Constraints on heavy flavour PDFs from LHC data

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Opportunities with Heavy Flavour at the EIC Workshop
Center for Frontiers in Nuclear Science, 04/11/2020

Center for Frontiers in Nuclear Science
Workshop series

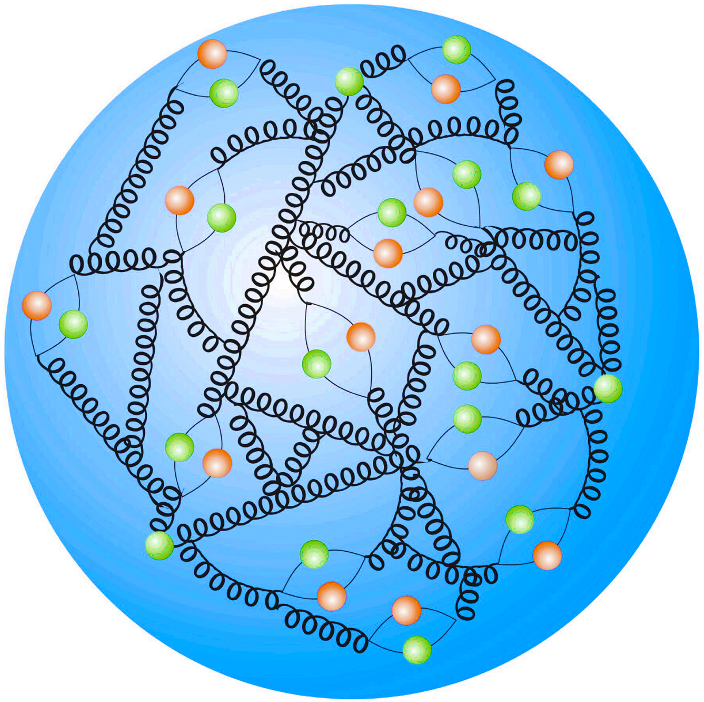
The many faces of the proton

a **QCD** bound state of **quarks** and **gluons**

$m_p \simeq 1 \text{ GeV}$

valence quarks: up & down

$m_{u,d} \simeq \text{few MeV}$



gluons

$m_g = 0$

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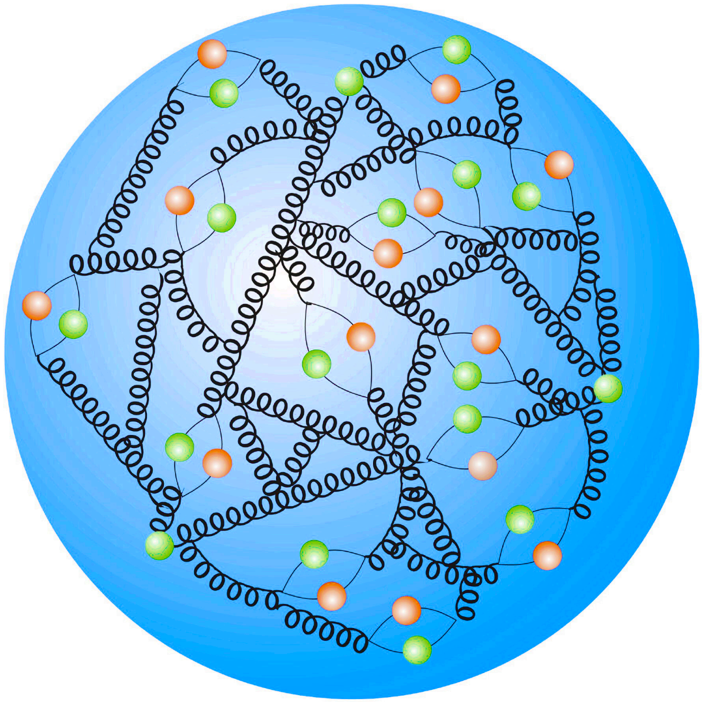

gluons

$m_g = 0$

strange quarks

$m_{u,d} \simeq 200 \text{ MeV}$

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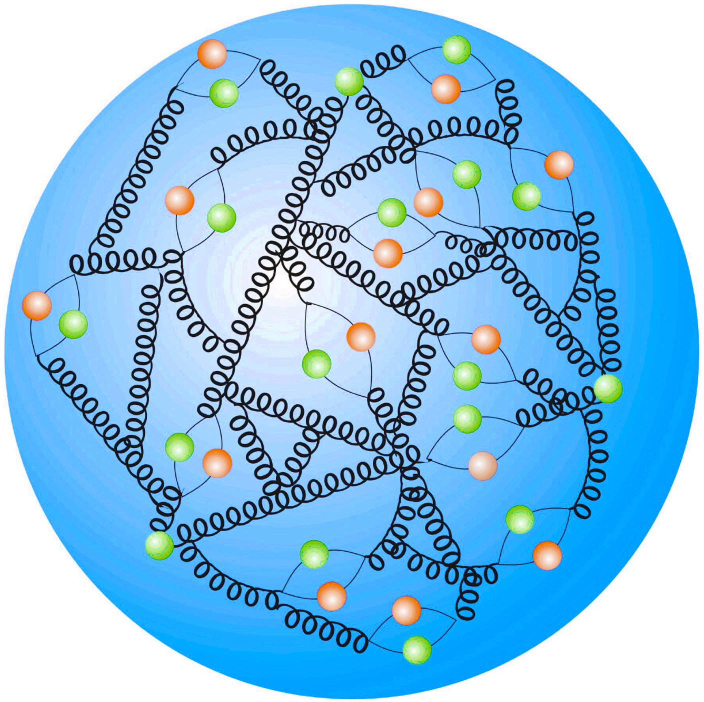

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strange quarks

$m_{u,d} \simeq 200 \text{ MeV}$

charm quarks?

$m_{u,d} \simeq 1.5 \text{ GeV}$

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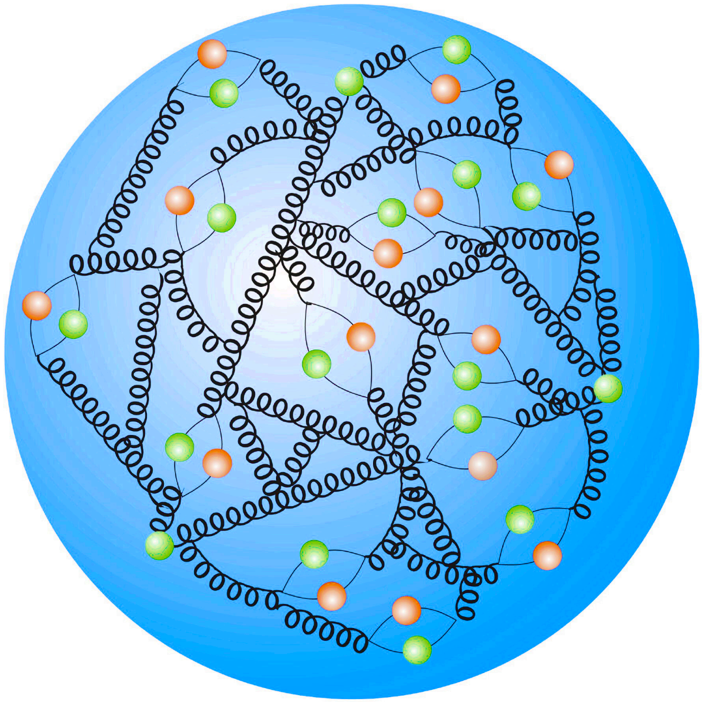

strange quarks

charm quarks?

bottom quarks?

leptons

photons

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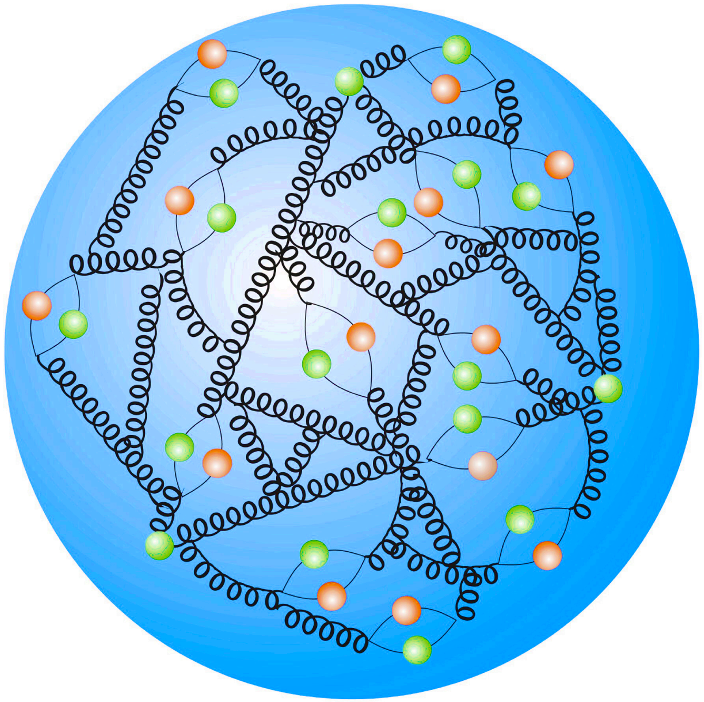

Higgs bosons?

weak bosons?

strange quarks

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leptons

photons

top quarks?

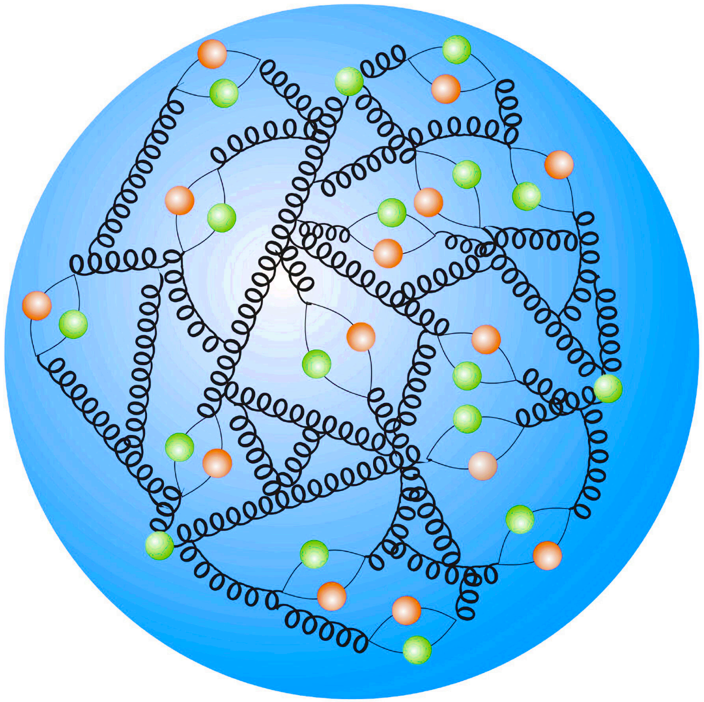
The many faces of the proton

``Heavy" flavour PDFs:

valence quarks: up & down

gluons

Higgs bosons?



weak bosons?

strange quarks

charm quarks?

bottom quarks?

leptons

top quarks?

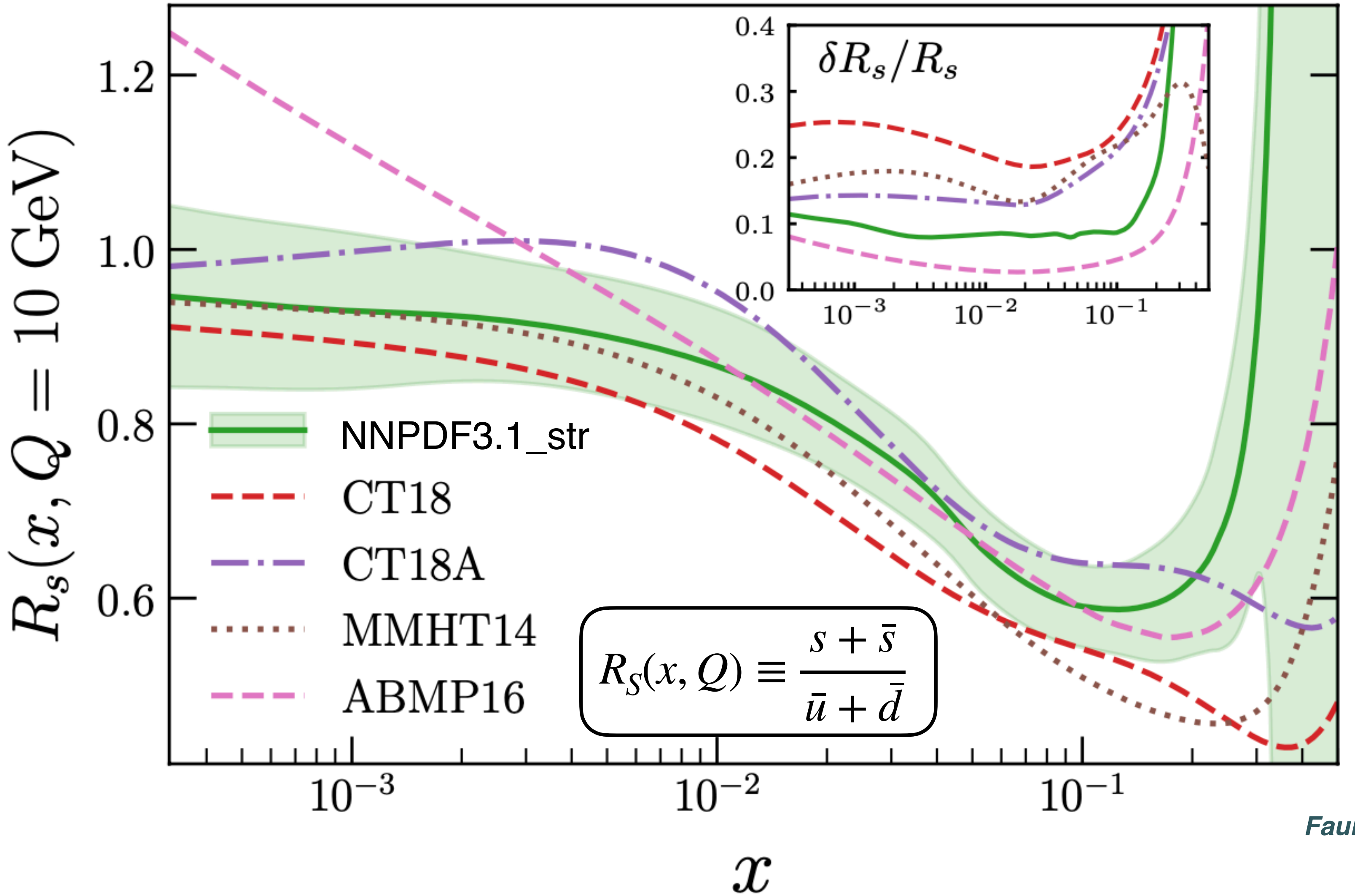
photons

The strange PDF

See ***Faura, Iranipour, Nocera, JR, Ubiali 20*** for all references

How strange is the proton?

