Parton Distributions for LO Monte Carlo Generators

Robert Thorne

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University College London

Royal Society Research Fellow

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Which order of partons should be used in LO Monte Carlo generators.

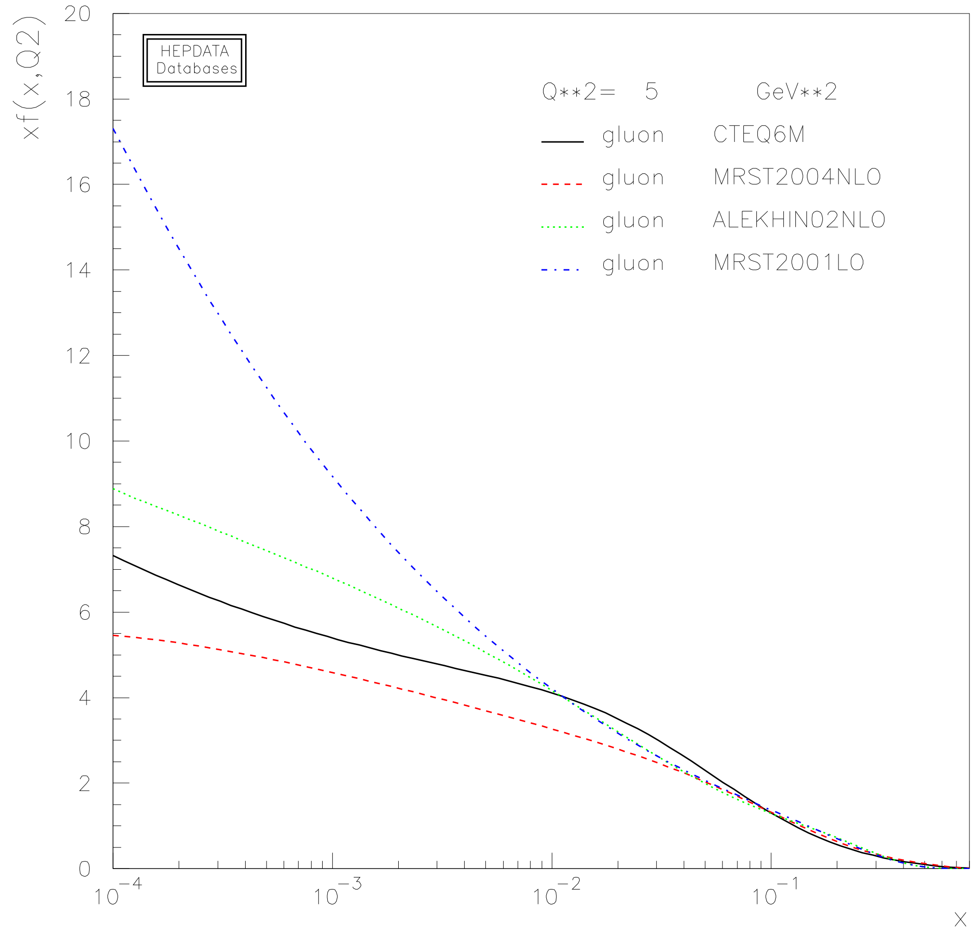
Enormous change in partons, especially gluon when going from LO $\rightarrow$ NLO.

LO partons are the usual one used with many LO Monte Carlo programs.

All such results should be treated with care.

Not NLO partons? Not a trivial issue.

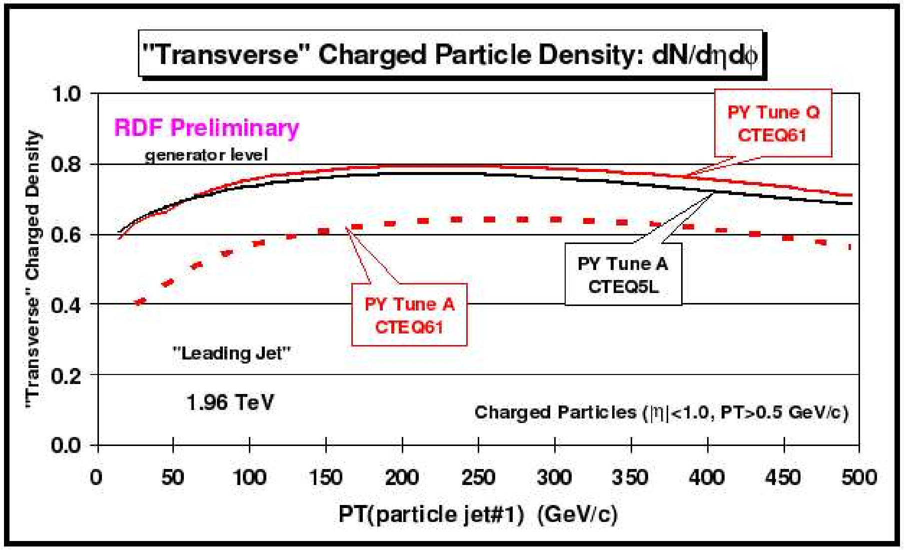
Full details of study in A. Shertsnev and R.S. Thorne, e-Print: arXiv:0711.2473 [hep-ph].

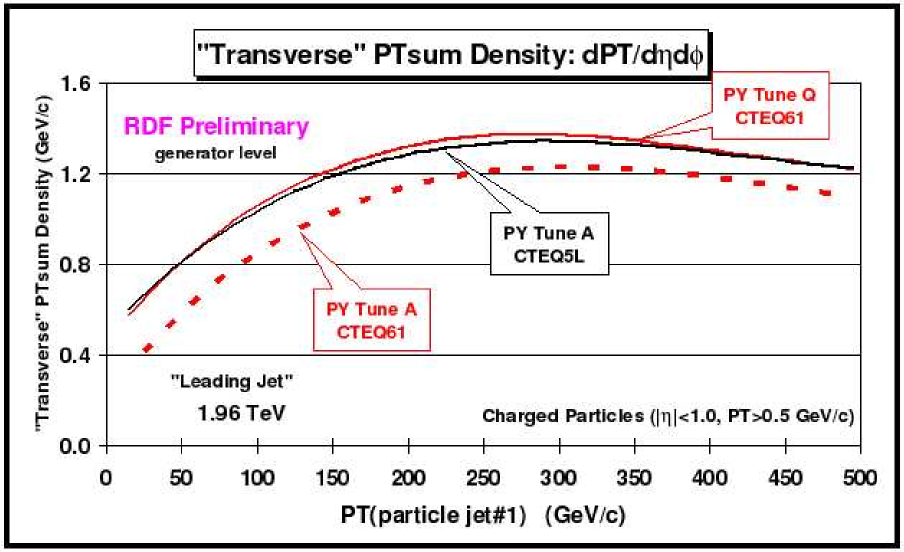


Already investigated in terms of tuning for underlying event (Field). See big difference between using CTEQ6L and CTEQ6.1M partons, mainly due to gluon.

Agreement can be reached by retuning. Will affect predictions for other quantities. Want universality.

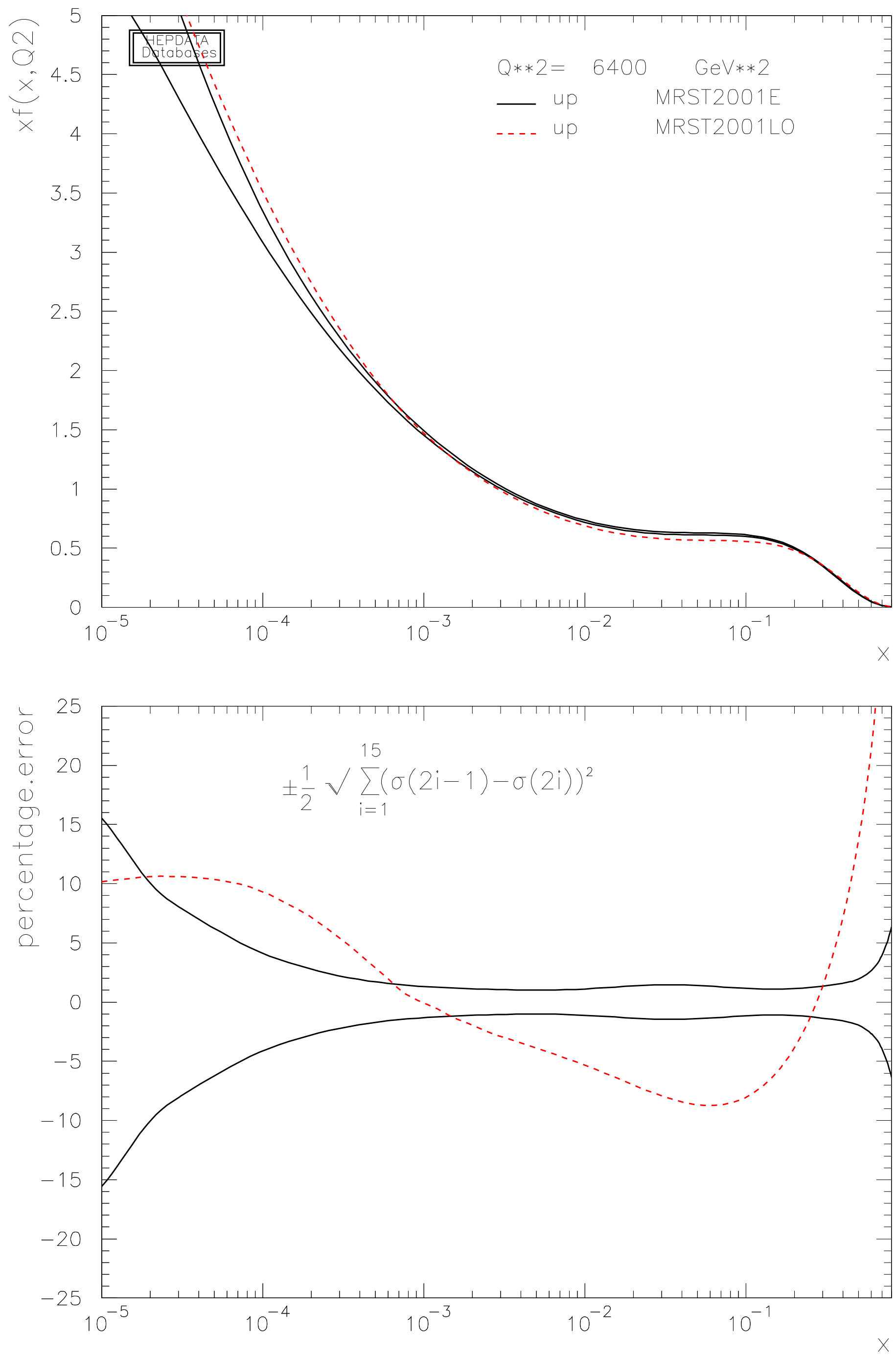
In order to investigate this look at indications from well-understood (simple) processes.





