LoopFest XV summary

Frank Petriello

LoopFest 2016
August 17, 2016

NORTHWESTERN UNIVERSITY

Argonne NATIONAL LABORATORY

- Thanks to the local organizers for such a wonderful conference and venue: Simone Marzani, Tobias Neumann, Vincent Theeuwes, Doreen Wackeroth, Ciaran Williams, Tracy Gasinski, Chang, Jeremy, Jia, Matthew, Michael, Roberto, Syed

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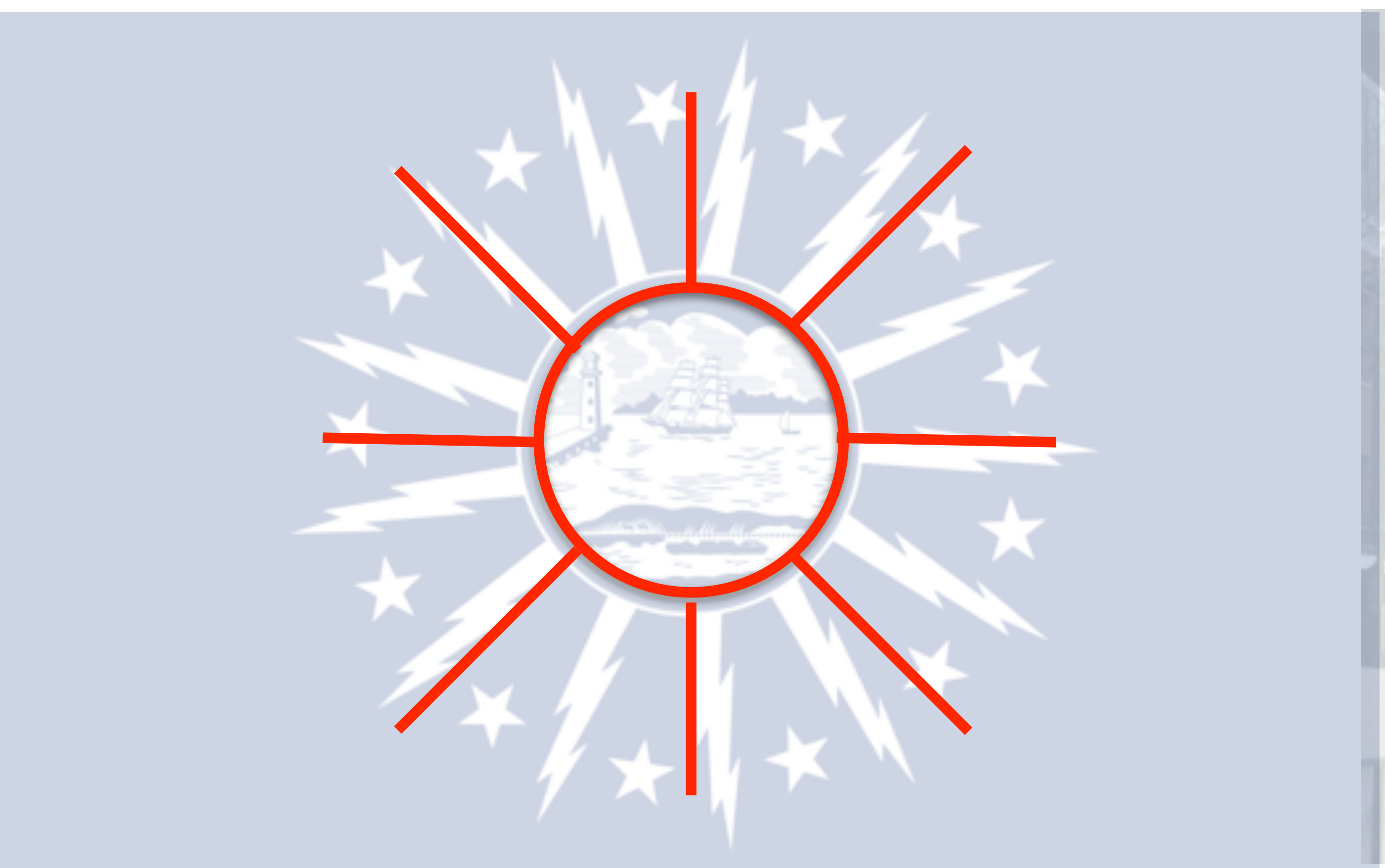
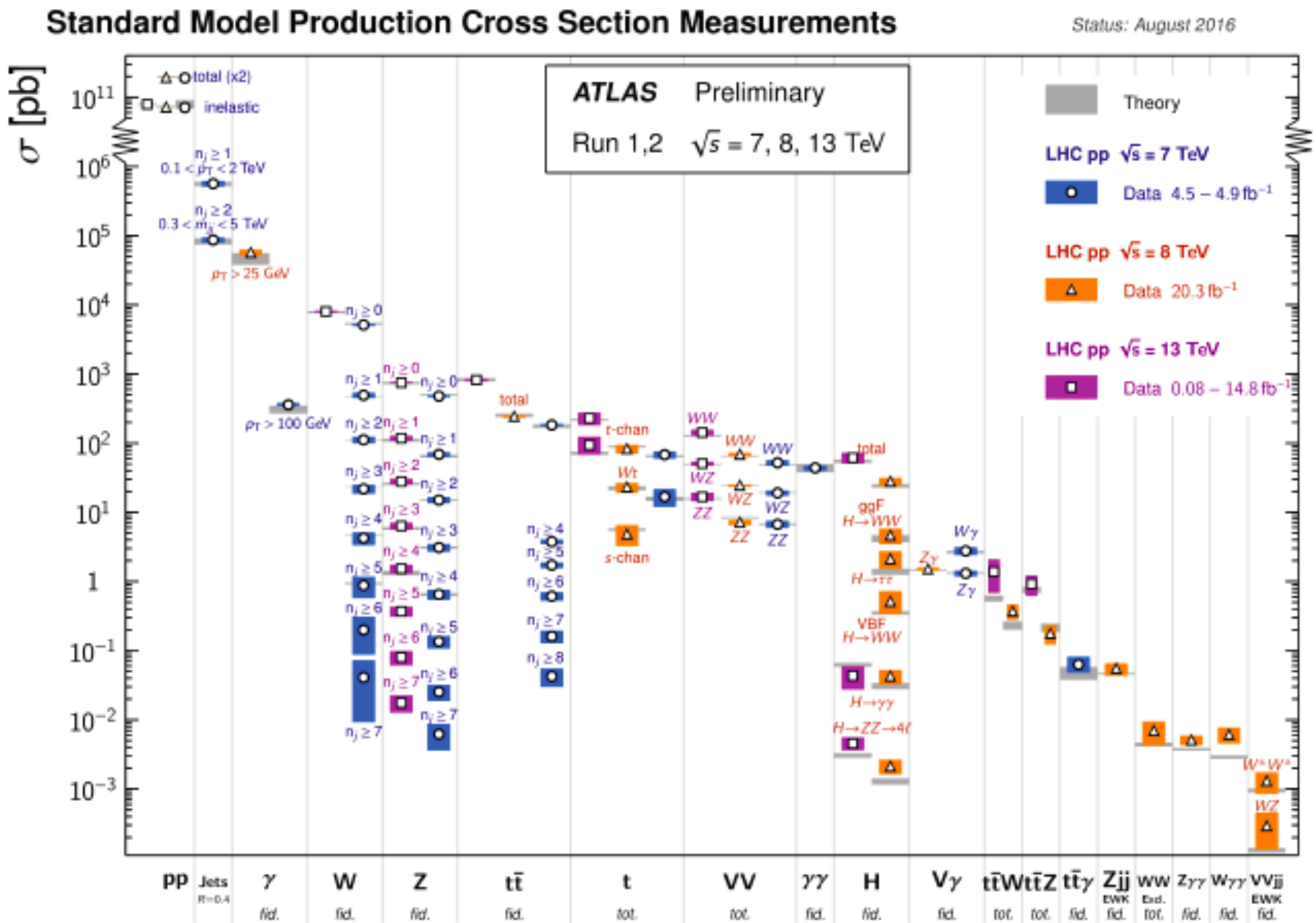


Both legs and loops are a natural fit in Buffalo!

The LHC circa 2016

- Impressive agreement between SM theory and experiment. There is agreement on cross sections spanning many orders of magnitudes and containing numerous final states.



J. Huston

The Lagrangian of Nature?

- With the discovery of a scalar particle having properties consistent with the SM Higgs boson, the Lagrangian of Nature appears complete.

$$\mathcal{L}_h^{SM} = |D_\mu H|^2 - \left(y_u \bar{Q}_L \tilde{H} u_R + y_d \bar{Q}_L H d_R + y_e \bar{L}_L H e_R + h.c.\right) - \lambda \left(H^\dagger H - \frac{v^2}{2}\right)^2$$

- The SM is *predictive*: given m_H, all couplings of the Higgs are now fixed.

$$m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{scale}) \pm 0.02\,(\text{other}) \pm 0.01\,(\text{theory})\ \text{GeV},$$

(ATLAS+CMS, 1503.07589, fit to 4l+2γ)

Tree-level couplings:

$$g_{hf^if^j} = -\frac{g m_f}{2 m_W}\delta^{ij}$$

$$g_{hVV} = g_V m_V$$

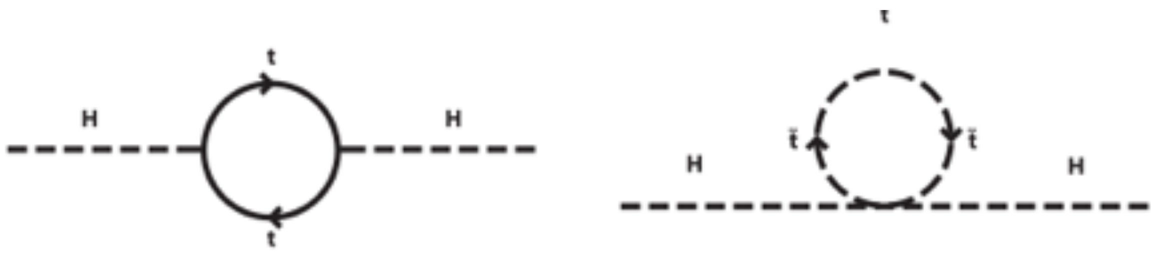
$$g_{hhh} = -\frac{3 m_H^2}{2 m_W}$$

Failures of the Standard Model

- Of course not! Numerous outstanding problems exist in the SM.
  - *Hierarchy problem:* no symmetry prevents the Higgs mass from being dragged by quantum corrections to the GUT/Planck scales

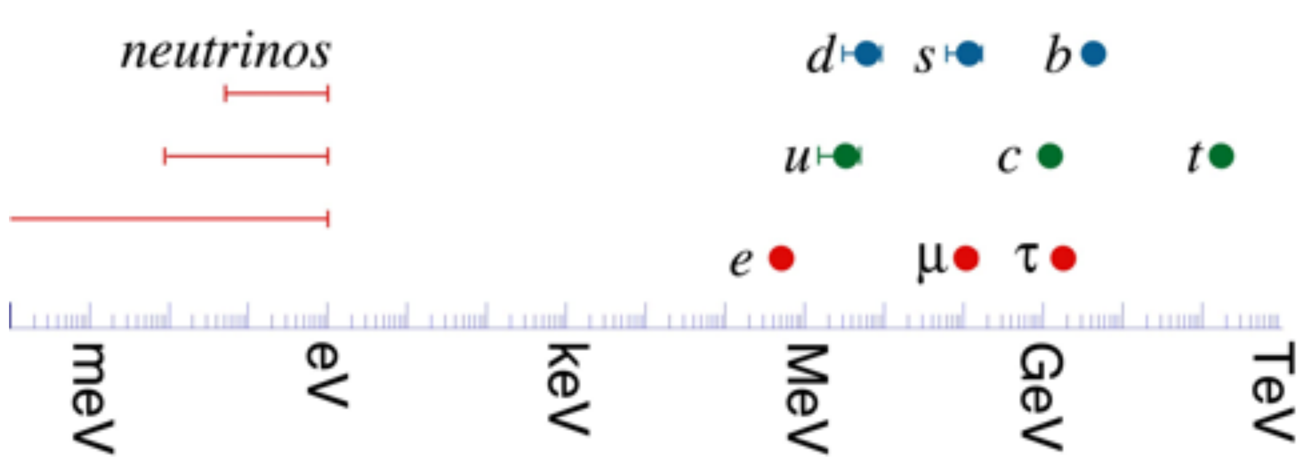
$$M^{gauge,ferm} \sim M^{bare}\{1 + a \ln \Lambda/M\}$$

$$(M^{Higgs})^2 \sim (M^{bare})^2 + \Lambda^2$$

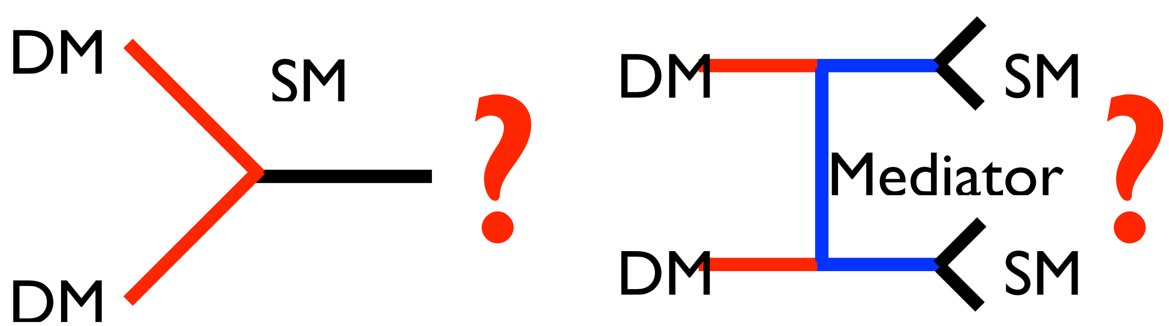


Resolved by TeV scale SUSY?

  - *The flavor puzzle:* what explains the observed masses and mixing?

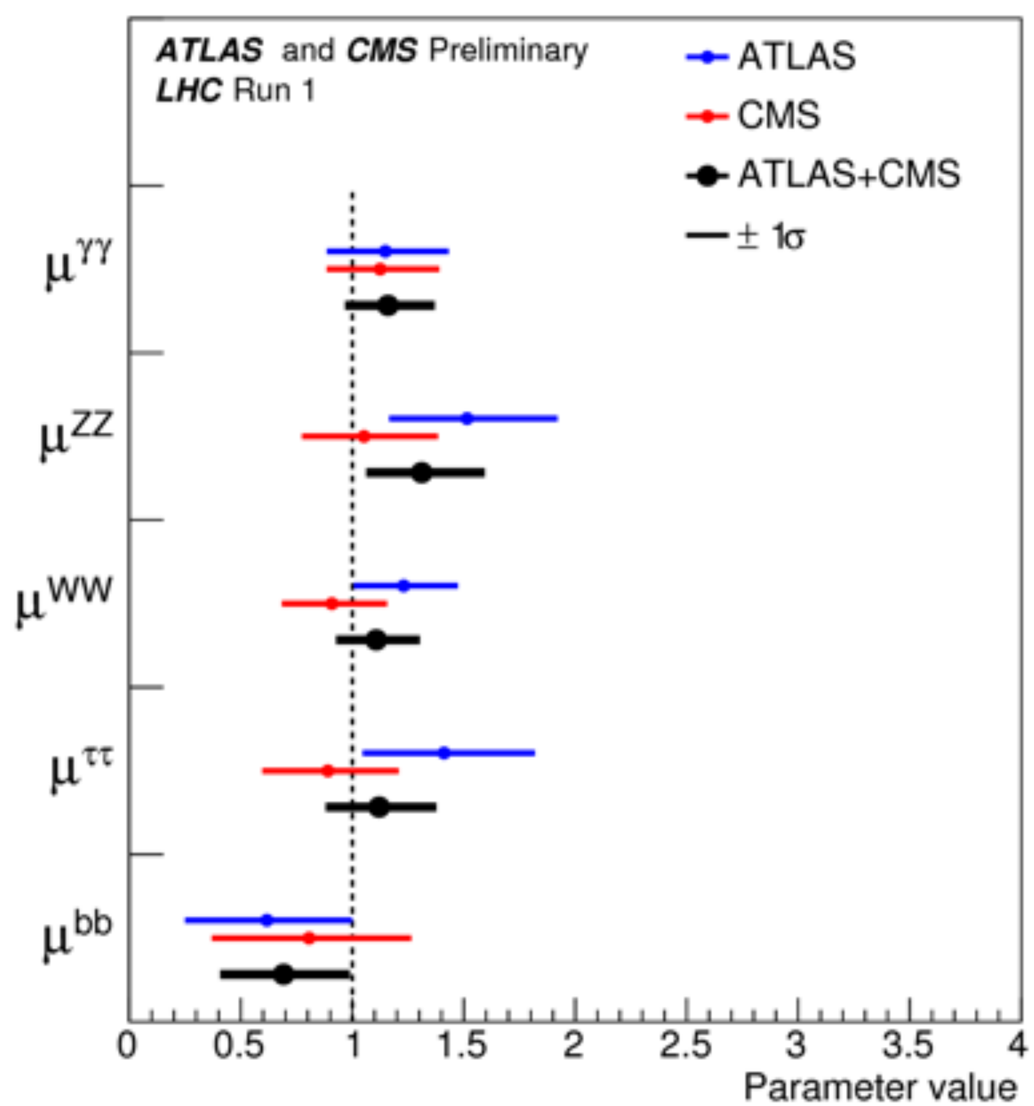


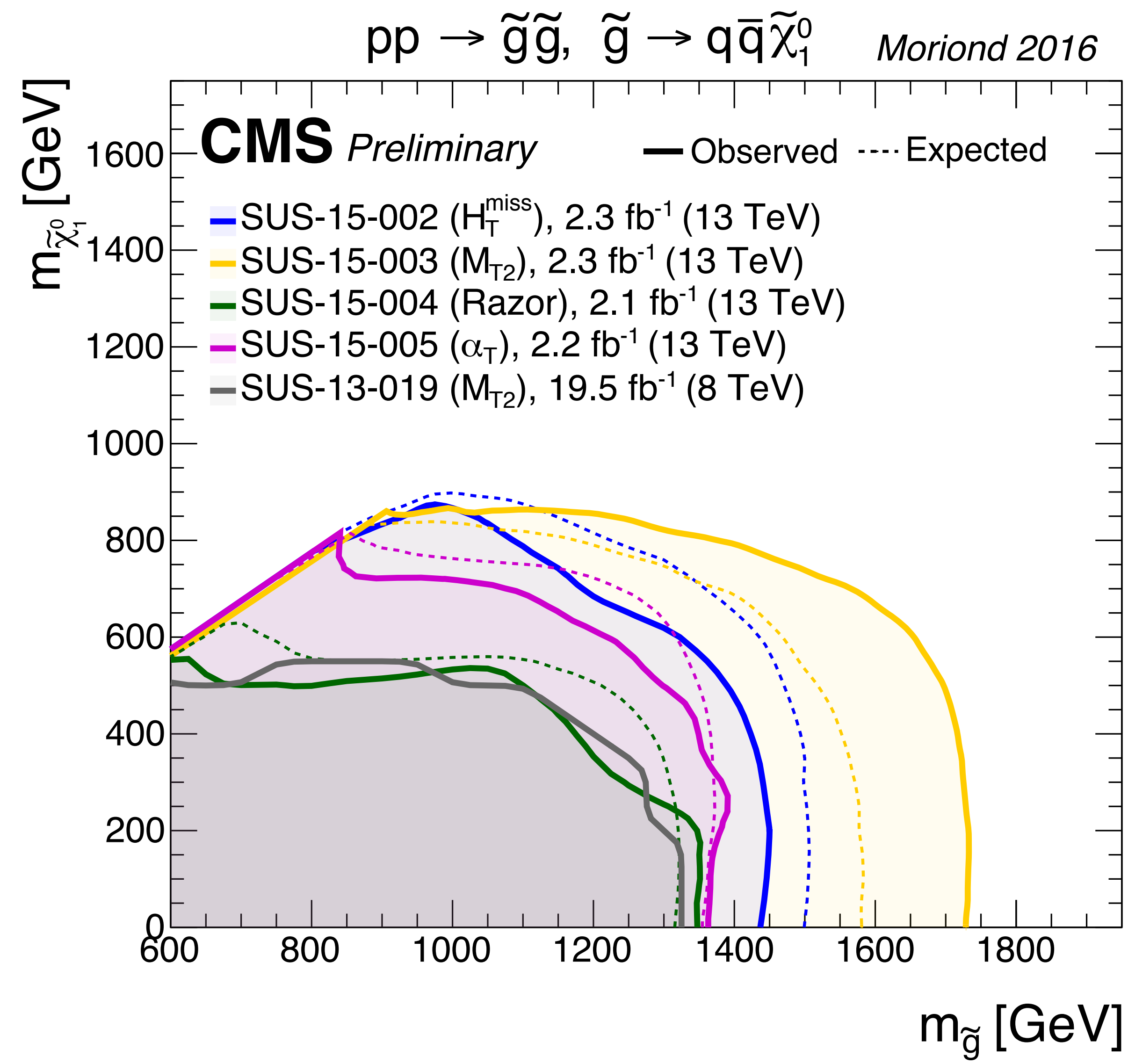
  - *Dark matter:* What are the new degrees of freedom that describe dark matter?



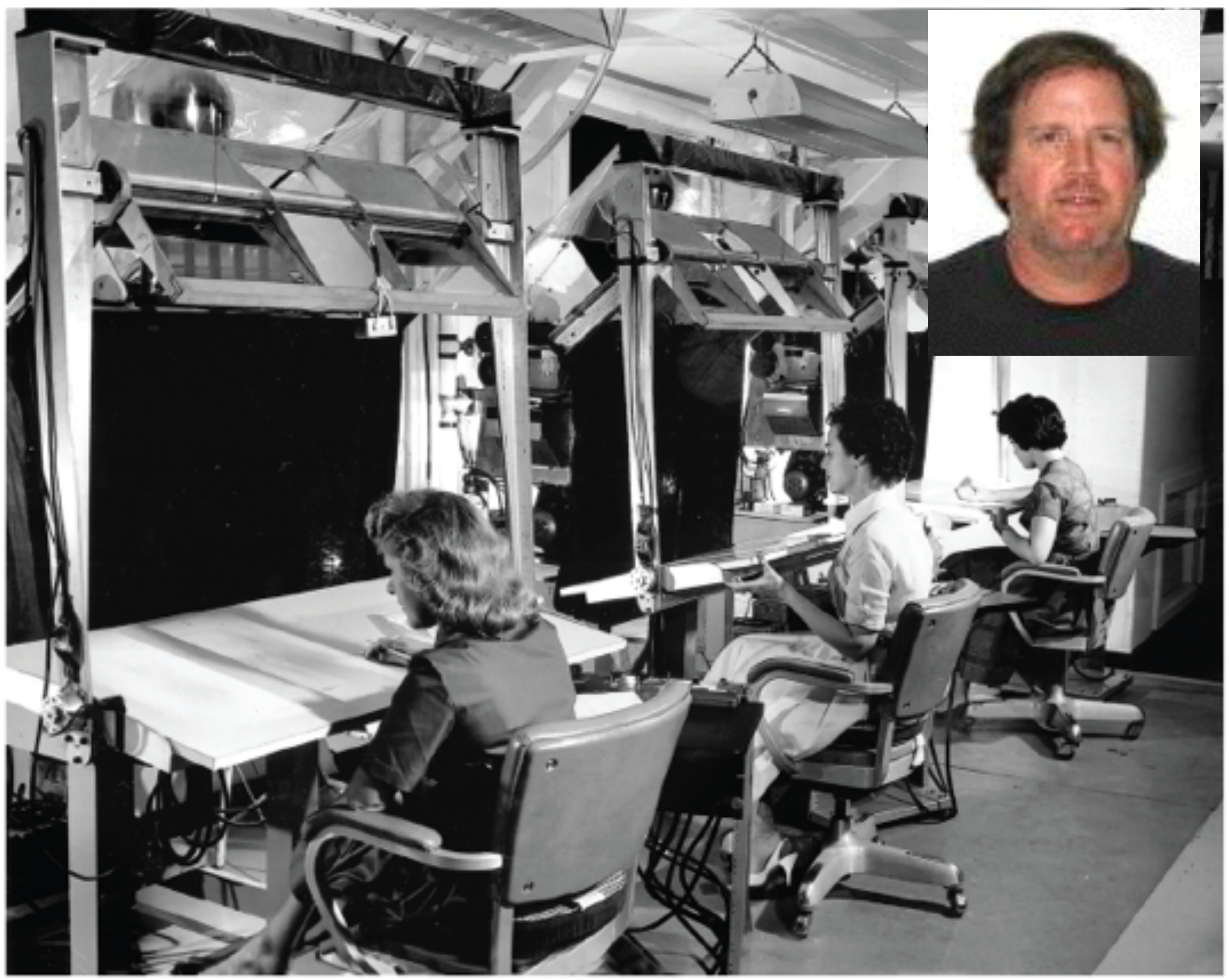
Experimental guidance

- No convincing evidence of new particles or BSM effects; Higgs looks SM-like, limits on SUSY and other new states over a TeV and increasing





If Joey and his group still haven't found any by next LoopFest:



