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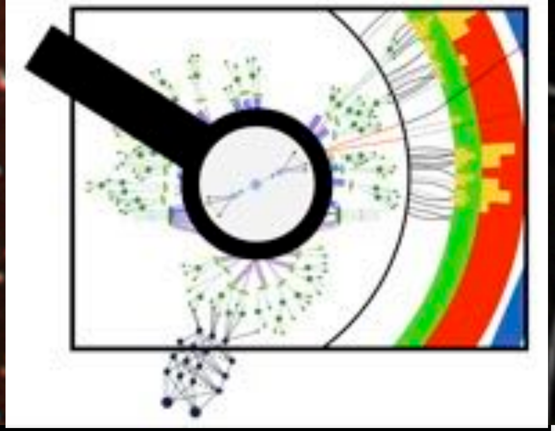
8 March - 21 May 2021

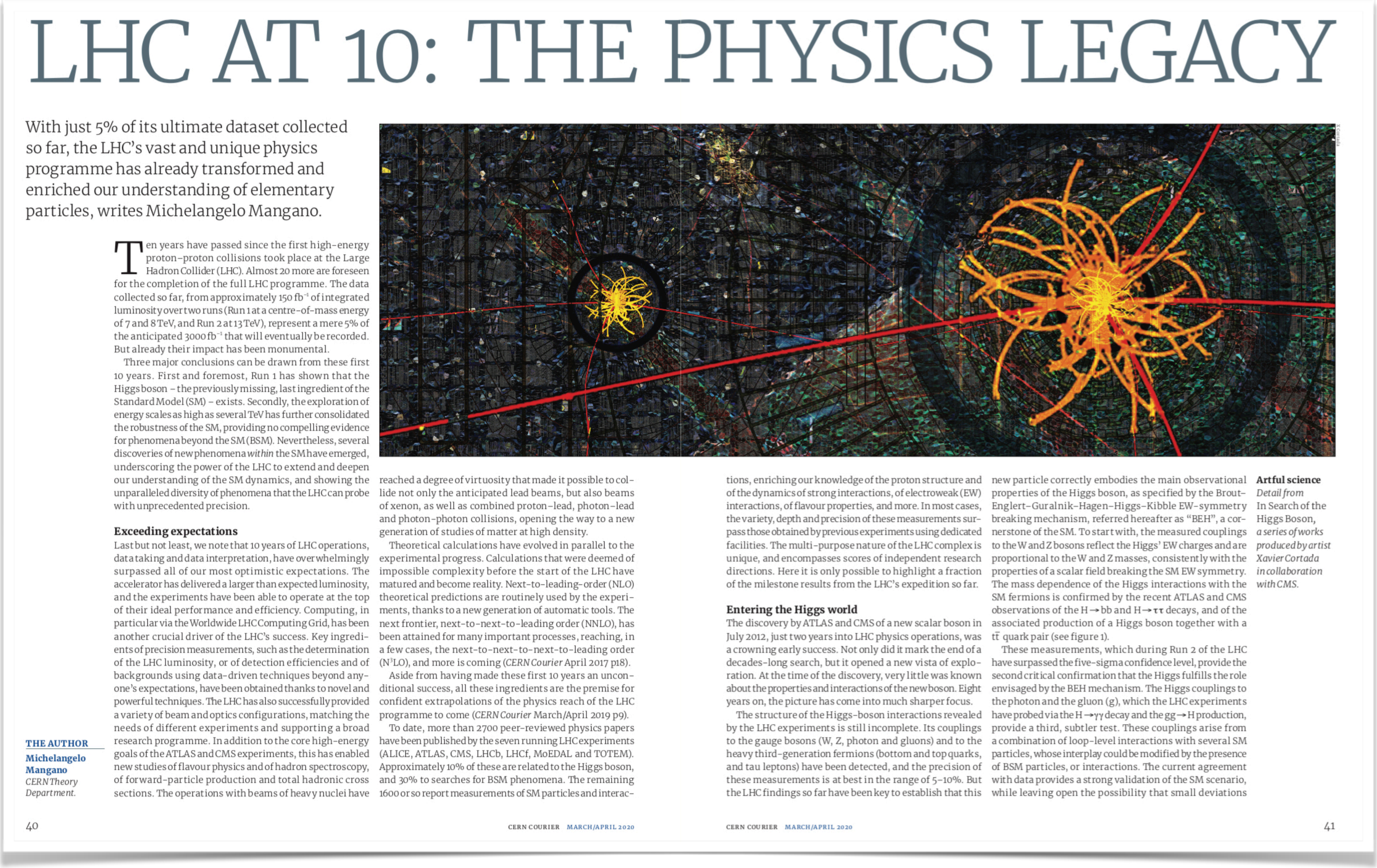


New Physics from Precision at High Energies
8 March - 21 May 2021

New physics and precision: a personal perspective

Michelangelo L. Mangano
Theory Department, CERN, Geneva

CERN Courier March/April 2020
https://arxiv.org/abs/2003.05976



LHC AT 10: THE PHYSICS LEGACY

With just 5% of its ultimate dataset collected so far, the LHC's vast and unique physics programme has already transformed and enriched our understanding of elementary particles, writes Michelangelo Mangano.

Ten years have passed since the first high-energy proton–proton collisions took place at the Large Hadron Collider (LHC). Almost 20 more are foreseen for the completion of the full LHC programme. The data collected so far, from approximately 150 fb^{-1} of integrated luminosity over two runs (Run 1 at a centre-of-mass energy of 7 and 8 TeV, and Run 2 at 13 TeV), represent a mere 5% of the anticipated 3000 fb^{-1} that will eventually be recorded. But already their impact has been monumental.

Three major conclusions can be drawn from these first 10 years. First and foremost, Run 1 has shown that the Higgs boson – the previously missing, last ingredient of the Standard Model (SM) – exists. Secondly, the exploration of energy scales as high as several TeV has further consolidated the robustness of the SM, providing no compelling evidence for phenomena beyond the SM (BSM). Nevertheless, several discoveries of new phenomena *within* the SM have emerged, underscoring the power of the LHC to extend and deepen our understanding of the SM dynamics, and showing the unparalleled diversity of phenomena that the LHC can probe with unprecedented precision.

Exceeding expectations

Last but not least, we note that 10 years of LHC operations, data taking and data interpretation, have overwhelmingly surpassed all of our most optimistic expectations. The accelerator has delivered a larger than expected luminosity, and the experiments have been able to operate at the top of their ideal performance and efficiency. Computing, in particular via the Worldwide LHC Computing Grid, has been another crucial driver of the LHC's success. Key ingredients of precision measurements, such as the determination of the LHC luminosity, or of detection efficiencies and of backgrounds using data-driven techniques beyond anyone's expectations, have been obtained thanks to novel and powerful techniques. The LHC has also successfully provided a variety of beam and optics configurations, matching the needs of different experiments and supporting a broad research programme. In addition to the core high-energy goals of the ATLAS and CMS experiments, this has enabled new studies of flavour physics and of hadron spectroscopy, of forward-particle production and total hadronic cross sections. The operations with beams of heavy nuclei have reached a degree of virtuosity that made it possible to collide not only the anticipated lead beams, but also beams of xenon, as well as combined proton–lead, photon–lead and photon–photon collisions, opening the way to a new generation of studies of matter at high density.

Theoretical calculations have evolved in parallel to the experimental progress. Calculations that were deemed of impossible complexity before the start of the LHC have matured and become reality. Next-to-leading-order (NLO) theoretical predictions are routinely used by the experiments, thanks to a new generation of automatic tools. The next frontier, next-to-next-to-leading order (NNLO), has been attained for many important processes, reaching, in a few cases, the next-to-next-to-next-to-leading order (N^{3}LO), and more is coming (*CERN Courier* April 2017 p18).

Aside from having made these first 10 years an unconditional success, all these ingredients are the premise for confident extrapolations of the physics reach of the LHC programme to come (*CERN Courier* March/April 2019 p9).

To date, more than 2700 peer-reviewed physics papers have been published by the seven running LHC experiments (ALICE, ATLAS, CMS, LHCb, LHCf, MoEDAL and TOTEM). Approximately 10% of these are related to the Higgs boson, and 30% to searches for BSM phenomena. The remaining 1600 or so report measurements of SM particles and interactions, enriching our knowledge of the proton structure and of the dynamics of strong interactions, of electroweak (EW) interactions, of flavour properties, and more. In most cases, the variety, depth and precision of these measurements surpass those obtained by previous experiments using dedicated facilities. The multi-purpose nature of the LHC complex is unique, and encompasses scores of independent research directions. Here it is only possible to highlight a fraction of the milestone results from the LHC's expedition so far.

Entering the Higgs world

The discovery by ATLAS and CMS of a new scalar boson in July 2012, just two years into LHC physics operations, was a crowning early success. Not only did it mark the end of a decades-long search, but it opened a new vista of exploration. At the time of the discovery, very little was known about the properties and interactions of the new boson. Eight years on, the picture has come into much sharper focus.

The structure of the Higgs-boson interactions revealed by the LHC experiments is still incomplete. Its couplings to the gauge bosons (W, Z, photon and gluons) and to the heavy third-generation fermions (bottom and top quarks, and tau leptons) have been detected, and the precision of these measurements is at best in the range of 5–10%. But the LHC findings so far have been key to establish that this new particle correctly embodies the main observational properties of the Higgs boson, as specified by the Brout–Englert–Guralnik–Hagen–Higgs–Kibble EW-symmetry breaking mechanism, referred hereafter as "BEH", a cornerstone of the SM. To start with, the measured couplings to the W and Z bosons reflect the Higgs' EW charges and are proportional to the W and Z masses, consistently with the properties of a scalar field breaking the SM EW symmetry. The mass dependence of the Higgs interactions with the SM fermions is confirmed by the recent ATLAS and CMS observations of the $H \rightarrow bb$ and $H \rightarrow \tau\tau$ decays, and of the associated production of a Higgs boson together with a $t\bar{t}$ quark pair (see figure 1).

These measurements, which during Run 2 of the LHC have surpassed the five-sigma confidence level, provide the second critical confirmation that the Higgs fulfills the role envisaged by the BEH mechanism. The Higgs couplings to the photon and the gluon (g), which the LHC experiments have probed via the $H \rightarrow \gamma\gamma$ decay and the $gg \rightarrow H$ production, provide a third, subtler test. These couplings arise from a combination of loop-level interactions with several SM particles, whose interplay could be modified by the presence of BSM particles, or interactions. The current agreement with data provides a strong validation of the SM scenario, while leaving open the possibility that small deviations

Artful science *Detail from* In Search of the Higgs Boson, *a series of works produced by artist Xavier Cortada in collaboration with CMS.*

THE AUTHOR
Michelangelo Mangano
CERN Theory Department.

The precision power of the LHC, its experiments, and TH input

- measured so far all that's been measurable!
- robust simulation of detector performance, complemented by huge statistics to enable data-driven determination of bgs and systematics
- accurate luminosity, O(< 2%) => absolute measurements
- large dynamic range, to challenge production dynamics and theoretical understanding/modeling over an immense range of configurations
- redundancy/synergy: measurements help other measurements (eg some data generate PDF constraints, which benefit other studies)
- greater reliance on ever more precise theoretical calculations
- unprecedented engagement of the TH community to improve the modeling, the interpretation, the planning:
  - re-interpretation tools, simplified models, EFT, …
- the Higgs exists, although nothing else beyond the SM showed up …
  - … but the spectrum of physics emerged from the LHC is far richer than expected !

LHC scientific production

About 3000 papers published/submitted to refereed journals by the 7 experiments (ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM, MoEDAL)

Of these:

~10% on Higgs (15% if ATLAS+CMS only)

~30% on searches for new physics (35% if ATLAS+CMS only)

~60% of the papers on SM measurements (jets, EW, top, b, HIs, …)

soon to be enriched by new experiments, expanding the physics programme and the reach (FASER, FASERnu, SND@LHC)

Not only Higgs and BSM !

and all of this, and more, falls under the domain of "precision" :

Flavour physics

- $B_{(s)} \to \mu\mu$
- D mixing and CP violation in the D system
- Measurement of the γ angle, CPV phase φ_s, …
- Lepton flavour universality in charge- and neutral-current semileptonic B decays => possible anomalies ?

QCD dynamics

- Countless precise measurements of hard cross sections, and improved determinations of the proton PDF
- Measurement of total, elastic, inelastic pp cross sections at different energies, new inputs for the understanding of the dominant reactions in pp collisions
- Exotic spectroscopy: discovery and study of new tetra- and penta-quarks, doubly heavy baryons, expected sensitivity to glueballs
- Discovery of QGP-like collective phenomena (long-range correlations, strange and charm enhancement, …) in "small" systems (pA and pp)

EW param's and dynamics

- m_W, m_{top}, $\sin^2\theta_W$
- EW interactions at the TeV scale (DY, VV, VVV, VBS, VBF, Higgs, …)

Remarks

- These 3000 papers reflect the underlying existence, at the LHC, of 100's of scientifically "independent" experiments, which historically would have required different detectors and facilities, built and operated by different communities

- On each of these topics the LHC expts are advancing the knowledge previously acquired by dedicated facilities
  - HERA → PDFs, B-factories → flavour, RHIC → HIs, LEP/SLC → EWPT, etc

- Even in the perspective of new dedicated facilities, eg SuperKEKB or EIC, LHC maintains a key role of competition and complementarity

I have a broad concept of "*new physics*", which includes SM phenomena, emerging from the data, that are unexpected, surprising, or simply poorly understood.

I consider as "new", and as a discovery, everything that is not obviously predictable, or that requires deeper study to be clarified, even if it belongs to the realm of SM phenomena.

From the concluding paragraph of the Courier article

The terms precision and discovery, applied to concrete results rather than projections, well characterise the LHC 10-year legacy. Precision is the keystone to consolidate our description of nature, increase the sensitivity to SM deviations, give credibility to discovery claims, and to constrain models when evaluating different microscopic origins of possible anomalies. The LHC has already fully succeeded in these goals.

The LHC has also proven to be a discovery machine, and in a context broader than just Higgs and BSM phenomena. Altogether, it delivered results that could not have been obtained otherwise, immensely enriching our understanding of nature.

On the value of measurements and precision

- Aside from exceptional moments in the development of the field, research is not about proving a theory is right or wrong, it's about finding out how things work
- We do not measure Higgs couplings precisely to **find** deviations from the SM. We measure them to **know** them!
- LEP's success was establishing SM's amazing predictive power!
- *Precision for the sake of it is not necessarily justified. Improving X10 the precision on m(electron) or m(proton) is not equivalent to improving X10 the Higgs couplings:*
  - *m(e) => just a parameter; m(p)=> just QCD dynamics; Higgs couplings => ???*
- … and who knows how important a given measurement can become, to assess the validity of a future theory?
  - the day some BSM signal is found somewhere, the available precision measurements, will be crucial to establish the nature of the signal, whether they agree or deviate from the SM

Having said that, there is no doubt that the intrinsic hope of each precision measurement IS to find deviations from the SM …

But, in practice, what do we do when precision data disagree with precise expectations, or among themselves ?

There are plenty of such deviations in HEP:

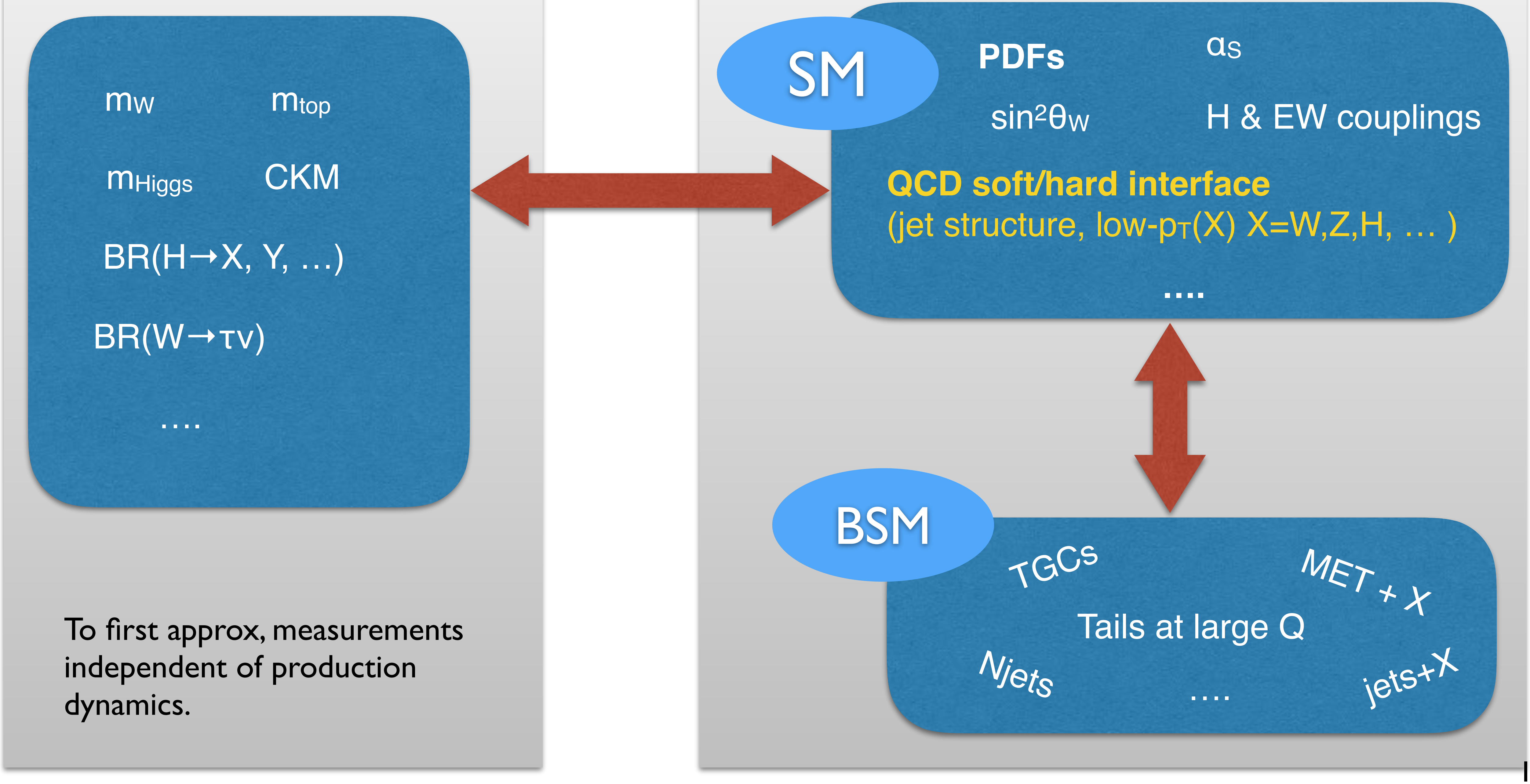
- $(g-2)_\mu$, $(g-2)_e$
- Several independent observables in charged and neutral-current B meson semileptonic decays (angular distributions, lepton flavour universality)
- $\sin^2\theta_{eff}$ from A^b_{FB} and A^e_{LR}
- ε'/ε, CKM unitarity,
- neutron lifetime puzzle ($\tau_{beam} > \tau_{bottle}$ @ 4σ)
- …

We've never dealt with indirect BSM discoveries at colliders, and it's not clear how we'll react to, eg, a small BR deviation in Higgs decays, or in jet cross sections.

The best we can do is to build the tools and the experience to validate predictions, and confirm deviations. A lot of physics will be learned along the way.

This talk focuses on this aspect of the relation precision vs new physics

The landscape of precision measurements



SM parameters and particle properties

m_W m_{top}

m_{Higgs} CKM

BR($H \to X, Y, \ldots$)

BR($W \to \tau\nu$)

….

To first approx, measurements independent of production dynamics.

Cross sections and differential distribution measurements

SM

PDFs α_S

$\sin^2\theta_W$ H & EW couplings

QCD soft/hard interface

(jet structure, low-$p_T(X)$ X=W,Z,H, …)

….

BSM

TGCs

MET + X

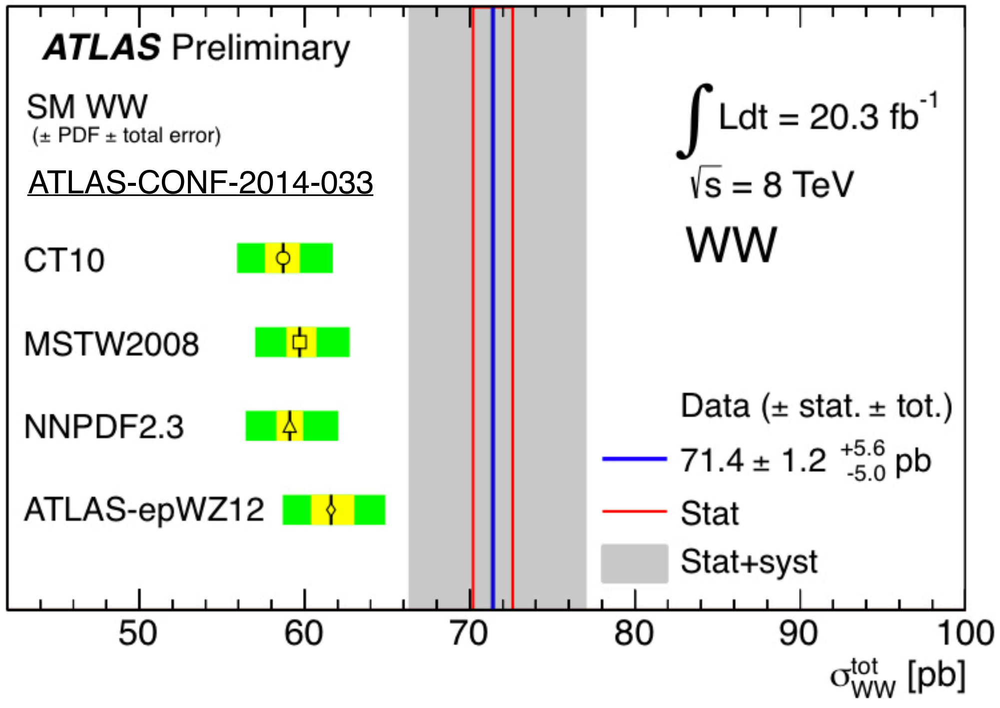
Tails at large Q

Njets

….

jets+X

Early run 1 σ(WW) measurements



CMS @ 8 TeV Phys.Lett.B 721 (2013) 190

$$\sigma_{CMS}(pp \to W^+W^-) = 69.9 \pm 2.8_{stat} \pm 5.6_{syst} \pm 3.1_{lum}\ \text{pb}$$

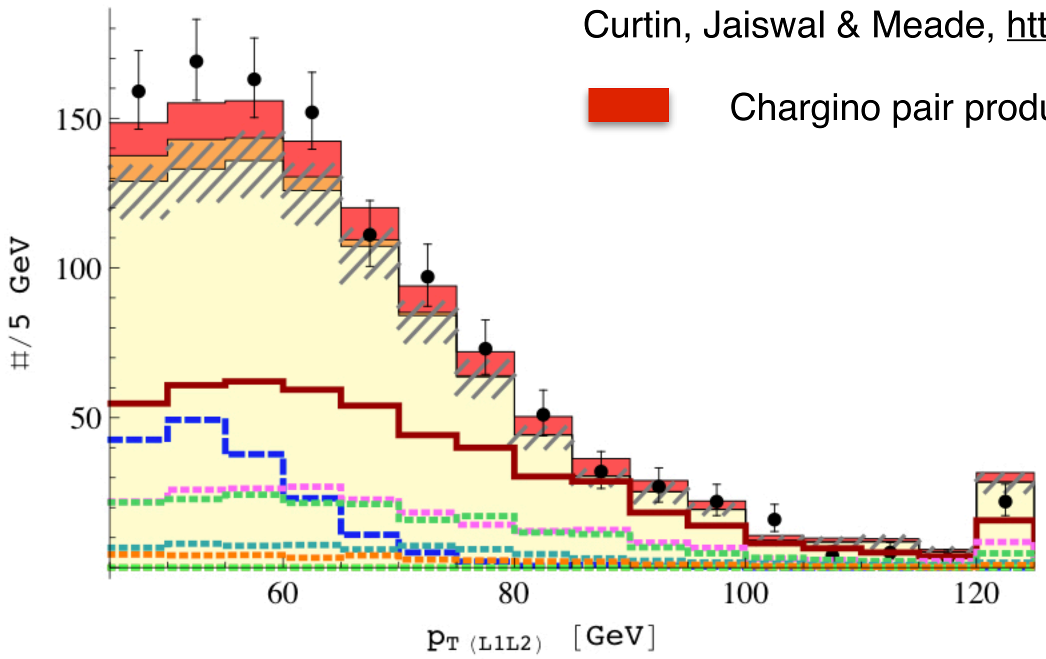
$$\sigma_{NLO}(pp \to W^+W^-) = 57.3 \begin{array}{c} +2.3 \\ -1.6 \end{array} \text{pb}$$

Similar discrepancies observed at 7 TeV

(ATLAS & CMS)

Δ(data/NLO, ATL+CMS) ~ 3 σ

perfect, well studied signature of SUSY chargino pair production!



