# Proton structure and hadron colliders phenomenology: SM craters and BSM physics

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MANCHESTER 1824
The University of Manchester

The University of Liverpool, November 18th 2015

All I know is that sometimes
you have to be wary of a miracle
too good to be true

all I know is that sometimes the
truth is contrary everything in
life you thought you knew...

Rush, “The wreckers”,
Clockwork Angels, 2012

## Motivations…

- LHC run-I unprecedented energies and accurate measurements: a new realm of precision and knowledge

- LHC run II: even more challenging, but definitely more exciting!

- Need of precise theory predictions and efficient tools for phenomenological analyses

- Need to set stringent tests on Standard Model and search for signatures of New Physics

## we all are eager to discover…

After the discovery of the Higgs boson, new physics interactions are the next urgent challenge for future programs at the LHC. But big problems still remain:

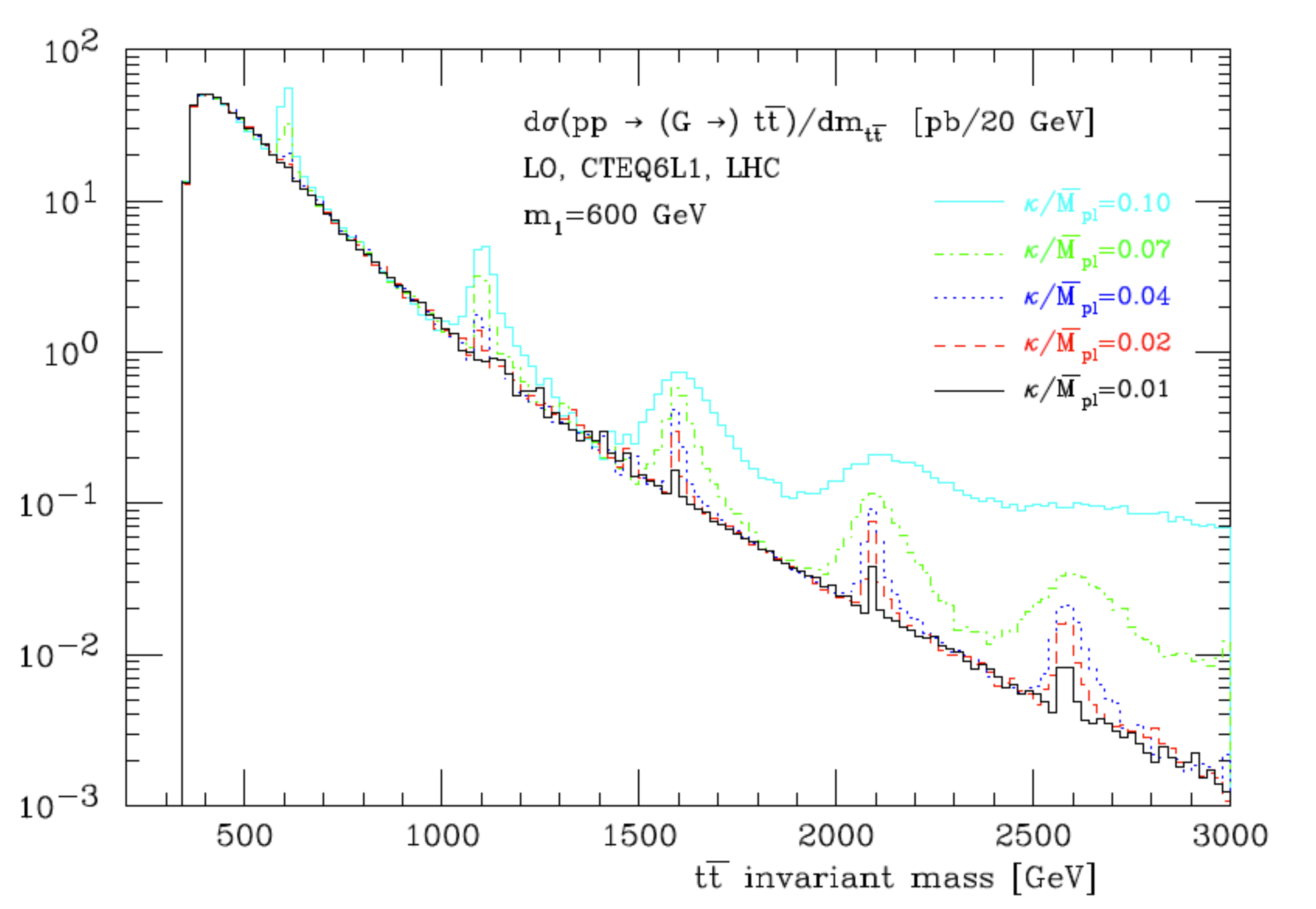
- Origin of particle mass
- Unification: is there a simple framework for unifying all particle interactions?
- The problem of flavour: why are there so many types of quarks and leptons?
- Origin of CP-violation
- Cosmological problems:

  - baryon-antibaryon asymmetry

  - dark matter and dark energy

**At the LHC new physics can occur through various kinds of signature**

- new bumps in an invariant mass distribution,




Maltoni, Frederix JHEP 2009

**At the LHC new physics can occur through various kinds of signature**

- new bumps in an invariant mass distribution,
- distortions in kinematic distributions,
- new final state particles,
- ….

These must be discriminated from a complex SM background

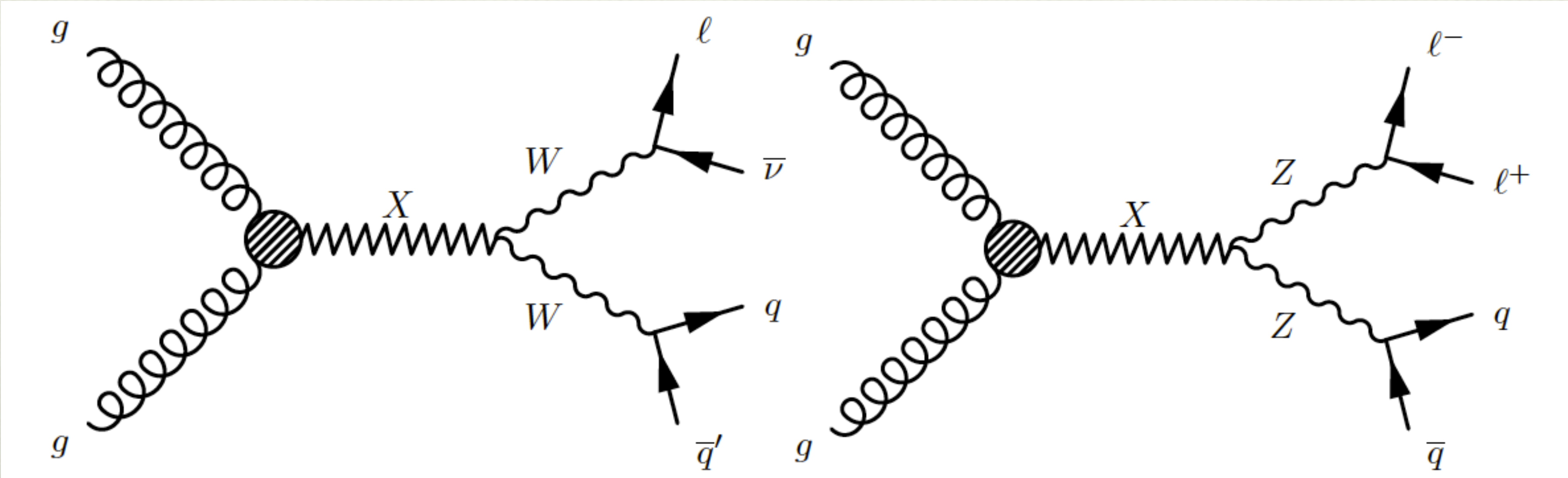
**In most cases, several factors limit the accuracy of theoretical predictions: scale dependence in pQCD calculations, knowledge of proton's structure, …**

The Standard Model is now under sever scrutiny

The ATLAS and CMS collaborations have recently observed tensions between SM theory and experimental measurements in the search for resonances decaying into WW, WZ, or ZZ boson pairs.

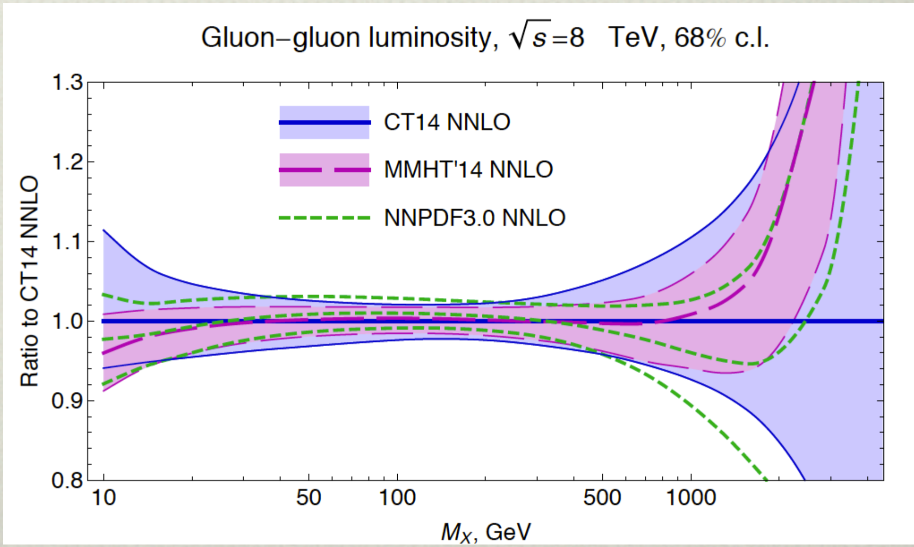
Higgs properties are also under investigation.

# Diboson production at the LHC



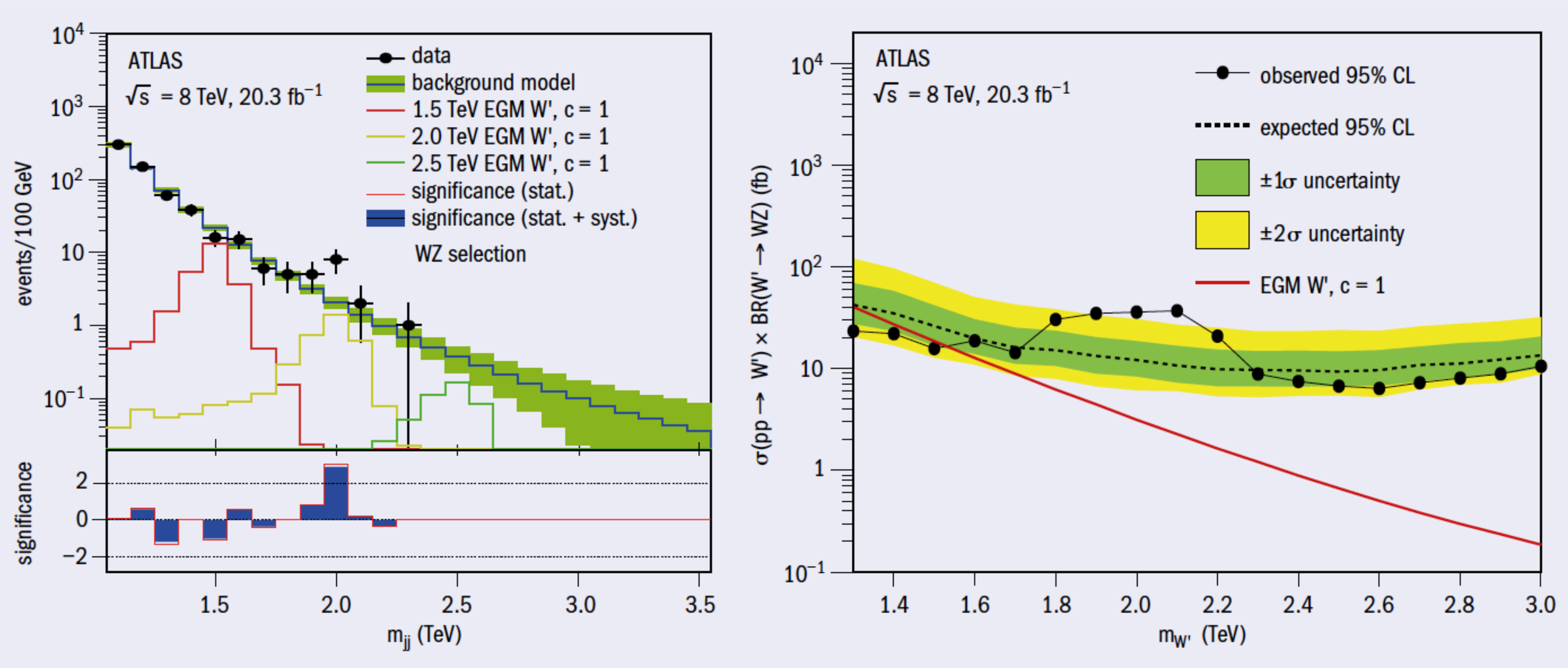

Gluon-gluon channel for the production of a generic resonance X decaying to WW and ZZ diboson pairs.

