Introduction for SM (loops, multi-legs) experimental

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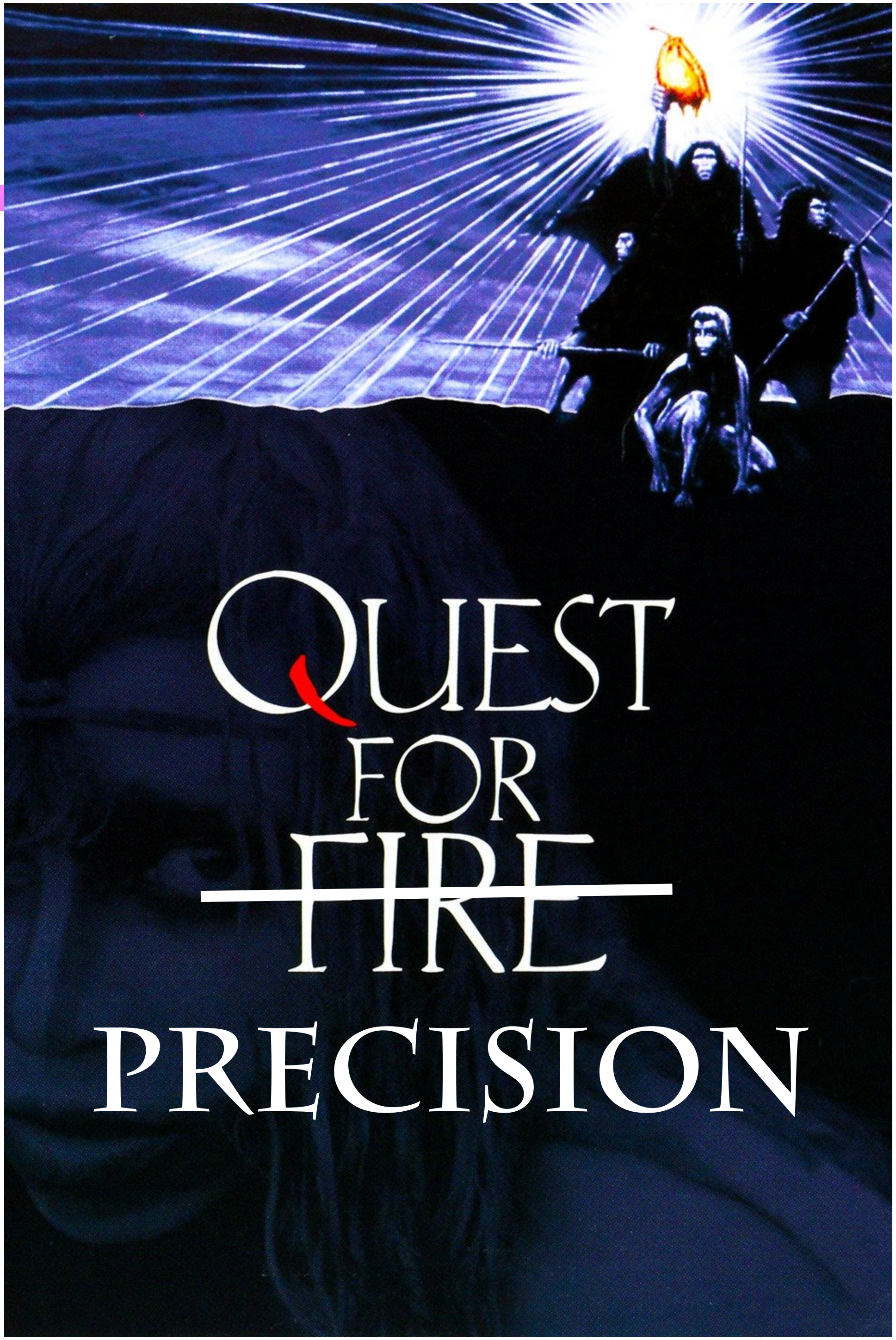
20! Years of the Les Houches Workshop

- It's clear by now that copious new physics isn't jumping out at us
- In order to better understand the SM, and especially, the Higgs sector, we have to extend our precision (as well as our kinematic reach)
- This may involve improvements on both the theoretical and experimental fronts, for example
  - measurements of photons, leptons, jets,boosted objects
  - extension of NNLO to 2->3 processes
  - (more) inclusion of EW effects
  - more precise PDFs, better understanding of precision of PDFs

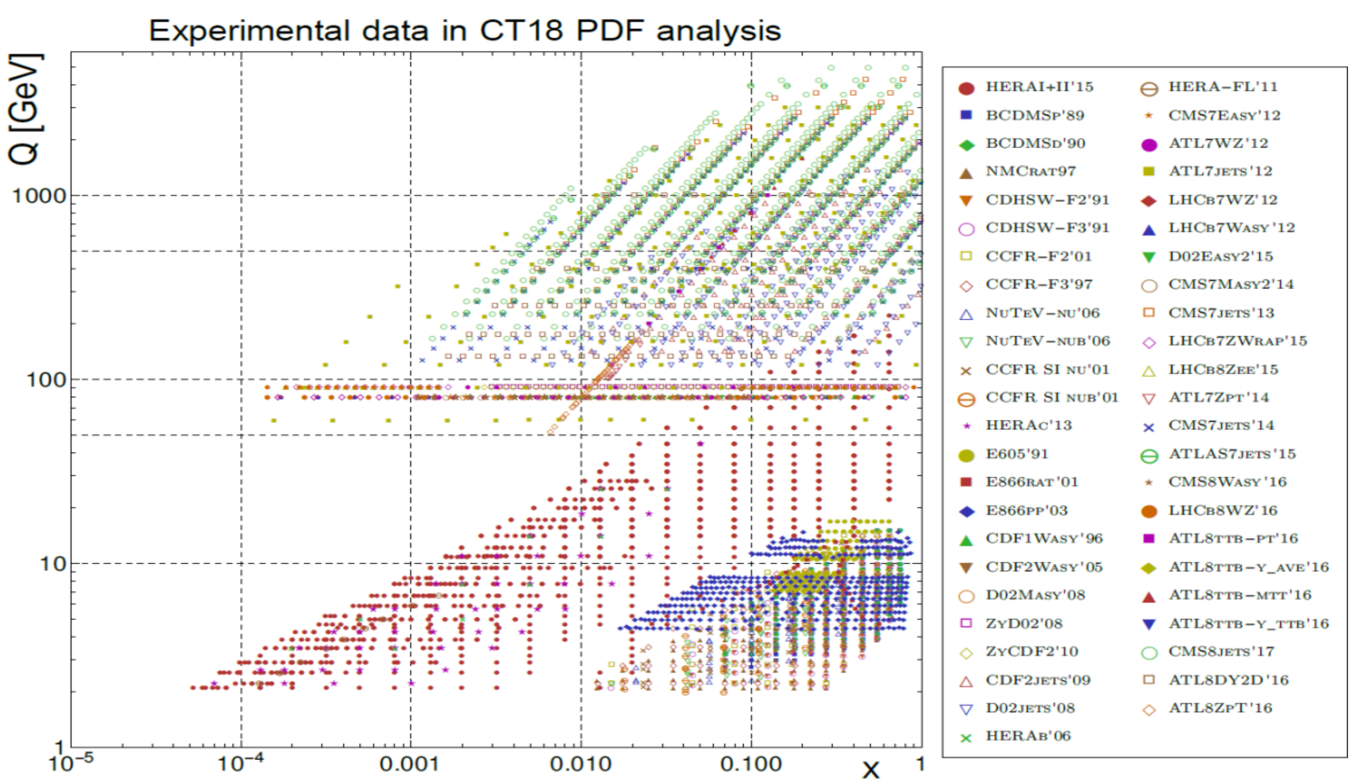


Some themes for Les Houches (non-musical)

- PDFs
  - benchmark studies/comparison of new generation of PDFs (will schedule session)
  - using NNLO grids (NNLOJET), ntuples, etc (see Alex's talk)
  - dealing with scale uncertainties in PDF fits (Stefano Forte will lead session Friday morning)
- photon isolation (Leandro Cieri will lead discussion Friday afternoon)
- ME(+PS)
  - better understanding of limits of precision for ME/ME+PS
  - uncertainties in matching PS with ME
  - better understanding of 'reasonable' scale uncertainties at NNLO
  - precision predictions in the high p_T frontier
    - carrying over from precision region to boosted region (Felix Ringer will lead a session on resummation in jets)
  - getting ready for NNLO 2->3; updates to the wishlist (see Alex's talk)

Global PDF fits

- There is a wide variety of data in modern global PDF analyses, over 3500 data points for CT18; similar for MMHT, NNPDF
- The data includes DIS, DY (including precision W/Z), jet production, top production, sensitive to PDFs over a wide kinematic range
- In CT PDF fits, there are three stages: preview (PDFSense), the global fit itself, and postview (Lagrange Multiplier)



How sensitive is an experiment to a PDF?
Can we know it **before** doing the global fit?

PDFsense predicts that HERA2 and the CMS jet data will have the largest impact

PDFSense estimates…

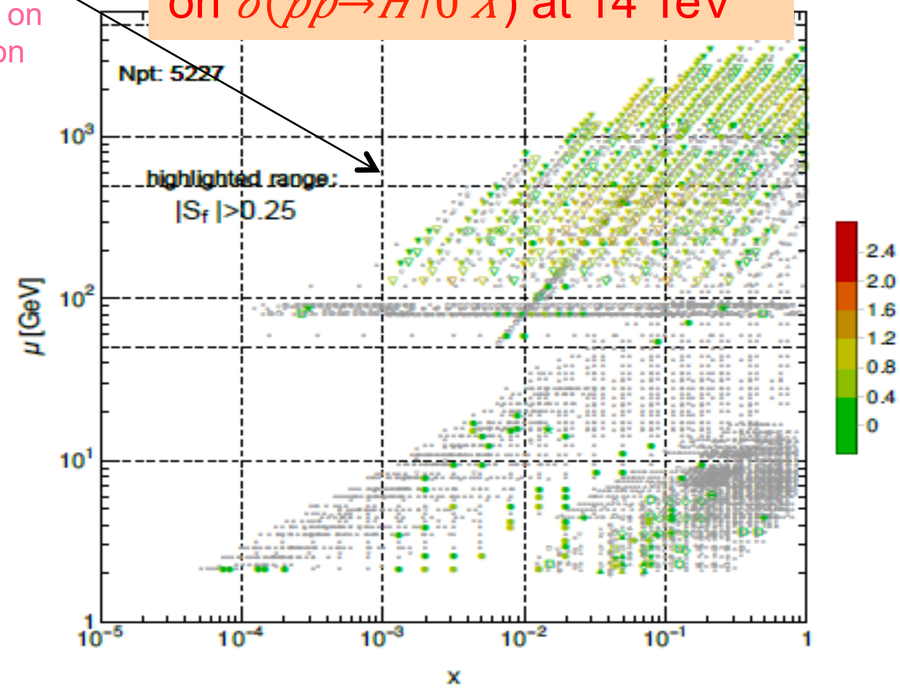
- ranking of strength of sensitivities of experimental data sets to PDF flavors without (re-)doing the full global fit
- impact on global fit requires both correlation and sensitivity

for example, HERAII, CMS jets provide information on gluon and on Higgs σ

					Rankings											
No.	Exp. ID	N_{pt}	$\sum_f \lvert S_f \rvert$	$\sum_f \langle \lvert S_f \rvert \rangle / N_f$	$\lvert S_{\bar{u}} \rvert$	$\langle \lvert S_{\bar{u}} \rvert \rangle$	$\lvert S_{\bar{d}} \rvert$	$\langle \lvert S_{\bar{d}} \rvert \rangle$	$\lvert S_g \rvert$	$\langle \lvert S_g \rvert \rangle$	$\lvert S_u \rvert$	$\langle \lvert S_u \rvert \rangle$	$\lvert S_d \rvert$	$\langle \lvert S_d \rvert \rangle$	$\lvert S_s \rvert$	$\langle \lvert S_s \rvert \rangle$
1	160	1120.	620.	0.0922	**A**	3	B		**A**	3	**A**	3	B		C	
2	**545**	288	397.	0.234	B	3	B	3	**A**	1	C		C	3	B	3
3	**542**	280	359.	0.217	B	3	B	3	**A**	1	C		C		B	3
4	201	238	225.	0.158	B	2	B	2			C	3				
5	111	86	218.	0.423	C	1	C	1		3	B	1	C	2		
6	204	368	206.	0.0942	B	3	C	3	C		C	3				
7	101	337	184.	0.0909	C				C		B	3	C			
8	104	123	169.	0.229			C	2			C	2	B	2		
9	102	250	141.	0.0938			C		C	3	C	3	C	3		
10	109	96	115.	0.199	C	2	C	2		3	C	2	C	3		
11	538	222	109.	0.0834					C	3						
12	110	69	89.3	0.216		3		3	C	2		3		2		3
13	**250**	84	82.9	0.165		3	C	3		3		3	C	2		
14	108	85	82.4	0.161		3		3		3		3	C	3		
15	**544**	236	79.8	0.0573					C	3						
16	268	82	79.3	0.161		3		3				3		3		3
17	**249**	66	78.3	0.198		3		2				3		2		3
18	**252**	94	68.5	0.121		3		3				3				3
19	203	30	66.6	0.37	C	1	C	1				3		2		
20	**245**	66	60.3	0.152		3		3		3		3		3		
21	124	38	58.9	0.258		3		3				3		3	C	1

