



J. Huston
Michigan State University
for the SM phenomenology group
(A. Huss, M. Pellen, P. Azzurri)

...it's been too long

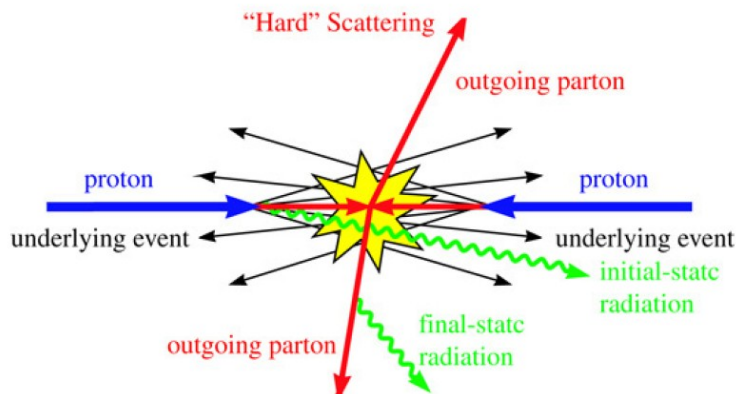
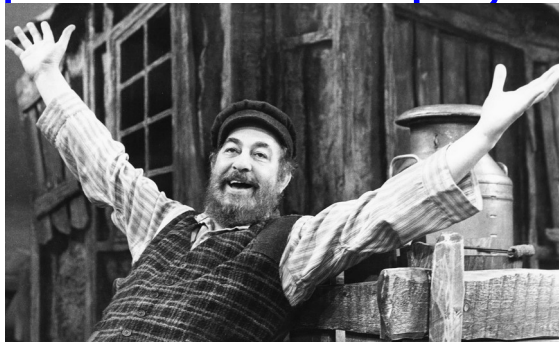
In memoriam

- Eric Pilon: one of the original organizers of Les Houches and the friend of many of us here
- « *Je parie que le cyclisme est génial au paradis* »



To quote Tevye in Fiddler on the Roof

- Precision!
- ...is one of the keys for better understanding the SM and looking for possible BSM physics



- PDFs, especially the determination of uncertainties
 - L_2 sensitivity, hopscotch, $\sim N^3LO$, $\sim N^3LO$ gluon and the Higgs
 - $\alpha_s(m_Z)$, especially determinations at the LHC
 - Matrix elements \rightarrow the LH wishlist \rightarrow experimental uncertainties that require theory improvements
 - STXS: multi-boson template cross sections for VBF/VBS
 - Jet algorithms: issues with heavy flavor, issues with NNLO comparisons
 - quark/gluon jet discrimination \rightarrow <https://arxiv.org/abs/2003.01700>
 - Photon vs photon+jet; agreement for the latter seems better at NNLO
 - m_W : where do we go from here?

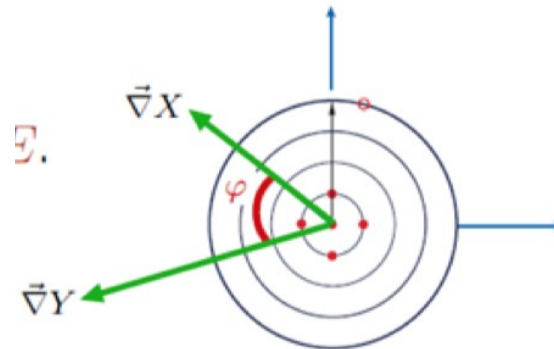
L₂ sensitivity: a new and powerful tool

$$S_{f,L_2}^H(E) \equiv \frac{\vec{\nabla} \chi_E^2 \cdot \vec{\nabla} f}{\Delta^H f}$$
$$= (\Delta^H \chi_E^2) C^H(f, \chi_E^2)$$

2nd Lagrangian technique

→ talk this week by
Pavel

- C^H represents the cosine of the correlation angle between PDF flavor f (or any defined quantity) and experimental χ^2



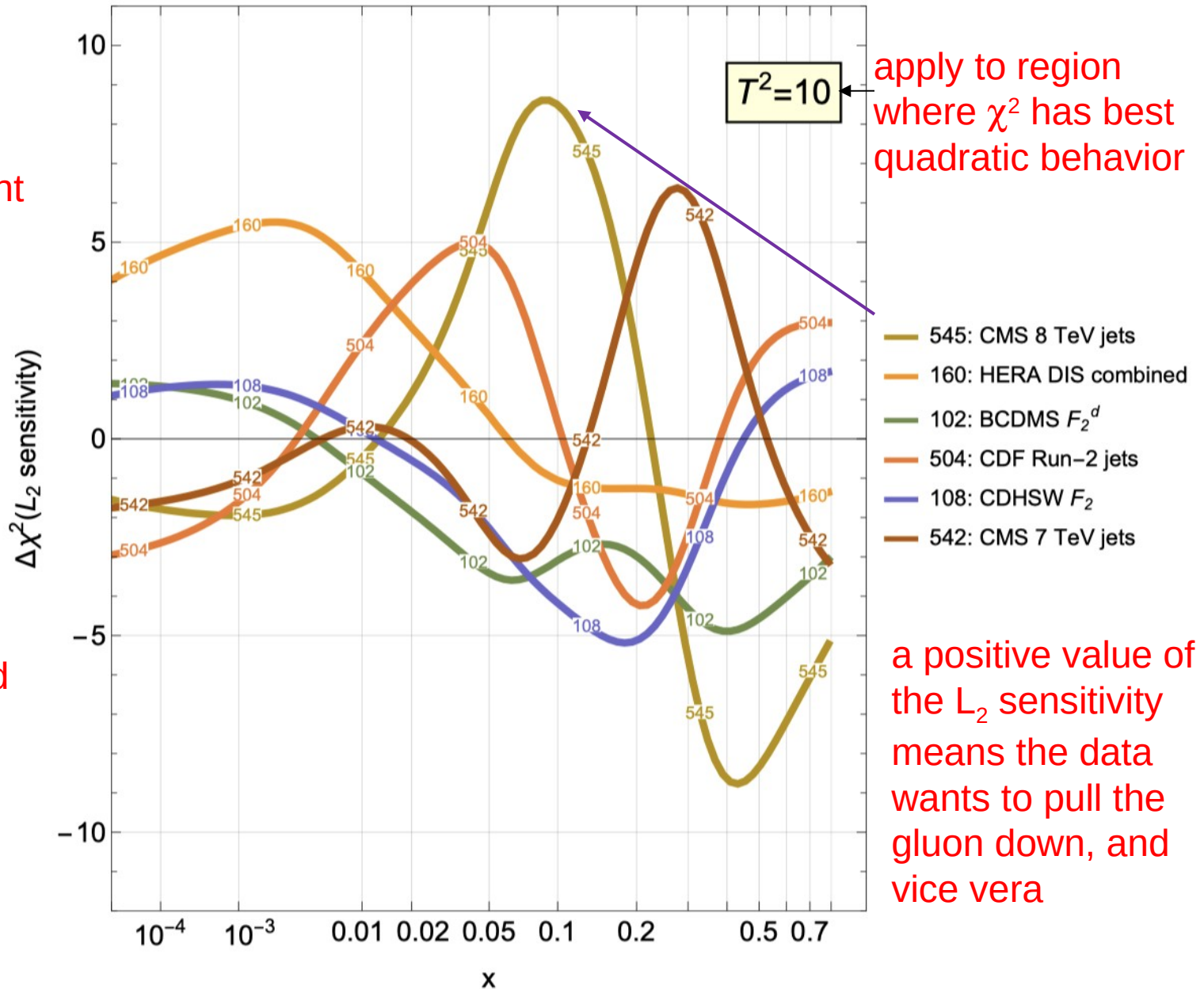
arXiv:2306.03918; many of
the authors in the room

The importance of an experiment for a particular PDF depends not only on the correlation of the cross section with that PDF, but the degree to which the cross section can determine that PDF.

CT18 NNLO
 $g(x, \underline{100 \text{ GeV}})$

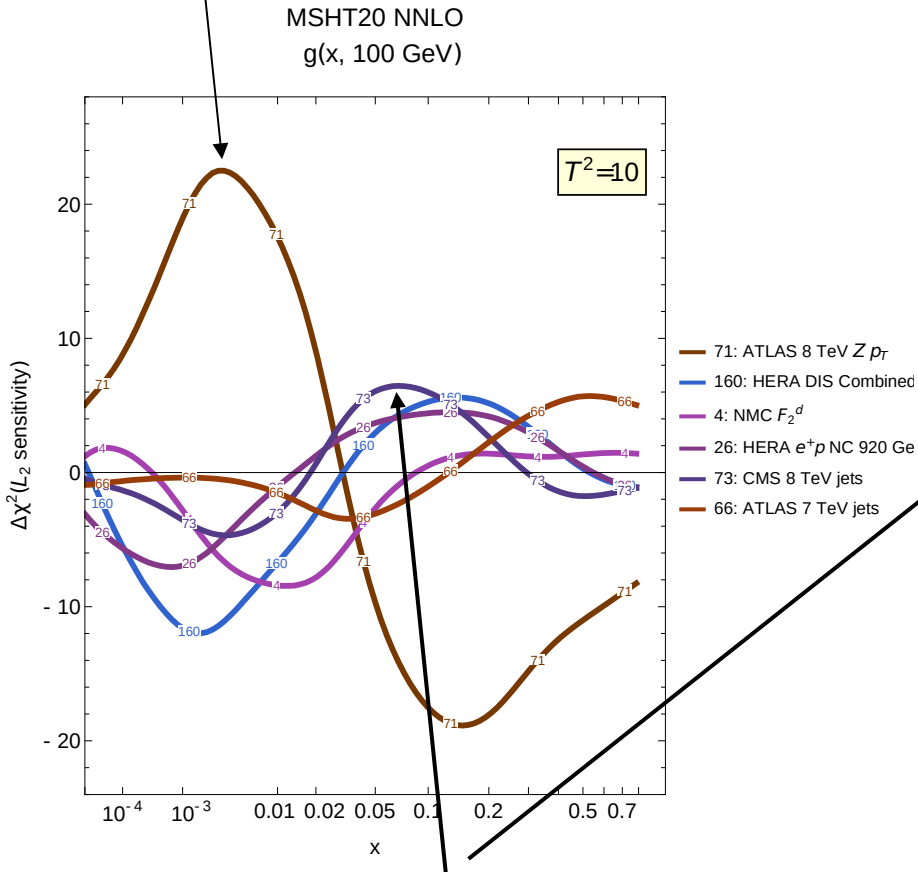
show only 6 most important experiments

by definition, there will be some tension. the sum should add to ~ 0 .

