PROTON STRUCTURE IN THE LHC ERA:

TESTING THE STANDARD MODEL AND SEARCHING FOR NEW PHYSICS

Katerina Lipka

HELMHOLTZ
SPITZENFORSCHUNG FÜR
GROSSE HERAUSFORDERUNGEN

DESY.

BERGISCHE
UNIVERSITÄT
WUPPERTAL

MODERN PICTURE OF VISIBLE MATTER

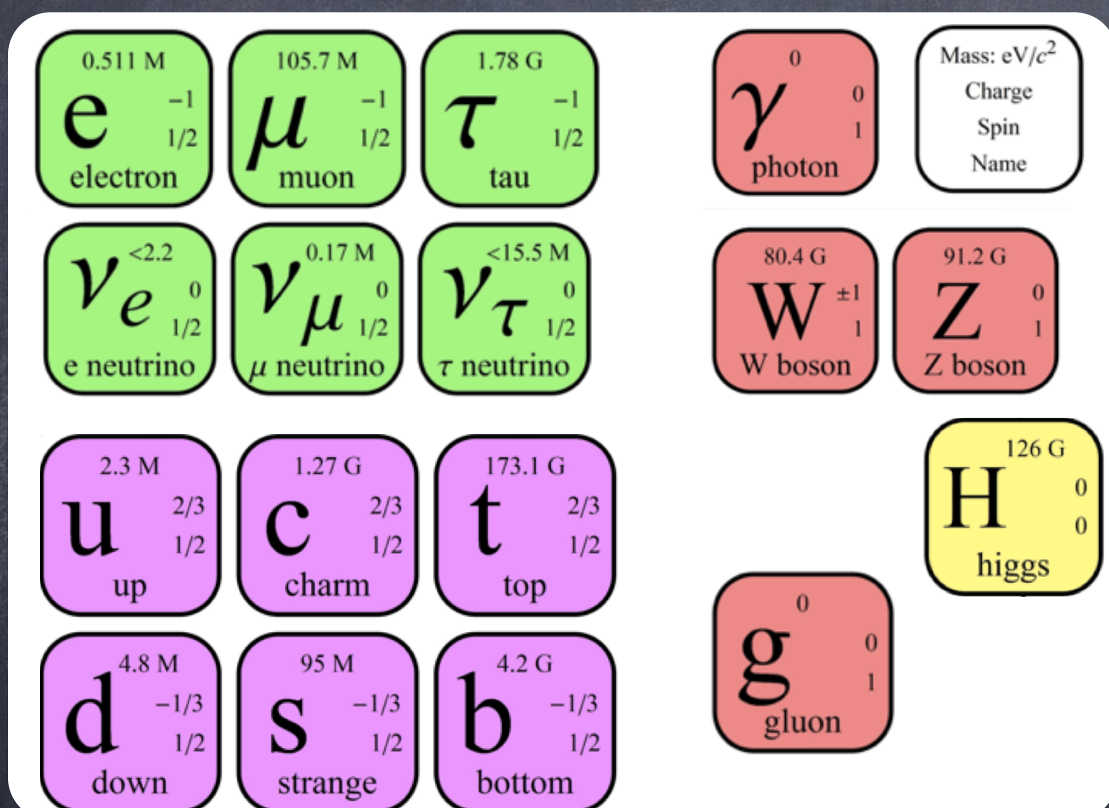
Standard Model of Particle Physics

- classifies fundamental particles and forces (*similar to Periodic Table in Chemistry*)

matter building blocks | force carriers | interaction

leptons

quarks



electromagnetism

electroweak force
thermonuclear reactions in the Sun

strong force
(holds matter together)

generates masses of elementary particles

MODERN PICTURE OF VISIBLE MATTER

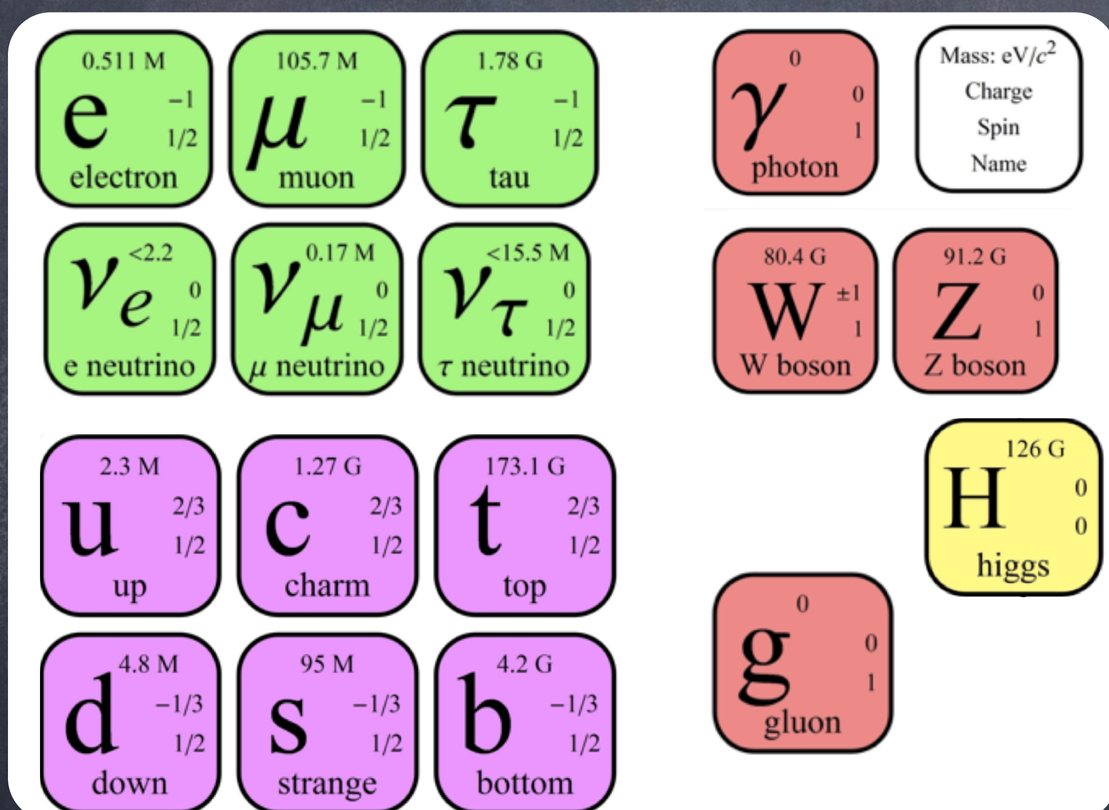
Standard Model of Particle Physics

- classifies fundamental particles and forces (*similar to Periodic Table in Chemistry*)

matter building blocks | **force carriers** | **interaction**

leptons

quarks



family: I II III

electromagnetism

electroweak force
thermonuclear reactions in the Sun

strong force
(holds matter together)

generates masses of elementary particles

MODERN PICTURE OF VISIBLE MATTER

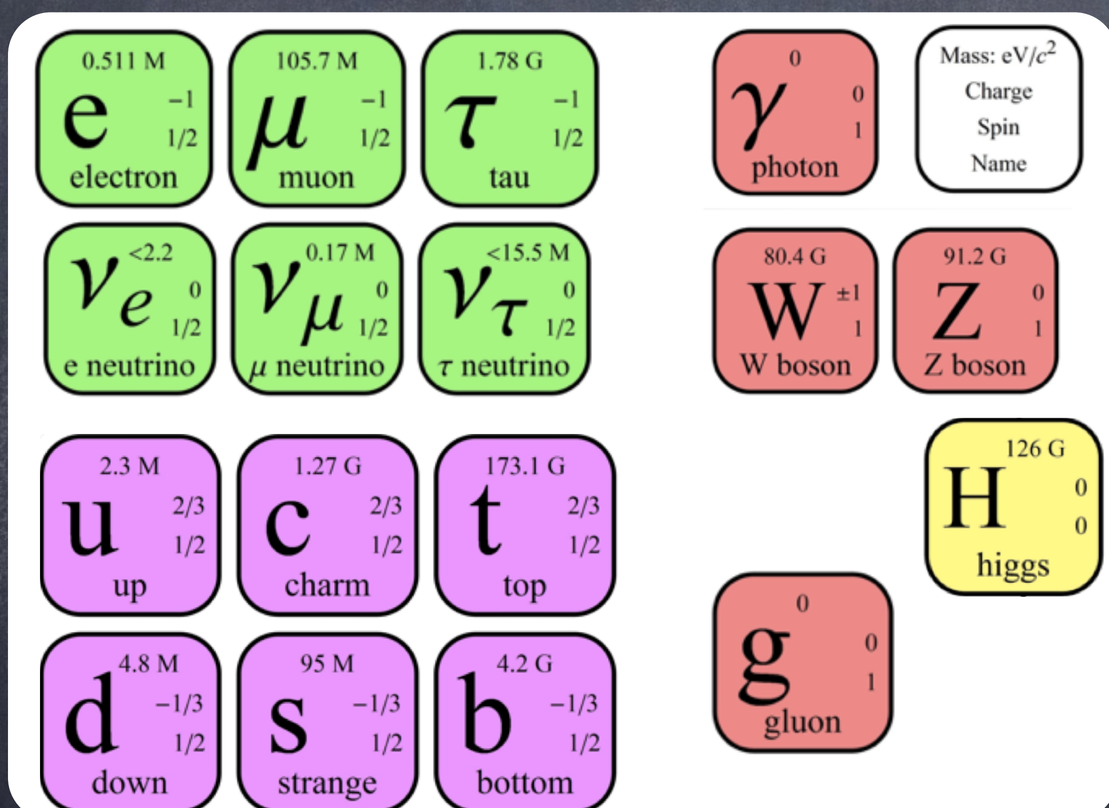
Standard Model of Particle Physics

- **classifies fundamental particles and forces (*similar to Periodic Table in Chemistry*)**

matter building blocks **force carriers** **interaction**

leptons

quarks



family: I II III

electromagnetism

electroweak force
thermonuclear reactions in the Sun

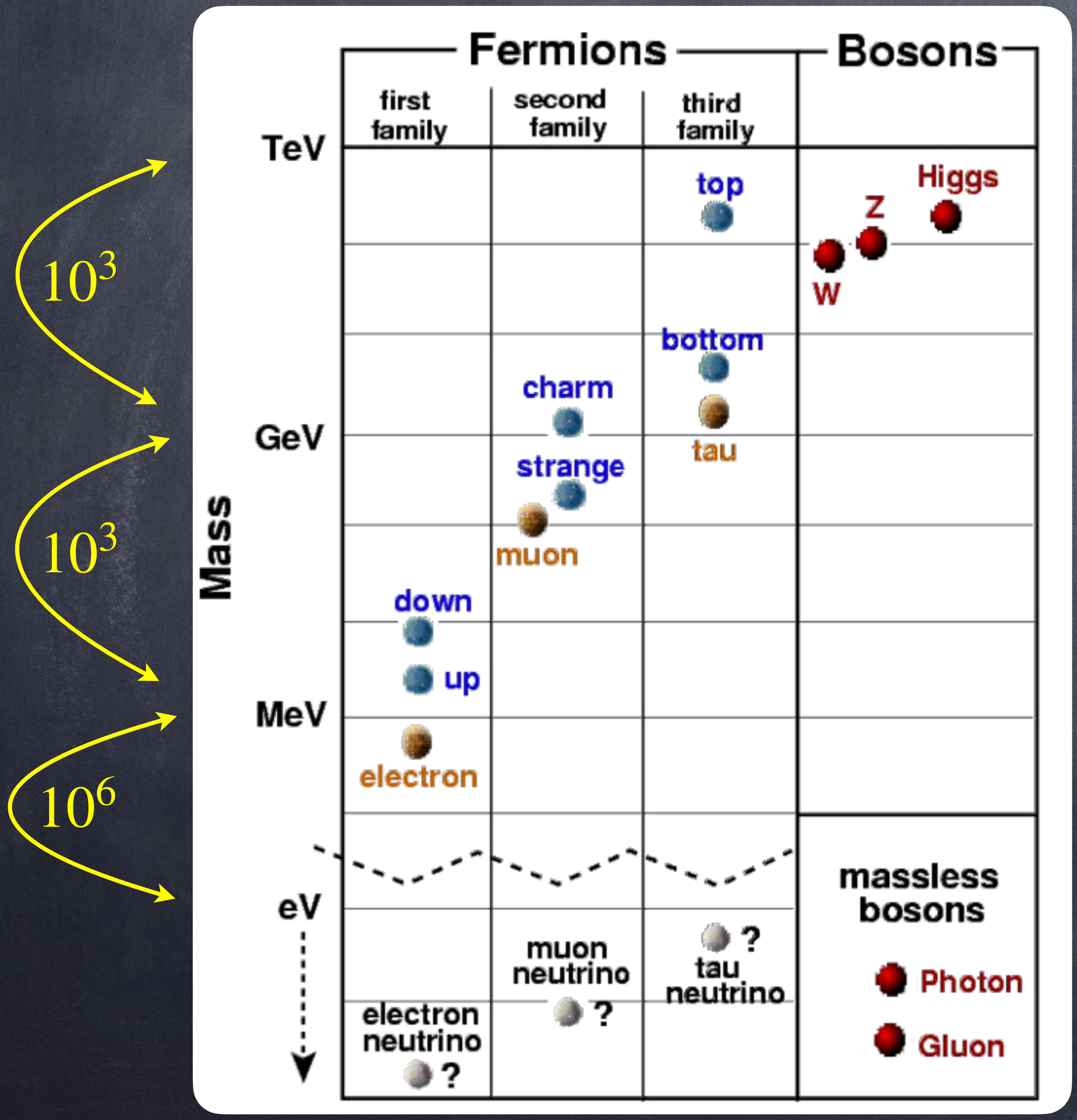
strong force
(holds matter together)

generates masses of elementary particles

- **parameters: masses of the elementary particles and couplings of interactions**

IS THIS PICTURE COMPREHENSIVE ?

- **the values of masses and couplings need to be found experimentally mass difference is a puzzle itself**



Masses span ~12 orders of magnitude
(and these are elementary!)

are they indeed elementary?

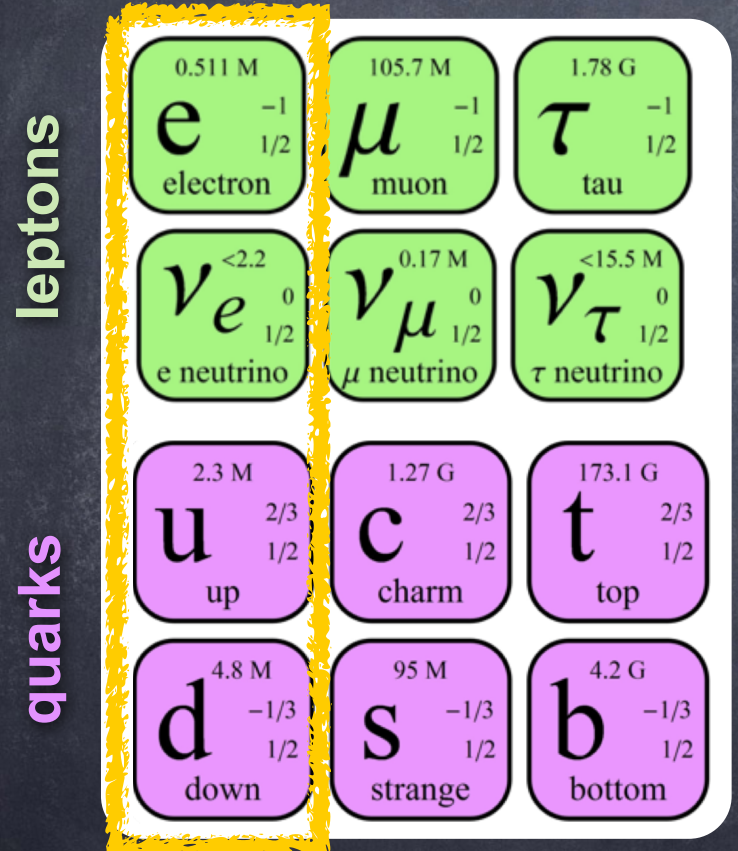
are there further interactions ?

window for New Physics!

IS THIS PICTURE COMPREHENSIVE ?

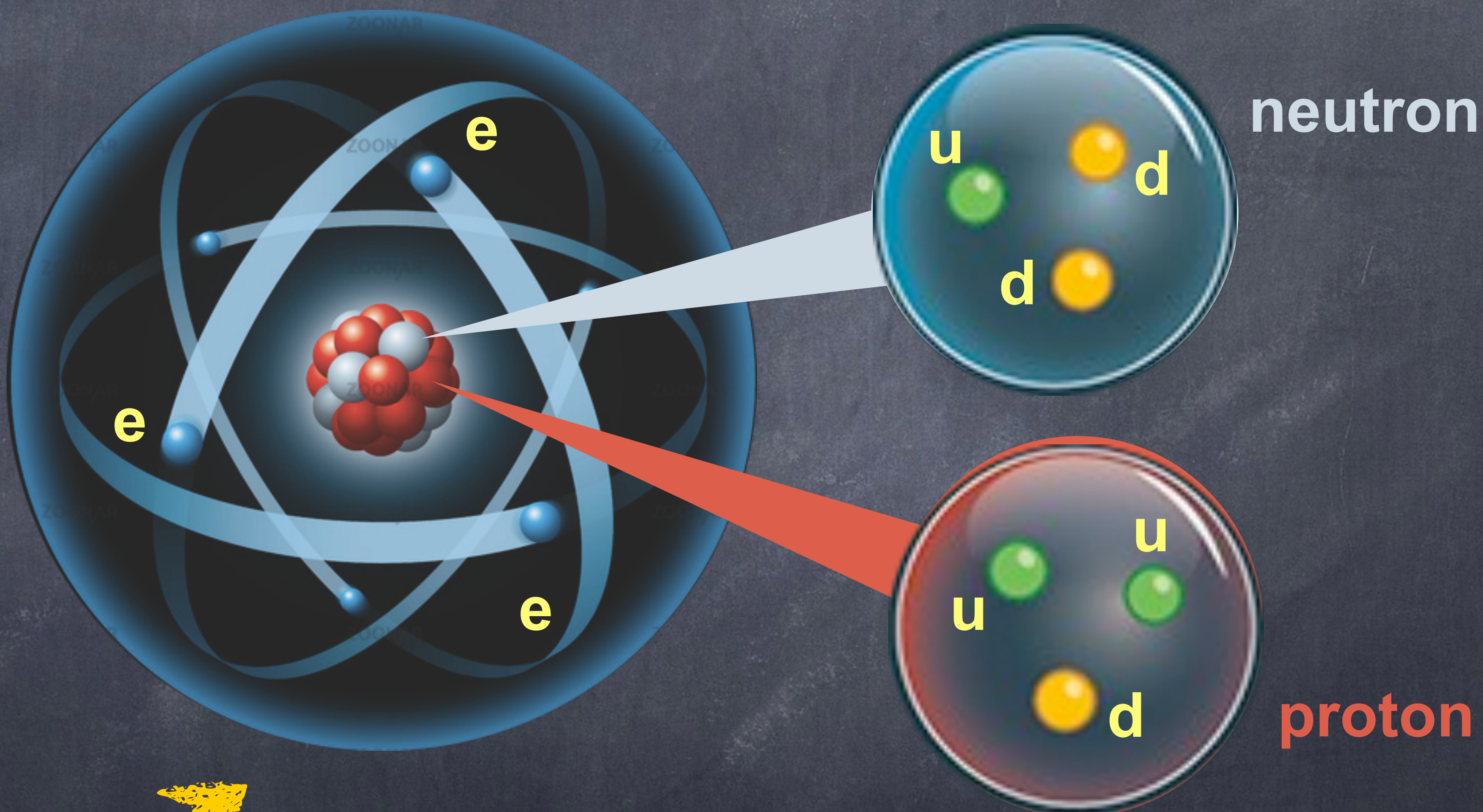
- the values of masses and couplings need to be found experimentally
- origin of the structure : why 3 generations?

matter building blocks



family: I II III

stable nuclear matter

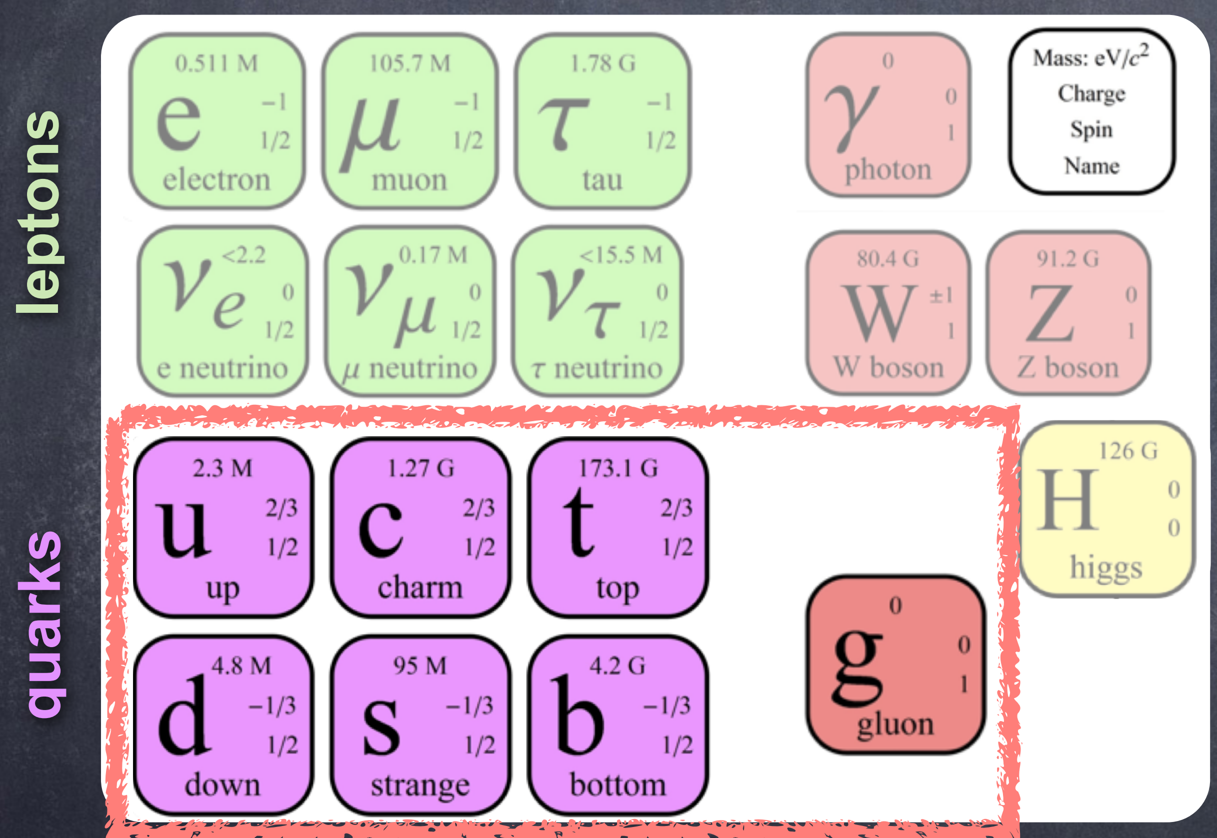


what is the reason ? window for New Physics!

THIS TALK: STRONG INTERACTION

- holds together nuclear matter and is responsible for its mass
- reach ~ nucleon size (1 fm)
- described by the Quantum Chromodynamics (QCD)

matter building blocks **force carriers** **interaction**



electromagnetism

electroweak force
thermonuclear reactions in the Sun

strong force
(holds matter together)

generates masses of elementary particles

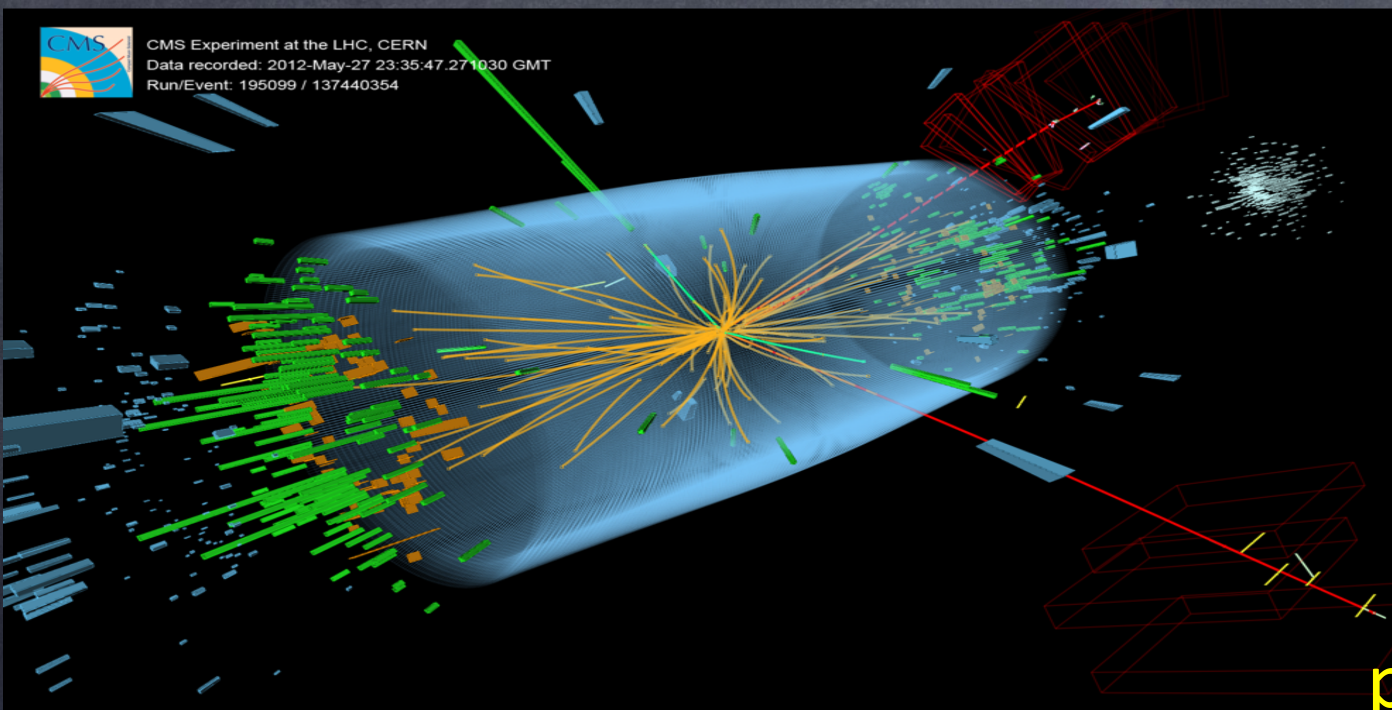
Properties (result of the underlying symmetry)

- **confinement:** quarks not observable as free particles

- **asymptotic freedom:** energy dependence of couplings and quark masses

THIS TALK: QCD AT HIGHEST ENERGIES

microscopes of particle physics: high-energy accelerators

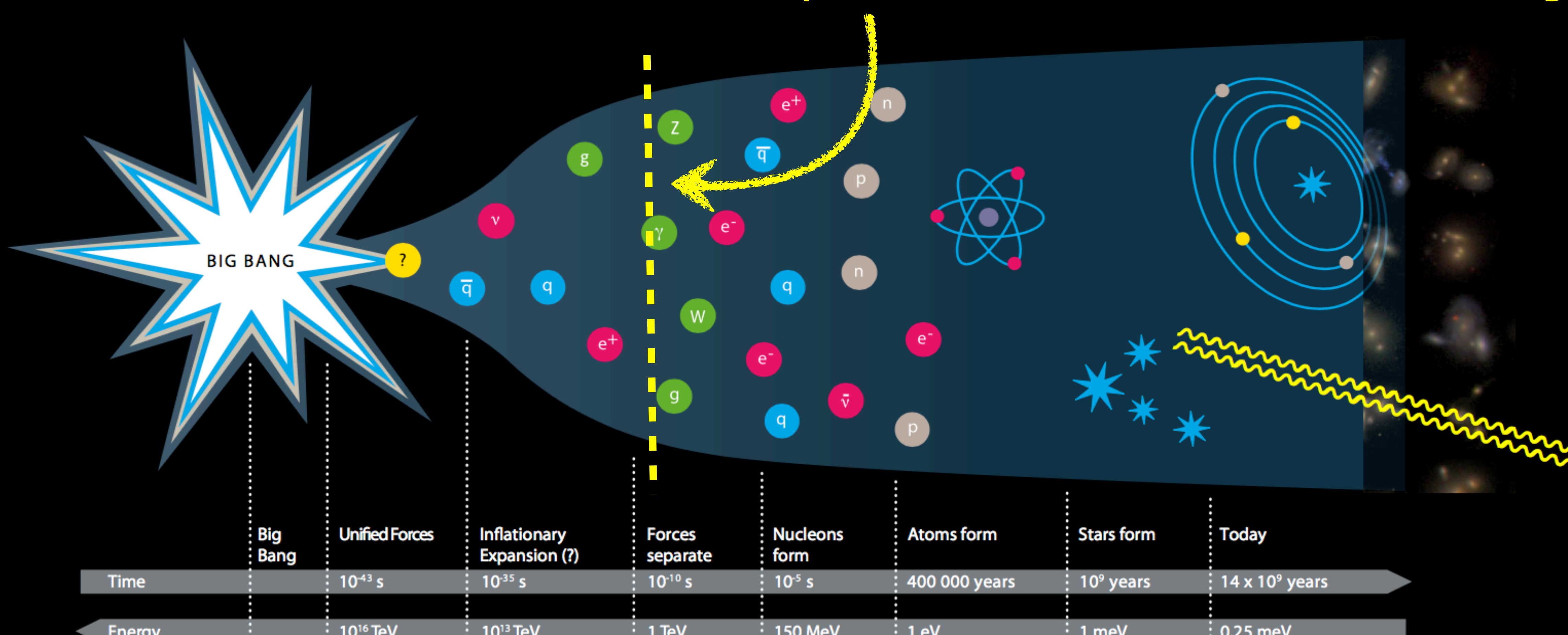


Large Hadron Collider @ CERN

the energy frontier

$\sqrt{s}$ ~ 2 - 14 TeV

probe ~10^{-12} second after the Big Bang



LARGE HADRON COLLIDER @ CERN

Circular accelerator (synchrotron) underground (100 m) tunnel 27 km long

Proton* beams bent by superconducting magnets of 8 T

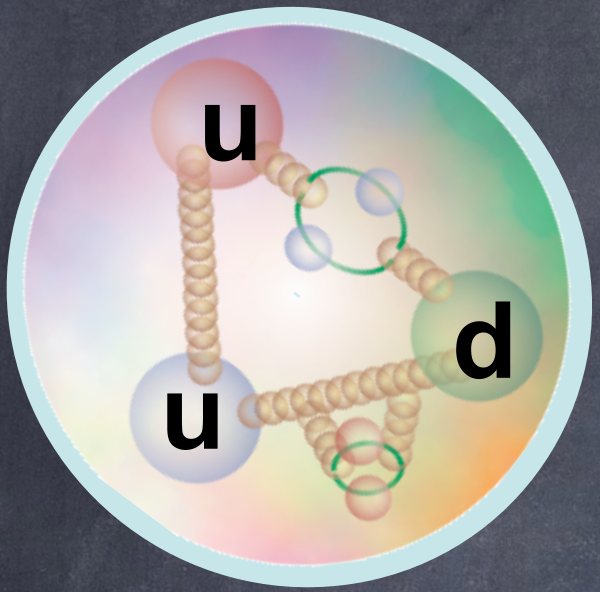
Experiments ATLAS, CMS, ALICE, LHCb

Proton collision centre-of-mass energies: 2.76, 5.02, 7, 8, 13, to start 13.6 TeV

