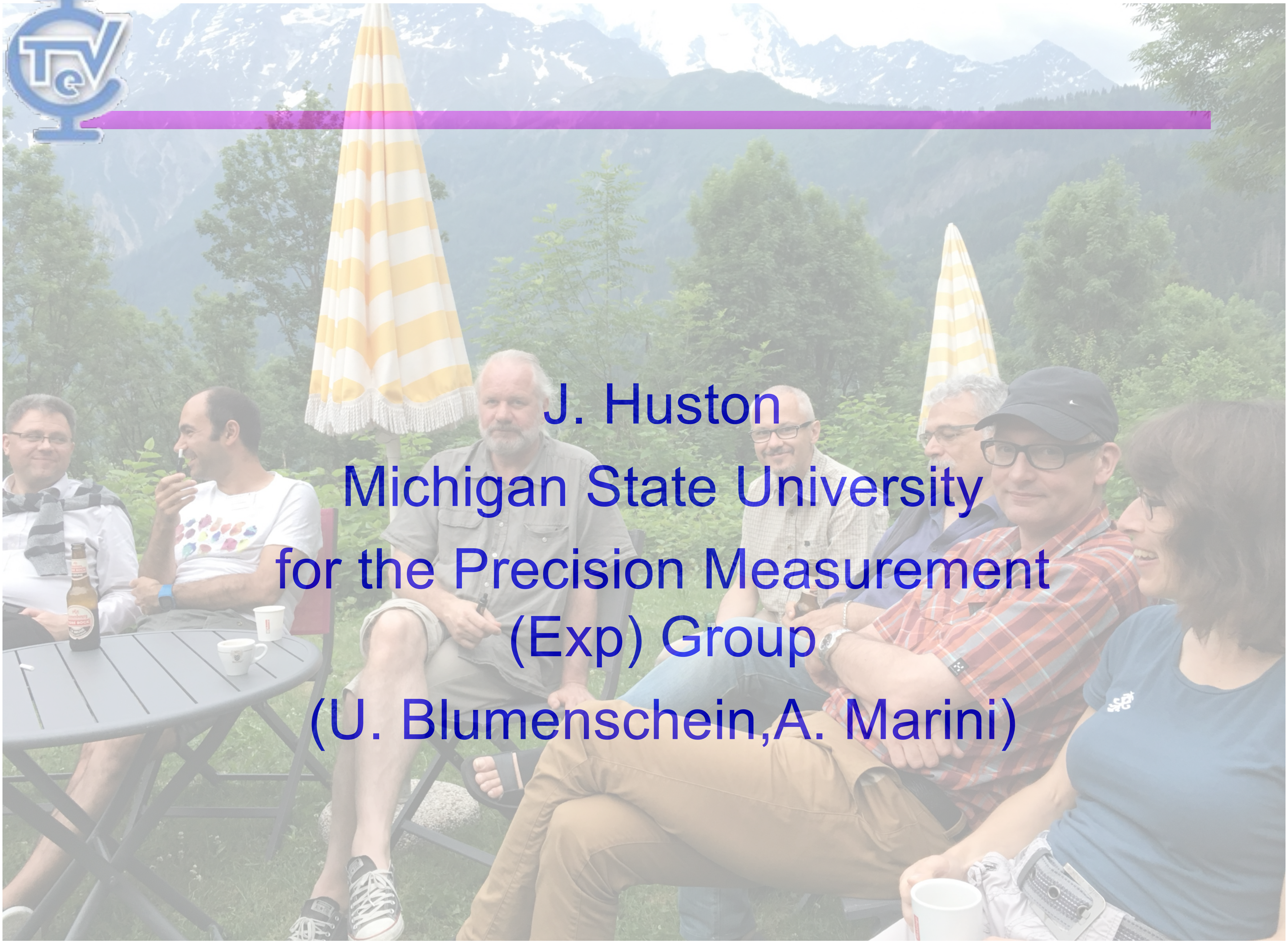


J. Huston

Michigan State University

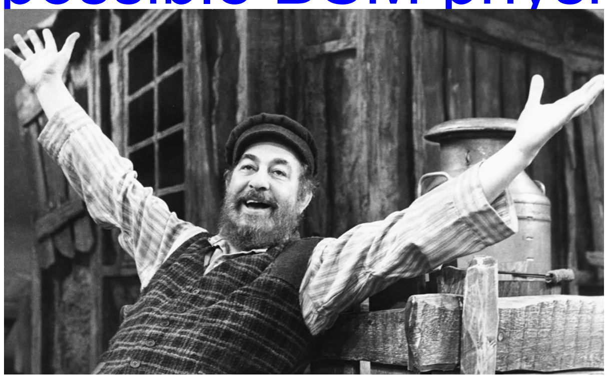
for the Precision Measurement (Exp) Group

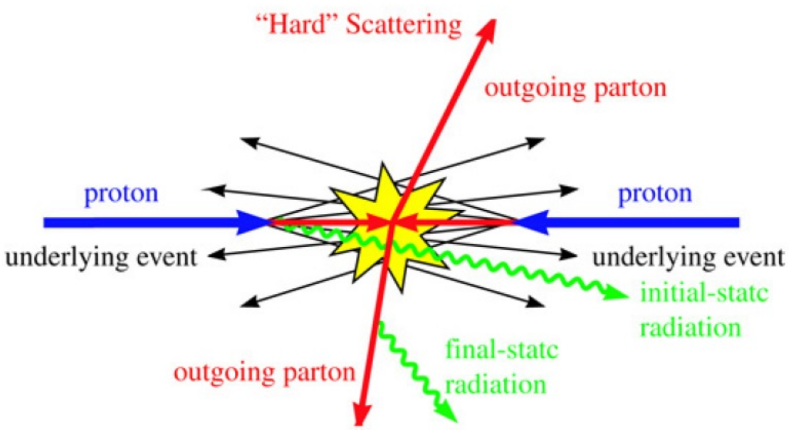
(U. Blumenschein,A. Marini)

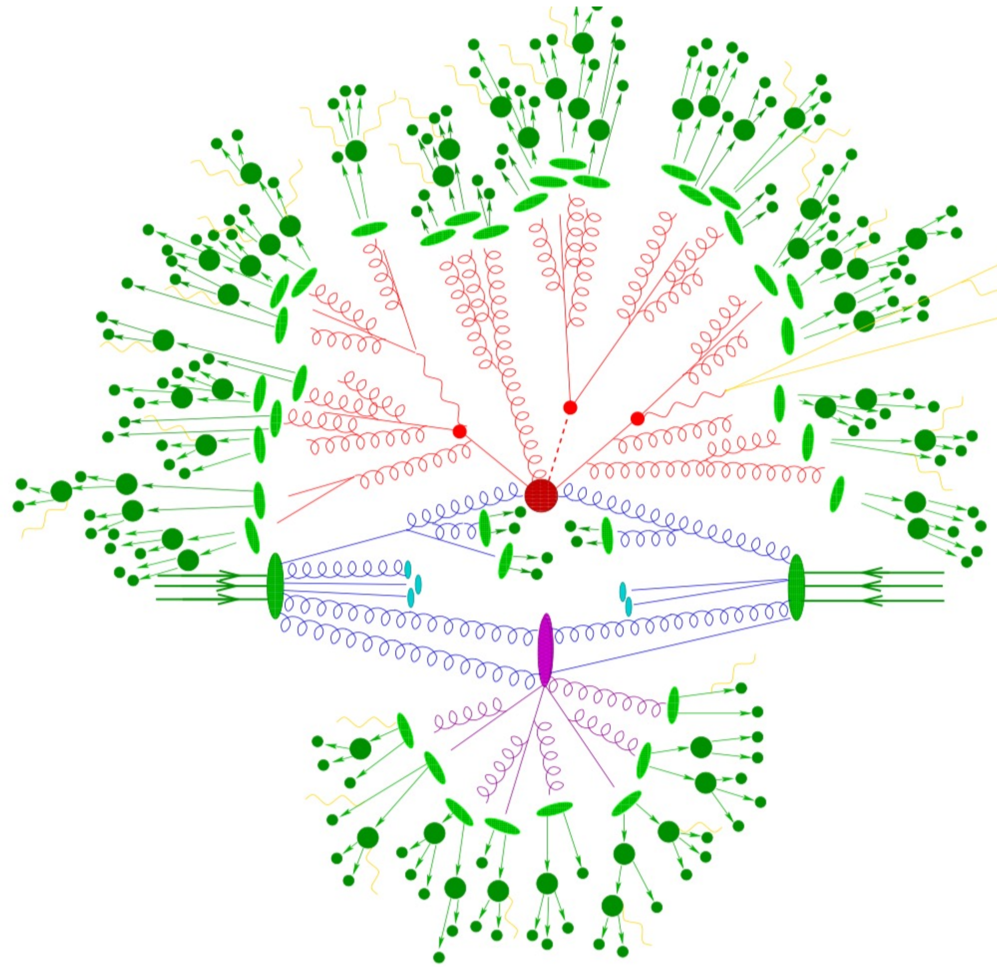
To quote Tevye in Fiddler on the Roof

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

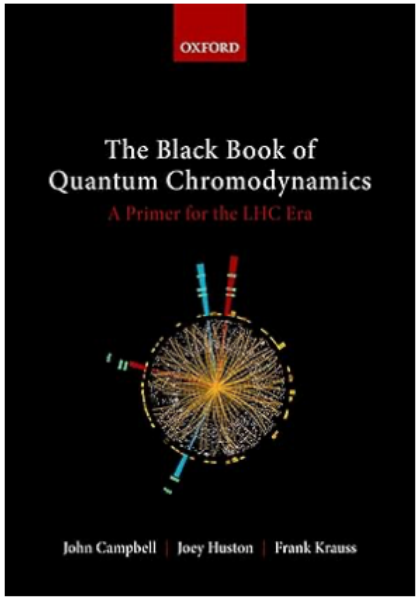
precision in matrix elements, jet reconstruction, PDFs, parton showers, non-perturbative corrections







…by the way, this picture is from the Black Book



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The Black Book of Quantum Chromodynamics: A Primer for the LHC Era Illustrated Edition, Kindle Edition

by John Campbell (Author), Joey Huston (Author), Frank Krauss (Author) | Format: Kindle Edition

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The Black Book of Quantum Chromodynamics is an in-depth introduction to the particle physics of current and future experiments at particle accelerators. The book offers the reader an overview of practically all aspects of the strong interaction necessary to understand and appreciate modern particle phenomenology at the energy frontier. It assumes a working knowledge of quantum field theory at the level of introductory textbooks used for advanced undergraduate or in standard postgraduate lectures. The book expands this knowledge with an intuitive understanding of relevant physical concepts, an introduction to modern techniques, and their application to the phenomenology of the strong interaction at the highest energies. Aimed at graduate students and researchers, it also serves as a comprehensive reference for LHC experimenters and theorists.

This book offers an exhaustive presentation of the technologies developed and used by practitioners in the field of fixed-

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The Les Houches wishlist (arXiv:2504.06689)

A. Huss, J. Huston, S. Jones, M. Pellen, R. Rontsch

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

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

2->3 at NNLO is current frontier; techniques almost complete

NNLO HTL probably most crucial; help with understanding VBF background

probably fine

effectively 2->2

soft Higgs approximation

~NNLO available; still need 2 loop virtuals but impact should be small, or is it? singularity structure is very complex

only 2->2, but with two masses

process	known	desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$ $\mathrm{NNLO}^{(t,t\times b)}_{\mathrm{QCD}}$ $\mathrm{N^{(1,1)}LO}^{(\mathrm{HTL})}_{\mathrm{QCD}\otimes\mathrm{EW}}$ $\mathrm{NLO_{QCD}}$	$\mathrm{N^4LO_{HTL}}$ (incl.)
$pp \to H + j$	$\mathrm{NNLO_{HTL}}$ $\mathrm{NLO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$	$\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{N^3LO_{HTL}}$ $\mathrm{NNLO_{QCD}}$
$pp \to H + 2j$	$\mathrm{NLO_{HTL}} \otimes \mathrm{LO_{QCD}}$ $\mathrm{N^3LO}^{(\mathrm{VBF}^*)}_{\mathrm{QCD}}$ (incl.) $\mathrm{NNLO}^{(\mathrm{VBF}^*)}_{\mathrm{QCD}}$ $\mathrm{NLO}^{(\mathrm{VBF})}_{\mathrm{EW}}$	$\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{N^3LO}^{(\mathrm{VBF}^*)}_{\mathrm{QCD}}$ $\mathrm{NNLO}^{(\mathrm{VBF})}_{\mathrm{QCD}}$ $\mathrm{NLO_{QCD}}$
$pp \to H + 3j$	$\mathrm{NLO_{HTL}}$ $\mathrm{NLO}^{(\mathrm{VBF})}_{\mathrm{QCD}}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{NNLO}^{(\mathrm{VBF}^*)}_{\mathrm{QCD}}$
$pp \to VH$	$\mathrm{N^3LO_{QCD}}$ (incl.)$+\mathrm{NLO_{EW}}$ $\mathrm{NLO}^{(t,b)}_{gg\to HZ}$	$\mathrm{N^3LO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$
$pp \to VH + j$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to HH$	$\mathrm{N^3LO_{HTL}} \otimes \mathrm{NLO_{QCD}}$ $\mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to HH + 2j$	$\mathrm{N^3LO}^{(\mathrm{VBF}^*)}_{\mathrm{QCD}}$ (incl.) $\mathrm{NNLO}^{(\mathrm{VBF}^*)}_{\mathrm{QCD}}$ $\mathrm{NLO}^{(\mathrm{VBF})}_{\mathrm{EW}}$	$\mathrm{NLO_{QCD}}$
$pp \to HHH$	$\mathrm{NNLO_{HTL}}$	$\mathrm{NLO_{QCD}}$
$pp \to H + t\bar{t}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{NNLO_{QCD}}$ (approx.)	$\mathrm{NNLO_{QCD}}$
$pp \to H + t/\bar{t}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$

e 2: Precision wish list: Higgs boson final states. $\mathrm{N^xLO}^{(\mathrm{VBF}^*)}_{\mathrm{QCD}}$ means a calculation using tructure function approximation. $V = W, Z$.