Curtin, Jaiswal & Meade, https://arxiv.org/pdf/1206.6888.pdf

🟥 Chargino pair production, m(χ±) = 110 GeV

Further TH developments

higher-order / resummation effects on jet-veto efficiency

- impact on reconstruction of σ_{TOT} from σ_{FID}
- strong reduction of data/TH discrepancy

Meade, Ramani & Zeng, http://arxiv.org/abs/1407.4481
Jaiswal & Okui, http://arxiv.org/abs/1407.4537
Monni & Zanderighi, http://arxiv.org/abs/1410.4745

Enters NNLO Gehrmann et al, http://arxiv.org/abs/1408.5243

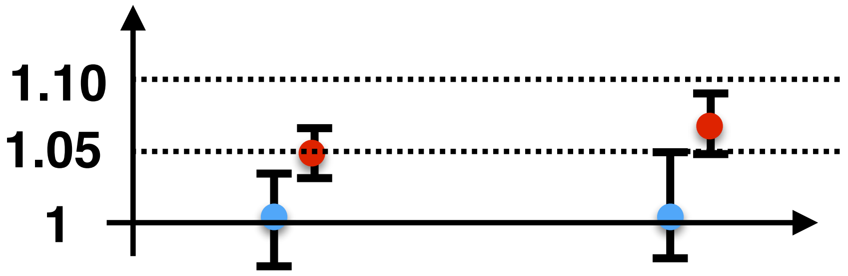
inclusive

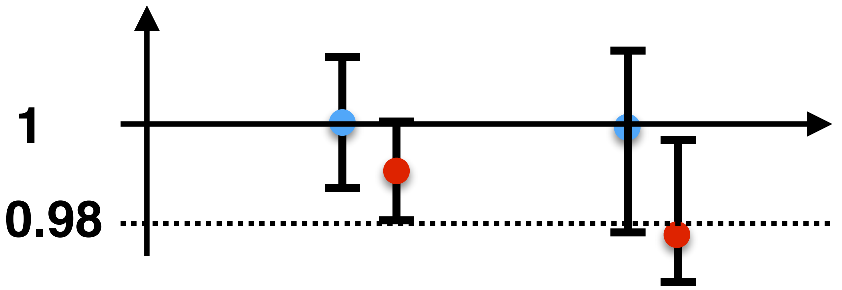
NLO' = NLO w. NNLO PDF

	$\sigma_{\text{inclusive}}$ [fb]		$\sigma/\sigma_{\text{NLO}} - 1$	
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
LO	$425.41(4)^{+2.8\%}_{-3.6\%}$	$778.99\ (8)^{+5.7\%}_{-6.7\%}$	-31.8%	-35.4%
NLO	$623.47(6)^{+3.6\%}_{-2.9\%}$	$1205.11(12)^{+3.9\%}_{-3.1\%}$	0	0
NLO′	$635.95(6)^{+3.6\%}_{-2.8\%}$	$1235.82(13)^{+3.9\%}_{-3.1\%}$	$+\ 2.0\%$	$+\ 2.5\%$
NLO′$+gg$	$655.83(8)^{+4.3\%}_{-3.3\%}$	$1286.81(13)^{+4.8\%}_{-3.7\%}$	$+\ 5.2\%$	$+\ 6.8\%$
NNLO	$690.4(5)^{+2.2\%}_{-1.9\%}$	$1370.9(11)^{+2.6\%}_{-2.3\%}$	$+10.7\%$	$+13.8\%$

fiducial

	$\sigma_{\text{fiducial}}(W^+W^-\text{-cuts})$ [fb]		$\sigma/\sigma_{\text{NLO}} - 1$	
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
LO	$147.23\ (2)^{+3.4\%}_{-4.4\%}$	$233.04(2)^{+6.6\%}_{-7.6\%}$	-3.8%	$-\ 1.3\%$
NLO	$153.07\ (2)^{+1.9\%}_{-1.6\%}$	$236.19(2)^{+2.8\%}_{-2.4\%}$	0	0
NLO’	$156.71\ (3)^{+1.8\%}_{-1.4\%}$	$243.82(4)^{+2.6\%}_{-2.2\%}$	$+2.4\%$	$+\ 3.2\%$
NLO’+gg	$166.41\ (3)^{+1.3\%}_{-1.3\%}$	$267.31(4)^{+1.5\%}_{-2.1\%}$	$+8.7\%$	$+13.2\%$
NNLO	$164.16(13)^{+1.3\%}_{-0.8\%}$	$261.5(2)^{+1.9\%}_{-1.2\%}$	$+7.2\%$	$+10.7\%$



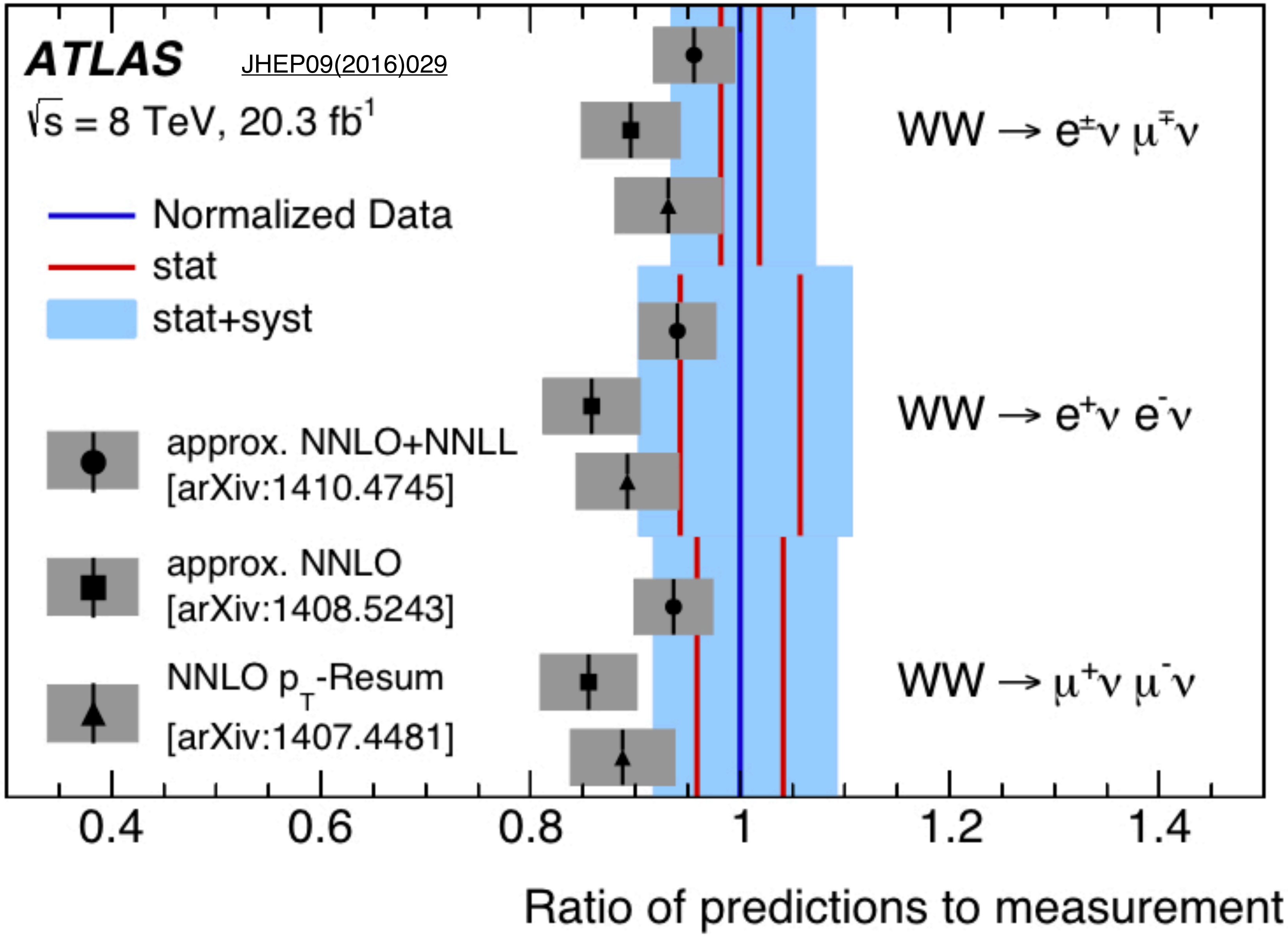


NNLO syst / [NLO’ + gg]

NLO’ + gg syst

Note: uncertainty estimate for NLO’+gg more reliable for fiducial than for inclusive rate

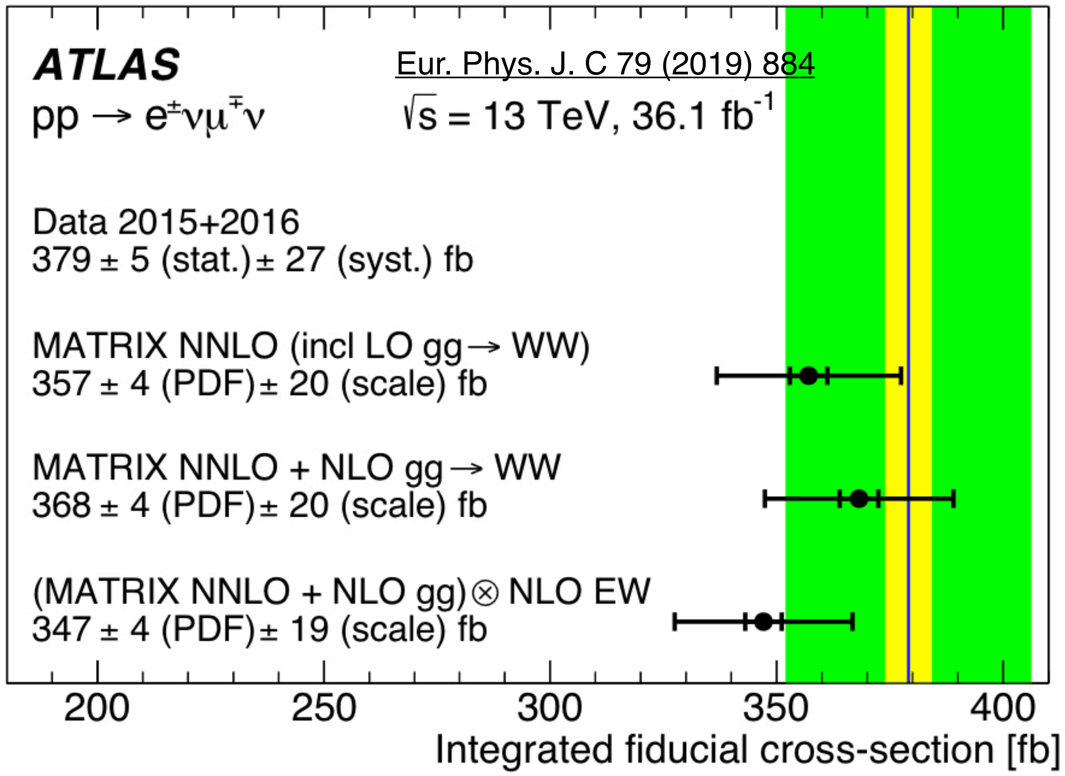
final 8 TeV comparison

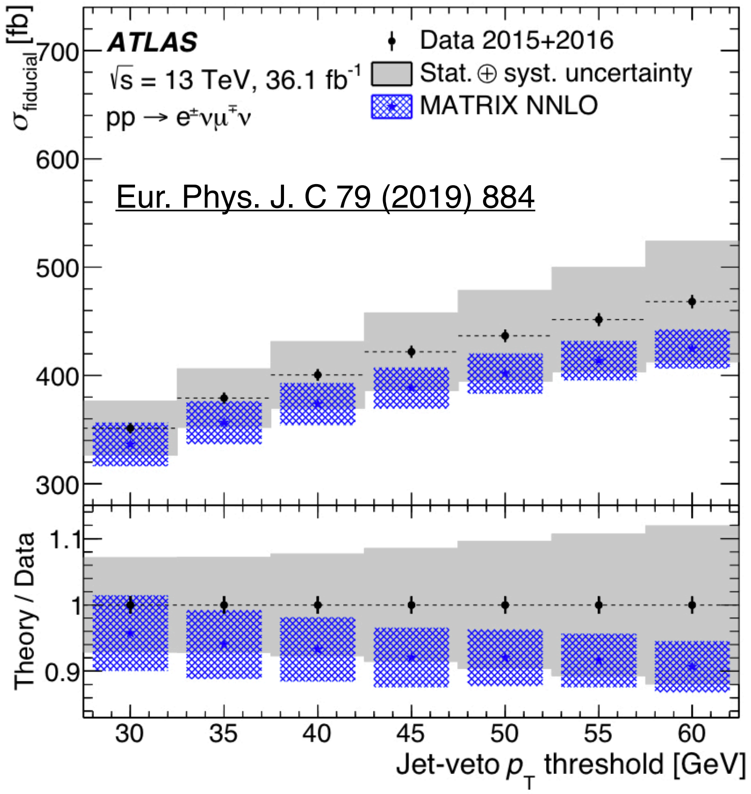


& similar agreement with CMS data

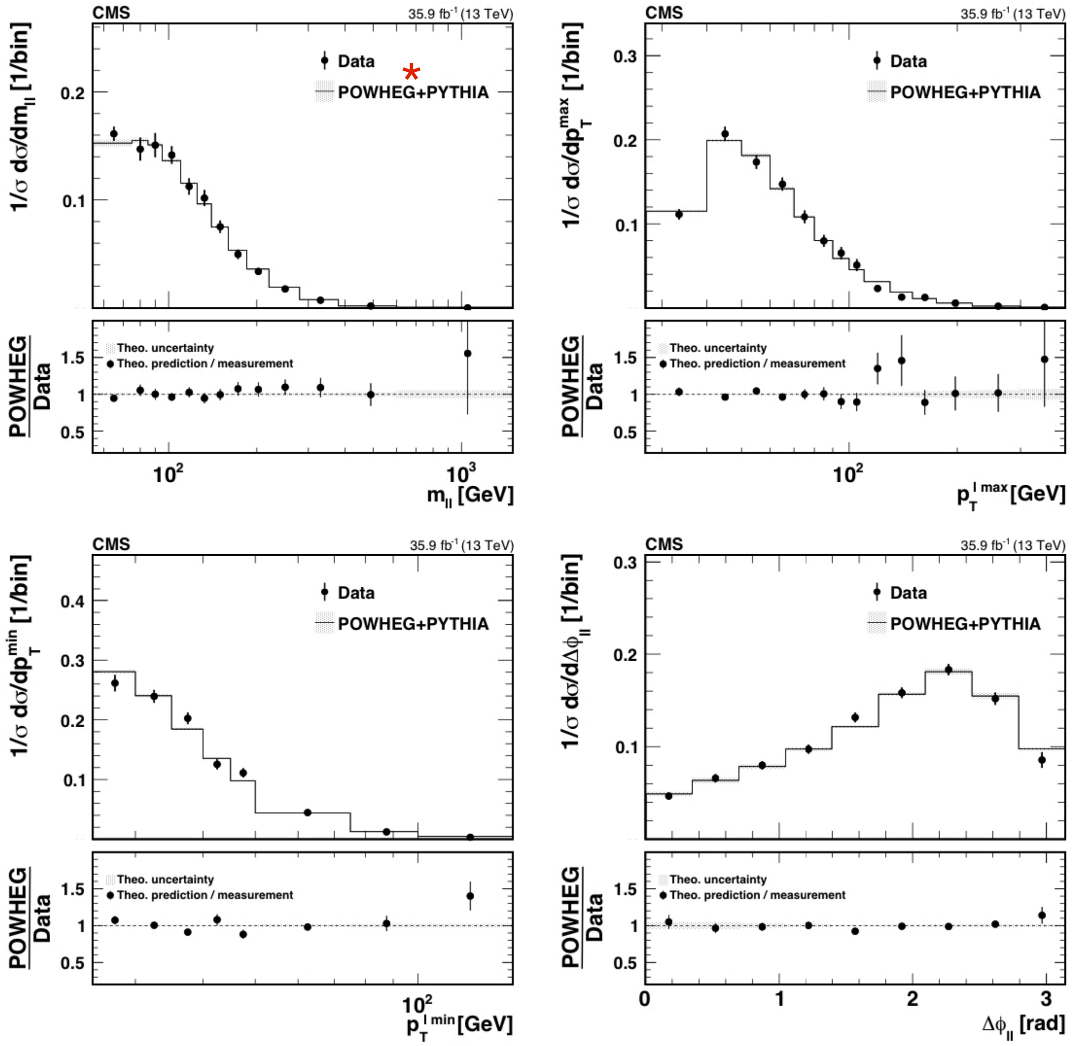
At 13 TeV

$\sigma_{\rm fid}$ = 1.53 ± 0.09 pb (CMS) vs 1.53 ± 0.04 pb (NNLO)

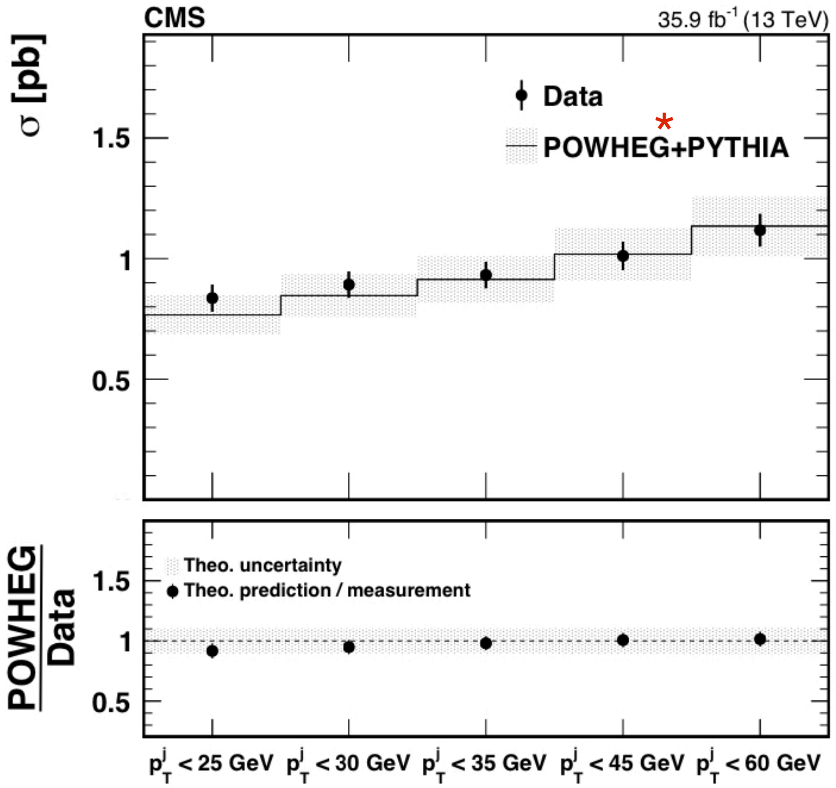




* POWHEG rewgt'd to NNLO



Phys.Rev.D 102 (2020) 9, 092001



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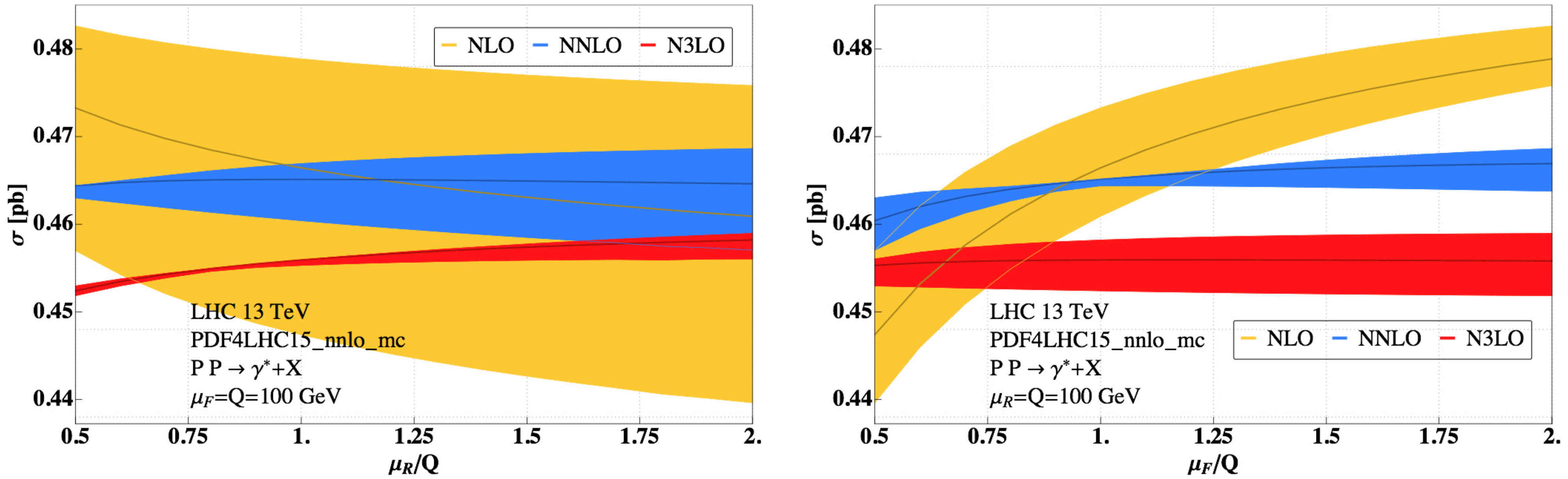
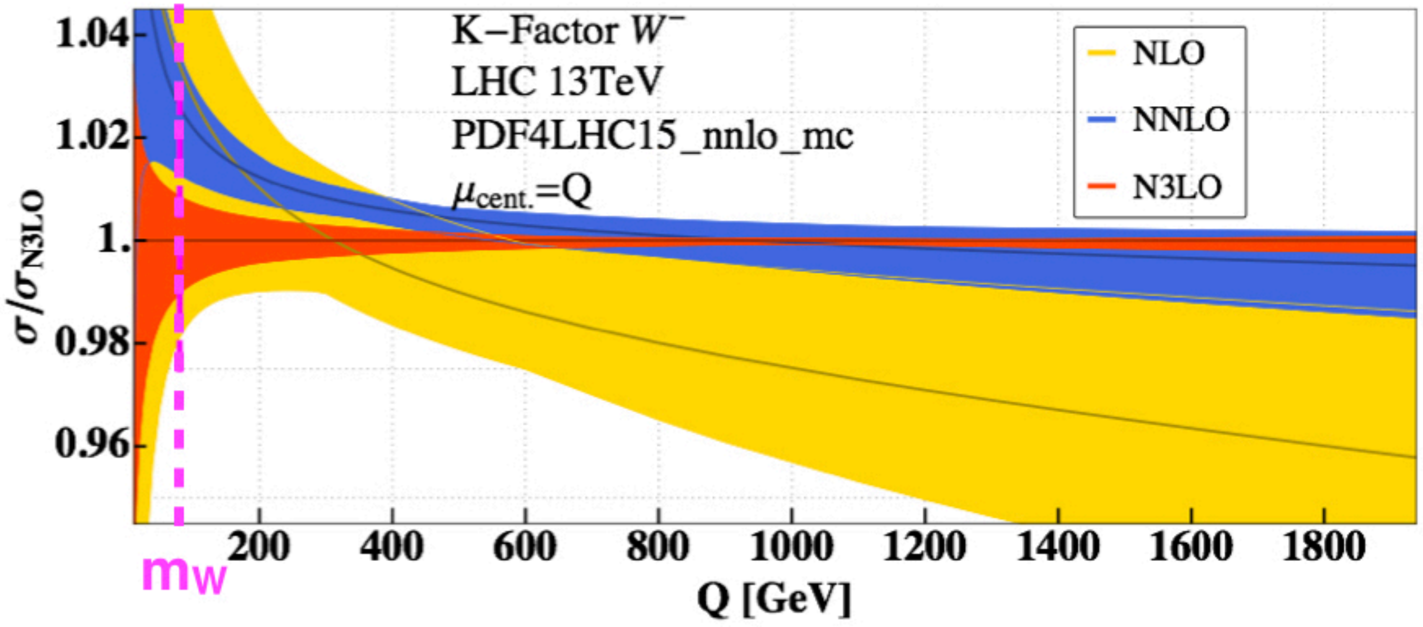
DY @ N^3LO

