Gluons and sea quarks in the proton at low scales

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY

Introduction

- outstanding question in QCD:
  relation between "current quarks" and "constituent quarks"
- starting from resolution scales $\mu \sim$ few GeV, how do parton distributions look like when resolution becomes more coarse?
- some scenarios for proton at low scale
  1. proton $= uud$, gluons and sea quarks from perturbative evolution
     Parisi, Petronzio '76; Novikov et al '77; Glück, Reya '77
  2. proton $=$ quarks and antiquarks, gluons from evolution
     have $\bar{q}$ e.g. from meson cloud Thomas '83
     or in quark-soliton model Diakokov et al '86
  3. proton $= UUD$ with "composite valence quarks" U, D containing antiquarks and gluons Altarelli et al '74

  gluons and sea quarks: focus of studies at EIC
- scenario 1. already disfavoured in early PDF fits by GRV
  required both g and $\bar{q}$ at starting scale of evolution
  Glück, Reya, Vogt '90, '92, '95... Jimenez-Delgado, Reya '14

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- nevertheless is still widely used to connect constituent quark models with PDFs and more complicated distributions: TMDs, GPDs, DPDs, . . .
- can conclusions of GRV/JR fits be confirmed/evaded?
  - evolve PDFs fitted by other groups backward to low scales?
    problem: backward evolution becomes unstable
  - here: evolve selected moments of PDFs backward
    and see if they become ≈ 0 at some point
- similar study was done for helicity and orbital angular momentum
  values from lattice QCD at $\mu = 2\,\mathrm{GeV}$
  comparison with constituent quark picture at low scales
  Altenbuchinger, Hägler, Weise, Henley '11

Caveats and limitations

- down to which μ is perturbative evolution of $\alpha_s(\mu)$ and PDFs reliable?
  - substantial work on nonperturbative behaviour of $\alpha_s(\mu)$ at low μ in models and lattice QCD
  - but not for PDF moments or PDFs
- PDFs defined by QCD operators renormalised in some scheme
  - no guarantee that interpretation as parton densities valid everywhere especially in $\overline{\text{MS}}$ scheme
  - studies in other "more physical" schemes could be interesting but am not aware of suitable schemes
- if $g(x)$ or $\bar{q}(x)$ zero at some scale, then will be negative at lower scales
  $\rightsquigarrow$ breakdown of parton interpretation

Moments of PDFs

- consider $n_F = 3$ active quark flavours, only quark flavour sums
- Mellin moments

$$Q(j,\mu) = \sum_{q=u,d,s} \int_0^1 dx\, x^{j-1}\, q(x,\mu) \qquad \overline{Q}(j,\mu) = \sum_{q=u,d,s} \int_0^1 dx\, x^{j-1}\, \bar{q}(x,\mu)$$

$$G(j,\mu) = \int_0^1 dx\, x^{j-1}\, g(x,\mu)$$

relation with local operators only for $Q(j) + \overline{Q}(j)$ and $G(j)$ when j even and for $Q(j) - \overline{Q}(j)$ when j odd

- scale evolution

$$\frac{d}{d\log\mu^2}\left[Q(j,\mu) - \overline{Q}(j,\mu)\right] = \gamma_{\text{ns}}\big(j,\alpha_s(\mu)\big)\left[Q(j,\mu) - \overline{Q}(j,\mu)\right]$$

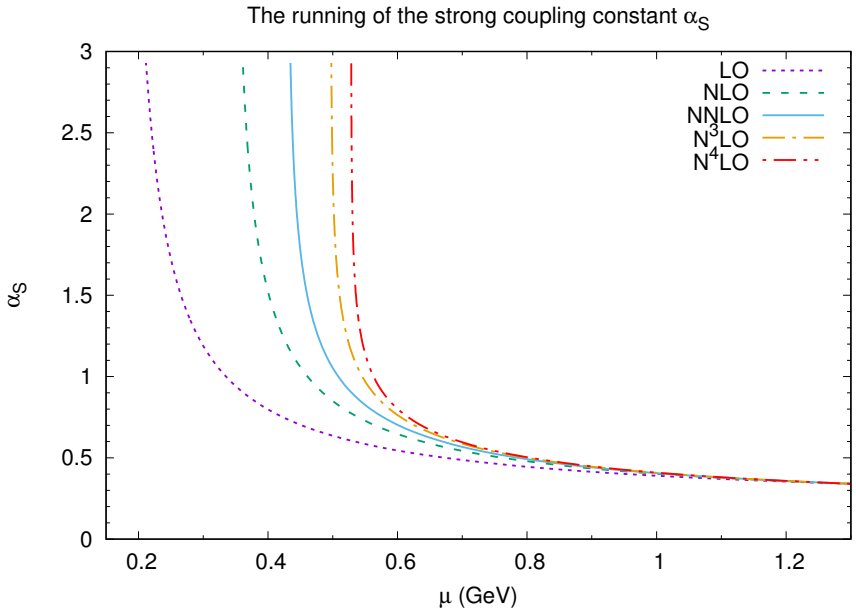
with $\gamma_{\text{ns}}(j,\alpha_s)$ = Mellin moment of DGLAP splitting function
analogous matrix equation for $Q(j) + \overline{Q}(j)$ and $G(j)$
solve numerically using Runge-Kutta method

