QCD uncertainties on Higgs and EWK measurables

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European Strategy for Particle Physics, Granada, 13 May 2019

Topics covered and input summarised

- How well can the Higgs boson couplings to fermions, gauge bosons and to itself be probed at current and future colliders?

- What are the theoretical developments in QCD and EWK needed to fully capitalize on the experimental data?

- Main documents covered:
  - Higgs Boson studies at future particle colliders *[arXiv:1905.03764]*
  - Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders
  - Precision calculations for high-energy collider processes
  - Monte Carlo event generators for high energy particle physics event simulation
  - Quantum Chromodynamics: Theory - Input for the European Particle Physics Strategy Update
  - *+ collider specific reports / studies*

Many thanks to S. Forte, K. Melnikov, G. Salam and PPG conveners for discussions

A snapshot: EWPO

	$\delta\Gamma_Z$ [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

$Zf\bar{f}$ vertex, dominant 3-loop EW, dominant 4-loop mixed QCD-EW

EWPO	Exp. direct error	Param. error	Main source	Theory uncert.
Γ_Z [MeV]	0.1	0.1	$\delta\alpha_s$	0.07
R_b [10^{-5}]	6	1	$\delta\alpha_s$	3
R_ℓ [10^{-3}]	1	1.3	$\delta\alpha_s$	0.7
$\sin^2\theta^\ell_{\rm eff}$ [10^{-5}]	0.5	1	$\delta(\Delta\alpha)$	0.7
M_W [MeV]	0.5	0.6	$\delta(\Delta\alpha)$	0.3

