J. Huston

Michigan State University

Experimental Introduction for (N)NLO Group Les Houches 2017

Making QCD Great Again

- I will concentrate on just a few topics, since Gudrun will be discussing issues related to NNLO calculations and Jesse on jet issues
- Mostly scale dependence and PDFs
- Following up on the Cambridge Workshop:Taming Unphysical Scales for Physical Predictions
- https://indico.cern.ch/event/555452/

…but first

- Follow-up of Higgs+jets studies from 2015
  - comparison of predictions and effects of parton showers on fixed order predictions for Higgs+jets
  - spoiler alert: parton showers affect fixed order cross sections basically only in Sudakov regions

Modulo scale choices, neither the addition of parton showers, or resummation a la STWZ or ResBos2 (resum for H+jet) seems to noticeablely affect the lead jet p_T cross section; unfolded data can be directly compared to fixed order (+NP)

Sherpa and Powheg NNLOPS agree with hj NNLO except at high p_T; Sherpa goes up and Powheg down; Sherpa uses $m_H/2$, Powheg CKKW/MiNLO

MEPS agrees with hj NNLO at low p_T; 10-20% lower at high p_T due to scale choice

Note agreement between NLO and NNLO

STWZ and ResBos2 agree with hj NNLO at low p_T; greater at high p_T due to different (common) scale choice ($m_H/2$); fixed, not dynamic like others

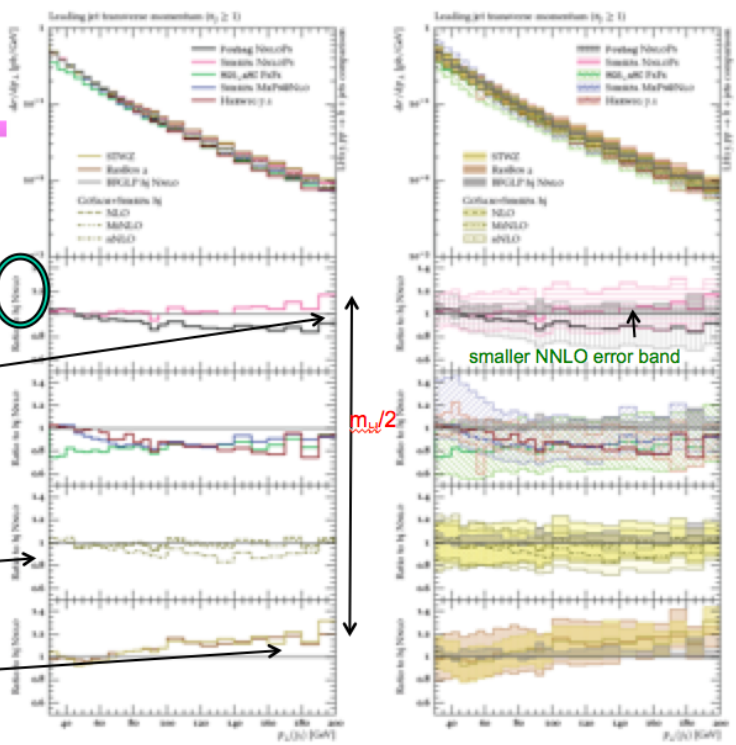


Fig. IV.14: The leading jet transverse momentum distribution for $h + \geq 1$-jet production, to the right (left) shown with (without) the uncertainty bands provided by the various calculations. The part below the main plot contains four ratio plots taken wrt. the NNLO result of the BFGLP group following the same strategy for grouping the predictions as before (NNLOPs versus NLO ME+PS versus fixed-order and resummation results).

…and not so much for inclusive observables such as the lead jet p_T for H+>=1 jet

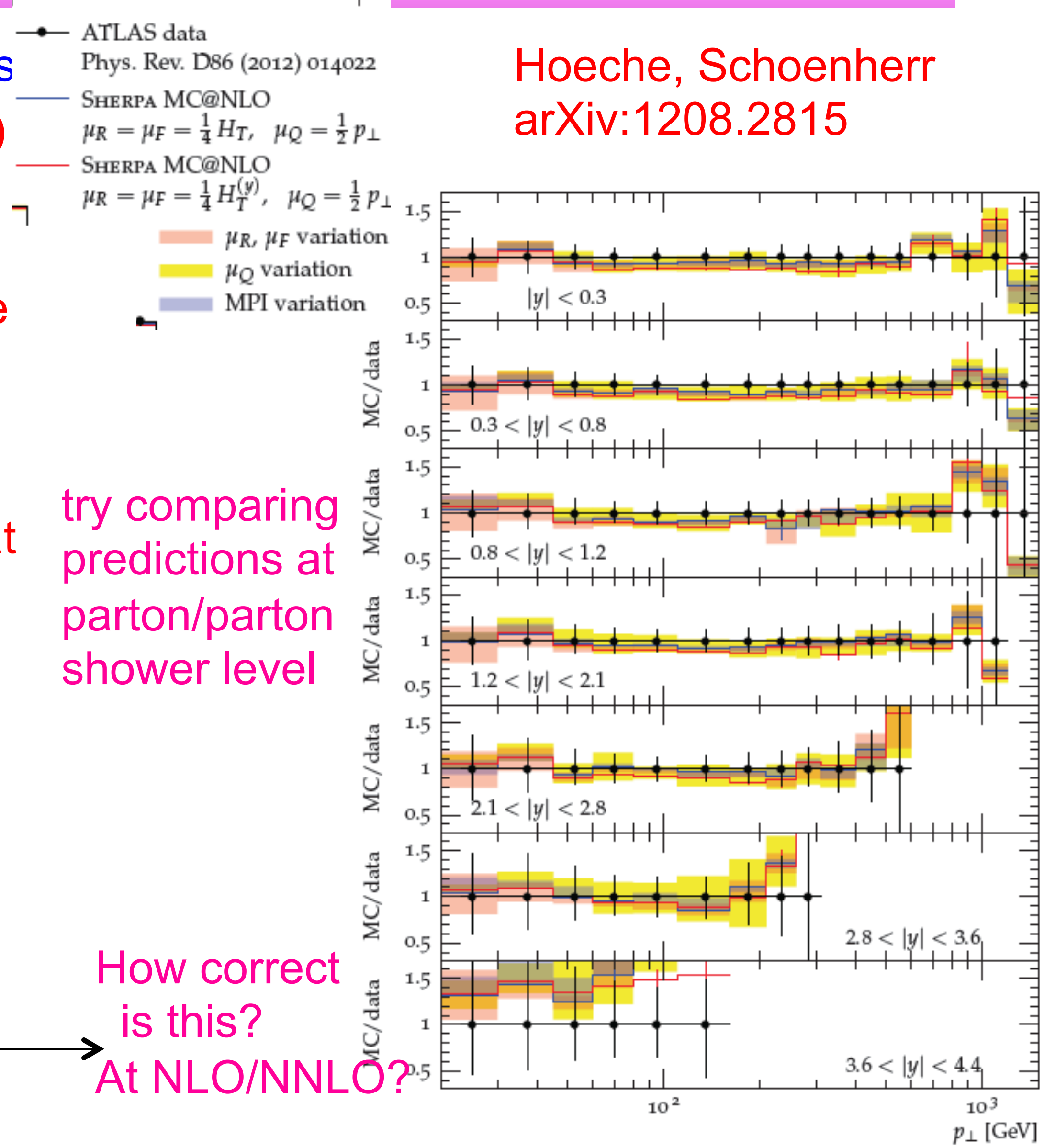
Inclusive jets

- This Les Houches try inclusive jets
  - PDF fits use fixed order (+NP) corrections
  - are we making a mistake, i.e. do the parton showers change the slope/normalization of the jet cross sections?
  - if so, then PDF fits may be in error, at least to the extent that jet production at the Tevatron and LHC affects the resulting PDFs
  - amazingly enough, there has been no systematic study
- Related
  - we determine hadronization effects from PS predictions and apply them to fixed order

Hoeche, Schoenherr
arXiv:1208.2815

try comparing predictions at parton/parton shower level

How correct is this?
At NLO/NNLO?