…kinematical distributions of sensitivities to the PDFs in the $\{x,\mu\}$ plane

Sensitivity to the PDF error on $\sigma(pp \to H^0 X)$ at 14 TeV



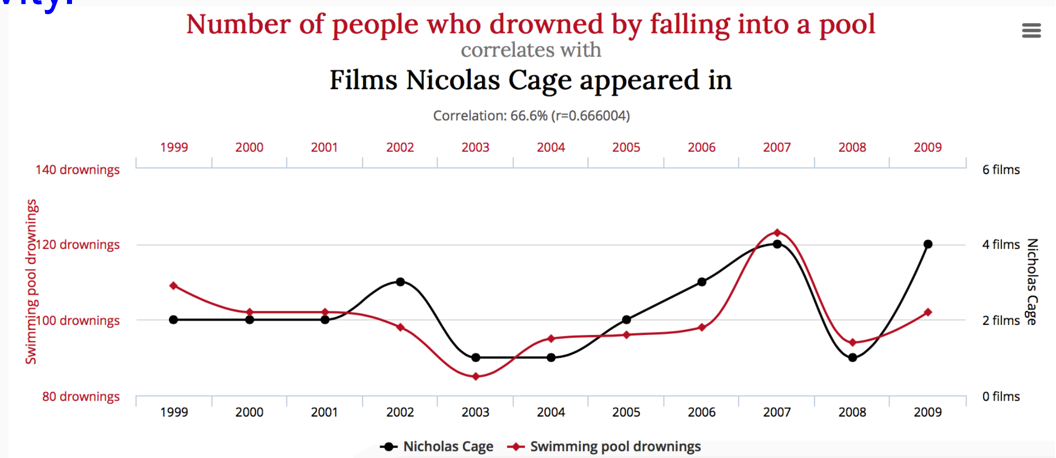
2018-03-05

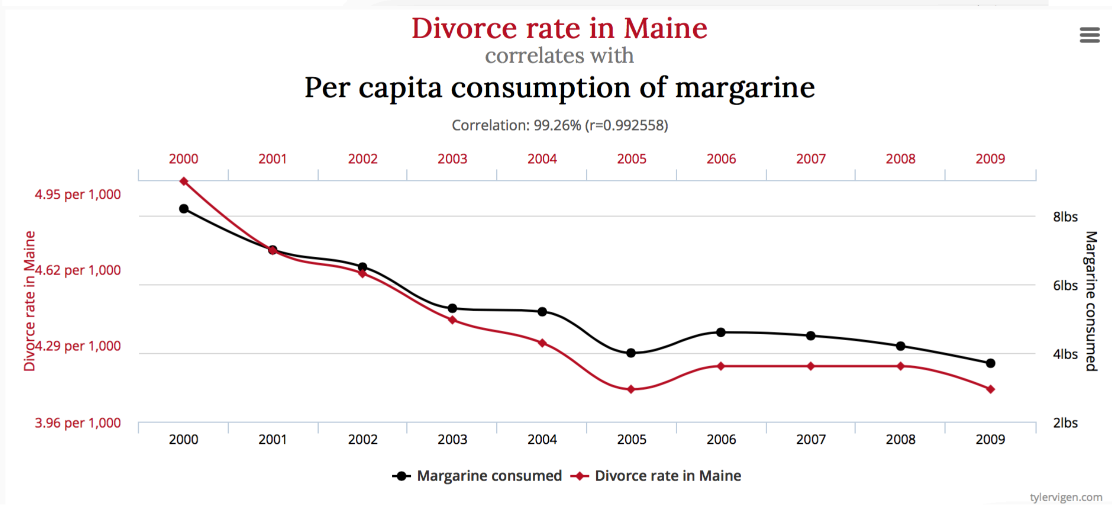
P. Nadolsky, xFitter workshop, Krakow

see for example http://metapdf.hepforge.org/PDFSense

Correlations

Correlations are important, but not sufficient. The statistical power of the data set also has to be there. The most effective data sets may have low correlation, but high sensitivity. Tensions within the data set also may reduce the ultimate sensitivity.





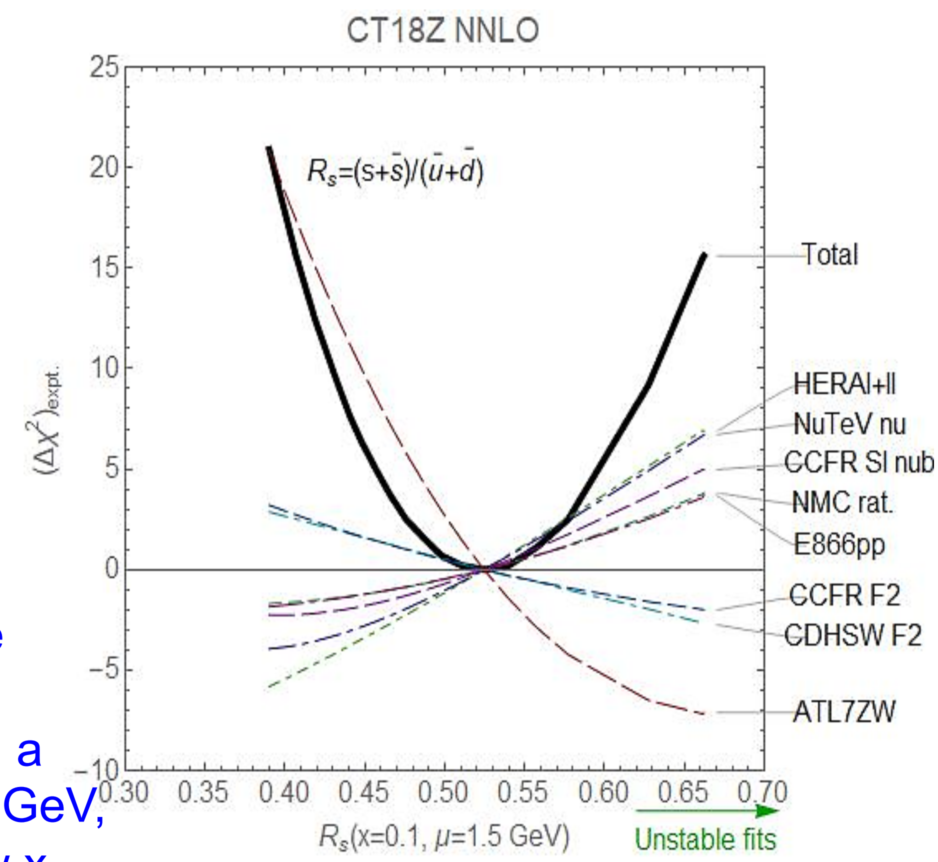
Treatment of new LHC data

- Include processes that have a sensitivity for the PDFs of interest, and for which NNLO predictions are available.
- Include as large a rapidity interval for the jet data as possible
  - for ATLAS this involves using the ATLAS de-correlation model, rather than using a single rapidity interval. Using a single rapidity interval may result in selection bias. The result is a worse χ^2 due to the remaining tensions in the ATLAS jet data, and a reduced sensitivity compared to the CMS jet data. .
- Use multiple t-tbar observables, possible using experimentally provided statistical correlations.
  - again, some of the observables are in tension with each other.
- NB: previous data (including CMS 7 TeV W,Z data) continue having an impact on global fits and tend to dilute the impact of new data

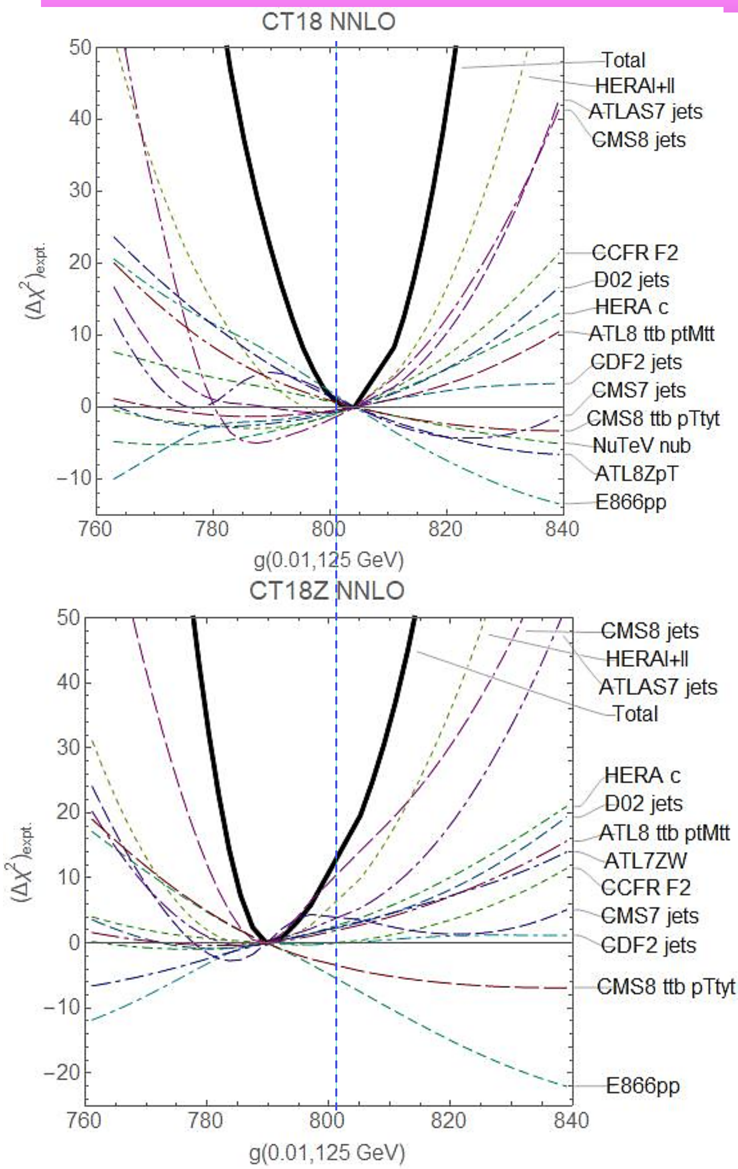
Lagrange Multiplier Scans

After the global fit is carried out, LM scans are very useful to determine how each data set contributes to the determination of a PDF in a specific kinematic region. A case study is the strangeness distribution, and the impact of the precision ATLAS W/Z data.

- LHCb W and Z (7,8 TeV) data prefer a larger strange in the small x region
- ATLAS 8 TeV Z pT data prefer a slightly larger strange
- NuTeV dimuon data strongly prefer smaller strange
- ATLAS 7 TeV precision W/Z strongly prefer larger strangeness; the ATLAS W/Z data has a fairly profound impact on our global fit
- Because the impact results in sizeable changes to some of the PDFs, we do not include this data set in CT18, but rather in a separate PDF, CT18Z; in addition m_c=1.4 GeV, and a slightly different scale is used at low x

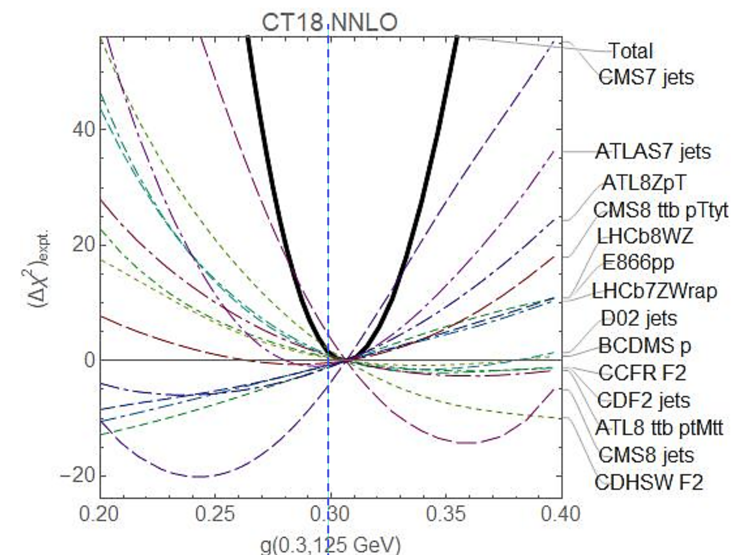


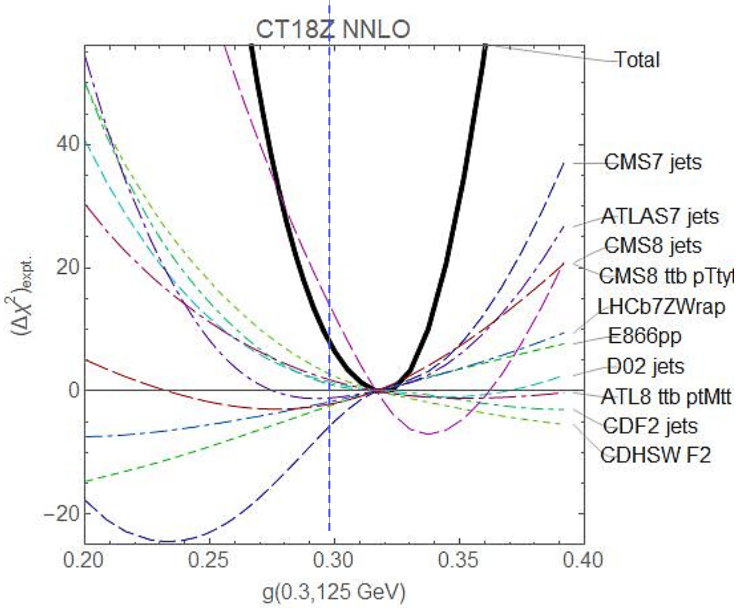
Lagrange Multiplier scan: $g(0.01, 125\ GeV)$



- Top: CT18
  - HERA1+II data set provides the **dominant constraint**, followed by ATLAS, CDF2,D02 jet production, HERA charm...
  - tt double differential cross sections provide weaker constraints
- Lower: CT18Z
  - a lower NNLO gluon in the Higgs production region than for CT14/CT18 as a result of
    - a special factorization scale in DIS that mildly improves χ^2 and approximates the effect of small-x resummation (largest impact on gluon/light quarks)
    - including ATLAS7 W/Z production (has largest impact on strange)
    - higher charm mass, m_c^{pole}=1.4 GeV

