incomplete draft of 2019-05-07
comments welcome

Theoretical path for QCD physics

Gavin Salam*
University of Oxford and All Souls College

Open Symposium – Update of the European Strategy for Particle Physics
Granada, May 2019

* *on leave from CERN TH department and from CNRS (LPTHE)*

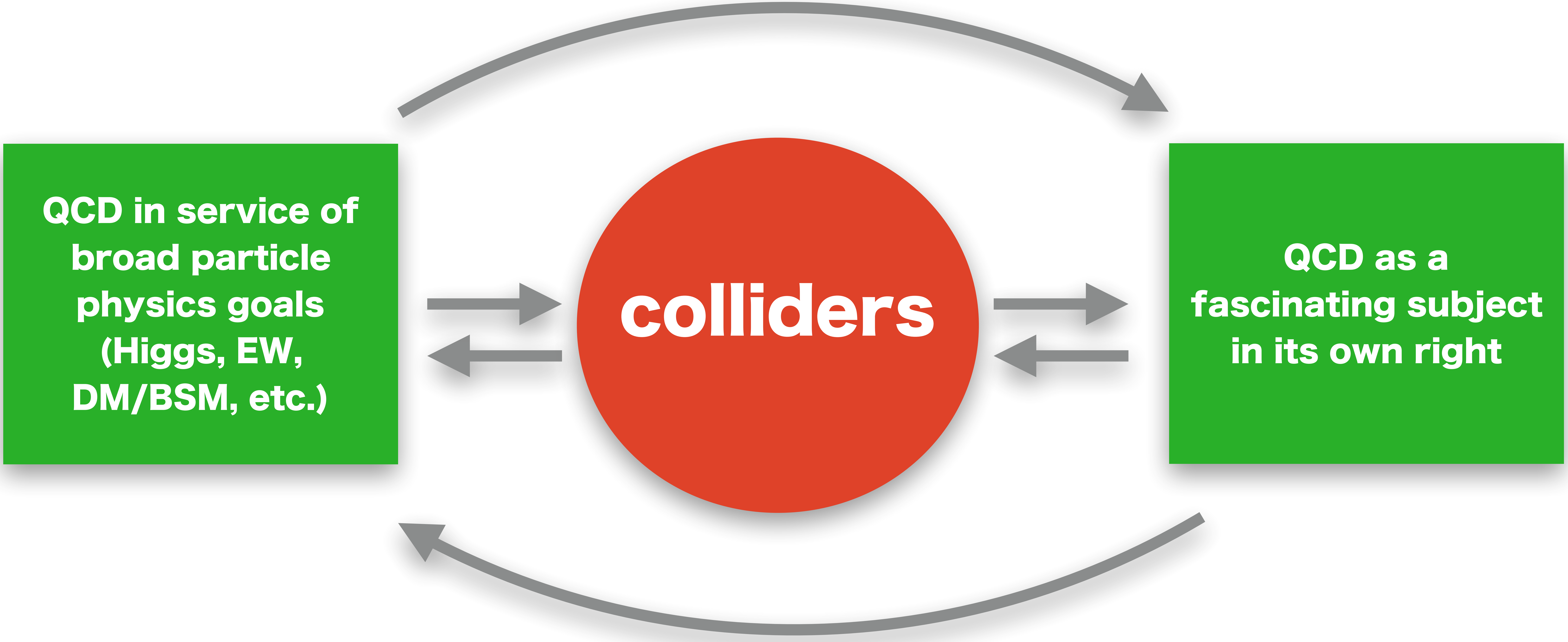
European Research Council
Established by the European Commission

