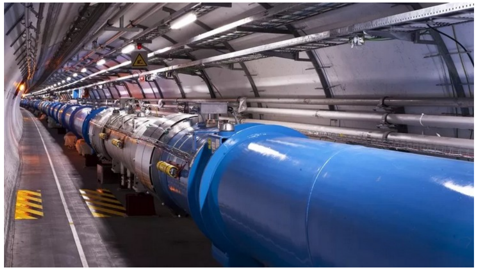
Precision predictions for hadron collider physics

René Poncelet

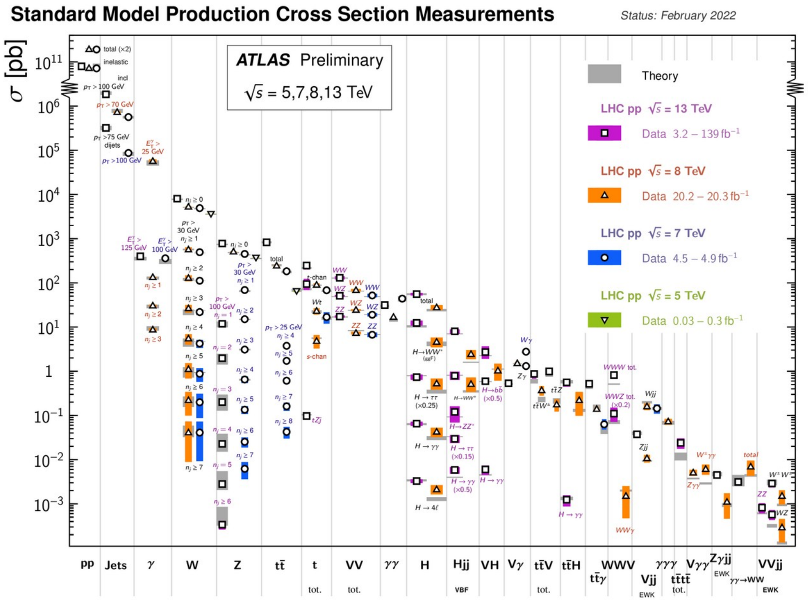
THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

