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US/Eastern timezone

March 2015

Precision measurements of alphas, PDF, role of PDF in high-mass BSM studies

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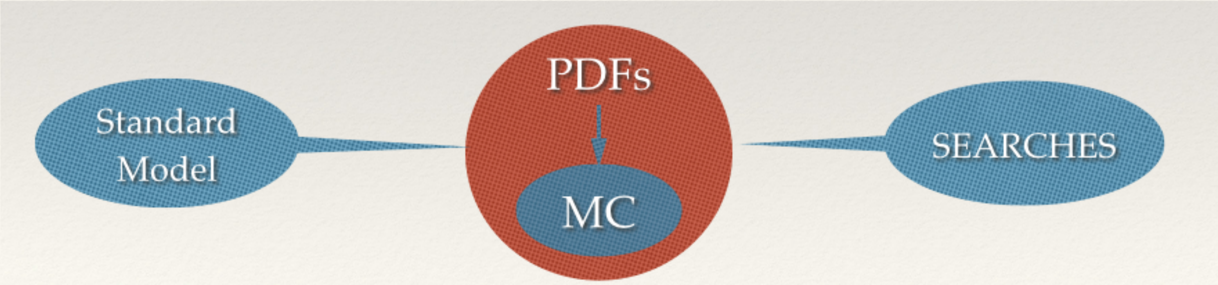
for the FCC study group

Many thanks to: David D'Enteria (ee), Michelangelo Mangano (hh), Max Klein (he)

[See also talks of F. Olness, M. Klein on Wednesday]

Introductory words

- We are at an interesting time in particle physics era:
  - LHC @ 13 TeV is about to rump up - how soon will it beat the 8 TeV searches?
  - HL-LHC - what can we gain from 300fb^{-1} to 3000fb^{-1}?
  - Today we look at the physics opportunities at 100 TeV (FCC)
    - The mass reaches of different collider setups can be quickly estimated
      - [http://collider-reach.web.cern.ch/collider-reach/]
- Discovery of new exciting physics relies on precise knowledge of proton structure.
  - PDFs are one of the main theory uncertainties in Mw measurement
  - PDFs are one of main theory uncertainties in Higgs production
  - PDF uncertainties very large (>100%) for new heavy particle production
  - PDF limit precise extraction of EW parameters and strong coupling
- Factorisation Theorem:
  - Cross section can be calculated by convoluting short distance partonic reactions with PDFs:
    - ep —> probes linear combination of PDFs
    - pp—> probes bi-linear combination of PDFs
  - PDFs cannot be calculated in perturbative QCD, however they are process independent (universal) and their evolution with the scale is predicted by pQCD:

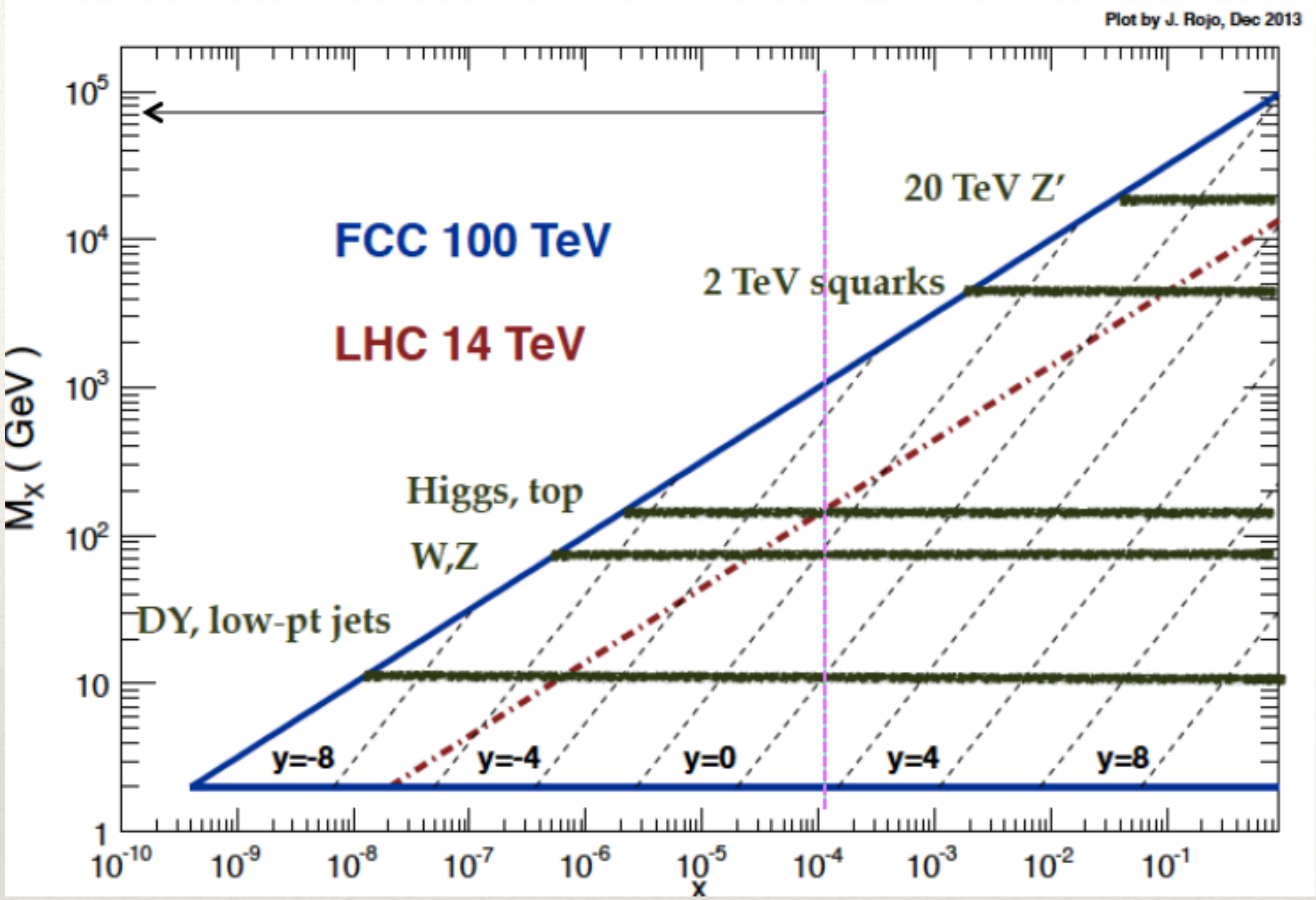


Improving PDFs with FCC

- FCC will access smaller x, larger Q^2
- Currently there is no data to constrain PDFs for $x < 10^{-4}$
  - we rely purely on extrapolation

  - Low x physics: we don’t know where at low x, BFKL effects start to become important

- Poor constraints as well for high x
  - PDFs at high masses (Q^2) rely on DLAP evolution
  - we know at large Q^2 EW effects also become important



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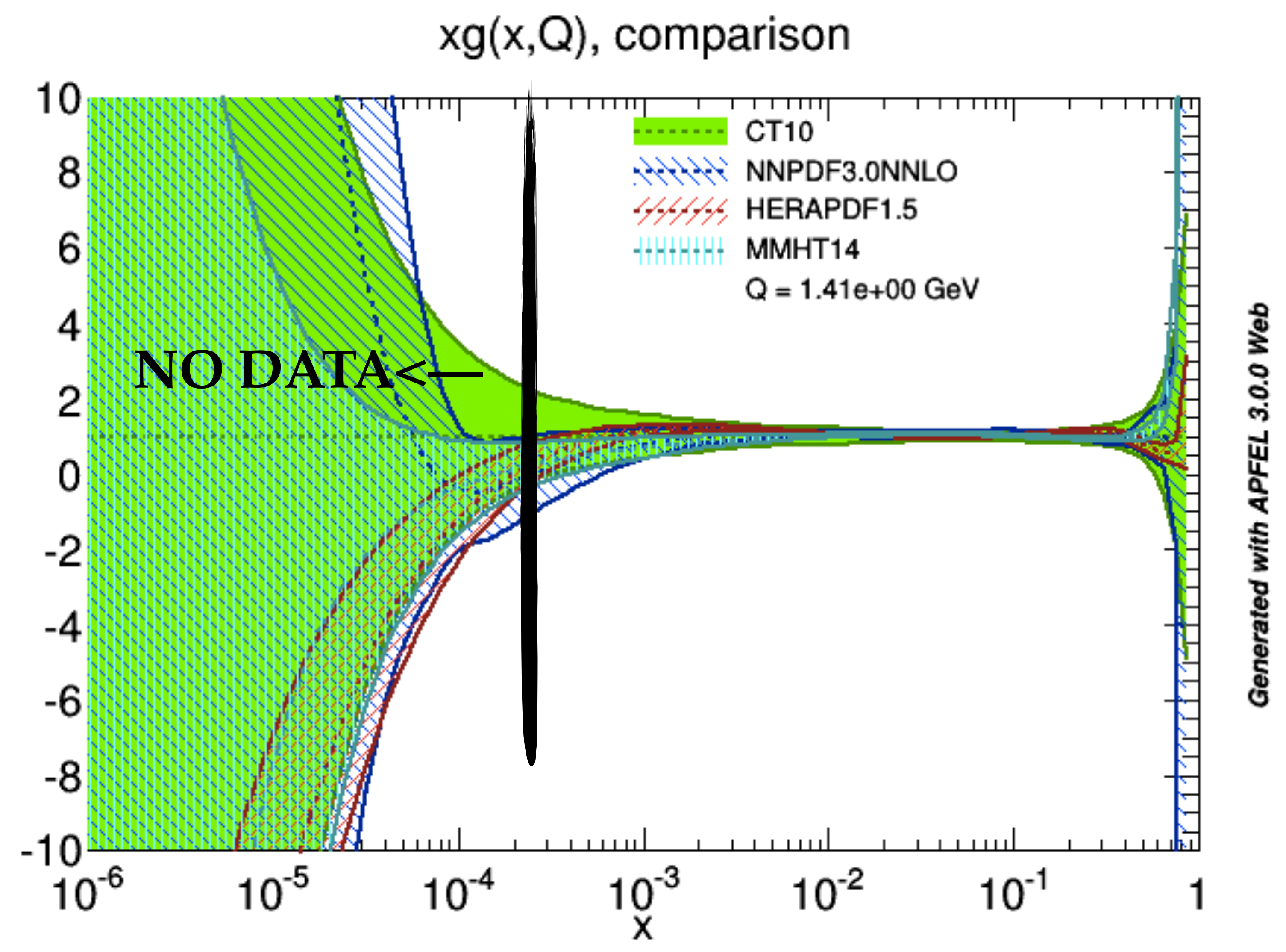
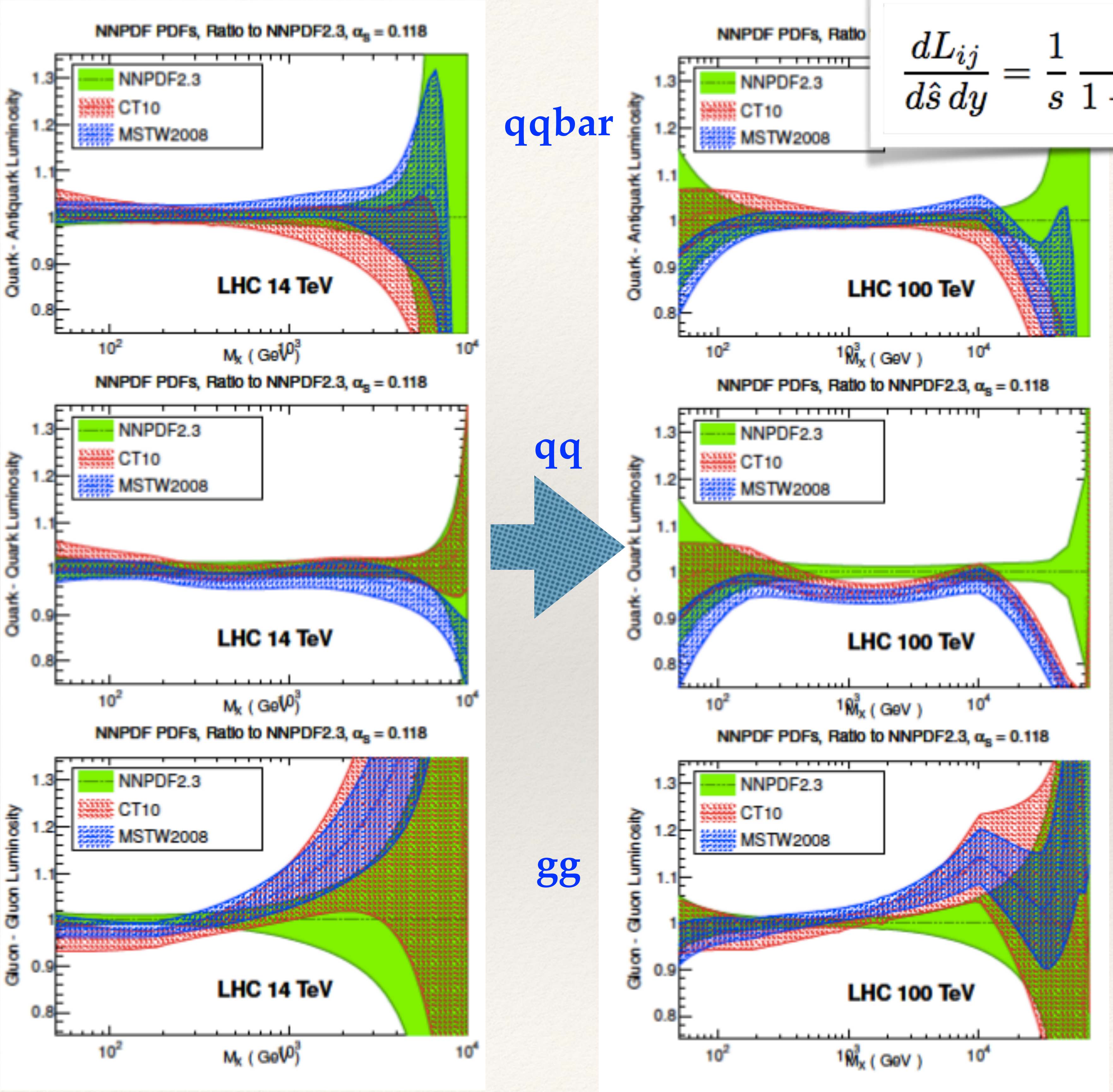


The 100 TeV data will be useful in determining PDFs in these new kinematic regions

Parton luminosities at different scales

$$\frac{dL_{ij}}{d\hat{s}\,dy} = \frac{1}{s}\,\frac{1}{1+\delta_{ij}}\left[f_i(x_1,\mu)f_j(x_2,\mu) + (1 \leftrightarrow 2)\right]$$

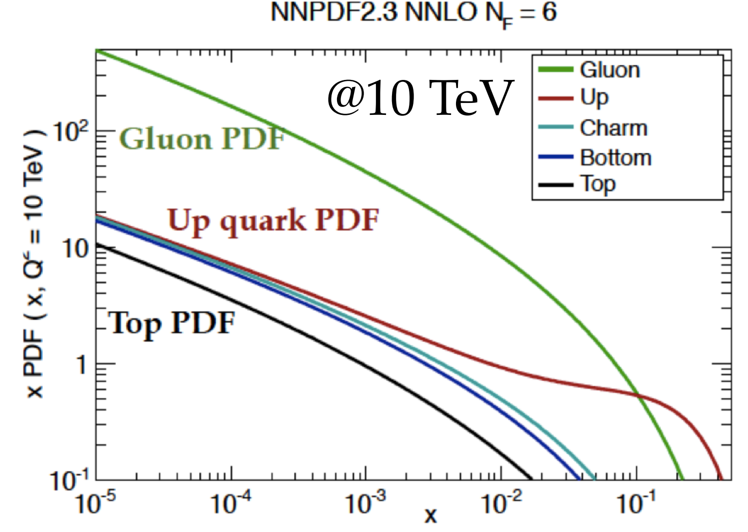


Remarks:

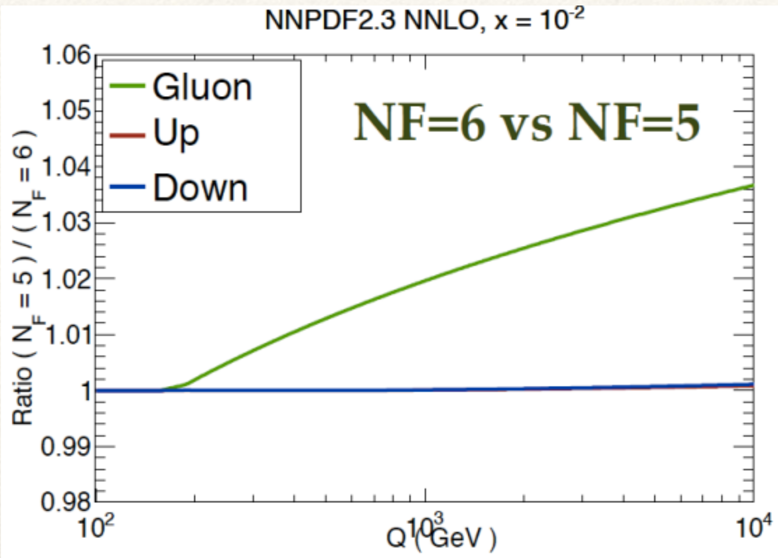
- high masses uncertain with current precision
- low masses become challenging at very high energy colliders

What can/will matter for FCC:

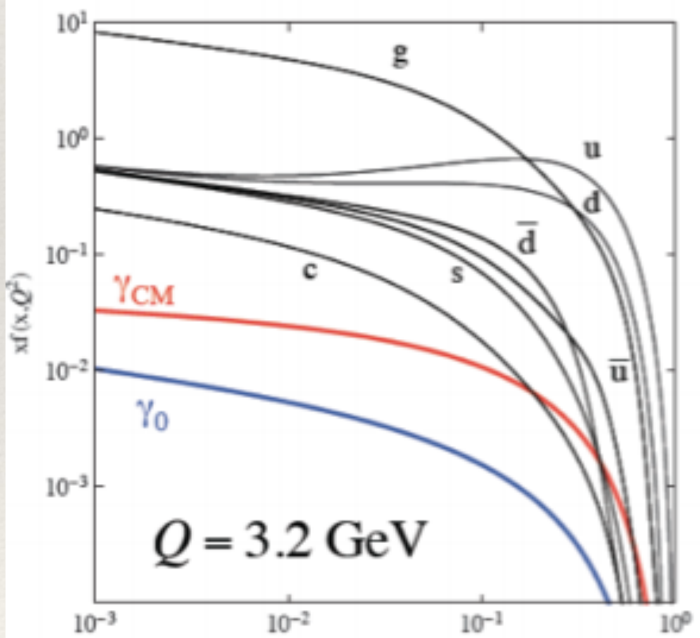
- **Top PDF:** at the very high Q^2, top becomes small and will have to be included as 6f PDFs



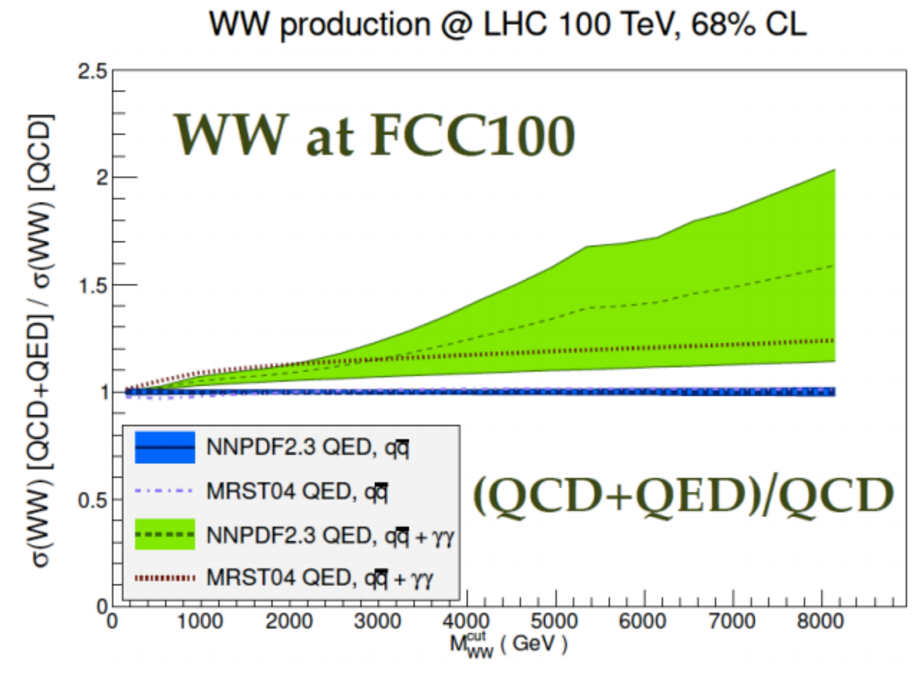
inclusion of top
affects the gluon



- **Photon PDF:** will become important as energies increase
  - the LHC is a $\gamma\gamma$ collider —> more photons at 100 TeV collider



substantial uncertainties
from large x-region



- **NNNLO PDFs:** might be needed if the scale is not a dominant uncertainty and the precision of the data is such that it needs a better theory discrimination

—> it's important to learn what is ok to absorb in PDF and what is not!