THE ROYAL SOCIETY

Theoretical path for QCD physics: main inputs

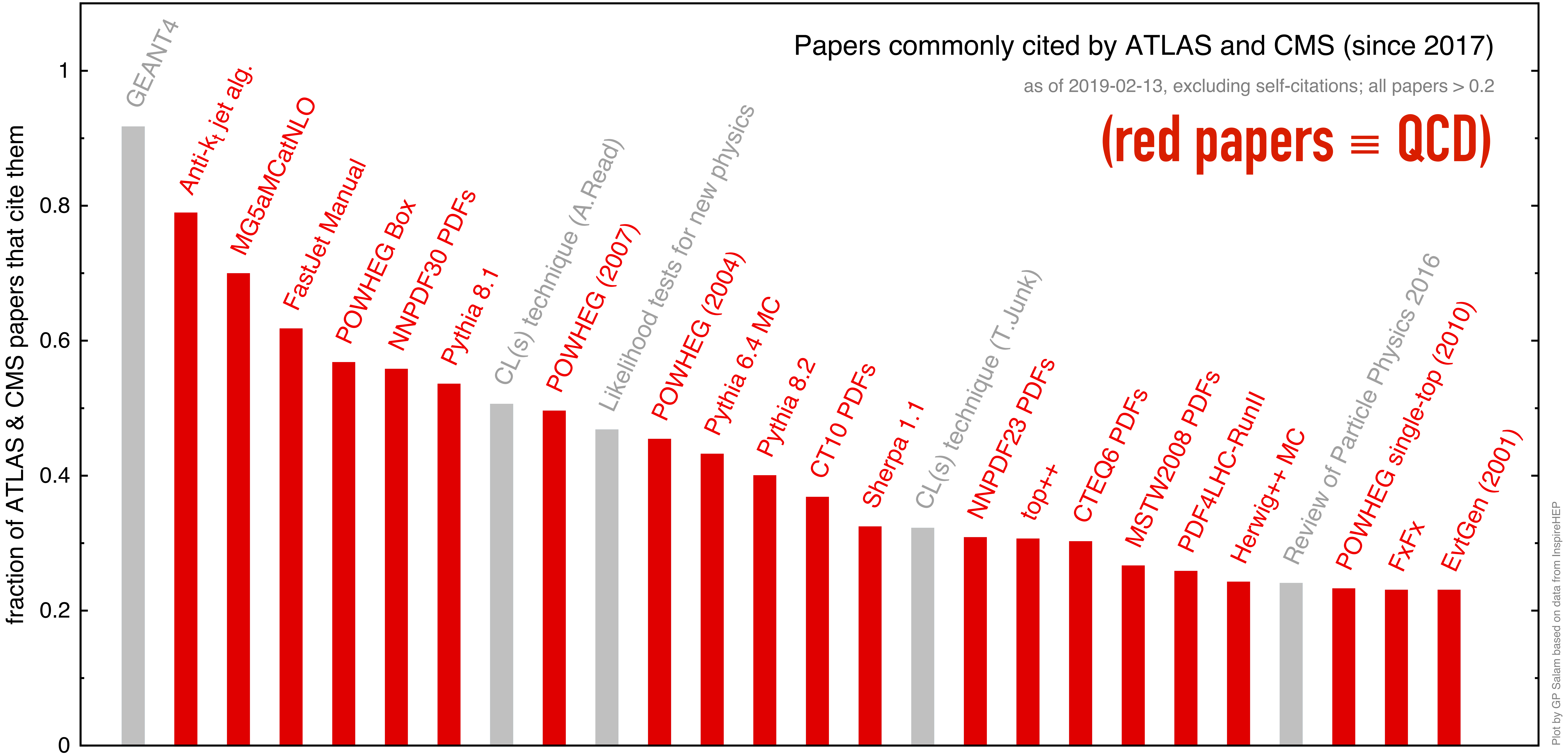
Id100	Precision calculations for high-energy collider processes
Id101	Theory Requirements and Possibilities for [ee colliders]
Id114	MC event generators for HEP physics event simulation
Id163	Quantum Chromodynamics: Theory

two broad roles for QCD



to maximally exploit HL-LHC

QCD theory is workhorse of LHC experiments



Need for precision @ HL-LHC

- illustrated in the case of Higgs physics
- theory uncertainty (PDF + strong coupling + missing higher orders) dominates in 7/9 channels
- this is **with the assumption of reduction by x2 in today's uncertainties**
- depending on channel, it can be the uncertainties for the signal or the background that dominates.

