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PDF4BSM
Parton Distributions in the Higgs Boson Era

erc
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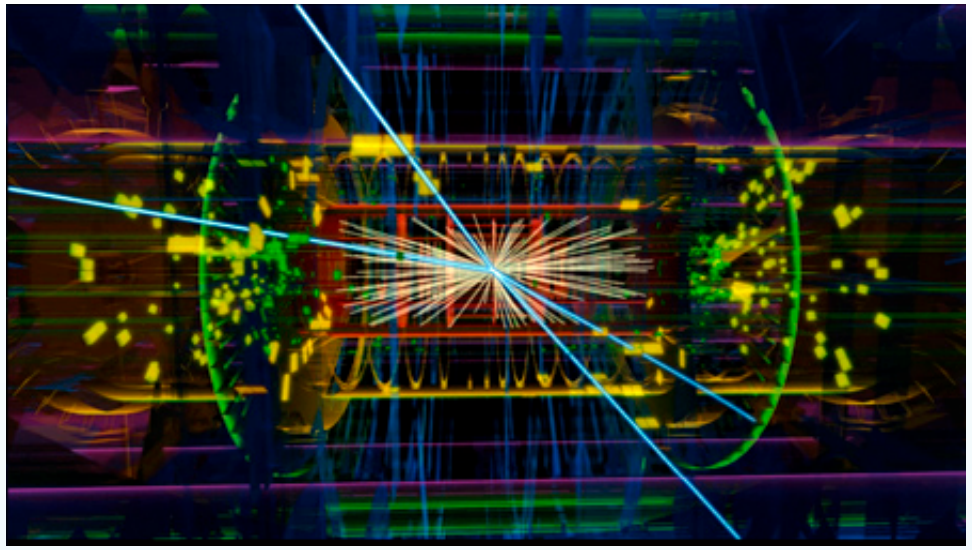
Nikhef

NWO
Netherlands Organisation
for Scientific Research

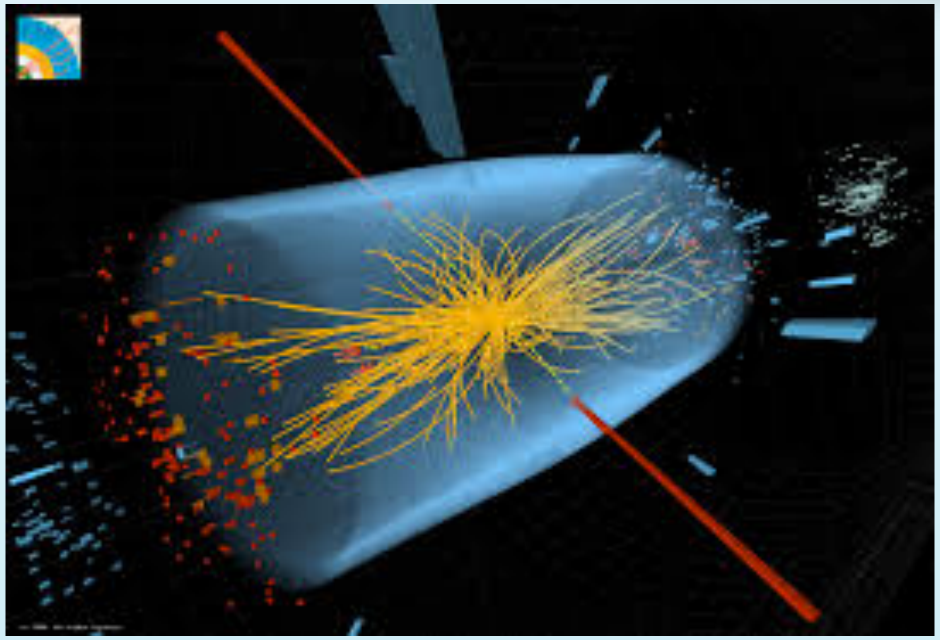
The structure of the proton in the LHC precision era

Juan Rojo
VU Amsterdam & Theory Group, Nikhef

Physikalisches Kolloquium
Department of Physics, University of Bonn, 12/4/2018



Exploring the high-energy frontier at the Large Hadron Collider



Outstanding questions in Particle Physics

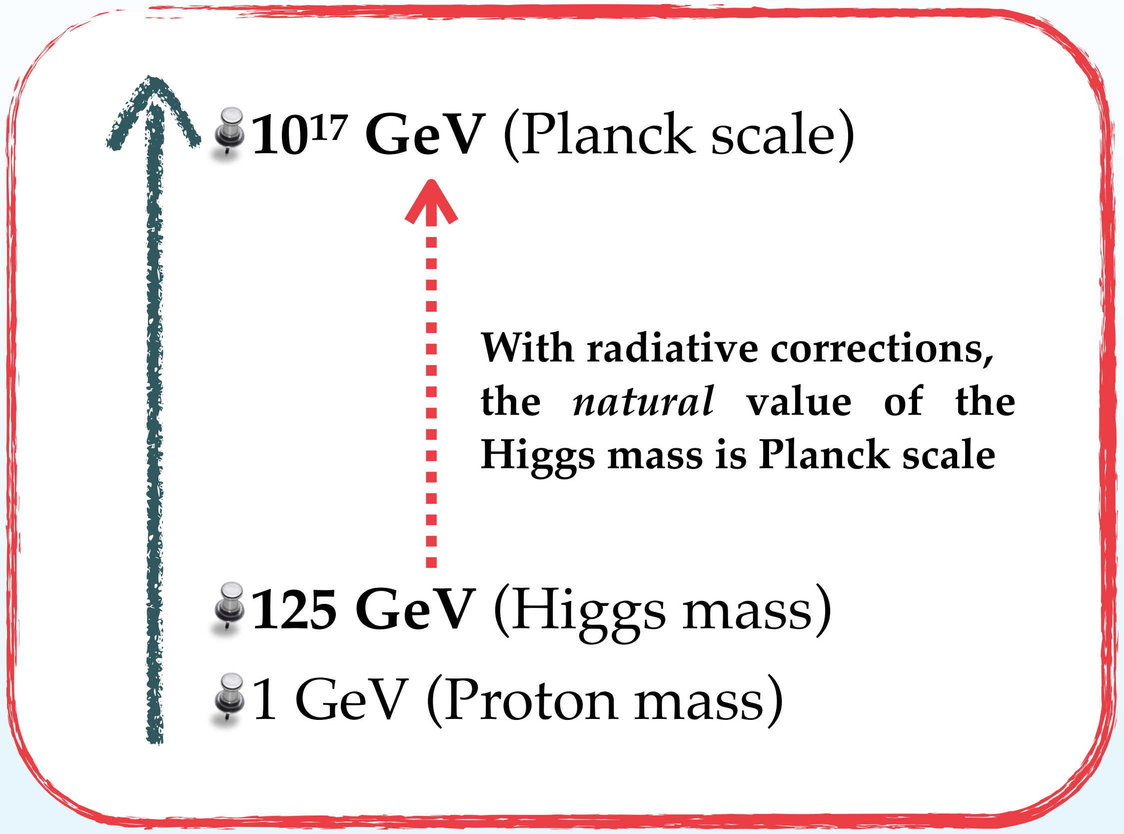
The Higgs boson

☑ Huge gap, 10^{17}, between **Higgs and Plank scales**

☑ **Elementary or composite**? Additional Higgs bosons?

☑ Coupling to **Dark Matter**? Role in cosmological phase transitions?

☑ Is the **vacuum state of the Universe** stable?

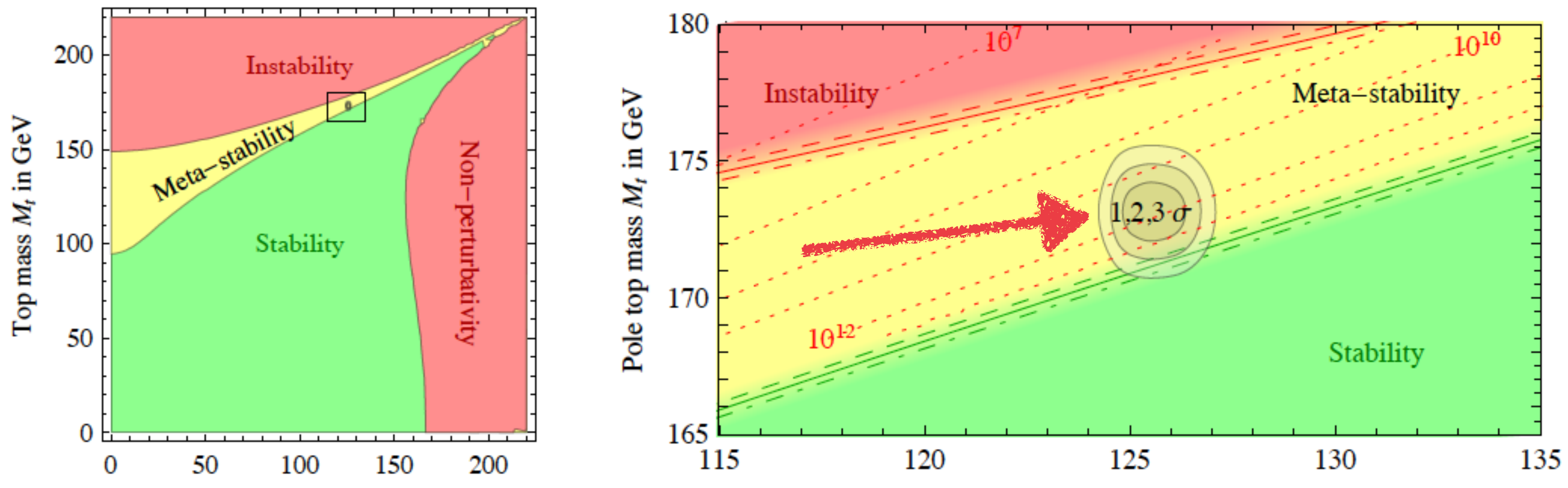


10^{17} GeV (Planck scale)

With radiative corrections, the *natural* value of the Higgs mass is Planck scale

125 GeV (Higgs mass)

1 GeV (Proton mass)



Degrassi et al 12

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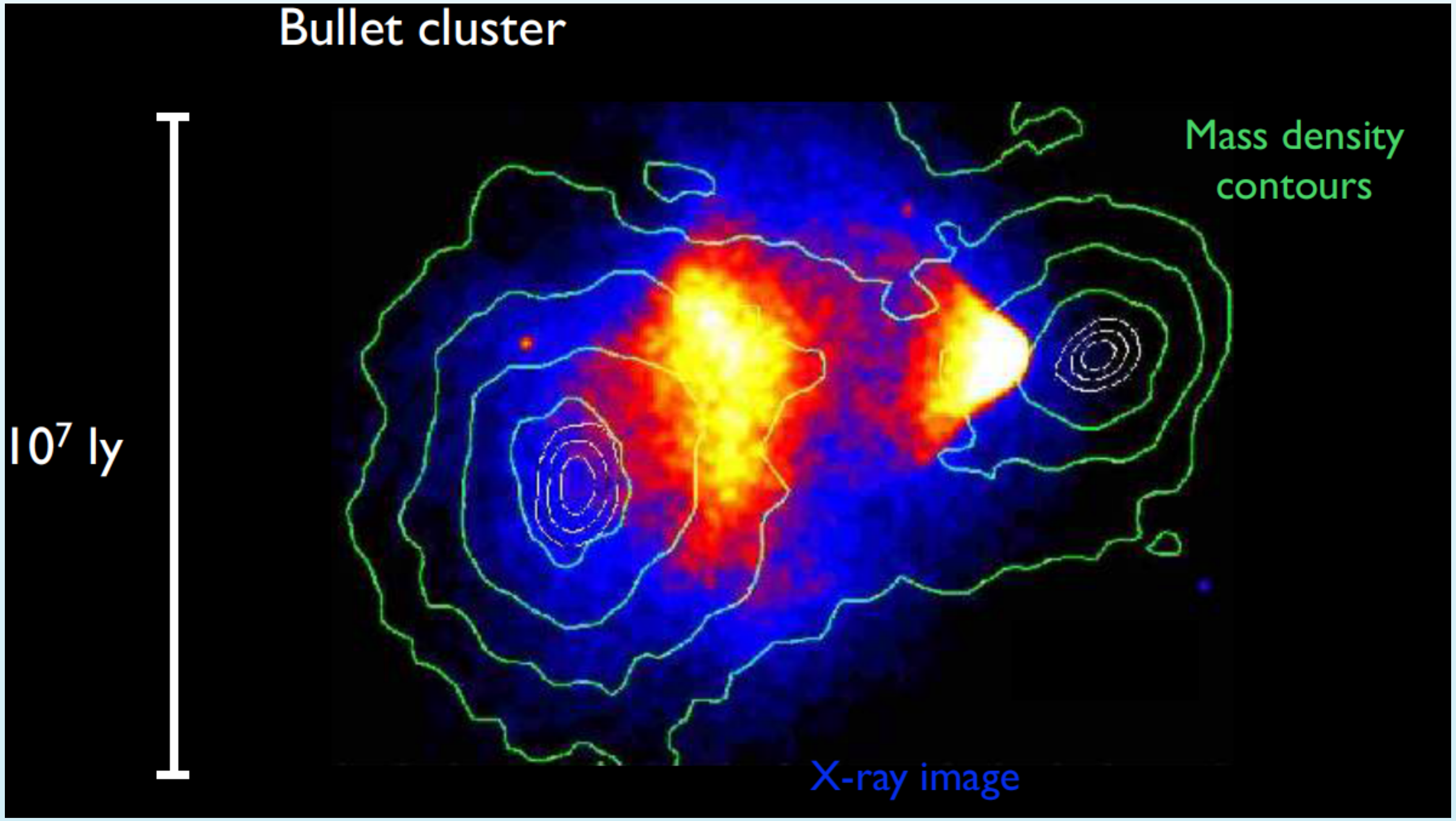
Dark Matter

☑ **Weakly interacting massive particles**? Sterile neutrinos? **Extremely light particles** (axions)?

☑ **Interactions** with Standard Model particles?

☑ What is the **structure of the Dark Sector**? Is Dark Matter self-interacting?



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Quarks and leptons

- ☑ **Why three families?** Can we explain **masses and mixings**?
- ☑ Origin of **Matter-Antimatter asymmetry** in the Universe?
- ☑ Are **neutrinos Majorana or Dirac**? CP violation in the lepton sector?

Dark Matter

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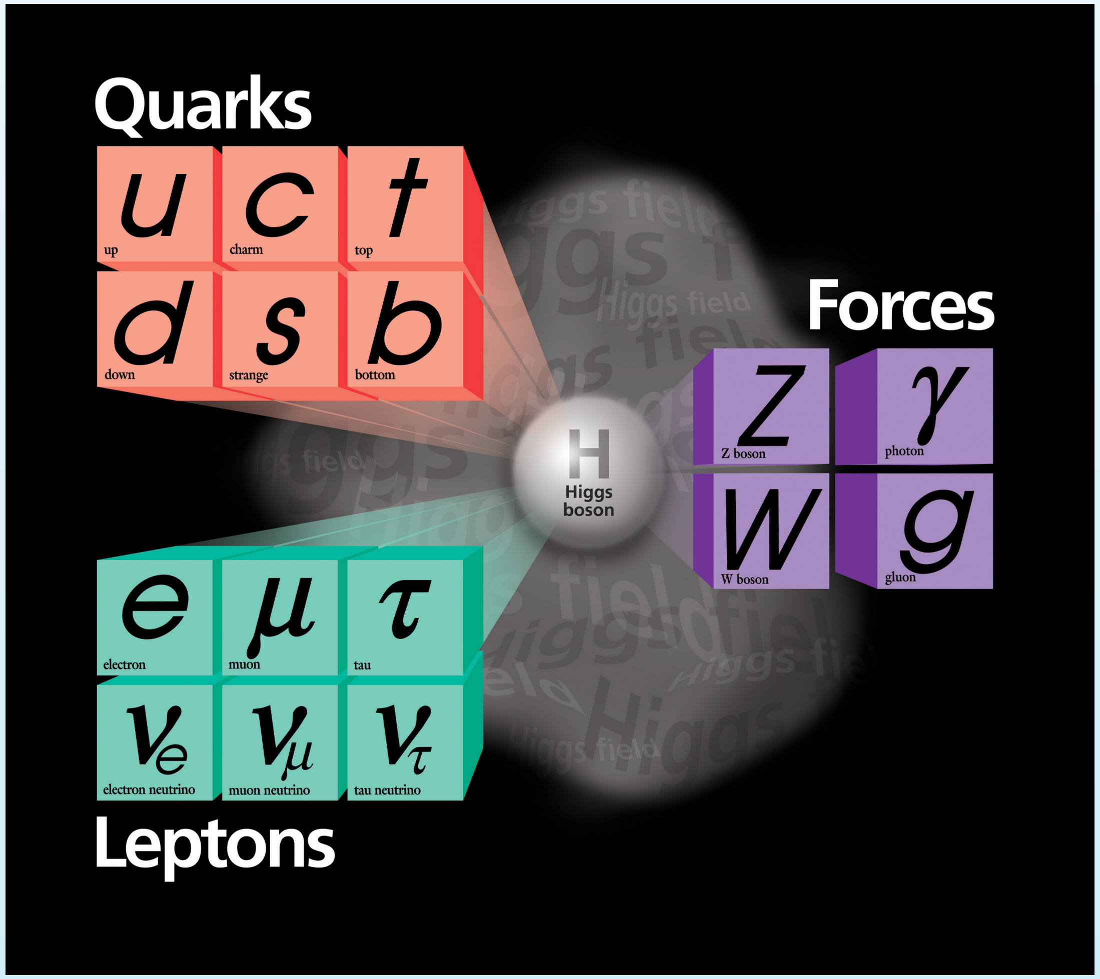

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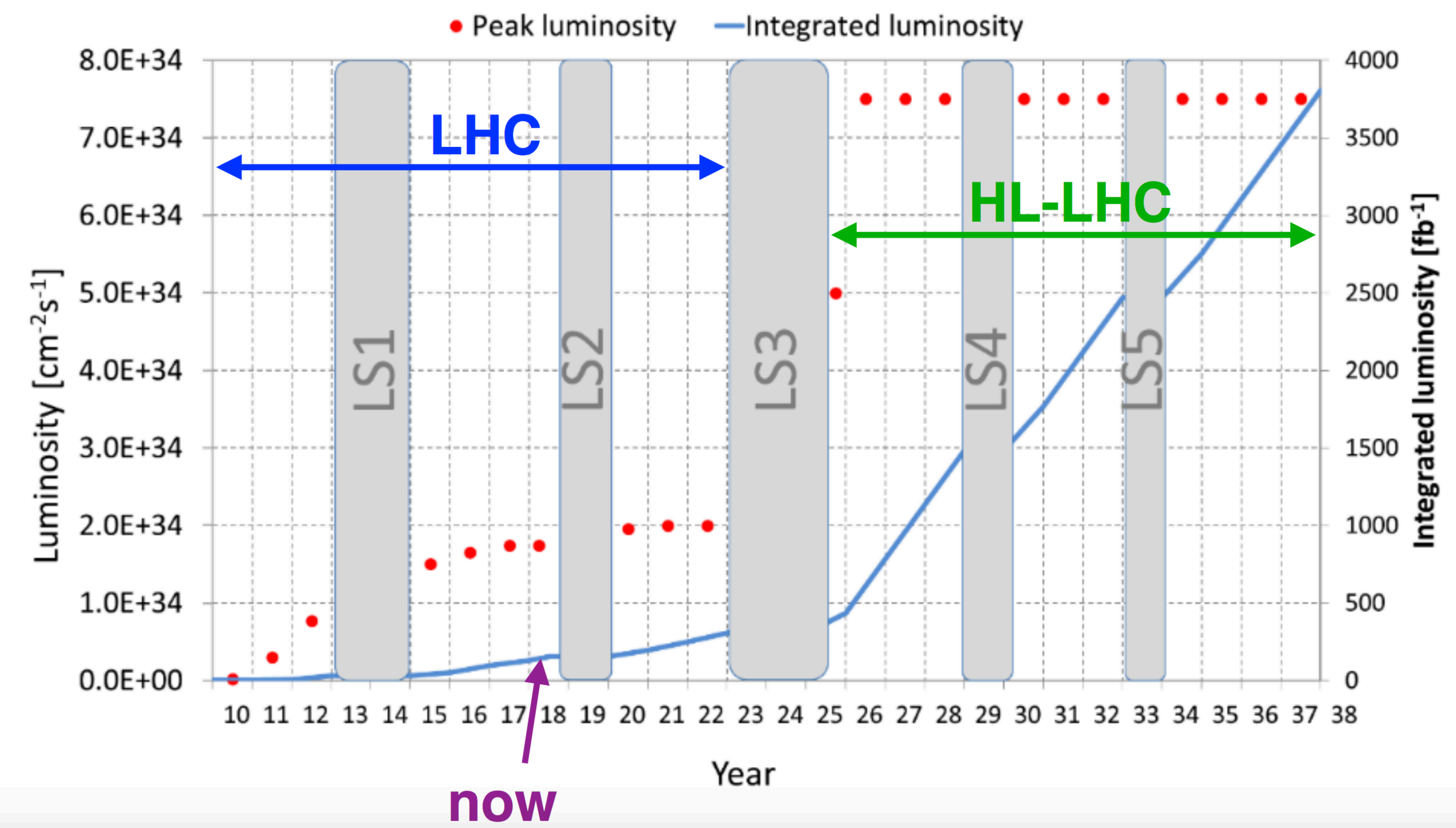
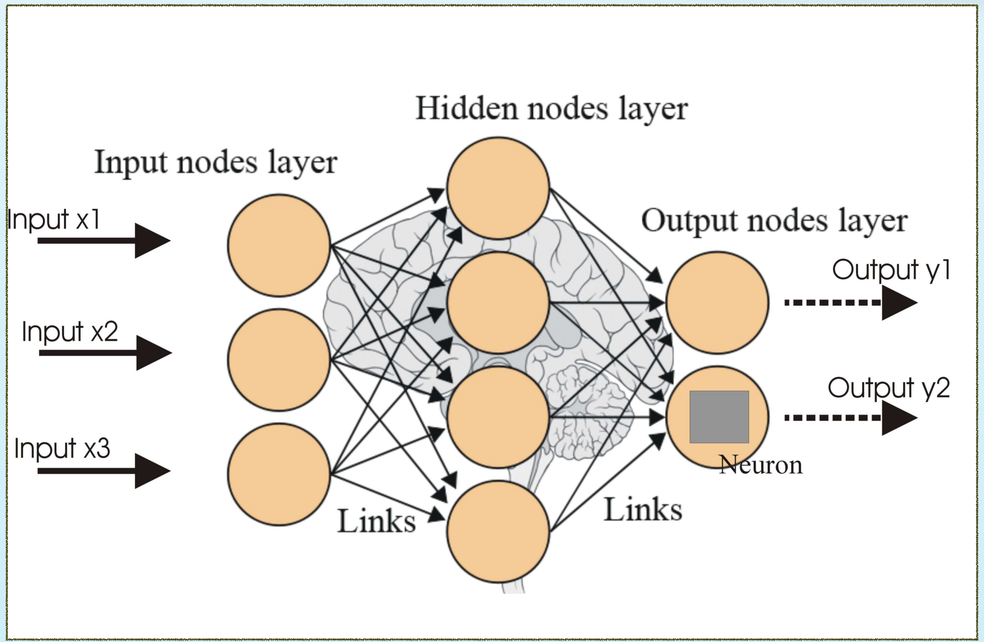


Many of these crucial questions can be addressed at the Large Hadron Collider

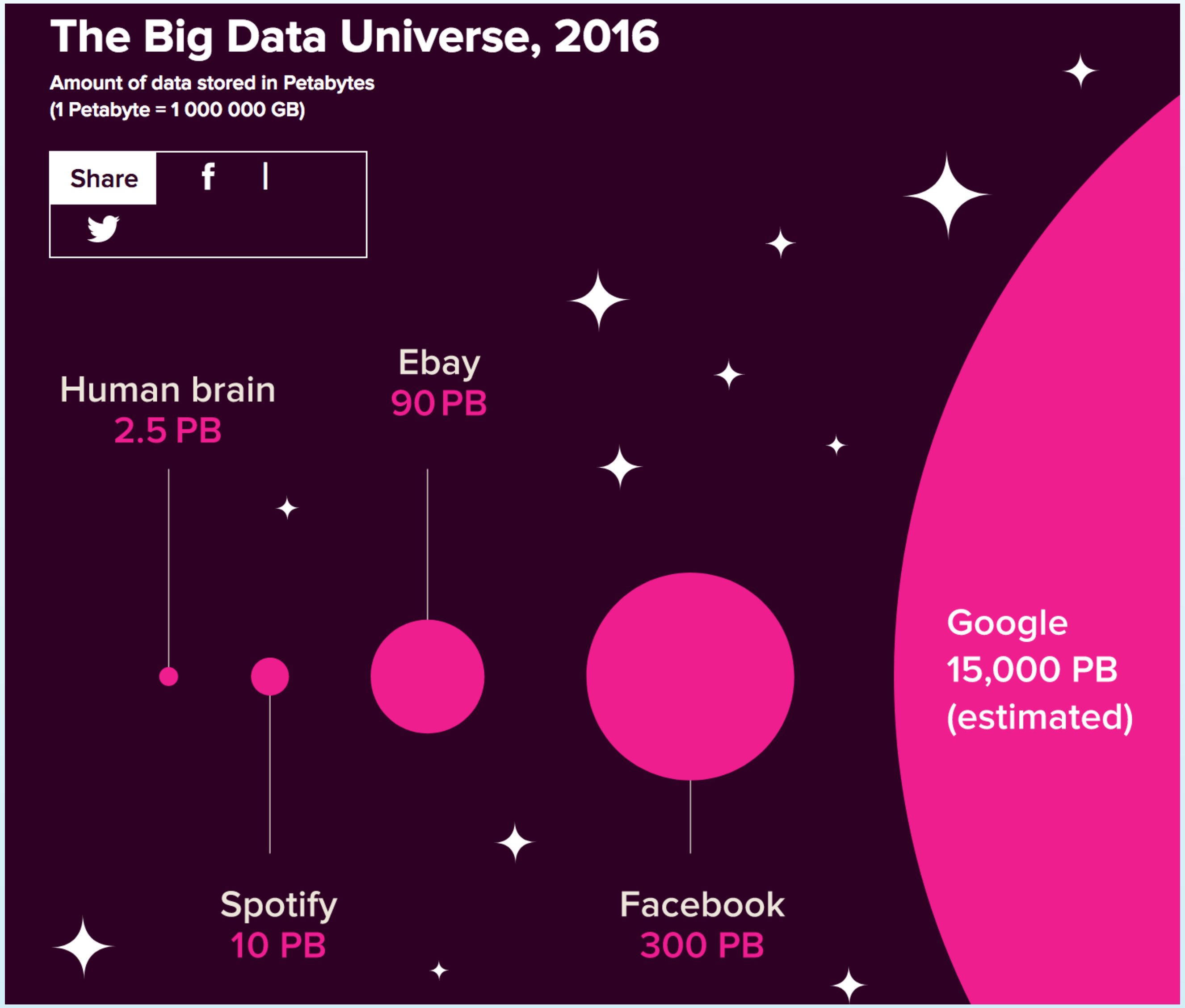
For the next 20 years, LHC will be the forefront of the exploration of the high-energy frontier

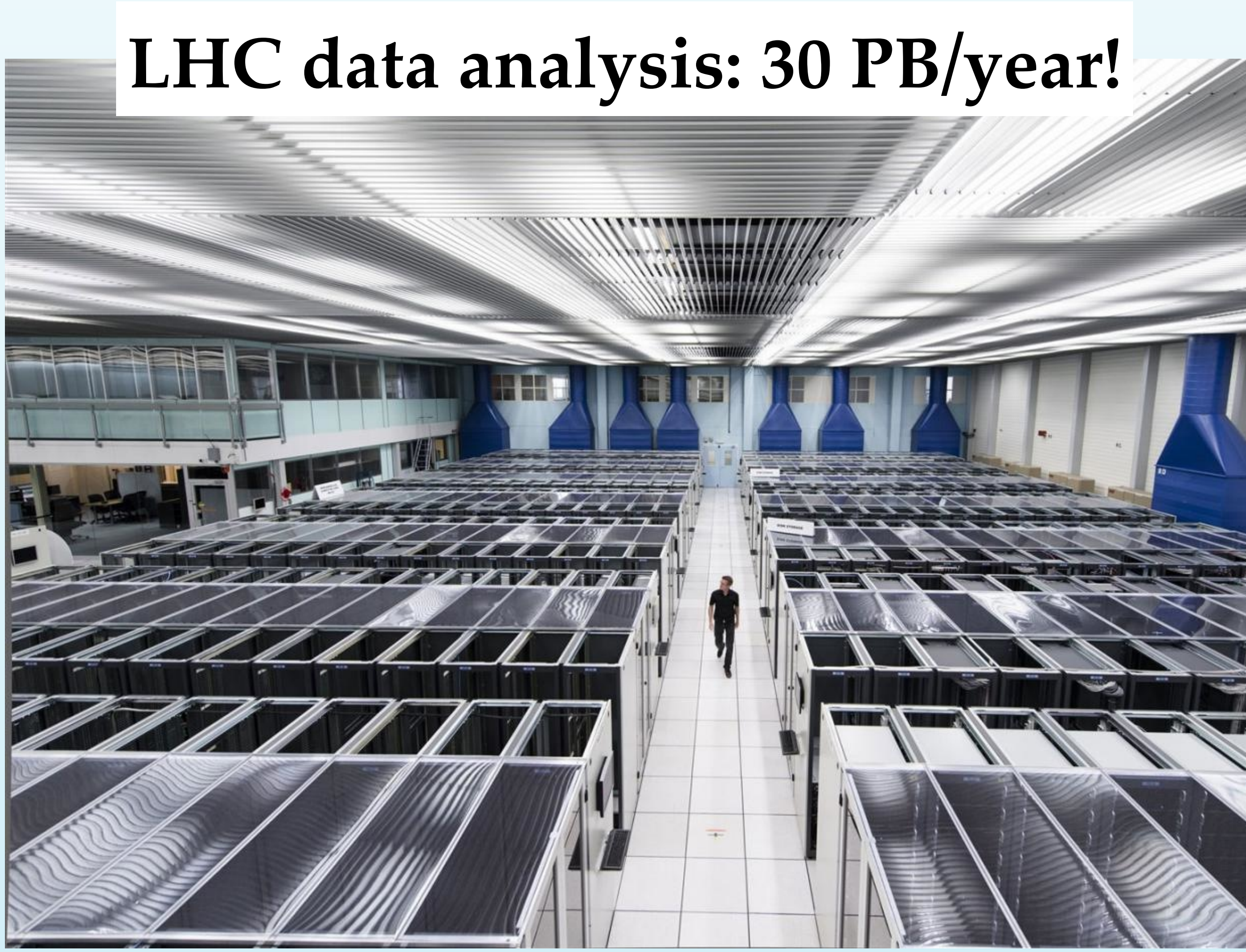
Machine Learning and Artificial Neural Networks at the LHC



Machine Learning at the LHC

- By **Machine Learning** we usually denote those families of computer algorithms that **learn how to excel on a task** based on a **large sample of examples**, rather than on some a priori fixed rules
- ML algorithms are nowadays ubiquitous, from **driverless cars** to **Amazon's purchase suggestions**, to **automated medical imaging recognition** to beating the words best players at Go and chess
- ML tools rely on the **efficient exploitation of immense datasets**. And the **LHC** has a lot of data!