Standard Model phenomenology at the LHC

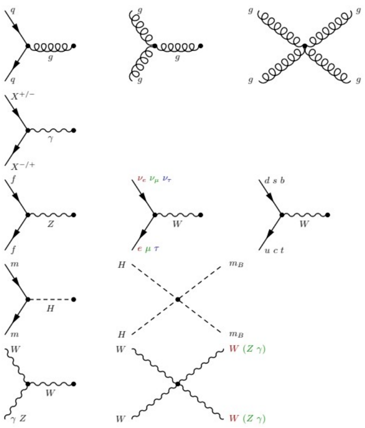
Scattering experiments



Credit: CERN

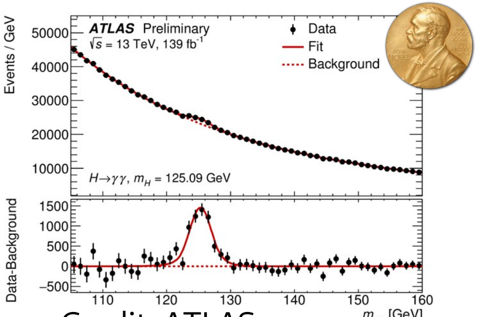


Theory/Model

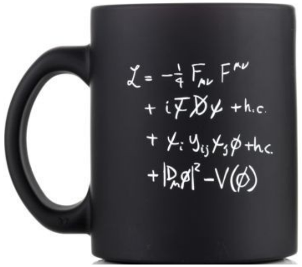


Credit: Jack Lindon, CERN

Higgs discovery 2012

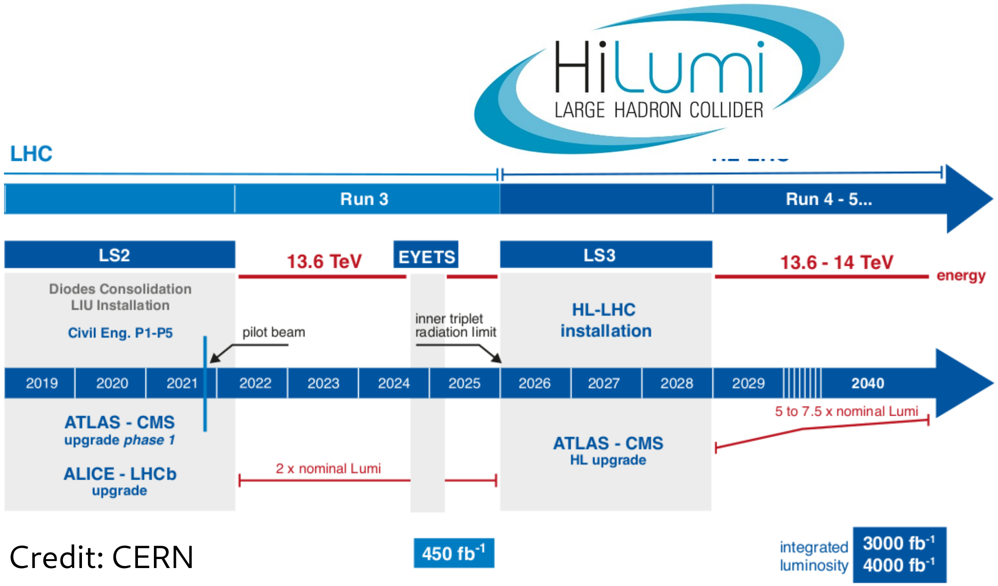


Credit: ATLAS



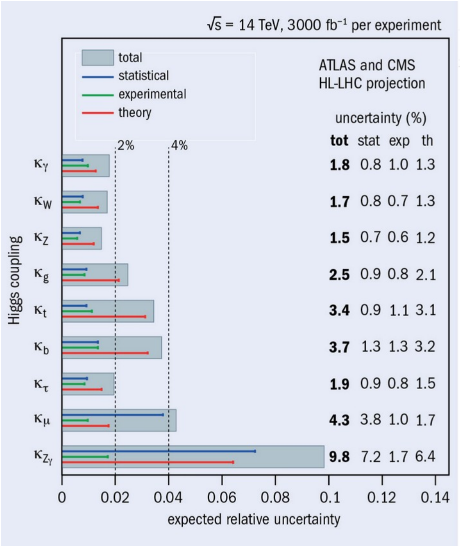
Credit: CERN

LHC Precision era and future experiments



Credit: CERN

Example:
projected Higgs couplings measurements



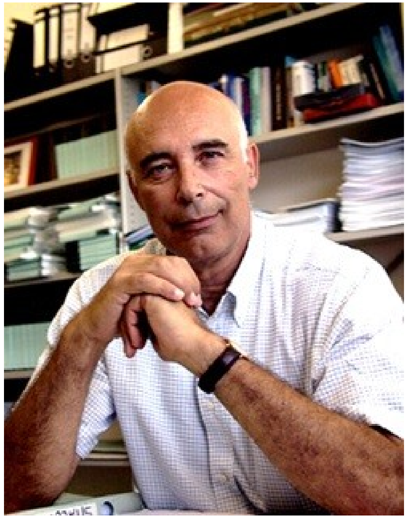
[1902.00134]

Theory input needed:

- Accurate → avoid wrong interpretation of excesses
- Precise → getting most out of our precious experiments

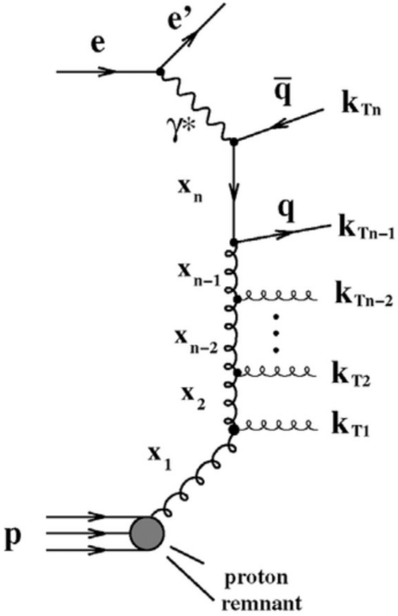
A pillar of precision phenomenology at hadron colliders

[Dokshitzer–Gribov–Lipatov–Altarelli–Parisi, ‘77]