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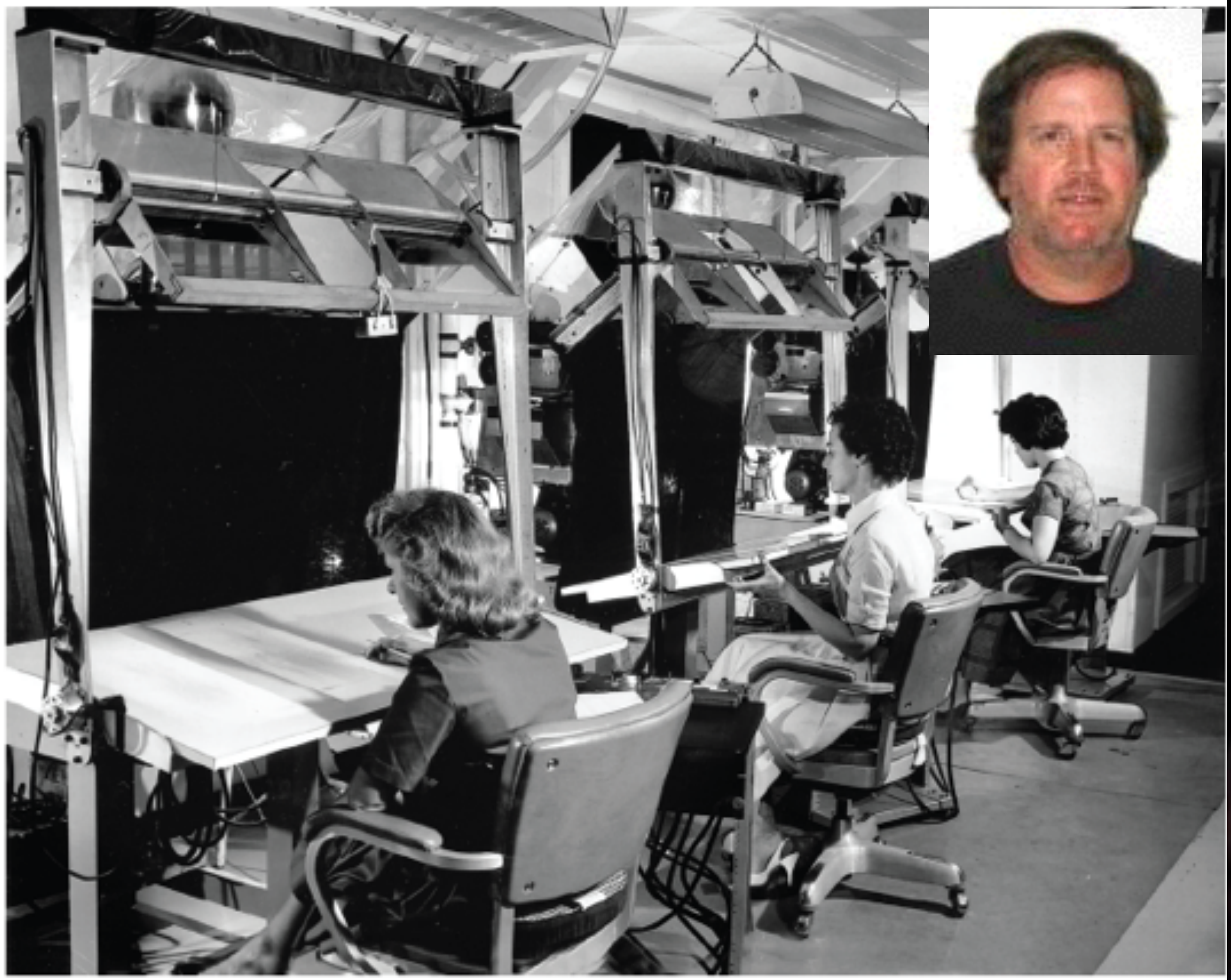
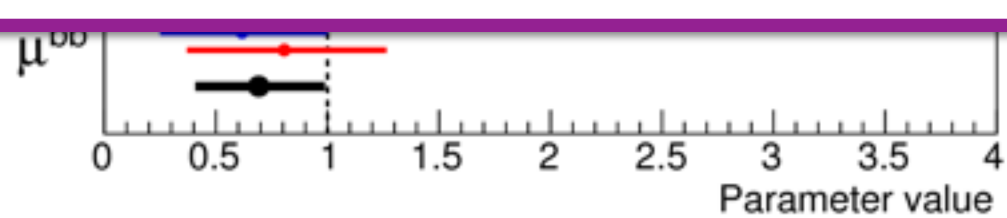


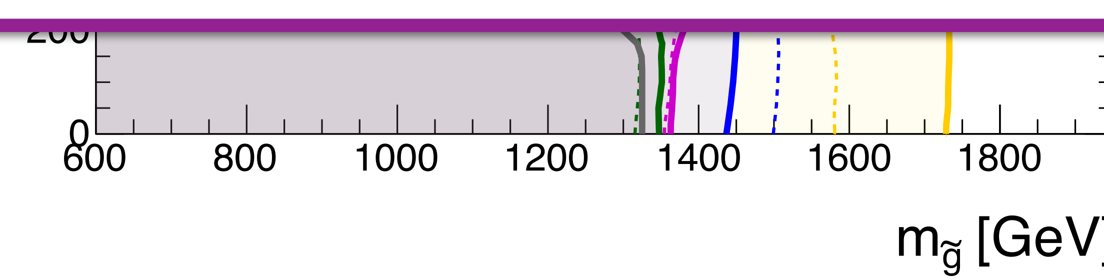
Experimental guidance

- No convincing evidence of new particles or BSM effects; Higgs looks SM-like, limits on SUSY and other new states over a TeV and increasing

Precision searches for subtle deviations from the SM that point to resolutions of these issues will become evermore important during Run II, especially if we continue to see no obvious new physics.

The work done by the LoopFest community has never been more important!





Fixed-order QCD calculations

- As many talks on NNLO results/codes as NLO

NLO:

- Jean-Nicolas Lang: RECOLA
- Raoul Roentsch: NLO for $gg \to VV$
- Christian Weiss: NLO in WHIZARD
- Lars Hofer: Collier
- Christian Reuschle: QCD and EW NLO with NLOX

NNLO:

- Walter Giele: MCFM@NNLO
- Alexander Huss: Z+j@NNLO
- Xiaohui Liu: NNLO with N-jettiness
- Marius Wiesemann: NNLO with MATRIX
- David Heymes: NNLO with STRIPPER

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NNLO session starting to have the same acronym soup as the NLO one:

STRIPPER: ?

(To the authors: what goes in this space?)

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hep-ph/9905323
May 1999

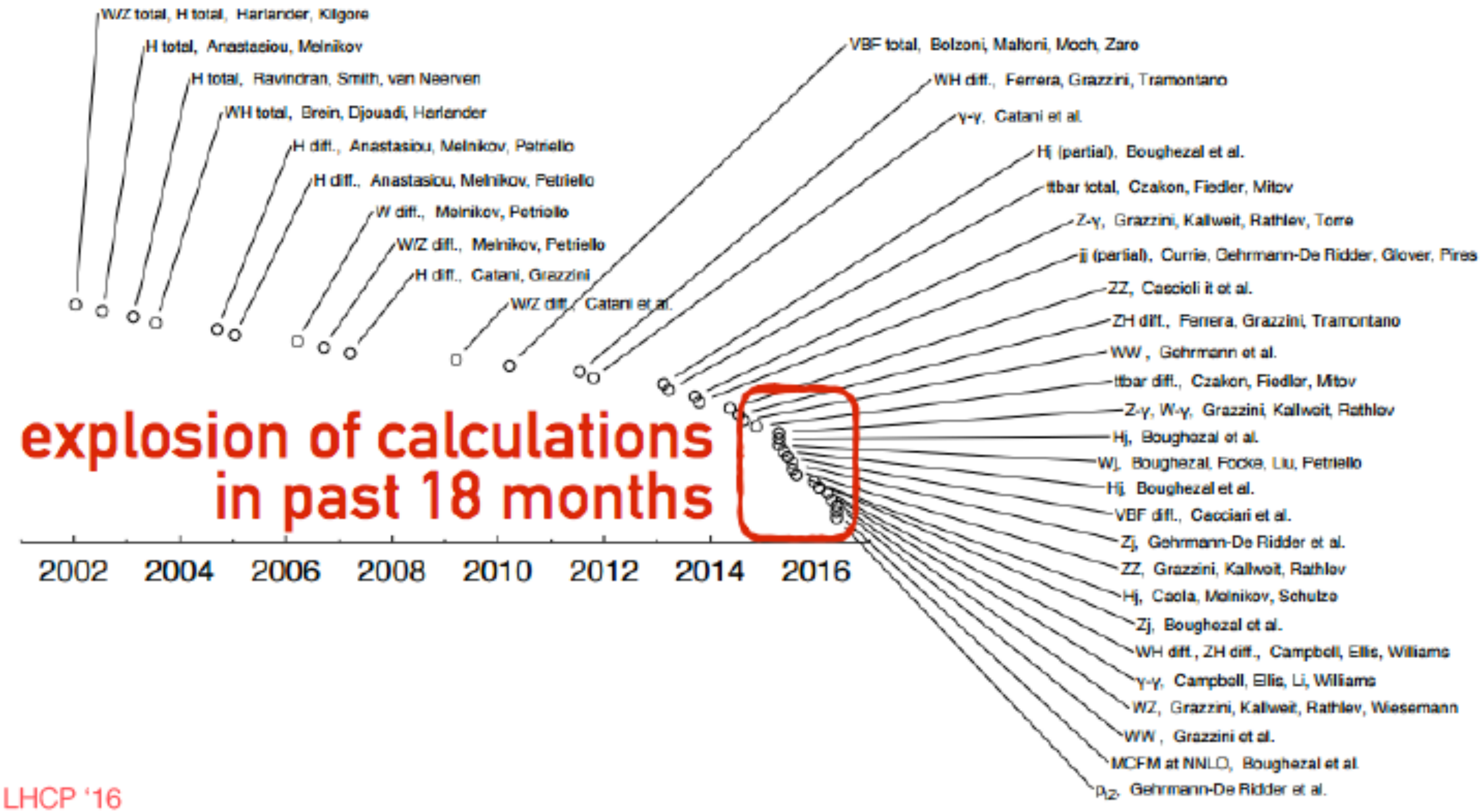
Analytical Result for Dimensionally Regularized
Massless On-shell Double Box

V.A. Smirnov[1]

Nuclear Physics Institute of Moscow State University
Moscow 119899, Russia

Abstract

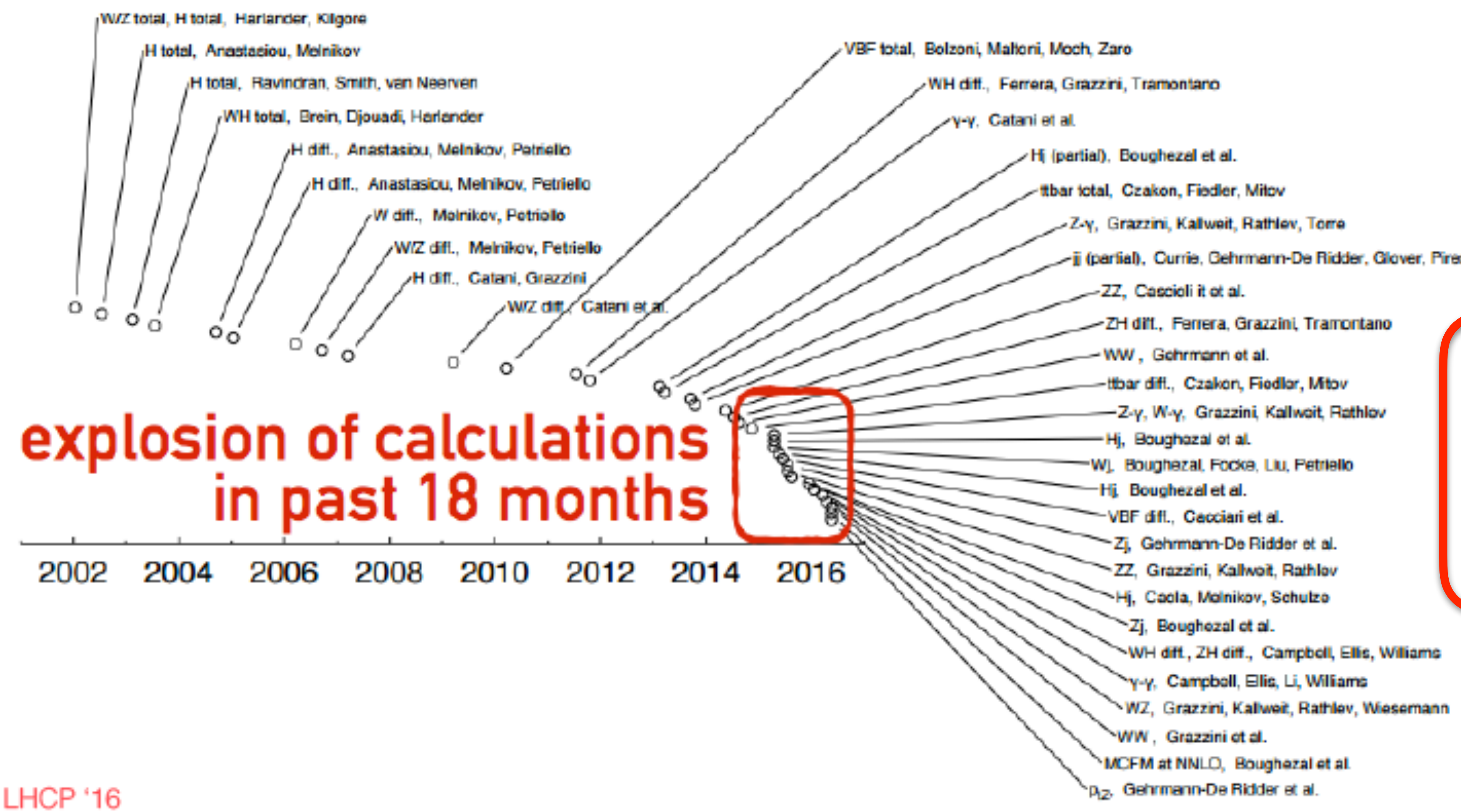
17 years after double-box breakthrough, NNLO QCD pheno for 2→2 is arriving in time for high-precision LHC data



Salam, LHCP '16

From L. Dixon, 2013 LoopFest closing talk:

- 2013 will be remembered as the year of $2 \rightarrow 2$ at NNLO



Salam, LHCP '16

False start by a few years! 2016 gets the medal

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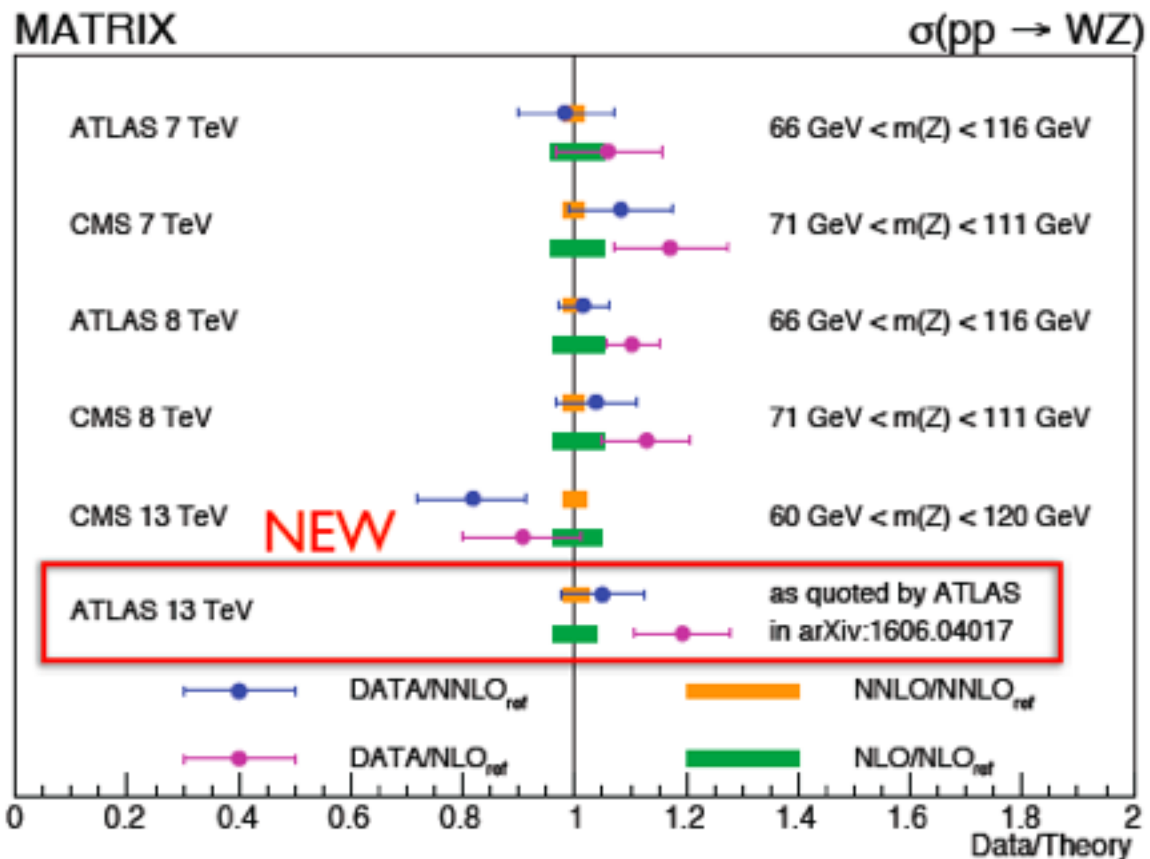
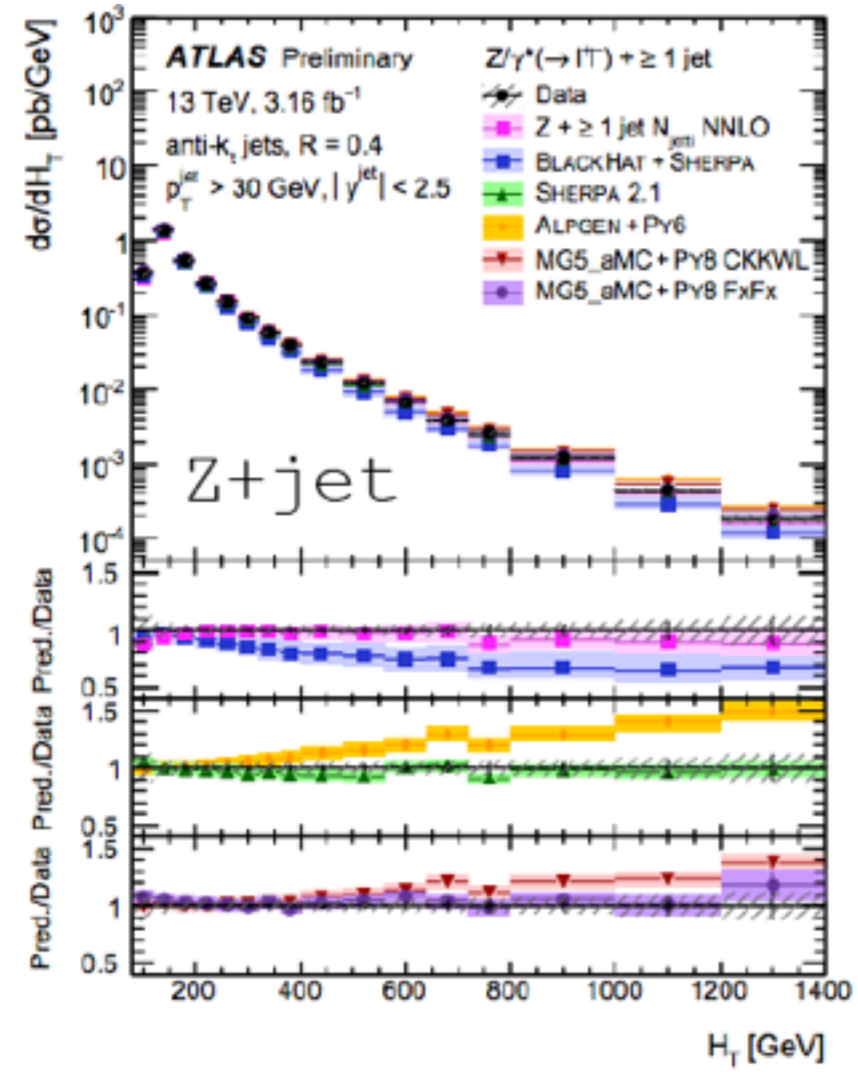
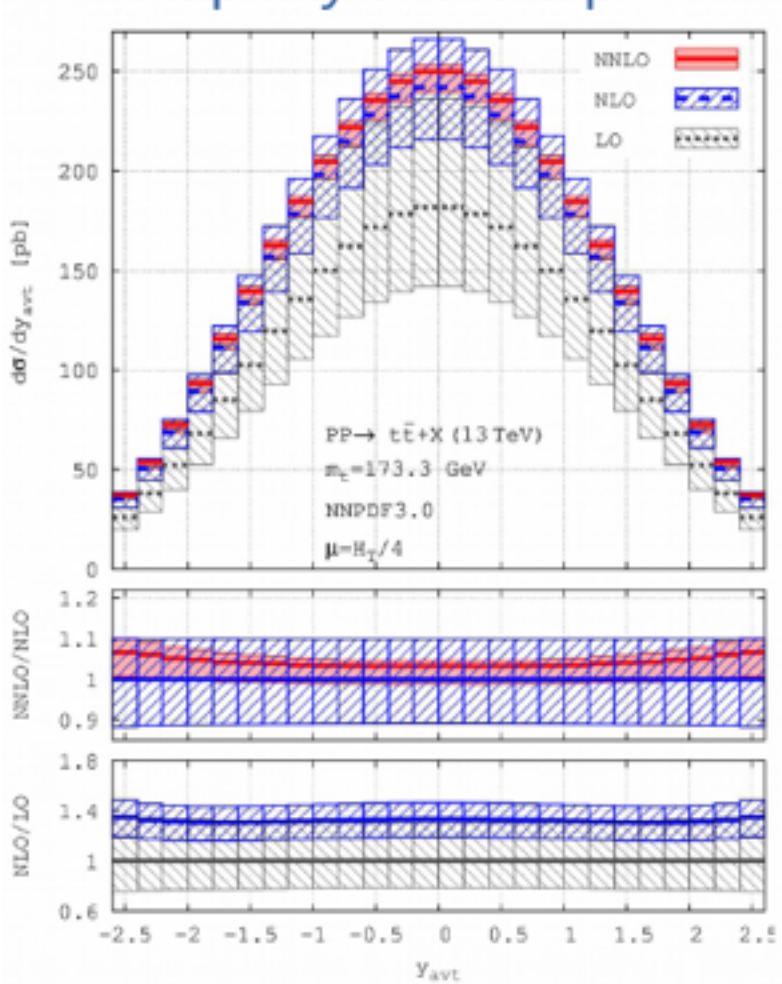