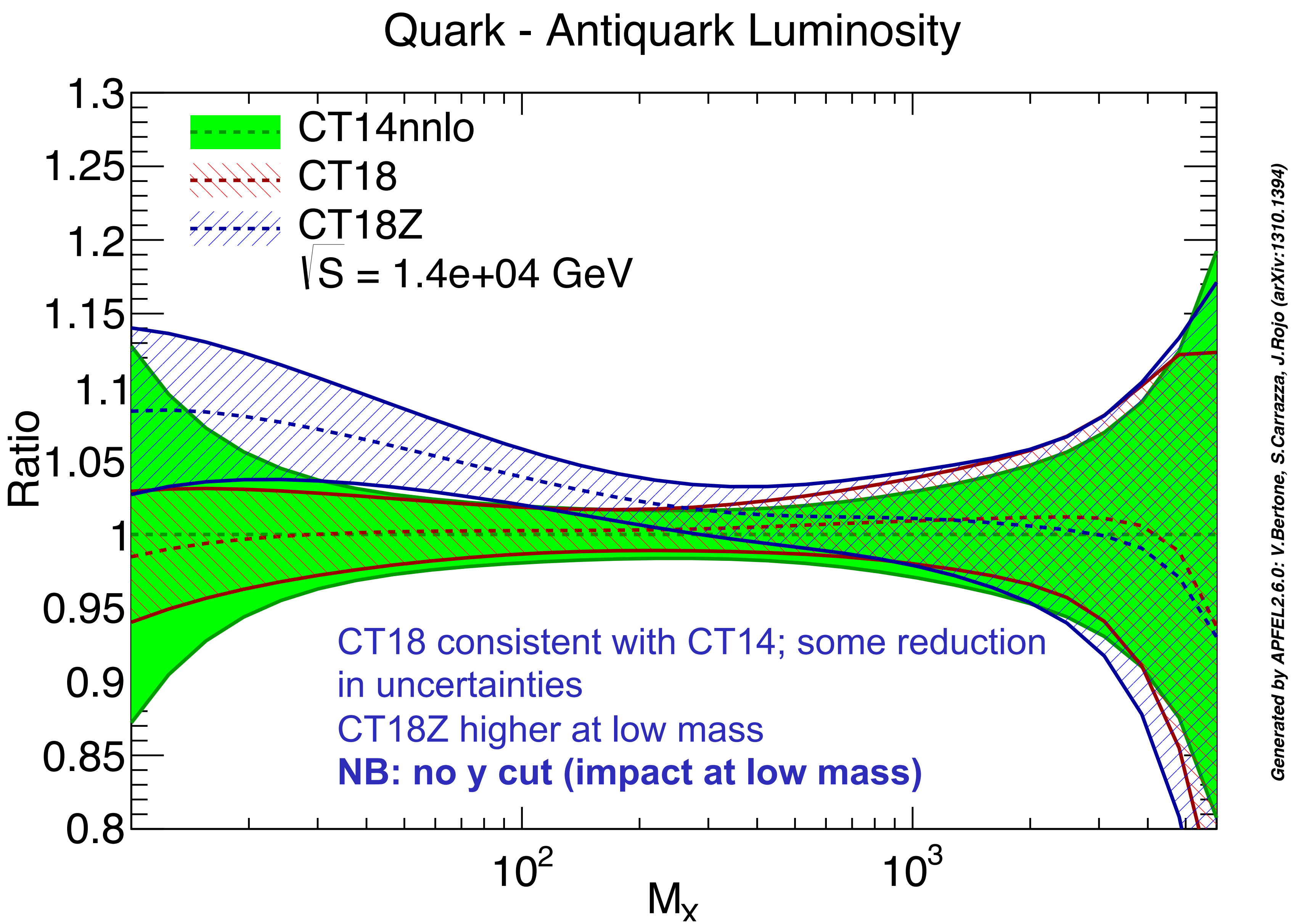
Lagrange Multiplier scan: $g(0.3, 125\ GeV)$



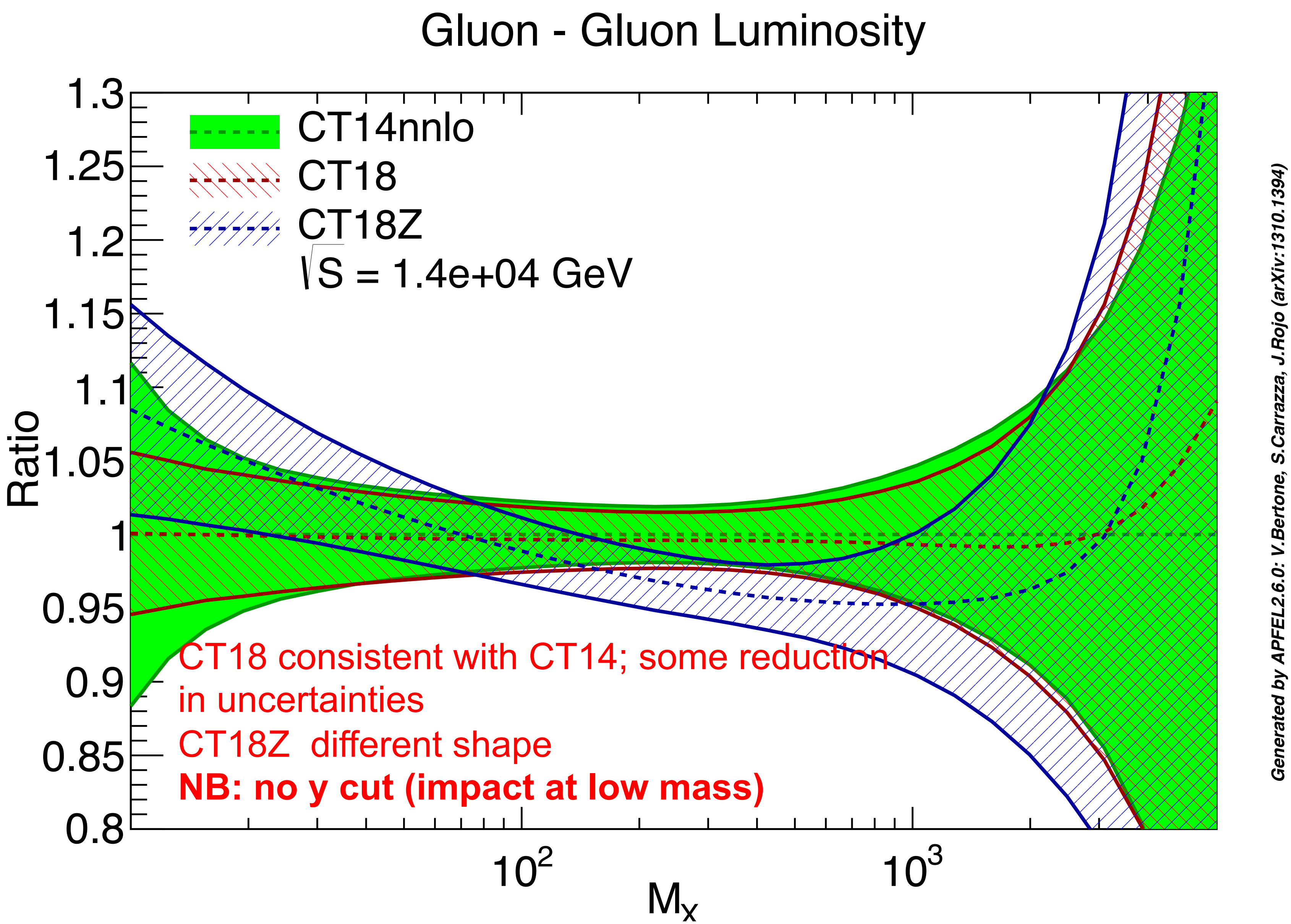


- Upper: CT18
- Lower: CT18Z
- Opposite pulls from ATLAS7/ CMS7 jet production on one hand, and CMS8 jet production on the other hand
- Similarly, ATLAS tt distributions (dm_{tt}, dp_T^t) and CMS double tt distributions ($dp_T^t dy_t$) at 8 TeV impose weak opposite pulls
- Constraints from ATLAS8 Z p_T production are moderate

