Parton Distribution Functions

for beginners

KAROL KOVAŘÍK

INSTITUT FÜR THEORETISCHE PHYSIK
WESTFÄLISCHE WILHELMS-UNIVERSITÄT
MÜNSTER

Westfälische
Wilhelms-Universität
Münster

Lecture 2

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Recap of Lecture 1

- *Parton Distribution Functions - parameterisation @ initial scale (DGLAP initial condition)*

CTEQ 6
hep-ph/0201195

$$x\, f_k(x, Q_0) = c_0\, x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4} x)^{c_5} \qquad k = u_v, d_v, g, \bar{u} + \bar{d}$$

$$\bar{d}(x, Q_0)/\bar{u}(x, Q_0) = c_0\, x^{c_1} (1-x)^{c_2} + (1 + c_3 x)(1-x)^{c_4}$$

$$s = \bar{s} = 0.2\,(\bar{u} + \bar{d}) \qquad c(x, Q_0^2) = b(x, Q_0^2) = 0$$

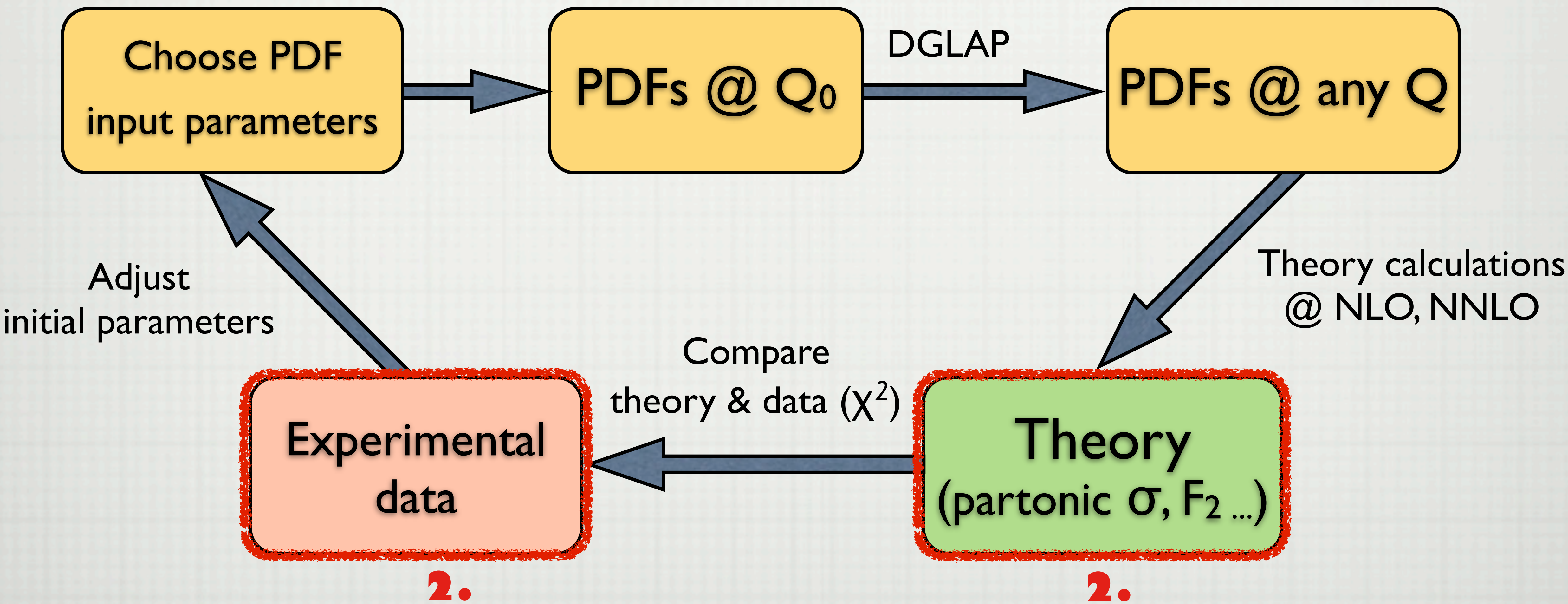
- *Parton Distribution Functions - Q dependance & evolution (DGLAP)*
  - all contributions together mix different PDF via DGLAP equations

$$\frac{d\, f_q(x, Q^2)}{d \log Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{\mathrm{d}\xi}{\xi} \left[P_{qq}\left(\frac{x}{\xi}\right) f_q(\xi, Q^2) + P_{qg}\left(\frac{x}{\xi}\right) f_g(\xi, Q^2) \right]$$

$$\frac{d\, f_g(x, Q^2)}{d \log Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{\mathrm{d}\xi}{\xi} \left[P_{gg}\left(\frac{x}{\xi}\right) f_g(\xi, Q^2) + P_{gq}\left(\frac{x}{\xi}\right) f_q(\xi, Q^2) \right]$$

Fitting PDF

- *Parton Distribution Functions*
    - how do we determine them ? What are the moving parts in a typical PDF fitting-machine ?



