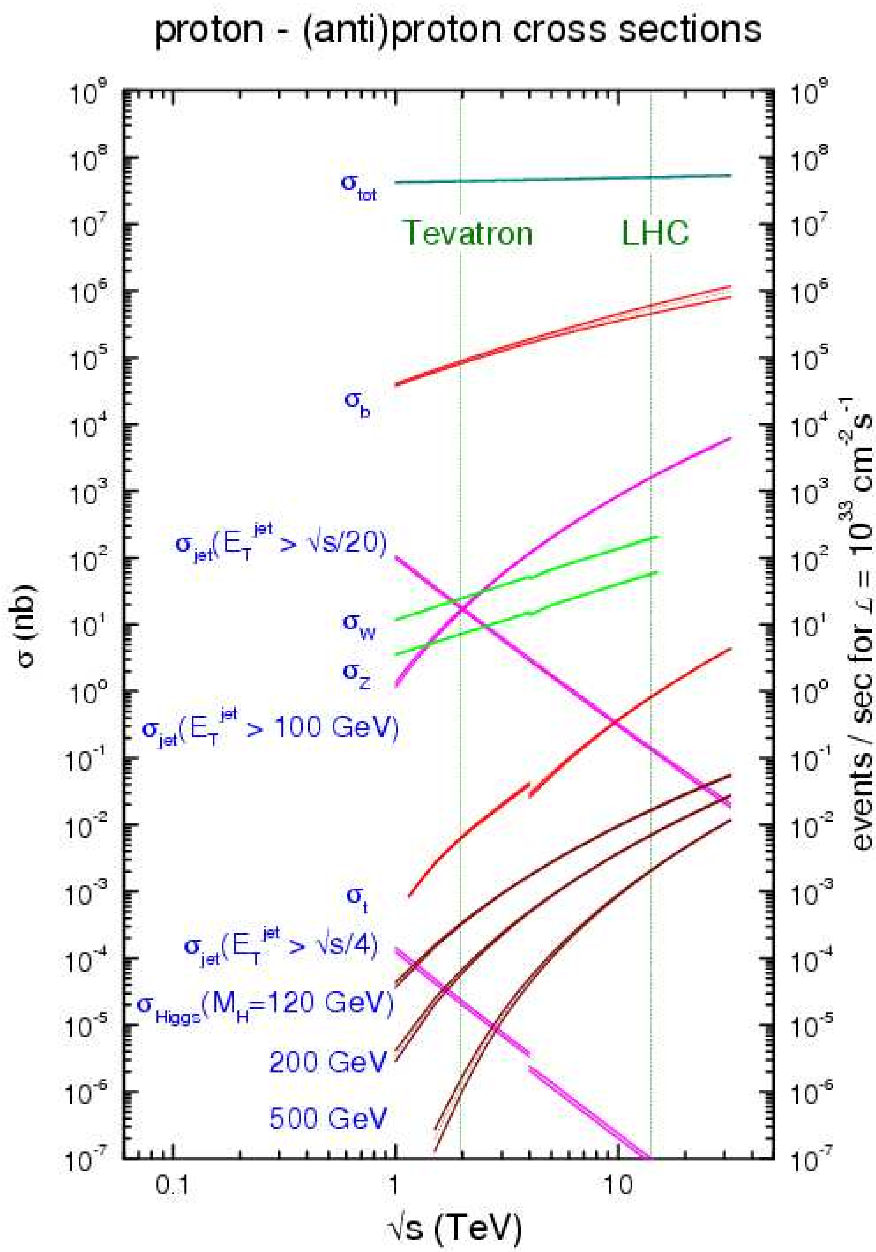
Smallish $x \sim 0.001 - 0.01$ parton distributions therefore vital for understanding the standard production processes at the LHC. However, even smaller (and higher) x required when one moves away from zero rapidity, e.g. when calculating total cross-section.

At each order in α_S each splitting function and cross-section obtains an extra power of $\ln(1/x)$ i.e. each goes like $\sim \alpha_s^m(Q^2)\ln^{m-1}(1/x)$.

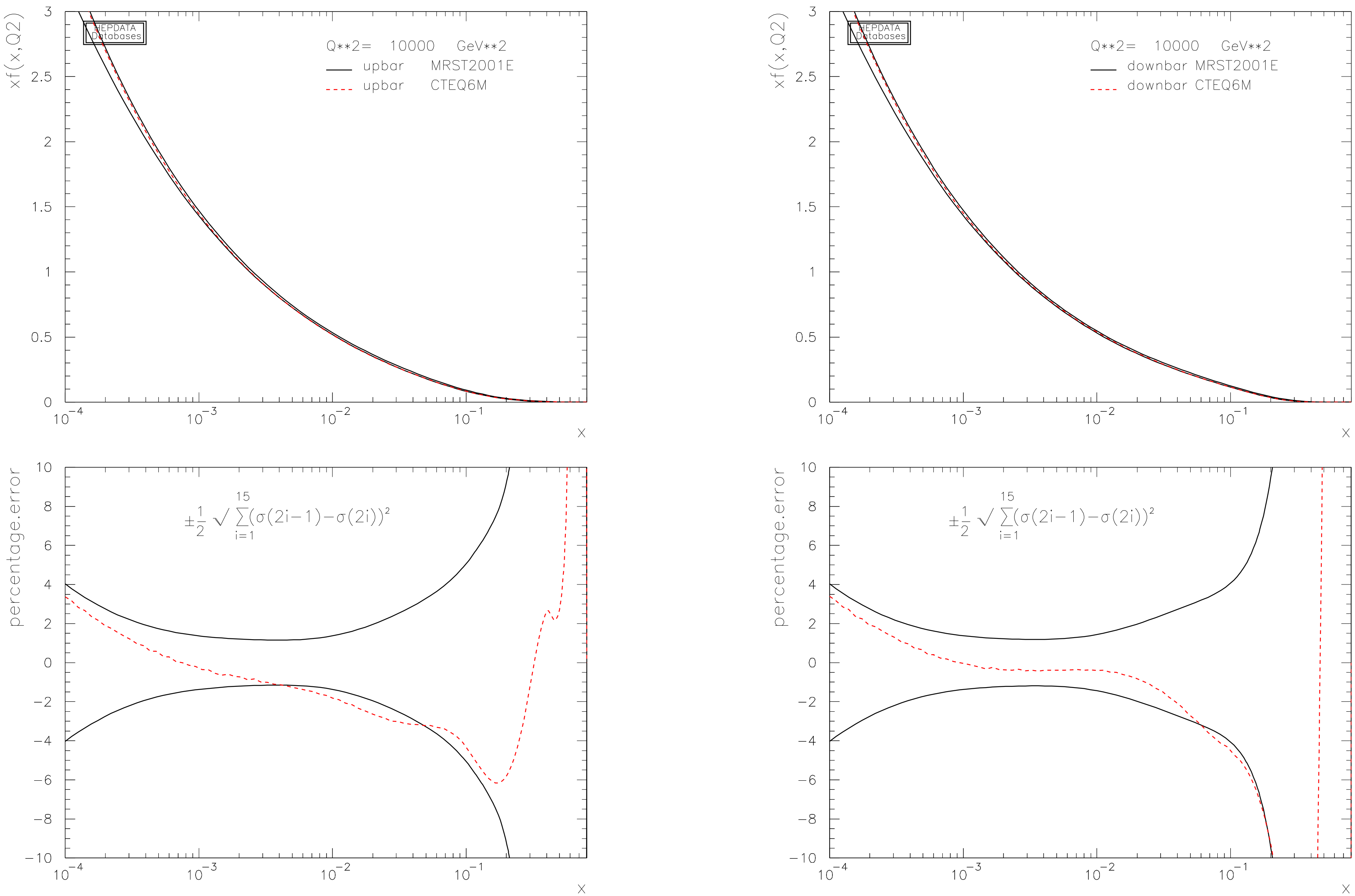


Early data will obviously give best indications for QCD and electroweak processes such as heavy quarks (including top), W and Z production, and high-p_T jets.

What is the precision of the predictions?



Uncertainty on MRST $\bar{u}$ and $\bar{d}$ distributions, along with CTEQ6. Central rapidity $x = 0.006$ is ideal for uncertainty in W, Z (Higgs?) at the LHC.



Current best (MRST) estimate with error from experimental uncertainty

$$\delta\sigma_{W,Z}^{\rm NLO}(\text{expt pdf}) = \pm 2\%$$

but note that there is a greater theoretical uncertainty in the prediction.

This is because the large rapidity W and Z total cross-sections sample very small x.

$\sigma(W^+)/\sigma(W^-)$ is **gold-plated**

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

since sea is u, d symmetric at small x, and using MRST2001E

$$\delta R_\pm(\text{expt. pdf}) = \pm 1.4\%$$

Assuming all other uncertainties cancel, this is probably the most accurate SM cross-section test at LHC.

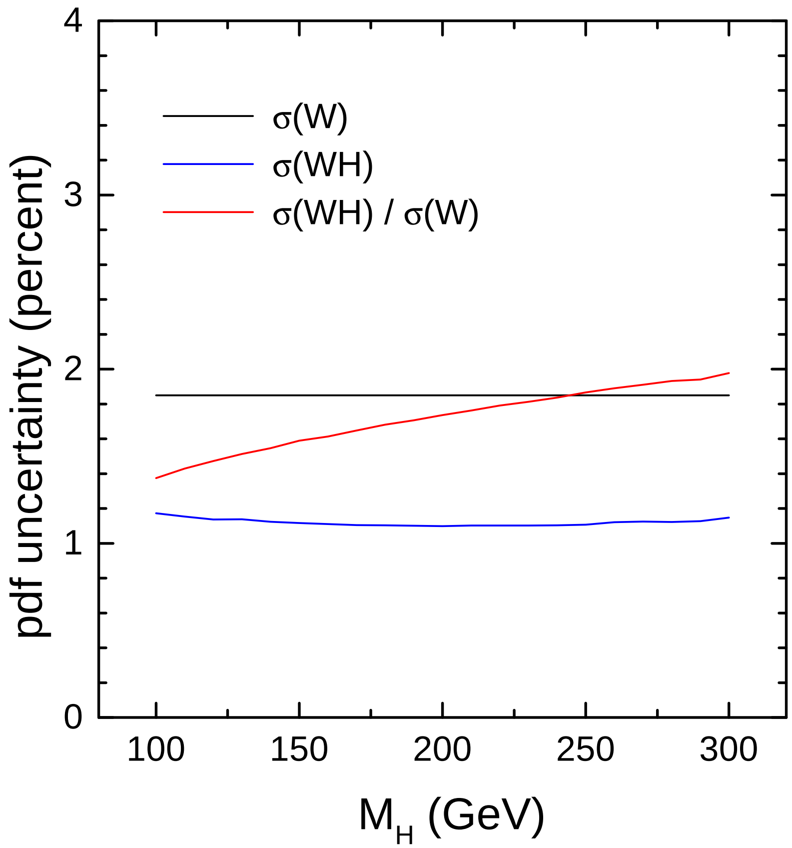
Could $\sigma(W)$ or $\sigma(Z)$ be used to calibrate other cross-sections, e.g. $\sigma(WH)$, $\sigma(Z')$?

