PHYSICS HIGHLIGHTS

OF A

FUTURE EP/EA COLLIDER

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ECFA MEETING

CERN, NOV. 19, 2015

HISTORY

eP option proposed since the beginning of the LHC

PHYSICS OF ep COLLISIONS IN THE TeV ENERGY RANGE

G. Altarelli*), B. Mele*) and R. Rückl,

CERN, Geneva, Switzerland

(Presented by G. Altarelli)

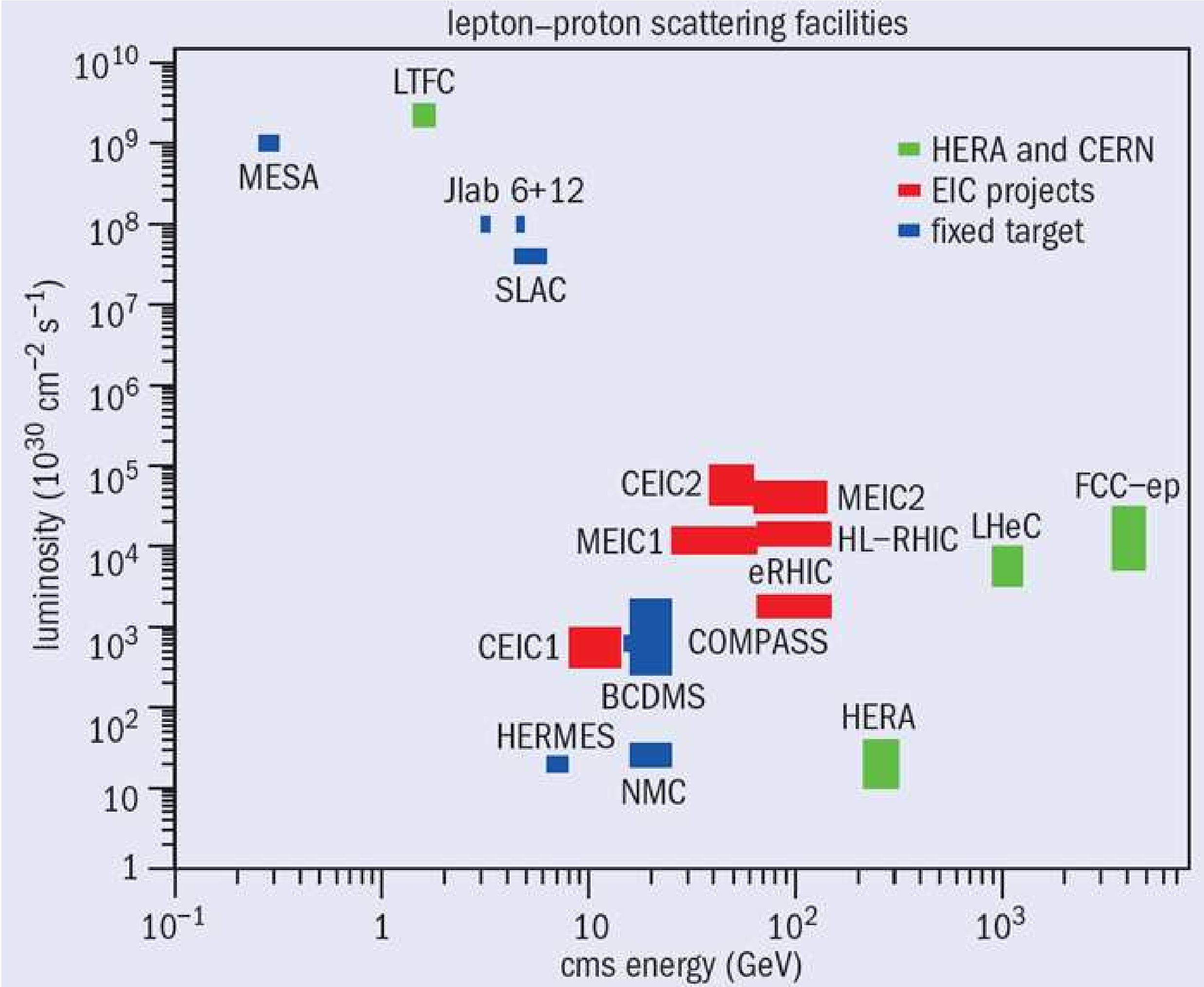
ABSTRACT

We study the physics of electron-proton collisions in the range of centre-of-mass energies between $\sqrt{s} \simeq 0.3$ TeV (HERA) and $\sqrt{s} \simeq (1-2)$ TeV. The latter energies would be achieved if the electron or positron beam of LEP $[E_e \simeq (50-100)$ GeV$]$ is made to collide with the proton beam of LHC $[E_p \simeq (5-10)$ TeV$]$.

CERN-ECFA workshop, Lausanne, March 1984:

a Large Hadron Collider in the LEP tunnel

PAST, PRESENT AND FUTURE EP FACILITIES



- LHEC: CDR PUBLISHED IN 2012
- EIC: "APPROVED AS A CONSTRUCTION RECOMMENDATION" BY NSAC OCT. 2015

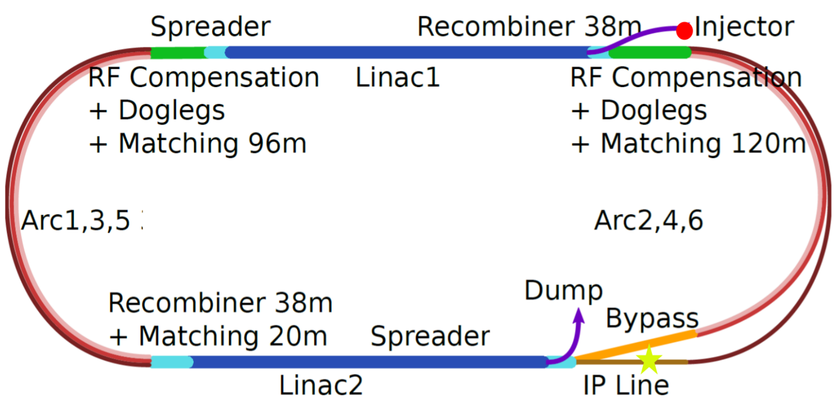
(CEIC2 no longer considered; MEIC2 lumi now $2-5\times10^{34}$; HL-RHIC lumi now $2-3\times10^{34}$)

THE LHeC

- RECIRCULATING LINAC WITH ENERGY RECOVERY
  $\rightarrow$ THREE ACCELERATING PASSES THROUGH EACH OF TWO 10 GeV LINACS
  $\Rightarrow$ 60 GeV ELECTRON BEAM

- COLLISIONS WITH ONE HL-LHC BEAM (PROTON OR ION)

LAYOUT

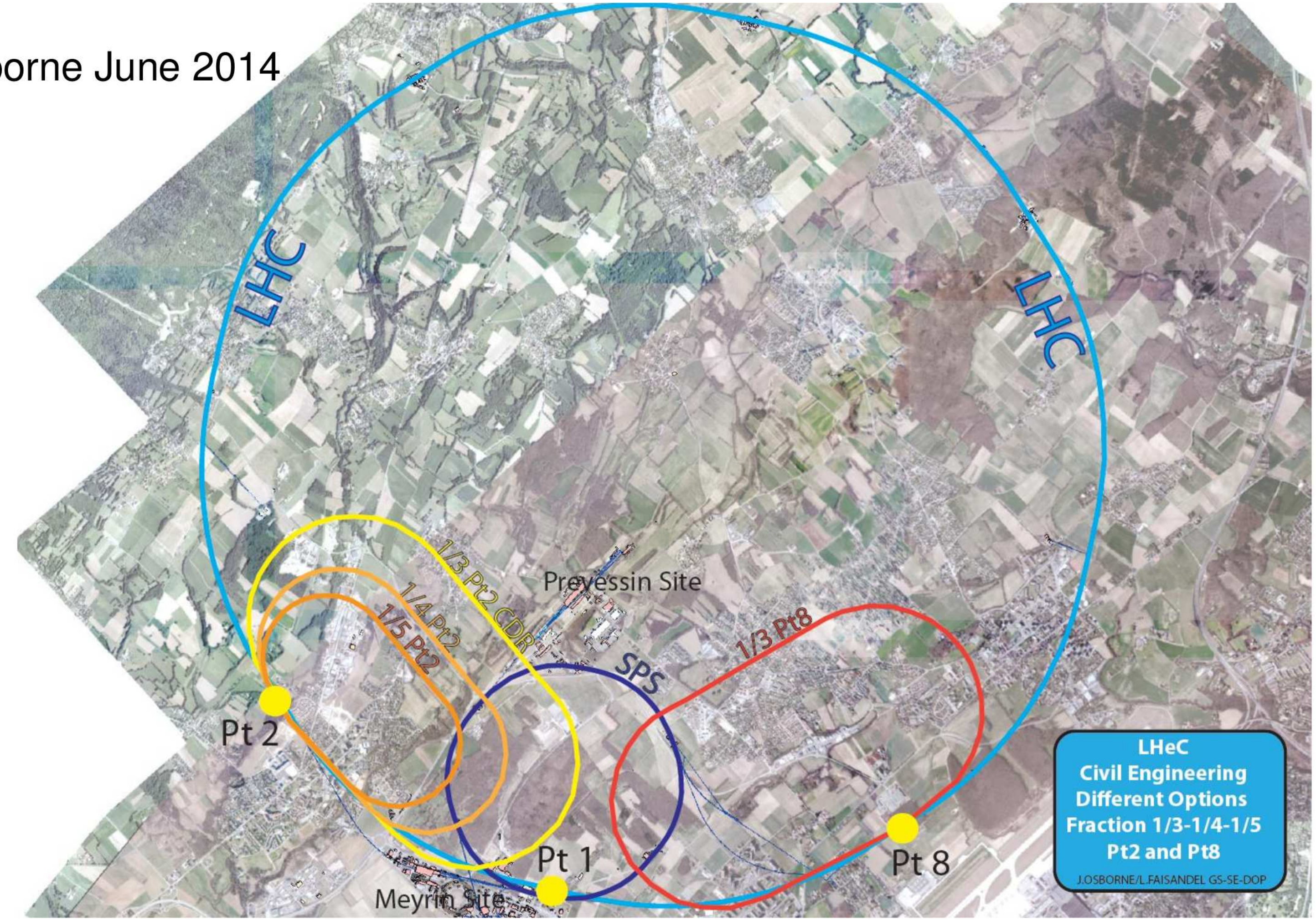


BASELINE PARAMETERS

10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [$10^{33}cm^{-2}s^{-1}$]	16	16
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20
Beta Funtion $\beta^*_{x,y}$ [m]	0.05	0.10
rms Beam size $\sigma^*_{x,y}$ [μm]	4	4
rms Beam divergence $\sigma'^*_{x,y}$ [μrad]	80	40
Beam Current @ IP[mA]	1112	25
Bunch Spacing [ns]	25	25
Bunch Population	$2.2*10^{11}$	$4*10^{9}$
Bunch charge [nC]	35	0.64

