The LHeC as Part of the HL-LHC Programme

XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects

12-16 April 2021

L. Aperio Bella

on behalf of the Large Hadron-Electron Collider at the HL-LHC community

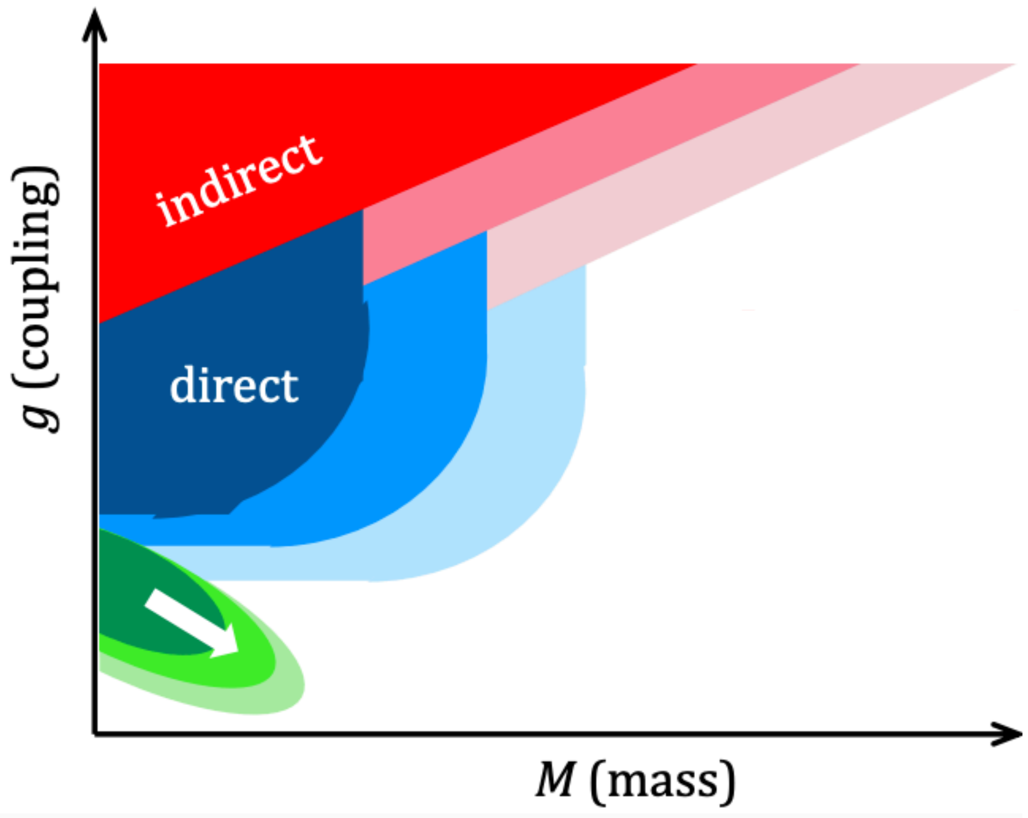
The duality of current and future particle physics program

Dark Matter ? Baryogenesis ? Strong CP ? Fermion mass spectrum & mixing ? unification of forces? Cosmological Constant ? EW hierarchy ? lepton flavour violation? substructure of matter?

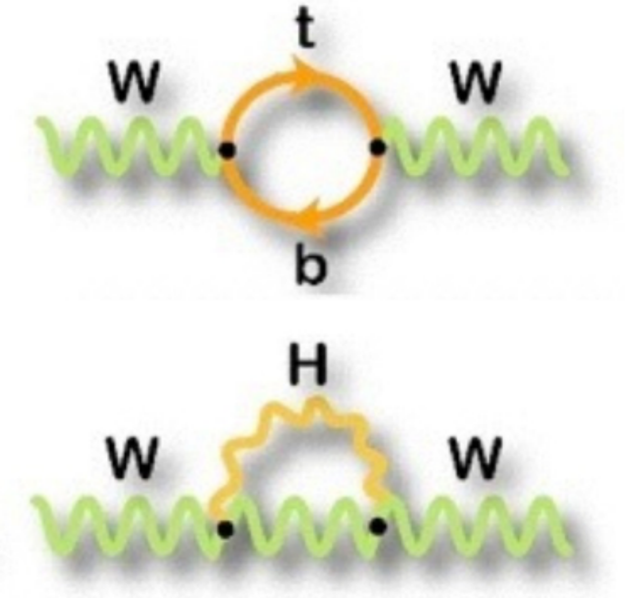
→ The goal of LHC and future experiment physics program is to find answers to these open questions

Paradigma of the current time: where to look for deviation of the standard model ? Currently there are two complementary approaches pursue:

Direct search of sign of new physics



Indirect search: In the absence of direct signals for new physics, precision measurements of fundamental EW parameter could be the groundbreaking path for the next discovery.

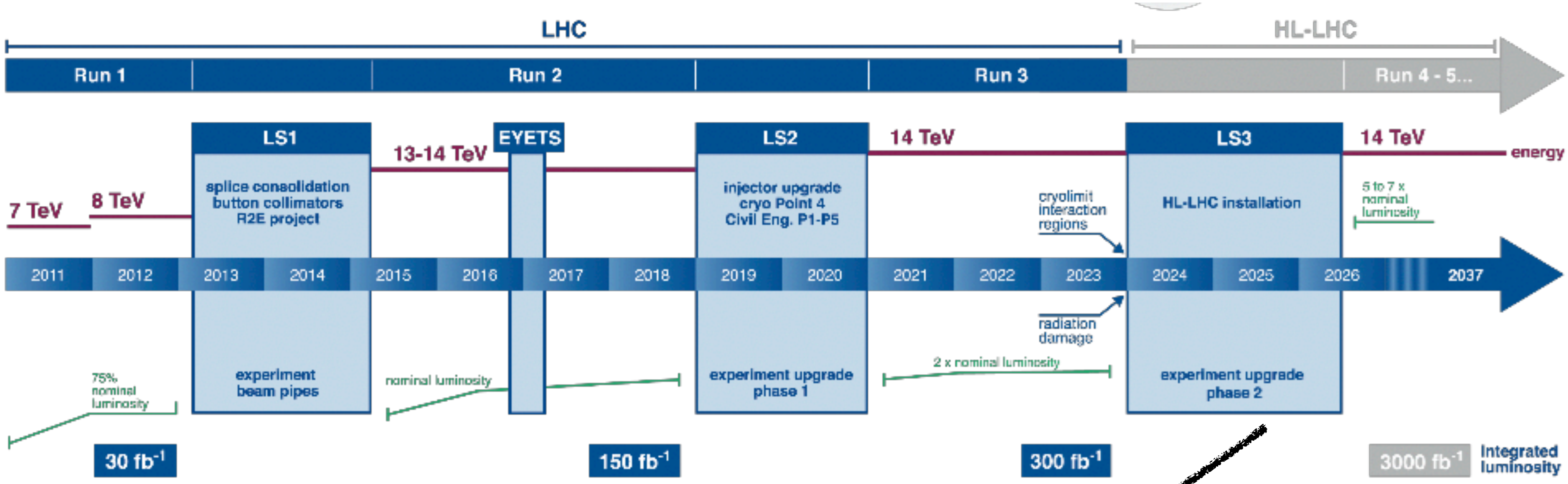


LHC is both: energy frontier AND high precision
With concurrent ep and pp operation in the HL phase we will achieve the ideal potential.

HL-LHC plan

Extraordinary results obtained with the LHC-Run2 physics program.
However real sensitivity potential on several milestone analysis for the LHC physics program will be reach only in the HL-LHC era

physic potential @HL-LHC



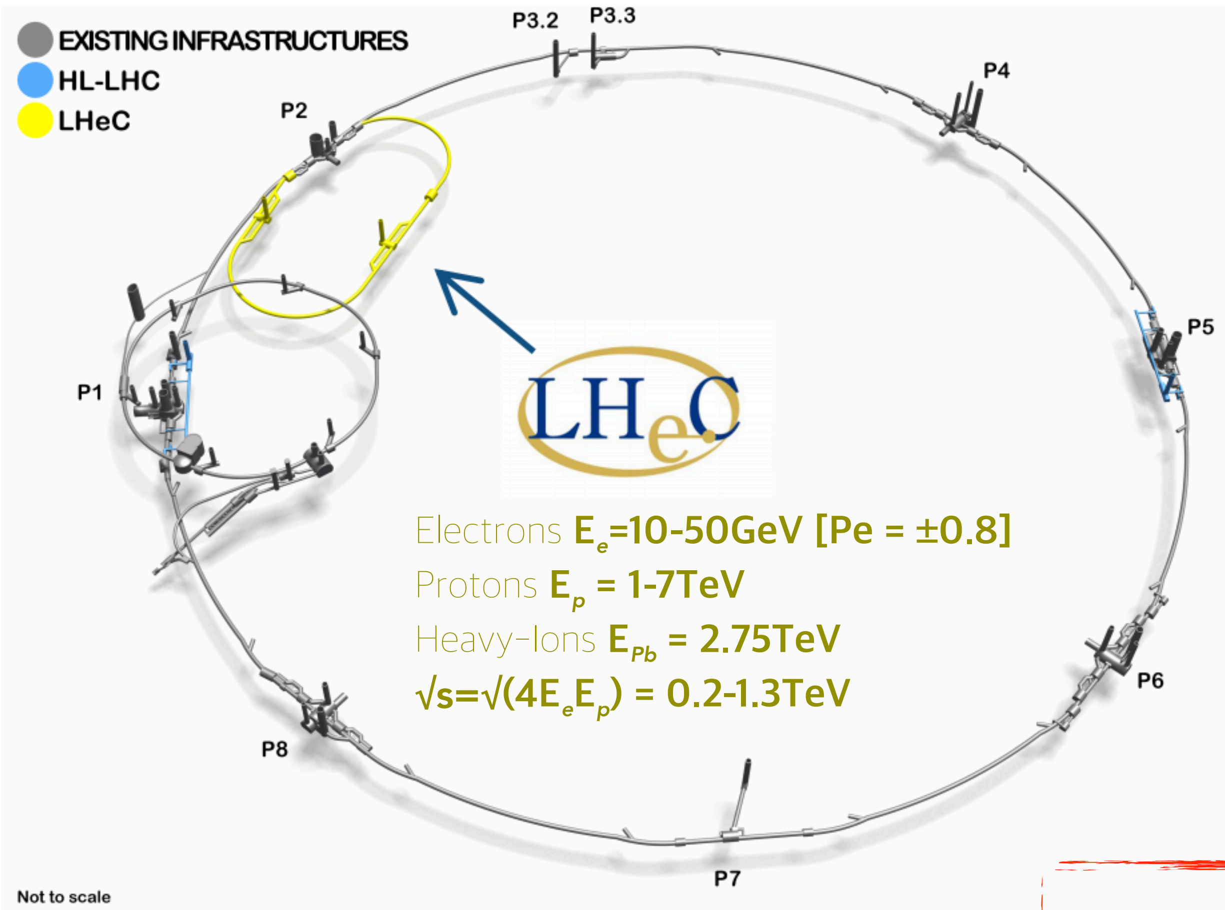
Extensive upgrades to accelerator complex to maximise physics reach

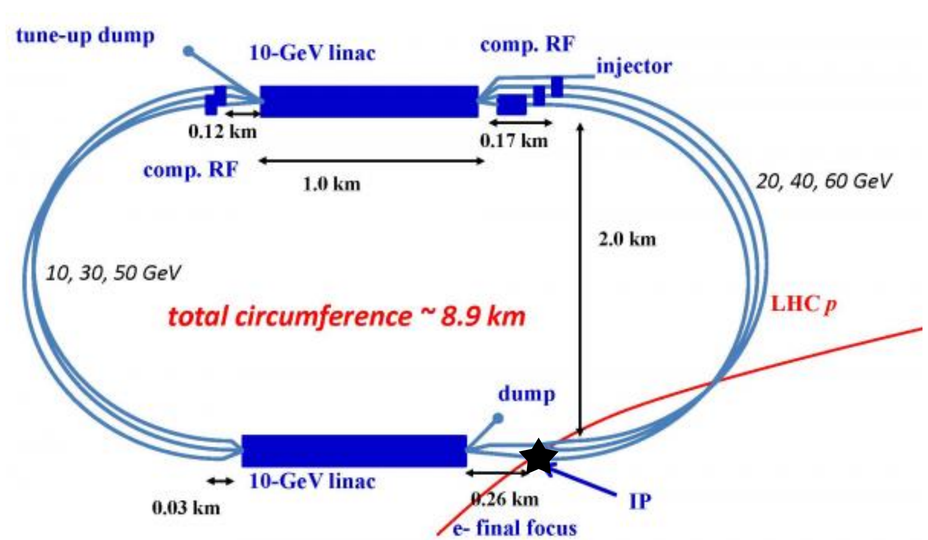
3000 fb-1 at 14 TeV (ultimately 4000 fb-1)

Instantaneous luminosity: 5 × 1034 cm−2 s−1 (ultimately 7.5 × 1034 cm−2)

Proton interactions per bunch crossing: < μ > ~ 140 (ultimately < μ > ~ 200)

LHeC basic concept





LHeC a next generation TeV energy electron-proton collider.

NEW: Electron-Ion collision extend the kinematic range by 3-4 orders

With √s=1.3TeV the LHeC would provide a **major extension of the DIS kinematic range** [down to x= 10-6 and covering high Q2] **as is required for the physics programme at the energy frontier.**

Accelerator complex based on multi-turn **energy-recovery linac (ERL) machines**

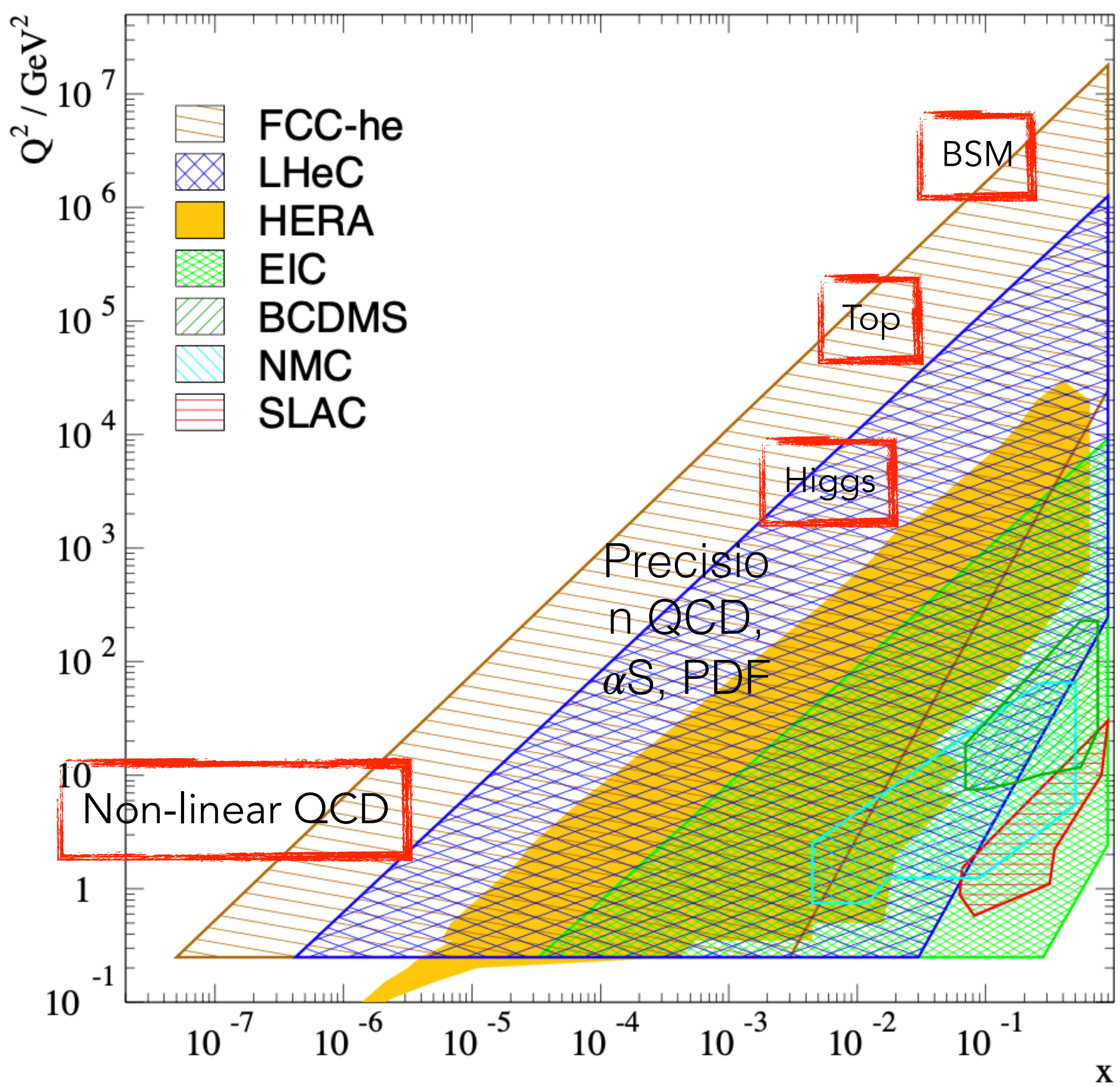
The electron-proton interaction does not disturb the protons beams **—> LHeC may operate synchronously with HL-LHC**

$\int dt \mathscr{L}$ = 1-2 ab^{-1}

see as well:
The Large Hadron-electron Collider at CERN: Status and Plans, Christian Schwanenberger
The ERL Facility PERLE at Orsay, Alex Bogacz

LHeC physics program

DIS: the cleanest high resolution microscope and a laboratory for new particles and new dynamics.



Physics program of LHeC:

- Parton Distributions - Resolving the Substructure of the Proton
- Exploration of Quantum Chromodynamics
- Extensive Electroweak and Top Quark Physics
- A novel Higgs Physics facility
- Potential for Discovery of new physics Beyond the Standard Model
- REVOLUTION in Nuclear Particle Physics with Electron-Ion Scattering at the LHeC

Influence of the LHeC on Physics at the HL-LHC :

With concurrent ep and pp operation, the LHeC would transform the LHC into a 3-beam, twin collider of greatly improved potential.

Through ultra-precise strong and electroweak measurements, the ep experiment can make the HL-LHC complex a much more powerful search and measurement laboratory than current expectations, based on pp only, do entail.

LHeC white paper [aka CDR update]

LHeC physics program

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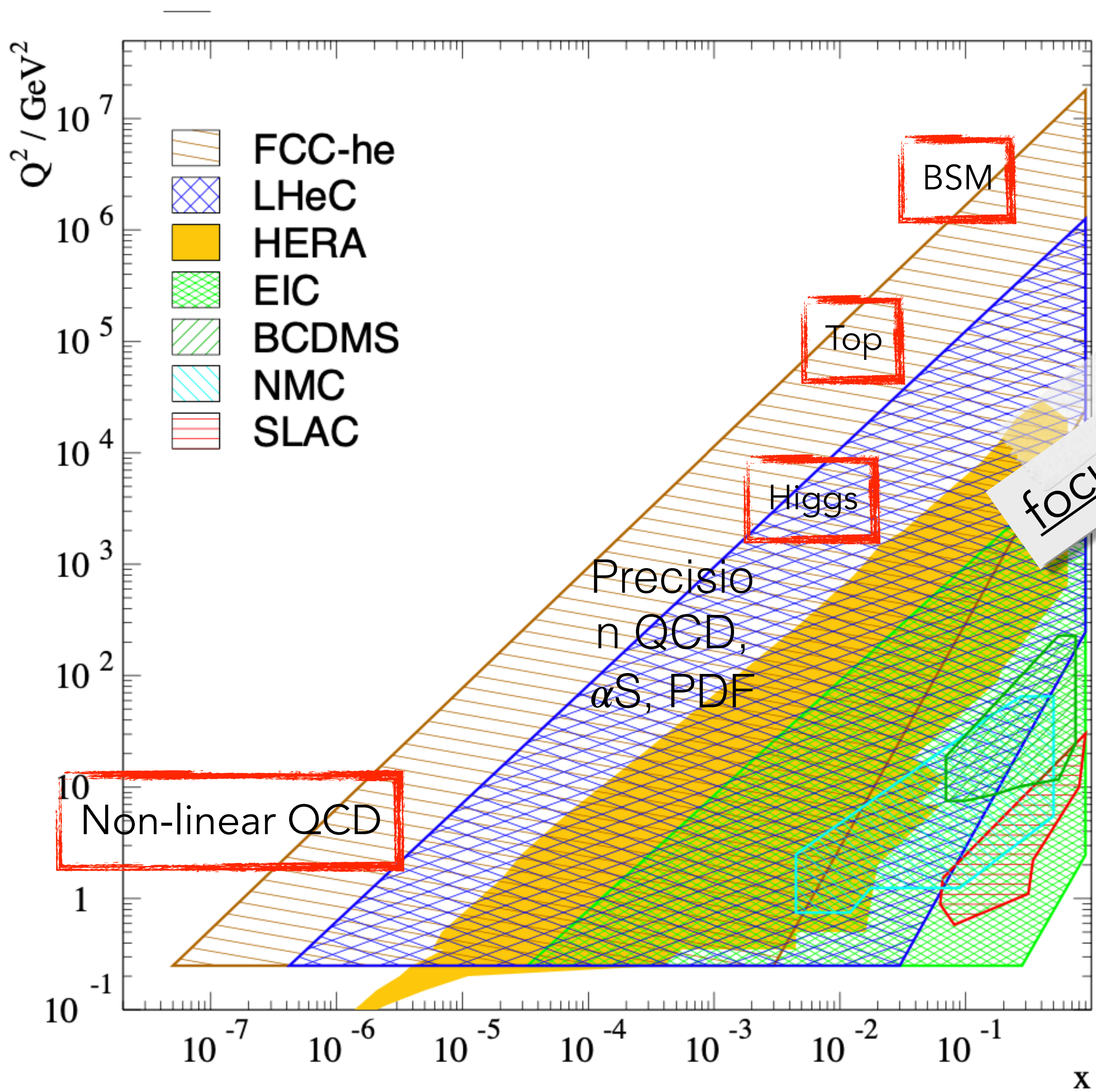

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focus of this talk

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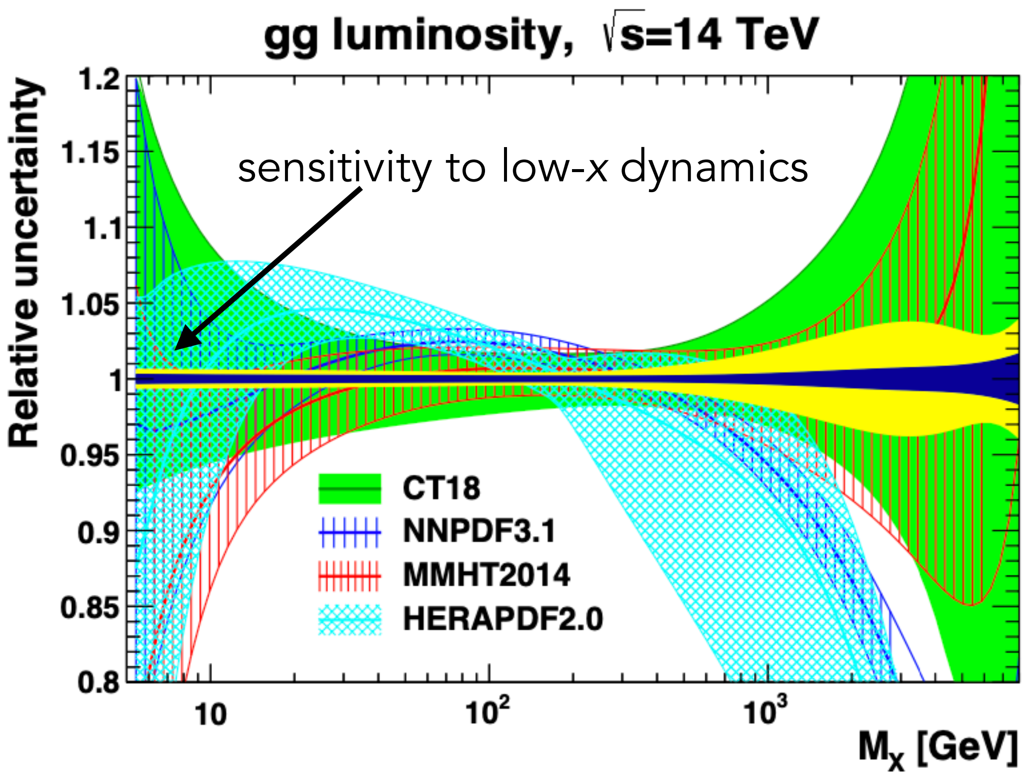
LHeC white paper [aka CDR update]

LHeC: Parton Distribution function

Energy frontier ep colliders unique resolution of partonic contents and dynamics inside the proton.