PDF sets

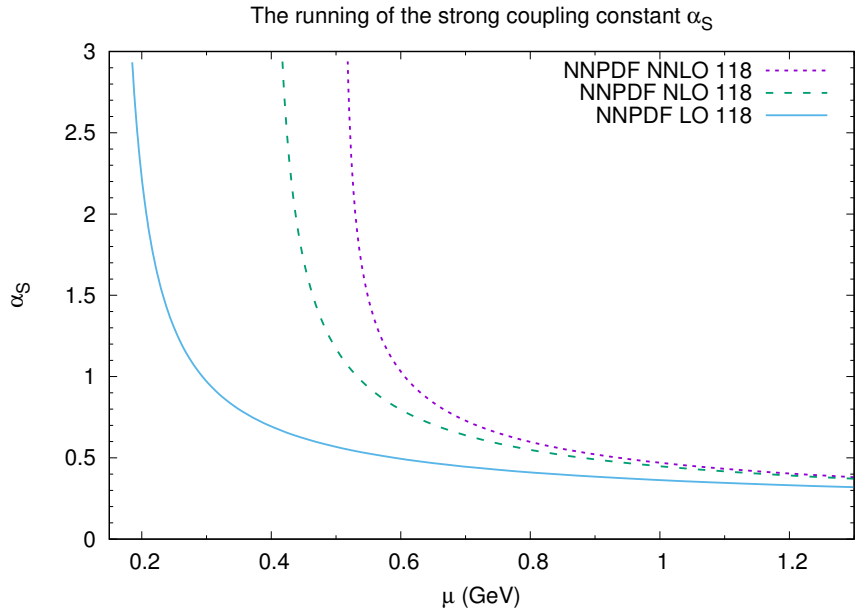
- use $\overline{\text{MS}}$ scheme for PDFs and $\gamma(j, \alpha_s)$ at LO, NLO, NNLO
  NNLO splitting fcts: Moch, Vermaseren, Vogt 2004
- take PDFs at scale $\mu_0 = 1.3\,\text{GeV}$ from LHAPDF interface
  scale chosen such that variable flavour number PDFs evaluated for $n_F = 3$
- choice of recent PDF sets to reflect different fitting methods,
  theory approaches, data selection etc.

set	LO	NLO	NNLO	remarks
ABMP 16			×	
CJ 15	×	×		special focus on large x region
CT 14		×	×	
HERAPDF 2.0	×	×	×	
JR 14		×	×	PDFs parameterised at $Q_0^2 = 0.8\,\text{GeV}^2$
MMHT 2014	×	×	×	
NNPDF 3.1	×	×	×	NNLO sets with $\alpha_s(M_Z) = 0.116, 0.118, 0.120$

Running coupling



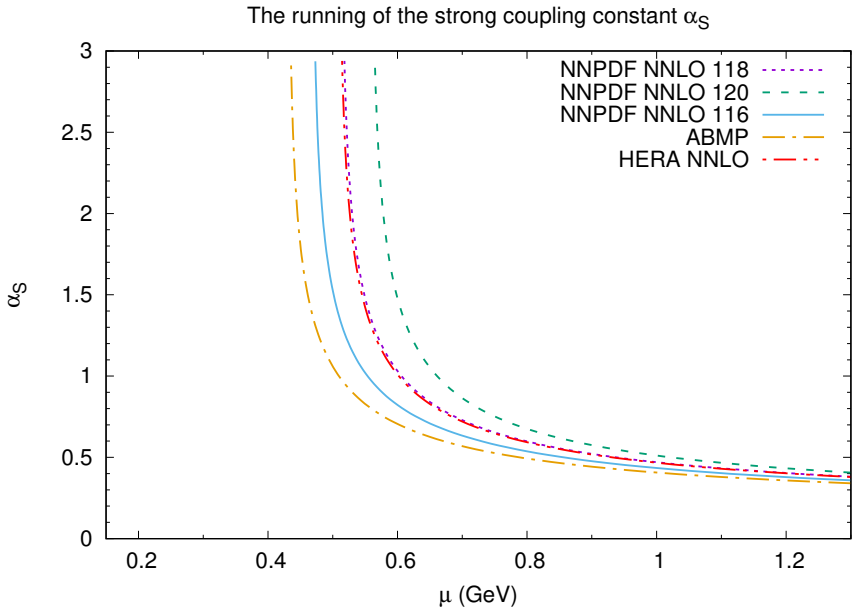
taking equal $\alpha_s(\mu_0)$



taking equal $\alpha_s(M_Z)$

- $\overline{\text{MS}}$ coupling perturbatively stable down to $\mu \sim 0.7$ to $0.8\,\text{GeV}$