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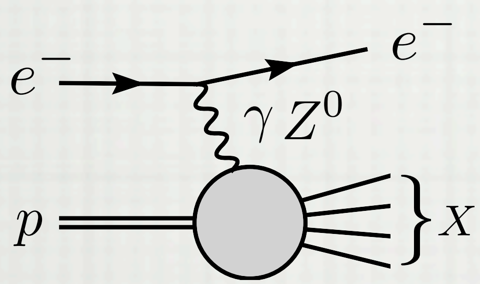
Fitting PDF

- *Parton Distribution Functions - experimental data & theory*
  - which data are included in a fit ? Which PDFs do they constrain ?
  - kinematic cuts on data
  - difference between global fits like CTEQ, MSTW, NNPDF and not so global HERApdf, ABM...

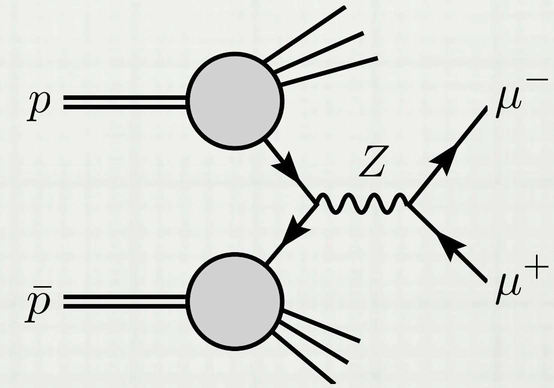
☑ *Neutral current DIS*

(HERA, SLAC, NMC, BCDMS)



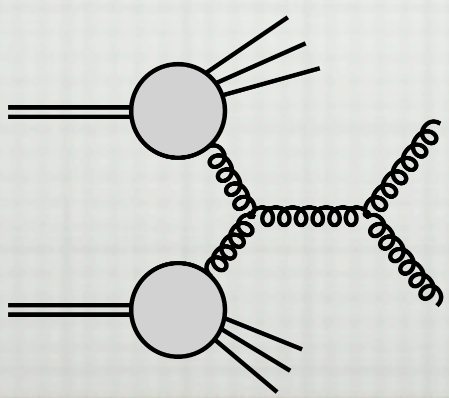
☑ *DY data (W,Z production) from Tevatron & LHC*

(E602, E866, D0, CDF, ATLAS, CMS)



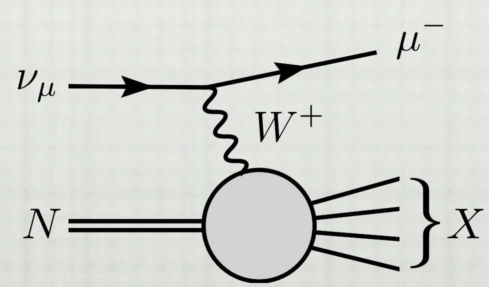
☑ *Jet data from Tevatron & LHC*

(D0,CDF, ATLAS, CMS)



☑ *Neutrino DIS & di-muon*

(CDHSW, CHORUS,NuTeV)

