The role of precision at the high-energy frontier

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Outline

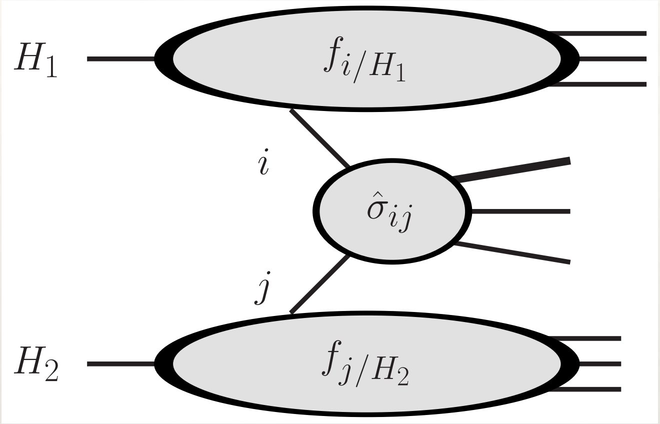
- Precision, accuracy, errors and uncertainty…
- …for physics at the (HL-)LHC
- …for physics at future future colliders
- Some prospects for new methods and tools towards yet further precision

Recommended: inputs to and talks at Granada Open Symposium

Apologies: credits in talk will be vastly inadequate

Theoretical colliders

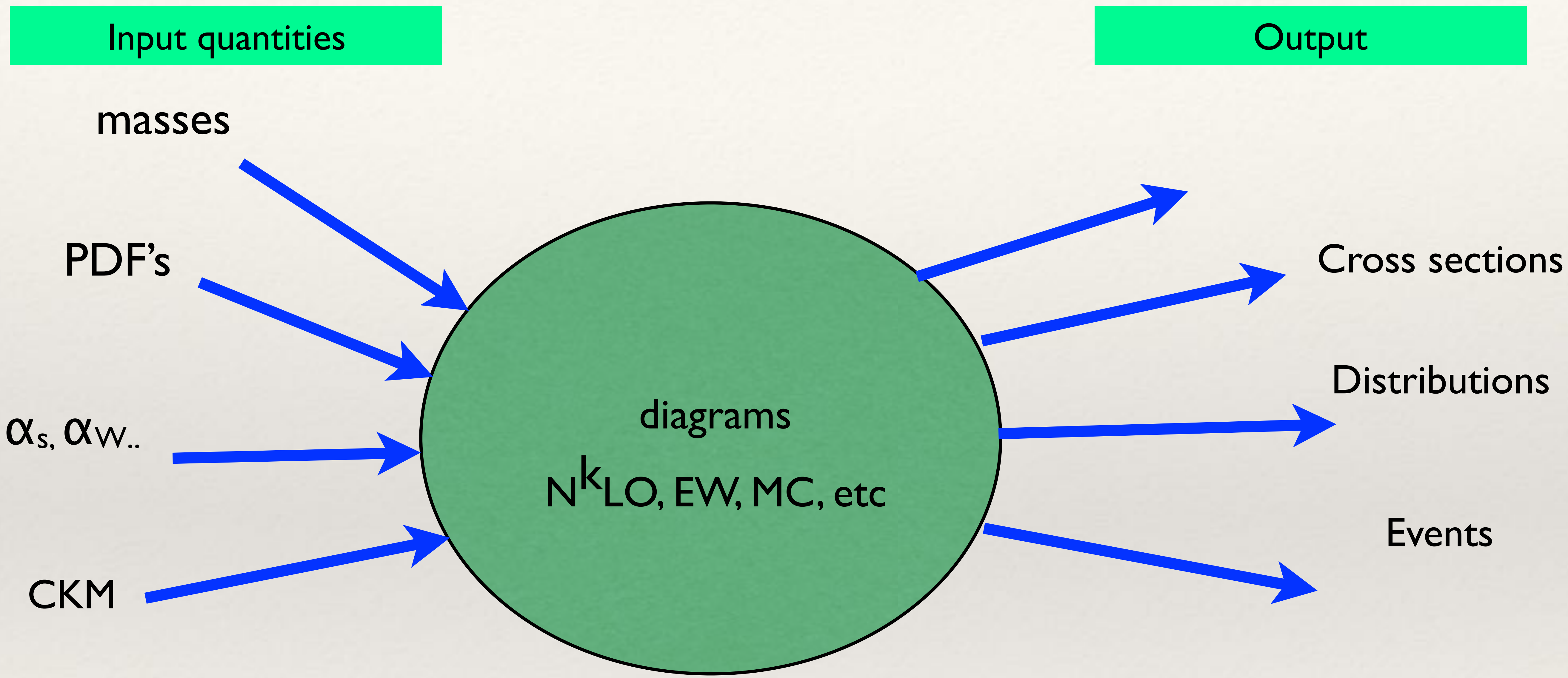
- Hadron collider
  - transformed into “parton collider” via parton distribution functions



$$d\sigma_{\mathrm{H_1H_2}}(\{X_n\}) = \sum_{i,j} \int_{\xi_{1,\mathrm{min}}}^{1} d\xi_1 \int_{\xi_{2,\mathrm{min}}}^{1} d\xi_2\, f_{i/\mathrm{H_1}}(\xi_1) f_{j/\mathrm{H_2}}(\xi_2)\, d\hat{\sigma}_{ij}(\xi_1, \xi_2, \{X_n\})\,,$$

  - compute partonic cross section in perturbation theory
  - infer (i.e. download) pdf
- Lepton collider: can do (partly) without pdf’s

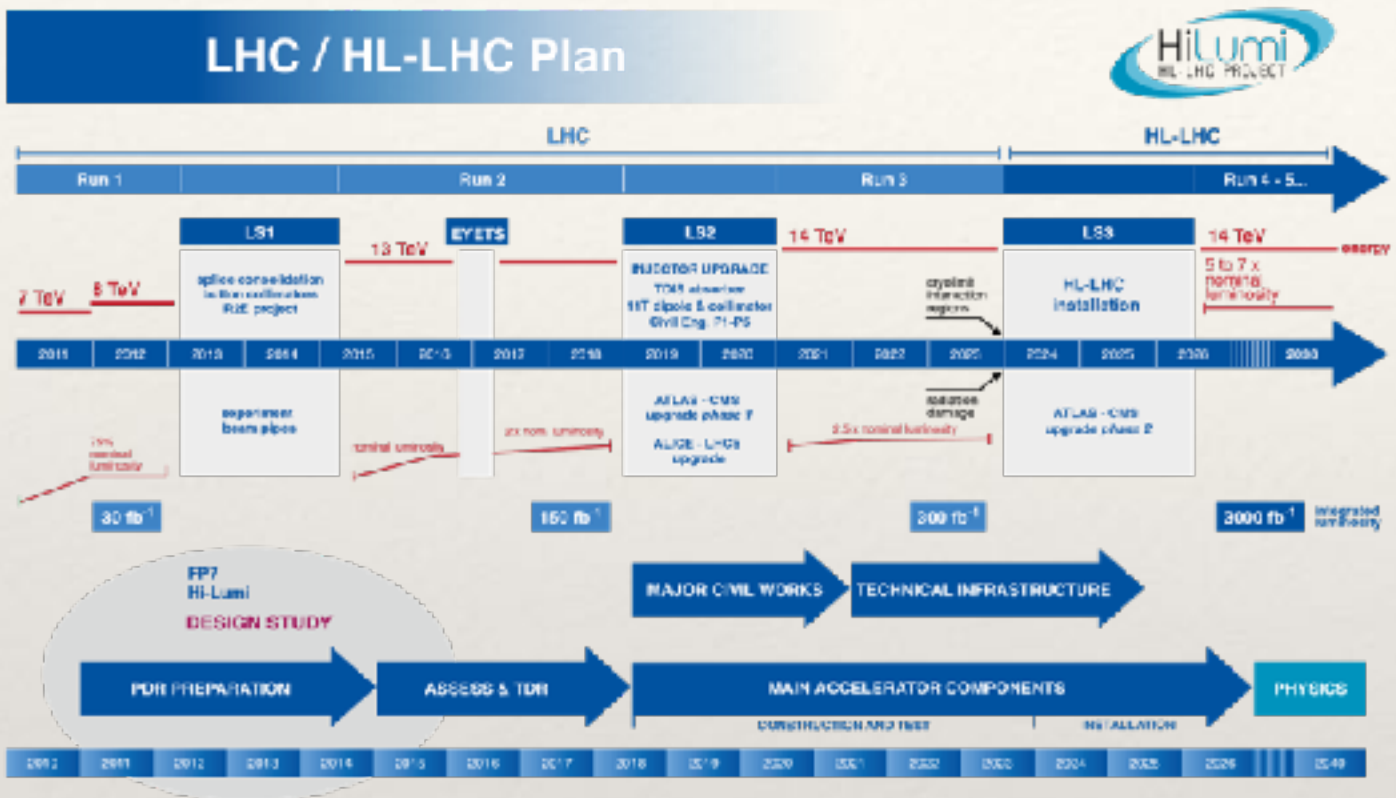
Collider physics



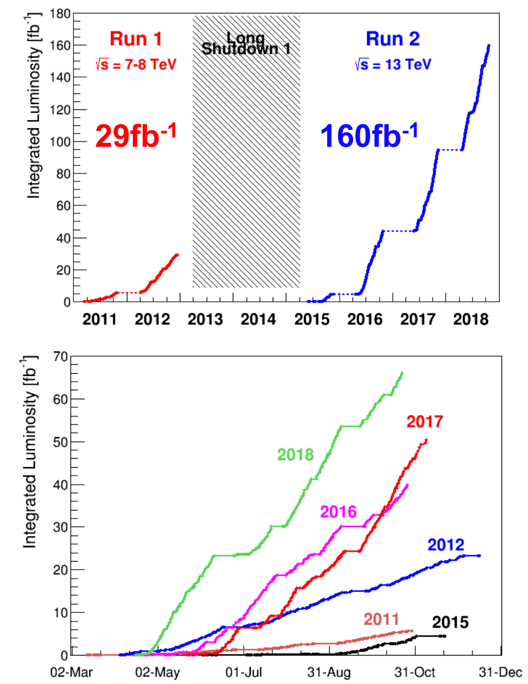
Goal: highly precise output

➡ Optimize precision of inputs

A lot of LHC data still to come



Run1 + Run 2 Luminosity Production



- Every year beats the record of the last!
- Integrated luminosity Run 2: 160fb^{-1}
- LHC total integrated proton-proton luminosity: **189fb^{-1}**

Period	Int. Luminosity [fb^{-1}]
Run 1	29.2
Run 2: 2015	4.2
Run 2: 2016	39.7
Run 2: 2017	50.2
Run 2: 2018	66
Total Run 1+ 2	189

31.10.2018

Source: *https://twiki.cern.ch/twiki/bin/viewauth/LhcMachine/LhcCoordinationMain*

At present we only have about 190 / 3000 ∿ 6.5 % of data yield after HL-LHC

Precision, accuracy, error and uncertainty

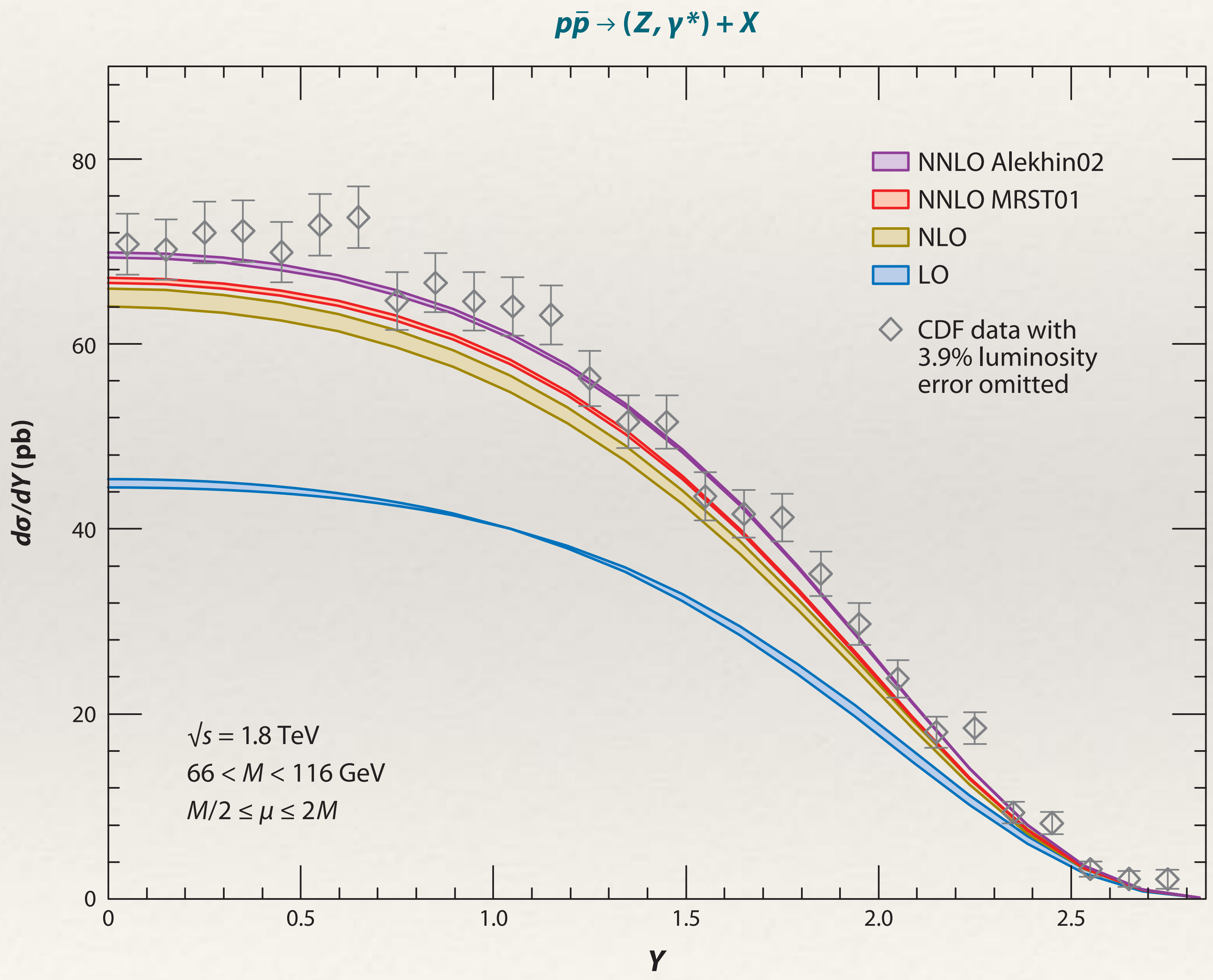
- A bit of terminology: for predictions for observable O

$$O^{[m]} = \sum_n^m c_n \alpha^n + \delta O^{[m]}$$

  - Precision: compute to order "m", large enough for uncertainty $\delta O^{[m]}$ to be small enough
  - But beware: it can a be small uncertainty on an incorrect result. It is then precise, but not accurate
  - Errors: a measure of accuracy
    - ✓ experimental: statistical and systematical
  - Uncertainty: indicates range in which true value could lie
- Confront prediction with measurement, all the more meaningful with small $\delta O^{[m]}$
- This is what we *should* be doing: a highly sophisticated instance of The Scientific Method