Running coupling

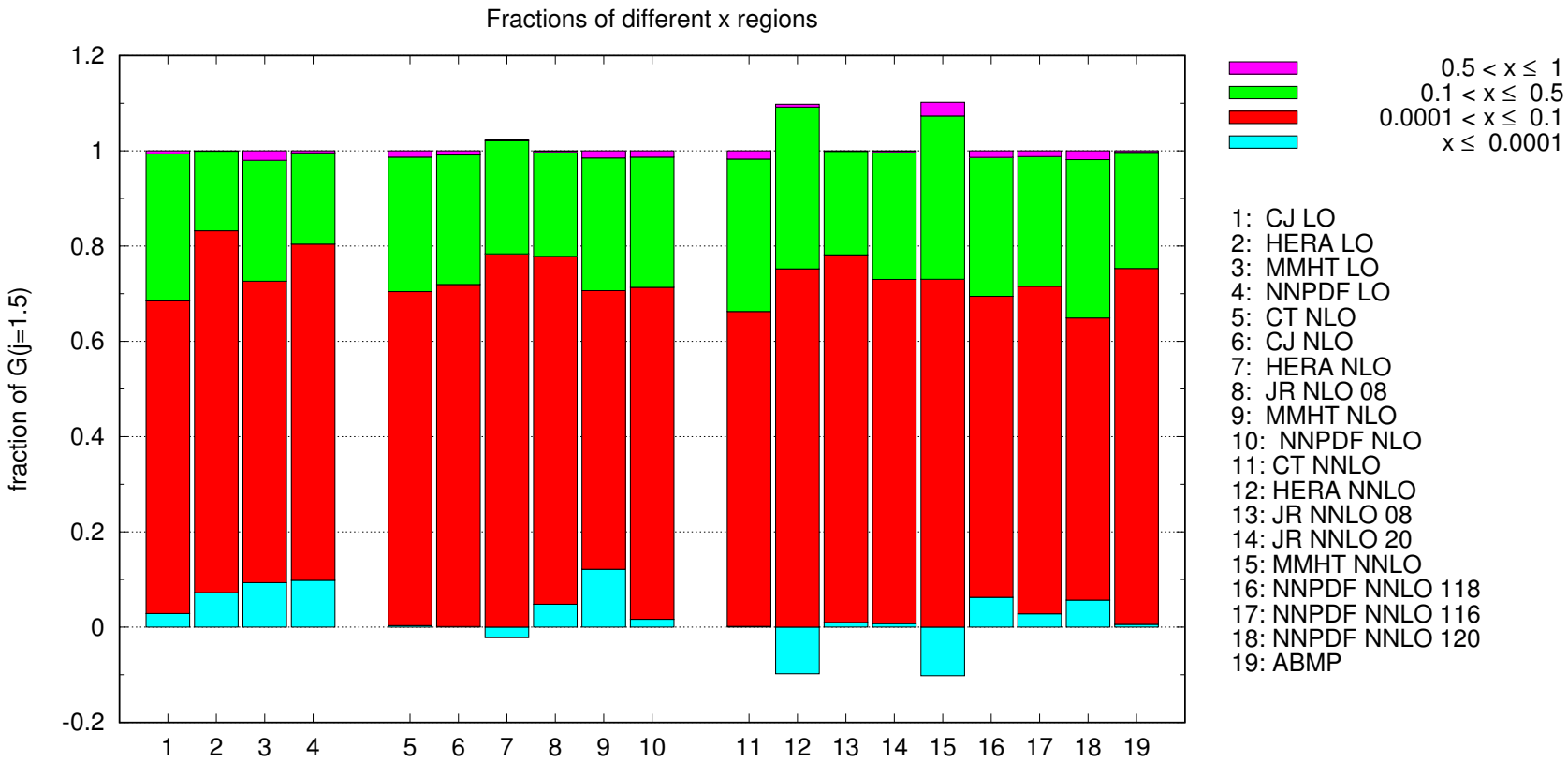


- considerable spread in α_s values between different PDF sets
- plot moments against α_s instead of μ if behaviour at small μ is important

Moments and x ranges

- study moments for $j = 1.5, 2, 2.5, 3$ to be sensitive to broad x range
- at starting scale μ_0 determine relative fraction of different x

gluon $j = 1.5$



Moments and x ranges

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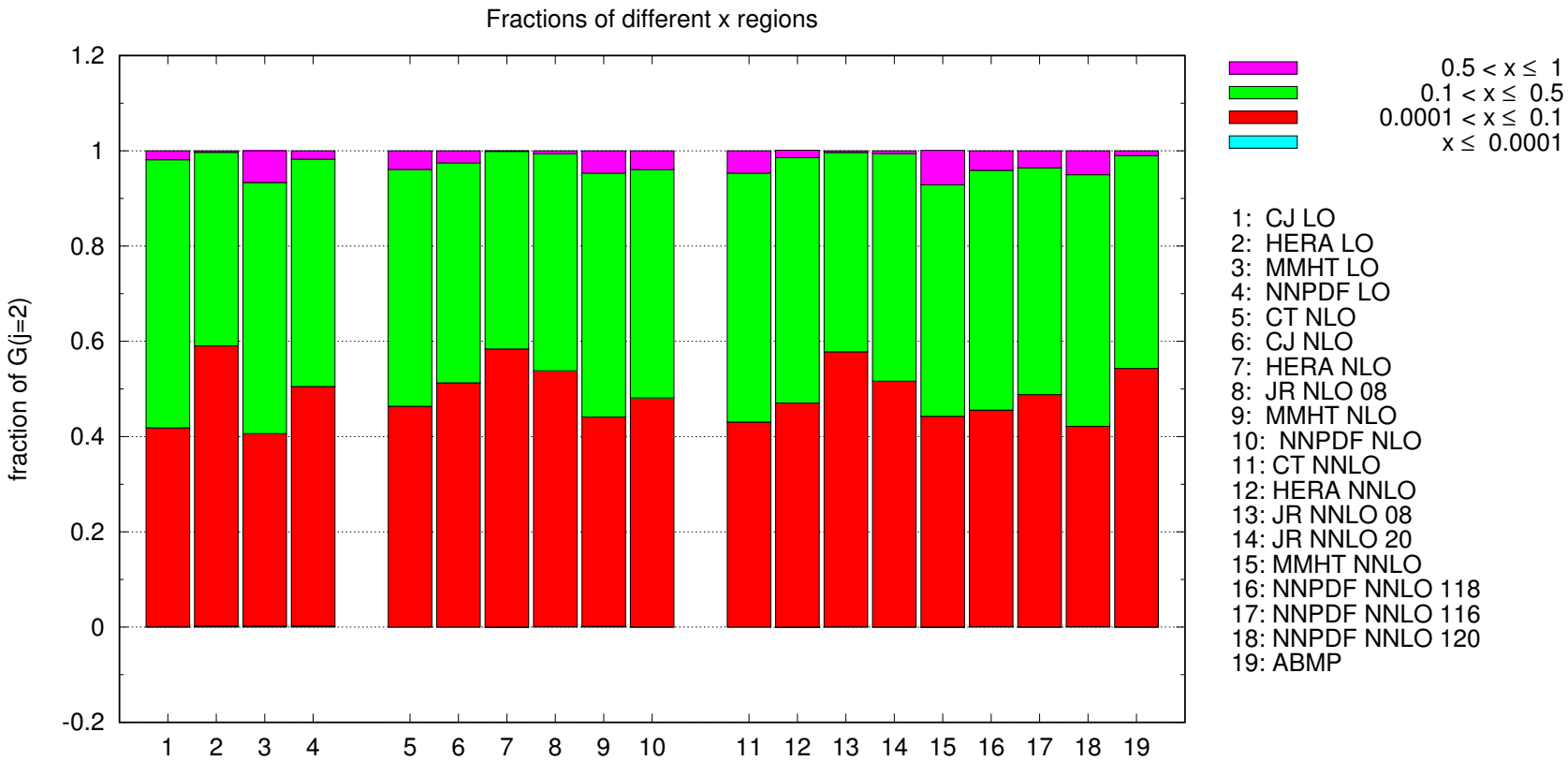
gluon $j = 2$