LHC data analysis: 30 PB/year!

Machine Learning in high-energy physics

- **Huge, fast growing field**, with new applications being proposed every day
- Here restrict ourselves to **two representative examples**: if you want to learn more about other applications, don't hesitate to ask!
- For further **overviews of ML applications to high-energy physics** and related fields please see

☑ ***Big data tools in Physics and Astronomy*** (Amsterdam, https://indico.cern.ch/event/622093/)

☑ *Machine learning for Phenomenology* (Durham, https://conference.ippp.dur.ac.uk/event/660/)

☑ *Inter-Experimental LHC Machine Learning WG* (https://iml.web.cern.ch/)

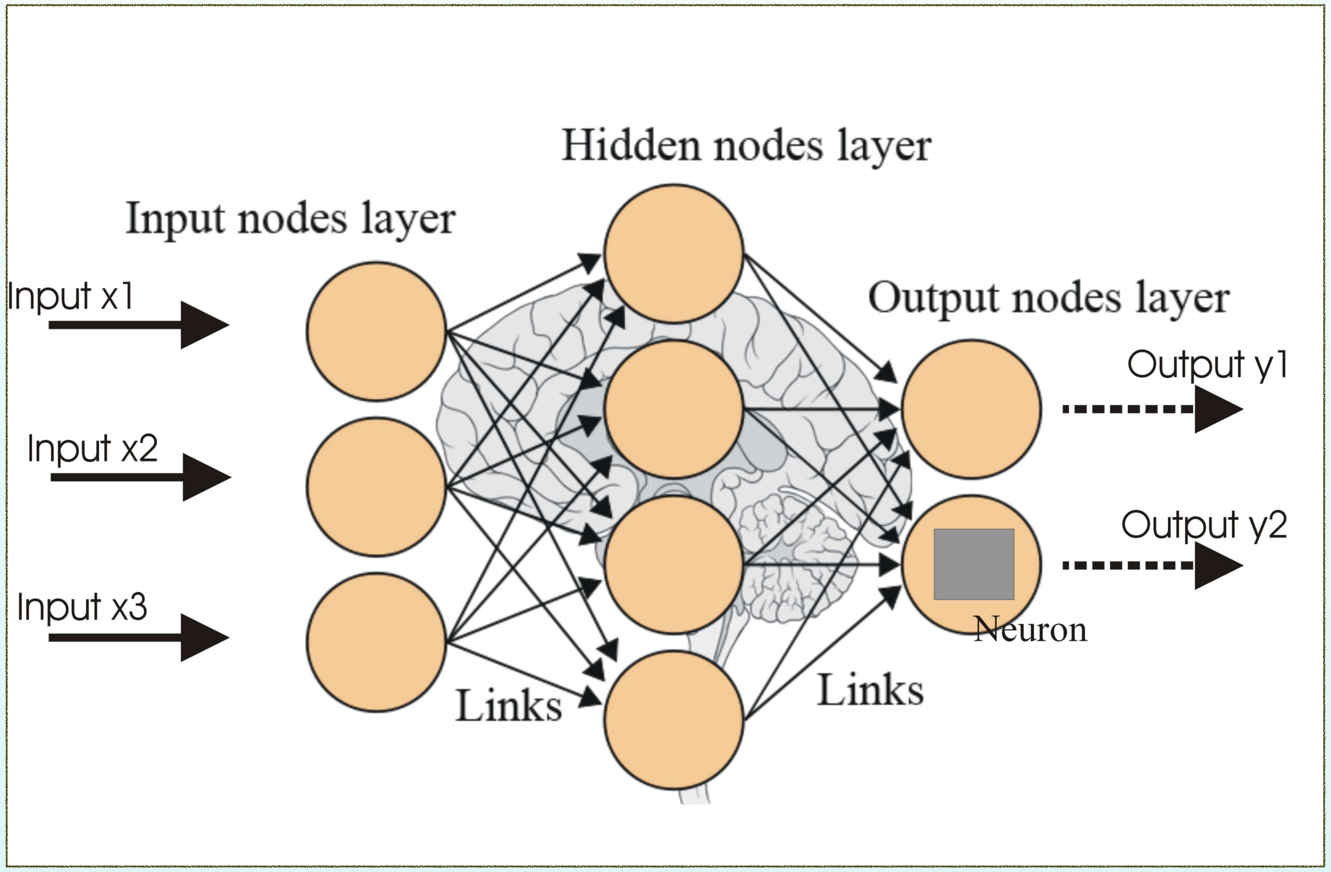
☑ *Accelerating searches for Dark Matter with Machine Learning* (https://indico.cern.ch/event/664842/)

☑ *CERN Data Science seminars* (https://indico.cern.ch/category/9320/)

Artificial Neural Networks

Inspired by **biological brain models**, **Artificial Neural Networks** (ANNs) are **mathematical algorithms** widely used in a wide range of applications, from **HEP** to **targeted marketing** and **finance forecasting**

From biological to artificial neural networks



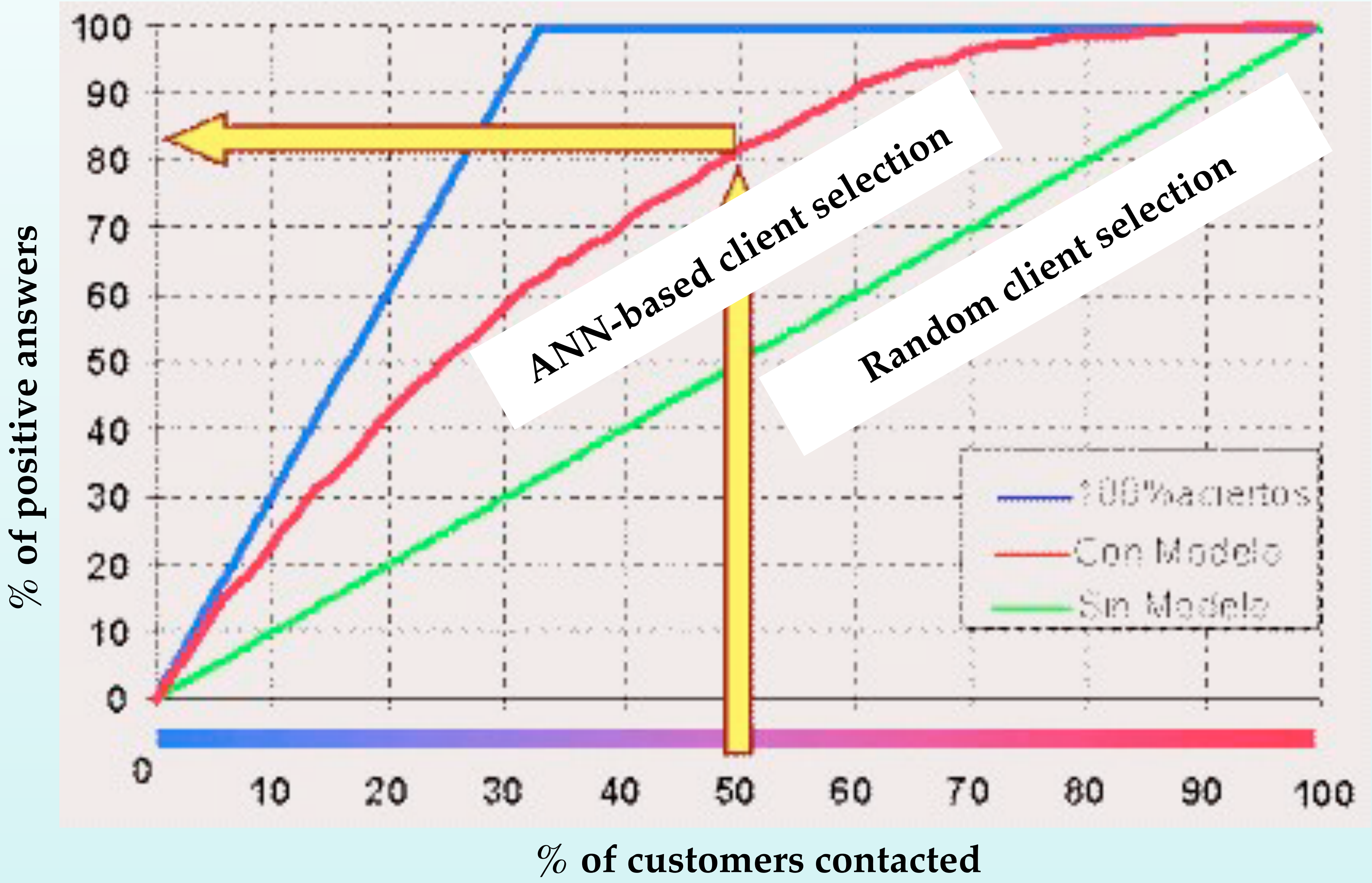
Artificial neural networks aim to excel where domains as their **evolution-driven counterparts outperforms traditional algorithms in tasks such as pattern recognition, forecasting, classification**, …

ANNs - a marketing example

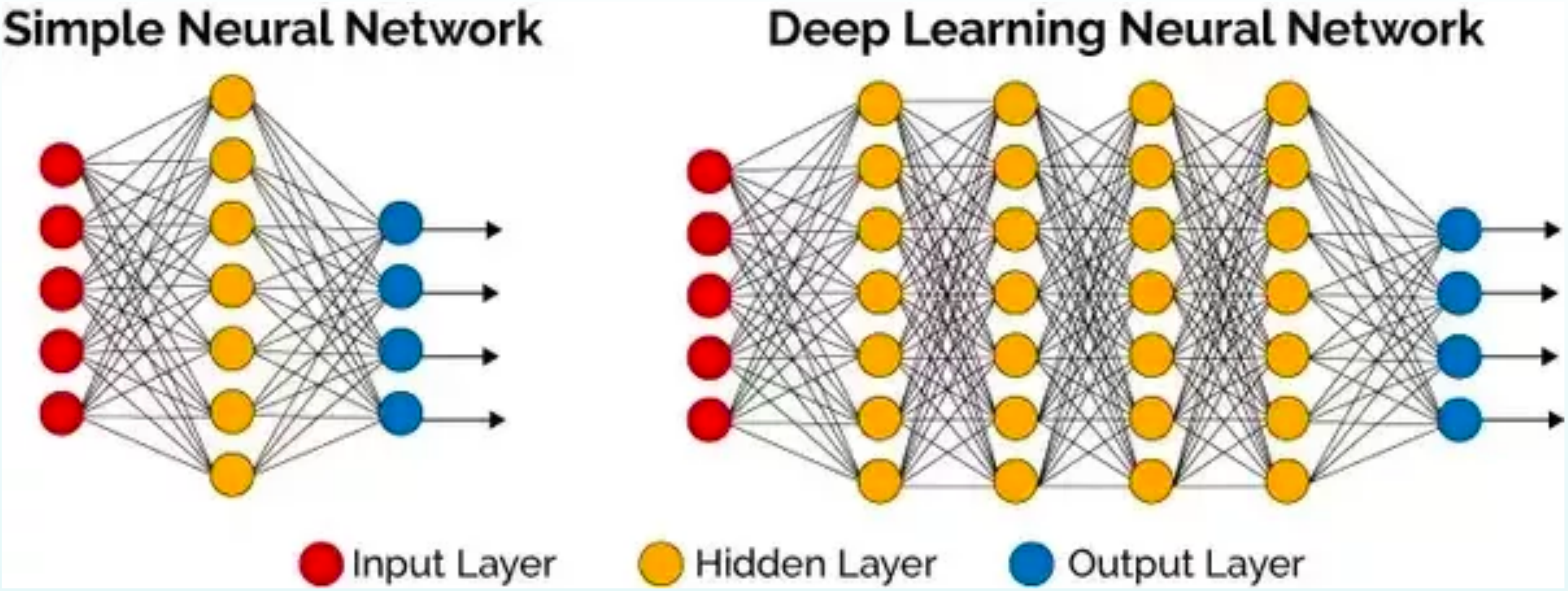
A bank wants to offer a new credit card to their clients. Two possible strategies:

- **Contact all customers**: slow and costly
- Contact **5%** of the customers, **train a ANN with their input** (savings, income, loans) and **their output** (yes/no) and use the information to **contact only clients likely to accept the product**

Cost-effective method to improve marketing performance!



Deep Neural Networks



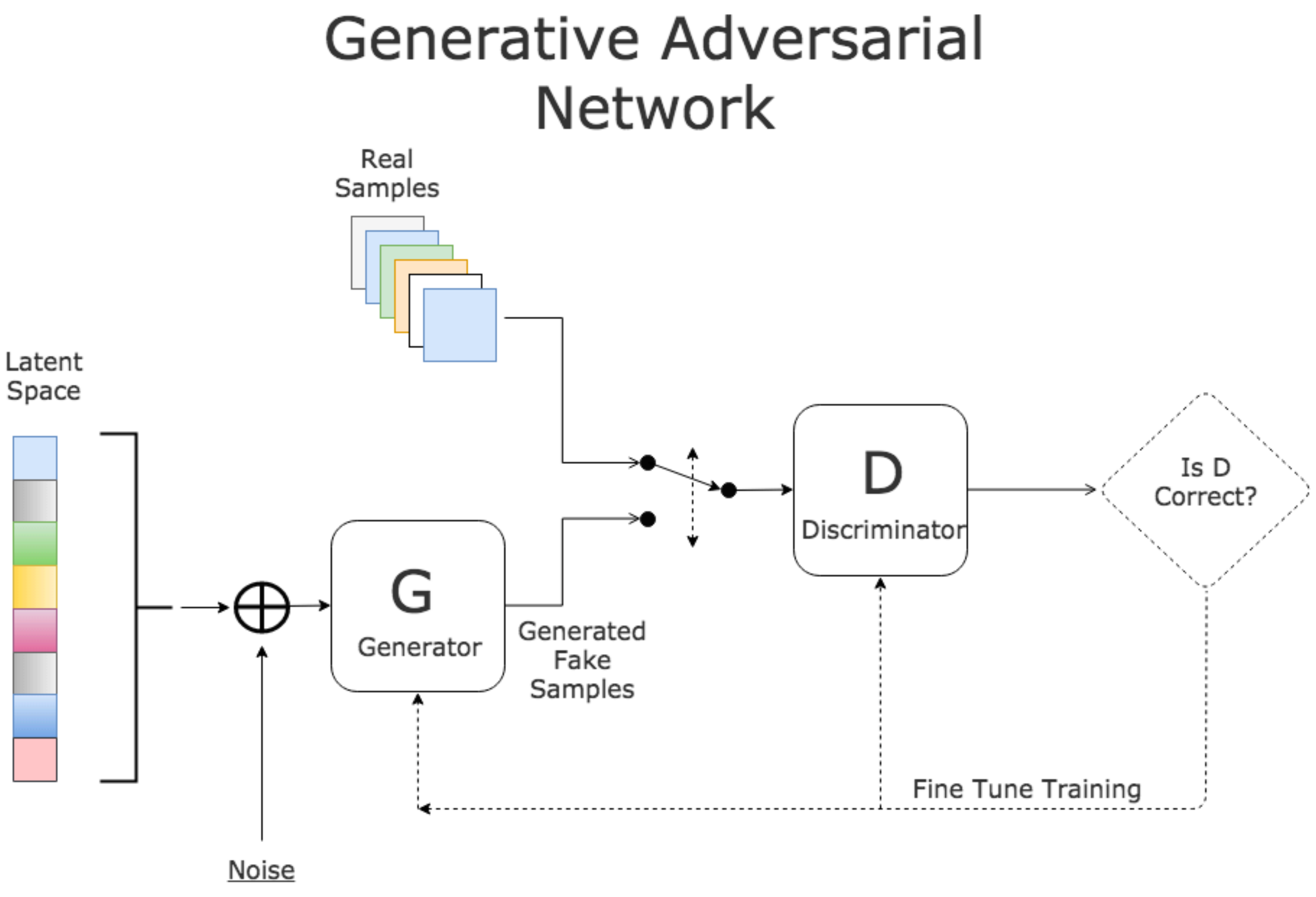
- A **Deep Neural Network (DNN)** is a standard multi-layer feed-forward perceptron with a large number of internal layers

- All types of neural nets eg **Recursive, Convolutional, Parametrised** etc can be made "deep" by adding more hidden layers

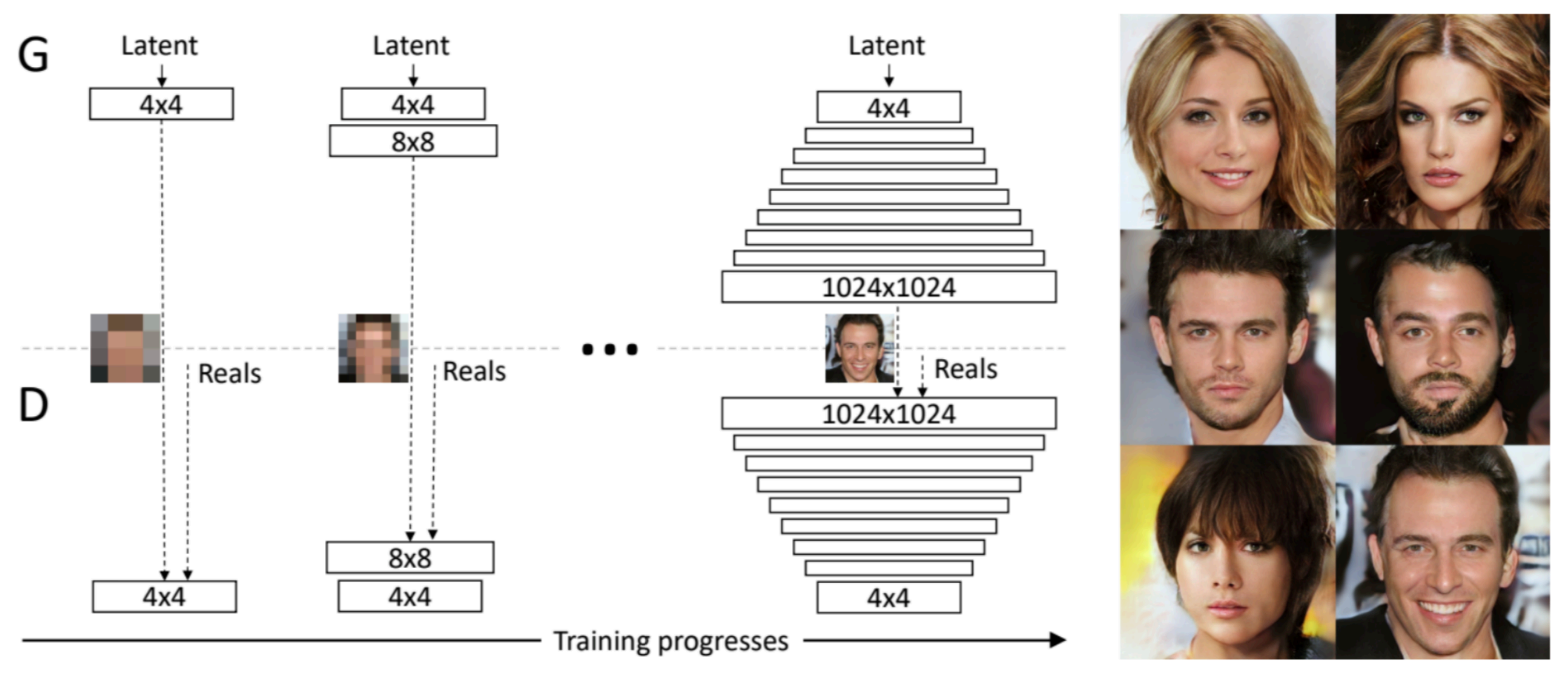
- For several applications, the **increased complexity** achieved this way leads to a significant improvement in performance

Generative Adversarial Networks

- New architecture for an **unsupervised neural network training** (unlabelled samples)
- Based on two **independent nets** that work separately and act as adversaries:
  - the **Discriminator (D)** undergoes training and plays the role of classifier, and
  - the **Generator (G)** and is tasked to generate random samples that **resemble real samples** with a twist rendering them as fake samples.



The many uses of GANs

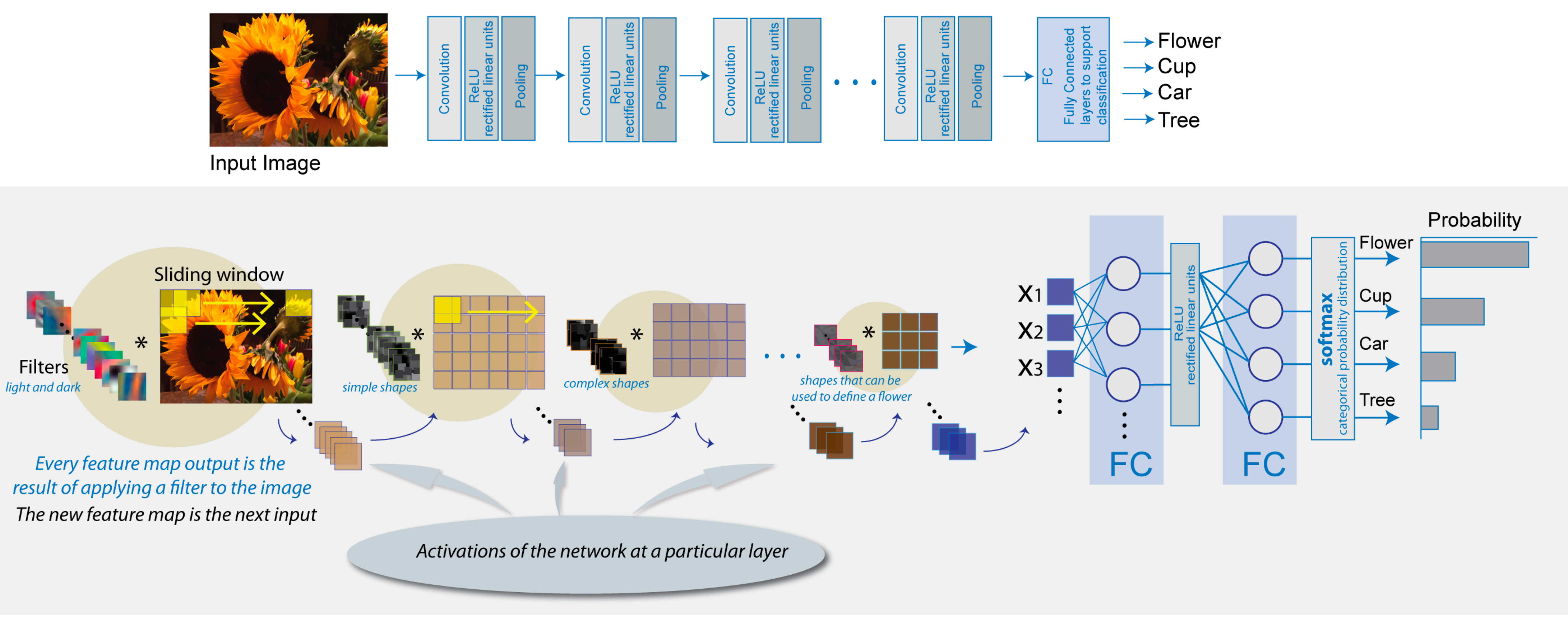


arXiv:1710.10196

Which one of these images are real and which ones are fake (generated by the GANs)?

