SM phenomenology experimental review

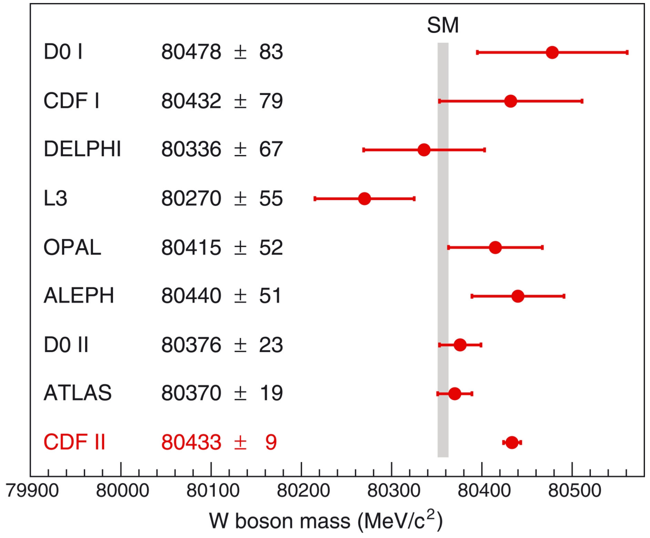
Paolo Azzurri, Joey Huston

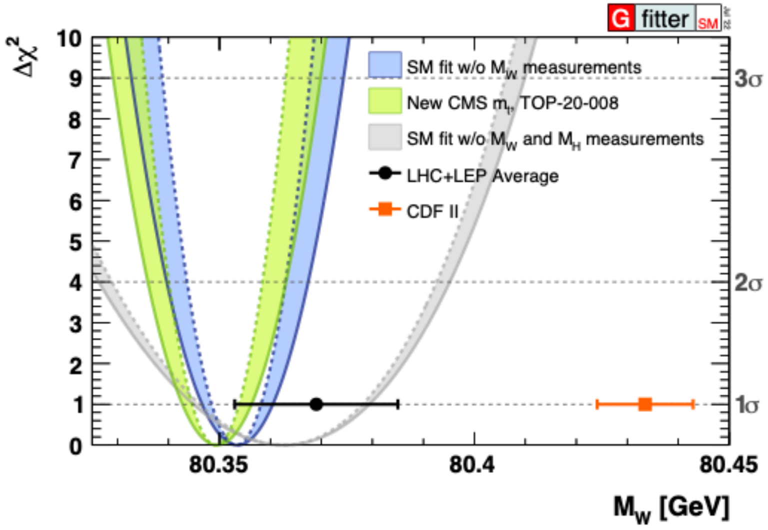
Les Houches - Physics at TeV Colliders - 2023

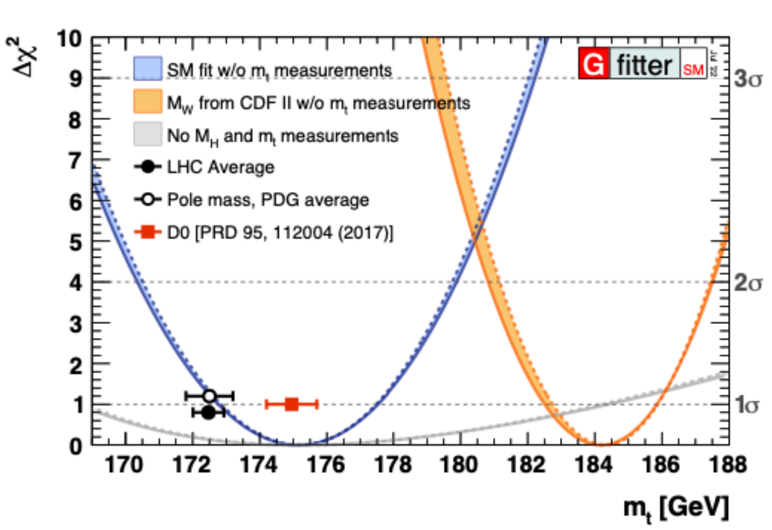
Outlook

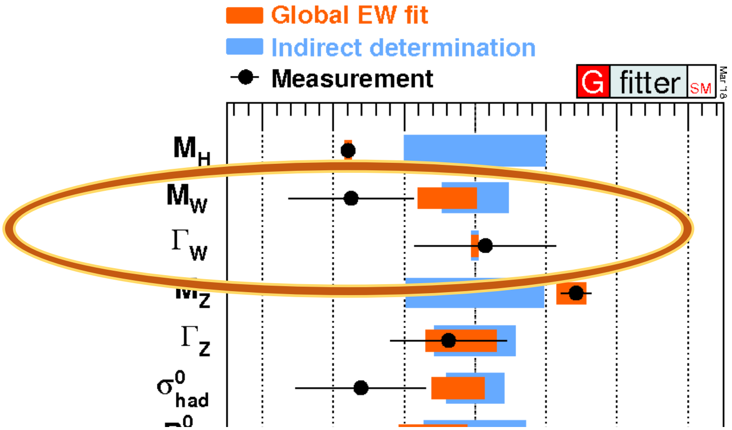
- W mass
- common cross section for VBF/VBS
- VBF Higgs comparisons
- PDFs
- alphaS

W mass









- (non-perturbative) modeling
- new ideas/methods (asymmetry)
- future determination at e+e-
- theory agnostic determinations (Tanmay Sarkar)

theory agnostic W mass fit

Fit production model with the data

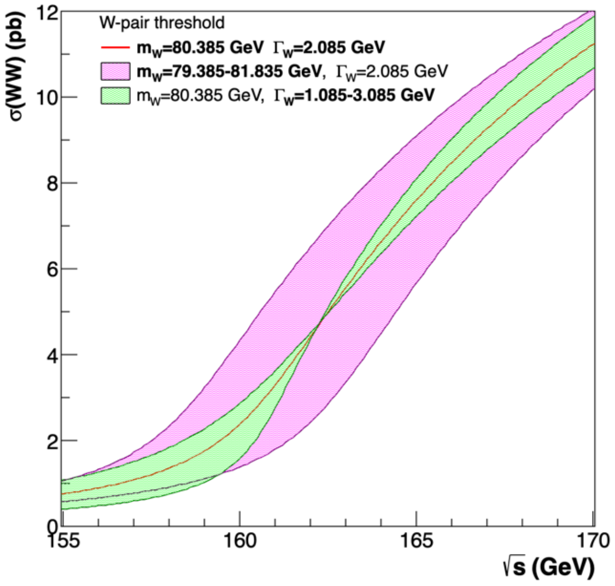
$$\frac{d\sigma}{d\Phi} \propto BW(Q)\times\frac{d^2\sigma}{dy\,dq_T}\cdot(1+\varepsilon_{UL}(y,q_T))\times(1+\cos\theta^2+\sum A_i\cdot(1+\varepsilon_i(y,q_T))\times P_i(\theta,\varphi))$$

- $BW, d^2\sigma/dy\,dq_T$ and A_i with possibly the best F.O. + logarithmic accuracy
- $\varepsilon_{UL}(y,q_T)$ and $\varepsilon_i(y,q_T)$ parametrize the missing higher orders
  - **to be profiled from *W* data only**

- A template-based fit of the data will be needed anyway
  - Templates of reco-level (pT,eta) built from samples of MC simulated events
  - Using an event-by-event reweighting according to Eq. (1) to build the templates. Use the pre-FSR lepton kinematics from the MC record to define Φ
- QED shower effects accounted for by MC simulation

⇒ **Tanmay Sarkar <tanmay.sarkar@cern.ch>**

future W mass @e+e-



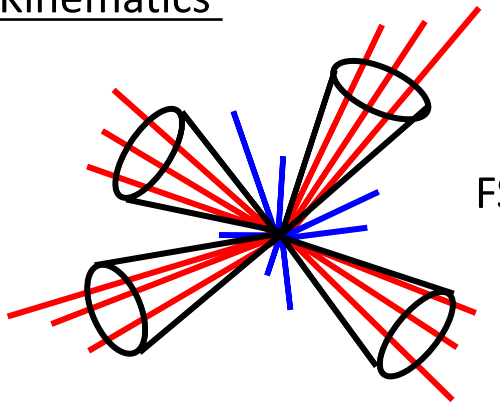
WW threshold cross sections

[10/ab] →Δm_W=0.3 MeV (stat)