Moments and x ranges

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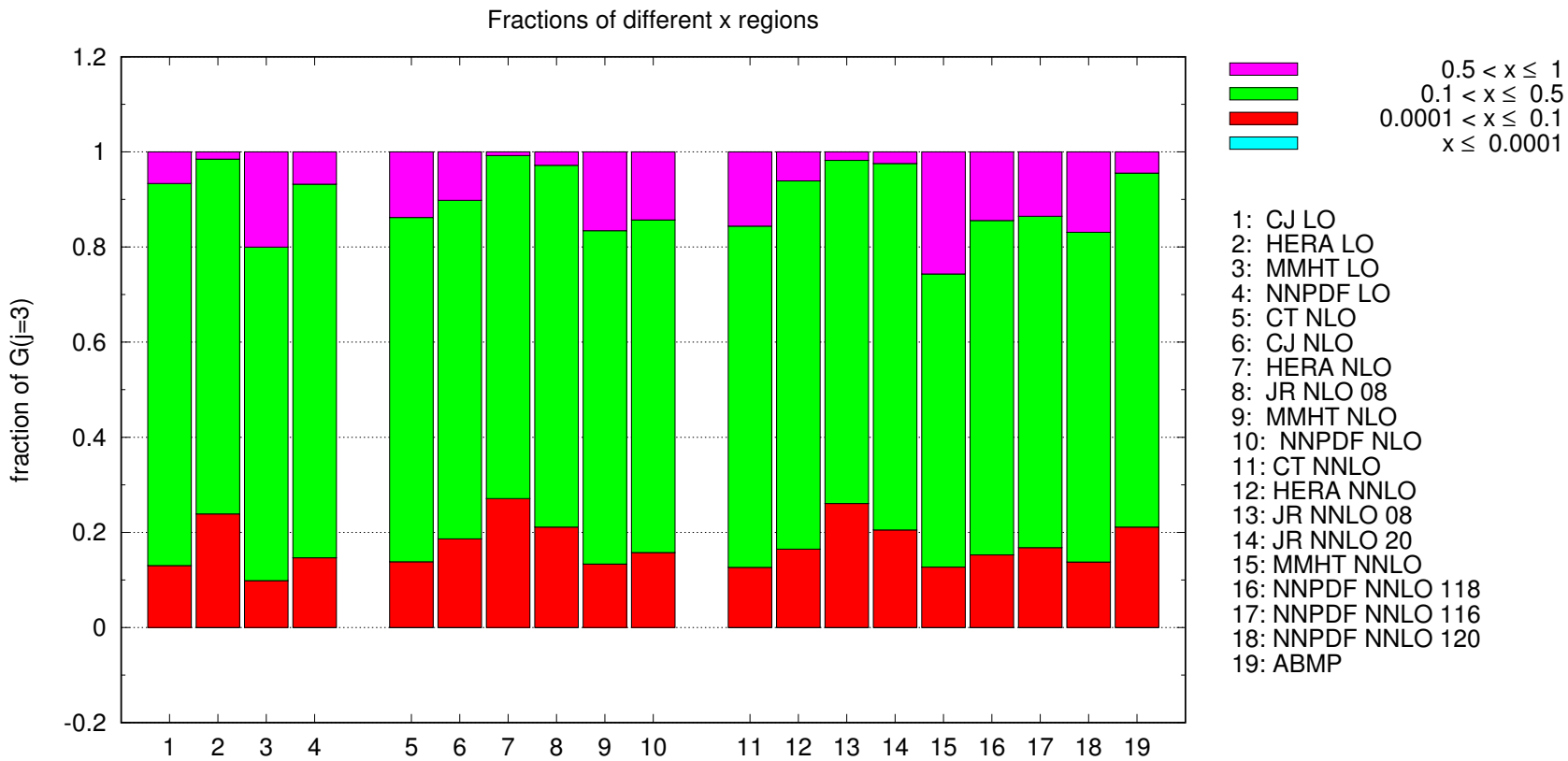
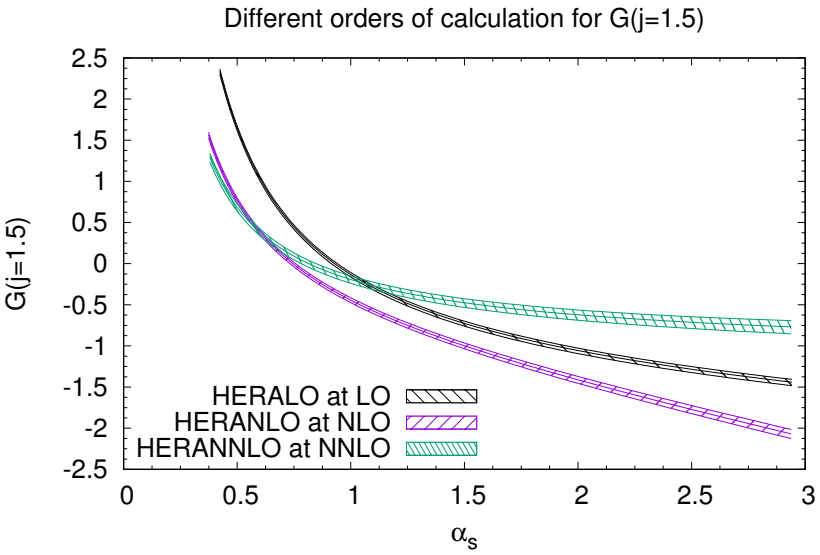
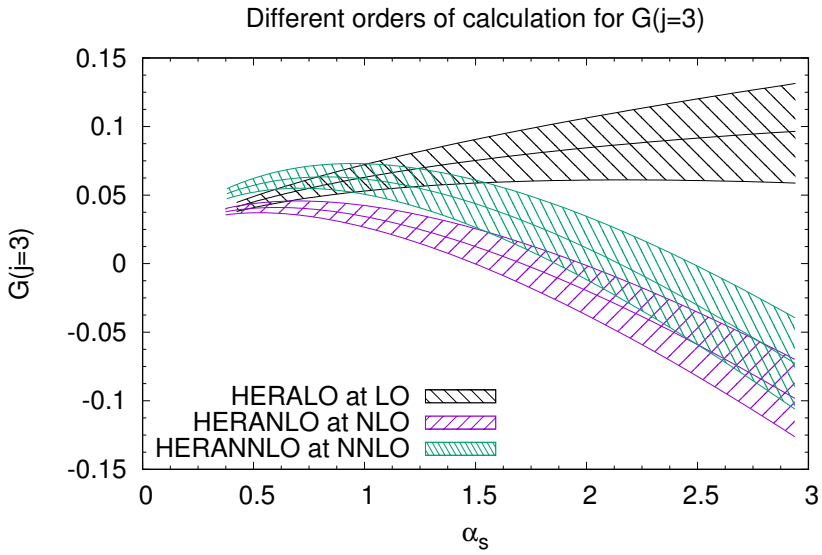
gluon $j = 3$