Convolutional Neural Networks

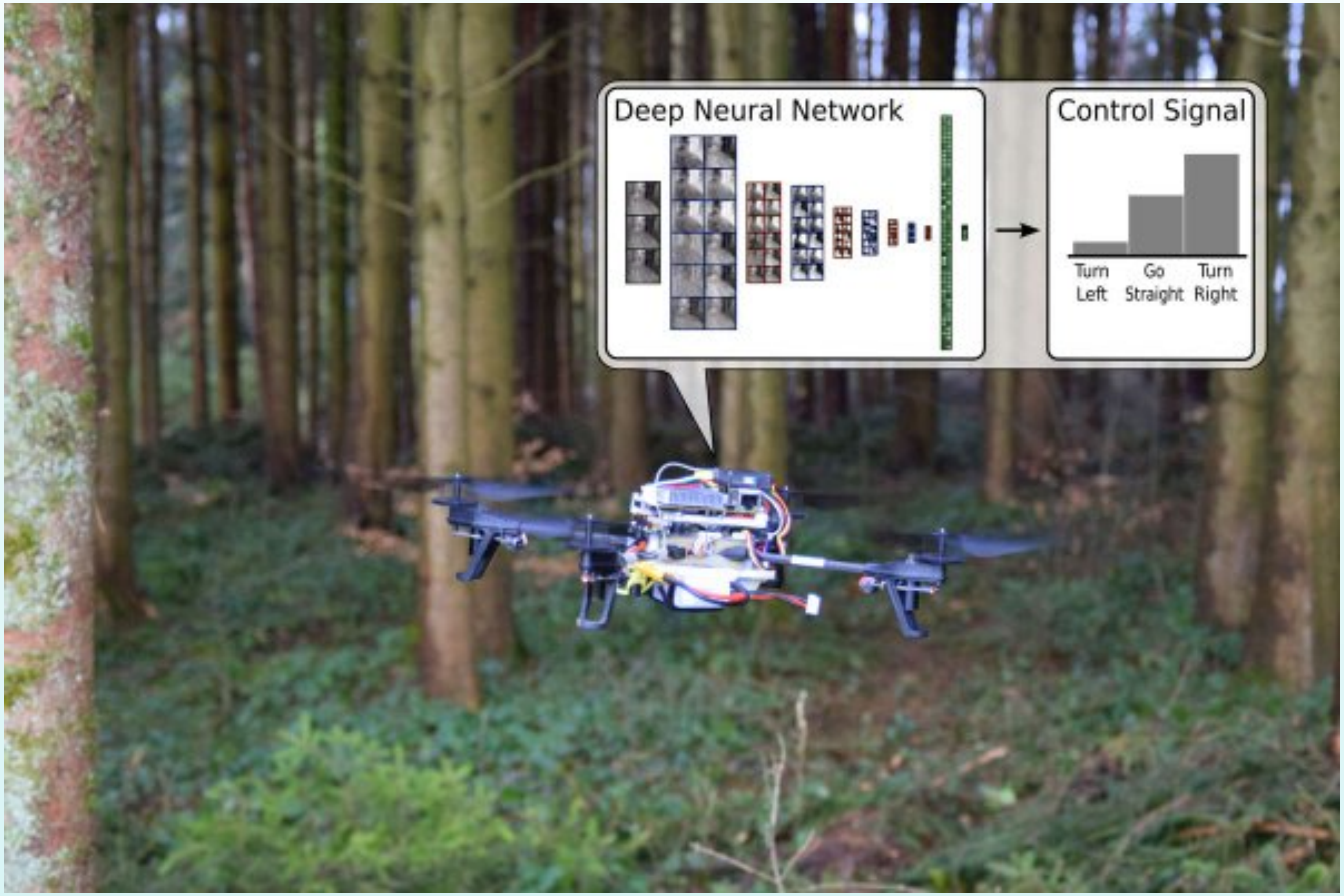
- Convolutional Neural Networks (CNNs) have convolutional layers based on **filters**
- Each **filter** maps a group of numbers into a number, reducing the dimensionality of the data
- Specially useful for **pattern recognition** (eg for self-driving vehicles)



mathworks.com

Convolutional Neural Networks

- ANNs can enable an **autonomous vision-control drone** to recognise and follow forest trails
- Image classifier operates directly on **pixel-level image intensities**
- If a trail is visible, the **software steers the drone** in the corresponding direction

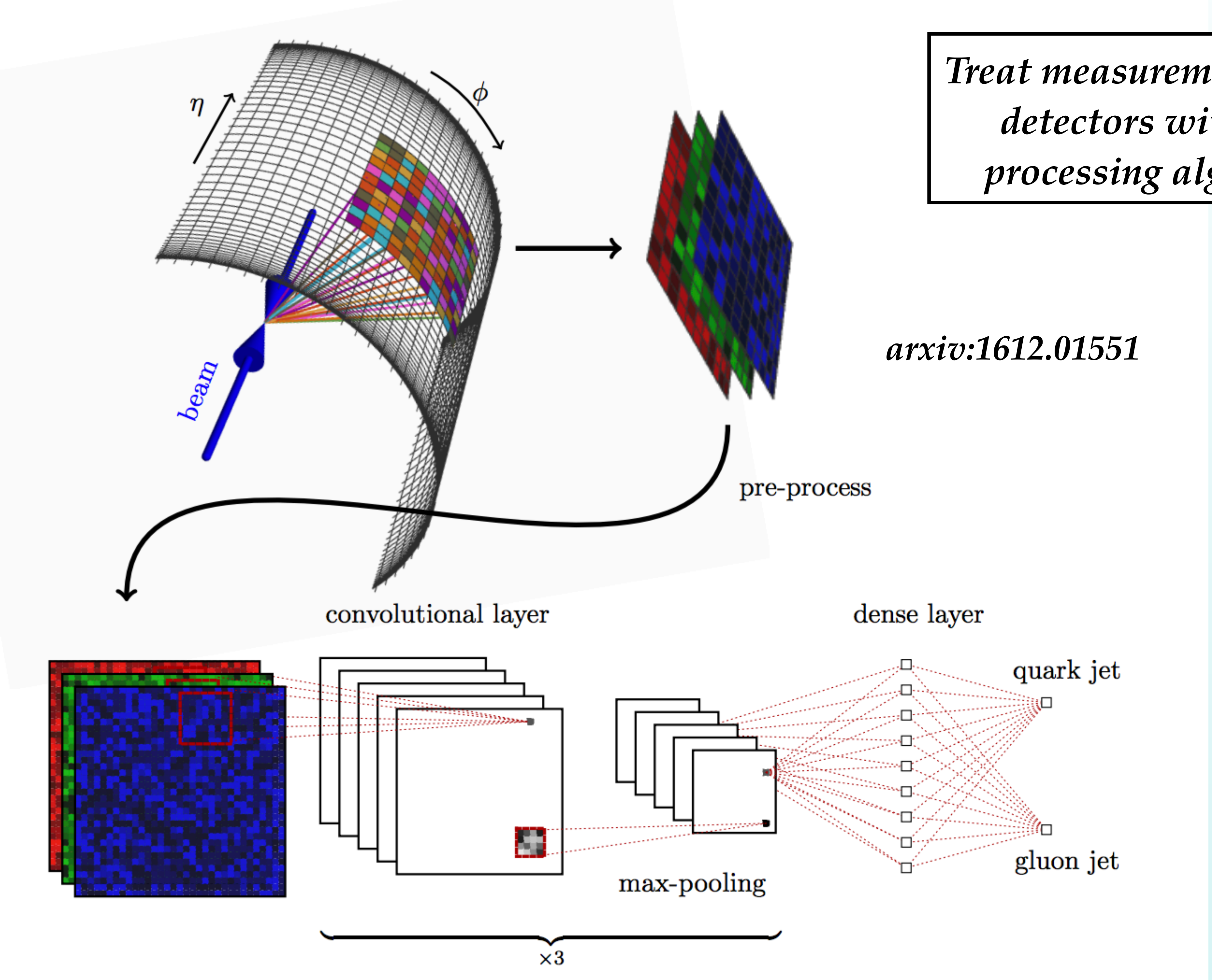


Giusti et al, IEEE Robotics and Automation Letters, 2016

Similar algorithms at work in self-driving cars!

Convolutional Neural Networks

The results of the **collisions of high-energy particles** can be treated analogously to **image processing** using Convolutional Neural Networks

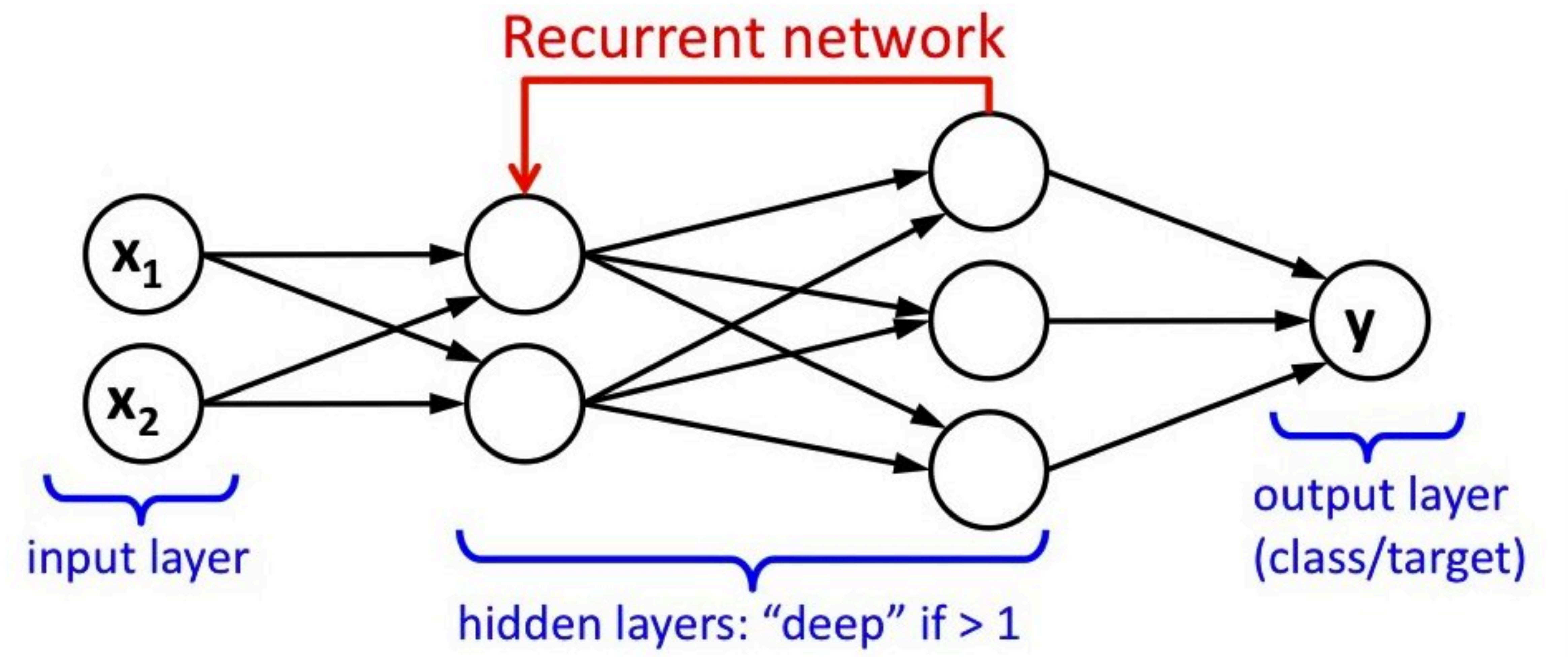


Treat measurements in HEP detectors with image processing algorithms!

arxiv:1612.01551

Recurrent Neural Networks

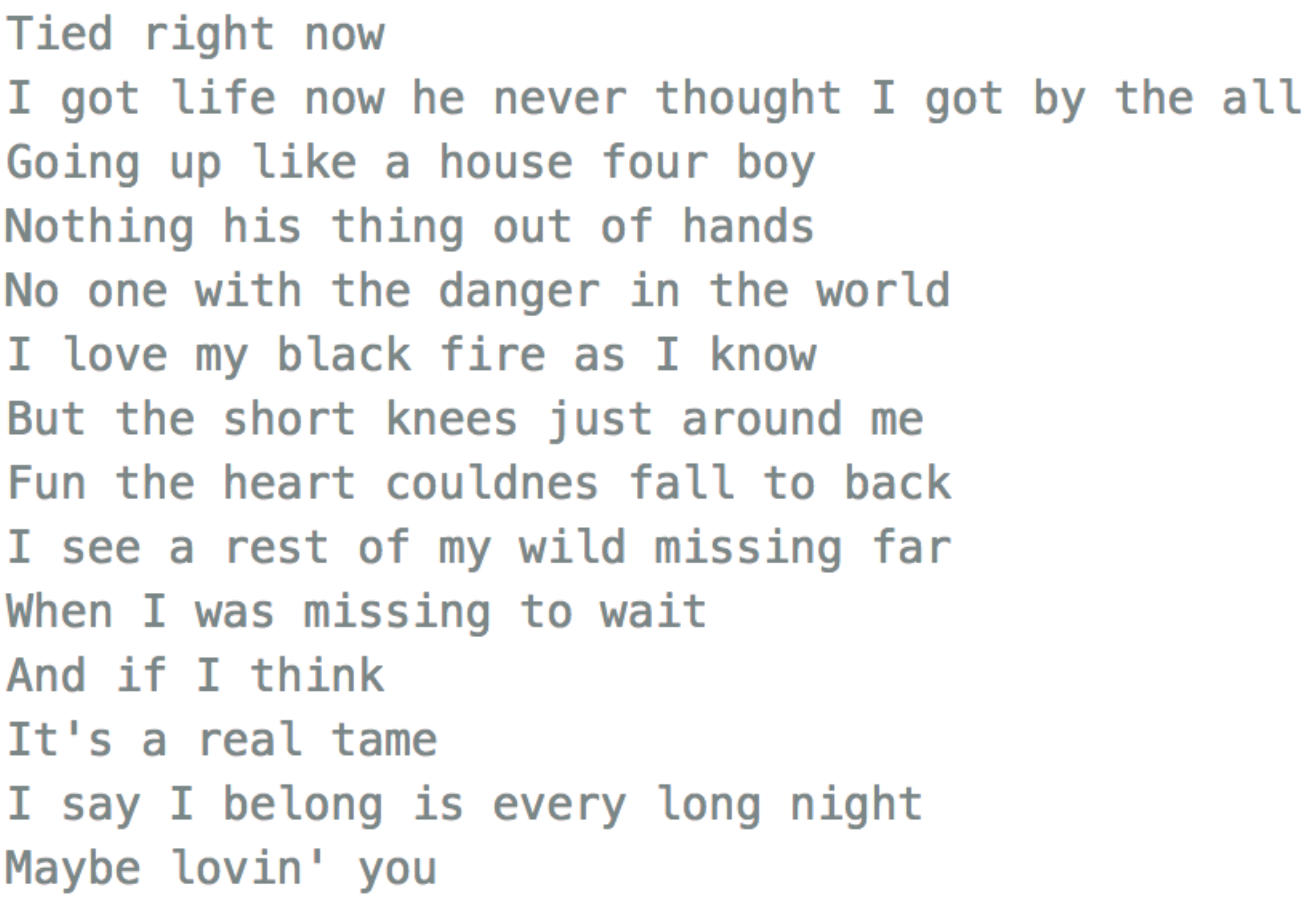
RNNs use as inputs not just the current “training examples” but also **what they have perceived previously**: they have a **built-in notion of time ordering** useful for time-dependent functions



The output of a RNN at time time, ***y(t),*** depends both on the current input example ***x(t)*** as well as of its previous output ***y(t-1)*** (or activation states of hidden neutrons at ***t-1***)

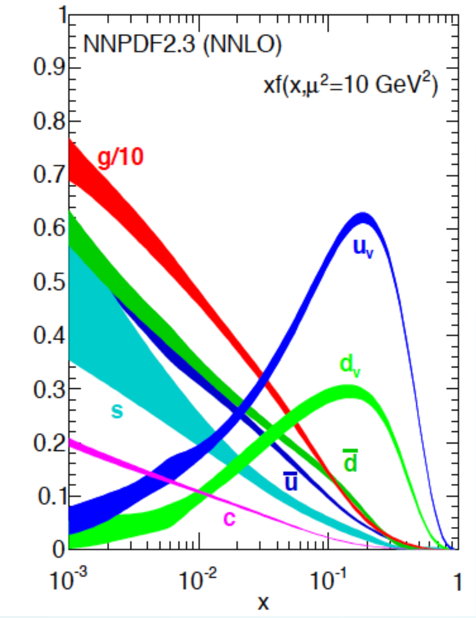
Recurrent Neural Networks

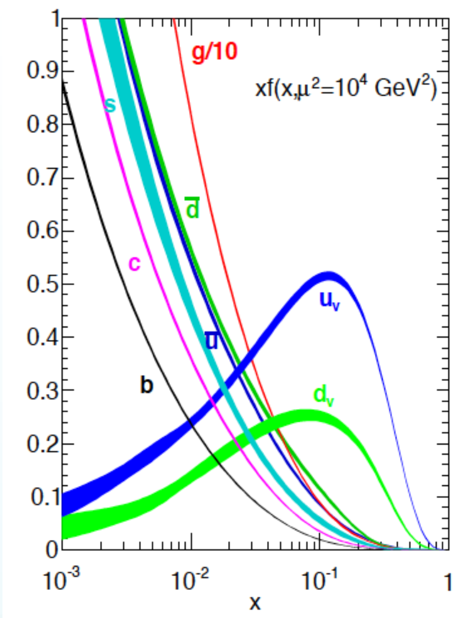
Lead to truly game-changer applications, such as **random generation of country song lyrics**



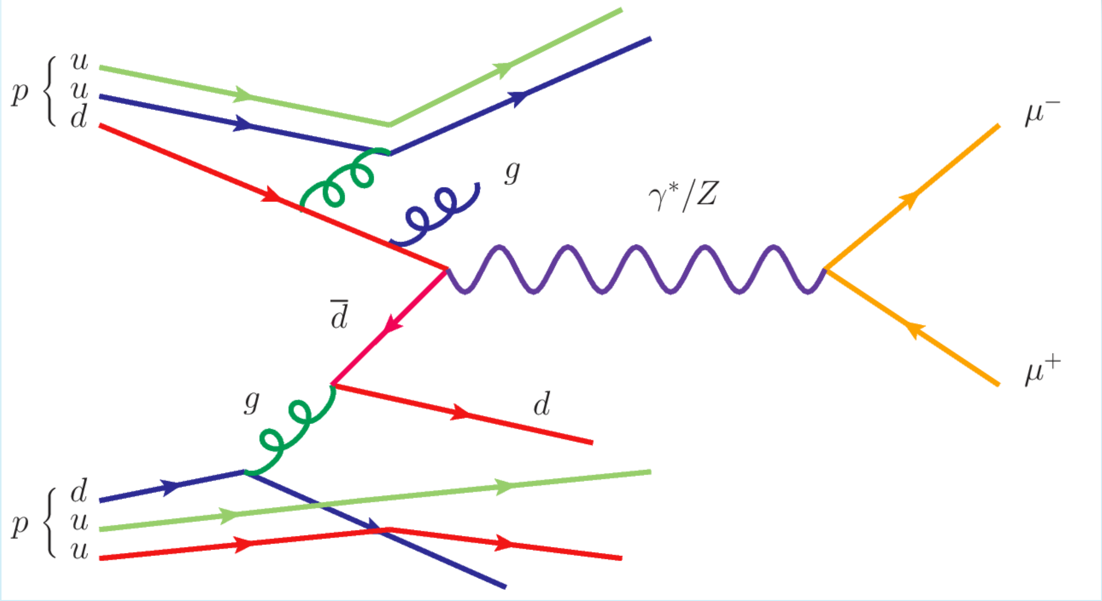
```
Tied right now
I got life now he never thought I got by the all
Going up like a house four boy
Nothing his thing out of hands
No one with the danger in the world
I love my black fire as I know
But the short knees just around me
Fun the heart couldnes fall to back
I see a rest of my wild missing far
When I was missing to wait
And if I think
It's a real tame
I say I belong is every long night
Maybe lovin' you
```

http://www.mattmoocar.me/blog/RNNCountryLyrics/



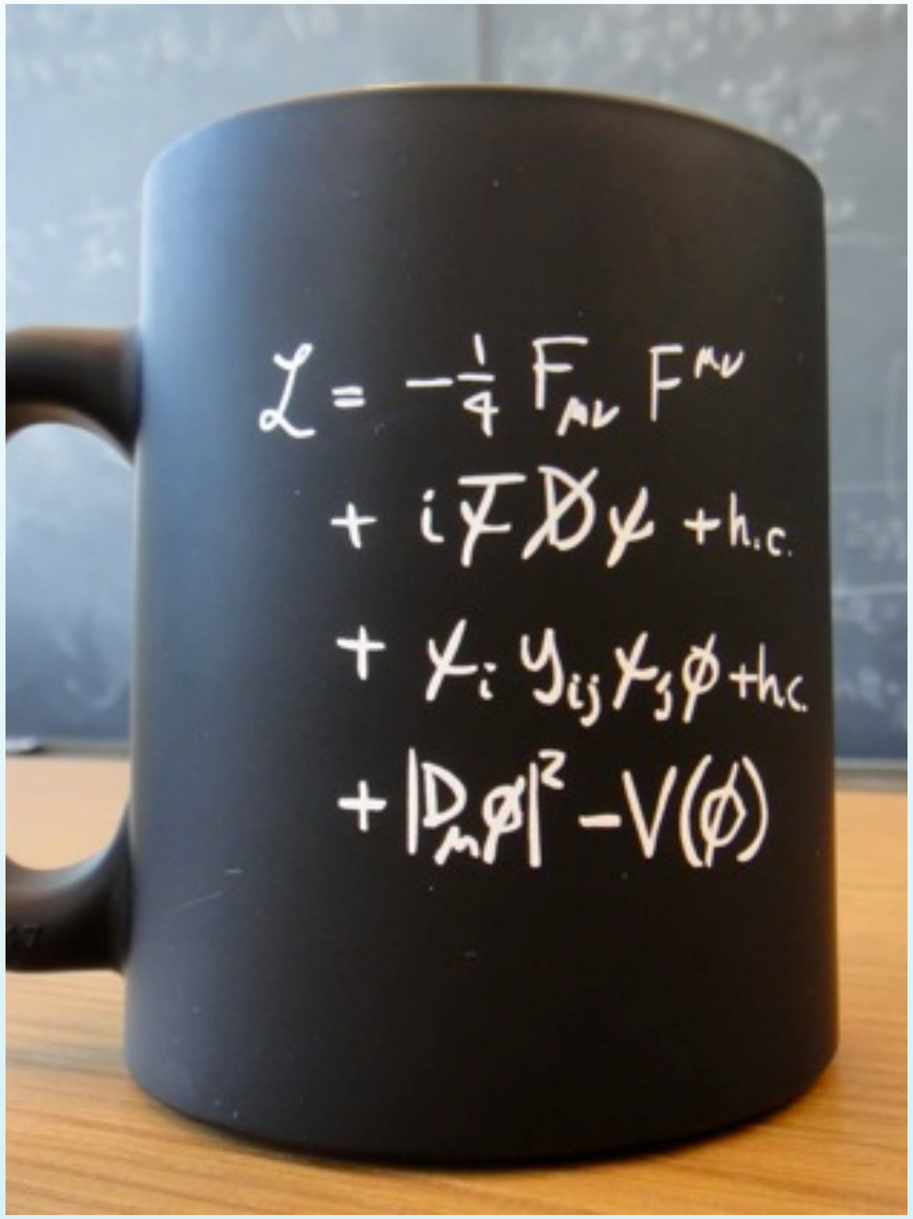


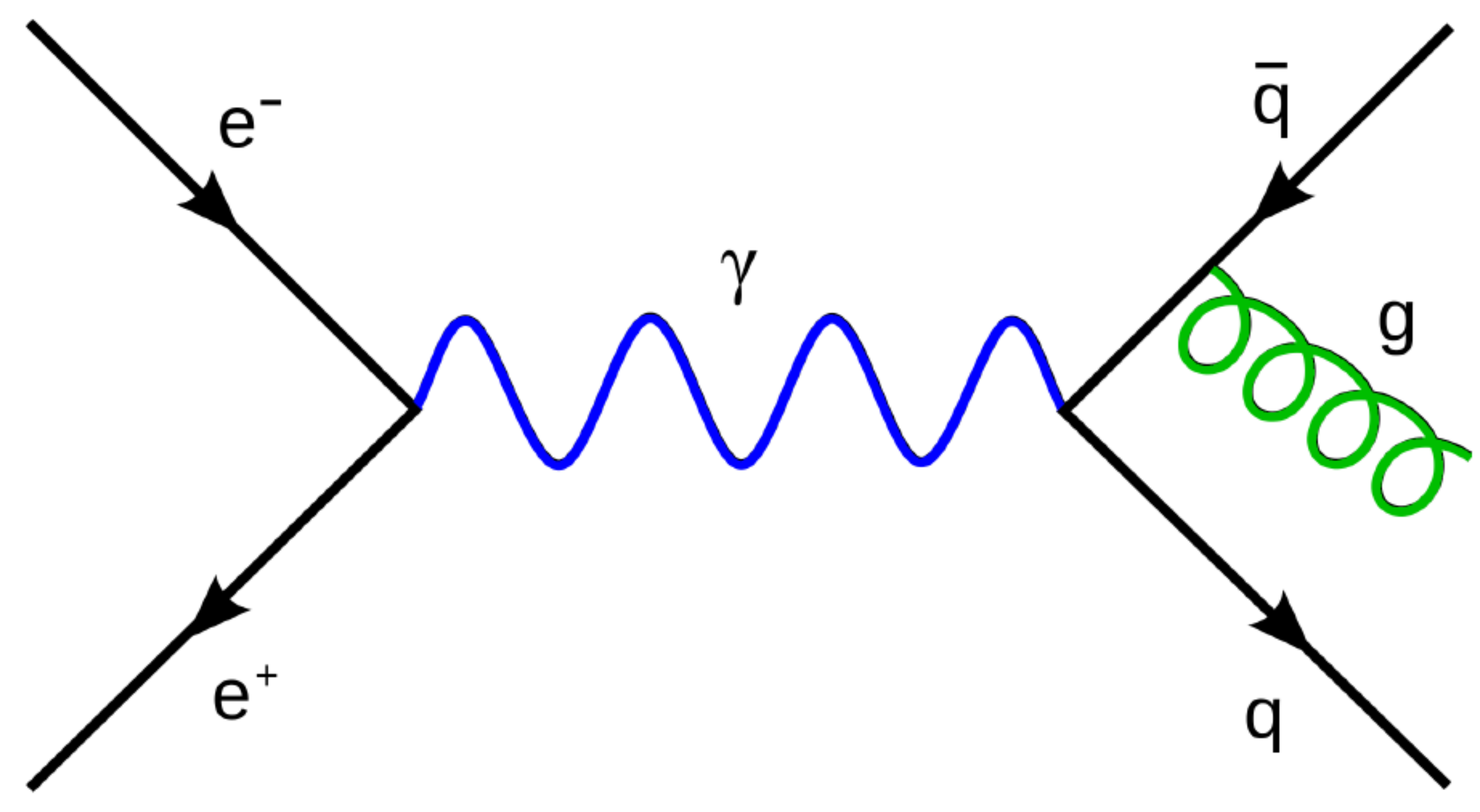
A crash course on parton distributions



Lepton vs Hadron Colliders

In high-energy **lepton colliders**, such as the **Large Electron-Positron Collider** (LEP) at CERN, the collisions involve **elementary particles** without substructure

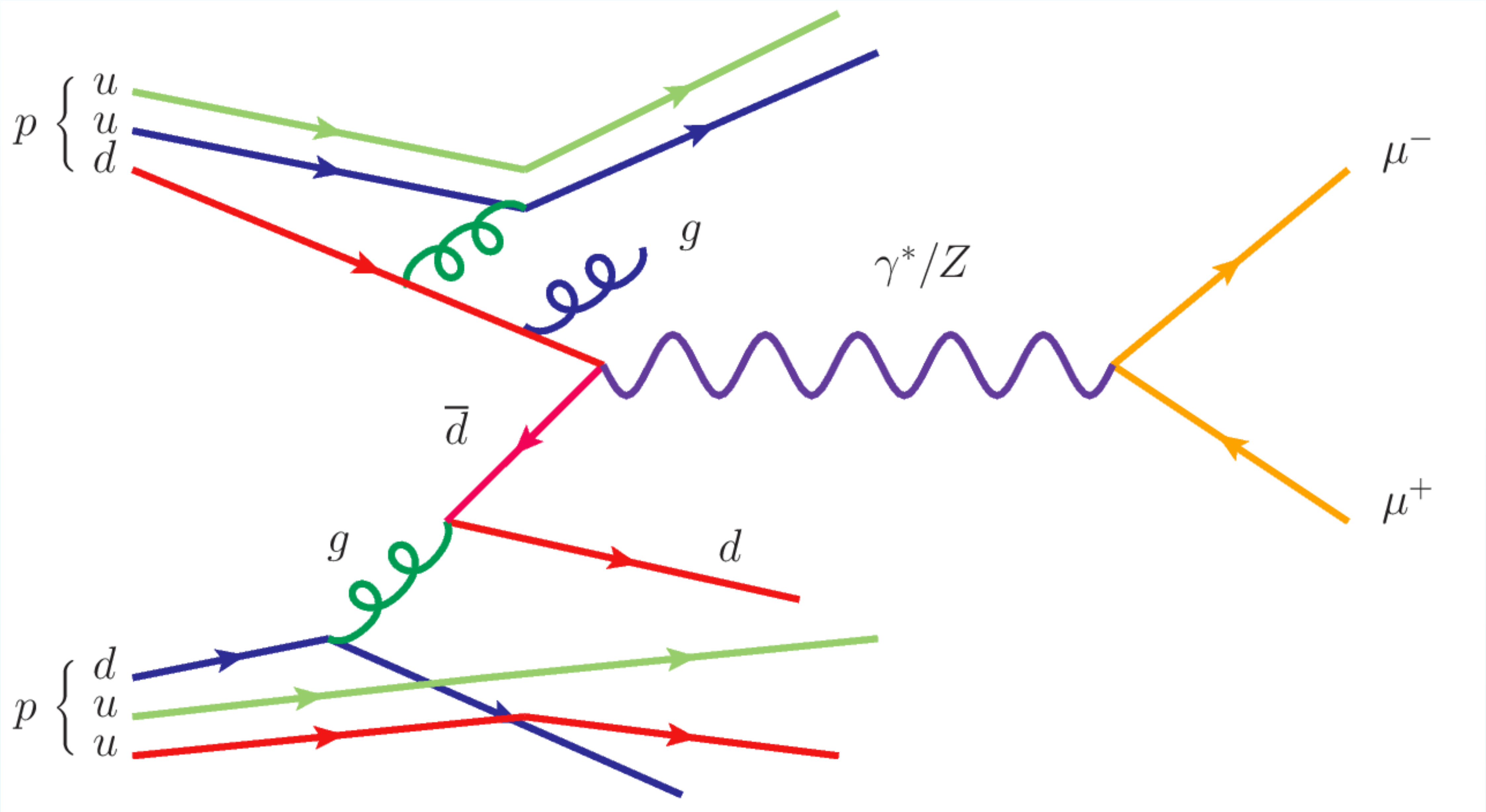




Cross-sections in lepton colliders can be computed in perturbation theory using the **Feynman rules of the Standard Model Lagrangian**