$\sigma(WH)$ 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)



Also, predictions from different groups differ in their predictions by much more than this, e.g. study by ZEUS/ATLAS parton analysis group of

$$\frac{(\sigma(W^+)-\sigma(W^-))}{(\sigma(W^+)+\sigma(W^-))}$$

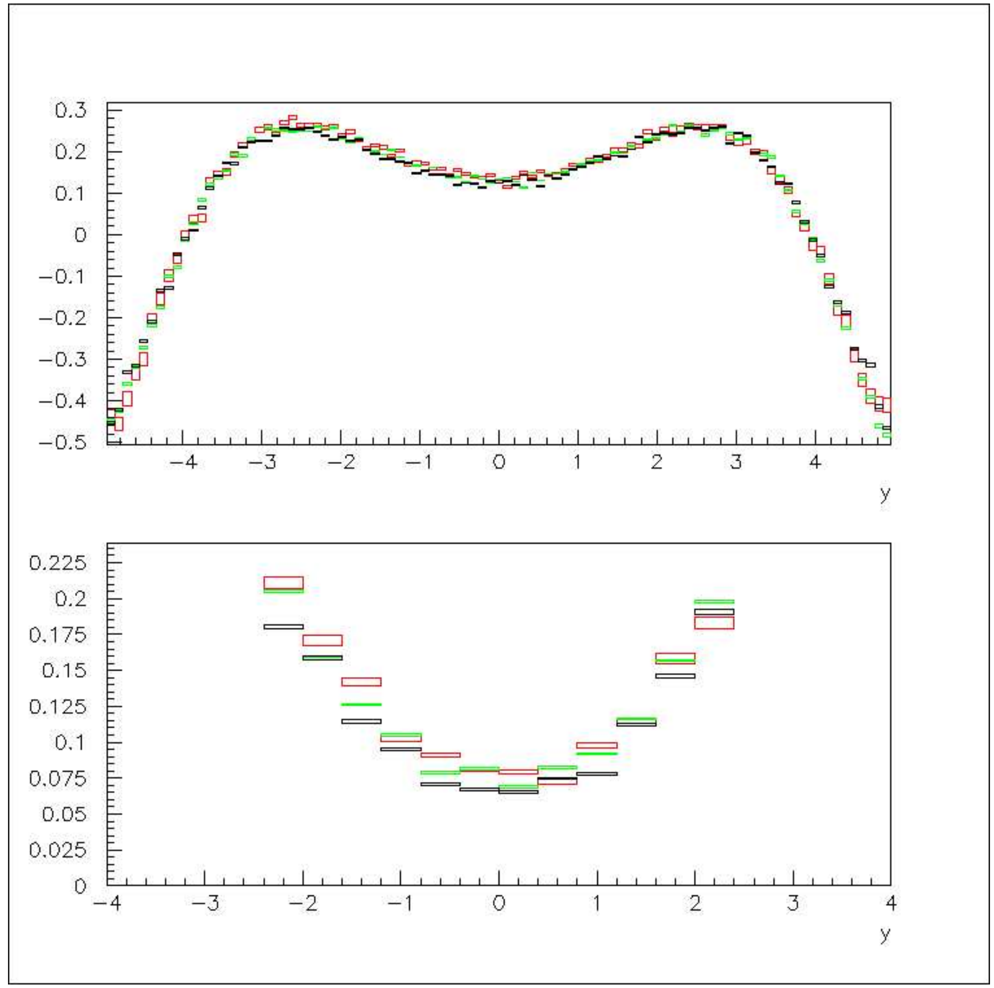
black – MRST

red – CTEQ

green – ZEUS

Different ideas about quark decomposition at lowish x, i.e. separation of valence and sea quarks.

Important to check with early data for reliability of other predictions.



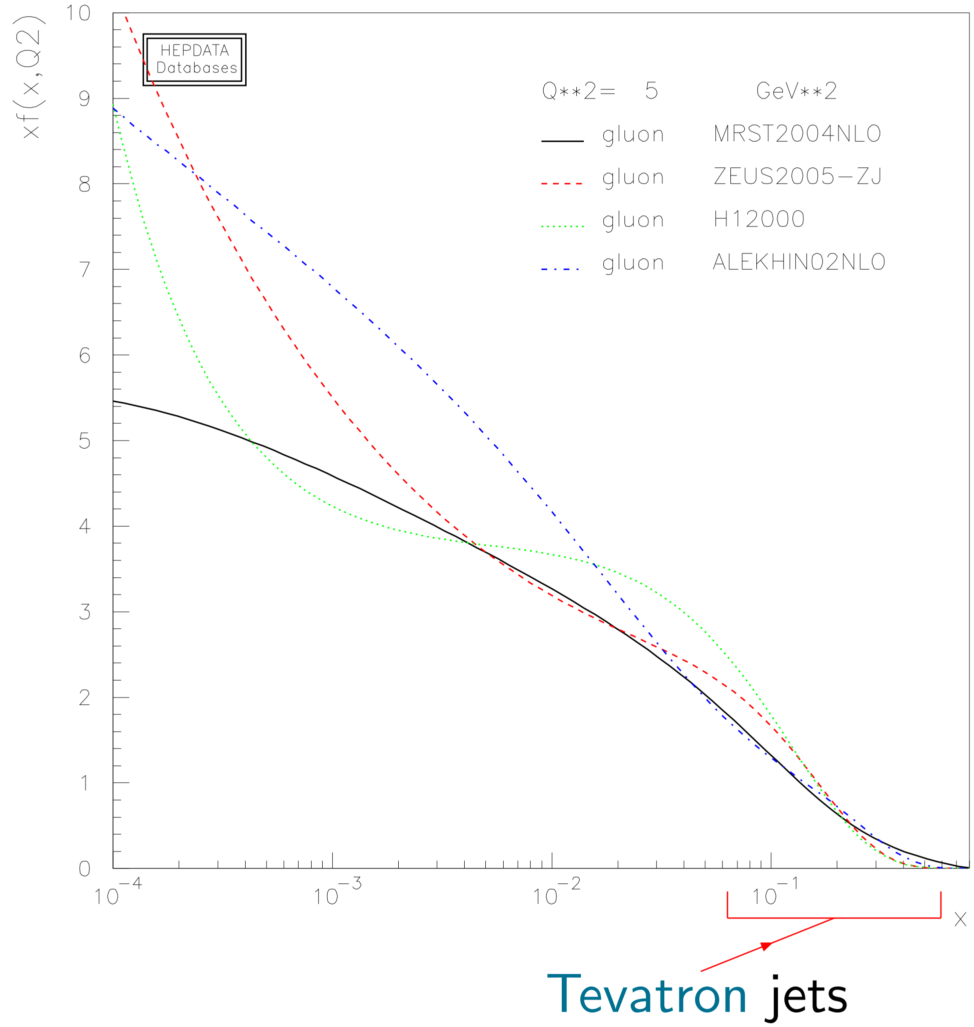
Different approaches to fits generally lead to similar uncertainty for measured quantities, but can lead to different central values. Must consider effect of assumptions made during fit and correctness of NLO QCD.

Gluon still very uncertain at low x and Q^2.

All partons fit to same small-x HERA data.

Very wide variety in gluon distributions – careful in use.

Much of the uncertainty due to the theoretical errors. Try to use early LHC data to minimize this. Not easy.



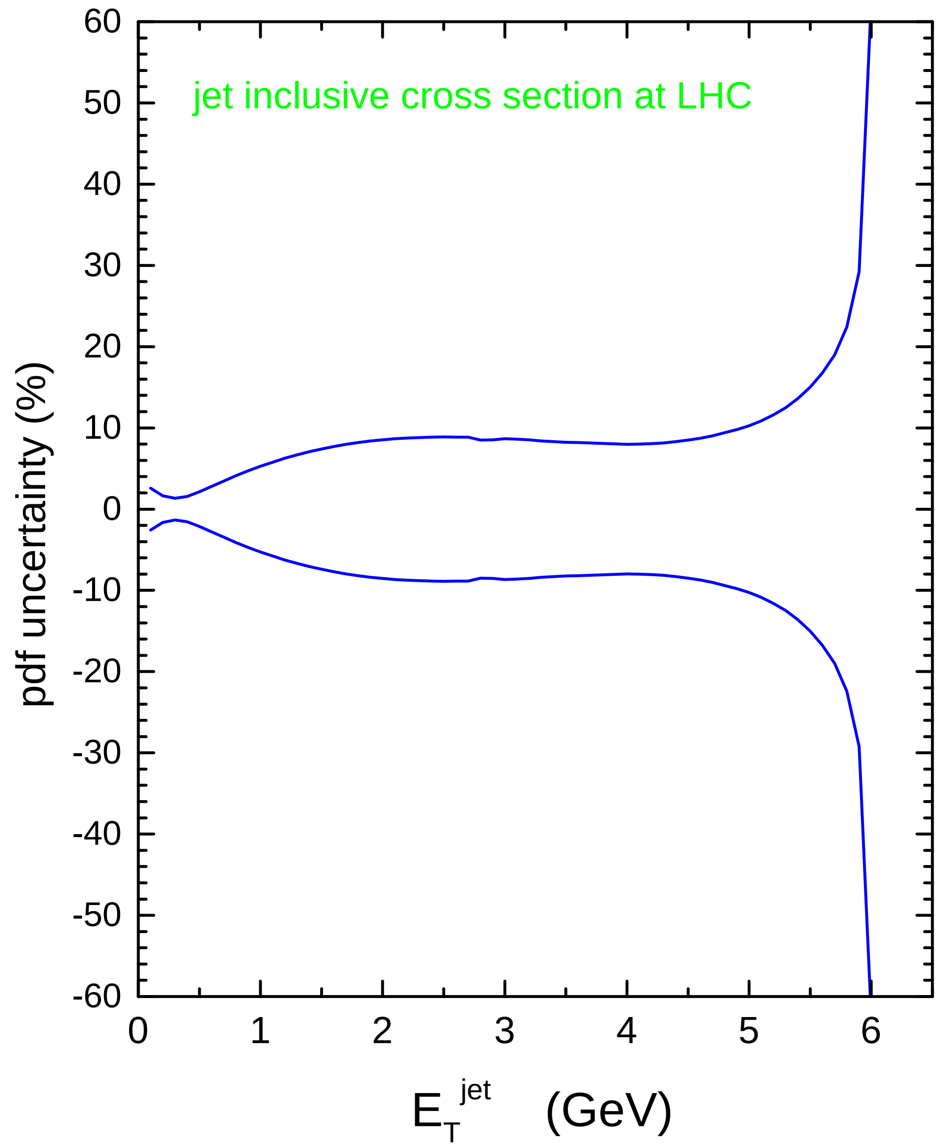
High-E_T Jets

The error on predictions for very high-E_T jets at the LHC is dominated by the parton uncertainties.