Les Houches 2023 wishlist
Huss, Huston,Jones,Pellen, Rontsch
arXiv:

3.1.5 $H+ \geq 2j$

LH21 status: VBF production known at $\mathrm{N^3LO_{QCD}}$ accuracy for the total cross section [553] and at $\mathrm{NNLO_{QCD}}$ accuracy differentially [147,304] in the "DIS" approximation [554]. LO Higgs decays $H \to WW^*$ and $H \to b\bar{b}$ were included to the $\mathrm{NNLO_{QCD}}$ description of the VBF production process in Ref. [293]. The double-virtual contributions to non-factorizable corrections are known in the eikonal approximation [555,556]. Full $\mathrm{NLO_{QCD}}$ corrections for $H+3j$ in the VBF channel available [557,558]. $H+ \leq 3j$ in the gluon fusion channel was studied in Ref. [559] and an assessment of the mass dependence of the various jet multiplicities was made in Ref. [560]; the impact of the top-quark mass in $H+1,2$ jets was studied in Ref. [561]; $\mathrm{NLO_{EW}}$ corrections to stable Higgs boson production in VBF calculated [562] and available in HAWK [563]. Mass effects in $H+2j$ at large energy are known within the "High Energy Jets" framework [521–526]. Parton shower and matching uncertainties for VBF Higgs productions have been studied in detail using PYTHIA and HERWIG matched to MADGRAPH5_aMC@NLO and POWHEG in Ref. [564]; the PYTHIA and VINCIA parton showers were compared in Ref. [565]. A comparative study of VBF Higgs production at fixed order and with parton shower Monte Carlos has been carried out in Ref. [342], as an outgrowth of Les Houches 2019.

The current experimental error on the $H+ \geq 2j$ cross section is on the order of 25% [532], 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 uncertainty. To achieve a theoretical uncertainty less than this value would require the calculation of $H+ \geq 2j$ to $\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}}$ in the gluon fusion production mode.

experimental justification
for precision theory

Les Houches 2023 -- Physics at TeV Colliders: Report on the Standard Model Precision Wishlist

#1

Alexander Huss (CERN), Joey Huston (Michigan State U.), Stephen Jones (Durham U., IPPP), Mathieu Pellen (Freiburg U.), Raoul Röntsch (INFN, Milan and U. Milan (main)) (Apr 9, 2025)

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Les Houches 2021—physics at TeV colliders: report on the standard model precision wishlist

#3

Alexander Huss (CERN), Joey Huston (Michigan State U.), Stephen Jones (Durham U., IPPP), Mathieu Pellen (Freiburg U.) (Jul 5, 2022)

Published in: *J.Phys.G* 50 (2023) 4, 043001 • Contribution to: PhysTeV 2021 • e-Print: 2207.02122 [hep-ph]

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Aspen study: summer 2024

- estimate size of higher order corrections using LO color flows (color annhilation channels)

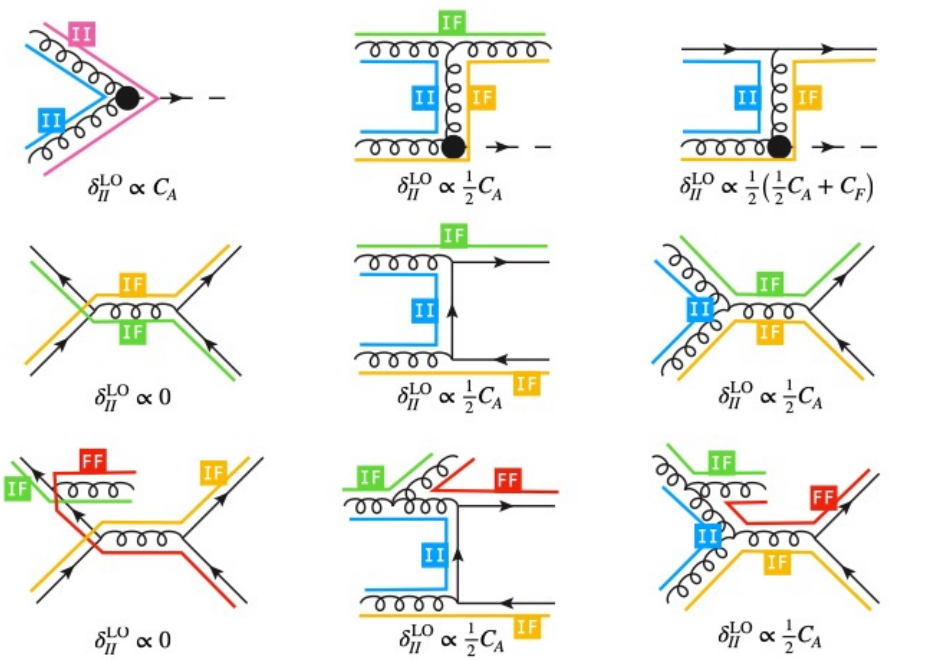

Figure 3: Examples of LC colour flows for various event types, with indications of initial-initi (II), initial-final (IF), and final-final (FF) colour-dipole connections and corresponding propos LO II colour factor, $\delta_{II}^{\rm LO}$.

δ_{II}	LO	NLO	NNLO	N3LO
$g=g$ (gg singlet)	$\frac{C_A\pi}{2}\alpha_s \sim 4.7\alpha_s$	$\frac{C_A^2\pi^2}{8}\alpha_s^2 \sim 11\alpha_s^2$	$\frac{C_A^3\pi^3}{48}\alpha_s^3 \sim 17\alpha_s^3$	$\frac{C_A^4\pi^4}{384}\alpha_s^4 \sim 21\alpha_s^4$
$g-g$ (gg octet)	$\frac{C_A\pi}{4}\alpha_s \sim 2.4\alpha_s$	$\frac{C_A^2\pi^2}{32}\alpha_s^2 \sim 2.8\alpha_s^2$	$\frac{C_A^3\pi^3}{384}\alpha_s^3 \sim 2.2\alpha_s^3$	$\frac{C_A^4\pi^4}{6144}\alpha_s^4 \sim 1.3\alpha_s^4$
$q-g$ (qg triplet)	$\sim 2.2\alpha_s$	$\sim 2.5\alpha_s^2$	$\sim 1.8\alpha_s^3$	$\sim 1.0\alpha_s^4$
$q-\bar{q}$ ($q\bar{q}$ singlet)	$\frac{C_F\pi}{2}\alpha_s \sim 2.1\alpha_s$	$\frac{C_F^2\pi^2}{8}\alpha_s^2 \sim 2.2\alpha_s^2$	$\frac{C_F^3\pi^3}{48}\alpha_s^3 \sim 1.5\alpha_s^3$	$\frac{C_F^4\pi^4}{384}\alpha_s^4 \sim 0.8\alpha_s^4$

Table 1: Estimated single-sided theory uncertainty due to missing II form-factor terms at the next order, ordered by colour channel.

To obtain a rough estimate of the size that may be expected for the initial-initial form factor for a generic process, we thus propose the following prescription at LO:

$$\delta_{II}^{\rm LO} = \frac{\pi\alpha_s(\mu_F^2)}{2}\left(C_A f_{gg1} + \frac{1}{2}C_A f_{gg8} + \frac{C_A+2C_F}{4} f_{qg3} + C_F f_{q\bar{q}1}\right), \qquad (2)$$

where f_{ijm} denotes the fraction of the LO cross section that corresponds to ij initial states in a colour-m channel[1]. At higher orders, the corresponding estimates are:

$$\text{NLO} \; : \; \frac{\pi^2\alpha_s^2(\mu_F^2)}{8}\left(C_A^2 f_{gg1} + \frac{1}{4}C_A^2 f_{gg8} + \left(\frac{C_A+2C_F}{4}\right)^2 f_{qg3} + C_F^2 f_{q\bar{q}1}\right), \qquad (3)$$

$$\text{NNLO} \; : \; \frac{C_A^3\pi^3\alpha_s^3(\mu_F^2)}{48}\left(C_A^3 f_{gg1} + \frac{1}{8}C_A^3 f_{gg8} + \left(\frac{C_A+2C_F}{4}\right)^3 f_{qg3} + C_F^3 f_{q\bar{q}1}\right), \qquad (4)$$

$$\text{N3LO} \; : \; \frac{C_A^4\pi^4\alpha_s^4(\mu_F^2)}{384}\left(C_A^4 f_{gg1} + \frac{1}{16}C_A^4 f_{gg8} + \left(\frac{C_A+2C_F}{4}\right)^4 f_{qg3} + C_F^4 f_{q\bar{q}1}\right), \qquad (5)$$

and the f_{ijm} fractions should *(presumably?)* likewise be estimated from the relevant N^{n}LO cross sections.

Possible to build on this at Les Houches?

See also p.80 of the Black Book (the Dixon conjecture):
$C_{i1}+C_{i2}-C_{f,max}$
Relative size of NLO corrections for a given process depends on the sum of the Casimir color factors for the initial state minus the Casimir factor for the largest color representation of the final state.

Les Houches Accords

1 language

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The **Les Houches Accords** are agreements between particle physicists to standardize the interface between the matrix element programs and the event generators used to calculate different quantities. The original accord was initially formed in 2001, at a conference in Les Houches, in the French Alps, before it was subsequently expanded.

In experimental high energy physics, several levels of computing are used to simulate data runs, including programs that generate matrix elements and ones that generate events. However, there are several programs for each of these tasks, such as CompHEP and MadGraph to generate matrix elements, and PYTHIA and HERWIG for event generation. Depending on specific properties of the particle decay that physicists are interested in, they may desire to use a certain program for these tasks, but before the Les Houches Accords, there was no general interface for communicating between the programs. This enables physicists to choose more freely between different programs. The Accords also make it easier to generate parton distribution functions, which are datasets used to calculate cross sections, for events.

