BSM physics at hadron colliders: constraints from global analyses

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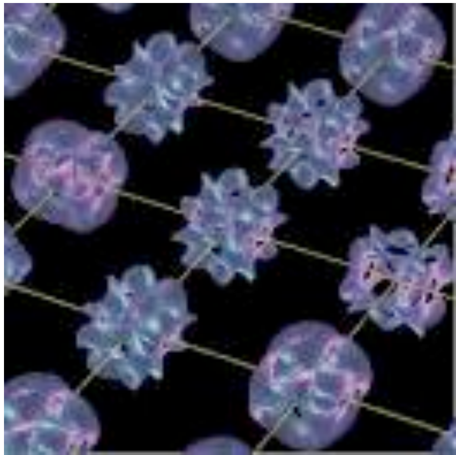
Several extensions of the Standard Model have been developed so far.

Many great ideas, motivated by the fact that SM is not perfect:
origin of mass,
strong CP problem,
neutrino oscillations,
matter–antimatter asymmetry,
dark matter and dark energy,
Hierarchy problem in connection with
spontaneous symmetry breaking – Higgs,
Gravity: SM does not explain it.

Supersymmetry

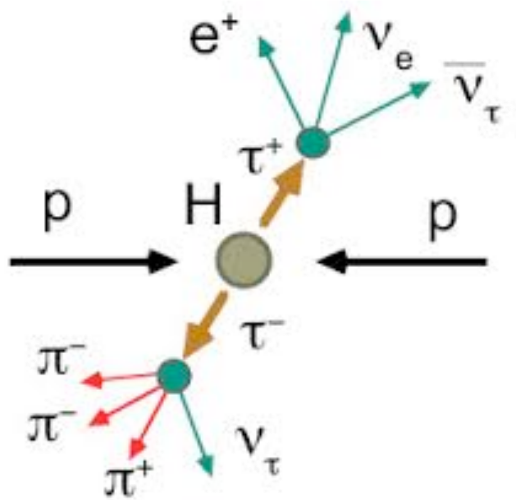
String Theory

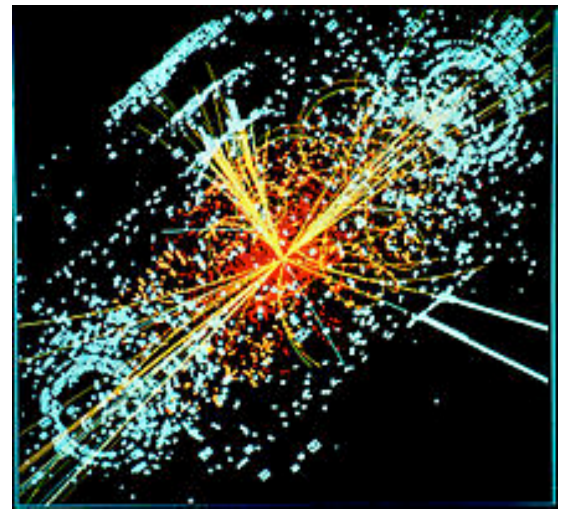
Extra dimensions



Let’s focus on high energy hadron-hadron collisions at the LHC

LHC is finally running (going for RUN II now)



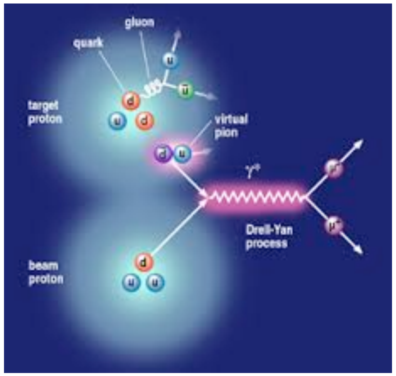


Theorists and Experimentalists are working hard
to search for New Physics signals

A lot of work goes in developing new techniques to separate
New Physics signals from the background

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

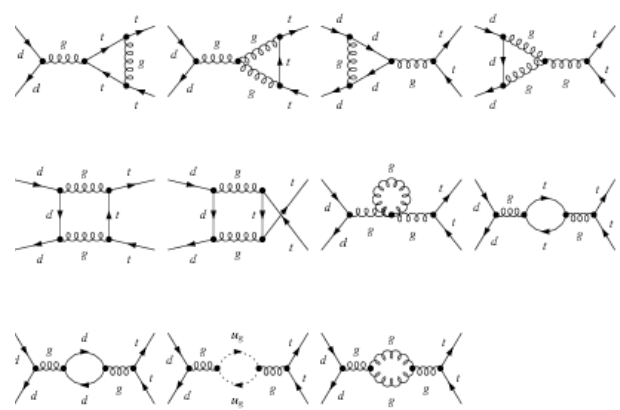
$$\sigma(\alpha_s(\mu_R^2), \mu_R^2, \mu_F^2)) = \sum_{a,b} \int_0^1 dx_1 dx_2 f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2)\ \hat{\sigma}^{a,b}(x_1, x_2; \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2) + \mathcal{O}\left(\frac{\Lambda_{QCD}^2}{Q^2}\right)$$



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

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

Effects of new physics impact hard scattering cross section:



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:

The general structure of the inclusive cross section for high-energy collisions involving hadron-hadron beams, lepton-hadrons, or hadron targets, is a convolution product where non-perturbative contributions (PDFs) and infrared-safe perturbatively calculable quantities (hard scatterings) are separated.

For Drell-Yan we have (Collins, Soper, Sterman (1984), (1985))

$$
\begin{aligned}
&\sigma(h_1 h_2 \to l^+ l^- + X) = \\
&\sum_{a,b} \int_{x_1}^{1} d\xi_1 \int_{x_2}^{1} d\xi_2 \, f_{h_1\to a}(\xi_1, \alpha_s(\mu_R), \mu_R, \mu_F) f_{h_2\to b}(\xi_2, \alpha_s(\mu_R), \mu_R, \mu_F) \\
&\times \hat{\sigma}^{ab}(\frac{x_1}{\xi_1}, \frac{x_2}{\xi_2}; \alpha_s(\mu_R), Q, \mu_F, \mu_R) + \mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right) \,,
\end{aligned}
$$

Complicated objects

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

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

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

$$W(w^-, 0) = P\left[e^{-ig_0 \int_0^{w^-} dy^- A^+_{(0)\alpha}(0, y^-, \mathbf{0}_\mathrm{T}) t_\alpha} \right]. \tag{3}$$

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. $\overline{\mathrm{MS}}$ scheme.

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.
Parton evolution is obtained in terms of integro-differential equations known as DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) equations

$$\frac{d\ f_i(x,\mu_R,\mu_F)}{d\log\mu_F} = \sum_{j=q\bar{q},g}\int_x^1 \frac{dy}{y} P_{ij}\left(\frac{x}{y};\alpha_s,\mu_R,\mu_F\right) f_j(y,\mu_R,\mu_F)\,, \qquad (4)$$

The evolution kernels or "splitting functions" P_{ij} are known at 3-loop for the unpolarized case. Moch, Vermaseren, Vogt (2004)

Universal objects

Gluons, quarks and antiquarks are the known constituents of the proton. Their distributions as a function of x and generic scale μ, at which partons are probed, are universal quantities that do not depend on the specific hard process under consideration.

Differently from the hard-scattering cross section, the analytic structure of the PDFs cannot be predicted by perturbative QCD, but has to be determined by comparing standard sets of cross sections, such as Eq. 1, to experimental measurements by using a variety of analytical methods.

For this reason PDFs are “data-driven” quantities.

Imagine you have a Standard Model extension that predicts the existence of new particles.

Let's suppose that new signatures can be found in hadronic reactions.

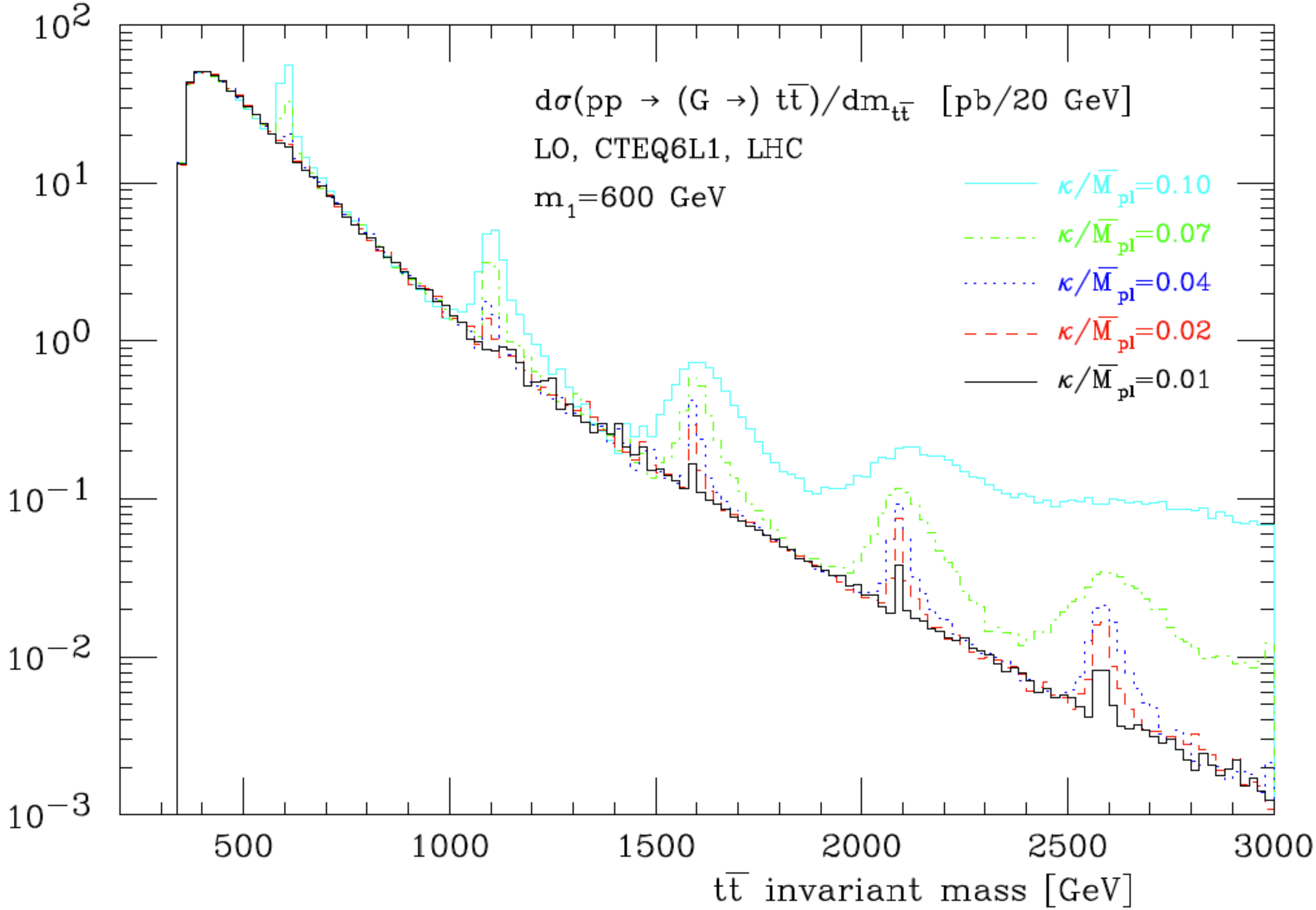
You might want to test it in high energy hadron-hadron collisions.

We can use what we learned from global analyses in QCD.

....and the fun/pain begins...