THE STRUCTURE OF THE NUCLEON*

**In the following I talk about the proton*

THE STRUCTURE OF THE PROTON

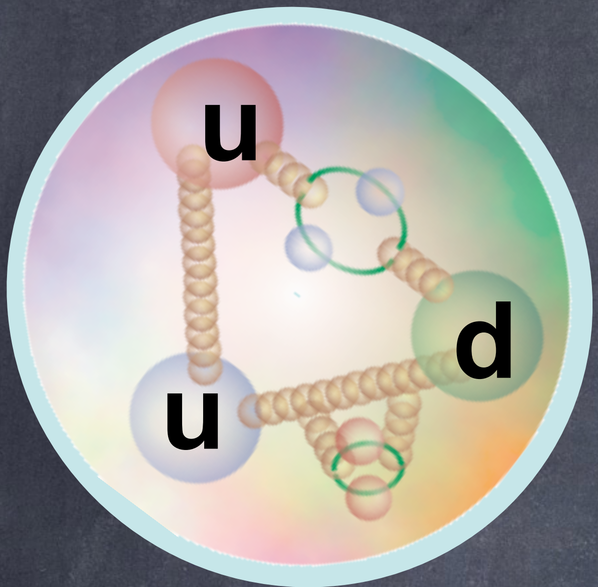


- made of point-like constituents ***partons*** (quarks & gluons)

  name by R. Feynman in 1969 for any constituent of a hadron

- ***valence quarks*** determine the quantum numbers
- quarks exchange ***gluons***, gluons split into ***sea quark pairs***
- **nucleon mass: energy of gluons and sea-quarks**

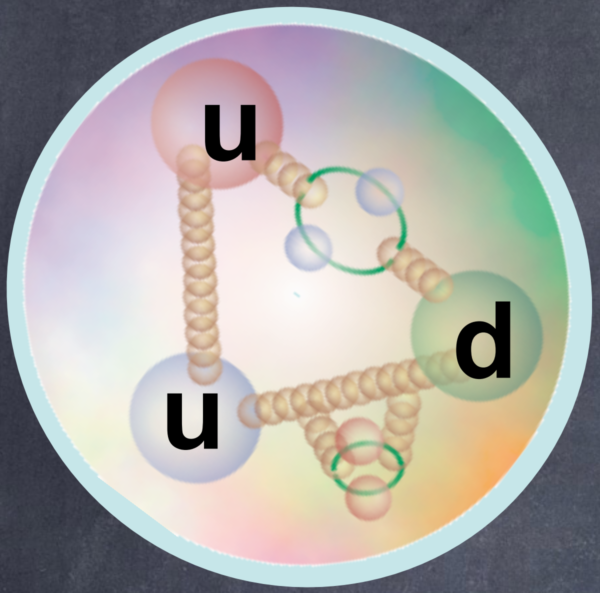
THE STRUCTURE OF THE PROTON



- made of point-like constituents *partons* (quarks & gluons)
- *valence quarks* determine the quantum numbers
- quarks exchange *gluons*, gluons split into *sea quark pairs*
- nucleon mass: energy of gluons and sea-quarks

- Parton Distribution Functions: *probability density $f_i(x,Q^2)$ finding a parton i in a proton carrying its momentum fraction x, as resolved at scale Q^2*

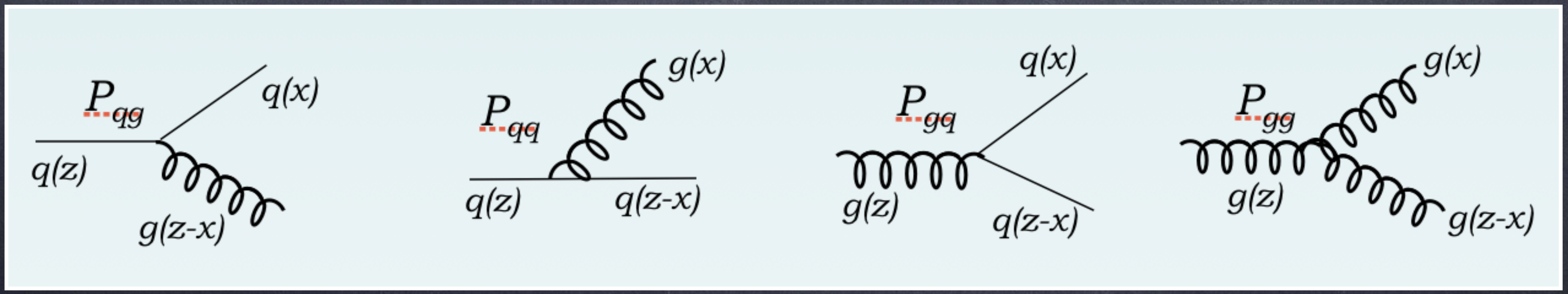
THE STRUCTURE OF THE PROTON



- made of point-like constituents *partons* (quarks & gluons)
- *valence quarks* determine the quantum numbers
- quarks exchange *gluons*, gluons split into *sea quark pairs*
- **nucleon mass: energy of gluons and sea-quarks**

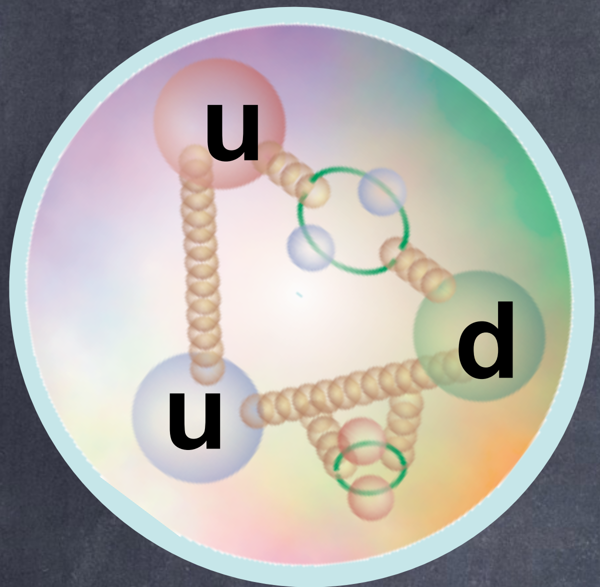
- **Parton Distribution Functions:** ***probability density $f_i(x,Q^2)$ finding a parton i in a proton carrying its momentum fraction x, as resolved at scale Q^2***

pQCD: quark-gluon exchange: PDF ~ probability to find a parton inside a parton represented by the universal splitting functions:



calculable via Dokshitzer-Gribov-Lipatov-Altarelli-Parisi equations

THE STRUCTURE OF THE PROTON



- made of point-like constituents *partons* (quarks & gluons)
- *valence quarks* determine the quantum numbers
- quarks exchange *gluons*, gluons split into *sea quark pairs*
- **nucleon mass: energy of gluons and sea-quarks**

- **Parton Distribution Functions:** ***probability density $f_i(x,Q^2)$ finding a parton i in a proton carrying its momentum fraction x, as resolved at scale Q^2***

NB: PDFs are defined at a certain order of pQCD.

At higher orders, PDF defines indeed probability to find a parton inside a parton.

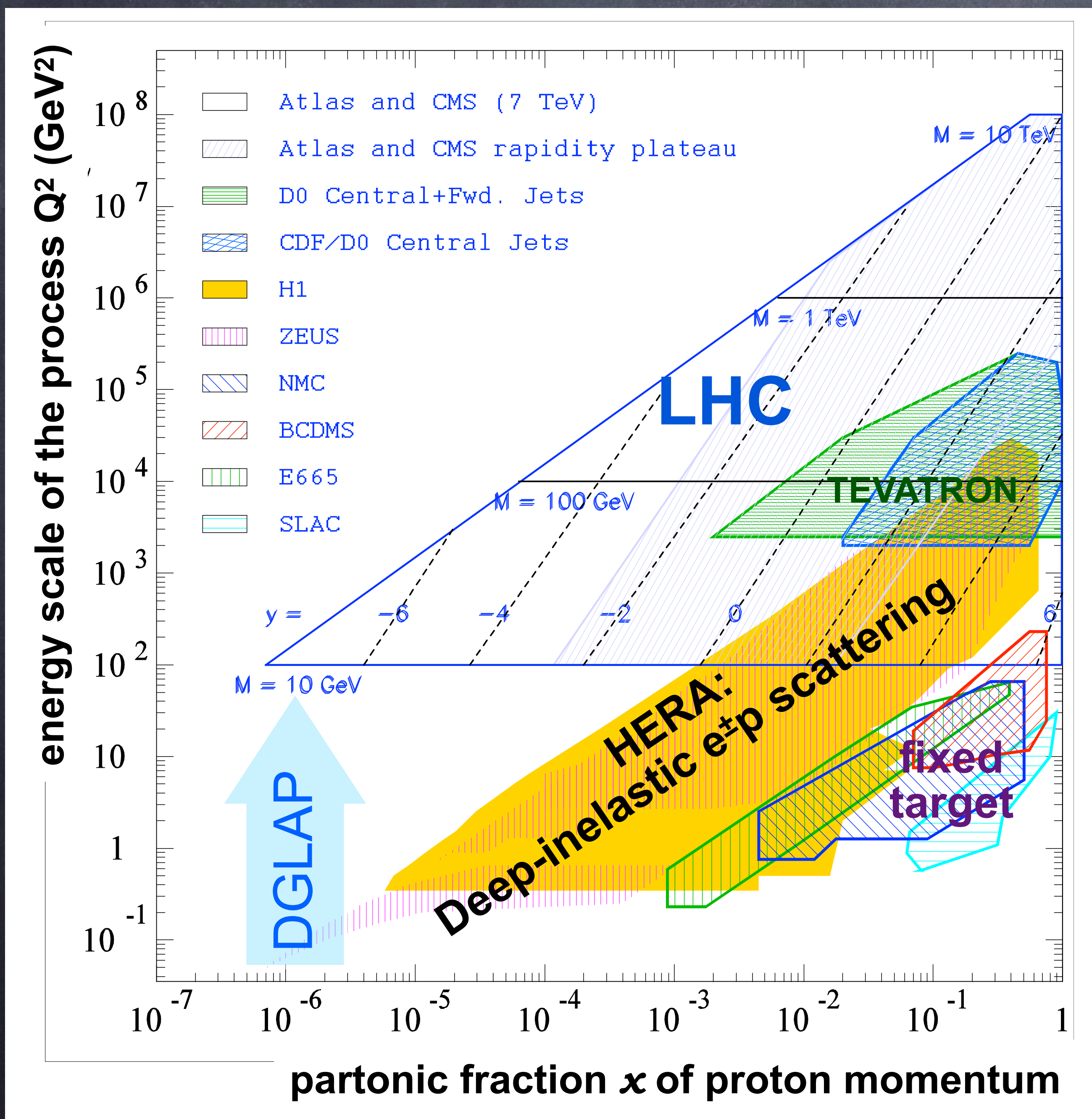
- Dependence on Q^2 calculable in perturbative QCD via DGLAP evolution equations
- Dependence on x is determined experimentally
- Parton Distribution Functions considered universal:

PROTON STRUCTURE PHENOMENOLOGY

Parton Distribution Functions

$f_i(Q^2, x)$

provided by theory ← → determined experimentally



$$\sigma_{ab\to X} = \sum_{ij} f_i \times f_j \otimes \hat{\sigma}_{ij\to X}$$

measured ($\sigma_{ab\to X}$)

calculated in pQCD ($\hat{\sigma}_{ij\to X}$)

- parameterised at an *evolution scale* $\mu^2{}_0$

  e.g. $f(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$
- evolved (DGLAP) to $\mu^2 > \mu^2{}_0$
- construct cross section predictions
- fit to the experimental data

PDFs are universal:

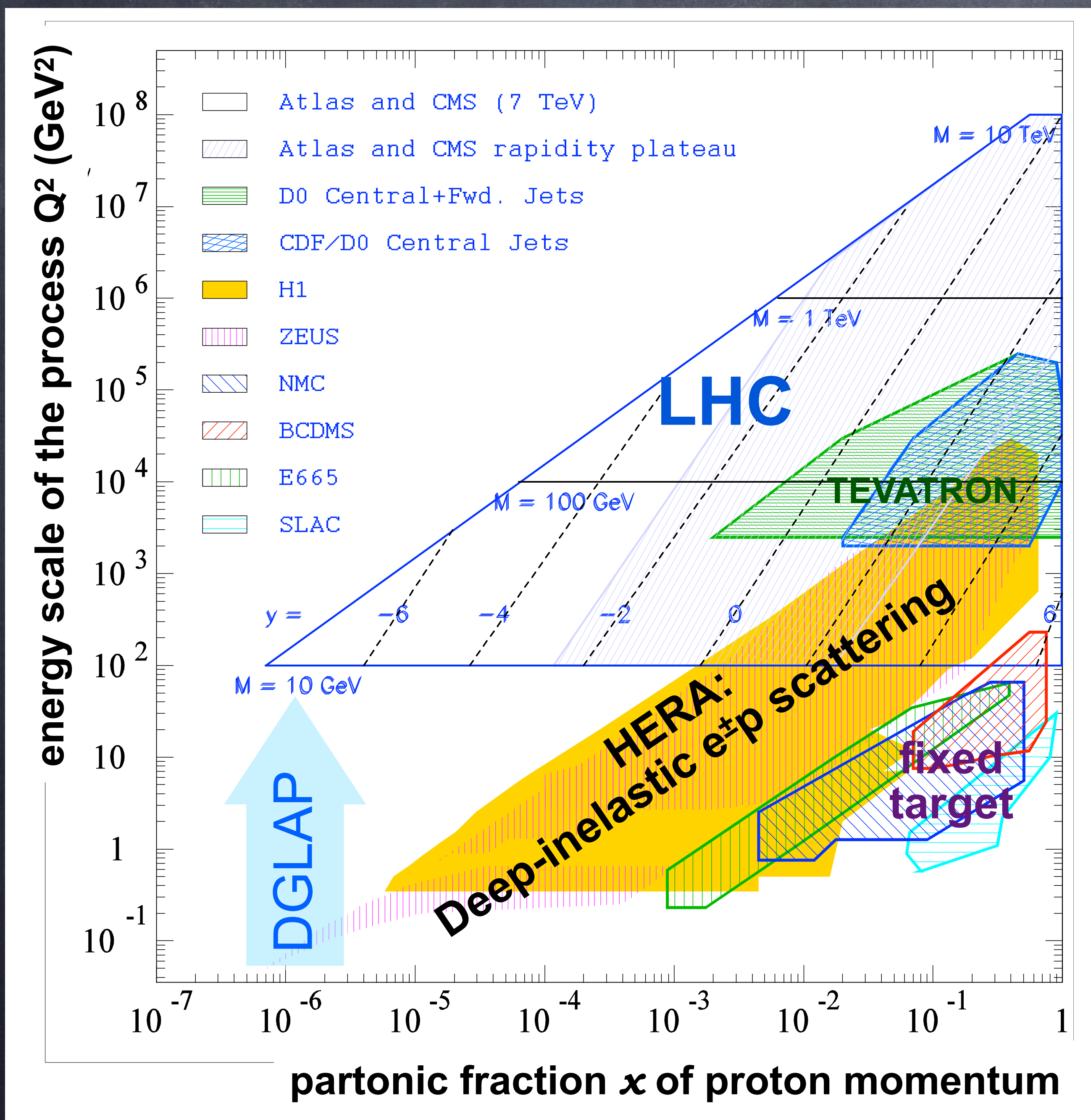
use different processes ($ab = lp, p\bar{p}, pp$)

PROTON STRUCTURE PHENOMENOLOGY

Parton Distribution Functions

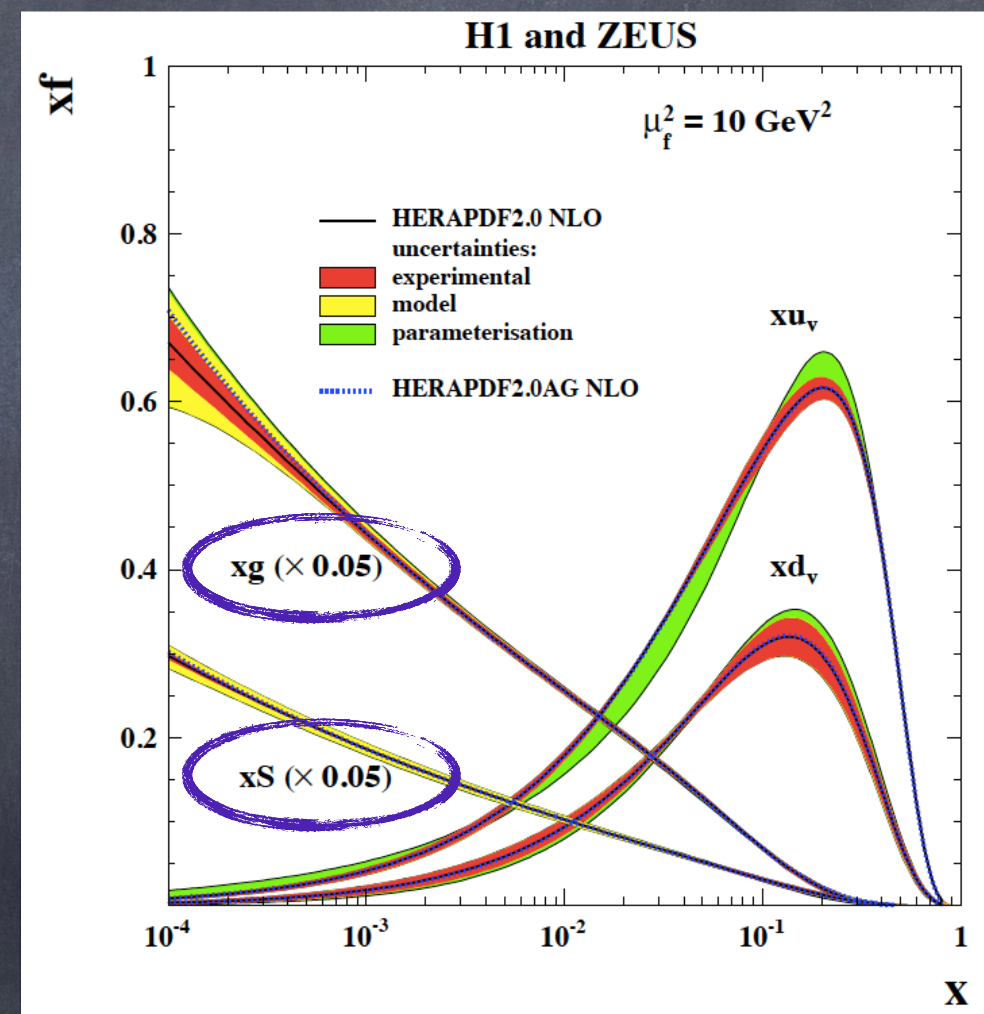
$f_i(Q^2, x)$

provided by theory ← → determined experimentally



Important for resulting PDFs:

- assumptions on masses of heavy quarks
- value of $\alpha_s(M_Z)$
- coverage of x by the experimental data
- uncertainties in data used

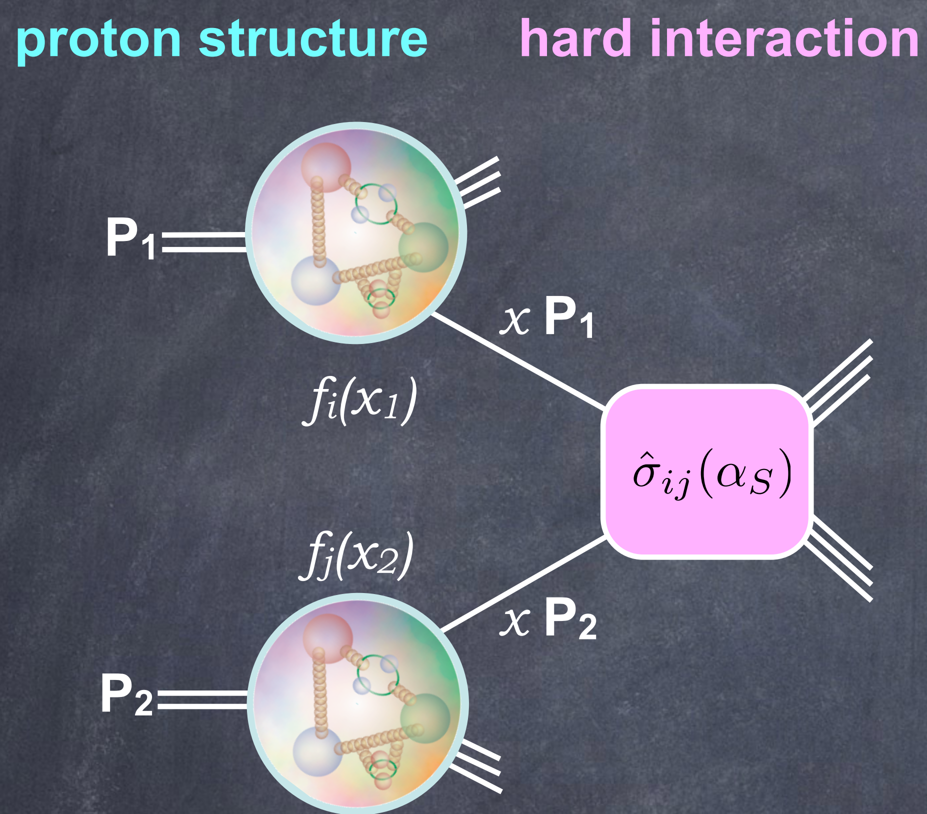


Basic data set: DIS at HERA at medium x

Impact of the LHC: low and high x

PROTON STRUCTURE @ LHC
precision QCD via
jets and top quark production

PARTICLE PRODUCTION @ LHC

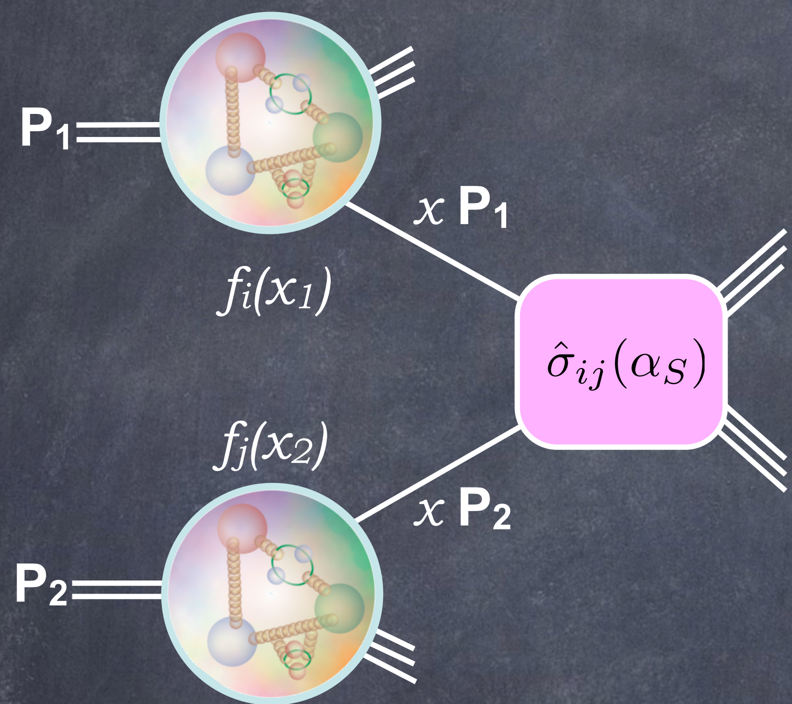


Factorisation: proton luminosity ⊗ sub-process ME

$$\sigma(s) = \sum_{i,j} \int_{\tau_0}^{1} \frac{d\tau}{\tau} \cdot \frac{dL_{ij}(\mu_F^2)}{d\tau} \cdot \hat{s} \cdot \hat{\sigma}_{ij}(\alpha_S, m_q, \mu_F, \mu_R)$$

PARTICLE PRODUCTION @ LHC

proton structure hard interaction



Factorisation: proton luminosity ⊗ sub-process ME

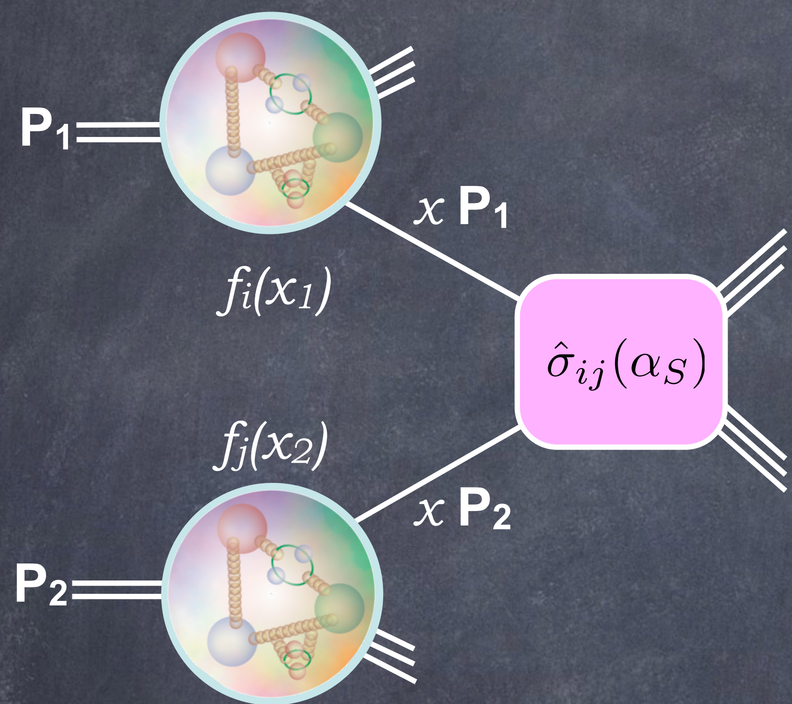
$$\sigma(s) = \sum_{i,j} \int_{\tau_0}^{1} \frac{d\tau}{\tau} \cdot \frac{dL_{ij}(\mu_F^2)}{d\tau} \cdot \hat{s} \cdot \hat{\sigma}_{ij}(\alpha_S, m_q, \mu_F, \mu_R)$$

functions of QCD scales μ,
strong coupling constant $\alpha_S(\mu)$, quark mass m_q

fundamental QCD parameters,
but have to be extracted from
experimental measurements

PARTICLE PRODUCTION @ LHC

proton structure **hard interaction**



Factorisation: proton luminosity ⊗ sub-process ME

$$\sigma(s) = \sum_{i,j} \int_{\tau_0}^{1} \frac{d\tau}{\tau} \cdot \frac{dL_{ij}(\mu_F^2)}{d\tau} \cdot \hat{s} \cdot \hat{\sigma}_{ij}(\alpha_S, m_q, \mu_F, \mu_R)$$

parton luminosity $\propto f_i(\mu, x_1) \cdot f_j(\mu, x_2)$

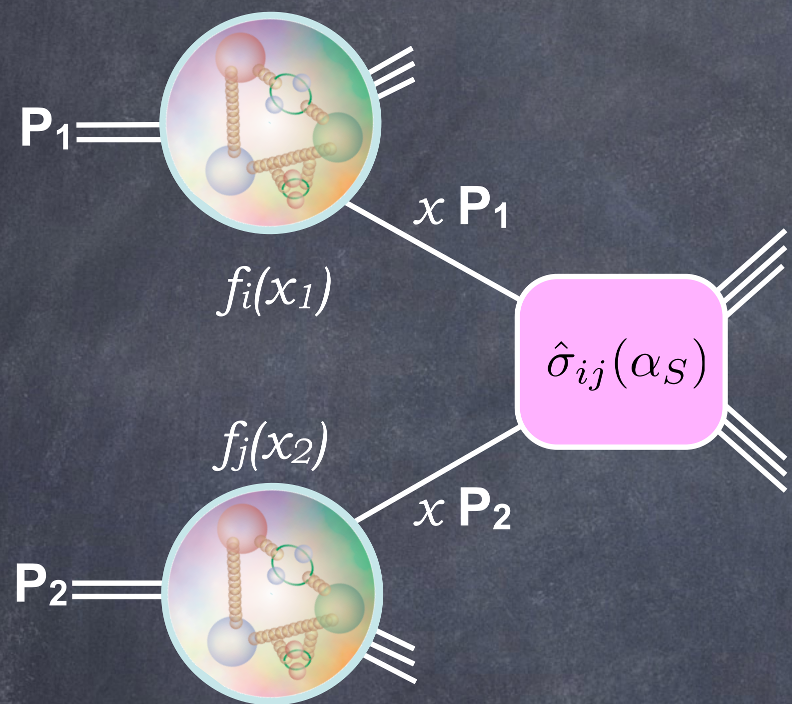
$f_i(\mu, x)$ - PDFs of each proton

calculated in pQCD (DLAP)

to be extracted experimentally

PARTICLE PRODUCTION @ LHC

proton structure **hard interaction**



Factorisation: proton luminosity ⊗ sub-process ME

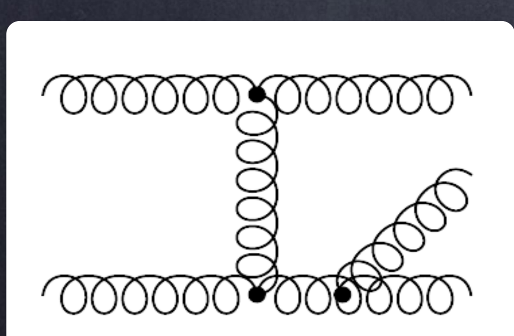
$$\sigma(s) = \sum_{i,j} \int_{\tau_0}^{1} \frac{d\tau}{\tau} \cdot \frac{dL_{ij}(\mu_F^2)}{d\tau} \cdot \hat{s} \cdot \hat{\sigma}_{ij}(\alpha_S, m_q, \mu_F, \mu_R)$$

parton luminosity $\propto f_i(\mu, x_1) \cdot f_j(\mu, x_2)$

$f_i(\mu, x)$ - PDFs of each proton

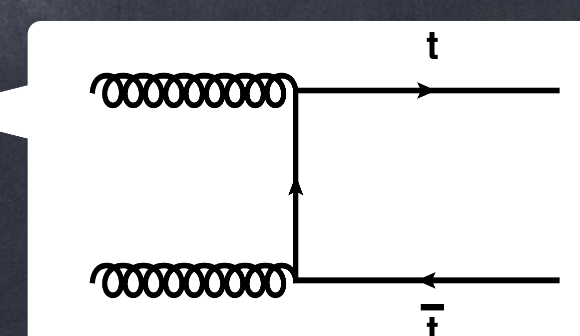
PDFs mostly determined from Deep Inelastic $e^{\pm}p$ Scattering data (HERA)

Many LHC processes provide additional information, most prominent:



