Prospects for α_s determination with LHeC

D. Britzger
Max-Planck-Institut für Physik München, Germany
for the LHeC Study Group

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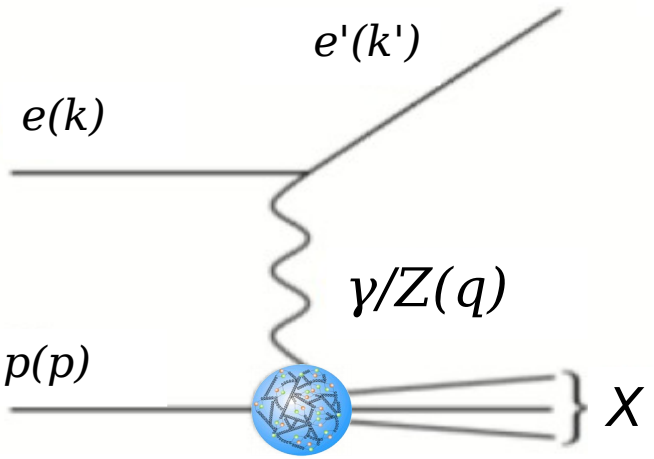
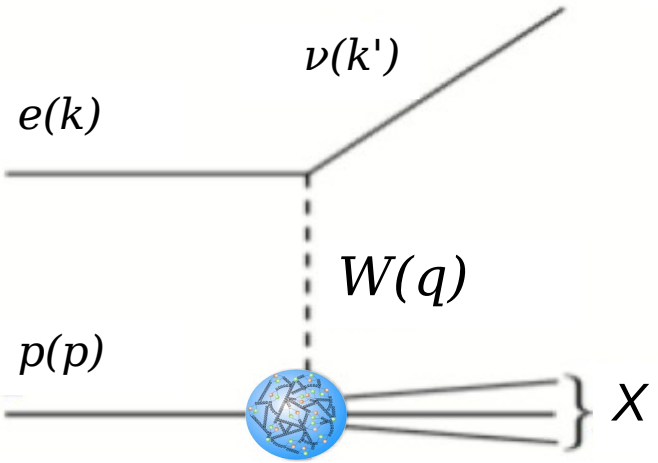
Deep-inelastic electron-proton scattering

Neutral current scattering
$ep \rightarrow e'X$



Charged current scattering
$ep \rightarrow \nu_e X$



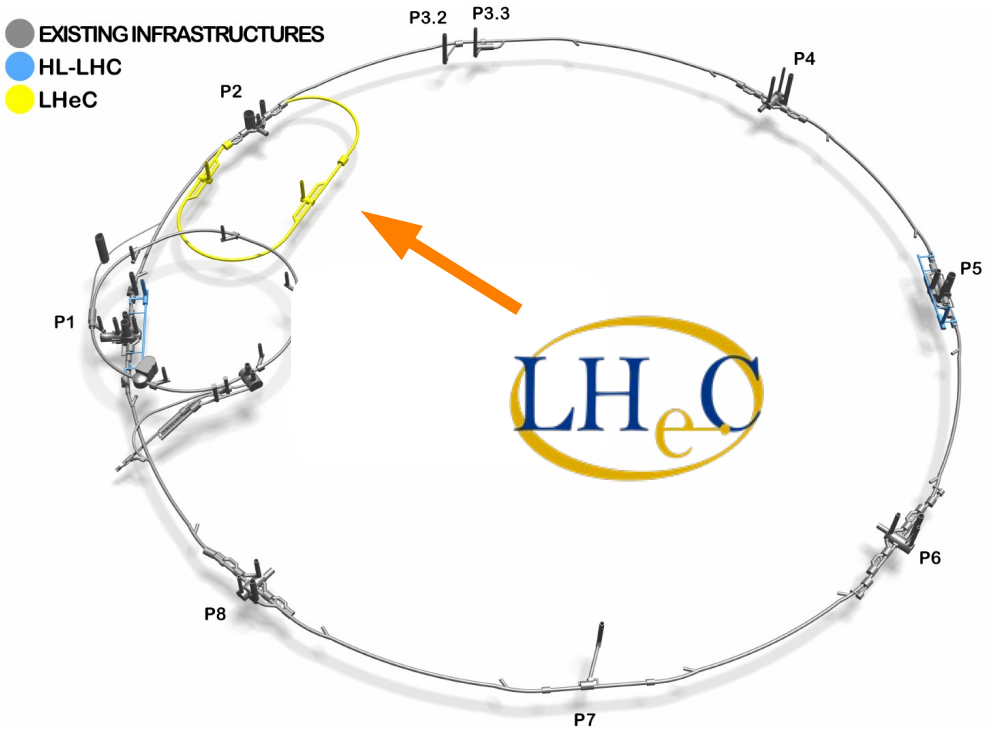
R-D. Heuer

"The point-like electron "probes" the interior of the proton via the electroweak force, while acting as a neutral observer with regard to the strong force."

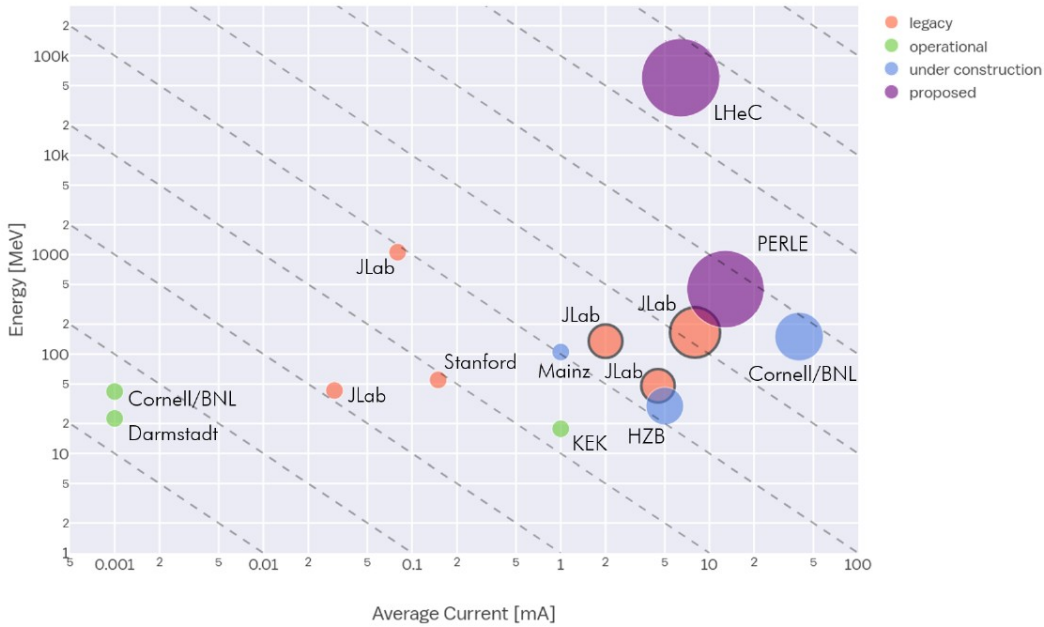
- Study the structure of the proton -> bound together by QCD dynamics

-> Ideal QCD laboratory

Future electron-proton collider at CERN: LHeC



ERL "landscape"



Electron ring attached to HL-LHC

- Energy recovery linac (ERL): E_e = 60 GeV (or 50 GeV)
- ESPPU: ERL is a "high-priority future initiative" for CERN