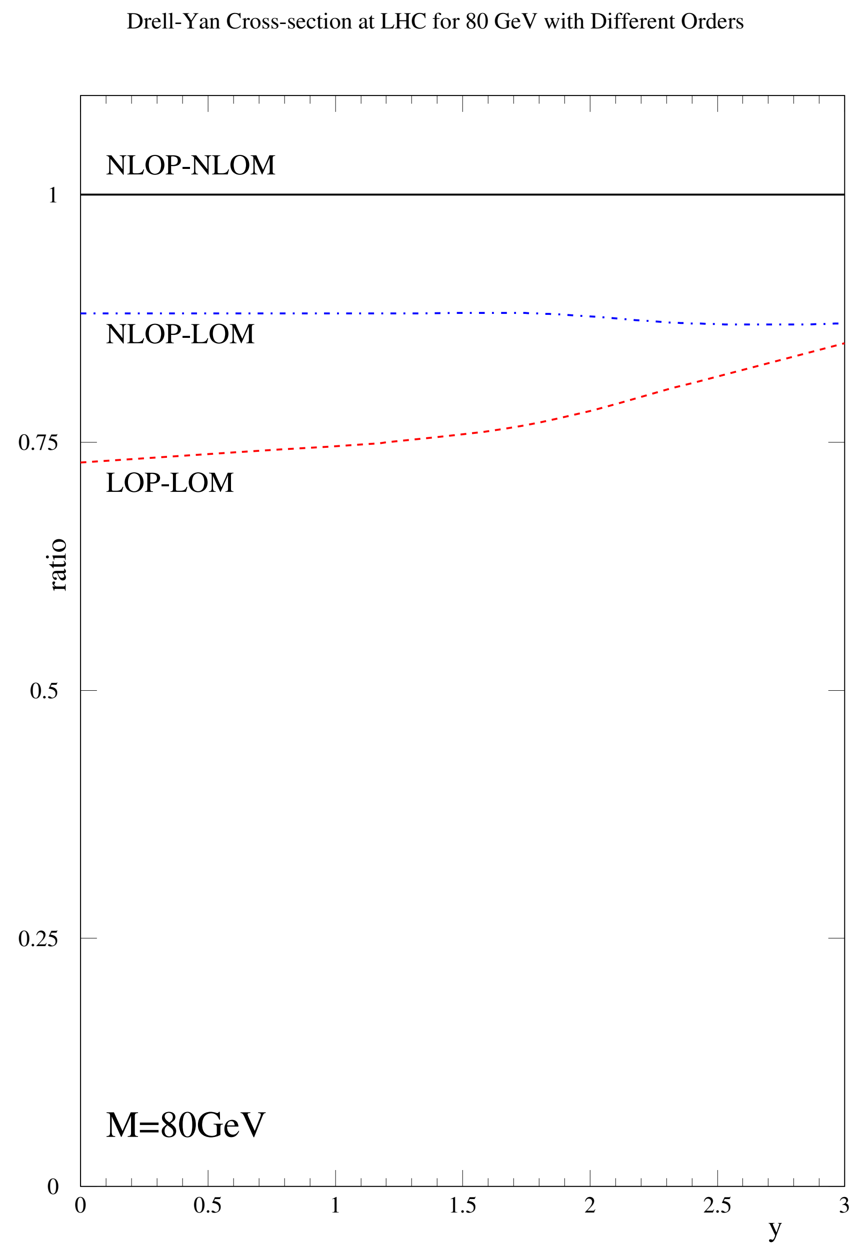
First note that the LO quarks over wide region of smaller x qualitatively smaller than NLO. Lack of additional quark evolution at NLO.

At high x $\ln(1-x)$ terms in NLO matrix elements lead to NLO quarks being smaller.



NLO partons lead to best shape for inclusive fixed order heavy boson production at the LHC.

Has lead to the proposal that NLO partons should always be used.

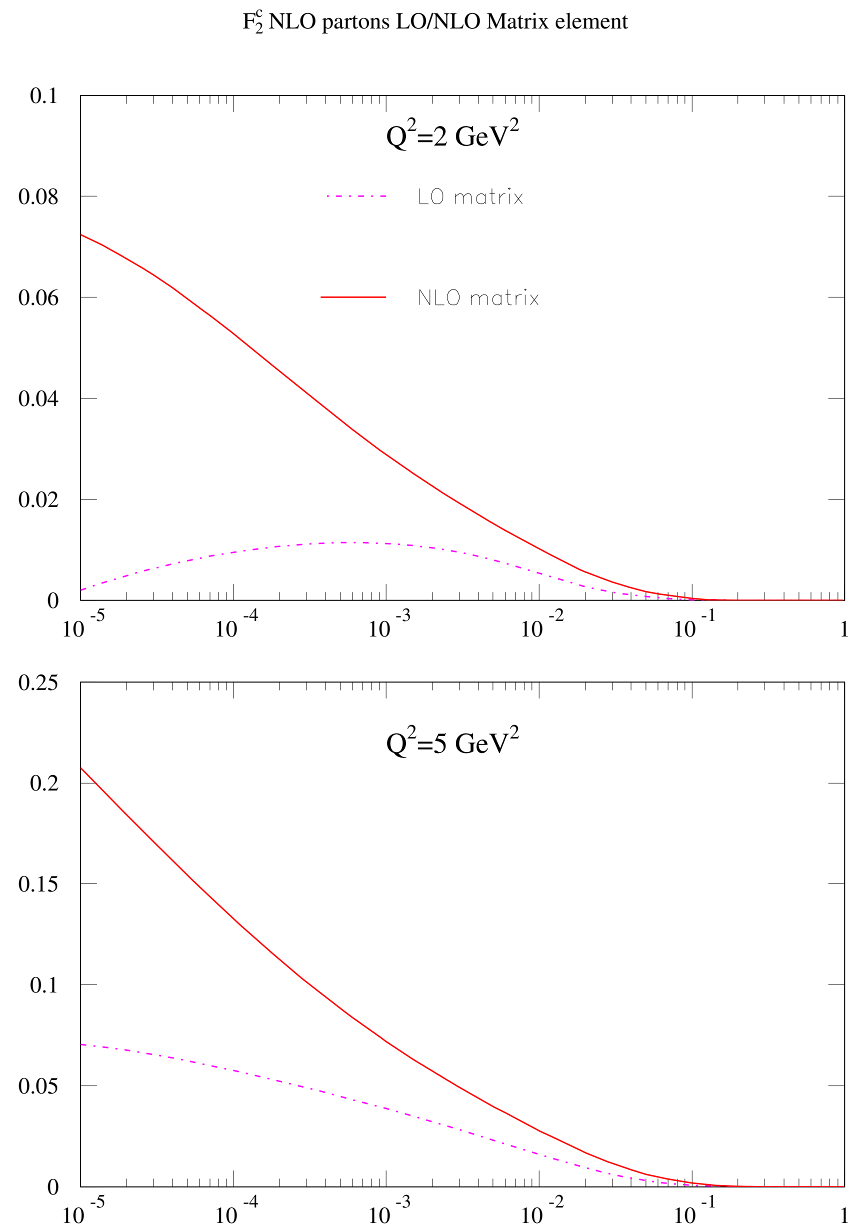


Small x *counter*-example. Consider production of charm in DIS. All charm produced in final state (FFNS).

NLO matrix element contain divergence at small x not present at LO.

Same issues in heavy flavour hadro-production.

Using NLO partons the LO matrix element result is well below the *truth* at low scales. Shape totally wrong.

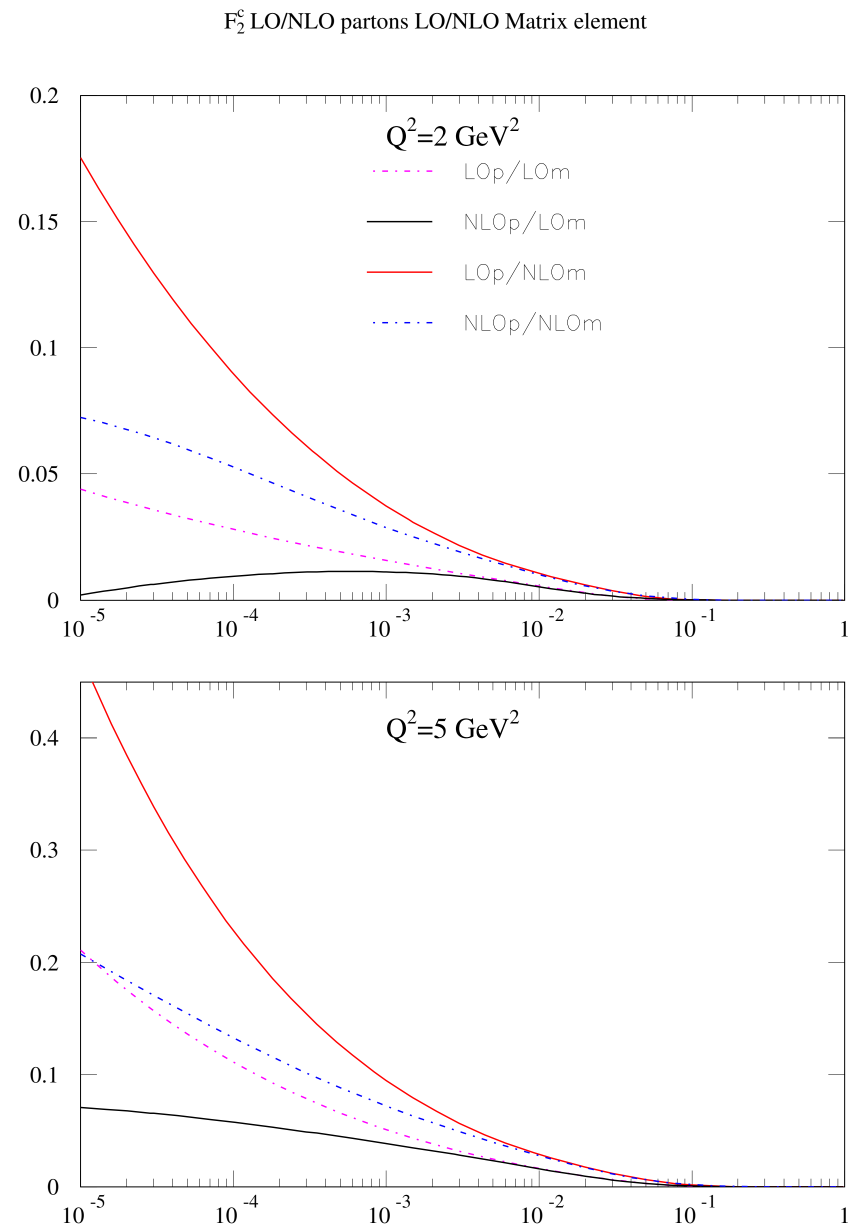


Consider using LO partons.

Using LO partons the NLO matrix element result is extremely large.

LO gluon is very large at small x since it has been extracted with missing enhancements at small x.

LO partons and LO matrix element more sensible. compensation between failings in both.



Conclusions - so far

Sometimes NLO partons better to use if only LO matrix elements are known.

Can get significant problems with shape if LO partons used.

But can be completely wrong at small x using NLO partons due to *zero*-counting of $\ln(1/x)$ terms.

Can we find some optimal partons which have most desirable features?

Need to understand difference between LO and NLO partons better.

At LO compared to NLO (and higher orders) missing terms in $\ln(1-x)$ and $\ln(1/x)$ in coefficient functions and/or evolution.

$\rightarrow$ partons at LO bigger at $x \rightarrow 1$ and at $x \rightarrow 0$ in order to compensate.

From momentum sum rule not enough partons to go around.

Leads to bad global fit at LO – partially compensated by LO extraction of $\alpha_S(M_Z^2) \geq 0.130$.

However, leads to suggestion (Sjostrand) that relaxing momentum sum rule at LO could make LO partons rather more like NLO partons where they are normally too small.

Resulting partons would still be bigger than NLO where necessary.