Sensitive to relatively poorly known high-x gluon.

Deviations in predictions for high-E_T jets possible sign of different BSM signals – extra dimensions, contact interactions *etc.*

How well could be disentangle these?

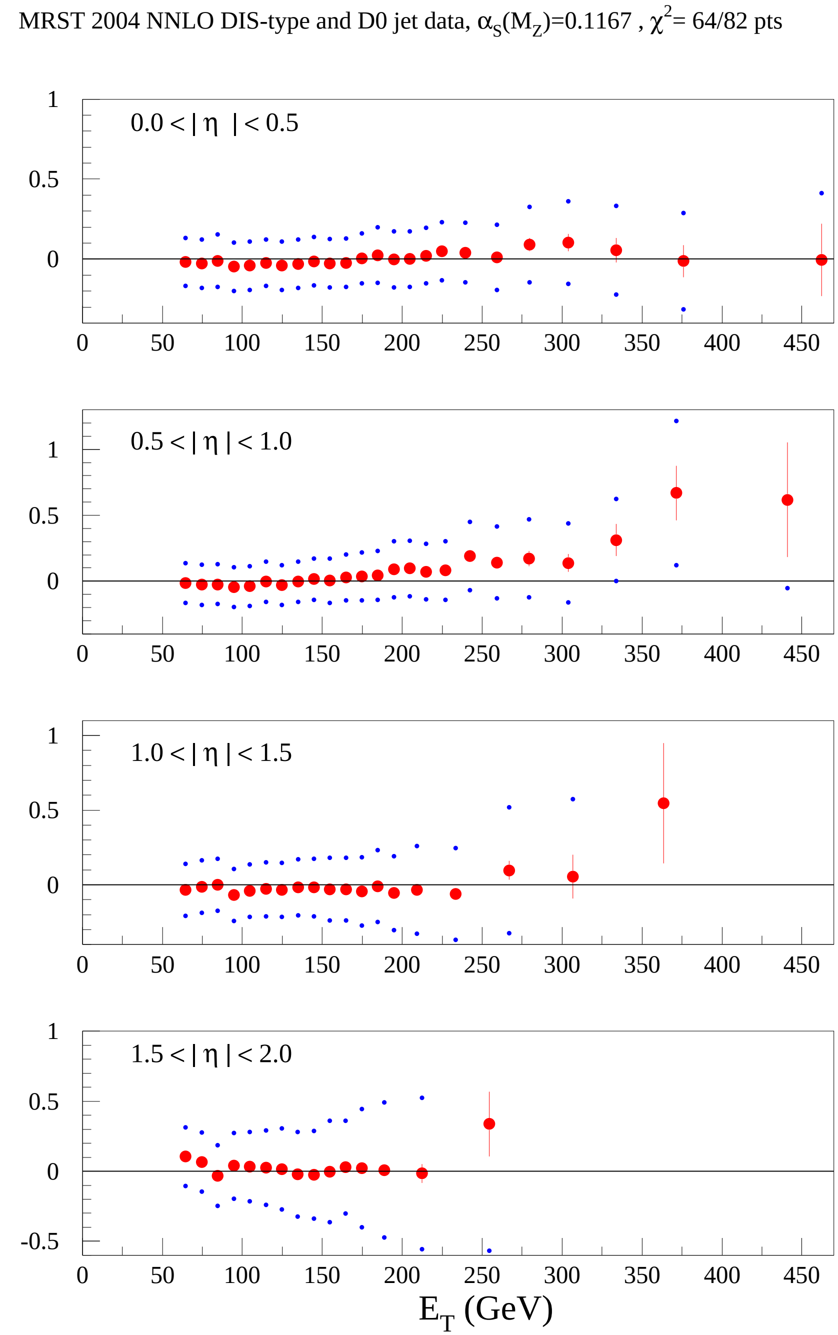


Fit to current Tevatron data excellent.

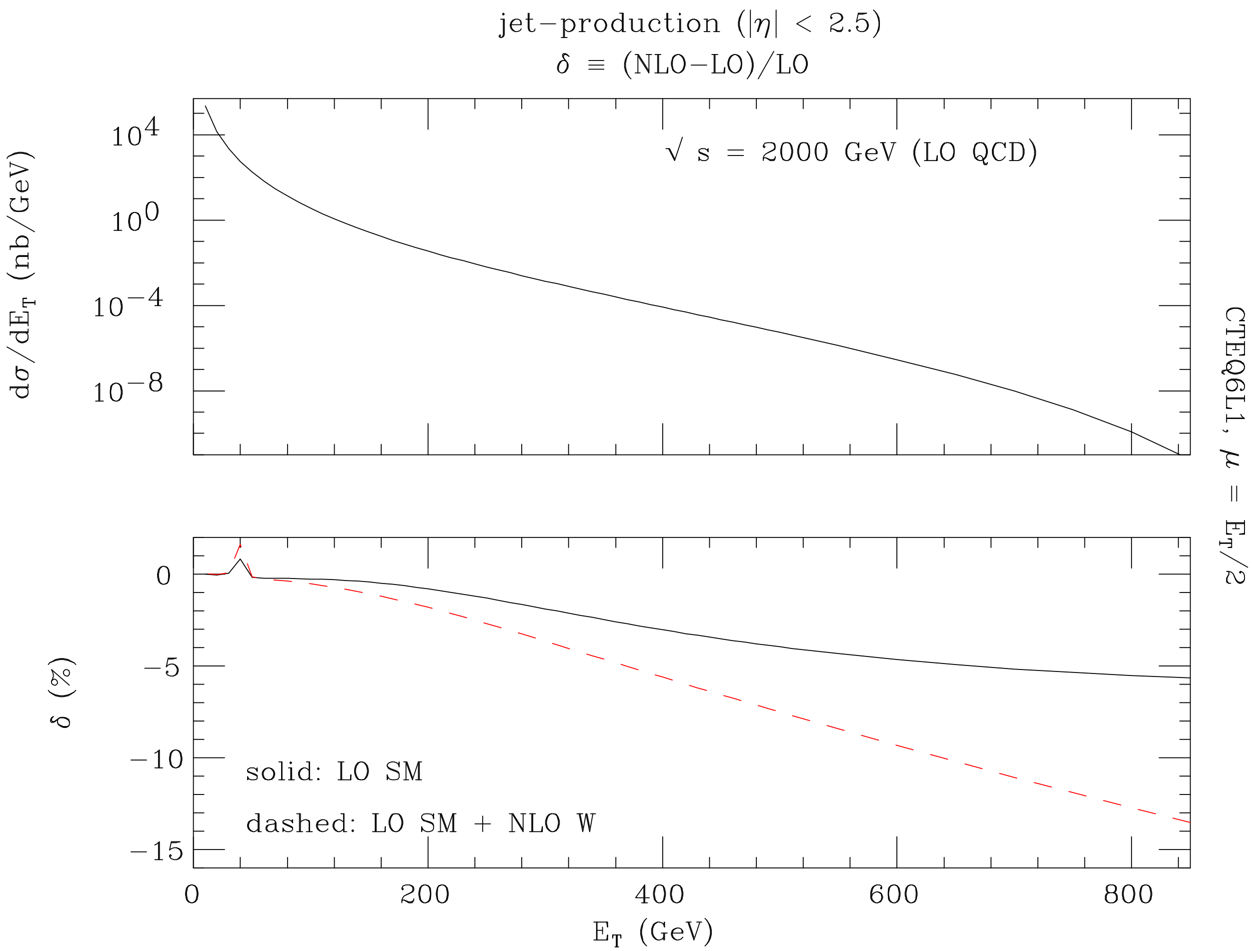
Comparison to D0 jet data for *physical gluon* MRST partons.

Measurements in different rapidity bins **extremely** useful in separating new physics from Standard Model.

Conclusively ruled out new physics in this at Tevatron.