…and by the way

- In light of the high luminosities in Run 2, both ATLAS and CMS use the Cacciari-Salam jet area subtraction scheme, where the pileup (and underlying event) is subtracted
- Then cross sections are corrected back to the hadron level, by effectively adding back the underlying event (from Monte Carlo, with uncertainties)
- I don't completely understand this
- I hope to find out more at Les Houches

Pileup subtraction using jet areas

Matteo Cacciari and Gavin P. Salam

LPTHE, Université P. et M. Curie – Paris 6,

Université D. Diderot – Paris 7, CNRS UMR 7589, Paris, France

arXiv:0707.1378

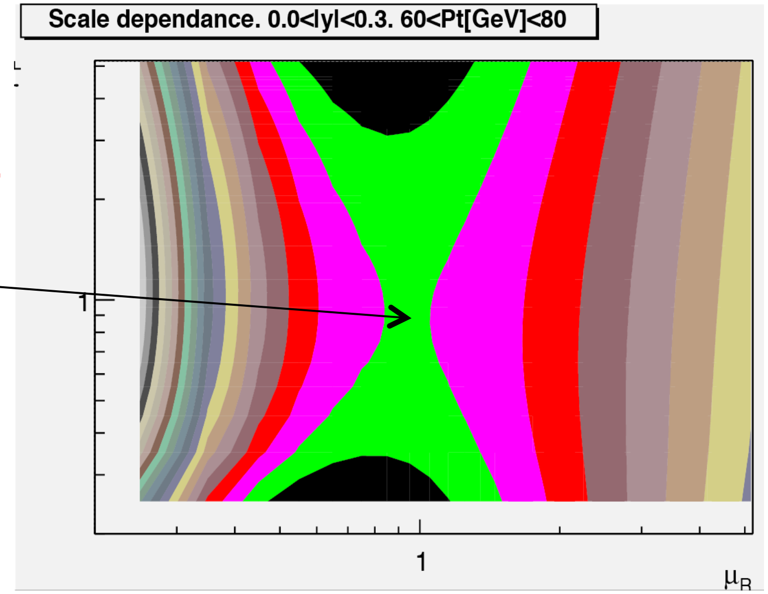
Scale choices

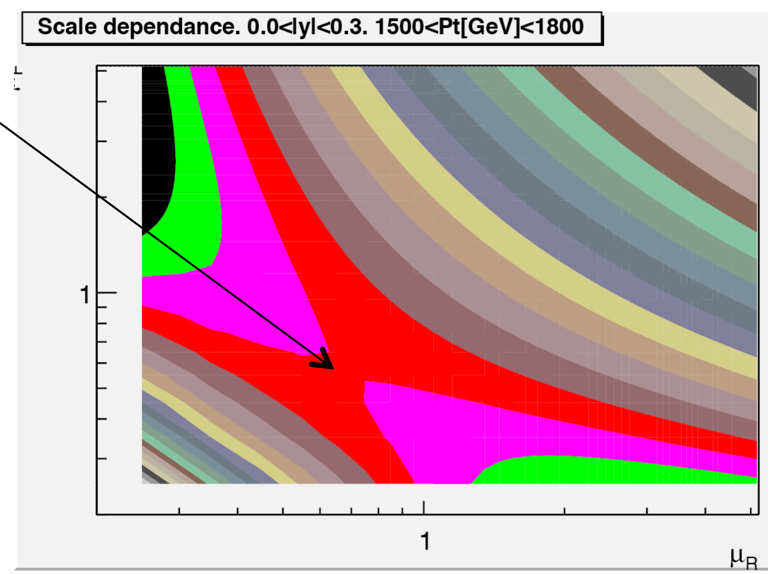
- Motivated choice of scale very important at NLO
- Still relevant at NNLO
- In some cases, relevant scale choice is obvious
  - p_T^{jet} for inclusive jet cross sections
  - …or should it be $p_T^{leadjet}$
- Does the preferred scale choice depend on the kinematics and/or the topology of the event?
  - if so, to what extent should this be taken into account?
- More and more NNLO calculations are becoming available allowing more data to be used in NNLO PDF fits
  - what are the best scales to use?
  - scale dependence may not be negligible, even at NNLO
- What about more complex situations, such as W+5 jets, or Higgs+3 jets, where there are multiple scales in the event?
- Does a global scale, like $H_T/2$ work (all the time)?
  - does it also depend on kinematics/topology?
- Why does it work?
- Can we make a connection to MC-like scales, such as with using a MINLO-approach?
  - work in progress, hopefully extended at Les Houches

Scale choices

- Take inclusive jet production at the LHC
- Canonical scale choice at the LHC is $\mu_r=\mu_f=1.0*p_T$
  - CTEQ6.6 used $0.5p_T$ for determination of PDFs
  - CT10/14 uses p_T
- Close to saddle point for low p_T
- But saddle point moves down for higher p_T (and the saddle region rotates)
- Saddle point also moves down for larger jet size
- For some kinematics, there is no saddle point
- Cross sections can even become negative for some scales of p_T