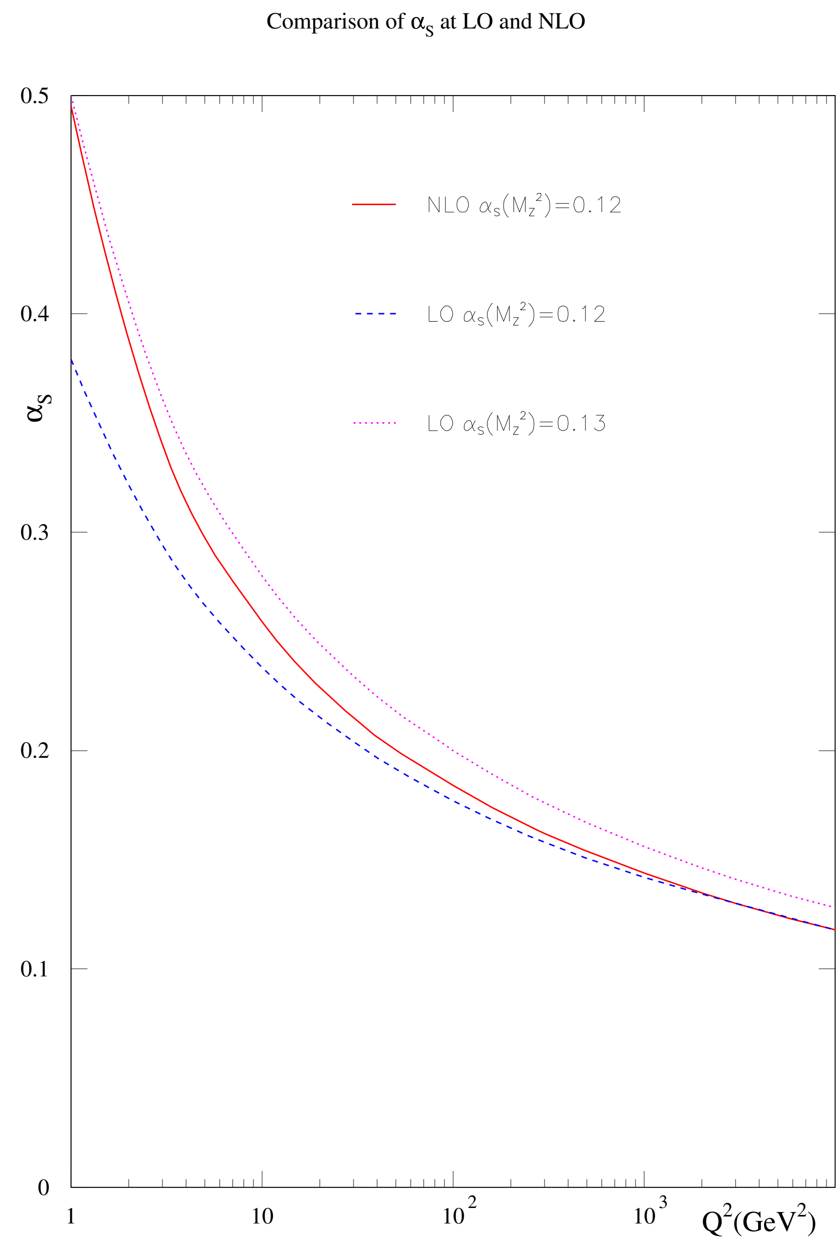
Also useful to use NLO definition of coupling constant.

Because of quicker running at NLO couplings with same value of $\alpha_S(M_Z^2)$ very different at lower scales where DIS data exists.

Near $Q^2 = 1\text{GeV}^2$ NLO coupling with $\alpha_S(M_Z^2) = 0.120$ similar to LO coupling with $\alpha_S(M_Z^2) = 0.130$.

Use of NLO coupling helps alleviate discrepancy between different orders.

NLO coupling already used in CTEQ LO partons and in Monte Carlo generators.



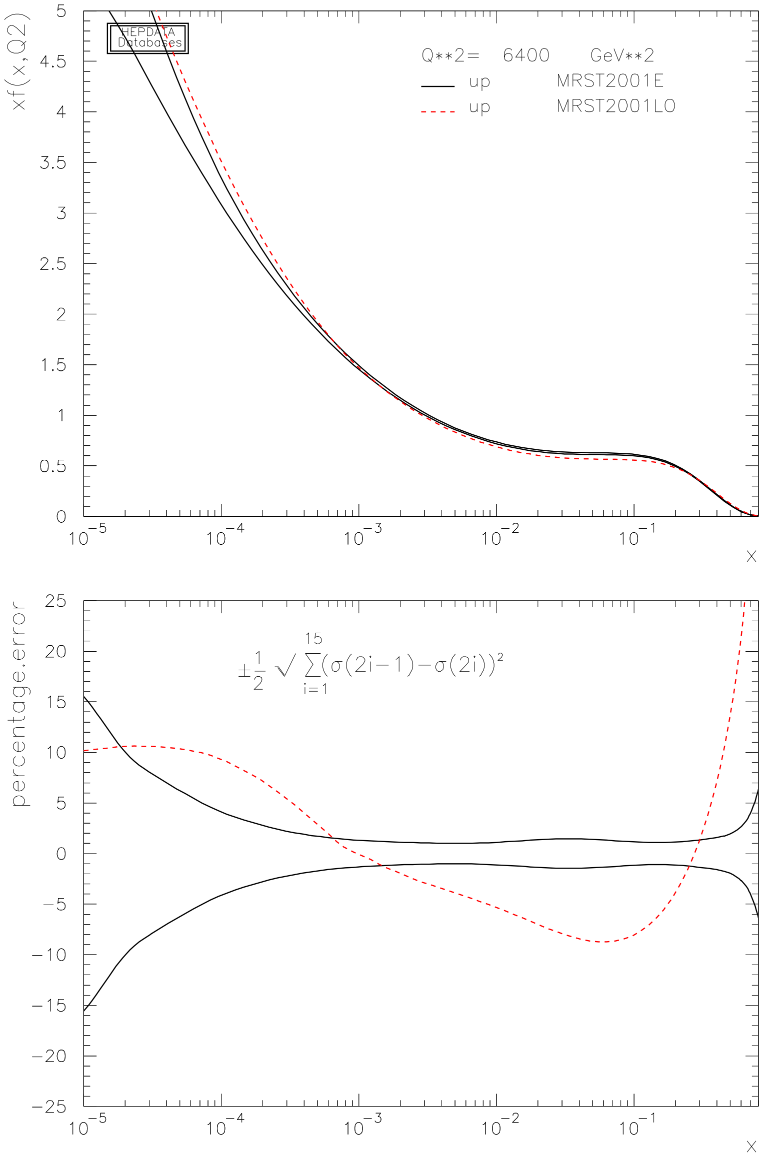
Relaxing momentum violation and allowing NLO definition of coupling does dramatically improve quality of LO global fit (K-factor of 1.3 necessary for fixed target Drell-Yan data).

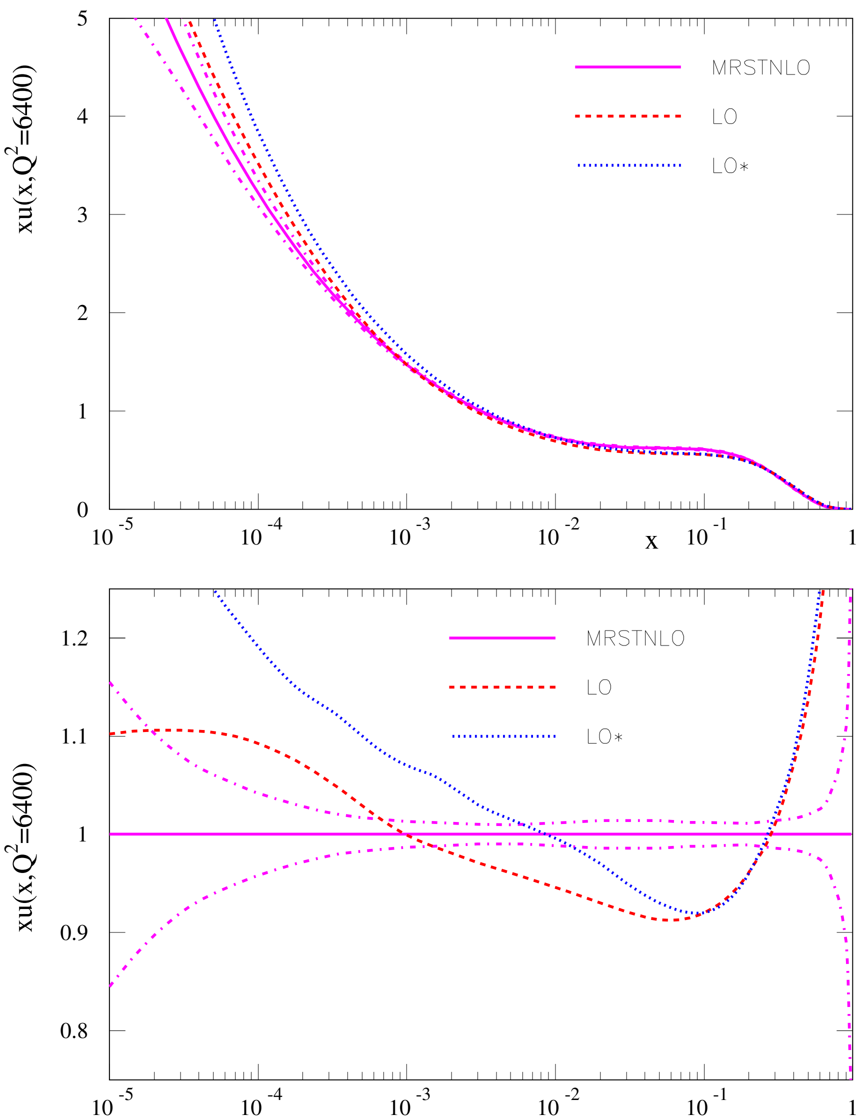
$\chi^2 = 3066/2235$ for standard LO fit becomes $\chi^2 = 2691/2235$. Big improvement in HERA data.

Momentum carried by input partons goes up to 113%. Much more similar to NLO partons, in particular at small x LO quark distributions evolve as quickly at NLO partons.

Using NLO definition $\alpha_S(M_Z^2) = 0.121$.

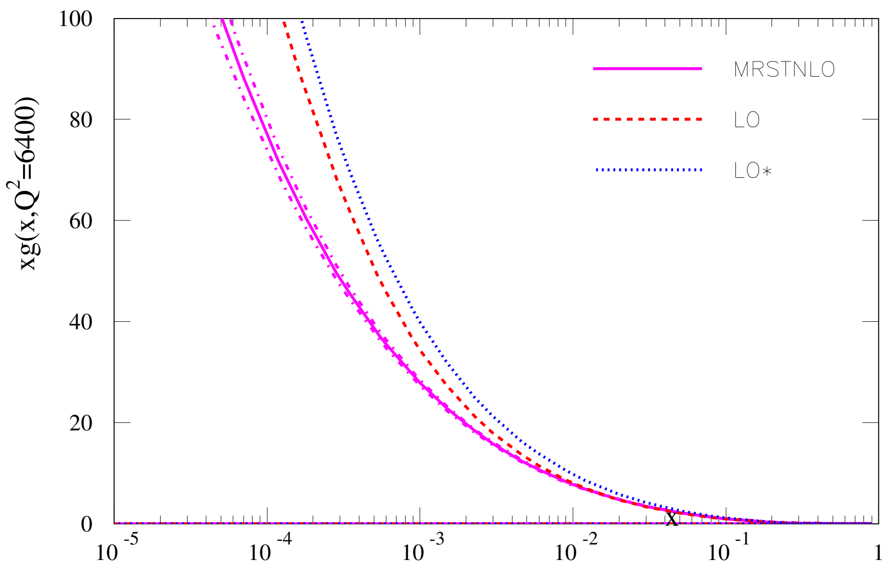
The LO* and NLO partons are more similar in this case, particularly for $x \sim 0.001 - 0.01$. (LO* often bigger – compensates for smaller cross-section at LO).

