Artificial Neural Networks, the Proton Structure, and Higgs Physics at the LHC

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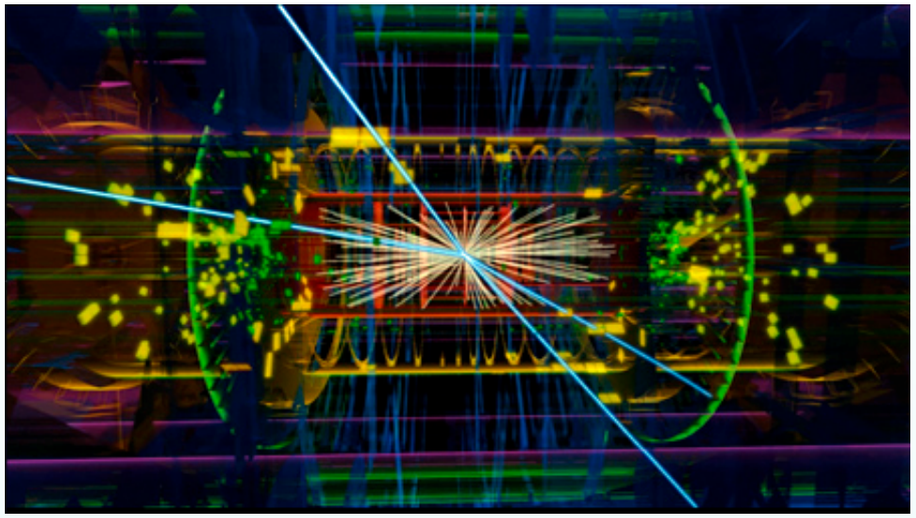
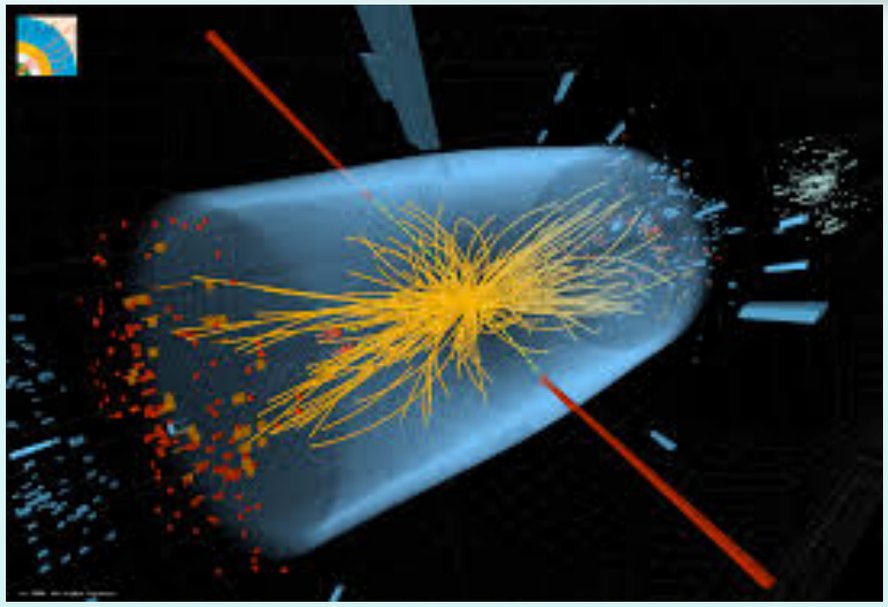
12th Biennial Symposium Trends in Theory 2017
Dutch Research School of Theoretical Physics (DRSTP)
Delfsen, 12/05/2017



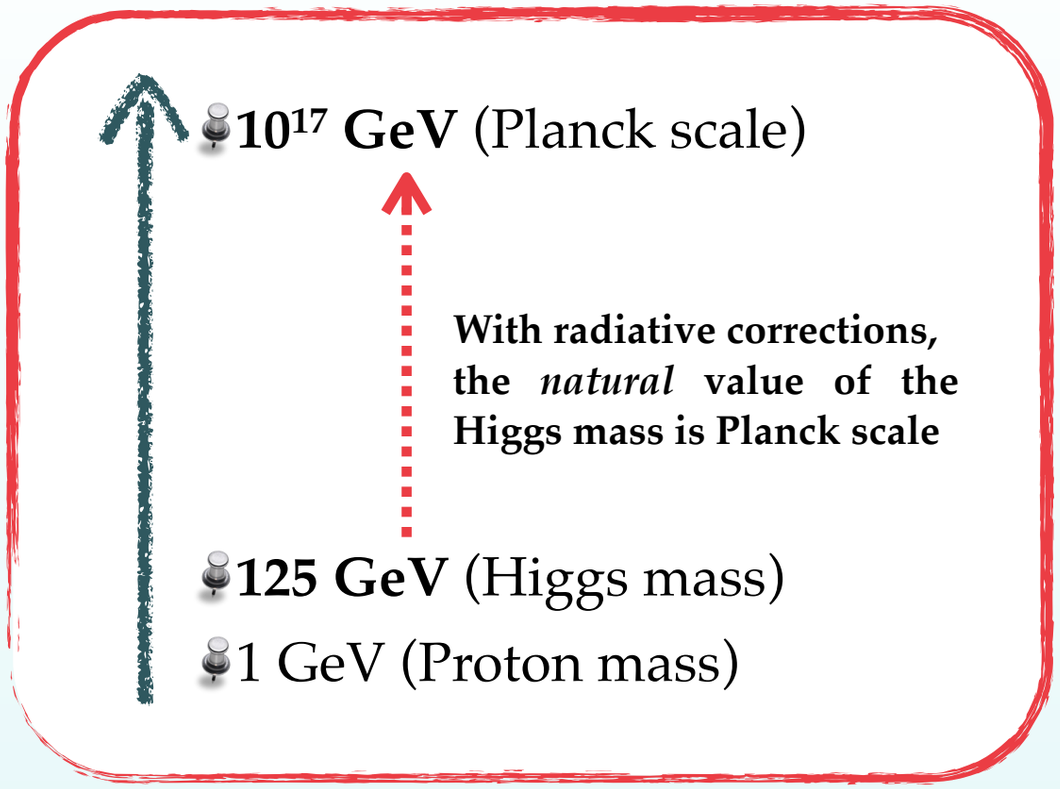
Exploring the high-energy frontier at the Large Hadron Collider

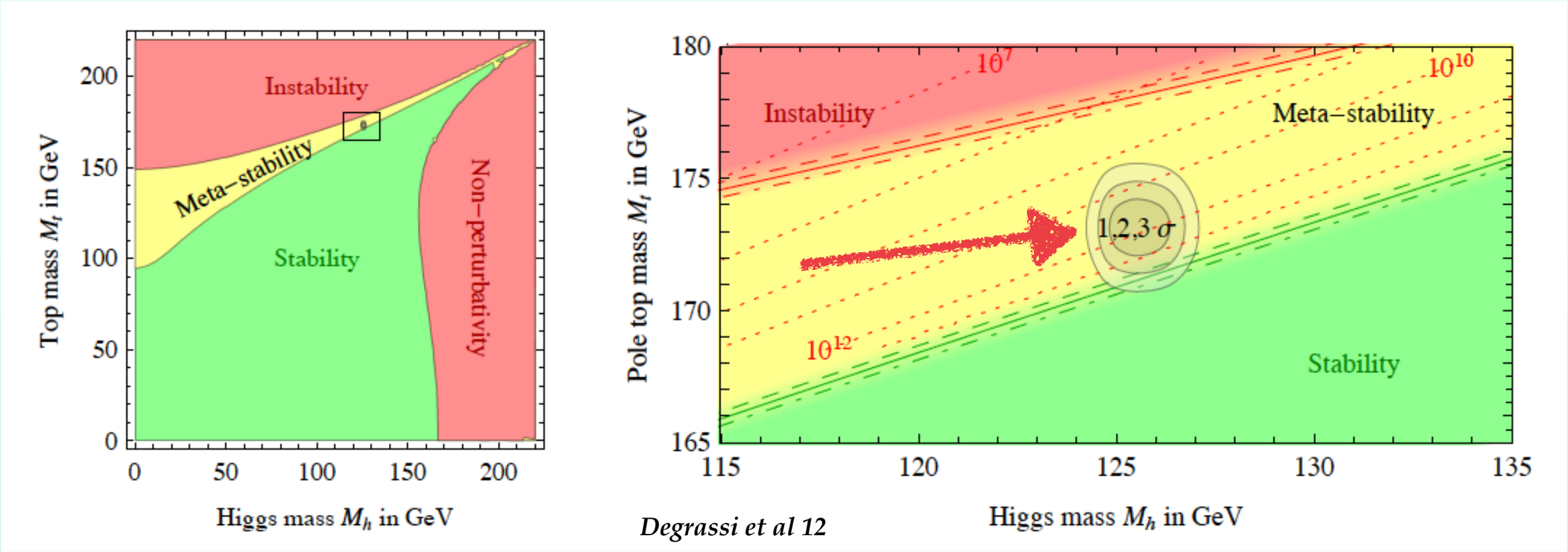


Outstanding questions in Particle Physics

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?





Degrassi et al 12

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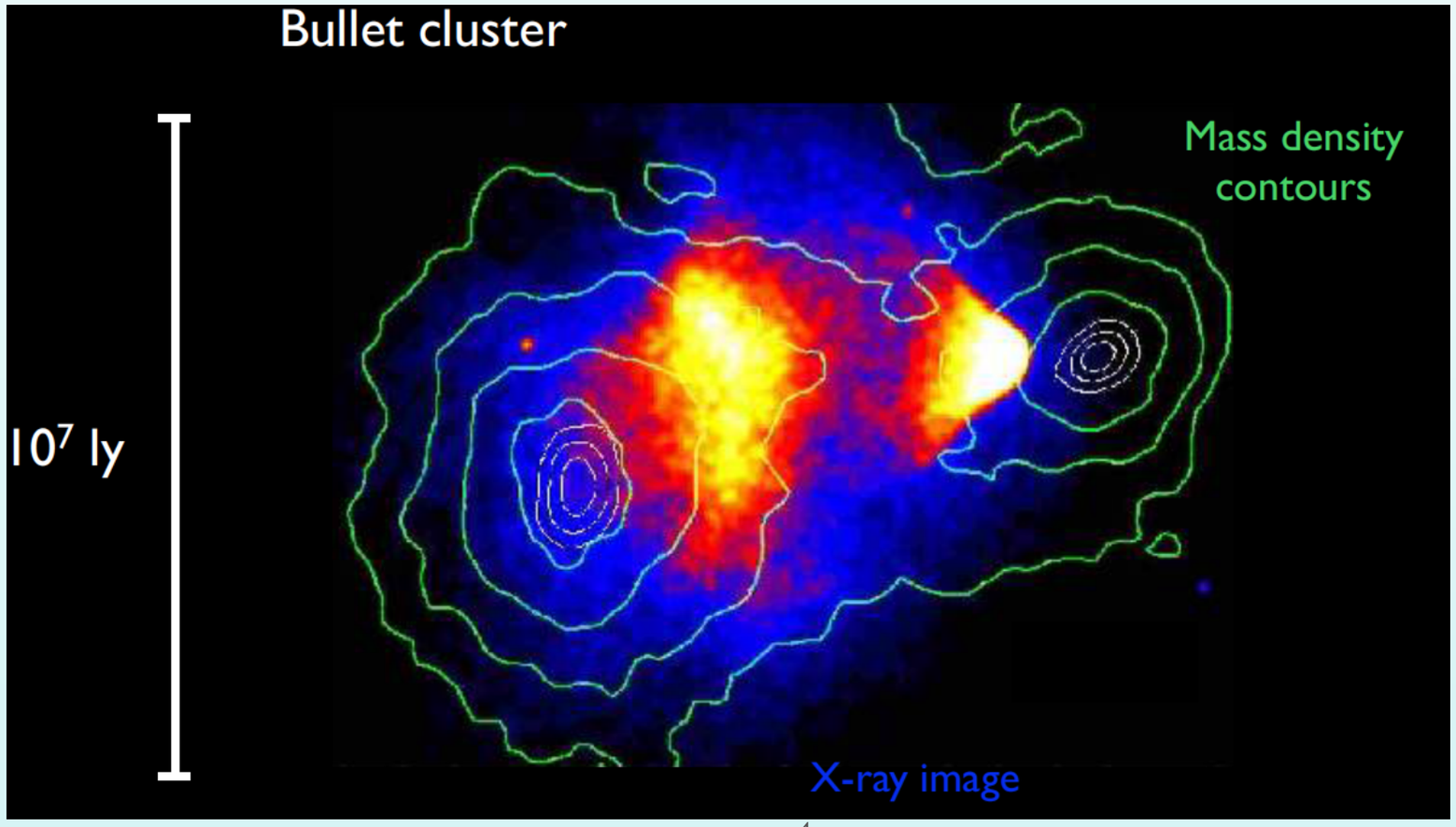
Dark Matter

- **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?

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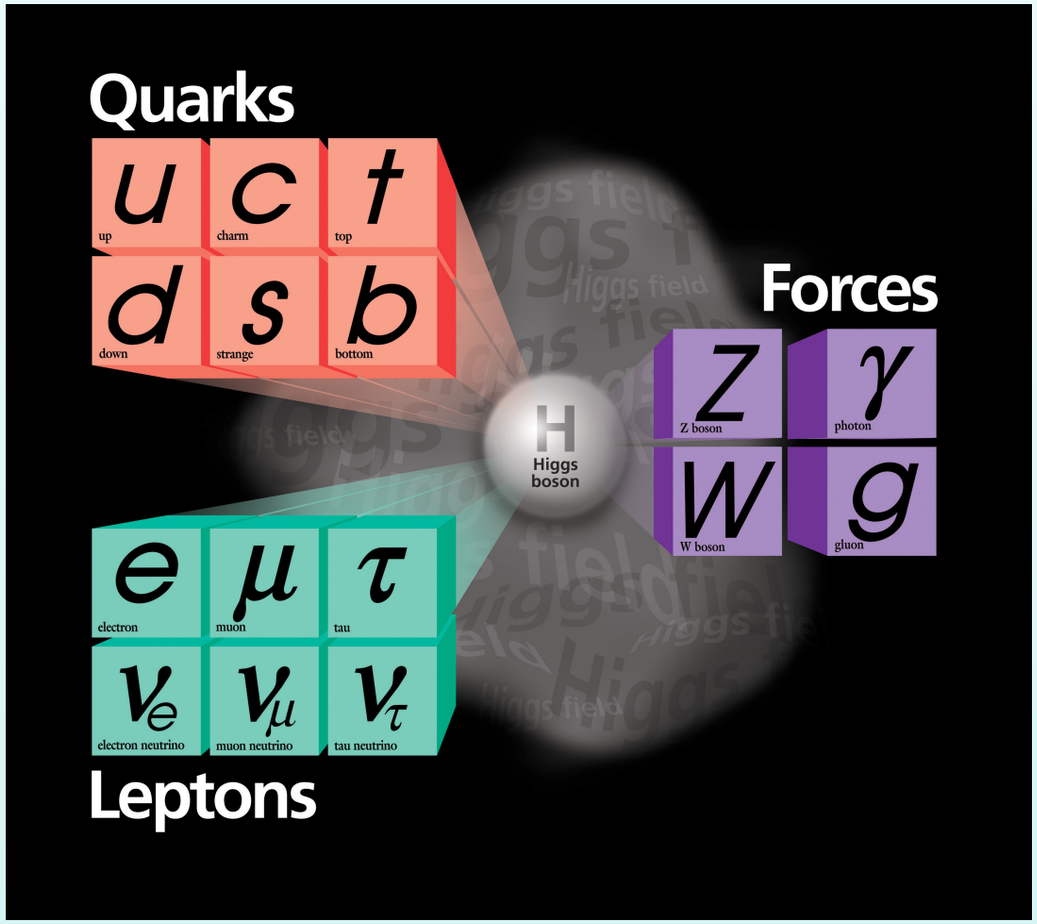

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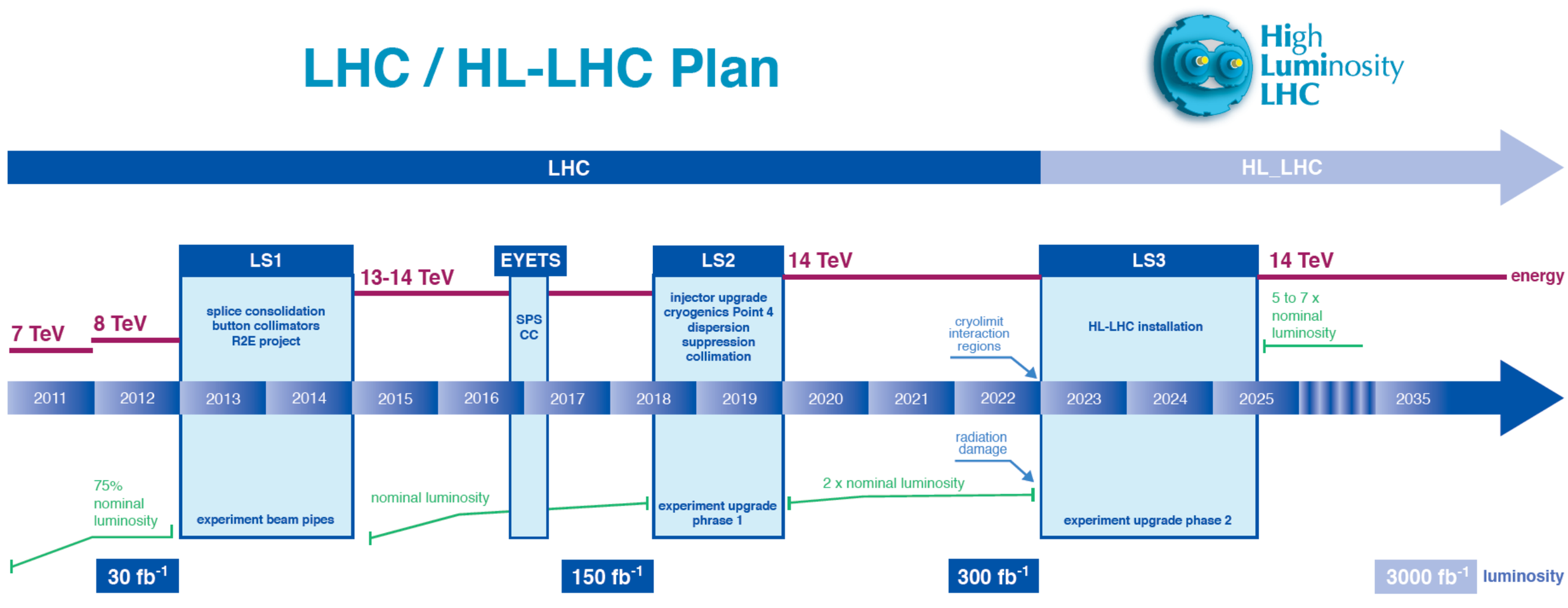
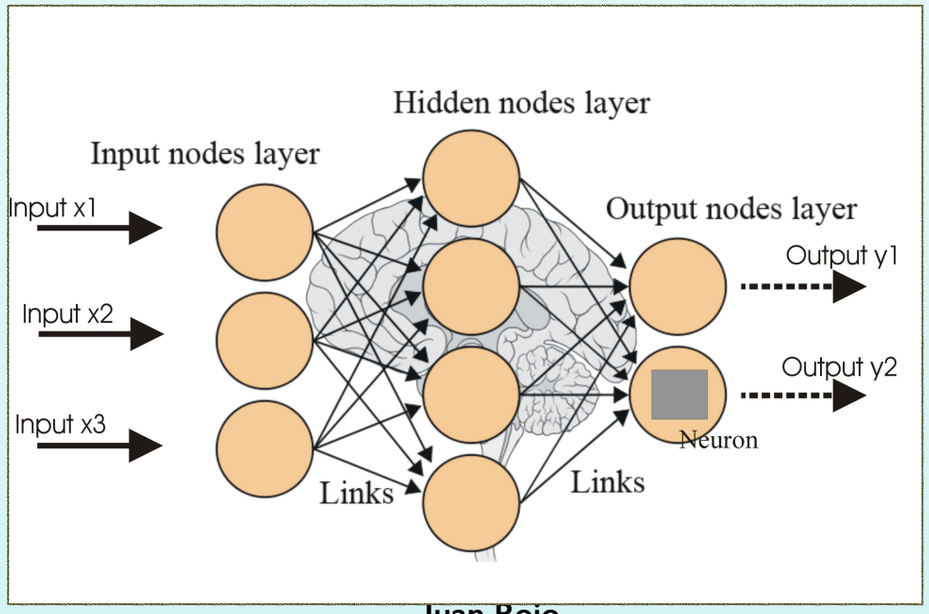