**SENSITIVITY TO GLUON PDFs**




CT14 PDFs :1506.07443

# Excess of events found in diboson production at ATLAS 8 TeV

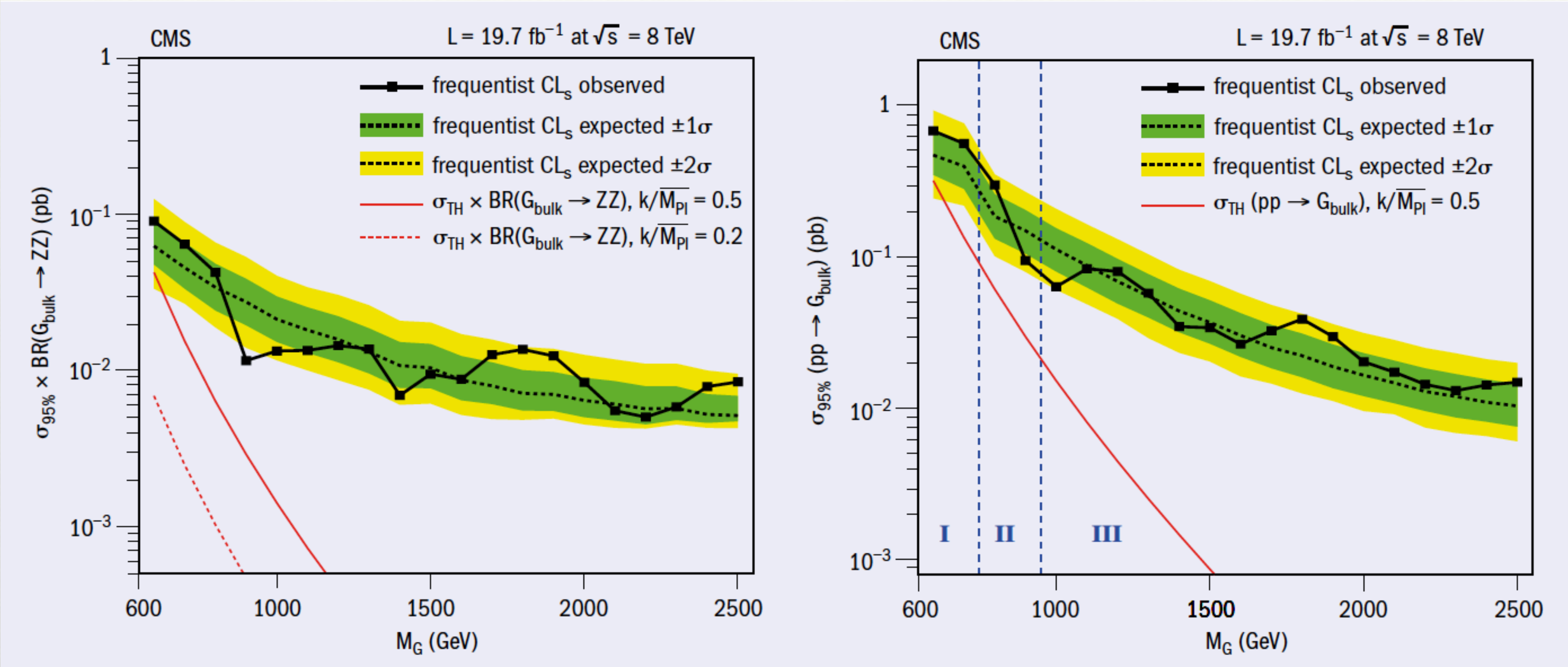



*Left: ATLAS non-leptonic $M_{WZ}$ data. Right: ATLAS σ × B exclusion for W' → WZ.*

Search for narrow resonances decaying into WW, WZ, or ZZ boson pairs. Diboson resonances of 1.3 to 3.0 TeV invariant mass are sought after using the invariant mass distribution of dijets.

ATLAS Coll. 1506.00962

# …and at CMS 8 TeV




*Left: CMS semi-leptonic X → ZZ exclusion. Right: CMS semi-leptonic + non-leptonic X → ZZ exclusion*

Search for massive resonances decaying into a quark and a vector boson (W or Z), or two vector bosons (WW, WZ, or ZZ). The signal is characterized by a peak in the dijet invariant mass distribution $m_{jj}$ over a continuous SM background, comprised mainly of multijet events from QCD processes.

CMS Coll. 1405.1994,1405.3447

**ATLAS**:

-Excesses in three non-leptonic invariant-mass regions, $M_{WW}$, $M_{WZ}$ and $M_{ZZ}$.

-No excess in the semi-leptonic events around 2 TeV.

Largest excess is in $M_{WZ}$ is centered at 2 TeV, with a 3.4$\sigma$ local, 2.5$\sigma$ global significance.

**CMS**:

-Excess in non-leptonic data, ~1.5$\sigma$ over the expected limit near $M_{VV}$ = 1.9 TeV.

-semi-leptonic data: ~2$\sigma$ excess near 1.8 TeV in the $l^+l^-$ V-jet;

-less than 1$\sigma$ in the $l\nu$ V-jet.

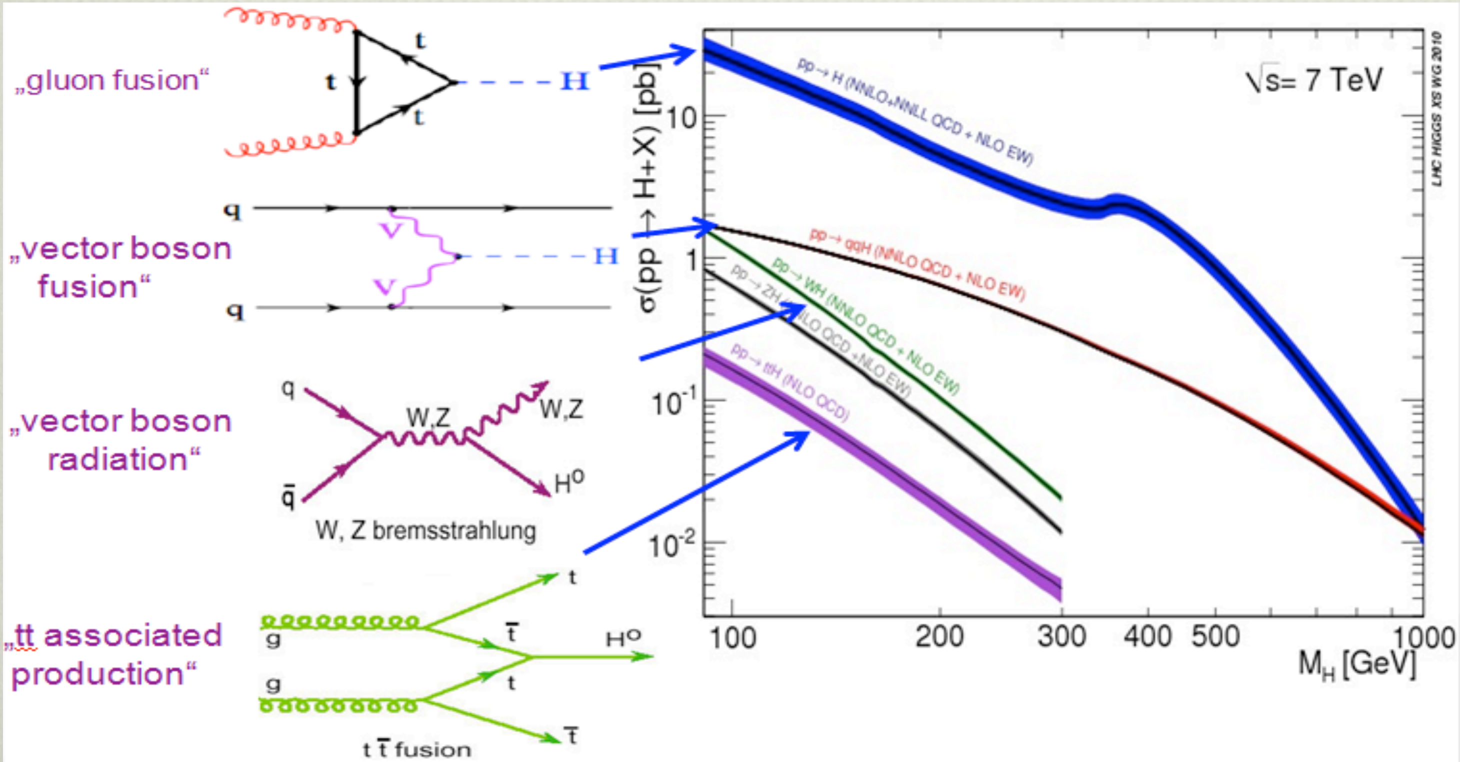
-semi-leptonic and non-leptonic data combined: still a 1.5-2$\sigma$ excess near 1.8 TeV

-No excesses with significances larger than 2$\sigma$ are observed.

## ATLAS and CMS searched also for resonant structures in VH production

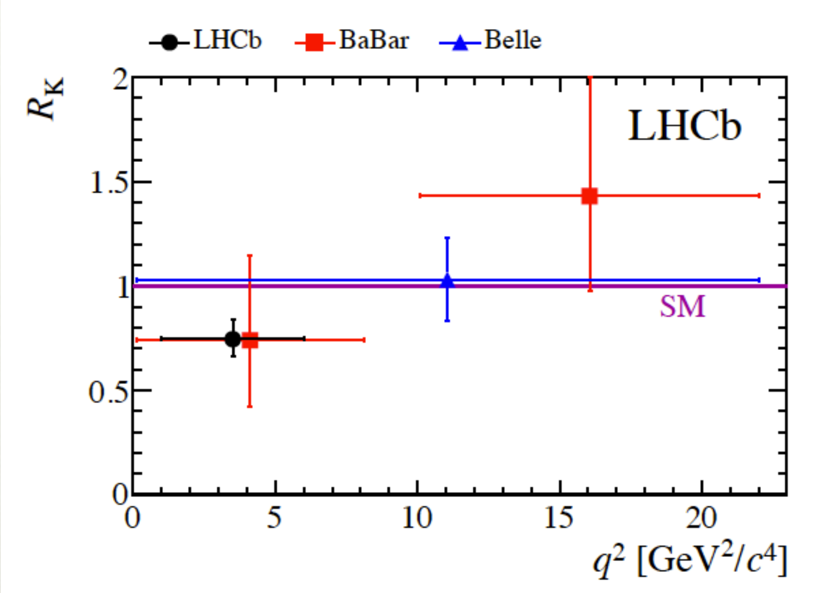
ATLAS looked in the channels $l\nu$ /l+l-/ $\nu\nu$ + bbbar with one and two b-tags.
-no deviation greater than $1\sigma$ from the expected background up to 1.9 TeV.

CMS looked in non-leptonic and semi-leptonic channels.
-observed tensions in the non-leptonic channel at 1.7 TeV
-WH $\rightarrow l\nu$ +bbbar: $2\sigma$ excess centered at 1.9 TeV in the electron, but not the muon data.



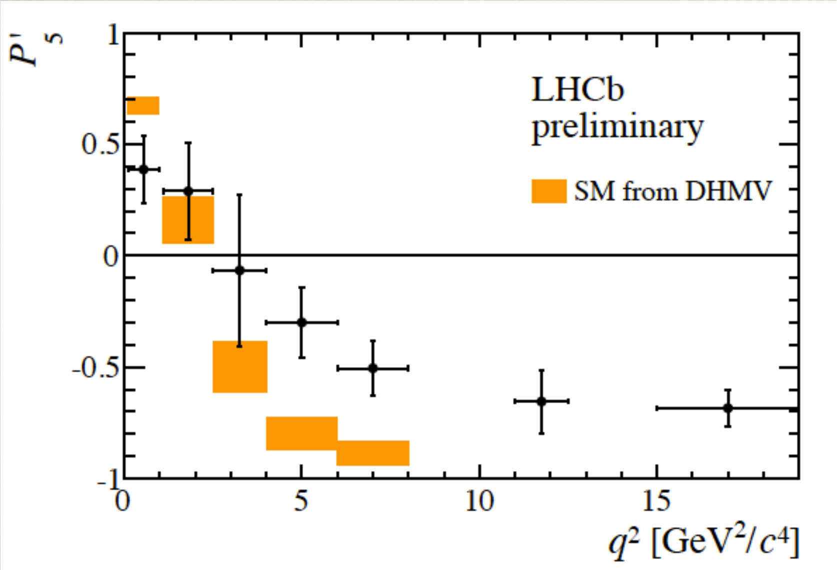

**VH sensitive to quark PDFs**

# …news from LHCb as well




$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+ \mu^+ \mu^-]}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+ e^+ e^-]}{dq^2} dq^2}$$

2.6 $\sigma$ deviation from SM




$$B^0 \to K^{*0} \mu^+ \mu^-$$

SM component $P'_5$ of the angular distribution is systematically lower than the data: 2.9 $\sigma$ discrepancy

**a new LHCb analysis will soon be released. Looking forward!**

LHCb Coll. 1506.00962

# many tantalizing explanations…

Extra heavy gauge bosons: a new weakly coupled W', Z' triplet that mixes slightly with the familiar W, Z.

Lepton non universality (LNU)

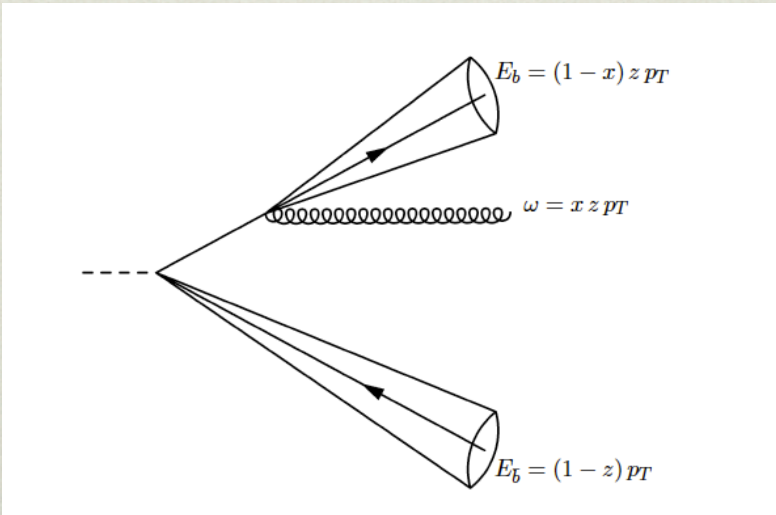
Composite Higgs boson: a triplet of $\rho$ -like vector bosons responsible for new strong interactions associated with H being a composite Higgs boson.