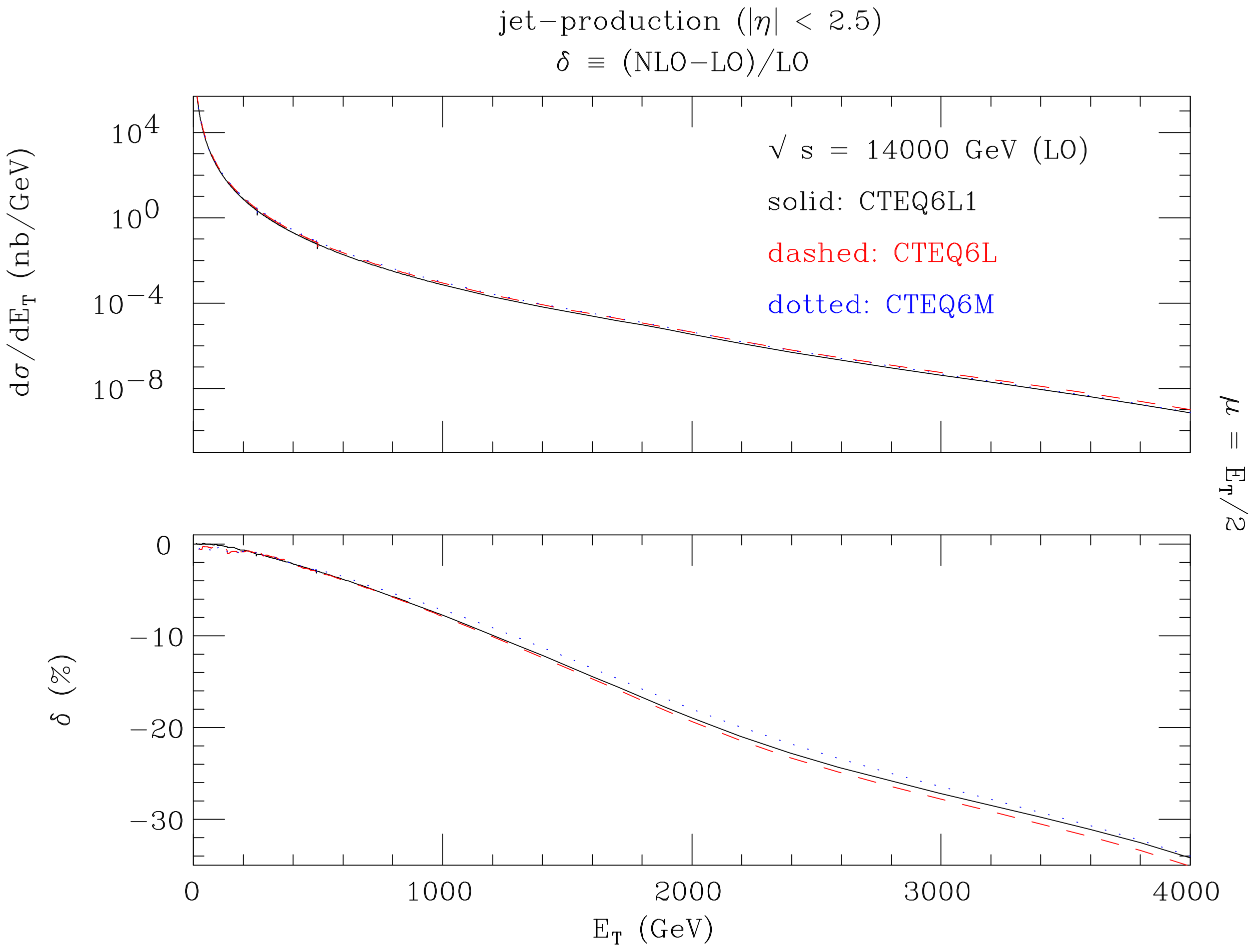


Weak corrections



Jet cross-section a major example – calculation by Moretti, Nolten, Ross, goes like $(1 - \frac{1}{3}C_F \frac{\alpha_W}{\pi} \log^2(E_T^2/M_W^2))$.

Dominated by quark-(anti)quark processes $\rightarrow \approx 6\%$ correction at $E_T = 450\mathrm{GeV}$.

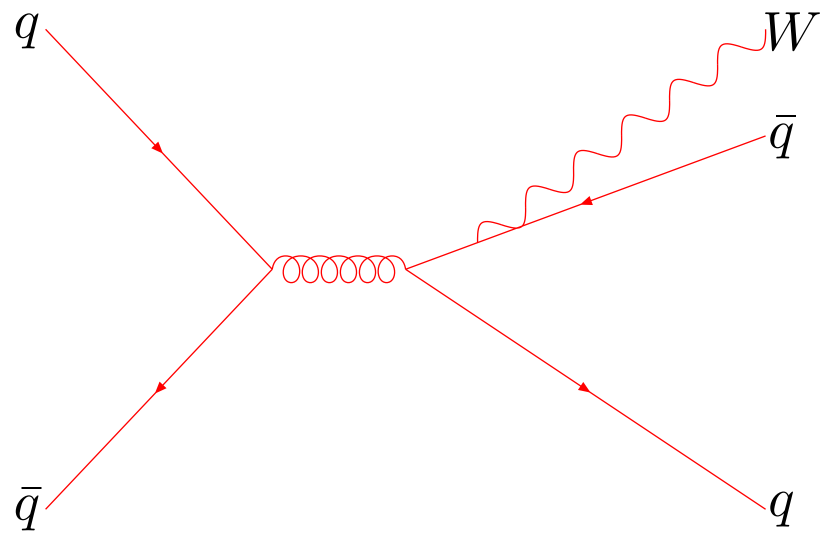


Much bigger at LHC energies. Up to 30%. Bigger than NLO QCD.

$\log^2(E_T^2/M_W^2)$ a very large number.

Similar results for corrections to other processes with a hard scale, e.g. Di-boson production (Accomando *et al*), large-p_T vector bosons (Kühn *et al*, Maina *et al*)...

Only virtual corrections. Must have contributions of the form



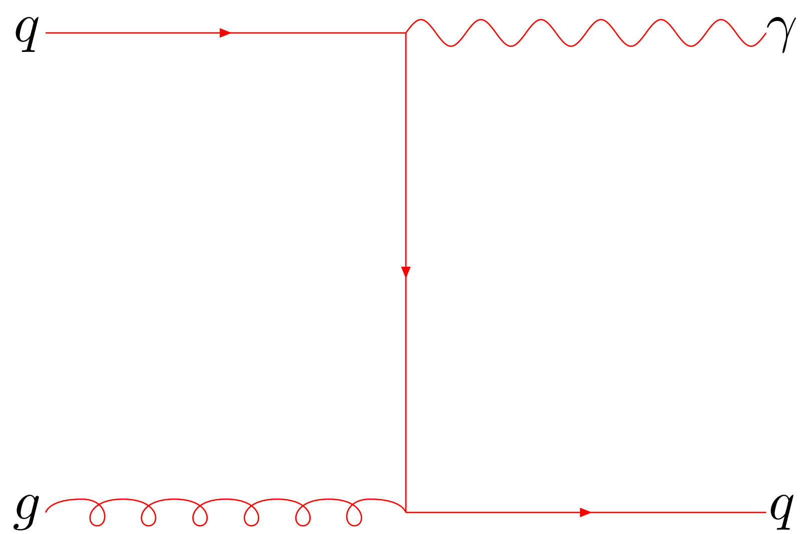
Some electroweak bosons included with jets – some almost collinear with quark, and many decaying into hadrons.

Opposite sign, potentially large contribution. However, perfect cancellation will not happen. Total effect very possibly still large. Similar situation in variety of processes.

Needs calculation and decisions on experimental definitions. Also need partons with QED corrections, i.e. a photon distribution (done -MRST) and perhaps with weak corrections (splitting functions derived – P Ciafaloni and Comelli).

$\ln(s/m_W^2)$ terms can also affect Γ_W extraction from the transverse mass distribution.

Prompt Photons



Prompt photon production is a complementary process to jet production.

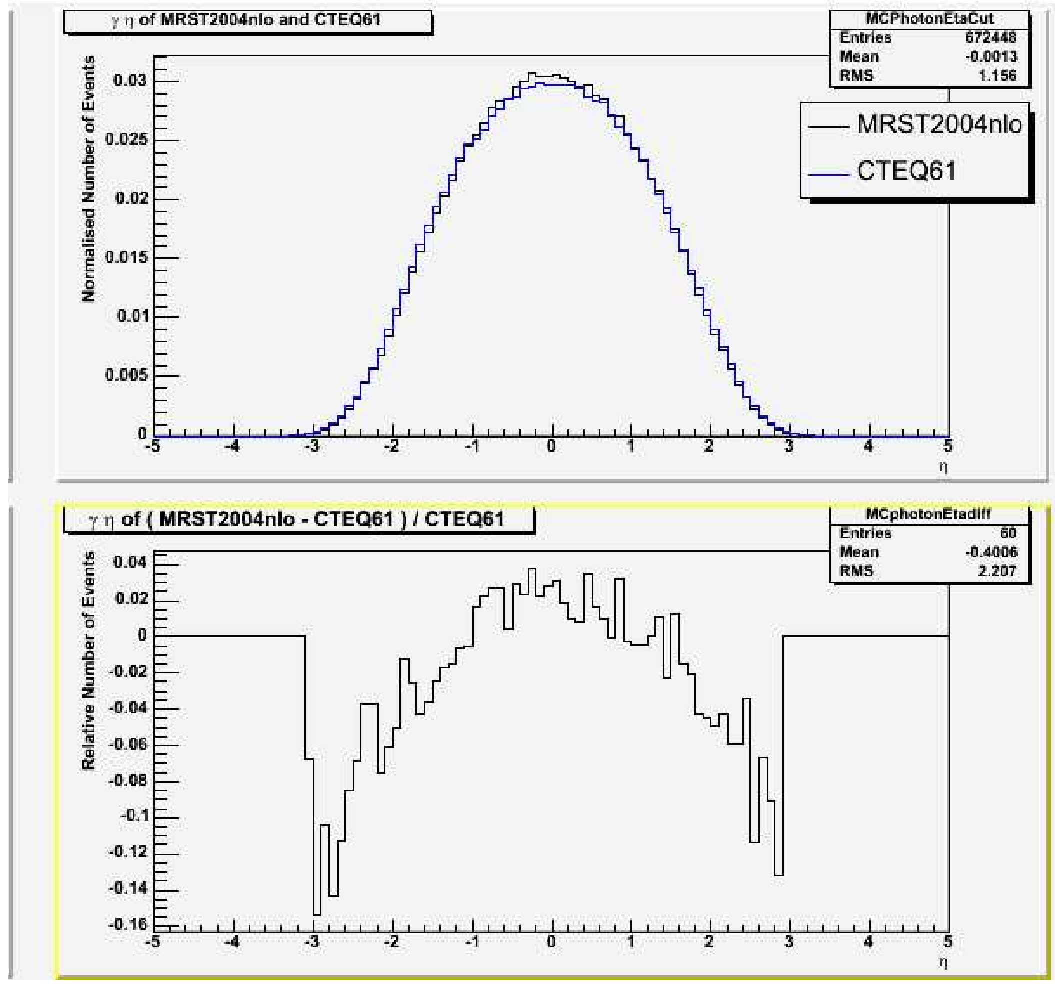
In principle this is also sensitive to the large x gluon – $x_T = 2p_T/\sqrt{s}$.

At low $p_T \sim 5 - 10\text{GeV}$ $d^2\sigma/dEdp_T$ has been contaminated by nonperturbative problems.