Many of these crucial questions can be addressed at the Large Hadron Collider

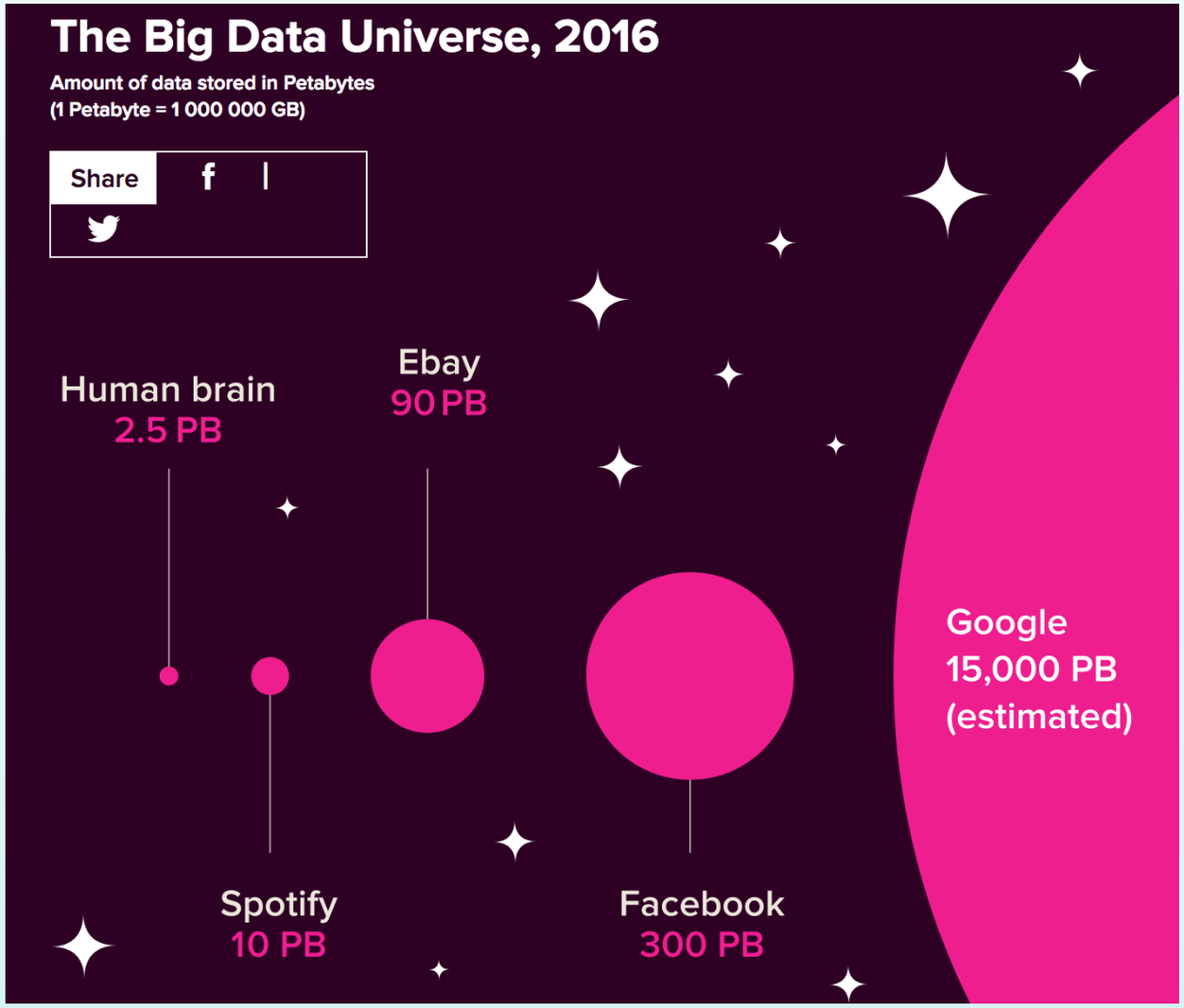
For the next 20 years, LHC will be the forefront of the exploration of the high-energy frontier

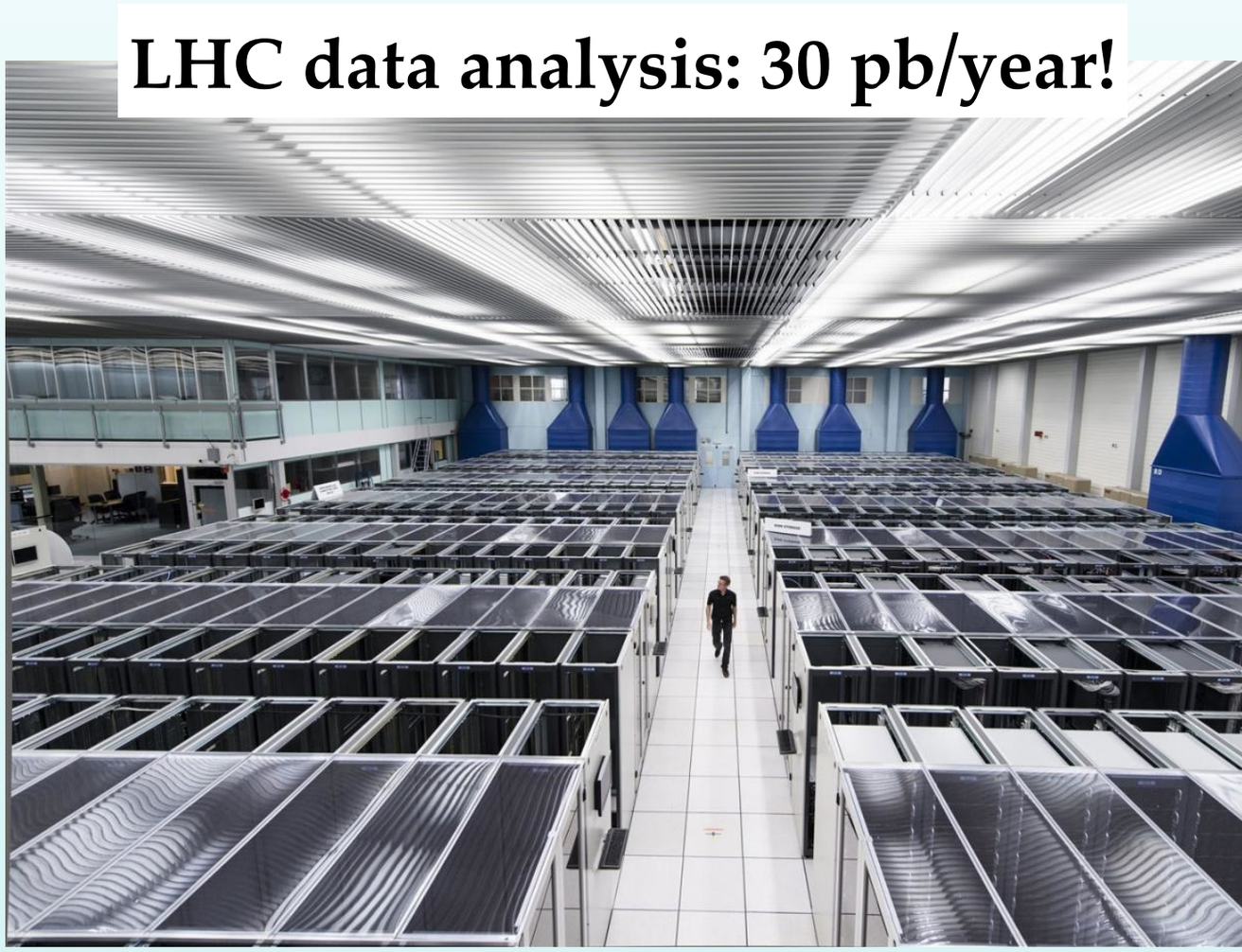
Machine Learning and Artificial Neural Networks



Machine Learning at the LHC

- By **Machine Learning** we usually understand 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!





Machine Learning at the LHC

- Several summary talks would be needed to cover the fascinating topic of **ML at LHC**!
- Here focus on a specific type of ML algorithms: **Artificial Neural Networks**

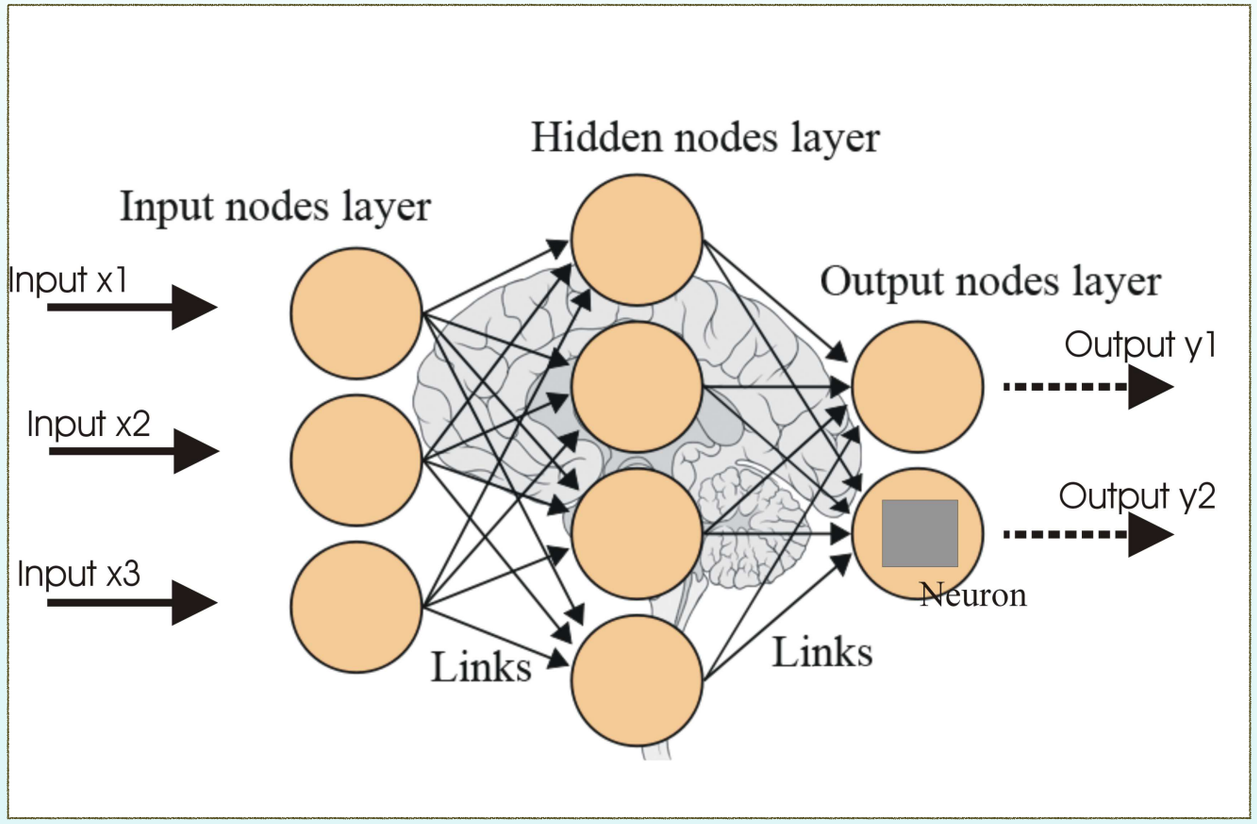
For the ML / Big data aficionados, please check the ``**Data Science at LHC**'' workshops''!

https://indico.fnal.gov/conferenceDisplay.py?confId=13497

Artificial Neural Networks

Inspired by **biological brain models**, **Artificial Neural Networks** 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



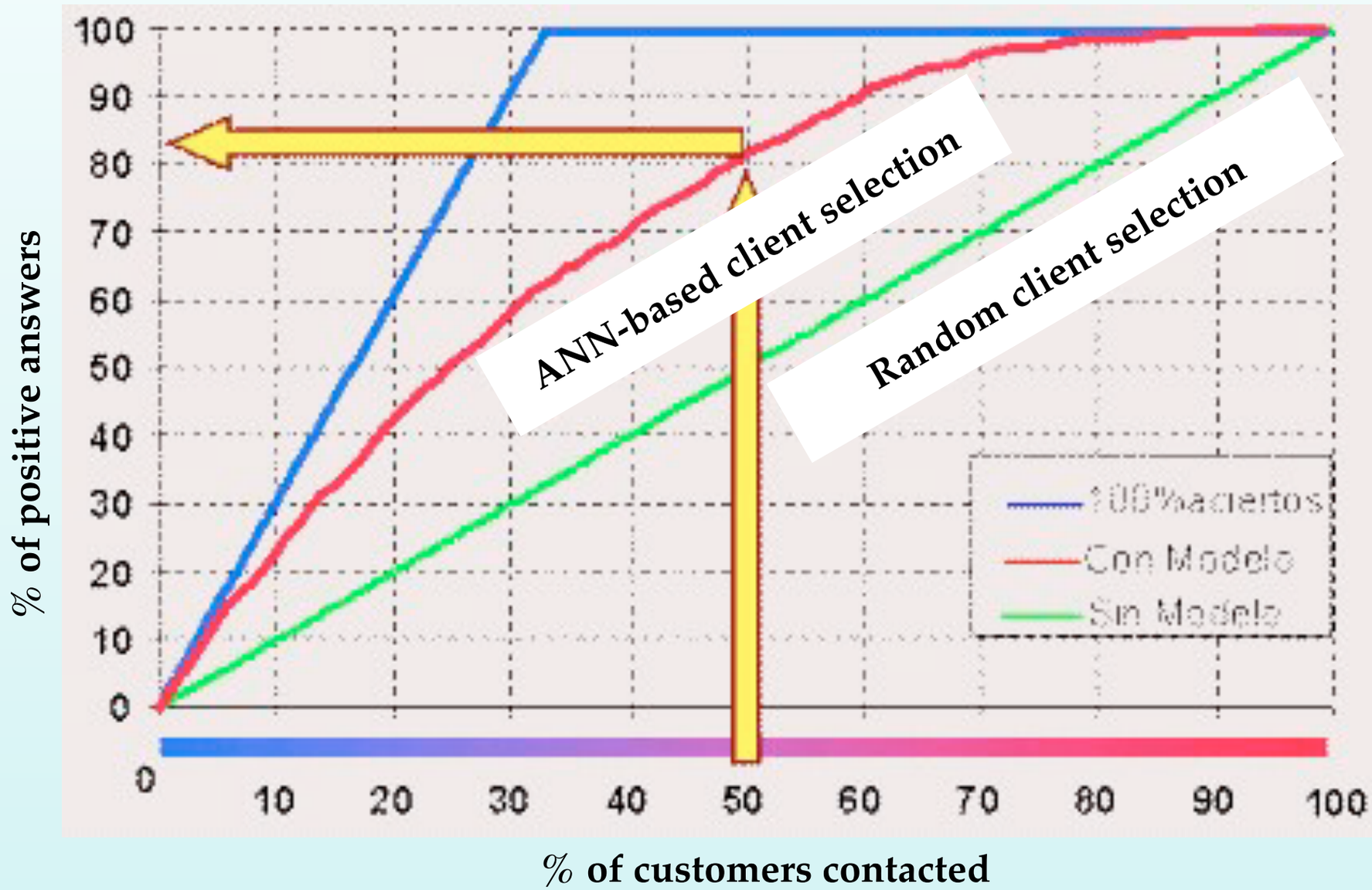
Artificial neural networks aim to excel where domains as their **evolution-driven counterparts outperforms traditional algorithms in tasks such as pattern recognition, forecasting, classification**, ...

ANNs - a marketing example

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

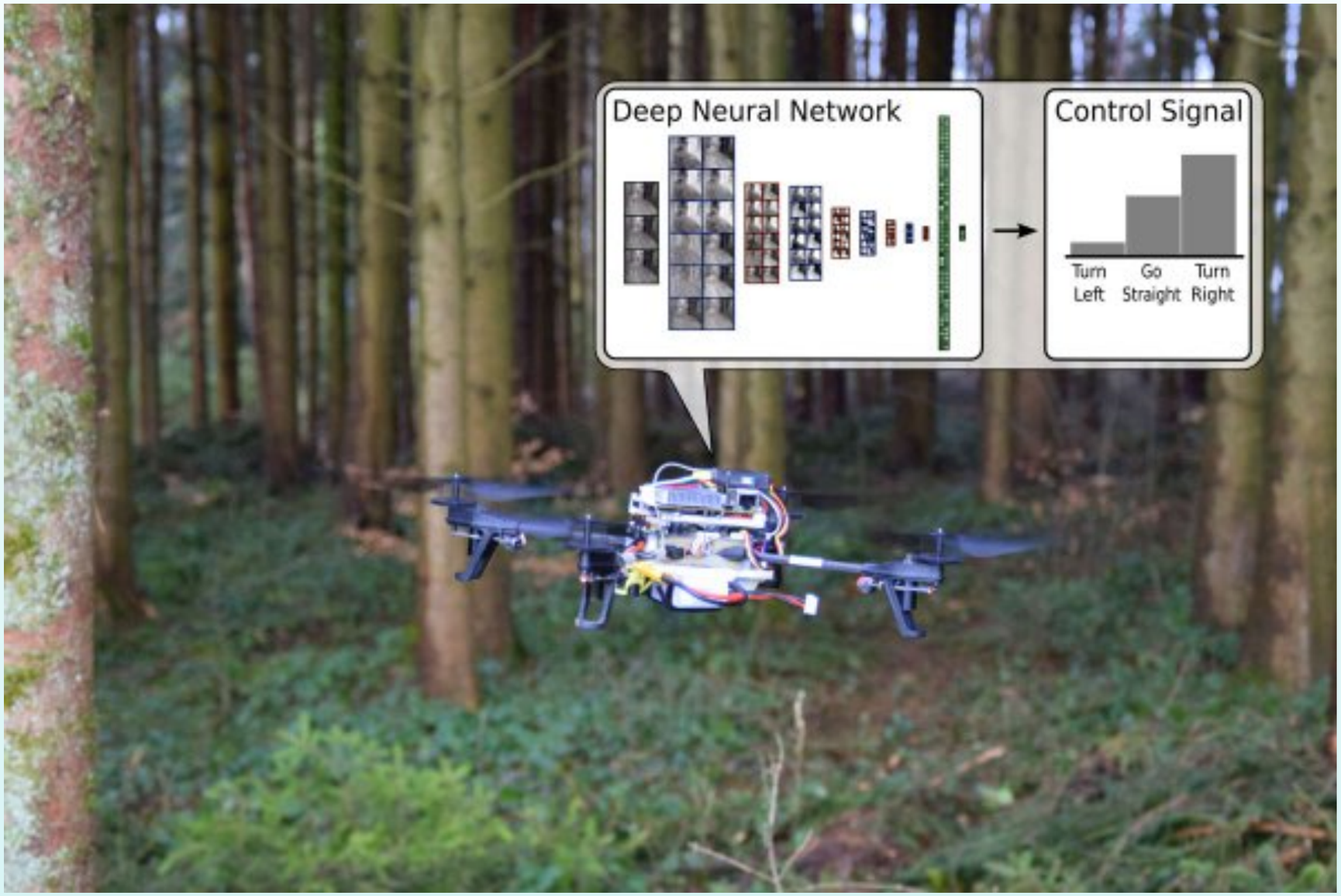
- **Contact all customers**: slow and costly
- Contact **5%** of the customers, **train a ANN with their input** (gender, income, loans) and **their output** (yes/no) and use the information to **contact only clients likely to accept the product**

Cost-effective method to improve marketing performance!