If both VV and VH bumps were to be discovered in Run II, they would suggest new interactions at or above a few TeV's

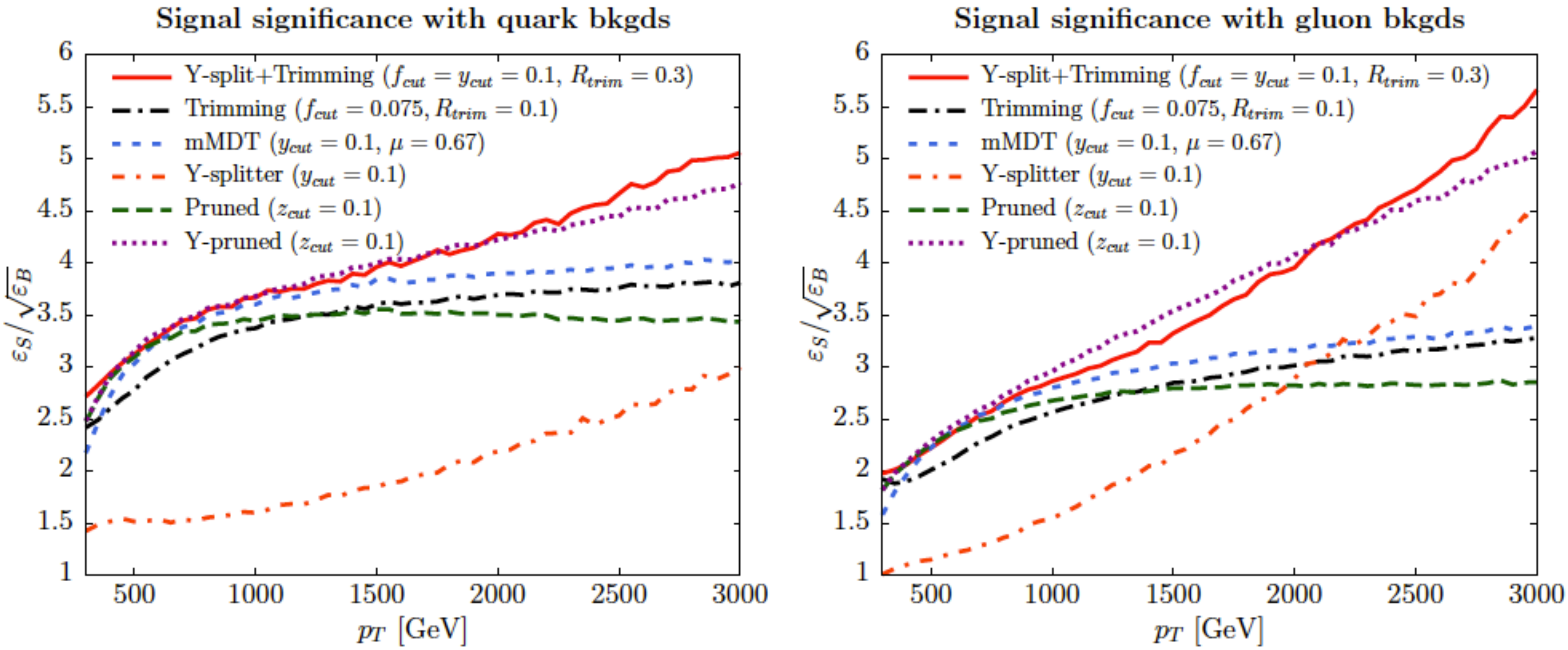

Yes it is exciting, but before getting too excited…

there are a few things which deserve a careful look

- It would be interesting to check whether excesses remain if new more sophisticated techniques to identify signal jets and reject the background are used.



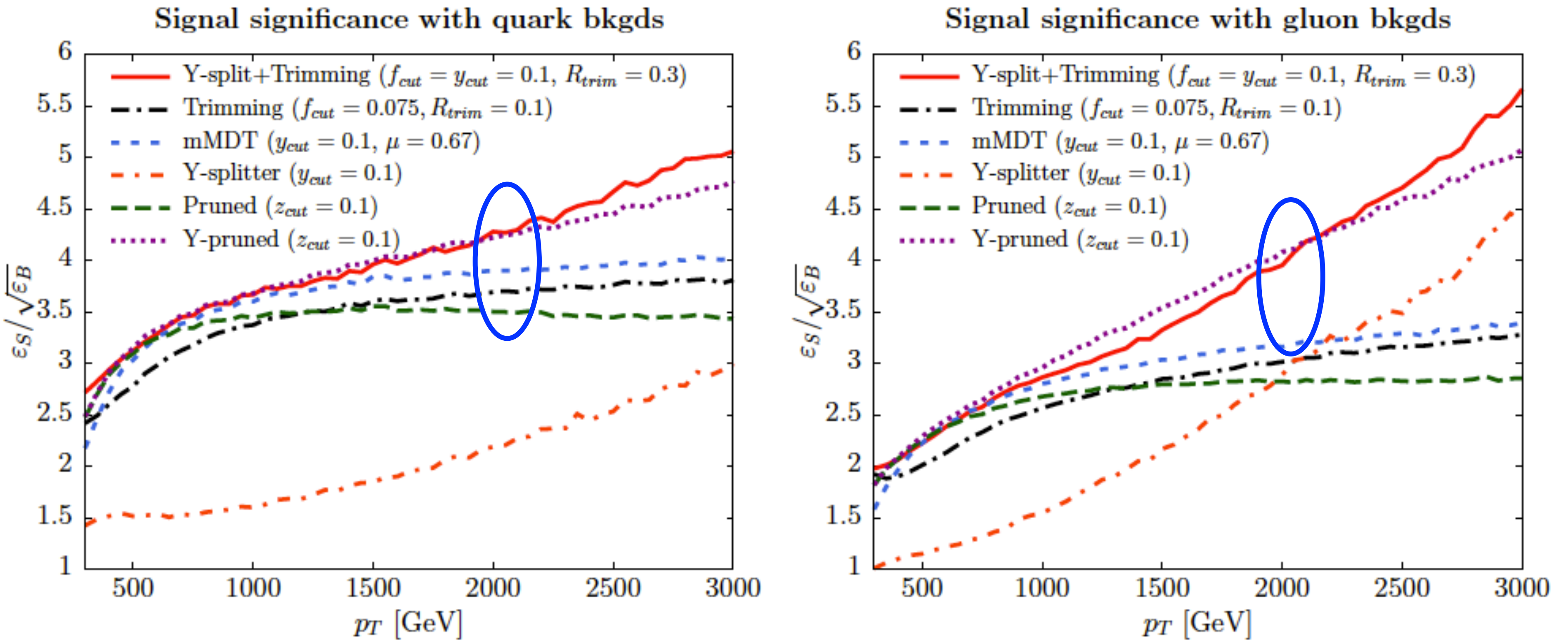
It is crucial to identify the signal correctly




Signal significance for tagging hadronic H jets with quark (left panel) and gluon (right panel) backgrounds using Herwig++ 2.7.0.
Comparison of signal significance for different algorithms at high pT .

Dasgupta, Powling, Siodmok, JHEP 2015

Kill the background, get the signal




Signal significance for tagging hadronic H jets with quark (left panel) and gluon (right panel) backgrounds using Herwig++ 2.7.0.
Comparison of signal significance for different algorithms at high pT .

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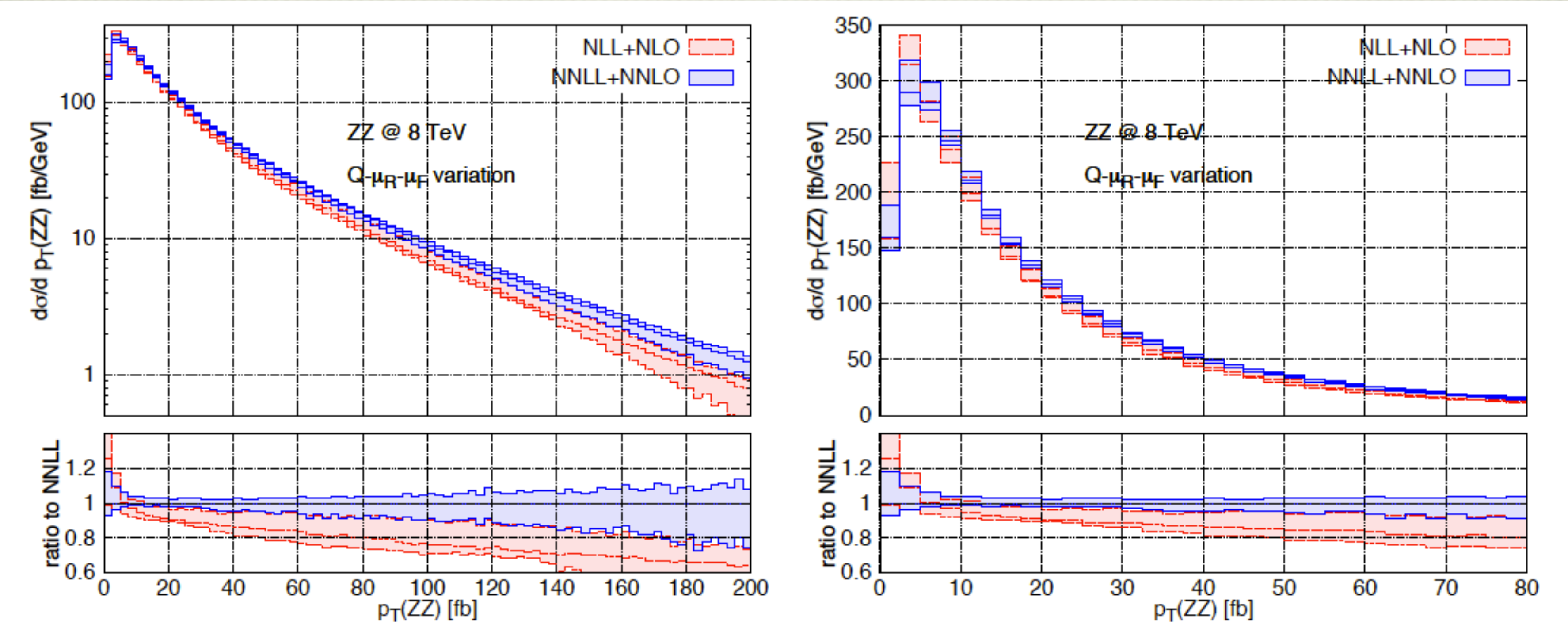
…also a better control on theory systematic uncertainties…

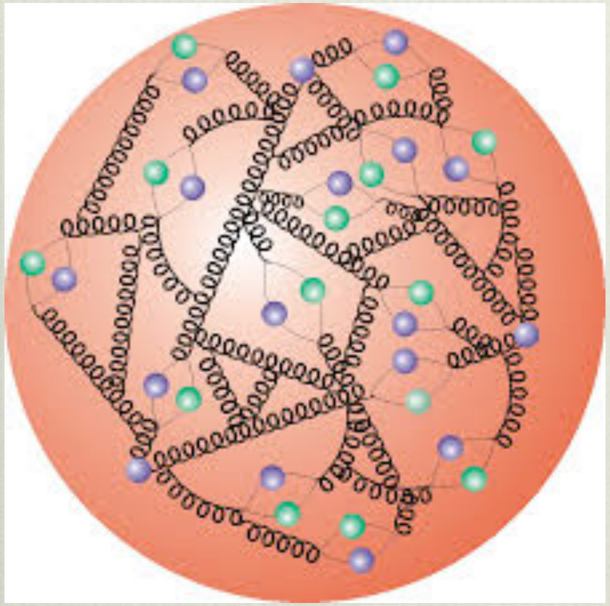
- Implementation of state-of-the-art NNLO calculation in order to reduce the scale dependence in the cross section

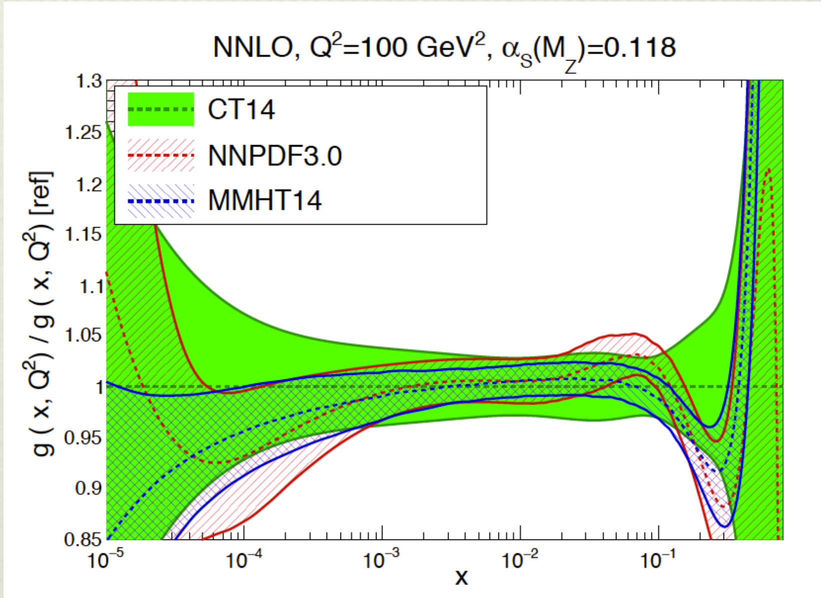



Grazzini, Kallweit, Rathlev, Wiesemann, JHEP 2015

…and of course proton's structure

- ❖ It would be interesting to check the impact of new generation PDFs obtained by using LHC data





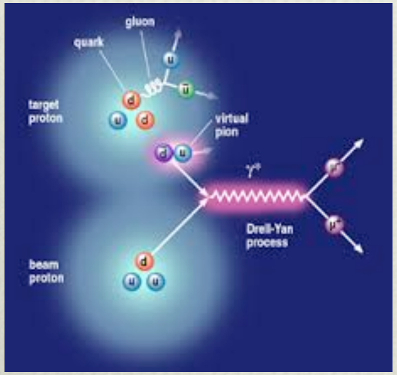

PDF for LHC run II recommendation, 1510.03865

**Excesses need to be validated at higher energies and higher luminosity at LHC run II**

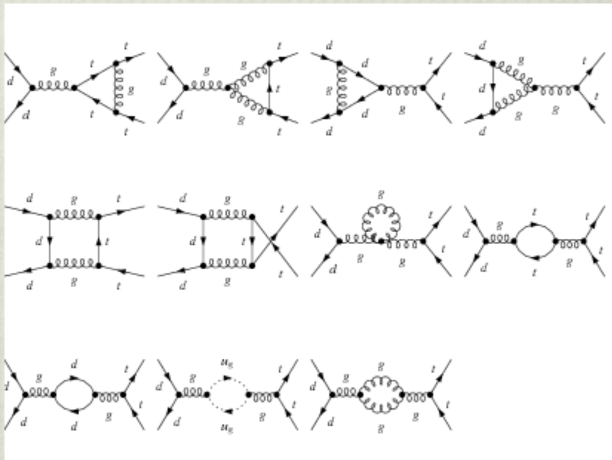
# the need of precision

# At the LHC everything boils down to factorization theorems in QCD

$$\sigma(\alpha_s(\mu_R^2),\mu_R^2,\mu_F^2)) = \sum_{a,b}\int_0^1 dx_1 dx_2 f_a(x_1,\mu_F^2) f_b(x_2,\mu_F^2)\ \hat{\sigma}^{a,b}(x_1,x_2;\alpha_s(\mu_R^2),\mu_R^2,\mu_F^2) + \mathcal{O}\left(\frac{\Lambda_{QCD}^2}{Q^2}\right)$$




Effects of new physics impact hard scattering cross section:



$$\frac{d\ f_a(x,\mu_F^2)}{d\log\mu_F^2} = \sum_{b=q,\bar{q},g}\int_x^1 \frac{dz}{z} P_{ab}\left(\frac{x}{z};\mu_F^2\right) f_b(z,\mu_F^2)$$

...and might also affect PDFs and their RG evolution (DGLAP).