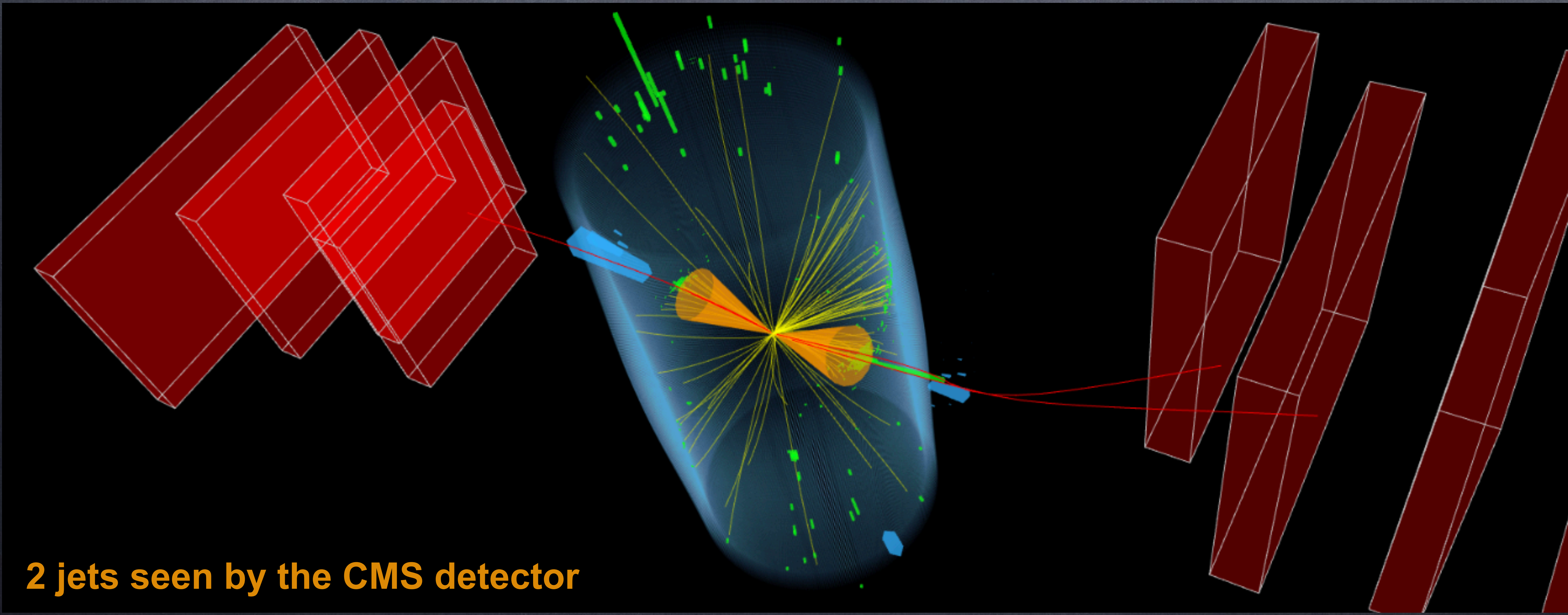
jet production:
$\alpha_S(\mu)$,
gluon at medium-high x

$t\bar{t}$ production:
$\alpha_S(\mu)$, m_t,
gluon at high x



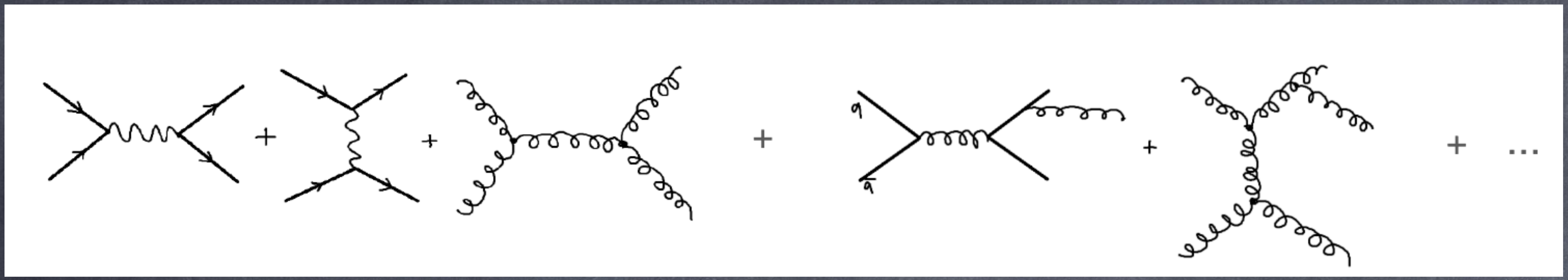
PROTON STRUCTURE AND QCD @ LHC VIA JET PRODUCTION

QCD confinement: quarks form collimated sprays of hadrons - jets



CERN CMS

JET PRODUCTION @ LHC: STRESS TEST FOR QCD

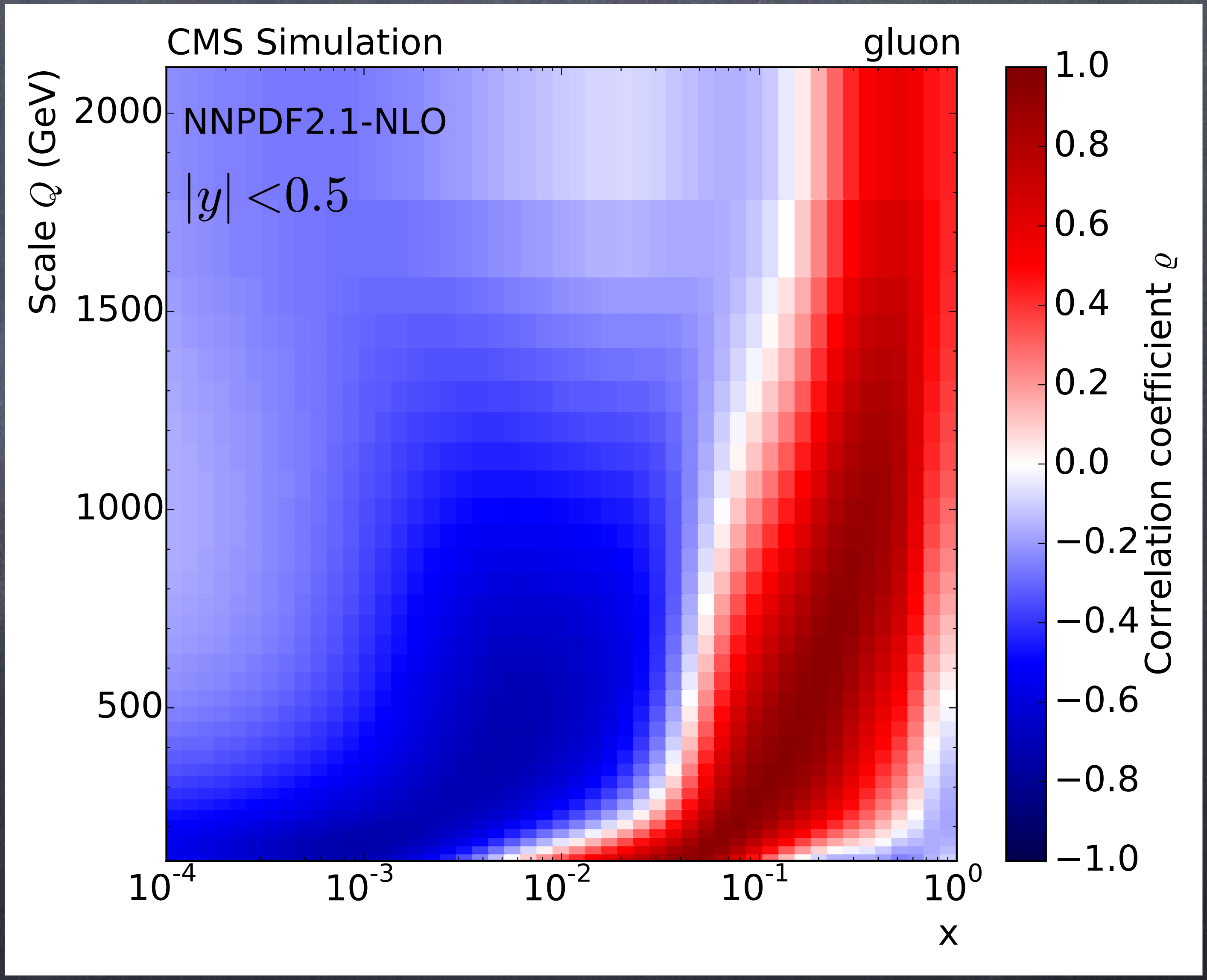


PDFs and $\alpha_S(m_Z)$

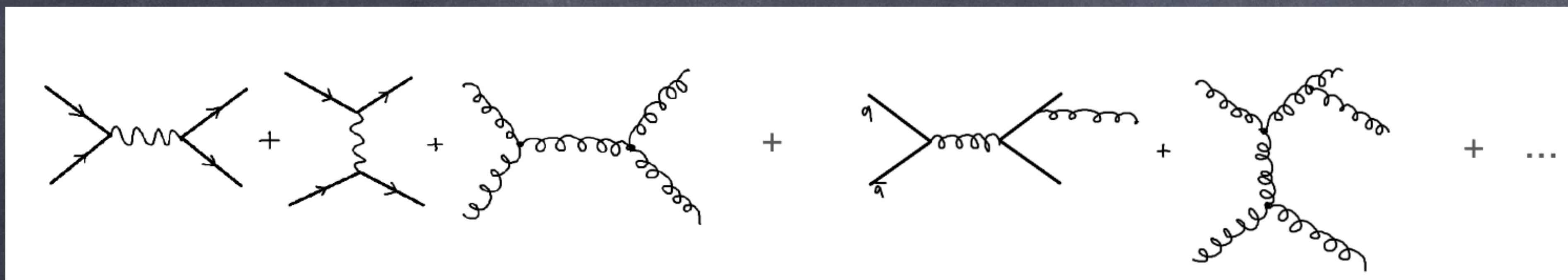
sensitivity to PDFs is quantified by correlation coefficients

(red: high sensitivity)

particular sensitive to the gluon at high x

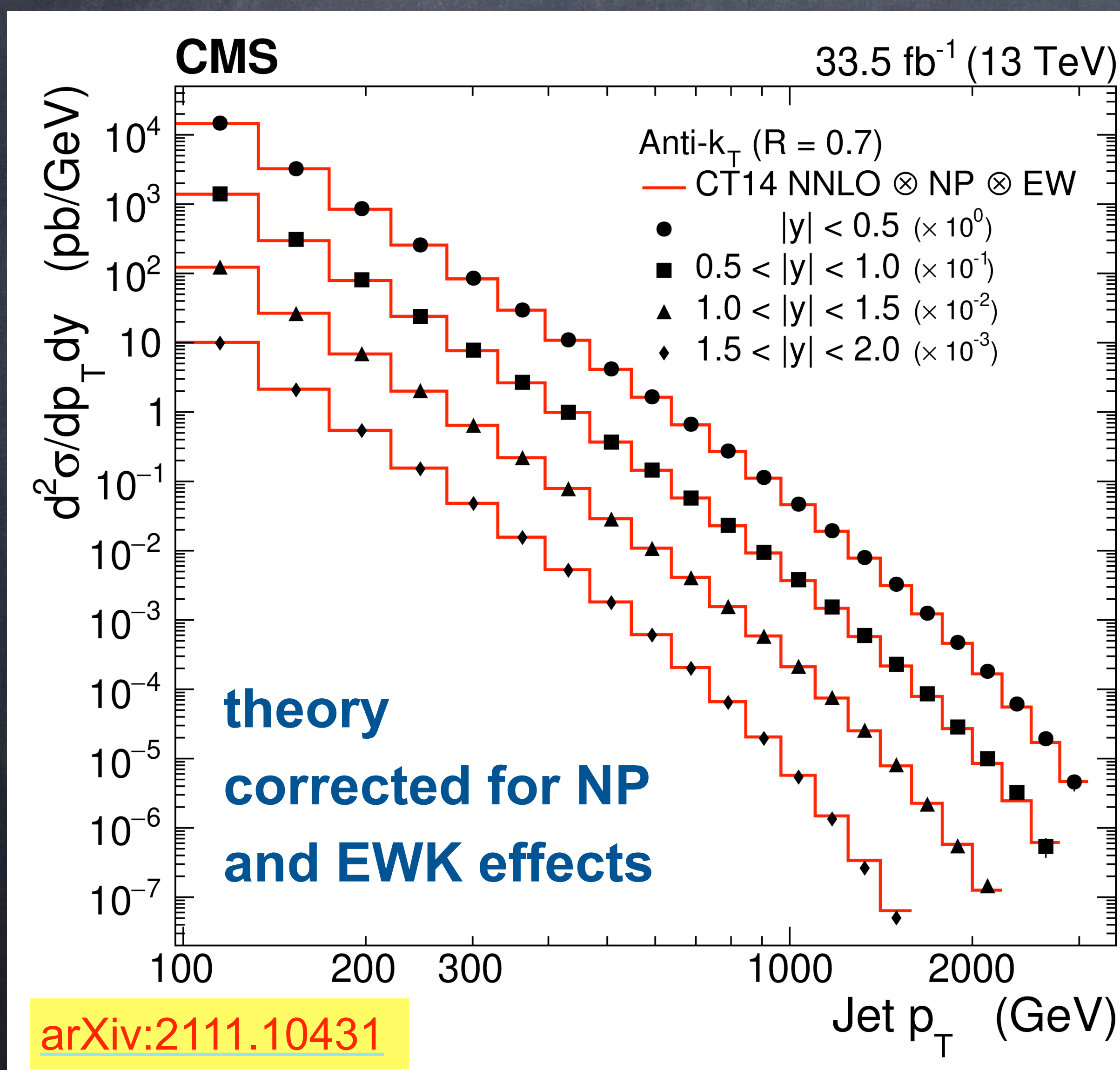


JET PRODUCTION @ LHC: STRESS TEST FOR QCD



PDFs and $\alpha_S(m_Z)$

Most recent CMS measurement: inclusive jets at 13 TeV: arXiv:2111.10431

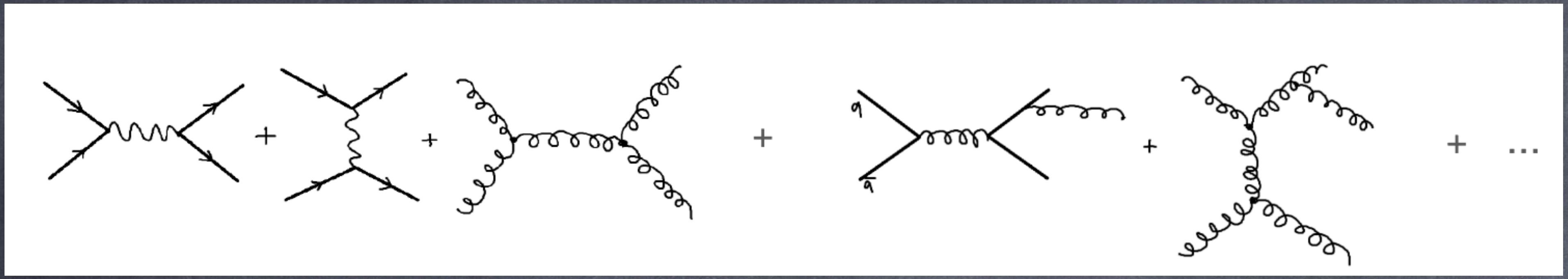


2-differential cross sections as a function of transverse momentum p_T of individual jet and rapidity y

Compared to QCD prediction at NNLO

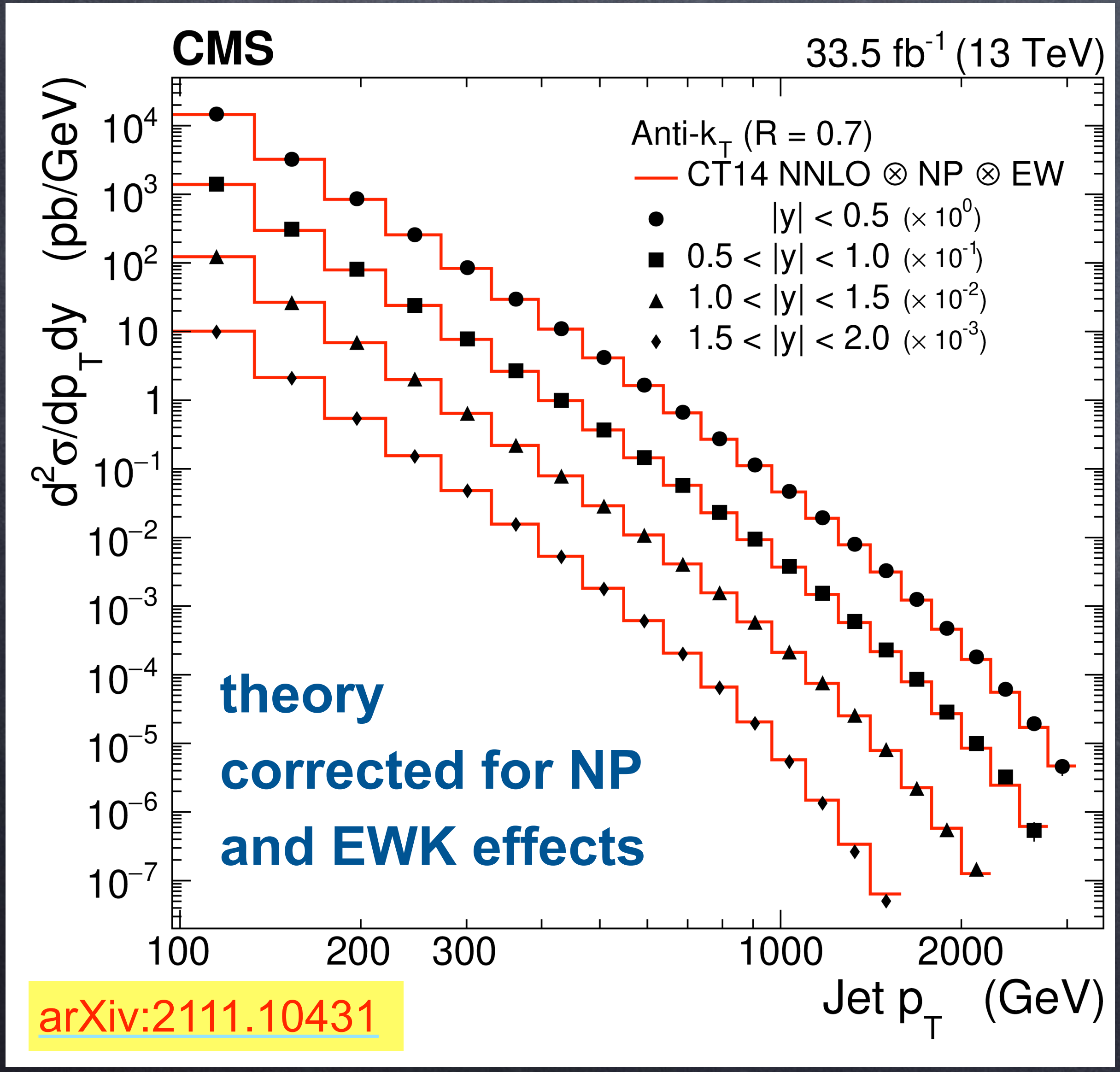
NB systematic uncertainty not shown!

JET PRODUCTION @ LHC: STRESS TEST FOR QCD

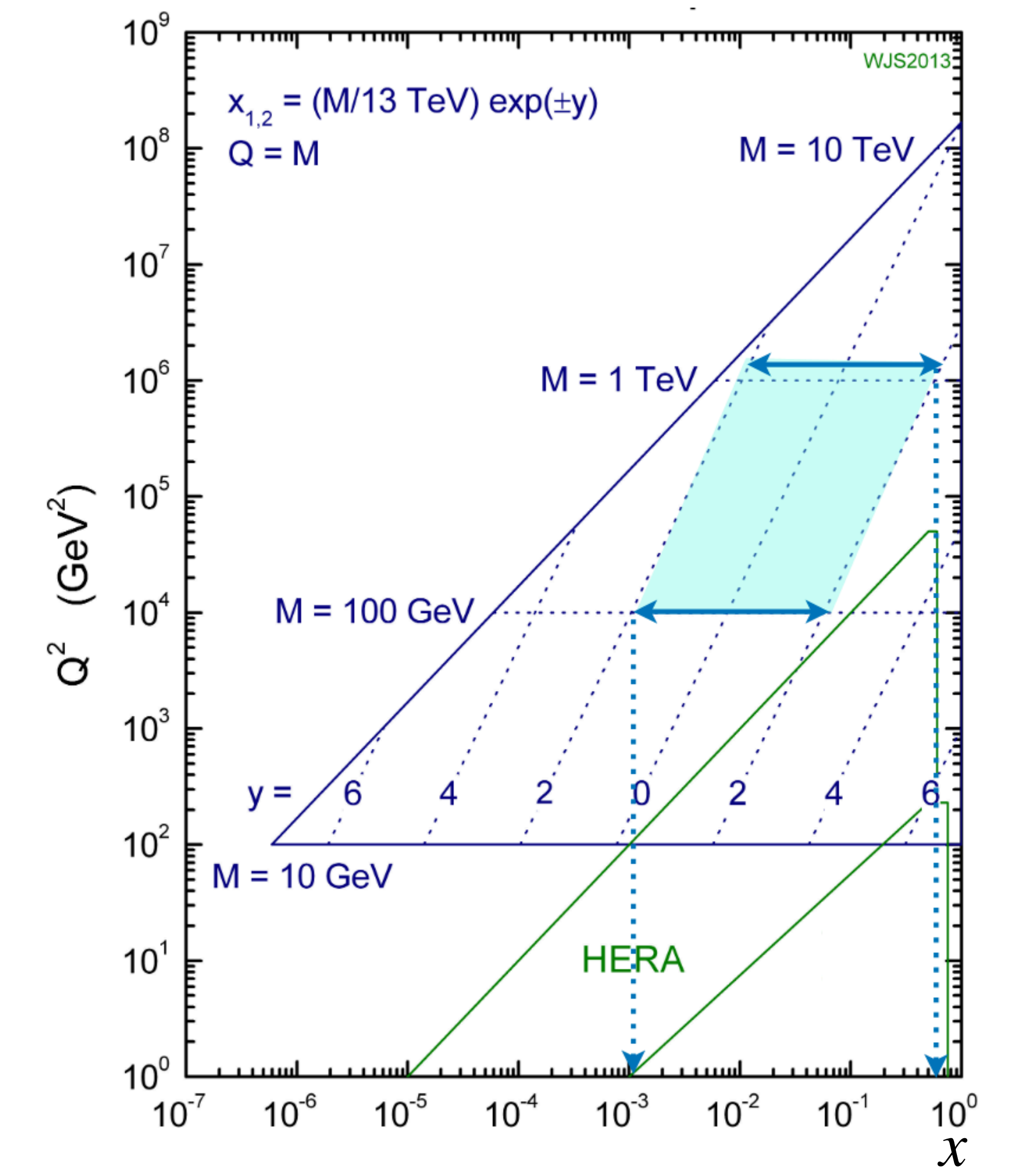


PDFs and $\alpha_S(m_Z)$

Most recent CMS measurement: probes the gluon distribution at high x

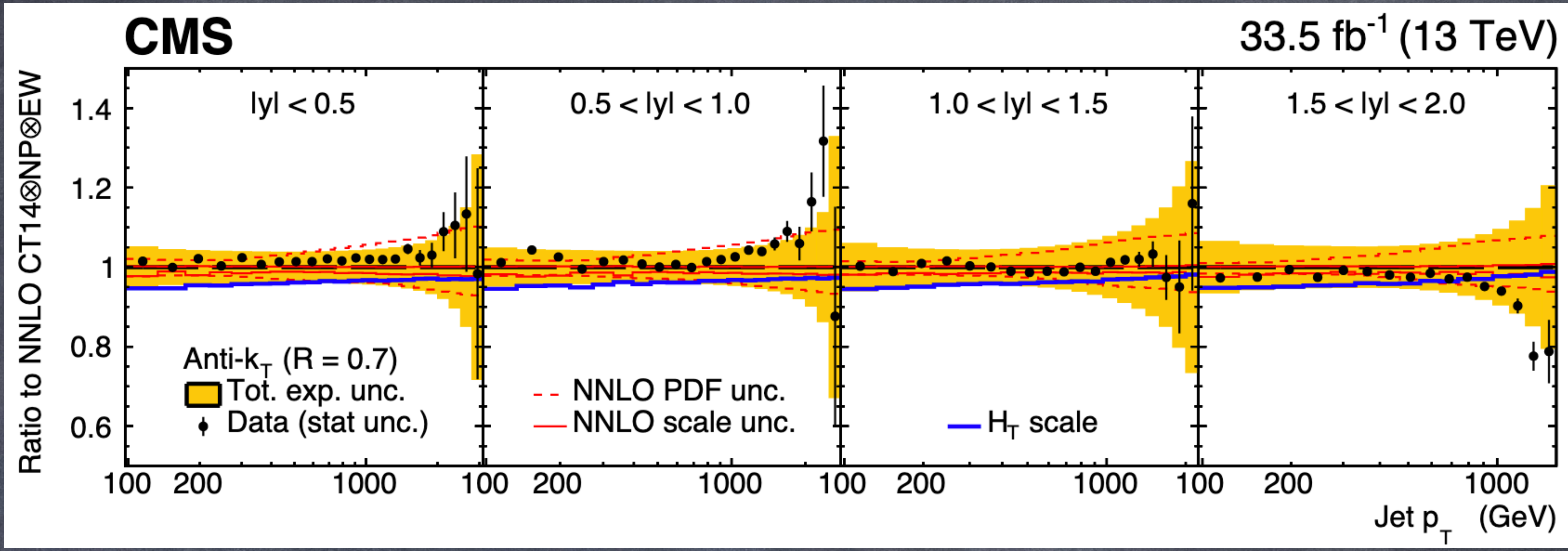


arXiv:2111.10431



JET PRODUCTION @ LHC: STRESS TEST FOR QCD

data vs NNLO



Appreciate tremendous effort and great success of the theory / tool development !

NNLO: [Currie, Glover, Pires, PRL118 (2017) 072002]
[Currie et al. , JHEP 10 (2018) 155]
[T. Gehrmann et al.,PoS RADCOR2017 (2018) 074]

NLOJet++ [Z. Nagy PRL 88 (2002) 122003, PRD 68 (2003) 094002]

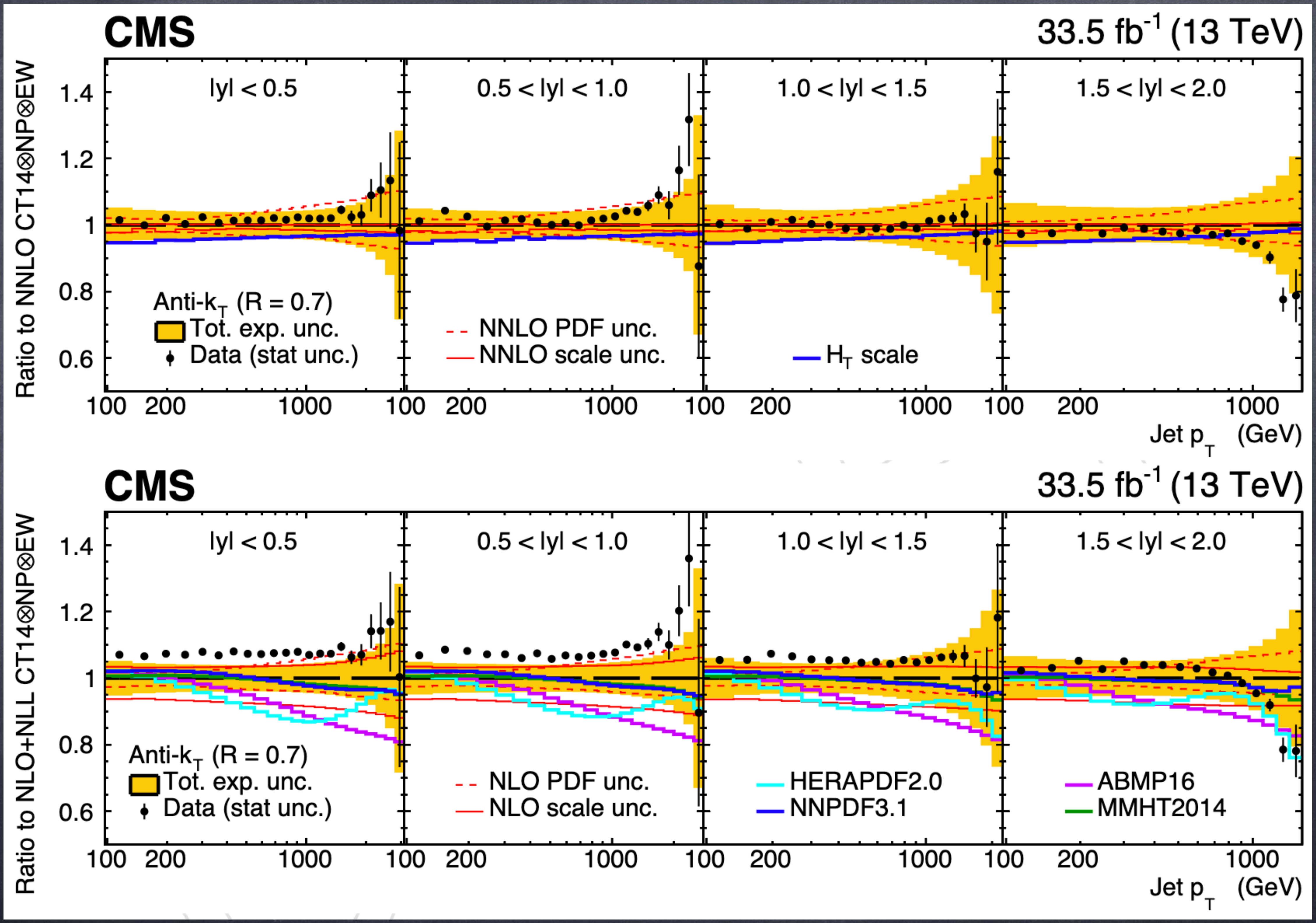
fastNLO [D. Britzger, K. Rabbertz, F. Stober, M. Wobisch, arXiv:1208.3641]