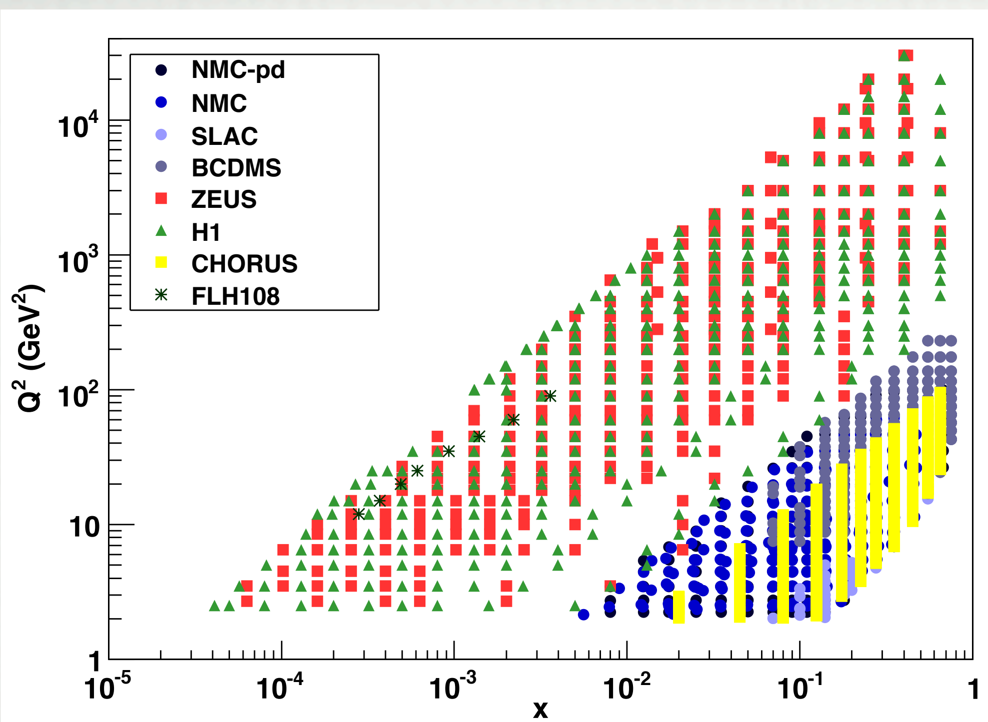


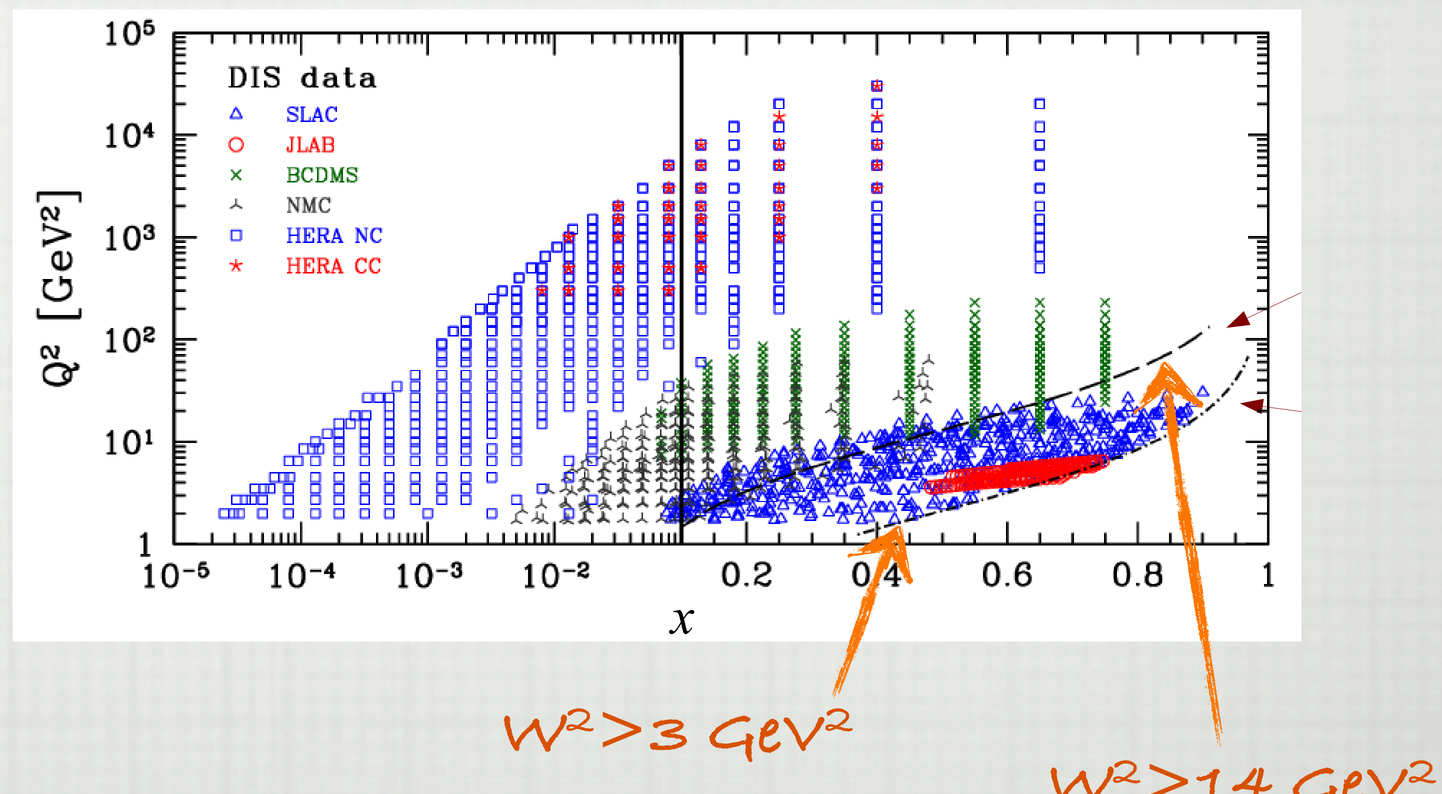
Fitting PDF

- *DIS data from HERA & fixed target experiments (SLAC,NMC,BCDMS)*
  - different observables used in the fit (HERA - $\frac{d\sigma}{dxdy}$, fixed target - $F_2(x, Q^2)$)

$$\frac{d\sigma}{dx\, dQ^2} \;=\; \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2 - y^2F_L \pm Y_-xF_3\right]\;,$$

  - motivation to still use fixed target is different coverage in x-Q^2 plane & sensitivity to large-x





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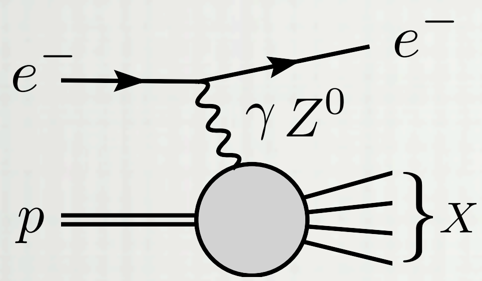
☑ *DIS data from HERA & fixed target experiments (SLAC,NMC,BCDMS)*



- DIS @ low Q - dominated by photon exchange
- DIS @ high Q - dominated by photon-Z interference

$$F_{1,2} = F_{1,2}^{\gamma\gamma} + \frac{2g_V}{4s_W^2 c_W^2}\frac{Q^2}{Q^2+M_Z^2}F_{1,2}^{\gamma Z} + \frac{g_V^2+a_V^2}{16 s_W^4 c_W^4}\frac{Q^4}{(Q^2+M_Z^2)^2}F_{1,2}^{ZZ}$$

$$F_3 = \frac{2a_V}{4s_W^2 c_W^2}\frac{Q^2}{Q^2+M_Z^2}F_3^{\gamma Z} + \frac{2g_V a_V}{16 s_W^4 c_W^4}\frac{Q^4}{(Q^2+M_Z^2)^2}F_3^{ZZ}\,,$$

sensitive to quark & anti-quark PDF @ LO