Example of precision vs accuracy

CDF Run 1 rapidity distribution of Z boson vs perturbation theory



Anastasiou, Dixon, Melnikov, Petriello '03

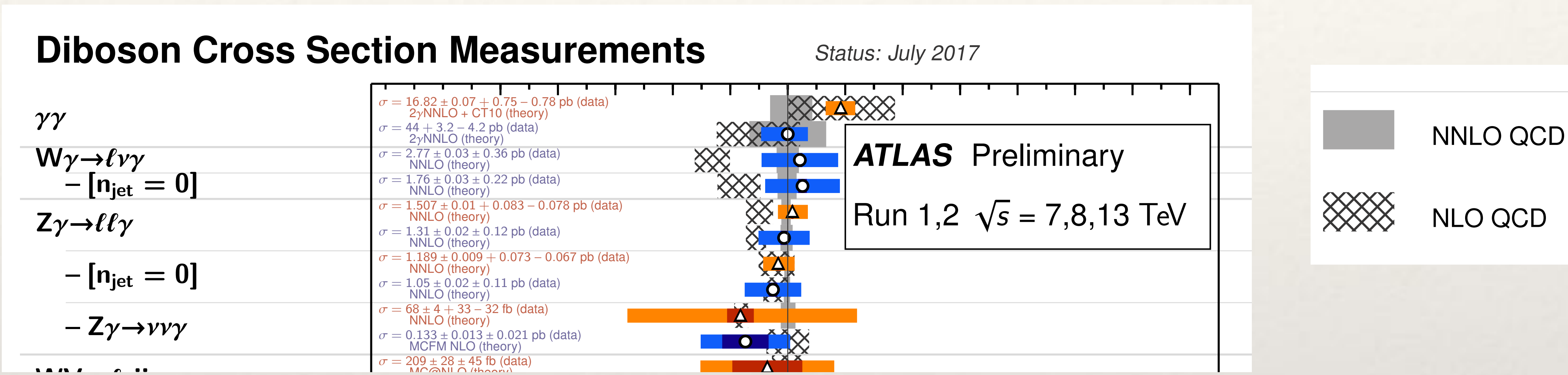
Purpose of precision: To Measure and Explore

- 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!

Michelangelo Mangano at SM@LHC '19, Zurich

Precision for SM and BSM

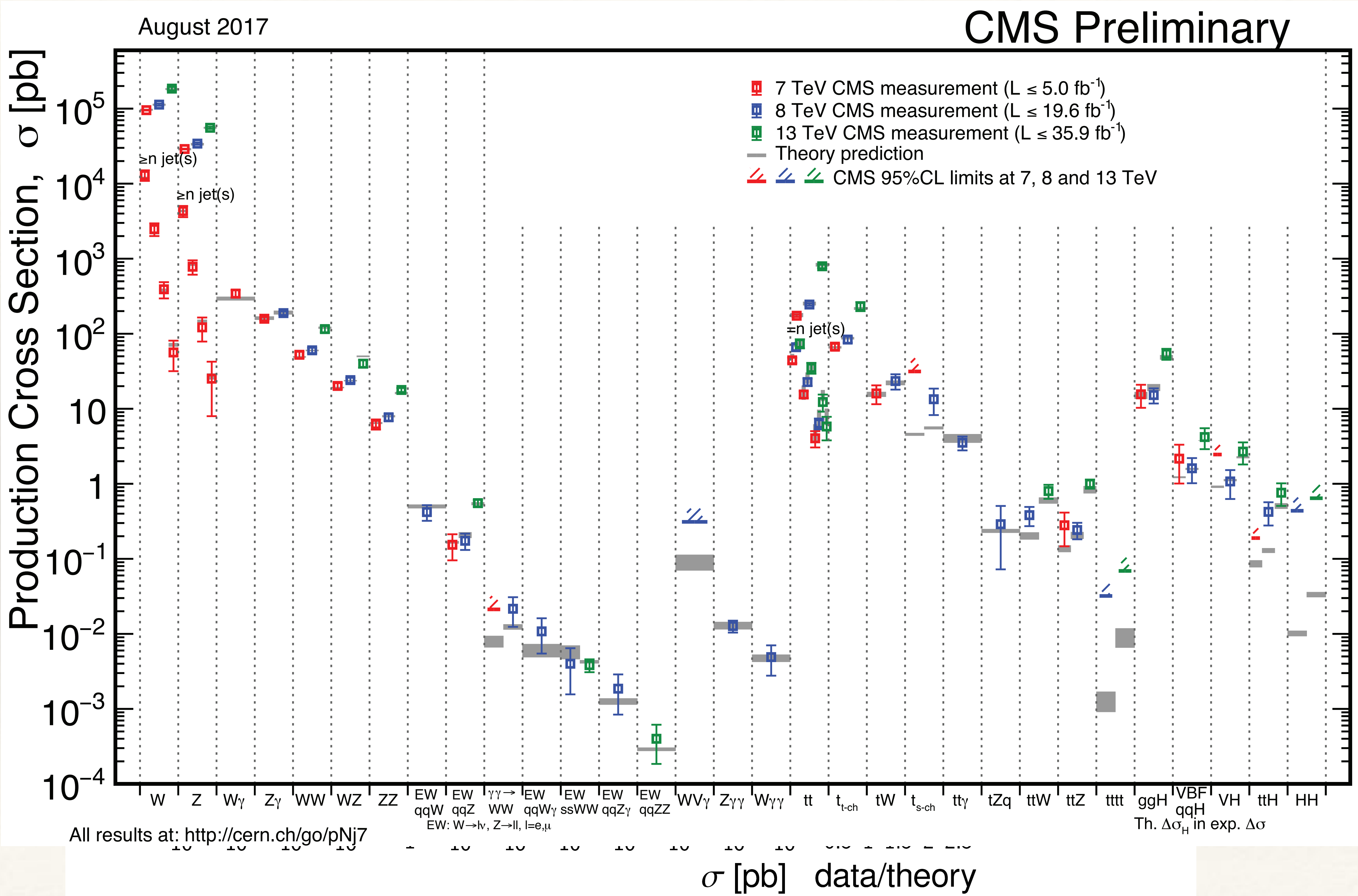
- Falsification
  - Compute promising SM observables to high precision for easier falsification by data



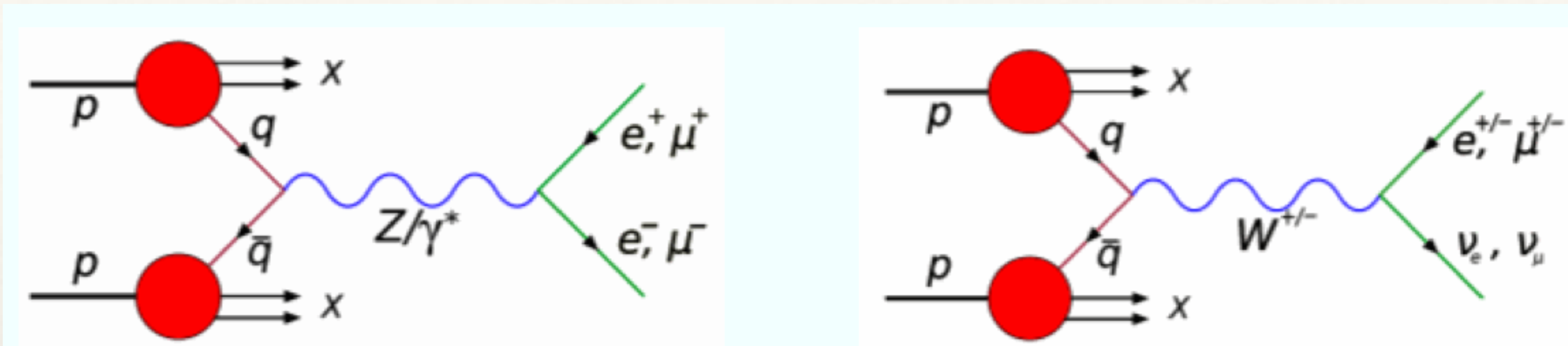
- Verification
  - Compute BSM influenced on selected observables to high precision
    - ✓ to ensure that the unique signatures are robust on HO corrections
    - ✓ to extract information (measurement or exclusion)

Precision for (HL-)LHC

So far excellent predictivity of SM at LHC



A core process at (HL-)LHC: Drell-Yan



- Sub percent level experimental error for Drell-Yan p_T spectrum, and other distributions
- Impact on W-mass, PDF-fits etc

Lorenzo Bianchini SM@LHC '19

q^V_T measurements at LHC

[1] Bizon et al., JHEP 12 (2018) 132
[2] Rottoli, Isaacson, EW workshop, Durham
[3] ATLAS, EPJC 78 (2018) 110

Theory:

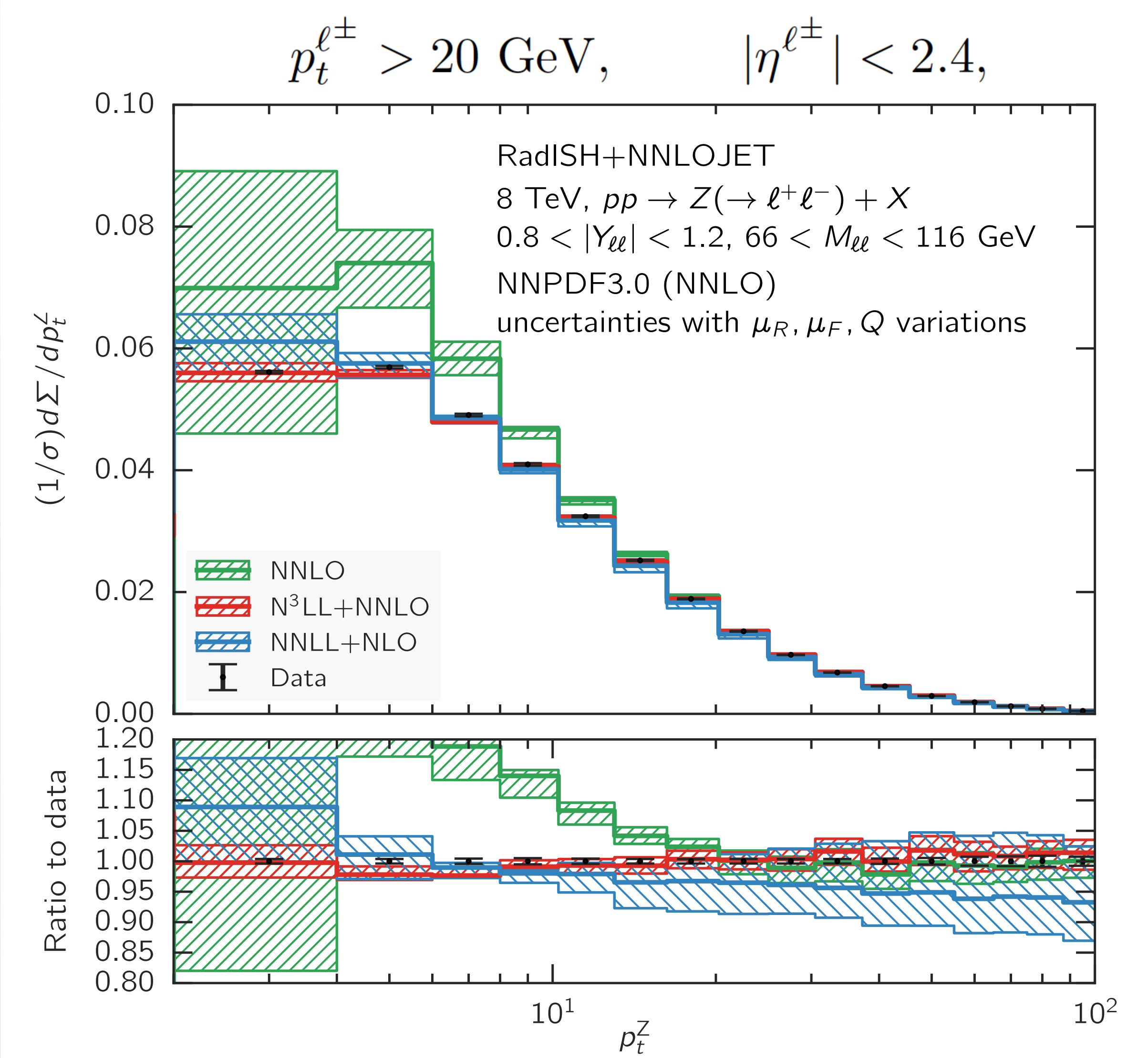
- $\sigma^{-1} d\sigma^V/dq_T$ ~ **5%**[1]
- $d\sigma^W / d\sigma^Z$ ~ **5%-10%**[2], **0.5%-2.5%**[3], **1-2%**[2] (depending on corr. scheme)

