Precision at the high-energy frontier

Workshop
Precision QCD@LHC
28-31 Jan., Hyderabad

SPARC
Scheme for Promotion of Academic and Research Collaboration

Adapted from talk at Gordon Research Conference

New Tools for the Next Generation of Particle Physics and Cosmology

Hong Kong, July 2019

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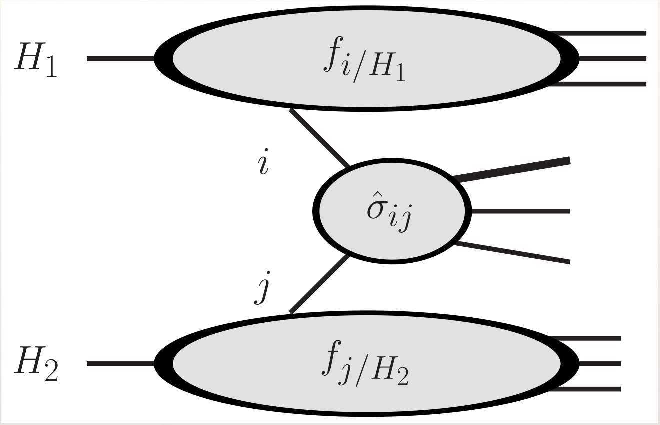
Outline

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

Apologies: are the credits in the talk complete and precise?
N.O.!

Theoretical colliders

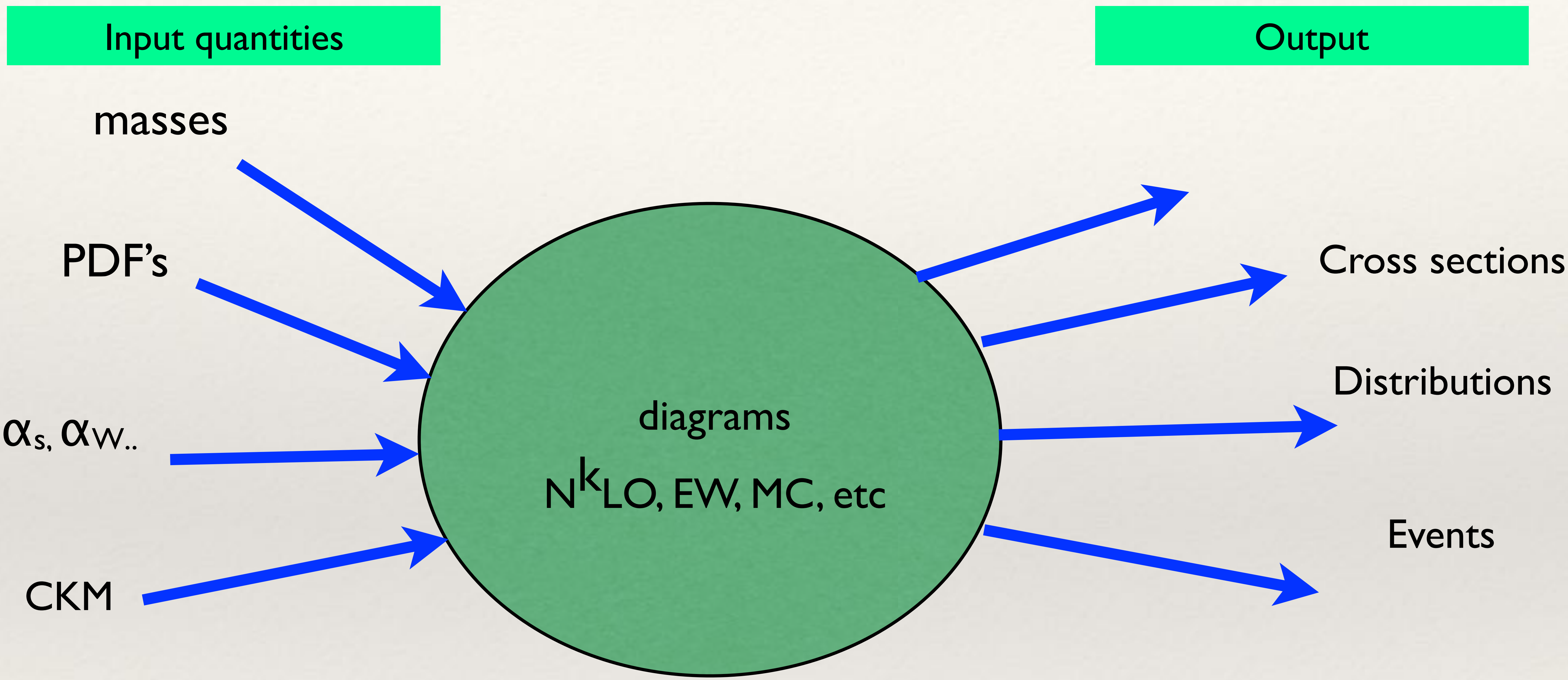
- Hadron collider
  - transformed into "parton collider" via parton distribution functions