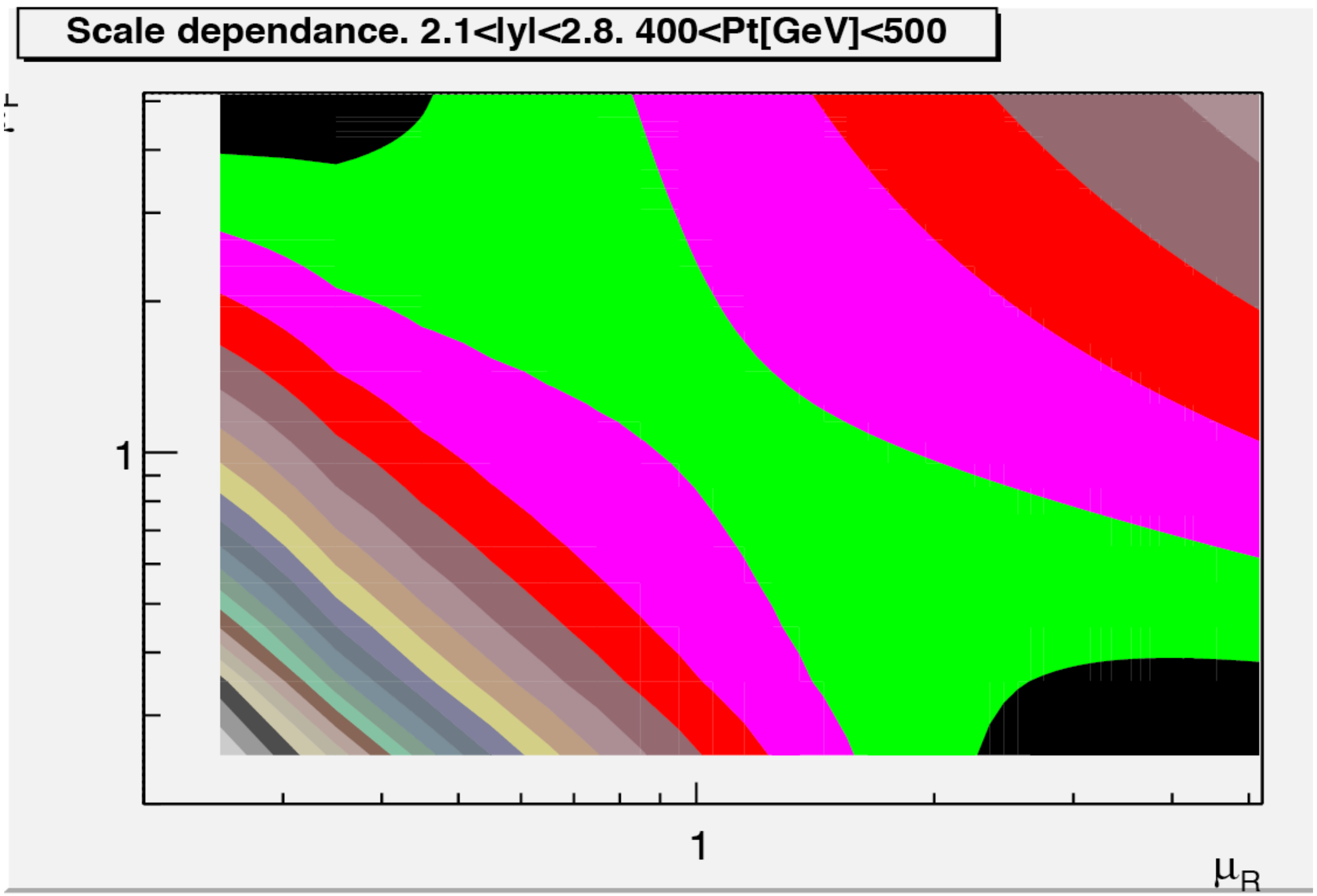
R=0.4
antikT





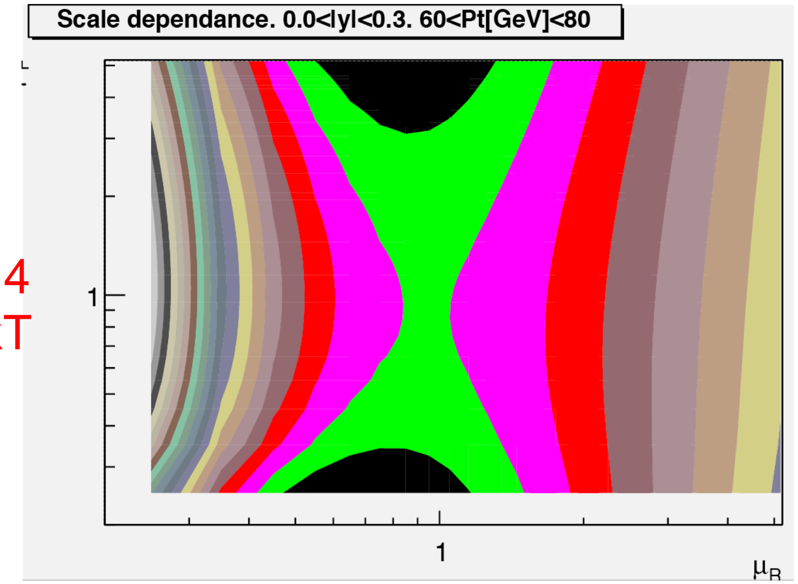
Scale dependence depends on rapidity

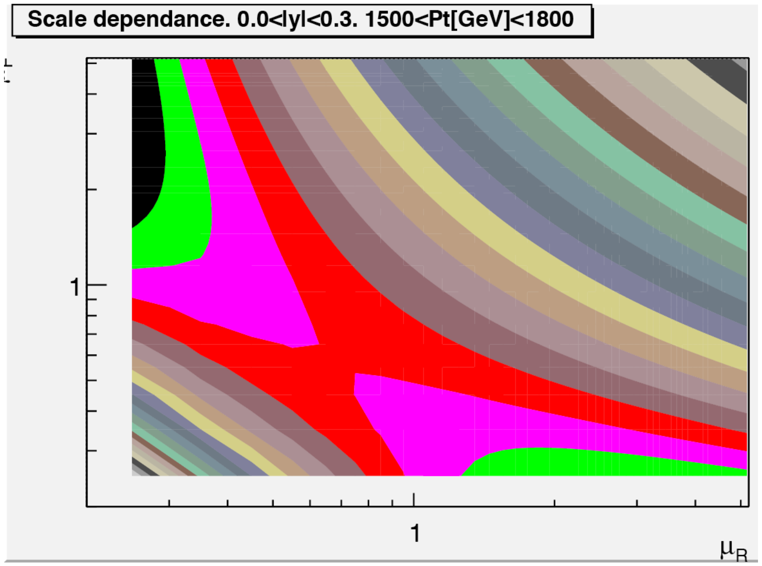
- The saddle point tends to move upwards in scale as the rapidity increases
- Is the physics changing; no, just the kinematics



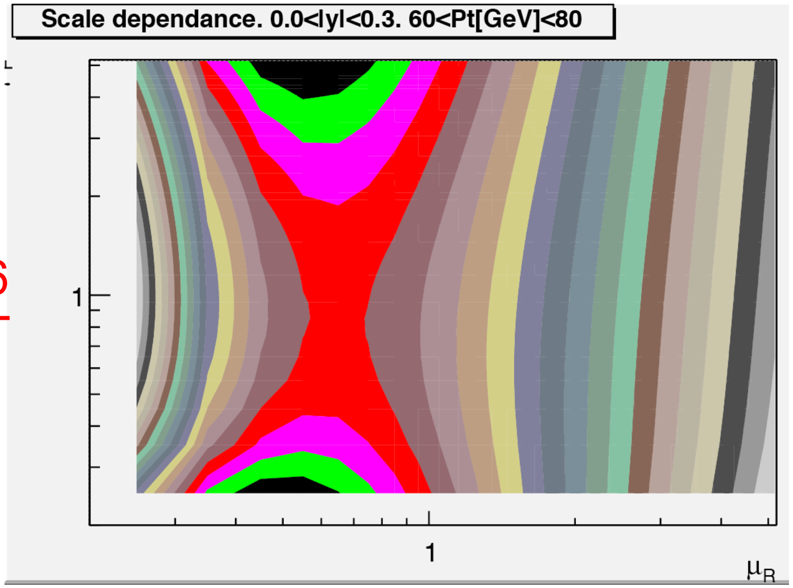
Scale dependence also depends on jet size