DGLAP:

$$Q^2 \frac{\partial}{\partial Q^2} \begin{pmatrix} q_i(x,Q^2) \\ \bar{q}_i(x,Q^2) \\ g(x,Q^2) \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi} \sum_j \int_x^1 \frac{d\xi}{\xi} \begin{pmatrix} P_{q_i q_j}(x/\xi) & 0 & P_{q_i g}(x/\xi) \\ 0 & P_{\bar{q}_i \bar{q}_j}(x/\xi) & P_{\bar{q}_i g}(x/\xi) \\ P_{g q_j}(x/\xi) & P_{g \bar{q}_j}(x/\xi) & P_{gg}(x/\xi) \end{pmatrix} \begin{pmatrix} q_j(\xi,Q^2) \\ \bar{q}_j(\xi,Q^2) \\ g(\xi,Q^2) \end{pmatrix}$$



[Zeus, hep-ph/0502029]

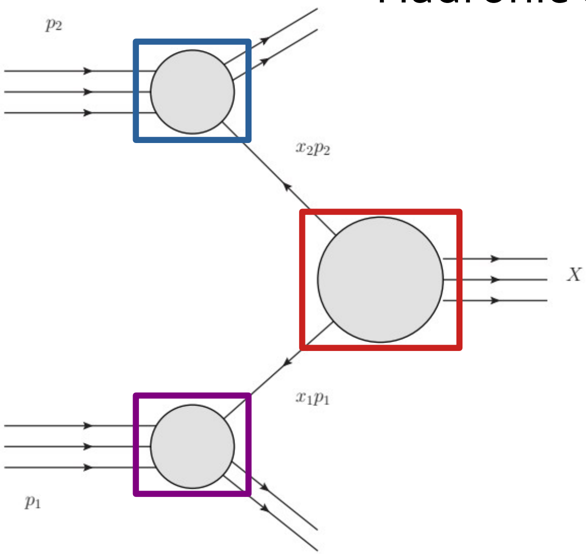
Evolution of the proton PDF with the energy:

→ Resummation of large logarithms from collinear emissions

→ correlation of processes at different energies
→ allows precise PDF determination

Basis of precision computation at hadron colliders today

Precision through higher orders



Hadronic cross section:

$$\sigma_{h_1 h_2 \to X} = \sum_{ij} \int_0^1 \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \phi_{i,h_1}(x_1, \mu_F^2) \phi_{j/h_2}(x_2, \mu_F^2) \hat{\sigma}_{ij \to X}(\alpha_s(\mu_R^2), \mu_R^2, \mu_F^2)$$

PDFs → DGLAP

Perturbative expansion of partonic cross section:

$$\hat{\sigma}_{ab \to X} = \underbrace{\alpha_s^0 \hat{\sigma}^{(0)}_{ab \to X}}_{\text{Leading order}} + \underbrace{\alpha_s^1 \hat{\sigma}^{(1)}_{ab \to X}}_{\text{Next-to-leading order}} + \underbrace{\alpha_s^2 \hat{\sigma}^{(2)}_{ab \to X}}_{\text{Next-to-next-to-leading order}} + \mathcal{O}(\alpha_s^3)$$

Uncertainty: $\alpha_s(m_Z) \approx 0.118$

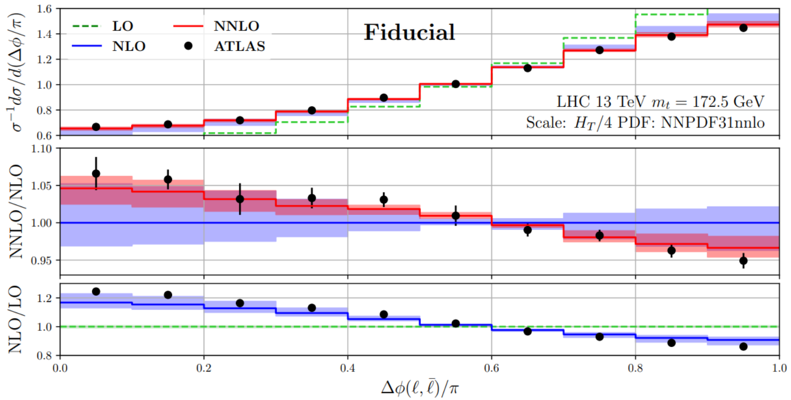
Order of magnitude	O(10%)	O(1%)