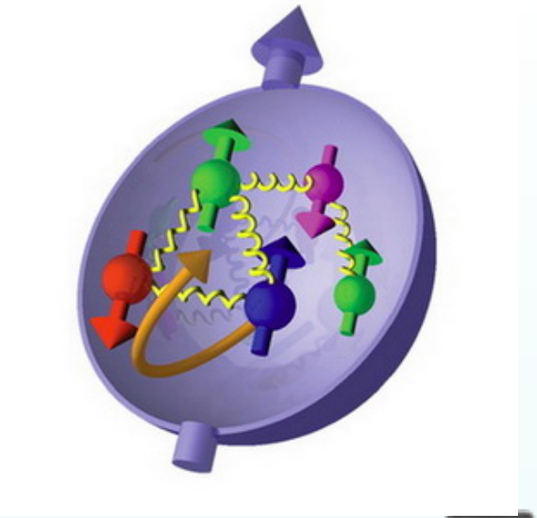
ANNs and pattern recognition

- ANNs can enable an **autonomous vision-control drone** to recognize 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

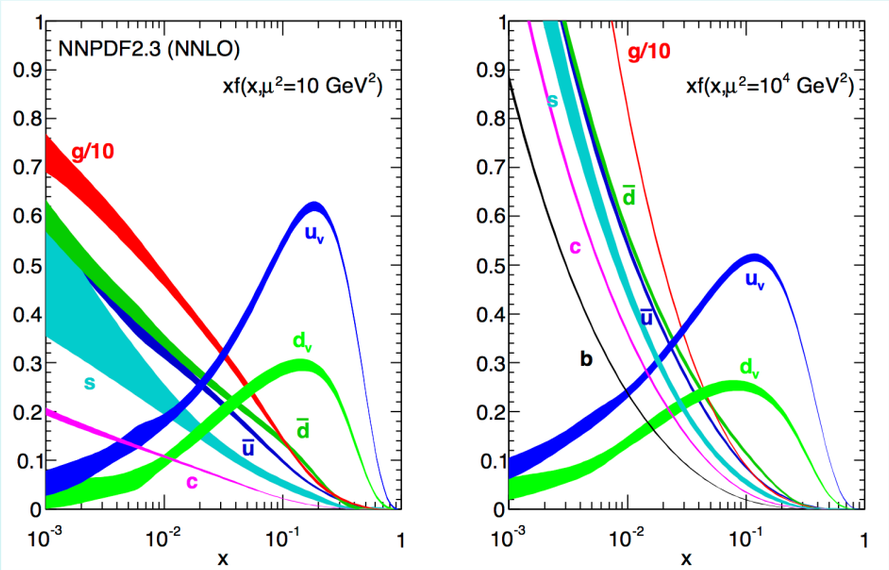


Giusti et al, IEEE Robotics and Automation Letters, 2016

Similar algorithms at work in self-driving cars!

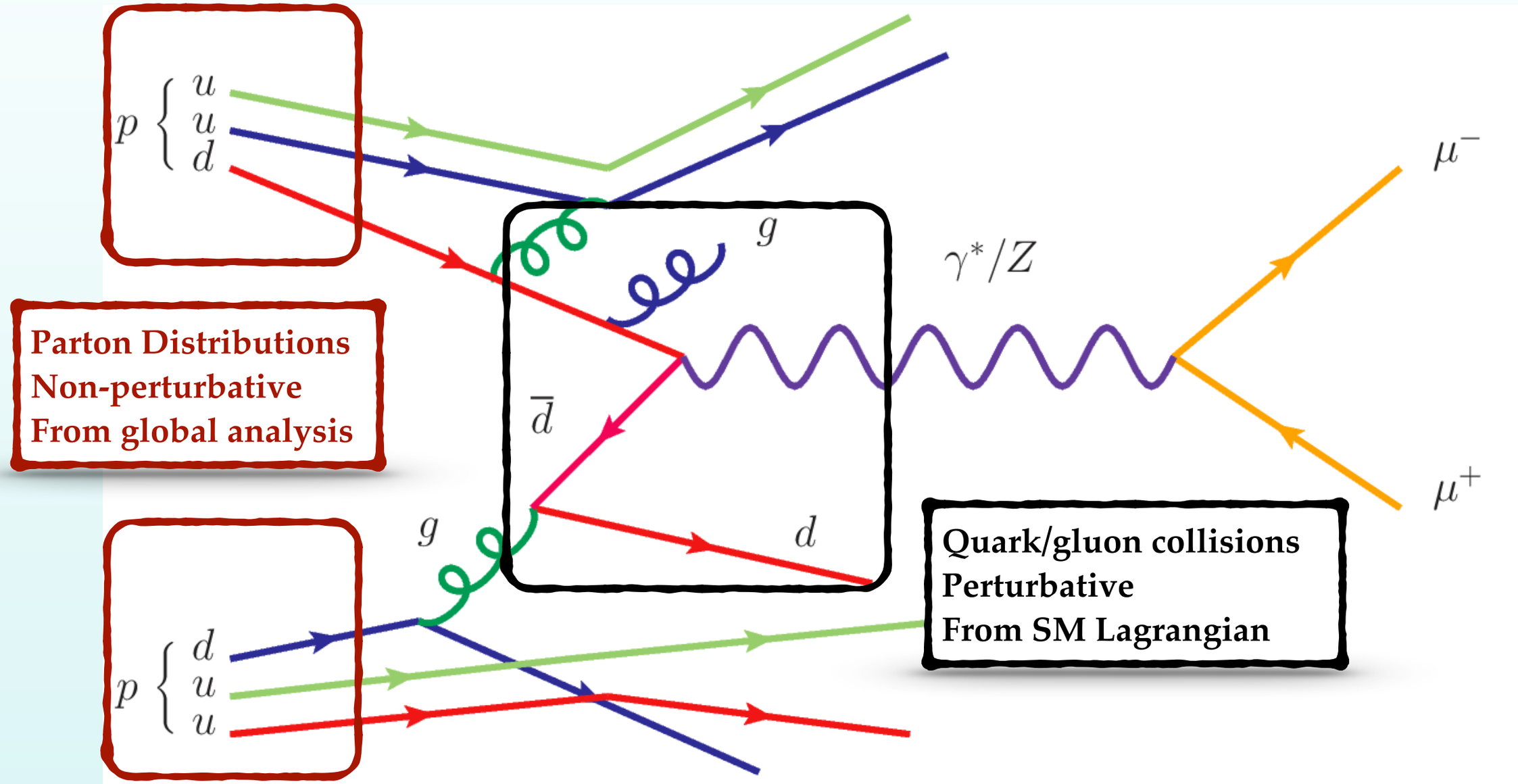


The inner life of protons : Parton Distribution Functions



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)



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**

$$\int_0^1 dx \left(g(x,Q) + \sum_q q(x,Q) \right) = 1$$

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

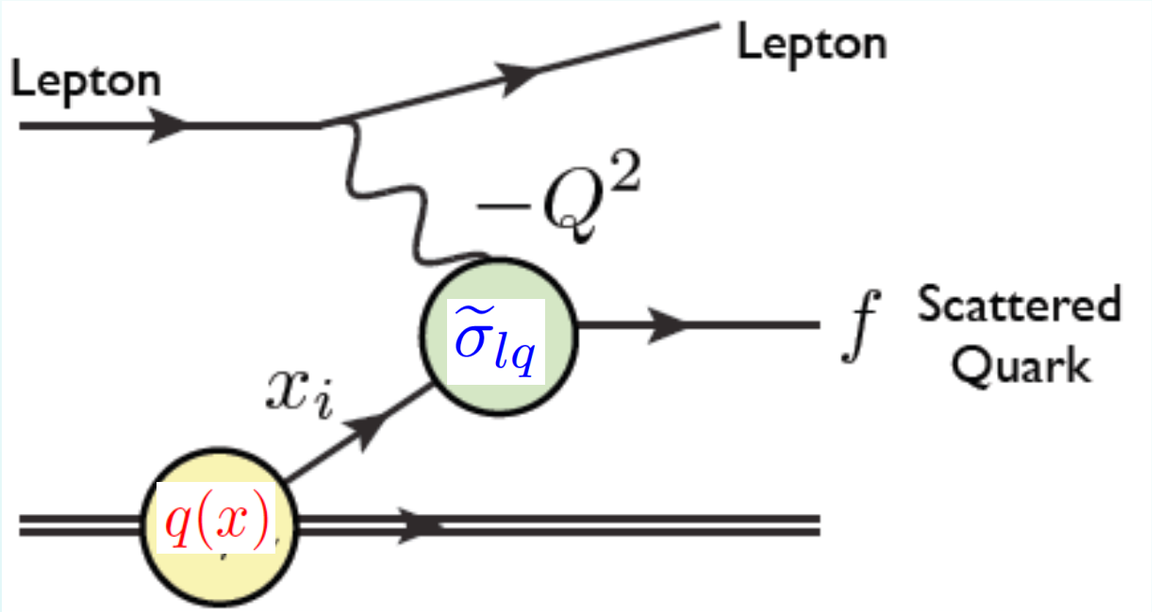
$$\frac{\partial g(x,Q)}{\partial \ln Q} = P_g(\alpha_s) \otimes g(x,Q) + P_q(\alpha_s) \otimes q(x,Q)$$

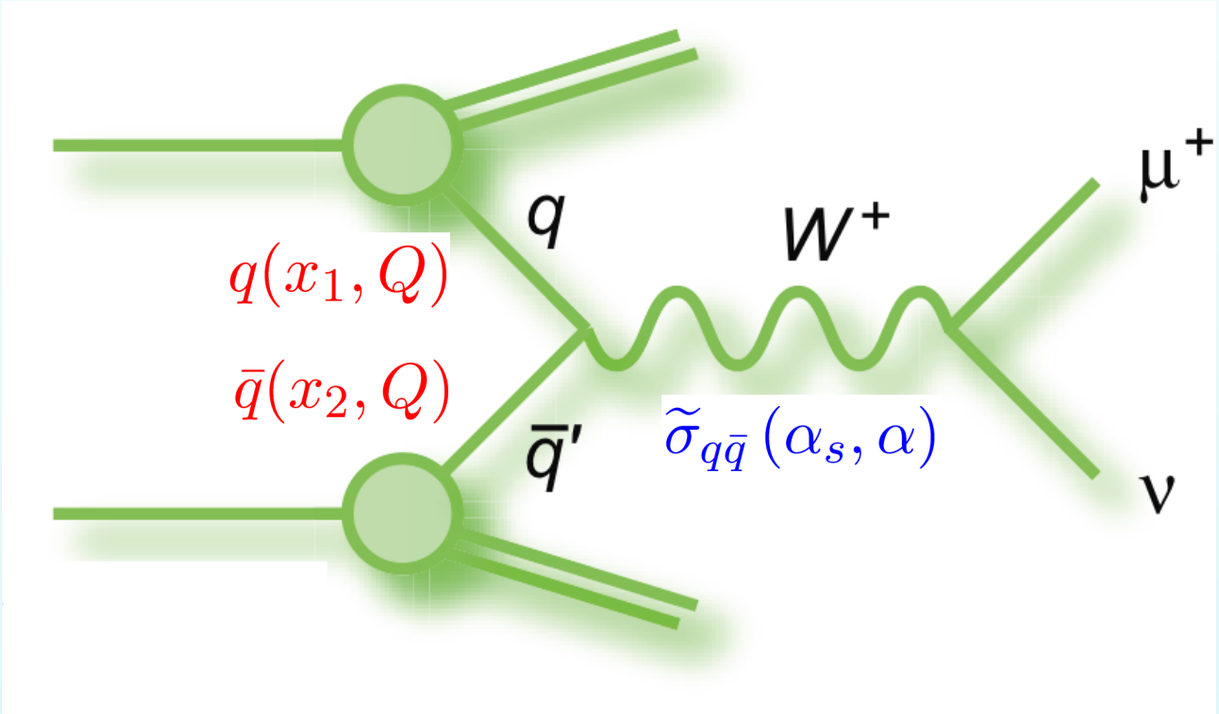
The Factorization Theorem

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

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

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





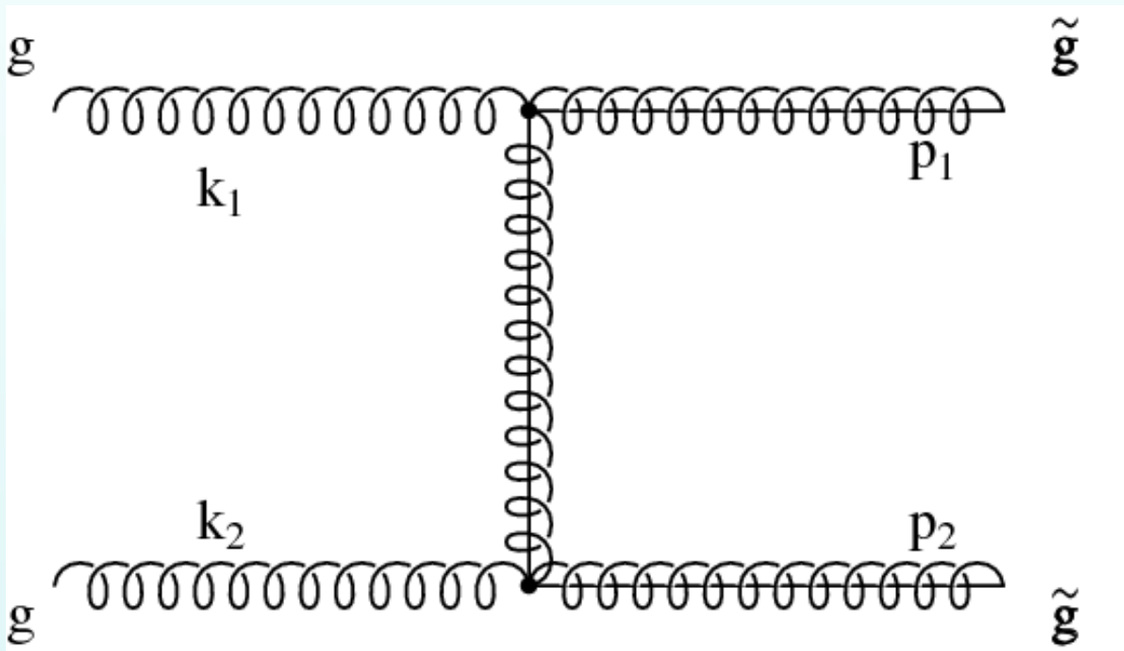
Determine PDFs in lepton-proton collisions ....

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

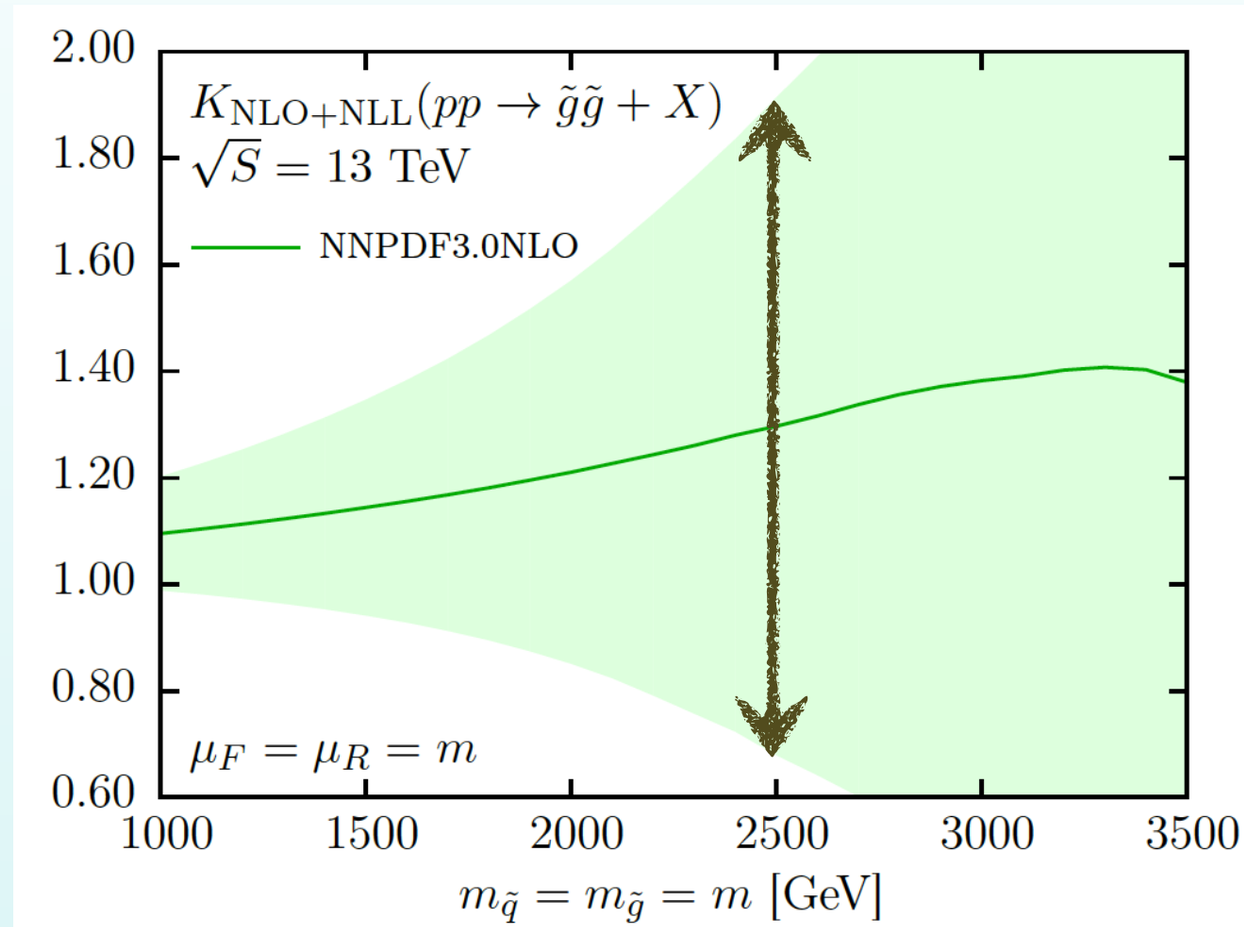
Beyond BSM discovery

PDF uncertainties in the production of **New Physics heavy resonances** can be al large as **100%!**

Crucial *i.e.* in searches for ***supersymmetry*** and any BSM scenario that predicts new heavy particles within the reach of the LHC



Gluino pair production at the LHC



Beenakker, Borchensky, Kramer, Kulesza, Laenen, Marzani, Rojo 13

*Unless we **improve PDF uncertainties**, even if we discover New Physics, it will be extremely **difficult to characterise the underlying BSM scenario***

ANNs as universal unbiased interpolants

ANNs provide **universal unbiased interpolants** to parametrize the non-perturbative dynamics that determines the **size and shape of the PDFs** from experimental data

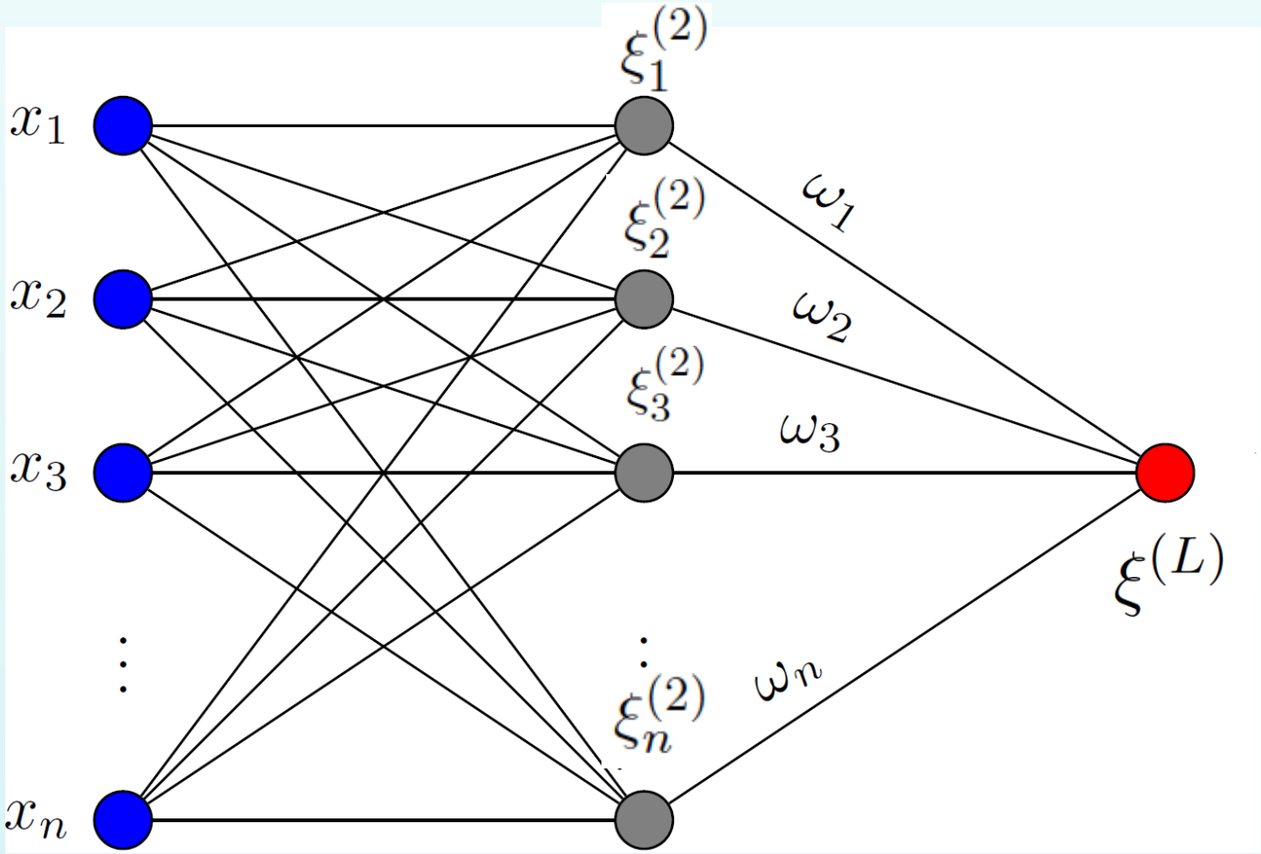
not from QCD!