Duhr, Dulat, Mistlberger
arxiv:2001.07717 , arxiv:2007.13313

$pp \to \gamma^*$



$pp \to W$



- **$N^3LO \cap N^2LO = \varnothing$ at $Q=m_{W,Z}$, and up to Q=400 GeV ….**
- **Very frustrating! TH syst below 1% at N^3LO, but $\Delta(N^3LO,N^2LO) \sim 2\,\sigma$!**
- **Good consistency however above Q~800 GeV**

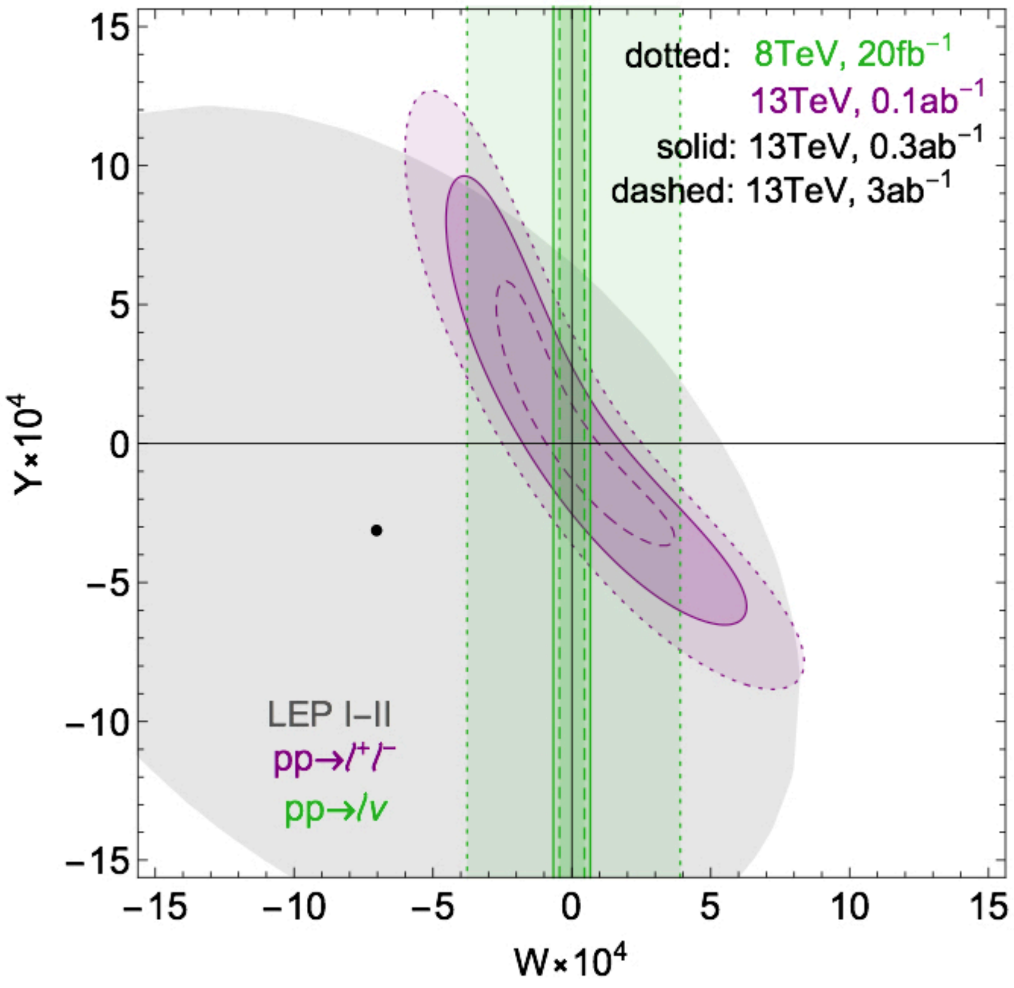
➡ **OK for searches at high mass in the $W^* \to \ell\nu$ channel**

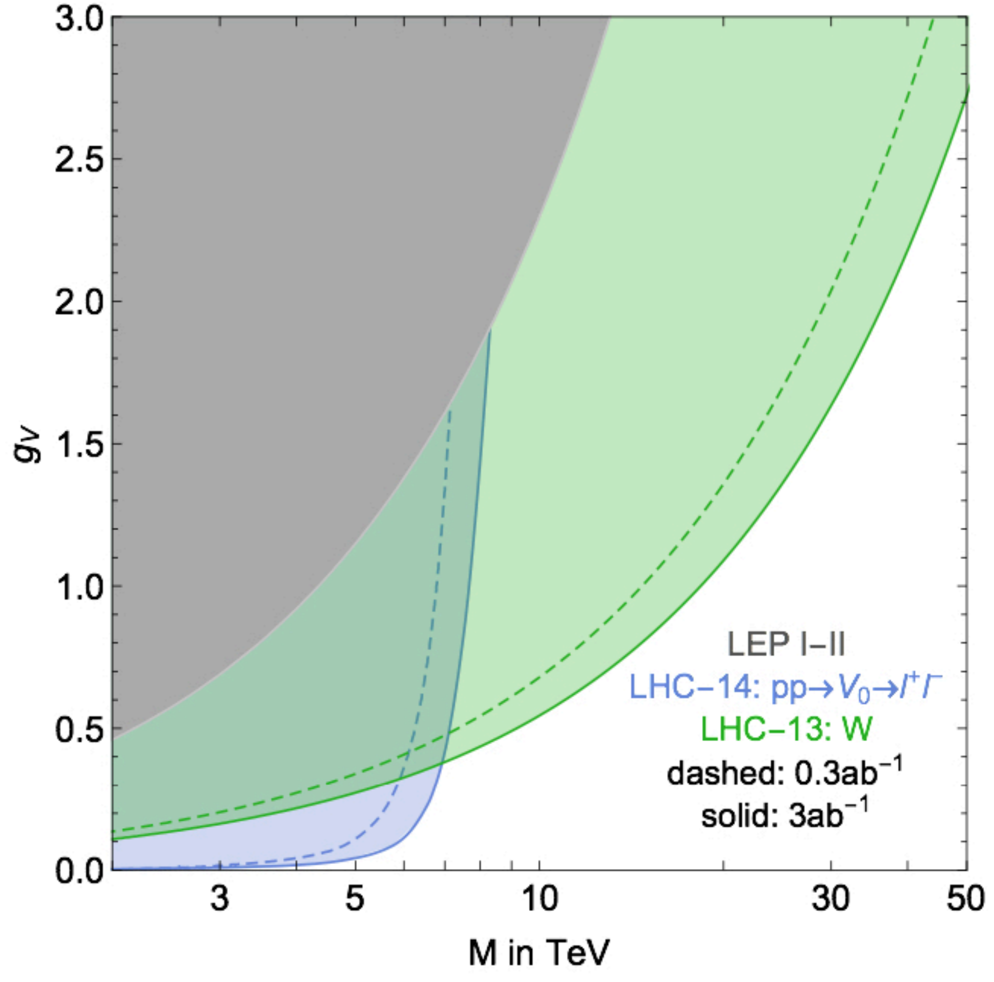
σ(DY) at high mass: sensitivity to W,Y param’s

Farina et al, https://arxiv.org/abs/1609.08157v2

	universal form factor ($\mathcal{L}$)	contact operator ($\mathcal{L}'$)
W	$-\frac{\mathrm{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$	$-\frac{g_2^2\mathrm{W}}{2m_W^2}J_L{}^a_\mu J_L{}^\mu_a$
Y	$-\frac{\mathrm{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$	$-\frac{g_1^2\mathrm{Y}}{2m_W^2}J_Y{}_\mu J_Y{}^\mu$

See also:
Running of α_{Weak} & sensitivity to BSM EW states:
Alves et al, https://arxiv.org/abs/1410.6810

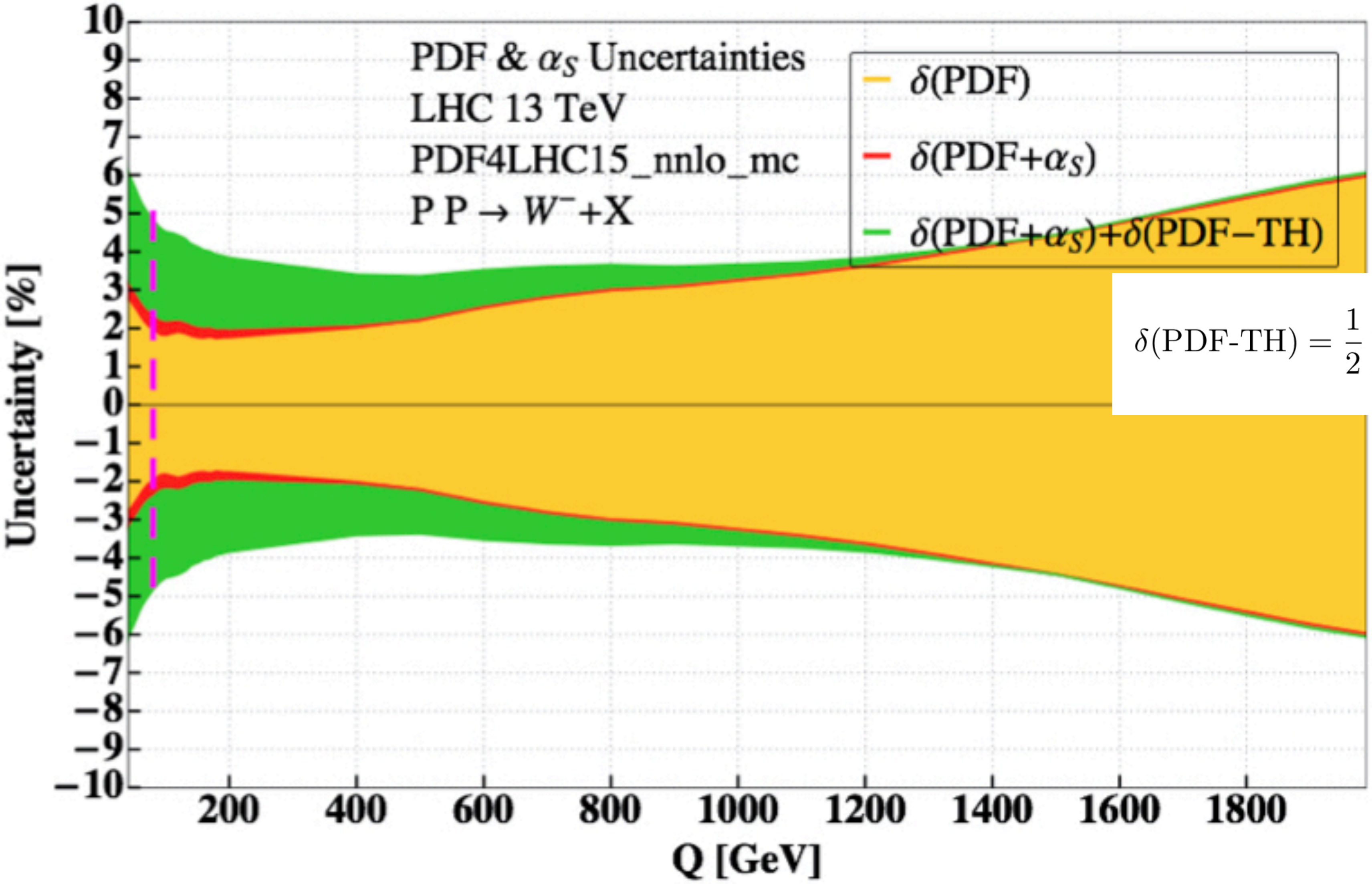




		LEP	ATLAS 8	CMS 8	LHC 13		100 TeV	ILC	TLEP	CEPC	ILC 500 GeV
luminosity		2×10^7 Z	19.7 fb^{-1}	20.3 fb^{-1}	0.3 ab^{-1}	3 ab^{-1}	10 ab^{-1}	10^9 Z	10^{12} Z	10^{10} Z	3 ab^{-1}
NC	W×10^4	[−19, 3]	[−3, 15]	[−5, 22]	±1.5	±0.8	±0.04	±4.2	±1.2	±3.6	±0.3
	Y×10^4	[−17, 4]	[−4, 24]	[−7, 41]	±2.3	±1.2	±0.06	±1.8	±1.5	±3.1	±0.2
CC	W×10^4	—	±3.9		±0.7	±0.45	±0.02	—	—	—	—

DY @ N^3LO

Duhr, Dulat, Mistlberger
arxiv:2001.07717 , arxiv:2007.13313

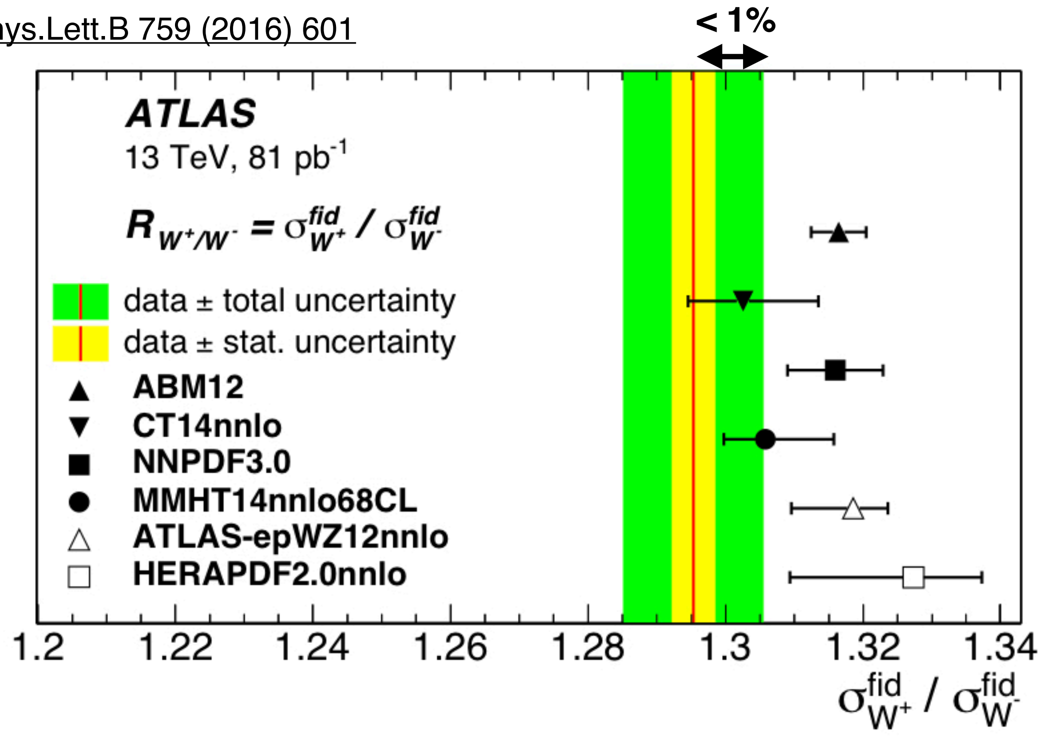


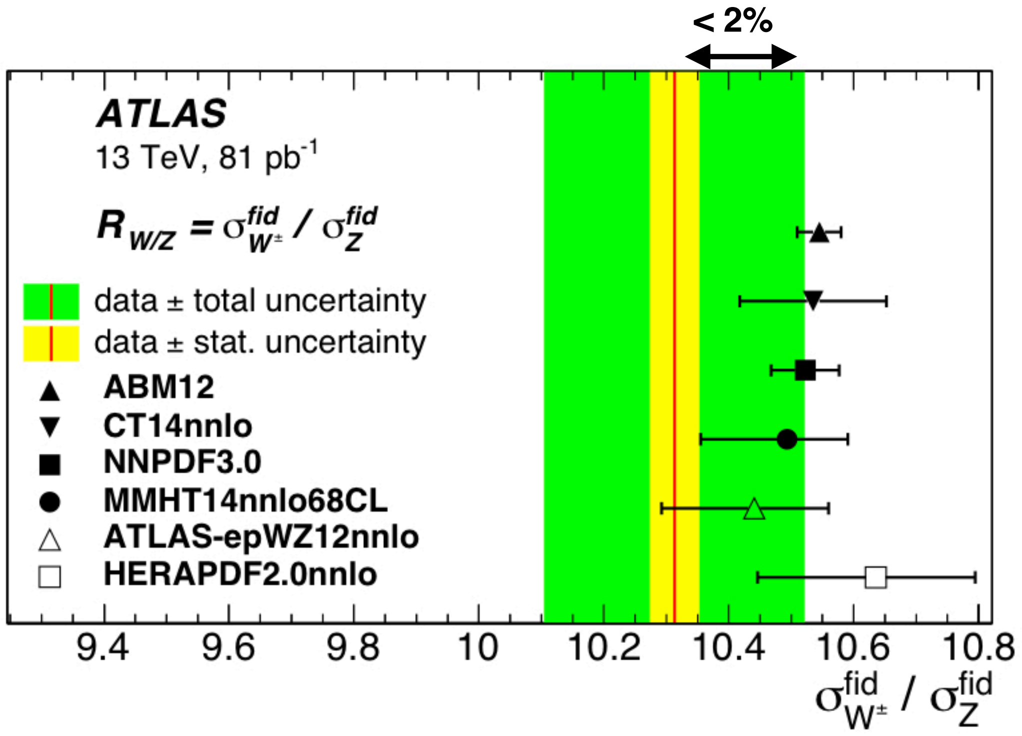
$$\delta(\text{PDF-TH}) = \frac{1}{2}\left|\frac{\sigma^{(2),\text{ NNLO-PDFs}}_{W^\pm} - \sigma^{(2),\text{ NLO-PDFs}}_{W^\pm}}{\sigma^{(2),\text{ NNLO-PDFs}}_{W^\pm}}\right|$$

- **N3LO – N2LO at Q=mW comparable to NNLO PDF uncertainty**
- **PDF uncertainty comparable to the (conservative) estimate of the PDF N^2LO↔N^3LO syst's**
- **Important cancellations among different partonic channels at Q=mW ⇒**
    - **potential sensitivity to the transition from NNLO PDF to the (unknown) N^3LO PDF**
    - **need to promote PDFs to N^3LO for a reliable use N^3LO results: this will take a long-long time.**
    - **Meanwhile need ideas for defensible assessment of the current N^2LO→N^3LO PDF systematics, a plan on how to gradually incorporate data and new calculations in the fits, etc**

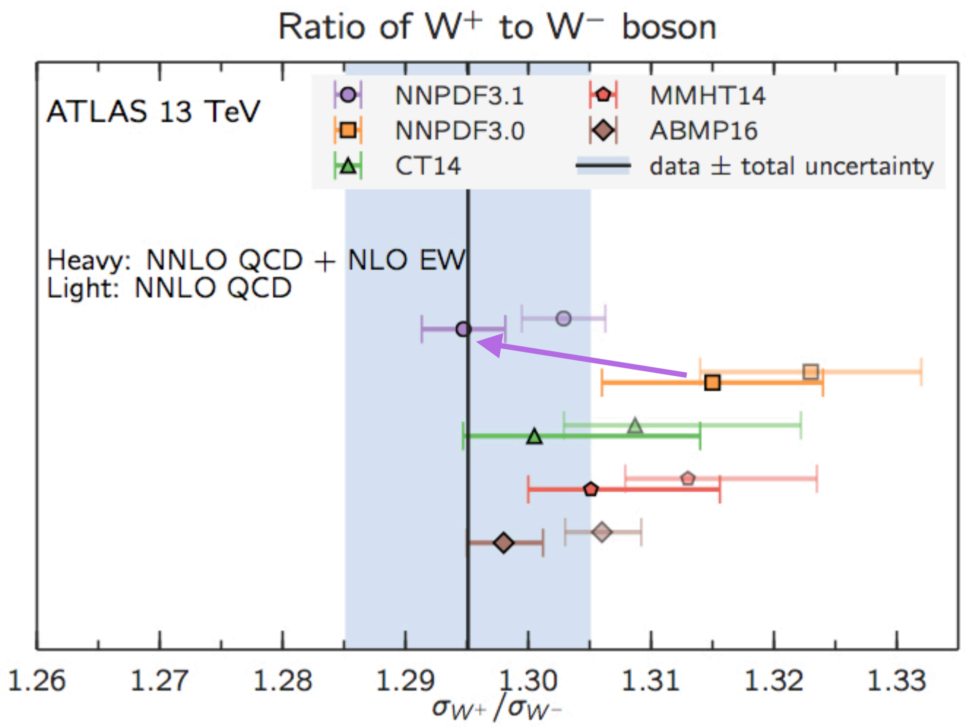
TH vs data, status at NNLO (N^{3}LO ~ N^{2}LO for ratios)

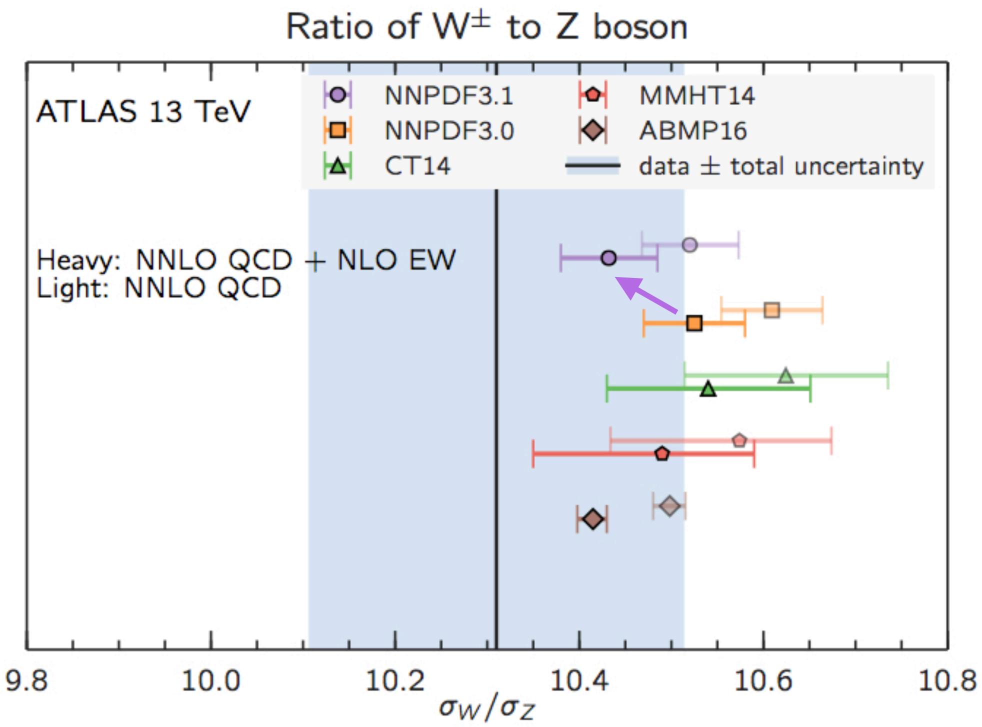
Phys.Lett.B 759 (2016) 601





Inclusion of DY, and other LHC, data, from NNPDF 3.0 to 3.1, Ball et al, https://arxiv.org/pdf/1706.00428.pdf

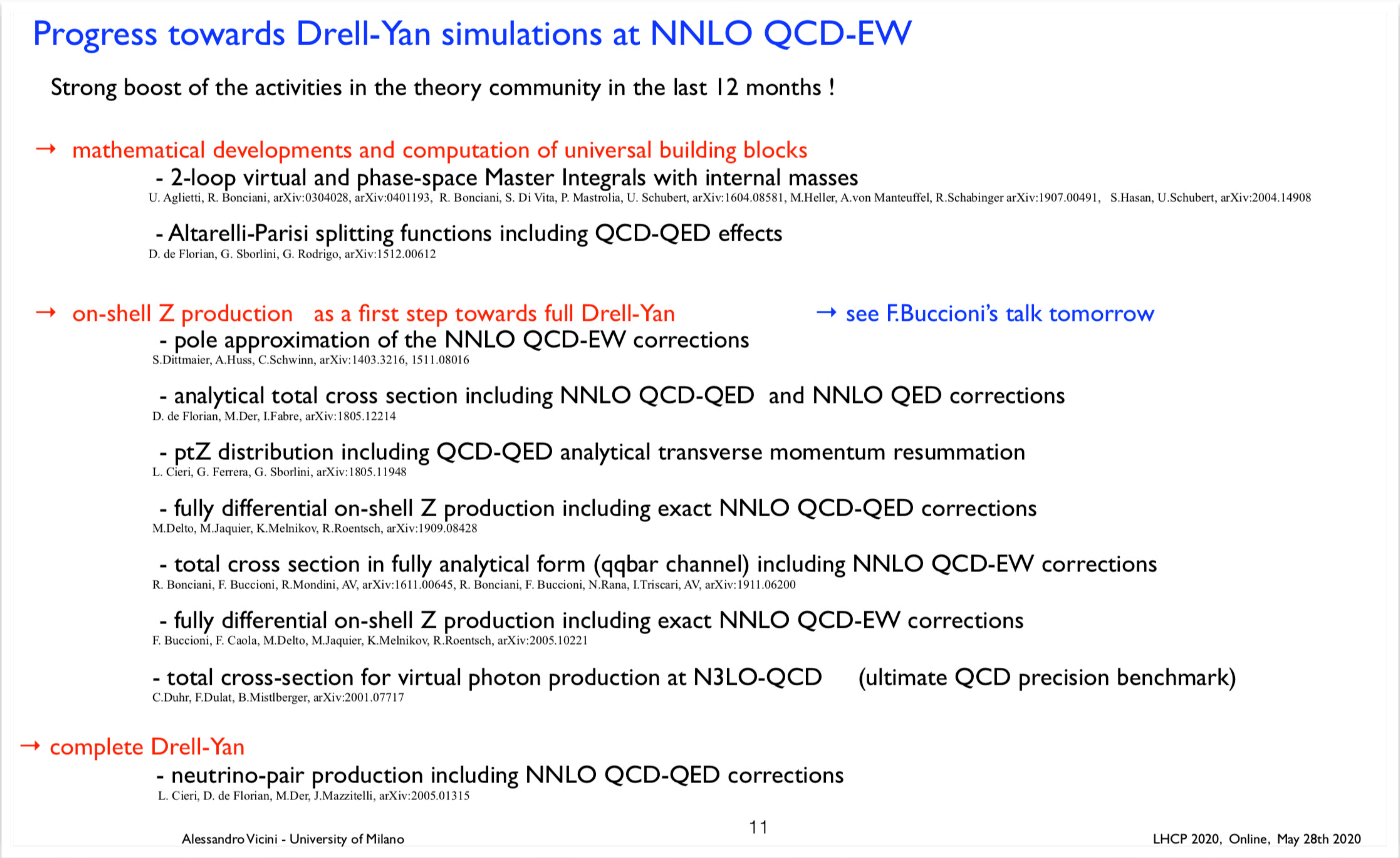




Note:

- EW corrections are important: their size is equal to half a σ!
- the DY data are not enough to fully pull σ_W/σ_Z to 1

Theoretical progress on EW corrections



Progress towards Drell-Yan simulations at NNLO QCD-EW

Strong boost of the activities in the theory community in the last 12 months !