FCC eh scenario

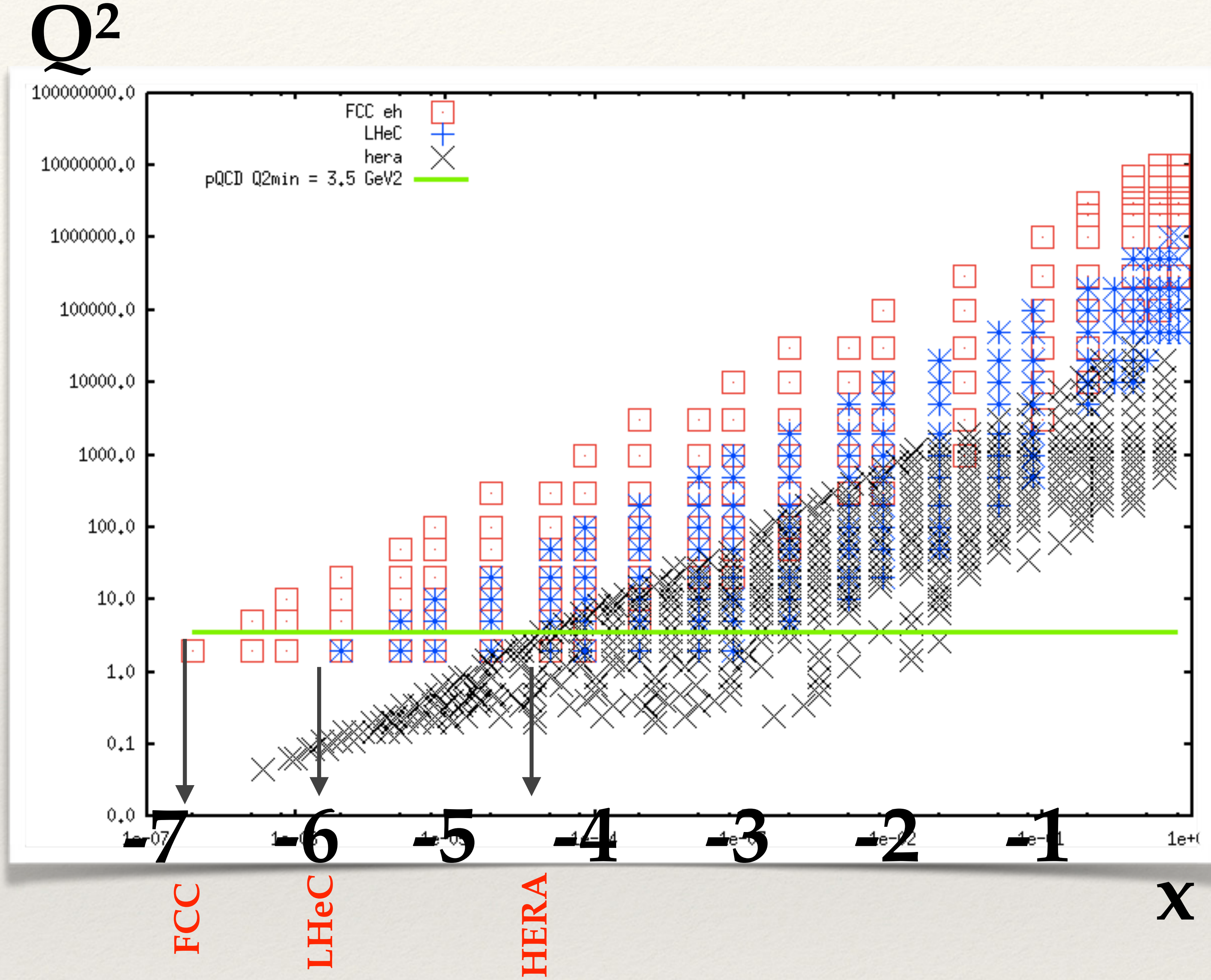
NEW

FCC eh study based on:

- Ep = 50 TeV, Ee = 100 GeV:
- polarised e- with negative polarisation -80%: 1000/fb, NC, CC

- Coverage:
  - down to 2x10-7 in x
  - up to 10,000,000 GeV^2 in Q^2

- Estimated Precision:
  - stat 0.1% - 30% (highest Q^2)
  - uncor 0.7%
  - sys ~1% - 5% (highest Q^2)



The kinematical coverage of FCCeh compared with the LHeC Scenario and HERA

but there is also the opportunity to partially explore these kinematic regions in advance using a possible LHeC

LHeC scenario (update since CDR)

NEW

Data sets used for the LHeC studies:

- Ep = 7 TeV, Ee = 60 GeV:
  - unpolarised e+: 5/fb NC, CC
  - polarised e- with negative polarisation -80%: 500/fb, NC, CC
  - polarised e- with positive polarisation +80%: 50/fb, NC, CC

- Dedicated measurements for F2c, F2b, strange and anti-strange
- -> constrain xc(x), xb(x), xs(x) and xsbar(x)

- Deuteron data NC, CC

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Volume 39 Number 7 July 2012 Article 075001

A Large Hadron Electron Collider at CERN

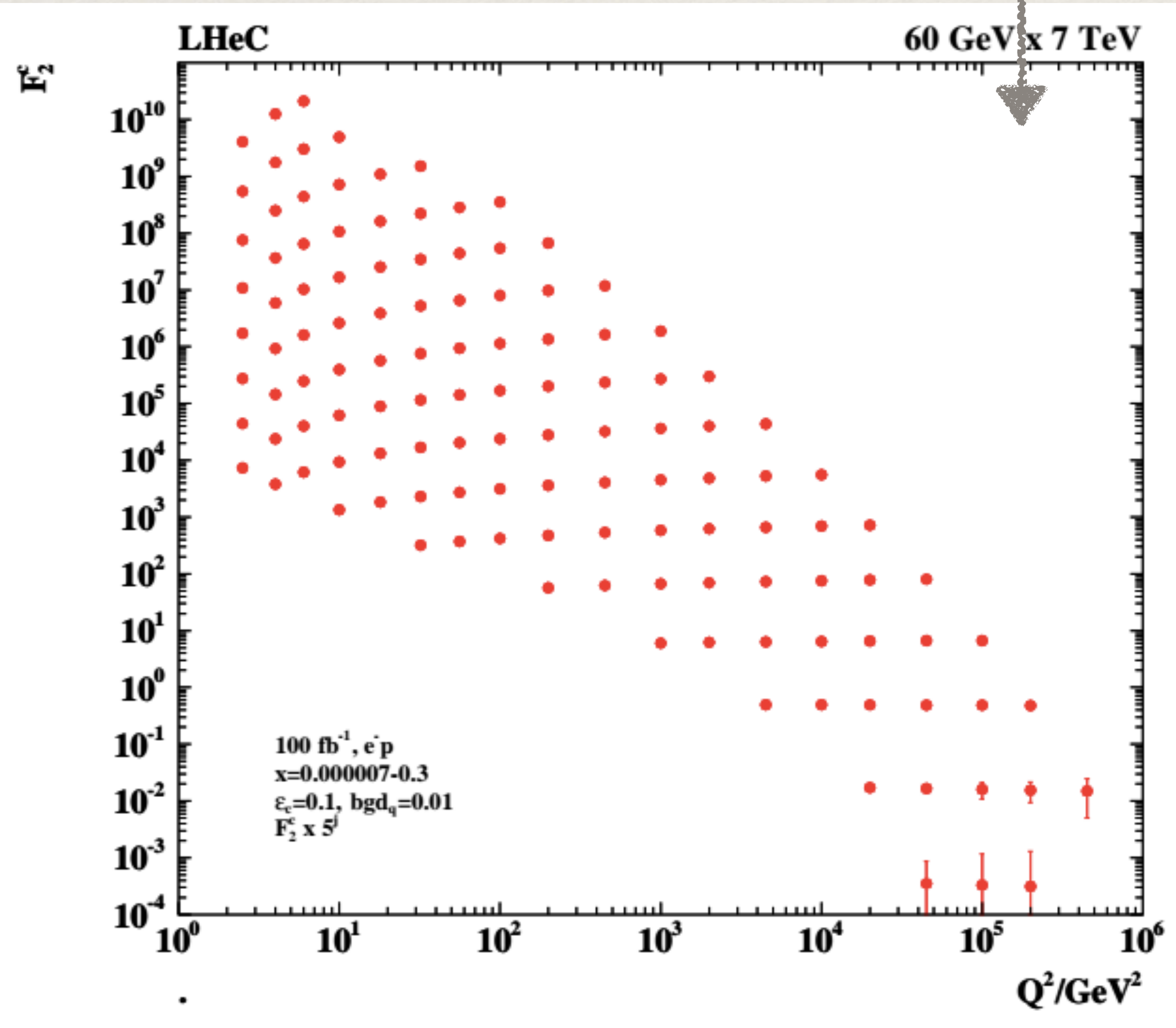
Report on the Physics and Design Concepts for Machine and Detector

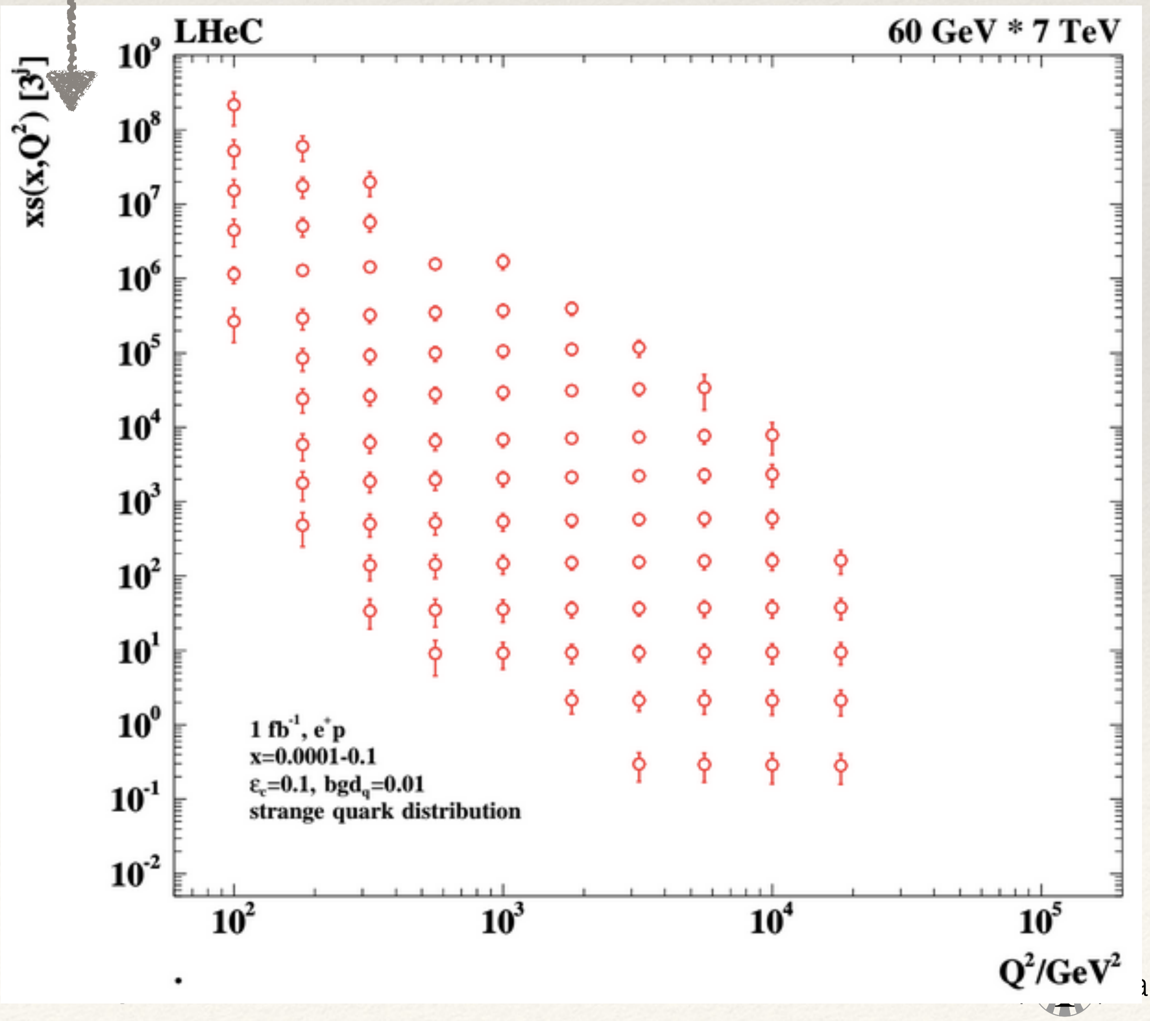
LHeC Study Group

arXiv:1206.2913

iopscience.org/jphysg

IOP Publishing



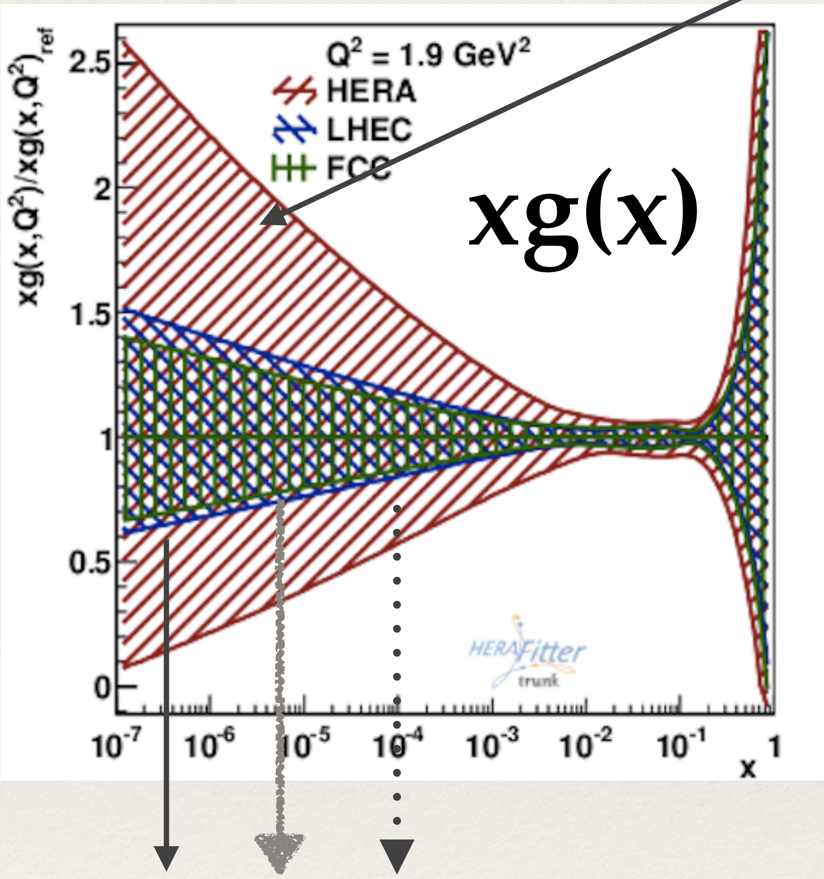


FCC eh vs LHeC vs HERA for PDFs

A new QCD Analysis performed using SM central predictions based on:
[HERAFitter - open source QCD fit platform: www.herafitter.org]

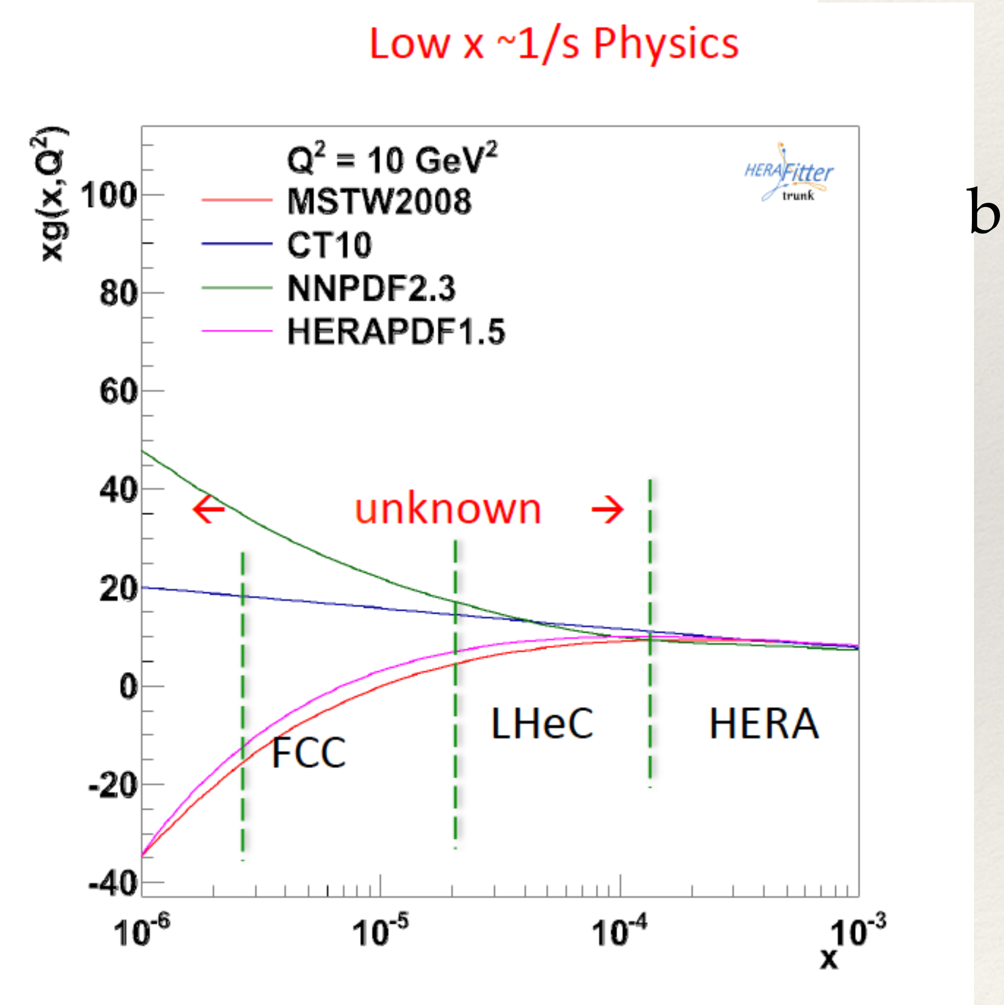
NEW

- simulated data
- evolved PDFs are **xg, xuv, xdv, xub, xdb, xstr**
- parametric form: **$xf(x)=Ax^B(1-x)^C(1+Dx+Ex^2)$ —> 14 free parameters**