Traditional approach

$$g(x, Q_0) = A_g (1-x)^{a_g} x^{-b_g} \left(1 + c_g \sqrt{s} + d_g x + \ldots\right)$$

NNPDF approach

$$g(x, Q_0) = A_g \mathrm{ANN}_g(x)$$



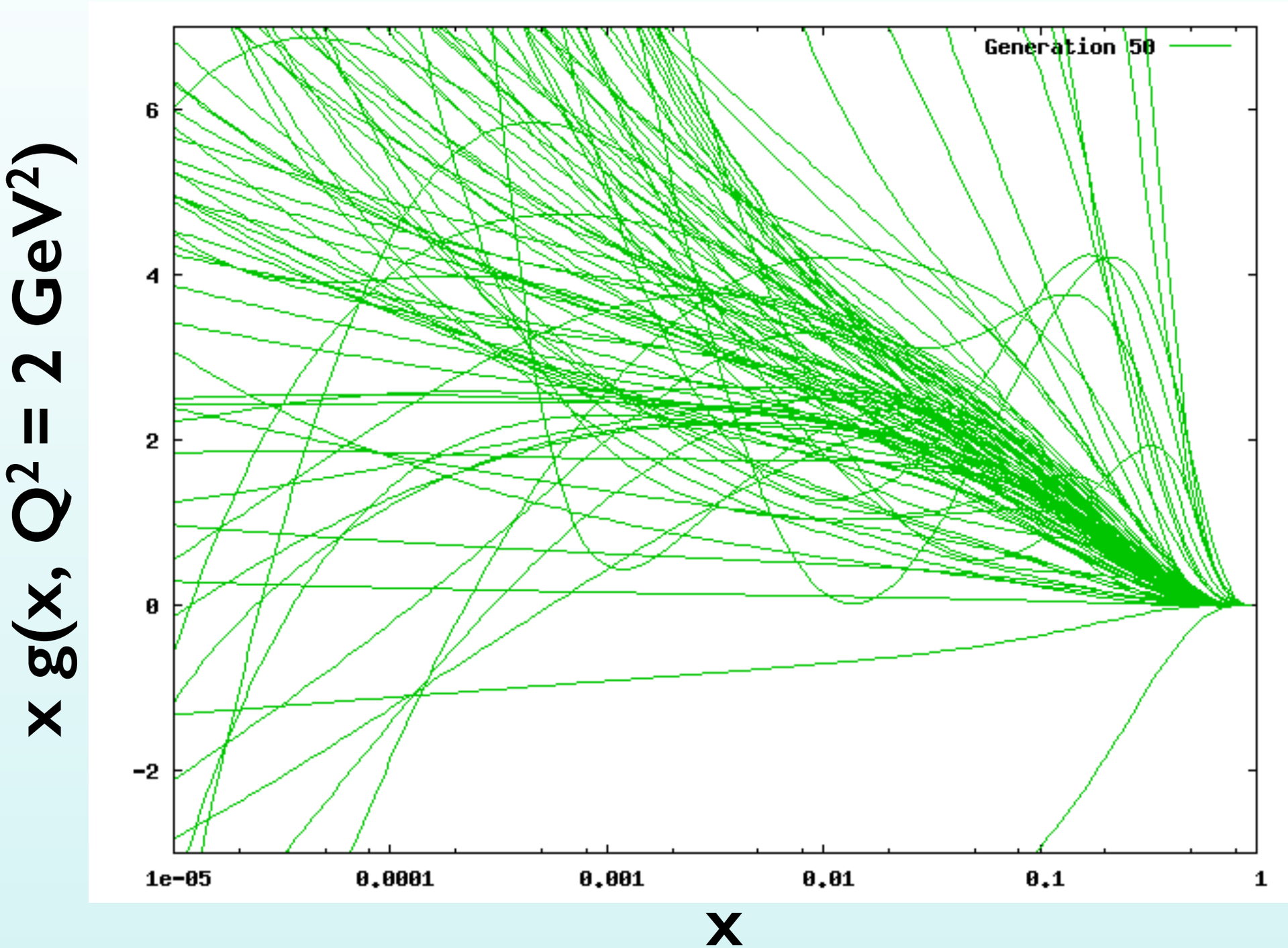
$$\mathrm{ANN}_g(x) = \xi^{(L)} = \mathcal{F}\left[\xi^{(1)}, \{\omega_{ij}^{(l)}\}, \{\theta_i^{(l)}\}\right]$$

$$\xi_i^{(l)} = g\left(\sum_{j=1}^{n_{l-1}} \omega_{ij}^{(l-1)} \xi_j^{(l-1)} - \theta_i^{(l)}\right)$$

- ANNs eliminate **theory bias** introduced in PDF fits from choice of *ad-hoc* functional forms
- NNPDF fits used **O(400) free parameters**, to be compared with O(10-20) in traditional PDFs. Results stable if **O(4000) parameters used!**

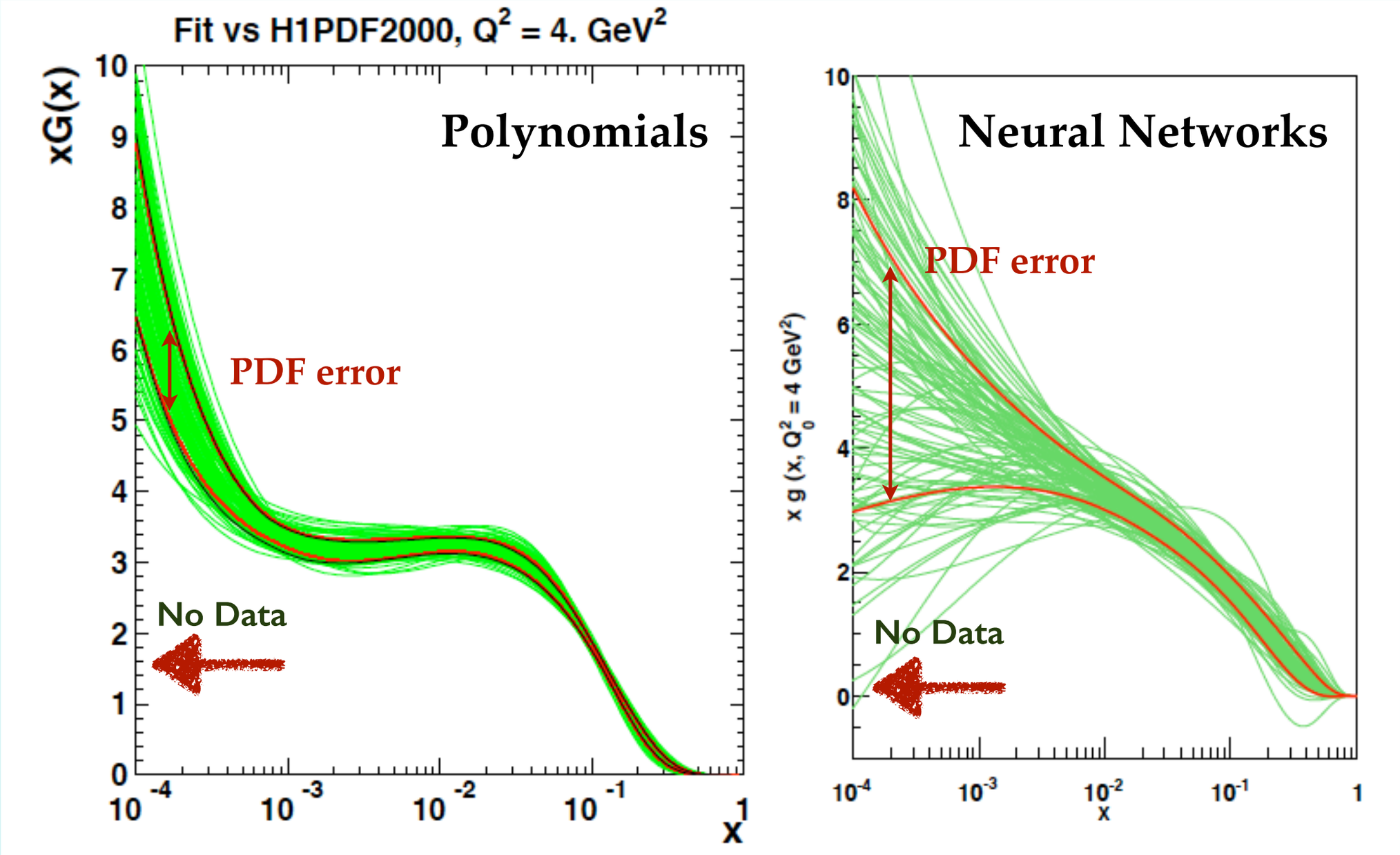
PDF Replica Neural Network Learning

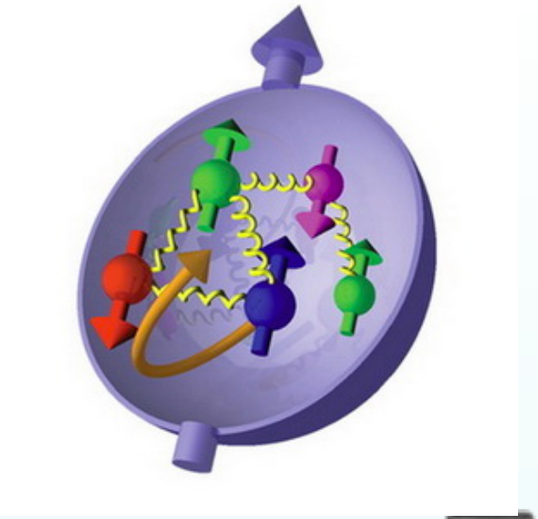
The minimisation of the **data vs theory χ^2** is performed using **Genetic Algorithms**
Each **green curve** corresponds to a **gluon PDF Monte Carlo** replica



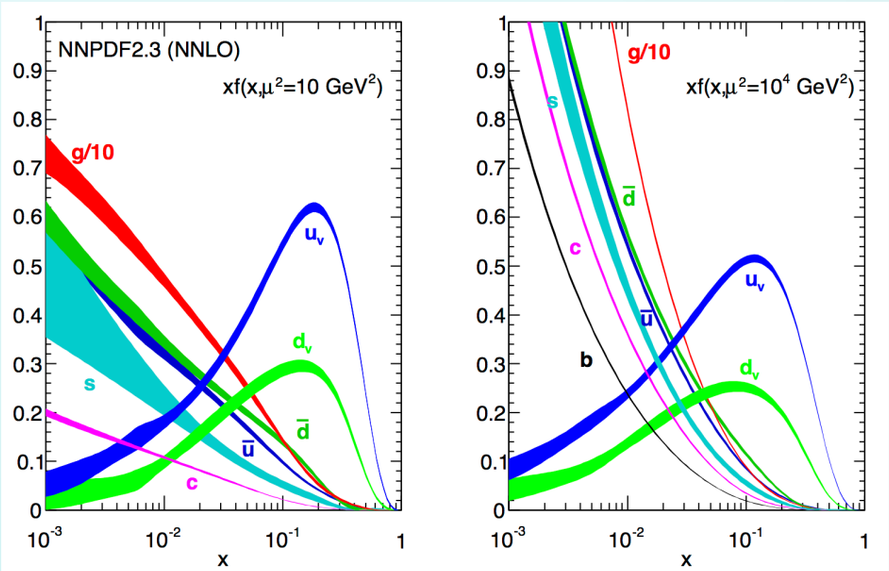
Artificial Neural Networks vs Polynomials

- Compare a **benchmark PDF analysis** where **the same dataset** is fitted with **Artificial Neural Networks** and with **standard polynomials,** other settings identical)
- **ANNs** avoid biasing the PDFs, **faithful extrapolation at small-x** (very few data, thus error blow up)

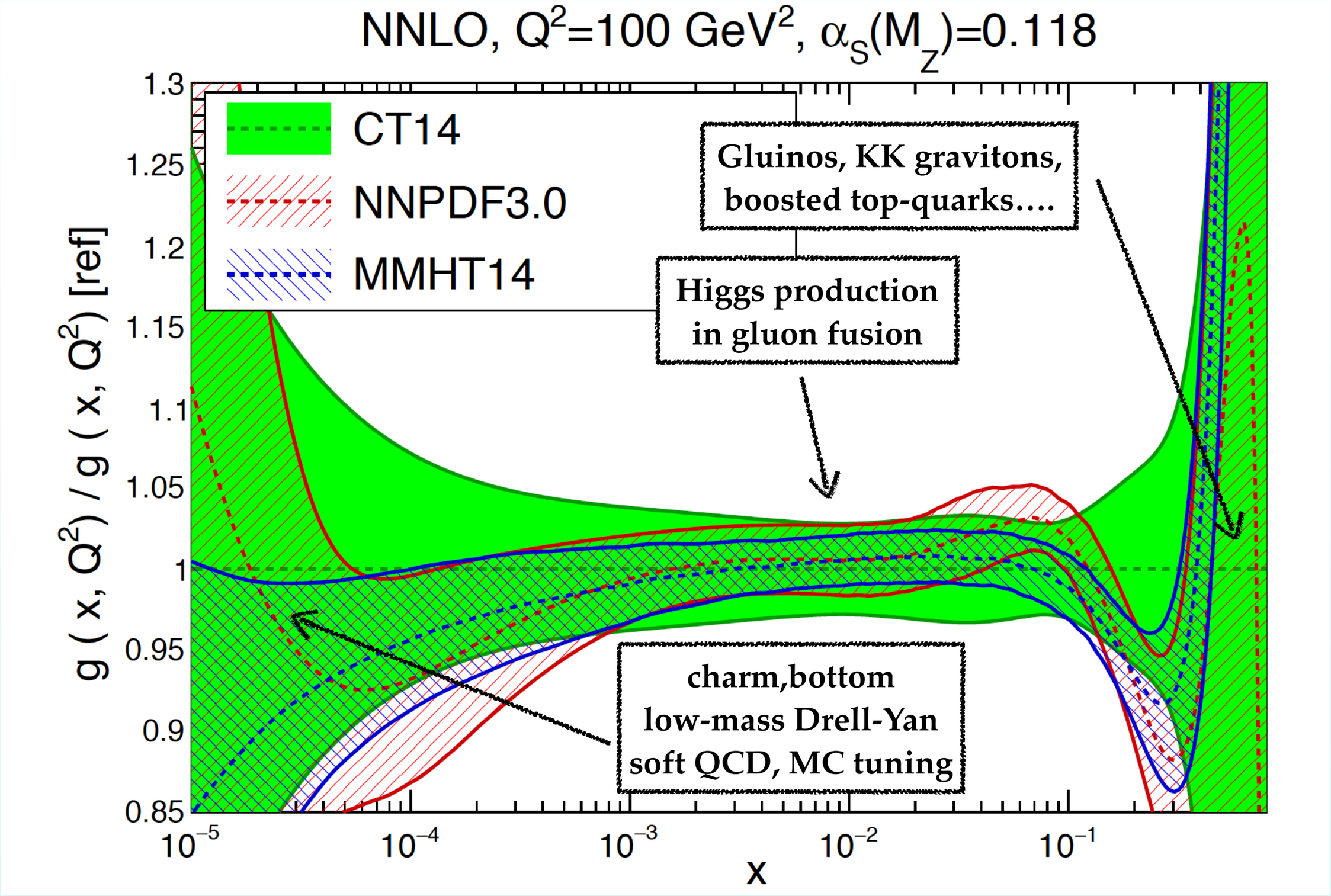




The Small-x Gluon and Ultra High Energy Astrophysics



One glue to bind them all

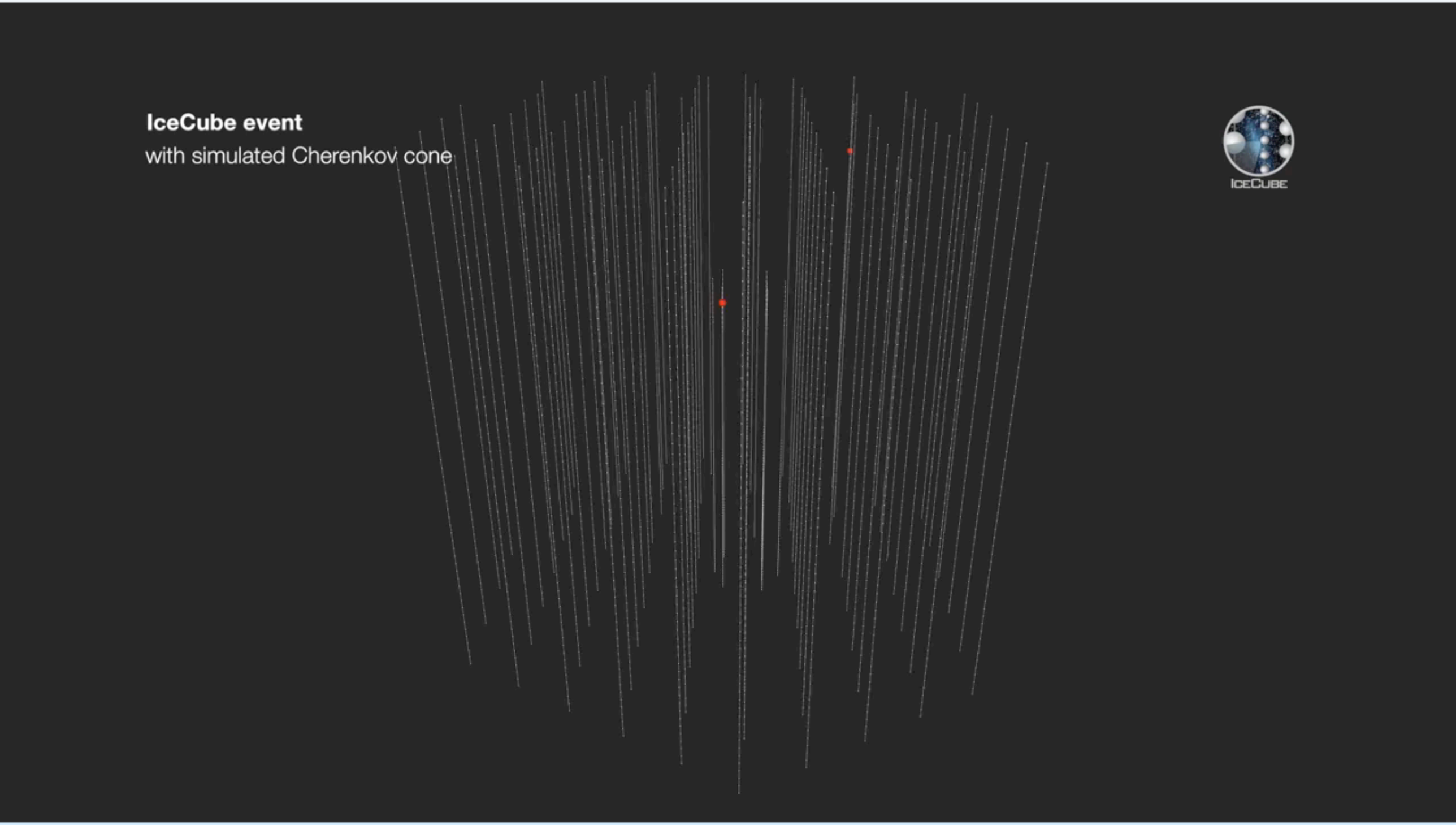


Exploit PDF-sensitive LHC measurements to **constrain the gluon from small to large-x!**