… and many more

JET PRODUCTION @ LHC: STRESS TEST FOR PDFs

data vs NNLO

data vs NLO+NLL



NLL resummation [Liu, Moch, Ringer, arXiv:1801.07284]
[J. Gao et al., arXiv:1207.0513]

dominant uncertainty: PDF

GETTING PDFs FROM JET DATA

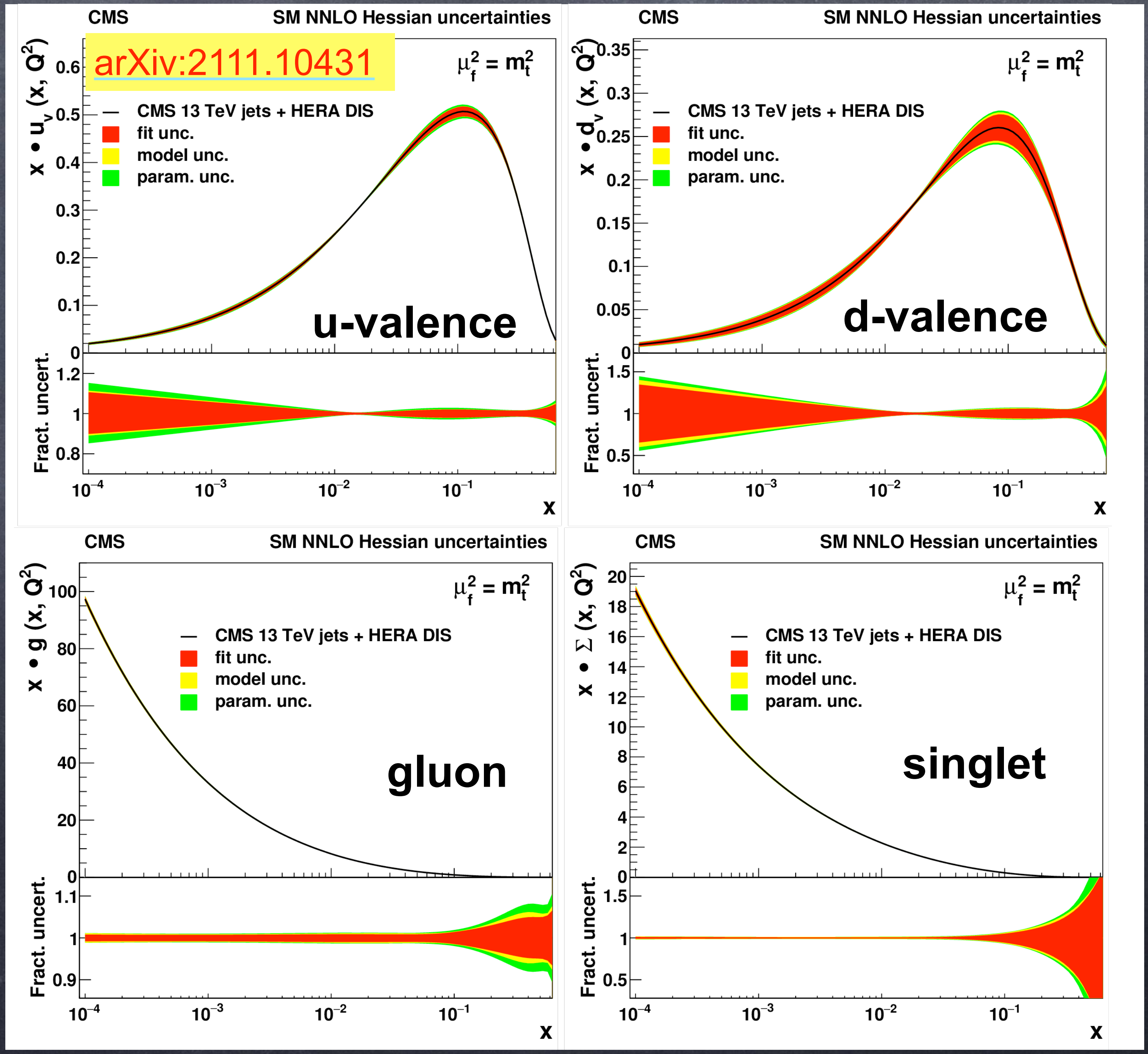
- **QCD fit at NNLO:** basis data - *ep* inclusive DIS cross sections (HERA) [arXiv:1506.06042]
  + CMS inclusive jets at 13 TeV [arXiv:2111.10431]

- **PDF + uncertainties from:**

uncertainties in exp. data

assumed values of quark masses
choice of factorisation/renormalisation scales in the theory prediction

uncertainties in parametrisation



GETTING PDFs + $\alpha_S(m_Z)$ FROM JET DATA

- **QCD fit at NNLO:** basis data - *ep* inclusive DIS cross sections (HERA) [arXiv:1506.06042]
  + CMS inclusive jets at 13 TeV [arXiv:2111.10431]

- **PDF + uncertainties from:**

uncertainties in exp. data

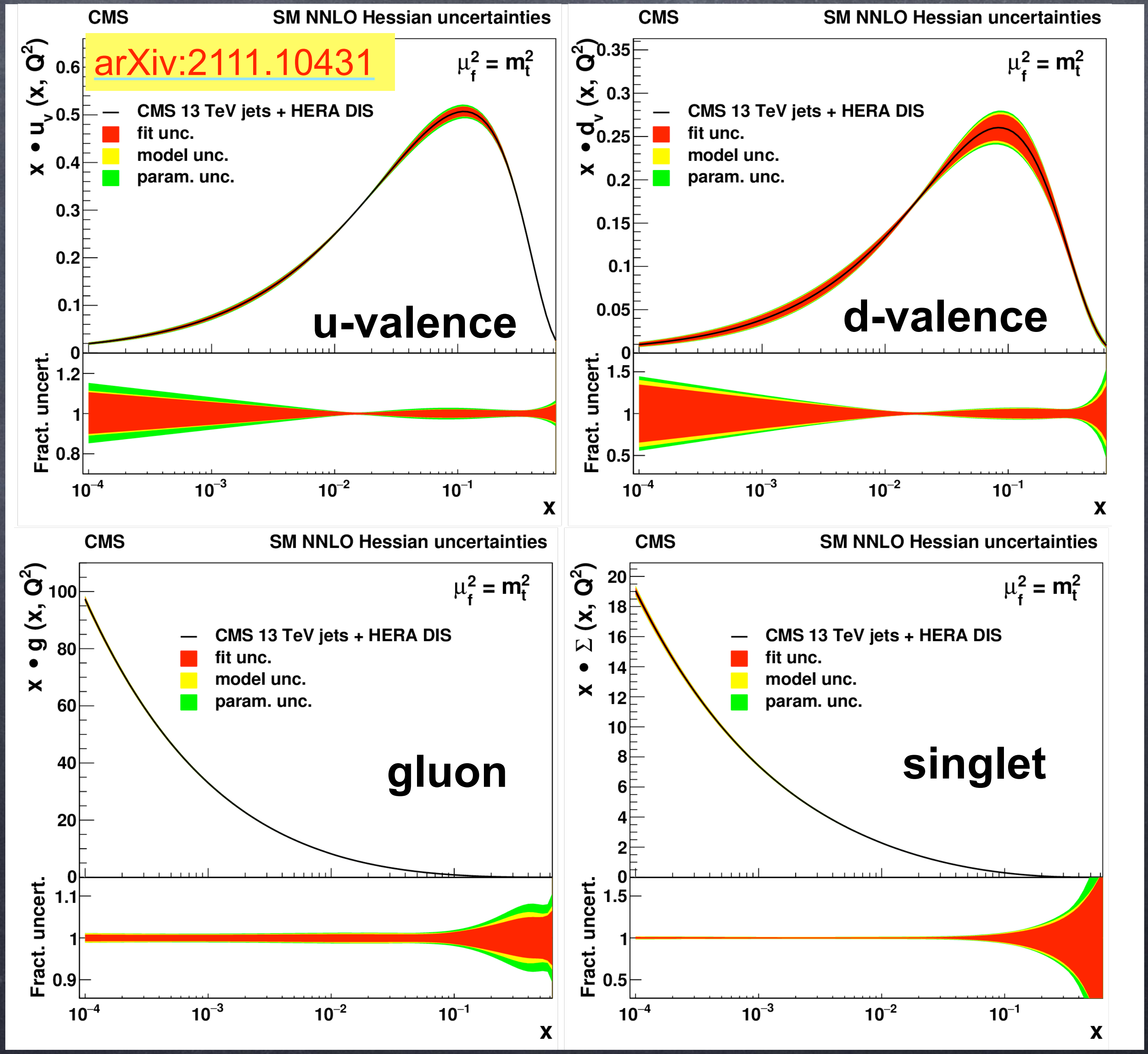
assumed values of quark masses
choice of factorisation/renormalisation scales in the theory prediction

uncertainties in parametrisation

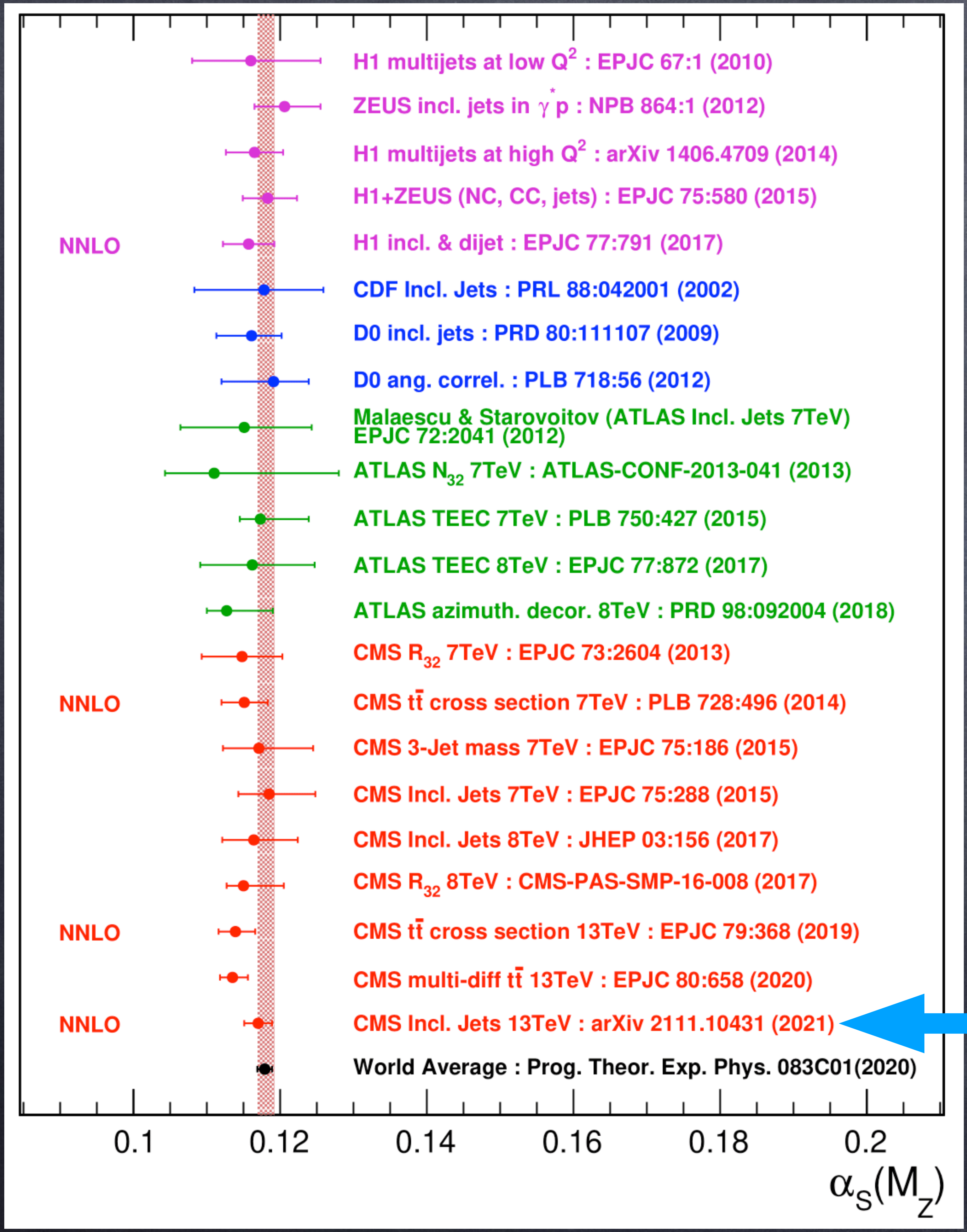
- **Strong coupling constant**

$$\alpha_S(m_Z) = 0.1170 \pm 0.0019$$

$$0.0014_{fit} \pm 0.0007_{model} \pm 0.0008_{scale} \pm 0.0001_{param}$$



NEW $\alpha_s(m_Z)$ VS EARLIER RESULTS



most precise single measurement
(error 1.6%)
mitigated dependence on PDFs

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

… AND GLUON GETS MORE PRECISE

- **QCD fit at NNLO:** basis data - *ep* inclusive DIS cross sections (HERA) [arXiv:1506.06042]
  + CMS inclusive jets at 13 TeV [arXiv:2111.10431]

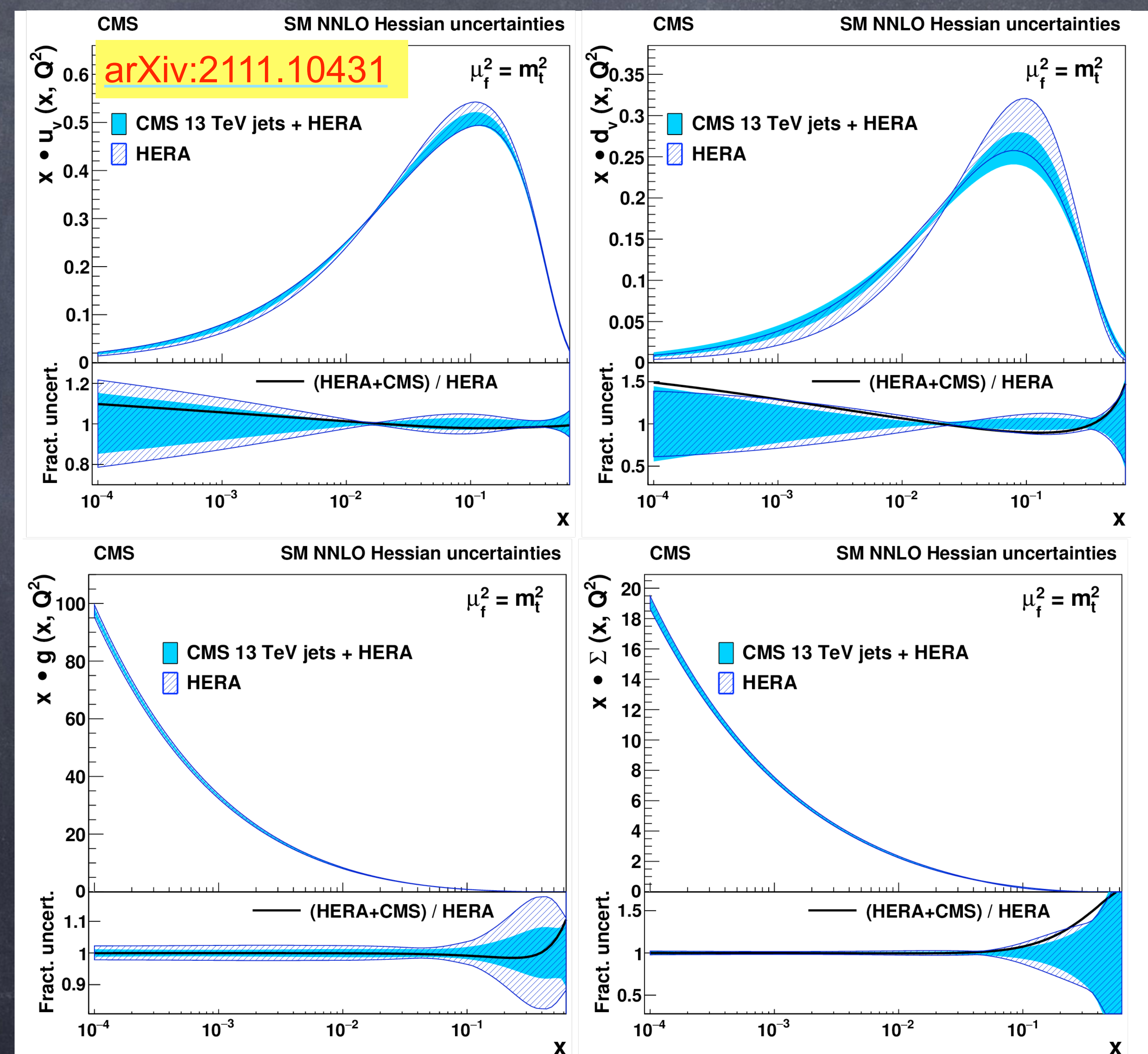
- **PDF + total uncertainties**

- **Strong coupling constant**

$$\alpha_S(m_Z) = 0.1170 \pm 0.0019$$

- **compared to HERA-only fit**

{ $\alpha_s(m_Z)$ fixed }



… AND GLUON GETS MORE PRECISE

- **QCD fit at NNLO:** basis data - *ep* inclusive DIS cross sections (HERA) [arXiv:1506.06042]
  + CMS inclusive jets at 13 TeV [arXiv:2111.10431]

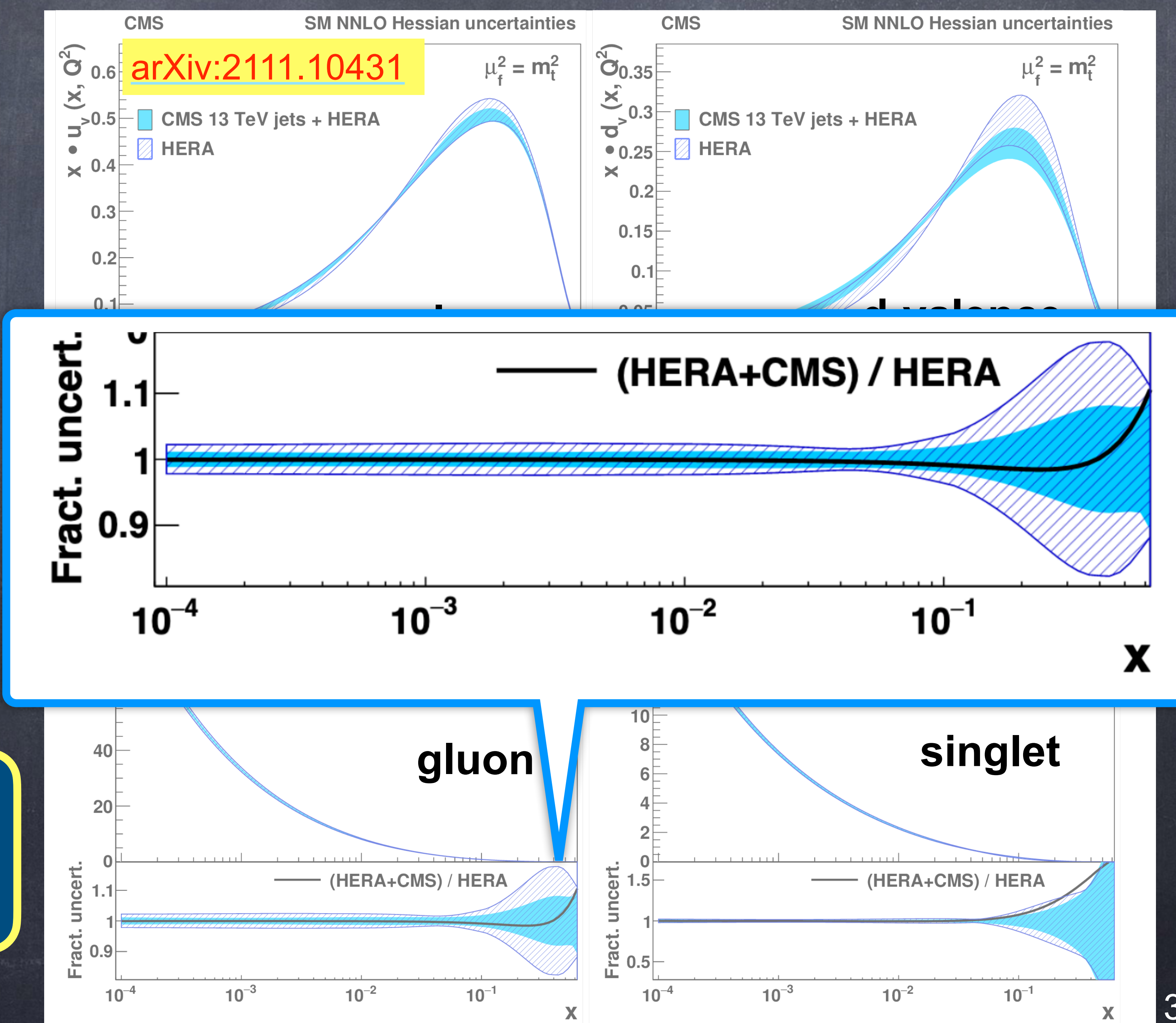
- **PDF + total uncertainties**

- **Strong coupling constant**

  $$\alpha_S(m_Z) = 0.1170 \pm 0.0019$$

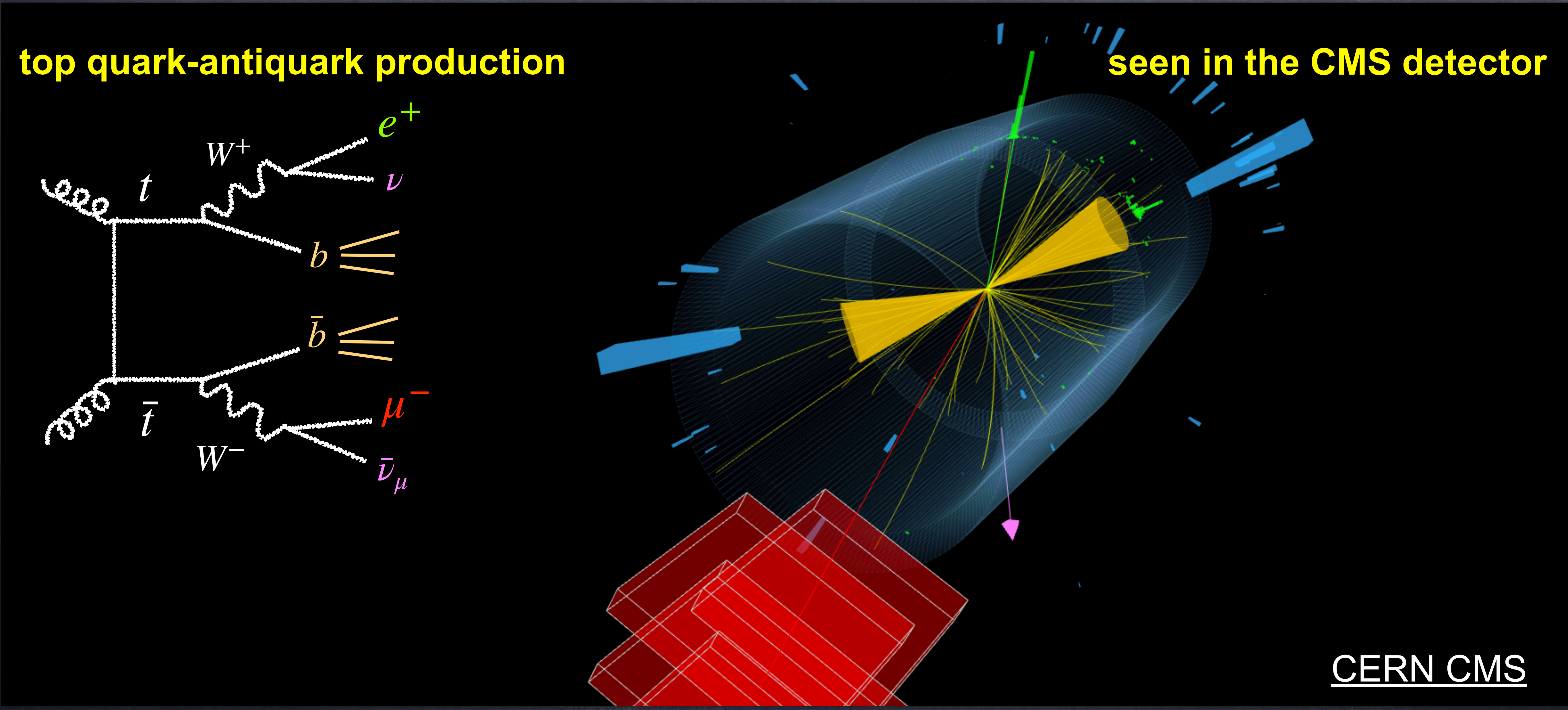
- **compared to HERA-only fit**
  { $\alpha_s(m_Z)$ **fixed** }

Improved precision of the gluon at high x !



PROTON STRUCTURE AND QCD @ LHC VIA TOP QUARK PAIR PRODUCTION

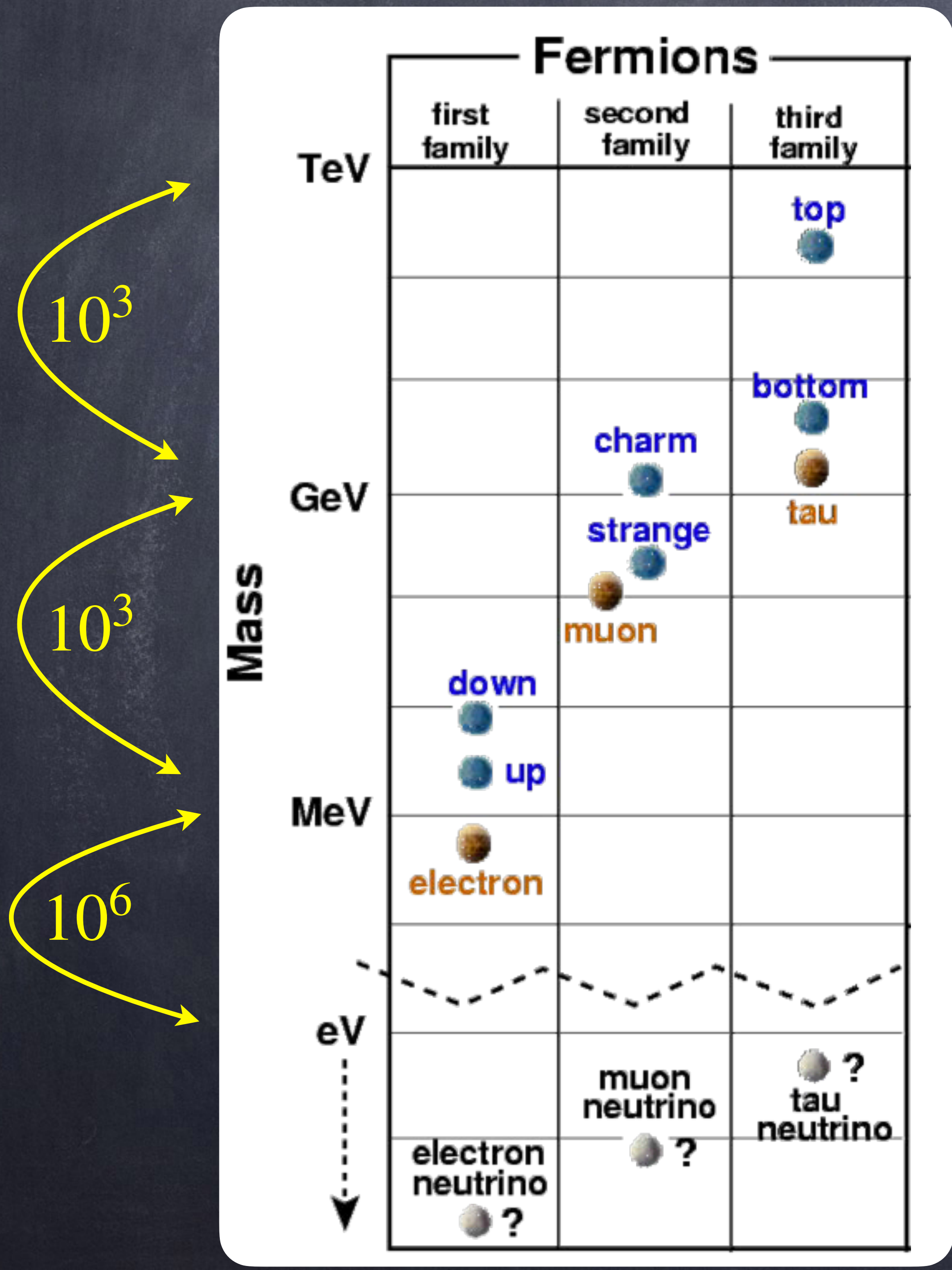
Too massive to form hadrons: top quark decays into W boson and b quark



TOP QUARK IN THE STANDARD MODEL

Most massive elementary particle known to date

Does not form hadrons: the only "bare" quark



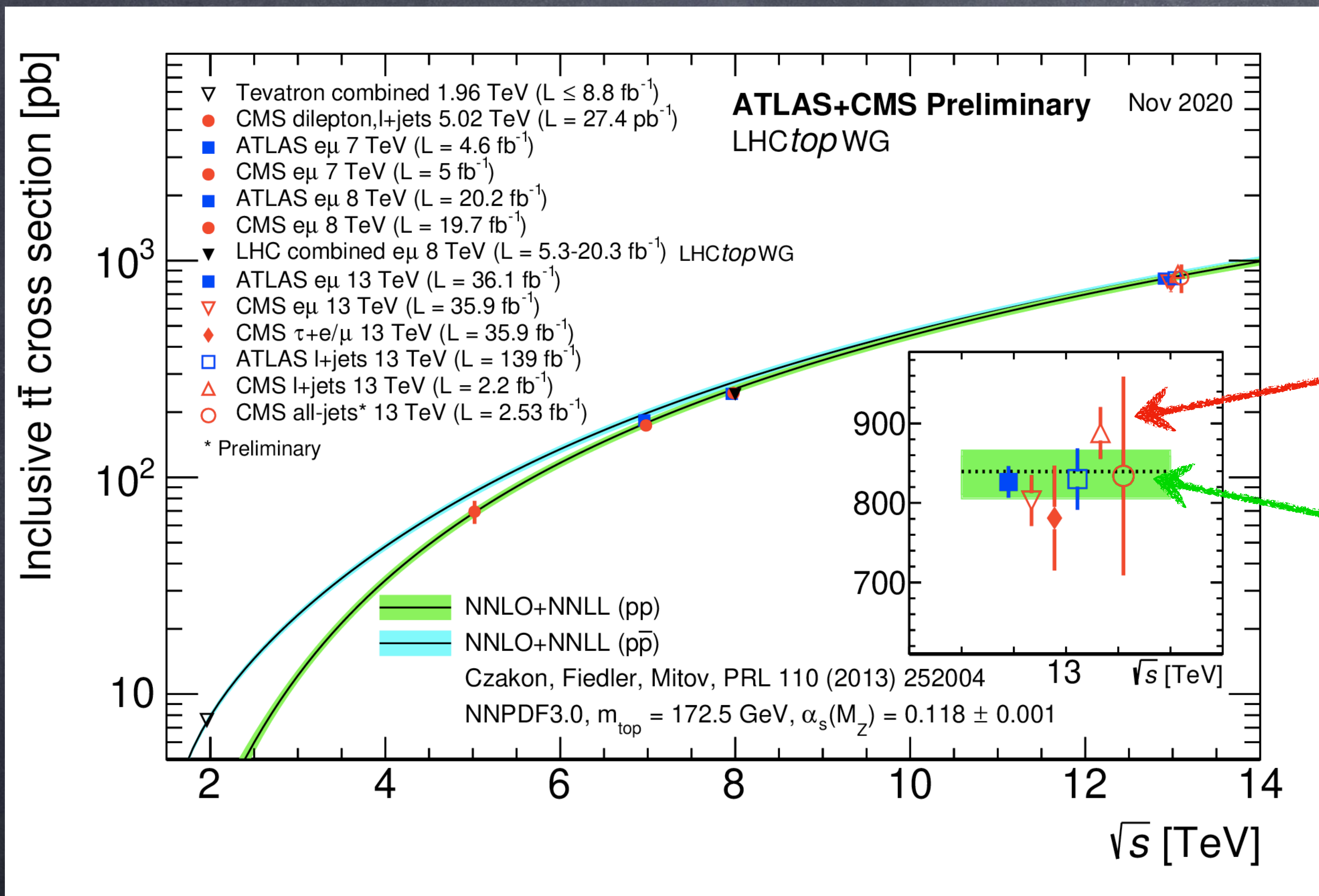
relation to M_H, M_W,
Higgs Yukawa coupling
strong coupling

the "elephant in the room"

for tests of QCD
and the Standard Model

NB: MEASUREMENTS OF QUARK MASSES

Experimental observable: cross section (inclusive or as a function of kinematics)



experimental data

theory prediction

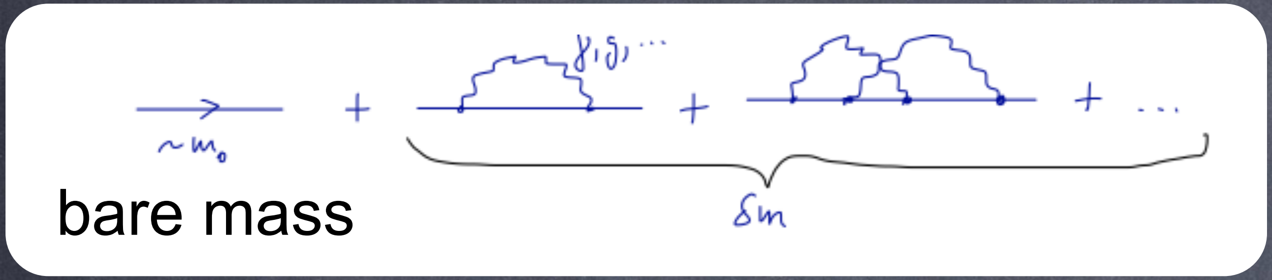
The measurement is compared to the theory prediction,

fundamental parameters of the theory are derived from this comparison

TOP QUARK MASS IN QCD

Beyond LO:

bare mass term in Lagrange density receives self-energy corrections δm



Renormalised mass $m_R = m_0 + \delta m$

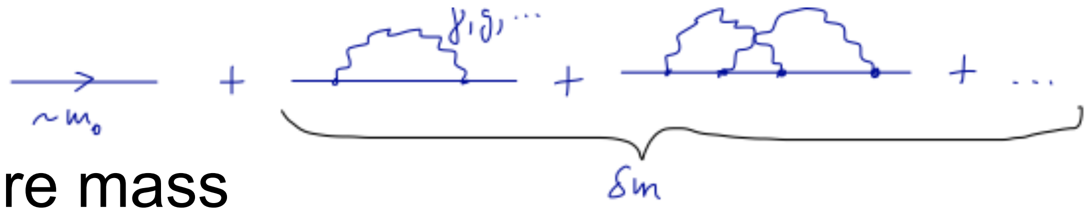
determined at scale $\mu \rightarrow$ finite