Lepton vs Hadron Colliders

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



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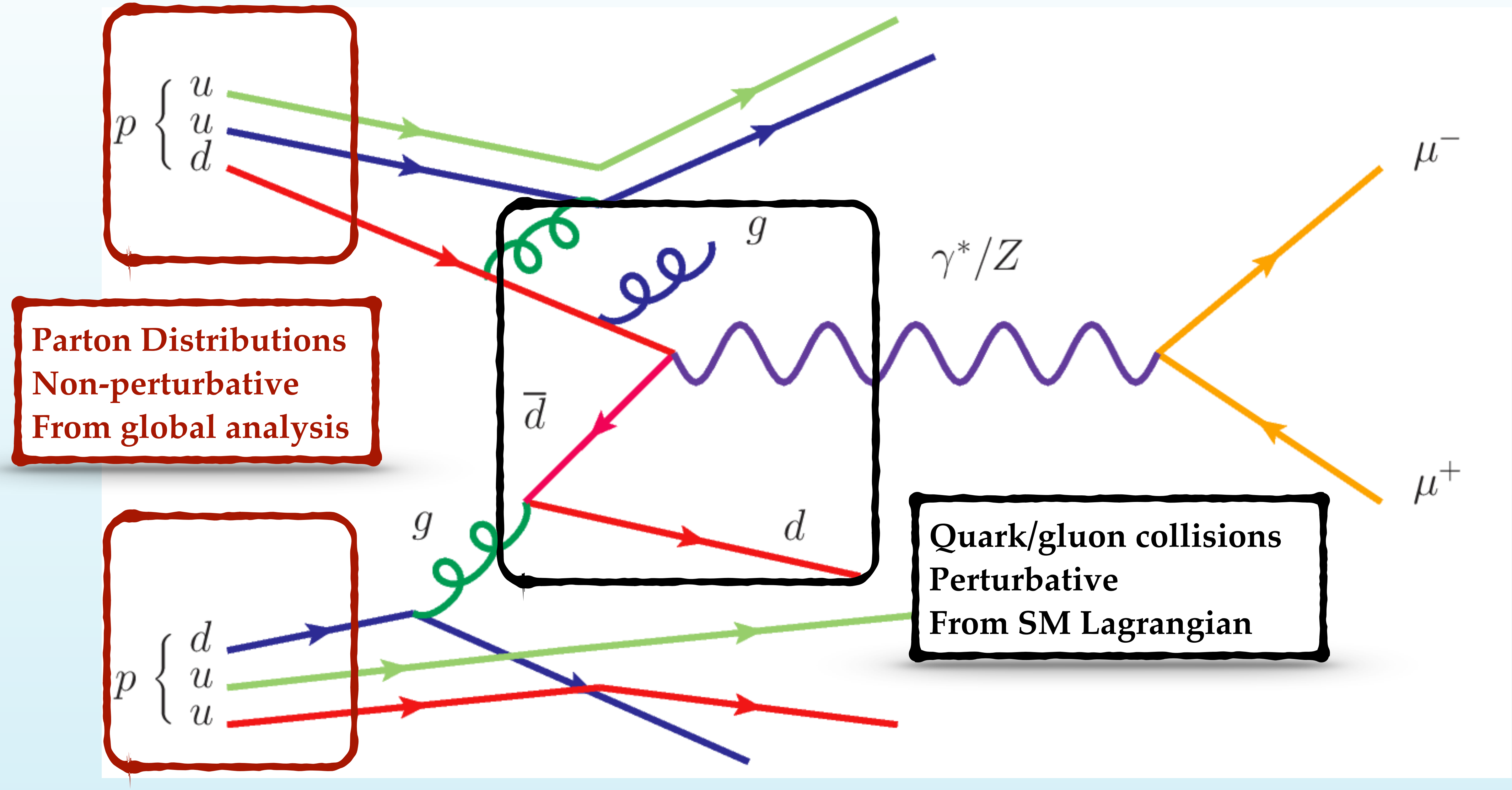

Parton Distributions
Non-perturbative
From global analysis

Quark/gluon collisions
Perturbative
From SM Lagrangian

Calculations of c**ross-sections** in hadron collisions require the combination of **perturbative, quark/gluon-initiated processes**, and **non-perturbative, parton distributions**, information

Parton Distributions

The distribution of energy that **quarks and gluons carry inside the proton** is quantified by the **Parton Distribution Functions (PDFs)**

$$g(x, Q)$$

Q: **Energy of the quark/gluon collision**
Inverse of the resolution length

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 the proton's momentum**

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- **Energy conservation** $$\int_0^1 dx\,\mathbf{x}\left(g(x,Q)+\sum_q q(x,Q)\right)=1$$

- **Dependence with quark/gluon collision energy Q** determined in perturbation theory

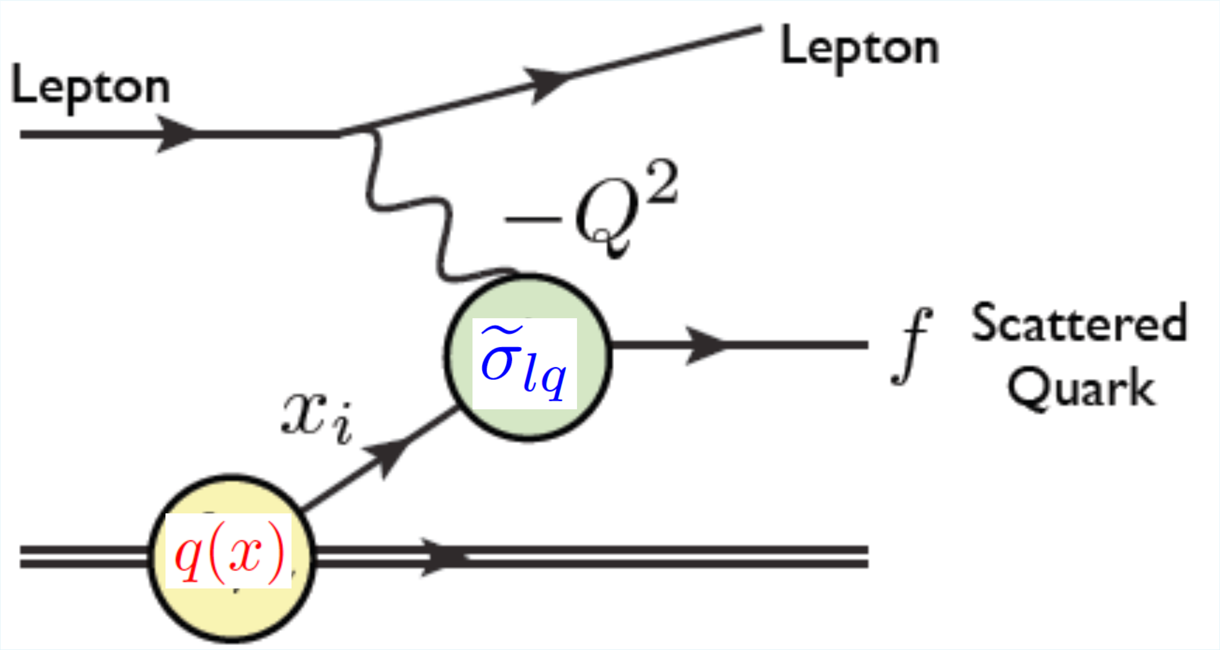
$$\frac{\partial g(x,Q)}{\partial \ln Q} = P_g\left(\alpha_s\right)\otimes g(x,Q) + P_q\left(\alpha_s\right)\otimes q(x,Q)$$

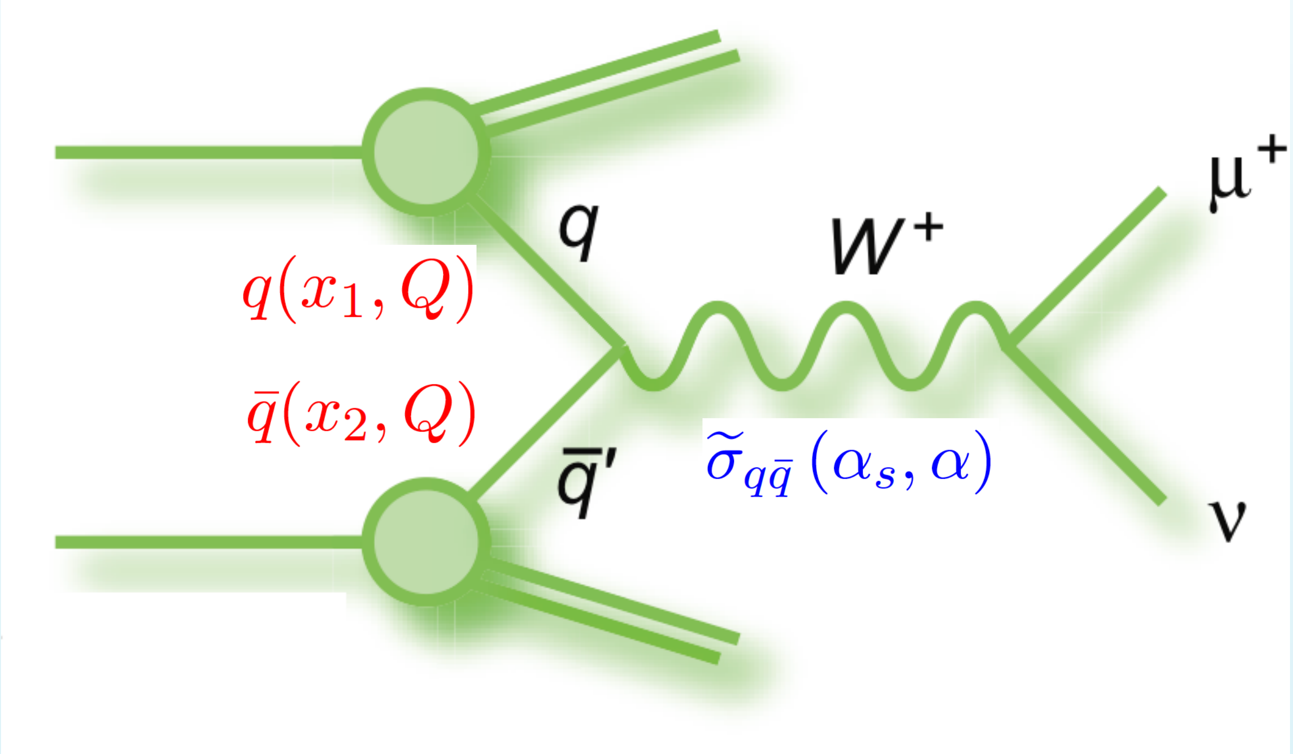
The QCD Factorization Theorem

The **QCD factorization theorem** guarantees **PDF universality: extract them from a subset of** process and use them to provide pure predictions for new processes

$$\sigma_{lp} \simeq \widetilde{\sigma}_{lq}\left(\alpha_s, \alpha\right) \otimes q(x, Q)$$

$$\sigma_{pp} \simeq \widetilde{\sigma}_{q\bar{q}}\left(\alpha_s, \alpha\right) \otimes q(x_1, Q) \otimes \bar{q}(x_2, Q)$$





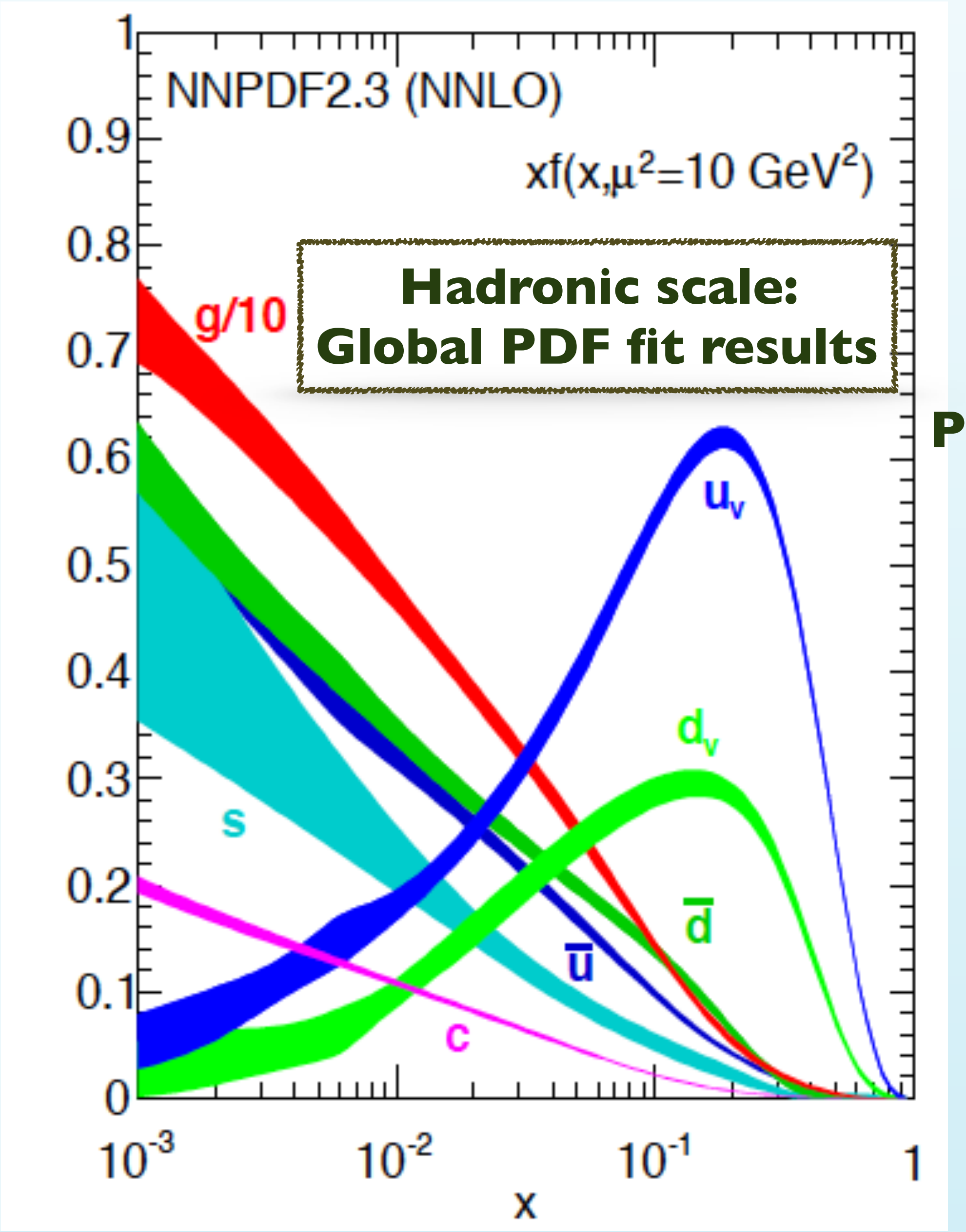
Determine PDFs in lepton-proton collisions ….

→

And use them to compute cross-sections in proton-proton collisions at the LHC

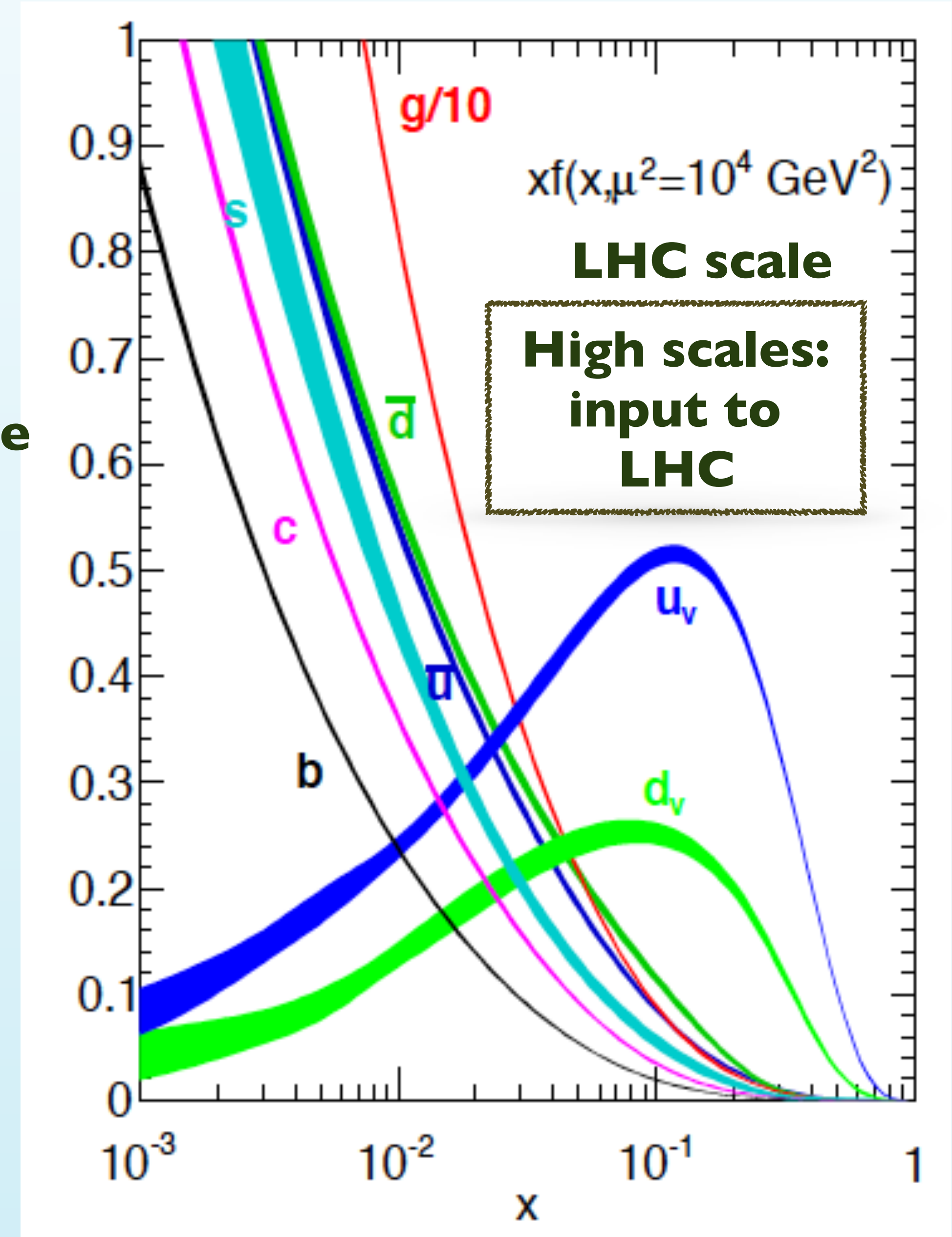
The global PDF analysis

- Combine **state-of-the-art theory calculations,** the **constraints from PDF-sensitive measurements** from different processes and colliders, and a **statistically robust fitting methodology**
- **Extract Parton Distributions** at hadronic scales of **a few GeV,** where non-perturbative QCD sets in
- Use **perturbative evolution** to compute PDFs at high scales as **input to LHC predictions**



Hadronic scale: Global PDF fit results

Perturbative Evolution



LHC scale

High scales: input to LHC

Why better PDFs?

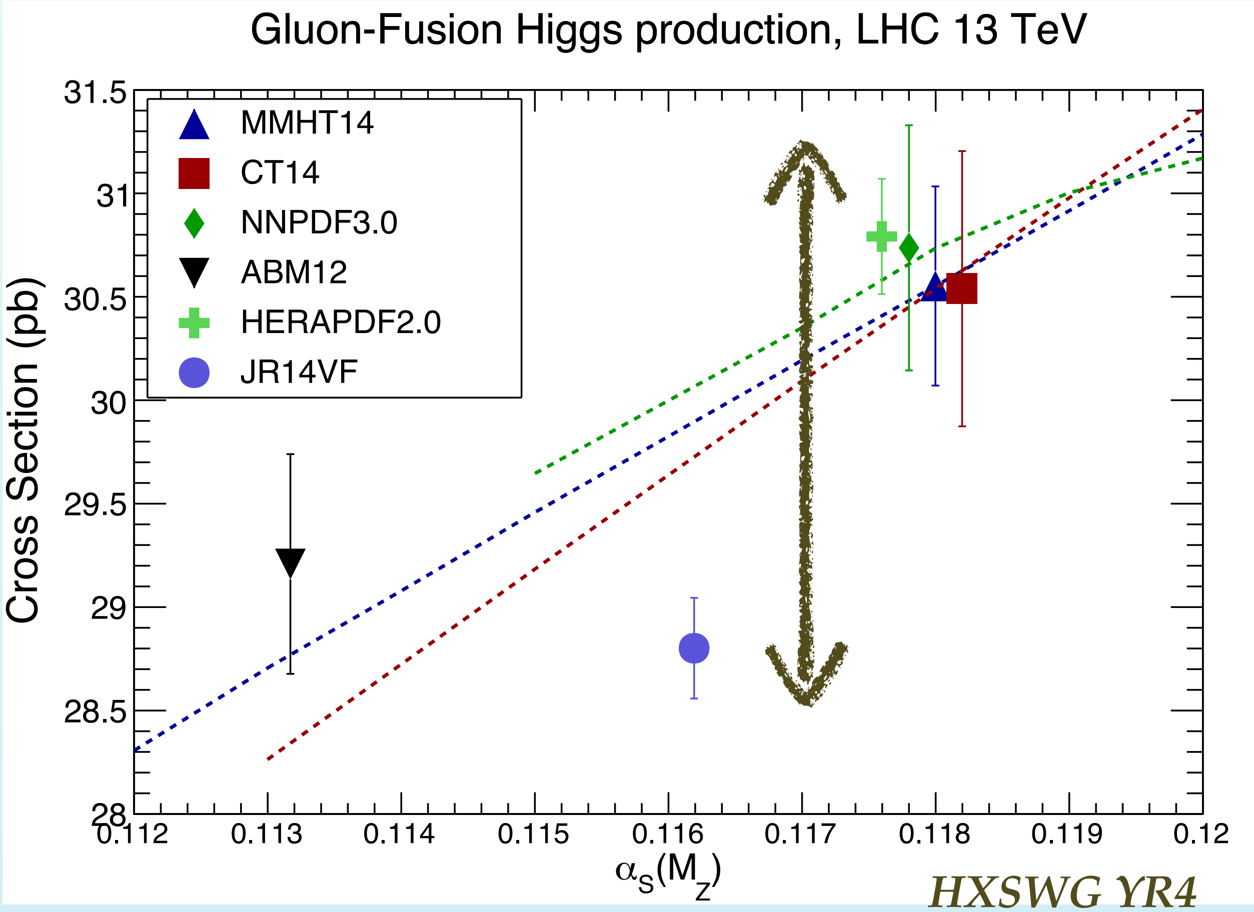
Dominant TH unc for M_W measurements at LHC

ATLAS 2017

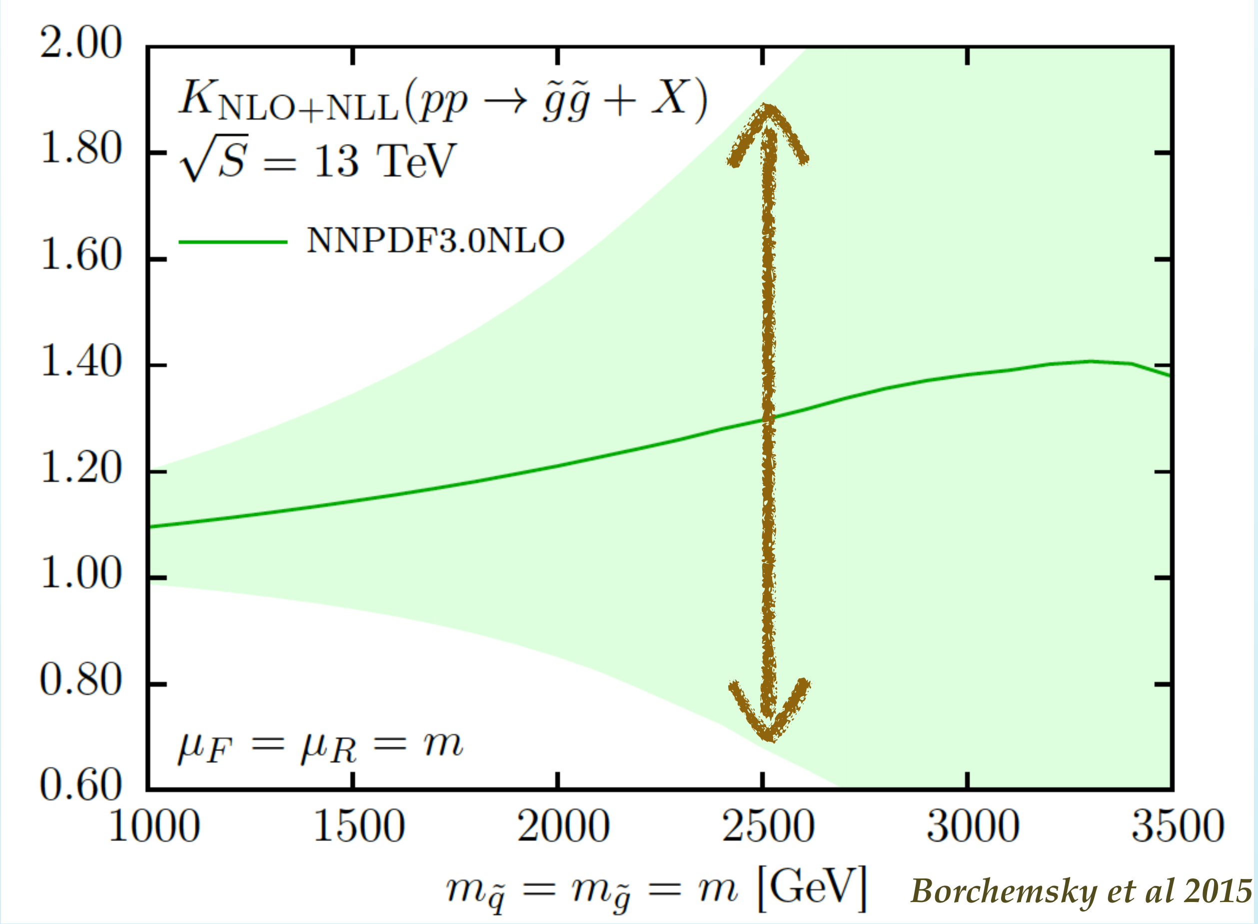
Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

Higgs coupling measurements

High-mass BSM cross-sections



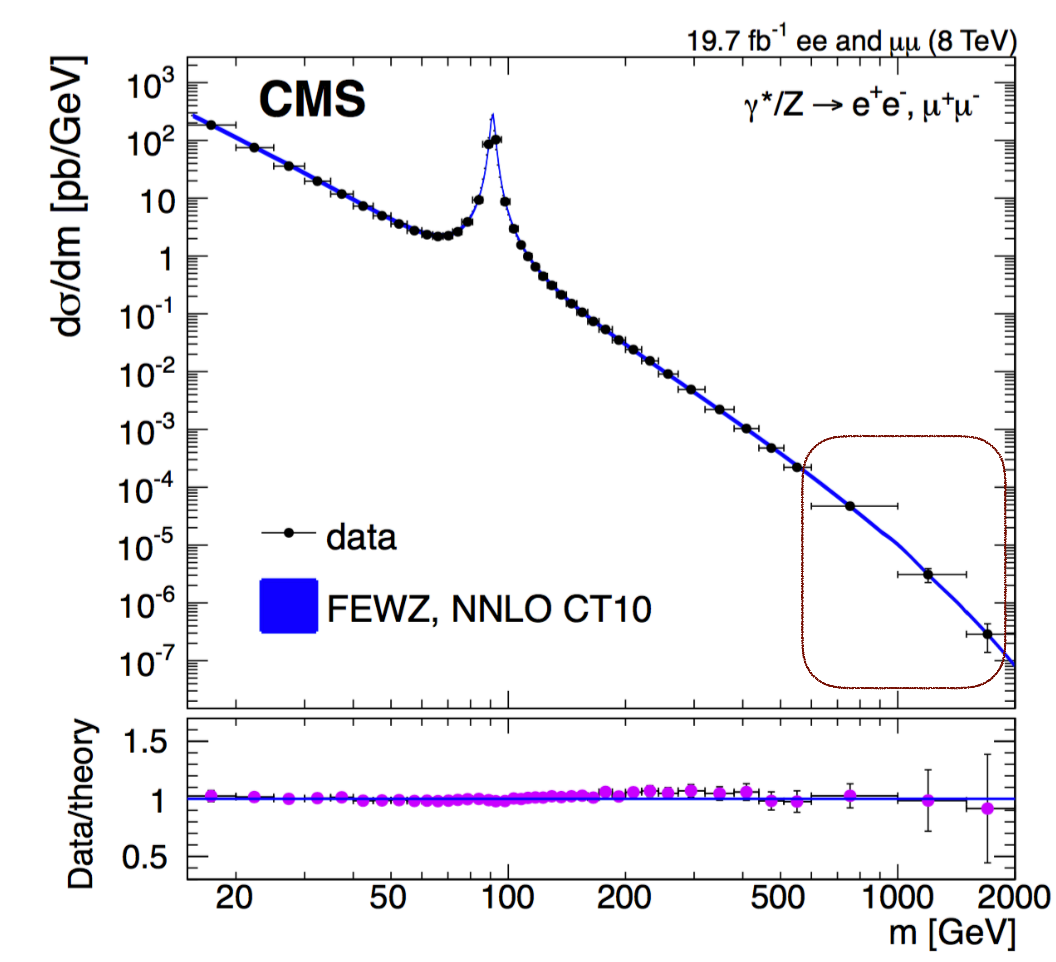
HXSWG YR4



Borchemsky et al 2015

Why better PDFs?