SITING OPTIONS

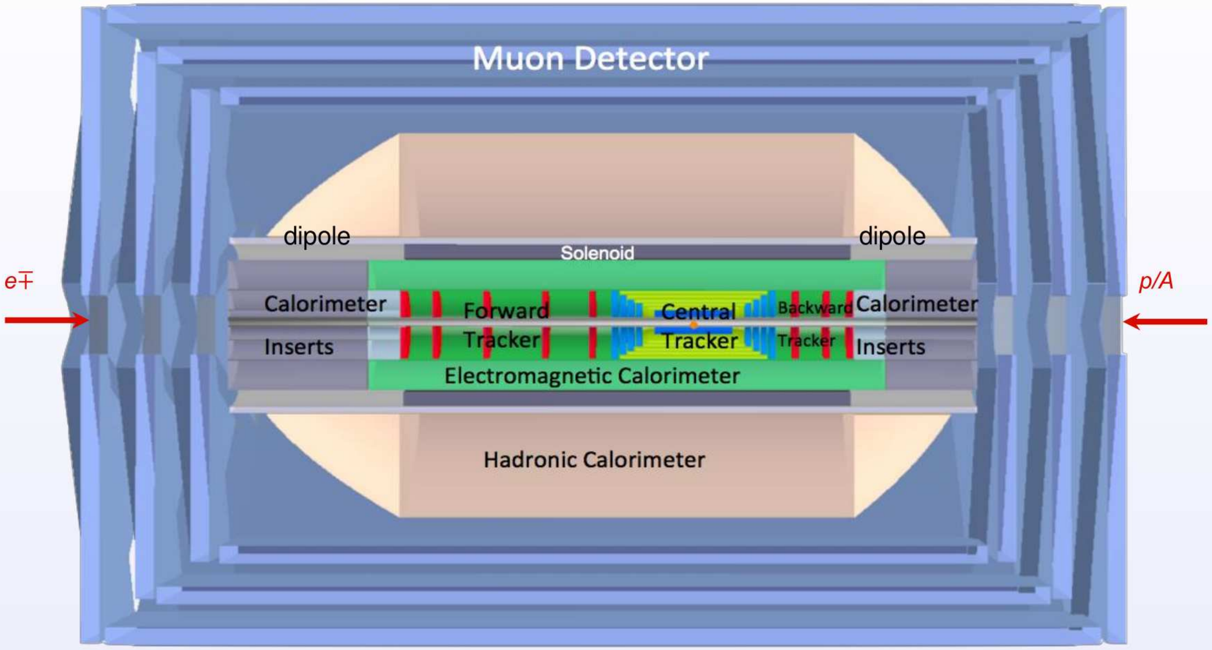
John Osborne June 2014



THE LHeC DETECTOR

LHeC

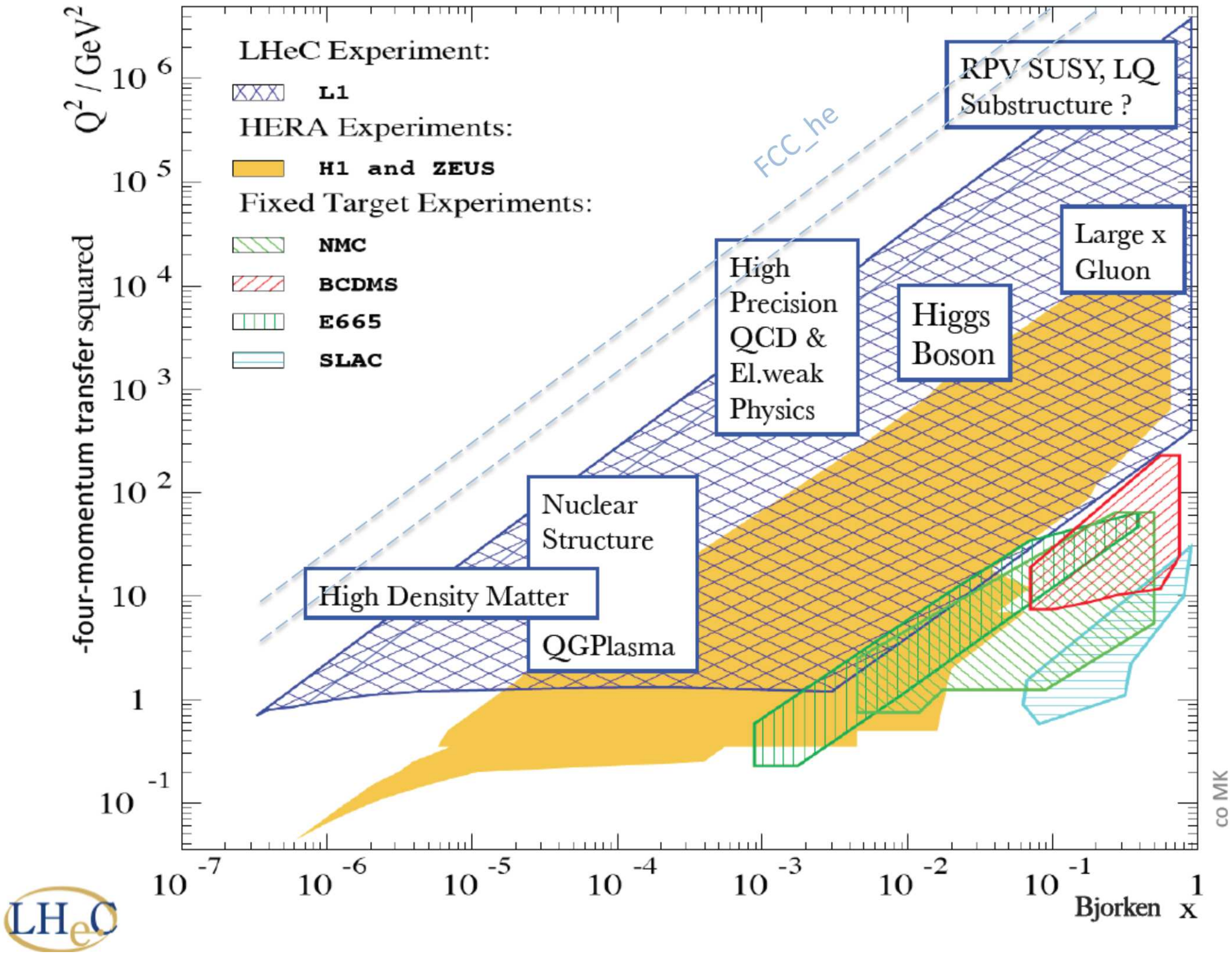
Baseline Detector



- Forward / backward asymmetry reflecting beam energies
- Present size 14m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)
- e/γ taggers ZDC, proton spectrometer integral to design from outset system providing tagging, no independent momentum measurement

LHeC: KINEMATIC COVERAGE

DEEP-INELASTIC SCATTERING

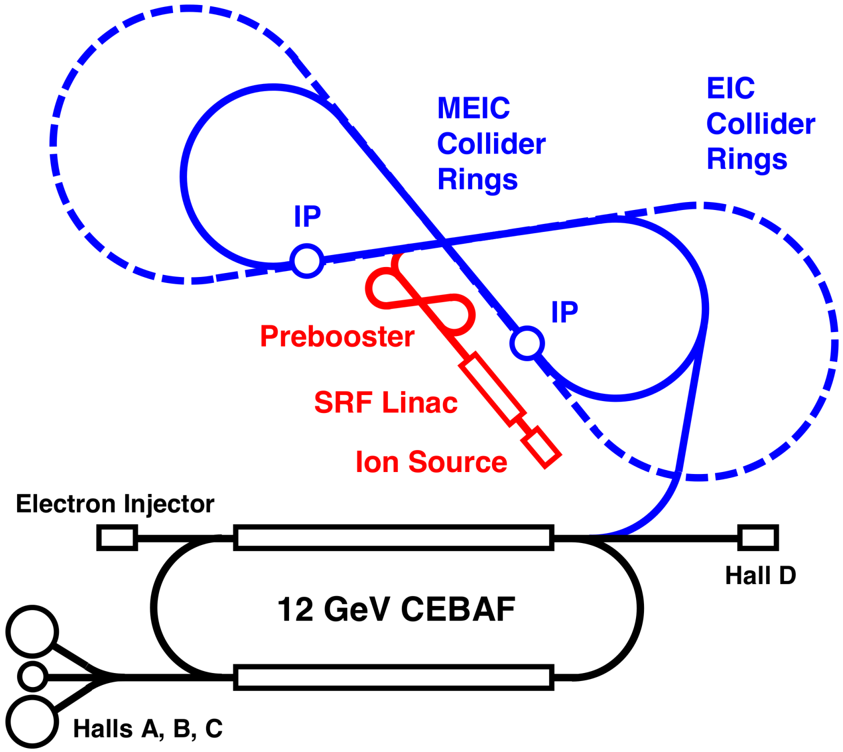


- VERY SMALL MOMENTUM FRACTIONS $x \lesssim 10^{-6}$ REACHED AT LOW SCALE $Q \sim 1$ GeV
- VERY LARGE SCALE $Q \sim 1$ TeV REACHED AT LARGE $x \sim 0.5$
- VERY LARGE $x \sim 0.9$ REACHED IN WIDE RANGE OF SCALES $10 \lesssim Q \lesssim 1000$ GeV

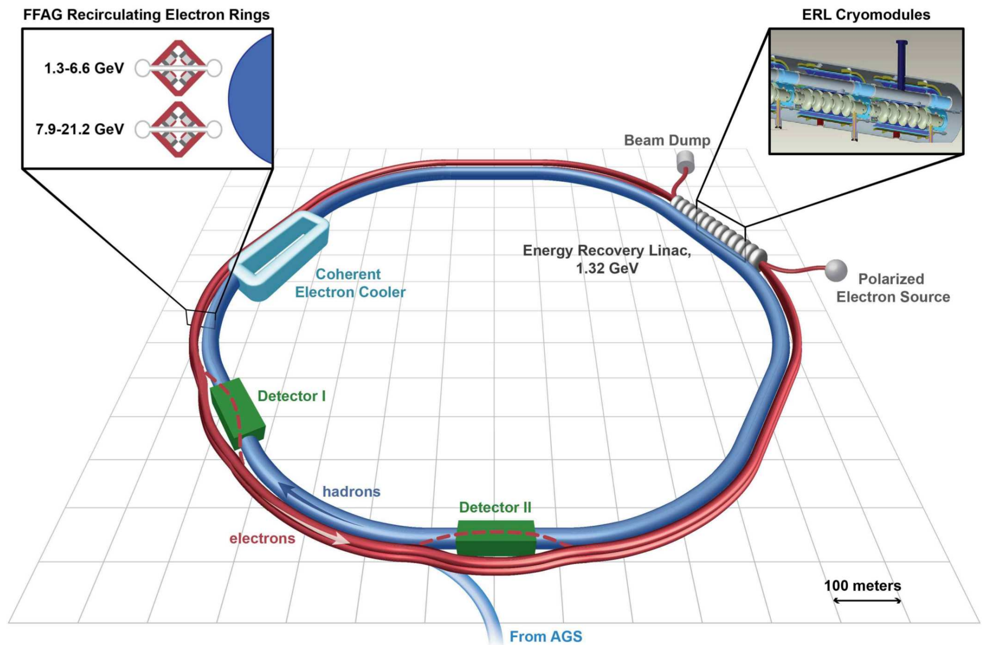
THE EIC

- TWO BASIC DESIGNS (JLAB VS. BNL); ENERGY-LUMI TRADEOFF
- e BEAM: $5 - 10$ GEV; VARIABLE CM ENERGY: $20 - 100$ GEV
- LUMI $10^{33} - 10^{34}$ CM^{-2} SEC^{-1}
- POLARIZED BEAMS AVAILABLE WITH e, p, d, ^3He
- WIDE RANGE OF NUCLEI FOR UNPOL. eA; LUMI PER NUCLEON SAME AS FOR e-p

JLAB LAYOUT (MEIC)



BNL LAYOUT (ERHIC)

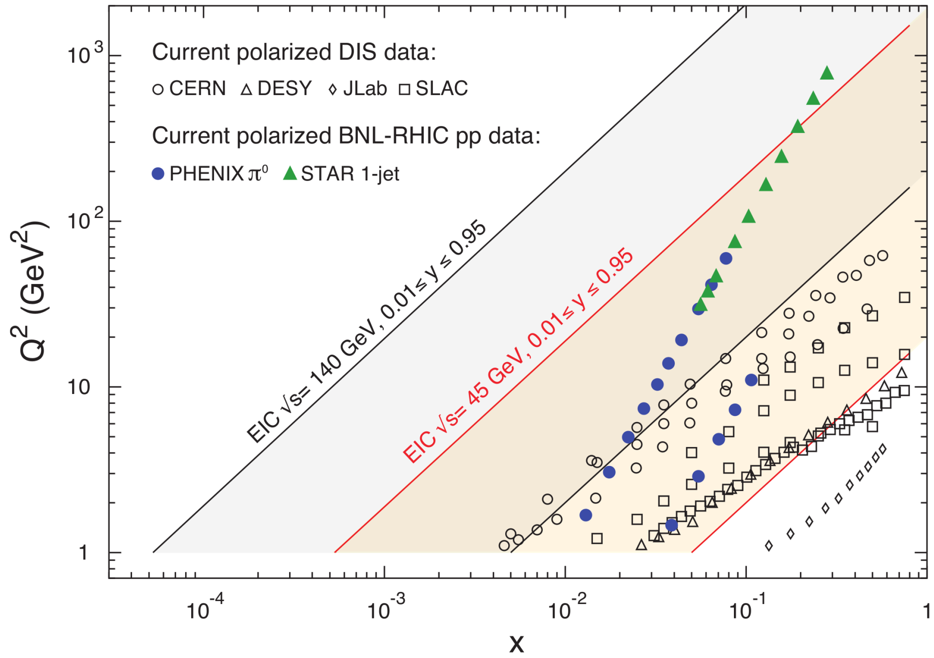


EIC: KINEMATIC COVERAGE

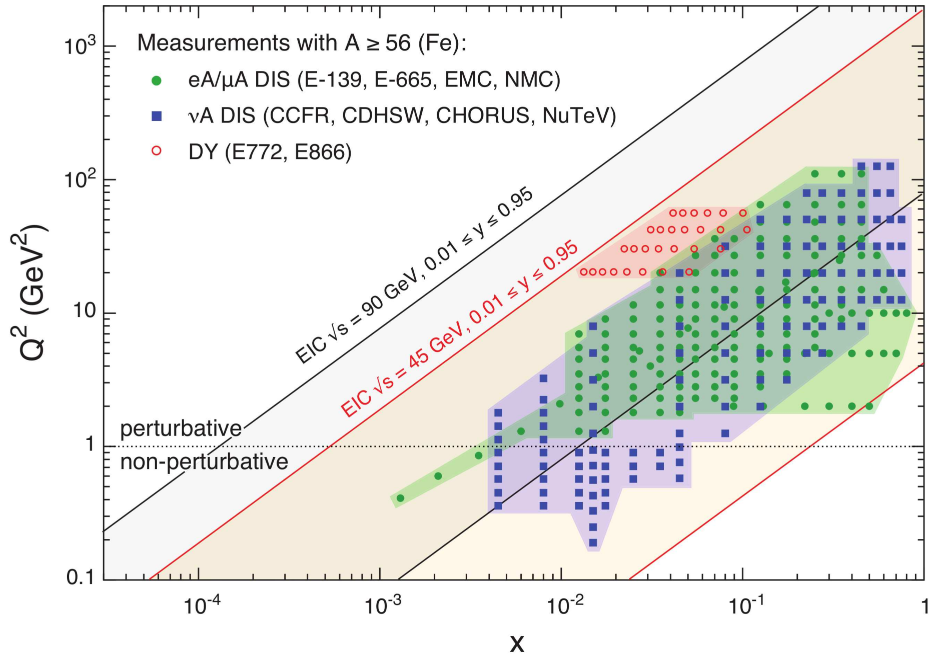
DEEP-INELASTIC SCATTERING

- SOMEWHAT LOWER ENERGY IN COMPARISON TO HERA
- MAIN STRENGTHS: POLARIZATION AND VARIETY OF NUCLEAR TARGETS
- POLARIZATION: UNIQUE OPTION

POLARIZED



NUCLEAR



PHYSICS AT THE LHeC

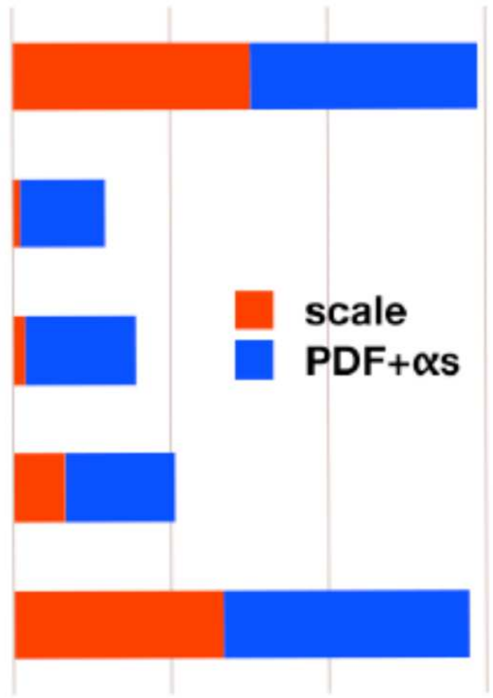
- PARTON DISTRIBUTIONS
  - PDF UNCERTAINTIES AT NNLO AND BEYOND
  - α_s
  - NUCLEAR PDFs
- PRECISION PHYSICS OF THE SM AND BEYOND
  - HIGGS COUPLINGS (b AND c) AND CP
  - SINGLE TOP (FCNC, V_{tb})
  - THE WEAK MIXING ANGLE
- "ALICE" PHYSICS
  - HIGH DENSITY QCD & SATURATION
  - DIFFRACTION

PARTON DISTRIBUTIONS

WHY WORRY ABOUT PDFs?