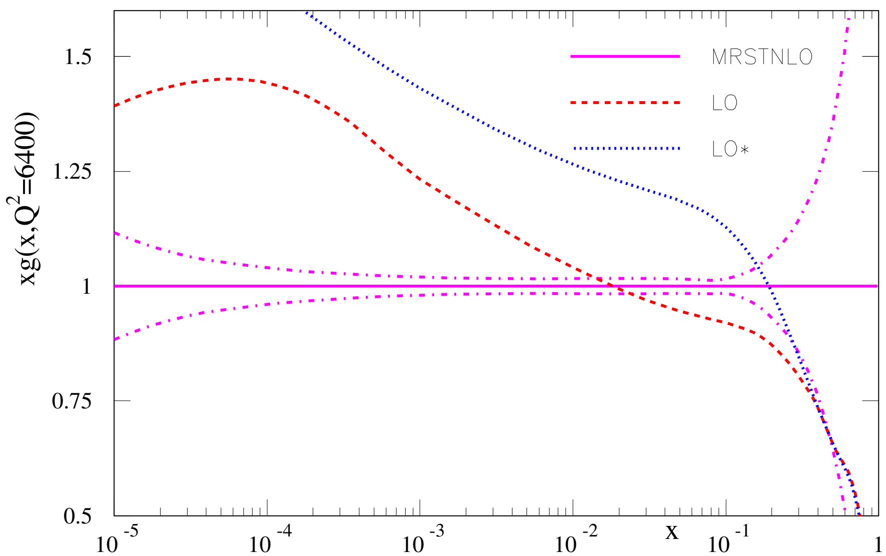




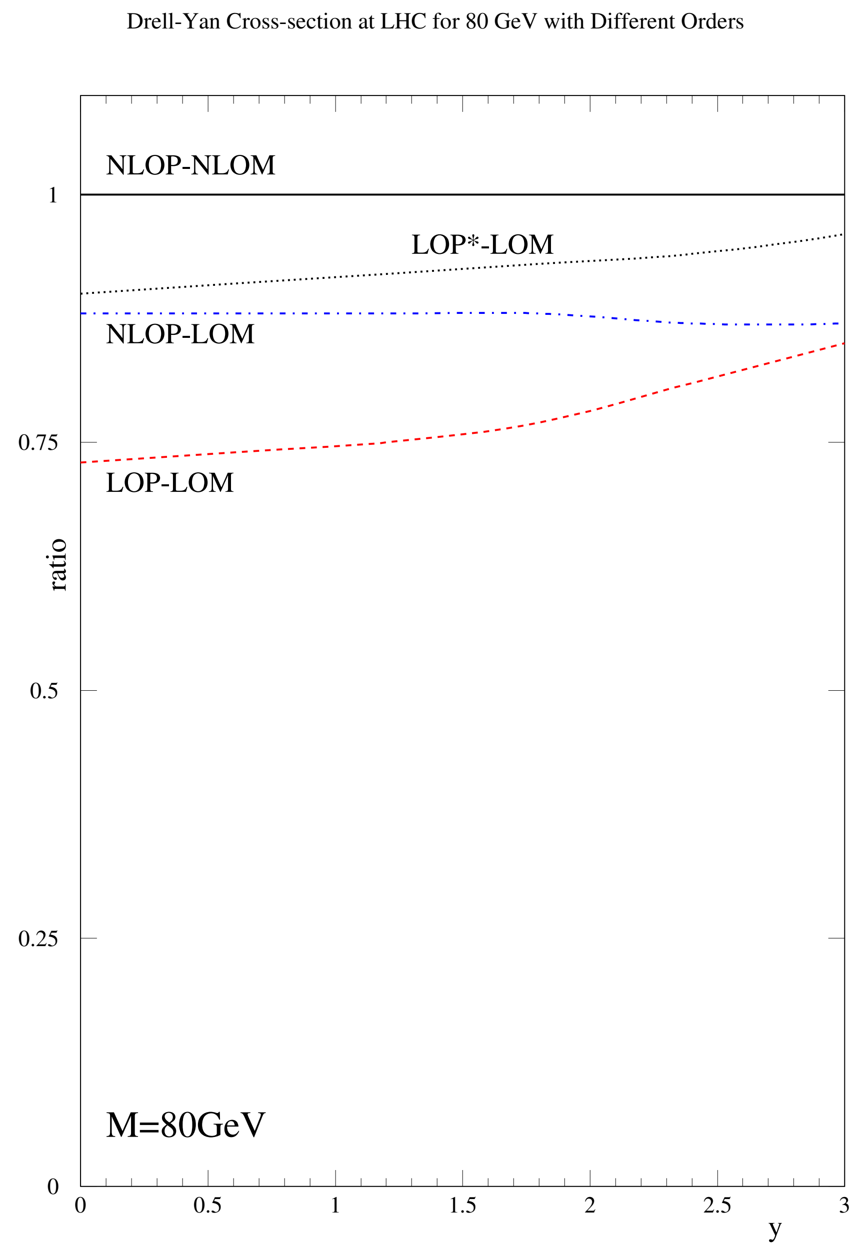
Similarly $g(x, Q^2)$ is significantly bigger at LO* than at LO, and much bigger than NLO at small x.

Should do better for gluon-gluon initiated processes (e.g. Higgs production where K-factors are often much greater than unity).

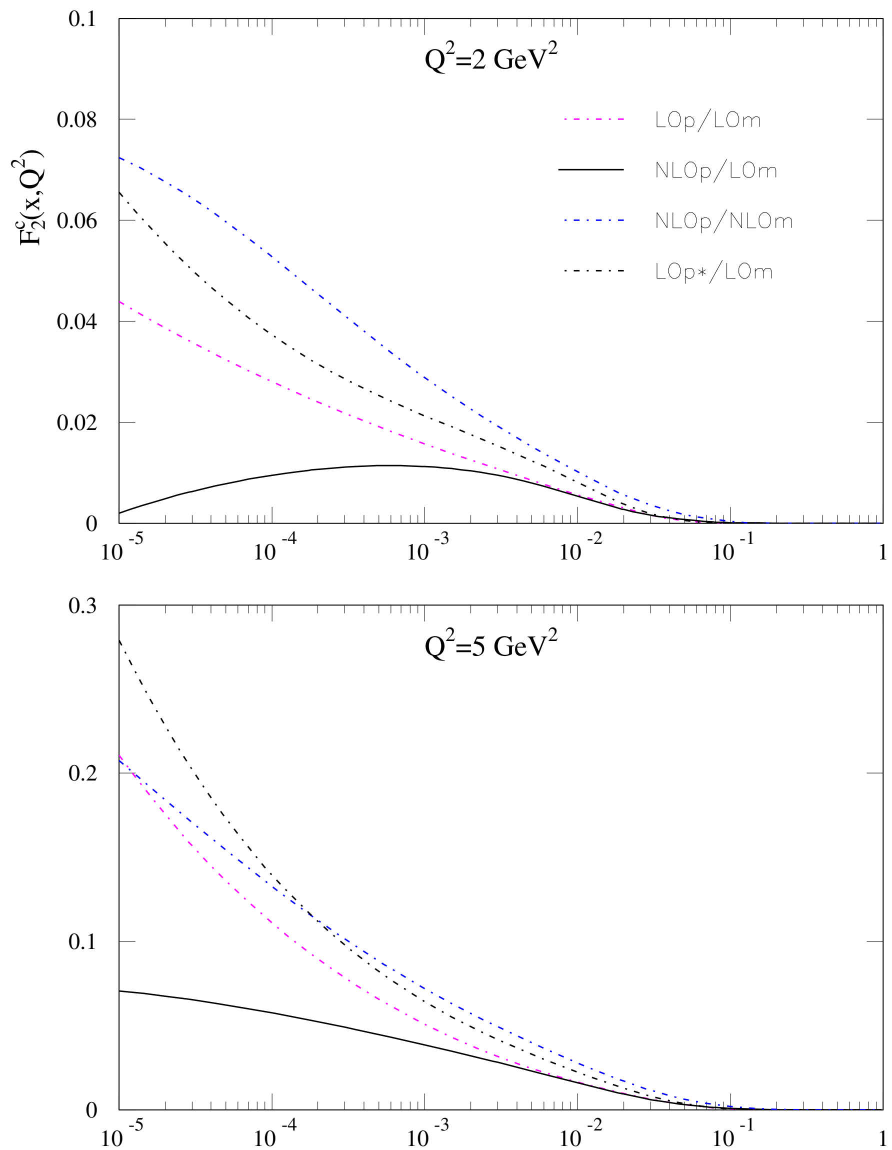




For LHC LO* partons lead to shape of comparable quality as NLO partons. Normalization better.



For charm structure function comparing all possibilities LO* partons and LO matrix element is indeed nearest to *truth* at low scales.



These are for totally inclusive, strictly fixed order calculations. Consider using generators (work with/by A Sherstnev) and include parton showering (i.e. use MC@NLO at NLO).

Consider first $Z \to \mu^+\mu^-$ production at the LHC with $p_T > 10\mathrm{GeV}$ and $|\eta| < 5$

NLO(ME)$\otimes$ NLO(pdf)$= 2.40nb$.

LO(ME)$\otimes$ LO(pdf)$= 1.85nb$.

LO(ME)$\otimes$ NLO(pdf)$= 1.98nb$.

LO(ME)$\otimes$ LO*(pdf)$= 2.19nb$.

With very similar relative results for $W \to \nu\mu$, i.e.