marked differences in the strange PDFs from **recent global analyses,** both for central values and for the size of its uncertainties

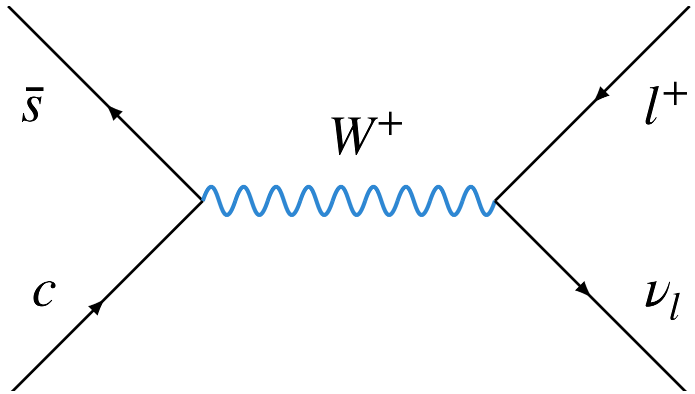


Faura et al 20

Constraining strangeness

the strange PDF can be constrained by different processes, both **collider** and **fixed-target**

inclusive Drell-Yan



sensitivity via correlation of ***W^+, W^+, Z*** distributions

ATLAS 7 TeV data: preference for ***R_S=1***

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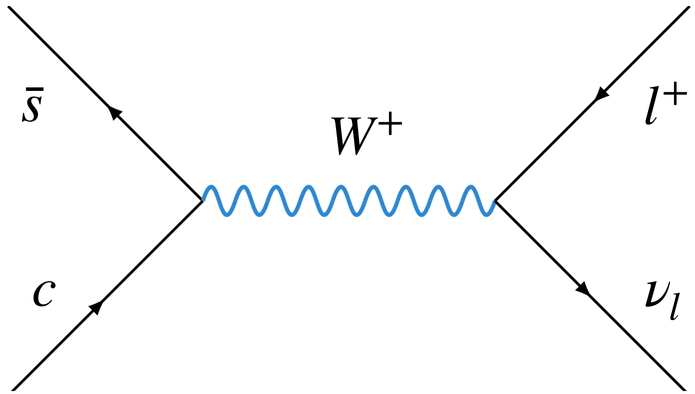

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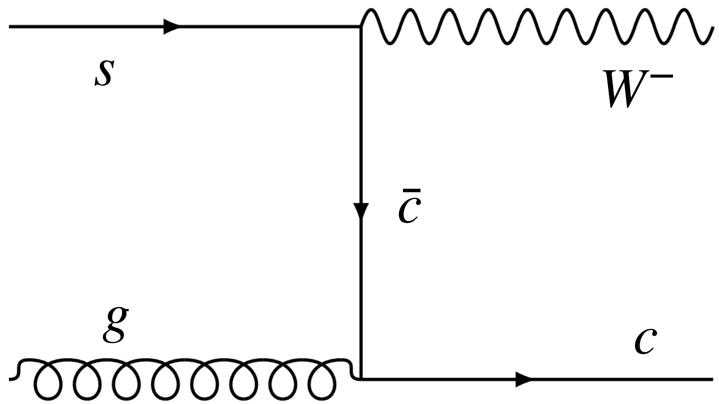
W+charm



direct sensitivity, but larger uncertainties

NNLO QCD corrections recently calculated

Czakon et al 20

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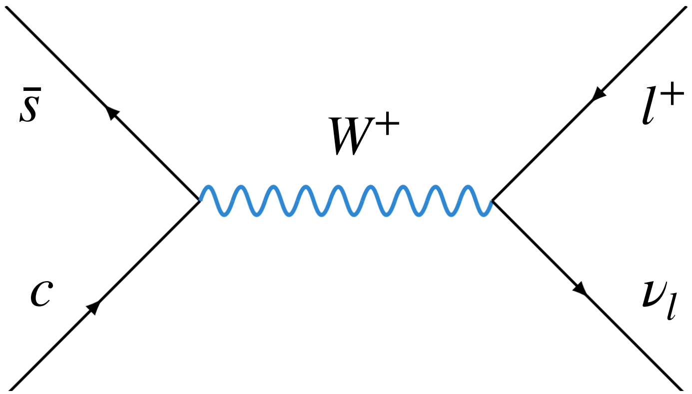
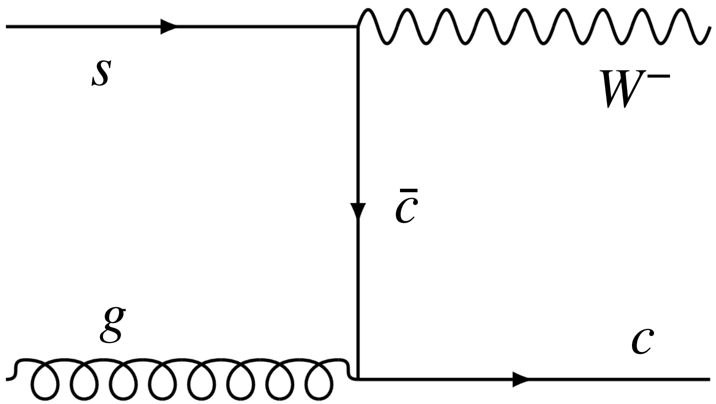
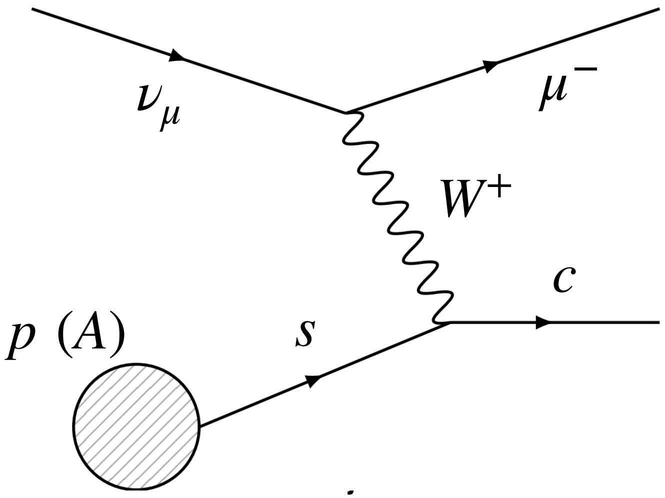


W+charm



Neutrino DIS



Characteristic opposite-sign **dimuon signature**

NNLO massive QCD corrections recently calculated

Gao et al 17

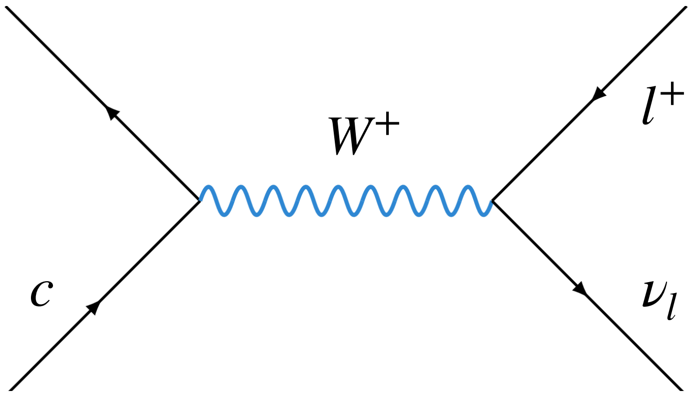
Traditionally associated with $R_S \approx$ ***0.5***

Theoretical issues w. nuclear PDFs and charm fragmentation

Constraining strangeness

the strange PDF can be constrained by different processes, both **collider** and **fixed-target**

inclusive Drell-Yan



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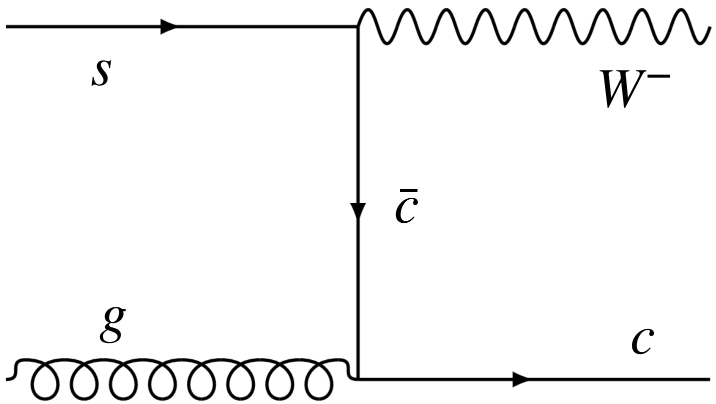

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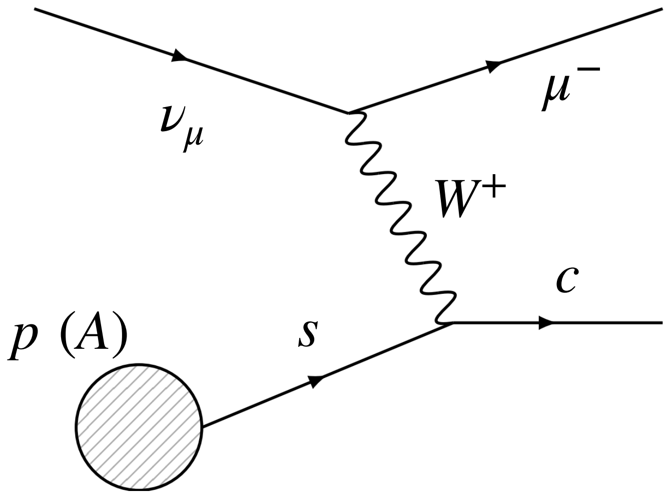
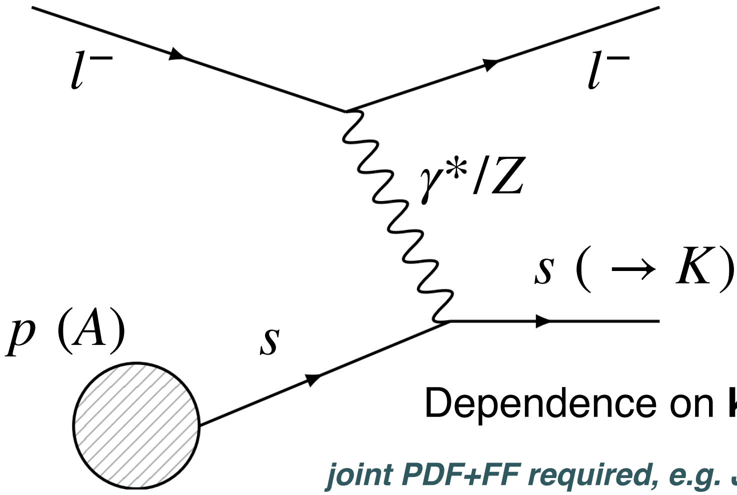


Semi-inclusive DIS



Dependence on **kaon FFs**

joint PDF+FF required, e.g. JAM analyses

How strange is the proton?

Why different groups obtain **different strange PDF determinations?**

- Different **input datasets**, *e.g.* including or not NuTeV/NOMAD, or ATLAS W,Z 2011
- Different **theory settings**, *e.g.* massive NNLO QCD corrections to neutrino DIS
- **Methodological** settings, *e.g.* treatment of charm PDF, uncertainty estimates

Do we really **understand** the proton strangeness?