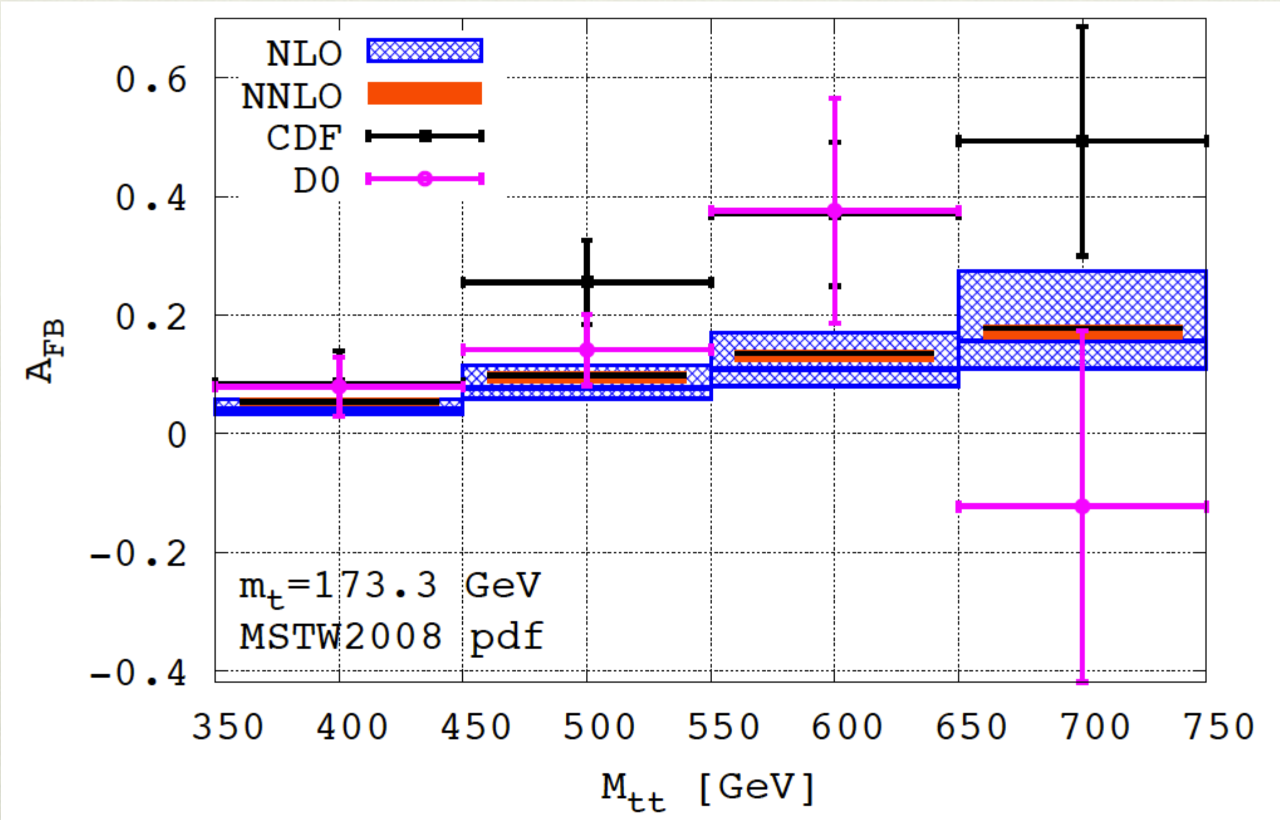
$P_{ab}$ is known at NNLO in QCD
Moch, Vermaseren, Vogt NPB 2004

Parton Distribution Functions (PDFs) of the proton map out the longitudinal momentum distribution of proton's constituent quarks and gluons.

$$\hat{\sigma}(x_1, x_2, \alpha_s(\mu_R^2), \mu_F^2, \mu_R^2)$$

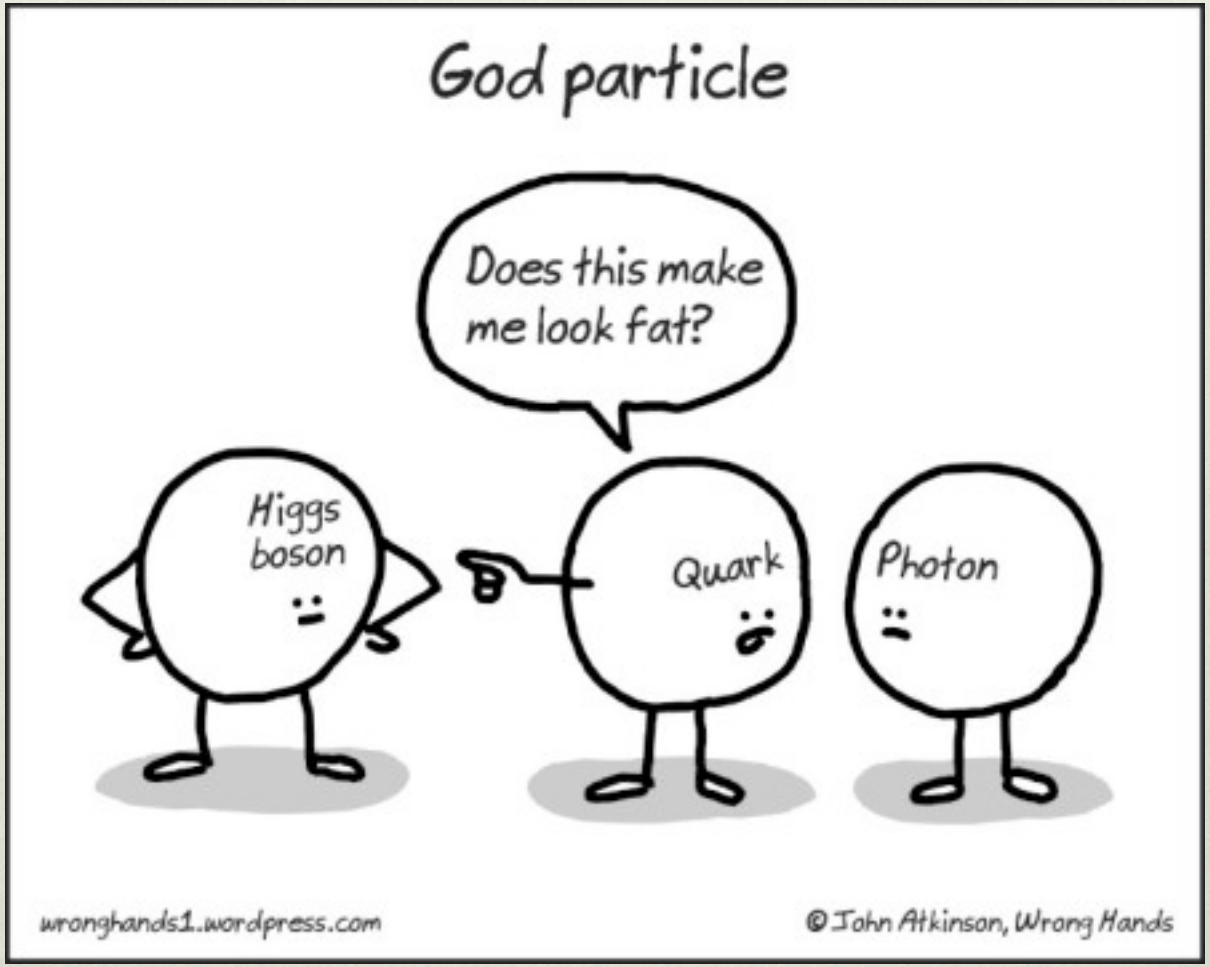
A few recent interesting higher order calculations

ttbar production at NNLO in QCD.
-inclusion of higher orders modified the cross section (enhancement);
-reduction of the systematic uncertainties due to scale dependence.

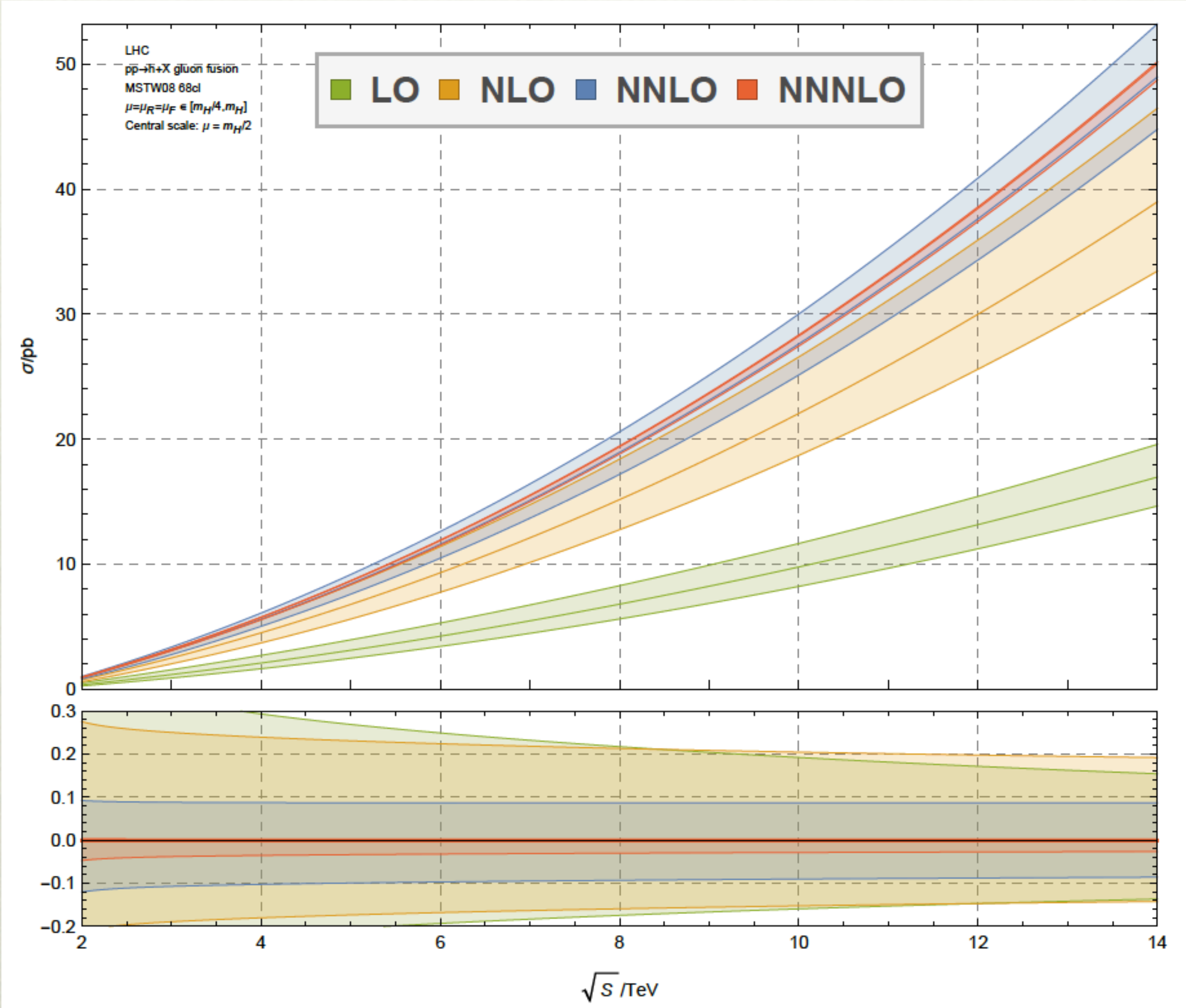



NNLO corrections to AFB bring the SM prediction for the inclusive asymmetry in agreement with the measurement of the DØ collaboration and about 1.5 $\sigma$ below the value measured by the CDF coll. at the Tevatron.

