What hides inside a proton? From heavy quarks and photons to leptons and Higgs bosons

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Graduate School Seminar series

Albert-Ludwigs-Universitat Freiburg

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Outline

Part I: parton distributions and proton structure

introductory material (pre-recorded)

- Why parton distributions?
- Deep-inelastic scattering and QCD factorisation
- Selected phenomenological applications

Part II: rare partonic components of the proton

- Heavy quarks in the proton: strange, charm, bottom
- Photons and leptons, and their many uses
- The proton at the TeV scale: from Higgs bosons to top quarks as patrons

Part I: Parton Distributions and Proton Structure

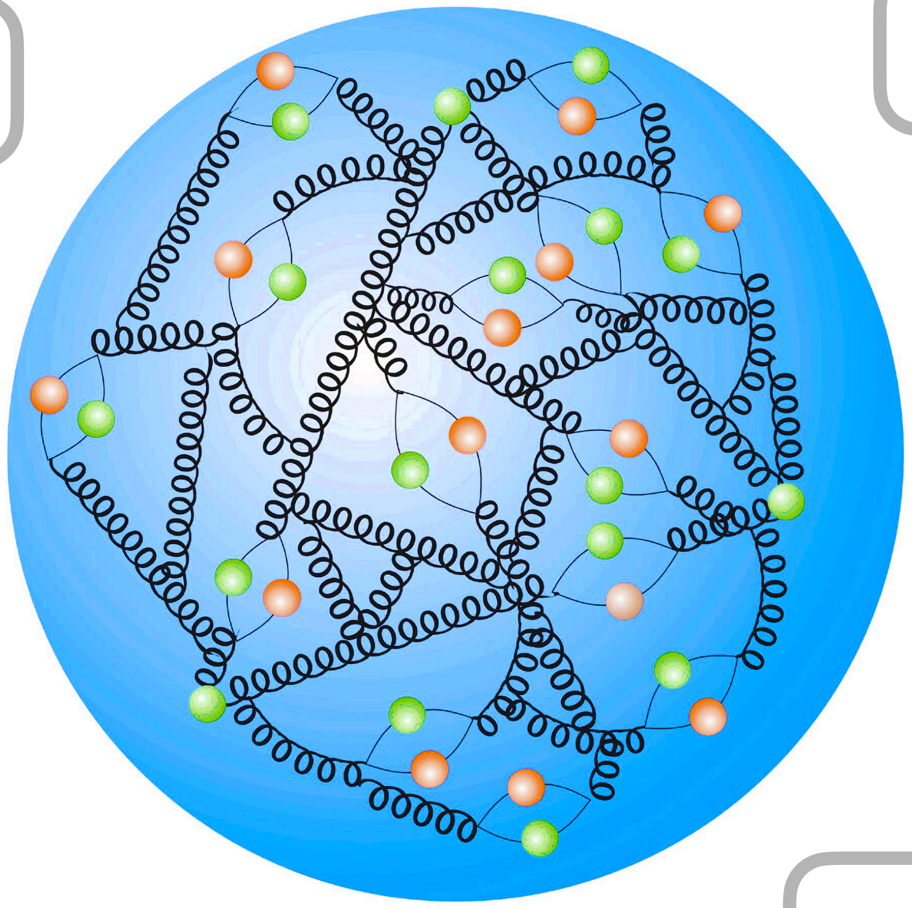
The inner life of protons

The many faces of the proton

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

Origin of mass?

Origin of spin?



Gluon-dominated matter?

3D imaging?

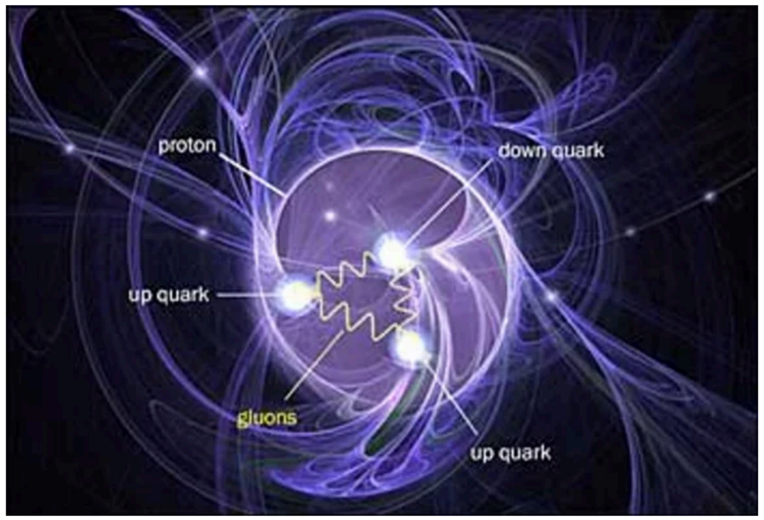
Heavy quark content?

Nuclear modifications?

The proton in the spotlight

THE SCIENCES

Proton Spin Mystery Gains a New Clue



Non-zero gluon polarisation

Scientific American (2014)

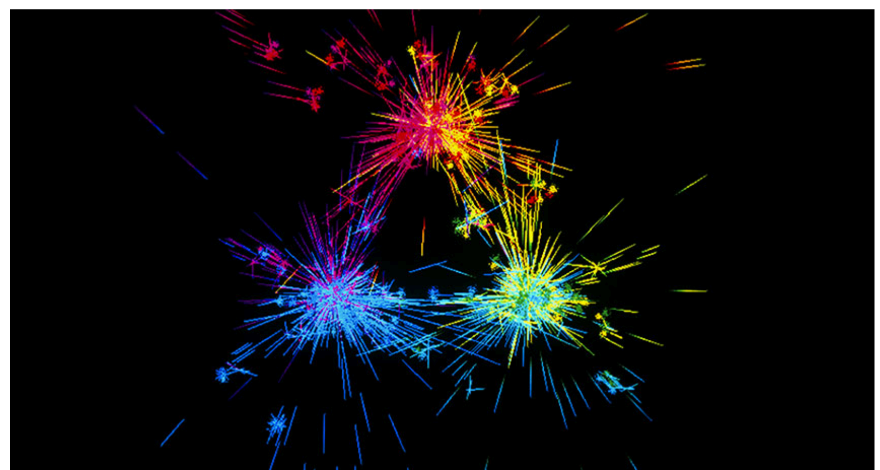
Nucleon pressure

NEWS PARTICLE PHYSICS

The inside of a proton endures more pressure than anything else we've seen

For the first time, scientists used experimental data to estimate the pressure inside a proton

BY EMILY CONOVER 1:18PM, MAY 16, 2018

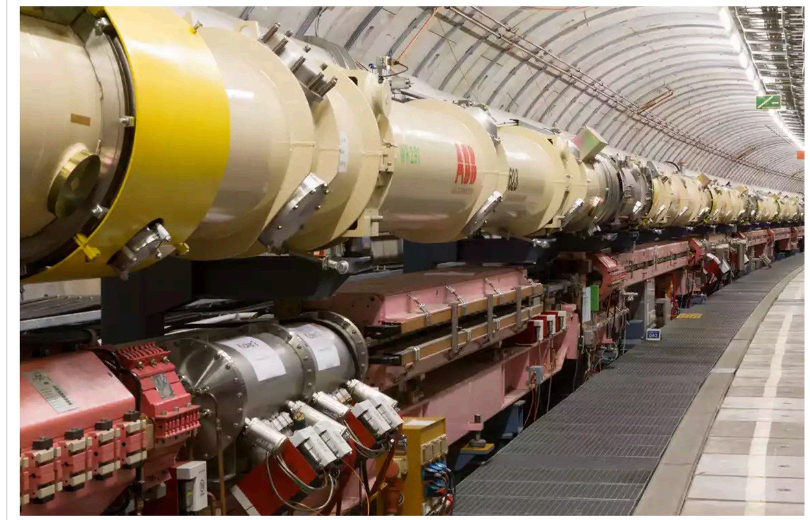


FEELING THE PRESSURE Extreme pressures are found within the proton, scientists report. The proton contains three particles called quarks (illustrated) as well as gluons, which hold the particle together.

Science News (2018)

After 40 years of studying the strong nuclear force, a revelation

This was the year that analysis of data finally backed up a prediction, made in the mid 1970s, of a surprising emergent behaviour in the strong nuclear force

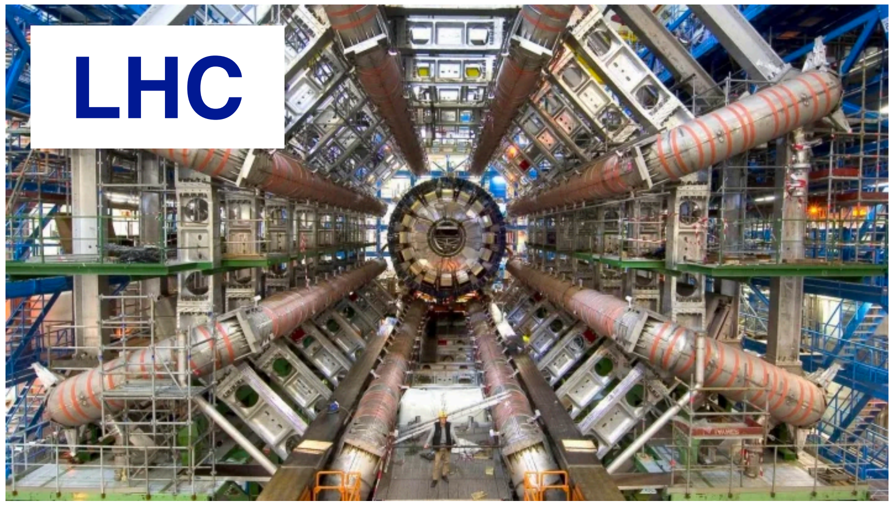


BFKL dynamics

The Guardian (2017)

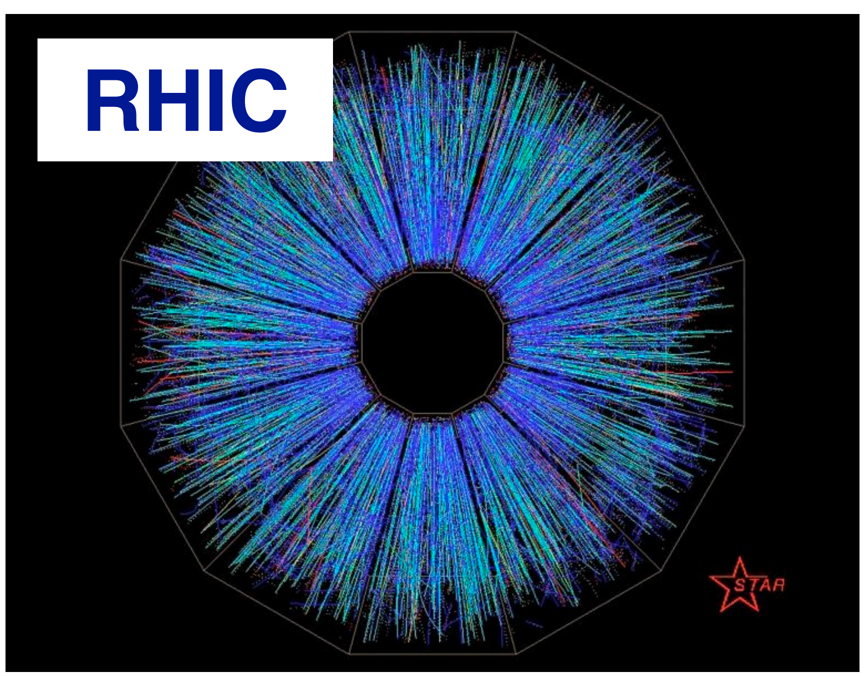
The proton keeps surprising us as an endless source of **fundamental discoveries**

From colliders to the cosmos



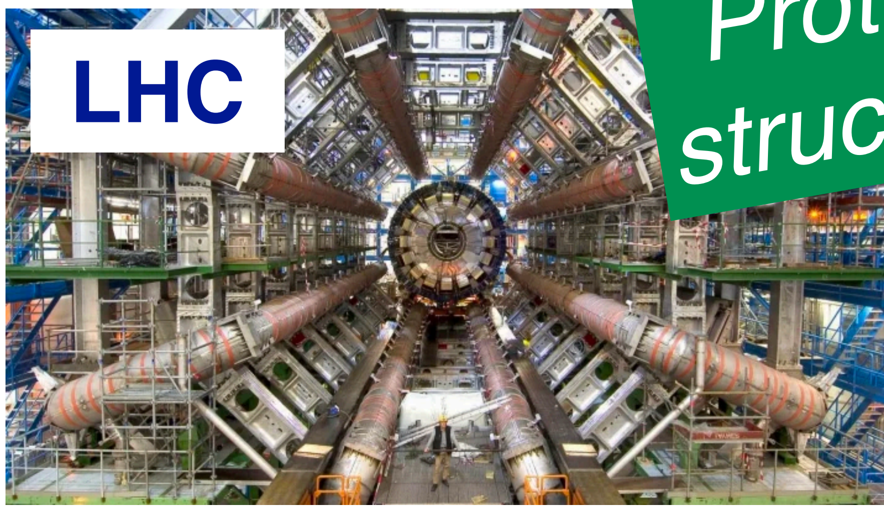
New **elementary particles** beyond the **Standard Model?**

Origins and properties of **cosmic neutrinos**?



Nature of **Quark-Gluon Plasma** in **heavy-ion collisions?**

From colliders to the cosmos



New **elementary particles** beyond the **Standard Model?**

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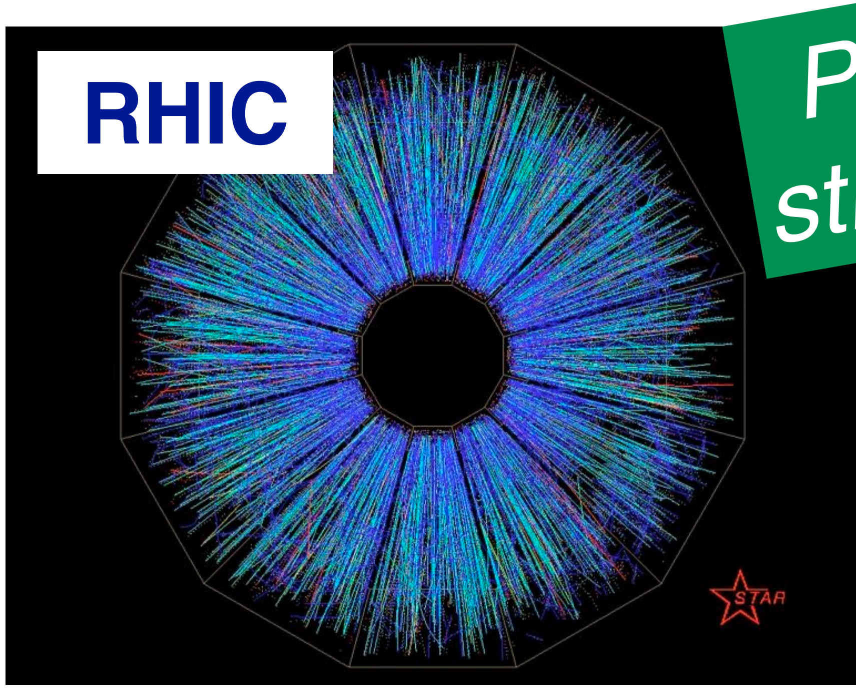
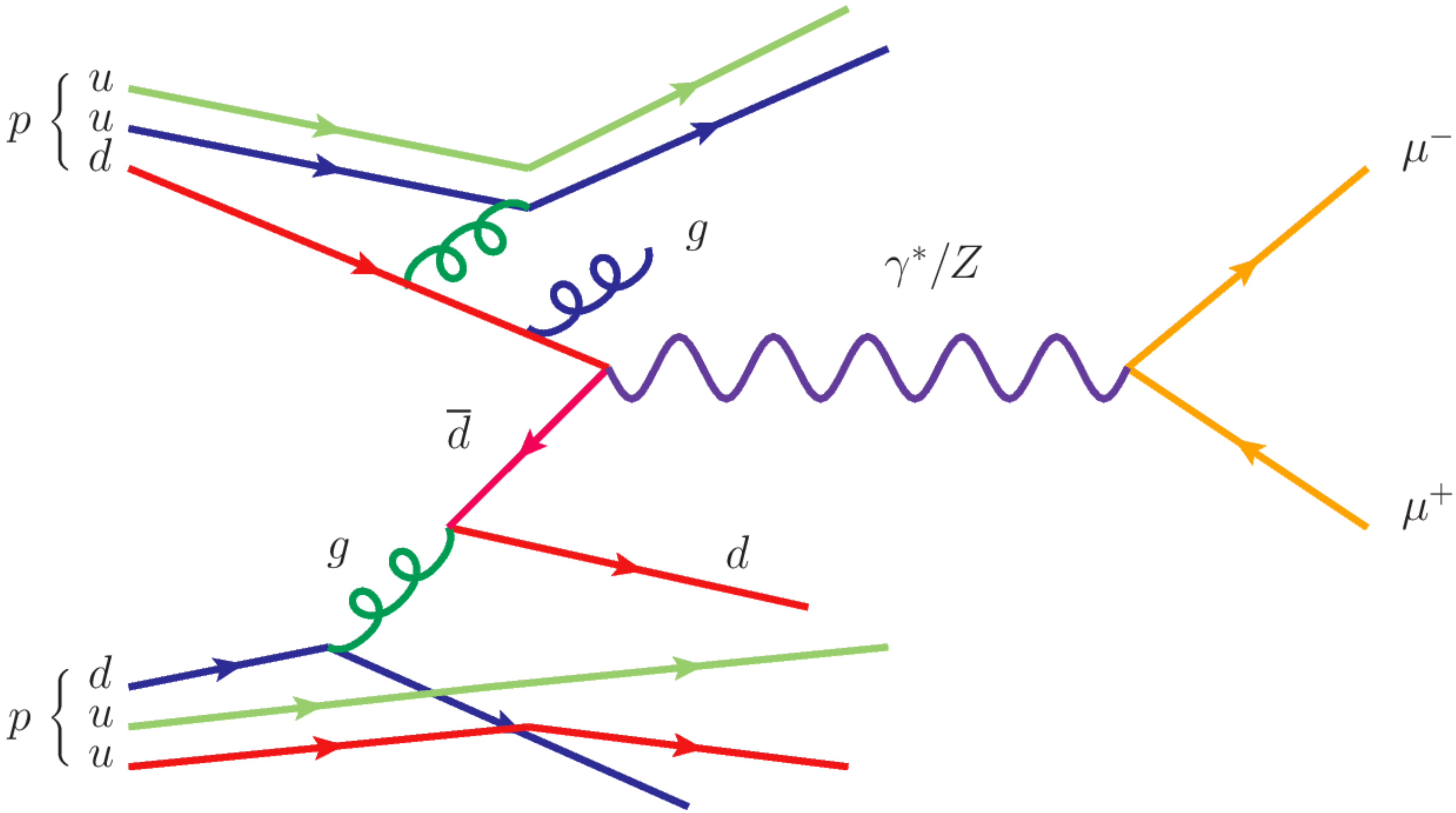


Nature of **Quark-Gluon Plasma** in **heavy-ion collisions?**

QCD factorisation and parton distributions

Parton Distributions

In high-energy **hadron colliders**, such as the LHC, the collisions involve **composite particles** (protons) with **internal structure** (quarks and gluons)



$$\frac{d\sigma(pp \to l^+l^-)}{dm_{ll}} = ?$$

Parton Distributions

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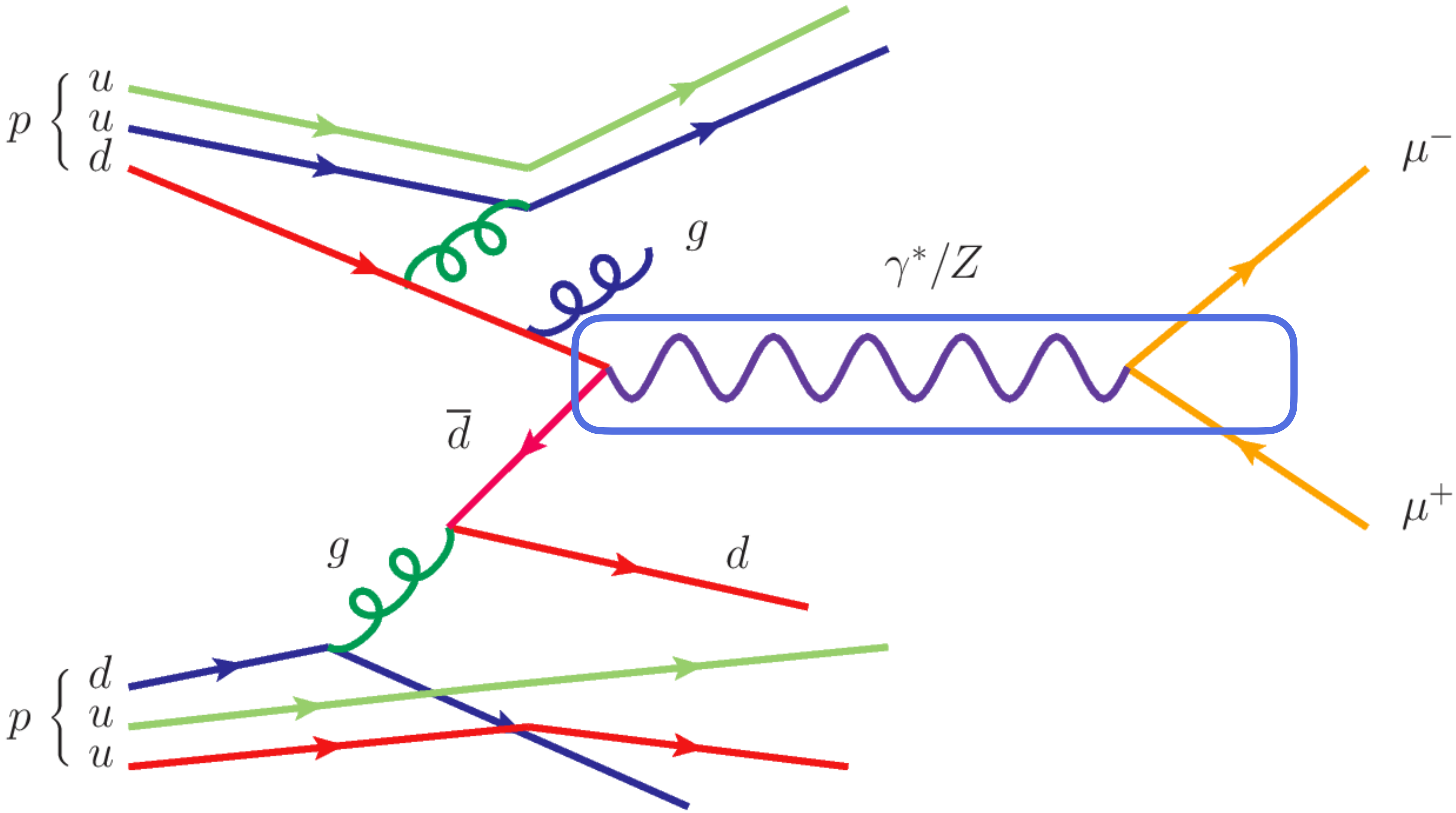
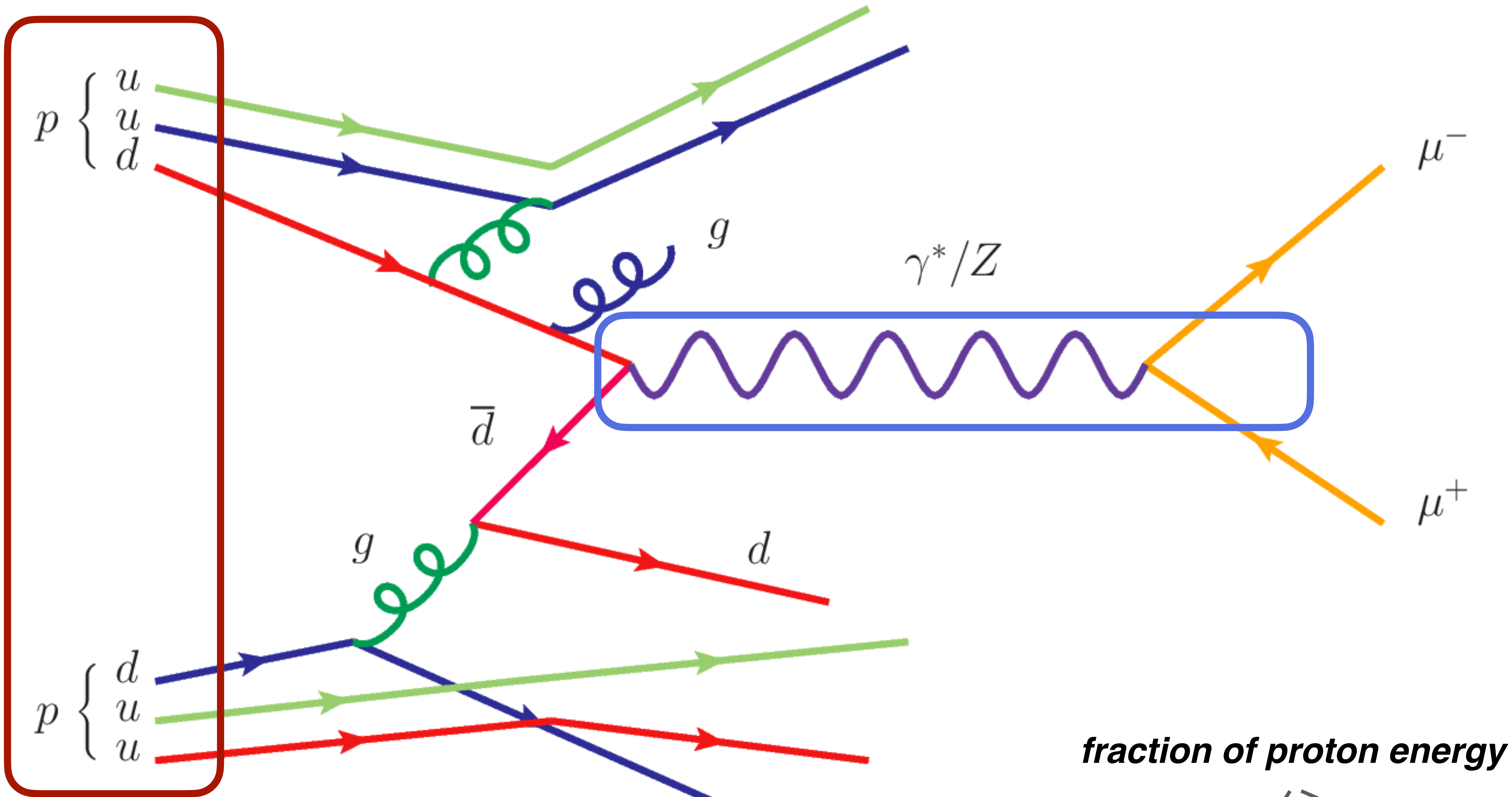


$$\frac{d\sigma(pp \to l^+l^-)}{dm_{ll}} = \frac{d\sigma(q_i\bar{q}_j \to l^+l^-)}{dm_{ll}} \otimes \ldots$$

Parton Distributions

In high-energy **hadron colliders**, such as the LHC, the collisions involve **composite particles** (protons) with **internal structure** (quarks and gluons)

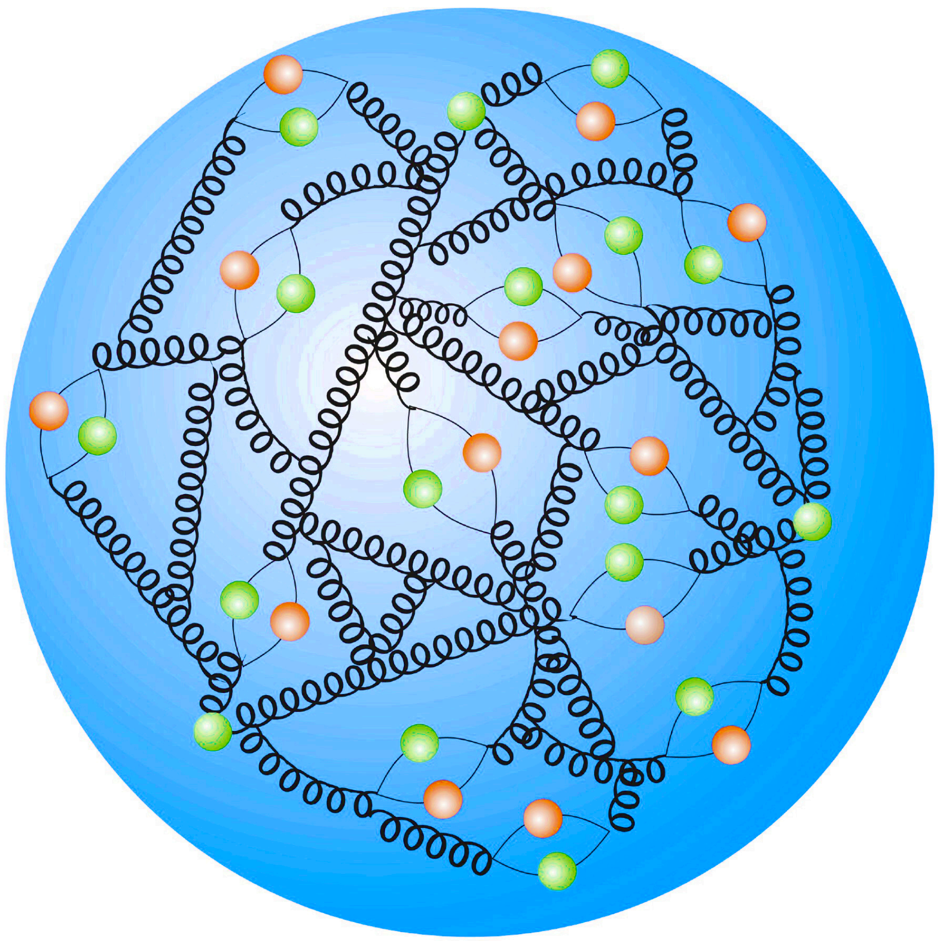


fraction of proton energy

$$\frac{d\sigma(pp \to l^+l^-)}{dm_{ll}} = \frac{d\sigma(q_i\bar{q}_j \to l^+l^-)}{dm_{ll}} \otimes \text{Prob}(q_i, x_1) \otimes \text{Prob}(\bar{q}_j, x_2)$$

Parton Distributions

Proton energy divided among constituents: **quarks** and **gluons**



Parton Distribution Functions (PDFs)

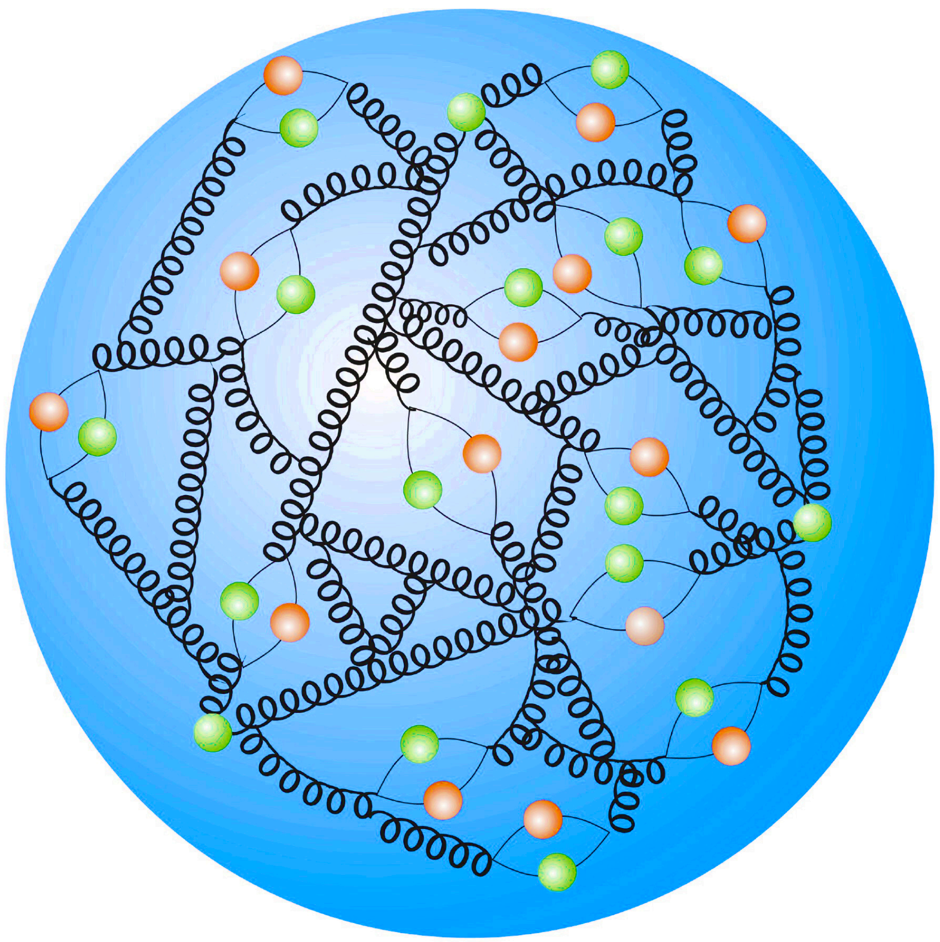
↓

Determine from **data:**

Global QCD analysis

Parton Distributions

Proton energy divided among constituents: **quarks** and **gluons**



Parton Distribution Functions (PDFs)

↓

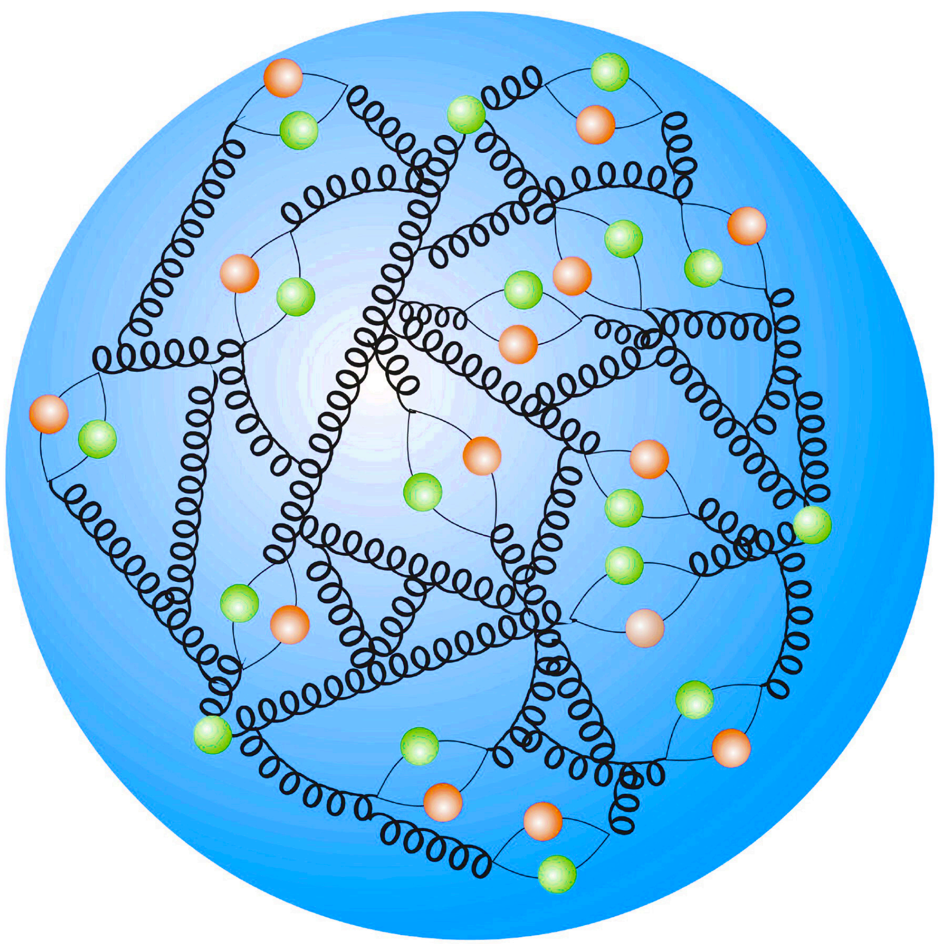
Determine from **data:**

Global QCD analysis

Lattice QCD starting to also make an impact

Parton Distributions

Proton energy divided among constituents: **quarks** and **gluons**



Parton Distribution Functions (PDFs)

Determine from **data:**

Global QCD analysis

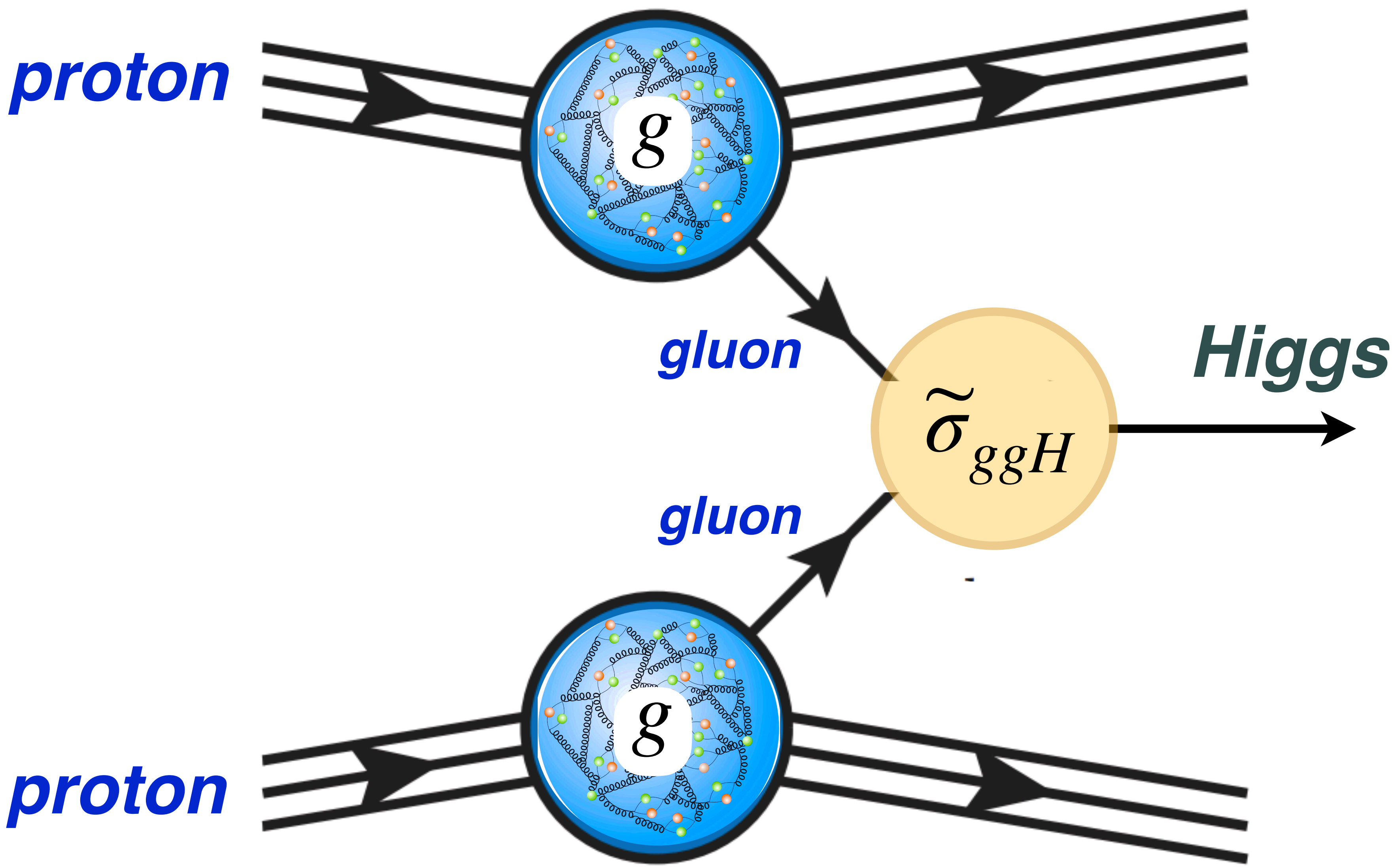
Mass? Spin?
Heavy quark content?
Novel QCD dynamics?

Theoretical predictions for LHC, RHIC, IceCube?