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

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

Collider physics

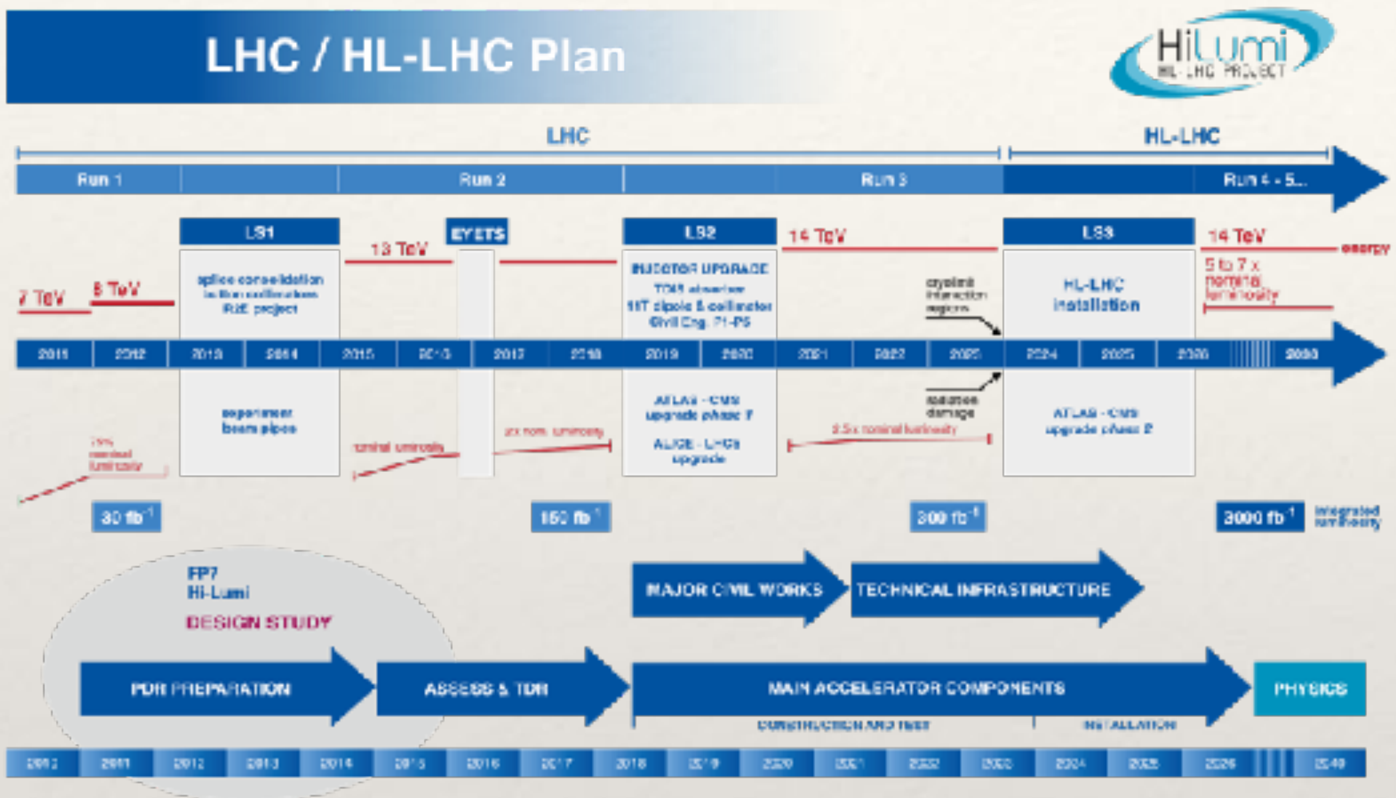


Goal: highly precise output

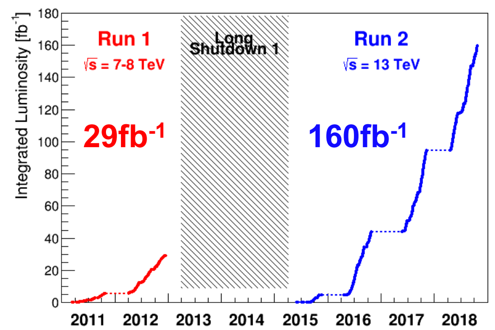
➡ Optimize precision of inputs

A lot of LHC data still to come

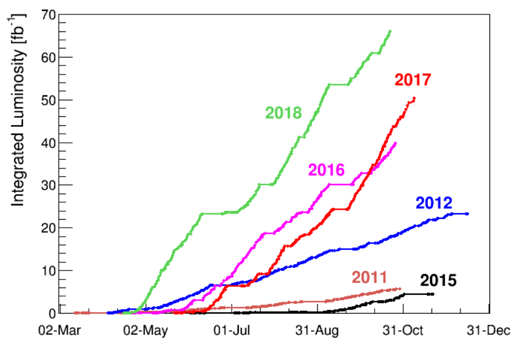
This workshop: Kajari Mazumdar



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*

14/12/2018 M. Schaumann, 191st CERN Council Open Session 12

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

Precision, accuracy, error and uncertainty

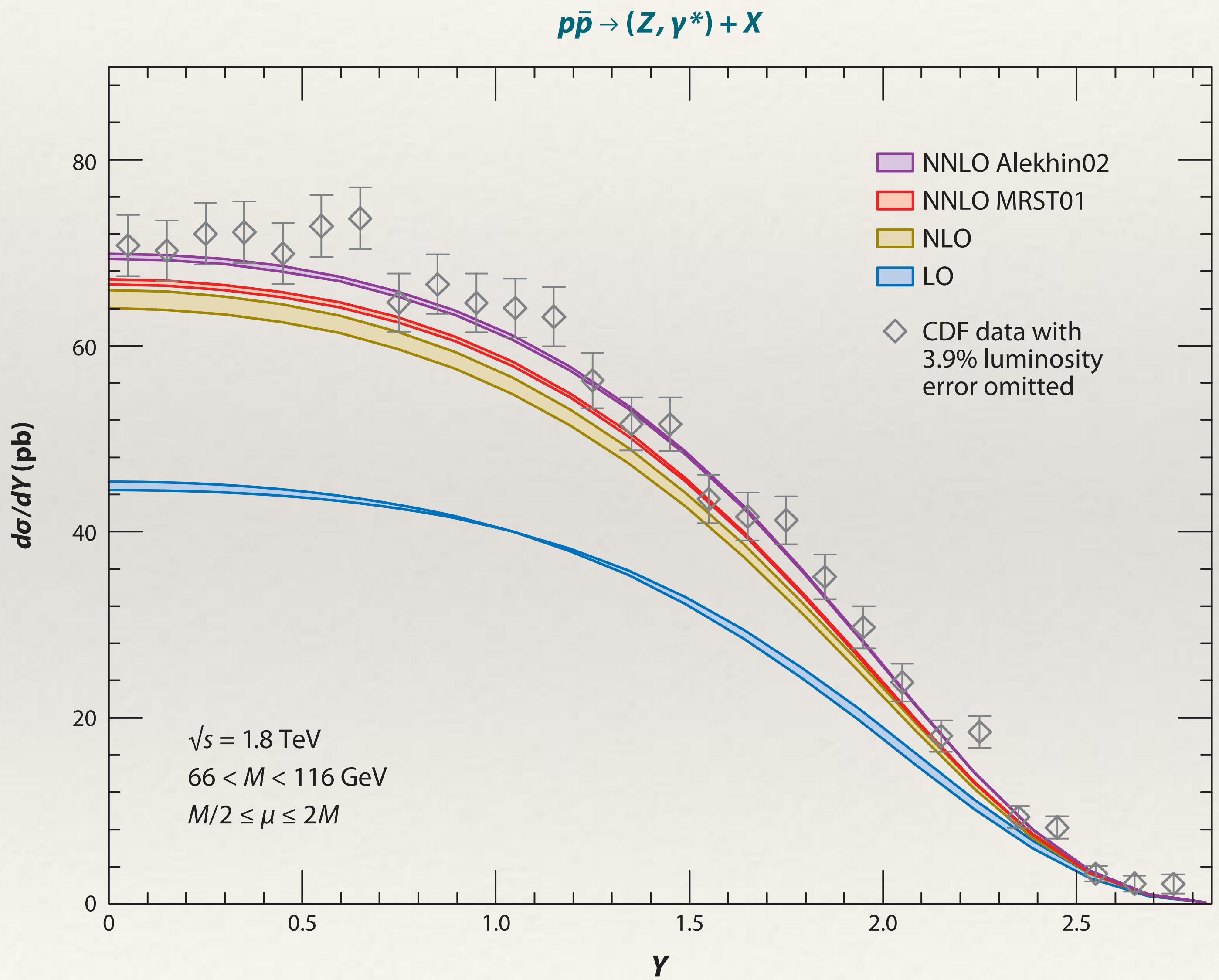
- A bit of terminology: for predictions for observable O

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

  - Precision: compute to order "m", large enough for $\delta O^{[m]}$ to be small enough
  - But beware: it can a be small variation 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

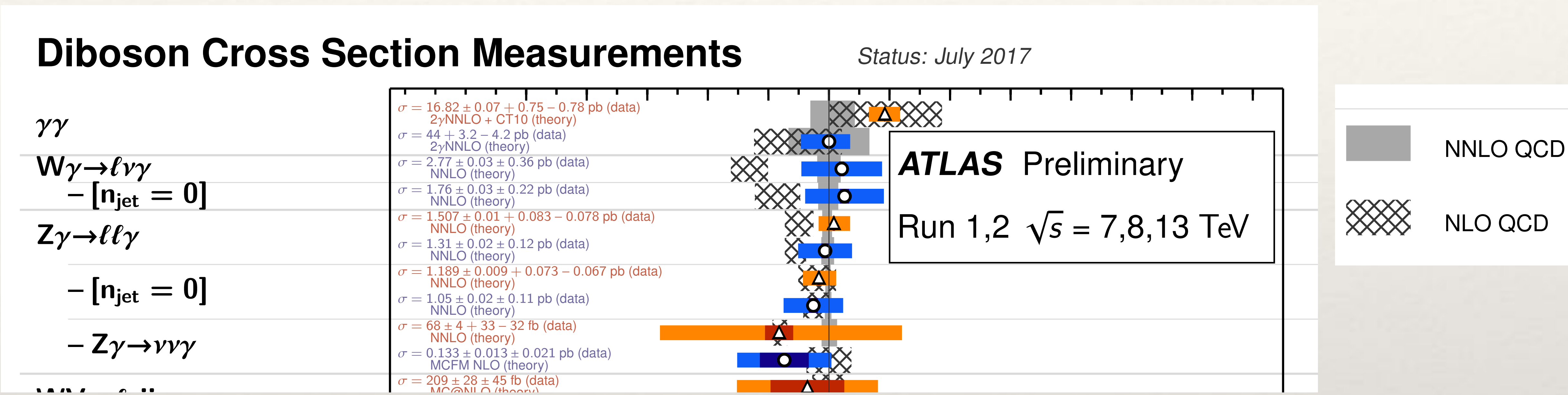
Purpose of precision: To Measure and Explore

- 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

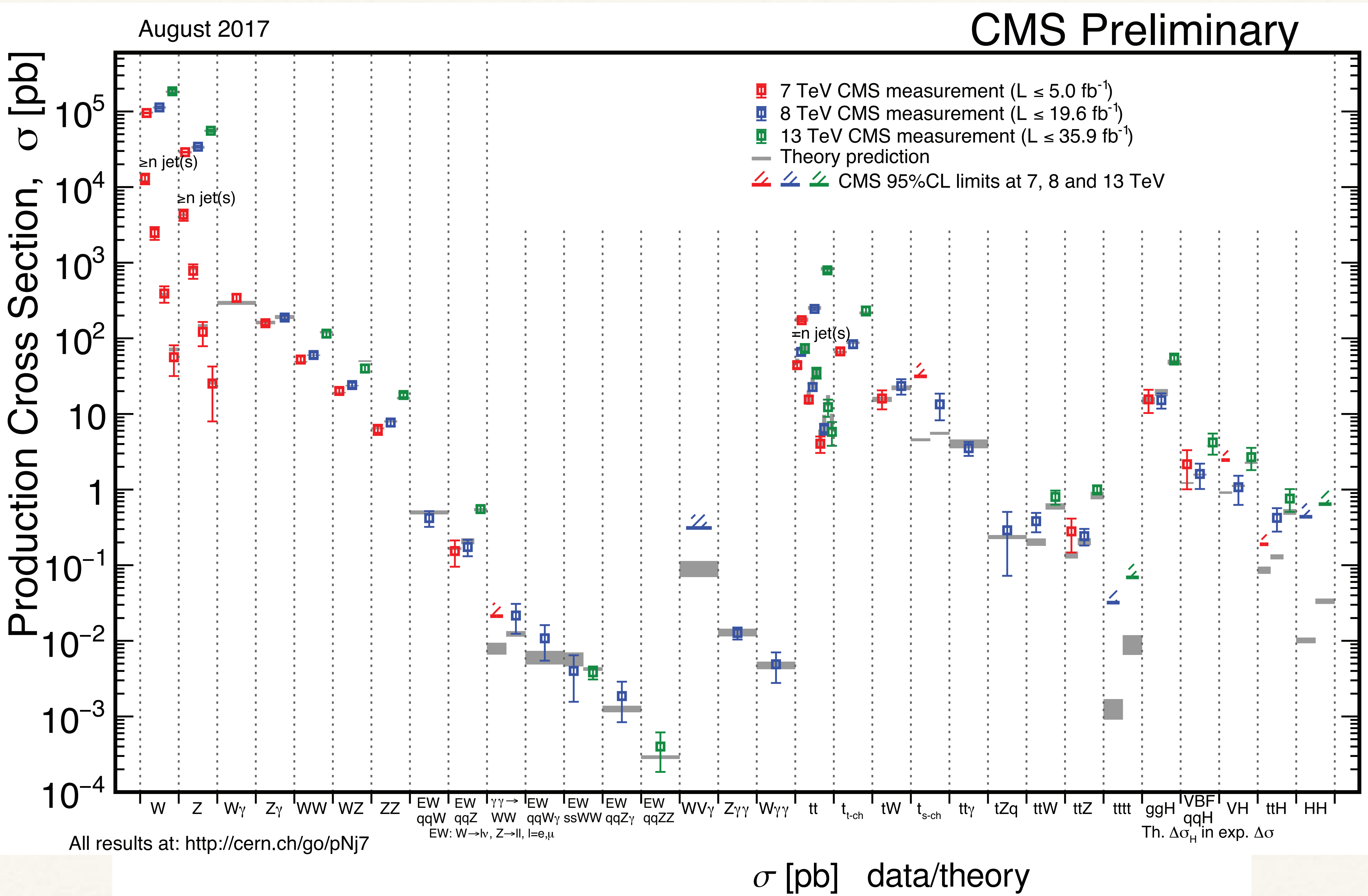
- Falsification
  - Compute promising SM observables to high precision for easier falsification by data