→ mathematical developments and computation of universal building blocks

- 2-loop virtual and phase-space Master Integrals with internal masses
  U. Aglietti, R. Bonciani, arXiv:0304028, arXiv:0401193, R. Bonciani, S. Di Vita, P. Mastrolia, U. Schubert, arXiv:1604.08581, M.Heller, A.von Manteuffel, R.Schabinger arXiv:1907.00491, S.Hasan, U.Schubert, arXiv:2004.14908
- Altarelli-Parisi splitting functions including QCD-QED effects
  D. de Florian, G. Sborlini, G. Rodrigo, arXiv:1512.00612

→ on-shell Z production as a first step towards full Drell-Yan → see F.Buccioni's talk tomorrow

- pole approximation of the NNLO QCD-EW corrections
  S.Dittmaier, A.Huss, C.Schwinn, arXiv:1403.3216, 1511.08016
- analytical total cross section including NNLO QCD-QED and NNLO QED corrections
  D. de Florian, M.Der, I.Fabre, arXiv:1805.12214
- ptZ distribution including QCD-QED analytical transverse momentum resummation
  L. Cieri, G. Ferrera, G. Sborlini, arXiv:1805.11948
- fully differential on-shell Z production including exact NNLO QCD-QED corrections
  M.Delto, M.Jaquier, K.Melnikov, R.Roentsch, arXiv:1909.08428
- total cross section in fully analytical form (qqbar channel) including NNLO QCD-EW corrections
  R. Bonciani, F. Buccioni, R.Mondini, AV, arXiv:1611.00645, R. Bonciani, F. Buccioni, N.Rana, I.Triscari, AV, arXiv:1911.06200
- fully differential on-shell Z production including exact NNLO QCD-EW corrections
  F. Buccioni, F. Caola, M.Delto, M.Jaquier, K.Melnikov, R.Roentsch, arXiv:2005.10221
- total cross-section for virtual photon production at N3LO-QCD (ultimate QCD precision benchmark)
  C.Duhr, F.Dulat, B.Mistlberger, arXiv:2001.07717

→ complete Drell-Yan

- neutrino-pair production including NNLO QCD-QED corrections
  L. Cieri, D. de Florian, M.Der, J.Mazzitelli, arXiv:2005.01315

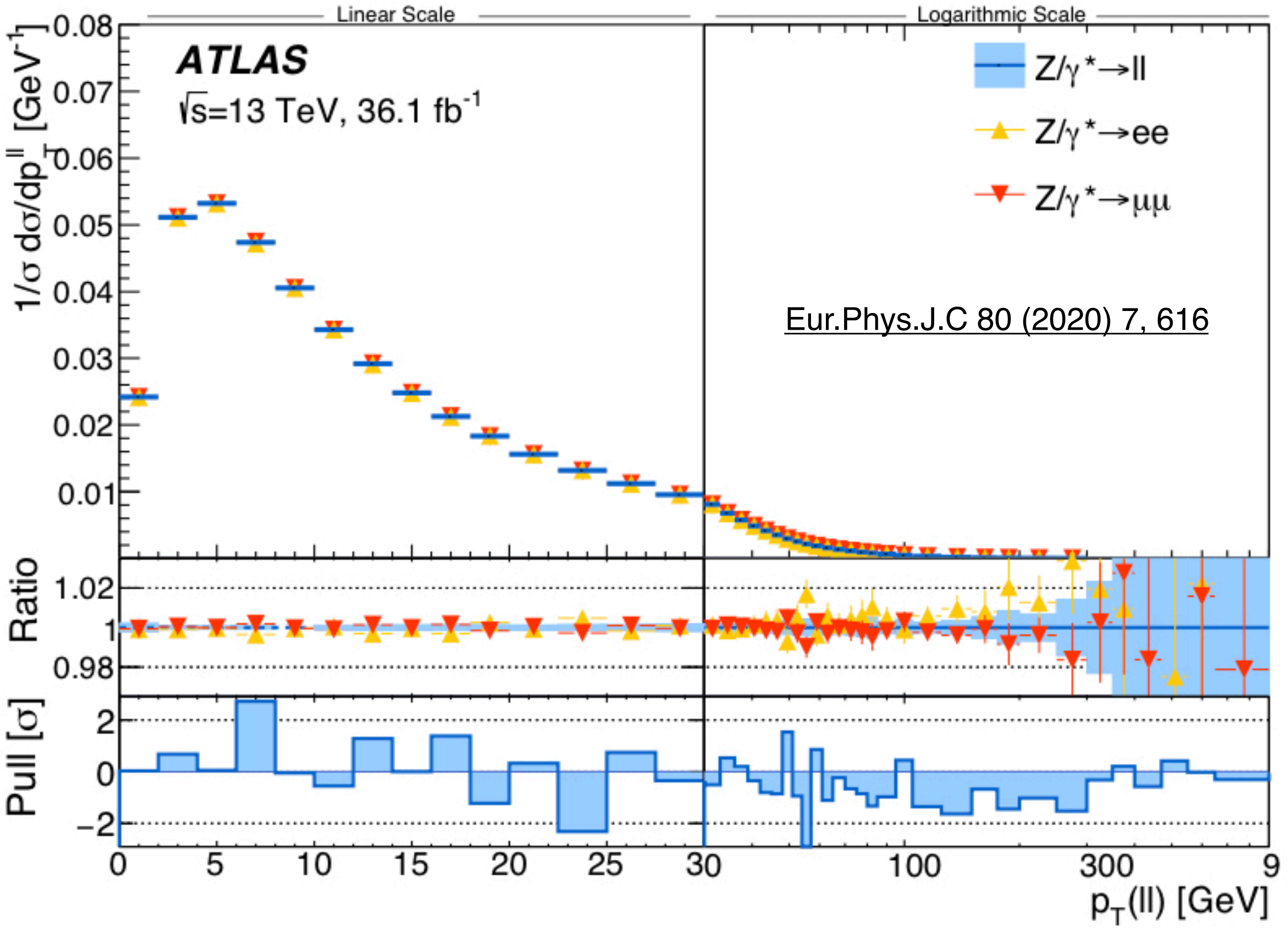
Alessandro Vicini - University of Milano 11 LHCP 2020, Online, May 28th 2020

A.Vicini at LHCP 2020

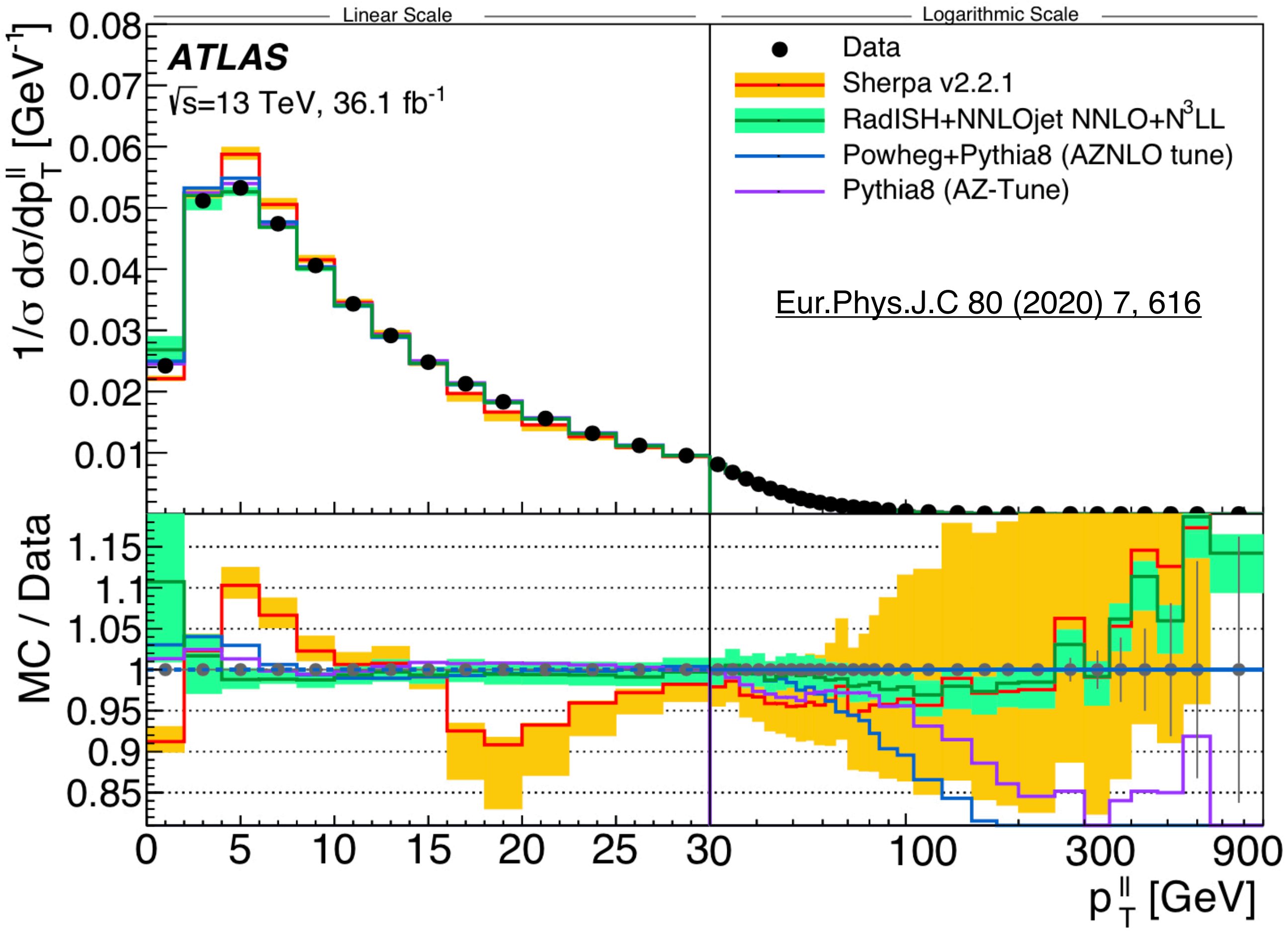
DY pt spectrum

Important for modeling of

- pt(W) (→impact on m_W measurement), pt(WW)
- pt(H) (→impact on σ_H, sensitivity to b,c loops, …)



Eur.Phys.J.C 80 (2020) 7, 616

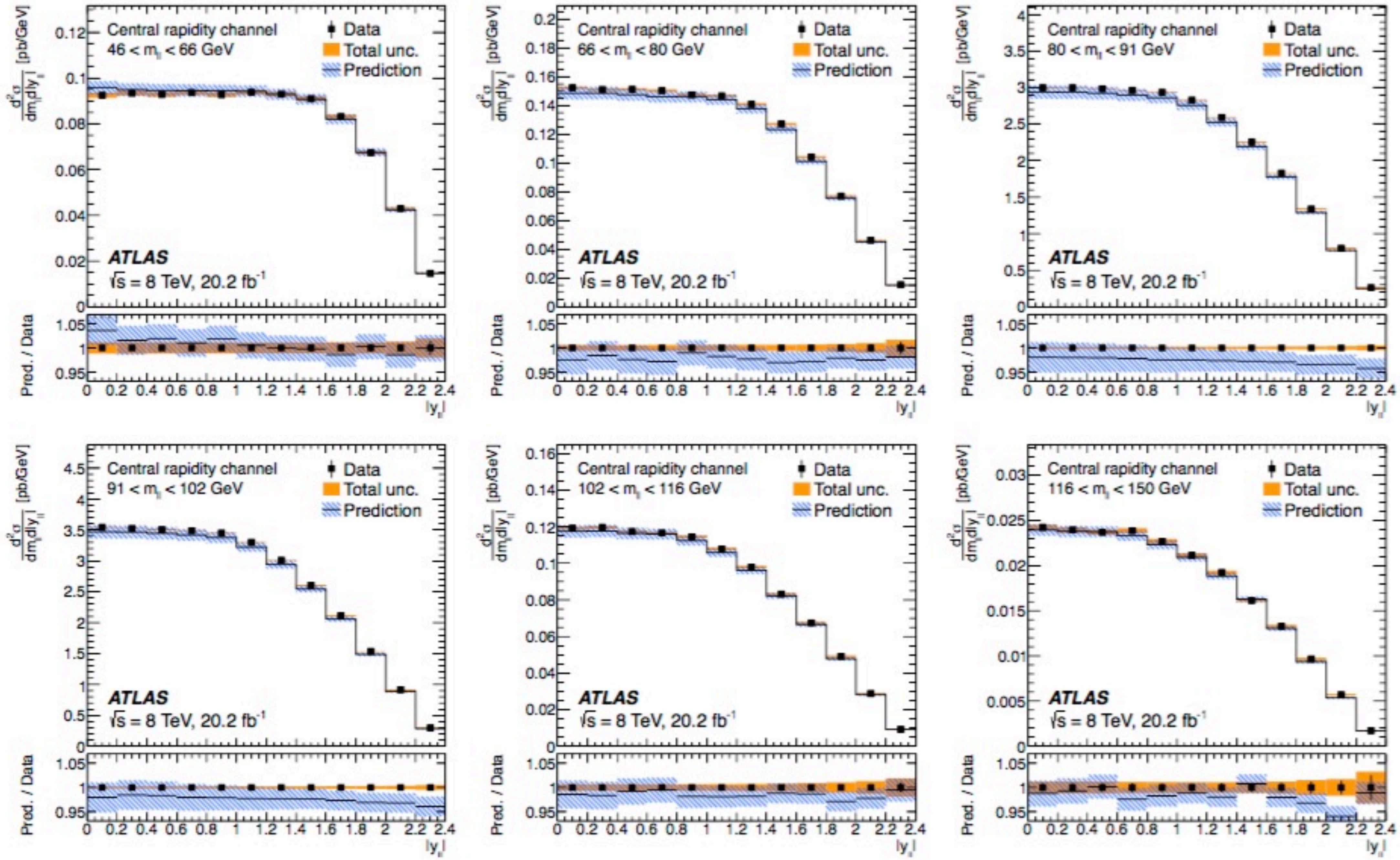


Eur.Phys.J.C 80 (2020) 7, 616

- Exptl precision on shape O(per mille) up to 100 GeV, better than 2% up to 2-300 GeV
- Challenging for TH to match this. At best 1-2% for pt=5–30 GeV, already extremely remarkable
- *RadiSH* (N^3LL+NNLO, Bizon et al, https://arxiv.org/abs/1905.05171) < 5% in the range [3-300] GeV!

Measurement of the Drell–Yan triple-differential cross section in *pp* collisions at $\sqrt{s} = 8$ TeV

arxiv:1710.05167

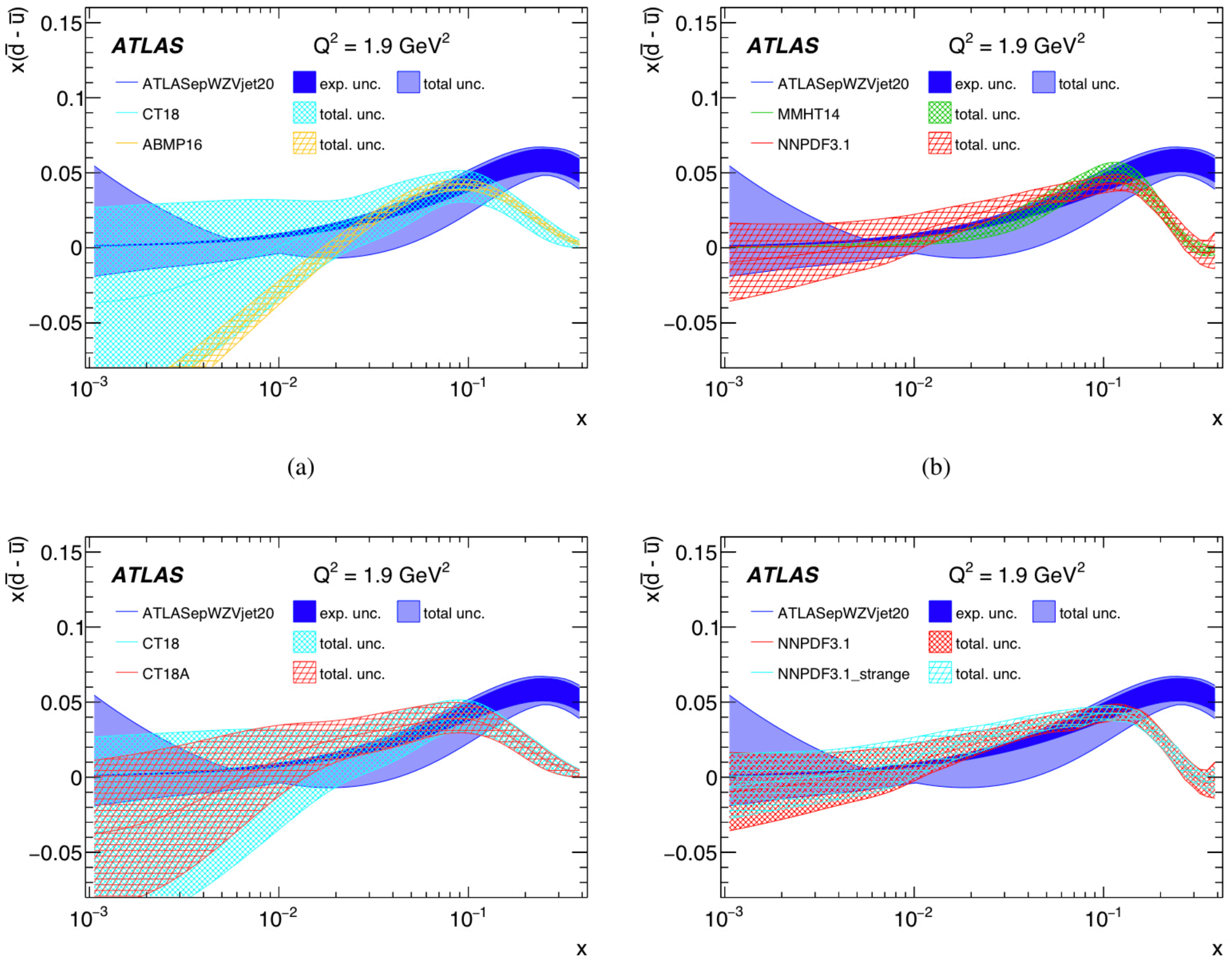


we must learn how to deal with the small - but significant - discrepancies that such %-level precision measurements expose … do they signal insufficient TH accuracy, the need to improve the proton PDFs, new physics ??

How do we avoid fitting away with PDFs / α_S possible mismodeling?