FCC LHeC HERA

HERA sensitivity stops at ~10^{-4}
—>uncer. driven by parametrisation



—> Level of agreement between Current Global PDFs

FCC eh allows for Low x phenomenology

NEW

LHeC scenario: impact of different sets

We can better constrain ALL the PDFs when adding on top of inclusive NC, CC:

- the measurements of the charm cross sections

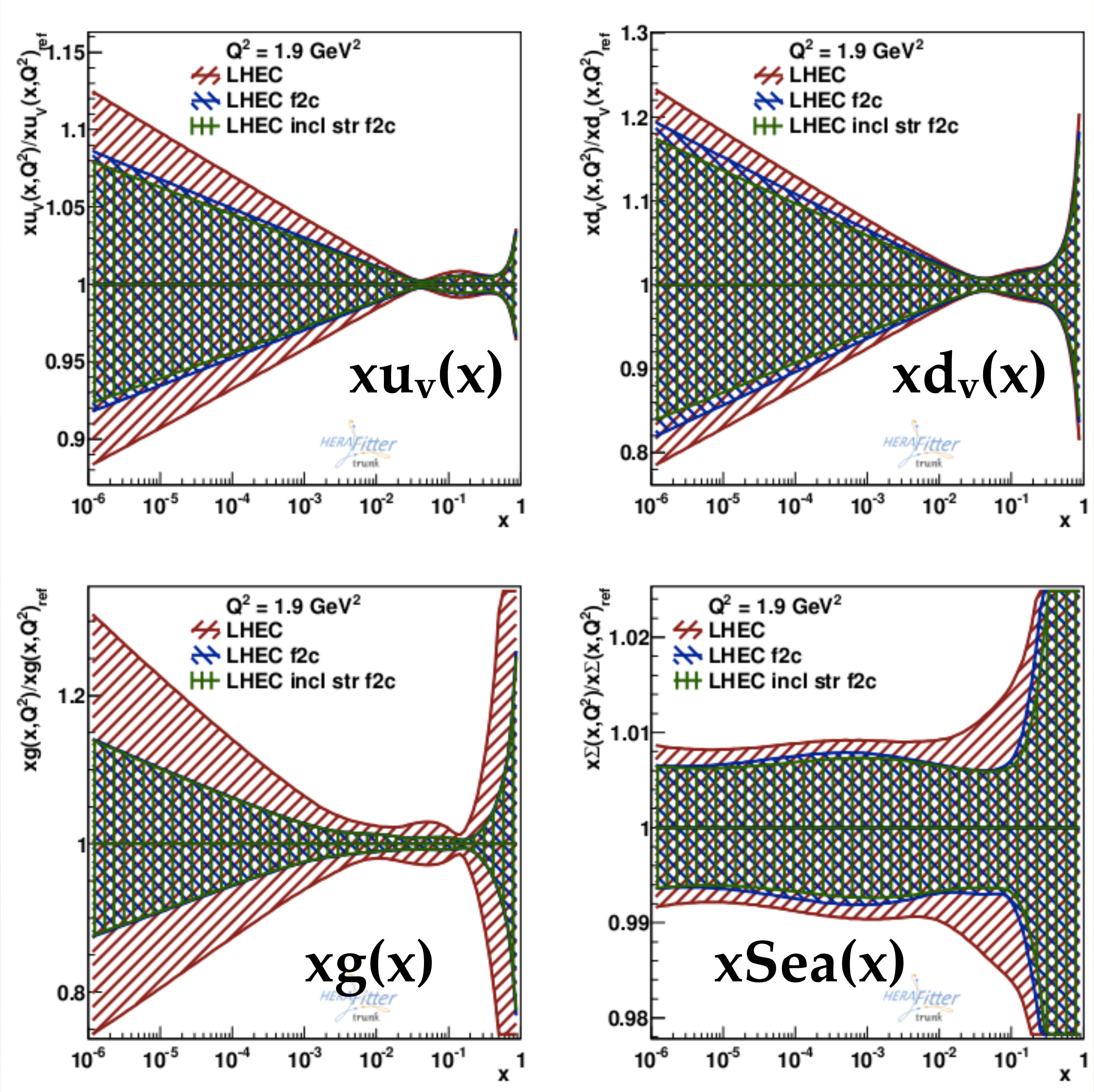
—> **sensitive to gluon, mc parameter**

- the measurements directly sensitive to strange quark distributions using charm tagging in the final state
  - $W+s \rightarrow c$ (for positron)
  - $W-\bar{s} \rightarrow \bar{c}$ (for electron)

—> **constrains strange quarks**

- the inclusive measurements using deuteron beam instead of protons:

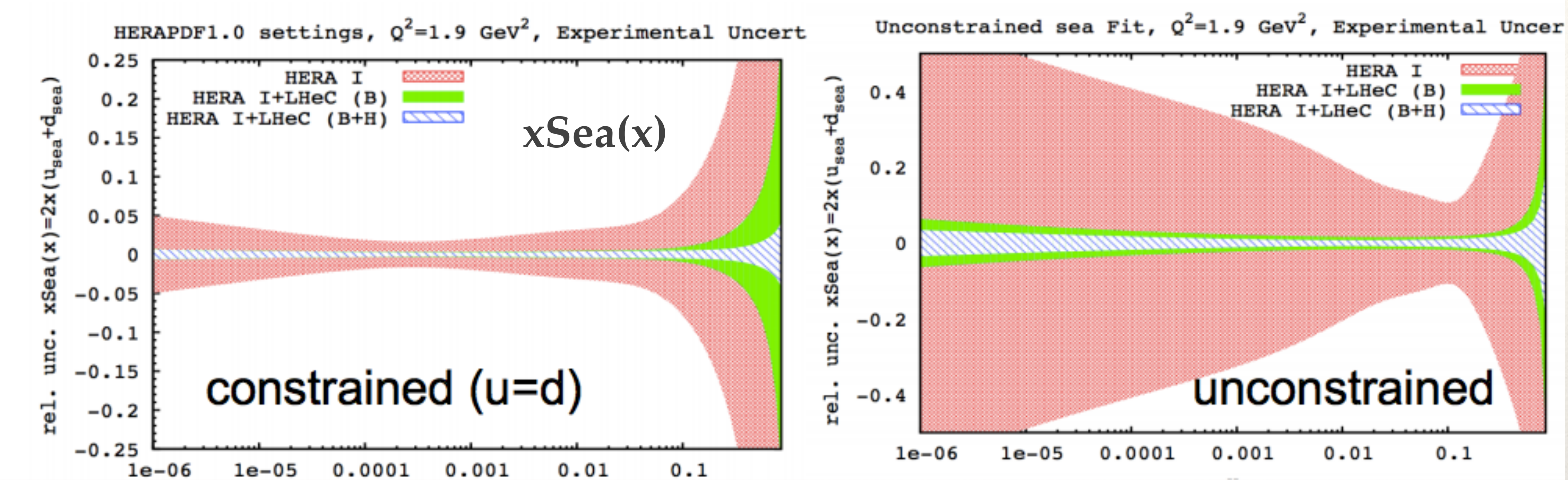
—> **constrains d_{val}**



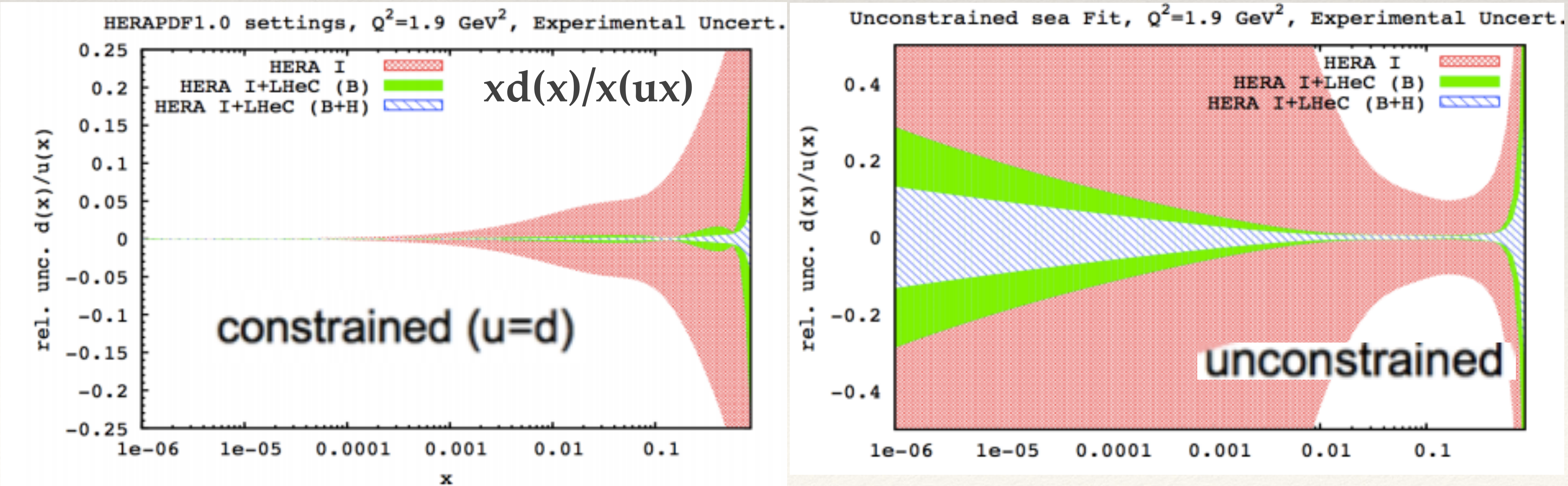
eh scenario can provide precisely all PDFs
Moreover, it can determine PDFs without relying on imposed constraints

LHeC PDFs with released assumptions

- It is usually imposed the constrain that at low x, xu(x)=xd(x) - but how low is low?

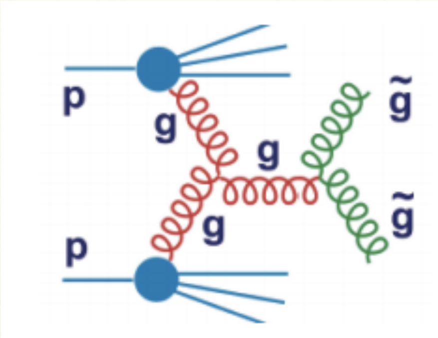


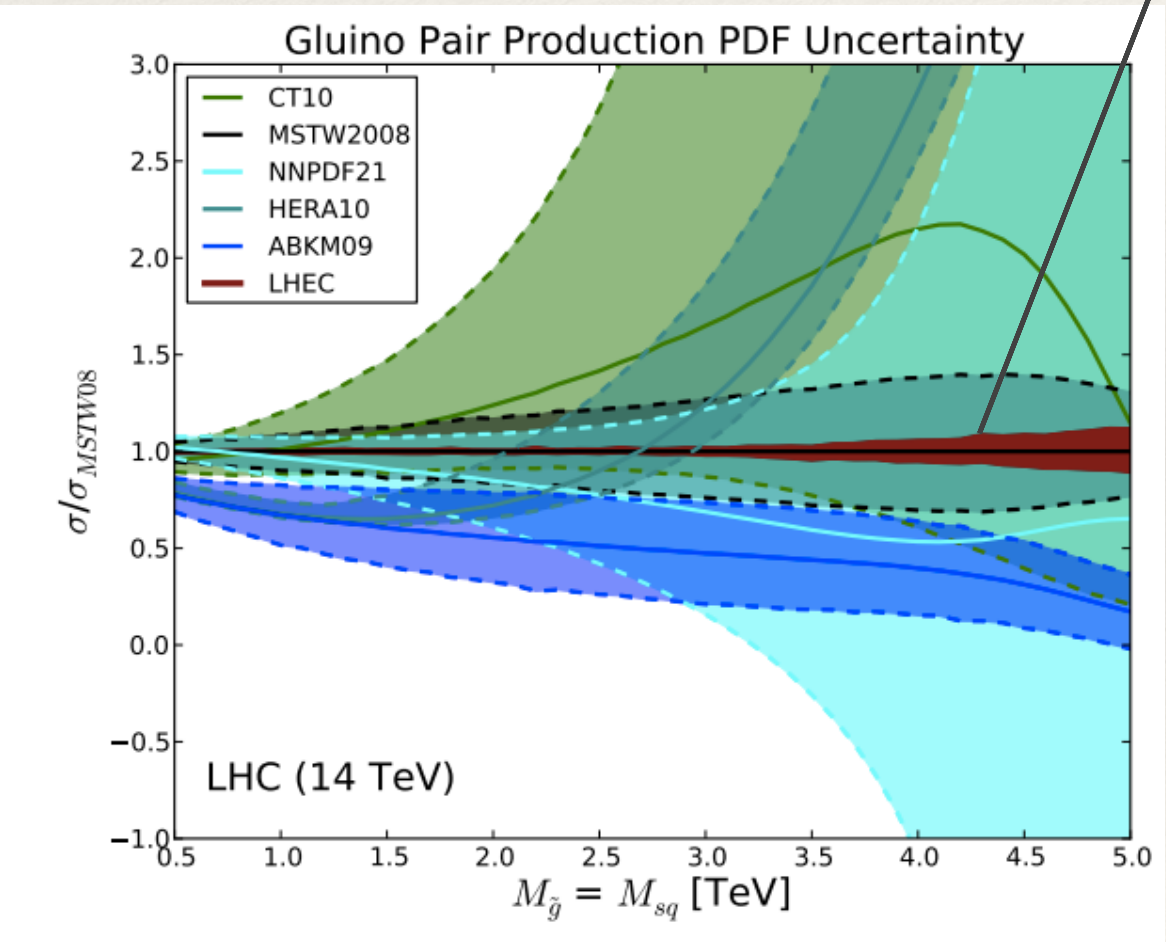
—> impact on d/u:



High Precision DIS data at high scale

- One of the dominant SUSY production channels is the gluino-gluino pair production:

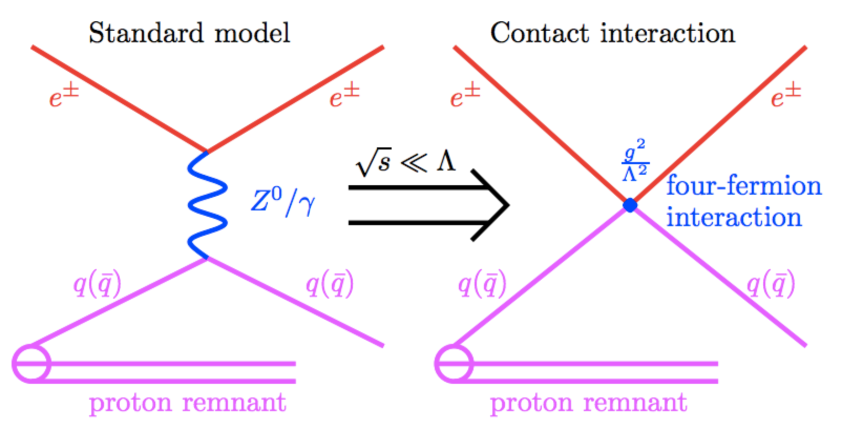


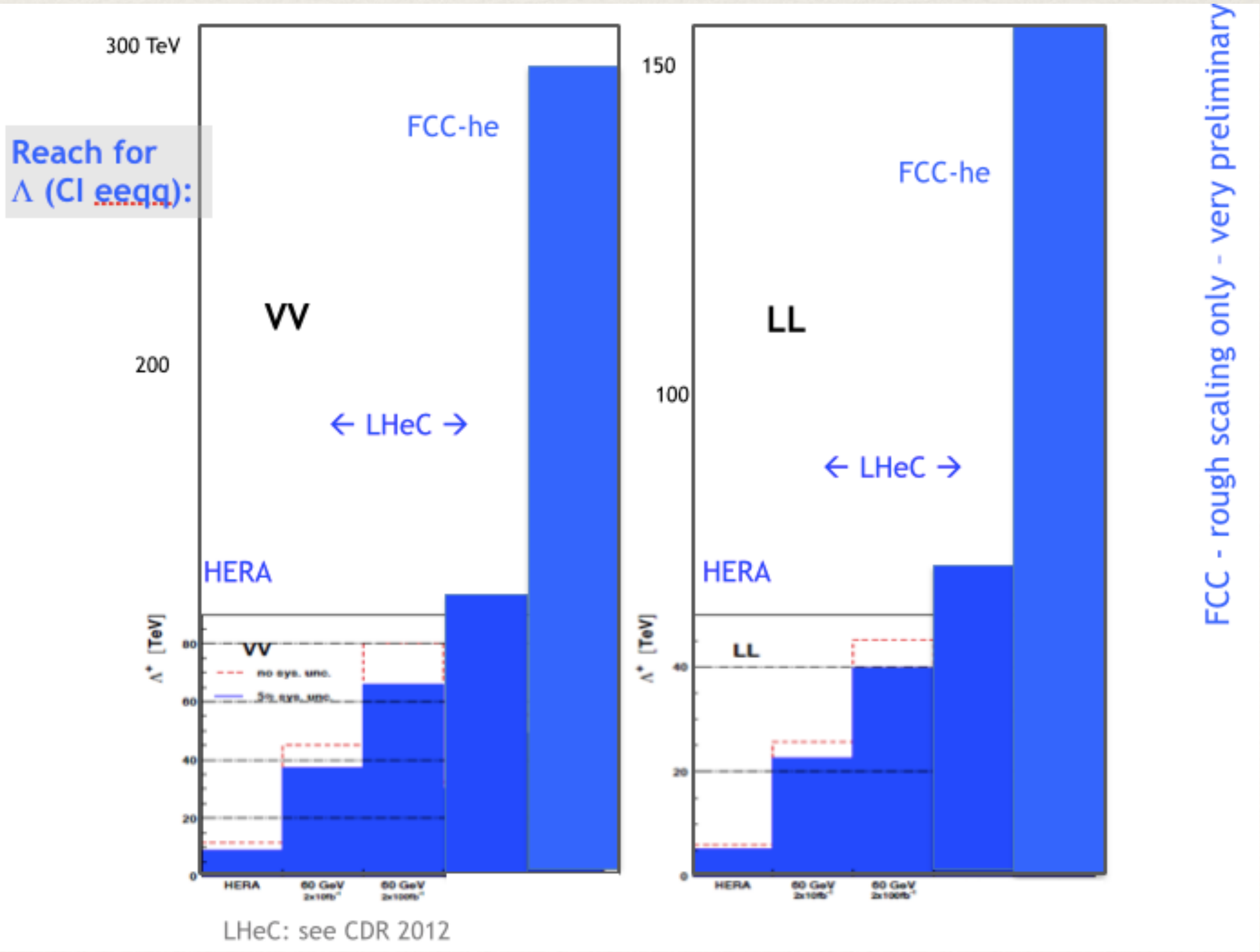


LHeC PDF set

predictability power of the production cross section suffers from high x PDF uncertainties

- The very high Q2 data would allow to search for CI (eeqq)





LHeC: see CDR 2012

FCC - rough scaling only - very preliminary

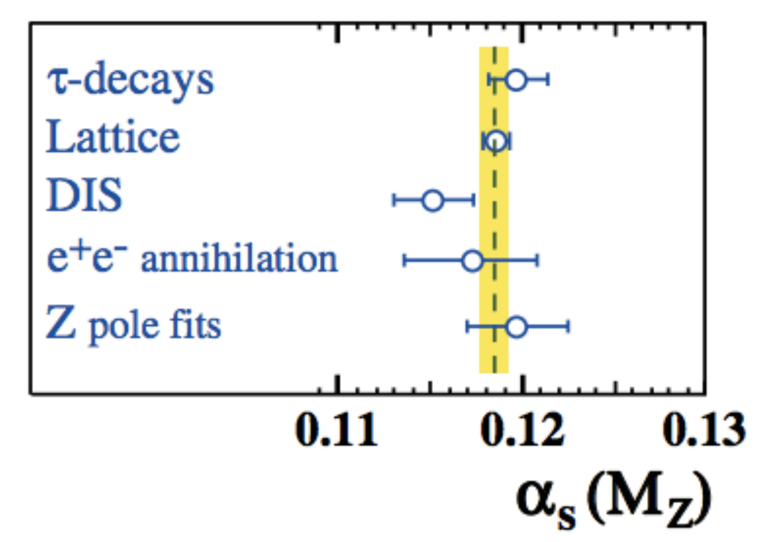
Strong coupling

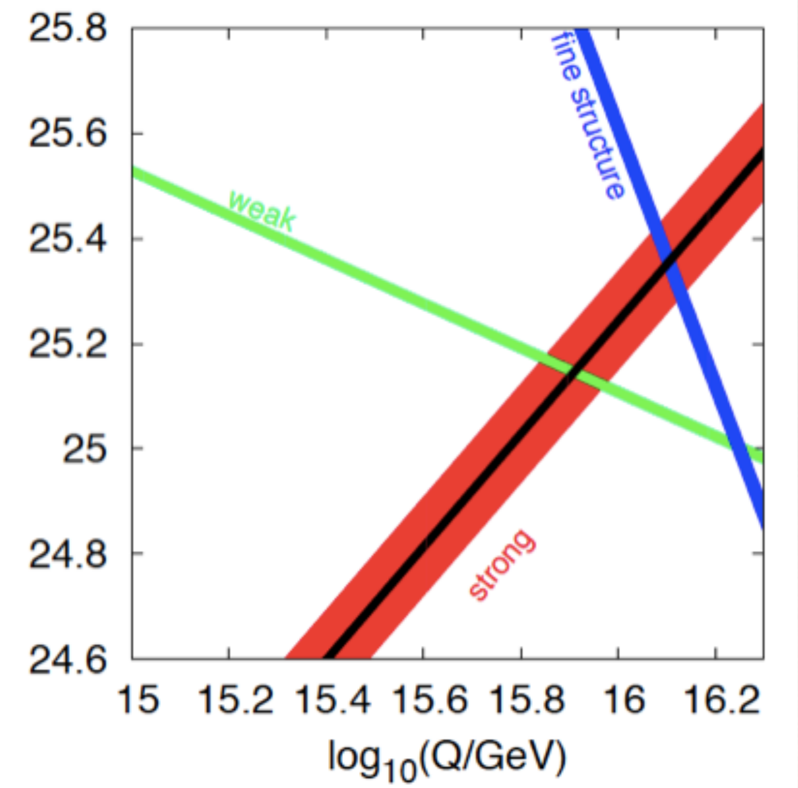
- The size of αs is not given by theory, but can be extracted from experimental measurements at e+e−, ep, pp, and pp¯ colliders, as well as from lattice QCD calculations.

