High-Energy Scattering

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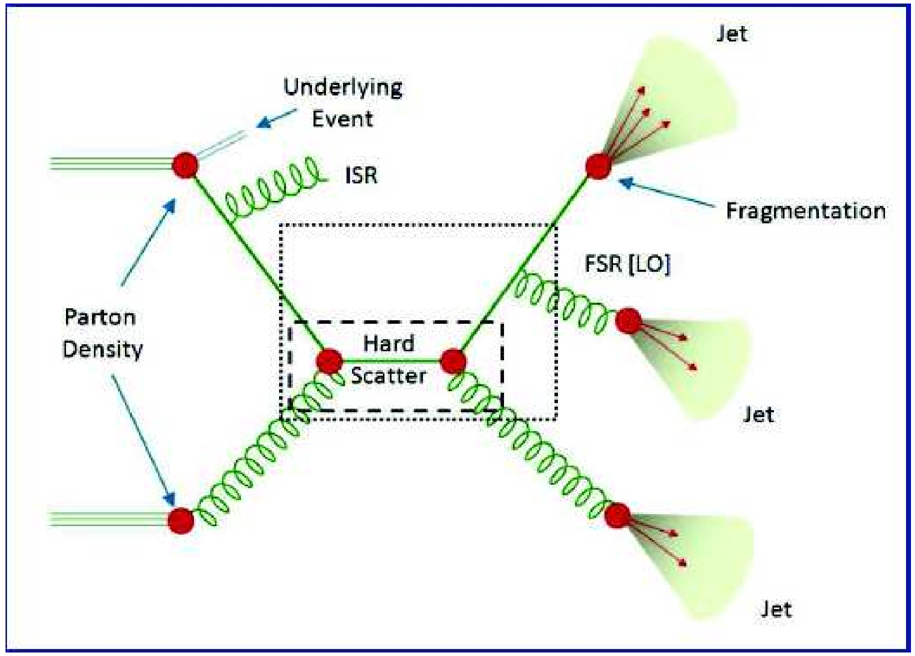
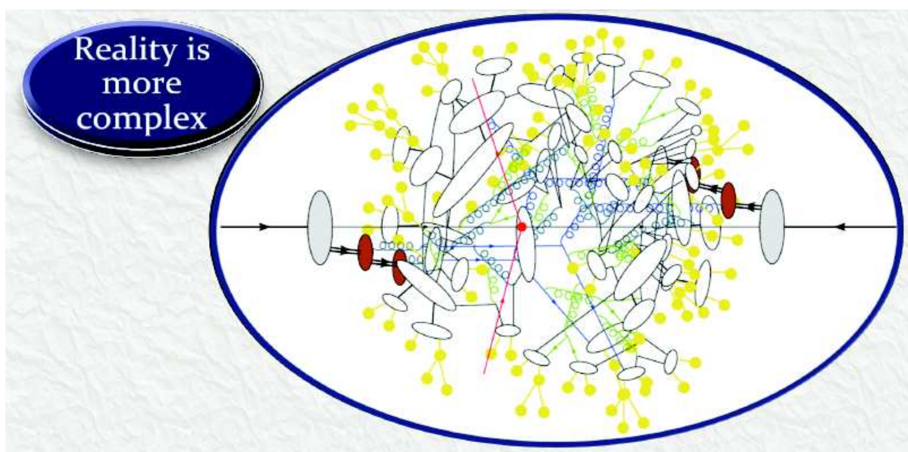
High energy scattering processes very complicated



Particularly in reality

Varelas EPS-2011



Need to consider piece-by-piece. Start with **Parton Distributions**

Strong force makes it difficult to perform analytic calculations for initial state.

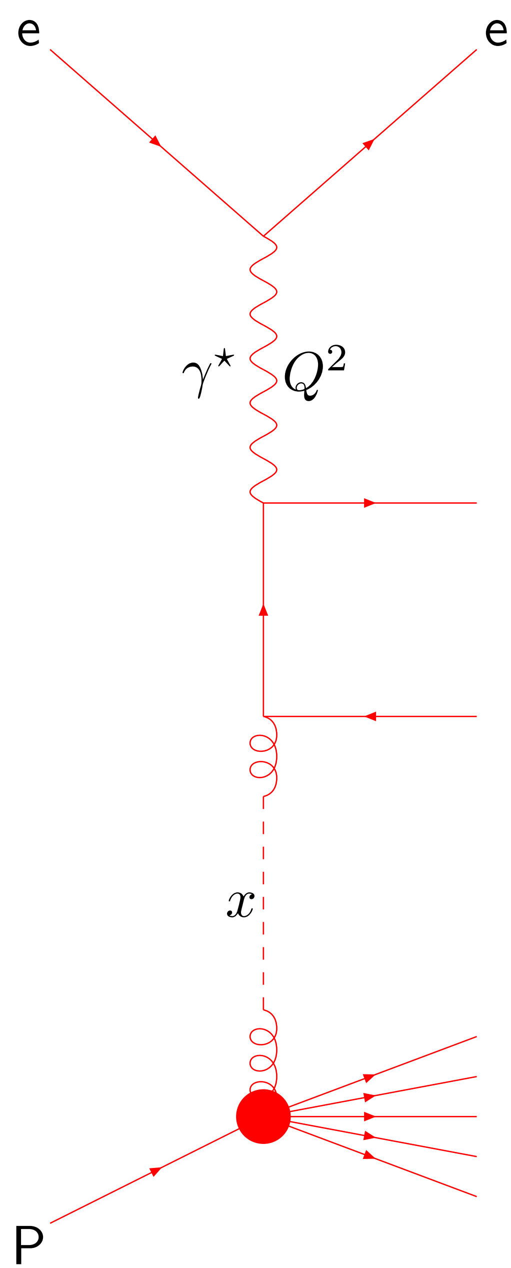
The weakening of $\alpha_S(\mu^2)$ at higher scales $\longrightarrow$ the **Factorization Theorem**.

Hadron scattering with an electron factorizes.

$F(x,Q^2) = \sum_i C_i(x) \otimes f_i(x,Q^2)$.

Q^2 – Scale of hard scattering

$x = \frac{Q^2}{2m\nu}$ – Momentum fraction of Parton (ν=energy transfer)

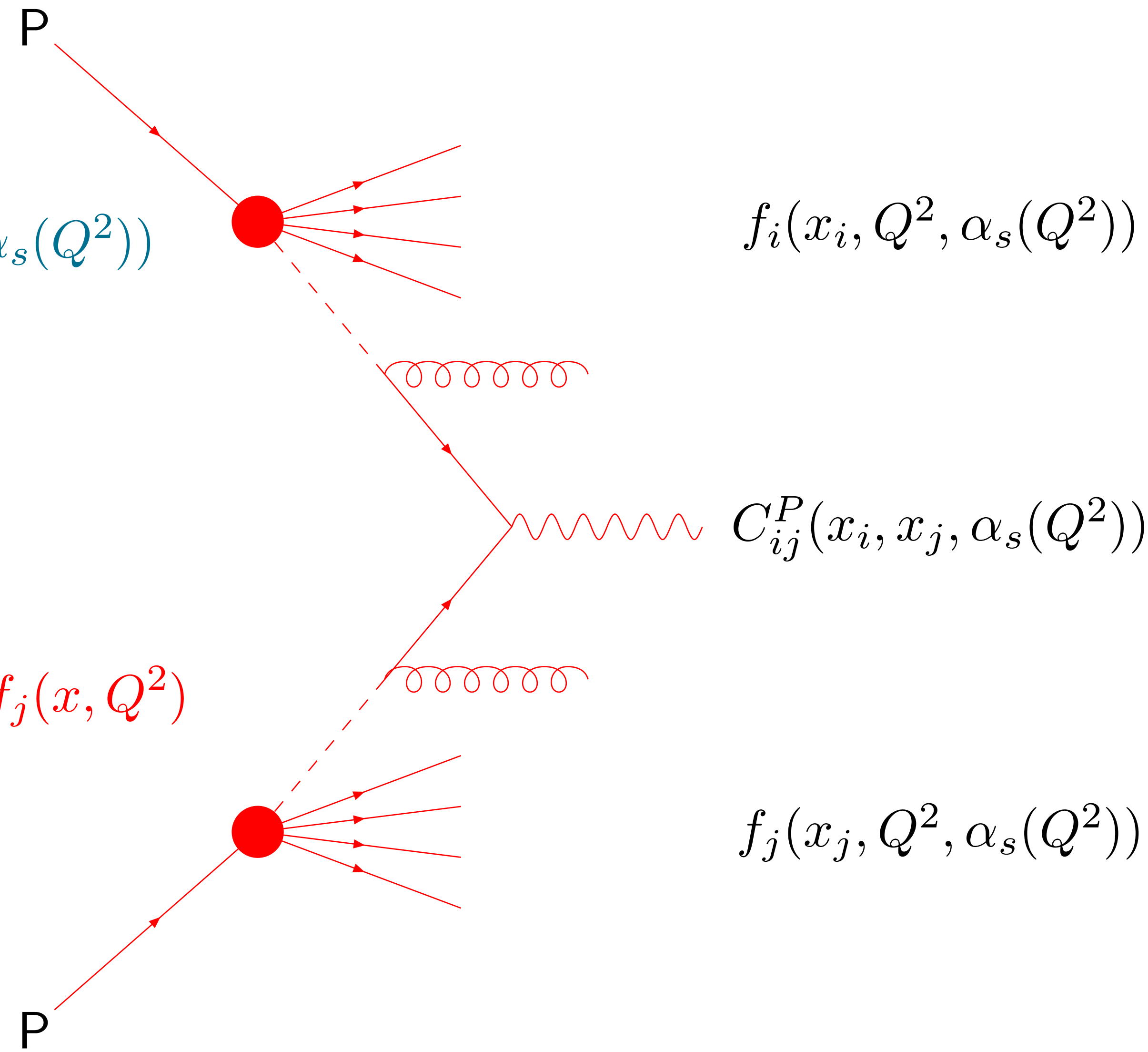


perturbative
calculable
coefficient function
$C_i^P(x, \alpha_s(Q^2))$

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

The coefficient functions $C_i^P(x, \alpha_s(Q^2))$ are process dependent but are calculable as a power-series in $\alpha_s(Q^2)$.

The parton distributions $f_i(x, Q^2, \alpha_s(Q^2))$ are process-independent, i.e. **universal**, and evolution with scale is calculable.

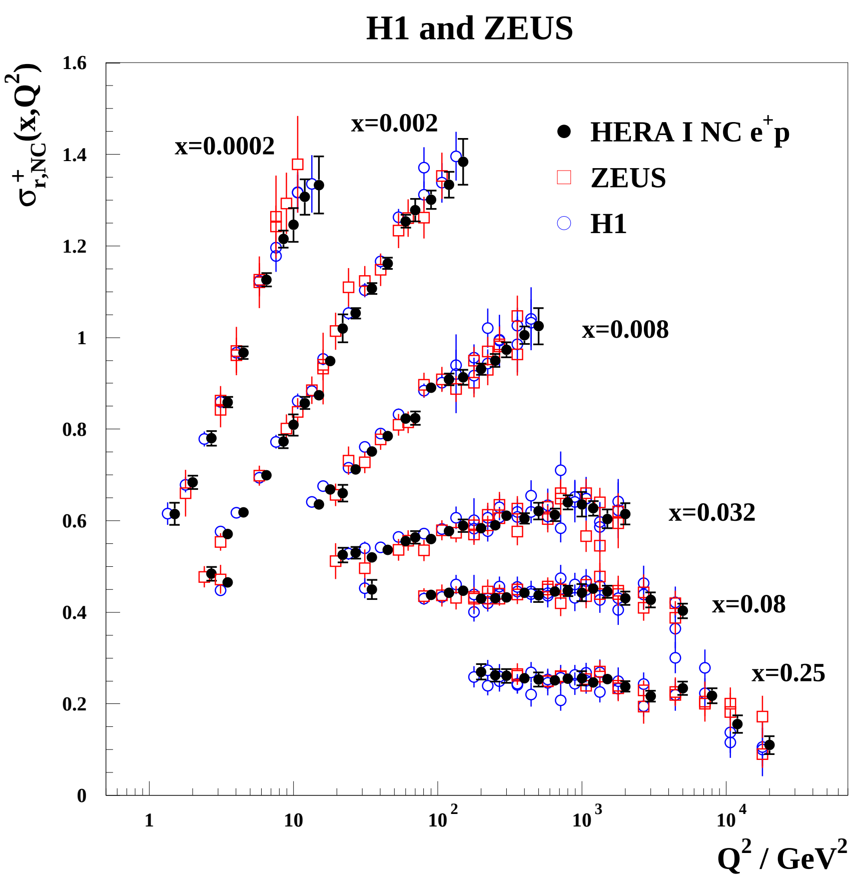


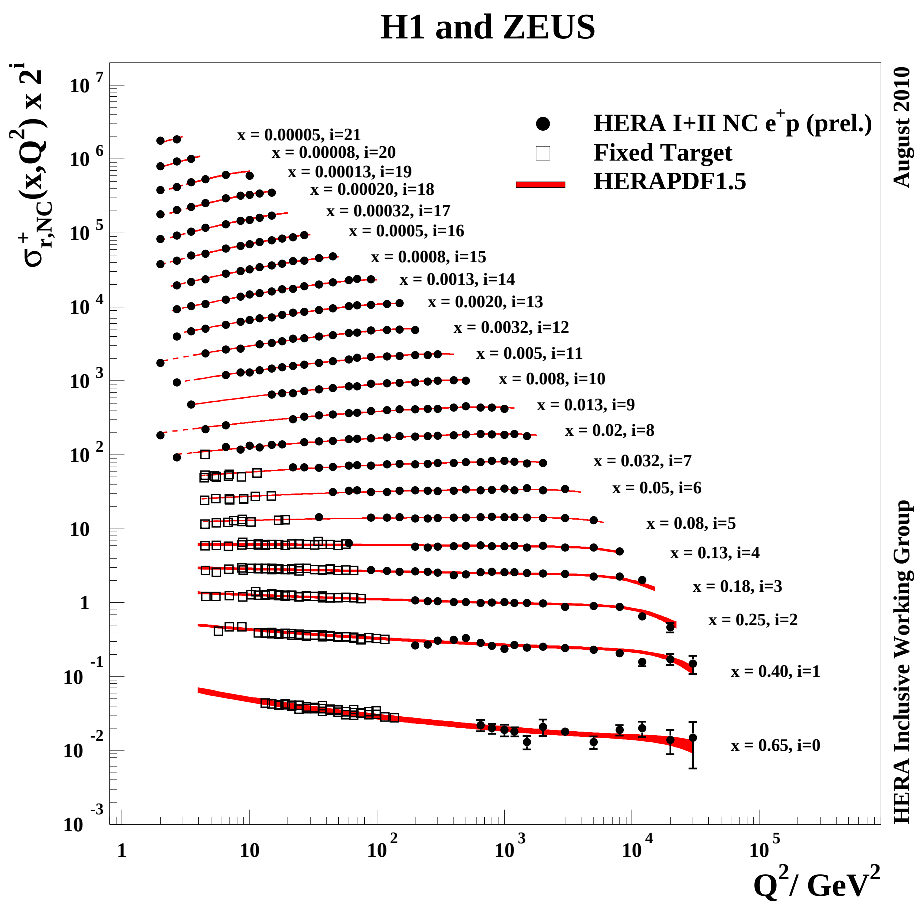
$$\frac{df_i(x, Q^2)}{d\ln Q^2} = \sum_j P_{ij}(x, \alpha_s(Q^2)) \otimes f_j(x, Q^2)$$

P_{ij} used at LO, NLO or increasingly NNLO accuracy.

Structure Functions

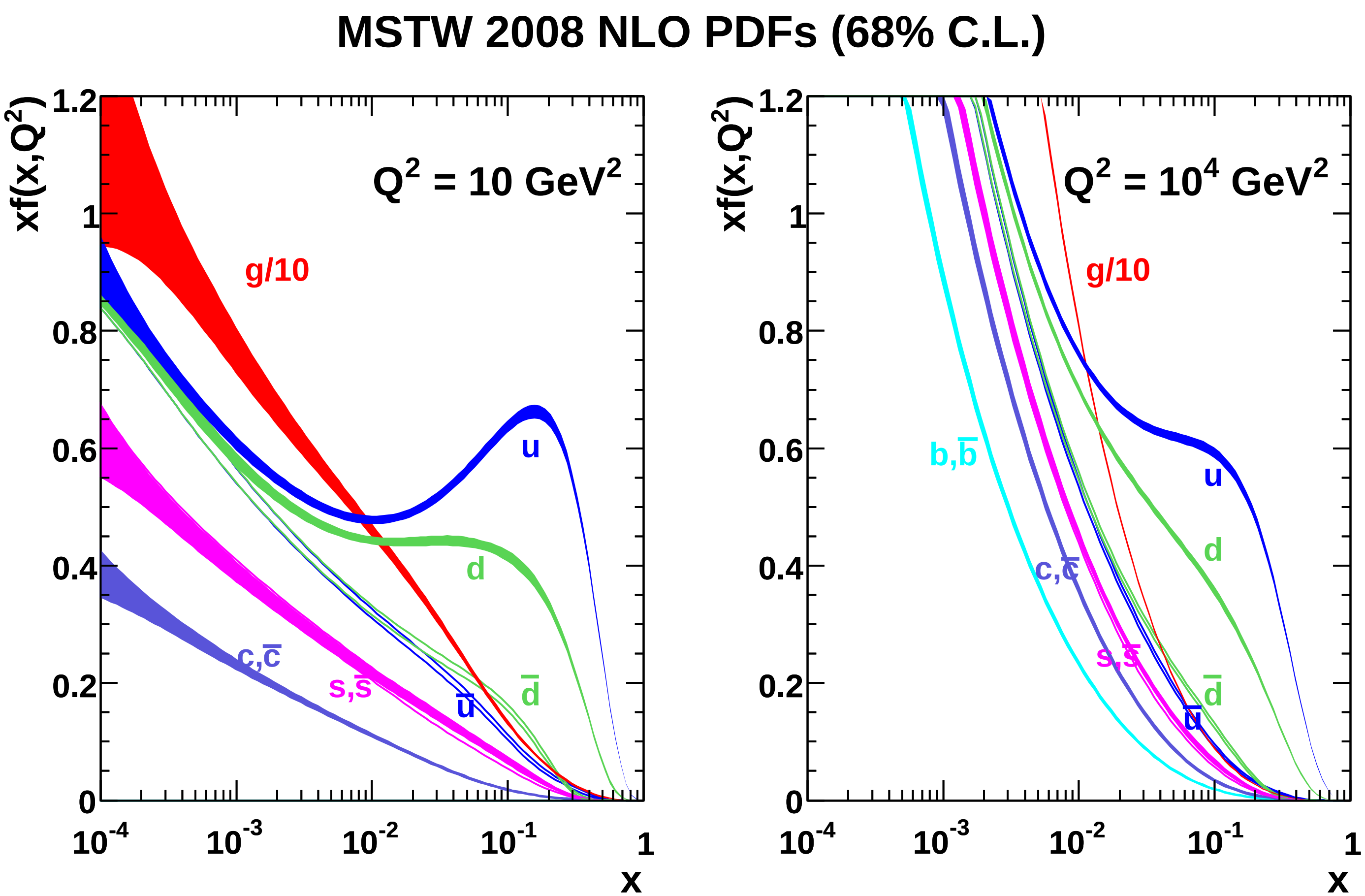
The single most important input to determining these PDFs is the combined ZEUS and H1 total HERA structure function data.





Precision comparable to 1% over a wide range of x and Q^2

Fits to all relevant data results in partons of the form shown.