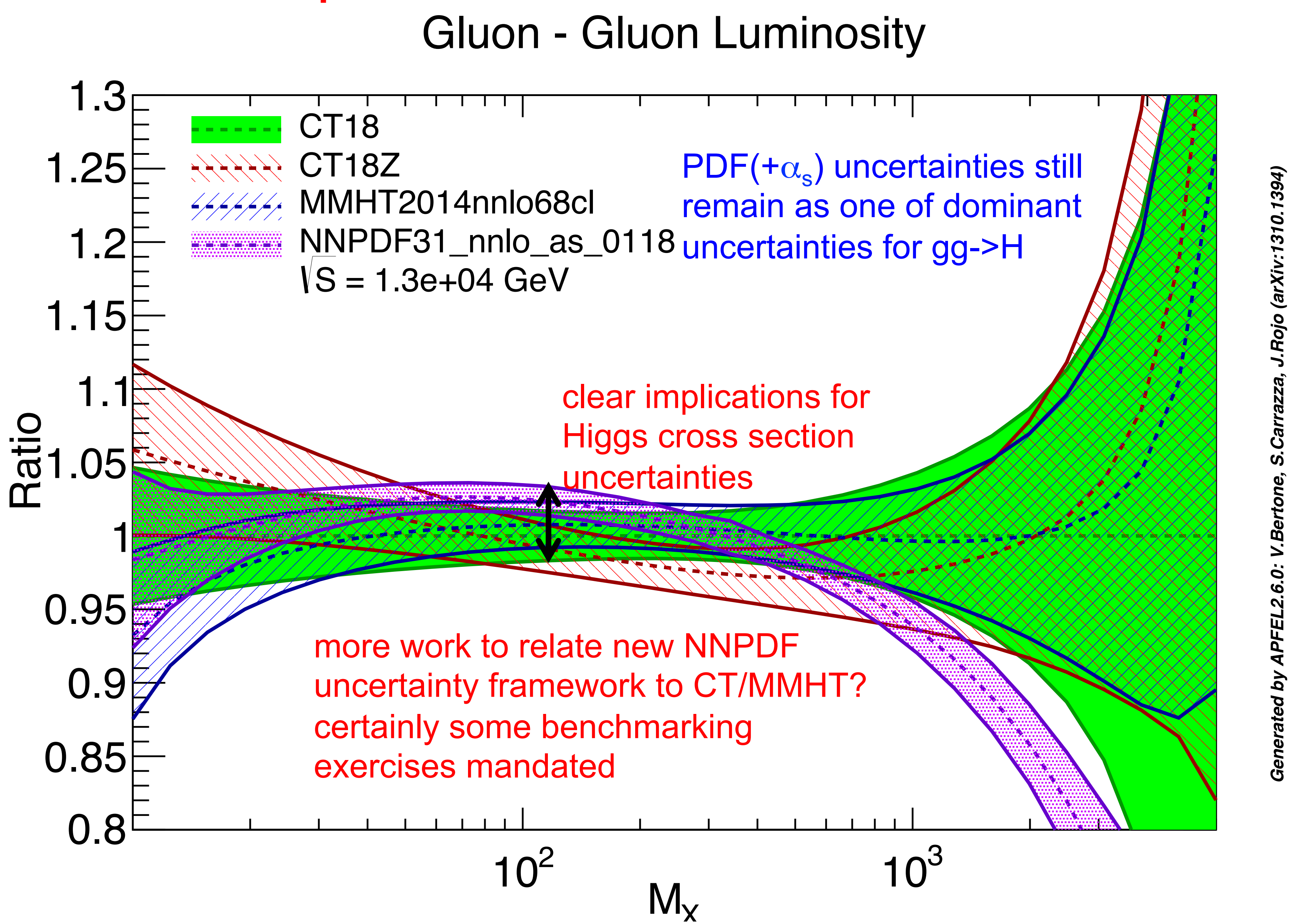
PDF luminosities



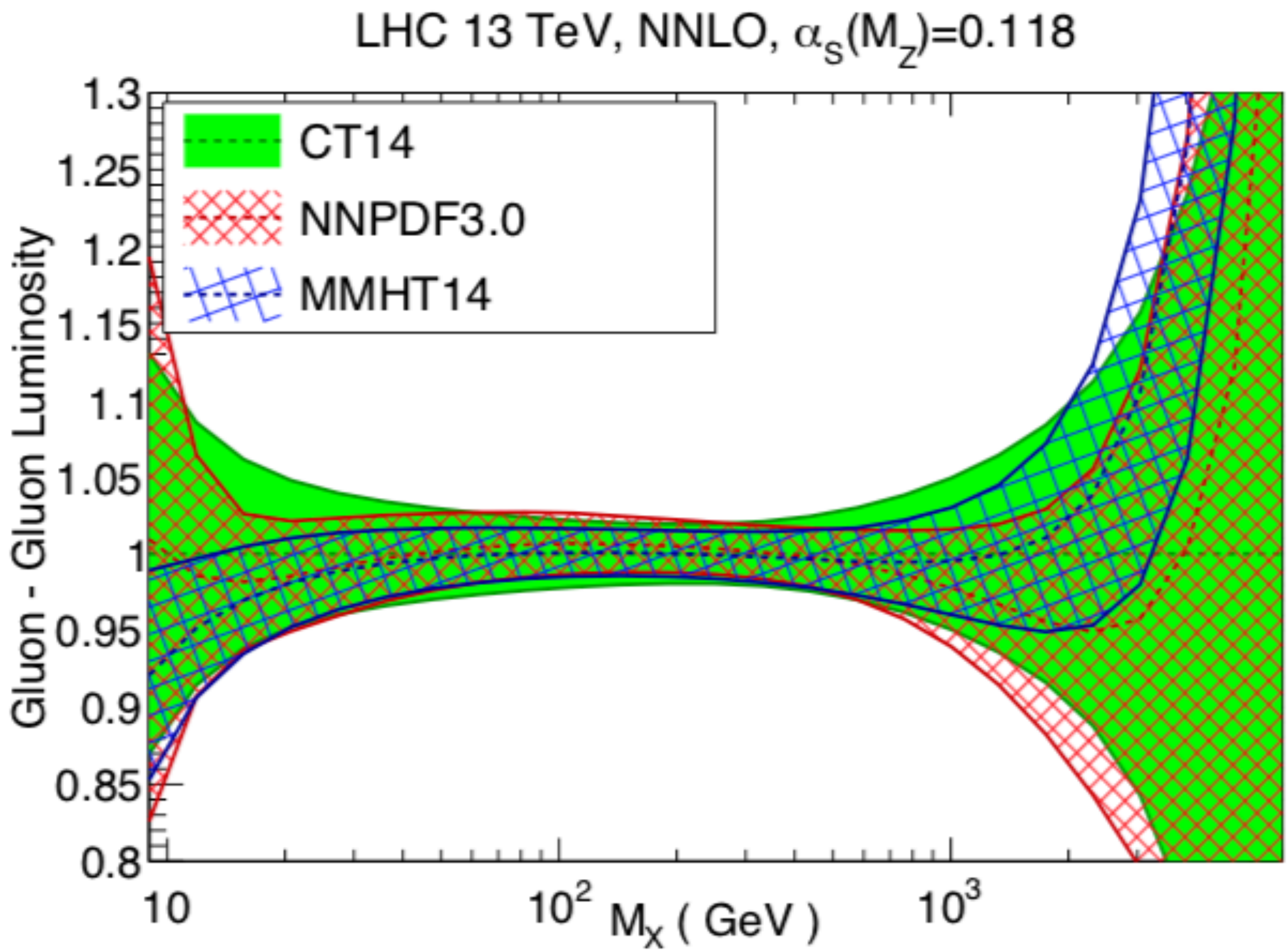
PDF luminosities



Now compare to MMHT2014 and NNPDF3.1

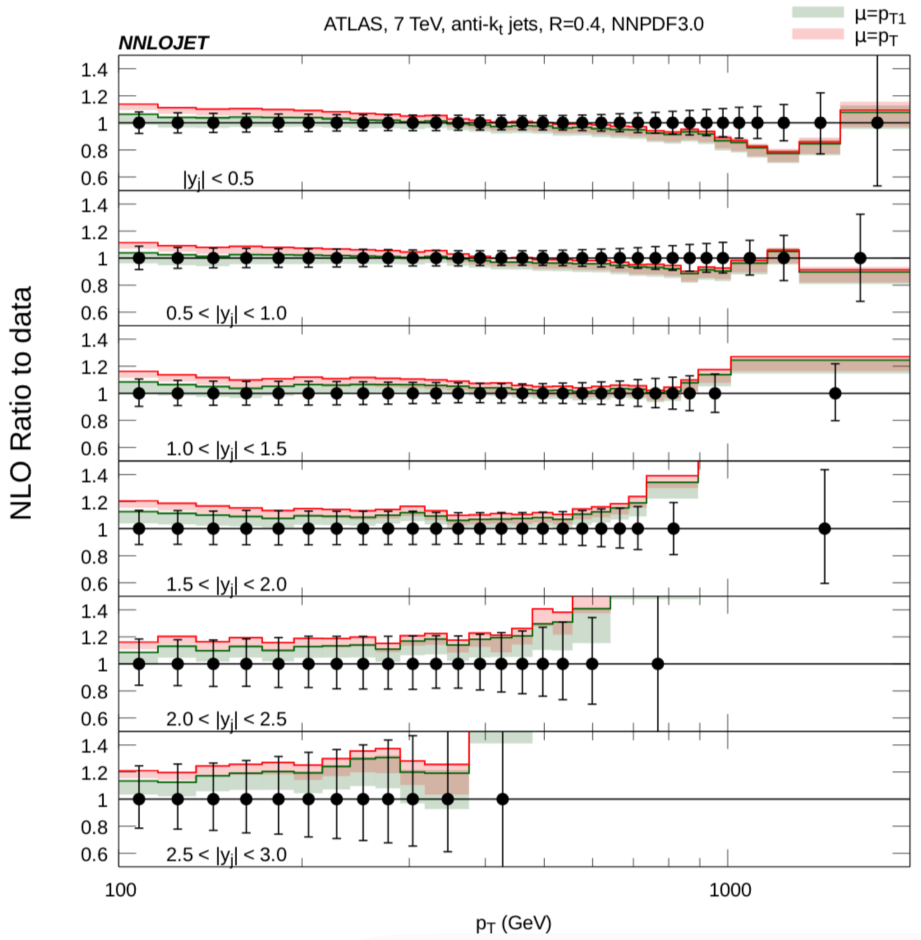


Previous level of agreement



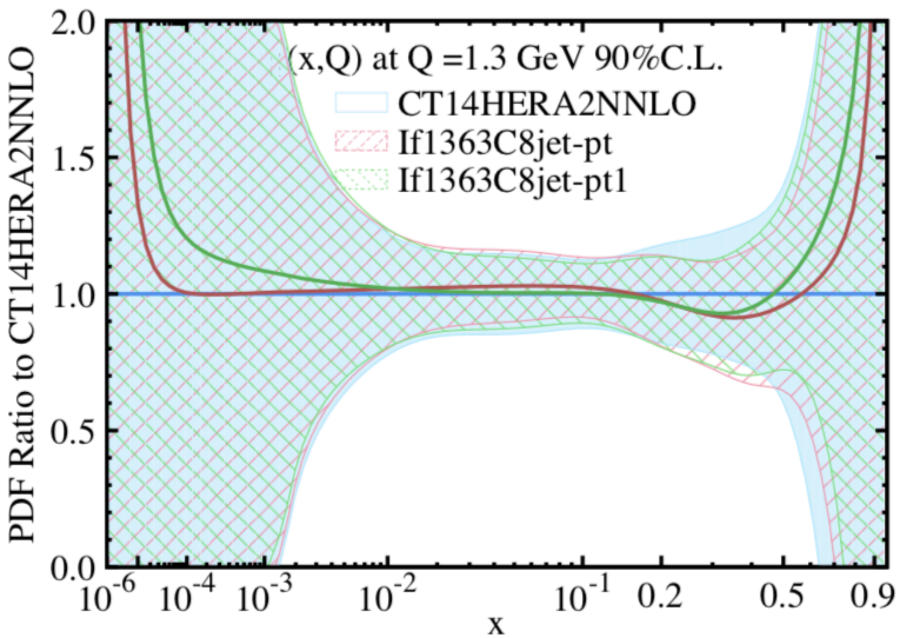
Scale choices prelude: p_T vs p_{T1}

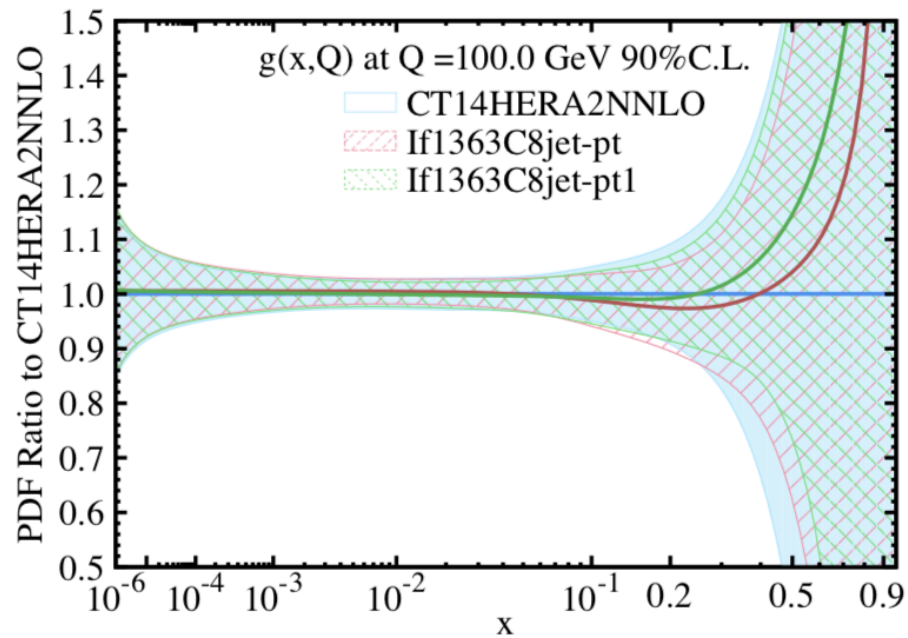
- Central scale choices should be related to the kinematics of the process
- For inclusive jet production, that scale should be related to the p_T of the jet (maybe taking rapidity into account when the jet is at high rapidity)
- But should the scale be the p_T of each individual jet, or the p_T of the jead jet in the event
- Non-negligible difference between scale choice of p_T (inclusive jet p_T) and lead jet p_T (p_{T1}) for NNLO predictions
  - could potentially result in different gluon distribution
- Nominal choice by PDF fitting groups is p_T



p_T vs p_{T1}

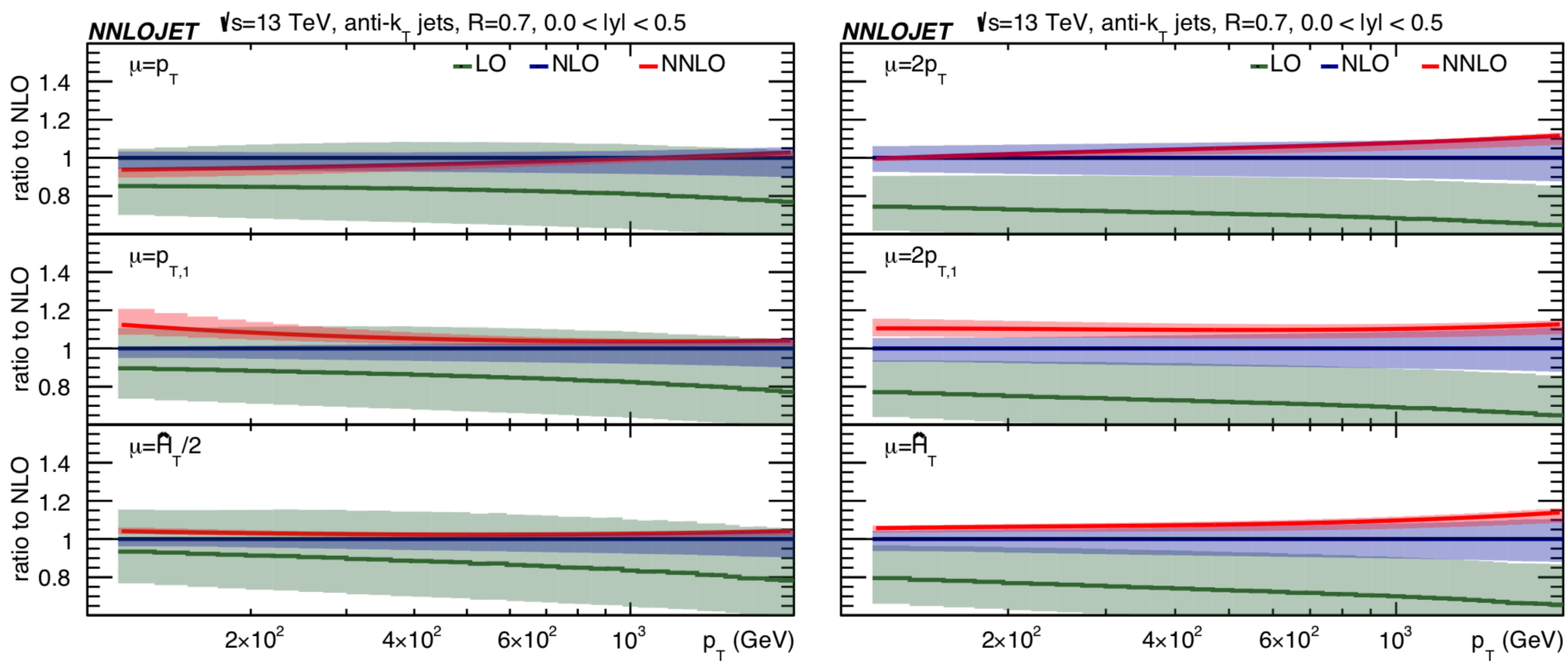
- In fact, fitted gluon is almost exactly the same in kinematic region where difference is important
- There is a resilience in the global fit due to other data present in this kinematic region (and evolution)





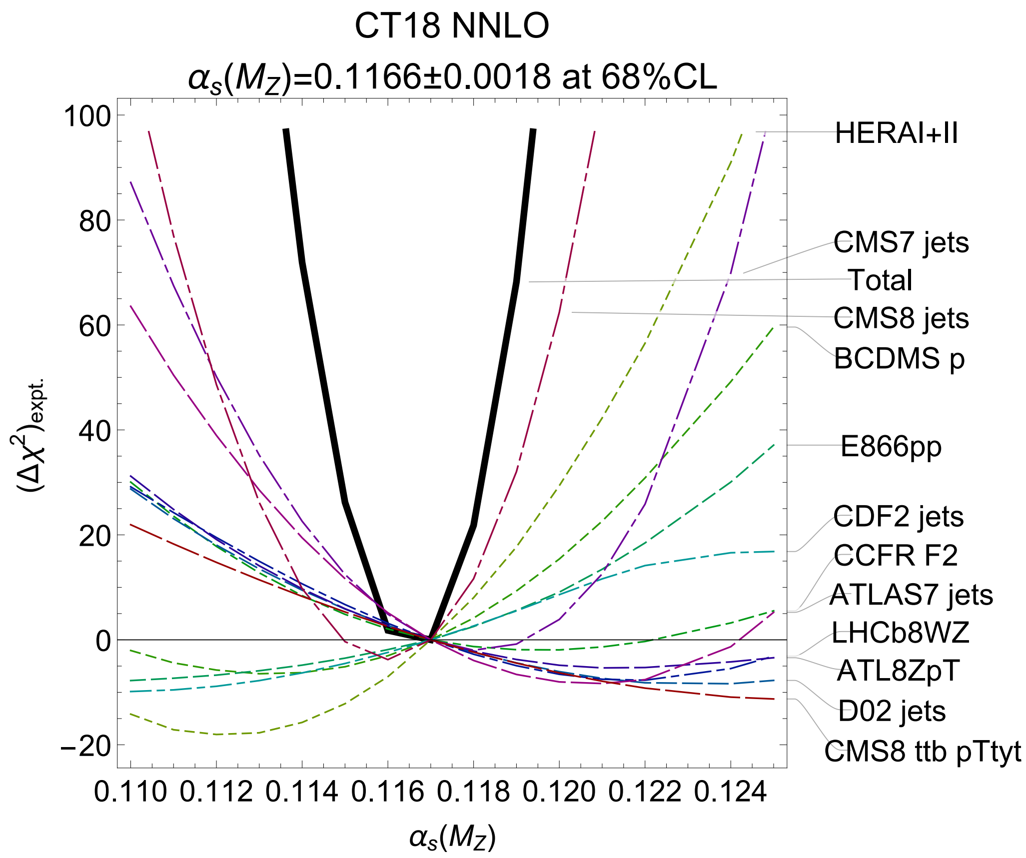
arXiv:1807.03692

- NNLOJET conclusions is that a scale of HT has the best properties, as far as convergence, stability are concerned->see Alex's talk



Aside

- Can also use LM method to examine sensitivity of different data sets to $\alpha_s(m_Z)$
- Klaus Rabbertz, Giulia Zanderighi and myself will be revising the PDG $\alpha_s(m_Z)$ determination this year
- It's clear that we will be using global fits and no longer restrict to fits of DIS data only
- Useful topic to discuss at Les Houches



