GHENT
UNIVERSITY

FACULTY OF SCIENCES

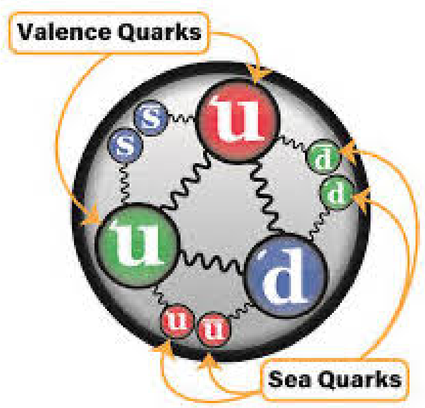
27TH OF JANUARY 2023

EVIDENCE FOR INTRINSIC CHARM QUARKS IN THE PROTON

GHENT UNIVERSITY

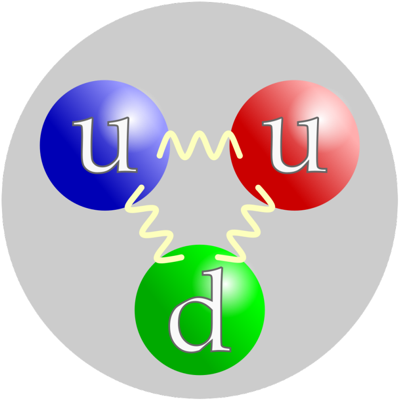
Abstract

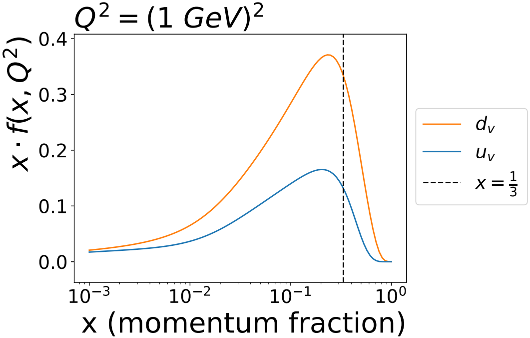
[. . .] The proton is a state of ***two up quarks and one down quark bound by gluons****, but quantum theory predicts that in addition there is an* ***infinite number of quark–antiquark pairs****. Both* ***light and heavy quarks****, [. . .], are revealed inside the proton in high-energy collisions. However,* ***it is unclear whether heavy quarks also exist as a part of the proton wavefunction****, which is determined by* ***non-perturbative dynamics*** *and accordingly unknown: so-called* ***intrinsic heavy quarks****.*



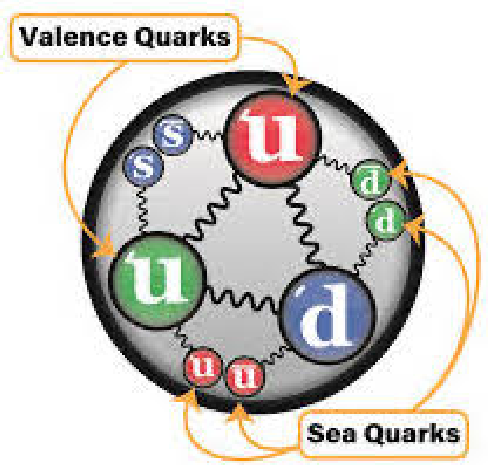
THE PROTON WAVEFUNCTION

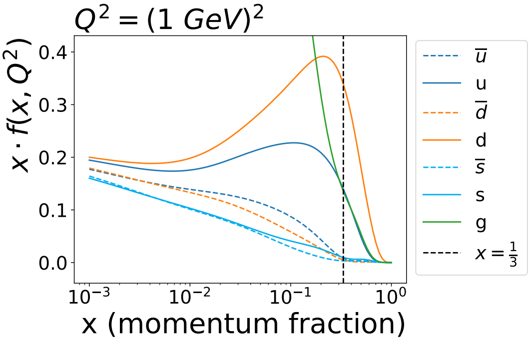
simple picture: proton = $\left|uud\right\rangle$