$\delta\alpha_s = 0.00015$

see S. Dittmaier's talk

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

$\delta\alpha_s = 0.0002$

$\delta m_t = 50$ MeV

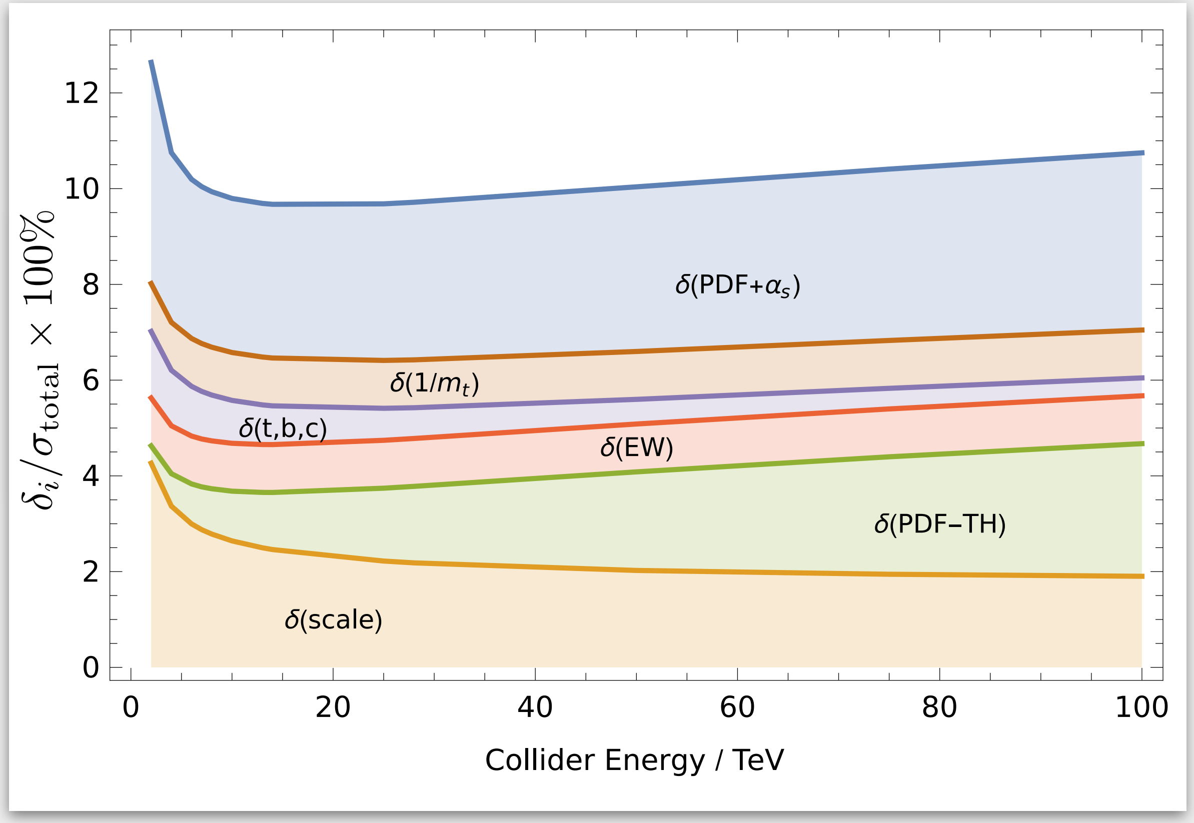
$\delta m_b = 13$ MeV

$\delta m_c = 7$ MeV

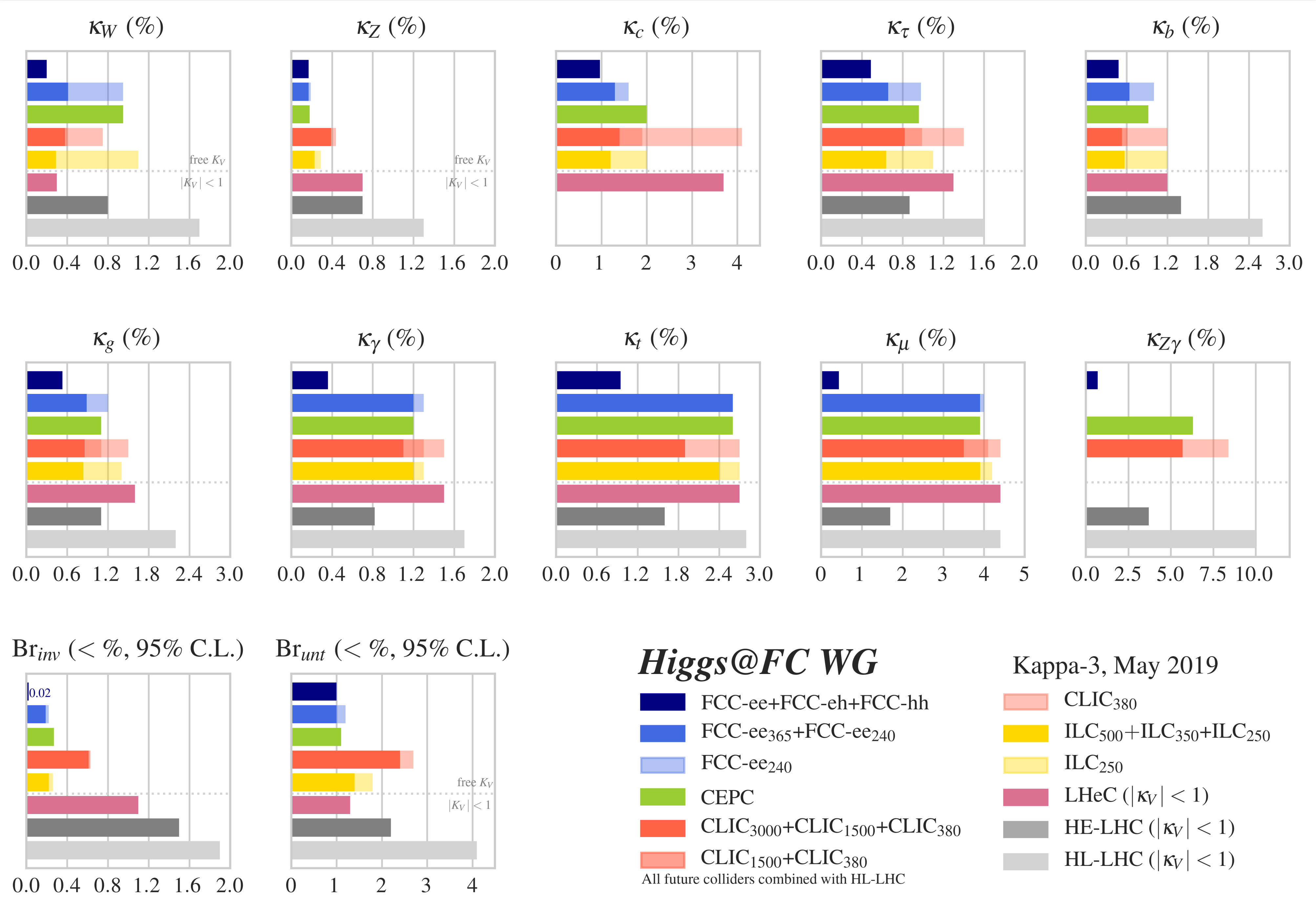
$\delta m_H = 10$ MeV

see S. Dittmaier's talk

HXSWG, extrapolation of current ggF uncertainties to high energy pp colliders



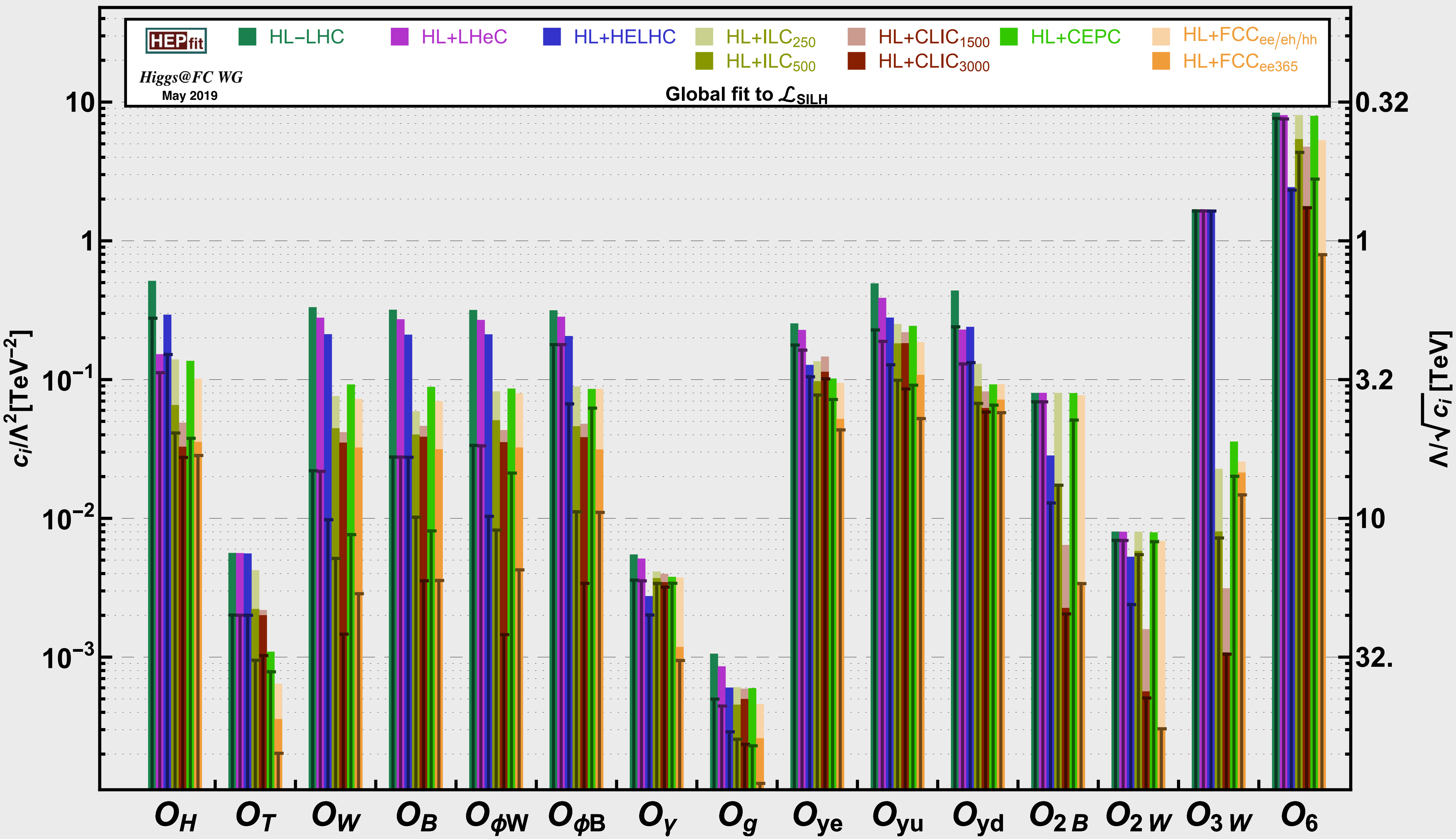
A snapshot: Higgs



QCD uncertainty on overall rates/Br:

- HL-LHC S2 [=today/2]
- future colliders: ~today/2 for Br, 1% at HE, 0.5% at LHeC, 1% total FCC-hh

A snapshot: Higgs



QCD uncertainty on overall rates/Br:

- HL-LHC S2 [=today/2]
- future colliders: ~today/2 for Br, 1% at HE, 0.5% at LHeC, 1% total FCC-hh

Some words of caution

1. TH uncertainties under SM assumptions. Both intrinsic and parametric uncertainties can changes in BSM scenarios

2. No correlations among theory uncertainties

   - Currently, we did not study the problem in enough detail to have a foolproof recipe for theory uncertainty correlations [*my personal opinion*]
   - Theories uncertainties are not exactly random variables…
   - It is becoming an important issues for many LHC physics. Examples:

     ✴*Higgs combinations/STXS*

     ✴*PDFs theory uncertainties*

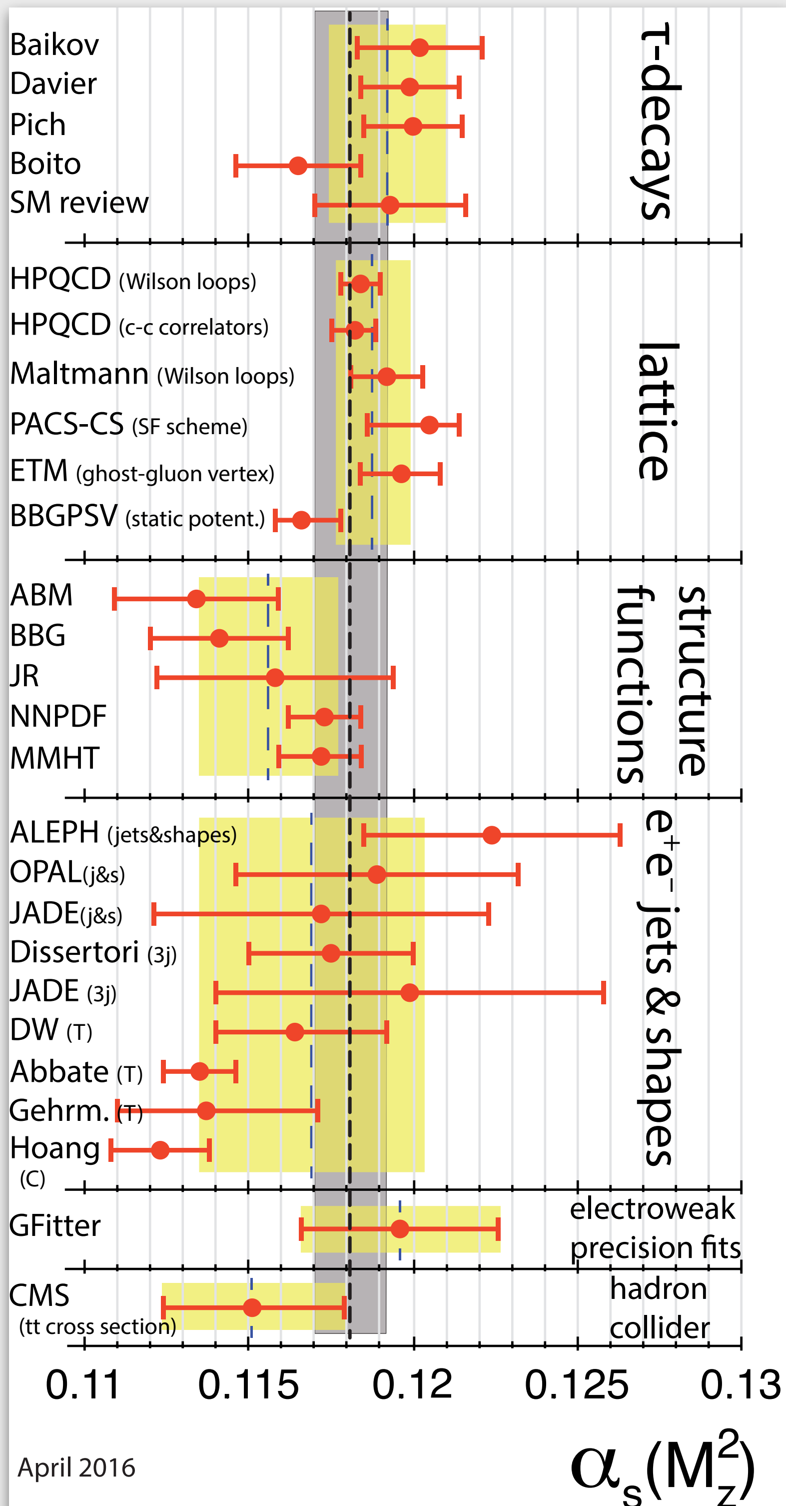
     ✴*Complicated background & interplay with MVAs, e.g.* $t\bar{t}H$ *vs* $t\bar{t}b\bar{b}$
   - Important to understand for a coherent treatment of uncertainties, a lot of effort going on right now → no longer a neglected issue, expect progress

Parameters: α_s

$\boxed{\delta\alpha_s = 0.0002}$ ⟶ *VERY CHALLENGING*

Current status

G. Salam, talk at "Future challenges for precision QCD" 2016



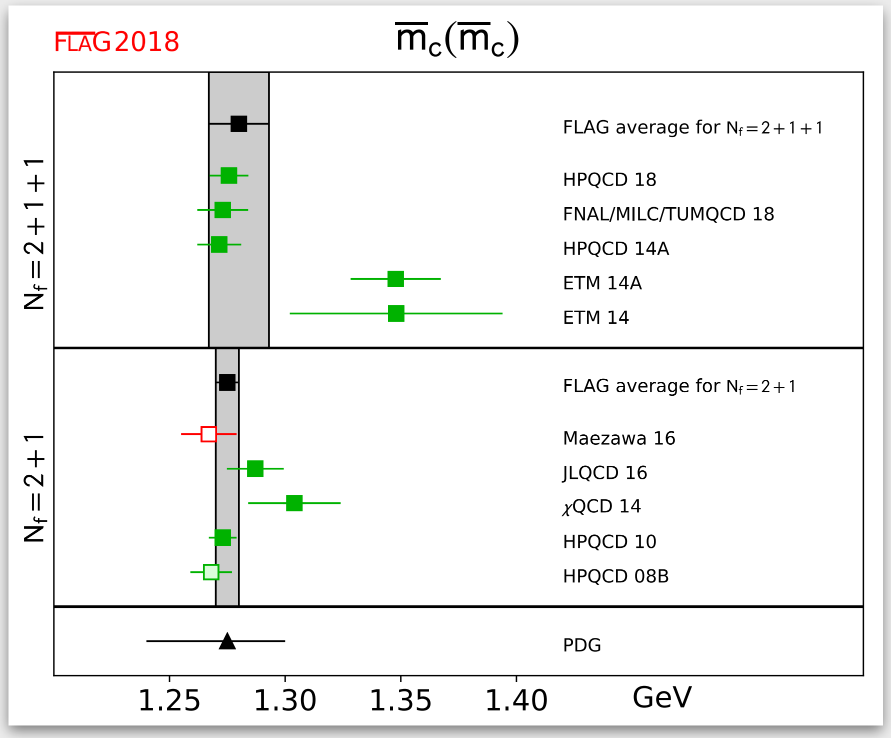
Prospects

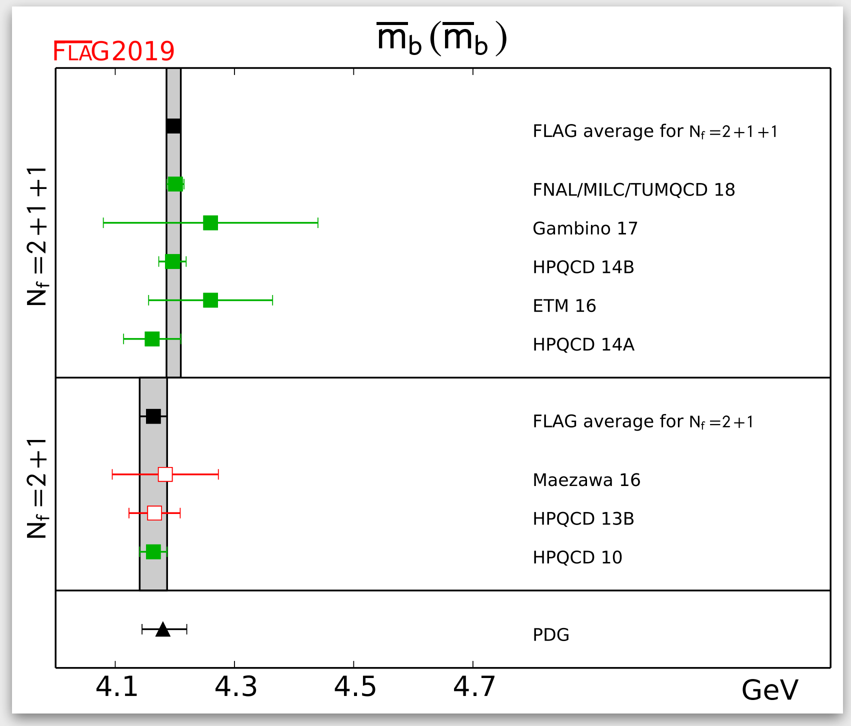
- e^+e^-, hadronic decays, global fits → potential to reach 0.15%. QCD-robust, but *sensitive to new physics contaminations*
- e^+e^-, event shapes/jet rates → good potential, but remember the LEP lesson
  - Thrust, C parameter: 0.113, 1%
  - Jet rates: 0.119, 1%
  - Must understand better underlying theory (*NP corrections, formally subleading terms…*)
- Hadron collider observables / PDF fits → very high accuracy, but same problems as PDF fits *(low Q contamination, theory uncertainties, correlations with PDFs)*
- Lattice very robust. Most robust determination → new approach. Assuming computer improvements → 0.3%, promising

