[Precision QCD] Physics Input to European Strategy Update

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Joint Snowmass 2021 EF05 / EF06 / EF07 Topical Group Meeting

(Precision QCD / Hadronic Structure & Forward QCD / Heavy Ions)

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

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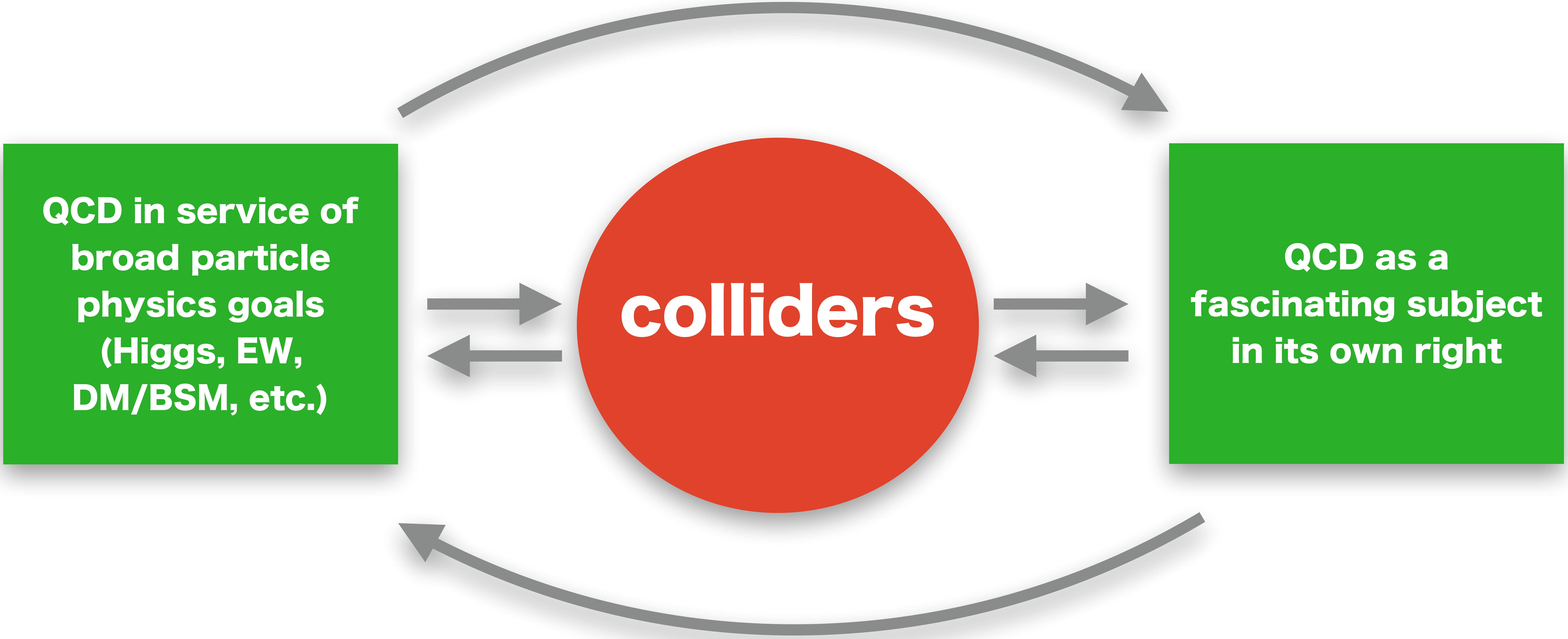
European Particle Physics Strategy Update (EPPSU), 2018 – 2020

- http://europeanstrategyupdate.web.cern.ch/welcome
- Major preparatory work on approved and proposed future colliders, e.g.
  - Report on the Physics at the HL-LHC, and Perspectives for the HE-LHC
  - FCC physics and design reports
- Submitted input: https://indico.cern.ch/event/765096/contributions/ (10pp/doc)
- Open Symposium (May 2019), including strong interactions session & summary
- Physics briefing book: arXiv:1910.11775 (strong interactions: section 4)
- January 2020: final closed meeting of European Strategy Group
- Strategy Approval: still ongoing

Time	Session	Speaker	Location	Slot
09:00	Scientific aspirations of the community in strong interactions	Thomas Gehrmann	Albeniz+Machuca Room, Granada Conference Center	09:00 - 09:20
	Discussion		Albeniz+Machuca Room, Granada Conference Center	09:20 - 09:30
	Experimental QCD physics at future pp and e+e- colliders	David d'Enterria	Albeniz+Machuca Room, Granada Conference Center	09:30 - 09:50
	Discussion		Albeniz+Machuca Room, Granada Conference Center	09:50 - 10:00
10:00	Theoretical path for QCD physics	Gavin Salam	Albeniz+Machuca Room, Granada Conference Center	10:00 - 10:20
	Discussion		Albeniz+Machuca Room, Granada Conference Center	10:20 - 10:35
	Reserve		Albeniz+Machuca Room, Granada Conference Center	10:35 - 10:50
	Coffee break		Albeniz+Machuca Room, Granada Conference Center	10:50 - 11:15
11:00	Strong Interaction physics with the (HL-)LHC pre-accelerator complex	Gunar Schnell	Albeniz+Machuca Room, Granada Conference Center	11:15 - 11:45
	Discussion		Albeniz+Machuca Room, Granada Conference Center	11:45 - 12:00
12:00	Precision QCD physics at low energies	Klaus Kirch	Albeniz+Machuca Room, Granada Conference Center	12:00 - 12:20
	Discussion		Albeniz+Machuca Room, Granada Conference Center	12:20 - 12:30
	Lattice QCD: challenges and opportunities	Hartmut Wittig	Albeniz+Machuca Room, Granada Conference Center	12:30 - 12:50
	Discussion		Albeniz+Machuca Room, Granada Conference Center	12:50 - 13:00
13:00	Fixed Target opportunities at the (HL-)LHC	Jean-Philippe Lansberg	Albeniz+Machuca Room, Granada Conference Center	13:00 - 13:20
	Discussion		Albeniz+Machuca Room, Granada Conference Center	13:20 - 13:30

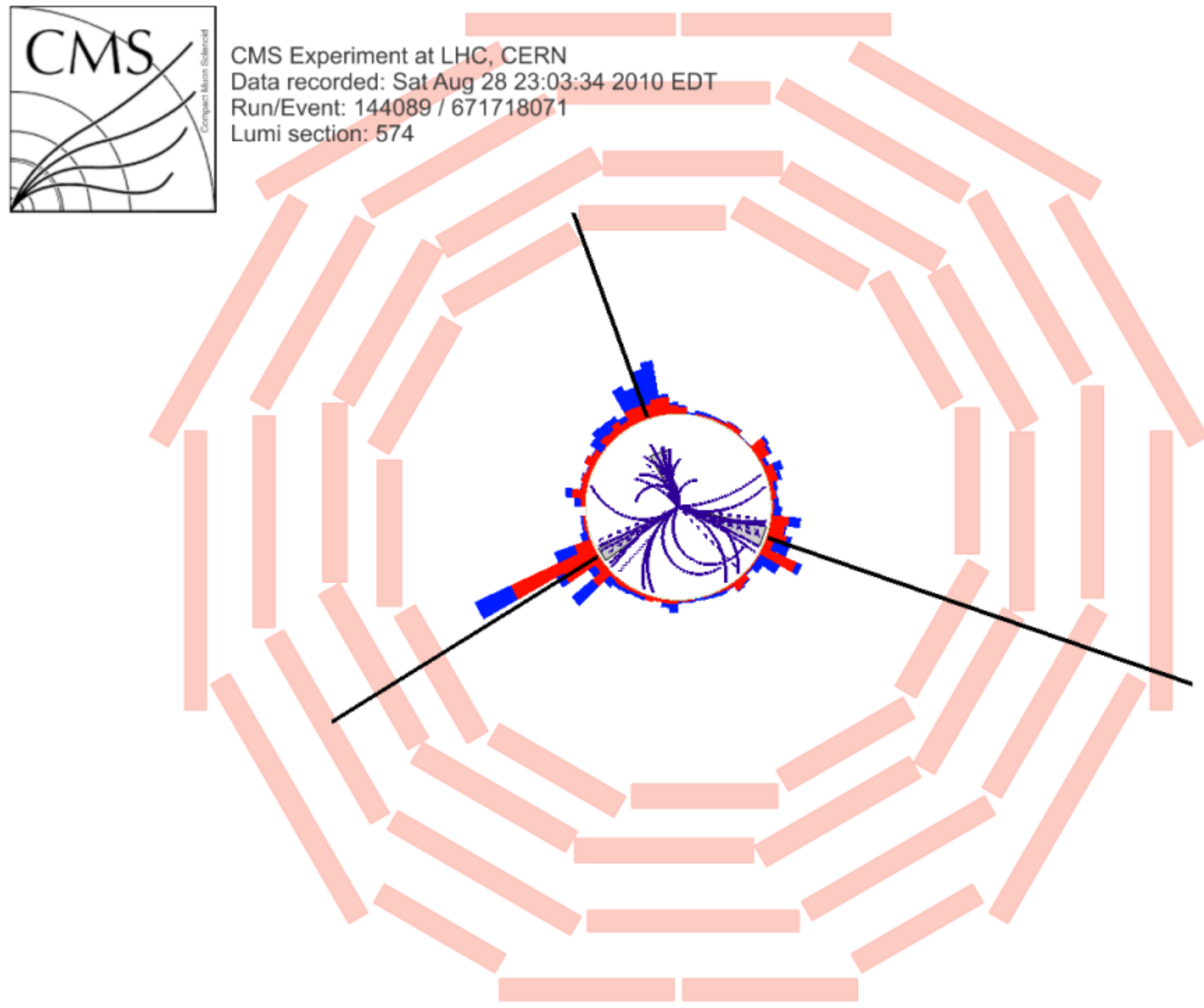
Time	Session	Speaker	Location	Slot
09:00	Theory challenges for Heavy Ion physics	Urs Wiedemann	Albeniz+Machuca Room, Granada Conference Center	09:00 - 09:20
	Discussion		Albeniz+Machuca Room, Granada Conference Center	09:20 - 09:30
	Heavy Ion collisions at (HL-)LHC	Johanna Stachel	Albeniz+Machuca Room, Granada Conference Center	09:30 - 09:50
	Discussion		Albeniz+Machuca Room, Granada Conference Center	09:50 - 10:00
10:00	Strong interaction physics at future eA colliders	Nestor Armesto Perez	Albeniz+Machuca Room, Granada Conference Center	10:00 - 10:20
	Discussion		Albeniz+Machuca Room, Granada Conference Center	10:20 - 10:30
	Reserve		Albeniz+Machuca Room, Granada Conference Center	10:30 - 10:45
	Coffee break		Albeniz+Machuca Room, Granada Conference Center	10:45 - 11:15
11:00	Emerging facilities around the world for strong interaction physics	Tetyana Galatyuk	Albeniz+Machuca Room, Granada Conference Center	11:15 - 11:35
	Discussion		Albeniz+Machuca Room, Granada Conference Center	11:35 - 11:45
	Synergies with astroparticle, nuclear and neutrino physics	Tanguy Pierog	Albeniz+Machuca Room, Granada Conference Center	11:45 - 12:05
12:00	Discussion		Albeniz+Machuca Room, Granada Conference Center	12:05 - 12:15
	Strong interaction physics at future ep colliders	Uta Klein	Albeniz+Machuca Room, Granada Conference Center	12:15 - 12:35
	Discussion		Albeniz+Machuca Room, Granada Conference Center	12:35 - 12:45
	What strong interaction physics can one do with the LHC after the HL-LHC?	Daniel Boer	Albeniz+Machuca Room, Granada Conference Center	12:45 - 12:55
13:00	Open discussion		Albeniz+Machuca Room, Granada Conference Center	12:55 - 13:15

two broad roles for QCD



Where do we stand?