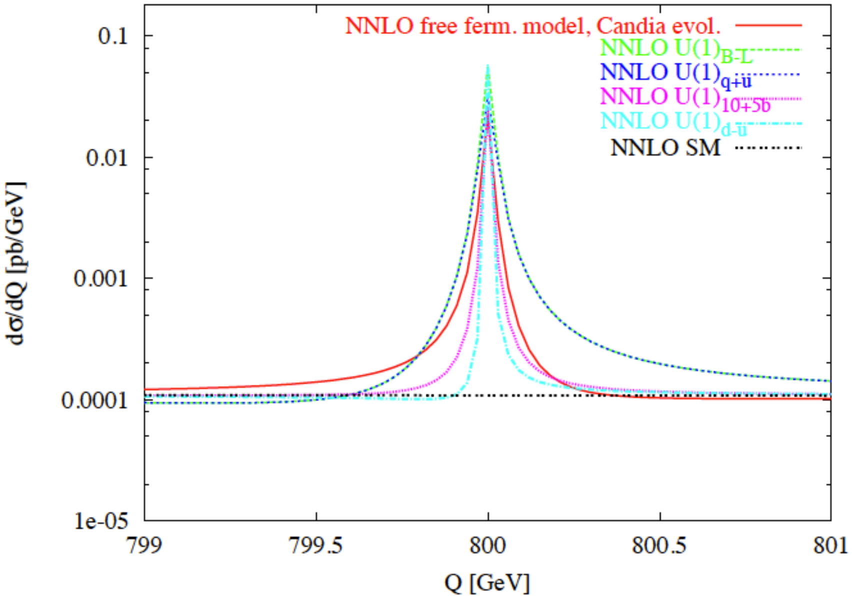
New physics signals predicted by a new model result in any kind of distortion of known SM distributions:

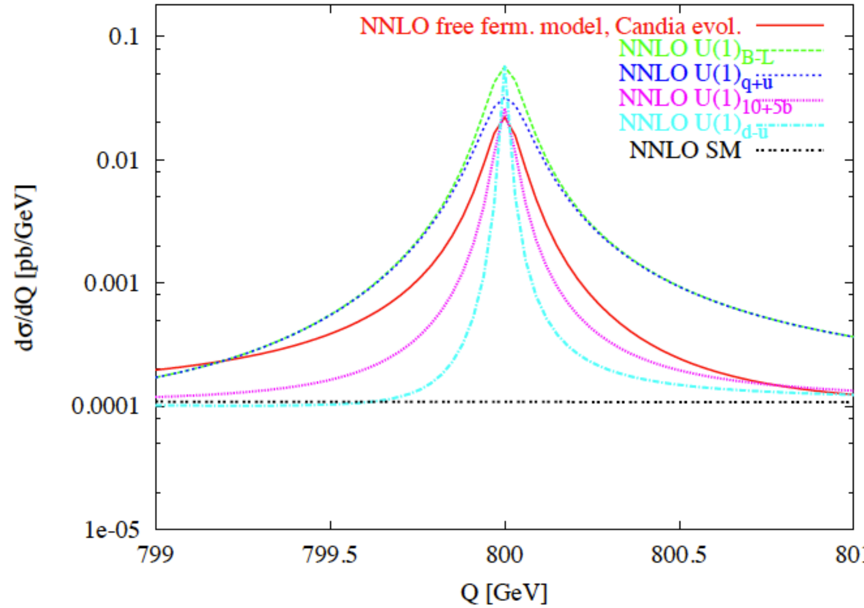
Searches for Gravitons:

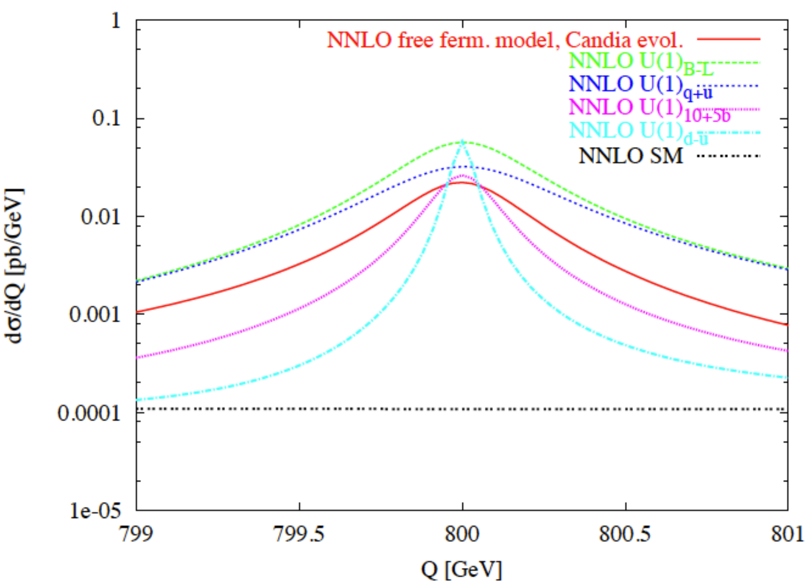


Spin-2 resonance: KK graviton modes on the ttbar invariant mass spectrum, Maltoni and Frederix, JHEP 2009

Searches for extra neutral currents, Z’s

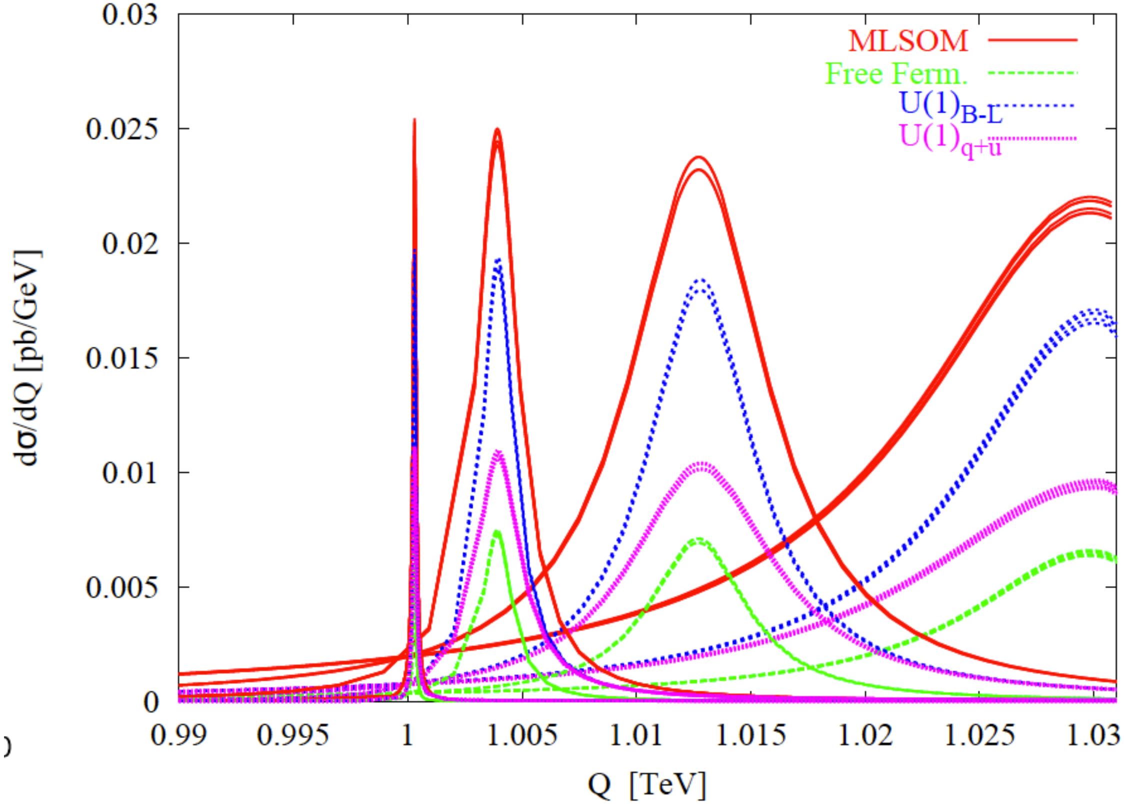




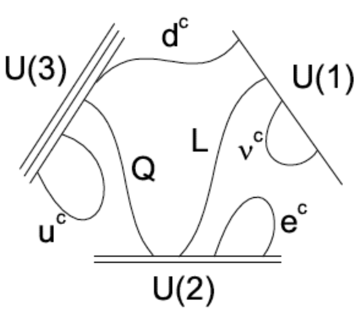


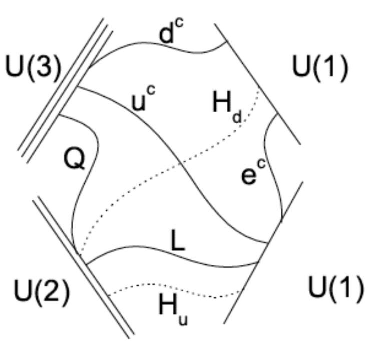
Z’s in Free fermionic Models: Tanβ=40
gz=0.05,0.1,0.2

Coriano’, Faraggi, M.G. PRD2008



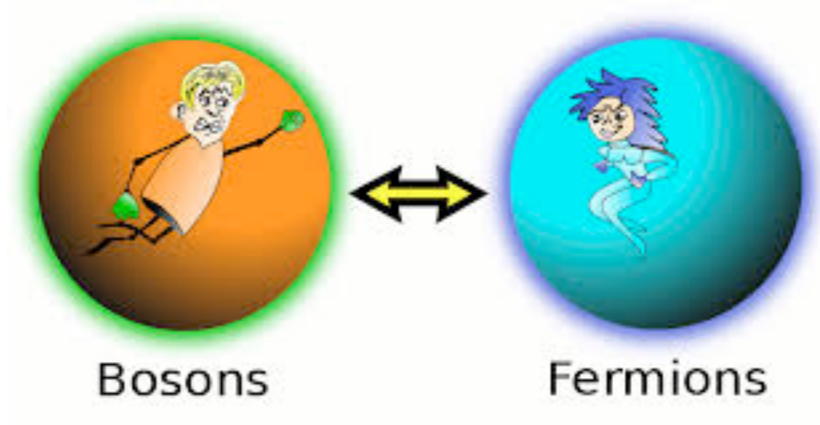
We can also have Z's from D-brane models that extend the symmetry group of the SM: U(3)xU(2)xU(1)xU(1)….

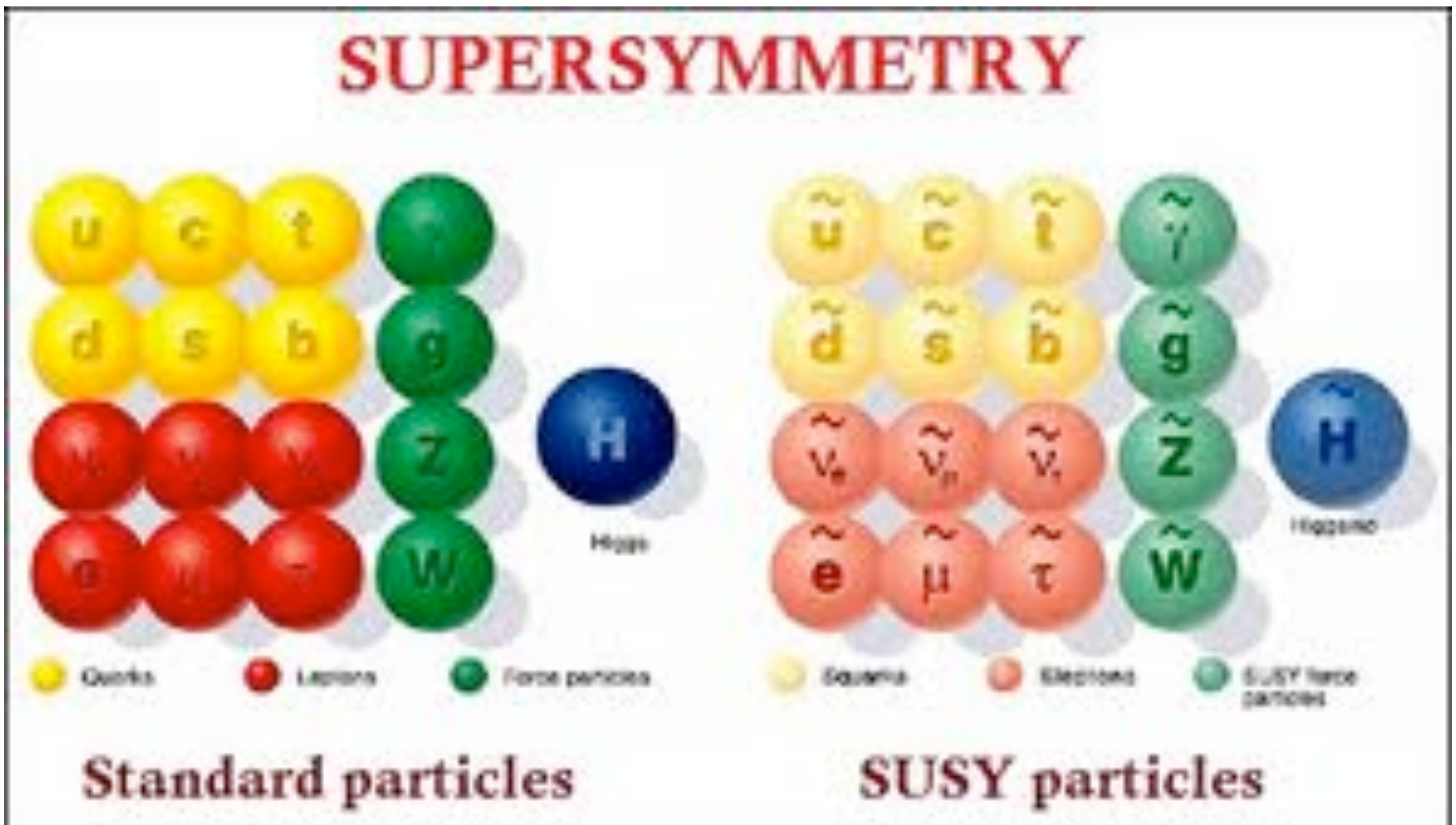




Z's from minimal low scale orientifold models

Armillis, Coriano', MG, Morelli NPB 2009 what about SUSY?