Czakon, Fiedler, Mitov PRL 2015


God particle
Does this make me look fat?
Higgs boson
Quark
Photon
wronghands1.wordpress.com
© John Atkinson, Wrong Hands

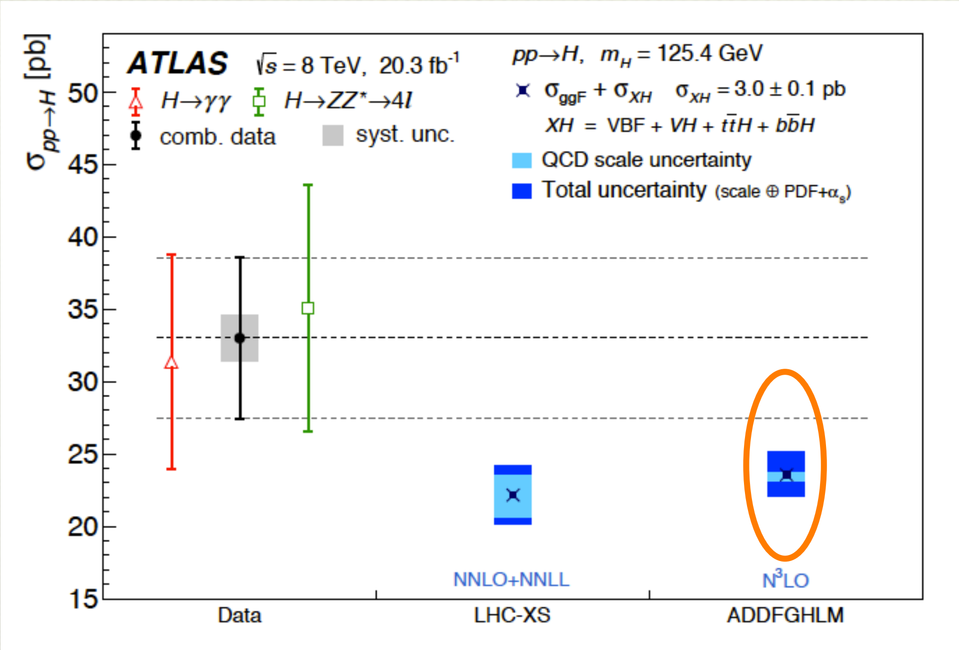
A lot of efforts going on for Higgs production at the LHC…for a good reason

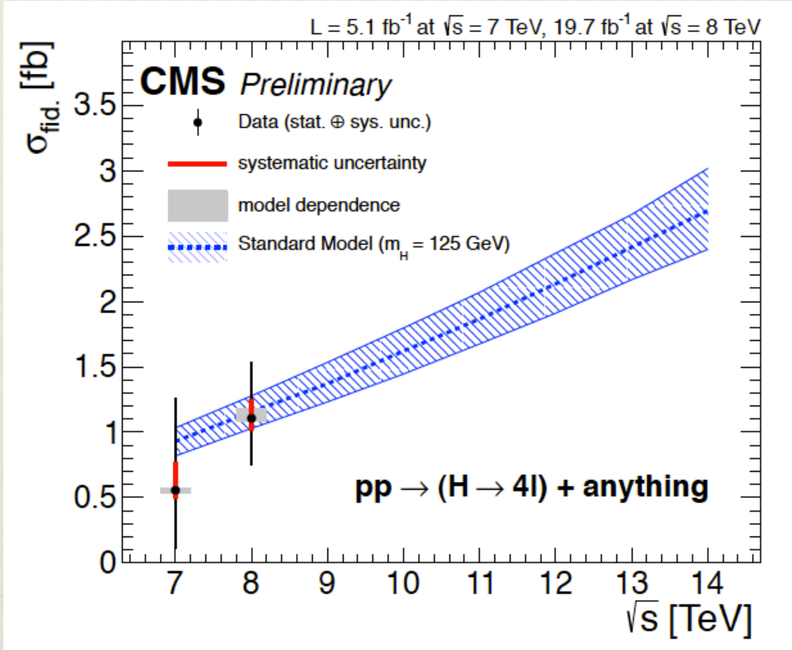


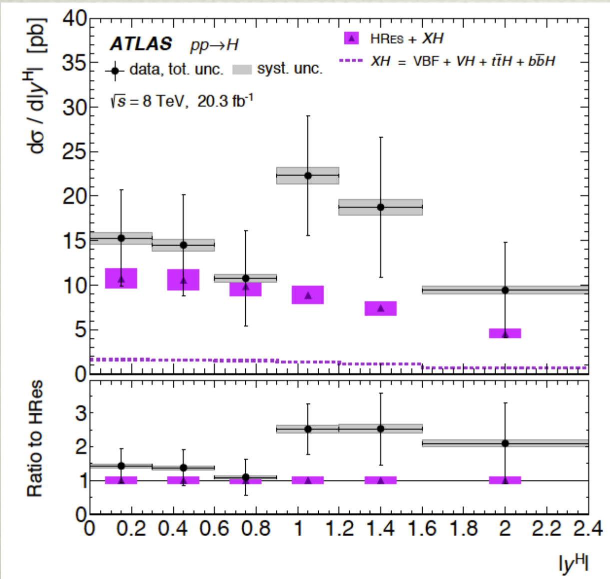

Higgs boson gluon-gluon fusion production
in N^3LO QCD

Anastasiou, Duhr, et al., PRL2015

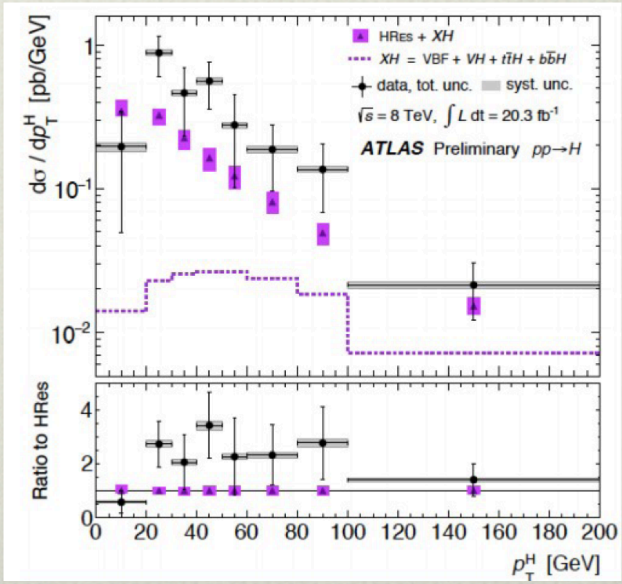
**Higgs production at the LHC**. ATLAS arxiv:1504.05833




Differential distributions: SM systematically lower than data



On the other hand

PDFs are a crucial limiting factor in the accuracy of theoretical predictions for many important observables at the LHC.

A lot of work is going on to pin down their uncertainties

Let’s take a closer look

# Why PDFs analysis is important ?

**Efforts in investigating the structure of the nucleon are crucial for a multitude of current and future high-energy physics programs.**

**Interpretation of experimental measurements at hadron colliders relies to large extent on the precise knowledge of fundamental QCD parameters and of parton distribution functions (PDFs) of the proton.**

- **Global QCD analysis of PDFs is a vast topic: I will not go through details here.**

- **It can be used to derive constraints on the existence and mass of new particles, independently of other information**

## Making a long story short…

Parton distribution functions (PDFs) of the proton are essential ingredients of factorization theorems in QCD:

DGLAP equation

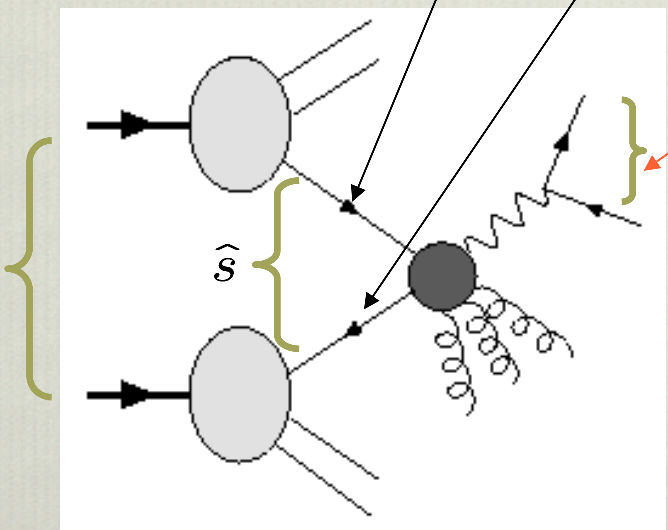
up to NNLO

$$\frac{d\ f(x,Q^2)}{d\log Q^2} = P(x,Q^2) \otimes f(x,Q^2)$$

$$P(x,Q^2) = \left(\frac{\alpha_s(Q^2)}{2\pi}\right) P^{(0)}(x) + \left(\frac{\alpha_s(Q^2)}{2\pi}\right)^2 P^{(1)}(x) + \left(\frac{\alpha_s(Q^2)}{2\pi}\right)^3 P^{(2)}(x)$$

# Factorization

$$\sigma(\alpha_s(\mu_R^2),\mu_R^2,\mu_F^2)) = \sum_{a,b}\int_0^1 dx_1 dx_2 f_a(x_1,\mu_F^2) f_b(x_2,\mu_F^2)\ \hat{\sigma}^{a,b}(x_1,x_2;\alpha_s(\mu_R^2),\mu_R^2,\mu_F^2) + \mathcal{O}\left(\frac{\Lambda_{QCD}^2}{Q^2}\right)$$




s = x1 x2 S

# Scale dependence

In the collinear picture, the use of RG invariance tells us how to predict scale dependence or "evolution" of PDFs by renormalization group equations (RGE's) once the "initial conditions" are given.

$$\frac{d\ f_i(x,\mu_R,\mu_F)}{d\log\mu_F} = \sum_{j=q\bar{q},g}\int_x^1 \frac{dy}{y} P_{ij}\left(\frac{x}{y};\alpha_s,\mu_R,\mu_F\right) f_j(y,\mu_R,\mu_F)$$

DGLAP

Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

$$P(x,Q^2) = \left(\frac{\alpha_s(Q^2)}{2\pi}\right) P^{(0)}(x) + \left(\frac{\alpha_s(Q^2)}{2\pi}\right)^2 P^{(1)}(x) + \left(\frac{\alpha_s(Q^2)}{2\pi}\right)^3 P^{(2)}(x)$$

# Splitting functions in QCD

$$\begin{aligned}
P^{(0)}_{\mathrm{ns}}(x) &= C_F\left(2p_{\mathrm{qq}}(x) + 3\delta(1-x)\right) \\
P^{(0)}_{\mathrm{ps}}(x) &= 0 \\
P^{(0)}_{\mathrm{qg}}(x) &= 2n_f\, p_{\mathrm{qg}}(x) \\
P^{(0)}_{\mathrm{gq}}(x) &= 2C_F\, p_{\mathrm{gq}}(x) \\
P^{(0)}_{\mathrm{gg}}(x) &= C_A\left(4p_{\mathrm{gg}}(x) + \frac{11}{3}\delta(1-x)\right) - \frac{2}{3}n_f\,\delta(1-x)
\end{aligned}$$

**LO 1973**

$$\begin{aligned}
P^{(1)+}_{\mathrm{ns}}(x) &= 4C_AC_F\Big(p_{\mathrm{qq}}(x)\Big[\frac{67}{18} - \zeta_2 + \frac{11}{6}\mathrm{H}_0 + \mathrm{H}_{0,0}\Big] + p_{\mathrm{qq}}(-x)\Big[\zeta_2 + 2\mathrm{H}_{-1,0} - \mathrm{H}_{0,0}\Big] \\
&\quad + \frac{14}{3}(1-x) + \delta(1-x)\Big[\frac{17}{24} + \frac{11}{3}\zeta_2 - 3\zeta_3\Big]\Big) - 4C_Fn_f\Big(p_{\mathrm{qq}}(x)\Big[\frac{5}{9} + \frac{1}{3}\mathrm{H}_0\Big] + \frac{2}{3}(1-x) \\
&\quad + \delta(1-x)\Big[\frac{1}{12} + \frac{2}{3}\zeta_2\Big]\Big) + 4C_F{}^2\Big(2p_{\mathrm{qq}}(x)\Big[\mathrm{H}_{1,0} - \frac{3}{4}\mathrm{H}_0 + \mathrm{H}_2\Big] - 2p_{\mathrm{qq}}(-x)\Big[\zeta_2 + 2\mathrm{H}_{-1,0} \\
&\quad - \mathrm{H}_{0,0}\Big] - (1-x)\Big[1 - \frac{3}{2}\mathrm{H}_0\Big] - \mathrm{H}_0 - (1+x)\mathrm{H}_{0,0} + \delta(1-x)\Big[\frac{3}{8} - 3\zeta_2 + 6\zeta_3\Big]\Big) \\
P^{(1)-}_{\mathrm{ns}}(x) &= P^{(1)+}_{\mathrm{ns}}(x) + 16C_F\Big(C_F - \frac{C_A}{2}\Big)\Big(p_{\mathrm{qq}}(-x)\Big[\zeta_2 + 2\mathrm{H}_{-1,0} - \mathrm{H}_{0,0}\Big] - 2(1-x) \\
&\quad - (1+x)\mathrm{H}_0\Big) \\
P^{(1)}_{\mathrm{ps}}(x) &= 4C_Fn_f\Big(\frac{20}{9}\frac{1}{x} - 2 + 6x - 4\mathrm{H}_0 + x^2\Big[\frac{8}{3}\mathrm{H}_0 - \frac{56}{9}\Big] + (1+x)\Big[5\mathrm{H}_0 - 2\mathrm{H}_{0,0}\Big]\Big) \\
P^{(1)}_{\mathrm{qg}}(x) &= 4C_An_f\Big(\frac{20}{9}\frac{1}{x} - 2 + 25x - 2p_{\mathrm{qg}}(-x)\mathrm{H}_{-1,0} - 2p_{\mathrm{qg}}(x)\mathrm{H}_{1,1} + x^2\Big[\frac{44}{3}\mathrm{H}_0 - \frac{218}{9}\Big] \\
&\quad + 4(1-x)\Big[\mathrm{H}_{0,0} - 2\mathrm{H}_0 + x\mathrm{H}_1\Big] - 4\zeta_2x - 6\mathrm{H}_{0,0} + 9\mathrm{H}_0\Big) + 4C_Fn_f\Big(2p_{\mathrm{qg}}(x)\Big[\mathrm{H}_{1,0} + \mathrm{H}_{1,1} + \mathrm{H}_2 \\
&\quad - \zeta_2\Big] + 4x^2\Big[\mathrm{H}_0 + \mathrm{H}_{0,0} + \frac{5}{2}\Big] + 2(1-x)\Big[\mathrm{H}_0 + \mathrm{H}_{0,0} - 2x\mathrm{H}_1 + \frac{29}{4}\Big] - \frac{15}{2} - \mathrm{H}_{0,0} - \frac{1}{2}\mathrm{H}_0\Big) \\
P^{(1)}_{\mathrm{gq}}(x) &= 4C_AC_F\Big(\frac{1}{x} + 2p_{\mathrm{gq}}(x)\Big[\mathrm{H}_{1,0} + \mathrm{H}_{1,1} + \mathrm{H}_2 - \frac{11}{6}\mathrm{H}_1\Big] - x^2\Big[\frac{8}{3}\mathrm{H}_0 - \frac{44}{9}\Big] + 4\zeta_2 - 2 \\
&\quad - 7\mathrm{H}_0 + 2\mathrm{H}_{0,0} - 2\mathrm{H}_1x + (1+x)\Big[2\mathrm{H}_{0,0} - 5\mathrm{H}_0 + \frac{37}{9}\Big] - 2p_{\mathrm{gq}}(-x)\mathrm{H}_{-1,0}\Big) - 4C_Fn_f\Big(\frac{2}{3}x \\
&\quad - p_{\mathrm{gq}}(x)\Big[\frac{2}{3}\mathrm{H}_1 - \frac{10}{9}\Big]\Big) + 4C_F{}^2\Big(p_{\mathrm{gq}}(x)\Big[3\mathrm{H}_1 - 2\mathrm{H}_{1,1}\Big] + (1+x)\Big[\mathrm{H}_{0,0} - \frac{7}{2} + \frac{7}{2}\mathrm{H}_0\Big] - 3\mathrm{H}_{0,0} \\
&\quad + 1 - \frac{3}{2}\mathrm{H}_0 + 2\mathrm{H}_1x\Big) \\
P^{(1)}_{\mathrm{gg}}(x) &= 4C_An_f\Big(1 - x - \frac{10}{9}p_{\mathrm{gg}}(x) - \frac{13}{9}\Big(\frac{1}{x} - x^2\Big) - \frac{2}{3}(1+x)\mathrm{H}_0 - \frac{2}{3}\delta(1-x)\Big) + 4C_A{}^2\Big(27 \\
&\quad + (1+x)\Big[\frac{11}{3}\mathrm{H}_0 + 8\mathrm{H}_{0,0} - \frac{27}{2}\Big] + 2p_{\mathrm{gg}}(-x)\Big[\mathrm{H}_{0,0} - 2\mathrm{H}_{-1,0} - \zeta_2\Big] - \frac{67}{9}\Big(\frac{1}{x} - x^2\Big) - 12\mathrm{H}_0 \\
&\quad - \frac{44}{3}x^2\mathrm{H}_0 + 2p_{\mathrm{gg}}(x)\Big[\frac{67}{18} - \zeta_2 + \mathrm{H}_{0,0} + 2\mathrm{H}_{1,0} + 2\mathrm{H}_2\Big] + \delta(1-x)\Big[\frac{8}{3} + 3\zeta_3\Big]\Big) + 4C_Fn_f\Big(2\mathrm{H}_0 \\
&\quad + \frac{2}{3}\frac{1}{x} + \frac{10}{3}x^2 - 12 + (1+x)\Big[4 - 5\mathrm{H}_0 - 2\mathrm{H}_{0,0}\Big] - \frac{1}{2}\delta(1 -
\end{aligned}$$