Experiment:

- $\sigma^{-1} d\sigma^Z/dq_T$ ~ **0.5-1%** with ~**2 GeV** bins
- $\sigma^{-1} d\sigma^W/dq_T$ ~ **1.5-2.5%** with ~**8 GeV** bins
- $d\sigma^W / d\sigma^Z$ ~ **2.5%** with ~**8 GeV** bins

Drell-Yan @ (HL-)LHC

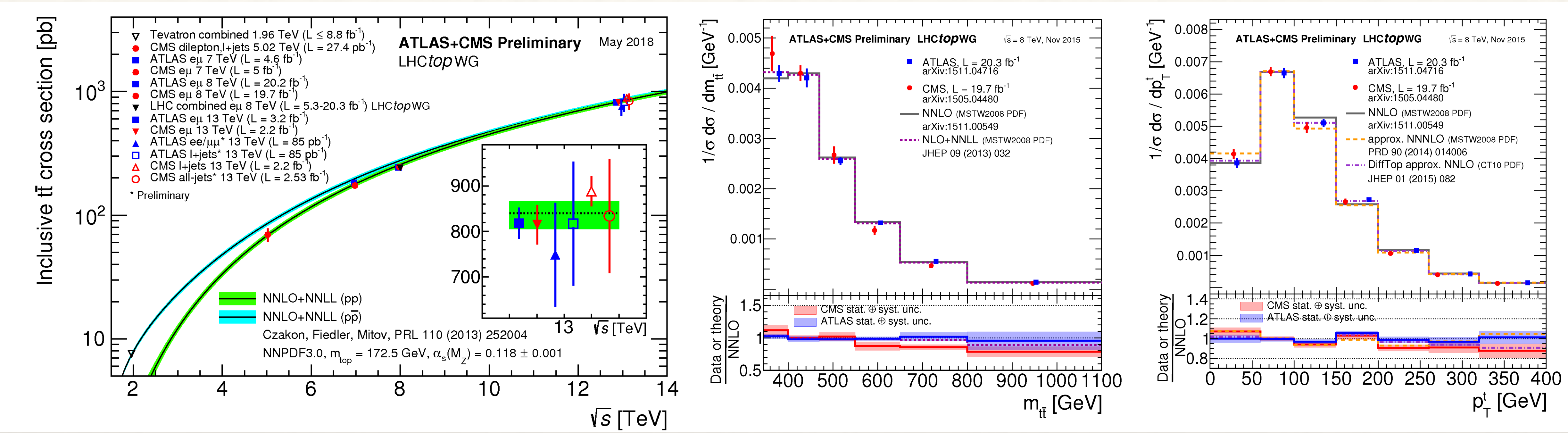
- Theory challenged!
- NNLO + N3LL better than NNLO alone
  - NLO + resummation not sufficient
- At this level many small effects must be assessed
  - N3LO + N4LL?
  - PDF uncertainties at 1%?
  - non-perturbative effects at small p_T
  - QED corrections (1-2%)
  - α_s uncertainty
- HL-LHC data will be much more challenging



Bizon, Chen, Gehrmann-de Ridder, Gehrmann, Glover, Huss, Monni, Re, Rottoli, Torrieli '18

Top quark pairs at (HL)-LHC

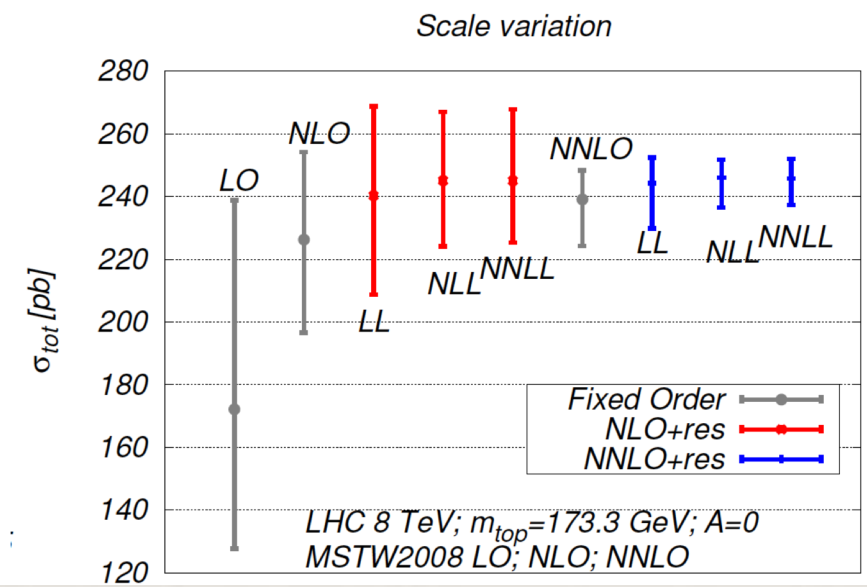
- We are already well into precision top quark physics era



- all-QCD process, NNLO corrections for cross sections.. Czakon, Fiedler, Mitov '13
- ..and for differential distributions Czakon, Heymes, Mitov '15,'16
- good enough now to be input for PDF fits

Precision for top quark pair production

- Value of higher orders for precision, and uncertainty budget



Concurrent uncertainties:

Scales ~ **3%**
pdf (at 68%cl) ~ **2-3%**
α_S (parametric) ~ **1.5%**
m_{top} (parametric) ~ **3%**

Soft gluon resummation makes a difference: **5%** → **3%**

Czakon, Fiedler, Mitov ‘13

- improvement due to higher orders and resummation clear
- all at the few percent level
- NLO EW also known

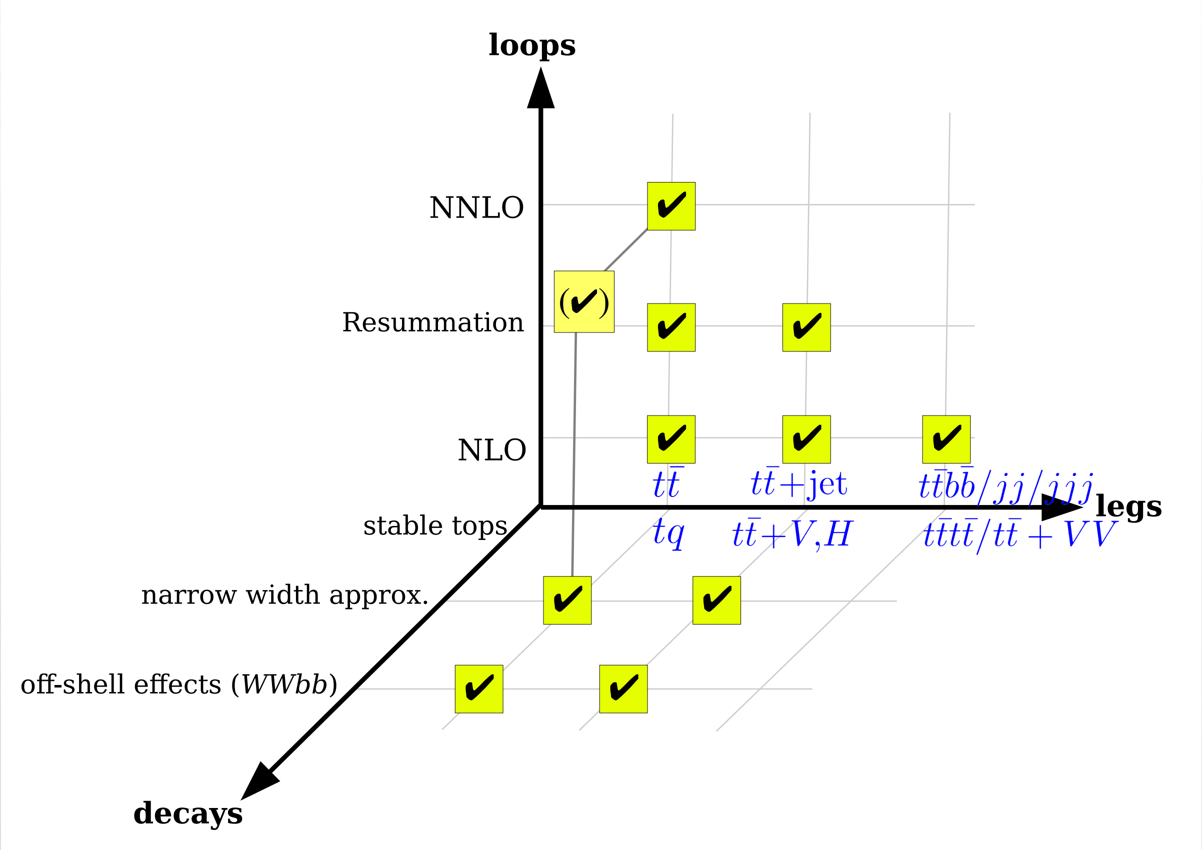
Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro ‘17

  - impact of photon-in-proton distribution notable

Theory for top pairs plus more

- Status of precision theory description in 3D

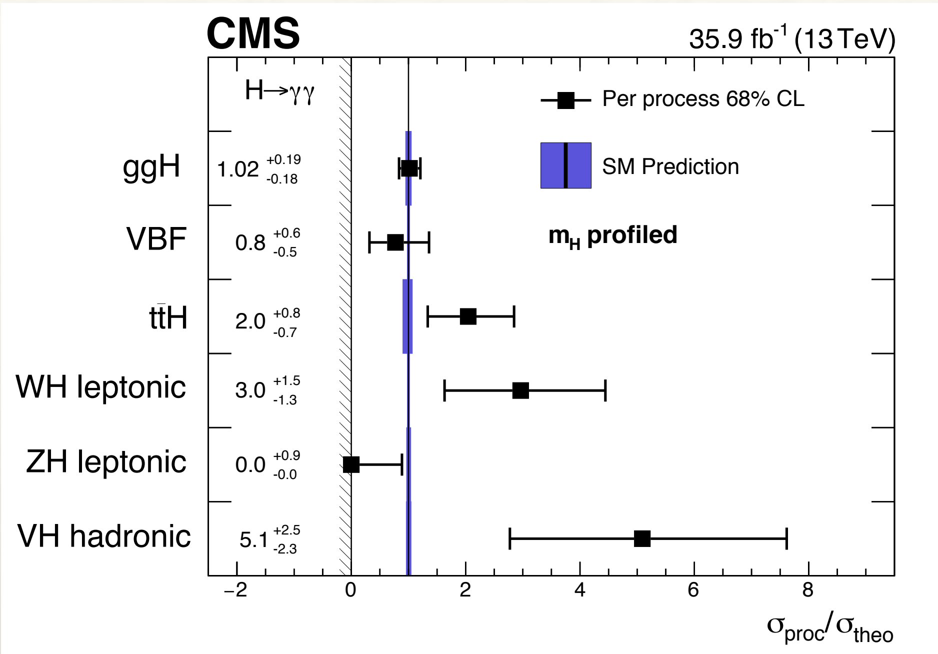
Markus Schulze at LHCP '18



- Again, smaller effects come to the fore when precision is high
  - narrow width approximation vs. full off-shell decay, all this at higher order
  - m_{top} definition and value - a guaranteed topic for lively debates
- Also here the experimental accuracies will be challenging theory

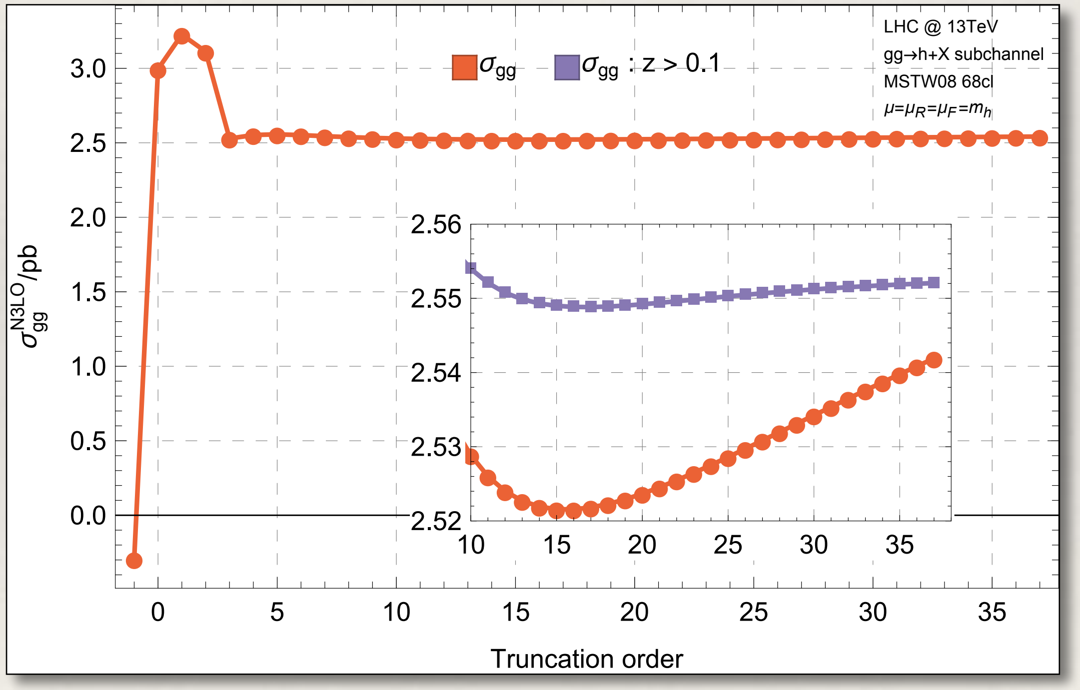
Higgs production at (HL-)LHC

- Status of Higgs production mechanisms vs theory: theory (just) ahead for now



Includes N3LO calculation:
7 Million 3-loop Feynman diagrams
2 months of running on 25K cores