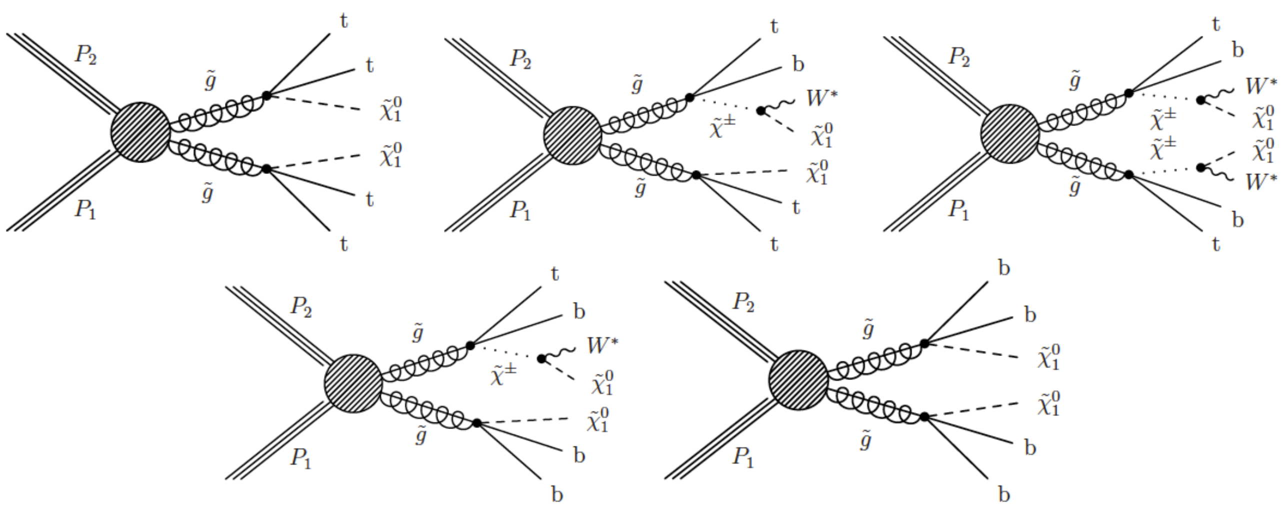


.....gluinos for example (tell you why in a moment)

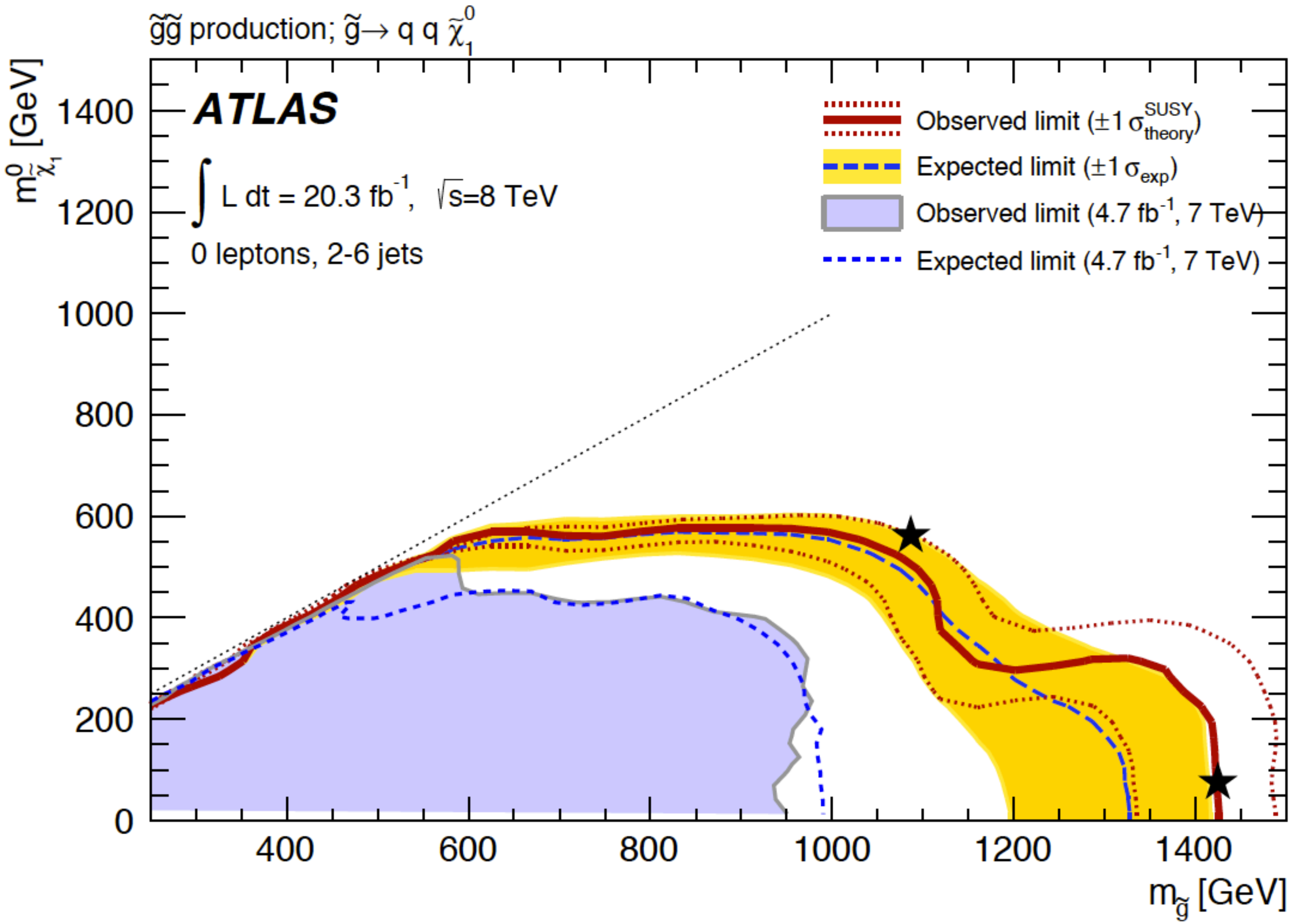
According to the recent LHC exclusion limits from ATLAS and CMS, it seems SUSY is having hard time when we search for direct signal.

Very stringent bound have been set by CMS and ATLAS up to 8 TeV.
$m_{\tilde{g}}$ < 1.3 TeV seem to be ruled out for several scenarios.

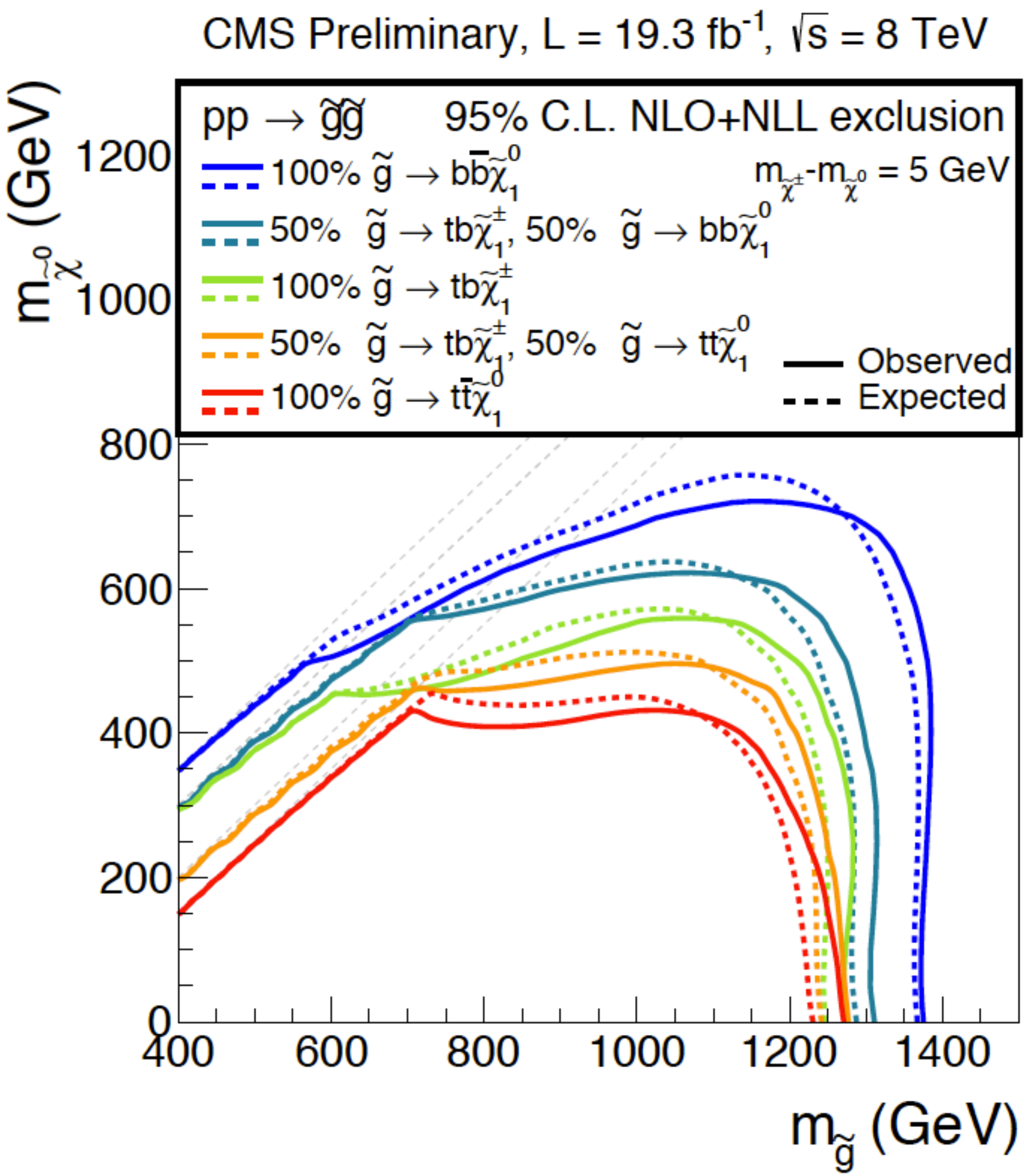
But it is difficult to have a complete conclusive answer also due to model-dependent assumptions.
LHC Run II results will tell us more.



Samples of event topologies of gluino-pair production



gluino pairs with decoupled squarks ATLAS 8 TeV. ATLAS Coll. **arXiv:1405.7875**



Limits on Gluon masses in simplified natural SUSY models. CMS Coll. SUS-14-011-pas

Now, we want to show that we can use PDFs to constrain SM model extensions predicting lighter versions of gluinos, independently of other information on such states.

Let’s take a simple example in which global analysis techniques are used to constrain existence and properties of “light” (mass ≤ 100 GeV) color-octet fermions.

If such particles exist, these affect the determination of PDFs of the proton already in an analysis at NLO.

Similar Studies made in the past for light gluinos:

Ruckl and Vogt, Z.Phys. C64 (1994),
Bluemlein and Botts PLB325 1994,
Berger, Nadolsky, Olness and Pumplin PRD71 2004,
Berger, MG, Lai, Nadolsky, Olness PRD 2010

Important to notice that:

Gluino with a mass of about 50-100 GeV is not typical in phenomenological models of SUSY breaking, nor of the results of experimental direct search analyses based on specific models of SUSY breaking and assumptions about mass relationships among SUSY states.

As long as the SUSY neutralino $\tilde{\chi}^0$ is lighter than the gluino, the typical decay process for a light gluino is $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0$, where q stands for a SM quark.
Missing energy would signal the presence of a neutralino.

However, for a small mass splitting $m_{\tilde{g}} - m_{\chi^0}$,
the gluino's decay into missing energy and soft quark jets would be undetected.

The analysis shown here is complementary to other approaches
for bounding the gluino mass, and it is in some respects more general
in that we make no assumptions about gluino's decay.