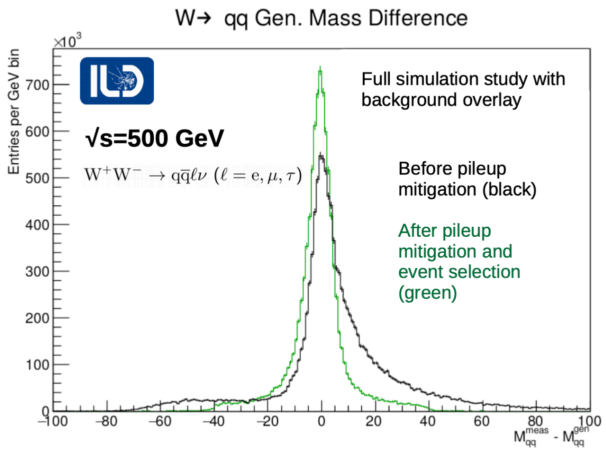
→ $\Delta\Gamma_W$=1 MeV (stat)

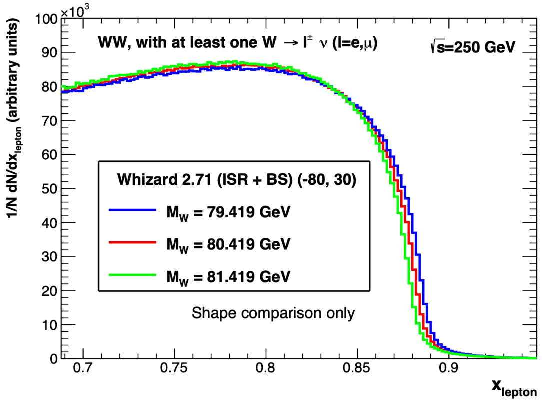
syst : Theory / E_{CM} / acceptance

Decays Kinematics



FSI (CR) effects





[2-5/ab @240-250 GeV] →Δm_W=0.5-1 MeV (stat)

2-5 MeV (syst)

syst Theory modeling (NP QCD)

E_{CM} / det calibration

⇒ ECFA W mass team :

PA; Josh Bendavid, Martin Beneke, Stefan Dittmaier, Simon Plätzer, Matthias Schott, Raimund Ströhmer, Graham Wilson, Jorge de Blas

common cross section for VBF/VBS

Current situation ; Disparate signal definitions (parton & particle level)
Examples for VBF (same/ worse situation for VBS)

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)

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)	

common cross section for VBF/VBS

Initial efforts to agree on common definitions in the context of the LHC EW WG3
(to be part of a multiboson YR) … did not converge

Leptons	$p_T > 25\,\text{GeV}$ and $\|\eta\| < 2.5$
Jets	$p_T > 25\,\text{GeV}$ and $\|y\| < 4.5$
$Z \to \ell\ell$	$N_\ell = 2$ (same flavour, opposite charge), $m_{\ell\ell} > 60$ GeV
$W \to \ell\nu$	$N_\ell = 1$
Object overlap	$\Delta R_{\text{min}}(\ell, j) > 0.4$
VBF topology	$N_{\text{jets}} \geq 2,\ p_T^{j1} > 50\,\text{GeV},\ p_T^{j2} > 30\,\text{GeV}$

"Tight" electroweak region selection		
Final state	Object	Selection requirements
All	**Charged leptons**	$\|\eta\| < 2.5$
	Photons	$p_T > 20$ GeV, $\|\eta\| < 2.4$, $\Delta R(\gamma, \ell) > 0.4$
	Jets	$p_T > 30$ GeV, $\|\eta\| < 5.0$, $\Delta R(\text{j}, \ell) > 0.4$ $\Delta R(\text{j}, \gamma) > 0.4$
	Dijet	$m_{\text{jj}} > 500$ GeV, $\|\Delta\eta_{\text{jj}}\| > 2.5$
	Fit region	m_{jj} : $[500, 800, 1200, 1600, 2000, \infty]$ GeV
Fully leptonic final states		
$W^\pm W^\pm$ / $W^\pm W^\mp$	**Charged leptons**	$p_T^{1,2} > 20$ GeV
	Kinematic	$p_T^{\text{miss}} > 20$ GeV, $m_{\ell\ell} > 20$ GeV
$W^\pm Z$	**Charged leptons**	$p_T^{z_1,z2,w} > 20/10/20$ GeV
	Kinematic	$p_T^{\text{miss}} > 20$ GeV, $m_{3\ell} > 100$ GeV, $\|m_{\ell\ell} - m_Z\| < 15$ GeV
ZZ	**Charged leptons**	$p_T^{1,2,3,4} > 20/10/5/5$ GeV
	Kinematic	$m_{\ell^+\ell^-} > 4$ GeV, $m_{4\ell} > 180$ GeV, $\|m_{\ell\ell} - m_Z\| < 15$ GeV
Leptonic and photonic final states		
$Z\gamma$	**Charged leptons**	$p_T^{1,2} > 20$ GeV
	Kinematic	$\|m_{\ell\ell} - m_Z\| < 15$ GeV
$W^\pm\gamma$	**Charged leptons**	$p_T^{1} > 30$ GeV
	Kinematic	$p_T^{\text{miss}} > 30$ GeV, $m_T^W > 30$ GeV

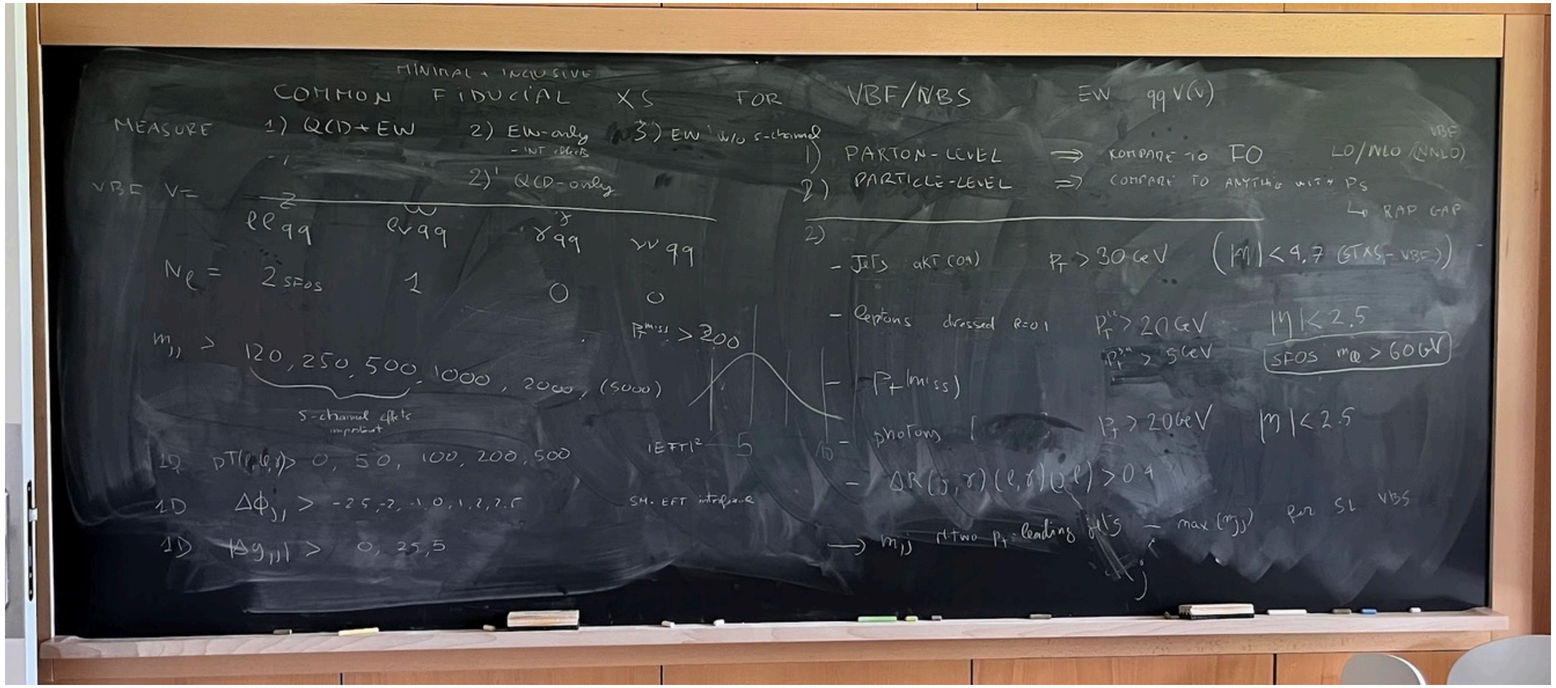
"Looser" VVjj region selection		
All	**Dijet**	$m_{\text{jj}} > 300$ GeV, $\|\Delta\eta_{\text{jj}}\| > 1.5$
	Fit region	m_{jj} : $[300, 400, 500, 800, 1200, 1600, 2000, \infty]$ GeV