Anastasiou, Duhr, Dulat, Herzog, Mistlberger '15



Mistlberger '18

- Calculation was done in "1-z" = soft expansion

$$\hat{\sigma}^{(3,N)}_{ij} = \delta_{ig}\,\delta_{jg}\,\hat{\sigma}^{(3)}_{\mathrm{SV}} + \sum_{n=0}^{N} c^{(n)}_{ij}\,(1-z)^n$$

  - to N=37..
  - full analytic result also available

J. de Blas et al, arXiv: 1905.03764

Higgs boson studies at future colliders

- In general, Higgs uncertainties at HL-LHC = 1/2 those of LHC
- FCC: well below 1%

F. Caola @ Granada

Higgs: parametric uncertainties

Decay	Partial width [keV]	current unc. $\Delta\Gamma/\Gamma$ [%]				future unc. $\Delta\Gamma/\Gamma$ [%]			
		$\mathrm{Th}_{\mathrm{Intr}}$	$\mathrm{Th}_{\mathrm{Par}}(m_q)$	$\mathrm{Th}_{\mathrm{Par}}(\alpha_s)$	$\mathrm{Th}_{\mathrm{Par}}(m_H)$	$\mathrm{Th}_{\mathrm{Intr}}$	$\mathrm{Th}_{\mathrm{Par}}(m_q)$	$\mathrm{Th}_{\mathrm{Par}}(\alpha_s)$	$\mathrm{Th}_{\mathrm{Par}}(m_H)$
$H \to b\bar{b}$	2379	< 0.4	1.4	0.4	–	0.2	0.6	< 0.1	–
$H \to \tau^+\tau^-$	256	< 0.3	–	–	–	< 0.1	–	–	–
$H \to c\bar{c}$	118	< 0.4	4.0	0.4	–	0.2	1.0	< 0.1	–
$H \to \mu^+\mu^-$	0.89	< 0.3	–	–	–	< 0.1	–	–	–
$H \to W^+W^-$	883	0.5	–	–	2.6	0.4	–	–	0.1
$H \to gg$	335	3.2	< 0.2	3.7	–	1.0	–	0.5	–
$H \to ZZ$	108	0.5	–	–	3.0	0.3	–	–	0.1
$H \to \gamma\gamma$	9.3	< 1.0	< 0.2	–	–	< 1.0	–	–	–
$H \to Z\gamma$	6.3	5.0	–	–	2.1	1.0	–	–	0.1

$\delta\alpha_s = 0.0002$ <= very hard but doable at M_Z

$\delta m_t = 50\ MeV$ <= OK at e^+e^- threshold scan

$\delta m_b = 13\ MeV$ <= OK

$\delta m_c = 7\ MeV$ <= OK

$\delta m_H = 10\ MeV$

see S. Dittmaier's talk

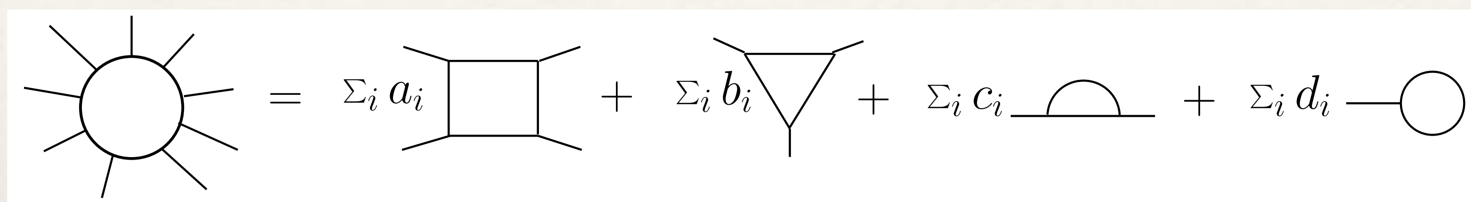
- ggF cross section: many sources of small uncertainties in theory description, need all to be beaten down

Status of QCD corrections for LHC

- The theory community has responded to the precision challenge very impressively in the last 20 years
- Started in 2005 with highly ambitious (at the time) Les Houches **wishlist** for NLO calculations. All done by 2011
- This lead to NLO revolution
- New frontier: NNLO and even N3LO
  - many new methods have been developed: healthy marketplace
- Resummation, parton showers
  - much progress here in each (higher precision), and their combination
- Also much improved:
  - PDFs, heavy quark masses, computing methods

The NLO "revolution"

- Clever new methods have led to a breakthrough in NLO calculations. Particular the calculation of the one-loop diagrams has been "solved" in full generality, and has been automatized.
  - Results now in codes such as aMC@NLO, Powheg Box, MCFM,…
- Basic notion: all one-loop amplitudes can written as a sum of boxes, triangle, bubbles and tadpoles

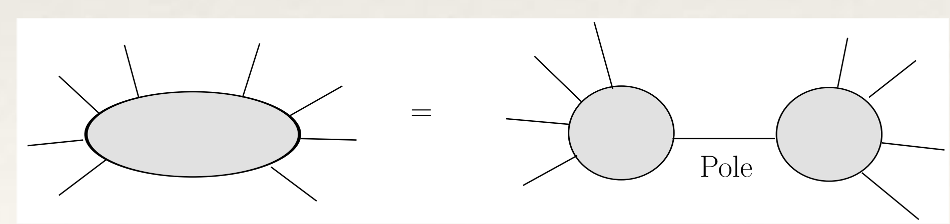


  - ✓ In essence because we live in 4 dimensions: every vector can be decomposed in at maximum four independent vectors

Vermaseren, van Neerven; Bern, Dixon, Kosower,...

$$\mathcal{M} = \sum_i a_i(D)\mathrm{Boxes}_i + \sum_i b_i(D)\mathrm{Triangles}_i + \sum_i c_i(D)\mathrm{Bubbles}_i + \sum_i d_i(D)\mathrm{Tadpoles}_i$$

- Job: find coefficients
  - can use (generalized) unitarity: determined them from cuts and poles



Status of higher order calculations in QCD

Order	$2 \to 1$	$2 \to 2$	$2 \to 3$	$2 \to 4$	$2 \to 5$	$2 \to 6$
1	LO					
α_s	NLO	LO				
α_s^2	NNLO	NLO	LO			
α_s^3	NNNLO	NNLO	NLO	LO		
α_s^4				NLO	LO	
α_s^5					NLO	LO
						NLO

etc

- LO well-understood, now more efficient than ever
- NLO: automatized, a flood of results
- NNLO: top quark production (single and pair), dijet production, 1-jet inclusive, ….
- NNNLO: Higgs production, $F_2(x,Q)$,

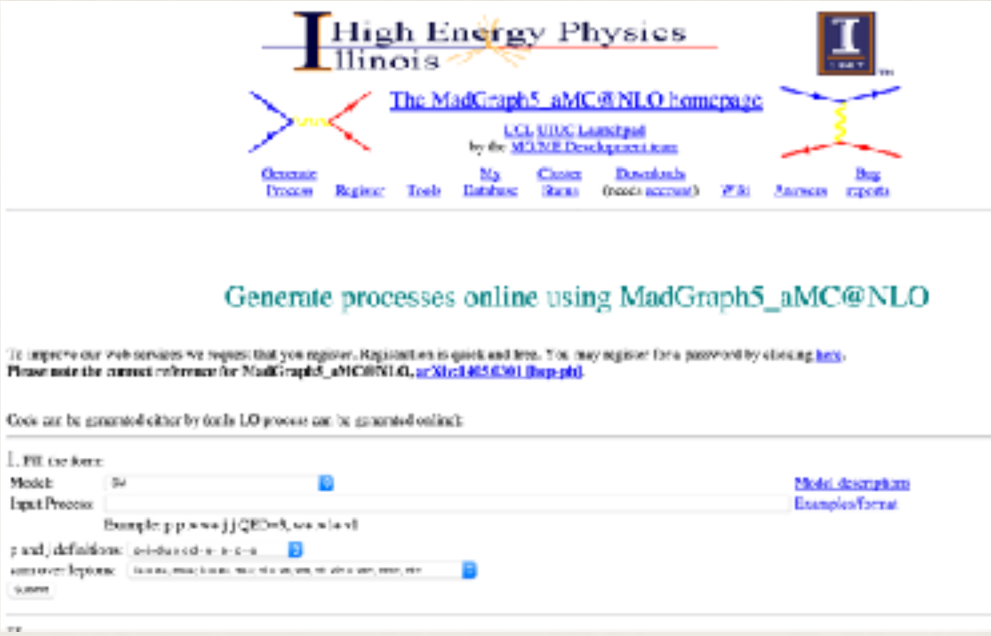
Automatic higher order calculations

- QCD NLO is automatized
  - no limitations in principle, but high multiplicity means longer running
  - including matching to parton showers: aMC@NLO in MadGraph5 framework

    Allwal, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Torrieli, Zaro '14
    approaching 4000 citations..
  - NLO EW now also included

    Frederix, Frixione, Hirschi, Maltoni, Pagani, Shao, Zaro '18
- POWHEG Box for NLO + PS

  Nason, Oleari; + Frxione, Aioli, Re '04 ff
  - general framework for NLO + PS



- HELAC-NLO

  Bevilacqua, Czakon, Garzelli, van Hameren, Kardos, Malamos
  Papadopoulos, Pitta, Worek, Shao '14
- Codes increasingly incorportated into exp'tl frameworks

NNLO QCD and NLO EW Les Houches Wishlist

Wishlist part 1 - Higgs (V=W,Z)

Process	known	desired	motivation
H	d\sigma @ NNLO QCD d\sigma @ NLO EW finite quark mass effects @ NLO	d\sigma @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H+j	d\sigma @ NNLO QCD (g only) d\sigma @ NLO EW	d\sigma @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H+2j	\sigma_tot(VBF) @ NNLO(DIS) QCD d\sigma(gg) @ NLO QCD d\sigma(VBF) @ NLO EW	d\sigma @ NNLO QCD + NLO EW	H couplings
H+V	d\sigma(V decays) @ NNLO QCD d\sigma @ NLO EW	with H→bb @ same accuracy	H couplings
t\bar tH	d\sigma(stable tops) @ NLO QCD	d\sigma(NWA top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	d\sigma @ LO QCD finite quark mass effects d\sigma @ NLO QCD large m_t limit	d\sigma @ NLO QCD finite quark mass effects d\sigma @ NNLO QCD	Higgs self coupling

Wishlist part 2 - jets and heavy quarks

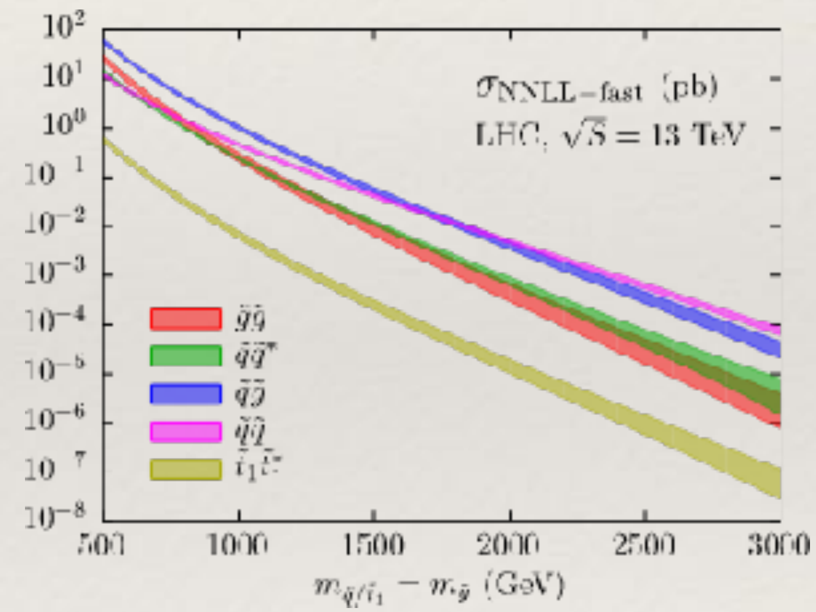
Process	known	desired	motivation
t\bar t	\sigma_tot @ NNLO QCD d\sigma(top decays) @ NLO QCD d\sigma(stable tops) @ NLO EW	d\sigma(top decays) @ NNLO QCD + NLO EW	precision top/QCD, gluon PDF effect of extra radiation at high rapidity top asymmetries

Precision for BSM

- Top - down BSM
  - assume new physics model, or a simplified version, compute signals including (QCD) corrections
  - much work here has been done for MSSM, compositie models etc
  - Example: NLO + NNLL resummed for squark-gluino production
    - ✓ includes threshold and Coulomb corrections
  - improves limit-setting for gluino masses etc.

Beenakker, Borchesnky, Kraemer, Kulesza, EL ‘16

Beneke, Piclum, Schwinn, Wever, ‘16



- Bottom-up BSM
  - be agnostic about new physics, parametrize it as effective theory

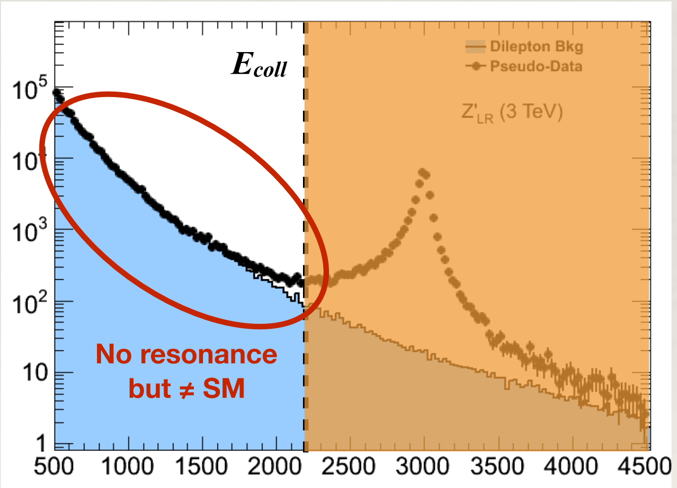
Standard Model Effective Theory

- To parametrize new physics, one can extend the Standard Model with invariant dimension-6 operators

$$\mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2} O_i^{[6]} + \text{hermitian conjugate}$$

  - Each operator i has a coefficient C_i. The scale of new physics is Λ, which we take to be of order 1 TeV.