Projections: see D. d'Enterria contribution in [arXiv:1512.05194]

Parameters: masses

1. Bottom, charm δm_b = 13 MeV, δm_c = 7 MeV





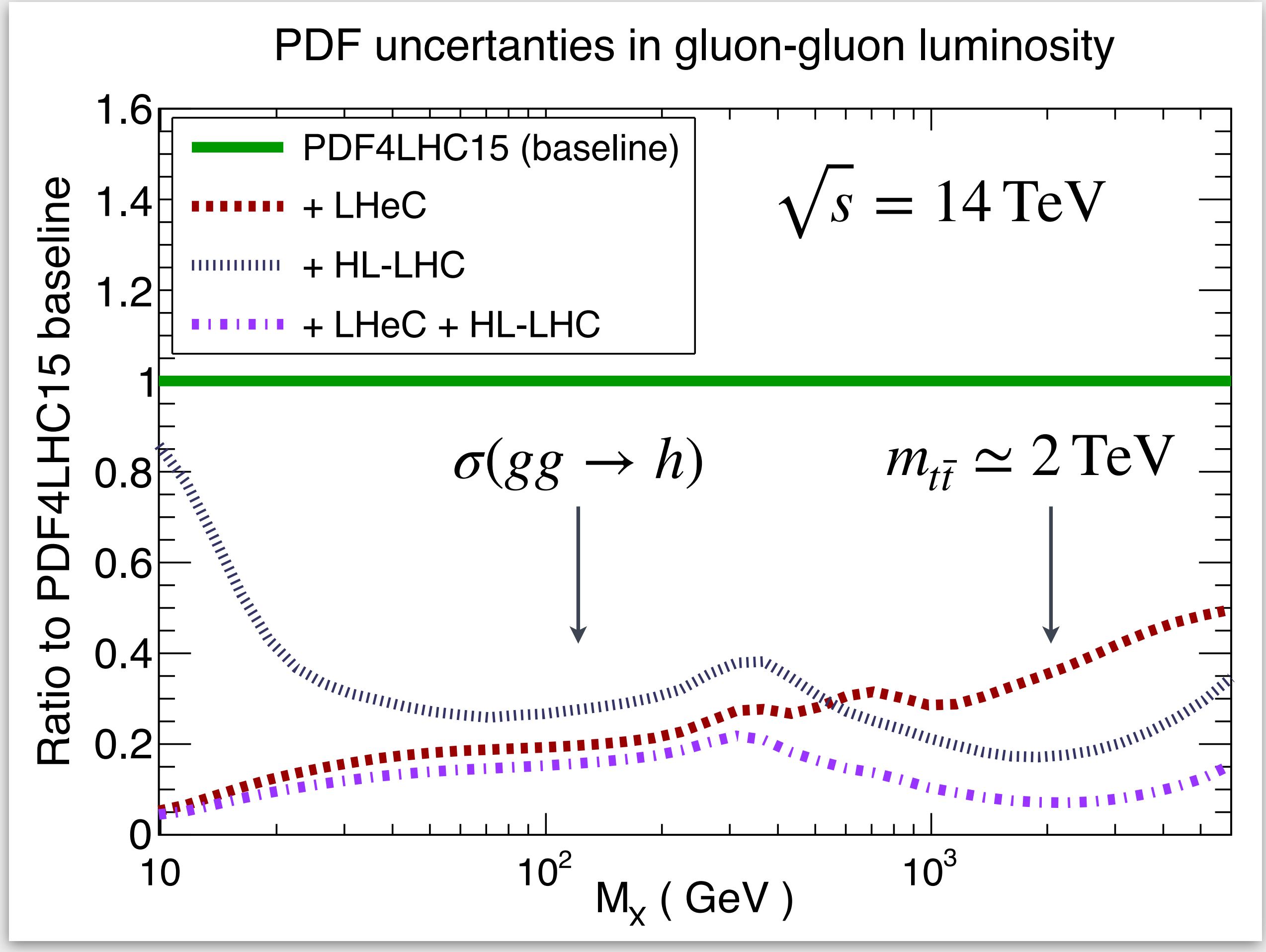
FLAG Review 2019

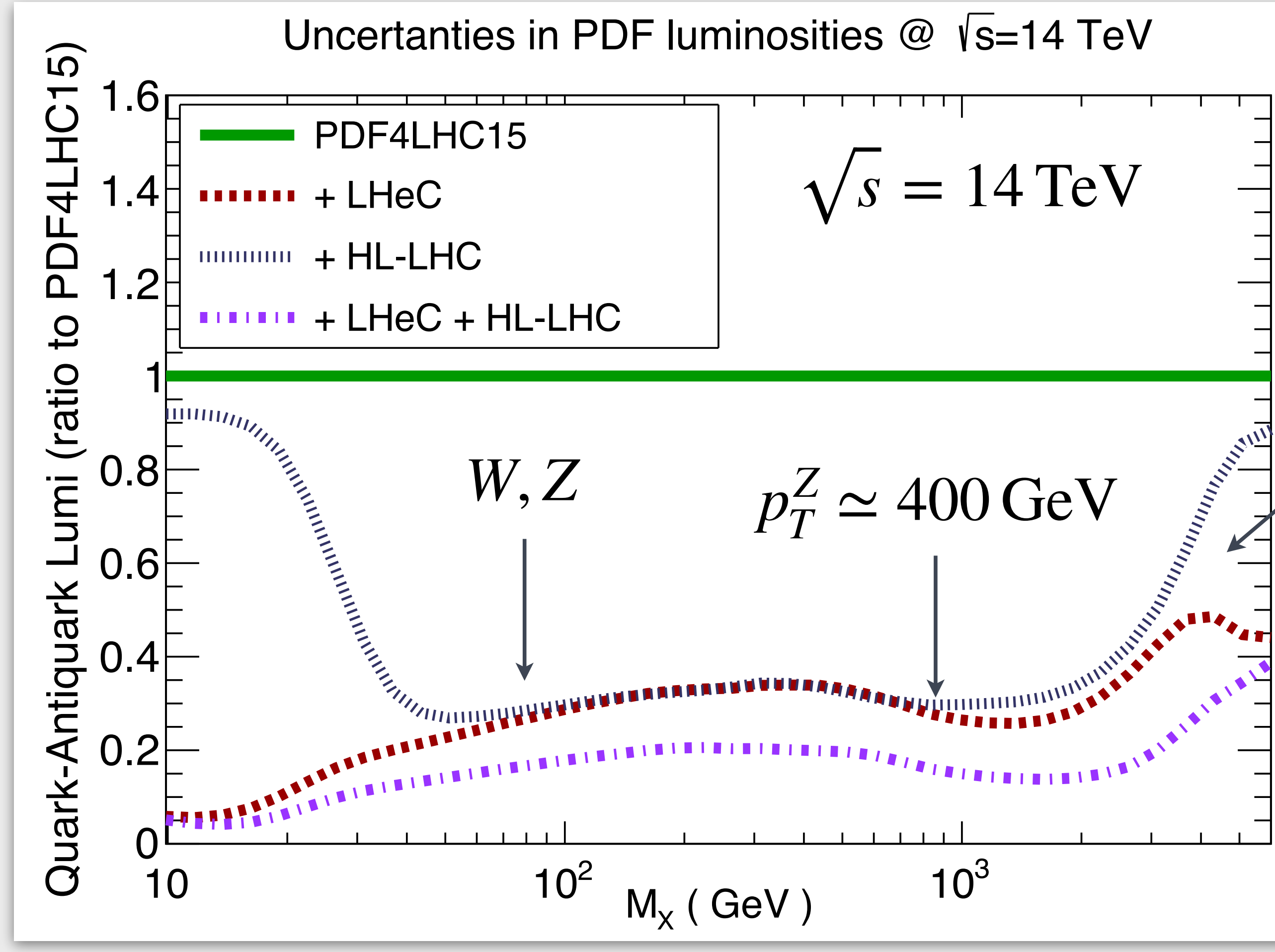
Very encouraging results, it seems [to me] well within reach