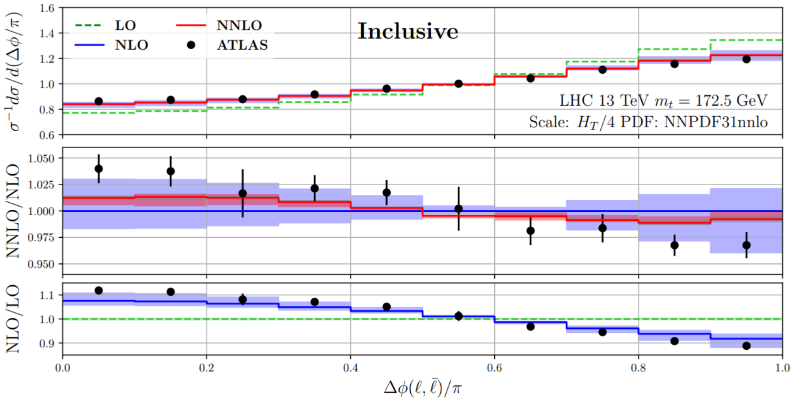
Next-to-next-to-leading order QCD needed to match experimental precision!
→ in some cases even next-to-next-to-next-to-leading order!

Accurate predictions, example: spin-correlations

[Behring, Czakon, Mitov, Papanastasiou, Poncelet'19
Czakon, Mitov, **Poncelet** '21]

Azimuthal correlations for leptons





Spin-density-matrix

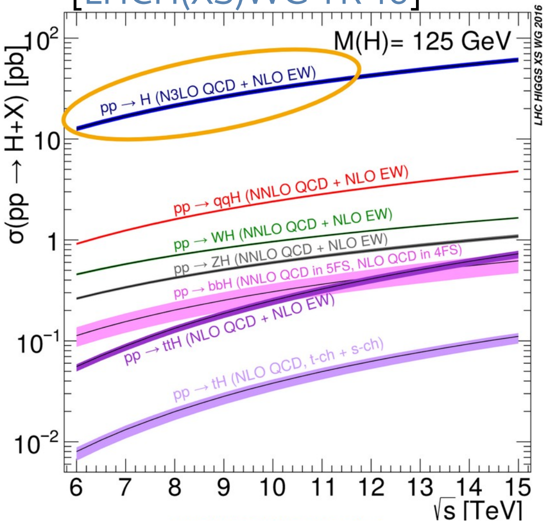
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_1^i\,\mathrm{d}\cos\theta_2^j} = \frac{1}{4}\left(1 + B_1^i\cos\theta_1^i + B_2^j\cos\theta_2^j - C_{ij}\cos\theta_1^i\cos\theta_2^j\right)$$