HIGGS PRODUCTION

		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
NNLO QCD +NLO EW	VBF	1.56 pb	2.9%
	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



(J. Campbell, HCP2012)

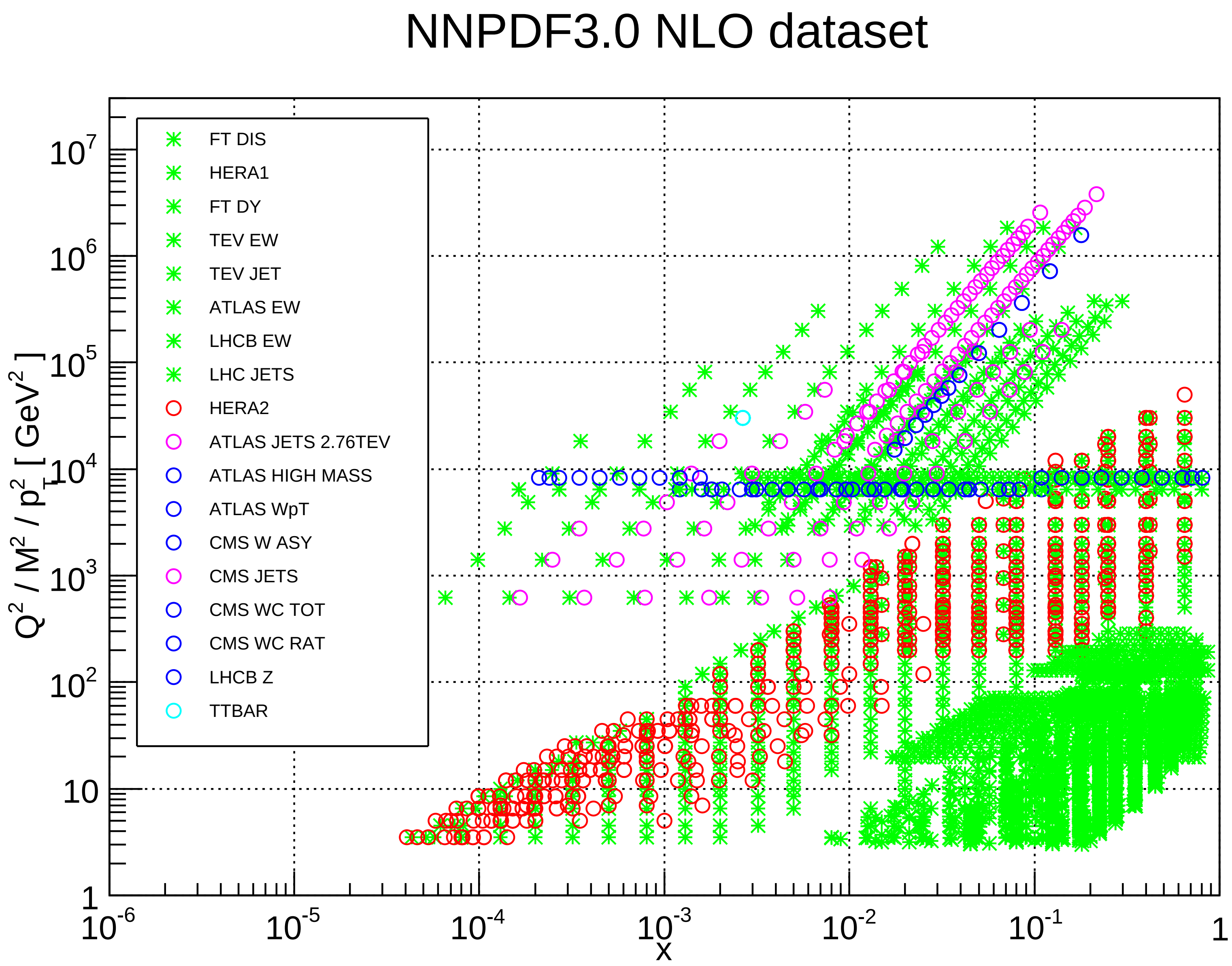
PDF UNCERTAINTY EITHER DOMINANT, OR VERY LARGE, OR BOTH

. . . AND NOT ONLY FOR THE HIGGS!

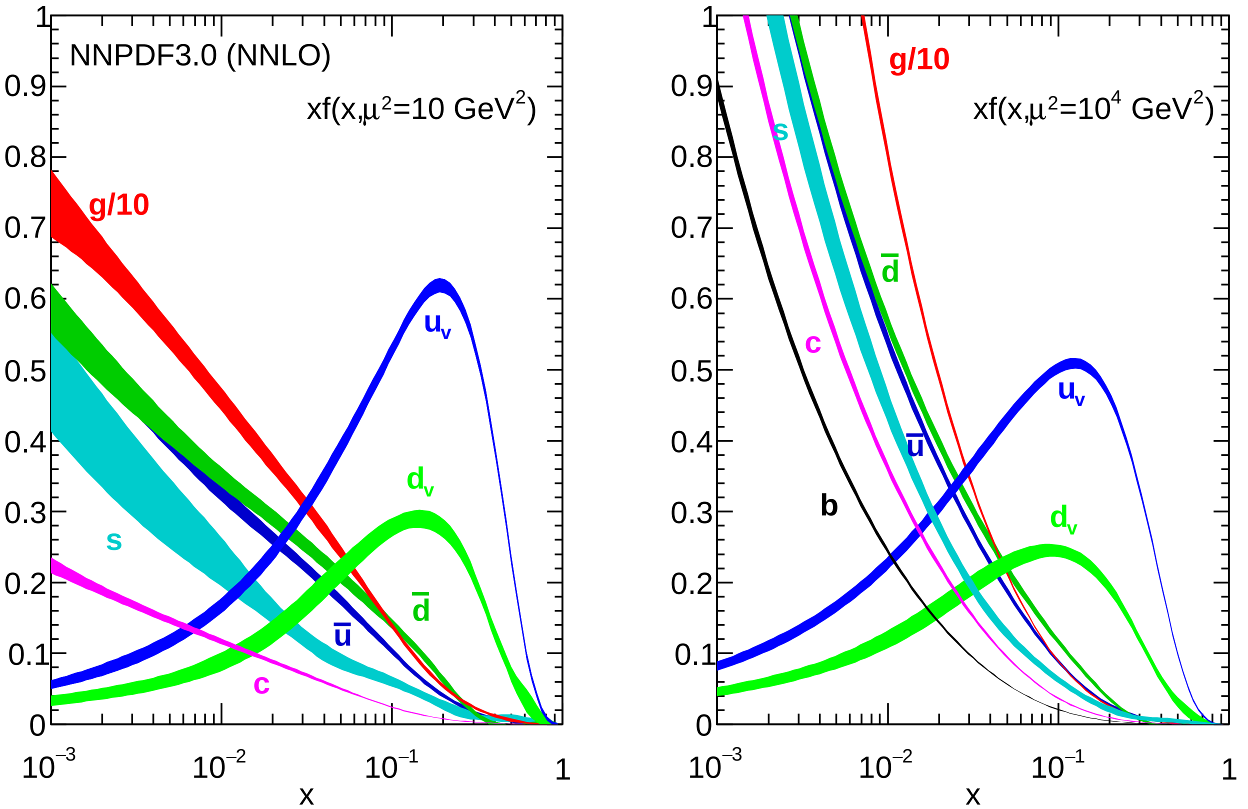
(W MASS DETERMINATION, NEW PHYSICS SEARCHES FOR HEAVY STATES,. . .)

PDFs TODAY:

KINEMATIC COVERAGE



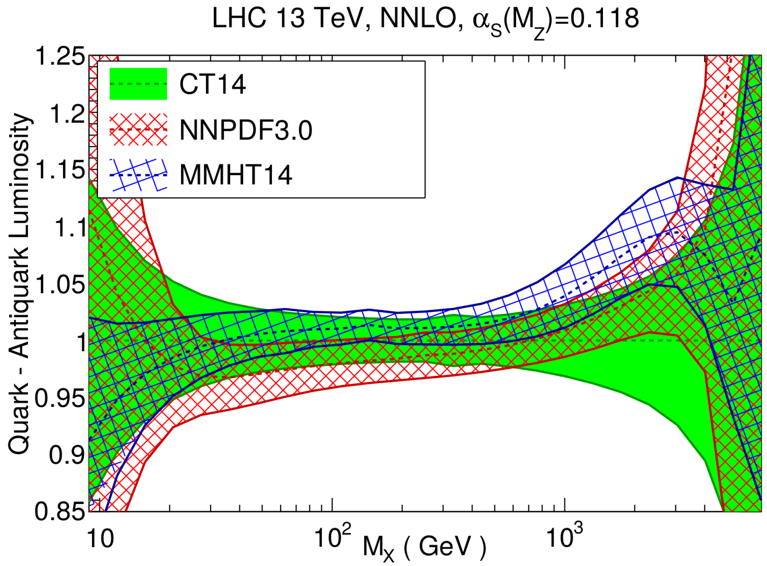
PDFs TODAY:
PDFS & UNCERTAINTIES



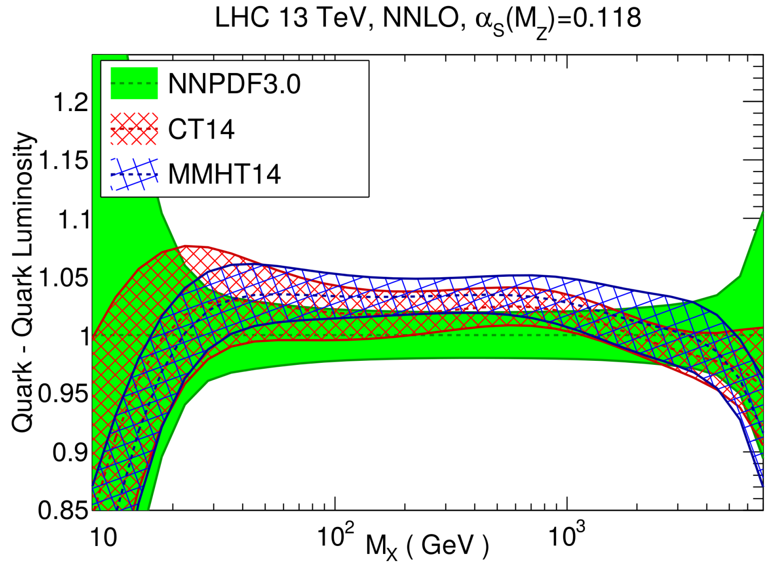
- LOWEST PDF UNCERTAINTIES $\sim 5\%$: $\Rightarrow$ GLUON AT SMALL x, VALENCE AT MEDIUM-LARGE x
- STRANGE AND SEA LESS WELL KNOWN
- LARGE UNCERTAINTIES AT SMALL AND LARGE x