M. Wiesemann

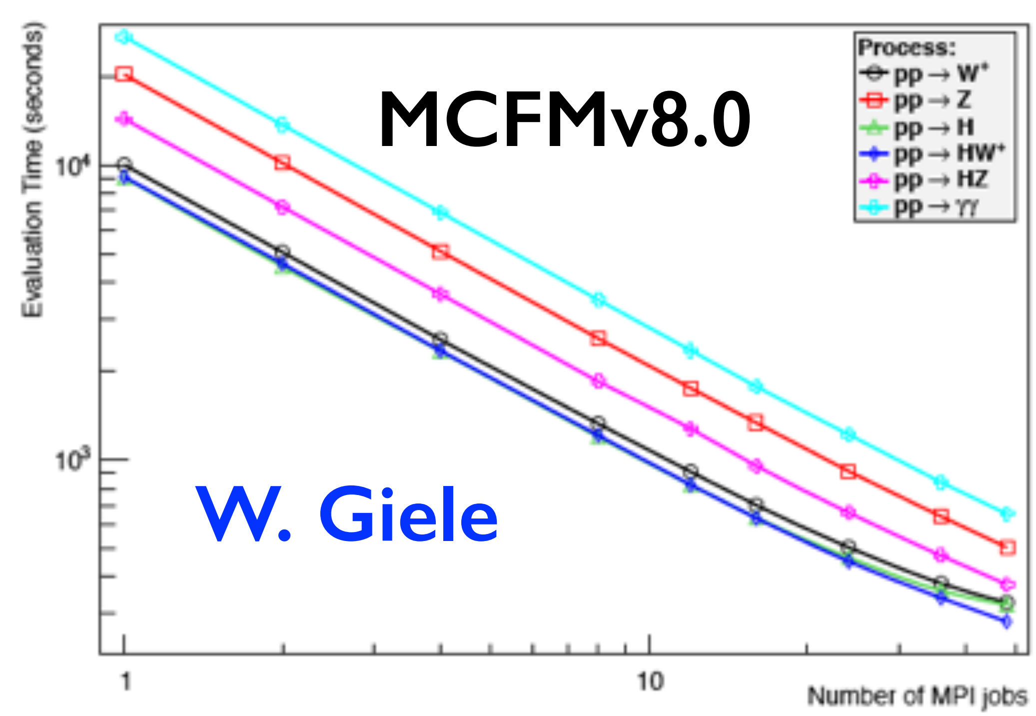


X. Liu

Rapidity of the top



D. Heymes

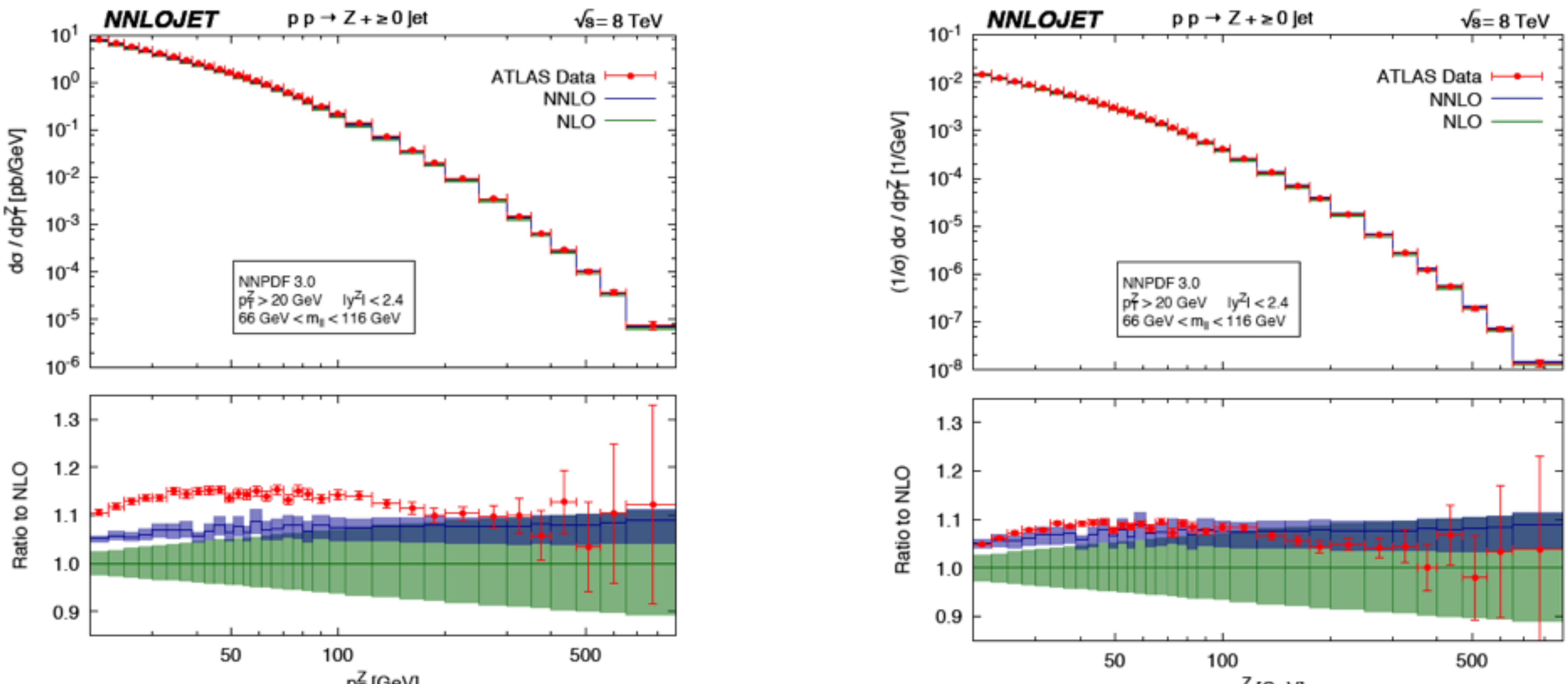


W. Giele

The Z-boson p_T spectrum

- The sub-percent experimental precision make this a stringent precision test of the SM, and illustrates the challenges to further improving precision at Run II

A. Huss

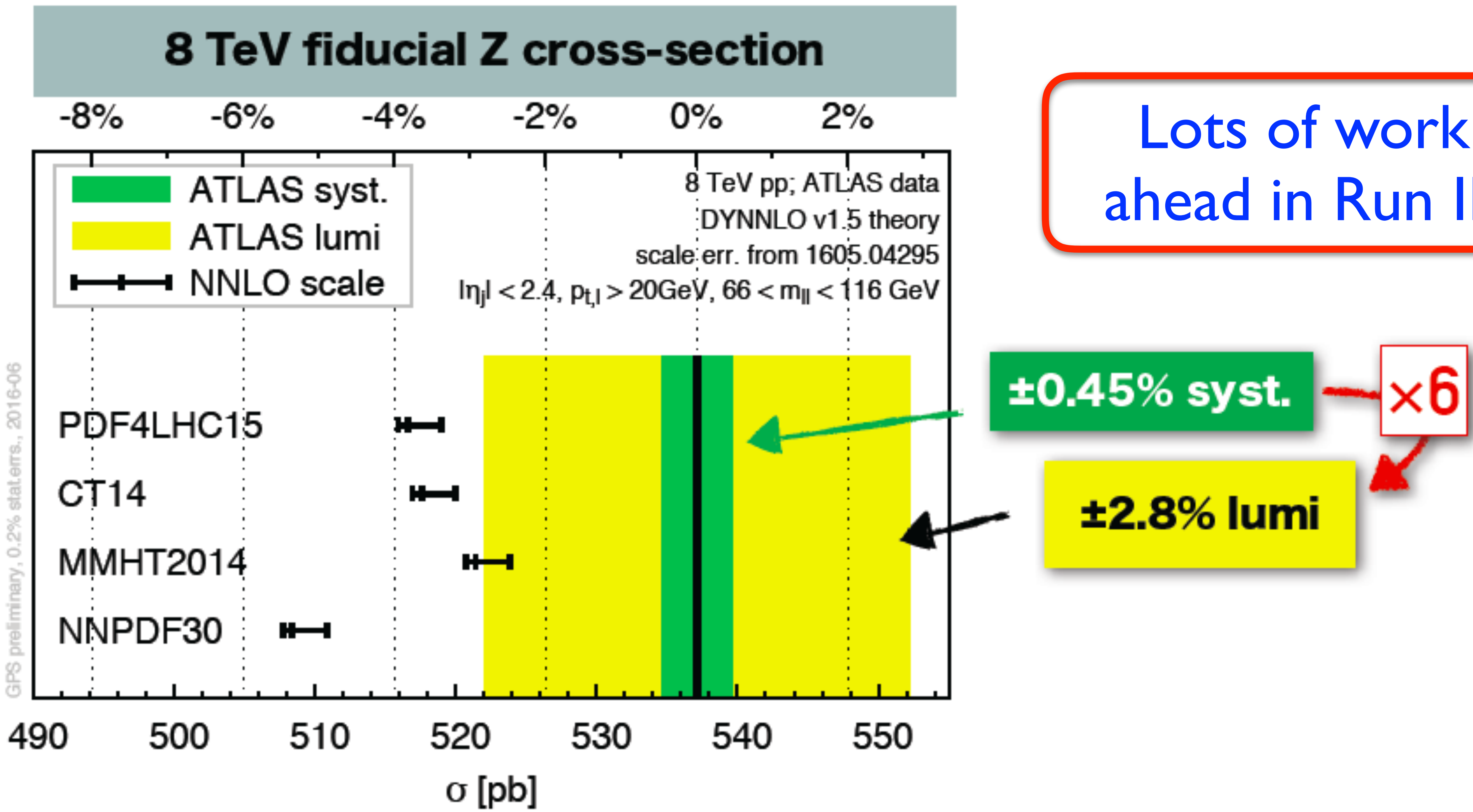


Normalizing to the fiducial Z cross section affects theory/data agreement

The Z-boson fiducial cross section

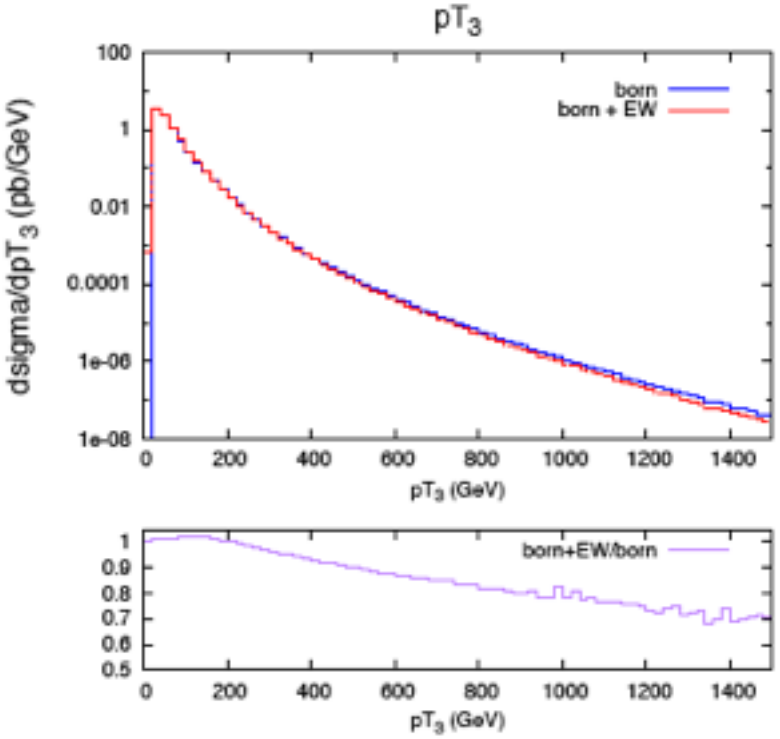
- Everything must be in place to achieve percent-level precision at Run II: theory, PDFs, parameters such as α_S, luminosity and experimental systematics

Lots of work ahead in Run II!



from G. Salam, LHCP 2016

Zb production with NLOX



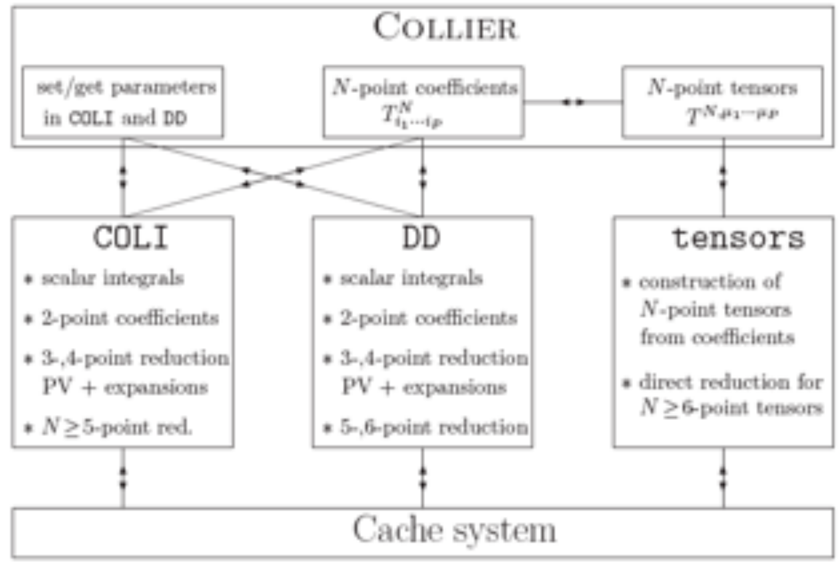
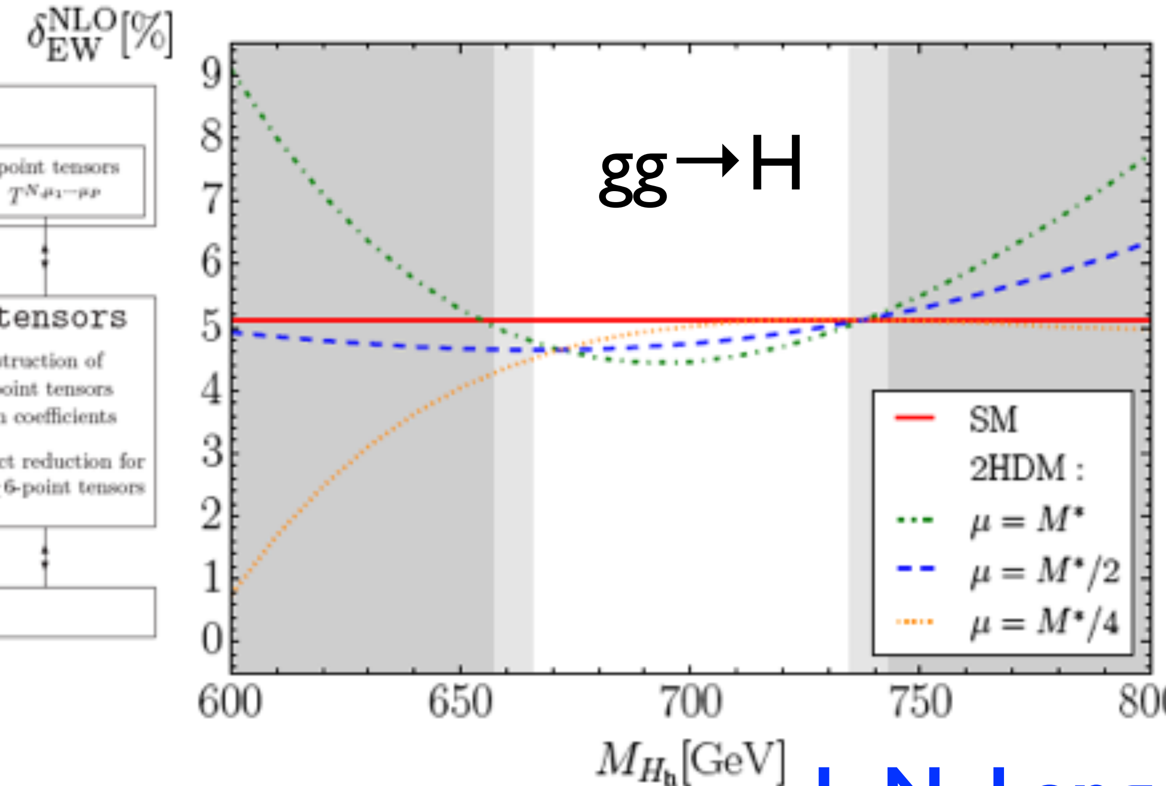


Figure 2: Structure of the library Collier.

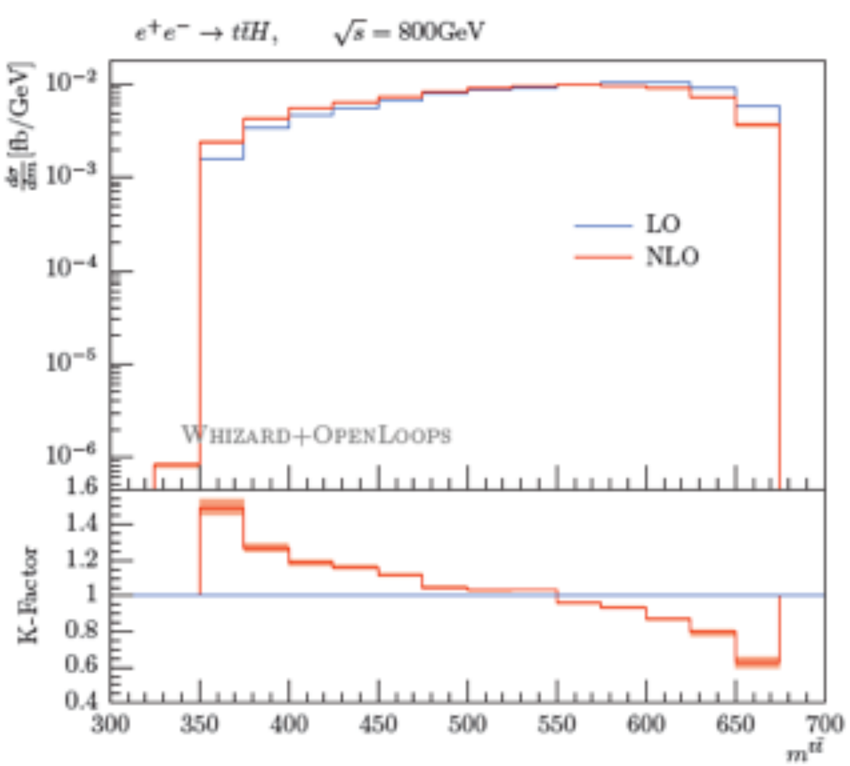
RECOLA 2.0 for SM and BSM physics



C. Reuschle

J. Hofer

J.-N. Lang



C. Weiss

NLO corrections to gg→VV computed

- gg contribution to pp → ZZ at NNLO increased by 80% at 8 TeV and 70% at 13 TeV
- This increases the NNLO corrections from 12% → 18% at 8 TeV and 16% → 23% at 13 TeV

$$\sigma_{\rm NLO} = 7.369^{+2.8\%}_{-2.3\%}\ \text{pb}$$

$$\sigma_{\rm NNLO} = 8.284^{+3.0\%}_{-2.3\%}\ \text{pb}$$

$$\sigma_{\rm NNLO+gg,NLO} = 8.7\ \text{pb}$$

(Cascioli *et. al.*, '14)

undecayed ZZ

R. Roentsch

New techniques for many loops

- Single most-talked about topic (by my counting): new methods and results for multi-loop integrals/amplitudes

- Stephen Martin: 3-loop vacuum integrals
- Andreas von Manteuffel: fields and 4-loop form factors
- Ayres Freitas: numerical techniques for 2-3 loop integrals
- Matthieu Jaquier: numerical unitarity at 2-loops
- Freddy Cachazo: QFT amplitudes from Riemann surfaces
- Lorenzo Tancredi: differential equations and dispersion relations for Feynman amplitudes
- Amedeo Primo: adaptive integrand decomposition
- William Torres Bobadilla: d-dimensional unitarity and color kinematics duality
- Falko Dulat: Iterated integrals in multi-Regge kinematics
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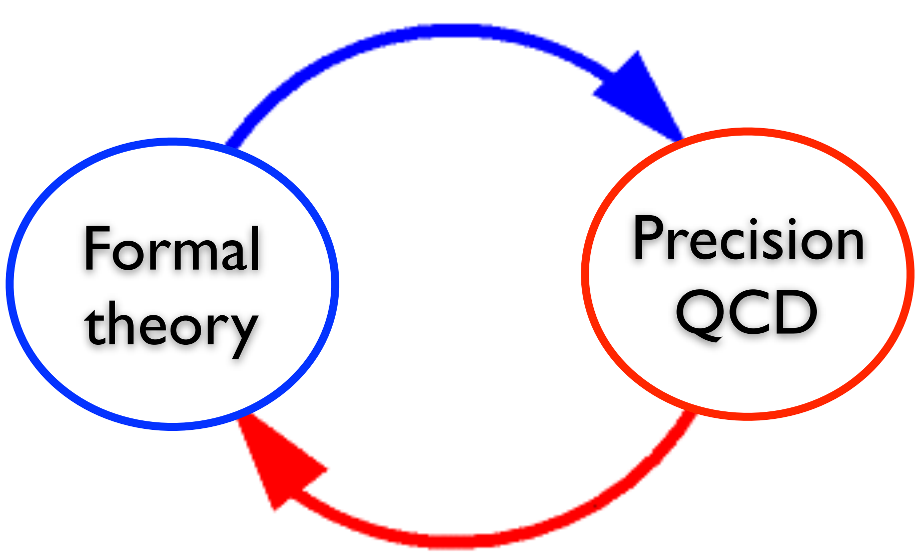

Intrinsic intellectual interest in studying mathematical structure of scattering amplitudes; healthy cross-talk with more formal theory

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- Subtraction hindered NNLO phenomenology for many years. Now solved (antennae, CoLoRFulNNLO, N-jettiness, sector-improved residues, qT, …)
- 2-loop $2\to2$ amplitudes now exhausted; need new methods for 2-loop amplitudes (and potentially more stable $2\to4$ NLO as an input to real-virtual corrections) to enable $2\to3$ and beyond at NNLO

Numerical improvement of Mellin-Barnes techniques:

Counter rotations not always successful:

$$\frac{1}{(2\pi i)^2}\int dz_1 dz_2\, 2(m^2)^{-2}\left(-\frac{p^2}{m^2}\right)^{-z_1-z_2} \times \frac{\Gamma(-z_2)\Gamma^3(1+z_2)\Gamma(-z_1-z_2)\Gamma(1+z_1+z_2)\Gamma(-1-z_1-2z_2)}{\Gamma(1-z_1)}$$

For $p^2 = m^2$ contour rotation has no effect

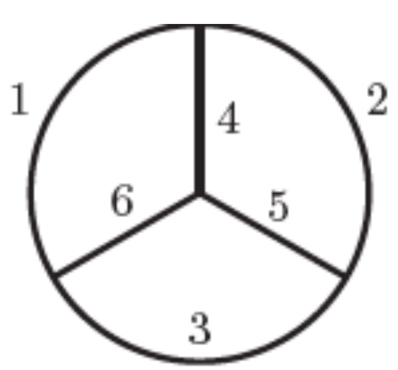
Shift countour: $z_1 = c_1 + iy_1,\ z_2 = c_2 + n + iy_2$

- Worst asymtotic behaviour of integrand for $y_1 \to -\infty$, $y_2 = 0$:
  $\sim y_1^{-2-2(c_2+n)}$ (for $n = 0$ and $c_2 = -0.7$: $\sim y_1^{-0.6}$)
- Pick up (finite number of) pole residues from contour shift

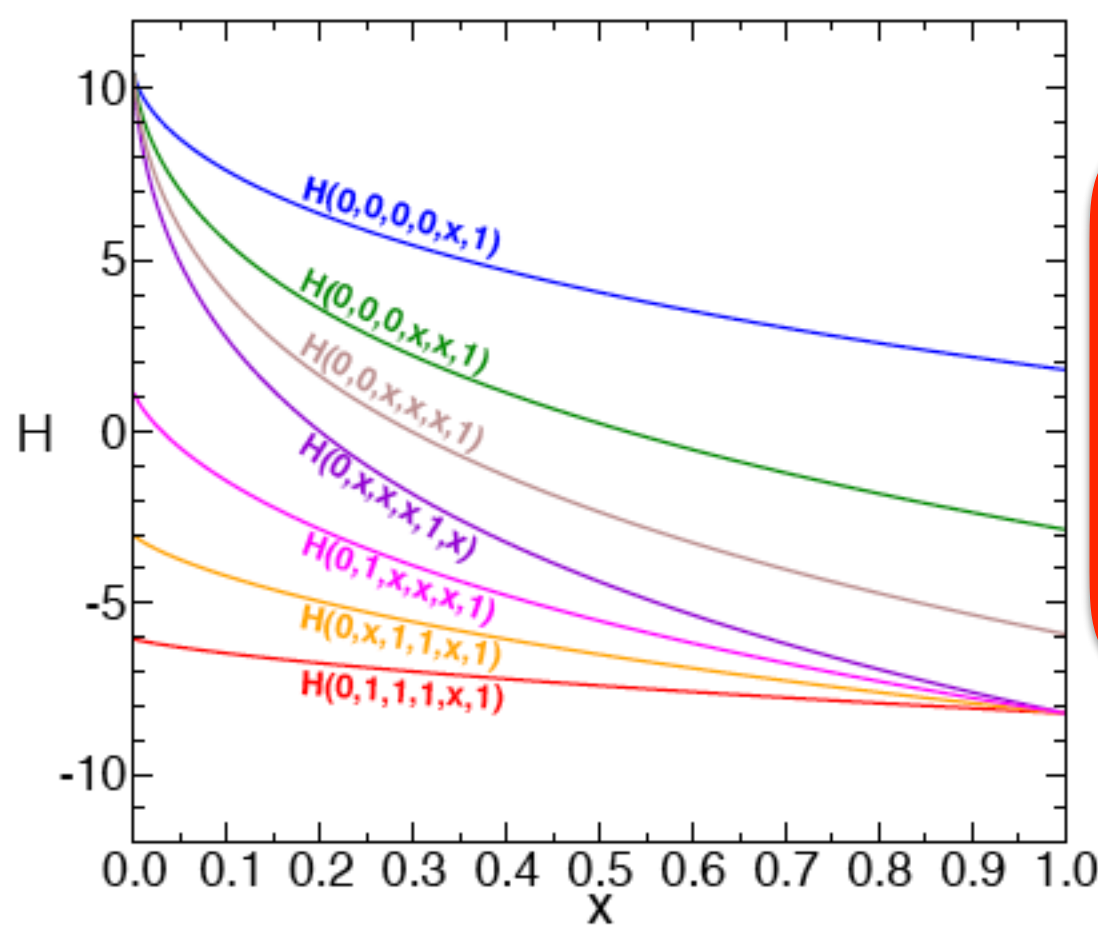
Enabled 2-loop bosons corrections to weak mixing angle for b-quarks

$$\frac{\sin^2\theta^{b}_{\rm eff}\big|_{\rm bos}}{\sin^2\theta^{b}_{\rm eff}} = -0.9855 \times 10^{-4}$$

A. Freitas



S. Martin



Public codes MBNumerics and 3VIL coming on line for 3-loop vacuum integrals; relevant for both SUSY and low-energy expansions