- No new particles, discoveries only through new interactions



- Procedure: include these extra operators (as new Feynman rules) in predictions, compare with data to set bounds on the C_i.

Precision for other future colliders

Precision of α_s

- Global average (various classes observables)

$$\alpha_s(M_Z^2) = 0.1181 \pm 0.0011$$

  - about 1% uncertainty, based on NNLO and above predictions
- We shall need ∼0.1% in the future
  - Higgs, top physics, EW precision tests
  - Higher jet-multiplicity observables

FCC-ee

from hadronic Z decays	$\delta\alpha_s$ <0.15%	*(today 2.5%)*
from hadronic W decays	$\delta\alpha_s$ < 0.2%	*(today 35%)*
from hadronic τ decays	$\delta\alpha_s$ < 1%	*(today 1.5%)*
event shapes	$\delta\alpha_s$ < 1%	*(today 2.9%)*

FCC-eh or LHeC

with DIS would be able to reach $\delta\alpha_s$ ~0.1-0.2%

FCC-hh

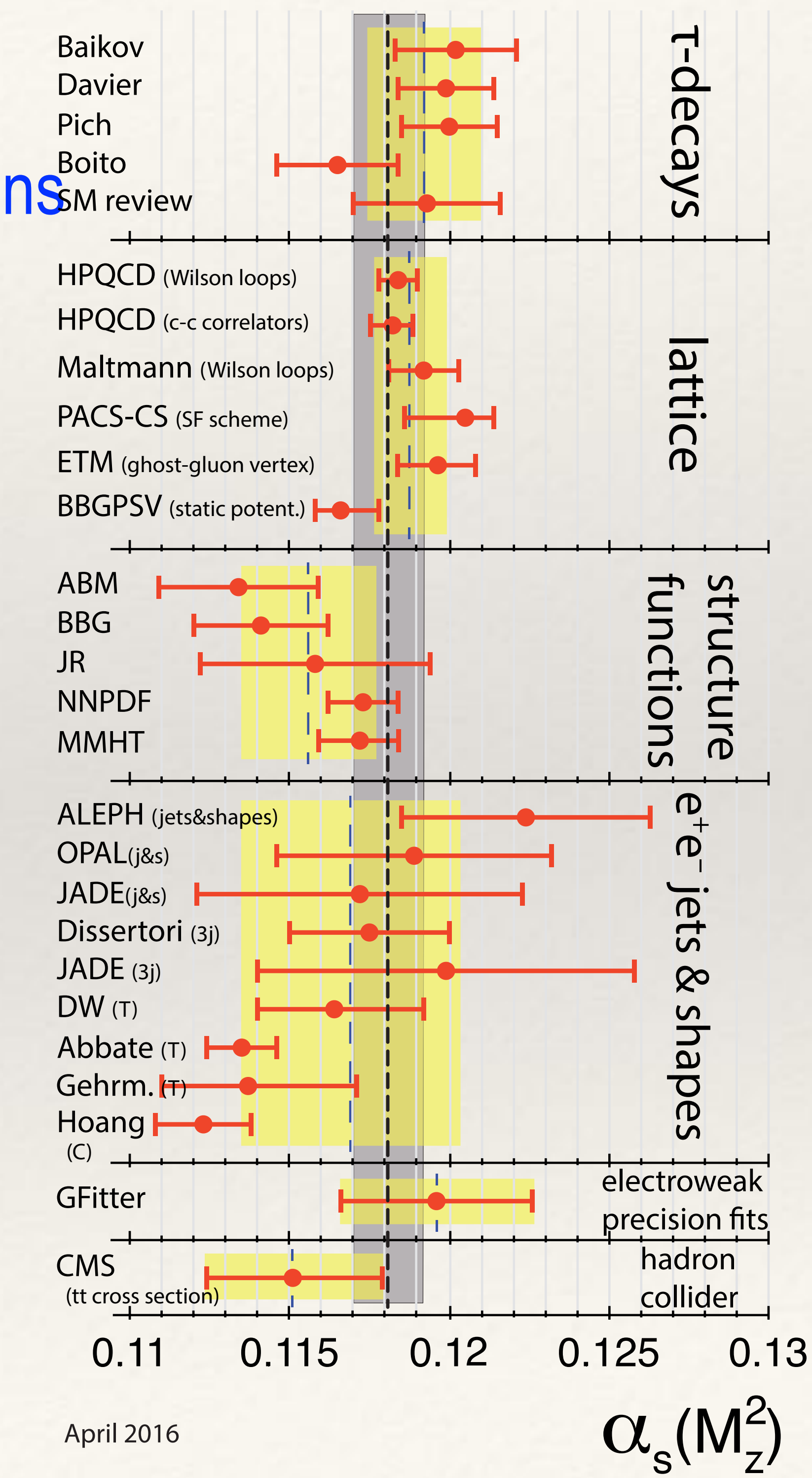
from top quark pair production

test the running of α_s up to 25 TeV (jet cross sections)

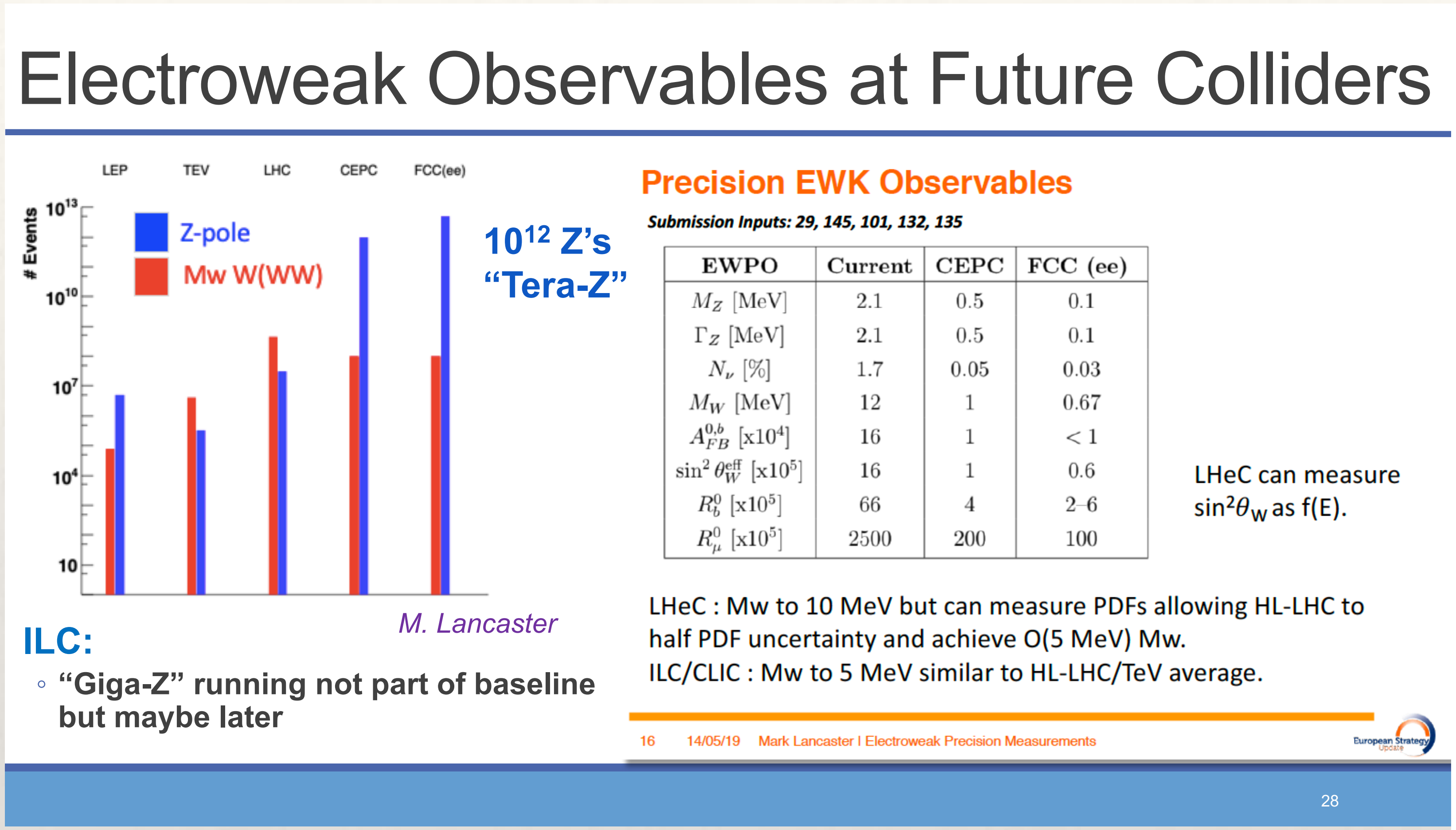
Lattice QCD

with adequate R&D on computing a robust calculation up to 0.3% precision might be within reach

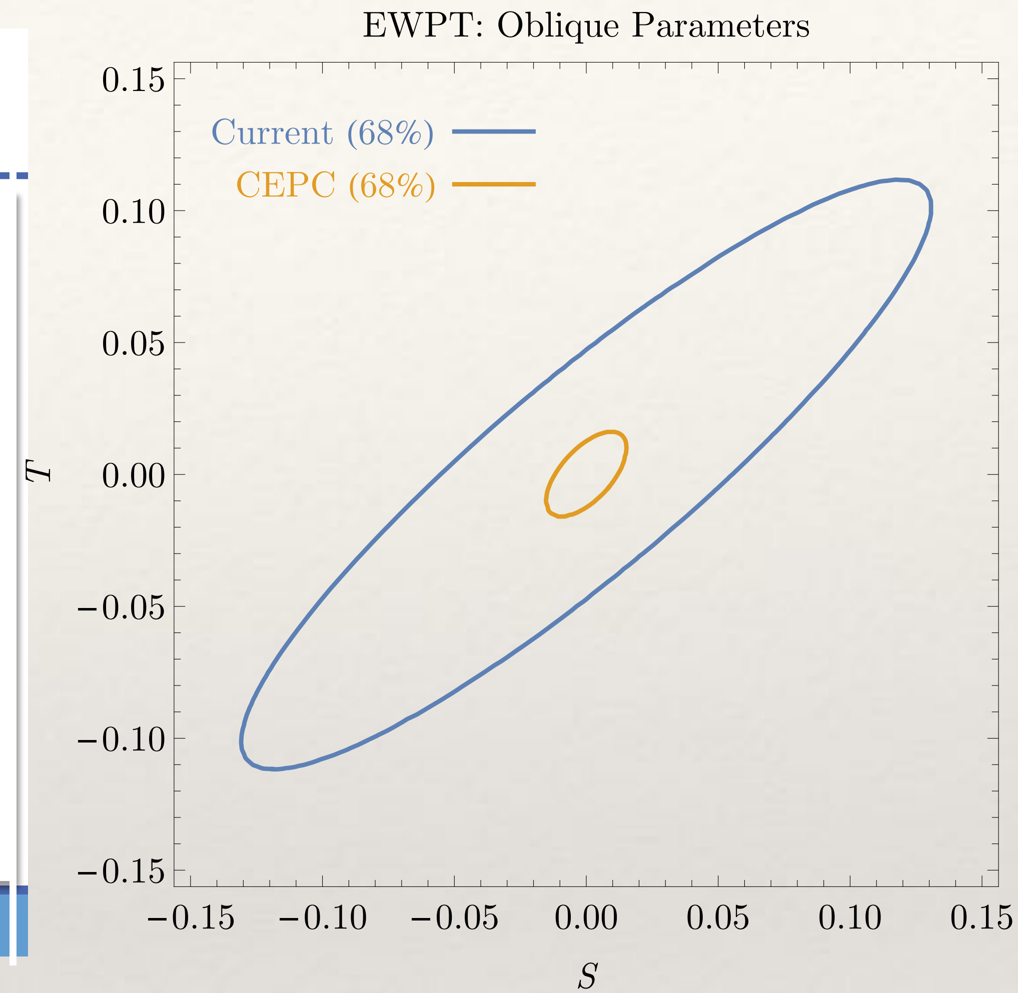
Bethke, Dissertori, Salam '18



EWPOs



EWPO	Current	CEPC	FCC (ee)
M_Z [MeV]	2.1	0.5	0.1
Γ_Z [MeV]	2.1	0.5	0.1
N_ν [%]	1.7	0.05	0.03
M_W [MeV]	12	1	0.67
$A_{FB}^{0,b}$ [x10^4]	16	1	< 1
$\sin^2\theta_W^{\rm eff}$ [x10^5]	16	1	0.6
R_b^0 [x10^5]	66	4	2–6
R_μ^0 [x10^5]	2500	200	100

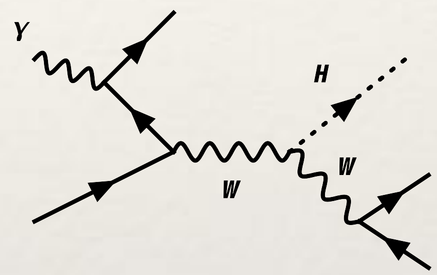


Top mass exp't error: 25 MeV expected
Theory one larger at present.