PDFs TODAY: PARTON LUMINOSITIES

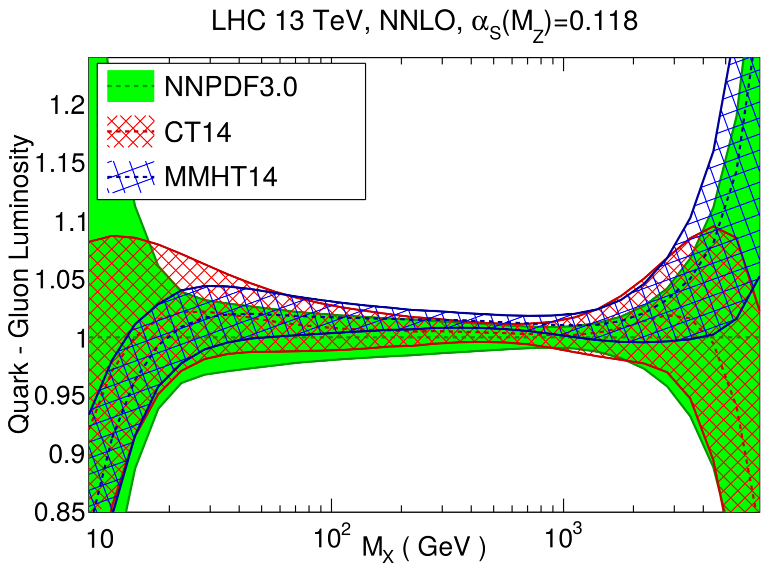
QUARK-ANTIQUARK



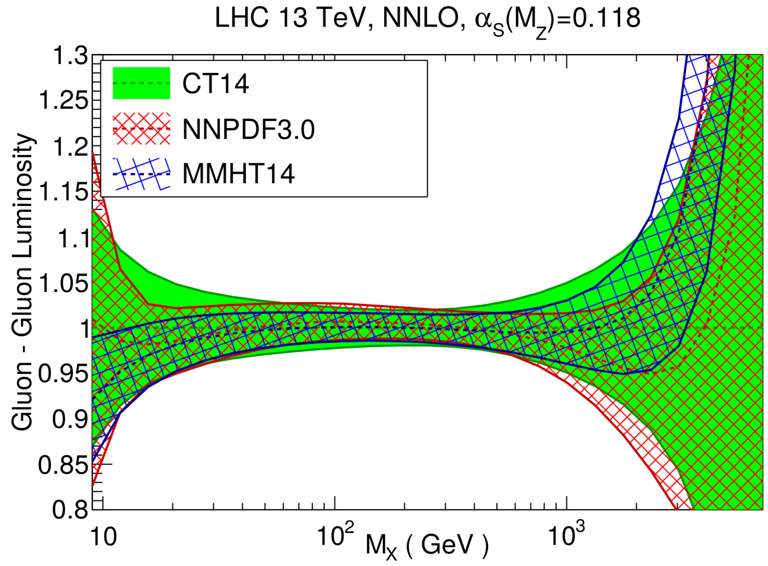
QUARK-QUARK



QUARK-GLUON



GLUON-GLUON

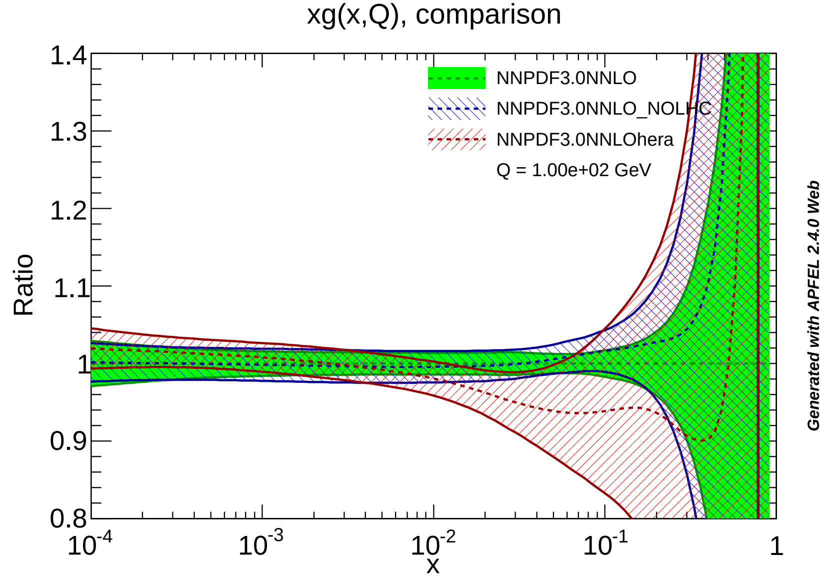


- CAN READ OFF PDF UNCERTAINTY
- UNCERTAINTIES BLOW UP FOR LIGHT ($\lesssim 10$ GeV) AND HEAVY ($\gtrsim 1$ TeV) FINAL STATES

HERA AND LHC DATA: WHAT IS THE RELATIVE IMPACT?

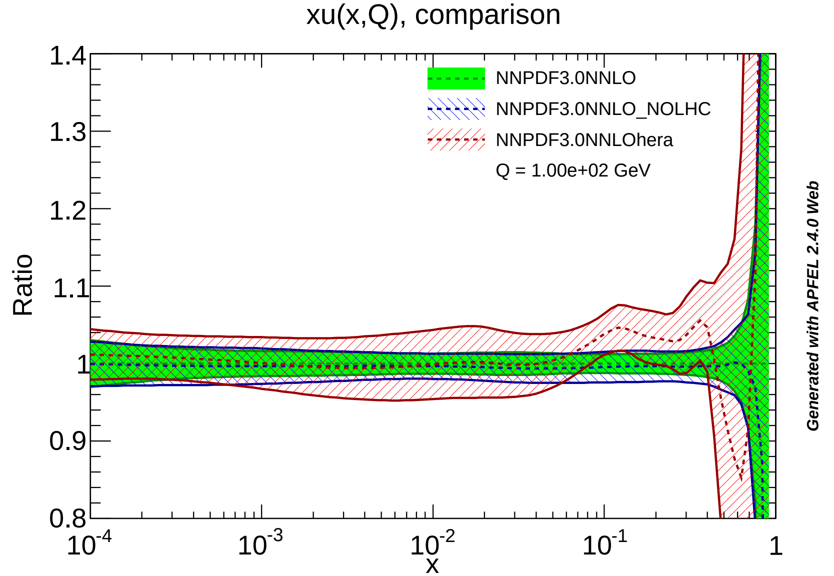
COMPARE PDF DETERMINED FROM FULL GLOBAL FIT, NO LHC DATA, ONLY HERA DATA:

GLUON

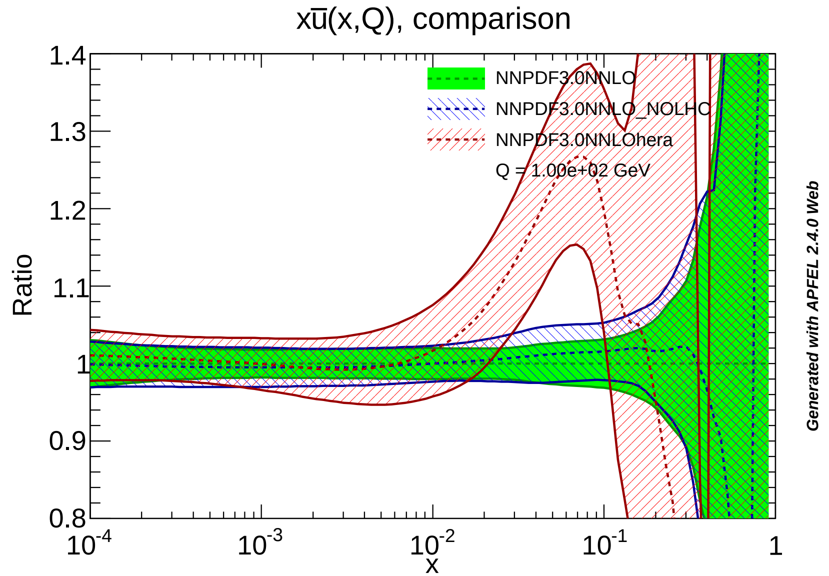


- IN REGIONS WHERE HERA DATA AVAILABLE, HERA ONLY UNCERTAINTY QUALITATIVELY COMPARABLE TO THAT OF GLOBAL FIT
- IMPACT OF LHC DATA MODERATE
- DIS DATA DRIVE THE GLOBAL FIT

UP



ANTIUP



HERA AND LHC DATA: WHAT IS THE RELATIVE IMPACT?

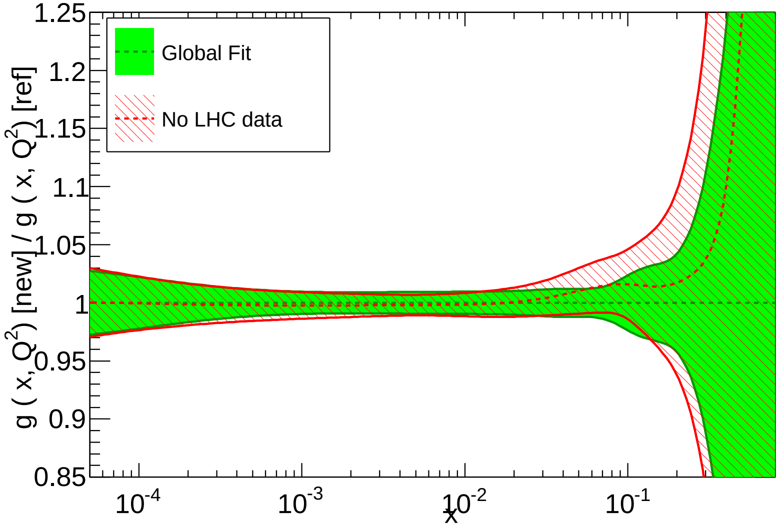
- OVERALL MEASURE OF IMPACT:
  $\varphi \Rightarrow$ FIT UNCERTAINTY/DATA UNCERTAINTY
- HERA-II IMPACT SIZABLE
- IMPACT OF LHC DATA MODERATE BUT VISIBLE
- IMPACT OF CMS OR ATLAS COMPARABLE TO (MODERATE) IMPACT OF NON-LHC, NON-HERA DATA

FRACTIONAL UNCERTAINTY

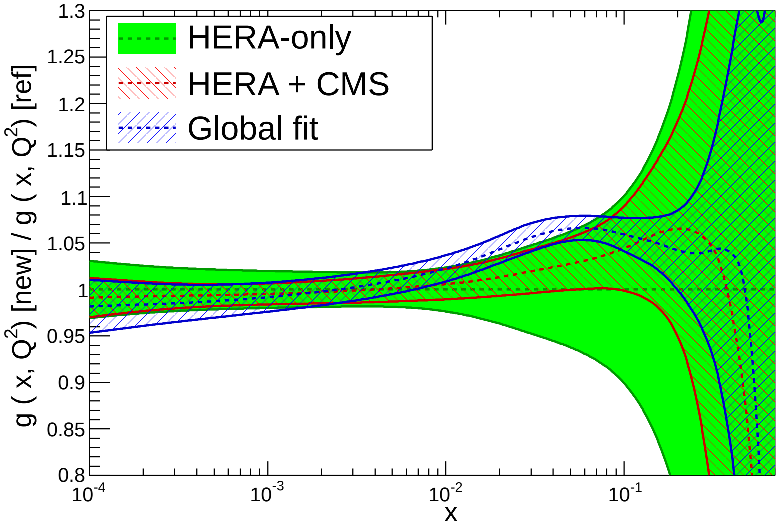
Dataset	φ NLO	φ NNLO
Global	0.291	0.302
HERA-I	0.453	0.439
HERA all	0.375	0.343
HERA+ATLAS	0.391	0.318
HERA+CMS	0.315	0.345
no LHC	0.312	0.316

THE GLUON

GLOBAL VS NO LHC



GLOBAL VS HERA+CMS

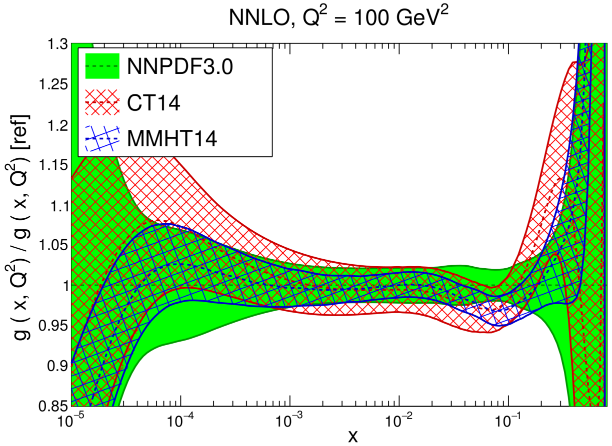


PDFS AT LHC RUN II

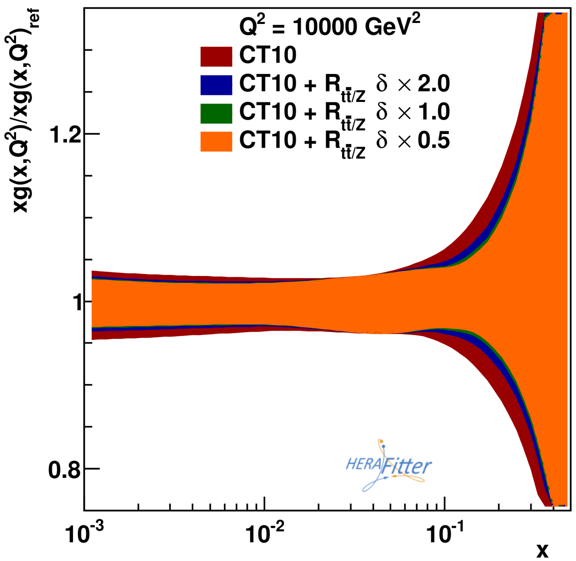
- DATA AT HIGHER CM ENERGY & INFO ON CORRELATION TO LOW ENERGY
  $\rightarrow$ EXTENDED KINEMATIC COVERAGE & REDUCED SYSTEMATICS
- EXPECT REDUCTION IN MODEL DEPENDENCE
- MODERATE REDUCTION IN UNCERTAINTY