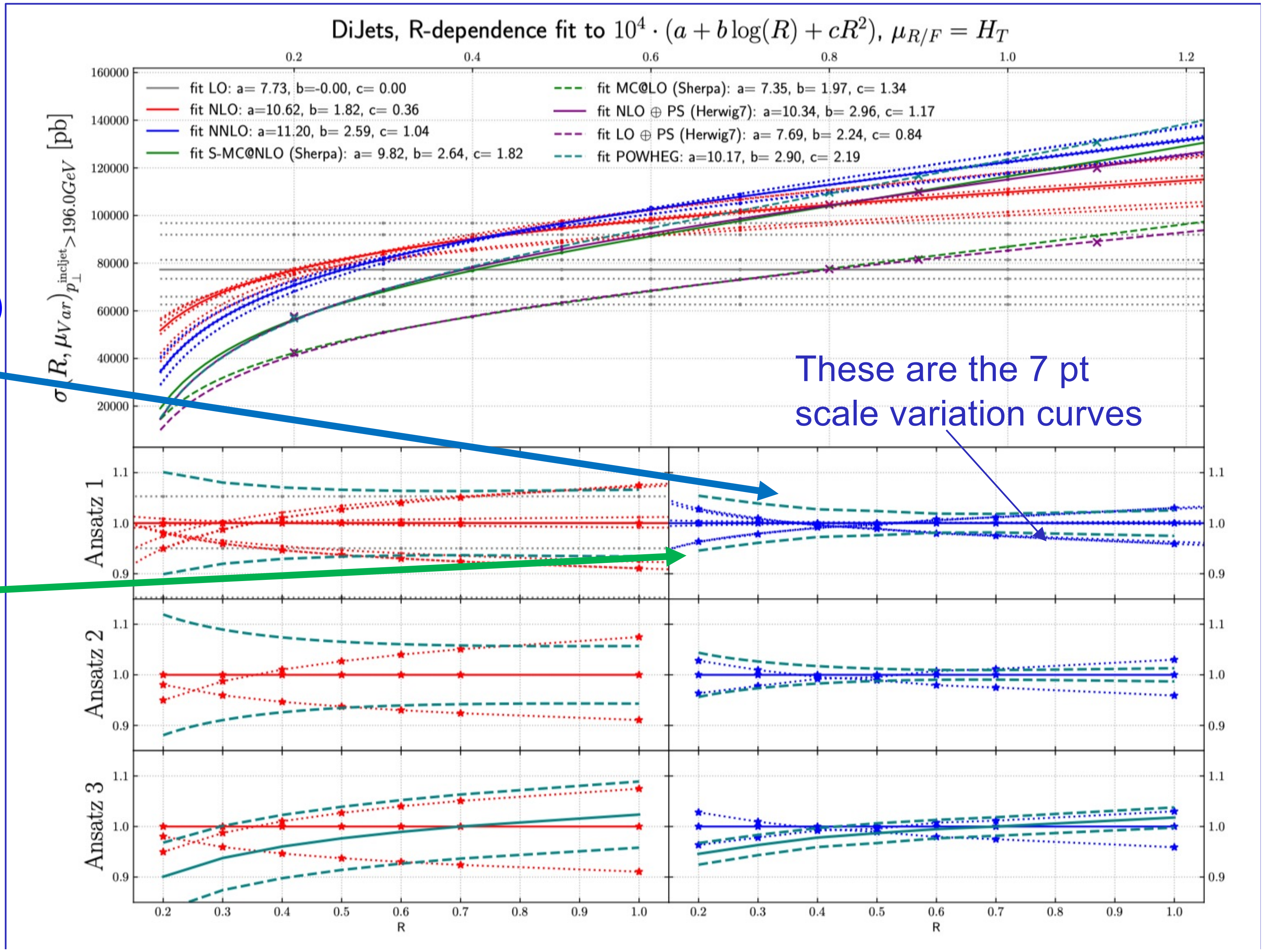
The original Accord defined a programmatic interface for transfer of event information, in terms of Fortran common blocks, but no data exchange file format was defined until 2006. Events that conform to the formats described in the Les Houches Accords are said to be in Les Houches Event format. or more often. LHE format.

The Les Houches perspective

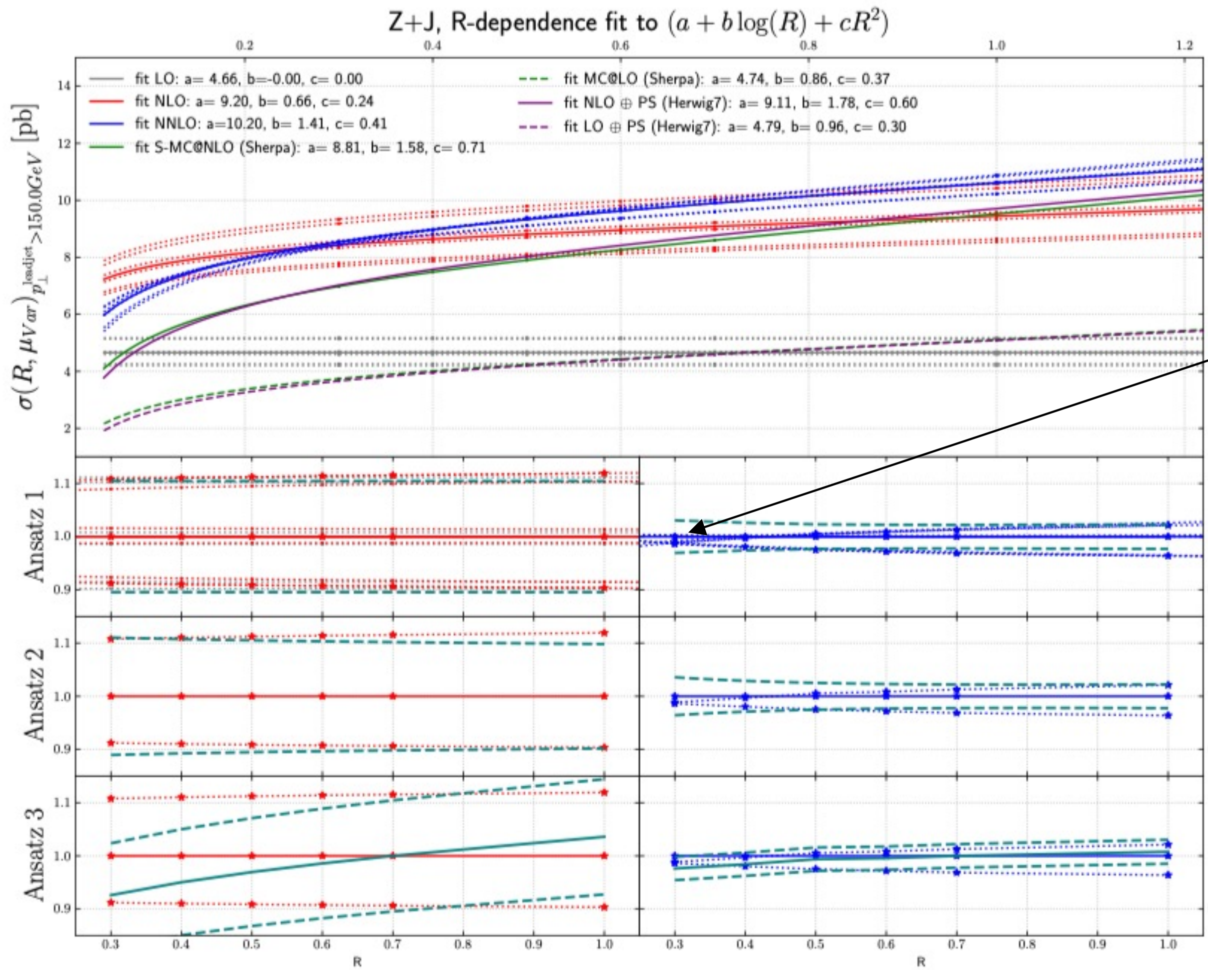
- To get a better understanding of the efficacy of theoretical predictions,compare to fixed order predictions at different orders, calculate the predictions as a function of jet radius above and below the nominal value(s), calculate the scale variation above and below the nominal 7-point range, and examine behavior as in different kinematic ranges

Jet algorithms and R-dependence: 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 3 jet at NNLO?
- **See Rene's talk re:NNLL**



Z+jet



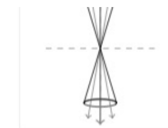
uncertainty is zero around R=0.3

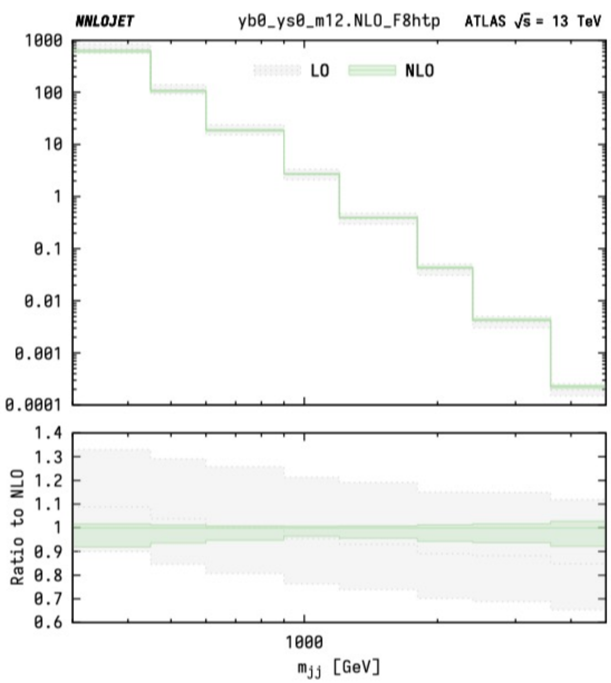
can Z+jet uncertainty ever be less than Z inclusive uncertainty?

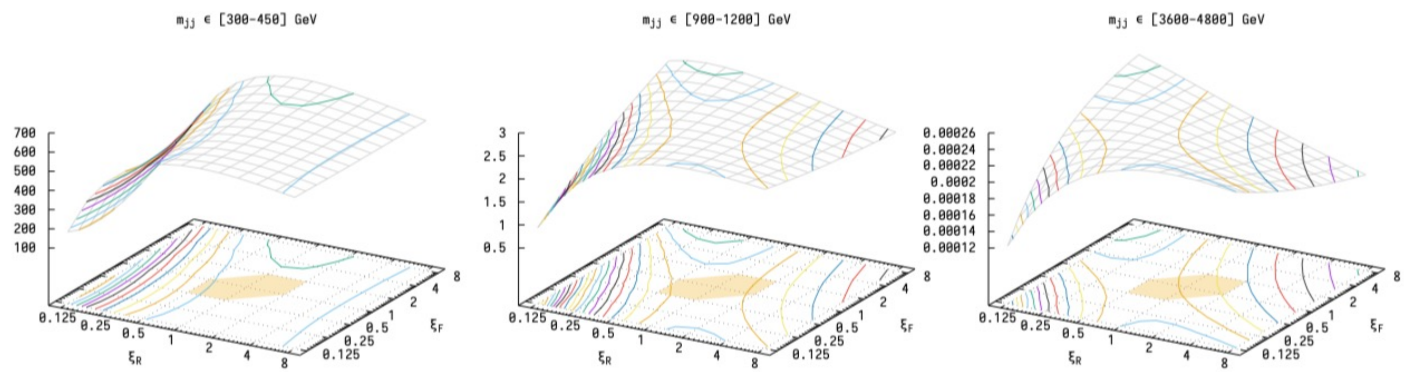
FIG. 8: The R-dependence of the cross sections at NLO, NNLO and NLO+PS are shown, for particular scale values, as a function of the jet radius,for $Z+\geq 1$ jet production, for leading jet transverse momenta above 150 GeV.

2-D plots for scale dependence

$d\sigma/dm_{jj}$ $\mu = \hat{H}_T$ $y_b \in [0,1]$ $y^* \in [0,1]$







This is for m_{jj}, rather than p_T^{jet}, but illustrates the idea of looking at the 2-D scale dependence to gain some insight into the behavior. Compare NNLO and NNLO+NNLL.

VBF production at 13 TeV: an outcome of LH19

A comparative study of Higgs boson production from vector-boson fusion

A. Buckley,[1] X. Chen,[2,3,4] J. Cruz-Martinez,[5] S. Ferrario Ravasio,[6,7] T. Gehrmann,[2] E.W.N. Glover,[7] S. Höche,[8] A. Huss,[9] J. Huston,[10] J. M. Lindert,[11] S. Plätzer,[12] and M. Schönherr[7]

[1]*School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, UK*
[2]*Institut für Theoretische Physik, Universität Zürich, CH-8057 Zürich, Switzerland*
[3]*Institute for Theoretical Physics, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany*
[4]*Institute for Astroparticle Physics, Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany*
[5]*Dipartimento di Fisica, Universita degli Studi di Milano and INFN, Sezione di Milano*
[6]*Centre for Theoretical Physics, Oxford University, Oxford, OX1 3PU, UK*
[7]*Institute for Particle Physics Phenomenology, Durham University, Durham, DH1 3LE, UK*
[8]*Fermi National Accelerator Laboratory, Batavia, IL, 60510, USA*
[9]*Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland*
[10]*Michigan State University, East Lansing, MI, 48824, USA*
[11]*Department of Physics and Astronomy, University of Sussex, Brighton BN1 9QH, UK*
[12]*Institute for Mathematics and Physics, University of Vienna, 1090 Wien, Austria*

The data taken in Run II at the Large Hadron Collider have started to probe Higgs boson production at high transverse momentum. Future data will provide a large sample of events with boosted Higgs boson topologies, allowing for a detailed understanding of electroweak Higgs boson plus two-jet production, and in particular the vector-boson fusion mode (VBF). We perform a detailed comparison of precision calculations for Higgs boson production in this channel, with particular emphasis on large Higgs boson transverse momenta, and on the jet radius dependence of the cross section. We study fixed-order predictions at next-to-leading order and next-to-next-to-leading order QCD, and compare the results to NLO plus parton shower (NLOPS) matched calculations. The impact of the NNLO corrections on the central predictions is mild, with inclusive scale uncertainties of the order of a few percent, which can increase with the imposition of kinematic cuts. We find good agreement between the fixed-order and matched calculations in non-Sudakov regions, and the various NLOPS predictions also agree well in the Sudakov regime. We analyze backgrounds to VBF Higgs boson production stemming from associated production, and from gluon-gluon fusion. At high Higgs boson transverse momenta, the Δy_{jj} and/or m_{jj} cuts typically used to enhance the VBF signal over background lead to a reduced efficiency. We examine this effect as a function of the jet radius and using different definitions of the tagging jets. QCD radiative corrections increase for all Higgs production modes with increasing Higgs boson p_T, but the proportionately larger increase in the gluon fusion channel results in a decrease of the gluon-gluon fusion background to electroweak Higgs plus two jet production upon requiring exclusive two-jet topologies. We study this effect in detail and contrast in particular a central jet veto with a global jet multiplicity requirement.