Scale uncertainties in PDF fits

- 2 recent papers
  - On the Consistent Use of Scale Variations in PDF fits and Predictions; arXiv:1811.08434; Harland-Lang and Thorne
  - A First Determination of Parton Distributions with Theoretical Uncertainties; arXiv:1905.04311; NNPDF
- Stefano Forte will lead a discussion on Friday morning

arXiv:1905.04311

- Main ideas
  - theory uncertainties are independent of experimental ones, so the two can be combined in quadrature
  - modify the χ^2 distribution to include a theory covariance matrix S along with the experimental covariance matrix C

$$S_{ij} = \frac{1}{N}\sum_k \Delta_i^{(k)}\Delta_j^{(k)}, \quad \chi^2 = \sum_{i,j=1}^{N_{\rm dat}} \left(D_i - T_i^{(0)}\right)(S+C)_{ij}^{-1}\left(D_j - T_j^{(0)}\right)$$

  - the Δ values for S are the expected shifts with respect to the central theory prediction, due to the theory uncertainties
  - the theory uncertainties are estimated by varying μ_R and μ_F
  - classify data sets included in global PDF fit as DIS NC, DIS CC, DY,jet,top
  - tie μ_F together for all processes, μ_R for processes of same type
  - validate application to NLO with NNLO
  - longer paper with NNLO results expected soon

Jet Cross Sections at the LHC and the Quest for Higher Precision (LH17, following up from LH15)

- Take advantage of the NNLO calculations available from NNLOJET for H+jet, Z+jet and dijet production
- Compare NNLO to NLO and to NLO+PS, as a function of jet radius from 0.3 to 1.0, using identical boundary conditions as much as possible
- Allows to check the consistency of matched predictions with fixed order predictions at NLO and NNLO, and to also compare matched predictions among themselves, i.e. to re-visit the 'parton shower systematic'
- Comparing predictions over a wide range of jet radii allows a better understanding of both perturbative and non-perturbative physics
    - a naïve calculation of the scale uncertainty at a fixed value of R can lead to an unrealistic estimate of the magnitude of that uncertainty
    - parton showering does a better job of describing jet shapes than fixed order does; the difference basically disappears at NNLO where the fixed order prediction for the jet shape has the possibility of two emissions
    - comparison of the non-perturbative corrections for Sherpa and Herwig as a function of R indicates the level of agreement/remaining uncertainties for these corrections; they're smaller than may be currently assumed

Jet cross sections at the LHC and the quest for higher precision

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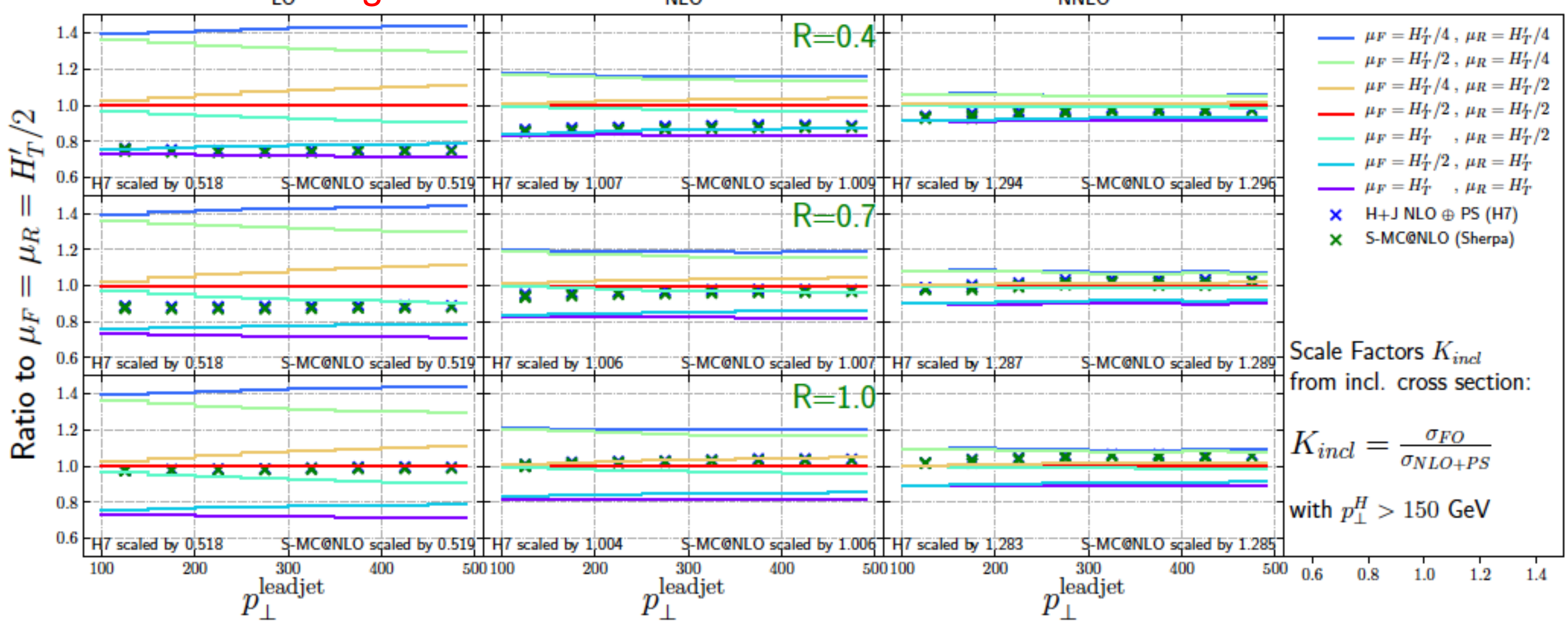
We perform a phenomenological study of Z plus jet, Higgs plus jet and di-jet production at the Large Hadron Collider. We investigate in particular the dependence of the leading jet cross section on the jet radius as a function of the jet transverse momentum. Theoretical predictions are obtained using perturbative QCD calculations at the next-to and next-to-next-to-leading order, using a range of renormalization and factorization scales. The fixed order predictions are compared to results obtained from matching next-to-leading order calculations to parton showers. A study of the scale dependence as a function of the jet radius is used to provide a better estimate of the scale uncertainty for small jet sizes. The non-perturbative corrections as a function of jet radius are estimated from different generators.

I. INTRODUCTION

The production of a single object like a Z or Higgs boson, or a jet, at high transverse momentum has been studied intensely in hadron collider environments, both theoretically and experimentally. These processes are used for measuring standard-model parameters, to constrain parton distribution functions (PDFs), and to understand backgrounds to new physics searches. They probe the structure of the QCD interactions in great detail. On the one hand, the large scales associated with the production of a high-p_T object make QCD perturbation theory a prime analysis tool. For $H/Z+\geq 1$ jet production, the large boson mass also provides a large scale to further stabilize

Scale variations as a function of R for lead jet for H+j

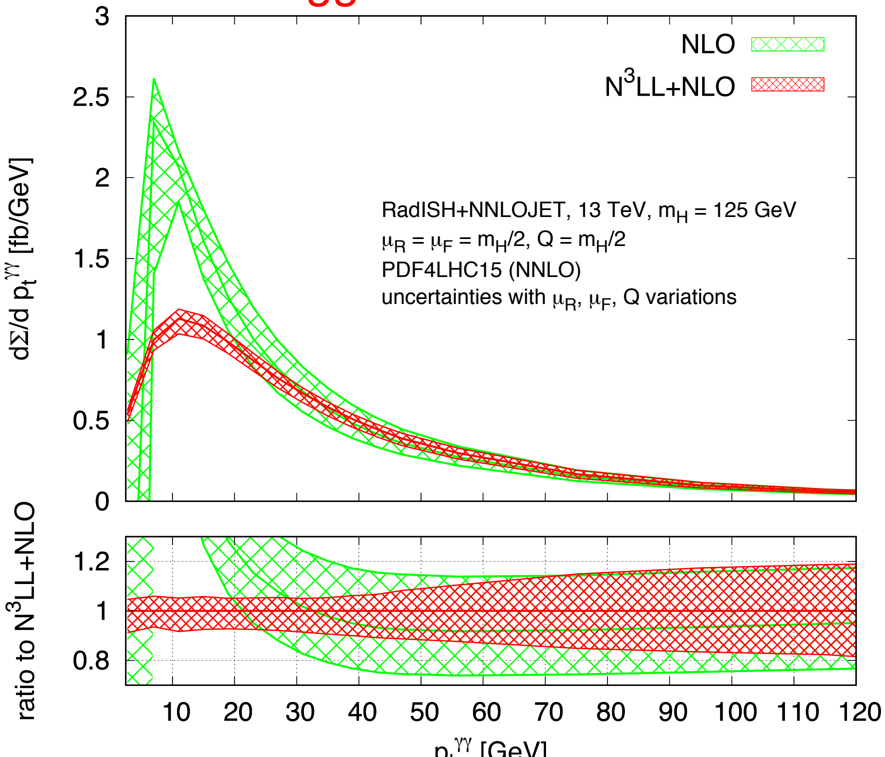
Error bands shrink from LO->NLO->NNLO; error bands shrink (somewhat) with decreasing R



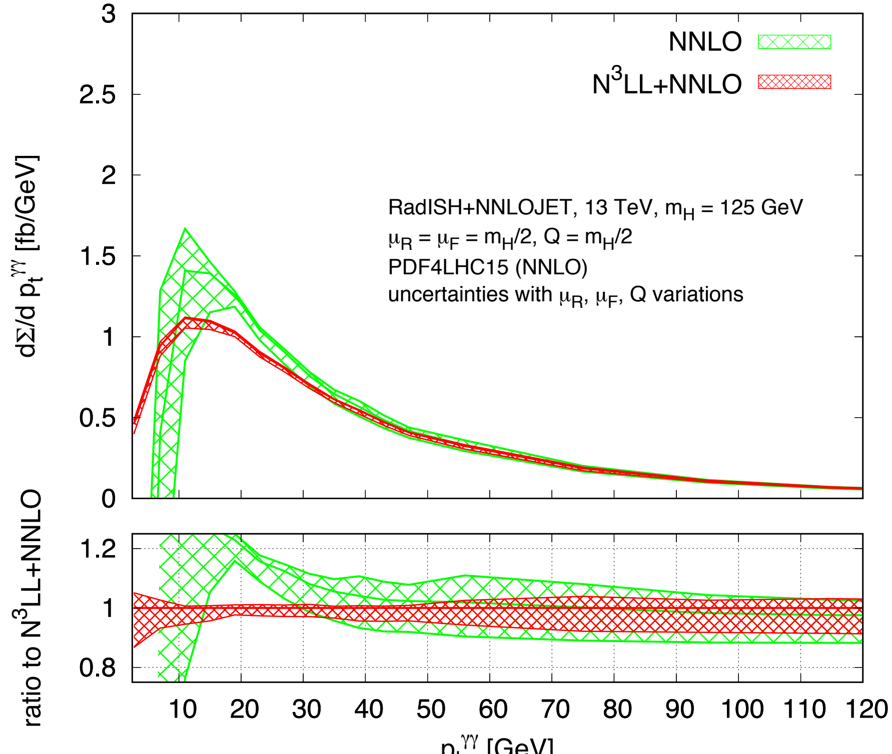
Predictions for Sherpa and Herwig within fixed order uncertainty bands at all orders for all R. For small R, ln R effects have to be resummed; parton shower Monte Carlos effectively do this. Impact is strongest for R<0.4. Differences with respect to parton shower Monte Carlos much smaller at (FO) NNLO than at NLO.

Aside: another comparison of fixed order and resummed

resummed prediction merges into NLO at around Higgs mass



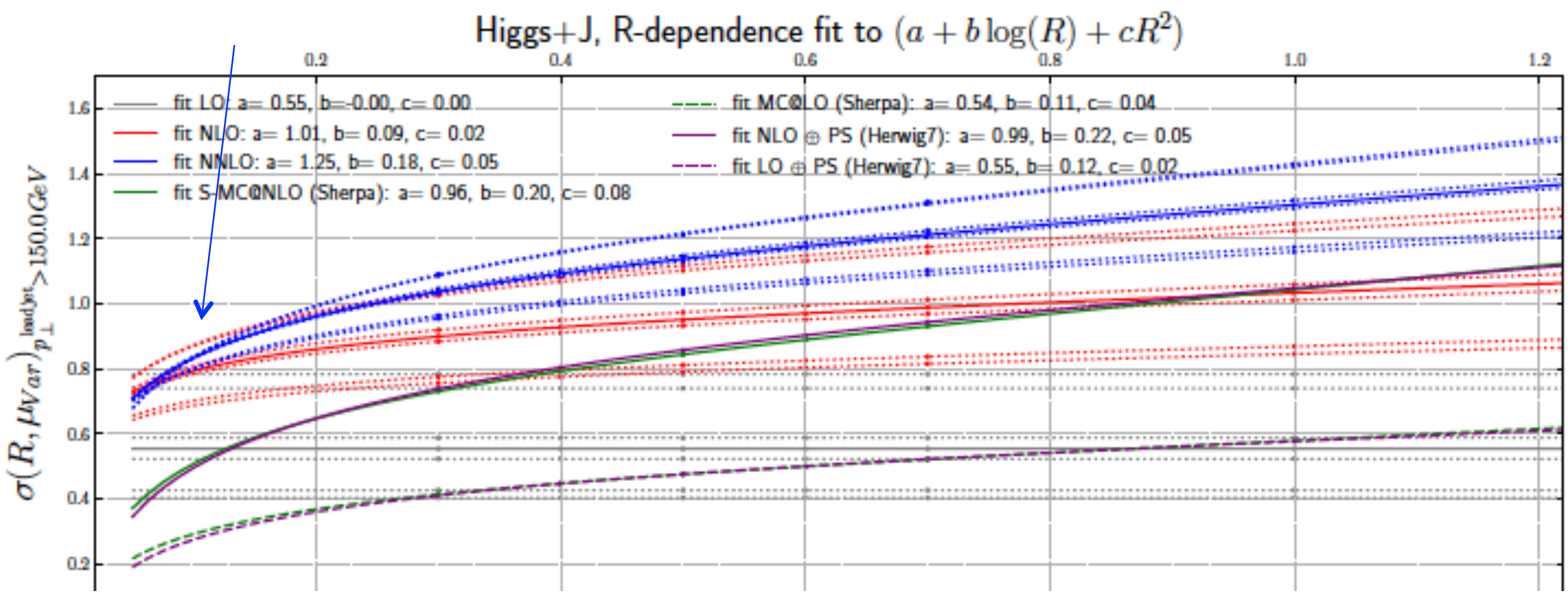
additional logs in NNLO result
In agreement at much lower p_T