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 )__)  _)(_  )  (  )   / )__)  )(_) )
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Package: finred
Author:  Andreas v. Manteuffel
```

features:

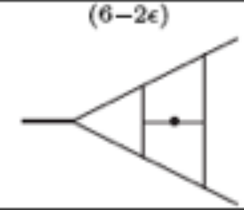
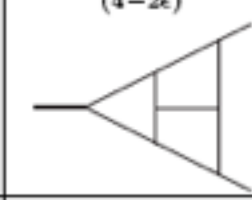
- C++11 implementation for univariate sparse matrices
- employs `flint` library
- parallelisation: SIMD, threads, MPI, batch
- equation filtering: eliminate redundant rows
- plus lots of IBP specific features
- much faster than Reduze 2

Improved IBP solver by finite field sampling; initial results for 4-loop gluon form factor

$$\Gamma_4^g|_{N_f^3} = C_A \left[\frac{64}{27}\zeta_3 - \frac{32}{81}\right]$$

A. v. Manteuffel

Let's continue with our three-loop form factor example

diagram $(6-2\epsilon)$	run time	relative accuracy	diagram $(4-2\epsilon)$	run time	relative accuracy
	128 s	5.12×10^{-6}		39094 s	9.91×10^{-4}

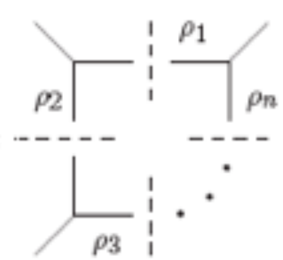
R. Schabinger

$$\mathcal{I}_{i_1 \ldots i_n} = \int \mathrm{d}^D\ell \frac{\sum_k c_k t^k(\ell)}{\rho_1 \cdots \rho_n} = \int \mathrm{d}^D\ell \frac{\sum_i c_i t^i_{master}(\ell) + \sum_j c_j t^j_{surface}(\ell)}{\rho_1 \cdots \rho_n}.$$

[Ossola, Papadopoulos, Pittau 06; Bern, Dixon, Kosower]

- The coefficients c_k can be determined on the cut [Bern, Dixon, Kosower 06],

M. Jaquier

$$\sum_k c_k t^k(\ell) = $$  (ℓ).

Attempts to improve IBP solution algorithms, or to extend successful integrand reduction idea to NNLO

A New One-Loop Integrand

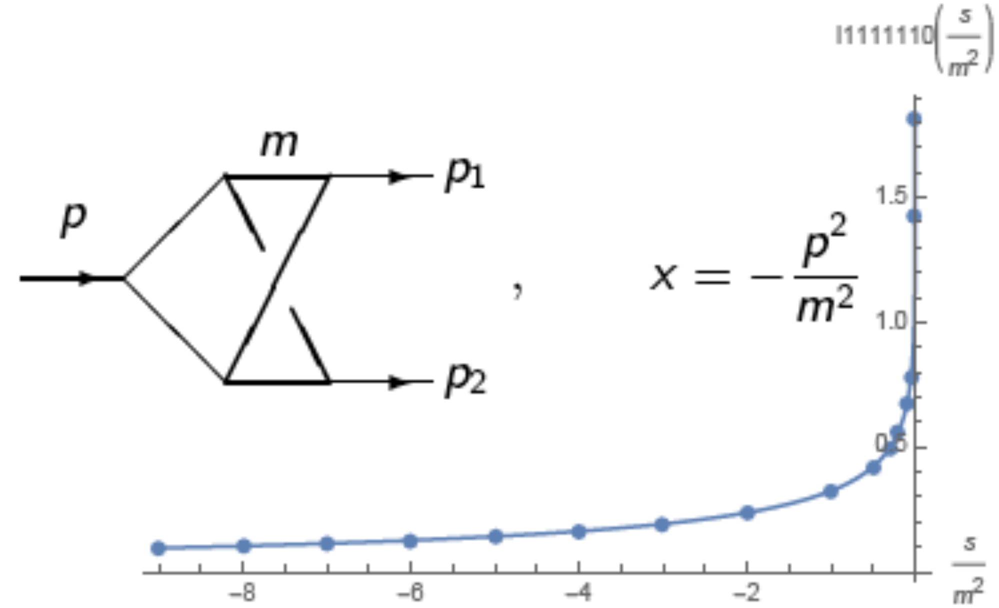
$$\mathcal{M}_n^{\text{1-loop}} = \int \frac{d^D\ell}{\ell^2} \int \prod_{a=1}^{n} \left[d\sigma_a \, \delta\!\left(\frac{\partial F}{\partial \sigma_a}\right)\right] \det \Psi(k_i k_b, k_a \ell, \epsilon, \sigma)$$

$$\Downarrow$$

$$\mathcal{M}_n^{\text{1-loop}} = \int \frac{d^D\ell}{\ell^2} \, \mathcal{I}(k_i k_b, k_a \ell)$$

No ℓ^2 dependence!

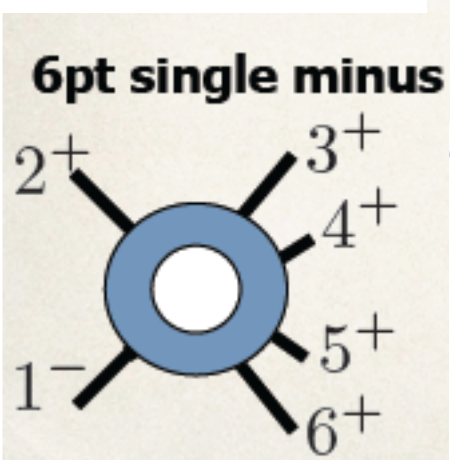
F. Cachazo



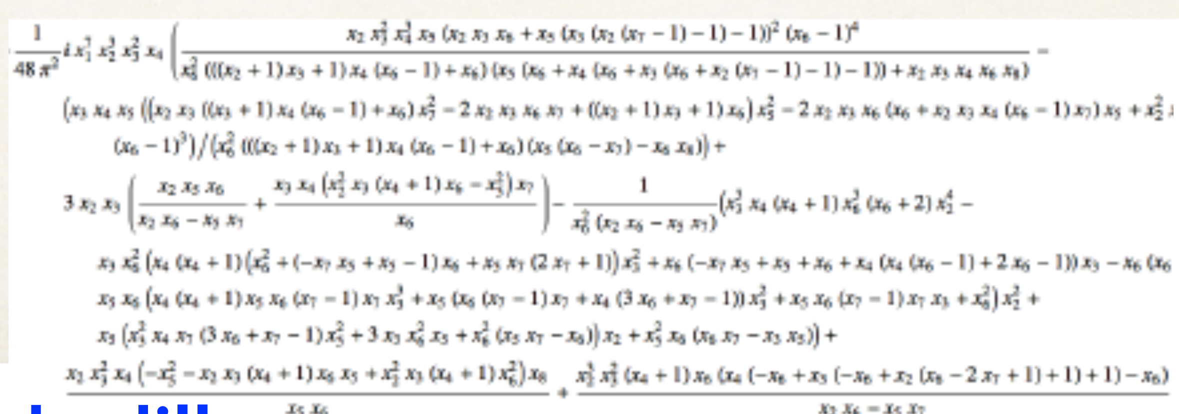
$$x = -\frac{p^2}{m^2}$$

Euclidean kinematics

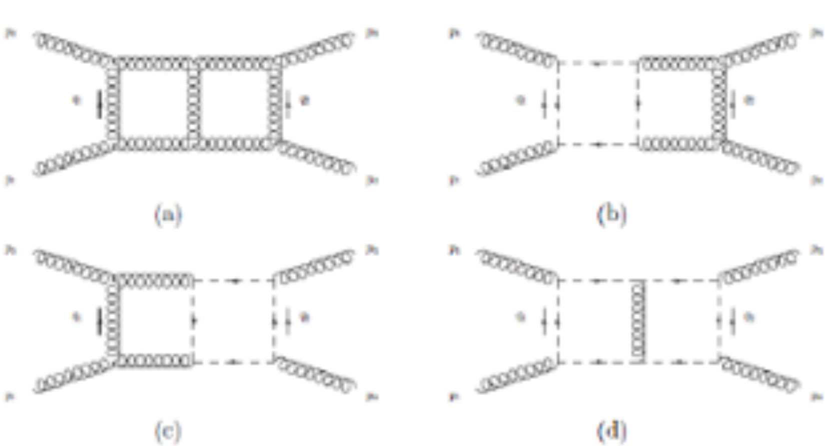
L. Tancredi



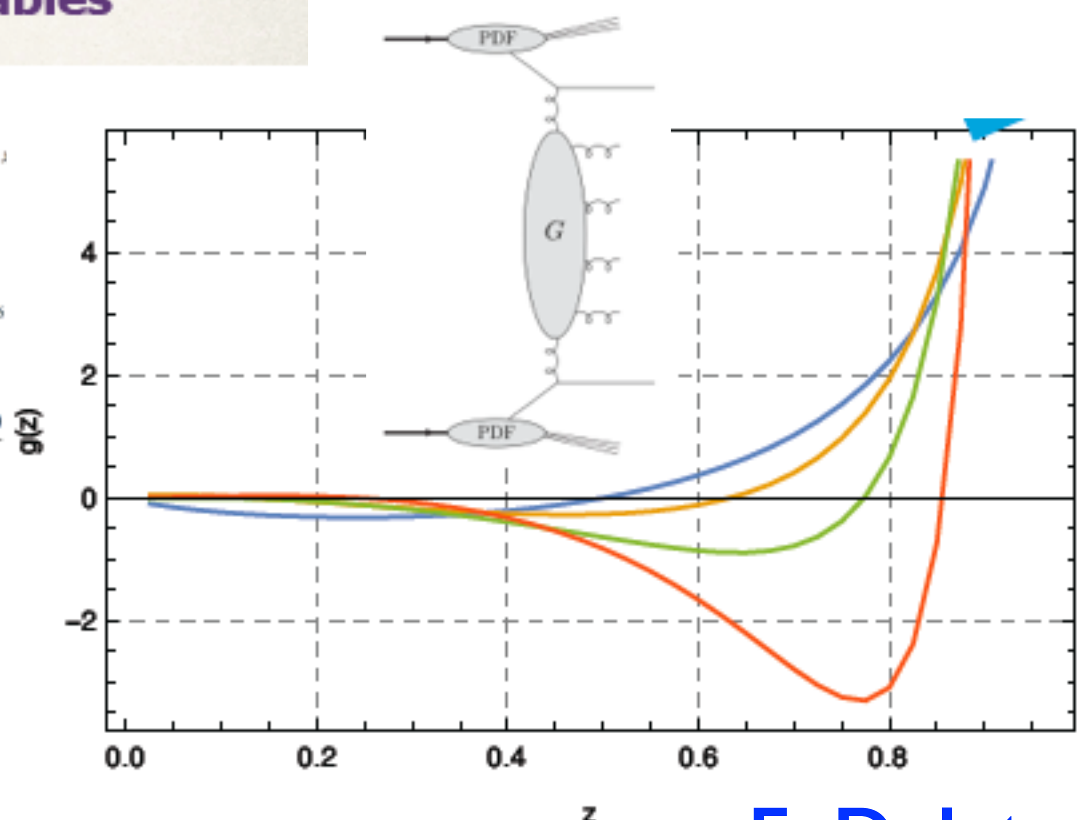
Write Lorentz invariant quantities in terms of 3n-10 variables



W. Torres Bobadilla



A. Primo



F. Dulat

$$A^{2-\text{loop}}(p_1^+, p_2^-, p_3^+, p_4^-)\Big|_{cut} = i\frac{\langle 2\,4\rangle^4}{\langle 1\,2\rangle\langle 2\,3\rangle\langle 3\,4\rangle\langle 4\,1\rangle}\left(\sum_{\alpha,\beta} c_{\alpha,\beta}\, I_4^{d\,(2)}[(q_1\cdot p_4)^\alpha\,(q_2\cdot p_1)^\beta]\right)$$

Precision Higgs calculations

- Large number of talks on precision calculations for Higgs physics

- Bernhard Mistlberger: differential distributions for precision Higgs physics
- Tobias Neumann: the Higgs at high p_T
- Stefano Forte: high energy resummation and the Higgs p_T
- Alexander Penin: light-quark mass effects in gluon-fusion Higgs production
- Vincent Theeuwes: soft gluon resummation for tth production
- Elisabetta Furlan: CP-even scalar boson production
- Timo Schmidt: BSM(SM) Higgs production in gluon fusion
- Matthias Kerner: HH production with full m_t dependence

- Global μ:

$$\mu = 1.18^{+0.15}_{-0.14} = 1.18 \pm 0.10(stat) \pm 0.07(expt)^{+0.08}_{-0.07}(theory)$$

- Theory error is competitive with other errors->theory improvements needed

Source of uncertainty	combined
Electron reconstruction and identification efficiencies	1.6%