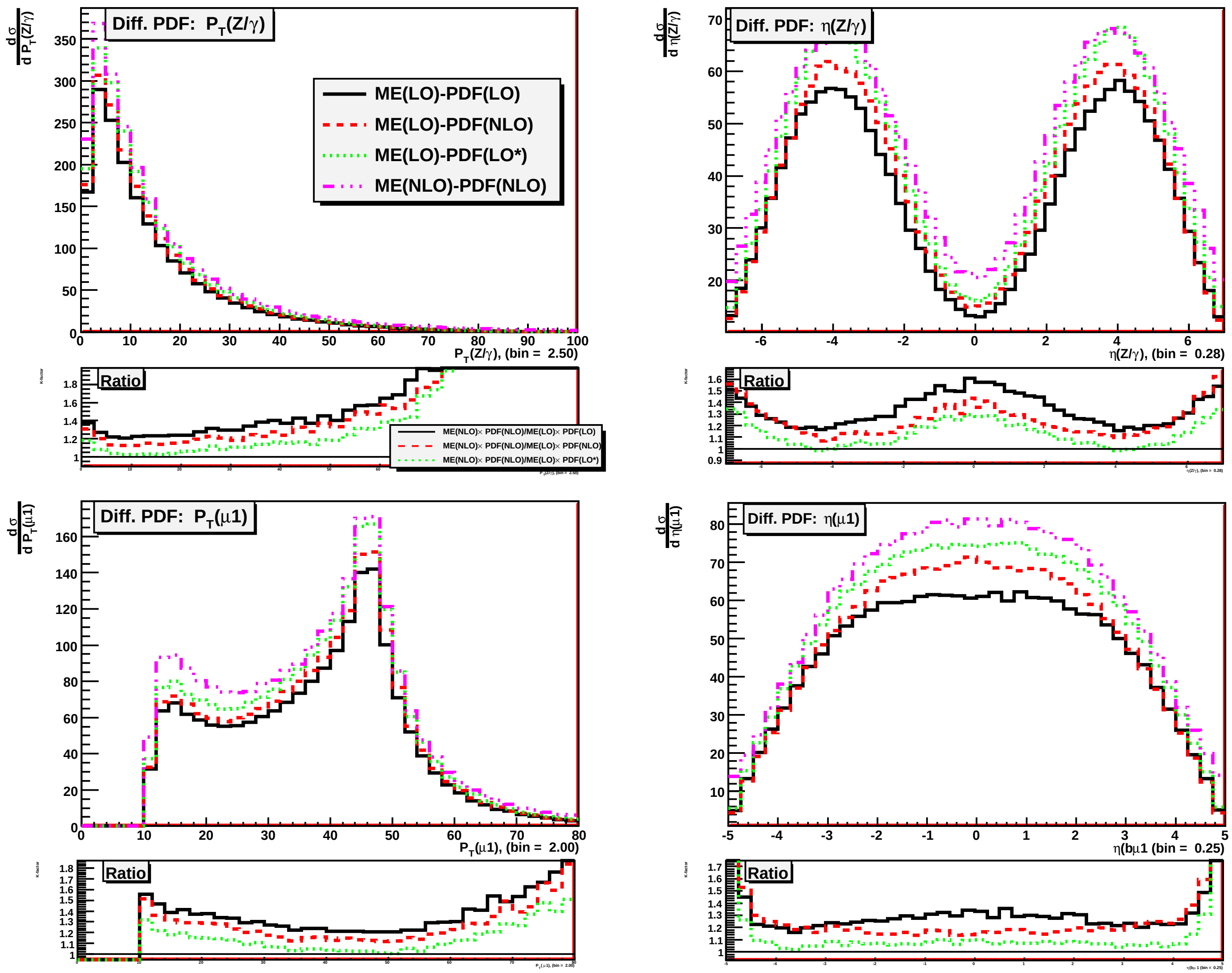
NLO(ME)$\otimes$ NLO(pdf)$= 21.1nb$.

LO(ME)$\otimes$ LO(pdf)$= 17.5nb$.

LO(ME)$\otimes$ NLO(pdf)$= 18.6nb$.

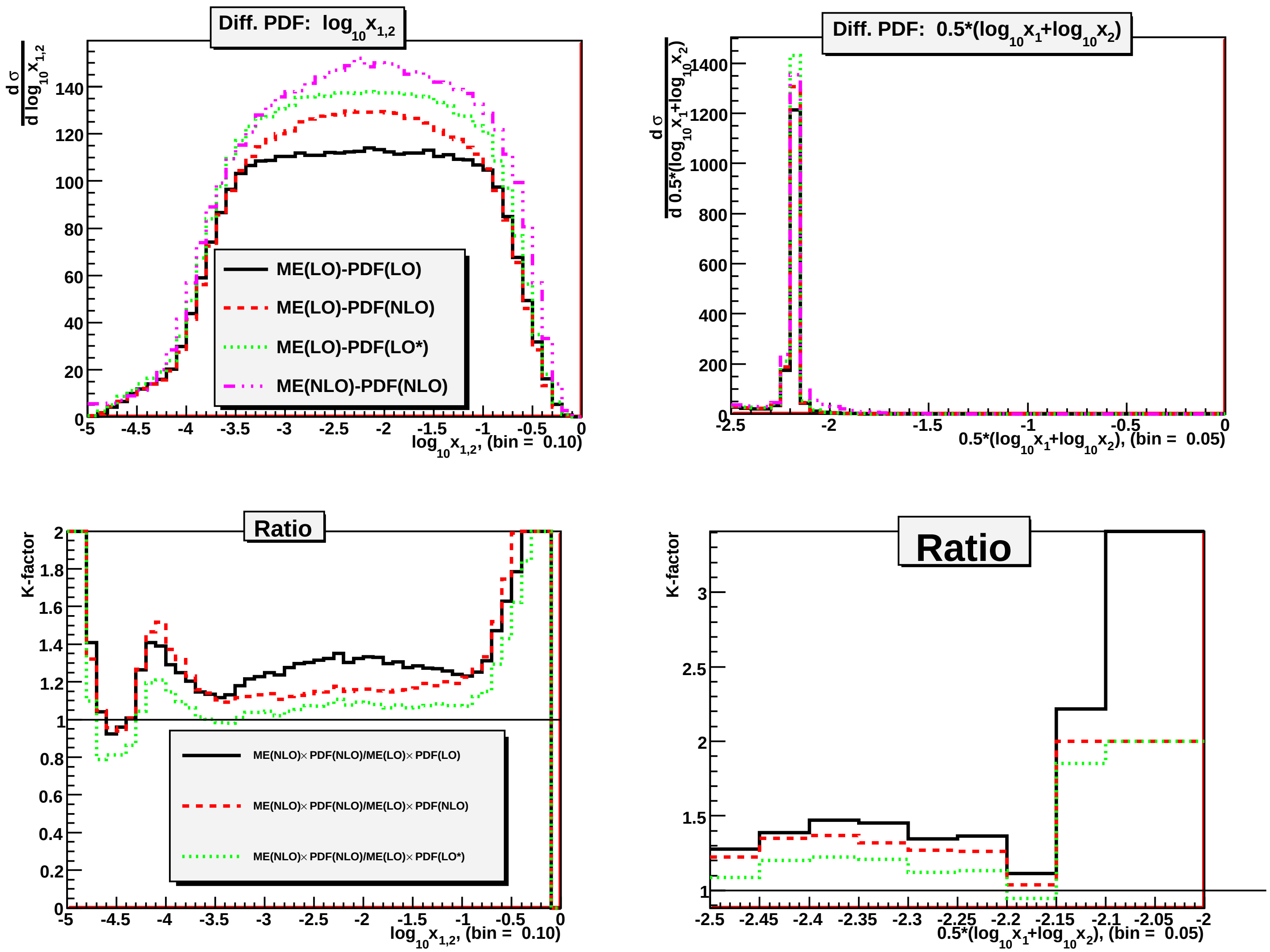
LO(ME)$\otimes$ LO*(pdf)$= 20.6nb$.

Also look at distributions for Z boson and final state muon.



Results using LO* partons clearly best. No parton can account for details of p_T-distribution due to hard emissions at NLO.

Examination of values of x sampled in cross-section shows that deficit in LO rates due to lack of partons for $x \sim 0.01$.



NLO partons have better distribution, but LO* are good in normalization and shape.

Consider Higgs ($130\mathrm{GeV}$) production from gg fusion at the LHC.

NLO(ME)$\otimes$ NLO(pdf)$= 38.0pb$.

LO(ME)$\otimes$ LO(pdf)$= 22.4pb$.

LO(ME)$\otimes$ NLO(pdf)$= 20.3pb$.

LO(ME)$\otimes$ LO*(pdf)$= 32.4pb$.

Similar for $t\bar{t}$ production.

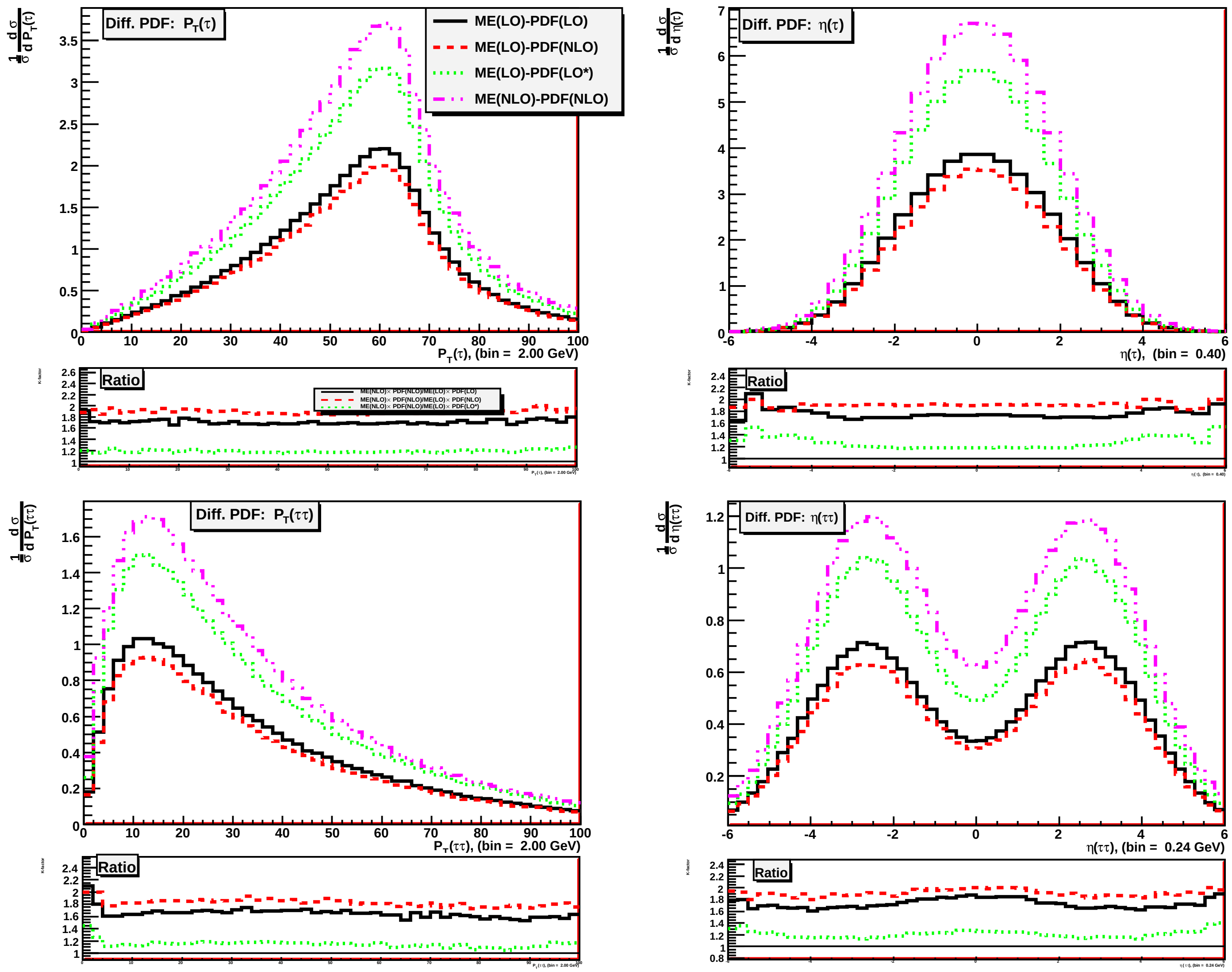
NLO(ME)$\otimes$ NLO(pdf)$= 813pb$.

LO(ME)$\otimes$ LO(pdf)$= 561pb$.

LO(ME)$\otimes$ NLO(pdf)$= 531pb$.

LO(ME)$\otimes$ LO*(pdf)$= 699pb$.

Also look at distributions with $H \to \tau^+\tau^-$ for single τ and $\tau^+\tau^-$ pair.



Results using LO* partons clearly best in normalization. All reasonable in shape.