Comparing different orders





- error bands of PDFs increase as μ decreases (α_s increases) but in general remain of moderate size
- differences between orders quickly increase at low scales even quantitatively (rise vs. fall)

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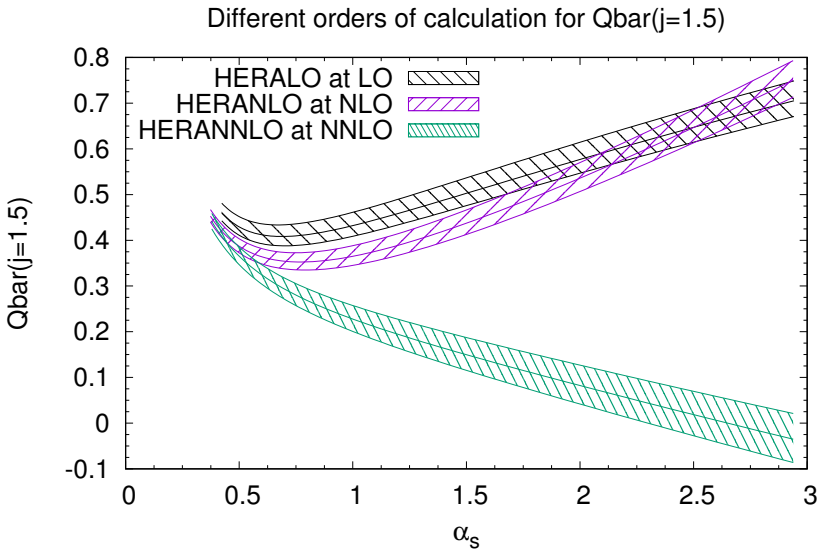