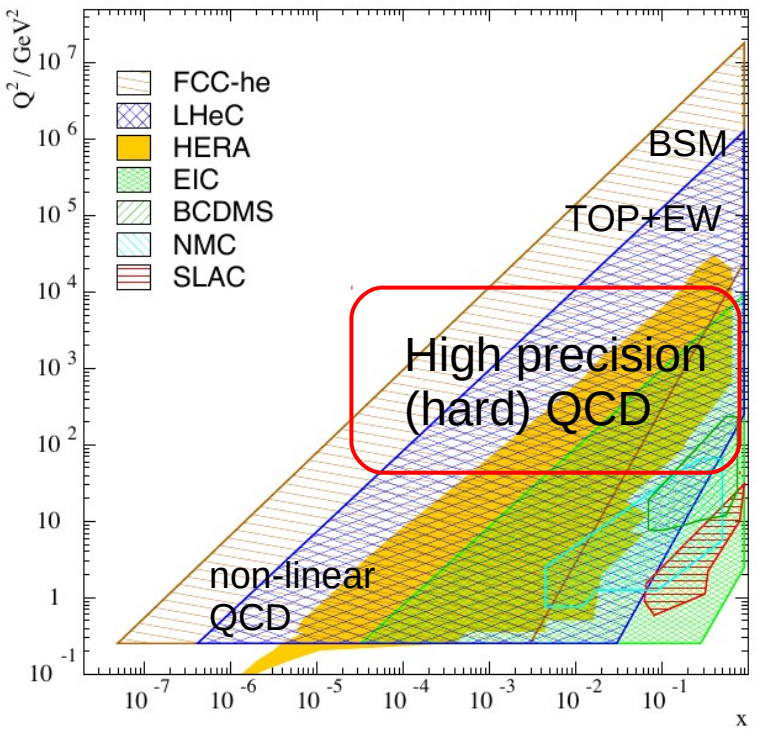
LHeC

- √s ~ 1.3 TeV
- Polarisation up to P_e ~ 80%
- Up to 1 ab^{-1} integrated luminosity

LHeC kinematic reach

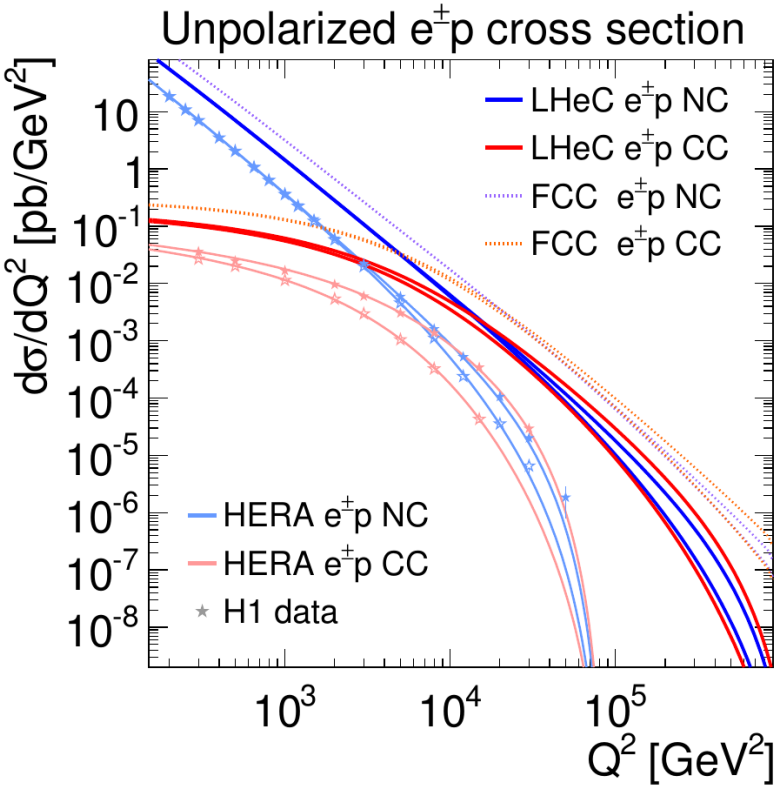
x-Q² plane

- Rich physics program at all scales
- Precision QCD: huge kinematic range



Unpolarised ep cross section

- NC & CC DIS cross section vs. Q^2



Huge luminosity of up to 3ab^{-1} further increases physics potential

α_s at LHeC

Inclusive NC/CC DIS

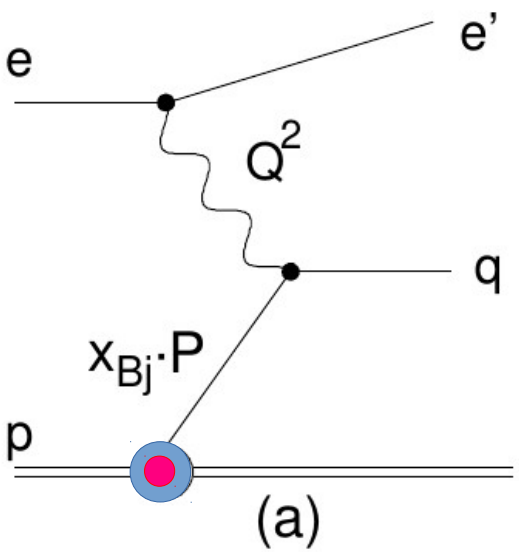
- *ep → e+X*
- Measured as function of $d^2\sigma/dxdQ^2$
- Commonly used for PDF determination
  → PDF+α_s

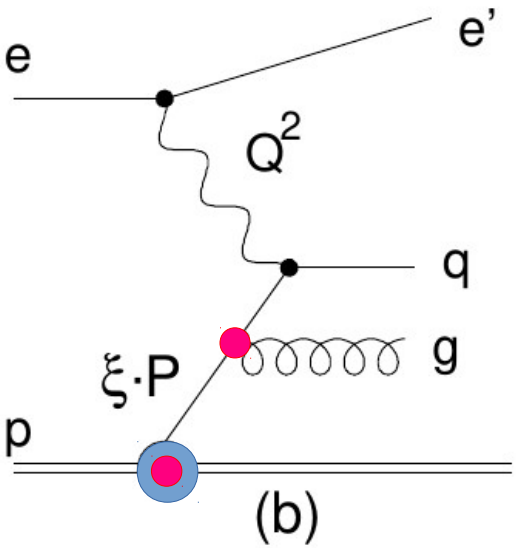
Jet production

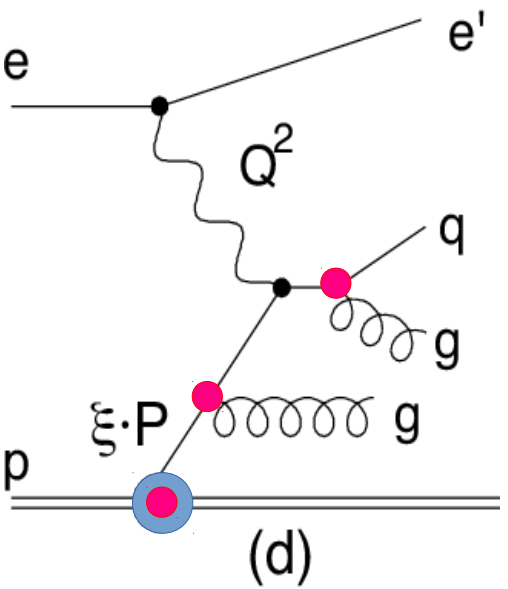
- *γp → jj*
  in Breit frame
- α_s at LO pQCD
- Inclusive jet & dijet observables

Further processes

- 3-jet, 4-jet production, etc…
- Event shapes, …
- jet radius dependence,...
- (jet) substructure observables, etc…
- low-x, low-Q^2, ...