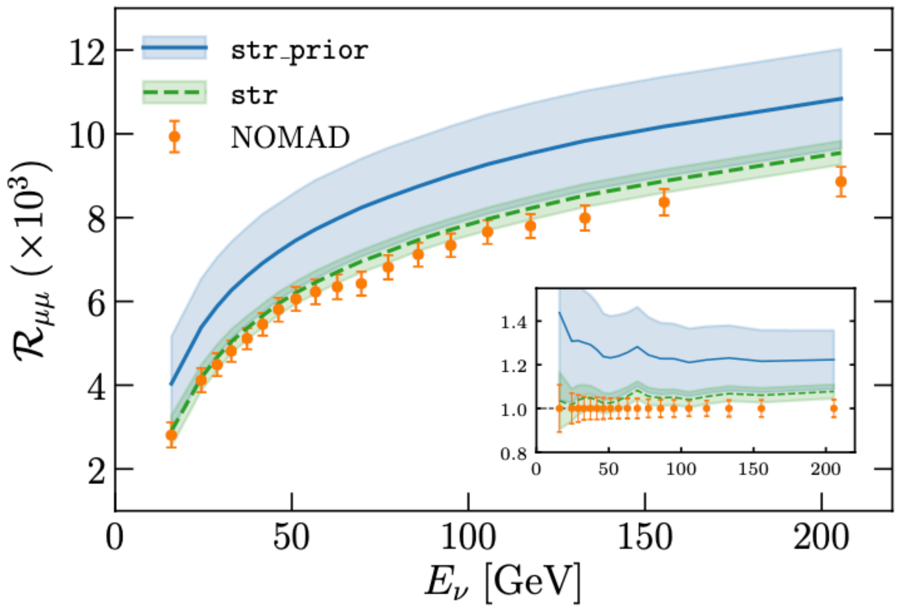
- Is there a tension between **collider** and **neutrino DIS** data?
- Is there a tension between i**nclusive *W,Z*** and ***W*+charm** data?
- Are constraints from different neutrino data consistent among them?

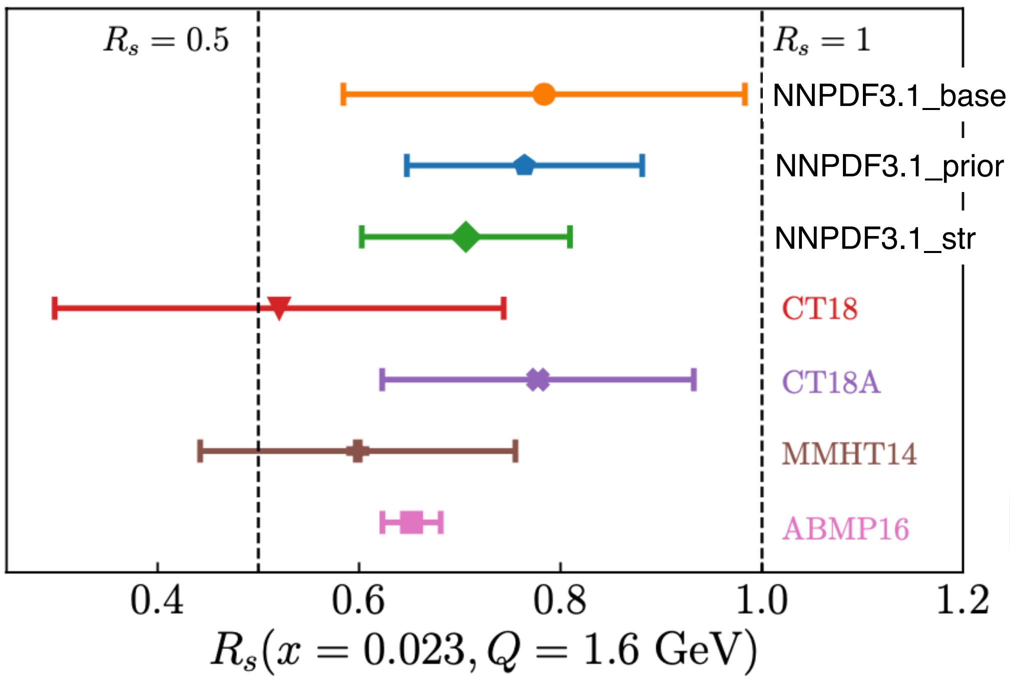
Is the proton strangeness **suppressed or symmetric** wrt the light quark sea?

How strange is the proton?

Reappraisal of the proton strangeness based combination of **all relevant experimental inputs**

Process	Dataset	$n_{\rm dat}$	$\chi^2_{\rm base}$	$\chi^2_{\rm pr}$	$\chi^2_{\rm str}$
νDIS ($\mu\mu$)		76/76/95/91/95	0.76	0.71	0.53
	NuTeV [9]	76/76/76/76/76	0.76	0.71	0.53
	NOMAD [10]	—/—/19/15/19	[9.3]	[8.8]	0.55
W, Z (incl.)		391/418/418/418/418	1.45	1.40	1.40
	ATLAS [12]	34/61/61/61/61	1.96	1.65	1.67
W+c		—/37/37/37/37	[0.73]	0.68	0.60
	CMS [17, 18]	—/15/15/15/15	[1.04]	0.98	0.96
	ATLAS [16]	—/22/22/22/22	[0.52]	0.48	0.42
W+jets	ATLAS [15]	—/32/32/32/32	[1.58]	1.18	1.18
Total		3981/4077/4096/4092/4096	1.18	1.17	1.17





- Satisfactory simultaneous description of all datasets
- No **evidence for tension** between datasets or groups of processes
- Sizeable constraints from **NOMAD neutrino DIS** data, consistent with collider data *see also ABM studies*
- Strong preference for a **moderately suppressed strangeness**

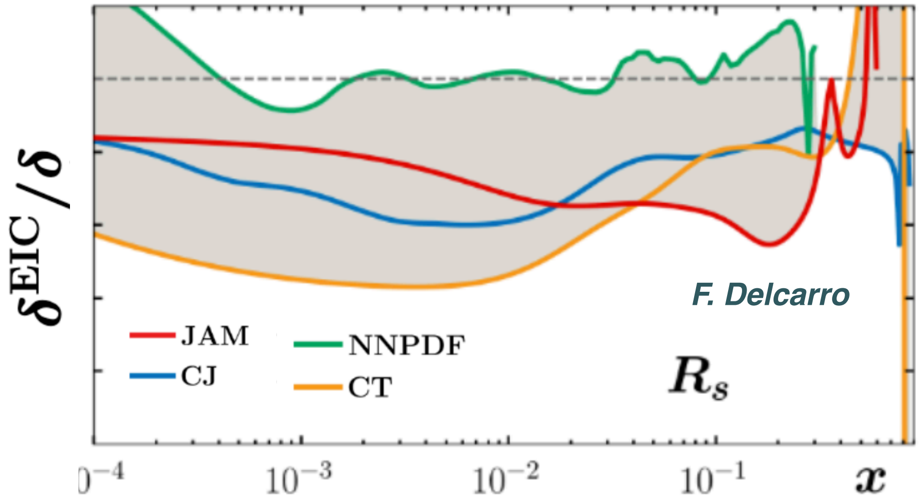
$$R_S(x = 0.023,\ Q = 1.6\ \text{GeV}) = 0.71 \pm 0.10$$

Faura et al 20

Strangeness @ EIC

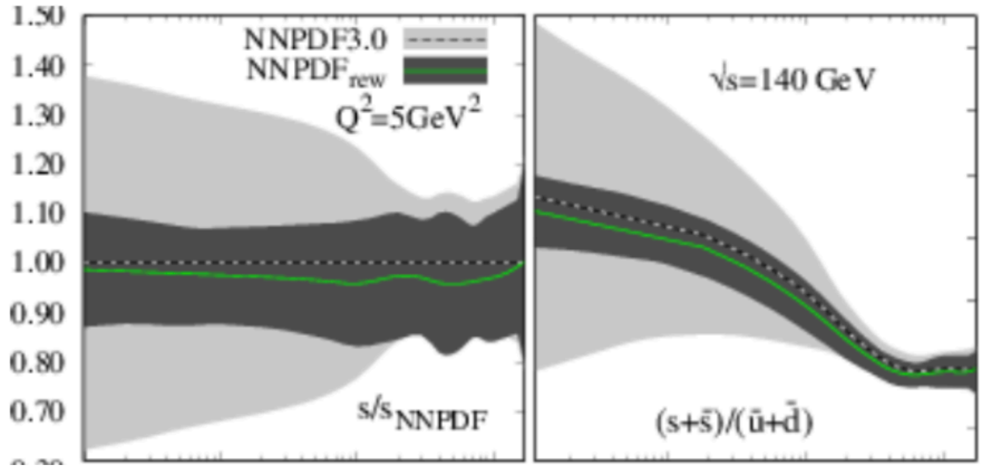
Can **future EIC measurements** provide information about the proton strangeness?

Inclusive DIS

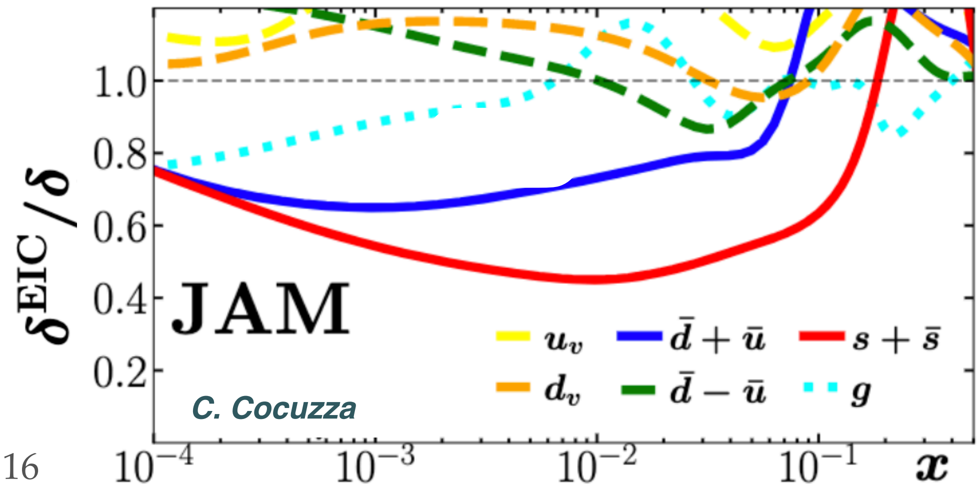


SIDIS on kaons

I. Borsa



Parity-violating DIS



- ☑ Plenty of exciting opportunities to **constrain strangeness at the EIC**
- ☑ The combination of inclusive DIS, SIDIS, and PVDIS will make possible a stringent determination of the strange content of protons

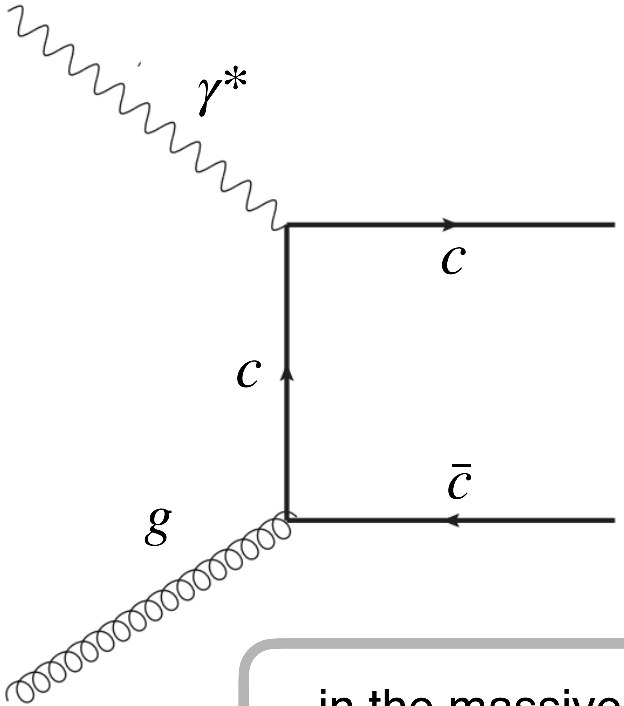
from EIC Yellow Report, in preparation

The charm PDF

A tale of three schemes

say you want to evaluate the **charm DIS structure function**. You have three options

☑ **Fixed-flavor scheme:** no charm PDF, charm mass effects accounted for exactly



$$F_2^c(x, Q^2) \propto \sum_{i=g,u,d,s} C_i^{(n_f)}(\alpha_s, Q^2/m_c^2) \otimes f_i^{(n_f)}$$

exact in **threshold region**

not appropriate to describe $Q^2 >> m_c^2$ region due to **large unresummed logs**

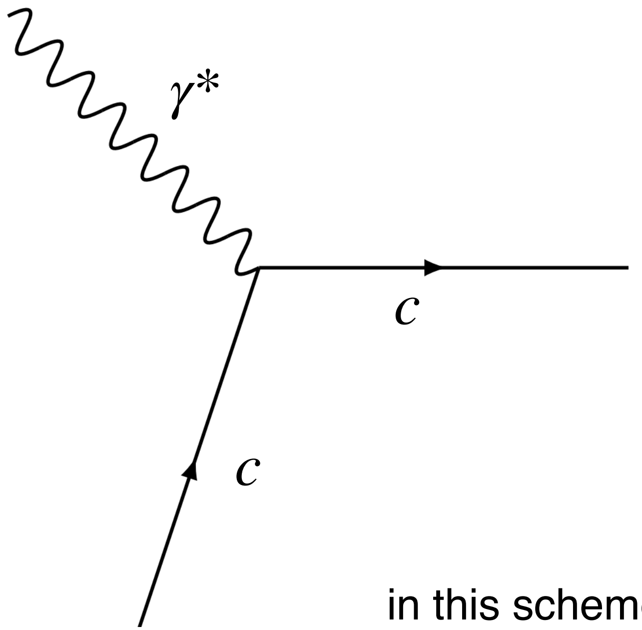
in the massive FFN scheme, **nothing to say** about the charm PDF

see also talks by Robert, Sven, Achim ...