The prompt flux at neutrino telescopes

Observation of Ultra-High Energy (UHE) neutrino events heralds start of **Neutrino Astronomy**

New window to the Universe, but interpretation of UHE data requires **control over backgrounds**



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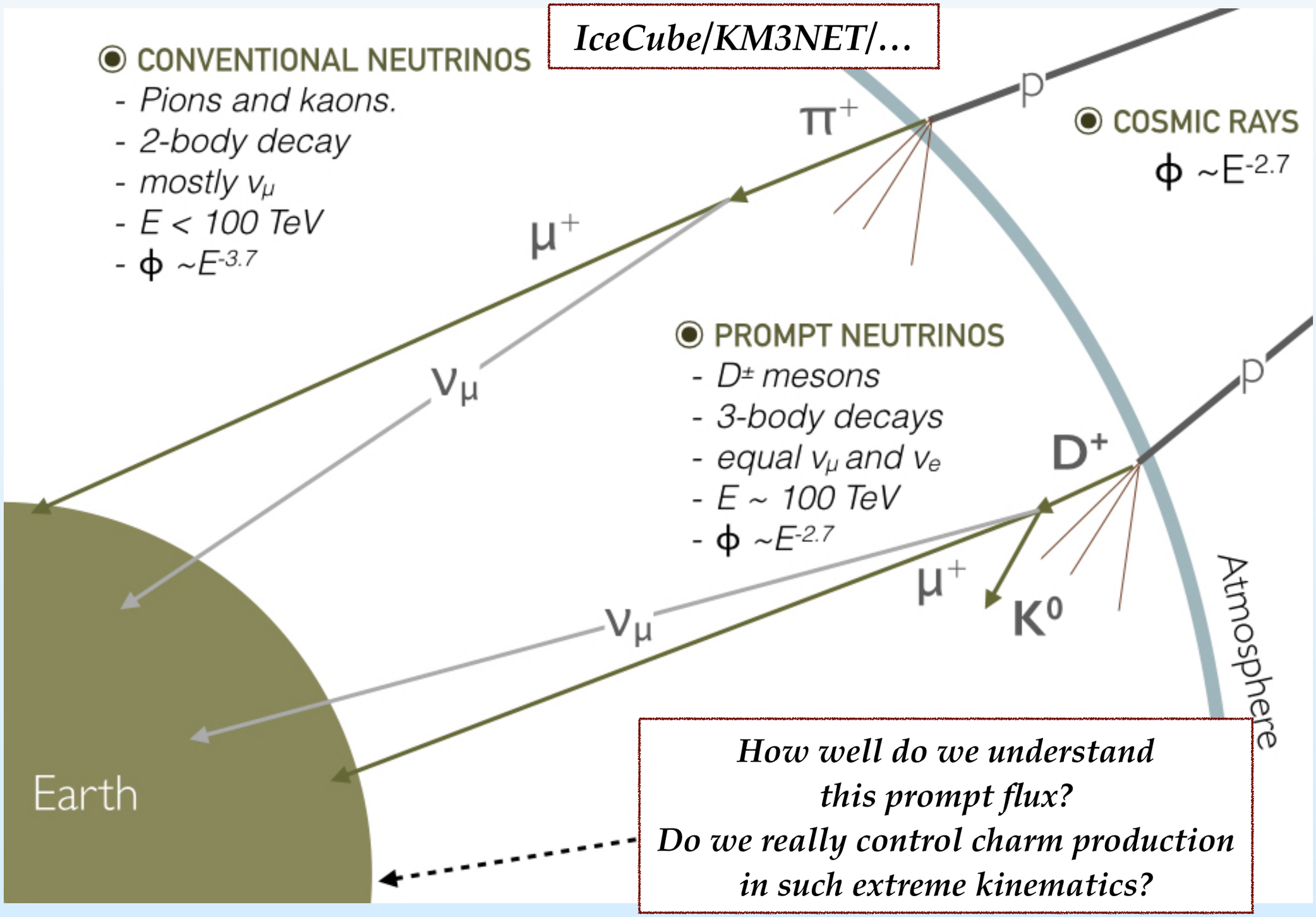
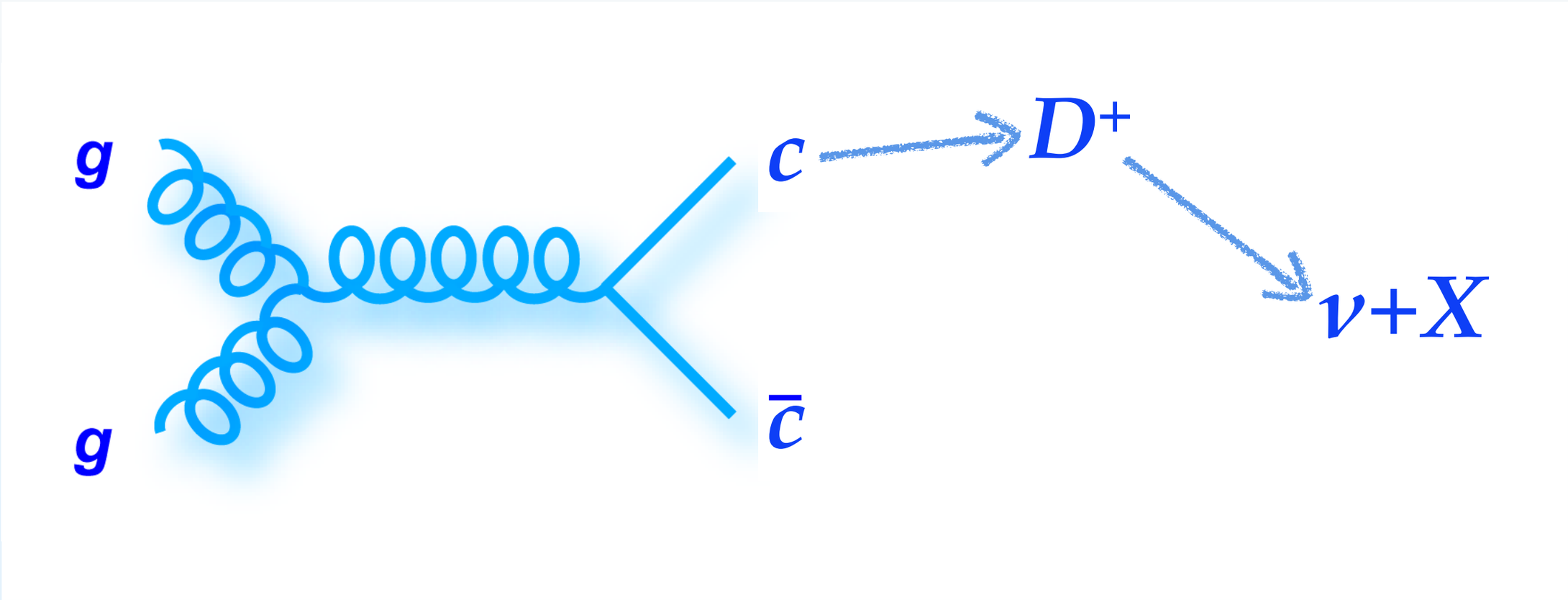
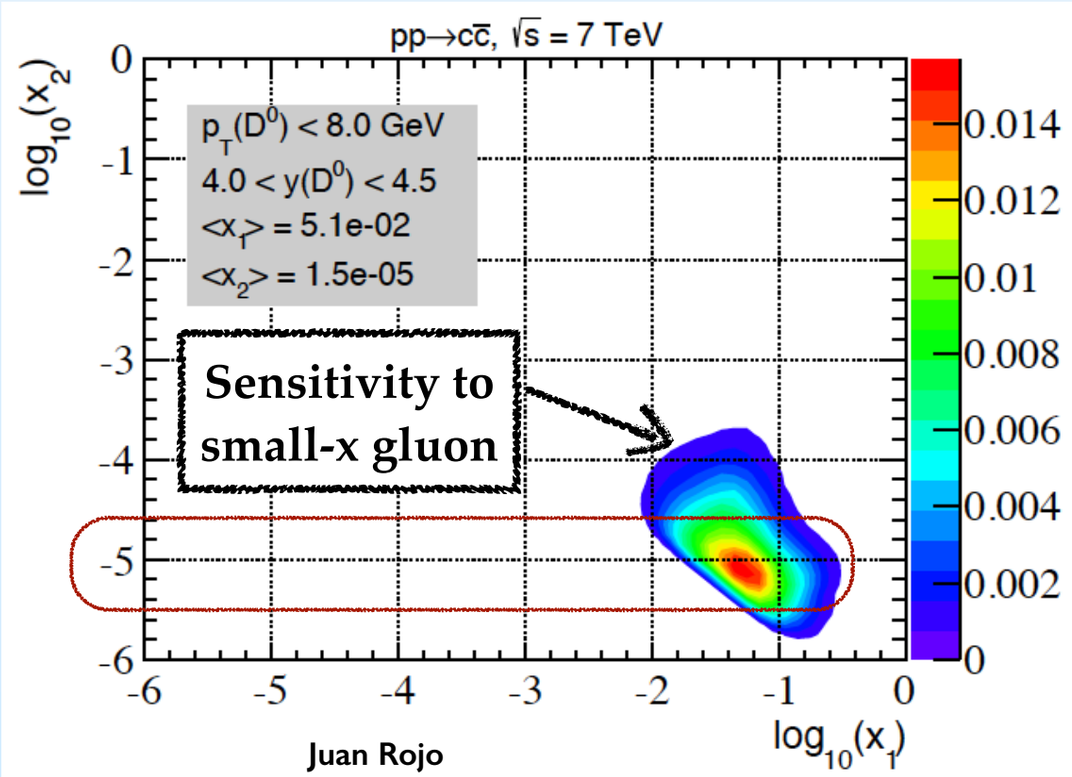


The low-x gluon from charm production





Lab frame $E_{lab} = (2m_p E_{CR})^{1/2}$

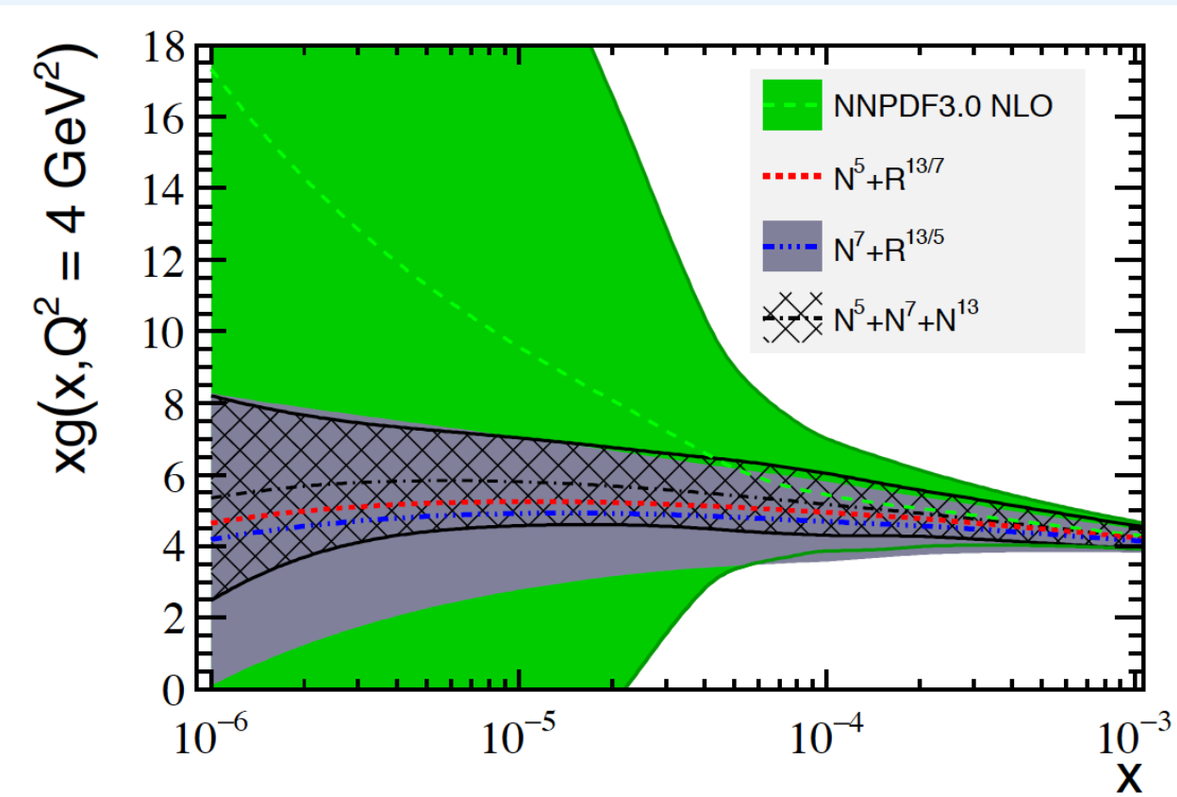
$E_{CR} = 100\ PeV \longrightarrow E_{lab} \approx 14\ TeV$

Overlap kinematics between charm production in UHE cosmic rays and at the LHC

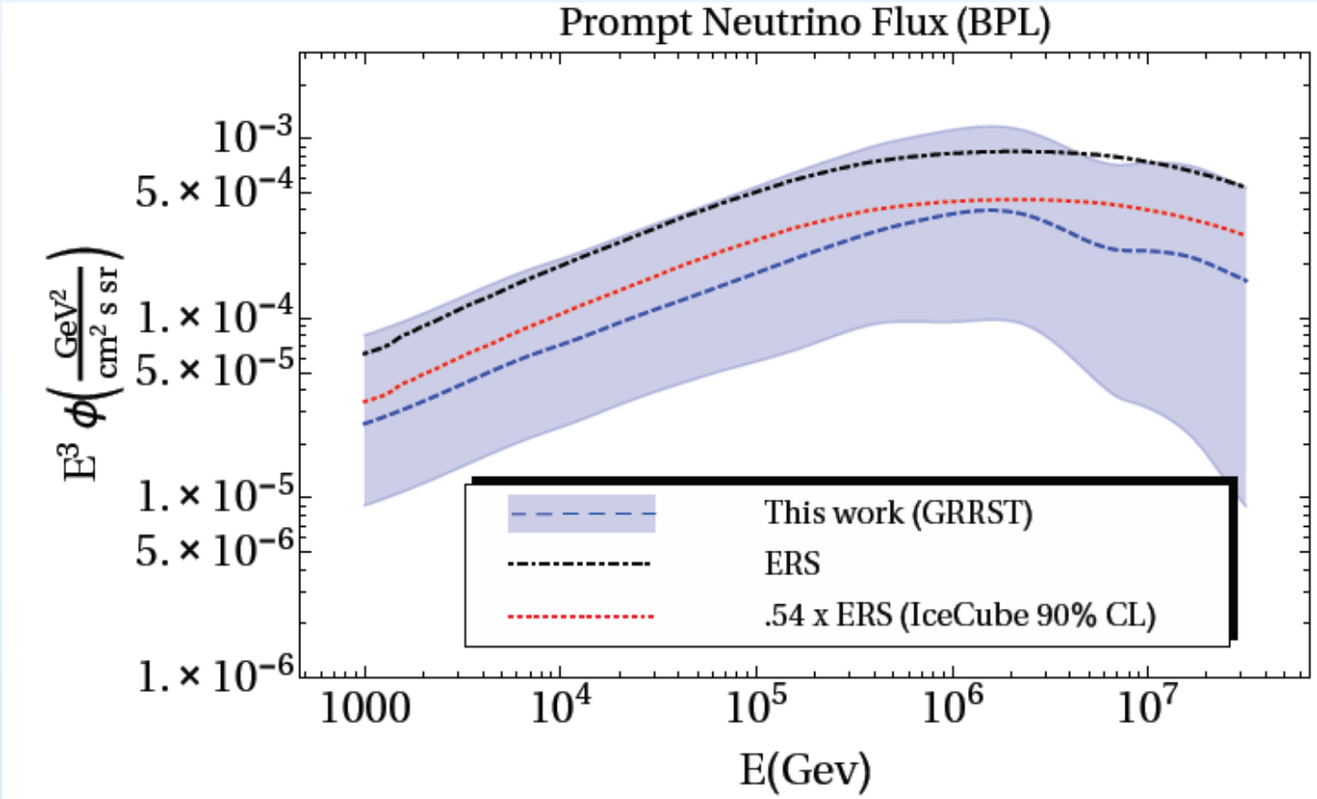
The low-x gluon from charm production

Strategy: use **LHC data** to provide state-of-the-art **predictions for backgrounds at neutrino telescopes**

- ☑ Include **LHCb forward charm production data** (5+7+13 TeV) in the global fit
- ☑ Validate **perturbative QCD calculations** on collider data, and **constrain the small-x gluon**
- ☑ Compute optimised predictions for **prompt neutrino fluxes at high energies**

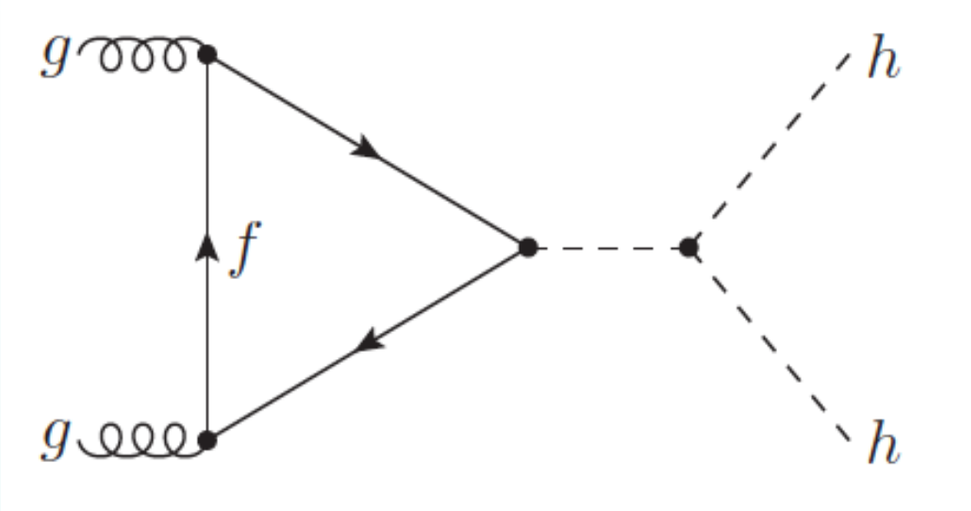


Gauld, Rojo 16

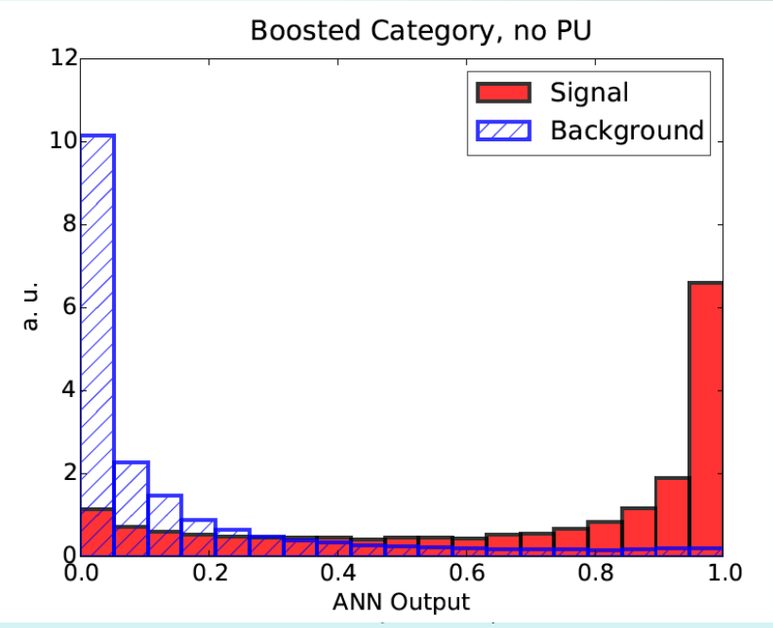


Gauld, Rojo, Rottoli, Sarkar, Talbert 15

We predict that detection of the prompt neutrino flux should be within reach!