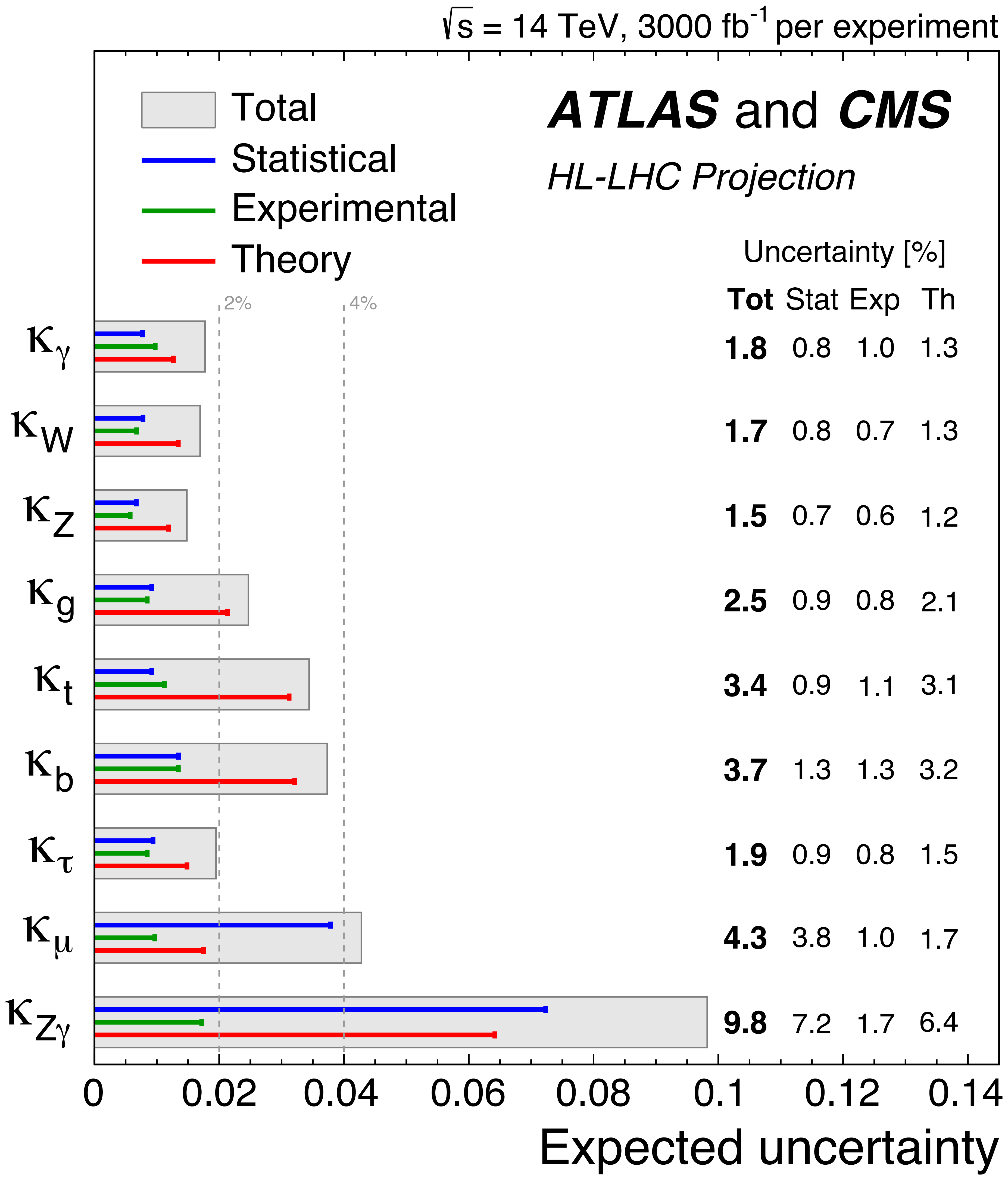


Figure 1. Projected uncertainties on κ_i, combining ATLAS and CMS: total (grey box), statistical (blue), experimental (green) and theory (red). From Ref. [2].

QCD theory anticipated / needed for full exploitation of HL-LHC

(1) Fixed-order / resummed calculations

- Core processes at high accuracy (2→1 and 2→2): 1%, N3LO
- Splitting functions at N3LO *(also needed for potential ep machines)*
- Complex processes at few percent accuracy
- Accuracy at high p_T
- Technical requirements for NLO multi-particle precision
- Multi-variate analyses / observables: performance and uncertainties
- Non-perturbative effects
- Resummation (incl. SCET)
- Accurate predictions for BSM effects