Global analysis to determine PDFs of the proton in the presence of "light" color-octet fermions/gluinos can be used to constrain their mass in a very general way

QCD GLOBAL ANALSYS OF DATA in a nutshell:

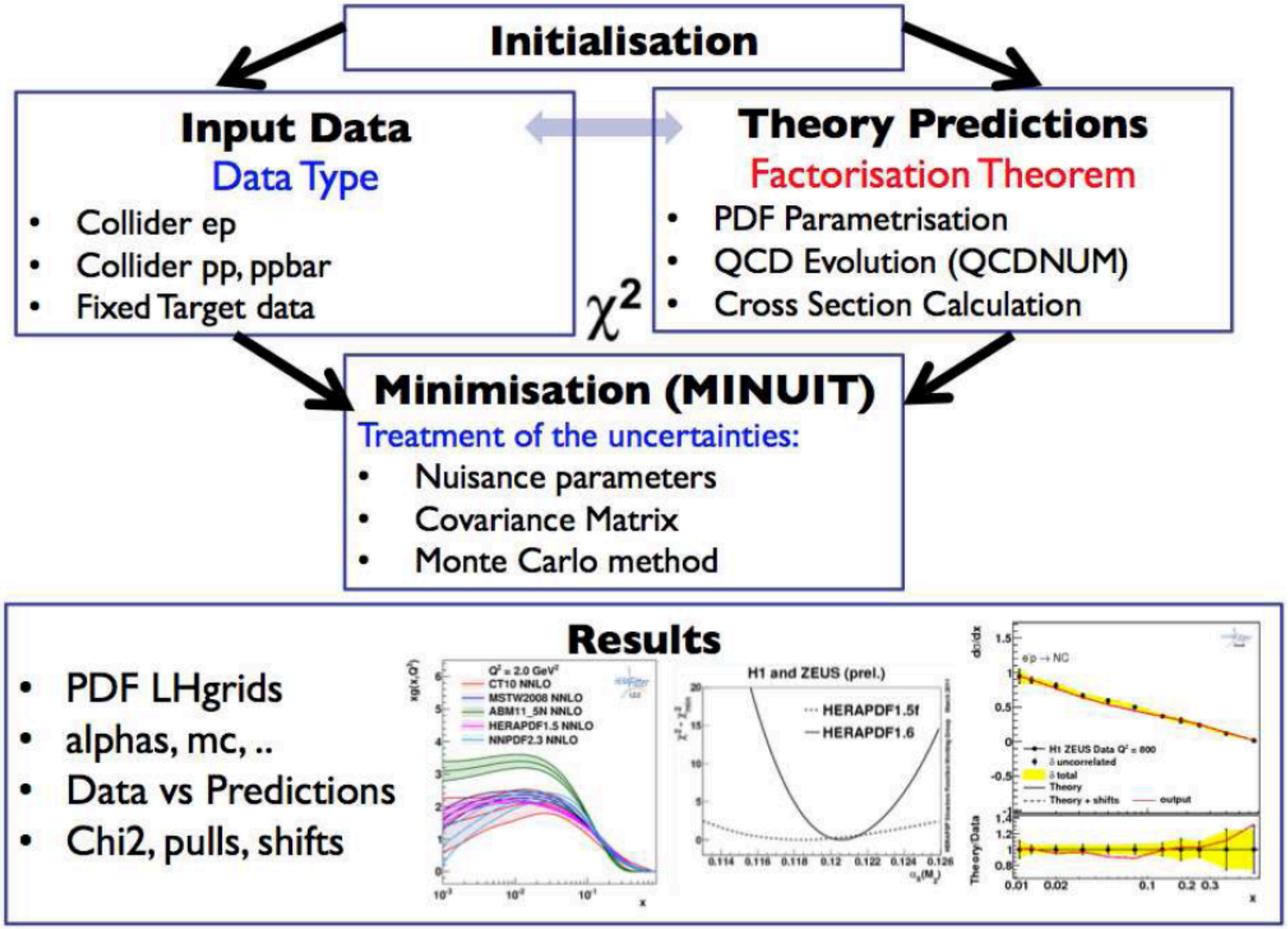
parton distribution functions (PDFs) of the proton are determined by comparing theoretical predictions for cross sections to the experimental data.

All rely heavily 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.

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

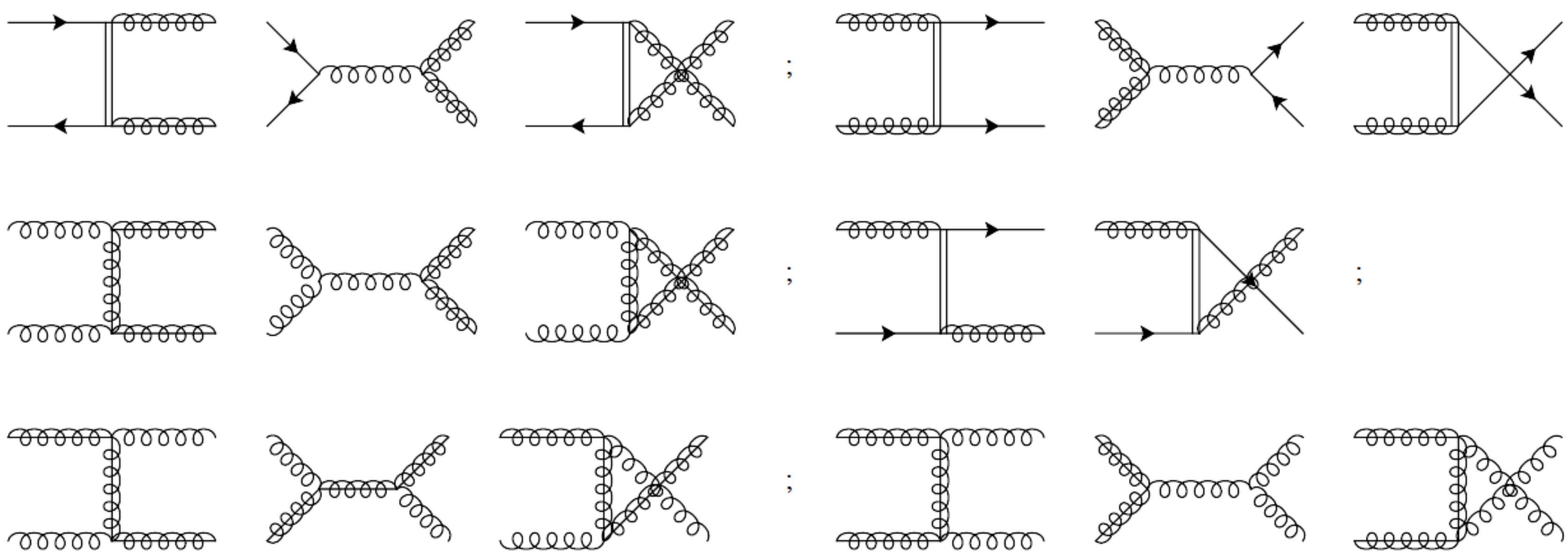
A little dramatization



Why using global analysis to determine PDFs of the proton ?

Under well-defined conditions, a relatively light strongly-interacting fundamental particle may be treated as a constituent of the colliding hadrons.

It will share the momentum of the parent hadron with the standard model quark, antiquark, and gluon partners. The experimental consequences of this picture become evident when the parent hadron is probed at a sufficiently large hard scale



Why using global analysis to determine PDFs of the proton ?

Under well-defined conditions, a relatively light strongly-interacting fundamental particle may be treated as a constituent of the colliding hadrons.

The example is carried out in the framework of the CT10 NLO (PRE-LHC) analysis.
Same set of data as the latest CT10 PDF fit.
(2753 data points from 35 experiments. No LHC data.)

The resulting PDFs are "BSM PDFs".

1) new colored states modify the evolution with hard scale Q of the strong coupling alphas.

2) in pQCD, the coupling of a color-octet fermion to quarks and gluons alters the set of evolution equations that governs the behavior of all PDFs, thus affecting many hadron scattering cross sections.

3) Moreover, production of the color-octet states will affect relevant observables, such as jet rates, whose cross sections are included in the global fits

The presence of color-octet fermions modifies the PDF fit in three ways:

1) It alters strong coupling constant alphas (Q),
thereby modifying the evolution of ordinary quark and gluon PDFs.

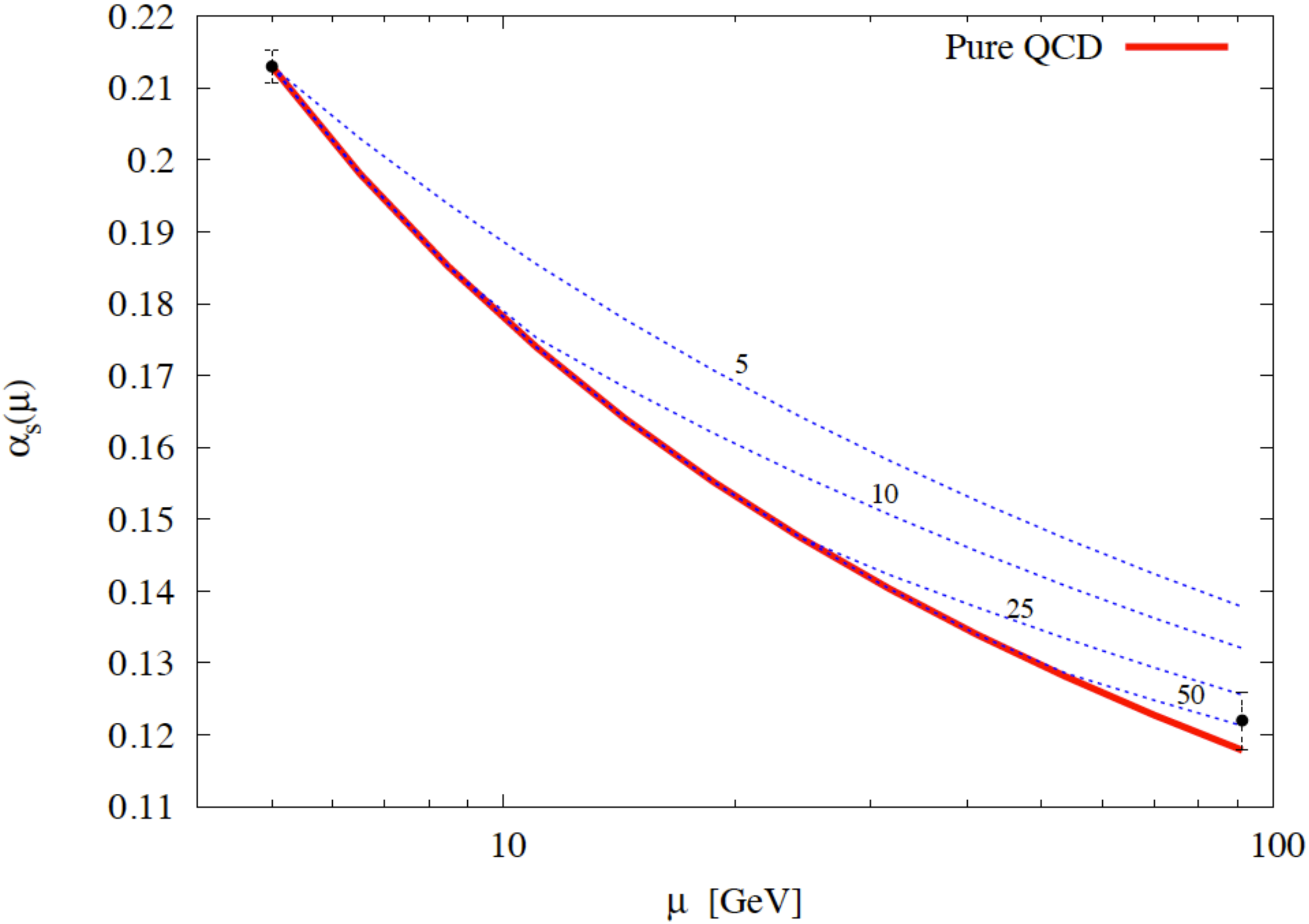
$$
\begin{aligned}
Q\frac{\partial}{\partial Q}\,\alpha_s(Q) &= -\frac{\alpha_s^2}{2\pi}\sum_{n=0}^{\infty}\beta_n\left(\frac{\alpha_s}{4\pi}\right)^n \\
&= -\left[\beta_0\frac{\alpha_s^2}{2\pi}+\beta_1\frac{\alpha_s^3}{2^3\pi^2}+\ldots\right].
\end{aligned}
$$

$$
\beta_0 = 11-\frac{2}{3}n_f-2n_{\tilde{g}}-\frac{1}{6}n_{\tilde{f}},
$$

$$
\beta_1 = 102-\frac{38}{3}n_f-48n_{\tilde{g}}-\frac{11}{3}n_{\tilde{f}}+\frac{13}{3}n_{\tilde{g}}n_{\tilde{f}},
$$

Modifications of the running of αs w.r.t. the SM

$m_{\tilde{g}}$ = 5, 10, 25, 50 GeV



It's important at this stage to have good constraints (precise exp. determination) on alphas(Q)

Composite alphas at low scale Q

$$\alpha_s(Q=5) = 0.218612 \pm 0.005757 \quad \text{from } \tau \text{ decay (see Baikov, Chetyrkin, Kuhn PRL101 2008)} \tag{4}$$

$$\alpha_s(Q=5) = 0.21435 \pm 0.00301 \quad \text{from heavy quarkonia (see Amsler } \textit{et. al.} \text{ PLB667 2008 ref. therein)} \tag{5}$$

$$\alpha_s(Q=5) = 0.20897 \pm 0.003925 \quad \text{from lattice QCD (see Amsler } \textit{et. al.} \text{ PLB667 2008)} \tag{6}$$

…evolved to the common scale Q = 5 GeV in pure QCD
and added as a weighted mean (as the published values are given at different low scales).