Determination of the parton distribution functions of the proton from ATLAS measurements of differential $W\pm$ and Z boson production in association with jets

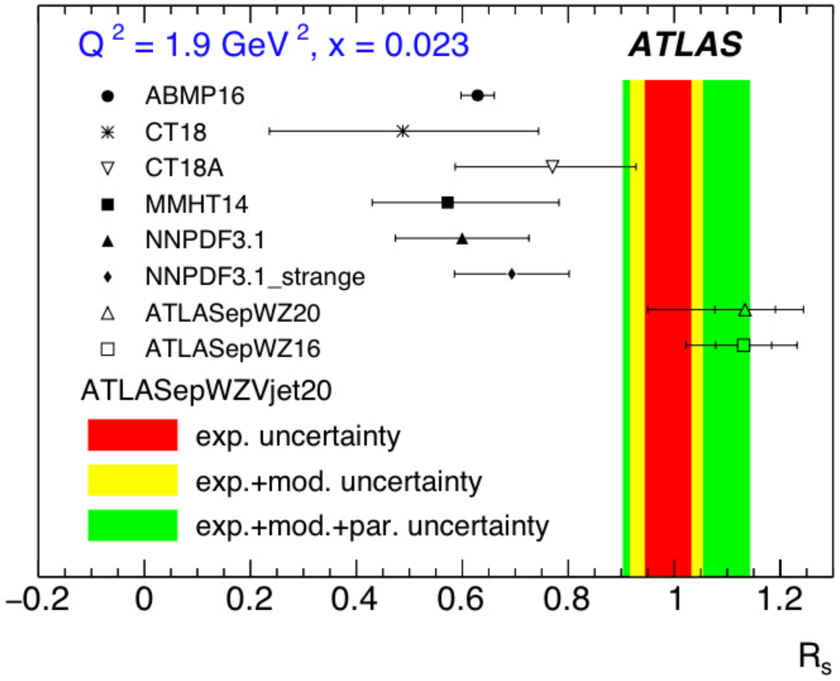
https://arxiv.org/abs/2101.05095

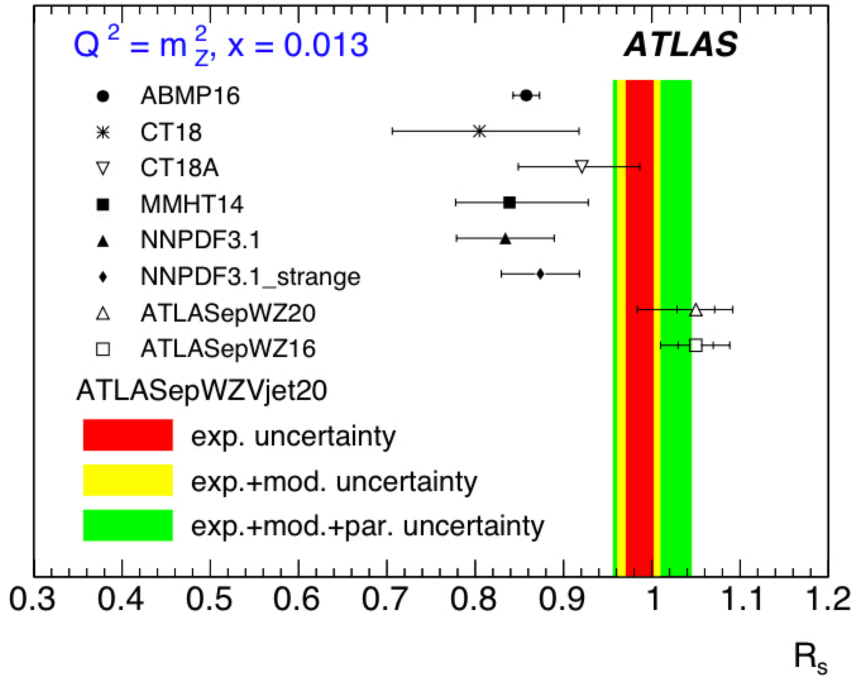


(a)

(b)

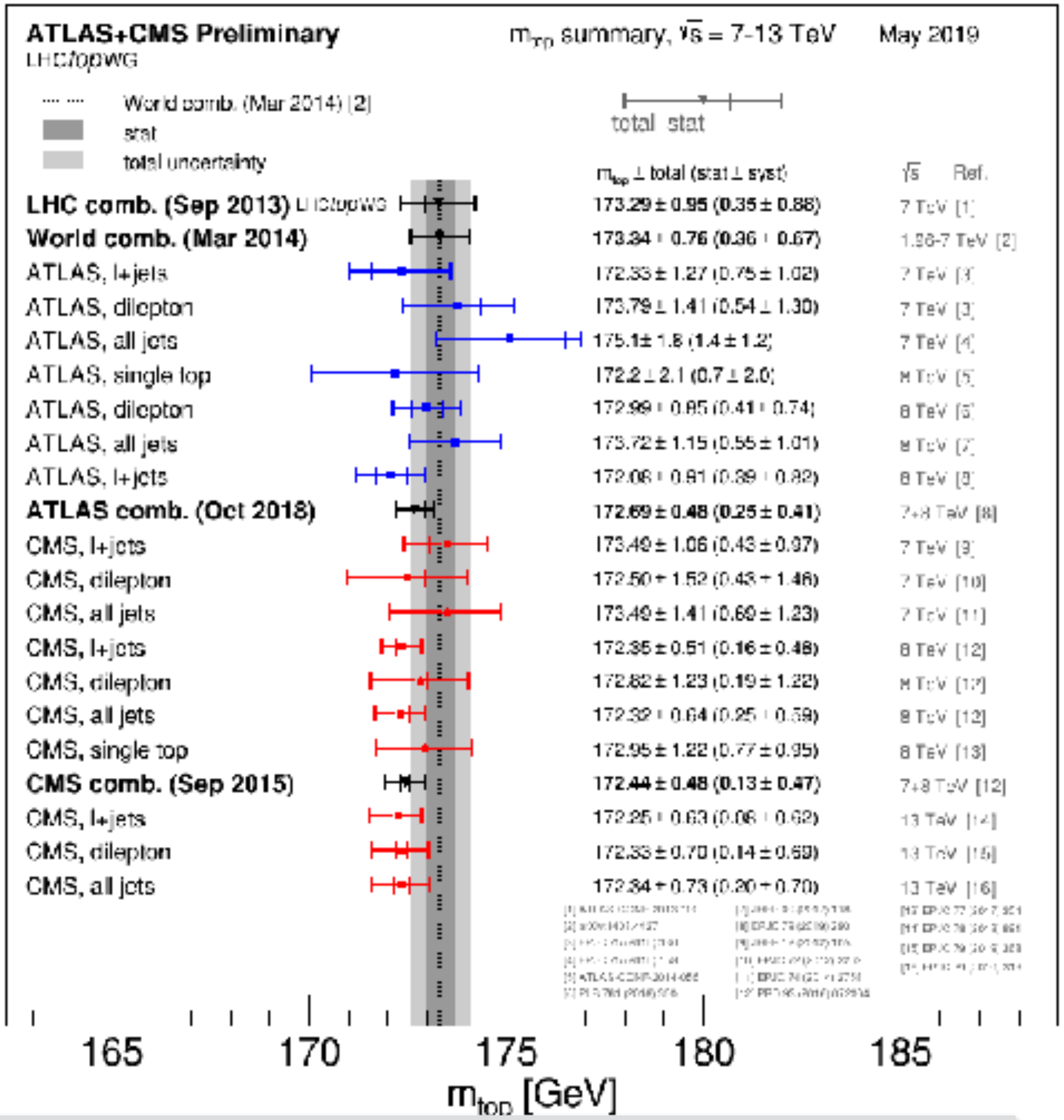
$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}},$$

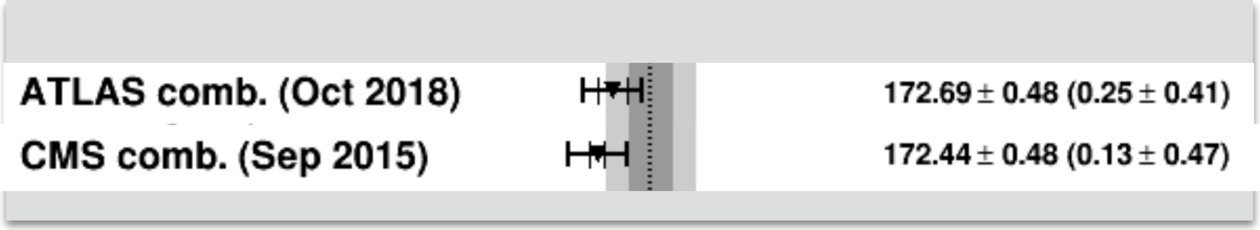




Top quark

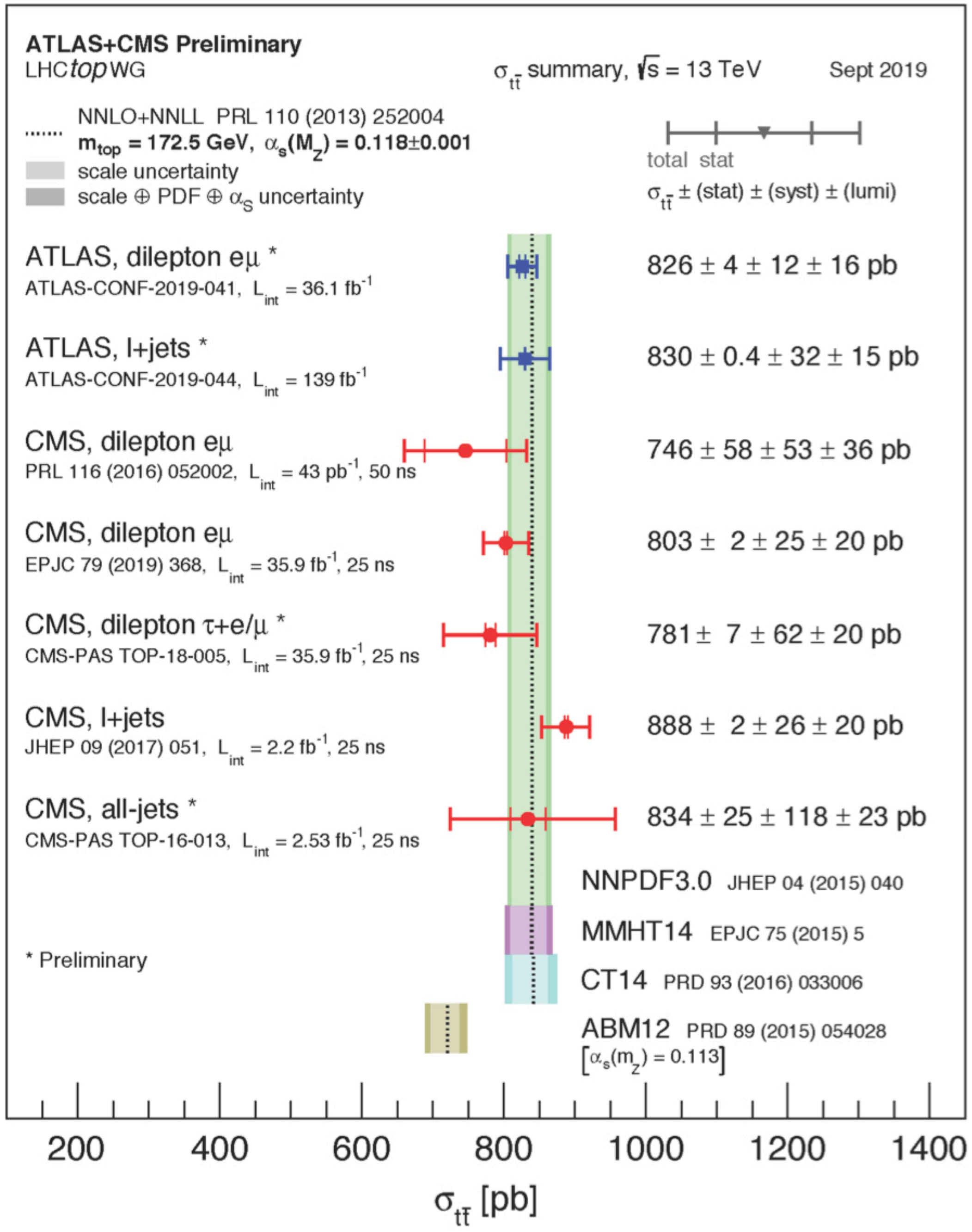
direct mass measurements





500 MeV <=> 3 per mille,
at the limit of TH m_{pole} interpretation systematics

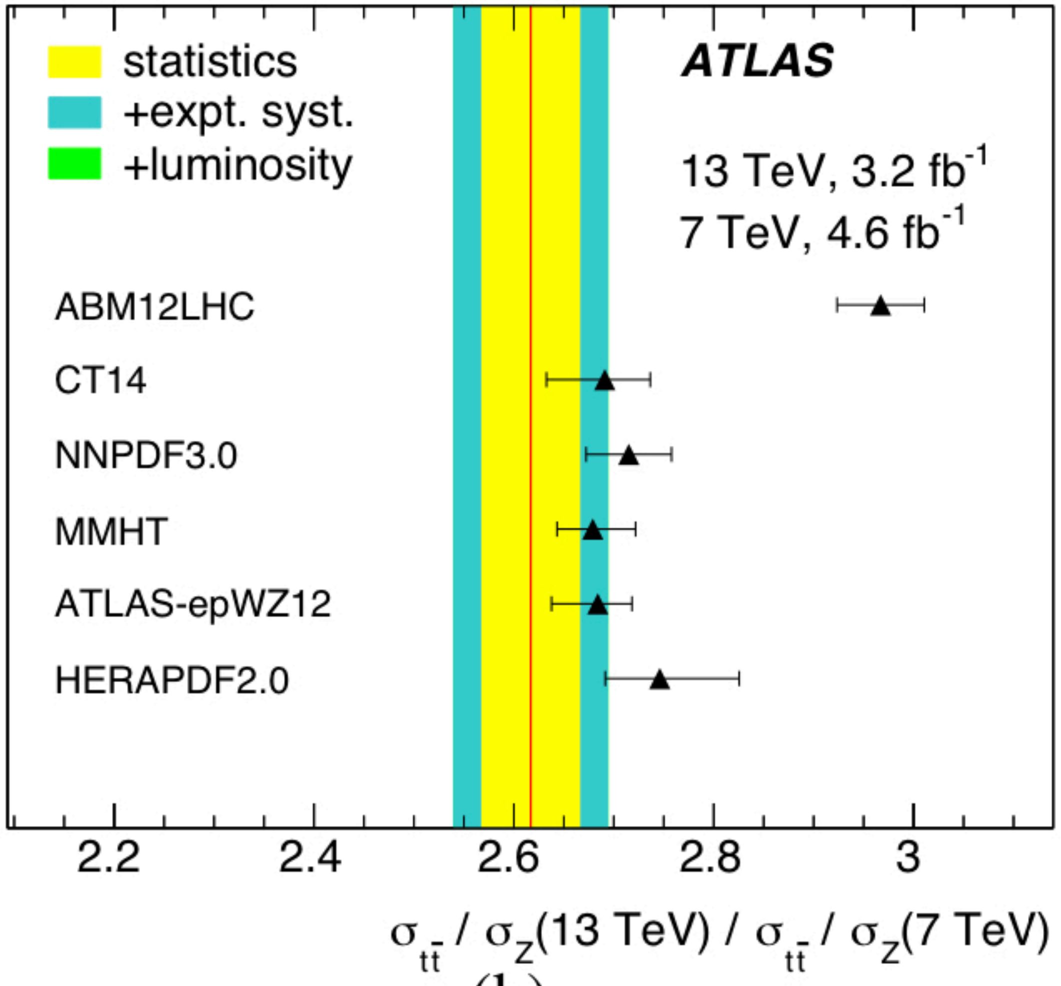
cross section measurements



1.5% syst 2% lumi, vs 3-4% TH

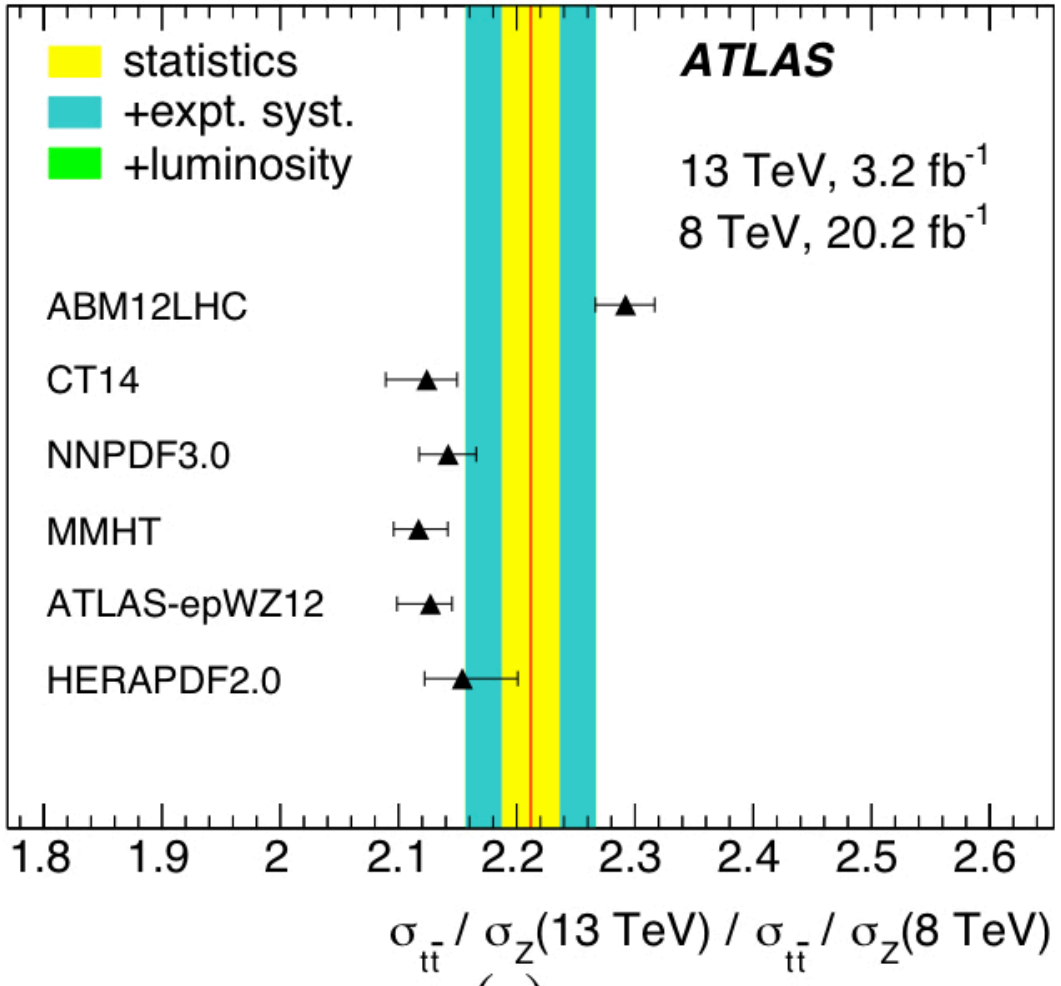
σ(tt)/σ(Z) and √S double ratios

https://arxiv.org/pdf/1910.08819.pdf



(b)

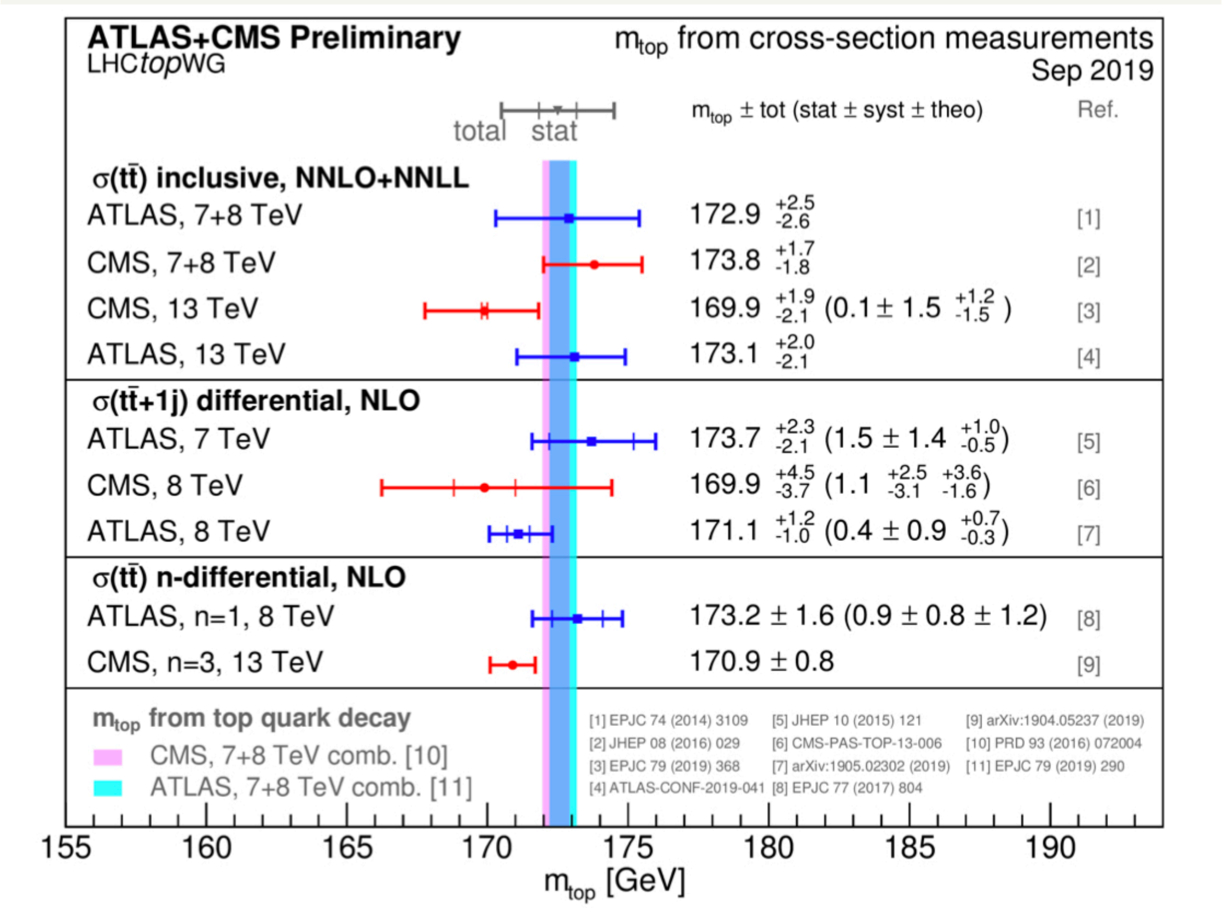
< 2.5%

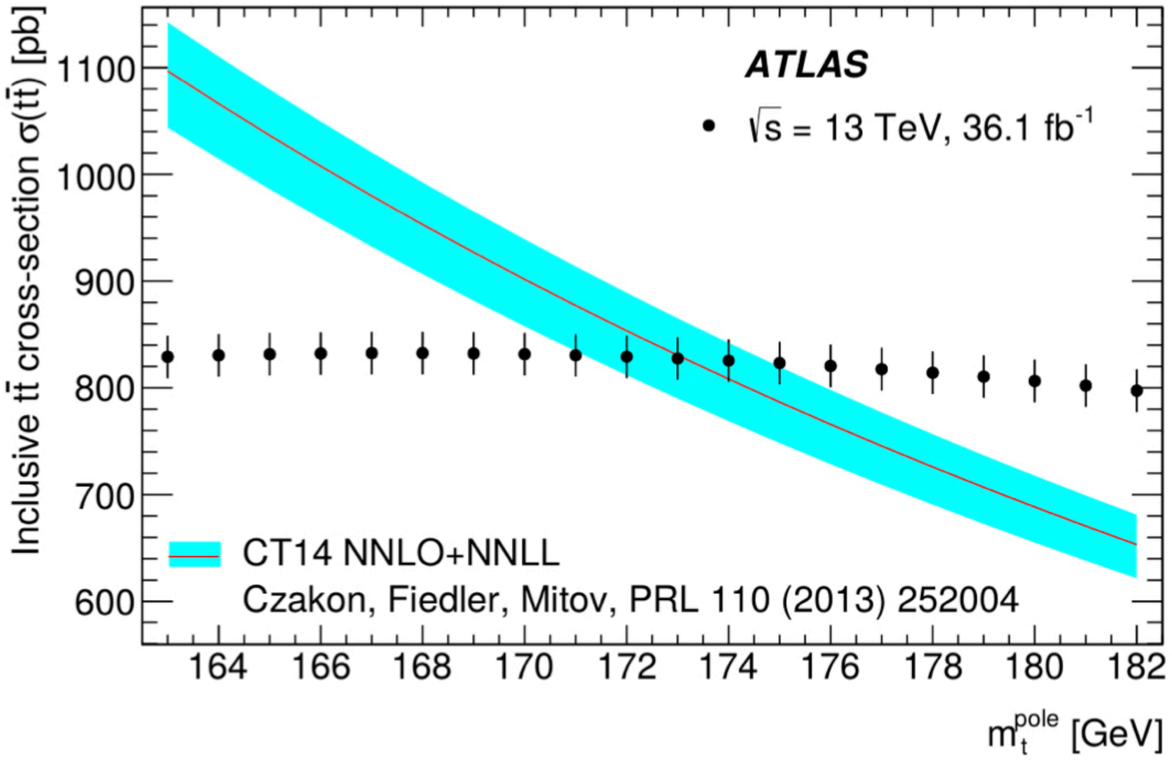


(c)

TH vs data OK to 1σ, but signs of a potential tension between 7 and 8 TeV data …
Can compromise the benefit of inclusion in global PDF fits, but of course we cannot choose which data we like and which we don’t !