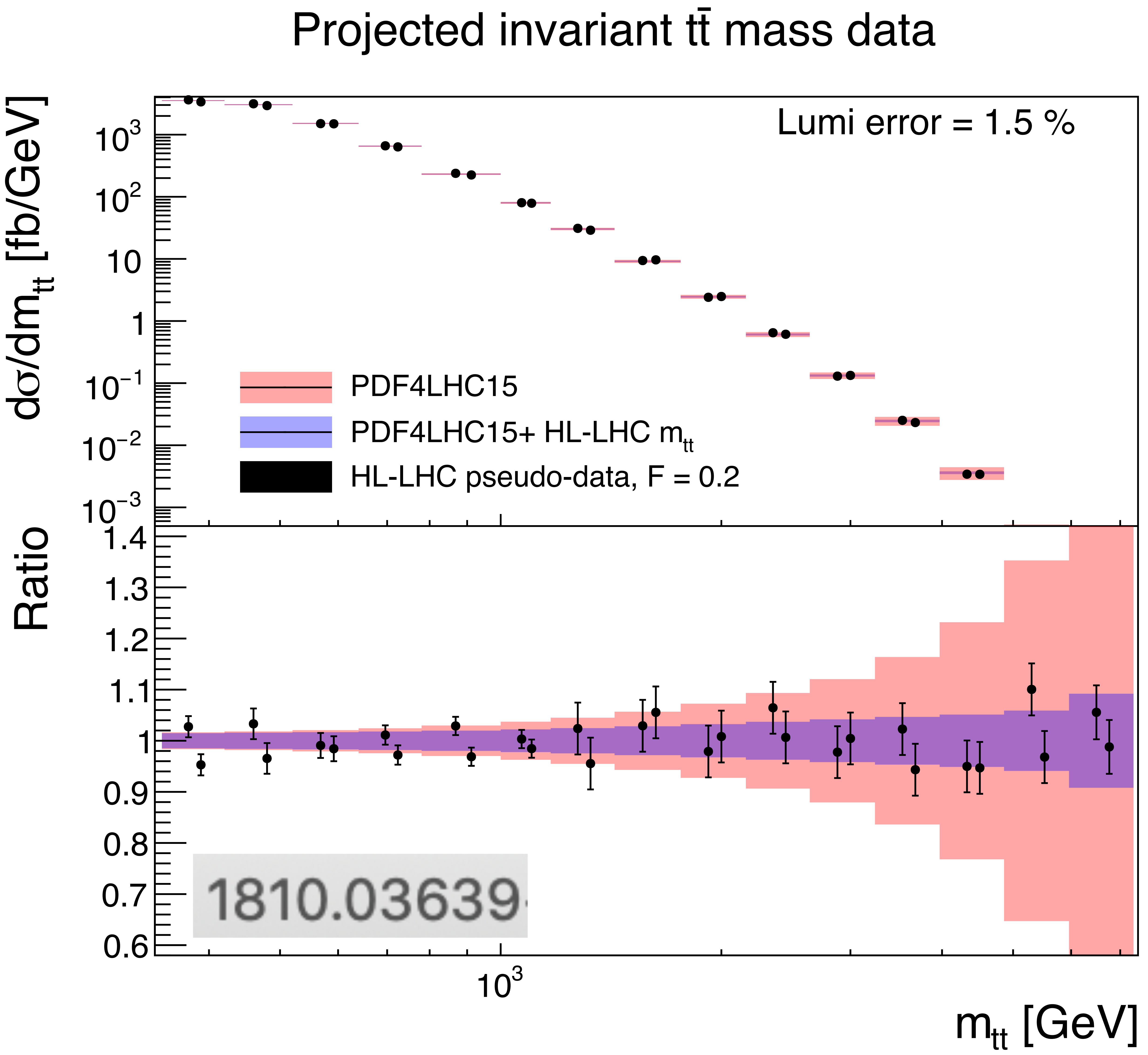
QCD theory anticipated / needed for full exploitation of HL-LHC

(2) General purpose Monte Carlo event-generator tools

- Perturbative improvements for Matching and Merging (e.g. generalisation of approaches for parton shower + NNLO merging,)
- Understanding & exploiting relation between parton-shower algorithms and resummation
- Phenomenological Models (hadronisation, underlying event, **also connects with HI physics, neutrino programmes, low energy QCD, various "beyond colliders" experiments, cosmic-ray physics**)

projected improvements in PDFs & strong coupling

- plot illustrates use of pseudodata with HL-LHC stats to obtain estimates of expected PDF uncertainties at HL-LHC
- PDF extractions will need to move to N3LO once available
- strong coupling remains contentious
  - tensions between different groups' extractions (PDFs, event shapes, and to a lesser extent lattice QCD)
  - what ultimate accuracy on 10-15 year timescae?