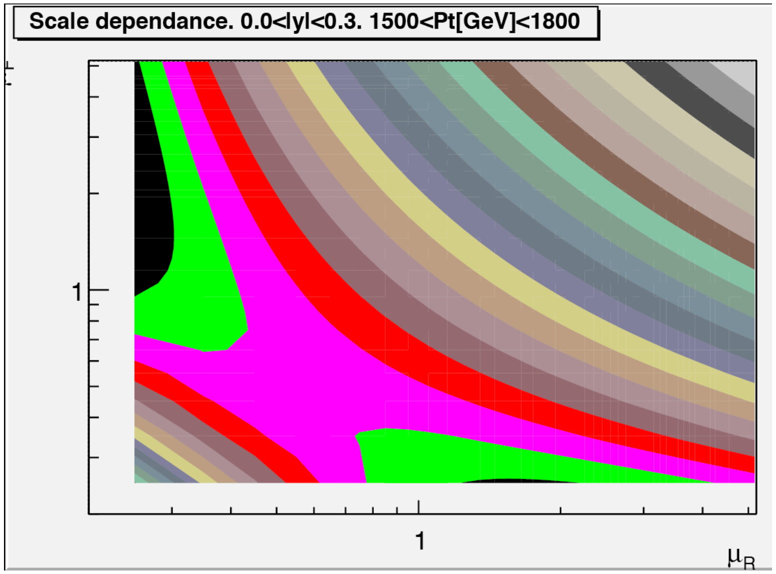
R=0.4
antikT





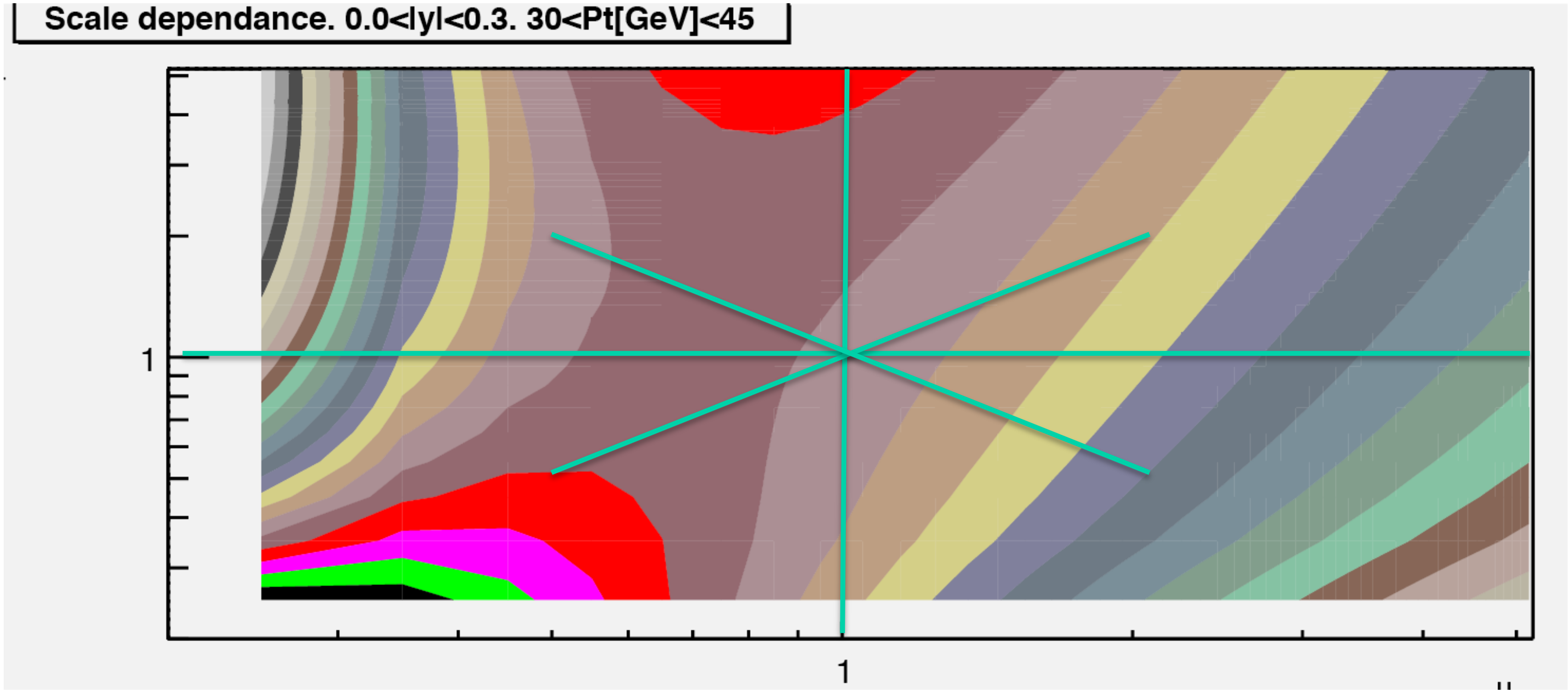
R=0.6
antikT





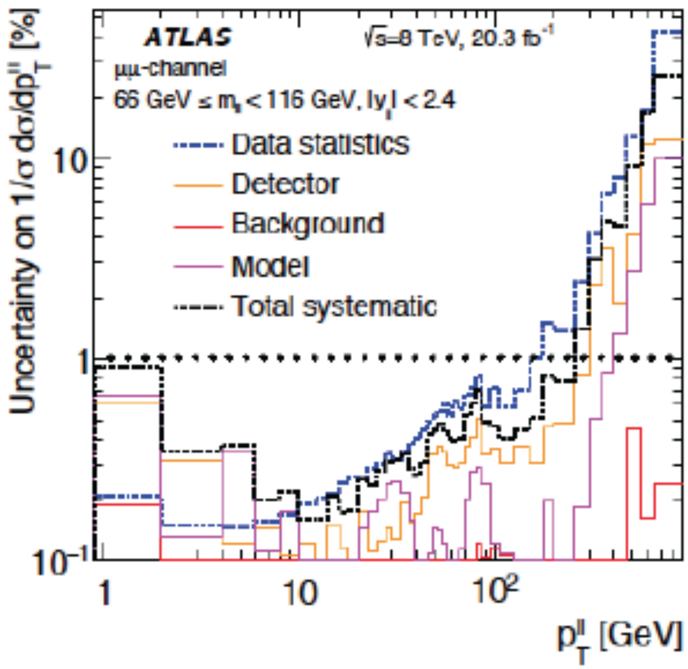
Scale variations

- Note that you may come up with a different estimate of the scale uncertainty depending on whether you use coherent or incoherent scale variations
- For many cross section, incoherent leads to smaller scale uncertainties

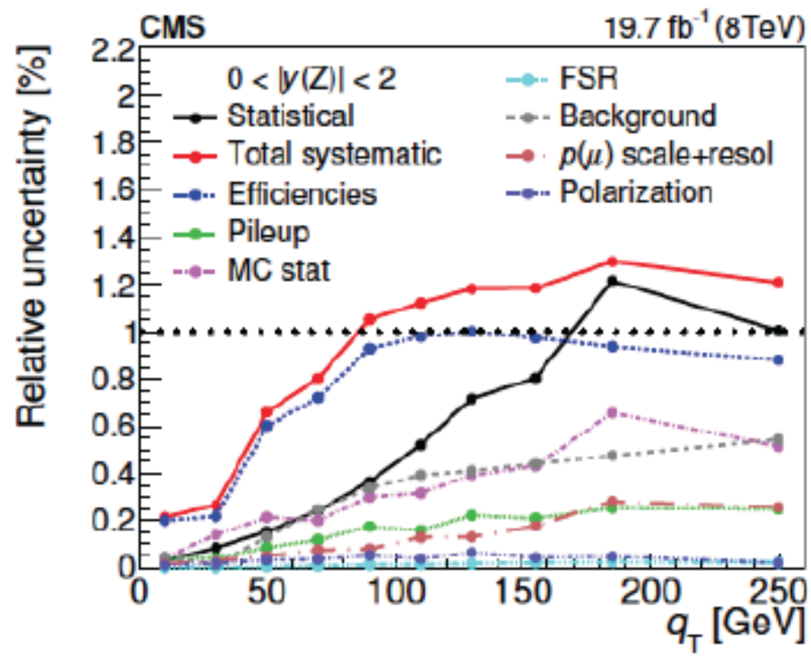


Data precision requires NNLO

- Luckily NNLO is available for most of the LHC processes that are essential for PDF fits (jets, top, Drell-Yan, photon/W/Z+jet)
- (Correlated) systematic errors can be so small that it can be difficult to get a good χ^2 in global PDF fits
- Jitter on K-factors (NNLO) often needs to be taken into account



ATLAS, arXiv: 1512.02192

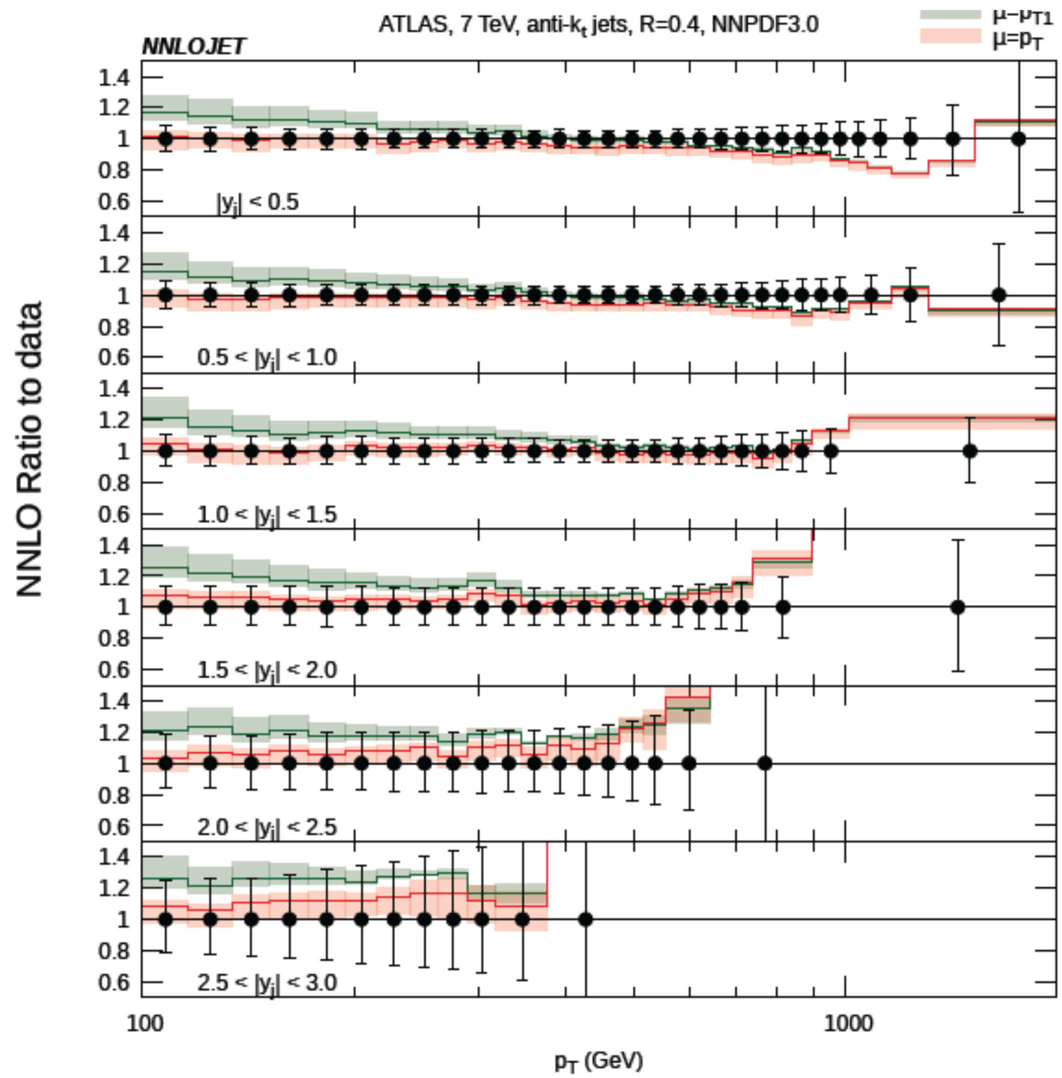


CMS, arXiv: 1504.03511

Inclusive jet production at NNLO

- Basically only process included in NNLO PDF fits not (until now) at NNLO
- Scale dependence greatly reduced…but sizeable differences between p_T^{jet} and $p_T^{leadjet}$
- Which scale choice is preferable? Difference larger than the nominal factor of 2 variation
- Religious wars: my opinion is that since this is an inclusive calculation, you should use an inclusive scale
    - ◆ this is not a classical Monte Carlo