Consider instead single top production with $t \to \mu + \nu + b$ production at the LHC. Now a t-channel process.

NLO(ME)$\otimes$ NLO(pdf)$= 259pb$.

LO(ME)$\otimes$ LO(pdf)$= 238pb$.

LO(ME)$\otimes$ NLO(pdf)$= 270pb$.

LO(ME)$\otimes$ LO*(pdf)$= 297b$.

Similar for other t-channel process vector boson production of Higgs + two jets using NLO code VBFNLO (Zeppenfeld *et al*).

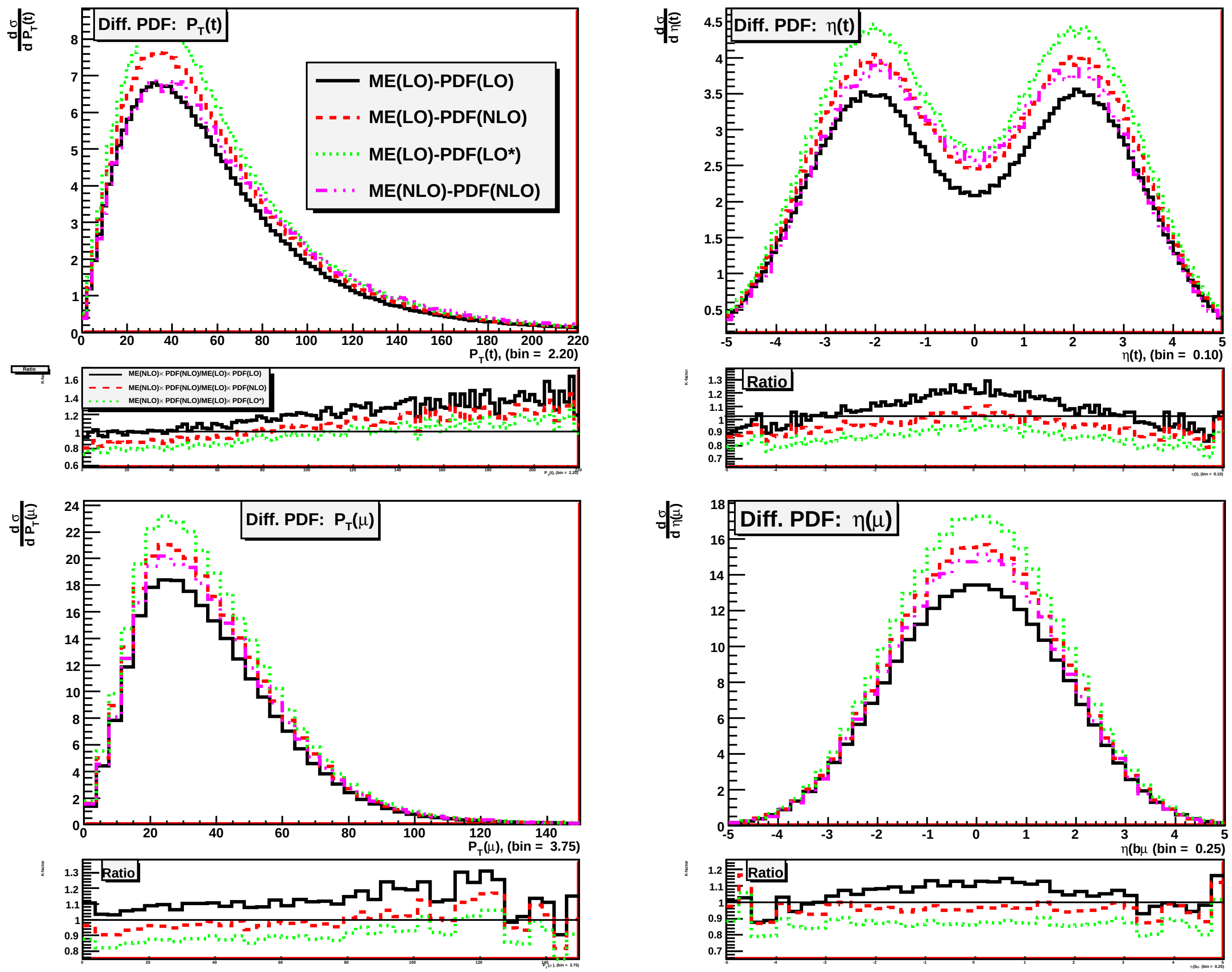
NLO(ME)$\otimes$ NLO(pdf)$= 4.52pb$.

LO(ME)$\otimes$ LO(pdf)$= 4.26pb$.

LO(ME)$\otimes$ NLO(pdf)$= 4.65pb$.

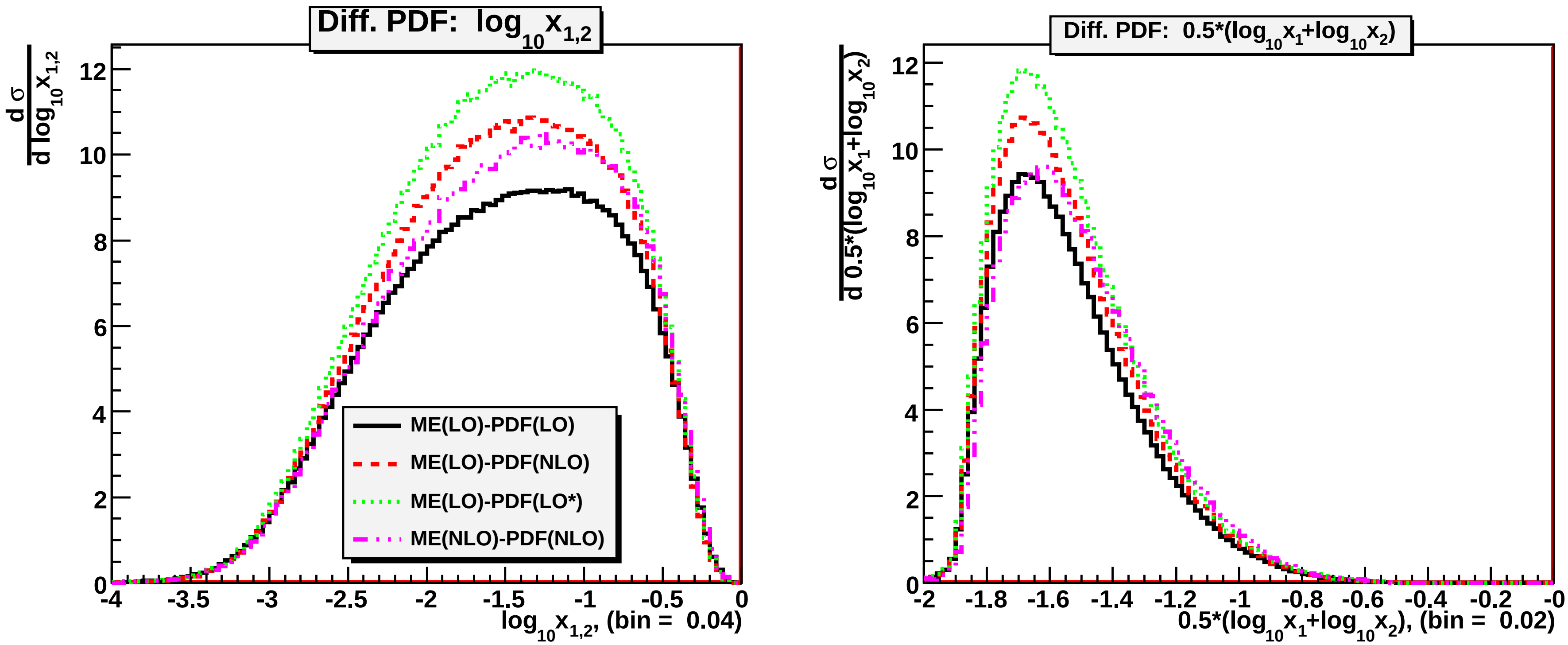
LO(ME)$\otimes$ LO*(pdf)$= 4.95pb$.

Also look at distributions for t and final state muon.



Results using LO* partons a bit high in normalization, but a better shape than LO which has the best normalization. No parton can account completely for details of p_T-distribution due to hard emissions at NLO. Similar for Higgs via VBF.

These processes probe the fairly high-x quarks, i.e. $x \sim 0.01 - 0.1$, but are much more smeared distributions than the s-channel processes.



Consider $b\bar{b}$ production with the included contribution for radiated $g \rightarrow b\bar{b}$ at the LHC. Noted contribution strictly NLO but vital for p_T-distribution and included in LO generators. Cuts $p_t > 20\mathrm{GeV}$, $|\eta(b)| < 5$, $\Delta R(b,b) > 0.5$.

NLO(ME)$\otimes$ NLO(pdf)$= 2.76\mu b$.

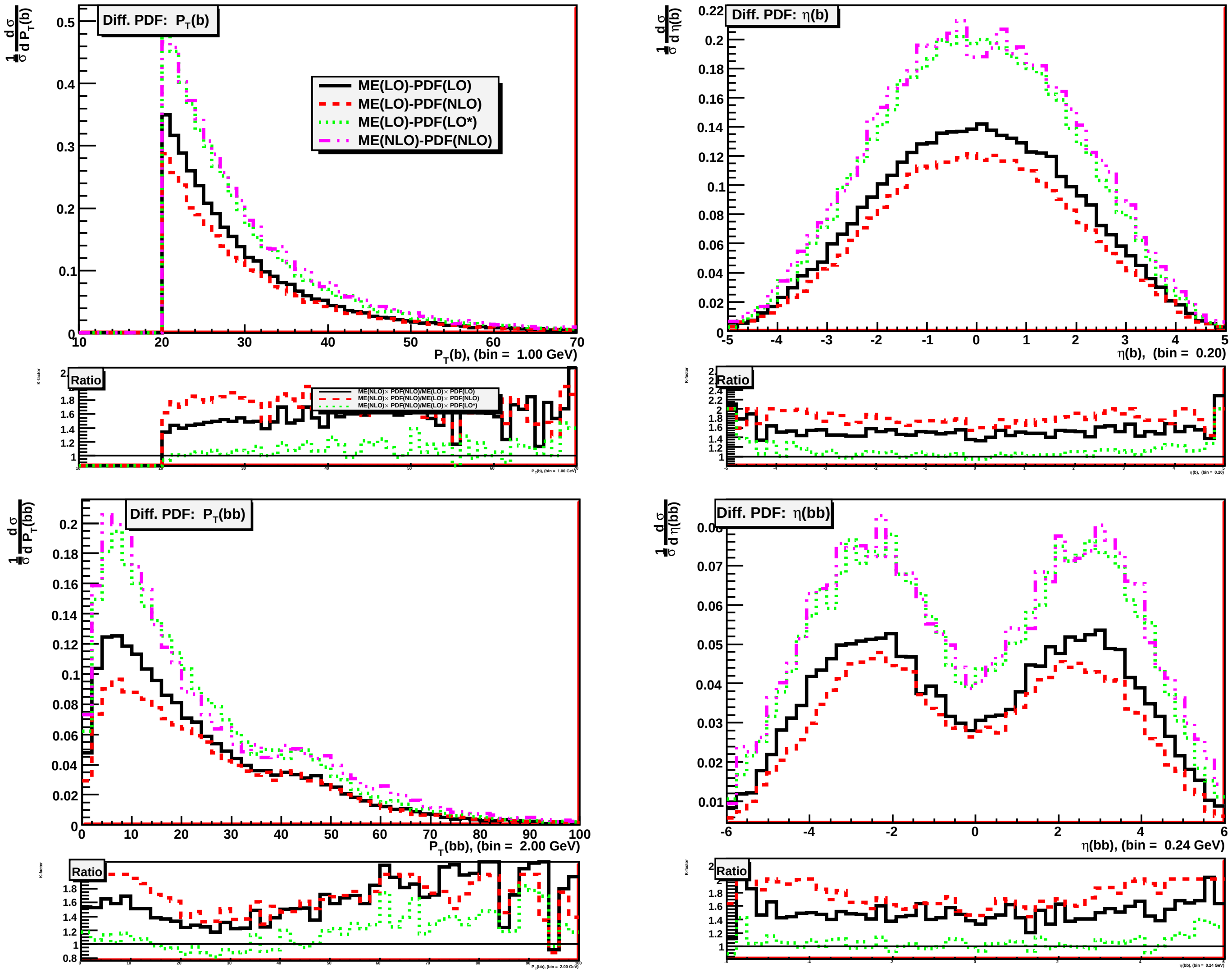
LO(ME)$\otimes$ LO(pdf)$= 1.85\mu b$.