Final state	Object	Selection requirements
WW VBS / $WWjj$	**leptons**	p_T >20 GeV, $\|\eta\| < 2.5$, same-sign
	jets	$p_{T,j1}$ >30 GeV, $p_{T,j1}$ >30 GeV, $\|\eta\| < 4.5$, $\Delta\eta_{jj}$ >2.5
same-sign	**final BSM region**	m_{jj}: 0.25-0.5 TeV, >0.5 TeV
$Z\gamma$ VBS / $Z\gamma jj$	**leptons**	p_T >35, $\|\eta\| < 2.5$
	photons	E_T >75, $\|\eta\| < 2.5$, $\Delta R(\ell/j, \gamma) > 0.4$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <10 GeV
	jets	$p_{T,j1}$ >30 GeV, $p_{T,j1}$ >30 GeV, $\|\eta\| < 4.5$, $\Delta\eta_{jj}$ >3.0
	final BSM region	m_{jj}>0.5 TeV
WZ VBS /	**leptons**	$p_{T,\text{lead}}$ >25 GeV, p_T >15 GeV, $\|\eta\| < 2.5$
	neutrinos	$(\sum \vec{p}_\nu) > 30$ GeV
	jets	$p_{T,j1}$ >55 GeV, $p_{T,j1}$ >40 GeV, $\|\eta\| < 4.5$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <25 GeV
	further jets	p_T >25 GeV, none in interval between leptons
	event	p_T^{balance} <0.15
	final BSM region	m_{WZ}: 0.8-1.0 TeV, >1.0 TeV
ZZ VBS / $ZZjj$	**leptons**	p_T >25 / 15 / 10 GeV (leading leptons), $\|\eta\| < 2.5$
	jets	$p_{T,j1}$ >55 GeV, $p_{T,j1}$ >40 GeV, $\|\eta\| < 4.5$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <25 GeV
	further jets	p_T >25 GeV, none in interval between leptons
	event	p_T^{balance} <0.15
	final BSM region	m_{WZ}: 0.8-1.0 TeV, >1.0 TeV

draft proposals

common cross section for VBF/VBS

Yacine Haddad, Mathieu Pellen , Gaetano Barone, PA, …



Focus on particle-level definitions . Use dredded leptons, jets , isolated photons

For each defined region measure

- 1) QCD+EW cross section
- 2) Pure EW cross section (-interference)
- 2') Pure QCD
- 3) EW - s-channel

1D bins of

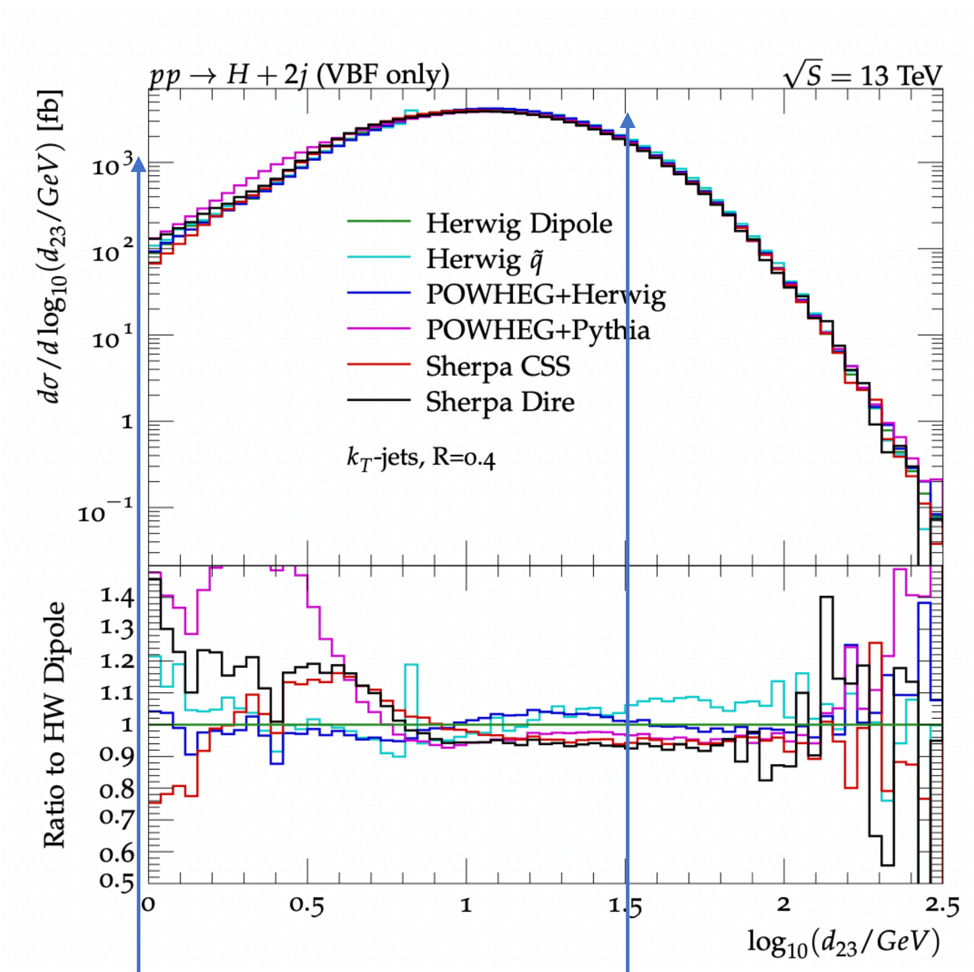
- Mjj > *120,250,500*,1000,2000,5000
- pT(l/ll,A) > 0, 50,200,500
- DeltaPhijj > -2.5, -2, -1, 0,1,2,2.5
- |D yjj| > 0, 2.5, 5

complete and iron out details ⇒ back to previous discussions with
Lorenzo Viliani, Jonas Lindert, Dag Gilbert, Guillelmo Gomez-Ceballos,, Narei Lorenzo,, Marco Zaro ..

⇒ LH2023 accord ?

[2105.11399](https://arxiv.org/abs/2105.11399)

VBF Higgs comparisons

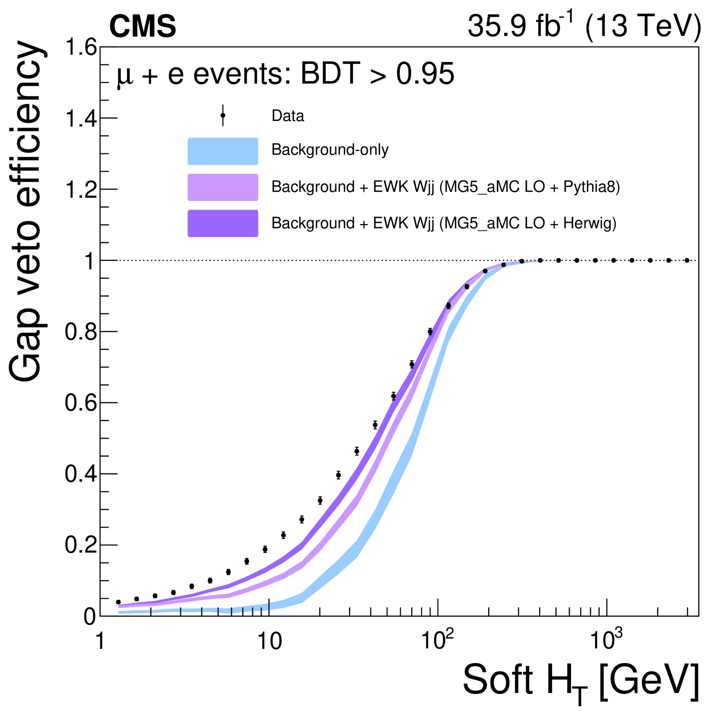


Jets are here

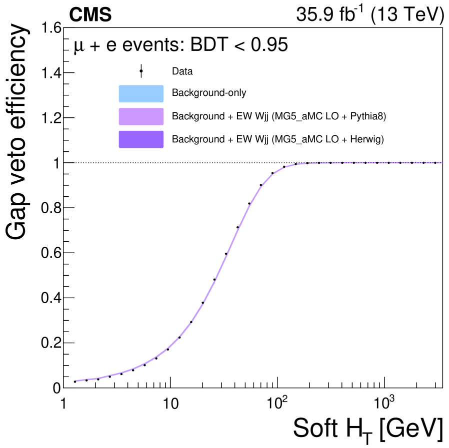
(experimentally)

Charged hadrons are here

EW W+ 2 jets



[CMS SMP-17-011](https://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-17-011/)



Use the charged tracks !