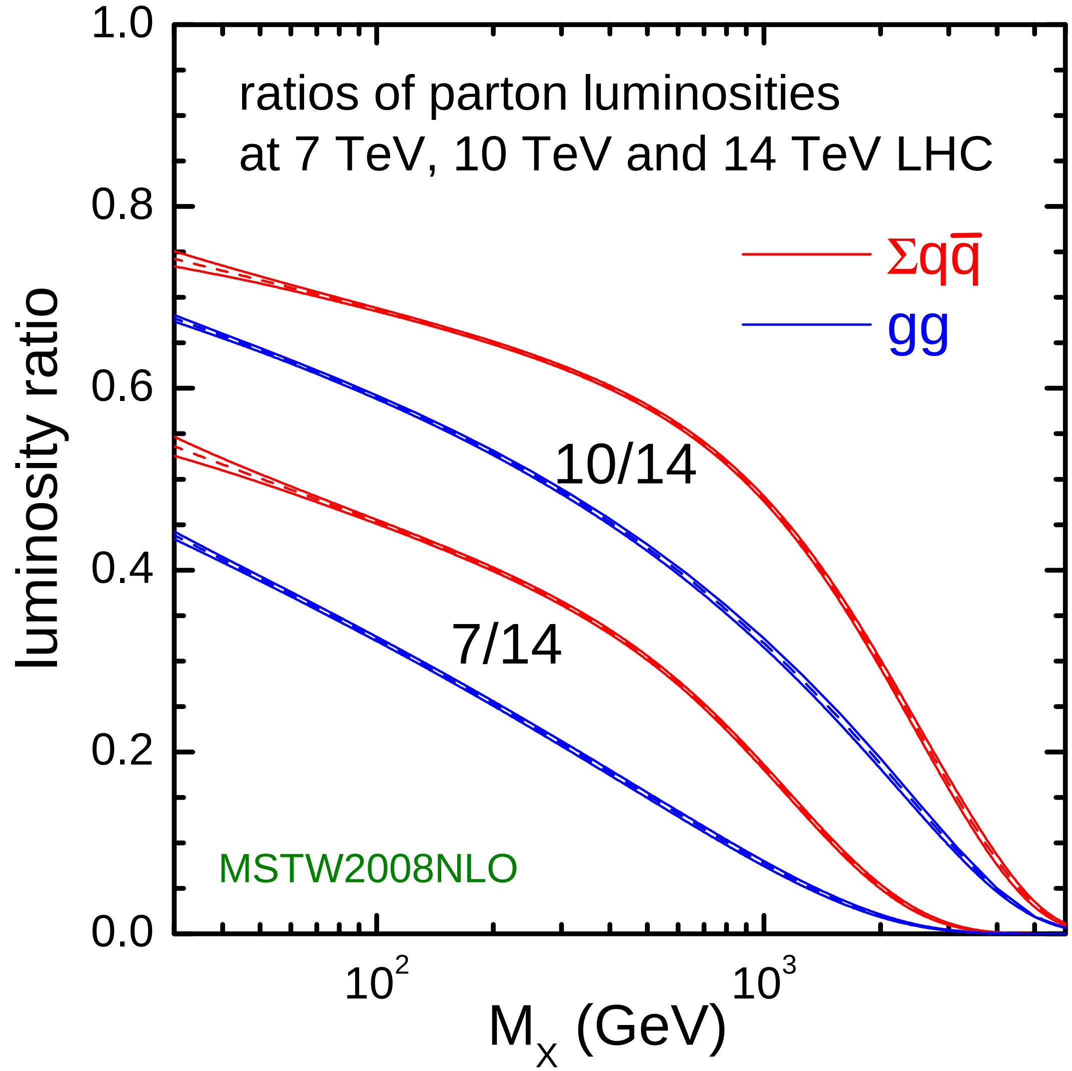
Various choices of PDF – MSTW, CTEQ, NNPDF, AB(K)M, HERA, Jimenez-Delgado *et al etc.*. All LHC cross-sections rely on our understanding of these partons.

Parton Luminosities

Parton distributions determine all production rates at the LHC.

The LHC is currently running at 7 TeV rather than the full 14 TeV.

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



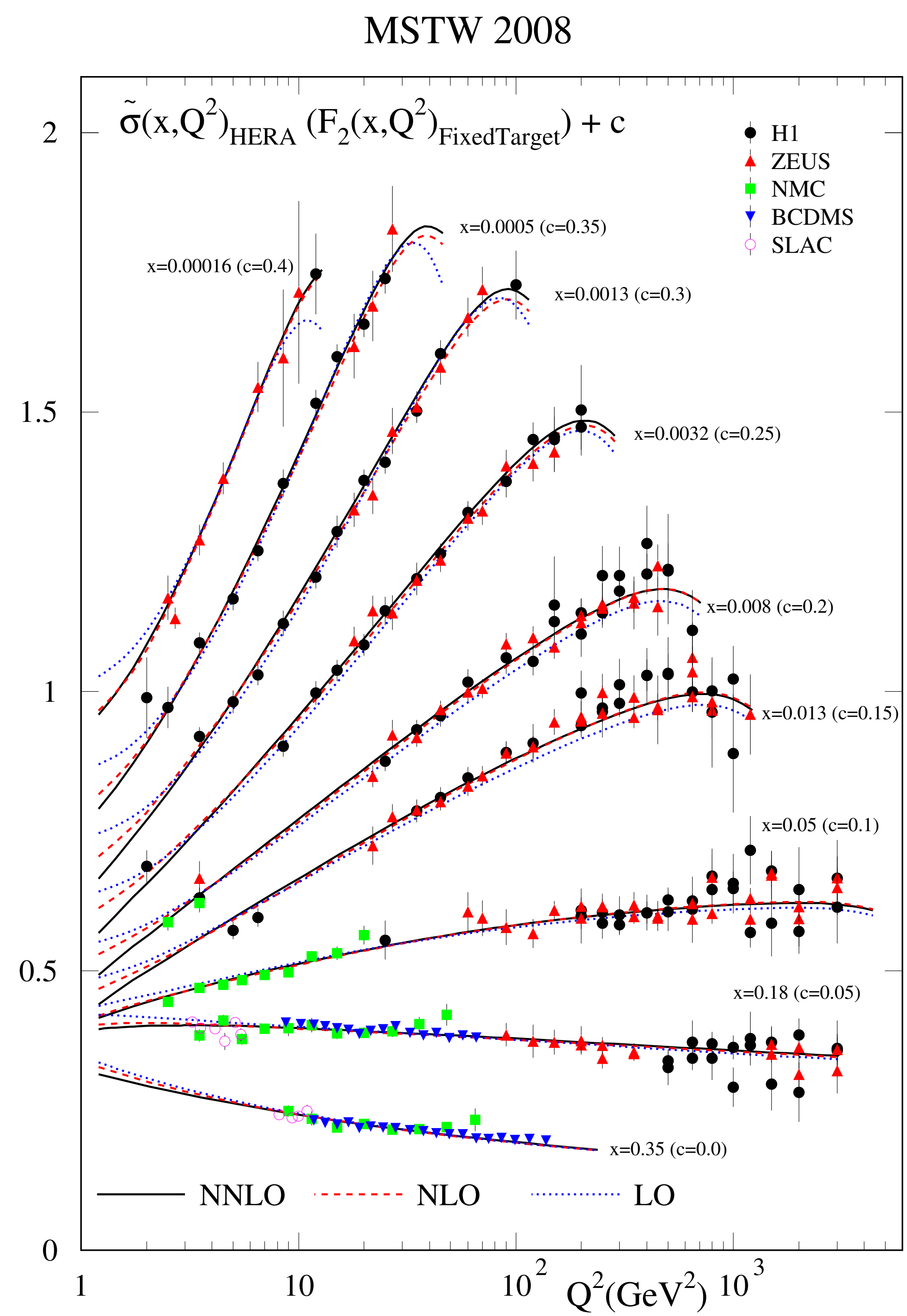
Perturbative Calculations

Although structure functions very directly related to quark distributions, there are perturbative corrections to evolution and cross-sections.

Default has long been NLO. Essentially well understood. Now starting to go further use NNLO frequently.

Improve consistency of fit very slightly (MSTW), and reduces α_S.

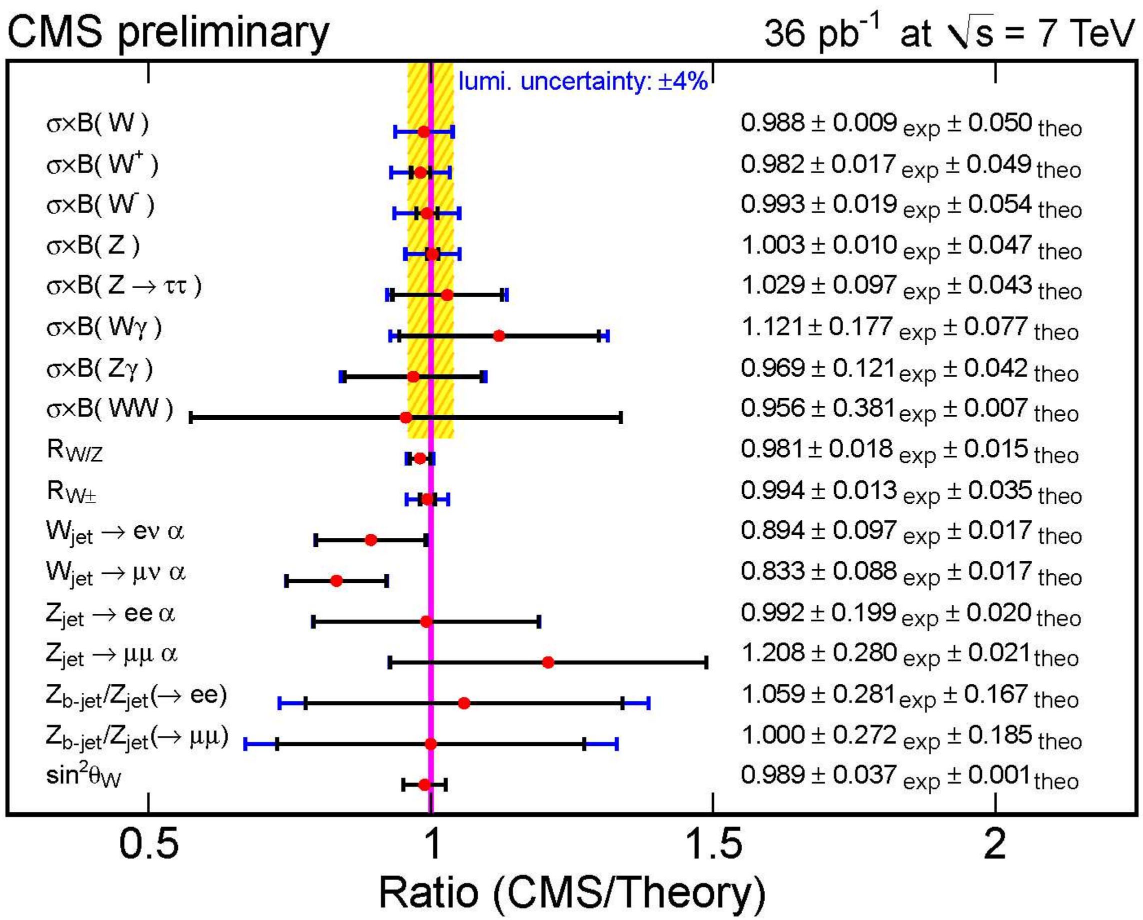
Fit to $F_2(x,Q^2)$ data. Slope poor (too flat) at LO, ok at NLO and better at NNLO.



Status of NLO and NNLO calculations

Start with fully inclusive quantities.

In general excellent agreement with cross sections measured at LHC.



Enormous number of processes calculated at NLO.

For example MCFM includes a wide variety in one overall framework (Ellis, Campbell and others).

Final state	Notes	Reference
W/Z		
diboson (W/Z/γ)	photon fragmentation, anomalous couplings	hep-ph/9905386, arXiv:1105.0020
Wbb	massless b-quark massive b quark	hep-ph/9810489 arXiv:1011.6647
Zbb	massless b-quark	hep-ph/0006304
W/Z+1 jet		
W/Z+2 jets		hep-ph/0202176, hep-ph/0308195
Wc	massive c-quark	hep-ph/0506289
Zb	5-flavour scheme	hep-ph/0312024
Zb+jet	5-flavour scheme	hep-ph/0510362

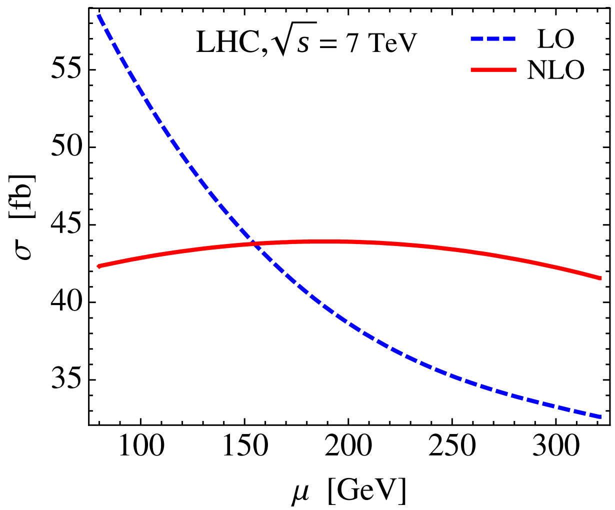
Final state	Notes	Reference
H (gluon fusion)		
H+1 jet (g.f.)	effective coupling	
H+2 jets (g.f.)	effective coupling	hep-ph/0608194, arXiv:1001.4495
WH/ZH		
H (WBF)		hep-ph/0403194
Hb	5-flavour scheme	hep-ph/0204093
t	s- and t-channel (5F), top decay included	hep-ph/0408158
t	t-channel (4F)	arXiv:0903.0005, arXiv:0907.3933
Wt	5-flavour scheme	hep-ph/0506289
top pairs	top decay included	

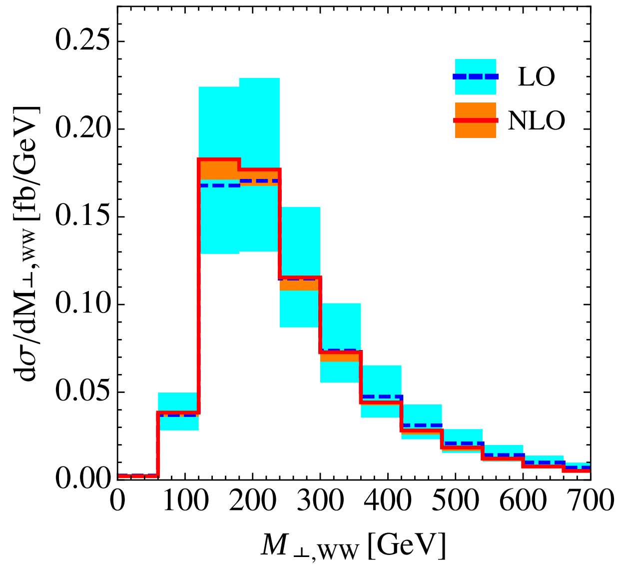
Dramatic improvement in automated calculation of NLO cross sections (Hirschi *et al*).

	Process	μ	n_{lf}	Cross section (pb) LO	NLO
a.1	$pp \to t\bar{t}$	m_{top}	5	123.76 ± 0.05	162.08 ± 0.12
a.2	$pp \to tj$	m_{top}	5	34.78 ± 0.03	41.03 ± 0.07
a.3	$pp \to tjj$	m_{top}	5	11.851 ± 0.006	13.71 ± 0.02
a.4	$pp \to t\bar{b}j$	$m_{top}/4$	4	25.62 ± 0.01	30.96 ± 0.06
a.5	$pp \to t\bar{b}jj$	$m_{top}/4$	4	8.195 ± 0.002	8.91 ± 0.01
b.1	$pp \to (W^+ \to)e^+\nu_e$	m_W	5	5072.5 ± 2.9	6146.2 ± 9.8
b.2	$pp \to (W^+ \to)e^+\nu_e\, j$	m_W	5	828.4 ± 0.8	1065.3 ± 1.8
b.3	$pp \to (W^+ \to)e^+\nu_e\, jj$	m_W	5	298.8 ± 0.4	300.3 ± 0.6
b.4	$pp \to (\gamma^*/Z \to)e^+e^-$	m_Z	5	1007.0 ± 0.1	1170.0 ± 2.4
b.5	$pp \to (\gamma^*/Z \to)e^+e^-\, j$	m_Z	5	156.11 ± 0.03	203.0 ± 0.2
b.6	$pp \to (\gamma^*/Z \to)e^+e^-\, jj$	m_Z	5	54.24 ± 0.02	56.69 ± 0.07
c.1	$pp \to (W^+ \to)e^+\nu_e b\bar{b}$	$m_W + 2m_b$	4	11.557 ± 0.005	22.95 ± 0.07
c.2	$pp \to (W^+ \to)e^+\nu_e t\bar{t}$	$m_W + 2m_{top}$	5	0.009415 ± 0.000003	0.01159 ± 0.00001
c.3	$pp \to (\gamma^*/Z \to)e^+e^- b\bar{b}$	$m_Z + 2m_b$	4	9.459 ± 0.004	15.31 ± 0.03
c.4	$pp \to (\gamma^*/Z \to)e^+e^- t\bar{t}$	$m_Z + 2m_{top}$	5	0.0035131 ± 0.0000004	0.004876 ± 0.000002
c.5	$pp \to \gamma t\bar{t}$	$2m_{top}$	5	0.2906 ± 0.0001	0.4169 ± 0.0003
d.1	$pp \to W^+W^-$	$2m_W$	4	29.976 ± 0.004	43.92 ± 0.03
d.2	$pp \to W^+W^-\, j$	$2m_W$	4	11.613 ± 0.002	15.174 ± 0.008
d.3	$pp \to W^+W^+\, jj$	$2m_W$	4	0.07048 ± 0.00004	0.1377 ± 0.0005
e.1	$pp \to HW^+$	$m_W + m_H$	5	0.3428 ± 0.0003	0.4455 ± 0.0003
e.2	$pp \to HW^+\, j$	$m_W + m_H$	5	0.1223 ± 0.0001	0.1501 ± 0.0002
e.3	$pp \to HZ$	$m_Z + m_H$	5	0.2781 ± 0.0001	0.3659 ± 0.0002
e.4	$pp \to HZ\, j$	$m_Z + m_H$	5	0.0988 ± 0.0001	0.1237 ± 0.0001
e.5	$pp \to Ht\bar{t}$	$m_{top} + m_H$	5	0.08896 ± 0.00001	0.09869 ± 0.00003
e.6	$pp \to Hb\bar{b}$	$m_b + m_H$	4	0.16510 ± 0.00009	0.2099 ± 0.0006
e.7	$pp \to Hjj$	m_H	5	1.104 ± 0.002	1.036 ± 0.002

Table 2: Results for total rates, possibly within cuts, at the 7 TeV LHC, obtained with MadFKS and MadLoop. The errors are due to the statistical uncertainty of Monte Carlo integration. See the text for details.

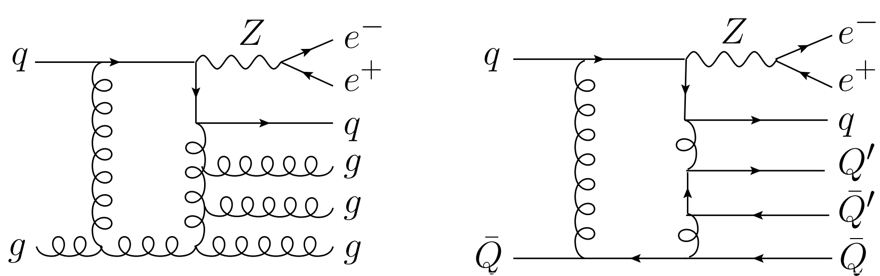
Enormous improvement in calculation of processes with many legs at NLO recently, e.g. $W^+W^- + jj$, Melia, et al.

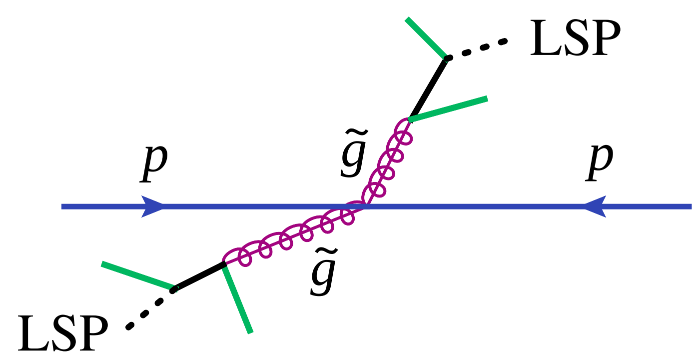




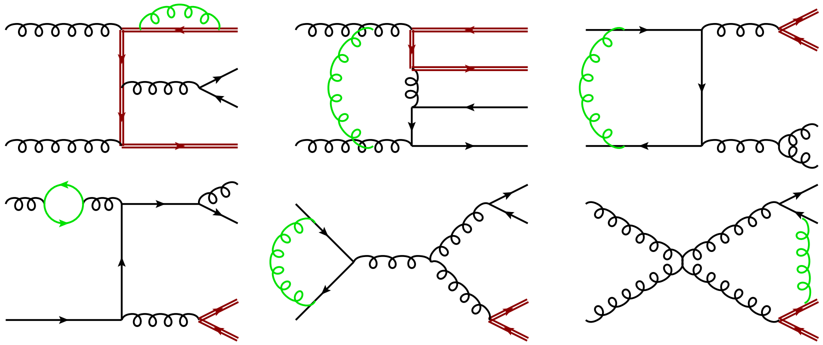
Huge improvement in scale uncertainty, which implies the same for theory uncertainty.