Extraction of m_{top} from σ(tt)





$$\frac{\Delta\sigma}{\sigma} = 2.5\,\%\,\frac{\Delta m_{top}}{\mathrm{GeV}}$$

σ_{TH} + Δ_{meas} , where Δ_{meas} = TH modeling + exp + lumi

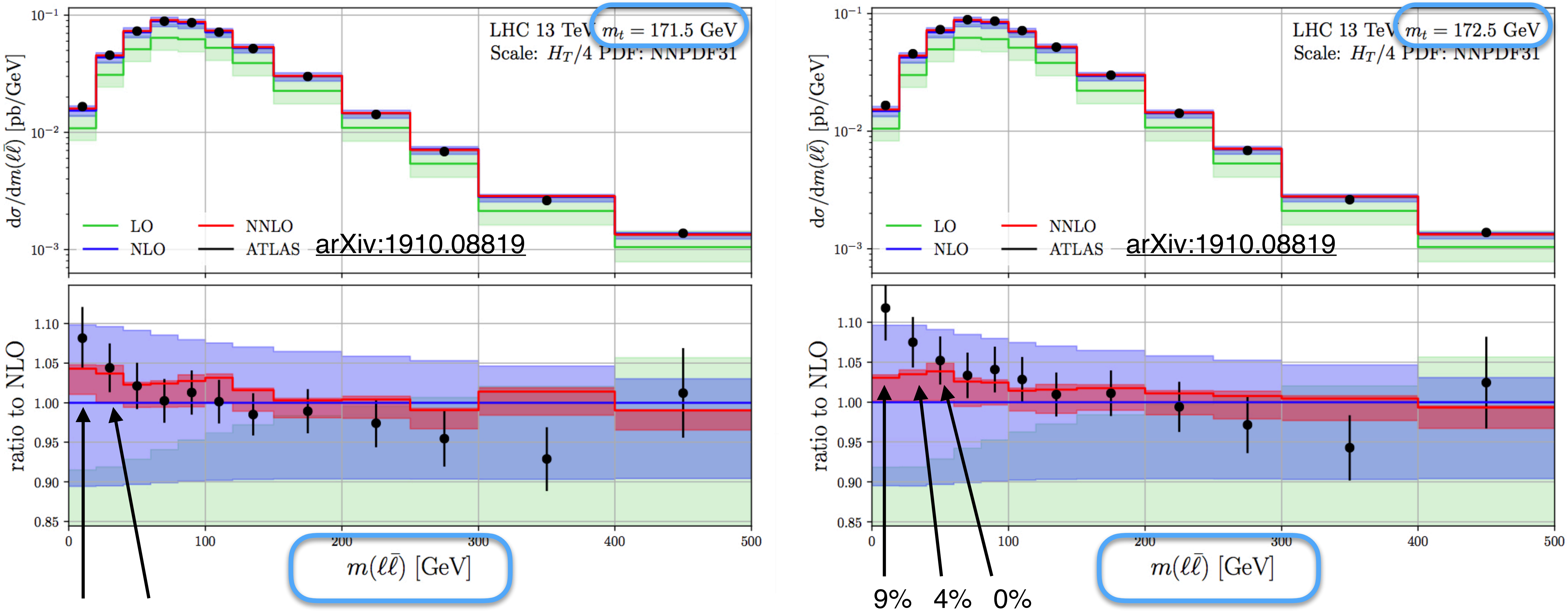
$$\Delta m_{top} = 1\ \mathrm{GeV} \times \frac{(\Delta\sigma/\sigma)}{2.5\,\%}$$

almost saturated by ΔL/L~2%

A sub-GeV determination of m_{top} from σ(tt) appears out of reach…

… or maybe not ?

Czakon, Mitov, Poncelet, arXiv:2008.11133



3% 0%

(TH–data)/data

9% 4% 0%

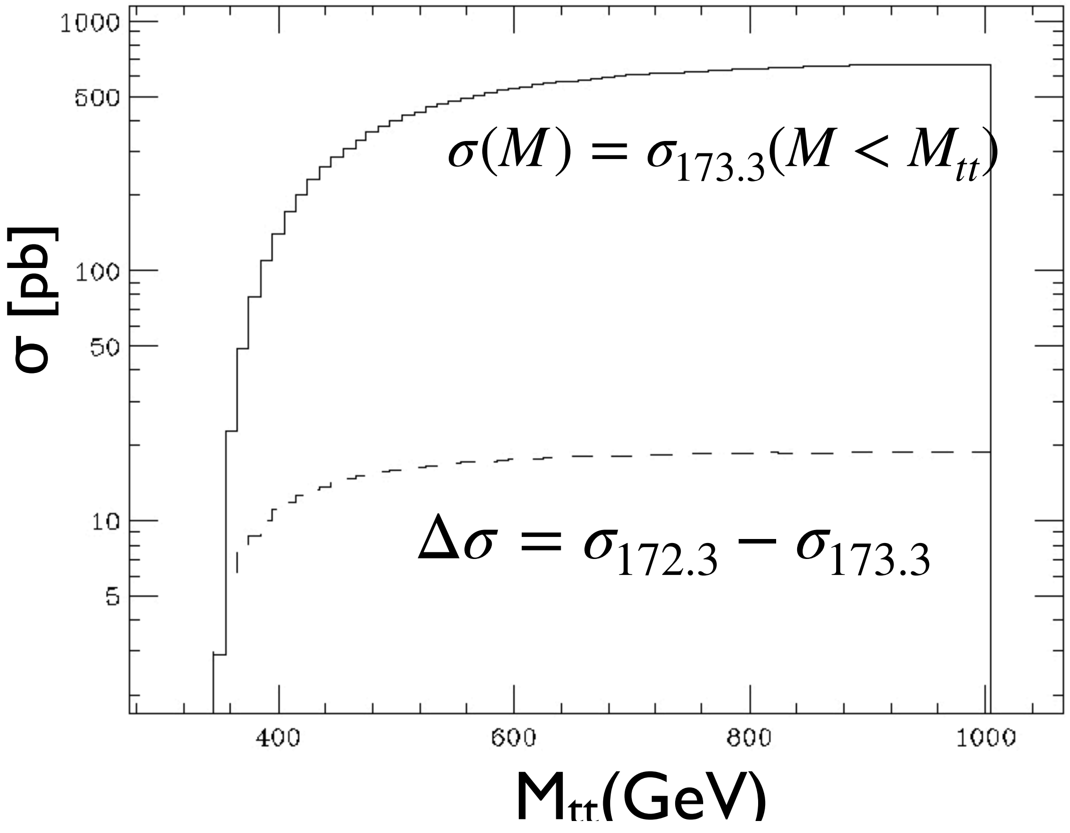
(TH–data)/data

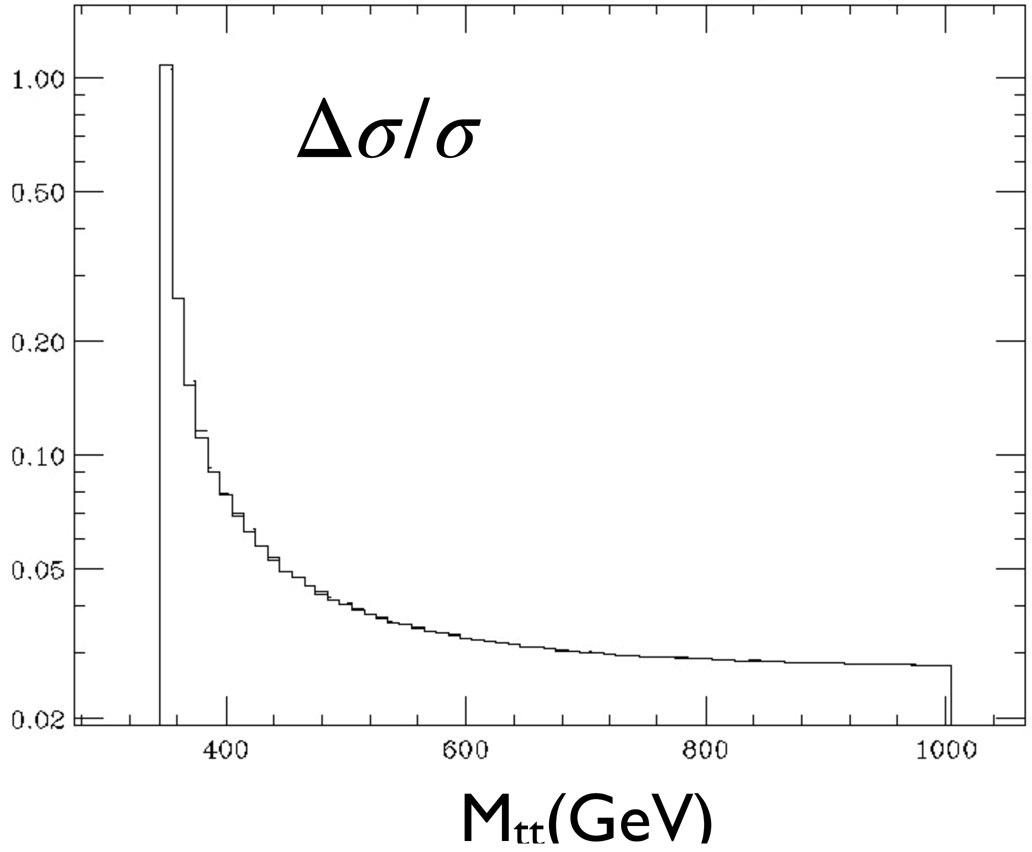
The $\sigma^{-1}\, d\sigma/dm \sim 2.5\%$ / GeV does not apply as an overall shift in distributions. It is focused at small p_T and small m(tt) (of which m(ll) is a crude proxy).

In the small-mtt bins, the dependence of the cross section on m_{top} can be large.

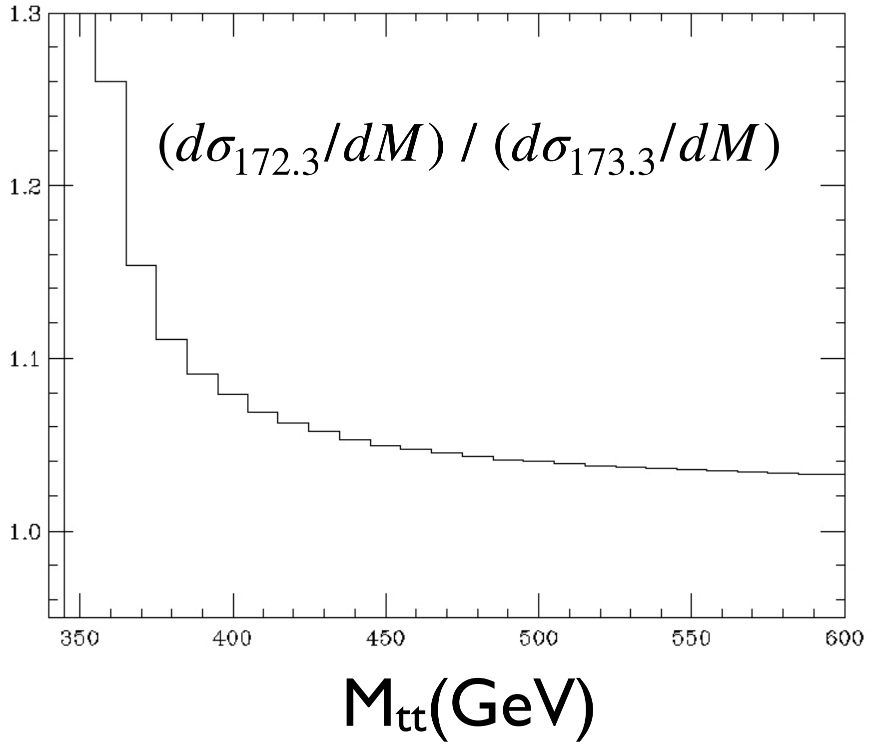
=> important to understand TH systematics at small mtt

looking near the tt threshold

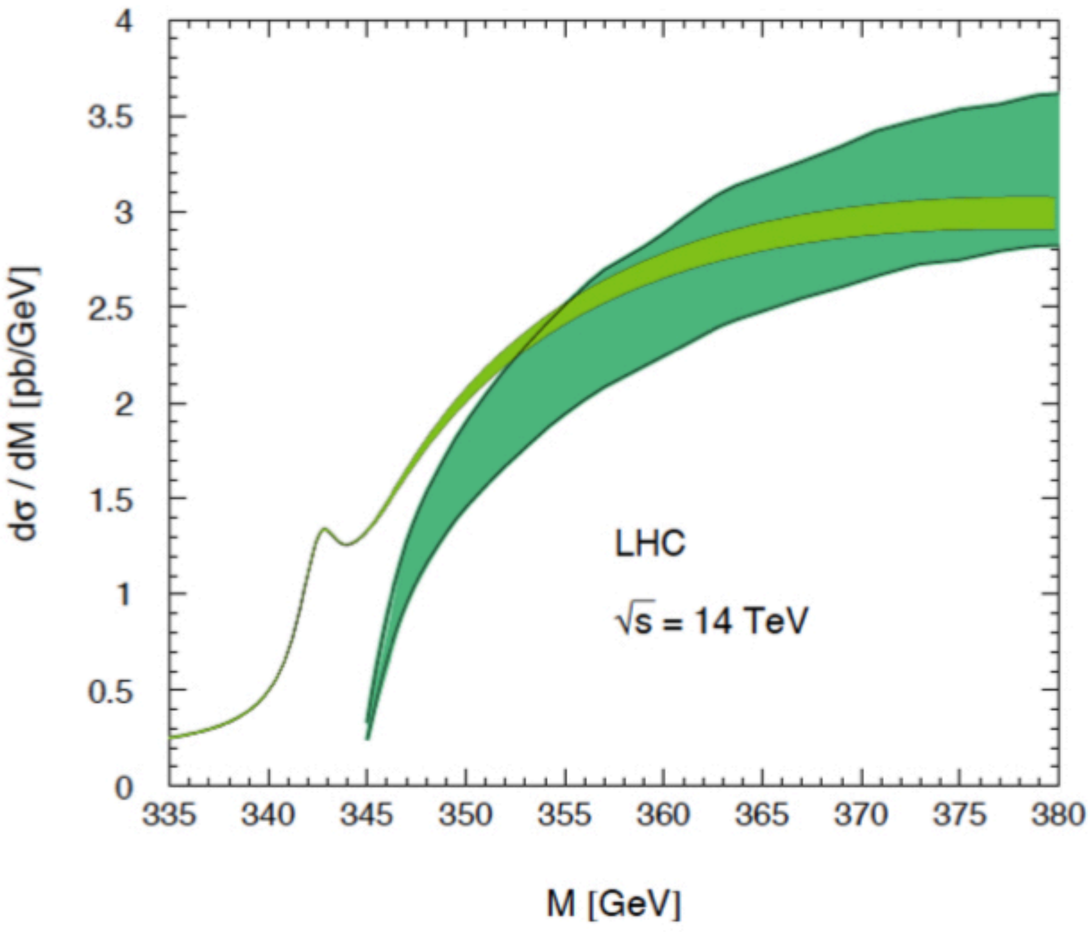




Δm_t = 1 GeV => $\Delta\sigma_{tot}/\sigma_{tot}$ ~2.5%, but the cross-section increase is of order 10% in the $M_{tt} < 400$ GeV range. *The XS sensitivity to m_{top} is concentrated around threshold*



Further effects near threshold

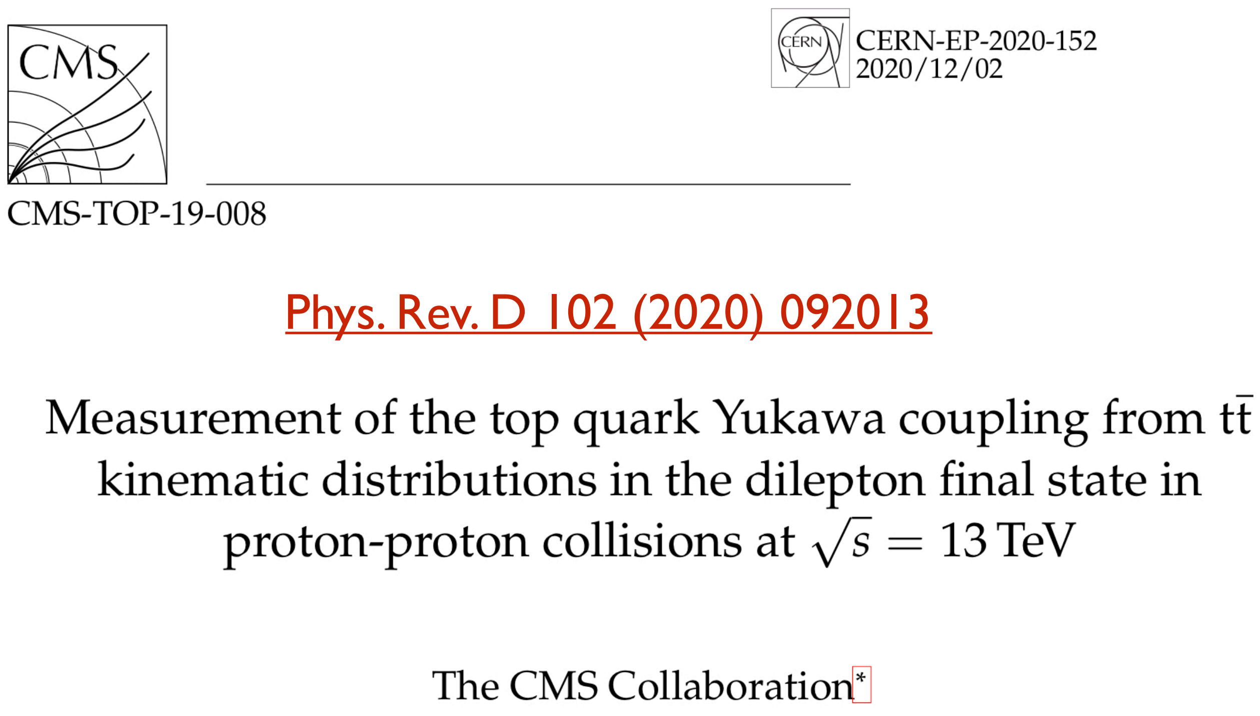


Bound state formation =>
resummation of Coulomb effects

Increase of σ in mass bin < 380 GeV
equivalent to Δm_{top}~1.4 GeV

W-L Ju et al, https://arxiv.org/pdf/2004.03088.pdf

Top Yukawa from virtual corrections



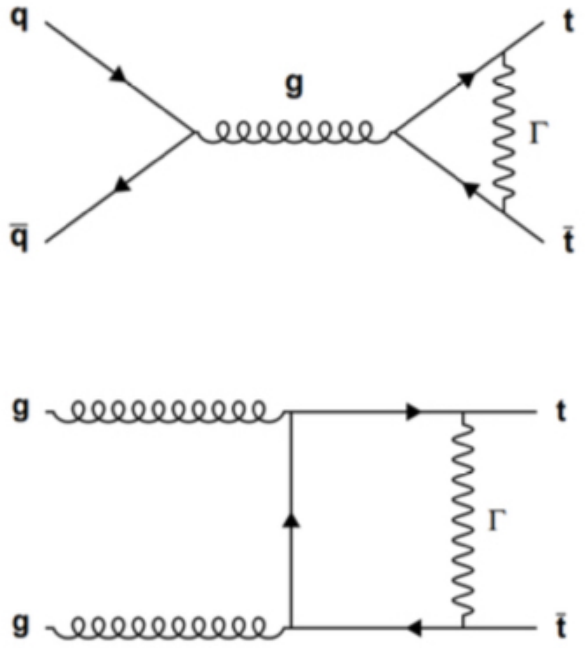
CMS-TOP-19-008

CERN-EP-2020-152
2020/12/02

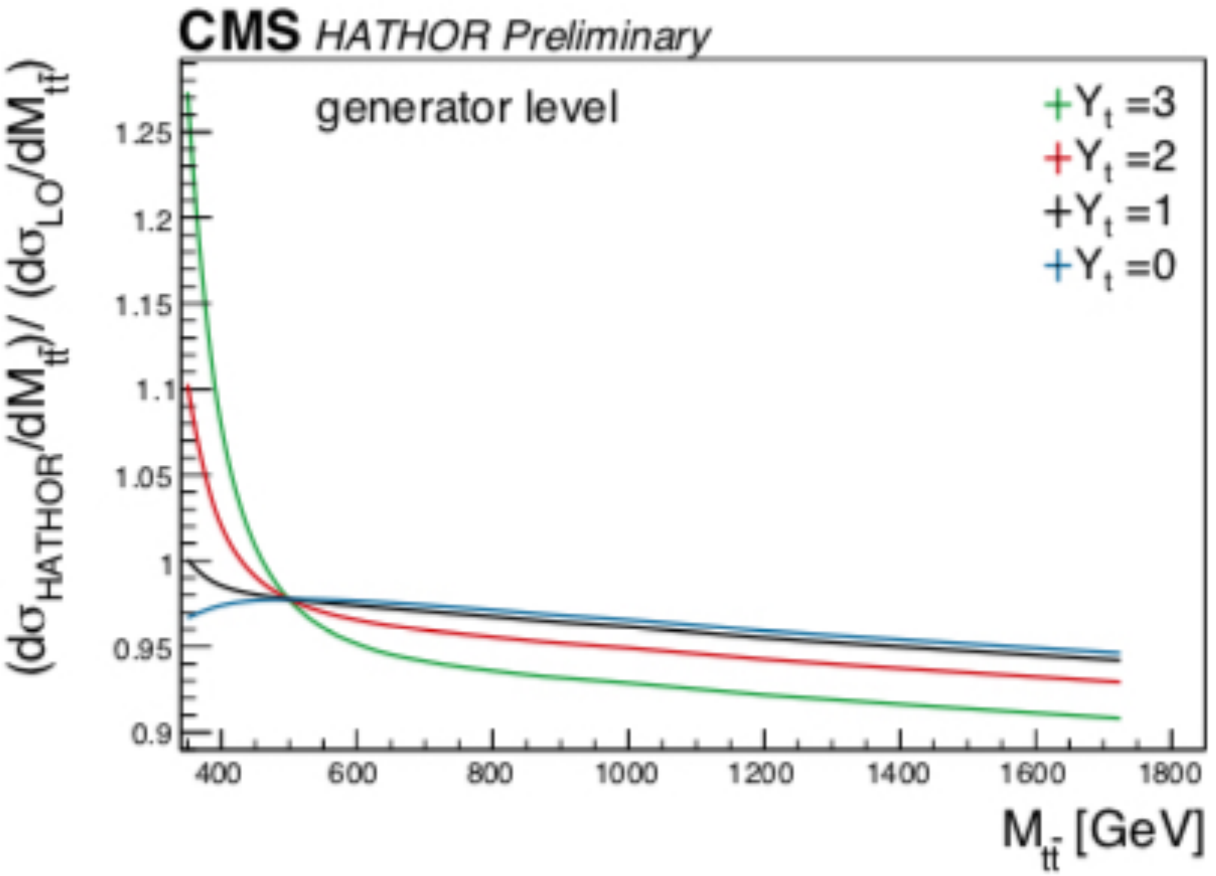
Phys. Rev. D 102 (2020) 092013

Measurement of the top quark Yukawa coupling from $t\bar{t}$ kinematic distributions in the dilepton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*



Γ=Z, H

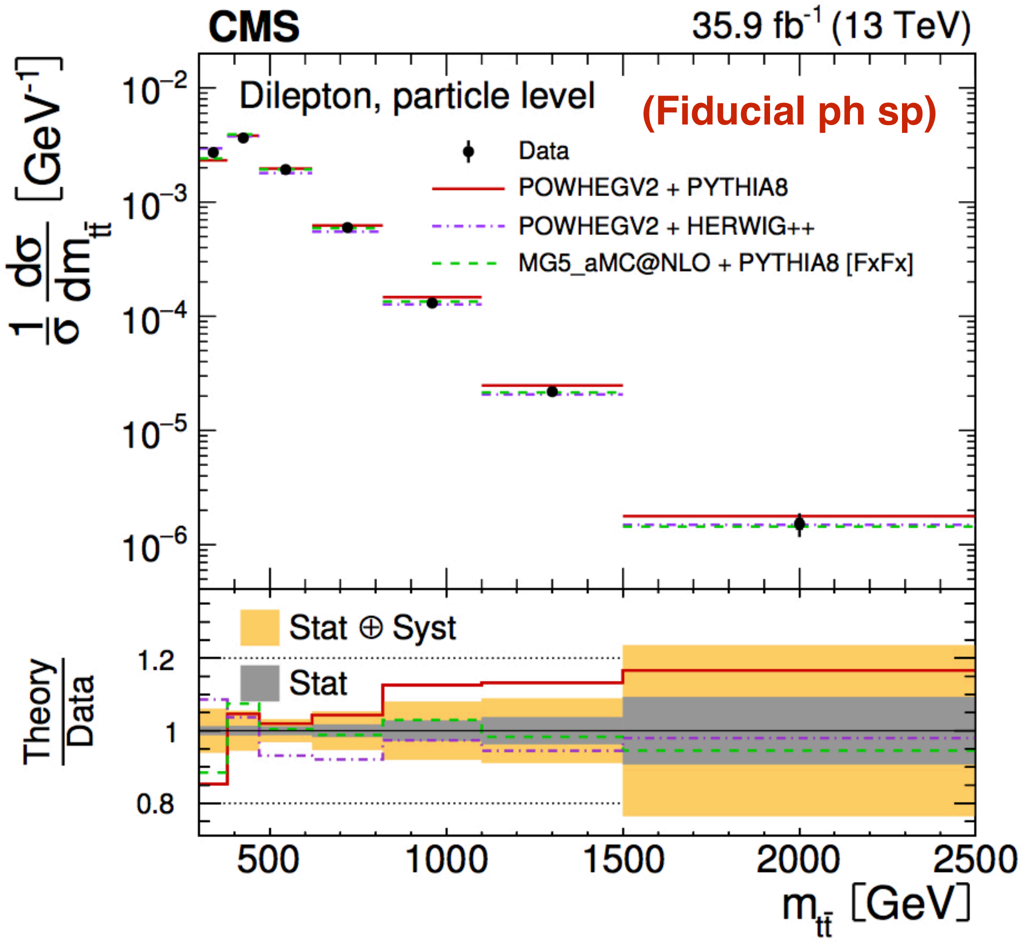


$$\Rightarrow \quad y_t = 1.16^{+0.24}_{-0.35}$$

(~0.5M events)