Lagrange density with renormalised mass m_R is scale-dependent

TOP QUARK MASS IN QCD

Beyond LO:

bare mass term in Lagrange density receives self-energy corrections δm



bare mass

Renormalised mass $m_R = m_0 + \delta m$

determined at scale $\mu \rightarrow$ finite

Lagrange density with renormalised mass m_R is scale-dependent

m_t becomes renormalisation-scheme dependent:

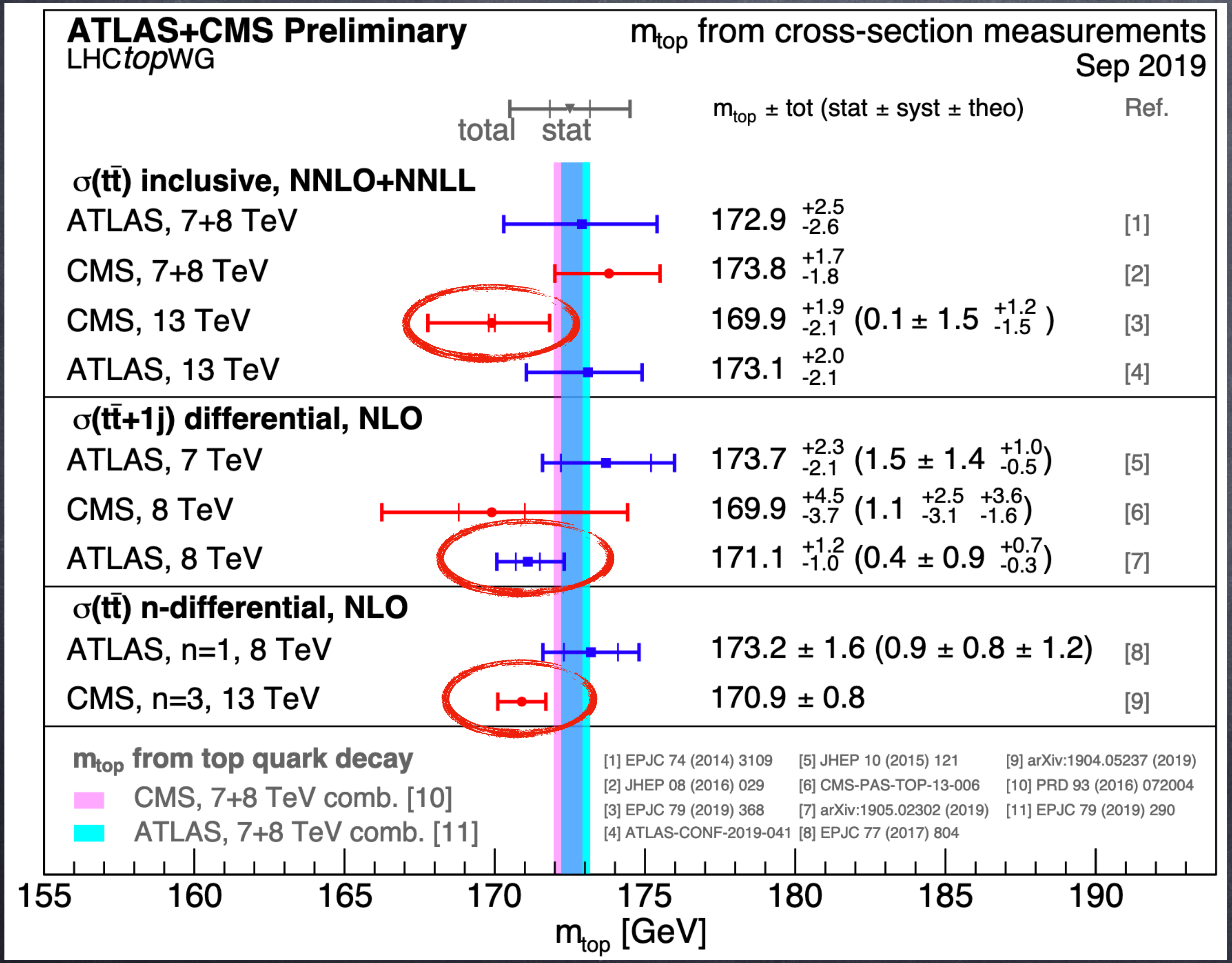
- **pole mass: m_t^{pole}** **the pole of the quark propagator (concept of free parton)**
  Good description of physics near $t\bar{t}$ production threshold

- **running mass $m_t(\mu)$** **valid above top-quark production threshold**
  e.g. $\overline{\text{MS}}$ mass
  running **follows Renormalisation Group Equations**
  value at a fixed scale $m_t(\mu)$ to be extracted from the data

TOP QUARK MASS MEASUREMENTS

Different methods of measurement - very different precision

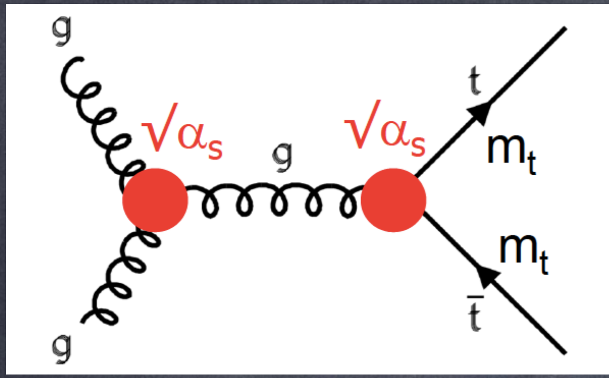
Theoretical interpretation of the extracted mass not always straightforward



only the results

on the pole mass are shown

TOTAL $t\bar{t}$ CROSS SECTION: GLUON AT HIGH x



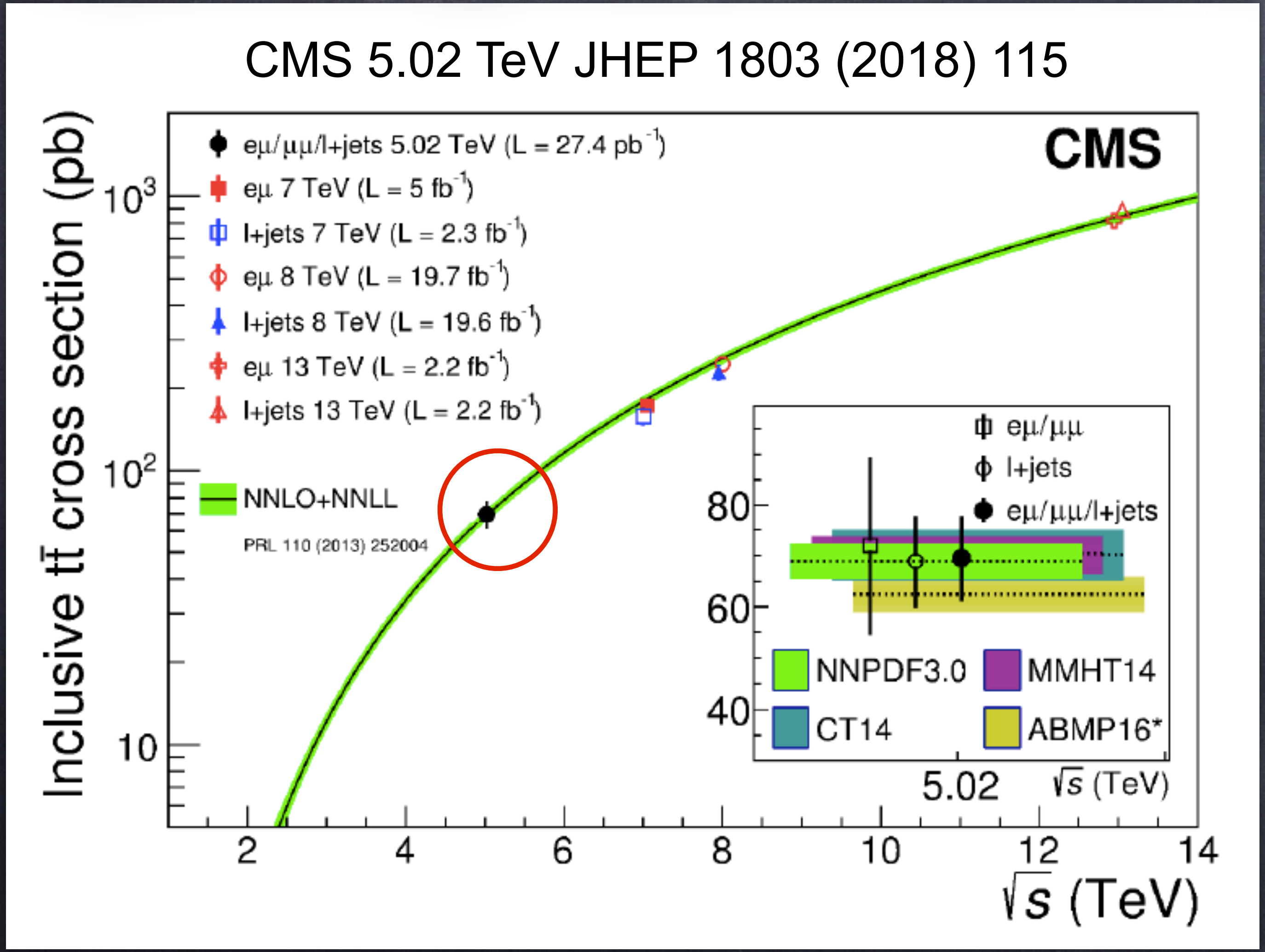
sensitive to the gluon PDF at high x, α_S and m_t

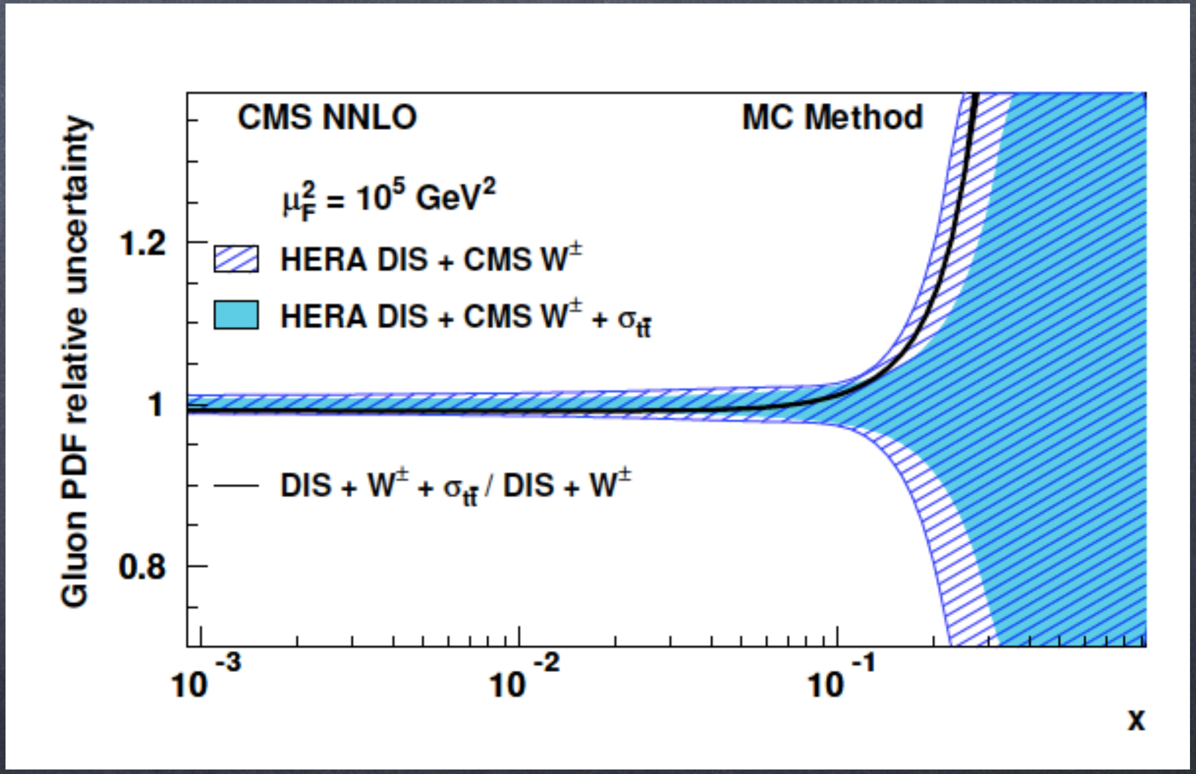
total $t\bar{t}$ cross section: PDF, α_S and m_t are correlated:

only one of the 3 parameters can be extracted

Impact of a single measurement in a PDF fit ($\alpha_S(m_Z)$ and m_t fixed)

CMS 5.02 TeV JHEP 1803 (2018) 115

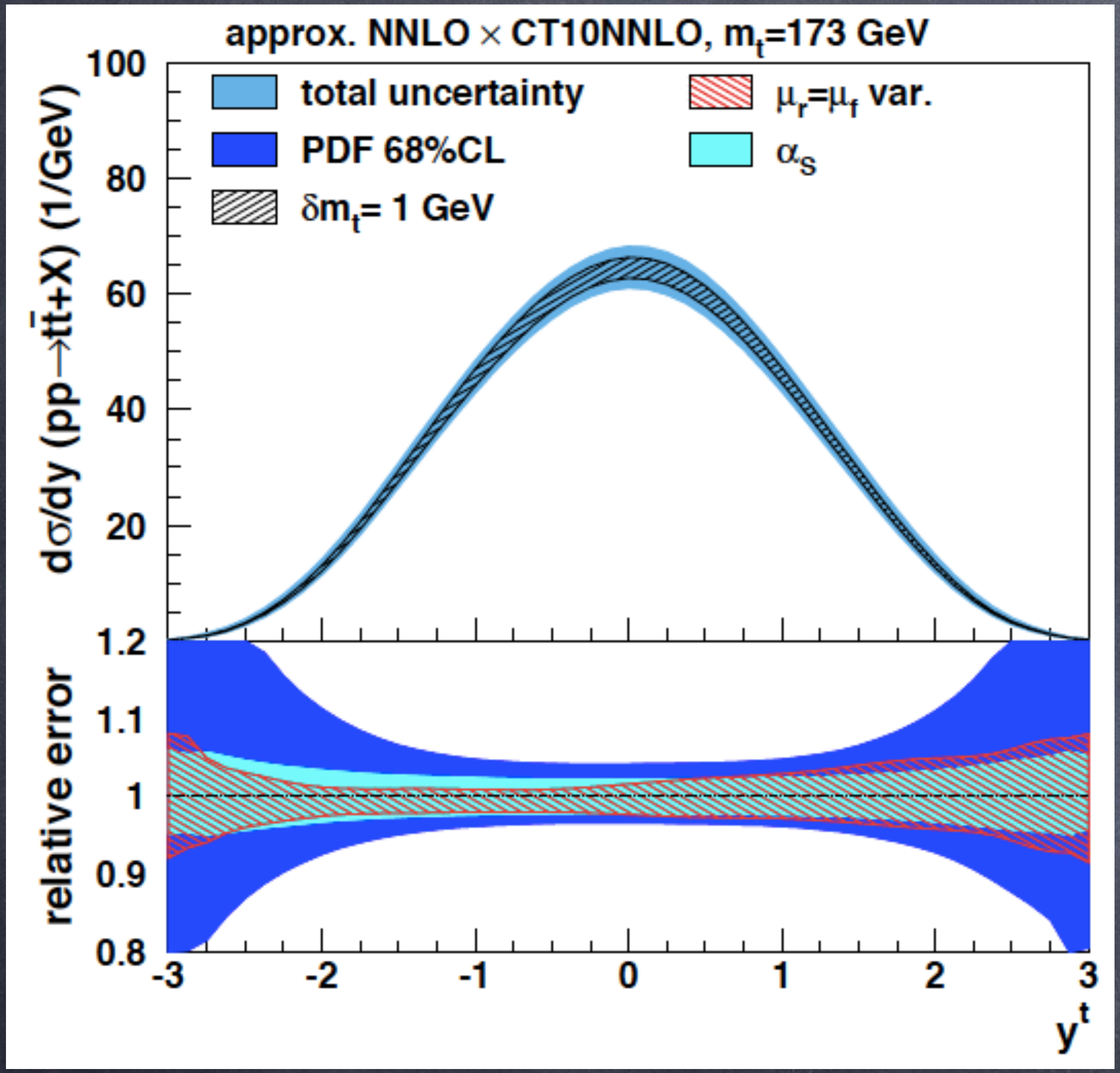




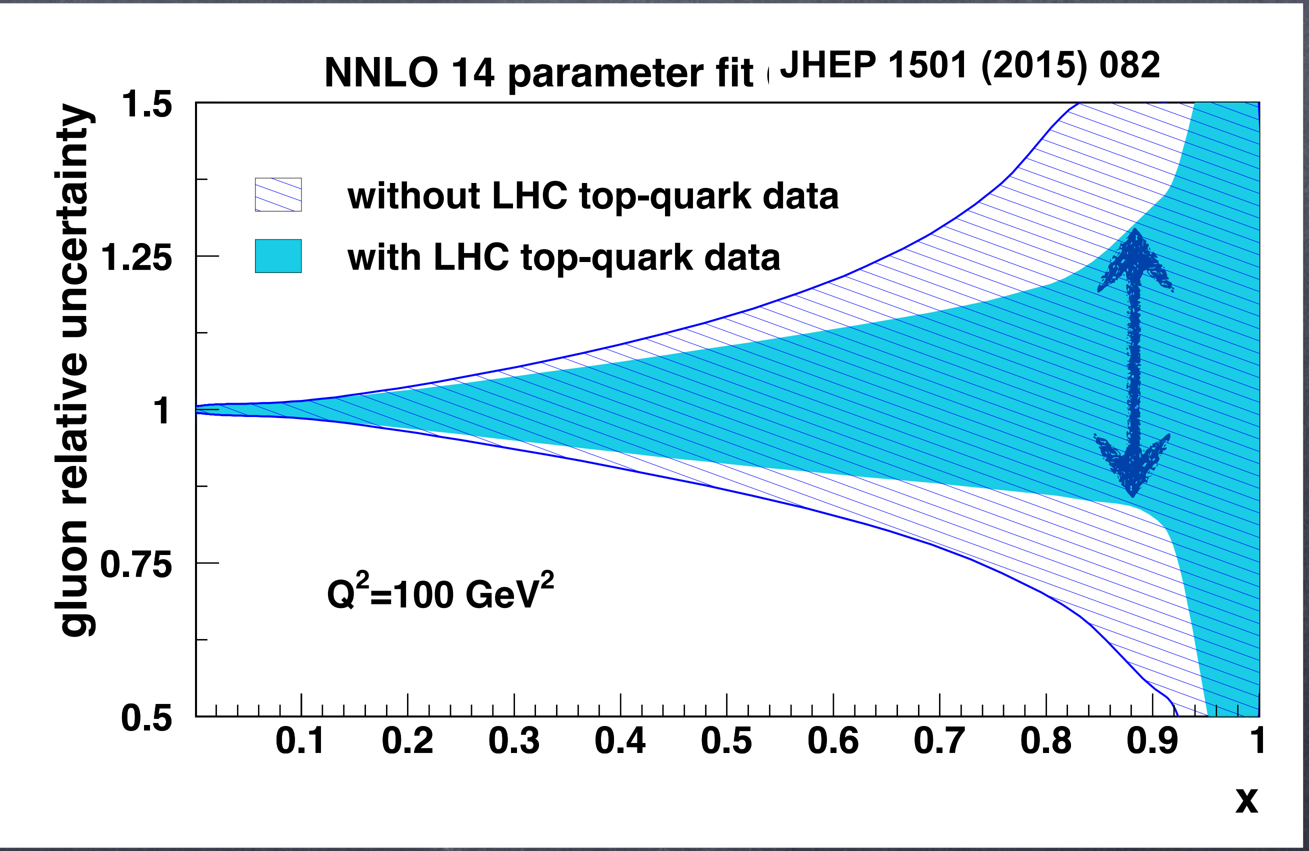
reduction of the uncertainty in the gluon distribution

SINGLE-DIFFERENTIAL $t\bar{t}$: GLUON AT HIGH x

More impact on PDF, α_S and m_t expected by using top quark kinematics



First QCD analysis of $t\bar{t}$ kinematics



Gluon PDF

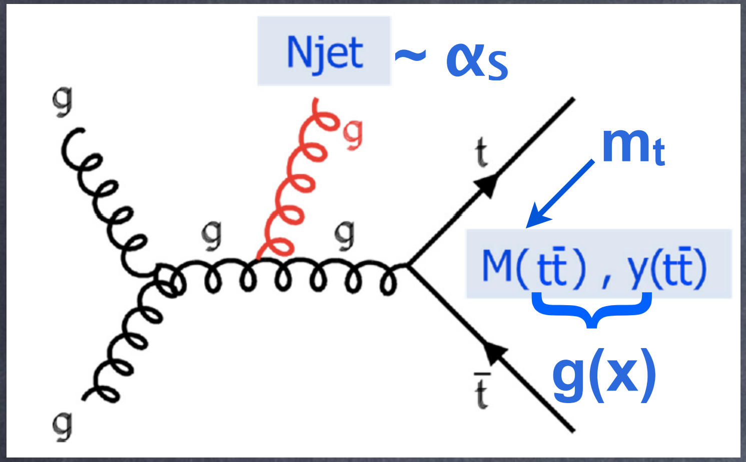
- alters the normalisation and shape
- dominant theory uncertainty

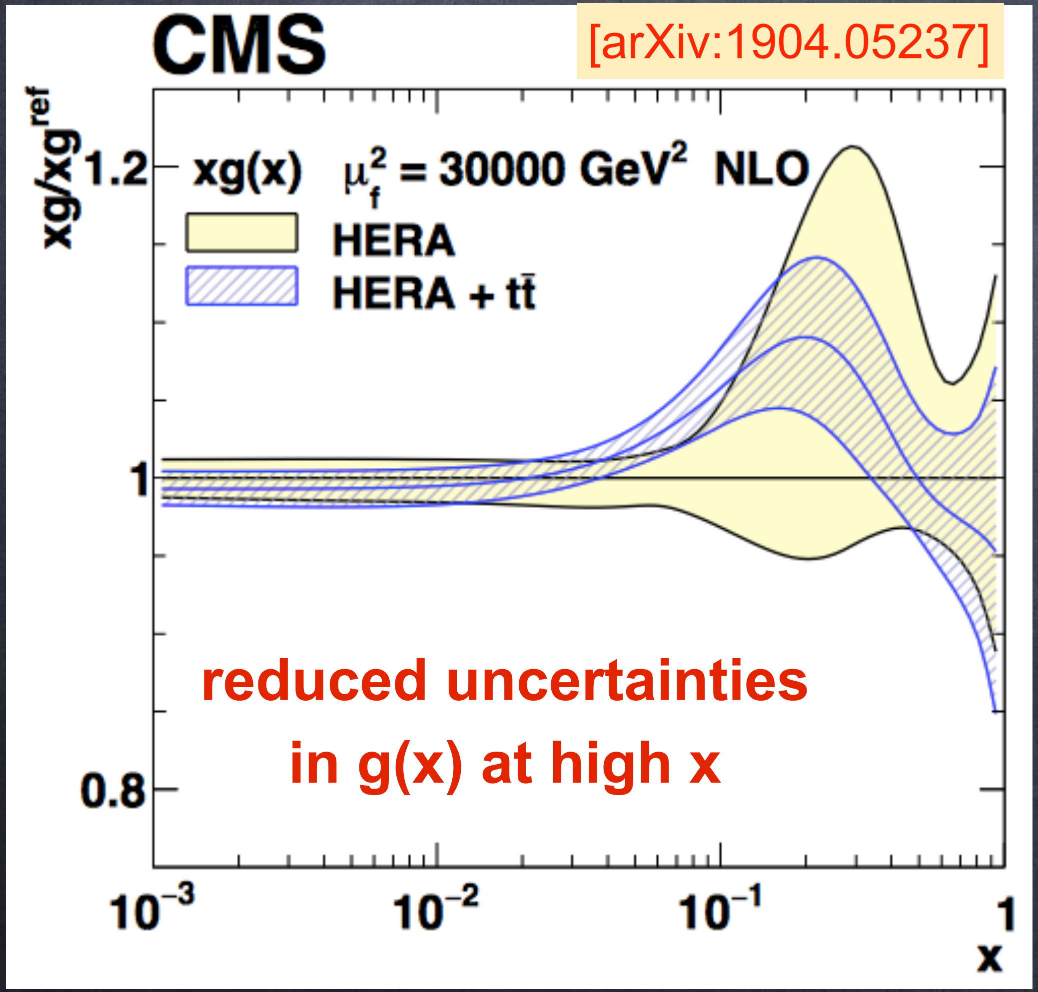
Smaller uncertainty in $g(x)$ for $x > 0.1$

Significant change in shape of the gluon

3-DIFFERENTIAL $t\bar{t}$: GLUON, α_S, m_t AT ONCE!