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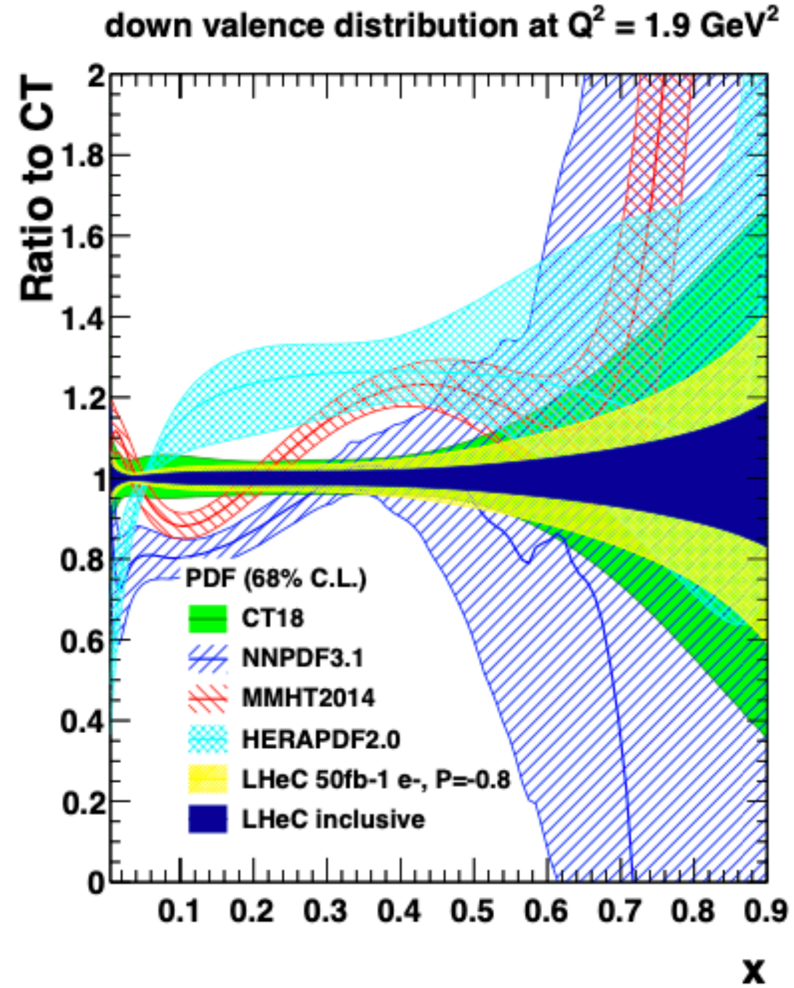


large x crucial for HL/HE–LHC and FCC searches; also relevant for DY, m_W

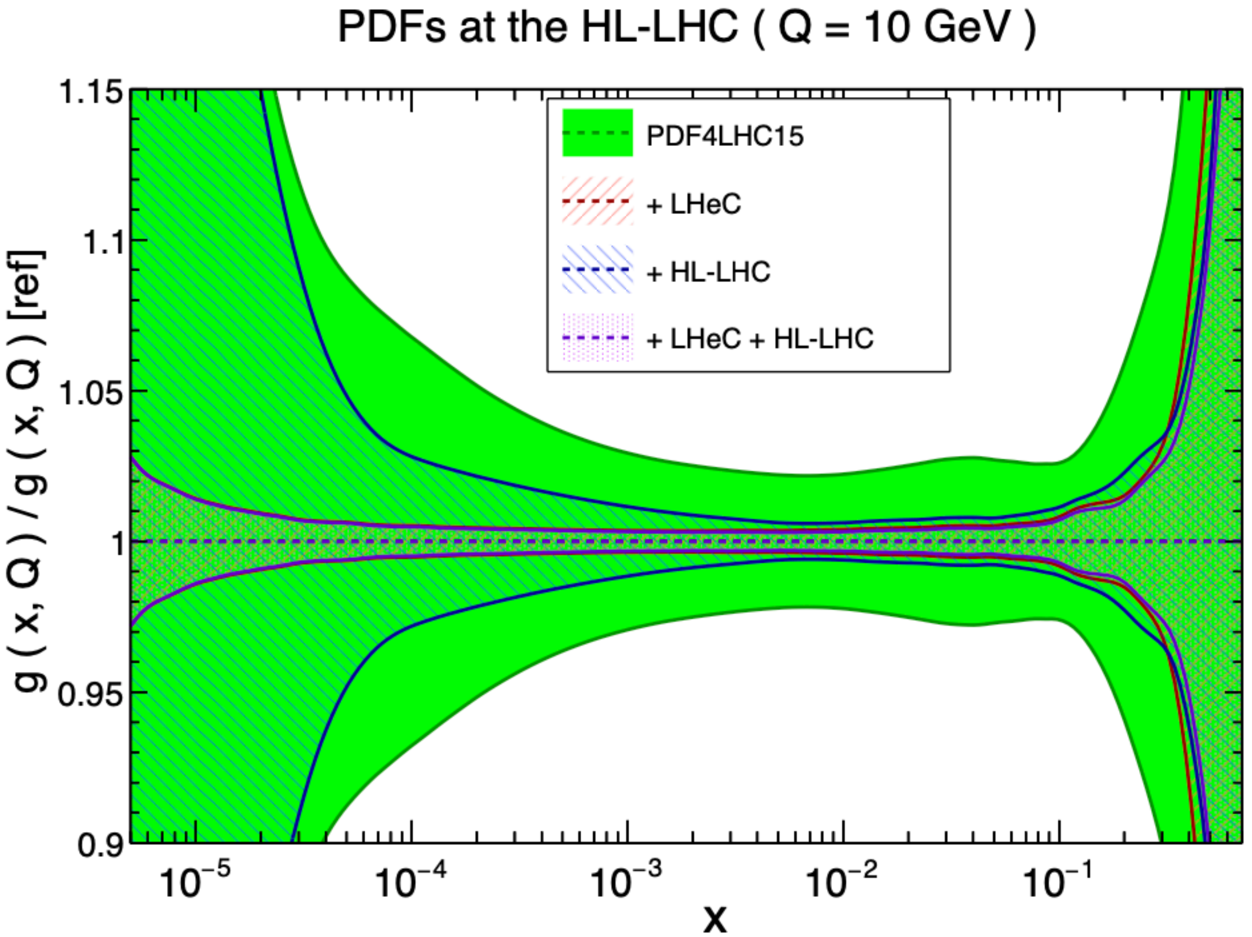
LHeC provides a single, coherent base for PDF determination to N3LO

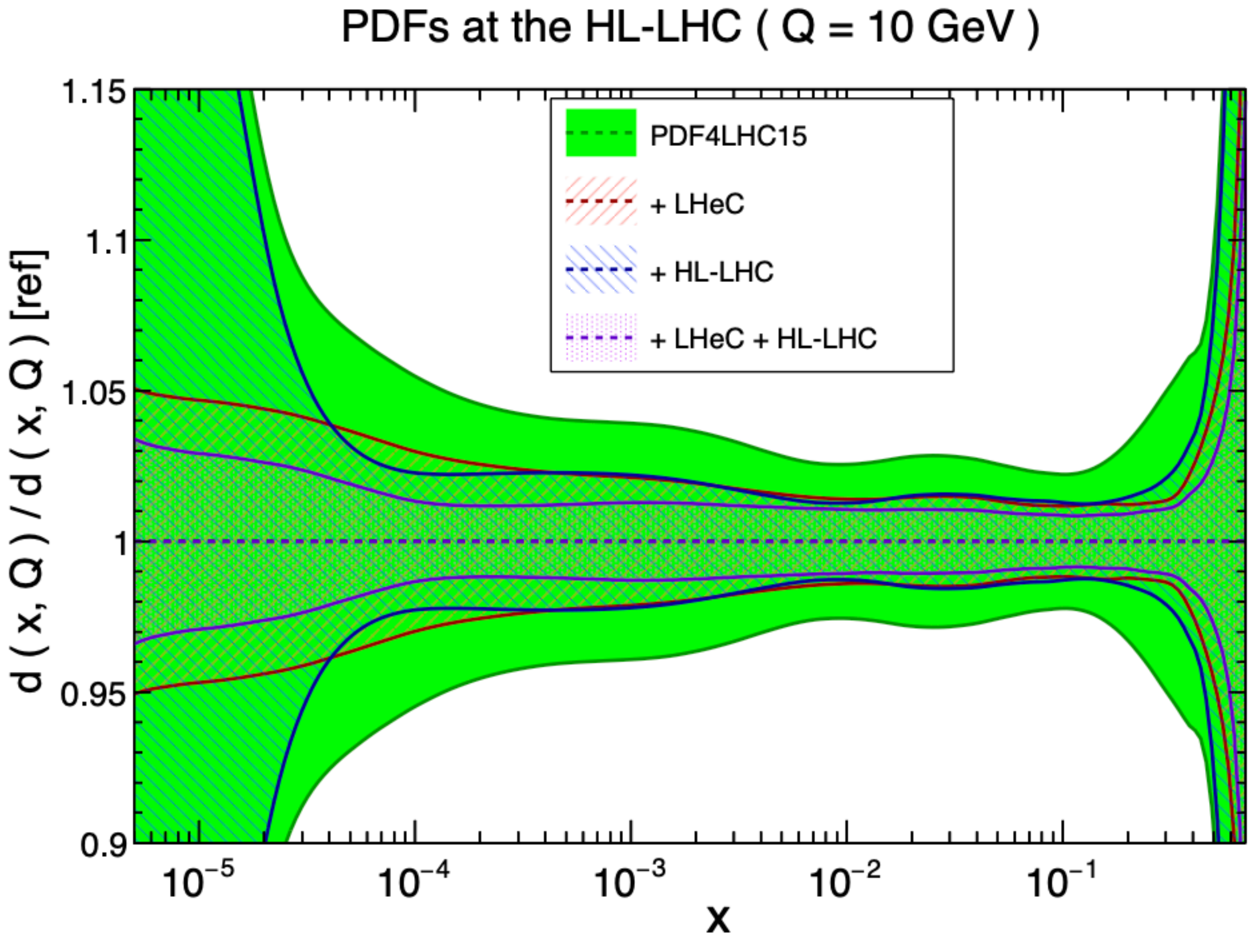
Essential input for full exploitation of current and future hadron colliders measurement (Higgs, BSM, EW, …) limited by PDF knowledge

For details:
Determination of the Parton Densities in the Proton at the LHeC, Claire Gwenlan

HL-LHC and LHeC are complementary in their PDF constraining abilities

Impact of HL-LHC/LHeC data on the 1-σ relative PDF uncertainties of g and down quark.





HL-LHC and LHeC complementarity reducing PDF errors in different x regions

eg. HL-LHC reduced high-x gluons while LHeC reduces low-x gluon

Combination of both HL-LHC and LHeC pseudodata nicely illustrate a clear and significant reduction in PDF uncertainties over a very wide range of x

LHeC is the correct and necessary complement to the pp collider.

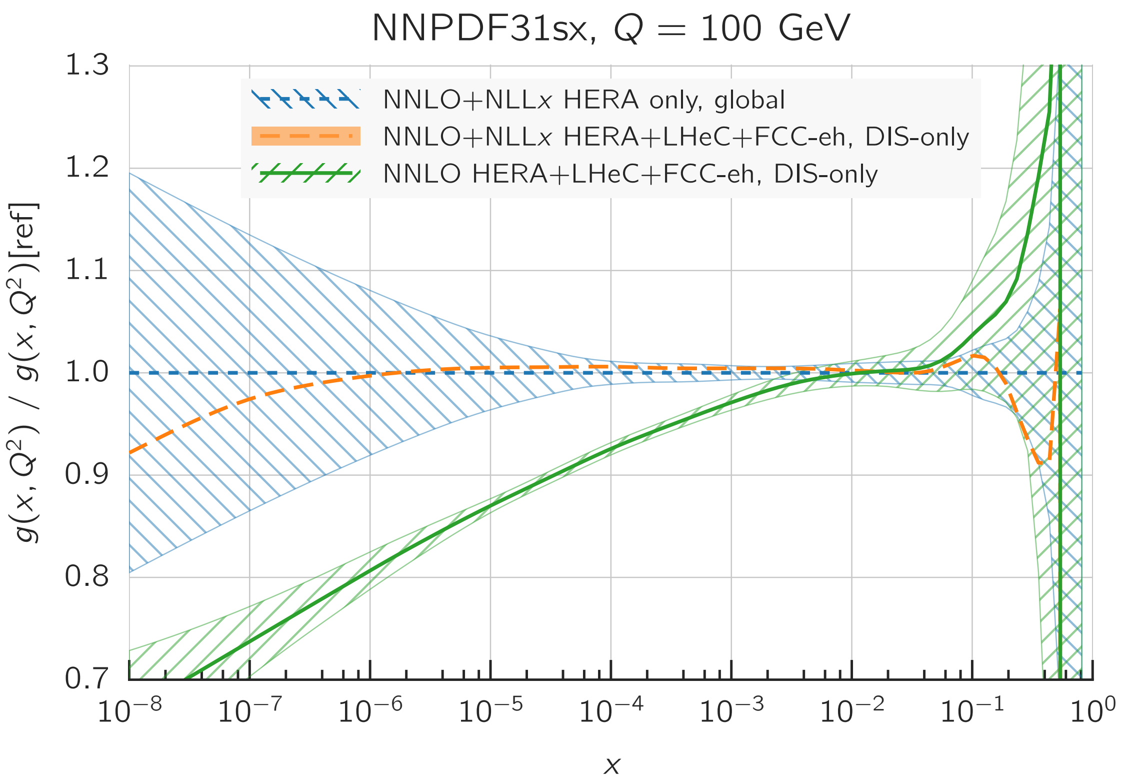
1906.10127

LHeC: QCD insight

α_s to permille exp. precision achievable with NC DIS jets

Unprecedented access to **novel kinematic regime** of DIS characterised by very small values of x

Ball,Bertone,Bonvini, Marzani,Rojo,Rottoli

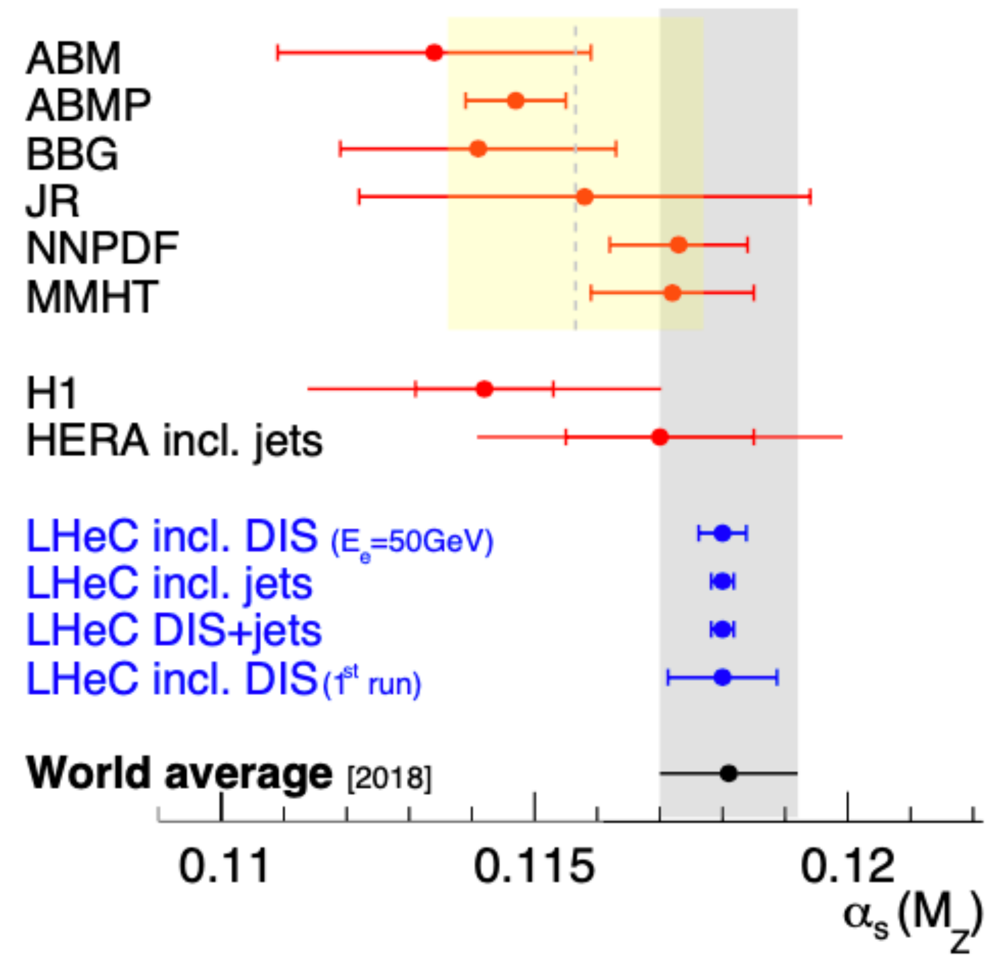


At **low-x new phenomena** my occur which go beyond the standard collinear perturbative description based on DGLAP evolution.

LHeC has large sensitivity and discriminatory power to pin down details of small x QCD dynamics

Physics program of LHeC:

- Parton Distributions - Resolving the Substructure of the Proton
- Exploration of Quantum Chromodynamics



LHeC can measure **α_s to per mille accuracy**

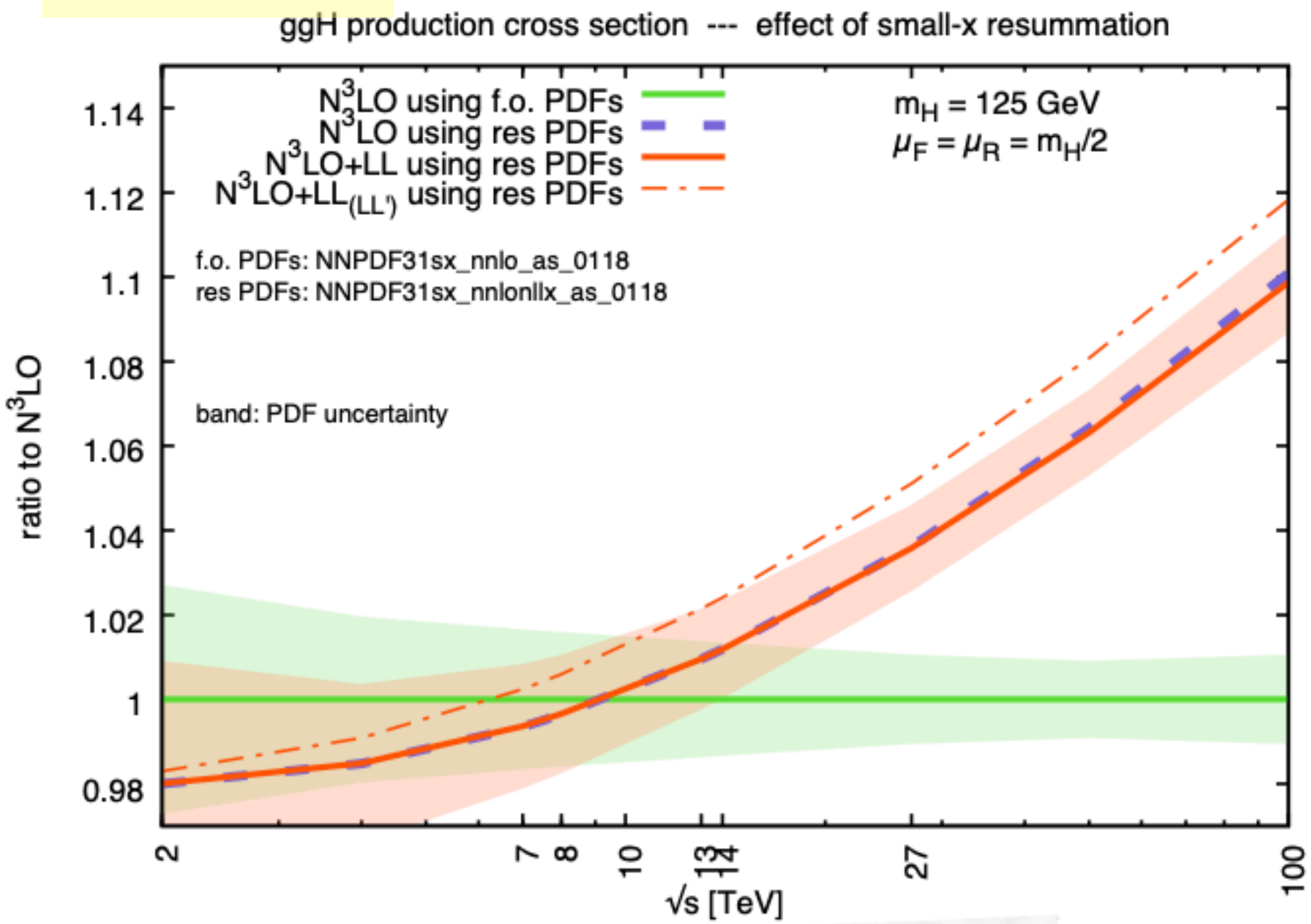
All α_s determinations from global fits based on NC/CC

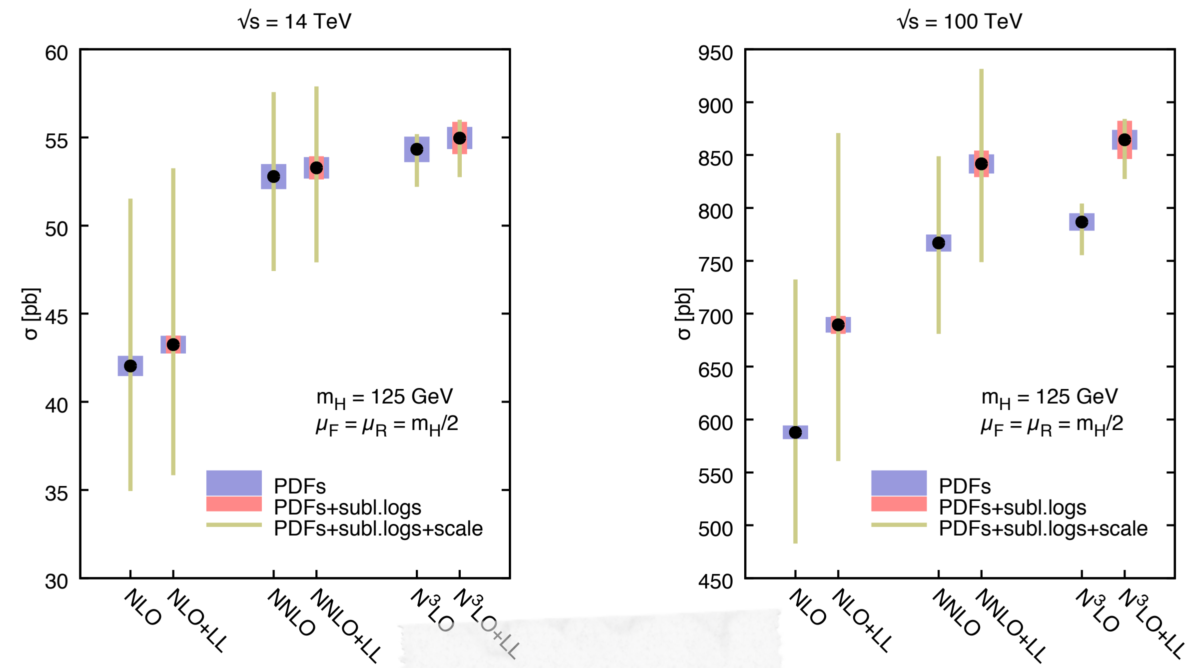
With the expected precision from LHeC the discrepancy between DIS data and lattice QCD framework/global electroweak fit will be resolved.

Impact of New Small-x Dynamics on Hadron Collider Physics

LHeC and FCC-eh have unprecedented kinematic reach to explore small x phenomena

arXiv:1812.07831





impact for LHC and even more for very low x values probed at FCC

effect of small x resummation on N3LO **Higgs cross section for HL-LHC** and future collider Higgs Xsection

For details:
Small-x Physics at the LHeC and FCC-eh, Anna Stasto

LHeC: EW and top physics

DIS data competitive/complementary in performing high precision measurements of **top properties**
Very wild and powerful **EW precision physics program**:

- Precise measurement of mW in the t-channel
- Precision measurements of the running of sin2qW

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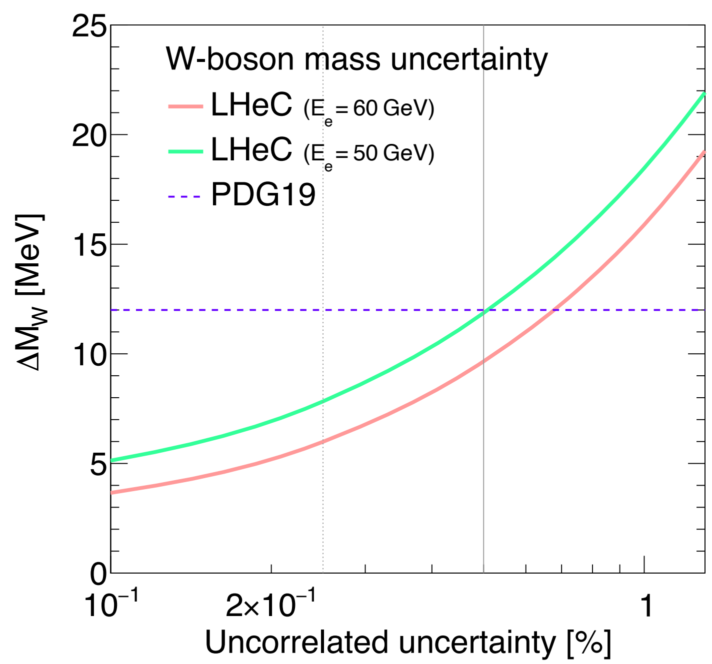
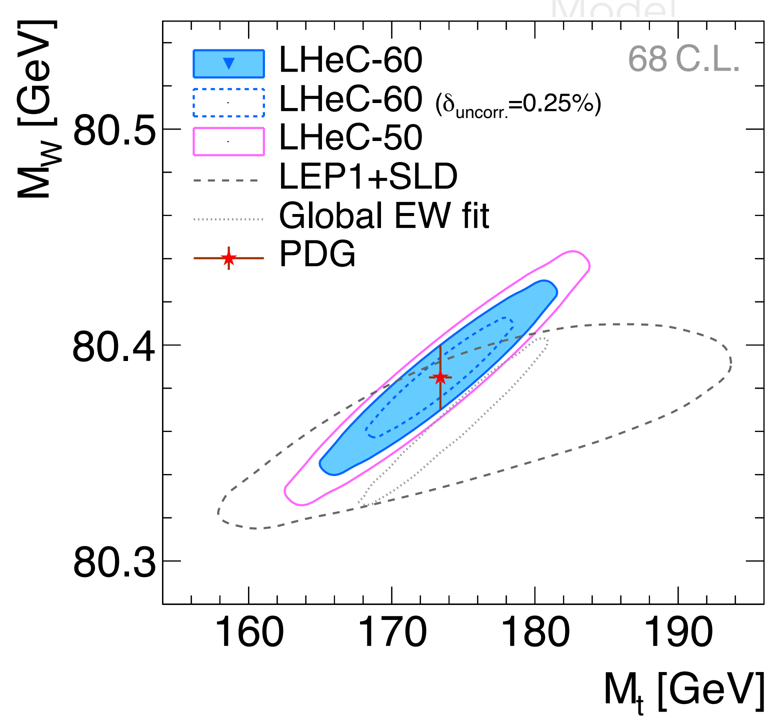
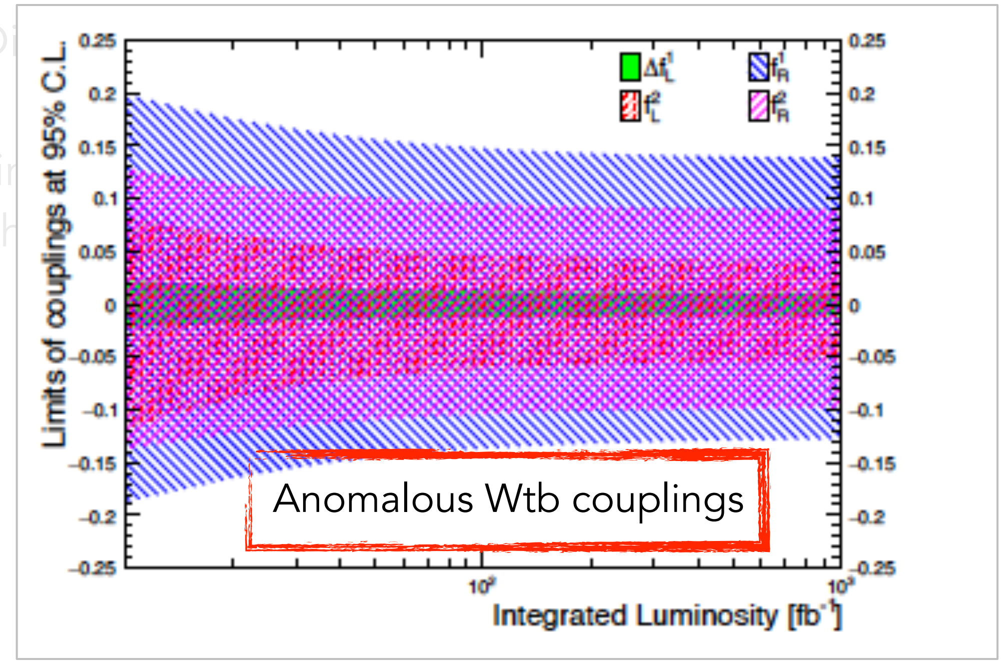
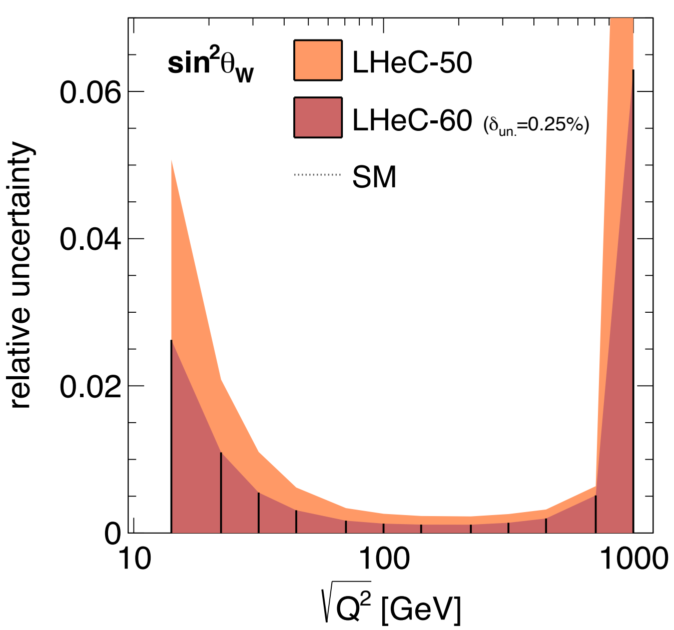
- Potential for Di
  Model