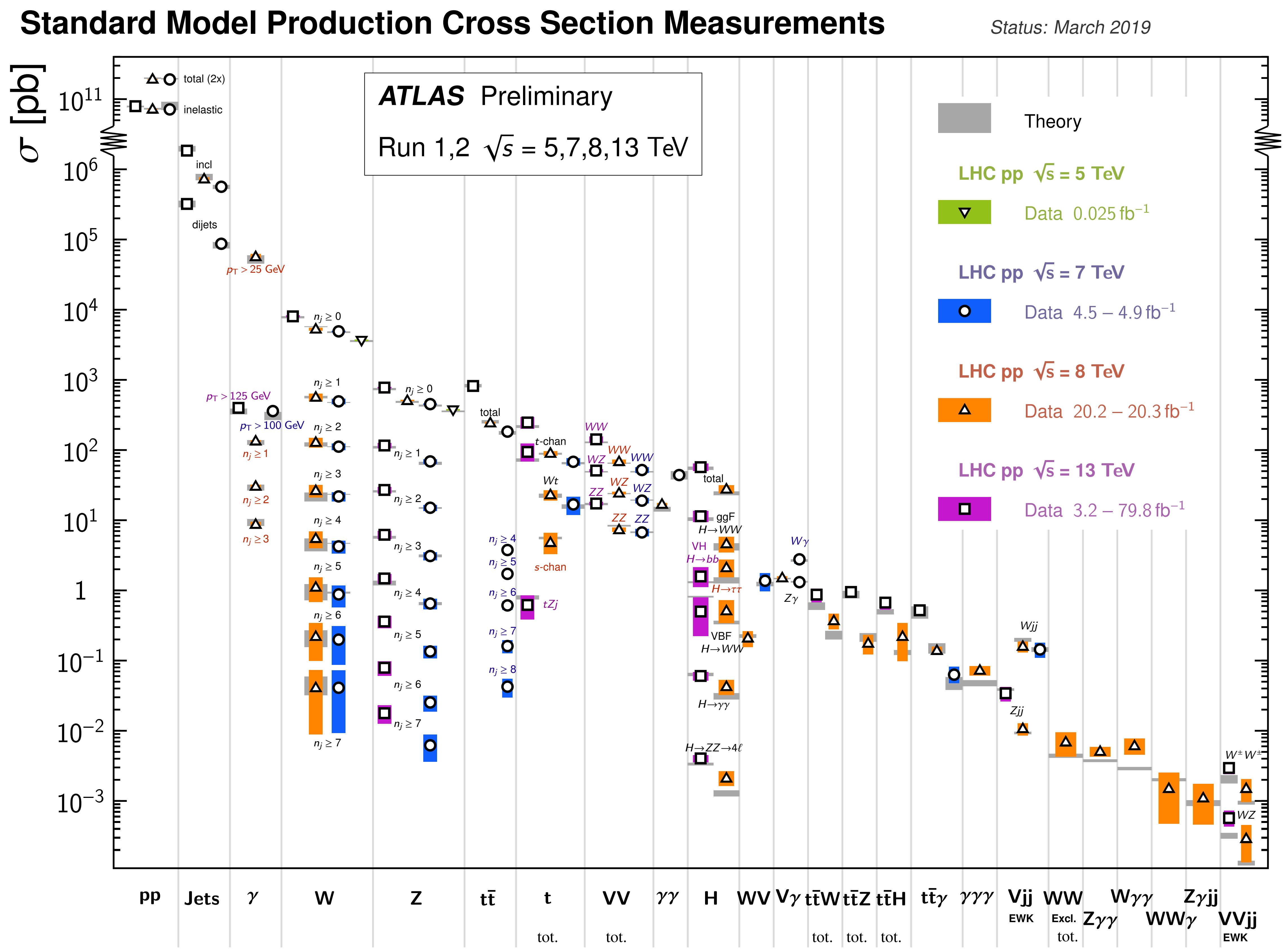
- QCD at high energies: weak coupling and asymptotic freedom
  - Perturbative QCD as quantitative framework
  - Dynamics of quarks and gluons
  - Jet observables were early test of QCD
  - Factorization separates weak from strong coupling effects



- Quantitative predictions
  - Multi-loop calculations for inclusive quantities
  - Higher orders (NLO, NNLO, …), resummation and parton shower simulation
  - Strong coupling dynamics parametrized in parton distributions, hadronization

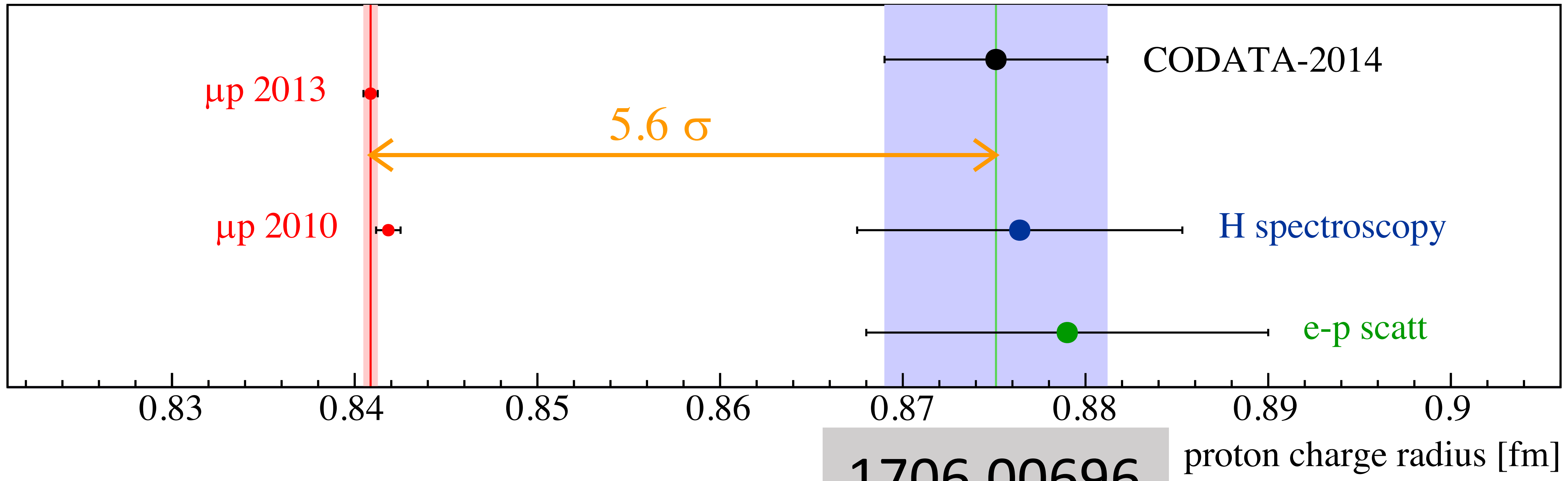
Where do we stand?

- Precision tests of the Standard Model
  - Measurements of masses and couplings
- Interplay of calculations and measurements
  - Accuracy on most cross sections ≳5%
  - Limited by PDFs, QCD corrections
- Perturbative QCD as analysis tool
  - Jet substructure techniques
  - Data-driven background predictions



Where do we stand?

- QCD at strong coupling: diverse research program
  - Hadron physics, low-energy dynamics, heavy ions
  - Precision spectroscopy of light hadrons ⟷ lattice QCD at high precision
  - Determination of hadron properties
    - Proton radius
    - Form factors
    - Nucleon structure