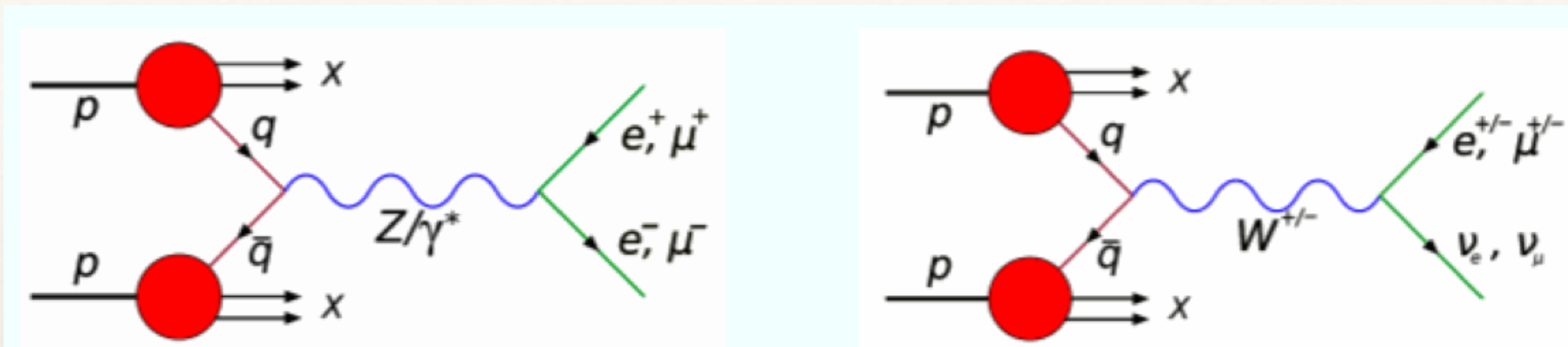
- Verification
  - Compute BSM influence on selected observables to high precision
    - ✓ to ensure that the unique signatures are robust under higher order corrections
    - ✓ to extract information (measurement or exclusion)

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)

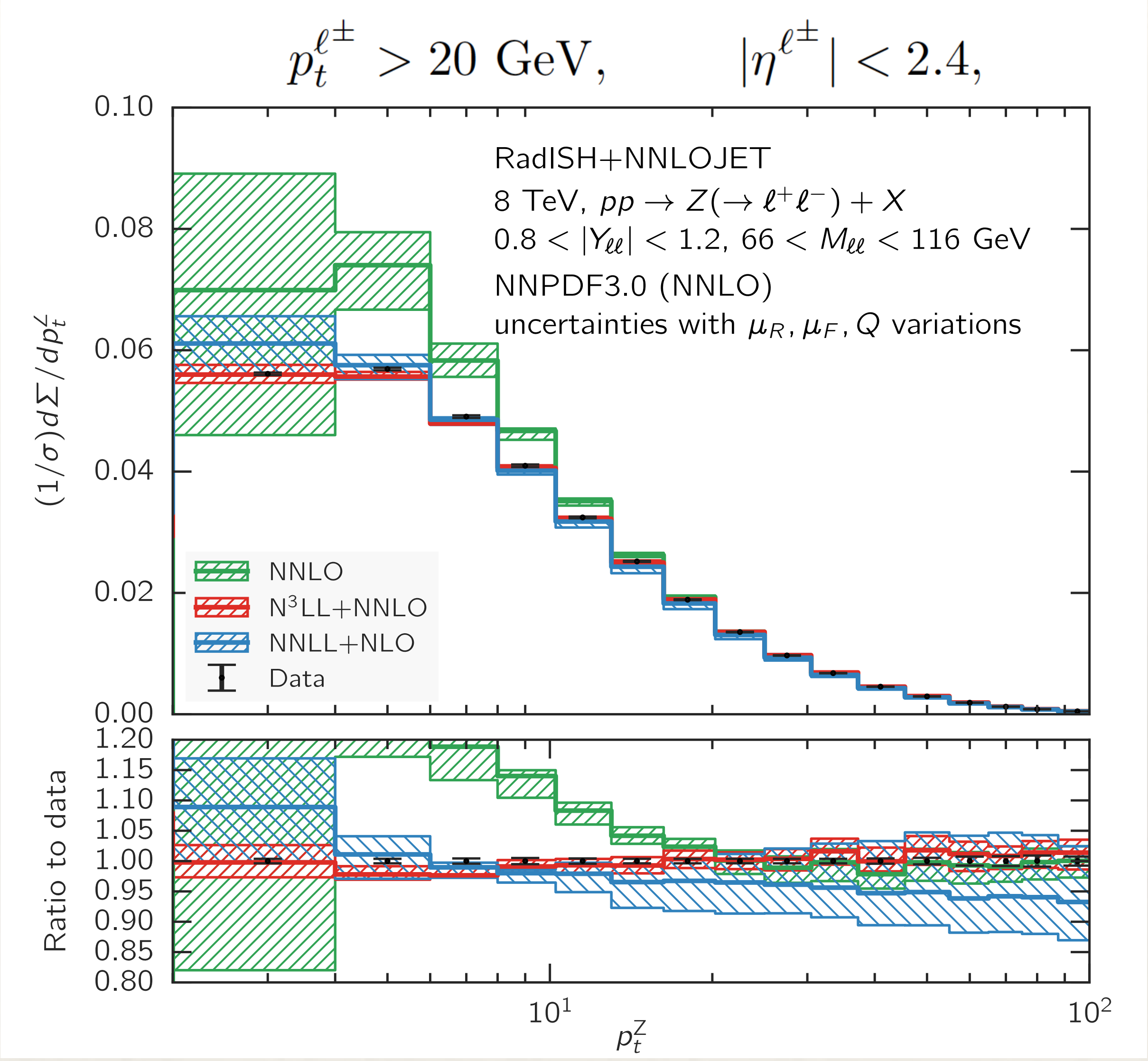
Experiment:

- $\sigma^{-1} d\sigma^Z/dq_T$ ~ **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

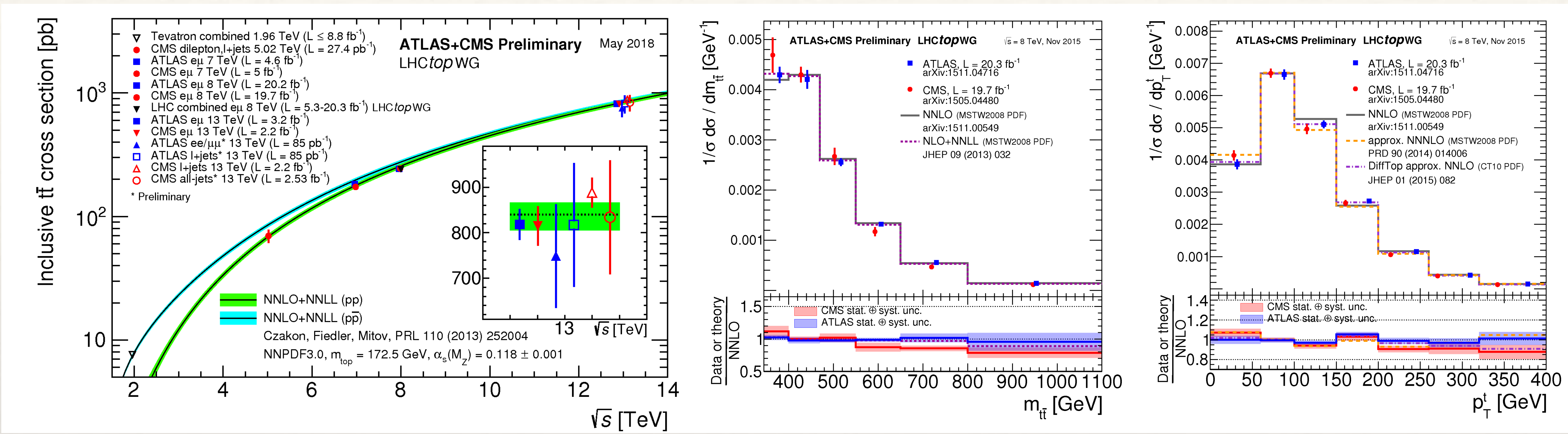
This workshop: Francesco Tramontano, Kajal Samanta



Bizon, Chen, Gehrmann-de Ridder, Gehrmann, Glover, Huss, Monni, Re, Rottoli, Torrieli '18
Duhr, Dulat, Mistlberger '20