2. Top mass: δm_t = 50 MeV

- Hadron colliders: with the current level of understanding of QCD → unlikely to control better than ~ Λ_{QCD}. Progress at this stage almost impossible to predict *(if no breakthrough, could be very limited)*
- High precision: e^+e^- threshold scan, can reach 50 MeV for short-distance masses. Very well-developed theory

Parameters: PDFs





Juan Rojo, SM@LHC 2019

Required improvements

- Theoretical uncertainties → first results appearing very soon
  Framework to investigate th. uncertainty, correlations available ~now
- High precision in the evolution → N^{3}LO splitting function. Massive calculations, but reasonable to expect it in the not far future
- Better understanding of specific kinematic regions (nuclear corrections, higher twist, saturation…). *With extended dataset: can afford to discard ``problematic" data (low Q^2…)*

Intrinsic uncertainties reduction

Highest precision: clean environment, simple observable → EWPO

- mostly from $Zf\bar{f}$ vertex
- pQCD works very well, but precision requires many QCD/EW loops

Results required:

- leading 3-loop $Zf\bar{f}$: $\alpha\alpha_s^2$, $n_f\,\alpha^2\alpha_s$, $n_f^2\,\alpha^3$
- also 4-loop QCD may be required
- full 2-loop completed recently

Typical problem: *many loops, few legs*

- well-established framework, massively difficult technical problems
- a remarkable amount of progress recently → expect new results
- no kinematics dependence → numerical approach

Also in this case, may need to consider more ``realistic” scenario

- $e^+e^- \to f^+f^-$, at 2-loops
- non-trivial kinematics, but 2-loop

Intrinsic uncertainties reduction

Highest precision: clean environment, simple observable → EWPO

- mostly from $Zf\bar{f}$ vertex
- pQCD works very well, but precision requires many QCD/EW loops

- Well-identified problems, clear path towards a solution
- Technically very challenging → will require focus in the community, and support

Also in this case, may need to consider more ``realistic” scenario

- $e^+e^- \to f^+f^-$, at 2-loops
- non-trivial kinematics, but 2-loop

Intrinsic uncertainties reduction

Higher statistics/energy: *can explore a broad range of interesting processes/observables*

- A very rich physics potential
- Would require less precision than EWPO, but more complex processes (many legs, non-trivial kinematics, much more involved phenomenological studies)
- High precision for H, V, top, jets. Already now very good control. Improvements non-trivial

In this situation, *QCD TH improvements along a single direction won't do*, concertated effort is required

- higher order QCD/EW calculations
- all-order resummation
- better parton showers
- better control over NP effects
- new pheno idea to maximise potential/stay away from ``dangerous" regions

Intrinsic uncertainties reduction

Example: *vector boson p_t, where we are and how to improve*

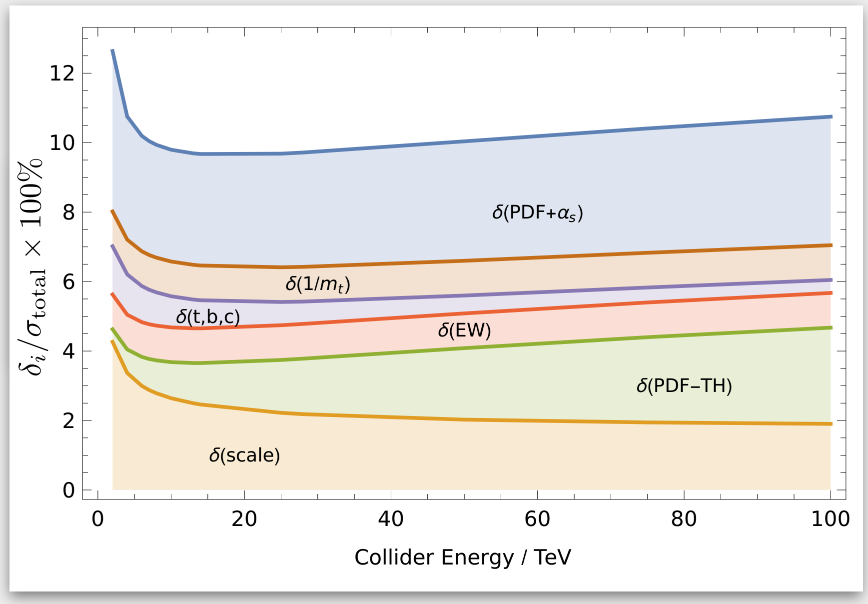
Summary

- Measurements of gauge boson p_T at the LHC require us to push theory predictions to the limits of perturbation theory and beyond
- Pattern of QCD (massless, except for thresholds in PDFs) corrections well understood, with residual **errors at the 3-5% level** across most of the spectrum
- Beyond this point, several effects become relevant:
  - **higher order QCD corrections** to the differential spectrum (i.e. N^4LL+N^3LO)
  - **PDF errors at the 1-3% level**: How to combine with the remaining perturbative error ? Are differences between sets really understood ? Theory uncertainties in PDFs ?
  - **NP corrections expected to be as large as 1-2%**, small-mass Drell-Yan could be exploited to constrain these in a data driven manner (high TH+EXP precision required, challenging for TMD PDFs)
  - **QED corrections at the ~1-2% level**, uncertainties can be potentially reduced
  - **bottom-quark mass corrections at the ~1-2% level**, calculation at small p_T feasible
  - parametric uncertainties, e.g**. strong coupling at the ~1% level**, currently hard to improve further

Intrinsic uncertainties reduction

Example: "*Higgs at the HL/HE-LHC*" *LHCHXSWG report*

ggF: many small sources of uncertainties that add up



Improving substantially on any of the current sources of uncertainty represents a major theoretical challenge that should be met in accordance with our ability to utilise said precision and with experimental capabilities. The

. . .