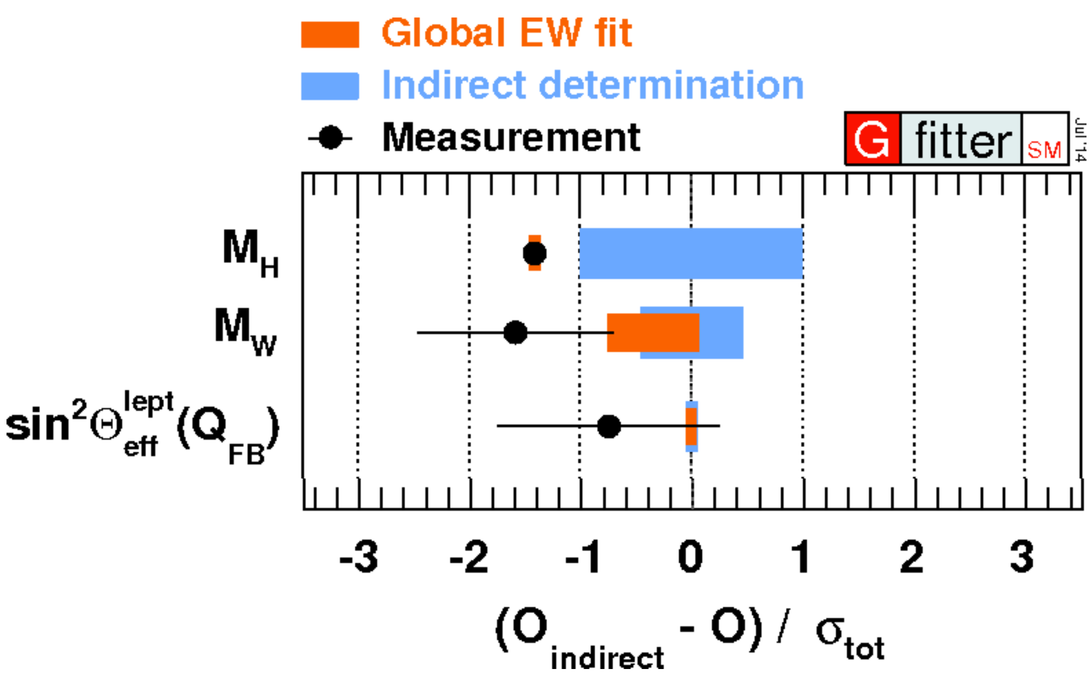


In contrast to α_{QED}, the evolution of $\sin^2\theta^W$ with Q^2 carries ~no uncertainty in the SM, so constitutes a powerful test of BSM, specific to ep.

For details:
Top physics at the LHeC and the FCC-eh, Mukesh Kumar
Precision electroweak measurements at the LHeC and the FCC-eh, Daniel Britzger

Extraction of the key parameter of SM in pp collision

One of the **goal of HL-LHC physics program:** tests of the consistency of the EW sector in the SM through high precision measurements of its fundamental parameters ($\sin^2\theta_W$ and m_W)



Indirect determination of both m_W and $\sin^2\theta^{eff}$ more precise then the experimental measurement:

- This call for a precise direct Measurement
  - ✓ Stringent test of the self consistency of the SM
  - ✓ might reveal sign of new physics

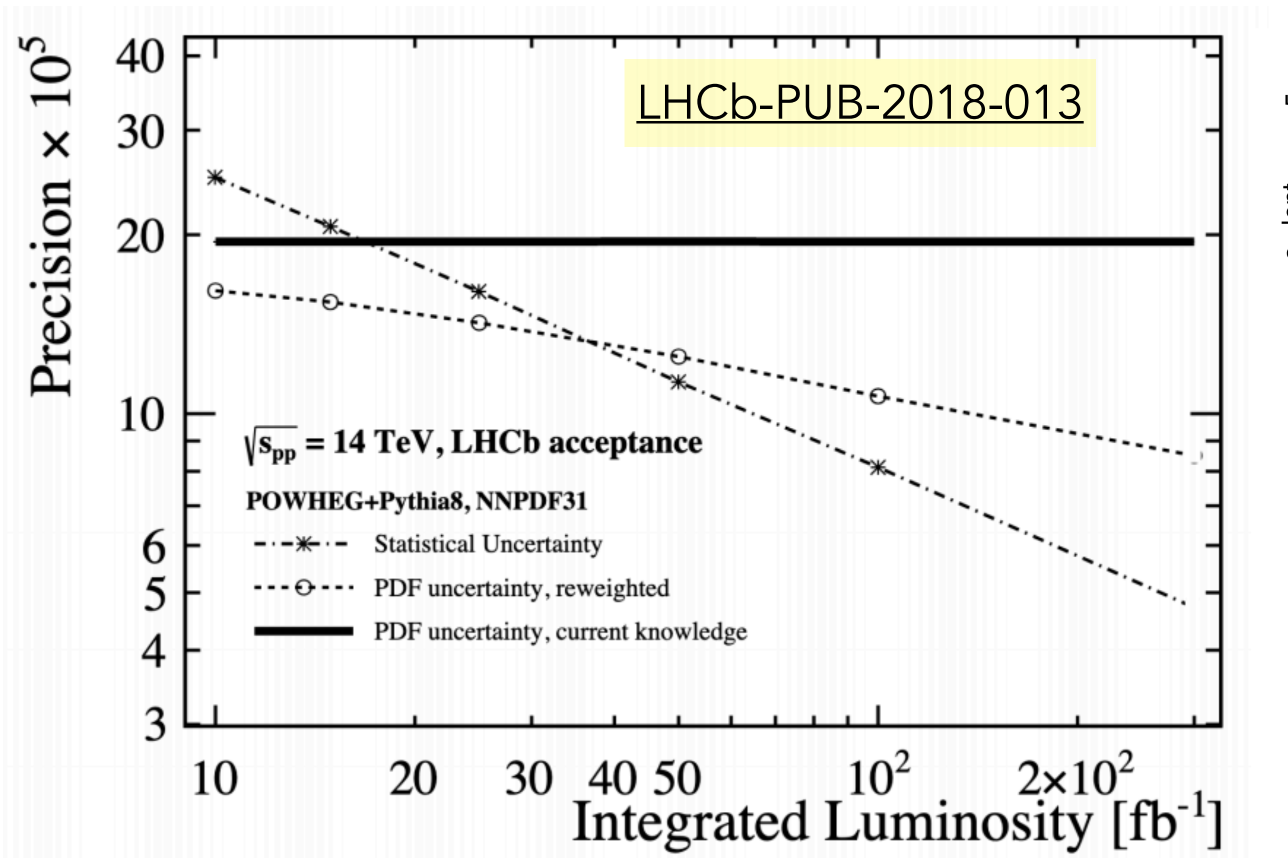
INDIRECT DETERMINATION	MEASUREMENT REQUIRED PRECISION	LHC MEASUREMENT
δm_W ±8 MeV	Call for δm_W^{exp} < 10 MeV	δm_W ±19 MeV
$\delta\sin^2\theta_{eff}$ ± 6x10^{-5}	$\delta\sin^2\theta_{eff}$ ± 20x10^{-5} corresponds to ±10MeV error in mw	$\delta\sin^2\theta_{eff}$ ± 36x10^{-5}

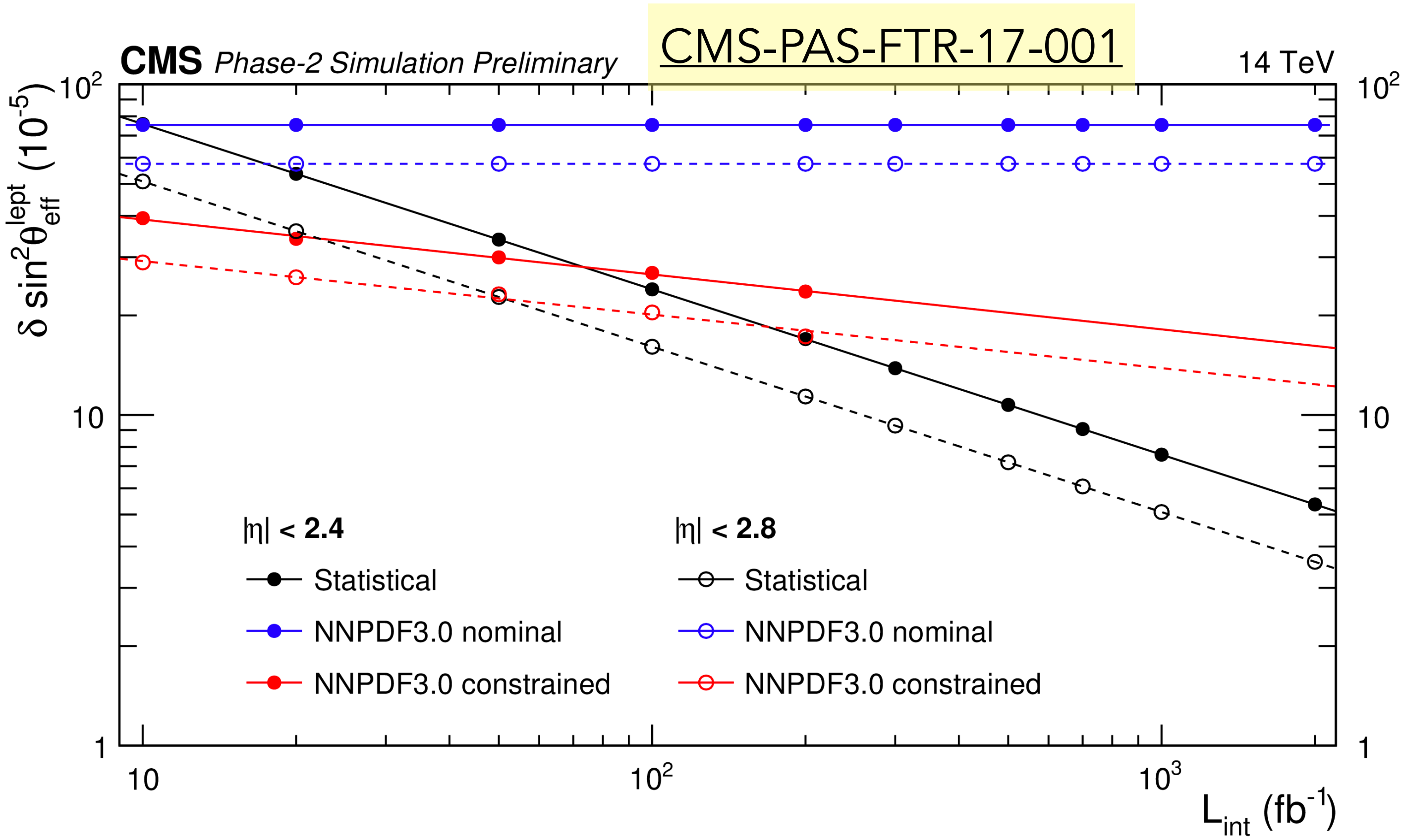
} ***measurement uncertainty dominated by PDF knowledge***

The EW precision measurements program at HL-LHC will highly **benefit from more precise knowledge of PDF.**

Weak mixing angle @HL-LHC

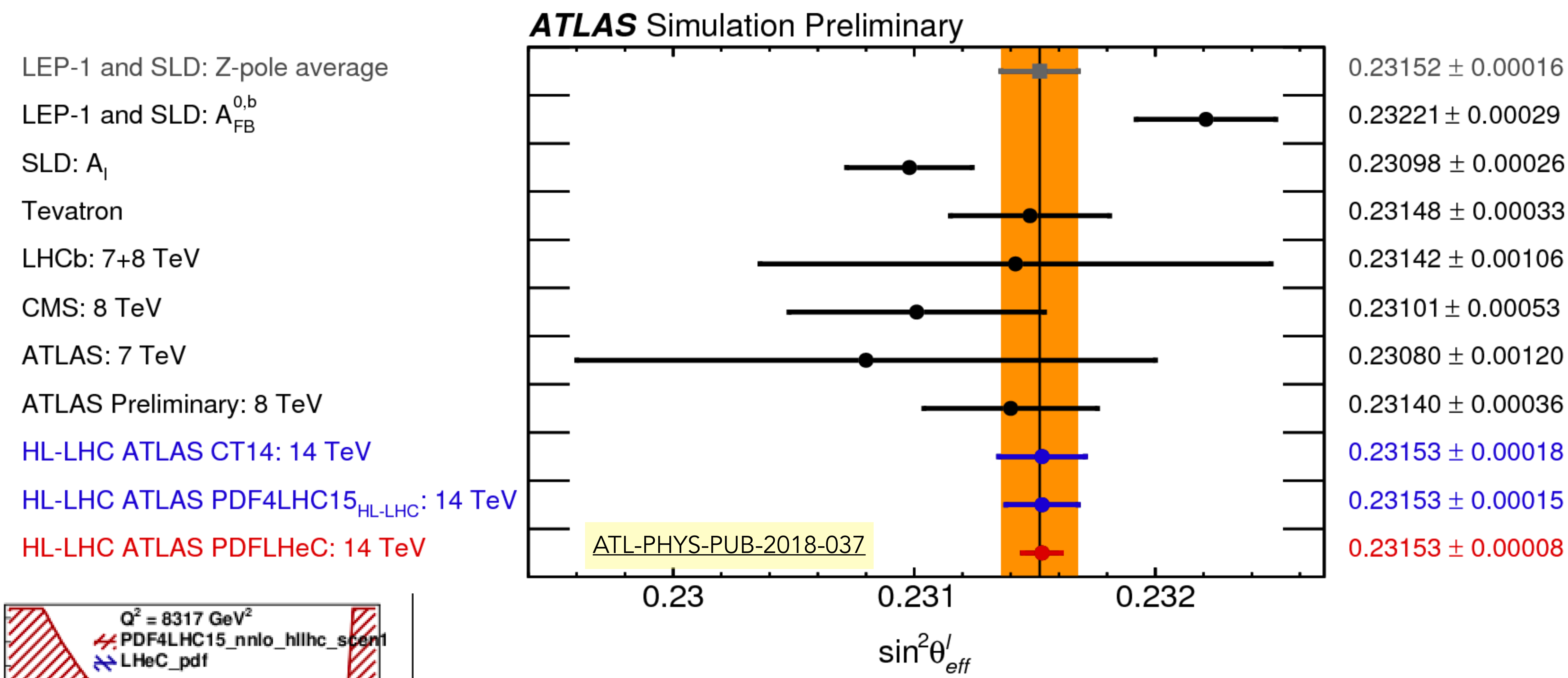
LHC experiments entered the precision electroweak race: New analysis techniques, including in-situ PDF profiling and event categorisation substantially reduced statistical and systematic uncertainties wrt previous LHC measurements.

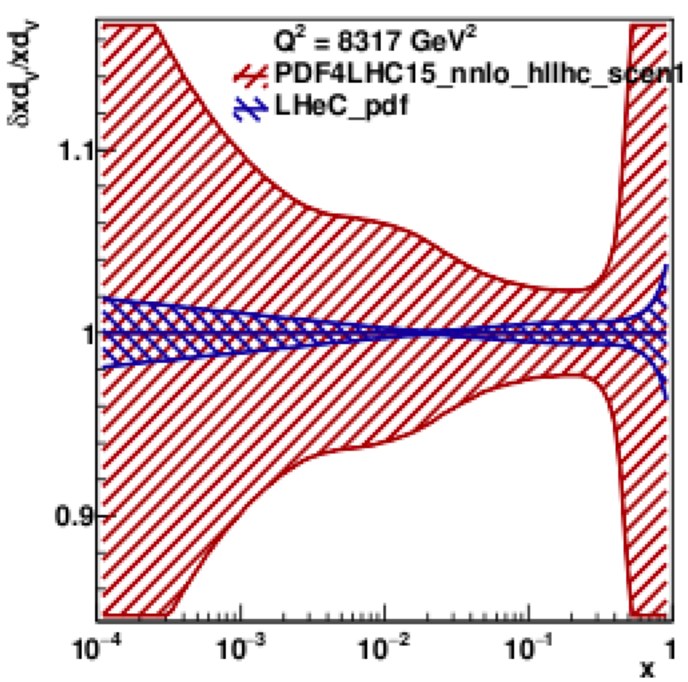




Current and future measurement at pp collider limited by PDF uncertainty

$\sin^2\theta_W$ extraction with LHeC data





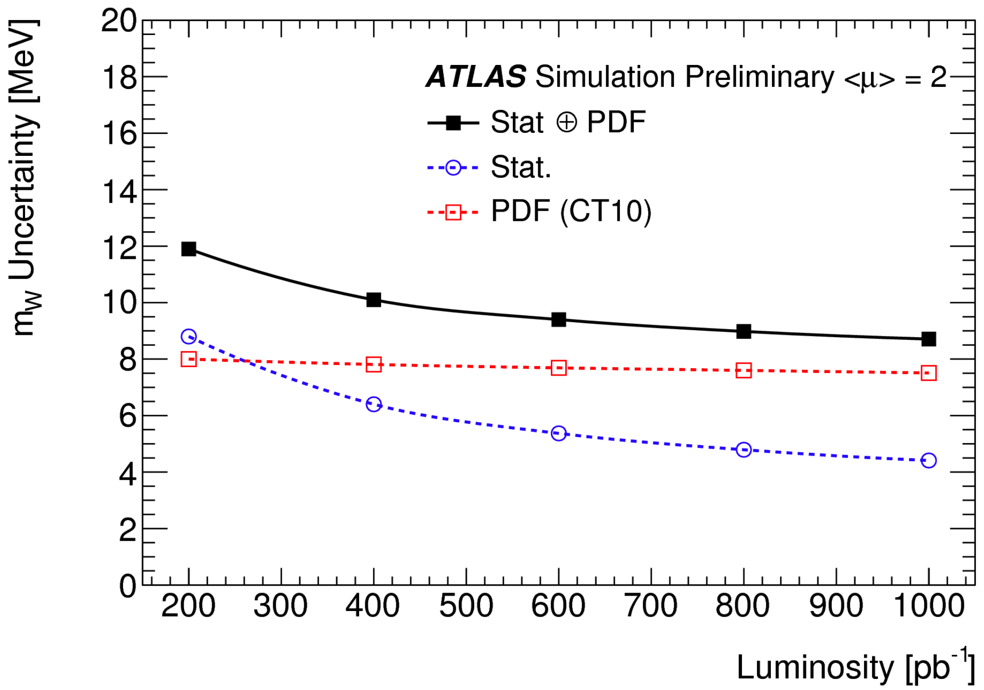
The expected sensitivity of the $\sin^2\theta_{eff}$ measurements is improved by **~20% using HL-LHC data/PDF sets**.

→ new DIS ep data (LHeC) would provide needed factor of 5 – 10 in PDF improvement to **exceed LEP precision**

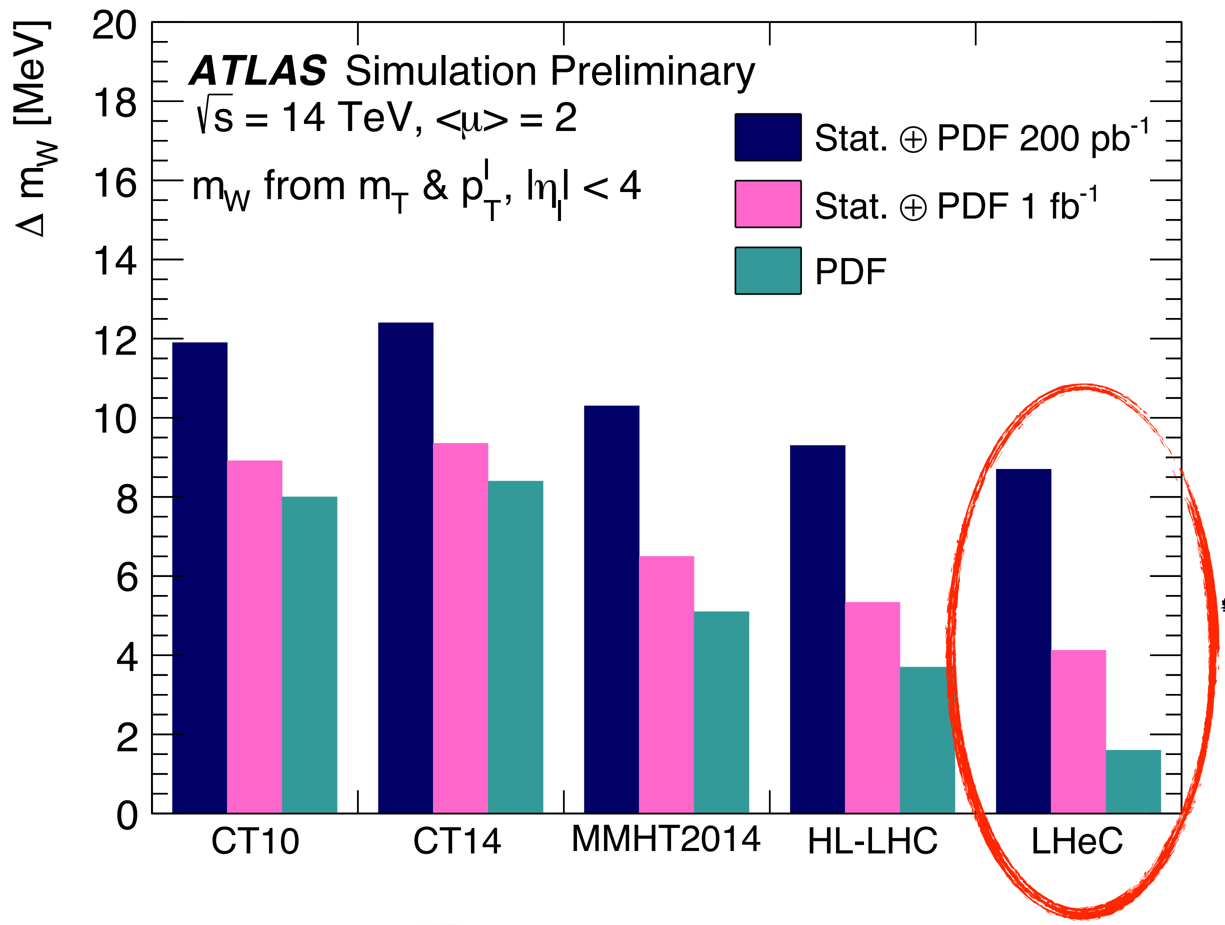
δm_W with LHeC input

m_W milestone measurement for consistency of SM and BSM teaches
Study of potential of m_W measurement with low pile-up runs, $<\mu>\sim 2$, at HL-LHC@14TeV

ATL-PHYS-PUB-2018-026



PDF uncertainty dominated by knowledge of valence quark PDFs (in particular d_V)



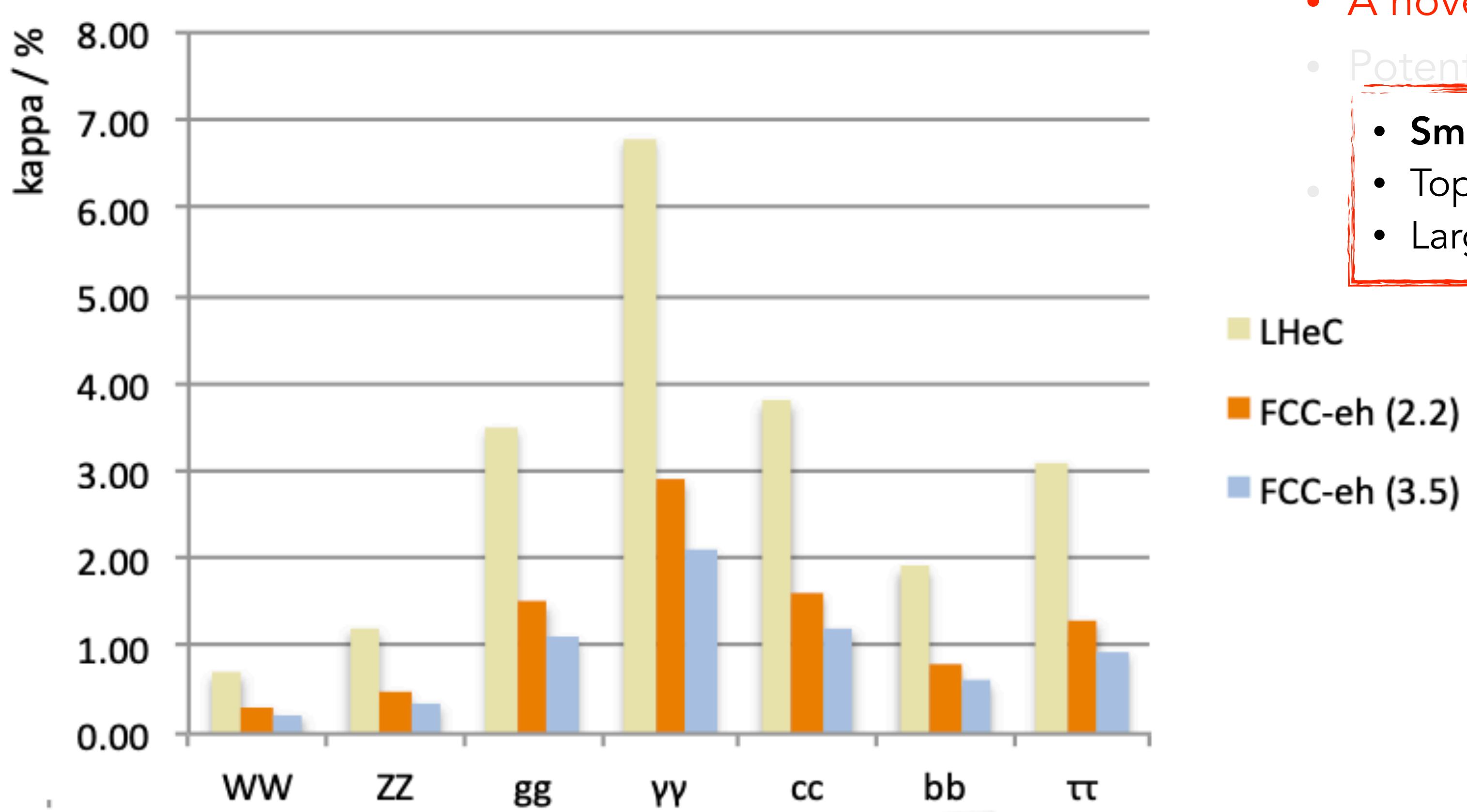
$\delta m_W^{PDF} \sim 2$MeV

Total uncertainty of $\delta m_W \sim$ **11(7) MeV** with 200(1000) pb^{-1} of data @HL-LHC. Future HL-LHC PDF set would reduce PDF uncertainty by **factor of 2**.