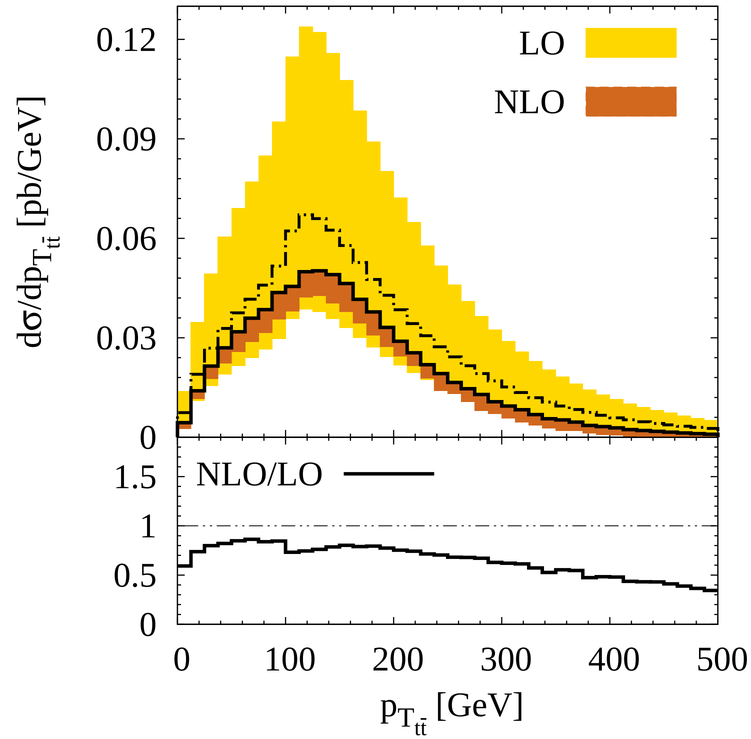
And with even more final state particles $Z + jjjj$, Ita et al, ($W = jjjj$ also known). Background to gluino pair production.





Another example, $t\bar{t} + jj$, Bevilacqua et al



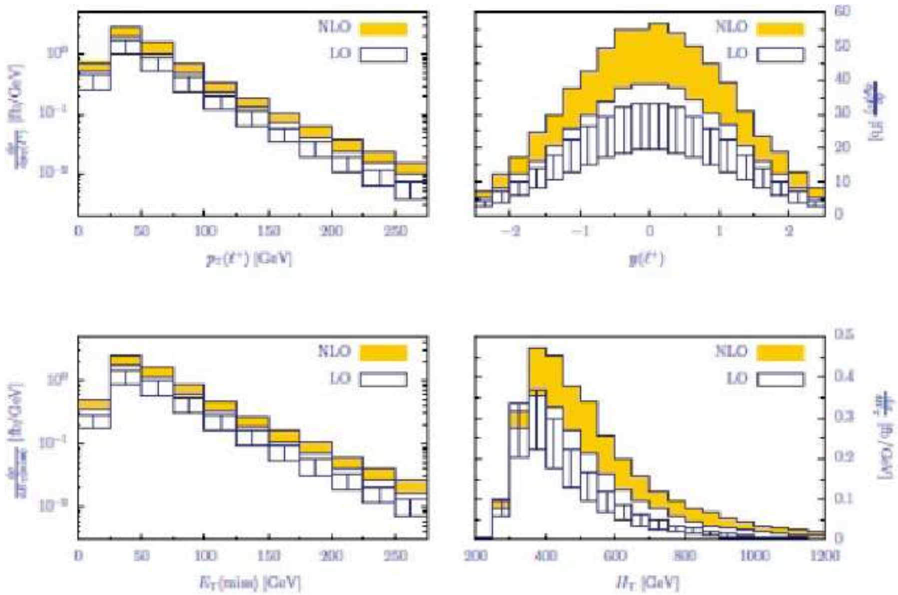


Sometimes at NLO little improvement in uncertainty, essentially because part of NLO is really LO.

For example Melnikov, Schulze and Scharf

The process $t\bar{t} + \gamma$ is an interesting SM signal

- We calculated $pp \to t\bar{t} + \gamma \to b\bar{b}\ \ell\nu\ jj + \gamma$ at NLO QCD



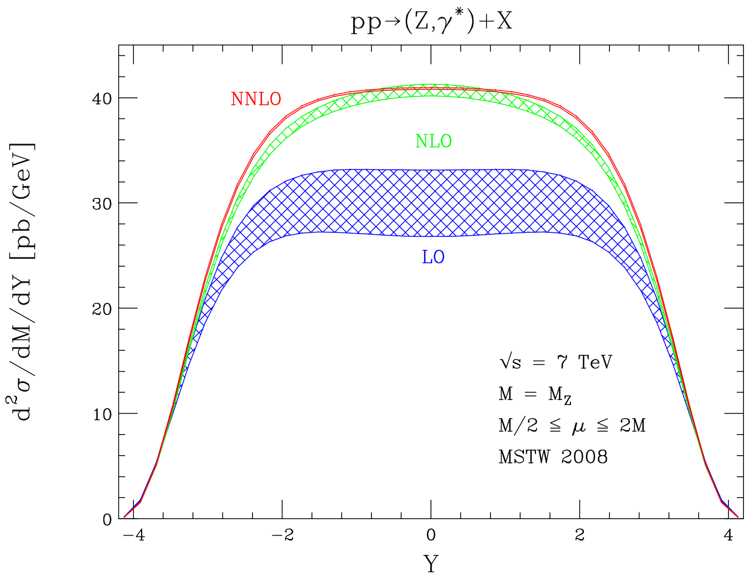
$$\sigma^{\mathrm{LO}}_{t\bar{t}\gamma} = 74.5^{+24.0}_{-16.9}\ \mathrm{fb}$$

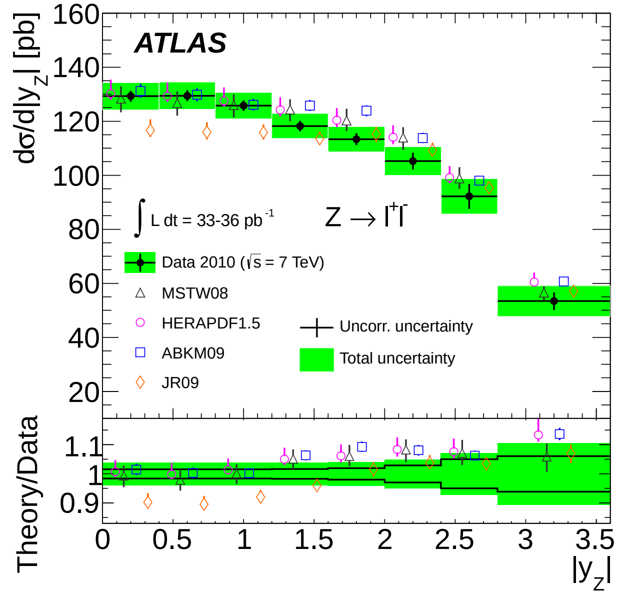
$$\sigma^{\mathrm{NLO}}_{t\bar{t}\gamma} = 138^{+30}_{-23}\ \mathrm{fb}$$

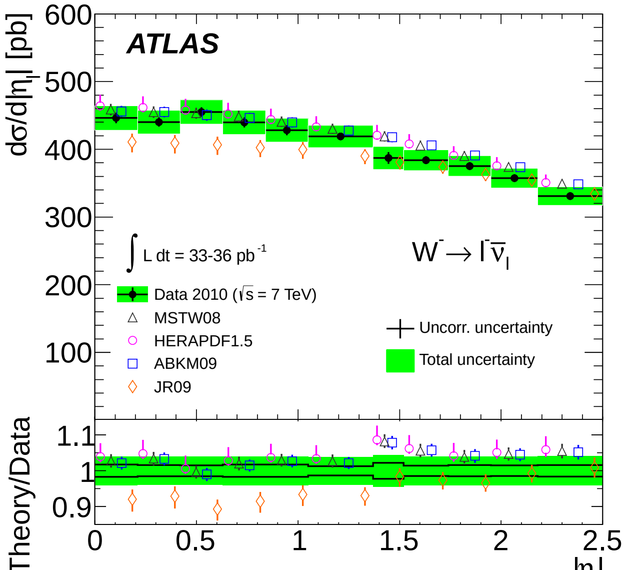
$$\sigma^{\mathrm{decay}}_{t\bar{t}\gamma} = 56\%\ \sigma^{\mathrm{tot}}_{t\bar{t}\gamma}$$

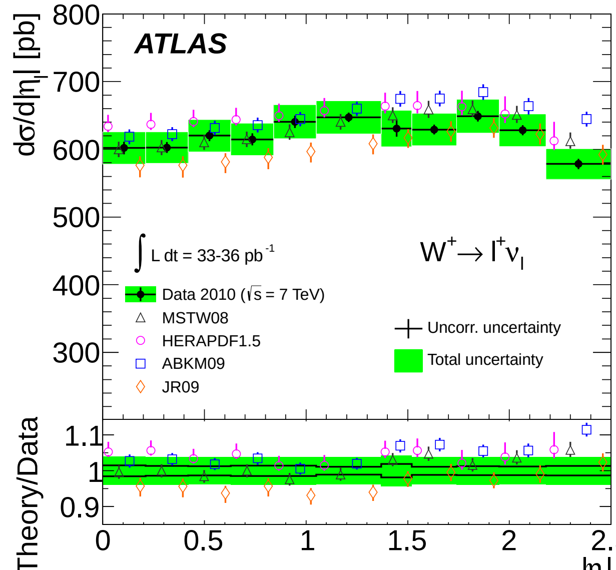
- large K-factor $\Rightarrow$ extra phase space for additional jet
- no reduction of scale dependence $\Rightarrow$ opening up of q-g channel at NLO

Progress at NNLO. Some final states known for LHC – W, Z, Higgs, ..









NNLO calculations in good agreement with LHC data. Theory (Anastasiou *et al*) uncertainty now tiny. Noticeable differences from PDF versions.

More complicated Final States.

$e^+e^- \to 3$ jets at NNLO

Method thoroughly tried and tested for partons only in the final state

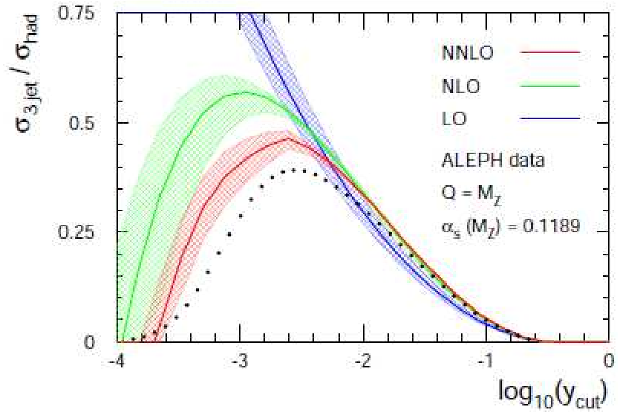
Gehrmann-De Ridder, Gehrmann, Heinrich, NG (07)

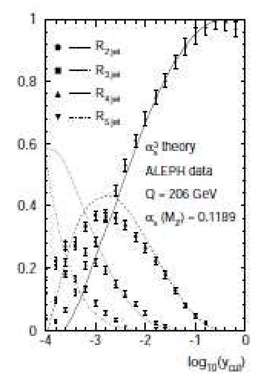
- ✓ NNLO corrections to jet rate small
  - ✓ stable perturbative prediction
  - ✓ resummation not needed
  - ✓ theory error below 2%
  - ✓ small hadronisation corrections
- ✓ α_s extraction from jet rates

Dissertori, Gehrmann-De Ridder, Gehrmann, Heinrich, Stenzel, NG (09)

- ✓ fit at $y_{cut} = 0.02$
- ✓ consistent results at other y_{cut}

$\alpha_s(M_Z) = 0.1175 \pm 0.0020(exp) \pm 0.0015(th)$





Glover St Andrews 2011.

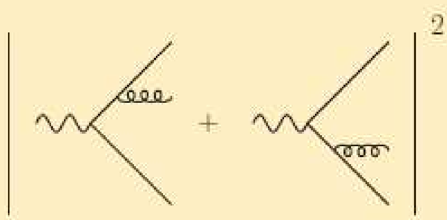
More Inclusive – Monte Carlos

Enormous recent progress in merging fixed order calculations with Monte Carlo generators.

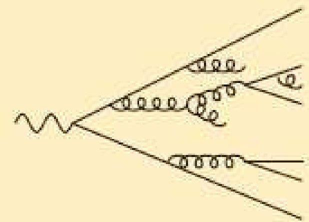
(NLO)ME vs. PS

Approaches to real emission corrections

(NLO) Matrix Element



Parton Shower



(NLO) Matrix Element:

\+ **Exact** to fixed order
– Perturbative series breaks down due to **large logarithms**

Parton Shower:

\+ Resums logarithms to **all orders**
– Only **approximation** to real emission ME

Combine Advantages ⇒ ME⊗PS, NLO⊗PS, MENLOPS

- avoid double-counting by dividing phase space ⇒ Q_{cut}
- **ME** to describe **hard radiation**, **PS** for **intrajet evolution**

Schönherr St Andrews 2011.

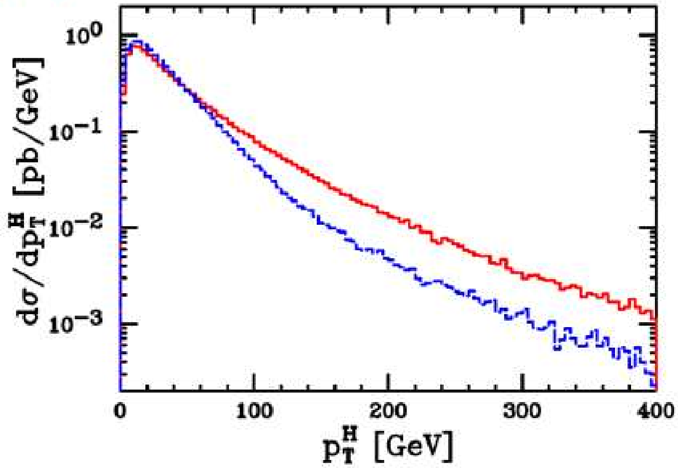
Different Approaches

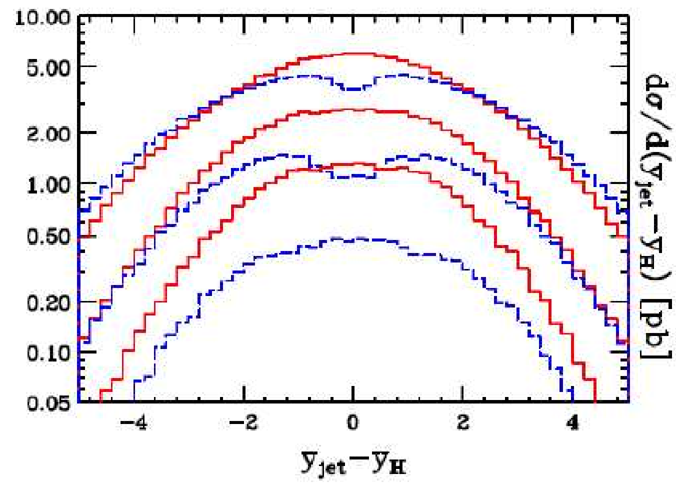
- The two approaches are the same to NLO.
- Differ in the subleading terms.
- In particular at large p_T

$$d\sigma \approx R(v,r)\, d\Phi_v\, d\Phi_r \qquad \text{MC@NLO}$$

$$d\sigma \approx \frac{\bar{B}(v)}{B(v)} R(v,r)\, d\Phi_v\, d\Phi_r$$

POWHEG





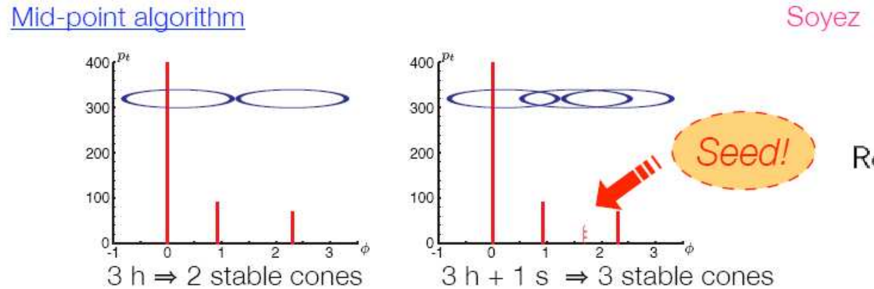
JHEP 0904:002,2009 Alioli et. al.

Forum 6th September

Richardson Cosener's House 2011

Developments in Perturbative QCD - Jets.

Long known that initial cone-based jet algorithms are generally infrared unsafe



Real life does not have infinities, but pert. infinity leaves a real-life trace

$$\alpha_s^2 + \alpha_s^3 + \alpha_s^4 \times \infty \to \alpha_s^2 + \alpha_s^3 + \alpha_s^4 \times \ln p_t/\Lambda \to \alpha_s^2 + \underbrace{\alpha_s^3 + \alpha_s^3}_{\text{BOTH WASTED}}$$

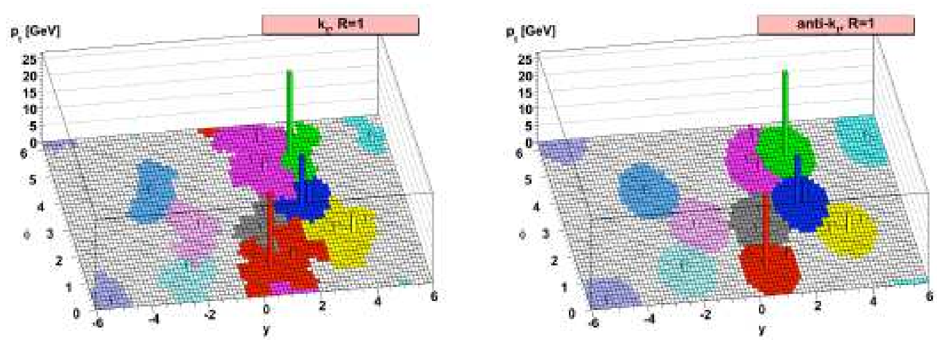
with quantitative finite consequences. "anti-k_t algorithm" combines all soft partons within "cone" with hard parton to produce cone-like jet definition.

Come back to recombination-type algorithms: Soyez

$$d_{ij} = \min(k_{t,i}^{2p}, k_{t,j}^{2p})\ (\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2)$$

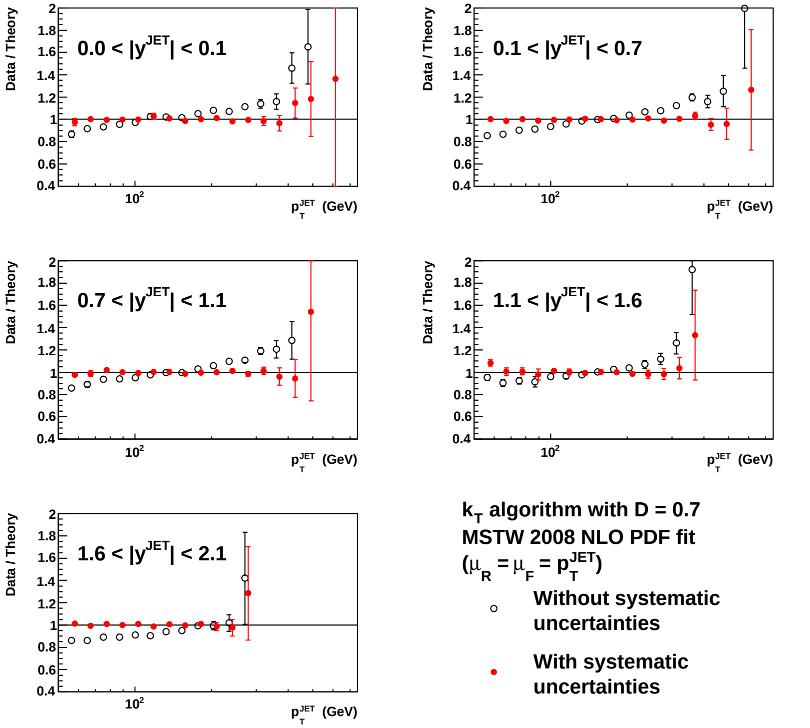
- $p = 1$: k_t algorithm
- $p = 0$: Aachen/Cambridge algorithm
- $p = -1$: anti-k_t algorithm [M.Cacciari, G.Salam, G.S.,JHEP 04 (08) 063]

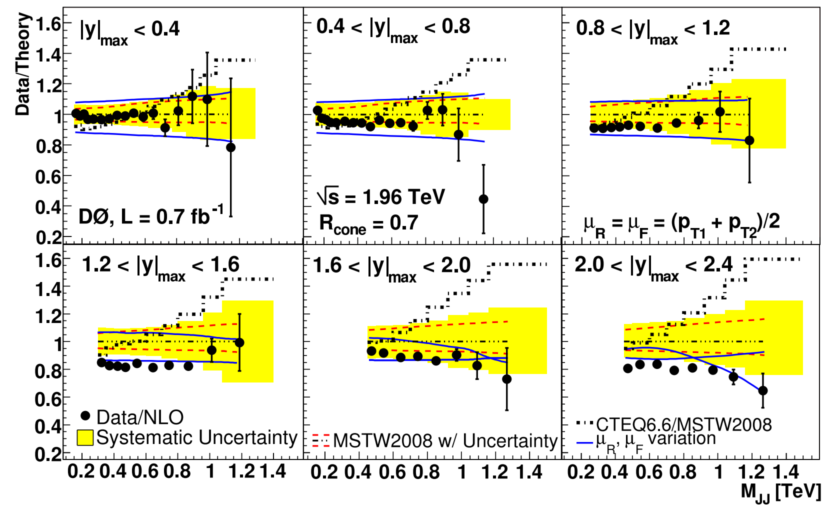
Hard event + homogeneous soft background



Jet production – Inclusive, Dijets and Three-Jets.