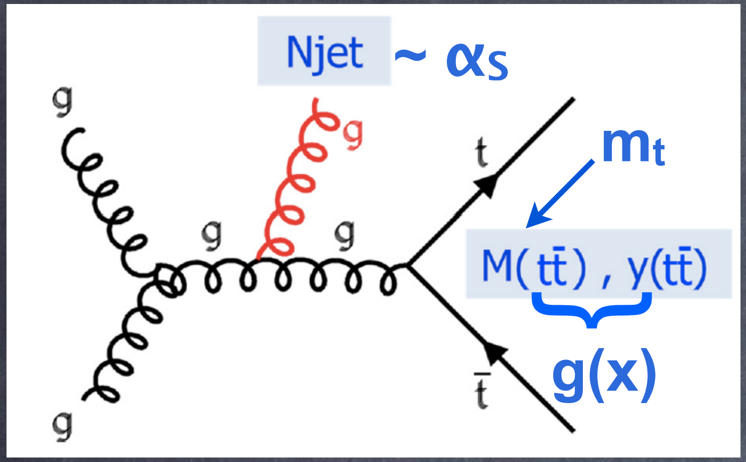
$t\bar{t}$ + 1 jet: enhance sensitivity to $g(x)$, $\alpha_S(m_Z), m_t$ and their correlations



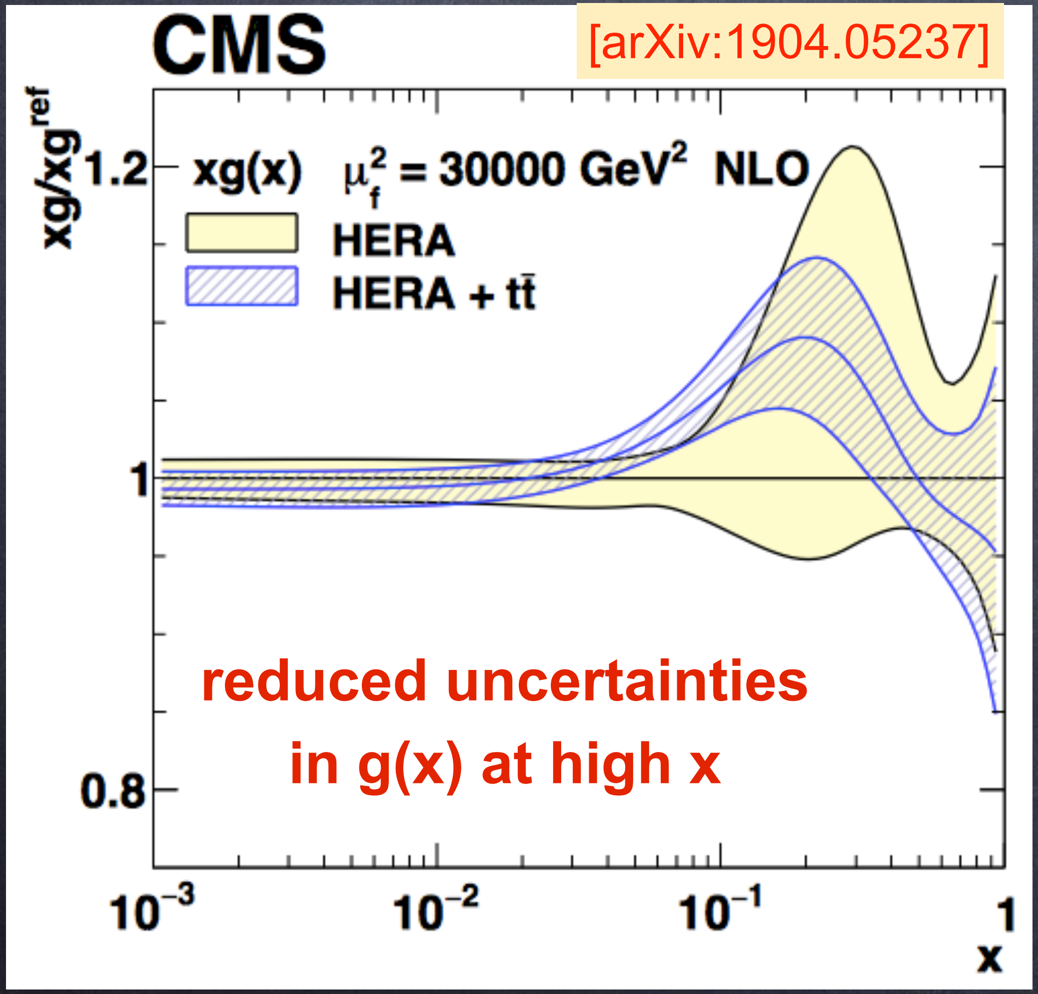


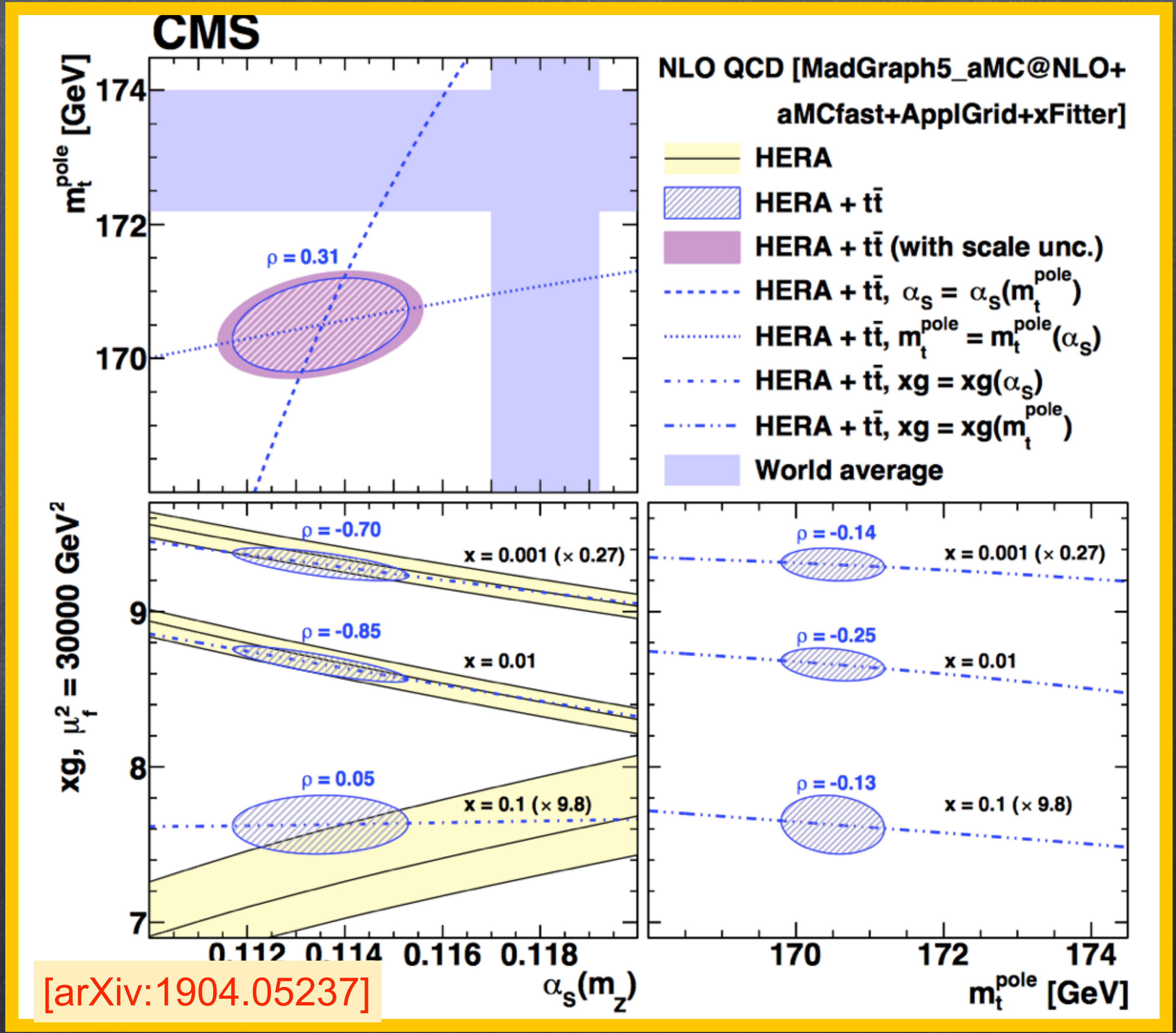
3-DIFFERENTIAL $t\bar{t}$: GLUON, α_S, m_t AT ONCE!

$t\bar{t}$ + 1 jet: enhance sensitivity to $g(x)$, $\alpha_S(m_Z), m_t$ and their correlations



first simultaneous extraction of QCD parameters with $t\bar{t}$ kinematics: correlations strongly reduced!

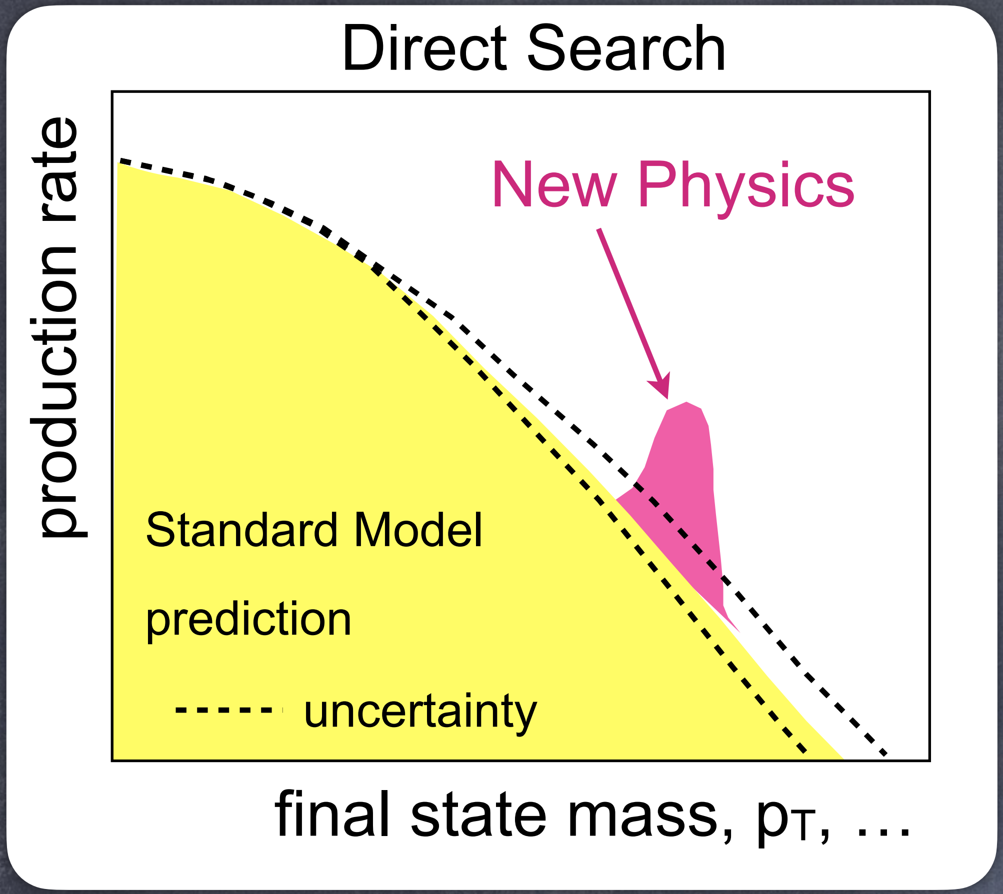


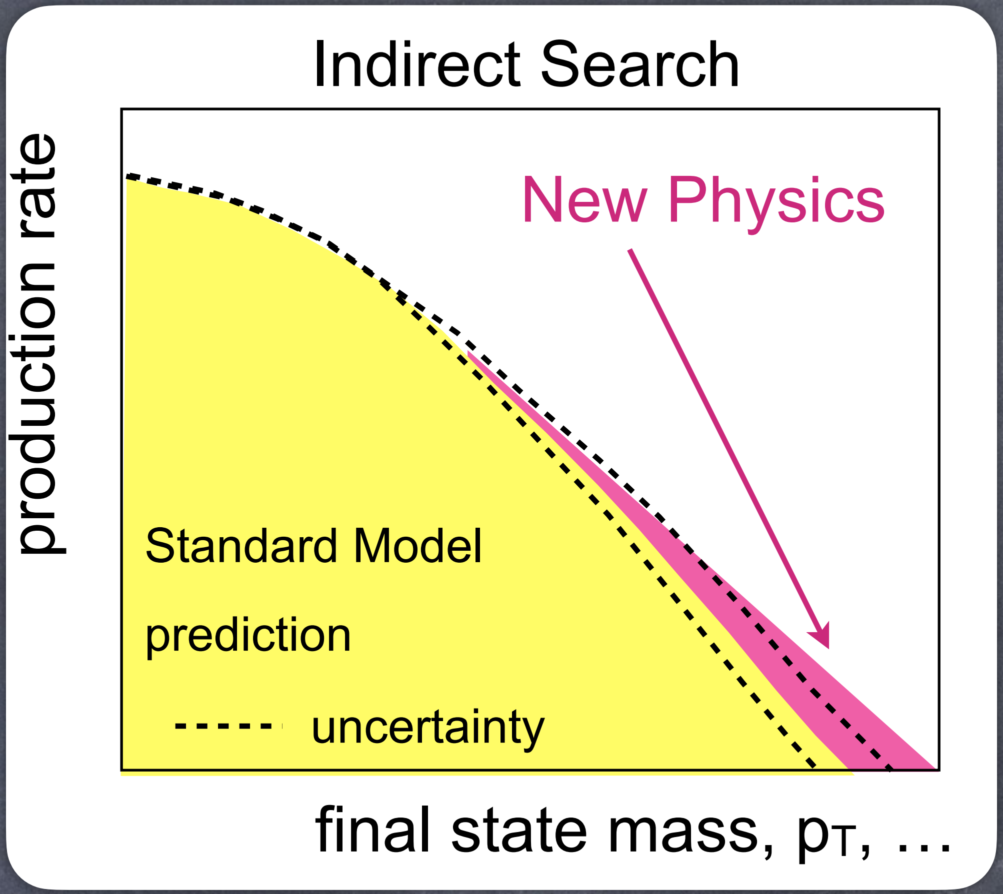


WHAT ABOUT NEW PHYSICS ?

INDIRECT SEARCHES WITH JETs AND $t\bar{t}$

ROLE OF QCD IN SEARCHES @ LHC





➡ look for non-SM 'bumps'

no signal observed, so far…

➡ look for excess over SM prediction

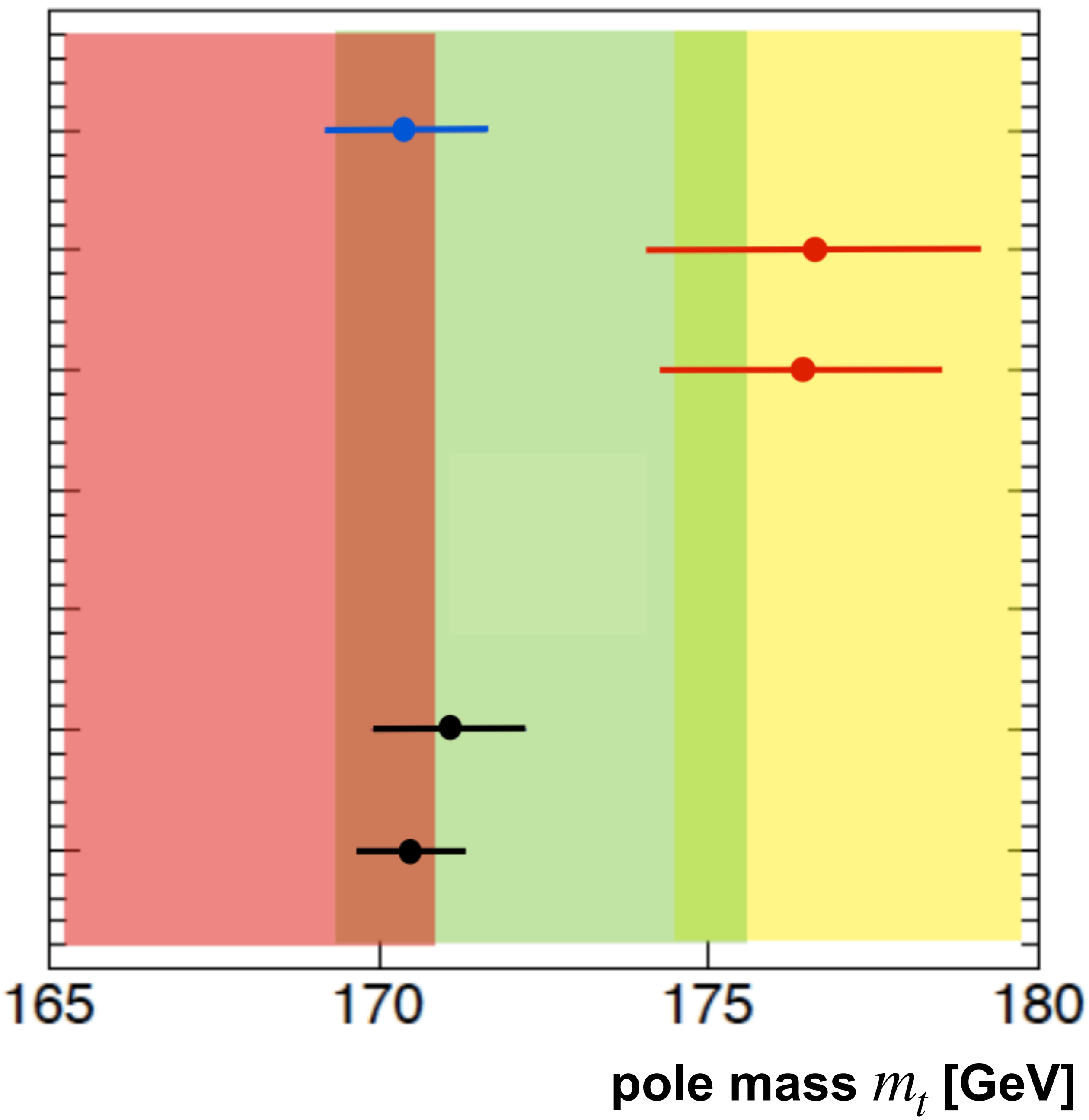
requires high precision !

"SM" means mostly QCD: uncertainties driven by PDFs, α_S and quark masses

TOP QUARK MASS AND NEW PHYSICS

In Standard Model, the relation of masses m_t, m_W, and m_H is strictly defined

use current values and precision of m_H and m_W



Need for New Physics at low energy scales
[S. Heinemeyer et al]

Need for New Physics at high energy scales
Universe Stability: meta-stable

Need for New Physics at high energy scales
Universe Stability: unstable

QCD Global Fit

Electroweak Fit: [HEPfit, GFitter]

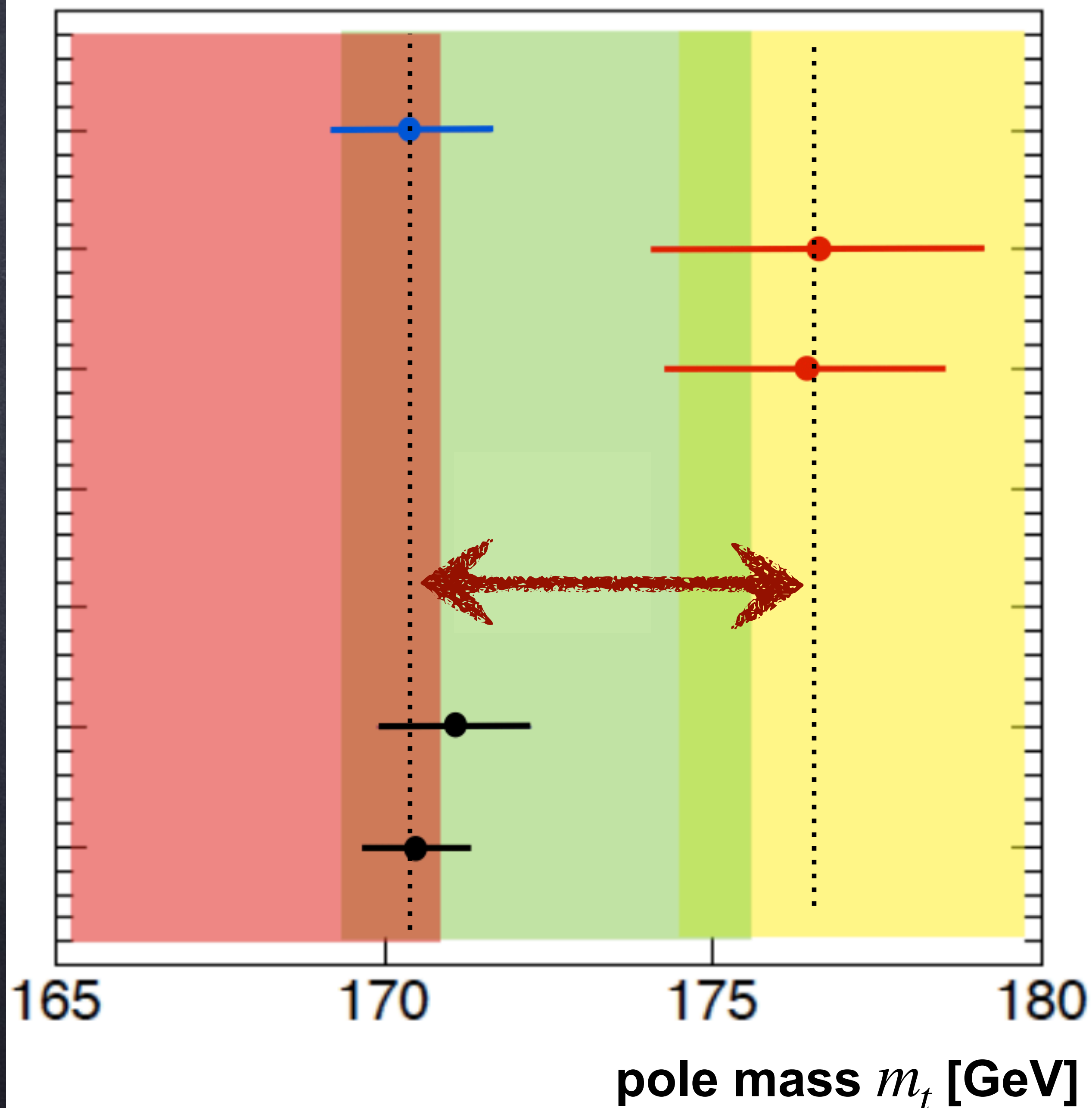
ATLAS & CMS measurements

courtesy J. Fuster

TOP QUARK MASS AND NEW PHYSICS

In Standard Model, the relation of masses m_t, m_W, and m_H is strictly defined

use current values and precision of m_H and m_W



Need for New Physics at low energy scales [S. Heinemeyer et al]

Need for New Physics at high energy scales
Universe Stability: meta-stable

Need for New Physics at high energy scales
Universe Stability: unstable

QCD Global Fit

Electroweak Fit: [HEPfit, GFitter]

ATLAS & CMS measurements

inconsistency (New Physics) found ?

Question of precision!

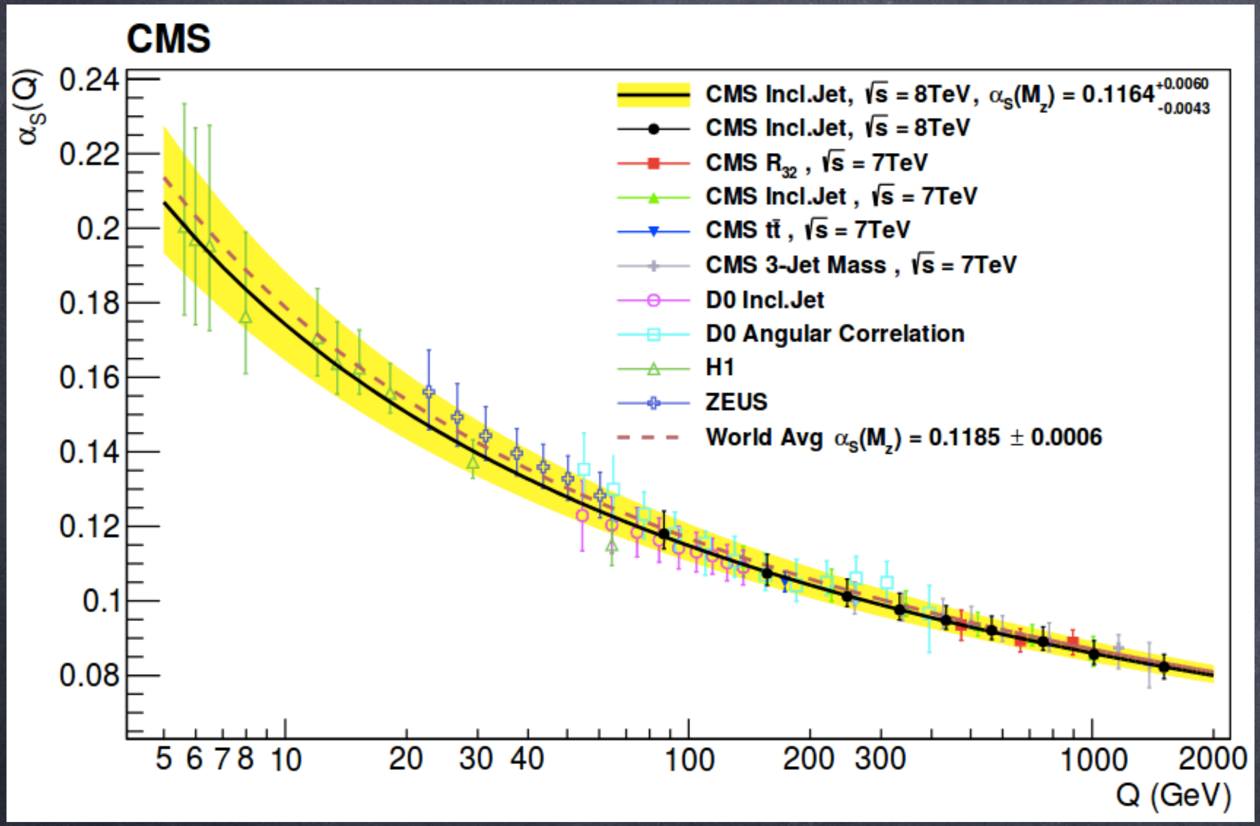
courtesy J. Fuster

TOP QUARK MASS AND NEW PHYSICS

QCD asymptotic freedom: energy dependence (“running”) of α_S and m_q

Running follows the QCD Renormalisation Group Equation

Strong coupling constant

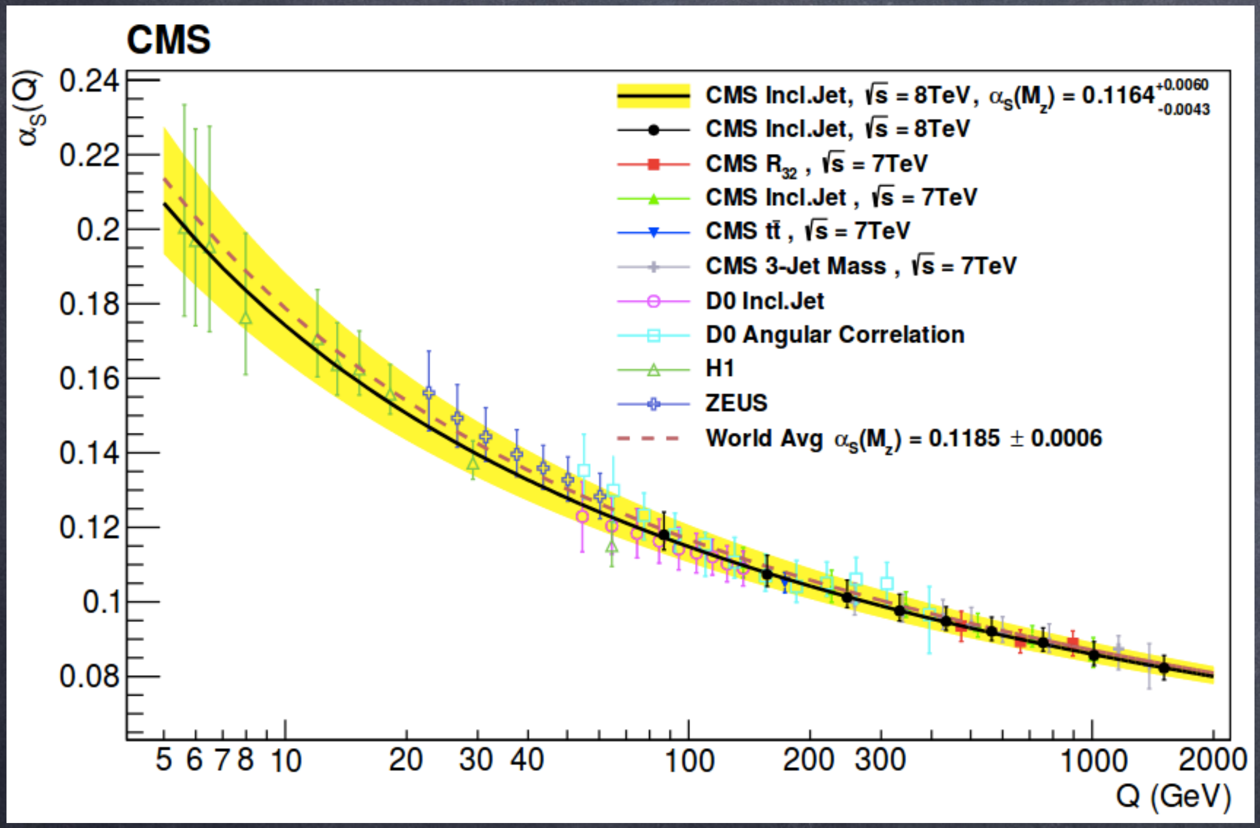


TOP QUARK MASS AND NEW PHYSICS

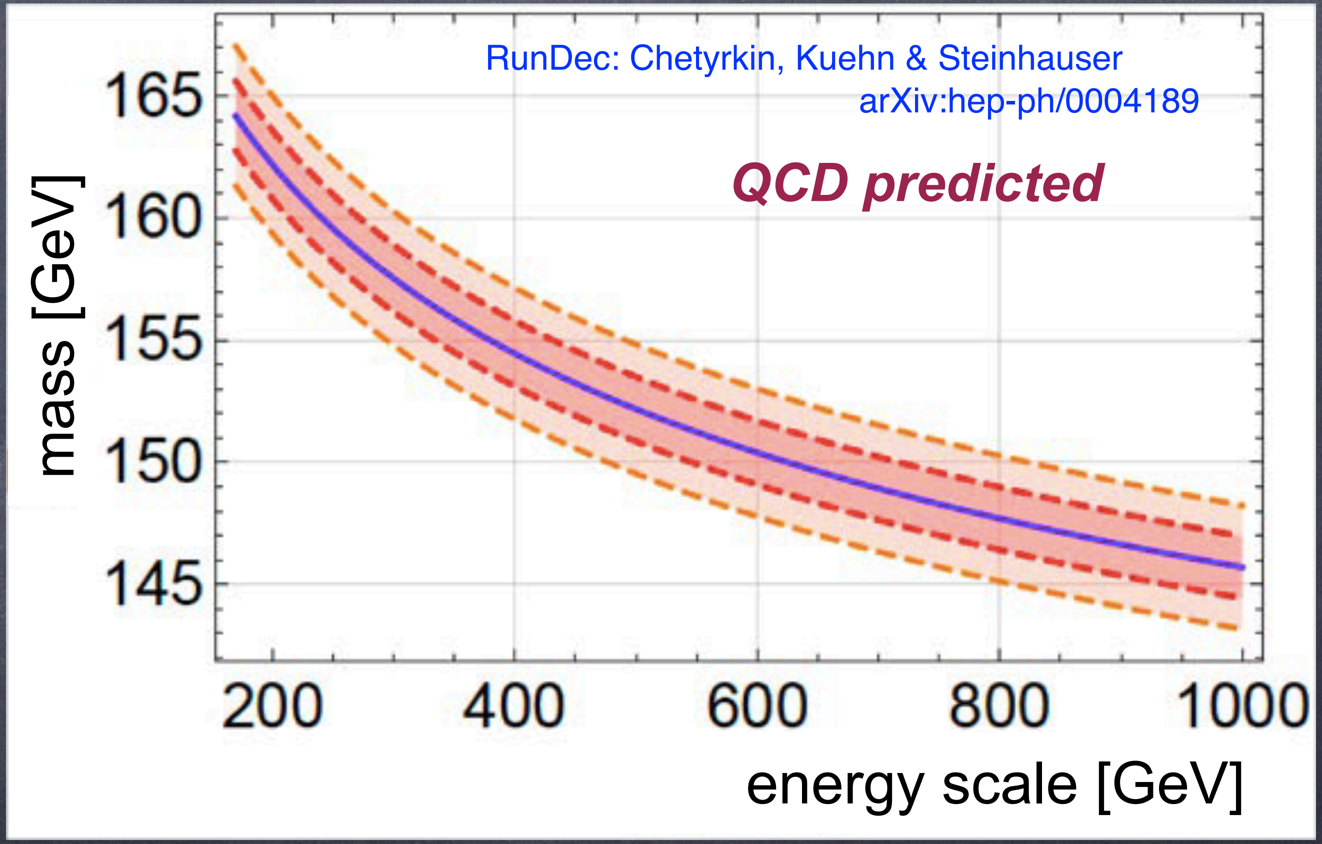
QCD asymptotic freedom: energy dependence ("running") of α_S and m_q