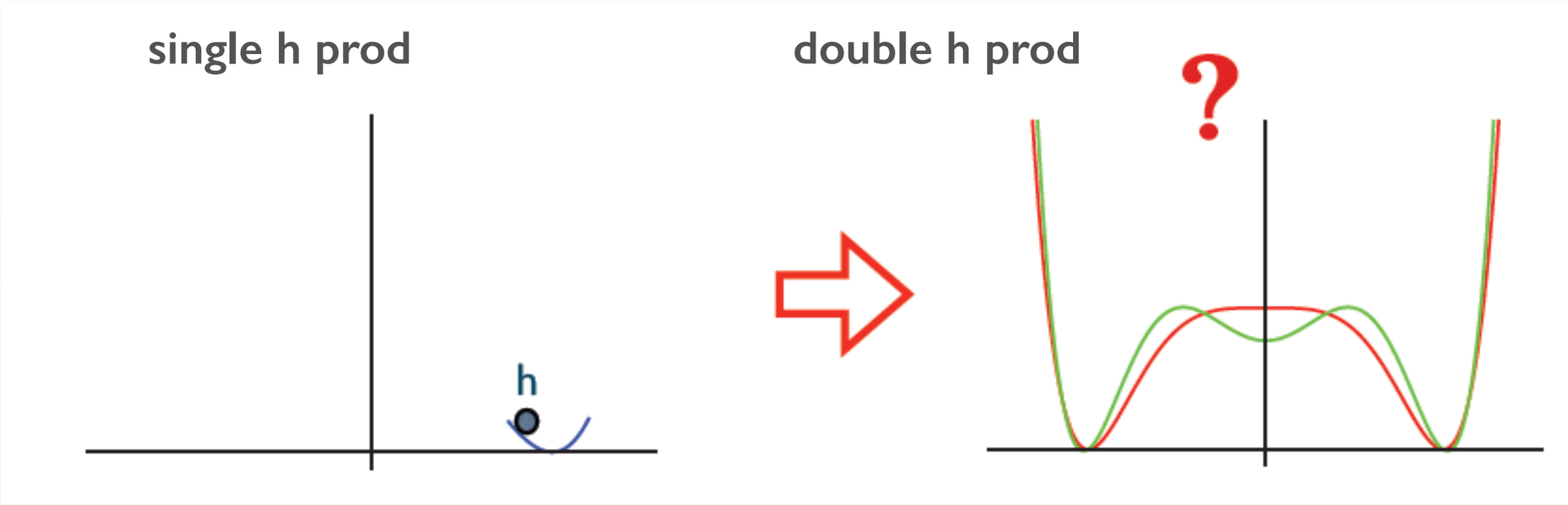


Does the God Particle talk to Itself?
Unravelling the Higgs Self-Coupling



Probing Electroweak Symmetry breaking

- **Current measurements** (couplings in single Higgs production) probe **Higgs potential close to minimum**
- Double Higgs production essential to **reconstruct the full Higgs potential** and clarify EWSB mechanism
- Higgs SM potential is *ad-hoc*: not fixed by the SM symmetries, **many other EWSB mechanisms conceivable**



Higgs mechanism

$$V(h) = m_h^2 h^\dagger h + \frac{1}{2}\lambda (h^\dagger h)^2$$

Coleman-Weinberg mechanism

$$V(h) \to \frac{1}{2}\lambda (h^\dagger h)^2 \log\left[\frac{(h^\dagger h)}{m^2}\right]$$

Each possibility associated to **completely different EWSB mechanism**, with crucial implications for the **hierarchy problem**, the structure of quantum field theory, and **New Physics at the EW scale**

Arkani-Hamed, Han, Mangano, Wang, arxiv:1511.06495

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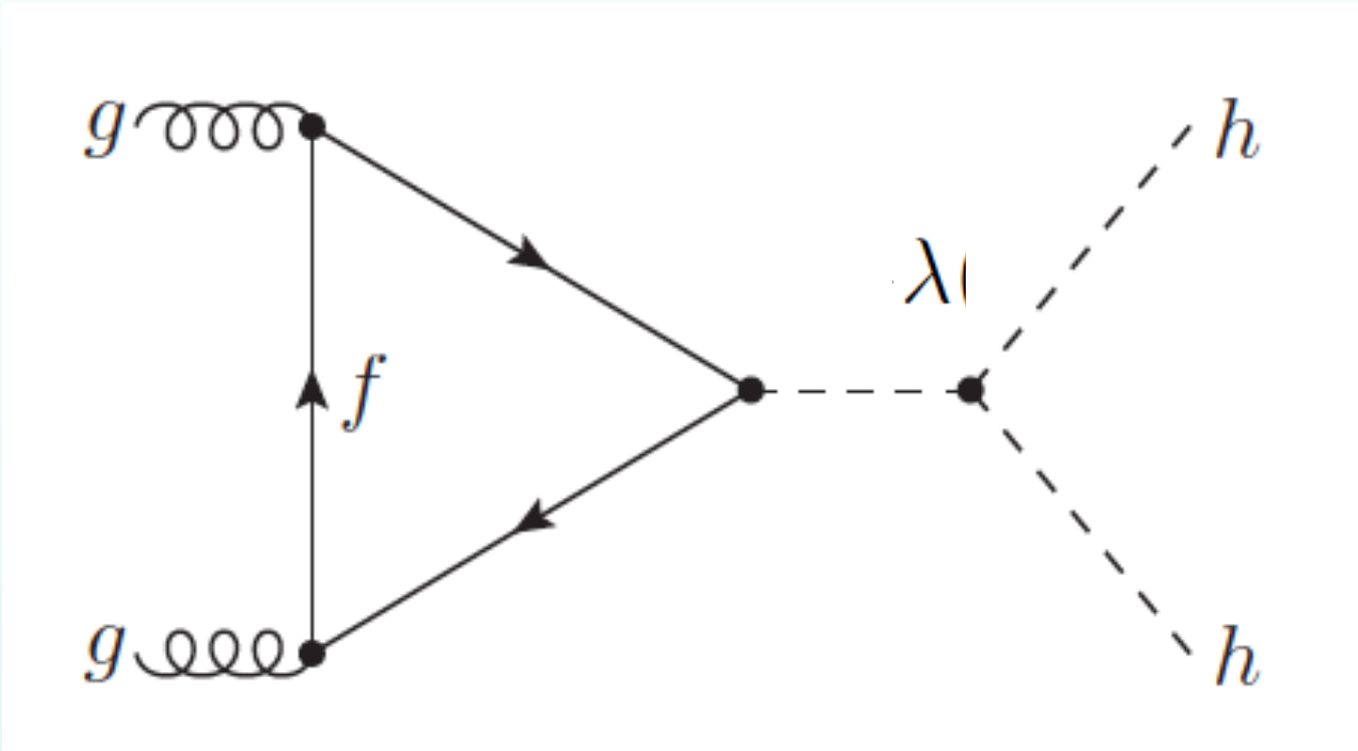

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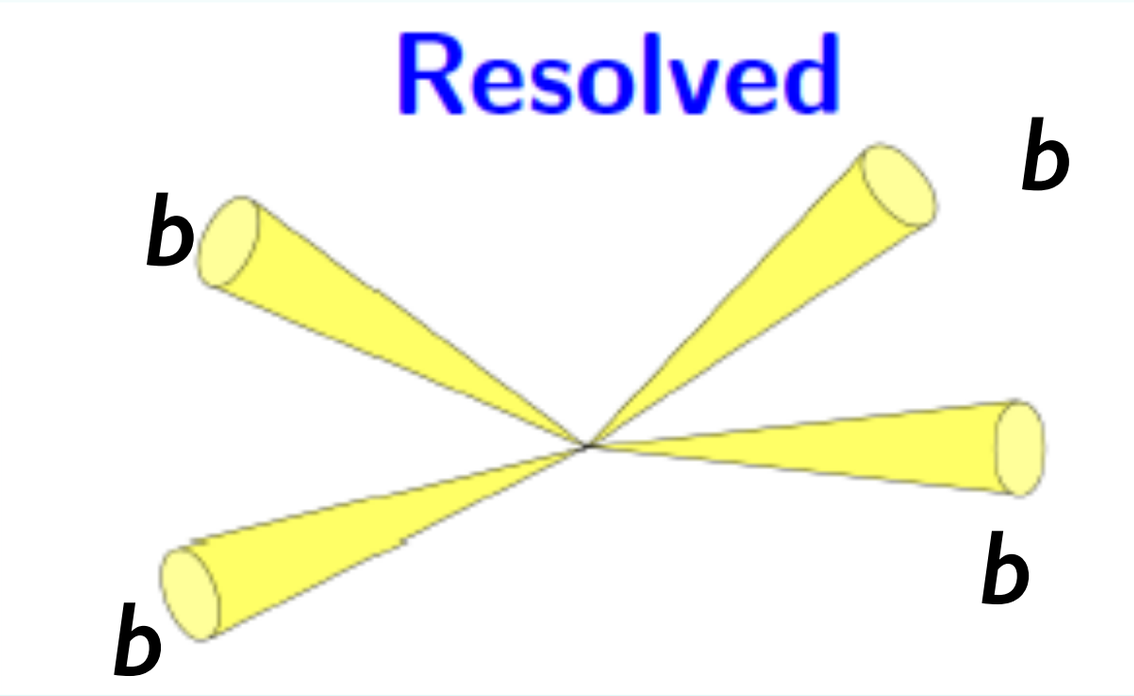
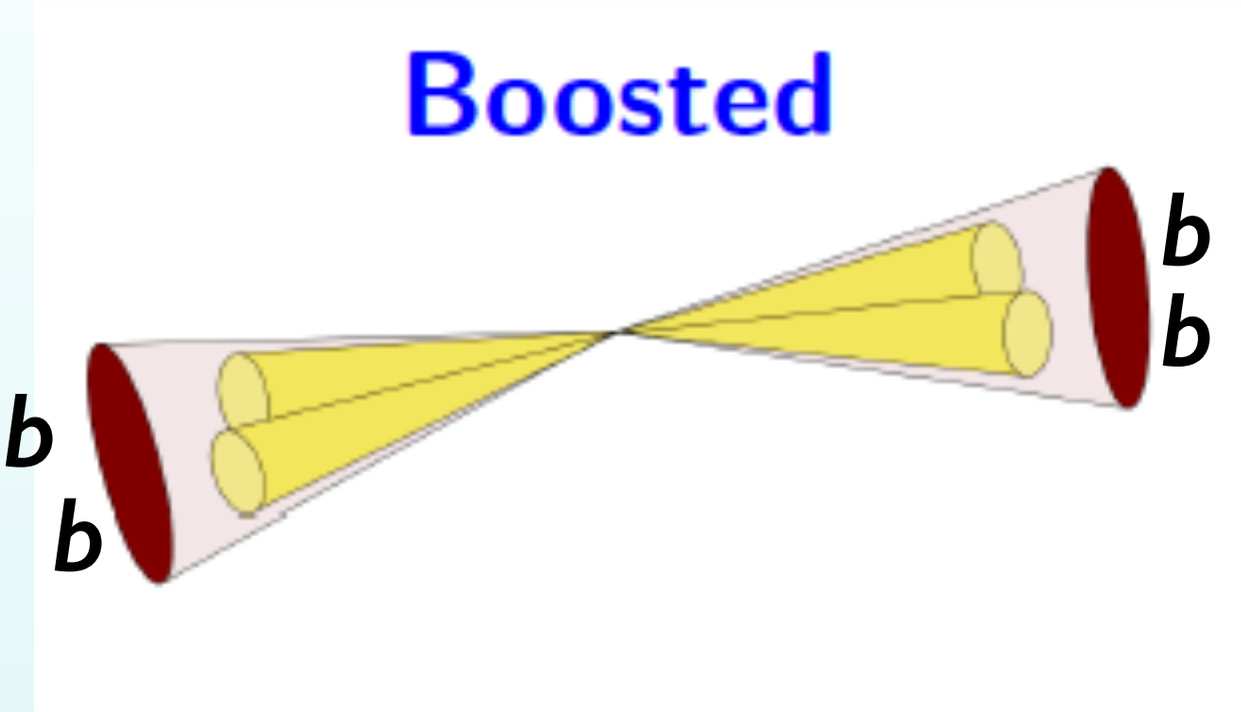
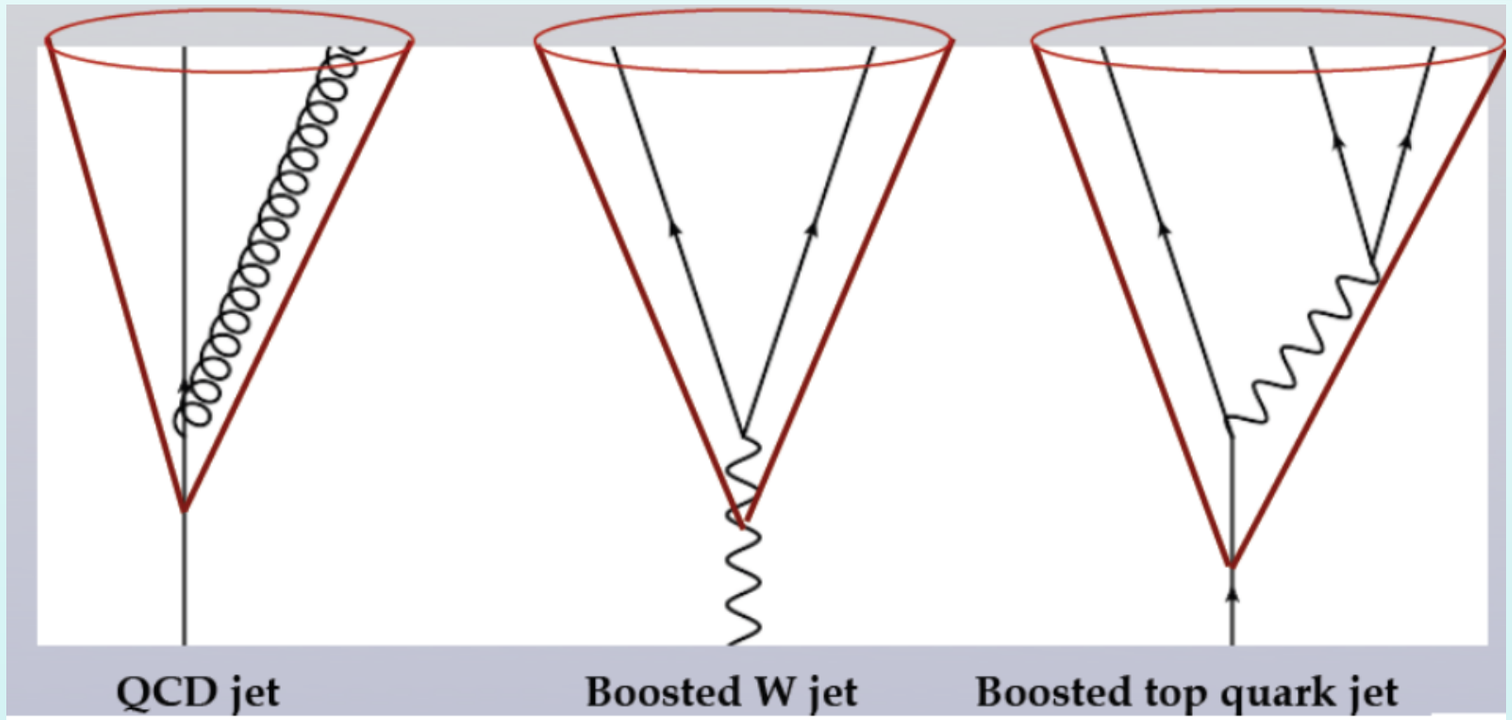
hh->bbbb: selection strategy

- Exploit **4b final state**: highest signal yields, but **overwhelming QCD background** (by orders of magnitude!)
- Carefully chosen selection strategies ensure that **all relevant event topologies can be reconstructed**