PDG world average: $\alpha_s(M_Z) = 0.1184 \pm 0.0006$

w/o lattice inputs: $\alpha_s(M_Z) = 0.1183 \pm 0.0012$

current precision ~1% (no lattice)



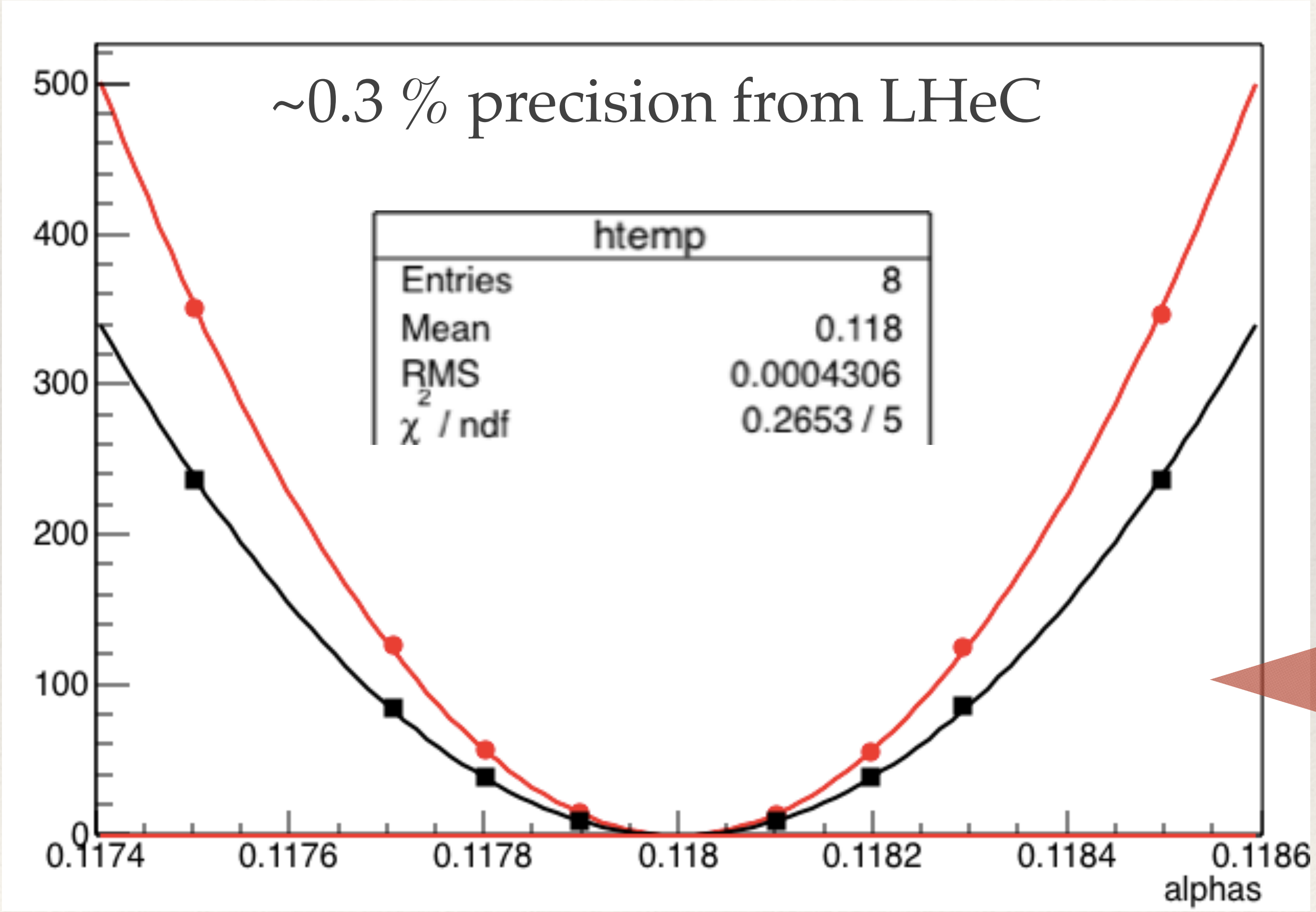


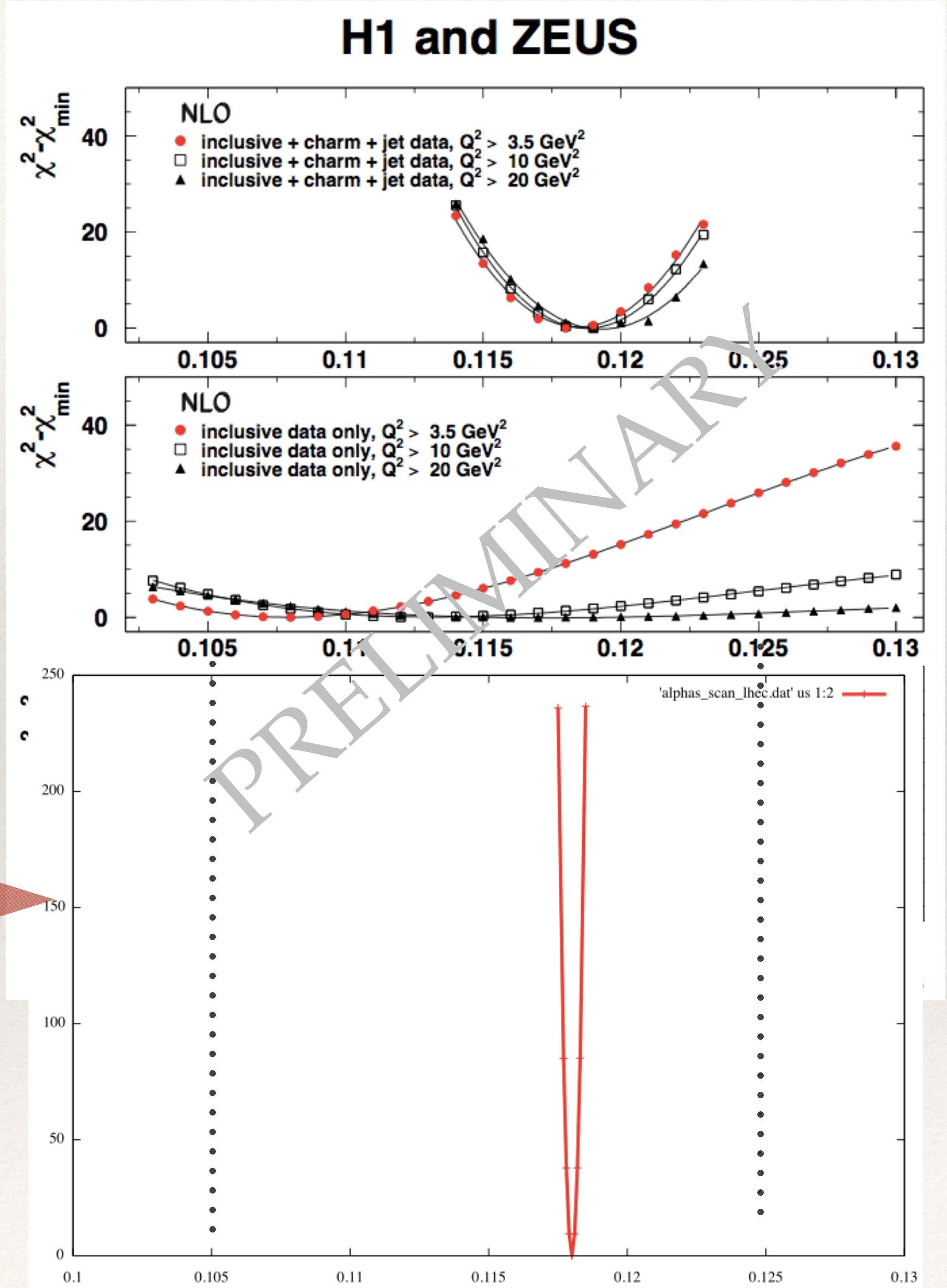
- However, one has to note that there are extractions of strong coupling with small uncertainties that are not consistent …

- Reducing the αs uncertainty would enable to constraining GUT, to more precise measurement of the partial width and the total width of the Higgs boson at future lepton colliders, for which exp. uncertainty is no longer a limiting factor.

Strong coupling from FCC eh

- The much reduced PDFs impose better constraints on various SM and BSM parameters:
  - alphas small in DIS or high with jets?
    [over 30 years old puzzle HERA couldn't solve]

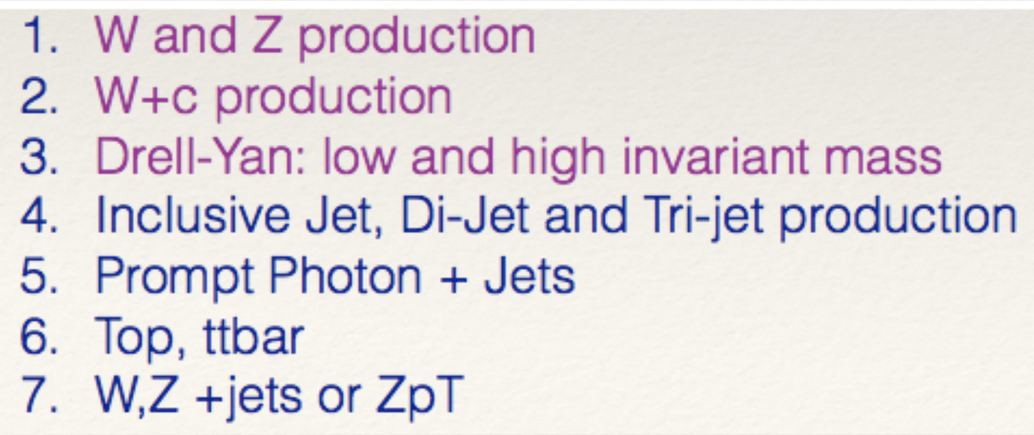

~0.3 % precision from LHeC



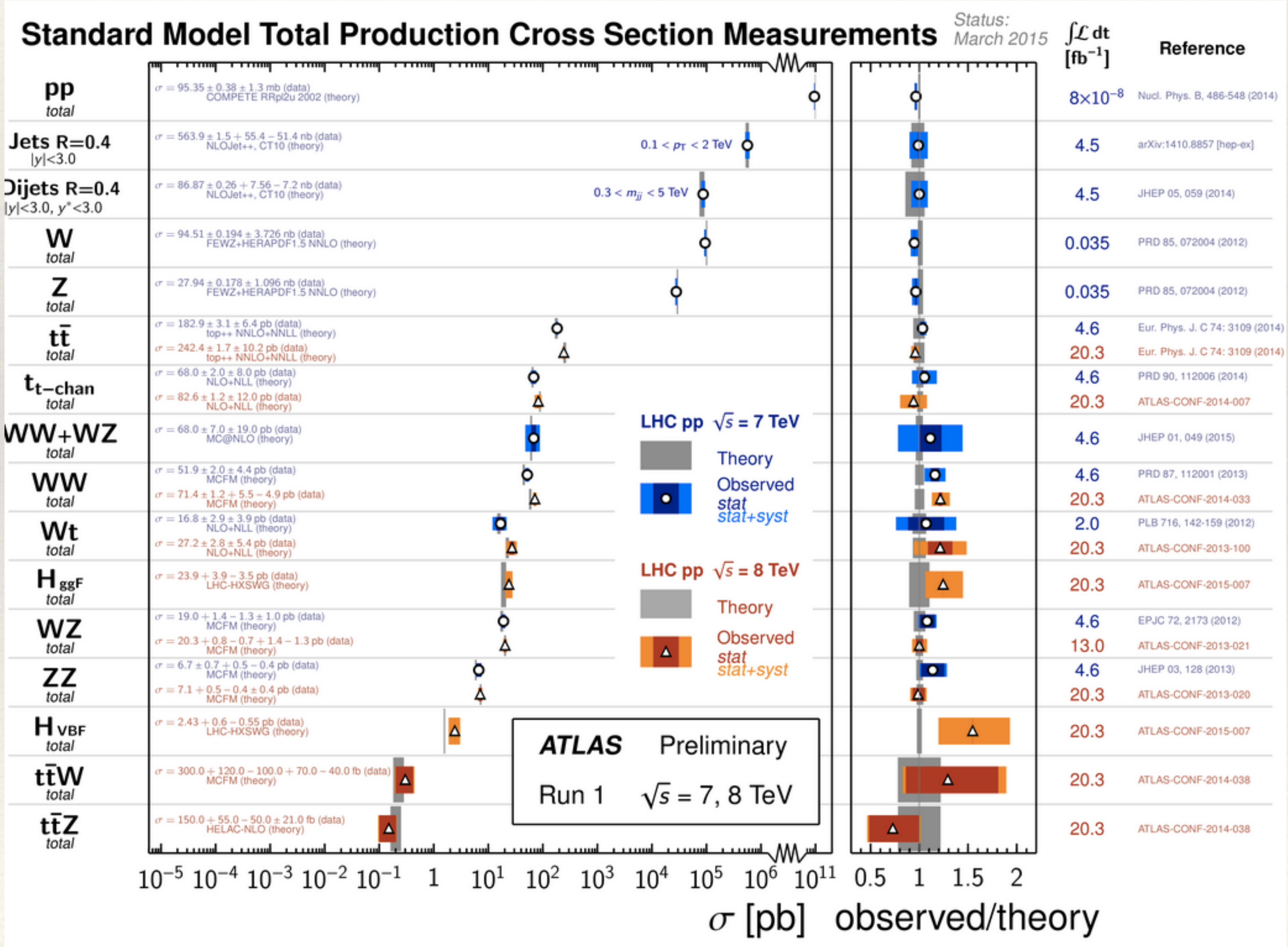
FCC hh

- Hadron colliders can give us more insight into the hard QCD, the PDFs, non-perturbative effects, and the least known fundamental constant -alphas
  - understanding QCD is essential for searches
    - it represents an enormous background
    - it is the dominating uncertainty for Higgs cross sections
- LHC Run 1 measurements are in remarkable agreement with SM predictions

—> PDF discrimination
—> PDF improvement

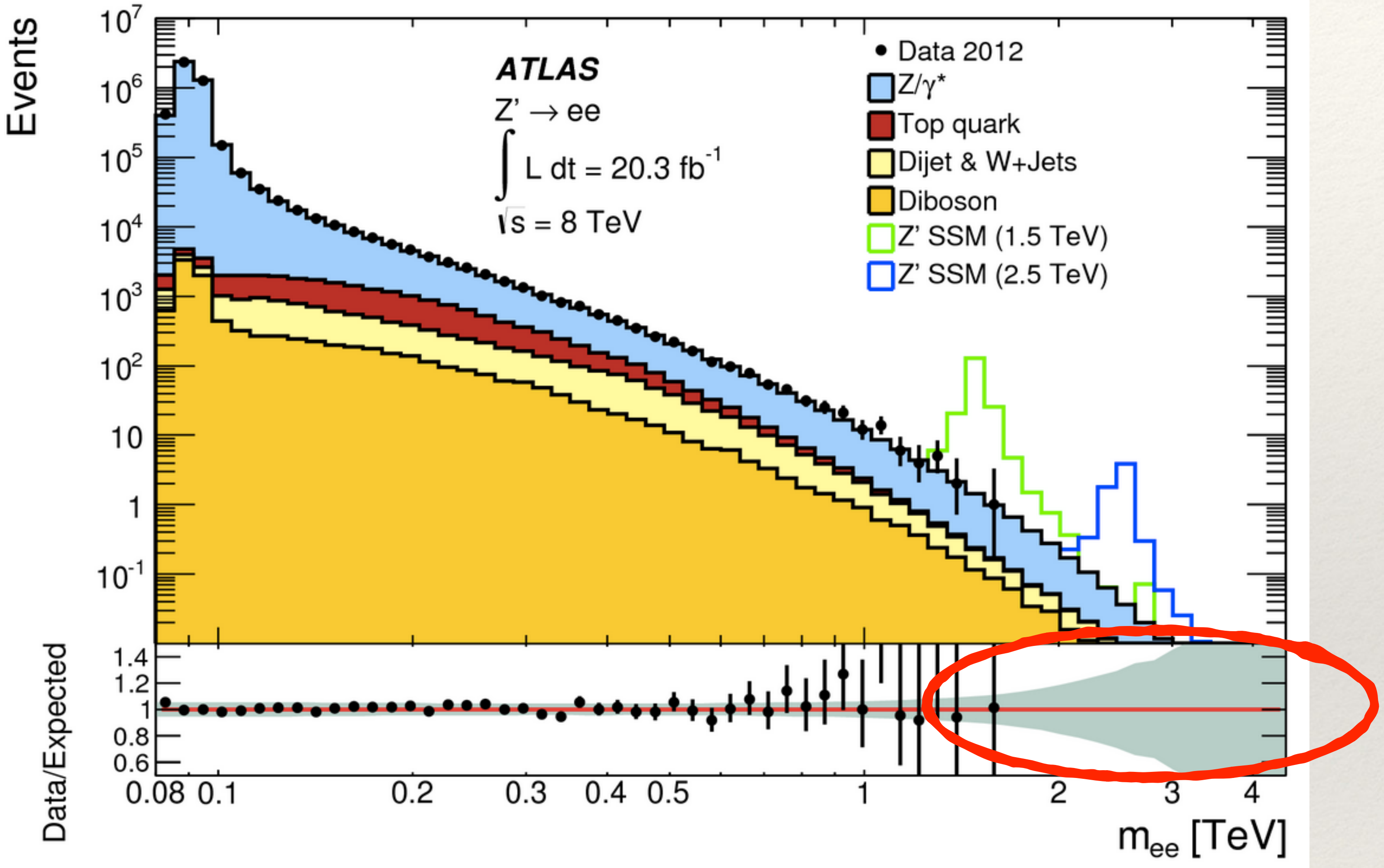


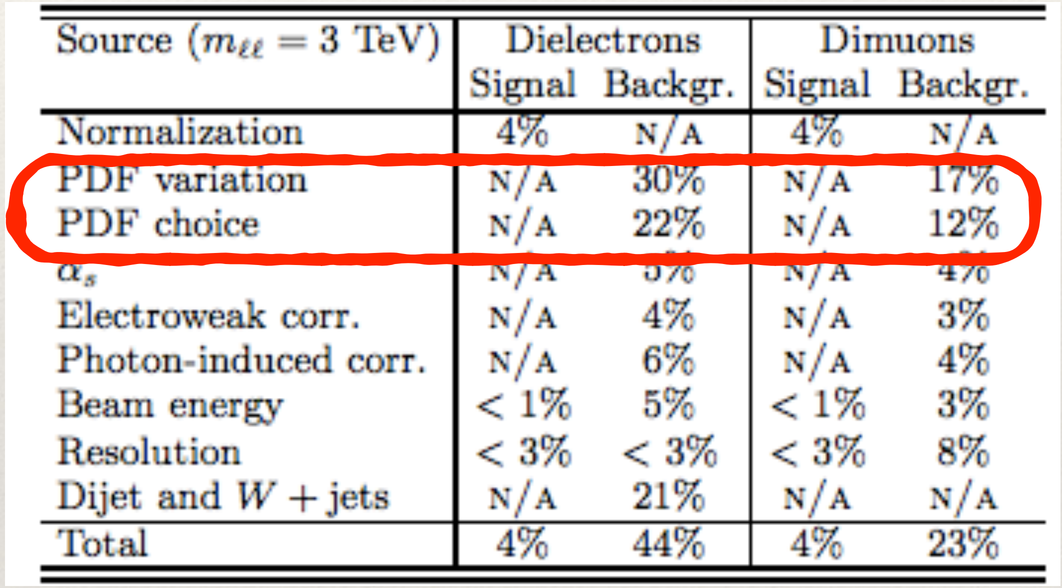
1. W and Z production
2. W+c production
3. Drell-Yan: low and high invariant mass
4. Inclusive Jet, Di-Jet and Tri-jet production
5. Prompt Photon + Jets
6. Top, ttbar
7. W,Z +jets or ZpT