What determines the size of PDF uncertainties?

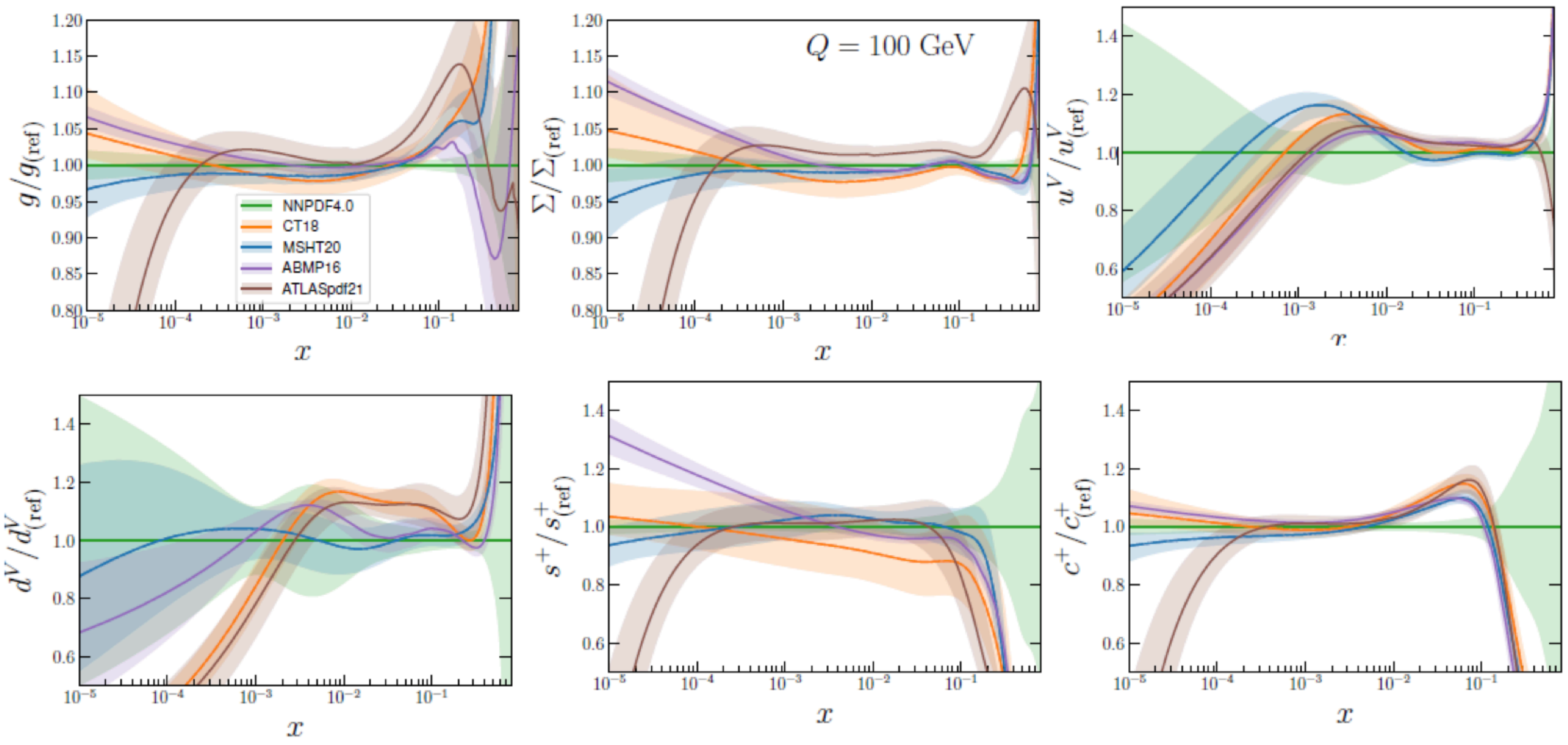
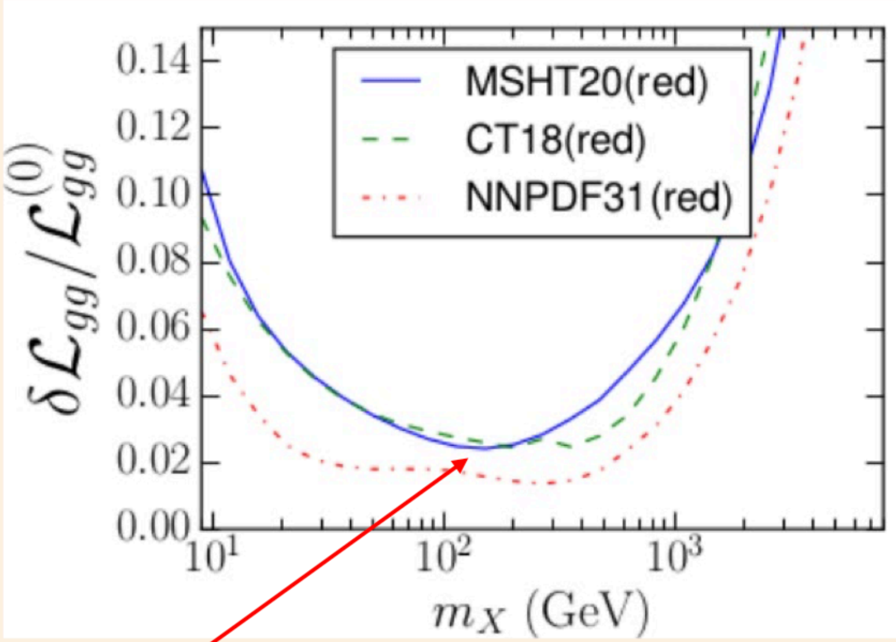


FIG. 2. Comparison of the PDFs at $Q = 100$ GeV. The PDFs shown are the N2LO sets of NNPDF4.0, CT18, MSHT20, ABMP16 with $\alpha_s(M_Z) = 0.118$, and ATLASpdf21. The ratio to the NNPDF4.0 central value and the relative 1σ uncertainty are shown for the gluon g, singlet Σ, total strangeness $s^+ = s + \bar{s}$, total charm $c^+ = c + \bar{c}$, up valence u^V and down valence d^V PDFs.

Figures from Snowmass'2021 whitepaper
"Proton structure at the precision frontier", arXiv:2203.13923

Tolerances explained by epistemic uncertainties

Relative PDF uncertainties on the gg luminosity at 14 TeV in three PDF4LHC21 fits to the **identical** reduced global data set



× 1.5 – 2 difference

While the fitted data sets are identical or similar in several such analyses, the differences in uncertainties can be explained by methodological choices adopted by the PDF fitting groups.