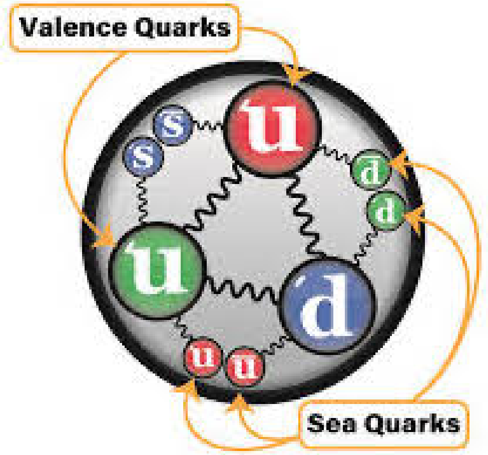


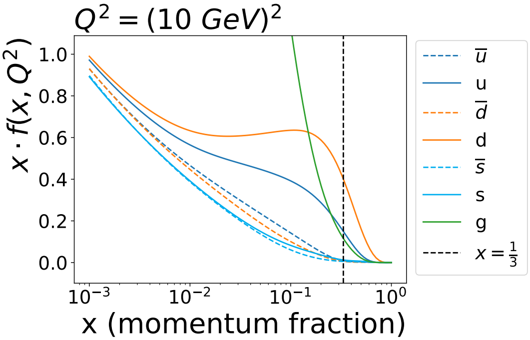
valence vs sea partons





Q^2 dependence (momentum transfer)





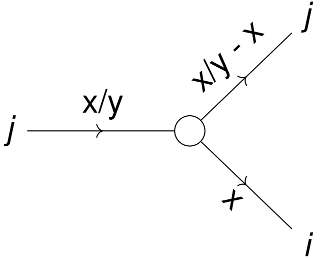
PDF EVOLUTION

DGLAP equations

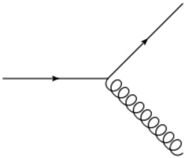
$$Q^2 \frac{d}{dQ^2} f_i(x, Q^2) = \sum_j \int_x^1 \frac{dy}{y} P_{ij}(x/y, a_s(Q^2)) \cdot f_j(y, Q^2)$$

Higher Q^2 = see more emissions from partons at higher momenta!

P_{ij} =

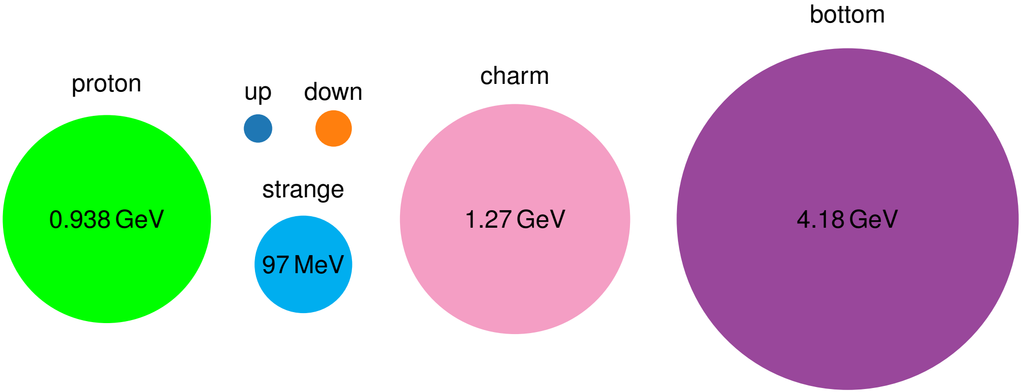


e.g. P_{gq} at LO =



Heavy quarks

DGLAP equations apply to **massless** quarks. What about **massive** quarks?



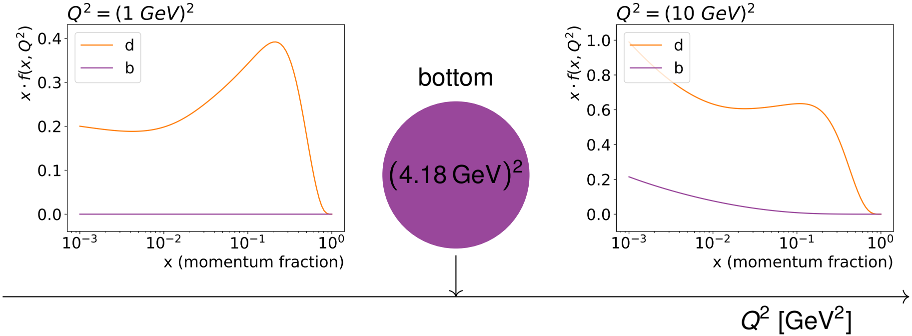
Heavy quarks

Via matrix element calculation (fixed order)

- assume zero pdf
- convergence issues at high Q^2

Include in PDFs (infinite order)

- neglect mass



Require continuity in physical observables!