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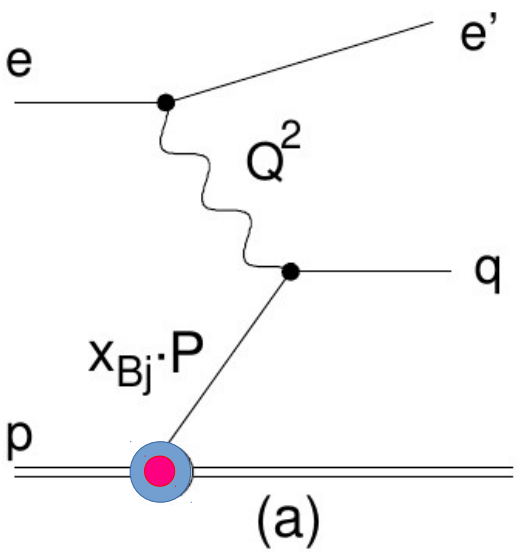

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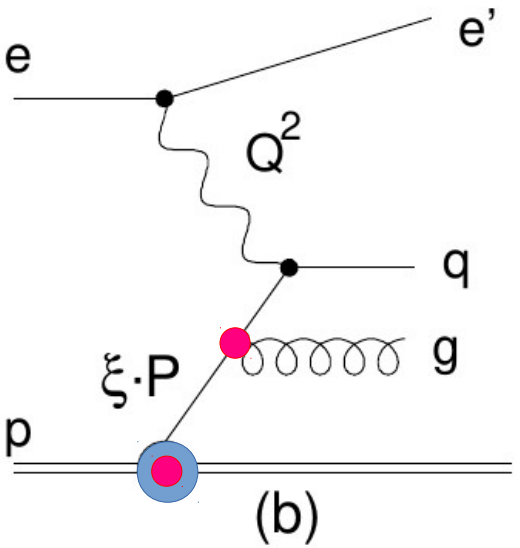

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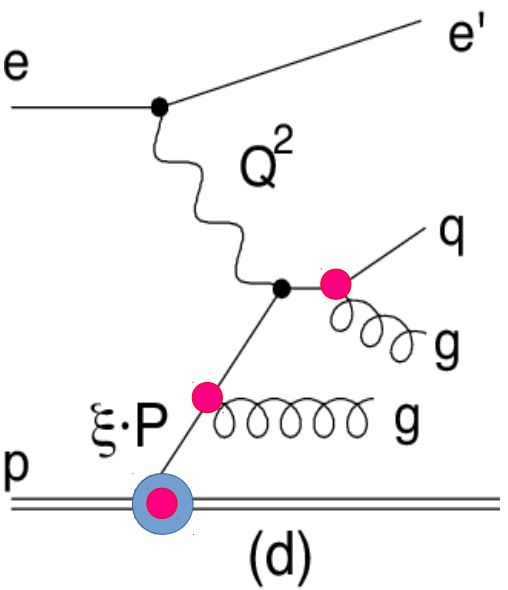
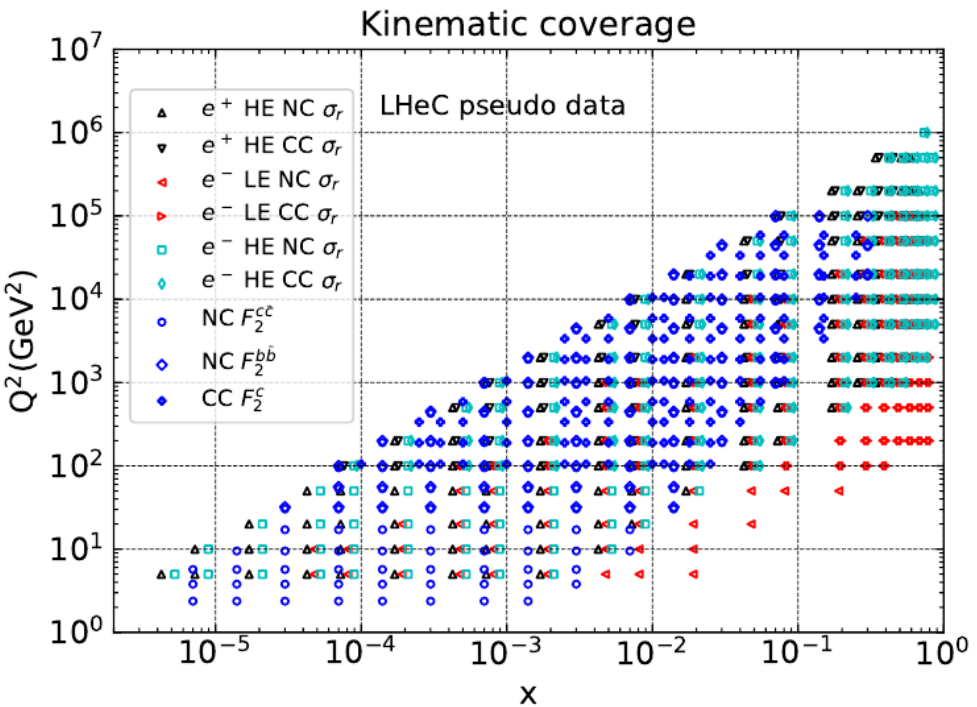


Methodology

Simulated inclusive NC/CC DIS data

- data points on x – Q^2 grid



Full uncertainty model

- statistical uncertainties
- systematic uncertainties
  - reasonable systematic uncertainties assumptions benchmarked with H1, CMS, ATLAS

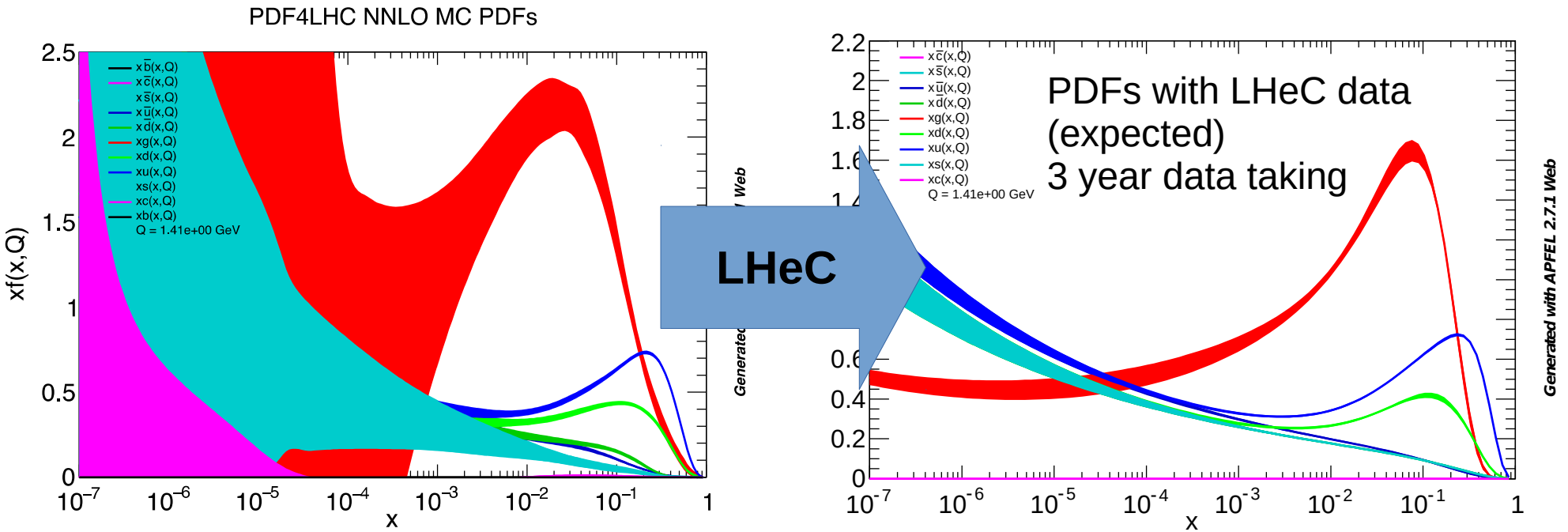
Source of uncertainty	Uncertainty
Scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %
Scattered electron polar angle	0.1 mrad
Hadronic energy scale $\Delta E_h/E_h$	0.5 %
Radiative corrections	0.3 %
Photoproduction background (for $y > 0.5$)	1 %
Global efficiency error	0.5 %