A tale of three schemes

say you want to evaluate the **charm DIS structure function**. You have three options

☑ **Zero-mass scheme:** charm PDF treated on the same footing as all other quark flavours



$$F_2^c(x, Q^2) \propto \sum_{i=g,u,d,s,c} C_i^{(n_f+1)}(\alpha_s) \otimes f_i^{(n_f+1)}$$

exact in far from threshold region

not appropriate to describe $Q^2 \gtrsim m_c^2$ region due to lack of **massive corrections**

in this scheme, the charm PDF above threshold is constructed from the nf=3 PDFs via **matching**. **If** there is no charm PDF for $n_f=3$ (assumption) then

$$f_c^{(n_f+1)} \propto \alpha_s \ln \frac{Q^2}{m_c^2} \left(P_{qg} \otimes f_g^{(n_f+1)} \right) + \mathcal{O}\left(\alpha_s^2\right)$$

the charm PDF is deterministically **generated from the gluon** (and light quark) PDFs

not much to say about charm PDF either in this case ….

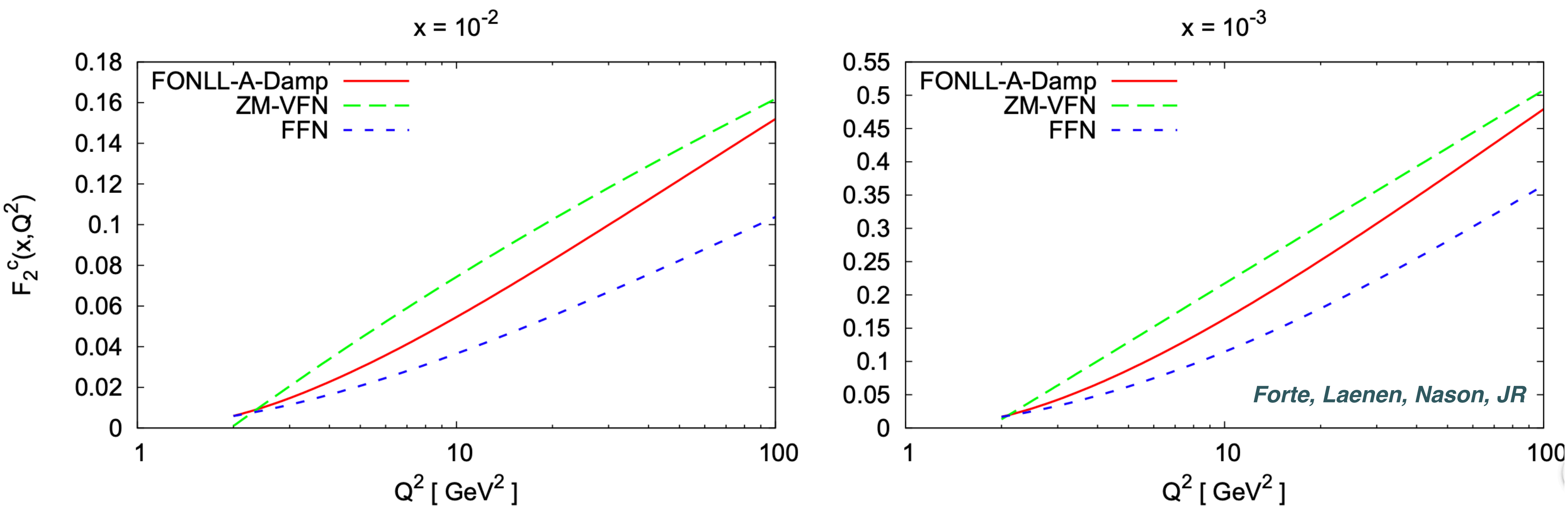
A tale of three schemes

say you want to evaluate the **charm DIS structure function**. You have three options

- ☑ **General-mass VFN scheme:** charm PDF treated on the same footing as all other quark flavours, massive effects included in coefficient functions

$$F_2^c(x,Q^2) \propto \sum_{i=g,u,d,s,c} C_i^{(\mathrm{GM})}(\alpha_s, Q^2/m_c^2) \otimes f_i^{(n_f+1)}$$

Systematically improvable, **reliable for all values of *Q*²** from threshold to collider scales



perturbative, intrinsic, and fitted charm

Let's work in the following in the GM-VFN scheme. The charm PDF above threshold is constructed from the n_f=3 PDFs via **matching** in three possible ways:

- ***Perturbative charm***: the charm PDF vanishes below threshold, then above threshold ($\mu_c \gtrsim m_c$) the charm PDF is deterministically **generated from the gluon** (and light quark) PDFs

$$f_c^{(n_f)} = 0 \quad \rightarrow \quad f_c^{(n_f+1)} \propto \alpha_s \ln \frac{Q^2}{m_c^2} \left(P_{qg} \otimes f_g^{(n_f+1)} \right) + \mathcal{O}\left(\alpha_s^2\right)$$

not much interesting to say about the charm PDF here

- ***Intrinsic charm***: a model for the charm PDF at the initial evolution scale (**below or at threshold**) is assumed. Then the charm PDF is this intrinsic component plus the perturbative component

$$f_c^{(n_f)}(x, Q_0) = Ax^2 \left[6x(1+x)\ln x + (1-x)(1+10x+x^2) \right]$$

BHPS model (scale independent)

the model parameters (*e.g.* normalisation) are extracted from comparison with data

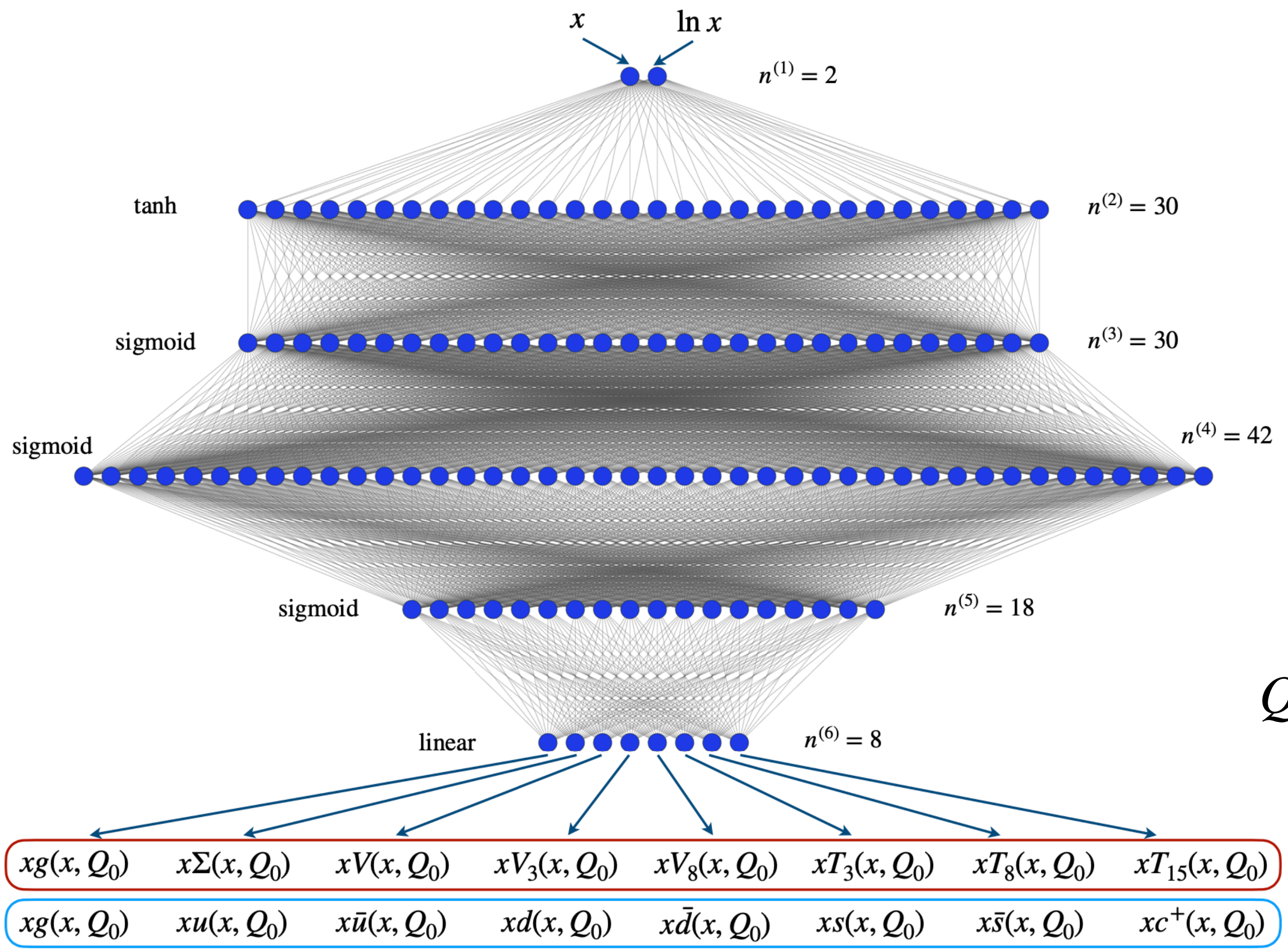
- ***Fitted charm***: no assumptions on possible intrinsic component are made. The charm is parametrised **above threshold** in exactly the same was as all other quark PDFs

$$f_c^{(n_f+1)}(x, Q_0) = x^{-\alpha_c}(1-x)^{\beta_c}\mathrm{NN}(x)$$

NNPDF approach

n.b. the GM-VFN structure functions need to be modified for a non-zero charm PDF in the n_f=3 scheme

perturbative, intrinsic, and fitted charm



NNPDF4.0 PDF parametrisation

$$Q_0 \geq m_c$$

evolution basis

flavor basis

- ***Fitted charm***: no assumptions on possible intrinsic component are made. The charm is parametrised **above threshold** in exactly the same was as all other quark PDFs

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NNPDF approach

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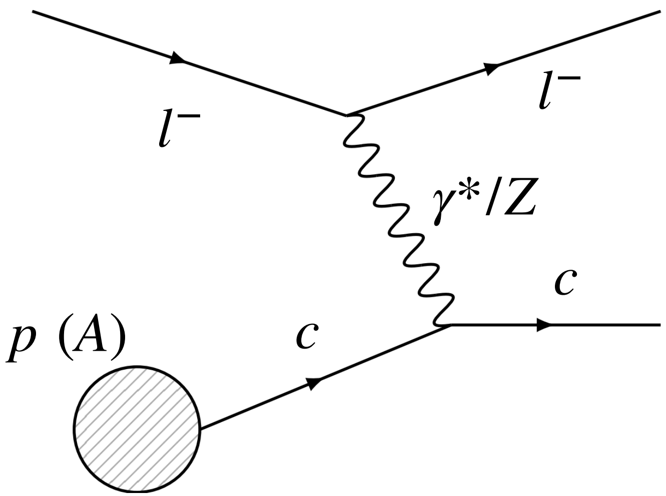
Constraining charm

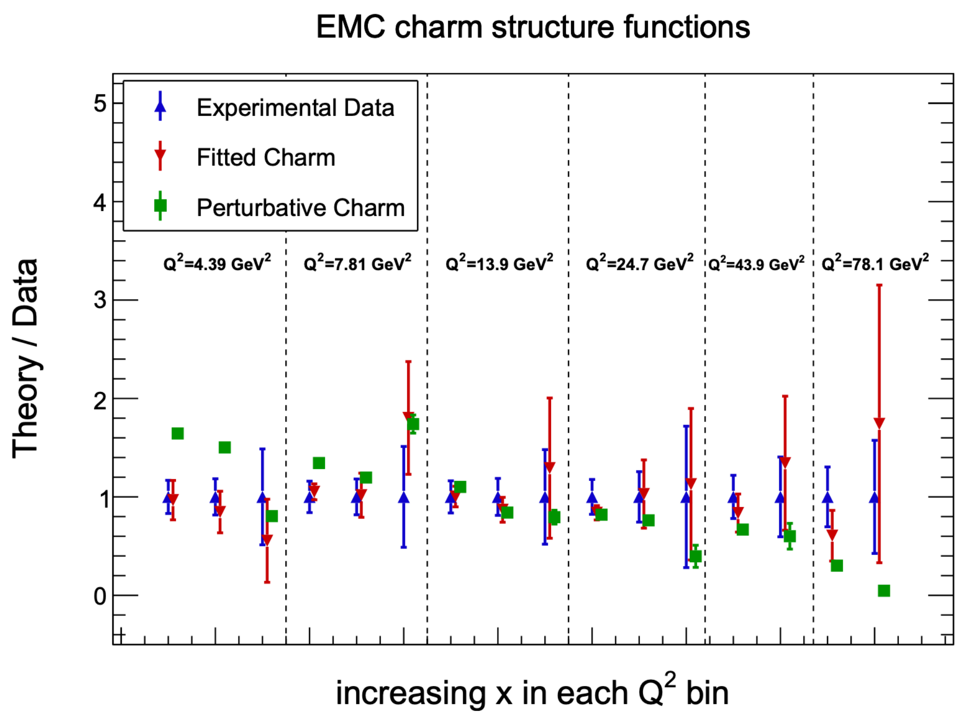
in the following, we assume that the charm PDF is either **fitted** or **intrinsic**
(perturbative charm cannot be constrained, since it is generated by DGLAP evolution)