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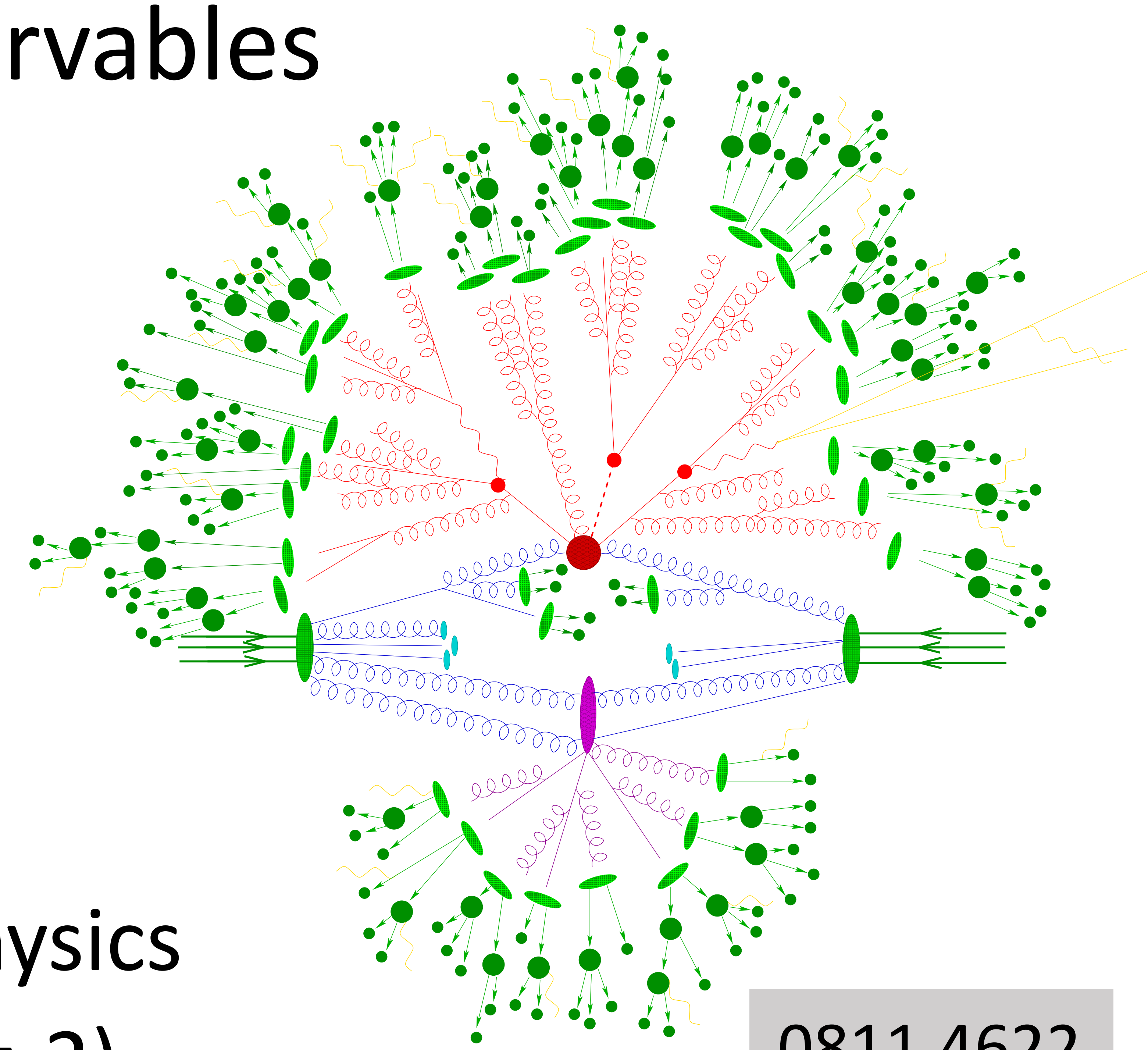
- Demands and drives new quantitative approaches
  - Understanding non-perturbative dynamics of QCD

Where do we stand?

- Crucial interplay between QCD at strong and at weak coupling
- Non-perturbative effects on precision collider observables
  - Parton distributions
  - Intrinsic transverse momentum
  - Soft underlying event and hadronization



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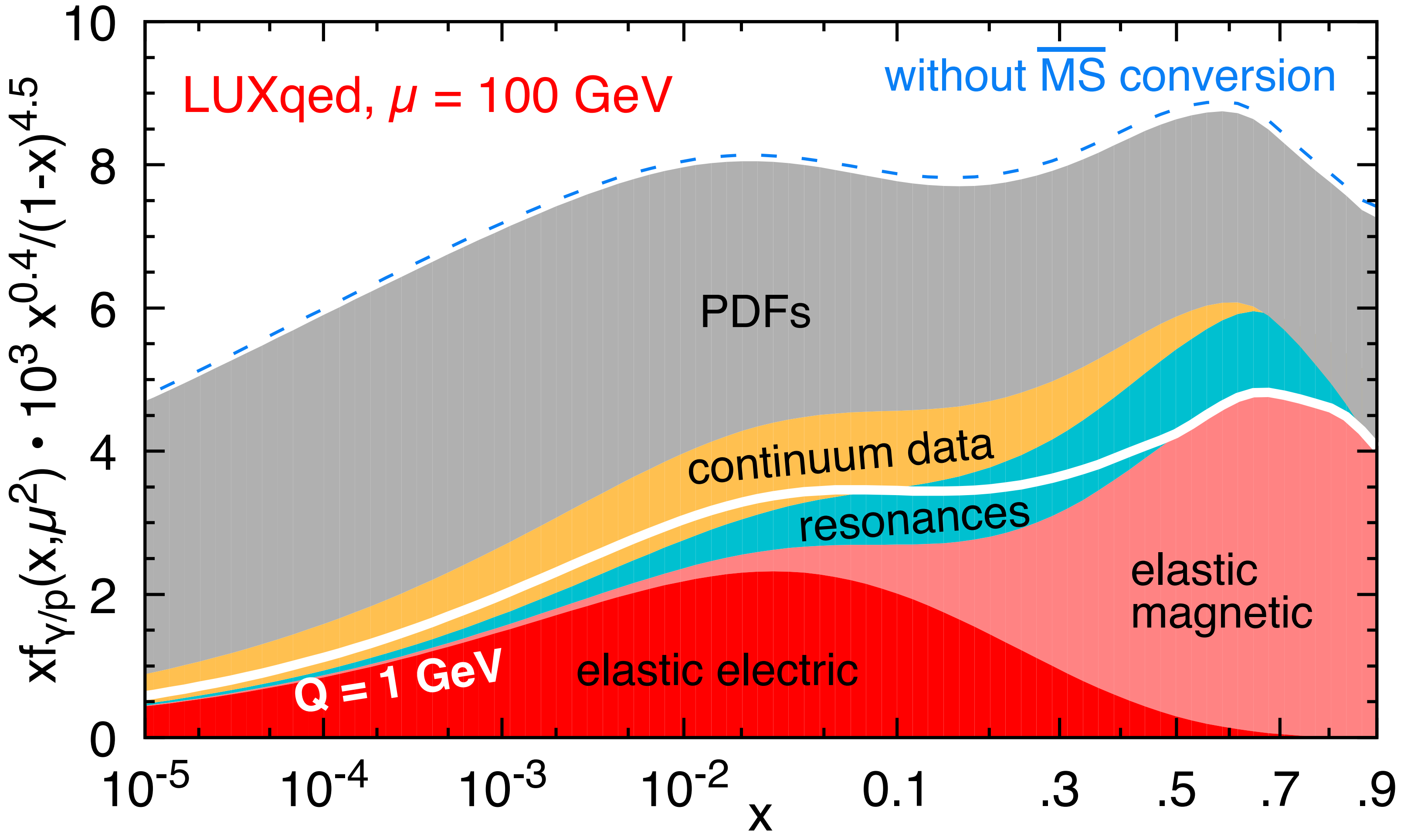
- Hadronic input to SM tests and BSM searches
  - Form factors in flavor physics
  - Hadronic cross sections in neutrino and astroparticle physics
  - Hadronic effects in QED precision observables: $\alpha(M_Z)$, $(g\text{-}2)_\mu$

Where do we stand?

- Feed-in and feed-back between strong and weak coupling QCD
- Example: photon content of the proton (photon PDF)
  - Important ingredient to EW corrections of collider processes
  - Required for precision predictions at highest energies
  - Previously ad-hoc models with large uncertainty
  - LUXqed
    - relate to elastic and inelastic form factors
    - Exploit low-energy data
    - Combine with perturbative QCD evolution
- Different motivation to address similar questions



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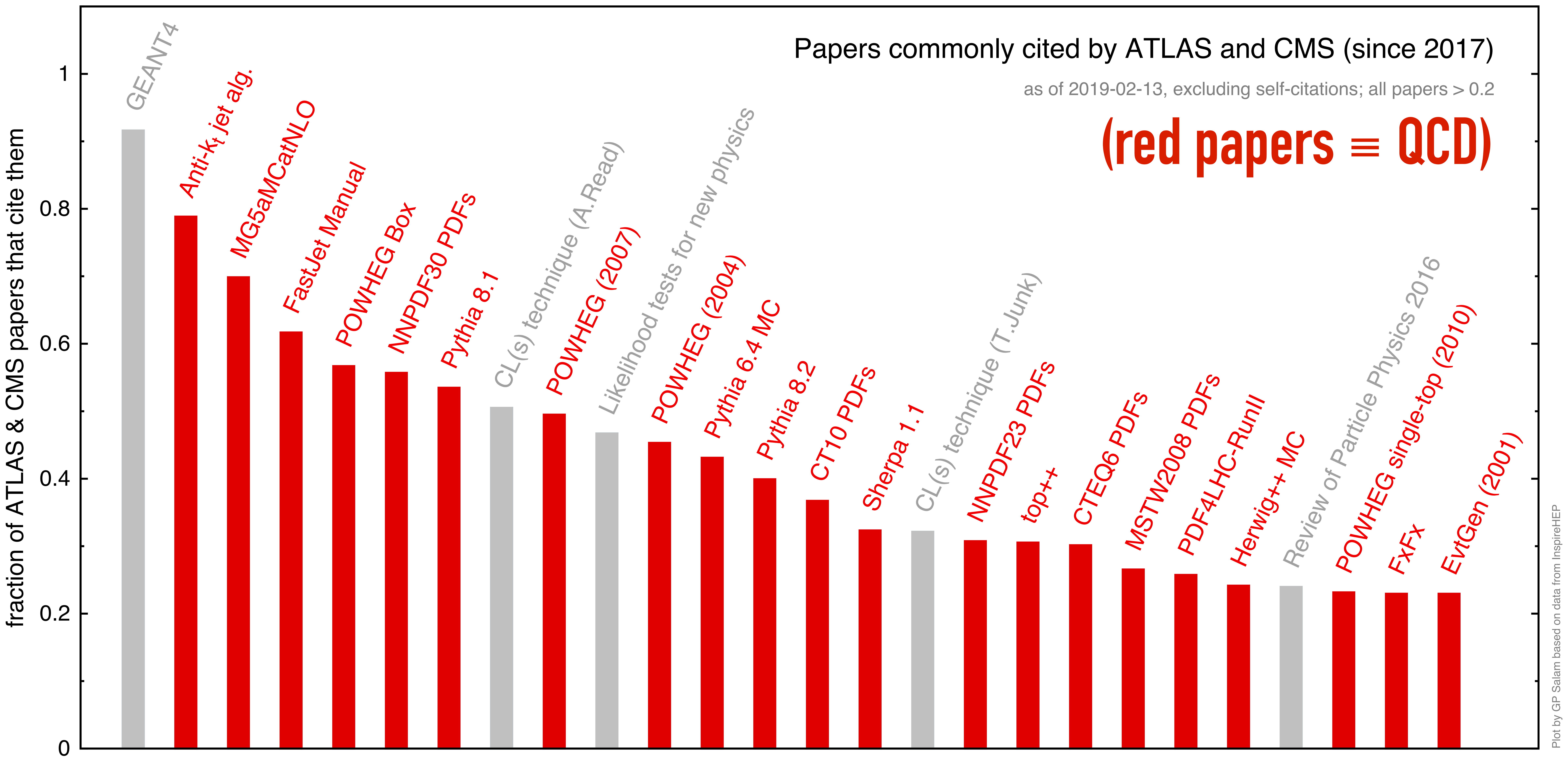
to maximally exploit HL-LHC

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.