Role of PDFs in BSM in DY processes

- PDFs are the dominant uncertainty in searches for Z′:
  - Di-electron invariant mass distributions with two selected Z' SSM signals:





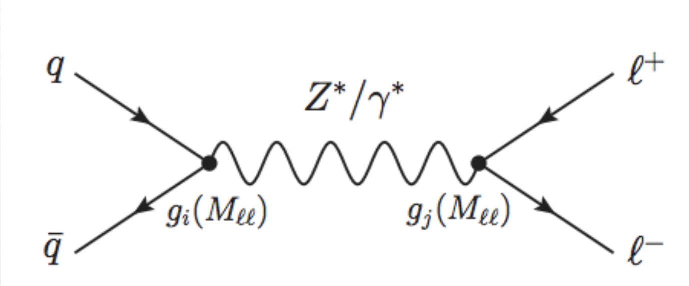
Source ($m_{\ell\ell} = 3$ TeV)	Dielectrons		Dimuons	
	Signal	Backgr.	Signal	Backgr.
Normalization	4%	N/A	4%	N/A
PDF variation	N/A	30%	N/A	17%
PDF choice	N/A	22%	N/A	12%
α_s	N/A	5%	N/A	4%
Electroweak corr.	N/A	4%	N/A	3%
Photon-induced corr.	N/A	6%	N/A	4%
Beam energy	< 1%	5%	< 1%	3%
Resolution	< 3%	< 3%	< 3%	8%
Dijet and $W +$ jets	N/A	21%	N/A	N/A
Total	4%	44%	4%	23%

Phys. Rev. D. 90, 052005 (2014)

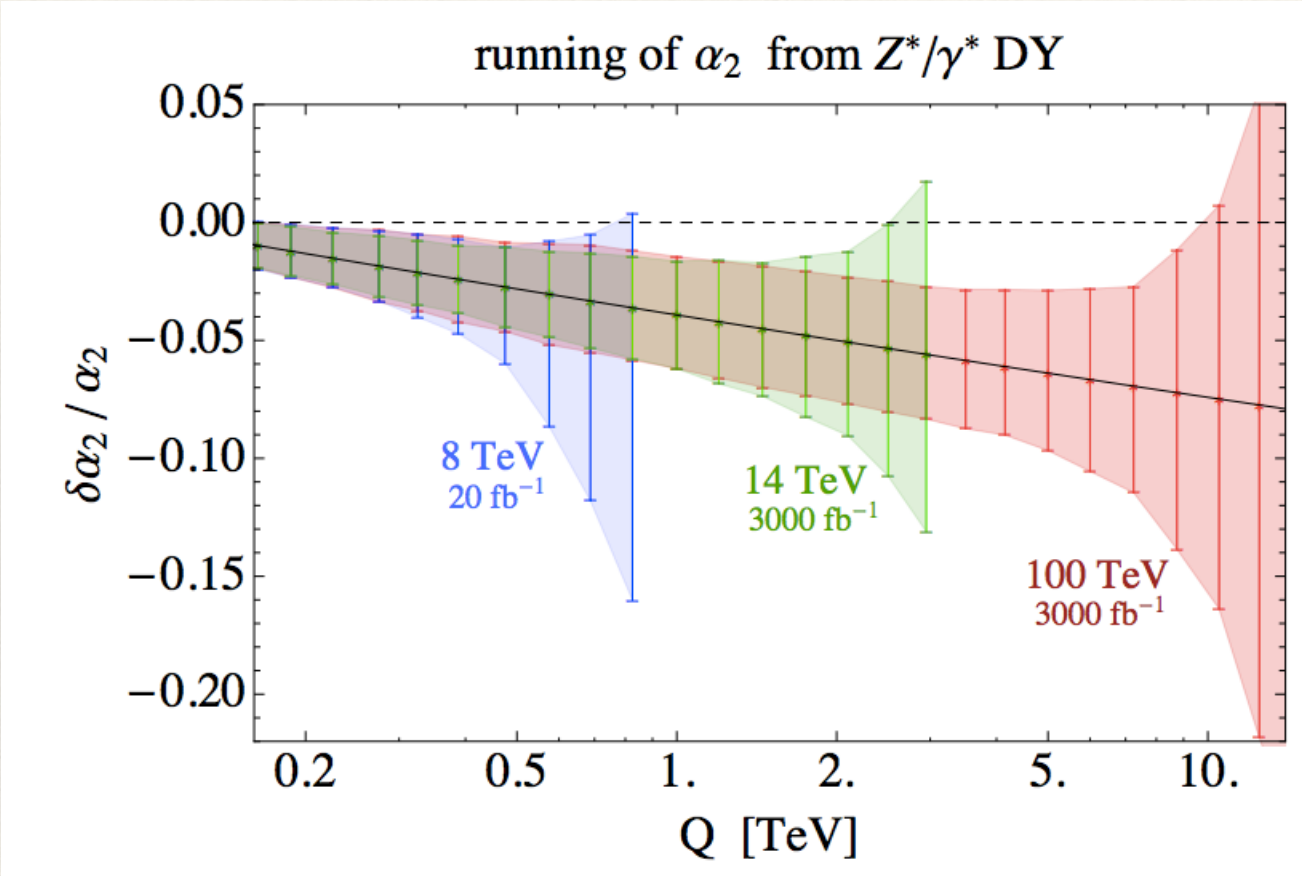
- It is important to constrain the PDFs to provide more discriminating powers:
  - PDF groups convergence
  - PDF uncertainties at high x

Running of EW coupling in DY processes

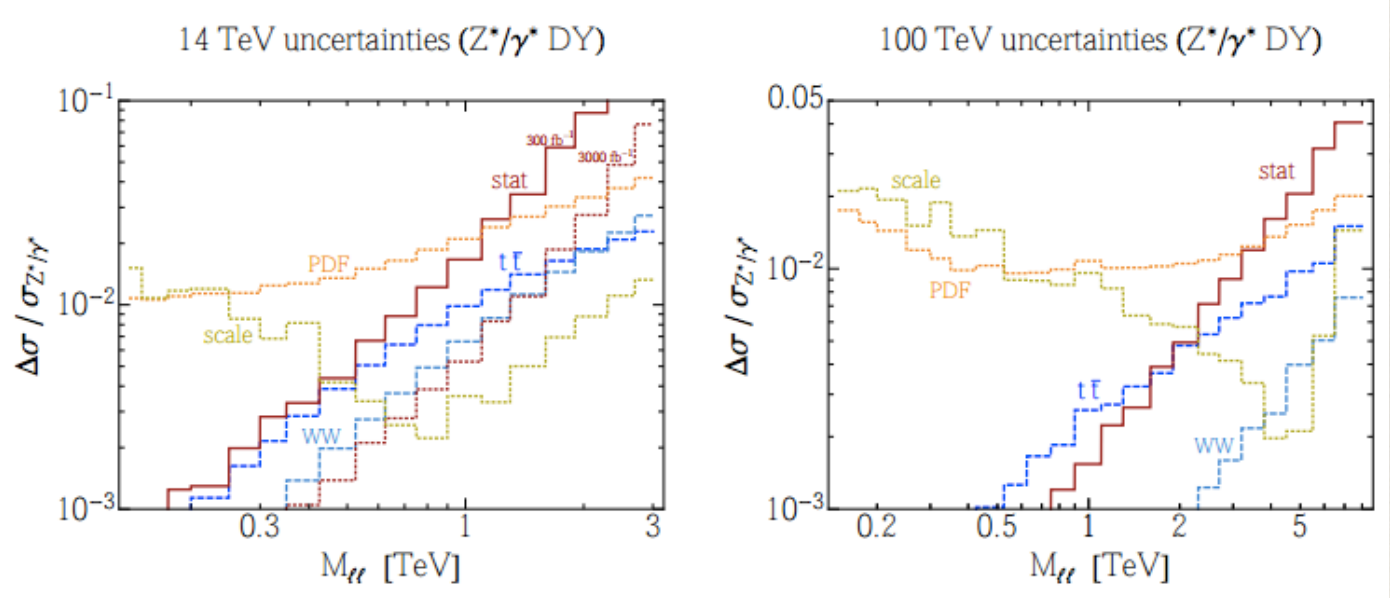
- Di-electron invariant mass distributions at different CoM energies and their dependence on the running of electroweak coupling can provide an interesting test of the SM:
    - only LEP has measured this before (up to ~200 GeV, just above the Mz)



—> the uncertainty is dominated by PDFs



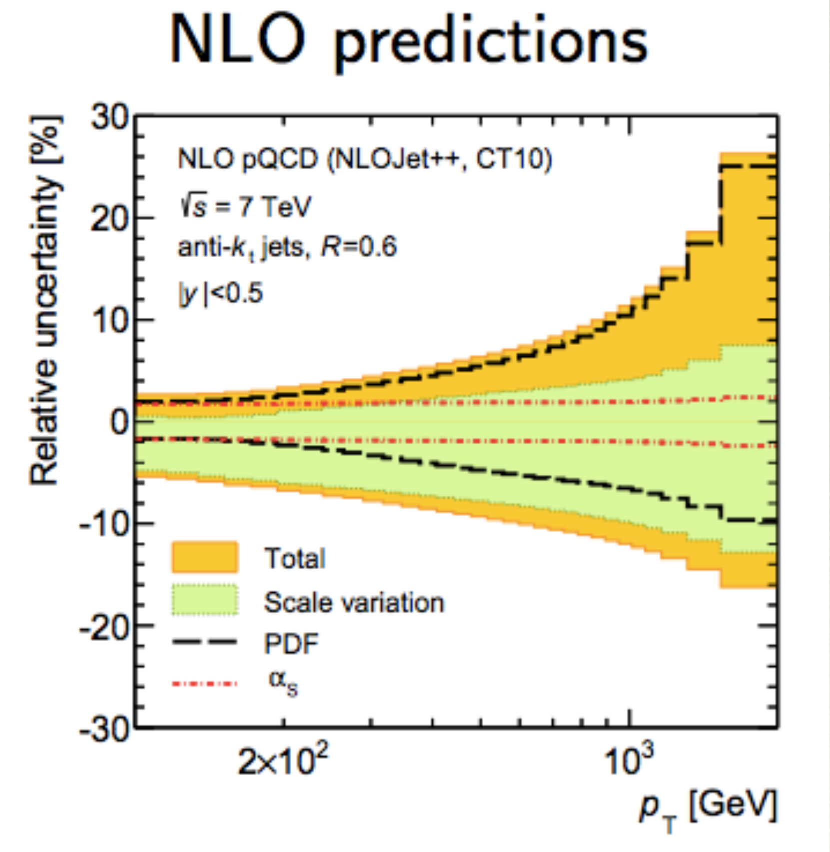
[arXiv:1410.6810v2]

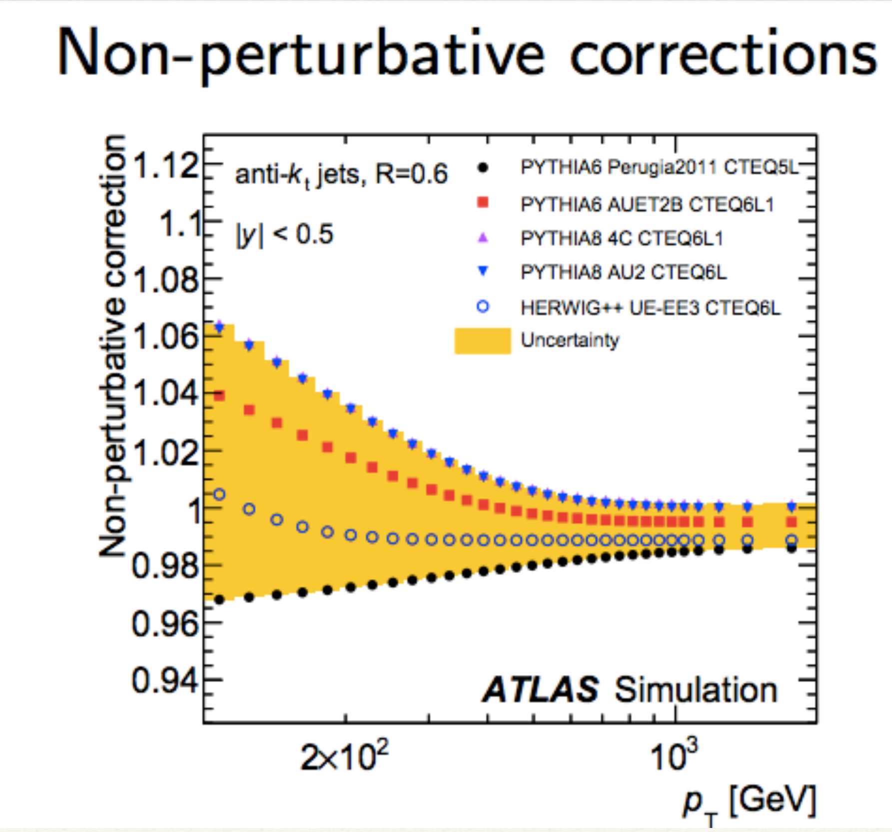


- It is important to constrain the PDFs to provide more discriminating powers:
    - PDF groups convergence
    - PDF uncertainties at high x

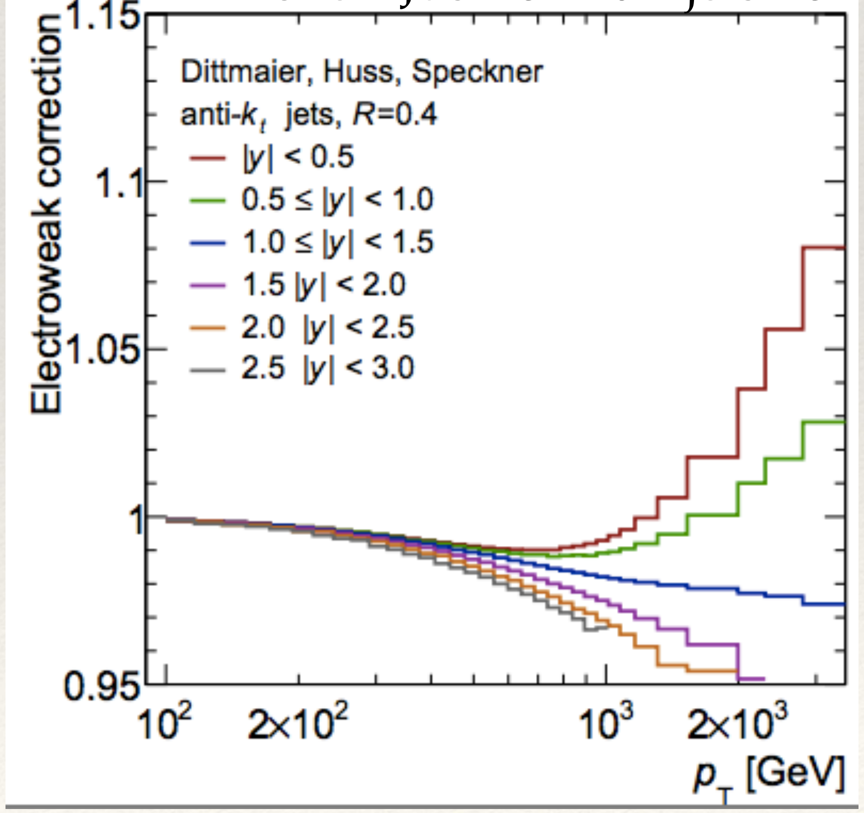
Jet measurements from "hh"

- Jet measurements can provide answers to questions such as:
  - is there any new physics?
  - do we have a good control of the underlying QCD?
- Control of the JER/JES precision an important task for the jet cross section measurements
- The jet NNLO calculations will open up new level of precision physics from "hh":
  - Non-perturbative corrections are reduced with increased scale
  - However, the EW corrections will play a more important role





@ 13TeV Just for R0.4 jets now



shown here from 7 TeV inclusive measurement

Strong coupling from hh

- The strong coupling determination in “hh" is usually limited by the NLO QCD calculation:
  - 3-Jet Mass measurement