Parton Distributions

$$N_{\mathrm{LHC}}(H) \sim g \otimes g \otimes \tilde{\sigma}_{ggH}$$

Parton Distributions



All-order structure: **QCD factorisation theorems**

Parton Distributions

$$g(x, Q)$$

Probability of **finding a gluon inside a proton**, carrying a fraction ***x*** of the proton momentum, when probed with energy ***Q***

x: fraction of proton momentum carried by gluon

Energy of hard-scattering reaction**:** inverse of resolution length

Dependence on *x* fixed by **non-perturbative QCD dynamics**: extract from experimental data

- **Energy conservation**: momentum sum rule

$$\int_0^1 dx\, x \left(\sum_{i=1}^{n_f} \left[q_i((x, Q^2) + \bar{q}_i(x, Q^2) \right] + g(x, Q^2) \right) = 1$$

- **Quark number conservation**: valence sum rules

$$\int_0^1 dx\, \left(u(x, Q^2) + \bar{u}(x, Q^2) \right) = 2$$

Parton Distributions

$$g(x, Q)$$

Probability of **finding a gluon inside a proton**, carrying a fraction ***x*** of the proton momentum, when probed with energy ***Q***

x: fraction of proton momentum carried by gluon

Energy of hard-scattering reaction**:** inverse of resolution length

Dependence on ***Q*** fixed by **perturbative QCD dynamics**: computed up to $\mathcal{O}\left(\alpha_s^4\right)$

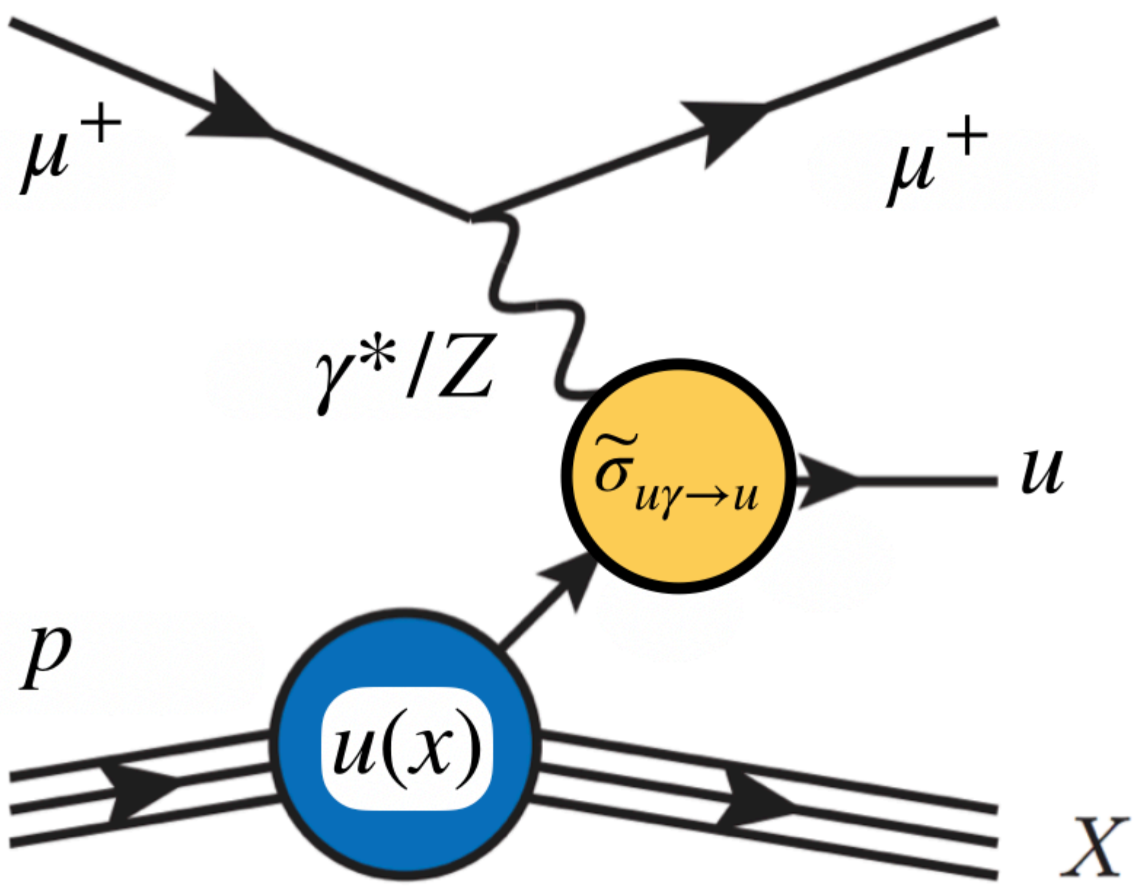
$$\frac{\partial}{\partial \ln Q^2} q_i(x, Q^2) = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(Q^2)\right) q_j(z, Q^2)$$

***DGLAP** parton evolution equations*

The Global QCD analysis paradigm

QCD factorisation theorems**: PDF universality**

$$\sigma_{l\,p\to\mu\,X} = \widetilde{\sigma}_{u\gamma\to u} \otimes u(x)$$

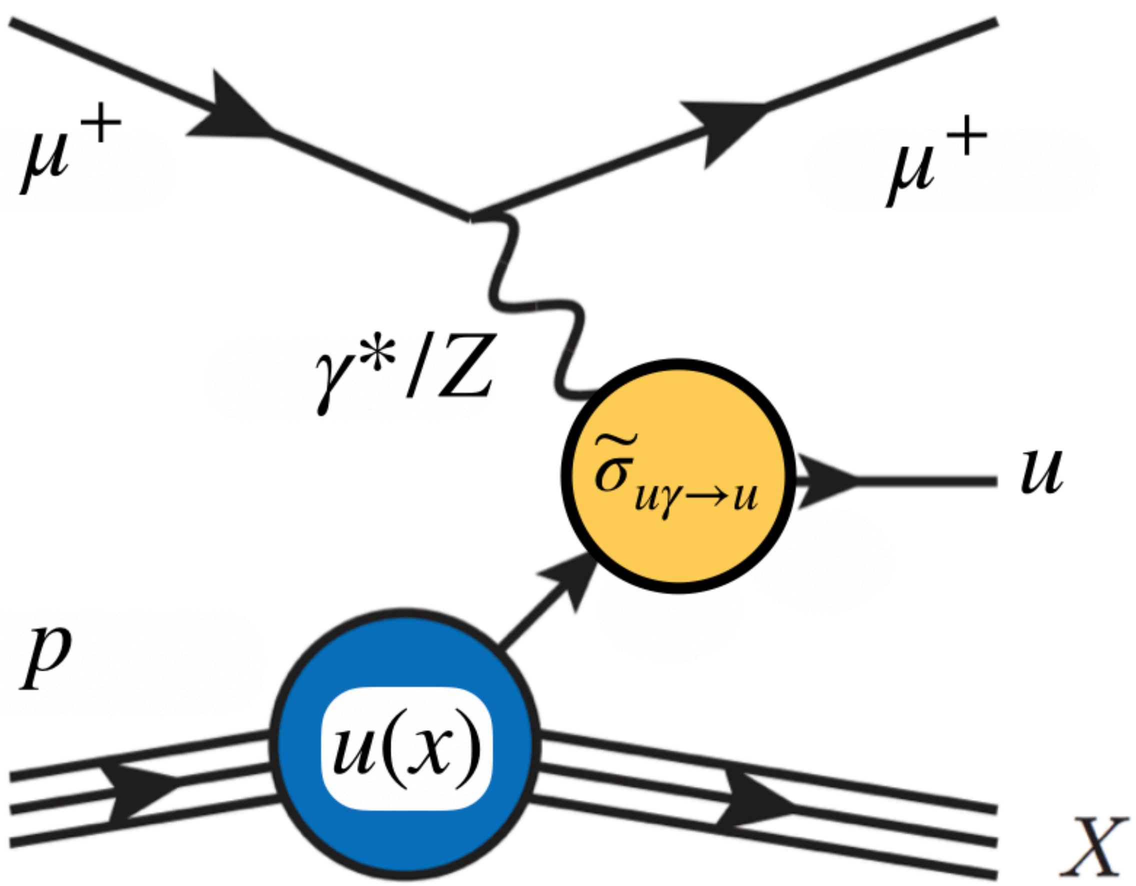


Determine PDFs from ***deep-inelastic scattering****…*

The Global QCD analysis paradigm

QCD factorisation theorems**: PDF universality**

$$\sigma_{l\,p\to\mu\,X} = \widetilde{\sigma}_{u\gamma\to u} \otimes u(x)$$



$$u(x) \simeq \frac{\sigma_{lp\to lX}\ \text{(exp)}}{\widetilde{\sigma}_{u\gamma^*\to u}\ \text{(QED theory)}}$$

leading-order calculations + only up quark in proton

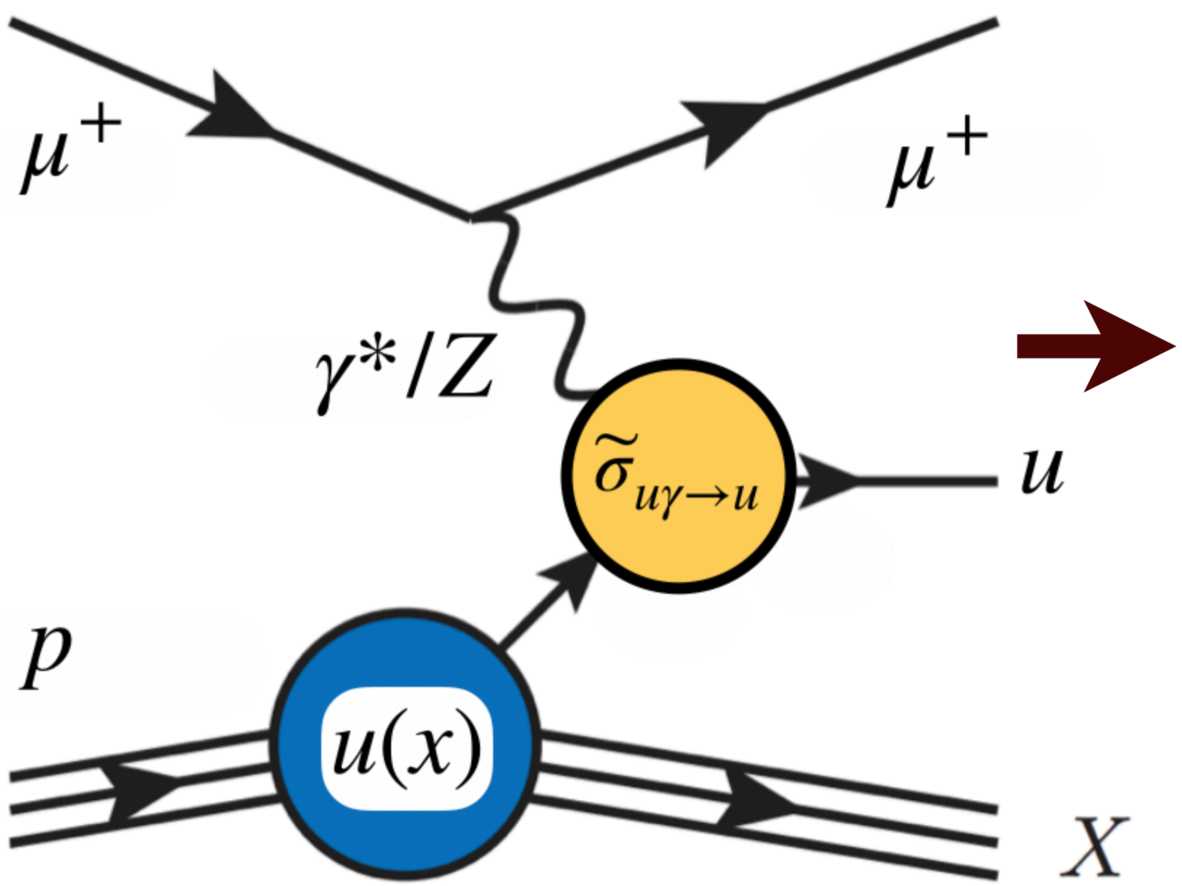
in general: introduce a parametrisation for the PDFs and fit their parameters from data

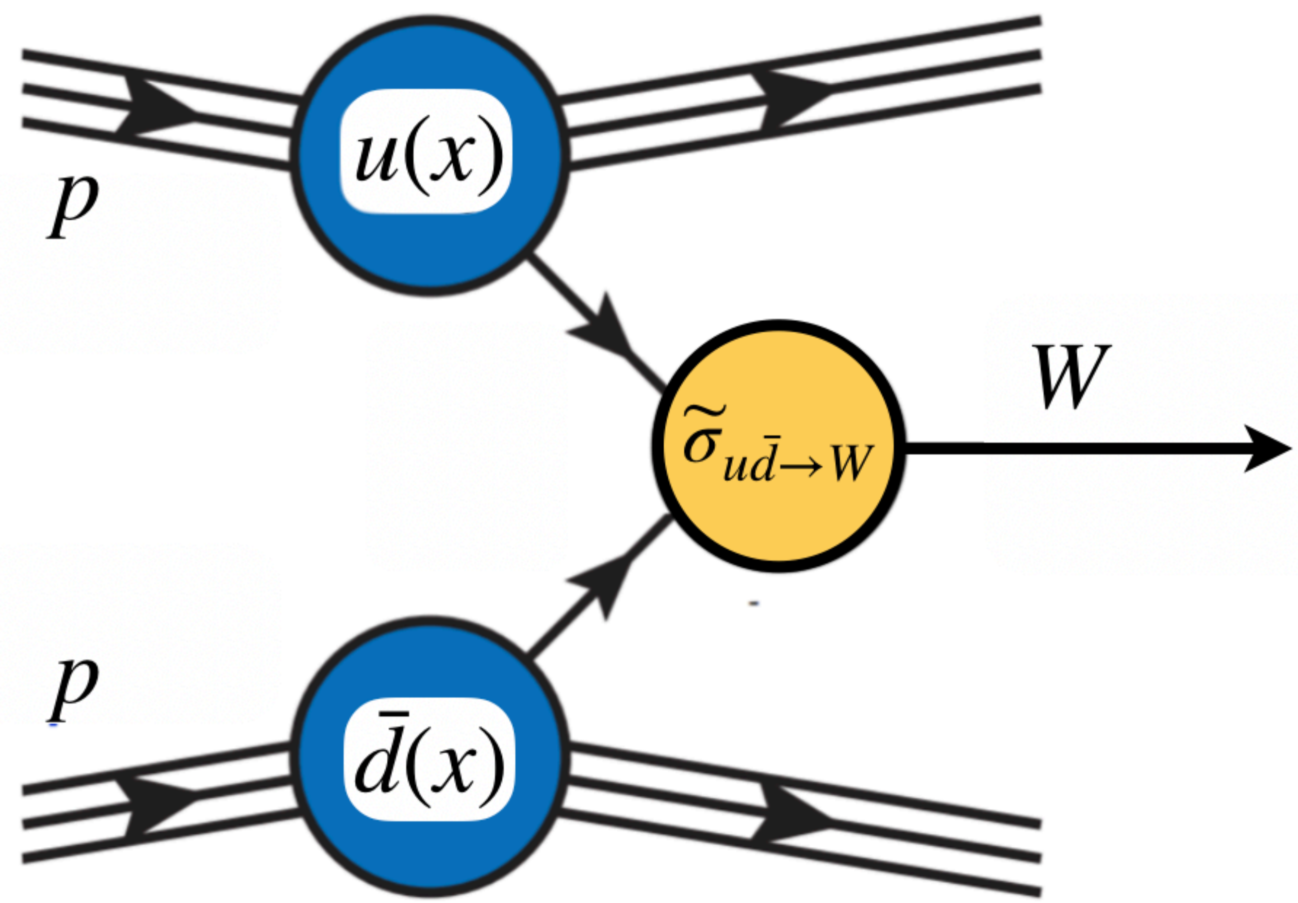
*Determine PDFs from **deep-inelastic scattering**…*

The Global QCD analysis paradigm

QCD factorisation theorems: **PDF universality**

$$\sigma_{l\,p\to\mu\,X} = \widetilde{\sigma}_{u\gamma\to u} \otimes u(x) \quad \rightarrow \quad \sigma_{p\,p\to W} = \widetilde{\sigma}_{u\bar{d}\to W} \otimes u(x) \otimes \bar{d}(x)$$

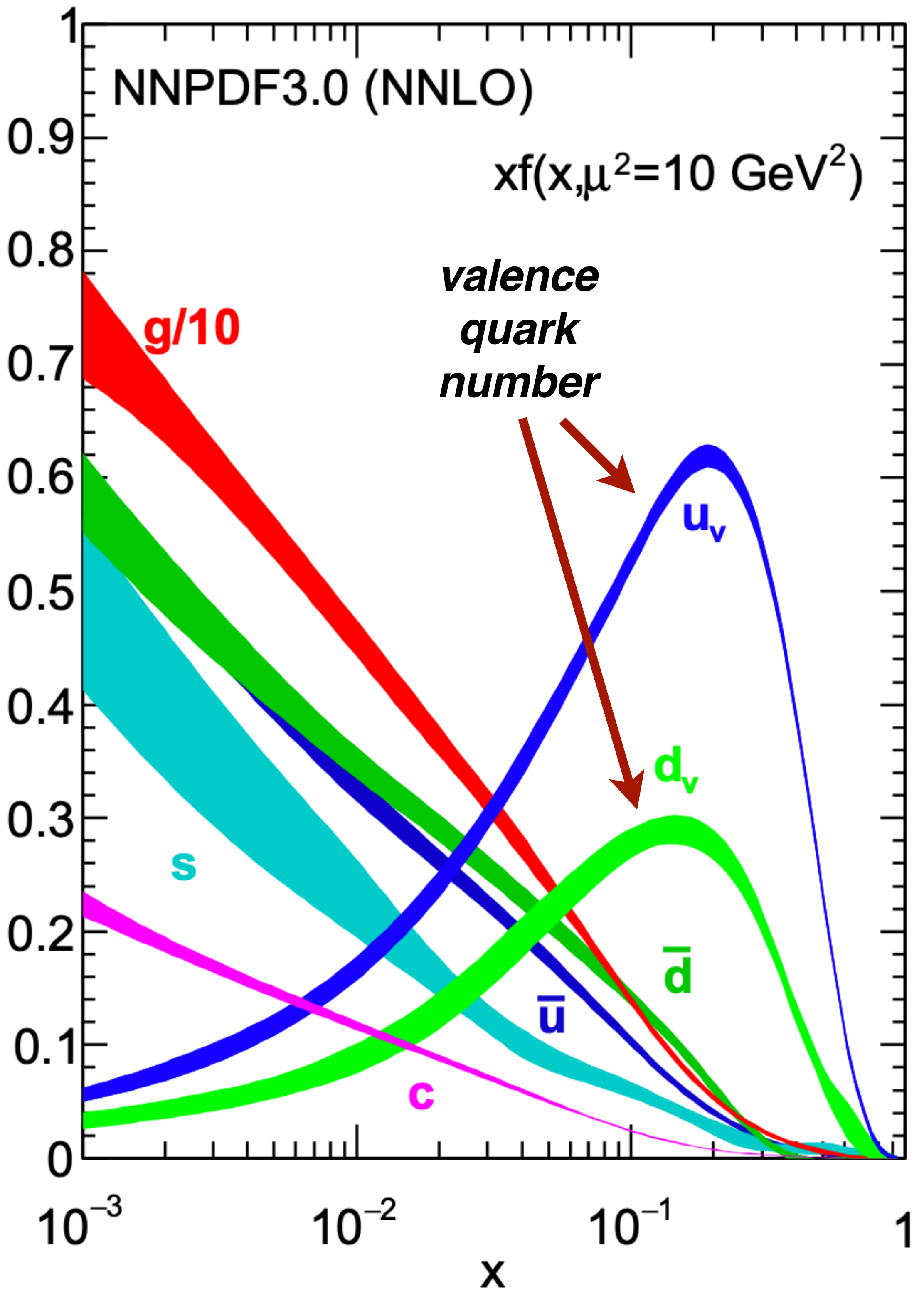




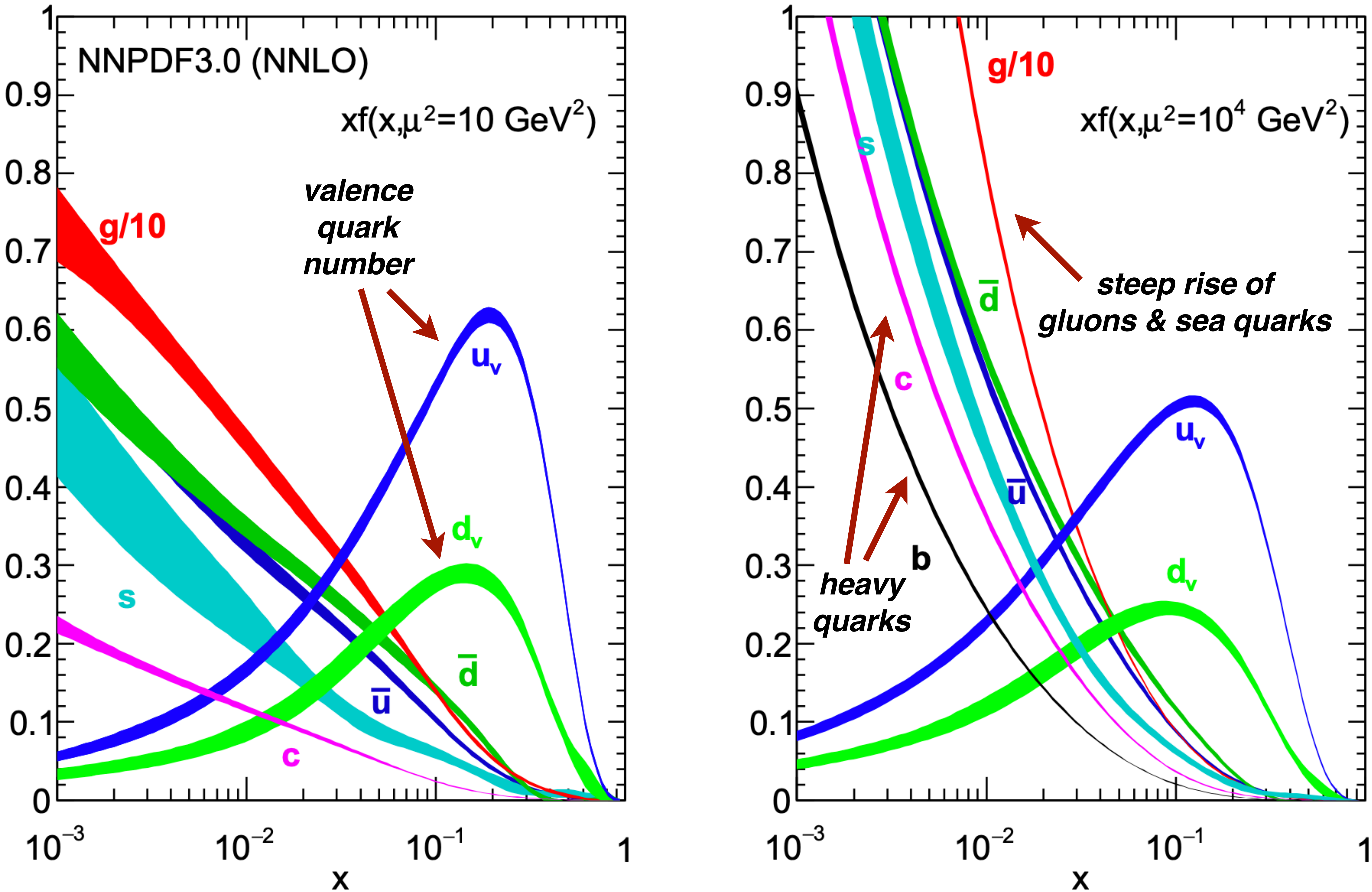
*Determine PDFs from **deep-inelastic scattering**…*

*… and use them to compute predictions for **proton-proton collisions***

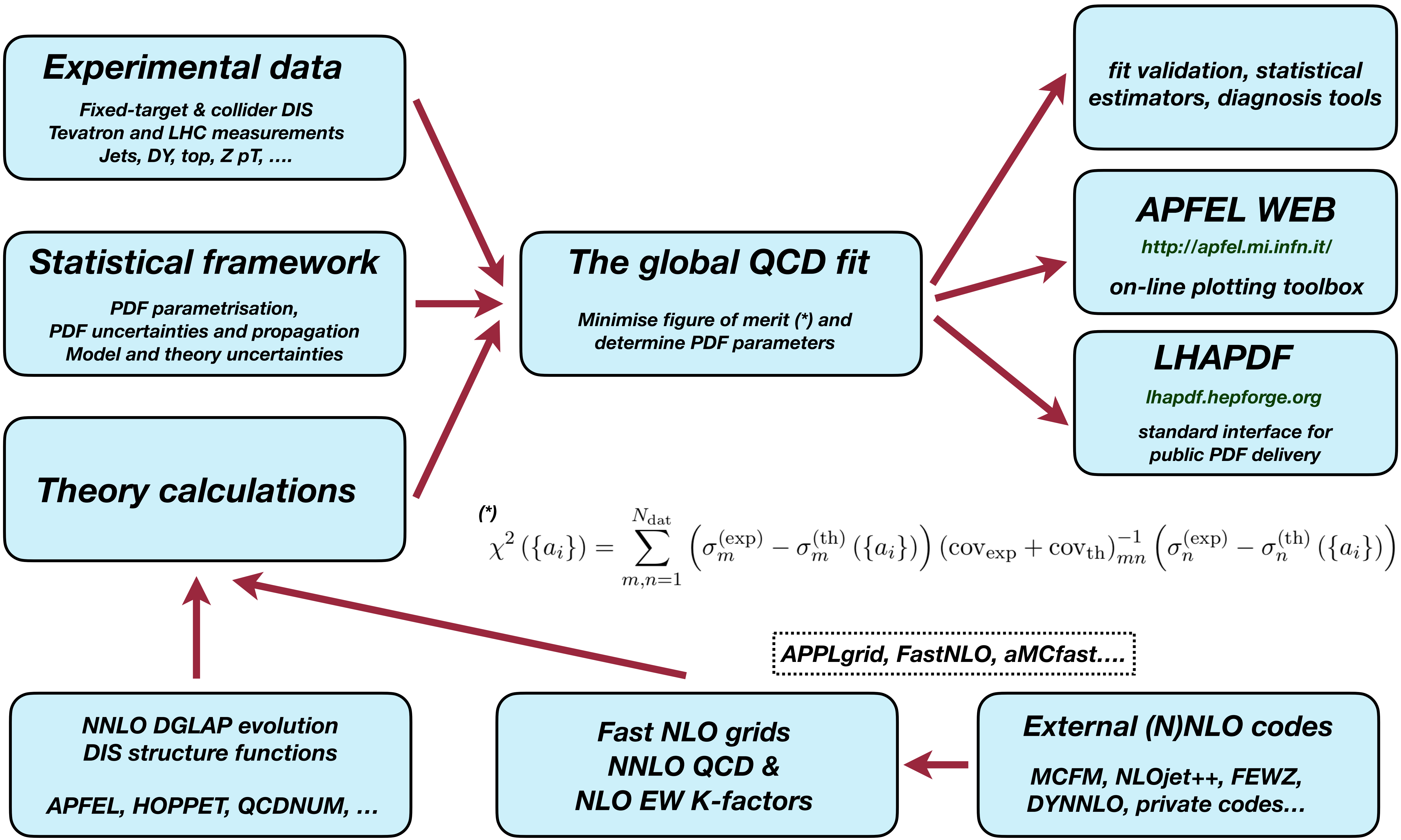
A proton structure snapshop



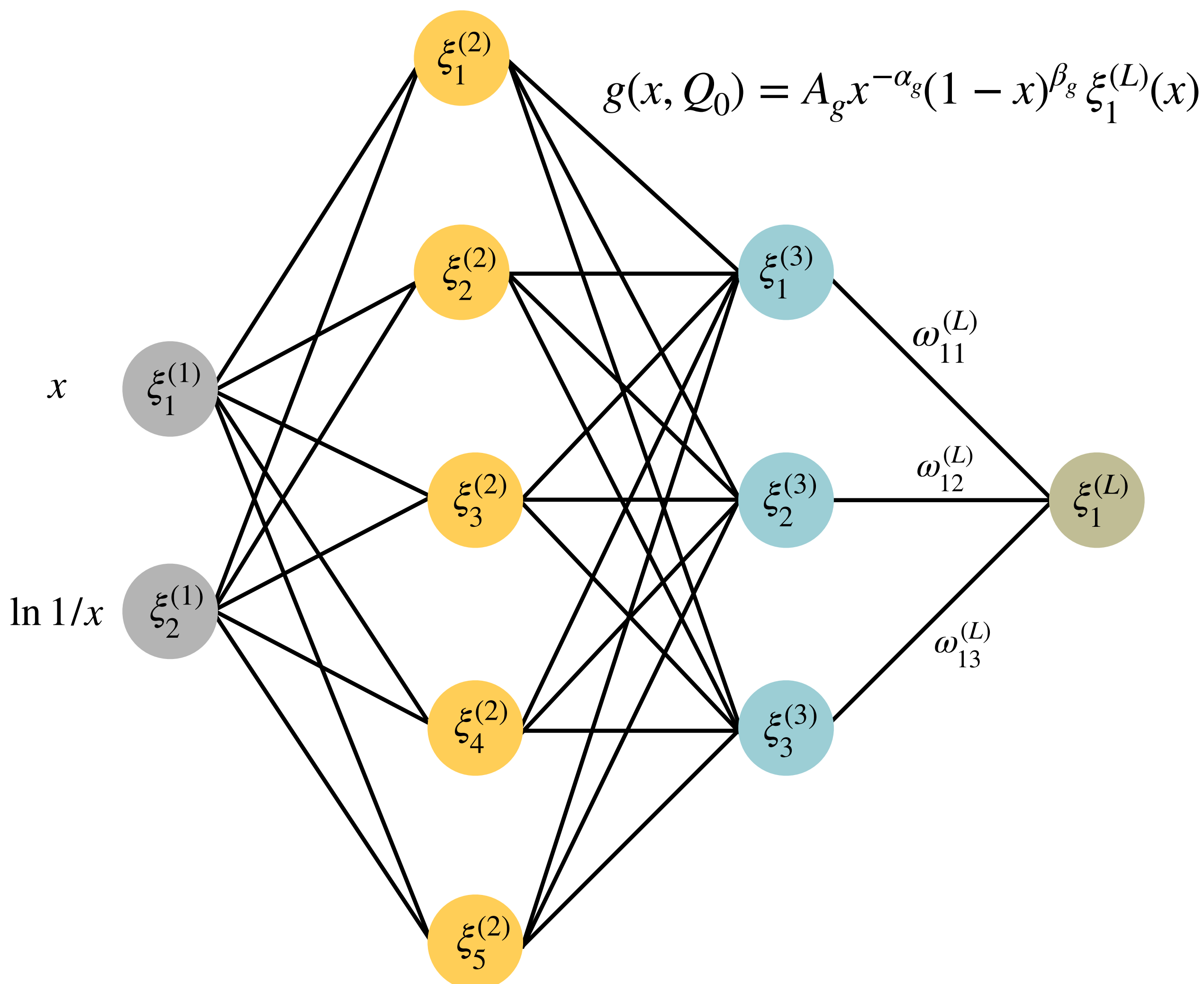
A proton structure snapshop



The global PDF fit pipeline



PDF parametrisation



- **Neural Networks** can be used universal unbiased interpolants to **parametrise PDFs**
- Removes model dependence: **unbiased learning** the physical laws from data
- Highly **redundant parametrisation:** identical results if O(10) increase in # free params

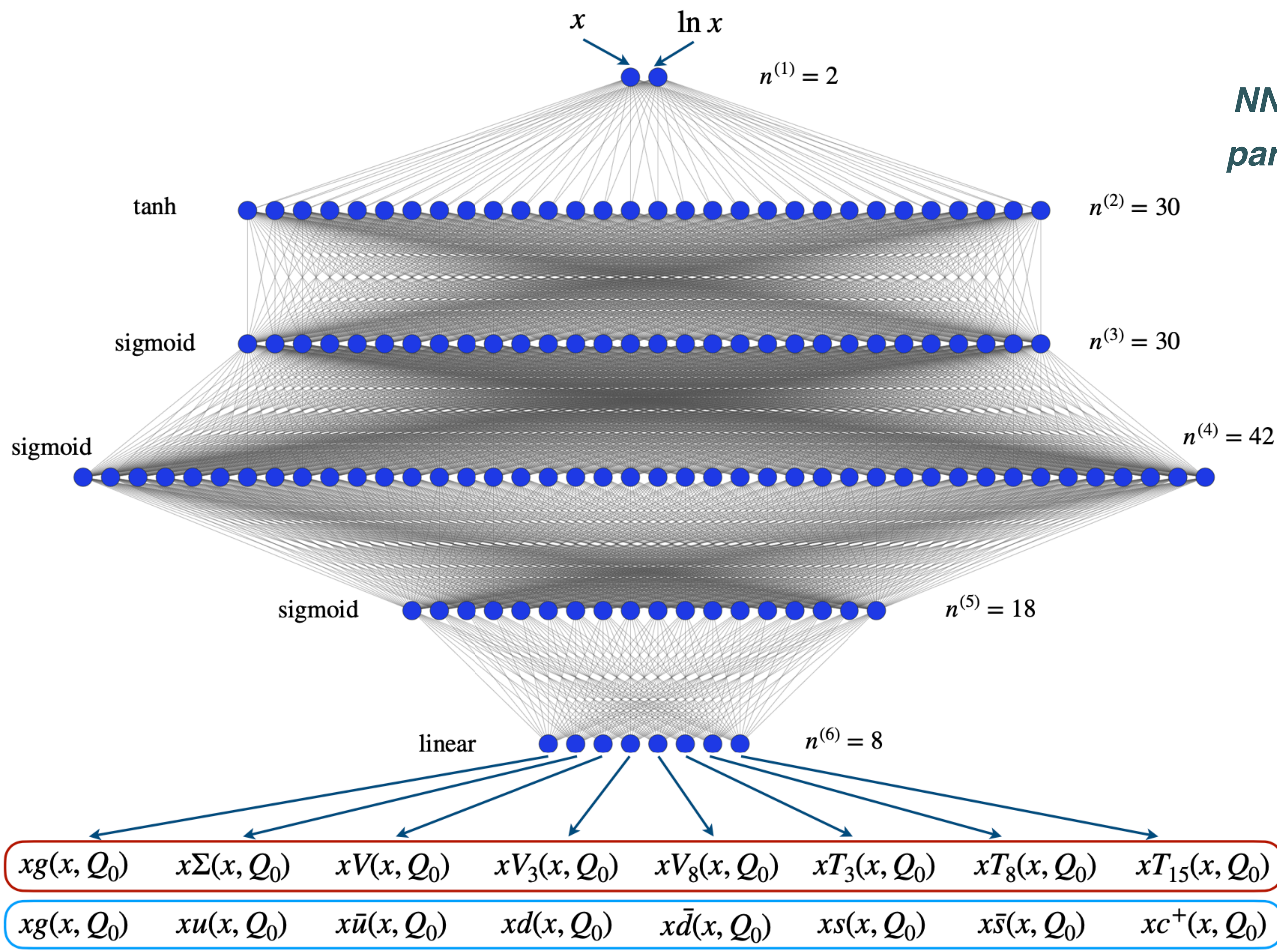
	Proton PDFs	*Nuclear PDFs*
Traditional	$g(x) \simeq x^{-b}(1-x)^c$	$R_g(x, A) \simeq (1 + bx + cx^2) \times A^d$
Neural Nets	$g(x) \simeq \mathrm{NN}(x)$	$R_g(x, A) \simeq \mathrm{NN}(x, A)$

x: *proton's* ***energy fraction*** *carried by gluons*

A: *number of protons + neutrons*

PDF parametrisation

NNPDF4.0 PDF parametrisation



evolution basis

flavor basis

$$f_i(x, Q_0) = x^{-\alpha_i}(1-x)^{\beta_i}\mathrm{NN}_i(x)$$

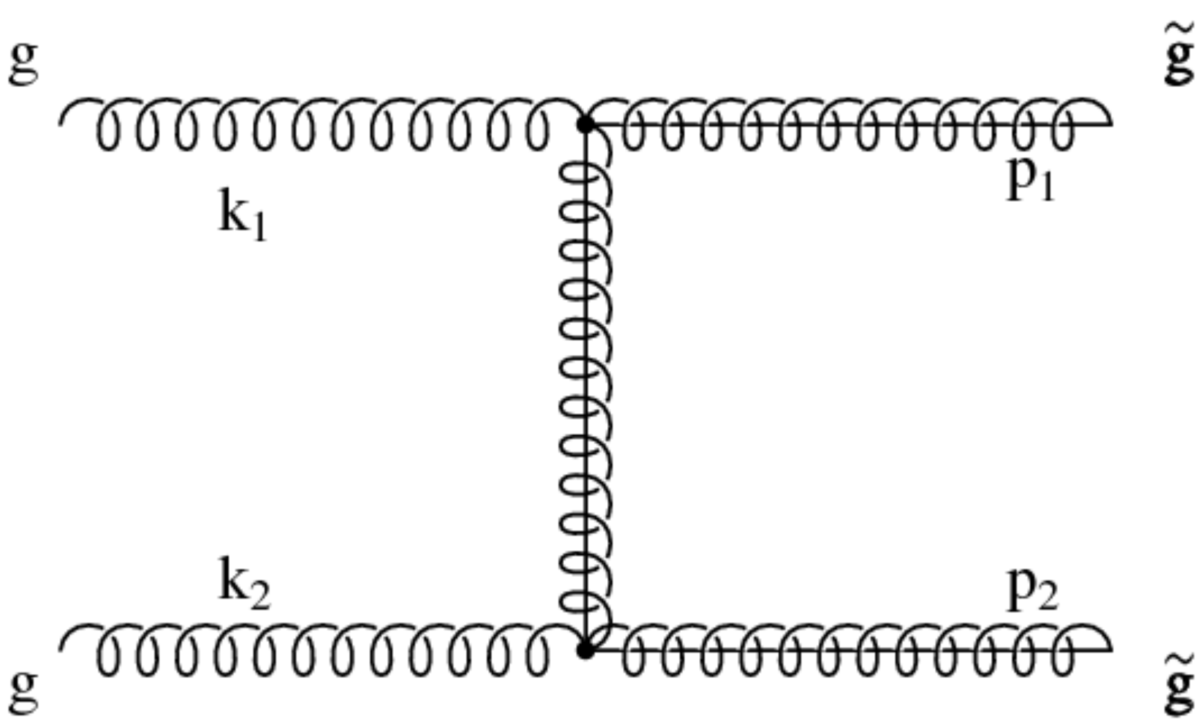
Phenomenological Applications

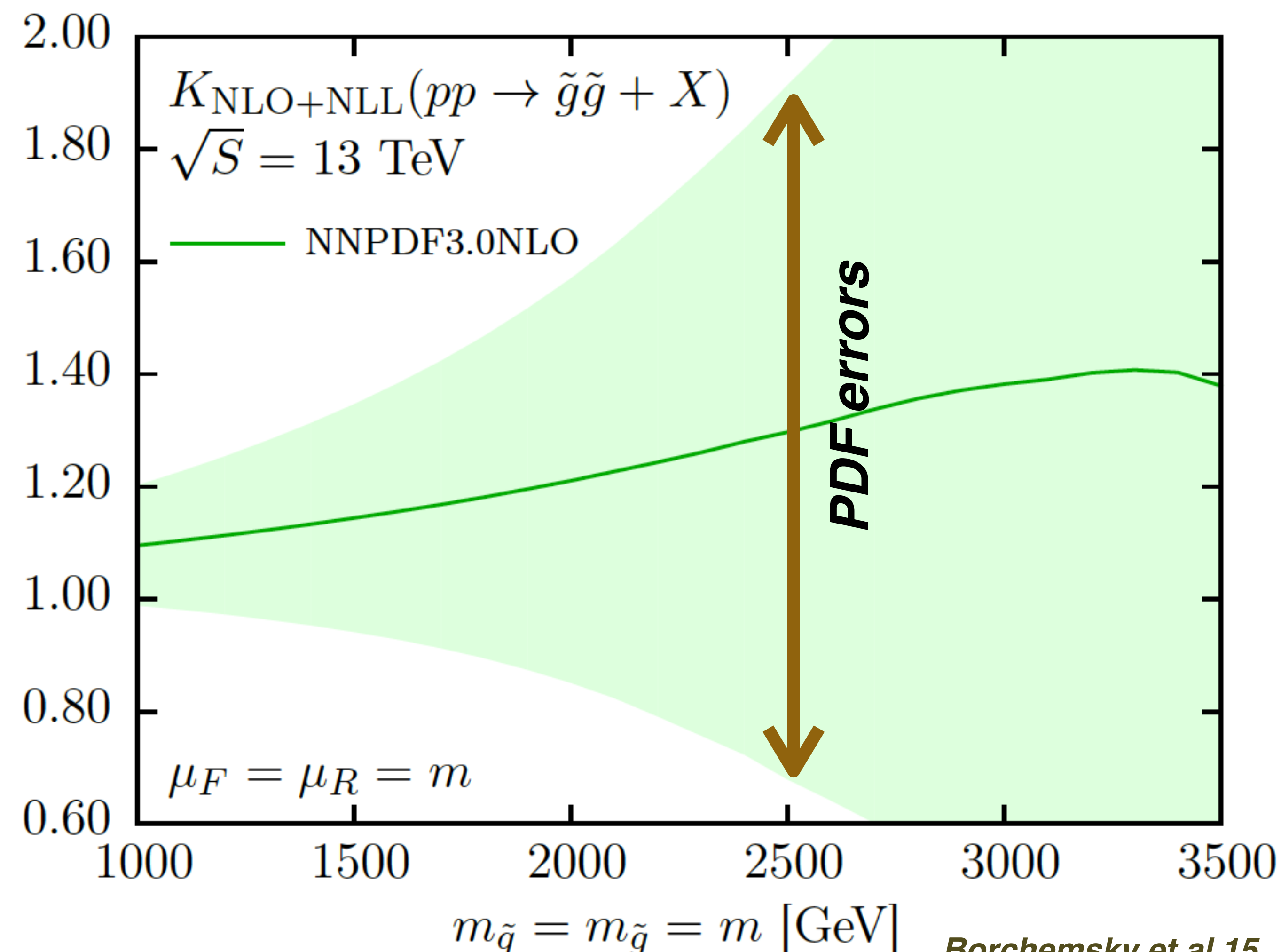
Why do we need better PDFs?

PDF uncertainties in the production of **New Physics heavy resonances** up to **100%**

Due to limited coverage of the **large Bjorken-*x* region**

gluino-pair production in supersymmetry





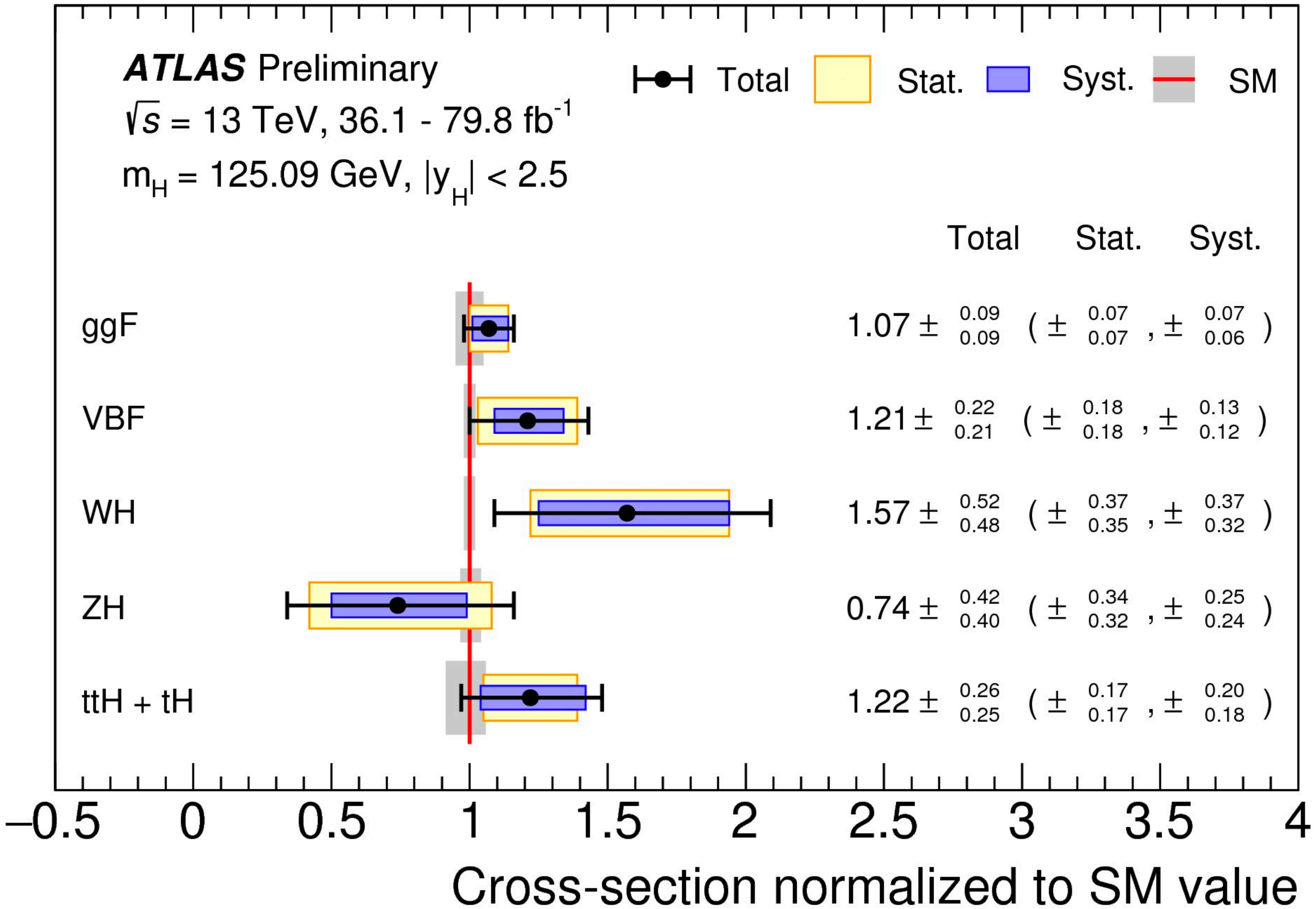
Borchemsky et al 15

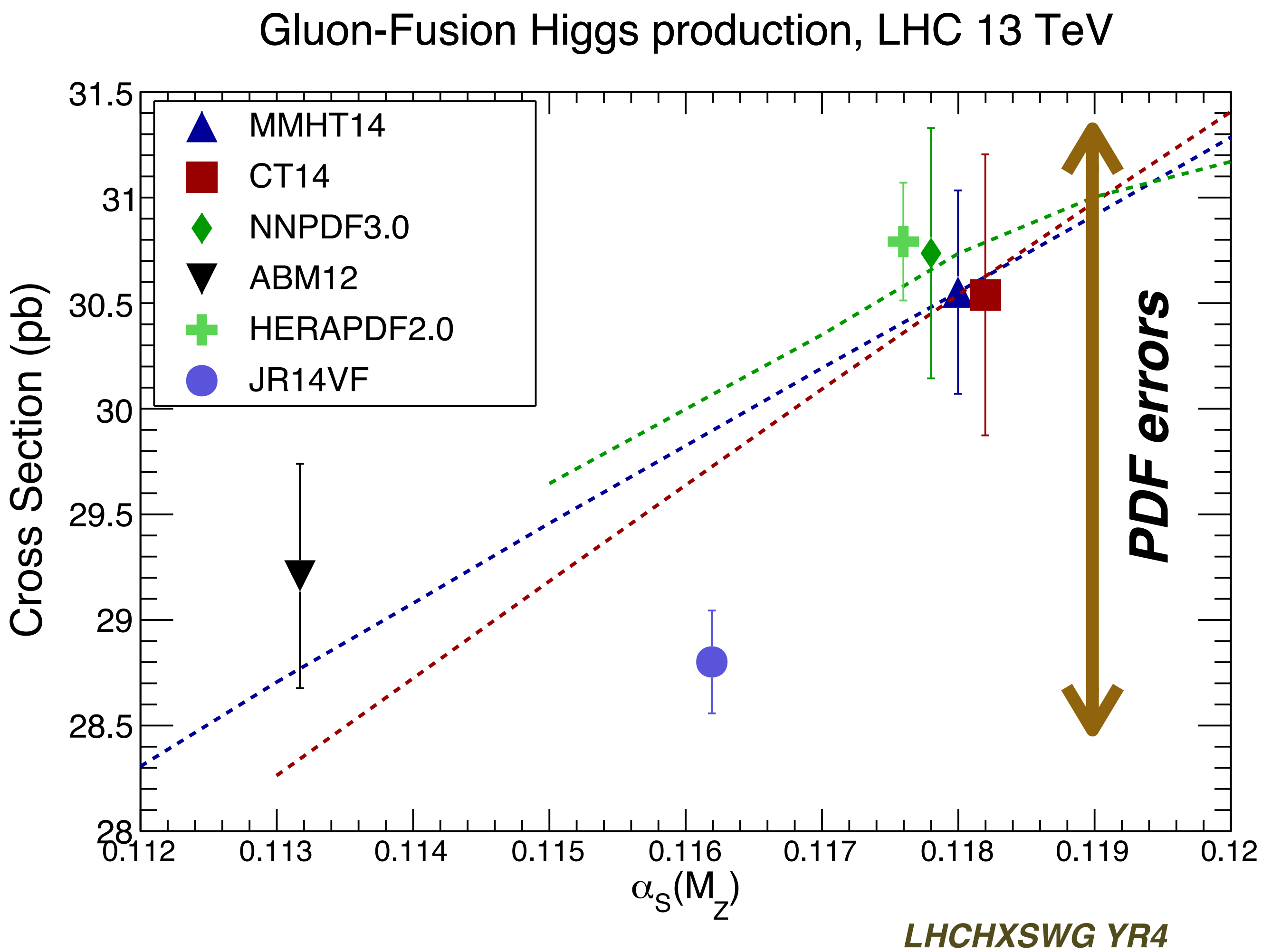
Why do we need better PDFs?

$$\frac{\Delta\sigma_h^{(\mathrm{BSM})}}{\sigma_h^{(\mathrm{SM})}} \simeq \frac{v^2}{\Lambda^2} = \text{few } \% \text{ for } \Lambda = \mathcal{O}(\mathrm{TeV})$$

Higgs coupling measurements **at the few percent level** (and below) are a must for indirect BSM searches

Inclusive Higgs production rates





Why do we need better PDFs?