low-energy QCD theory

- e.g. for flavour→ see talks in flavour session
- for hadron structure → see lattice talk (Wittig) in this session

to maximally exploit proposed future colliders (ee, eh, hh)

future e+e- colliders

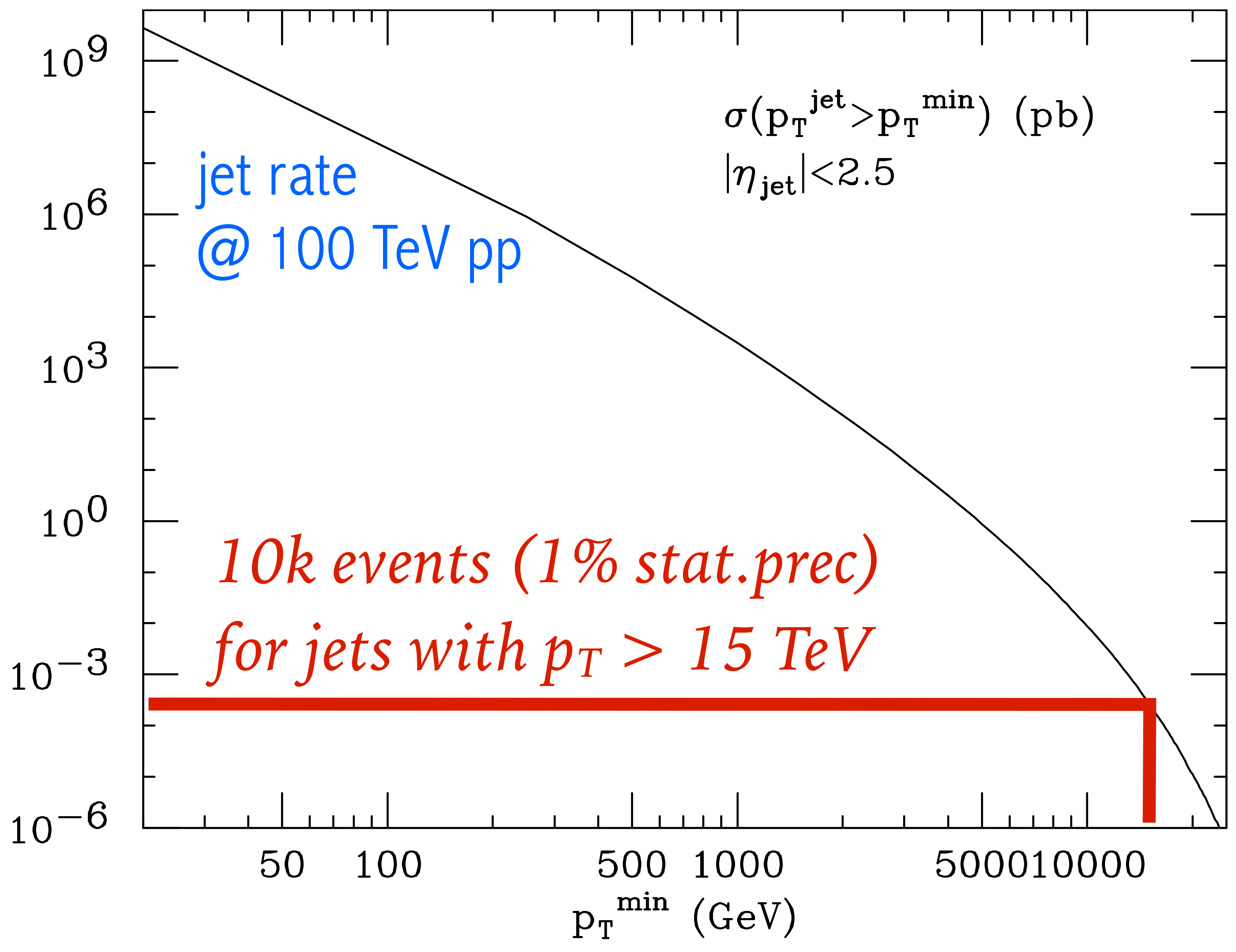
- 3-loop and partial 4-loop calculations of Zff vertex for Tera-Z for EW pseudo-observables
- precision for decays, e.g. in Higgs physics and top-quark physics
- new generations of MC programs for QED and EW effects, understanding two-photon physics