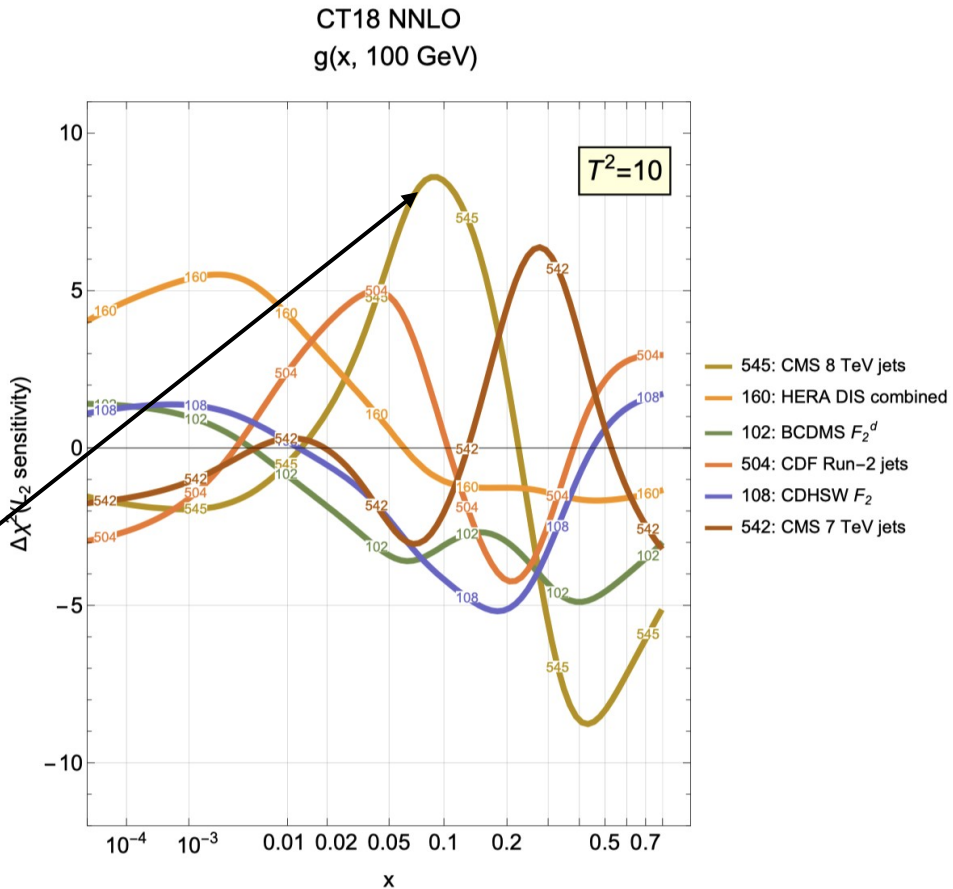


MSHT20 and CT18

Note importance of ATLAS Z p_T data
(also, Z p_T data poorly fit at NNLO)



CMS 8 TeV jet data play a similar role as in CT18

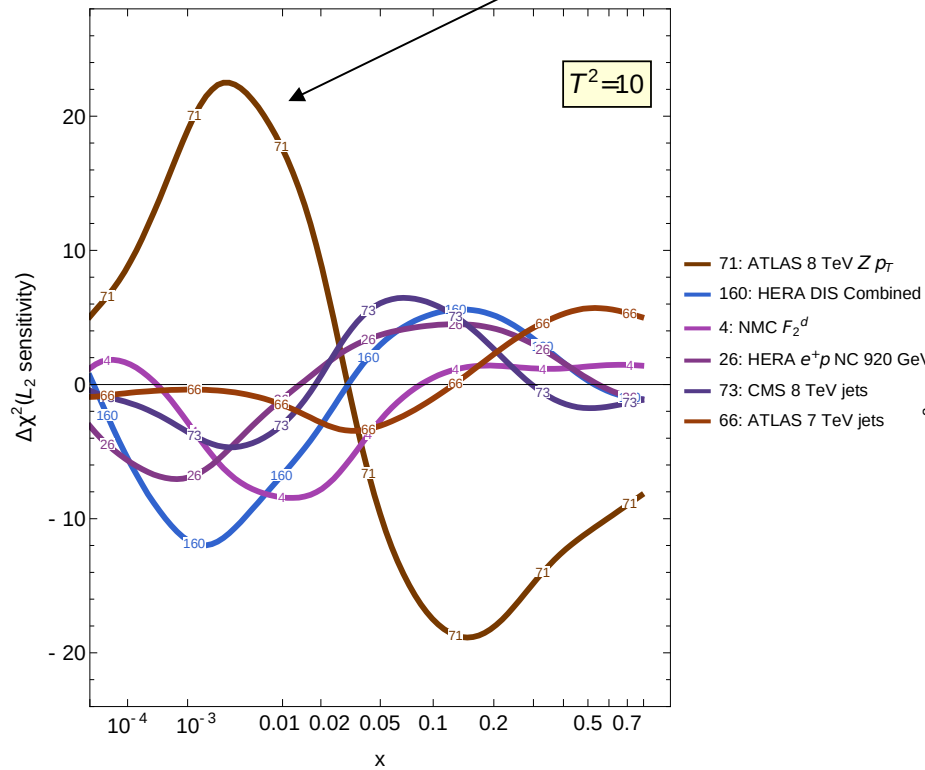


ATLAS Z p_T not one of 6 most important experiments (more restrictive kinematic region)

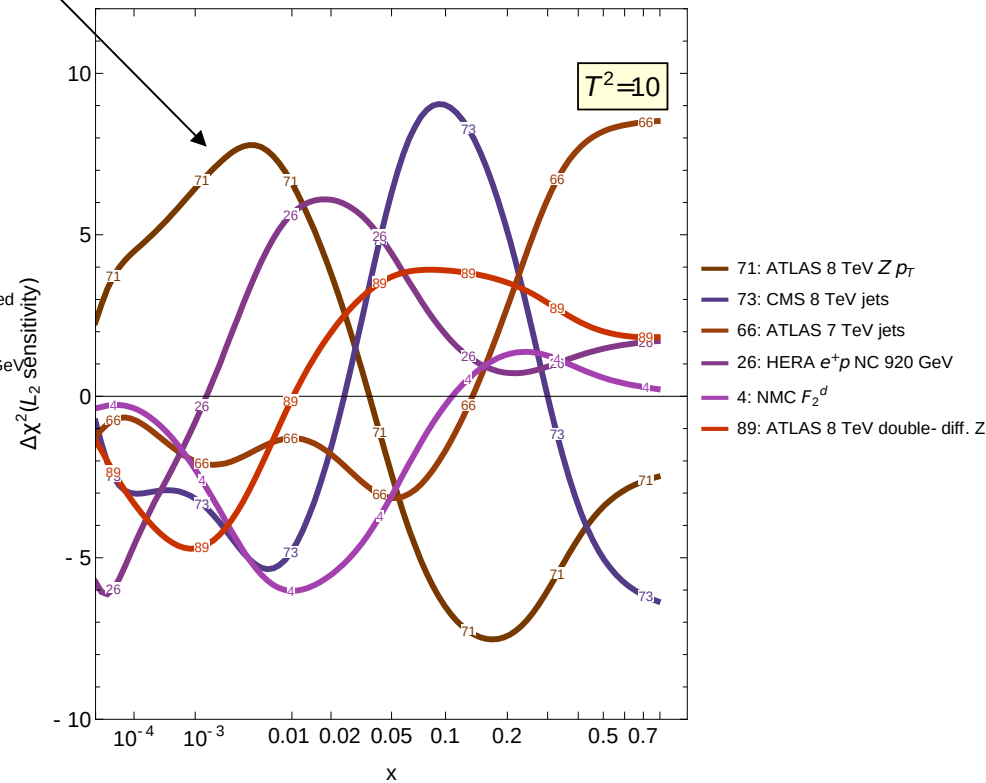
MSHT20 NNLO and aN3LO

shape of L_2 sensitivity similar for two PDFs, but absolute value of $Z p_T$ decreased by almost a factor of 3; significant change in low x gluon

MSHT20 NNLO
 $g(x, 100 \text{ GeV})$



MSHT20 approx. N3LO
 $g(x, 100 \text{ GeV})$



PDF+ $\alpha_s(m_Z)$

- Precision physics at the LHC, and specifically for Higgs boson production, requires precise determinations of PDFs and of $\alpha_s(m_Z)$