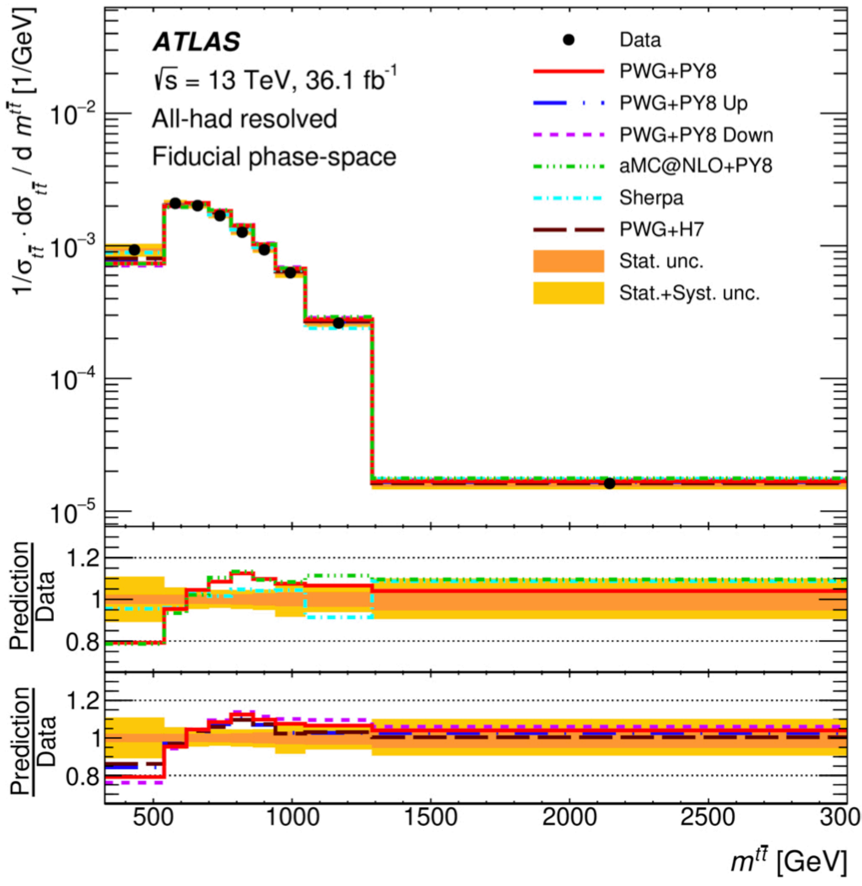
cfr projected ±10% precision

with 10^6 ee→tt @ 350-365 GeV

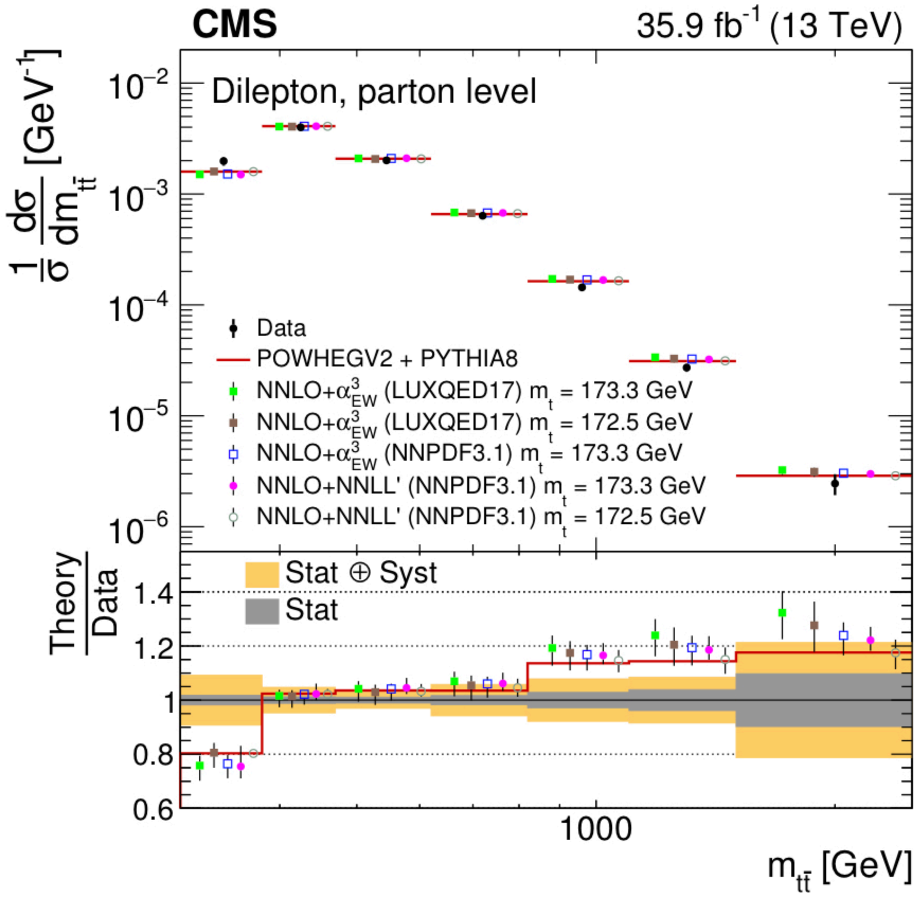


(Fiducial ph sp)

http://dx.doi.org/10.1007/JHEP02(2019)149



https://arxiv.org/pdf/2006.09274.pdf

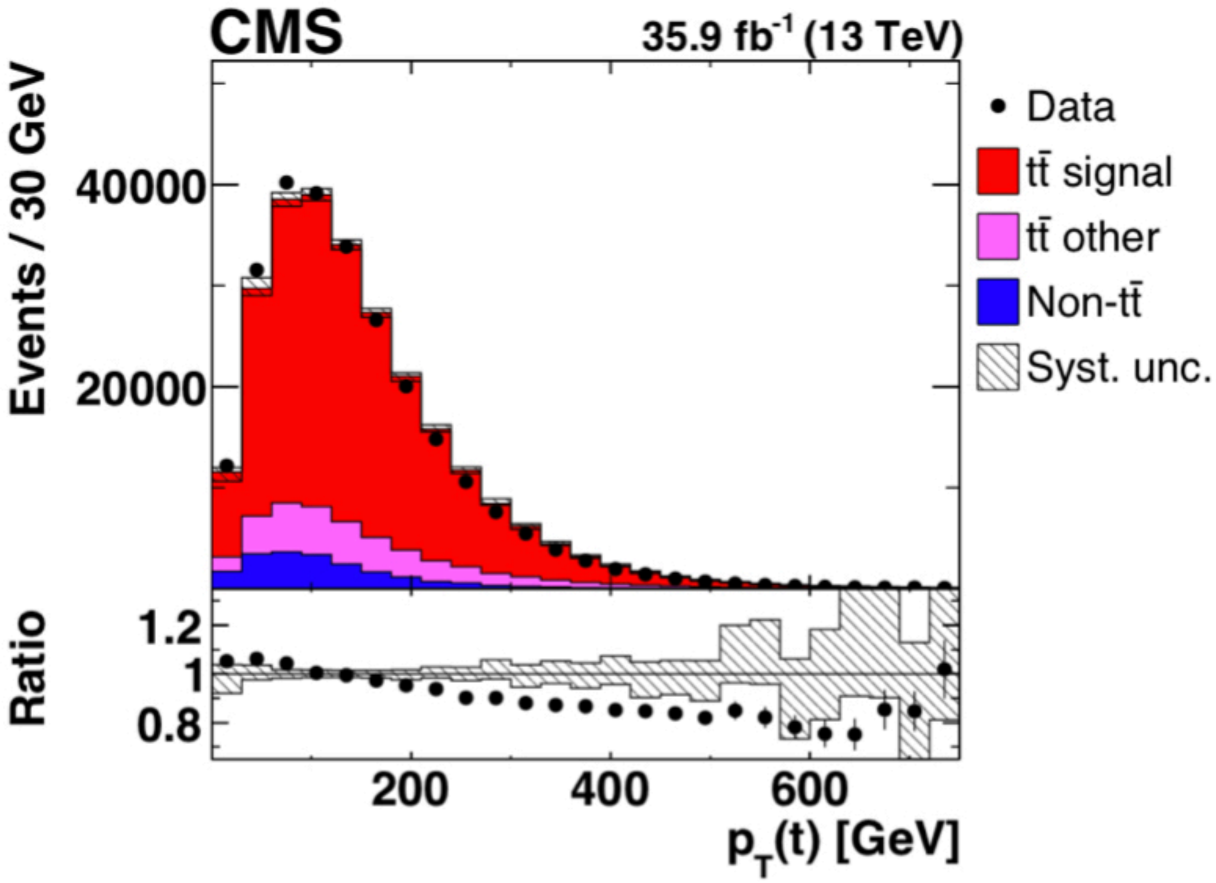


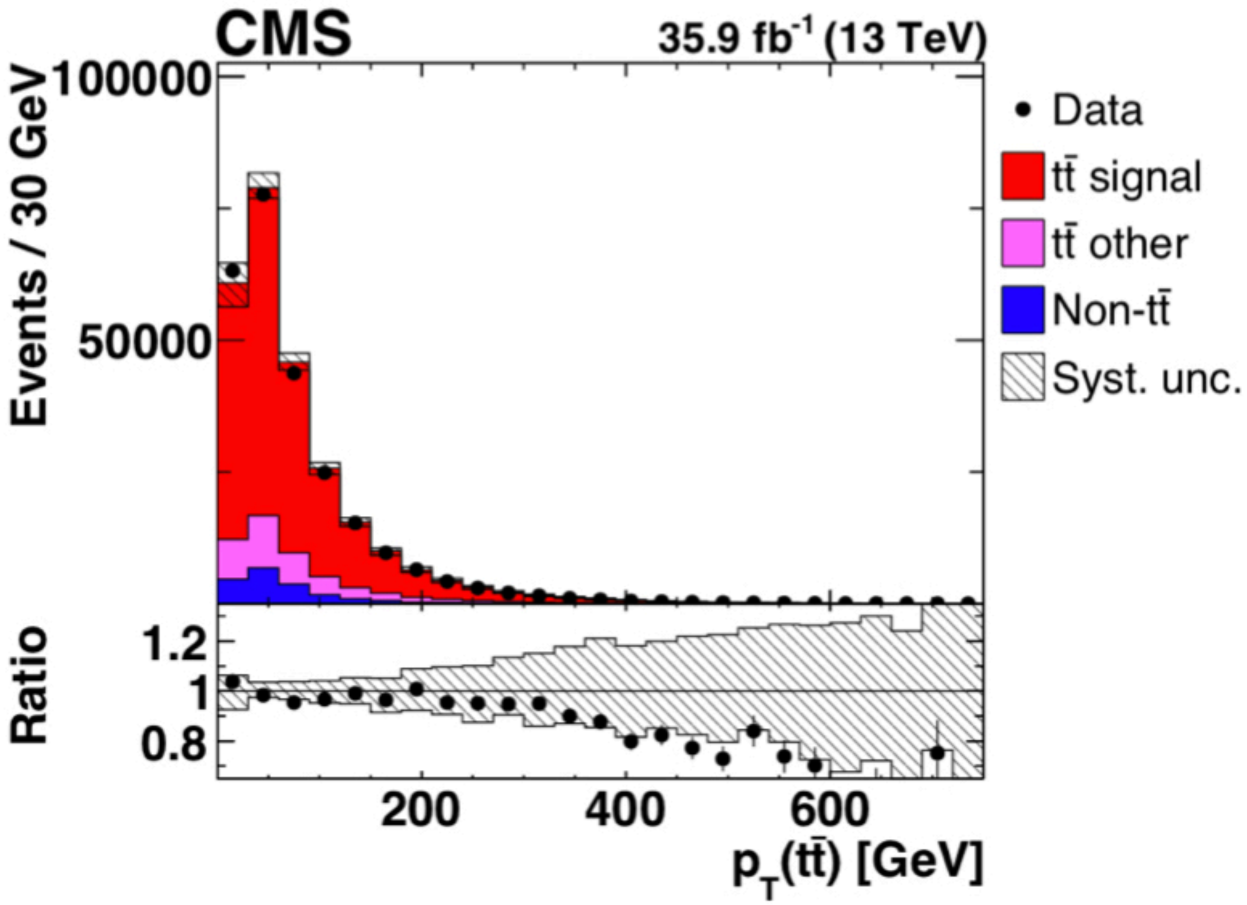
Given all factors that enter in shaping the threshold behaviour at mtt < 400 GeV, it will take some more work to extract robust and precise determinations of m_{top} and other properties (eg y_{top}).

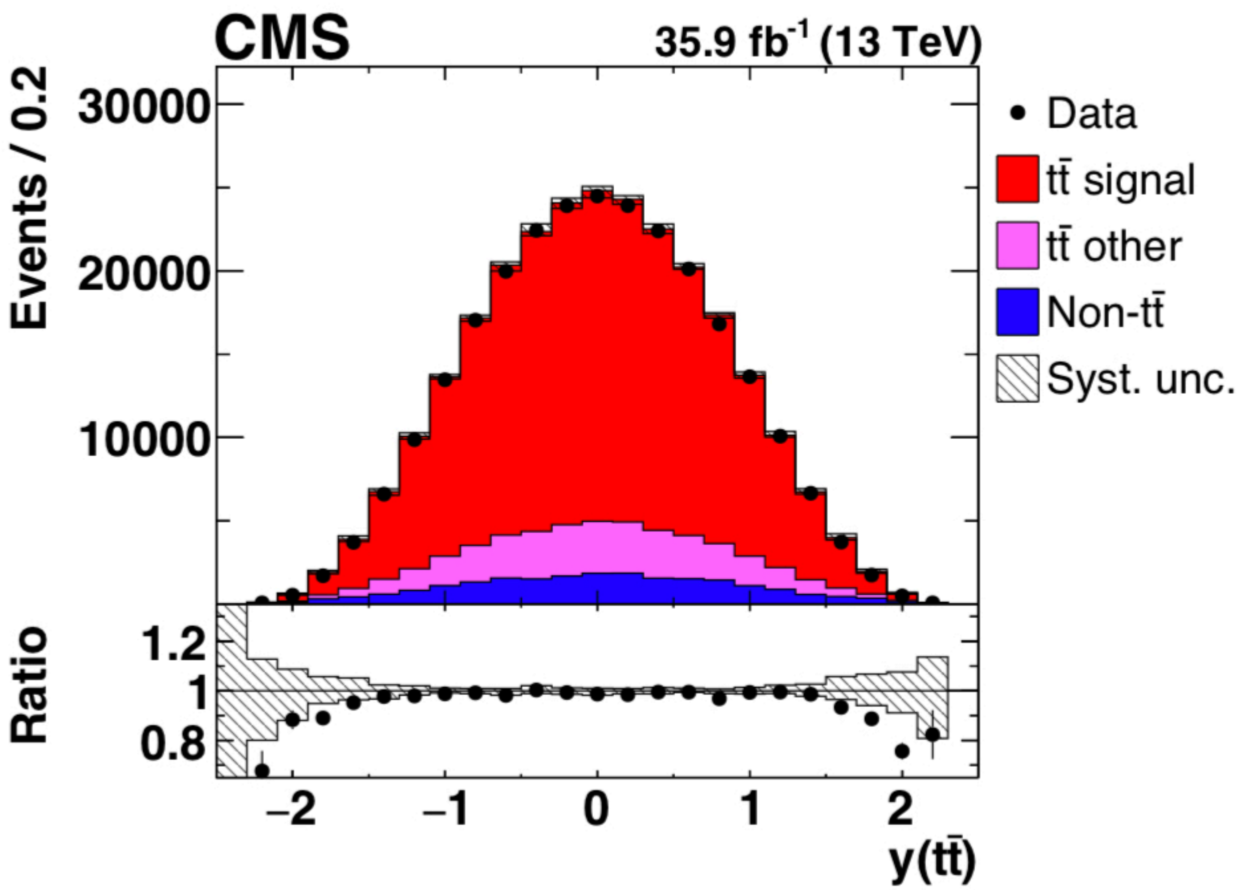
But this is a super-interesting dynamical region to explore!

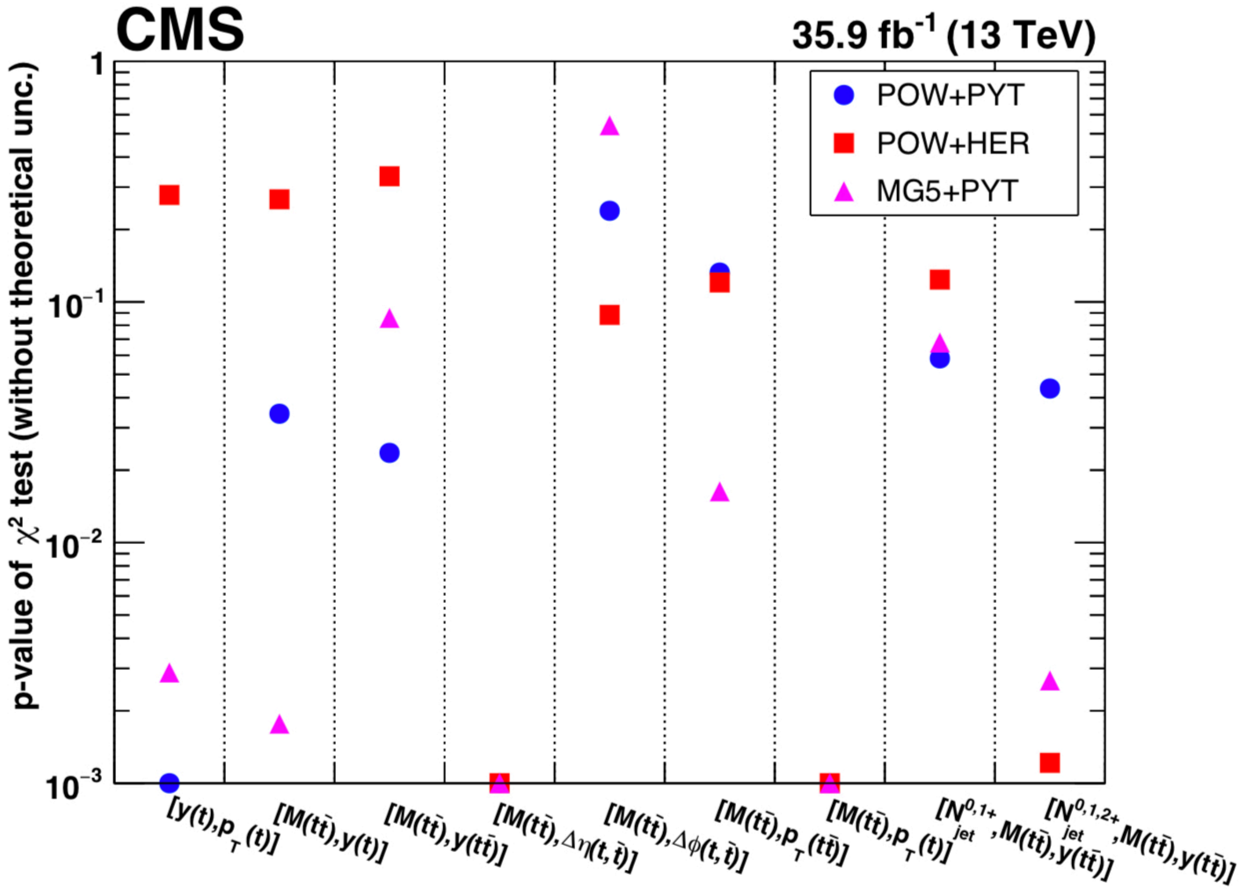
CMS: fitting m_t, α_S, PDF from ttbar production

http://arxiv.org/abs/arXiv:1904.05237









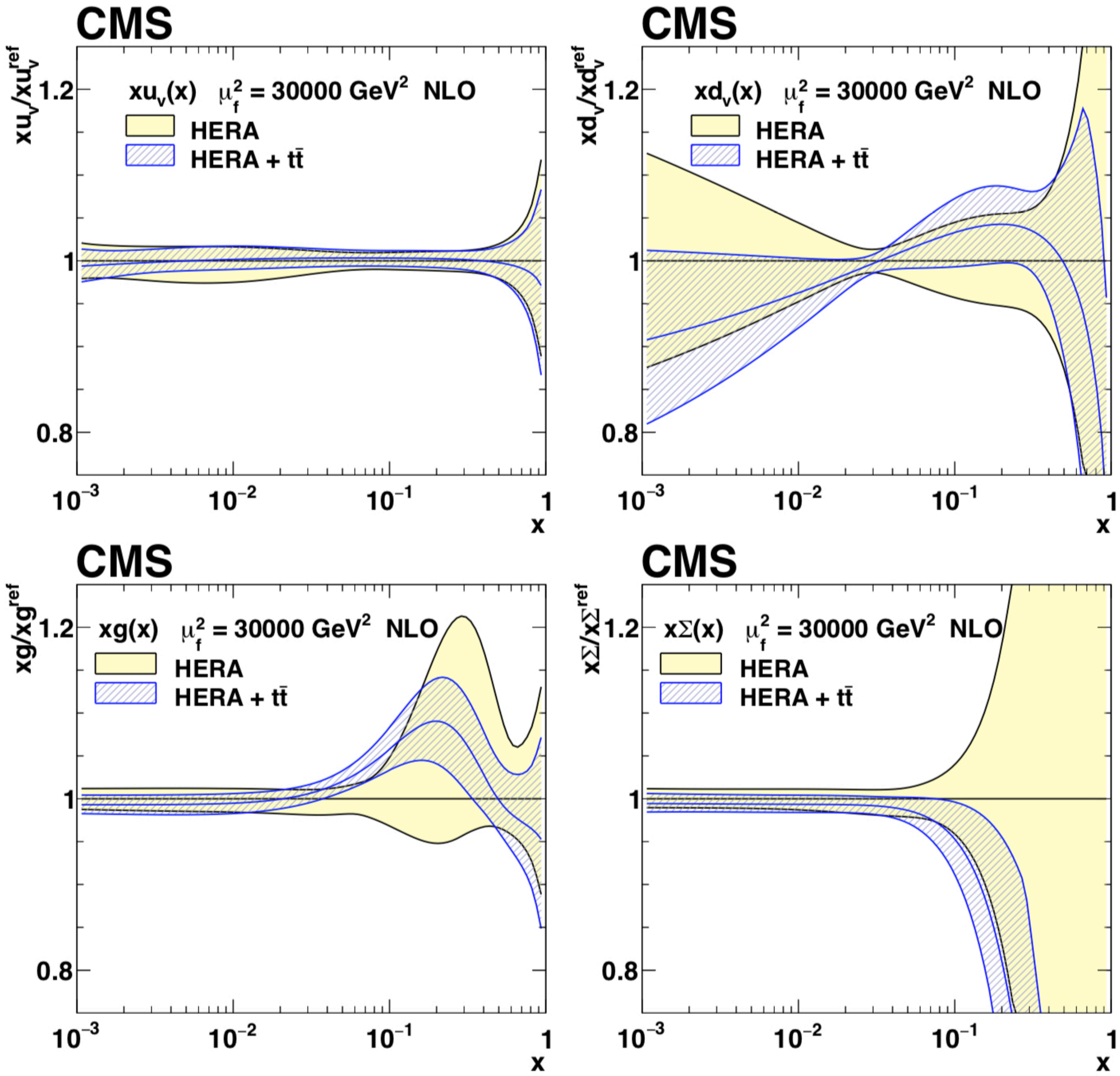
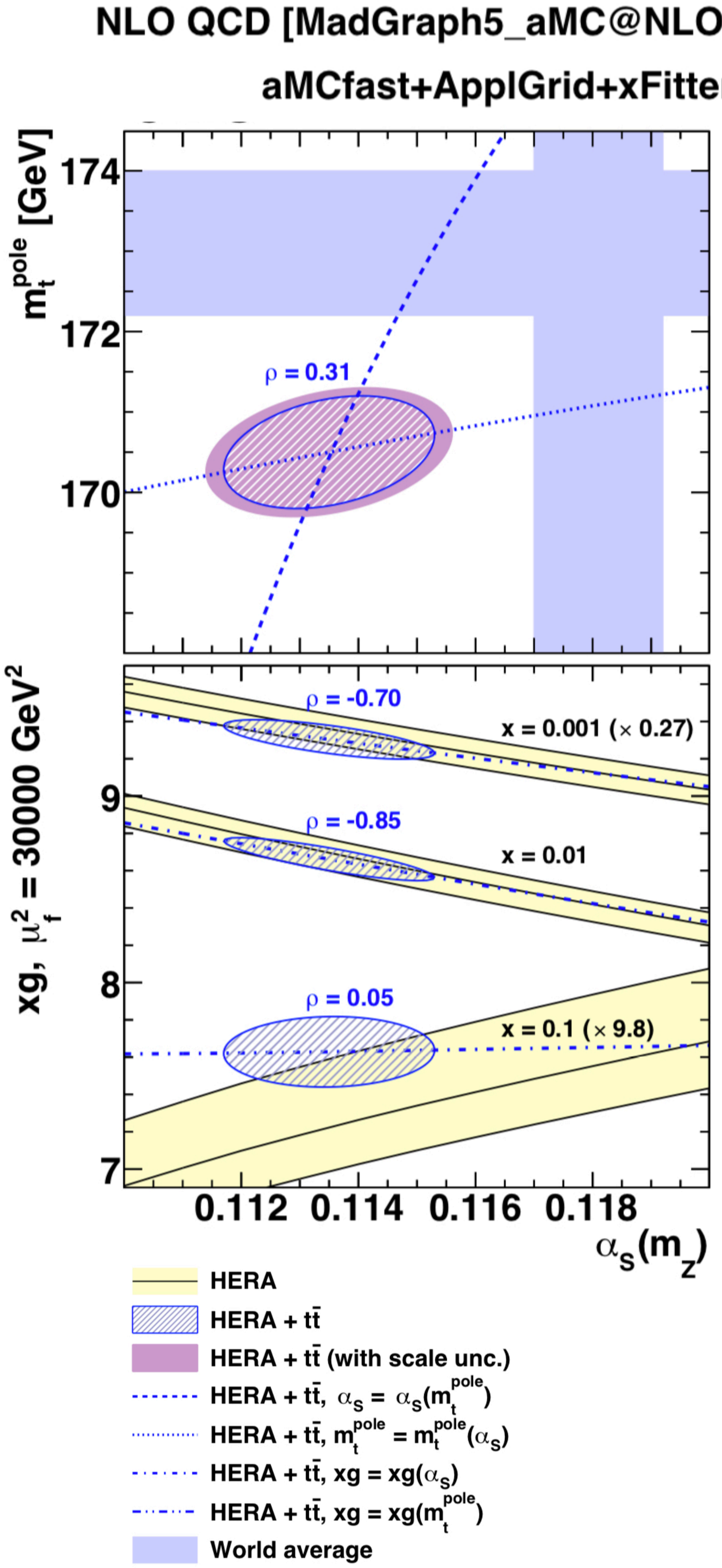


Figure 22: The PDFs with their total uncertainties in the fit using the HERA DIS data only, and the HERA DIS and $t\bar{t}$ data. The results are normalised to the PDFs obtained using the HERA DIS data only.