Coefficient	LO ($\times 10^3$)	NLO ($\times 10^3$)	NNLO ($\times 10^3$)	CMS ($\times 10^3$)
B_1^k	1^{+0}_{-0} [sc] ± 1 [mc]	1^{+0}_{-1} [sc] ± 2 [mc]	-1^{+0}_{-1} [sc] ± 4 [mc]	5 ± 23
B_1^r	0^{+0}_{-0} [sc] ± 1 [mc]	0^{+1}_{-0} [sc] ± 2 [mc]	0^{+1}_{-2} [sc] ± 2 [mc]	-23 ± 17
B_1^n	0^{+0}_{-0} [sc] ± 1 [mc]	3^{+1}_{-1} [sc] ± 1 [mc]	4^{+1}_{-0} [sc] ± 3 [mc]	6 ± 13
B_2^k	0^{+0}_{-0} [sc] ± 1 [mc]	0^{+0}_{-1} [sc] ± 1 [mc]	-5^{+2}_{-3} [sc] ± 3 [mc]	7 ± 23
B_2^r	0^{+0}_{-0} [sc] ± 1 [mc]	0^{+2}_{-0} [sc] ± 1 [mc]	-2^{+0}_{-1} [sc] ± 2 [mc]	-10 ± 20
B_2^n	0^{+0}_{-0} [sc] ± 1 [mc]	-2^{+0}_{-1} [sc] ± 1 [mc]	-3^{+1}_{-0} [sc] ± 3 [mc]	17 ± 13
C_{kk}	324^{+7}_{-7} [sc] ± 1 [mc]	330^{+2}_{-2} [sc] ± 3 [mc]	323^{+2}_{-5} [sc] ± 6 [mc]	300 ± 38
C_{rr}	6^{+5}_{-5} [sc] ± 1 [mc]	58^{+18}_{-12} [sc] ± 2 [mc]	69^{+8}_{-7} [sc] ± 3 [mc]	81 ± 32
C_{nn}	332^{+1}_{-0} [sc] ± 1 [mc]	330^{+1}_{-1} [sc] ± 2 [mc]	326^{+1}_{-1} [sc] ± 4 [mc]	329 ± 20
$C_{nr} + C_{rn}$	1^{+0}_{-0} [sc] ± 1 [mc]	-1^{+1}_{-0} [sc] ± 3 [mc]	-4^{+4}_{-0} [sc] ± 6 [mc]	-4 ± 37
$C_{nr} - C_{rn}$	0^{+0}_{-1} [sc] ± 1 [mc]	-1^{+1}_{-0} [sc] ± 2 [mc]	2^{+4}_{-2} [sc] ± 8 [mc]	-1 ± 38
$C_{nk} + C_{kn}$	0^{+0}_{-0} [sc] ± 1 [mc]	2^{+1}_{-0} [sc] ± 1 [mc]	3^{+4}_{-1} [sc] ± 3 [mc]	-43 ± 41
$C_{nk} - C_{kn}$	1^{+0}_{-0} [sc] ± 1 [mc]	1^{+1}_{-1} [sc] ± 2 [mc]	6^{+0}_{-2} [sc] ± 7 [mc]	40 ± 29
$C_{rk} + C_{kr}$	-229^{+4}_{-4} [sc] ± 1 [mc]	-203^{+9}_{-7} [sc] ± 2 [mc]	-194^{+8}_{-6} [sc] ± 7 [mc]	-193 ± 64
$C_{rk} - C_{kr}$	1^{+0}_{-0} [sc] ± 1 [mc]	1^{+0}_{-1} [sc] ± 4 [mc]	-1^{+1}_{-3} [sc] ± 5 [mc]	57 ± 46

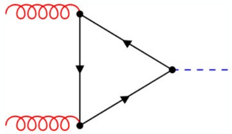
[CMS 1907.03729]

Precision example: Quark-mass effects in Higgs production

[LHCH(XS)WG YR'16]



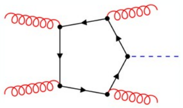
Higgs-production in gluon fusion, main uncertainties:

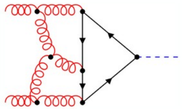


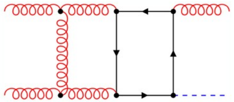
δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
+0.10 pb −1.15 pb	±0.18 pb	±0.56 pb	±0.49 pb	±0.40 pb	±0.49 pb
+0.21% −2.37%	±0.37%	±1.16%	±1%	±0.83%	±1%

Second-order corrections to top-bottom interference effects with full mass dependence!

[Czakon, Eschment, Niggetiedt, **Poncelet**, Schellenberger: 2312.09896, 2407.12413]