- We require fixed order calculations to agree within machine accuracy; there are many choices for resummed calculations
- I don't think there has been a comprehensive comparison of the different resummed predictions for quantities such as above, as well as various vetoed observables

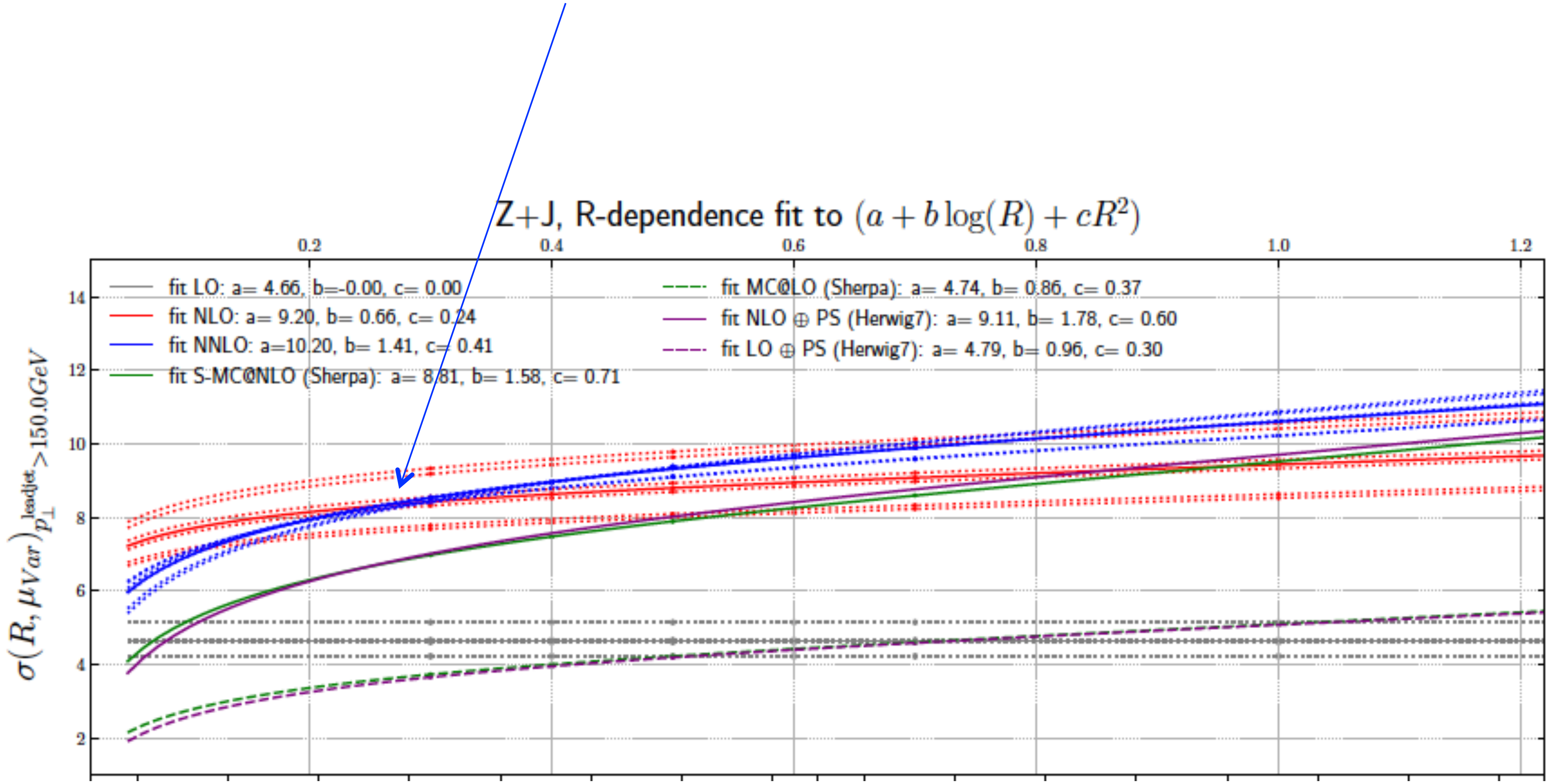
Back to quest paper: R-dependence of scale uncertainty (H+j)

- Look at R-dependence of scale uncertainty at LO, NLO and NNLO
- Fit to functional form a+b*log(R)+cR^2
  - motivated by logarithmic behaviour scaling of cross section with jet size R and an area-dependent contribution from ISR (see original EKS papers)
- Scale uncertainty given by distance between top and bottom curves of given color (blue for NNLO; red for NLO)
- Scale dependence decreases as R decreases; scale uncertainty goes to zero for R~0.1



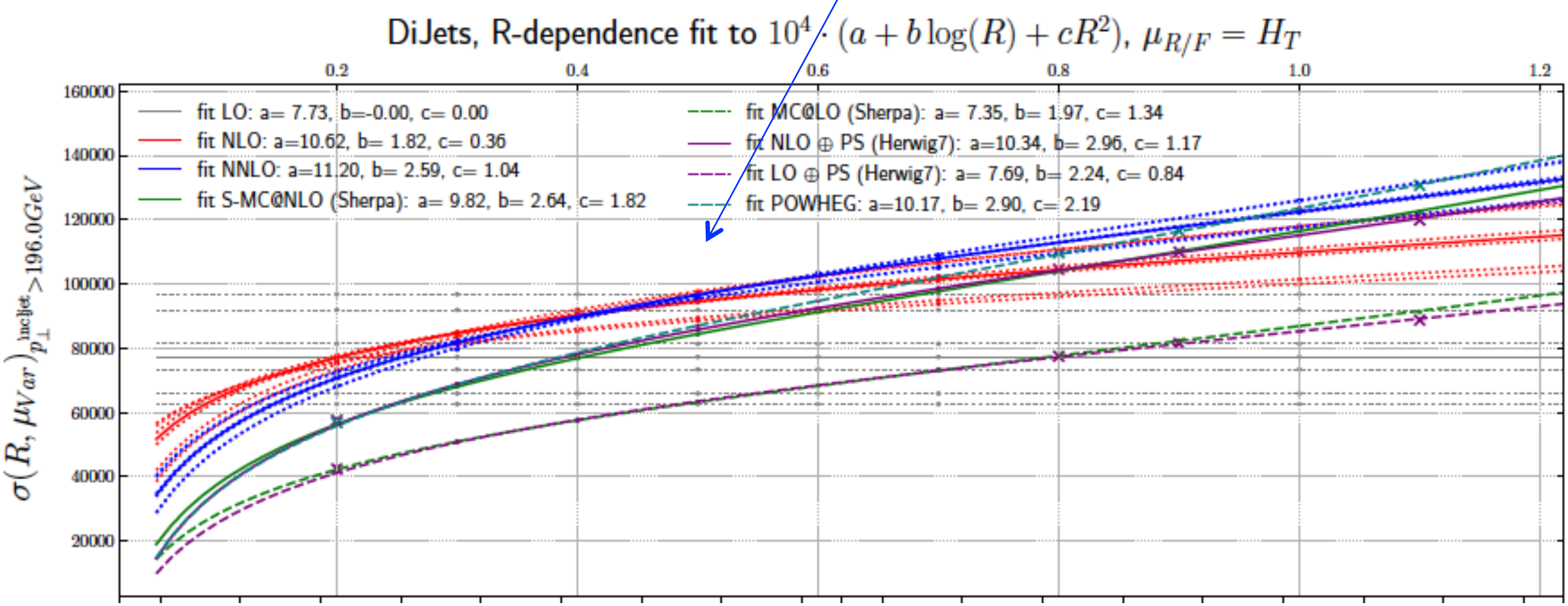
R-dependence of scale uncertainty (Z+j)

- Again, scale dependence decreases from LO->NLO->NNLO and as R decreases
- Scale uncertainty at NNLO~0 for R=0.3



R-dependence of scale uncertainty (dijet)

- Scale dependence at NNLO~0 for R=0.4



Scale dependence re-visited

- By looking at the scale dependence as a function of R, it becomes clear that there can be an artificial reduction of the 'true' scale dependence due to accidental cancellations resulting from the restriction in phase space, even for R values for which the scale uncertainty is not zero
- Idea: view the differential cross section as a combination of a fixed-order term and the normalized all-orders result (1602.01110), i.e. the production of a parton and then the fragmentation of that parton into a jet of size R
    - combine through multiplicative matching
    - re-expand to fixed order

$$\sigma(R) = \sigma(R_0)\frac{\sigma(R)}{\sigma(R_0)} \approx \sigma(R_0)\cdot\left(1 + \alpha_S\,\partial_{\alpha_S}\frac{\sigma(R)}{\sigma(R_0)}\Big|_{\alpha_S=0} + \alpha_S^2\,\partial^2_{\alpha_S}\frac{\sigma(R)}{\sigma(R_0)}\Big|_{\alpha_S=0}\right)\,.$$

- There are several possible choices as to the implementation of the factorization on RHS

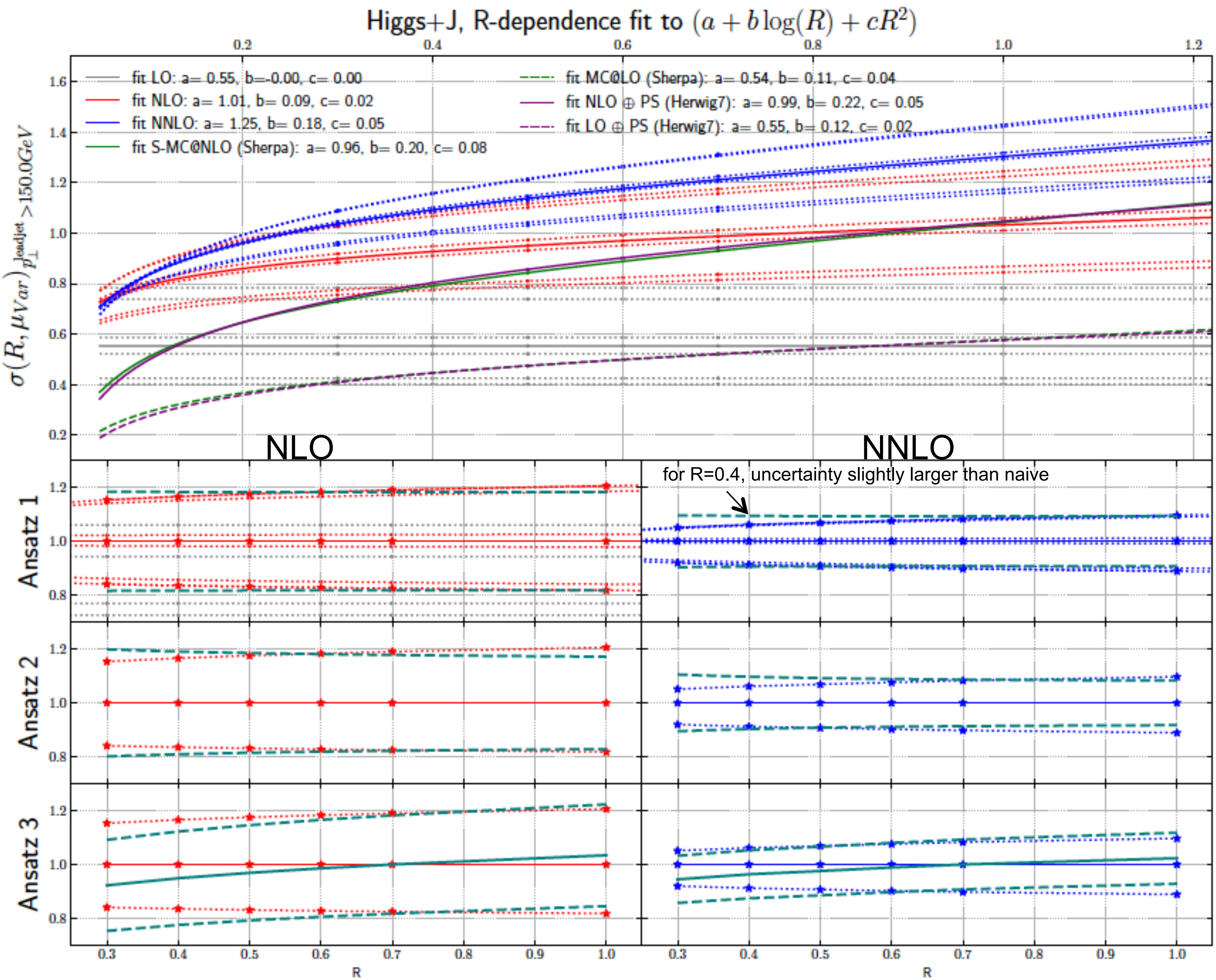
Ansatz

$$\sigma(R) = \sigma(R_0)\frac{\sigma(R)}{\sigma(R_0)} \approx \sigma(R_0)\cdot\left(1 + \alpha_S\,\partial_{\alpha_S}\frac{\sigma(R)}{\sigma(R_0)}\Big|_{\alpha_S=0} + \alpha_S^2\,\partial^2_{\alpha_S}\frac{\sigma(R)}{\sigma(R_0)}\Big|_{\alpha_S=0}\right)\;.$$