NNPDF3.1' and especially 4.0 (based on the NN's+ MC technique) tend to give smaller nominal uncertainties in data-constrained regions than CT18 or MSHT20

Epistemic uncertainties explain many such differences

Details in **arXiv:2203.05506**, **arXiv:2205.10444**

L_2 sensitivity:a new and powerful tool

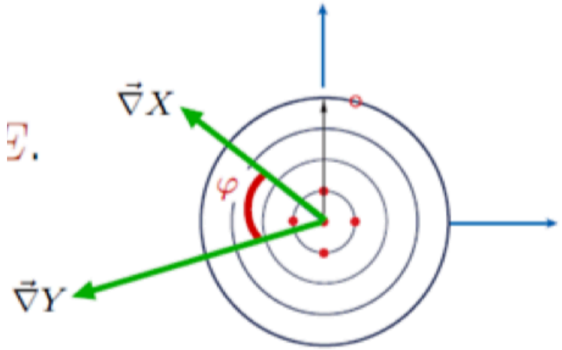
$$S^{\mathrm{H}}_{f,L2}(E) \equiv \frac{\vec{\nabla}\chi^2_E \cdot \vec{\nabla} f}{\Delta^{\mathrm{H}} f} = \left(\Delta^{\mathrm{H}}\chi^2_E\right)\ C^{\mathrm{H}}(f,\chi^2_E)$$

2^{nd} 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

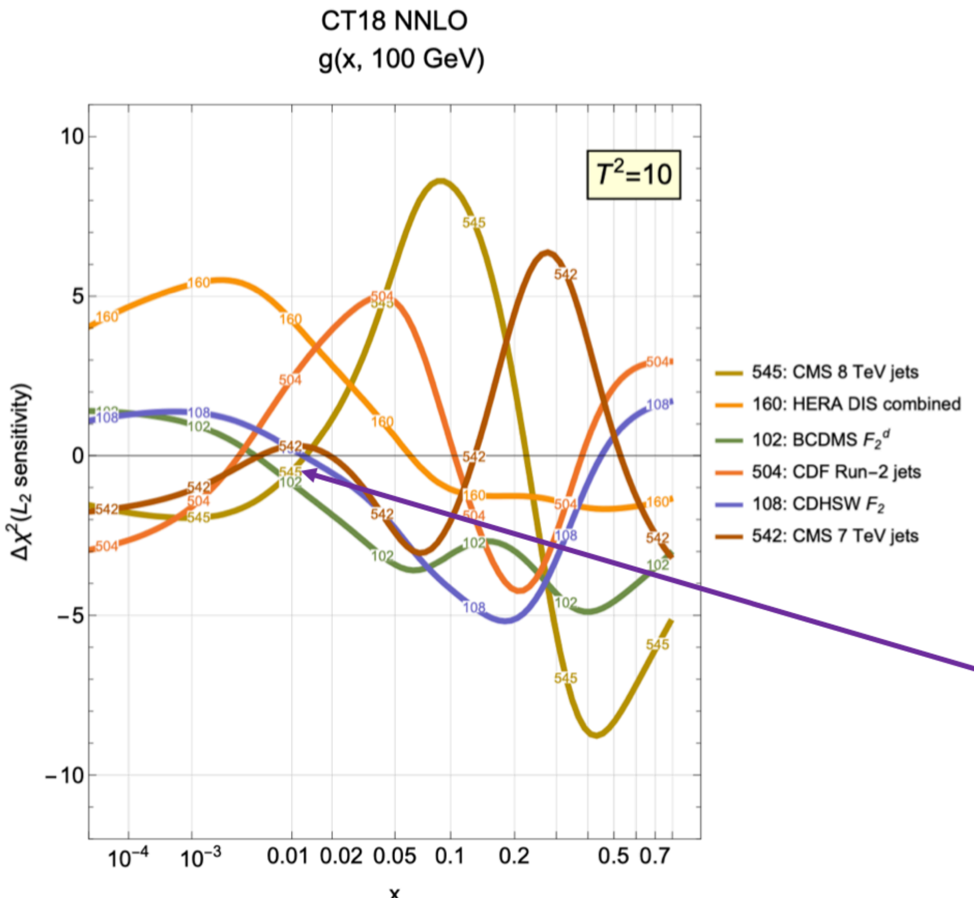


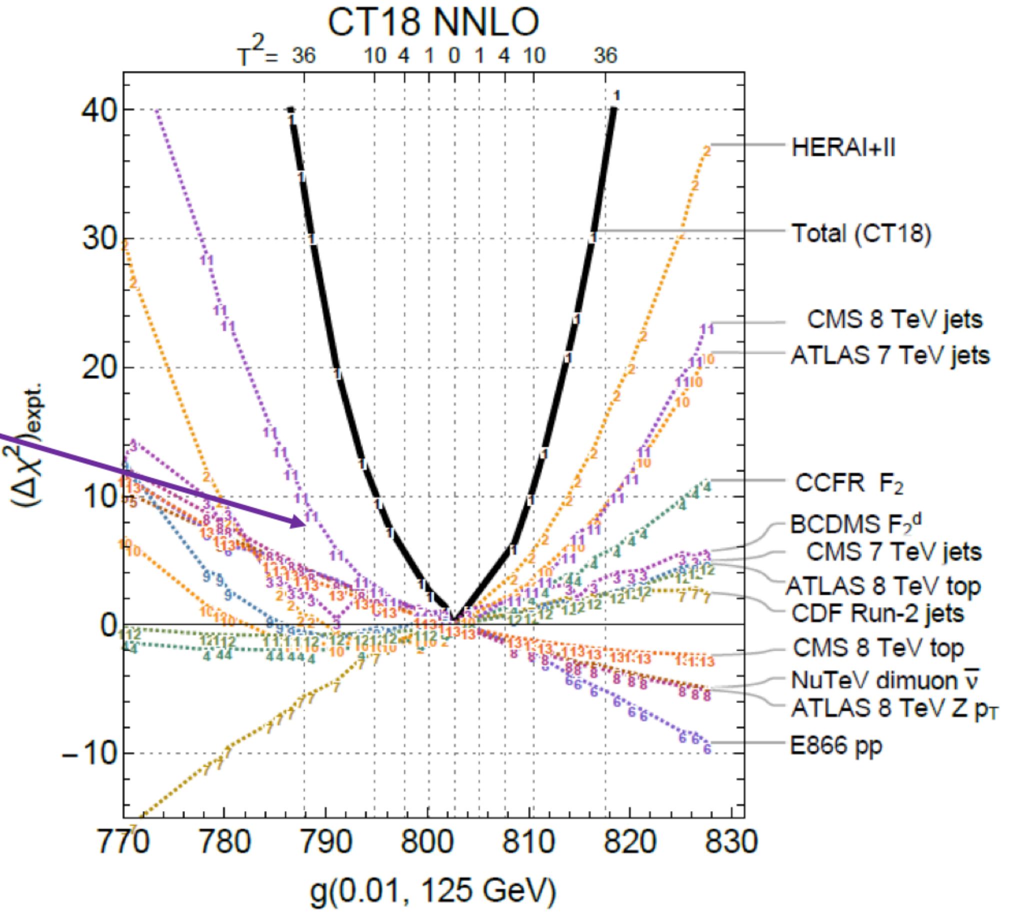
The importance of an experiment for a particular PDF depends not only on the correlation of the cross section with that PDF, but the degree to which the cross section can determine that PDF.

- Typically used with Hessian, but can also be defined for the MC PDF approach

Compare to LM scans

(focus on CMS 8 TeV jets, IDs=545 and 11)





Project: many LHC data sets have bad χ^2 and/or need systematic error Decorrelation to achieve acceptable χ^2

Some of these data sets are not used by global PDF fits because of this

Use L_2 sensitivity to see how the PDF information is/is not degraded before decorrelation

PDF wish list for systematic uncertainties

A proposal

1. More complete representations for experimental likelihoods that do not need reverse engineering
2. Agreed-upon nomenclature for leading syst. sources
3. Is reducing dimensionality of published correlation matrices advisable? Is their a standard for it? E.g., fewer nuisance parameters; collect less relevant/certain nuisance parameters into one uncorrelated error; etc.
4. Mathematical consistency of covariance/correlation matrices (see Z. Kassabov et al.)
5. How do different implementations of syst. errors affect pulls on PDFs? L_2 sensitivities to nuisance parameters
6. …

Final remarks

Epistemic uncertainty (due to parametrization, methodology, parametrization/NN architecture, smoothness, data tensions, model for syst. errors, ...) is increasingly important in NNLO global fits as experimental and theoretical uncertainties decrease

Nominal PDF uncertainties in high-stake measurements (ATLAS W mass, Higgs cross sections…) thus should be tested for *control of tensions* and *robustness of sampling over acceptable methodologies.*

Smoothness of Hessian and NN PDFs is another such aspect associated with the prior that should be explored.

Such tests can be done outside of the PDF fits.