CMS-PAS-SMP-12-027 (2013)
ATLAS-CONF-2014-045

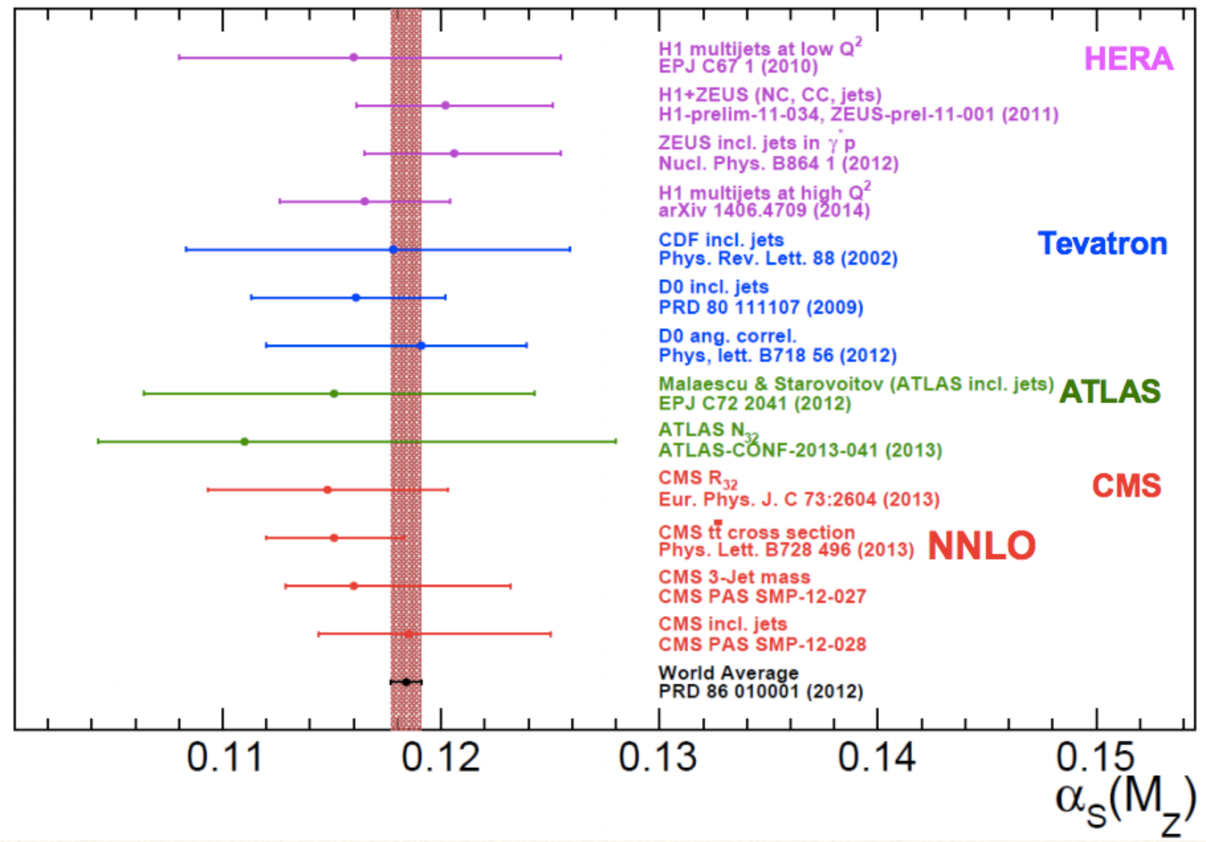
$$\alpha_S(M_Z) = 0.1160^{+0.0025}_{-0.0023}(\mathrm{exp, PDF, NP})^{+0.0068}_{-0.0021}(\mathrm{scale})$$

    - ratio measurements reduce the PDF and other common uncertainties
      - still dominated by the current theory uncertainties

CMS, EPJC 73 (2013) 2604

$$\alpha_s(M_Z) = 0.1148 \pm 0.0014\,(\mathrm{exp}) \pm 0.0018\,(\mathrm{PDF}) \pm 0.0050\,(\mathrm{theory})$$

  - Inclusive, Dijet jets
  - Top pair production —> calculations at NNLO

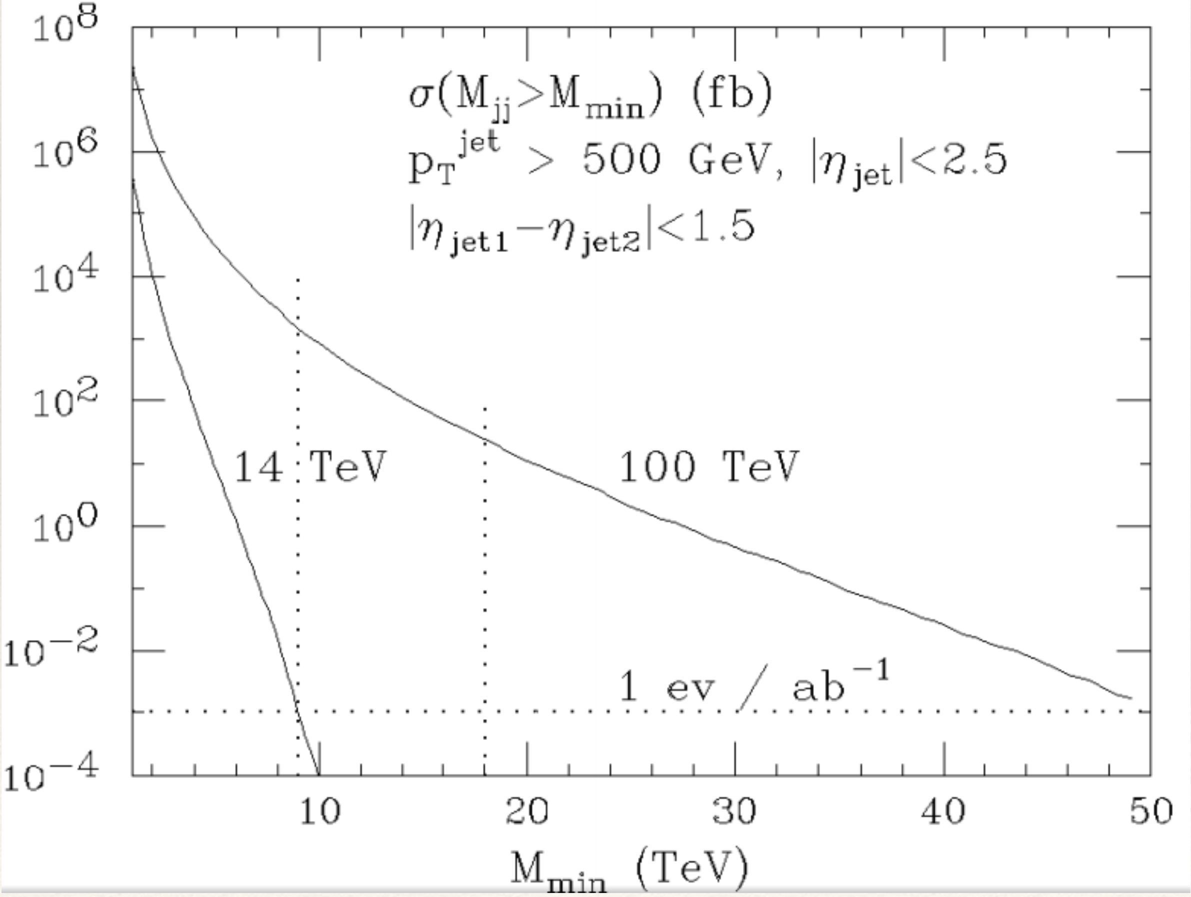


$\Delta\alpha_S/\alpha_S$

exp	theor
0.7%	3.3%
0.7%	4.9%
1.2%	4.6%
1.7%	1.3%
1.6%	4.1%

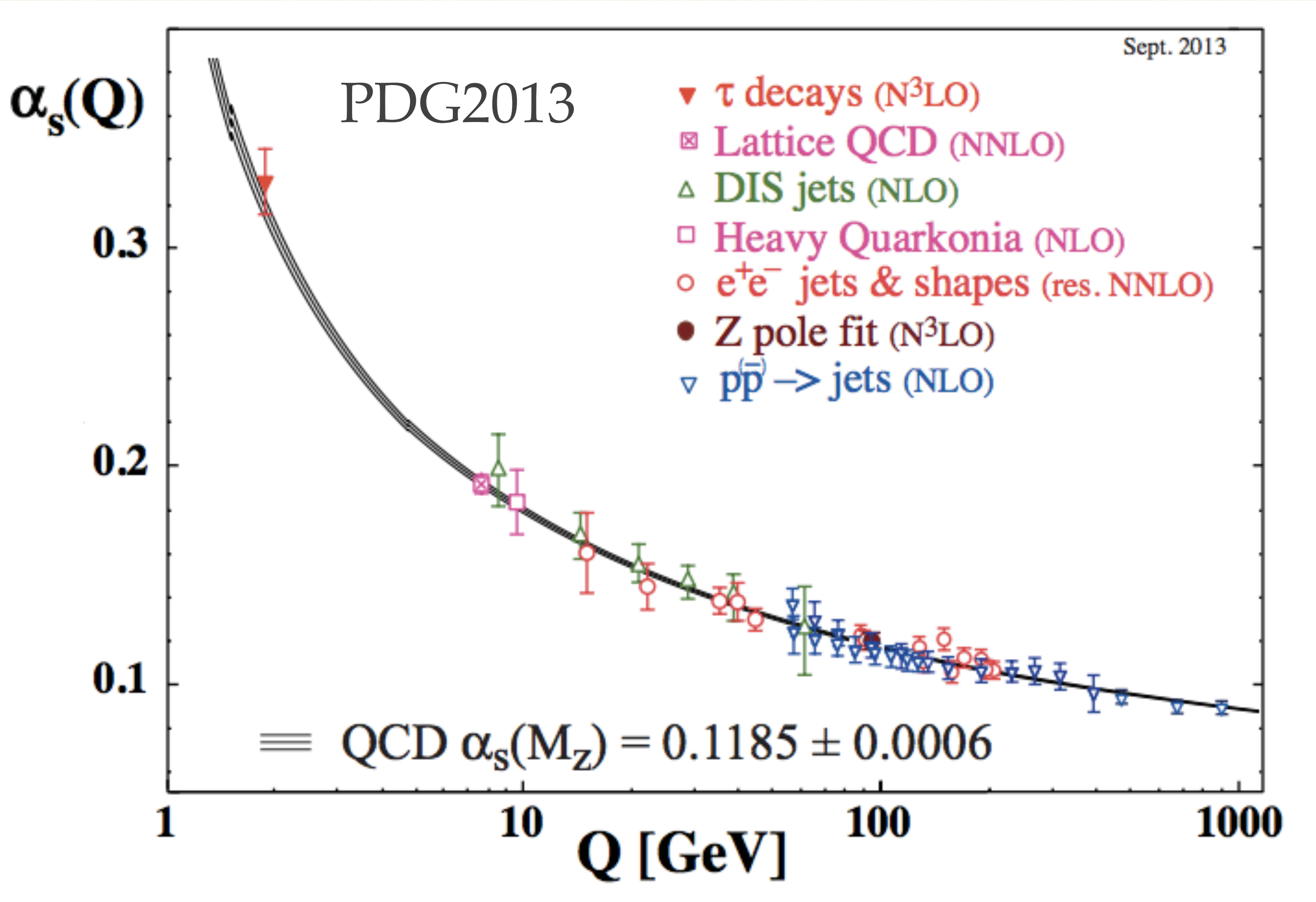
—> **challenging to get it below 1% precision**

jets @ 100 TeV: slow running of alphas?



Rates for dijets with mass above a threshold

Strong coupling from hh



limited by the NLO QCD calculation:

$^{+0.0068}_{-0.0021}$ (scale)

CMS-PAS-SMP-12-027 (2013)

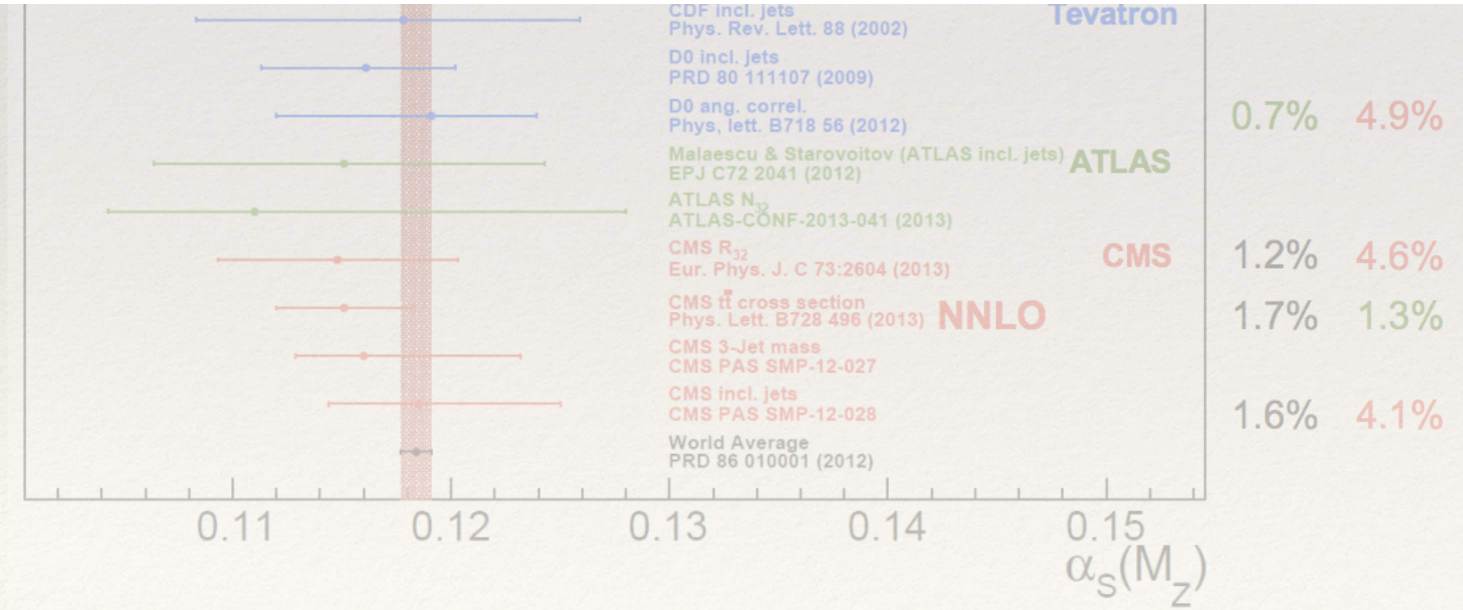
ATLAS-CONF-2014-045

r common uncertainties

CMS, EPJC 73 (2013) 2604

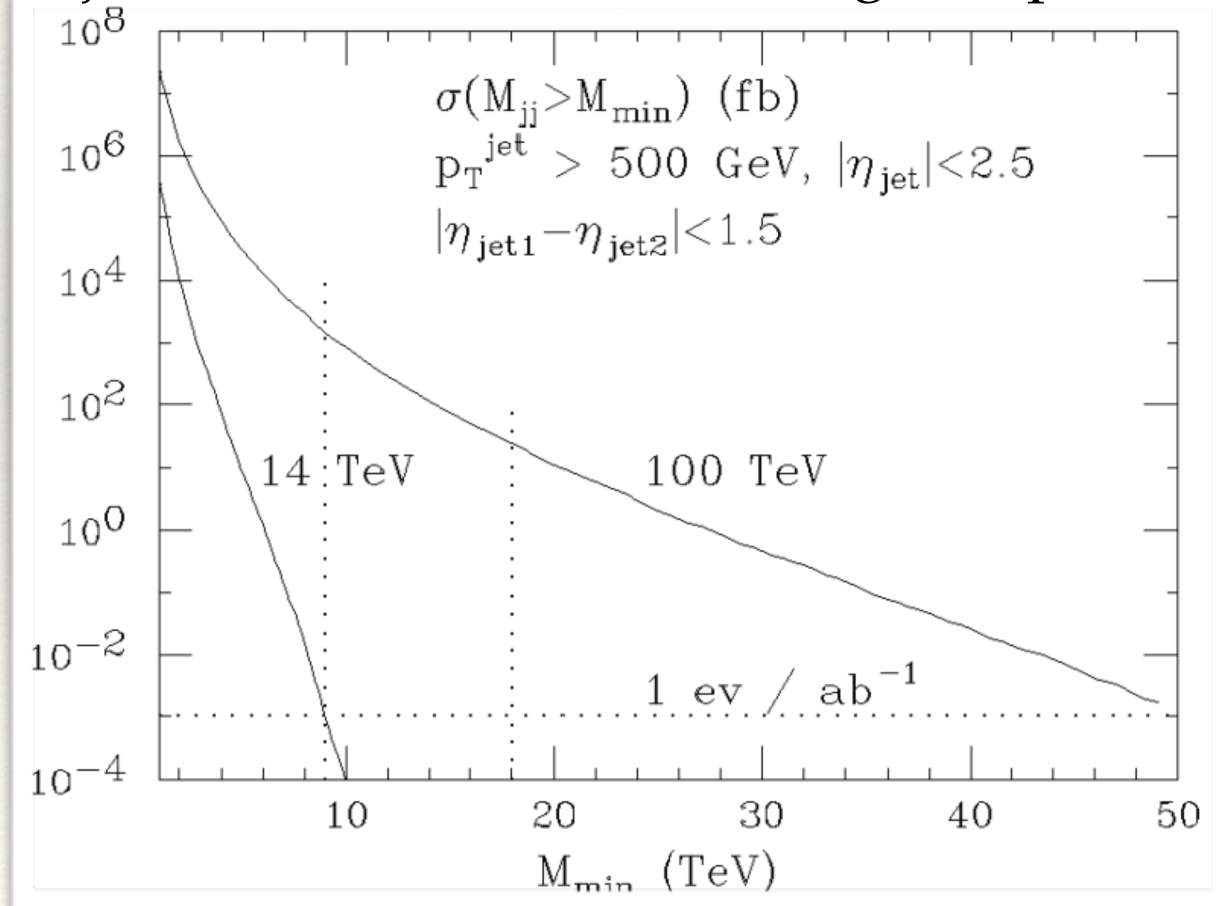
ertainties

8 (PDF) ± 0.0050 (theory)



—> challenging to get it below 1% precision

jets @ 100 TeV: slow running of alphas?

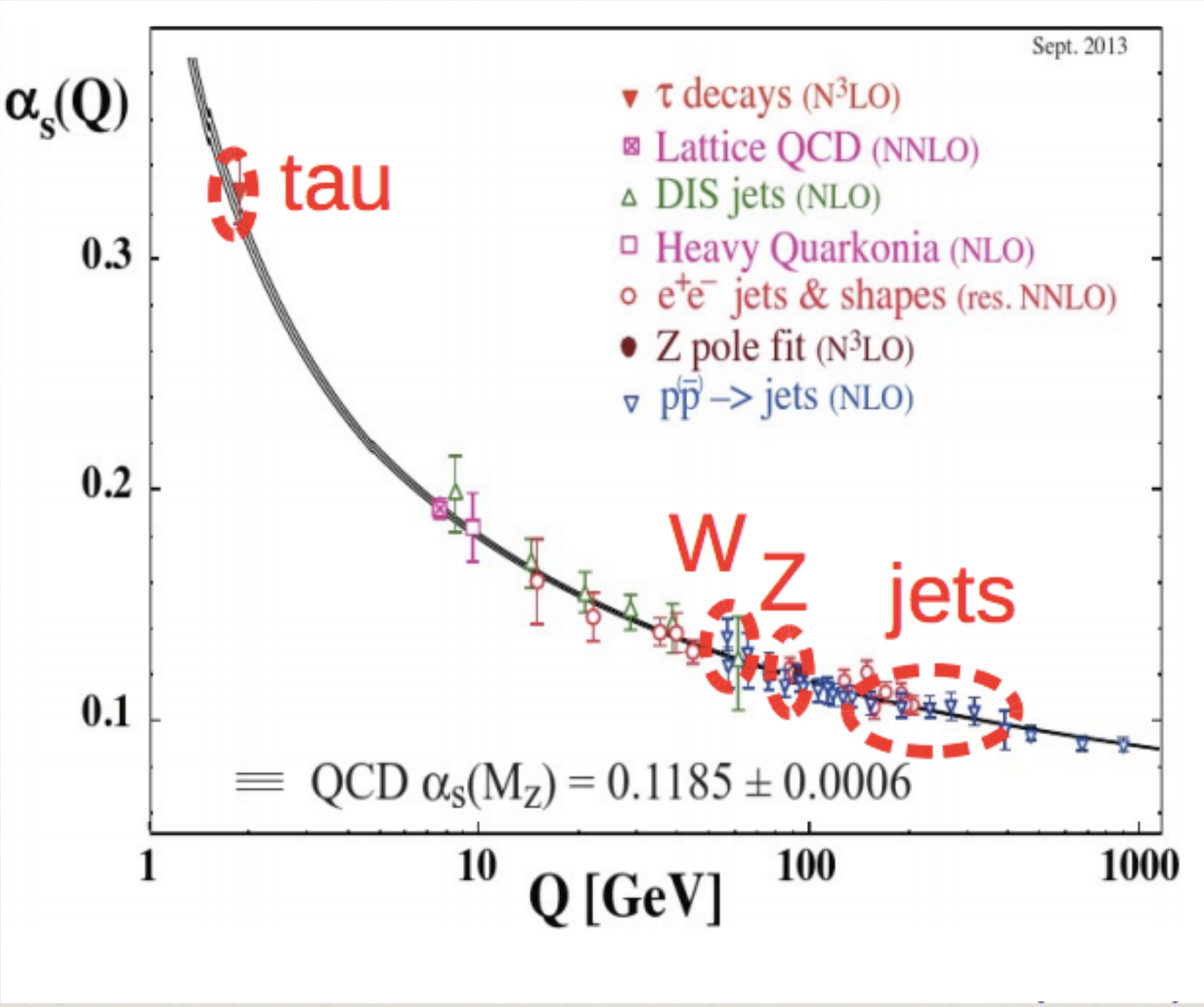


Rates for dijets with mass above a threshold

FCC e^+e^-: alphas

- The e^+e^- collisions provide a very clean environment with fully controlled initial-state to probe q,g dynamics:
  - No QCD "underlying event"
  - Smaller QCD radiation (only in final-state)
  - Smaller non-pQCD uncertainties (no PDFs)