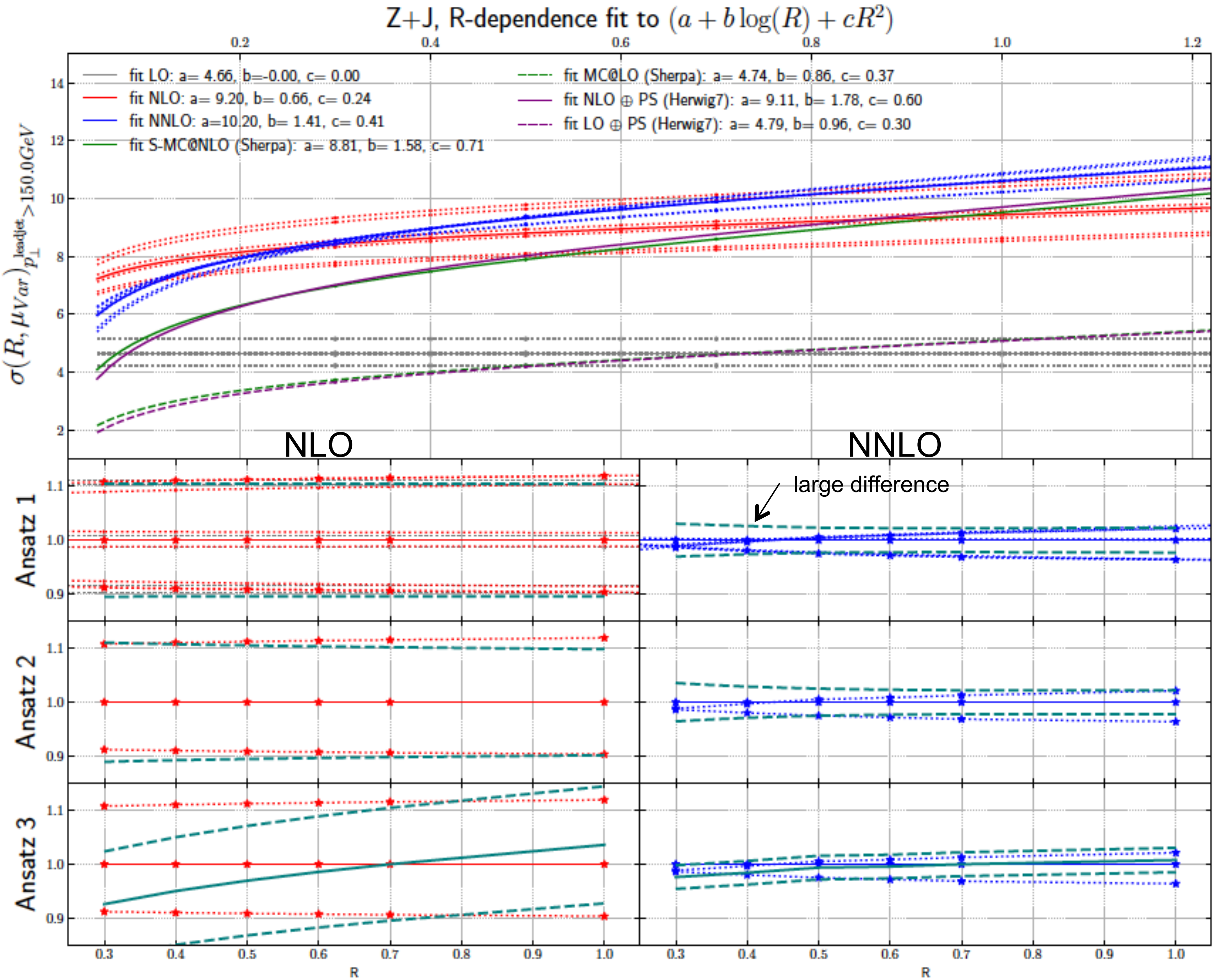
1. $\sigma(R)/\sigma(R_o)$ on RHS not expanded, and combine the parton and fragmentation uncertainties in quadrature
2. Determine scale uncertainties from fits to coefficients a,b and c and combine them in quadrature

$$f(R) = a + b\log(R) + cR^2$$

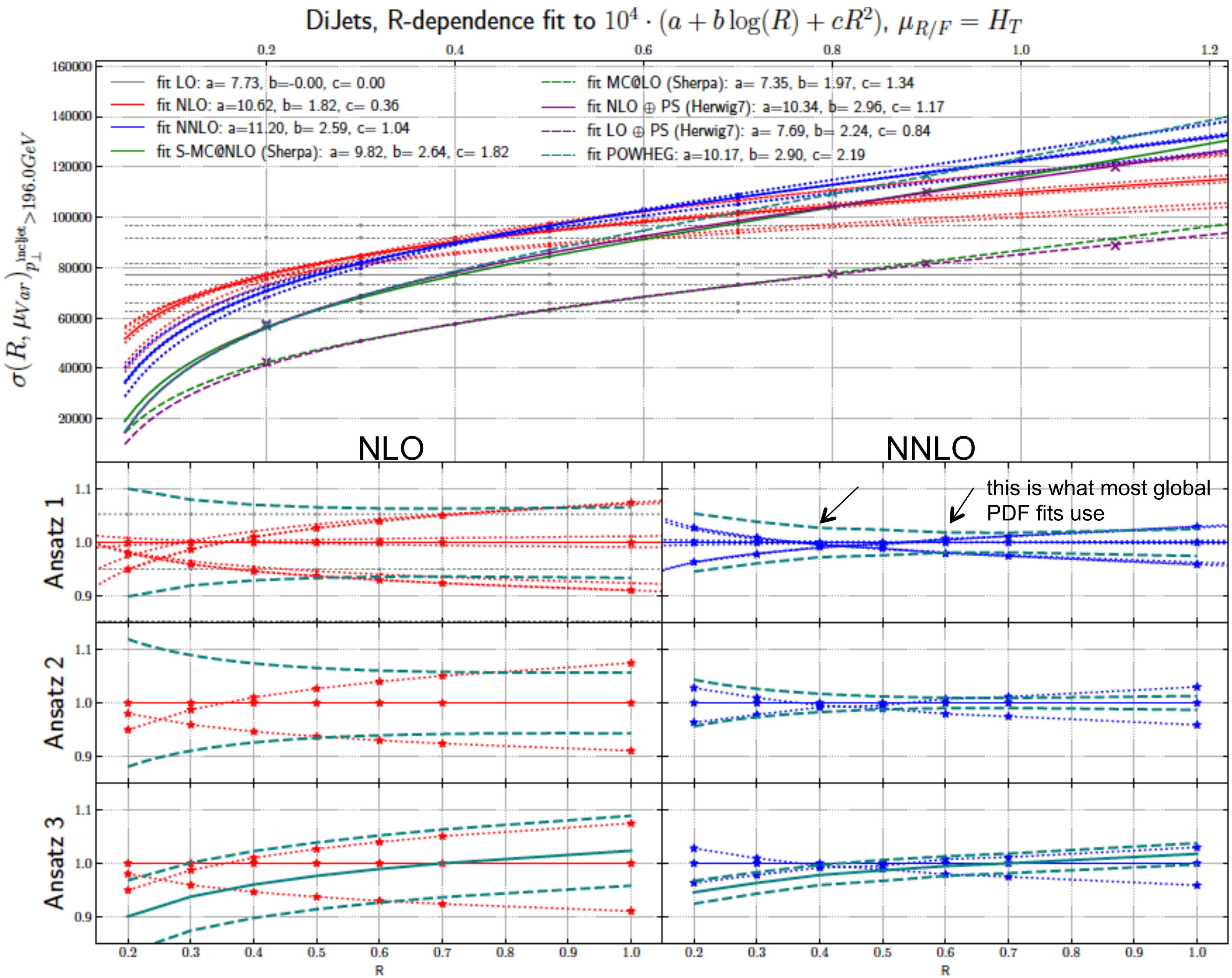
3. Original ansatz in 1602.01110; use the expansion shown on the top of the slide



Higgs+J, R-dependence fit to $(a + b\log(R) + cR^2)$
fit LO: a= 0.55, b=-0.00, c= 0.00
fit NLO: a= 1.01, b= 0.09, c= 0.02
fit NNLO: a= 1.25, b= 0.18, c= 0.05
fit S-MC@NLO (Sherpa): a= 0.96, b= 0.20, c= 0.08
fit MC@LO (Sherpa): a= 0.54, b= 0.11, c= 0.04
fit NLO ⊕ PS (Herwig7): a= 0.99, b= 0.22, c= 0.05
fit LO ⊕ PS (Herwig7): a= 0.55, b= 0.12, c= 0.02
$\sigma(R, \mu_{Var})_{p_\perp^{\mathrm{leadjet}} > 150.0 GeV}$
NLO
NNLO
for R=0.4, uncertainty slightly larger than naive
Ansatz 1
Ansatz 2
Ansatz 3
R



Z+J, R-dependence fit to $(a + b\log(R) + cR^2)$
fit LO: a= 4.66, b=-0.00, c= 0.00
fit NLO: a= 9.20, b= 0.66, c= 0.24
fit NNLO: a=10.20, b= 1.41, c= 0.41
fit S-MC@NLO (Sherpa): a= 8.81, b= 1.58, c= 0.71
fit MC@LO (Sherpa): a= 4.74, b= 0.86, c= 0.37
fit NLO ⊕ PS (Herwig7): a= 9.11, b= 1.78, c= 0.60
fit LO ⊕ PS (Herwig7): a= 4.79, b= 0.96, c= 0.30
$\sigma(R, \mu_{Var})_{p_\perp^{\mathrm{leadjet}} > 150.0 GeV}$
NLO
NNLO
large difference
Ansatz 1
Ansatz 2
Ansatz 3
R
R



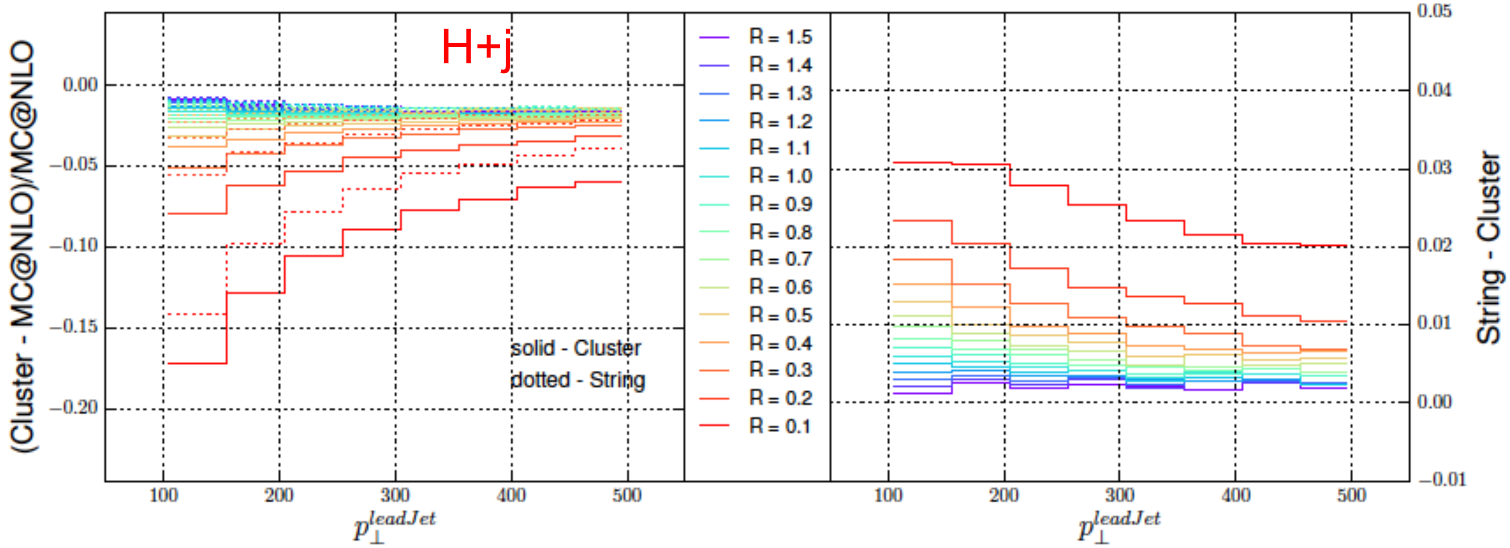
DiJets, R-dependence fit to $10^4 \cdot (a + b\log(R) + cR^2)$, $\mu_{R/F} = H_T$
fit LO: a= 7.73, b=-0.00, c= 0.00
fit NLO: a=10.62, b= 1.82, c= 0.36
fit NNLO: a=11.20, b= 2.59, c= 1.04
fit S-MC@NLO (Sherpa): a= 9.82, b= 2.64, c= 1.82
fit MC@LO (Sherpa): a= 7.35, b= 1.97, c= 1.34
fit NLO ⊕ PS (Herwig7): a=10.34, b= 2.96, c= 1.17
fit LO ⊕ PS (Herwig7): a= 7.69, b= 2.24, c= 0.84
fit POWHEG: a=10.17, b= 2.90, c= 2.19
$\sigma(R, \mu_{Var})_{p_\perp^{\rm incljet} > 196.0 GeV}$
NLO
NNLO
this is what most global PDF fits use
Ansatz 1
Ansatz 2
Ansatz 3
R

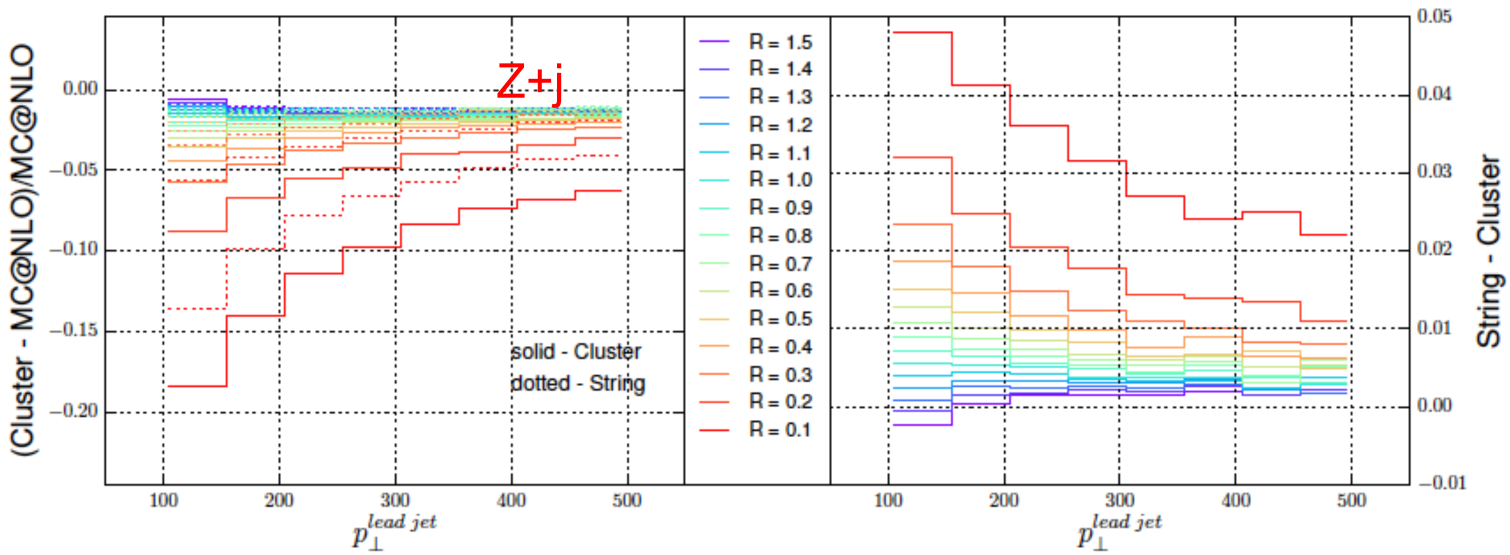
Thoughts

- Ansatz 1 and 2 give essentially the same (and more reasonable) scale uncertainties
- Ansatz 3 gives a more reasonable scale dependence as well, but changes the central prediction at small R
- For this reason, we prefer ansatz's 1 and 2
- This has implications for scale uncertainties used for ATLAS/CMS results
- We'd like to further explore these implications in LH2019