Future **LHeC** PDF set would reduce PDF uncertainty by **factor of 5-6** reaching: $\delta m_W < 8(5)$ MeV

LHeC: Higgs factory

DIS data as new Higgs factory ?



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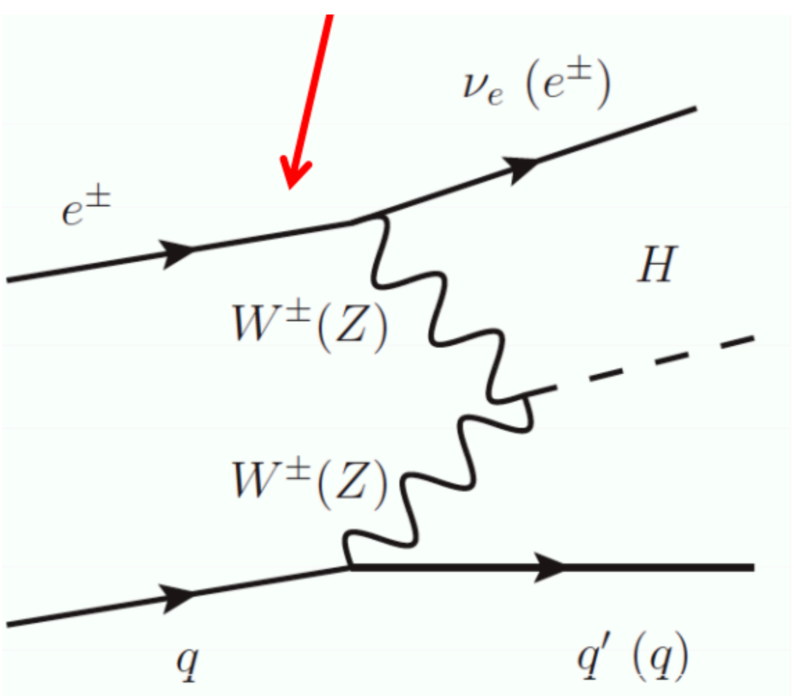
- **Small theoretical uncertainties**
- Topological requirements effective in background suppression
- Large S/B w.r.t. pp, e.g. in h→bb expect S/B=3

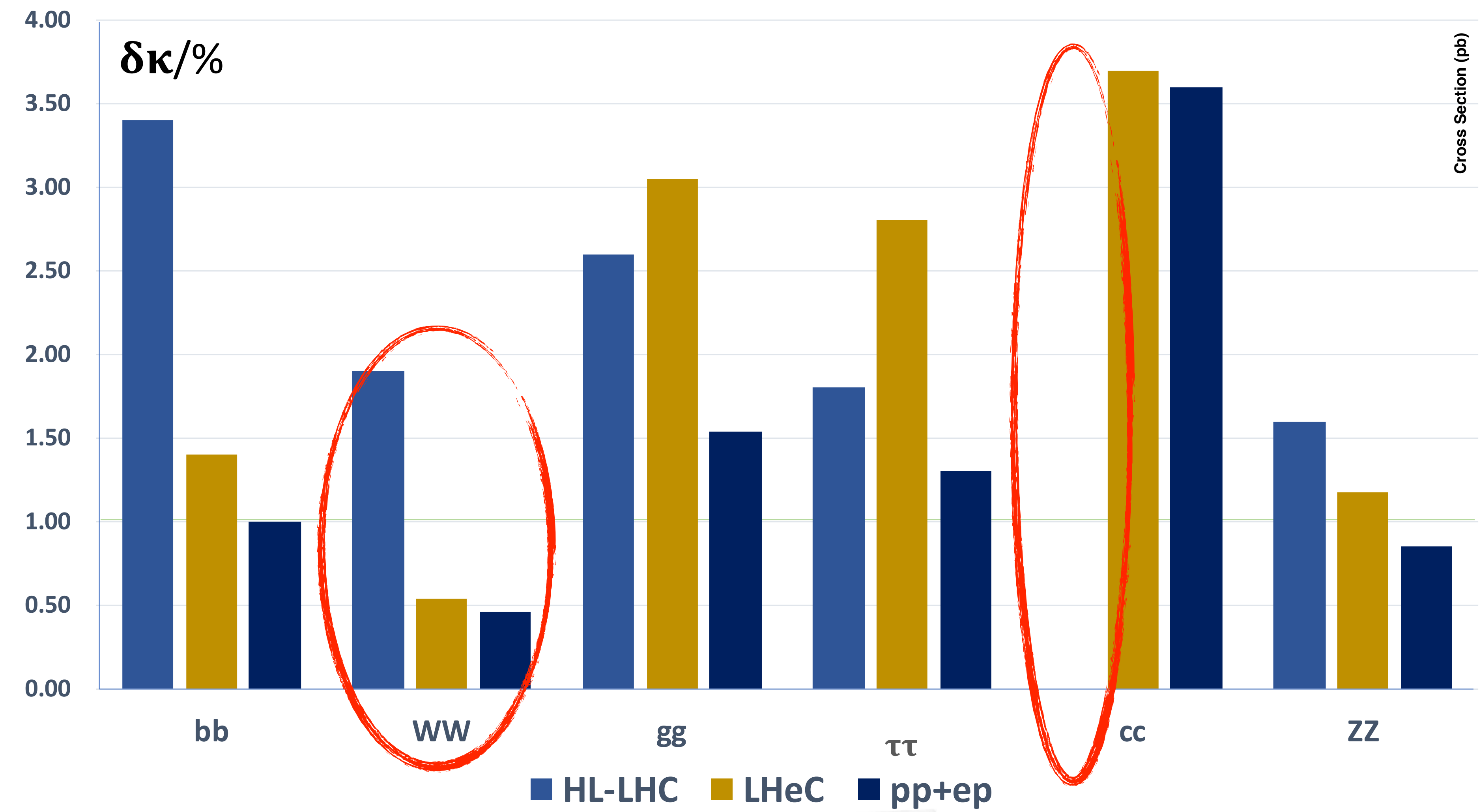


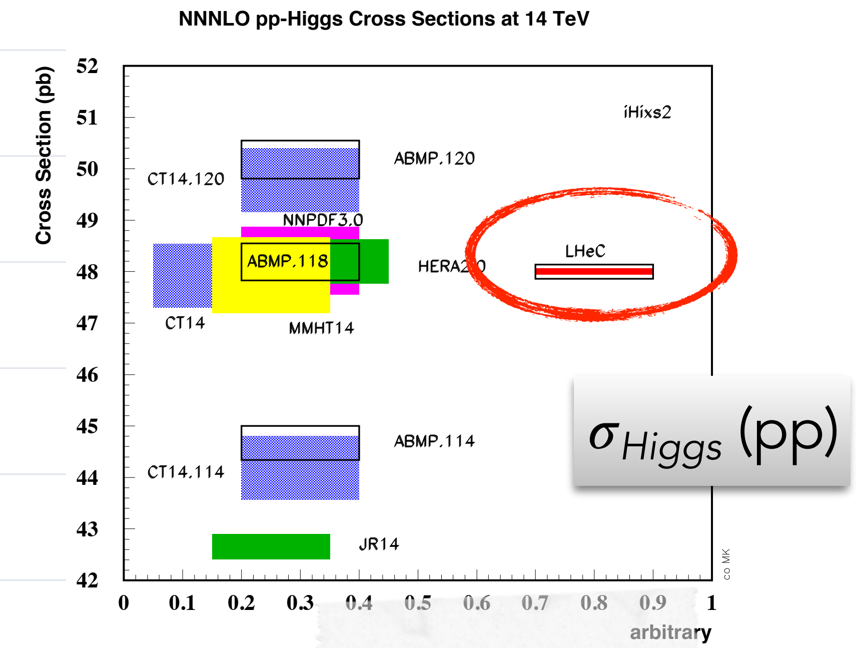
prospect for high precision measurement of Higgs couplings at future ep collider:
- Very high precision due to CC+NC DIS in clean environment in ep scattering
- Mainly WWH production + charm-direct coupling

Fully complementarity with pp.

For details:
Higgs physics at the LHeC and the FCC-eh, Uta Klein

SM Higgs couplings: Combine the complementary measurements for best physics outcome





What are the true PDF errors in σ_{Higgs} (pp) ? with LHeC input: Can achieve <0.5% precision in pdf uncertainty $\delta\sigma$=[0.3(pdf) + 0.2 (αs)]

- Combining pp with ep coupling results turns the LHC into a precision machine:
  - Reach <1%-<2% precision depending on coupling for pp+ep
  - ep adds charm direct coupling.
- Analysis in EFT framework work in progress (aTGCs in ep..)
- Competitive and complementary to e+e- as well!

LHeC: BSM physics program

The LHeC can probe sensitive regions of phase space difficult of access at LHC and complement results (FCC-eh opens higher energy regime)

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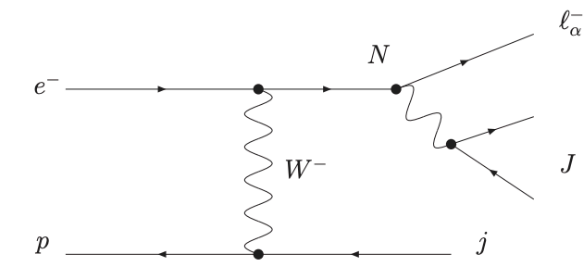
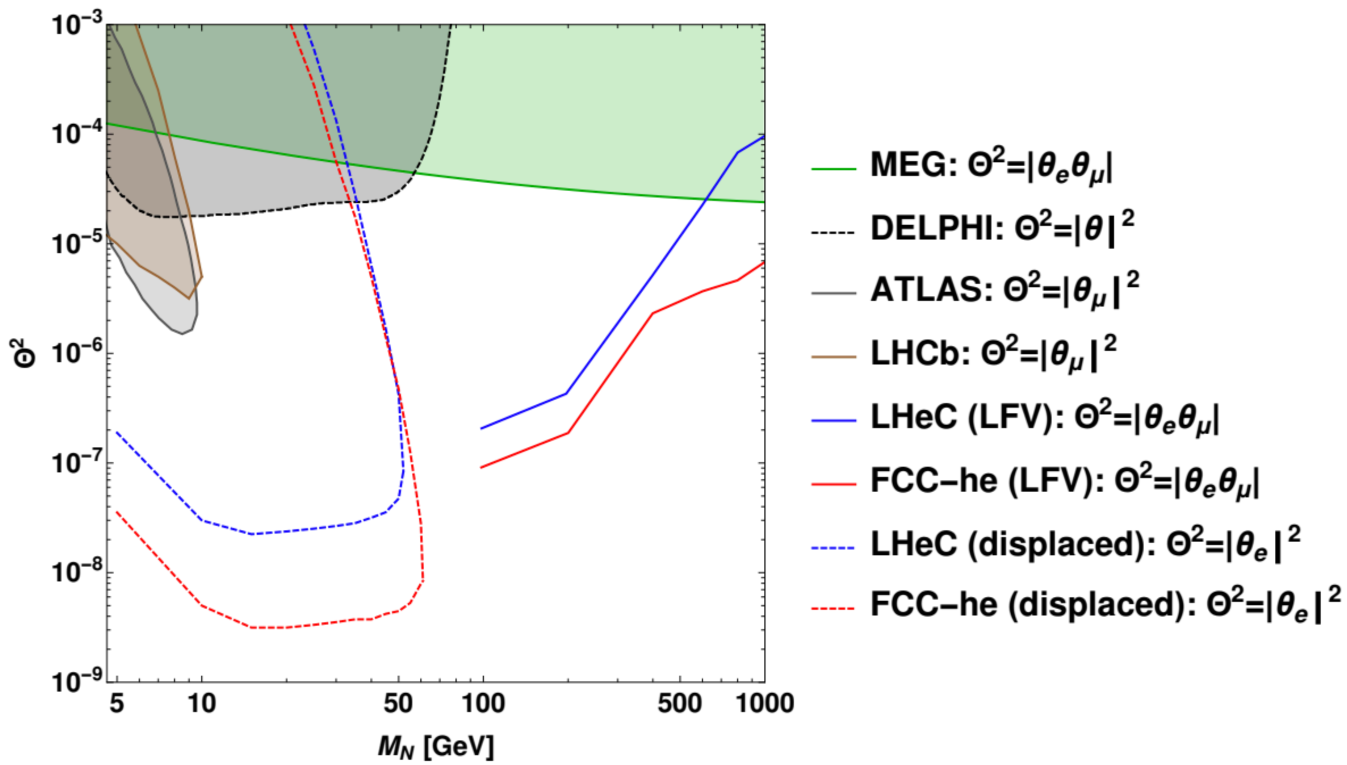
Heavy Neutrinos

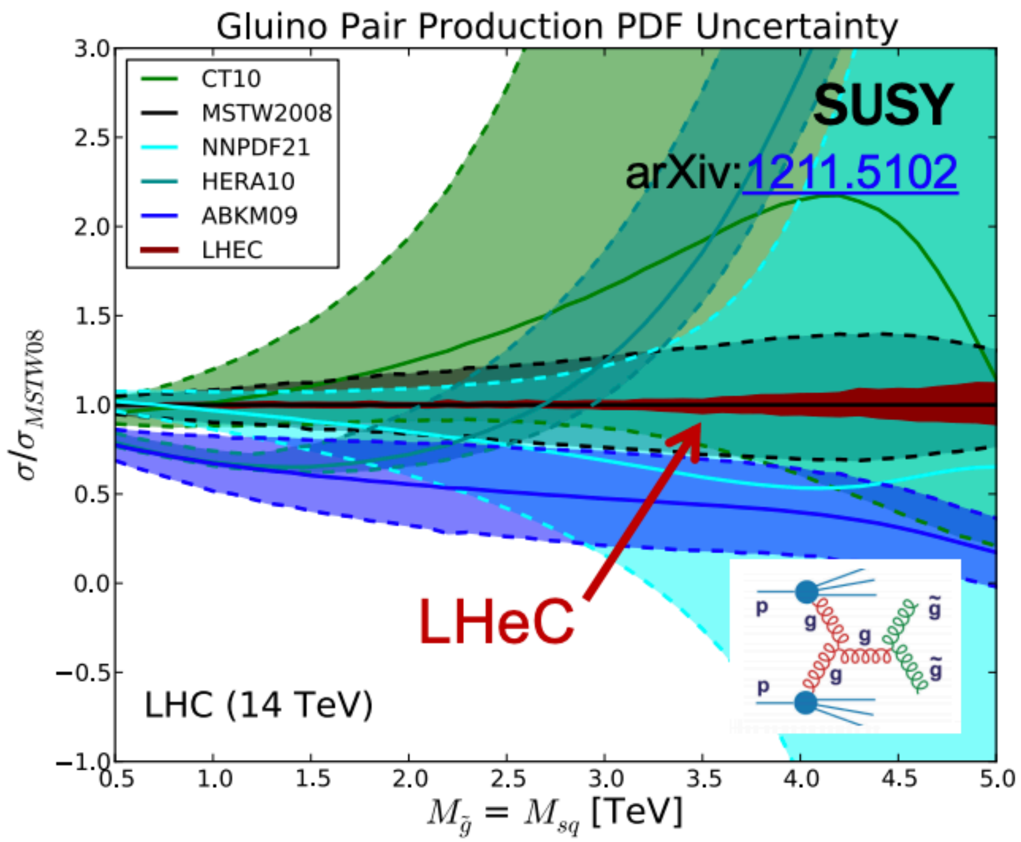




@LHeC Large luminosity and low number of backgrounds.
Compared to LHC:
no QCD interactions between initial states
Excellent for: BSM with mass scale ~ v_{EW}.
eg. heavy scalar boson (Higgsinos), sterile neutrinos.
The LHeC can probe sensitive regions of phase space difficult of access at LHC and complement results (FCC-eh opens higher energy regime)

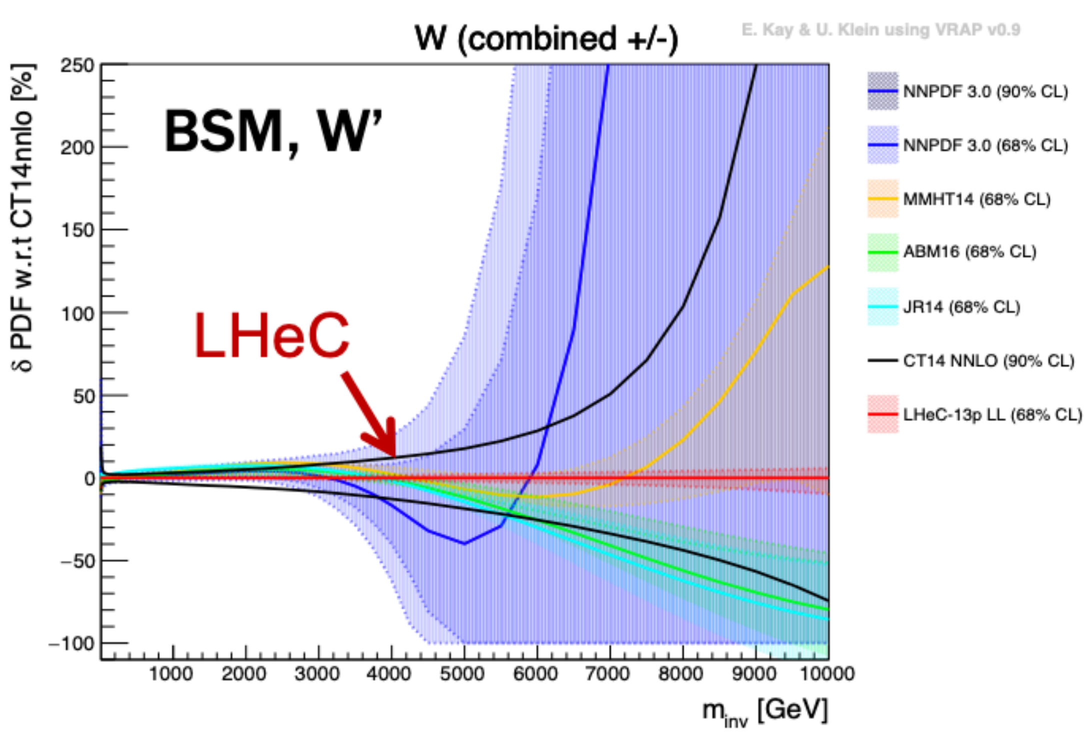
For details:
BSM Physics at the LHeC and the FCC-eh, Oliver Fischer

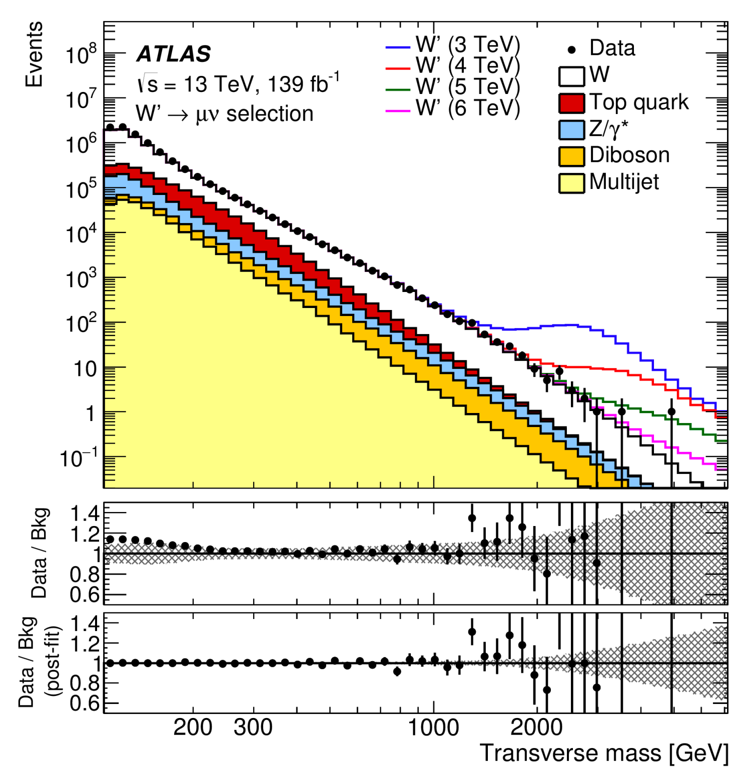
Future collider BSM program



BSM searches and other processes at high scales limited by **(lack of) knowledge of large x gluon and quark pdfs** (eg. top, SUSY, LQs, extra heavy bosons, …)

PDF Data from the LHeC would make this contribution negligible compared to other sources of uncertainty. The increase in sensitivity would correspond to an increase in centre-of-mass energy by approximately 5 to 10%.