Far cleaner probe of the perturbative gluon at the LHC at much higher $p_T \geq 330\text{GeV}$. Also sensitive to electroweak corrections (Kühn *et al*), $\rightarrow$ consistency check.

Study by Hollins notices differences between MRST and CTEQ gluons. At $p_T = 350\text{GeV}$, $\eta = 0$ corresponds to $x = 0.05$.

Important to have cross-checks.



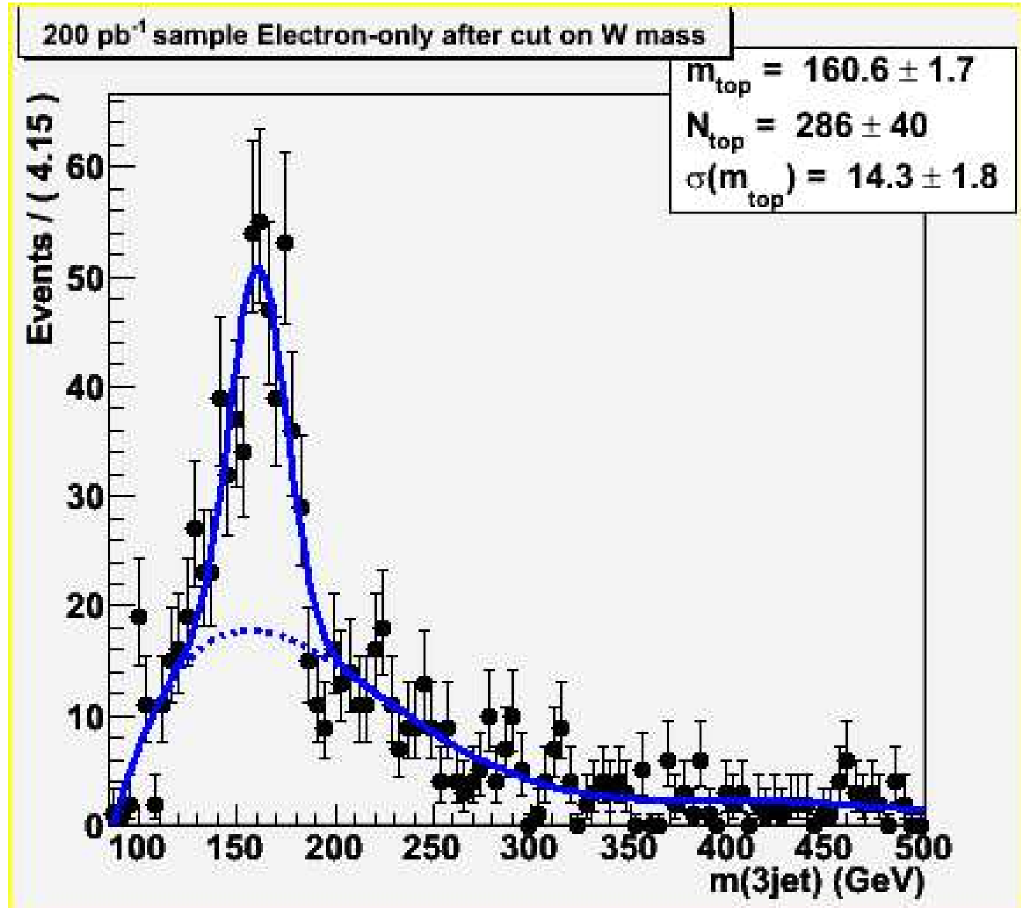
Interesting test of QCD with early running is top quark cross-section.

Leading to precision studies with larger integrated luminosity.

Sort of measurement possible (with b tagging) shown opposite.

At Tevatron – $85\%\ q\bar{q}$ annihilation and $15\%\ gg$.

At LHC – $10\%\ q\bar{q}$ annihilation and $90\%\ gg$.

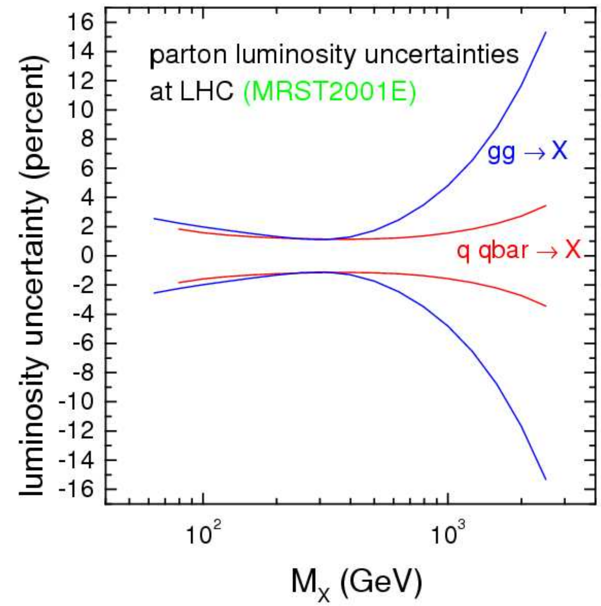


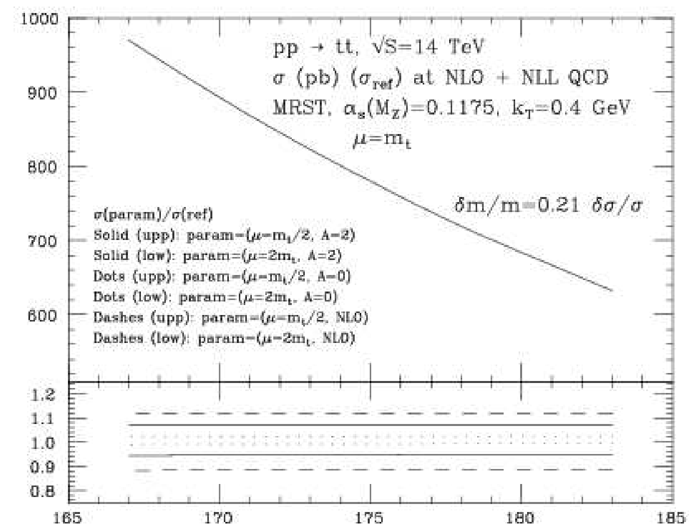
Uncertainty due to partons reduced significantly at LHC compared to Tevatron due to smaller x and constraints from HERA. Approx 2% compared to 7%. Potentially some test of parton evolution to high scales and of parton uncertainties.

Uncertainty due to perturbative cross-section often overestimated.

Scale uncertainty (probably ok in this case) 12% from simple NLO but only 5% from (one version of) NLO+NLL threshold resummation.

Overall theoretical prediction has $\sim 8\%$ uncertainty. Measurement near this good test of QCD (assuming m_t) already well known.



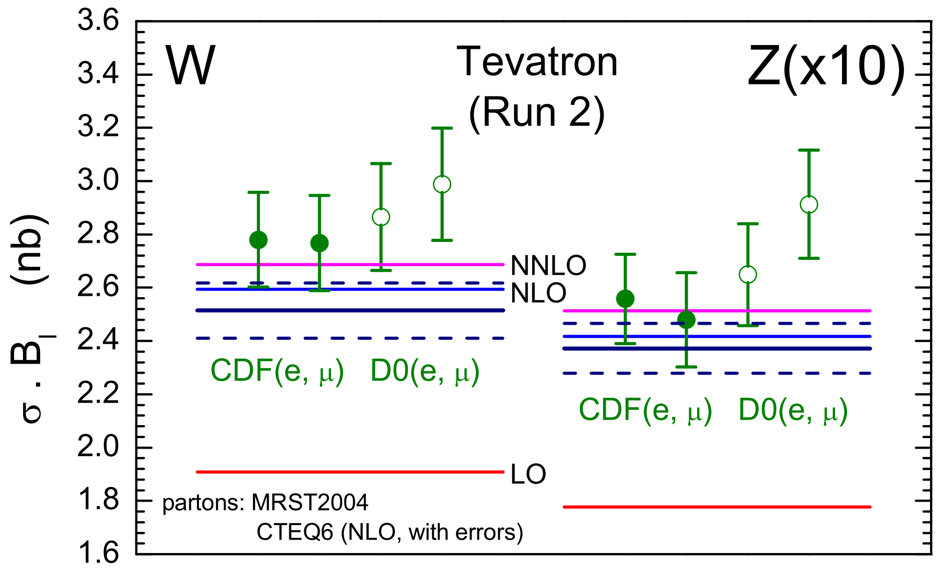


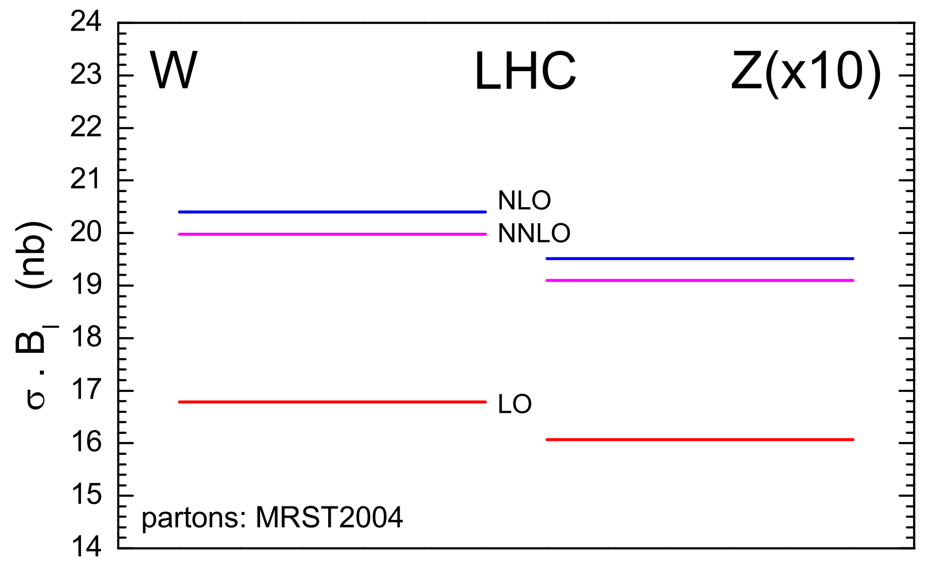
Most accurate absolute prediction in principle – W and Z production.