- BSM physics could manifest as **subtle deviations** wrt to the Standard Model predictions
- Even for high-mass resonances, **PDF uncertainties degrade or limit many BSM searches**
- The robustness of **global stress-tests of the SM** (electroweak fit, SM Effective Field Theory analysis) relies crucially in high-precision theoretical calculations



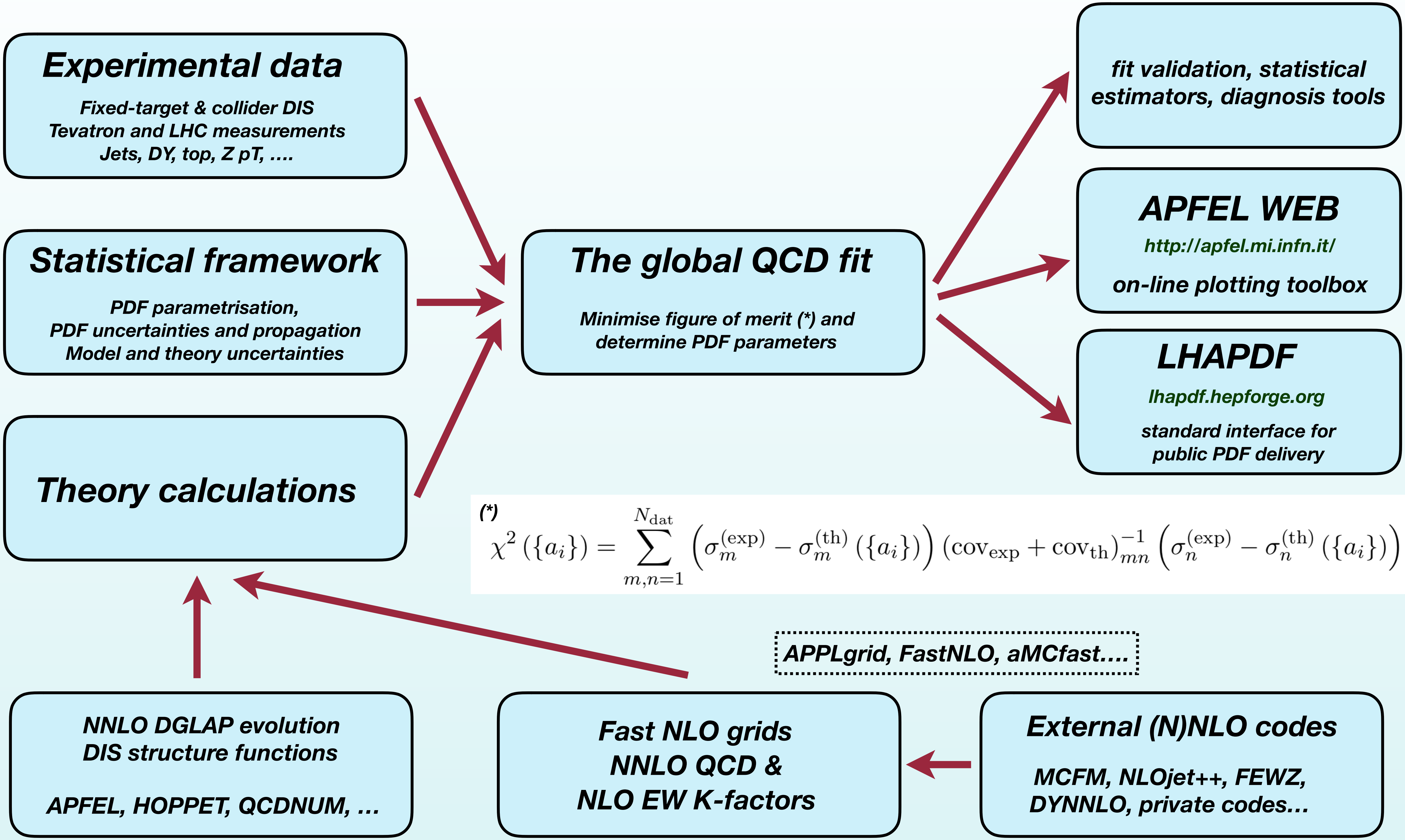
SMEFT expansion

$$\sigma(E) = \sigma_{SM}(E)\left(1 + \epsilon\frac{m_{SM}^2}{m_W^2} + \boxed{\epsilon\frac{E^2}{m_W^2}} + \dots\right)$$

For $\mathbf{E} \simeq \mathbf{1}$ **TeV**, a measurement with $\delta\sigma/\sigma \simeq \mathbf{10\%}$ is sensitive to $\epsilon \simeq \mathcal{O}(\mathbf{0.1\%})$!

BSM physics might very well hiding itself in the tails of LHC distributions, but need to make sure first that PDF uncertainties are under control

The global QCD fit machinery



Experimental data

Fixed-target & collider DIS
Tevatron and LHC measurements
Jets, DY, top, Z pT, ….

Statistical framework

PDF parametrisation,
PDF uncertainties and propagation
Model and theory uncertainties

Theory calculations

The global QCD fit

Minimise figure of merit (*) and determine PDF parameters

fit validation, statistical estimators, diagnosis tools

APFEL WEB

http://apfel.mi.infn.it/

on-line plotting toolbox

LHAPDF

lhapdf.hepforge.org

standard interface for public PDF delivery

(*)

$$\chi^2\left(\{a_i\}\right) = \sum_{m,n=1}^{N_{\rm dat}} \left(\sigma_m^{(\rm exp)} - \sigma_m^{(\rm th)}\left(\{a_i\}\right)\right)\left(\mathrm{cov}_{\rm exp} + \mathrm{cov}_{\rm th}\right)^{-1}_{mn}\left(\sigma_n^{(\rm exp)} - \sigma_n^{(\rm th)}\left(\{a_i\}\right)\right)$$

APPLgrid, FastNLO, aMCfast….

NNLO DGLAP evolution
DIS structure functions

APFEL, HOPPET, QCDNUM, …

Fast NLO grids
NNLO QCD &
NLO EW K-factors

External (N)NLO codes

MCFM, NLOjet++, FEWZ,
DYNNLO, private codes…

The NNPDF approach

A **novel approach to PDF determination**, improving the limitations of the traditional PDF fitting methods with the use of **advanced statistical techniques** such as **machine learning** and **multivariate analysis**

Non-perturbative PDF parametrization

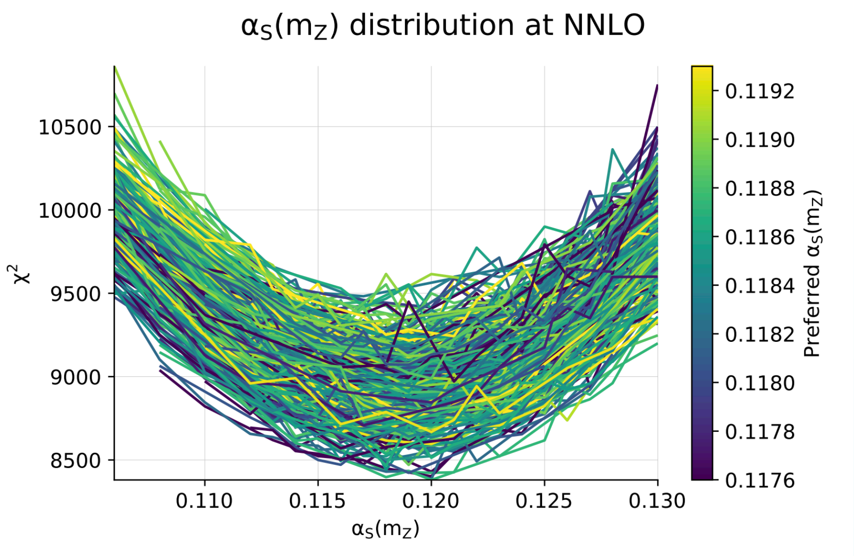
- **Traditional approach**: based on **restrictive functional forms** leading to strong theoretical bias
- **NNPDF solution**: use **Artificial Neural Networks** as universal unbiased interpolants

PDF uncertainties and propagation to LHC calculations

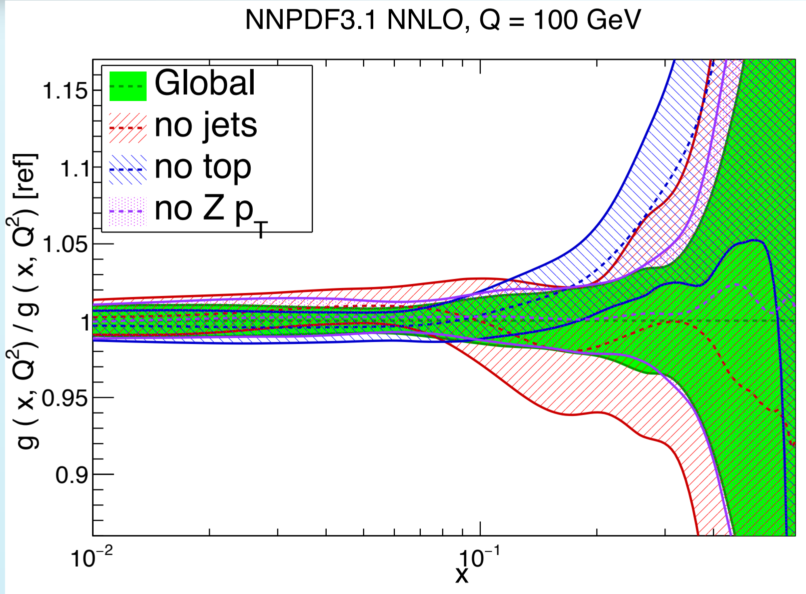
- **Traditional approach**: limited to Gaussian/linear approximation
- **NNPDF solution**: based on the **Monte Carlo replica method** to create a probability distribution in the space of PDFs. Specially critical in **extrapolation regions** (**i.e.** high-*x*) for New Physics searches

Fitting technique

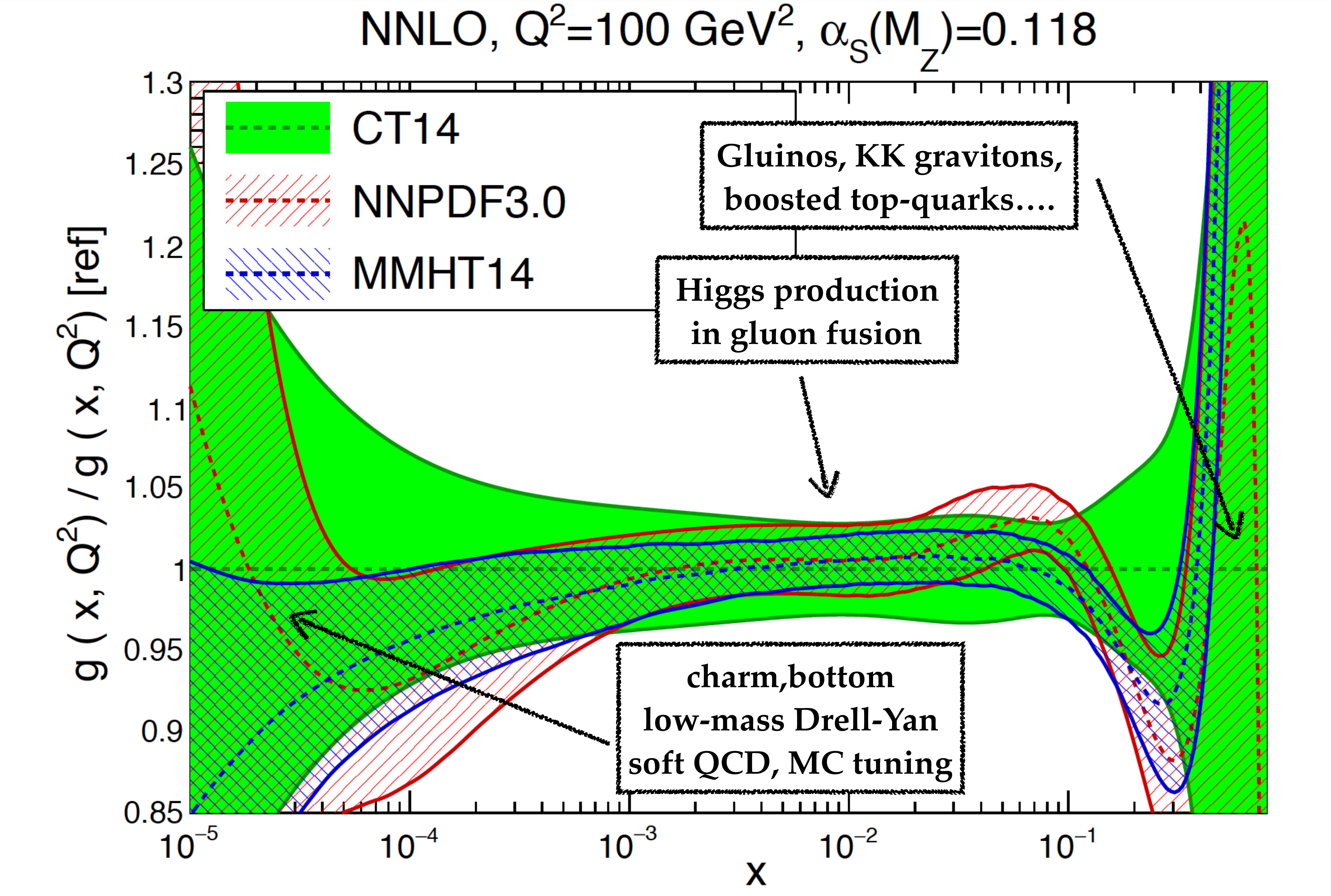
- **Traditional approach**: deterministic minimization of χ^2**, flat directions** problem
- **NNPDF solution**: **Genetic Algorithms** to explore efficiently the vast parameter space, with **cross-validation** to avoid fitting stat fluctuations



The structure of the proton and LHC phenomenology



One glue to bind them all



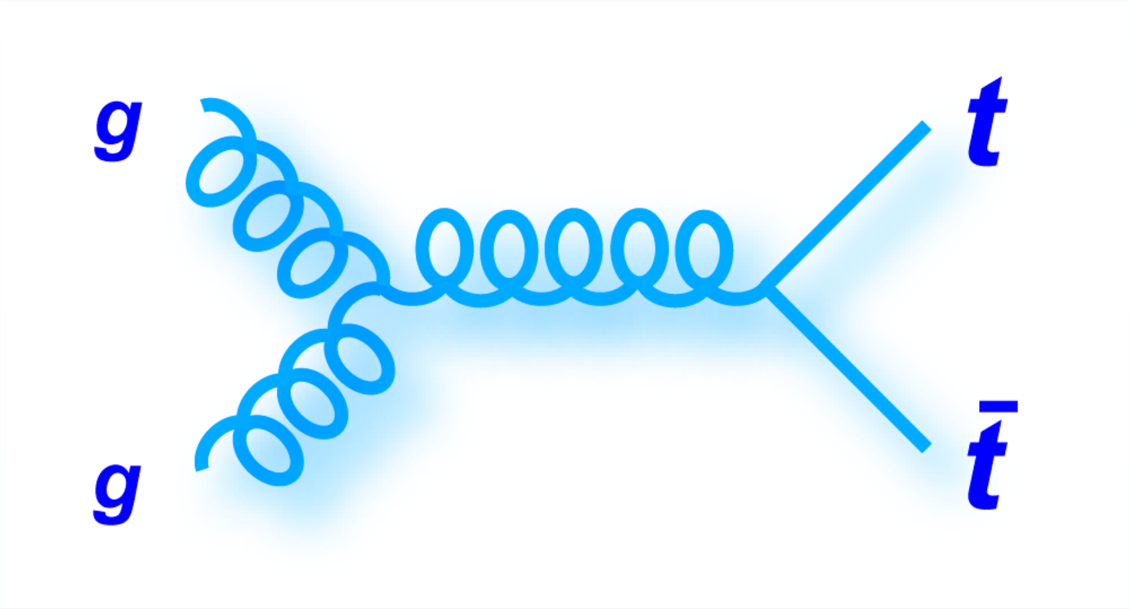
Gluinos, KK gravitons, boosted top-quarks….

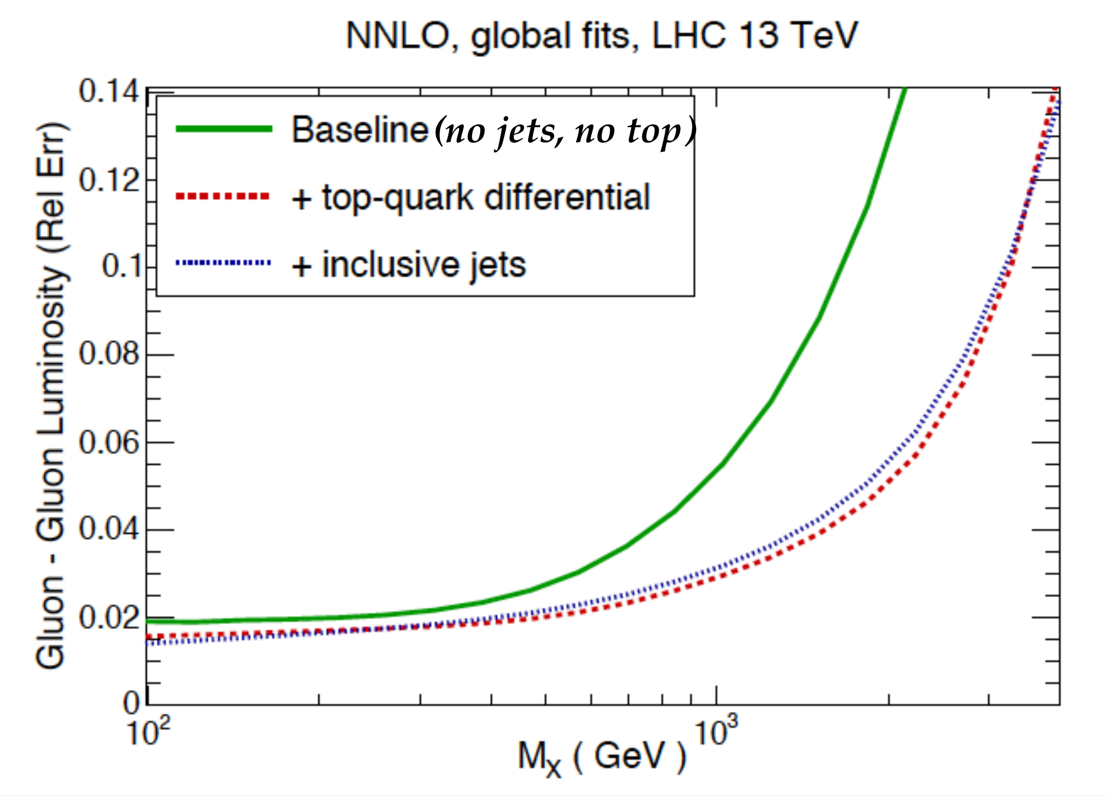
Higgs production in gluon fusion

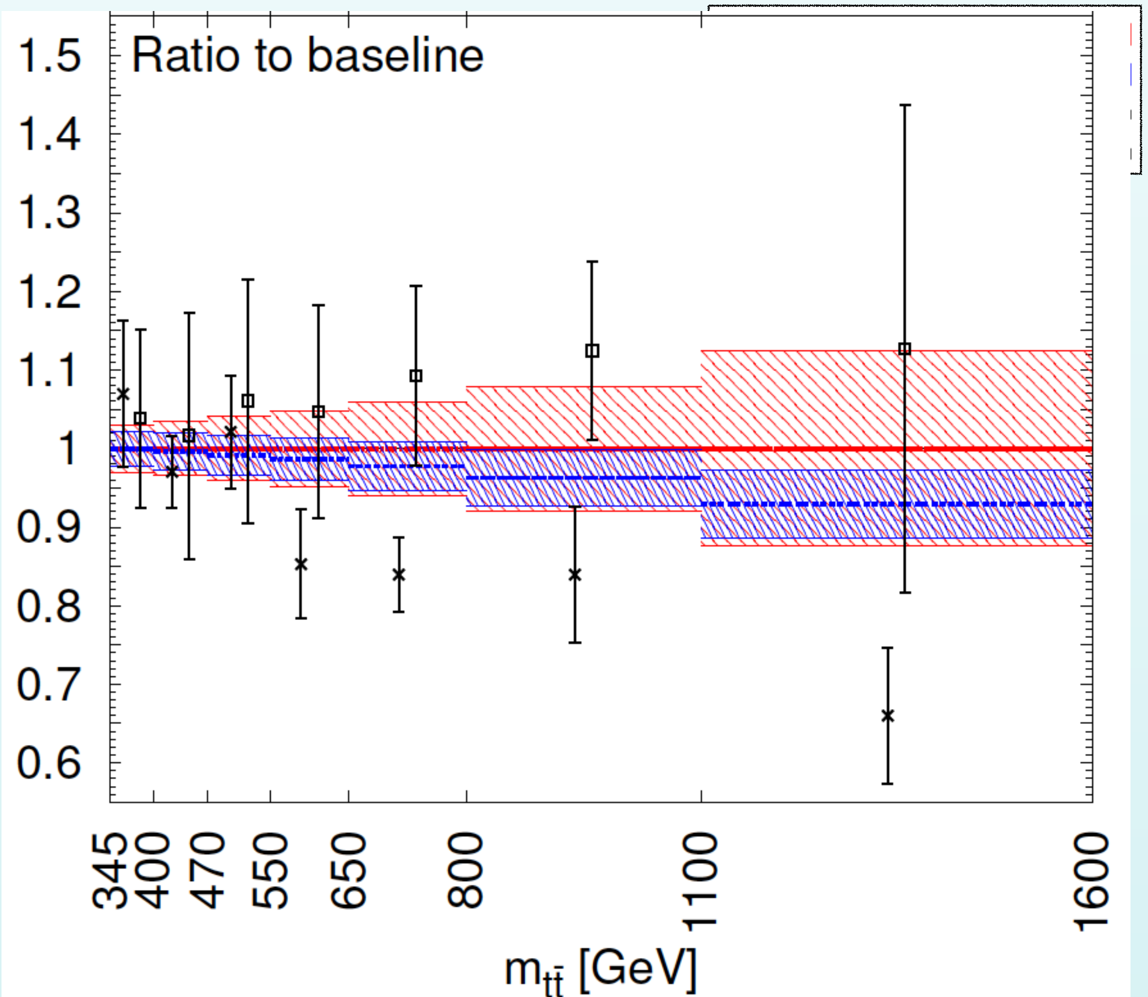
charm,bottom
low-mass Drell-Yan
soft QCD, MC tuning

At the LHC, precise knowledge of the gluon is required **from small-x to large-x**

The large-x gluon from differential top quarks







- Top-quark production driven by **gluon-gluon scattering**

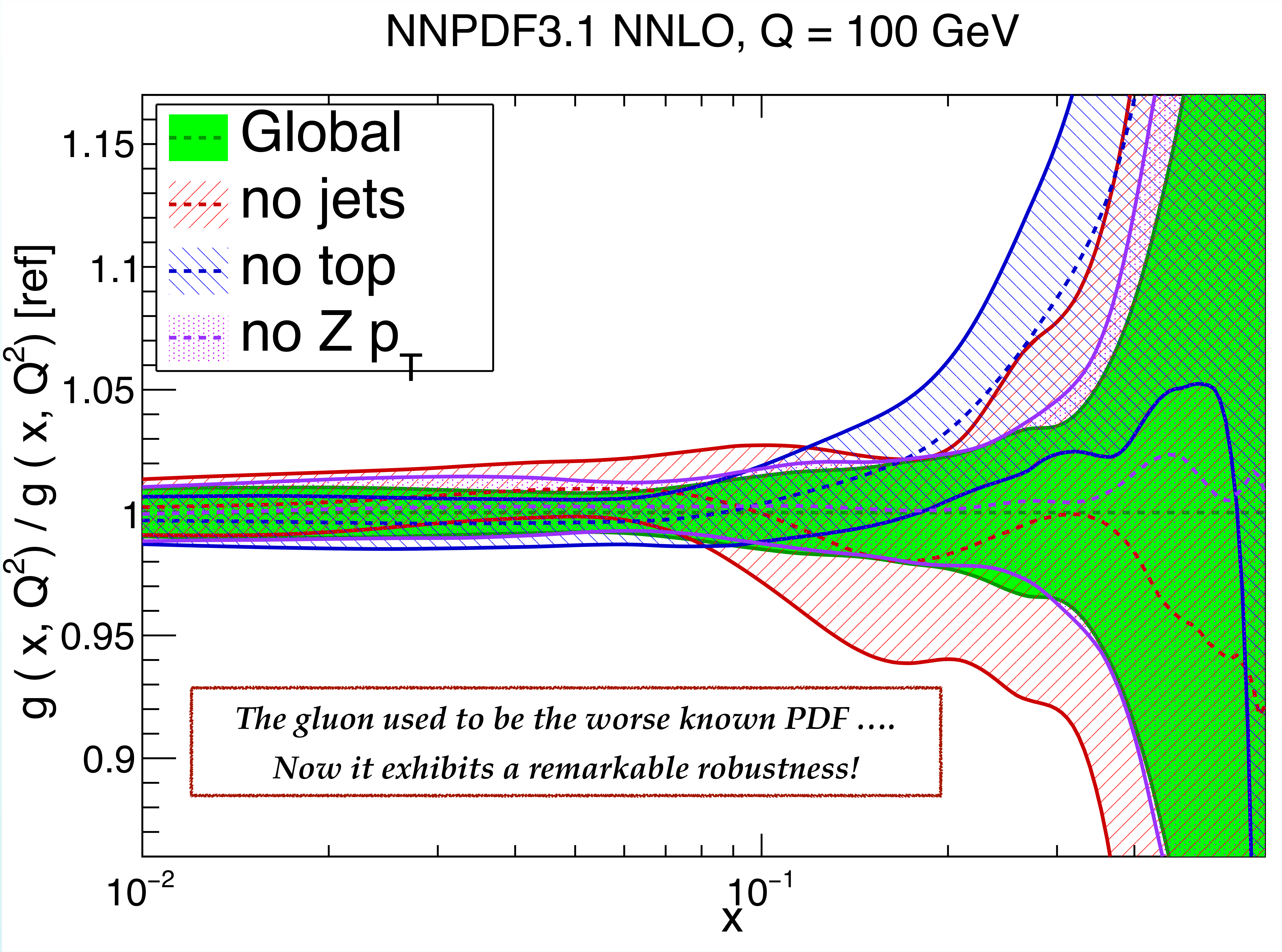
- **NNLO calculations for stable top quarks** available *Czakon, Mitov et al 2015-2017*

- **Data from ATLAS and CMS at 8 TeV** available with breakdown of systematic uncertainties

- Included **differential top data into NNPDF3.0**: constraints on the **large-*x* gluon** comparable to those of inclusive jet production *Czakon et al 2017*

- Improved theory uncertainties in **regions crucial for BSM searches**, *i.e.*, $\mathbf{m_{tt} > 1}$ **TeV** (while fitting only $\mathbf{y_t}$ and $\mathbf{y_{tt}}$)

One (upgraded) glue to bind them all



The gluon used to be the worse known PDF ….

Now it exhibits a remarkable robustness!