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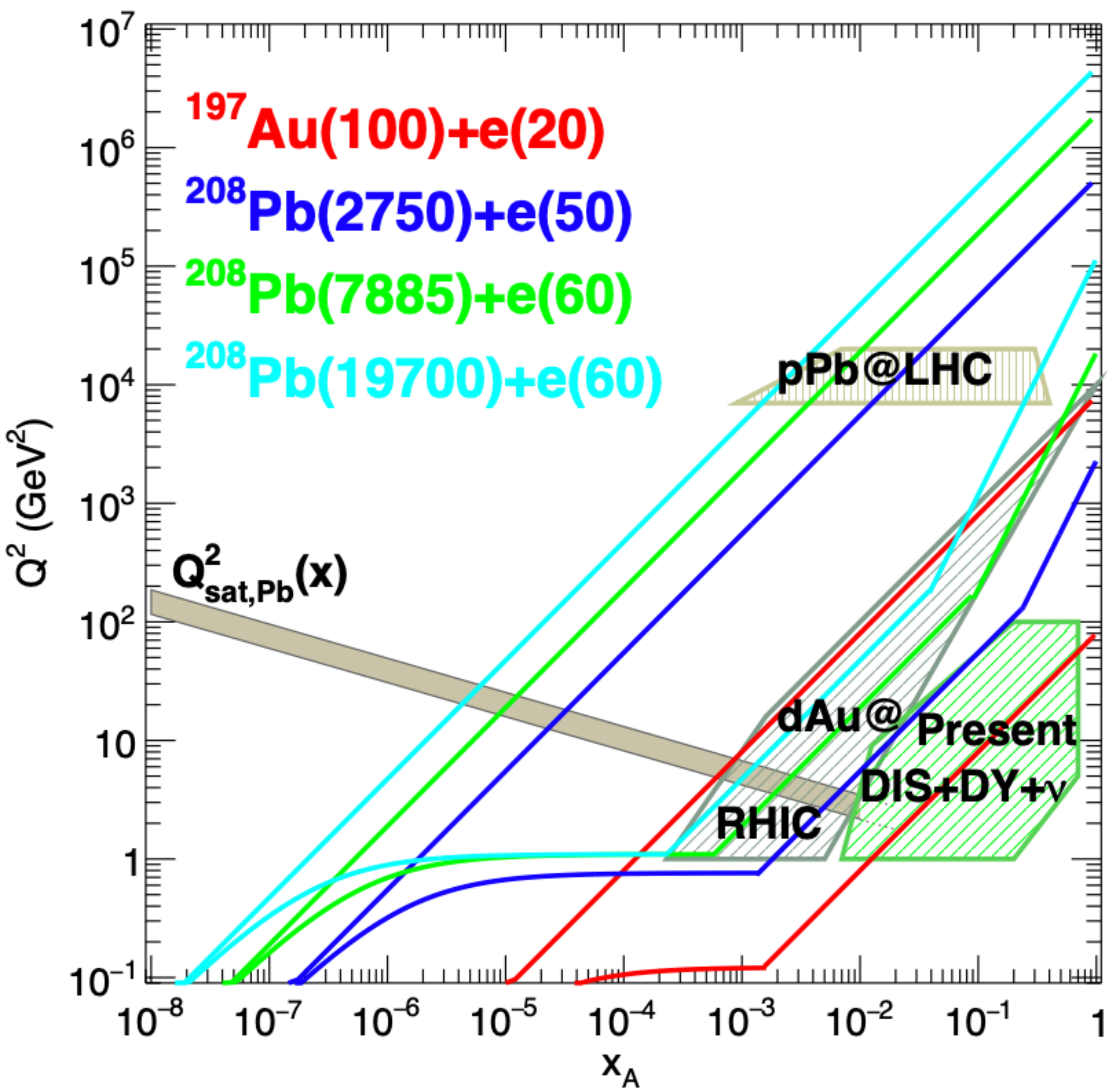
LHeC: e-A scattering

Unique nuclear/HI physics programme

Extension of fixed target range by 10 $^{3-4}$

nPDFs independent of pPDFs



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Joint eA/ep and pp/pA/AA physics in a common apparatus is probably an **ideal for new heavy ion physics to very high precision.**

A common/dual/joint experiment would have unprecedented reach into physics

For details:
Electron-Ion Collisions at the LHeC and FCC-eh, Heikki Mäntysaari

Partons in Nuclei

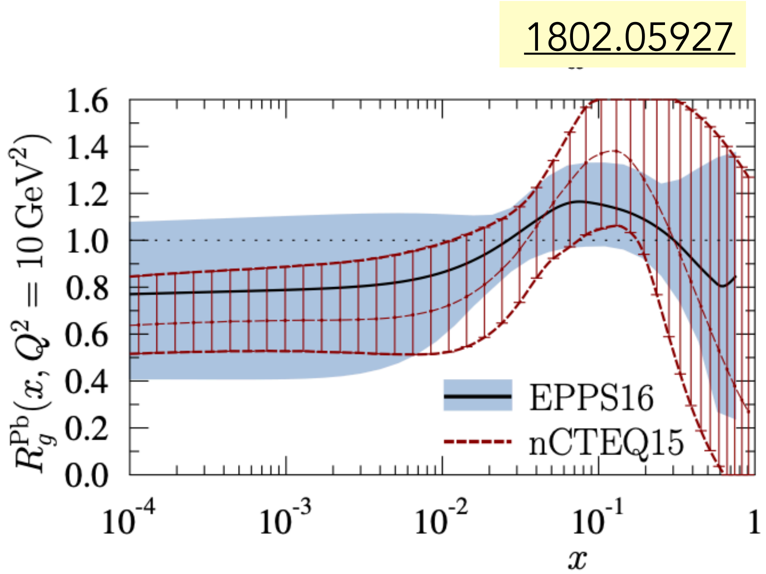
LHeC data allows for a direct determination of Pb PDF

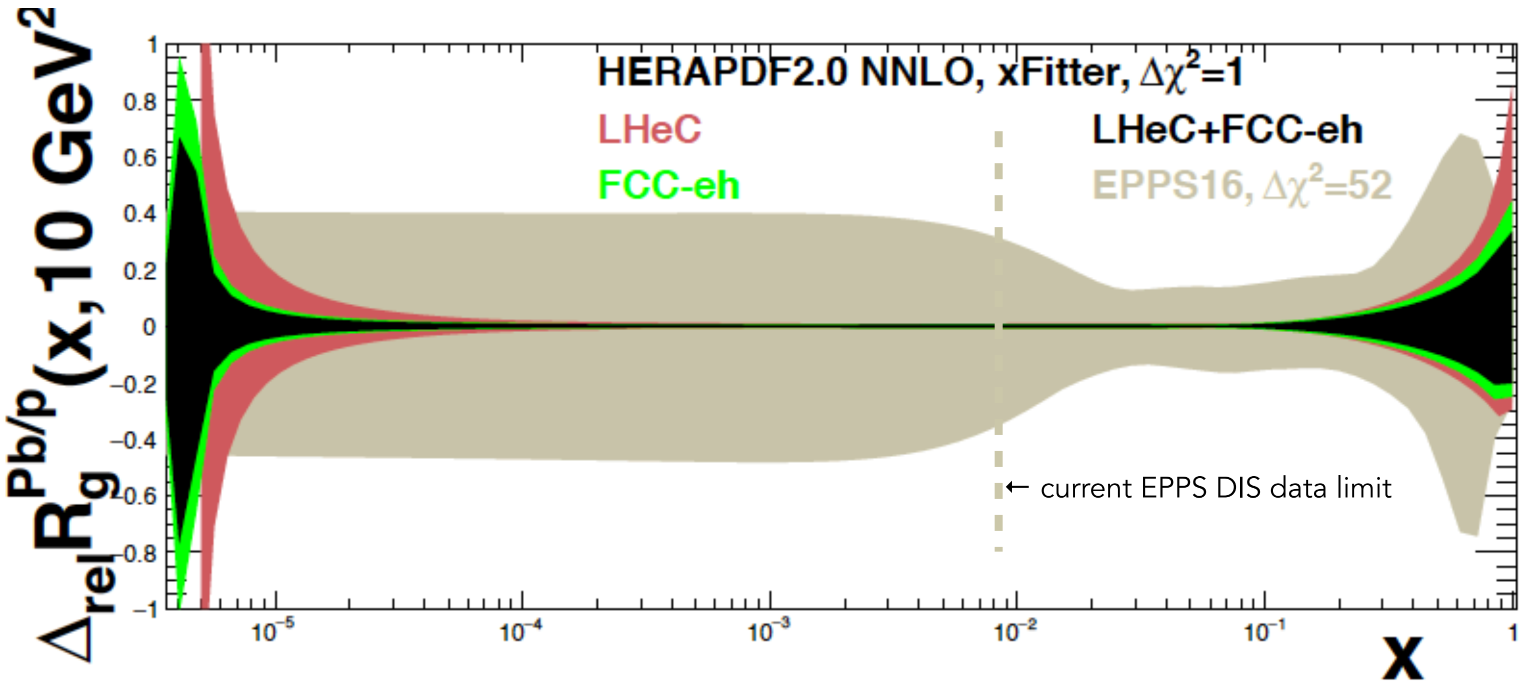
Estimates ultimately achievable experimental precision: uncertainty < 10% down to x ~ few × 10^{-5}

Direct measurements of R:

$$R_i(x,Q^2) = \frac{f_i^A(x,Q^2)}{A f_i^p(x,Q^2)}, \quad i = u,d,s,c,b,g,\ldots,$$

present status → on xg Pb/p





Direct determination of R_g with proton and lead data allows to DISENTANGLE small- x dynamics from nuclear effects.
Huge improvement over the EPPS16 global fit → Precision test for QCD of QGP, shadowing, antishadowing, de-confinement, saturation..

conclusion

"The LHeC group believes that diversity (at the energy frontier too) is key to help particle physics theory to restore its predictive power." (cit. Max Klein)

LHeC Physics Program: Unique microscope of substructure (not resolved!), empowers LHC searches and Higgs measurements challenging e+e- , Discovery in electroweak and strong i.a. sector, Revolution of HI physics

It is **crucial** to maintain the culture of energy frontier **DIS**, develop its novel technology and prepare **exploiting its potential** for the future of high energy physics.

LHeC white paper [aka CDR update]

CERN-ACC-Note-2020-0002
Geneva, July 28, 2020

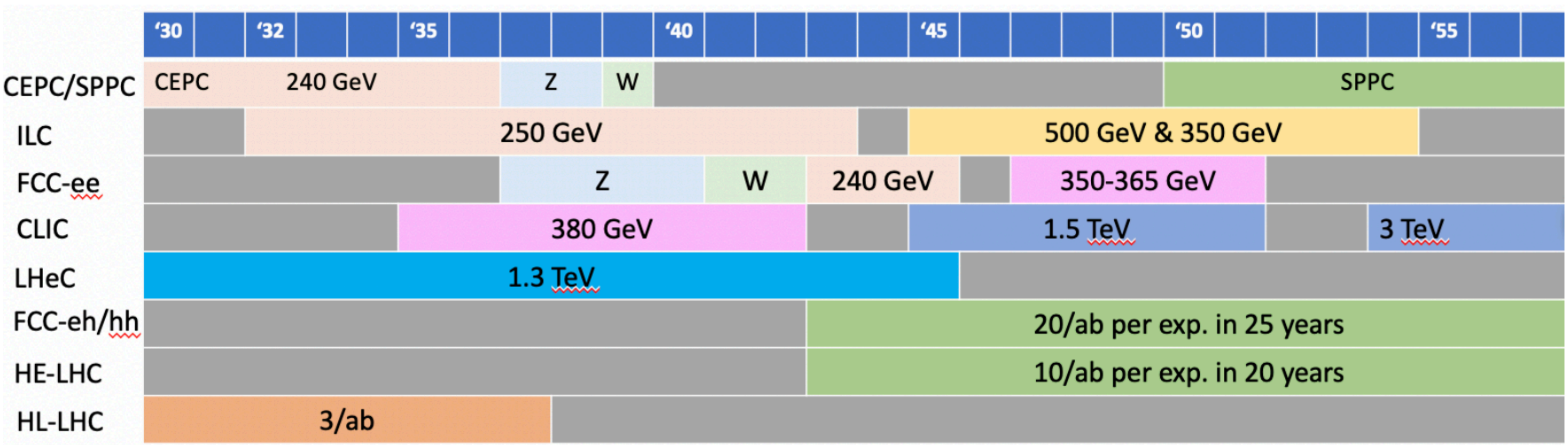
The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group

To be submitted to J. Phys. G

bonus slides

Future Colliders: $\sqrt{s}$ and tentative timescales

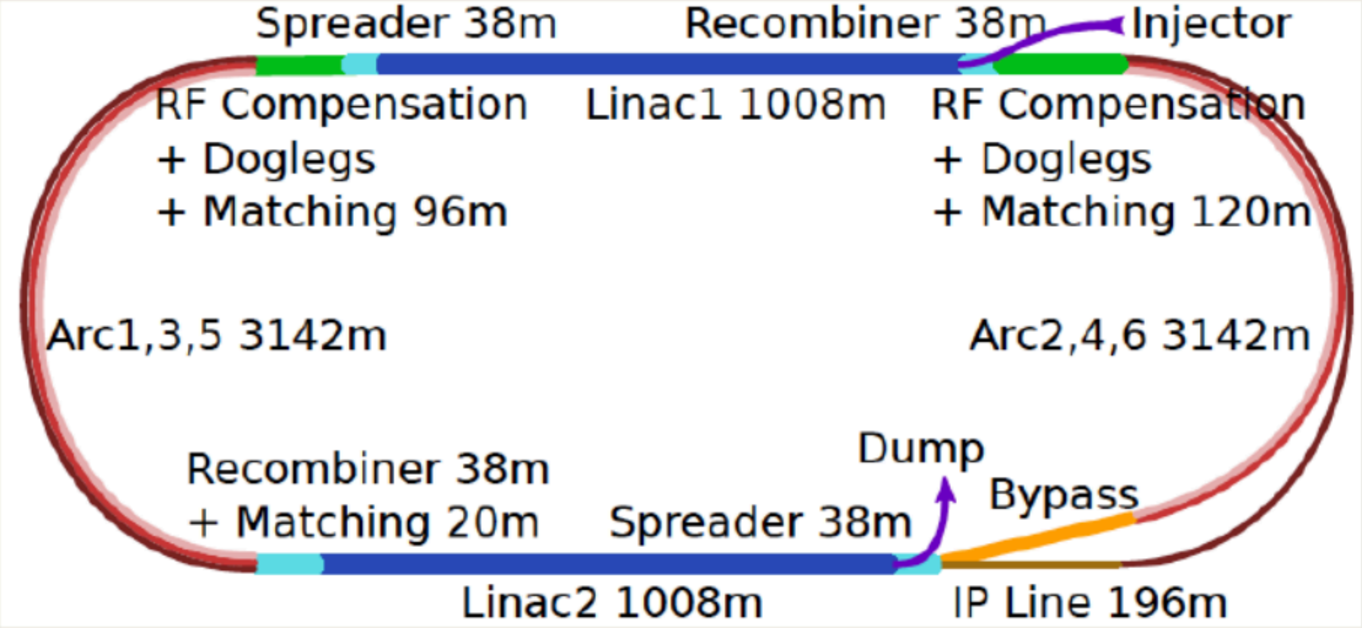


LHeC basic concept:

Energy $\sqrt{s} = \sqrt{(4\, E_e\, E_p)}$ = 0.2-1.3 TeV
electrons: E_e=10-60 GeV, protons: E_p=1-7 TeV, ions Pb: E=2.75 TeV

LHeC: a next generation TeV energy electron-proton collider. Large coverage of kinematic DIS range, down to 10^{-6} in x owing to high energy and approaching x=1 due to high luminosity. Electron-ion collisions extend the kinematic range by 3-4 orders of magnitude since HERA missed its electron-ion collider phase.

Default layout of the ERL configuration for the LHeC



A recent review on the project and physics: MK, arXiv:1802.04317

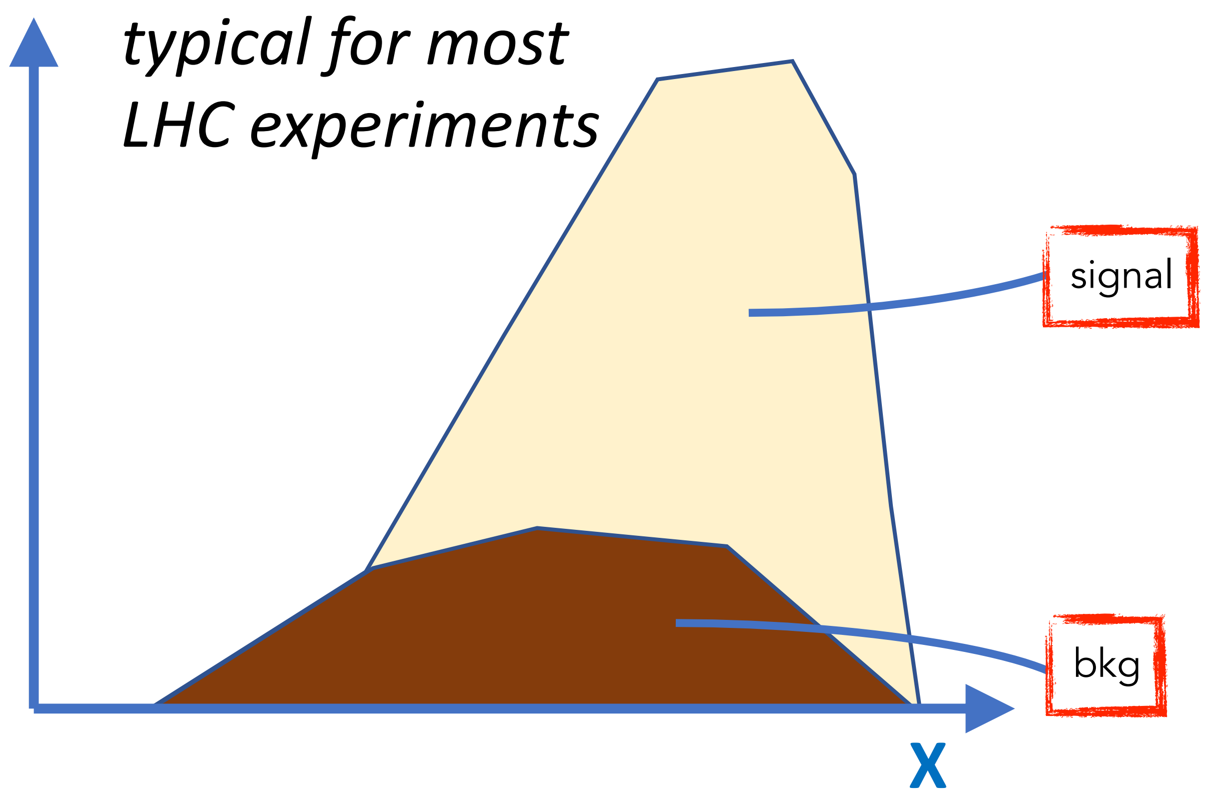
An intense electron beam (20mA current) is accelerated in three passes through two 1km linacs in an energy recovery linac racetrack configuration, which is positioned tangentially to the LHC (at IP2, or L for FCC).

The electron-proton interaction does not disturb the proton beams in a noticeable manner. Thus the LHeC may operate synchronously with the LHC. The installation of the ERL is in a separate tunnel, while the detector installation requires a typical LHC shutdown length of two years. The whole project concept therefore is that of adding instrumentation and providing crucial new physics, i.e. of making the LHC physics richer and thus sustaining its HL phase.

Luminosity:
$10^{34}\ cm^{-2}\, s^{-1} \rightarrow O(1)\ ab^{-1}$ in 10 years

This is 1000 times higher than HERA, owing to the high beam brightness of the HL-LHC, the large electron current from the ERL and may be achieved through the interaction of matched e and p beams at a β* below 10cm.

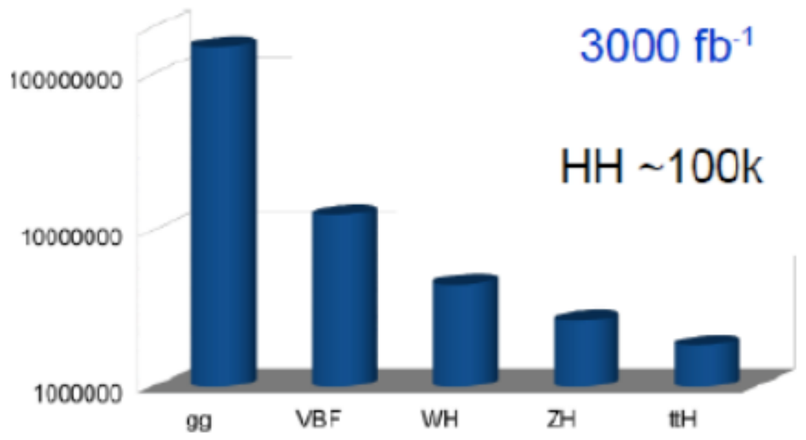
Why we need more insight in QCD?

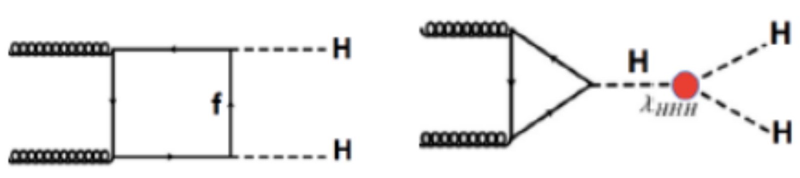


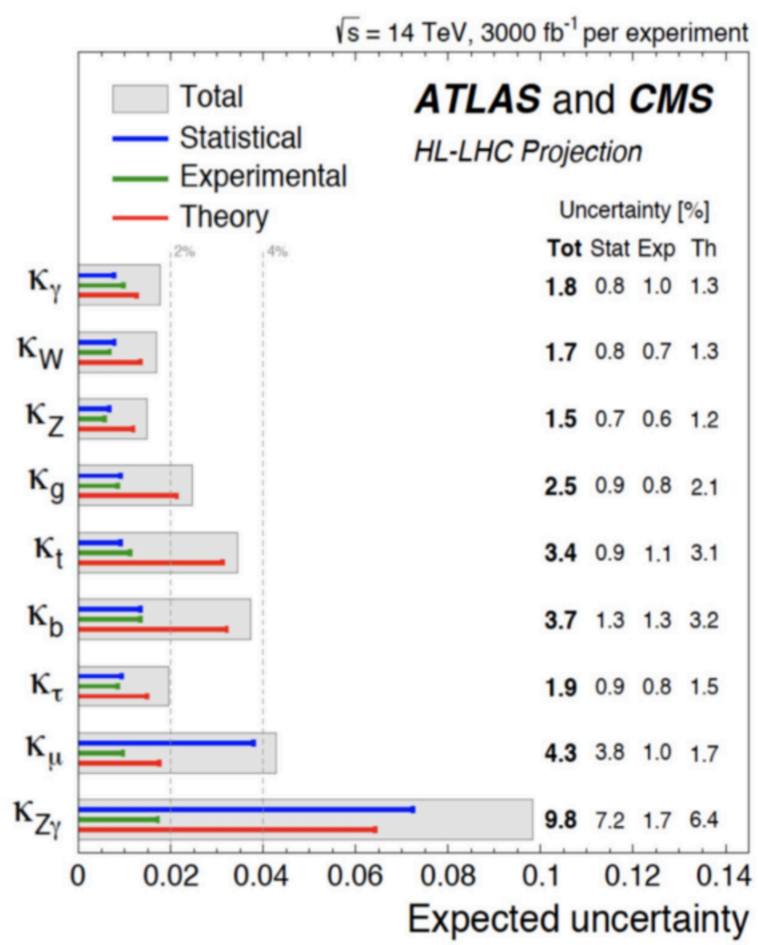
reference

- Though QCD is not per se the main driving force behind pp collider, **QCD is crucial for many LHC/ future collider measurements** (signals & backgrounds):
  - High-precision α_s : Affects SM fits/tests, all hadronic cross sections & decays
  - N^nLO+N^nLL corrections: Needed for all x-sections with initial/final hadrons
  - High-precision (n)PDFs: In h-h collisions, affects all precision W,Z,H (mid-x) measurements, all BSM searches (high-x), & beyond-DGLAP (low-x) studies.
  - sMany-body QCD: Partonic collective behaviour in high particle-density systems, Colour reconnection in “central” h+h collisions; impact on fundamental quantities in jetty final-states (mW , mtop extractions,…),
  - Non-pQCD: Control of hadronization+diffraction+... is basic at FCC-pp with O(1.000) pileup, backgds,...

HL-LHC Higgs program

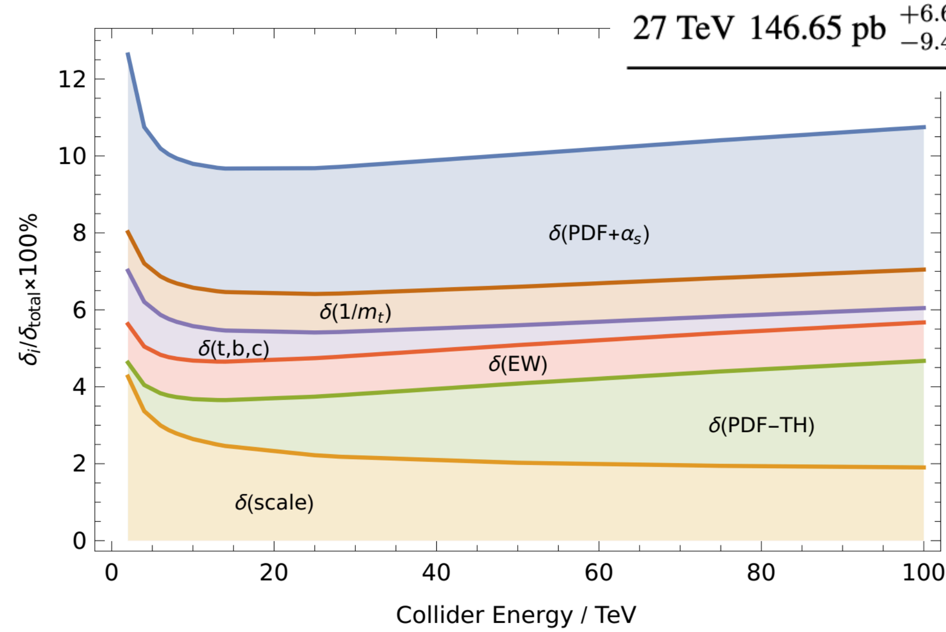






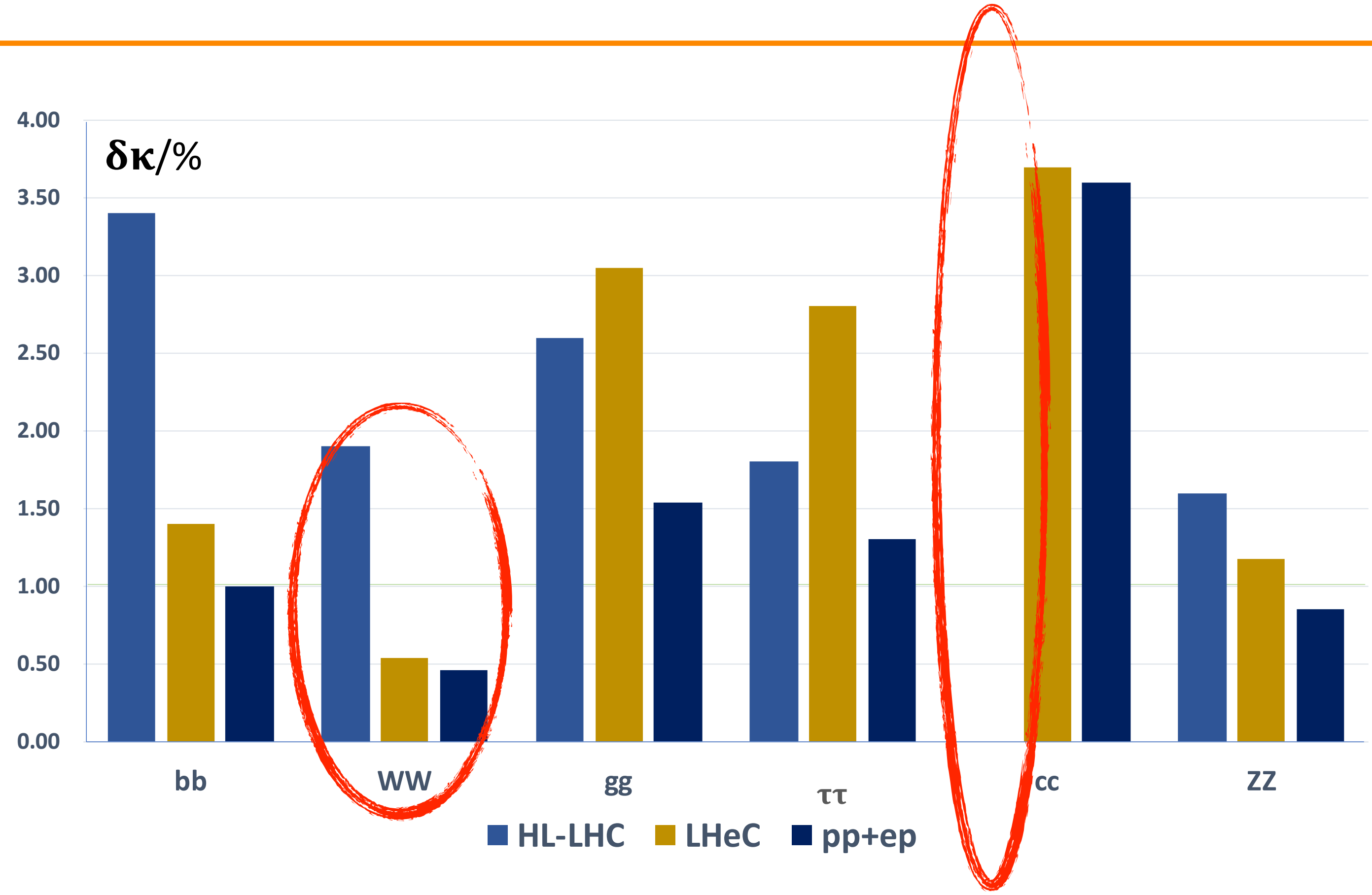
- HL-LHC program will expand the Higgs physics reach:
  - Exploration of Higgs potential (hh production)
  - Sensitivity to rare decays involving new physics
  - Extend BSM Higgs searches (extra scalars, BSM Higgs resonances, exotic decays…)
  - 2-4% precision for many of the Higgs couplings.
- However ***theoretical uncertainty remains the largest component for most measurement.***

$\sqrt{s}$	σ	δ(theory)	δ(PDF)	$\delta(\alpha_s)$
13 TeV	48.61 pb	$^{+2.08\text{pb}}_{-3.15\text{pb}}$ $\left(^{+4.27\%}_{-6.49\%}\right)$	± 0.89 pb ($\pm 1.85\%$)	$^{+1.24\text{pb}}_{-1.26\text{pb}}$ $\left(^{+2.59\%}_{-2.62\%}\right)$
14 TeV	54.72 pb	$^{+2.35\text{pb}}_{-3.54\text{pb}}$ $\left(^{+4.28\%}_{-6.46\%}\right)$	± 1.00 pb ($\pm 1.85\%$)	$^{+1.40\text{pb}}_{-1.41\text{pb}}$ $\left(^{+2.60\%}_{-2.62\%}\right)$
27 TeV	146.65 pb	$^{+6.65\text{pb}}_{-9.44\text{pb}}$ $\left(^{+4.53\%}_{-6.43\%}\right)$	± 2.81 pb ($\pm 1.95\%$)	$^{+3.88\text{pb}}_{-3.82\text{pb}}$ $\left(^{+2.69\%}_{-2.64\%}\right)$



1902.00134

SM Higgs couplings: Combine the complementary measurements for best physics outcome



Combining pp with ep results turns the LHC into a precision machine:

Reach <1%-<2% precision depending on coupling for pp+ep

ep adds charm.