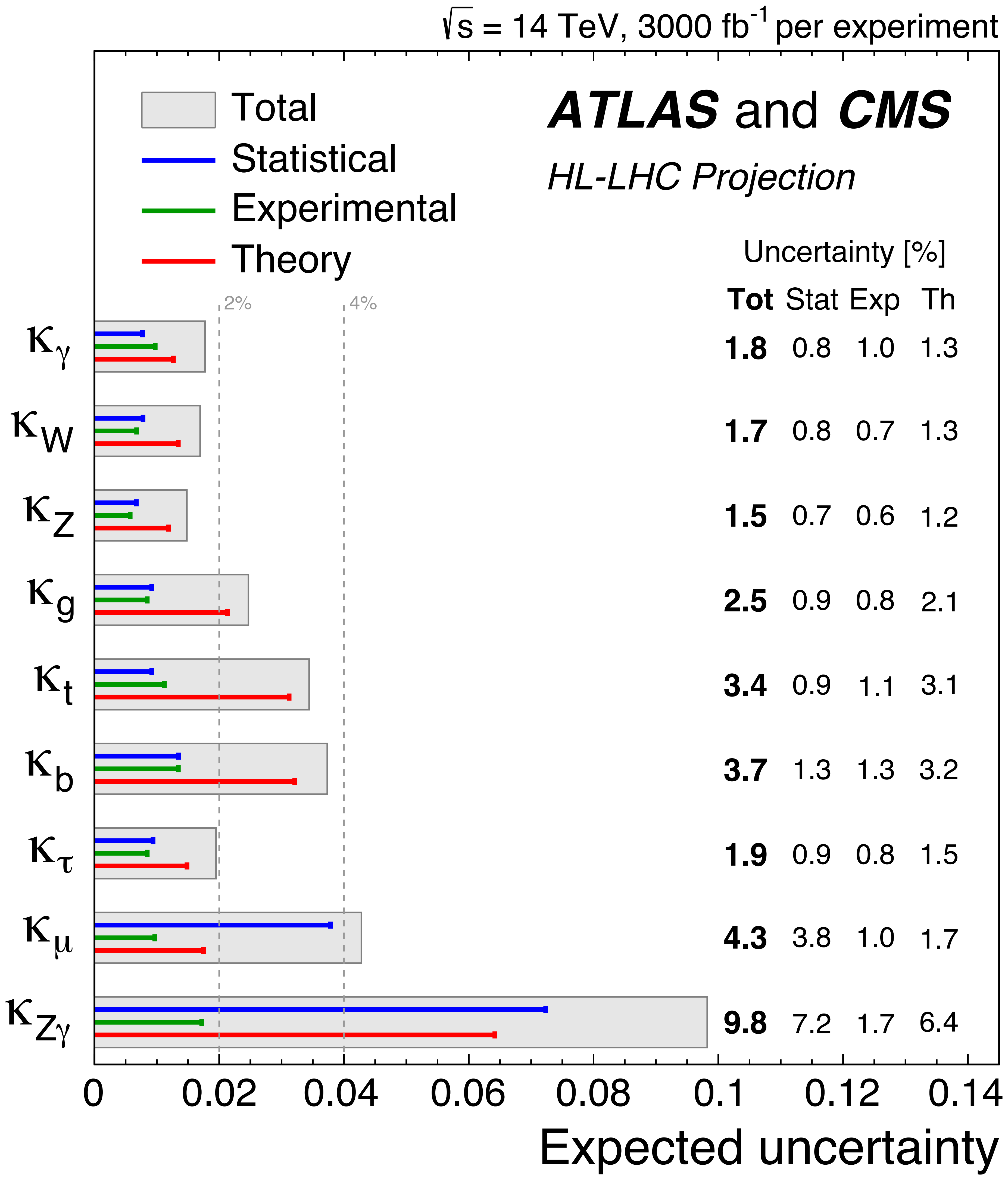


Figure 1. Projected uncertainties on κ_i, combining ATLAS and CMS: total (grey box), statistical (blue), experimental (green) and theory (red). From Ref. [2].

gluon fusion Higgs theory uncertainties

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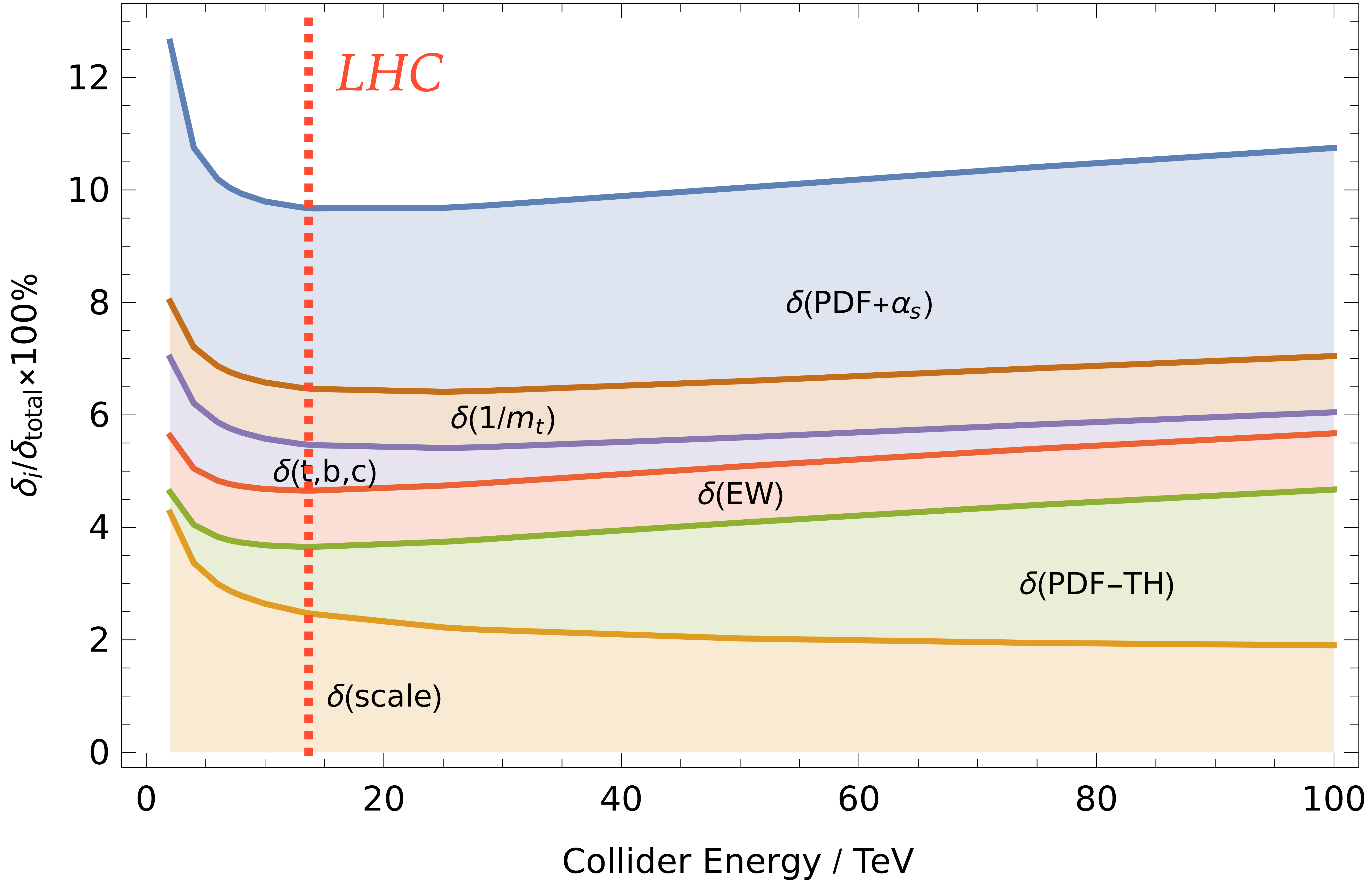


Fig. 1: The figure shows the linear sum of the different sources of relative uncertainties as a function of the collider energy. Each coloured band represents the size of one particular source of uncertainty as described in the text. The component $\delta(\mathrm{PDF} + \alpha_S)$ corresponds to the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

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

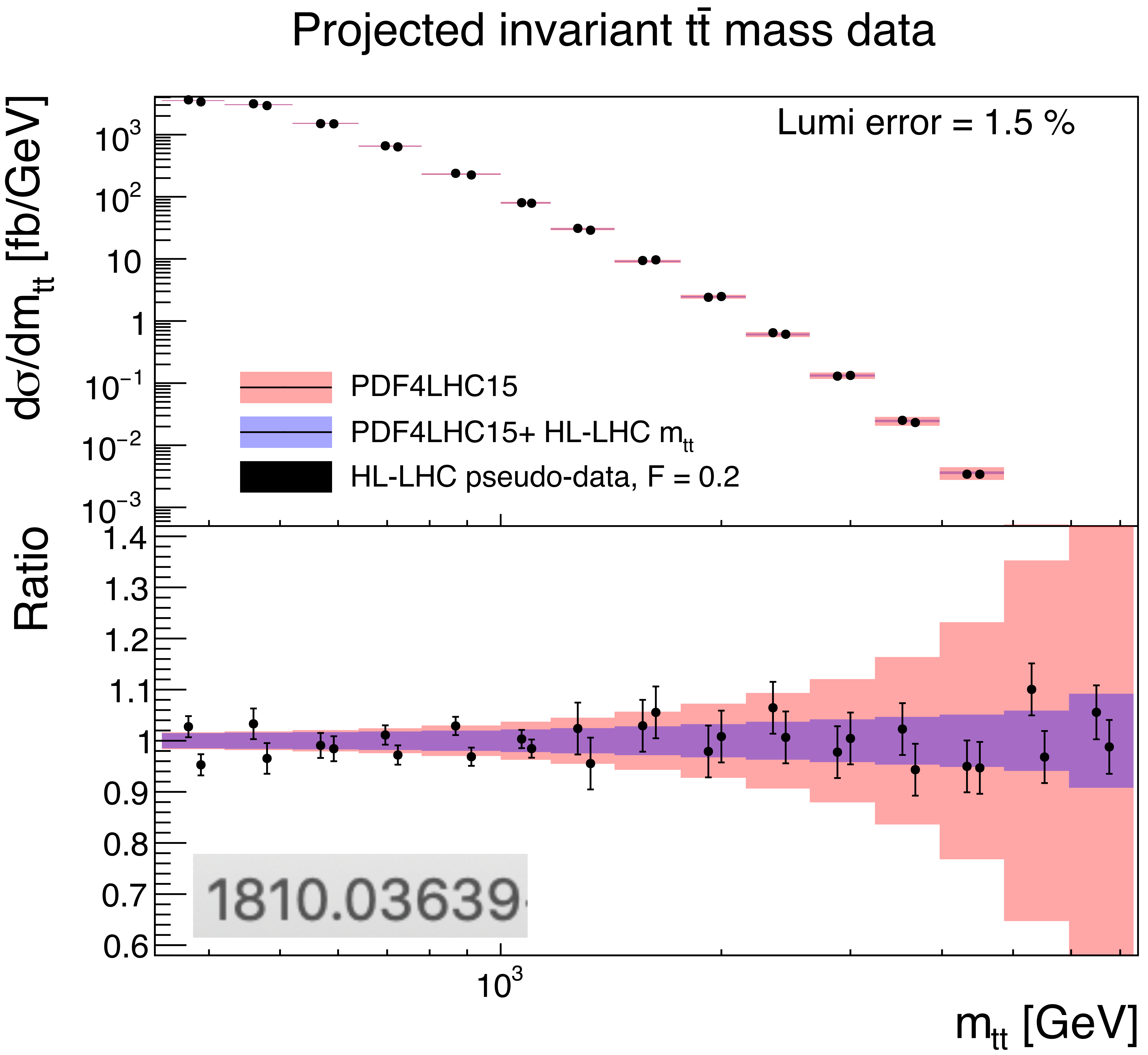
QCD theory anticipated / needed for full exploitation of HL-LHC