PDG 2022

$$\alpha_s(M_Z^2) = 0.1179 \pm 0.0009$$

Gluon-gluon fusion into Higgs

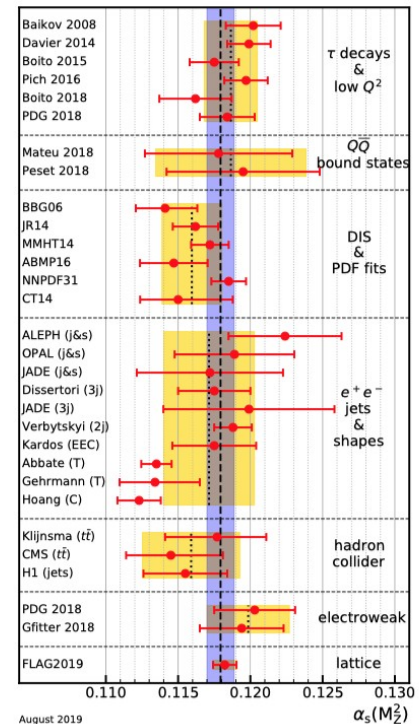
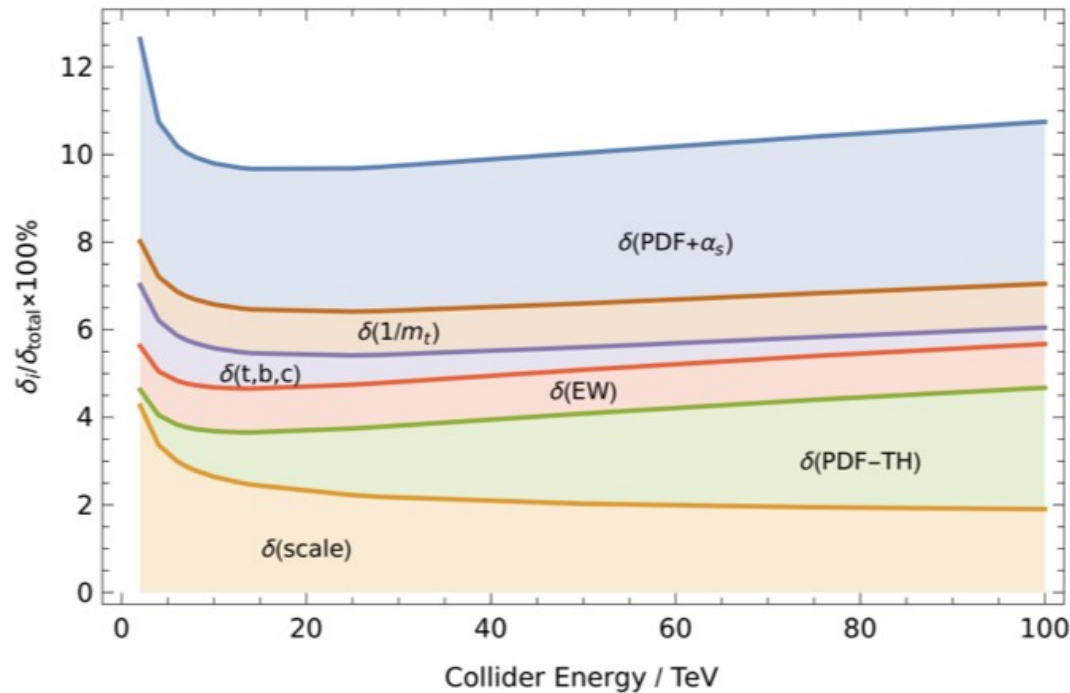
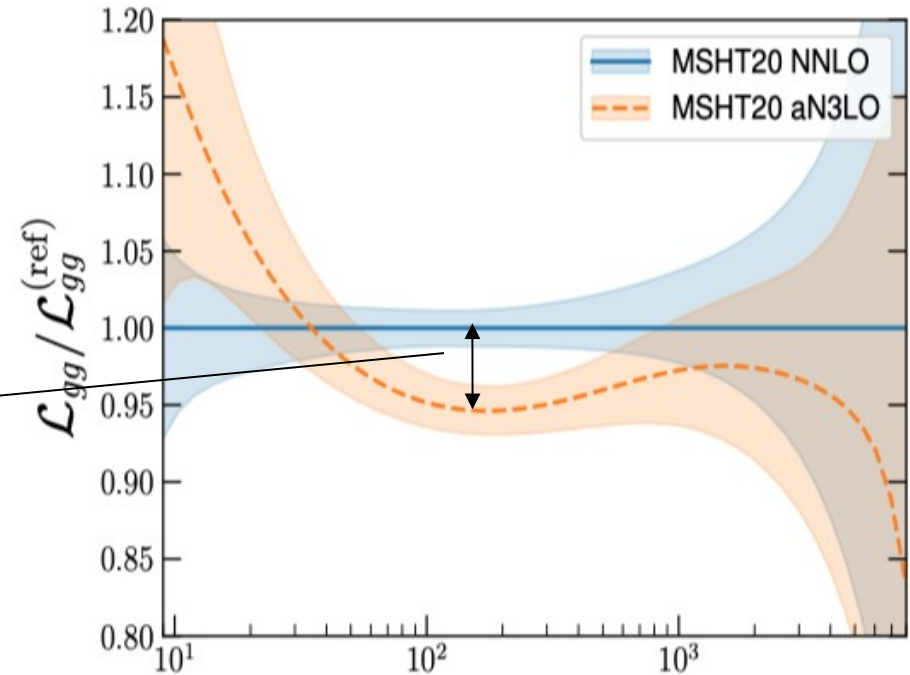
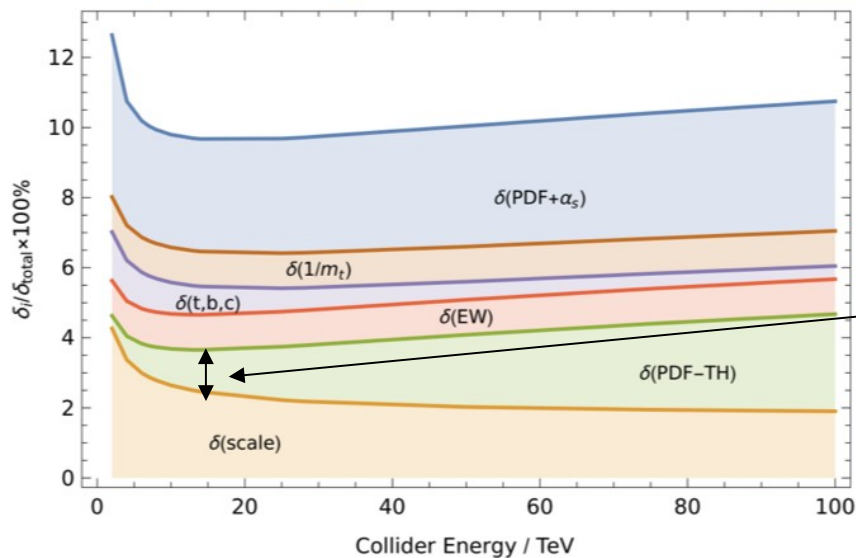


Figure 9.2: Summary of determinations of $\alpha_s(M_Z^2)$ from the seven sub-fields discussed in the text. The yellow (light shaded) bands and dotted lines indicate the pre-average values of each sub-field. The dashed line and blue (dark shaded) band represent the final world average value of $\alpha_s(M_Z^2)$.

Impact of aN3LO

- gg PDF luminosity at aN3LO at Higgs mass $\sim 5\%$ lower than nominal NNLO MSHT20
- If correct, then our benchmark cross sections for ggF are wrong \longrightarrow talk this week by Tom Cridge

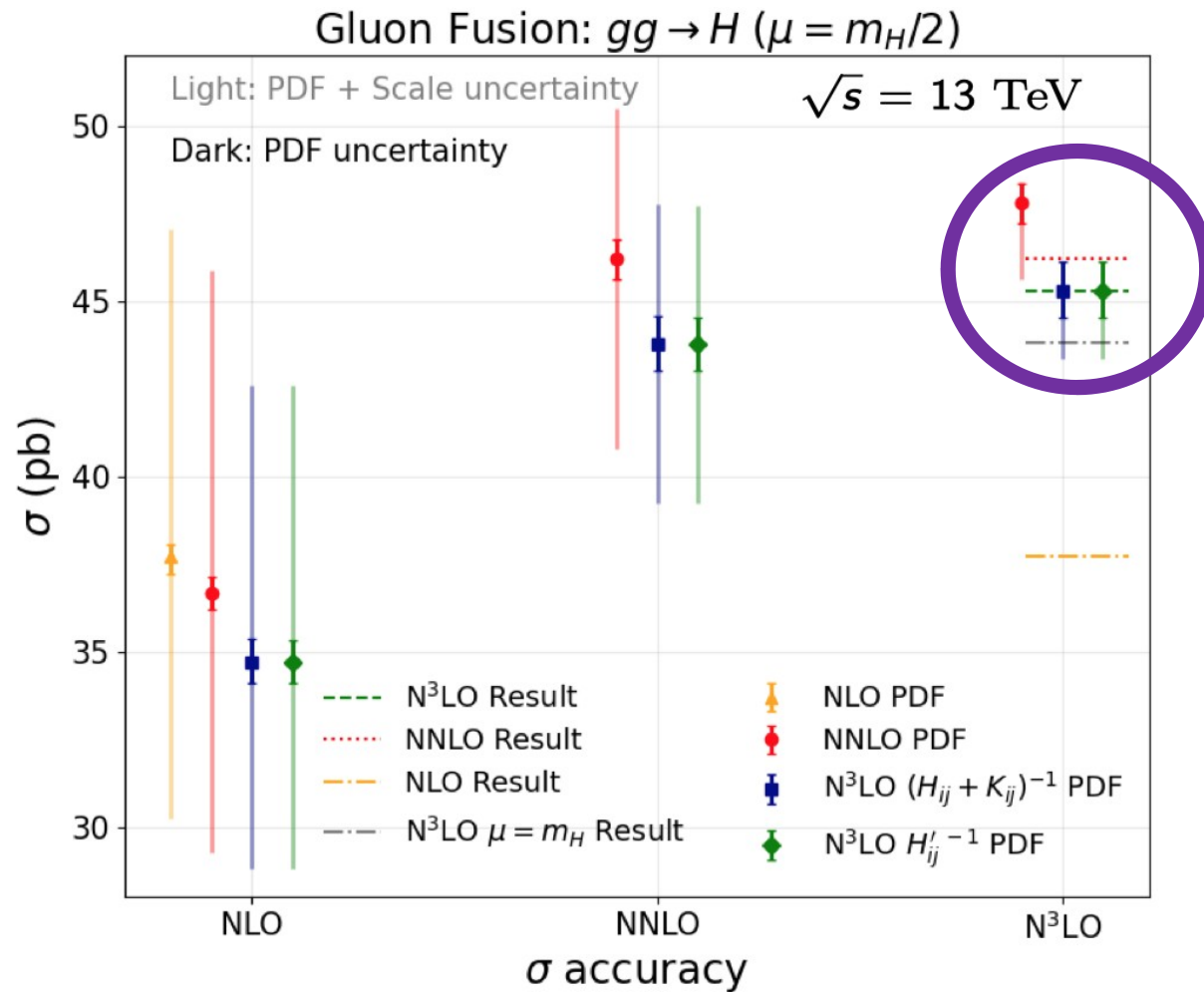
Gluon-gluon fusion into Higgs



- How robust are the aN3LO PDFs, and in particular the splitting functions? News from NNPDF? BTW, Simone still owes me a response.

...but on the bright side

- This would mean that the ggF cross section is more convergent



Les Houches 2021: Physics at TeV Colliders: Report on the Standard Model Precision Wishlist

arXiv:2207.02122

Alexander Huss¹, Joey Huston², Stephen Jones³, Mathieu Pellen⁴

process	known	desired
$pp \rightarrow H$	$N^3\text{LO}_{\text{HTL}}$	$N^4\text{LO}_{\text{HTL}}$ (incl.)
	$\text{NNLO}_{\text{QCD}}^{(t)}$	
	$N^{(1,1)}\text{LO}_{\text{QCD}\otimes\text{EW}}^{(\text{HTL})}$	$\text{NNLO}_{\text{QCD}}^{(b,c)}$
$pp \rightarrow H + j$	NNLO_{HTL}	$\text{NNLO}_{\text{HTL}} \otimes \text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$
	NLO_{QCD}	
	$N^{(1,1)}\text{LO}_{\text{QCD}\otimes\text{EW}}$	
$pp \rightarrow H + 2j$	$\text{NLO}_{\text{HTL}} \otimes \text{LO}_{\text{QCD}}$	$\text{NNLO}_{\text{HTL}} \otimes \text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$
	$N^3\text{LO}_{\text{QCD}}^{(\text{VBF}^*)}$ (incl.)	
	$\text{NNLO}_{\text{QCD}}^{(\text{VBF}^*)}$	
	$\text{NLO}_{\text{EW}}^{(\text{VBF})}$	
$pp \rightarrow H + 3j$	NLO_{HTL}	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$
	$\text{NLO}_{\text{QCD}}^{(\text{VBF})}$	
$pp \rightarrow VH$	$\text{NNLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	
	$\text{NLO}_{gg \rightarrow HZ}^{(t,b)}$	
$pp \rightarrow VH + j$	NNLO_{QCD}	$\text{NNLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$
	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	
$pp \rightarrow HH$	$N^3\text{LO}_{\text{HTL}} \otimes \text{NLO}_{\text{QCD}}$	NLO_{EW}
	$N^3\text{LO}_{\text{QCD}}^{(\text{VBF}^*)}$ (incl.)	
$pp \rightarrow HH + 2j$	$\text{NNLO}_{\text{QCD}}^{(\text{VBF}^*)}$	
	$\text{NLO}_{\text{EW}}^{(\text{VBF})}$	
$pp \rightarrow HHH$	NNLO_{HTL}	
$pp \rightarrow H + t\bar{t}$	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	NNLO_{QCD}
	NNLO_{QCD} (off-diag.)	
$pp \rightarrow H + t/\bar{t}$		NNLO_{QCD}
	NLO_{QCD}	

$H + \geq 2j$: *LH19 status*: VBF production known at $N^3\text{LO}_{\text{HTL}}$ accuracy for the total cross section [426] and at NNLO_{HTL} accuracy differentially [172, 280] in the “DIS” approximation [427]; non-factorizable QCD effects beyond this approximation studied in Refs. [428]. Full NLO_{QCD} corrections for $H + 3j$ in the VBF channel available [429, 430]. $H + \leq 3j$ in the gluon fusion channel was studied in Ref. [431] and an assessment of the various dependence of the various jet multiplicities was made in Ref. [432]; NLO_{EW} corrections to stable Higgs boson production in VBF calculated [433] and available in HAWK [434]. Mass effects in $H + 2j$ at large energy are known within the “High Energy Jets” framework [435–440].