Composite alphas at high scale Q: you can proceed in two ways

* Assume a fixed value of $\alpha s(MZ) = 0.118$;

* Go with floating $\alpha s(MZ)$, constrained by an assumed high-Q data point, $\alpha s(MZ) = 0.123 \pm 0.004$.

The presence of color-octet fermions modifies the PDF fit in three ways:

2) DGLAP equations are extended to account for the new processes:

$$Q^2 \frac{d}{dQ^2} \begin{pmatrix} \Sigma(x, Q^2) \\ g(x, Q^2) \\ \tilde{g}(x, Q^2) \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi} \times$$

$$\times \int_x^1 \frac{dy}{y} \begin{pmatrix} P_{\Sigma\Sigma}^{NLO}(x/y) & P_{\Sigma g}^{NLO}(x/y) & P_{\Sigma\tilde{g}}^{LO}(x/y) \\ P_{g\Sigma}^{NLO}(x/y) & P_{gg}^{NLO}(x/y) & P_{g\tilde{g}}^{LO}(x/y) \\ P_{\tilde{g}\Sigma}^{LO}(x/y) & P_{\tilde{g}g}^{LO}(x/y) & P_{\tilde{g}\tilde{g}}^{LO}(x/y) \end{pmatrix} \begin{pmatrix} \Sigma(y, Q^2) \\ g(y, Q^2) \\ \tilde{g}(y, Q^2) \end{pmatrix} \quad (1)$$

$$\Sigma(x, Q^2) = \sum_{i=u,d,s,\ldots} (q_i(x, Q^2) + \bar{q}_i(x, Q^2)). \quad (2)$$

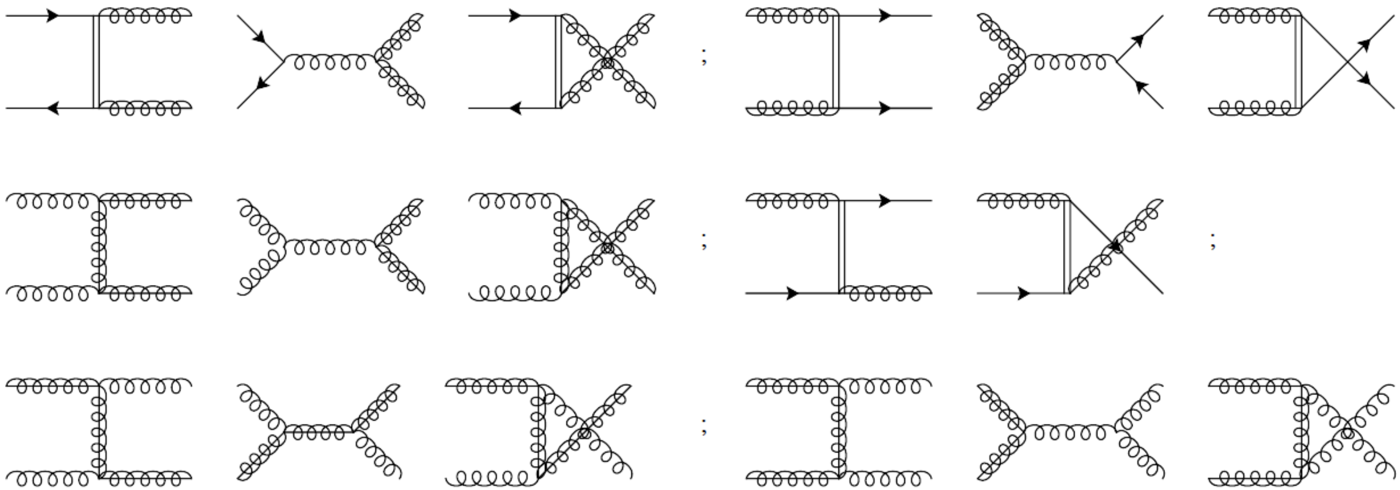
$\Sigma(x, Q^2)$, $g(x, Q^2)$, and $\tilde{g}(x, Q^2)$ are the singlet quark, gluon, and gluino distributions. In the x-range $[10^{-5}, 0.7]$ $\tilde{g}(x, Q^2) << g(x, Q^2)$ and $\tilde{g}(x, Q^2) << q(x, Q^2)$.

We include the gluino terms in the splitting functions at LO, without sacrificing the overall NLO accuracy of the whole fit.

The presence of color-octet fermions modifies the PDF fit in three ways:

3) Color-octet fermions contribute to some hard scattering processes.
In jet production, LO gluino terms with massive kinematics are included.

In DIS and vector boson production gluino hard scattering terms are of order O(αs^2) and can be neglected for this specific study.



The 2 → 2 hard scattering contributions with two “gluinos” in the initial or final states are illustrated in Fig. 1. We assume that the masses of the squarks are large enough that diagrams containing a “squark” propagator are negligible. The remaining “SUSY” diagrams can be evaluated in the the S-ACOT factorization scheme, in order to simplify treatment of the “gluino” mass dependence.

Few remarks on perturbative calculations in SUSY QCD

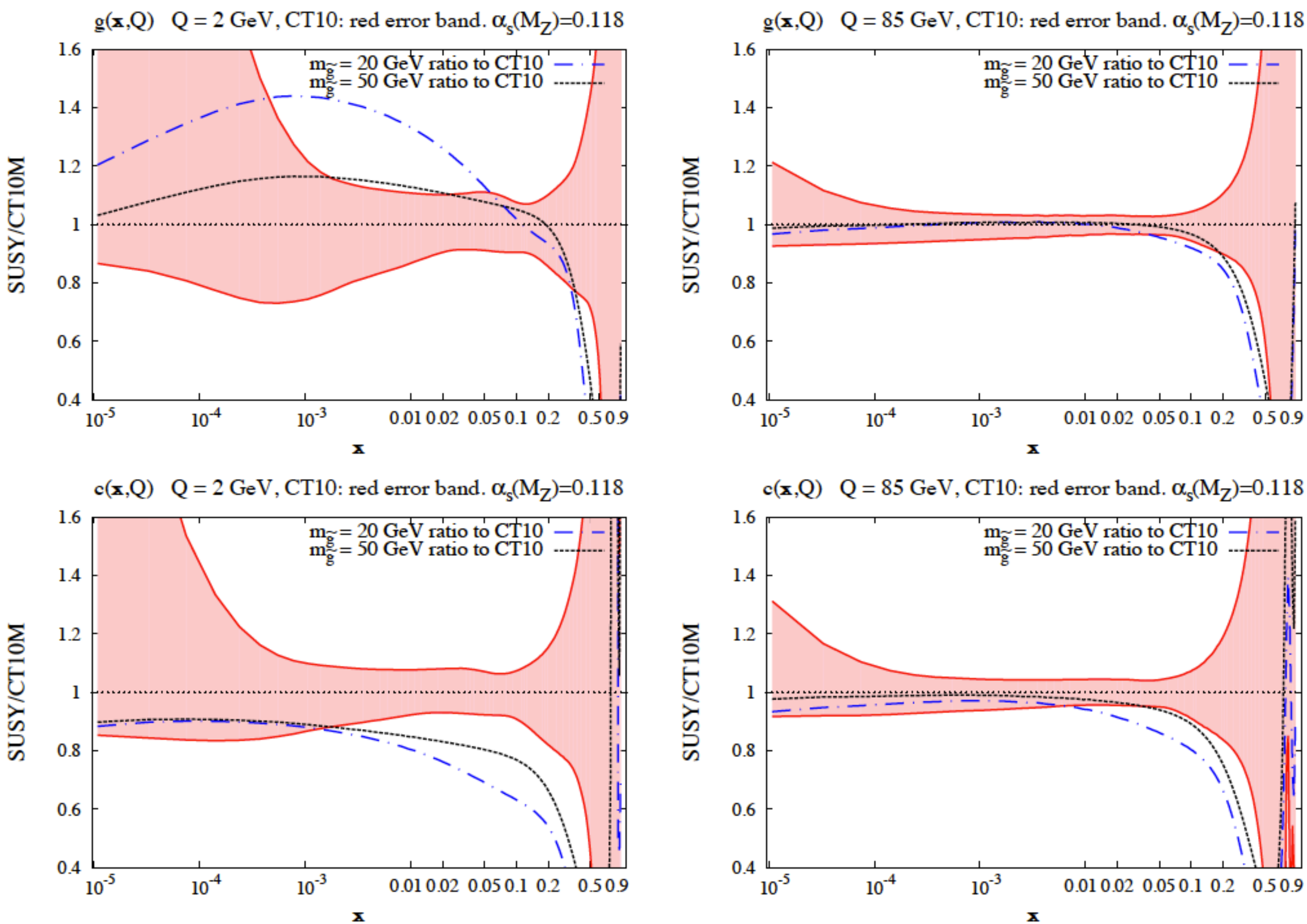
NLO SUSY-QCD corrections to gluino production known for a long time:
Beenakker, Höpker, Spira, Zerwas, NPB492, (1997)

Improvement beyond NLO (threshold enhanced logarithms):

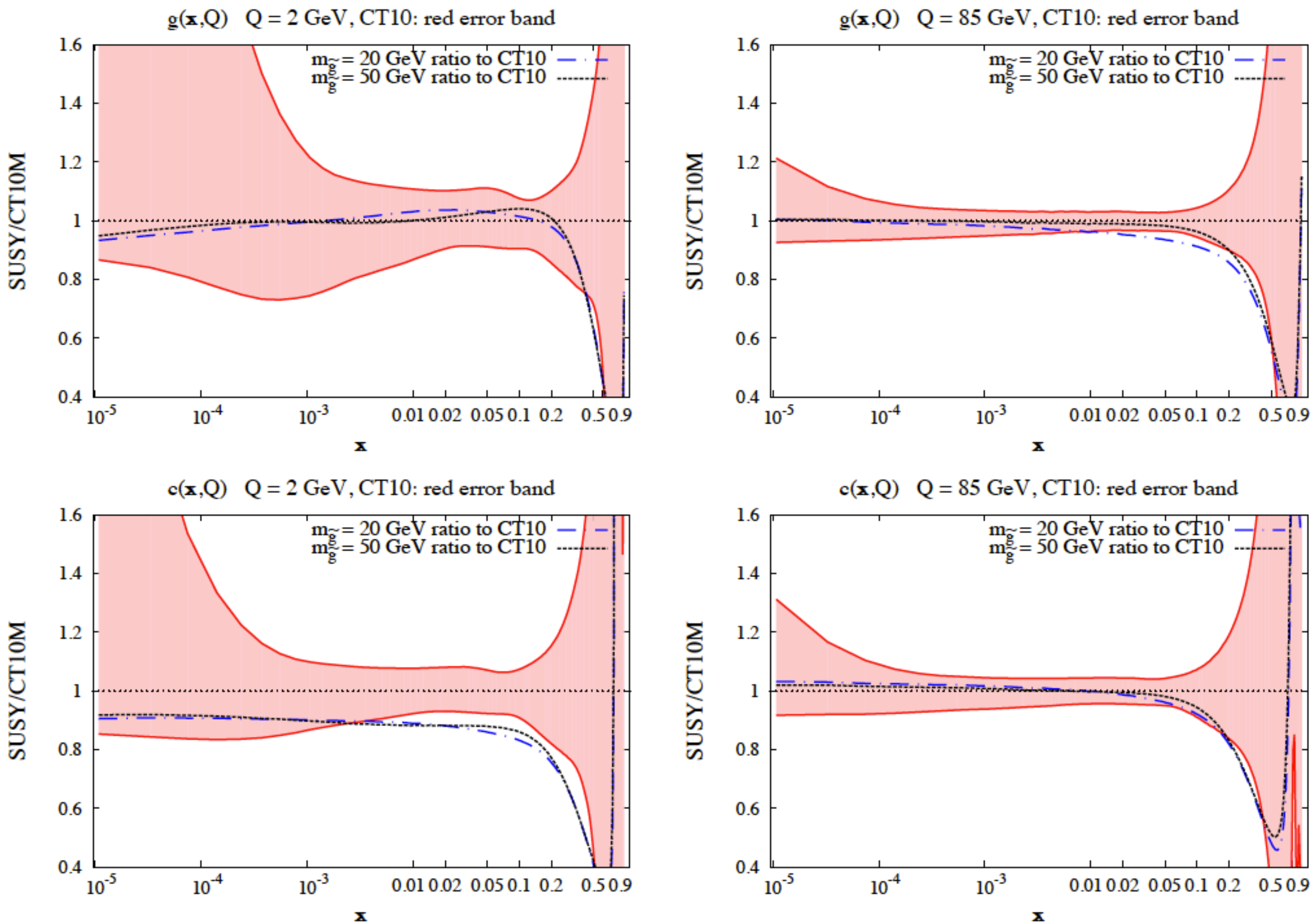
Kulesza, Motyka, PRL102 (2009); PRD80 (2009);
Beenakker et al., JHEP (2009);
Langenfeld, Moch, Pfoh JHEP (2012).