- quarks & anti-quarks enter together with different weights depending on the exchange vector boson
- access interference comparing different helicity leptons & electrons/positrons

$$F_2^{\gamma\gamma}(x,Q^2) = x\sum_q e_q^2\left[q(x,Q^2)+\bar{q}(x,Q^2)\right] \qquad \text{photon}$$

NC DIS

$$F_2^{\gamma Z}(x,Q^2) = x\sum_i B_i\left[q_i(x,Q^2)+\bar{q}_i(x,Q^2)\right] \qquad \text{photon-Z interference}$$

$$xF_3^{\gamma Z}(x,Q^2) = x\sum_i D_i\left[q_i(x,Q^2)-\bar{q}_i(x,Q^2)\right] \qquad \text{photon-Z interference}$$

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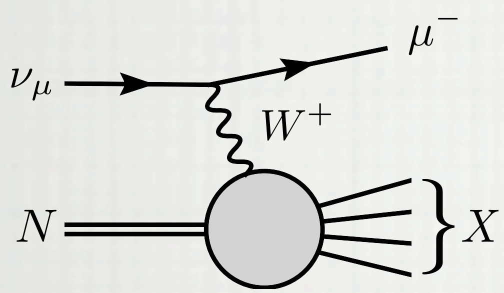
Neutrino DIS & di-muon (CDHSW, CHORUS,NuTeV)



- neutrino DIS contributes to $F_2(x, Q^2)$ and $F_3(x, Q^2)$
- different PDF combinations contribute to flavor separation together with NC DIS

$$F_2(x, Q^2) = x \sum_q \left[q(x, Q^2) + \bar{q}(x, Q^2) \right]$$

$$xF_3(x, Q^2) = x \sum_q \left[q(x, Q^2) - \bar{q}(x, Q^2) \right]$$

- neutrino DIS data on protons are scarce and hard to come by (WA21/22)
- neutrino DIS typically taken on nuclei - need for nuclear corrections