Charm production in DIS



Only measurements of **F_2^c at large-*x*** are sensitive
EMC data from the 80s available …

NNPDF 16



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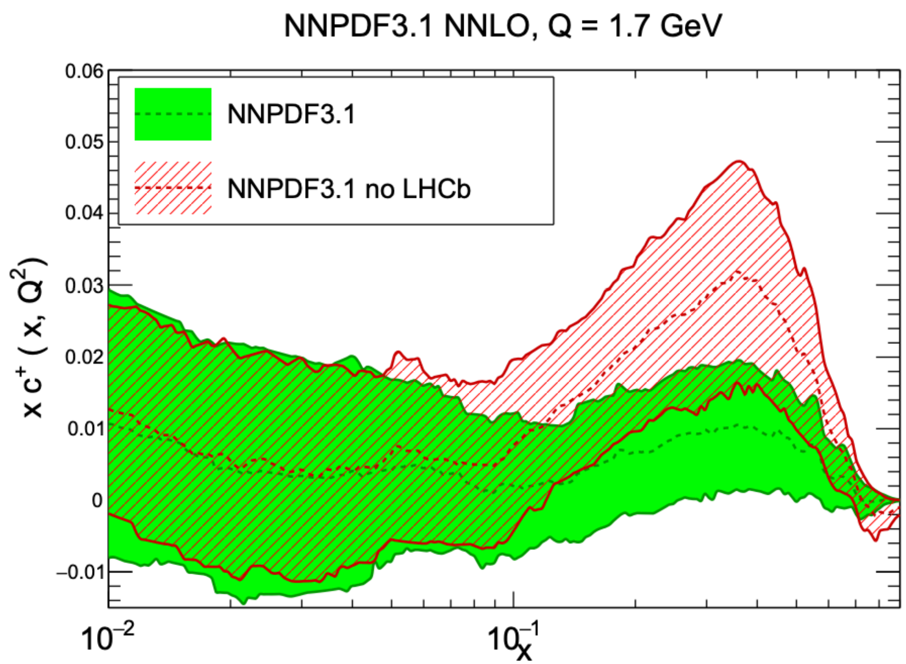
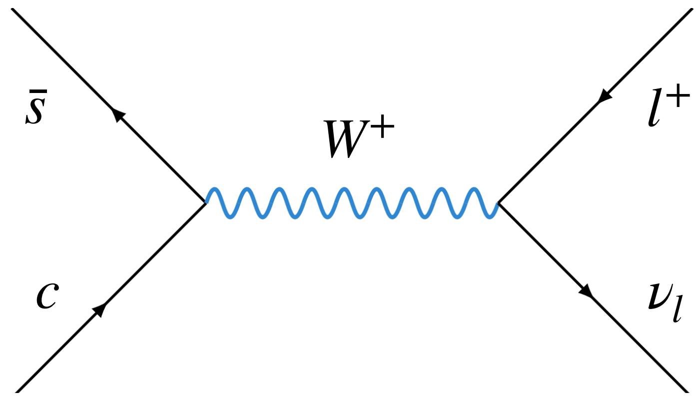


Inclusive DY

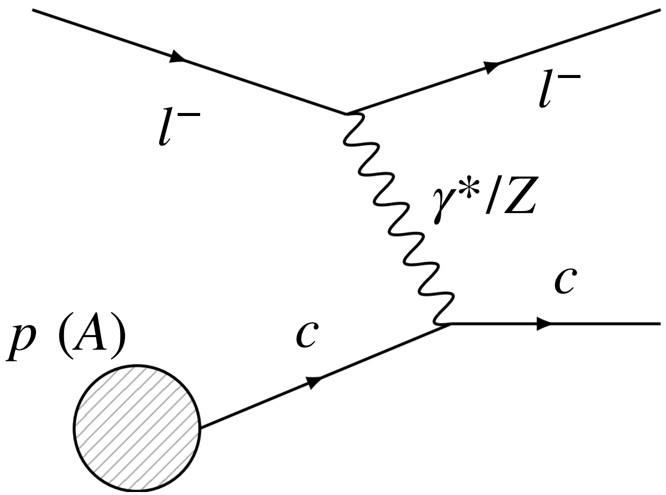


Indirect sensitivity, but high-precision measurements available

LHCb data in forward region specially powerful

Constraining charm

Charm production in DIS



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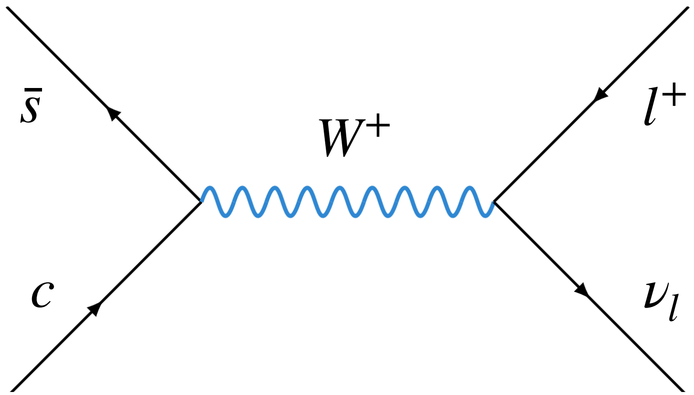
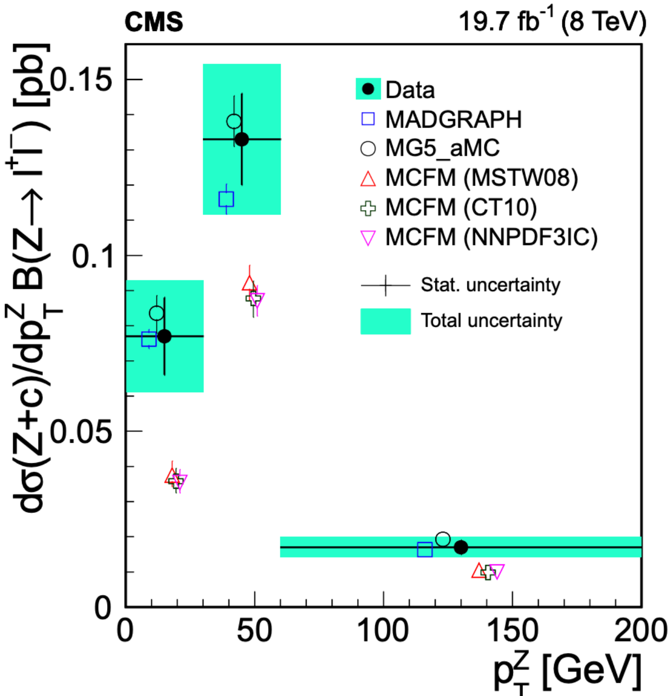
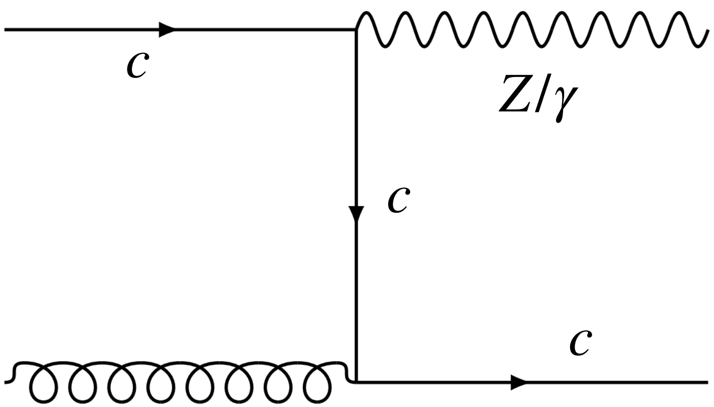


Direct sensitivity, but requires going to **high-p_T**

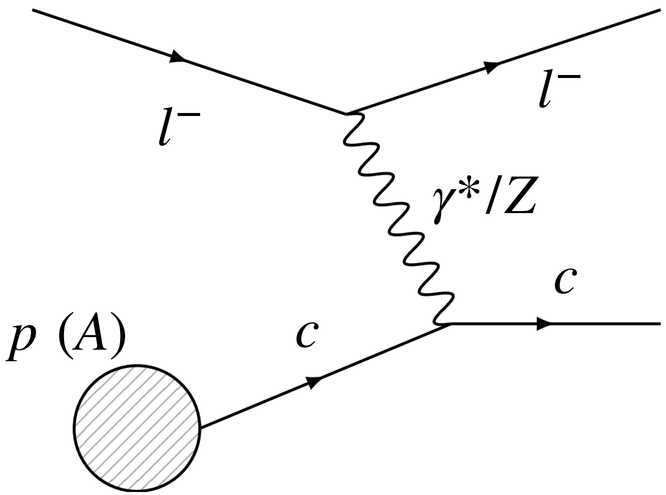


Z/γ+charm



Constraining charm

Charm production in DIS



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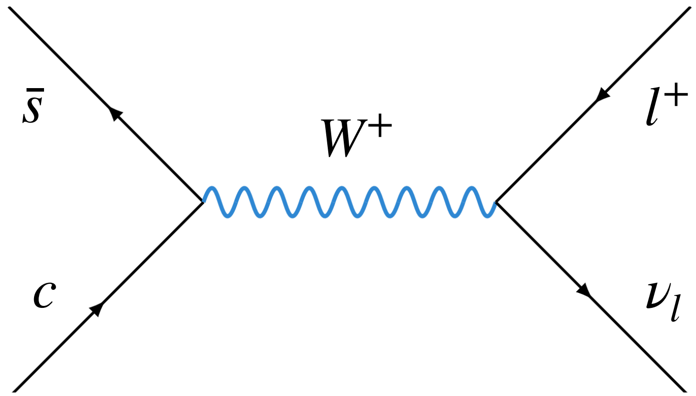

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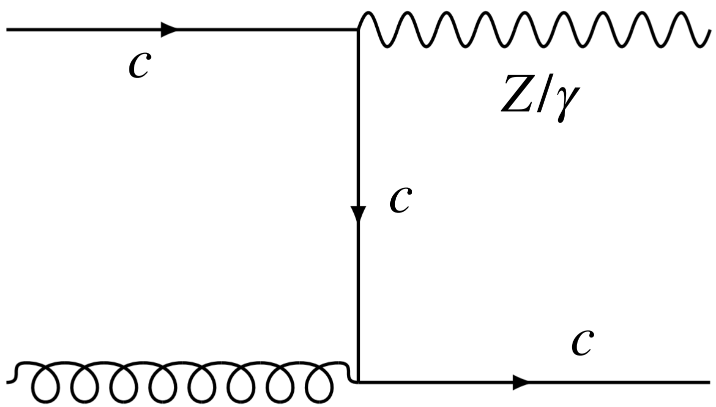