includes NNLOJET, Sherpa, Herwig and Powheg authors …from LH2019

arXiv:2105.11399

comprehensive comparison of the above programs for VBF production (no hadronization/UE); ggF H+2j from Sherpa

original goal was to have ggF predictions from Herwig and Powheg as well, but that fell through; **it is in the new paper**

Very interesting R-dependence

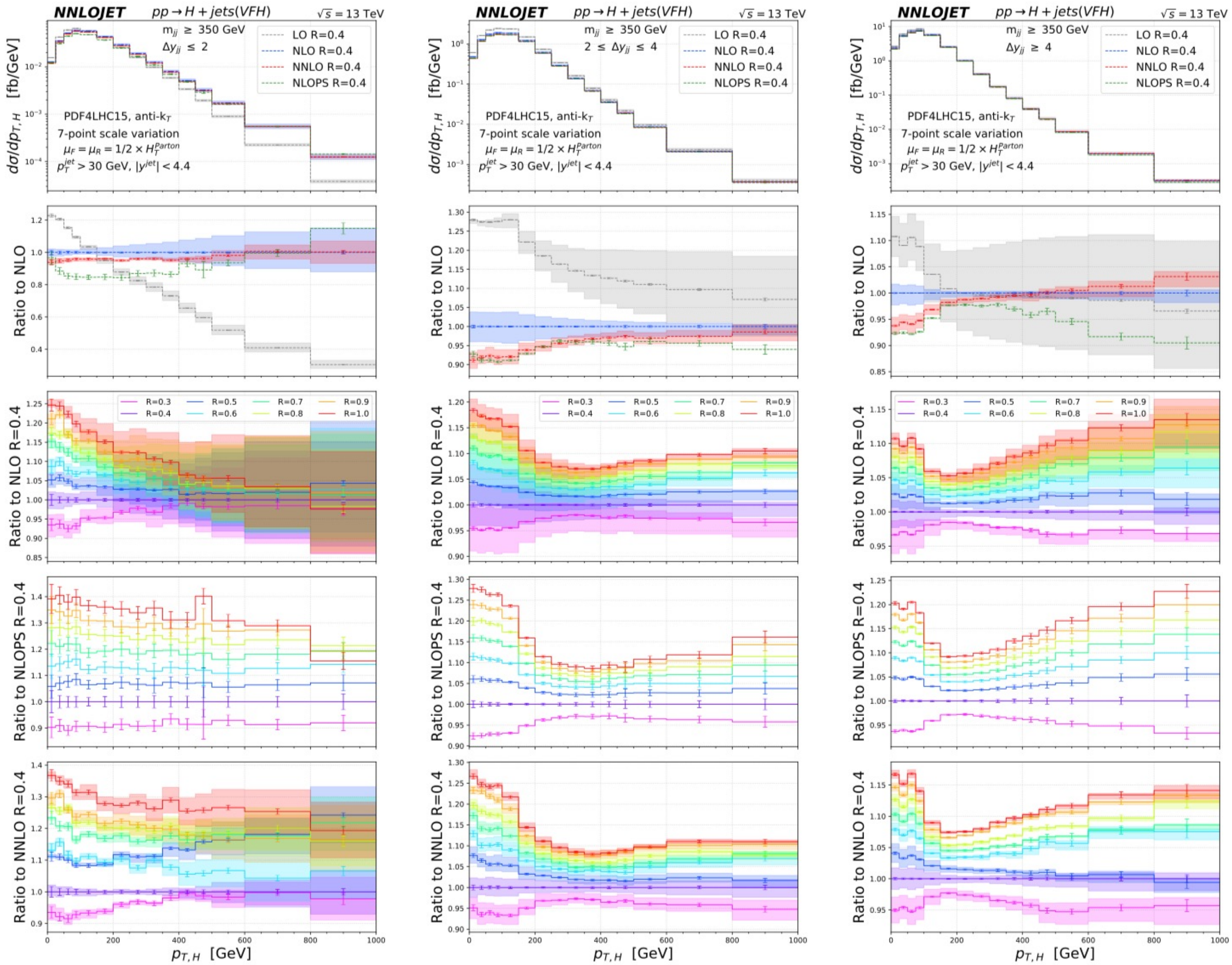


FIG. 19. The Higgs boson transverse momentum distribution from the VBF sub-process as a function of jet radius using the *heavy-center* (left), *heavy-intermediate* (middle) and *heavy-forward* (right) cuts.

Comparison of predictions for VBF signal

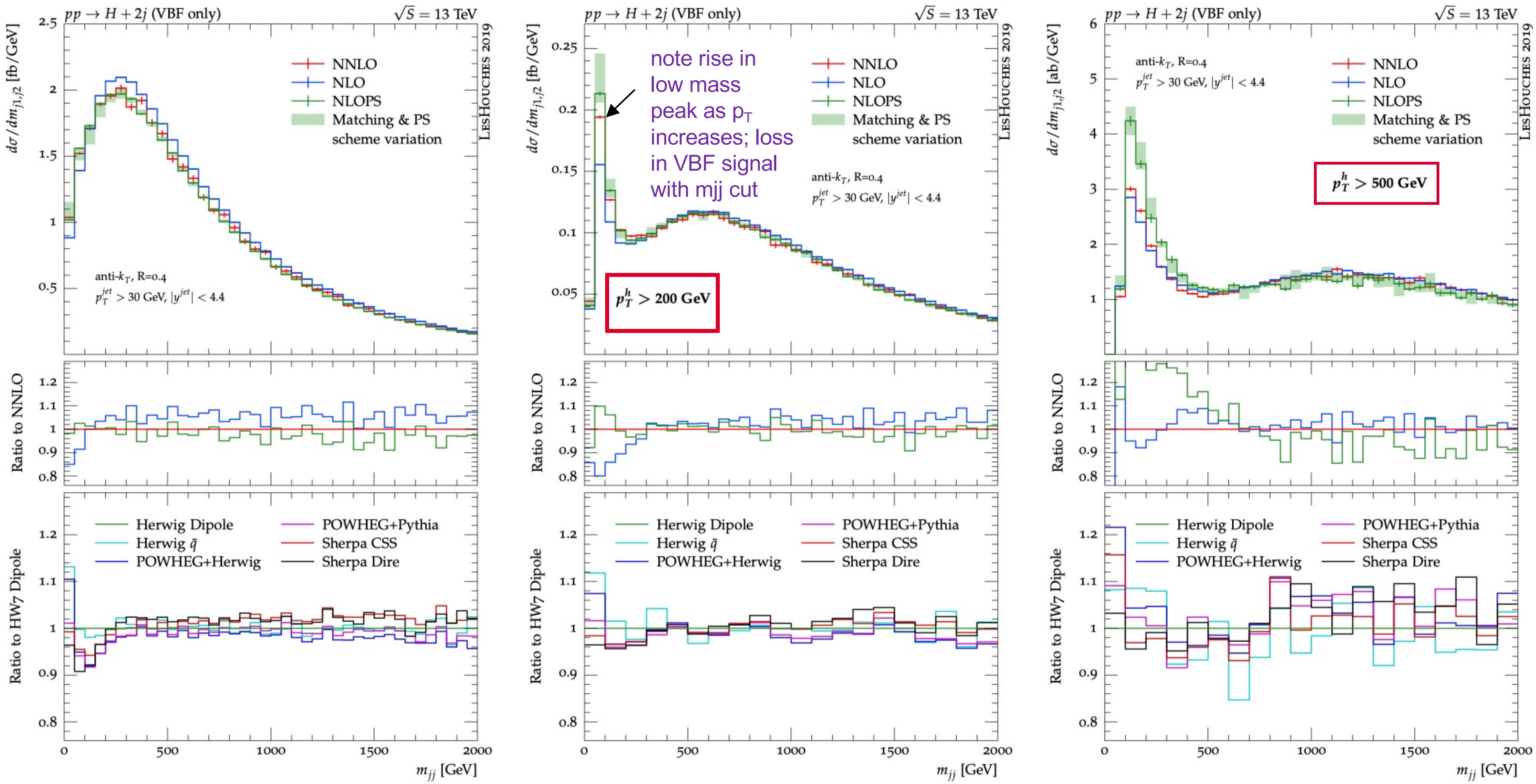


FIG. 23. Dijet invariant mass distribution. The left panels show inclusive predictions, while the middle and right panels show results for a minimum Higgs transverse momentum of 200 and 500 GeV. See Fig. 21 and the main text for details.

Note small dependence on parton showers

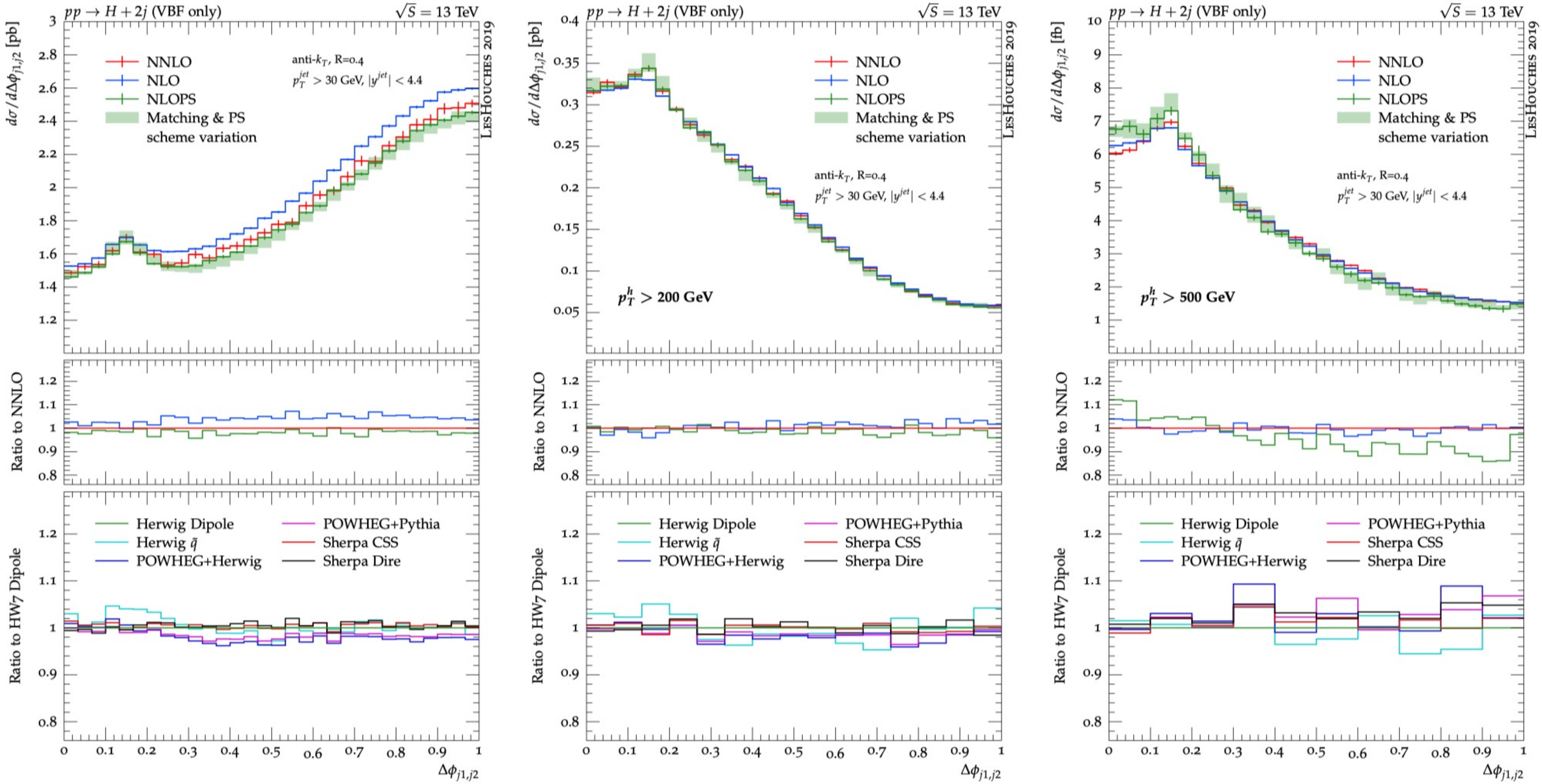


FIG. 24. $\Delta\phi_{jj}$ distribution, using the two leading jets. The left panels show inclusive predictions, while the middle and right panels show results for a minimum Higgs transverse momentum of 200 and 500 GeV. See Fig. 21 and the main text for details.