Charge current DIS on proton (HERA)

- neutrino DIS can be replaced by CC DIS on protons (still experimentally challenging)

$$F_2^{W^\pm}(x, Q^2) = x(\bar{u} \pm d \pm s + \bar{c})$$

Fitting PDF

☑ *DIS @ NLO*

sensitive to gluon PDF @ NLO

- breaking of Bjorken scaling at small x driven by gluon PDF

$$Q^2 \frac{\mathrm{d}F_2}{\mathrm{d}Q^2} = \frac{\alpha_S}{2\pi} \sum e_i^2 \int_x^1 \frac{\mathrm{d}y}{y} P_{qg}(y) f_g(x/y, Q^2)$$

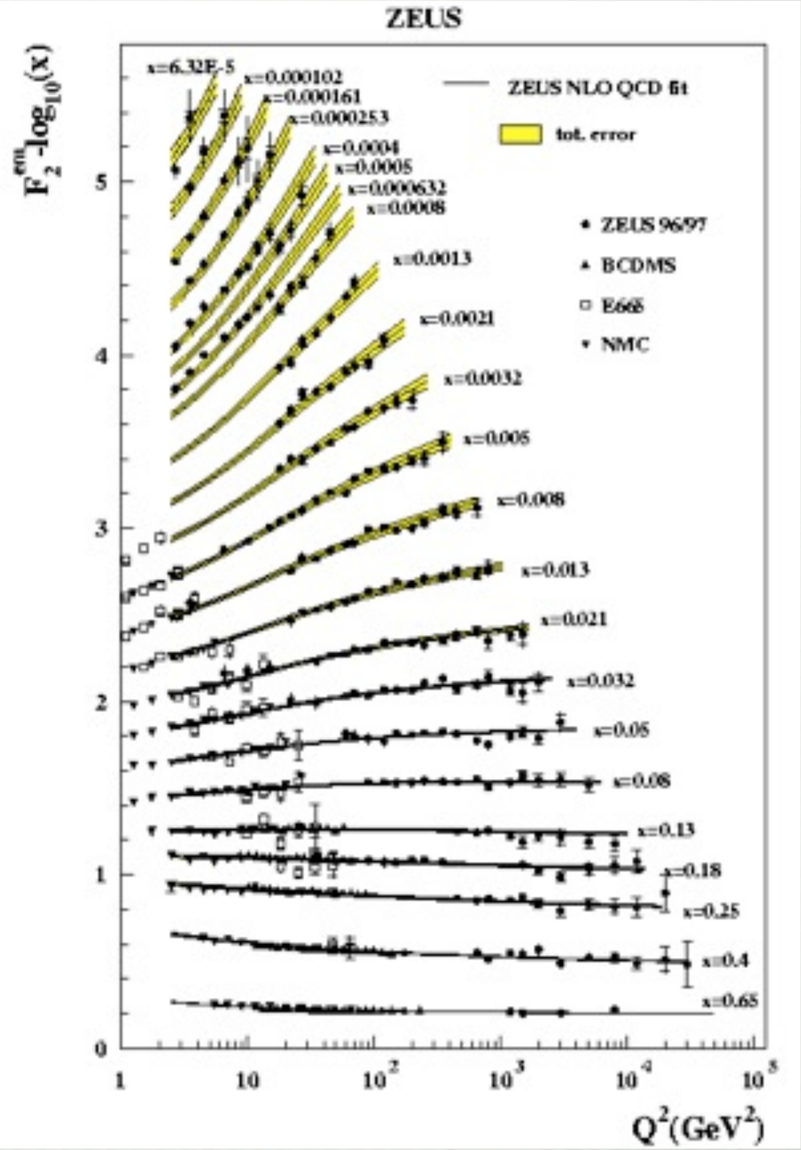
- longitudinal structure function $F_L(x, Q^2)$

$$F_L(x, Q^2) = F_2(x, Q^2) - 2xF_1(x, Q^2) = 0$$

Callan-Gross relation @ LO

  - gluon not subdominant in $F_L(x, Q^2)$ as in $F_2(x, Q^2)$
  - experimental separation of $F_2(x, Q^2)$ and $F_L(x, Q^2)$ requires measurements at different $\sqrt{s}$ - lower statistics

- using differential cross-section in the fit - effective separation of structure functions