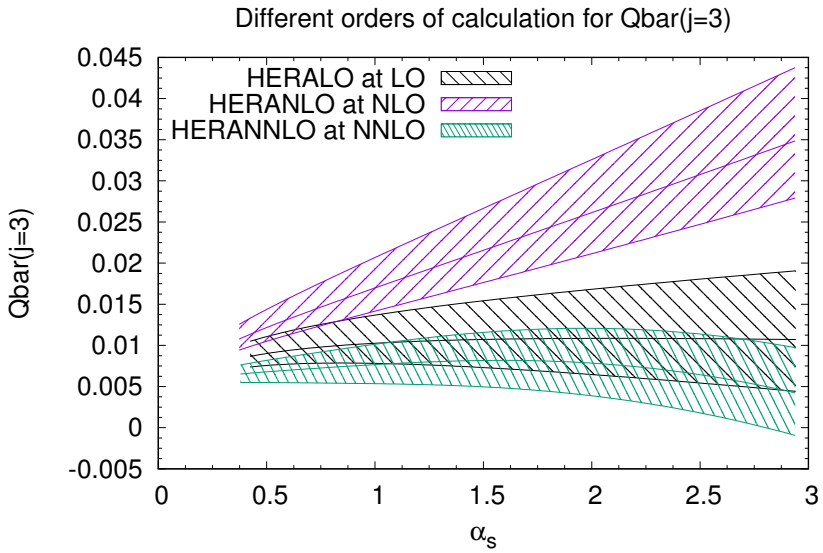

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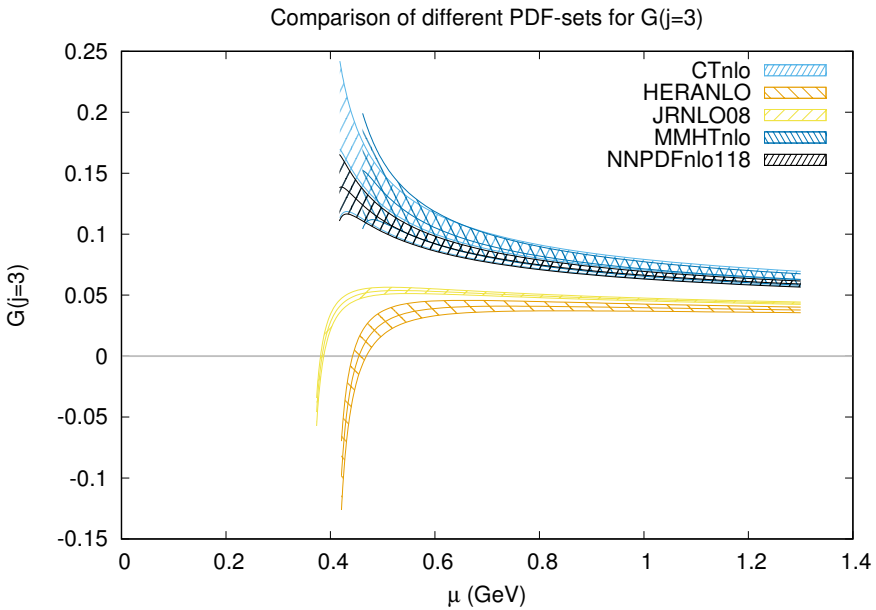
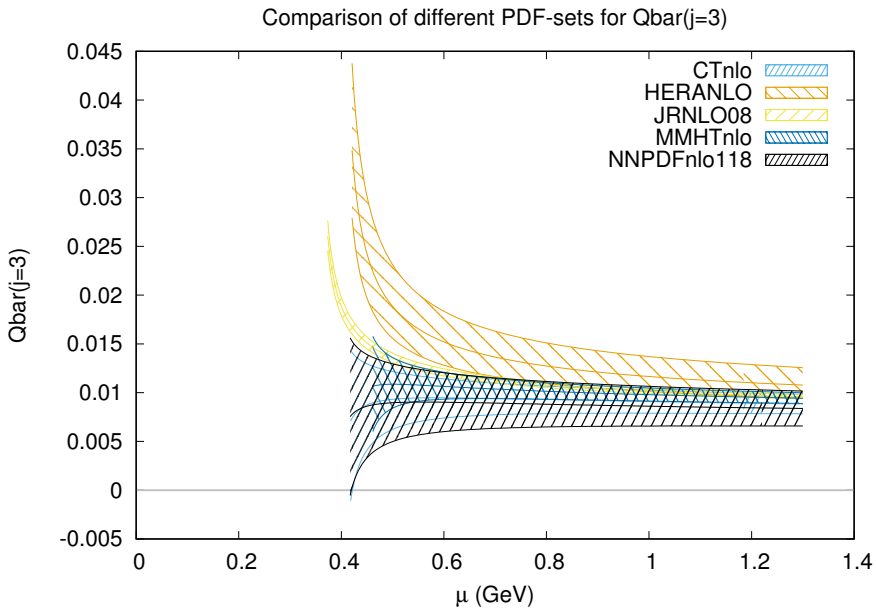
Comparing different sets



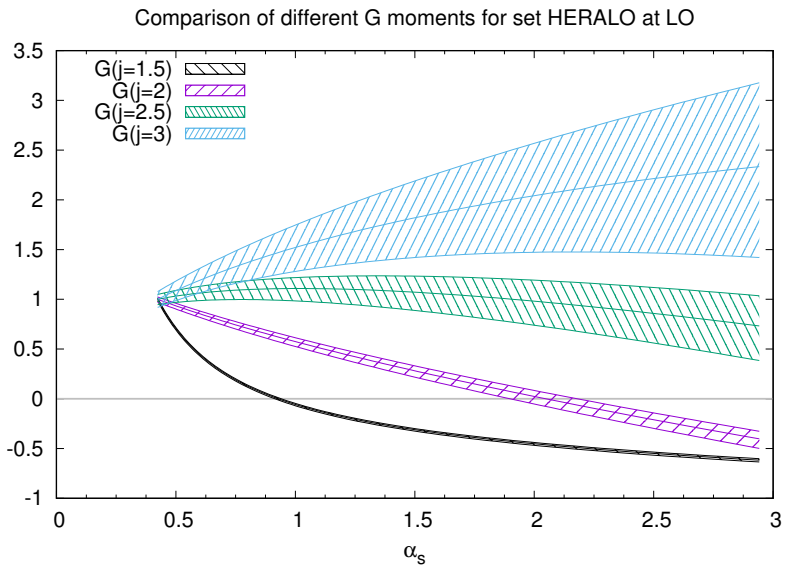


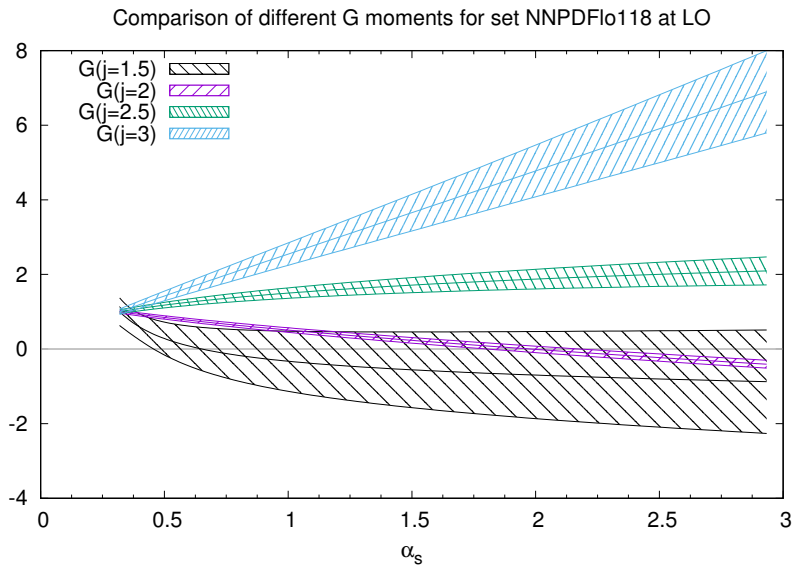
- PDF sets may differ in qualitative behaviour