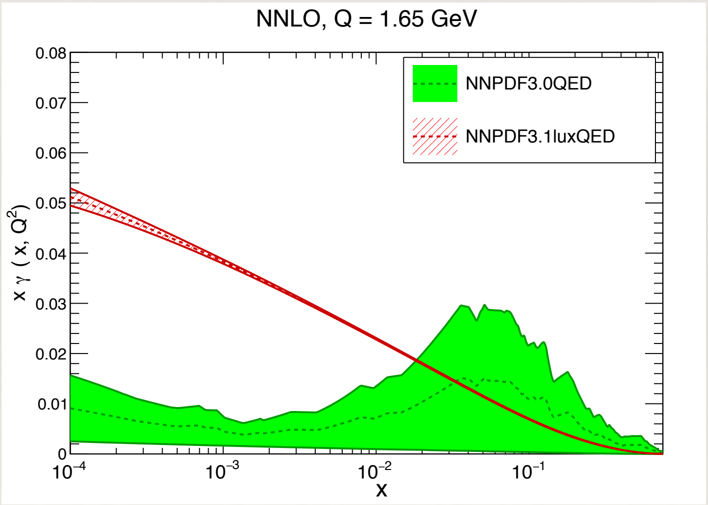
Electroweak corrections

- QED corrections are also becoming quite important at the LHC
  - NNLO in QCD = NLO in EW
  - Photons in protons: LUXqed formalism
    - ✓ Extract from precise ep data → large increase in precision! (% level)

Manohar, Nason, Salam, Zanderighi '17



$$L^{\mu\nu}W_{\mu\nu}\ \text{(DIS)} = \hat{\sigma}_{e\gamma} \otimes f_{\gamma/p}\ (\gamma\text{PDF})$$



- EW loop corrections: many scales
  - particular relevant for EW precision observables
  - at large p_T in hadron colliders

High precision at lepton collider: Higgs couplings

Improvements w.r.t. HL-LHC

M. Cepeda

@ Granada

Kappa-framework

	LHeC *	HE-LHC *	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
κ_W *	5.7	2.1	1.5	5.9	2.3	4.2	4.5	1.8	1.8	4.1	8.5
κ_Z *	1.9	1.9	4.5	5.7	3.0	3.3	3.3	7.2	6.8	7.6	7.6
κ_g	1.4	2.0	1.6	2.6	1.5	2.0	2.6	2.0	1.8	2.5	4.2
κ_γ	1.1	2.1	1.3	1.4	1.1	1.3	1.5	1.4	1.3	1.4	4.7
κ_c	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
κ_t	1.0	1.7	1.0	1.2	1.0	1.5	1.5	1.1	1.1	1.1	2.9
κ_b	2.2	1.9	2.2	4.6	2.2	4.3	4.9	2.8	2.6	4.1	5.4
κ_μ	1.0	2.6	1.0	1.1	1.0	1.1	1.3	1.1	1.1	1.1	≥ 10
κ_τ	1.2	1.8	1.5	2.5	1.1	1.6	2.0	1.7	1.6	2.4	3.3
Br_{inv}	1.7	1.3	7.3	8.6	3.0	3.1	3.1	7.0	8.6	≥ 10	≥ 10
Br_{unt} *	3.2	1.9	2.3	2.9	1.5	1.7	1.7	3.7	3.4	4.1	4.1
Br_{unt} **			⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆

(*) $|\kappa_V| \leq 1$ applied for hadron colliders (**) Not requiring $|\kappa_V| \leq 1$ (⋆) Not measured in HL-LHC

EFT-framework

prel.

	LHeC	HE-LHC	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.2	7.7	≥ 10	5.5	≥ 10	≥ 10	6.9	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	6.7	≥ 10	4.9	≥ 10	≥ 10	6.3	7.0	≥ 10	≥ 10
$g^{eff}_{H\gamma\gamma}$	1.7	1.3	2.8	3.4	2.6	3.1	3.4	3.1	3.1	3.1	≥ 10
$g^{eff}_{HZ\gamma}$	1.1	2.4	1.1	1.6	1.1	2.3	3.0	1.7	1.1	1.2	≥ 10
g^{eff}_{Hgg}	1.4	1.7	2.0	2.8	1.7	2.3	2.9	2.8	2.3	2.7	4.5
g^{eff}_{Htt}	1.1	1.7	1.1	1.2	1.1	1.4	1.4	1.1	1.1	1.1	1.8
g^{eff}_{Hcc}	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
g^{eff}_{Hbb}	2.7	1.5	6.1	9.8	5.1	≥ 10	≥ 10	7.6	7.3	9.1	≥ 10
$g^{eff}_{H\tau\tau}$	1.6	1.3	4.1	5.8	2.7	3.8	4.8	5.0	5.0	6.1	7.8
$g^{eff}_{H\mu\mu}$	1.2	1.8	1.3	1.4	1.3	1.4	1.6	1.4	1.4	1.4	≥ 10
$\delta g_{1Z}[\times 10^2]$	1.3	1.4	6.7	≥ 10	≥ 10	≥ 10	≥ 10	7.3	7.8	≥ 10	≥ 10
$\delta\kappa_\gamma[\times 10^2]$	1.3	1.2	≥ 10	≥ 10	≥ 10	≥ 10	$\geq 10^2$	≥ 10	≥ 10	≥ 10	≥ 10
$\lambda_Z[\times 10^2]$	1.1	1.0	≥ 10	$\geq 10^2$	≥ 10	$\geq 10^2$	$\geq 10^3$	≥ 10	≥ 10	≥ 10	≥ 10

SMEFT ND (⋆) not measured in HL-LHC

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Some prospects for more precision

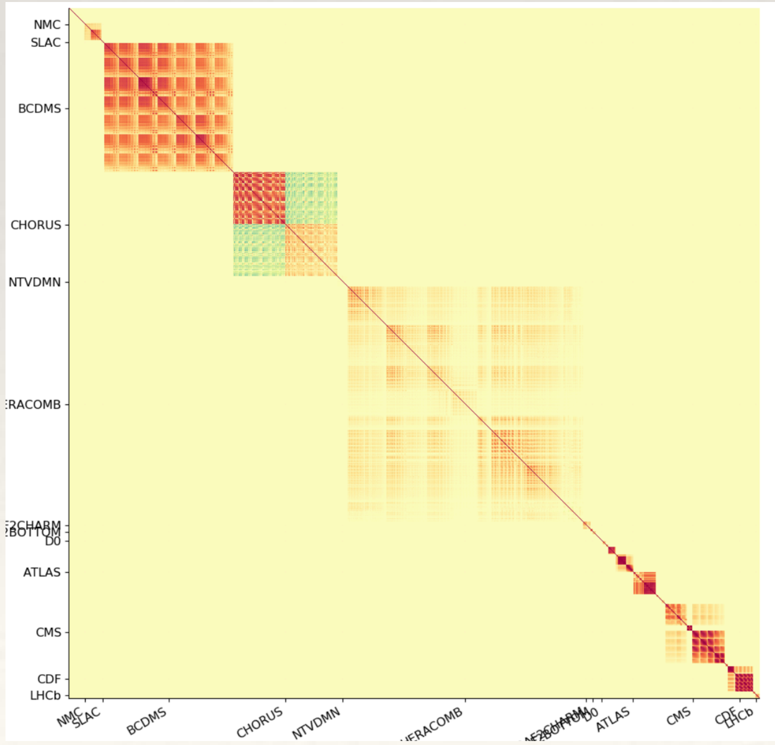
News from PDFs: theory errors

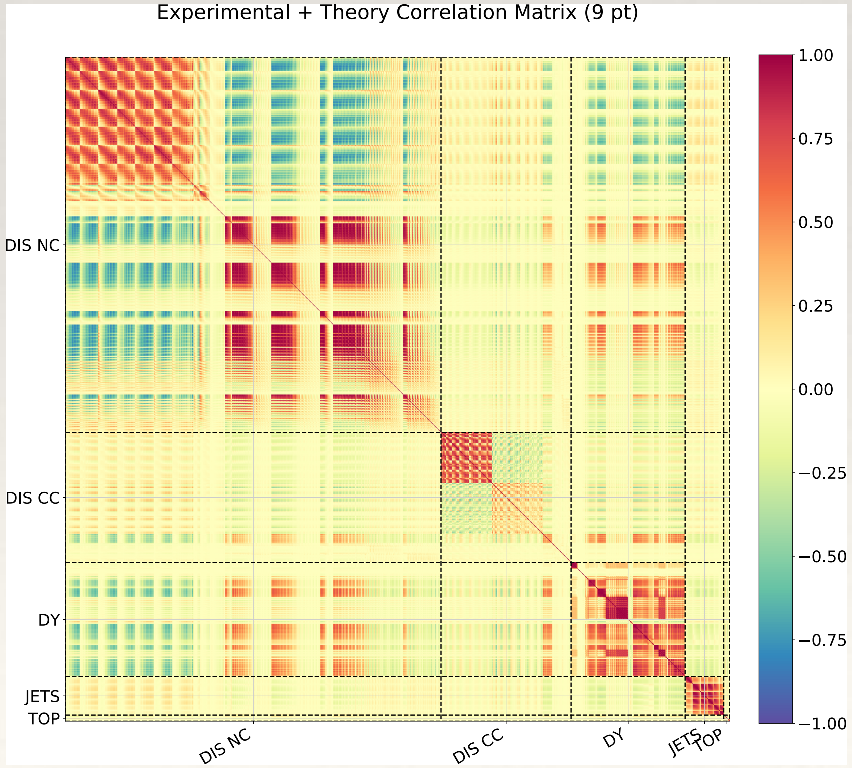
NNPDF collab.'19

- PDF errors dominant for many LHC predictions. Thus far they only reflect the uncertainties of measurements and their correlations
- First step in including uncertainties from Missing Higher Orders, by fitting PDF's for a set of μ_R, μ_F values, and from there sum the exp.("C") and th. ("S") covariance matrix

$$\chi^2 = \sum_{i,j=1}^{N_{\rm dat}} \left(D_i - T_i^{(0)}\right) (S+C)^{-1}_{ij} \left(D_j - T_j^{(0)}\right)$$

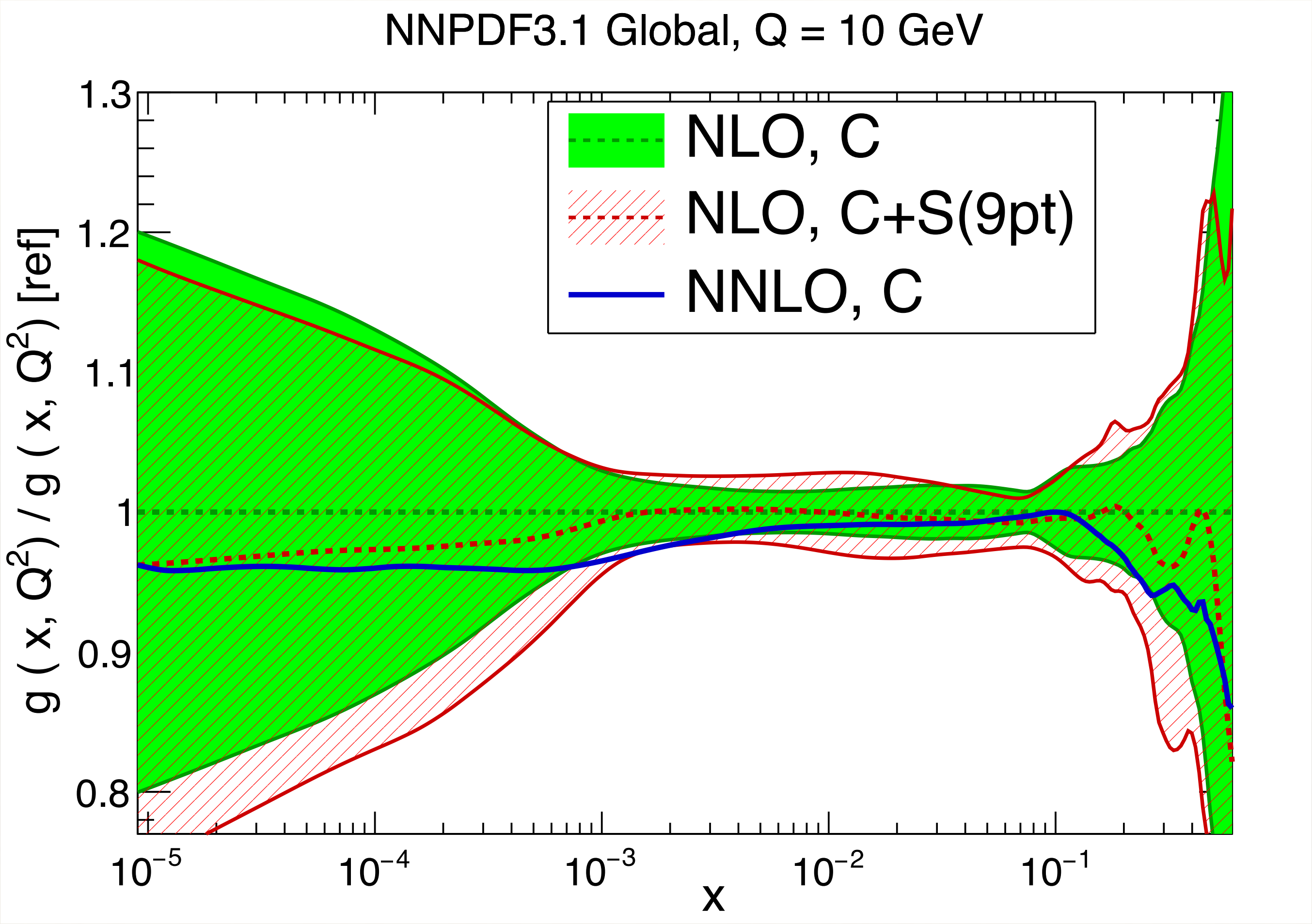
- Introduces much more correlations between experimental inputs





News from PDFs: theory errors

- Validation: see at NLO if the NNLO central value is in the MHO uncertainty band
- Looks ok:



QCD precision at REALLY high order I

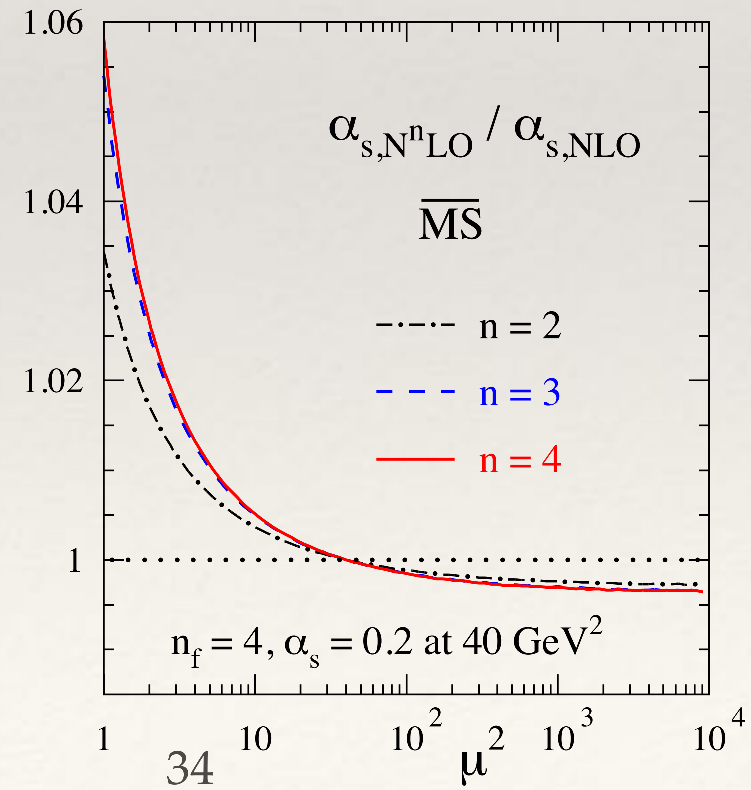
- **five**-loop QCD beta function
  - first done for SU(3) , then for SU(N)
    - ✓ using R* method to extract divergences
    - ✓ 6 days on 32 core machine
  - five loop expansion in MSbar scheme very benign

$$\widetilde{\beta}(\alpha_s, n_f = 4) = 1 + 0.490197\,\alpha_s + 0.308790\,\alpha_s^2 + 0.485901\,\alpha_s^3 + 0.280601\,\alpha_s^4 + \ldots$$

    - ✓ less than 1% change due to 5-loop term, even at α_s=0.47

Baikov, Chetyrkin, Kühn '16
Herzog, Ruijl, Ueda, Vermaseren, Vogt '17,

- implications for running coupling:



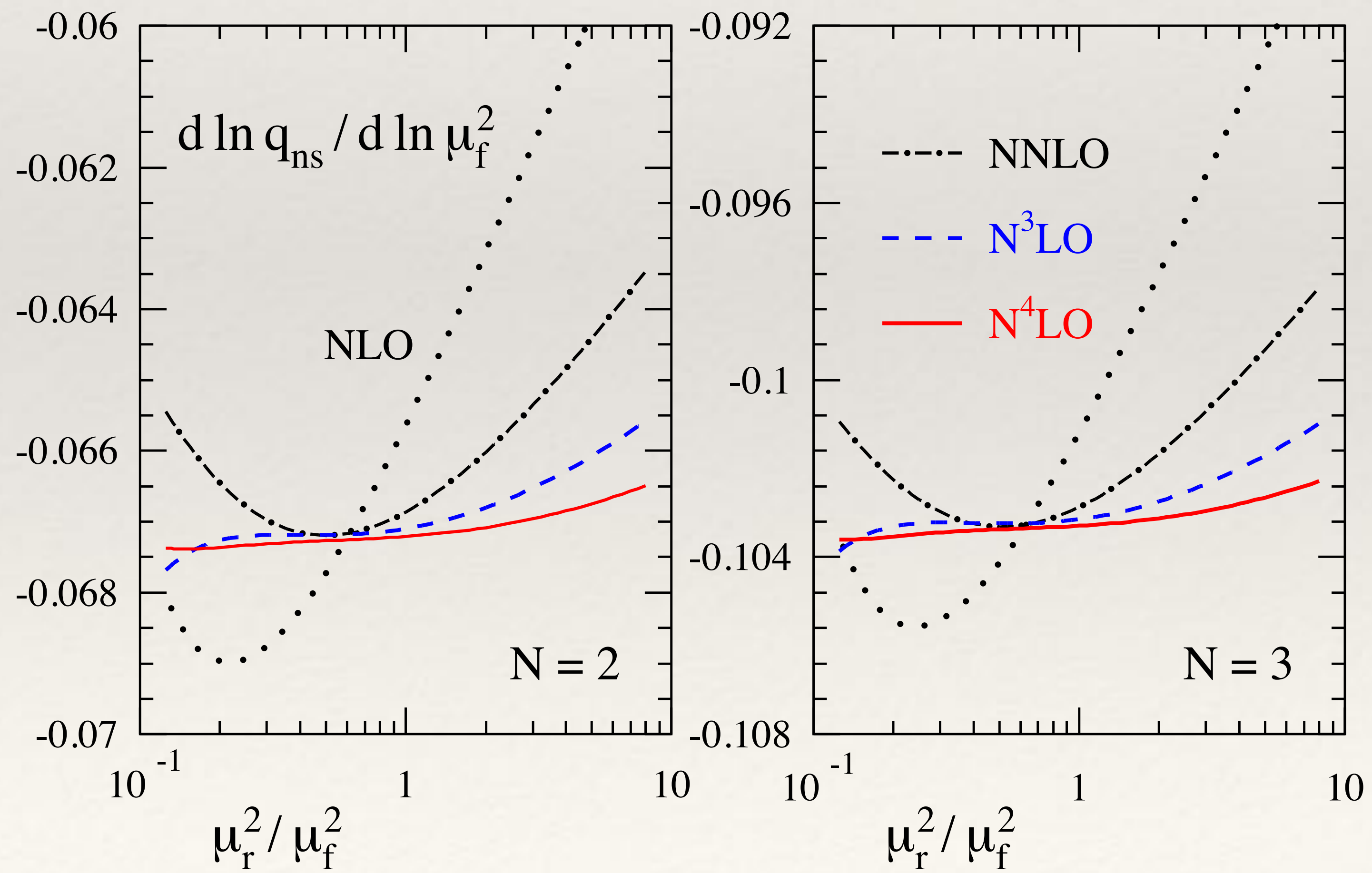
QCD precision at REALLY high order II

- QCD splitting functions at four and five loops

$$\frac{\partial}{\partial \ln \mu^2} f_i(x,\mu^2) = \int_x^1 \frac{dy}{y} P_{ik}\big(y, \alpha_s(\mu^2)\big)\, f_k\Big(\frac{x}{y}, \mu^2\Big) \qquad P = a_s P^{(0)} + a_s^2 P^{(1)} + a_s^3 P^{(2)} + a_s^4 P^{(3)} + \dots$$

  - at three loops (NNLO) known analytically; at 4 loops in part numerically, at 5 loops some moments

Herzog, Moch, Ruijl, Ueda, Vermaseren, Vogt '18,



Prospects for further QCD accuracy

- There is a "vibrant" community addressing NNLO for $2 \longrightarrow 3$, N3LO and beyond
- Involves progress in
  - loop diagrams: analytical and numerical approaches
  - IR divergence management, new subtraction mechanisms, phase space slicing making a comeback
  - Shuffle/Hopf algebra of polylogs to 3rd order $\longrightarrow$ elliptic integrals
  - threshold expansions
  - automation, computing methods

Soft logarithms at next-to-leading power

- General soft expansion for 2→1 processes

$$\frac{d\sigma}{dz} = \sum_{n=0}^{\infty} \left(\frac{\alpha_s}{\pi}\right)^n \sum_{m=0}^{2n-1} \left\{ c_{nm}^{(-1)} \left.\frac{\log^m(1-z)}{1-z}\right|_+ + c_{nm}^{(0)} \log^m(1-z) + \ldots \right\}$$

- NLP logarithm organization
  - exhibit all-order patterns. Leading logarithmic resummation now achieved for a number of reacions

$$\hat{\sigma}_{\rm LO}^{(gg)}(Q^2) \exp\left\{\frac{2\alpha_s C_A}{\pi} \log^2(N)\right\} \left(1 + \frac{2\alpha_s C_F}{\pi} \frac{\log N}{N}\right)$$

Beneke, Broggio, Garny, Jaskiewicz, Vernazza, Szafron, Wang '18
Bahjat-Abbas, Bonocore, EL, Magnea, Sinninghe-Damsté, Vernazza, White '19
Moult, Stewart, Vita, Xhu '18

  - technology also used to extend phase space slicing methods for NNLO calculations (using N-jettiness) to NLP
    - ✓ for much better numerical behavior

Elliptic progress: from math for loops

- Polylogarithms appear after doing loop integrals

$$\mathrm{Li}_1(x) = -\log(1-x)\,, \quad \mathrm{Li}_n(x) = \int_0^x \frac{dx'}{x'}\mathrm{Li}_{n-1}(x')$$

  - and more generallly multiple polylogarithms (MPL's)

$$G(a_1,\ldots,a_n;x) = \int_0^x \frac{dt}{t-a_1}\,G(a_2,\ldots,a_n;t)$$

- They obey a "shuffle algebra"

$$G(a_1,\ldots,a_k;x)\,G(a_{k+1},\ldots,a_{k+l};x) = \sum_{\sigma\in\Sigma(k,l)} G(a_{\sigma(1)},\ldots,a_{\sigma(k+l)};x)$$

  - which can greatly simplify results. Its math properties help compute loop integrals

- At two loop and certainly beyond "elliptic" functions start appearing, including

$$\mathrm{K}(\lambda) = \int_0^1 \frac{dt}{\sqrt{(1-t^2)(1-\lambda t^2)}}\,, \quad \mathrm{E}(\lambda) = \int_0^1 dt\,\sqrt{\frac{1-\lambda t^2}{1-t^2}}$$

  - extensions of MPL technology to elliptic case are appearing

Broedel, Duhr, Dulat, Penante, Tancredi '19

Computing progress: analytical, numerical

- Computer algebra!
  - Many dedicated mathematica packages for categorizing loop diagrams (FIRE, REDUZE, …)
  - Most powerful language, especially for high loops: FORM — J. Vermaseren
    - ✓ still under active development. Recent: FORCER, code that writes other code
- Monte Carlo technology
  - improved parton showers, matching to fixed order

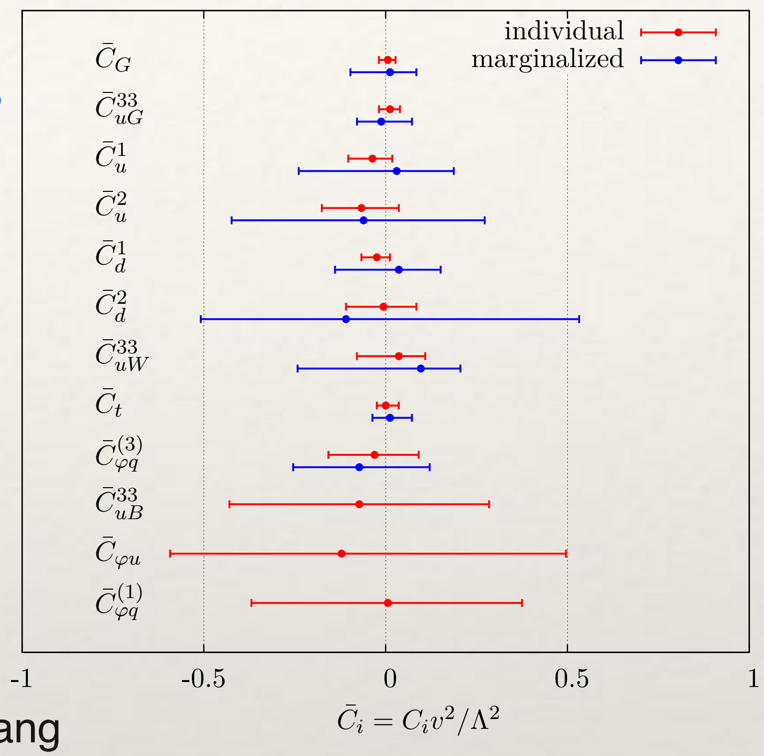
IMPORTANT:
As for other areas, for future progress we cannot take the **new talent** entering precision calculations for granted.

Support, including **recognition**, for creating/maintaining tools and technical innovations will be needed!