arXiv:1705.08205



K-factor dependence

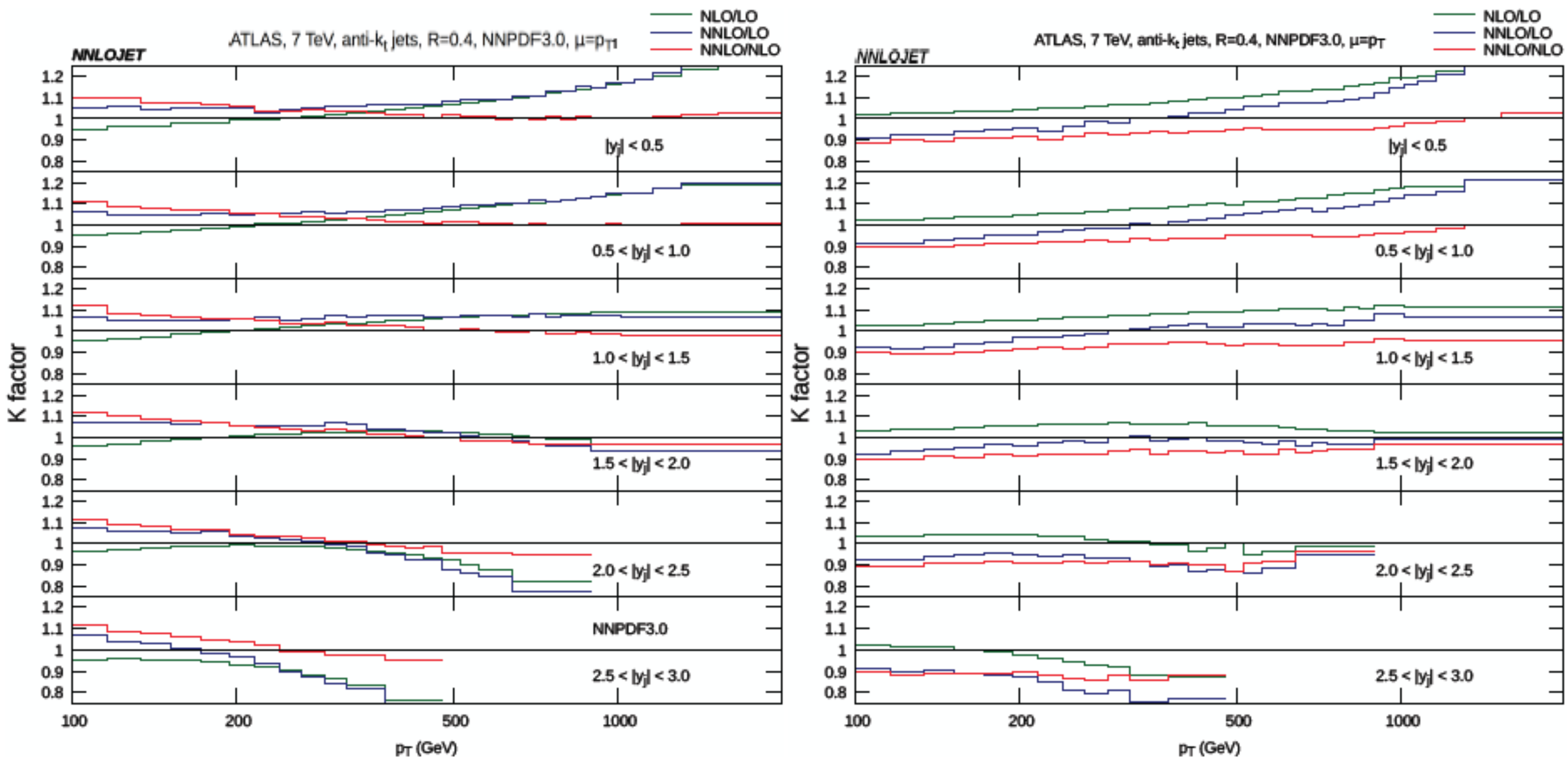


Figure 1 – NLO/LO (green), NNLO/NLO (red) and NNLO/LO (blue) k-factors for jet production at $\sqrt{s} = 7$ TeV. The lines correspond to the double differential k-factors (ratios of perturbative predictions in the perturbative expansion) for $p_T > 100$ GeV and across six rapidity $|y|$ slices. Lines correspond to theoretical predictions evaluated with NNLO PDFs from NNPDF3.0 and central scale choice $\mu = p_{T1}$ (left plot) and $\mu = p_T$ (right plot).

Dijet production

arxiv:1705.10271

- Two scales: p_T and m_{jj}
- Can be very different in the forward-backward region (large y*)
- With scales of p_T, can even end up with negative cross sections in the large y* region at NLO (don't know at NNLO)
- Ameliorated using a scale of m_{jj} (scale dependence shifting higher)

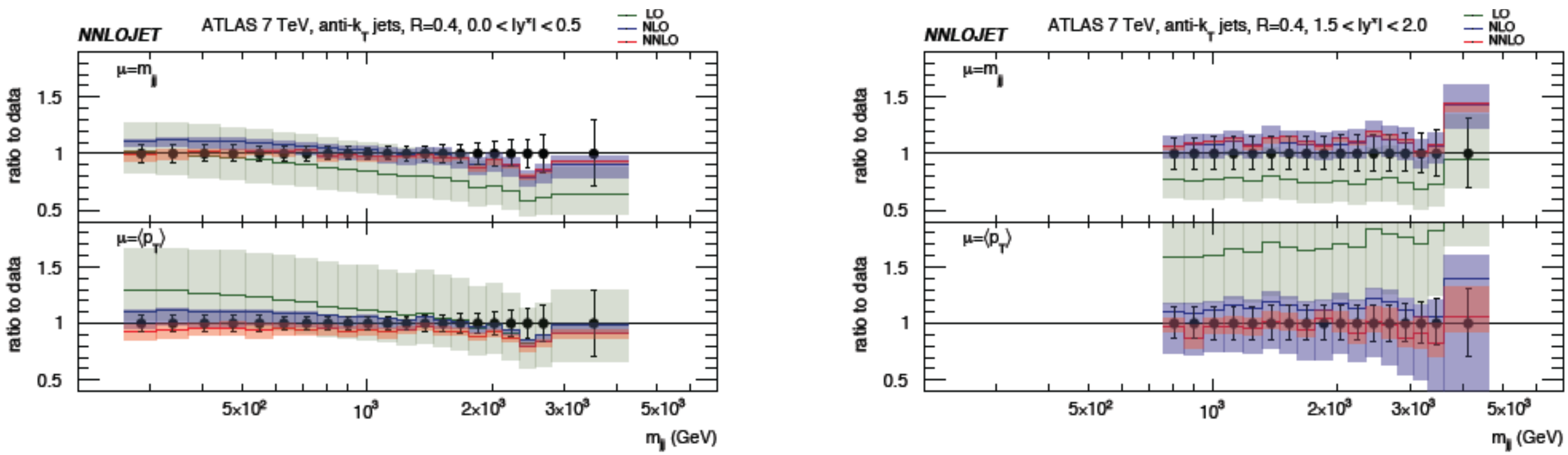


FIG. 1: Ratio of theory predictions to data for $0.0 < |y^*| < 0.5$ (left) and $1.5 < |y^*| < 2.0$ (right) for the scale choices $\mu = m_{jj}$ (top) and $\mu = \langle p_T \rangle$ (bottom) at LO (green), NLO (blue) and NNLO (red). Scale bands represent variation of the cross section by varying the scales independently by factors of 2 and 0.5.

What else (for inclusive jets)?

- There are tensions between ATLAS and CMS jet data
- There are tensions within the ATLAS jet data (between rapidity intervals)
- We know that the jet data as a function of rapidity have to be consistent, i.e. PDF's are universal
- Even with very precise data, it may be difficult to reduce PDF uncertainties in global PDF fits, due to these conflicts; this requires a comprehensive exploration by PDF groups

- Many/most of LHC measurements made with the antikT jet algorithm with R=0.4; a few processes measured at multiple jet sizes->this provides more information
- Are there important ln R terms that should be resummed for best accuracy?