Reasonable stability order by order for (quark-dominated) W and Z cross-sections.

This fairly good convergence is largely guaranteed because the quarks are fit directly to data.

Also true for rapidity distribution – known at NNLO.

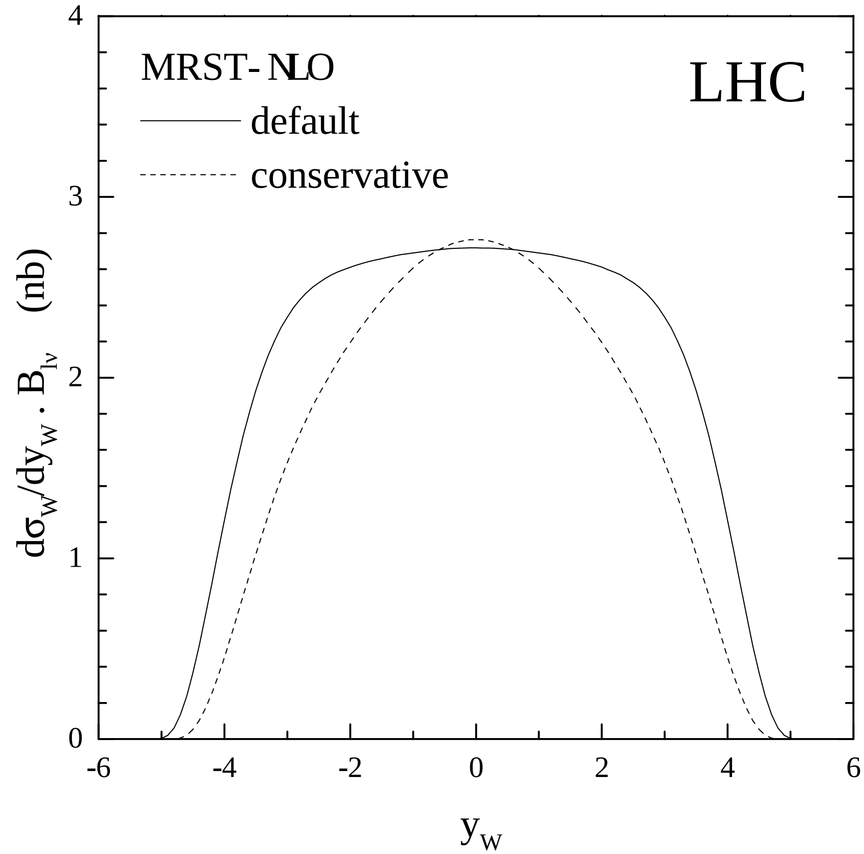




Some doubt in predictions at high rapidity.

Comparison of prediction for $(d\sigma_W/dy_W)$ for the standard MRST partons and a set which represents the possible type of theoretical uncertainty in this region when working at NLO.

Good stability at central rapidity – $x = 0.005$.

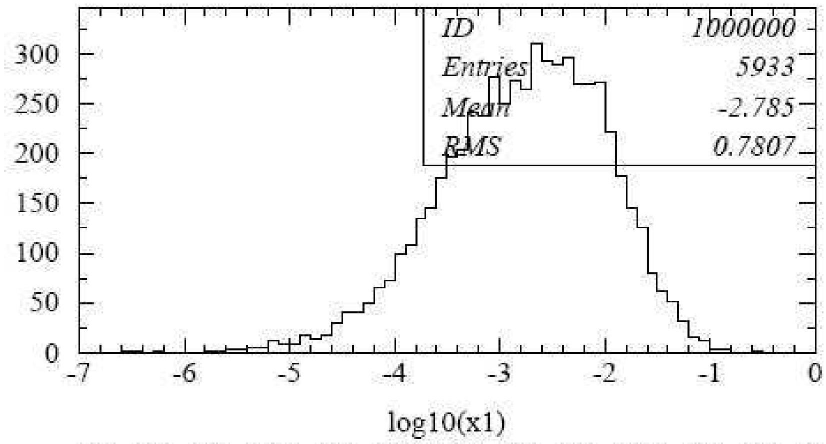


Increased uncertainty if worrying about theory for very small x.

Study by Rizvi. Good reach at ATLAS if low p_T-trigger.

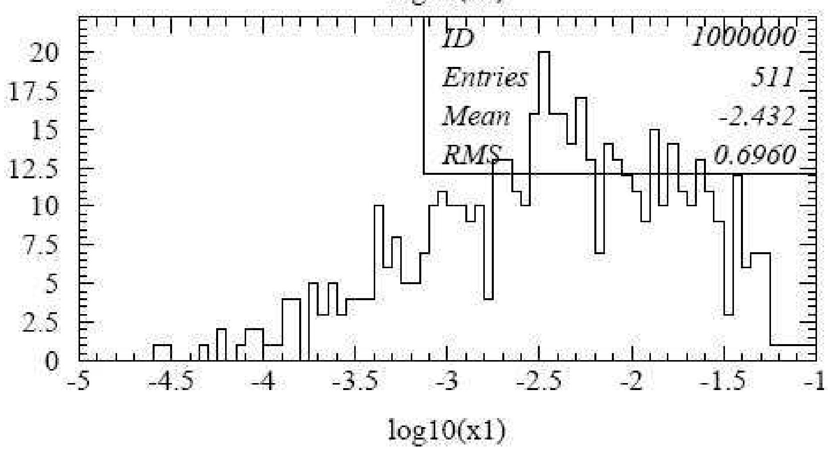
Measurement Feasibility 08/05/06

x of parton producing Drell-Yan pair



After P_T > 6 GeV for one fermion

Can reach x~10^{-5}



After P_T > 20 GeV for one fermion

Need low P_T trigger

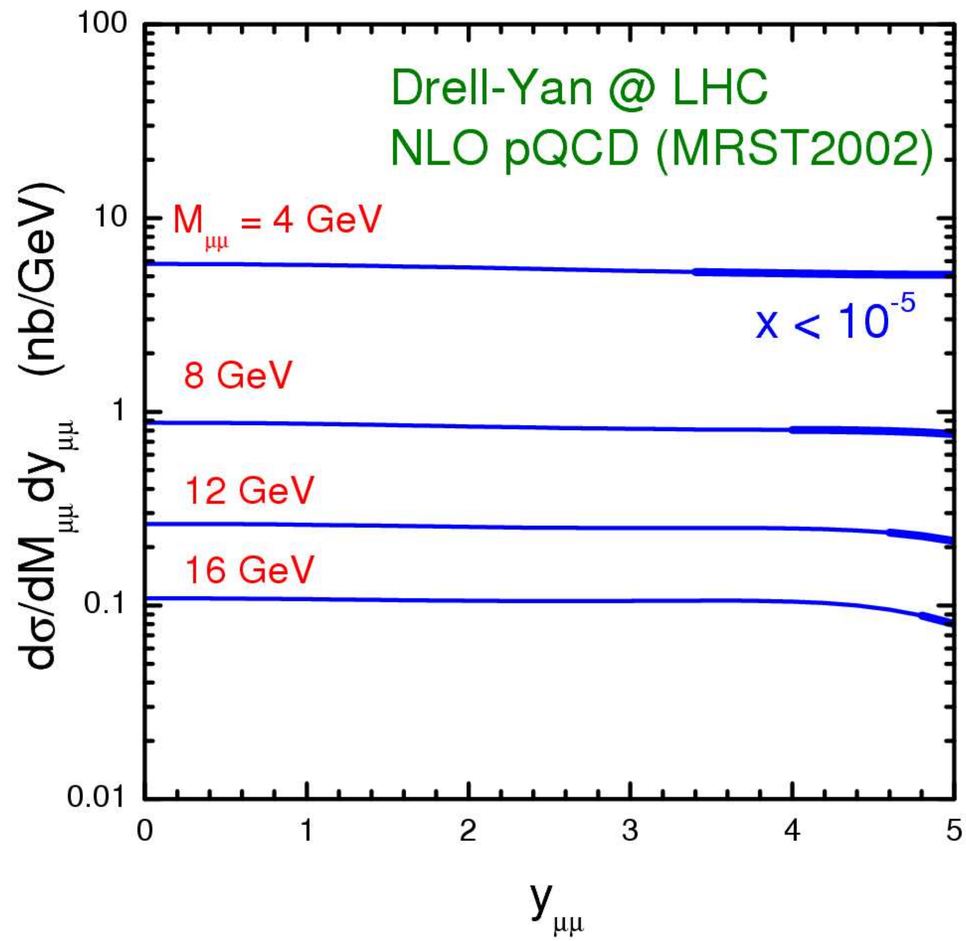
Eram Rizvi 12

Possible to get to very low values of x at the LHC.