In Ref. [441] parton-shower and matching uncertainties for VBF Higgs production were studied in detail using PYTHIA and HERWIG. The study found that varying just the renormalisation, factorisation and shower scales underestimates the theoretical uncertainty. Instead, by comparing different parton shower Monte Carlos the authors observe differences at the level of 10% for NLO accurate observables and 20% for LO accurate observables. The work also highlighted the importance of the choice of appropriate recoil schemes in order not to obtain unphysical enhancements for VBF topologies.

NNLO_{QCD} corrections to VBF Higgs production with $H \rightarrow b\bar{b}$ and $H \rightarrow WW^*$ decays were computed for fiducial cross sections in Ref. [273], using the nested soft-collinear subtraction scheme. These results have recently been extended to include also anomalous HVV interactions [442].

A comparative study of VBF Higgs production at fixed order and with parton shower Monte Carlo has been carried out over a wide range of Higgs boson transverse momenta [335]. This was an outgrowth of Les Houches 2019. One interesting discovery is that, at very high Higgs boson p_T , current implementations of ME+PS Monte Carlo do not provide a completely accurate description of the VBF production mechanism. Rather than the nominal $2 \rightarrow 3$ process, high- p_T VBF Higgs production becomes effectively a $2 \rightarrow 2$ process, with the second tagging jet becoming soft with respect to the hard scattering scale. This then requires the use of two factorization scales in the ME+PS VBF calculation to take into account this disparity.

The non-factorisable NNLO_{QCD} correction to VBF production was studied in Ref. [443] and found to be small.

The impact of the top-quark mass in $H + 1, 2$ jets was studied in Ref. [444]. For $H + 1$ jet, good agreement with the full NLO_{QCD} result was observed when including the top-quark mass in the real radiation and rescaling the virtual contribution in the HTL by the full Born result. NLO differential predictions for $H + 2$ jet were computed using this approximation and the relative correction was found to be very similar to the NLO_{HTL} prediction, although the absolute predictions differed significantly.

The current experimental error on the $H + \geq 2j$ cross section is on the order of 25% [424], again dominated by statistical errors, and again for the diphoton final state, by the fit statistical error. With the same assumptions as above, for 3000 fb^{-1} , the statistical error will reduce to the order of 3.5%. If the systematic errors remain the same, at approximately 12% (in this case the largest systematic error is from the jet energy scale uncertainty and the jet energy resolution uncertainty), a total uncertainty of approximately 12.5% would result, less than the current theoretical

¹: Precision wish list: Higgs boson final states. $N^x\text{LO}_{\text{QCD}}^{(\text{VBF}^*)}$ means a calculation using structure function approximation. $V = W, Z$.

From the theorist to the experimentalist

- NNLO is needed for PDF fitting/precise comparison to data
- Frontier is being extended to 2->3 processes
- ...but even for 2->2, programs are often not public, and those that are public may take large CPU resources
- ...this can be true even if NNLO grids are being used; grids can be useful for PDF fitting, for example
- There is progress in improving the ease of use, with some of the experts here with us

- A relatively new tool is HighTEA

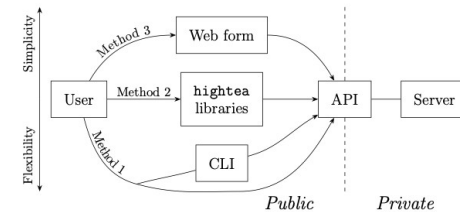


Figure 1. High-level structure of HighTEA. Shown are library's main components together with the three access methods. The vertical dashed line delineates the separation of public and private components.

- Talk this week by Rene Poncelet
- Refreshments will be served



The sausage-making of α_s

- We (PDG) divide the determinations into 7 categories and take an unweighted fit for each category.
- The 6 non-lattice measurements are then averaged with the lattice average provided by the FLAG group

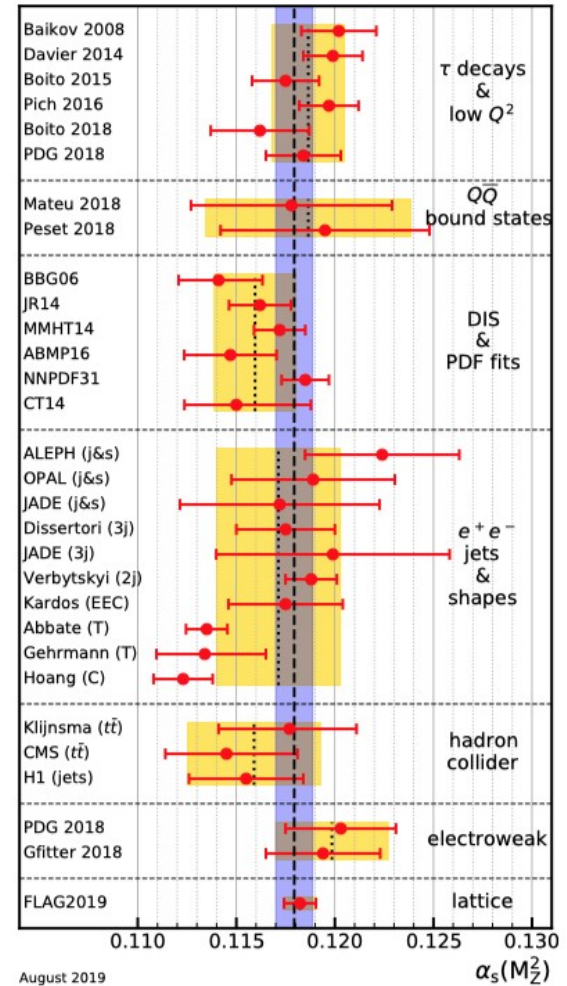
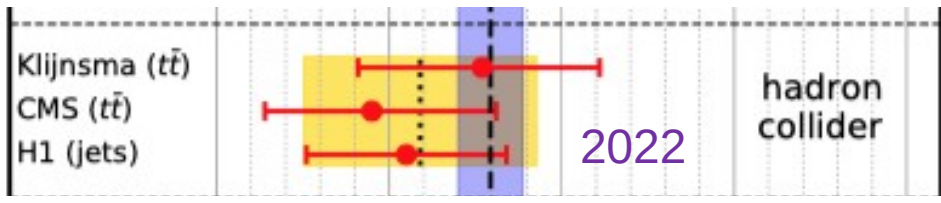


Figure 9.2: Summary of determinations of $\alpha_s(M_Z^2)$ from the seven sub-fields discussed in the text. The yellow (light shaded) bands and dotted lines indicate the pre-average values of each sub-field. The dashed line and blue (dark shaded) band represent the final world average value of $\alpha_s(M_Z^2)$.

Collider measurements of α_s

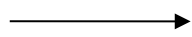
- As the number of NNLO calculations has increased, there have been a growing number of determinations of $\alpha_s(m_Z)$ at that order (or higher) from the LHC experiments that have nominal uncertainties that rival the full world average uncertainty



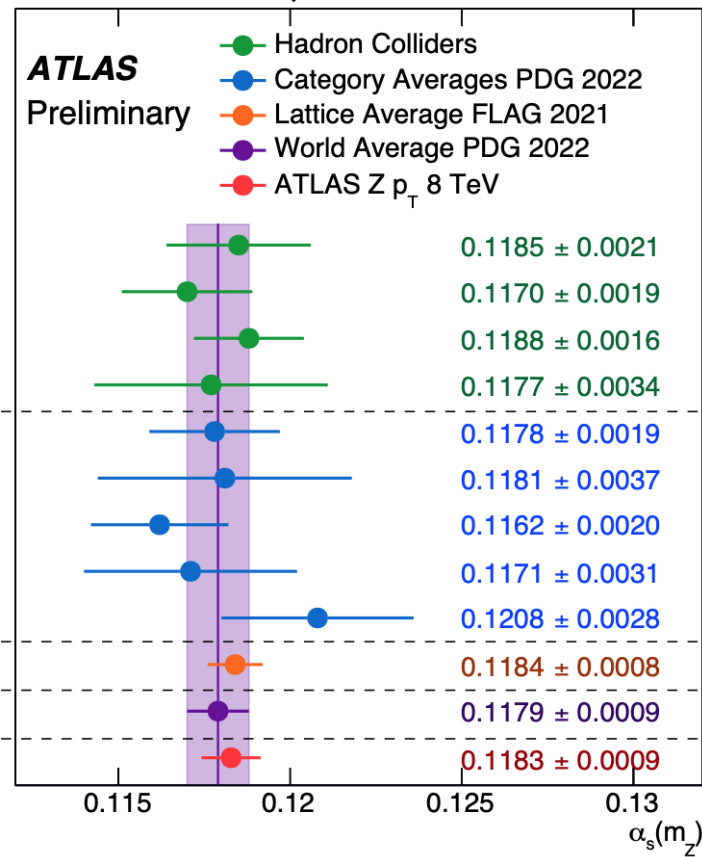
- $Z p_T$
- event shapes

- It would be nice to understand those uncertainties better, especially if PDF uncertainties are taken into account