Top quark pairs at (HL)-LHC

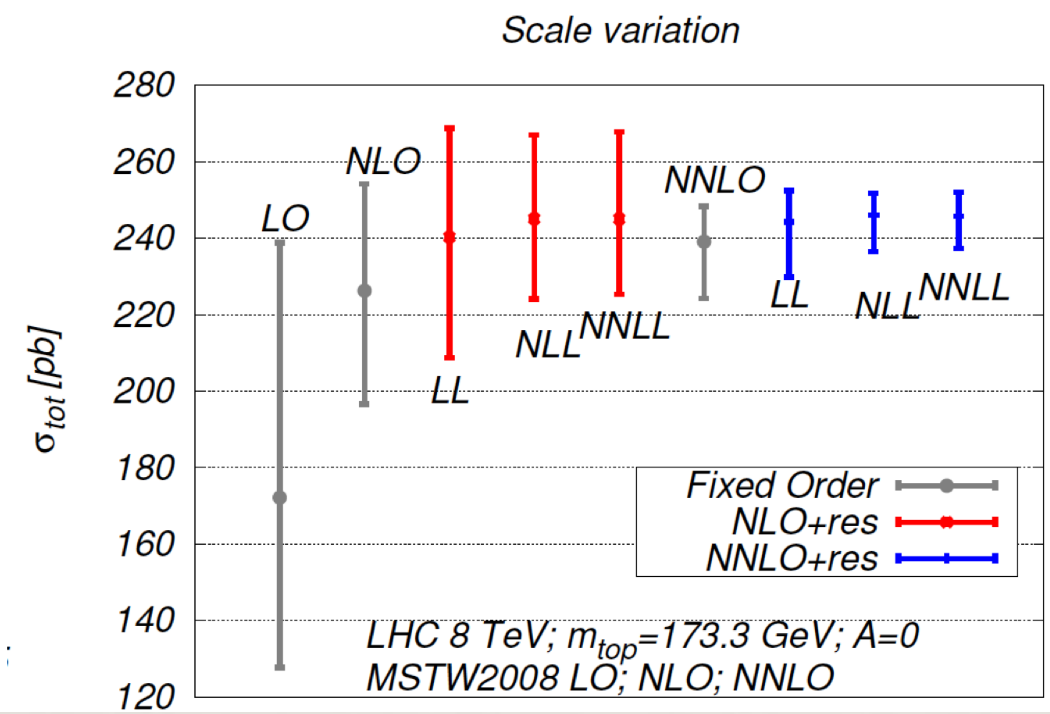
- We are already well into precision top quark physics era



- 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

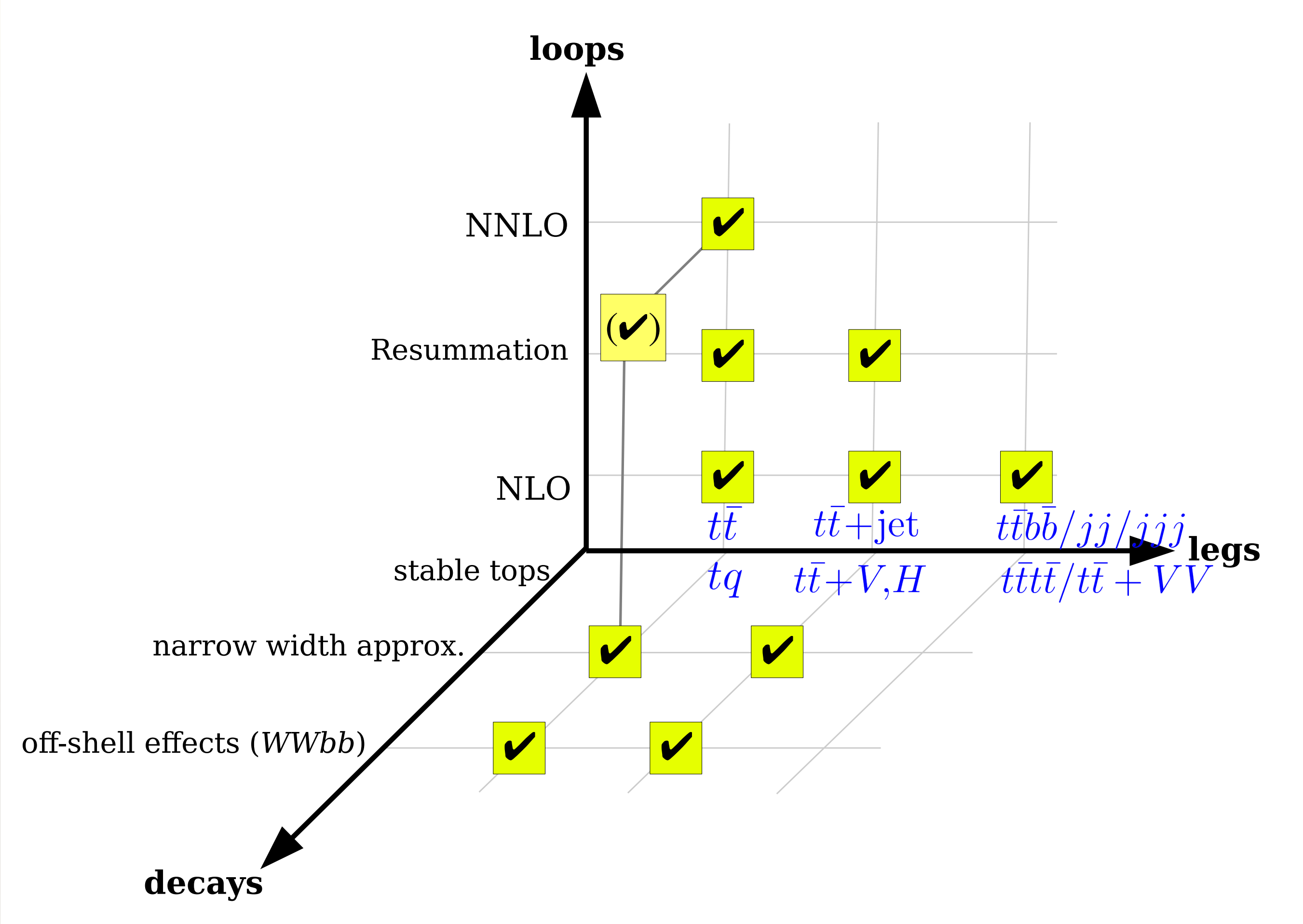
Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro '17

  - impact of photon-in-proton distribution notable (depending on PDF set)

Theory for top pairs plus more

- Status of precision theory description in 3D

Markus Schulze at LHCP '18

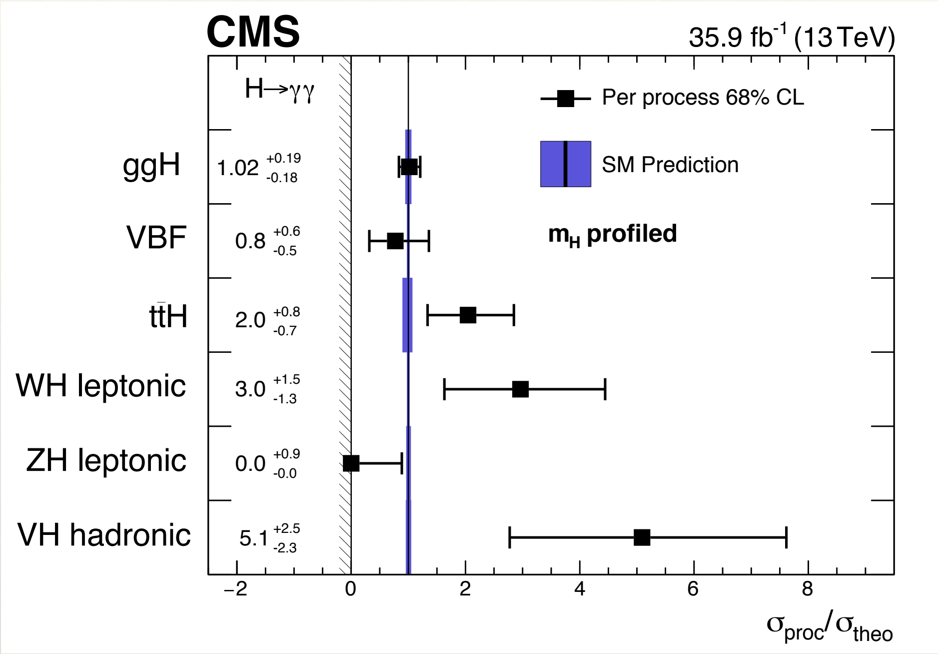


- Again, smaller effects come to the fore when precision is high
  - narrow width approximation vs. full off-shell decay, all this at higher order
  - m_{top} definition and value - a guaranteed topic for lively debates
- Also here the experimental accuracies will be challenging theory