Electron isolation and impact parameter selection	0.5%
Electron trigger efficiency	<0.2%
$\ell\ell + ee$ backgrounds	1.3%
Muon reconstruction and identification efficiencies	1.5%
Muon trigger efficiency	0.2%
$\ell\ell + \mu\mu$ backgrounds	1.2%
QCD scale uncertainty	6.5%
PDF, α_s uncertainty	6.0%
$H \rightarrow ZZ^*$ branching ratio uncertainty	4.0%

ZZ

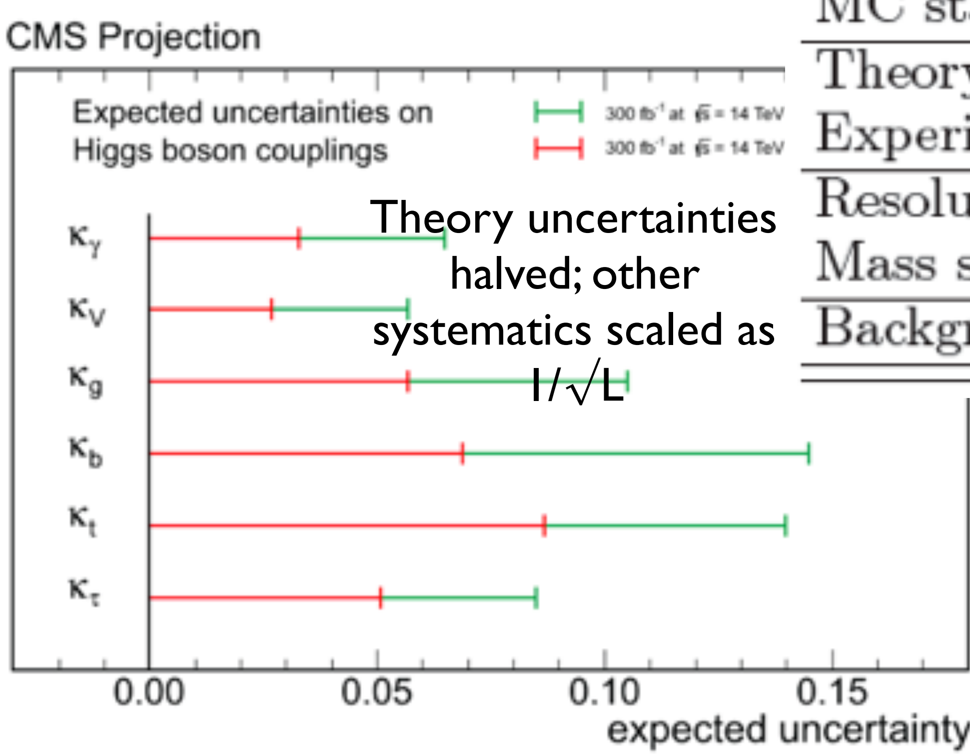
J. Huston

YY

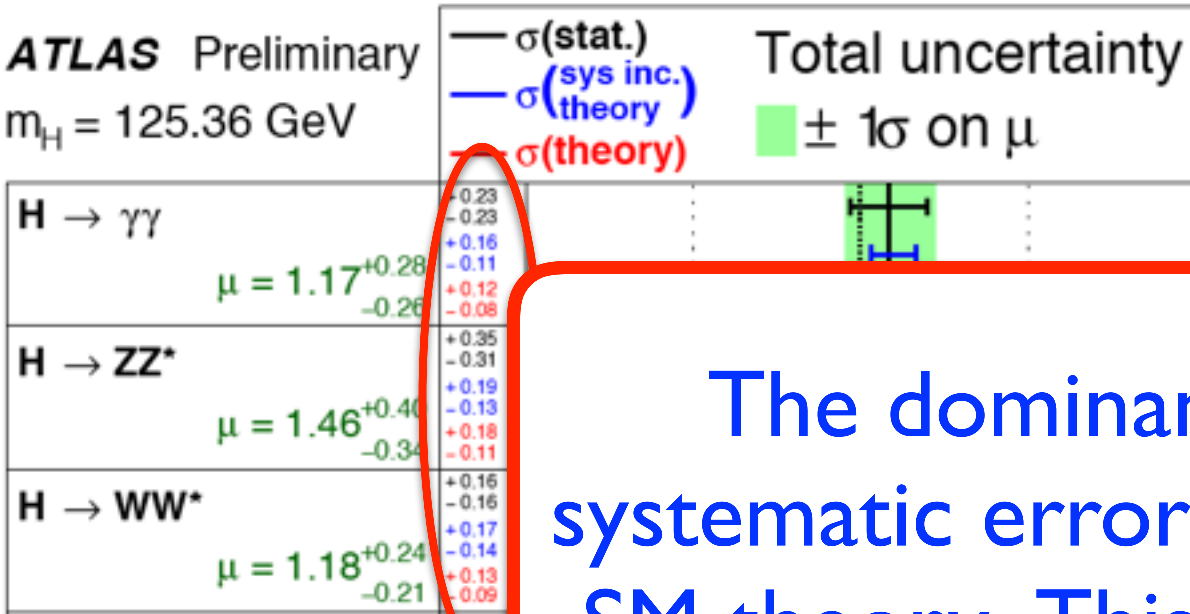
Uncertainty group	$\sigma_\mu^{\text{syst.}}$
Theory (yield)	0.09
Experimental (yield)	0.02
Luminosity	0.03
MC statistics	< 0.01
Theory (migrations)	0.03
Experimental (migrations)	0.02
Resolution	0.07
Mass scale	0.02
Background shape	0.02

WW

Source	Error +	Error −	Plot of error (scaled by 100)
Data statistics	0.16	0.15	
Signal regions	0.12	0.12	
Profiled control regions	0.10	0.10	
Profiled signal regions	-	-	-
MC statistics	0.04	0.04	
Theoretical systematics	0.15	0.12	
Signal $H \rightarrow WW^*$ $\mathcal{B}$	0.05	0.04	
Signal ggF cross section	0.09	0.07	
Signal ggF acceptance	0.05	0.04	
Signal VBF cross section	0.01	0.01	
Signal VBF acceptance	0.02	0.01	
Background WW	0.06	0.06	
Background top quark	0.03	0.03	
Background misid. factor	0.05	0.05	
Others	0.02	0.02	
Experimental systematics	0.07	0.06	
Background misid. factor	0.03	0.03	
Bkg. $Z/\gamma^* \rightarrow ee, \mu\mu$	0.02	0.02	
Muons and electrons	0.04	0.04	
Missing transv. momentum	0.02	0.02	
Jets	0.03	0.02	
Others	0.03	0.02	



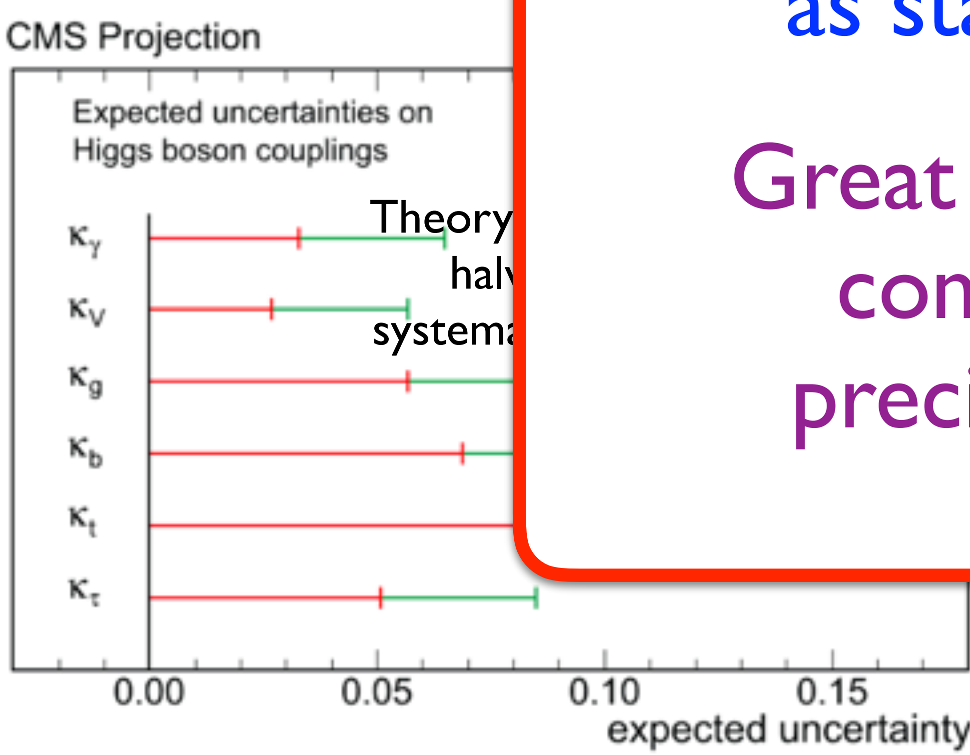
Theory uncertainties halved; other systematics scaled as 1/√L



Source of uncertainty	combined
Electron reconstruction and identification efficiencies	1.6%
Electron isolation and impact parameter selection	0.5%
Electron trigger efficiency	<0.2%
$\ell\ell + ee$ backgrounds	1.3%
Muon reconstruction and identification efficiencies	1.5%
Muon trigger efficiency	0.2%
$\ell\ell + \mu\mu$ backgrounds	1.2%
	6.5%
	6.0%
	4.0%

The dominant component of the systematic error on the signal strength is SM theory. This threatens to become a limiting factor in interpretation of Run II as statistical errors decrease.

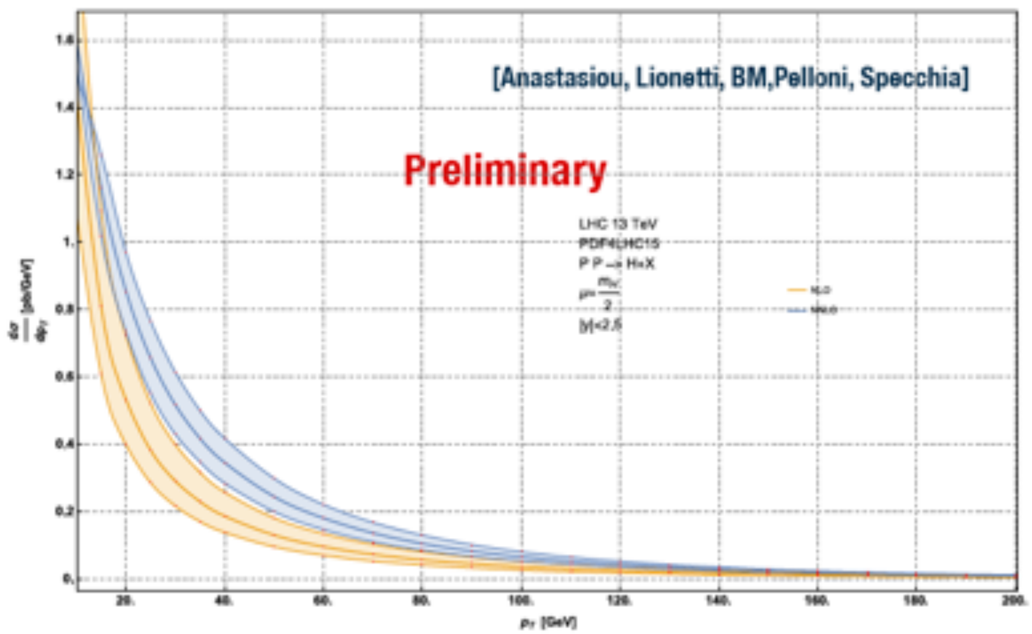
Great progress by the LoopFest community in meeting this precision challenge of Run II!



		...ror	Plot of error (scaled by 100)
		–	
		0.15	
		0.12	
		0.10	
		-	
		0.04	
		0.12	
		0.04	
		0.07	
		0.04	
		0.01	
		0.01	
		0.06	
		0.03	
		0.05	
		0.02	
		0.06	
		0.03	
		0.02	
Muons and electrons	0.04	0.04	
Missing transv. momentum	0.02	0.02	
Jets	0.03	0.02	
Others	0.03	0.02	

Lots of progress on Higgs pT!

NNLO PT Distribution

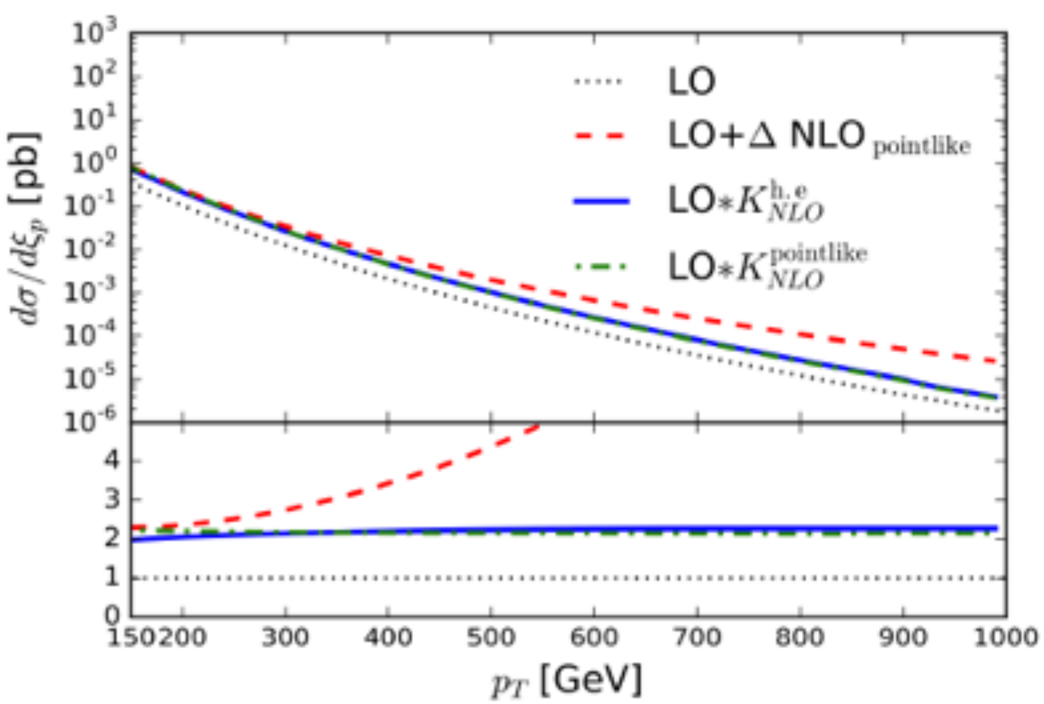


|Y|< 2.5

B. Mistlberger

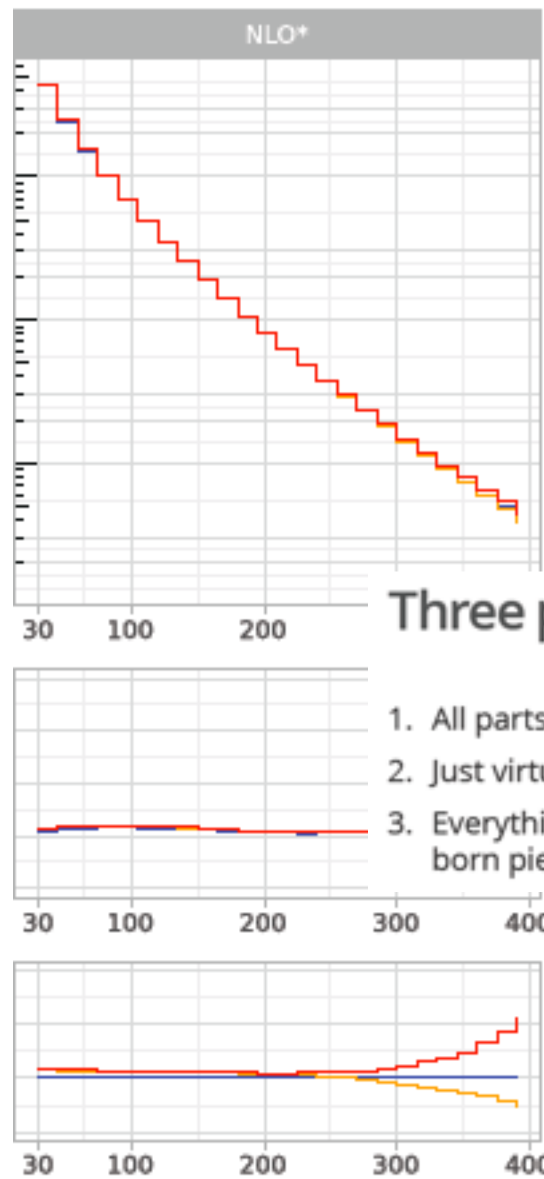
$$\frac{d\sigma_{pp\to H+j}}{dp_\perp^2} = \frac{d\sigma^{(0)}_{pp\to H+j}}{dp_\perp^2}\left\{1 - \frac{3m_b^2}{m_H^2}L^2\left[1 - \frac{x}{12}\left(1-\tau^3+\tau^4\right) + \frac{x^2}{48}\left(\frac{4}{15} - \tau^3 + 2\tau^4 - \frac{7\tau^5}{5} + \frac{2\tau^6}{5}\right) + \mathcal{O}(x^3)\right] + \mathcal{O}(m_b^4)\right\}$$

A. Penin



- BEST APPROX AT LARGE p_t : EXACT LO× HE K-FACTOR
- UNCERTAINTY DRIVEN BY HE APPROX (ABOUT 30% AT LHC 13)
- POINTLIKE NLO FAILS FOR $p_t \gtrsim m_t$

S. Forte



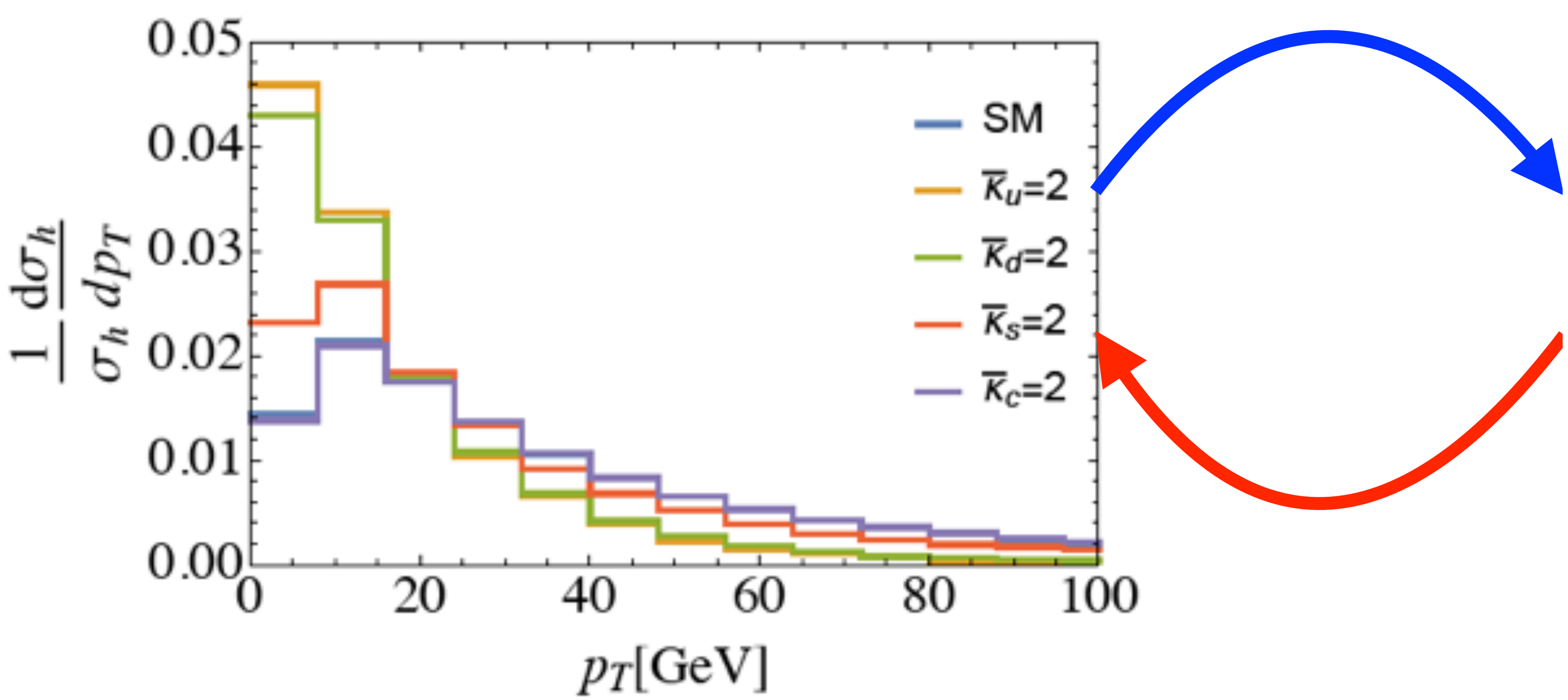
Three progressive approximations

1. All parts in the asymptotic expansion: born, real and virtual pieces
2. Just virtual corrections in the asymptotic expansion, born and real m_t -exact