- Heavy bSM physics beyond the direct reach of the LHC can be **parametrised in a model-independent** in terms of a **complete** basis of higher-dimensional operators: this is the **Standard Model Effective Field Theory**

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4}\mathcal{O}_j^{(8)} + \ldots ,$$

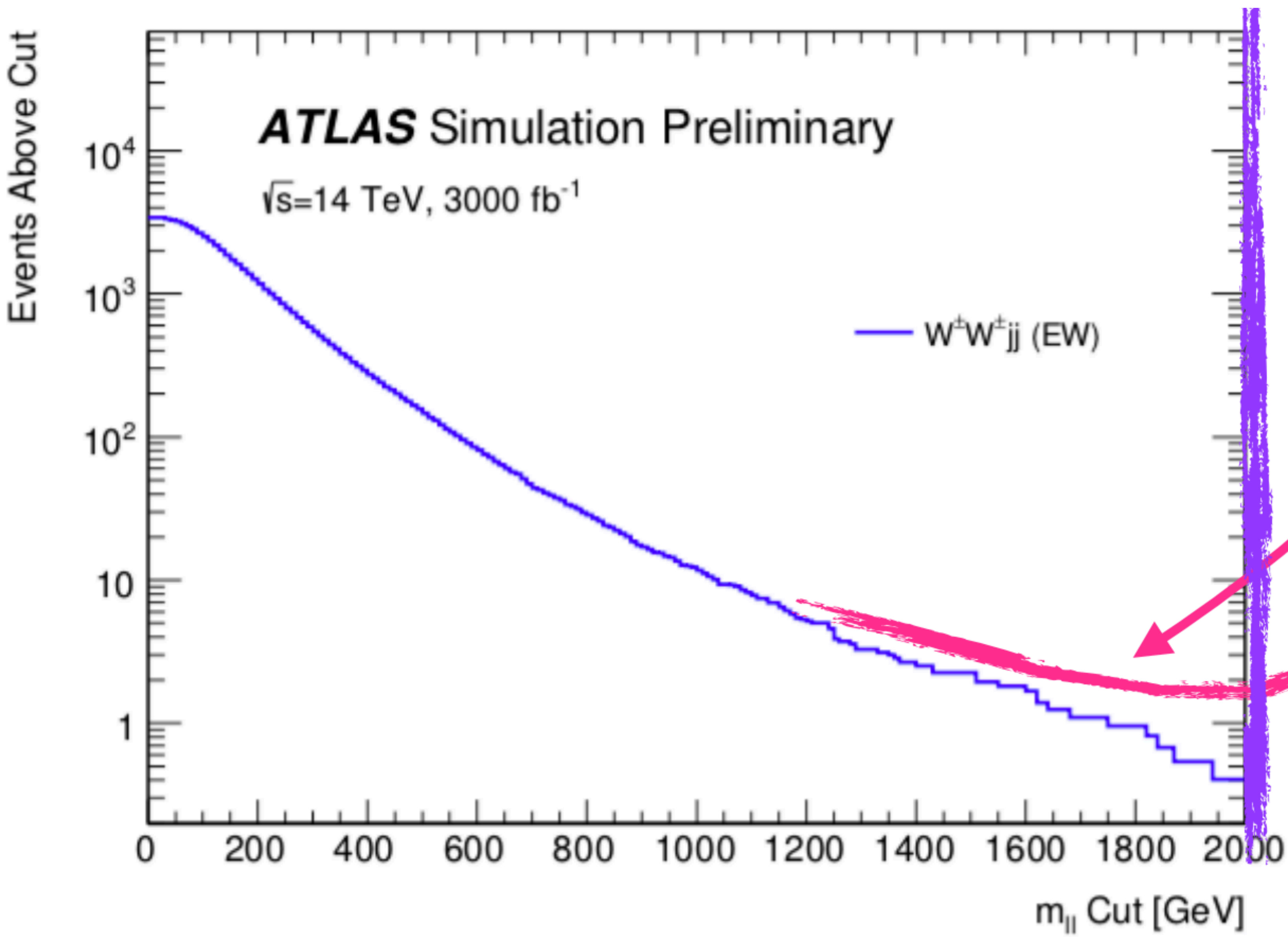
- Some operators induce **growth with the partonic centre-of-mass energy**: increased sensitivity in LHC cross-sections in the TeV region

$$\sigma(E) = \sigma_{\rm SM}(E)\left(1 + \sum_i^{N_{d6}} \omega_i \frac{c_i\, m_{\rm SM}^2}{\Lambda^2} + \sum_i^{N_{d6}} \widetilde{\omega}_i \frac{c_i\, E^2}{\Lambda^2} + \mathcal{O}\left(\Lambda^{-4}\right)\right)$$

*enhanced sensitivity from **TeV-scale processes:***
unique feature of LHC

Why do we need better PDFs?

Deviation from SM prediction in high energy tails?



CA Lee, HL/HE-LHC Jamboree, 1 March 2019

Why do we need better PDFs?

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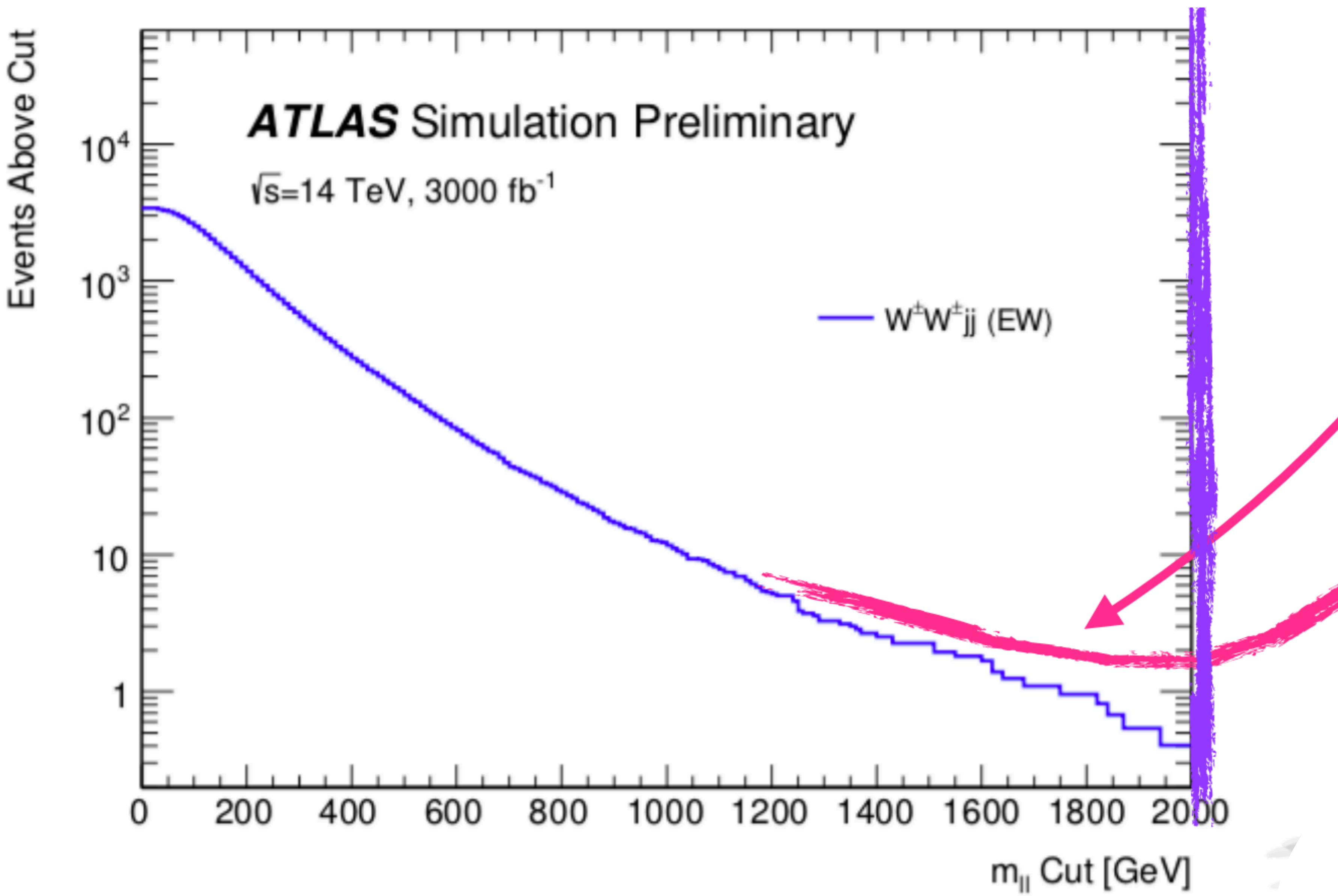
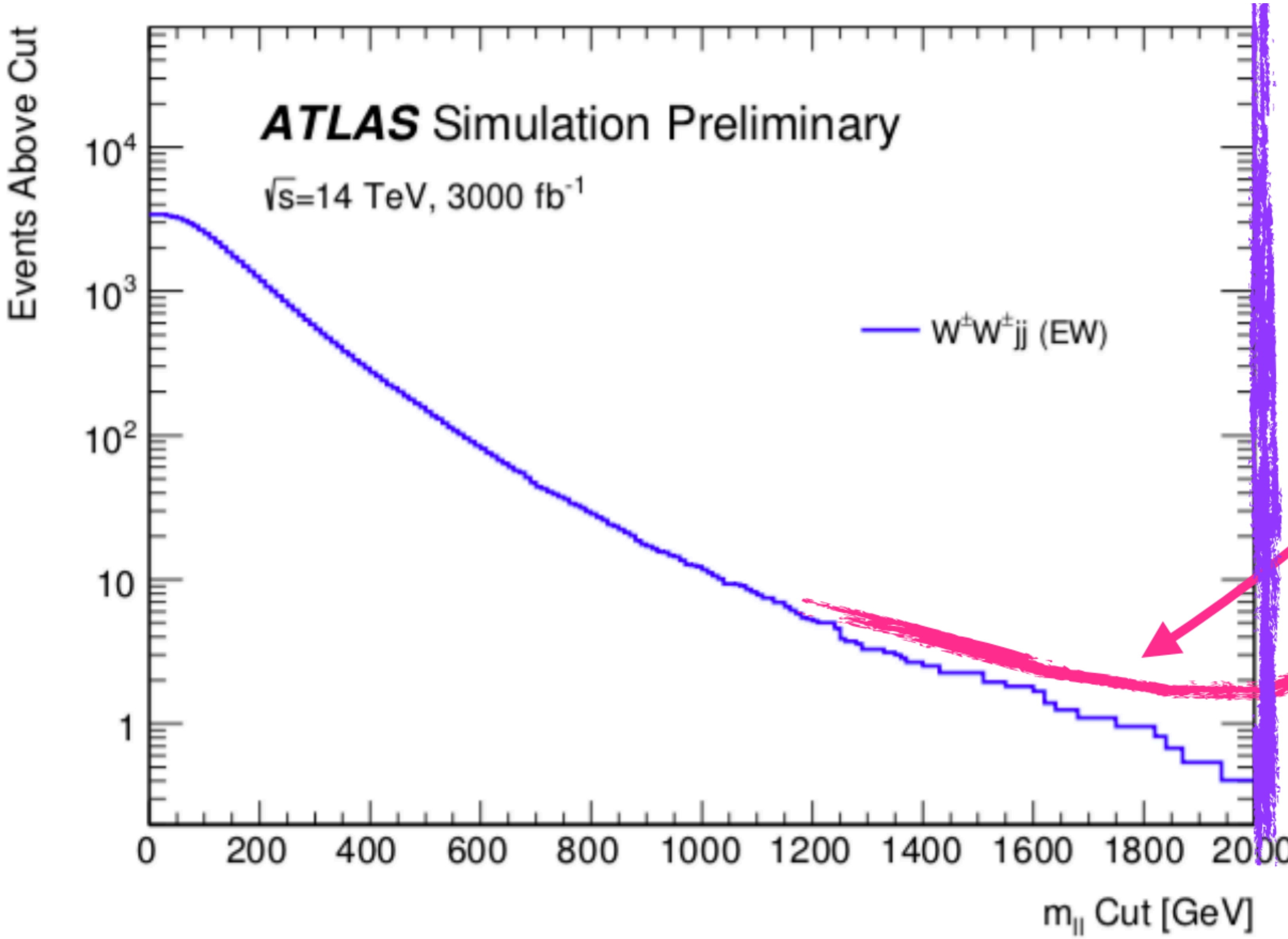


CA Lee, HL/HE-LHC Jamboree, 1 March 2019

SMEFT interpretation: from a massive particle at high energies …

Why do we need better PDFs?

Deviation from SM prediction in high energy tails?



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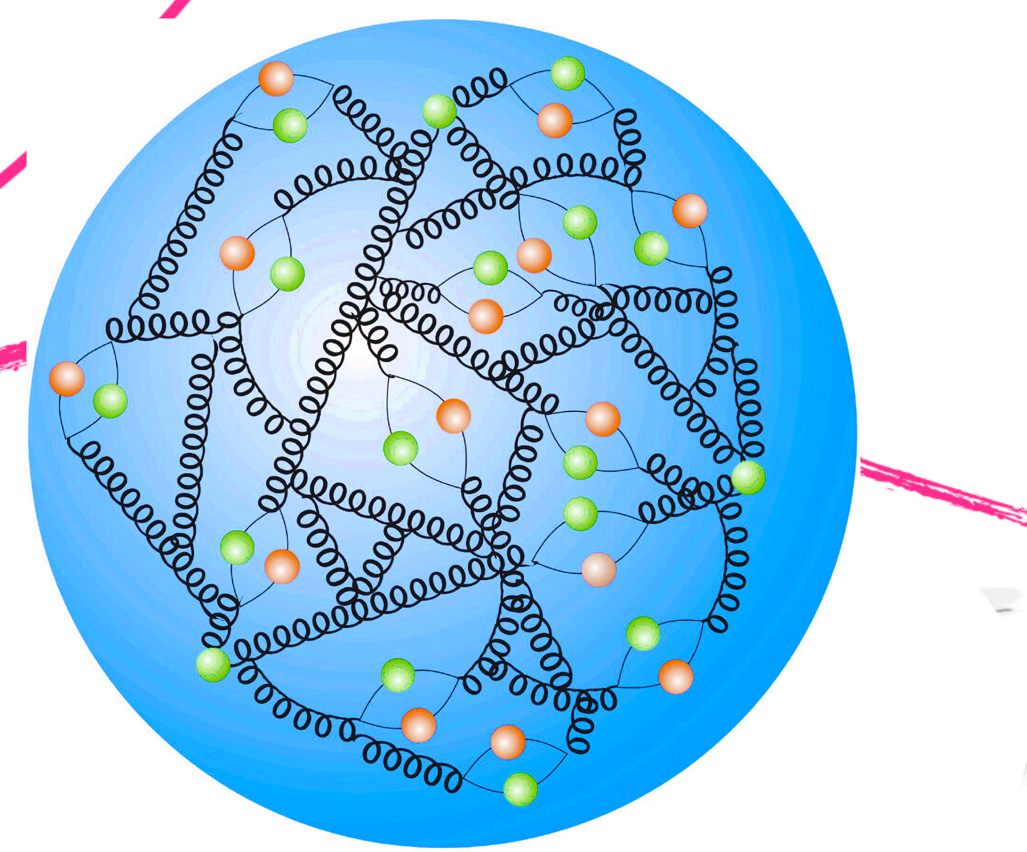
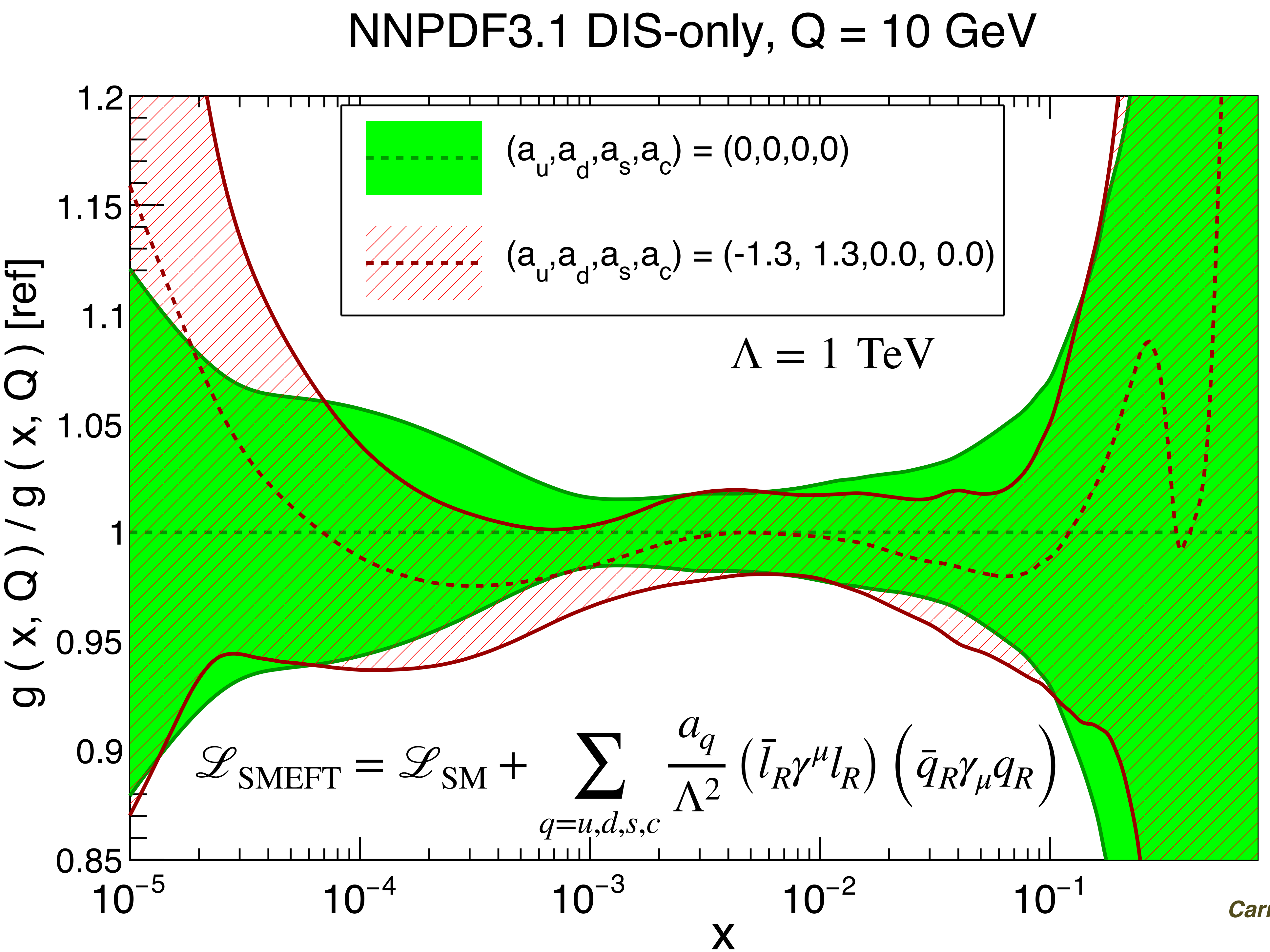


…or reflecting our limited understating of proton structure?

Impact on the PDFs

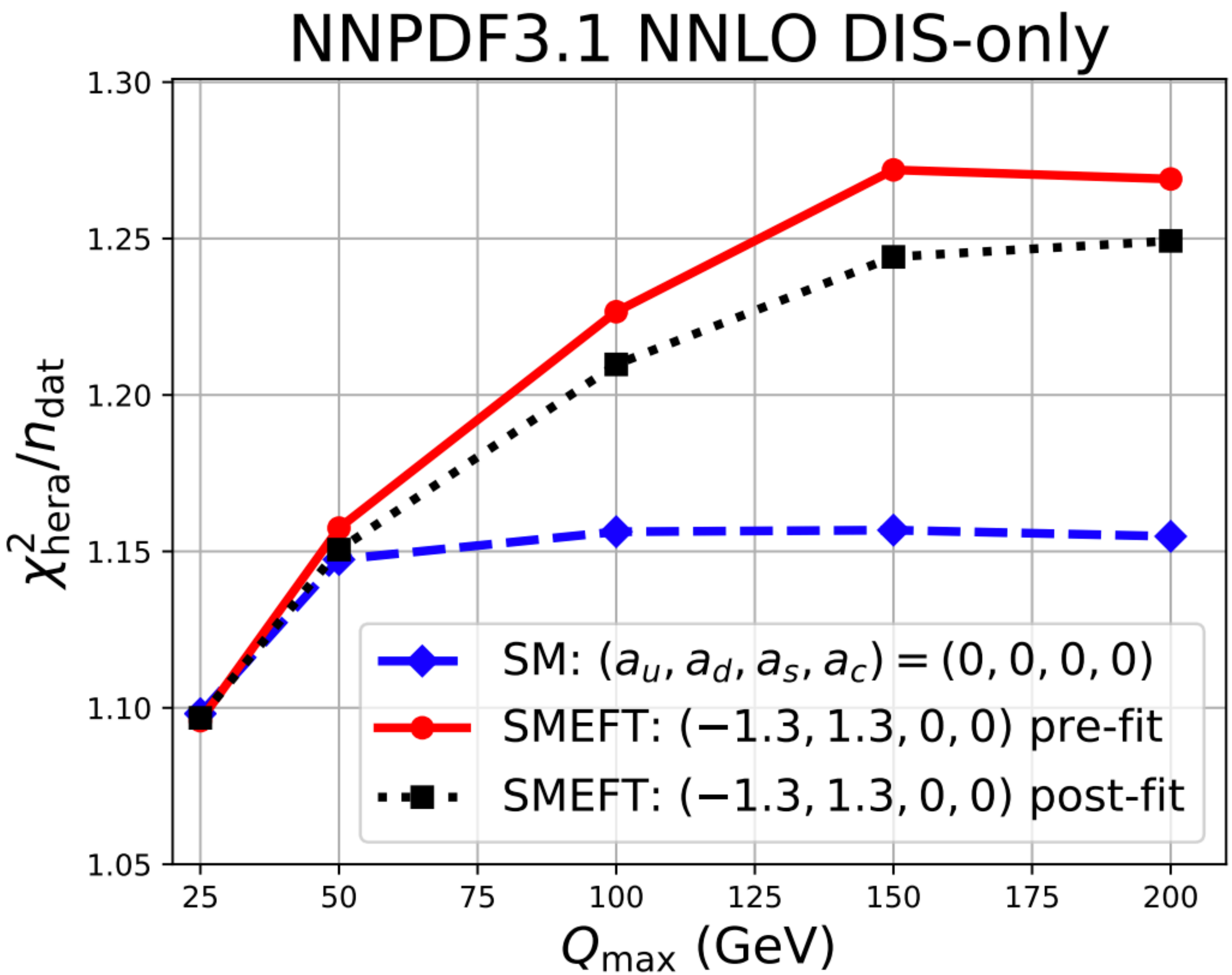
PDF determinations can be extended to the **SMEFT**: partonic matrix elements include the effects of dimension-six operators



Carrazza et al 19

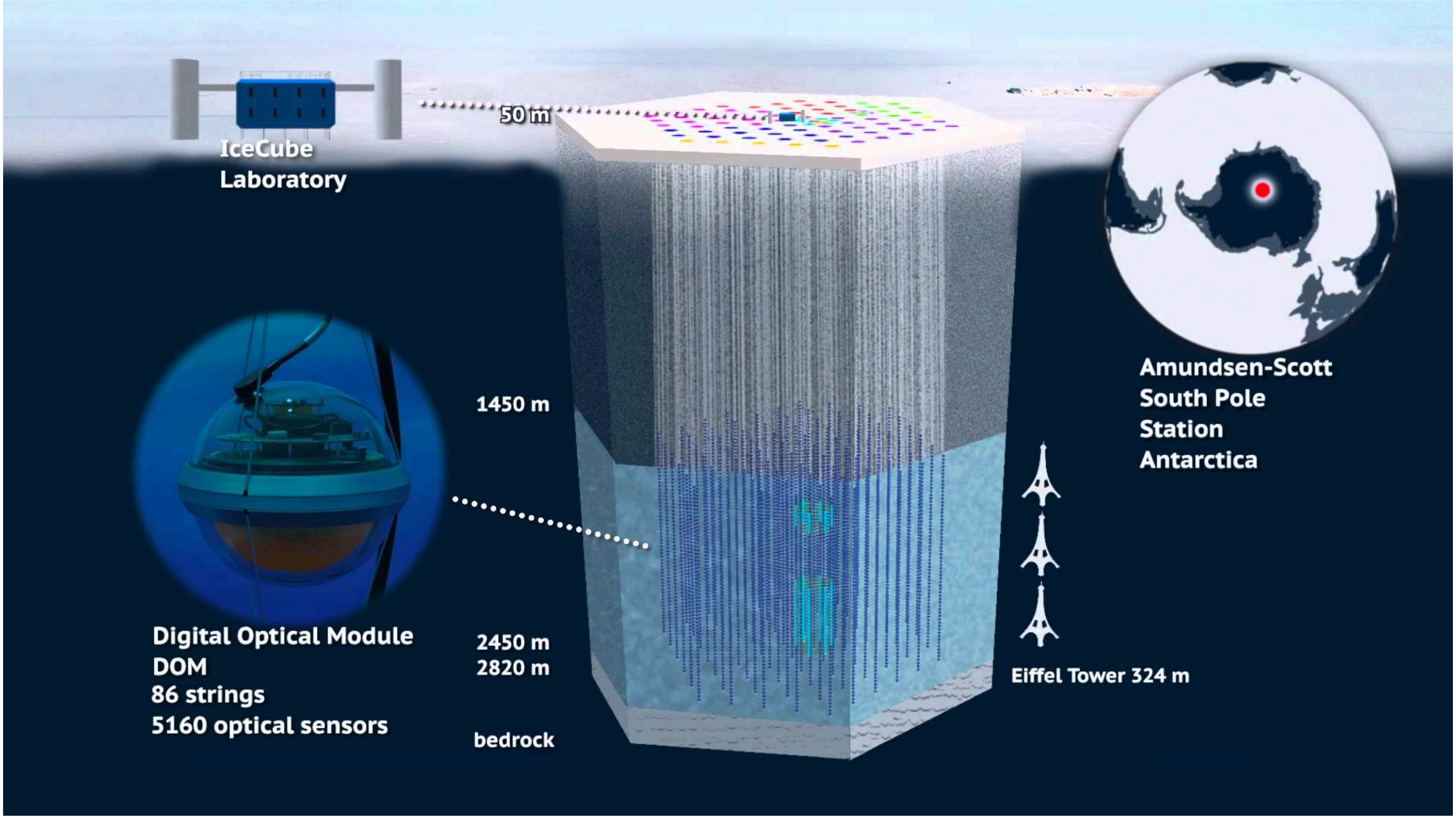
Impact on the PDFs

Tell-tale sign of SMEFT effects: **rapid variation with *Q*** (DGLAP evolution slower)



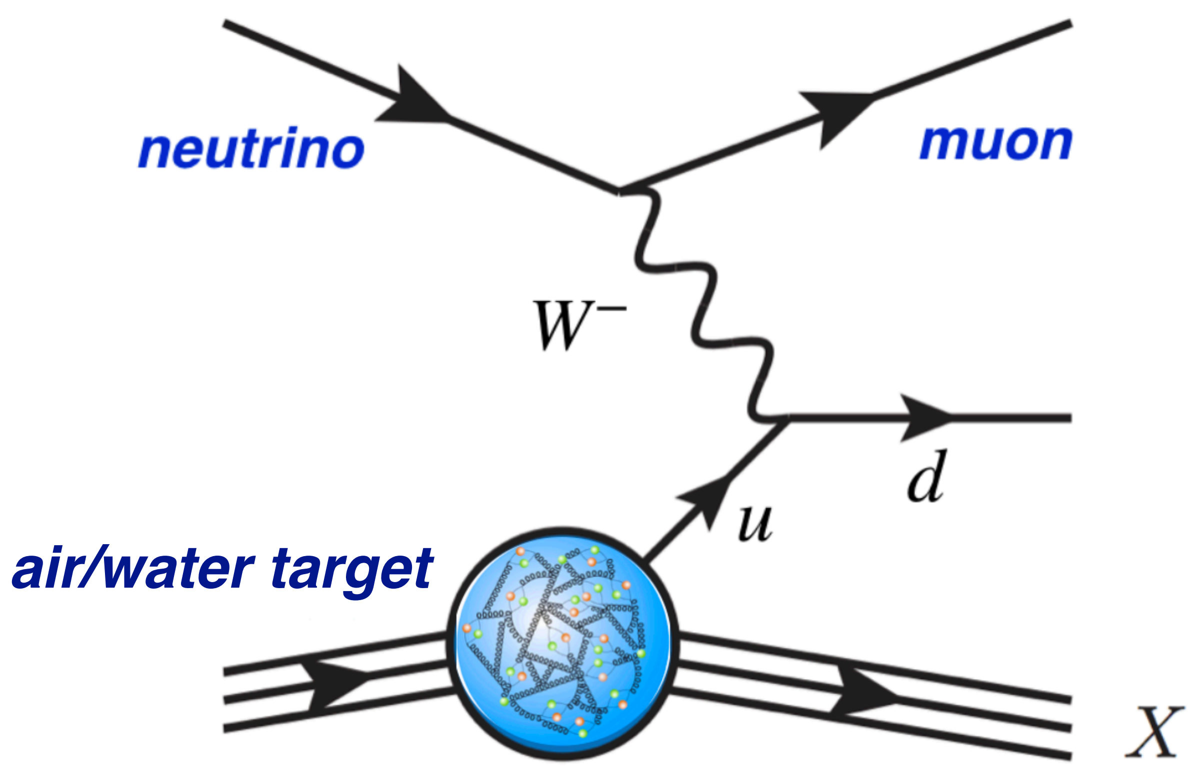
Neutrino telescopes

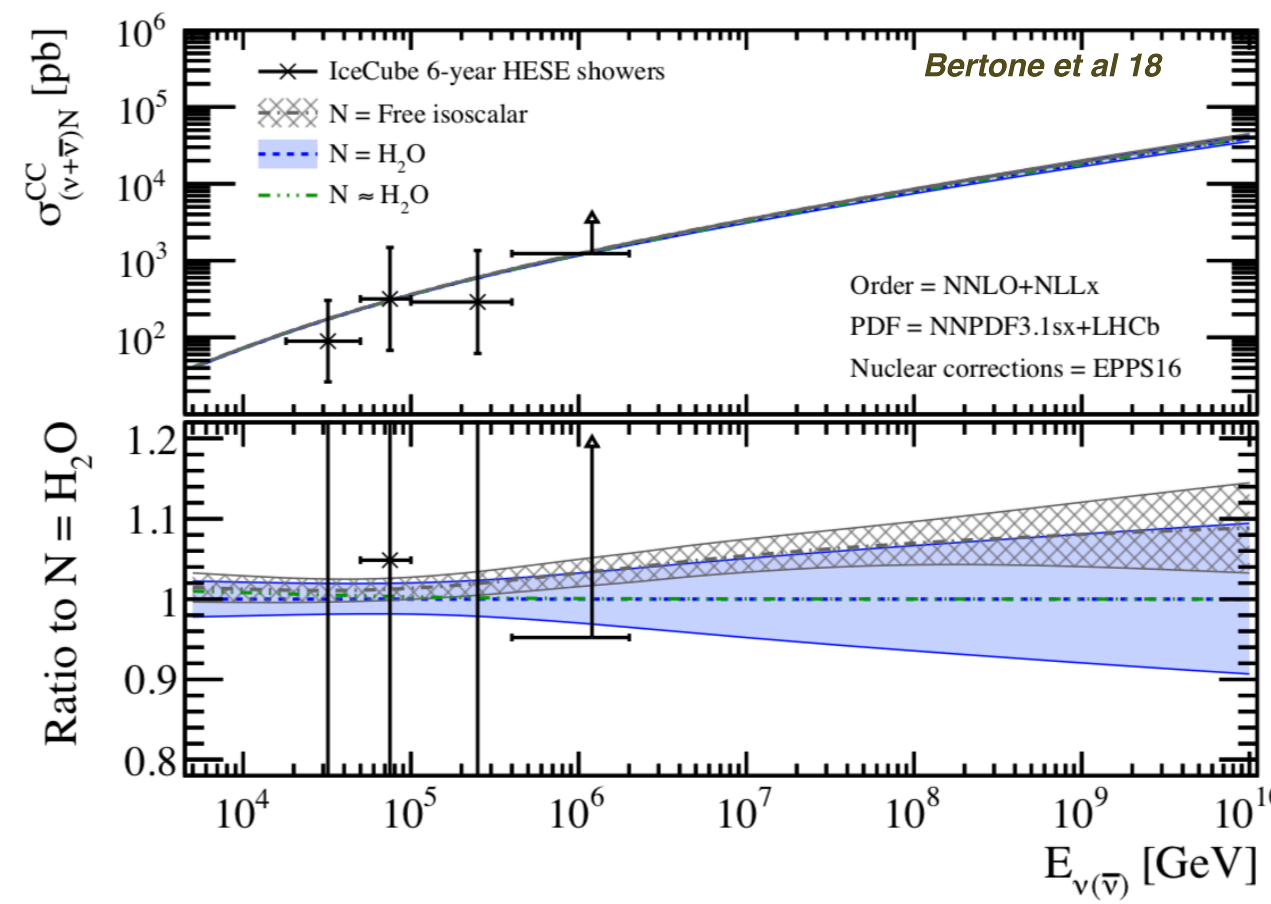
Ultra-high energy (UHE) neutrinos: novel window to the **extreme Universe**



Neutrino telescopes as QCD microscopes

Ultra-high energy (cosmic) neutrino *- nucleus scattering:*
unique probe of ***small-x PDFs and QCD***

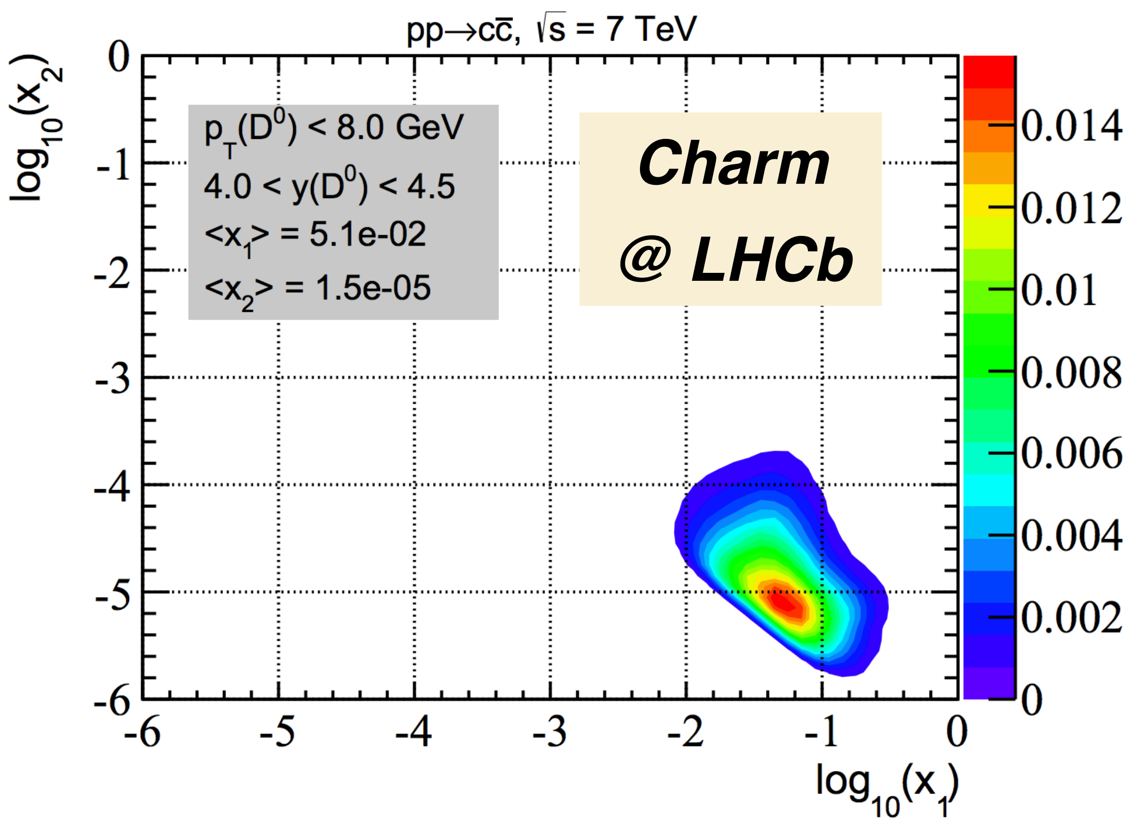




Bertone, Gauld, JR 18

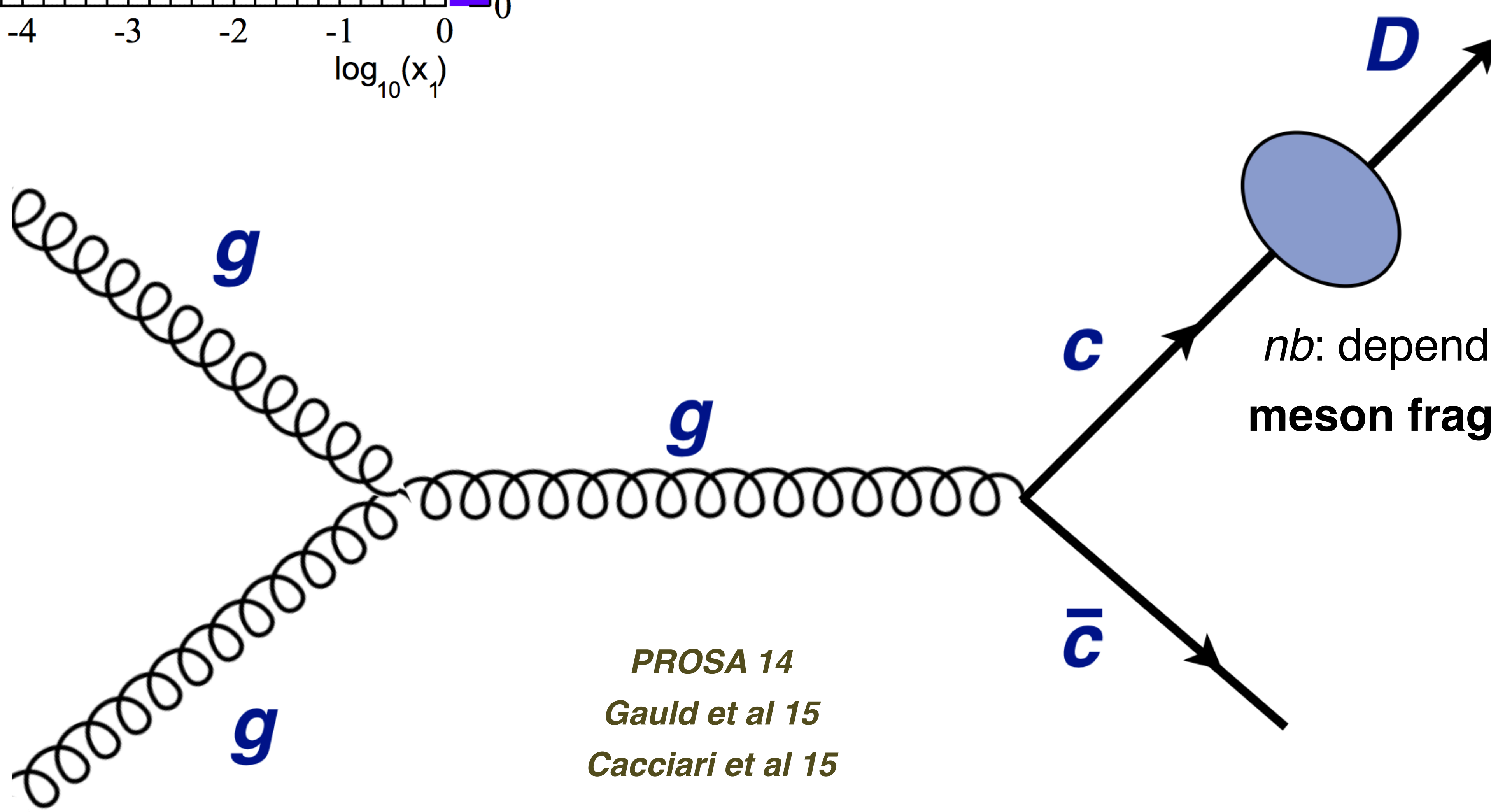
Sensitive to **small-*x* quarks** (and gluons via evolution) down to **x** ≃ **10^{-8}** at **Q** ≃ **M_W**

Forward charm production



LHC: charm production from **gluon-gluon scattering**

LHCb: forward coverage, Charm probes down to **x** ≃ **10^{-6}** !