Higgs production at (HL-)LHC

This workshop: Satyajit Seth, Maguni Malakhud

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



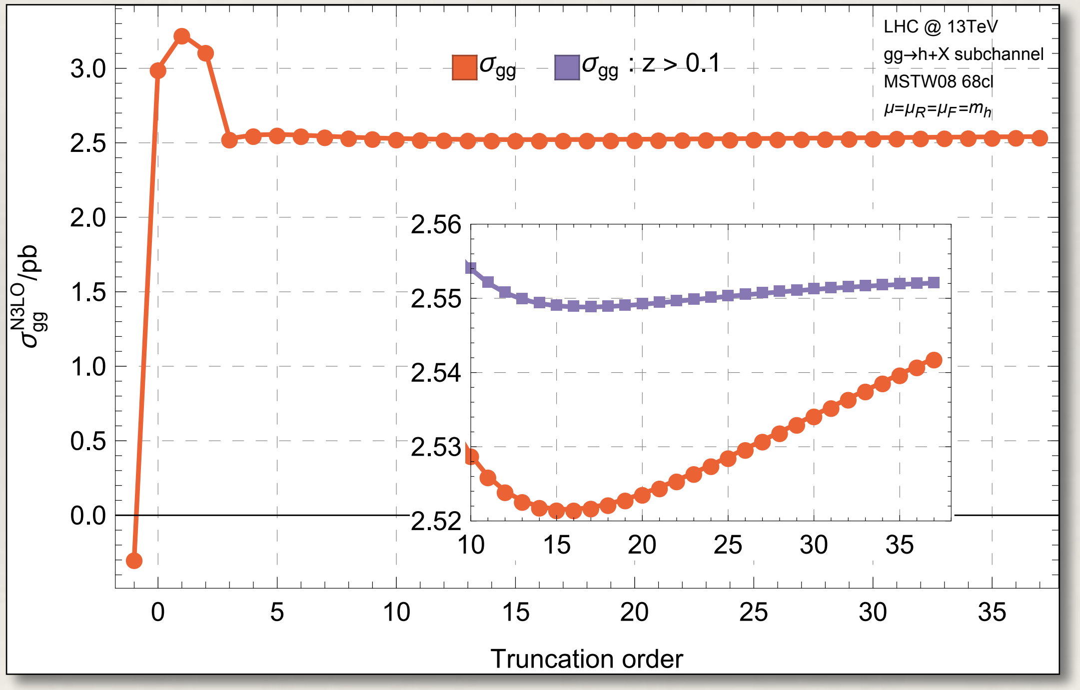
Includes N3LO calculation:
7 Million 3-loop Feynman diagrams
2 months of running on 25K cores

Anastasiou, Duhr, Dulat, Herzog, Mistlberger '15

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

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

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



Mistlberger '18

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

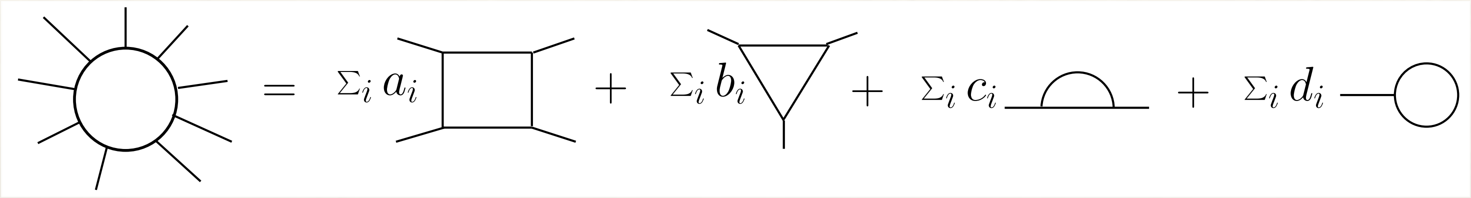
- ggF cross section: many sources of small uncertainties in theory description, all need to be beaten down

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 led to NLO revolution
- New frontier: NNLO and even N3LO
  - many new methods have been developed: healthy marketplace. See also this workshop!
- 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, GoSam, Powheg Box, MCFM,…
- Basic notion: all one-loop amplitudes can written as a sum of boxes, triangle, bubbles and tadpoles

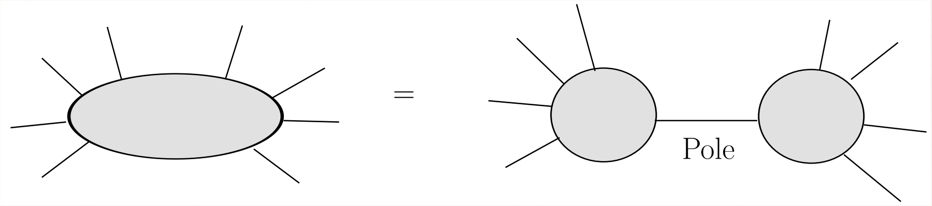


  - ✓ In essence because we live in 4 dimensions: every vector can be decomposed in at maximum four independent vectors

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

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

- 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

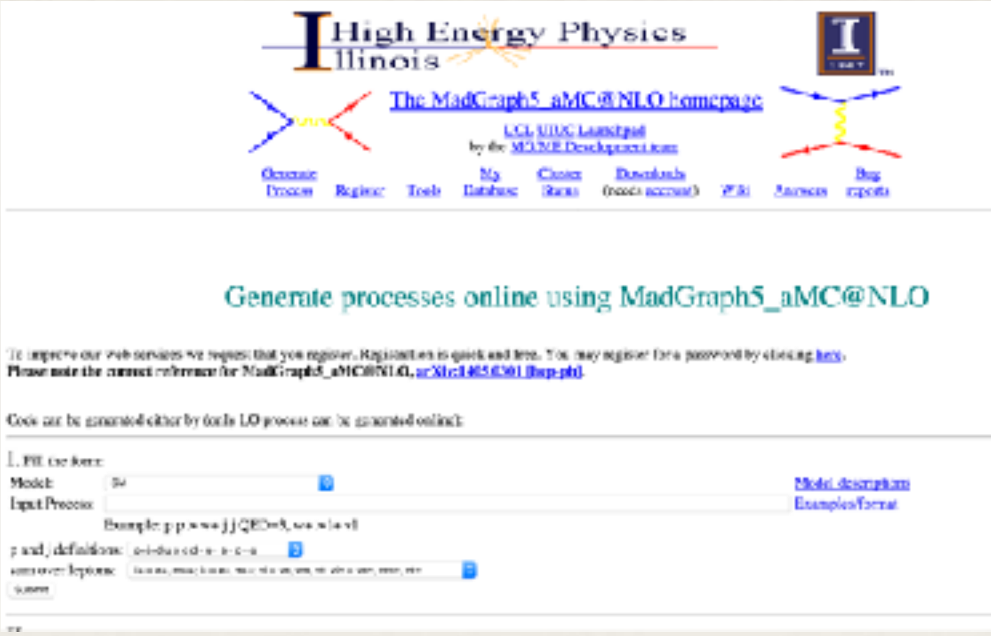
- LO well-understood, now more efficient than ever
- NLO: automatized, a flood of results
- NNLO: top quark production (single and pair), dijet production, 1-jet inclusive, ...
- NNNLO: Drell-Yan, Higgs production, $F_2(x,Q)$,

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

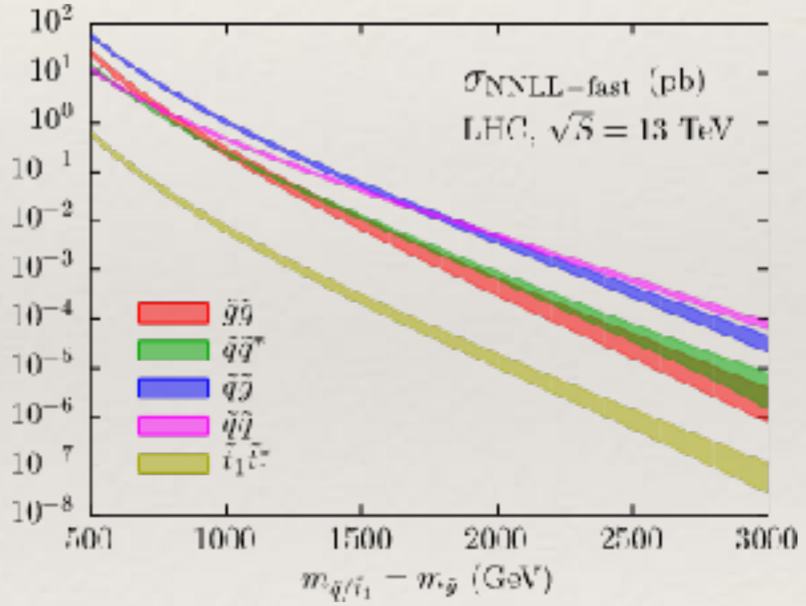
Process	known	desired	motivation
t\bar t	\sigma_tot @ NNLO QCD d\sigma(top decays) @ NLO QCD d\sigma(stable tops) @ NLO EW	d\sigma(top decays) @ NNLO QCD + NLO EW	precision top/QCD, gluon PDF effect of extra radiation at high rapidity top asymmetries

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, composite 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