A summary of cross sections calculations can be found in:
Kramer, Kulezsa, Mangano et al. 2014

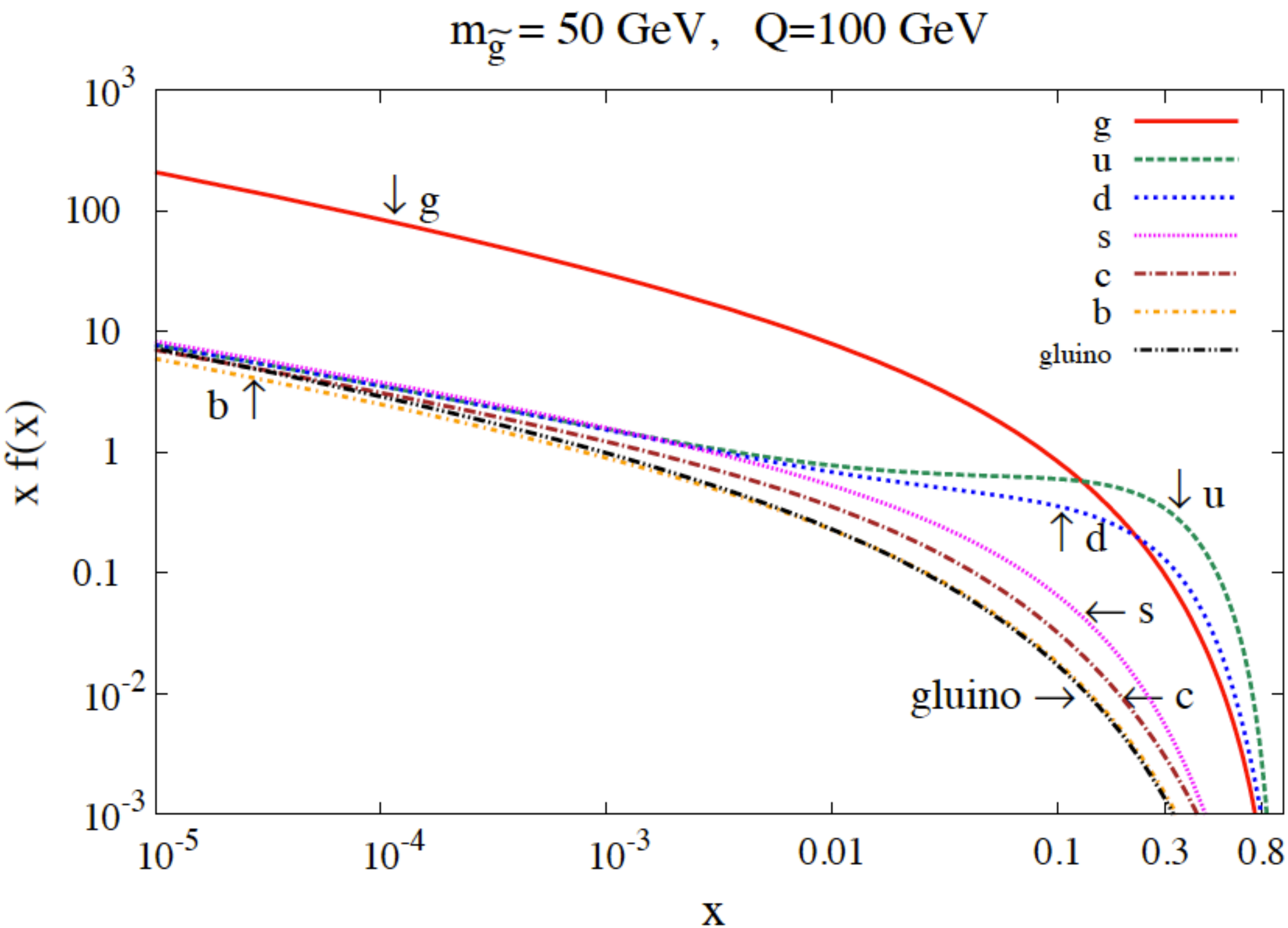
Results for the gluon in the PDF fit with fixed value of alphas(MZ)=0.118

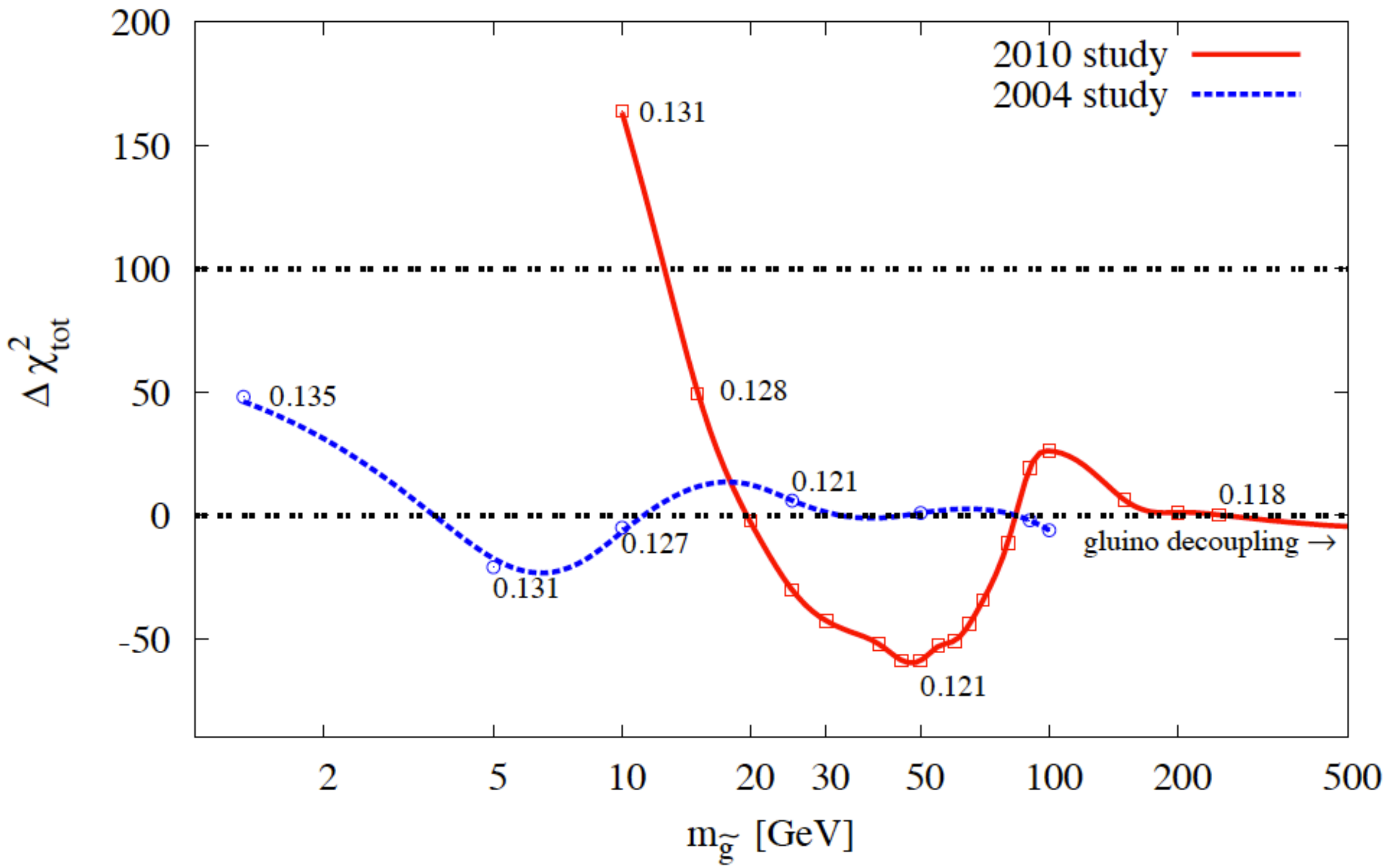


Results for the gluon in the PDF fit with floating alphas(MZ).



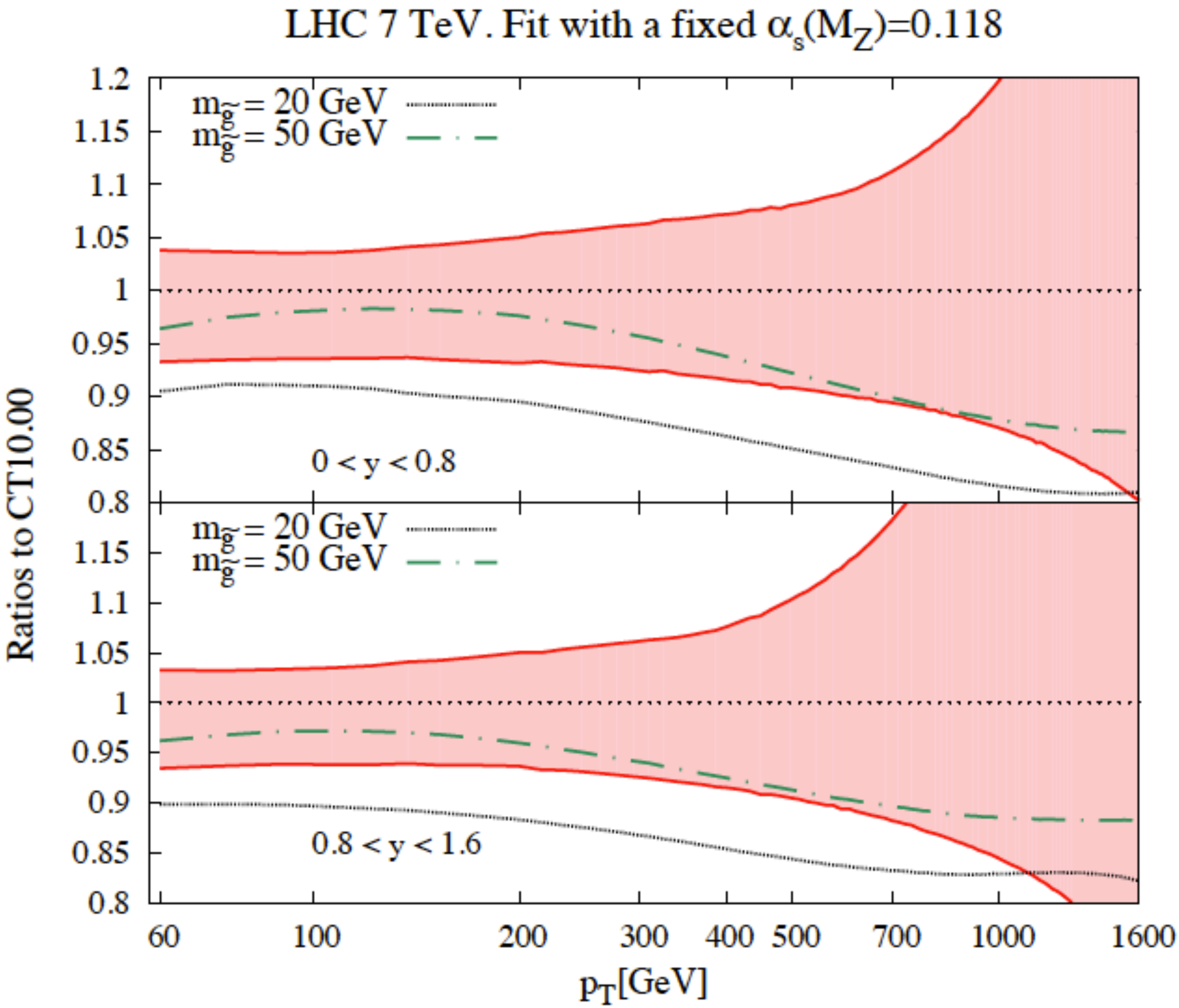
What about the other PDFs ?