How to decide - Essential Criteria   For X+jet

Nigel Glover
Scales Workshop
Cambridge
March 2017

- ✓ Convergence - corrections should be moderate over whole of phase space
  Need explicit calculation to check this
- ✓ In the Born limit, the scales collapse onto M_X

$$\checkmark \quad \sqrt{M_X^2 + p_{TX}^2} \to M_X, \qquad ✗ \quad p_{TZ} \to 0$$

- ✓ In the massless limit, the scales collapse onto scales used for jets

$$\sqrt{M_X^2 + p_{TX}^2} \to \not{M}_X \quad p_{TX}$$

- ✓ In the multiparticle limit, the scales allow for X radiation in multi jet events

$$H_T'(n) \to H_T'(n+1),$$

- ✓ and is smooth when fewer jets are identified,

$$H_T'(n) \to H_T'(n-1),$$

- ✓ How well the scale choice matches onto resummations/parton showers
- ➠ In fact, this is an issue relating to accuracy and precision

How to identify the dynamic scale? for tT

- By performing a number of fully differential calculations for top-pair production at the LHC based on the following set of functional forms:

$$\mu_0 \sim m_t \ ,$$

$$\mu_0 \sim m_T = \sqrt{m_t^2 + p_T^2} \ ,$$

$$\mu_0 \sim H_T = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2} \ ,$$

$$\mu_0 \sim H_T' = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2} + \sum_i p_{T,i} \ ,$$

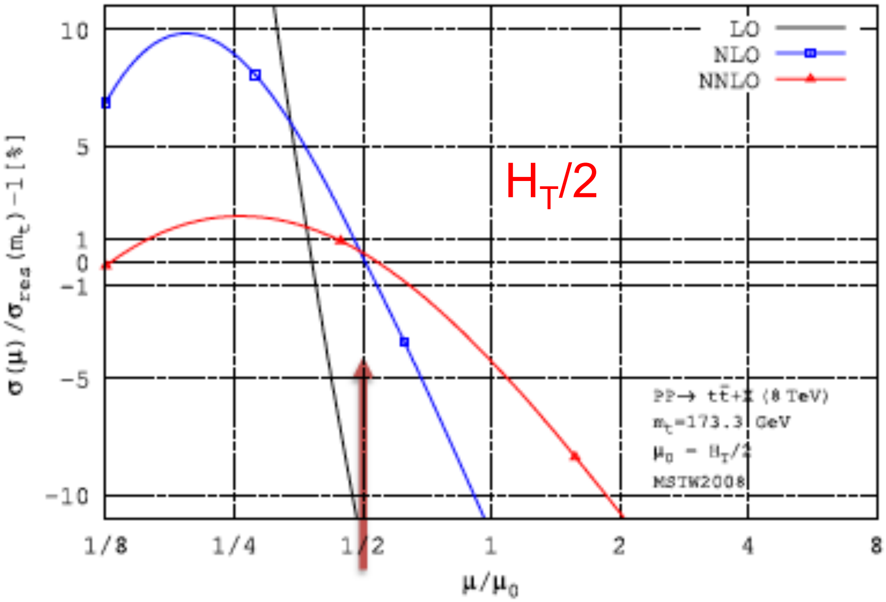
$$\mu_0 \sim E_T = \sqrt{\sqrt{m_t^2 + p_{T,t}^2}\sqrt{m_t^2 + p_{T,\bar{t}}^2}} \ ,$$

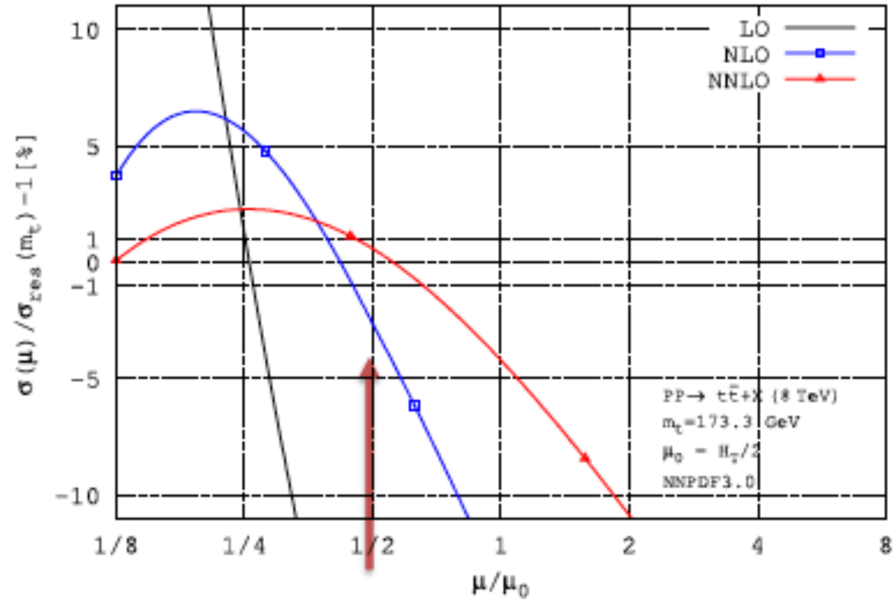
$$\mu_0 \sim H_{T,\mathrm{int}} = \sqrt{(m_t/2)^2 + p_{T,t}^2} + \sqrt{(m_t/2)^2 + p_{T,\bar{t}}^2} \ ,$$

$$\mu_0 \sim m_{t\bar{t}} \ ,$$

NOTE: the coefficients above are arbitrary and should be fixed together with the functional form!

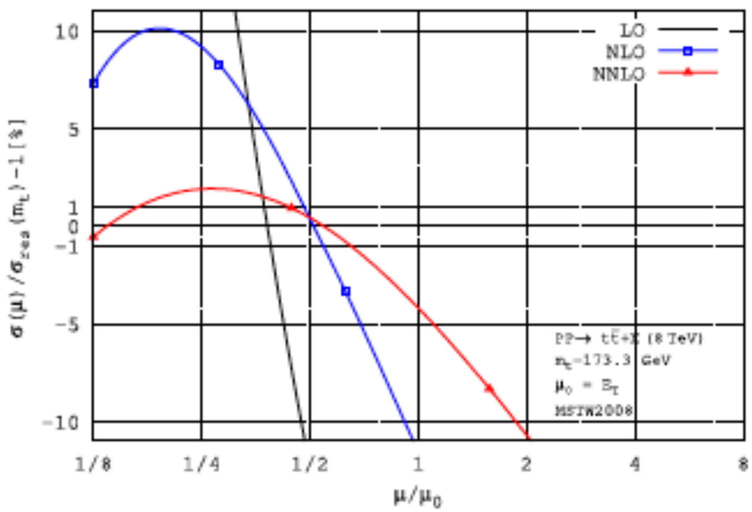
- Total cross-section with various dynamic scales and for different PDF's

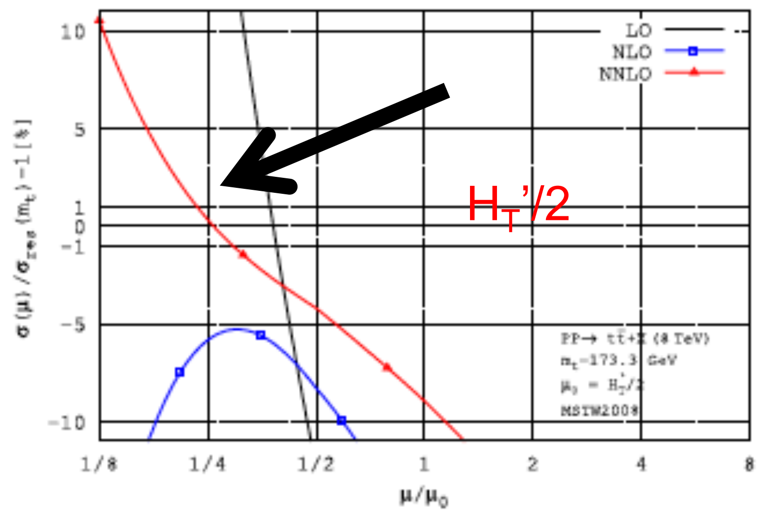




- The total x-section with dynamic scale == resumed x-section with fixed scale
  - Effect of resummation for 'best' scale is negligible (0.5% effect)

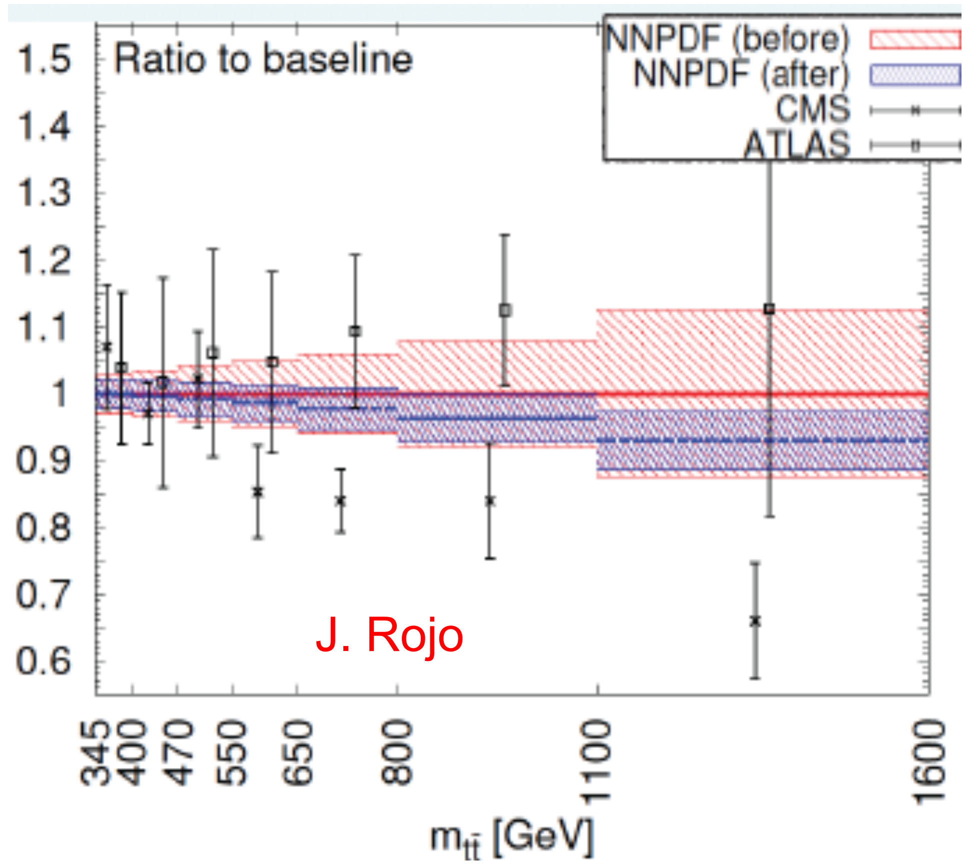
Two less-optimal scales:





Top production in PDF fits

- Tops at the LHC are produced primarily by gg fusion, so great handle on the gluon distribution, especially at high x
- Several observables that provide information
  - m_{tT}
  - y_{tT}
  - y_T
  - p_T^t
  - p_T^{tT}
- But, there is tension not only between ATLAS and CMS, but also between observables within each experiment, which cover similar x ranges



How to deal with the tension and provide better constraints on the gluon distribution?

Google document for Cambridge Scales Workshop

- https://docs.google.com/document/d/1h1WM_6m-Y2MhShxi7glW87FFBuK0rpWeK9AIB3nn-pE/edit?pref=2&pli=1

Summary questions for workshop

1. Collect information of processes/scale choices that do not work - can we understand why some scales work well for some observables for a given process, but not for others (as for example for tT)
2. Collect information on processes/scale choices where PDFs give very different answers - as for example for tT; this must be due to specific initial states, for example gq
3. What exactly do we expect for scale dependence at NNLO? My generic expectation is a flatter parabola than at NLO; this is not the case, however, for inclusive jet production - can we understand what logs are "active" based on the scale dependence shape, especially for those scale choices that seem aberrant.
4. Do we expect the optimal scales to decrease as the order increases? If so, why? The argument for jet production at NLO was that since you are probing inside the jet, you shouldn't use the full value of the jet pT, but more like pT/2 (this, however, turned out to be a very geometric argument, i.e. it varies with jet size and algorithm)
5. How should the optimal scale (and range of scale uncertainty) depend upon the jet size/algorithm (although the latter is mostly moot at the LHC as antikT is universal); how should the optimal scale depend on the rapidity and transverse momentum of the observable->need 2D understanding as discussed below
6. Is quickness of convergence the best tool for choosing a scale? -as a corollary, should the scale choice result in flat differential K-factors, a la HT/2 for Blackhat+Sherpa

7. Can local scale choices such as MINLO motivate the form of global dynamic scales -this is being tested with H+jets, W+jets and tT+jets; in the first two cases, the result for 1 jet can also be related to the NNLO result
8. Are we currently estimating scale uncertainties correctly? We seem to be working somewhat blindly in our scale variations of mu_R, mu_F up and down by a factor of 2; where possible, I would advocate looking at the 2-D scale variation to understand the logs better; this is relatively straightforward at NLO, and will become increasingly so at NNLO with the new versions of applgrid/fastNLO; something more like the Olness-Soper technique may be preferred
9. Can SCET provide motivation for optimal scales, at least for processes where SCET has been applied? How can we test this/generalize this? -as a corollary, does knowing the color structures at a given order help to understand the best scales to use, as Matt → Schwartz said
10. Ratios of cross sections; we can categorize situations where the choice of the same (or similar) scale for the numerator and denominator is warranted; in order of strength of validity -ratio of same cross section at different energies
    - ratio of same cross section at different rapidities
    - ratio of n/n-1 jet cross sections; note that "naive" Stewart-Tackmann would hold that these are two completely independent processes and thus are uncorrelated
    - ratio of X+n jet/Y+ n jet, where X and Y are similar, i.e. W and Z
    - ratio of X+n jet/Y+ n jet, where X and Y are dissimilar, i.e. W and H

Precise predictions for V+jets dark matter backgrounds

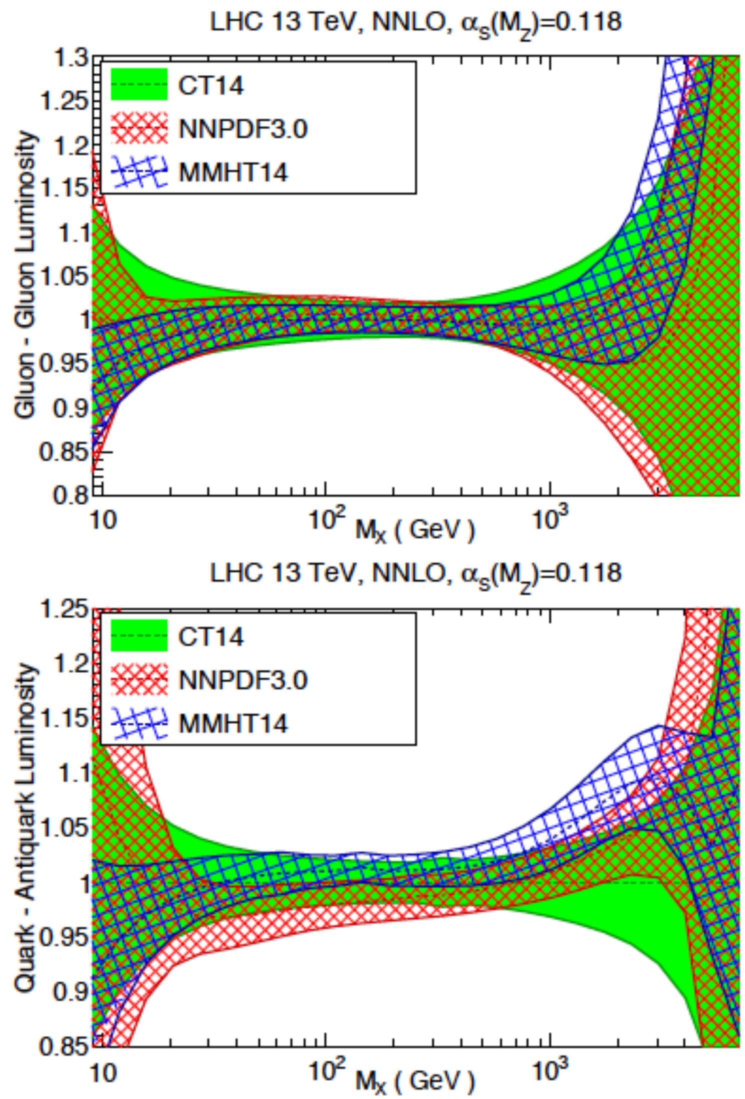
J. M. Lindert[1], S. Pozzorini[2], R. Boughezal[3], J. M. Campbell[4], A. Denner[5], S. Dittmaier[6], A. Gehrmann-De Ridder[2,7], T. Gehrmann[2], N. Glover[1], A. Huss[7], S. Kallweit[8], P. Maierhöfer[6], M. L. Mangano[8], T.A. Morgan[1], A. Mück[9], F. Petriello[3,10]. G. P. Salam*[8]. M. Schönherr[2]. and C. Williams[11]

Abstract

High-energy jets recoiling against missing transverse energy (MET) are powerful probes of dark matter at the LHC. Searches based on large MET signatures require a precise control of the $Z(\nu\bar{\nu})$+ jet background in the signal region. This can be achieved by taking accurate data in control regions dominated by $Z(\ell^+\ell^-)$+ jet, $W(\ell\nu)$+ jet and γ+ jet production, and extrapolating to the $Z(\nu\bar{\nu})$+ jet background by means of precise theoretical predictions. In this context, recent advances in perturbative calculations open the door to significant sensitivity improvements in dark matter searches. In this spirit, we present a combination of state-of-the-art calculations for all relevant V+ jets processes, including throughout NNLO QCD corrections and NLO electroweak corrections supplemented by Sudakov logarithms at two loops. Predictions at parton level are provided together with detailed recommendations for their usage in experimental analyses based on the reweighting of Monte Carlo samples. Particular attention is devoted to the estimate of theoretical uncertainties in the framework of dark matter searches, where subtle aspects such as correlations across different V+ jet processes play a key role. The anticipated theoretical uncertainty in the $Z(\nu\bar{\nu})$+ jet background is at the few percent level up to the TeV range.