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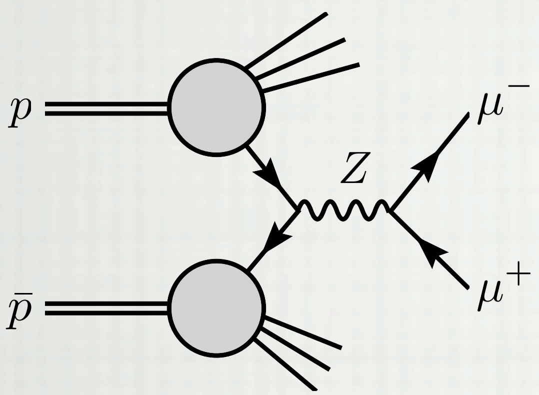
Fitting PDF

☑ *Drell-Yan lepton pair production (W,Z production)*



- DY dominated by photon exchange away from W & Z resonances

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2\mathrm{d}y} = \frac{4\pi\alpha^2}{9Q^2 s}\sum_i e_i^2\left[q_i(x_a,Q^2)\bar{q}_i(x_b,Q^2) + a \leftrightarrow b\right]$$

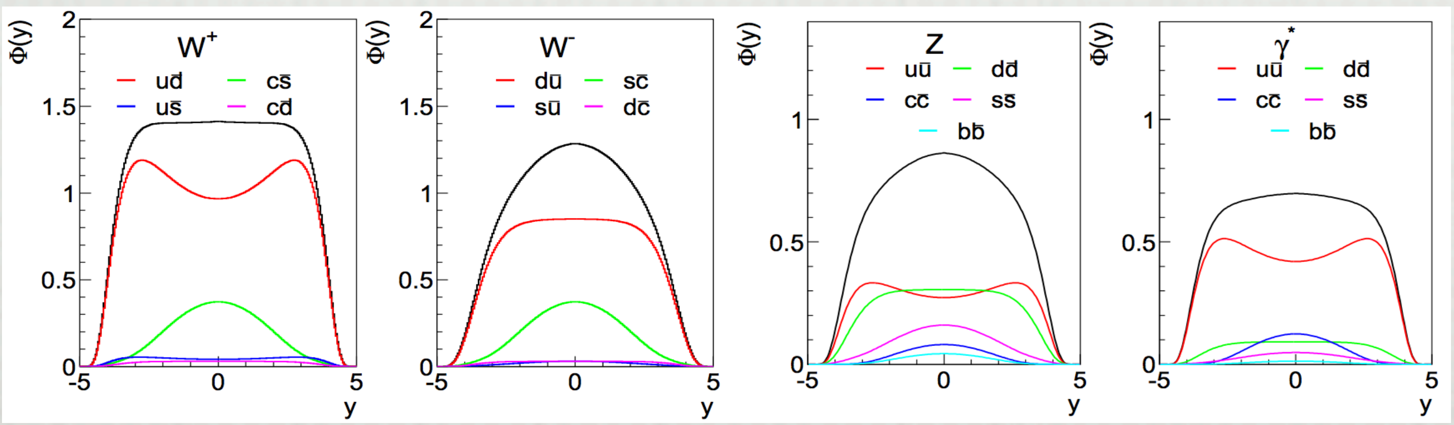
$$Q^2 = (p_l + p_{\bar{l}})^2 \qquad x_{a,b} = \frac{Q}{\sqrt{s}}\exp(\pm y)$$

- DY at the W & Z resonances - different PDF combinations

$$\frac{\mathrm{d}\sigma^W}{\mathrm{d}y} = \frac{\sqrt{2}\pi G_F m_W^2}{3s}\sum_{i,j}|V_{ij}^{\mathrm{CKM}}|\left[q_i(x_a,Q^2)\bar{q}_j(x_b,Q^2) + a \leftrightarrow b\right]$$

$$\frac{\mathrm{d}\sigma^Z}{\mathrm{d}y} = \frac{\sqrt{2}\pi G_F m_Z^2}{3s}\sum_i (V_i^2 + A_i^2)\left[q_i(x_a,Q^2)\bar{q}_i(x_b,Q^2) + a \leftrightarrow b\right]$$