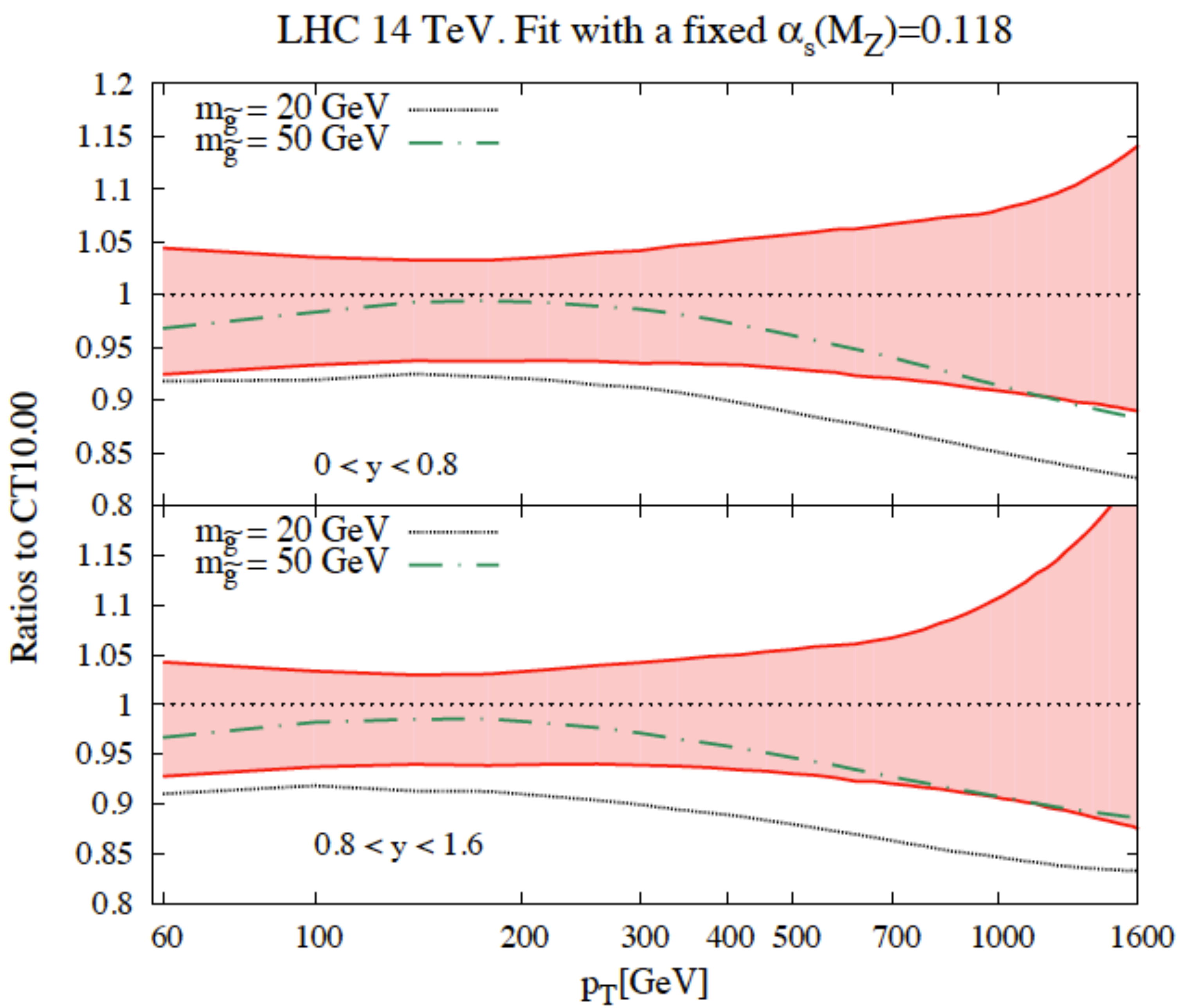


$$\chi^2_{tot} = \chi^2_{h.s.} + \chi^2_{\alpha_s} \qquad \Delta\chi^2 \equiv \chi^2_{SUSY}(m_{\tilde{g}}) - \chi^2_{CT10}$$

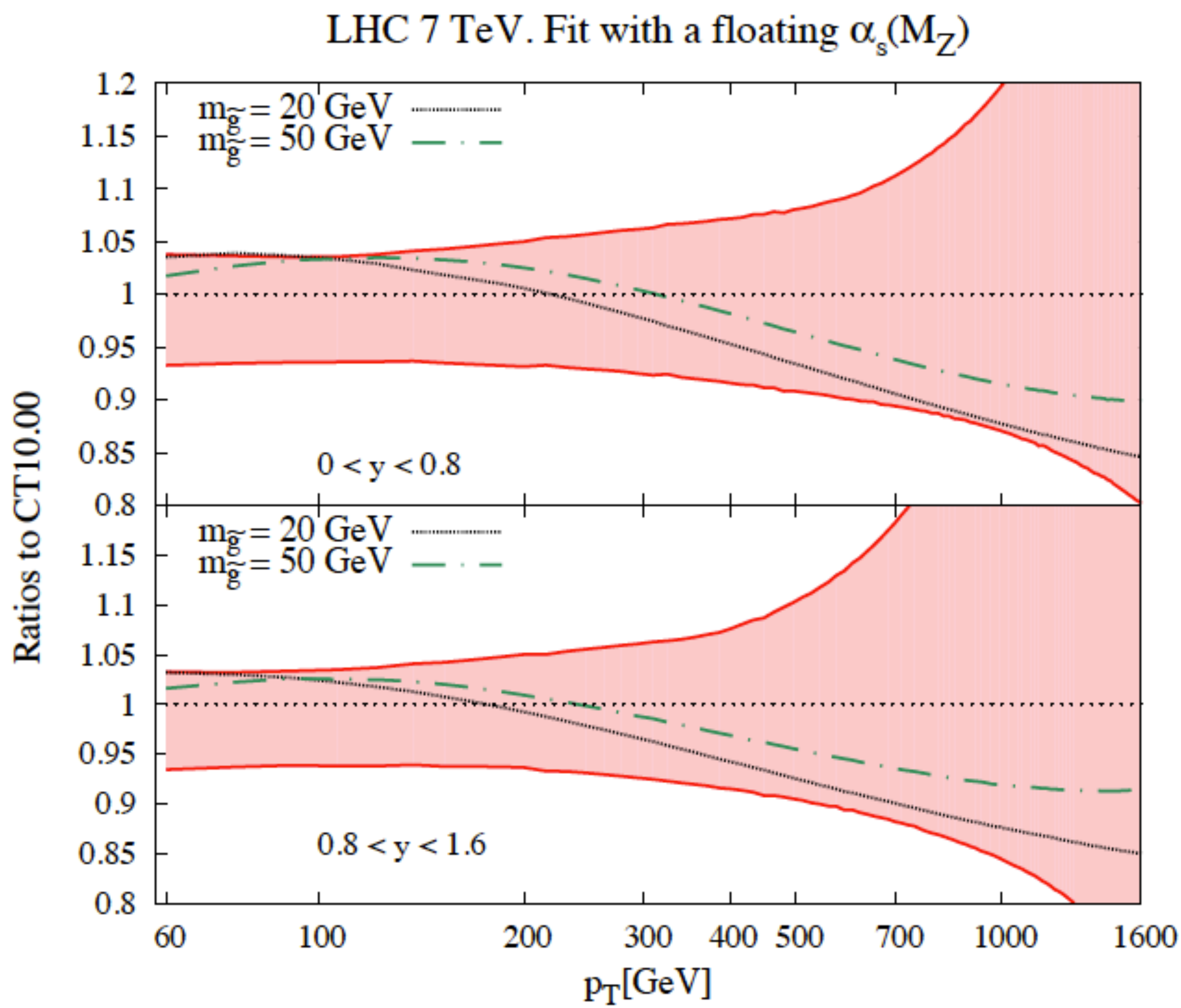
Where the total chi2 as a function of the mass of the color-octet fermion is the sum of that of the Hadron scattering data, i.e., DIS, vector boson production, and jet production; and chiαs is the contribution from the direct constraints on αs.



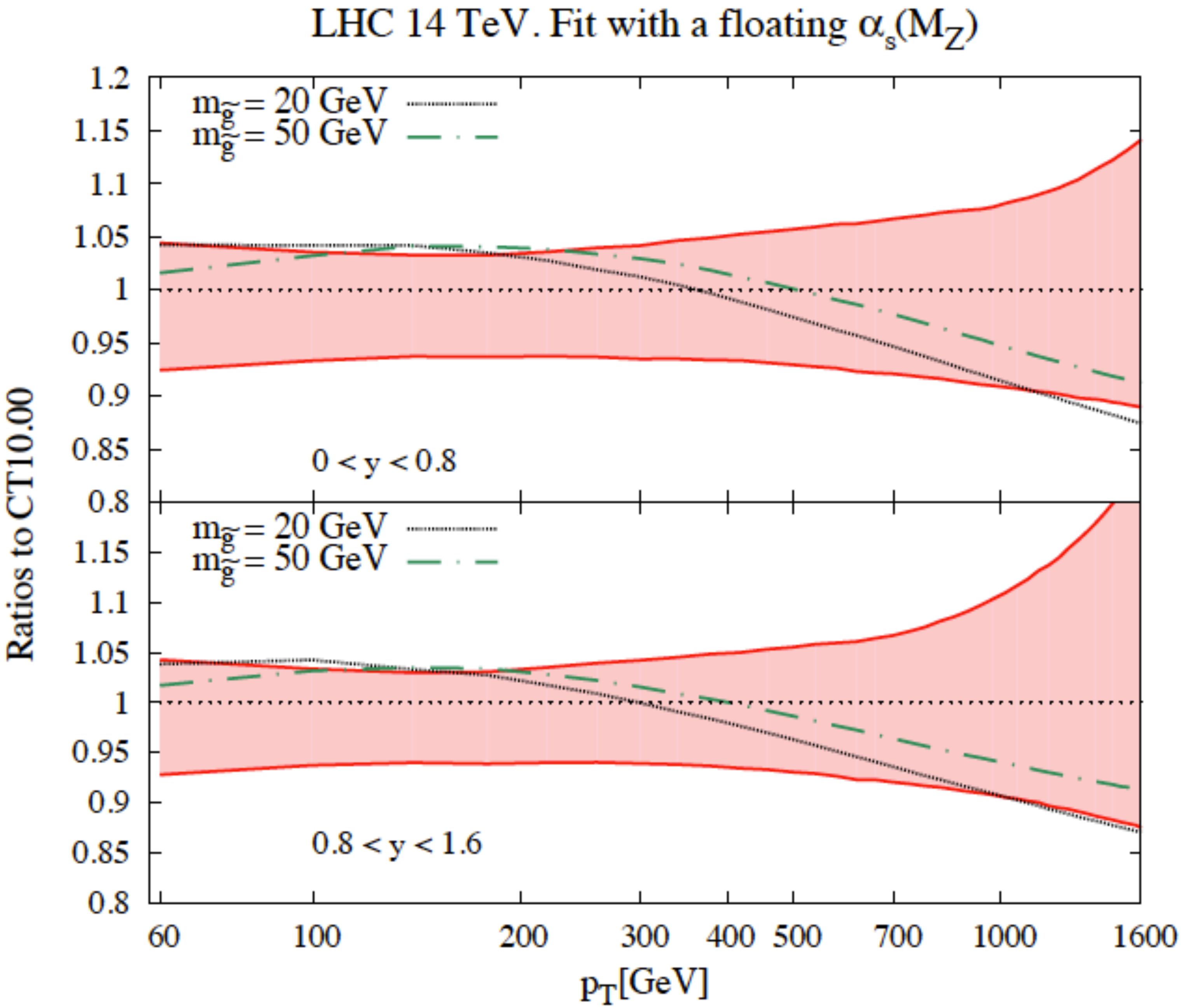
Ratios of single-inclusive jet cross sections



LHC 14 TeV. Fit with a fixed $\alpha_s(M_Z)$=0.118
Ratios to CT10.00
$m_{\tilde{g}}$ = 20 GeV
$m_{\tilde{g}}$ = 50 GeV
0 < y < 0.8
0.8 < y < 1.6
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
60
100
200
300
400
500
700
1000
1600
p_T[GeV]



LHC 7 TeV. Fit with a floating $\alpha_s(M_Z)$
$m_{\tilde{g}}$ = 20 GeV
$m_{\tilde{g}}$ = 50 GeV
0 < y < 0.8
0.8 < y < 1.6
Ratios to CT10.00
p_T[GeV]
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
60
100
200
300
400
500
700
1000
1600



LHC 14 TeV. Fit with a floating $\alpha_s(M_Z)$
$m_{\tilde{g}}$ = 20 GeV
$m_{\tilde{g}}$ = 50 GeV
0 < y < 0.8
$m_{\tilde{g}}$ = 20 GeV
$m_{\tilde{g}}$ = 50 GeV
0.8 < y < 1.6
Ratios to CT10.00
p_T[GeV]
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
60
100
200
300
400
500
700
1000
1600

Main conclusion from this exercise:

Color-octet fermions with mass smaller than 50 GeV are excluded.

It will be very interesting to see how the result would change if new data from LHC are included in a similar analysis.

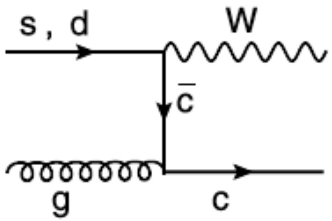
Remaining part of this talk:

recent analyses on strangeness;

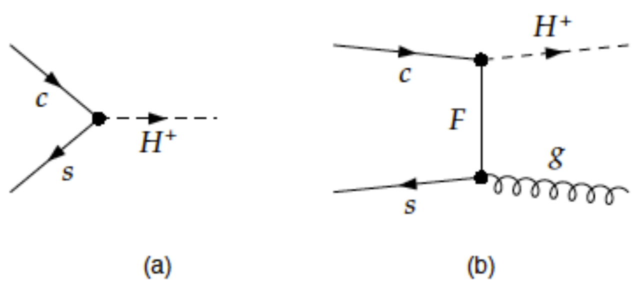
the HERAFITTER platform

strange quark: important for SM and BSM physics

- Associated production of W and a c-quark at hadron coll.