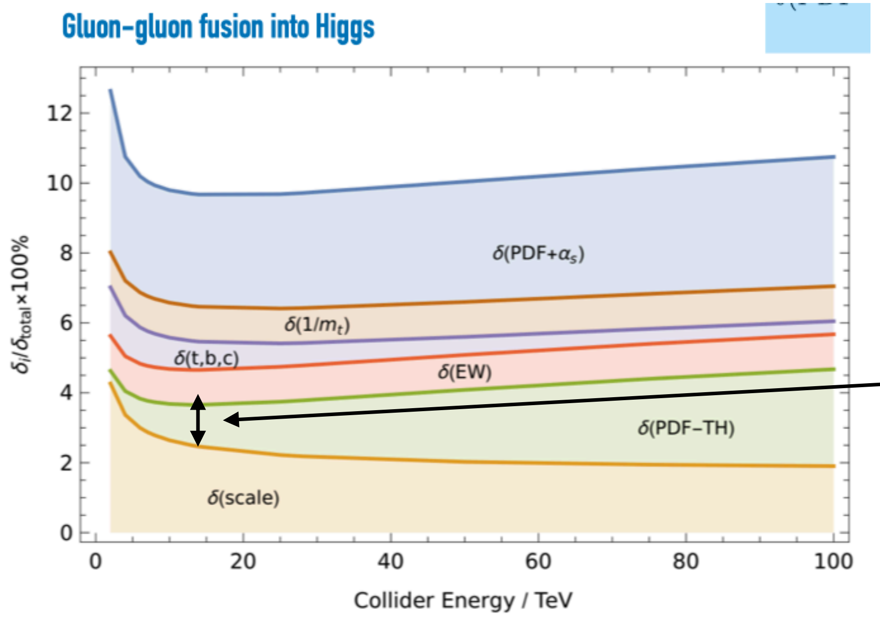
Tools for such studies exist using published PDFs and codes: L_2 sensitivities and hopscotch scans.

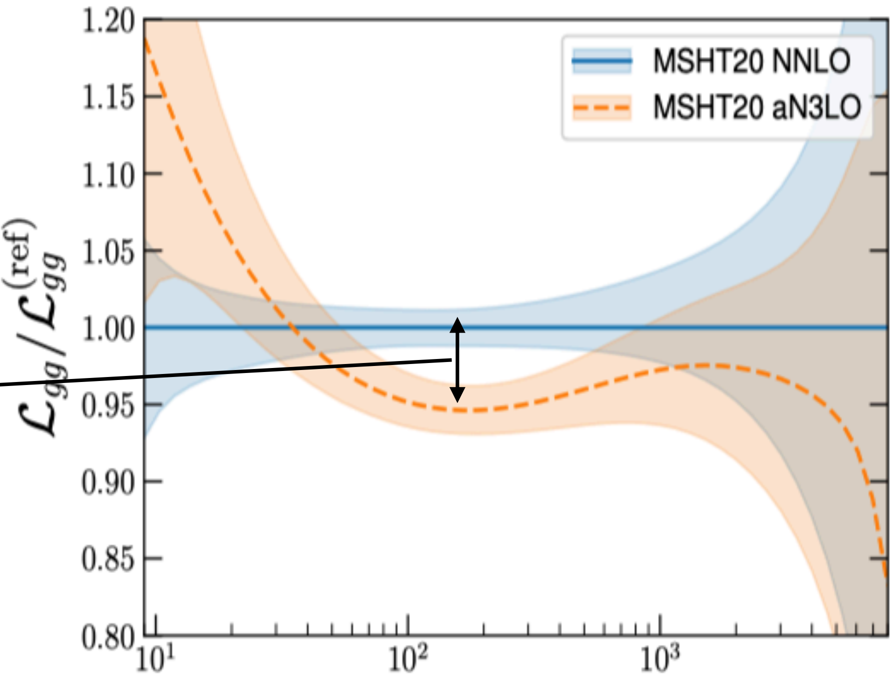
This is also necessary for combination of PDFs including data correlations
[LHC EW, Jet & Vector boson WGs, https://tinyurl.com/4wcnd8xn; https://tinyurl.com/2p8d8ba3; https://tinyurl.com/2p8tcn5b; Ball, Forte, Stegeman, arXiv:2110.08274].

The ambiguity in NNLO PDFs due to the χ^2 definition is significant. Must consider better formats to propagate experimental likelihoods into the PDF uncertainties. *[See also Cranmer, Prosper, et al., arXiv:2109.04981].*

Impact of aN3LO

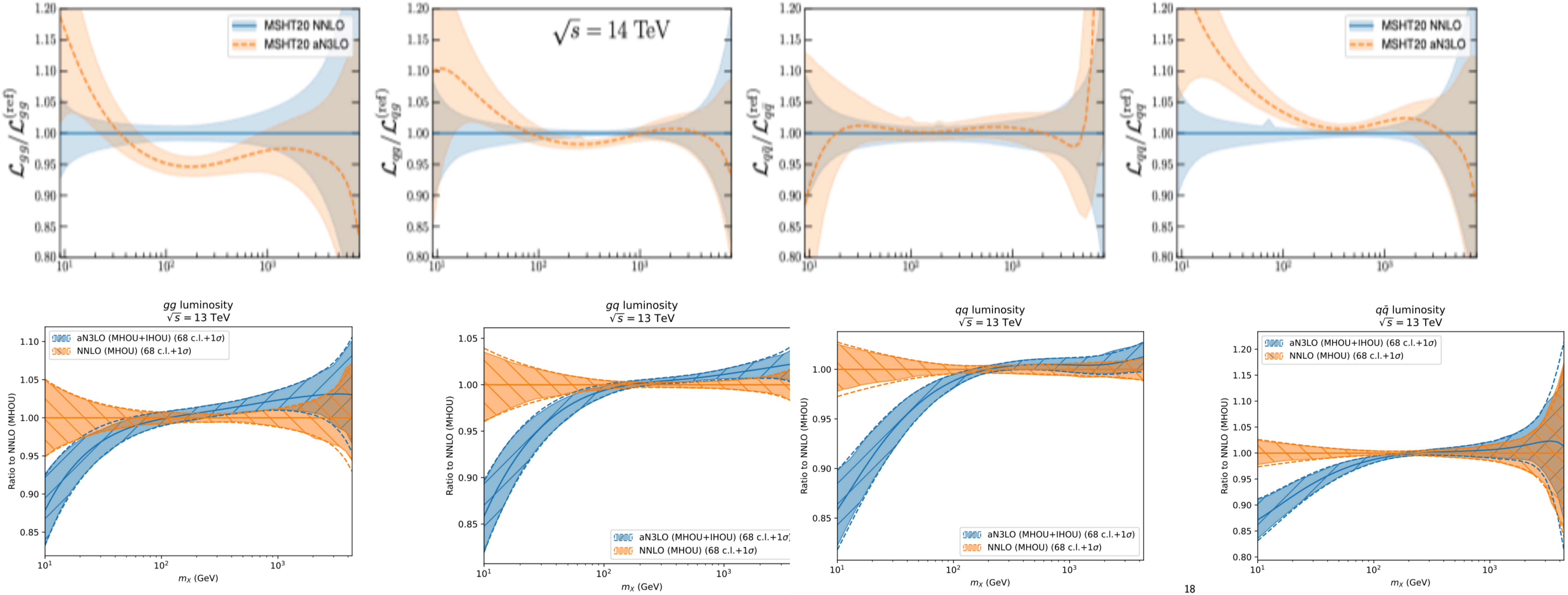
- gg PDF luminosity at aN3LO (MSHT20) at Higgs mass ~5% lower than nominal NNLO MSHT20
- If correct, then our benchmark cross sections for ggF are wrong





- How robust are the aN3LO PDFs, and in particular the splitting functions?

aN3LO PDF luminosities:

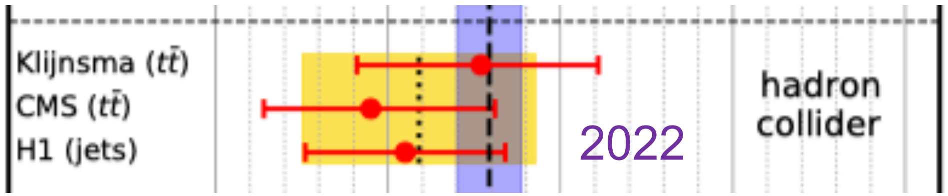


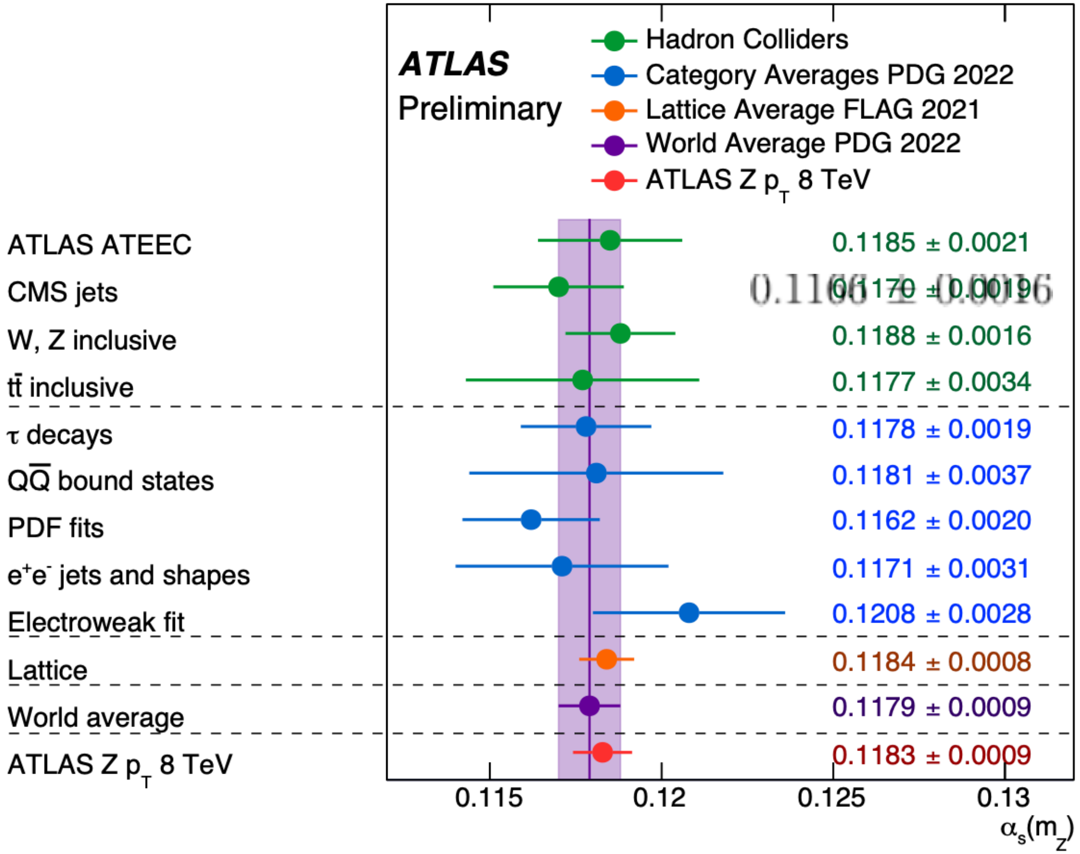
Note different color schemes for the two predictions.

Gluon differences possibly due to differences in P_{gg} splitting functions? Needs more investigation.

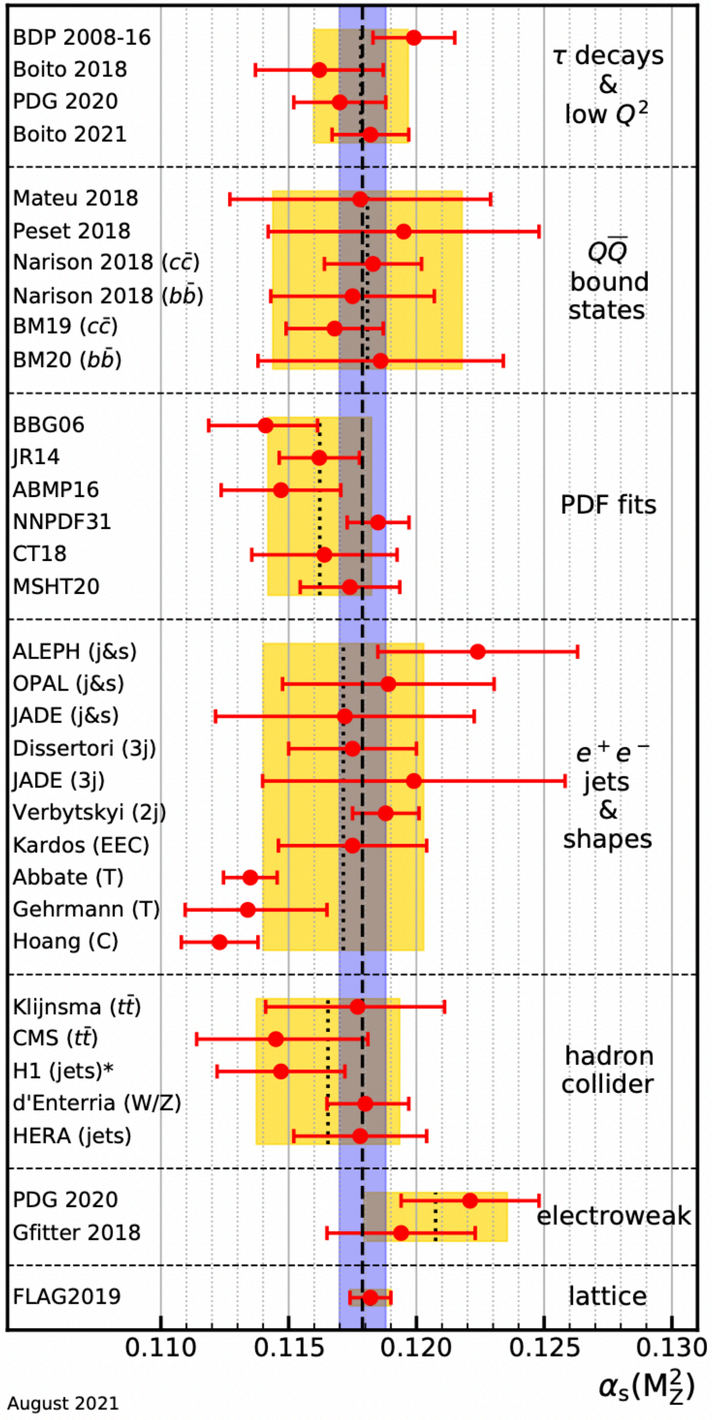
Collider measurements of α_s

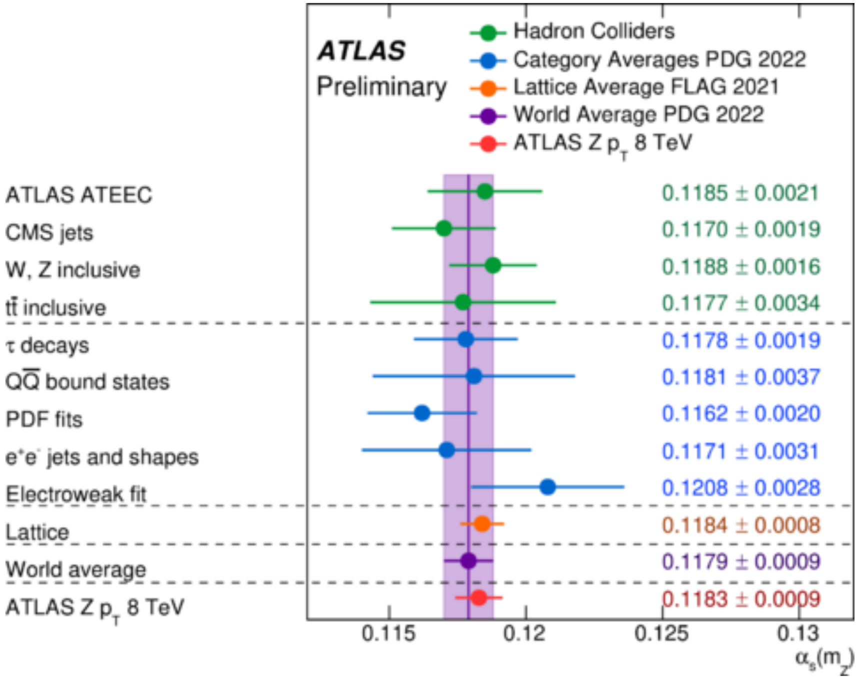
- As the number of NNLO calculations has increased, there have been a growing number of determinations of $\alpha_s(m_Z)$ at that order (or higher) from the LHC experiments that have nominal uncertainties that rival the full world average uncertainty
  - Z p_T
  - event shapes
- It would be nice to understand those uncertainties better, especially if PDF uncertainties are taken into account





N^3LL+N^3LO →





ATLAS-CONF-2023-015

Experimental uncertainty	+0.00044	-0.00044
PDF uncertainty	+0.00051	-0.00051
Scale variations uncertainties	+0.00042	-0.00042
Matching to fixed order	0	-0.00008
Non-perturbative model	+0.00012	-0.00020
Flavour model	+0.00021	-0.00029
QED ISR	+0.00014	-0.00014
N4LL approximation	+0.00004	-0.00004
Total	+0.00084	-0.00088