CDF Run II inclusive jet data, χ^2 = 56 for 76 pts.

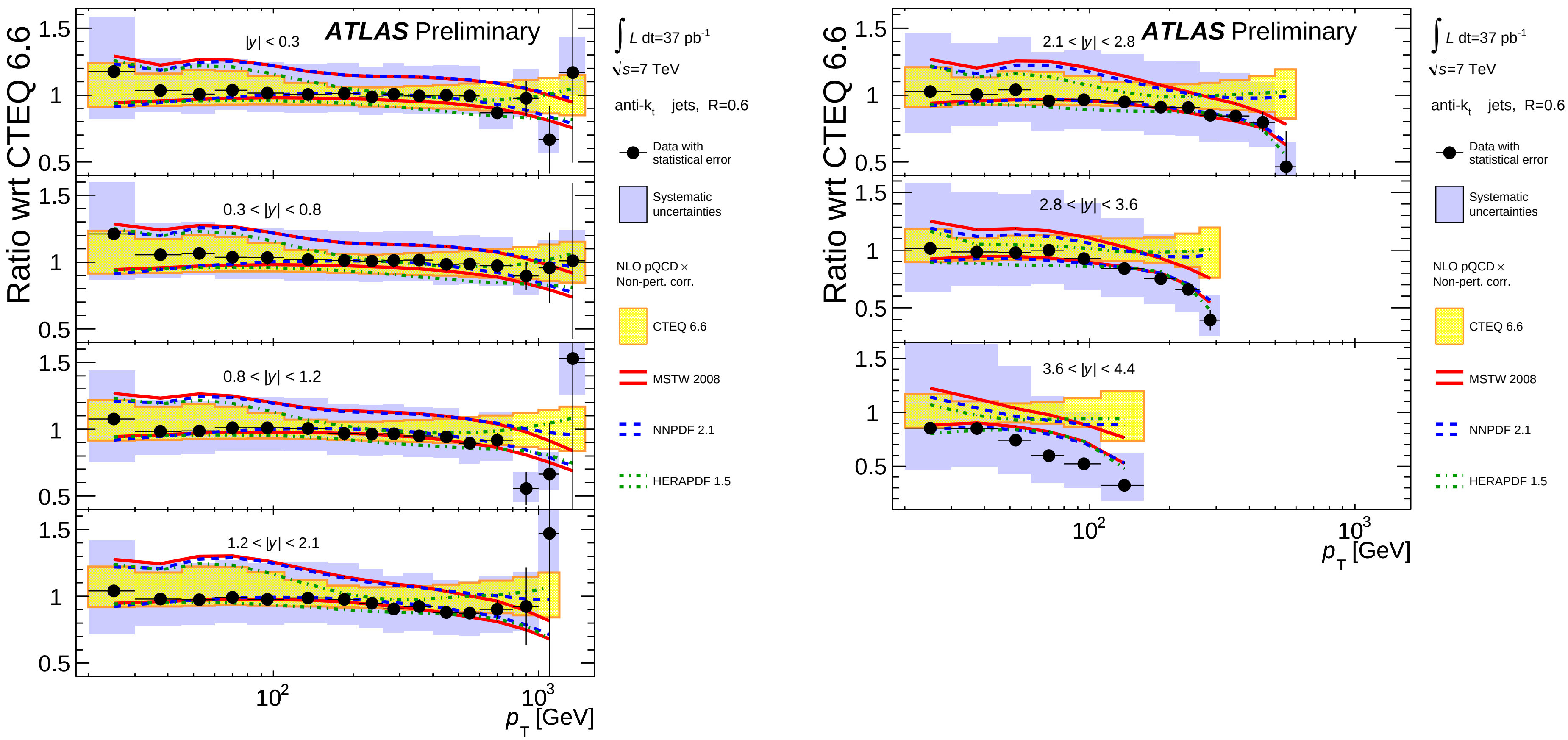




Easy to get excellent agreement with Tevatron inclusive jets.

A bit harder with dijets. Problems with theory at high M_{JJ} and y. Related to choice of scale of function of p_T?

Recent results from D0 on three jets cross sections discriminate between PDFs. See backup.

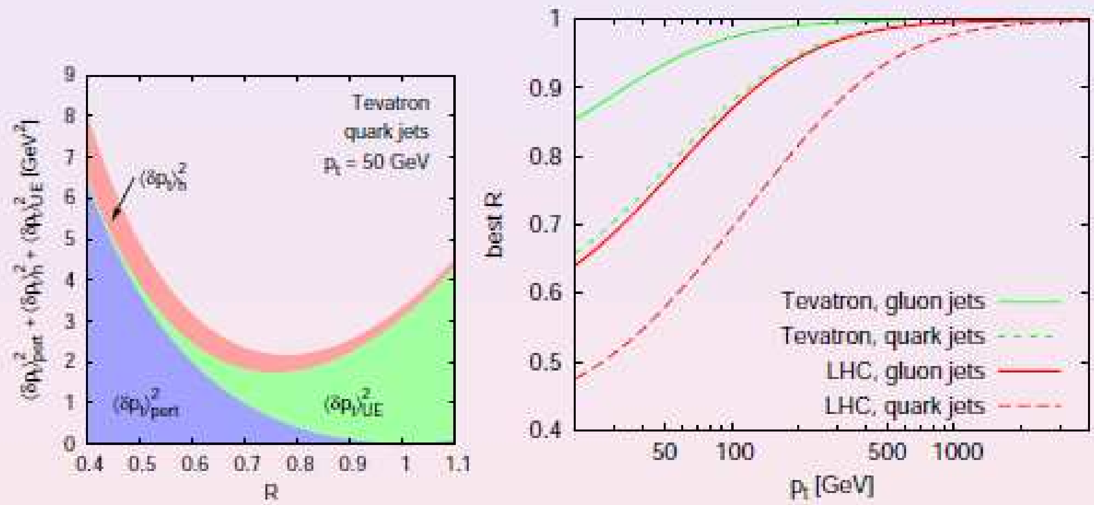


Jets at LHC Starting to discriminate between PDFs and test QCD, but size of correlated errors makes comparison to the PDFs by eye very difficult.

Possible problems with NLO calculations at high p_T and y even for inclusive jets. Full NNLO desirable.

Knowing R dependence gives rise to concept of optimal R values. Based on minimising

$$\langle \delta p_t^2 \rangle = \langle \delta p_t \rangle_{\mathrm{h}}^2 + \langle \delta p_t \rangle_{\mathrm{UE}}^2 + \langle \delta p_t \rangle_{\mathrm{PT}}^2$$

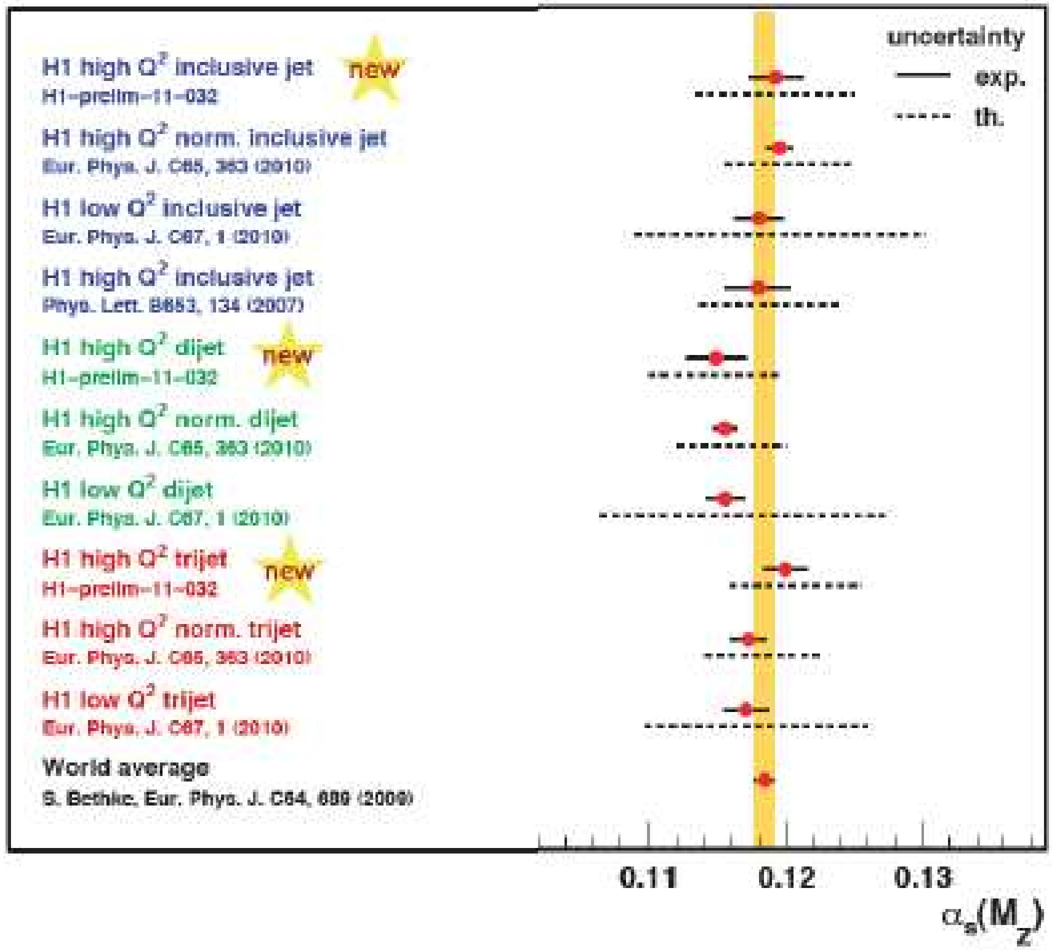


At high p_t one should use a larger R -minimises perturbative effect. Likewise for gluon jets a larger R is suggested. For LHC smaller R values than Tevatron.

Dasgupta

Different considerations require different values of R for jets. However, currently ATLAS and CMS use $R = 0.4, 0.6$ and $R = 0.5, 0.7$ respectively. A common value would be nice.

HERA Jets



Measurement of jets at HERA leads to many measurements of α_S. All in agreement with world average. Limited by theory uncertainty due to NLO calculation.

Values of $\alpha_S(M_Z^2)$ from PDF fits.

Converging on general agreement that the NNLO values of α_S are $0.0002 - 0.0003$ smaller than the NLO values of α_S?

MSTW08 – $\alpha_S(M_Z^2) = 0.1202 \to 0.1171$.

ABKM09 – $\alpha_S(M_Z^2) = 0.1179 \to 0.1135$.

GJR/JR – $\alpha_S(M_Z^2) = 0.1145 \to 0.1124$.

NNPDF2.1 – $\alpha_S(M_Z^2) = 0.1191 \to 0.1174$.

CT10.1 – $\alpha_S(M_Z^2) = 0.1196 \to 0.1180$(both prelim – PDF4LHC, DESY July).

HERAPDF1.6 – $\alpha_S(M_Z^2) = 0.1202$ at NLO and general preference for ~ 0.1176 at NNLO.

Central values differ far more than NLO $\to$ NNLO trend.

Potential Improvements Using LHeC

case	cut [Q^2 in GeV^2]	α_S	$\pm$uncertainty	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	0.11529	0.002238	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.12203	0.000995	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.11680	0.000180	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.11796	0.000199	0.17
LHeC only (14p)	$Q^2 > 20.$	0.11602	0.000292	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11769	0.000132	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.11831	0.000238	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.11839	0.000304	0.26

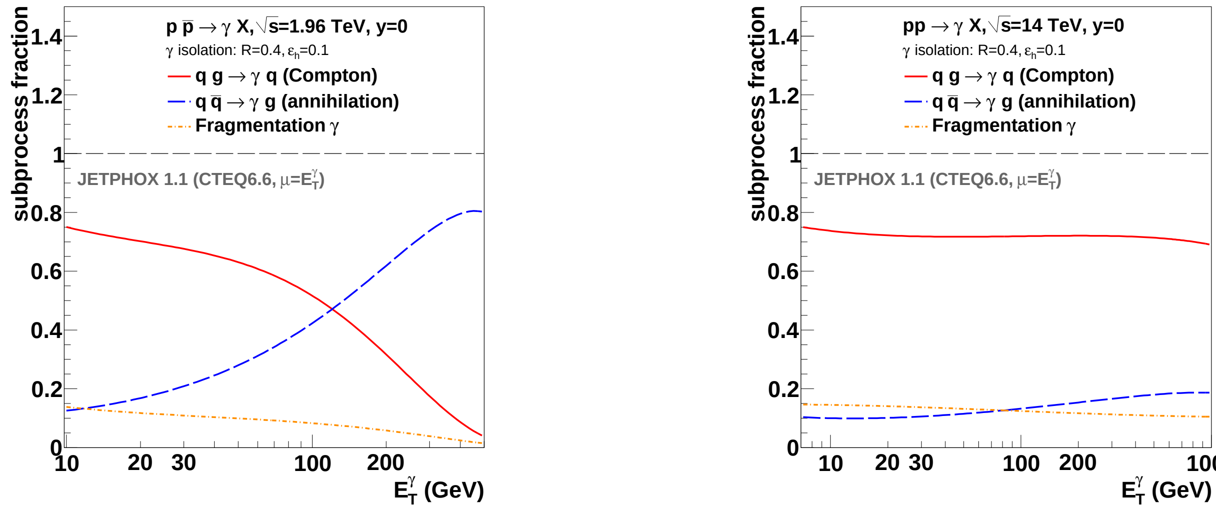
Table 4.4: Results of NLO QCD fits to HERA data (top, without and with jets) to the simulated LHeC data alone and to their combination. Here 10p or 14p denotes two different sets of parametrisations, one, with 10 parameters, the mimimum parameter set used in [37] and the other one with four extra parameters

Klein/Radescu

Can get enormous improvement in experimental error on $\alpha_S(M_Z^2)$ from evolution of structure functions and other processes, including jets.

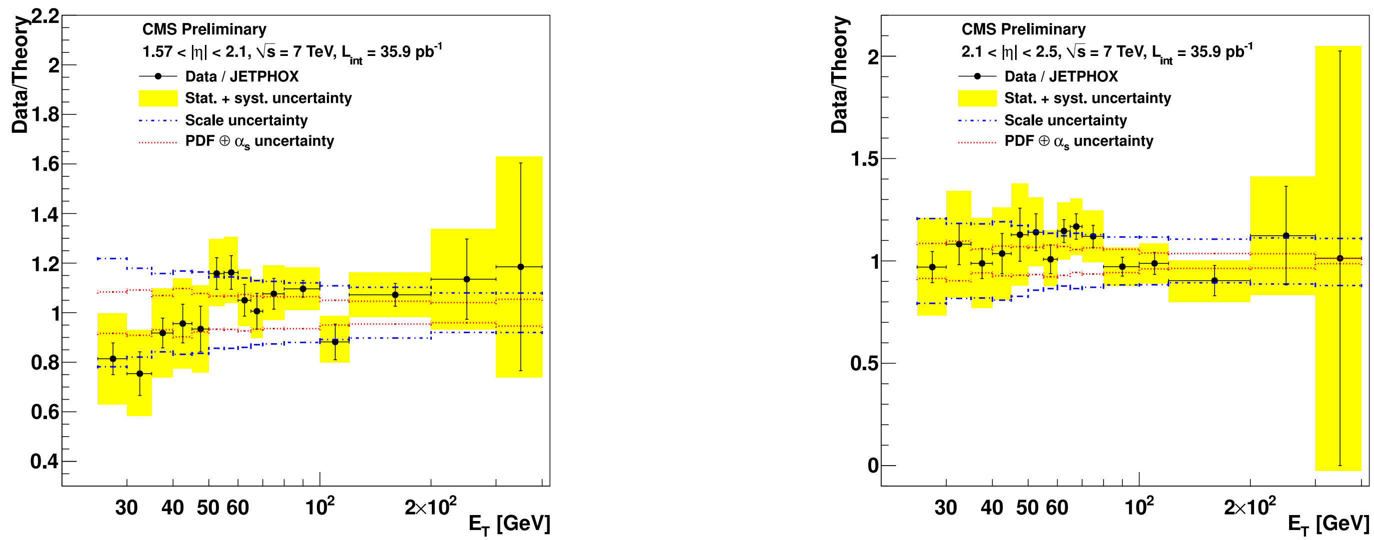
However, must remember that there is always a theory uncertainty, and it will be a great challenge to QCD theory to make the most of such results. Some current limitations, e.g. charm mass uncertainty, would be automatically improved by LHeC itself.

Prompt Photons



Ichou, d'Enterria

Much better sensitivity to gluons at the LHC than Tevatron from prompt photon production, and much safer than fixed target experiments where nonperturbative corrections very large. Important discriminator in principle. Photon isolation necessary.



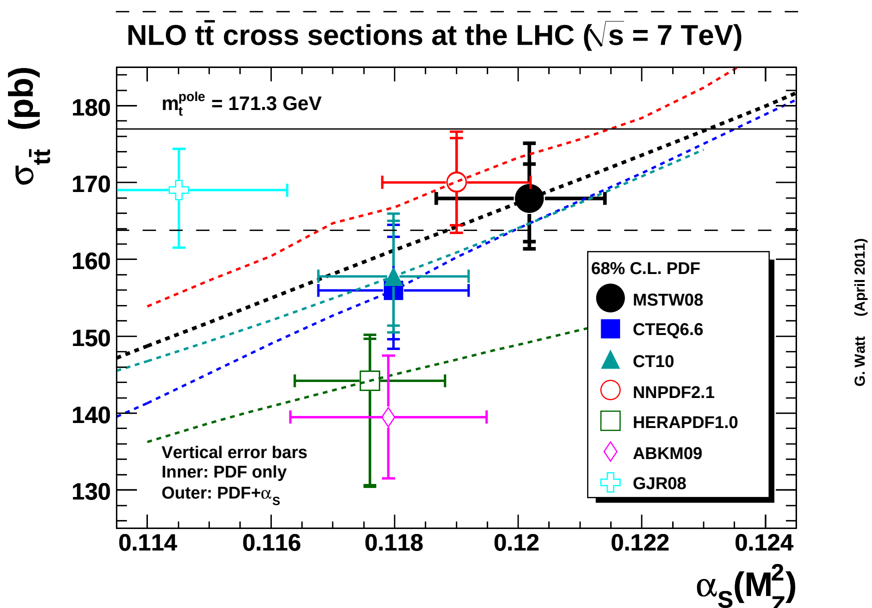
Top-antitop Cross-section Inclusive cross-section known approximately to NNLO

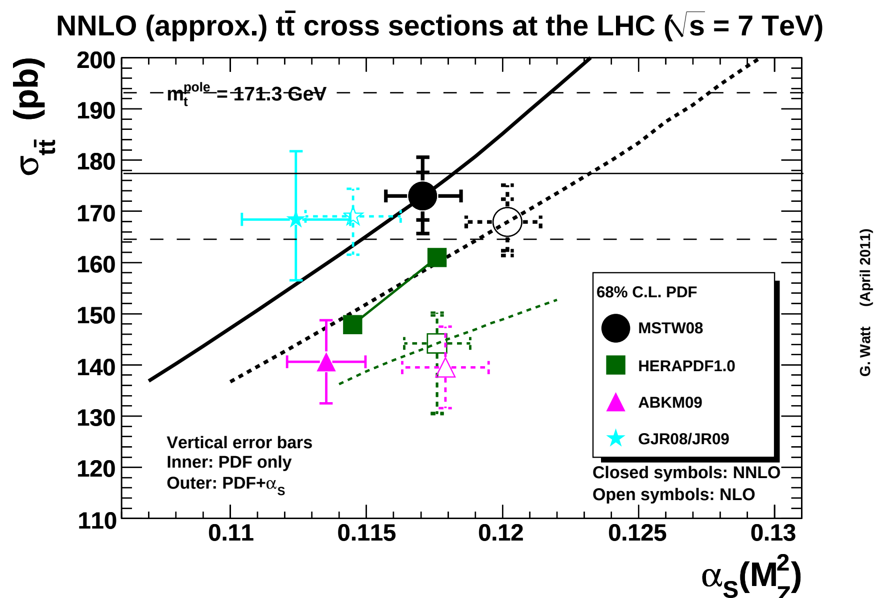
Intrinsic theory uncertainty not very large – for example, recent NNLL calculation by Beneke et al.