- FCC vs. LEP: Orders-of-magnitude higher statistics (a bit higher Q2)
  - aim for experimental and theoretical precision on alphaS measurement via:
    - hadronic τ decays, heavy quarkonia decays, jet rates, event shapes, Z decay rates



- Known today with ~1% uncertainty (worst of all couplings)

Strong coupling from e+e-

- **Hadronic final states:**
    - The theoretical predictions up to NNLO and the re-summation up to NNLL or N3LL
        - theoretical uncertainties though 1-3% , hadronisation effects ~1-2%
    - Typical experimental uncertainty about 1%
    - **For FCC prospects —> difficult to foresee that the overall uncertainty on alphas <1%**
- **Hadronic Z, W decay widths:**
    - An accurate determination of αs due to precise theoretical calculations up to N3LO and suppressed non-perturbative effects

$$R_Z \equiv R_l^0 \equiv \frac{\Gamma(Z \to \text{hadrons})}{\Gamma(Z \to \text{leptons})} = R_Z^{\text{EW}} N_C (1 + \underbrace{\delta_{\text{QCD}} + \delta_{\text{m}} + \delta_{\text{np}}}_{\text{QCD, mass, NP corrections}}),$$

- LEP results using NNLO calculations —>
-
$$\alpha_s(M_Z^2) = 0.1226 \pm \underline{0.0038(\text{exp})} \, {}^{+0.0028}_{-0.0005} (\mu = {}^{2}_{0.25} M_Z) \, \cancel{{}^{+0.0033}_{-0.0}} (M_H = {}^{900}_{100} \text{ GeV}) \\ \pm 0.0002 (M_{\text{top}} = \pm 5 \text{ GeV}) \pm 0.0002 (\text{renormal. schemes})$$
- **The LEP measurement is mainly limited by lepton statistics —> FCC ee expect 10^{12} Z event stat**
- Use the W hadronic width , statistical limited for LEP, but an interesting prospect for FCC ee

- **Hadronic τ decay width**

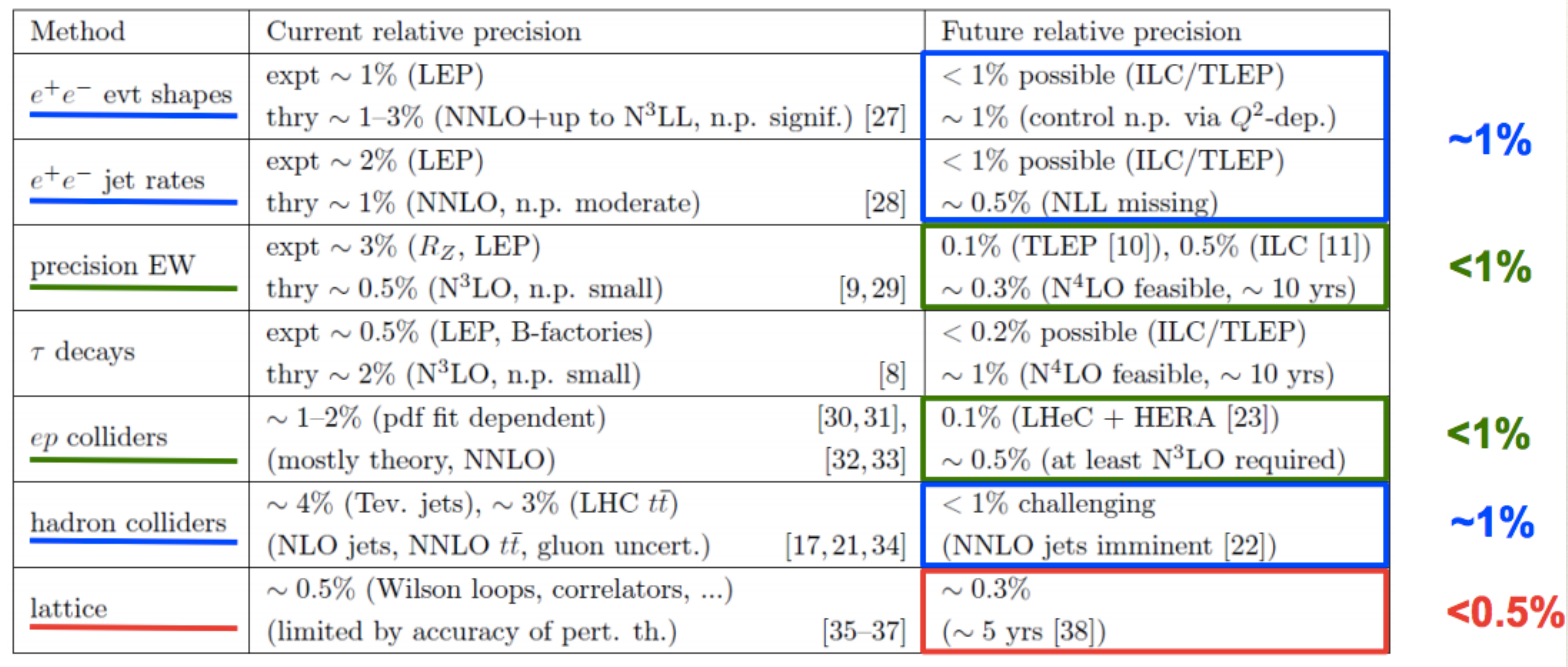
$$R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = S_{\text{EW}} N_C (1 + \delta_{\text{QCD}} + \delta_{\text{np}}),$$

    - LEP fit simultaneously αs and the non-perturbative coefficients by measuring various moments of the τ spectral function
    - **challenging to get uncertainty <1%**

Summary of current alphas uncert.

http://arxiv.org/pdf/1310.5189v1.pdf

(snow mass report)



Method	Current relative precision	Future relative precision
e^+e^- evt shapes	expt $\sim 1\%$ (LEP) thry ~ 1–3% (NNLO+up to N^{3}LL, n.p. signif.) [27]	$< 1\%$ possible (ILC/TLEP) $\sim 1\%$ (control n.p. via Q^2-dep.)
e^+e^- jet rates	expt $\sim 2\%$ (LEP) thry $\sim 1\%$ (NNLO, n.p. moderate) [28]	$< 1\%$ possible (ILC/TLEP) $\sim 0.5\%$ (NLL missing)
precision EW	expt $\sim 3\%$ (R_Z, LEP) thry $\sim 0.5\%$ (N^{3}LO, n.p. small) [9, 29]	0.1% (TLEP [10]), 0.5% (ILC [11]) $\sim 0.3\%$ (N^{4}LO feasible, $\sim$ 10 yrs)
τ decays	expt $\sim 0.5\%$ (LEP, B-factories) thry $\sim 2\%$ (N^{3}LO, n.p. small) [8]	$< 0.2\%$ possible (ILC/TLEP) $\sim 1\%$ (N^{4}LO feasible, $\sim$ 10 yrs)
ep colliders	~ 1–2% (pdf fit dependent) [30, 31], (mostly theory, NNLO) [32, 33]	0.1% (LHeC + HERA [23]) $\sim 0.5\%$ (at least N^{3}LO required)
hadron colliders	$\sim 4\%$ (Tev. jets), $\sim 3\%$ (LHC $t\bar{t}$) (NLO jets, NNLO $t\bar{t}$, gluon uncert.) [17, 21, 34]	$< 1\%$ challenging (NNLO jets imminent [22])
lattice	$\sim 0.5\%$ (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]	$\sim 0.3\%$ ($\sim$ 5 yrs [38])

~1%

<1%

<1%

~1%

<0.5%

- **per mile accuracy can test QCD Lattice calculations**

Summary

- FCC opens up an incredible possibility to widen the search hunt for new physics:
    - Precision of PDFs and alphas are crucial ingredient for optimising the chances
    - Tool development to allow for efficient means to interpret the results.

- Synergy between FCC study groups for ee, eh, hh
    - QCD physics objectives at FCC hh
        - Control of QCD background for searches —> need precise PDFs and alphas

    - QCD physics at FCC eh objectives
        - Control of PDFs, alphas, low x phenomenology.

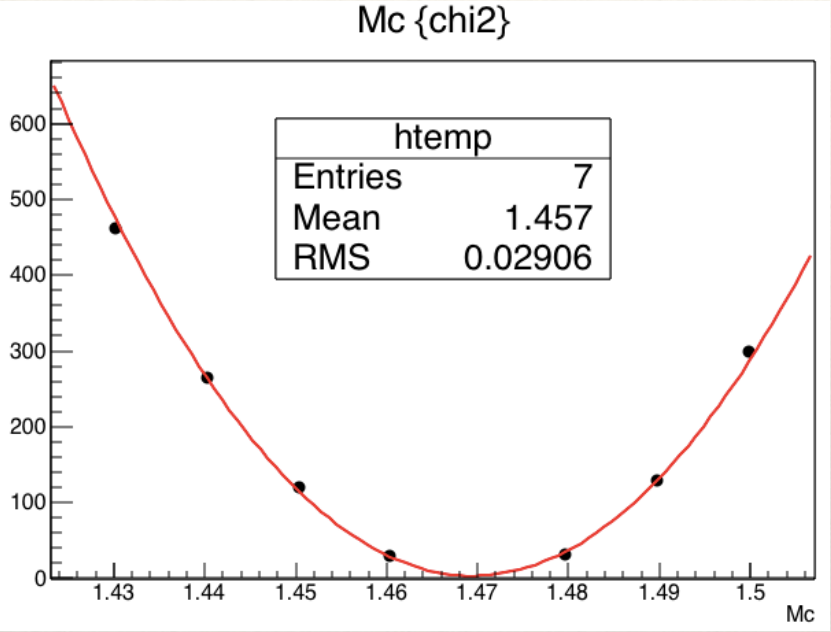
    - QCD physics objectives at FCC ee:
        - High-precision (<1% uncertainty) strong coupling determination

Extra …

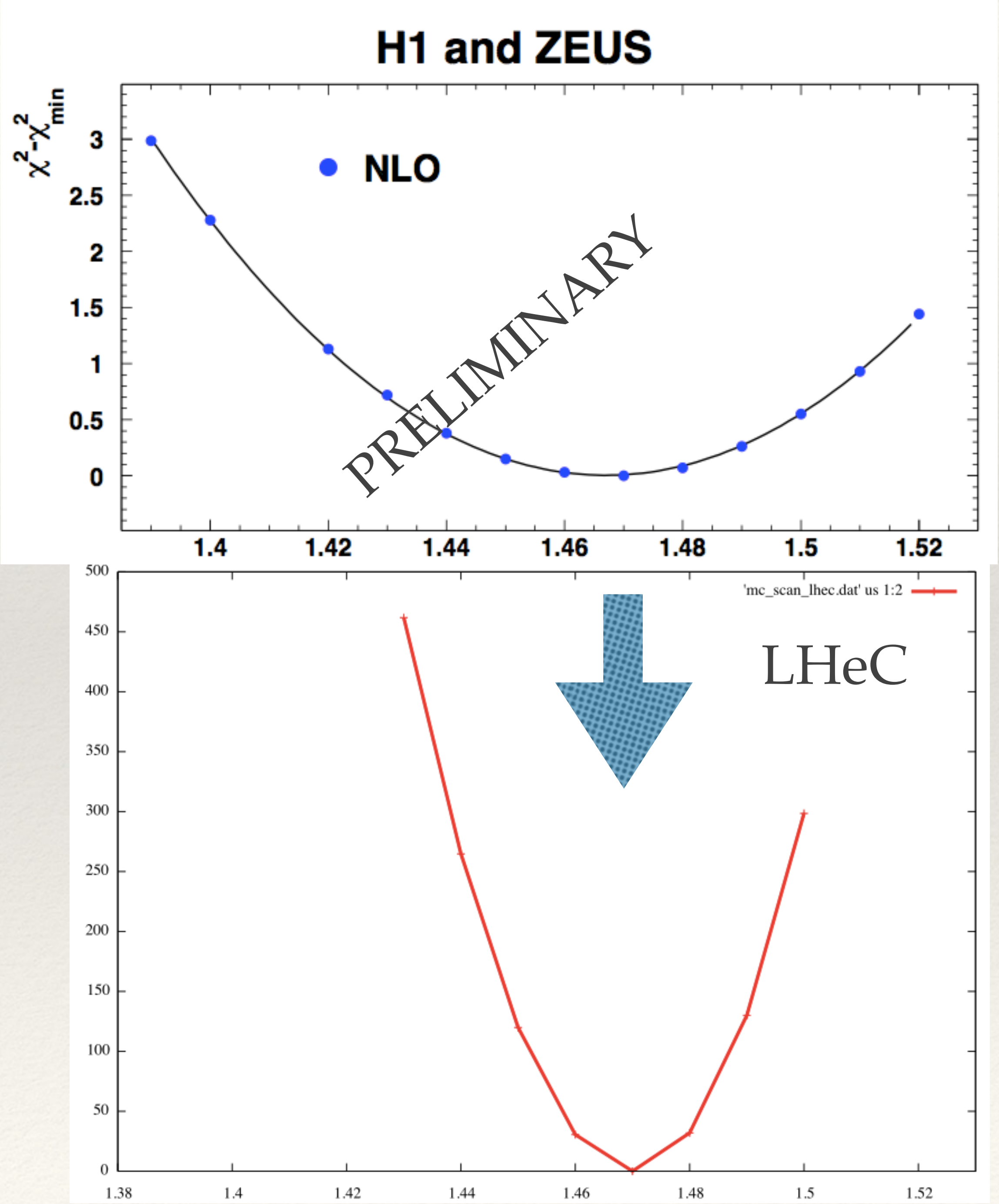
- not necessarily useful

Implications:

- The much reduced PDFs impose better constraints on various SM and BSM parameters
    - charm mass value used in the GM-VFNS

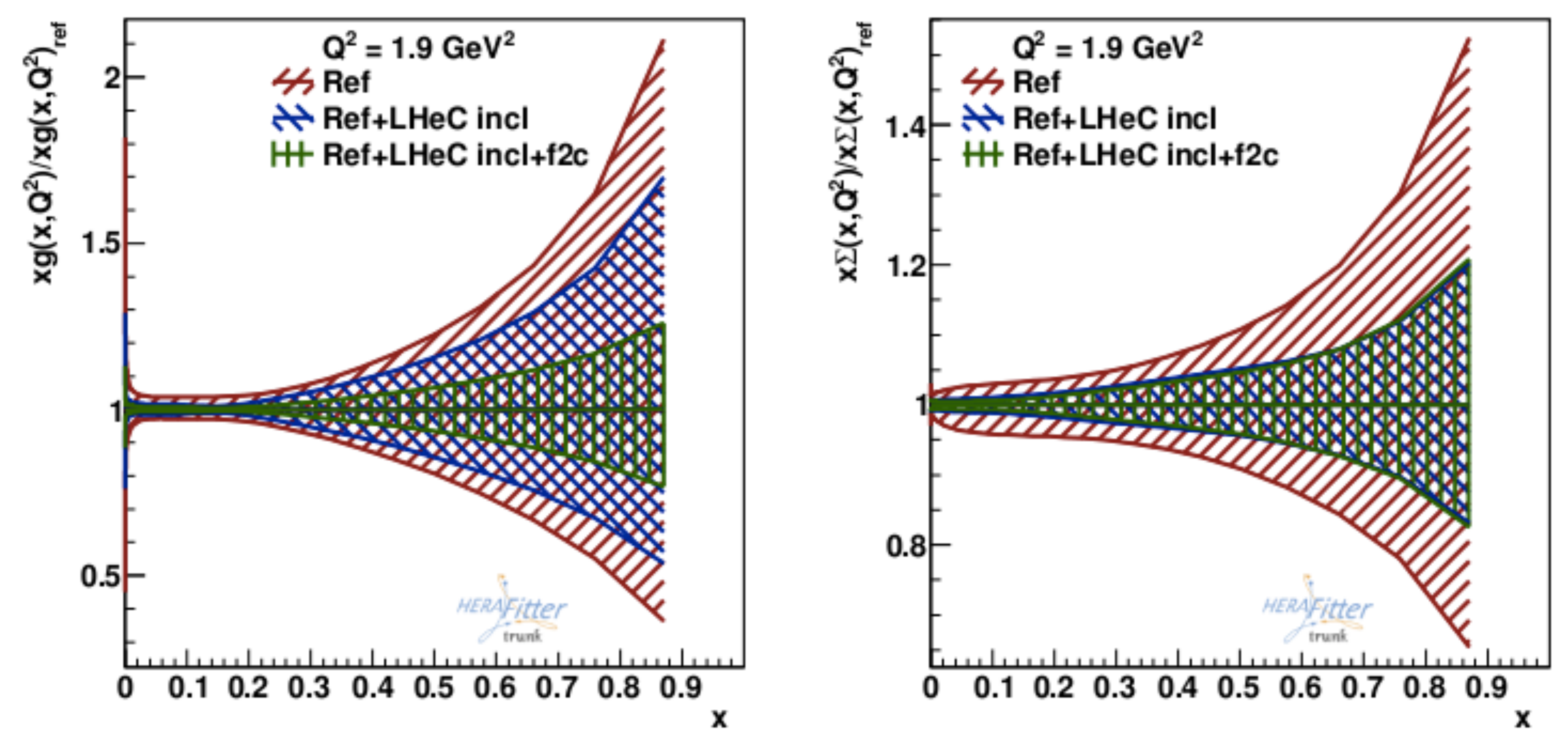


3 MeV precision



Impact of LHeC vs World data

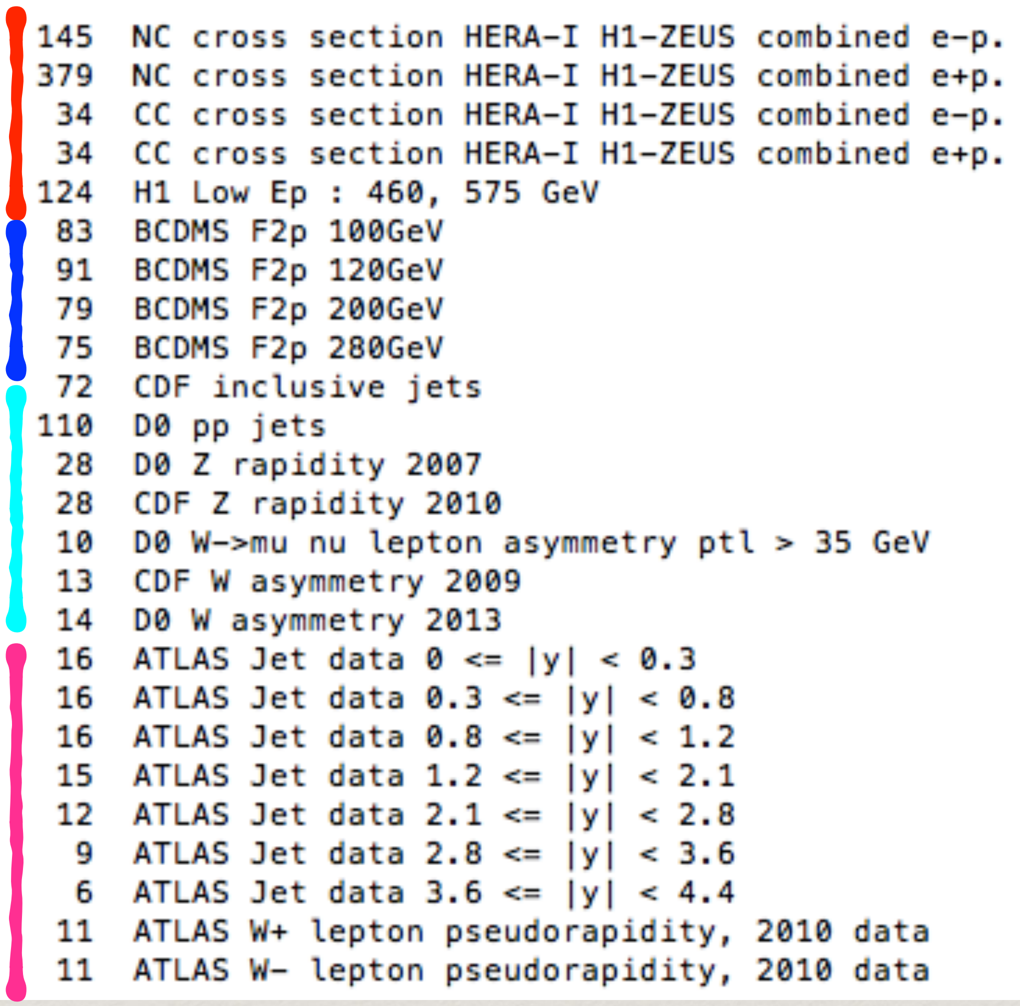
- when adding LHeC data on top of world data (Ref)