Direct photon production and PDF fits

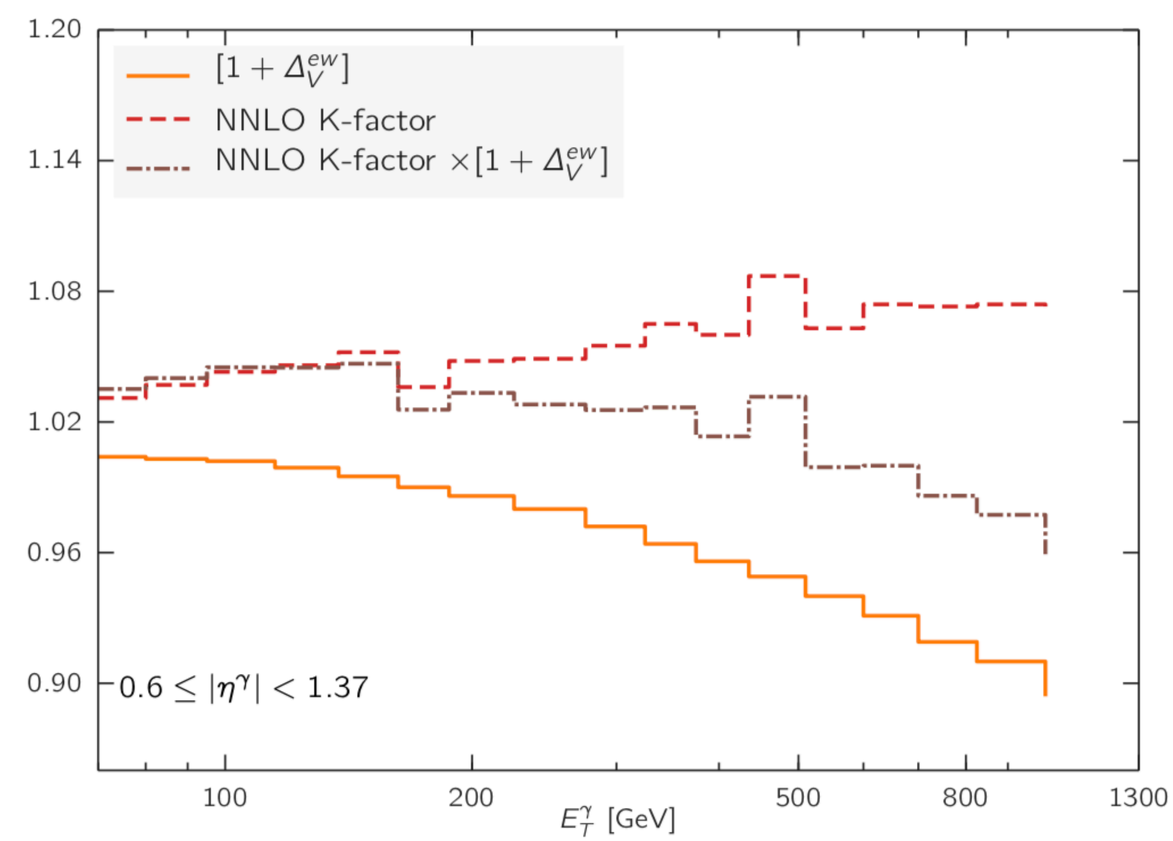
- Recently we have revisited the impact of LHC photon data into the global PDF fit, specifically the ATLAS 8 TeV data

Campbell, Rojo, Slade, Williams 18

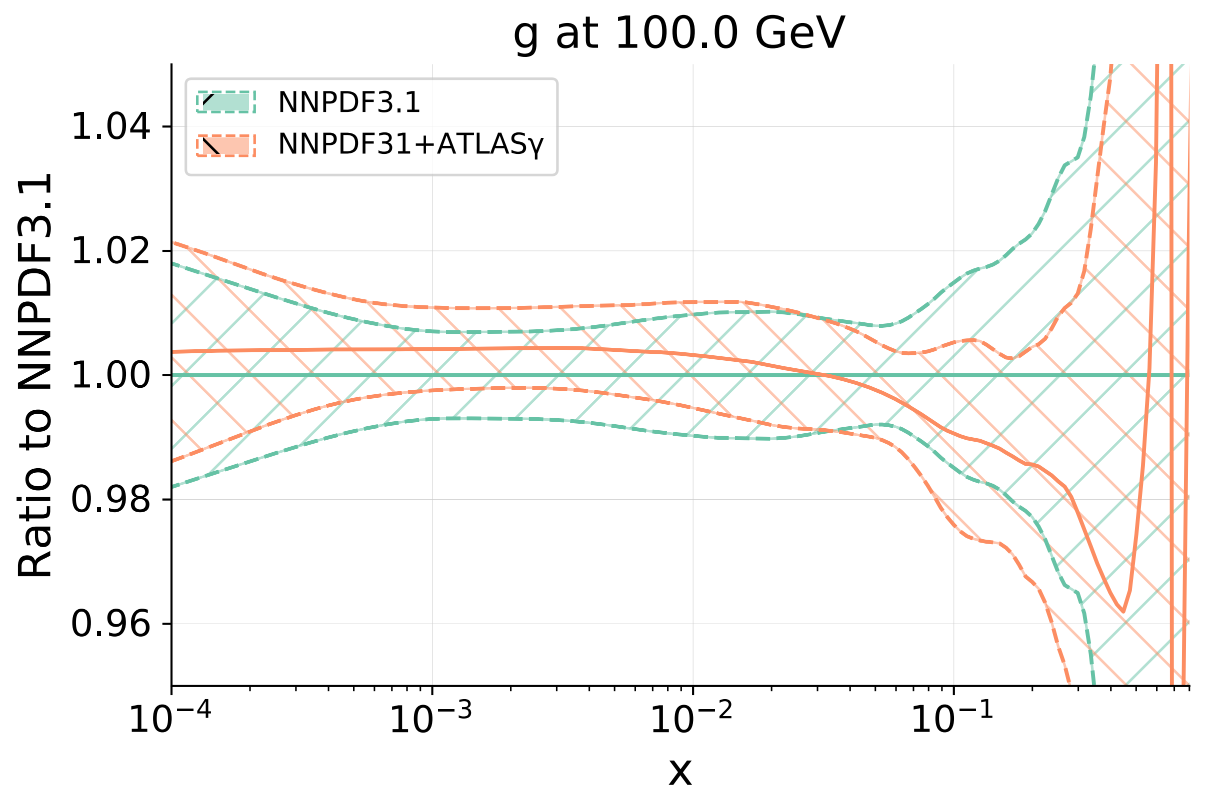
- Theory based on **NNLO QCD** and **LL electroweak** calculations

- Moderate impact on the medium-x gluon, consistent with previous studies at NLO

- Good consistency with the rest of gluon-sensitive experiments in NNPDF3.1



	NNPDF3.1	NNPDF3.1+ATLASγ
Fixed-target lepton DIS	1.207	1.203
Fixed-target neutrino DIS	1.081	1.087
HERA	1.166	1.169
Fixed-target Drell-Yan	1.241	1.242
Collider Drell-Yan	1.356	1.346
Top-quark pair production	1.065	1.049
Inclusive jets	0.939	0.915
Z p_T	0.997	0.980
Total dataset	**1.148**	**1.146**

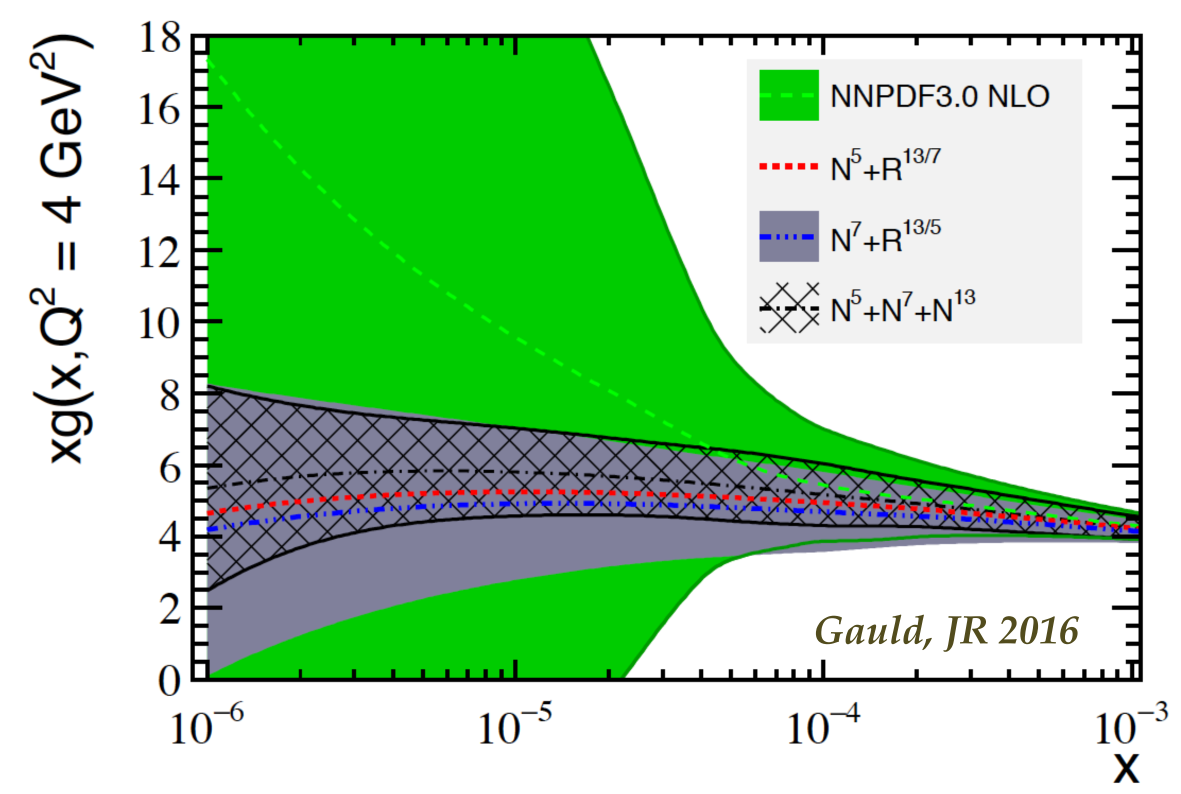


The small-x gluon from forward charm production

- **D and B meson production from LHCb** allow accessing the **gluon down to x=10^{-6}**, well below the HERA coverage

PROSA 2015, Gauld et al 2015

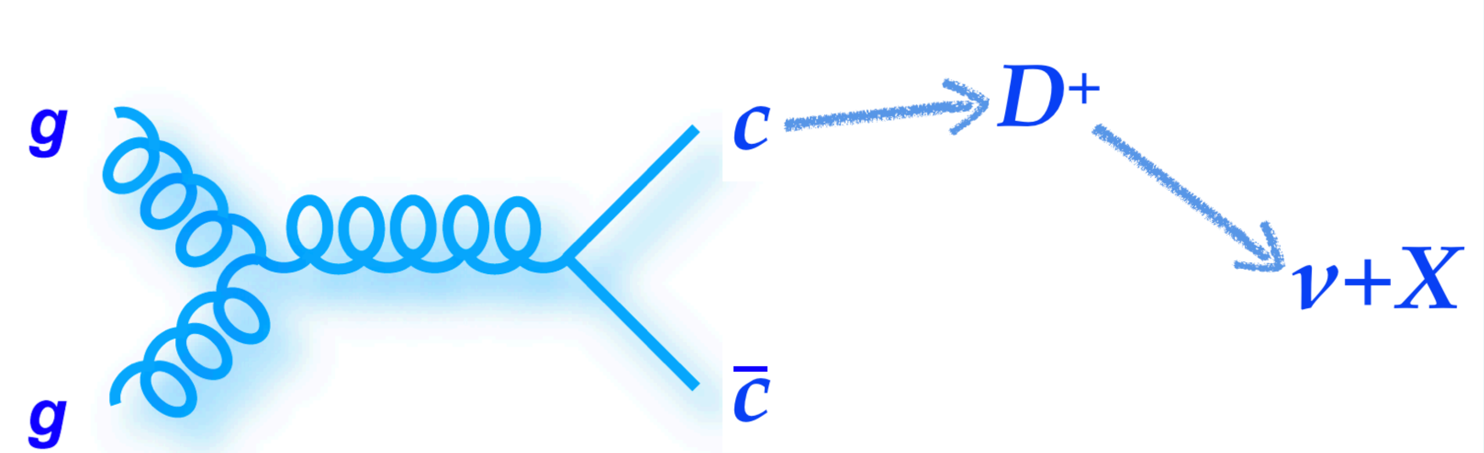
- Gluon PDF errors **reduced by up to a factor 10!**
- Allows robust estimate for the ***prompt neutrino flux***, the main background for astrophysical neutrinos at IceCube
- Precision calculation of the **UHE neutrino-nucleus cross-section**, with few-percent TH errors up to $E_\nu=10^{12}$ GeV

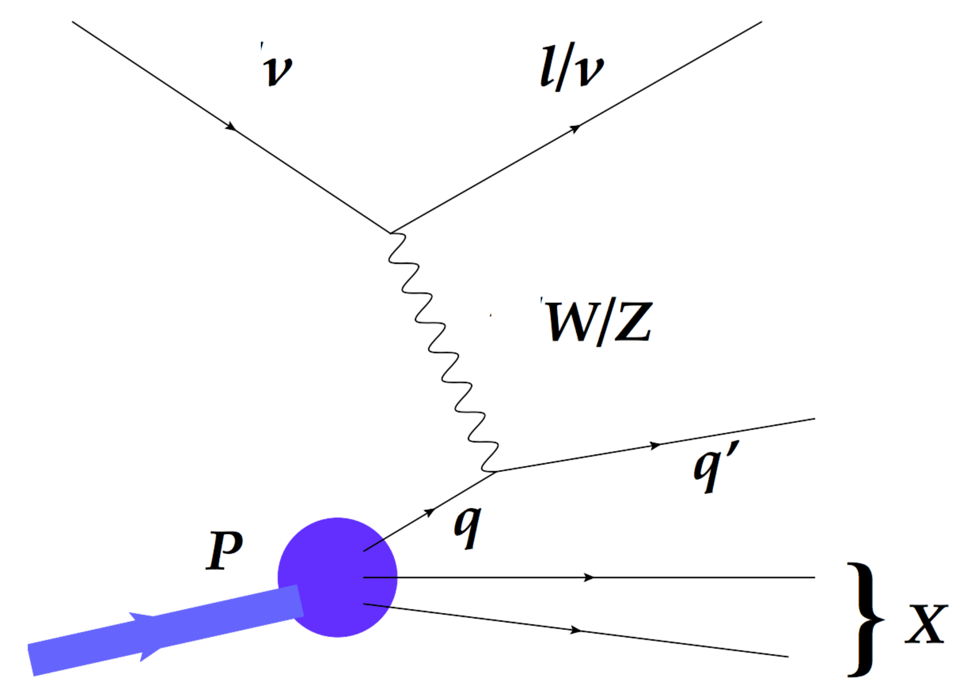


Gauld, JR 2016

Prompt neutrino flux at IceCube

UHE neutrino-nucleus xsecs





The small-x gluon from forward charm production

- **D and B meson production from LHCb** allow accessing the **gluon down to $x \simeq 10^{-6}$**, well below the HERA coverage

PROSA 2015, Gauld et al 2015

- Gluon PDF errors **reduced by up to a factor 10!**

- Allows robust estimate for the ***prompt neutrino flux***, the main background for astrophysical neutrinos at IceCube

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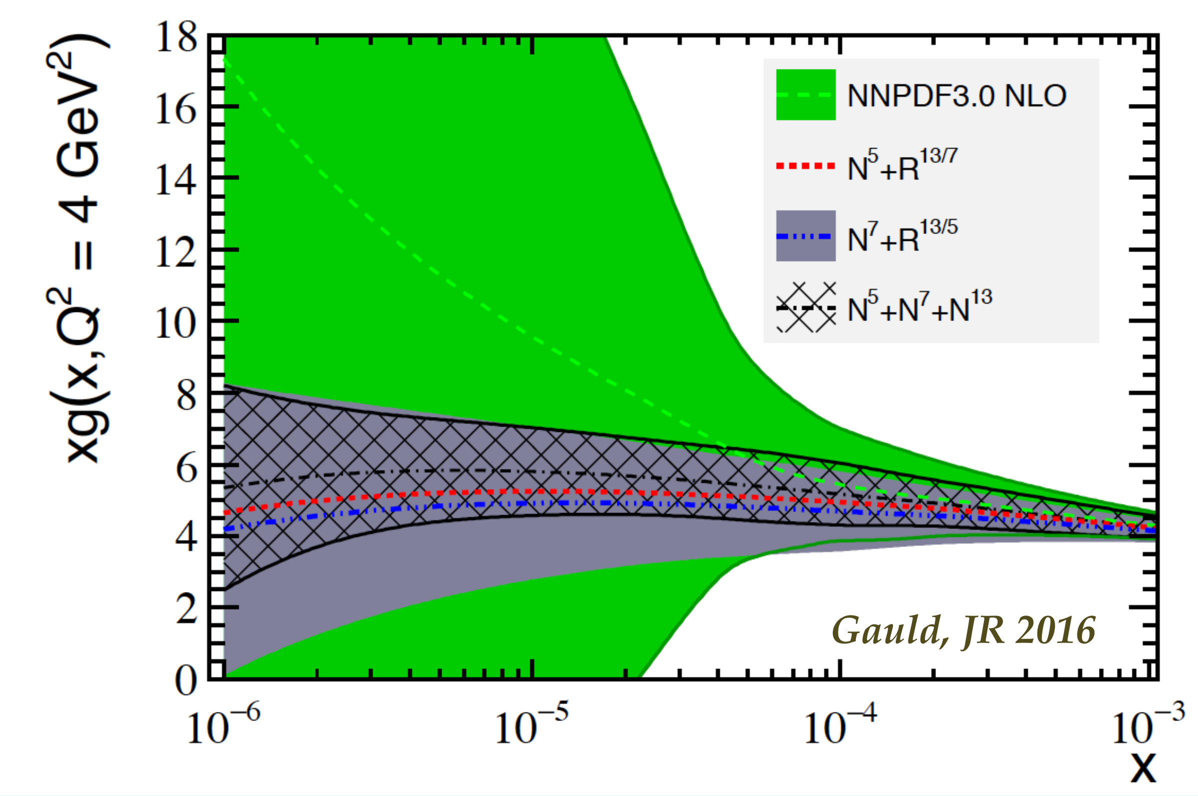
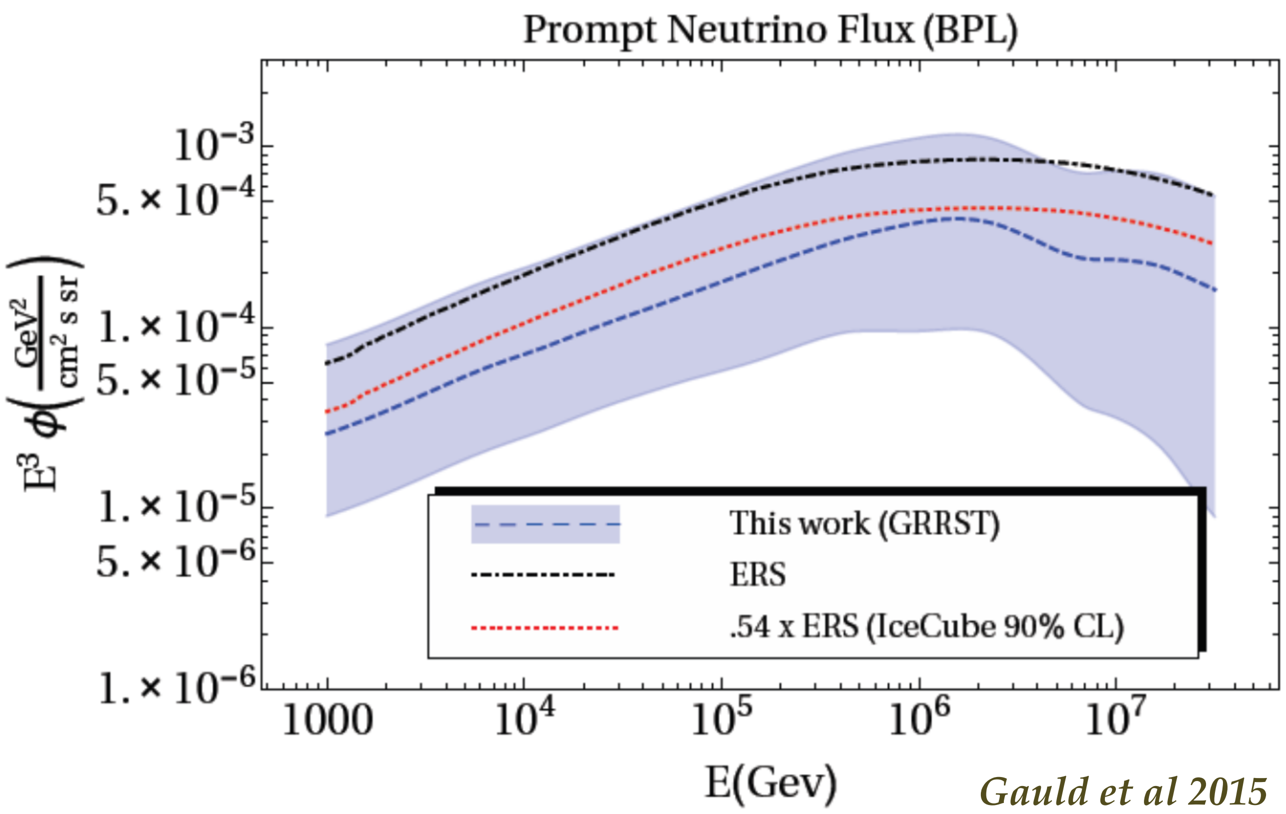


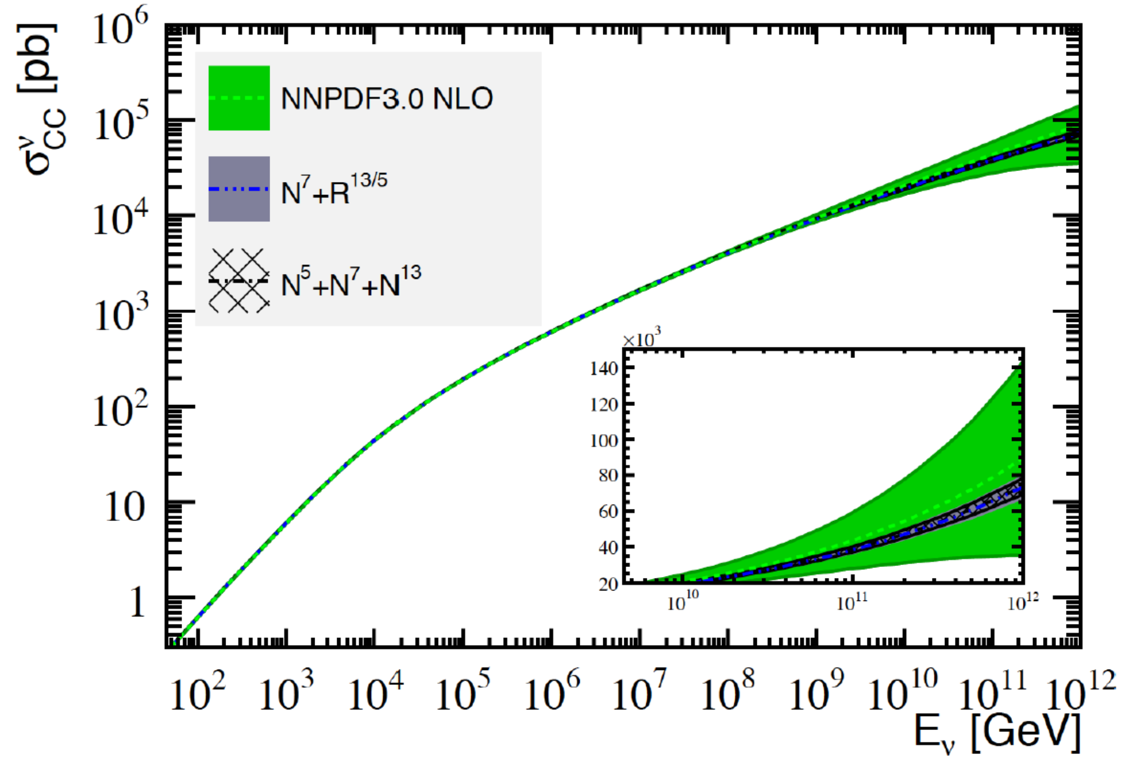
Gauld, JR 2016

Prompt neutrino flux at IceCube



Gauld et al 2015

UHE neutrino-nucleus xsecs

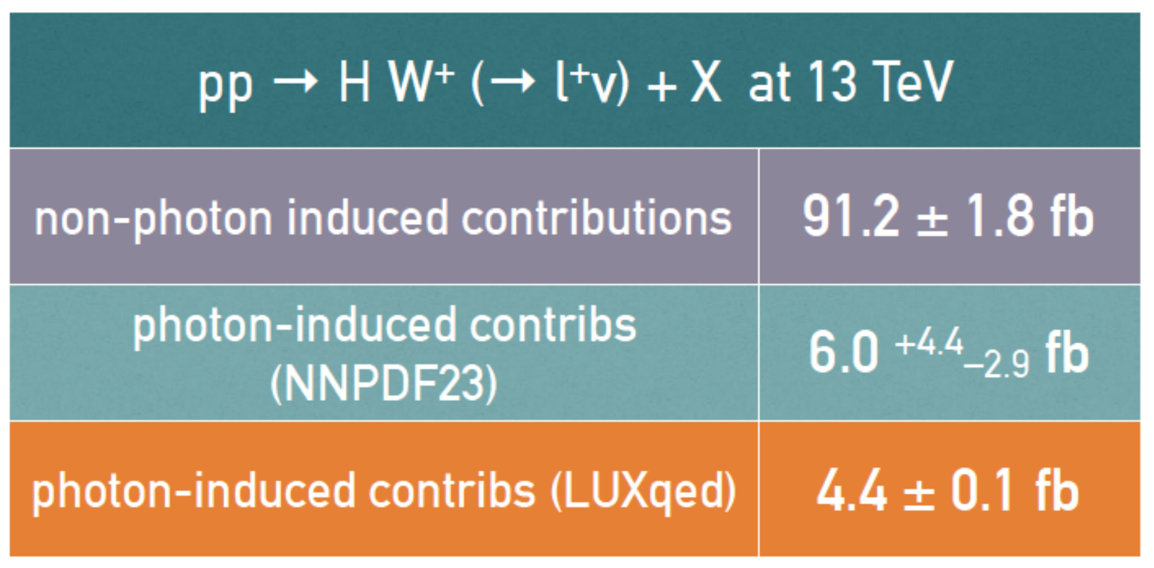


How bright is the proton?

- The calculation of **QED and electroweak corrections to hadron collider processes** requires by consistency to introduce the PDF of the photon in the proton, **$\gamma(x,Q)$**
- The first model-independent determination of **$\gamma(x,Q)$** from LHC *W,Z* data was **NNPDF2.3QED**, which however affected by **large uncertainties**, due to the limited experimental information
- Recently, **$\gamma(x,Q)$ computed** in terms of the well-known **inclusive structure functions F_2 and F_L**: the resulting photon PDF, exhibits now **few-percent uncertainties**

$$x\gamma(x,\mu) = \frac{1}{2\pi\alpha(\mu)} \int_x^1 \frac{dz}{z} \left\{ \int_{Q^2_{\rm min}}^{\mu^2/(1-z)} \frac{dQ^2}{Q^2} \alpha^2(Q^2) \left[- z^2 F_L(x/z,Q^2) \right.\right.$$

$$\left.\left. + \left(zP_{\gamma q}(z) + \frac{2x^2 m_p^2}{Q^2} \right) F_2(x/z,Q^2) \right] - \alpha^2(\mu) z^2 F_2(x/z,\mu^2) \right\} + \mathcal{O}\left(\alpha\alpha_s, \alpha^2\right)$$



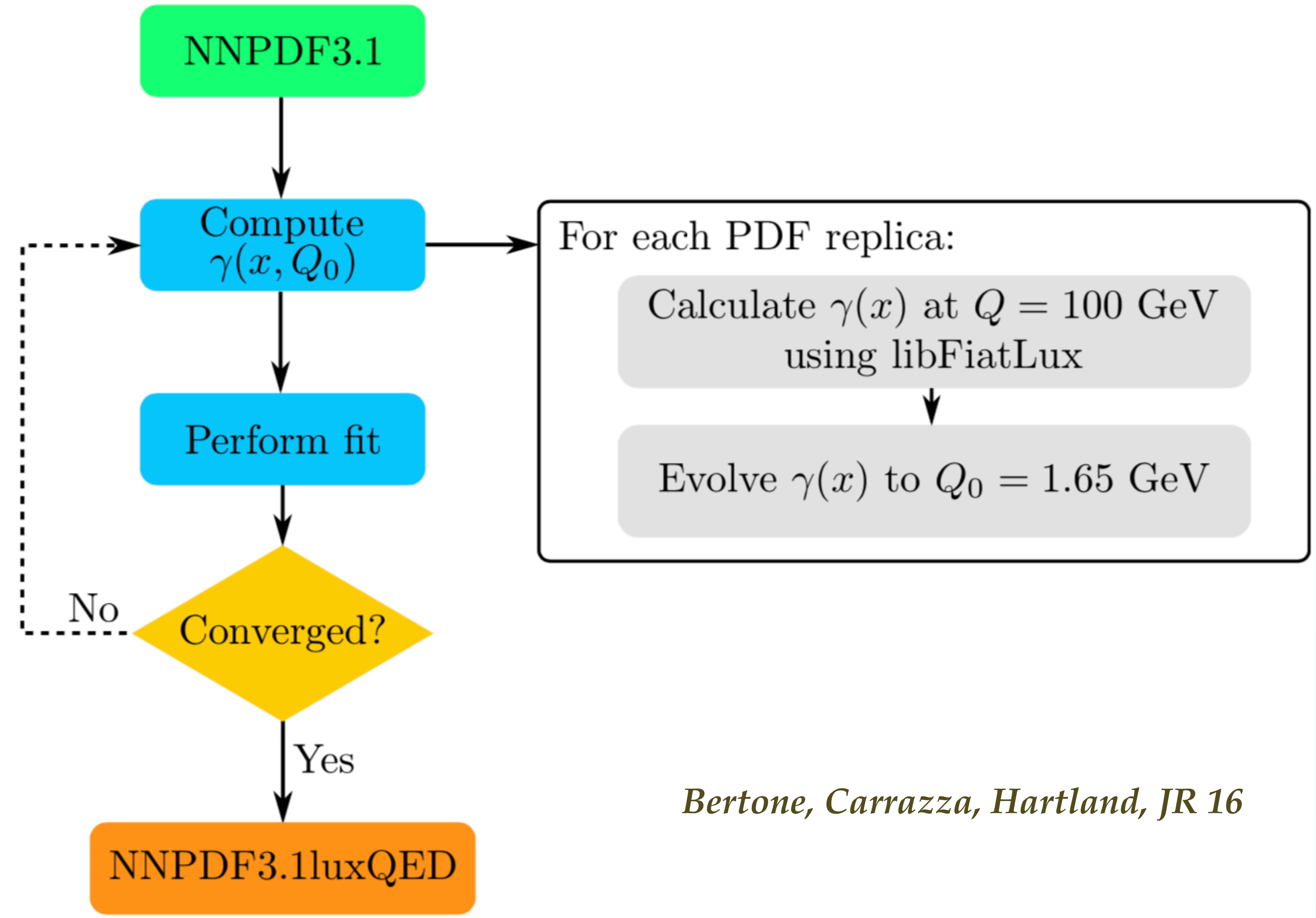
pp → H W+ (→ l+ν) + X at 13 TeV	
non-photon induced contributions	91.2 ± 1.8 fb
photon-induced contribs (NNPDF23)	6.0 $^{+4.4}_{-2.9}$ fb
photon-induced contribs (LUXqed)	4.4 ± 0.1 fb

Manohar, Nason, Salam, Zanderighi, 16-17

Crucial implications for LHC pheno: high-precision determination of photon-initiated (PI) contributions

Illuminating the photon content of the proton

- **NNPDF3.1luxQED**: variant of the NNPDF3.1 global analysis supplemented by
  - the LUXqed theoretical constraints,
  - NLO QED corrections to DGLAP evolution, and
  - NLO QED coefficients functions in DIS
- Iterative procedure: photon PDF recomputed at each iteration until convergence is achieved



NNPDF3.1

Compute $\gamma(x, Q_0)$

Perform fit

Converged?