N^3LL+N^3LO

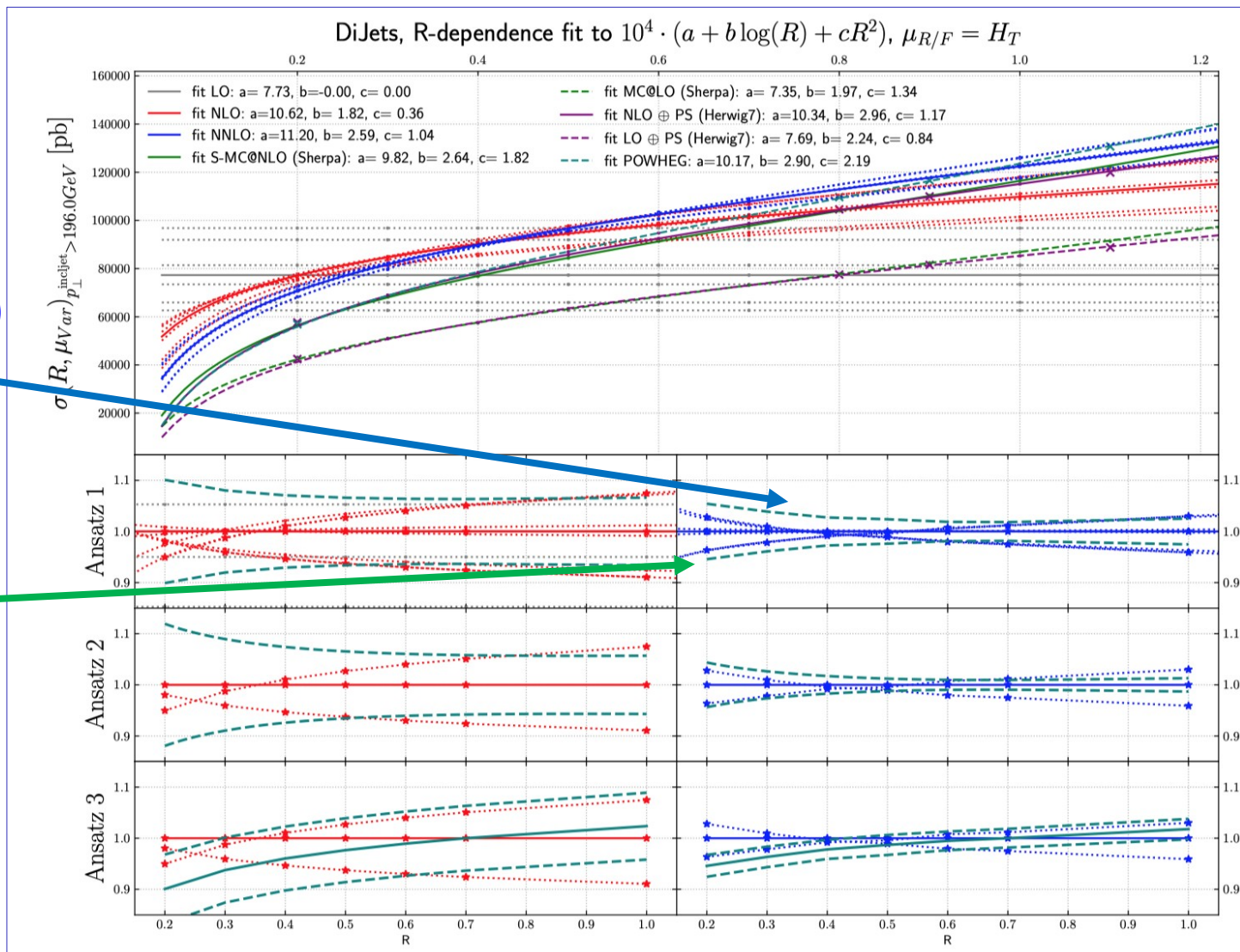


ATLAS ATEEC	
CMS jets	
W, Z inclusive	
$t\bar{t}$ inclusive	
τ decays	
$Q\bar{Q}$ bound states	
PDF fits	
e^+e^- jets and shapes	
Electroweak fit	
Lattice	
World average	
ATLAS Z p_T 8 TeV	



Jet algorithms: arXiv:1903.12563 (LH17)

- At NNLO, there are accidental cancellations, that lead to an artificially low scale uncertainty for processes with small R (0.4) jets
- Prescriptions for restoring reasonable uncertainty estimate
- Similar for Z+jet; H+jet ok
- Look at for 3 jet at NNLO?
- A Les Houches accord?**

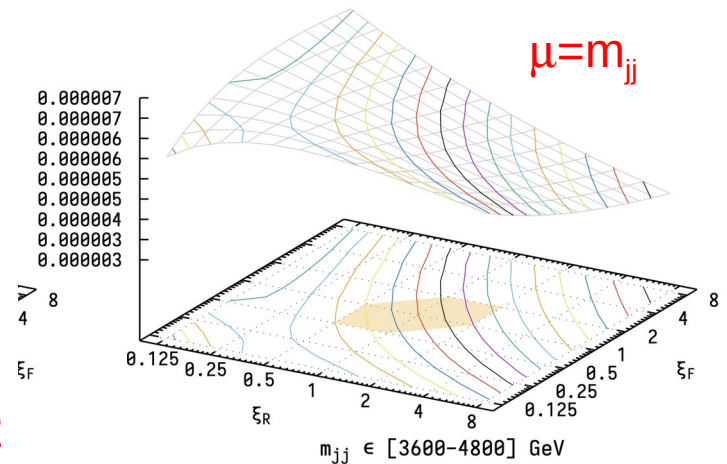


Scale choices

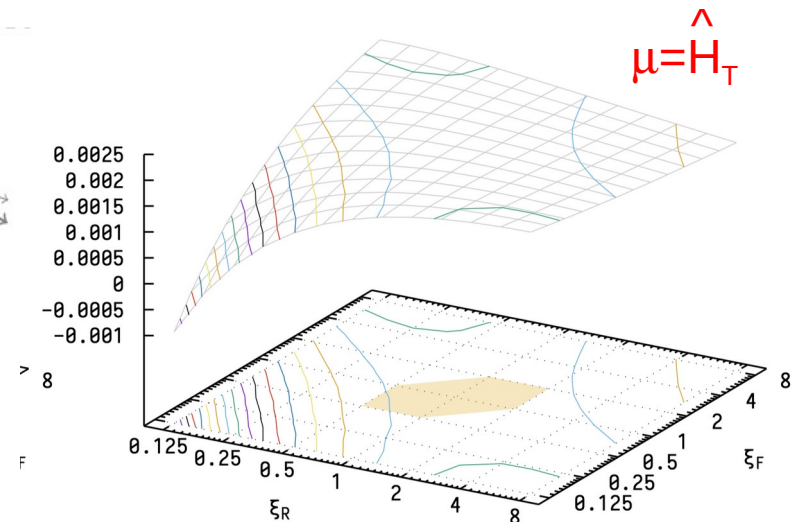
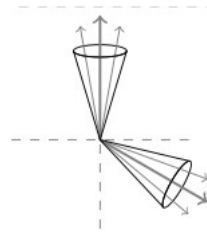
- Even at NNLO, the parametric scale choice can be important
- This is worthwhile to investigate further
- With grids, can explore the scale dependence in 2D, which I've always found to be illuminating

Alex Huss: dijet at NNLO

$m_{jj} \in [3600-4800]$ GeV

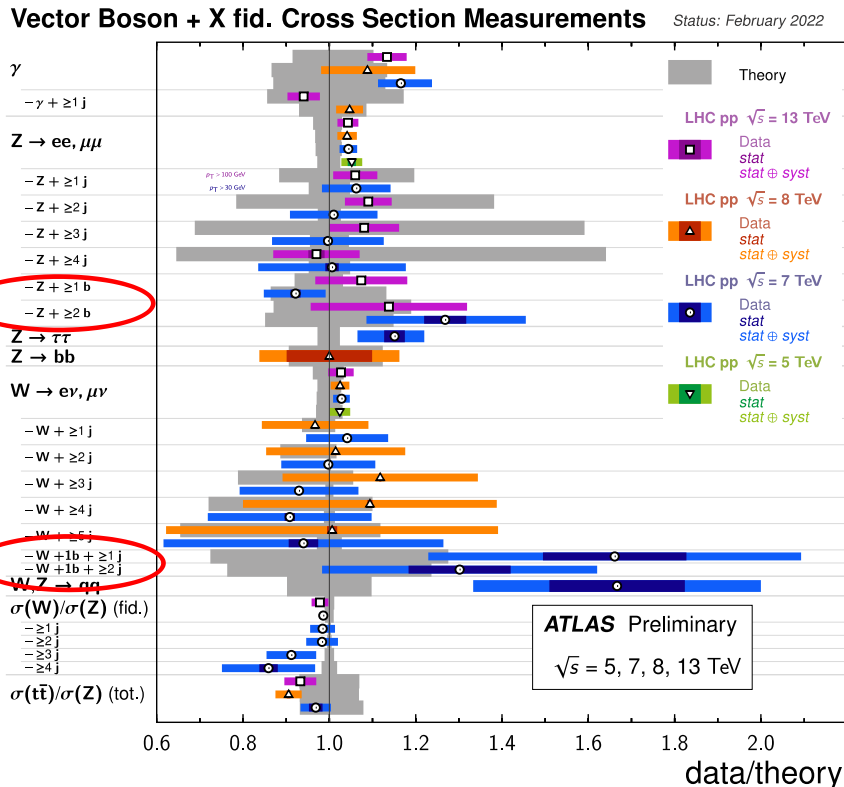


$y_b=1-2$
 $y^*=1-2$



Jets with heavy flavor

- Associated production of vector bosons with heavy flavour is an important precision test of pQCD in the presence of two mass scales, and can also provide critical information on heavy quark PDFs such as the charm and strange distributions; N.B. NNLO calculations needed for PDF fits
- Can also serve as a background to new physics



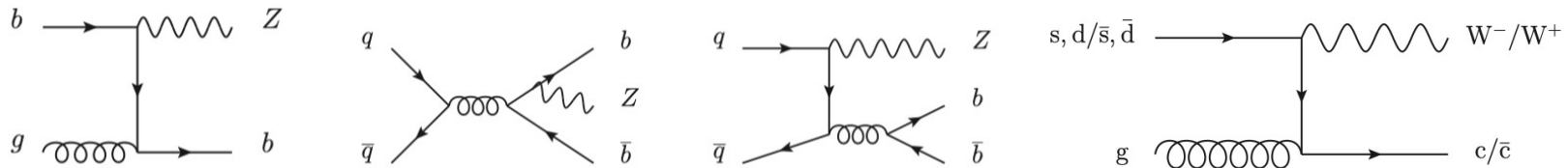
process	known	desired
$pp \rightarrow V$	$N^3\text{LO}_{\text{QCD}}^{(\epsilon \rightarrow 0)}$ (incl.) $N^3\text{LO}_{\text{QCD}}$ (incl., γ^*) NNLO _{QCD} NLO _{EW}	$N^3\text{LO}_{\text{QCD}} + N^2\text{LO}_{\text{EW}} + N^{(1,1)}\text{LO}_{\text{QCD} \otimes \text{EW}}$
$pp \rightarrow VV'$	NNLO _{QCD} + NLO _{EW} + NLO _{QCD} (<i>gg</i> channel)	NLO _{QCD} (<i>gg</i> channel, w/ massive loops)
$pp \rightarrow V + j$	NNLO _{QCD} + NLO _{EW}	hadronic decays
$pp \rightarrow V + 2j$	NLO _{QCD} + NLO _{EW} NLO _{EW}	NNLO _{QCD}
$pp \rightarrow V + b\bar{b}$	NLO _{QCD}	NNLO _{QCD} + NLO _{EW}
$pp \rightarrow VV' + 1j$	NLO _{QCD} NLO _{EW} (w/o decays)	NLO _{QCD} + NLO _{EW}
$pp \rightarrow VV' + 2j$	NLO _{QCD}	NLO _{QCD} + NLO _{EW}
$pp \rightarrow W^+W^+ + 2j$	NLO _{QCD} + NLO _{EW}	
$pp \rightarrow W^+Z + 2j$	NLO _{QCD} + NLO _{EW}	
$pp \rightarrow VV'V''$	NLO _{QCD} NLO _{EW} (w/o decays)	NLO _{QCD} + NLO _{EW}
$pp \rightarrow W^+W^+W^-$	NLO _{QCD} + NLO _{EW}	
$pp \rightarrow \gamma\gamma$	NNLO _{QCD} + NLO _{EW}	
$pp \rightarrow \gamma + j$	NNLO _{QCD} + NLO _{EW}	→ will add $\gamma+c/b$
$pp \rightarrow \gamma\gamma + j$	NLO _{QCD} NLO _{EW}	NNLO _{QCD} + NLO _{EW}
$pp \rightarrow \gamma\gamma\gamma$	NNLO _{QCD}	

Table I.3: Precision wish list: vector boson final states. $V = W, Z$ and $V', V'' = W, Z, \gamma$. Full leptonic decays are understood if not stated otherwise.