SMEFT and top physics

Brown, Buckley, Englert, Ferrando, Galler, Miller, More, Russell, White, Warrack

- TopFitter
  - Confront LHC and Tevatron top data with theory, including operators (14)
    - ✓ pair production (+ vector boson) and single top
  - Experimental uncertainties as given
  - Theoretical ones: vary scales, and use PDF uncertainties
  - NLO effects via SM K-factors



- Top flavour-changing interactions, global analysis

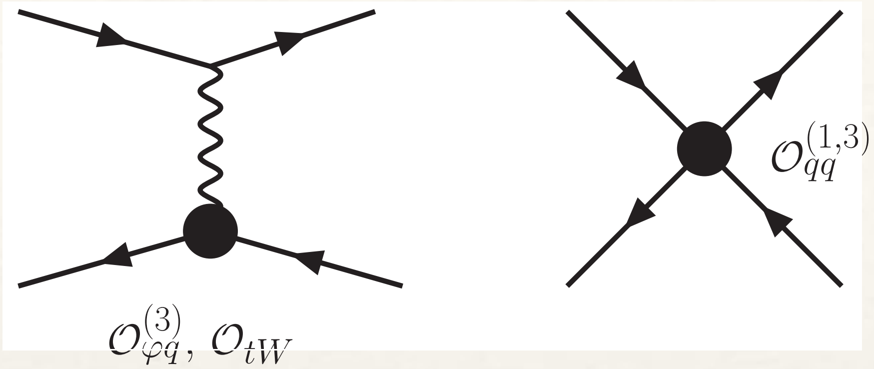
Durieux, Maltoni, Zhang

  - Top pair and single top contributions
  - Include NLO for SM included
  - Include also running and mixing for operators
- Recent note on common standards in EFT approach by all involved

Aguilar-Saavedra et al arXiv:1802.07237

Dimension-6 operators for single top in t-channel

de Beurs, EL, Vreeswijk,Vryonidou '18



- For single top production in the t-channel, only 3 operators matter!

$$
\begin{aligned}
O_{\varphi Q}^{(3)} &= i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q) \\
O_{tW} &= y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W_{\mu\nu}^I \\
O_{qQ,rs}^{(3)} &= \left(\bar{q}_r \gamma^\mu \tau^I q_s\right)\left(\bar{Q}\gamma_\mu \tau^I Q\right)
\end{aligned}
$$

- Easier to get info on each operator separately
- Effects will be small, hence we should also include QCD corrections to SM
- They will affect the cross section, and differential distributions, in different ways
  - used MadGraph5_aMC@NLO

Effect on amplitudes and cross sections

- How do these operators modify single top scattering amplitudes and the cross section?
  - Amplitude

$$\mathcal{M} = \mathcal{M}_{\rm SM} + \sum_i \frac{1{\rm TeV}^2}{\Lambda^2} C_i\, \mathcal{M}_i$$

  - Squared amplitude

$$|\mathcal{M}|^2 = |\mathcal{M}|^2_{\rm SM} + \sum_i \frac{1{\rm TeV}^2}{\Lambda^2} C_i\, 2{\rm Re}\,(\mathcal{M}^*_{\rm SM}\, \mathcal{M}_i) + \sum_{i\leq j} \frac{1{\rm TeV}^4}{\Lambda^4} C_i C_j\, |\mathcal{M}|^2_{i,j}$$

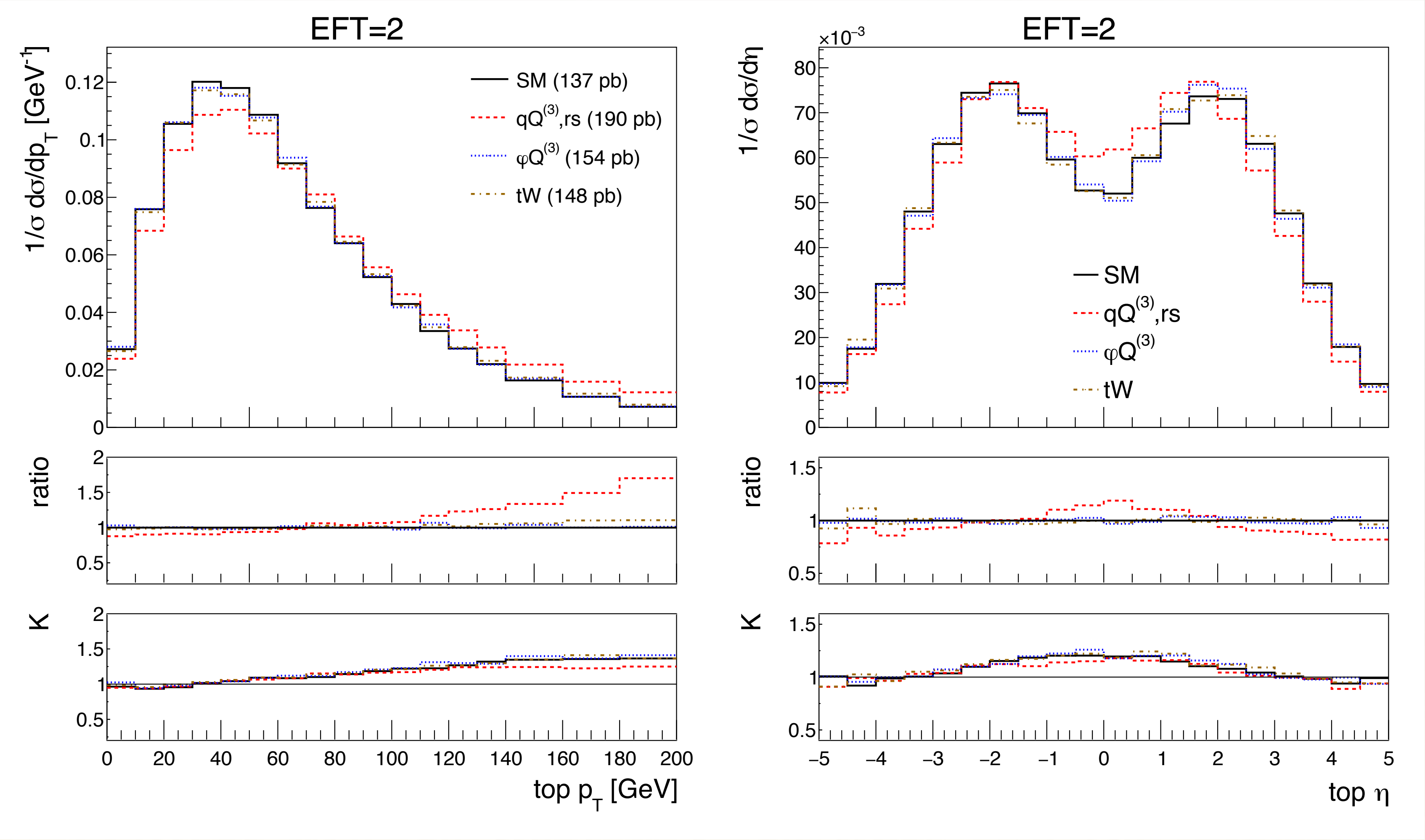
  - Cross sections

$$\sigma = \sigma_{\rm SM} + \sum_i \frac{1{\rm TeV}^2}{\Lambda^2} C_i\, \sigma_i + \sum_{i\leq j} \frac{1{\rm TeV}^4}{\Lambda^4} C_i C_j\, \sigma_{i,j}$$

- NLO QCD needed in order to make C_i corrections stand out from $\sigma_{\rm SM}(\mu, \alpha_s(\mu))$

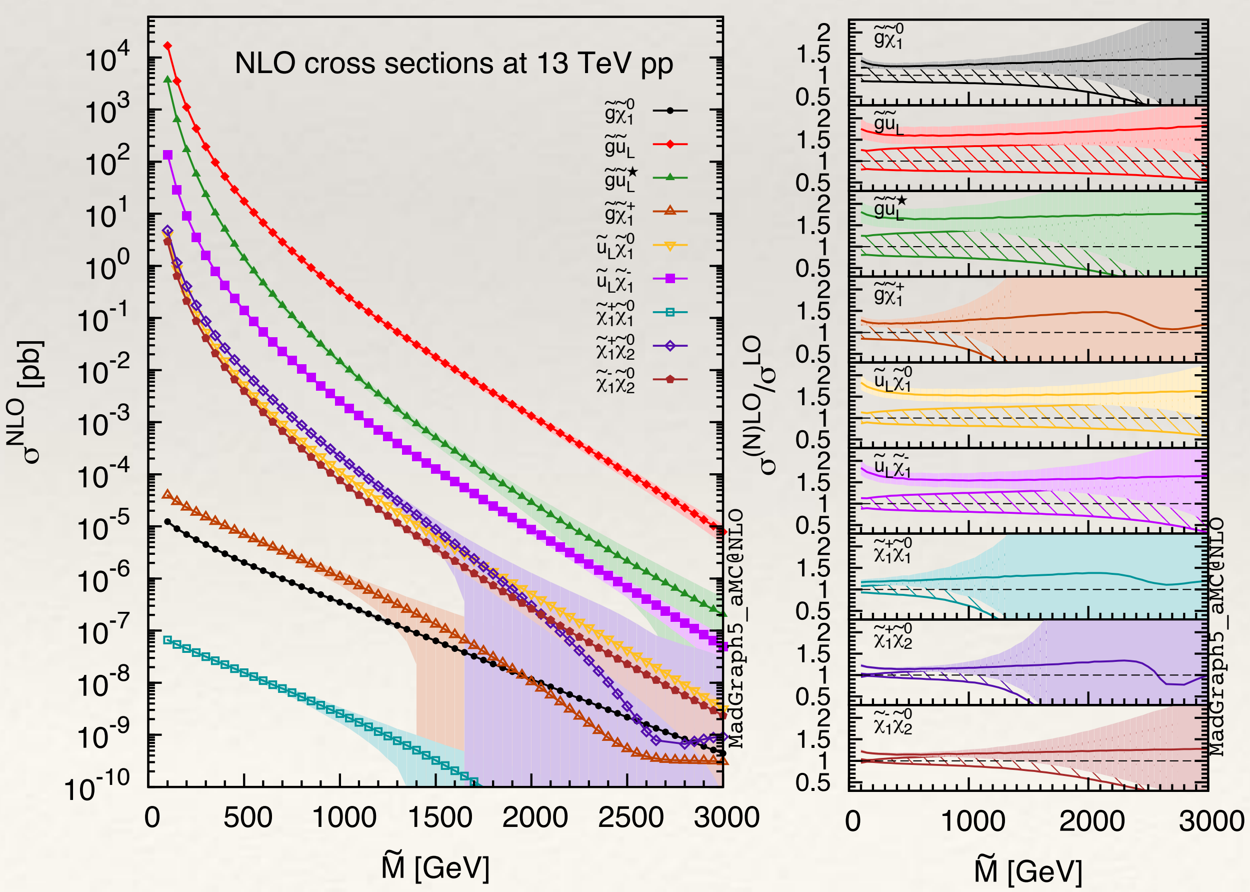
SMEFT single top distributions at NLO

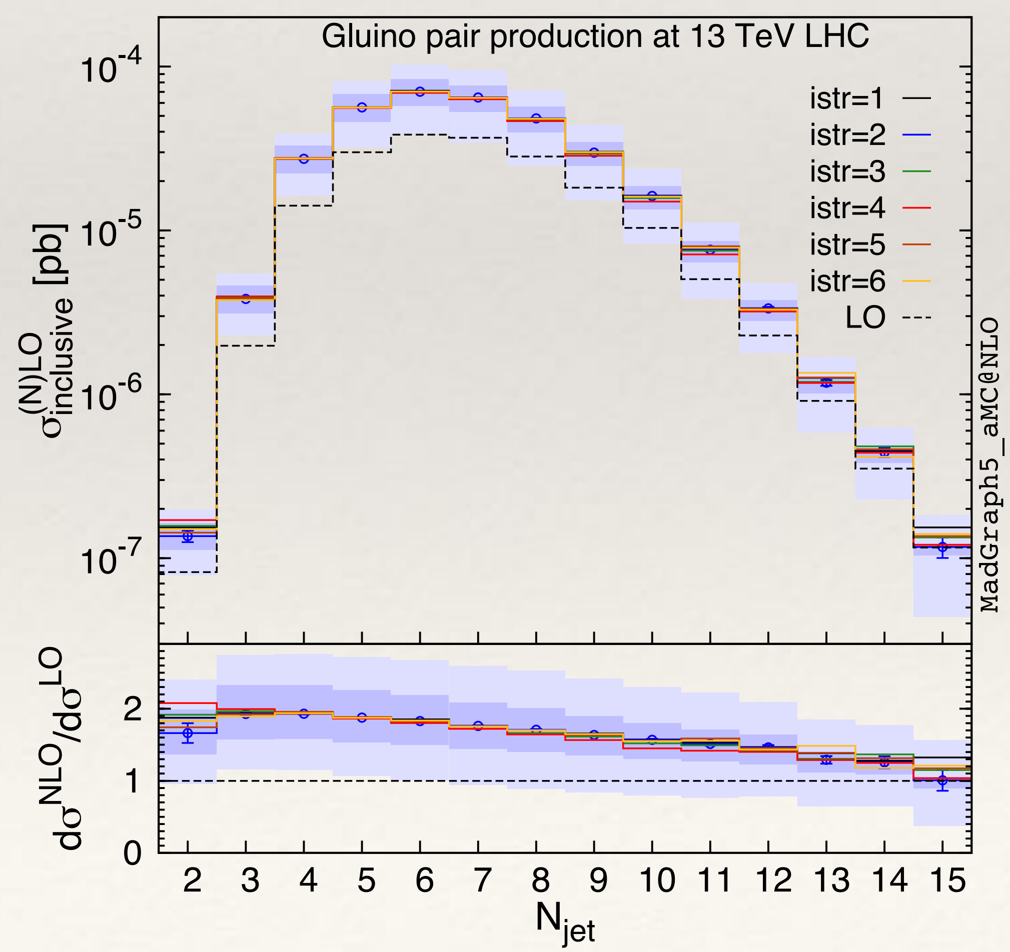
- Wbj production then W-decay via MadSpin, parton showering with Pythia8
- Top quark p_T and η normalized distributions
    - Four-fermion operator different shape. QCD corrections at large pT and central rapidity notable
    - Allow for new physics operators in production and decay (EFT=2)



Next steps in automation in MG5_aMC@NLO

- (Not yet NNLO…)
- SMEFT@NLO is fully included
  - but renormalization group running and mixing of all the operators still to be done
- MSSM@NLO is under construction. Two example plots [thanks to M. Zaro]
  - susy pair production at NLO; # jets in gluino pair production after decay and ps
  -





Imprecise and somewhat uncertain outlook

- With only the first few percent of LHC data acquired, experiment will demand high theoretical precision
  - not just NLO or NNLO, small other effects come into play
- Theory community is meeting the challenge, with quite spectacular progress in the last 15 years

S. Dittmaier @ Granada

> Can theory provide the necessary precision?
>
> ↪ Optimists: "Yes. No show-stoppers seen, great progress can be anticipated."
>
> Sceptics: "Enormous challenge! Conceptual progress difficult to extrapolate."

- New ideas, methods and talent give reason for optimism
  - with sufficient support, recognition and resources