- Charged Higgs production: $c + \bar{s} \to H^+$; $c + \bar{s} \to H^+ + 1\text{-jet}$: 2HDM, SUSY searches,...



- strange asym. $[s(x) - \bar{s}(x)] \to$ "NuteV Anomaly"

$$R^- = \frac{\sigma^{\nu}_{NC} - \sigma^{\bar{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\bar{\nu}}_{CC}} = \frac{1}{2} - \sin^2\theta_W \tag{5}$$

NuteV $\Rightarrow \sin^2\theta_W = 0.2277 \pm 0.0016$

LEP $\Rightarrow \sin^2\theta_W = 0.2227 \pm 0.00037$

The Paschos-Wolfenstein ratio

SM corrections

$$R^- = \frac{1}{2} - s_W^2 - \left[\delta N \frac{\int x(u_v - d_v)dx}{\int x(u_v + d_v)dx} + \frac{\int x(s - \bar{s})dx}{\int x(u_v + d_v)dx}\right] \left[1 - \frac{7}{3}s_W^2 + \frac{4\alpha_s}{9\pi}\left(\frac{1}{2} - s_W^2\right)\right]$$

1st term: Neutron excess $\delta N \equiv (A - 2Z)/A$

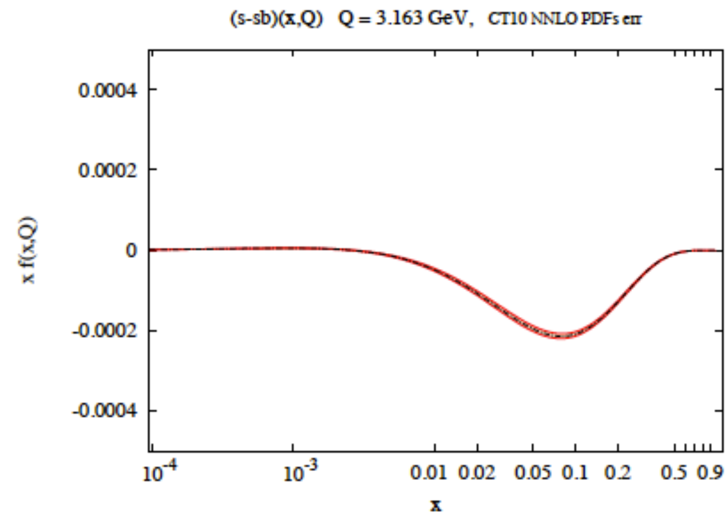
2nd term: strange asymmetry

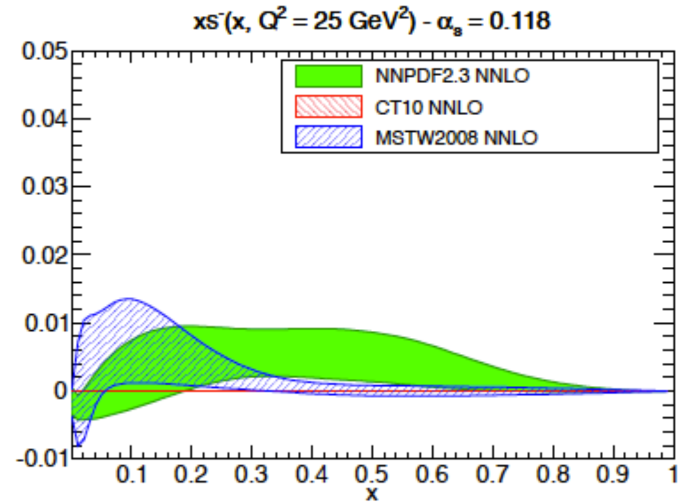
3rd term: NLO corrections

These corrections were carefully investigated by many authors (Barone et. al.), Davidson et al. (also including scenarios of new physics)

Strangeness asymmetry

- QCD evolution tells us that $s(x) - \bar{s}(x) \neq$, but it's small
- CTEQ6.5 analysis: no experimental evidence for asymmetric strangeness inside the proton.
- recent (pre-LHC) NNPDF study: still large uncertainty in the asymmetric strangeness.
- new LHC data on differential $W + c$ distribution will put more constraints on strangeness.

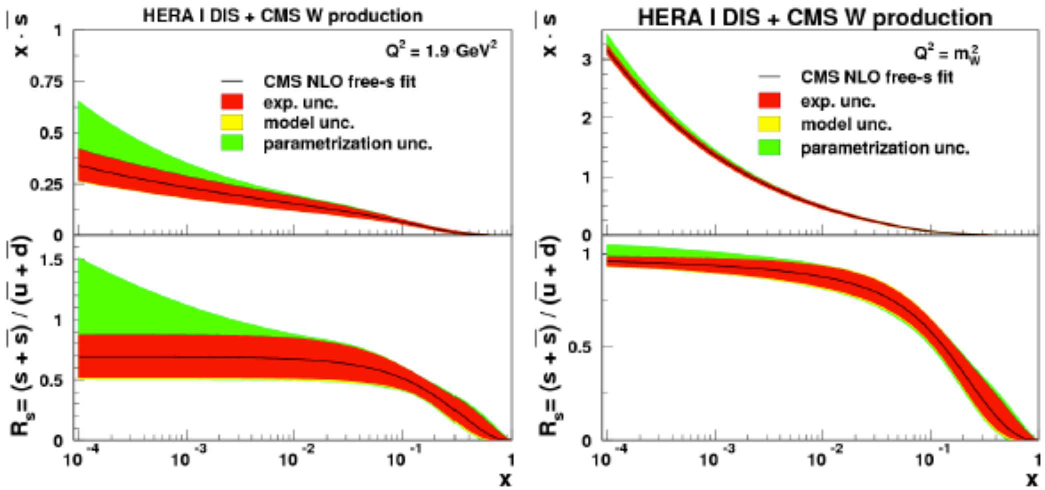


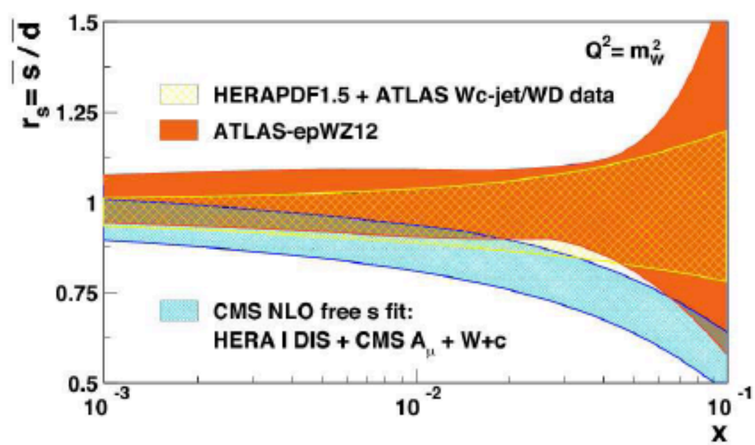


Sufficient to eliminate NuTeV anomaly

New measurements from LHC 7 TeV

The CMS and ATLAS collaboration recently released two measurements for the $W + c$ total and differential cross section together with two different analyses for the determination of $r_s(x, Q^2) = \bar{s}/\bar{d}$: arXiv:1312.6283 (CMS); arXiv:1402.6263 (ATLAS)



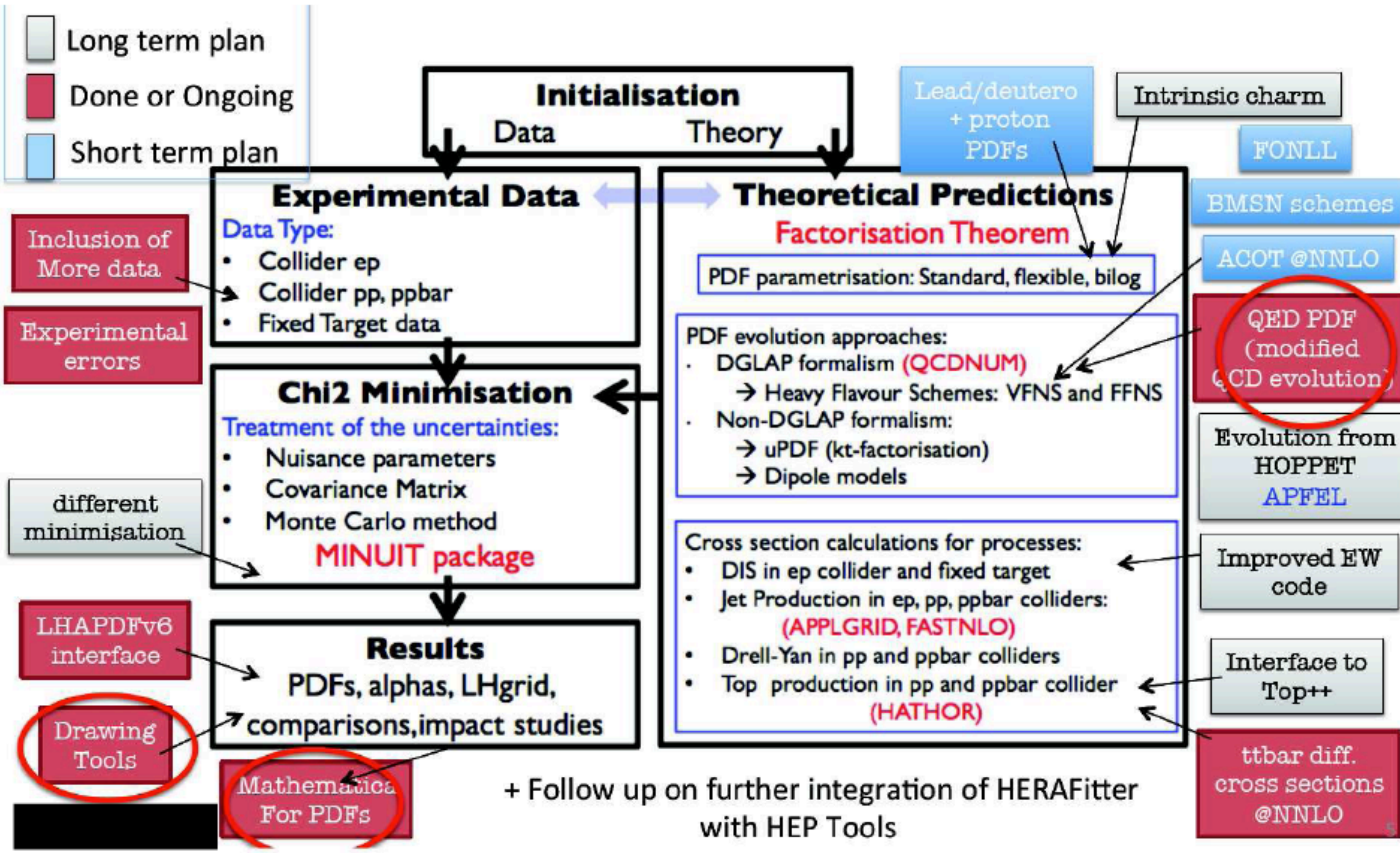


Tools development: HERAFITTER

- HERAFITTER is an open-source package which provides a framework for the determination of PDFs of the proton and for multifold analyses in Quantum Chromodynamics (QCD)
- Measurements of lepton-proton DIS and of proton-proton (proton-antiproton) collisions at hadron colliders are included and used to probe and constrain the partonic content of the proton.
- Currently is extensively used by experimental collaborations HERA, CMS, ATLAS.
- broad choice of options for the treatment of the experimental uncertainties,
- represents a common environment where a large number of theoretical calculations and methods can be used to perform detailed QCD analyses.

The HERAFITTER platform

A large number of analyses



Conclusions and main messages:

Constraining new physics is absolutely non trivial.

New ideas have to be validated against measurements.
Things have to be measured and compared with theory predictions.

Having accurate theory predictions takes a lot of efforts
because a large number of details have to be taken into account.

The accuracy of the available measurements
and how precise you can calculate are crucial factors in the game.

Techniques employed in global analyses in QCD are an extremely powerful tool.

BACKUP

Accuracy definition

According to the Les Houches 2014 agreement (arXiv:1405.1067) the accuracy in perturbative calculations is given by

- LO $\equiv \mathcal{O}(1)$
- NLO QCD $\equiv \mathcal{O}(\alpha_s)$
- NNLO QCD $\equiv \mathcal{O}(\alpha_s^2)$
- NNLO QCD + EW $\equiv \mathcal{O}(\alpha_{em}\alpha_s)$
- NNNLO QCD $\equiv \mathcal{O}(\alpha_s^3)$