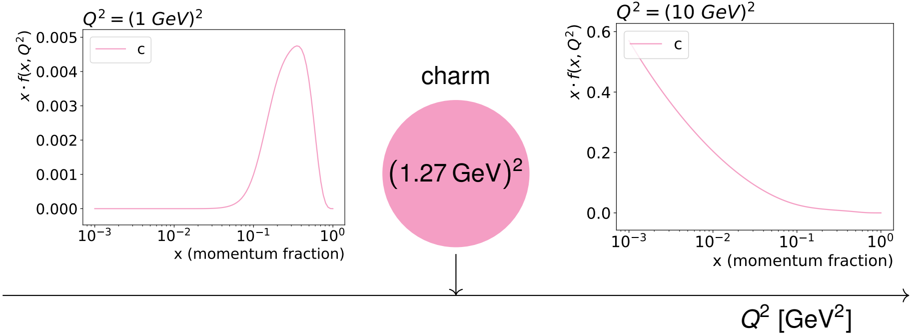
Intrinsic or extrinsic?

Via matrix element calculation (fixed order)

- assume zero pdf or not? (non-perturbative)
- convergence issues at high Q^2

Include in PDFs (infinite order)

- neglect mass



Require continuity in physical observables!

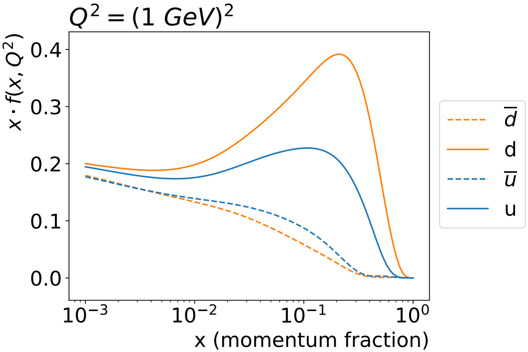
VALENCE VS INTRINSIC

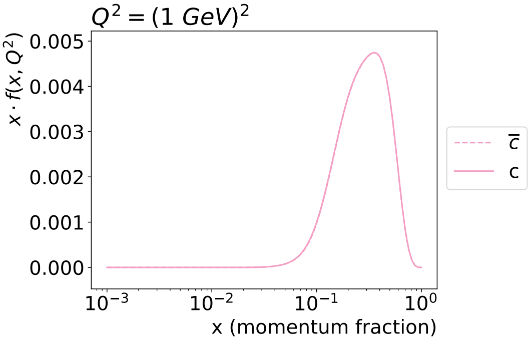
Valence $=$ net excess quarks vs antiquarks

- $\int_0^1 (q(x) - \overline{q}(x))dx \neq 0$
- is also intrinsic

Intrinsic $=$ non-perturbative pdf

- not necessarily valence
- but possibly $q(x) \neq \overline{q}(x)$





Charm: intrinsic or not?

Q^2 [GeV^2]

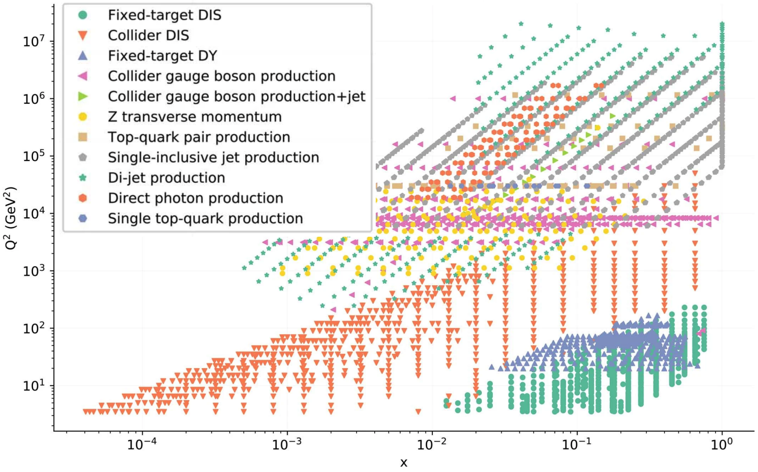
Step 1: DETERMINE $n_F = 4$ PDF FROM DATA