VbB has been known at NLO for some time, and matched to parton showers. WbB known at NLO with up to 3 extra jets. Recently, the two-loop corrections to the WbB amplitude have been calculated (PRL127.012001) Non-planar master integrals still to be calculated.

V+HF

- A heavy flavor quark can be present in the initial state or produced through gluon splitting



- The calculation can be performed in a scheme where there are only 4 parton flavours (4FNS) or in which the b-quark is included (5-FNS)
- The kinematics can drive the subprocess for the production, as for example, whether the final state heavy quark (jet) has to pass only some minimum p_T requirement, or whether it has to roughly balance the boson transverse momentum
- If it's the former, then the final state c or b quark is likely to arise through gluon splitting, especially given the additional gluon splittings that may occur in a parton shower (*JHEP* 02 (2018) 059)
 - this effect is more pronounced if there is a hierarchy of scales, i.e. $p_T^{\text{jet}} \gg p_T^{\text{charm}}$ (would be useful to measure differentially in p_T^{jet})

Jet tagging

- There is also the issue of how the heavy flavor jet is tagged; the theory predictions use a flavor tagging k_T jet algorithm in which the distance between pseudo-jets i and j (d_{ij}) are dependent on the flavour of the considered partons

$$d_{ij} = \frac{\Delta y_{ij}^2 + \Delta \phi_{ij}^2}{R^2} \begin{cases} \max(k_{Ti}, k_{Tj})^2 & \text{if softer of } i, j \text{ is flavored} \\ \min(k_{Ti}, k_{Tj})^2 & \text{if softer of } i, j \text{ is unflavored} \end{cases}$$

- $d_{i\beta} = \begin{cases} \max(k_{Ti}, k_{T\beta}(y_i))^2 & \text{if } i \text{ is flavored} \\ \min(k_{Ti}, k_{T\beta}(y_i))^2 & \text{if } i \text{ is unflavored} \end{cases}$ **flavour-dependent**

- The experimental measurements typically use the anti- k_T jet algorithm with later flavor identification (*Eur.Phys.J.C* 47 (2006) 113)

Jet tagging

- There has been a great deal of activity on the theory side regarding IR-safe algorithms for use in the NNLO calculations
- All use information not typically available in experimental settings, e.g. the measurement of all b-quarks in the event
- An unfolding procedure is needed to transform the two jet algorithms so that the theory can be compared to the data with the minimum of additional assumptions
- Many of the experts are here; this would be a good place to come to some consensus, and maybe even another **Les Houches Accord**

Common fiducial cross sections in VBF/VBS

Current situation ; Disparate signal definitions.
 Example for VBF (same/ worse situation for VBS)

TABLE II. Summary of VBF W production cross sections measured at the LHC in the $\ell\nu jj$ final state with different m_{jj} definitions and different proton collision energies. All cross sections are for a single lepton flavor.

m_{jj} cut	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	$\sqrt{s} = 13$ TeV
120 GeV			6.23 ± 0.62 pb (CMS Collaboration, 2020b)
500 GeV	2.76 ± 0.67 pb (ATLAS Collaboration, 2017g)	2.89 ± 0.51 pb (ATLAS Collaboration, 2017g)	
1 TeV		0.42 ± 0.10 pb (CMS Collaboration, 2016)	

TABLE I. Summary of VBF Z production cross sections measured at the LHC in the $\ell\ell jj$ final state with different m_{jj} definitions and different proton collision energies. All quoted cross sections are for a single lepton flavor.

m_{jj} cut	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	$\sqrt{s} = 13$ TeV
120 GeV	154 ± 58 fb (CMS Collaboration, 2013b)	174 ± 43 fb (CMS Collaboration, 2015d)	534 ± 60 fb (CMS Collaboration, 2018a)
250 GeV		54.7 ± 11.2 fb (ATLAS Collaboration, 2014e)	119 ± 26 fb (ATLAS Collaboration, 2017c)
1 TeV		10.7 ± 2.1 fb (ATLAS Collaboration, 2014e)	37.4 ± 6.5 fb (ATLAS Collaboration, 2021)

Summary

- I haven't been enough involved with machine learning

Summary

- ...so I asked chatGPT to write my summary for me

Summary (JH+chatGPT)

- Main Objectives:

1. Explore physics phenomena at TeV colliders.
2. Foster collaboration among researchers in the field.
3. Address theoretical and experimental challenges.
4. Discuss latest results and future prospects.

- Key Topics:

1. Standard Model (SM) Measurements
 1. Precise SM predictions and tests.
 2. Electroweak and QCD processes.
 3. Top quark and Higgs boson studies.
2. Beyond the Standard Model (BSM) Physics
 1. Supersymmetry (SUSY) searches.
 2. Dark matter and neutrino physics.
 3. Extra dimensions and new symmetries.
3. Collider and Detector Upgrades
 1. Machine and beam parameters.
 2. Detector technologies and performance.
 3. High-luminosity upgrades and future facilities.

4. Monte Carlo Simulations and Data Analysis

1. Event generation and simulations.
2. Reconstruction techniques and algorithms.
3. Statistical methods and uncertainties.

5. Theory and Phenomenology

4. New models and particle interpretations.
5. Precision calculations and effective field theories.
6. Collider signatures and phenomenological implications.

- Participants:

- Leading physicists, theorists, and experimentalists.
- Early career researchers and graduate students.
- Representatives from academia and research institutions.
- Industry experts in detector technology and simulations.

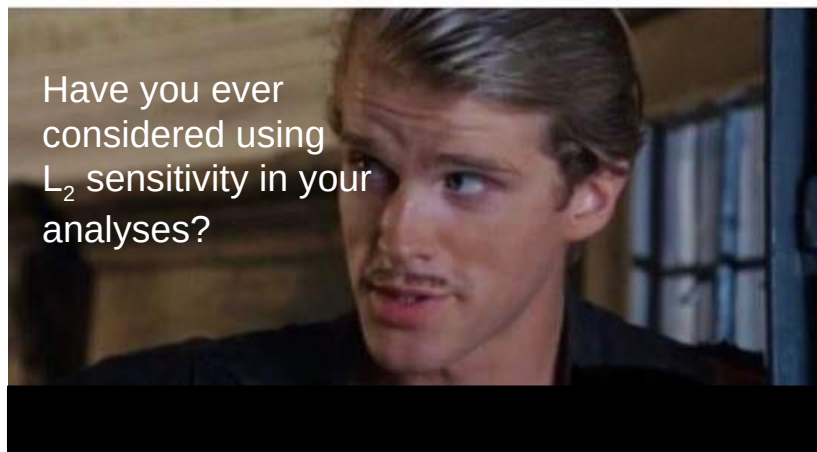
- Outcomes:

1. Knowledge exchange and collaboration initiation.
2. Identification of open questions and future research directions.

- 3. Dissemination of latest findings through publications and presentations.**

4. Strengthening the foundation for future TeV collider experiments.

- [Closing Slide: Les Houches Workshop on



...so one thing that is missing
Is a reference to The
Princess Bride

I mentioned this to chatGPT

-
- [Closing Slide: Les Houches Workshop on Physics at TeV Colliders] As the great Inigo Montoya from The Princess Bride said, "I hope we can have lots of chances to collaborate and explore the mysteries of physics at TeV colliders!" Thank you for your attention! Questions and discussions are welcome.

...also work in the word inconceivable

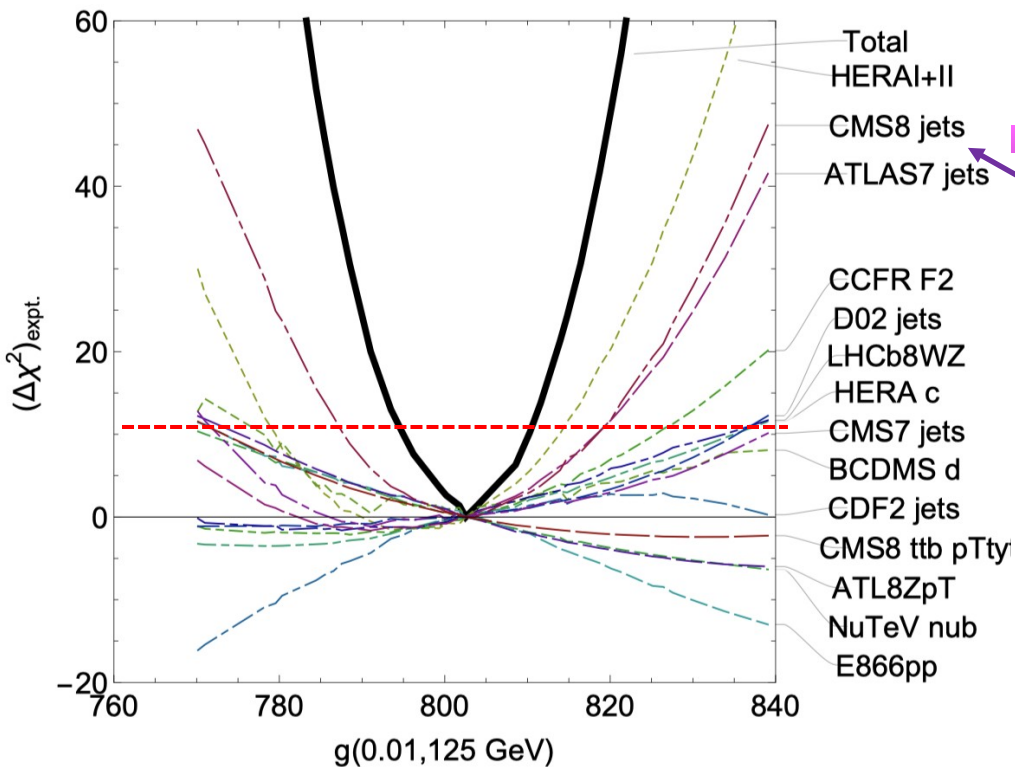
[Closing Slide: Les Houches Workshop on Physics at TeV Colliders] In the wise words of Inigo Montoya from The Princess Bride, "I hope we can have lots of chances to collaborate and explore the mysteries of physics at TeV colliders! **And remember, the discoveries we make might just be inconceivable!**" Thank you for your attention! Questions and

Extra

What is the L_2 sensitivity?