**NLO: 1980**

Curci Furmanski Petronzio;
Floratos et al.

It took several years to make a step further in the perturbative expansion

Moch, Vermaseren, Vogt
**2004**

# PDFs are complicated objects

The formal definition of PDFs in QCD, contains all the complications of "real life": UV regulator in DR, gauge invariance.
J.Collins (2011)

$$f_{(0)\,j/h}(\xi) = \int \frac{dw^-}{2\pi}\, e^{-i\xi P^+ w^-} \langle P|\overline{\psi}_j^{(0)}(0, w^-, \mathbf{0}_\mathrm{T}) W(w^-, 0) \frac{\gamma^+}{2} \psi_j^{(0)}(0)|P\rangle_\mathrm{c}$$

that is for quarks, where the Wilson-line factor is

$$W(w^-, 0) = P\left[ e^{-ig_0 \int_0^{w^-} dy^- A^+_{(0)\alpha}(0, y^-, \mathbf{0}_\mathrm{T}) t_\alpha} \right]$$

Similarly to the case of renormalization scheme, a set of rules has to be provided in order to define the PDFs when a cross section calculation is performed, e.g. MSbar scheme.

## Universal objects

Gluons, quarks and antiquarks are the known constituents of the proton.

Their distributions as a function of $x$ and generic scale $\mu$, at which partons are probed, are universal quantities that do not depend on the specific hard process under consideration.

Differently from hard-scattering cross sections, the full analytic structure of the PDFs cannot be predicted by perturbative QCD,

but

has to be determined by comparing standard sets of cross sections to experimental measurements by using a variety of analytical and statistical methods.

**For this reason PDFs are "data-driven" quantities.**

# QCD GLOBAL ANALYSIS OF DATA in a nutshell:

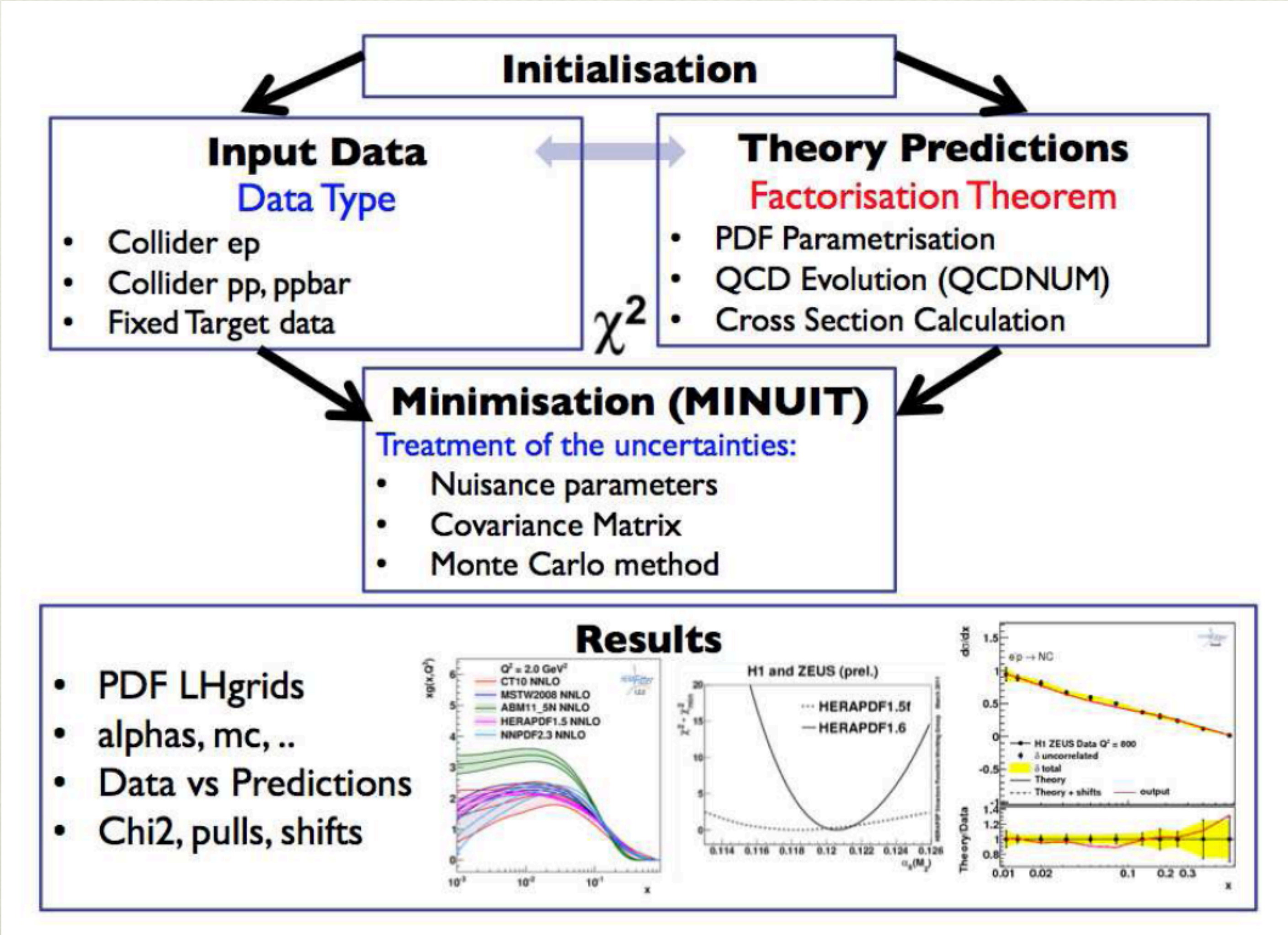
PDFs of the proton are determined by comparing theoretical predictions for cross sections to the experimental data.

Heavily rely on calculations based on QCD and the QCD-parton picture, with the PDFs (and fragmentation) as essential input.

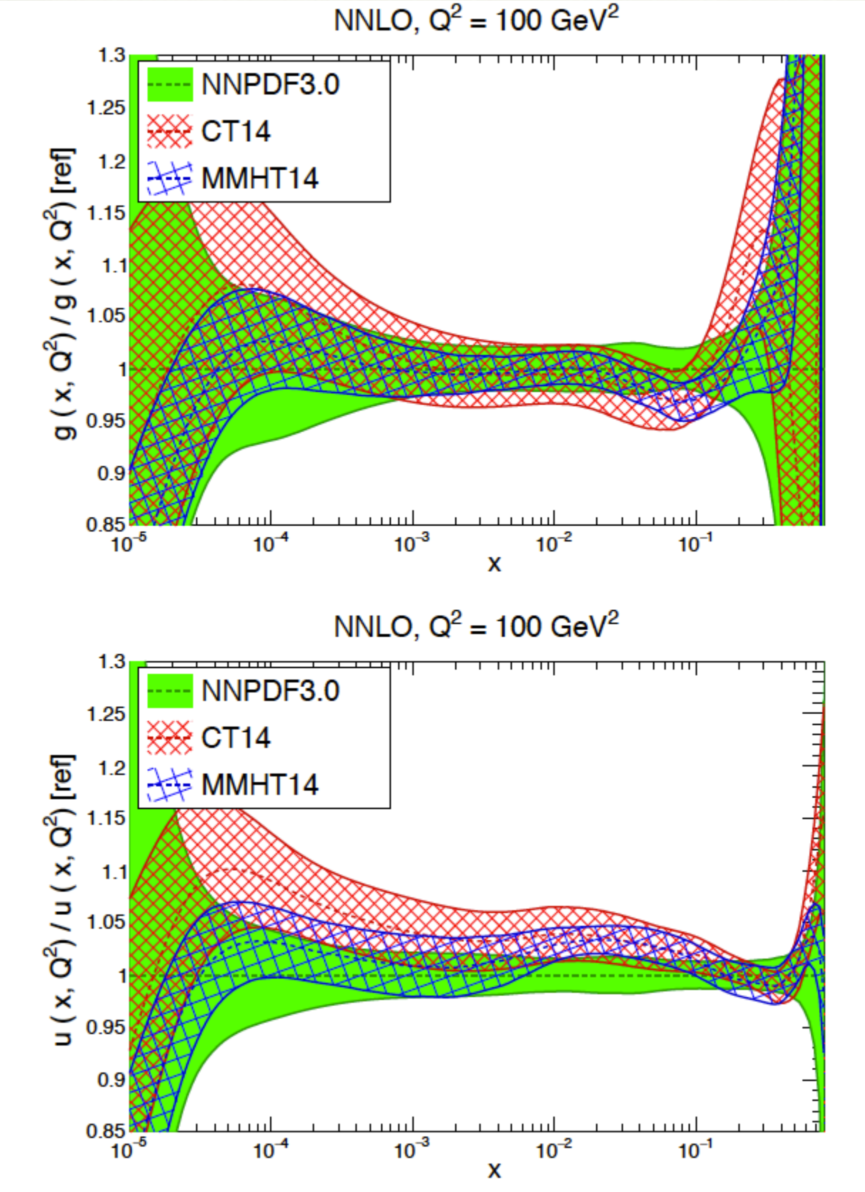
The (non-perturbative) PDFs at some given momentum scale are determined by using an eigenvector-basis approach to the Hessian method.
(or by using other approaches like neural networks i.e. NNPDFs)

Different analyses
different PDF groups i.e. CTEQ, MMHT, NNPDF, ABM, HERAPDF, JR, use different methodologies in their fits.

A little dramatization



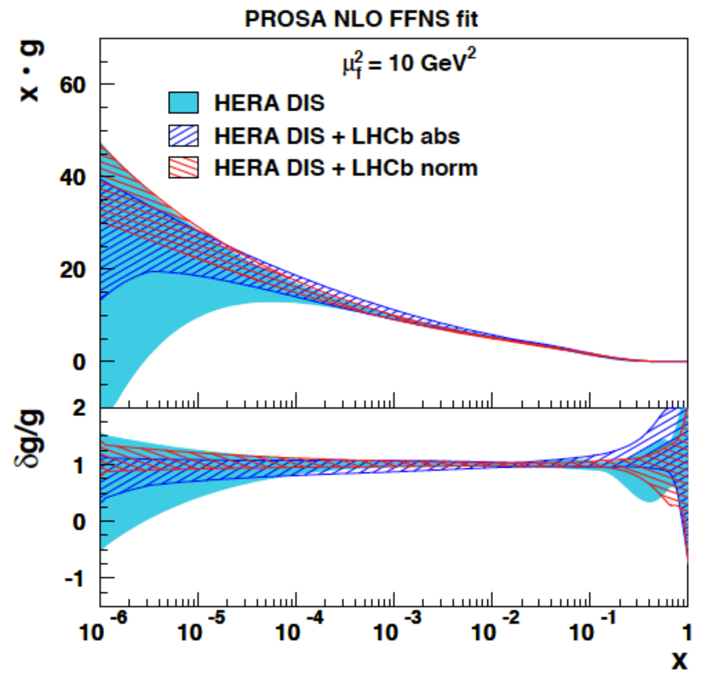
# Recent efforts in comparisons/benchmarking

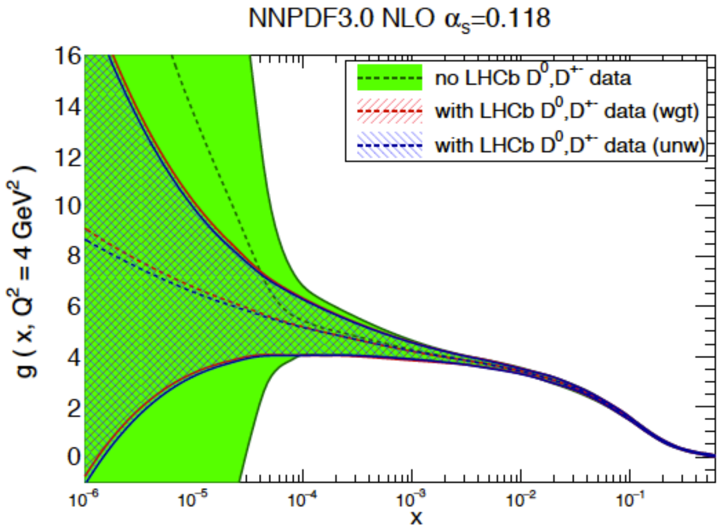



Comparison of PDFs at *Q*^2 = 10^2 GeV^2 between the NNPDF3.0, CT14 and MMHT14 sets at NNLO, with $\alpha_s(M_Z) = 0.118$.