LO(ME)$\otimes$ NLO(pdf)$= 1.56\mu b$.

LO(ME)$\otimes$ LO*(pdf)$= 2.63\mu b$.

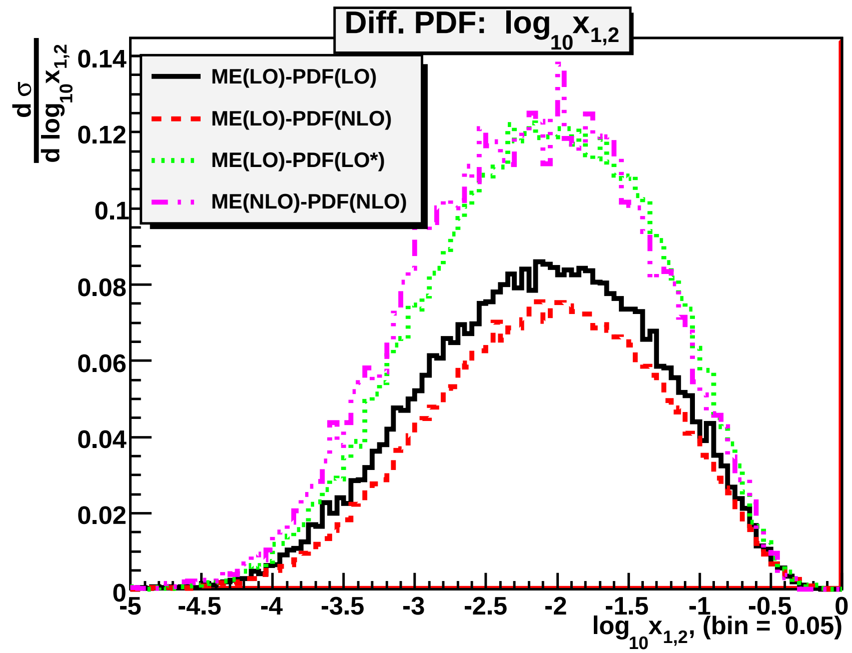
This process probes the fairly small x gluon, i.e. $x \sim 0.001$, so NLO partons are worst due to small gluon at small x.

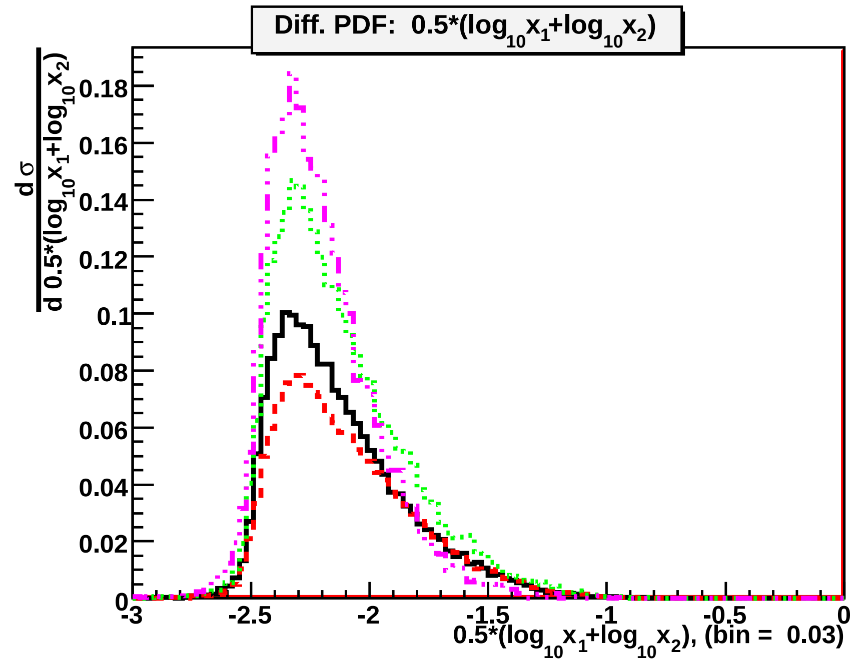
Also look at distributions for single b and $b\bar{b}$ pair.



Results using LO* partons clearly best in normalization. NLO worst and problems with shape at low scales (i.e. small x).

This probes the fairly small-x quarks, i.e. x down to 0.0001.





Similar for di-jet production (using JETRAD). Cuts $p_t > 20\mathrm{GeV}$, $|\eta(b)| < 5$, $\Delta R(j,j) > 0.5$.

NLO(ME)$\otimes$ NLO(pdf)$= 183\mu b$.

LO(ME)$\otimes$ LO(pdf)$= 150\mu b$.

LO(ME)$\otimes$ NLO(pdf)$= 116\mu b$.

LO(ME)$\otimes$ LO*(pdf)$= 178\mu b$.

This process probes also the fairly small x gluon, so NLO partons are again worst.

Very similar for $W + j$ production (using MCFM)

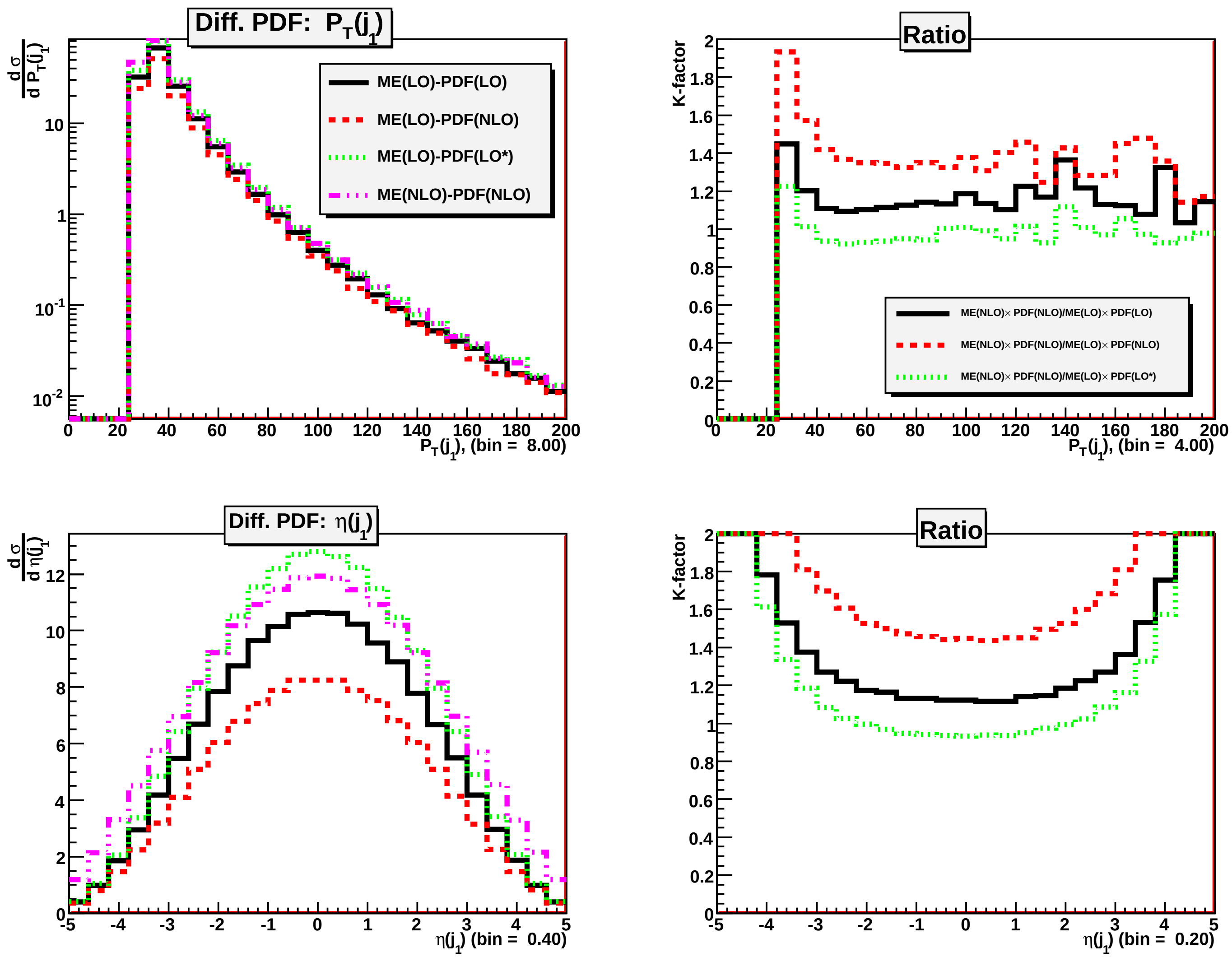
NLO(ME)$\otimes$ NLO(pdf)$= 21.1nb$.

LO(ME)$\otimes$ LO(pdf)$= 17.5\mu b$.

LO(ME)$\otimes$ NLO(pdf)$= 18.6\mu b$.

LO(ME)$\otimes$ LO*(pdf)$= 20.6\mu b$.

Also look at distributions for di-jets



Results using LO* partons clearly best in normalization. NLO again worst at low scales (i.e. small x).

NLO **Corrections**

Various reasons why NLO matrix elements may give large corrections.

- $1/z$ divergent terms in matrix elements.

- Large corrections from soft-gluon emissions near the edge of phase space, i.e. large threshold corrections.

- Large correction from analytic continuation from space-like to time-like region, i.e. $1 + \alpha_S C_F/2$ factor in Drell-Yan production.

W, Z, Higgs and $t\bar{t}$, b-production and jet production (including $W + j$) all have NLO enhancements from at least one of these sources. In each case the enhancement of LO* partons compared to LO compensates to some extent (often surprisingly well).

t-channel processes do not have these type of large corrections, and for e.g. single t or Higgs via vector boson fusion the NLO matrix-element correction is small. In these cases LO* over-compensate.

However, leaves shape of distributions more-or-less unchanged. Unless probe very small-x partons enhancement from LO* partons is not that big. But these processes do not probe very small-x too much by the nature of processes.

More recent developments - change of argument of coupling constant.

Monte Carlo generators use scale $p_t^2 = Q^2 * (1 - z)$ for the coupling constant in initial state parton branching rather than the standard PDF choice of Q^2. Automatically incorporates leading log corrections at high z.

Incorporated this scale in P_{qq} splitting function (by far most important effect at high z and x) in a parton number conserving manner - nonsinglet evolution still conserves number of valence quarks.