- DY helps better determine (anti-)quark PDFs



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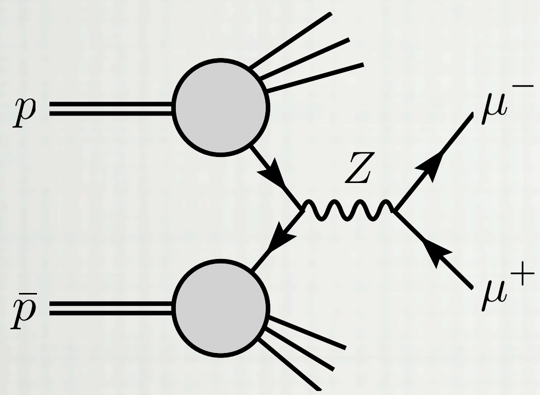
Fitting PDF

☑ *Drell-Yan lepton pair production (W,Z production)*



- different asymmetries & ratios sensitive to different combinations of PDFs

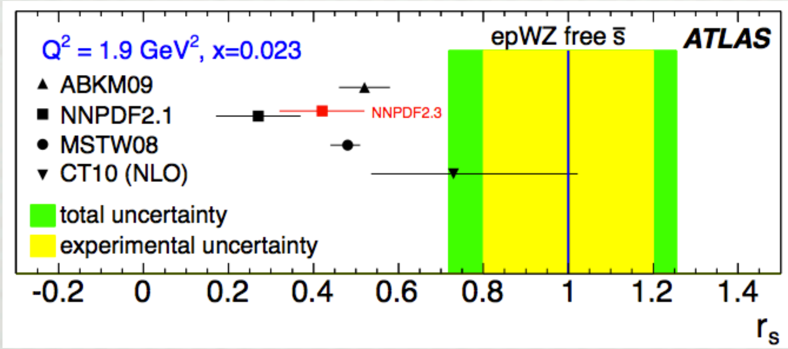
$$\frac{\sigma_{W^+} - \sigma_{W^-}}{\sigma_{W^+} + \sigma_{W^-}} \sim \frac{u_v(x_1) - d_v(x_1)}{u(x_1) + d(x_1)} \qquad \frac{\sigma_{W^+}}{\sigma_{W^-}} \sim \frac{u(x_1)\bar{d}(x_2)}{d(x_1)\bar{u}(x_2)} \sim \frac{u(x_1)}{d(x_1)}$$

$$\frac{\sigma_{W^+} + \sigma_{W^-}}{\sigma_Z} \sim \frac{u(x_1) + d(x_1)}{0.29u(x_1) + 0.37d(x_1)}$$

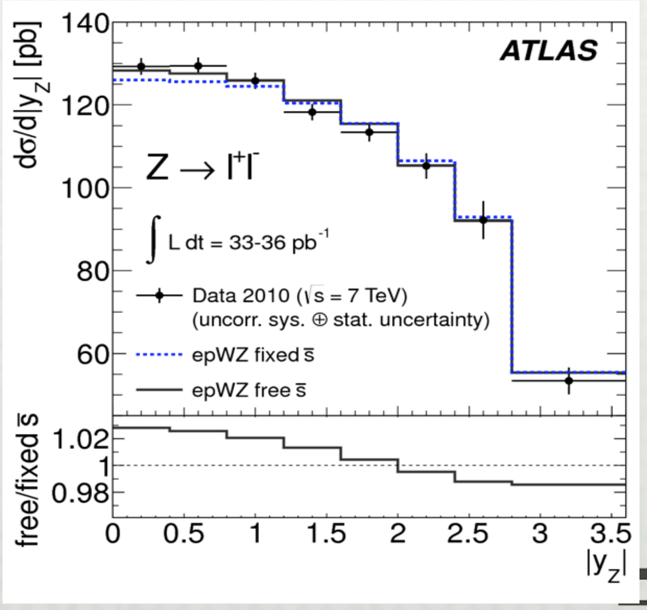
- Z cross-section + rapidity distribution used to extract strange quark PDF

typical assumptions related to strange PDF (motivated by di-muon DIS data)

$$s(x,Q) = \bar{s}(x,Q)$$
$$s(x,Q) = r_s d(x,Q) \qquad r_s \sim 0.75$$



arXiv:1203.4051 [hep-ex]



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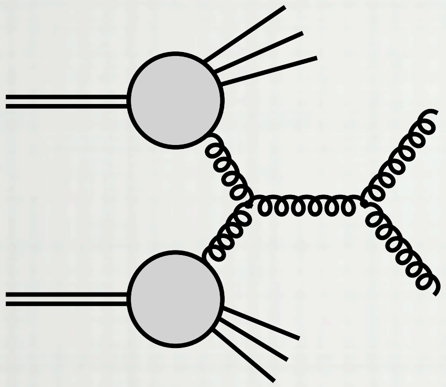
Fitting PDF