- Methodology: Full "PDF fit" is performed, similar to HERAPDF/xfitter
- PDF results also evaluated by NNPDF [SciPost Phys. 7 (2019) 051]

PDFs from inclusive NC/CC DIS

Inclusive NC/CC DIS

→ main input to nowadays and future PDF determinations



LHeC

- Important improvements to all aspects of PDFs: low-*x*, high-*x*, valence, sea, ***gluon***, ...

α_s from inclusive NC/CC DIS

α_s from inclusive NC/CC DIS data

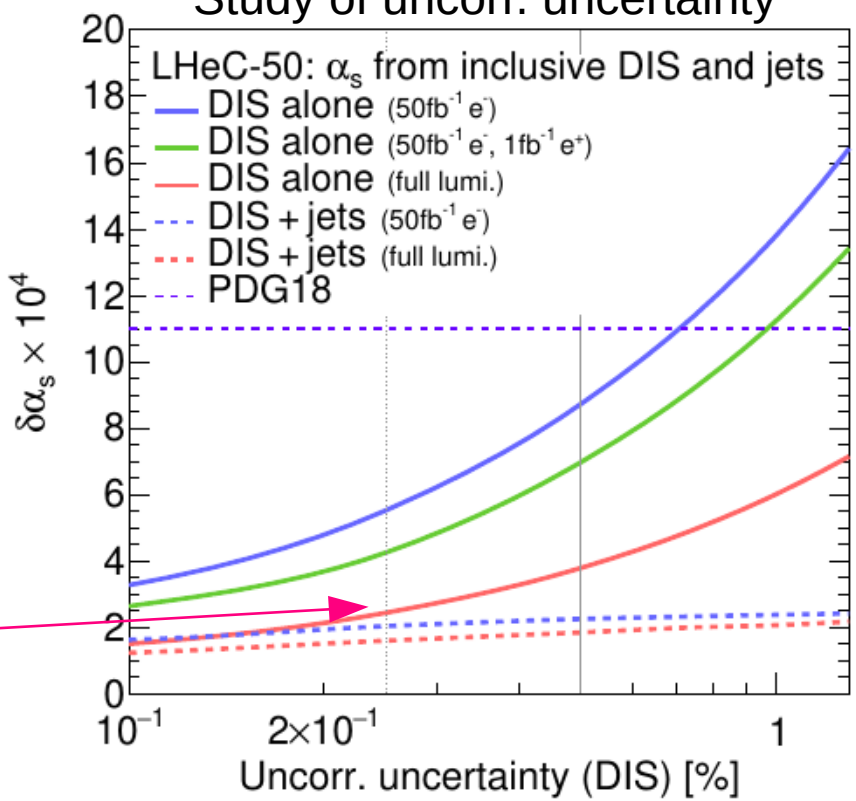
- Simultaneous determination of PDFs and α_s
- NNLO QCD

Three LHeC scenarios

- first 3 years of data taking ($50fb^{-1}$)
- … plus positron data ($1fb^{-1}$)
- full LHeC data set ($1ab^{-1}$) :

$$\Delta\alpha_s(M_Z)(\text{incl. DIS}) = \pm 0.00022_{(\text{exp+PDF})}$$

Study of uncorr. uncertainty



→ Better than **2 per-mille** experimental uncertainty

→ Already per-mille uncertainty after 1 year data taking

→ with additional data, e.g. HERA, further improvements are expected down to **~1 per-mille**

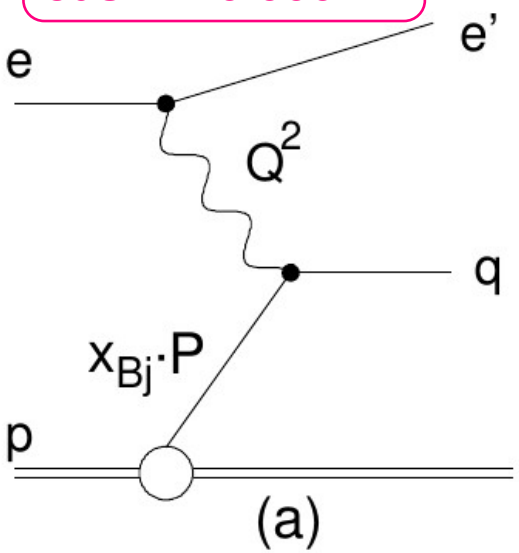
LHeC-CDR-2012

α_s at LHeC

Inclusive NC/CC DIS

- *ep → e+X*
- Measured as function of $d^2\sigma/dxdQ^2$
- Commonly used for PDF determination
  → PDF+α_s

$\delta\alpha s = \pm 0.00022$



Jet production

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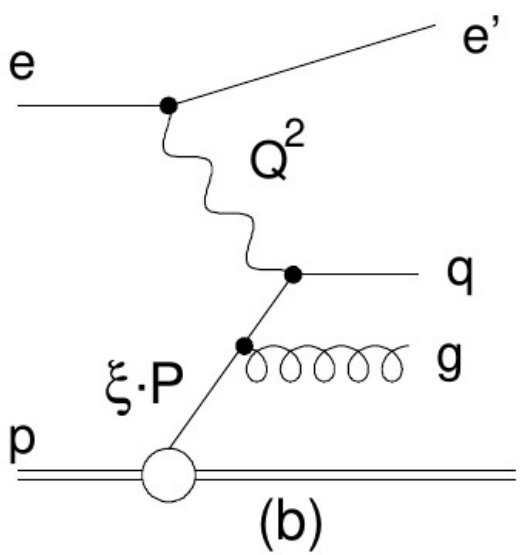
- α_s at LO pQCD
- Inclusive jet & dijet observables