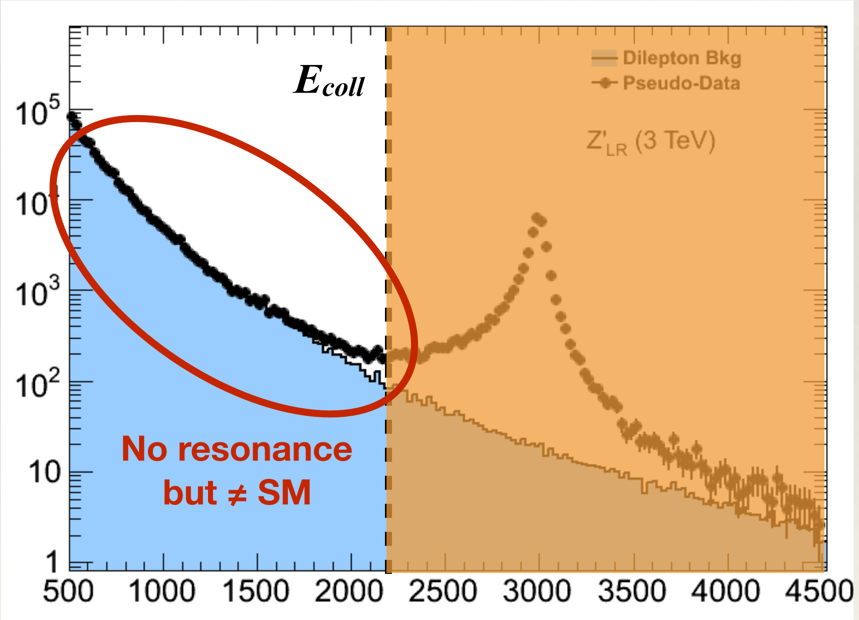
Standard Model Effective Theory

- 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

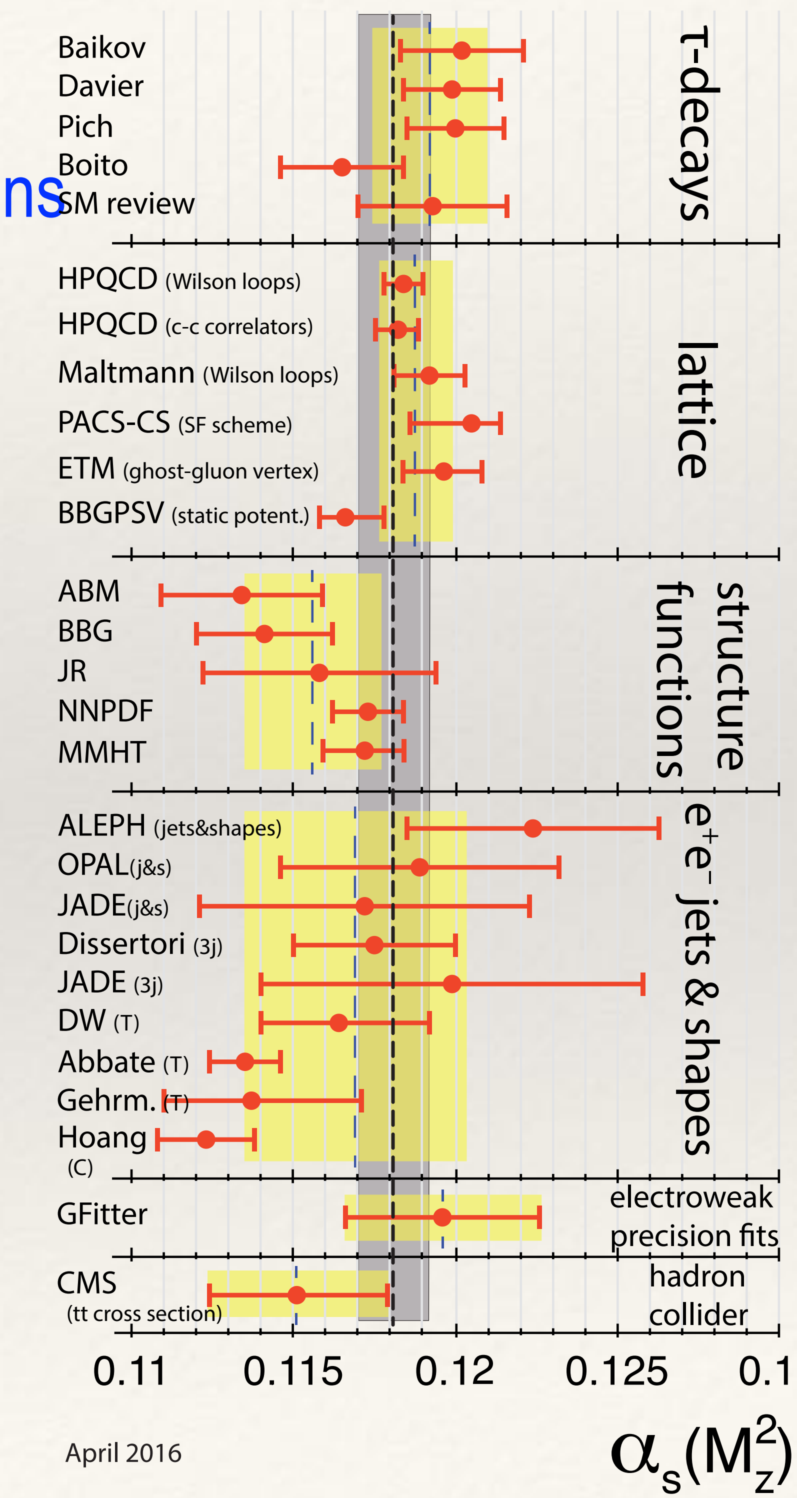
from top quark pair production

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

Lattice QCD

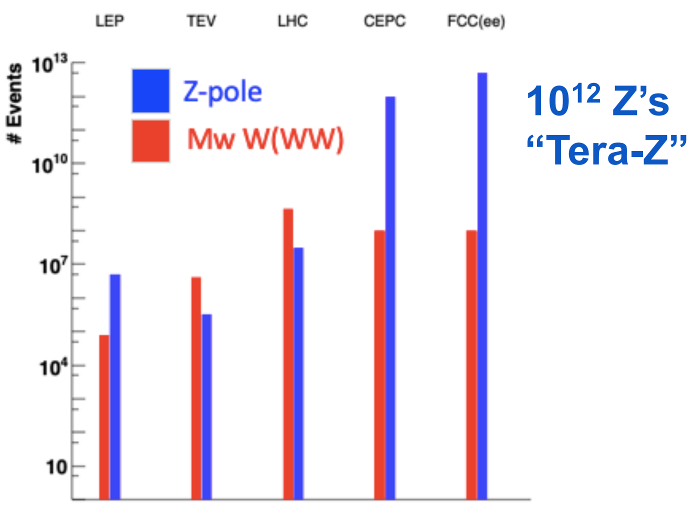
with adequate R&D on computing a robust calculation up to 0.3% precision might be within reach

Bethke, Dissertori, Salam '16



EWPOs

Electroweak Observables at Future Colliders



10^{12} Z's "Tera-Z"

M. Lancaster

ILC:
- **"Giga-Z" running not part of baseline but maybe later**

Precision EWK Observables

Submission Inputs: 29, 145, 101, 132, 135

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

LHeC can measure $\sin^2\theta_W$ as f(E).

LHeC : Mw to 10 MeV but can measure PDFs allowing HL-LHC to half PDF uncertainty and achieve O(5 MeV) Mw.
ILC/CLIC : Mw to 5 MeV similar to HL-LHC/TeV average.

16 14/05/19 Mark Lancaster I Electroweak Precision Measurements

European Strategy Update

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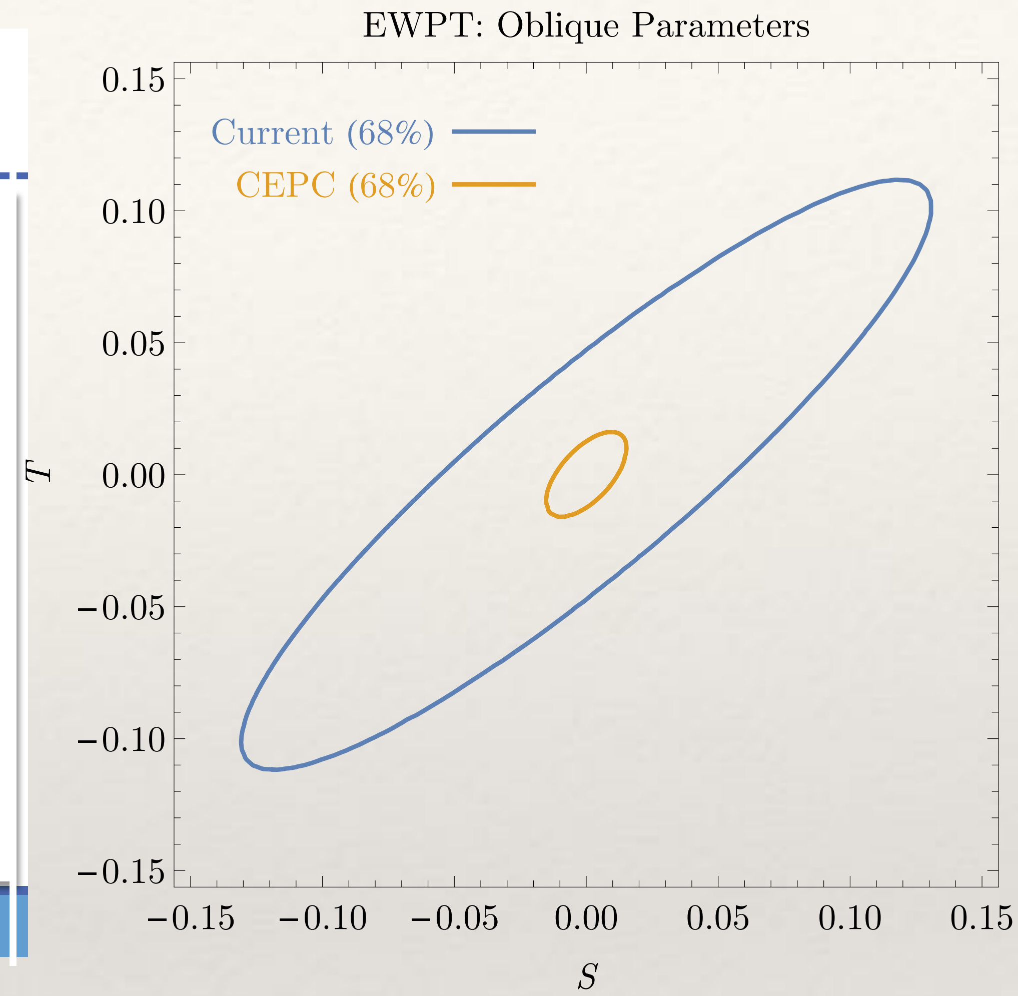
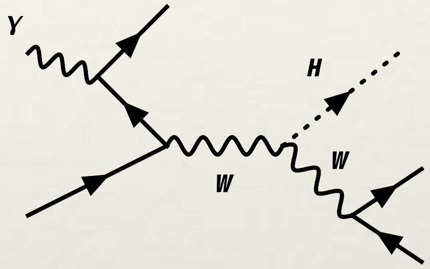


Top mass exp't error: 25 MeV expected
Theory one larger at present.