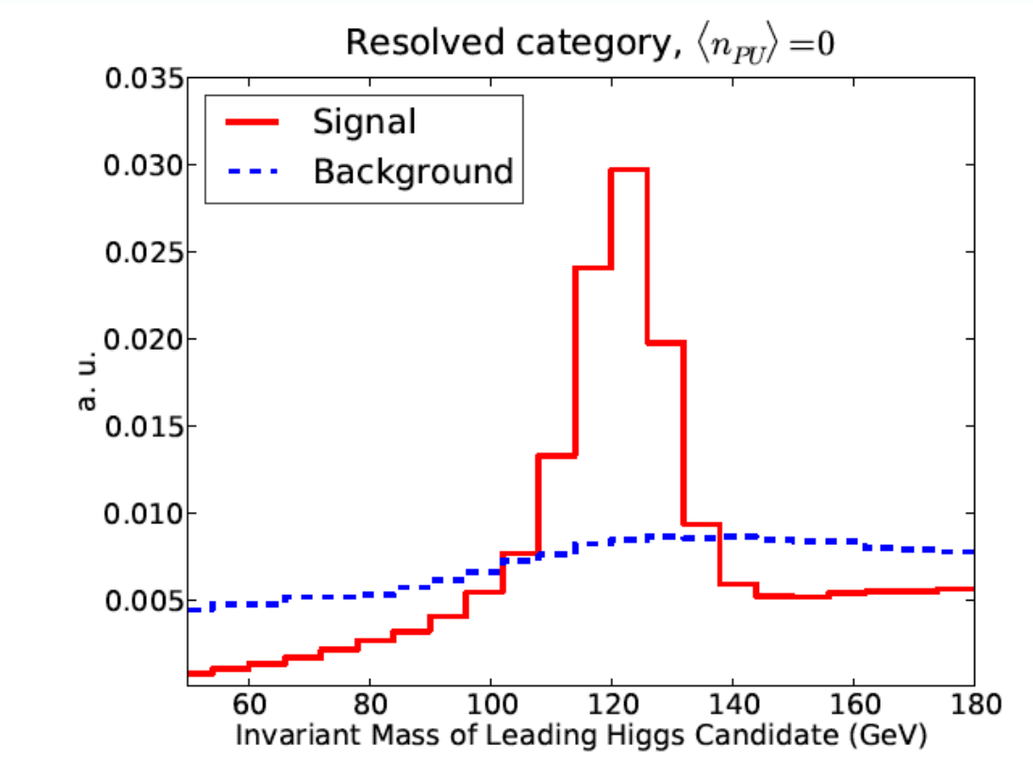


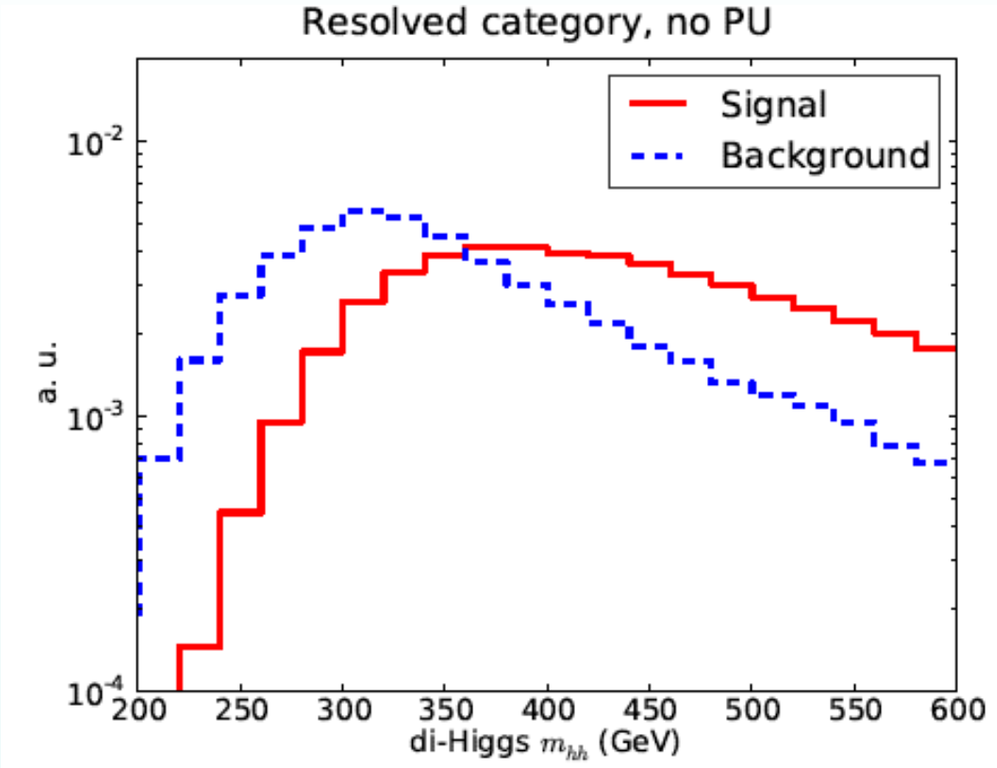


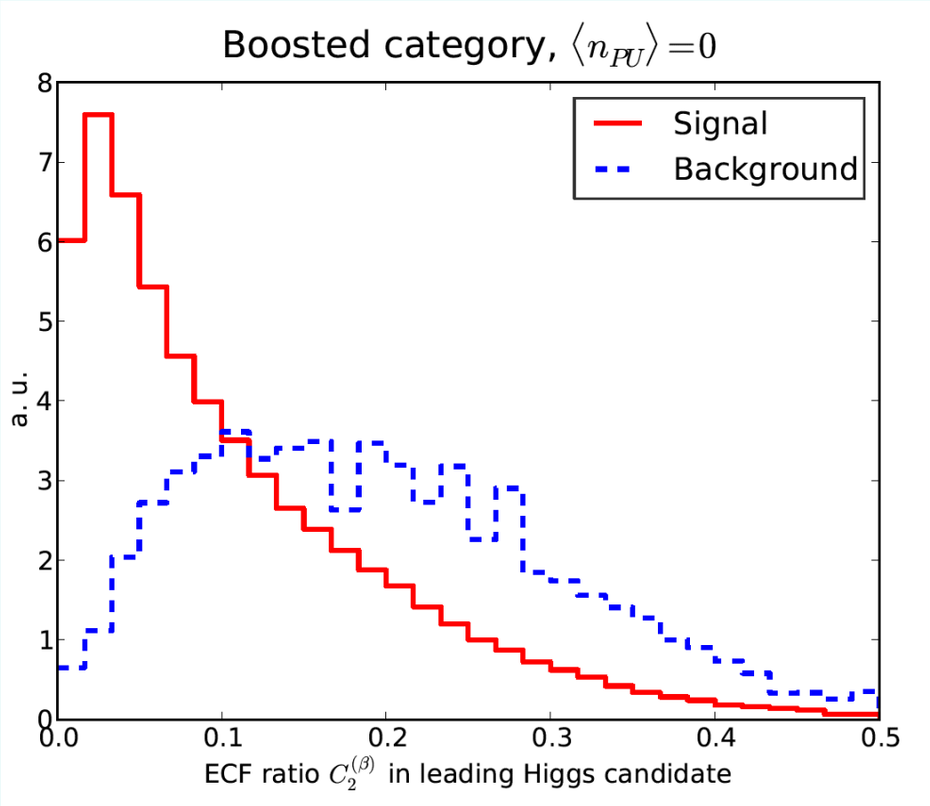
Recent progress in **jet substructure** techniques important to reduced QCD background in the **boosted regime**

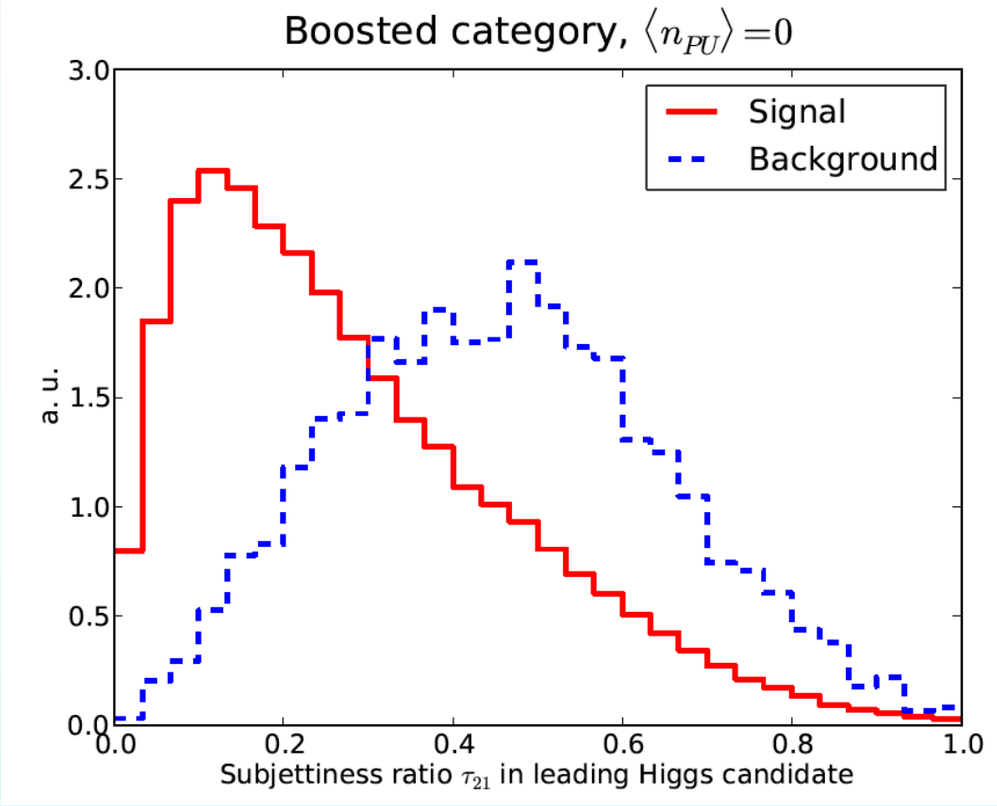


di-Higgs kinematic distributions









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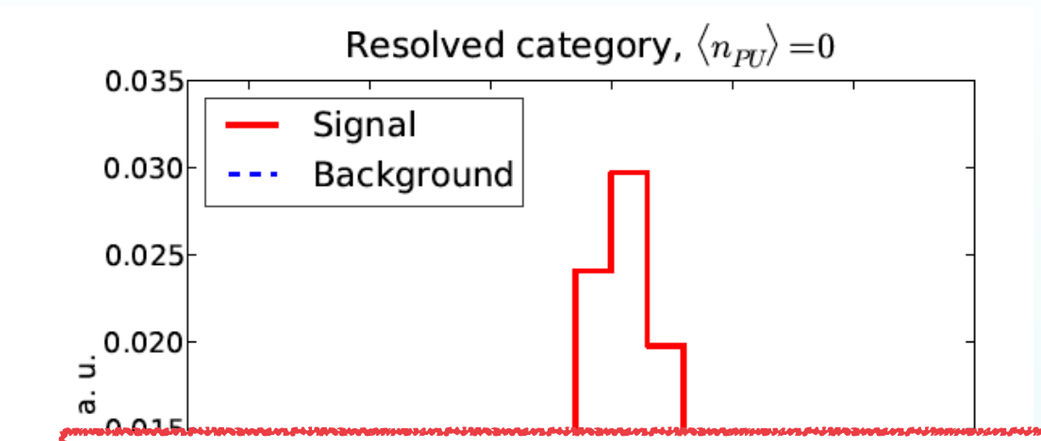
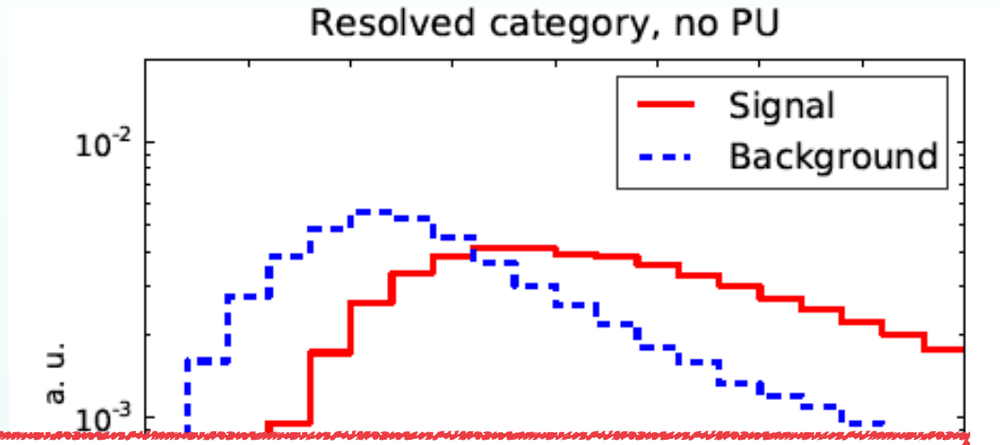
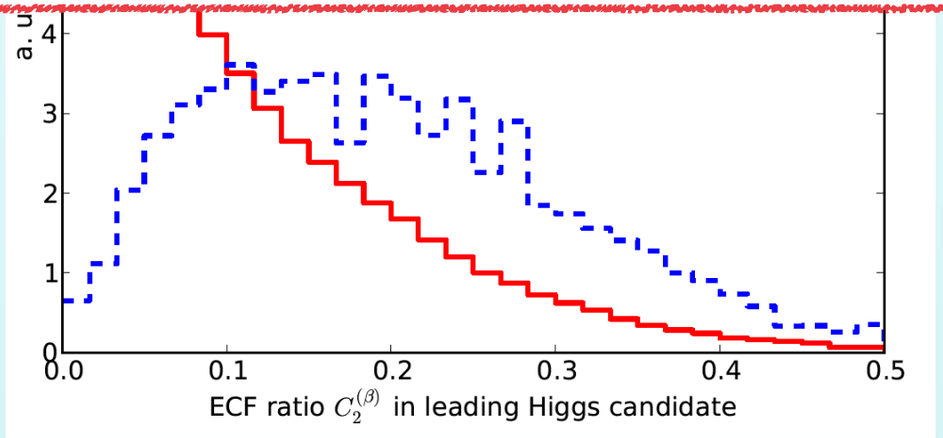


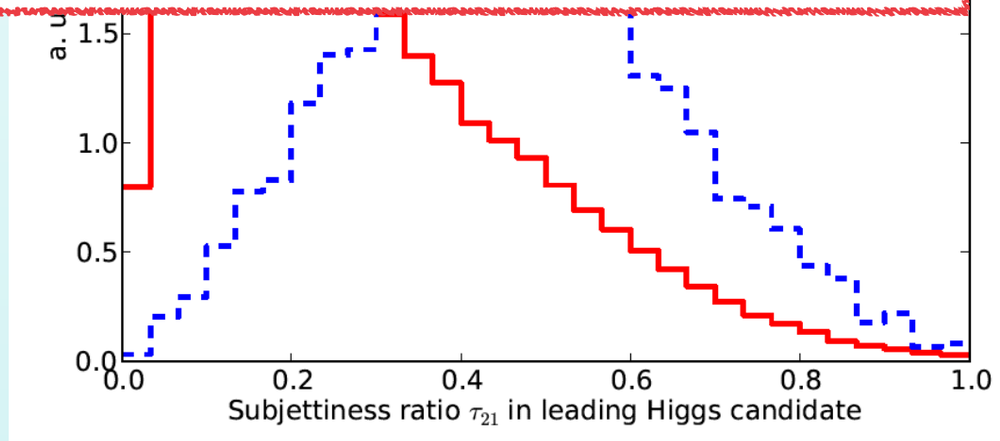


Many kinematic variables can be used to **disentangle signal and background**

How do we select which ones to use? And the optical cuts? And the cross-correlations among variables?

We don't need to! Use **ML methods to identify automatically** the combination of kinematical variables with the highest discrimination power!





Multivariate techniques

Input

Higgs pT

Higgs m

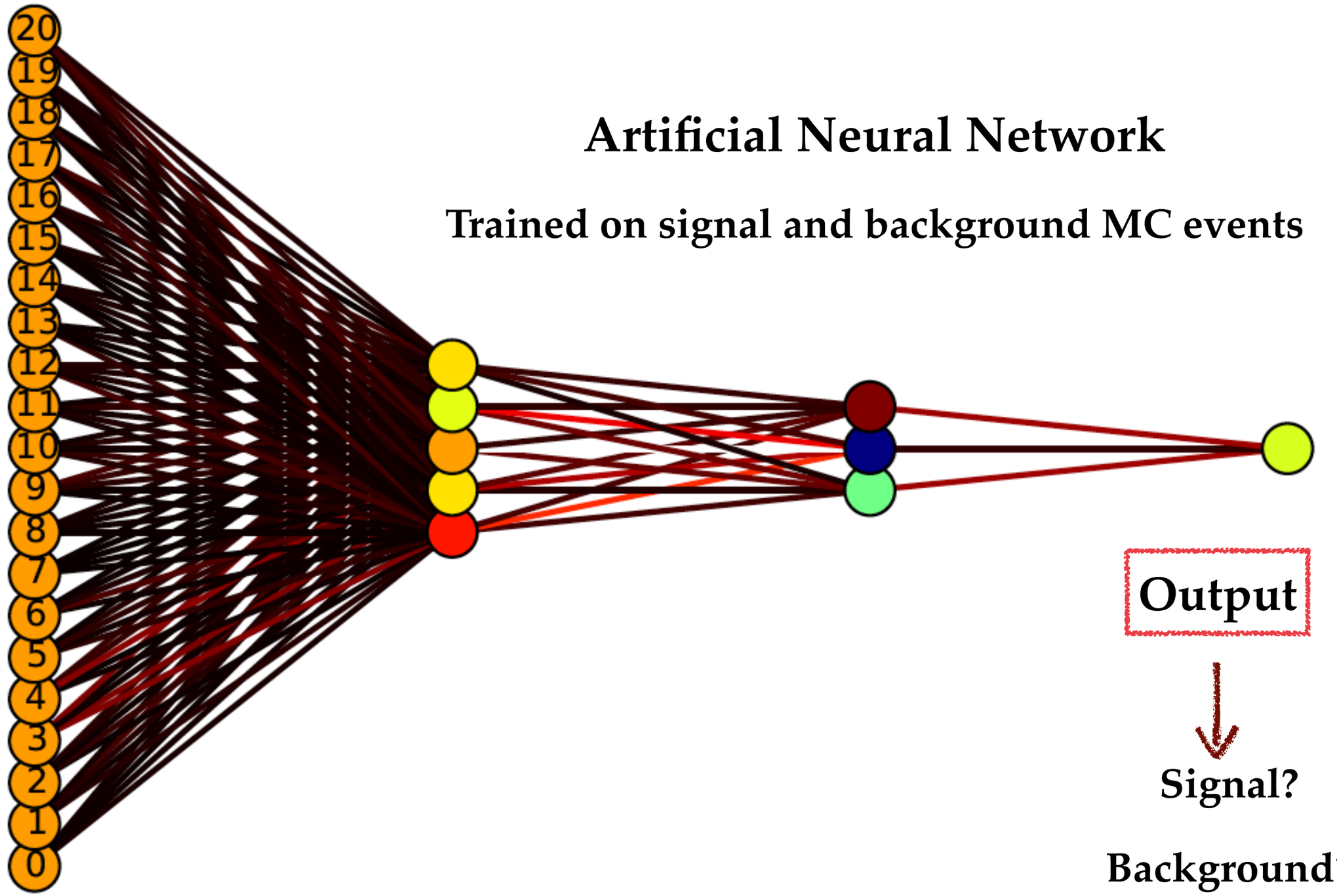
di-Higgs m

ECF

τ_{12}

Subjet pT

.....



Artificial Neural Network

Trained on signal and background MC events

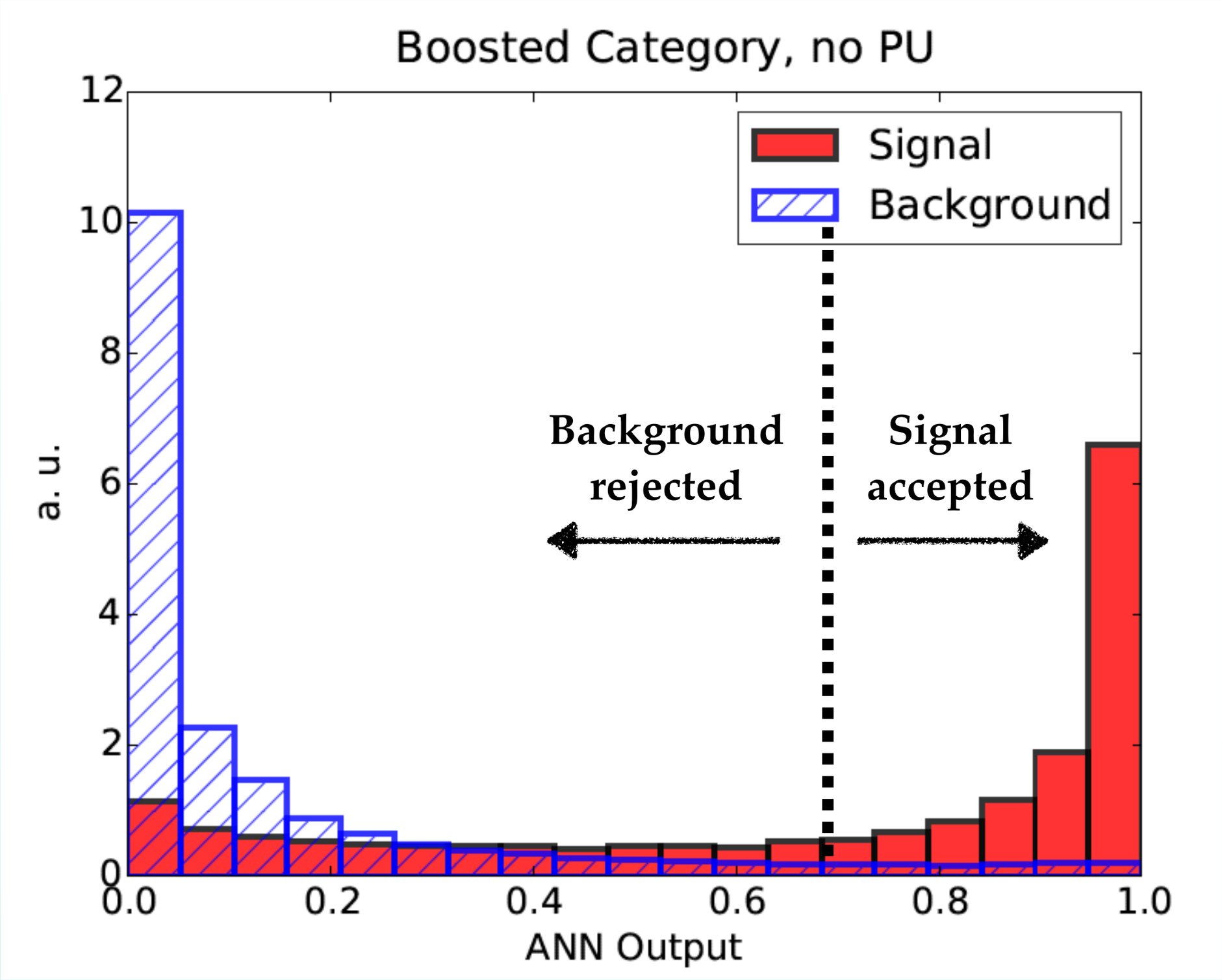
Output

Signal?

Background?