Analysis in EFT framework work in progress (aTGCs in ep..)

Competitive and complementary to e+e-

pp: Higgs production in pp comes predominantly (~80%) from ggà H : high rates crucial for rare decays However, only small VBF fraction
Pile-up in pp at 5 1034 cm-2 s-1 is 150@25ns
FCC-hh: pile-up 500-1000 (!)
S/B very small for bb Final precision in pp needs accurate N3LO PDFs & αS

ep: Higgs production comes uniquely from either CC or NC DIS via VBF → Clean bb final state, S/B >1
Clean, precise reconstruction and easy distinction of ZZH and WWH without pile-up: <0.1@LHeC up to 1@FCCeh
events VBF: Small theoretical uncertainties!

- the higher-order corrections are small. For the total CC process they were estimated to be of the order of only 1% for the QCD part, subject to cut dependencies yielding shape changes up to 20%, and −5% for the QED part (with a weak dependence on the PDF choice). The smallness of the QCD corrections was attributed mainly to the absorption of gluon and quark radiation effects in the evolution of the parton distributions (PDFs). The PDFs will be measured with very high precision at any of the ep colliders here considered, thus allowing a unique self-consistency of Higgs cross section measurements.

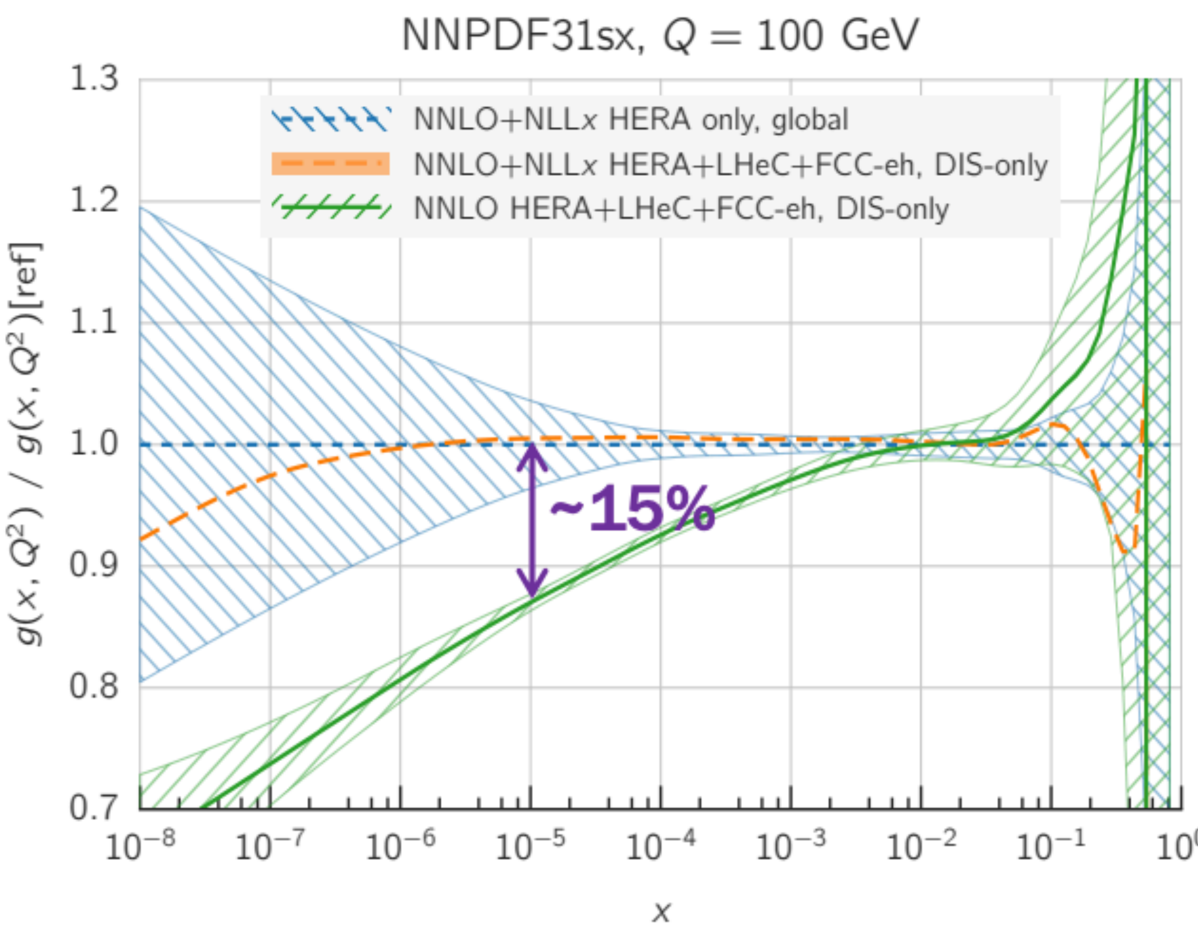
small-x resummation

more info

- NNLO+NLLx resummed calculation used to produce **LHeC** and **FCC-eh** simulated inclusive NC and CC pseudo-data
- then, fitted using **NNLO (DGLAP only)** vs. **NNLO+NLLx**

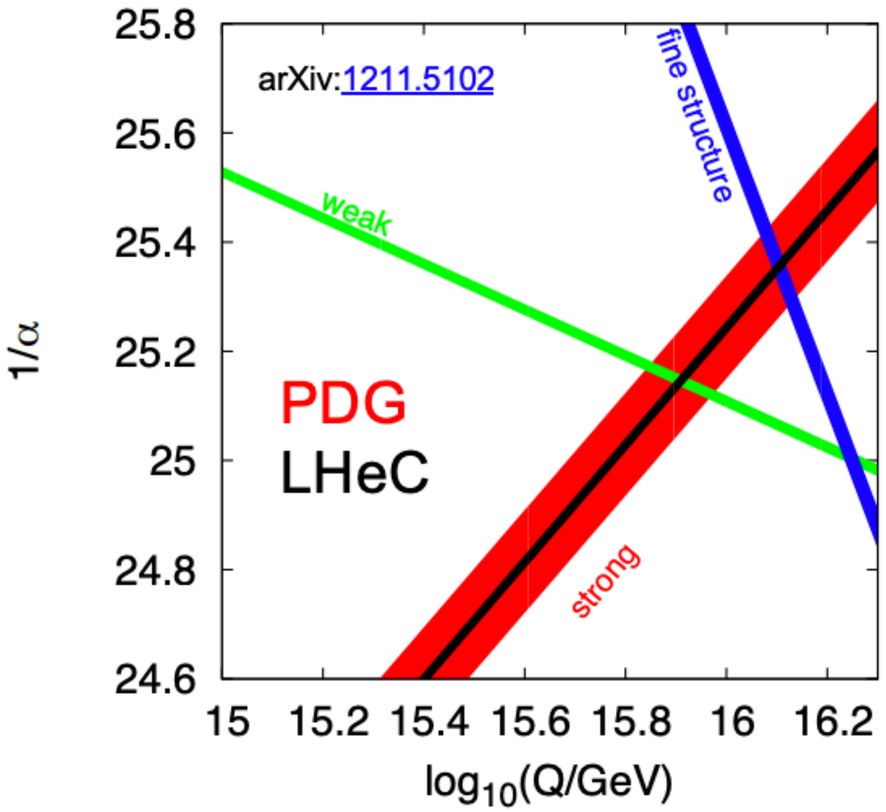
•	**X^2 per DOF**	LHeC / FCC-eh
•	**NNLO:**	**1.71 / 2.72**
•	**NNLO+NLLx**	**1.22 / 1.34**

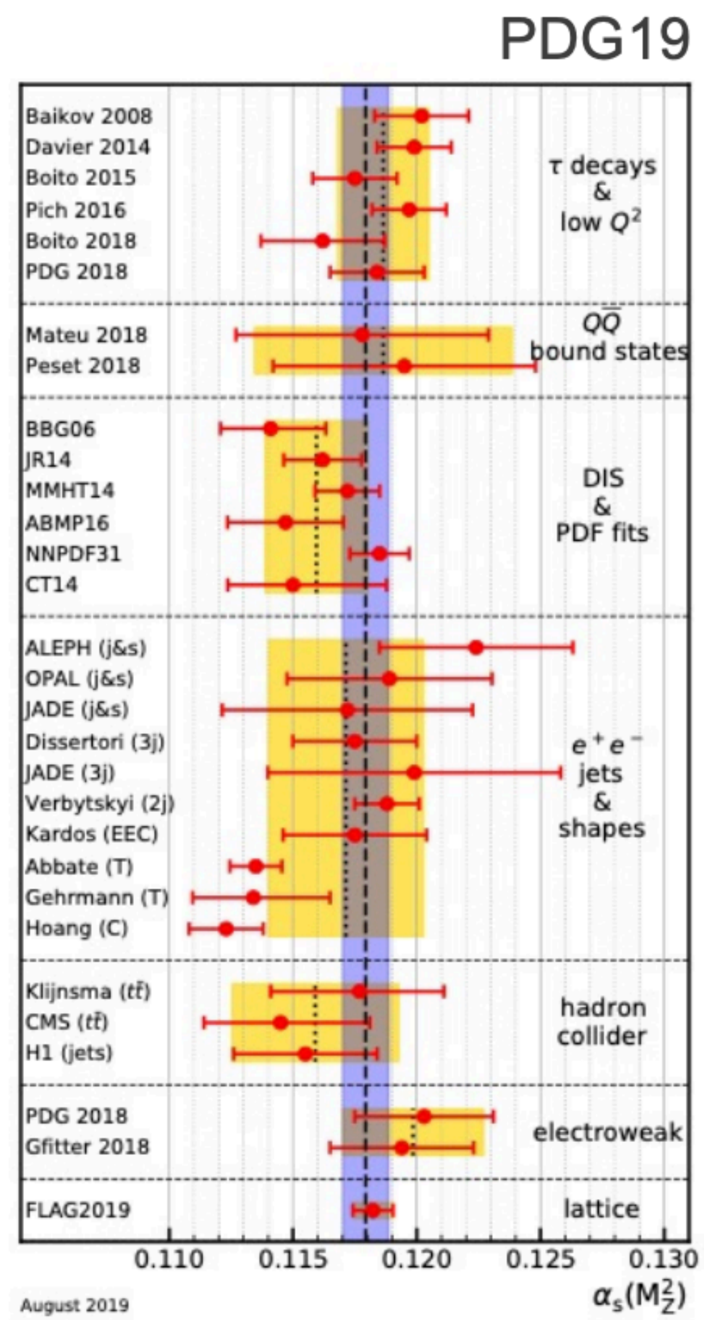
- substantial difference in extracted gluon (10 (15)% at $x=10^{-4}$ (10^{-5}))
- much larger than precision with which gluon can be determined using LHeC or FCC-eh DIS data



- **large sensitivity and discriminatory power to pin down details of small x QCD dynamics**

strong coupling





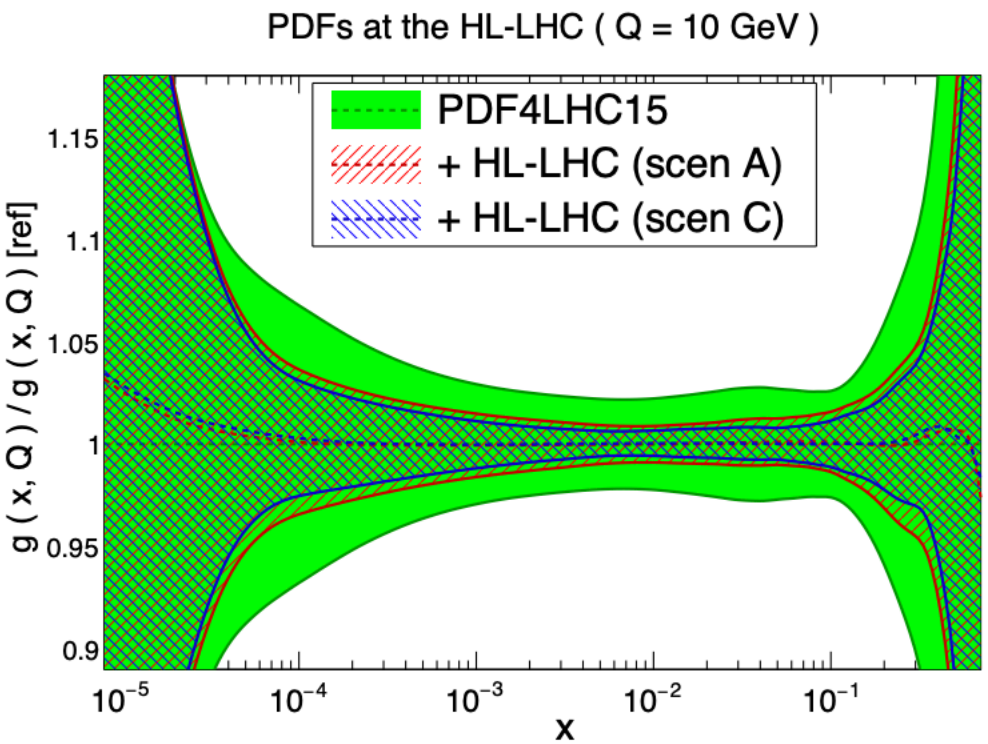
- **αs is the least known coupling**
- needed: for cross section predictions, including Higgs; to constrain GUT scenarios, etc.
- measurements not all consistent:– what is true central value, uncertainty? is αs(DIS) lower than world average? role of lattice QCD?

world ave. $\alpha_s(M_Z^2) = 0.1179 \pm 0.0010$

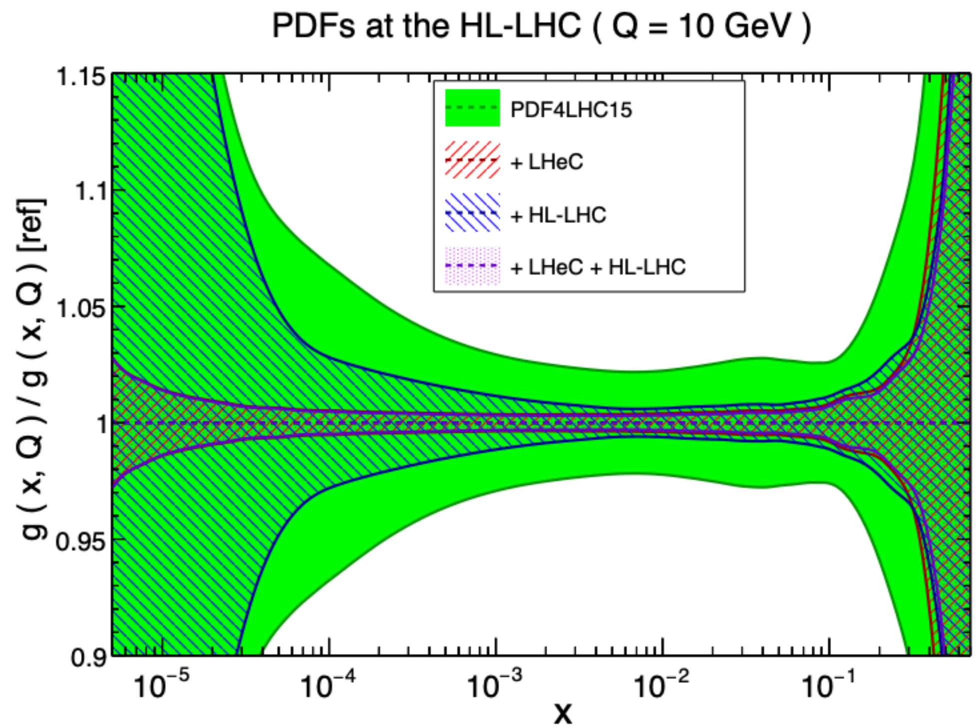
For details:
Determination of the Parton Densities in the Proton at the LHeC, Claire Gwenlan

Prospect PDF for HL-LHC

more info



R. Abdul Khalek, S. Bailey, J. Gao, LHL, J. Rojo. Eur.Phys.J. C78 (2018) no.11, 962

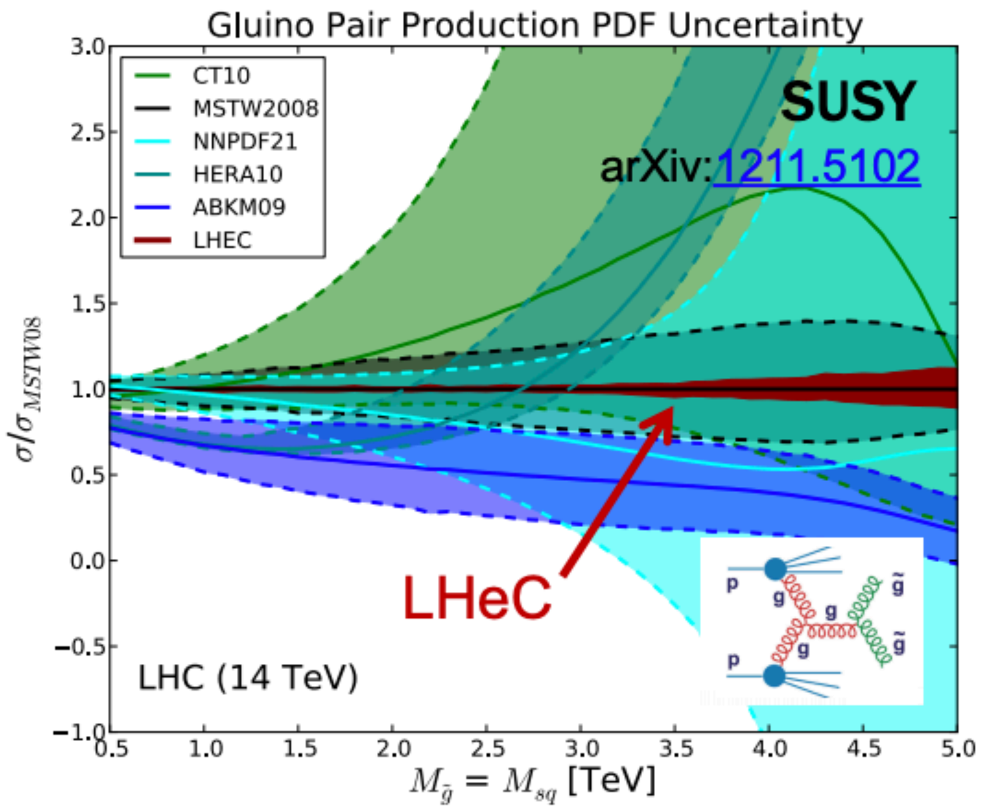


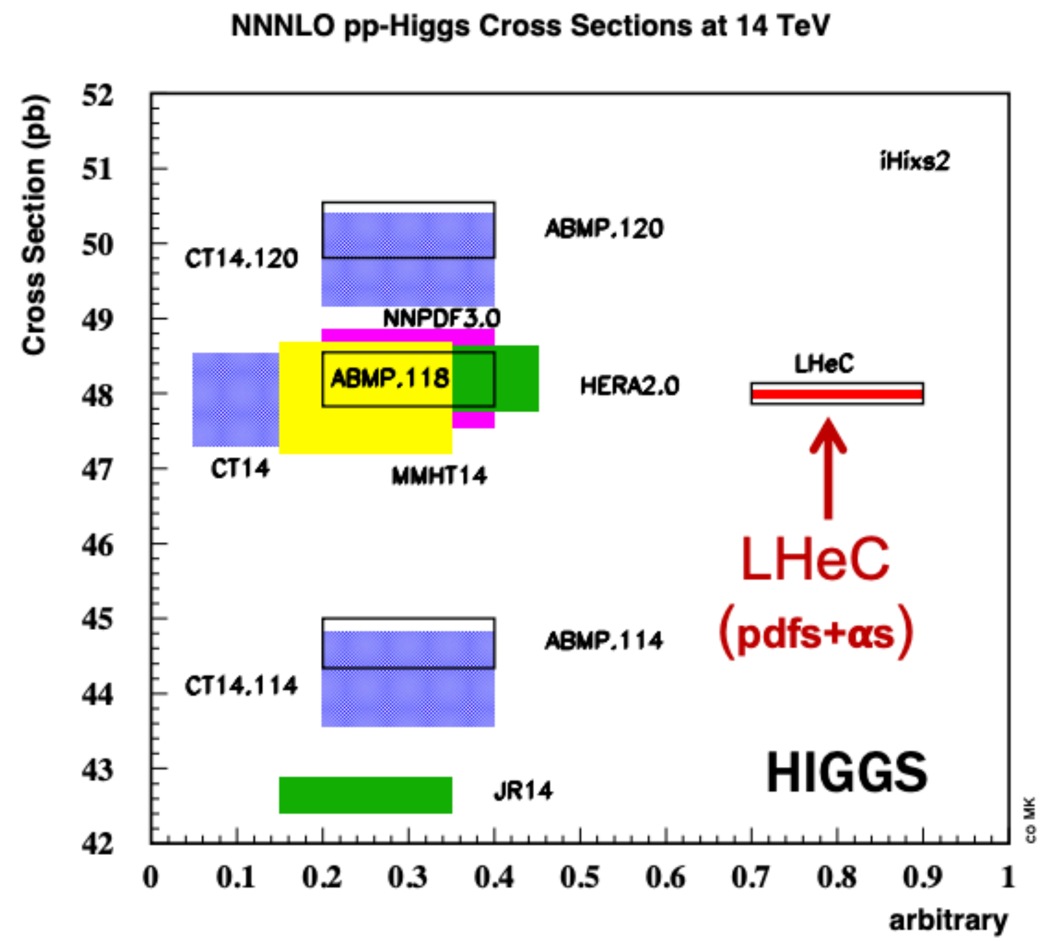
R. Abdul Khalek, S. Bailey, J. Gao, LHL, J. Rojo. SciPost Phys. 7, 051 (2019)