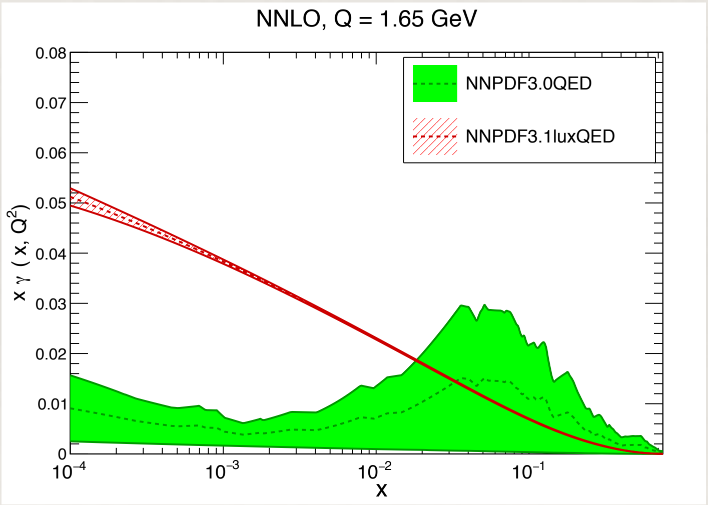
Electroweak corrections

- 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



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



- 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

Some prospects for more precision

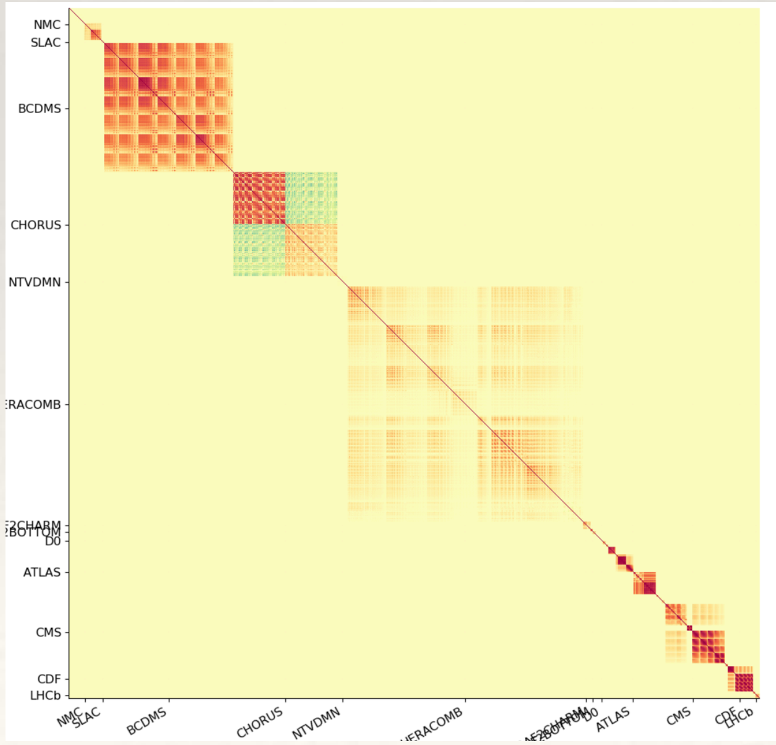
News from PDFs: theory errors

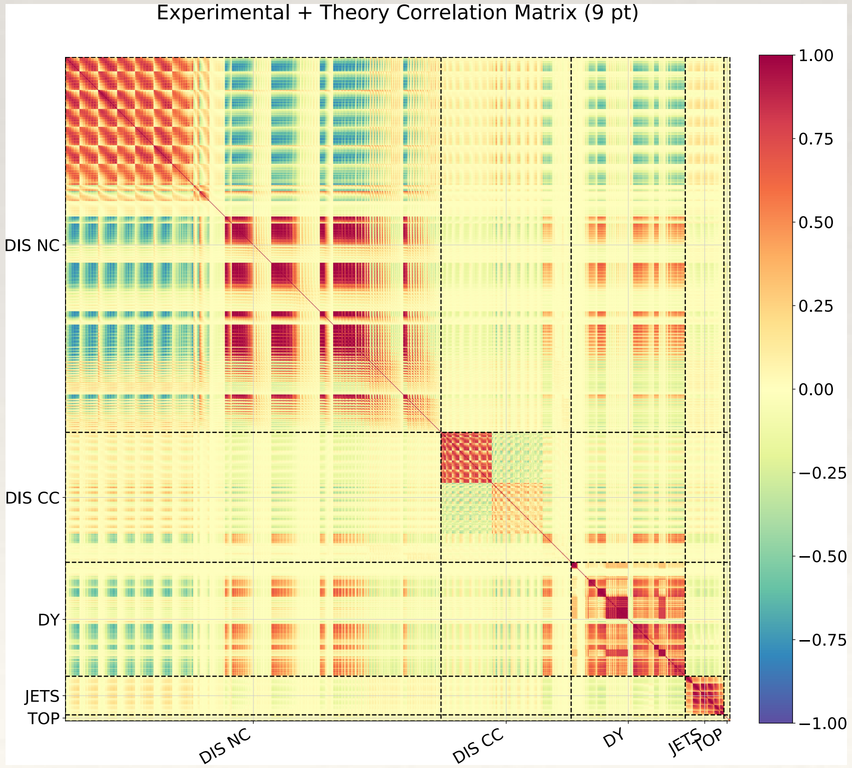
NNPDF collab.'19

- 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

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

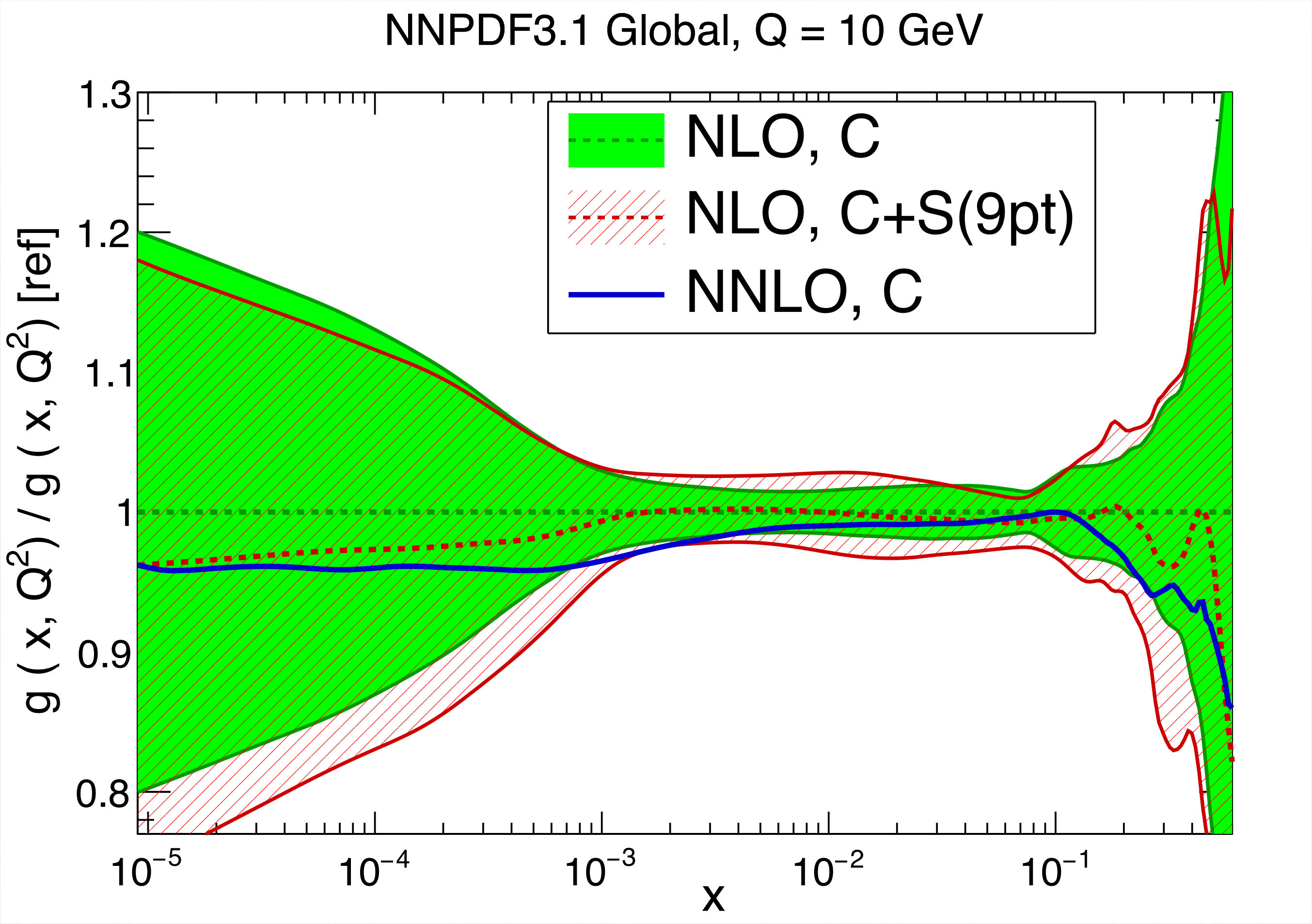
- Introduces much more correlations between experimental inputs