It is obvious that the future precision of experimental measurement of Higgs boson properties will challenge the theoretical community. Achieving a significant improvement of our current theoretical understanding of the Higgs boson and its interactions will inspire us to push the boundaries of our capabilities to predict and extract information. New ways of utilising

+ *extreme kinematics [boosted, off-shell…]*

- *VBF:* NNLO beyond DIS, NNLOPS, control over MPI (+had)
- *VH:* gg→ZZ, realistic final states ($H\to b\bar{b}$), PS
- *tth:* NNLO, precision in $t\bar{t}b\bar{b}$ (higher orders, shower, connection with MVA…)

Path towards precision: QCD

1. Within perturbation theory

- Fixed-order: NNLO for 2→3 reactions, N^{3}LO for standard candles, EFTs
  - non-trivial improvement over current technology (multi-loop amplitudes, IR subtraction schemes, efficient NLO 2→4, extreme regions…)
  - may require going beyond ``standard" approach to perturbative calculations.
    - *$t\bar{t}$@N^{3}LO: $\delta\sigma \neq R+V$, non-analytic $|\alpha_s|$ terms* [see M. Beneke, Ruiz-Fermenia 1606.02434, Melnikov, Vainshtein, Voloshin 1402.5690]
    - Jets: factorisation violation [see e.g. Catani, de Florian, Rodrigo 1112.4405]

- All-order
  - High accuracy, more exclusive/combined resummation. Understanding subleading terms
  - Better parton showers
    - *Generic fixed-order/PS merging at high formal accuracy*
    - Beyond (N)LL shower
    - Beyond leading color

genuinely new conceptual development required

Path towards precision: QCD

2. Beyond perturbation theory

- Better control/understanding over (some) NP effects
  - eventually, limiting factor for many analysis (e.g. now: m_t)
  - NP ~ $1/\Lambda^k$. *Very little known.*
  - *k=1,2 massively different in practice → systematic understanding of scaling would be already useful*
  - *At least to some extent, can be done from first principles*

- Beyond first principles
  - NP aspects in the shower: hadronization models etc…

3. Pheno studies

- How to maximise physics potential
- Stay away from problematic regions
- Identify new observables/fiducial regions
- Study correlations, connections with MVAs…

Path towards precision: QCD

Would require both significant improvement over current state-of-the-art

- Technically very challenging, but judging from progress in the last 10 years not unreasonable
- Would require focus, dedication and support

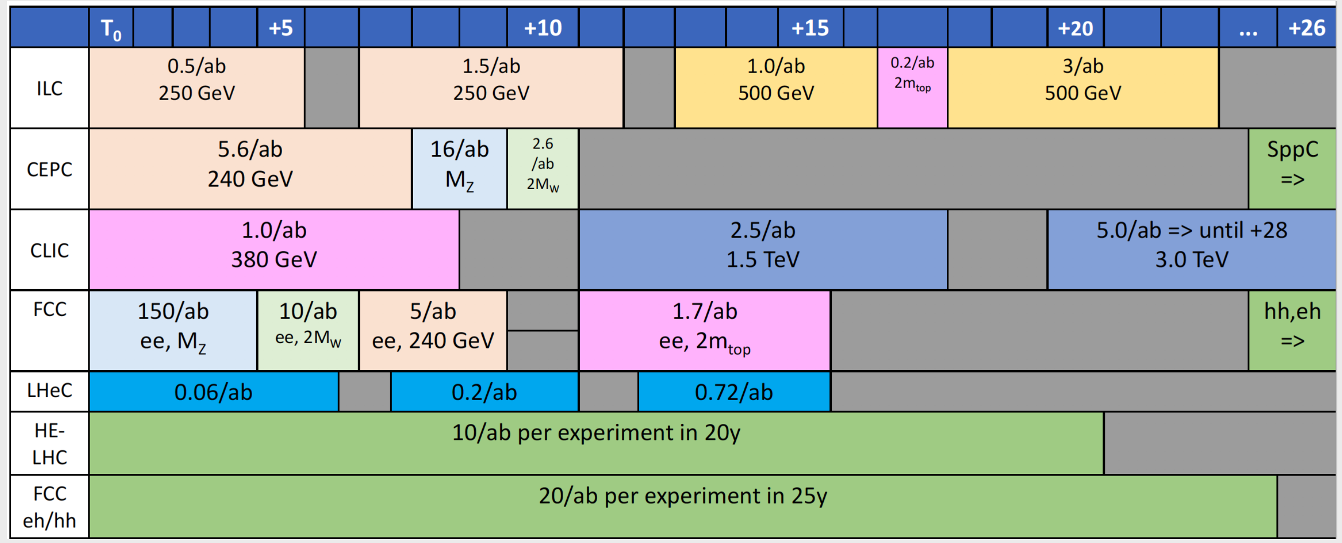
Would also require genuinely new conceptual breakthrough in QCD → much more difficult to predict

- Going from 20% to 10% qualitatively different than going from 10-5% to $\lnsim$ 1%
- Significant development beyond current standard framework will be required

[Sociological issues (large groups, very long projects, more and more technical…) → *see also QCD session tomorrow*]