Challenge of these works: hard to assess that we're not fitting away in the PDF or m_t some inadequacy of the TH modeling….

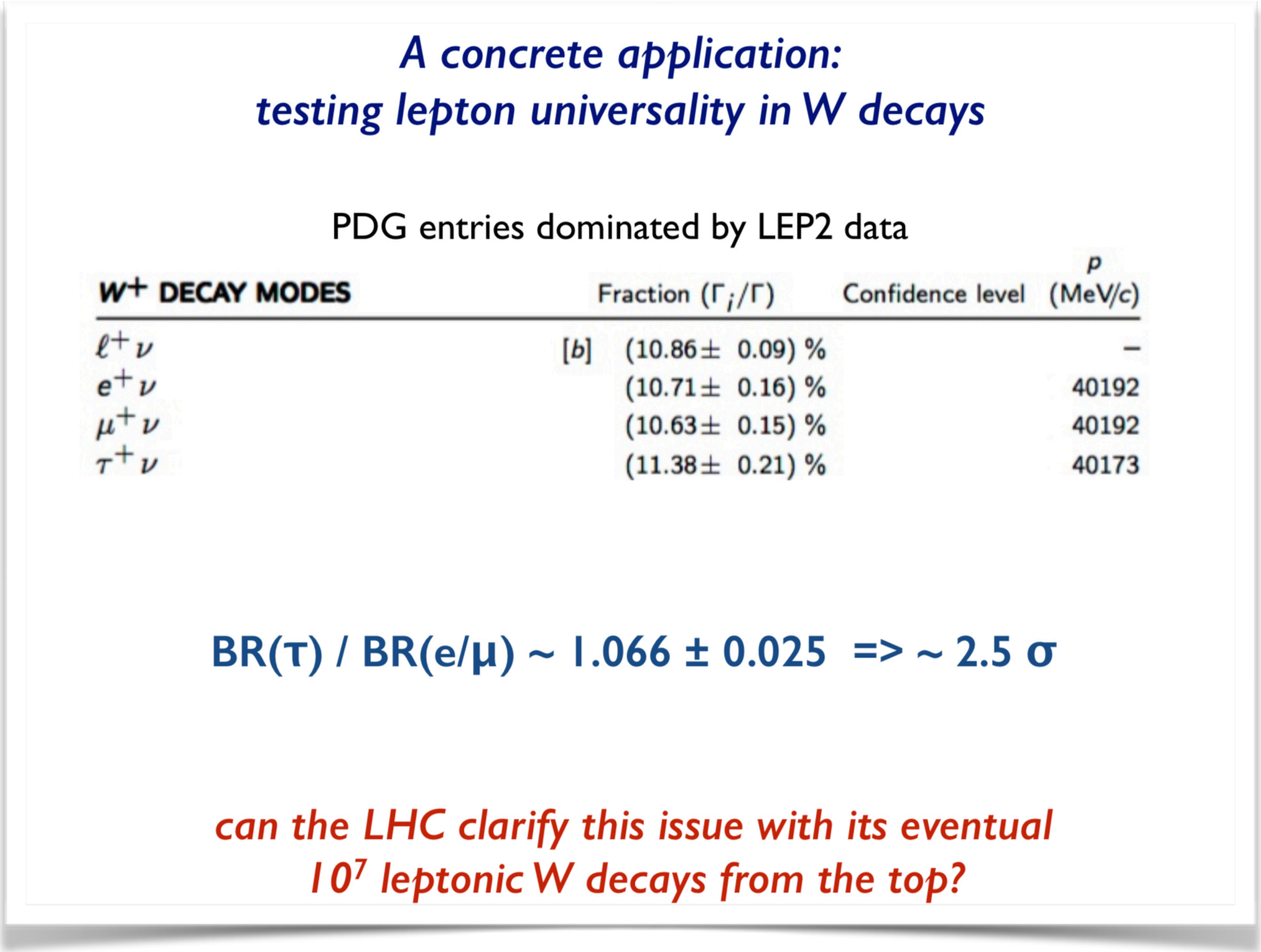
More varied use of top quark events

σ_{tot}(14 TeV) ~ 1 nb

- 3×10^9 top pairs produced in 3 ab^{-1}
- ⇒ O(10^8) events triggered with one top fully reconstructed and charge-tagged, to allow the fully inclusive study of the second top decay.
- In addition to the search for non-(t→Wb) decays, study:
  - O(10^8) fully inclusive t→Wb decays
    - 10^8 fully charge-tagged b hadrons
    - rare and forbidden W decays
    - 3 10^7 W→charm (exercise charm-tagging algos ?)
    - **10^7 W→tau decays**

only with the top …

From a talk I gave at SEARCH2016 in Oxford, inspired by remarks by Roberto Tenchini:



A concrete application:
testing lepton universality in W decays

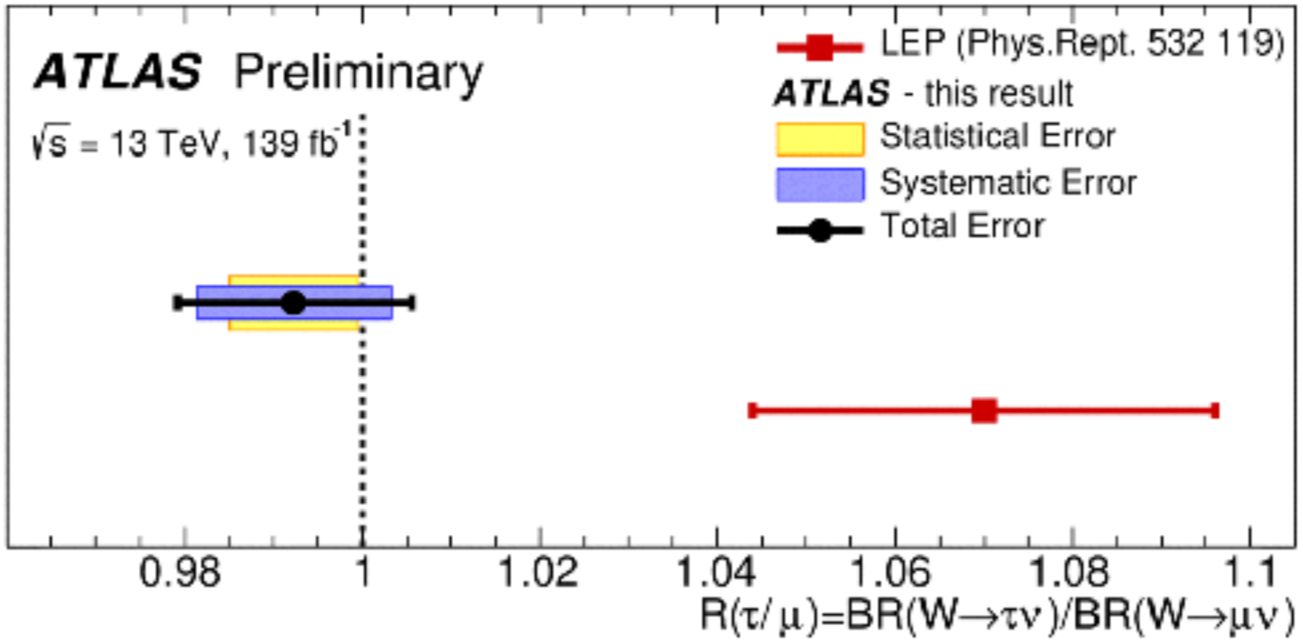
PDG entries dominated by LEP2 data

W^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\ell^+\nu$	[b]	(10.86 ± 0.09) %		–
$e^+\nu$		(10.71 ± 0.16) %		40192
$\mu^+\nu$		(10.63 ± 0.15) %		40192
$\tau^+\nu$		(11.38 ± 0.21) %		40173

BR(τ) / BR(e/μ) ~ 1.066 ± 0.025 => ~ 2.5 σ

can the LHC clarify this issue with its eventual 10^7 leptonic W decays from the top?

ATLAS 2020: https://arxiv.org/abs/2007.14040



LEP:
***BR*(W→τν)/*BR*(W→μν) = 1.066 ± 0.025**

ATLAS:
***BR*(W→τν)/*BR*(W→μν) = 0.992 ± 0.013**

what more, with higher stat ?

- improve the precision
- study the τ spectrum
    - explore possible scalar couplings ($t \rightarrow bH^{\pm}$ [$\rightarrow \tau\nu$]) through
        - τ momentum
        - spin correlations

More opportunities with W decays

Exclusive decays (eg $W \to \pi^\pm \gamma$, 3π)

CMS PRL 122, 151802 (2019), 77fb^{-1} @ 13 TeV :

$$BR(W \to 3\pi) < 1.01 \times 10^{-6}$$

*** what is the ultimate sensitivity? Use of W from t decays?**

*** these measurements help validating the TH estimates of exclusive Higgs decays, relevant to understand $H \to V\gamma$ ($V=\rho, \varphi, \psi$)**

few words in relation to the Higgs

I won’t even try to touch on the infinite literature and immense work that’s being put into sharpening the tools for precision Higgs physics at the LHC and beyond!

Importance of standalone precise “ratios-of-BRs" measurements:

- independent of α_S, m_b, m_c, Γ_{inv} systematics
- sensitive to BSM effects that typically influence BRs in different ways. Eg

BR(H→γγ)/BR(H→ZZ*)

loop-level tree-level

BR(H→μμ)/BR(H→ZZ*)

2nd gen’n Yukawa gauge coupling

BR(H→γγ)/BR(H→Zγ)

different EW charges in the loops of the two procs

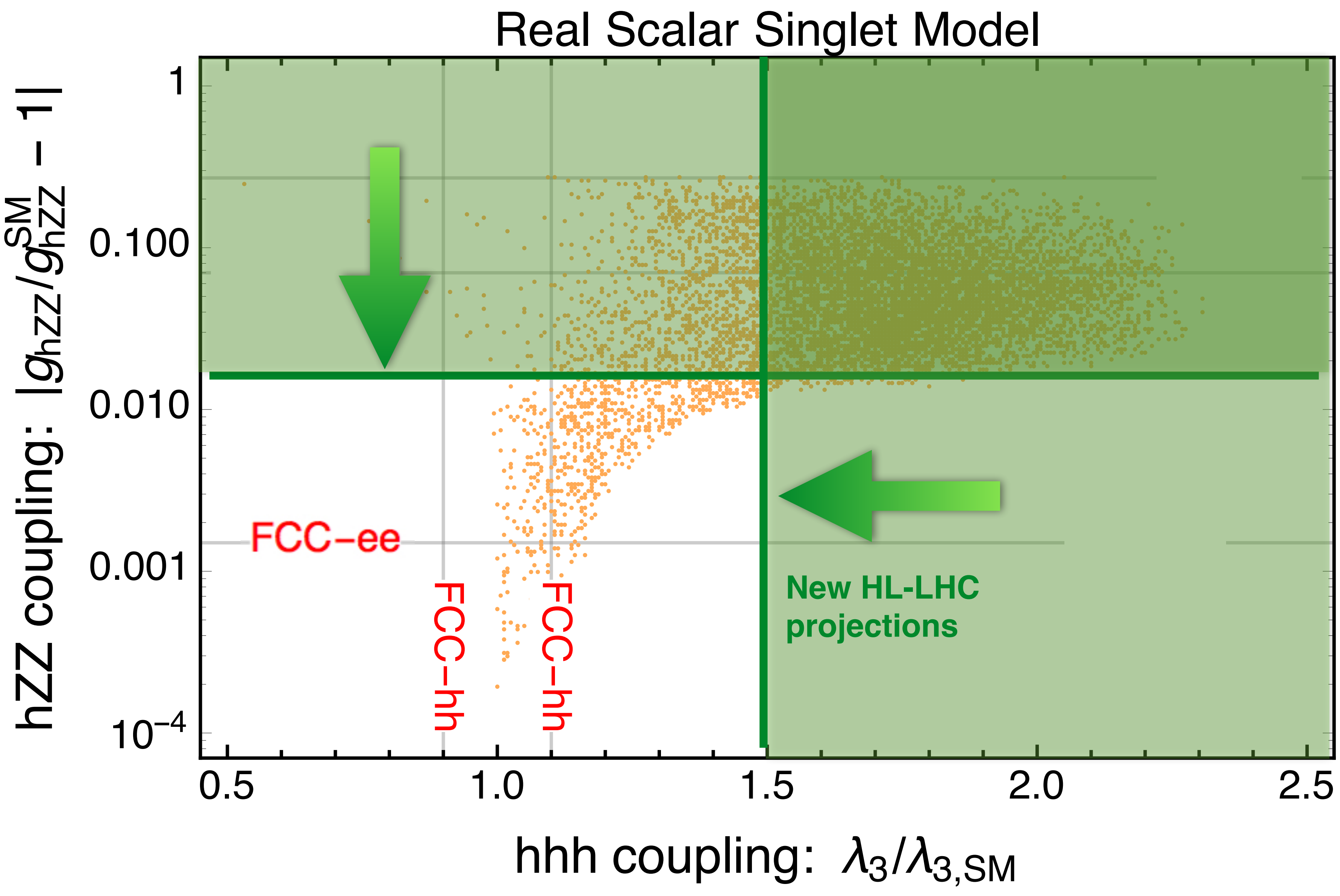
BR(H→inv)/BR(H→γγ)

tree-level neutral loop-level charged

Possible work: study impact of precise ratio measurements in the context of specific BSM models, set targets. Any special opportunities?

Constraints on models with 1st order phase transition

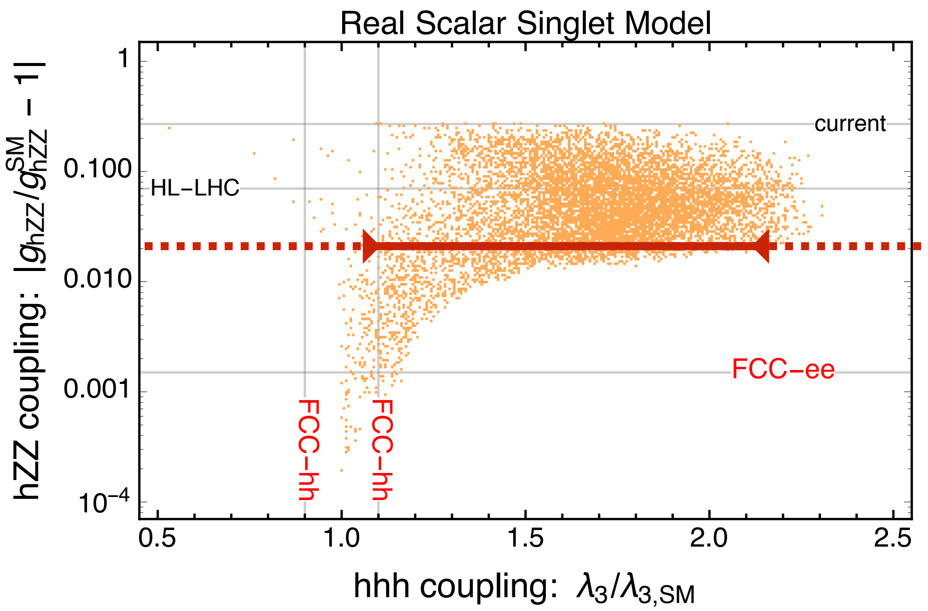
$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$



Bringing the HL-LHC sensitivity to the ±50% level, makes a big dent in this class of BSM models!

Remarks

- Apparently, adding the self-coupling constraint does not add much in terms of exclusion power, wrt the HZZ coupling measurement …
- … BUT, should HZZ deviate from the SM, λ_{HHH} is necessary to break the degeneracy among all parameter sets leading to the same HZZ prediction

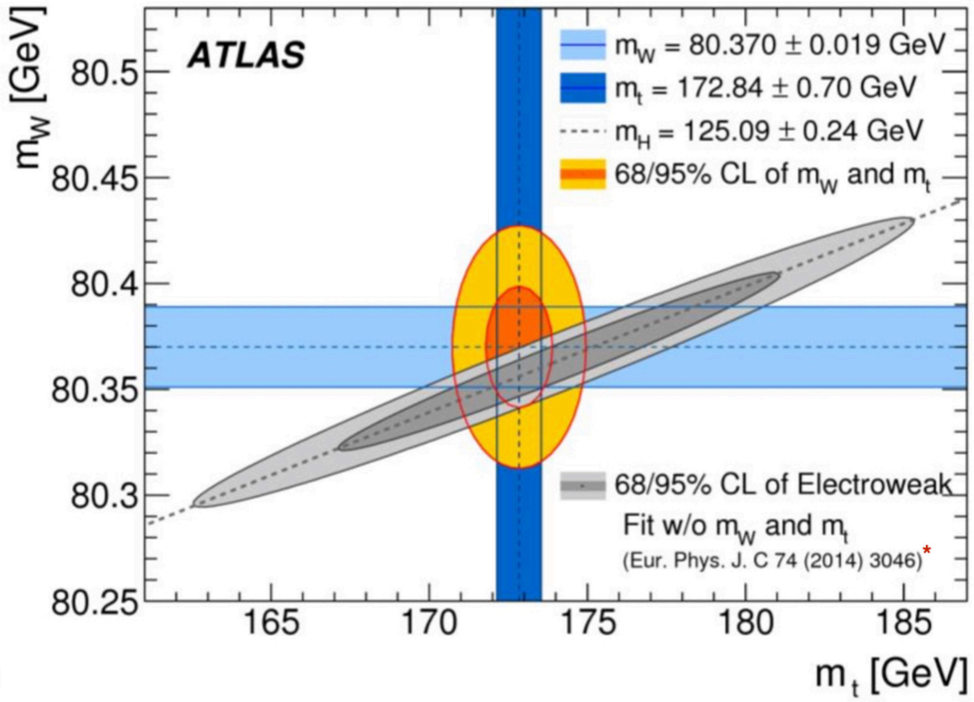


- The concept of *“which experiment sets a better constraint on a given parameter”* is a very limited comparison criterion, which looses value as we move from *“setting limits”* to *“diagnosing observed discrepancies”*
- Likewise, it’s often said that some observable sets better limits than others: “all known models predict deviations in X larger than deviations in Y, so we better focus on X”. But once X is observed to deviate, knowing the value of Y could be absolutely crucial ….
- Redundancy and complementarity of observables is of paramount importance

note

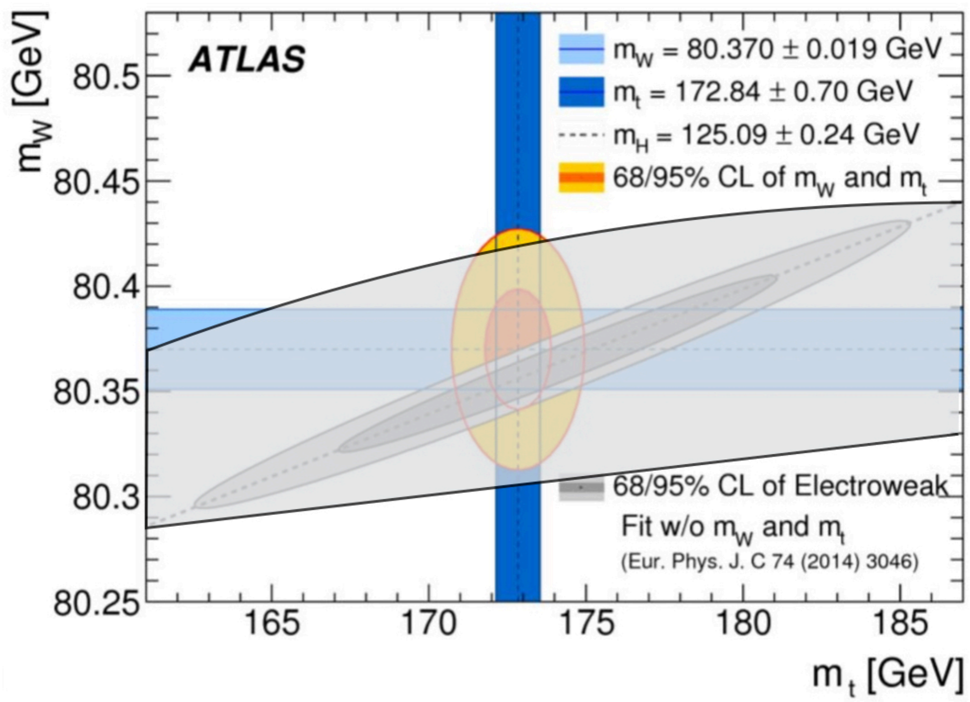
- Even though the Higgs properties appear so far fully SM, even the very knowledge of its mass puts under a different quantitative perspective the relation between m_{top} and m_W, and indirectly constrains BSM scenarios:

EW fit with LHC value of mH



vs

EW fit without LHC value of mH



- More in general, we don't need precise measurements to disagree with the SM, for them to be useful!
  - precise measurements of the SM consistency will, one day, provide critical constraints on BSM models proposed to explain possible future anomalies

Final remarks

- The LHC is so rich, it's hard to get bored!
- Precision is a mantra that allows to explore unexpected avenues, with guaranteed returns in terms of richer and new knowledge
- New physics hides behind every corner at the LHC: so many things we don't know, or don't know ***precisely*** enough!