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

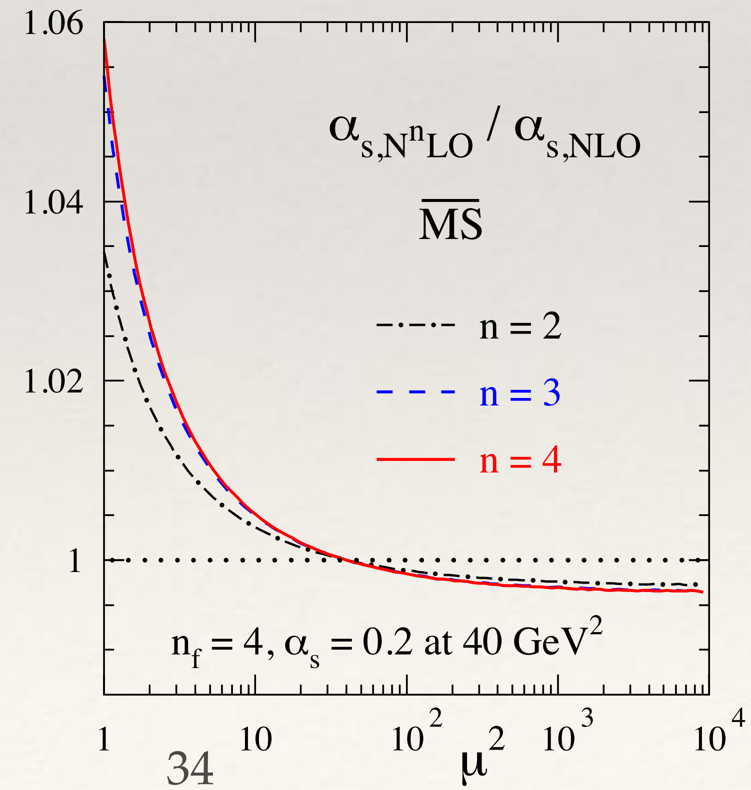
- **five**-loop QCD beta function
  - first done for SU(3) , then for SU(N)
    - ✓ using R* method to extract divergences
    - ✓ 6 days on 32 core machine
  - five loop expansion in MSbar scheme very benign

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

    - ✓ 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,
Chetyrkin, Falcioni, Herzog, Vermaseren, ‘17

- implications for running coupling:



QCD precision at REALLY high order II

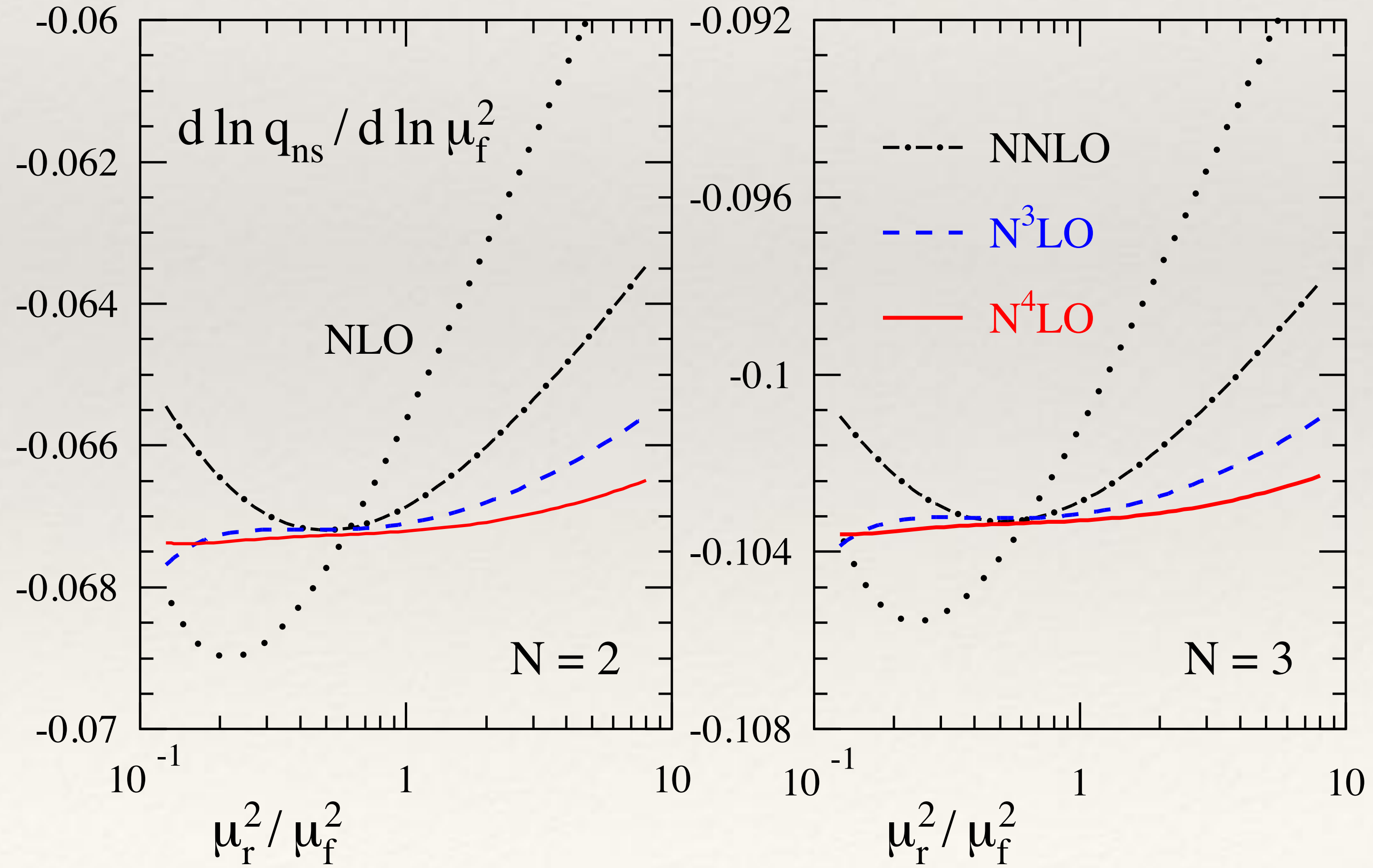
- QCD splitting functions at four and five loops

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

  - 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 $2 \to 3$, N3LO and beyond

This workshop: Wouter Waalewijn, Darren Scott, Ankita Budraja, Giulo Falcioni, Amlan Chakraborty, A.H. Ajjath A.H, Pooja Mukherjee, V. Ravindran

- Involves progress in
  - loop diagrams: analytical and numerical approaches
  - IR divergence management, new subtraction mechanisms, phase space slicing making a comeback

    This workshop: Chiara Signorile-Signorile, Lorenzo Magnea

  - Shuffle/Hopf algebra of polylogs to 3rd order $\to$ elliptic integrals
  - threshold expansions
  - automation, computing methods

Soft logarithms at next-to-leading power

- General soft expansion for 2⟶1 processes

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

- 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

This workshop: Leonardo Vernazza, Melissa van Beekveld

Elliptic progress: from math for loops

This workshop: Ekta Chaubey, Manoy Mandal

- 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

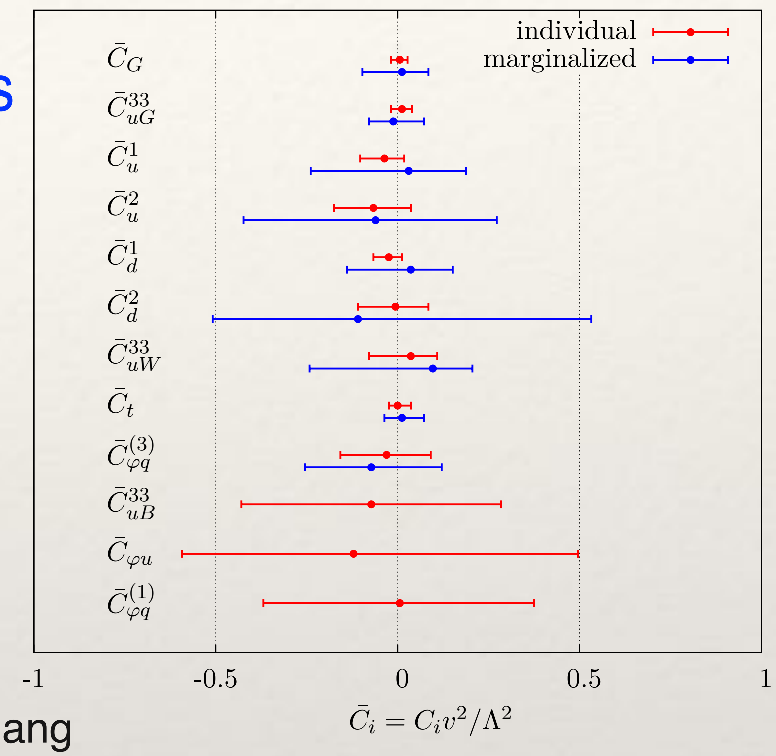
IMPORTANT:
As for other areas, for future progress we cannot take the **new talent** entering precision calculations for granted.

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

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 (This Workshop!) give much reason for optimism!

Finally, as we are near the end of this workshop

A word of thanks..

from all of us

to Anurag, Neelima
to Abhinava, Ayan, Shubham, Sourav

For combining precision and fun
with great accuracy!