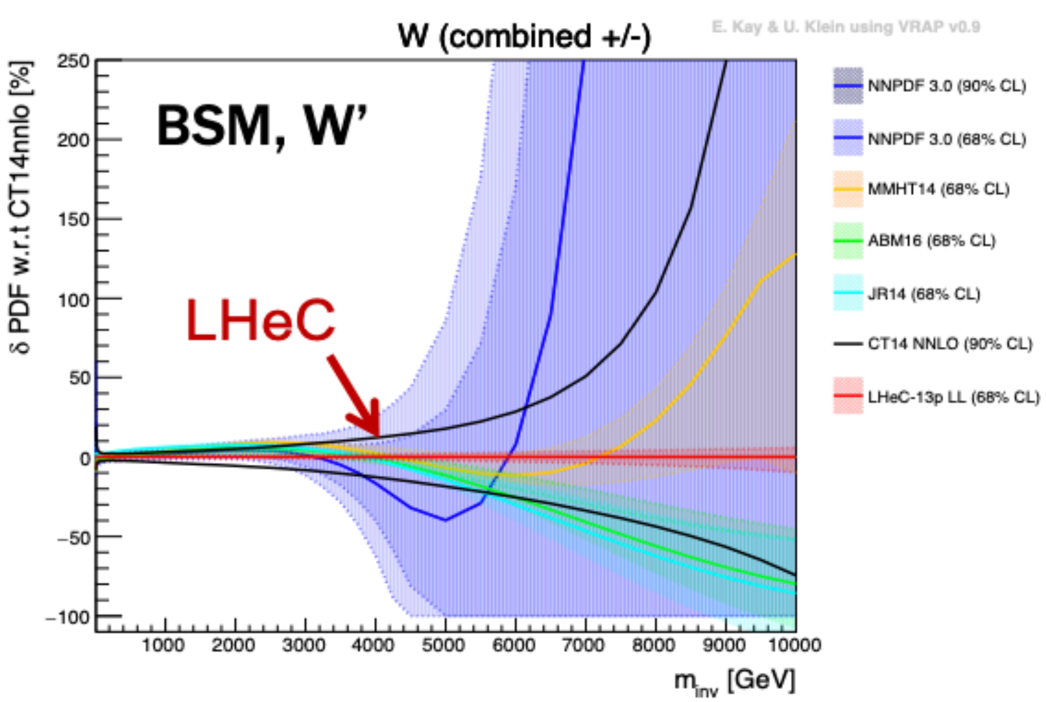
- Exercise trying to quantify the precision of the PDF at the end of the HL-LHC running and use them in the systematic estimate of the experimental extrapolations
- pseudo-data generated for various inputs: top Drell-Yan, iso photons, W+charm, W and Z in the forward region, inclusive jets…
- Scenario A(C) corresponds to factor 2(5) reduction of uncertainties on exp. inputs.
- **LHeC could provide improvement of a factor 5 on PDF uncertainties**

PDF reduction

reference





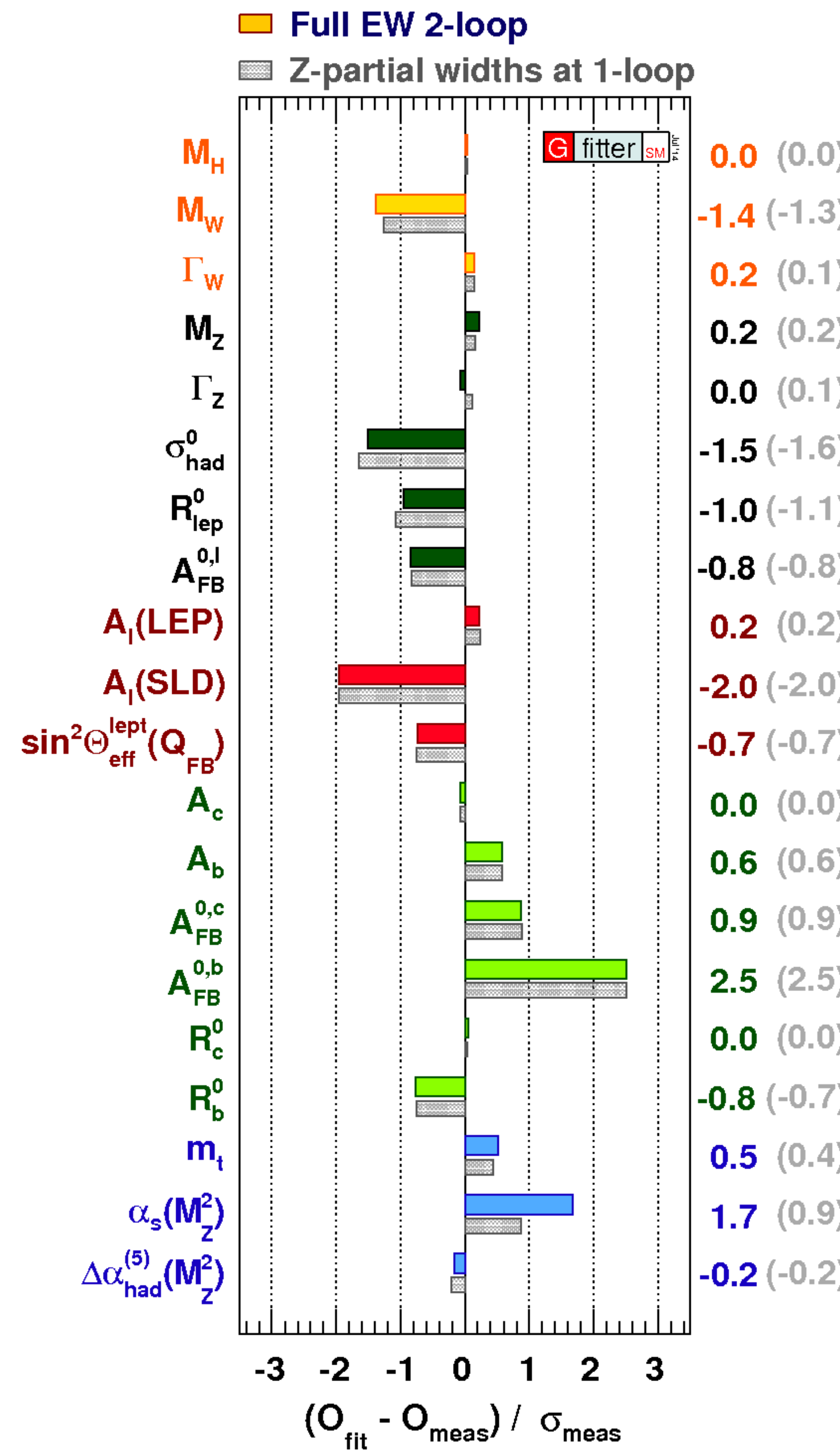


- **external**, reliable, precise **pdfs** needed for **range extension** and **interpretation**
- **BSM**, gluons and quarks at large x (SUSY, LQs, additional high mass bosons, …)
- **Higgs**, theory uncert. dominated by **pdfs+αs**
- SM parameters, EG. **MW**, **$\sin^2\theta W$** (see white paper)

How to test SM?

- In the recent past, the global electroweak fit was able to predict the masses of the top quark and Higgs boson before their discovery
- Relations between electroweak observables can be predicted now at 2-loop level
- Precise measurements of the electroweak parameters allow stringent test of the self consistency of the SM $\Longrightarrow$ Looking for hints of physics beyond the SM.

Indirect searches: *look for deviations from SM predictions* due to quantum loop effects of new virtual particles



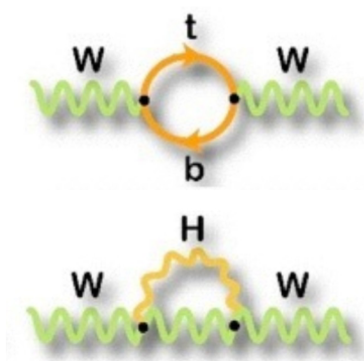
The EW sector

The electroweak gauge sector of the Standard Model is constrained by three precisely measured parameters

$$\alpha = 1/137.035999139(31)$$
$$G_F = 1.1663787(6) \times 10^{-5}\ \text{GeV}^{-2}$$
$$m_Z = 91.1876(21)\ \text{GeV}$$

At tree level, other EW parameters can be expressed as

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F\left(1 - m_W^2/m_Z^2\right)(1-\Delta r)}$$
$$\sin^2_{\text{eff}}\theta_W = \left(1 - \frac{m_W^2}{m_Z^2}\right)\kappa$$
$$\Gamma_W = \frac{3G_F m_W^3}{2\sqrt{2}\pi}\rho$$



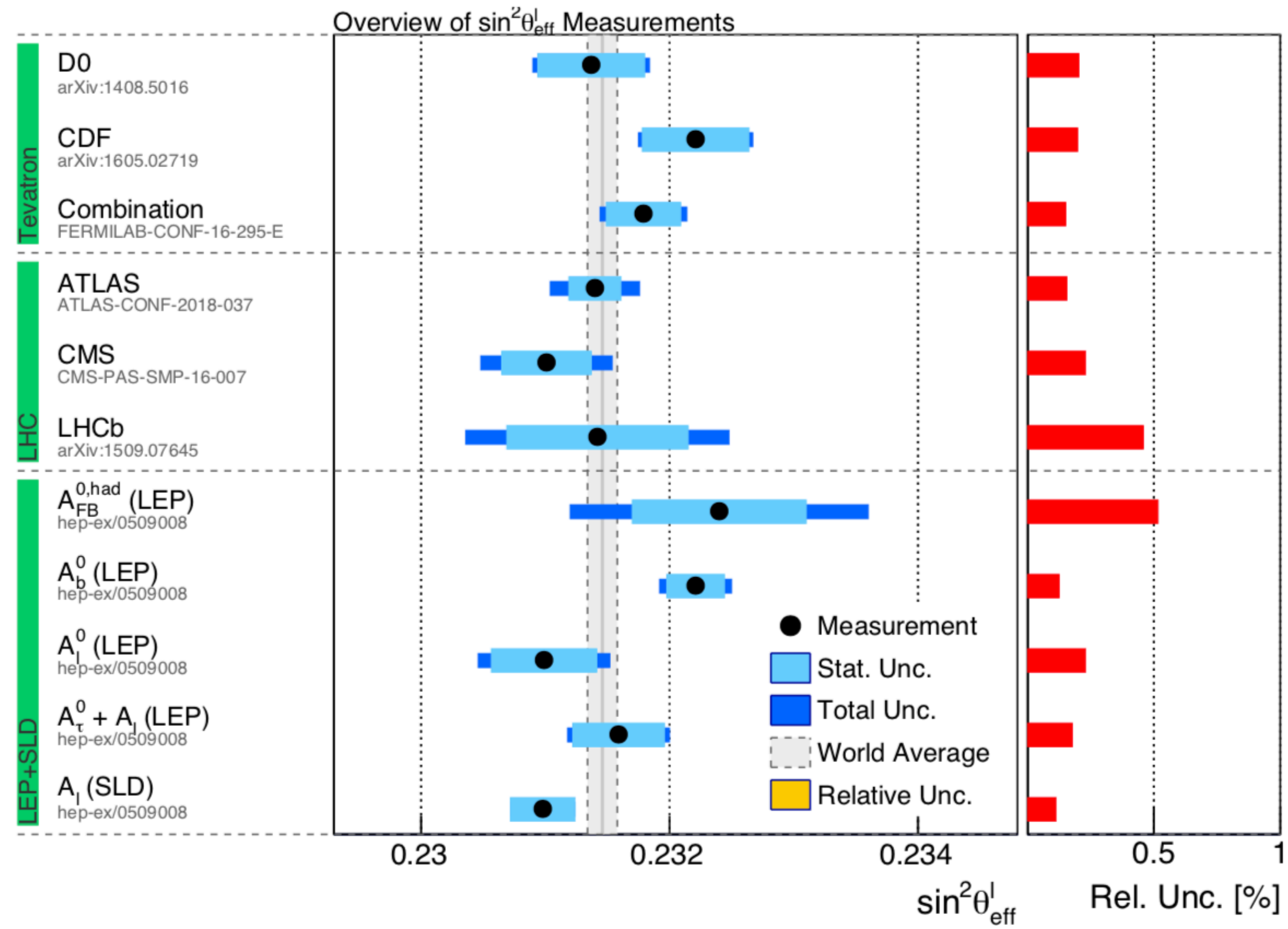
In SM, Δr reflects loop corrections and depends on m_t^2 and $\ln(m_H)$

Higher order corrections modify these relations, and determine sensitivity to other particle masses and couplings

κ are EW loop corrections

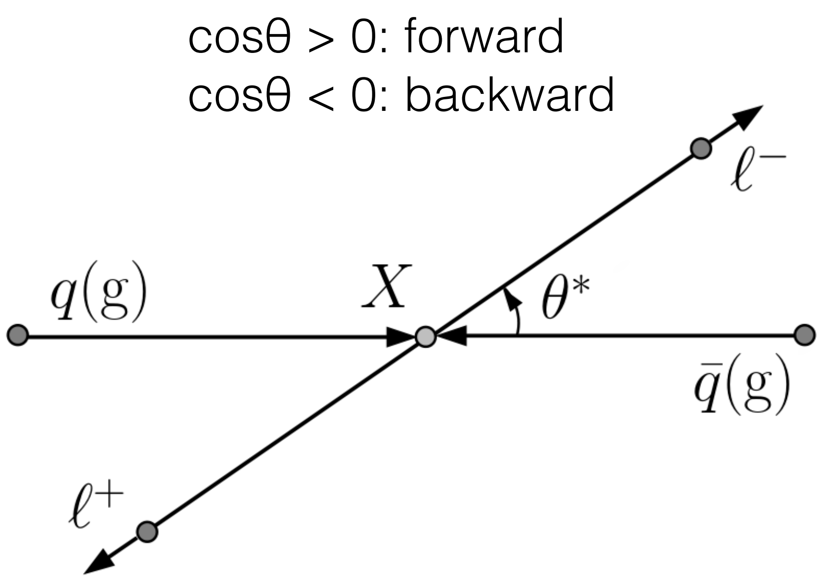
Weak Mixing Angle

- Discrepancy of LEP and SLD measurement on $\sin^2\theta_W$ triggered quite some interest in recent years
- Problem at Hadron colliders: Do not know incoming fermion direction on an event-by-event basis
- to extract $\sin^2\theta_{eff}$ exploit forward-backward asymmetry (**A_{FB}**) **of DY process**



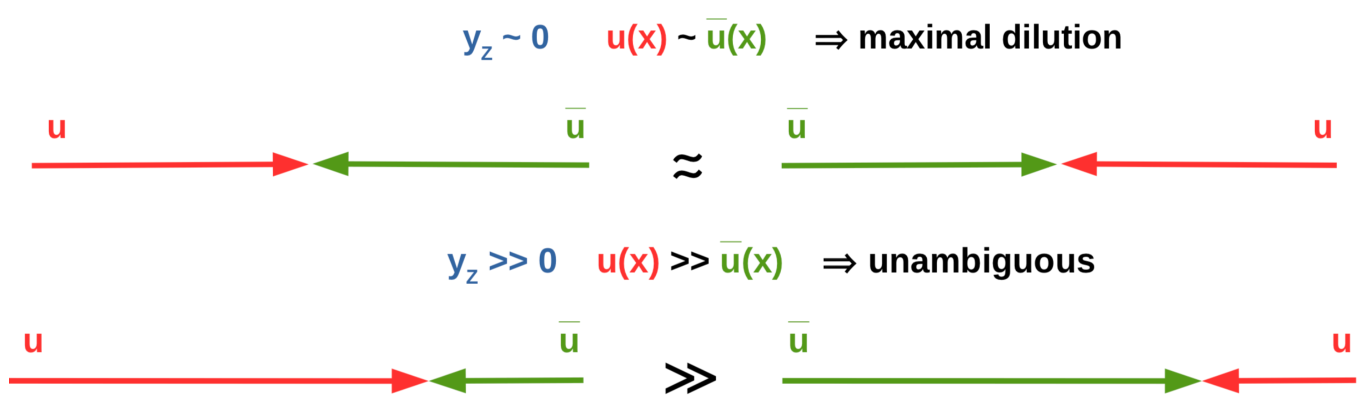
Indirect Determination:	$\sin^2\theta_{eff} = 0.23151 \pm 0.00006$
World average:	$\sin^2\theta_{eff} = 0.23151 \pm 0.00014$
Combination at hadron colliders:	$\sin^2\theta_{eff} = 0.23140 \pm 0.00023$

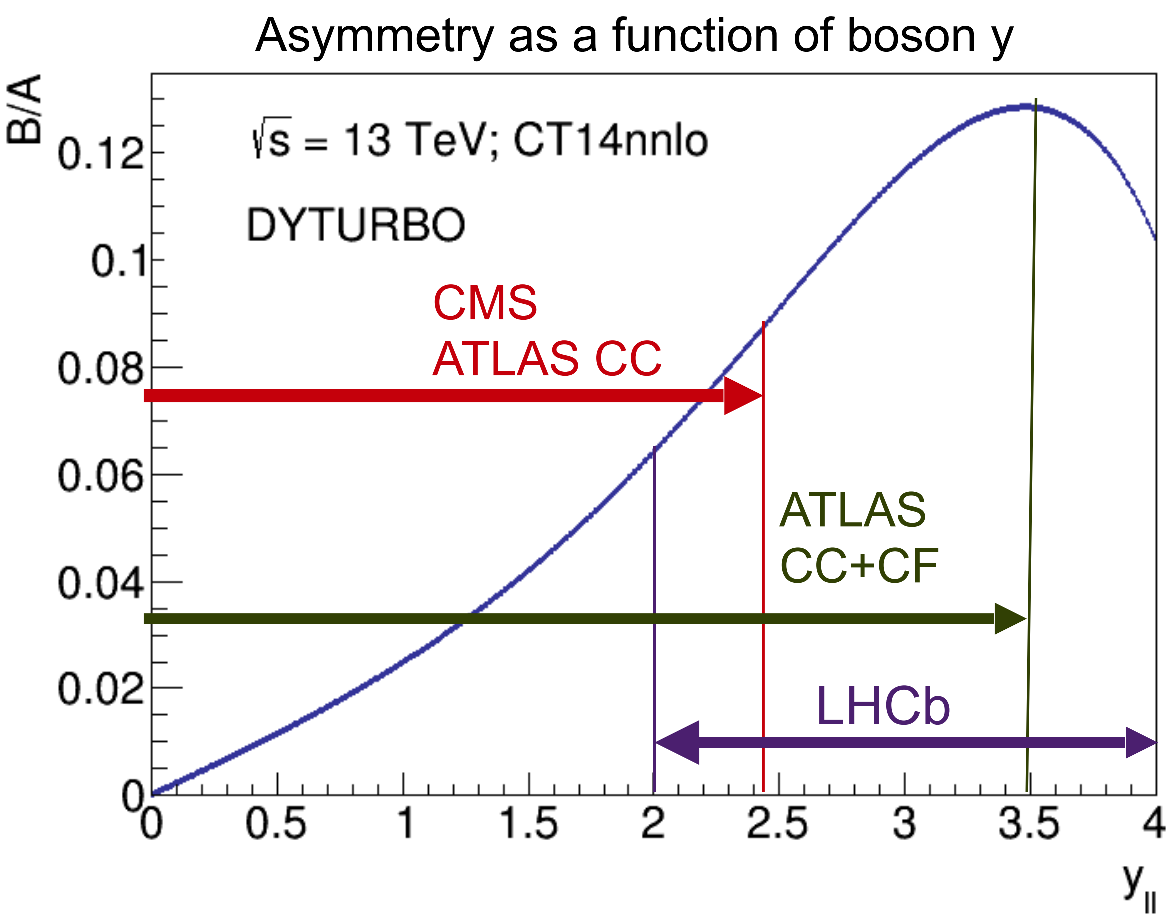
Z forward-backward asymmetry@LHC



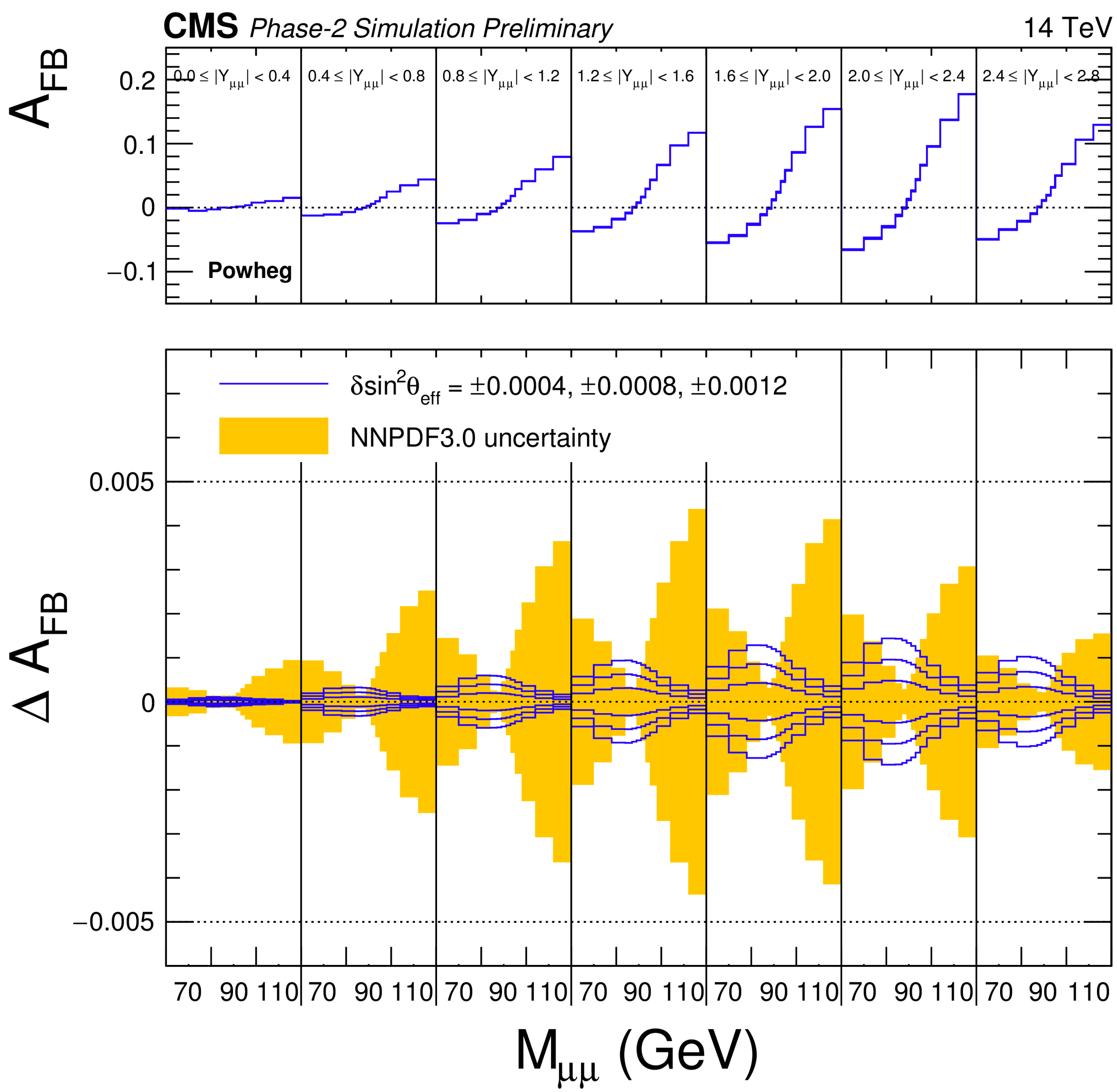
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{8}\frac{B}{A}$$

- The orientation of the incoming quark is unknown
  - Use θ* scattering angle defined in the Collins-Soper frame, with z-axis orientation defined by the Z rapidity
- In pp collisions, it is more likely to be in the same orientation as the Z boson, due to the u/ubar and d/dbar valence asymmetry





weak mixing angle @LHC/HL-LHC

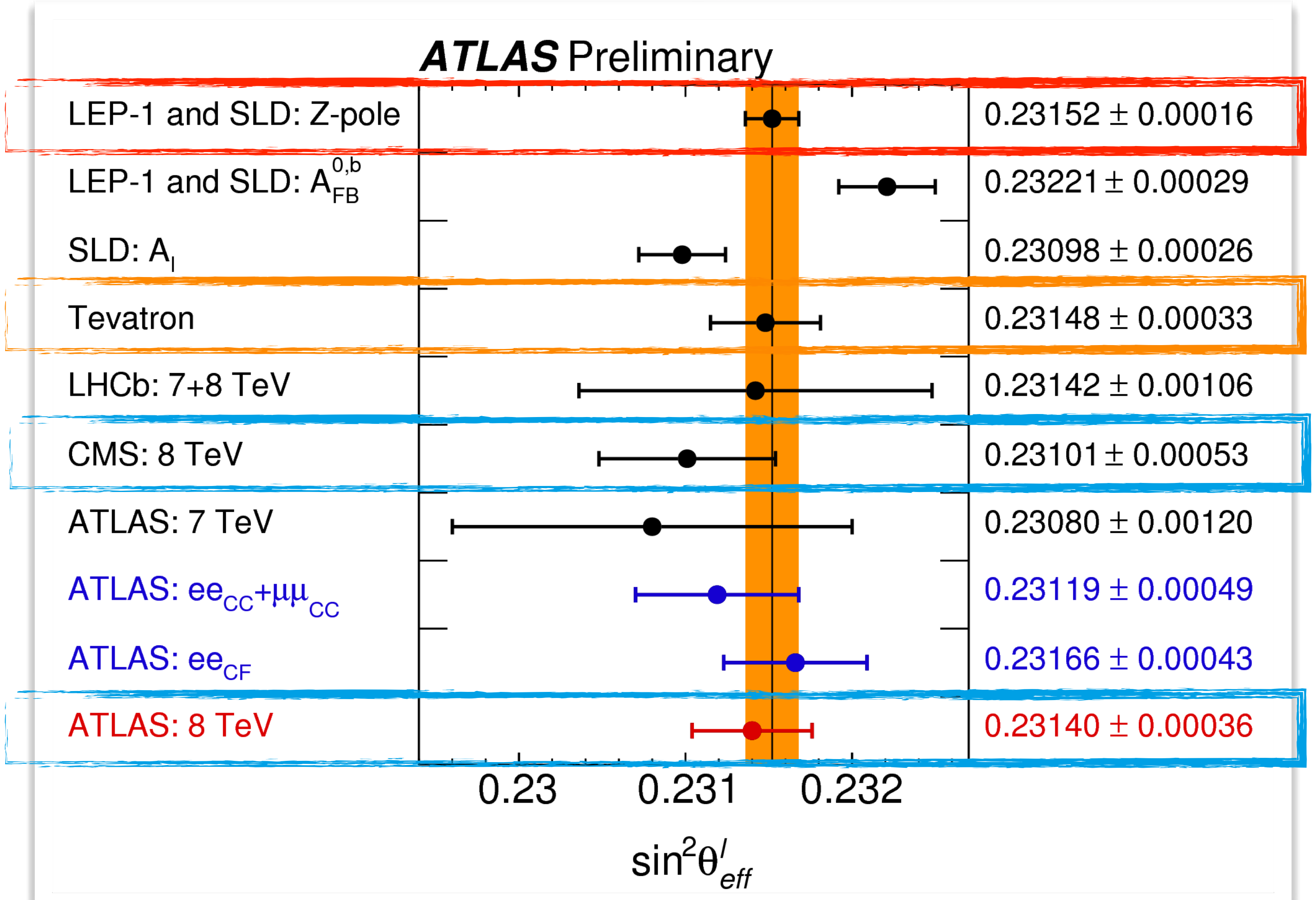


AFB strongly depend on PDF uncertainty ⇒ dominant systematic for the extraction of $\sin^2\theta_{eff}$