Conclusion: VBF parton showering under good control

…from Sherpa study, non-perturbative effects also under good control

…but what about the background from ggF (outgrowth of LH2023)

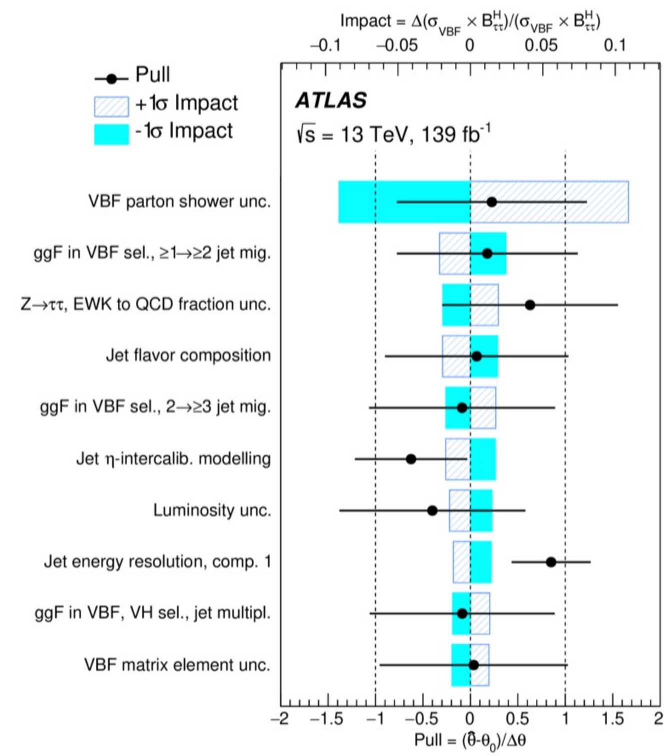
- We ran at fixed order at 13.6 TeV, as well as ME+PS predictions **for ggF** from Sherpa, Powheg+Pythia and Powheg+Herwig
- Involving NNLOJET, Powheg, Pythia, Herwig and Sherpa authors
- …as well as Ahmed Tarek and myself from ATLAS, and Yacine Haddad from CMS

Theory uncertainty relative sizes in **typical** VBF measurements

	VBF H	ggH (in VBF-enriched region)
PDF	<1%	<3%
QCD scale	<1%	**2-20%**
UE	<1.5%	<2-3%
Parton shower	**5-15%**	**4-10%**

Stephen Jones

- We would like to reduce/understand the systematics for VBF **and its backgrounds** that result from parton shower variations and non-perturbative tunes



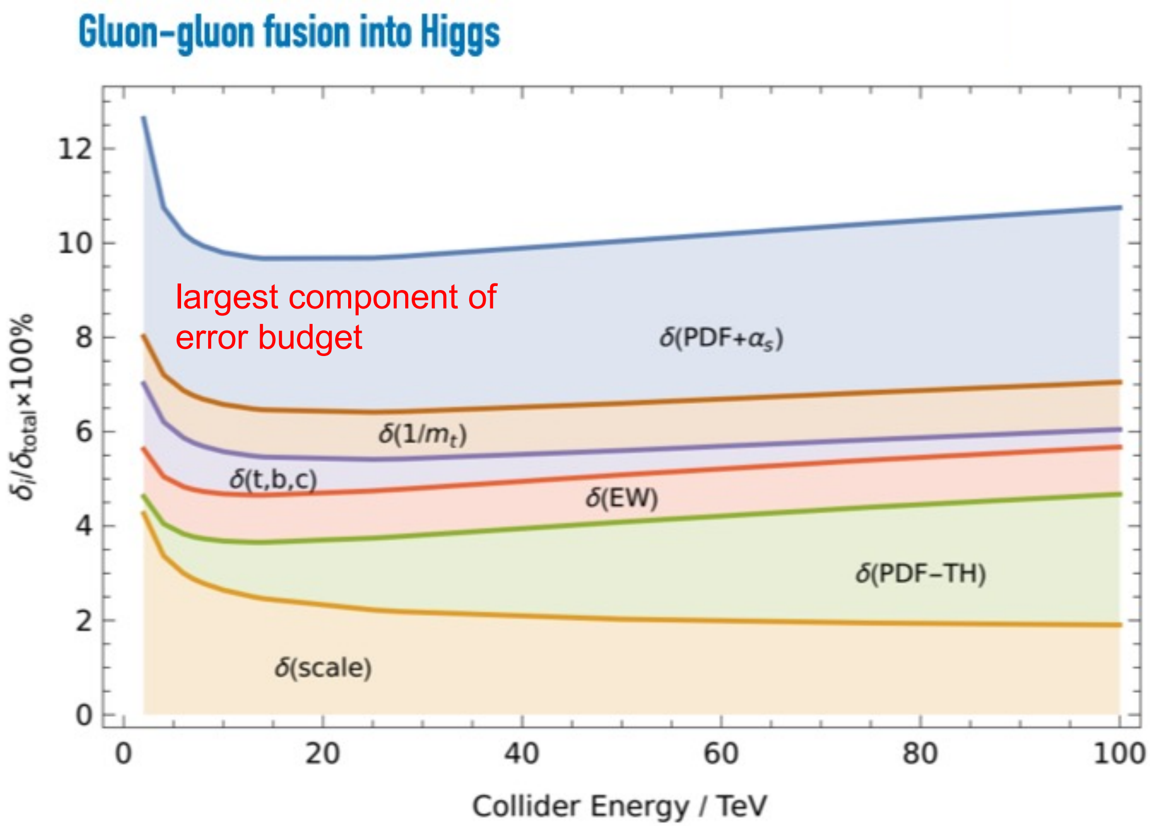
Example: ranking plot of theory uncertainty of the μ_{VBF} measurement in HTau

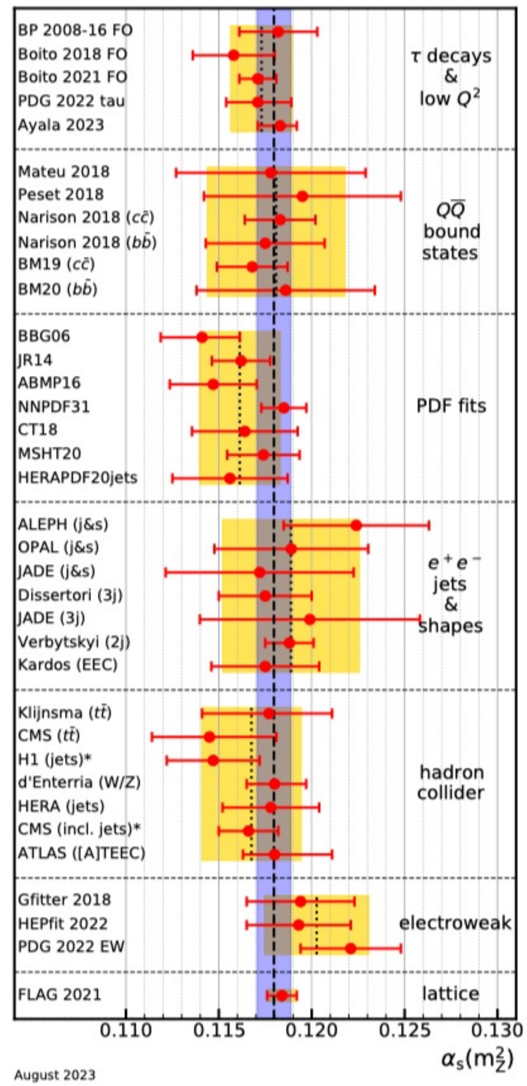
Basic idea for study of ggF H+2 jet background

- Compare inclusive ME+PS predictions to fixed-order; confirm agreement in phase spaces where expected
- Compare predictions with first jet at NLO, 2nd at LO (MINNLOPS, Powheg H+jet) to predictions with both jets at NLO (Sherpa ME+PS) or 2nd jet at NLO (Sherpa H+2 jet MC@NLO, Powheg H+2 jets); the latter involves new technique using Powheg-box with Born suppression and Powheg hooks in Pythia
- Compare at parton shower level, hadron level; so far, comparison at hadron level Powheg+Herwig H+2 jets at NLO not possible, but studies of non-perturbative effects with Powheg+Pythia, Sherpa indicate that non-perturbative effects have little impact
- Compare results at R=0.4 and 0.7
- Analysis basically complete; need to finish writing the paper
- **Basic conclusion: all is well; experimental estimates of larger uncertainties may not be warranted**
- All predictions in Rivet, will be made available to experiments

PDF+$\alpha_s(m_Z)$

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

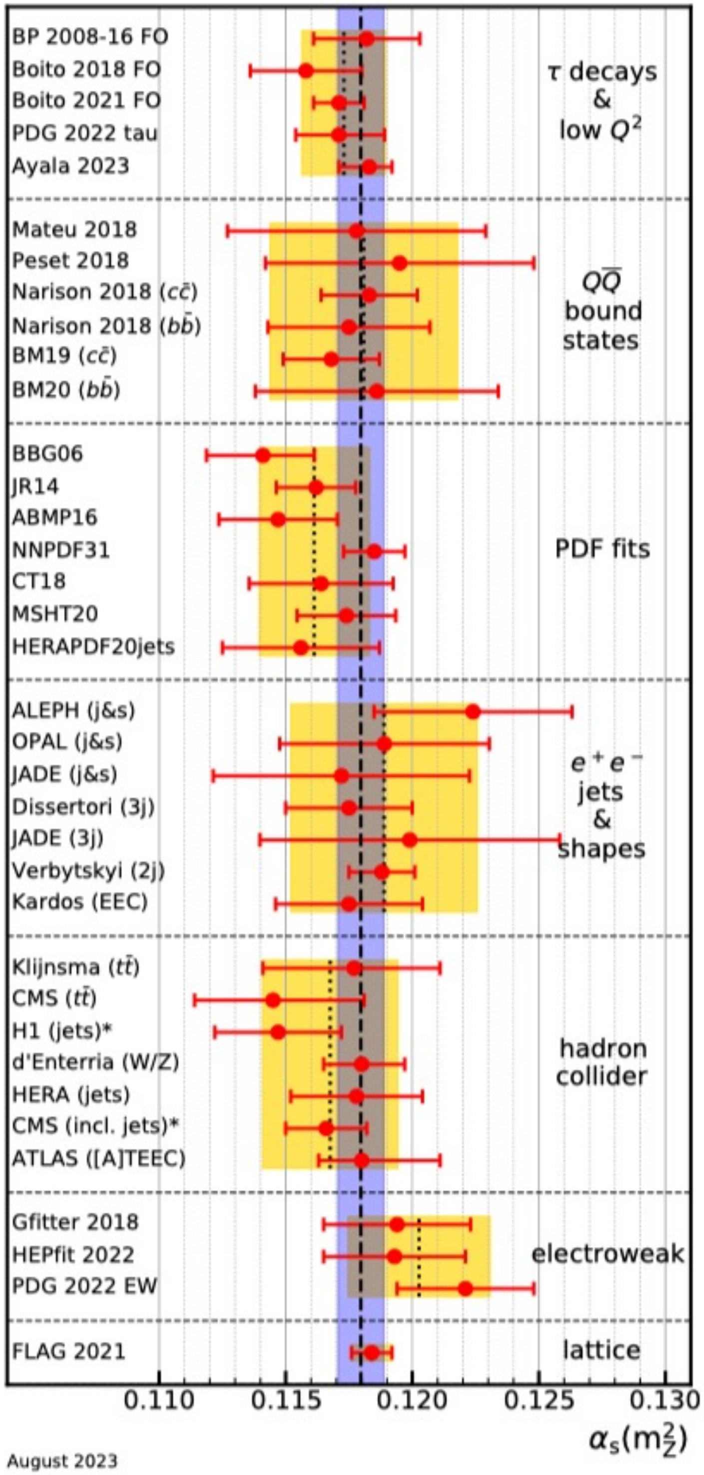




PDF fits often do not have explicit estimate of theory uncertainty

issue of whether necessary to do simultaneous PDF fit; * == fit

new version of ePump will allow simultaneous fit of $\alpha_s(m_Z)$ with new data



$$\alpha_s(m_Z^2) = 0.1173 \pm 0.0017,$$

$$\alpha_s(m_Z^2) = 0.1181 \pm 0.0037,$$

unweighted averages of central value and uncertainties within sub-fields; impact of correlations reduced