Data getting precise. Main uncertainty in choice of PDFs, not in individual uncertainty but choice of set. Correlated to Higgs predictions.

		Tevatron	LHC ($\sqrt{s} = 7\,\text{TeV}$)	LHC ($\sqrt{s} = 14\,\text{TeV}$)
$\text{NNLO}^{\text{1PI}}_{\text{app}}$	(Ref. [41])	$7.08^{+0.20}_{-0.24}$	163^{+7}_{-5}	920^{+60}_{-39}
$\text{NNLO}^{\text{1PI}_{\text{SCET}}}_{\text{app}}$	(Ref. [42])	$6.63^{+0.00}_{-0.27}$	155^{+3}_{-2}	851^{+25}_{-5}
$\text{NNLO}^{\text{PIM}_{\text{SCET}}}_{\text{app}}$	(Ref. [38])	$6.62^{+0.05}_{-0.40}$	155^{+8}_{-8}	860^{+46}_{-43}
$\text{NNLL}^{\text{1PI}_{\text{SCET}}}$	(Ref. [42])	$6.55^{+0.16}_{-0.14}$	150^{+7}_{-7}	824^{+41}_{-44}
$\text{NNLL}^{\text{PIM}_{\text{SCET}}}$	(Ref. [38])	$6.46^{+0.18}_{-0.19}$	147^{+7}_{-6}	811^{+45}_{-42}
NNLL_2	this work	$7.22^{+0.31}_{-0.47}$	163^{+7}_{-8}	896^{+40}_{-37}

Plots by G. Watt – modified by RST ATLAS preliminary combined $\sigma_{t\bar{t}} = 176^{+16}_{-13}\text{pb}$.





Differences between groups significant at NLO, and at NNLO.

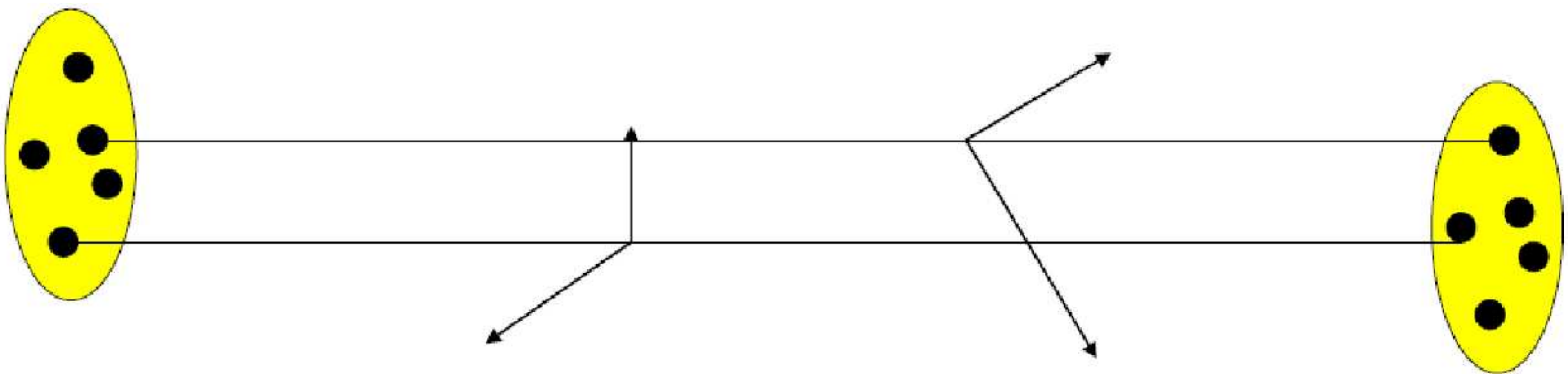
Multiparton Interactions

If the interactions occur independently they should follow Poissonian statistics.

$$P_n = \frac{\langle n \rangle^n}{n} \exp - \langle n \rangle$$

But we must also consider energy-momentum conservation, which suppresses large numbers of scatterings.

Also need to model the spatial distribution on partons.



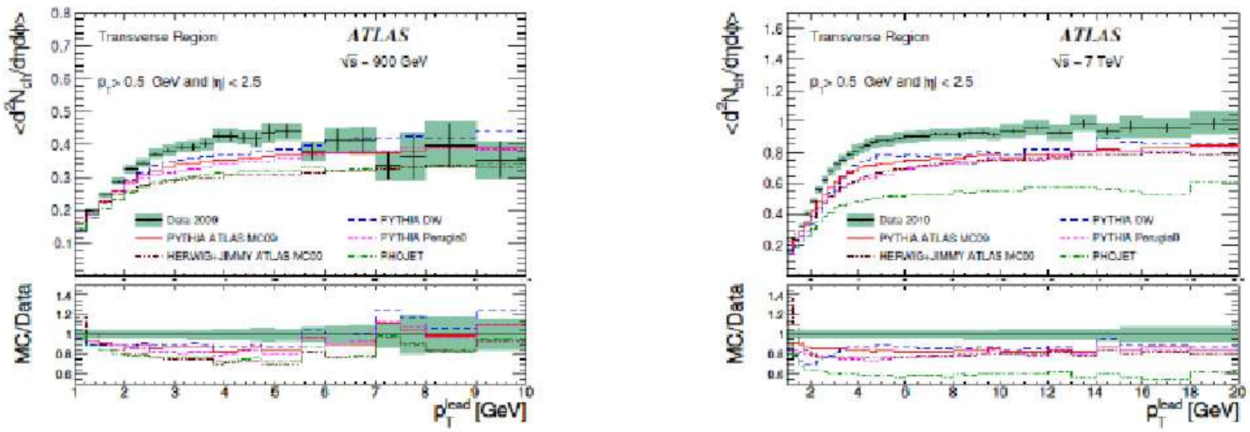
The cross-section can then be regulated either by a cut-off $p_{T,\min}$ or smoothing parameter p_{T0}, e.g. $\frac{d\sigma}{dp_T^2} \propto \frac{\alpha_S^2(p_T^2+p_{T0}^2)}{(p_T^2+p_{T0}^2)^2}$, either usually about $2\mathrm{GeV}$ for the best tune.

Typically about 2-3 interactions per event at the Tevatron and 4-5 at the LHC.

ATLAS underlying event results

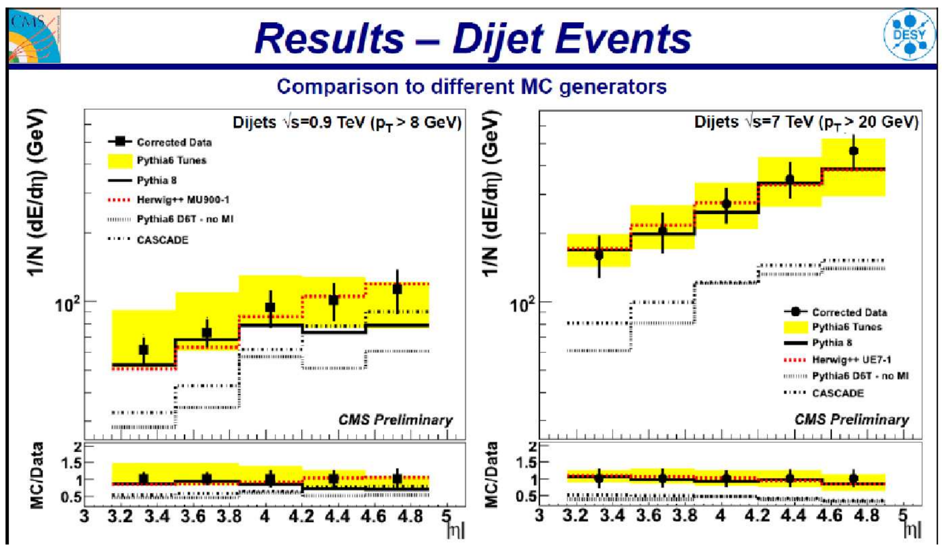
Leading charged track N_{ch} and $\sum p_T$, $p_T > 500$ MeV (arXiv:1012.0791)

900 GeV 7 TeV



Buckley SM@LHC

Comparison to CMS data after retuning

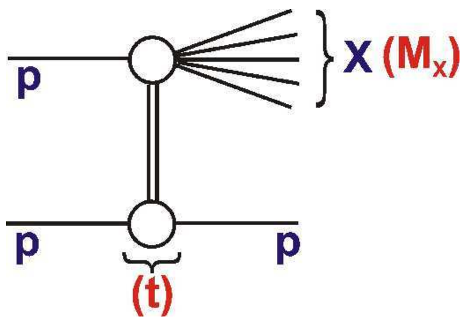


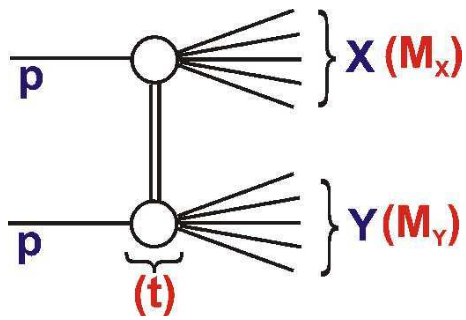
Knutson DIS2011

Large contribution from multiple interactions. Improved theory important here. There have been some recent developments

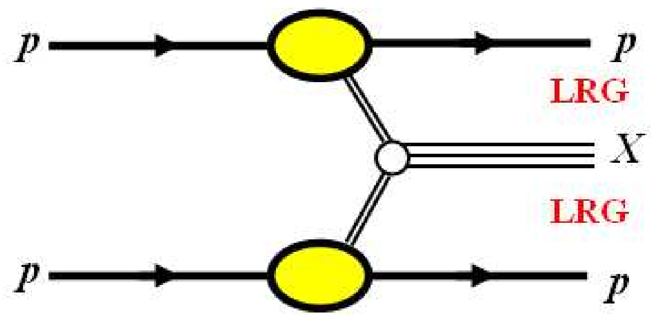
Diffraction at the LHC

Potentially either single or double diffraction can occur (and central exclusive production). Accompanied by large rapidity gaps.

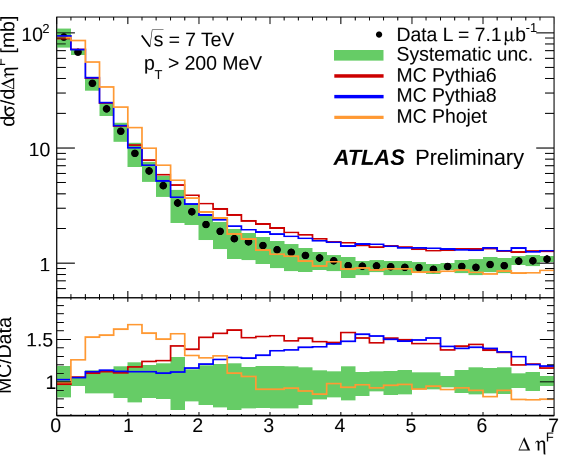


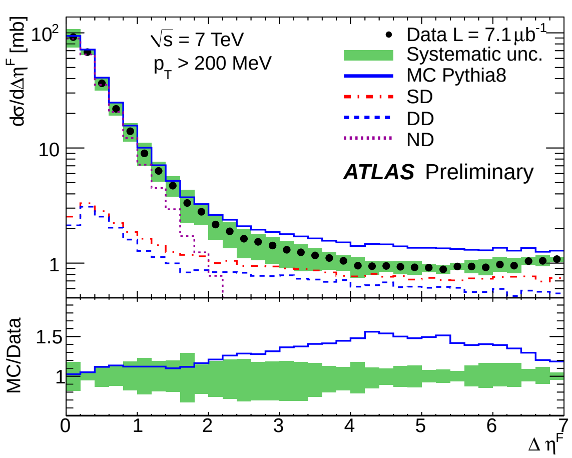


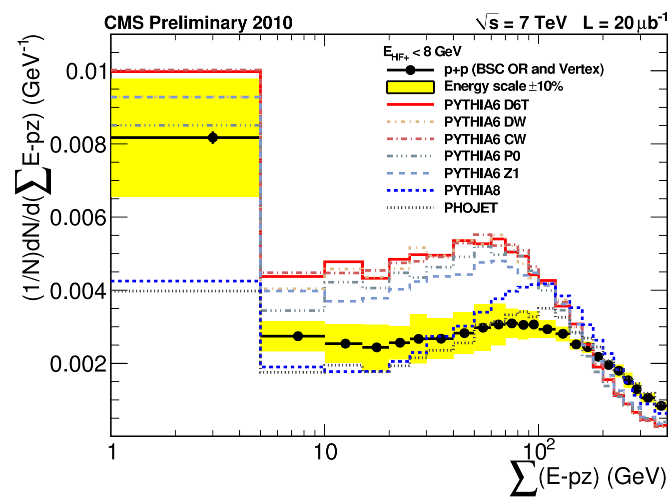
also



However, not so easy to define experimentally. ATLAS use a large forward rapidity gap definition and CMS base the definition on energy in forward detectors and/or $\Sigma E - p_z \propto$ Pomeron energy (with option of additional $\Delta\eta \sim 2$).

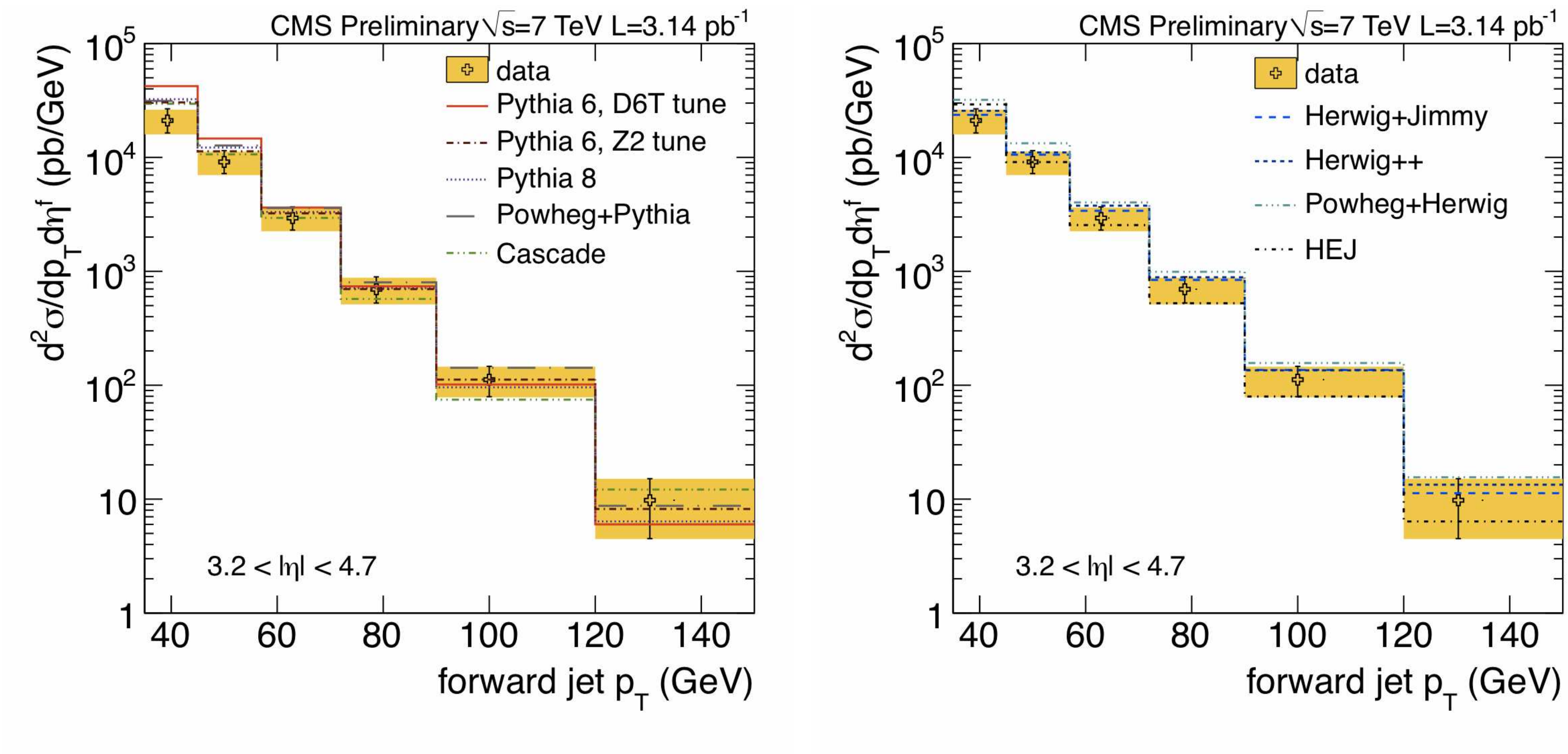






Similar (in some senses) process – production of one central jet and one forward jet.

Guaranteed imbalance of partons, one at small x.



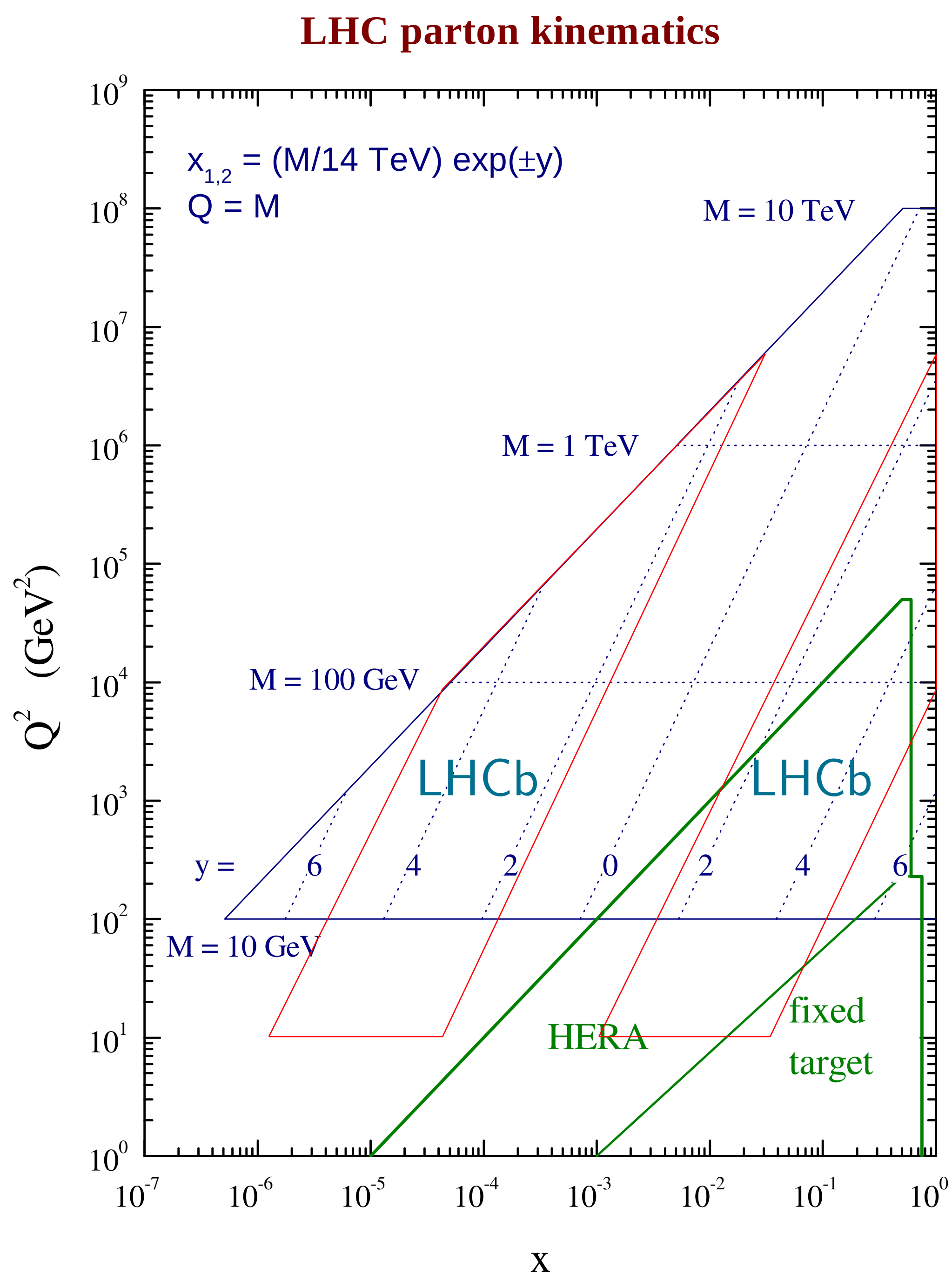
LHC and Parton x

The kinematic range for particle production at the LHC is shown.