(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 timescale?



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

future e+e- colliders

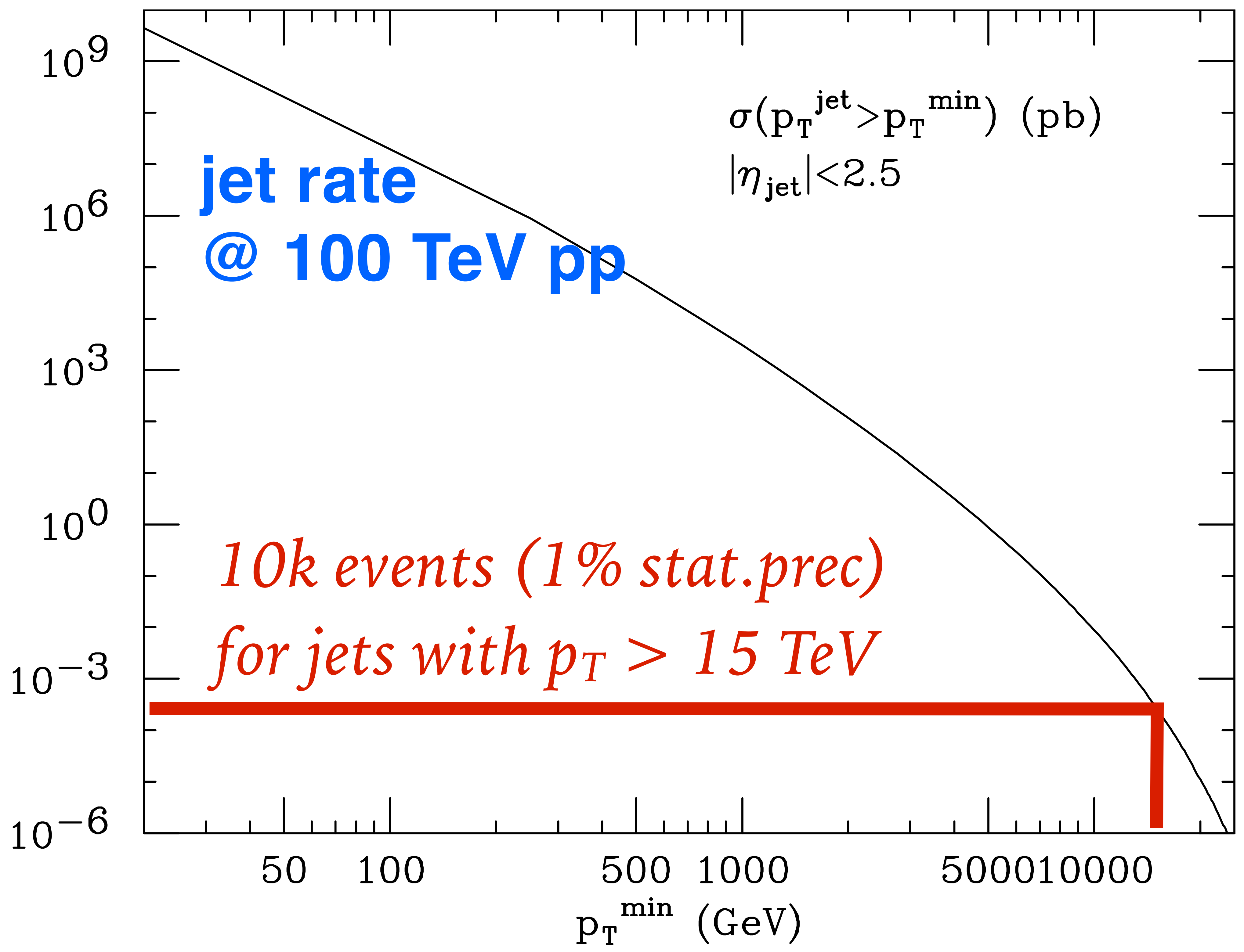
- 3-loop and partial 4-loop calculations of Zff vertex for Tera-Z for EW pseudo-observables
- precision for decays, e.g. in Higgs physics and top-quark physics
- new generations of MC programs for QED and EW effects, understanding two-photon physics