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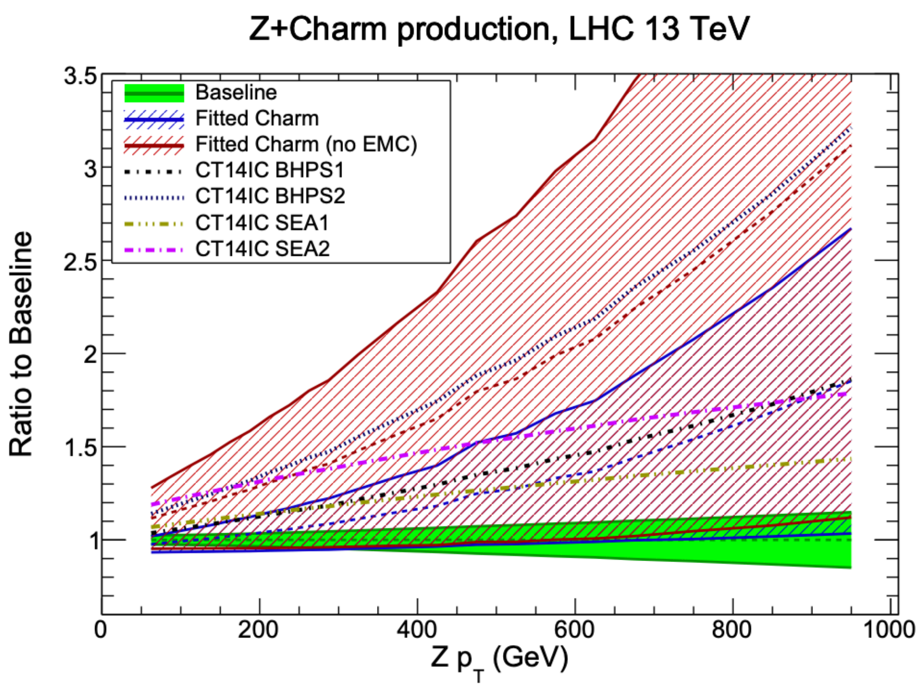
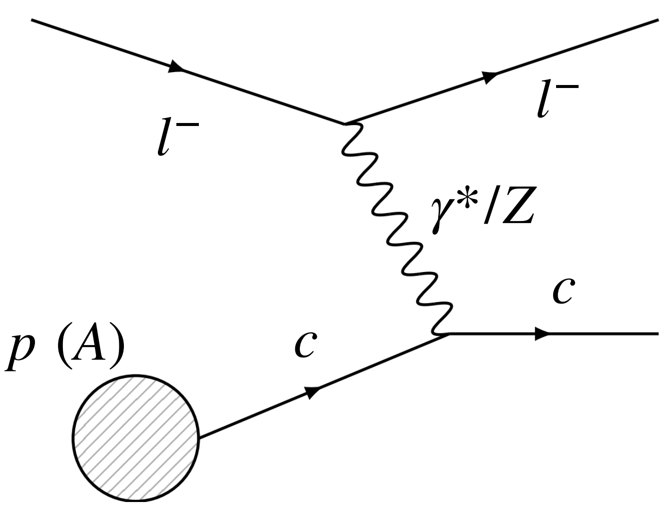


Constraining charm

Charm production in DIS



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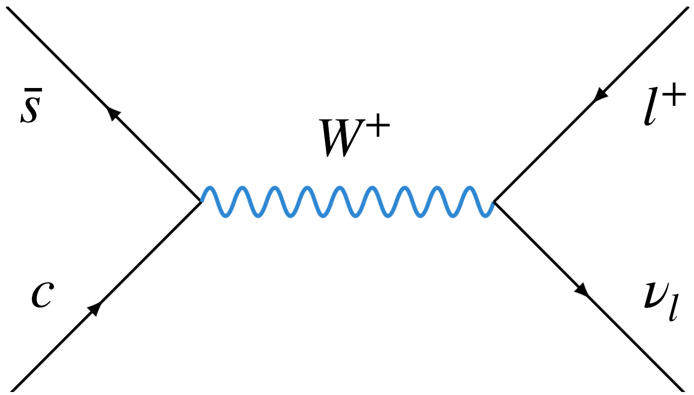
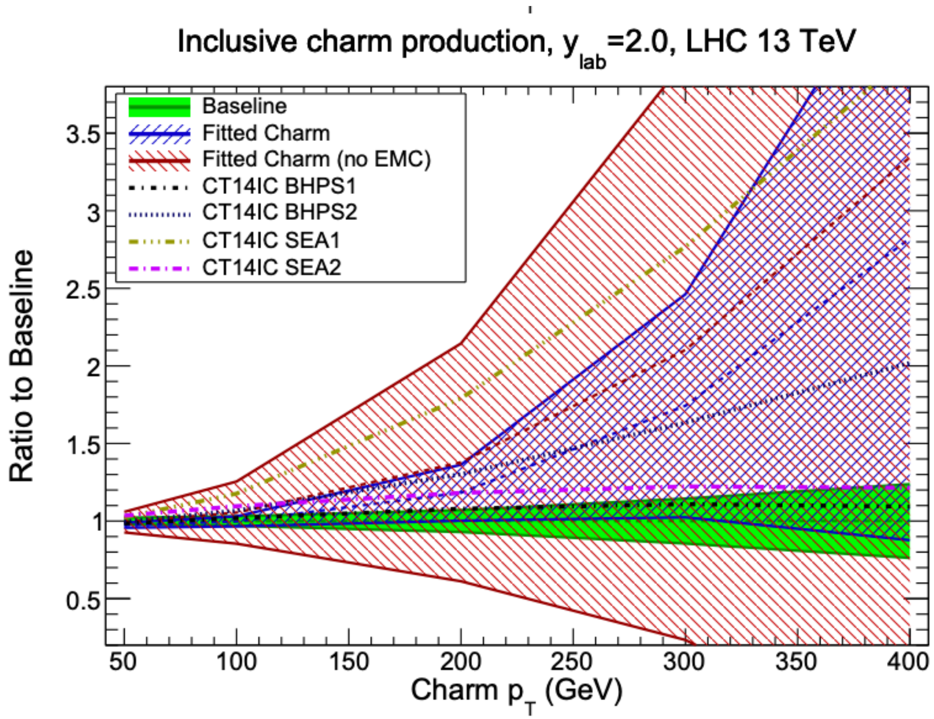
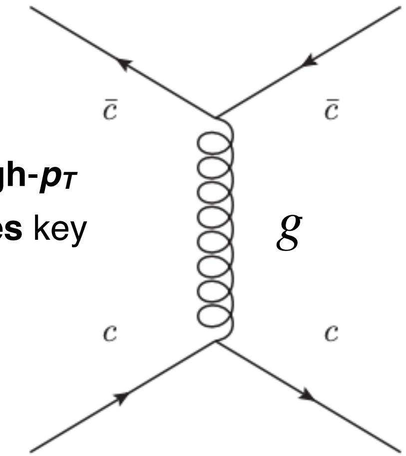


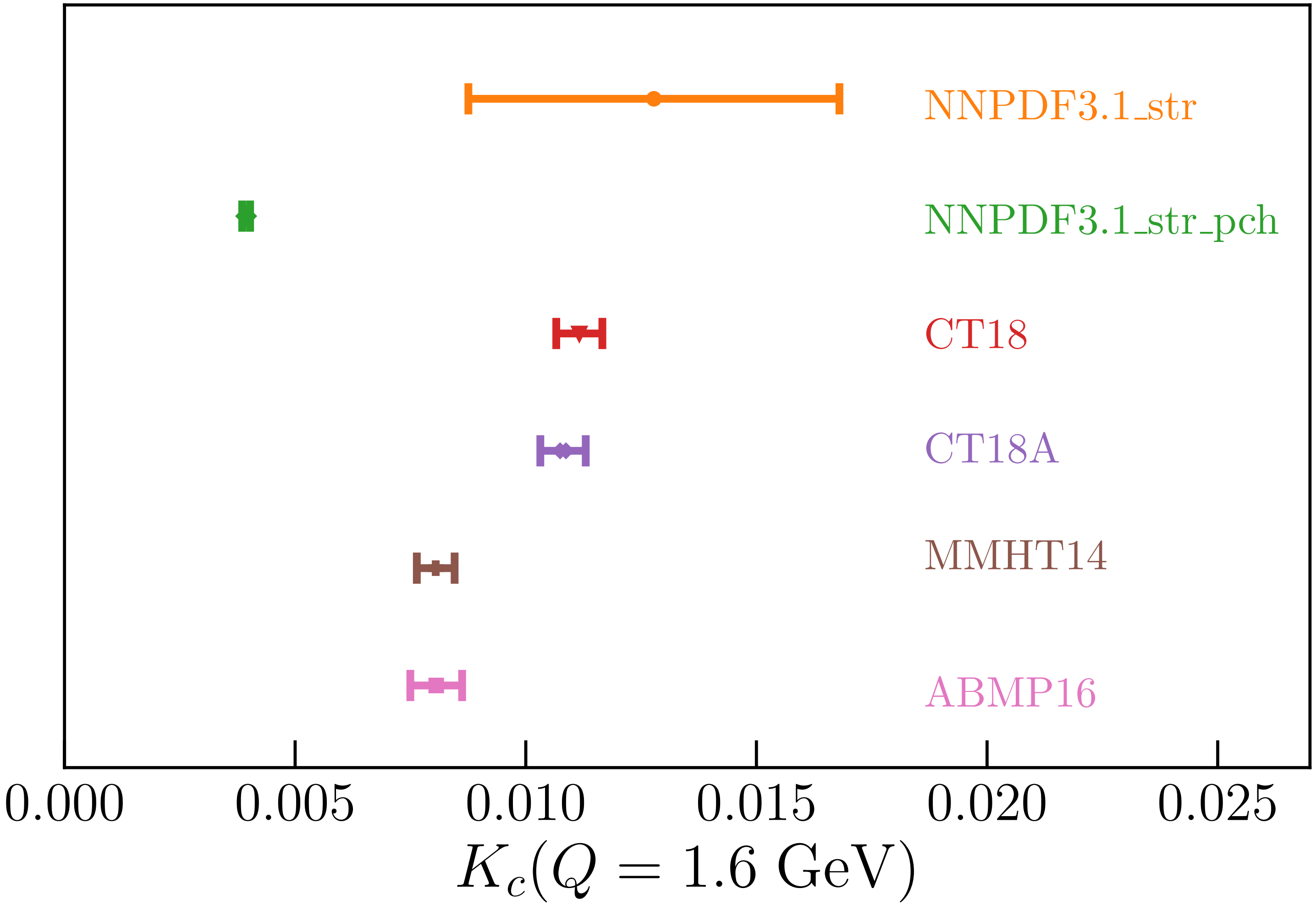


Open charm production

also here going to **high-p_T** and/or **large rapidities** key to optimise sensitivity



How charming is the proton?



fitted charm

perturbative charm

perturbative charm

perturbative charm

perturbative charm

perturbative charm

$$K_c(Q) \equiv \frac{\int_0^1 dx\ (c + \bar{c})}{\int_0^1 dx\ \left(u^+ + d^+ + s^+\right)}$$

momentum fraction carried by charm in units of that of the light quarks

different for each group

- ☑ perturbative charm results are sensitive to choice of value of charm mass
- ☑ current data favour a **non-zero charm component** in the n_f=3 scheme

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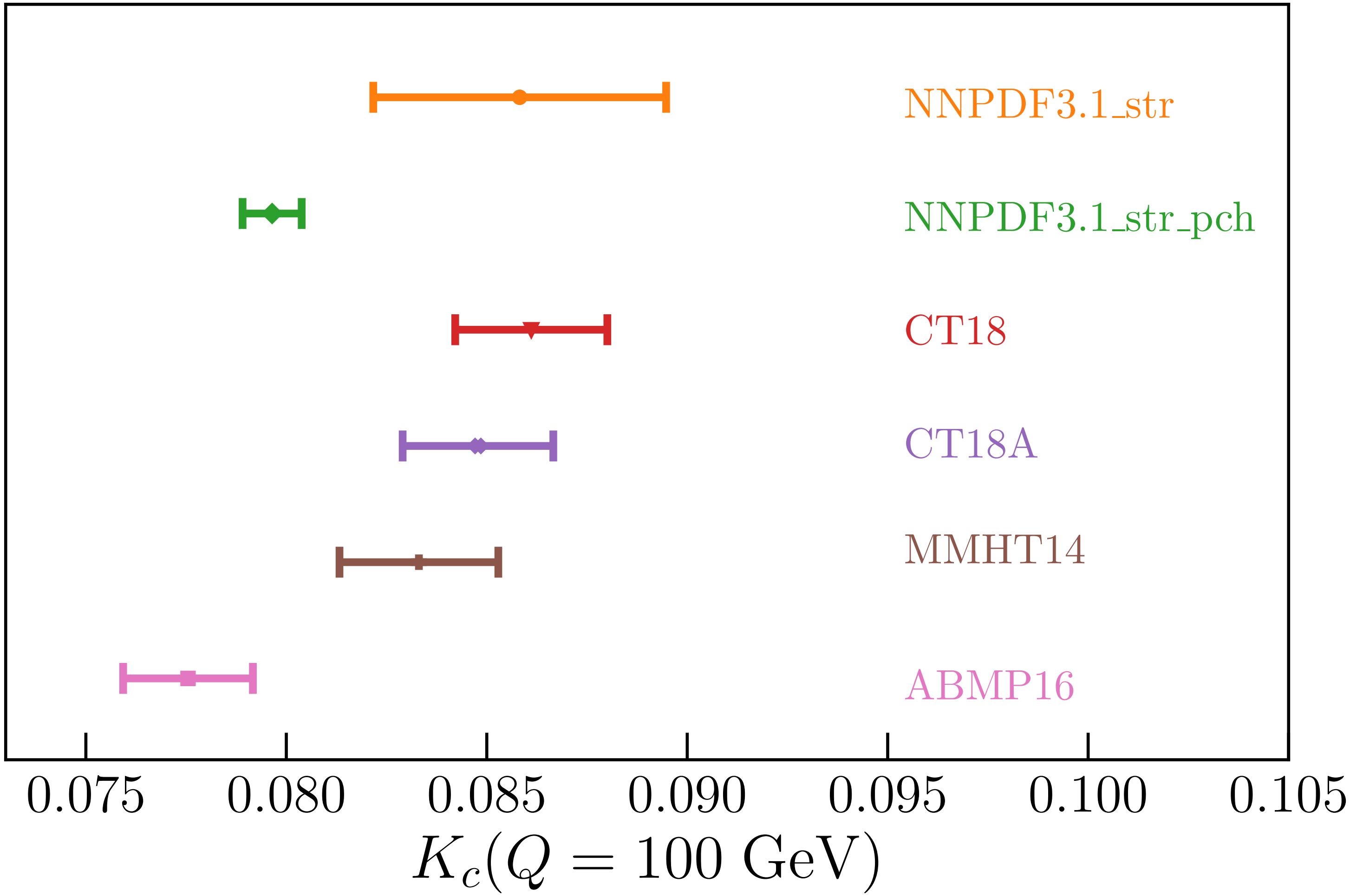

