Precision QCD for collider experiments

Dr. rer. nat. Rene Poncelet

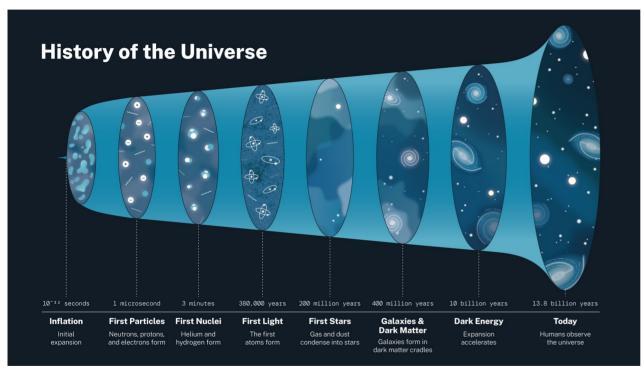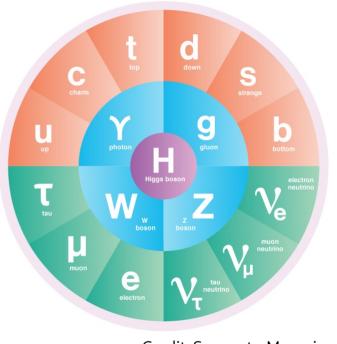|	
Since Oct 2021	**Leverhulme Early Career Fellow** Cavendish Laboratory, Cambridge
2018 - 2021	**Research Associate (PostDoc)** Cavendish Laboratory, Cambridge
2015 - 2018	**PhD** RWTH Aachen University, Aachen
2010 - 2015	**Bachelor/Master of Science Physics** Georg-August University, Göttingen

LEVERHULME TRUST

Isaac Newton Trust

UNIVERSITY OF CAMBRIDGE

What is the universe made of and where does it come from?

Credit: NASA

Credit: SymmetryMagazine

QUARKS LEPTONS BOSONS HIGGS BOSON

What are the fundamental building blocks of matter?

Scattering experiments
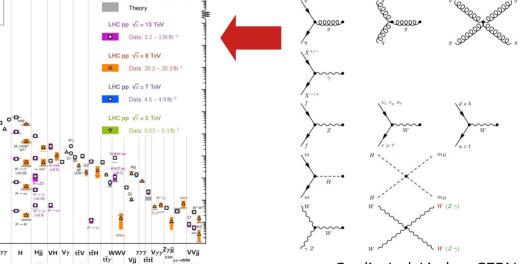
Credit: CERN

Credit: ATLAS

Theory/Model
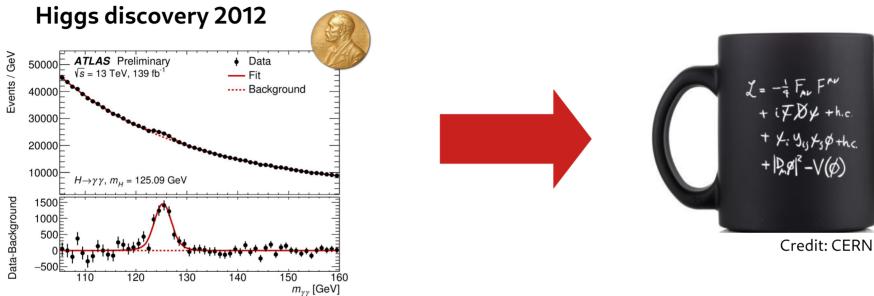
Credit: Jack Lindon, CERN

Standard Model of Particle Physics and beyond
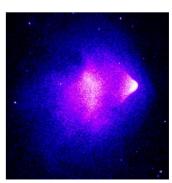
Higgs discovery 2012

Credit: ATLAS
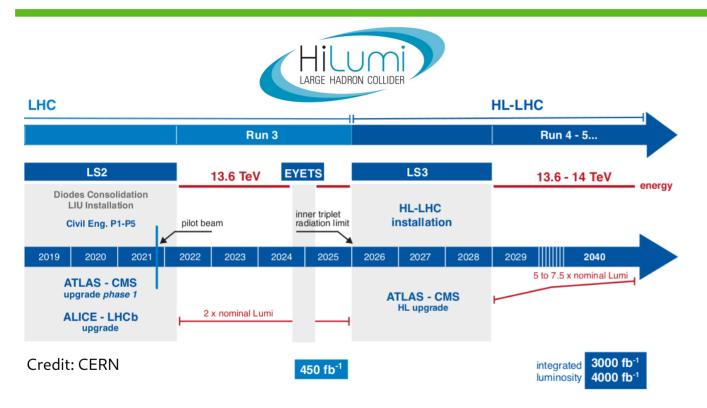
BUT:
- Is the Higgs a fundamental scalar?
- What is dark matter?
- Why is there a matter-anti-matter asymmetry?
- ...