From PDF4LHC 1507.00556 (July 2015)

# Constraints on the gluon at low *x* from c and b prod. at LHCb

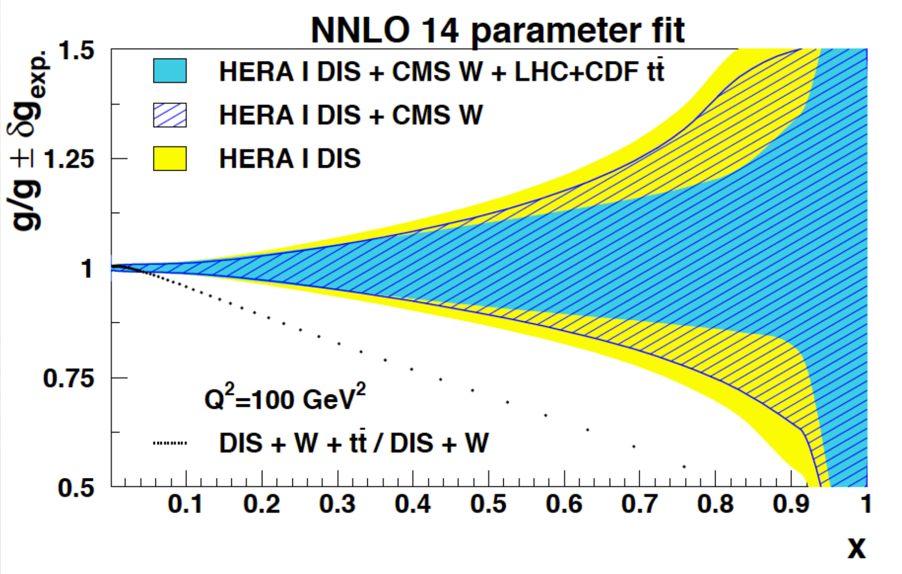


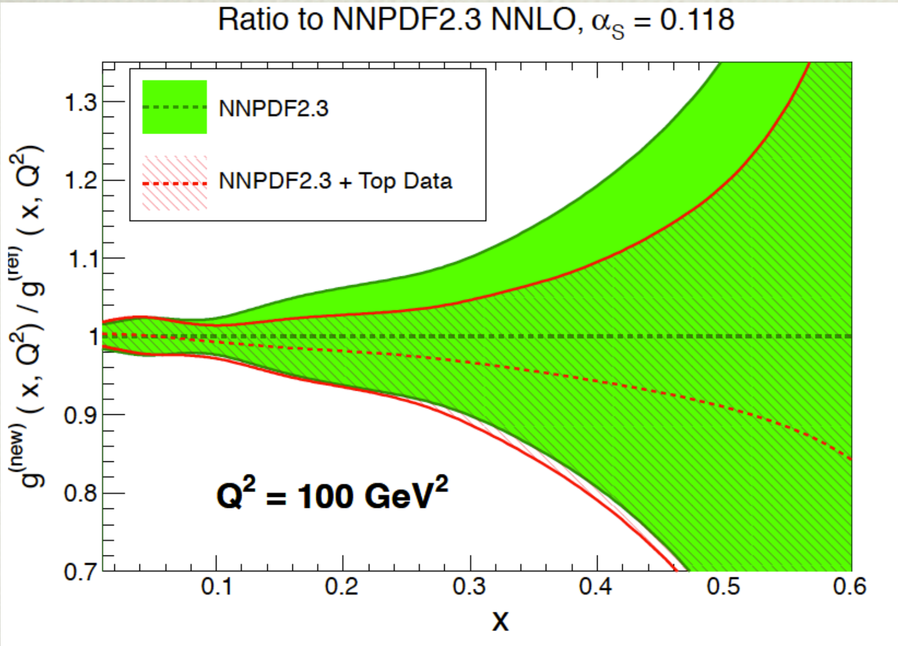

"Impact of heavy-flavour production cross sections measured by the LHCb experiment on parton distribution functions at low *x*"
Zenaiev *et al.*, PROSA Collaboration
EPJC 2015

"Charm production in the forward region: constraints on the small-x gluon and backgrounds for neutrino astronomy"
Gauld, Rojo, Rottoli, Talbert,
1506.08025 (2015)

# Constraints on the gluon at large *x* from ttbar data at the LHC




NNLO PDF analysis including tot. inclusive and differential ttbar cross sec. LHC data
M.G., Lipka, Moch, JHEP 2015



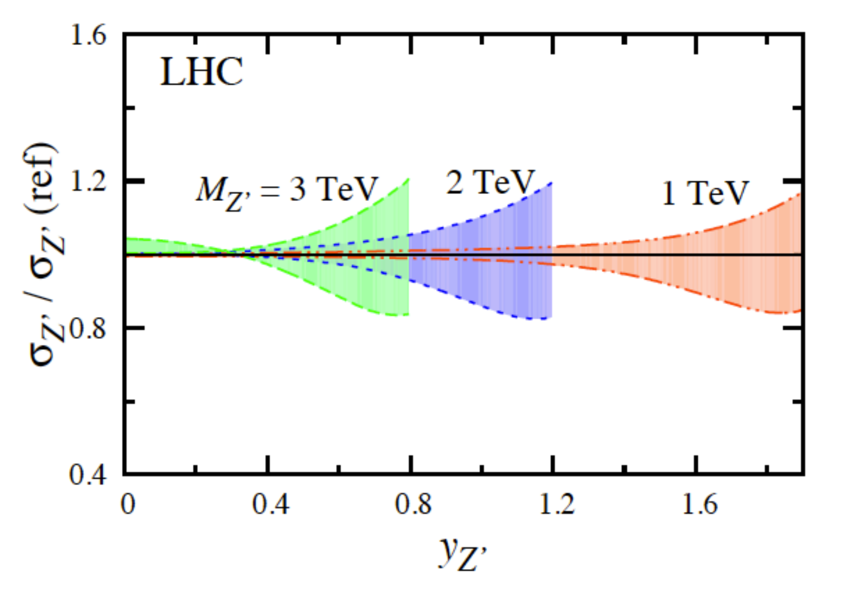

PDF Reweighting using ttbar total inclusive cross sec. LHC data
Czakon, Mangano, Mitov, Rojo JHEP 2013

# W' and Z' heavy bosons

Heavy boson production at hadron colliders probe PDFs at large x where these are currently poorly known.

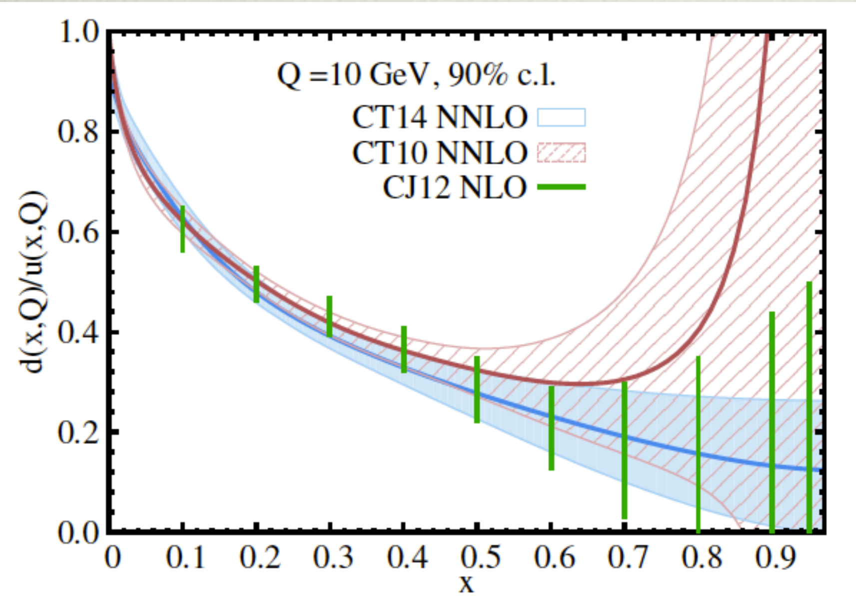
Definitely need to improve on this. Work is in progress, but it is crucial to have new clean measurements that probe PDFs at large x

# Impact of PDFs at large x in Z' production at the LHC



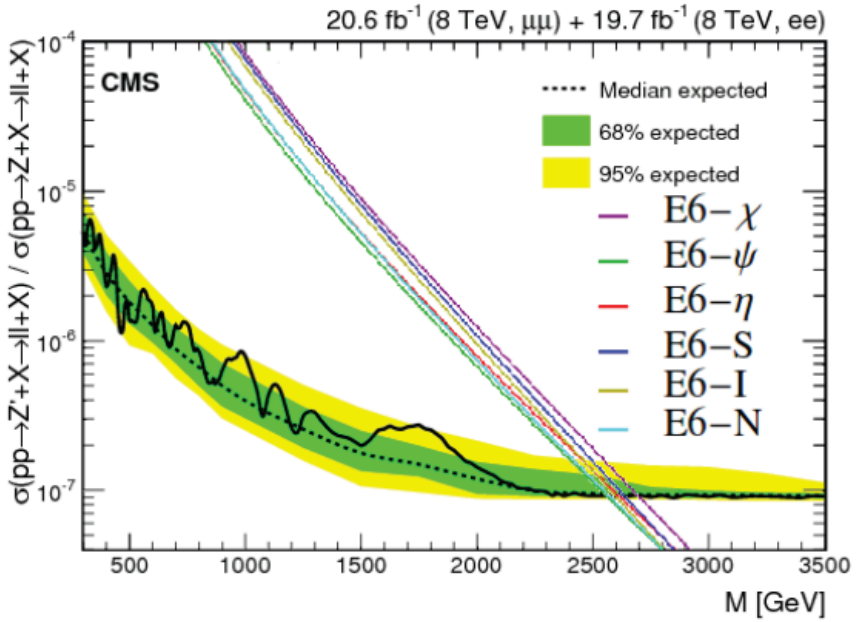

cross sections as a function of the rapidity, computed from CJ PDFs with maximum and minimum nuclear corrections, relative to the reference cross sections Z',W'(ref) calculated using the central CJ PDF set

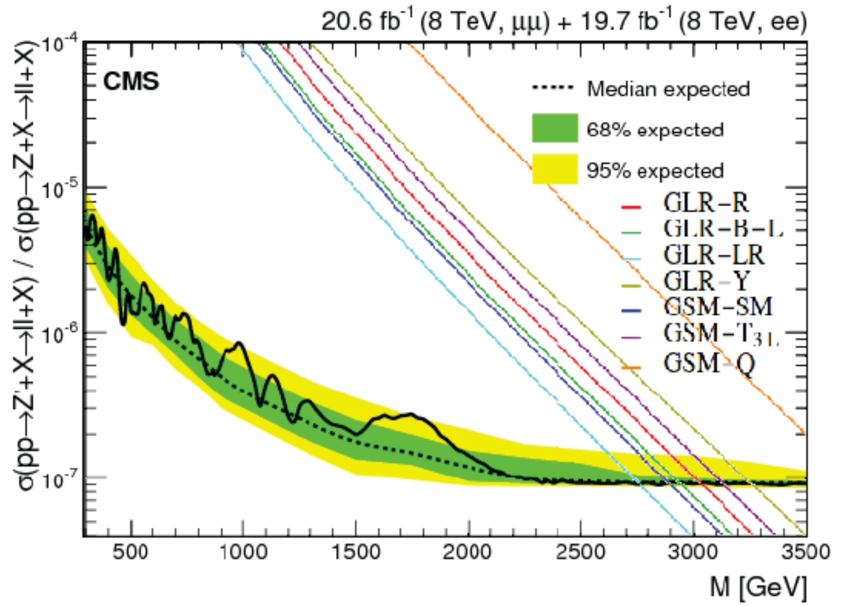
Brady, Accardi, Melnitchouk, Owens
JHEP 2014




dbar/ubar quark ratio in the recent CT14 NNLO analysis including LHC run I data
Dulat, Hou, Gao, M.G., et al. 1506.07443

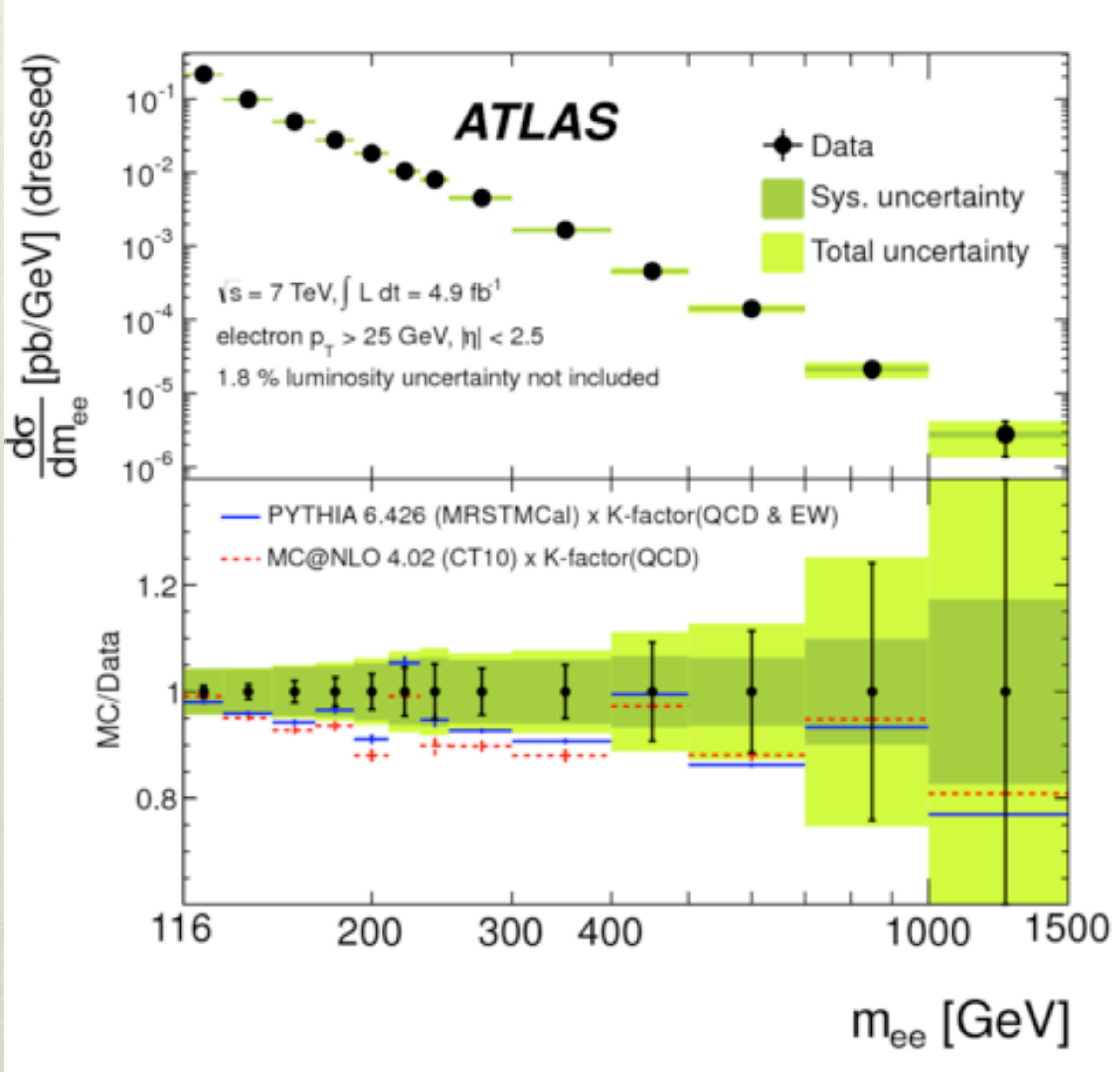
❖ Many theoretical models predicting extra Z' and W's.