What else for PDFs?

- The global PDF groups (CT, MMHT, NNPDF) have achieved good precision, especially for gg
- But have they achieved good accuracy?
- One way of understanding the accuracy is if new data leads to refinements of current PDFs, rather than leads to new conflicts
- We also need to consider the scale uncertainties in global PDF fits
  - less impact at NNLO than at NLO, but still may be important
- There is an NNLO revolution going on, but we need good access to the results for PDF fitting
  - session on Wed



10th Les Houches

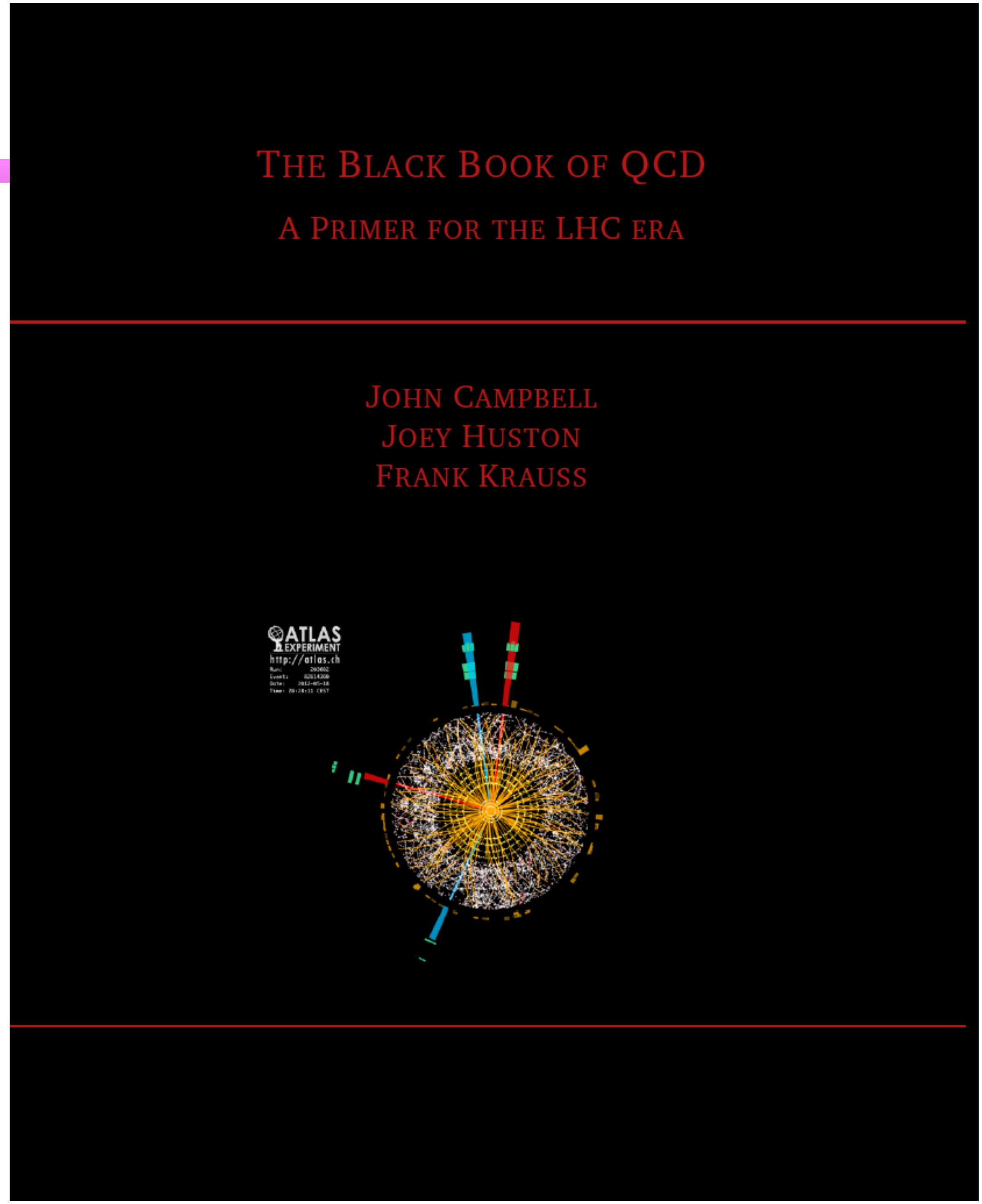
- At the first Les Houches, the non-French attendees asked the French attendees what a Houches was.
- …and no one knew
- Turns out it wasn't a French word per se but a Gallic word, meaning a small plot of land near a building used for cultivation

Les Houches 2017

- As an American, I expect to be asked the meaning of *covfefe*
- I think it means a small plot of hair on top of a head, that looks too bad to be a wig
- But I think it should play a role in the 2017 Les Houches theme song


LoopFest XVII
second half of July 2018
Michigan State University

In production
available December 2017



Another scheme

- F. Olness and D. Soper, arXiv: 0907.5052
- Define x_1 and x_2

$$x_1 = \log_2\left(\frac{\mu_{\rm uv}}{P_T/2}\right)$$

$$x_2 = \log_2\left(\frac{\mu_{\rm col}}{P_T/2}\right)$$

- Make a circle of radius |x|=2 around a central scale (could be saddle point, or could be some canonical scale) and evaluate the scale uncertainty

$$\left[\frac{d\sigma(x_1,x_2)}{dP_T}\right]_{\rm NLO} \approx \left[\frac{d\sigma(0,0)}{dP_T}\right]_{\rm NLO} [1 + P(\vec{x})]$$

where

$$P(\vec{x}) = \sum_J x_J A_J + \sum_{J,K} x_J M_{JK} x_K$$

A_J and M_{JK} carry information on the scale dependence beyond NLO

$$\mathcal{E}^2_{\rm scale} = \frac{1}{2\pi}\int_0^{2\pi} d\theta\ P(|\vec{x}|\cos\theta, |\vec{x}|\sin\theta)^2$$

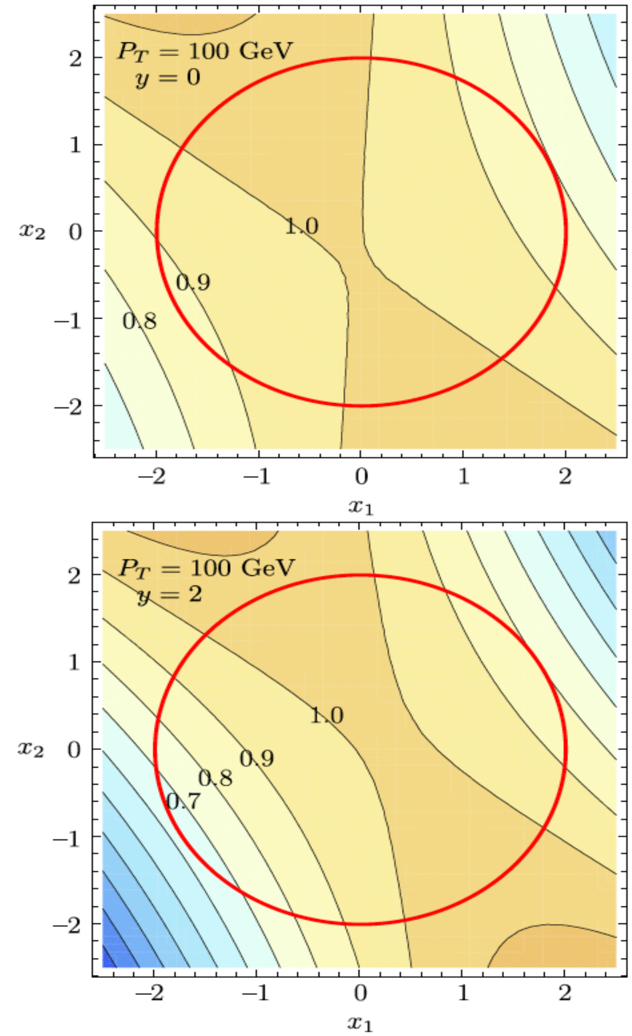


Figure 2: Contour plot of the jet cross section in the $\{x_1, x_2\}$ plane for the Tevatron ($\sqrt{s} = 1960$ GeV) with $P_T = 100$ GeV and a) central rapidity $y = 0$ and b) forward rapidity $y = 2$. We plot the ratio of the cross section compared to the central value at $\{x_1, x_2\} = \{0, 0\}$. Contour lines are drawn at intervals of 0.10. The (red) circle is at radius $|x| = 2$.