Further processes

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- Event shapes, …
- jet radius dependence,...
- (jet) substructure observables, etc…
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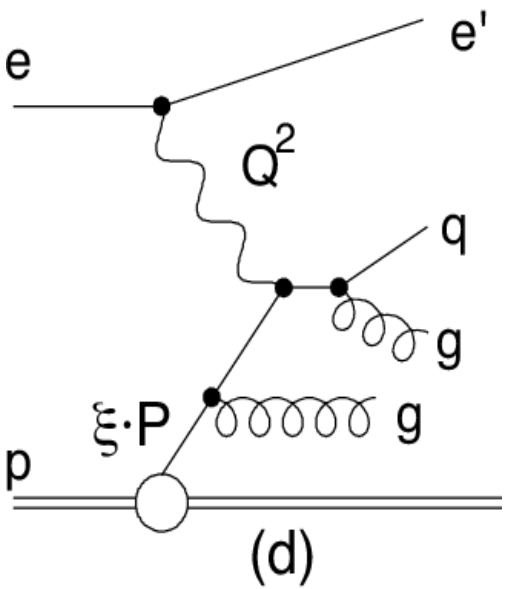
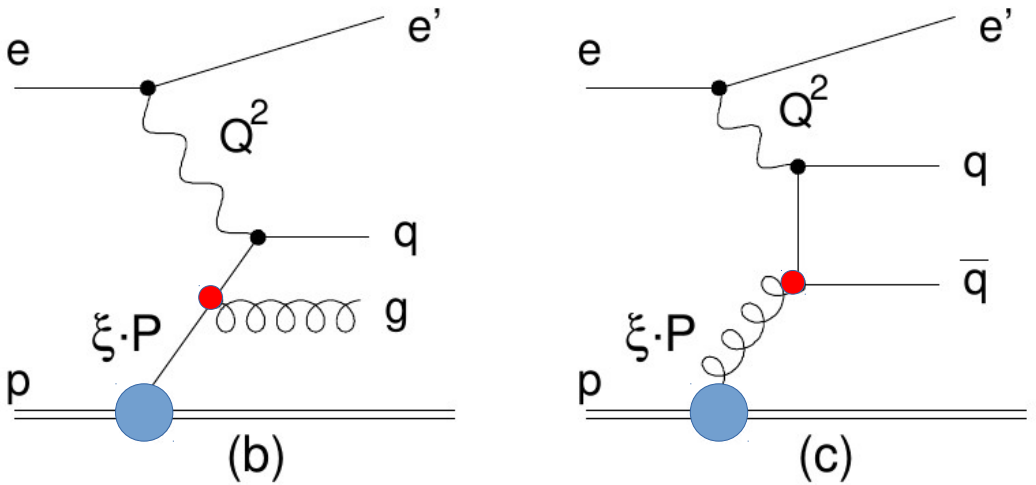


Jet production in (NC) DIS – Breit frame



Jet cross sections in NC DIS

- Measured in Breit frame: 2 → 2 process: γp → jj

$$\sigma = f_{\mu_0} \otimes P_{\mu_0 \to \mu_F}(\alpha_s(M_z)) \otimes \hat{\sigma}(\alpha_s(M_z), \mu)$$

- Proportional to α_s at leading-order
- NNLO predictions available (NNLOJET) for inclusive jet and dijet cross sections

Inclusive jets at LHeC

Simulated inclusive jet cross sections

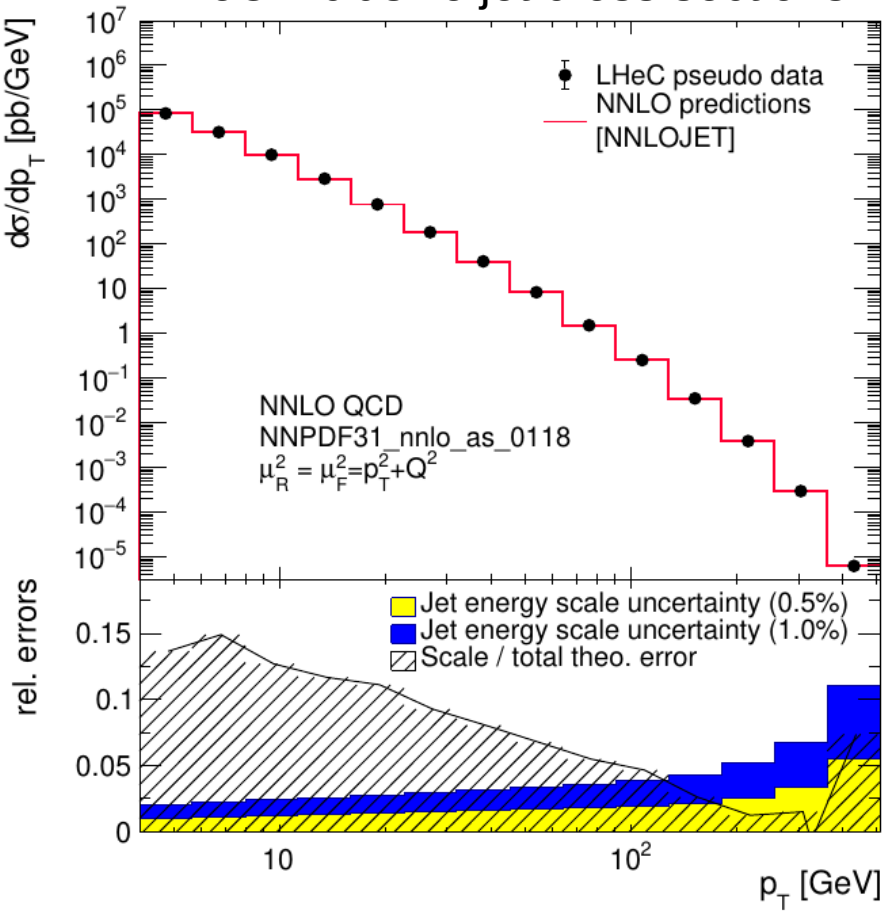
- NNLOJET (Gehrmann et al.) + fastNLO
- $x_{min} \sim 0.5 * 10^{-5}$
- $8 < Q^2 < 500000\ GeV^2$
- $p^T_{jet} > 4\ GeV$, $-5 < \eta_{lab} < 5$

Full set of (systematic) uncertainties

Exp. uncertainty	Shift	Size on σ [%]
Statistics with $1\,ab^{-1}$	min. 0.15 %	0.15 –5
Electron energy	0.1 %	0.02 –0.62
Polar angle	2 mrad	0.02 –0.48
Calorimeter noise	±20 MeV	0.01 –0.74
Jet energy scale (JES)	0.5 %	0.2 –4.4
Uncorrelated uncert.	0.6 %	0.6
Normalisation uncert.	1.0 %	1.0

→ uncertainties benchmarked with H1, ZEUS, ATLAS, CMS

LHeC inclusive jet cross sections



σ spans almost 10 orders of magnitude

α_s from inclusive jet cross sections

Perform a fit of pQCD to simulated inclusive jet cross sections

- NNLO predictions [Gehrman et al.]
- 'double-differential' inclusive jet cross sections $d\sigma/dp_T dQ^2$

  509 cross section (data) values
- Fit accounts for αs-dependent terms in matrix elements, and PDFs.

$$\sigma = f_{\mu_0} \otimes P_{\mu_0 \to \mu_F}(\alpha_s(M_z)) \otimes \hat{\sigma}(\alpha_s(M_z), \mu)$$

α_s from LHeC inclusive jets

$$\Delta\alpha_s(M_Z)(\text{jets}) = \pm 0.00013_{(\text{exp})} \pm 0.00010_{(\text{PDF})}$$