fitted charm

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perturbative charm

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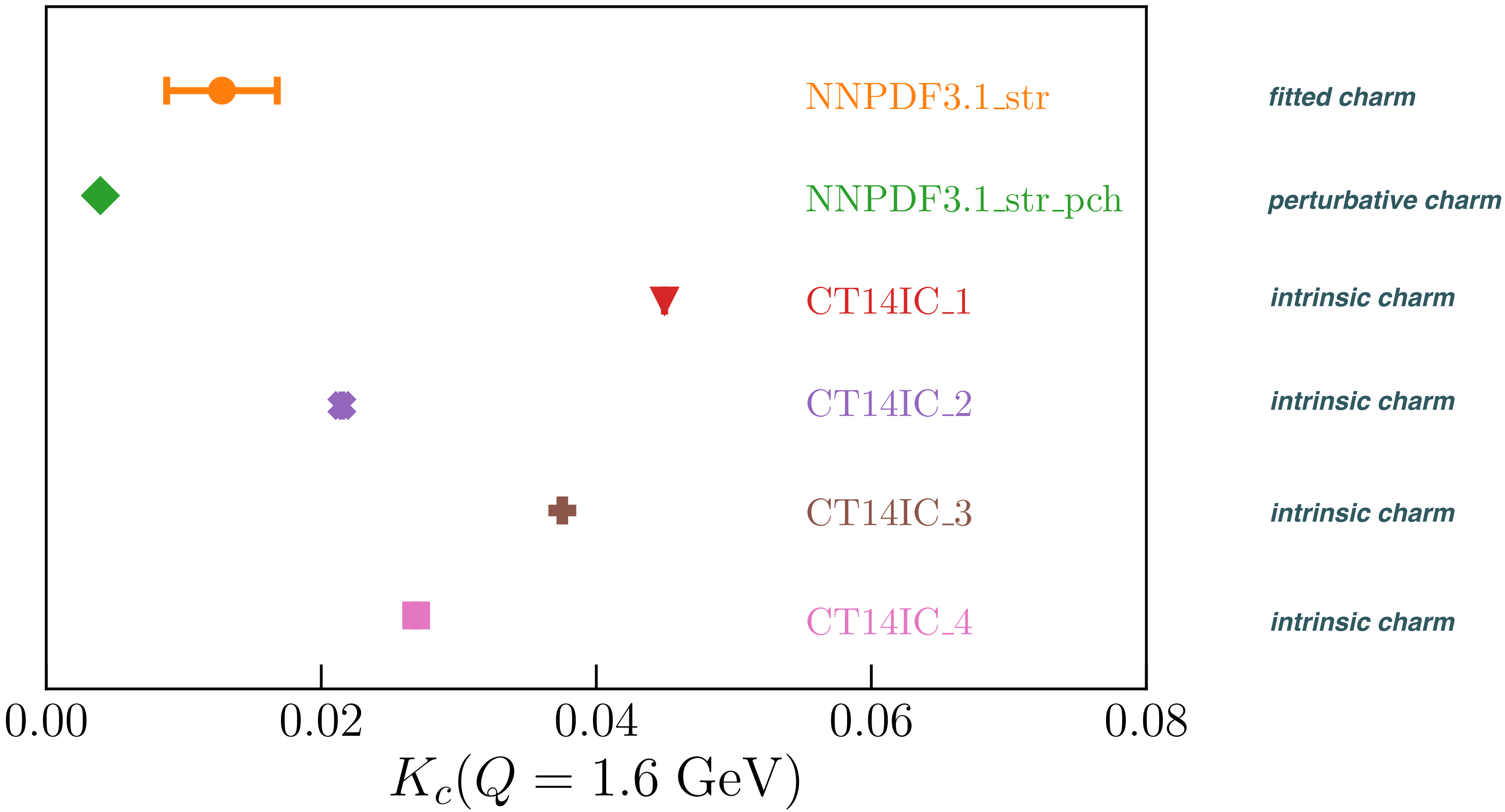
$$K_c(Q) \equiv \frac{\int_0^1 dx\ (c+\bar{c})}{\int_0^1 dx\ \left(u^+ + d^+ + s^+\right)}$$

momentum fraction carried by charm in units of that of the light quarks

- ☑ perturbative charm results are sensitive to choice of value of charm mass
- ☑ current data favour a **non-zero charm component** in the n_f=3 scheme

How charming is the proton?



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- ☑ The **most extreme IC models** from CT14 are in marked tension with the NNPDF3.1 fitted charm
- ☑ (Some of these models are extreme on purpose)

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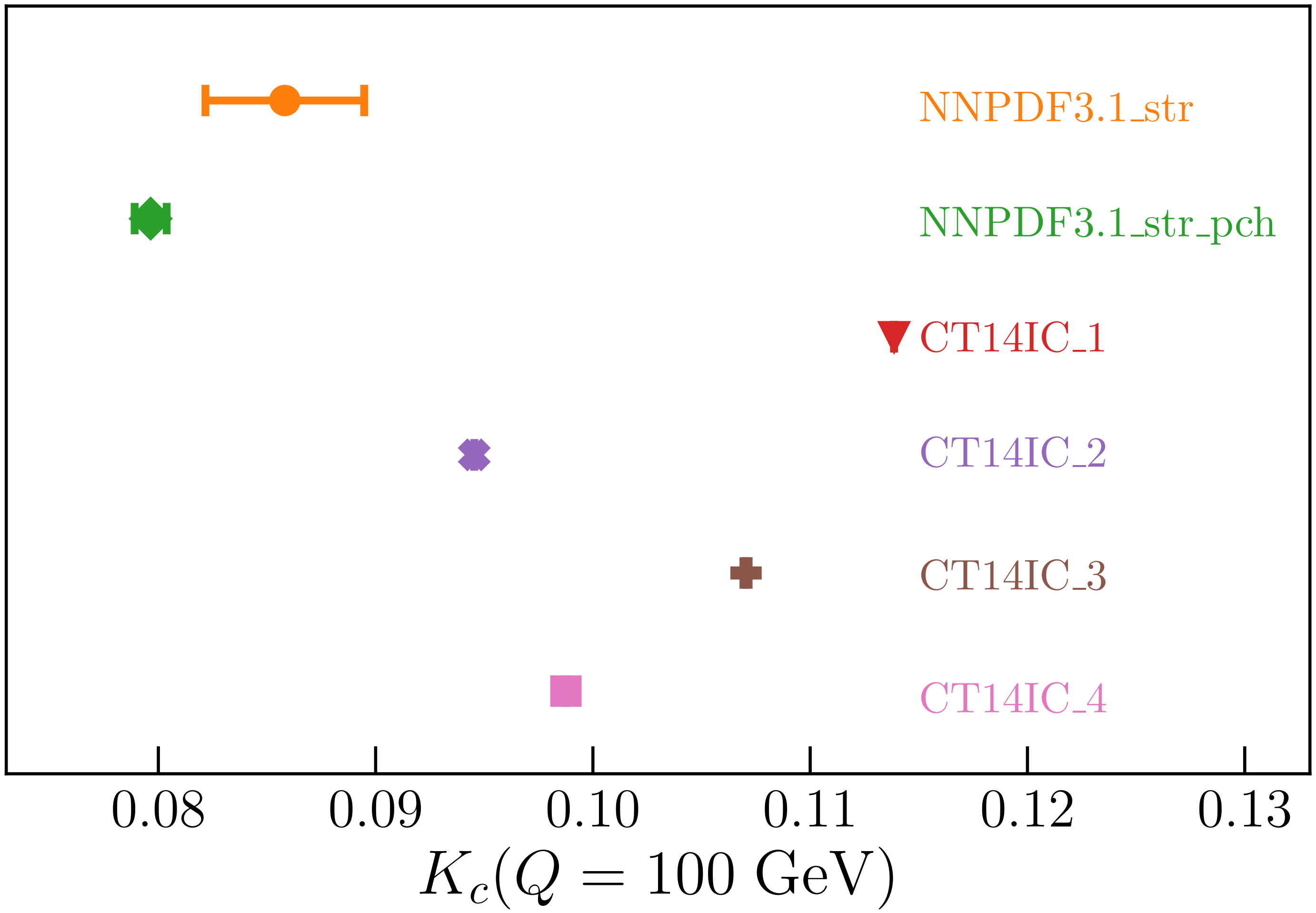

fitted charm

perturbative charm

intrinsic charm

intrinsic charm

intrinsic charm

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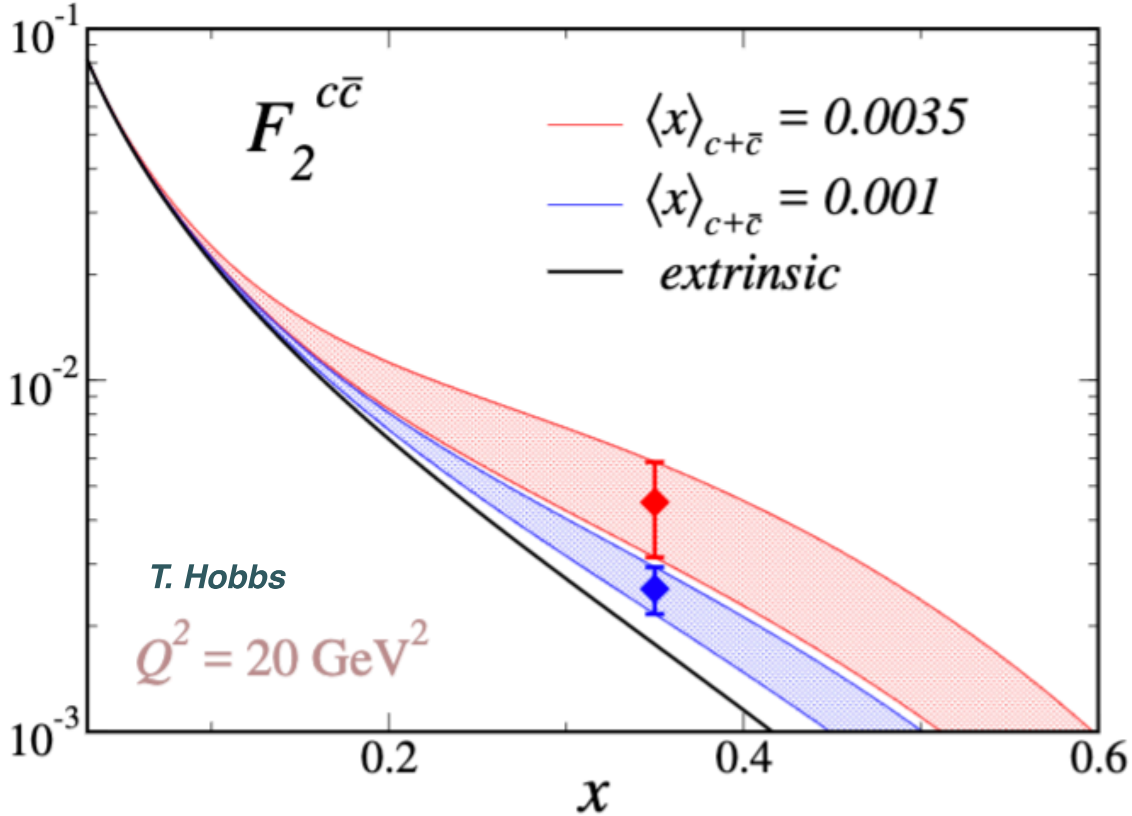
Charm @ EIC

Can **future EIC measurements** provide information about the proton charmness?



from EIC Yellow Report, in preparation

- Plenty of exciting opportunities to **constrain charmness at the EIC**
- In particular, the measurement of the **charm structure function at large-*x*** provides a very clean probe of the charm PDF and its various possible modifications

The bottom PDF

Intrinsic bottom?