Hadronization corrections for H+j, Z+j for Sherpa, with string and cluster fragmentation

difference between NLO matched and hadronized results using default tuning

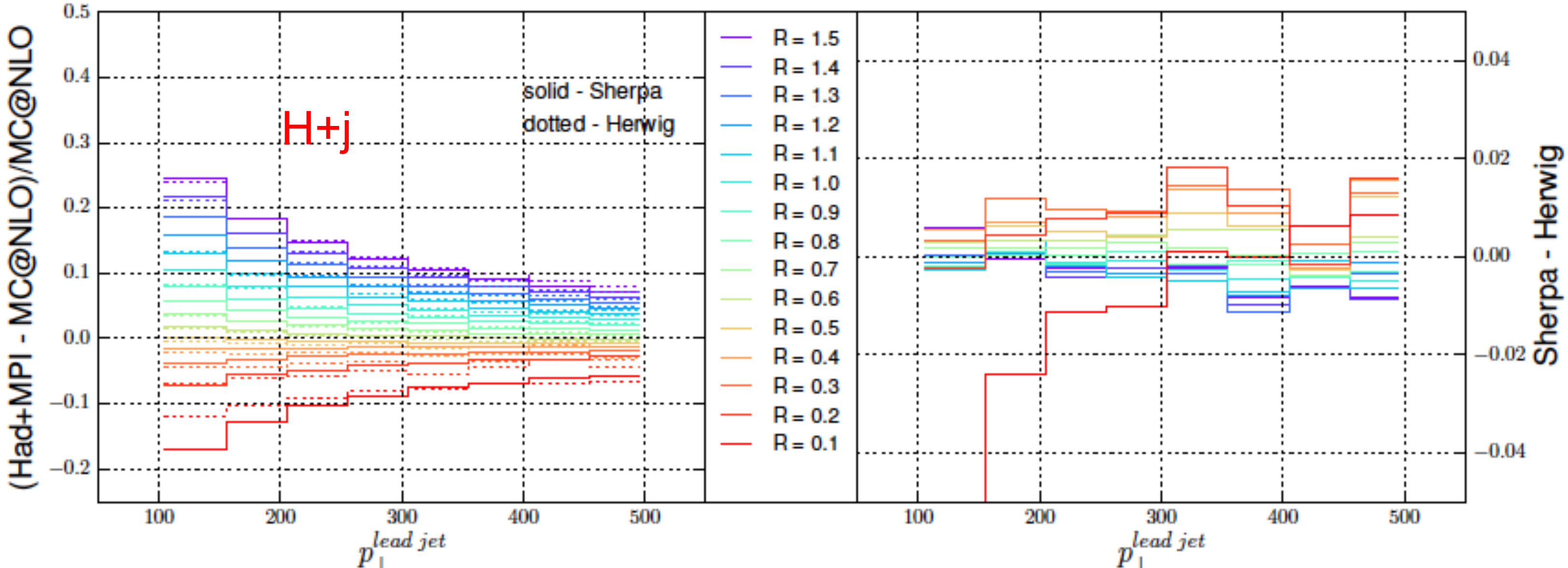




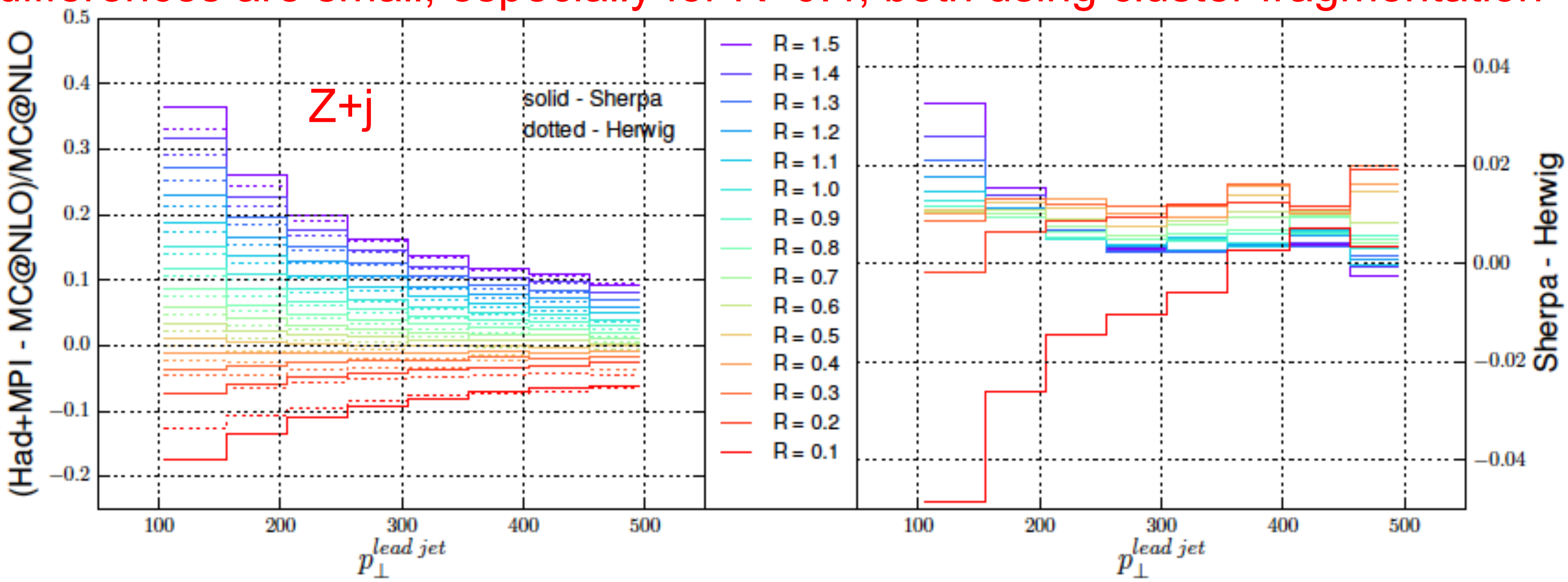
for R>0.4, differences between string and cluster fragmentation are small (<2%)

string fragmentation as implemented in Pythia

Differences between Sherpa and Herwig for hadronization + MPI



differences are small, especially for R=0.4, both using cluster fragmentation



Summary (redacted)

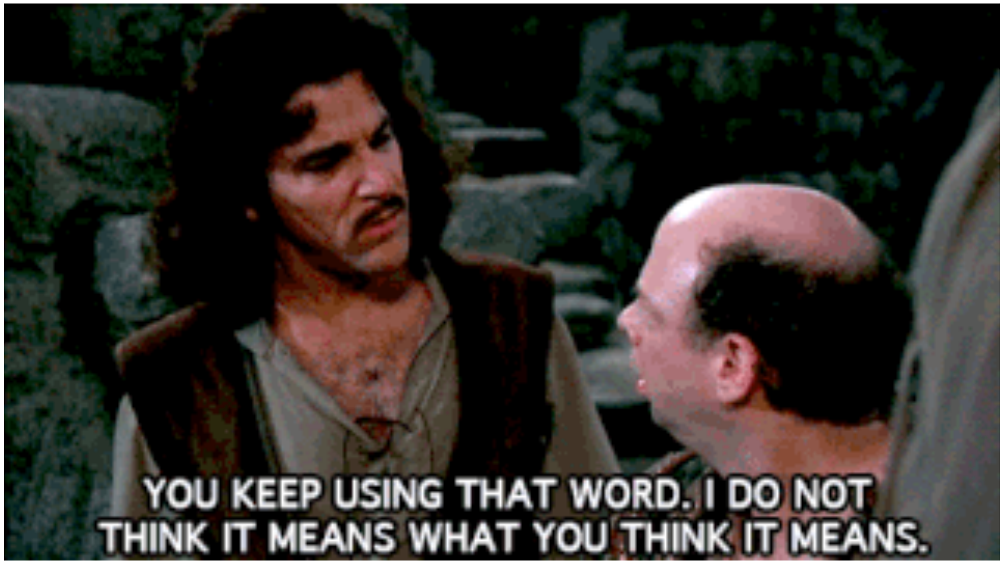
- Harm to ongoing analysis [redacted]
- Harm to ongoing calculation [redacted]
- Harm to ongoing analysis [redacted]
- Harm to ongoing analysis [redacted]
- Harm to ongoing calculation [redacted]
- Harm to ongoing accord [redacted]

Summary (unredacted)

- Searches for new physics, as well as a better understanding of standard model physics, require an increasing level of precision, both for measurement and for theory
- On the theory side, an increase in precision also requires an increase in precision for the inputs to the calculations (i.e. PDFs, $\alpha_s(m_Z)$...)
  - we will need to understand the impact of the new LHC data on the PDFs and their uncertainties
- For differential distributions, the highest level of precision is obtained with NNLO calculations
- Matched NLO+PS start from less-accurate fixed order results, but provide a more complete description of event structure, including resummation effects at leading log accuracy
- Most physics measurements at the LHC make use of small R(~0.4) jets; there can be differences between FO and NLO+PS predictions due to different estimates of jet shapes; these differences can be comparable to the size of the scale uncertainty

Summary (unredacted)

- Accidental cancellations can lead to unphysical estimates for the scale uncertainties for small R jets
- Hadronization and MPI corrections agree to within a few percent between Sherpa and Herwig (and between cluster and string)
  - and Pythia, since the Powheg results in the study used Pythia for parton showering and non-perturbative physics
- I'll step on the Monte Carlo speaker's toes, and say that the point above cannot be overemphasized; we need to better quantify the phrase **parton shower Monte Carlo uncertainties**



Les Houches Accord

- We expect parton-shower matched predictions to differ from the underlying fixed-order results in regions where
  - there is a large sensitivity to the jet shape
  - there is a restriction in phase space such that soft gluon resummation effects become important
  - the observable contains multiple disparate scales
  - the observable is sensitive to higher multiplicity final states than described by the fixed-order prediction
- Such differences should be smaller at NNLO than at NLO
- Large parton shower effects in the absence of the any of the points above should be viewed with suspicion
- ...as should large differences between parton shower (or resummed) predictions
- We do not expect non-perturbative tuning parameters to have large impacts on inclusive cross sections at high p_T

Even the Flash likes our book.

These are large logs

These are not

before resummation

after resummation

next-to-next-to leading logs

next to leading logs

leading logs

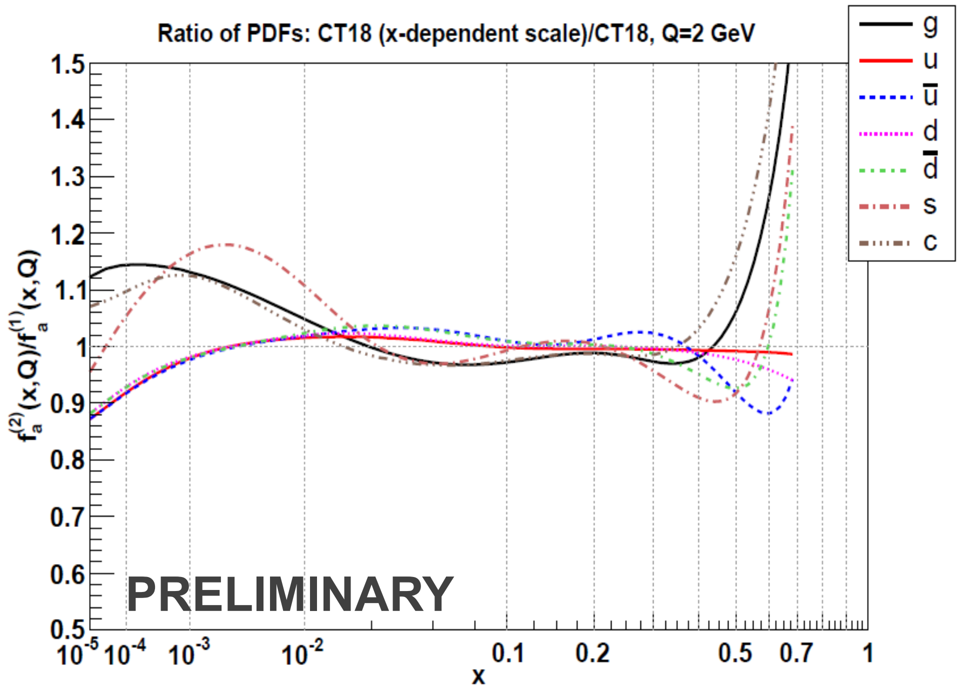
Theoretical uncertainty in DIS

- Mild NNLO theoretical uncertainties in large DIS data sets have a non-negligible impact on the global χ^2
- The following x-dependent factorization scale at NNLO improves the description of the CTEQ-TEA DIS sets by mimicking
  - missing N^3LO terms at x<0.001
  - small-x/saturation terms at x<0.001

$$\mu^2_{DIS,X} = 0.8^2 \left(Q^2 + \frac{0.3\ GeV^2}{x^{0.3}} \right)$$

- CT18Z uses a combination of $\mu_{DIS,x}$ (preferred by DIS) and an increased m_c^{pole}-1.4 GeV (preferred by LHC vector boson production, disfavored by DIS)

X-dependent DIS scale, effect on PDFs



using $\mu_{DIS,x}$ in a fixed-order NNLO cross xection has a similar effect to small-x resummation/saturation. In particular, the gluon and strange PDF are enhanced at x<0.01