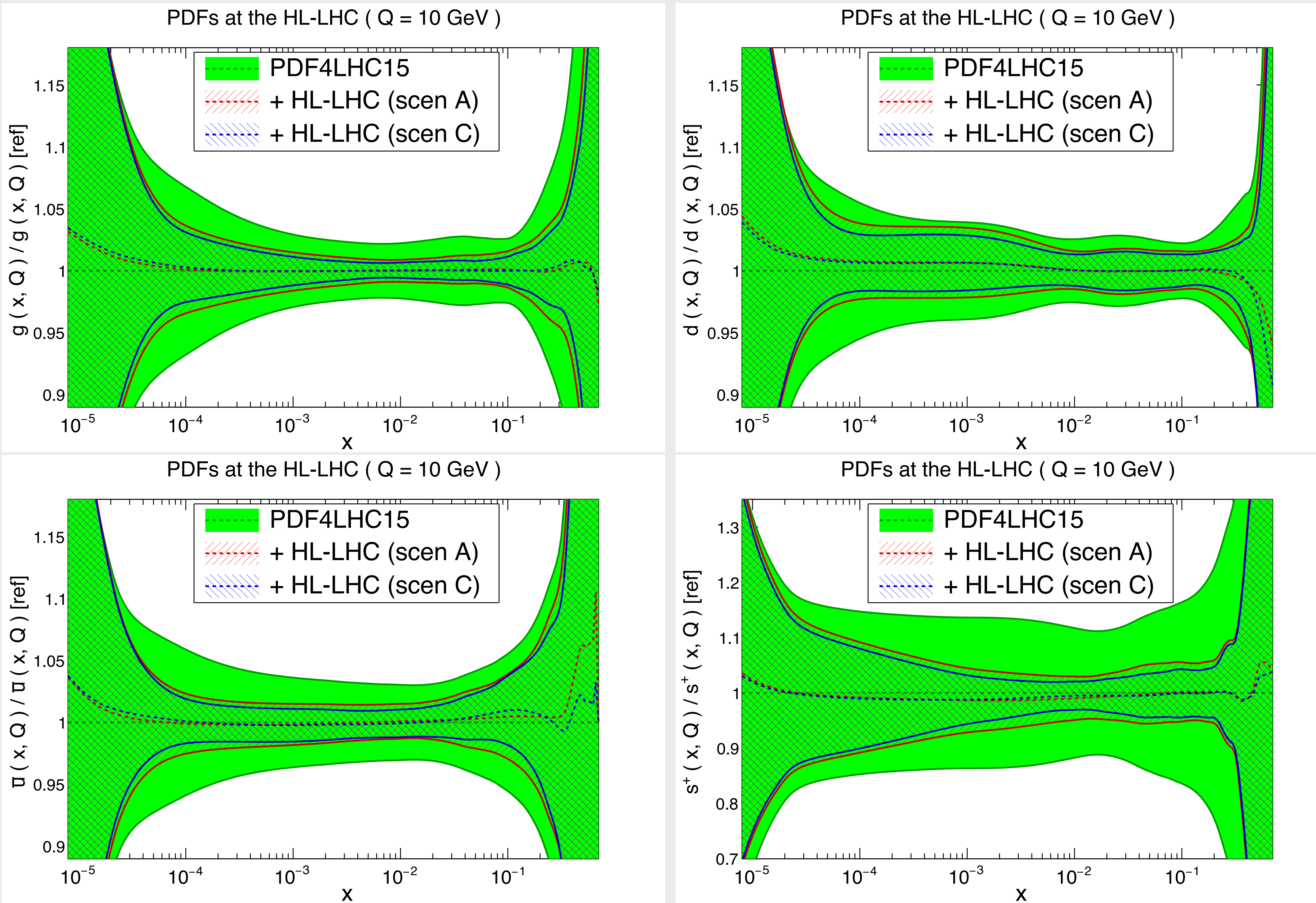
Thank you very much

Back-up



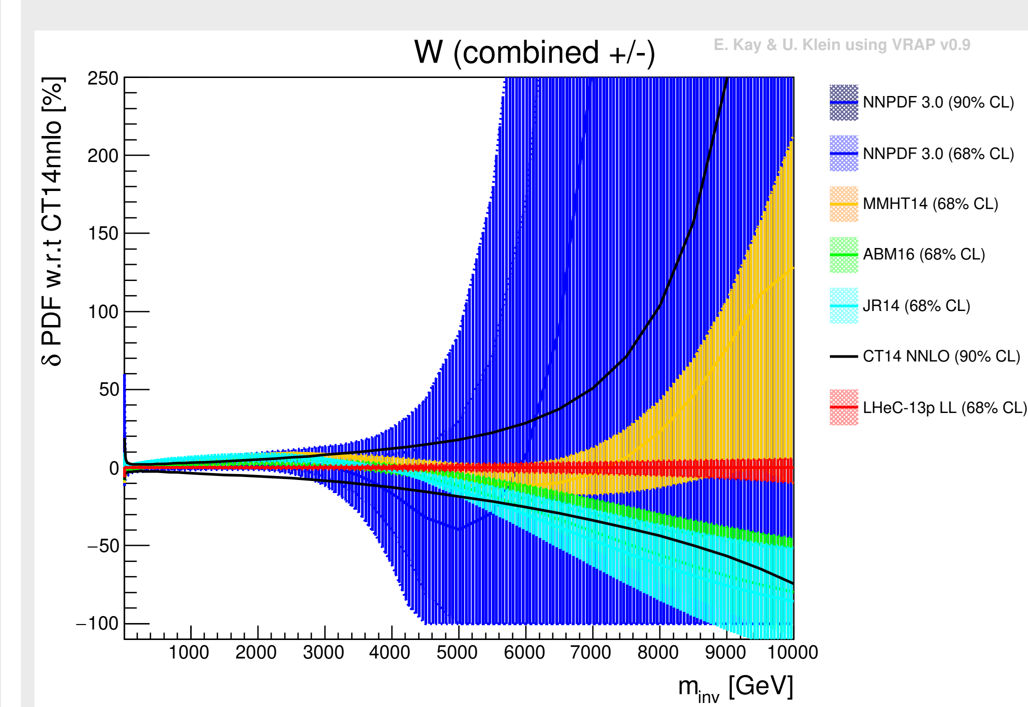
Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]$ cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[10]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	HE-LHC
FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	$\pm80/\pm30$	1	1.35/2.7	2.0	11.5	[3, 11]	ILC$_{250}$
		350 GeV	$\pm80/\pm30$	1	1.6	0.2	1		ILC$_{350}$
		500 GeV	$\pm80/\pm30$	1	1.8/3.6	4.0	8.5		ILC$_{500}$
							(+1)		(1y SD after 250 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	$\pm80/0$	1	1.5	1.0	8	[12]	CLIC$_{380}$
		1.5 TeV	$\pm80/0$	1	3.7	2.5	7		CLIC$_{1500}$
		3.0 TeV	$\pm80/0$	1	6.0	5.0	8		CLIC$_{3000}$
							(+4)		(2y SDs between energy stages)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[9]	LHeC
HE-LHeC	ep	2.6 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