No

Yes

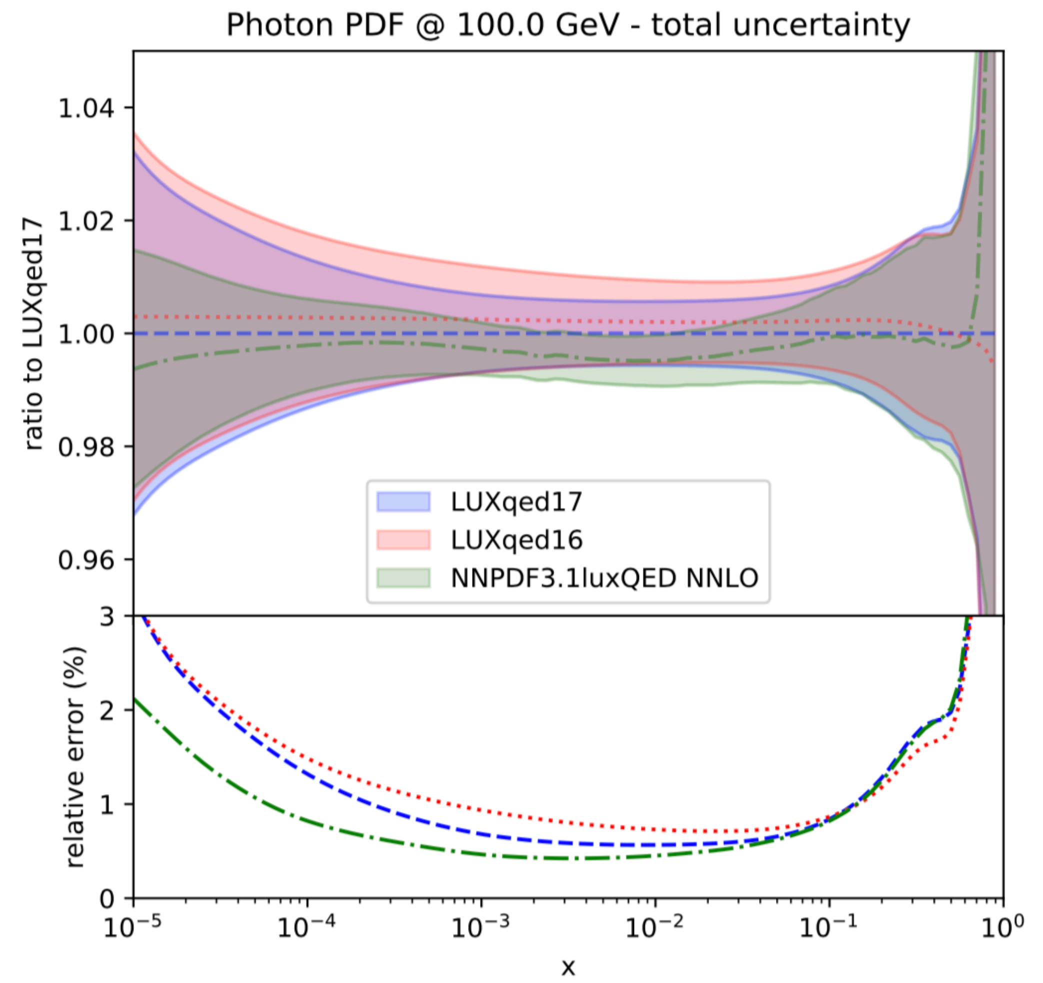
NNPDF3.1luxQED

For each PDF replica:

Calculate $\gamma(x)$ at $Q = 100$ GeV using libFiatLux

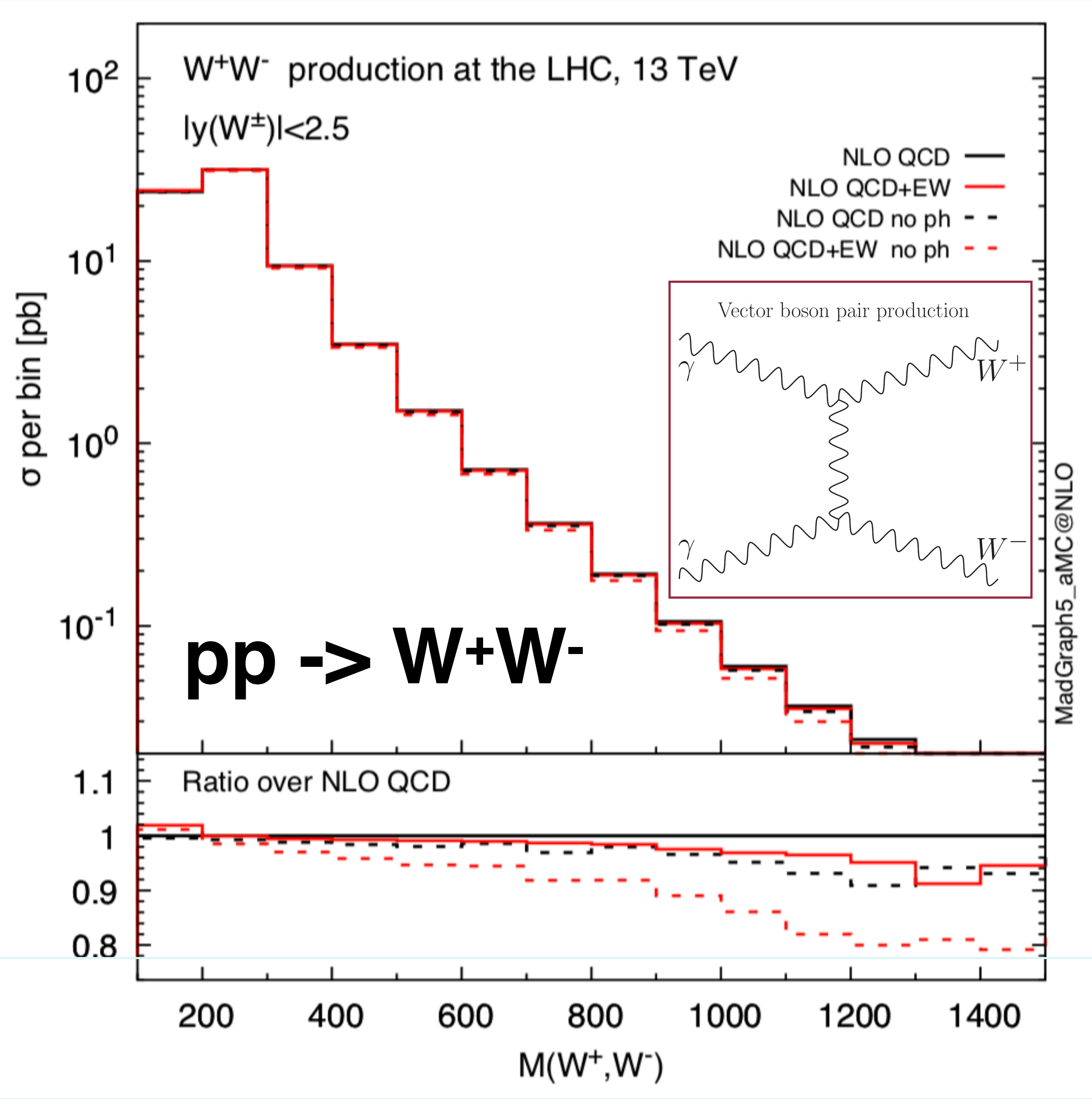
Evolve $\gamma(x)$ to $Q_0 = 1.65$ GeV

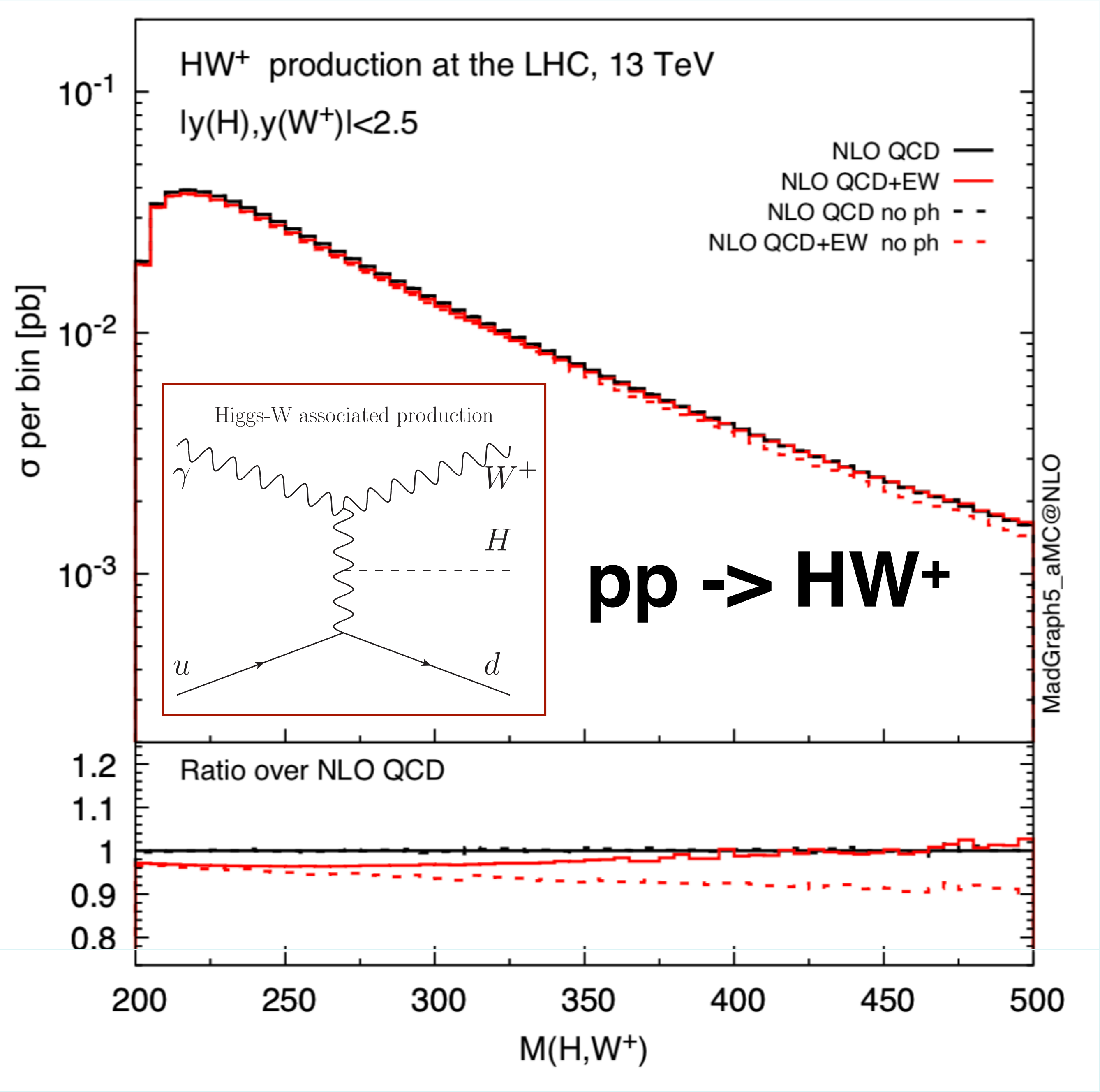
Bertone, Carrazza, Hartland, JR 16



Photon-initiated processes at the LHC

- At high mass **PI contributions and NLO EW corrections have opposite sign**, and thus in general one expects a partial cancellation among them
- This seems to be the case for many processes: **once PI effects included, NLO EW corrections rather small**

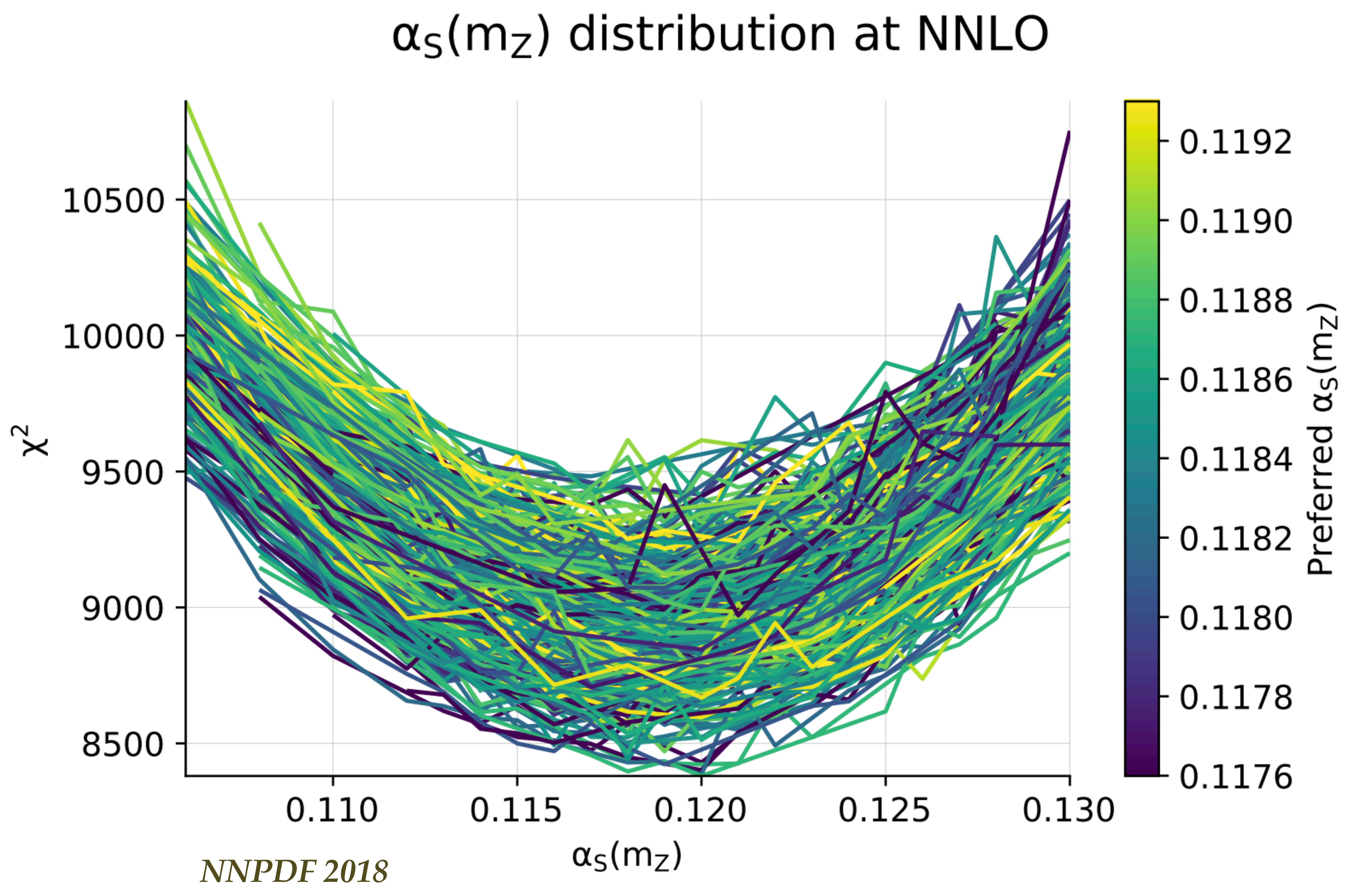




Bertone, Carrazza, Pagani, Rojo, Vicini, Zaro (in preparation)

Precision determination of $\alpha_S(m_Z)$

- Determination of the strong coupling constant using the new **Monte Carlo correlated replica** method
- In a nutshell, carry out an **independent $\alpha_S(m_Z)$ fit for each MC replica** to determine its complete probability distribution accounting for all correlations with the PDFs



Precision determination of $\alpha_S(m_Z)$

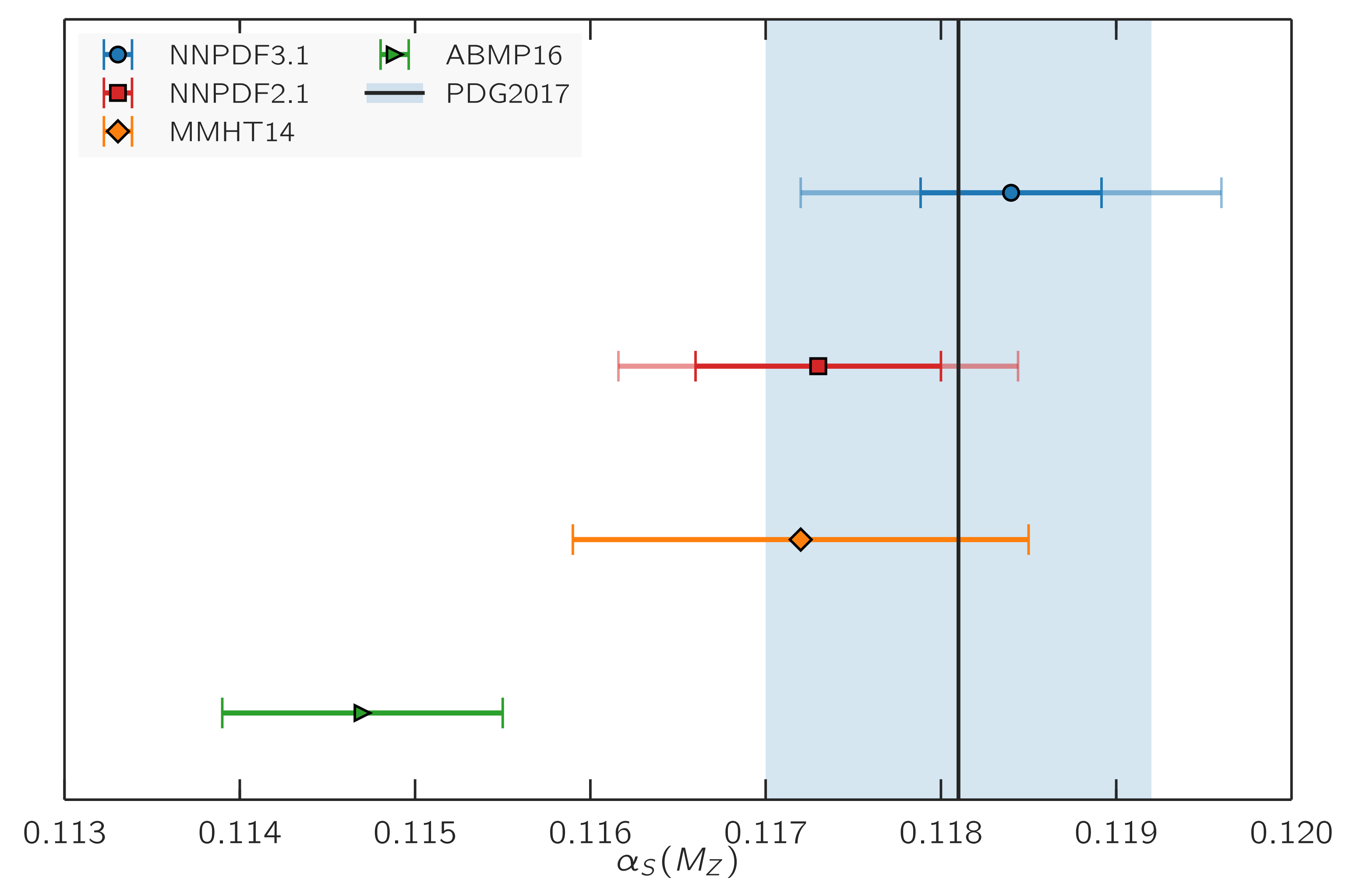
- Fit of $\alpha_S(m_Z)$ based NNPDF3.1NNLO, where **all collider processes are treated using exact NNLO theory**

- First ever determination of the strong coupling based on a **global NNLO analysis** with inclusive jet, top quark pair production, Z transverse momentum distributions: various **complementary handles!**

$$\alpha_s^{\rm NNLO}(m_Z) = 0.1185 \pm 0.0005^{\rm exp}\ (0.4\%)$$

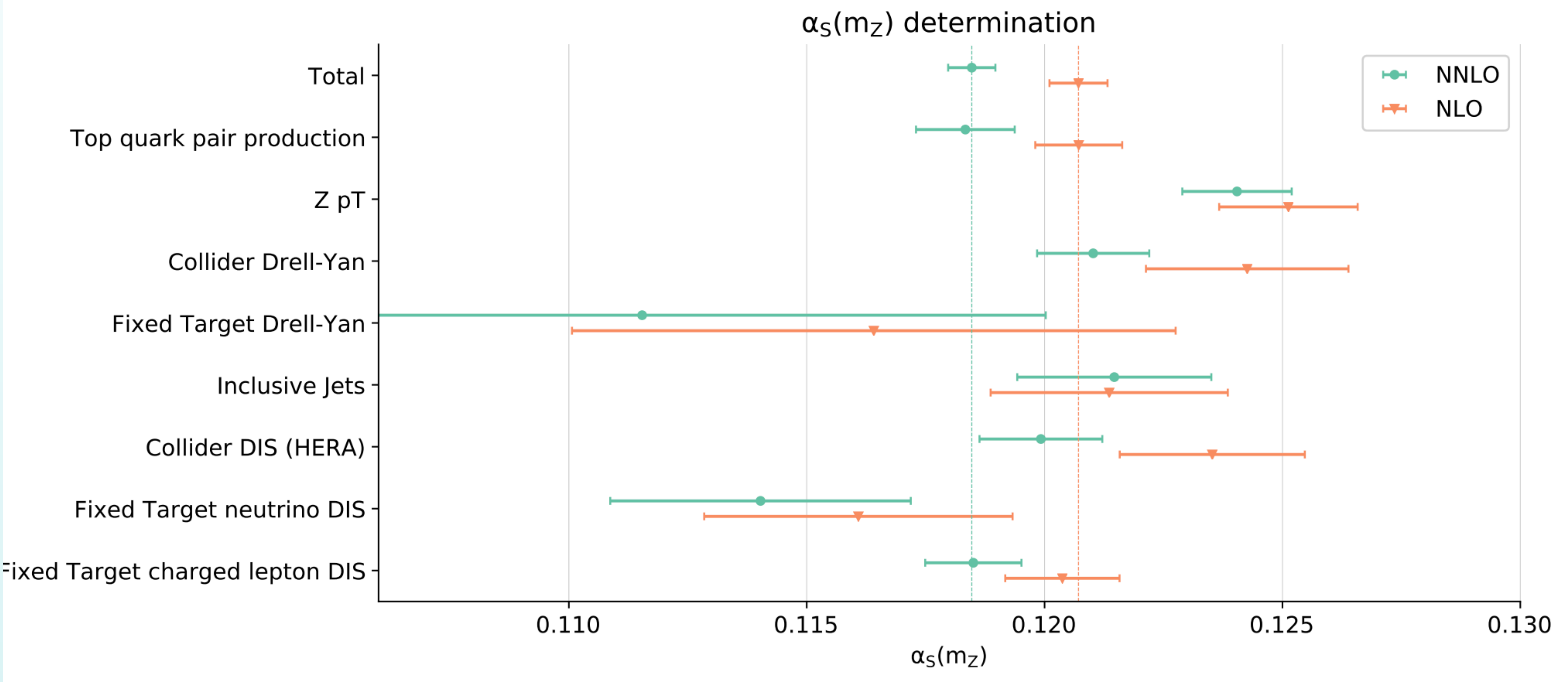
$$\Delta\alpha_s^{\rm pert} \equiv |\alpha_s^{\rm NNLO} - \alpha_s^{\rm NLO}| = 0.0022$$

$$\delta\alpha_s^{\rm mhou} \simeq 0.0011$$



Precision determination of $\alpha_S(m_Z)$

- Significant constraints from top quark pair, *Z pT*, and inclusive jets ….
- But also from fixed-target NC DIS structure functions and from collider DIS and DY data
- Main limitation of the fit is the **poor control over the MHOUs**: once these are accounted for, the global PDF fit would become **one of the most competitive methods** to extract $\alpha_S(m_Z)$



Parton distributions with BFKL resummation

- **Perturbative fixed-order QCD calculations** have been extremely successful in describing a wealth of data from proton-proton and electron-proton collisions
- There are theoretical reasons that eventually we need to go beyond DGLAP: at small-x, **logarithmically enhanced terms in *1/x* become dominant** and need to be resummed to all orders
- ***BFKL/high-energy/small-x resummation*** can be matched to the **DGLAP collinear framework**, and thus be included into a standard PDF analysis

DGLAP Evolution in Q^2

$$\mu^2 \frac{\partial}{\partial \mu^2} f_i(x,\mu^2) = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(\mu^2)\right) f_j(z,\mu^2),$$