Credit: CERN
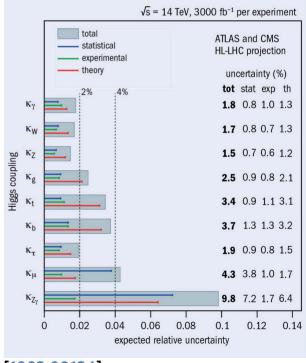
Credit: NASA

LHC Precision era and future experiments
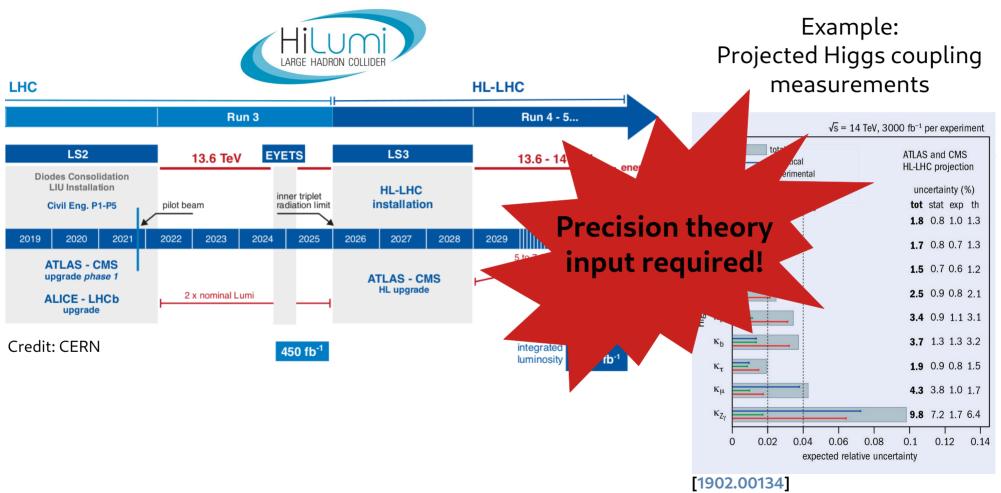
Example:
Projected Higgs coupling measurements

Credit: CERN

LHC Precision era and future experiments

Credit: CERN

Example:
Projected Higgs coupling measurements

Precision theory input required!

√s = 14 TeV, 3000 fb⁻¹ per experiment

ATLAS and CMS HL-LHC projection

[1902.00134]
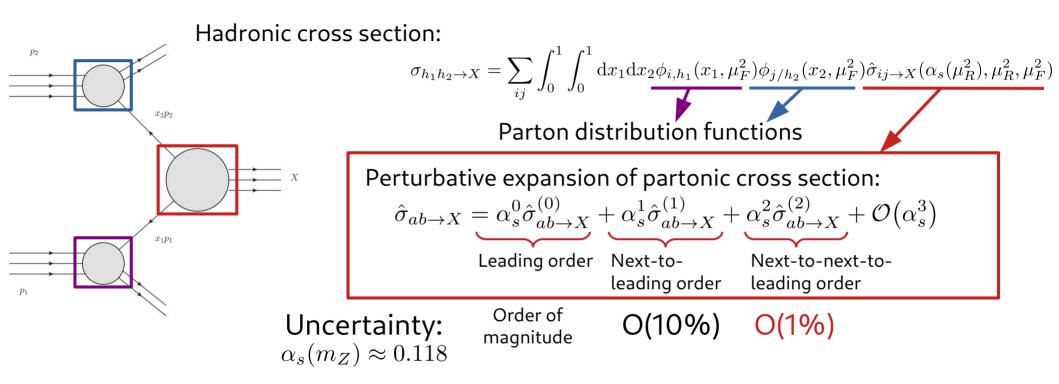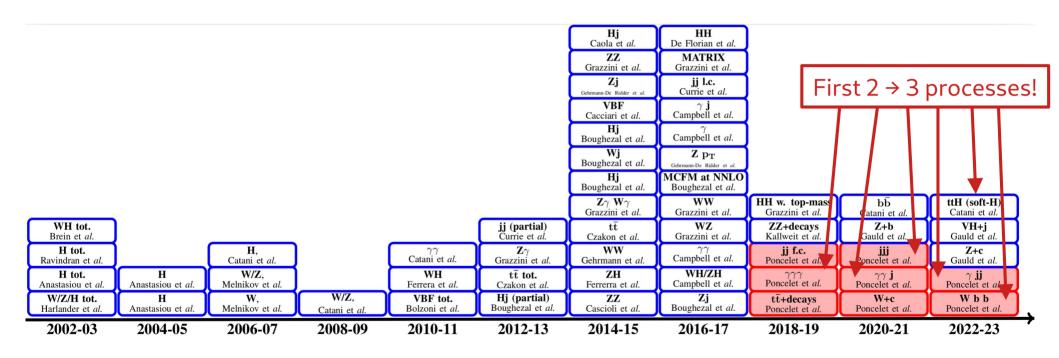
Precision through higher orders