3. Everything but the two-loop integrals exact in m_t :
   born piece of the virtual correction two-loop interference is m_t -exact

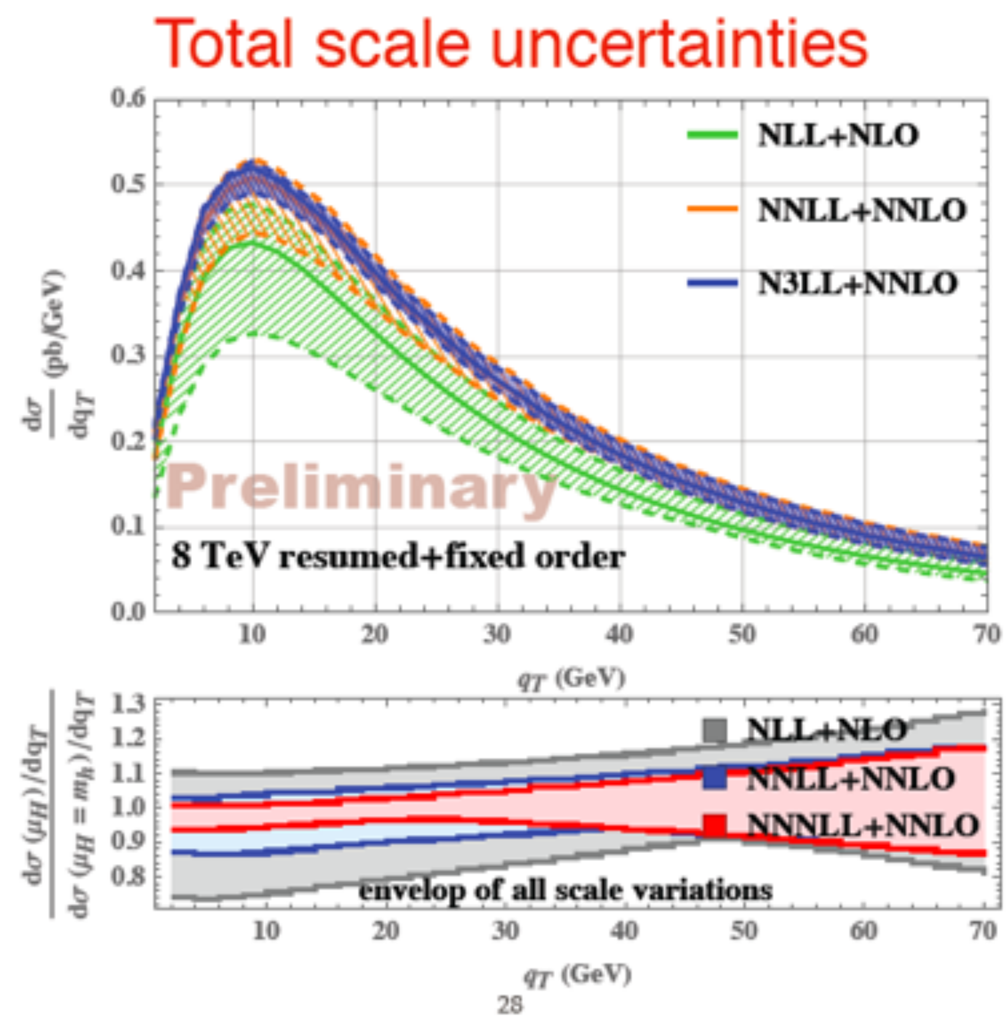
T. Neumann

The Higgs p_T and Yukawa couplings

- Part of a vibrant recent activity on the measurement of light Higgs couplings at the LHC and future colliders (exclusive decays, charm tagging, novel production modes, event shapes, …)

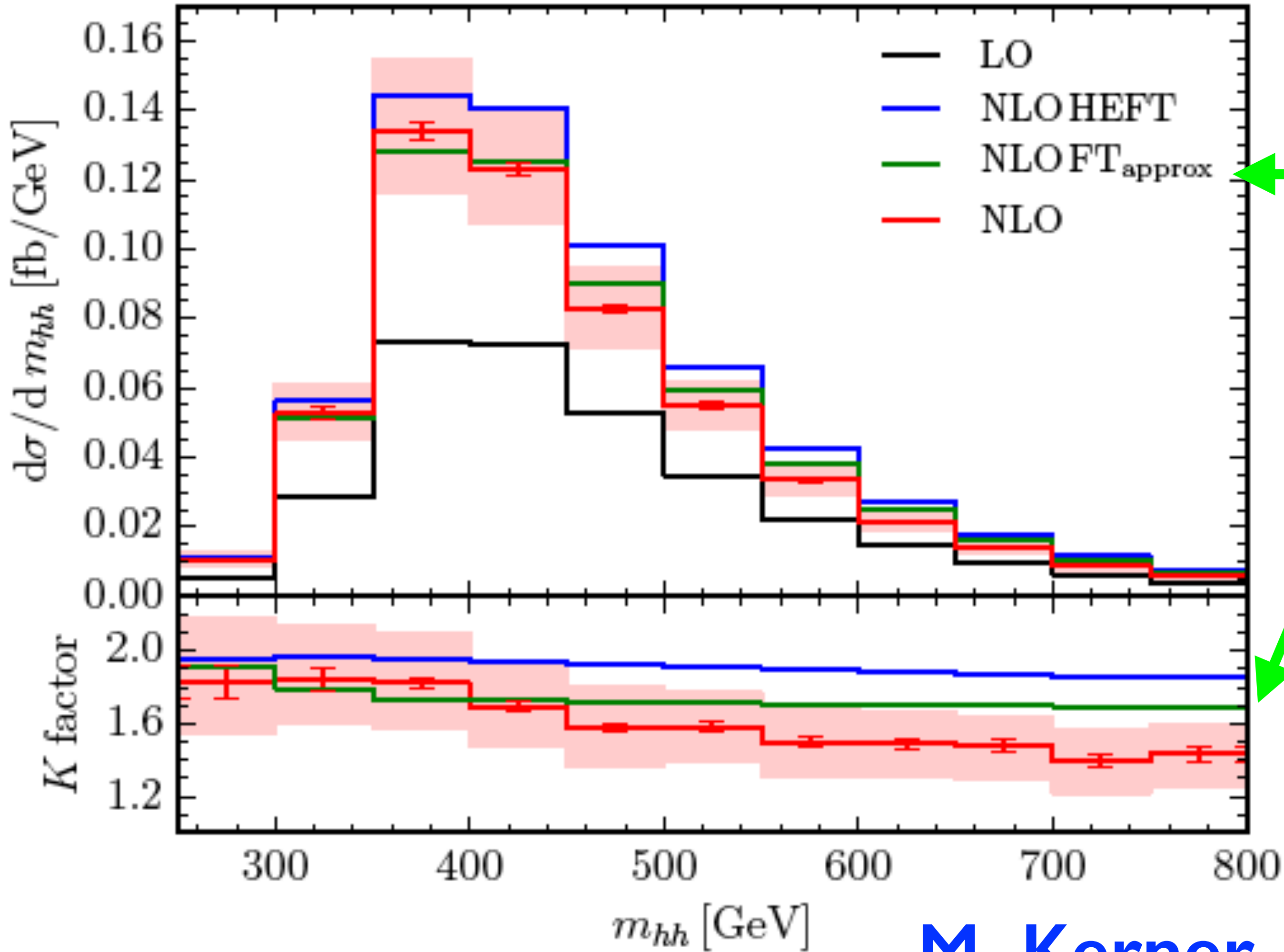


Soreq, Zhu, Zupan (2016);
Bishara, Haisch, Monni, Re (2016)



H. Zhu

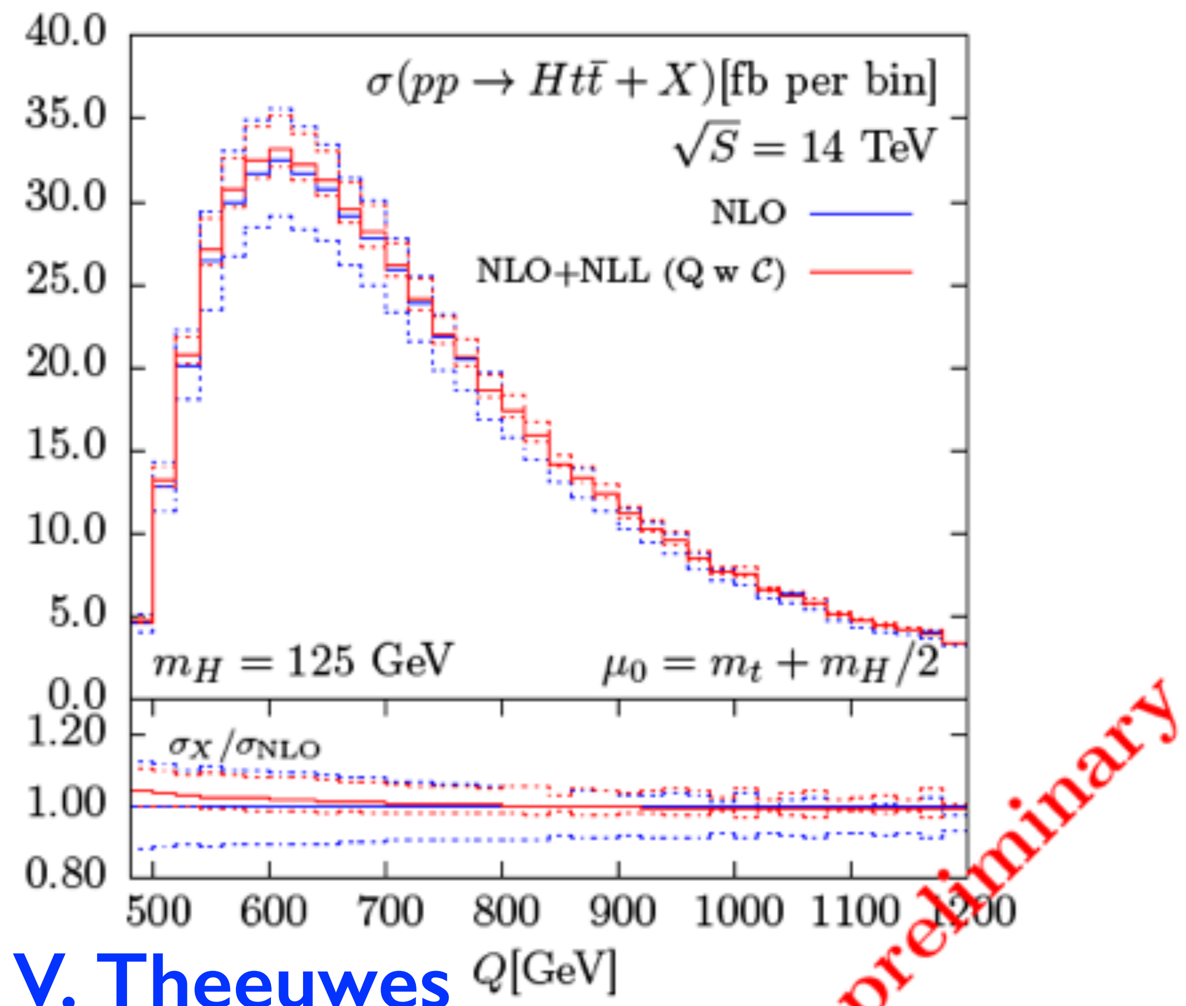
Nice example of healthy cross-talk between new ideas and the precision calculations they motivate



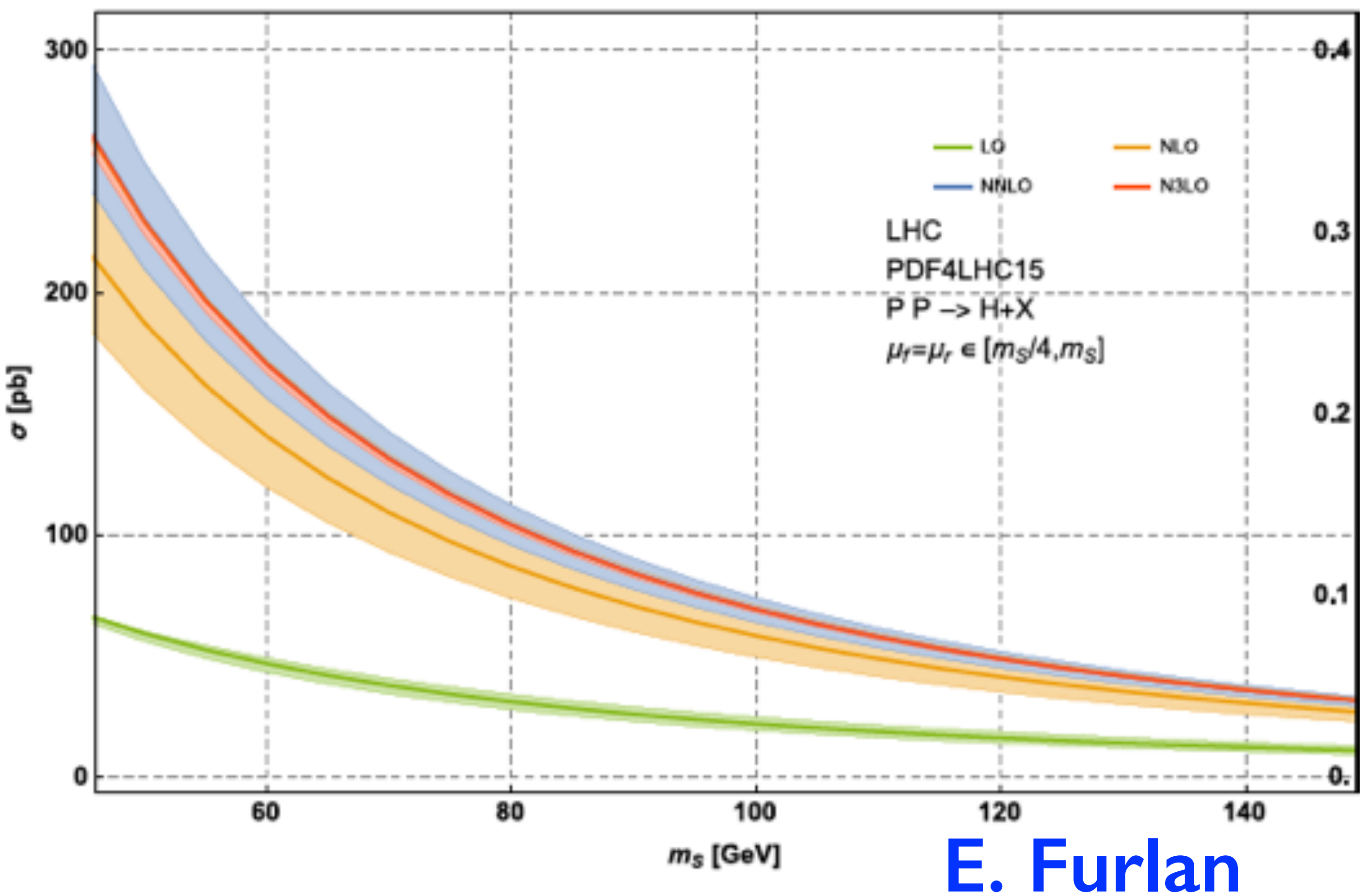
M. Kerner

Including exact m_t in real radiation, but not virtual, doesn't reproduce shape of K-factor

ttH production stable against threshold logs beyond NLO



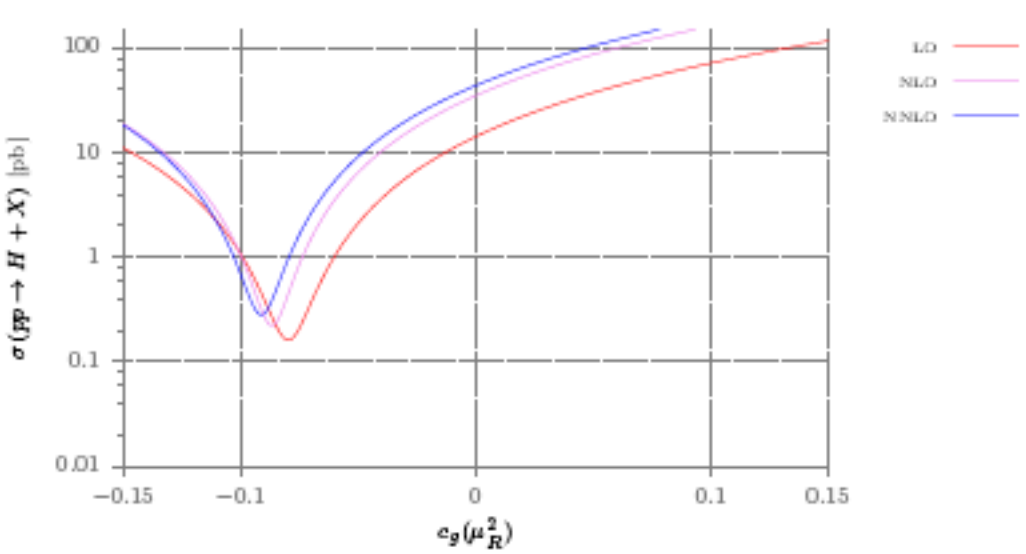
V. Theeuwes



E. Furlan

High-precision cross sections for BSM Higgs and scalar production now available

- Novel coupling c_g consistently included at NNLO in HIGLU [*Spira et al.* (1995)], resummation effects not yet examined.



(a) Total hadr. cxn by variation of the novel coupling c_g

T. Schmidt

PDFs and other input parameters

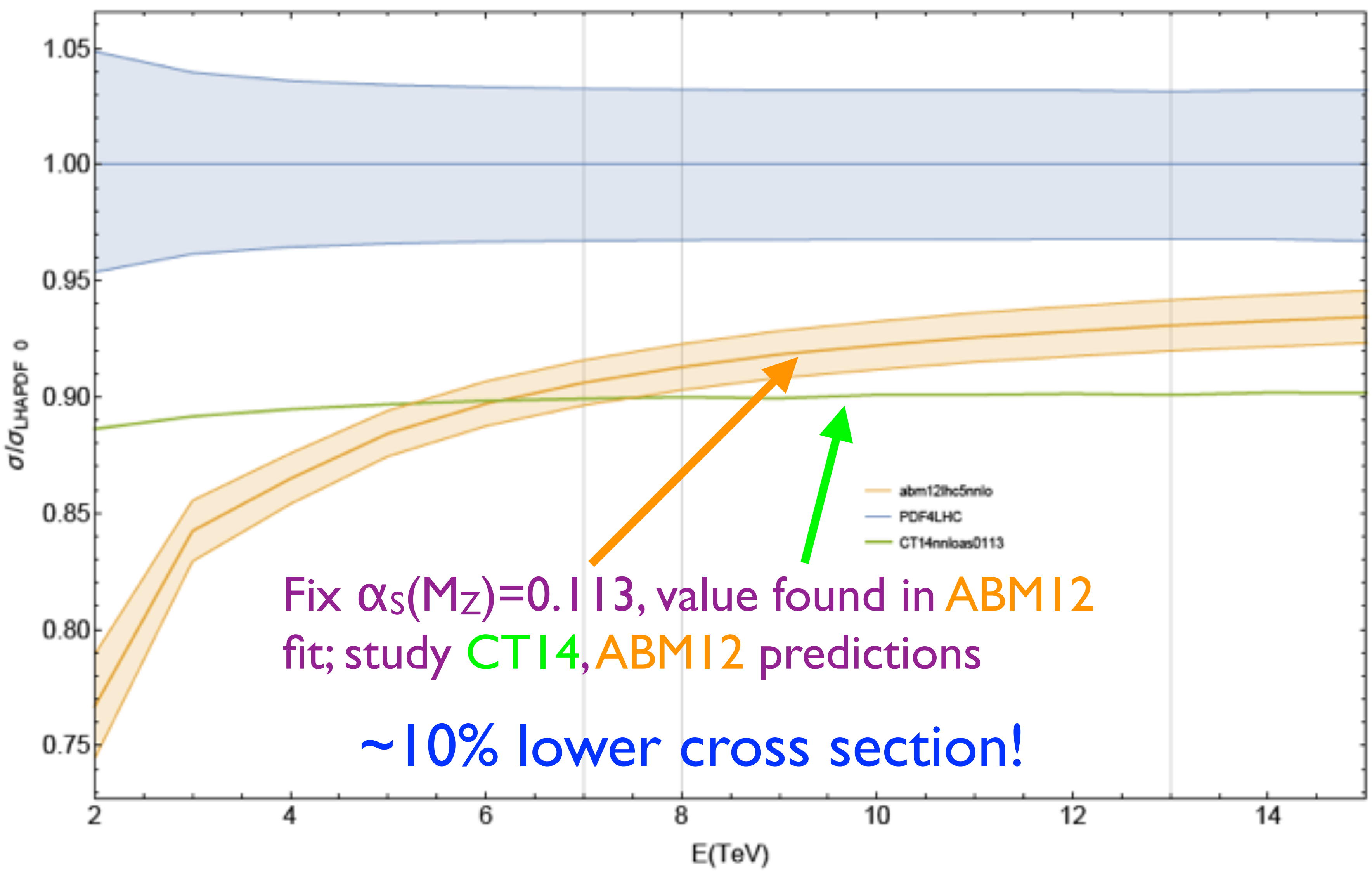
- Several talks on precision input parameter/PDF determinations

- Richard Ball: charm content of the proton
- Giulia Zanderighi: the photon PDF
- Arnd Behring: 3-loop massive operator matrix elements for DIS
- Peter Marquard: relating the Mbar and on-shell top mass

PDFs and other input parameters

- LHC Higgs XSWG assumes PDF4LHC $\alpha_S(M_Z)$: 0.1180±0.0015
- Several fits prefer lower $\alpha_S(M_Z)$; LO ggH~α_S^2⇒strong parametric dependence!

1602.00695



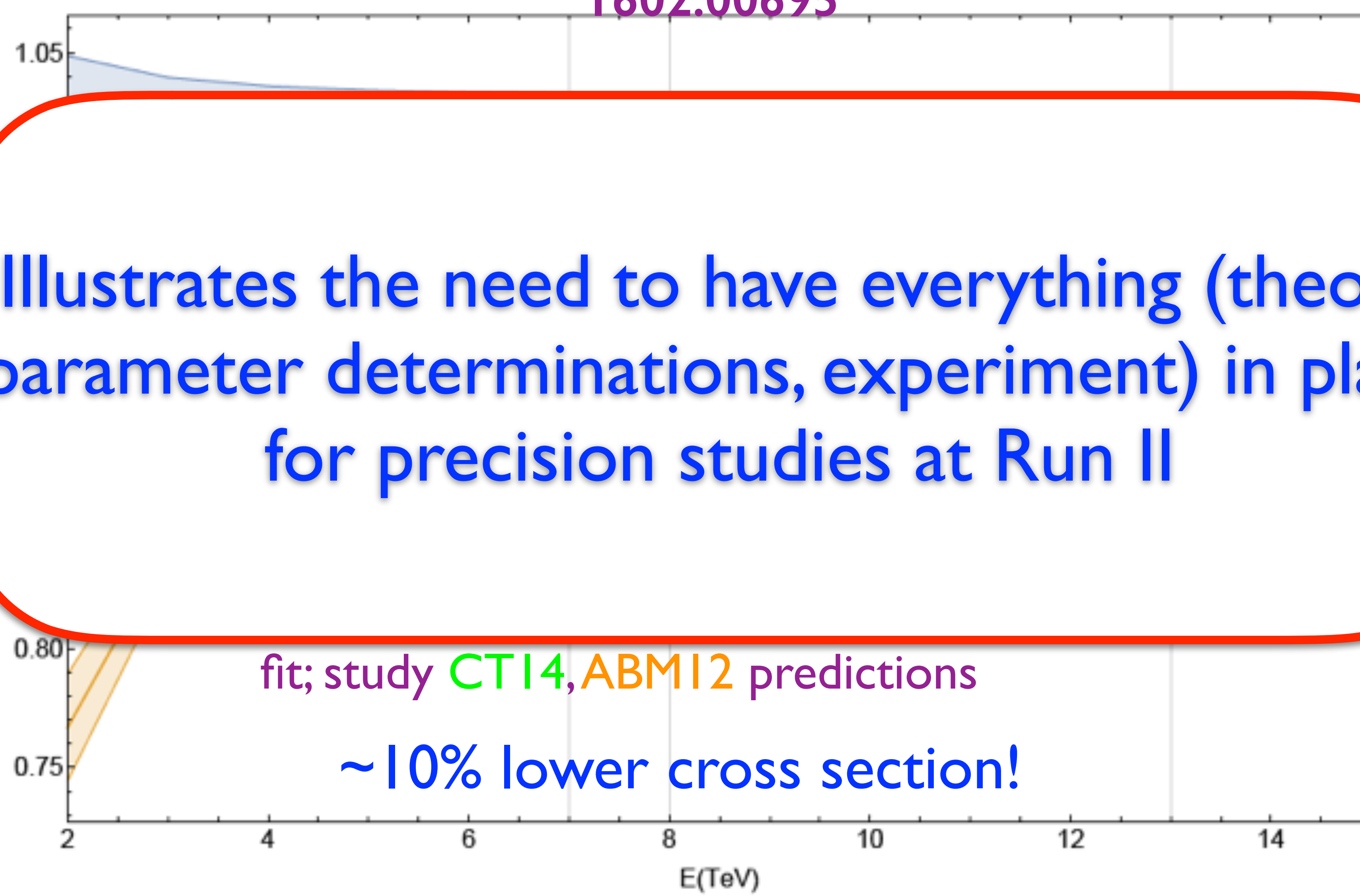
Fix $\alpha_S(M_Z)$=0.113, value found in ABM12 fit; study CT14, ABM12 predictions

~10% lower cross section!

PDFs and other input parameters

- LHC Higgs XSWG assumes PDF4LHC $\alpha_S(M_Z)$: 0.1180±0.0015
- Several fits prefer lower $\alpha_S(M_Z)$; LO ggH~α_S^2⇒strong parametric dependence!

1602.00695

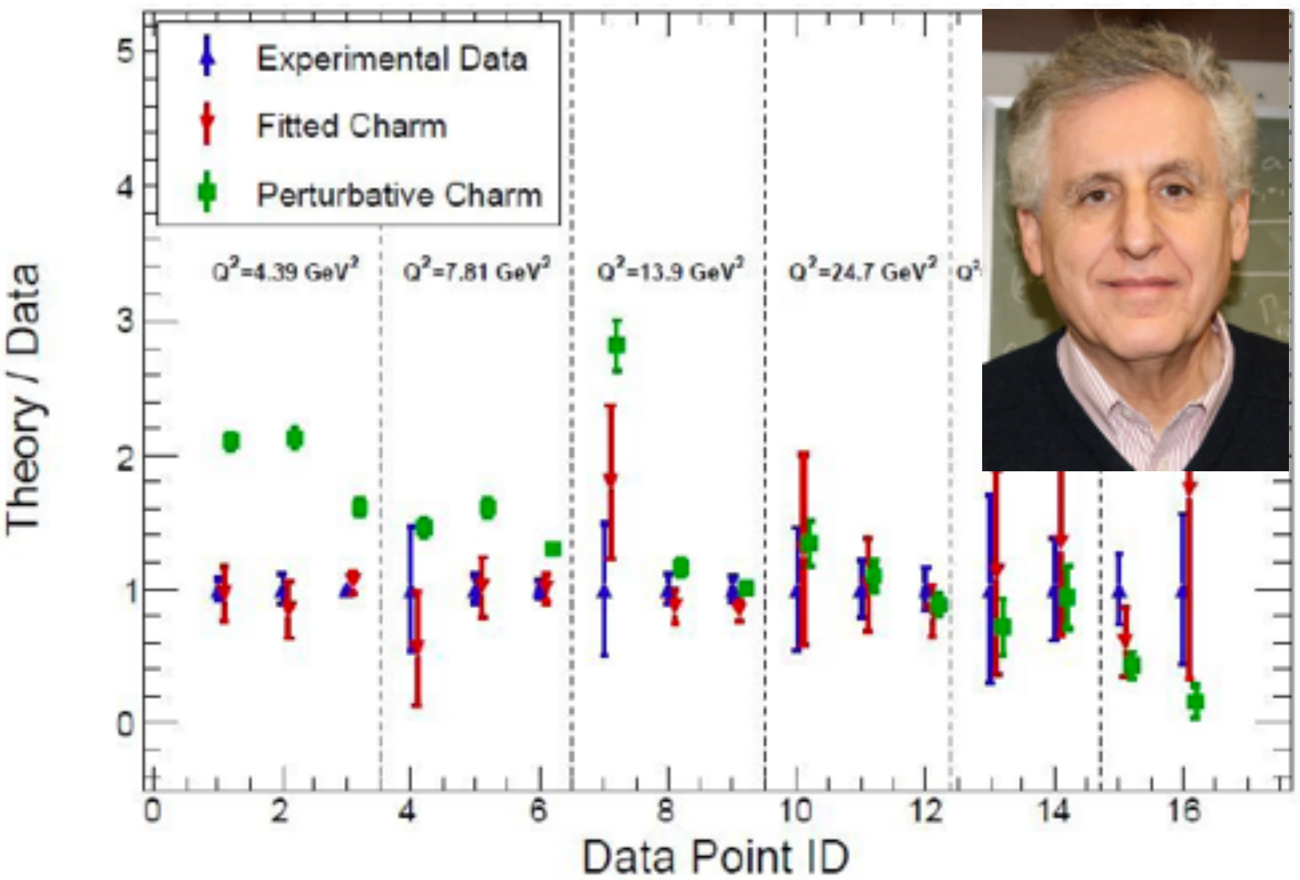


Illustrates the need to have everything (theory, parameter determinations, experiment) in place for precision studies at Run II

fit; study CT14, ABM12 predictions

~10% lower cross section!

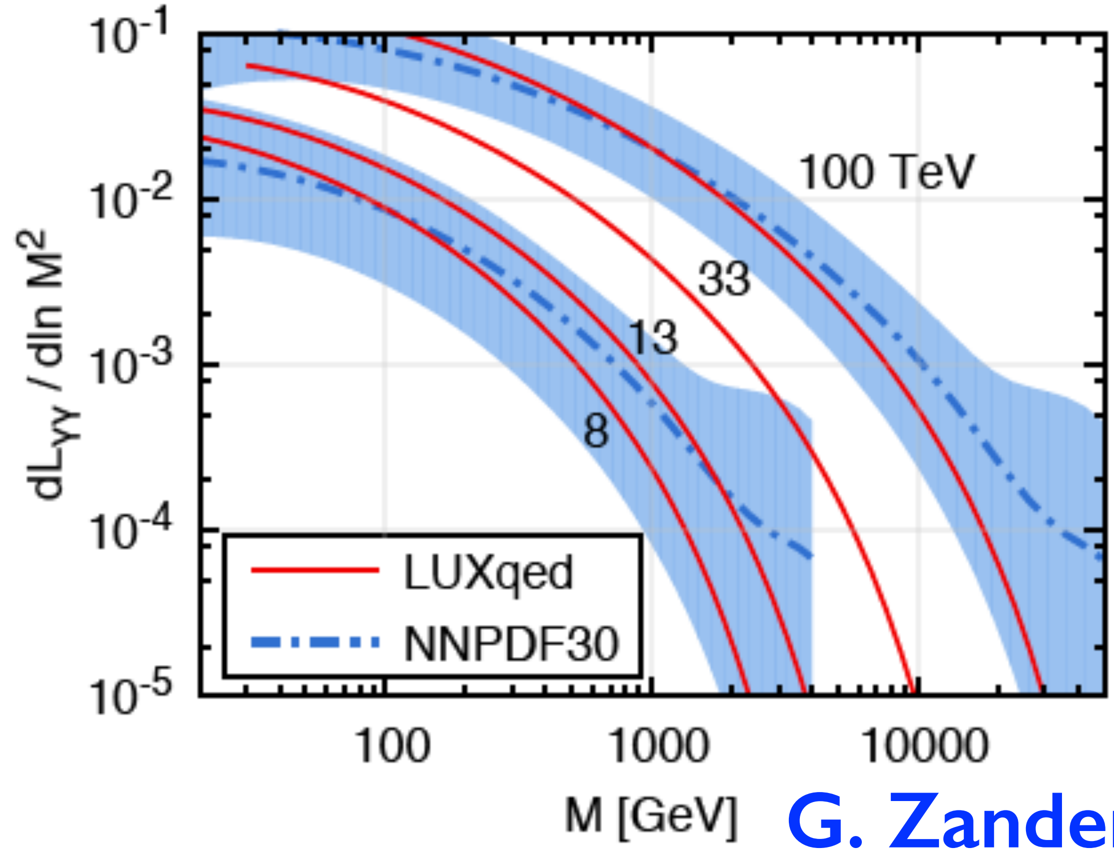
EMC charm structure functions



Strong evidence for fitted charm

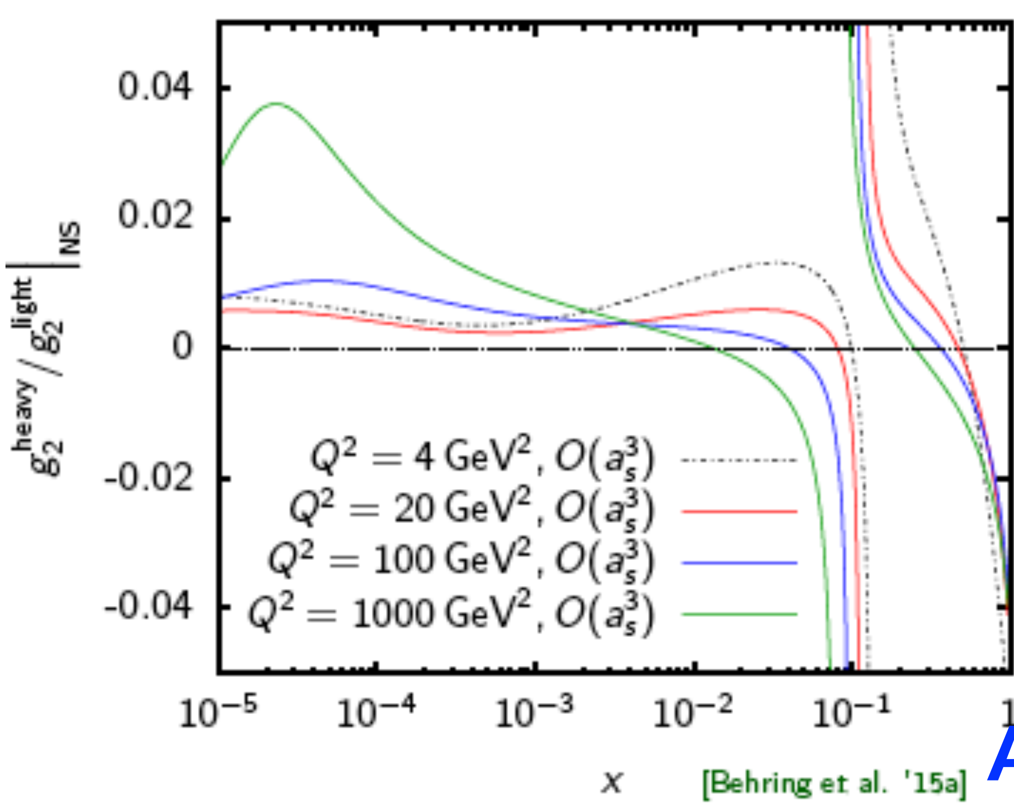
R. Ball

New determination of photon PDF



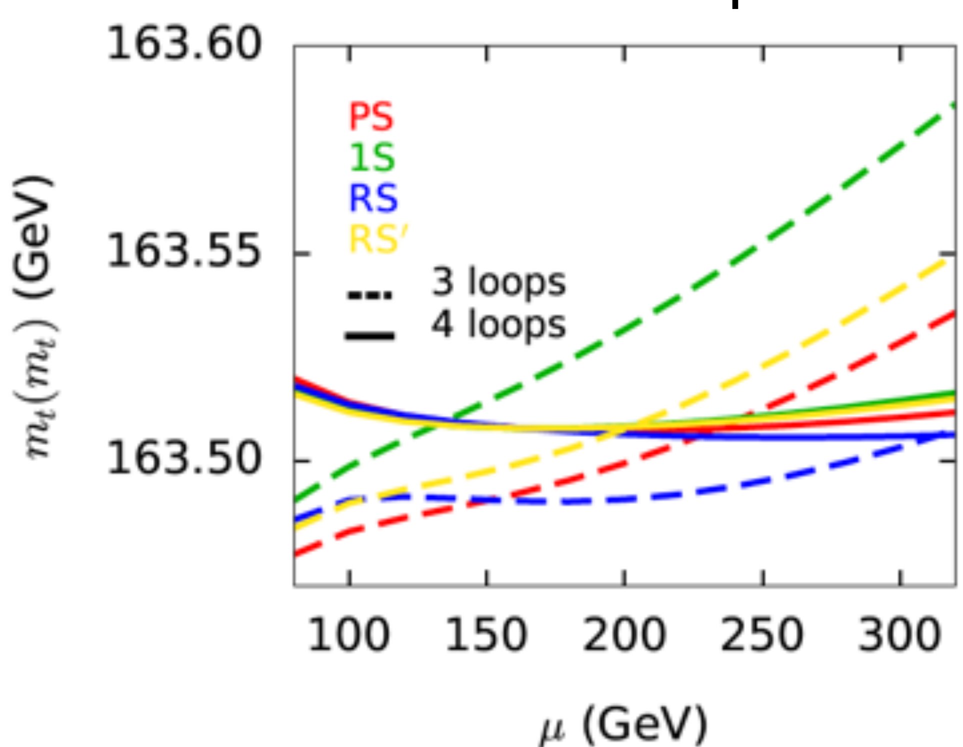
G. Zanderighi

Heavy flavor contribution to structure functions



A. Behring

Conversion between top-mass schemes



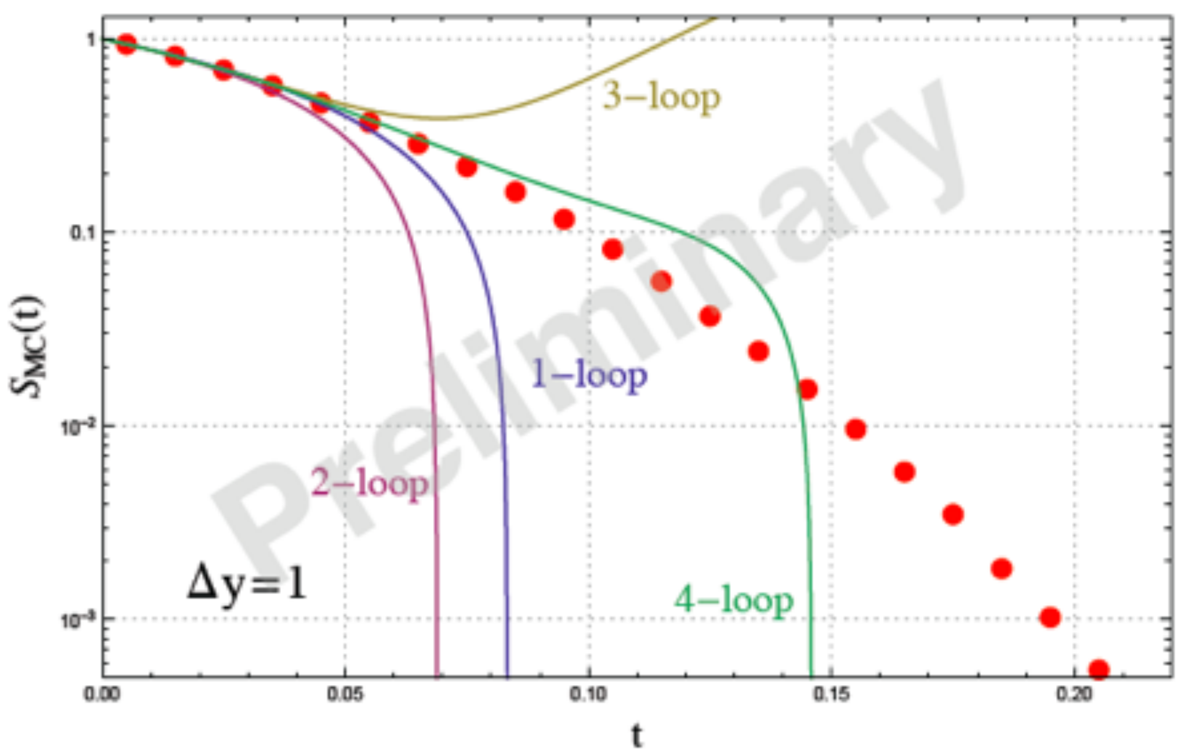
P. Marquard

Effective field theory techniques

- Several talks on effective field theory techniques and resummation in QCD

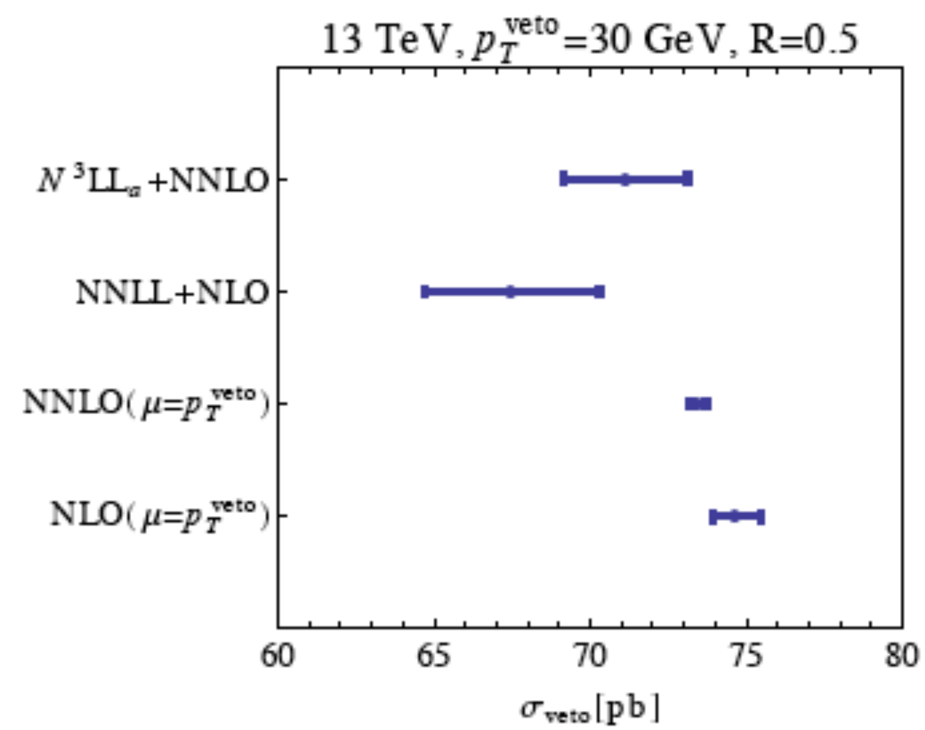
- Matthias Neubert: factorization and resummation of jet cross sections
- HuaXing Zhu: the Higgs p_T at N^3LL
- Mao Zeng: jet veto resummation for the WW cross section
- Nikolaos Kidonakis: resummation for top quark production

New understanding of non-global logs



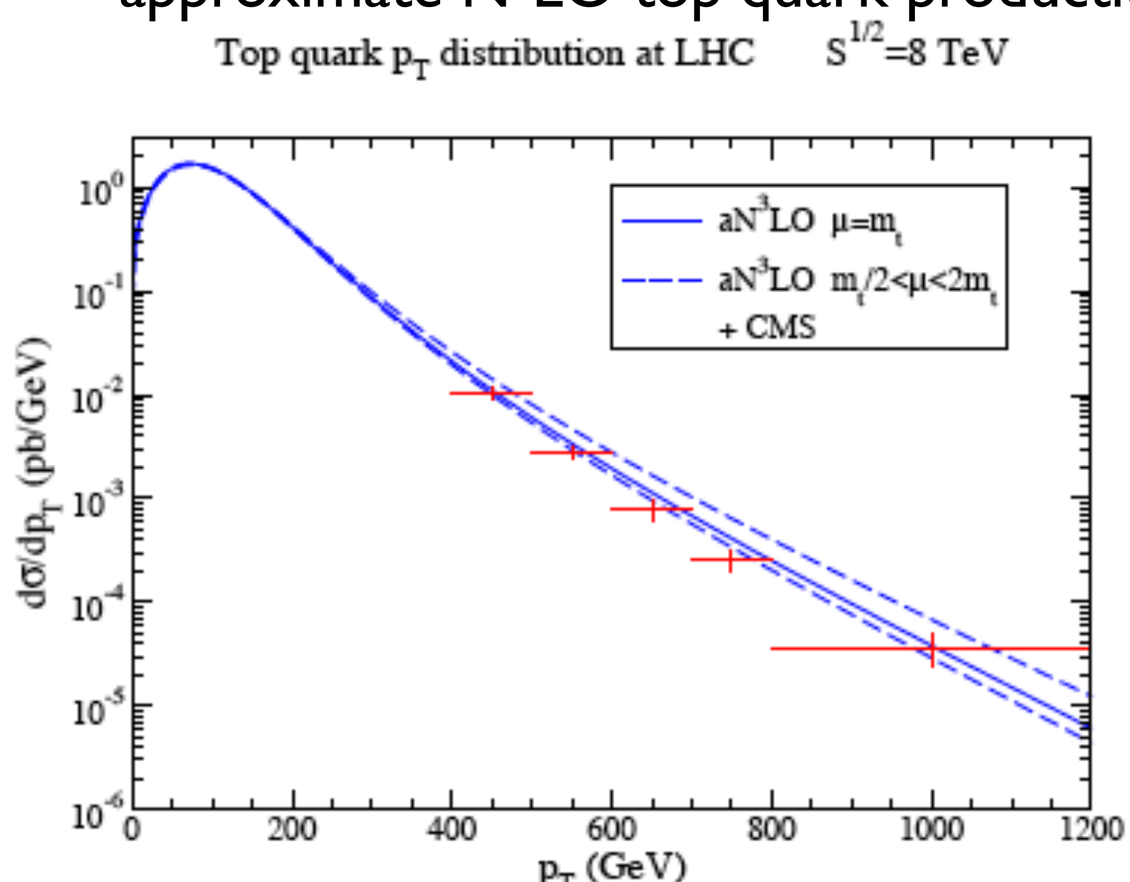
M. Neubert

Jet veto resummation for WW production



M. Zeng

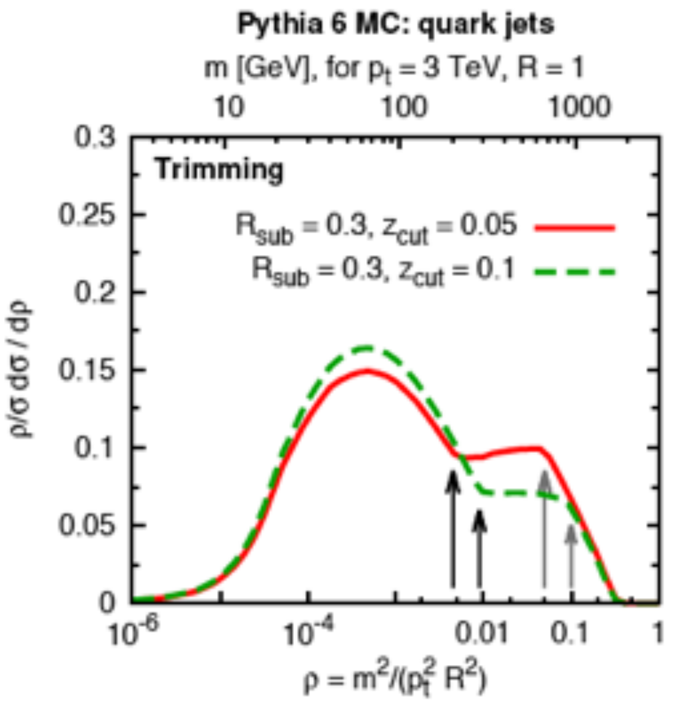
approximate N^{3}LO top quark production

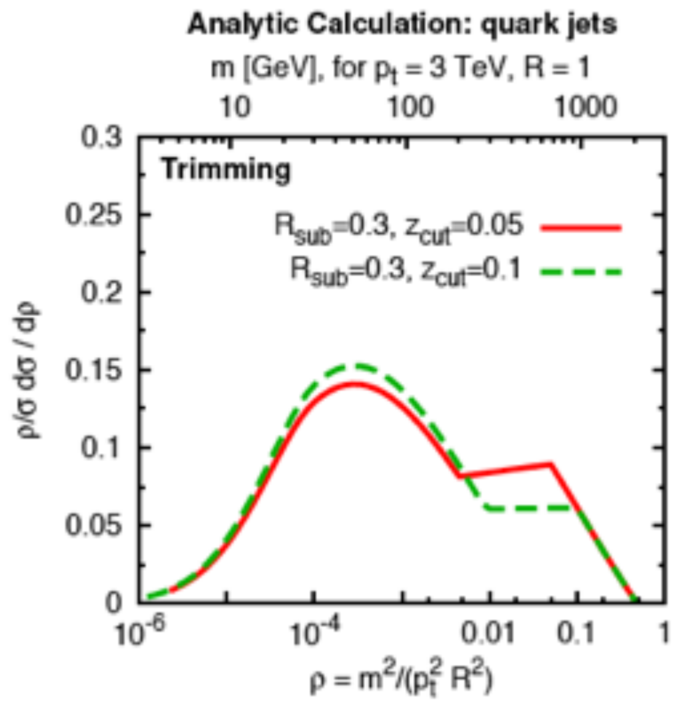