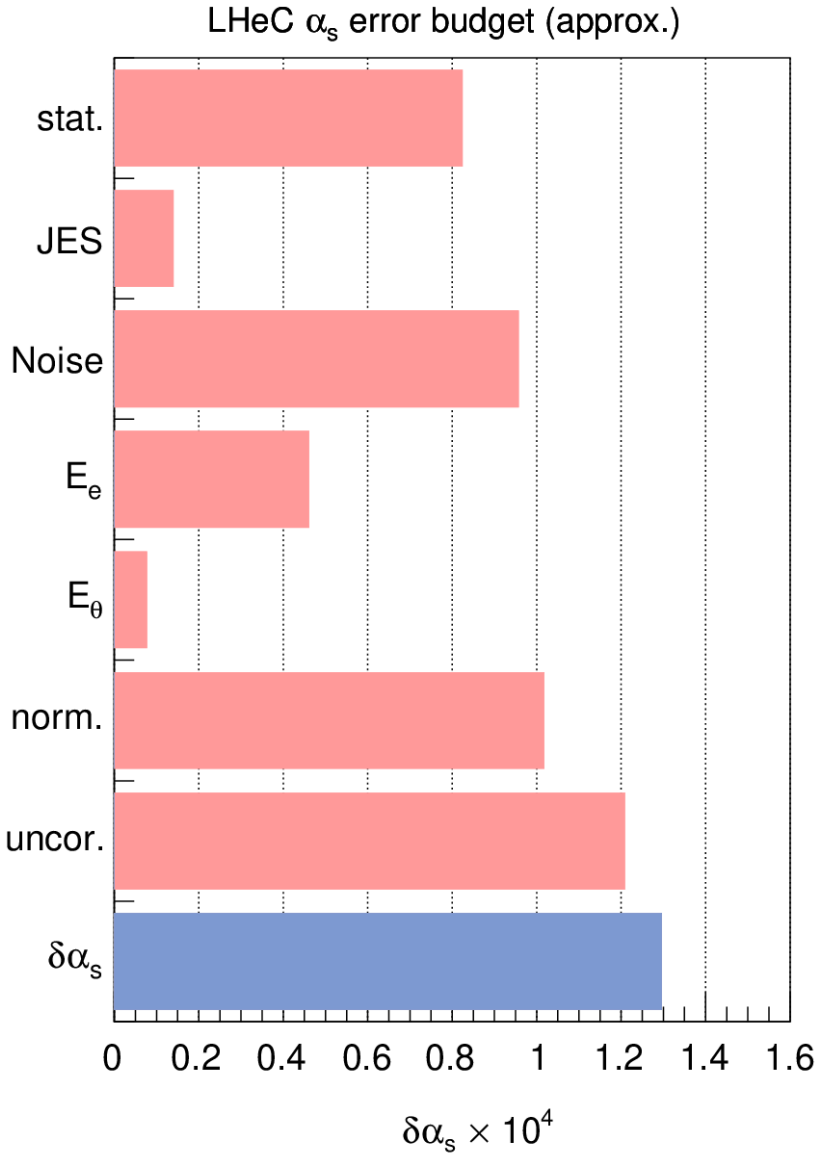
- Experimental uncertainty about 1.1 permille
- 'extra' PDF uncertainty estimated from LHeC PDF set (about below 1 permille)

Error budget

Estimate size of individual uncertainty

Reasonable results

- statistics not negligible ($\Delta\sigma$(stat) >= 0.15%)
- Uncorrelated uncertainty dominant
- Calo-Noise more important than JES
  - → shape more similar to α_s dependence
  - → more important at lower p_T
- Electron uncertainties negligible
- Normalisation uncertainty important
  - → albeit it is finally constraint by fit
- PDF uncert (NNPDF31) ~ 0.0002 [not shown]



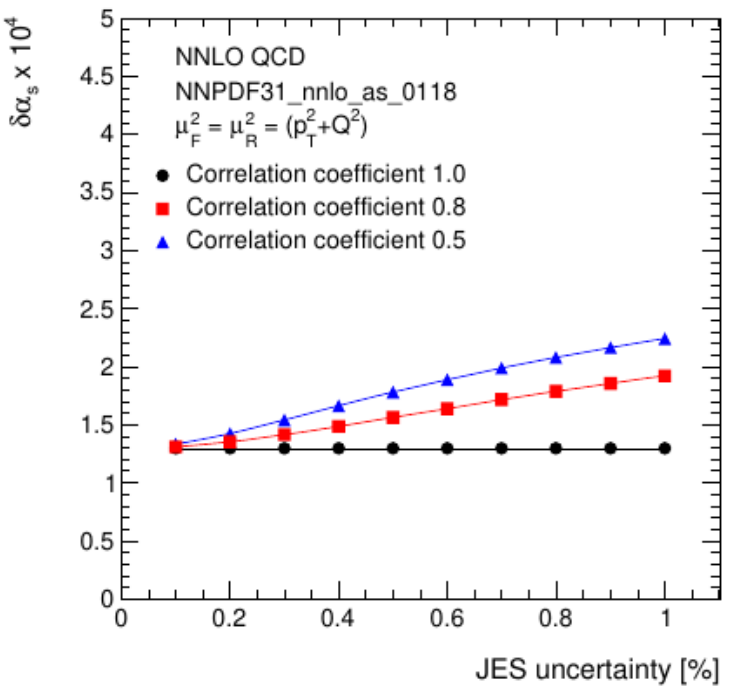
Experimental uncertainties

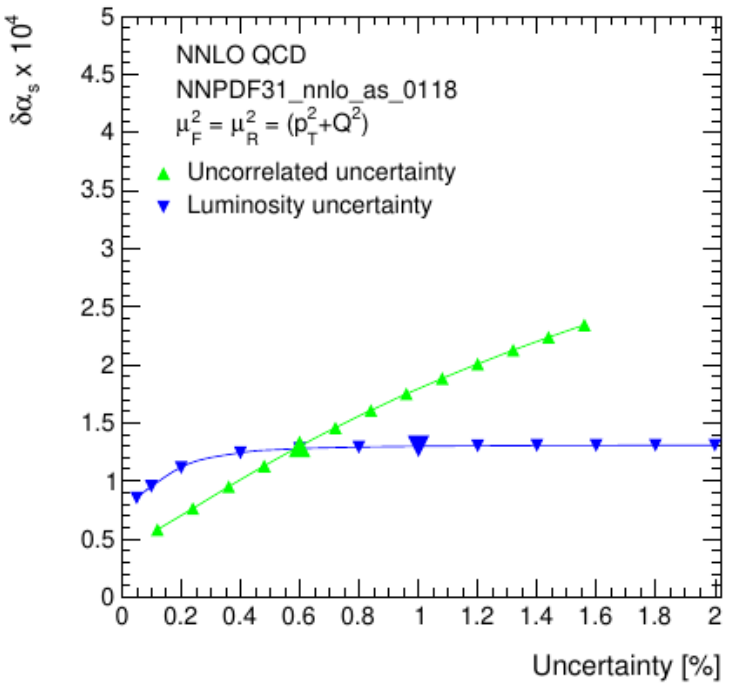
Jet energy scale uncertainty

- 0.5% JES can likely be achieved
- Correlation coefficient of JES unknown
  → pessimistic assumptions yield only moderate increase of α_s-uncertianty

Normalisation and uncorr. uncertainty

- $\delta\alpha_s$ insensitive to size of norm. uncertainty
- Strong dependence on uncorrelated uncert.
  → Challenging to control for real data