Hadronic cross section:

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

Parton distribution functions

Perturbative expansion of partonic cross section:

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

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!

The NNLO QCD revolution

First 2 → 3 processes!

2002-03	2004-05	2006-07	2008-09	2010-11	2012-13	2014-15	2016-17	2018-19	2020-21	2022-23
						Hj Caola et *al.*	**HH** De Florian et *al.*			
						ZZ Grazzini et *al.*	**MATRIX** Grazzini et *al.*			
						Zj Gehrmann-De Ridder et *al.*	**jj l.c.** Currie et *al.*			
						VBF Cacciari et *al.*	γ **j** Campbell et *al.*			
						Hj Boughezal et *al.*	γ Campbell et *al.*			
						Wj Boughezal et *al.*	**Z** p_T Gehrmann-De Ridder et *al.*			
						Hj Boughezal et *al.*	**MCFM at NNLO** Boughezal et *al.*			
						Zγ **W**γ Grazzini et *al.*	**WW** Grazzini et *al.*	**HH w. top-mass** Grazzini et *al.*	**b**$\bar{\text{b}}$ Catani et *al.*	**ttH (soft-H)** Catani et *al.*
WH tot. Brein et *al.*					**jj (partial)** Currie et *al.*	**t**$\bar{\text{t}}$ Czakon et *al.*	**WZ** Grazzini et *al.*	**ZZ+decays** Kallweit et *al.*	**Z+b** Gauld et *al.*	**VH+j** Gauld et *al.*
H tot. Ravindran et *al.*		**H,** Catani et *al.*		$\gamma\gamma$ Catani et *al.*	**Z**γ Grazzini et *al.*	**WW** Gehrmann et *al.*	$\gamma\gamma$ Campbell et *al.*	**jj f.c.** Poncelet et *al.*	**jjj** Poncelet et *al.*	**Z+c** Gauld et *al.*
H tot. Anastasiou et *al.*	**H** Anastasiou et *al.*	**W/Z,** Melnikov et *al.*		**WH** Ferrera et *al.*	**t**$\bar{\text{t}}$ **tot.** Czakon et *al.*	**ZH** Ferrerra et *al.*	**WH/ZH** Campbell et *al.*	$\gamma\gamma\gamma$ Poncelet et *al.*	$\gamma\gamma$ **j** Poncelet et *al.*	γ **jj** Poncelet et *al.*
W/Z/H tot. Harlander et *al.*	**H** Anastasiou et *al.*	**W,** Melnikov et *al.*	**W/Z,** Catani et *al.*	**VBF tot.** Bolzoni et *al.*	**Hj (partial)** Boughezal et *al.*	**ZZ** Cascioli et *al.*	**Zj** Boughezal et *al.*	**t**$\bar{\text{t}}$**+decays** Poncelet et *al.*	**W+c** Poncelet et *al.*	**W b b** Poncelet et *al.*

Example: strong coupling & multi-jets

ATLAS

Particle-level TEEC

$\sqrt{s}$ = 13 TeV; 139 fb^{-1}

anti-k$_t$ R = 0.4

p$_T$ > 60 GeV

$|\eta|$ < 2.4

$\mu_{R,F} = \hat{H}_T$

$\alpha_s(m_Z)$ = 0.1180
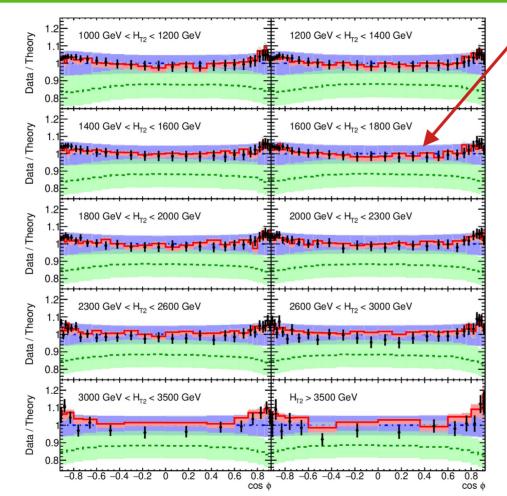
NNPDF 3.0 (NNLO)