Our considerations about the charm PDF (perturbative vs fitted vs intrinsic) apply equally well to the bottom PDF, though here on expects deviations from the perturbative picture to be quite suppressed

In **all PDF analysis to date**, the bottom PDF is always **generated dynamically via DGLAP** from light quarks and gluons

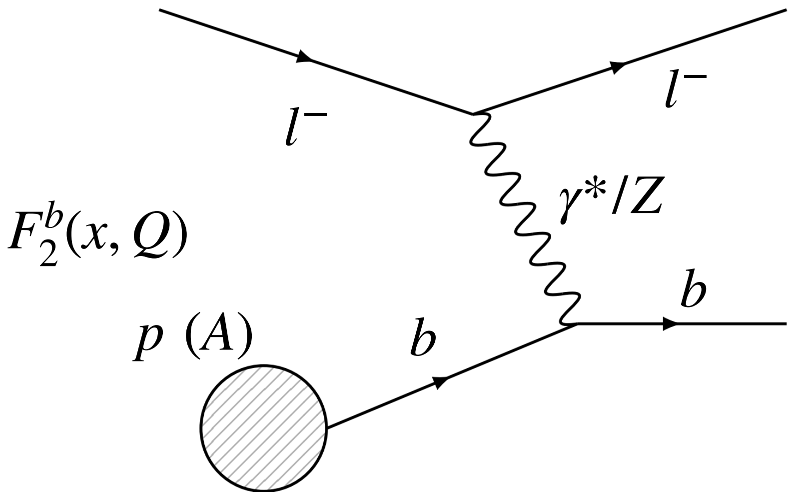
$$f_b^{(n_f+1)} \propto \alpha_s \ln \frac{Q^2}{m_b^2} \left(P_{qg} \otimes f_g^{(n_f+1)} \right) + \mathcal{O}\left(\alpha_s^2\right)$$

Assume that there is a "**non-perturbative**" component to the bottom PDF.
How we could constrain it?

same as for strange and charm: look for processes directly or indirectly sensitive to **bottom quarks in the initial state of the reaction**

Constraining bottom

Bottom production in DIS



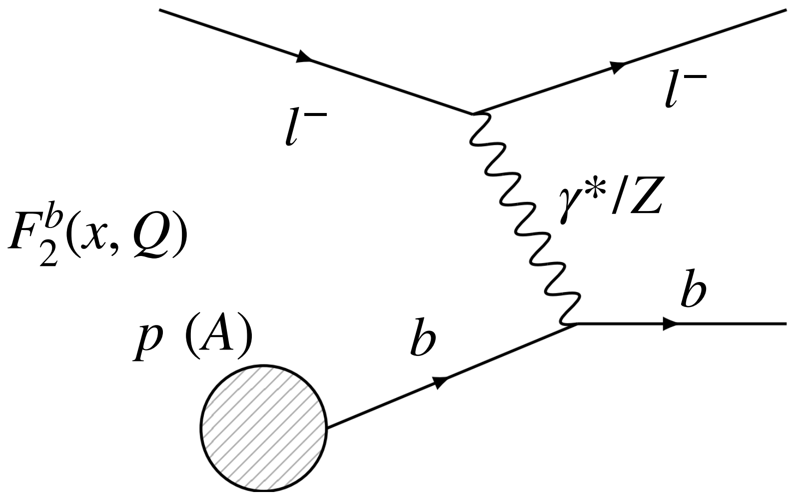
much smaller rates than for charm…..

e.g. at HERA charm can be up to 25%

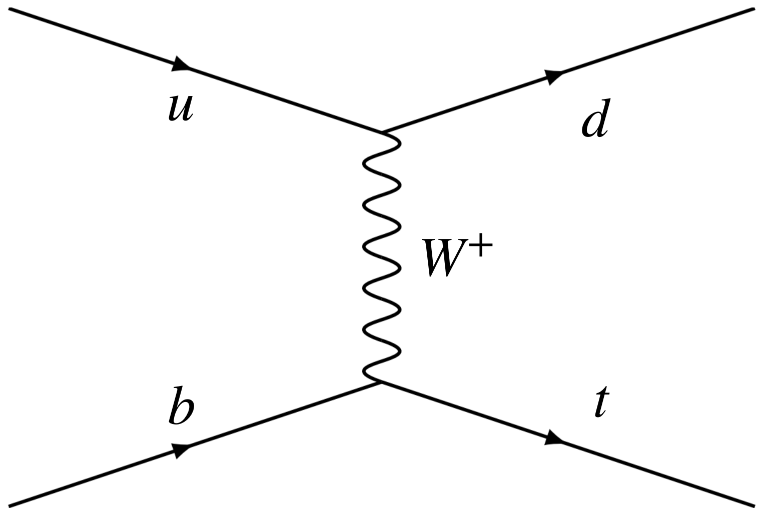
while bottom is 1%

Constraining bottom

Bottom production in DIS



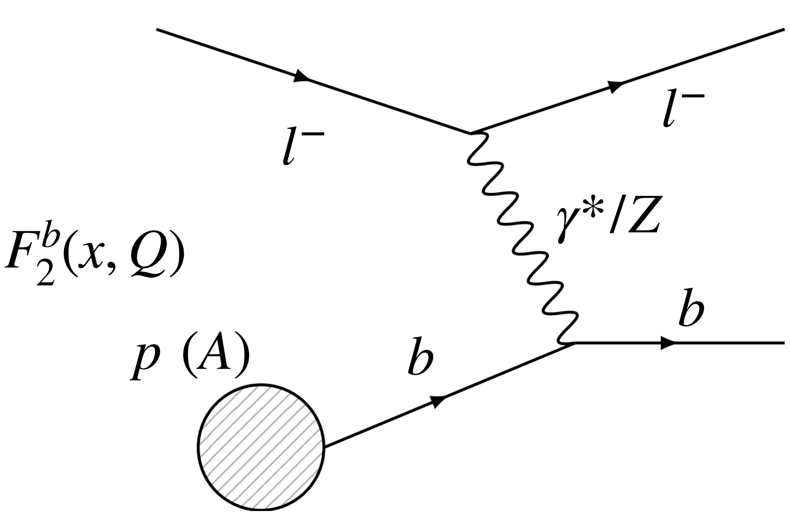
Single top production



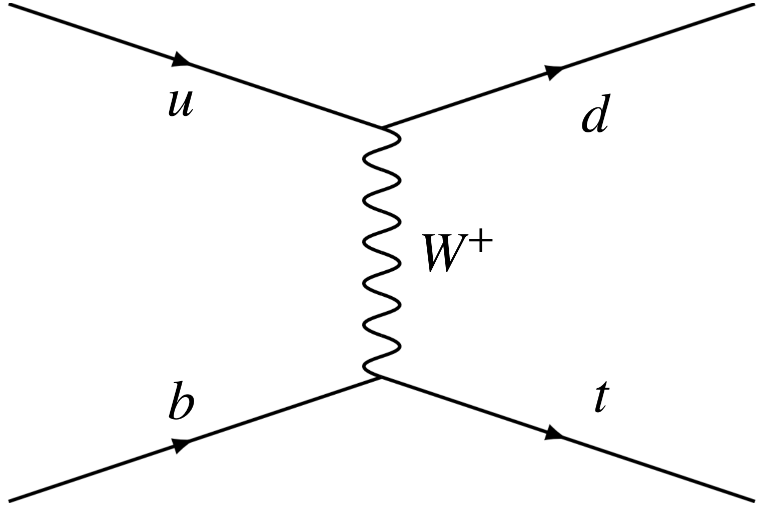
requires **matched scheme** to account for bottom quark mass corrections

Constraining bottom

Bottom production in DIS



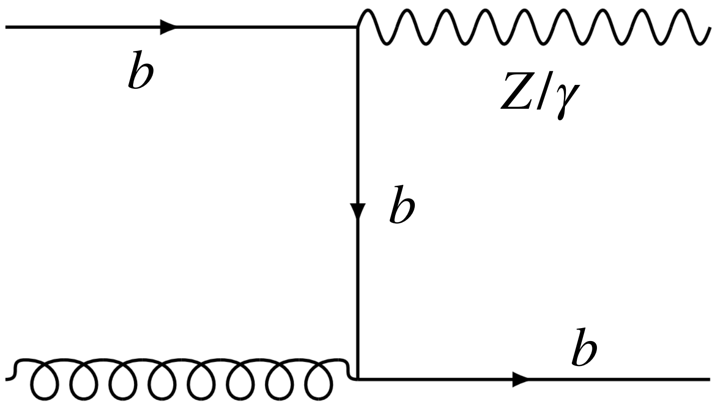
Single top production

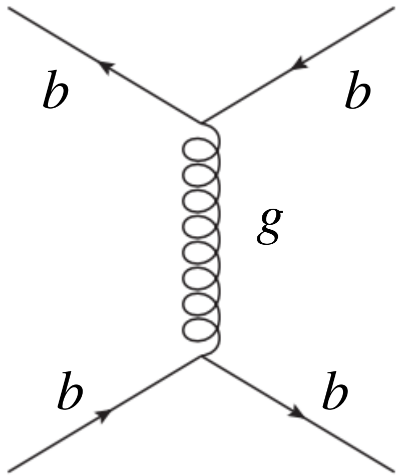


Z/γ+bottom

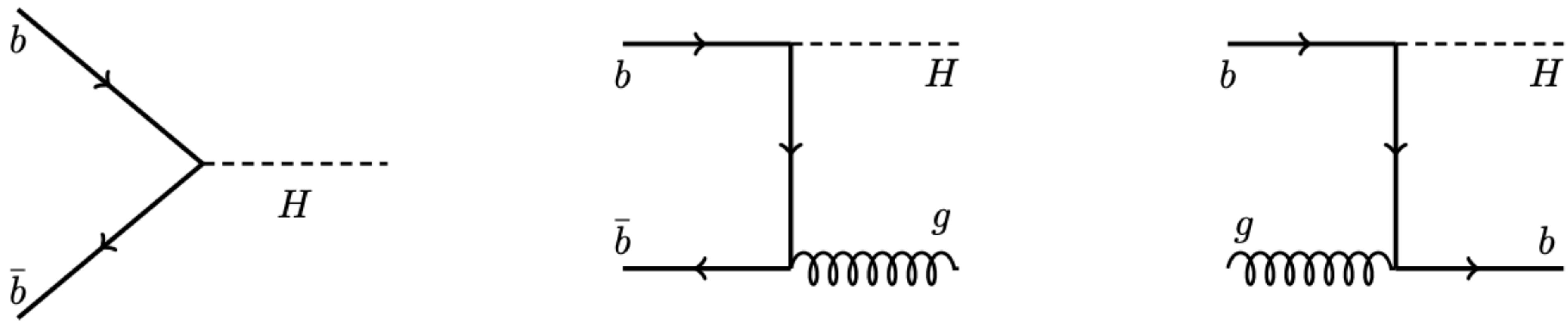
so far no one has interpreted these processes assuming an **``intrinsic'' bottom PDF ....**

Open charm production



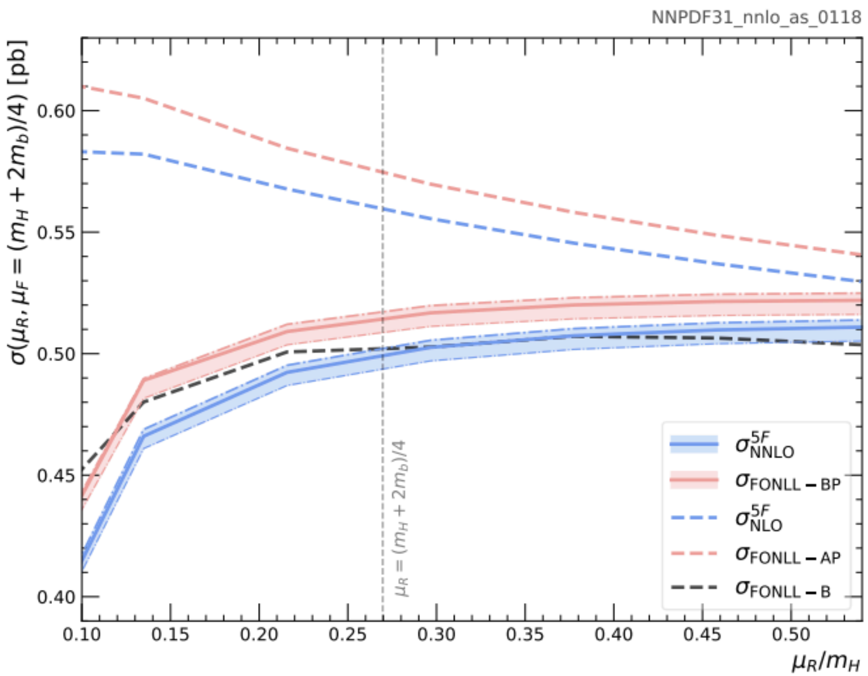


Impact of parametrised bottom



It has been recently shown, for the case of **Higgs production in bottom fusion**, how a matched scheme for processes involving initial-state bottom quarks simplifies the calculation provided a **fitted bottom PDF is introduced**

Forte, Giani, Napoletano 19



Irrespective of whether or not the proton contains a non-perturbative bottom component, **fitting the bottom PDF** might be advantageous for precision phenomenology

Summary and outlook

The accurate determination of **heavy flavour PDFs** is an essential ingredient for **LHC phenomenology** and will play a key role for the **EIC physics program**

- ☑ A global interpretation of strangeness-sensitive processes reveals a nice **overall consistency** and the lack of any significant tension
- ☑ In particular, the NOMAD neutrino DIS data imposes stringent constraints, without worsening description of collider data
- ☑ Going further requires accounting for SIDIS data: **simultaneous PDF+FF determination**
- ☑ Much progress in theoretical and phenomenological understanding of the **charm PDF**, with several measurements providing direct information (but still open issues)
- ☑ Some **preference for a non-perturbative charm component**, but most extreme IC models disfavoured by LHC data
- ☑ **Fitting the bottom PDFs** has never been attempted: could be beneficial for precision LHC phenomenology!

Summary and outlook

The accurate determination of **heavy flavour PDFs** is an essential ingredient for **LHC phenomenology** and will play a key role for the **EIC physics program**

The Electron Ion Collider will open a new frontier for heavy flavour PDF studies!