nb: dependence on **D meson fragmentation**

PROSA 14
Gauld et al 15
Cacciari et al 15

Forward charm production

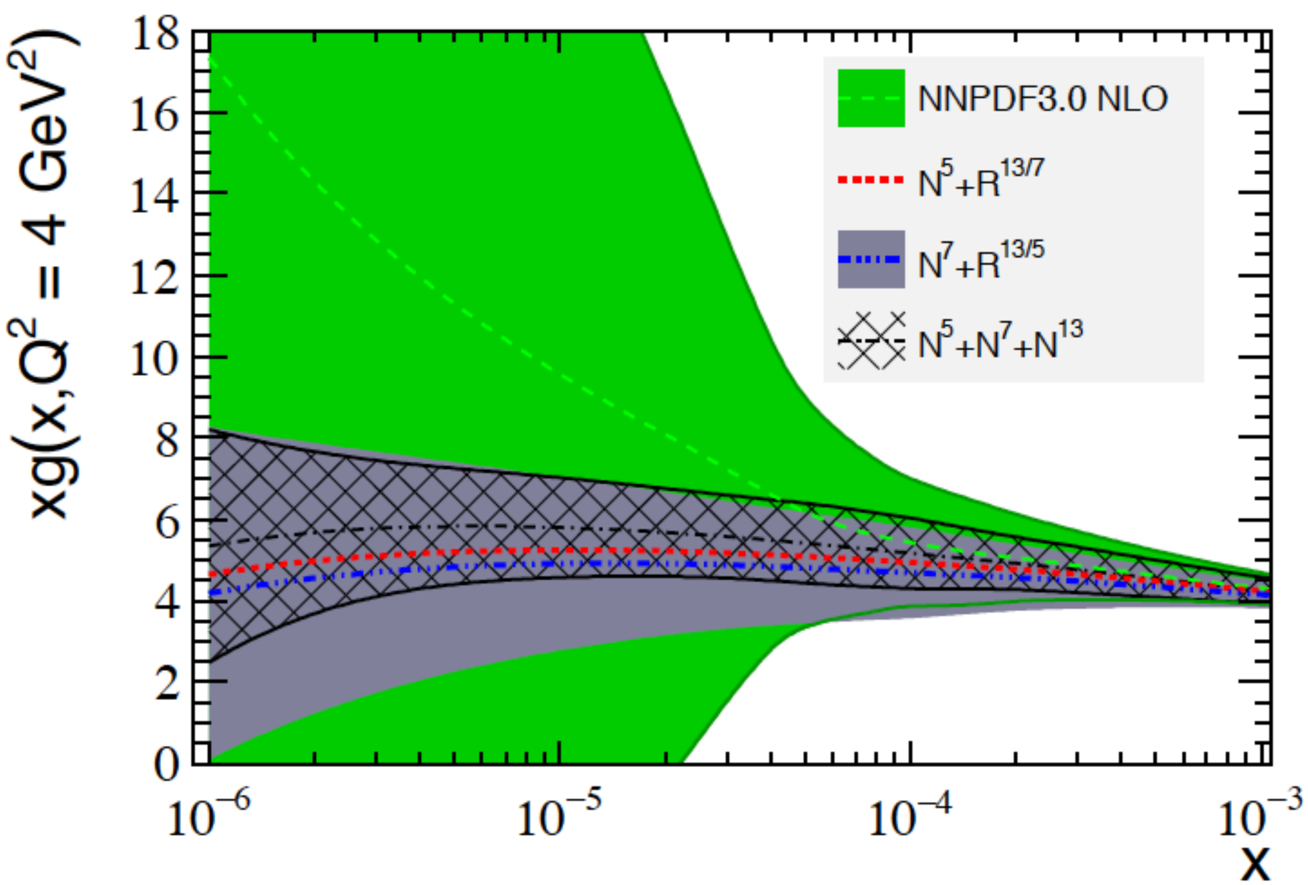
- Include LHCb D meson production at **5, 7, 13 TeV**
- Fit **normalised distributions** & **ratios between CoM energies** to reduce MHOUs

$$N_X^{ij} = \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_i^D d(p_T^D)_j} \Bigg/ \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_{\mathrm{ref}}^D d(p_T^D)_j},$$

$$R_{13/X}^{ij} = \frac{d^2\sigma(13\ \mathrm{TeV})}{dy_i^D d(p_T^D)_j} \Bigg/ \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_i^D d(p_T^D)_j}$$

gluon PDF uncertainties reduced by **factor 10** at **x** ≃ **10^{-6}**

Excellent description of all LHCb datasets and ratios (after **errata** corrected)

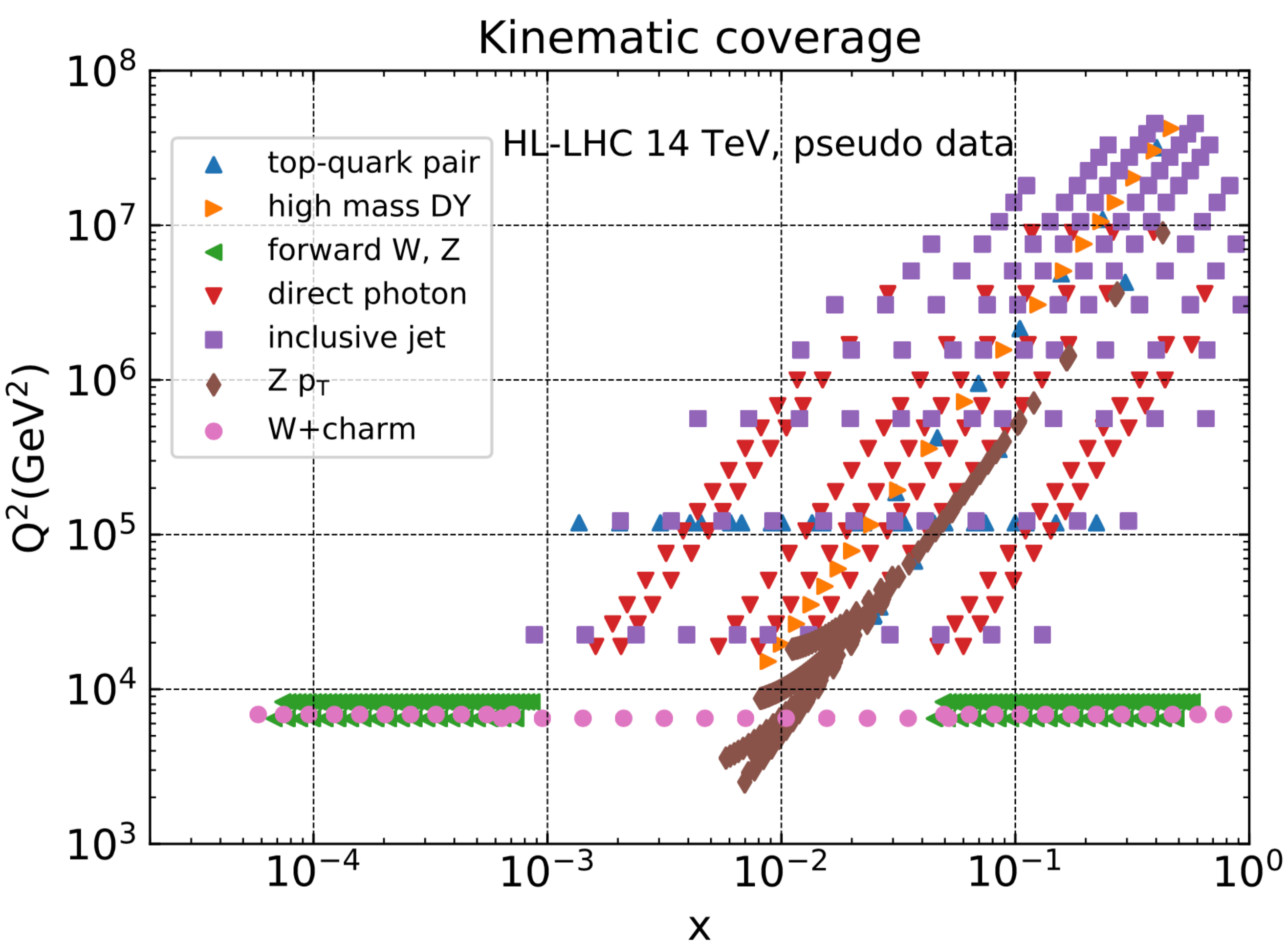


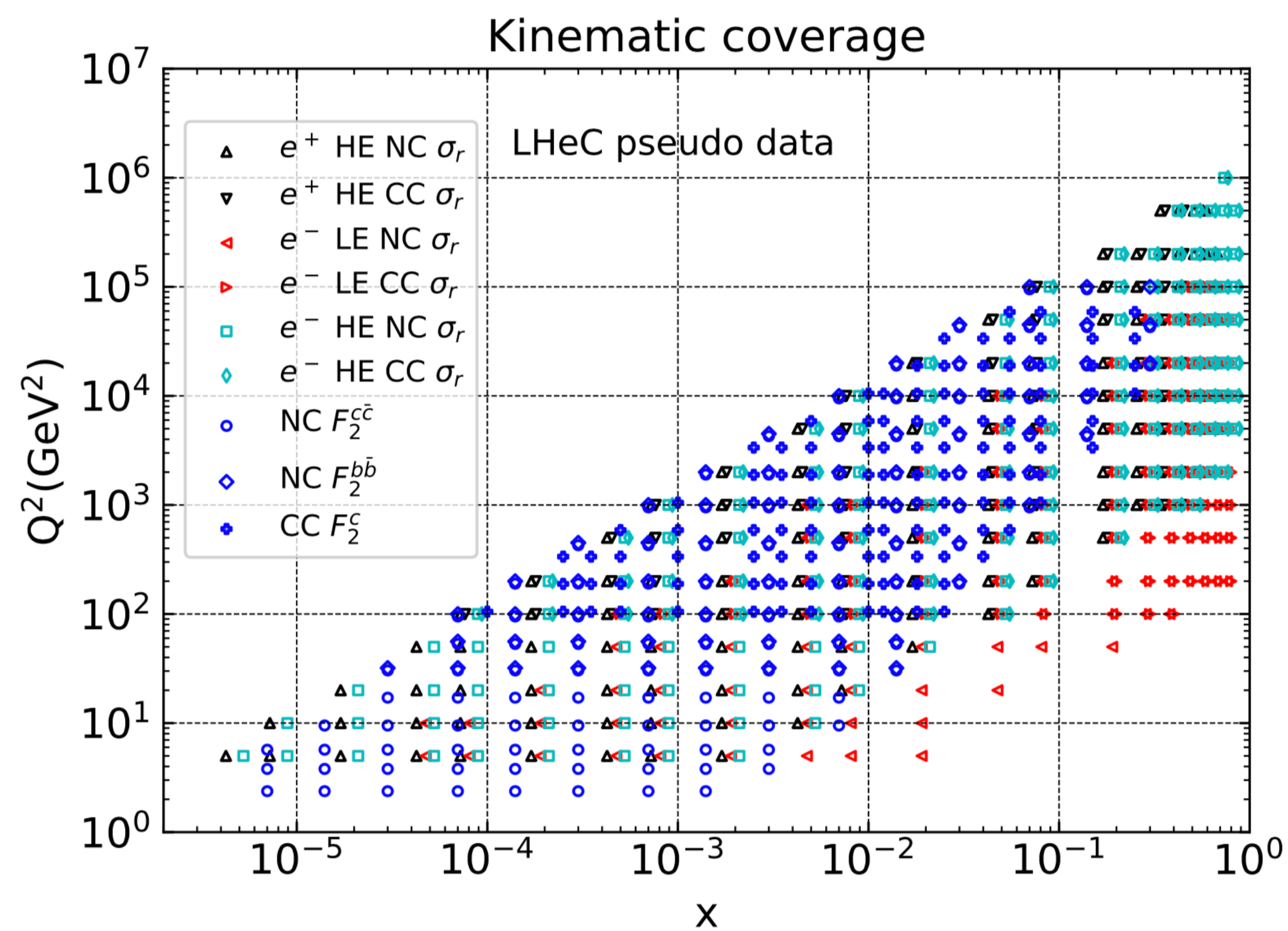
$N_5(84)$	$N_7(79)$	$N_{13}(126)$	$R_{13/5}(107)$	$R_{13/7}(102)$
1.97	1.21	2.36	1.36	0.80
0.86	0.72	1.14	1.35	0.81
1.31	**0.91**	1.58	1.36	0.82
0.74	0.66	**1.01**	1.38	0.80
1.08	0.81	1.27	**1.29**	0.80
1.53	0.99	1.73	1.30	**0.81**
1.07	0.81	1.34	1.35	**0.81**
0.82	**0.70**	1.07	**1.35**	0.81
0.84	**0.71**	**1.10**	1.36	0.81

Gauld, JR 16

Towards ultimate PDFs at the HL-LHC and LHeC

Exploit **novel facilities** for precision studies of the proton structure

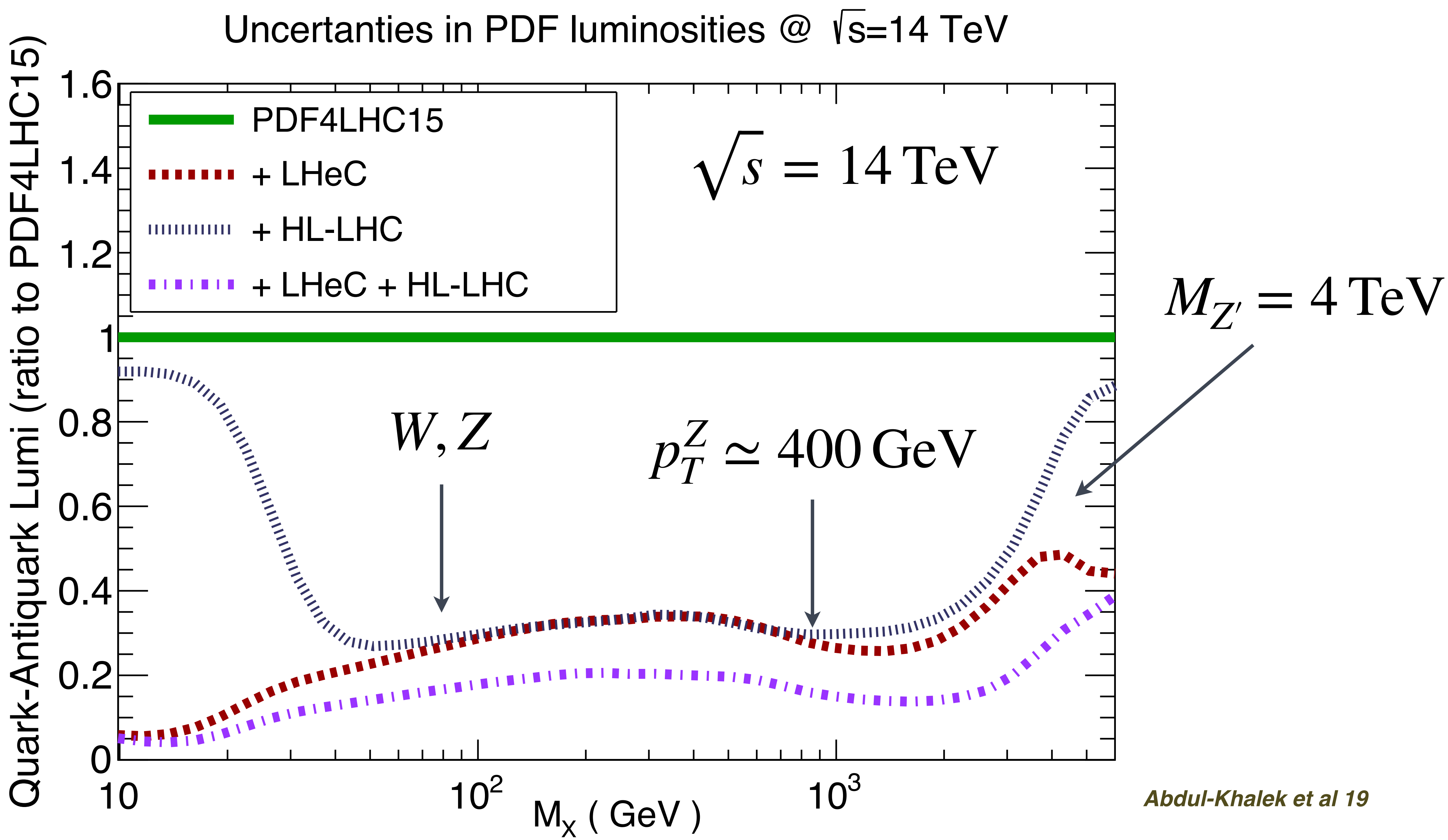




Fully **complementary** in terms of PDF constraints, possible synchronous operation

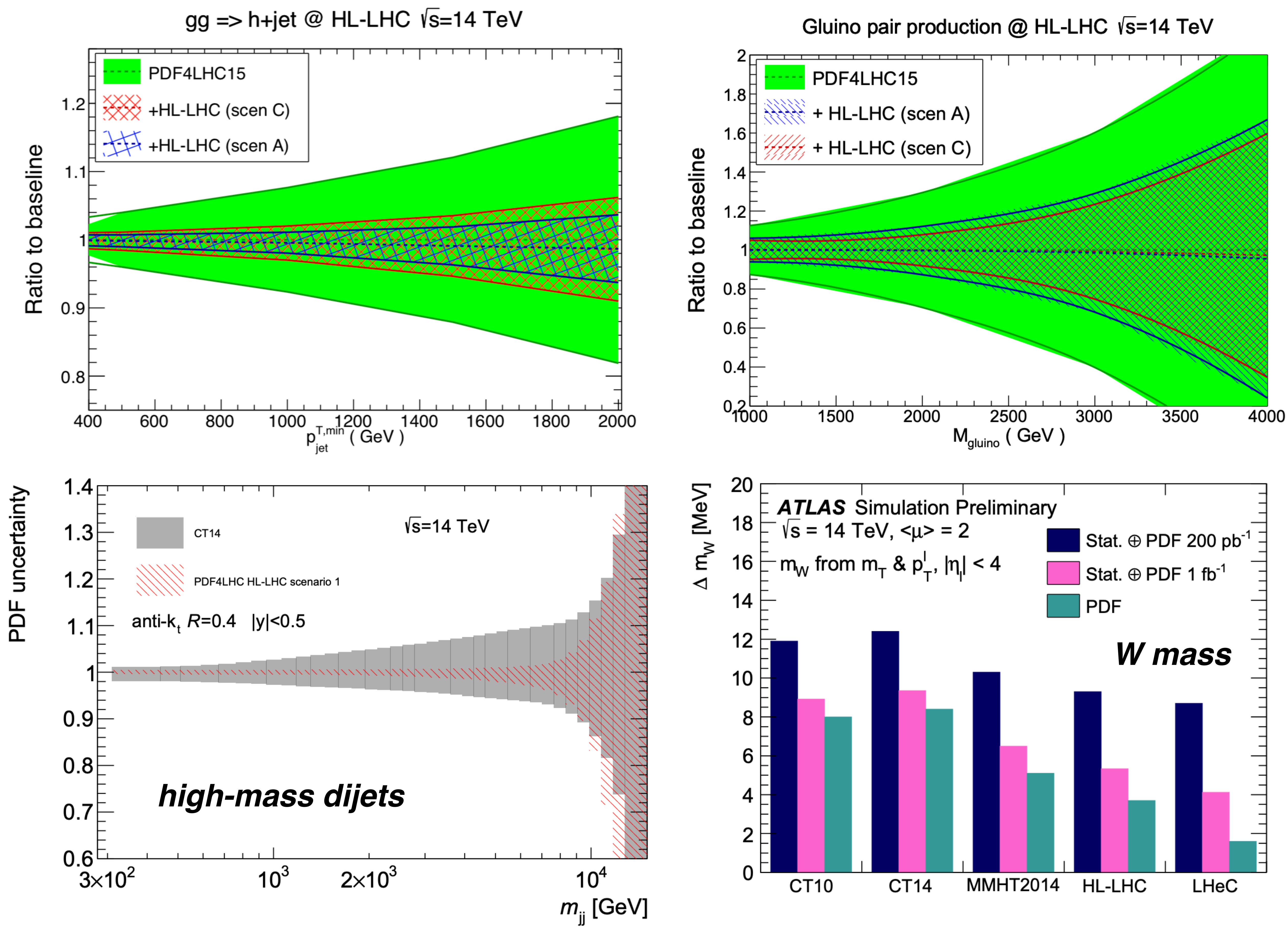
Towards ultimate PDFs at the HL-LHC and LHeC

Quantify the ultimate **PDF constraining power** of HL-LHC and LHeC



A reduction of PDF uncertainties by **up to a factor 10** could be within reach

Impact on phenomenology



Part I Summary

The accurate determination of the **quark and gluon structure of the proton** is an essential ingredient for **LHC phenomenology** and **beyond**

- PDF determinations allow us to probe **novel phenomena in QCD and address long-standing questions**: do the protons contain heavy quarks? Are there new gluon-dominated states of matter at high energies? Where does the proton spin come from?

- PDFs are also crucial for a **wide array of phenomenology**, from Higgs characterisation at the LHC to high0energy neutrino telescopes and heavy ion collisions

- In the second part of the talk we will focus on the **rare components of the proton,** beyond the well-known valence quarks and gluons. These include the strange, charm, and bottom quarks, photons and leptons, and even Higgs and gauge bosons at extremely large energies

Part II: Rare partonic components of the proton

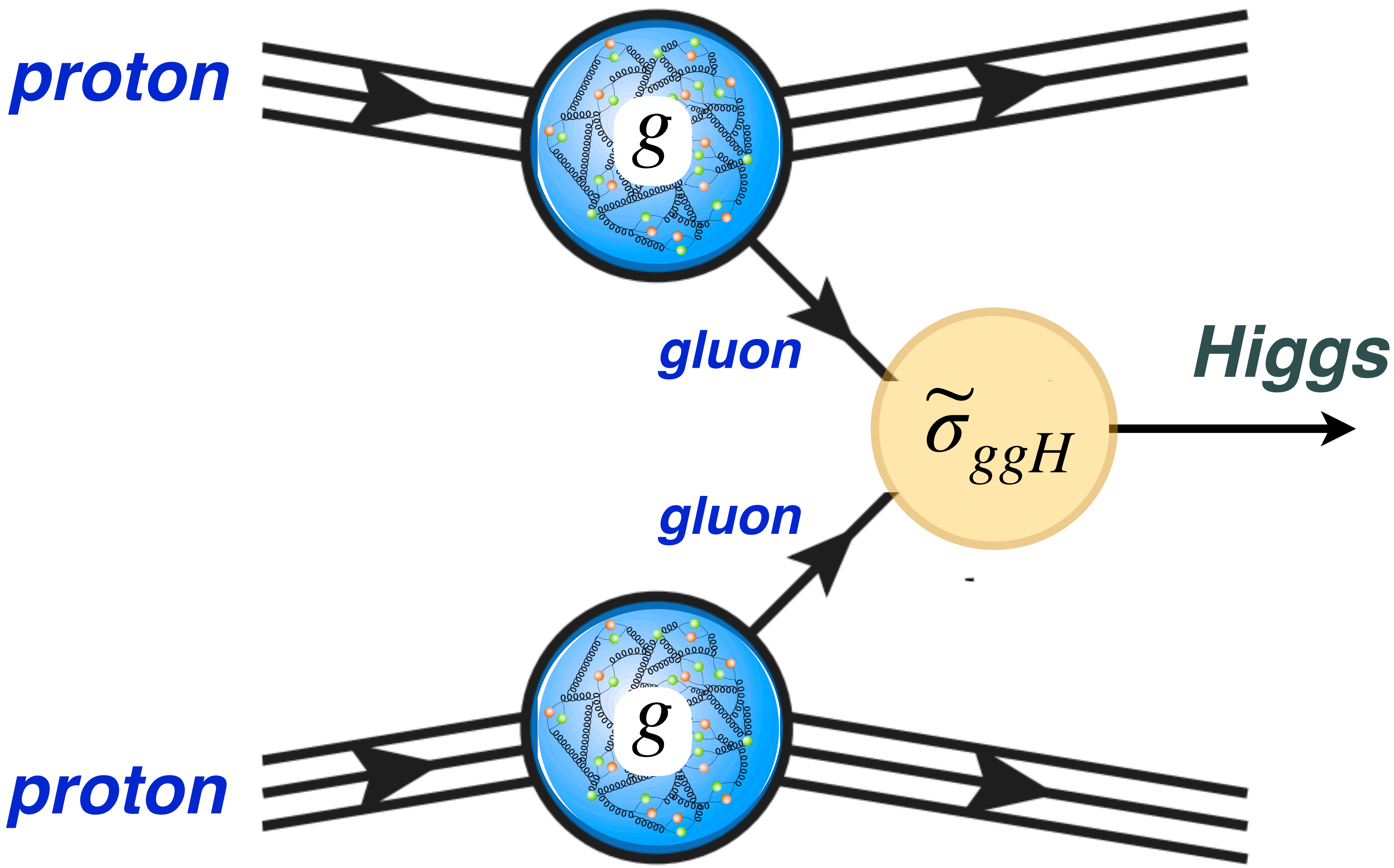
The inner life of protons

brief recap of the introductory material

Parton Distributions

$$N_{\mathrm{LHC}}(H) \sim g \otimes g \otimes \widetilde{\sigma}_{ggH}$$

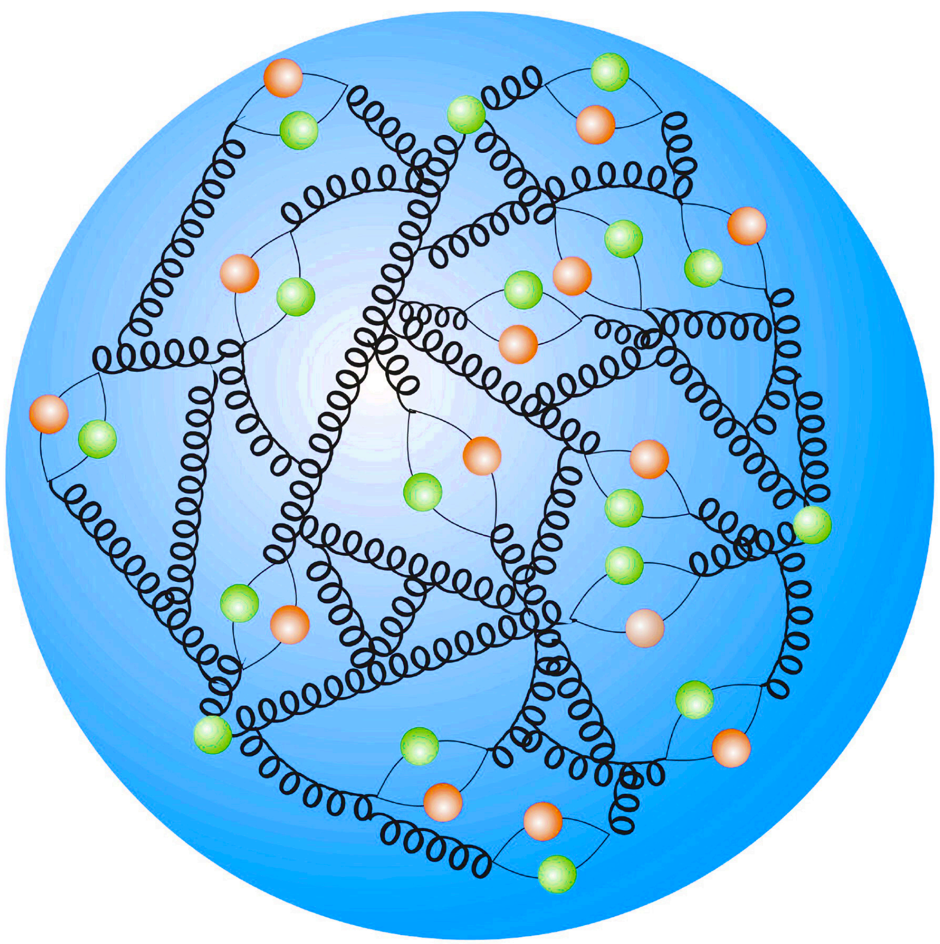
Parton Distributions ***Partonic cross-sections***



All-order structure: **QCD factorisation theorems**

Parton Distributions

Proton energy divided among constituents: **quarks** and **gluons**



Parton Distribution Functions (PDFs)

Determine from **data:**

Global QCD analysis

Mass? Spin?
Heavy quark content?
Novel QCD dynamics?

Theoretical predictions for LHC, RHIC, IceCube?

Parton Distributions

$$g(x, Q)$$

Energy of hard-scattering reaction**:** inverse of resolution length

Probability of **finding a gluon inside a proton**, carrying a fraction ***x*** of the proton momentum, when probed with energy ***Q***

x: fraction of proton momentum carried by gluon

Dependence on *x* fixed by **non-perturbative QCD dynamics**: extract from experimental data

e.g. $g(x, Q_0^2) = A_g x^{\alpha_g}(1-x)^{\beta_g}$ ***introduce a model, extract its parameters from data***

$$\int_0^1 dx\, x \left(\sum_{i=1}^{n_f} \left[q_i((x, Q^2) + \bar{q}_i(x, Q^2) \right] + g(x, Q^2) \right) = 1$$

momentum sum rule (energy conservation)

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momentum sum rule (energy conservation)

Dependence on ***Q*** fixed by **perturbative QCD dynamics**: computed up to $\mathcal{O}\left(\alpha_s^4\right)$

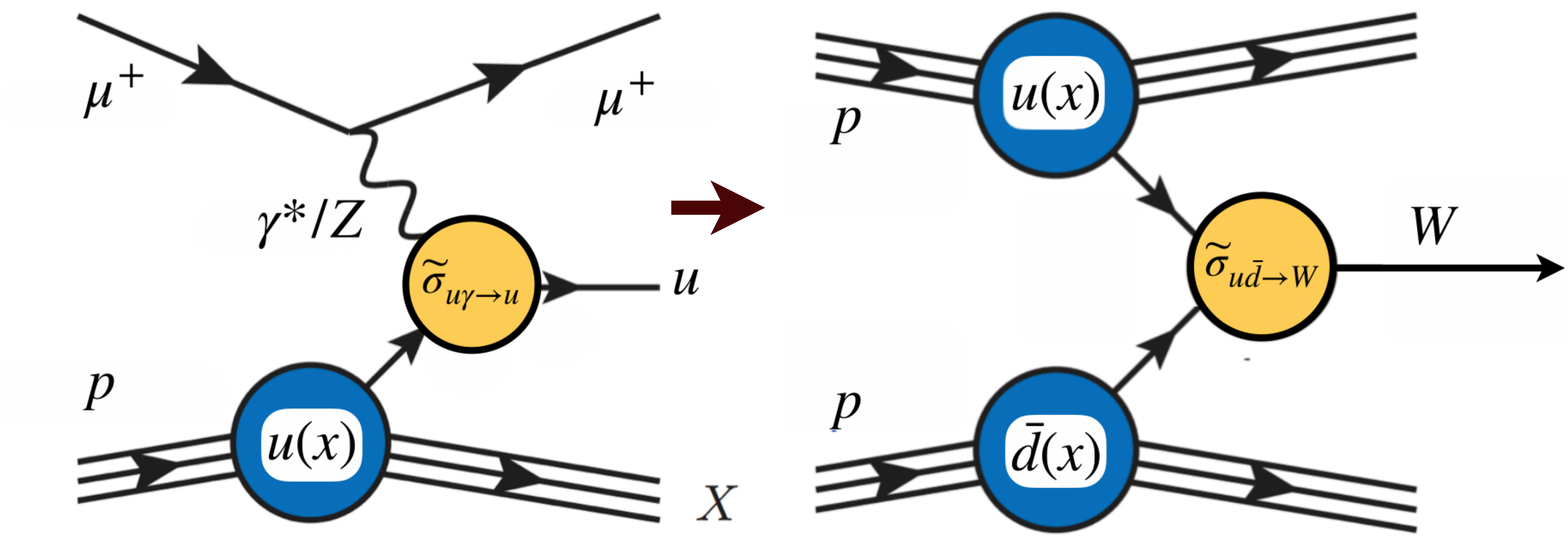
$$\frac{\partial}{\partial \ln Q^2} q_i(x, Q^2) = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(Q^2) \right) q_j(z, Q^2)$$

DGLAP evolution equations

The Global QCD analysis paradigm

QCD factorisation theorems: **PDF universality**

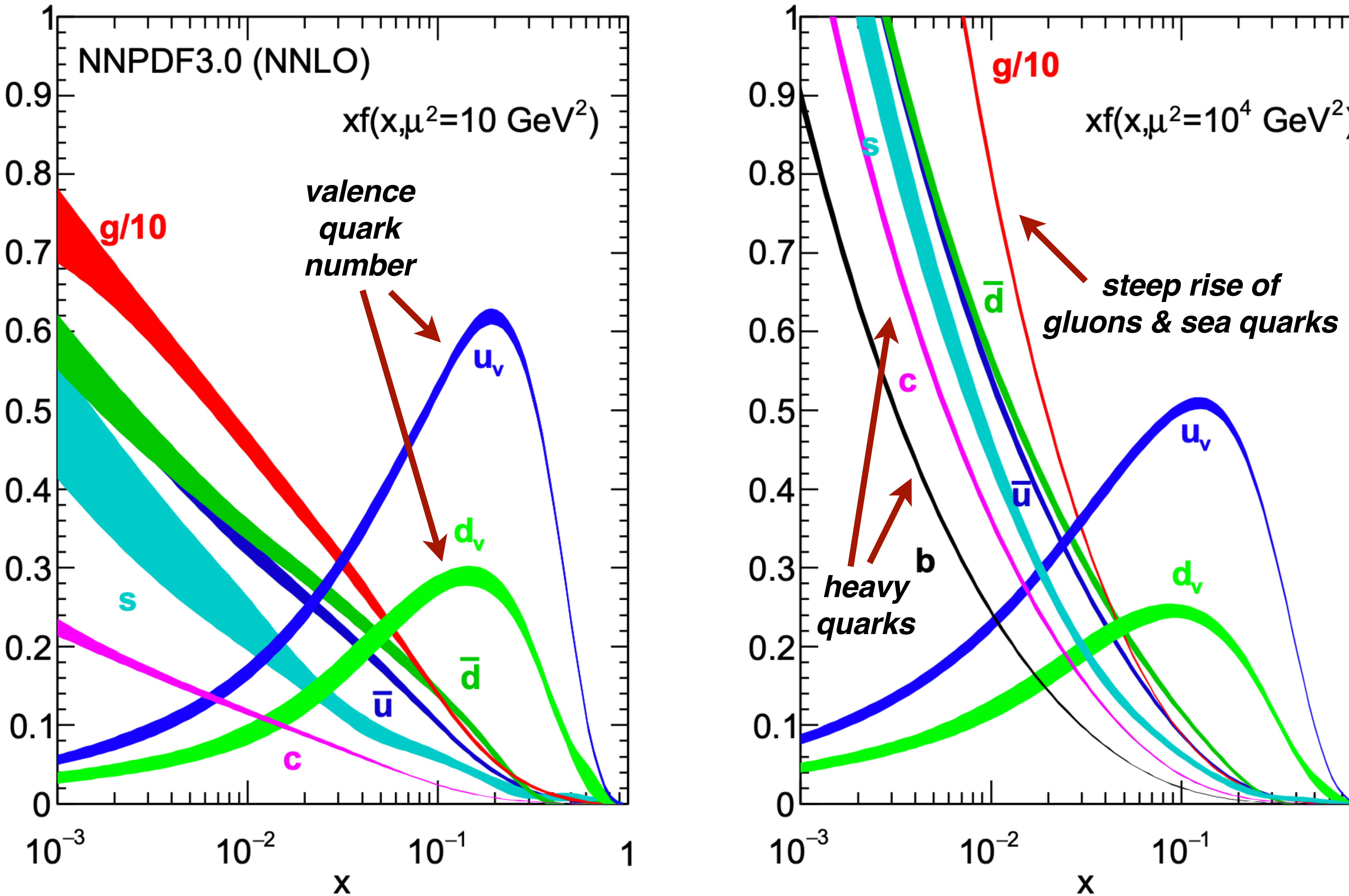
$$\sigma_{\mu p\to\mu X} = \tilde{\sigma}_{u\gamma^*\to u} \otimes u(x) \quad \rightarrow \quad \sigma_{pp\to W} = \tilde{\sigma}_{u\bar{d}\to W} \otimes u(x) \otimes \bar{d}(x)$$



*Determine PDFs from **deep-inelastic scattering**…*

*… and use them to compute predictions for **proton-proton collisions***

A proton structure snapshop



the heavy quark content of the proton

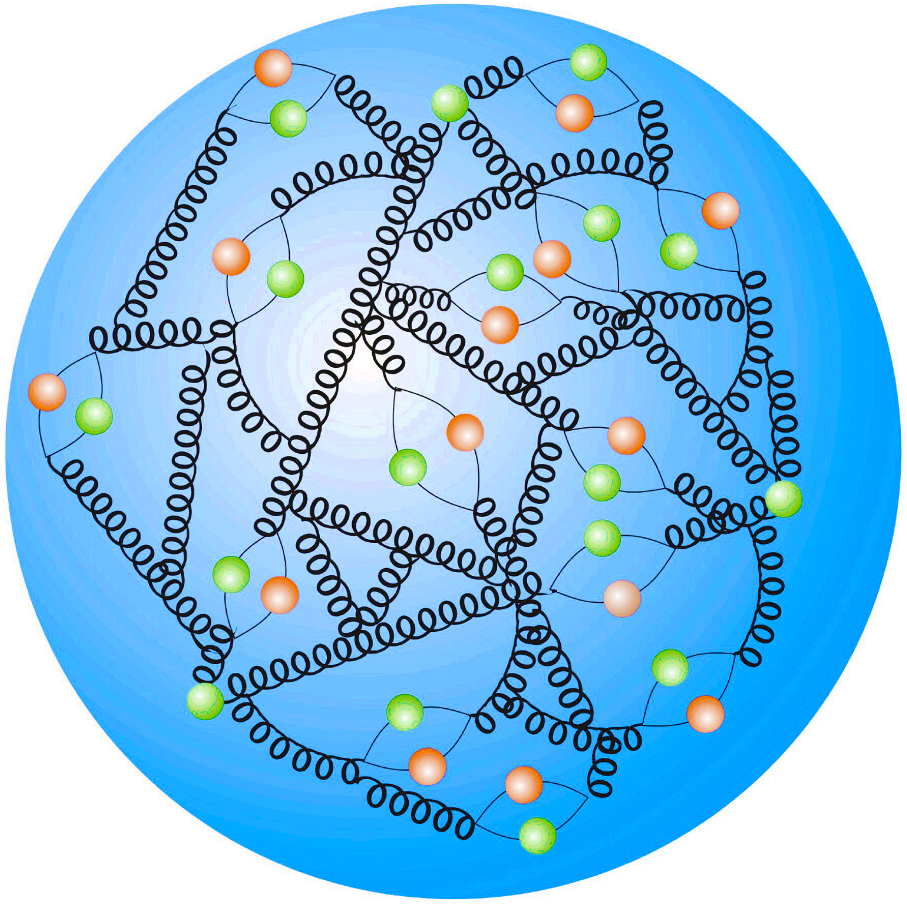
The many faces of the proton

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

$m_p \simeq 1$ GeV

valence quarks: up & down

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



gluons

$m_g = 0$

gluons and valence quarks are the best understood components of the proton

The many faces of the proton

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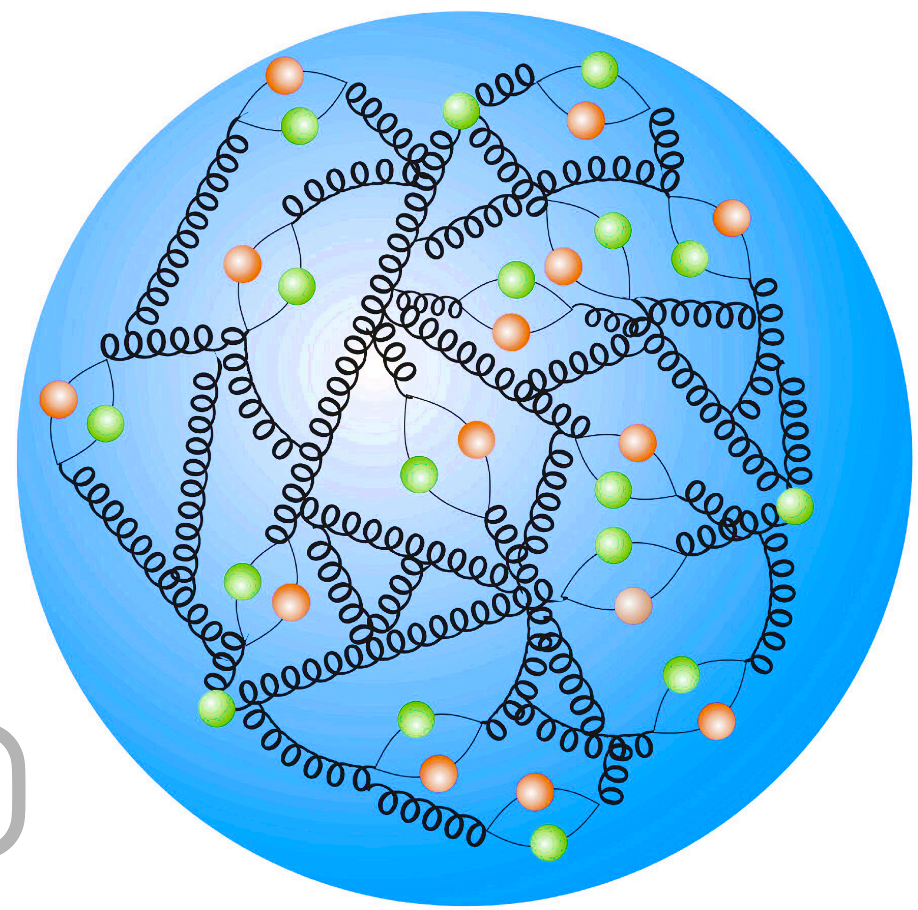


gluons

$m_g = 0$

strange quarks?

$m_s \simeq 200$ MeV

charm quarks?

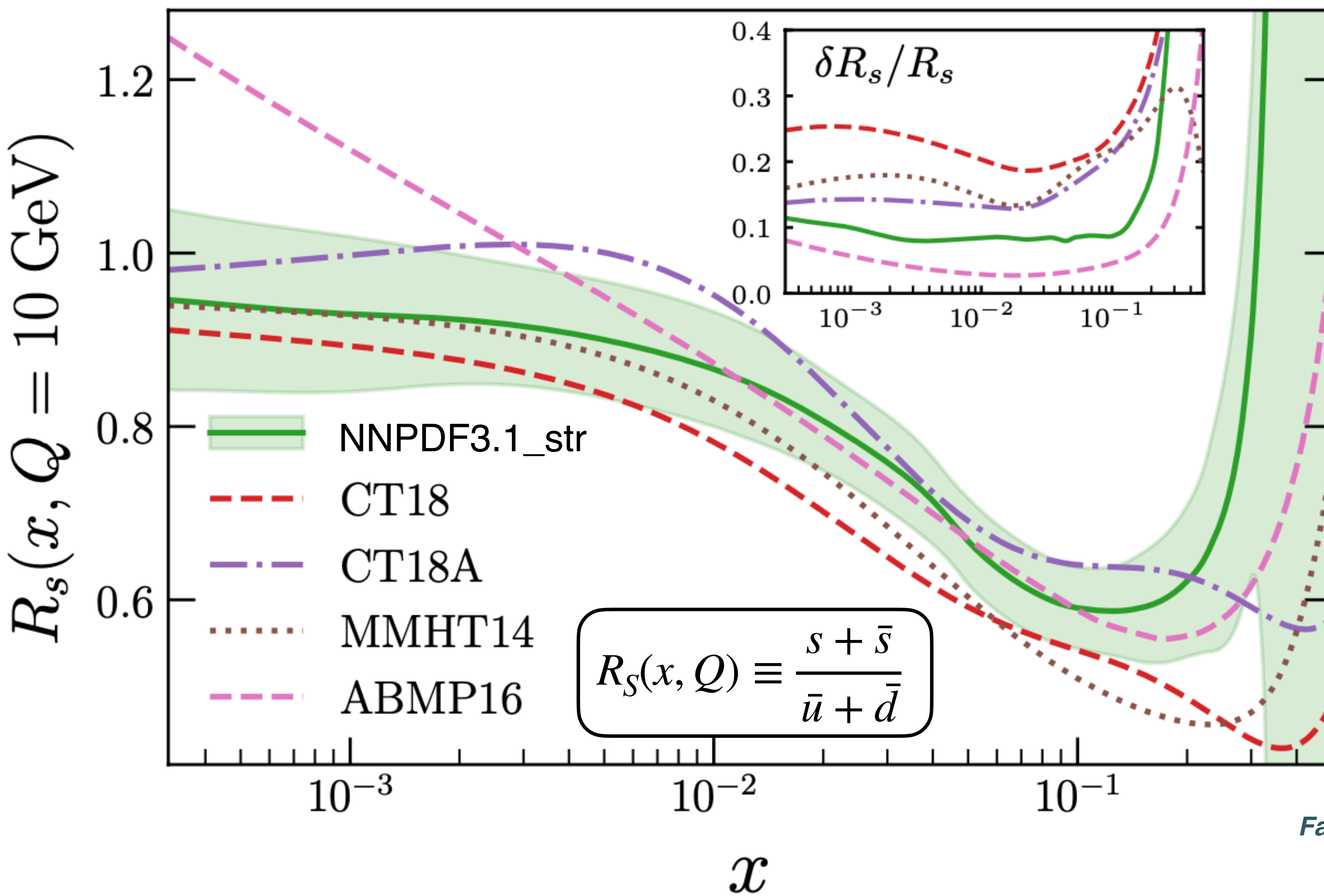
$m_c \simeq 1.5$ GeV

bottom quarks?