$$\alpha_s(M_Z^2) = 0.1161 \pm 0.0022,$$

$$\alpha_s(m_Z^2) = 0.1189 \pm 0.0037.$$

some results removed due to underestimate of NP uncertainties

$$\alpha_s(m_Z^2) = 0.1157 \pm 0.0021$$

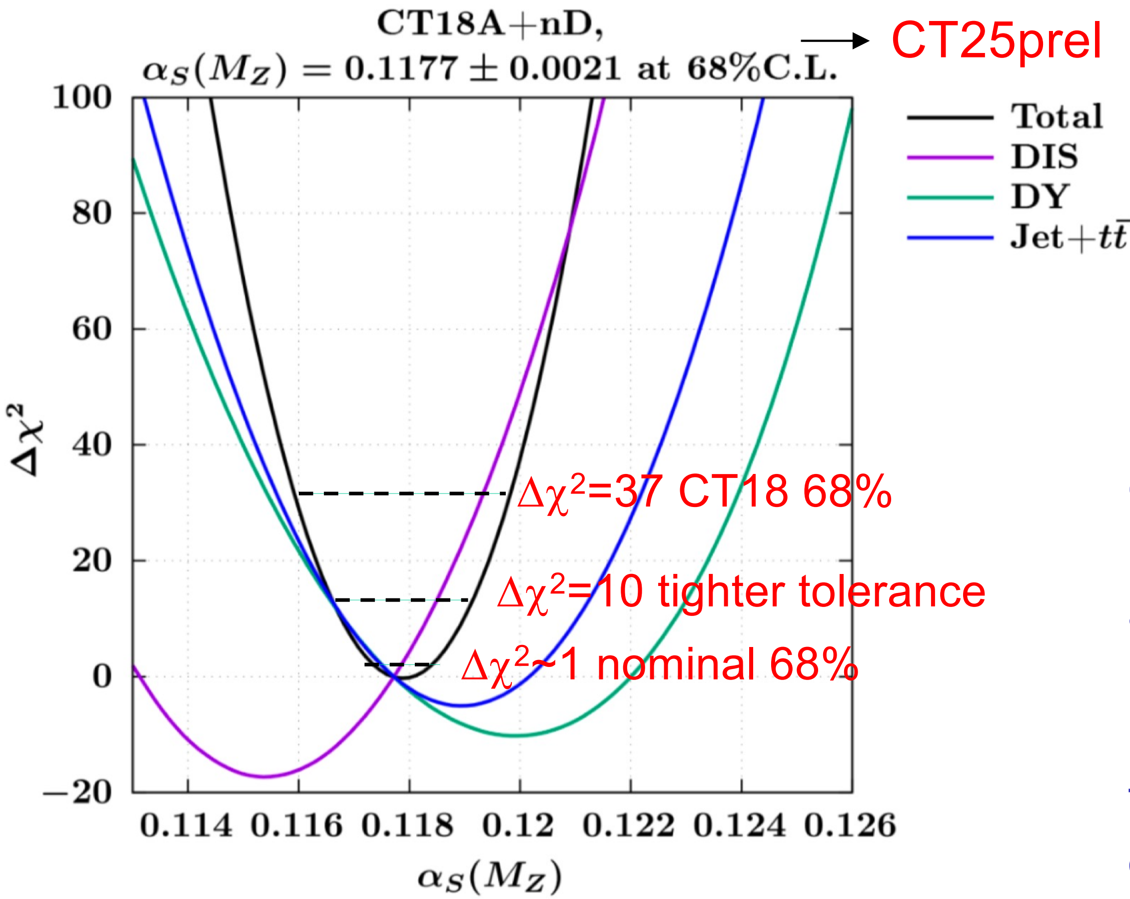
$$\alpha_s(m_Z^2) = 0.1168 \pm 0.0027,$$

if use only H1 and CMS, which used PDF fit

$$\alpha_s(m_Z^2) = 0.1203 \pm 0.0028,$$

combination of first 6 pre-averages using χ^2 averaging gives

$$0.1175 \pm 0.0010$$



- Tension between DIS data and collider data
- Smaller tension between jet+tT and DY
- Result is parabolic (by definition), but $\Delta\chi^2$ near one does not reflect the spread of the information that goes into the determination

CT25prel All data with weight=1	Total	DIS	DY	Jet+tt
# of data points	4450	2381	876	1193
Minimal χ^2 value	5346	2714	1100	1531
$(\alpha_s, \Delta\alpha_s)$ with $\Delta\chi^2 = 37$	0.1177, 0.0021	0.1152 , 0.0043	0.1197, 0.0044	0.1189, 0.0035
$(\alpha_s, \Delta\alpha_s)$ with $\Delta\chi^2 = 10$	0.1177, 0.0012	0.1152, 0.0030	0.1197, 0.0031	0.1189, 0.0021

A few words about PDG

- A non-lattice result was determined from sub-fields 1-6 using a χ^2-averaging method

$$\alpha_s(M_Z^2) = 0.1175 \pm 0.0010\,, \qquad \text{(without lattice)}$$

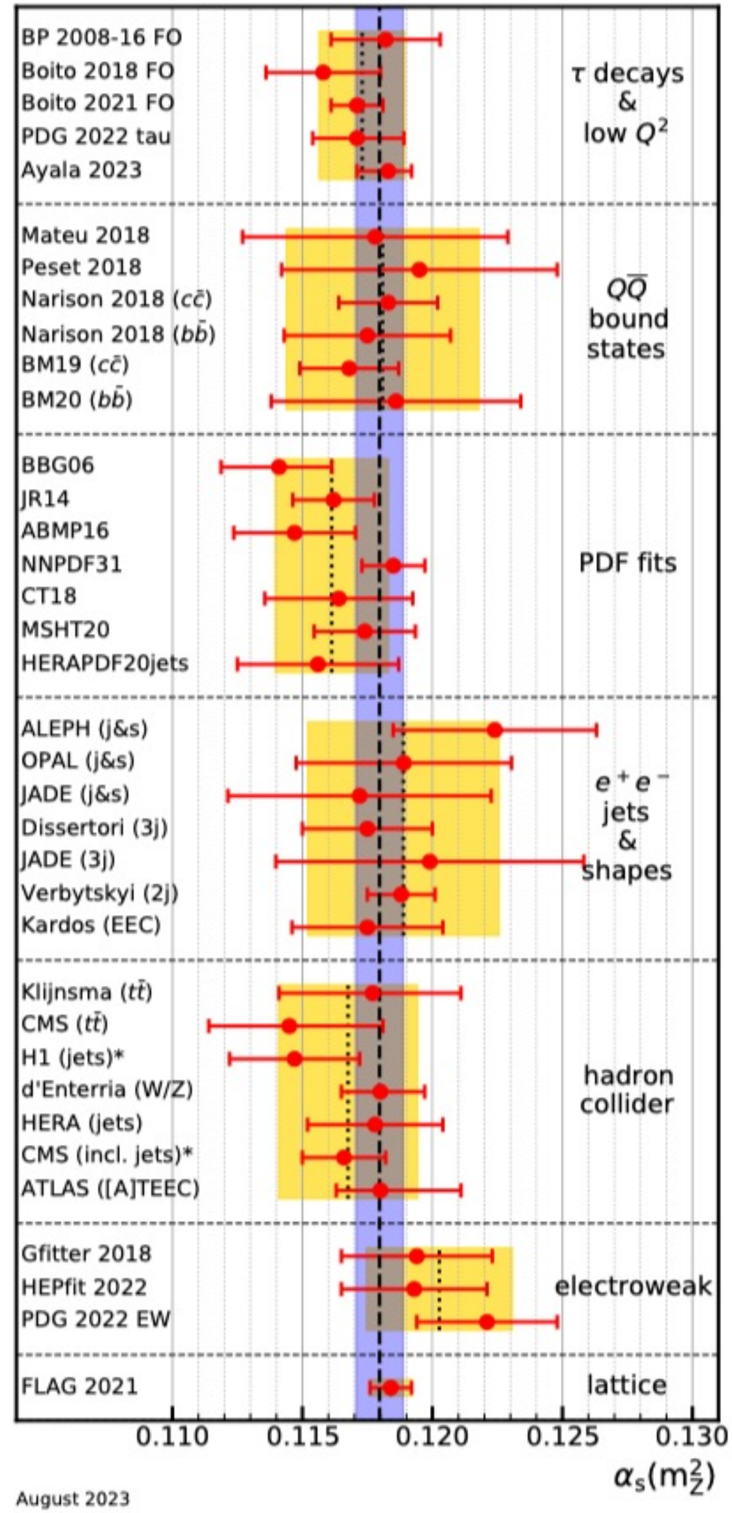
$$\overline{0.1178 \pm 0.0005} \qquad \text{weighted}$$

- FLAG result itself is an average and is taken as is

$$\alpha_s(m_Z^2) = 0.1184 \pm 0.0008 \qquad \text{(lattice)}$$

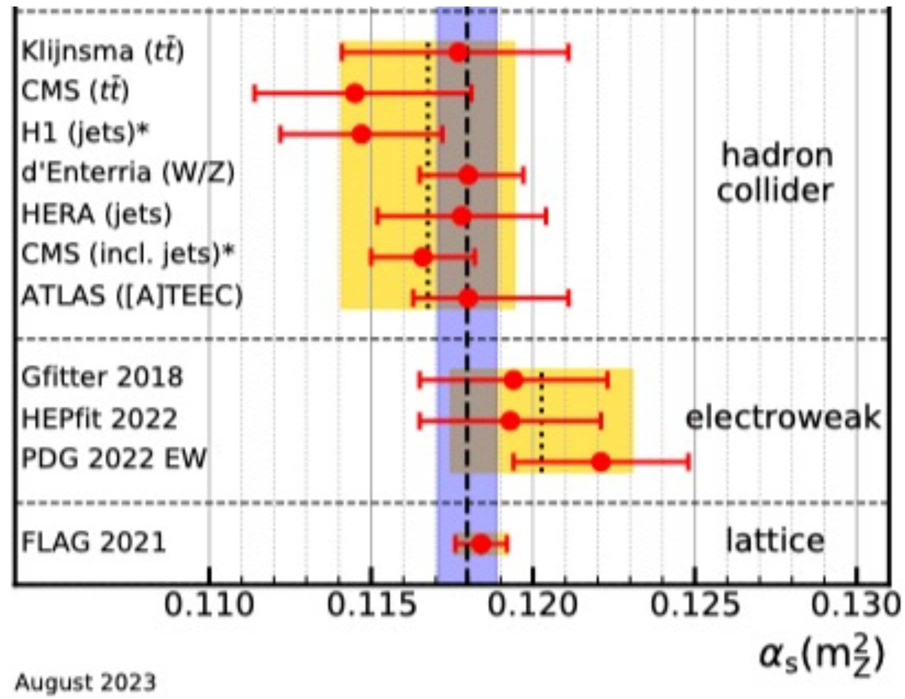
- **Note that the uncertainty for the data-driven determination is similar to that from lattice; lattice error will come down faster than non-lattice**
- Combine two numbers in un-weighted average, and take uncertainty as an average of the two uncertainties (conservative)

$$\alpha_s(m_Z^2) = 0.1180 \pm 0.0009 \qquad \text{(PDG 2023 average)}$$



Collider measurement of $\alpha_s(m_Z)$

- Number of such measurements, now mostly with concurrent PDF fits growing, especially with new calculations being available at NNLO
- Dedicated discussion of α_s from LHC on Monday June 23; Stefano Camarda to come down



PDFs:aN3LO (can we retire the N3LO PDF uncertainty?)

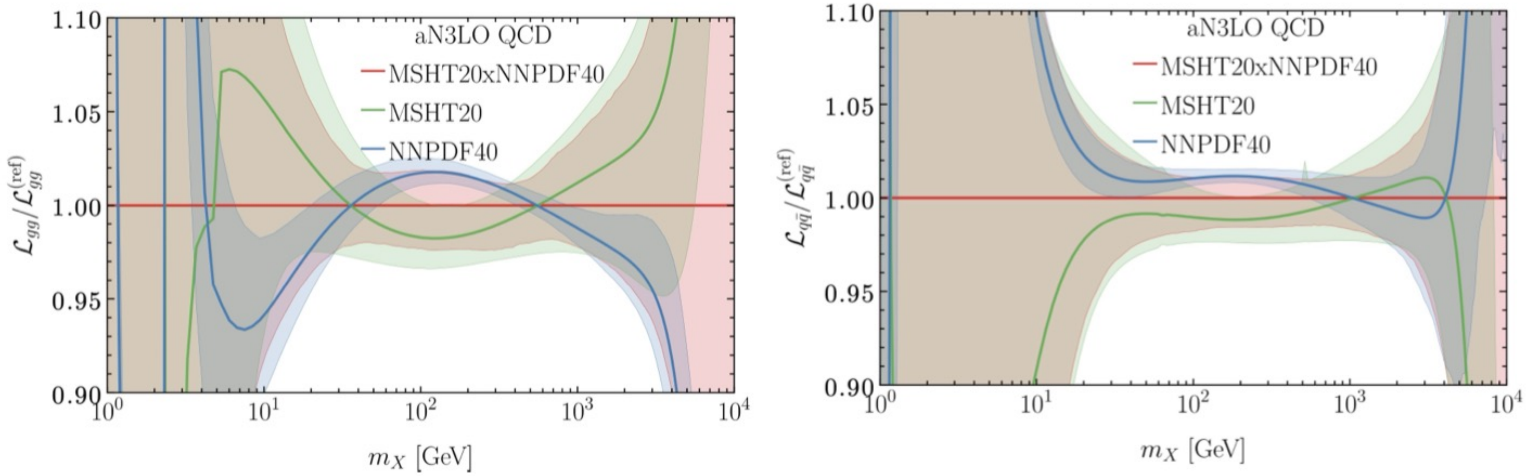


Fig. 1: A comparison of the aN3LO PDF luminosities for MSHT20 and NNPDF4.0 to their combination (MSHT20xNNPDF40) for gg (left) and $q\bar{q}$ (right).