	$\delta\Gamma_Z$ [MeV]	δR_l $[10^{-4}]$	δR_b $[10^{-5}]$	$\delta \sin^{2,l}_{eff} \theta$ $[10^{-6}]$
Present EWPO theoretical uncertainties				
EXP-2018	2.3	250	66	160
TH-2018	0.4	60	10	45
EWPO theoretical uncertainties when FCC-ee will start				
EXP-FCC-ee	0.1	10	$2 \div 6$	6
TH-FCC-ee	0.07	7	3	7

Table 1: *Comparison for selected precision observables of present experimental measurements (EXP-2018), current theory errors (TH-2018), FCC-ee precision goals at the end of the Tera-Z run (EXP-FCC-ee) and rough estimates of the theory errors assuming that electroweak 3-loop corrections and the dominant 4-loop EW-QCD corrections are available at the start of FCC-ee (TH-FCC-ee). Based on discussion in [2].*

future pp colliders

- combination of higher energies and luminosities will continue to push potential for precision
- need for precision will extend to high transverse momenta → requires improved treatment of EW corrections, including mixed QCD-EW effects



- very high-multiplicity final states, possibly involving multiple scales → needs understanding of regions of validity of perturbation theory, interplay with parton showers, etc., including for EW objects

QCD as the object of study

QCD as object of study in its own right

Many directions of theoretical work, which go hand-in-hand with corresponding planned experimental programmes

- **structure of hadrons** (more info e.g. in other talks in this session)
  - generalised parton distributions (GPDs)
  - double parton distributions (DPDs $\leftrightarrow$ multiparton interactions in MC event generators)
  - small-x & saturation (including connections with nuclear structure)
  - low momentum transfer scattering (e.g. for forward physics, cosmic ray fragmentation)
  - spin
- **exotic hadrons**
- **connections with formal theory** (e.g. structures of amplitudes N=4 SUSY, supergravity, etc., understanding special observables like energy-energy-correlations)

resources & the next generation

issues of long-term support

- many of the problems involve long-term efforts with increasingly large collaborations
  - ensure funding for projects that last longer than typical funding cycles
- support for codes:
  - state-of-the-art physics codes, often developed in small groups, but long-term maintenance needs dedicated efforts
  - the “glue” codes (e.g. LHAPDF, HepMC): may not be seen as “physics” by funding agencies, but support & evolution essential for long-term smooth operation of the field
- computing aspects
  - adapting codes to new architectures
  - availability of state-of-the-art hardware (e.g. hundreds of GPUs, very high-memory machines)
  - many university groups can’t afford to keep up with disparate landscape of hardware. How best to share nationally and internationally?

development paths for incoming / early-stage researchers

- early-stage researchers need recognition for a variety of types of contribution (e.g. including the technical work that simply "makes things work" but that comes neither with glory nor even necessarily papers)
- how do we ensure recognition for early-stage researchers working within the medium-sized teams ($O(10)$ researchers) that are increasingly common?
- specialisation v. broad training
  - successful projects need skills that span interface with maths (incl. computer algebra), interface with computing, machine-learning, and a range of physics/pheno applications → **individuals specialise**
  - at same time we need to ensure future generation can combine specific expertise with broad physics ability within the field

Summary

QCD theory summary

- Advances in QCD theory are essential to exploit HL-LHC and future colliders (and already built into some projections!)
- They will involve a wide range of topics, spanning calculations of amplitudes to Monte Carlo event generations, including phenomenological work to connect with data
- Theory advance can bring light also on many topics of intrinsic interest in QCD, including proton structure, exotic hadrons, connections with "theorists's theories" like N=4 SUSY
- Continued support of QCD theory is essential for success of European collider programme, and community needs to keep in mind
  - recognition of contributions of early-stage researchers as teams grow larger
  - funding support for increasingly long-term theory projects
  - computing (access to hardware and expertise)

backup

gluon fusion Higgs theory uncertainties

1902.00134.