GLUON

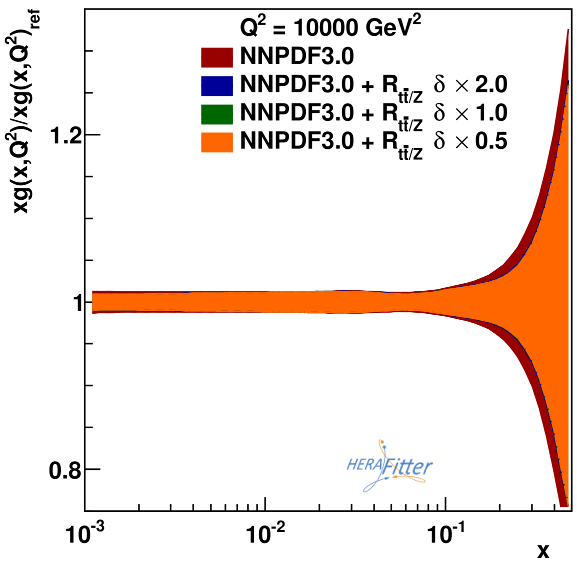
NOW



CTEQ AFTER RUN II



NNPDF AFTER RUN II



(PDF4LHC: 1507.00556)

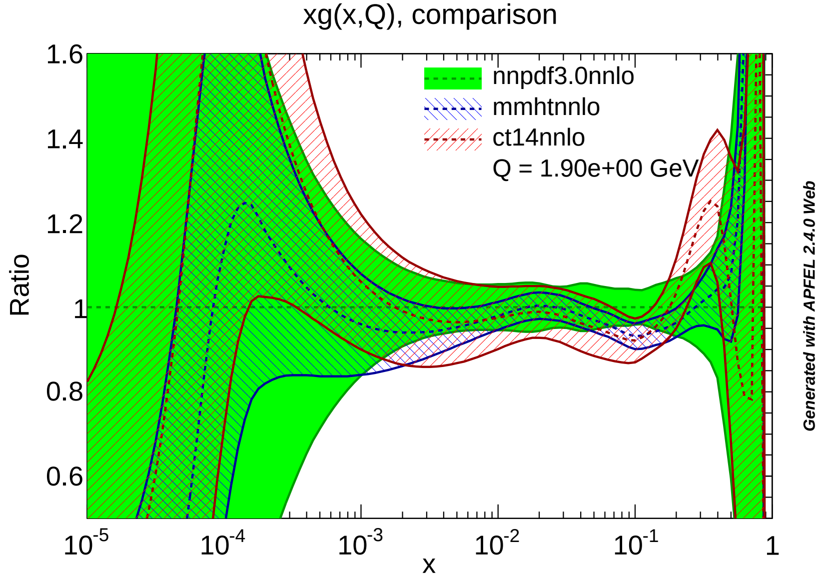
VERY DIFFICULT TO REDUCE UNCERTAINTIES BELOW 3-4% LEVEL
AT A HADRON COLLIDER

PDFs at the LHeC

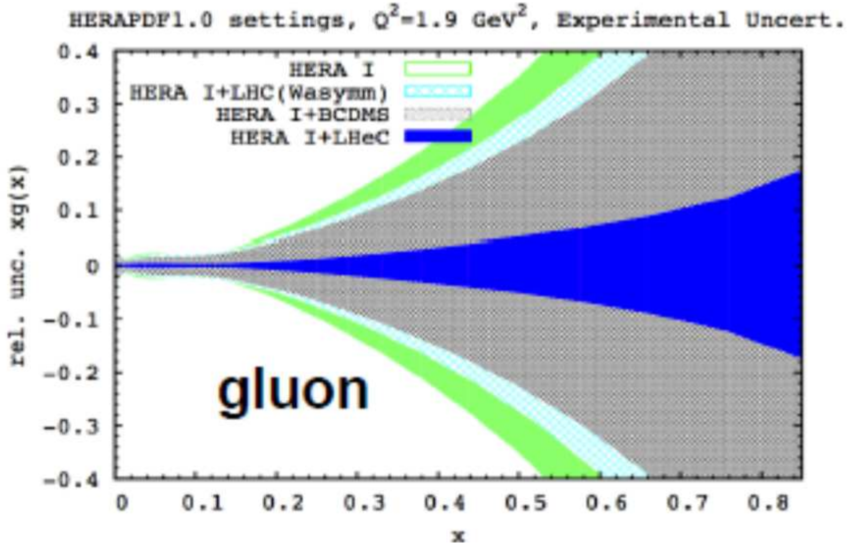
- UNCERTAINTIES DOWN TO PERCENT LEVEL IN WIDE KINEMATIC REGION
- WITH DEUTERON BEAMS, FULL LIGHT FLAVOR DECOMPOSITION
- THANKS TO HIGH ENERGY, NC+CC ⇒ PRECISION STRANGENESS DETERMINATION

GLUON

NOW



AT THE LHeC

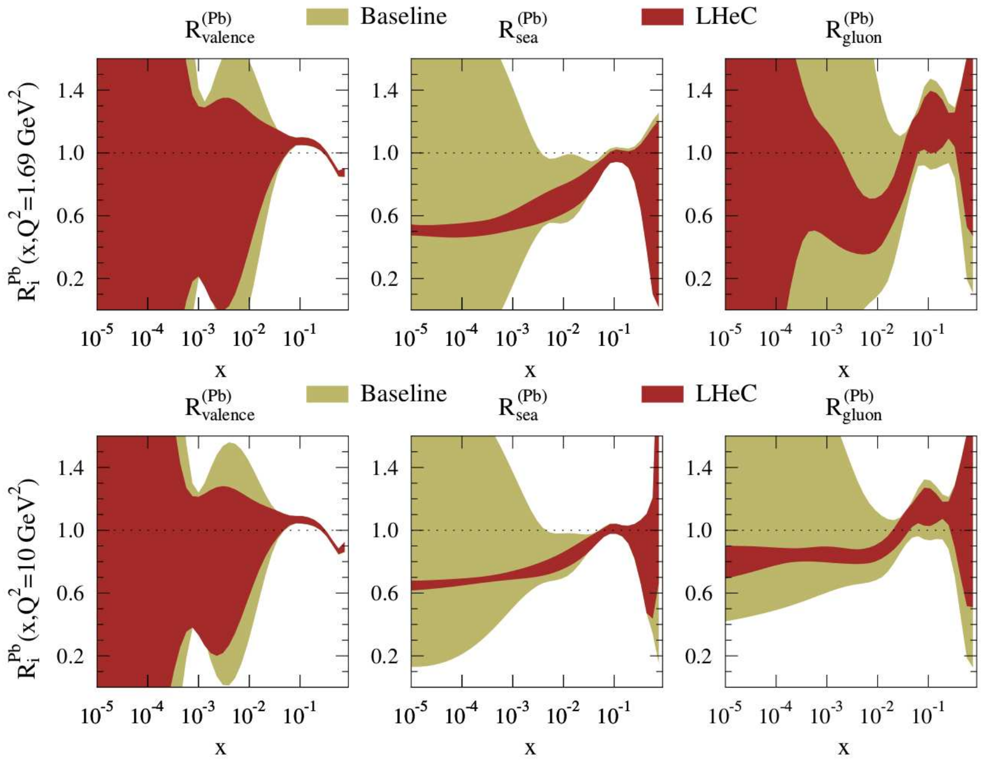


(A. Cooper-Sarkar & Voica Radescu, 2015)

WITH THE LHeC, PDF UNCERTAINTY ON HIGGS PRODUCTION CHANNELS ESSENTIALLY REMOVED (PART OF BACKGROUND NOISE)

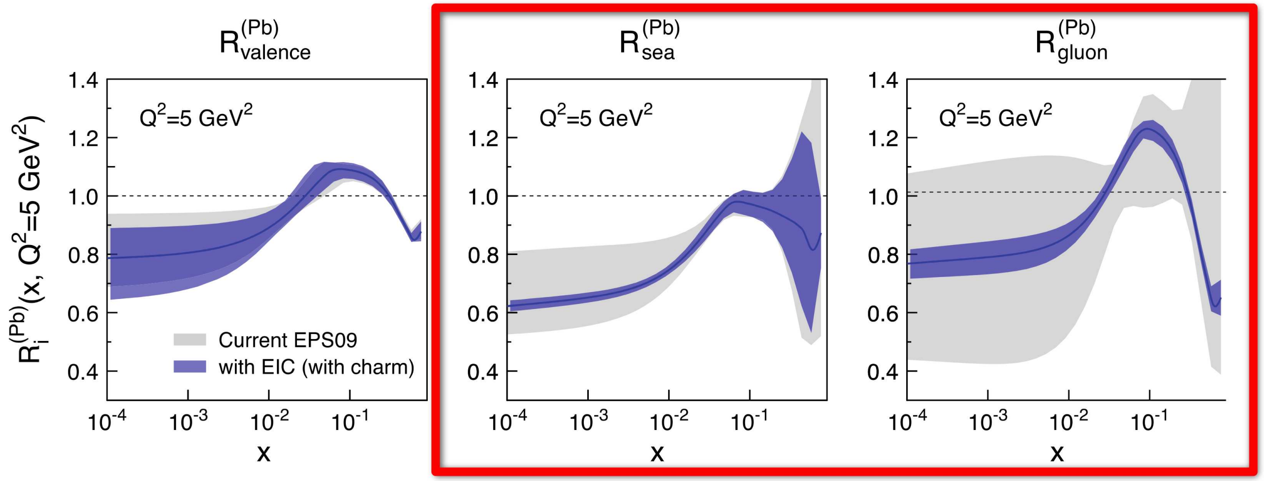
NUCLEAR PDFS AT THE LHEC (AND EIC)

NPDFS AT THE LHEC



- HUGE ENLARGEMENT IN KINEMATIC REGION
- HUGE INCREASE IN PRECISION AT SMALL x
- EIC PERFORMANCE SIMILAR BUT AT LOWER ENERGY

NPDFS AT THE EIC

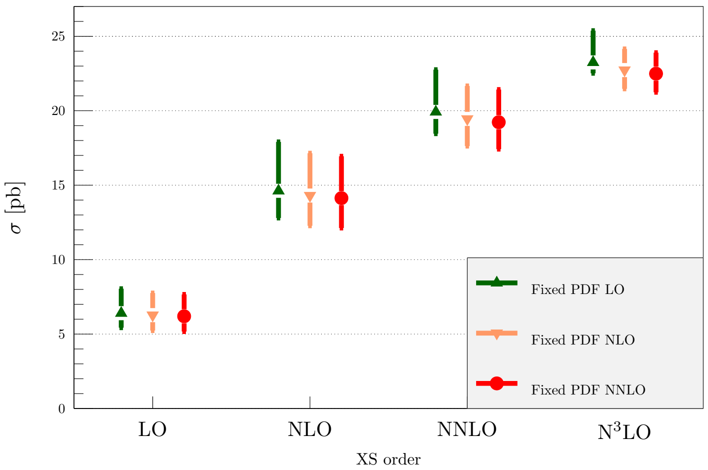


N^{3}LO PDFs:

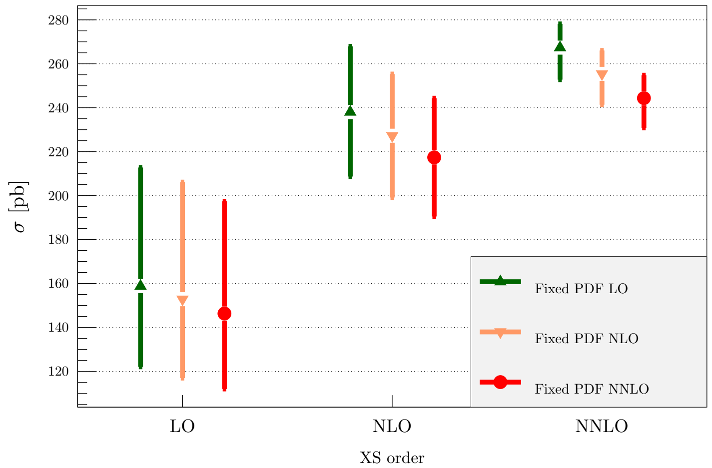
- NEEDED AT THE 1% ACCURACY LEVEL
- IMPACT OF N^3LO DEPENDS ON PROCESS:
  - HIGGS GLUON FUSION: PERTURBATIVE DEP. OF PDF NEGLIGIBLE IN COMPARISON TO MATRIX ELEMENT $\Rightarrow$ N^{3}LO NOT NEEDED
  - TOP: PERTURBATIVE DEP. OF PDF SMALLER, BUT NOT NEGLIGIBLE IN COMPARISON TO MATRIX ELEMENT, ANTICORRELATED TO IT $\Rightarrow$ N^{3}LO NECESSARY

SCALE UNCERTAINTY & DEP. ON PERTURBATIVE ORDER

HIGGS



TOP



(s.f., Isgrò, Vita, 2014)

- N^{3}LO DIS COEFFICIENT FUNCTIONS KNOWN
- BOTTLENECK: N^3LO ANOMALOUS DIMENSIONS
- N^{3}LO JETS UNLIKELY TO BE AVAILABLE ANY TIME SOON

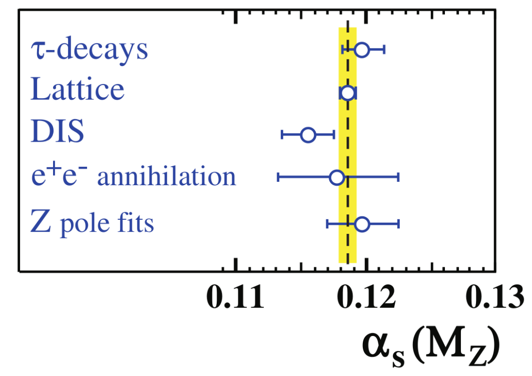
THE VALUE OF α_s

- PDG VALUE (AUGUST 2014): $\alpha_s(M_Z) = 0.1185 \pm 0.0006$
- HXSWG/PDF4LHC RECOMMENDS $\alpha_s(M_Z) = 0.118 \pm 0.0015$
- THIS IS A $\sim 5\%$ UNCERTAINTY ON HIGGS IN GLUON FUSION

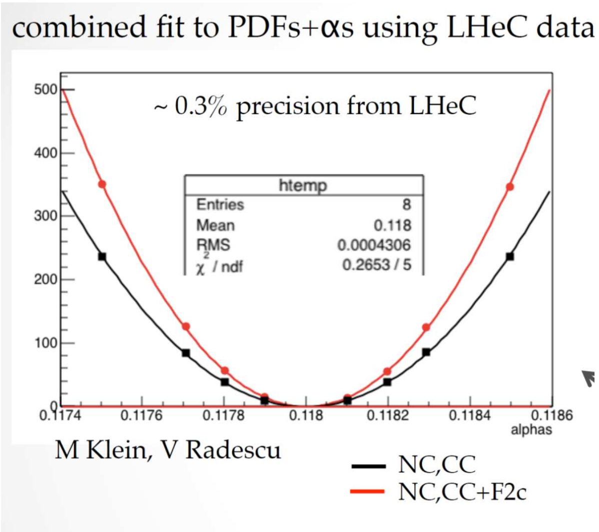
PROGRESS EXPECTED?