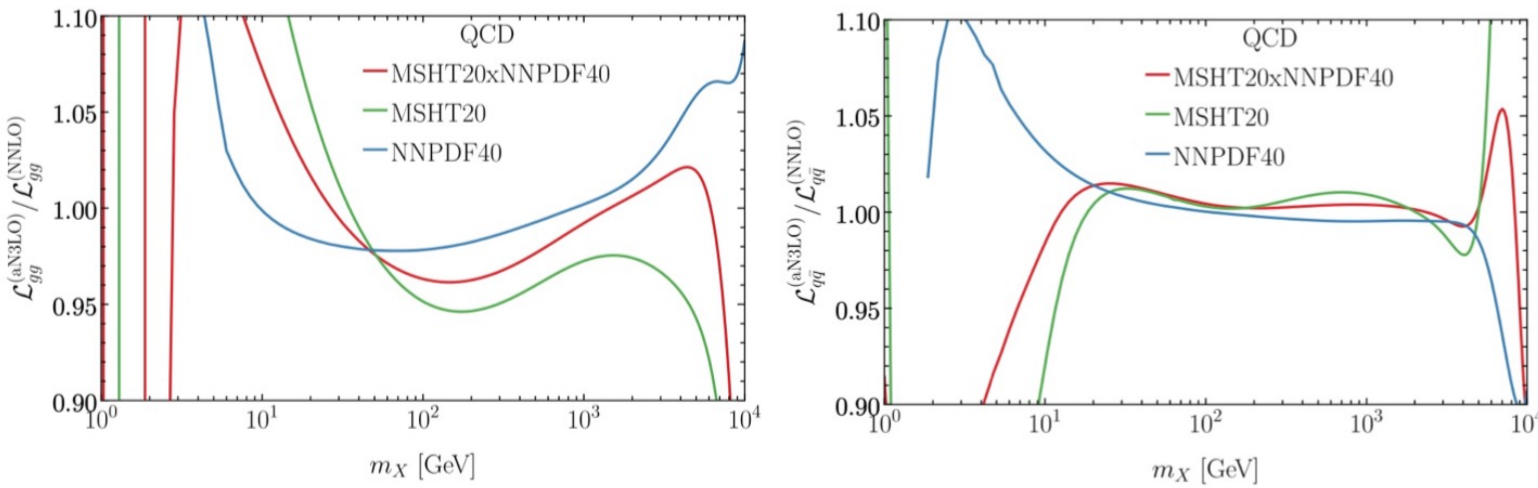
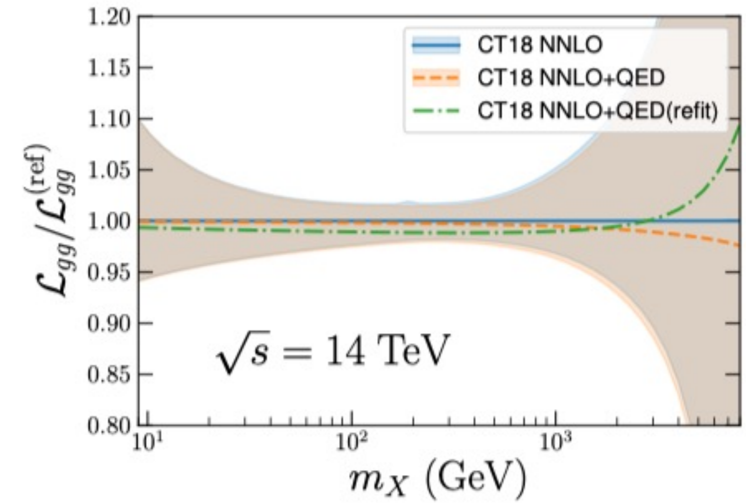
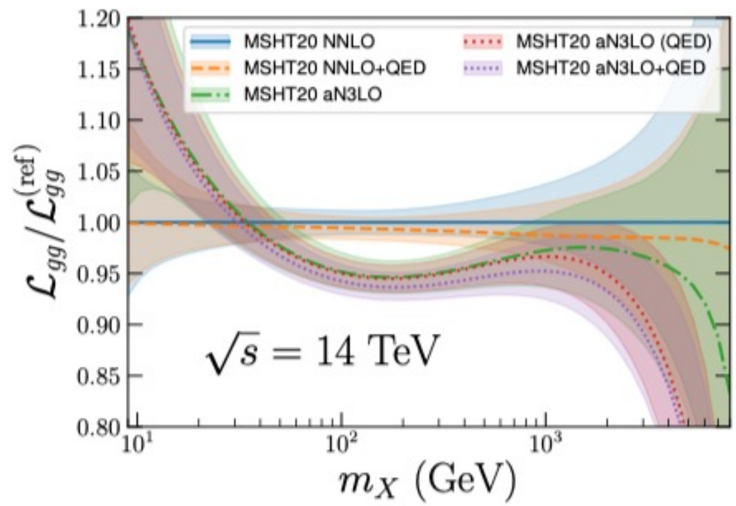


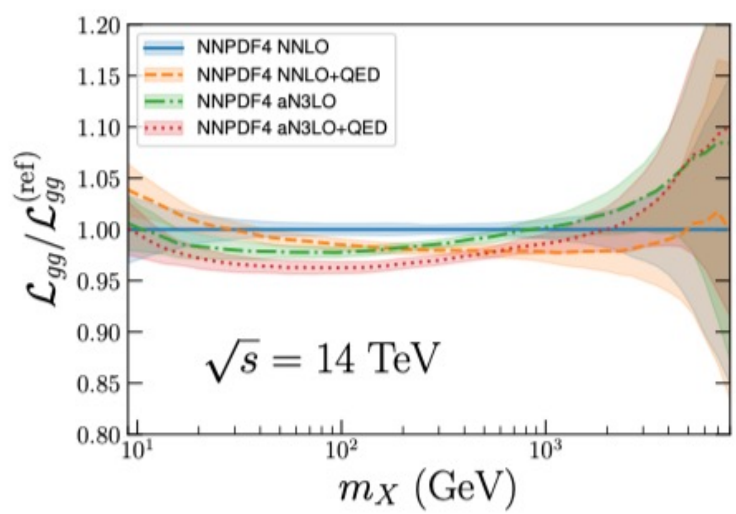
Fig. 2: A comparison of the ratio of the aN3LO PDF luminosities to the NNLO PDF luminosities for MSHT20 and NNPDF4.0 and for their combination (MSHT20xNNPDF40) for gg (left) and $q\bar{q}$ (right).

QED corrections to PDFs

- We all agree on how much momentum the photon PDF takes (~0.4%), constrained by LUX-QED
- Where we differ is the impact of including the photon in the fit on the ggF Higgs cross section
  - ~1% lower for CT18 and MSHT20
  - ~2% lower for NNPDF4.0
  - small, but we’re talking about a tight error budget for the Higgs cross section calculation
- Tom, Juan and I are all here at Les Houches
- Can we arrive at a better understanding?







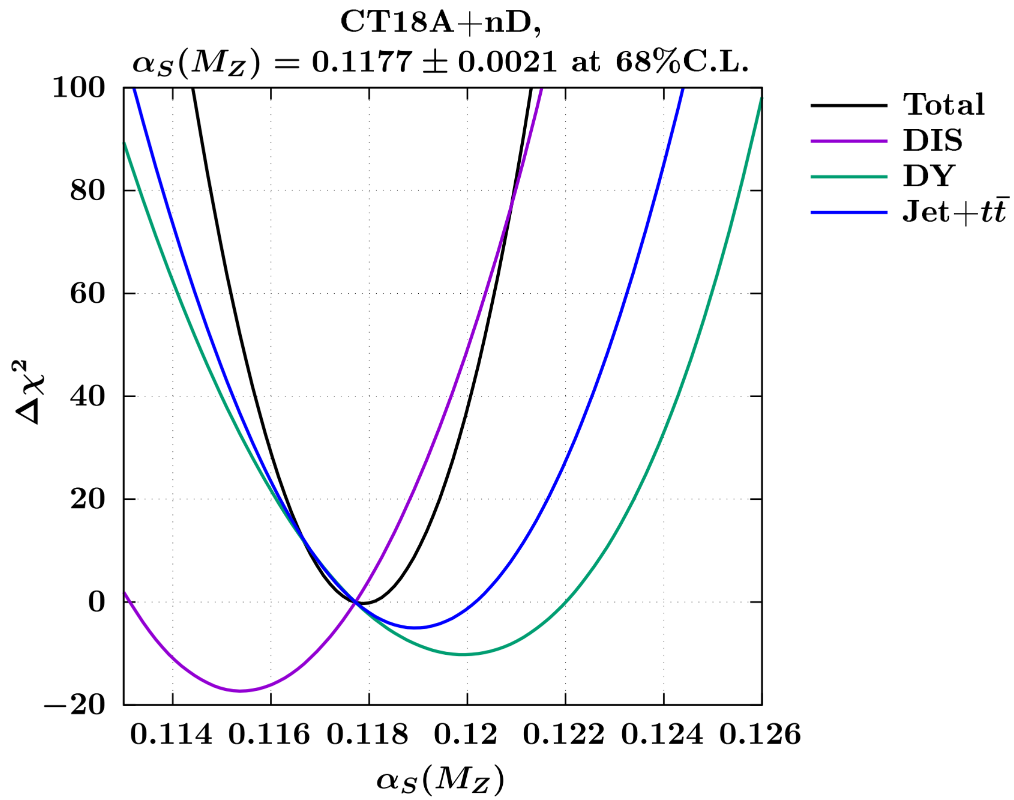
Other ideas, overlapping with other groups

- PDF uncertainties and the weak mixing angle (dedicated session?)
- Heavy flavor jet algorithms, and the quest for an understanding of g->cC, bB in Monte Carlos (Lund plane)
  - see jet/MC talks
- A comprehensive study of theoretical uncertainties for one ME+PS process (e.g. Higgs+jets through ggF), examining the interplay between the nominal MEPS uncertainties (merging/matching,…) and the logarithmic accuracy of the parton shower; not all elements in place, but perhaps enough to get a start
- …your idea here

extras

Combining three measurements

- Consider the fit shown in the plot
- It is easy to see that there is a large tension between DIS and other data sets.
- Treat each of the sets (DIS, DY, Jet +$t\bar{t}$) as independent and identically distributed measurements of α_s
- $\chi^2_{tot} = \sum_i \chi^2_i$
- Mean and Error given by minimizing
- $\tilde{\chi}^2 = \sum_i \frac{(\alpha_{s_i} - \bar{\alpha}_s)}{\sigma_i^2}$
- $\bar{\alpha}_s = \sigma^2_{tot} \sum_i \frac{\alpha_{s_i}}{\sigma_i^2}$, $\frac{1}{\sigma^2_{tot}} = \sum_i \frac{1}{\sigma_i^2}$
- Large Tension: $\frac{\tilde{\chi}^2}{dof} \simeq 17$
- **Yet small uncertainty: $\bar{\alpha}_s = 0.1179 \pm 0.000329$ ($\Delta\chi^2$=1)**
- The small difference with α_s given in plot shows good agreement with quadratic approximation.



	DIS	DY	Jet +$t\bar{t}$	$\bar{\alpha}_s$
$\alpha_s \times 10^3$ at min of χ_i^2	115.9	119.9	118.9	**117.9**
Error ($\sigma_i \times 10^3$) ($\Delta\chi_i^2 = 1$)	0.553	0.655	0.539	**0.329**

How to handle this situation?

GMM and Scaling Errors

- PDG proposal: scale errors by a factor e_s to make fits more consistent, i.e. each $\sigma_i \rightarrow e_s\, \sigma_i$
- $e_{s_{PDG}} = \sqrt{\frac{\tilde{\chi}^2}{dof}} \simeq 4.1$ so that each $\sigma_i \rightarrow 4.1 \times \sigma_i$ and $\frac{\tilde{\chi}^2}{dof} \rightarrow 1$
- Caveat: For very large $\sqrt{\frac{\tilde{\chi}^2}{dof}}$, PDG recommends making an educated guess of the uncertainty rather than scaling the errors.
- Alternate: use GMM and Information criteria to determine if the posterior (probability of theory given data) is better modeled with a uni-modal (usual χ^2) or by a multi-modal distribution. Then use the best distribution (uni-modal or multi-modal) to determine the uncertainty.

K=1

K>=2

How many Gaussians? How do we determine K?

arXiv: 2406.01664

Akaike Information Criterion (AIC)
(Akaike, 1974)
Bayesian Information Criterion (BIC)
Schwarz (Ann Stat 1978, 6:461–464)

$$\mathrm{AIC} = N_{\mathrm{parm}} \log N_{\mathrm{pt}} - 2\log L\big|_{\theta=\hat{\theta}},$$
$$\mathrm{BIC} = 2N_{\mathrm{parm}} - 2\log L\big|_{\theta=\hat{\theta}}.$$

$$N_{\mathrm{parm}} = 2K + (K-1).$$

Use the lowest values of AIC & BIC to determine the best value of K and avoids over-fitting.