Multivariate techniques

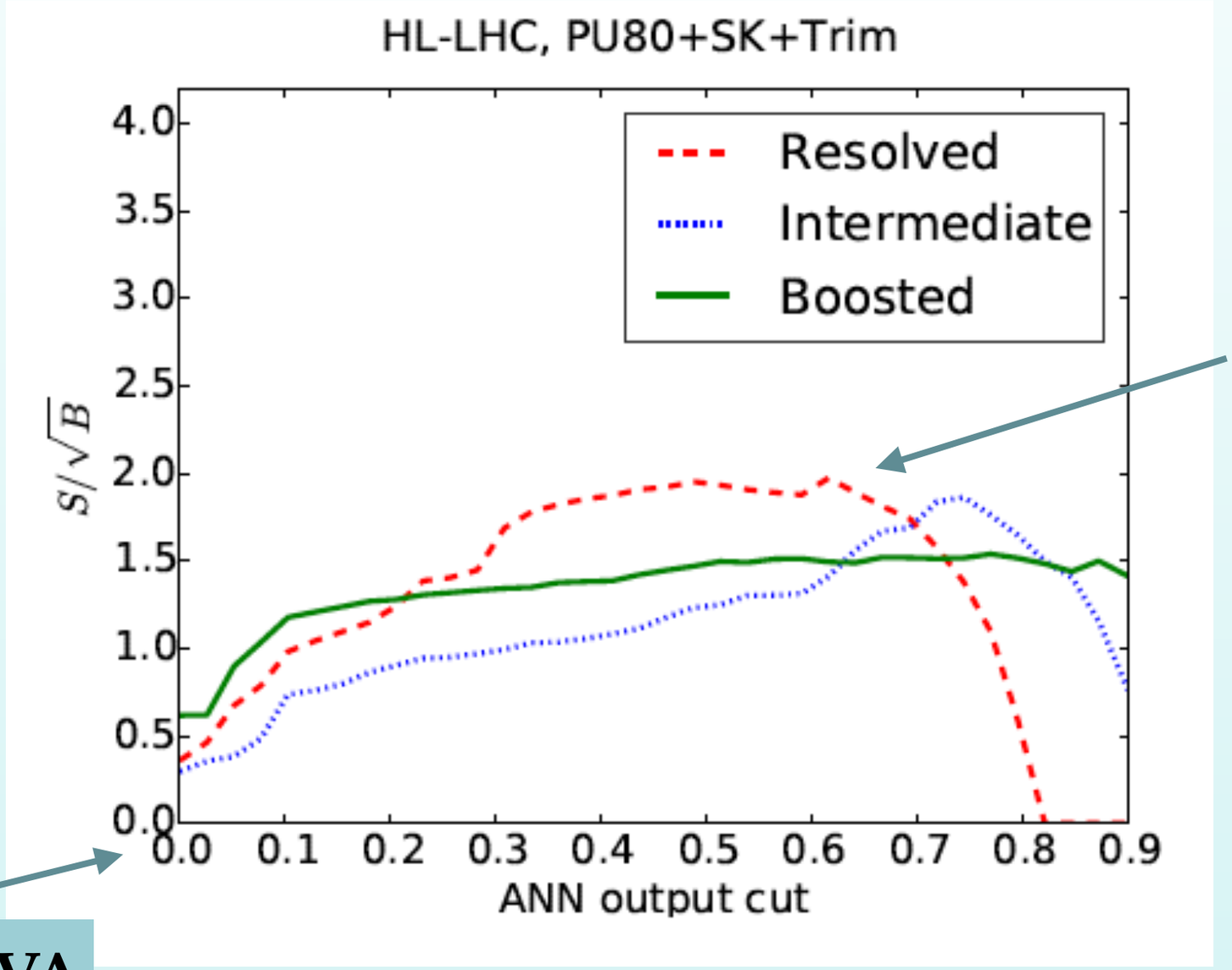
Combining information from all kinematic variables in MVA: **excellent signal/background discrimination**



Discovering Higgs self-interactions

ML techniques allow to **substantially improve the signal significance** for this process **observe Higgs pair production in the 4b final state** at the HL-LHC. Observation (maybe discovery) within reach!

$$\left(\frac{S}{\sqrt{B_{4b}}}\right)_{\text{tot}} \simeq 4.7\ (1.5)\,, \quad \mathcal{L} = 3000\ (300)\ \text{fb}^{-1}$$

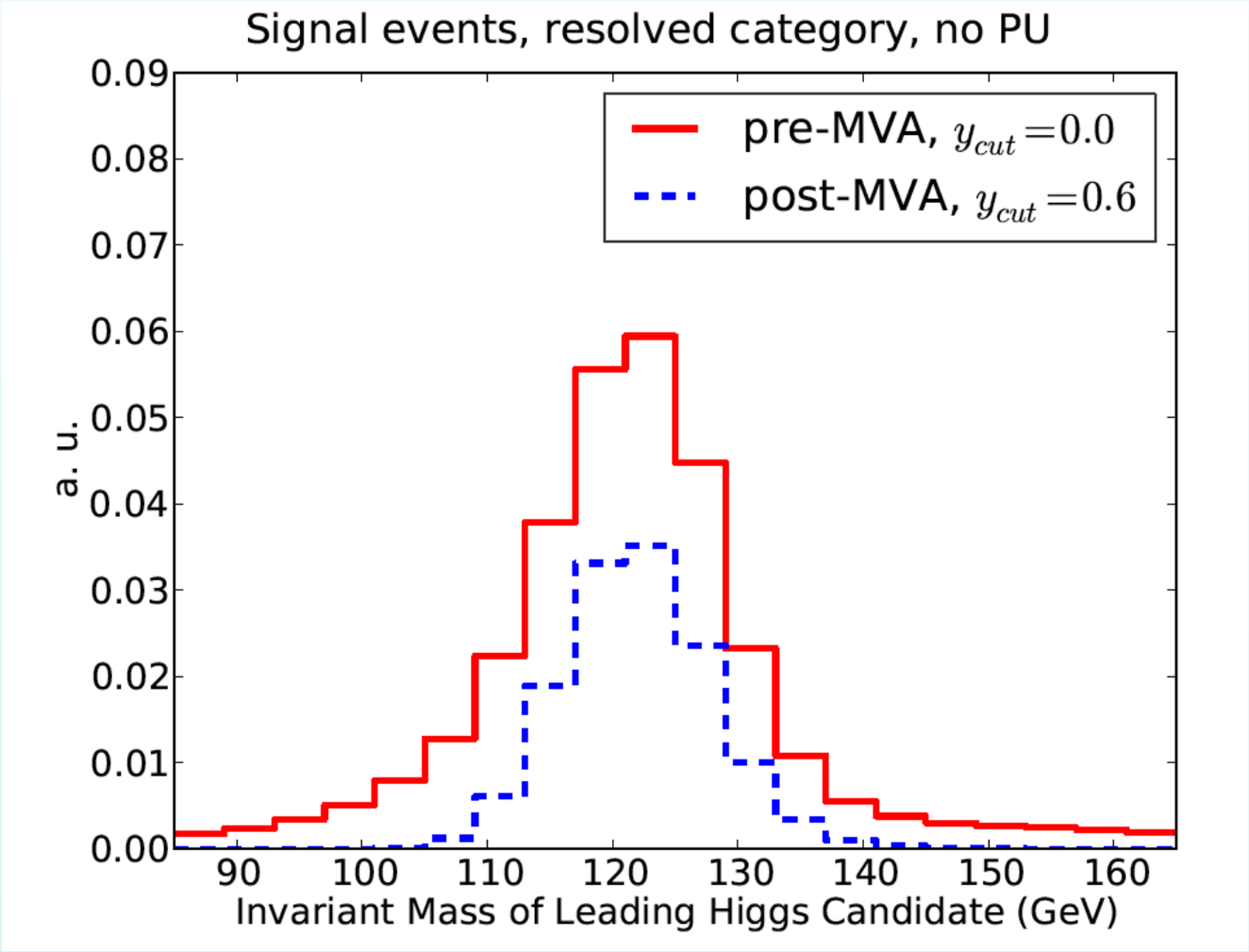


Post MVA

Pre-MVA

Opening the Black Box

- ANNs are sometimes criticised by being **black boxes**, with little understanding of what happens inside them
- But ANNs are simply a **set of combined kinematical cuts**, nothing mysterious in them!
- Kin distributions **after and before the ANN cut** allow determining the **effective kinematic cuts** being optimised by the MVA, which would allow a cut-based analysis



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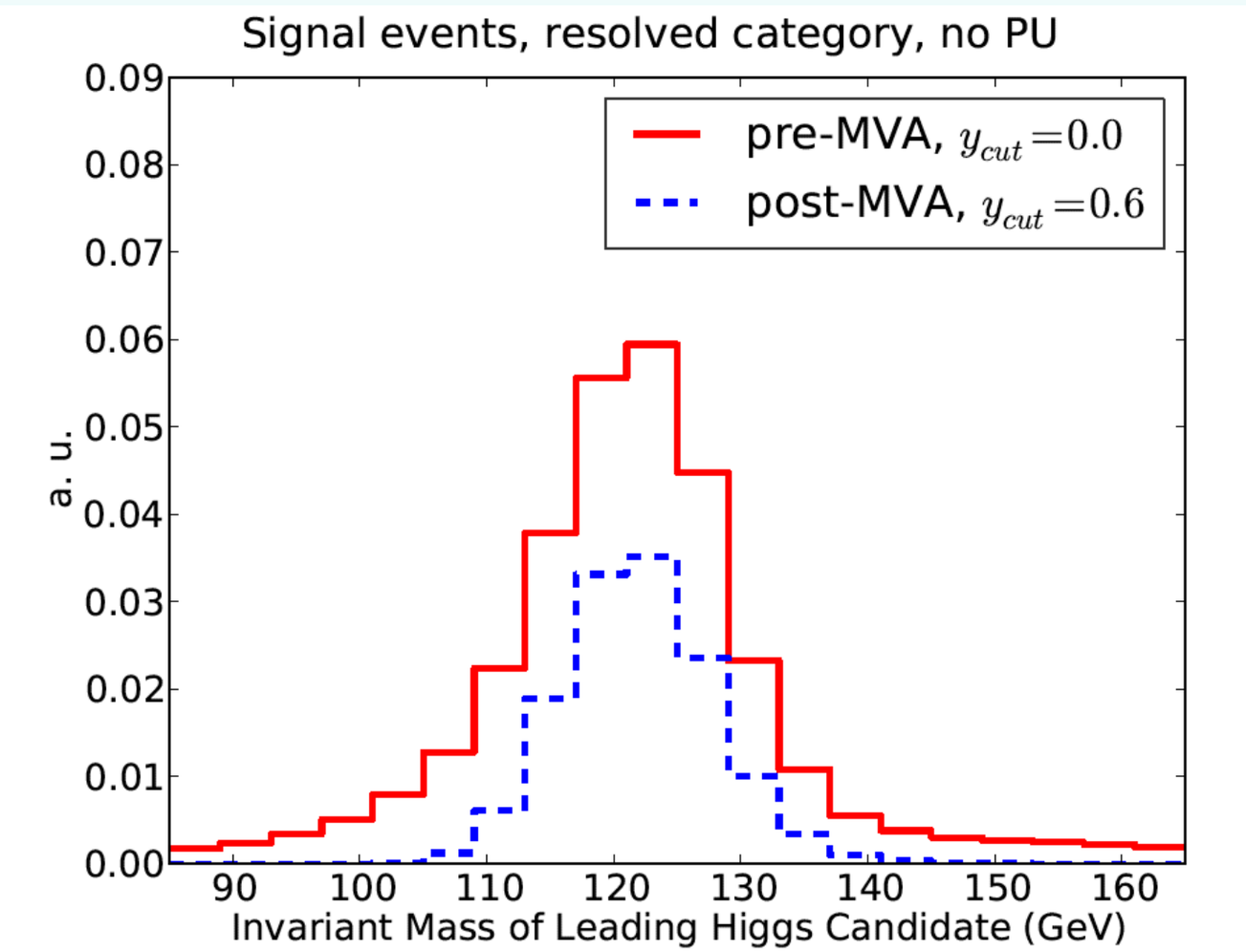
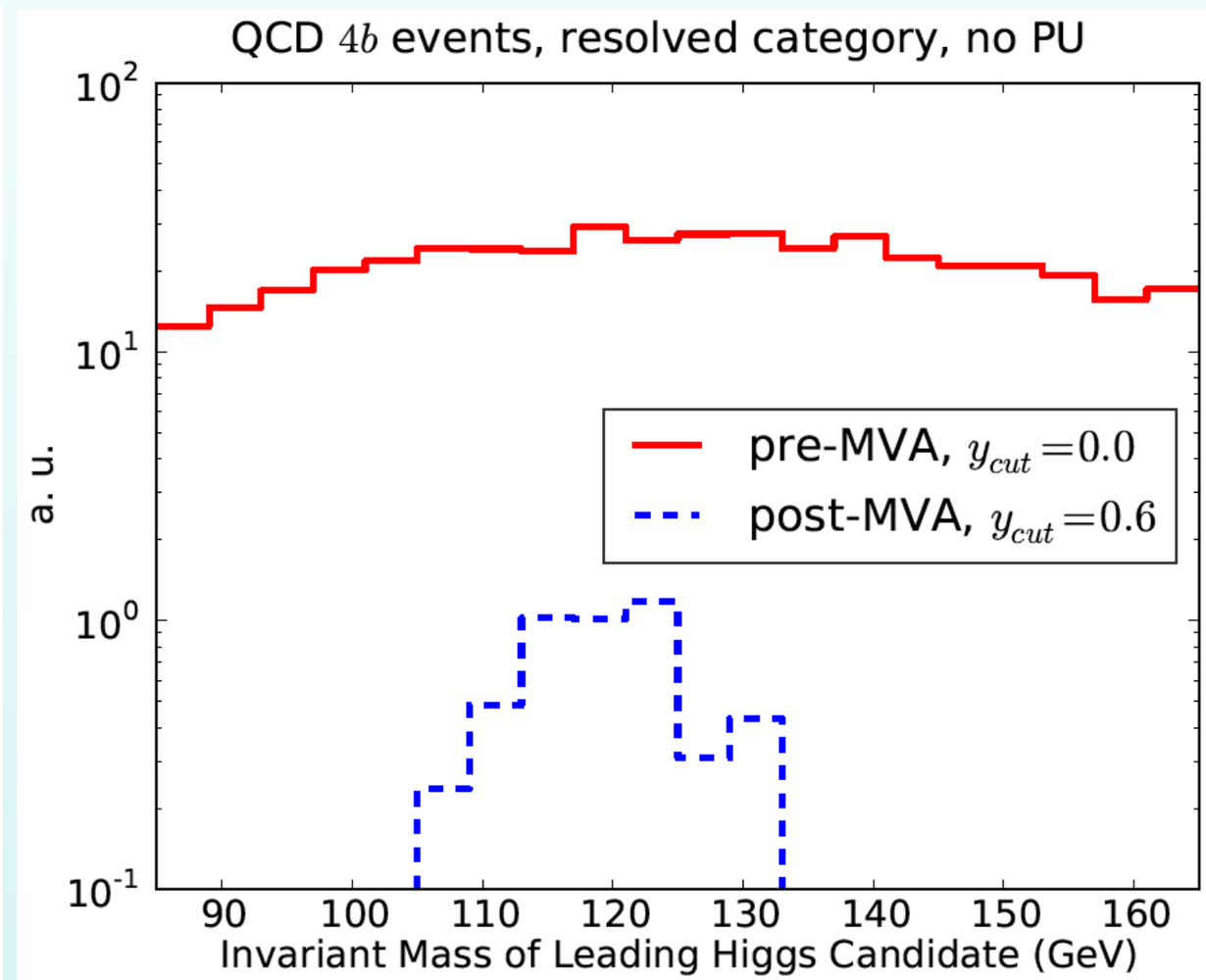




The MVA sculpts a Higgs peak in the QCD background!

ANNs and LHC phenomenology

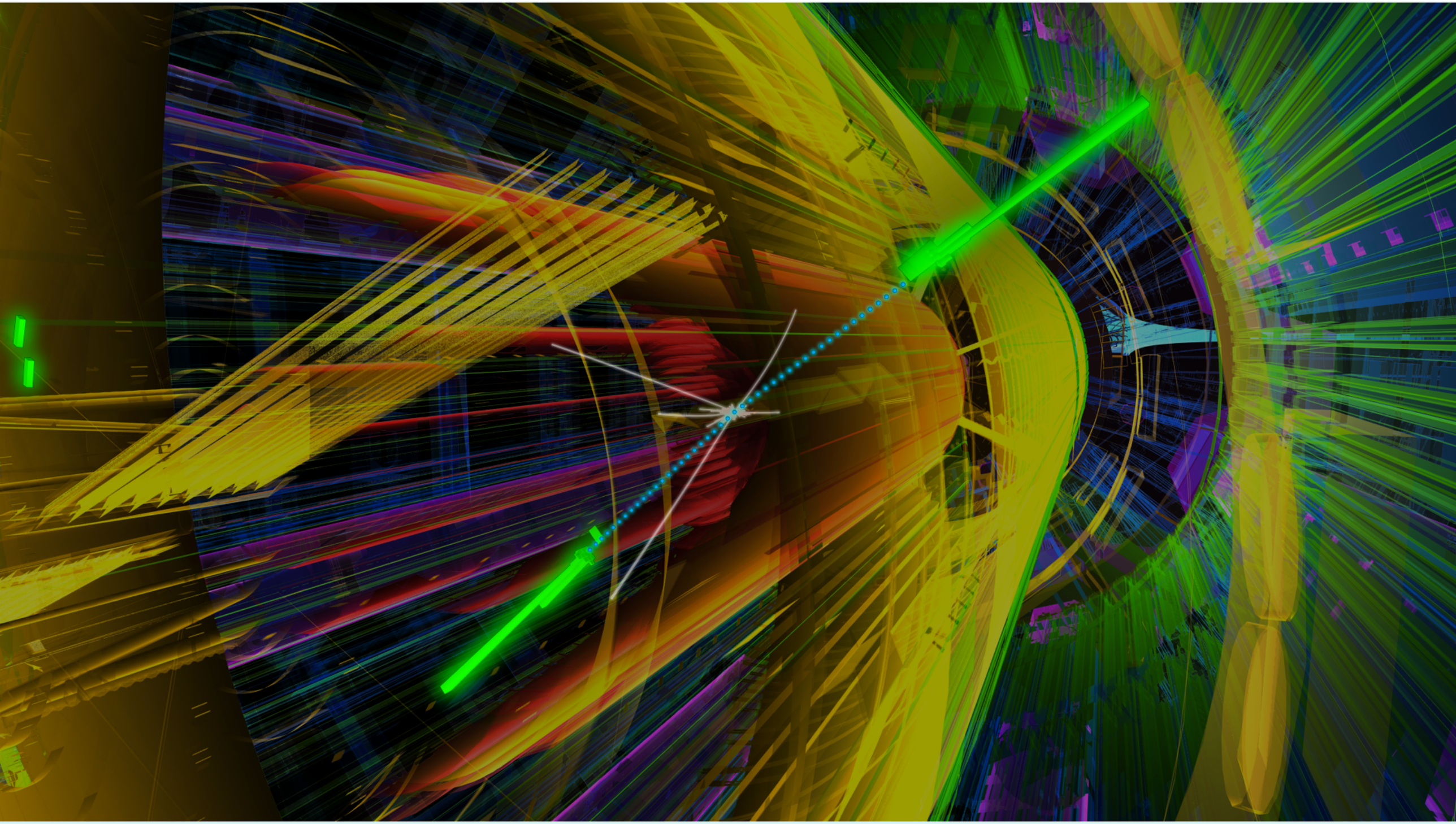
- **Machine Learning algorithms** are already **transforming our world**, from the way we move, shop and heal ourselves, to our understanding of what makes us unique as humans

- In the context of **LHC data analysis and interpretation, ML tools are ubiquitous**, from event selection deep in the detector chain (triggering) to bottom-quark tagging and automated BSM models classification (and exclusion)

- Artificial Neural Networks can be used as **universal unbiased interpolators in global analysis of the proton structure**, with implications from BSM heavy particle production to ultra-high energy neutrino astrophysics

- ANNs can also be used as **classifiers (discriminators) between signal and background** in very busy collision environments, improving LHC physics prospects *i.e.* for **Higgs pair production**

Fascinating times ahead at the high-energy frontier!



And stay tuned for news from the LHC!

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