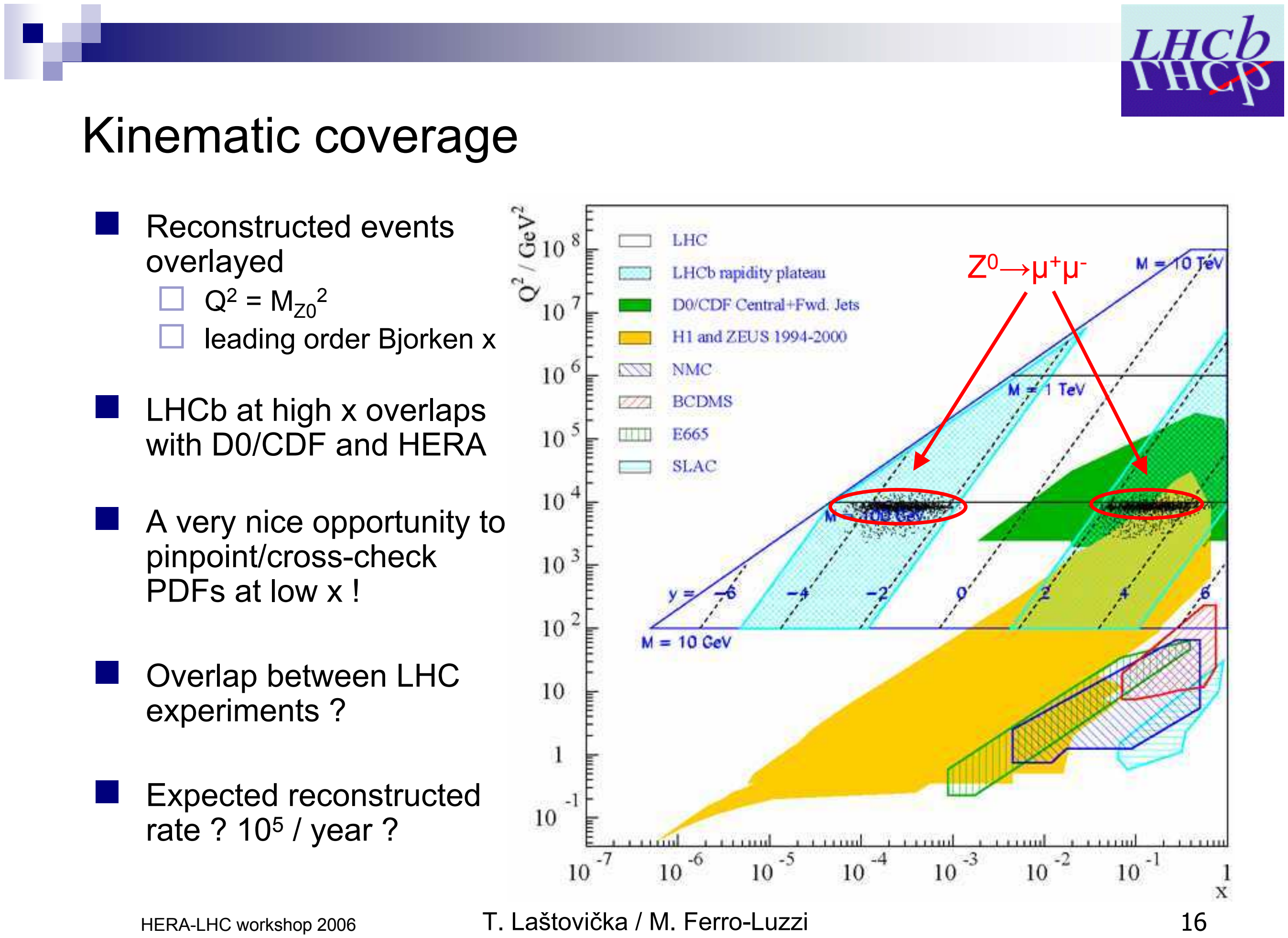
ALICE in pp mode at $10^{31} cm^{-2} s^{-1}$ with forward muon detection.

Can probe below $x = 10^{-5}$ – beyond range tested at HERA.

Interesting for QCD people.



Useful early measurement at LHCb – even probe very small x with high rapidity Z (Lastovicka, Ferro-Luzzi).

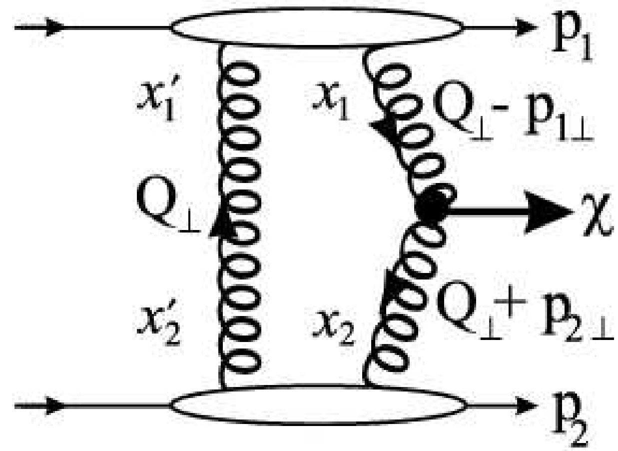


At lowest rapidity $y = 1.8$ good test of parton distributions but could be luminosity monitor if cross-checked with ATLAS, CMS and QCD calculations. Interesting Standard Model Physics at LHCb as well as vital flavour physics.

Also cause to worry about diffraction at the LHC, i.e. central production with large rapidity gaps and tagged protons.

Predictions by Khoze *et al.*, Boonekamp *et al.*, e.g.

$\sigma \propto \hat{S}^2 | \int \frac{dQ_T^2}{Q_T^4} f_g(x_1, x_1', \mu^2, Q_T^2) f_g(x_2, x_2', \mu^2, Q_T^2)|^2$



i.e. skewed parton distributions and $\hat{S}^2$ is the gap survival probability. (Diffractive parton distributions non-universal.)

Perturbative part fairly reliable, $\hat{S}^2 \approx 0.025$ at LHC but rather uncertain.

Signal for $H \rightarrow b\bar{b}$ approx. 10 events for $60 fb^{-1}$ for $m_H \sim 120\mathrm{GeV}$. Background similar. Enhancements for signal for light SUSY Higgs.

Signal takes a long time, but uncertainty in prediction quantified by comparison with diffractive high-E_T dijet production (as a distribution of $R_{jj} = M_{jj}/M_X \leq 1$) or diffractive J/Ψ.

Conclusions

Few possibilities for seeing signs of new physics with early data. $Z' \sim 1\mathrm{TeV}$ possible but unlikely and lowest mass SUSY possible. Early Higgs discovery if $m_H \sim 170\mathrm{GeV}$? (Could be bad news.)

Currently predict cross-sections at the LHC with uncertainties due to errors on existing data rather small – $\sim 1-5\%$ for most LHC quantities (not highest E_T). Ratios often don't reduce uncertainties unless theoretical uncertainties cancel.

Uncertainty from assumptions and theoretical sources comparable or often much larger, e.g. exact matrix element corrections to Monte Carlos. Can shift central values of predictions significantly. Electroweak corrections potentially large at very high energies – $\ln^2(E^2/M_W^2)$. Requires careful definitions of theory and measurement.

Looking at as wide a range of rapidity good for disentangling high-energy and QCD. Measurement at high rapidities, e.g. W, Z would be useful in testing QCD, and particularly quantities sensitive to low x at low scales, e.g. low mass Drell-Yan.

Existing theory often the dominant source of uncertainty. Much progress – more processes at NLO (including Monte Carlos), some at NNLO including partons, resummations ... In some cases only LO which is not really enough. Important for early LHC data to check if further corrections needed for real precision.

Results from LHC/LP Study Working Group (Bourilkov).

Table 1: Cross-sections for Drell-Yan pairs (e^+e^-) with PYTHIA 6.206, rapidity < 2.5. The errors shown are the PDF uncertainties.

PDF set	Comment	xsec [pb]	PDF uncertainty %
$81 < M < 101$ GeV			
CTEQ6	LHAPDF	1065 ± 46	4.4
MRST2002	LHAPDF	1091 ± ...	3
Fermi2002	LHAPDF	853 ± 18	2.2

Comparison of $\sigma_W \cdot B_{l\nu}$ for MRST2002 and Alekhin partons.

PDF set	Comment	xsec [nb]	PDF uncertainty
Alekhin	Tevatron	2.73	± 0.05 (tot)
MRST2002	Tevatron	2.59	± 0.03 (expt)
CTEQ6	Tevatron	2.54	± 0.10 (expt)
Alekhin	LHC	215	± 6 (tot)
MRST2002	LHC	204	± 4 (expt)
CTEQ6	LHC	205	± 8 (expt)

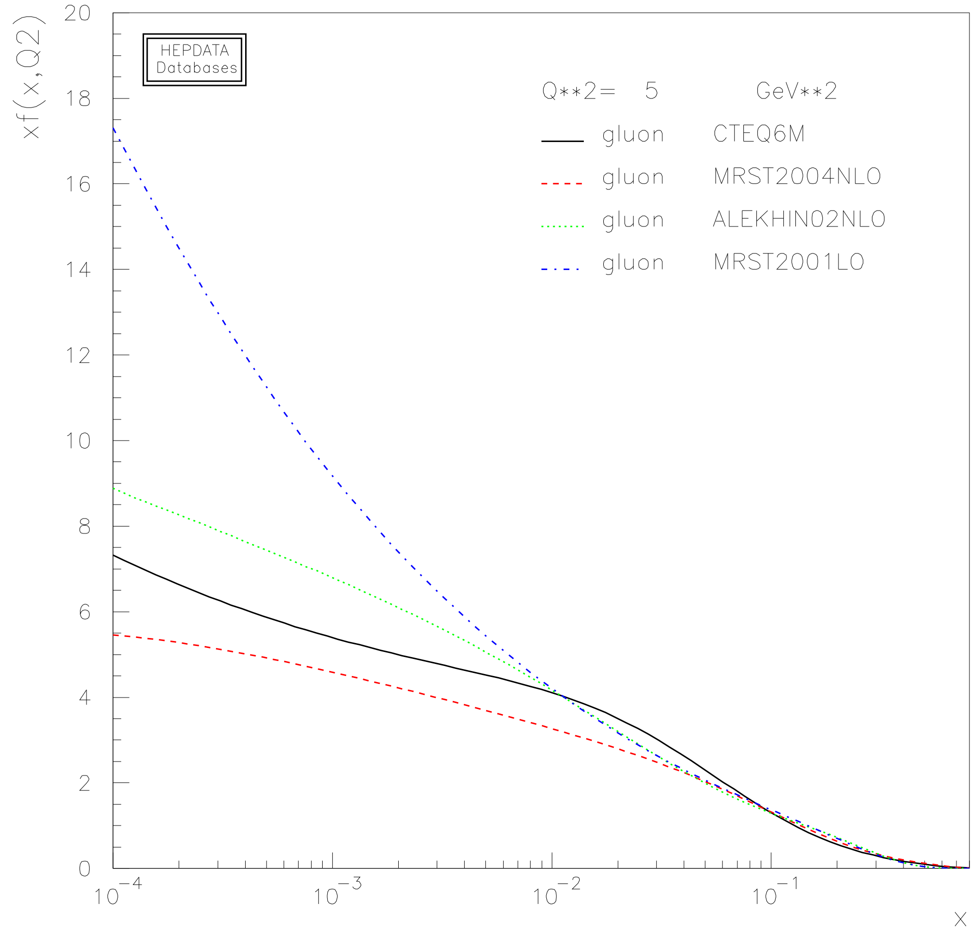
In both cases differences (mainly) due to detailed constraint (by data) on quark decomposition.

LO partons in some regions qualitatively different to all NLO and NNLO partons. Due to important missing NLO corrections in splitting functions.

Can lead to wrong conclusions on size of small-x gluon, and conclusions on shadowing *etc.*

Nevertheless, LO partons are the appropriate ones to use with many LO Monte Carlo programs.

All such results should be treated with care.