	$\delta\Gamma_Z$ [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

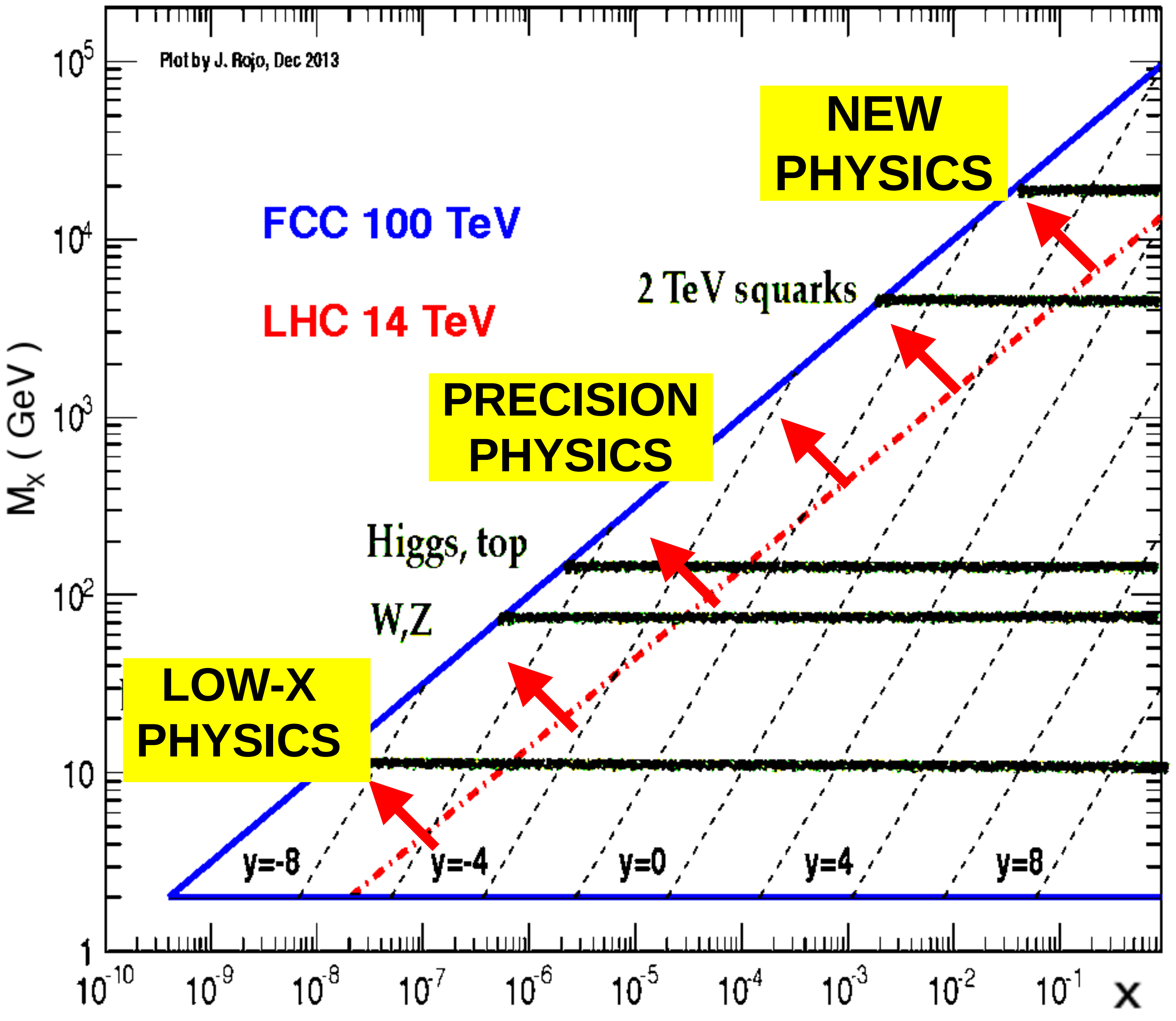


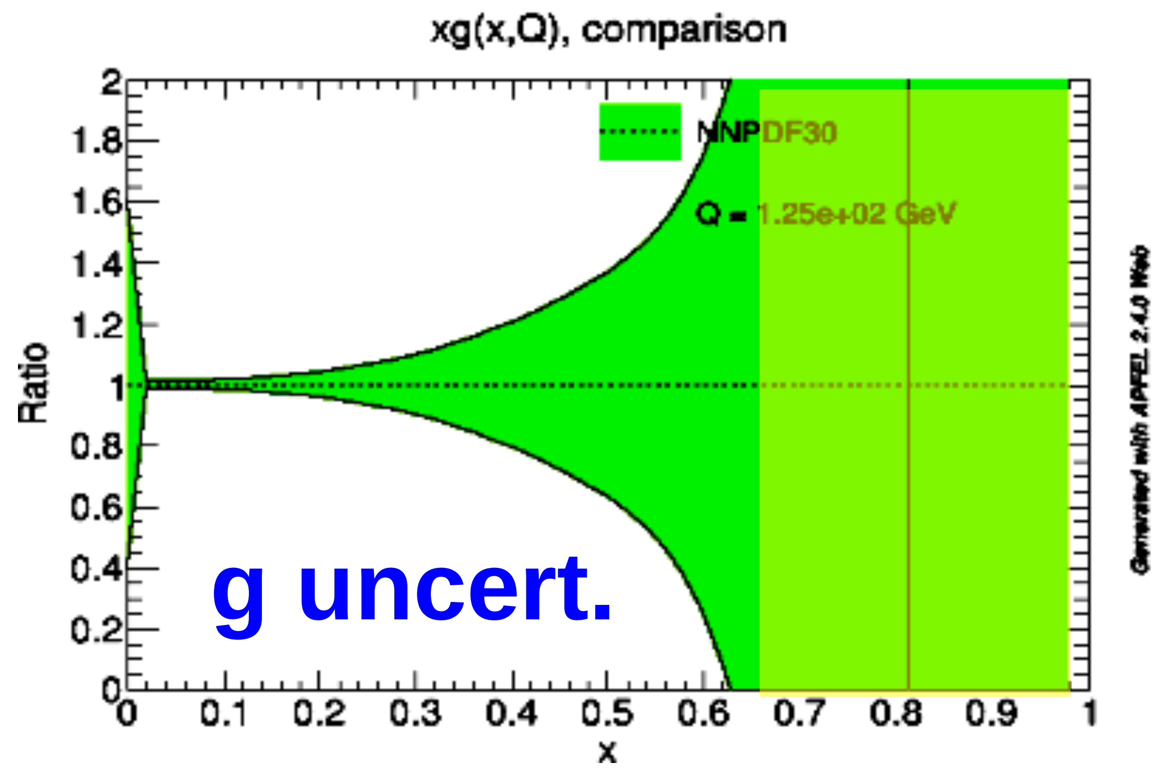
- very high-multiplicity final states, possibly involving multiple scales → needs understanding of regions of validity of perturbation theory, interplay with parton showers, etc., including for EW objects

PDFs: Still work to do for FCC...

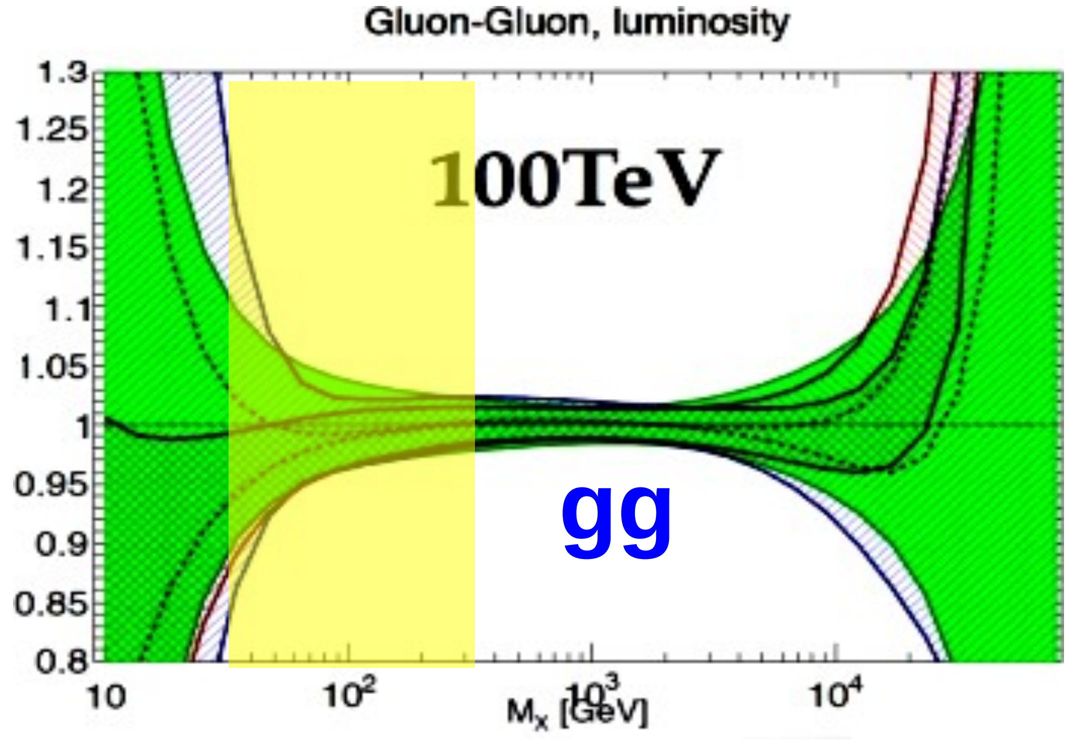
- Still large PDF uncertainties in pp at 100 TeV in key (x,Q^2) regions:

from David d'Enterria's EPPSU talk

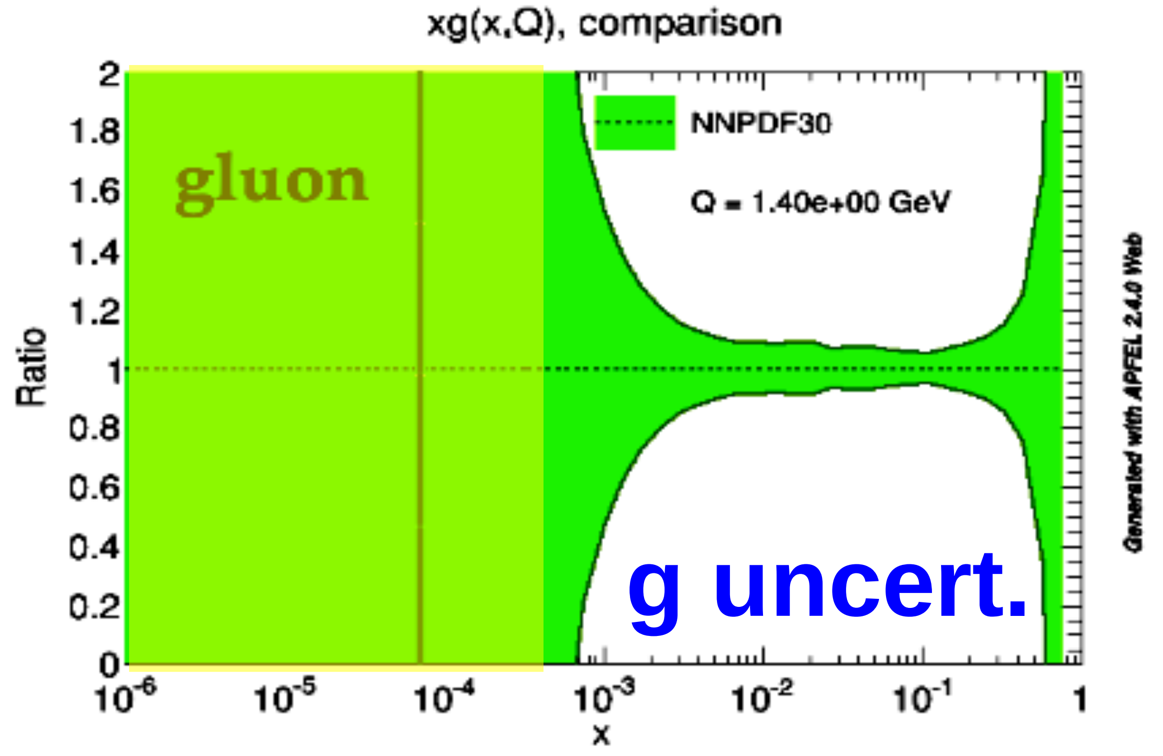




High-x



Mid-x



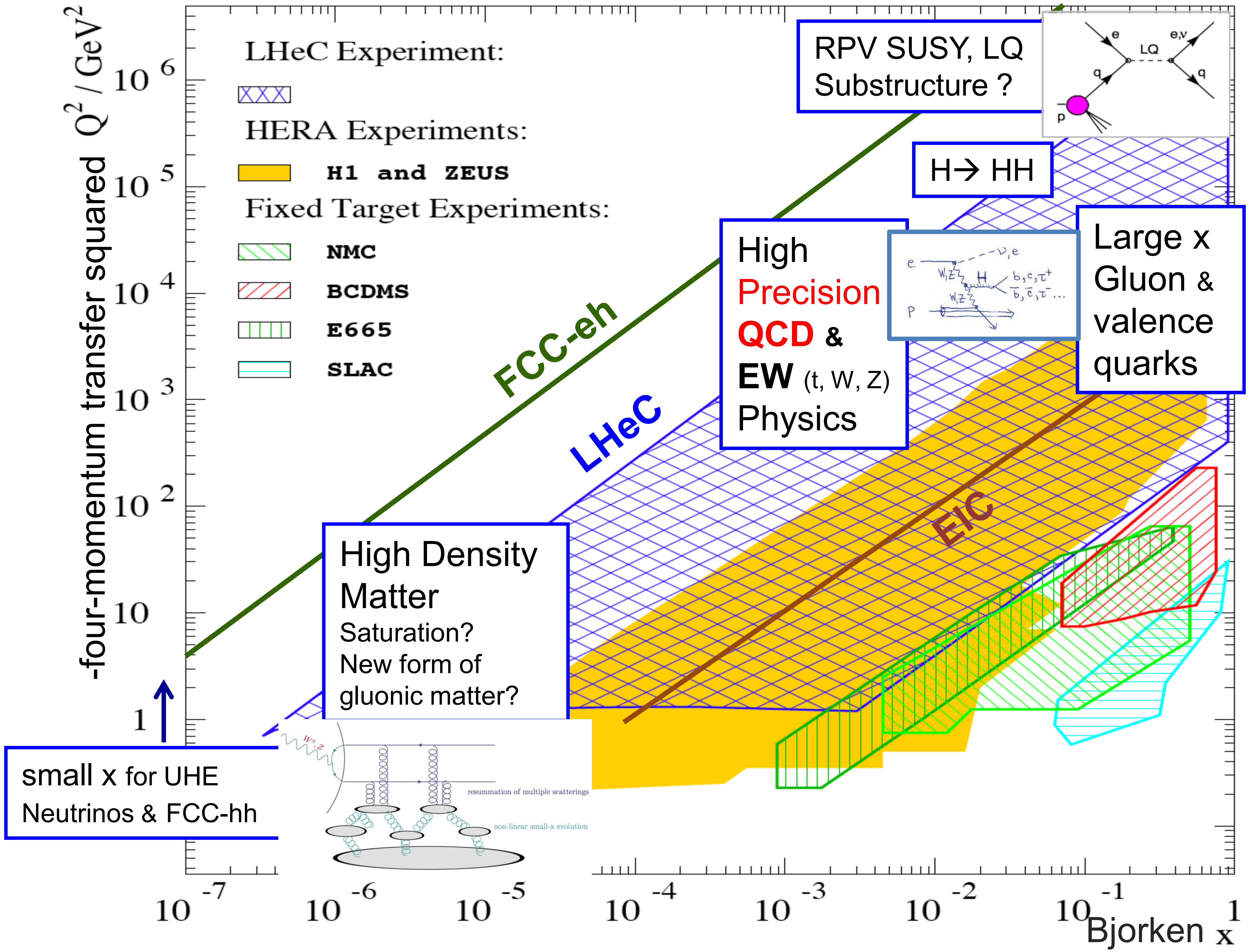
Low-x

- FCC-ep required to reach O(1%) uncertainty for σ(W,Z,H) at FCC-pp

The ep Physics at the Energy Frontier

and unfold hadron sub-structure for LHC and FCC-hh unambiguously

from Uta Klein's EPPSU talk



New ep colliders beyond HERA c.m.s.