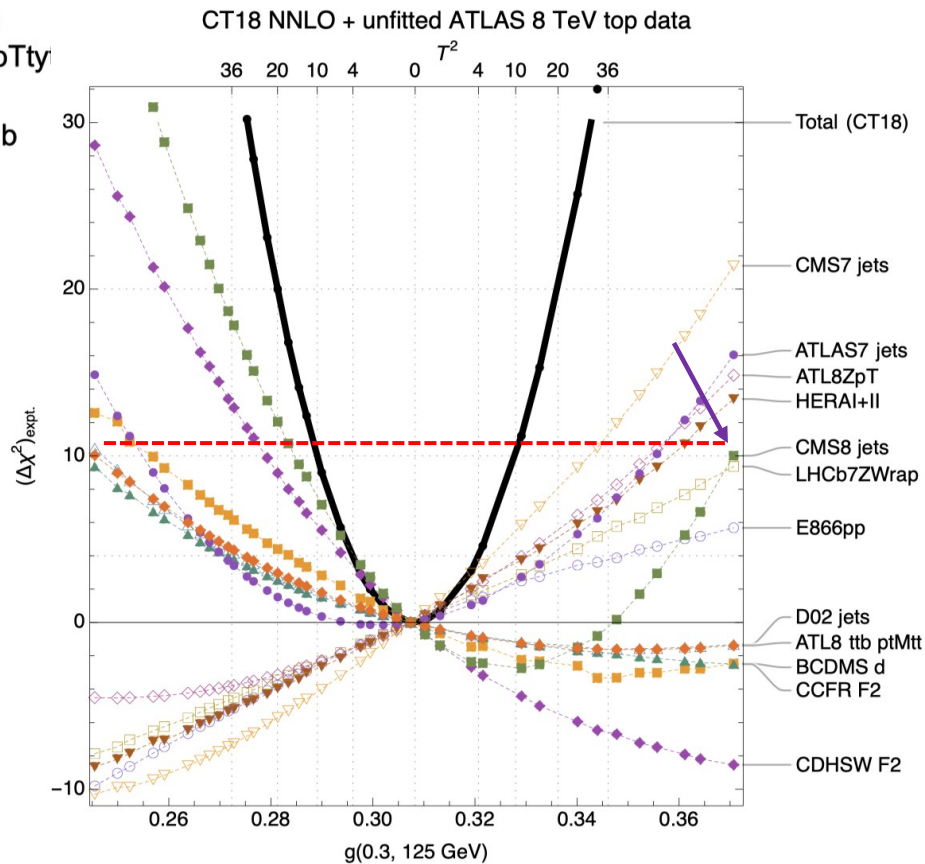
- The L_2 sensitivity provides a visualization of what is happening inside the PDF fit
- It can be considered as a faster version of Lagrange Multiplier scans (but dependent on the Gaussian approximation)
- The L_2 sensitivity streamlines comparisons among independent analyses, using the log-likelihood (χ^2) values for the fitted experiments and the error PDFs
- Both the L_2 and LM methods explore the parametric dependence of the χ^2 function in the vicinity of the global minimum
- The L_2 sensitivity has been used internally by CT (in CT18), by the PDF4LHC21 benchmarking group (to determine which data sets should be in the reduced PDF fit used for benchmarking), and now by CT, MSHT and ATLASpdf in this paper

CT18 NNLO

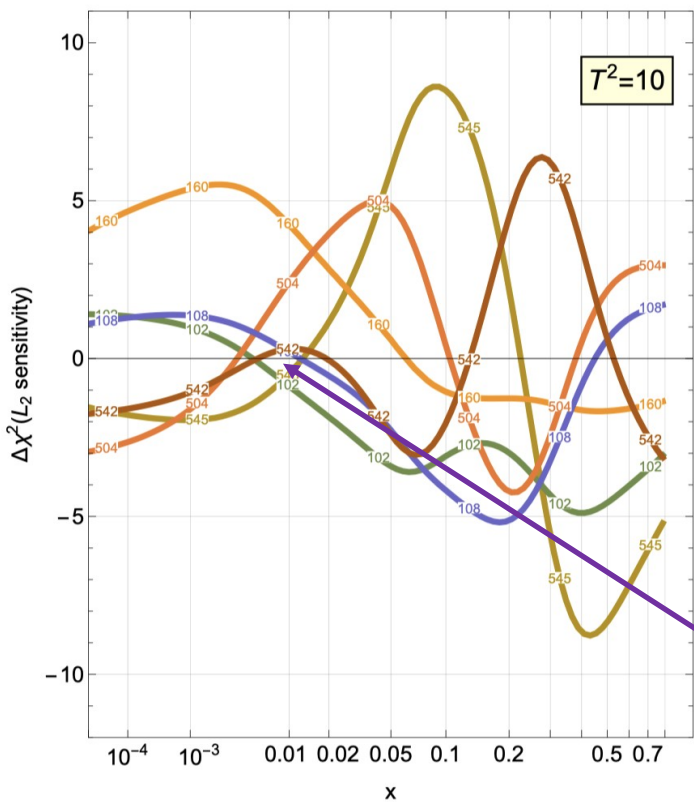


compare to LM scans of the gluon at $x=0.01$ and $x=0.3$

Lagrange Multiplier Scans

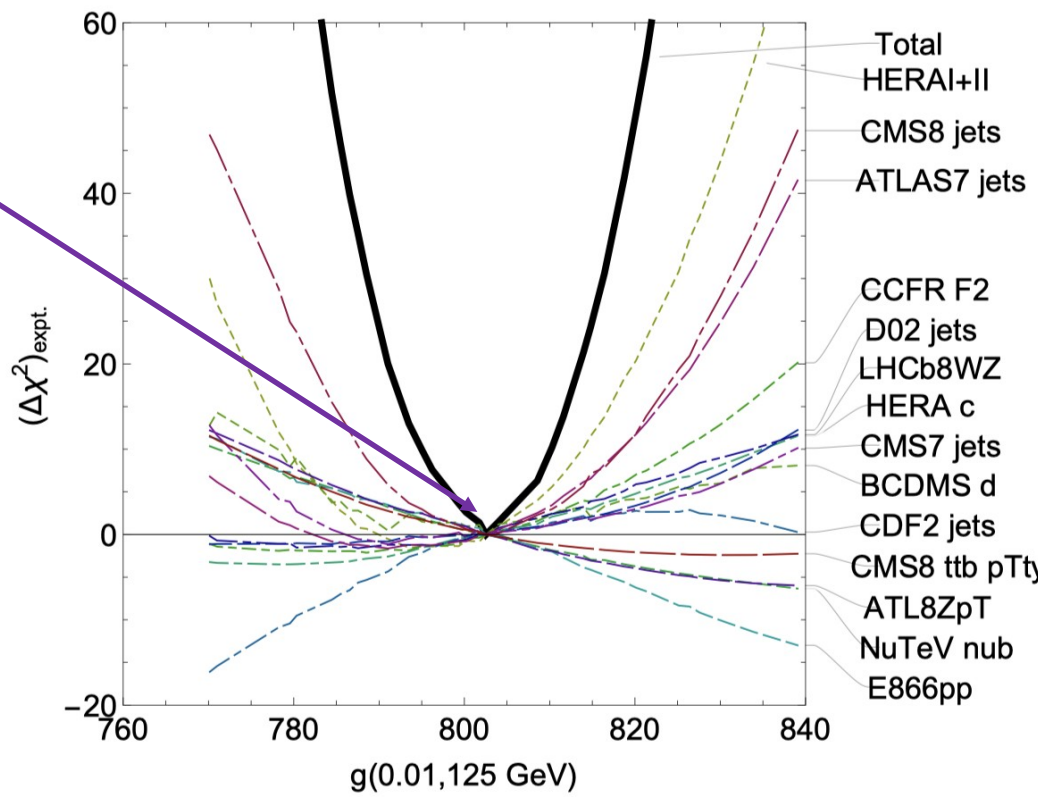


CT18 NNLO
 $g(x, 100 \text{ GeV})$

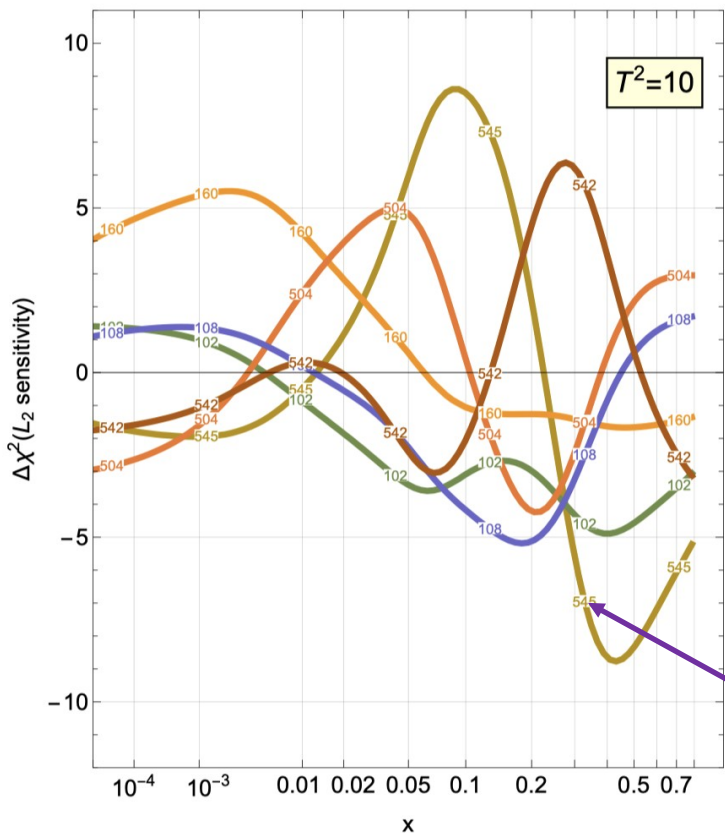


- 545: CMS 8 TeV jets
- 160: HERA DIS combined
- 102: BCDMS F_2^d
- 504: CDF Run-2 jets
- 108: CDHSW F_2
- 542: CMS 7 TeV jets