$m_b \simeq 4.5$ GeV

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

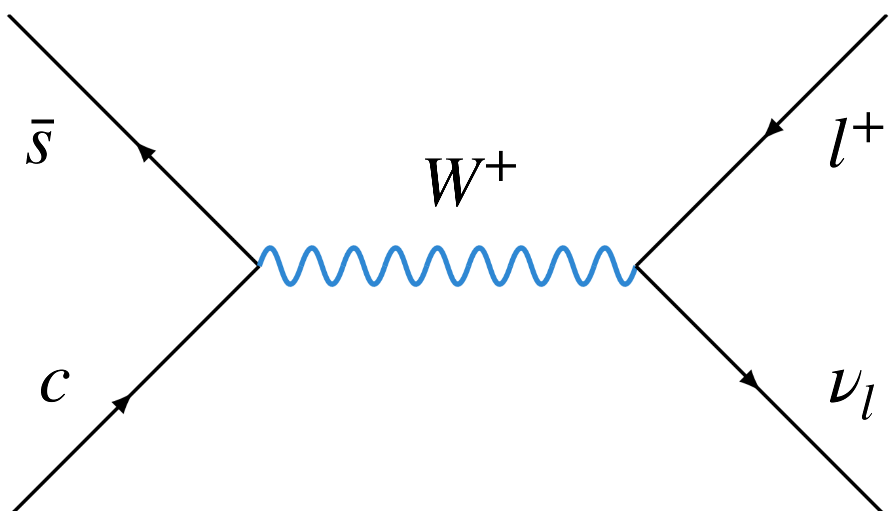


Faura et al 20

Constraining strangeness

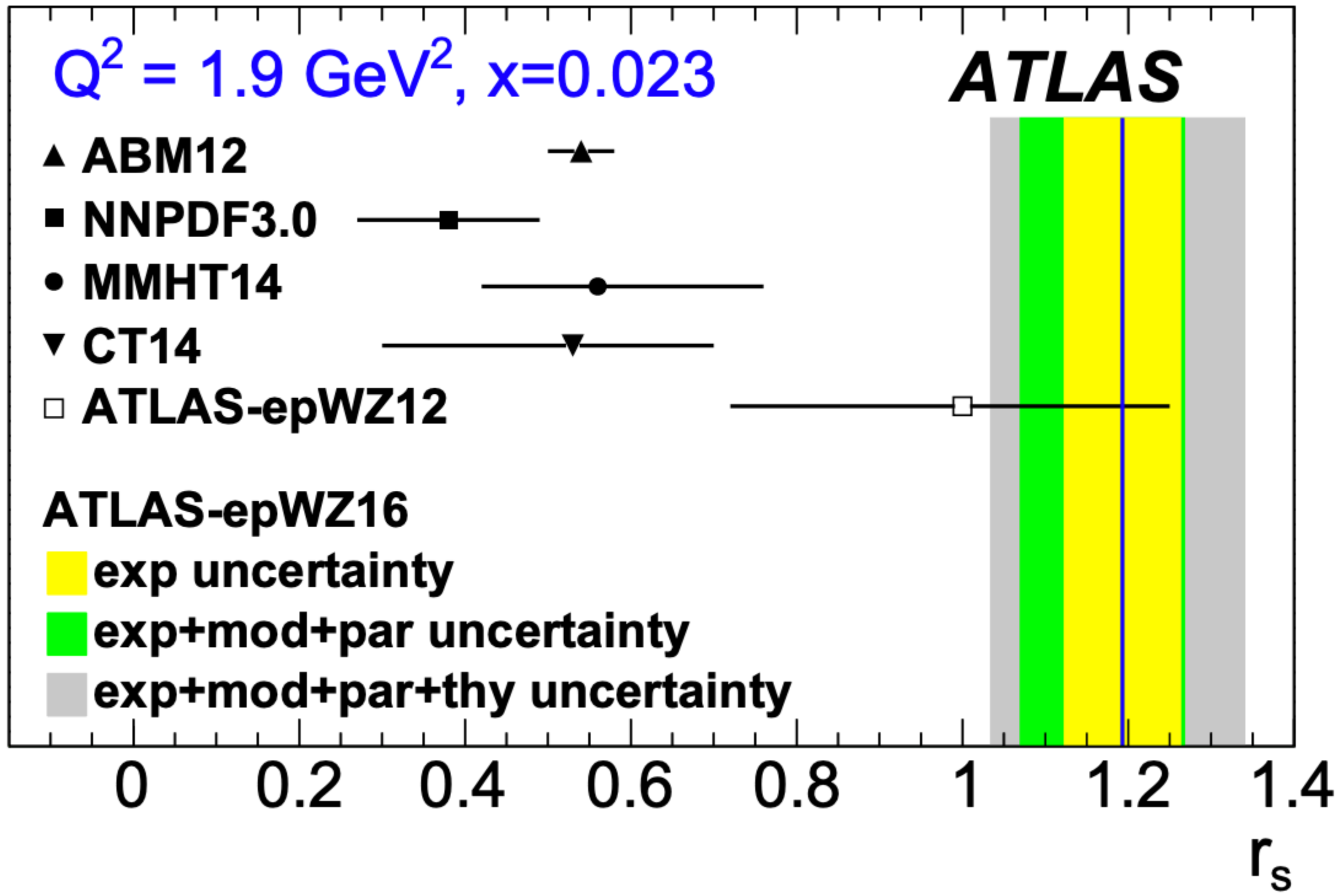
the strange PDF can be constrained by different processes, both **collider** and **fixed-target**

inclusive Drell-Yan



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

ATLAS 7 TeV data: preference for $\boldsymbol{R_S=1}$



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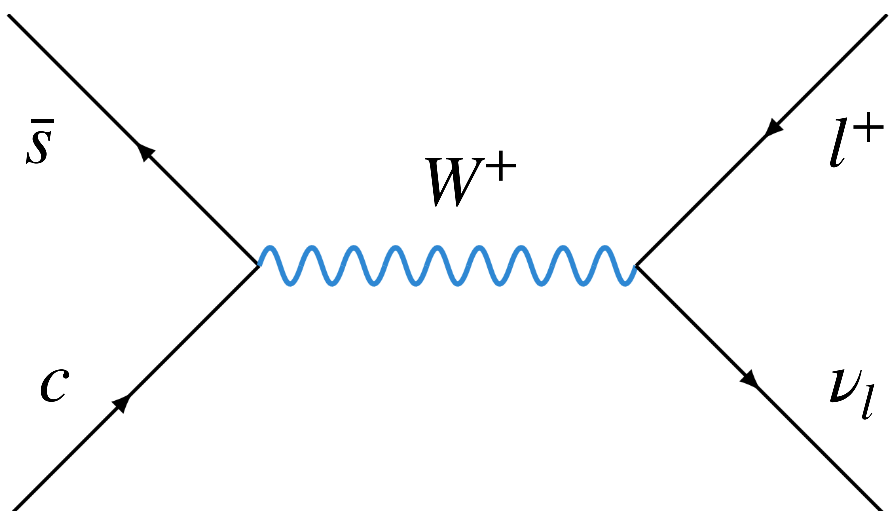

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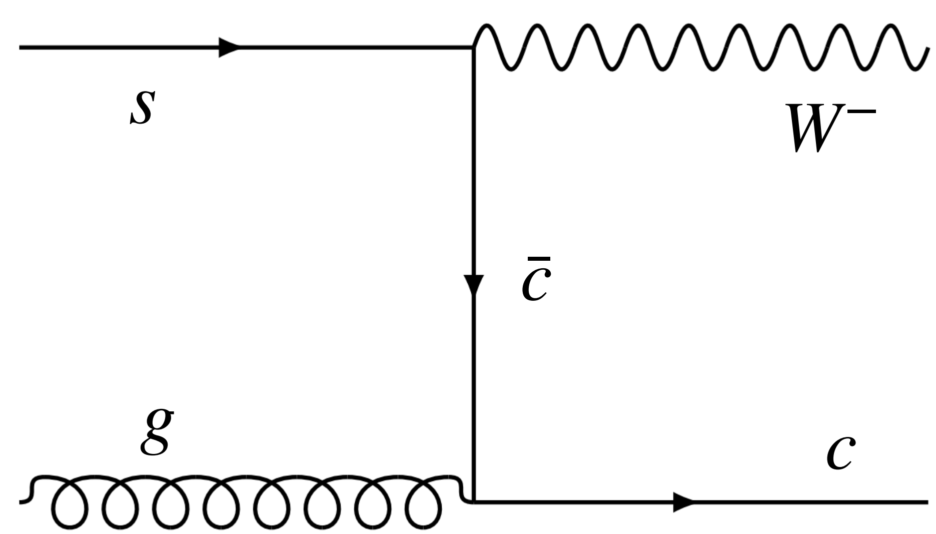
W+charm



direct sensitivity, but larger uncertainties

NNLO QCD corrections recently calculated

Czakon et al 20

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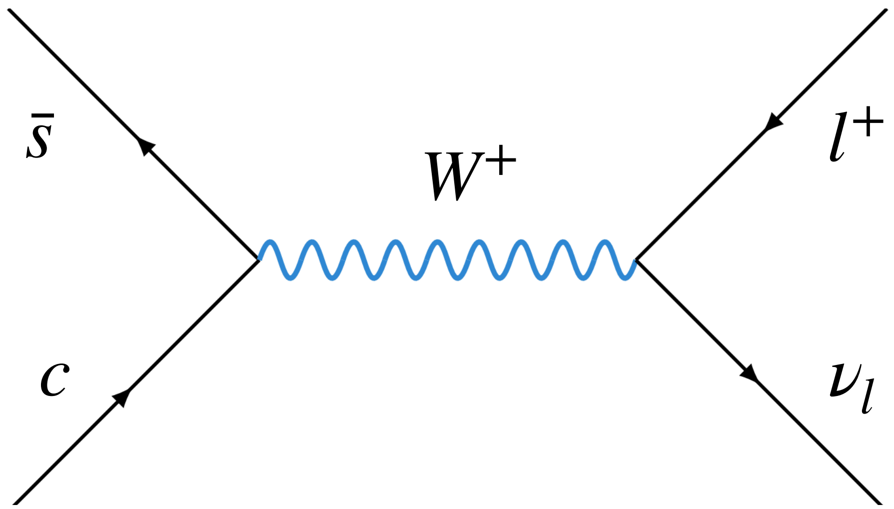
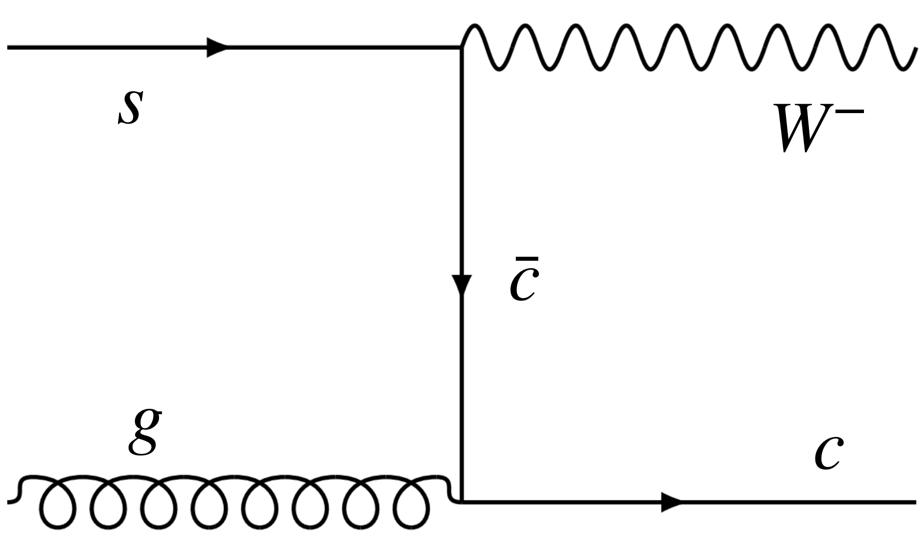
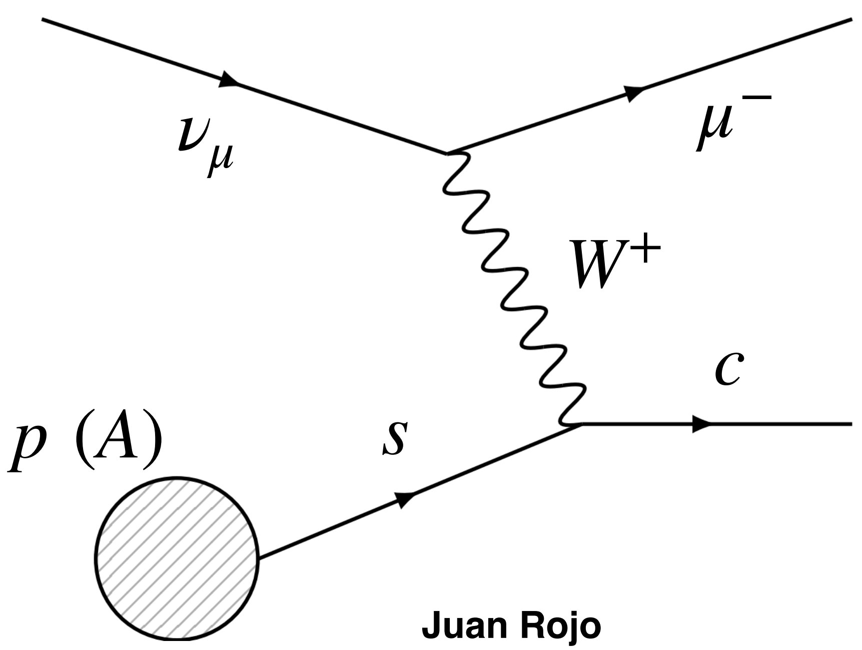
inclusive Drell-Yan



W+charm



Neutrino DIS



Characteristic opposite-sign **dimuon signature**

NNLO massive QCD corrections recently calculated

Gao et al 17

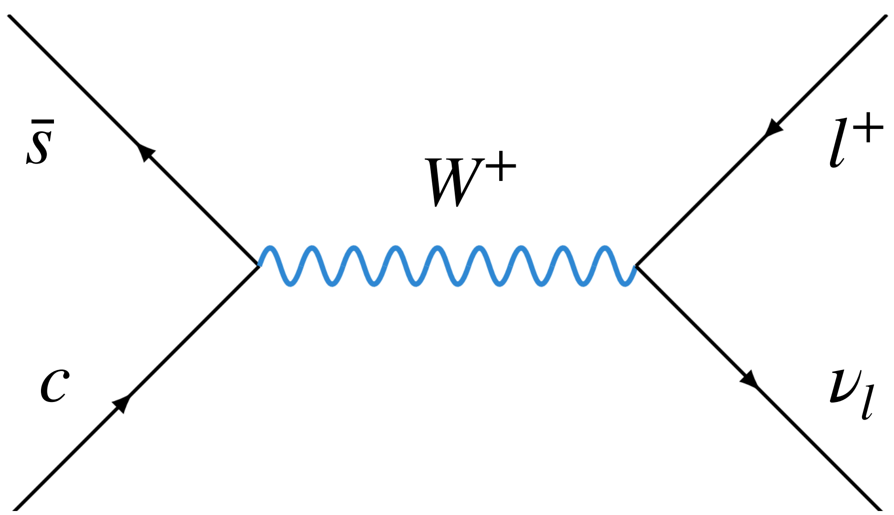
Traditionally associated with $\boldsymbol{R_S \approx 0.5}$

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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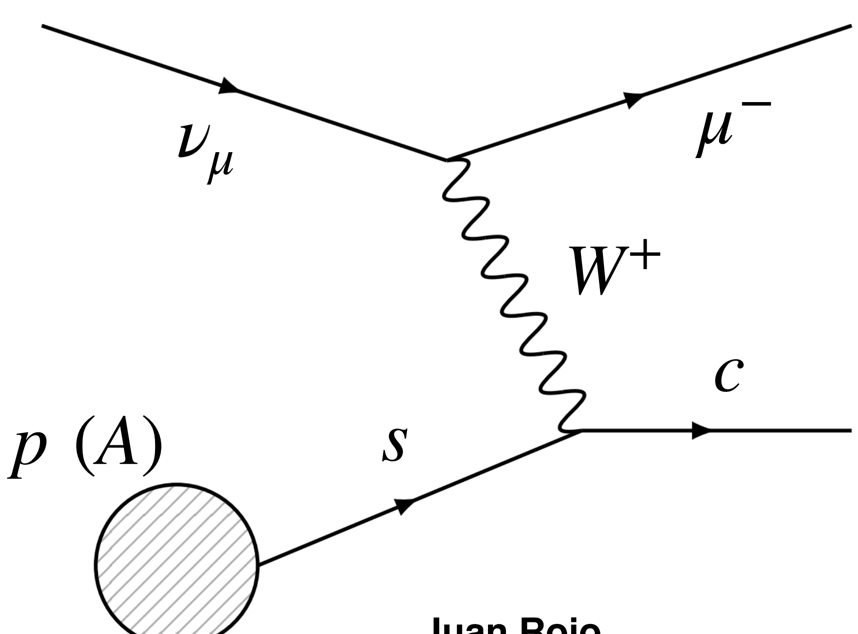

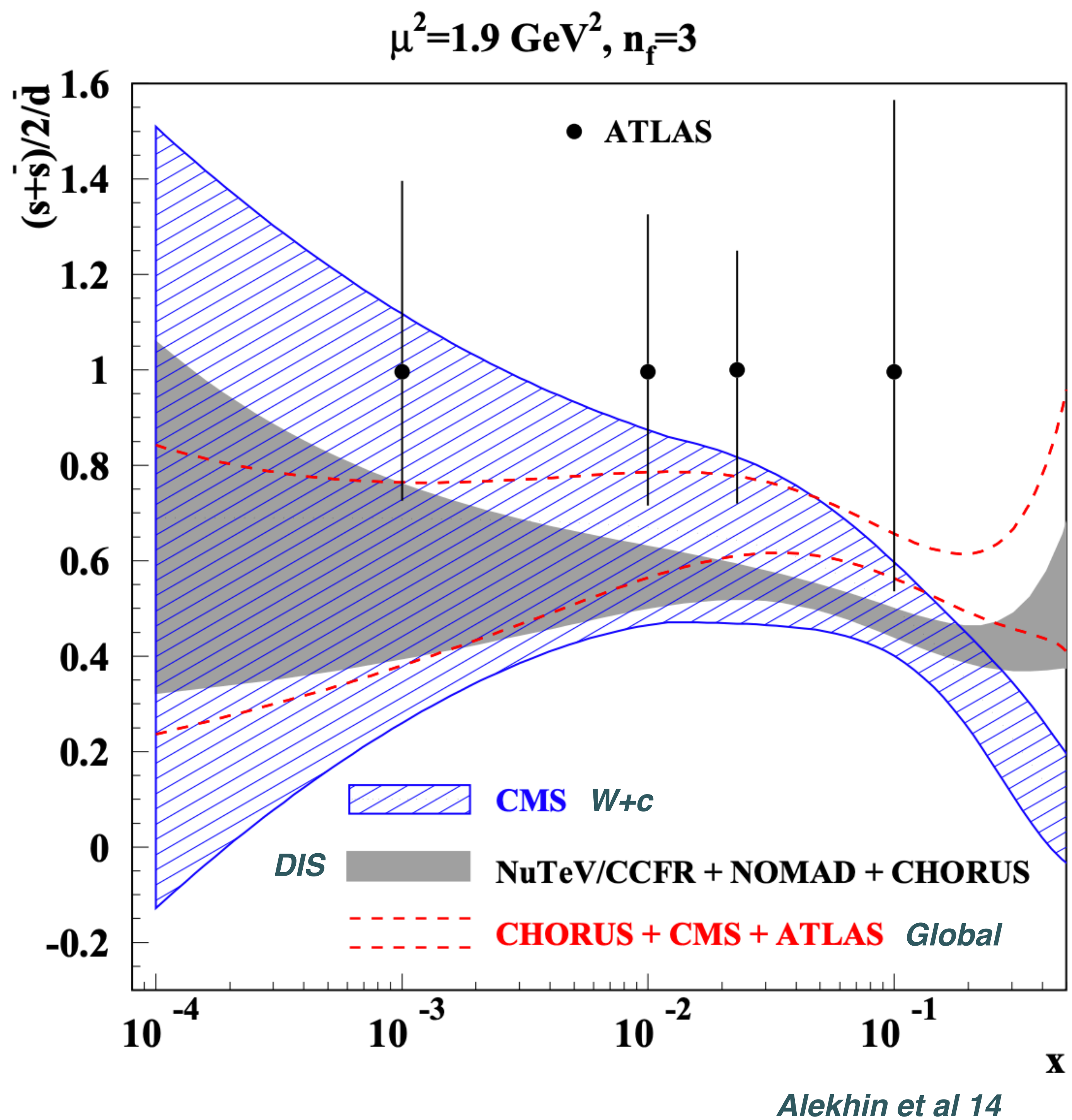

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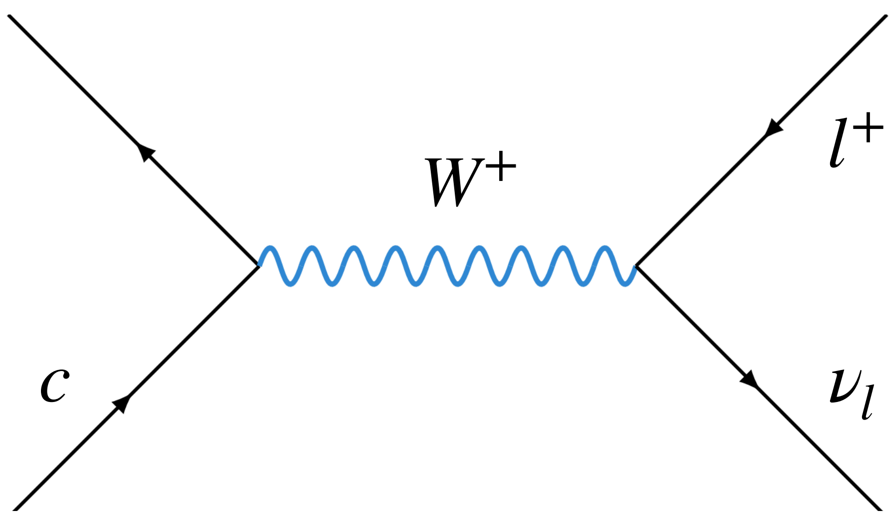
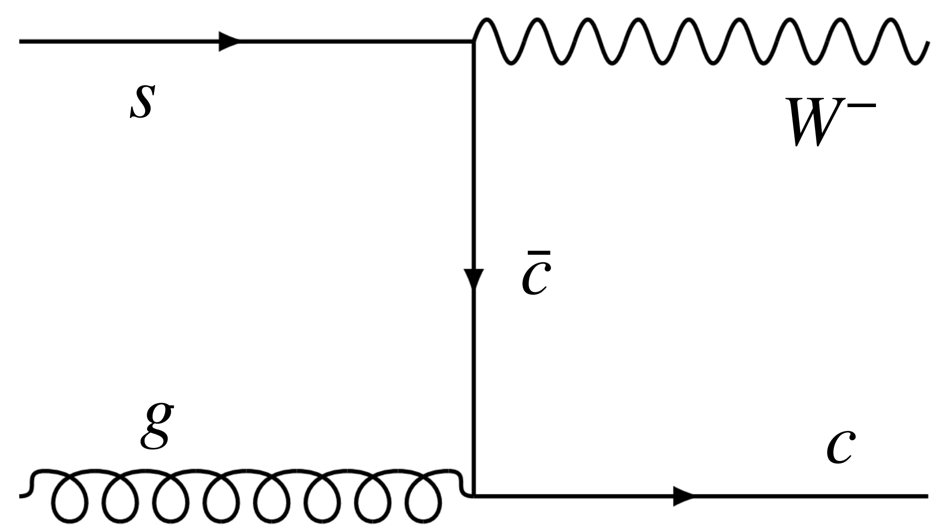
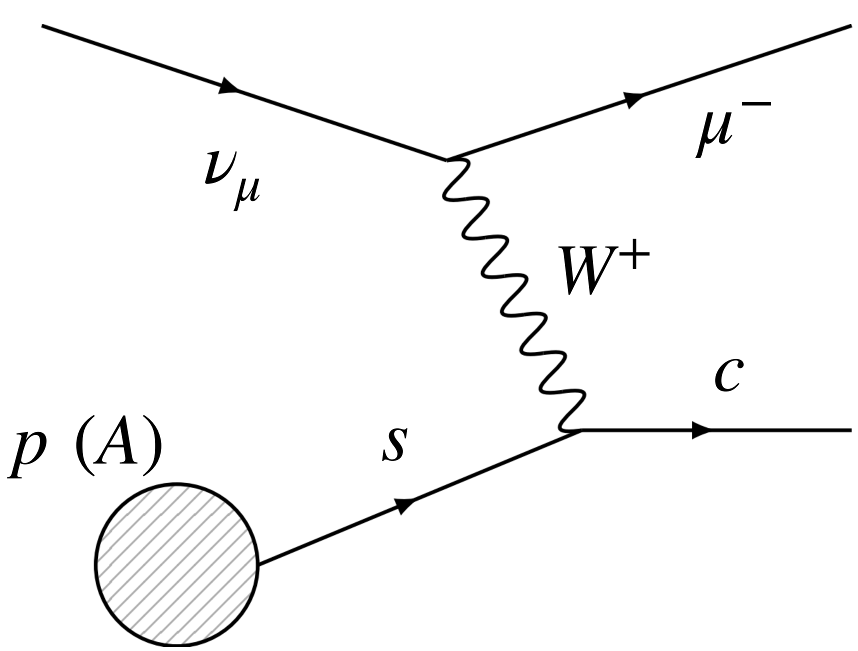


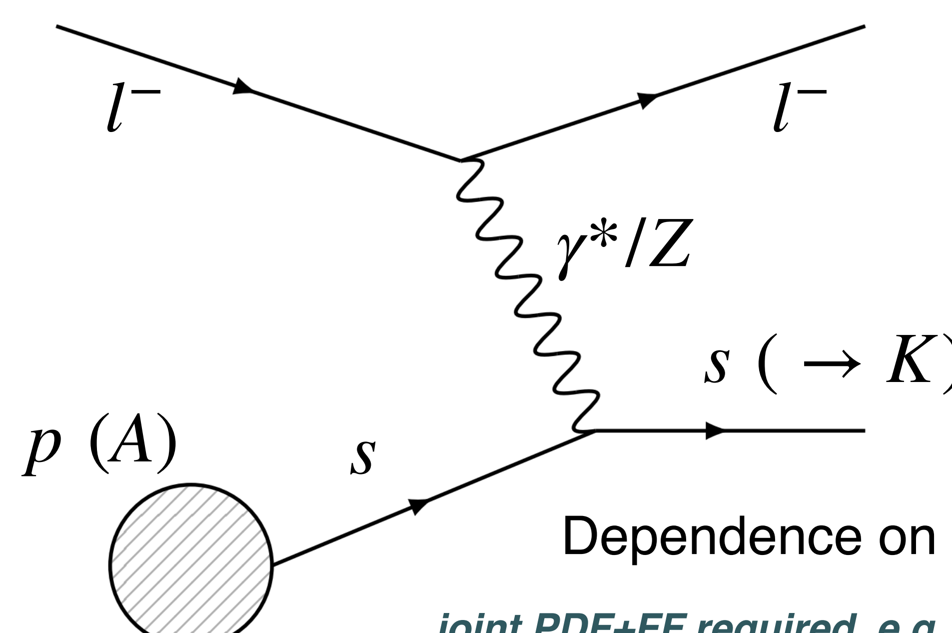
W+charm



Neutrino DIS



Semi-inclusive DIS



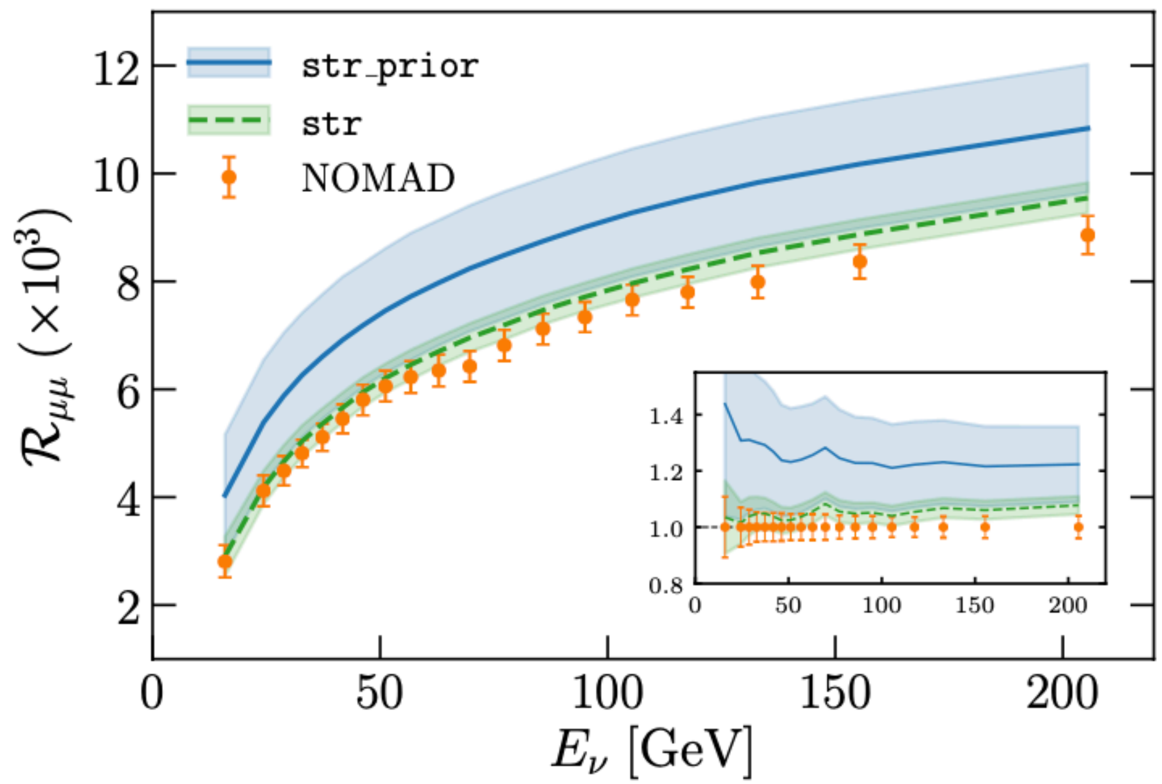
Dependence on **kaon FFs**

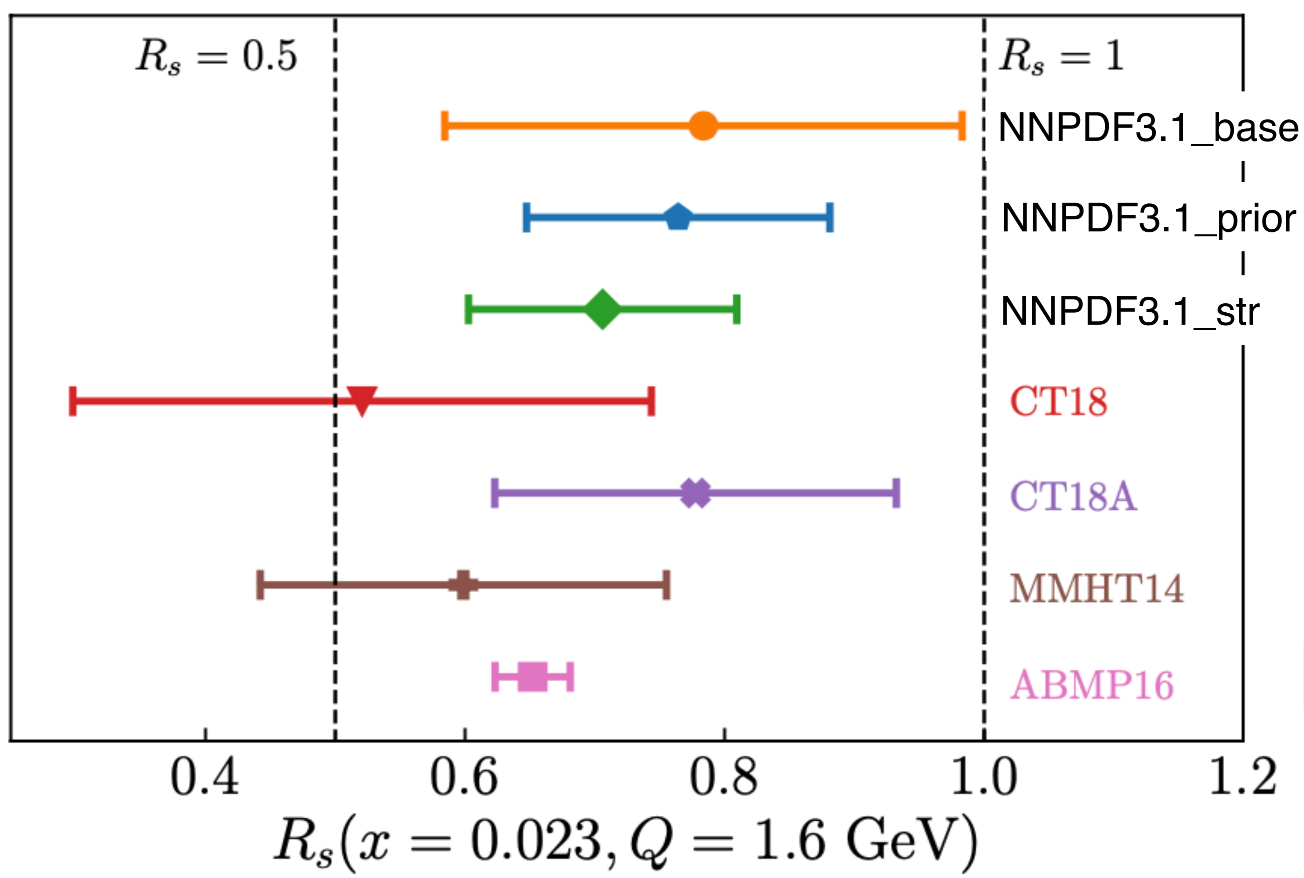
joint PDF+FF required, e.g. JAM analyses

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
- Strong preference for a **moderately suppressed strangeness**

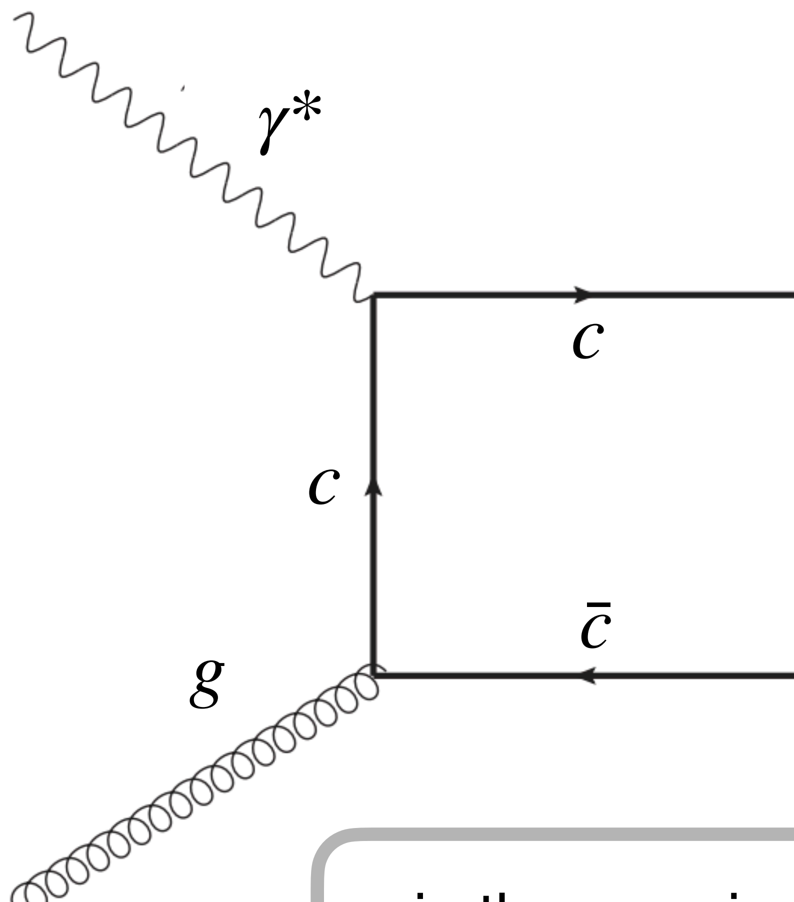
$$R_S(x = 0.023,\ Q = 1.6\ \text{GeV}) = 0.71 \pm 0.10$$

Faura et al 20

A charming proton

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**

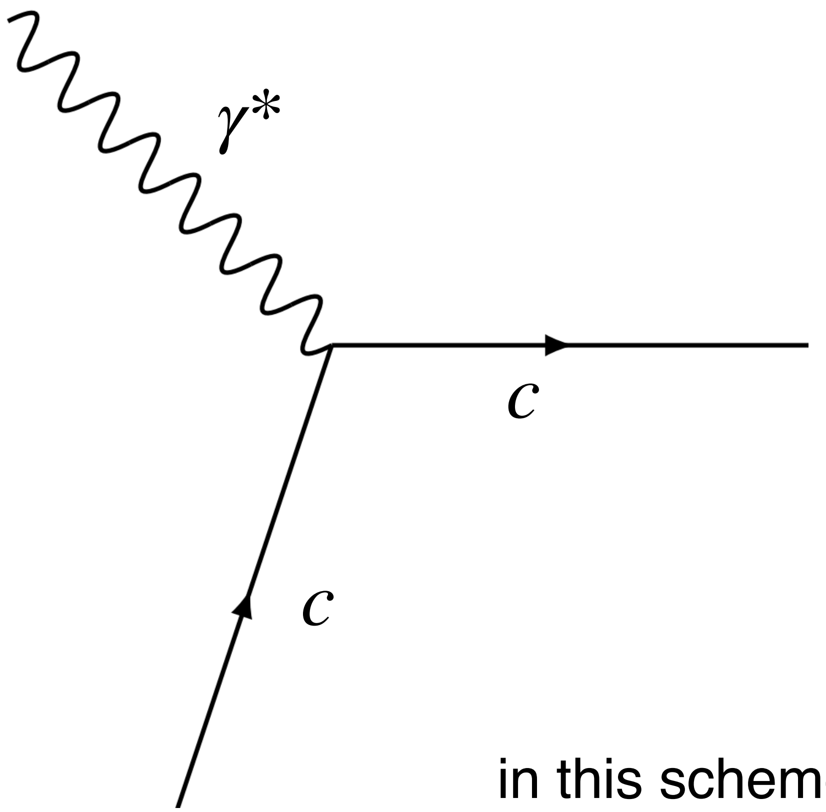
not appropriate to describe ***Q*² >> *m*$_c$²** region due to **large unresummed logs**

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

A charming proton

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 ….