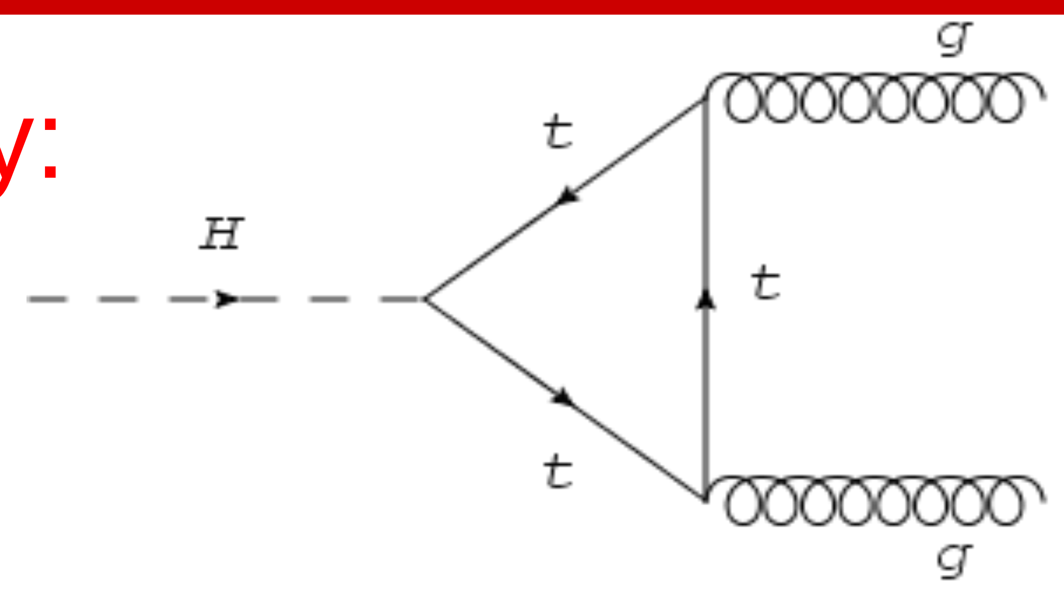
Extensions of both x and Q^2 ranges are crucial for pp experiments and HEP theory developments;

HERA established the validity of pQCD down to x > 10^{-4} (DGLAP) due to a very high lever arm in Q^2:

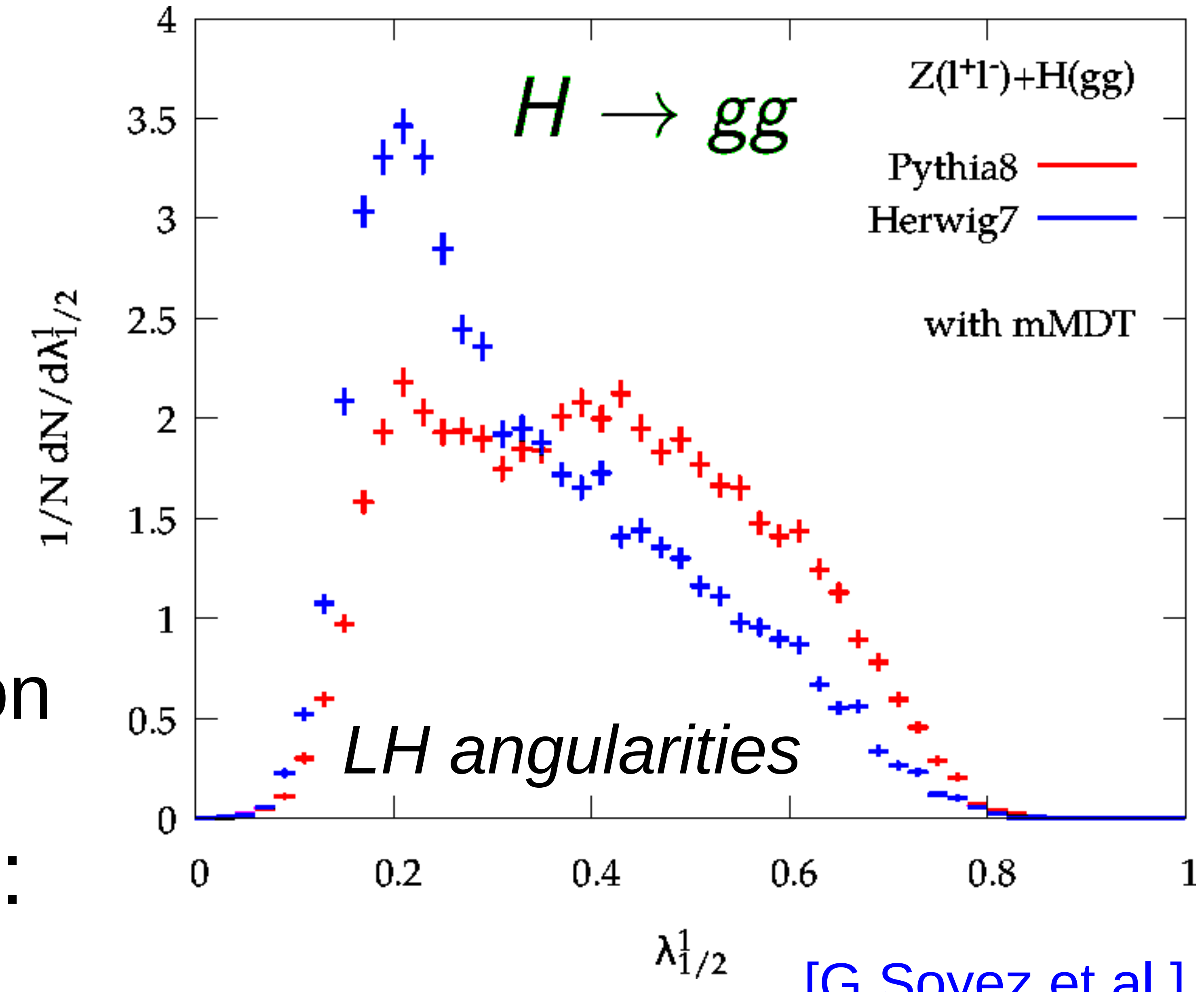
→ high luminosity colliders with high c.m.s. energy of 1.3 – 3.5 TeV

High-precision gluon & quark jet studies (FCC-ee)

- Exploit FCC-ee H(gg) as a "pure gluon" factory: H→gg (BR~8% accurately known) provides O(100.000) extra-clean digluon events.



- Multiple handles to study gluon radiation & g-jet properties:
  - Gluon vs. quark via H→gg vs. Z→qq (Profit from excellent g,b separation)
  - Gluon vs. quark via Z→bbg vs. Z→qq(g) (g in one hemisphere recoiling against 2-b-jets in the other).
  - Vary E_{jet} range via ISR: $e^+e^-\to Z^*,\gamma^*\to jj(\gamma)$
  - Vary jet radius: small-R down to calo resolution



[G.Soyez et al.]

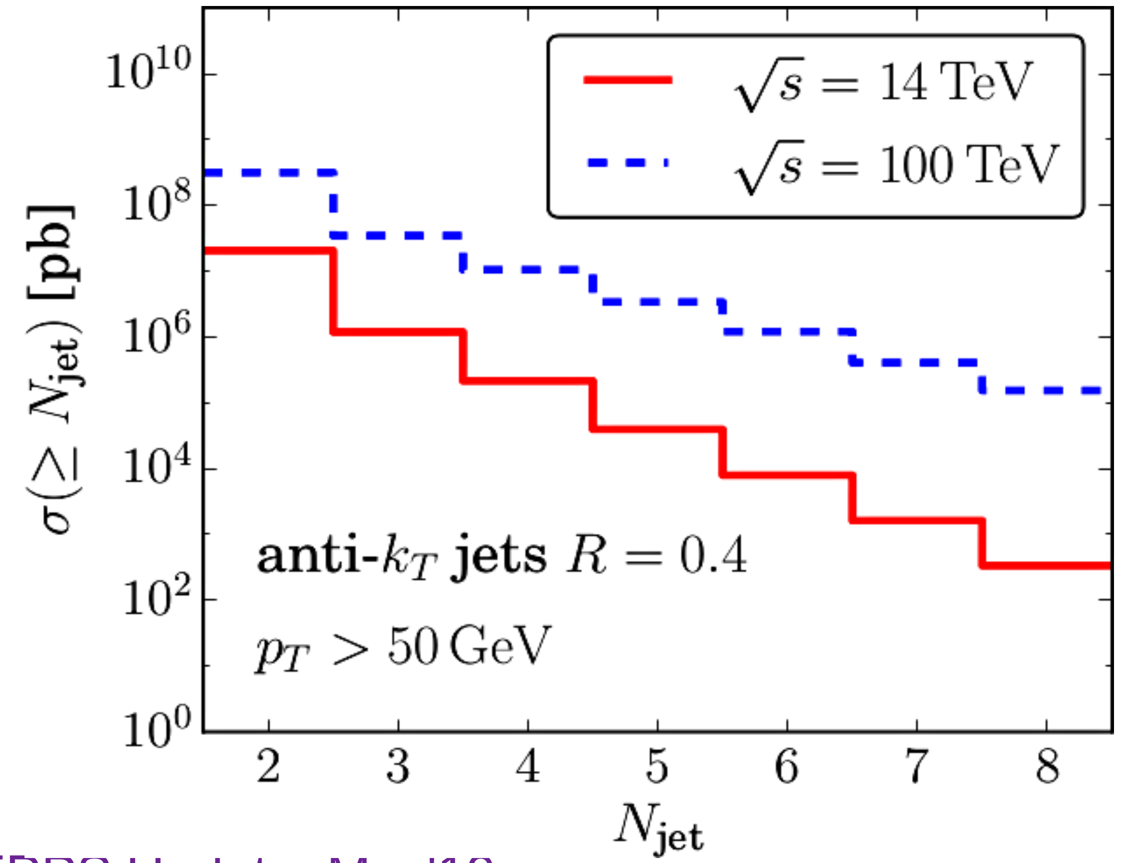
- Multiple high-precision analyses at hand:
  - BSM: Improve q/g/Q discrimination tools
  - pQCD: Check N^nLO antenna functions. High-precision QCD coupling.
  - non-pQCD: Gluon fragmentation: Octet neutralization? (zero-charge gluon jet with rap gaps). Colour reconnection? Glueballs ? Leading η's,baryons?