Searching for zeroes

- plot different moments for given set (normalised to value at μ_0)
  look for cases where all $G(j)$ or all $\overline{Q}(j)$ have zero at one scale
- gluon

  for all LO sets high moments stay positive
  at some scale $G(1.5)$ becomes zero or consistent with zero





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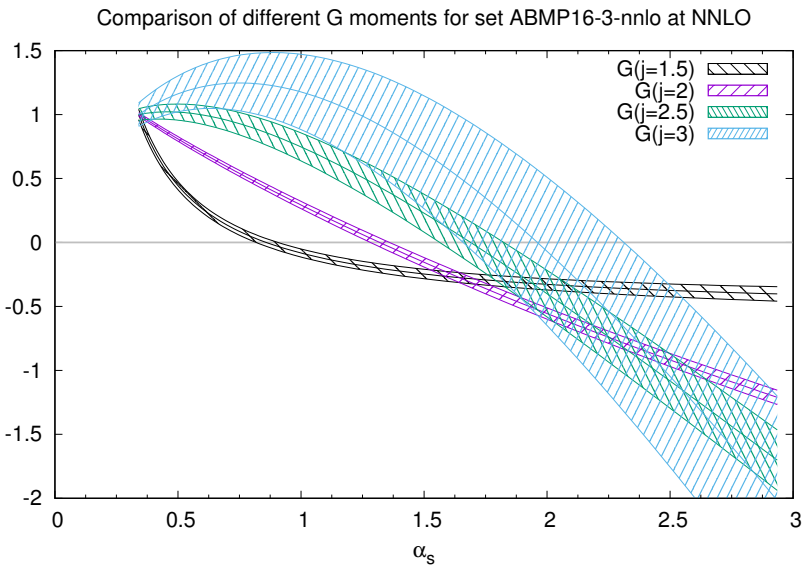
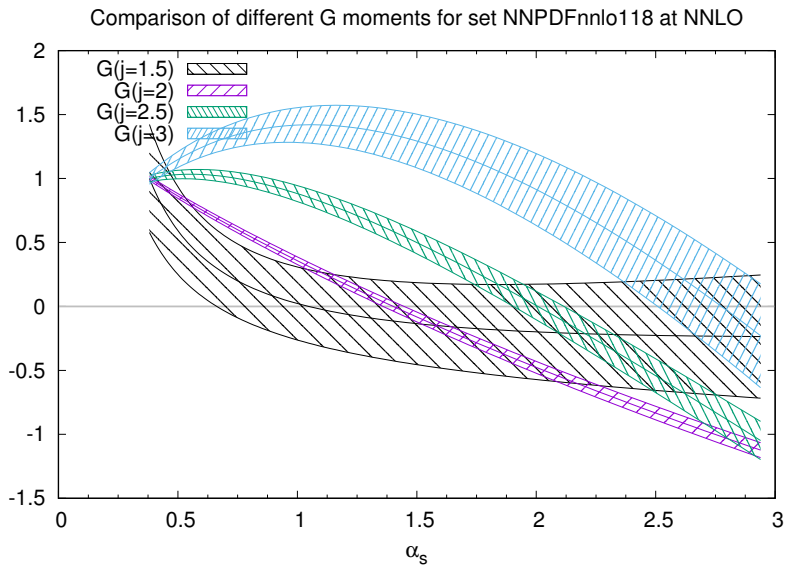
  in several NLO and NNLO sets all moments have zeroes
  but earlier for low j and later for high j





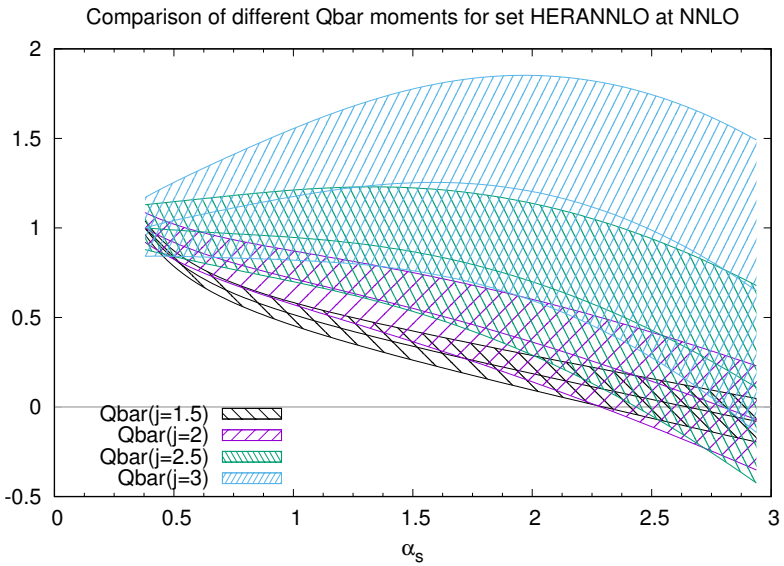
$\rightsquigarrow$ with decreasing μ gluon < 0 first for small and then for larger x