- different couplings of u- and d-type quarks
- yll direction depends on the relative content of valence and sea quarks

- The expected sensitivity to particle level A_{FB} as a function of m_{ll}
- PDF band correspond to PDF uncertainty without inset constraint.
  - The imperfect knowledge of the PDF results in sizeable uncertainties in A_{FB}, in particular in regions where the absolute value of the asymmetry is large, i.e. at high and low m_{ll}. On the contrary, near the Z boson mass peak, the effect of varying $\sin^2\theta_{eff}$ is maximal, while being significantly smaller at high and low masses.

summary weak mixing angle @LHC

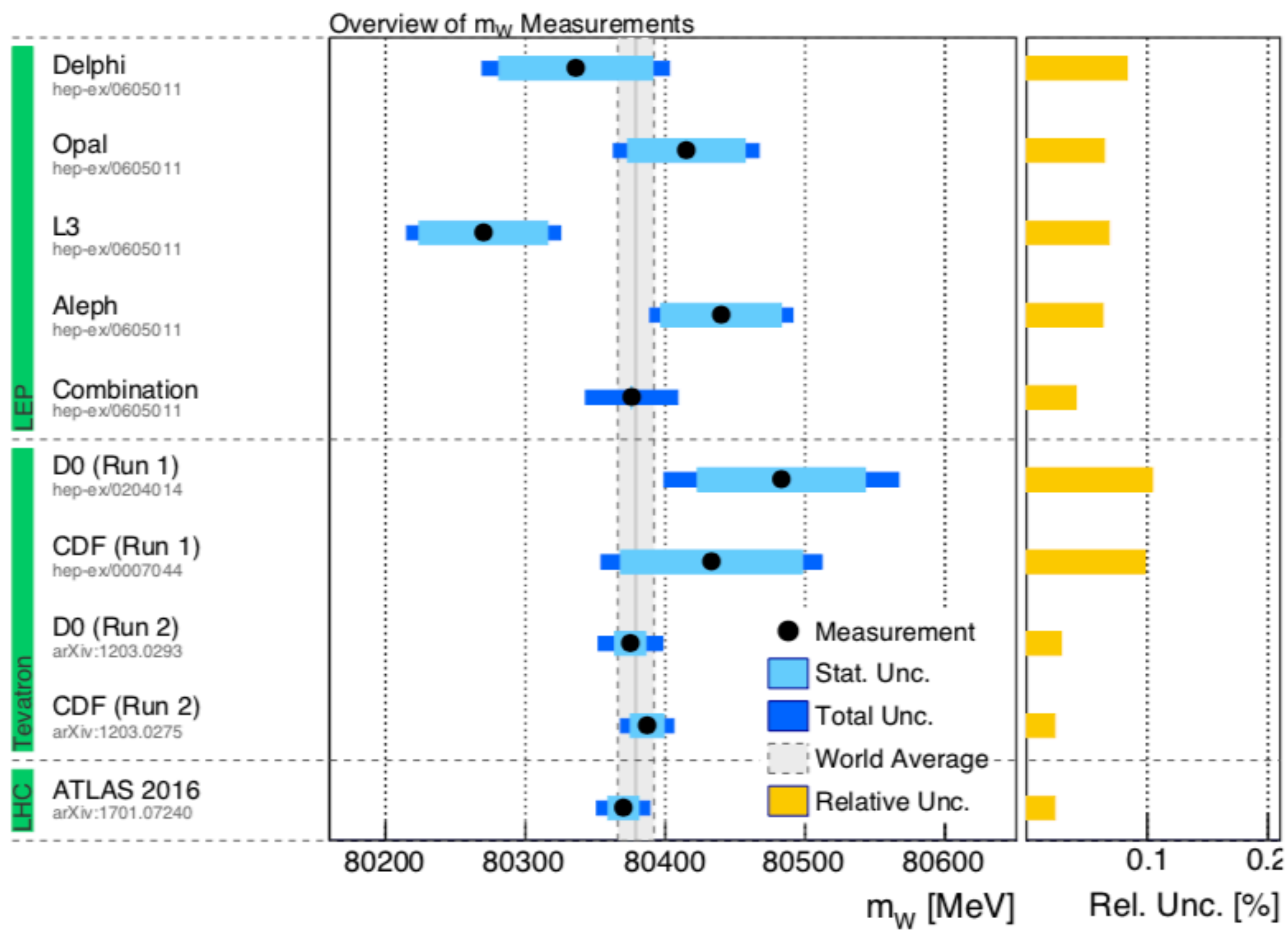


New analysis techniques, including in-situ PDF profiling and analysis categorisation → statistical and systematic uncertainties are significantly reduced relative to previous CMS and ATLAS measurements.

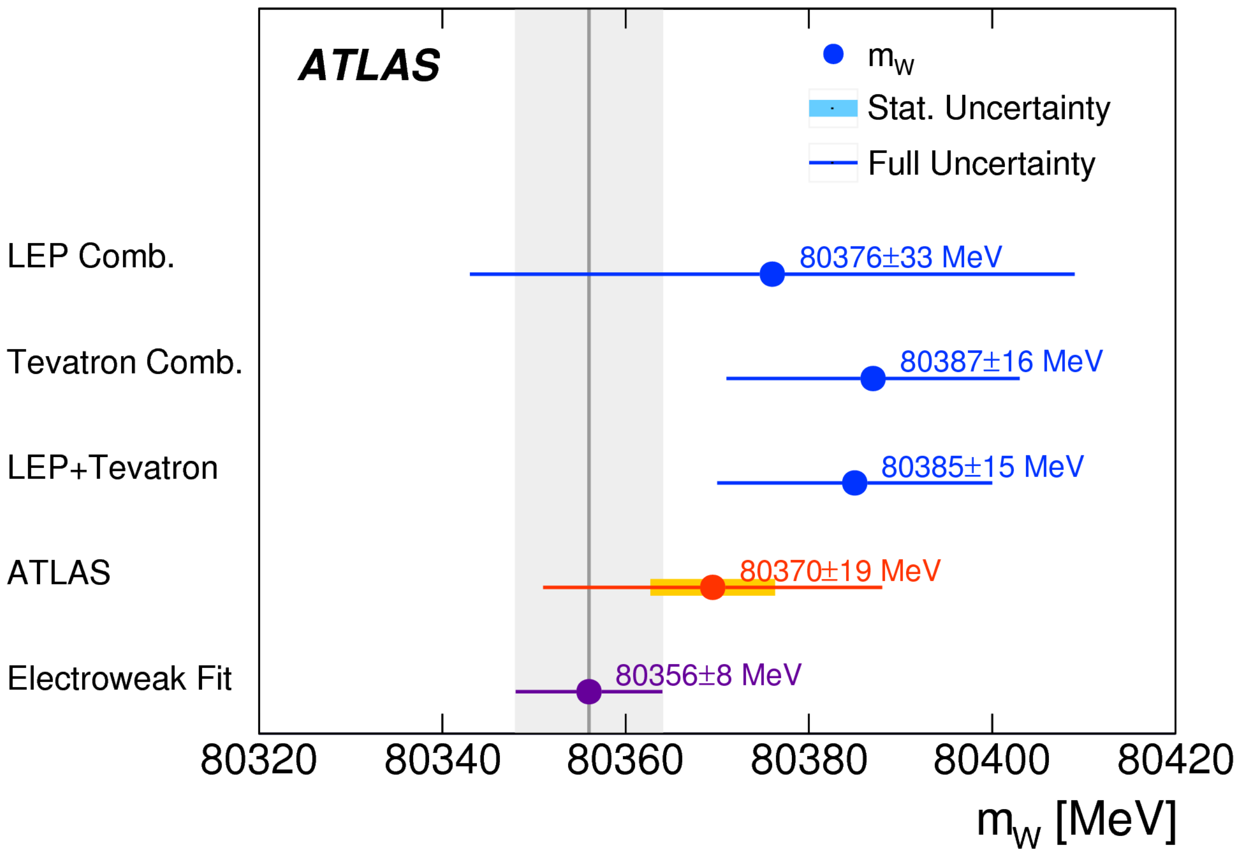
Approaching precision of Tevatron combination

The W mass @hadron collider

- Same basic measurement principle at Tevatron and LHC
  - ✓ Using a template fit approach to p^l_T and m_T
- Uncertainties dominated by model-uncertainties
  - ✓ PDFs, angular coefficients
  - ✓ Transverse momentum spectrum of the W boson
- Tevatron and LHC results currently at similar level of precision



W mass measurement with ATLAS experiment



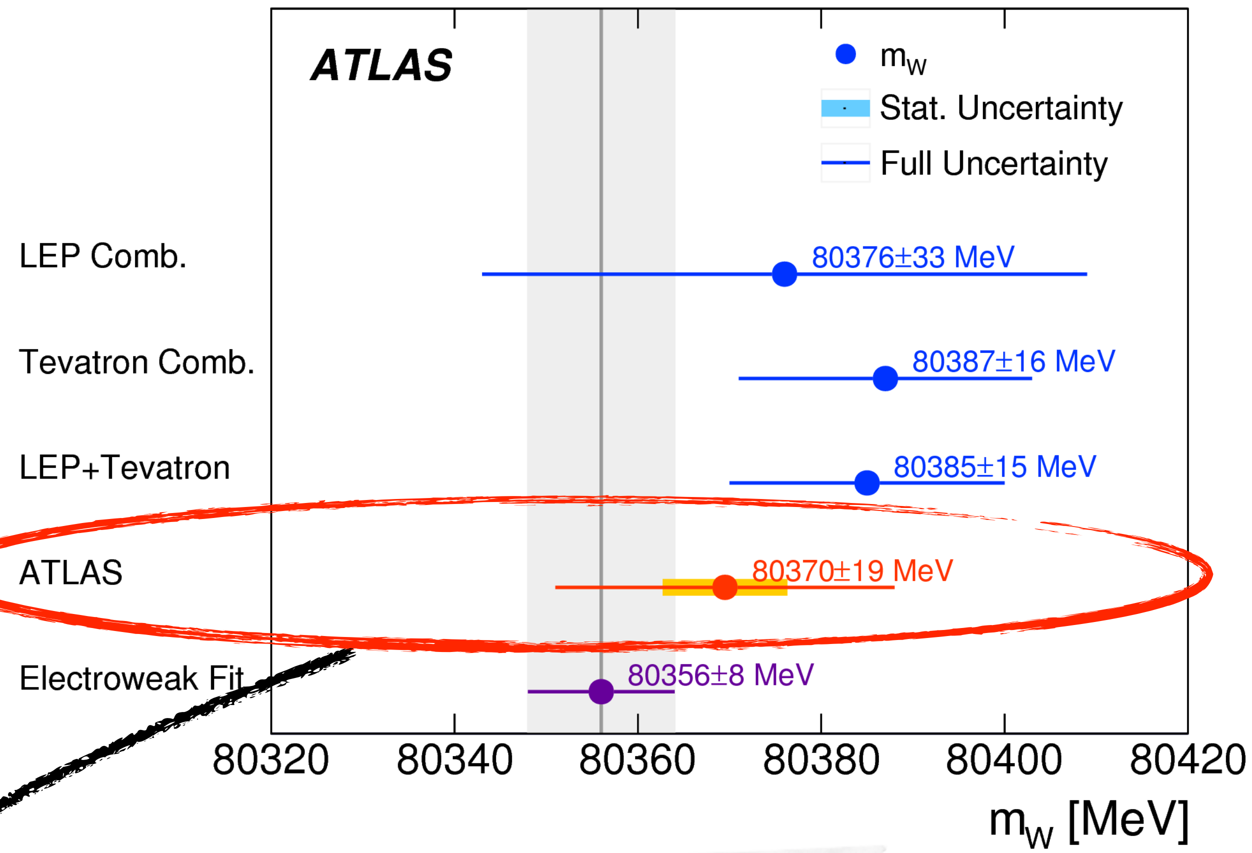
19 MeV is still far from the target of 8 MeV set by the electroweak fit how can we improve ?

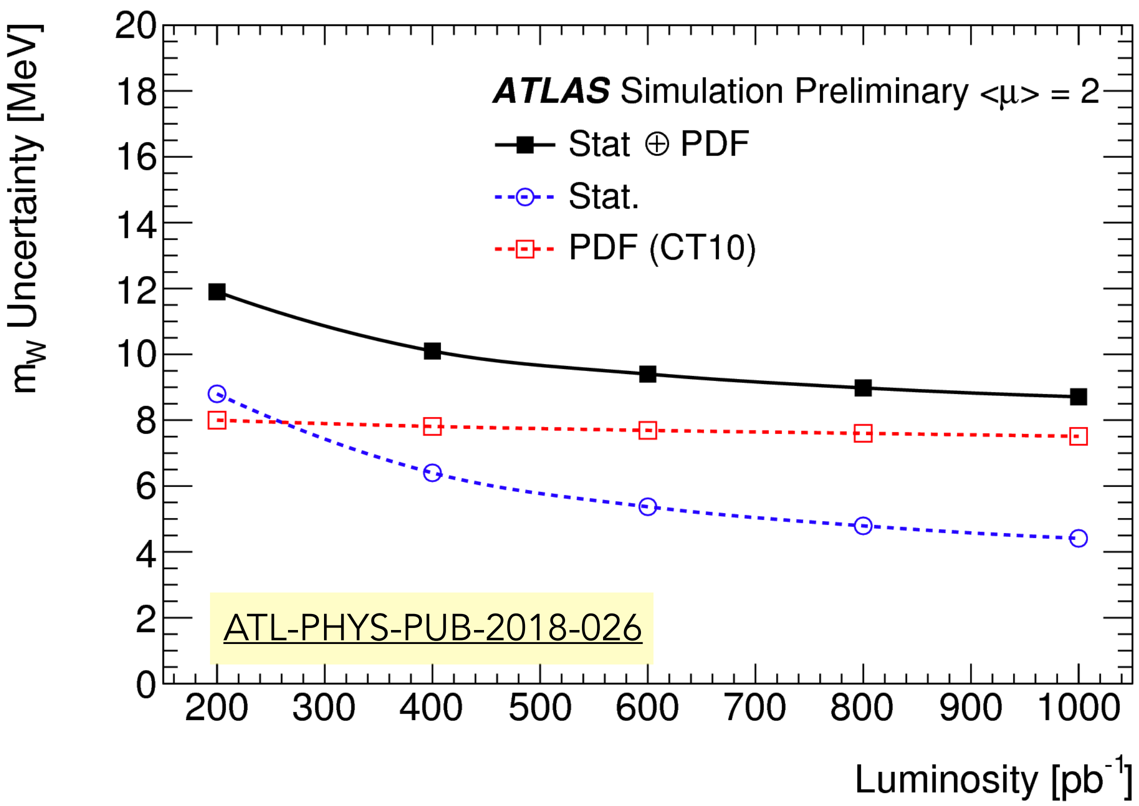
Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

stat. = 6.8 MeV exp. syst = 10.6 MeV mod. syst =13.6 MeV

m_W = 80370 +- 19 MeV

W mass measurement with ATLAS experiment



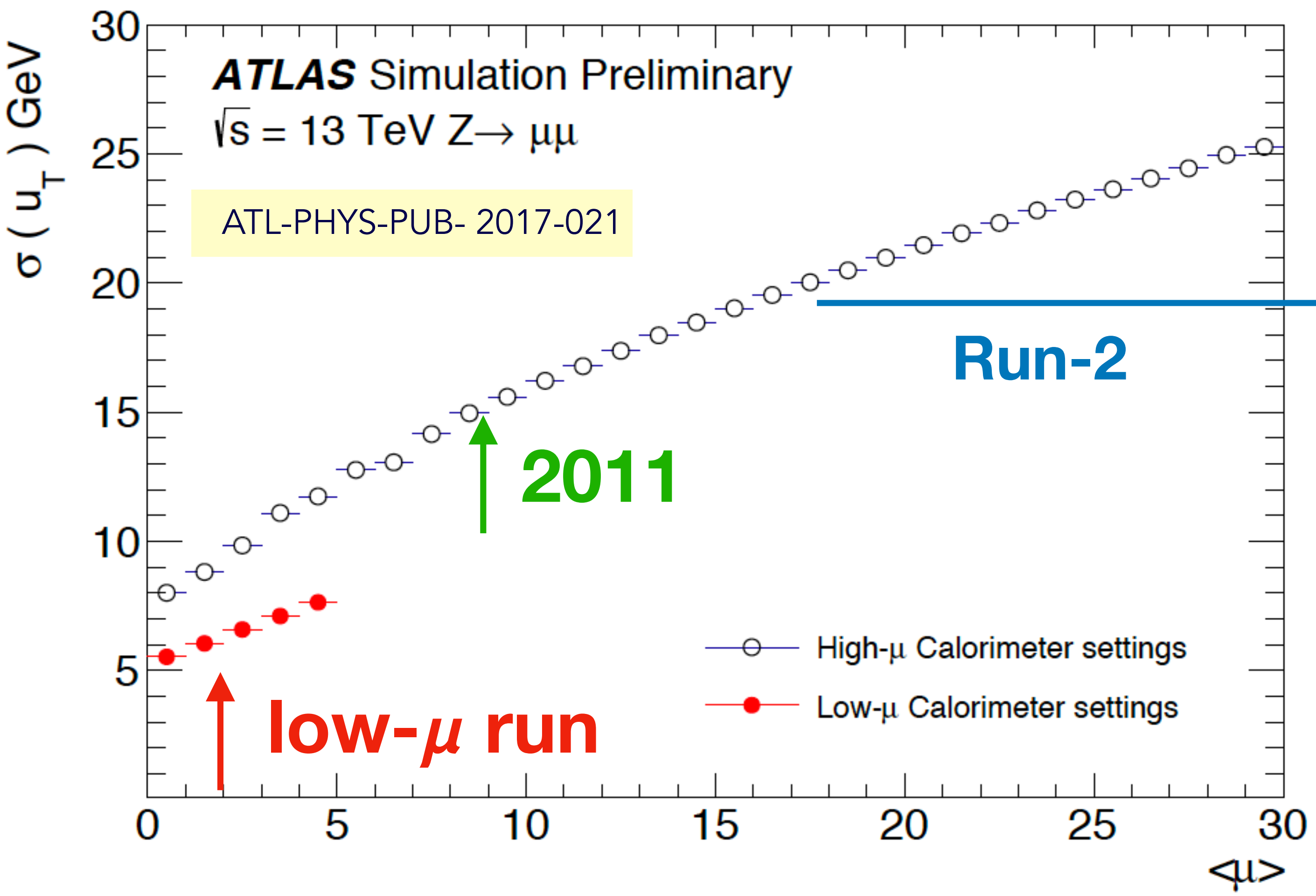


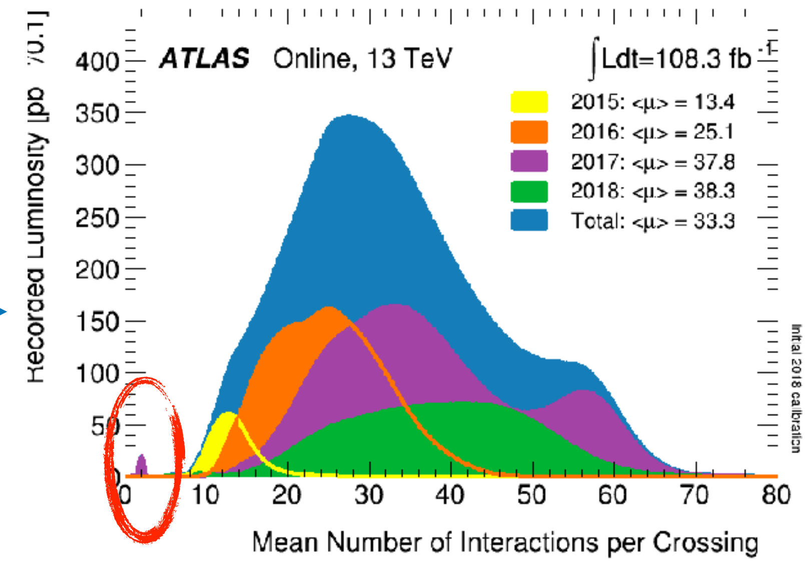
Uncertainties dominated by model-uncertainties:

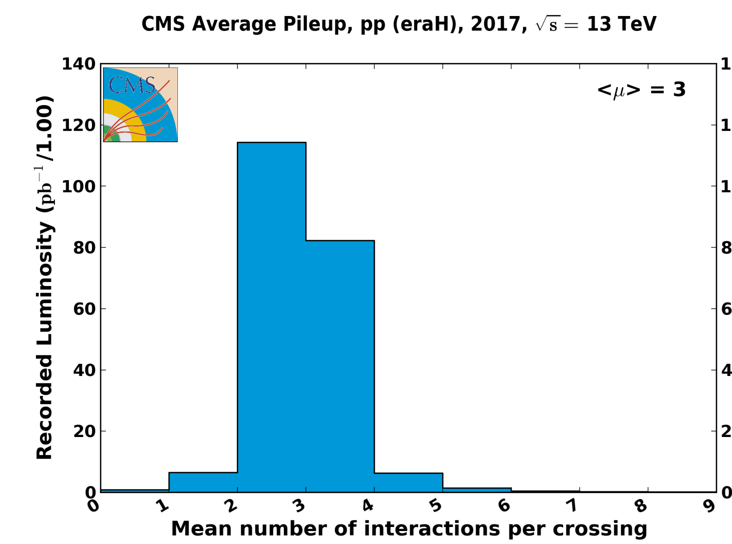
- PDFs [9 MeV]
- Transverse momentum spectrum of the W boson [8 MeV]

PDF uncertainty Dominated by knowledge of valence quark PDFs (in particular d_v)

low-Pileup Data







Both ATLAS and CMS collected @340 pb^{-1} of data collected @13TeV with **low Pileup <μ> =2**

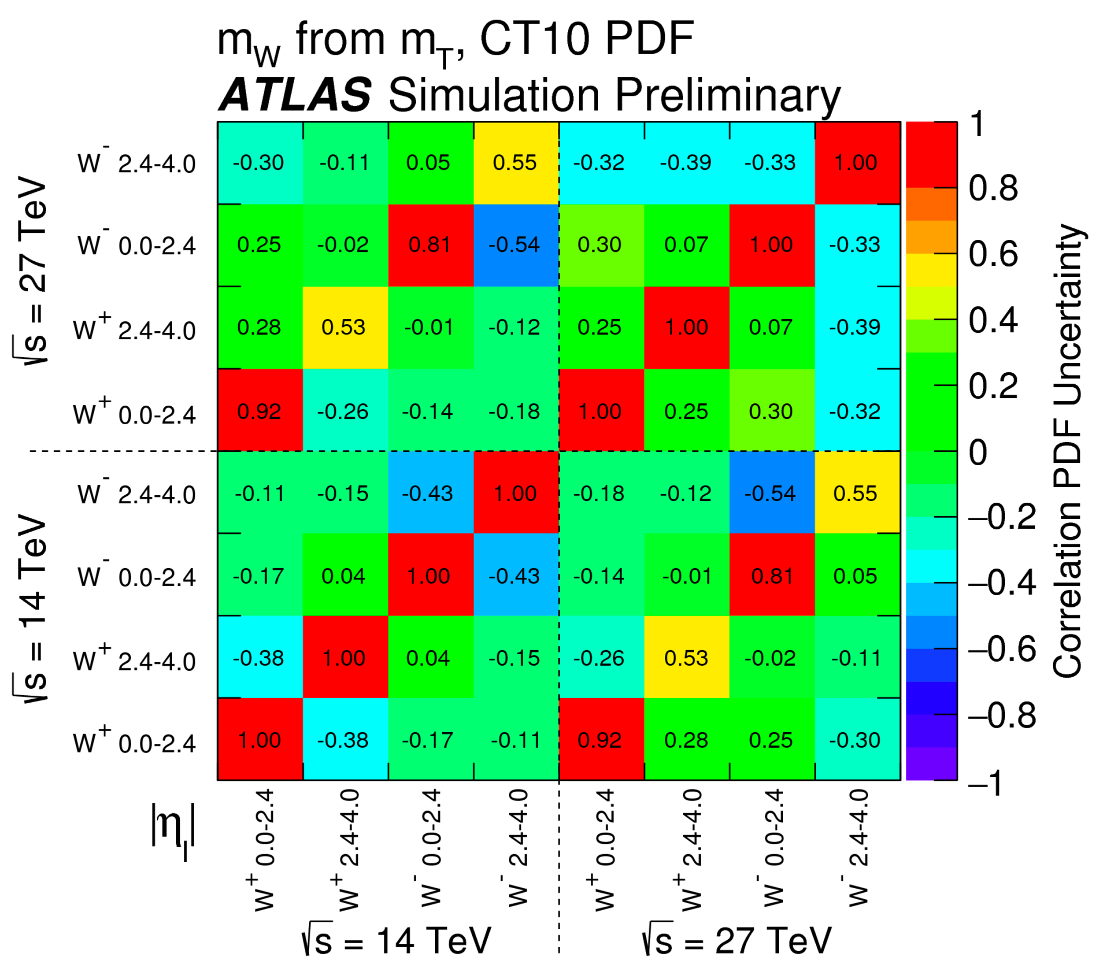
fantastic opportunity for W precision measurement!

better understanding the physics modelling of the W mass measurement will allow to reach **10 MeV precision !**

Futher in the future of W mass measurement

Study of potential of low pile-up runs, $<\mu>\sim 2$, at HL-LHC@14TeV and HE-LHC@27TeV. **200 pb-1** per week, yielding **~1M candidate/week**

- Major **reduction of uncertainty** can be achieved due to:
  - ✓ *Optimal reconstruction of missing transverse momentum → better recoil resolution*
  - ✓ *Extended coverage with new tracking detector → ITk coverage from* $|\eta| < 2.5$ *to* $|\eta| < 4$
  - ✓ *combining central and forward ranges brings significant reduction in the PDF unc. →probe new region of x at* $Q^2 \sim m_W$



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