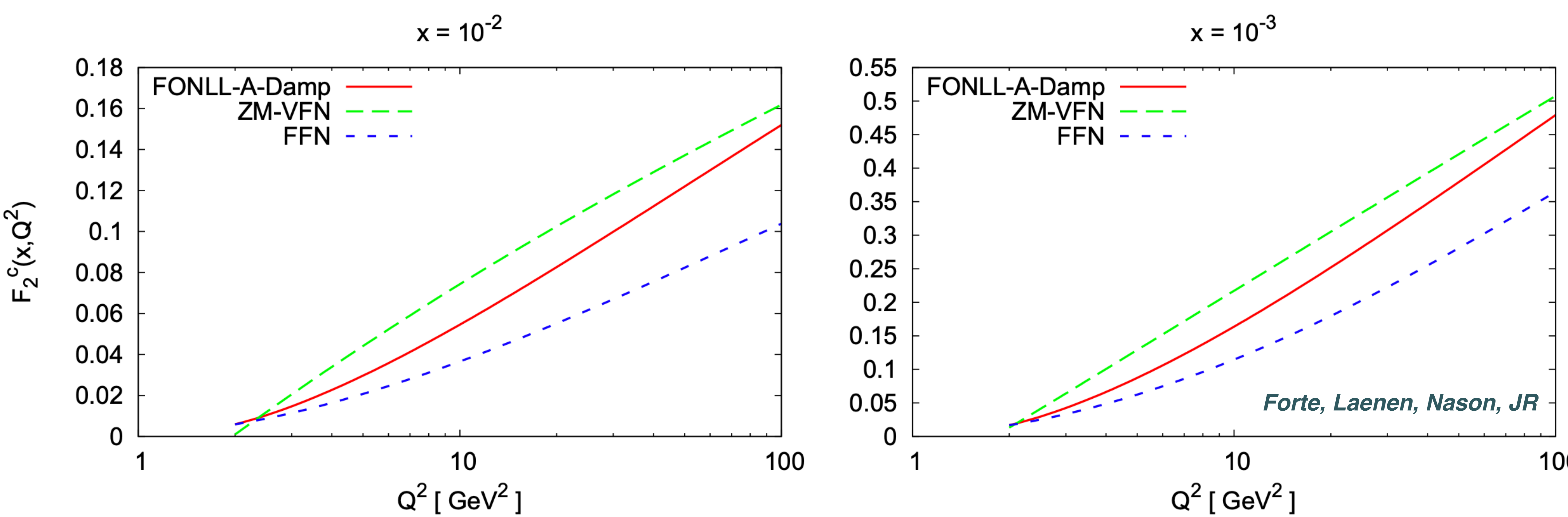
A charming proton

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

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

BHPS model (scale independent)

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

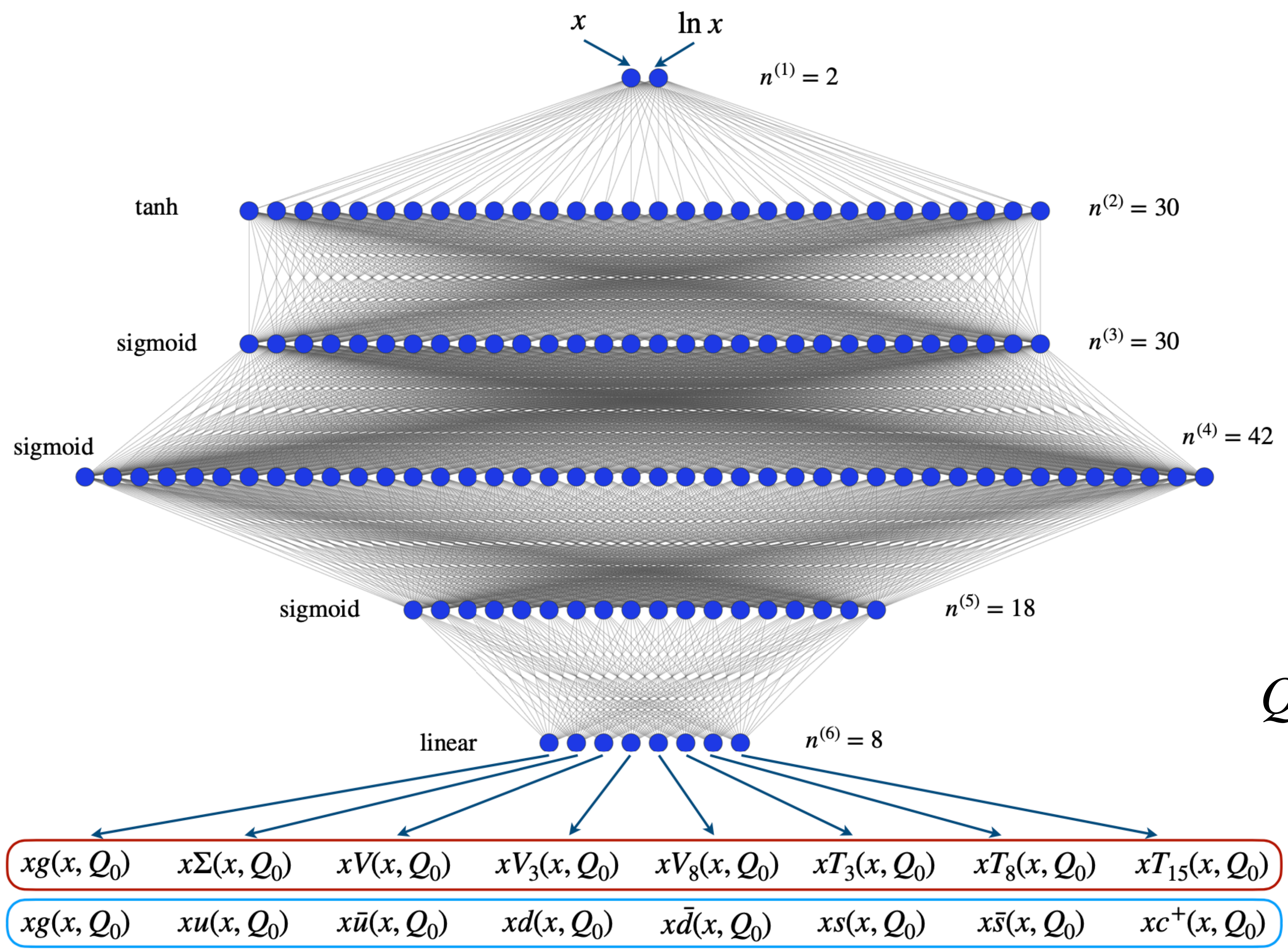
- ***Fitted charm***: no assumptions on possible intrinsic component are made. The charm is parametrised **above threshold** in exactly the same was as all other quark PDFs

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

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

$$Q_0 \geq m_c$$

- ***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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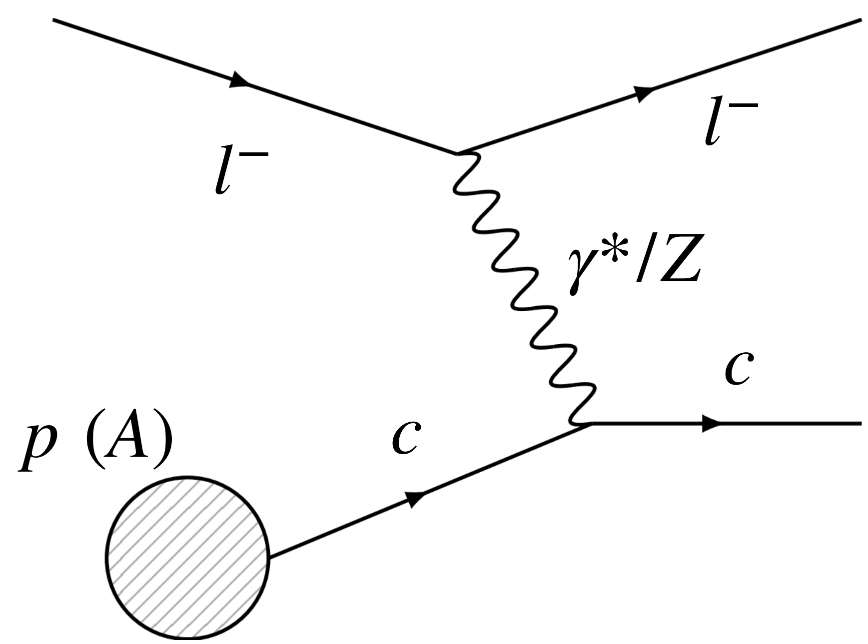
Constraining charm

in the following, we assume that the charm PDF is either **fitted** or **intrinsic**

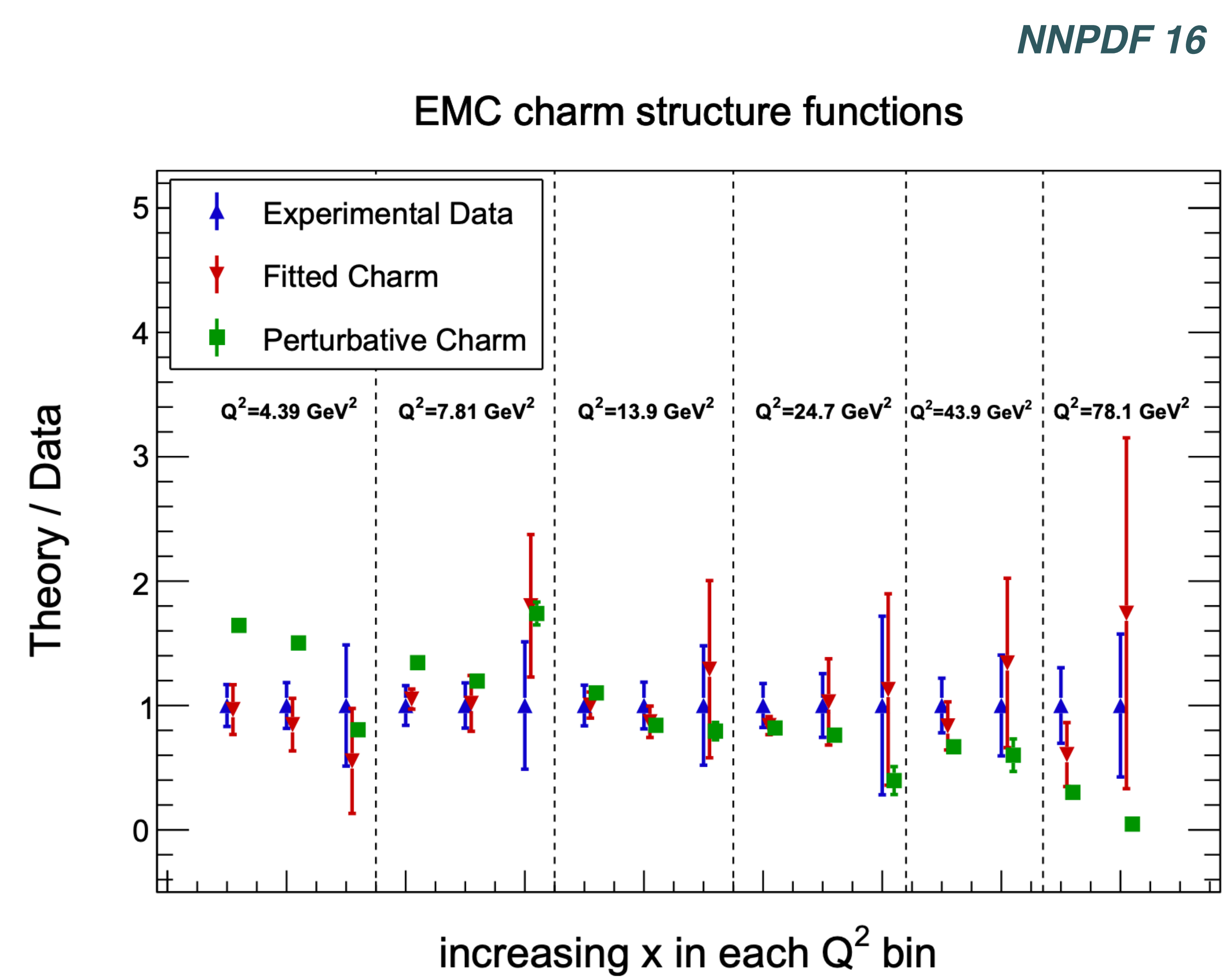
(perturbative charm cannot be constrained, since it is generated by DGLAP evolution)

Charm production in DIS



Only measurements of F_2^c **at large-*x*** are sensitive

EMC data from the 80s available …



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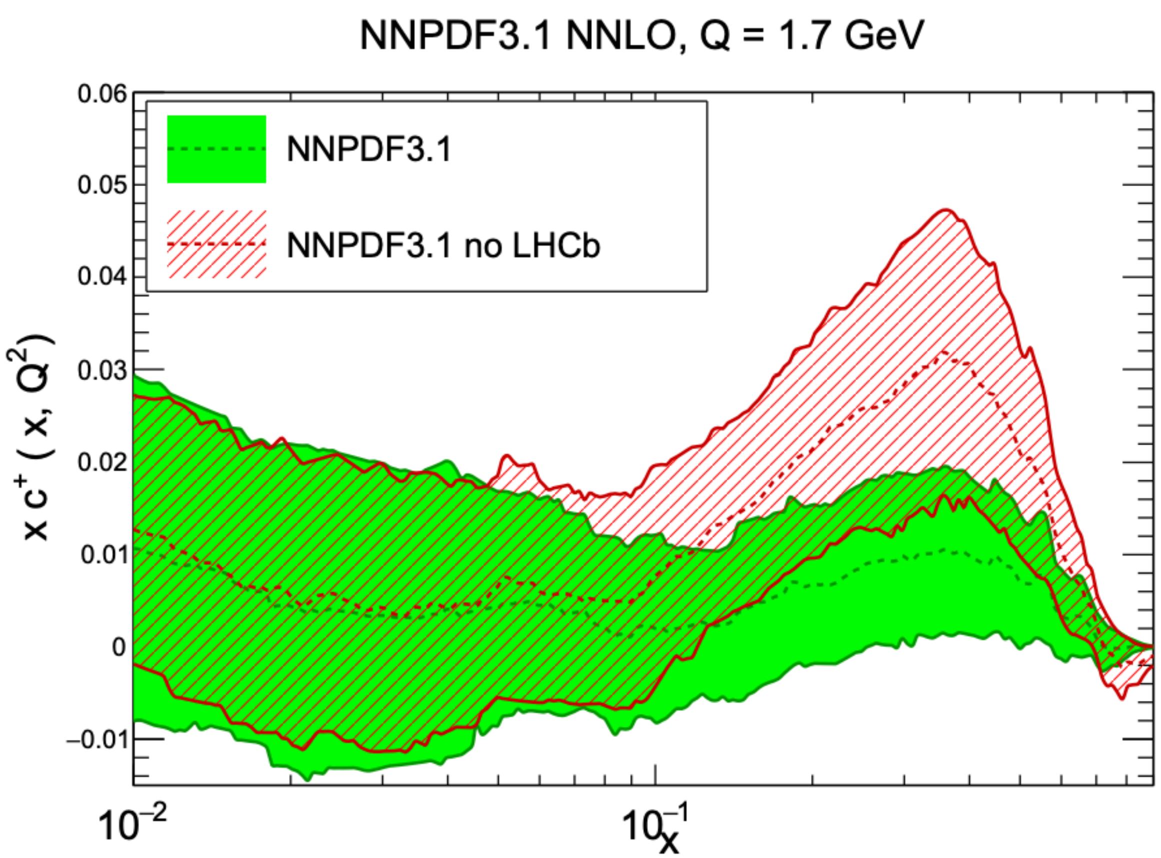
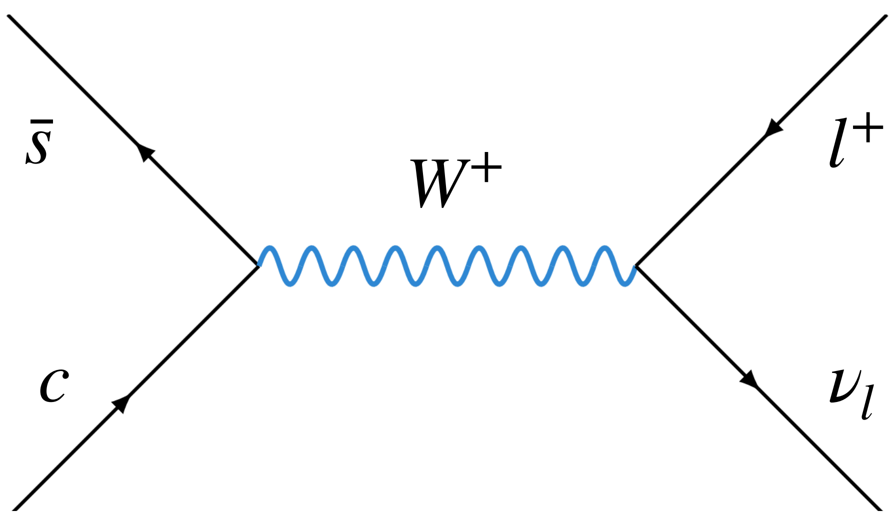


Inclusive DY

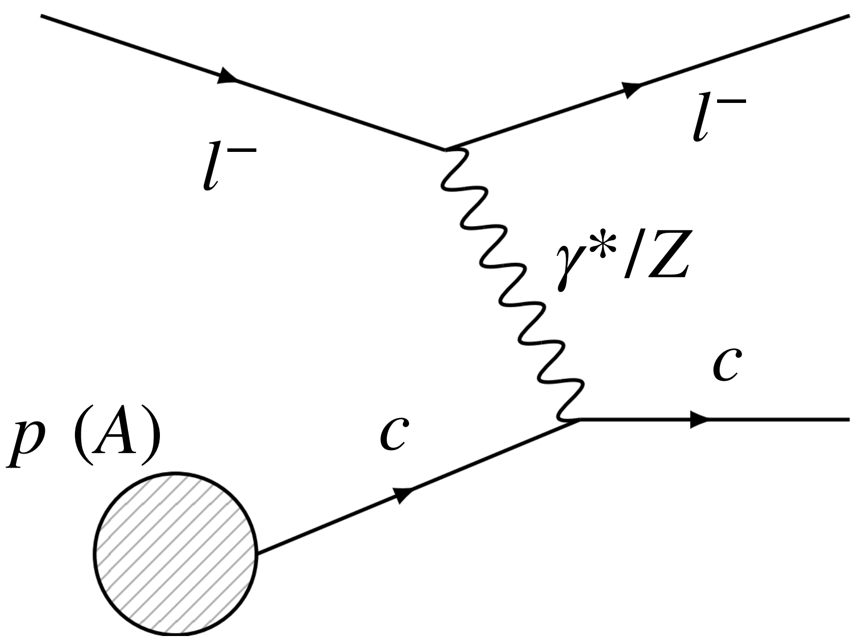


Indirect sensitivity, but high-precision measurements available

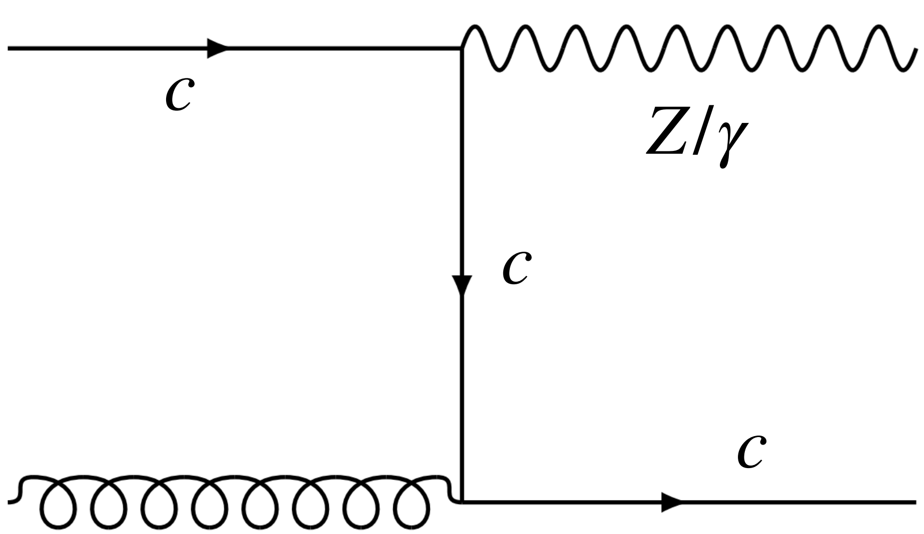
LHCb data in forward region specially powerful

Constraining charm

Charm production in DIS



Z/γ+charm



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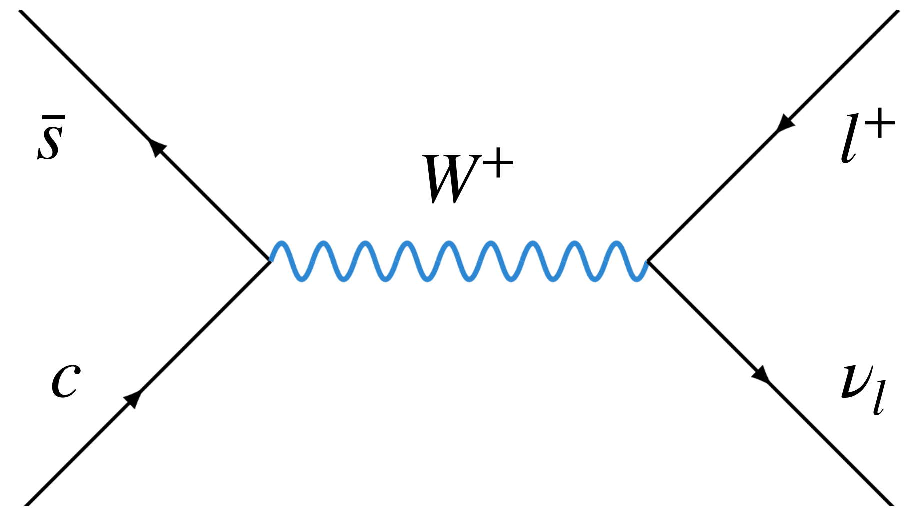
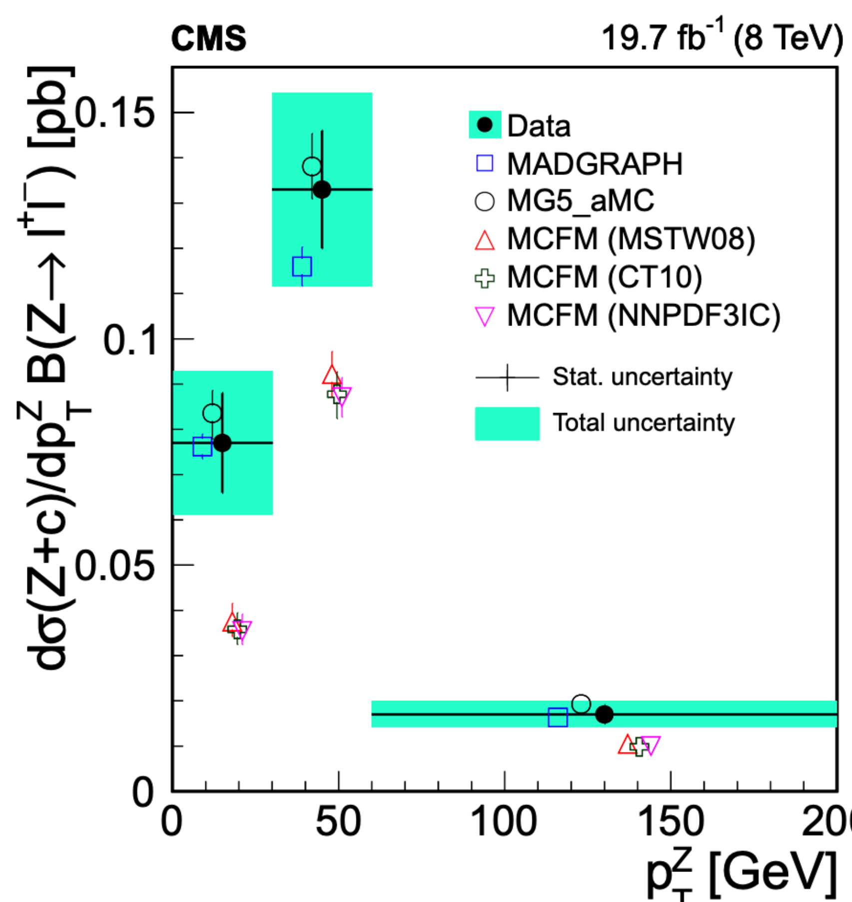
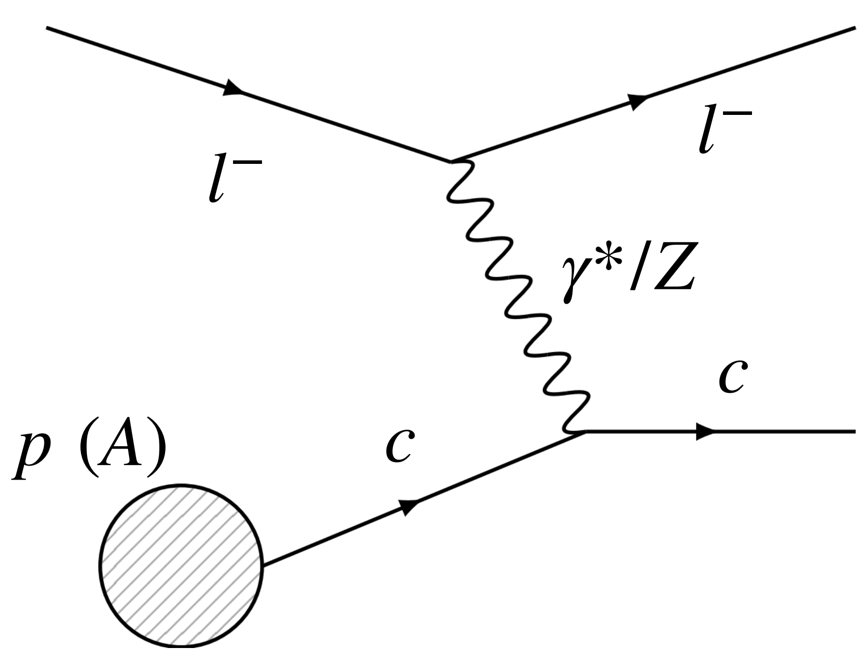


Direct sensitivity, but requires going to **high-p_T**



Constraining charm

Charm production in DIS



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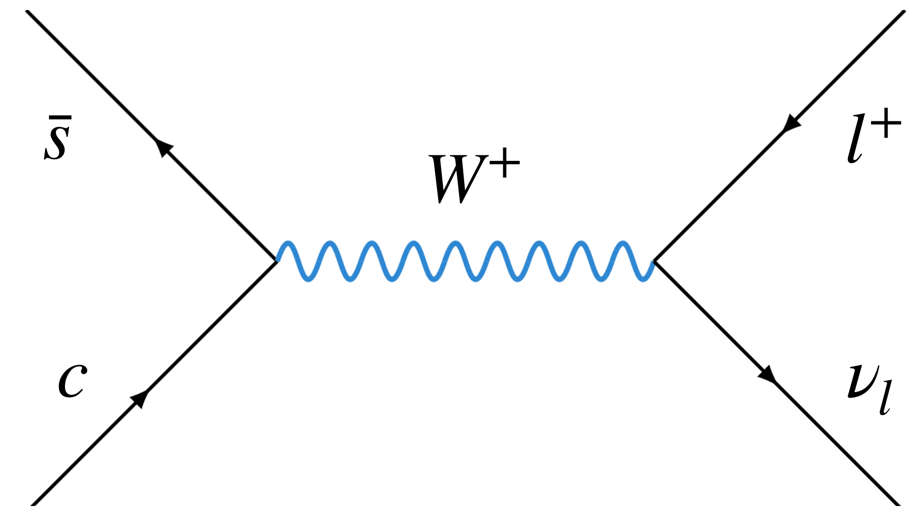
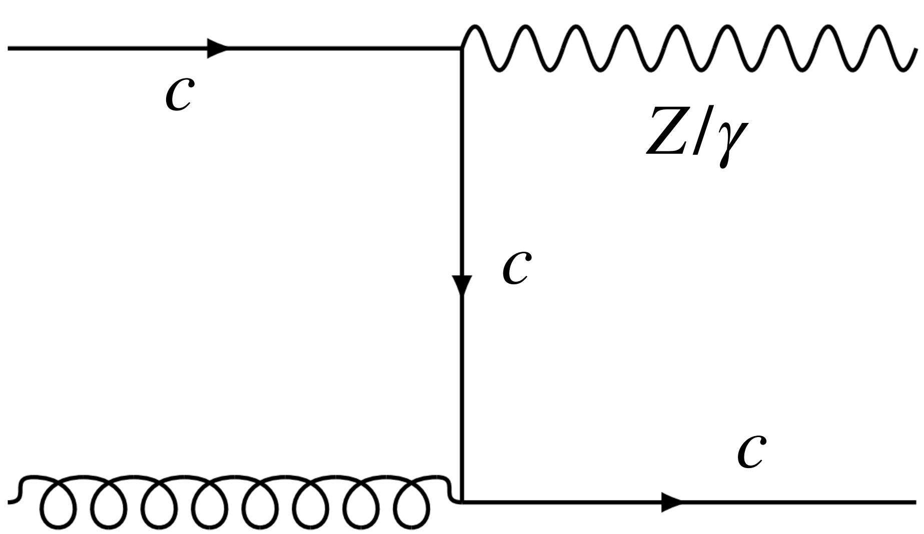


Z/ɣ+charm



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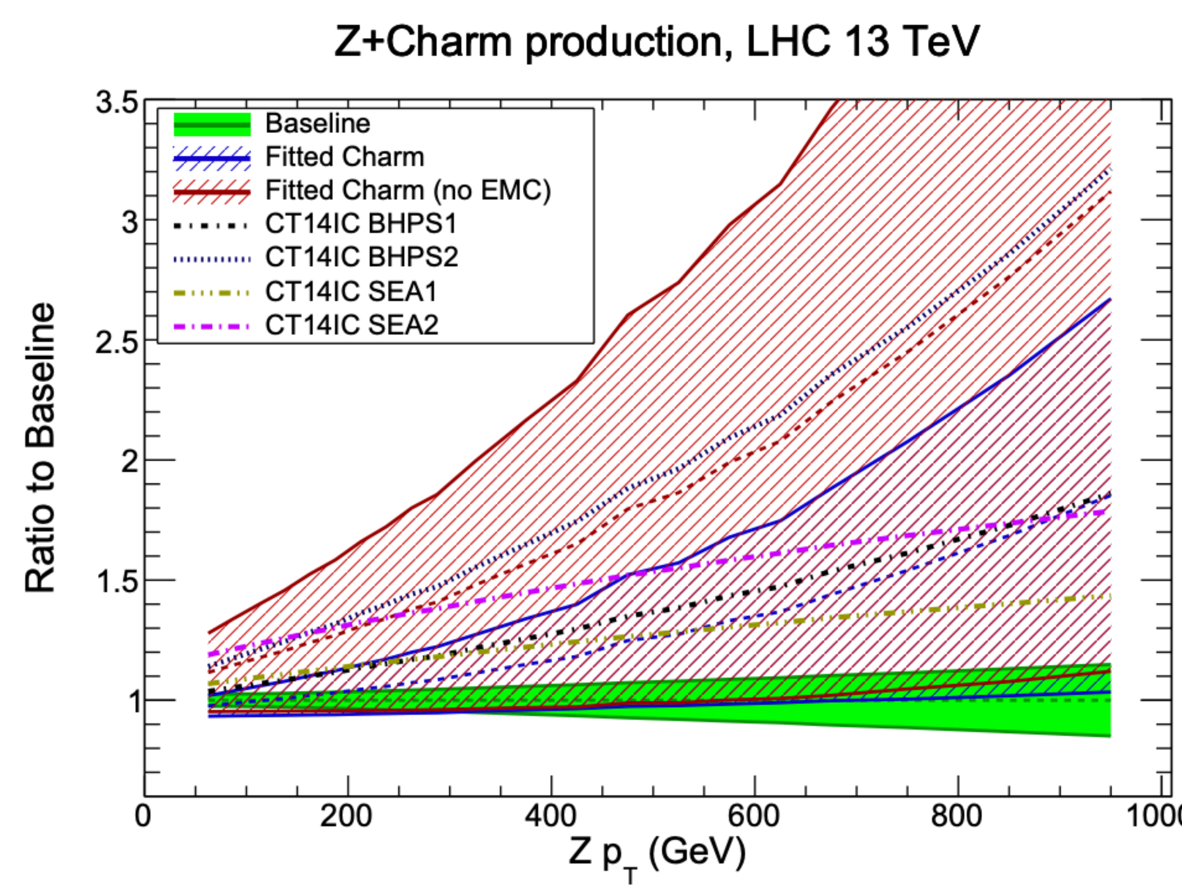
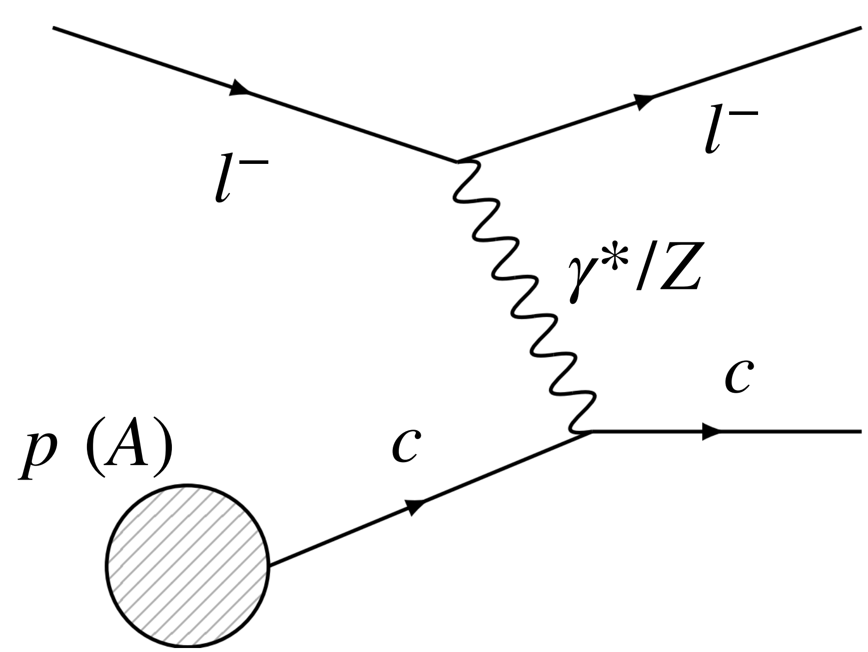
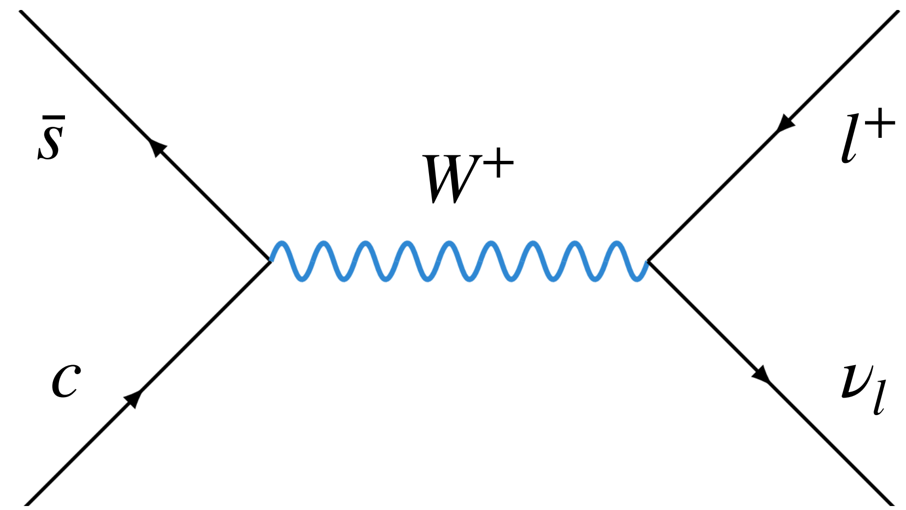


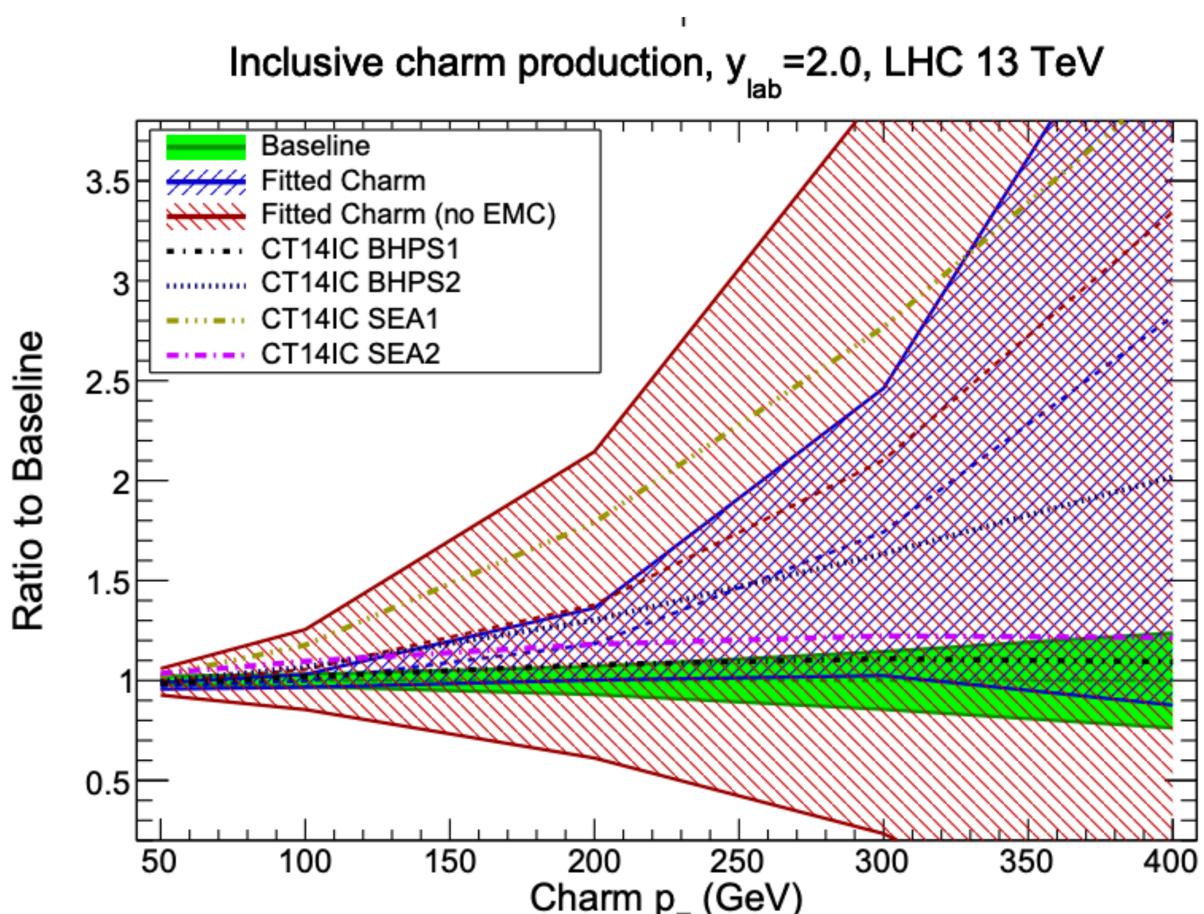
Constraining charm

Charm production in DIS



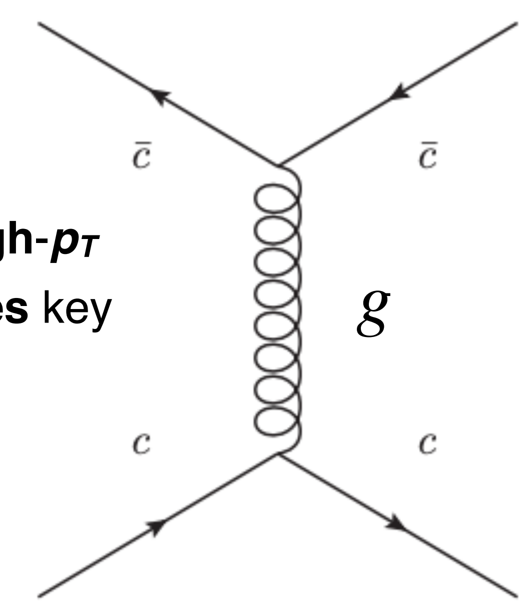
Inclusive DY



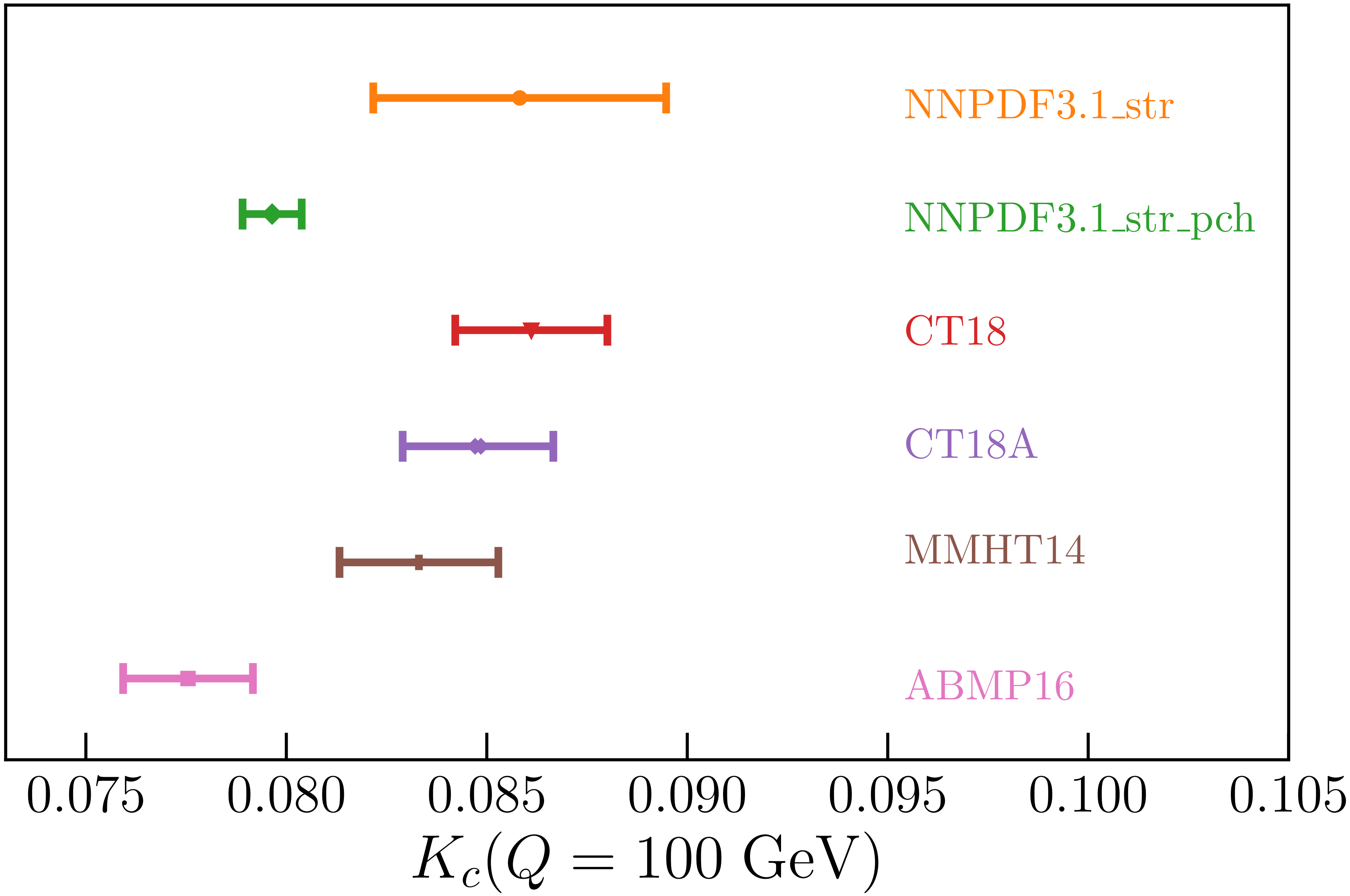


Open charm production

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

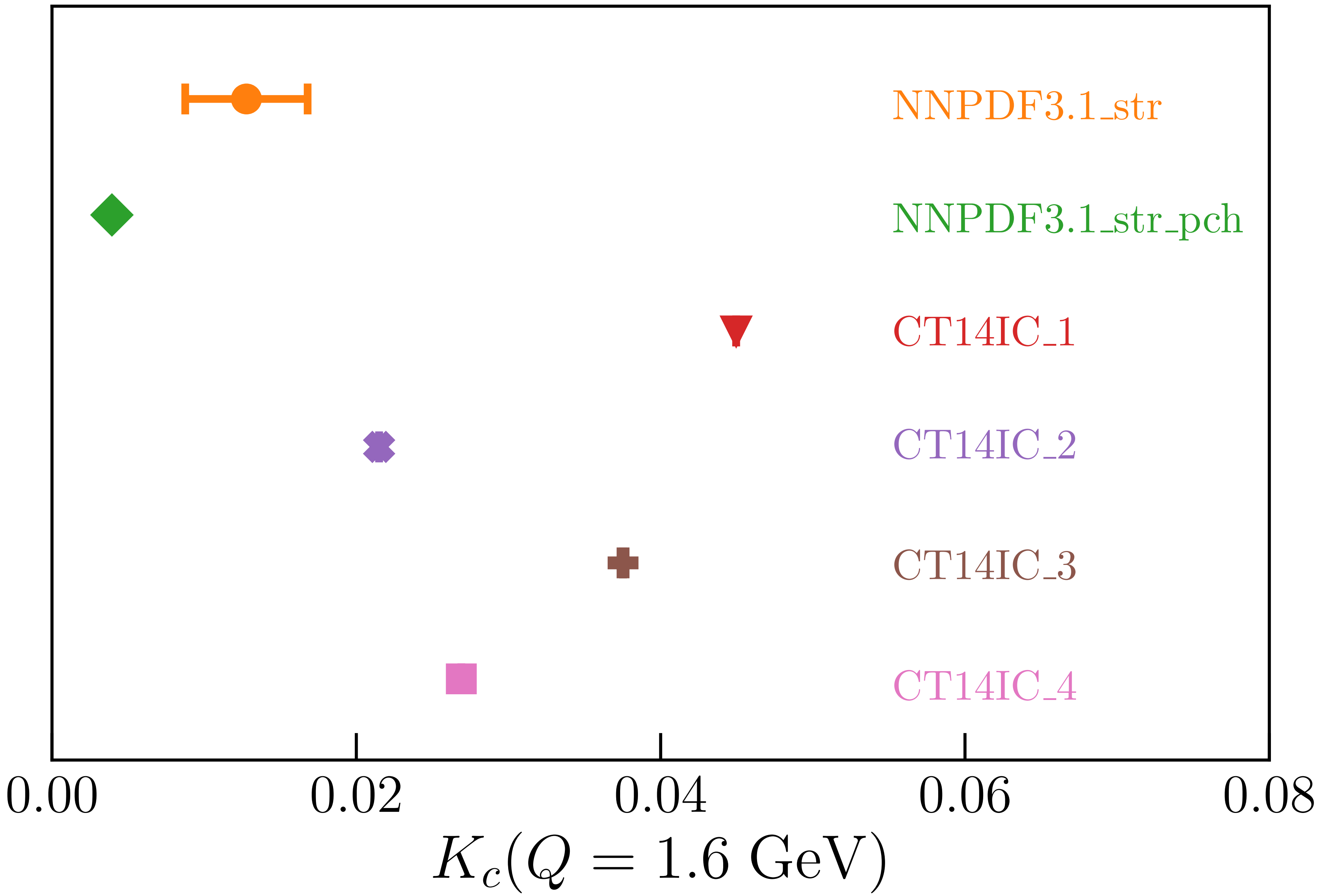
perturbative charm

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

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

- ☑ 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?



fitted charm

perturbative charm

intrinsic charm

intrinsic charm

intrinsic charm

intrinsic 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

- ☑ 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)

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

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

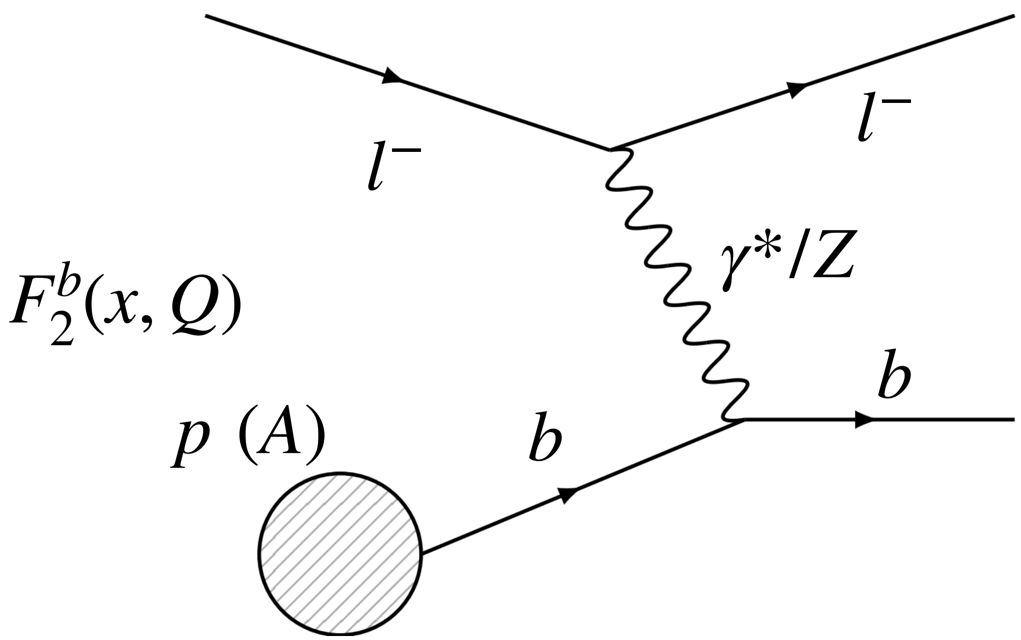
Assume that there is a **"non-perturbative"** component to the bottom PDF.