PDF set	$\alpha_s(m_Z)$	PDF uncertainty	g [GeV^2]	q [GeV^4]	χ^2/dof
MSHT20 [32]	0.11839	0.00040	0.44	-0.07	96.0 /69
NNPDF40 [78]	0.11779	0.00024	0.50	-0.08	116.0/69
CT18A [79]	0.11982	0.00050	0.36	-0.03	97.7 /69
HERAPDF20 [63]	0.11890	0.00027	0.40	-0.04	132.3/69

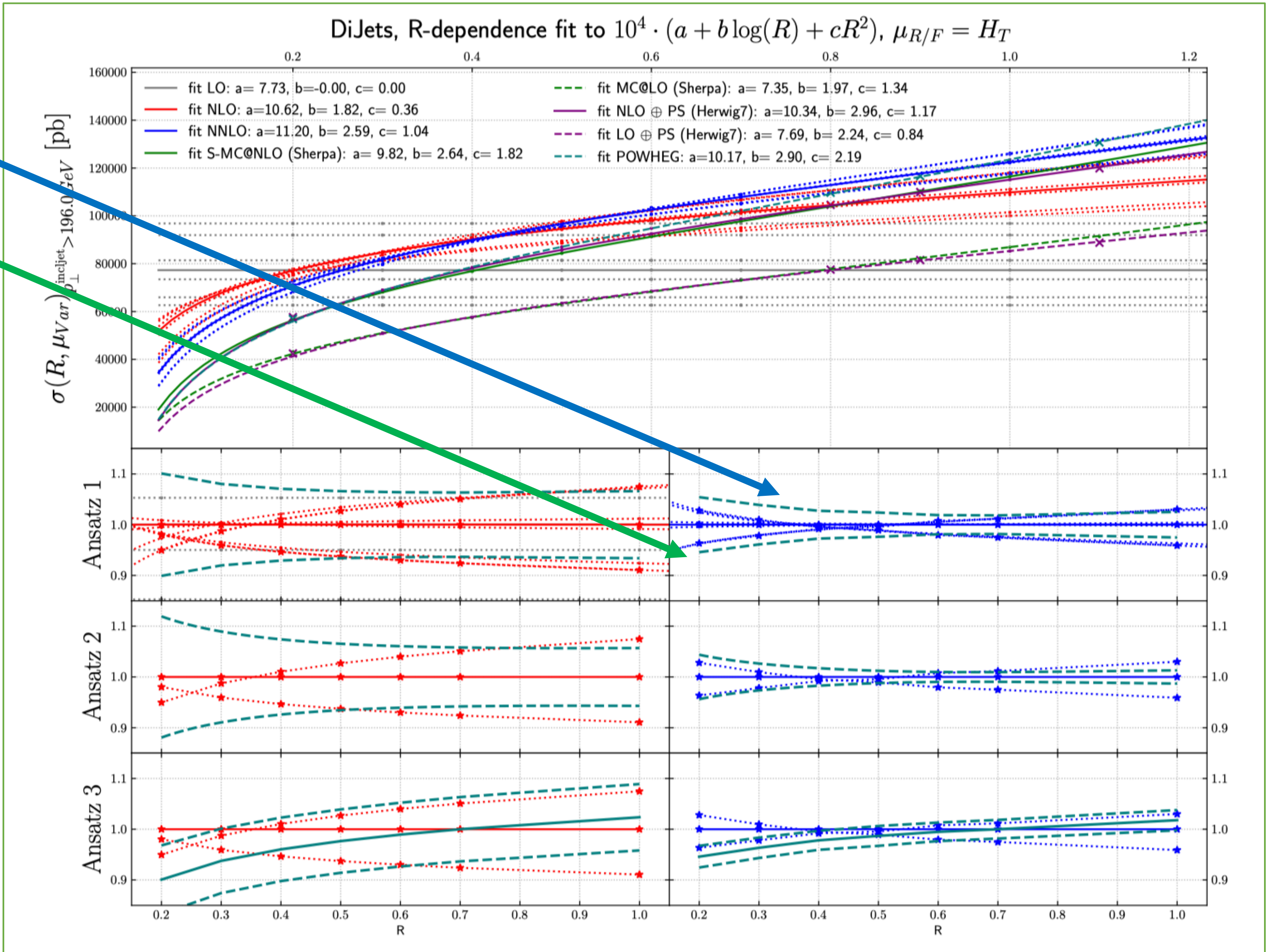
revisit PDF uncertainties and interplay in fits

New LHC results that can potentially be included in a world average

Exp.	$\sqrt{s}$ / TeV	Lumi / fb^{-1}	Theory	Obs.	$\alpha_s(M_Z)$	$\Delta\alpha_s$ exp	$\Delta\alpha_s$ oth	$\Delta\alpha_s$ scl	Ref.
CMS	13	33.5	NNLO	Jet pT	0.1166	14 (NP)	7	4	JHEP12 (2022) 035
ATLAS	13	139	NNLO	TEEC	0.1175	6	12	+32 -11	2301.09351
ATLAS	13	139	NNLO	ATEEC	0.1185	9	11	+22 -2	2301.09351
CMS	13	36.3	NNLO	2D m_{jj}	0.1201	12 (NP)	9	8	SMP-21-008
CMS	13	36.3	NNLO	3D m_{jj}	0.1201	10 (NP)	10	5	SMP-21-008
ATLAS	8	20.2	N4LLa+ N3LO	Z pT	0.1183	4	6	4	CONF-2023-015

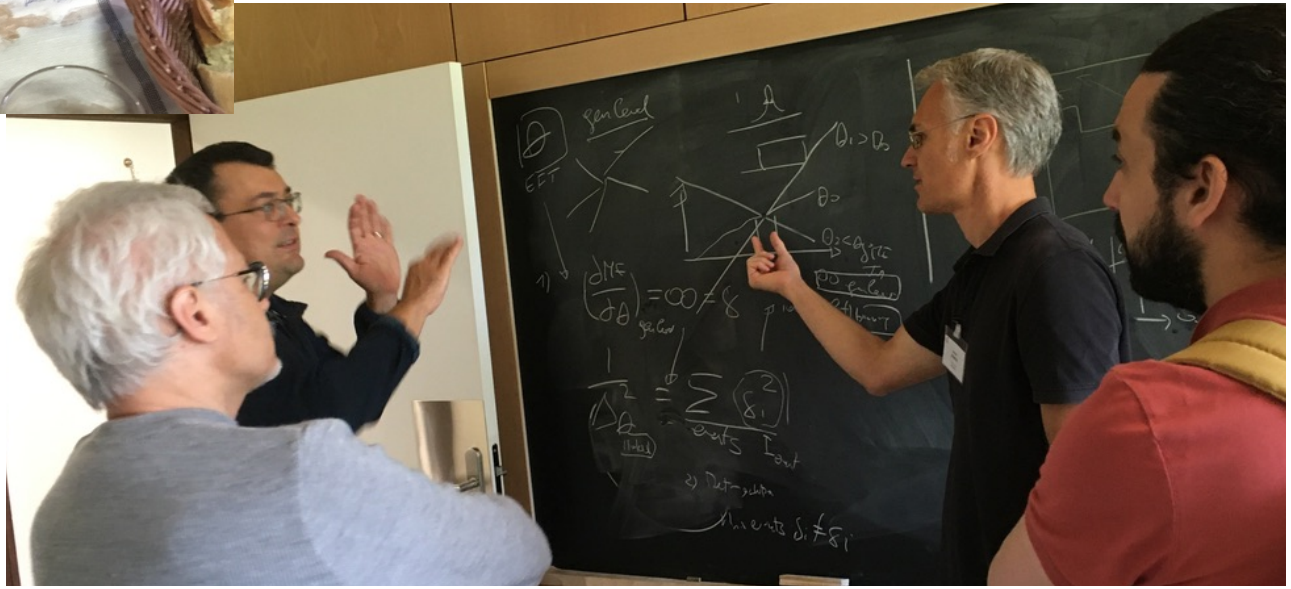
Jet algorithms: arXiv:1903.12563 (LH17)

- 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?**
- Didn't have time to further pursue this at Les Houches, but it will be an ongoing project.



Thank you

for the great time here



including some unexpected developments ☺