- PDG IS AN AN AVERAGE OF AVERAGES, SOME OF WHICH INCLUDE MUTUALLY INCONSISTENT VALUES BY UP TO FOUR-FIVE σ
- LITTLE PROGRESS FOR MANY YEARS: PDG 1998-2006 $\Delta\alpha_s(M_Z) = 0.002$; PDG 2010-2014 $\Delta\alpha_s(M_Z) = 0.0006 \div 0.0008$ (CHANGE OF AUTHOR)

α_s DETERMINATIONS IN PDG



α_s AT THE LHEC

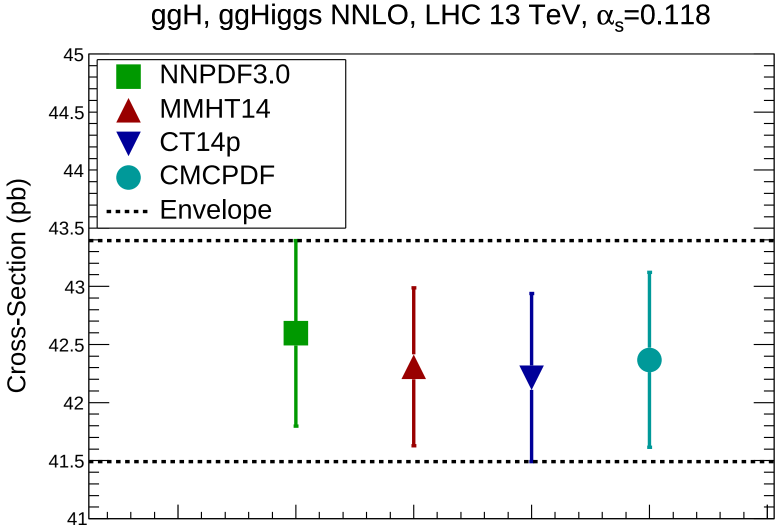


- ACCURATE SIMULTANEOUS DETERMINATION OF α_s AND THE GLUON POSSIBLE THANKS TO BIG LEVER ARM IN Q^2
- LONG-STANDING ISSUE WITH α_s FROM DIS CAN BE RESOLVED

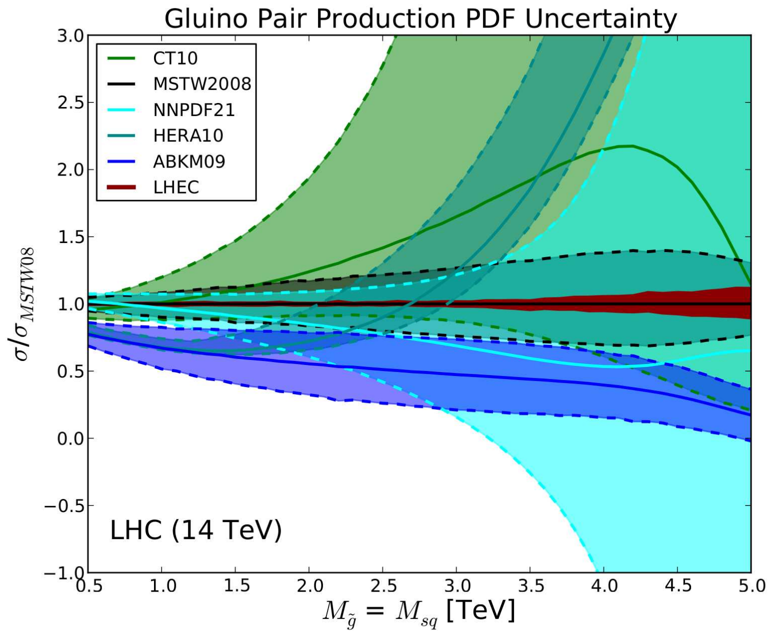
PDFs: SUMMARY

- ACCURATE PDFs REQUIRED BOTH FOR PRECISION AND DISCOVERY
- WITHOUT LHeC EXTREMELY DIFFICULT TO GO BELOW 3% UNCERTAINTY IN PRECISION PHYSICS REGION
- WITHOUT LHeC EXTREMELY DIFFICULT TO REDUCE CURRENT 100% UNCERTAINTY IN DISCOVERY REGION
- WITHOUT LHeC EXTREMELY DIFFICULT TO REDUCE CURRENT 1-2% UNCERTAINTY ON α_s

HIGGS IN GLUON FUSION: NOW

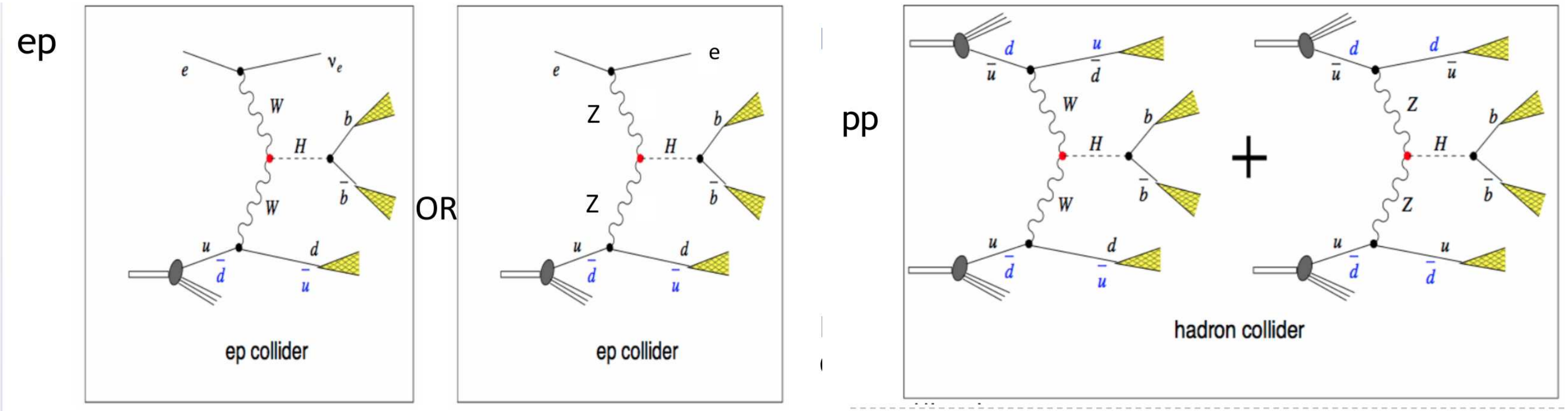


GLUINO PRODUCTION: WITH OR W/O LHeC



PRECISION PHYSICS

HIGGS PRODUCTION
EP VS. PP



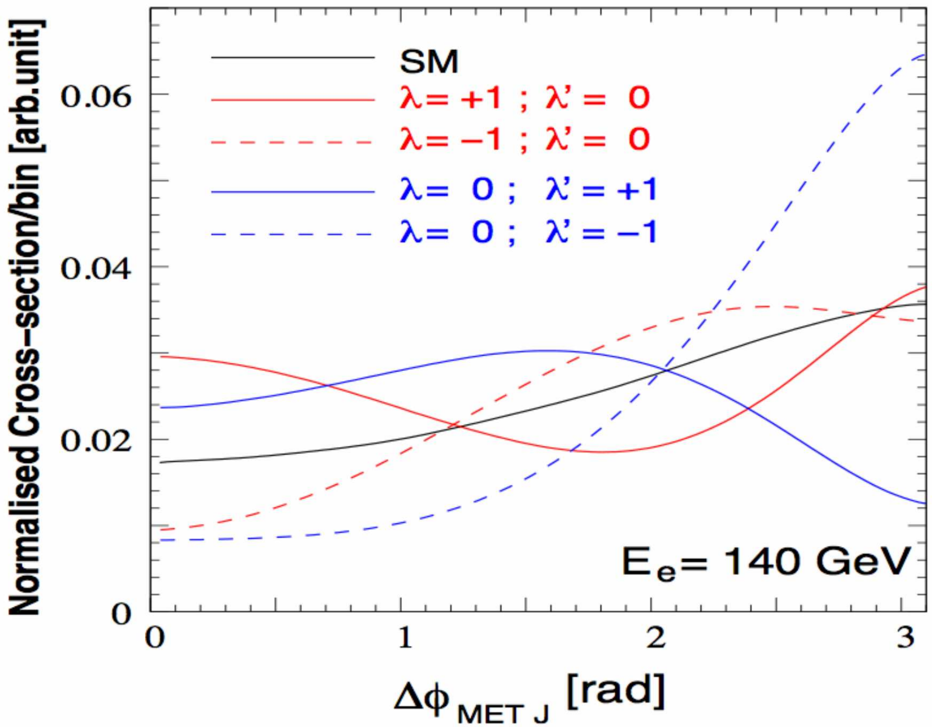
- Higgs produced in CC or NC interactions
- clean signal and ZZH vs. WWH separation $\Rightarrow$ probe of HWW vertex $\rightarrow$ Higgs CP properties
- direction of FS quark well defined $\rightarrow$ accurate $b\bar{b}$ decay measurement

HIGGS PHYSICS AT THE LHeC

TENSOR COUPLINGS TO WW

- PARAMETRIZE HWW VERTEX AS
  $\gamma^{mu\nu} = -g^{\mu\nu} + \frac{1}{m_W^2}\left[\lambda\left(p_1 \cdot p_2 g^{\mu\nu} - p_1^{\mu} p_2^{\nu}\right) + i\lambda' \epsilon^{\mu\nu\rho\sigma}\right]$; SM: $\lambda = \lambda' = 0$

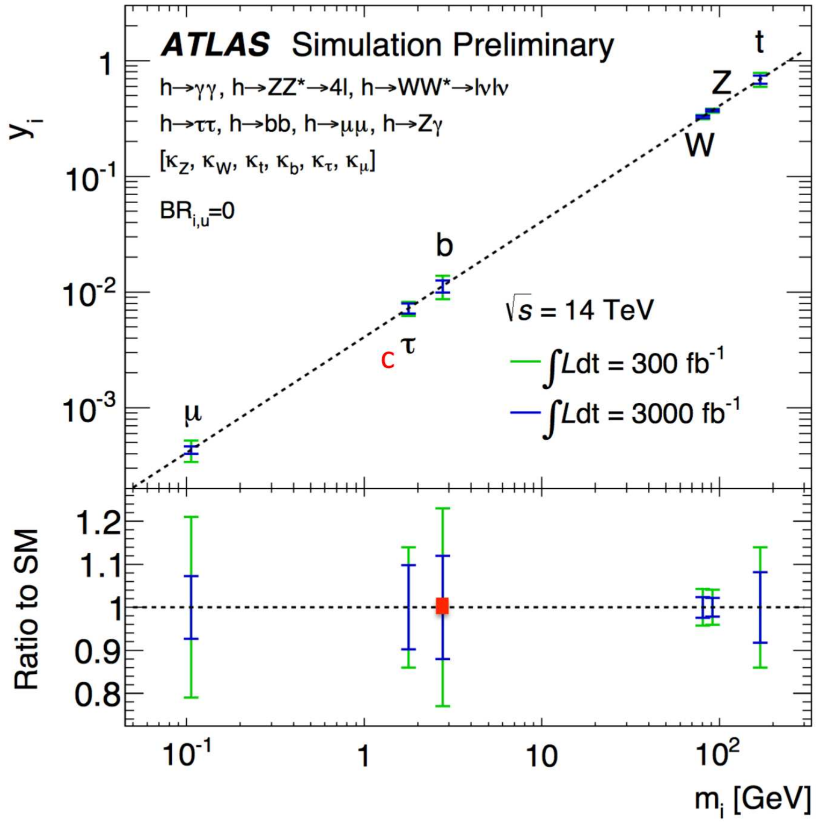
- MEASURE AZIMUTHAL DISTRIBUTION BETWEEN NEUTRINO ($E_t^{\rm miss}$) & JETS $\rightarrow$ SENSITIVE PROBE OF HIGGS CP PROPERTIES