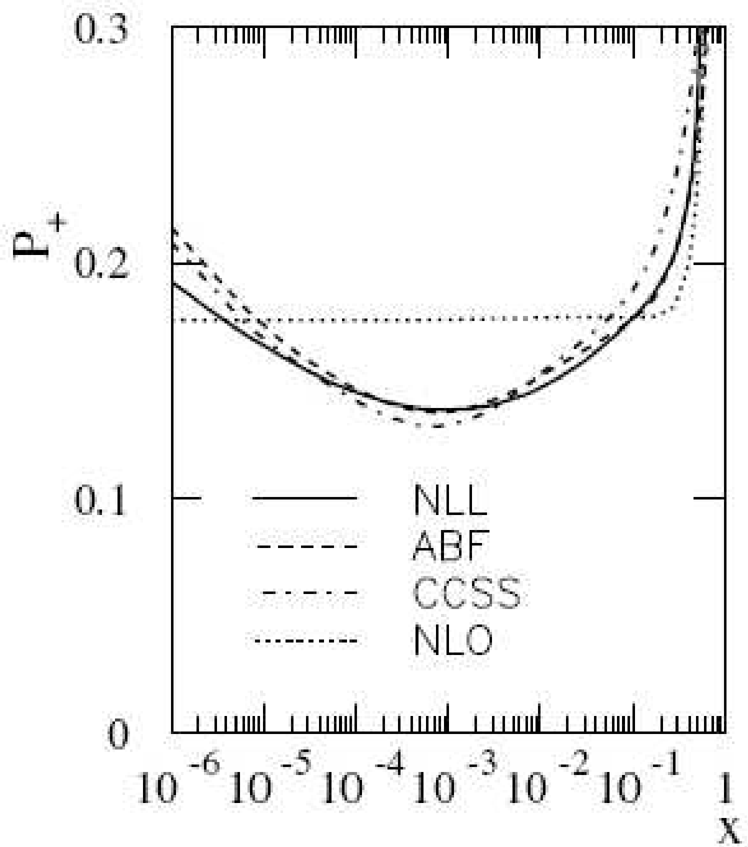
$$x_{1,2} = x_0 \exp(\pm y), \quad x_0 = \frac{M}{\sqrt{s}}.$$

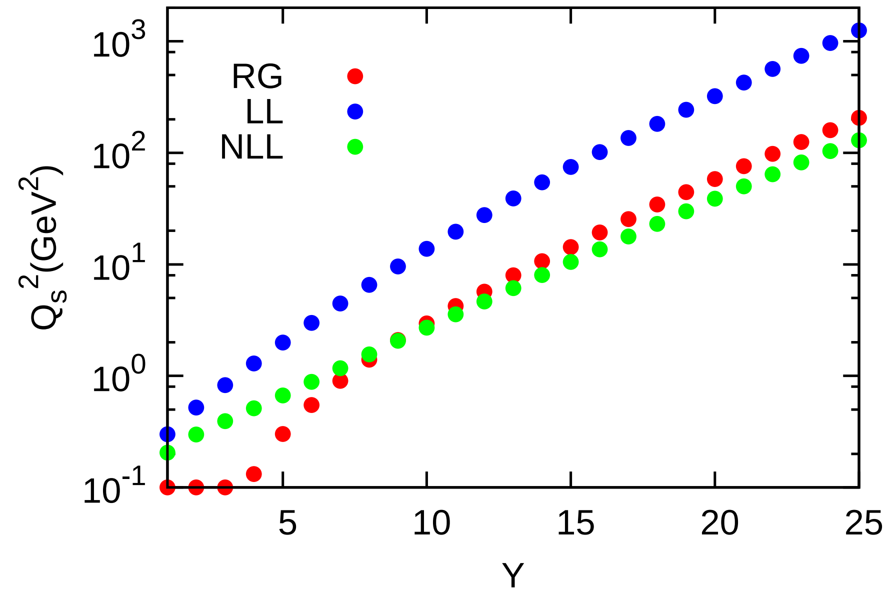
Smallish $x \sim 0.001 - 0.01$ parton distributions therefore vital for understanding the standard production processes at the LHC, and must trust QCD evolution from lower scales.

However, even smaller (and higher) x required when one moves away from zero rapidity, e.g. when calculating total cross-sections.



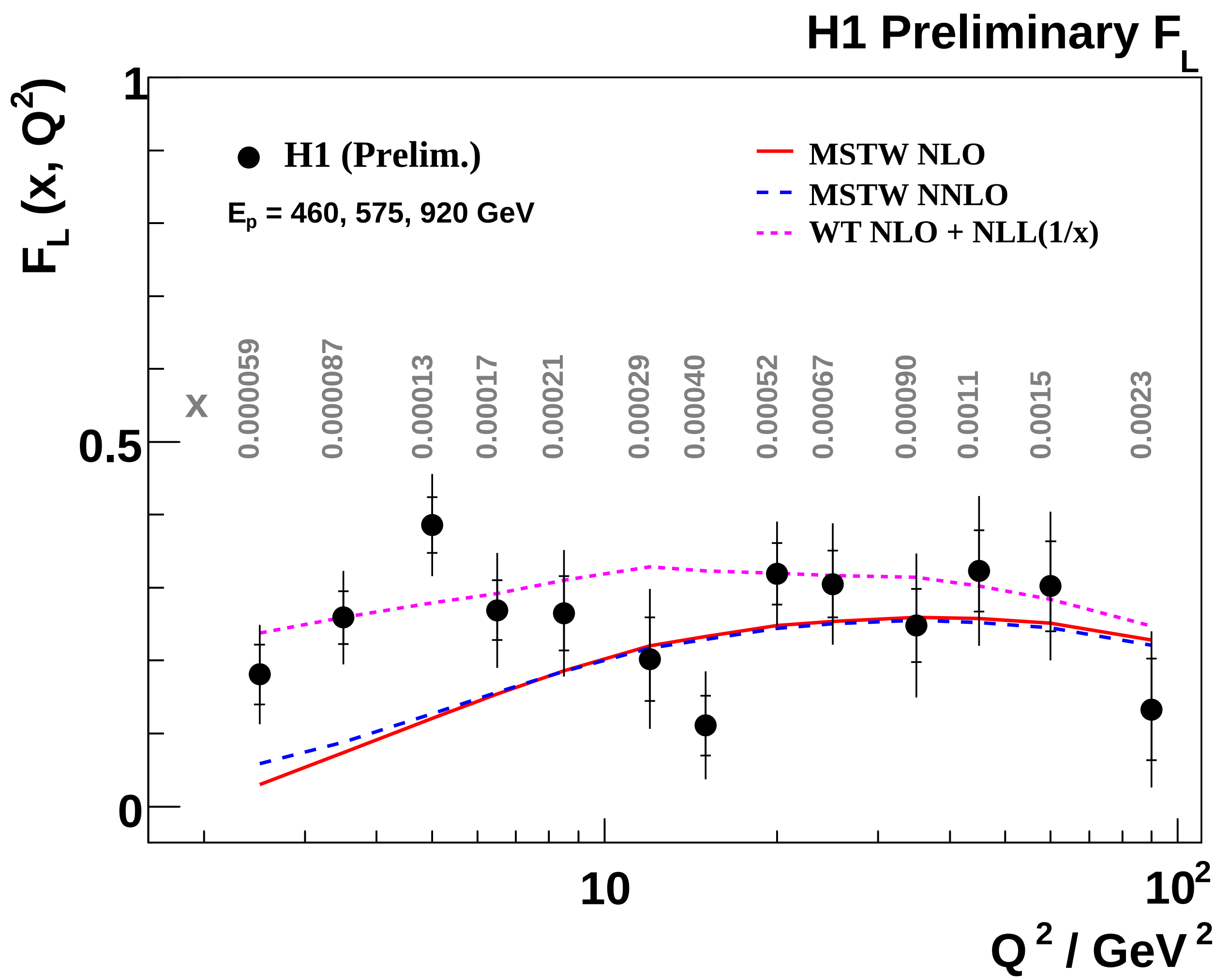
Some fits to new combined HERA structure function data using saturation inspired models. Seems fairly successful. But not necessary.





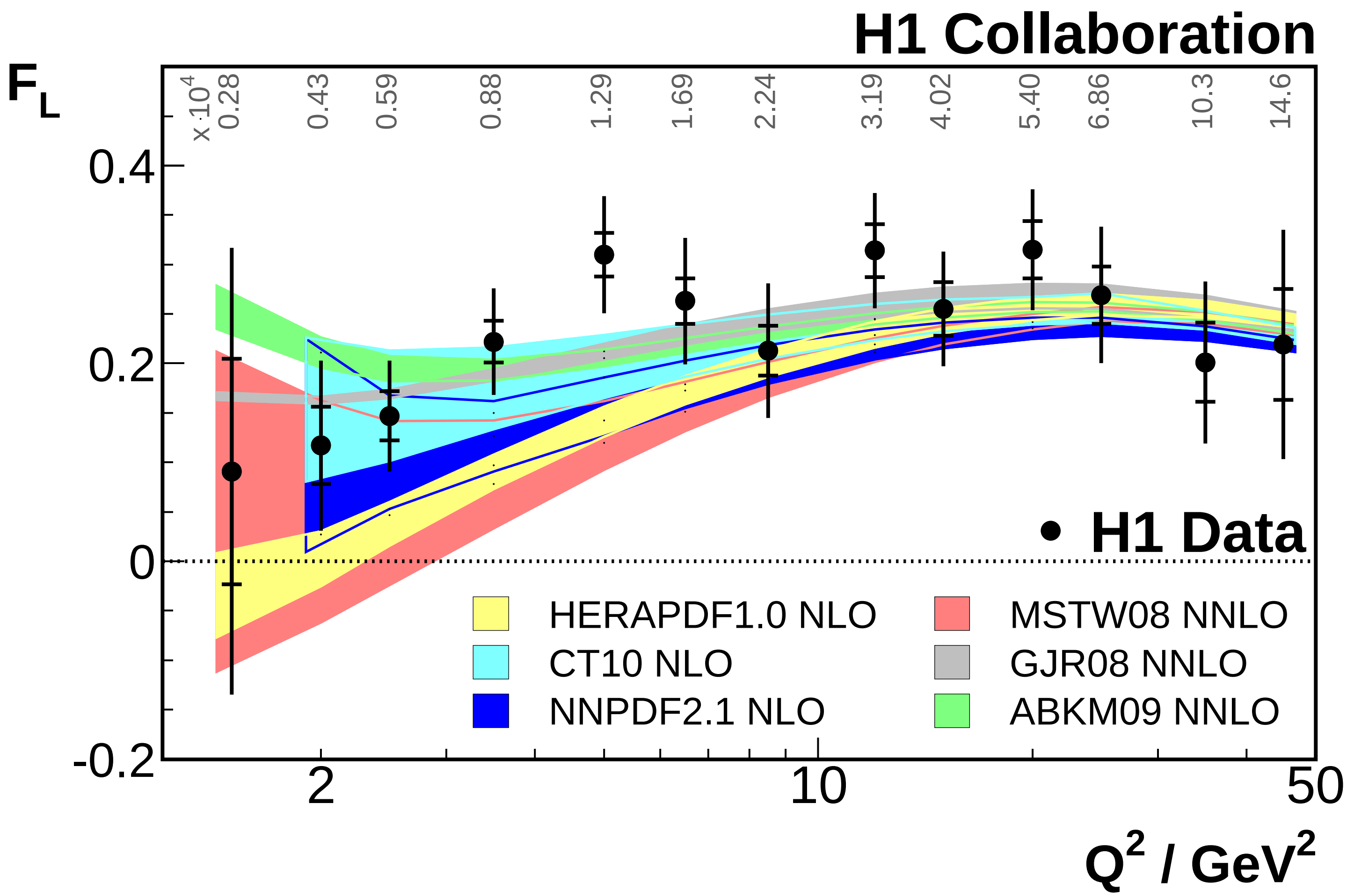
Agreed among all groups that full resummation of small-x logarithms leads to dip in splitting functions at fairly small x before rise at very small x.

Actually delays saturation compared to more naive calculations Avsar et al. Full resummation perhaps important before saturation for nucleon colliders.



Comparison to H1 prelim data on $F_L(x, Q^2)$ at low Q^2, only within White-RT approach, suggests resummations may be important.

Could possibly give a few percent effect on Higgs cross sections.

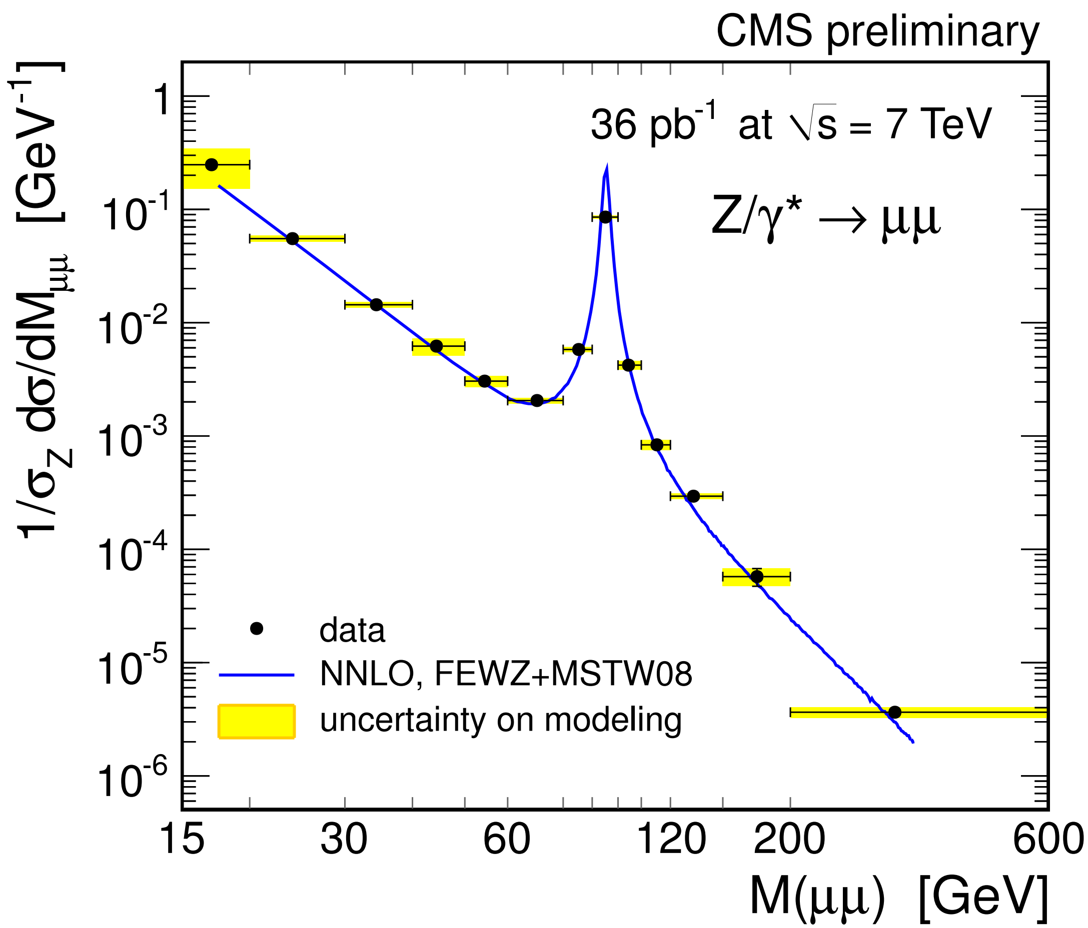


However, quite a large PDF uncertainty (in general) and even larger spread, at fixed order (though differences in definition of order).

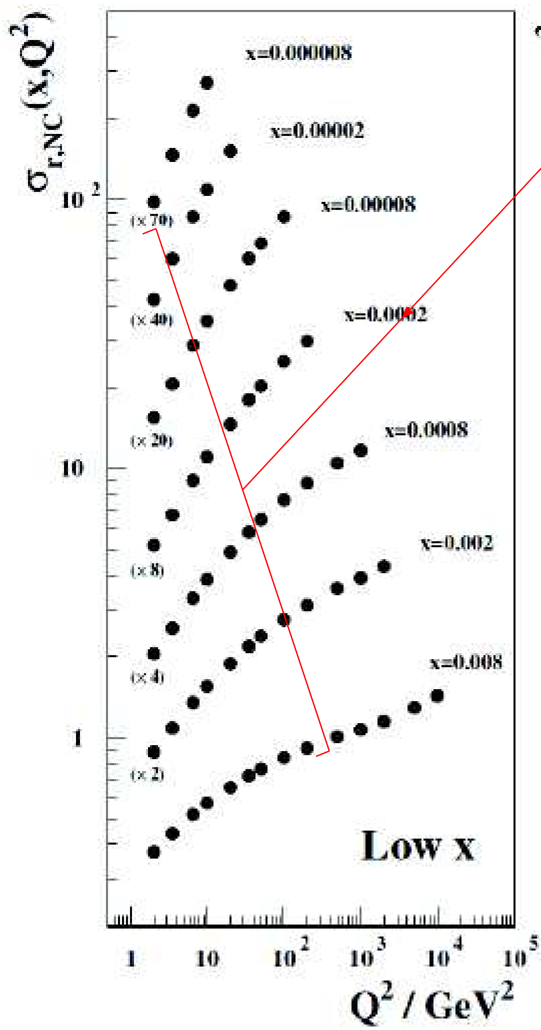
Small-x effects could be seen in low-mass Drell-Yan at LHC.

Good agreement with NNLO from CMS

Probably want lowest mass and high rapidity $\rightarrow$ LHCb. Investigate in detail here.



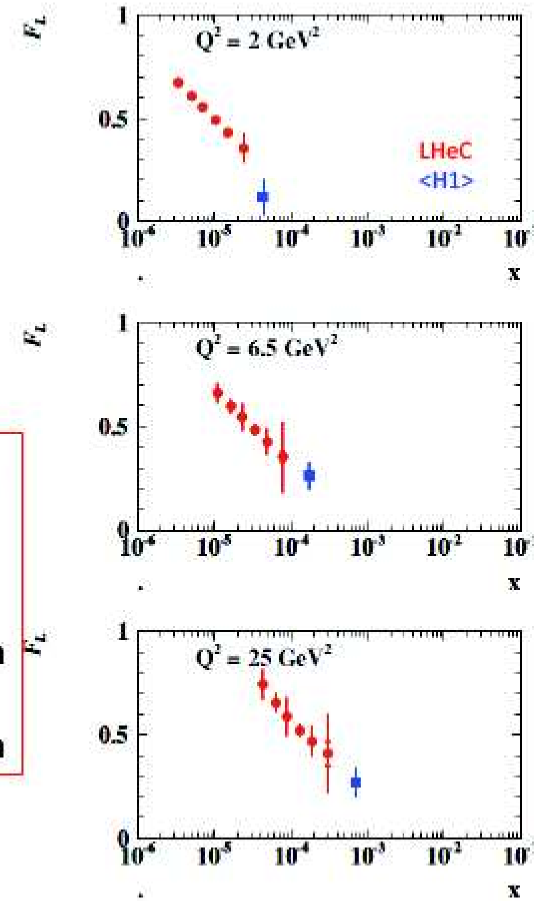
Perfect place to investigate this would be LHeC – (Klein CERN)



Gluon input

Hera limit with much larger errors

F_2 and F_L crucial to discover gluon saturation in ep in DIS region



Likely to see evidence of resummation and/or saturation (even in proton collisions). Might be difficult to disentangle the two.