Running follows the QCD Renormalisation Group Equation

Strong coupling constant



Top quark mass



Fundamental test of QCD

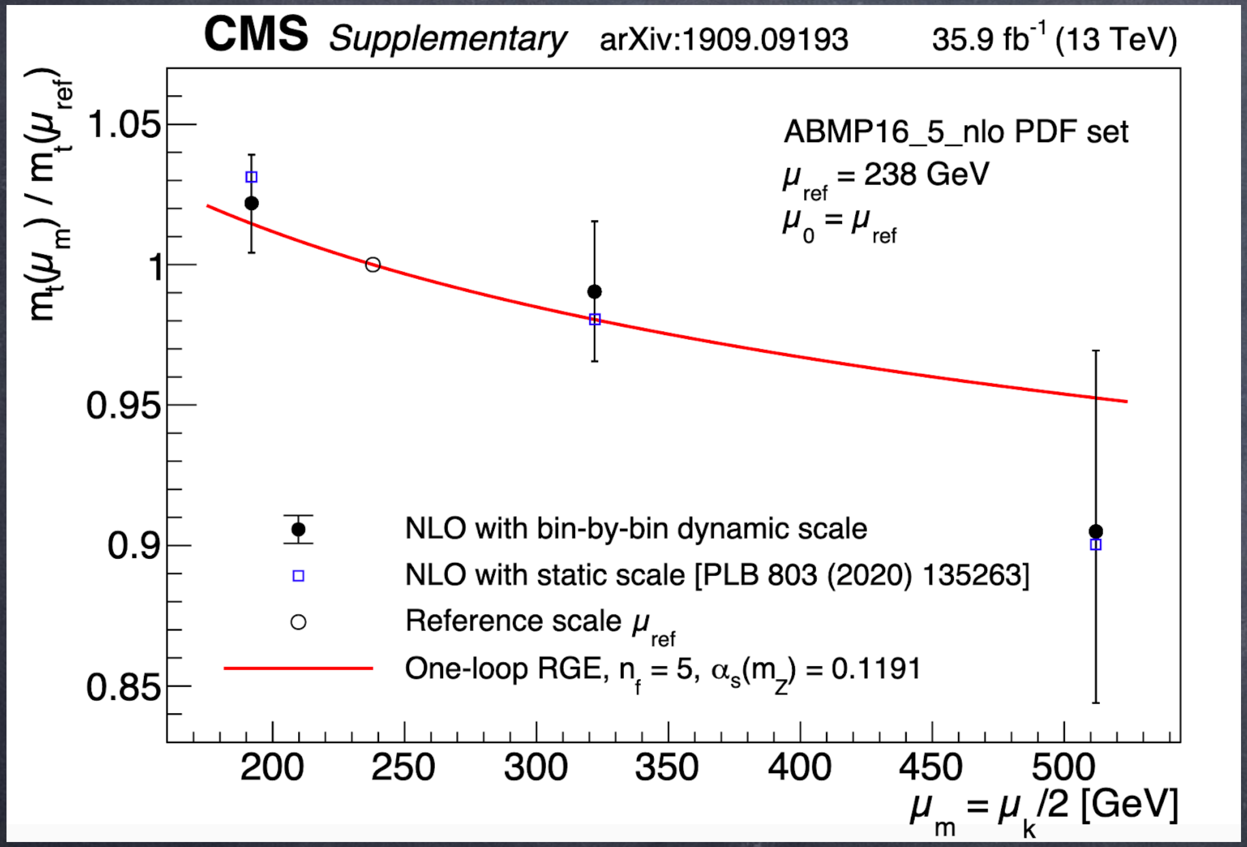
Probe of Physics beyond the Standard Model

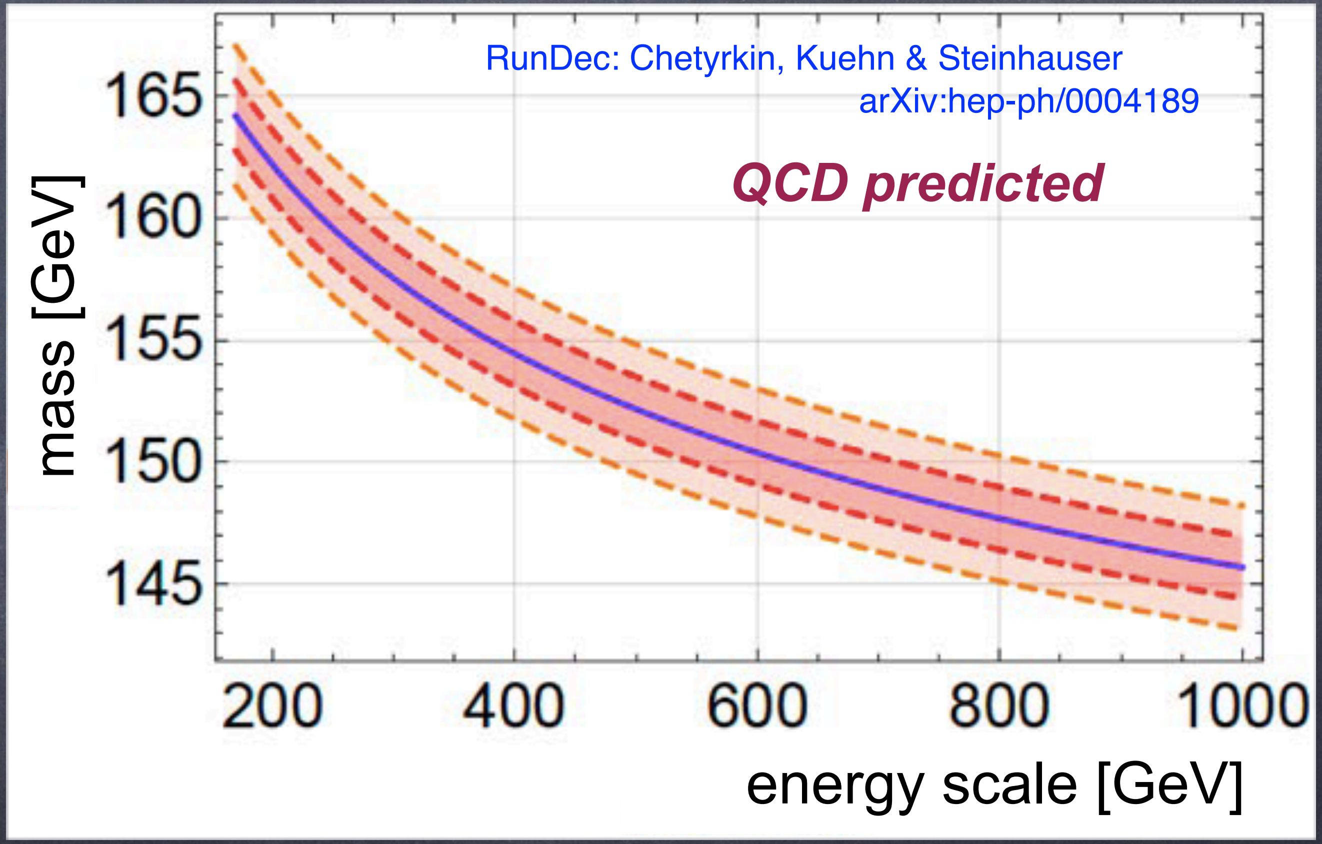
TOP QUARK MASS AND NEW PHYSICS

Running of quark masses demonstrated for charm and beauty quarks

First measurement of the top quark mass running:

Top quark mass





New Physics would modify the running of the top quark mass

TOP QUARK MASS AND NEW PHYSICS

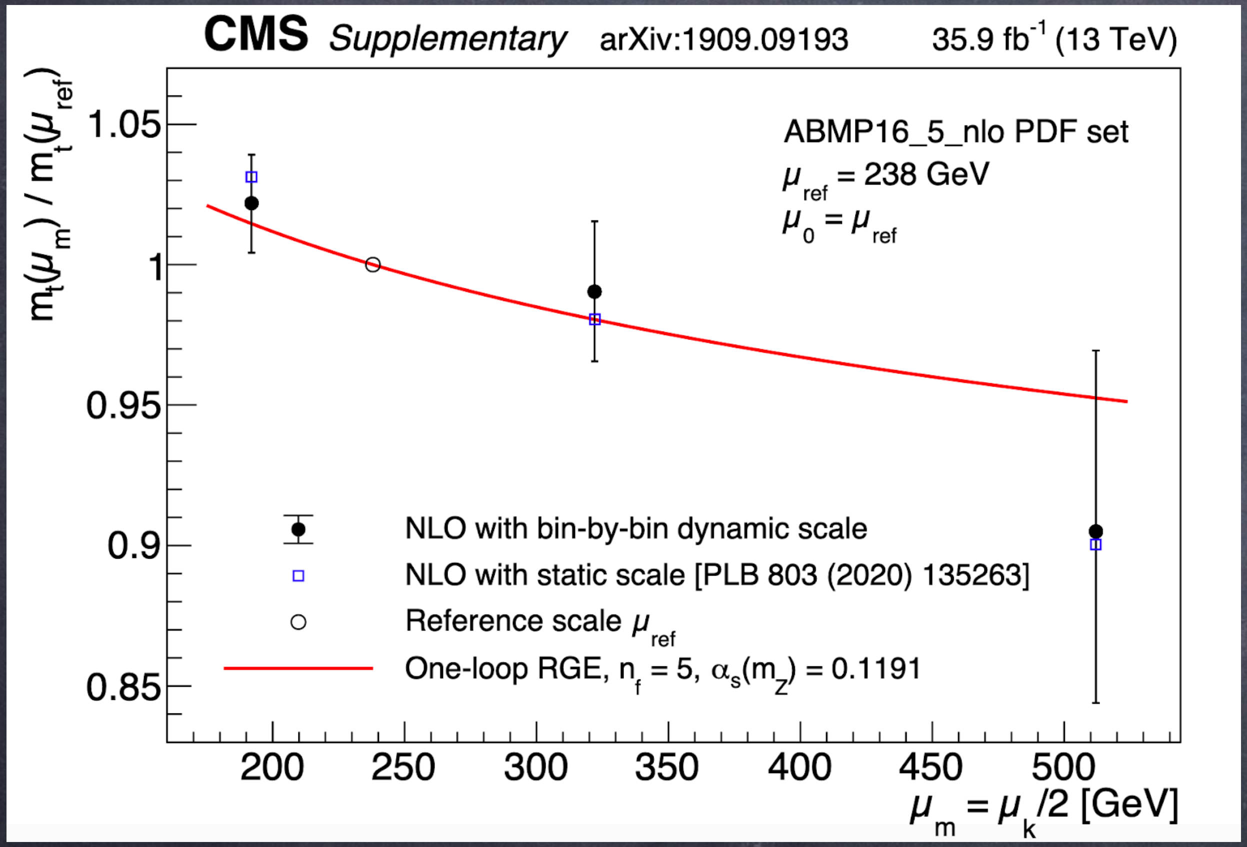
"Toy example" of possible New Physics interpretations:

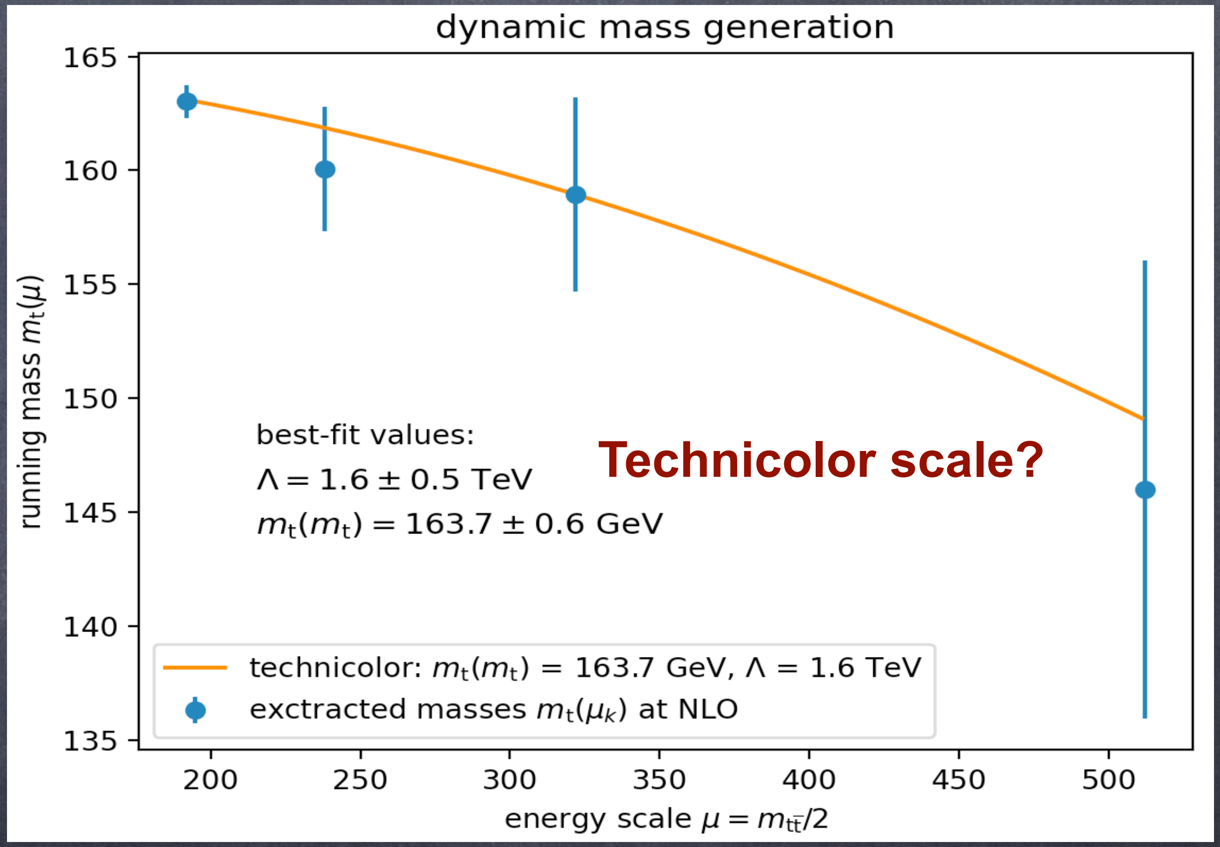
Investigate scenarios where fermion mass is generated dynamically

e.g. [PRL 94 (2005) 241801]

for $\mu \ll \Lambda \qquad m_t(\mu) = m_t(\mu)\dfrac{1-(m_t/\Lambda)^2}{1-(\mu/\Lambda)^2}$

Top quark mass





please don't interpret this as New Physics

Good agreement with QCD?

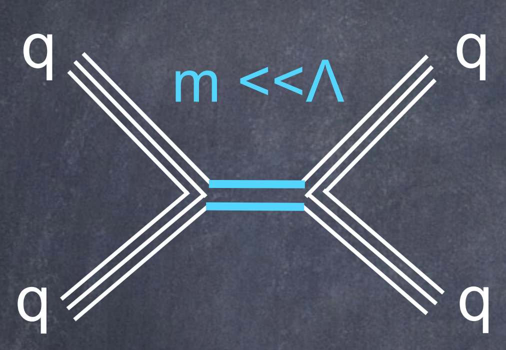
Question of precision in measurement and theory

JETS PROBING NEW PHYSICS

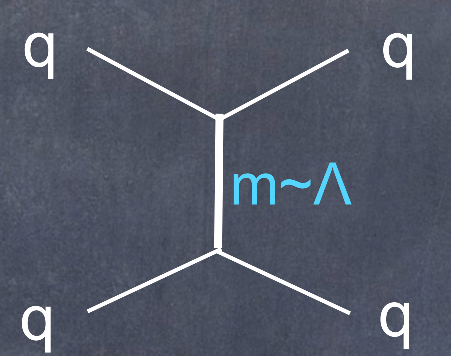
Examples of new phenomena appearing in jet final states:

- Quark compositeness, excited quarks: new interaction at a scale Λ
- New interactions from massive particles exchange

compositeness



new interactions

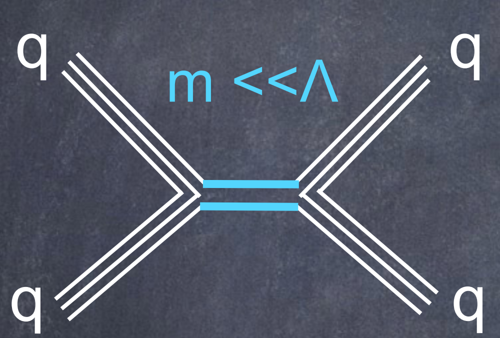


JETS PROBING NEW PHYSICS

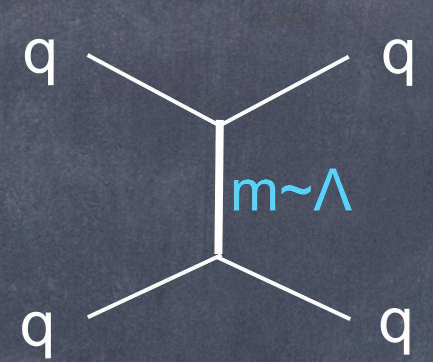
Examples of new phenomena appearing in jet final states:

- Quark compositeness, excited quarks: new interaction at a scale Λ
- New interactions from massive particles exchange

compositeness



new interactions



New Physics effectively modelled as Contact Interaction (CI):

SM+EFT Lagrangian

$$L_{eff} = L_{SM} + \frac{2\pi \cdot c_i}{\Lambda^2} \mathcal{O}_i^{d=6}$$

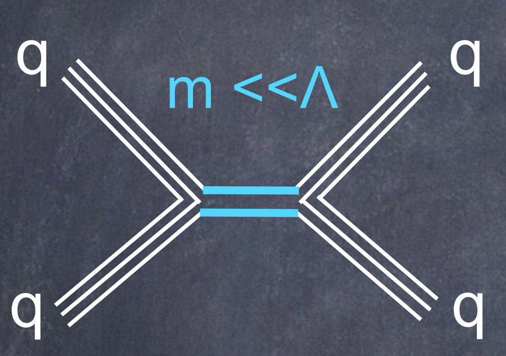
Wilson coefficients

JETS PROBING NEW PHYSICS

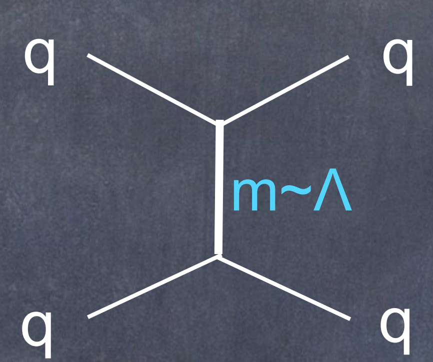
Examples of new phenomena appearing in jet final states:

- Quark compositeness, excited quarks: new interaction at a scale Λ
- New interactions from massive particles exchange

compositeness



new interactions



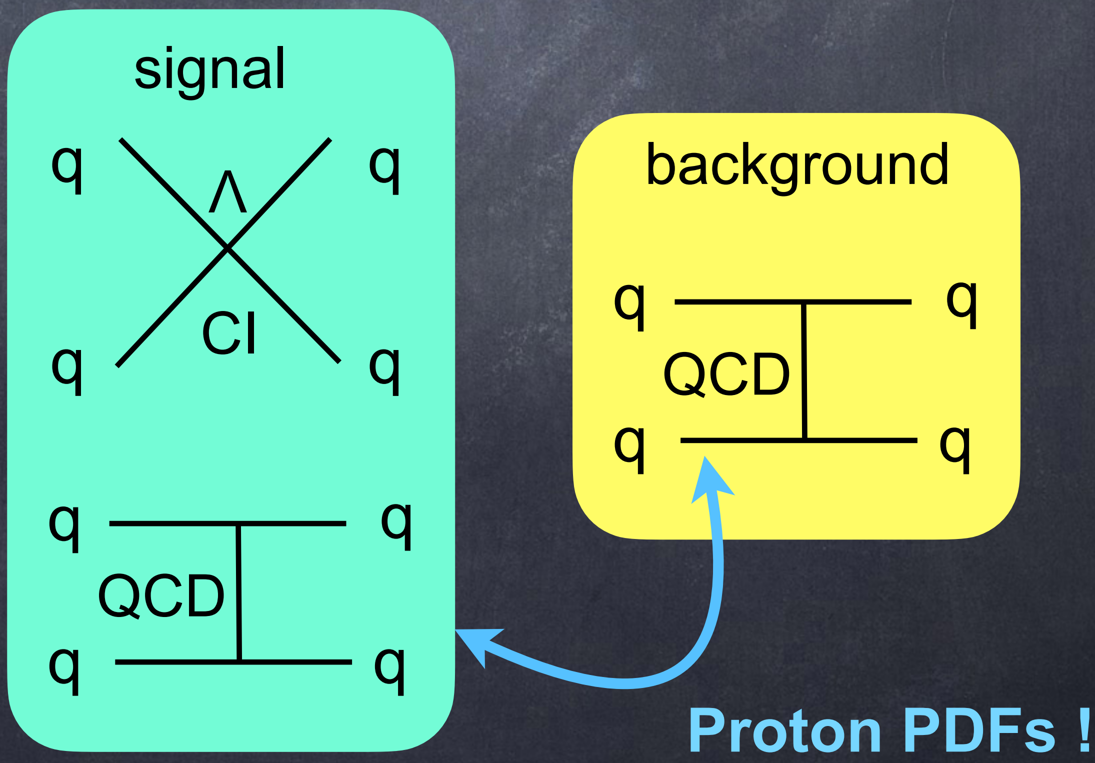
New Physics effectively modelled as Contact Interaction (CI):

SM+EFT Lagrangian

$$L_{eff} = L_{SM} + \frac{2\pi \cdot c_i}{\Lambda^2} \mathcal{O}_i^{d=6}$$

Wilson coefficients

expect new phenomena to appear: deviations of jet kinematics spectra from the SM expectation

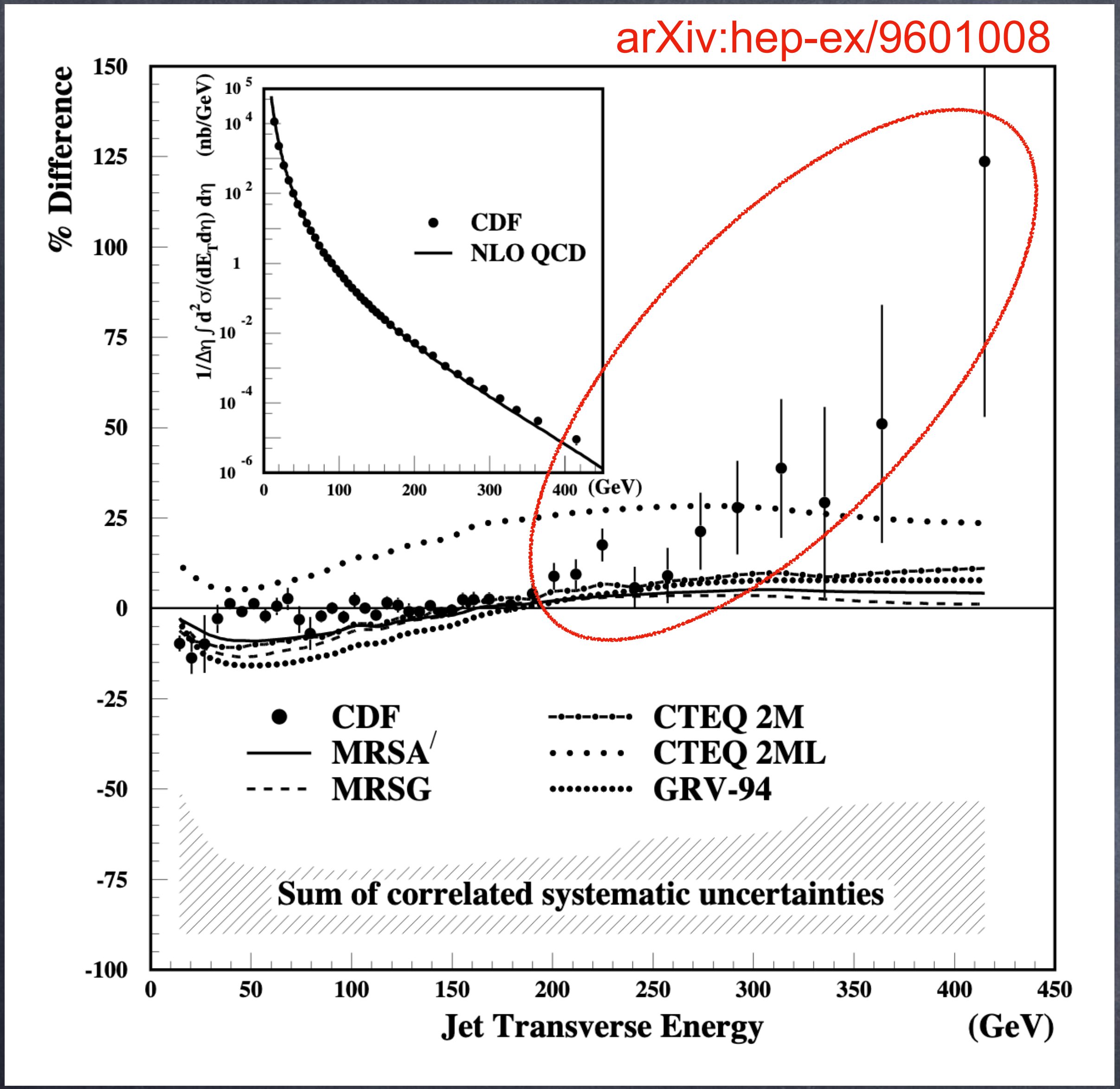


challenge: separate signal/background

disadvantage: rely on QCD precision

MIND THE BIAS DUE TO PDFs!

CDF Run I ($\sqrt{s} = 1.8$ TeV)

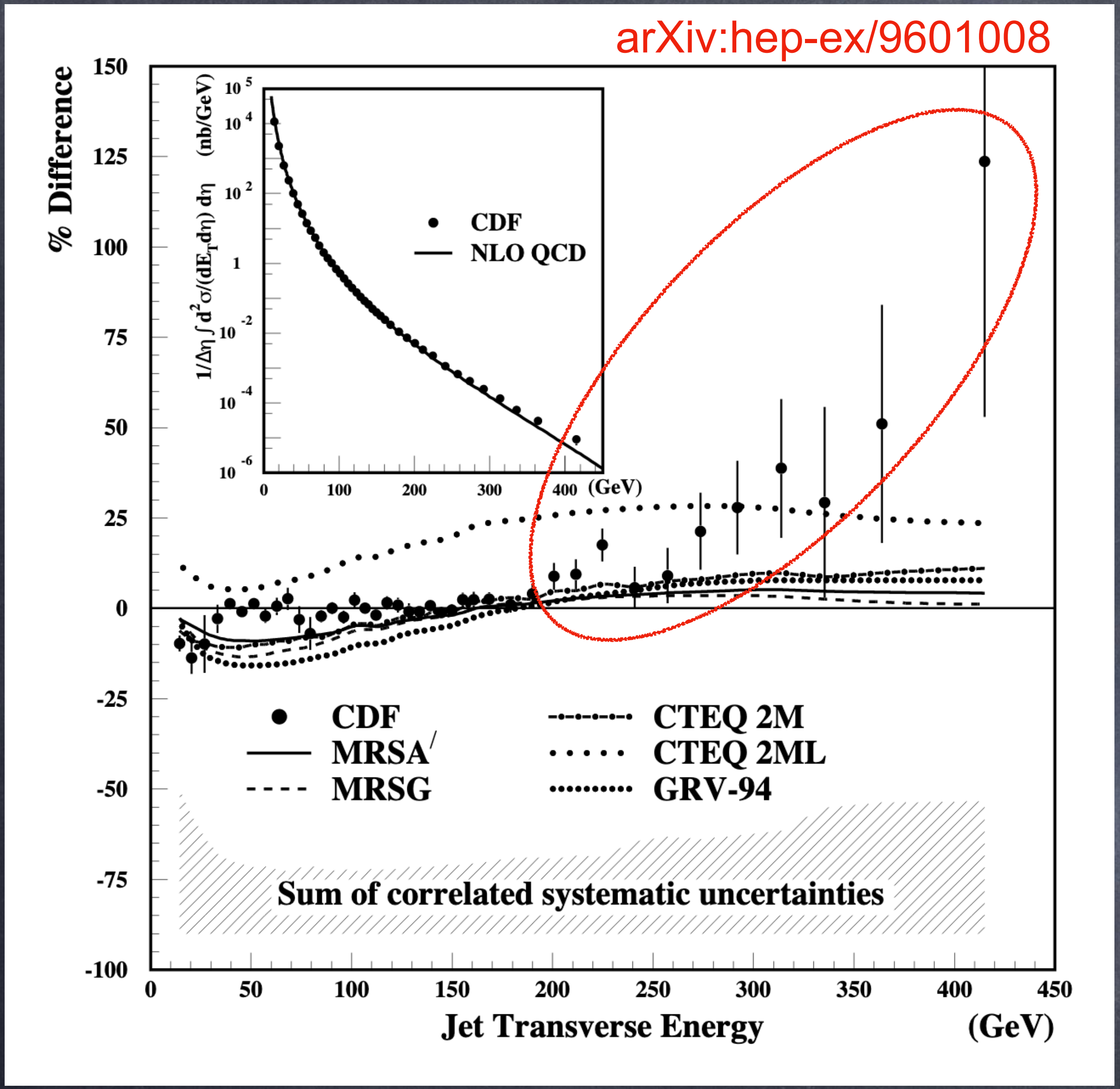


data >> theory at high scale

new physics found ?

MIND THE BIAS DUE TO PDFs!

CDF Run I ($\sqrt{s} = 1.8$ TeV)

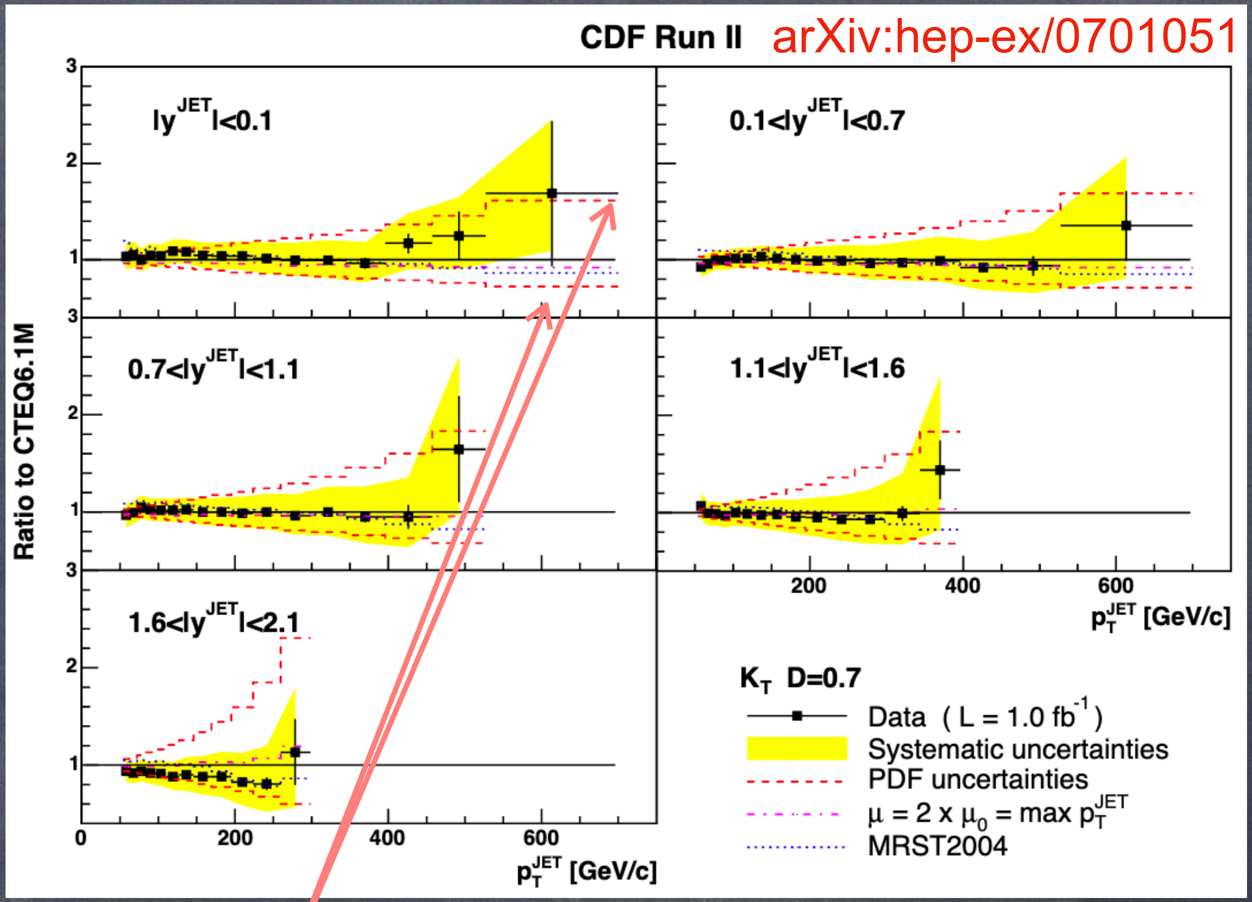


data >> theory at high scale

new physics found ?