- ● Data
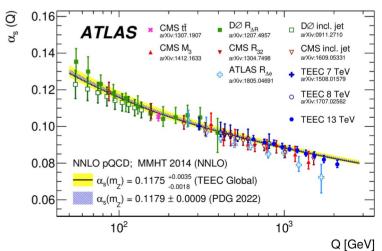- - - - LO
- - · - NLO
- ▬ NNLO

NNLO QCD for three jets

- *Czakon, Mitov,* ***Poncelet***
  Phys.Rev.Lett. 127 (2021) 15, 152001
- *Alvarez, Cantero, Czakon, Llorente, Mitov,*
  Poncelet JHEP 03 (2023) 129

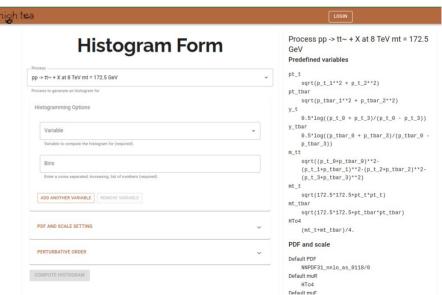## ATLAS: α_s extraction

- [2301.09351]

HighTEA: High energy Theory Event Analyser

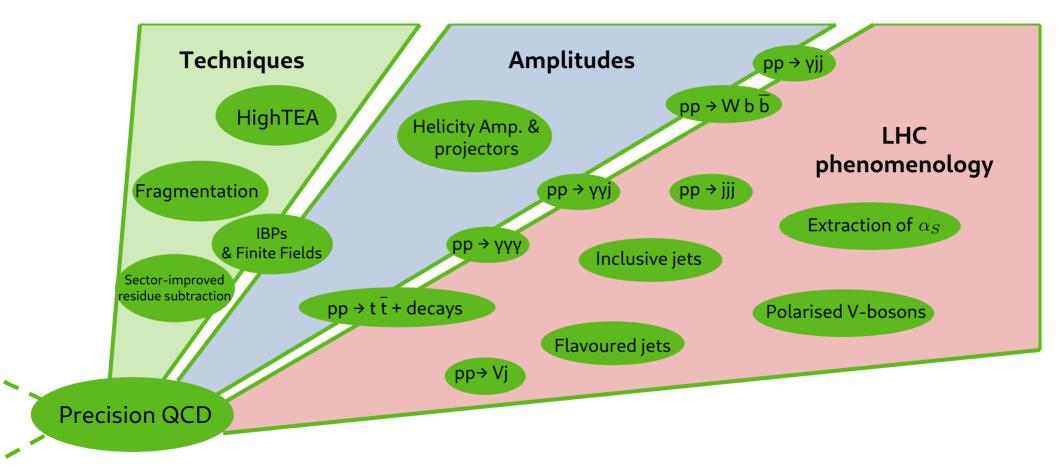Czakon, Kassabov, Mitov, **Poncelet**, Popescu
[2304.05993]

- Highly efficient higher order computations through re-weighting techniques

- Easy user interface

- Many applications:
  → User defined observables
  → PDF fits
  → SMEFT constraints
  → Outreach