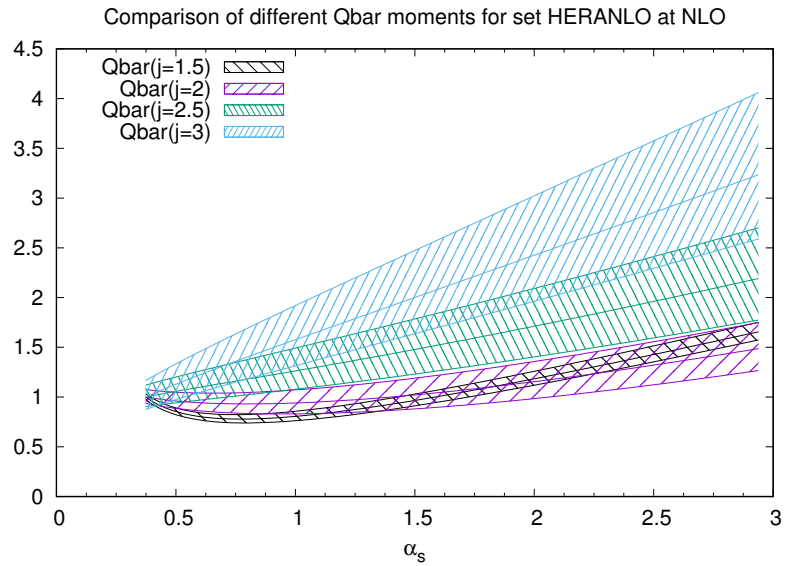
$\rightsquigarrow$ parton interpretation lost

Searching for zeroes

- plot different moments for given set (normalised to value at μ_0)
  look for cases where all $G(j)$ or all $\overline{Q}(j)$ have zero at one scale
- antiquarks

  for HERAPDF NNLO set all moments approach zero at very low μ
  for all other sets at least one moment remains clearly > 0





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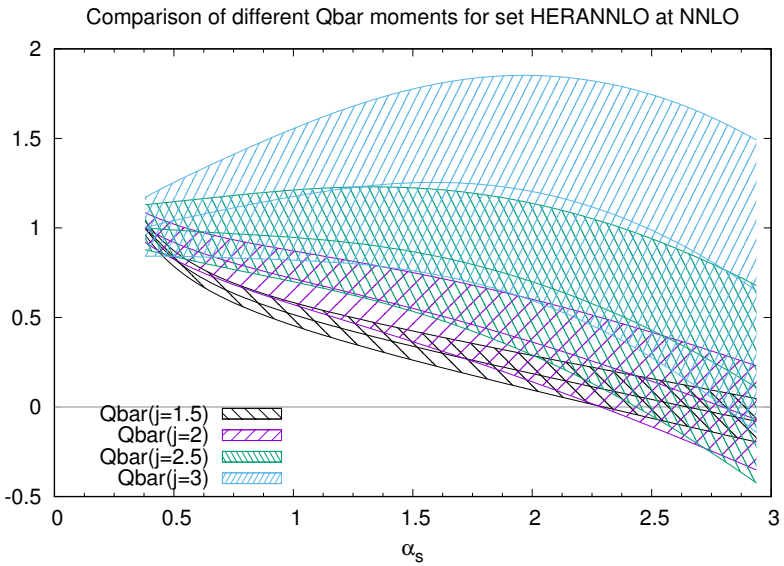
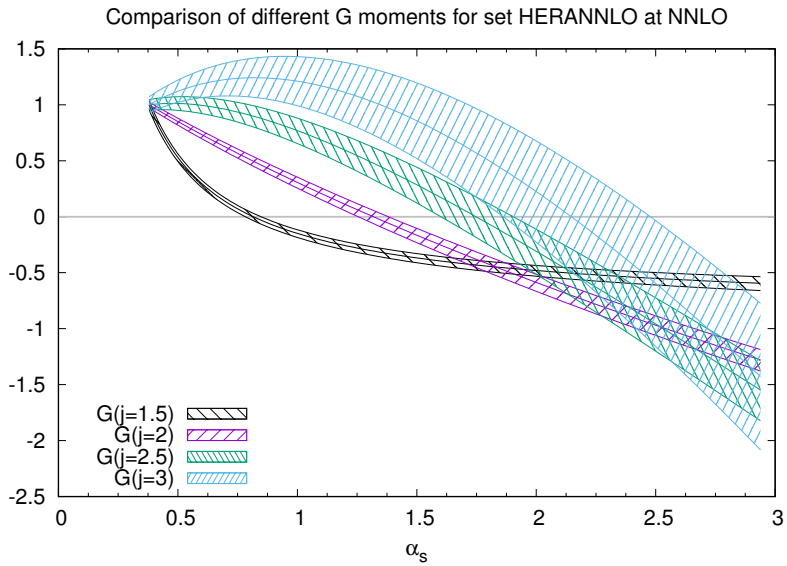
  for HERAPDF NNLO set all moments approach zero
  but this happens at very low scale, where all gluon moments < 0





$\rightsquigarrow$ parton interpretation lost

Summary

- in no PDF set are moments consistent with either $g(x)$ or $\bar{q}(x)$ zero or close to zero at any scale
- scenarios ruled out in which proton PDFs generated by perturbative radiation starting with only quarks at low scale fully confirms conclusions of fits by GRV, JR
- moments indicate that at low scales $g(x) < 0$ for small x then parton interpretation is lost
  $G(1.5) = \int_0^1 dx\, \sqrt{x} g(x)$ turns negative somewhere below $\mu = 0.8\,\mathrm{GeV}$
  except for PDF sets where error on $G(1.5)$ consistent with either sign
- possible paths toward explaining observed PDFs starting from low scales?
  - intrinsic, nonperturbatively generated gluons and sea quarks
  - nonperturbative modification of scale evolution
  - alternative scheme to $\overline{\mathrm{MS}}$ for defining PDFs