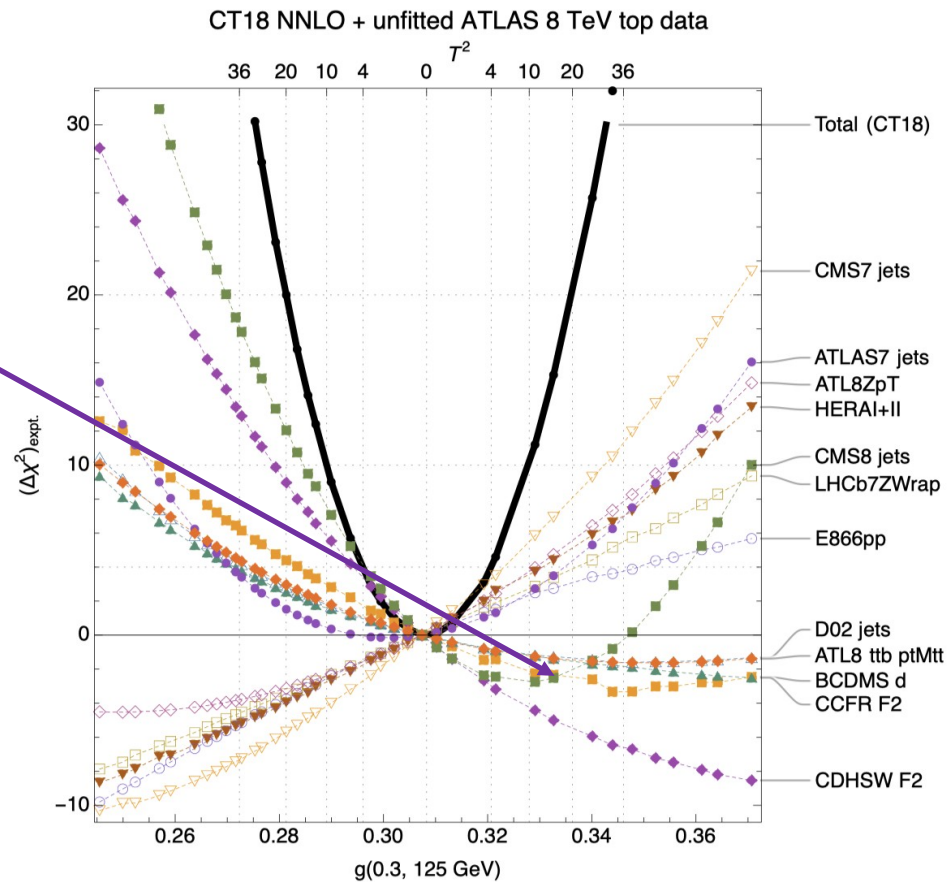
CT18 NNLO



CT18 NNLO
 $g(x, 100 \text{ GeV})$

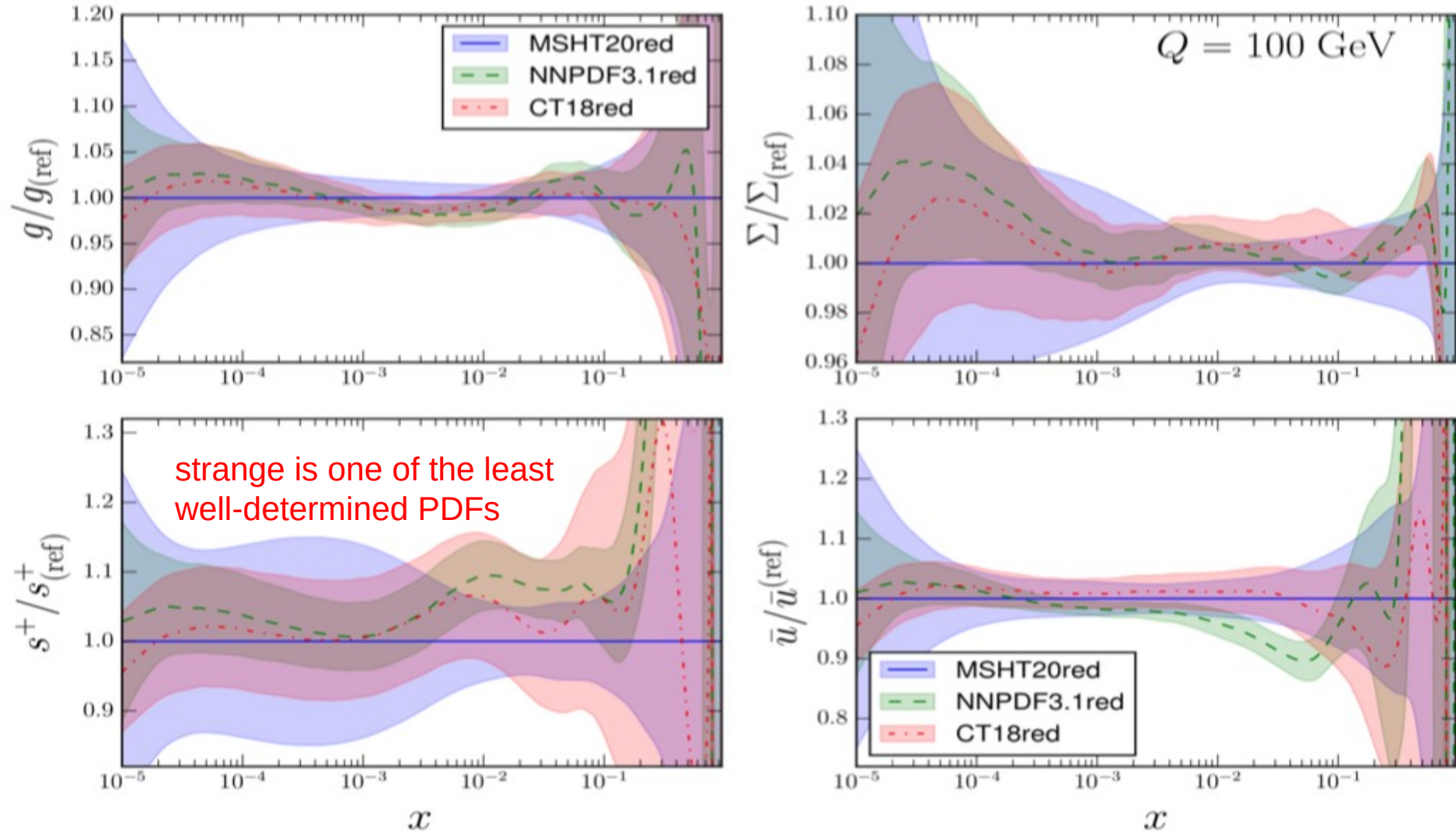


- 545: CMS 8 TeV jets
- 160: HERA DIS combined
- 102: BCDMS F_2^d
- 504: CDF Run-2 jets
- 108: CDHSW F_2
- 542: CMS 7 TeV jet



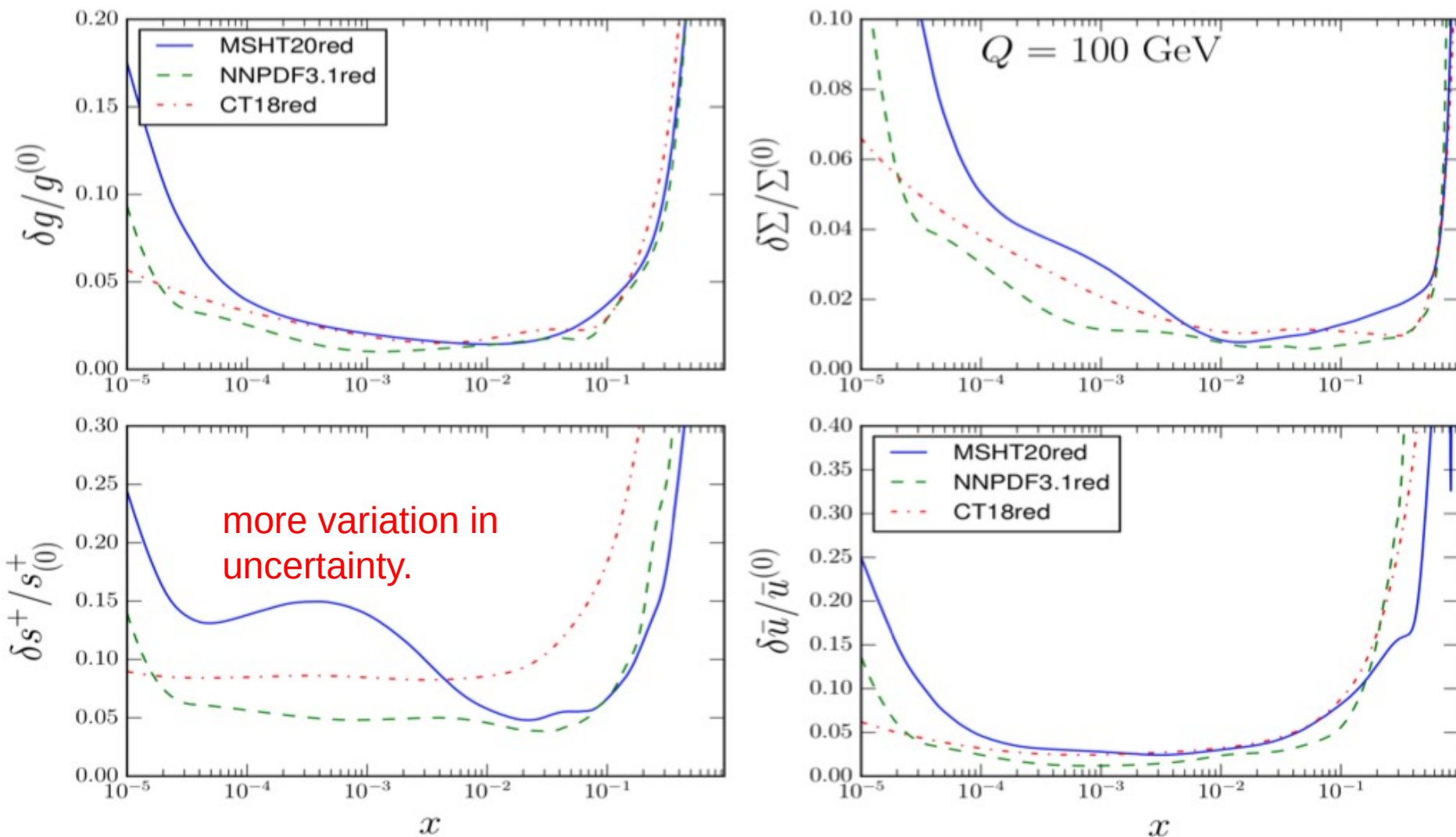
Reduced fits

Reasonable agreement for the most part.



Uncertainties

Uncertainties increased with respect to full global fits



PDF luminosities