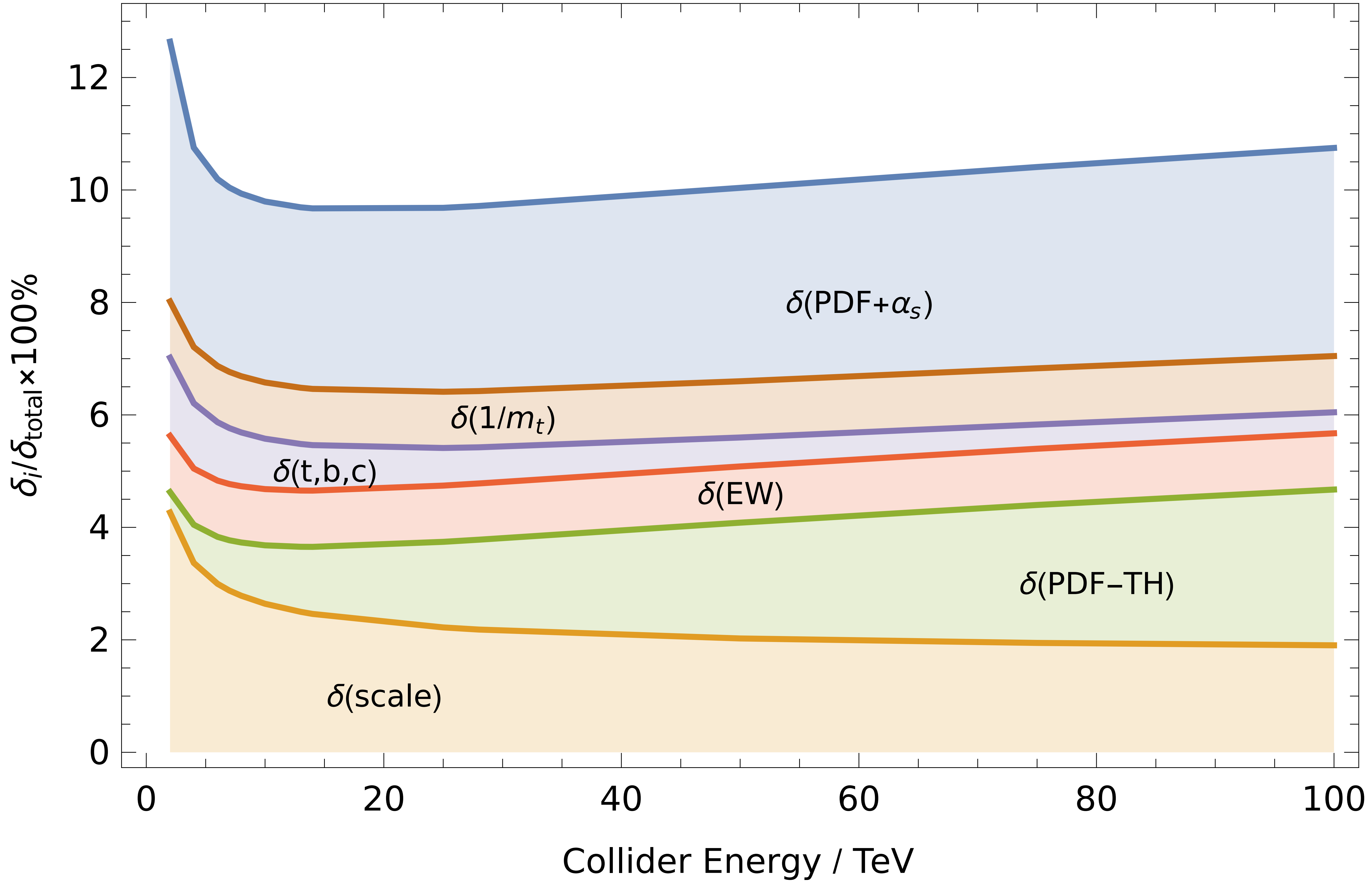


Fig. 1: The figure shows the linear sum of the different sources of relative uncertainties as a function of the collider energy. Each coloured band represents the size of one particular source of uncertainty as described in the text. The component $\delta(\mathrm{PDF} + \alpha_S)$ corresponds to the uncertainties due to our imprecise knowledge of the strong coupling constant and of parton distribution functions combined in quadrature.