HIGGS PHYSICS AT THE LHeC

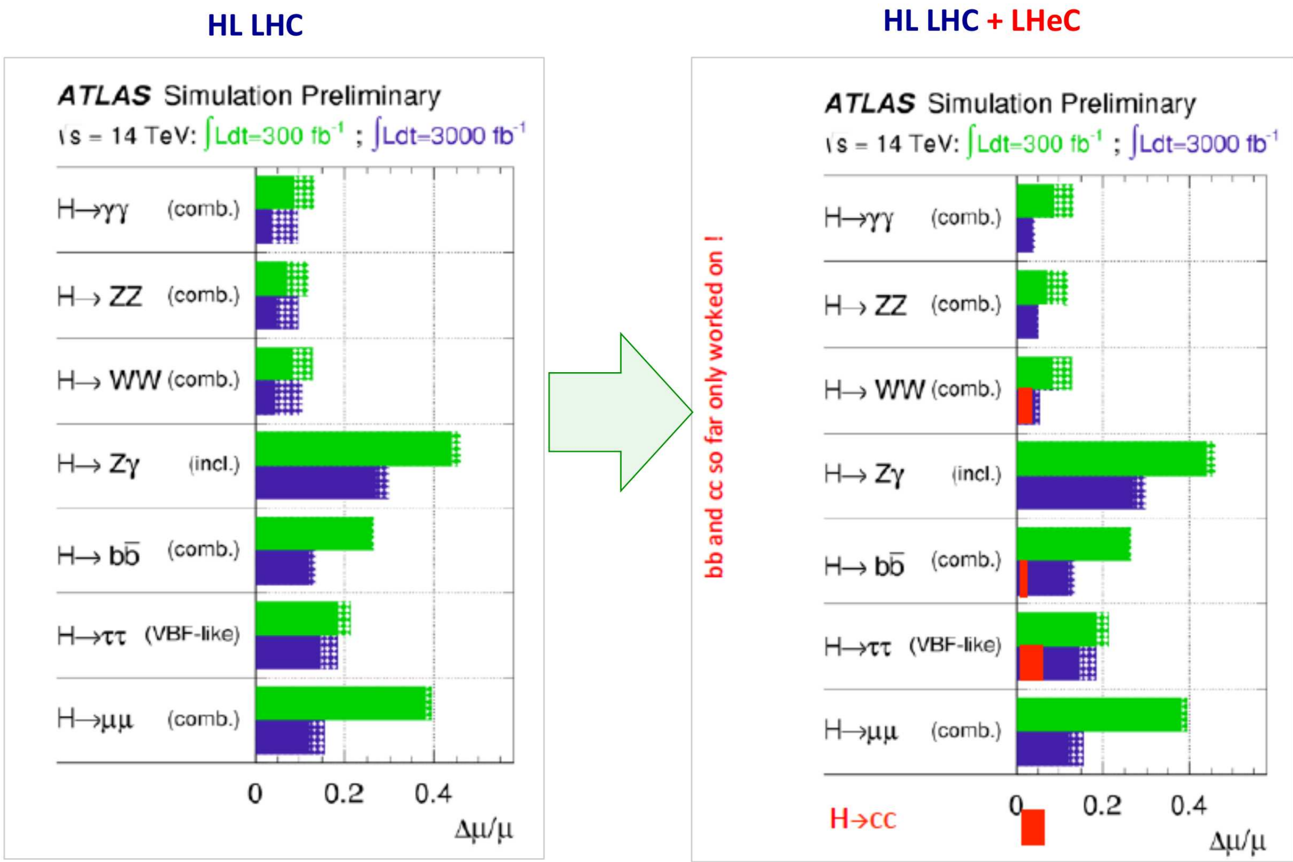
THE $H\bar{b}b$ COUPLING

- FORWARD JET TAGGING $\Rightarrow$ VERY CLEAN SIGNAL AGAINST SMALL $\bar{b}bj$ NC & CC BACKGROUND WITH CUT-BASED ANALYSIS
- MEASURE COUPLING WITH 4% PRECISION WITH 100 fb^{-1}
  10 fb^{-1} = one month = 1100 $H \to \bar{b}b$ events
- $\tau\tau$ ABOUT 10% PRECISION; EVEN $\bar{c}c$ MEASURABLE



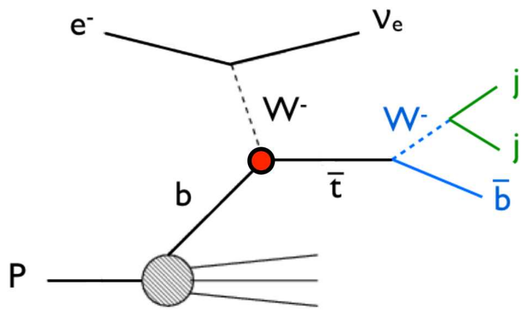
HIGGS PHYSICS AT THE LHEC

SUMMARY

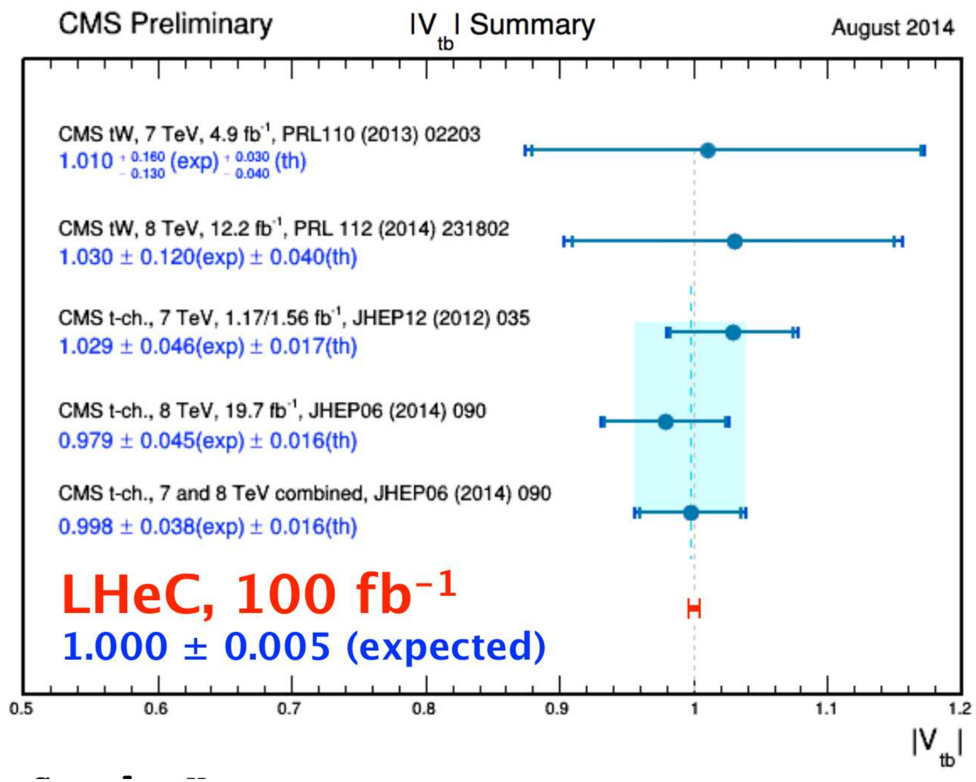


- GLUON FUSION AND W FUSION $\Rightarrow$ PDF+α_s UNCERTAINTY REMOVED (hatched bands)
- $H\bar{b}b$ MEASURED TO PERCENTAGE PRECISION;
- $\tau\tau$ AND $\bar{c}c$ ALSO MEASURABLE

TOP PHYSICS AT THE LHEC
THE V_{tb} CKM MATRIX ELEMENT

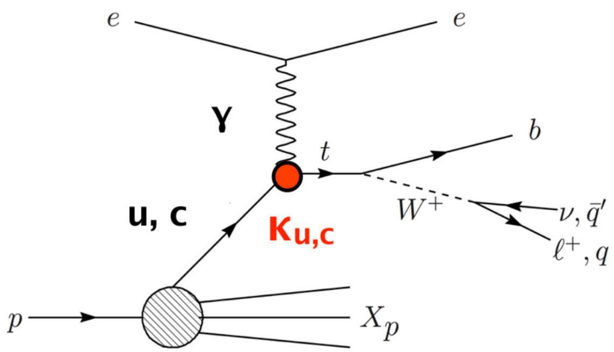


- CLEAN DEEP-INELASTIC SINGLE TOP PRODUCTION
- $100\ \mathrm{fb}^{-1} \Rightarrow \sim 10^6$ SINGLE TOP DIS EVENTS $\Rightarrow \Delta V_{tb} = 0.005$ PRECISION

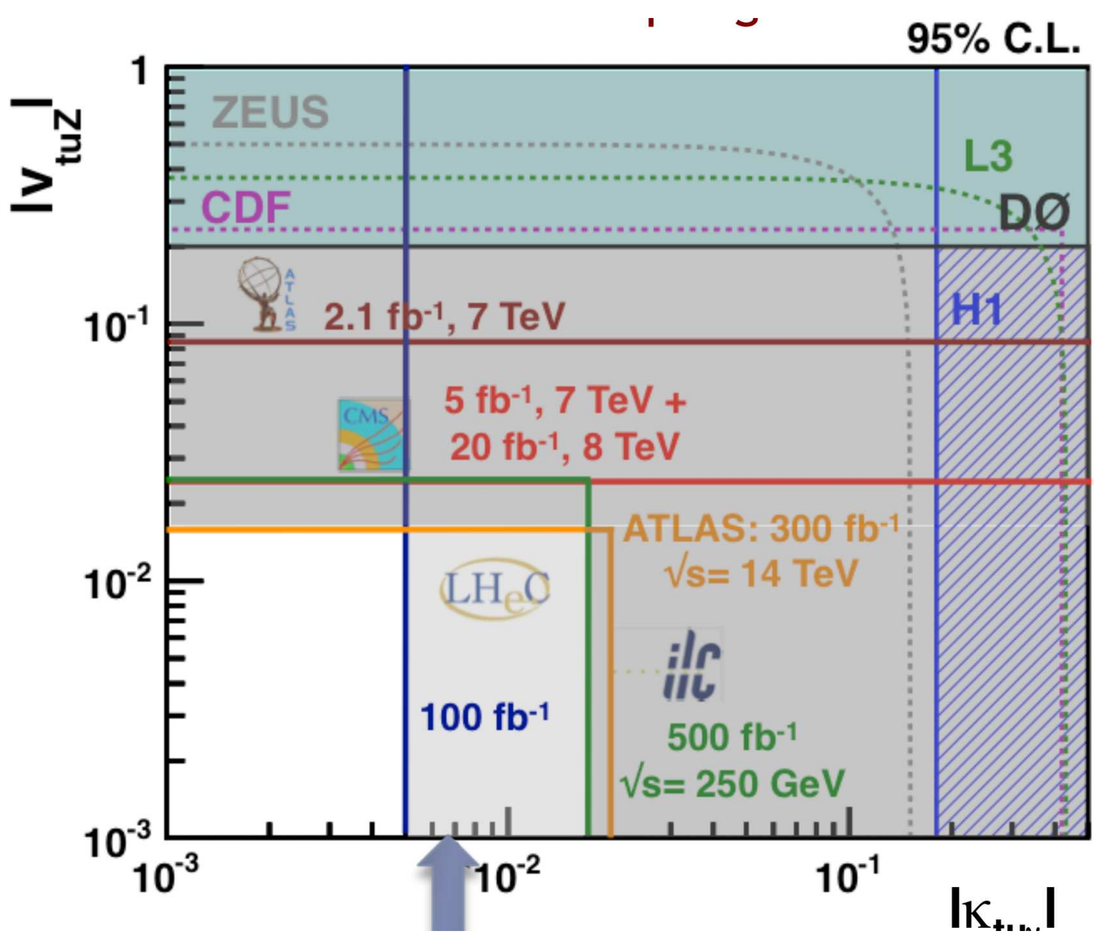


TOP PHYSICS AT THE LHeC

FCNC

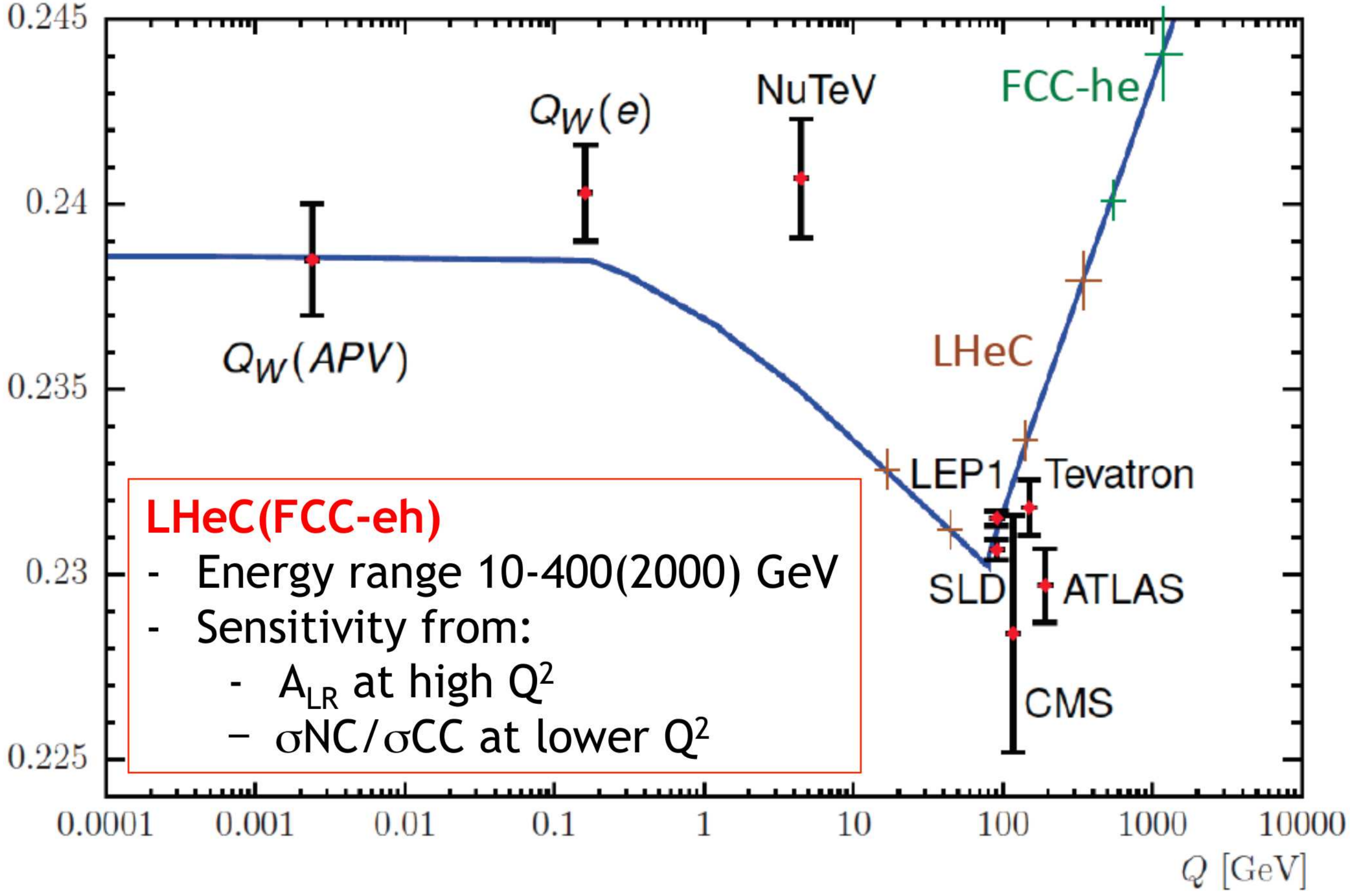


- CLEAN DEEP-INELASTIC SINGLE TOP PRODUCTION
- TEST ANOMALOUS COUPLINGS
- $100\ \text{fb}^{-1} \Rightarrow \sim 10^6$ SINGLE TOP DIS EVENTS $\Rightarrow$ FCNC $O\left(\frac{\kappa}{\Lambda}\right)$; $\Lambda = 1$ TeV, DISCOVERY FOR $\kappa \sim 10^{-3}$