Strong tension

Weak tension due to large uncertainty

Consistent but data fluctuated

Consistent - No fluctuation

		$K=1$	$K=2$	$K=3$	$K=4$
case-1	AIC	-102.2	**-203.6**	-194.9	-187.9
	BIC	-106.1	**-211.2**	-206.4	-203.2
N_{pt}=100	$-\log L$	-55.0	**-109.6**	-109.2	**-109.6**
case-2	AIC	**-21.2**	-15.4	-7.9	-0.2
	BIC	**-25.0**	-23.0	-19.3	-15.5
N_{pt}=100	$-\log L$	-14.5	-15.5	**-15.7**	**-15.7**
case-3	AIC	-219.3	**-220.2**	-212.8	-205.0
	BIC	-223.2	**-227.8**	-224.3	-220.3
N_{pt}=100	$-\log L$	-113.6	**-117.9**	**-117.9**	-118.1
case-4	AIC	**-117.8**	-109.9	-102.1	-94.3
	BIC	**-121.6**	-117.6	-113.6	-109.6
N_{pt}=50	$-\log L$	**-62.8**	**-62.8**	**-62.8**	**-62.8**
case-5	AIC	**-169.3**	-161.5	-153.6	-145.8
	BIC	**-173.1**	-169.1	-165.1	-161.1
N_{pt}=50	$-\log L$	**-88.6**	**-88.6**	**-88.6**	**-88.6**

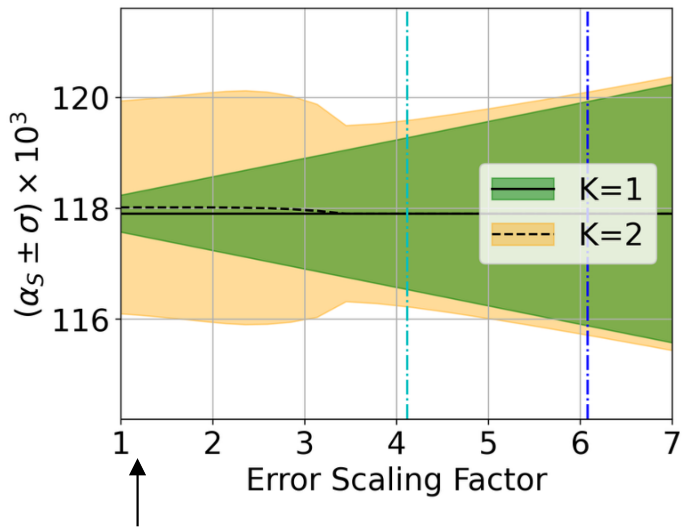
$$\pi(Y|\vec{\theta}) = \prod_{j=1}^{N_{\mathrm{pt}}} \pi(y_j, \Delta y_j|\vec{\theta}) = \prod_{j=1}^{N_{\mathrm{pt}}} \sum_{i=1}^{K} \omega_i \mathcal{N}(y_j, \Delta y_j|\theta_i),$$

$$0 \le \omega_k \le 1 \quad \text{and} \quad \sum_k \omega_k = 1,$$

Preliminary results

- GMM (K=2) (Yellow shaded)
  - $\alpha_s \pm \sigma = 0.11801 \pm 0.00192$
- $e_{s_{PDG}} \sim 4.1$ *(Green shaded, Cyan line)*
  - $\alpha_s \pm \sigma = 0.11795 \pm 0.00135$
- $e_s \sim 6.1$ (Green shaded, Blue line)
  - $\alpha_s \pm \sigma = 0.11795 \pm 0.0020$
- Caveat: This is just preliminary. How we partition the data sets does have an impact on uncertainty determination. More complete study is underway

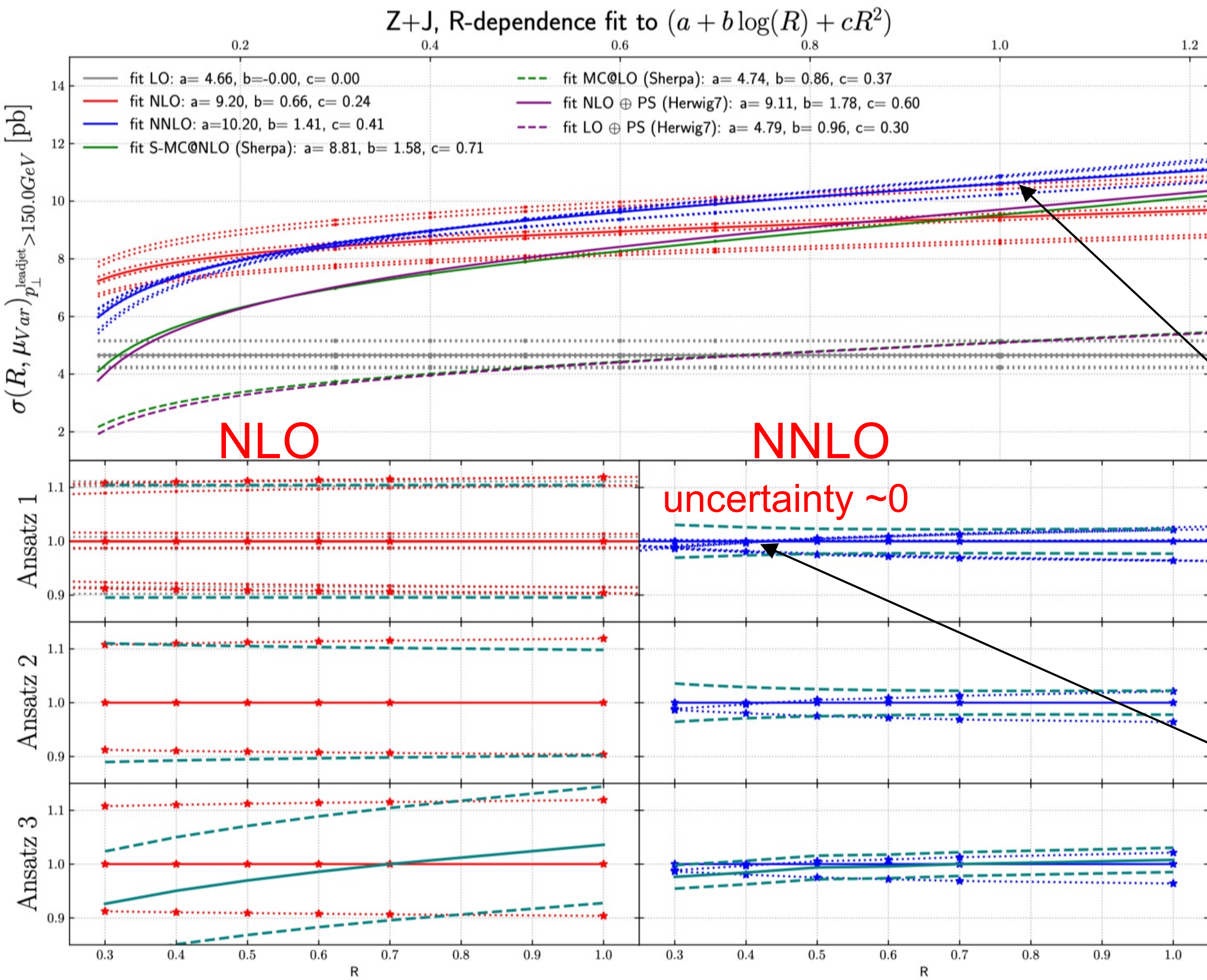
# of modes	Loss	AIC	BIC
K=1	18.09	37.27	38.17
K=2	**3.69**	**10.67**	**13.37**
K=3	14.29	21.82	26.33
K=4	14.8	24.02	30.33



using a nominal tolerance for results with tensions as seen in the α_s determinations would result in a large underestimate of the uncertainty

Stay tuned to this channel

Fixed order at NNLO: small R jets. Why is the uncertainty so small?



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

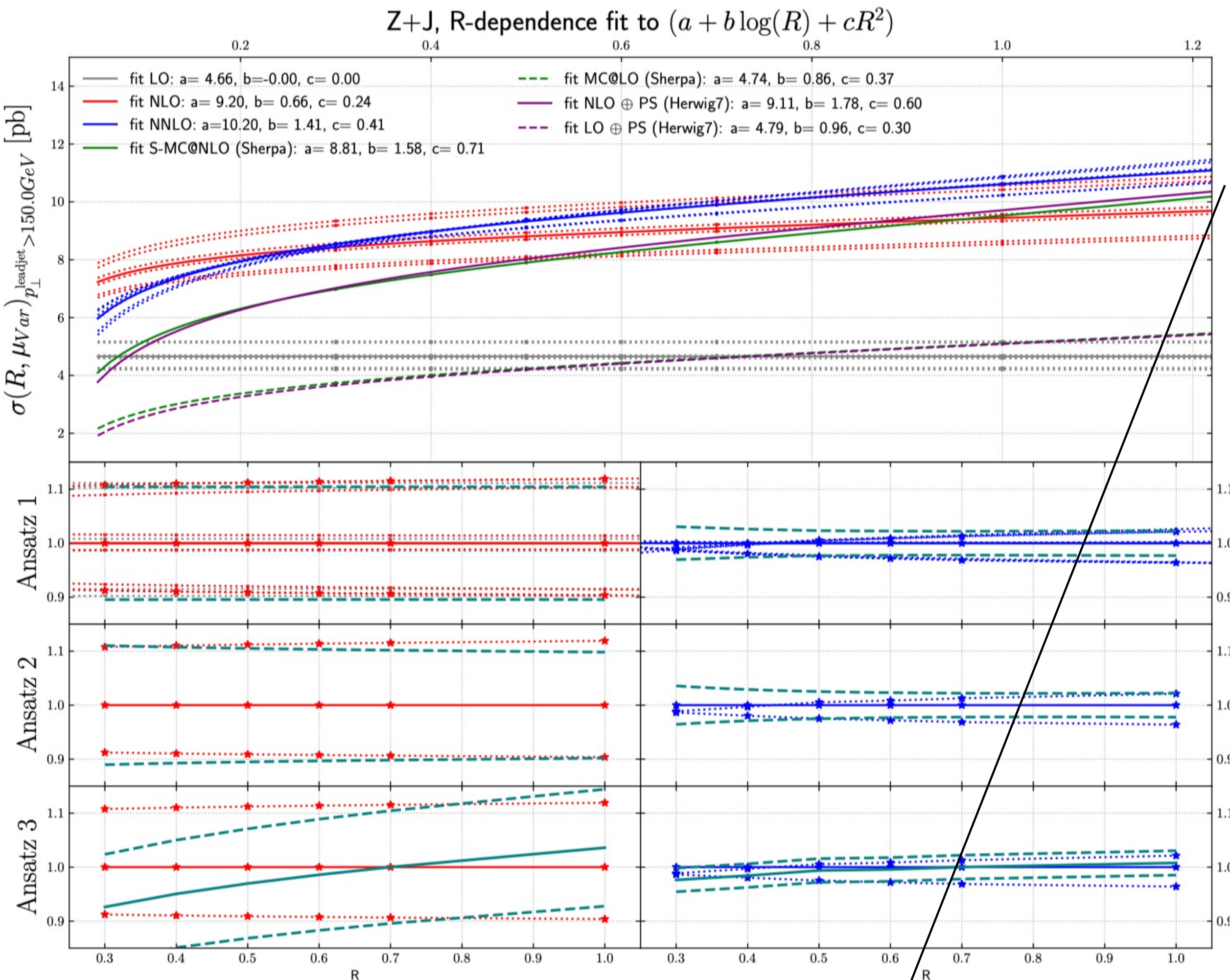
Parametrize R dependence according to form shown above; log R term includes effects of radiation inside jet; R^2 term takes into account ISR. Do so for each scale from 7-point scale variation.

There can be accidental cancellations of logarithmically enhanced higher order corrections that appear both as a result of scale variations and as a result of phase space restrictions.

Definition of a jet implies an exclusive measurement and effectively acts as a veto on real-radiative corrections that fall outside the jet area.

arxiv:1903.12563

What to do?



Expand cross section around reference value R_o (typically 0.7); add in quadrature uncertainty from two first two terms.

Three different ansatze to do this. Ansatz 3 is original from Gavin Salam et al. We proposed Ansatze 1 and 2 as more reasonable (preserves central value).

Result is a larger uncertainty, roughly independent of R, with no accidental zeroes.

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

PDG value of $\alpha_s(m_Z)$

- Every two years, the QCD section in the Particle Data Book is updated; part of that update is a review of the world average of $\alpha_s(m_Z)$, revising it to include the impact of new measurements and calculations
- The last revision was in 2023; which means I'm going to have a busy summer this year
- The selection of results to include in the α_s averaging are restricted by the following considerations:
  - published in a peer-reviewed paper at the time of the report (or is based on a summary of results that have been published in a peer-reviewed journal, such as the FLAG report)
  - based on the most complete perturbative predictions of at least NNLO accuracy, accompanied by reliable estimates of all experimental and theoretical uncertainties