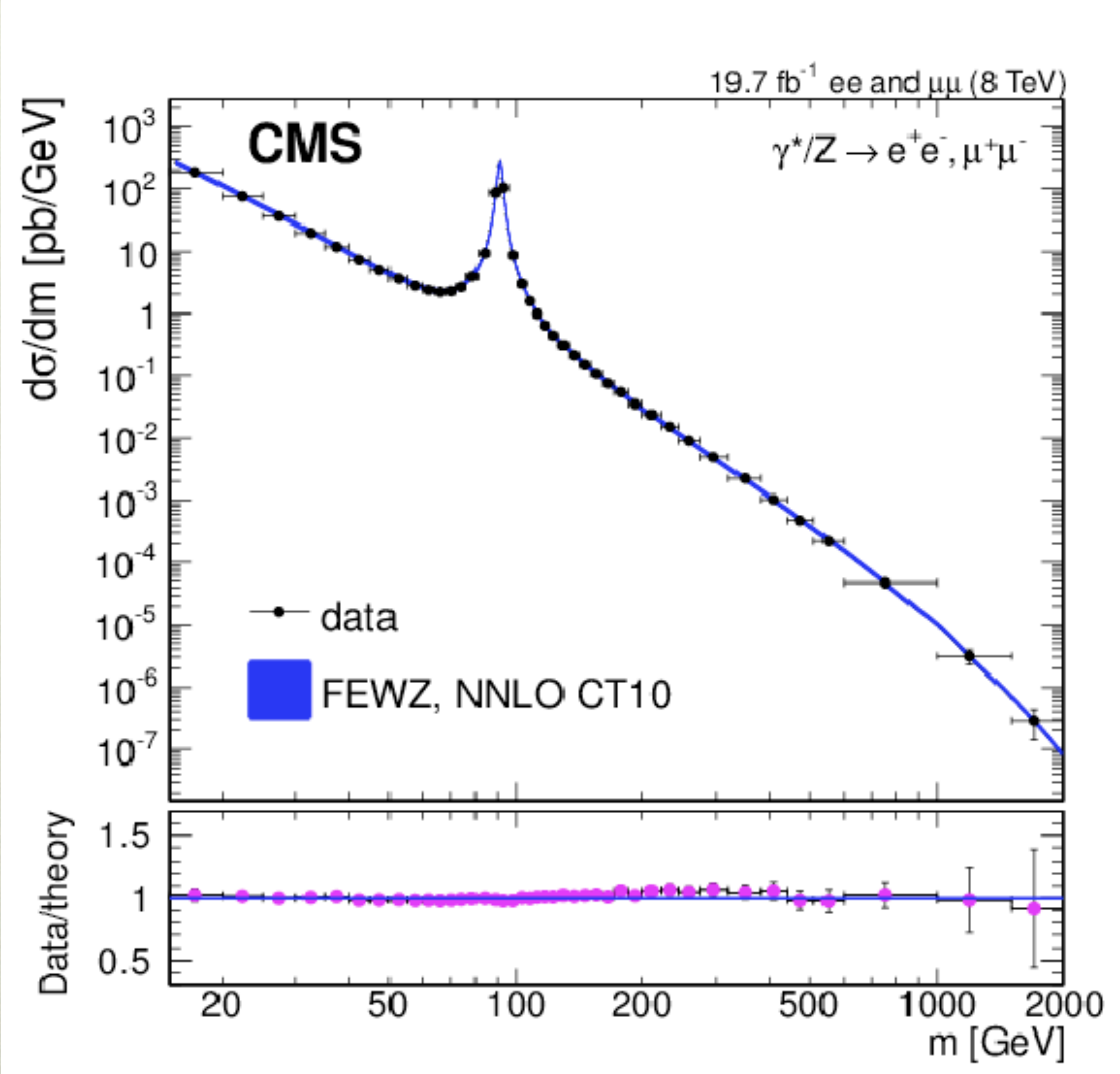




upper bound on Z' boson production cross section in Drell-Yan normalized to the SM cross section on the Z-boson peak.
Accomando Moretti, Fiaschi, et al., 1503.02672

So far, no luck in direct bump searches at the LHC

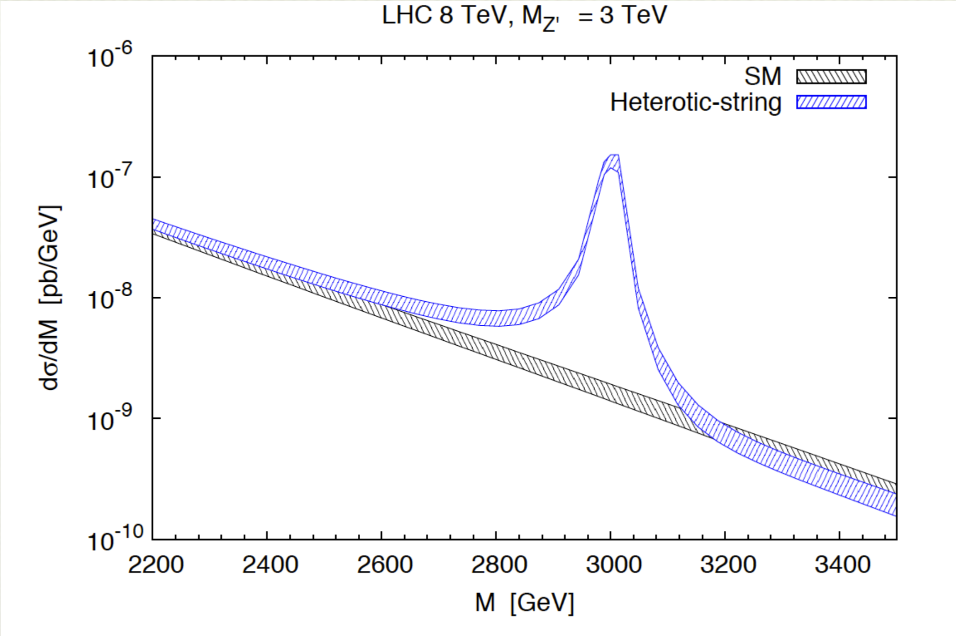


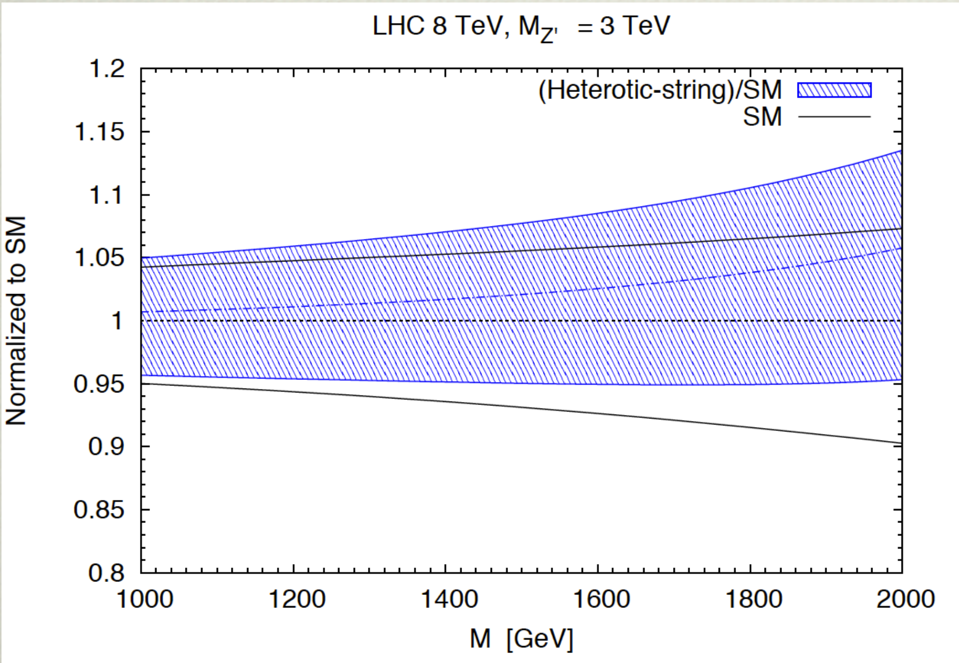

Standard Model Drell-Yan invariant mass distribution at ATLAS 7 TeV (electrons)




Standard Model Drell-Yan invariant mass distribution at CMS 8 TeV

## Bump searches in Drell-Yan



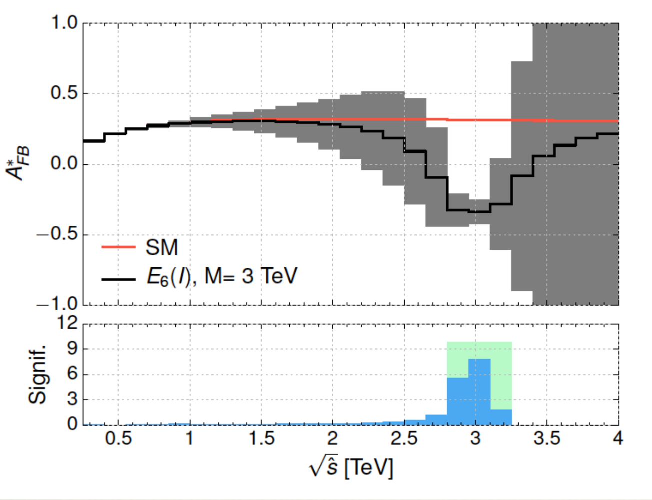




Some recent Z' proposal from Heterotic string inspired models

M.G., Faraggi EPJC 2015

PDF uncertainties are large

# Asymmetries as a complementary tool for Z' and W' searches



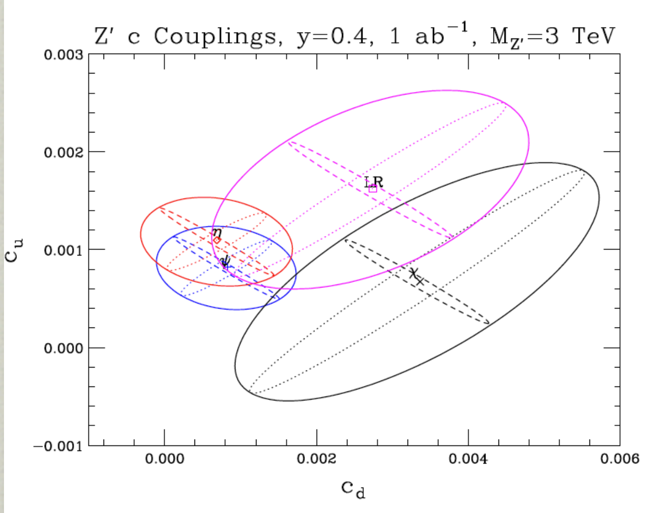

AFB in di-lepton production.
Not only discriminates among
different models, but also good for discovery

Accomando, Moretti, Fiaschi et al., 1503.02672

$$d\hat{\sigma}_F = \int_0^1 \frac{d\hat{\sigma}}{d\cos\theta_l^*} d\cos\theta_l^*$$

$$d\hat{\sigma}_B = \int_{-1}^0 \frac{d\hat{\sigma}}{d\cos\theta_l^*} d\cos\theta_l^*$$

$$A_{FB} = \frac{d\hat{\sigma}_F - d\hat{\sigma}_B}{d\hat{\sigma}_F + d\hat{\sigma}_B}$$




Simulated measurements of cu cd couplings at the LHC
Dashed ellipses are the statistical errors expected
for Mz' = 3 TeV and 1 ab^-1 of data,
the dotted ellipses are the current estimated
PDF errors, and the solid ellipses denote the
combined errors.

Petriello and Quackenbush, PRD 2008

# Conclusions

We have illustrated recent results from experiments at the run I of the LHC which seem to point towards SM craters

If discrepancies/excesses will be stay at LHC run II the presence of New Physics signals will be confirmed.
Exciting time ahead for theorists and experimentalists!

On the other hand, all analyses must be improved by using new sophisticated tools and new state-of-the-art precision calculations.

Perhaps discrepancies are only related to statistic fluctuations, maybe not.
LHC Run II will tell.

LHC is a very complicated machine and many experiments are going on:
we cannot expect that everything work perfectly all at once, but:

**WE CAN'T STOP THINKING BIG!**