Quality of fit improves by ~ 50 units, mainly for high-x structure functions where resummation speeds evolution.

Allows $\alpha_S(M_Z^2)$ to lower to 0.115.

Input partons now carry 117% momentum, but this now falls with Q^2 since modified coupling leads to increased branching of high-x quarks.

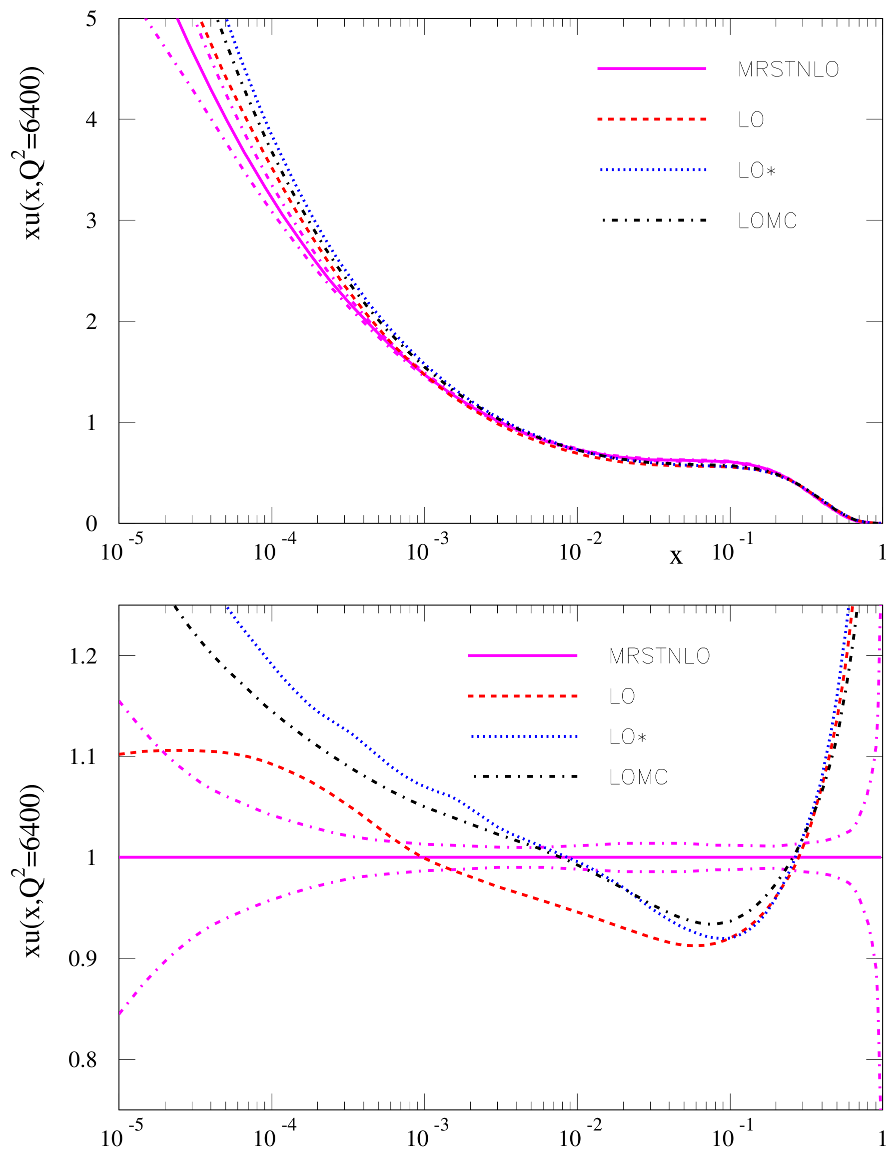
Overall change in partons LOMC compared to LO* very modest.

For quarks the LOMC distributions have a slightly different shape to those at LO*.

LOMC far more similar to LO* than to LO and NLO.

Very similar to LO* for $x = 0.005$, so W, Z production much the same.

Slightly smaller at very low x and also significantly smaller at very high x where change in coupling speeds evolution (more like NLO here).

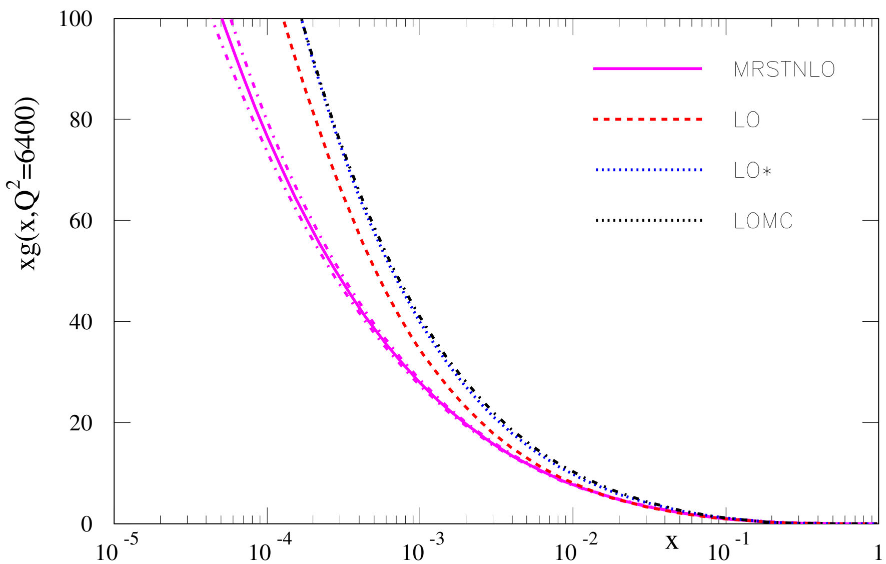


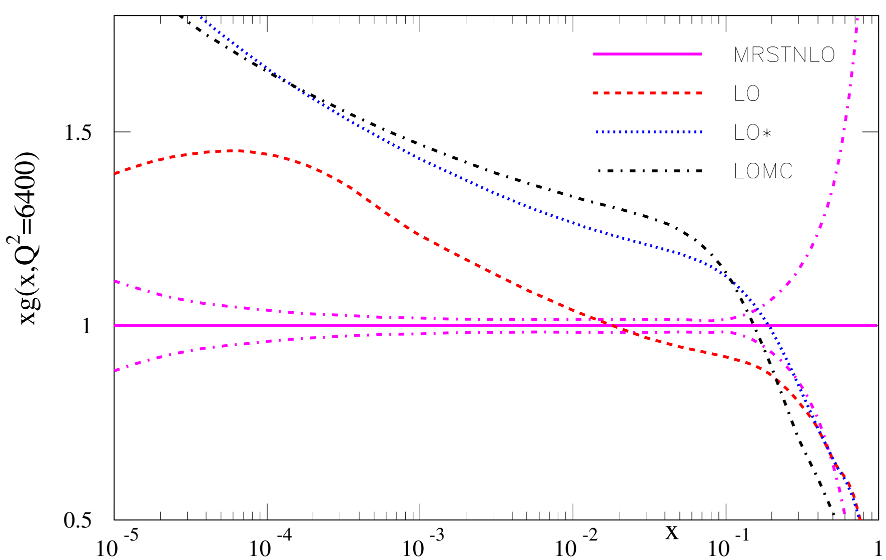
Similarly $g(x, Q^2)$ is a few percent bigger at LOMC than at LO* for $x \sim 0.01$, and still much bigger than NLO at small x.

LOMC far more similar to LO* than to LO and NLO.

Gluon-gluon initiated processes e.g. Higgs production and jets $\propto \alpha_S^2$, so small decrease in coupling compensates largely for increase in gluon for $x \sim 0.01$.

Nothing other than minor quantitative changes in all previous results on cross-sections.





Conclusions

Neither standard LO and NLO partons ideal for LO generators.

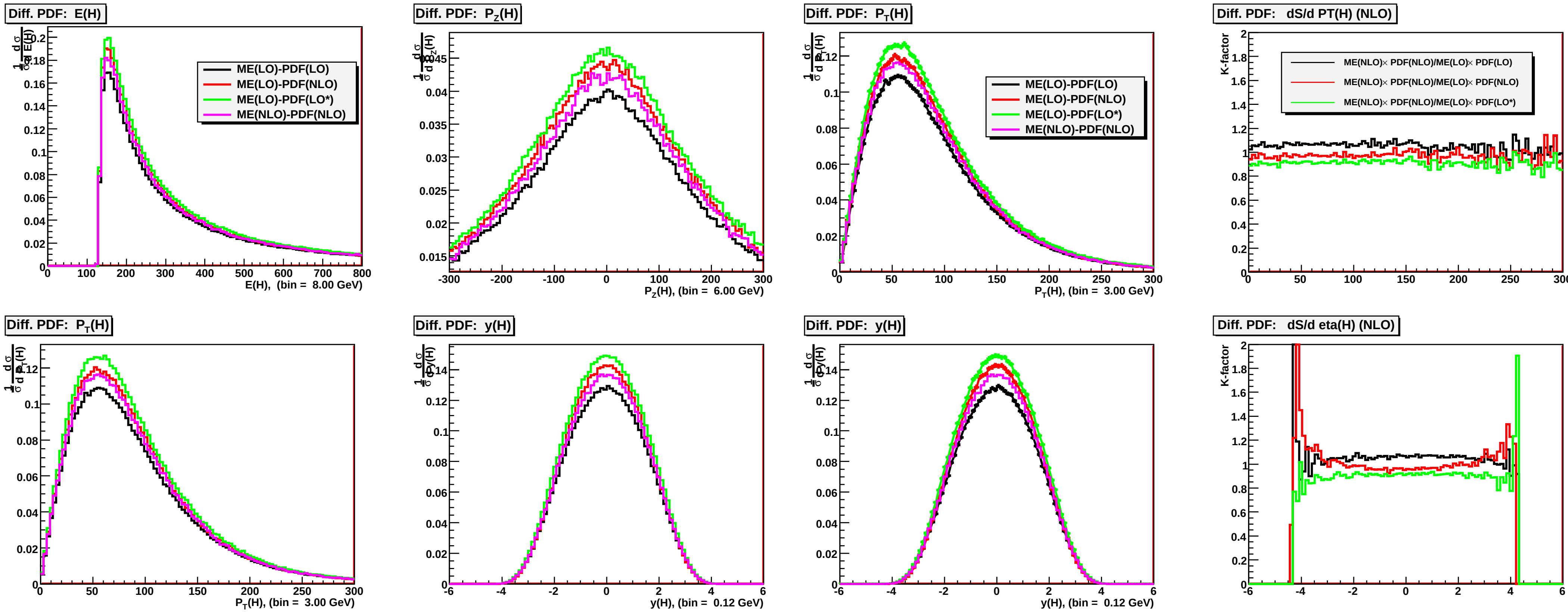
NLO gluon much smaller at small $x \rightarrow$ qualitative changes. LO quarks usually too small.

Introduce modified LO partons, i.e. momentum violation plus NLO coupling constant, and now Monte Carlo-inspired scale choice.

Comparison with processes where NLO known suggests modified LO partons usually provides most reliable results – especially if sensitive to smallish x. Additional partons allowed by extra momentum compensate semi-universally for higher orders.

Not always most accurate way to predict full NLO cross-sections (t-channel processes). However, never badly wrong for any particular parton in any particular range, unlike standard fixed order.

Also look at distributions for Higgs via VBF.



Results using LO* partons a bit high in normalization. NLO partons a little off in rapidity distribution.