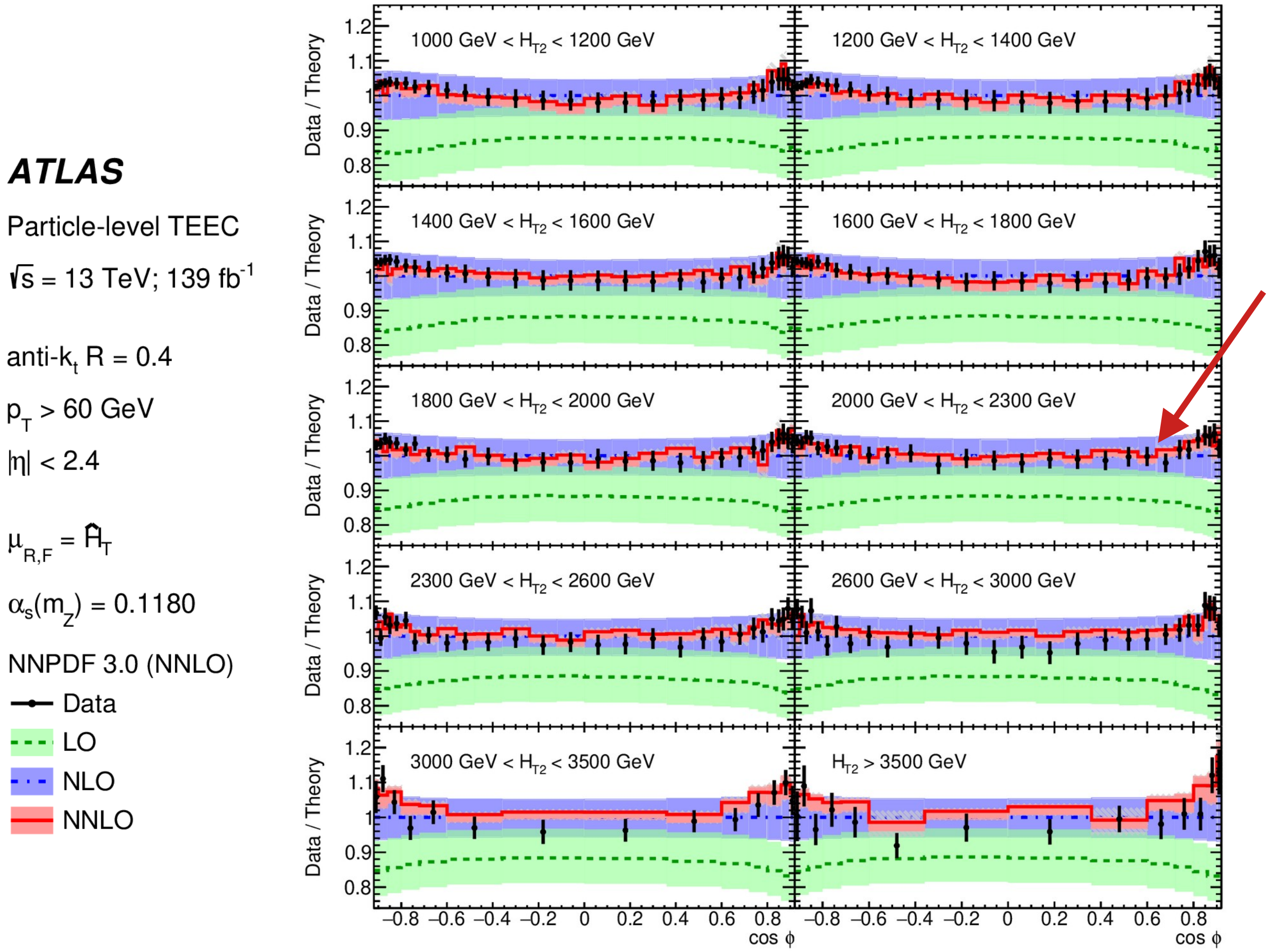




Renorm. scheme	$\overline{\text{MS}}$	on-shell
$\mathcal{O}(\alpha_s^2)$	-1.11	-1.98
LO	$-1.11^{+0.28}_{-0.43}$	$-1.98^{+0.38}_{-0.53}$
$\mathcal{O}(\alpha_s^3)$	-0.65	-0.44
NLO	$-1.76^{+0.27}_{-0.28}$	$-2.42^{+0.19}_{-0.12}$
$\mathcal{O}(\alpha_s^4)$	$+0.02$	$+0.43$
NNLO	$-1.74(2)^{+0.13}_{-0.03}$	$-1.99(2)^{+0.29}_{-0.15}$

$\overline{\text{MS}}$ vs. on-shell scheme:
→ first agreement at NNLO!