CDF Run II ($\sqrt{s} = 1.96$ TeV):

...now considering PDF uncertainties



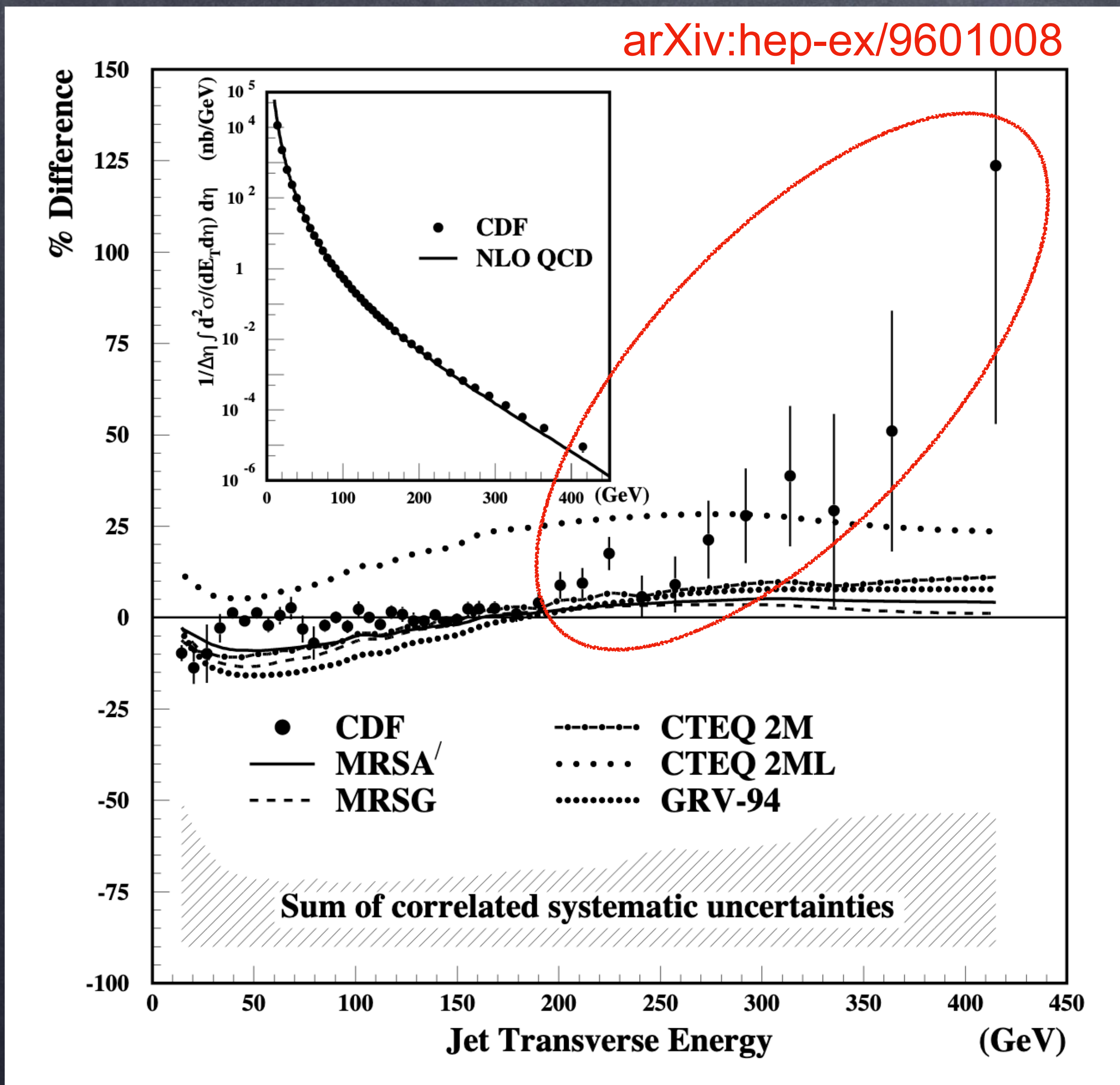
large uncertainty in the theory prediction

(due to error in the gluon distribution)

→ no new physics, just accuracy of QCD

MIND THE BIAS DUE TO PDFs!

CDF Run I ($\sqrt{s} = 1.8$ TeV)

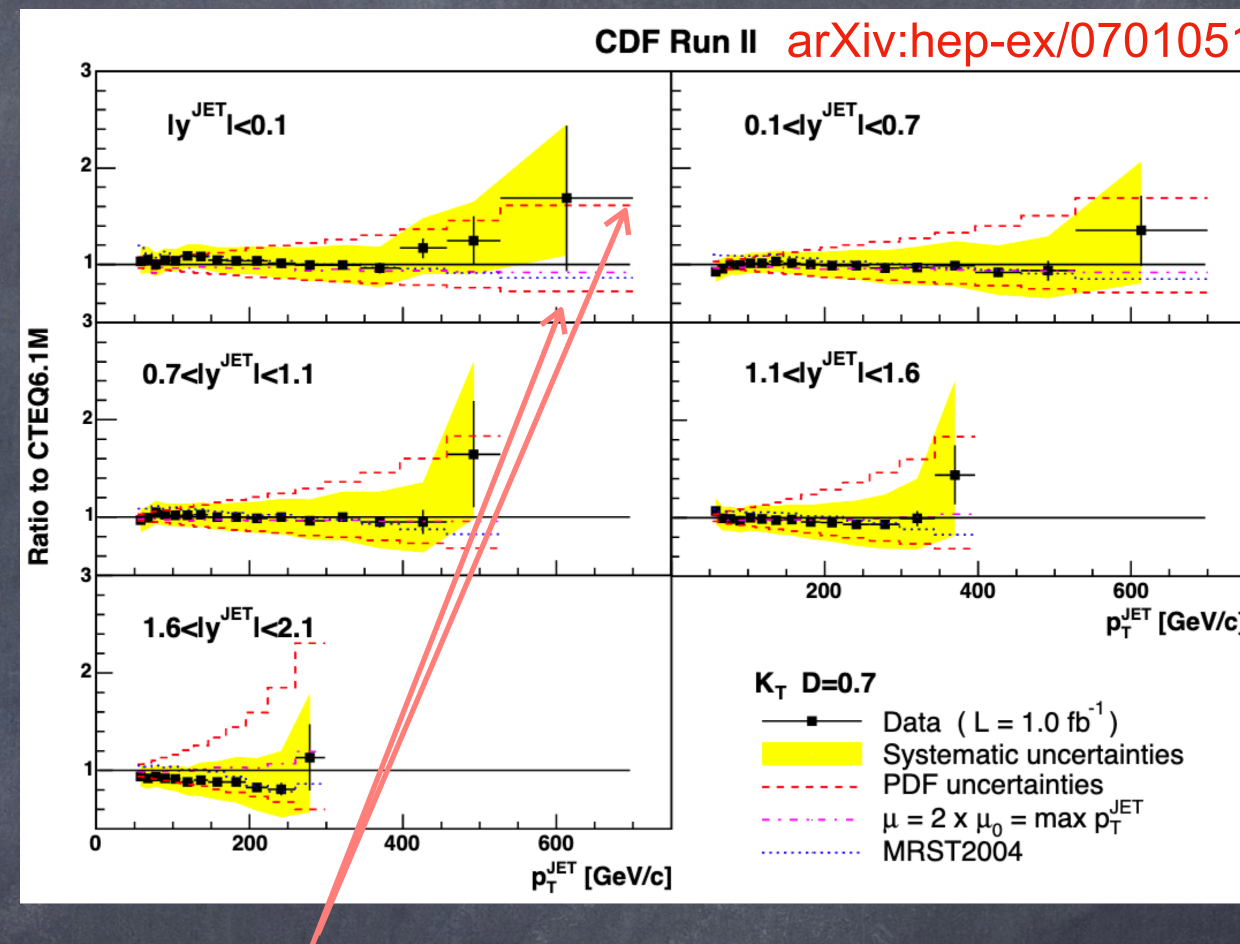


data >> theory at high scale

new physics found ?

CDF Run II ($\sqrt{s} = 1.96$ TeV):

...now considering PDF uncertainties



large uncertainty in the theory prediction

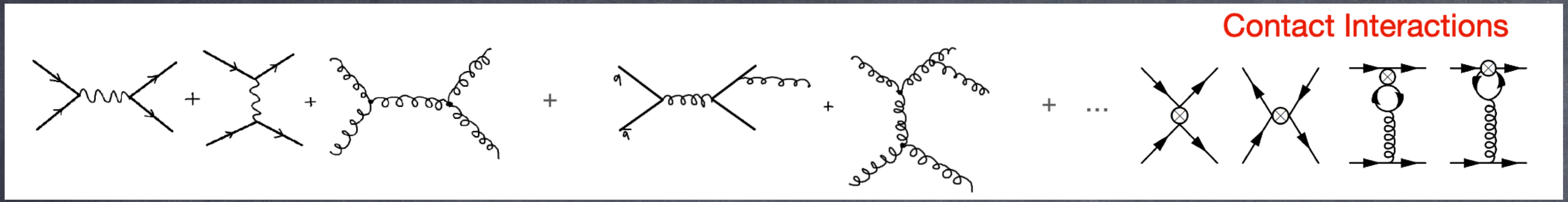
(due to error in the gluon distribution)

→ no new physics, just accuracy of QCD

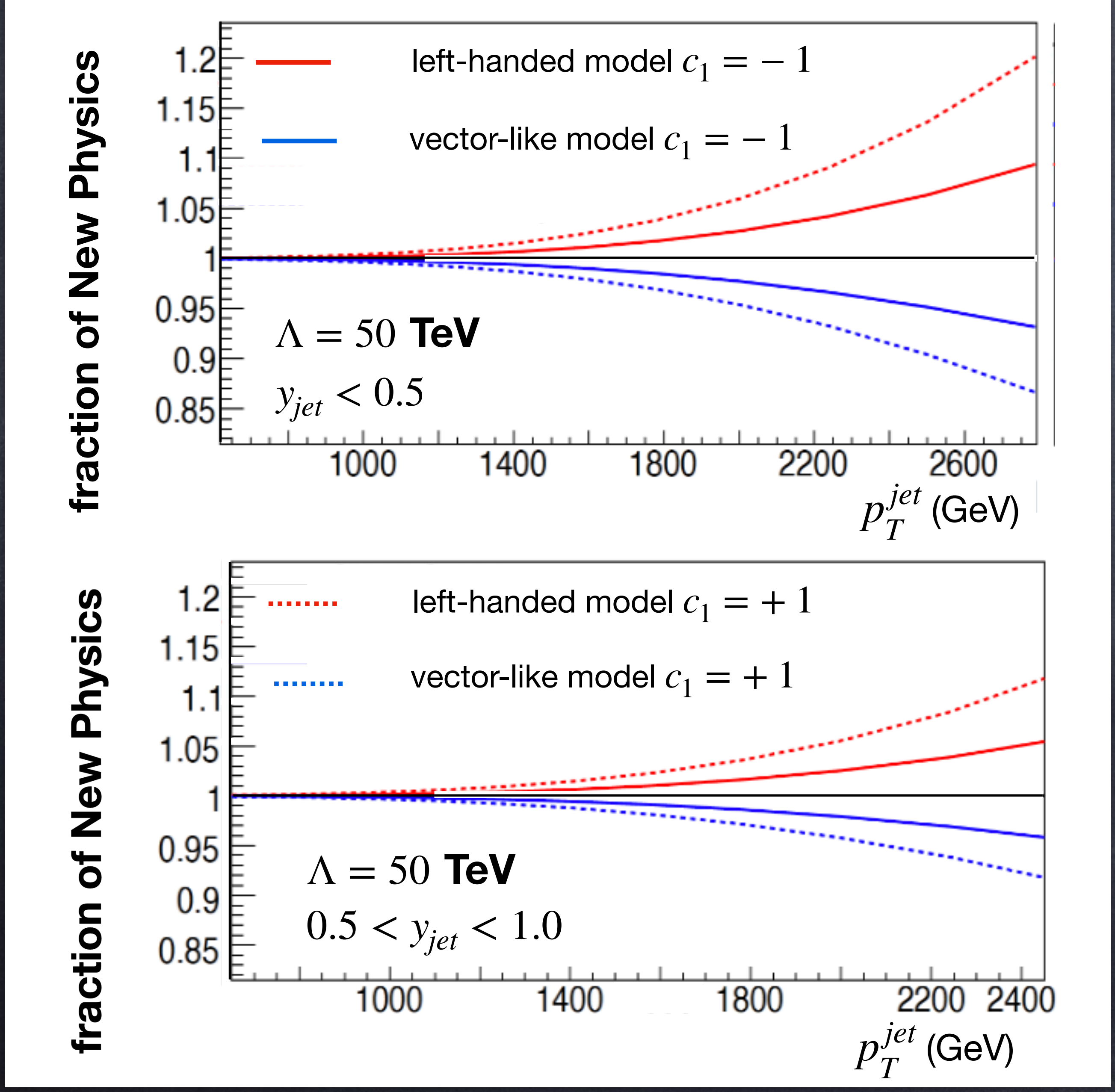
Conceptual problem - bias due to using the same data for PDF extraction :

high-p_T jet production constraints best the gluon distribution at high x

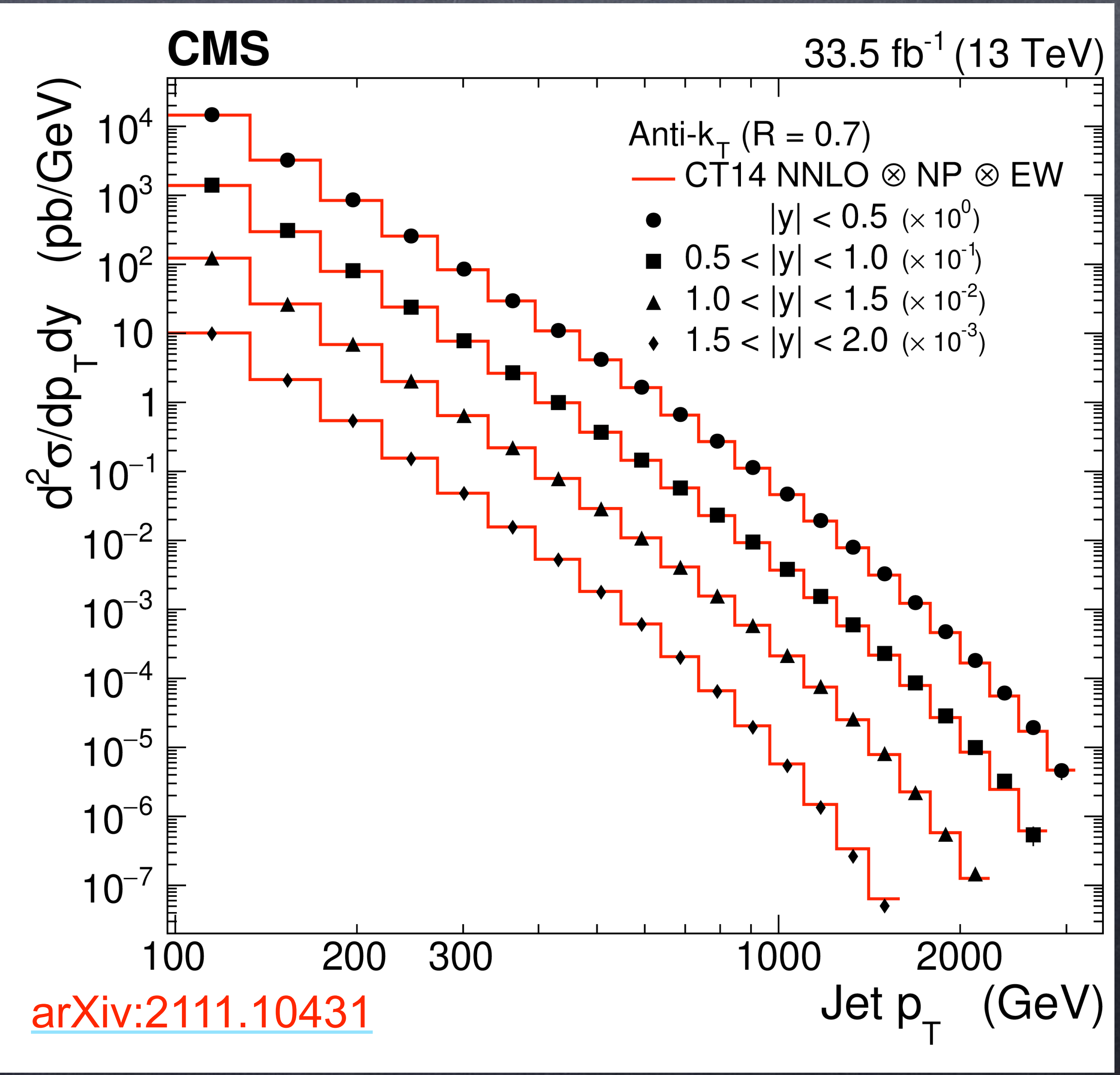
JET PRODUCTION AT LHC: PROBE OF SM + CI



CI expected to show up at high p_T and central y:



Use inclusive jet production at 13 TeV to constrain SM + EFT



arXiv:2111.10431

SMEFT - ALL AT ONCE: PDF + α_s + m_t + CI

- **SMEFT fit @ NLO:** basic data - ep inclusive DIS cross sections (HERA) [arXiv:1506.06042]

  + CMS inclusive jets at 13 TeV [arXiv:2111.10431]

  + CMS 3-D $t\bar{t}$ cross sections [arXiv:1904.05237]

- **jet x-section predictions: QCD NLO+NLL + EFT 4-quark CI (3 models tested)**

SMEFT - ALL AT ONCE: PDF + α_s + m_t + CI

- **SMEFT fit @ NLO:** basic data - *ep* inclusive DIS cross sections (HERA) [arXiv:1506.06042]
  + CMS inclusive jets at 13 TeV [arXiv:2111.10431]
  + CMS 3-D $t\bar{t}$ cross sections [arXiv:1904.05237]:
- **jet x-section predictions: QCD NLO+NLL + EFT 4-quark CI (3 models tested)**

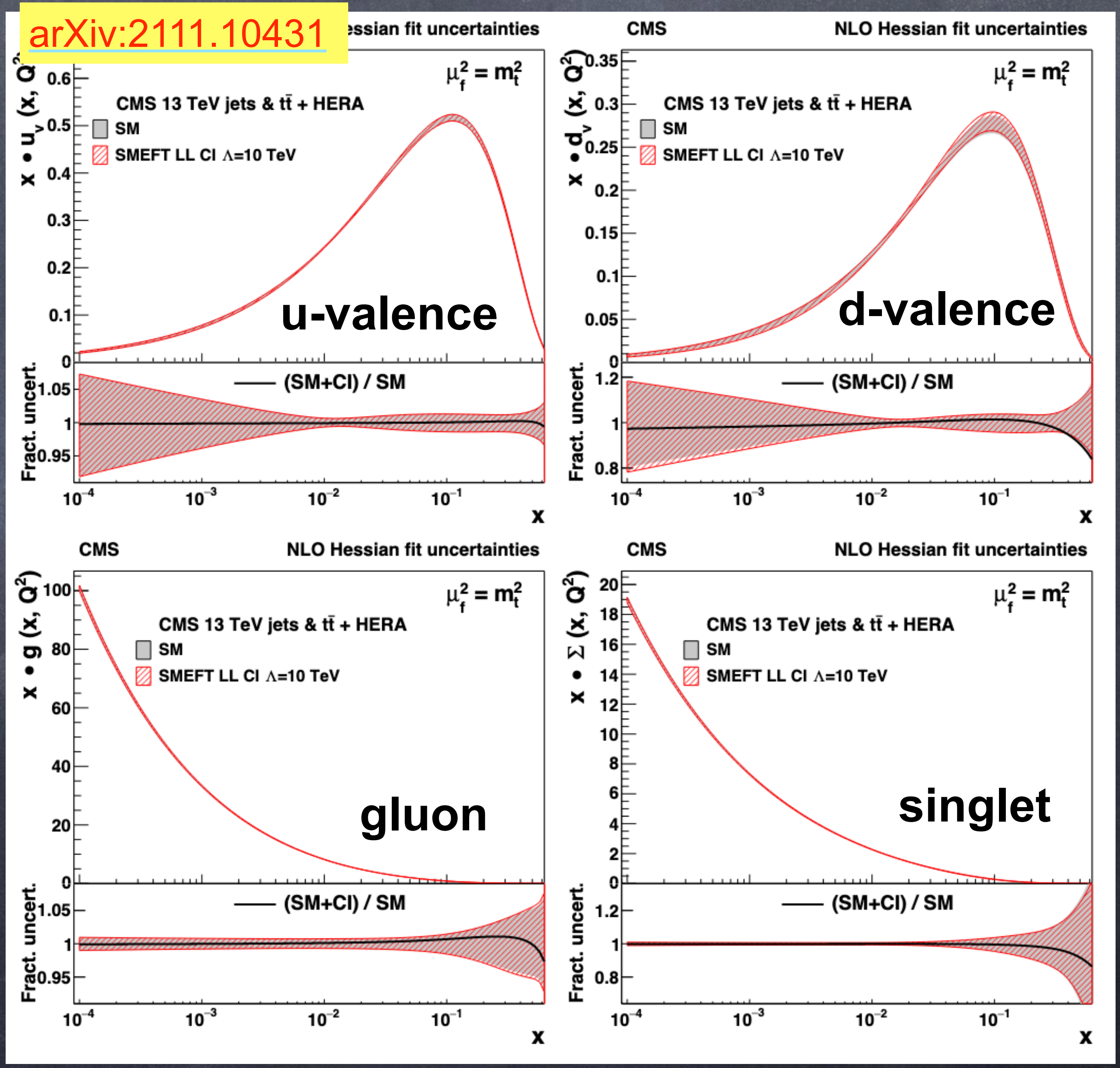
- **QCD parameters (NLO):**

$$\alpha_S(m_Z) = 0.1187 \pm 0.0033$$

NB: in agreement with WA

$$m_t^{pole} = 170.4 \pm 0.7 \text{ GeV}$$

NB: the most precise!



SMEFT - ALL AT ONCE: PDF + α_s + m_t + CI

- **SMEFT fit @ NLO:** basic data - *ep* inclusive DIS cross sections (HERA) [arXiv:1506.06042]
  + CMS inclusive jets at 13 TeV [arXiv:2111.10431]
  + CMS 3-D $t\bar{t}$ cross sections [arXiv:1904.05237]:
- **jet x-section predictions: QCD NLO+NLL + EFT 4-quark CI (3 models tested)**

- **QCD parameters (NLO):**

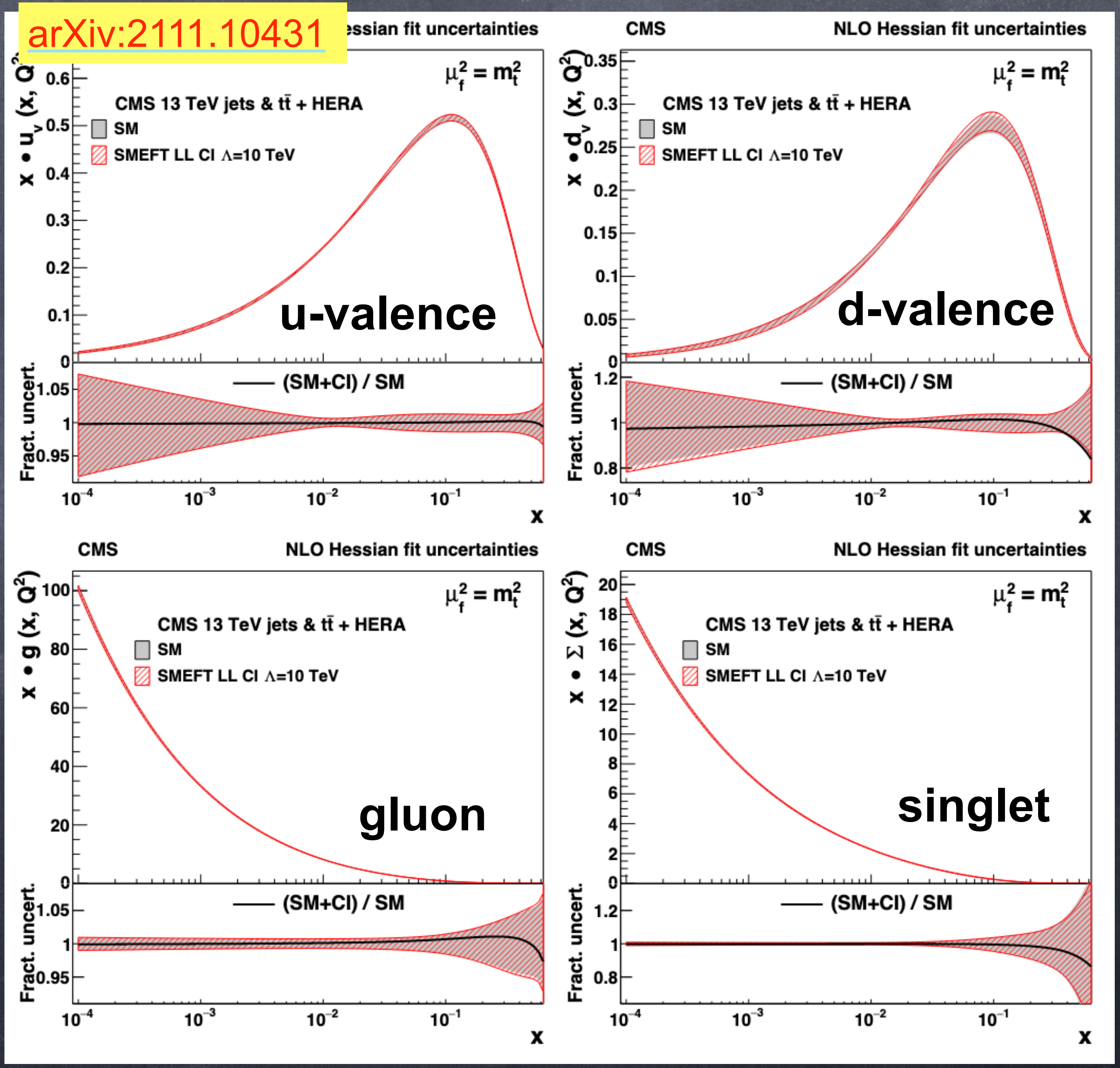
$$\alpha_S(m_Z) = 0.1187 \pm 0.0033$$

$$m_t^{pole} = 170.4 \pm 0.7 \text{ GeV}$$

- **CI parameters ($\Lambda = 10$ TeV):**

$$c_1^L = -0.07 \pm 0.02_{exp} \pm 0.01_{mod+par}$$

SM +BSM obtained simultaneously !

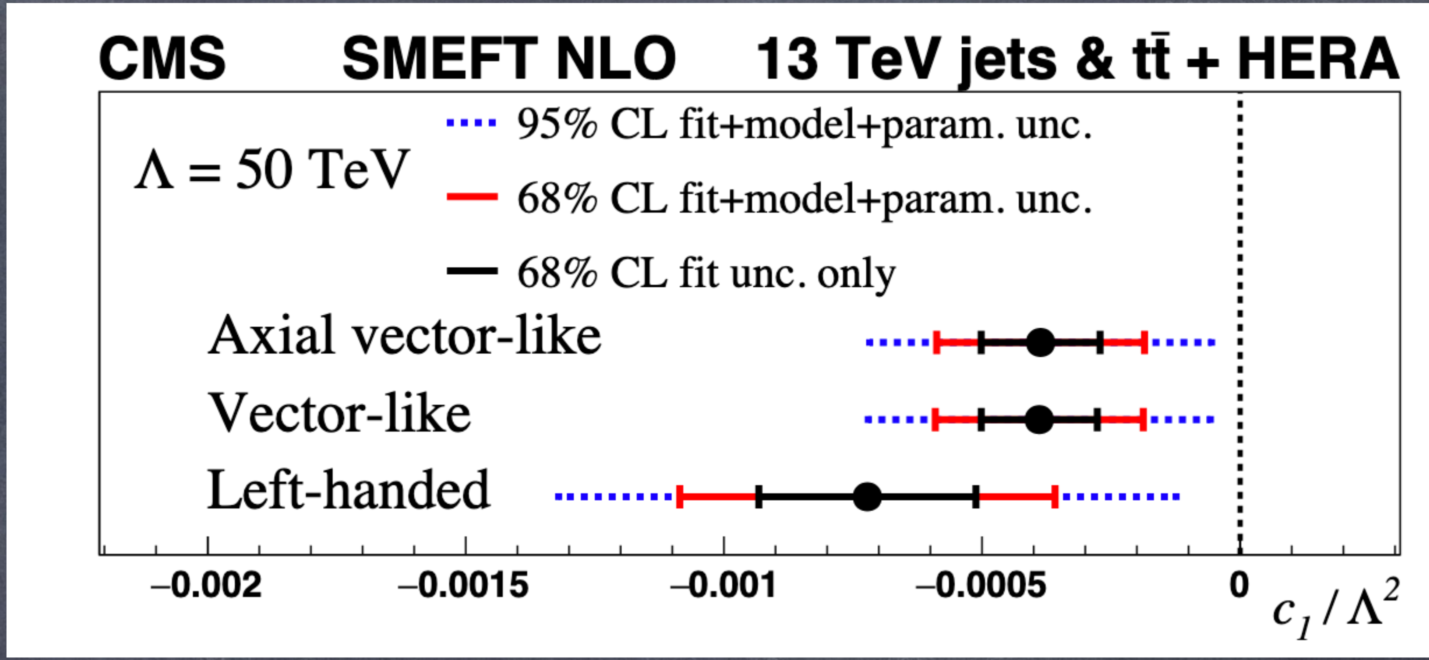


SMEFT - ALL AT ONCE: PDF + α_s + m_t + CI

- **SMEFT fit @ NLO:** basic data - ep inclusive DIS cross sections (HERA) [arXiv:1506.06042]
  + CMS inclusive jets at 13 TeV [arXiv:2111.10431]
  + CMS 3-D $t\bar{t}$ cross sections [arXiv:1904.05237]:
- **jet x-section predictions: QCD NLO+NLL + EFT 4-quark CI (3 models tested)**
- **QCD parameters (NLO):**

$$\alpha_S(m_Z) = 0.1187 \pm 0.0033$$

$$m_t^{pole} = 170.4 \pm 0.7 \text{ GeV}$$



- **CI parameters ($\Lambda = 10$ TeV):**

$$c_1^L = -0.07 \pm 0.02_{exp} \pm 0.01_{mod+par}$$

correspond to 95% exclusion limits for Λ ($c_1 = -1$):

LL : $\Lambda > 24$ **TeV** ATLAS [arXiv:1703.09127]: > 22 TeV

V: $\Lambda > 32$ **TeV**

AV: $\Lambda > 31$ **TeV**

SM +BSM
obtained simultaneously !

SUMMARY

- LHC remains a QCD machine : proton structure does matter
- Precision of the QCD parameters and PDFs defines LHC discovery potential
- Top quark and Jet production best instruments to test Standard Model
- … and pave the way towards global interpretation in terms of New Physics

THANKS FOR LISTENING !