LHeC vs World data

NEW

- adding LHeC data on top of world data (Ref) - at the starting scale:



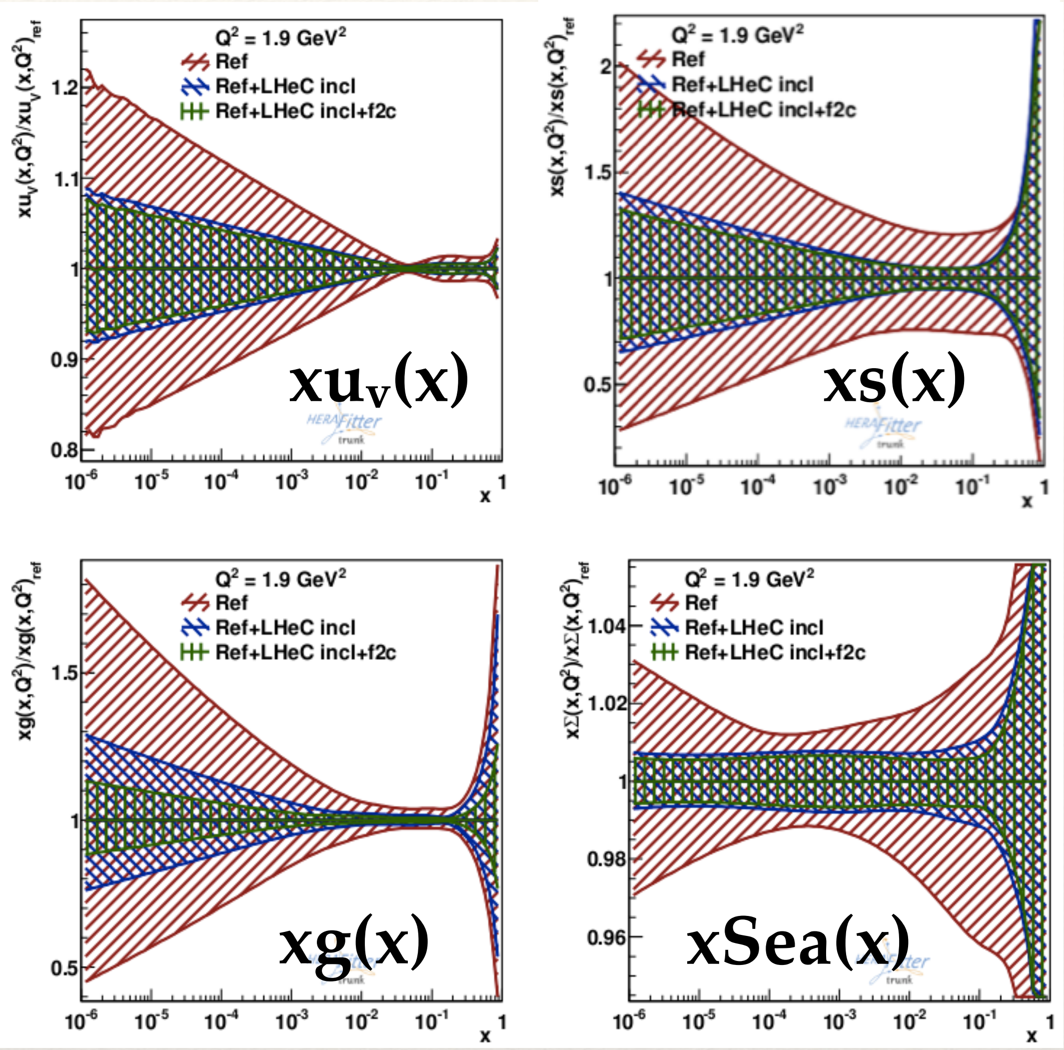
HERA

Fix. Targ.

Tevat.

LHC

```
145  NC cross section HERA-I H1-ZEUS combined e-p.
379  NC cross section HERA-I H1-ZEUS combined e+p.
 34  CC cross section HERA-I H1-ZEUS combined e-p.
 34  CC cross section HERA-I H1-ZEUS combined e+p.
124  H1 Low Ep : 460, 575 GeV
 83  BCDMS F2p 100GeV
 91  BCDMS F2p 120GeV
 79  BCDMS F2p 200GeV
 75  BCDMS F2p 280GeV
 72  CDF inclusive jets
110  D0 pp jets
 28  D0 Z rapidity 2007
 28  CDF Z rapidity 2010
 10  D0 W->mu nu lepton asymmetry ptl > 35 GeV
 13  CDF W asymmetry 2009
 14  D0 W asymmetry 2013
 16  ATLAS Jet data 0 <= |y| < 0.3
 16  ATLAS Jet data 0.3 <= |y| < 0.8
 16  ATLAS Jet data 0.8 <= |y| < 1.2
 15  ATLAS Jet data 1.2 <= |y| < 2.1
 12  ATLAS Jet data 2.1 <= |y| < 2.8
  9  ATLAS Jet data 2.8 <= |y| < 3.6
  6  ATLAS Jet data 3.6 <= |y| < 4.4
 11  ATLAS W+ lepton pseudorapidity, 2010 data
 11  ATLAS W- lepton pseudorapidity, 2010 data
```

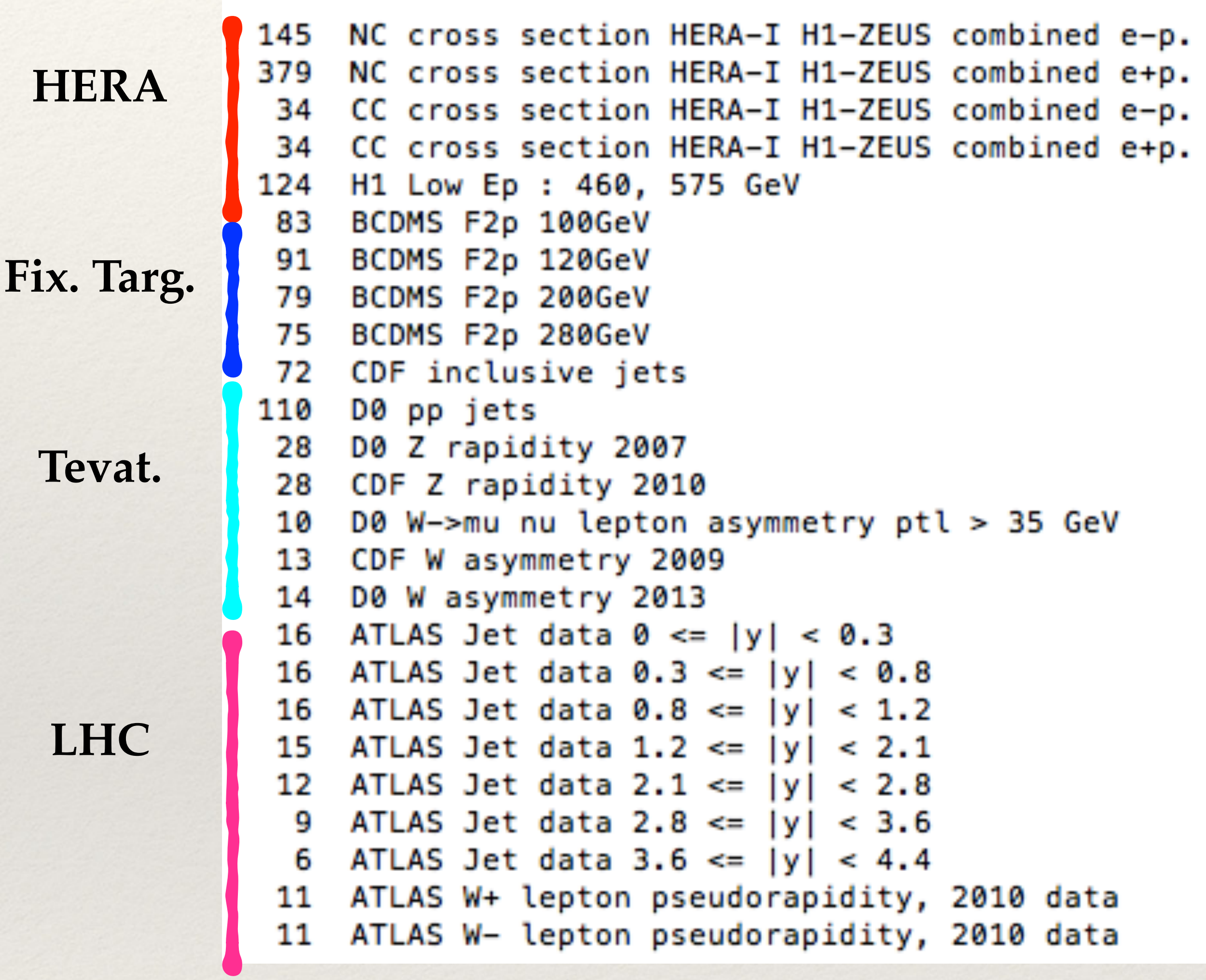


—> eh scenario can provide precisely all PDFs

Moreover, it can determine PDFs without relying on imposed constraints

LHeC vs World data

- when adding LHeC data on top of world data (Ref) - at the starting scale:



```
145  NC cross section HERA-I H1-ZEUS combined e-p.
379  NC cross section HERA-I H1-ZEUS combined e+p.
 34  CC cross section HERA-I H1-ZEUS combined e-p.
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```
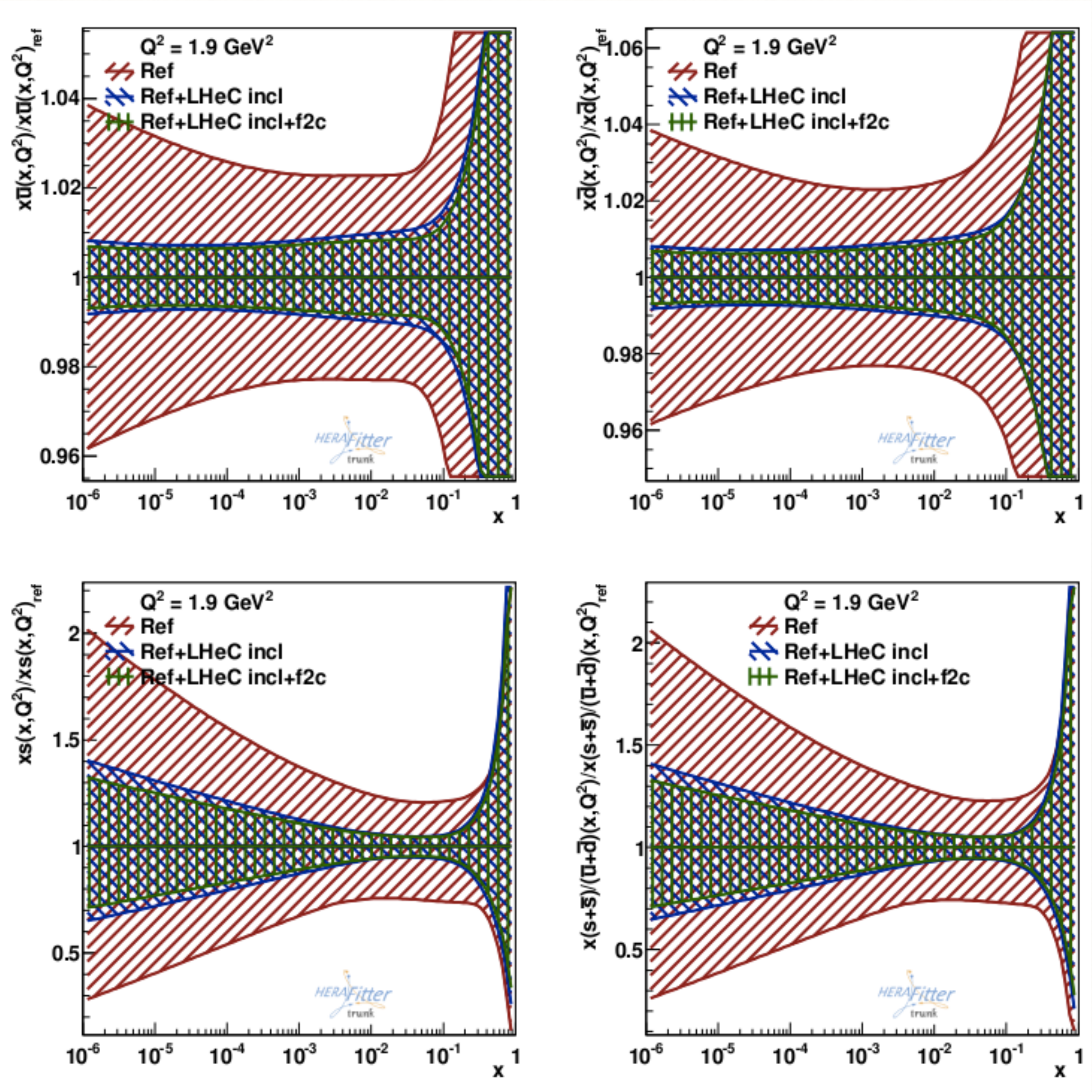
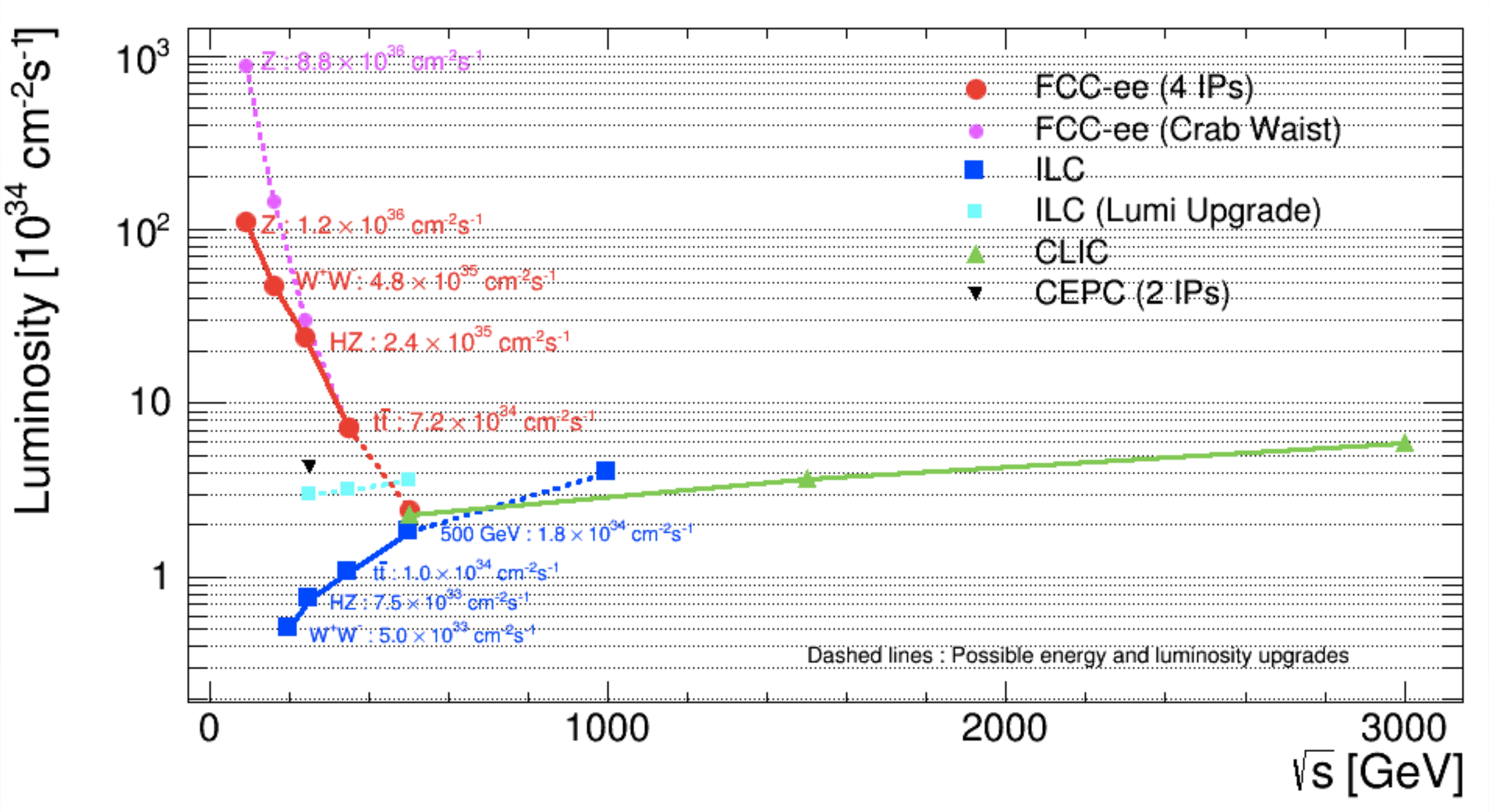



FCC e^+e^-


Luminosity [10^{34} cm^{-2}s^{-1}]
10^3
10^2
10
1
0
1000
2000
3000
$\sqrt{s}$ [GeV]
Z : 8.8 × 10^{36} cm^{-2}s^{-1}
Z : 1.2 × 10^{36} cm^{-2}s^{-1}
W^+W^- : 4.8 × 10^{35} cm^{-2}s^{-1}
HZ : 2.4 × 10^{35} cm^{-2}s^{-1}
$t\bar{t}$: 7.2 × 10^{34} cm^{-2}s^{-1}
500 GeV : 1.8 × 10^{34} cm^{-2}s^{-1}
$t\bar{t}$: 1.0 × 10^{34} cm^{-2}s^{-1}
HZ : 7.5 × 10^{33} cm^{-2}s^{-1}
W^+W^- : 5.0 × 10^{33} cm^{-2}s^{-1}
● FCC-ee (4 IPs)
● FCC-ee (Crab Waist)
■ ILC
■ ILC (Lumi Upgrade)
▲ CLIC
▼ CEPC (2 IPs)
Dashed lines : Possible energy and luminosity upgrades

FCC hh

- 100 TeV pp beams gives access to new particles up to 30 TeV mass range, which is beyond the LHC reach and with increased precision compared to LHC

- Dedicated working group formed to study the discovery reach for high-mass objects and the access precision reach for Higgs and EWSB:
  - study the limiting systematics (i.e. PDFs, alphas..)
  - study the prospects for improved measurements for the SM EW parameters (i.e. mW, Z, sinTheta, etc.)
  - identify unique scenarios