Precision example: strong-coupling from TEEC



NNLO QCD for three jets

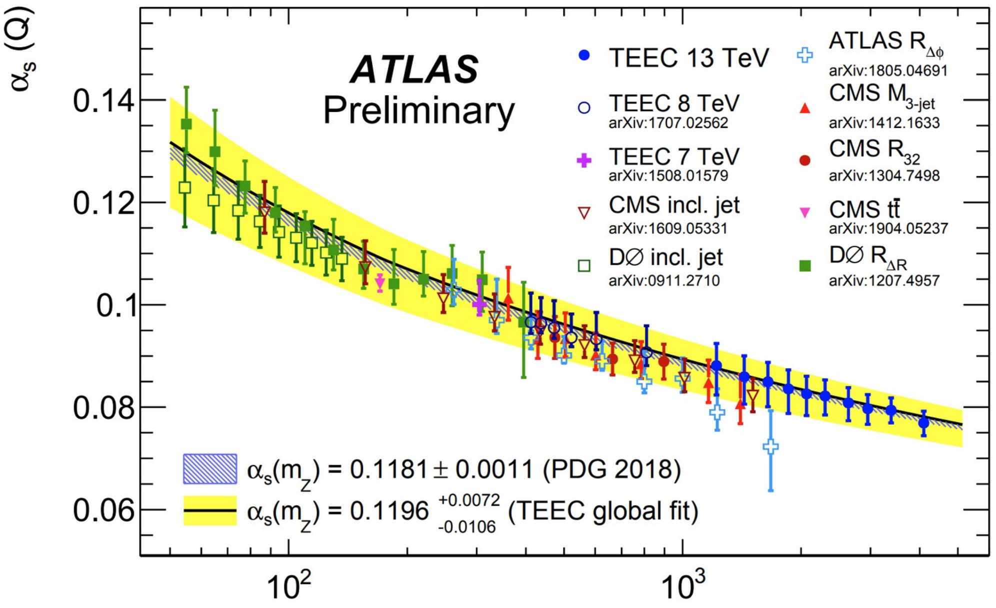
- [Czakon, Mitov, **Poncelet** 2106.05331]
- [Alvarez, Cantero, Czakon, Llorente, Mitov, **Poncelet** 2301.01086]

ATLAS: α_s extraction

- [ATLAS 2301.09351]

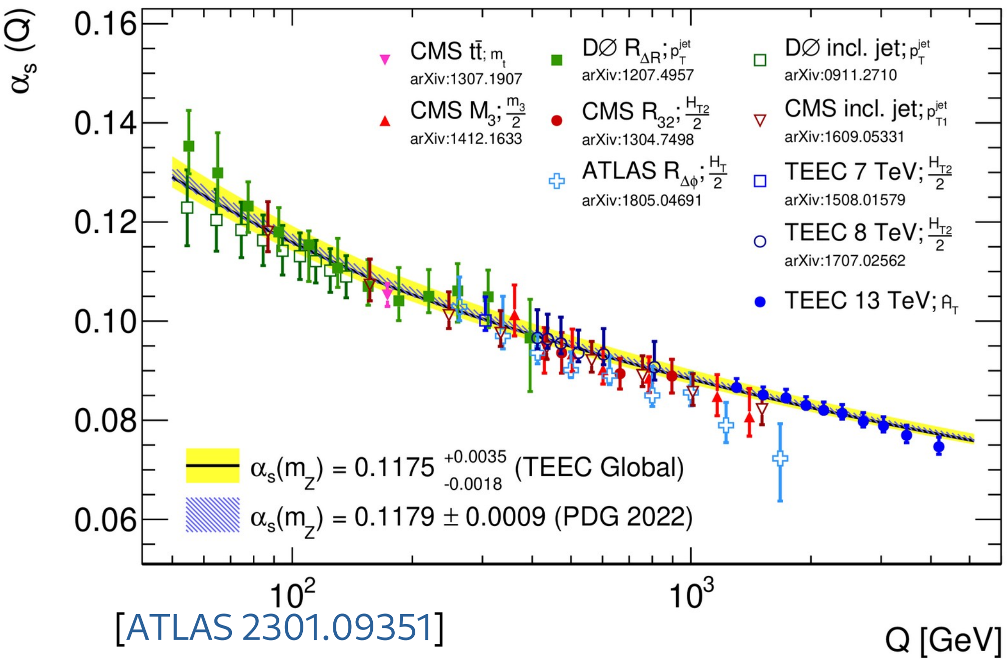
Precision example: strong-coupling from TEEC