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

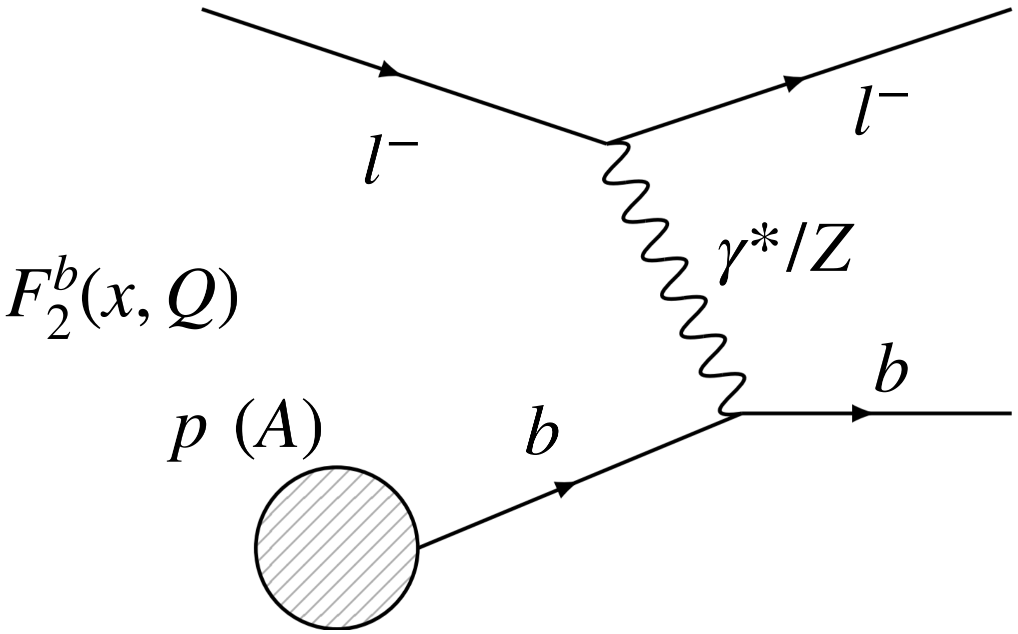
Bottom production in DIS



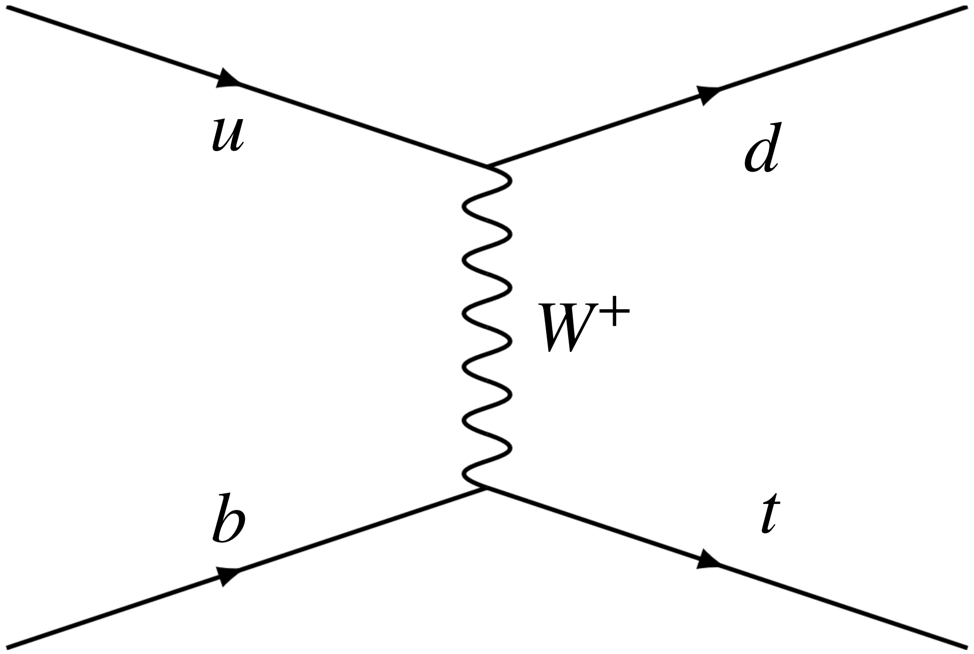
much smaller rates than for charm…..
e.g. at HERA charm can be up to 25%
while bottom is 1%

Constraining bottom

Bottom production in DIS



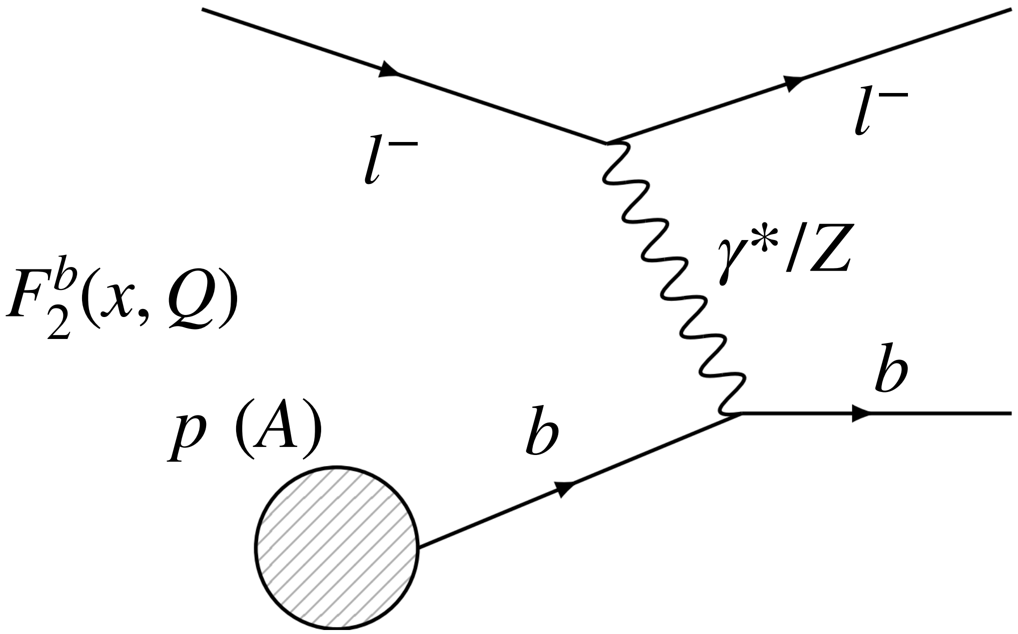
Single top production



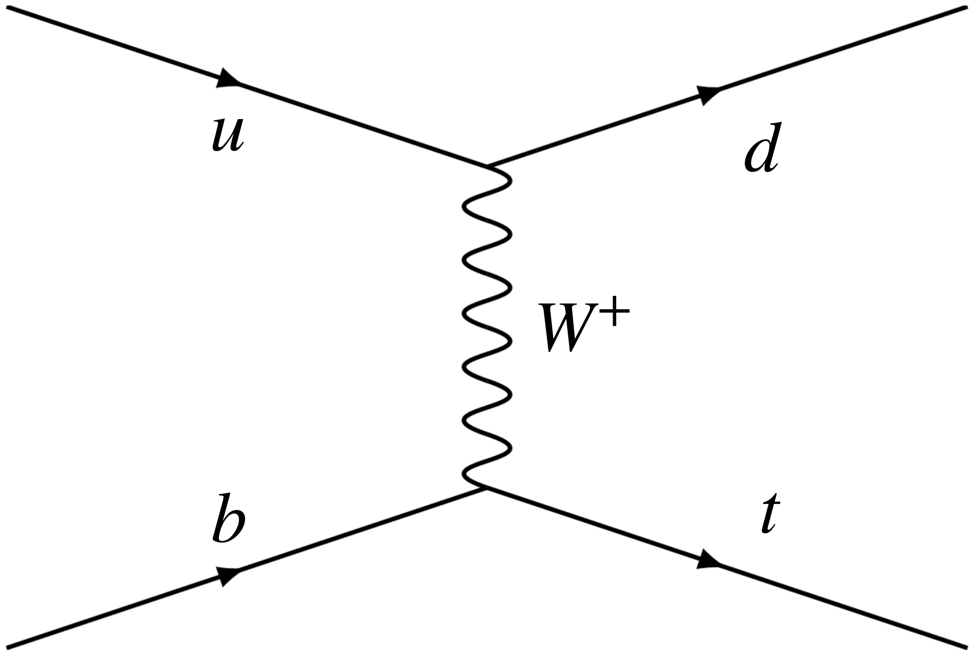
requires **matched scheme** to account for bottom quark mass corrections

Constraining bottom

Bottom production in DIS

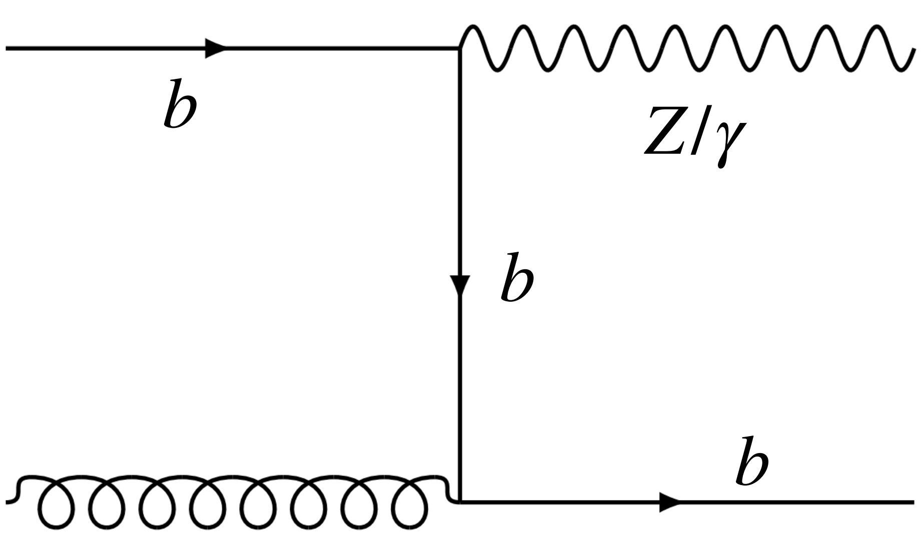


Single top production

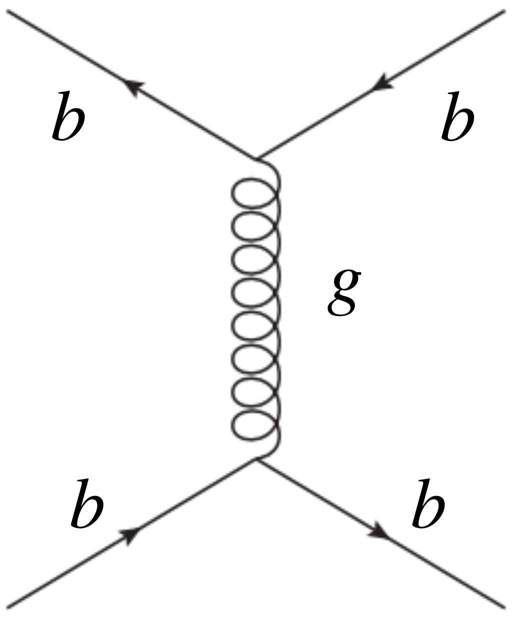


so far no one has interpreted these processes assuming an **``intrinsic" bottom PDF ….**

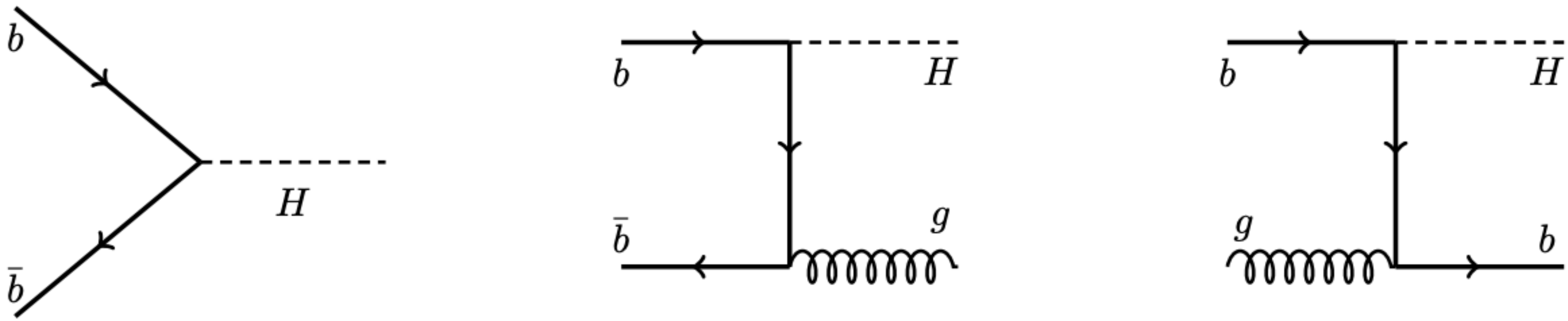
Z/ɣ+bottom



Open charm production

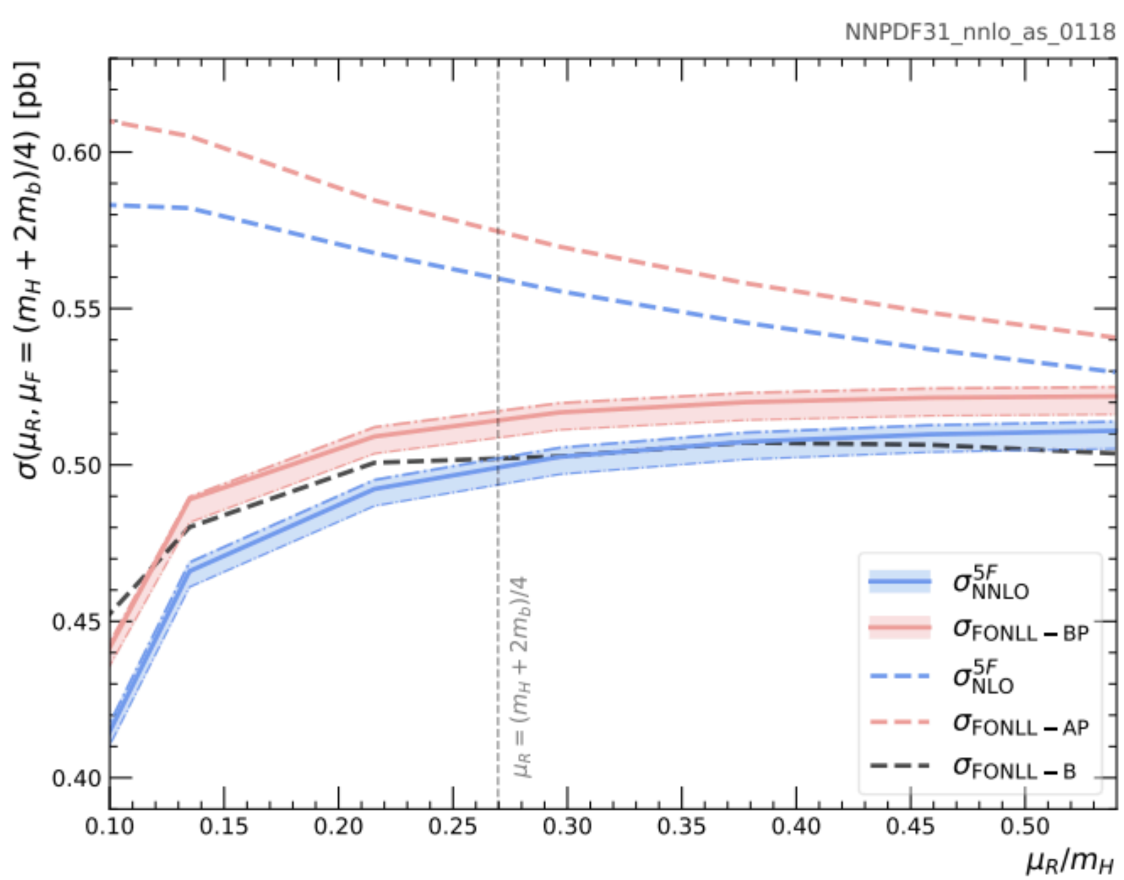


Impact of parametrised bottom



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

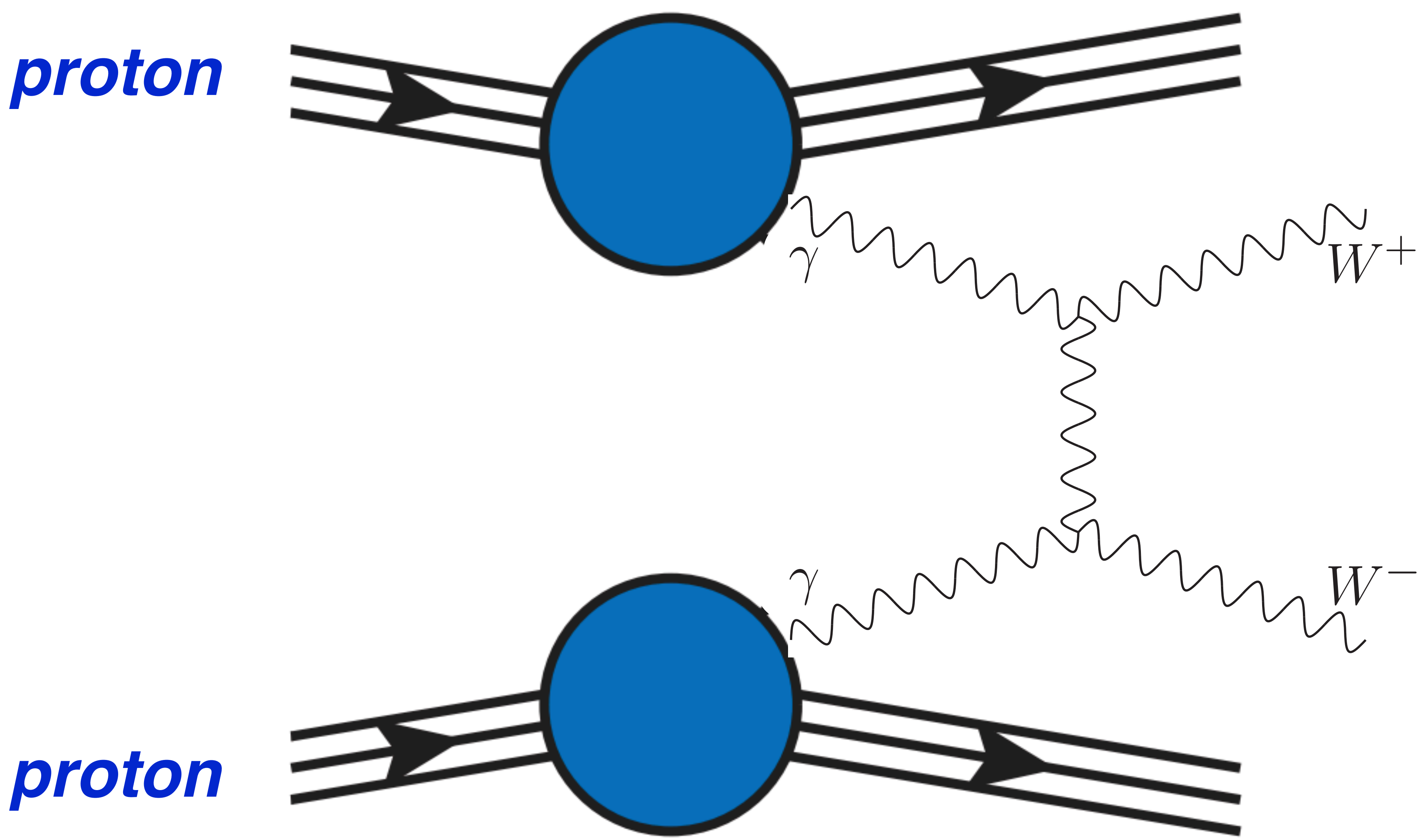


Irrespective of whether or not the proton contains a non-perturbative bottom component, **fitting the bottom PDF** might be advantageous for precision phenomenology

photons and leptons as partons

Let there be light: the photon PDF

- The proton contains not only quark and gluons as constituents: also **photons!**
- Required for consistent implementation of **QED/weak corrections** at the LHC



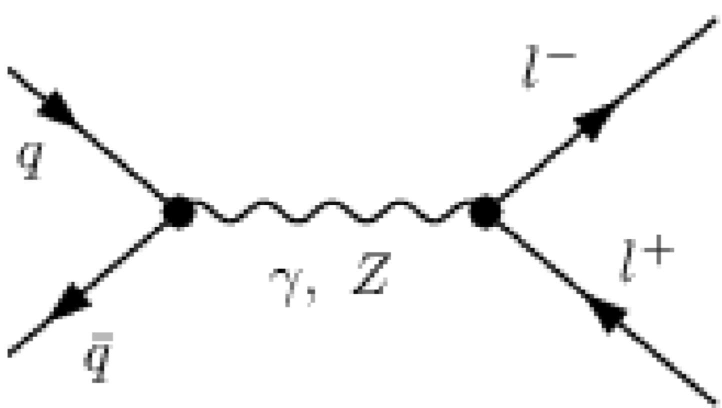
The luminous proton

Naively, QED and weak corrections appear to be not relevant for LHC physics, since the electroweak couplings are suppressed as compared to the QCD one. However, one notes that:

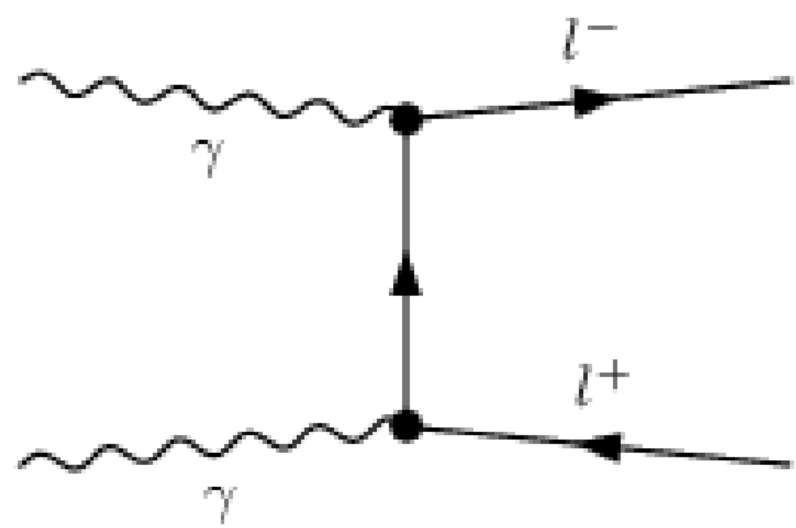
- **NNLO QCD** and **NLO electroweak** corrections are of the same order of magnitude

$$\alpha_s^2(M_Z) \sim \frac{1}{70}\,, \qquad \alpha_{\rm EM}(M_Z^2) \sim \frac{1}{130}$$

- In the presence of QED effects, new **photon-initiated processes** become available:



Drell-Yan (quark-antiquark annihilation)



Photon-induced "Drell-Yan"

- The **DGLAP evolution** with QED effects mixes quarks and gluons with photons

How can we determine the **photon content of the proton?**

The photon PDF

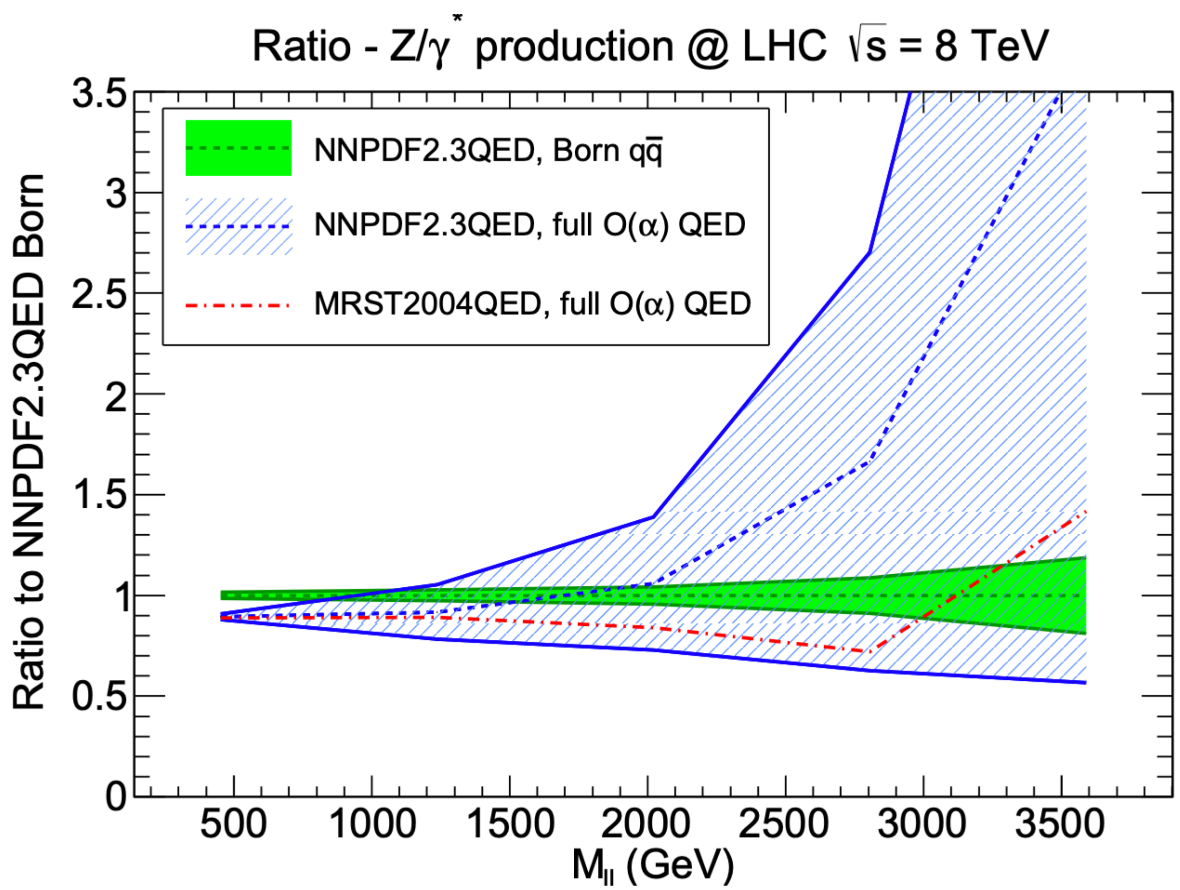
MRST2004QED

First attempts: models assuming that the photon PDF is **radiated off the light quarks**

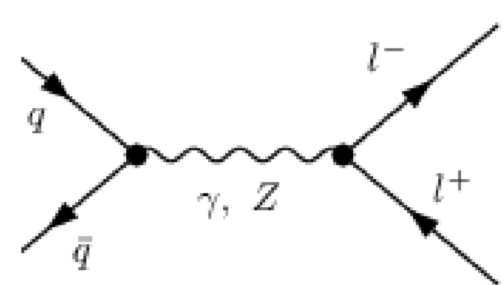
$$\gamma(x,Q_0^2)=\frac{\alpha}{2\pi}\left[\frac{4}{9}\log\left(\frac{Q_0^2}{m_u^2}\right)u(x,Q_0)+\frac{1}{9}\log\left(\frac{Q_0^2}{m_d^2}\right)d(x,Q_0)\right]\otimes\frac{1+(1-x)^2}{x}$$

up quark PDF *down quark PDF* *splitting function*

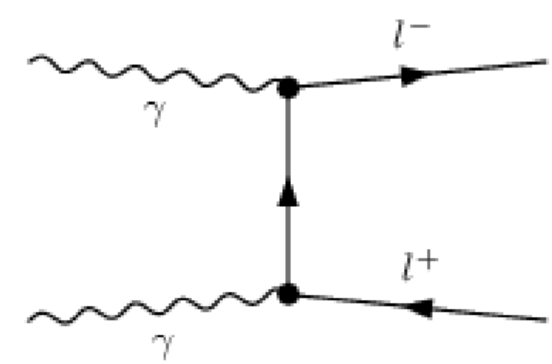
A **model-independent determination** (same footing as light quarks) was performed by NNPDF



NNPDF2.3QED



Born qq



Full QED

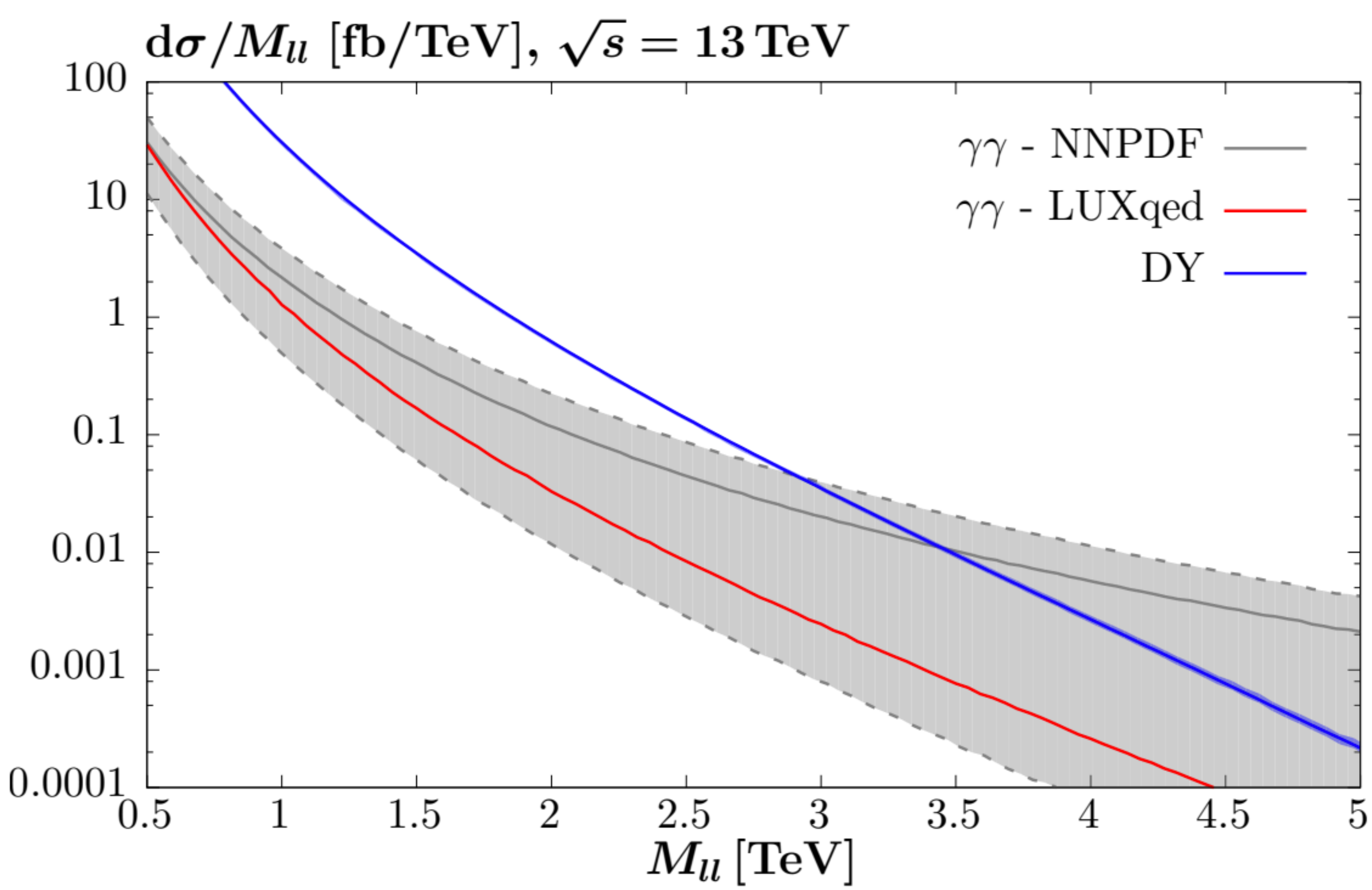
large uncertainties due to limited experimental information

The photon PDF

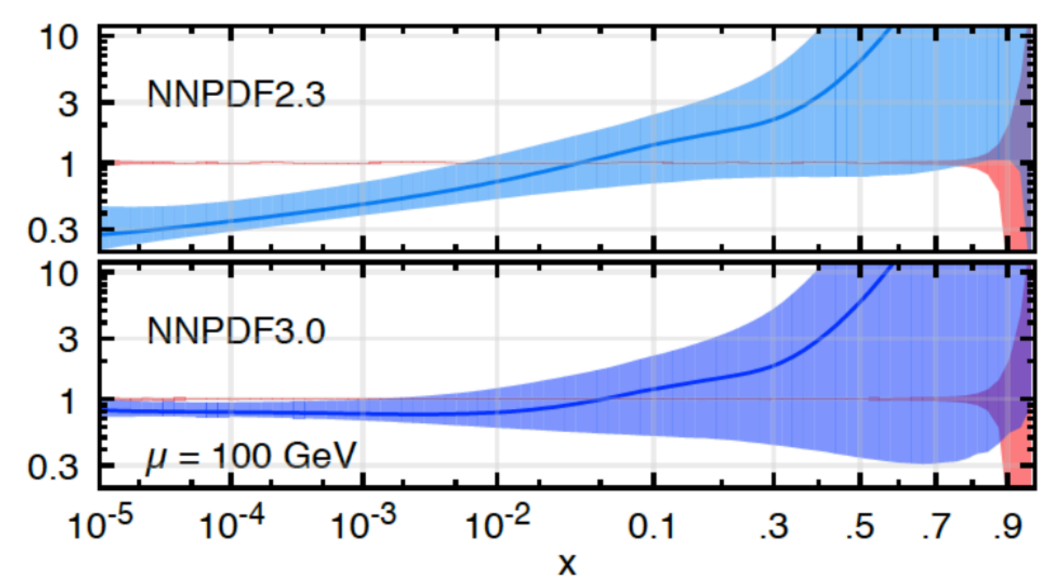
In 2016 it was demonstrated that the photon PDF is a **derived quantity** expressed in terms of the (well-known) inclusive DIS structure functions

$$x\gamma(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)}\int_x^1 \frac{dz}{z}\left\{\int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2}\alpha^2(Q^2)\left[\left(zp_{\gamma q}(z)+\frac{2x^2m_p^2}{Q^2}\right)F_2\left(\frac{x}{z},Q^2\right)-z^2F_L\left(\frac{x}{z},Q^2\right)\right]\right.$$
$$\left. -\,\alpha^2(\mu^2)z^2F_2\left(\frac{x}{z},\mu^2\right)\right\}.$$

Manohar et al 16,17

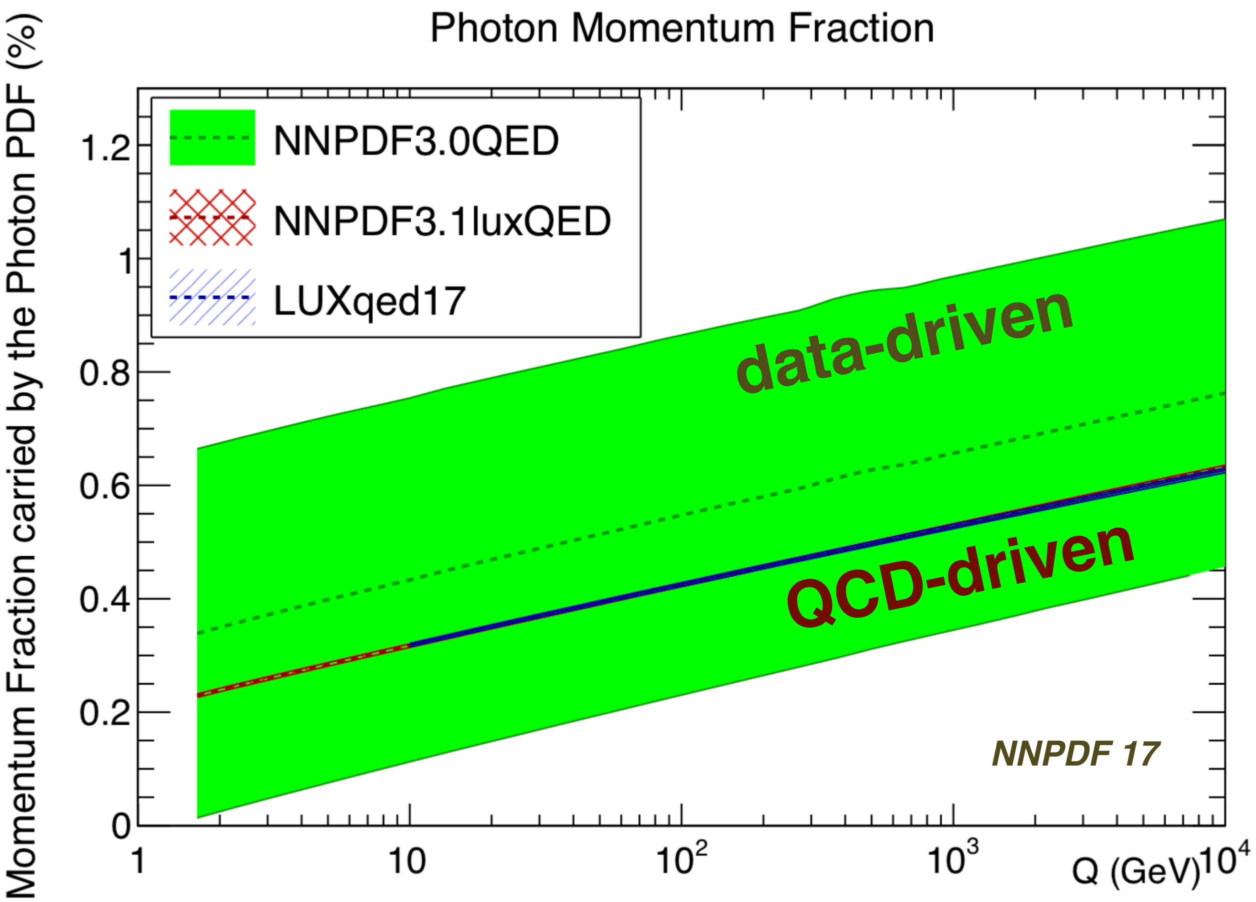


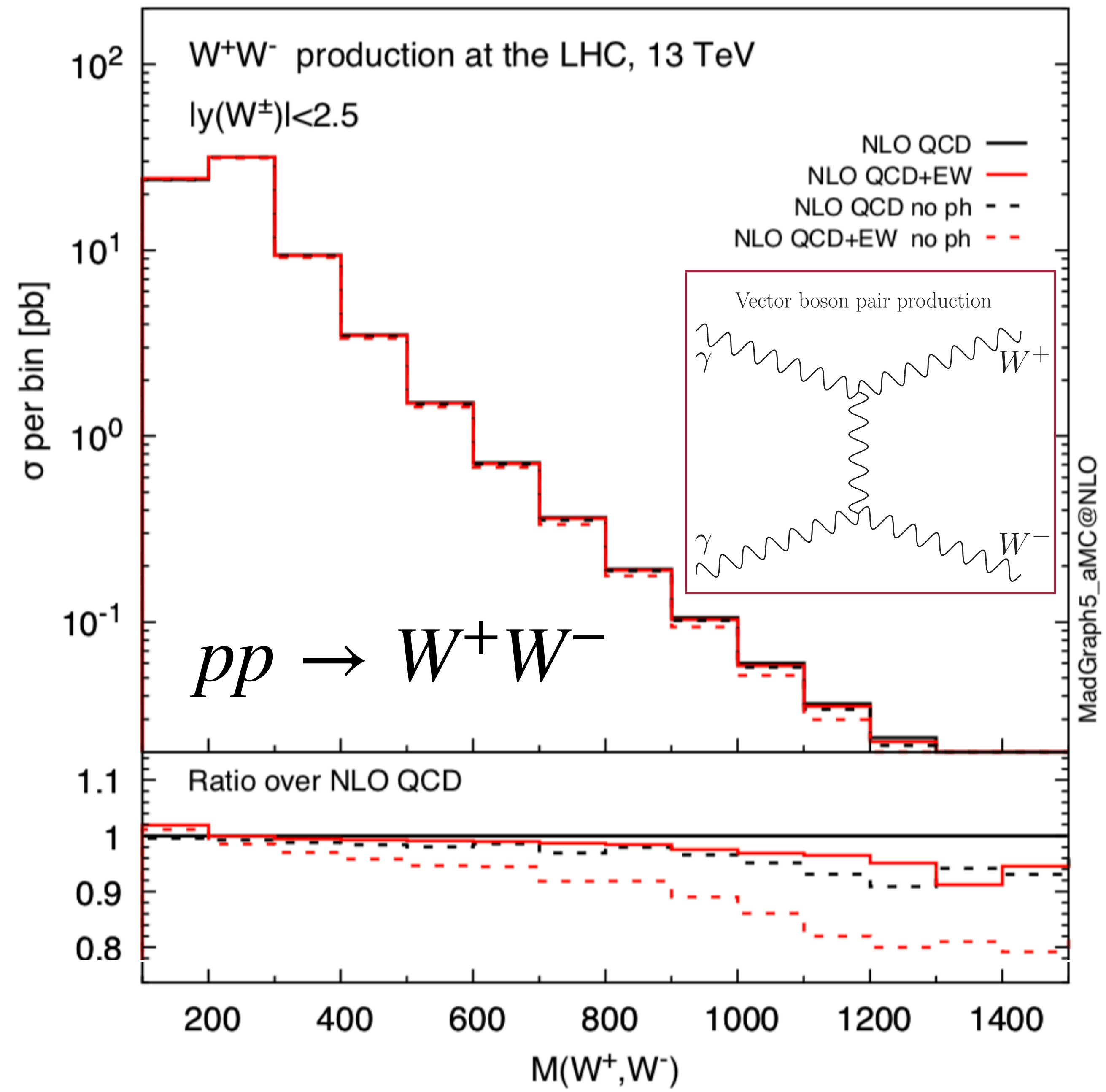
Makes possible precision phenomenology for **photon-initiated contributions**



Let there be light

The **photonic content of nucleons** is now determined with high precision, and combined with EW effects for the most accurate QCD+EW productions for LHC cross-sections





Up to 0.5% of proton's momentum ***carried by photons***

Leptons in the proton

The same considerations that motivated the inclusion of the photon PDF indicate that, at some level, **leptons can also be treated as partonic components** (since they mix with the photon via the QED DGLAP evolution equations)