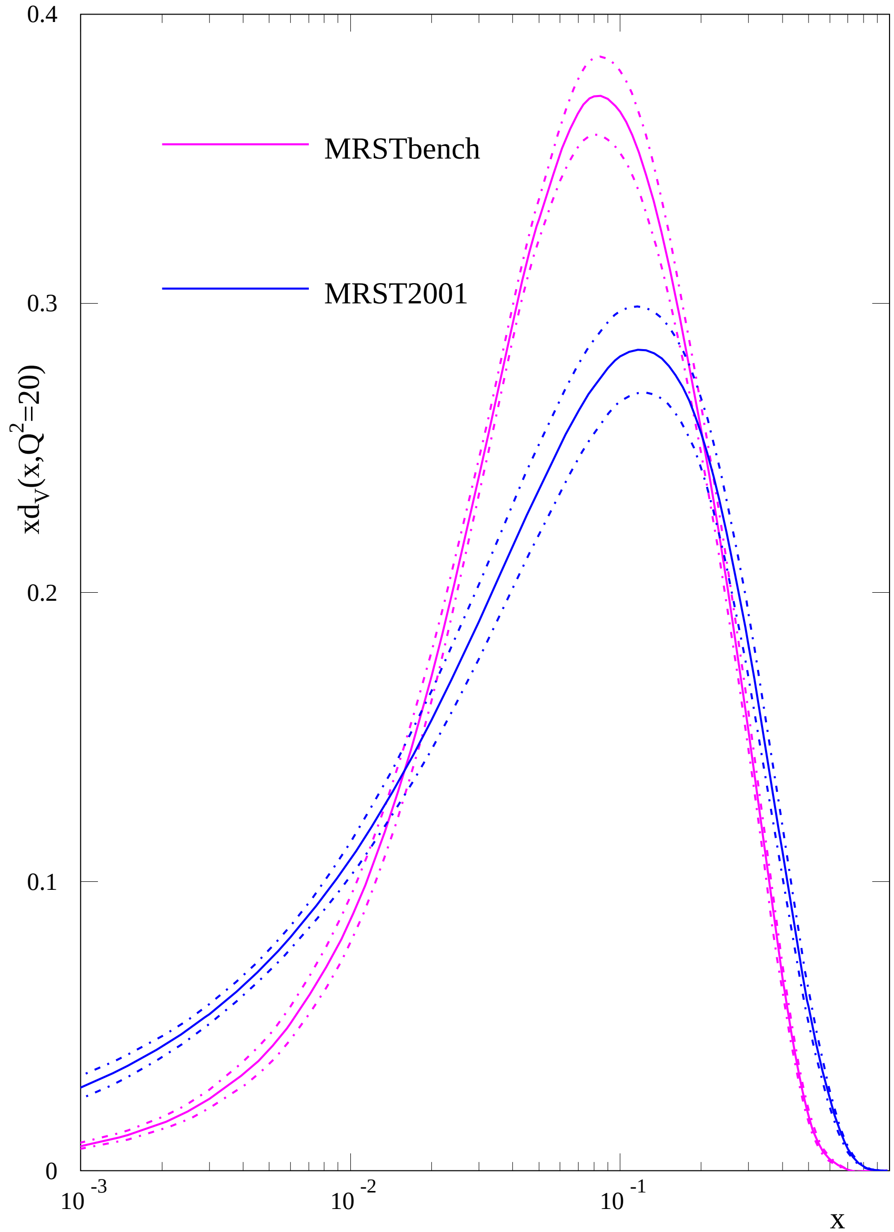
Back to HERA-LHC benchmark partons.

How do partons from very conservative, structure function only data compare to global partons?

Compare to MRST01 partons with uncertainty from $\Delta\chi^2 = 50$.

Enormous difference in central values.

Errors similar.



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.

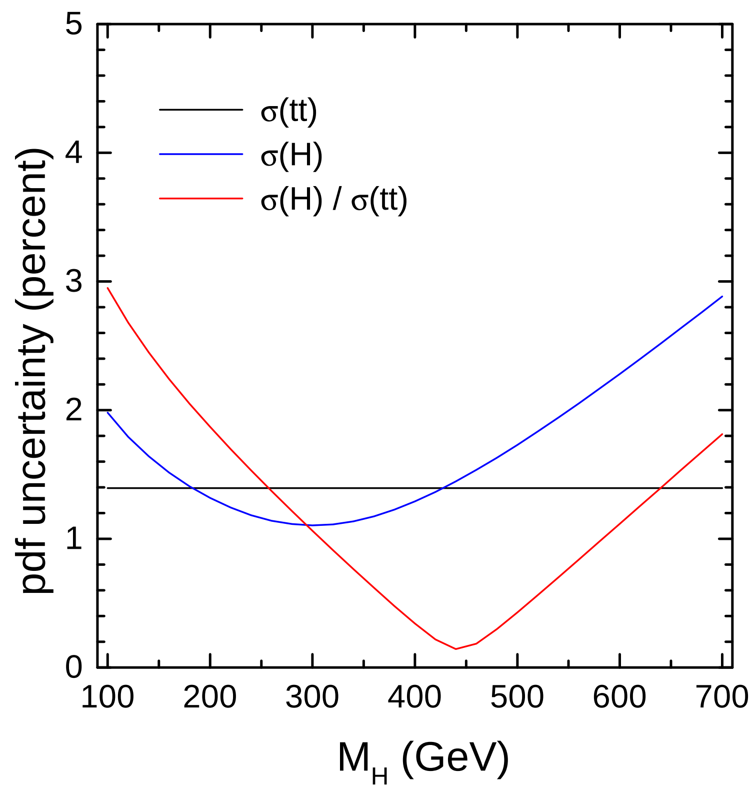
However, a light (SM or MSSM) Higgs dominantly produced via $gg \to H$ and the cross-section has small pdf uncertainty because $g(x)$ at small x is well constrained by HERA DIS data.

Current best (MRST) estimate, for $M_H = 120$ GeV: $\delta\sigma_H^{\rm NLO}(\text{expt pdf}) = \pm 2 - 3\%$ with less sensitivity to small x than $\sigma(W)$.

Much smaller than the uncertainty from higher-order corrections, for example, Catani et al,

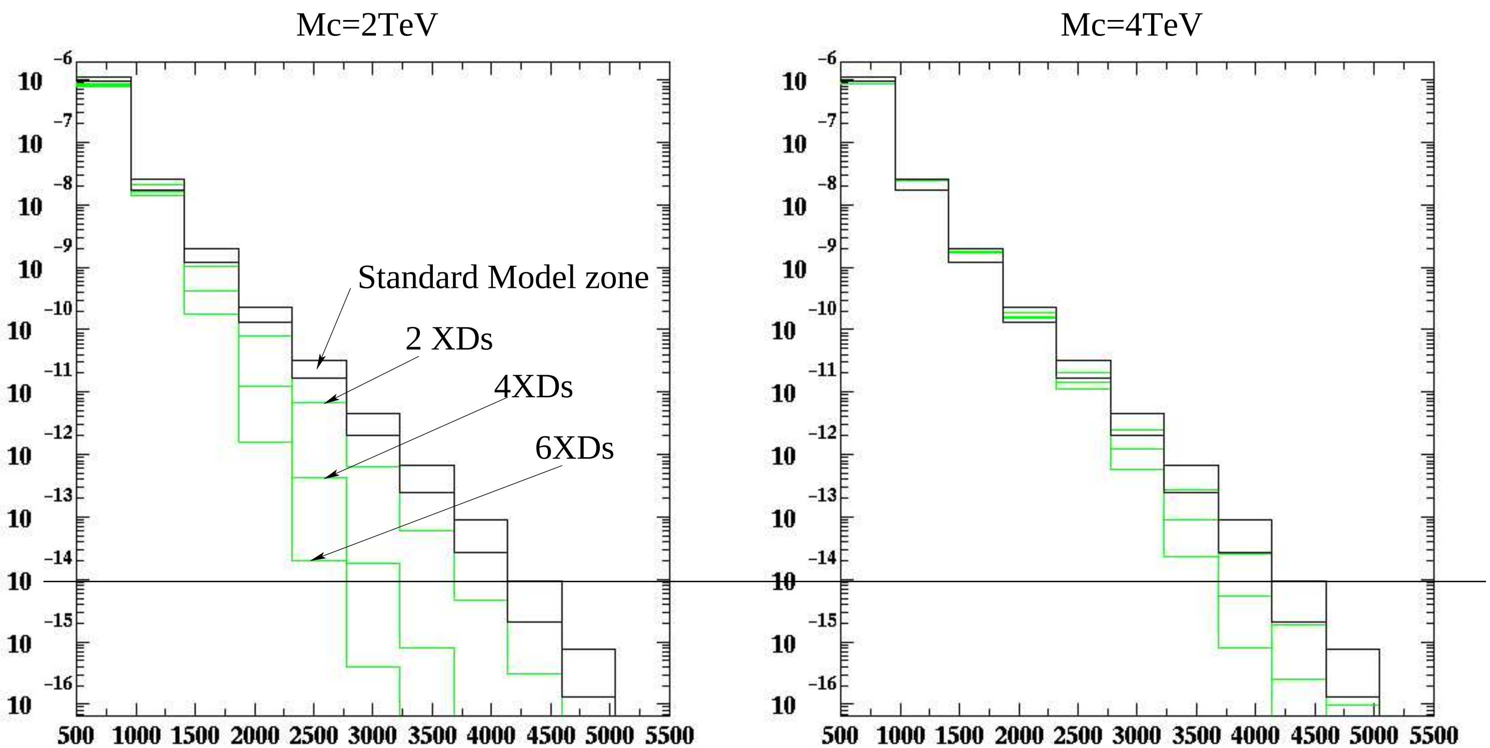
$\delta\sigma_H^{\rm NNLL}(\text{scale variation}) = \pm 8\%$

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



Comparison of variations in dijet production from large extra dimensions (alters running of $\alpha_S(Q^2)$) with given compactification scale and from uncertainties in $g(x, Q^2)$ (Ferrag).

Limit on M_C changes from $5\text{TeV} \rightarrow 2\text{TeV}$. Depends on particular parton set and uncertainties.



Horizontal line – one year (very optimistic) projected LHC running.

Search at Tevatron for enhancement in jets with b quarks.

Produces upper limit on parameter $\tan\beta$.