N. Kidonakis

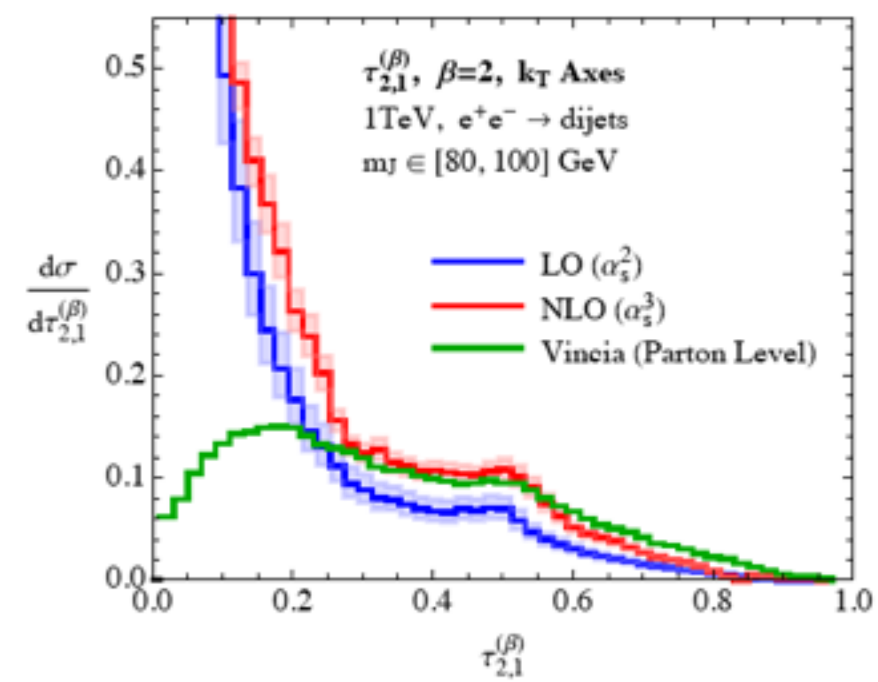
Precision QCD for jet substructure

- Missing at this LoopFest: precision QCD calculations of jet substructure observables





Dasgupta, Fregoso, Marzani, Salam (2013)



Larkoski, Moult (2015)

From D. Kosower, 2014 LoopFest closing talk: "too important a field to be left to the phenomenologists"

Want analytic understanding of what comes out of parton shower simulations!

Electroweak corrections

- Several talks on advances in electroweak corrections

- Laura Reina: precision EW fits
- Christian Bauer: EW Sudakovs for virtual and real radiation
- Jia Zhou: weak corrections in MCFM
- Stefano di Vita: Mixed QCD-EW corrections for Drell-Yan
- Marek Schoenherr: EW corrections for vector boson plus jet production

Improvements on Higgs coupling fits when EWPO included

Flavor universality

$(\kappa_f \to \kappa_u, \kappa_d, \kappa_l)$

Higgs only

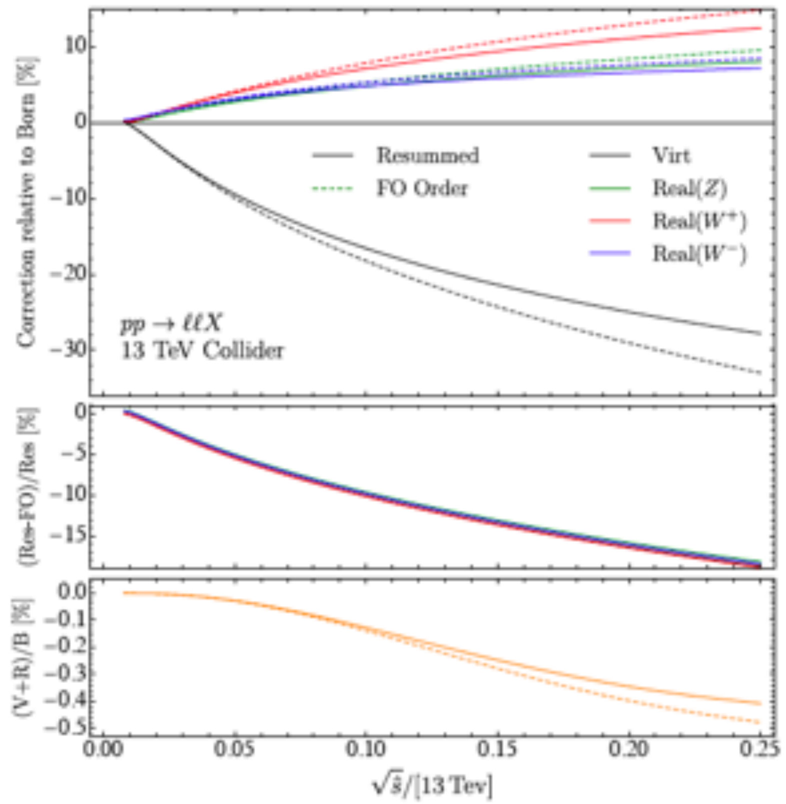
	68%	95%	correlation			
κ_V	0.97 ± 0.08	[0.80, 1.13]	1.00			
κ_l	1.01 ± 0.14	[0.73, 1.30]	0.54	1.00		
κ_u	0.97 ± 0.13	[0.73, 1.25]	0.42	0.41	1.00	
κ_d	0.91 ± 0.21	[0.48, 1.35]	0.81	0.61	0.77	1.00

Higgs+EWPO

	68%	95%	correlation			
κ_V	1.02 ± 0.02	[0.99, 1.06]	1.00			
κ_l	1.07 ± 0.12	[0.82, 1.32]	0.15	1.00		
κ_u	1.01 ± 0.12	[0.79, 1.27]	0.10	0.24	1.00	
κ_d	1.01 ± 0.13	[0.76, 1.30]	0.31	0.38	0.78	1.00

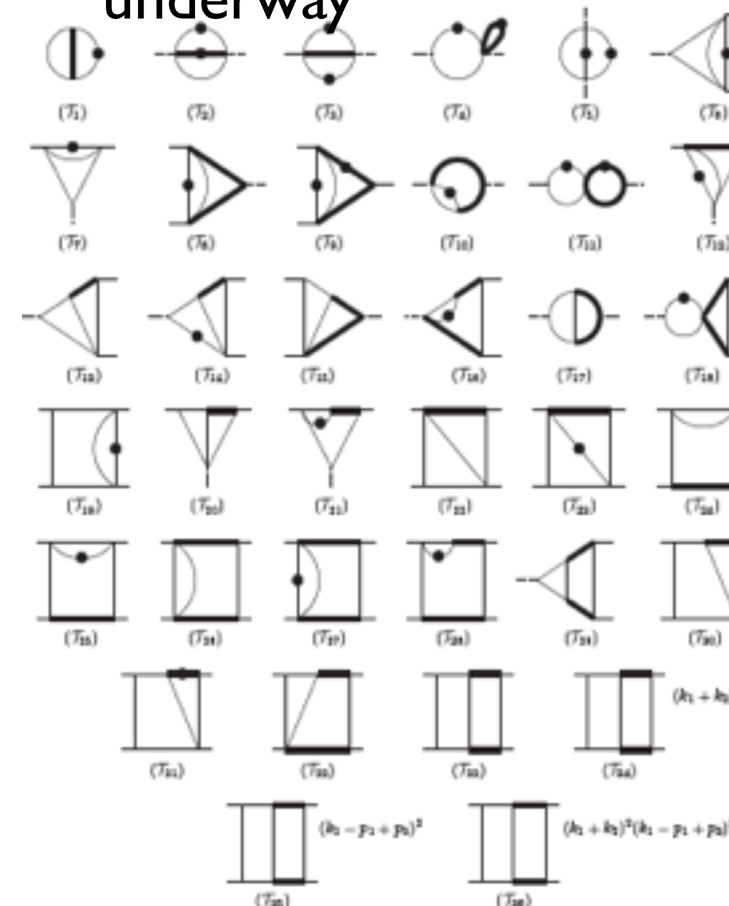
L. Reina

Importance of EW Sudakov resummation in real radiation



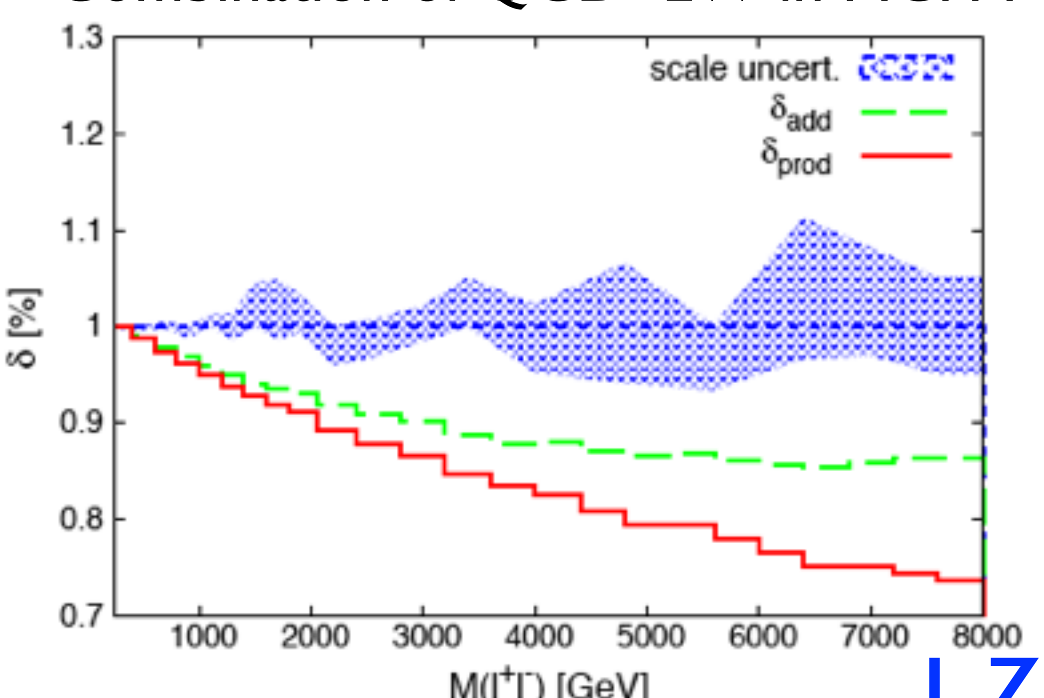
C. Bauer

Mixed QCD-EW for DY underway

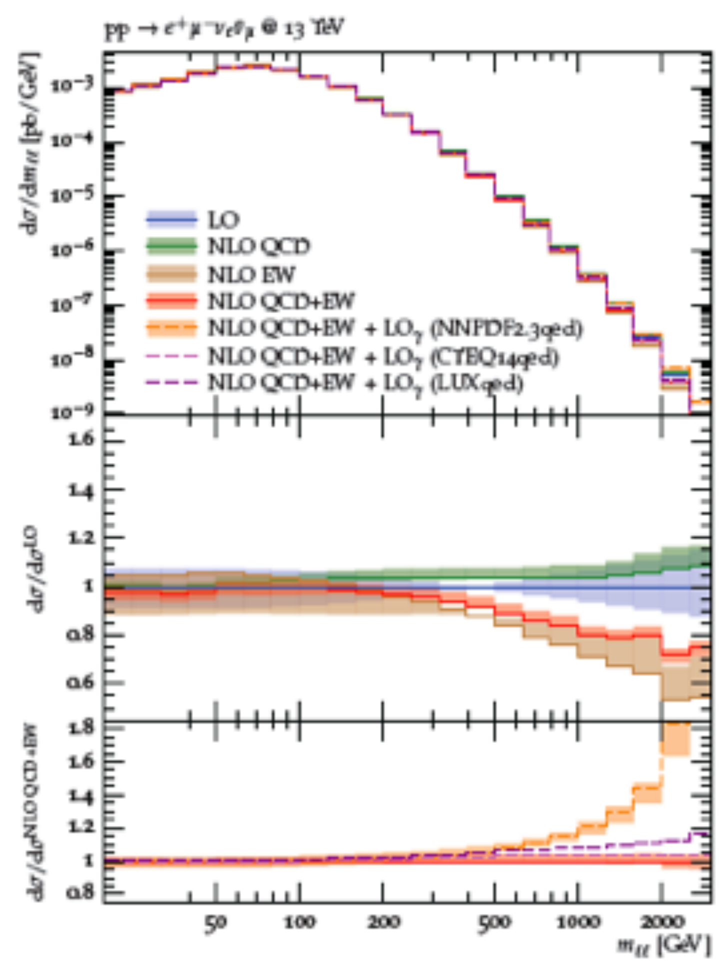


S. Di Vita

Combination of QCD+EW in MCFM



J. Zhou

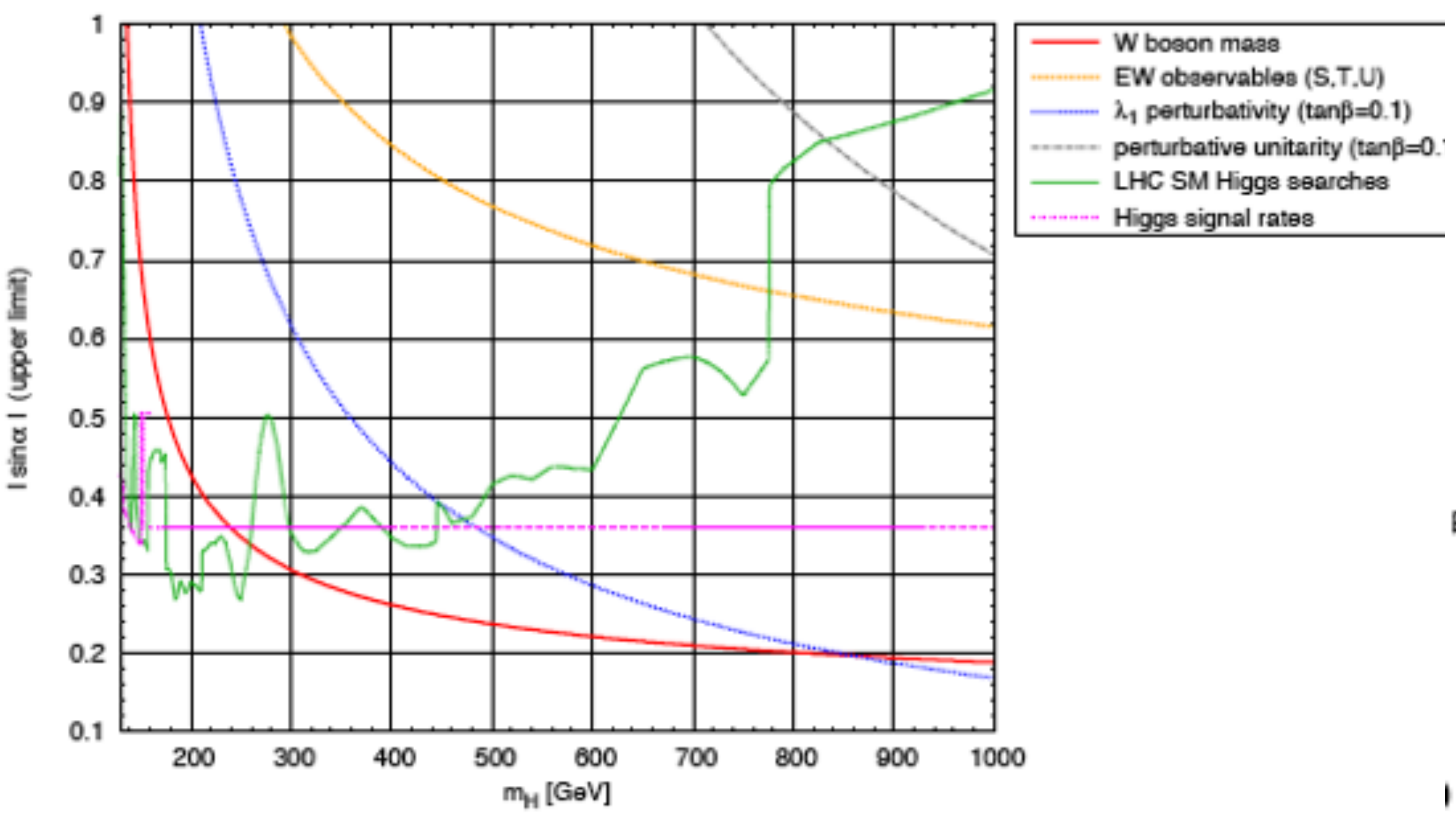


M. Schoenherr

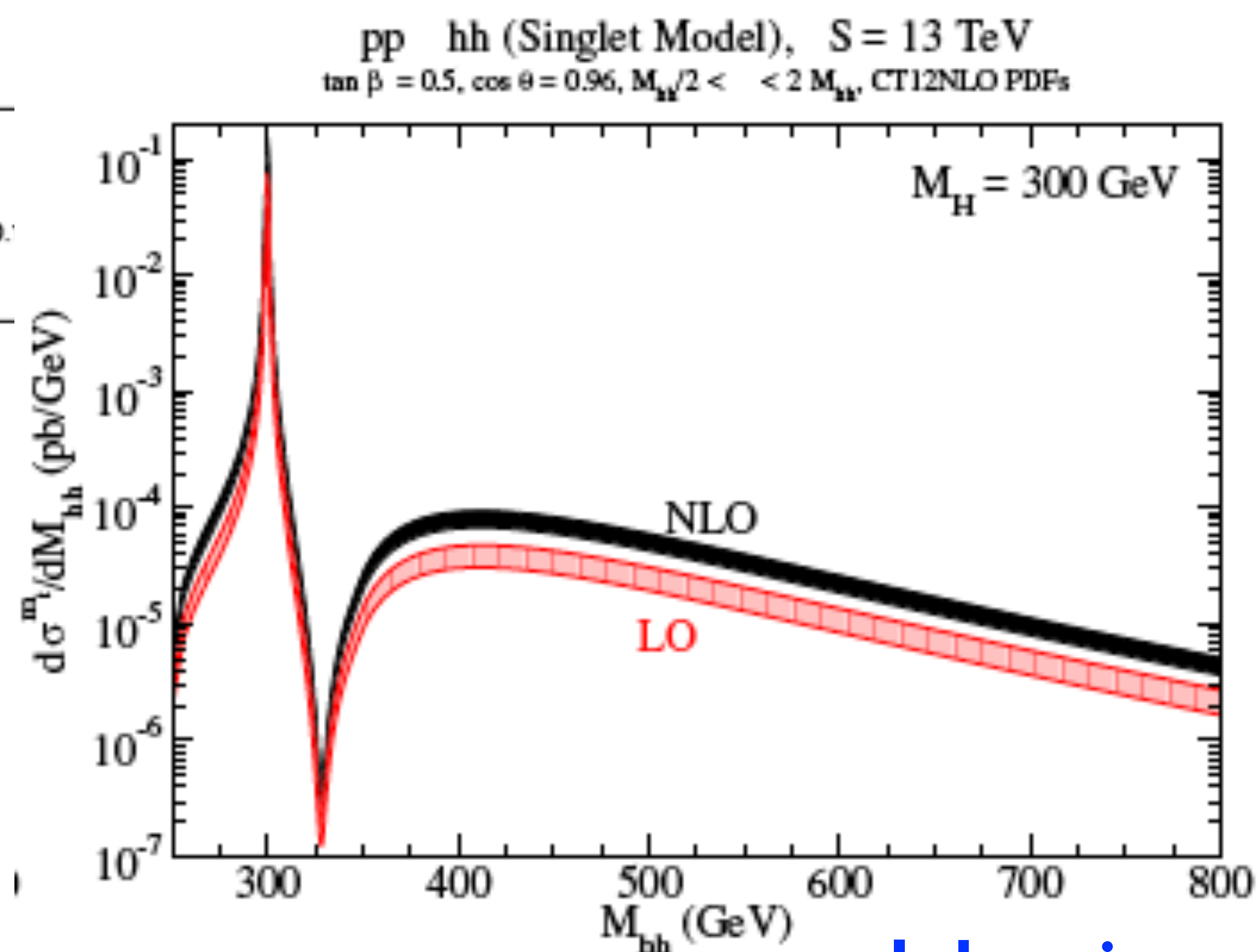
Higher order corrections for BSM

- A few talks on higher-order corrections for BSM physics

- Tania Robens: EW renormalization of the Higgs single extension
- Ian Lewis: Higgs physics and the singlet extended model



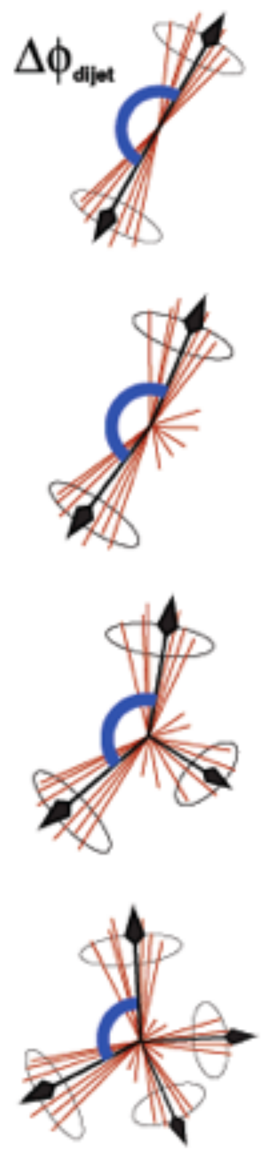
T. Robens

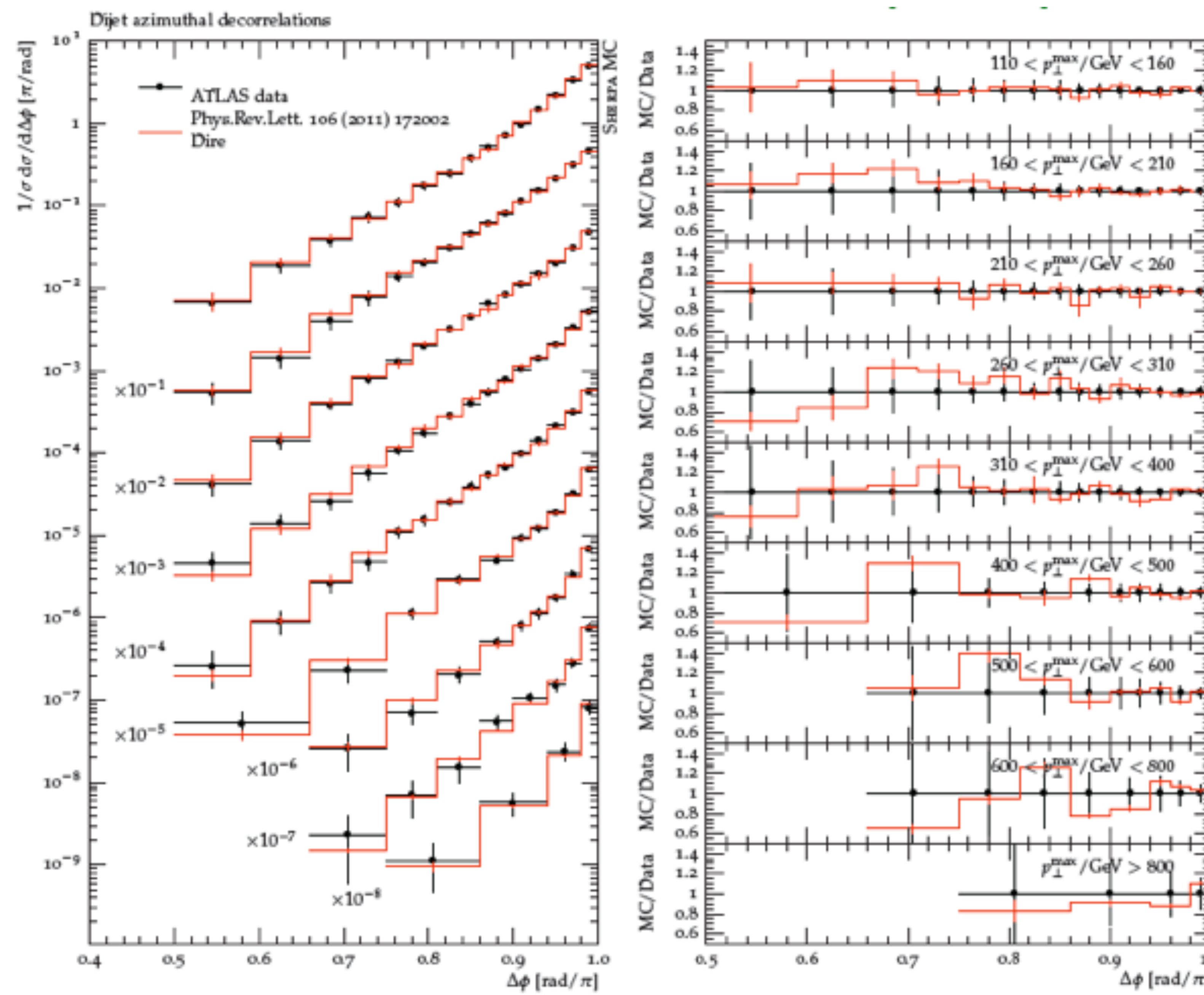


I. Lewis

Parton shower evolution

- Only a single talk on parton shower developments
  - 2016: 1 talk
  - 2015: 8 talks (joint Radcor-LoopFest)
  - 2014: 2 talks
  - 2013: 5 talks
  - 2012: 5 talks
  - 2011: 3 talks
  - 2010: 4 talks





S. Hoeche

The impact of our field

From Z. Bern, 2012 LoopFest closing talk:

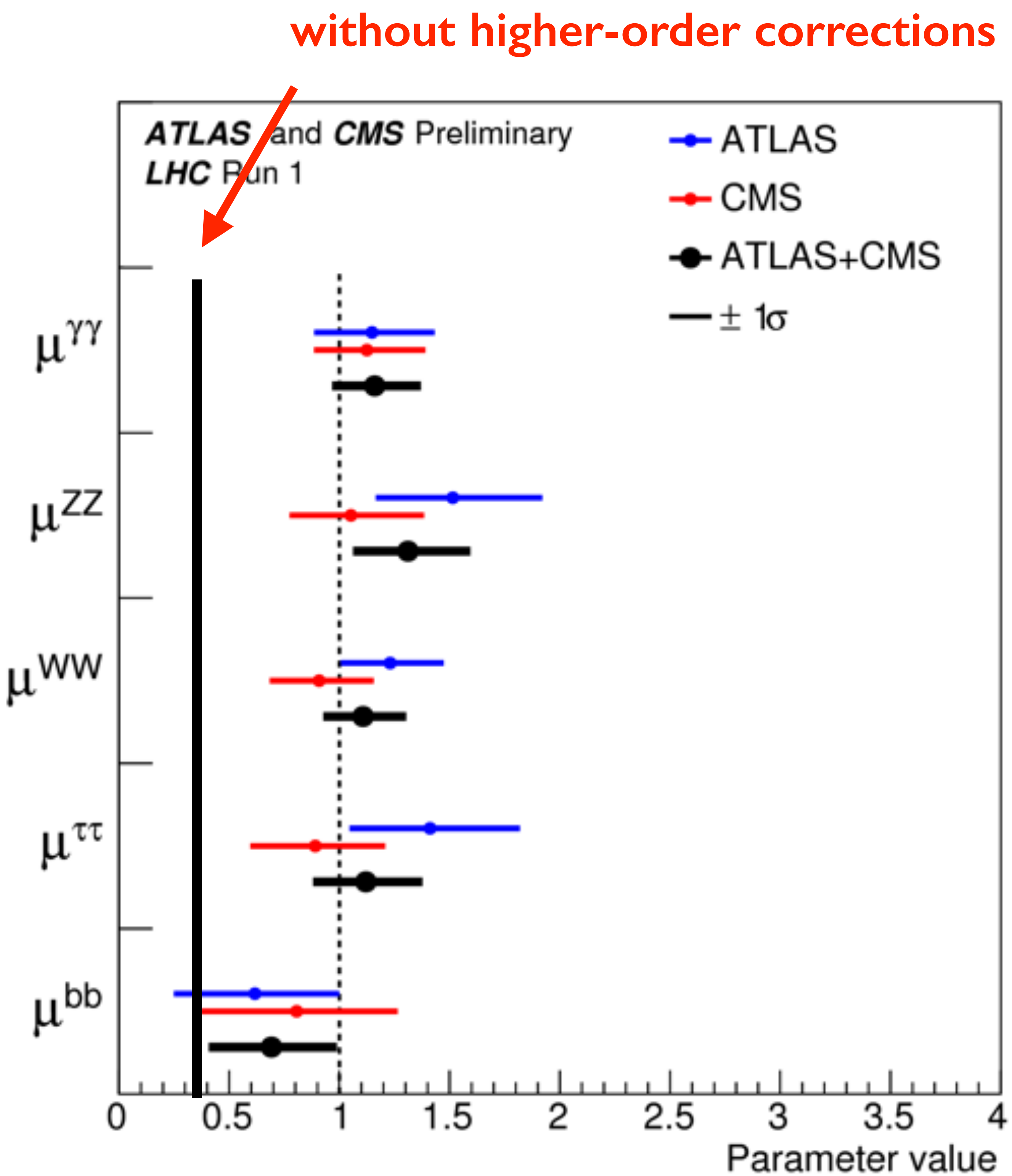
Question:

What should we do to ensure that we have a long-lasting impact?

Answer: When people look back in 10 years they should say:

1) **A great discovery was made at the LHC because of what we did.**
2) **Fundamental theoretical breakthroughs emerged from work in collider phenomenology.**

The impact of our field



- Proper interpretation of the Higgs (and discovery in the WW channel) is just one example of a great LHC result impossible without the work of the LoopFest community

1) A great discovery was made at the LHC because of what we did. ✓

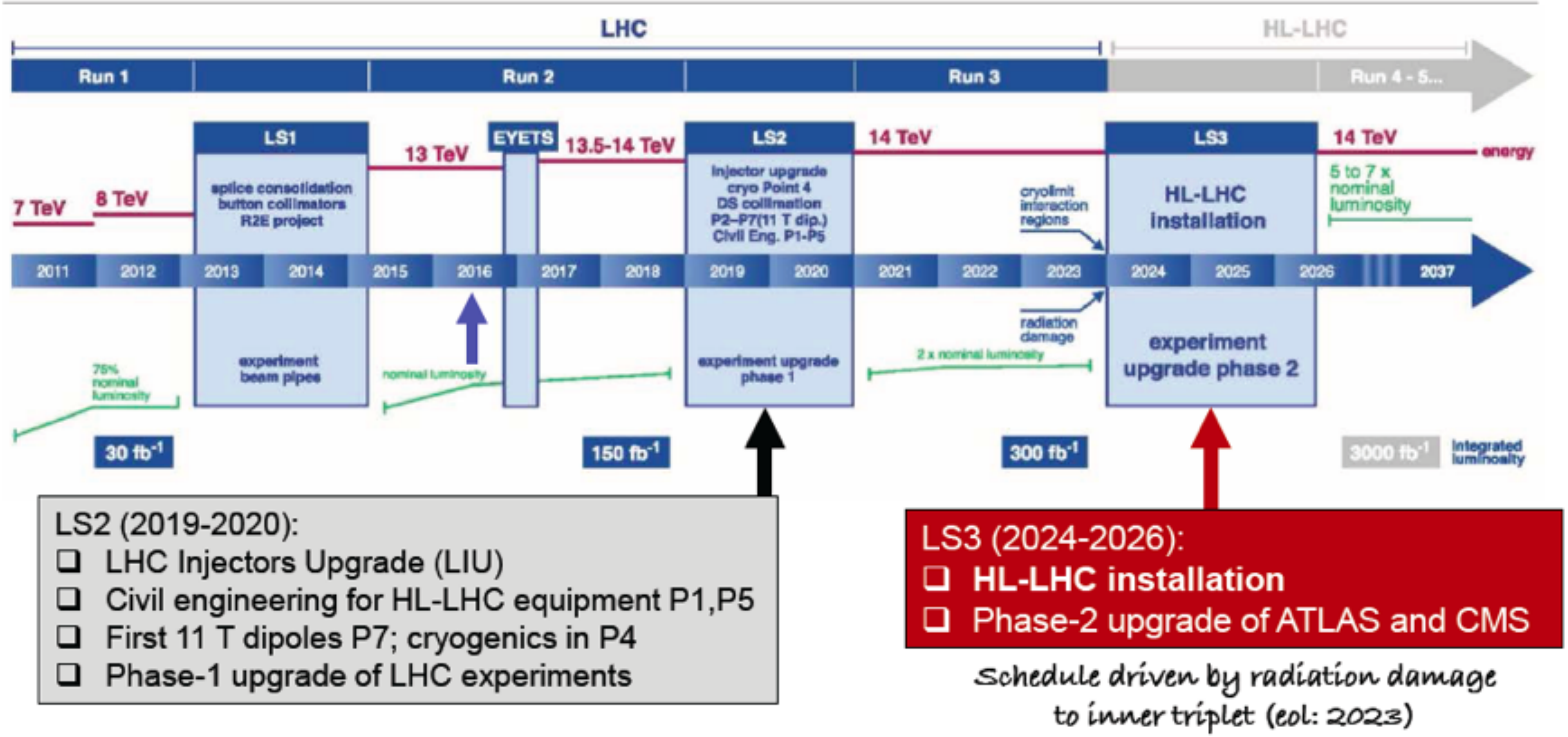
We should be vocal about our indispensable contributions to this effort!

Focusing on the future

- LHC has a further ~20-year life span, including HL-LHC running

HL-LHC schedule

E. Elsen, LHCP 2016



Should we just keep doing what we've been doing?

Focusing on the future