Summary

Over the past couple of decades our understanding of hard scattering at particle colliders has improved enormously.

We have recently (very in one case) lost two high-energy colliders, HERA and the Tevatron, but both have provided a wealth of data making strong interaction physics a truly precision study. There are many final results to come out still, from both.

This has driven and been accompanied by a vast improvement in theory. We are obtaining a very complete set of processes calculated at NLO, and there is a move to automation. A few of the most standard processes are known at NNLO along with distributions. Threshold resummations often provide approximations to full NNLO. Full NNLO for hadronic jet rate and top cross section a priority.

Many interesting results appearing at the LHC, extending the kinematic range and starting to distinguish between PDFs, and test QCD. Generally need at least NLO. Monte Carlos interfaced to NLO or large multiplicity matrix elements much more. Differences to be understood better.

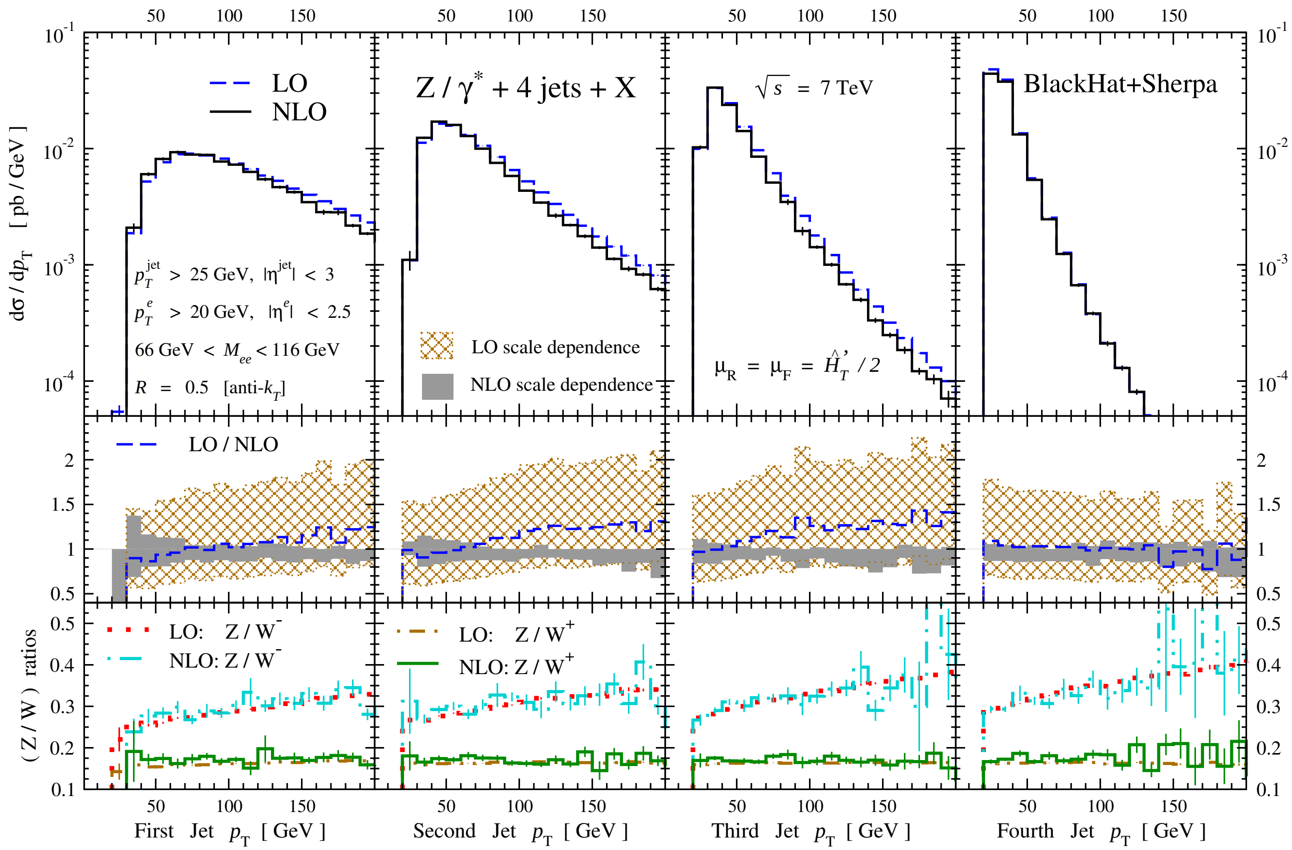
The LHC may address long-standing issues in perturbative QCD, like small-x resummation, saturation, and improve determinations of $\alpha_S(M_Z^2)$. A study which is essential for all the other physics being studied and discoveries to be made.

Backup Slides

NLO Corrections.

And with even more final state particles $Z + jjjj$, Ita et al, ($W = jjjj$ also known).

Scale uncertainty much reduced.



Progress at NNLO.

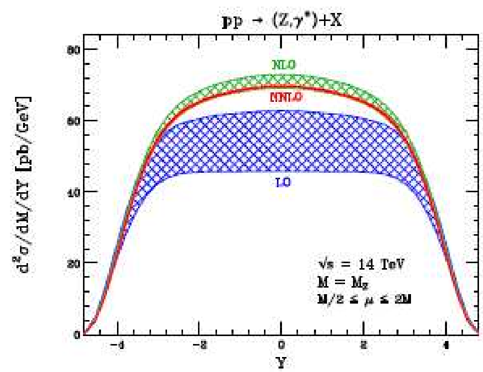
NNLO calculations for $2 \to 2$ processes

$$\mathrm{d}\sigma = \sum_{i,j} \int \frac{d\xi_1}{\xi_1}\frac{d\xi_2}{\xi_2} f_i(\xi_1,\mu_F^2) f_j(\xi_2,\mu_F^2) \mathrm{d}\hat{\sigma}_{ij}(\alpha_s(\mu_R),\mu_R,\mu_F)$$

$$\mathrm{d}\hat{\sigma}_{ij} = \mathrm{d}\hat{\sigma}_{ij}^{LO} + \left(\frac{\alpha_s(\mu_R)}{2\pi}\right)\mathrm{d}\hat{\sigma}_{ij}^{NLO} + \left(\frac{\alpha_s(\mu_R)}{2\pi}\right)^2 \mathrm{d}\hat{\sigma}_{ij}^{NNLO} + \mathcal{O}(\alpha_s^3)$$

Processes of interest

- ✓ $pp \to 2$ jets
- ✓ $pp \to \gamma$+jets
- ✓ $pp \to \gamma\gamma$
- ✓ $pp \to V$+jet
- ✓ $pp \to t\bar{t}$
- ✓ $pp \to VV$
- ✓ $pp \to H$+jet
- ✓ $\ldots$



Massively reduced theoretical error

Anastasiou, Dixon, Melnikov, Petriello (04)

Glover St Andrews 2011.

Applications to LHC processes

- ✓ All relevant matrix elements for $pp \to 2$ jet and $pp \to V+1$ jet processes available for some time
- ✓ Can expect to have parton-level NNLO predictions for $pp \to 2$ jet and $pp \to V+1$ jet in next couple of years
- ✓ Hope for significant reduction in theory (renormalisation scale/factorisation scale) dependence
- ✓ LHC already has increased dynamic range for jet studies - rapidity, transverse energy.
- ✓ Combined with excellent experimental jet energy scale uncertainty, there is the opportunity for improved measurements of
  - ✓ Parton distributions
  - ✓ Strong coupling
  - ✓ Internal structure of the jet
  - ✓ Rapidity gaps between the jets

Glover St Andrews 2011

NLO Monte Carlos

Available processes*

	POWHEG			MC@NLO	
Process	POWHEG-BOX	HERWIG++	SHERPA	MC@NLO	aMC@NLO
$e^+e^- \to jj$	✗	✓	✓	✗	✗
DIS	✗	✓	✓	✓	✗
$pp \to W/Z$	✓	✓	✓	✓	✗
$pp \to H$ (GF)	✓	✓	✓	✓	✗
$pp \to V + H$	✗	✓	✓	✓	✗
$pp \to VV$	✗	✓	✓	✓	✗
VBF	✓	✓	in prep.	✗	✗
$pp \to Q\bar{Q}$	✓	✗	✗	✓	✗
$pp \to Q\bar{Q} + j$	✓	✗	✗	✗	✗
single-top	✓	✗	✗	✓	✗
$pp \to V + j$	✓	✗	in prep.	✗	✗
$pp \to V + jj$	in prep.	✗	in prep.	✗	✗
$pp \to H + j$ (GF)	✗	✗	in prep.	✗	✗
$pp \to H + t\bar{t}$	✓	✗	✗	✗	✓
$pp \to W^+W^+jj$	✓	✗	✗	✗	✗
$pp \to V + b\bar{b}$	✓	✗	in prep.	✗	✓
diphotons	?	✓	in prep.	✗	✗
dijets	✓	✗	in prep.	✗	✗

*Table includes SM processes presented so far. Automated codes and toolkits can, in principle, be used for any process.

Schönherr St Andrews 2011.

Pros and Cons

POWHEG

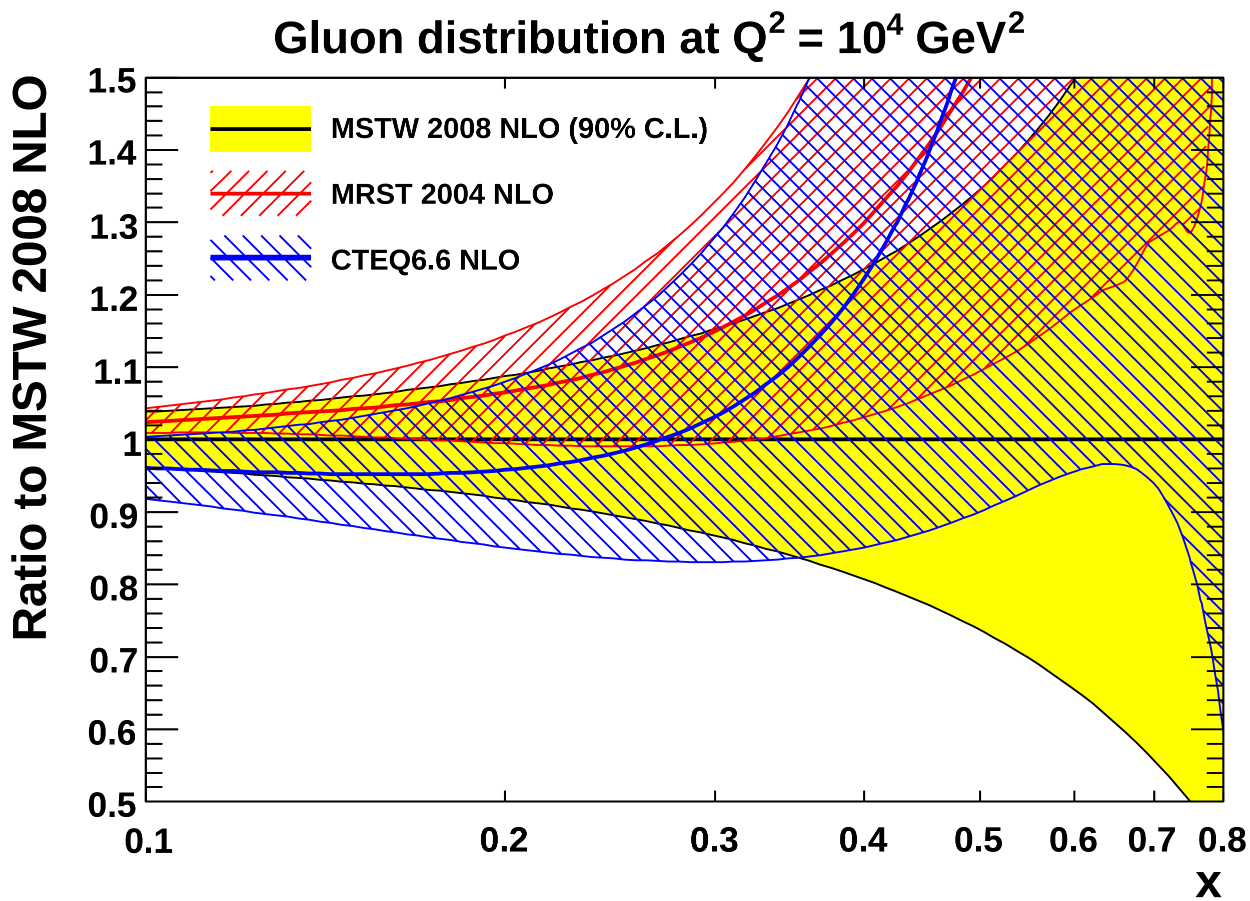
- Positive weights.
- Implementation doesn't depend on the shower algorithm.
- Needs changes to shower algorithm for non-p_T ordered showers.
- Differs from shower and NLO results, but changes can be made to give NLO result at large p_{T}.

MC@NLO

- Negative weights
- Implementation depends on the specific shower algorithm used.
- No changes to parton shower.
- Reduces to the exact shower result at low p_T and NLO result at high p_T

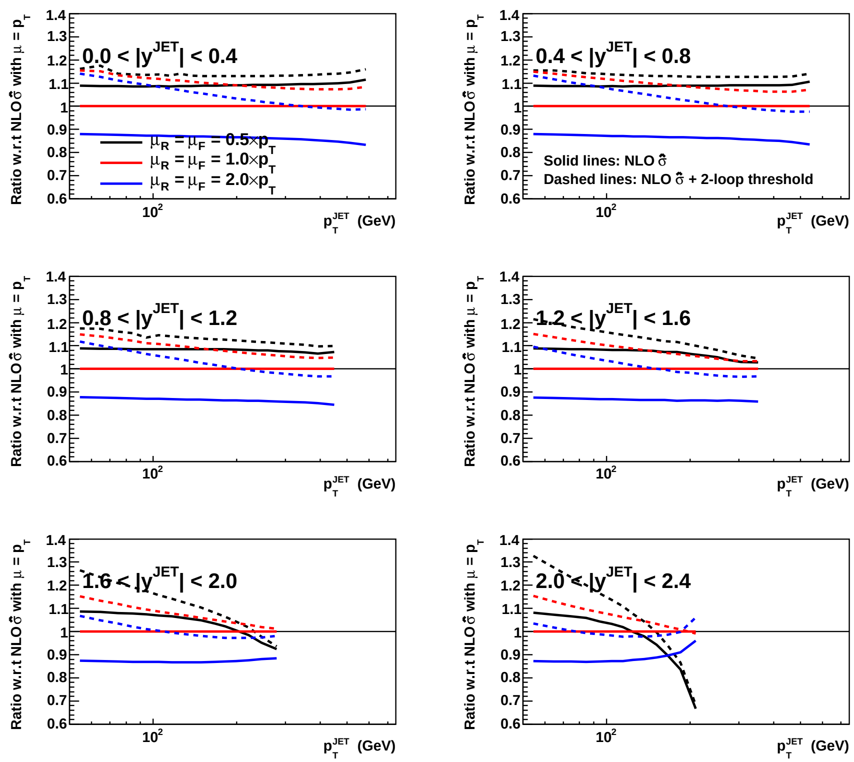
Richardson Cosener's House 2011

From personal experience, fitting to Run II Tevatron high-E_T jet data, with improved jet algorithms (k_T algorithm for CDF) results in a significant change in the gluon.

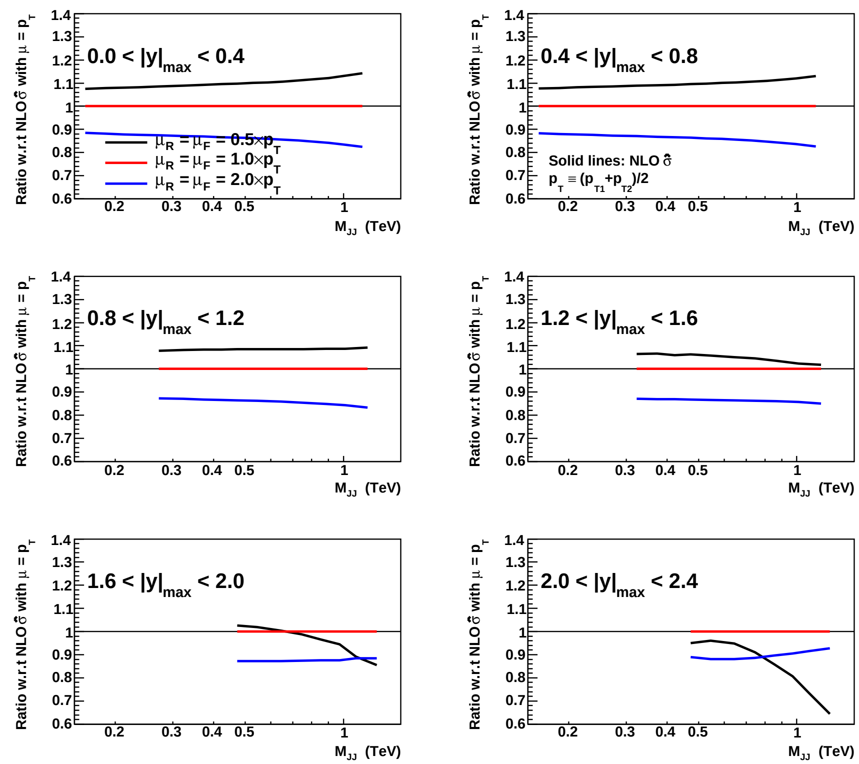


Due to improvements in algorithms?

DØ Run II inclusive jet data (cone, R = 0.7)
(Ratio w.r.t. NLO $\hat{\sigma}$ with $\mu = p_T$ using MSTW08 NNLO PDFs)



DØ Run II dijet data (cone, R = 0.7)
(Ratio w.r.t. NLO $\hat{\sigma}$ with $\mu = p_T$ using MSTW08 NNLO PDFs)

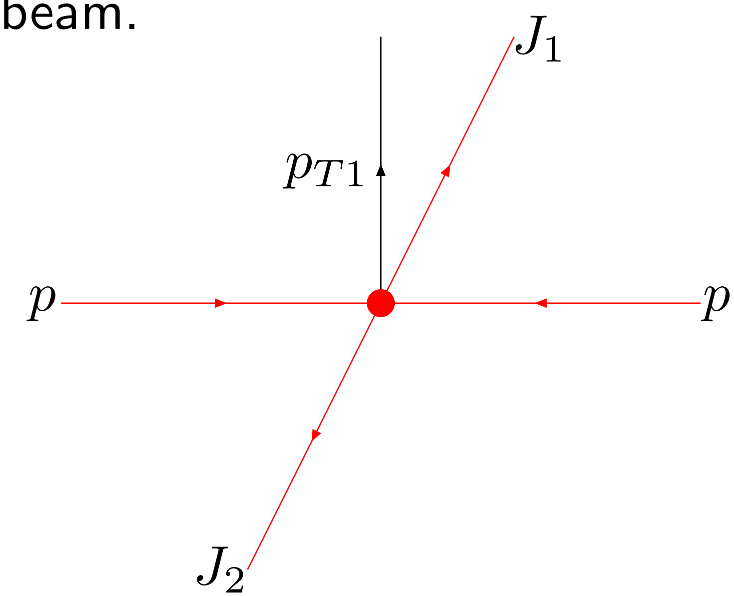


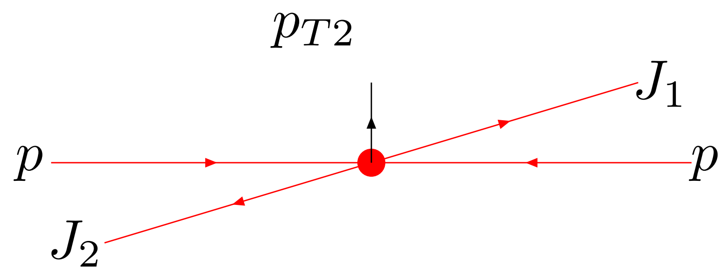
Shape of corrections as function of p_T at NLO and also at approx. NNLO in inclusive case. Problem at highest p_T and rapidity even for inclusive jets.

NNLO uses threshold (Kidonakis and Owens) approx. for Tevatron jets (see also de Florian and Vogelsang).

NNLO approximation aids stability – always worst at high-p_T i.e. high-x. Includes large $\ln(p_T/\mu)$ terms predicted by renormalisation group.