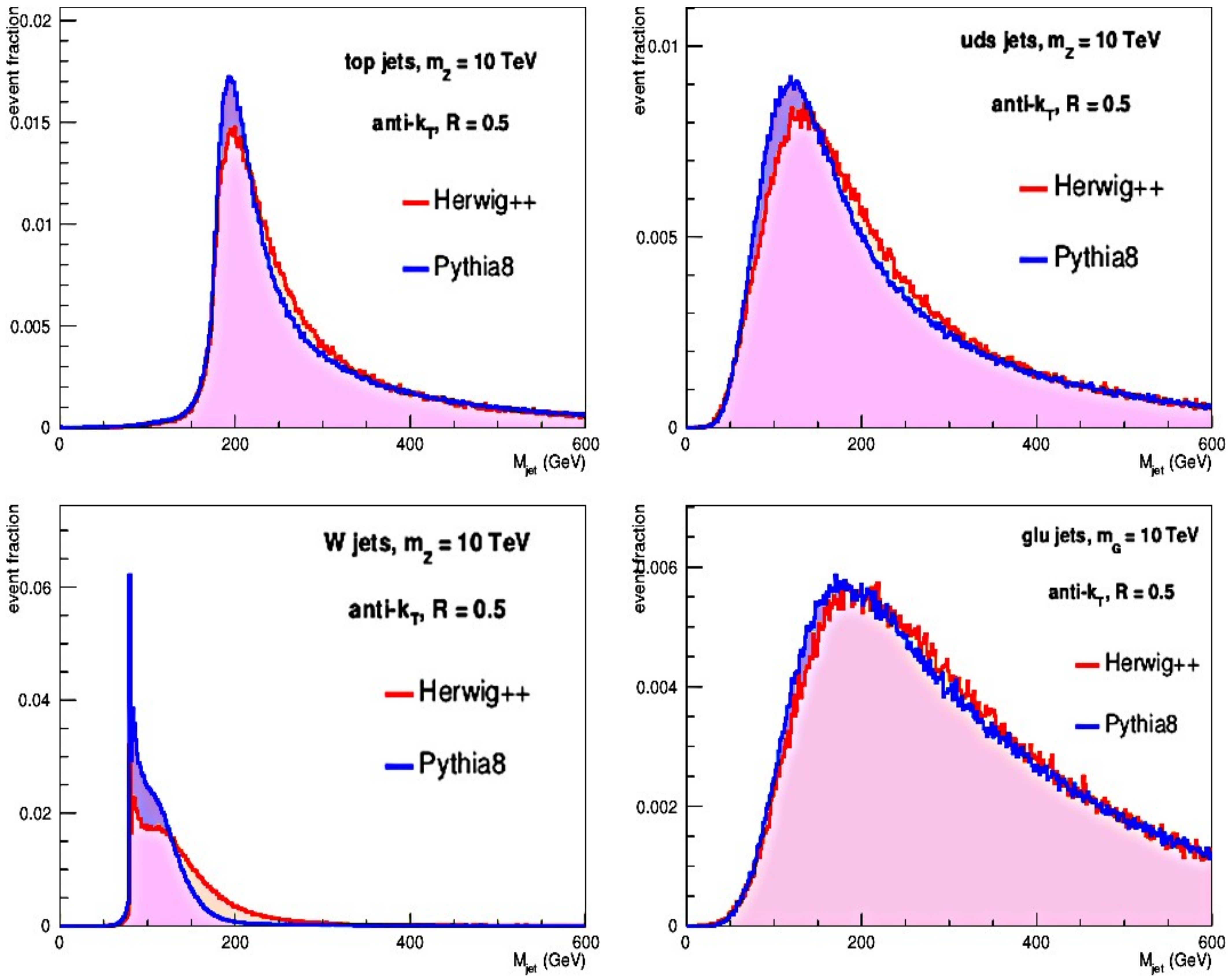
from David d'Enterria's EPPSU talk

Highly-boosted jets, multijets (FCC-pp)

- Proton-proton collisions at 100 TeV provide unique conditions to produce & study highly-boosted objects: top, W, Z, H, R_{BSM}(jj),...
  Resolving small angular dijet sep. $\Delta R \approx 2M(jj)/p_T(j)$.
- Jet substructure: key to separate dijets from QCD & (un)coloured resonance decays, e.g.
  $R_{10\text{-TeV}} \rightarrow$ tt,qq,gg,WW
- Diffs. in MC generators for quark vs. gluon jets (& jet radius).
- Also unique multijet (N>>10) BSM, QCD studies

from David d'Enterria's EPPSU talk





[FCC-pp, arXiv:1607.01831]

resources & the next generation

incoming / early-stage researchers and subsequent career development

- 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

issues of long-term support

- 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 subsequent long-term maintenance & user-support of successful codes often requires substantial dedicated expert time, which can be a substantial burden
  - the “glue” codes (e.g. LHAPDF, HepMC): may not be seen as physics by funding agencies, but support (people/resources) & evolution essential for long-term smooth operation of the field
  - “mechanisms need to be developed to share the effort between event generator projects and their user communities” [Id114] (& we need to ensure that conditions are attractive for those who do this well, e.g. in terms of career recognition)
- 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?

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 advances 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 structure for increasingly long-term theory projects
  - positions and career development for individuals who provide essential “support” roles (maintenance of widely used tools, interfacing with & support for users, …)
  - computing (access to hardware and expertise)

backup

gluon fusion Higgs theory uncertainties

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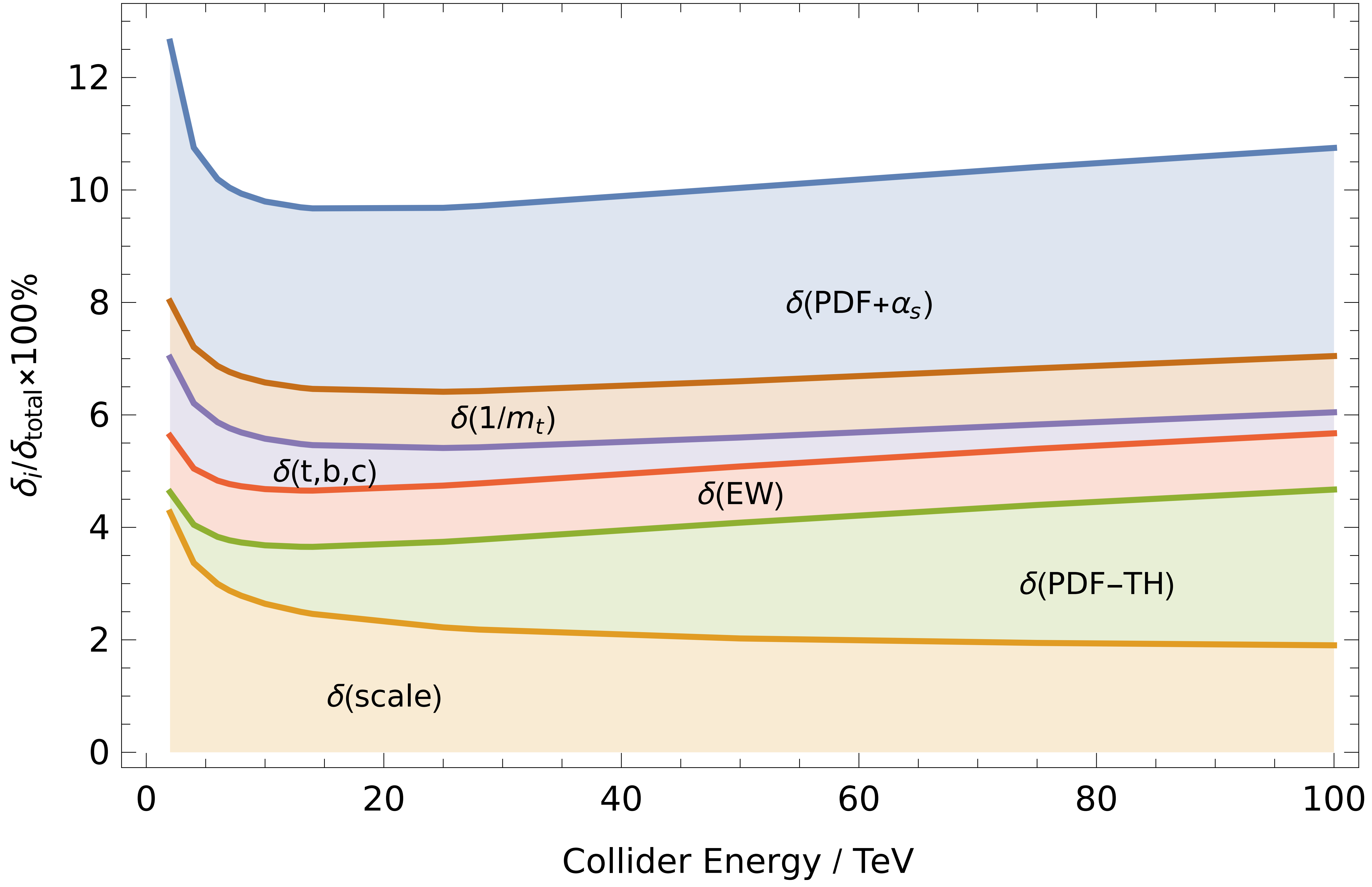

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Theoretical path for QCD physics: main inputs

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