$(1.27\,\mathrm{GeV})^2$ Step 2: EVOLVE TO m_c

Step 3: TRANSFORM TO $n_F = 3$ AND (NON-)ZERO PDF

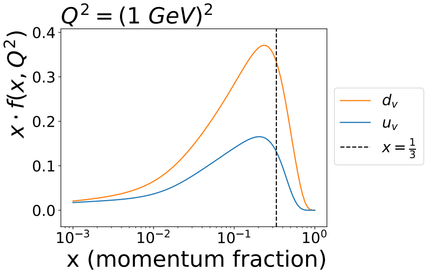
Measuring the 4*FS* PDFs

- parametrize at Q_0 using neural networks
- pick measurement at scale Q
- evolve PDFs
- constrain



NNPDF4.0

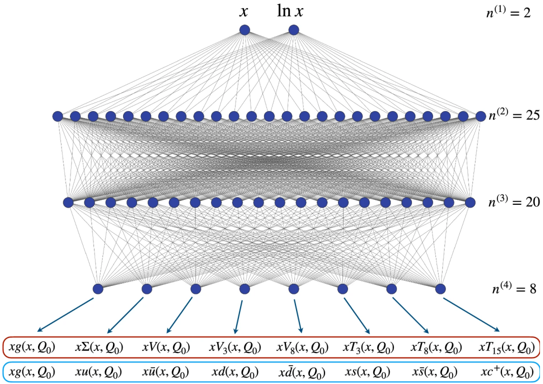
- $xf(x, Q_0) = \underbrace{A_k x^{1-a_k} (1-x)^{\beta_k}}_{\text{preprocessing}} \underbrace{NN_k\left(x, Q_0 \mid \vec{\theta}\right)}_{\text{neural net}}$
- apply theoretical constraints
  - total momentum fraction: $\sum_k \int_0^1 xf_k(x, Q)dx = 1$
  - valence vs sea: $\int_0^1 \left[u(x, Q) - \overline{u}(x, Q)\right] dx = 2$
  - positive g, u, d, and s PDFs
  - ...
- which pdf basis?
  - flavour: g, u, d, s, c + anti
  - evolution: linear combination
  - charm: $c^+ = c + \overline{c}$



NNPDF4.0

- neural net (unbiased)
- automatic optimization hyperparameters
  - depth and extent of network
  - choice of minimizer
  - learning rate
  - activation function
  - ...

$\rightarrow$ 1500 configurations scanned!



CHARM: INTRINSIC OR NOT?

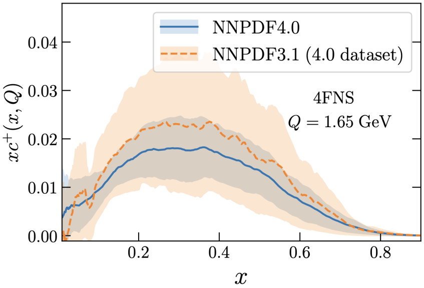
Q^2 [GeV^2]

Step 1: DETERMINE $n_F = 4$ PDF FROM DATA (at 1.65 GeV)

$(1.27\,\text{GeV})^2$ Step 2: EVOLVE TO m_c

Step 3: TRANSFORM TO $n_F = 3$ using

$$c^+ = c + \bar{c}$$



CHARM: INTRINSIC OR NOT?

Q^2 [GeV^2]

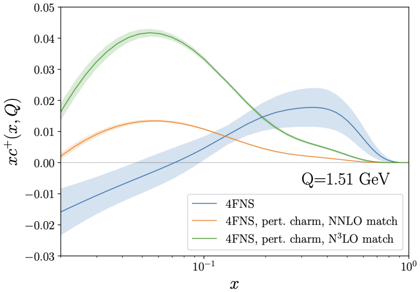
Step 1: DETERMINE $n_F = 4$ PDF FROM DATA (at 1.65 GeV)

$(1.51\text{ GeV})^2$ Step 2: EVOLVE TO m_c AT POLE MASS

Step 3: TRANSFORM TO $n_F = 3$ using

$$c^+ = c + \bar{c}$$

\+ purely perturbative charm at $N^{2,3}LO$



CHARM: INTRINSIC OR NOT?