BFKL Evolution in x

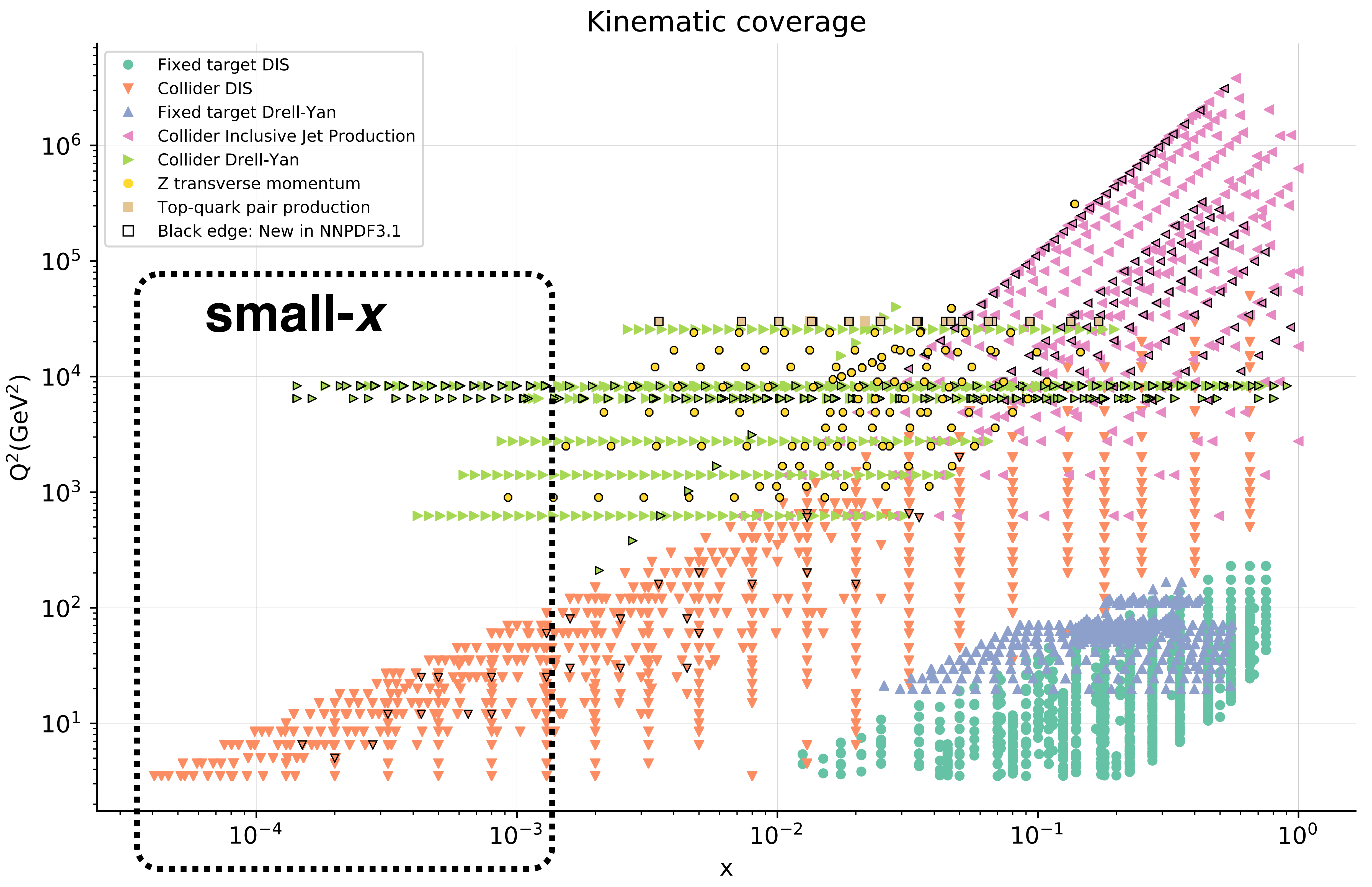
$$-x\frac{d}{dx} f_+(x,\mu^2) = \int_0^\infty \frac{d\nu^2}{\nu^2} K\left(\frac{\mu^2}{\nu^2}, \alpha_s\right) f_+(x,\nu^2)$$

Within small-*x* resummation, the **N^kLO fixed-order DGLAP splitting functions** are complemented with the **N^hLL*x* contributions from BKFL**

ABF, CCSS, TW + others, 94-08

$$P_{ij}^{\mathrm{N}^k\mathrm{LO}+\mathrm{N}^h\mathrm{LL}x}(x) = P_{ij}^{\mathrm{N}^k\mathrm{LO}}(x) + \Delta_k P_{ij}^{\mathrm{N}^h\mathrm{LL}x}(x),$$

A new world at small-x

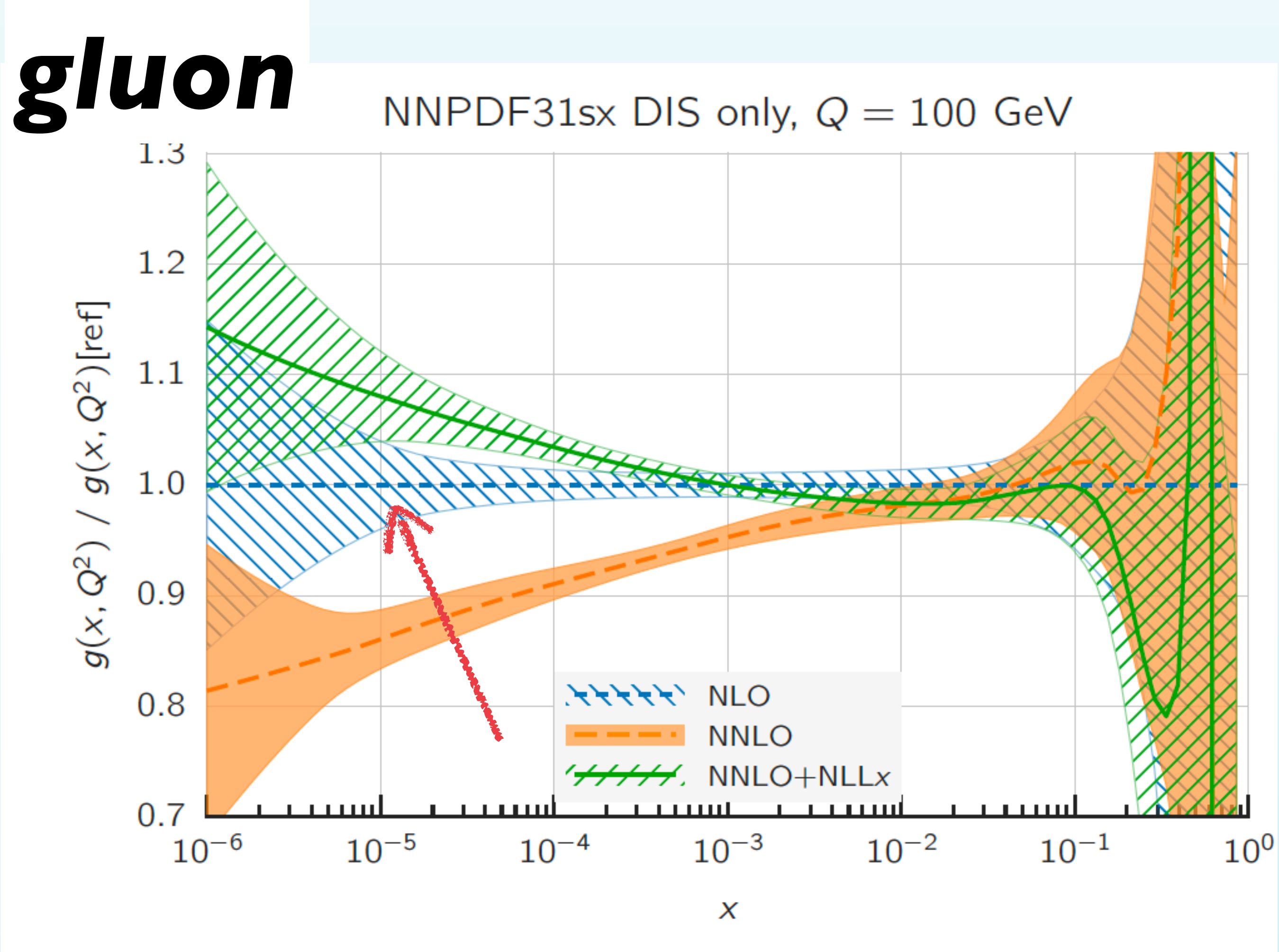


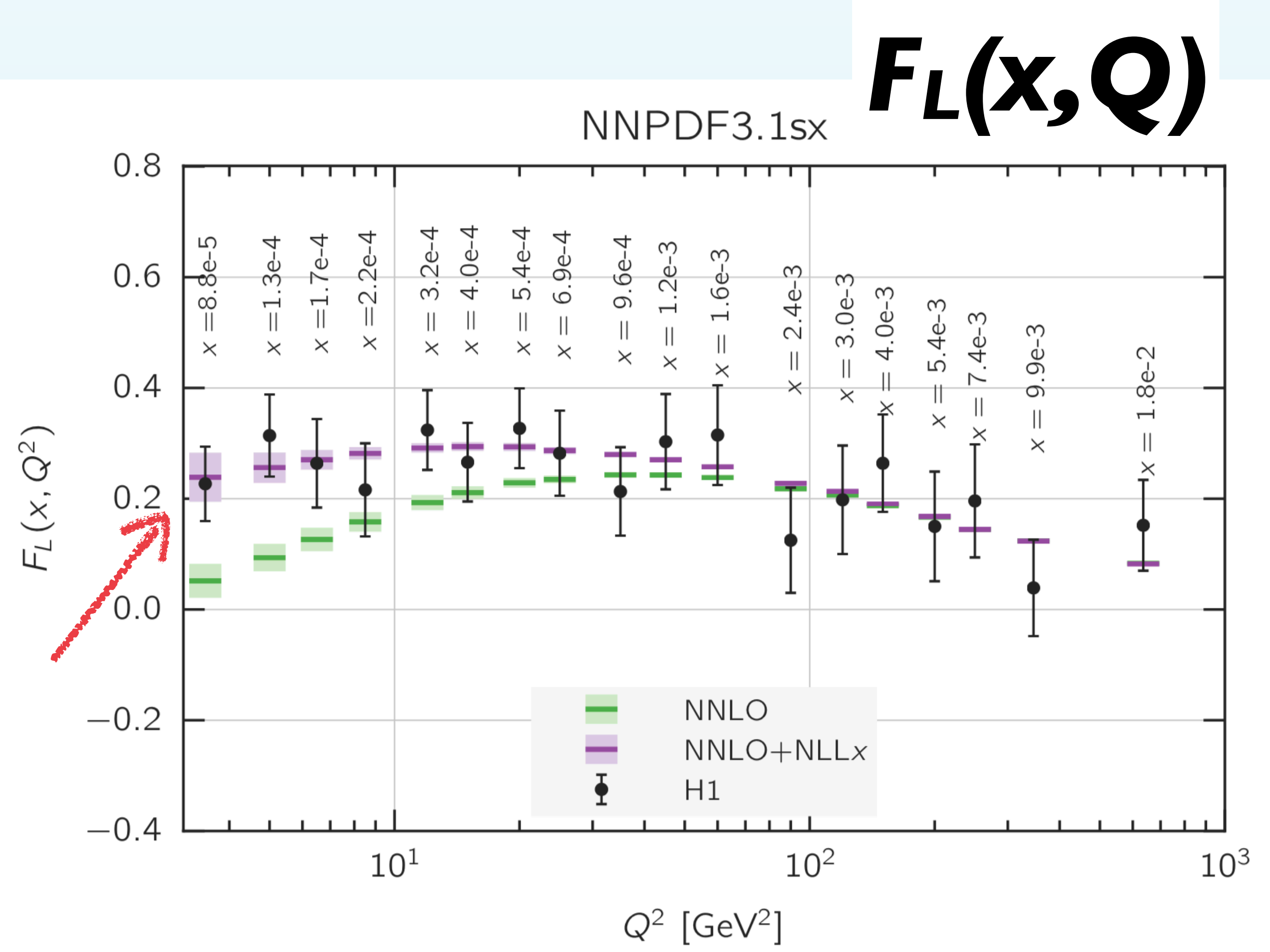
A new world at small-x

- Ultimately, the need for (or lack of) BKFL resummation in **ep and pp collider data** can only be assessed by performing a **global PDF analysis based on (N)NLO+NLLx theory**

- Theoretical tools are now available: **HELL for NLL*x* resummation**, interfaced to **APFEL**

- NNPDF3.1 (N)NLO+NLL fits **stabilize the perturbative PDF expansion at small-*x***, in particular for the gluon, and markedly improve the **fit quality to the small-*x* HERA data**

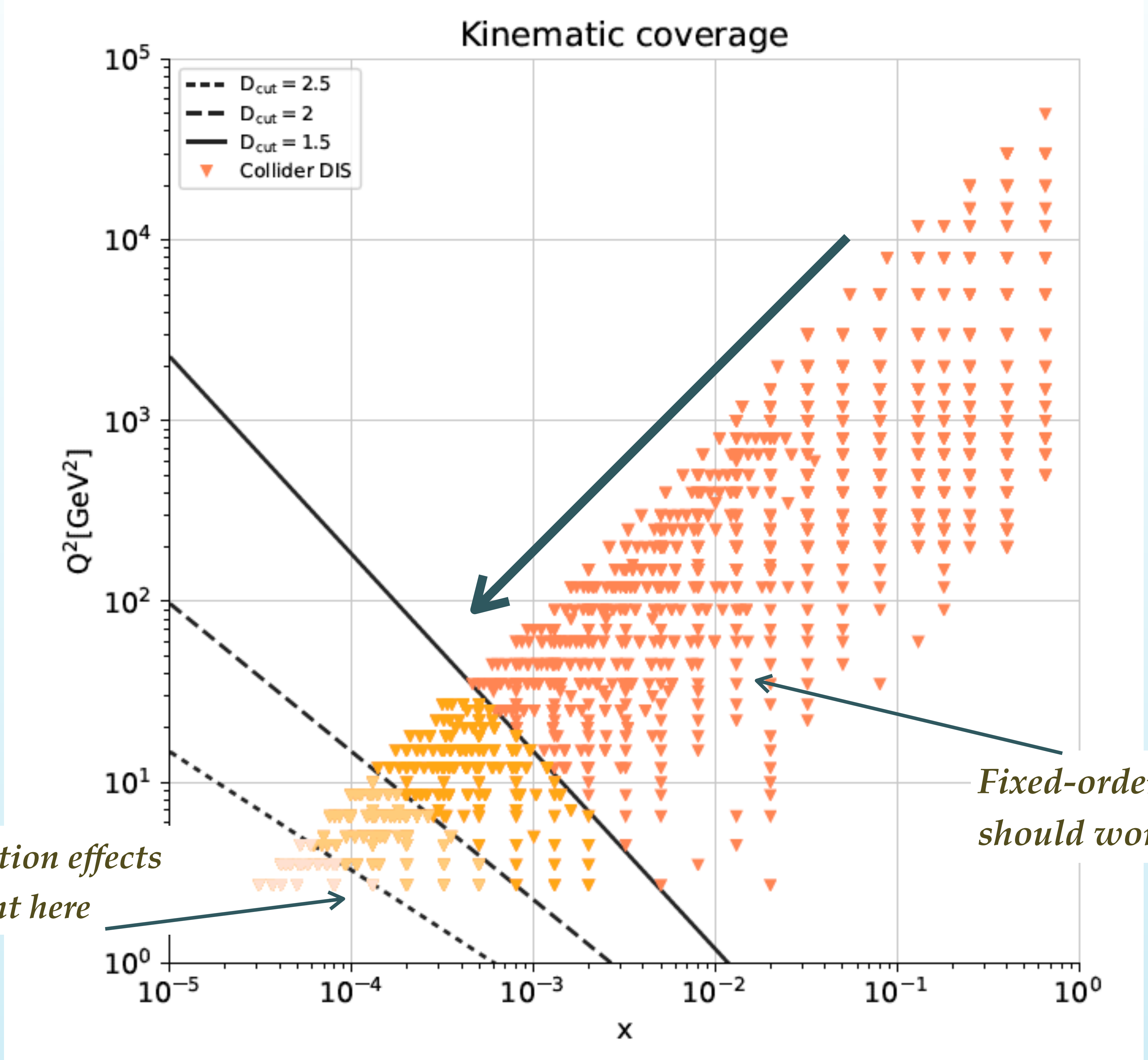




Ball, Bertone, Bonvini, Marzani, JR,Rottoli 16

Evidence for BFKL dynamics in HERA data

In order to assess the impact of small-x resummation for the description of the small-*x* and Q^2 HERA data, compute the χ^2 **removing data points in the region where resummation effects are expected**



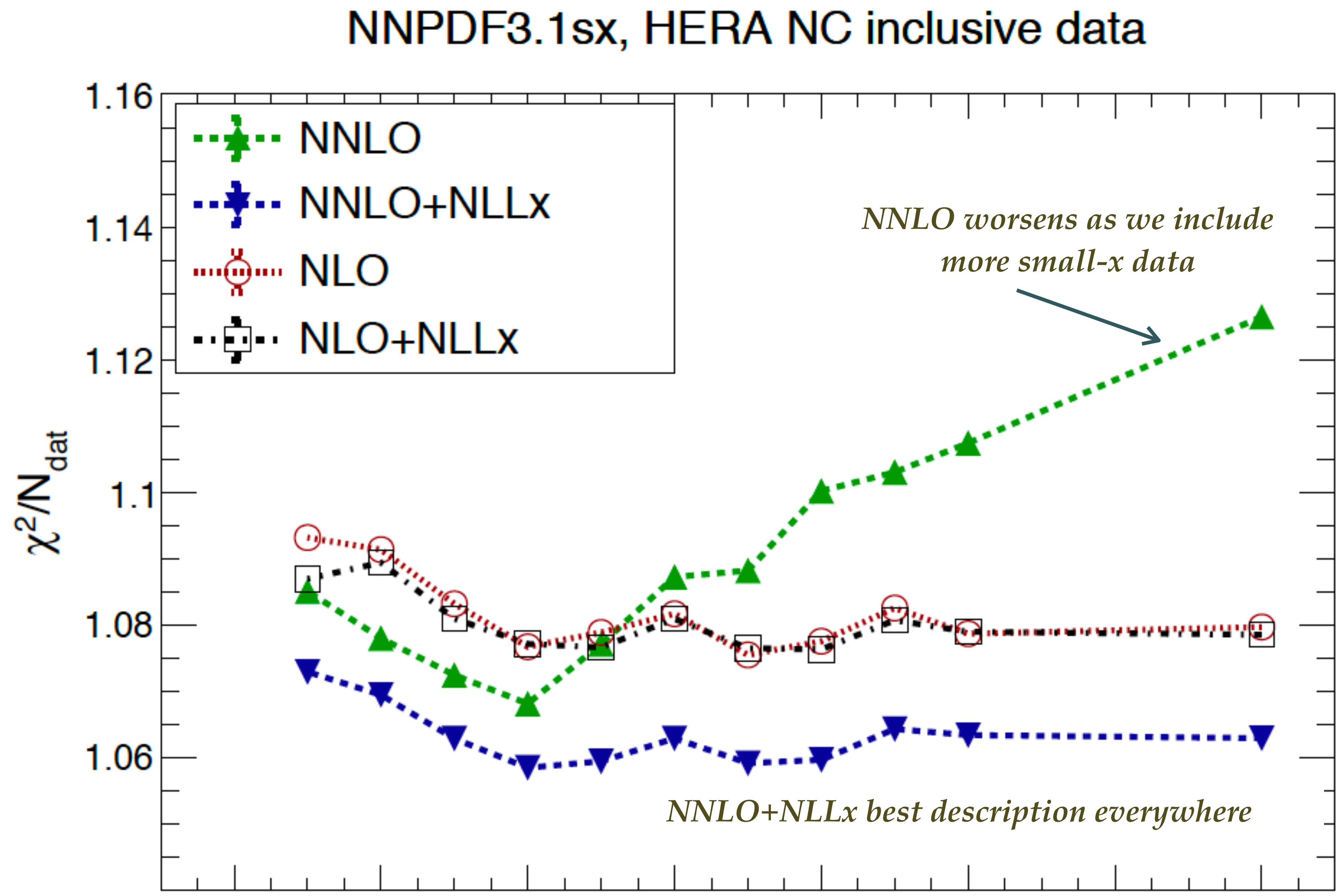
Fixed-order theory should work fine here

Small-x resummation effects could be important here

Evidence for BFKL dynamics in HERA data

Using **NNLO+NLL*x* theory, the NNLO instability at small-*x* of the χ^2 disappears**

Excellent fit quality to **inclusive and charm HERA** data achieved in the **entire (x,Q^2) region**



NNPDF3.1sx, HERA NC inclusive data

NNLO worsens as we include more small-x data

NNLO+NLLx best description everywhere

Including more low-x, low Q data

Nunca es tarde si la dicha es buena

Science
Life and Physics

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

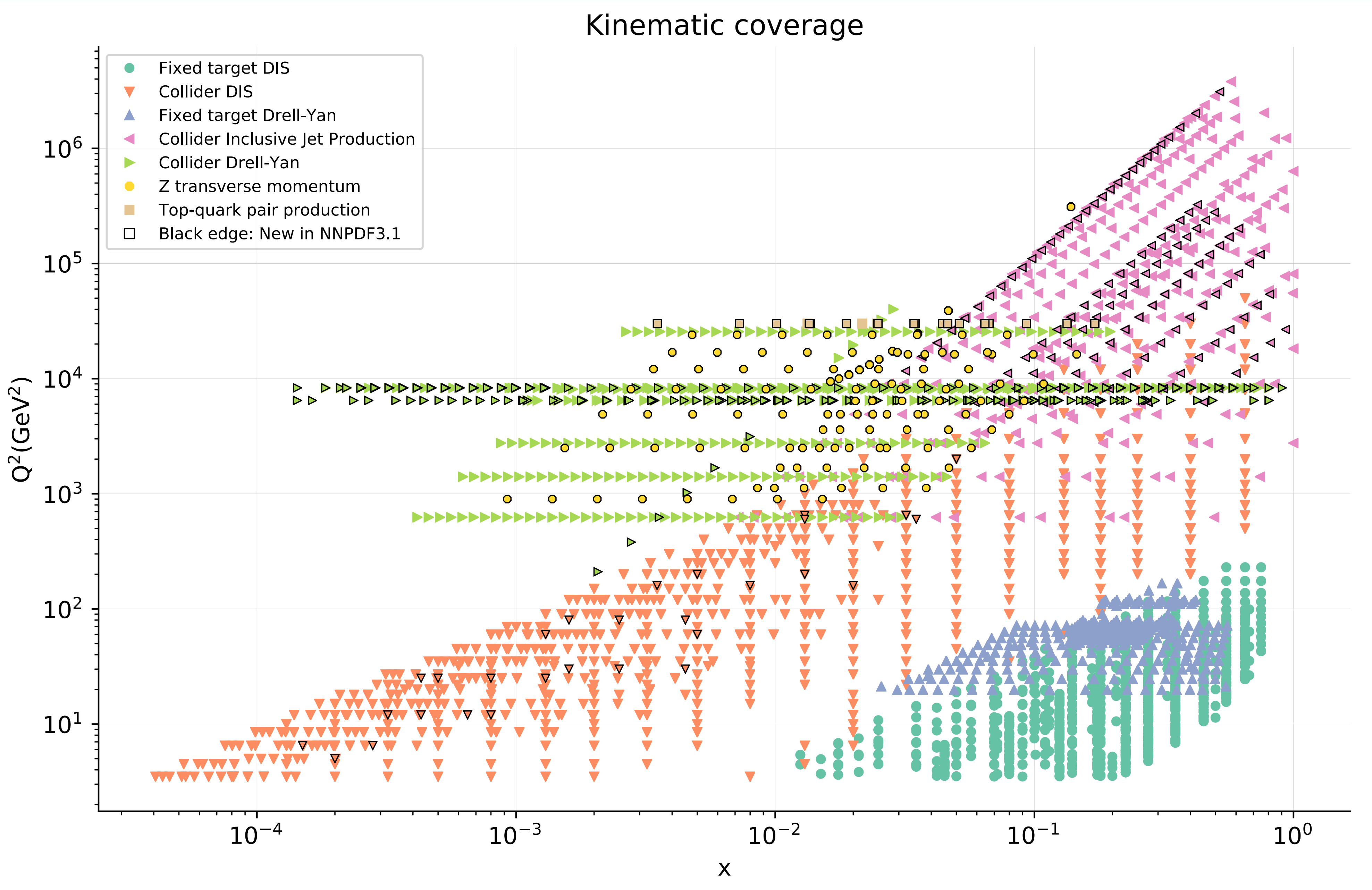
Jon Butterworth
@jonmbutterworth
Thu 28 Dec 2017 17.30 GMT

529 | 59

In the mid 1970s, four Soviet physicists, Batlisky, Fadin, Kuraev and Lipatov, made some predictions involving the strong nuclear force which would lead to their initials entering the lore. "BFKL" became a shorthand for a difficult-to-

Jon Butterworth,
the Guardian, 28/12/2018

The global QCD fit machinery



Global PDF fits: highly non-trivial validation of the **QCD factorisation framework**:

i) *including* ***O(5000) data*** *points,*

ii) *from* ***O(50) experiments****,*

iii) *several of them with* ***≈1% errors****,*

yet still manage to achieve $\chi^2/N_{dat} \approx 1$!

Summary and outlook

- Recent developments in our understanding of the **quark and gluon structure of the proton** have been driven by a combination of:

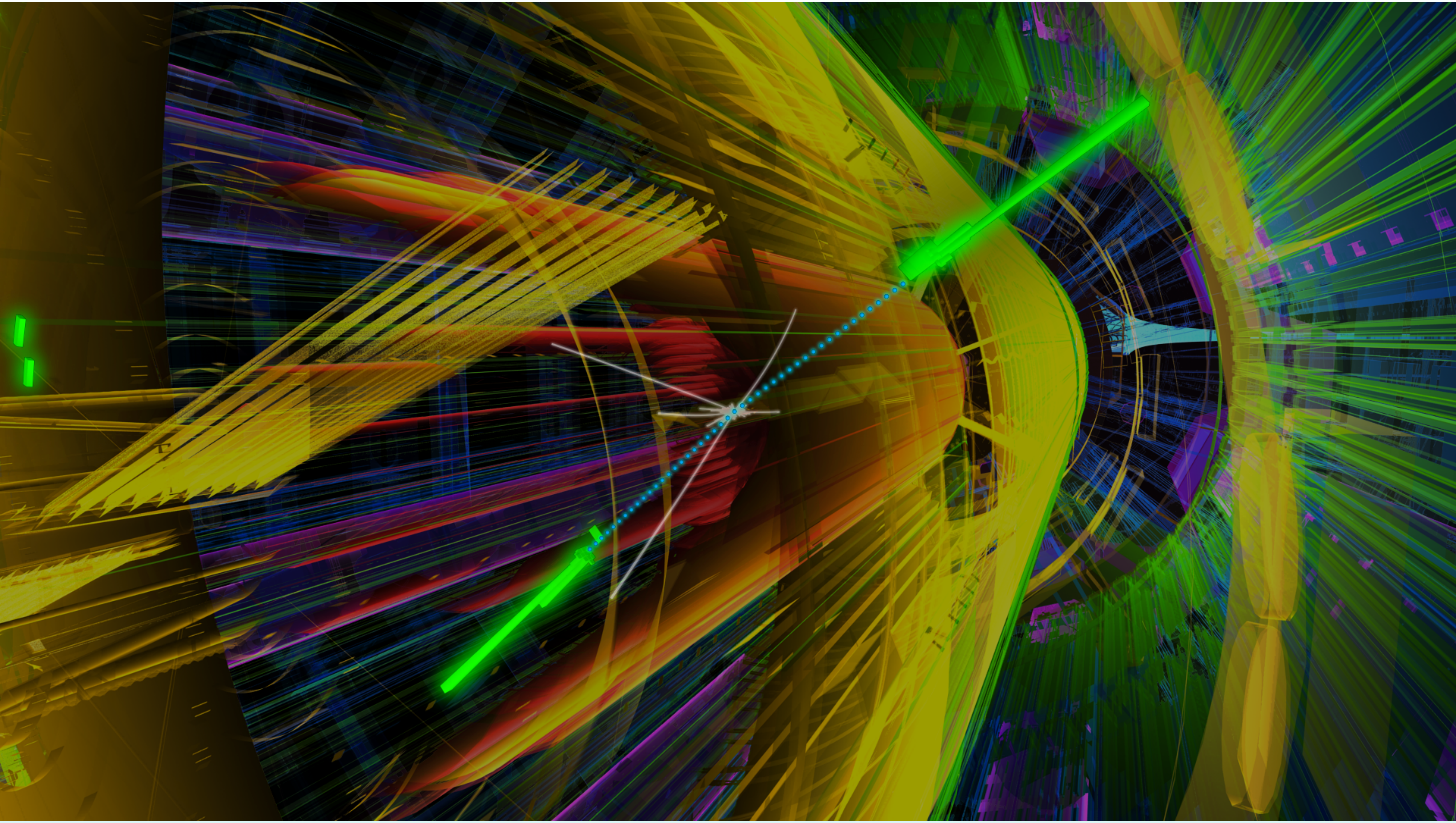
  - ☑ **Theory**: Progress in NNLO QCD and NLO EW calculations for many collider processes: differential top pairs, inclusive jets, the Z transverse momentum … Also the calculation of the photon PDF in terms of DIS structure functions

  - ☑ **Data**: a wealth of high-precision measurements from HERA, Tevatron, ATLAS, CMS and LHCb, in several cases with sub-percent uncertainties.

  - ☑ **Methodology**: fitted charm PDF, combination/reduction methods for different PDFs, new software for PDF fits, fast NLO/NNLO interfaces, ….

- Improvements for **many Run II analysis**: Higgs couplings, M_W measurements, heavy BSM particle production, precision SM studies, SMEFT fits, MC validation, …

Fascinating times ahead at the high-energy frontier!



Stay posted for news from the LHC!

Fascinating times ahead at the high-energy frontier!

Thanks for your attention!

Stay posted for news from the LHC!