THE ELECTROWEAK MIXING ANGLE

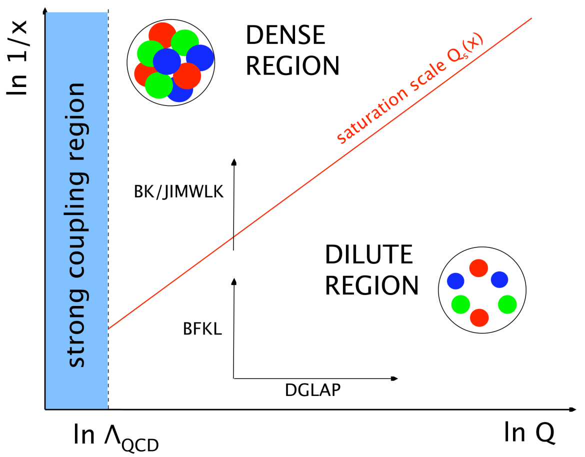
- CAN EXTRACT $\sin^2\theta_W$ FROM CC/NC DIS RATIOS & FROM SEPARATION OF γZ INTERFERENCE FROM PURE Z EXCHANGE (e^+ VS. e^- DIS)
- CAN MEASURE MIXING ANGLE FOR SEVERAL Q^2 VALUES TO HIGH ACCURACY $\Rightarrow$ TEST OF SCALE DEPENDENCE

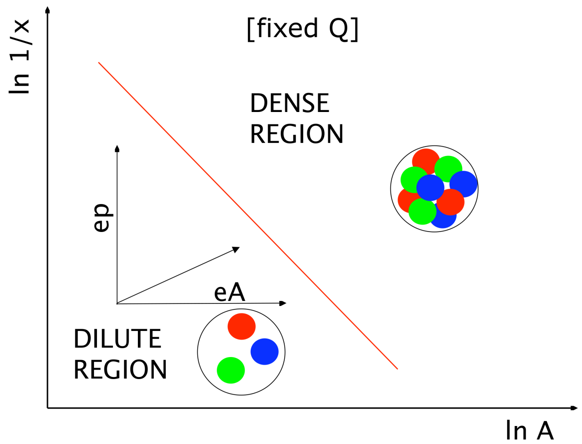


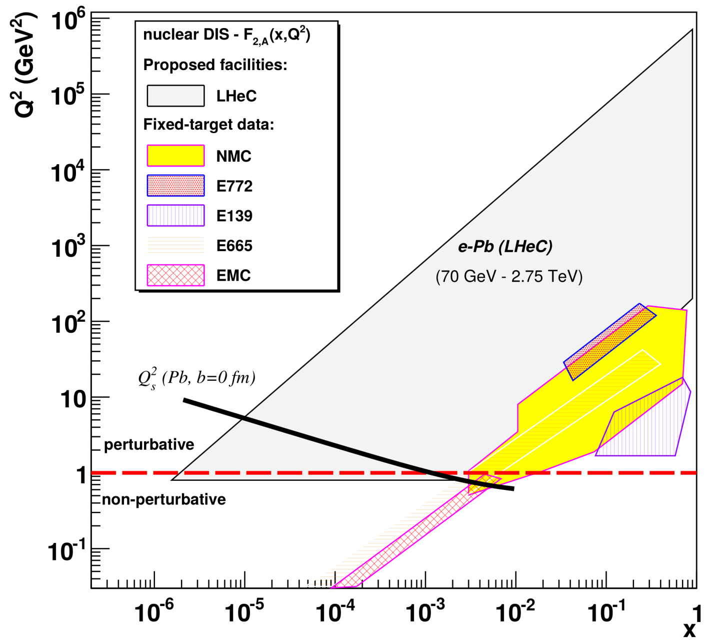
"ALICE" PHYSICS

LHeC: THE MECCA OF HIGH-DENSITY QCD

- “LINEAR” ALTARELLI-PARISI EVOLUTION: AT LOW MOMENTUM FRACTION, GLUON AND SEA PDFs RISE ⇒ UNITARITY VIOLATION?
- PARTON RECOMBINATION SETS IN ⇒ NONLINEAR EVOLUTION
- NEW PHASE OF QCD MATTER ⇒ COLOR GLASS CONDENSATE
- TRANSITION HAPPENS AT LOW x, HIGH A

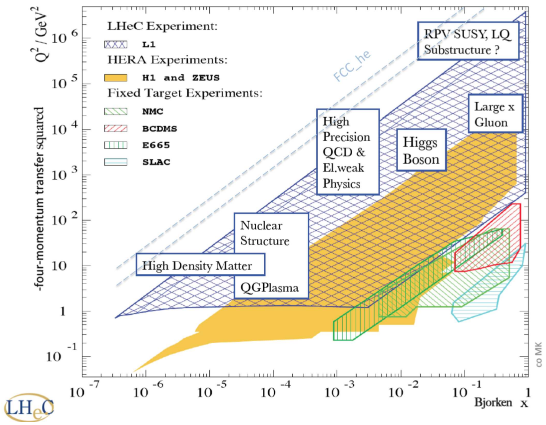


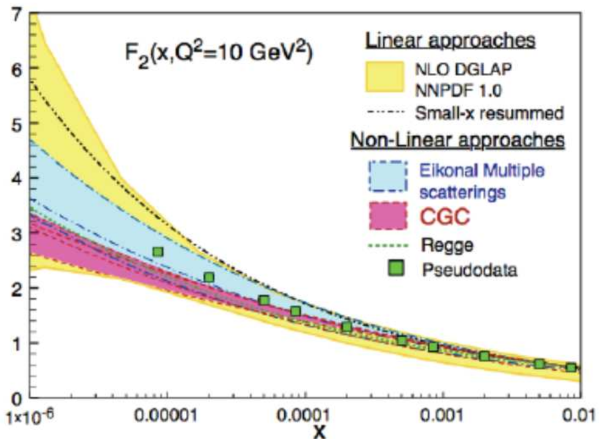


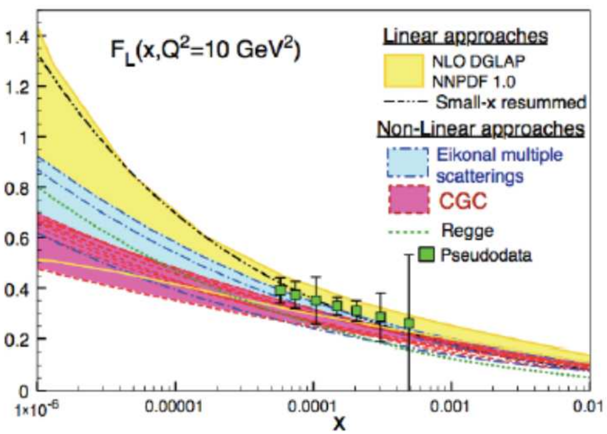


HIGH-DENSITY QCD: SATURATION

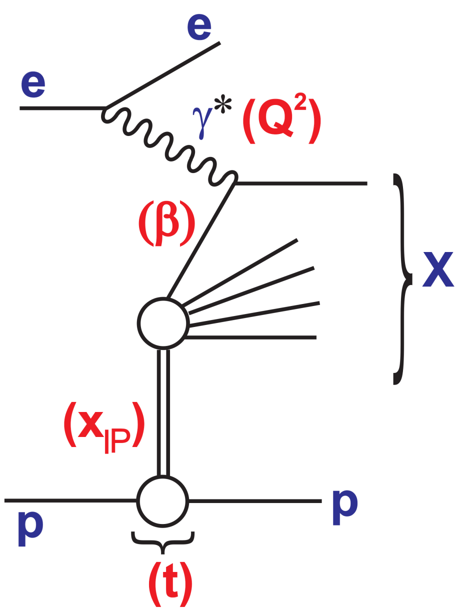
- F_2 AND F_L SEPARATELY DEPEND ON GLUON & ON EVOLUTION MECHANISM $\Rightarrow$ MEASURING BOTH PINS DOWN GLUON & EVOLUTION
- WHERE AND HOW IS ALTARELLI-PARISI RISE QUENCHED?
- UNDERSTANDING OF NON-LINEAR QCD REGIME STILL TENTATIVE
- MODELS/THEORIES CAN BE TESTED & DISENTANGLED



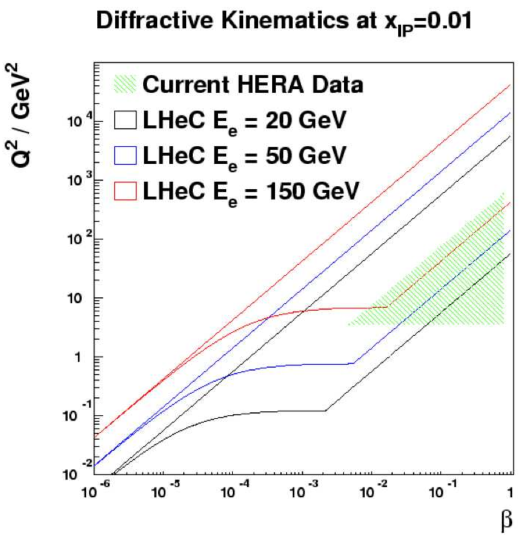


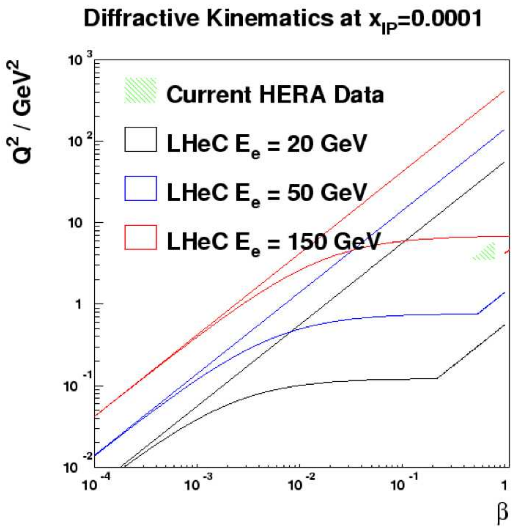


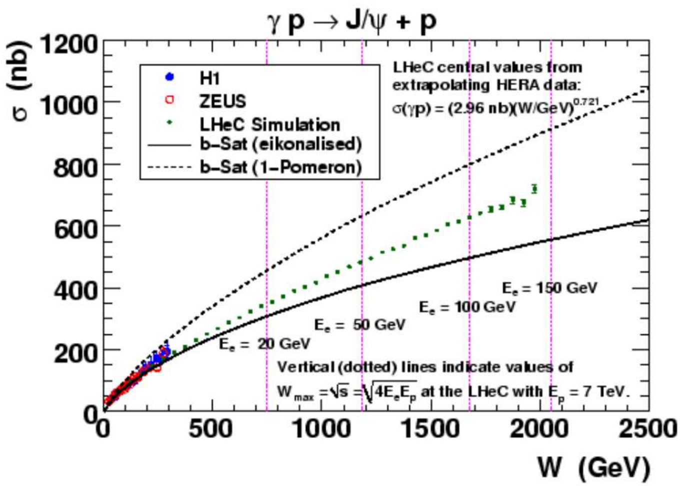
HIGH-DENSITY QCD: DIFFRACTION



- DIFFRACTION PROBES FACTORIZATION & PERTURBATIVE-NONPERTURBATIVE INTERFACE
- ENHANCED GLUON SENSITIVITY
- ACCESS TO TRANSVERSE DEGREES OF FREEEDOM







CONCLUSION

SUMMARY

- The main impact of the LHeC is PDF+α_s uncertainties at 1% or below

- The LHeC is a top-Higgs factory with the potential of very clean measurements in specific channels

- The LHeC is the mecca of high-density QCD