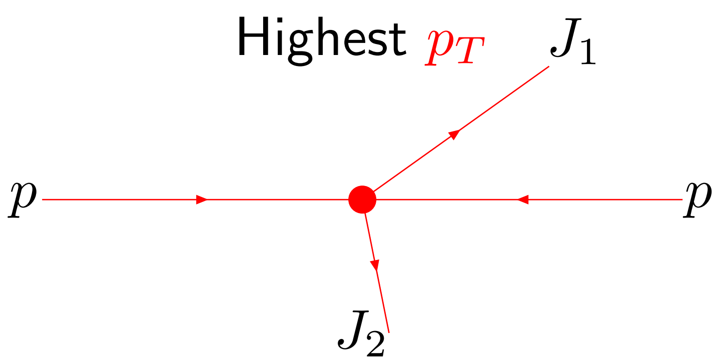
Consider two dijet processes with similar energy jets, but with one at much smaller angle to beam.



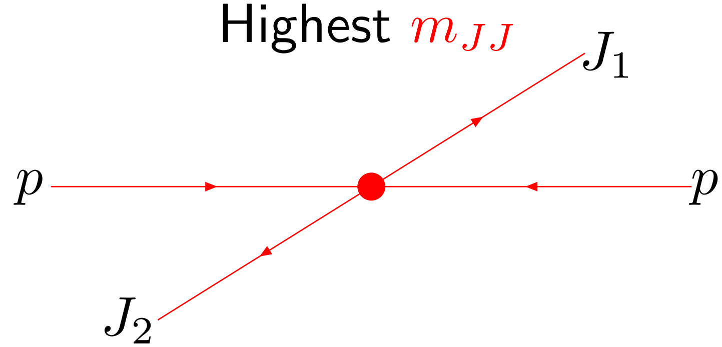


Generally use scale based entirely on p_T. Is the second event really that much less hard than the first?

Highest p_T

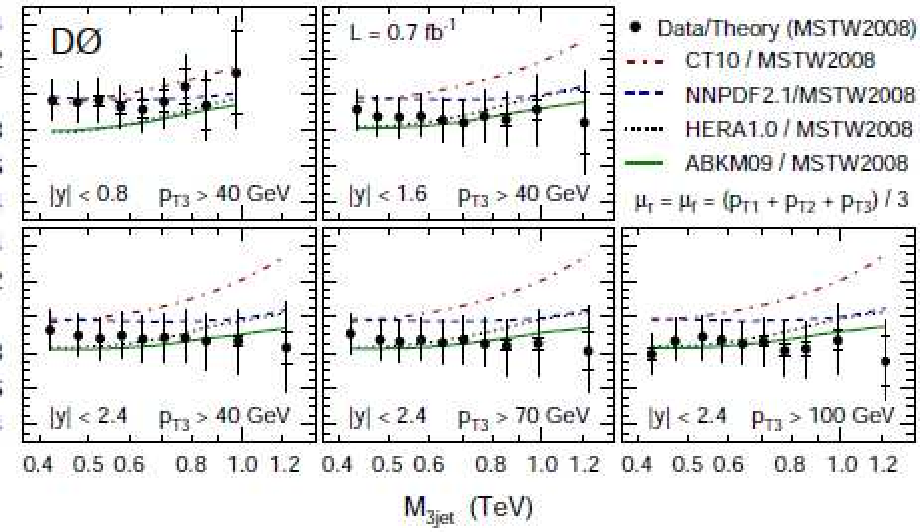


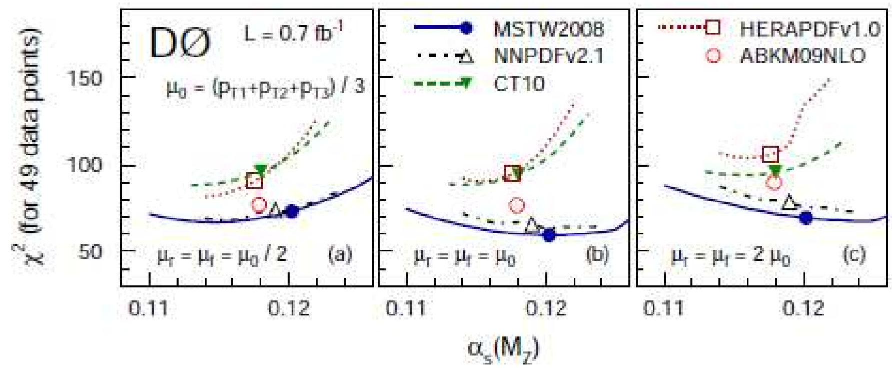
Highest m_{JJ}



In first case one x very large other quite small, in second both x values very large. In both cases p_T not too large.

Recent results from D0 on three jets cross sections.





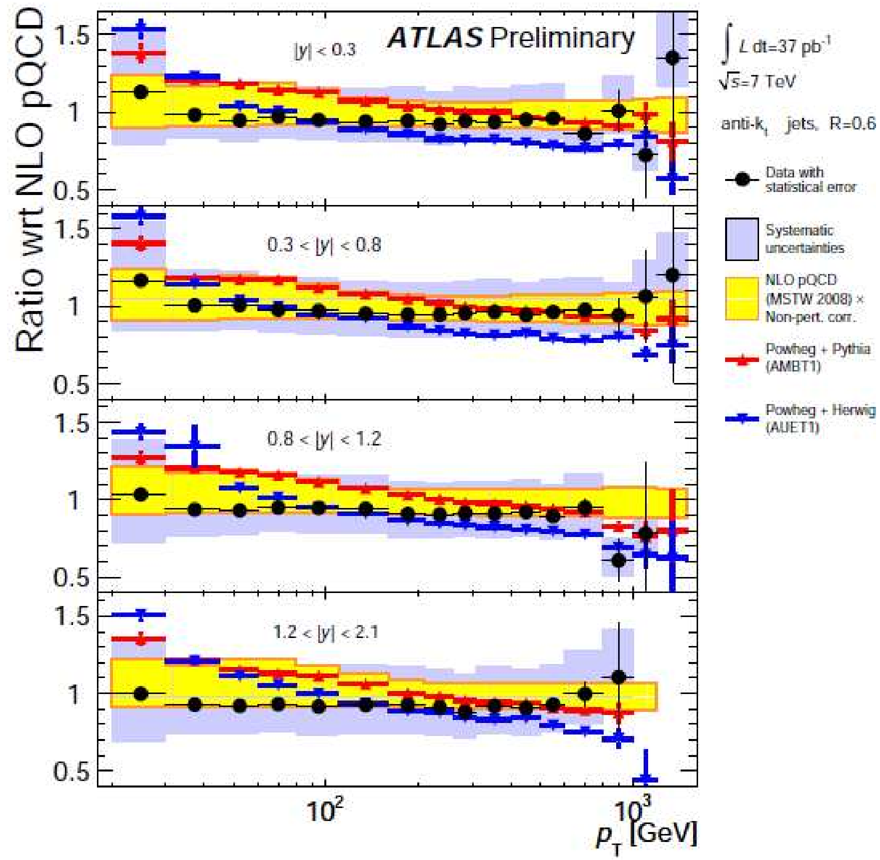
Seems like an excellent way to present significance of results. Groups can then study effects on central values uncertainties (consistency) *etc.*.

TABLE II: χ^2 values between data and theory for different PDF parametrizations in the order of decreasing χ^2, for all 49 data points.

PDF set	Default $\alpha_s(M_Z)$	χ^2 at $\mu_r = \mu_f = \mu_0$ for default $\alpha_s(M_Z)$	χ^2_{minimum}
HERAPDFv1.0	0.1176	95.1	81.7
CT10	0.1180	94.5	88.2
ABKM09NLO	0.1179	76.5	76.5
NNPDFv2.1	0.1190	65.9	63.3
MSTW2008NLO	0.1202	59.5	59.5

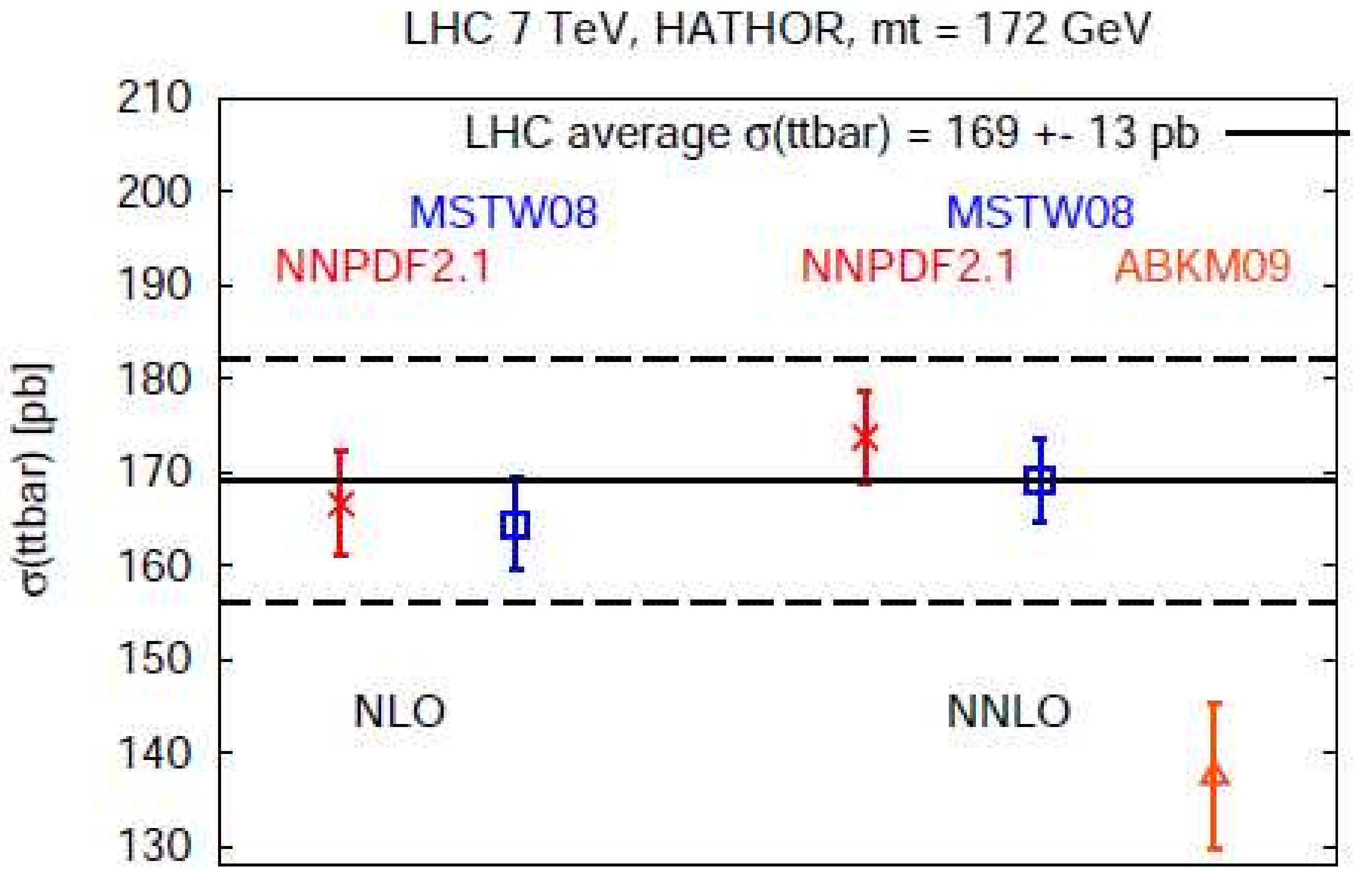
Inclusive Jets: NLOJET++ vs. PowHeg

- A significant difference between NLOJET++, PowHeg+Pythia and PowHeg+Herwig was observed
- NLO Matrix Element in good agreement between NLOJET++ and PowHeg
- Indication of uncertainties due to non-perturbative effects?



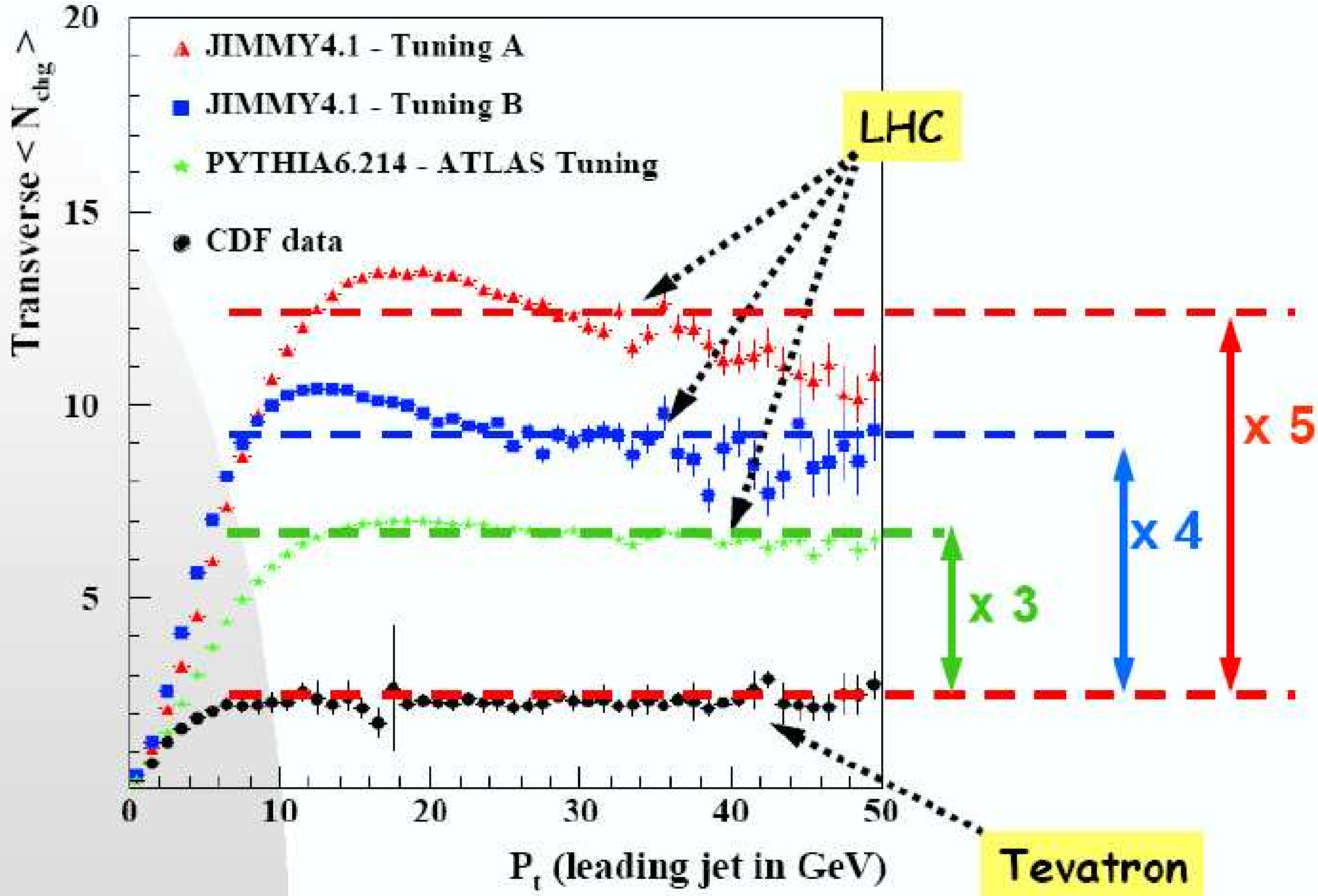
However, use of POWHEG leads to a big variation compared to standard NLO, and a big variation depending on Monte Carlo tune.

Implications for PDFs.



NNPDF NNLO prediction slightly bigger than MSTW, but use $\alpha_S = 0.119$ – not preferred value? General very good agreement

LHC predictions: JIMMY4.1 Tunings A and B vs. PYTHIA6.214 – ATLAS Tuning (DC2)

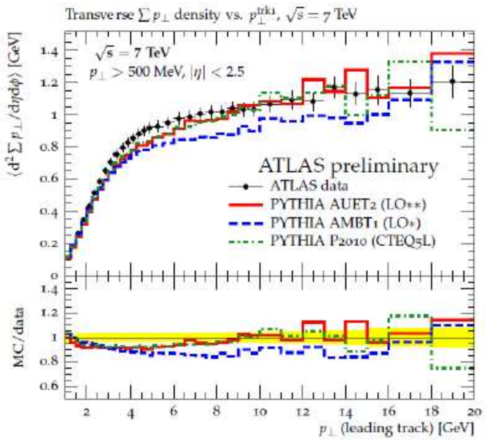


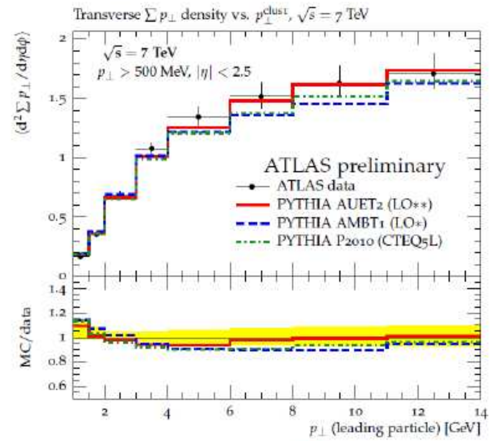
A. M. Moraes

Minimum-bias and the Underlying Event at the LHC

5th November 2004

New Pythia 6 tune to ATLAS data: AUET2

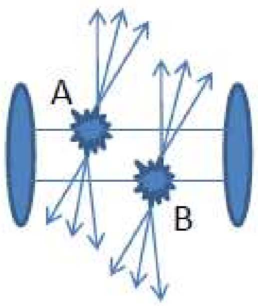




- Improvement w.r.t. AMBT1, "turn-over region" undershot
- Similar agreement for track- and calorimeter based UE measurements

However, to be more theoretically correct multi-parton distribution functions should be used.

Cross Section for DPS



Assuming only the factorisation of the hard processes A and B, the DPS cross section may be written as:

$$\sigma_D^{(A,B)} = \underbrace{\frac{m}{2}}_{\text{Symmetry factor}} \sum_{i,j,k,l} \int \overbrace{\Gamma_h^{ik}(x_1, x_2, \mathrm{b}; Q_A, Q_B)\,\Gamma_h^{jl}(x_1', x_2', \mathrm{b}; Q_A, Q_B)}^{\text{Two-parton generalised PDF (2pGPD)}}$$

$$\times \underbrace{\hat{\sigma}_{ij}^{A}(x_1, x_1')\,\hat{\sigma}_{kl}^{B}(x_2, x_2')}_{\text{Parton level cross sections}}\, dx_1\, dx_1'\, dx_2\, dx_2'\, d^2\mathrm{b}$$

The vector **b** in the 2pGPDs corresponds to the vector separation in transverse space between the two partons described by the 2pGPD.

DPS differs from SPS in that the cross section may not naturally be expressed in terms of PDFs depending only on *x* arguments. The 2pGPDs in the DPS cross section must share a common **b** in order that both pairs of partons can meet and interact – one cannot integrate independently over the transverse separation arguments of each PDF and obtain PDFs depending only on *x* arguments, as one can in the SPS case. 4

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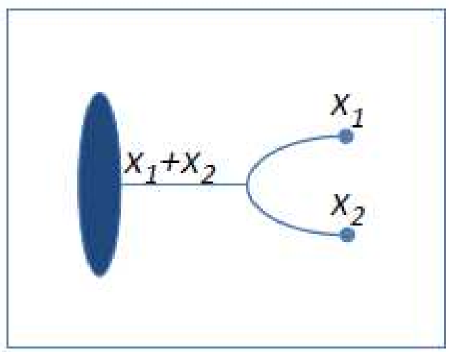
Pictorial Representation of the dDGLAP equation

$$\begin{aligned}\frac{dD_h^{j_1j_2}(x_1,x_2;t)}{dt} = \frac{\alpha_s(t)}{2\pi}\Bigg[&\sum_{j_1'}\int_{x_1}^{1-x_2}\frac{dx_1'}{x_1'}D_h^{j_1'j_2}(x_1',x_2;t)P_{j_1'\to j_1}\left(\frac{x_1}{x_1'}\right)\\ &+\sum_{j_2'}\int_{x_2}^{1-x_1}\frac{dx_2'}{x_2'}D_h^{j_1j_2'}(x_1,x_2';t)P_{j_2'\to j_2}\left(\frac{x_2}{x_2'}\right)\\ &\boxed{+\sum_{j'}D_h^{j'}(x_1+x_2;t)\frac{1}{x_1+x_2}P_{j'\to j_1j_2}\left(\frac{x_1}{x_1+x_2}\right)\Bigg]}\end{aligned}$$

'sPDF feed' term



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Some fits to new combined HERA structure function data using saturation inspired models Albacete et al.

Seems fairly successful, as before. But not necessary.