NLO QCD



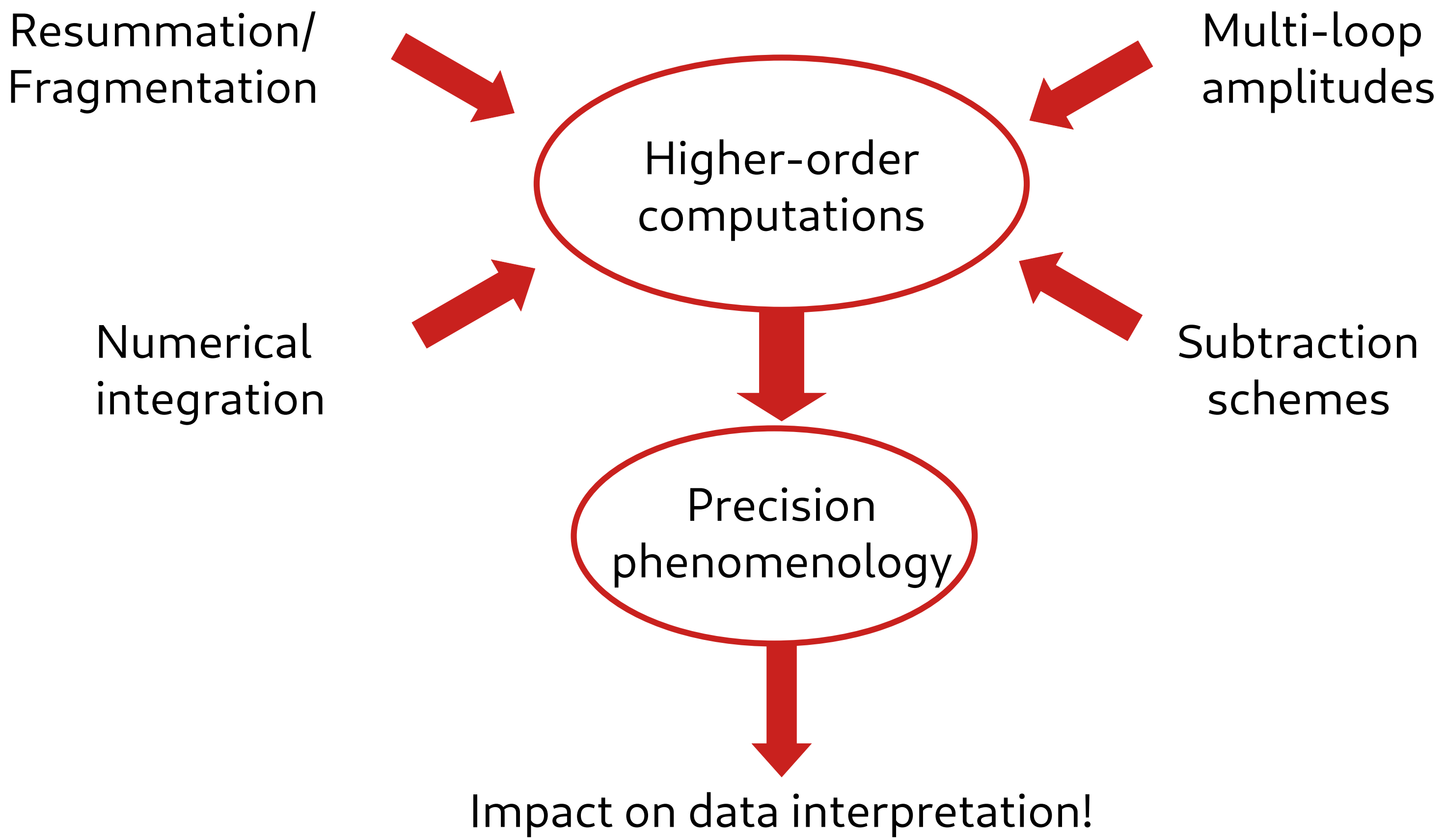
[ATLAS-CONF-2020-025]

NNLO QCD



[ATLAS 2301.09351]

From calculations to phenomenology



Conclusions

Predictions are essential for data interpretation. We need them

- accurate → avoid wrong interpretation of excesses
- precise → getting most out of our precious experiments

QCD calculations went a long way from '77 to today:

→ Miles stones like NNLO QCD multi-jet production and
N3LO QCD for simple inclusive processes

→ Next challenge: full automation of NNLO QCD and incorporation into Monte Carlos
(main bottlenecks: multi-loop amplitudes, parton-shower matching)

→ A lot of space for surprises and novel ideas!

Many thanks to all my collaborators,
in particular to my mentors Michal Czakon and Alexander Mitov!
Thank you!