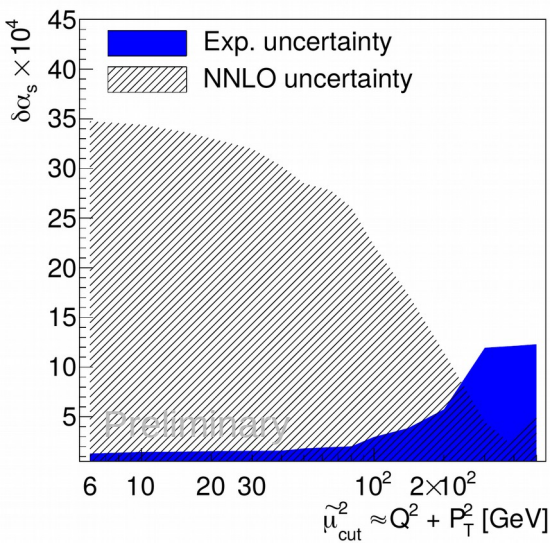
pQCD theory uncertainty

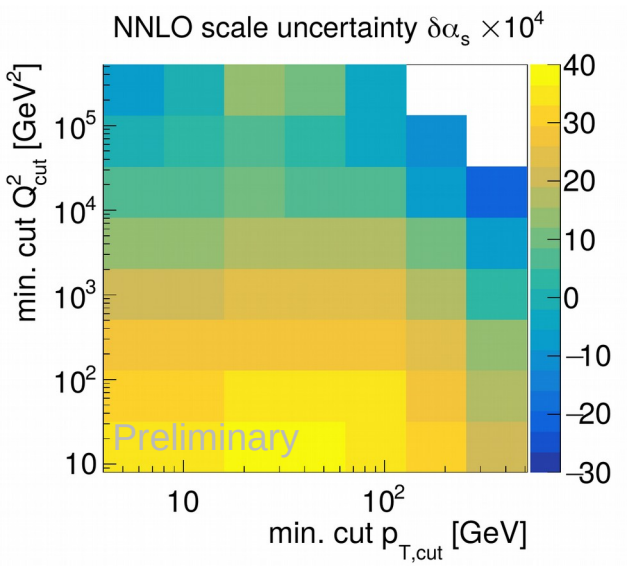
Due to asymptotic freedom in pQCD

- scale uncertainty and experimental uncertainties are <u>always</u> a trade-off

Scale uncertainty from NNLO predictions

- about: $\delta\alpha_s$(scale) ~ ±0.0035
- Restrict data to higher p_T or Q^2: NNLO-scale uncertainty reduces to $\delta\alpha_s$ ~ ±0.001





Improved theoretical predictions will be needed. N3LO in 2030s?

Running from inclusive jets

α_s determination at different μ_r intervals

→ study α_s 'running'

Use as scale: $\mu_R^2 = Q^2 + p_T^2$

High experimental sensitivity and

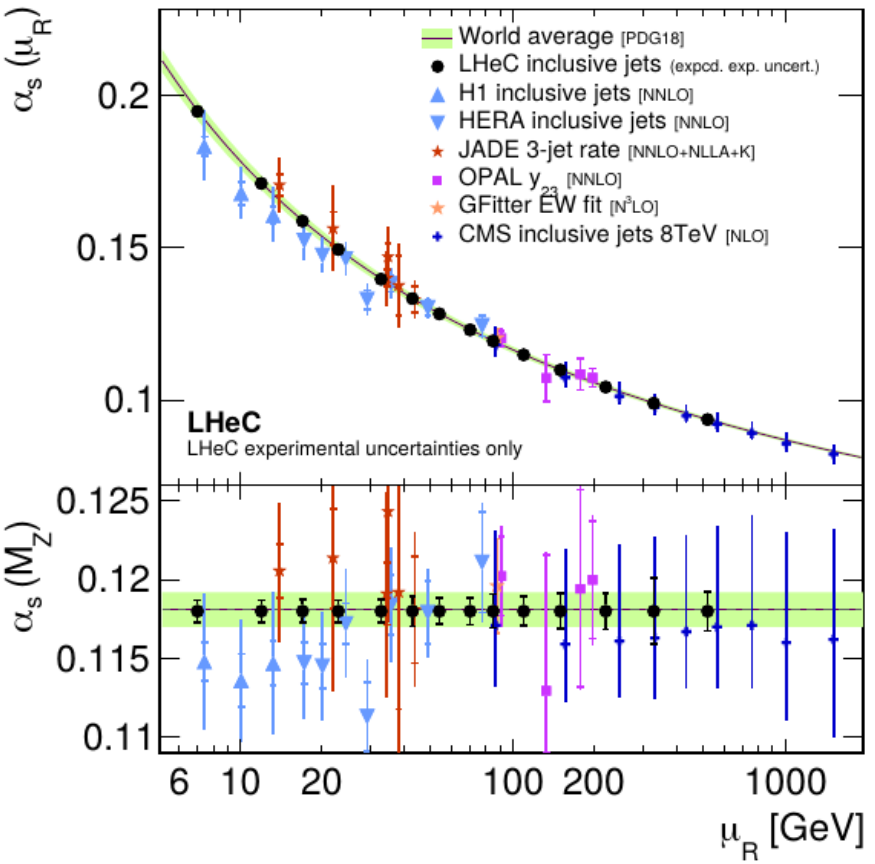
Large kinematic region

- $6 < \mu_R < 600$ GeV

Experimental uncertainty typically

- for all μ_R-intervals

  $\delta\alpha_s \sim 0.0007 – 0.0011$



Great improvement over other (jet-based) measurements

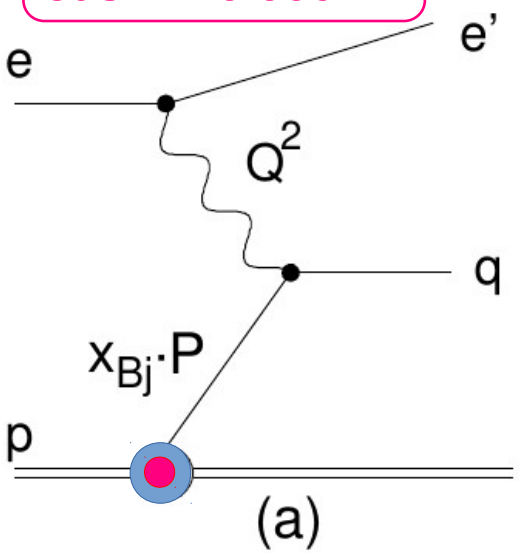
LHeC uniquely 'connects' low scales (O(GeV)) with high scales (O(m_Z))

α_s at LHeC

Inclusive NC/CC DIS

- *ep → e+X*
- Measured as function of $d^2\sigma/dxdQ^2$
- Commonly used for PDF determination
  → PDF+α_s

δαs = ± 0.00022



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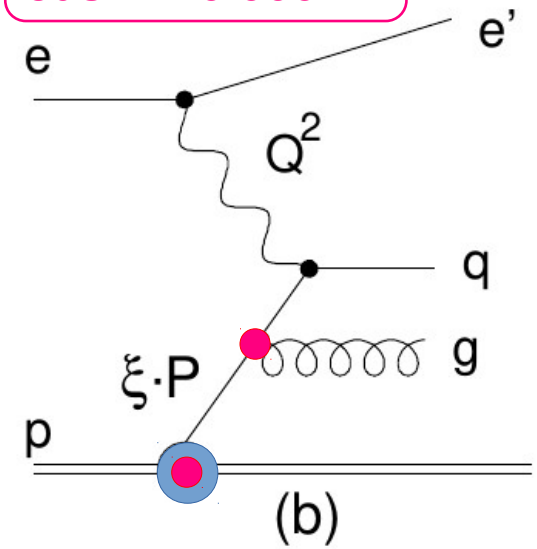
δαs = ± 0.00017