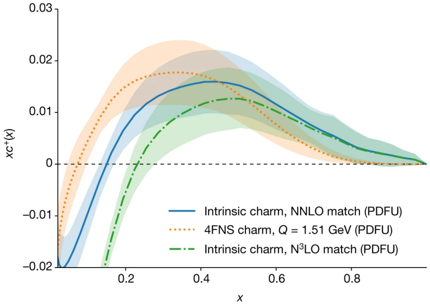
Q^2 [GeV^2]

Step 1: DETERMINE $n_F = 4$ PDF FROM DATA (at 1.65 GeV)

$(1.51\ \text{GeV})^2$ Step 2: EVOLVE TO m_c AT POLE MASS

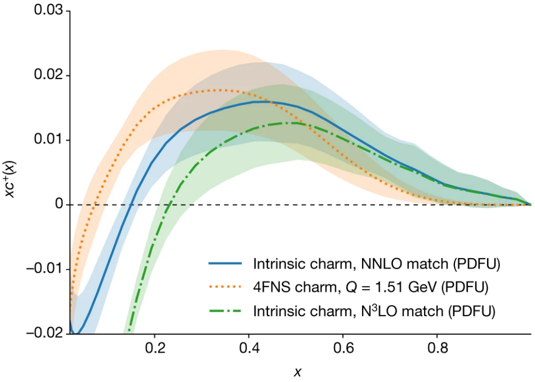
Step 3: TRANSFORM TO $n_F = 3$ using *NNLO* or *N^{3}LO*

$$c^+ = c + \bar{c}$$



Evidence for intrinsic charm!

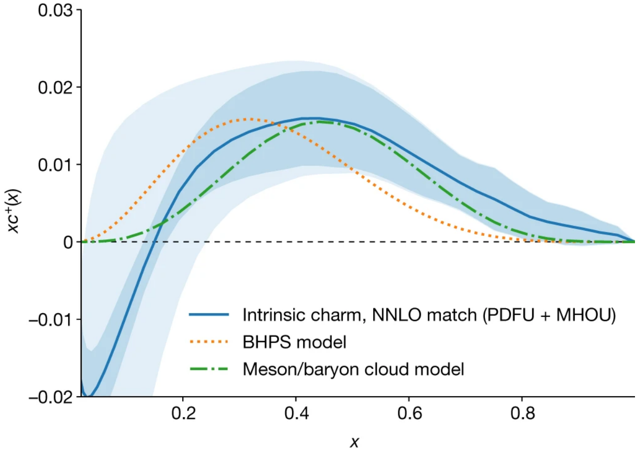
- 3σ deviation from zero (full data set)
  - 2.5σ excluding validation data
- uncertainties
  - right: statistical
  - missing higher-order uncertainties [MHOU]
    - *NNLO* (blue) vs *N^3LO* (green)
- stable results w.r.t.
  - SM parameters (m_c)
  - methodology 4FS fit
  - dataset variations



THEORY PREDICTIONS FOR INTRINSIC CHARM

- predict shape, not normalization
- BHPS: analytic calculation of $c(x)$ in $|uudc\bar{c}\rangle$ assuming $m_c \gg$ other p_T, m
- non-perturbative meson baryon fluctuations like

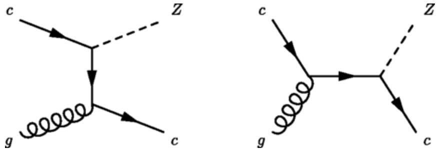
$$p \to \Lambda_c^+ + \overline{D}^0$$

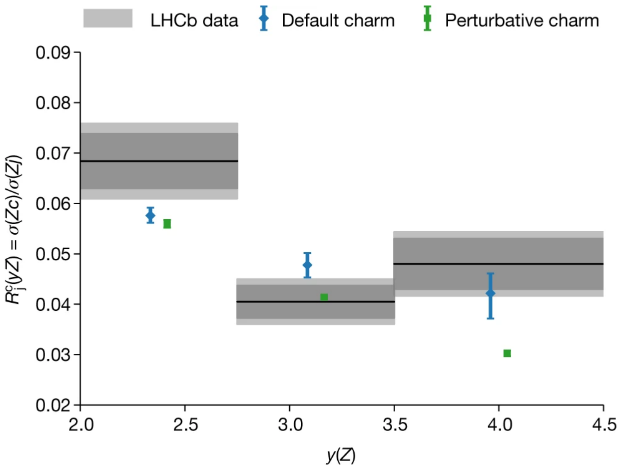


LHCb validation

$$\mathcal{R}_j^c = \frac{\sigma(Z + c\text{-jet})}{Z + \text{jets}}$$

differentially in Z rapidity y





SUMMARY

- Machine learning to fit PDFs
- dataset from LHC and HERA (DIS)
- disentangle intrinsic from radiative charm (3σ evidence)
- agreement with modelling
- confirmed with LHCb