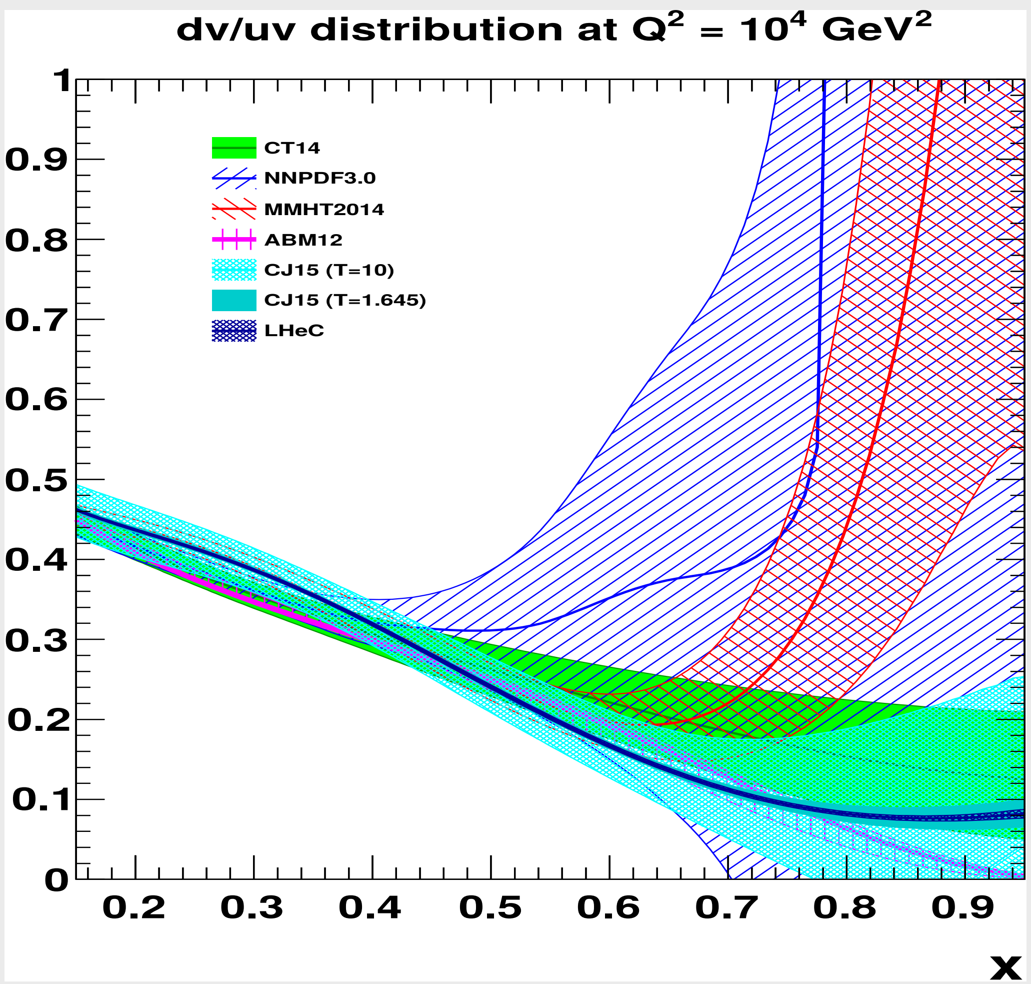
PDFs: HL-LHC

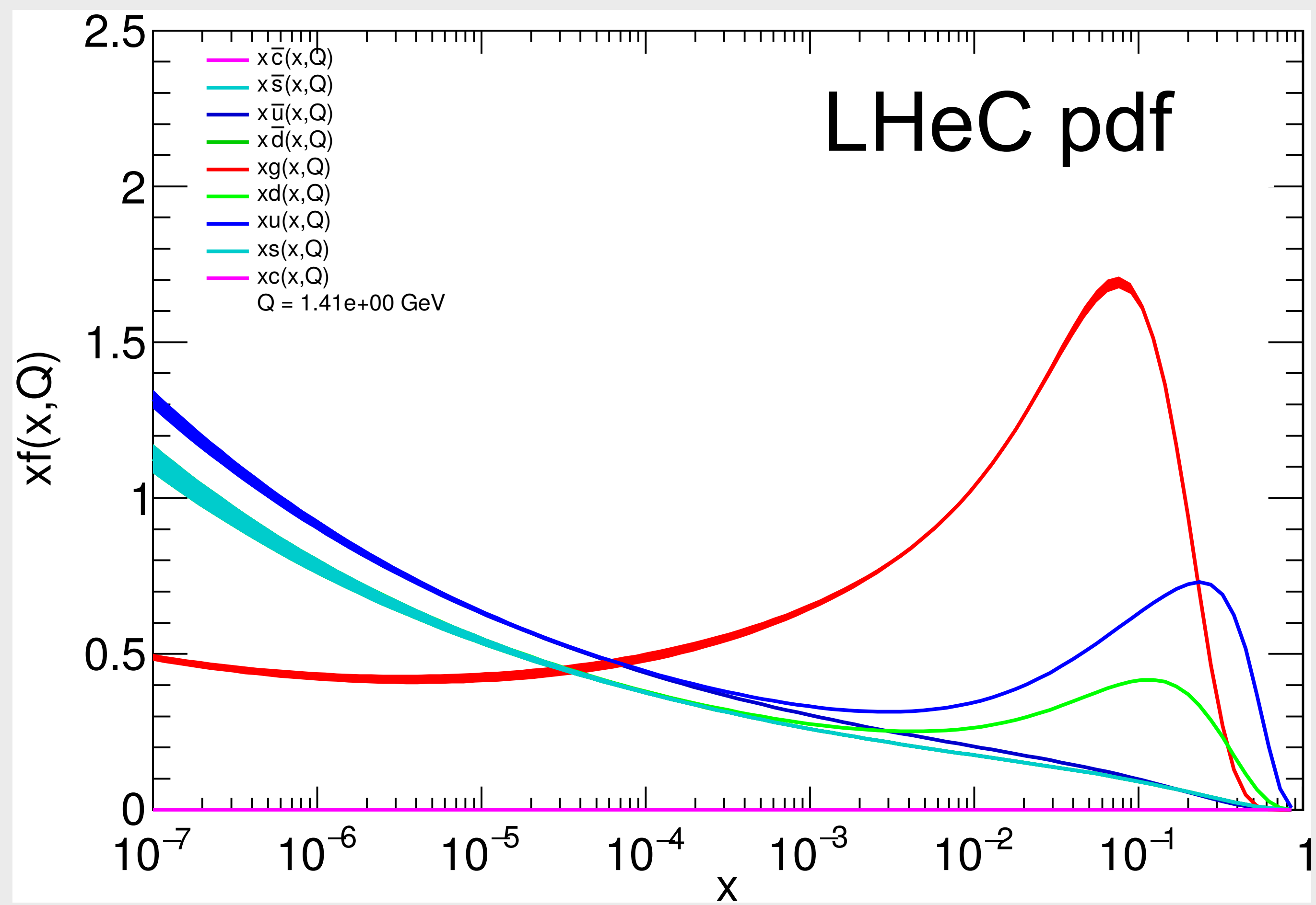


PDFs at the HL-LHC (Q = 10 GeV)
PDF4LHC15
+ HL-LHC (scen A)
+ HL-LHC (scen C)
g (x, Q) / g (x, Q) [ref]
x
PDFs at the HL-LHC (Q = 10 GeV)
PDF4LHC15
+ HL-LHC (scen A)
+ HL-LHC (scen C)
d (x, Q) / d (x, Q) [ref]
x
PDFs at the HL-LHC (Q = 10 GeV)
PDF4LHC15
+ HL-LHC (scen A)
+ HL-LHC (scen C)
ū (x, Q) / ū (x, Q) [ref]
x
PDFs at the HL-LHC (Q = 10 GeV)
PDF4LHC15
+ HL-LHC (scen A)
+ HL-LHC (scen C)
s⁺ (x, Q) / s⁺ (x, Q) [ref]
x

PDFs: LHeC


W (combined +/-)
E. Kay & U. Klein using VRAP v0.9
δ PDF w.r.t CT14nnlo [%]
NNPDF 3.0 (90% CL)
NNPDF 3.0 (68% CL)
MMHT14 (68% CL)
ABM16 (68% CL)
JR14 (68% CL)
CT14 NNLO (90% CL)
LHeC-13p LL (68% CL)
m_inv [GeV]


dv/uv distribution at Q² = 10⁴ GeV²
CT14
NNPDF3.0
MMHT2014
ABM12
CJ15 (T=10)
CJ15 (T=1.645)
LHeC
x


LHeC pdf
x c̄(x,Q)
x s̄(x,Q)
x ū(x,Q)
x d̄(x,Q)
xg(x,Q)
xd(x,Q)
xu(x,Q)
xs(x,Q)
xc(x,Q)
Q = 1.41e+00 GeV
xf(x,Q)
x

pp collider	Cross Section σ [pb] Total	ggH	VBF	WH	ZH	$t\bar{t}H$	tH	$ggHH$
LHC (13 TeV)	56	48.6	3.77	1.36	0.88	0.510	0.074	0.031
HL-LHC	62	54.7	4.26	1.50	0.99	0.613	0.090	0.037
HE-LHC	168	147	11.8	3.40	2.47	2.86	0.418	0.140
FCC$_{hh}$	936	802	69	15.7	11.4	32.1	4.70	1.22

e^+e^- collider ($\mathscr{P}_{e^-}/\mathscr{P}_{e^+}$)	Cross Section σ [fb] Total	VBF CC/NC	ZH	$t\bar{t}H$	ZHH (CC VBF)
CEPC	199	6.19/0.28	192.6		
FCC$_{ee}$	199	6.19/0.28	192.6		
ILC$_{250}$ (-80/30)	313	15.4/0.70	297		
ILC$_{500}$ (-80/30)	262	158/7.8	96	0.41	0.2
CLIC$_{380}$ (0/0)	160	40/7.4	113	–	0.029 (0.0020)
CLIC$_{1500}$(0/0)	329	290/30	7.5	1.3	0.082 (0.207)
CLIC$_{3000}$(0/0)	532	480/49	2	0.48	0.037 (0.77)
CLIC$_{380}$ (-80/0)	209	68/8.7	133	–	0.034 (0.0024)
CLIC$_{1500}$(-80/0)	574	528/35	8.8	1.70	0.97 (0.37)
CLIC$_{3000}$(-80/0)	921	860/57	2.4	0.61	0.043 (1.38)
CLIC$_{380}$ (+80/0)	112	13/6.0	93	–	0.024 (0.0016)
CLIC$_{1500}$(+80/0)	91	59/24	6.2	0.89	0.068 (0.045)
CLIC$_{3000}$(+80/0)	138	96/40	1.7	0.34	0.30 (1.56)

e^-p collider ($\mathscr{P}_{e^-}$)	Cross Section σ [fb] Total	VBF	tH	HH (CC VBF)
LHeC (0)	130	110/20	0.07	0.01
HE-LHeC (0)	247	206/41	0.37	0.04
FCC$_{eh}$ (0)	674	547/127	4.2	0.26
LHeC (-80)	221	197/24	0.12	0.02
HE-LHeC (-80)	420	372/48	0.67	0.07
FCC$_{eh}$ (-80)	1189	1040/149	7.6	0.47