Further processes

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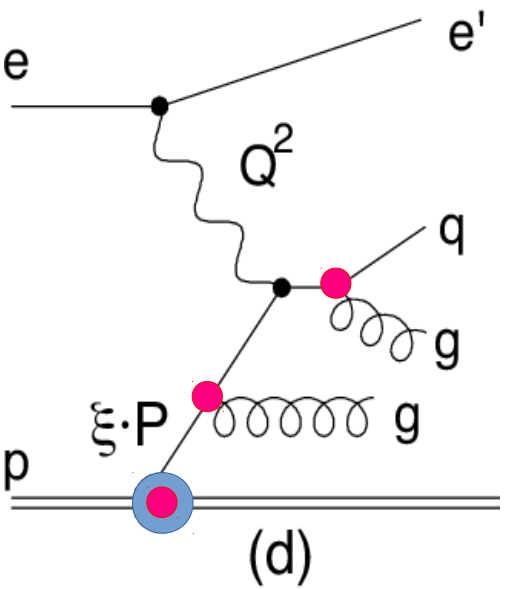
- Event shapes, …
- jet radius dependence, (jet) substructure observables ...
- low-x, low-Q^2, …
- photoproduction, ...



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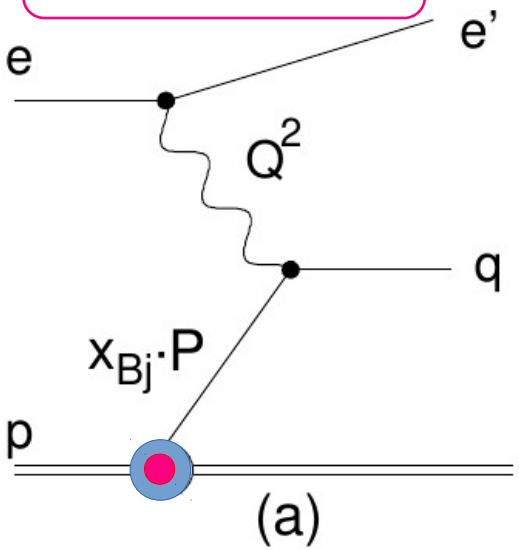

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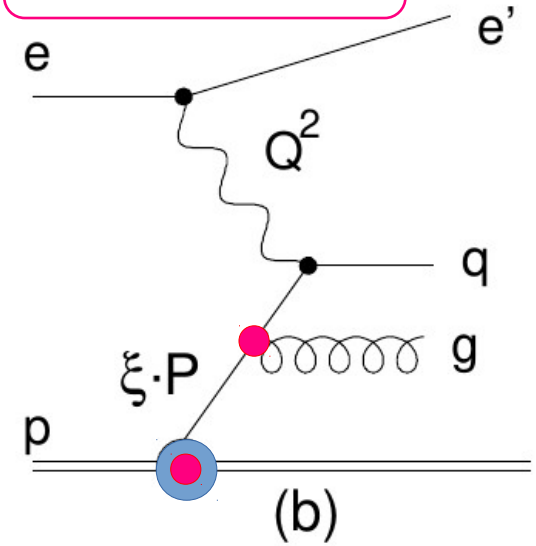
δαs = ± 0.00017



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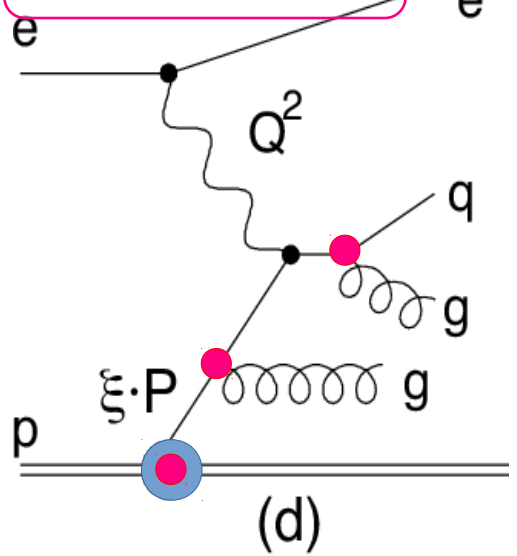
δαs = ± 0.000??



Summary of α_s at LHeC

LHeC is an ideal QCD laboratory

- LHeC connects low-scale to Z-pole and beyond with high experimental precision

Inclusive NC/DIS

→ 'indirect' determination from QCD dynamics

$$\Delta\alpha_s(M_Z)(\text{incl. DIS}) = \pm 0.00022_{(\text{exp+PDF})}$$

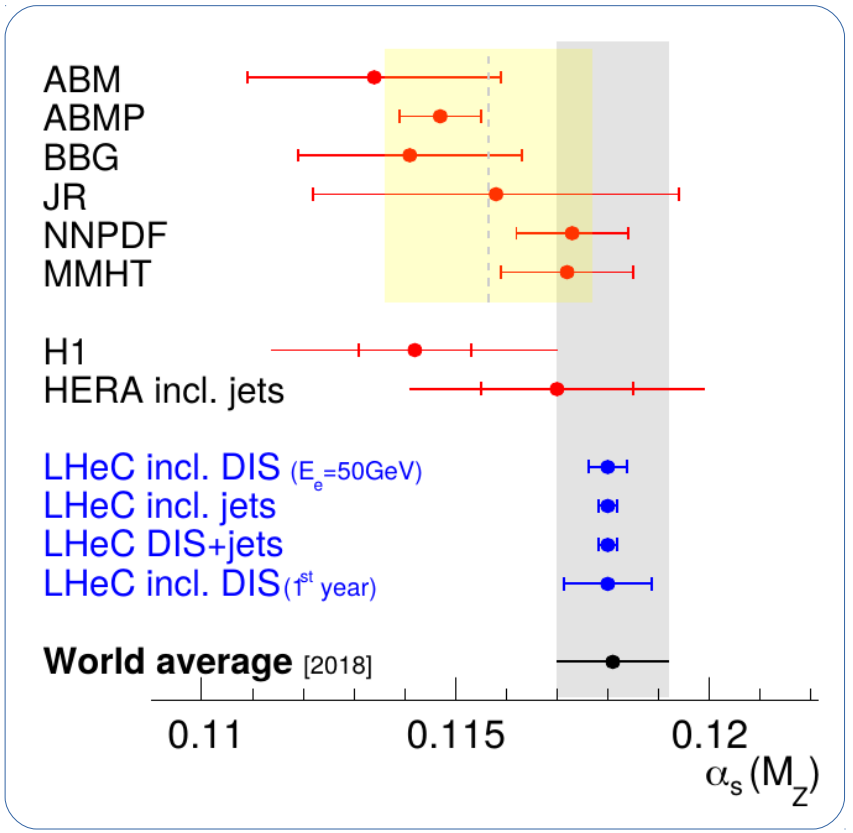
Inclusive jet cross sections

→ α_s from direct measurement of a QCD-jet

$$\Delta\alpha_s(M_Z)(\text{jets}) = \pm 0.00013_{(\text{exp})} \pm 0.00010_{(\text{PDF})}$$

Taking jet data <u>and</u> inclusive DIS data

$$\Delta\alpha_s(M_Z)(\text{incl. DIS \& jets}) = \pm 0.00018_{(\text{exp+PDF})}$$



→ ***pQCD theory may be the limiting factor for ultimate precision for α_s***