- Public online access:
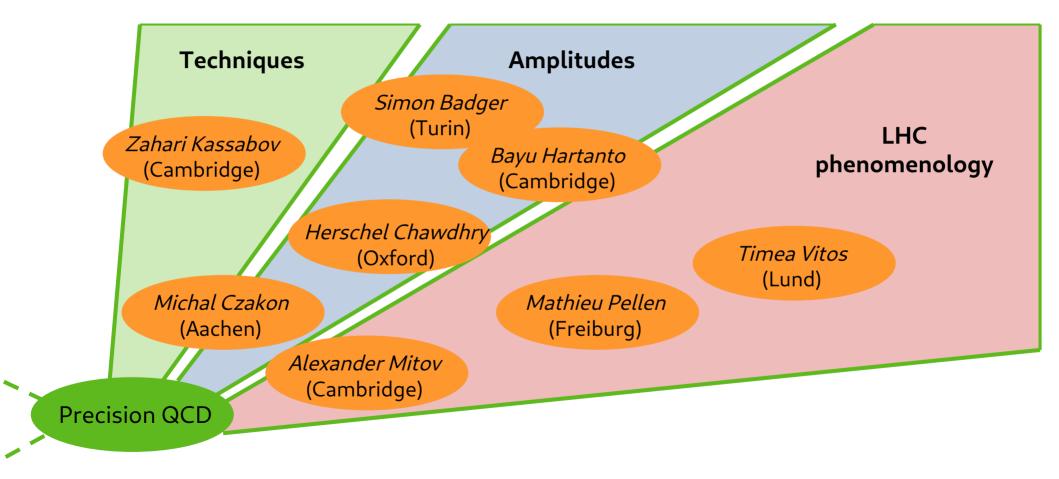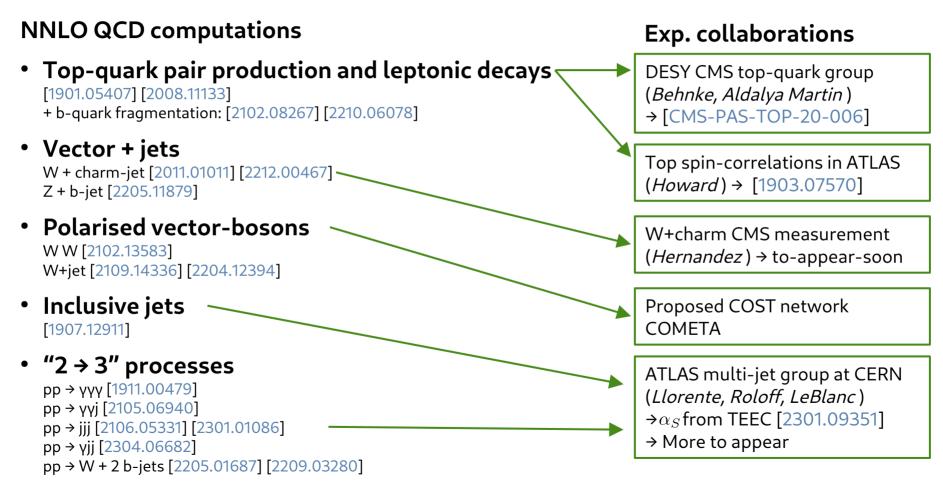
https://www.precision.hep.phy.cam.ac.uk/hightea

Research context

Research network

Rene Poncelet

Experimental collaborations

NNLO QCD computations

- **Top-quark pair production and leptonic decays**
  [1901.05407] [2008.11133]
  + b-quark fragmentation: [2102.08267] [2210.06078]

- **Vector + jets**
  W + charm-jet [2011.01011] [2212.00467]
  Z + b-jet [2205.11879]

- **Polarised vector-bosons**
  W W [2102.13583]
  W+jet [2109.14336] [2204.12394]

- **Inclusive jets**
  [1907.12911]

- **"2 → 3" processes**
  pp → γγγ [1911.00479]
  pp → γγj [2105.06940]
  pp → jjj [2106.05331] [2301.01086]
  pp → γjj [2304.06682]
  pp → W + 2 b-jets [2205.01687] [2209.03280]

Exp. collaborations

DESY CMS top-quark group
(*Behnke, Aldalya Martin*)
→ [CMS-PAS-TOP-20-006]

Top spin-correlations in ATLAS
(*Howard*) → [1903.07570]

W+charm CMS measurement
(*Hernandez*) → to-appear-soon

Proposed COST network
COMETA

ATLAS multi-jet group at CERN
(*Llorente, Roloff, LeBlanc*)
→ α_S from TEEC [2301.09351]
→ More to appear

Future directions

**The provider for
precision QCD predictions**

→ extending process portfolio
→ branching out to other colliders
→ development of public tool like HighTEA
→ towards full higher-order event simulations

Experimental communities
LHC, EIC, RHIC, FCC (-ee,-hh,-eh)

Theory/Amplitudes
community

Increasing interest also here at the IFJ PAN

Near future projects

Modern MC integration/sampling

- Interdisciplinary work with
  Steffen Schumann (Göttingen) & *David Yallup* (Kalvi Institute Cambridge)

- 1) "Nested sampling"   → phase space explorations
  2) "Normalising flows" → phase space sampler using Neural Networks

NNLO with massive bosons: V + 2-jet, VV + 1-jet

- A lot to do: amplitudes + cross sections → rich phenomenology!

N3LO QCD for 2 → 2 processes

- First with slicing methods then towards local N3LO subtraction schemes
  (→ *Sebastian Sapeta* (Cracow))

Summary