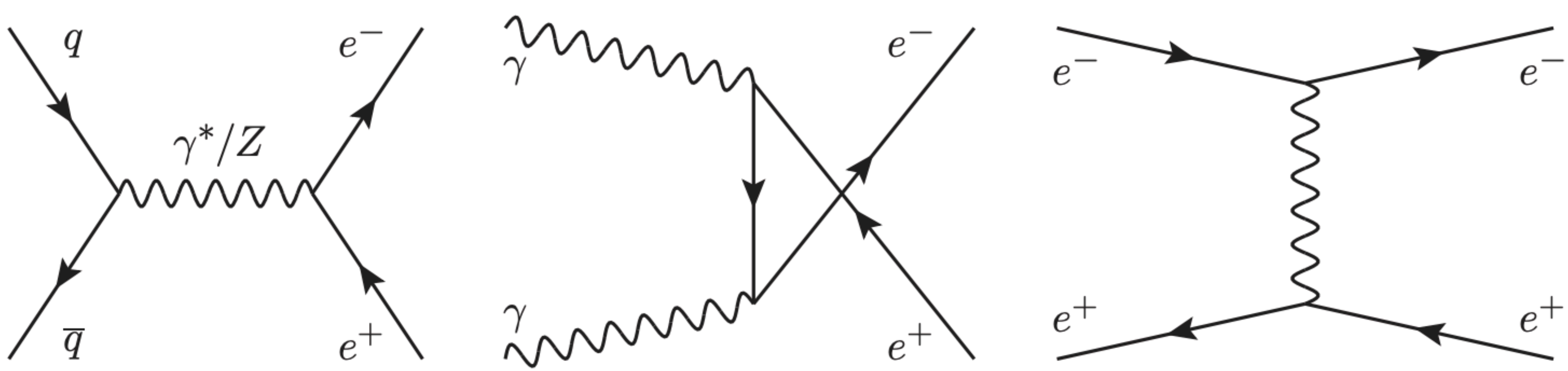
Lepton PDFs $$\ell^-(x,Q_0)=\ell^+(x,Q_0)=\frac{\alpha(Q_0)}{4\pi}\ln\left(\frac{Q_0^2}{m_\ell^2}\right)\int_x^1\frac{dy}{y}P^{(0)}_{\ell\gamma}\left(\frac{x}{y}\right)\gamma(y,Q_0)$$ ***Photon PDF***

DGLAP kernel

The lepton PDF is (QED) perturbatively generated from photon PDF

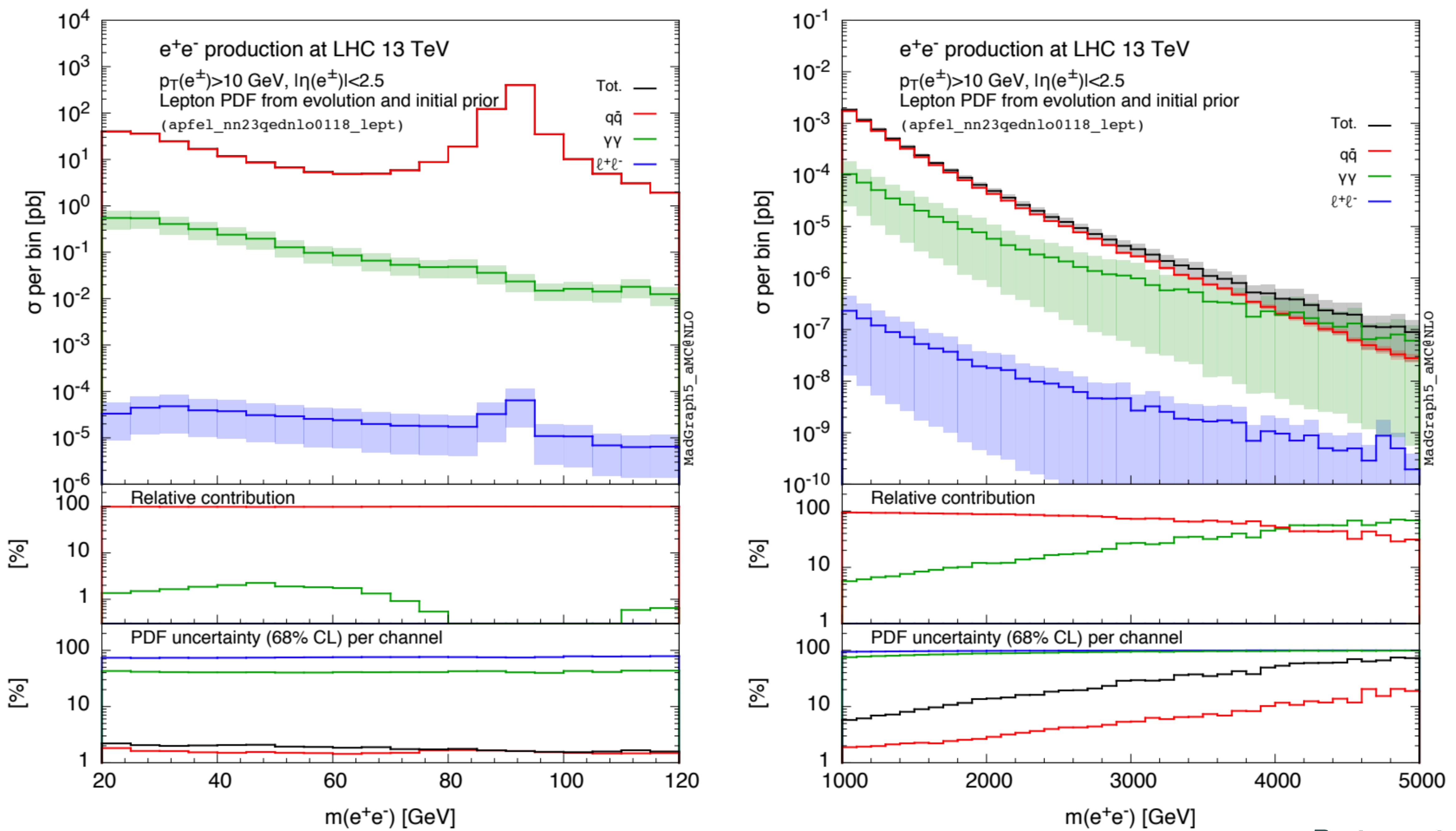
the above relation however is not accurate since it misses O(α) corrections from lepton evolution

The presence of lepton PDFs opens new channels for processes of phenomenological relevance



Leptons in the proton

An initial study assumed that the **lepton PDFs vanish at the proton mass,** $Q_0 \simeq 1$ GeV
then generated perturbatively from the photon via DGLAP evolution $\ell^-(x, Q_0) = \ell^+(x, Q_0) = 0$



Bertone et al 15

Large uncertainties in the lepton PDF inherited from NNPDF2.3QED photon

Leptons in the proton

Earlier this year the LUXqed formalism was extended to leptons, showing that lepton PDFs can be expressed in terms of DIS structure functions and QED splitting functions

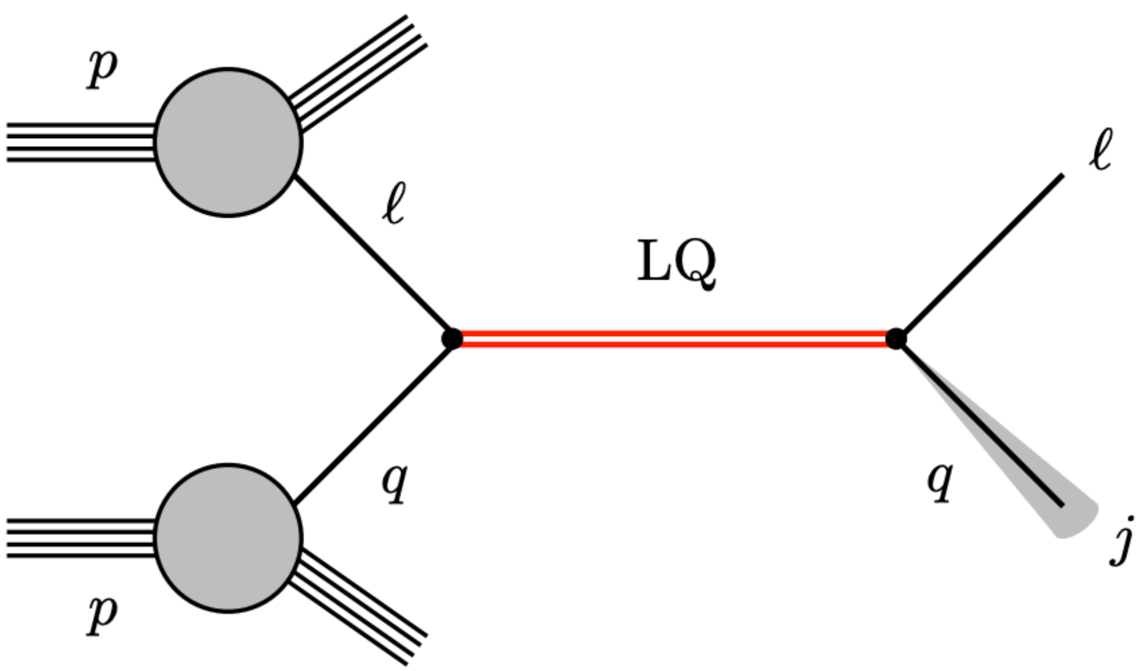
$$
\begin{aligned}
x_\ell f_\ell(x_\ell,\mu_F^2) = &\left(\frac{1}{2\pi}\right)^2 \int_{x_\ell}^1 \frac{\mathrm{d}x}{x} z_\ell \int_x^1 \frac{\mathrm{d}z}{z} \int_{\frac{m_\mathrm{p}^2 x^2}{1-z}}^{\frac{\mu_F^2}{1-z}} \frac{\mathrm{d}Q^2}{Q^2} \alpha^2(Q^2) \\
&\left\{ P_{\ell\gamma}(z_\ell) \log \frac{\mu_\mathrm{F}^2}{(1-z_\ell) z_\ell \left(Q^2 + \frac{m_\ell^2}{z_\ell(1-z_\ell)}\right)} \left[F_2\left(z P_{\gamma q}(z) + \frac{2 m_\mathrm{p}^2 x^2}{Q^2}\right) - F_L z^2\right] \right. \\
&+ F_2 \left[4(z-2)^2 z_\ell(1-z_\ell) - (1 + 4 z_\ell(1-z_\ell))\, z P_{\gamma q}(z)\right] \\
&+ F_L z^2 P_{\ell\gamma}(z_\ell) - \frac{2 m_\mathrm{p}^2 x^2}{Q^2} F_2 - \left(F_2 \frac{2 m_\mathrm{p}^2 x^2}{Q^2} - z^2 F_L\right) 4 z_\ell (1-z_\ell) \\
&+ \frac{m_\ell^2 F_2}{m_\ell^2 + Q^2 z_\ell(1-z_\ell)} \left[z P_{\gamma q}(z) - 8 z_\ell(1-z_\ell)\left(1 - z - \frac{m_\mathrm{p}^2 x^2}{Q^2}\right) + \frac{2 m_\mathrm{p}^2 x^2}{Q^2}\right] \\
&\left. - \frac{m_\ell^2 F_L z^2}{m_\ell^2 + Q^2 z_\ell(1-z_\ell)} \left[2 - P_{\ell\gamma}(z_\ell)\right] \right\}. \qquad (2.25)
\end{aligned}
$$

Buonocore et al 20

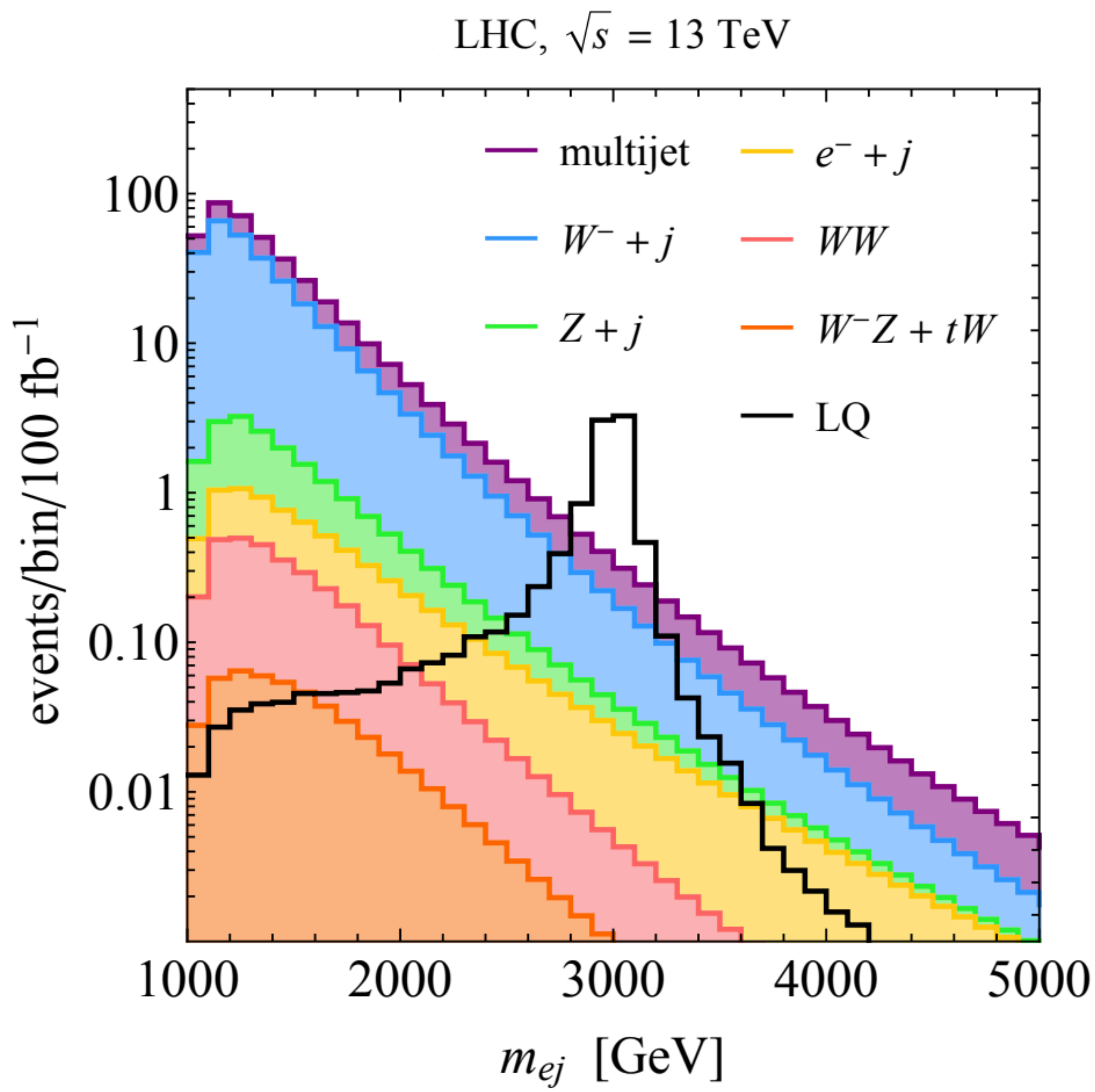
this implies that, like in the photon, we can **evaluate the lepton PDFs with high precision**

The LHC as a lepton-quark collider

The presence of lepton PDFs as partons offers remarkable new opportunities to search for BSM physics, *e.g.* in this case the **resonant production of leptoquarks** become possible



Buonocore et al 20



Another nice illustration of the unexpected applications that proton studies provide!

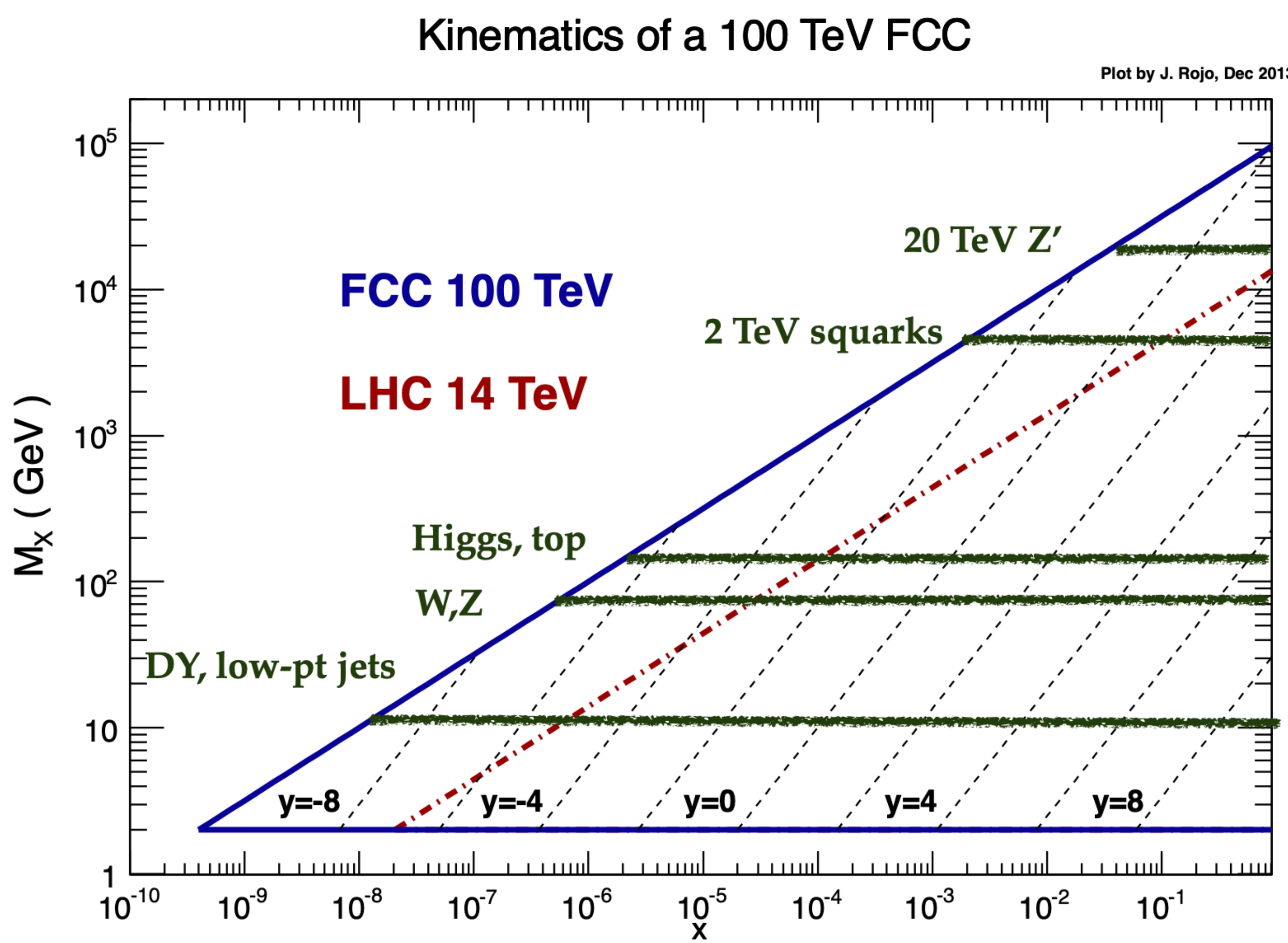
The proton at TeV scales: From Higgs to top quarks

The proton with TeV resolution

In the same way that we treat charm and bottom quarks as massless partons, if we go at **high enough energies** do we also need to treat the top quark as massless and include a **top PDF**?

In the same way that we have to account for photon and lepton PDFs in the presence of QED effects, if we go **at high enough energies** do we also need to account for weak effects in the DGLAP evolution equations and introduce **PDFs for the weak gauge and Higgs bosons**?

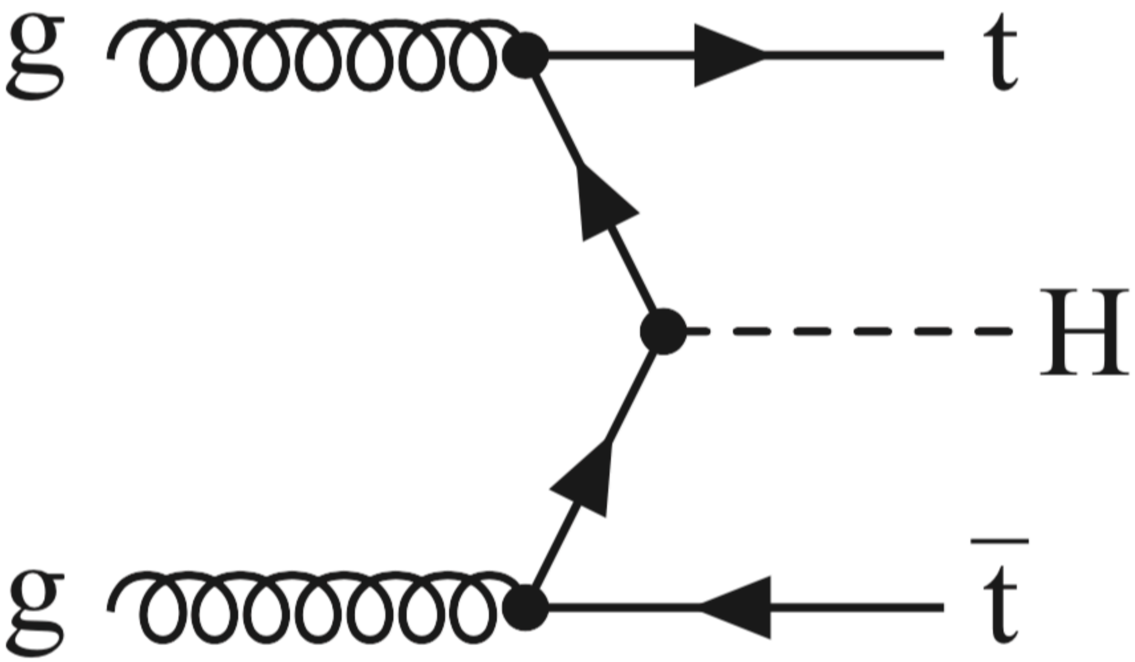
these questions are now academic, but might become relevant at a **100 TeV pp collider**



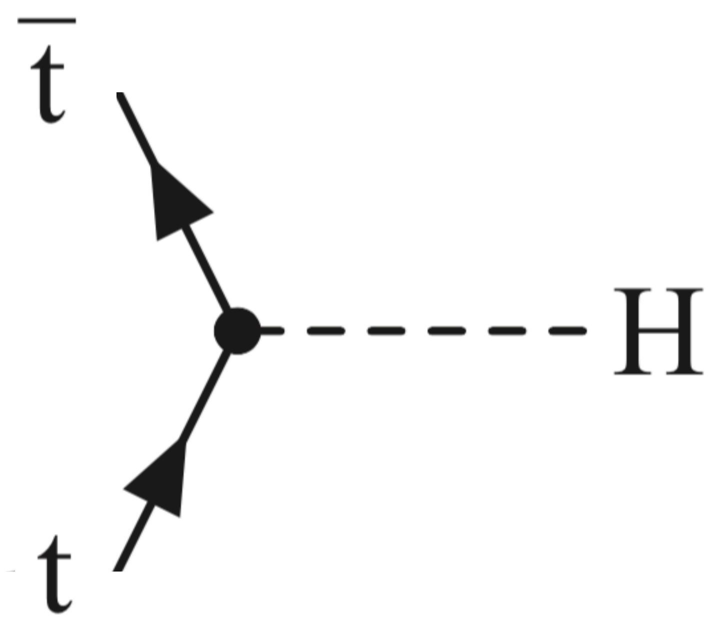
FCC Yellow Reports 16

The top quark as parton

Consider the production of a **heavy scalar particle** at 100 TeV. Two calculation methods:



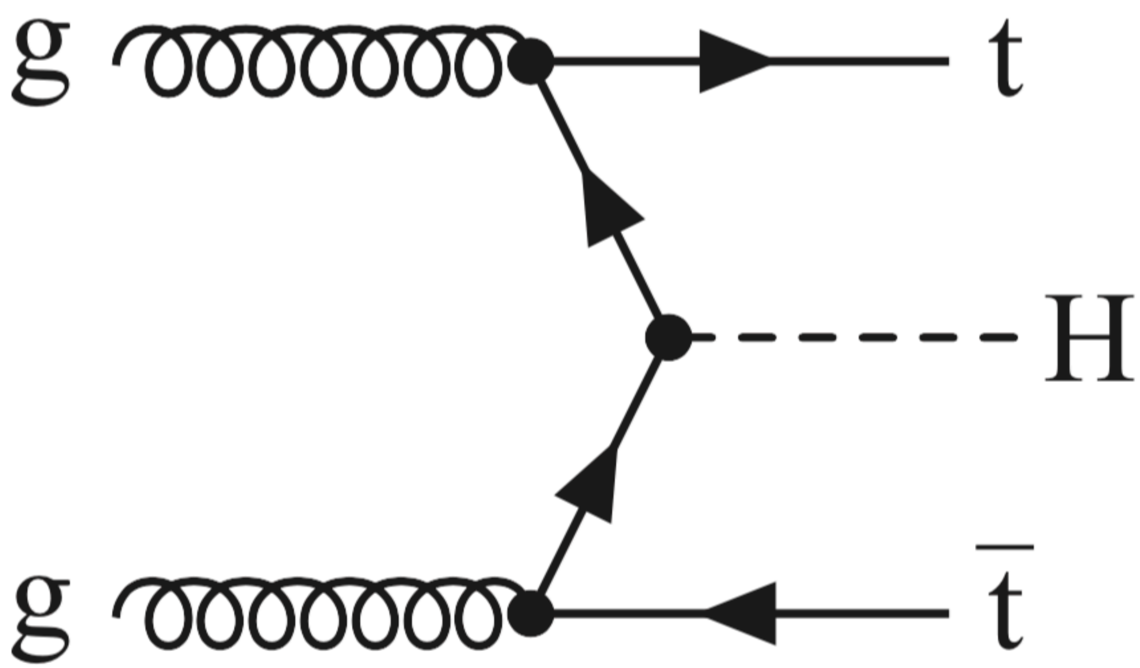
Top as massive particle: gg => ttH



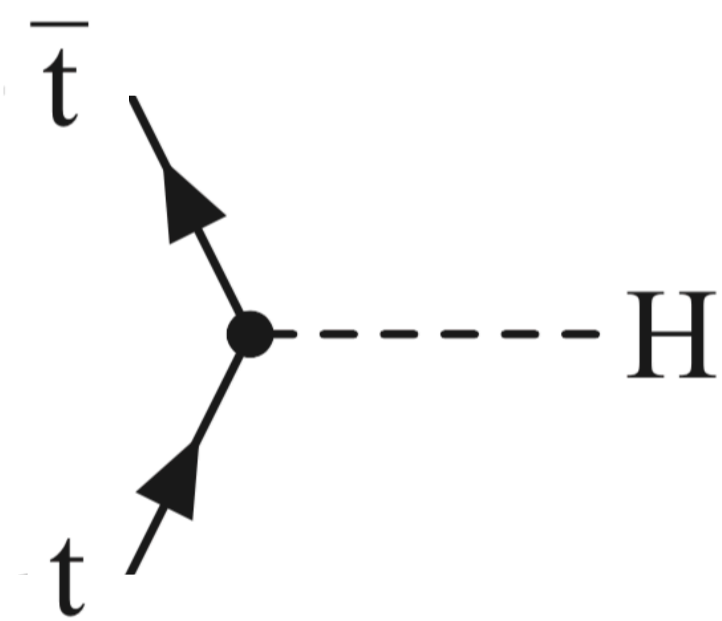
Top as parton: tt => H

The top quark as parton

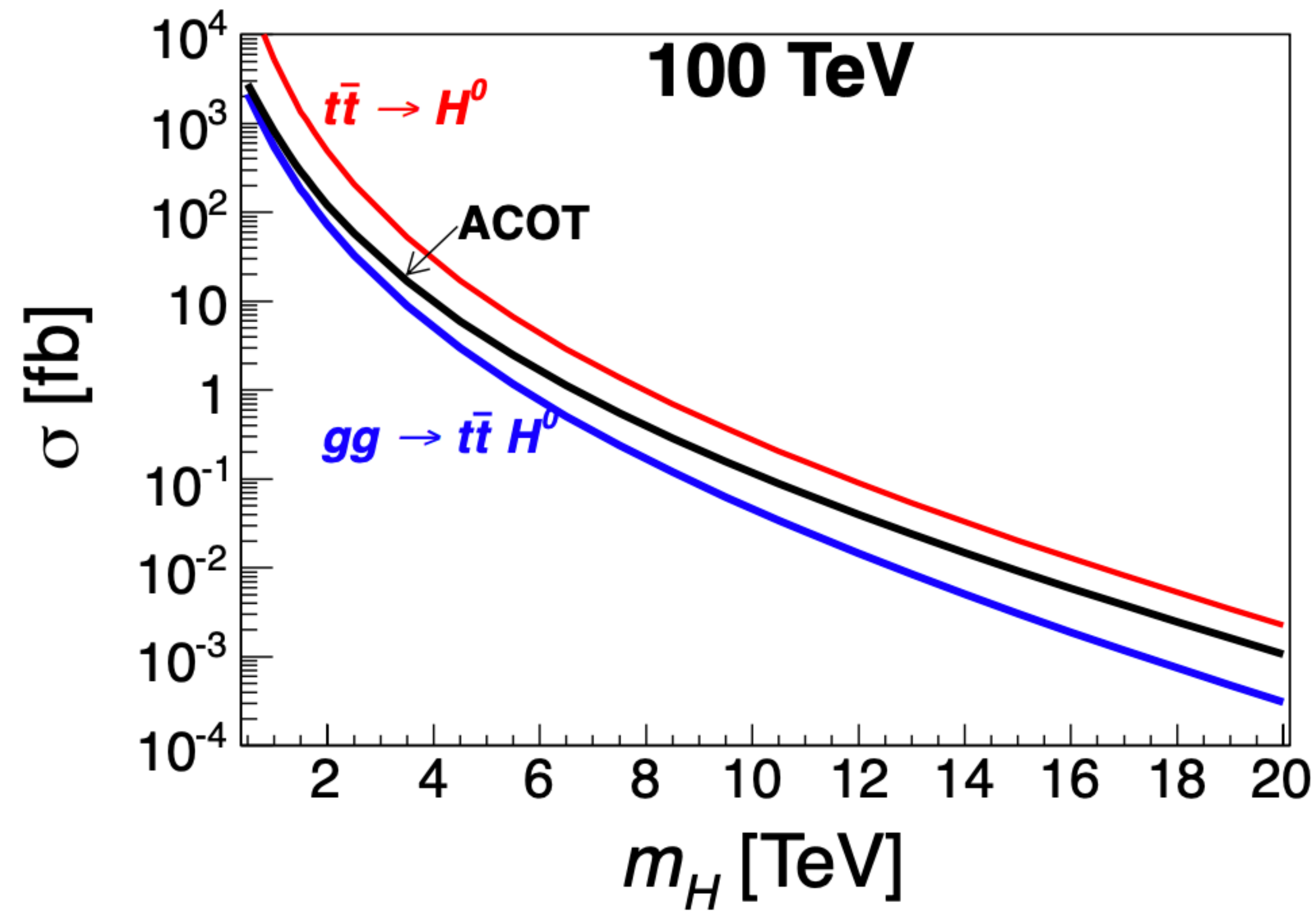
Consider the production of a **heavy scalar particle** at 100 TeV. Two calculation methods:



Top as massive particle: gg => ttH



Top as parton: tt => H



Even at 100 TeV, **top mass effects cannot be neglected** and it is not advantageous to treat the top quark as a parton

Han et al 14, Dawson et al 14

SM Parton Distributions

Assuming that we can neglect all fermion and boson masses (including Higgs) at **very high energies**, one can write the full set of SM evolution equations

$$q\frac{\partial}{\partial q}f_i(x,q) = \sum_I \frac{\alpha_I(q)}{\pi}\left[P^V_{i,I}(q)\,f_i(x,q) + \sum_j C_{ij,I}\int_x^{z^{ij,I}_{\max}(q)} \mathrm{d}z\,P^R_{ij,I}(z)f_j(x/z,q)\right]$$

sum over QCD and EW couplings

Ciafaloni, Comelli 05
Bauer, Webber 17

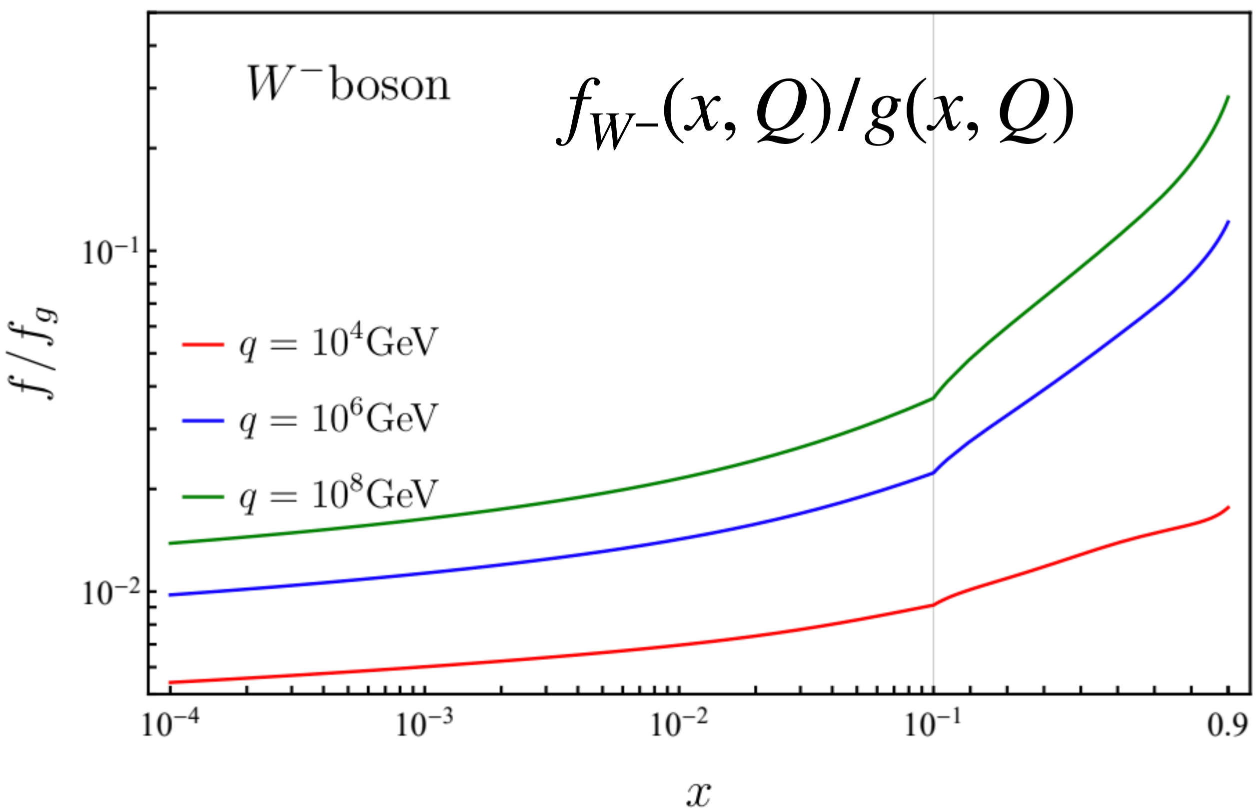
and ends up with **52 ``SM PDFs",** where e.g. right and left handed quarks evolve separately

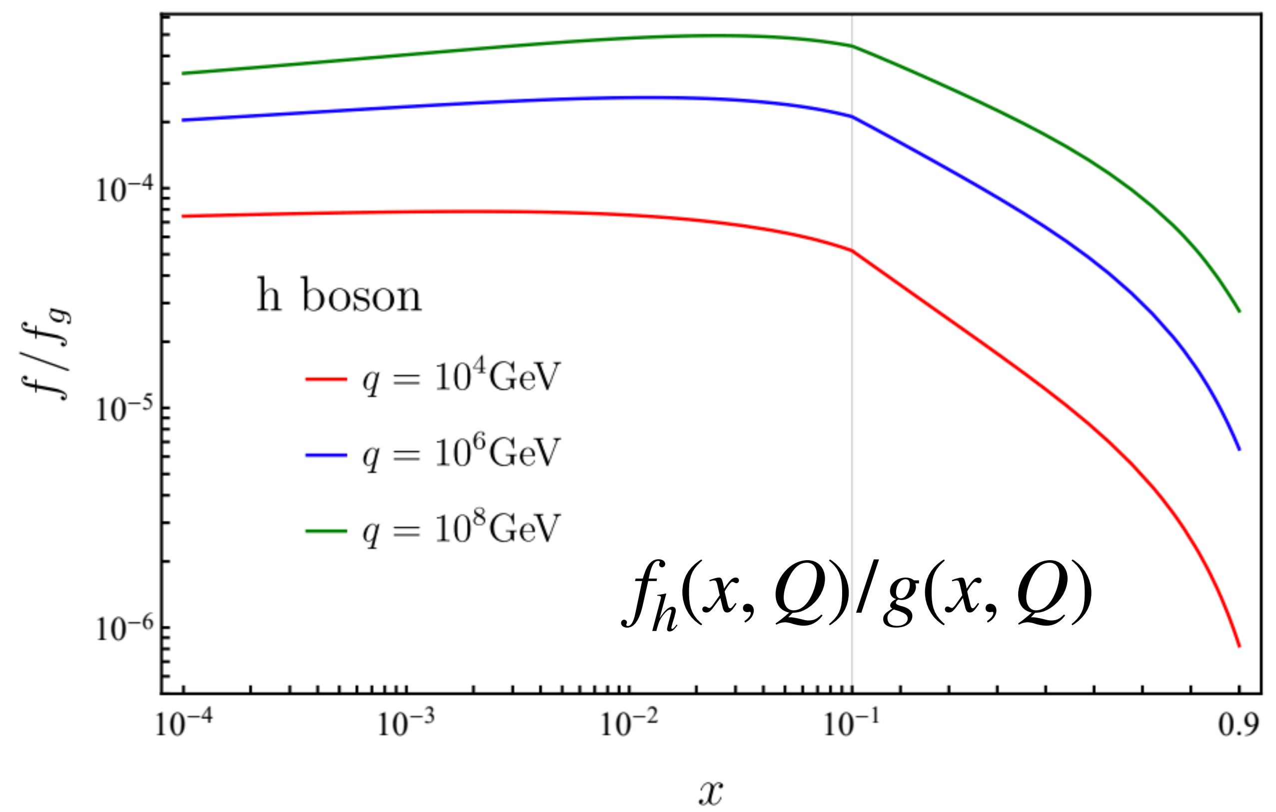
$\{\mathbf{T},\mathrm{CP}\}$	fields
$\{0,+\}$	$2n_g \times q_R\,, n_g \times \ell_R\,, n_g \times q_L\,, n_g \times \ell_L\,, g\,, W\,, B\,, H$
$\{0,-\}$	$2n_g \times q_R\,, n_g \times \ell_R\,, n_g \times q_L\,, n_g \times \ell_L\,, H$
$\{1,+\}$	$n_g \times q_L\,, n_g \times \ell_L\,, BW, H$
$\{1,-\}$	$n_g \times q_L\,, n_g \times \ell_L\,, W, H$
$\{2,+\}$	W

n_g = # generations

These PDFs can be perturbatively generated from the usual **quark, gluon and photon PDFs** at some matching scale around 100 GeV

SM Parton Distributions

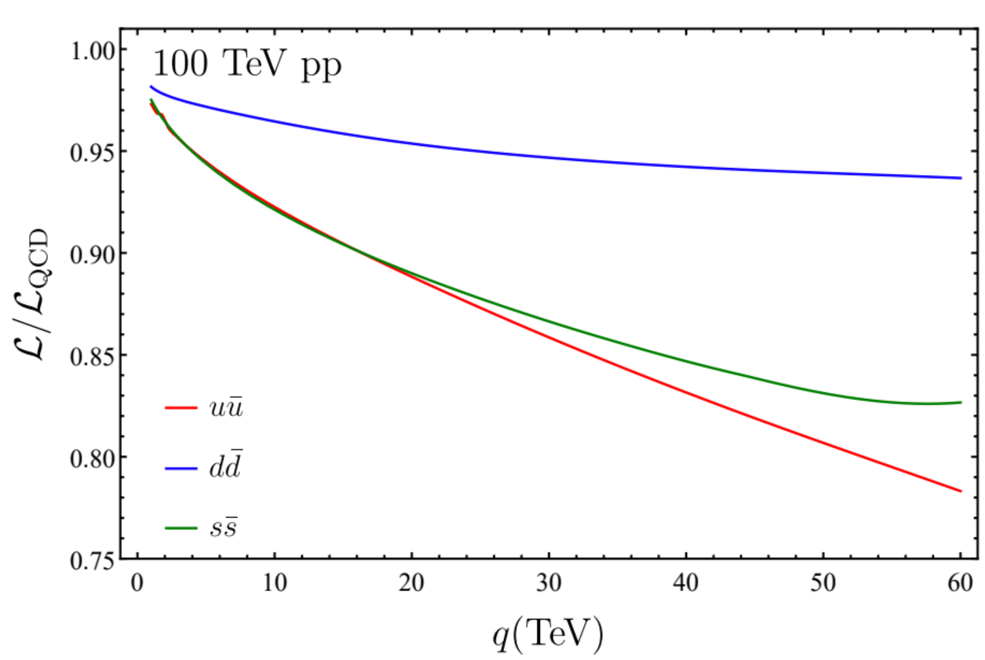


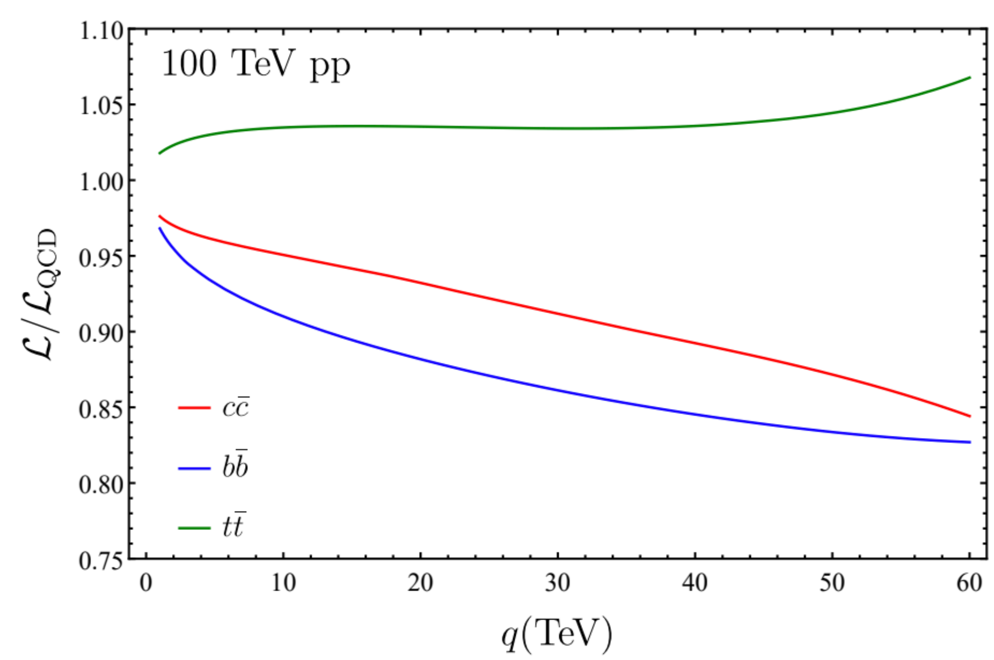


for *Q=10 TeV*, the W boson PDF can become a few percent of the gluon PDF

even for *Q=10 TeV*, the Higgs boson PDF is less than 0.1% of the gluon PDF

*If a 100 TeV collider is built, **electroweak PDFs** might play an important role for many processes*





Summary and outlook

The accurate determination of the **quark and gluon structure of the proton** is an essential ingredient for **LHC phenomenology** and **beyond**

- Recent progress in our understanding of the **strange and charm content of the proton**, but still several important open questions. What about intrinsic bottom?

- **QED effects and the photon PDF** are now a standard ingredient of global PDF determinations, with photon- and lepton-initiated processes now computable with high precision

- At very high energies, one needs to account for the **full gauge structure of the SM** in the evolution equations: Higgs and gauge boson PDFs, quark PDF polarisation ….

The fascinating study of the proton structure never stops surprising us, stay tuned!