- Independently from what Run II finds, there will be a continued need for precision calculations and simulations throughout the LHC program. But what happens to the precision community when the experiment ends?

Motivational speaker 1:

"I try to learn from the past, but I plan for the future by focusing exclusively on the present. That's where the fun is."

Motivational speaker 2:

"Part of being a winner is knowing when enough is enough. Sometimes you have to give up the fight and walk away, and move on to something that's more productive."

- What will you do if nothing new is found in the first few years of Run II? Keep focusing on LHC data, or look for other possible applications of precision technology?

Focusing on the future

- Independently from what Run II finds, there will be a continued need for precision calculations and simulations throughout the LHC program. But what happens to the precision community when the experiment ends?

Motivational speaker 1:

"I try to learn from the past, but I plan for the future by focusing exclusively on the present. That's where the fun is." - *Donald Trump*

Motivational speaker 2:

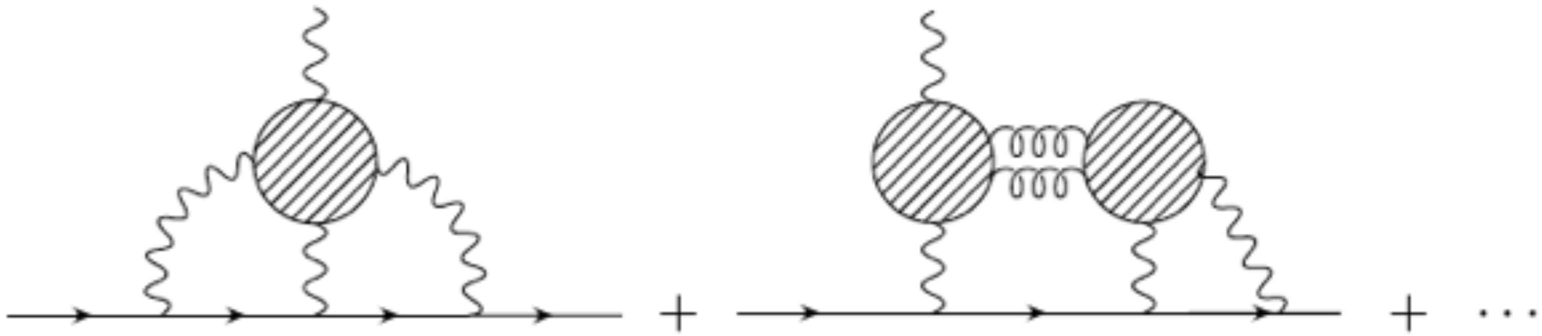
"Part of being a winner is knowing when enough is enough. Sometimes you have to give up the fight and walk away, and move on to something that's more productive." - *Donald Trump*

Find another motivational speaker!

Other experiments needing precision

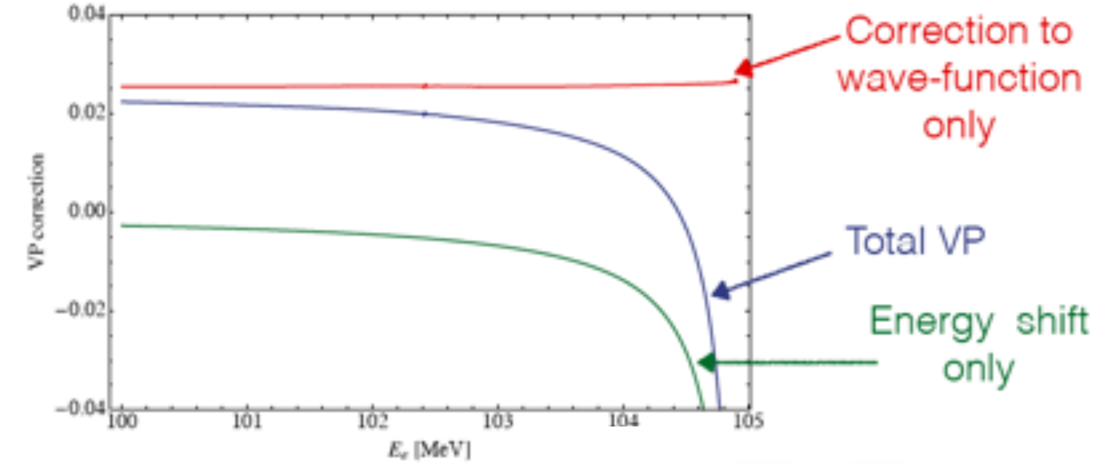
- Glad to see several talks on low-energy precision probes of new physics, focusing on new experiments such as the FNAL g-2 and mu2e

- Thomas Blum: hadronic light-by-light on the lattice
- Tao Liu: 4-loop electron contribution to the muon g-2
- Andrzej Czarnecki: radiative corrections to the bound electron g-factor
- Robert Szafron: decay of a bound muon

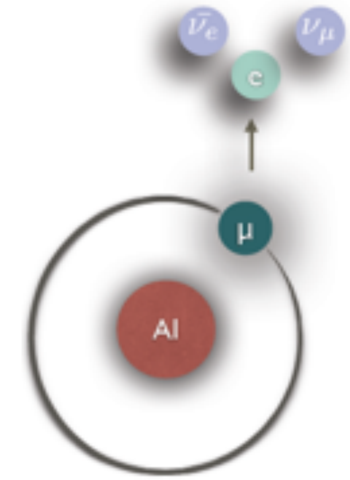


$$a_\mu^{\rm cHLbL} = 11.60 \pm 0.96 \times 10^{-10}$$
$$a_\mu^{\rm dHLbL} = -6.25 \pm 0.80 \times 10^{-10}$$
$$a_\mu^{\rm HLbL} = 5.35 \pm 1.35 \times 10^{-10}$$

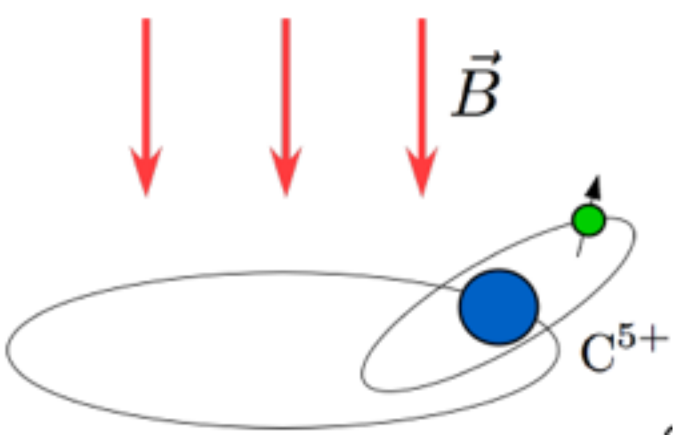
T. Blum



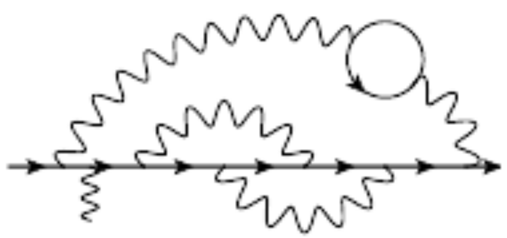
R. Szafron



$$\delta E_{a-s} = \frac{\alpha^2 (Z\alpha)^5}{\pi n^3}\left(\frac{\mu}{m}\right)^3 m\,[-7.72381(4)]$$



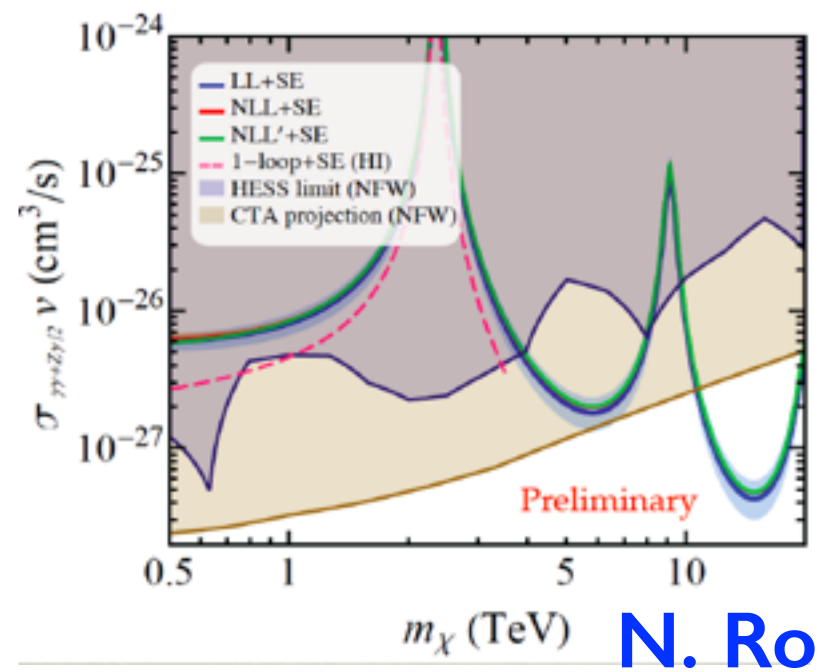
A. Czarnecki



T. Liu

$A_3^{(8)}(m_\mu/m_e, m_\mu/m_\tau)$

group	our work	[Aoyama et al. 2012]
I(a)	0.00320905(1)	0.003209(0)
I(b) + I(c)	0.00442289(2)	0.004422(0)
II(b) + II(c)	−0.02865753(1)	−0.028650(2)
IV(a)	0.08374757(9)	0.083739(36)



N. Rodd

Other experiments needing precision

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- Thomas Blum: hadronic light-by-light on the lattice
- Tao Liu: 4-loop electron contribution to the muon g-2
- Andrzej Czarnecki: radiative corrections to the bound electron g-factor
- Robert Szafron: decay of a bound muon
- N. Rodd: radiative corrections to DM annihilation

- What other experiments can we think about?
  - 100 TeV pp collider: great, just rerun codes after changing $\sqrt{s}$! (and after debugging NaNs, and checking for expansions in $1/m_{top}$, ...)
  - Electron Ion Collider: a precision QCD machine, expected to be one of the new facilities in the US
  - Neutrino physics: also expected to be a major new US facility; application of SCET ideas expected to improve modeling of neutrino-nucleon cross section (R. Hill (2016))
  - Dark matter: in this conference ⇒ **N. Rodd**

See you at LoopFest XVI at Argonne National Laboratory!