☑ *Jet data from Tevatron & LHC (D0, CDF, ATLAS, CMS)*



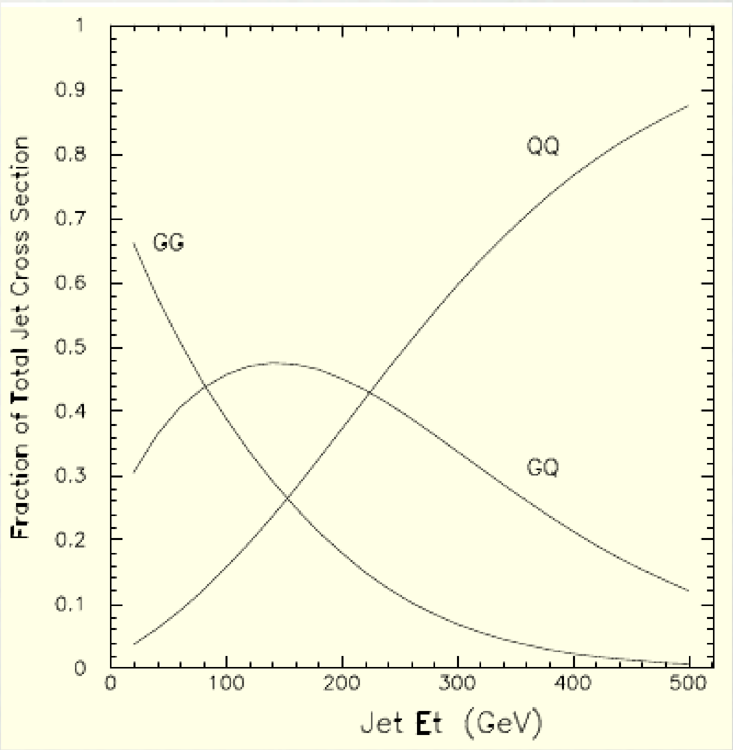
- hadronic jet production at leading order proceeds through

$$qq \rightarrow qq \qquad qg \rightarrow qg \qquad gg \rightarrow gg$$

- qq subprocess dominates high-Et jets but gluon important enough to allow jet data to put constraints on large-x gluon PDF

- combined with low-x constraints on gluon PDF from DIS and with sum rules one has strong constraints on the gluon PDF

- additional direct probes of gluon PDF needed to constrain the gluon PDF at mid-x and large-x for future searches e.g. SUSY @ LHC



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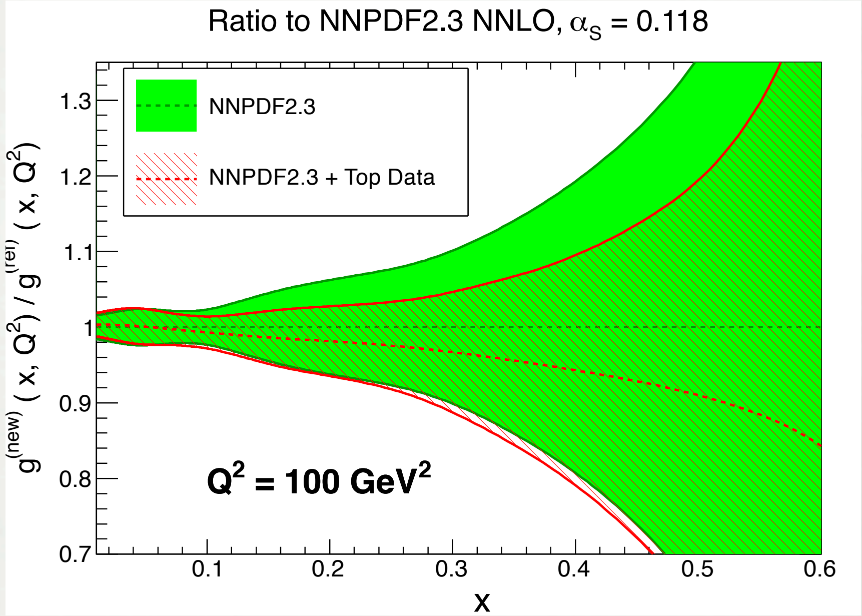
Fitting PDF

- *Using LHC data in Parton Distribution Functions*
  - Motto: "Yesterday's signal is today's background"

arXiv:1301.7215



☑ *Top pair production*

sensitive to gluon PDF at high-x

- very precise top pair production expected from LHC top-factory
- ratios of top/anti-top cross-sections sensitive also to u/d

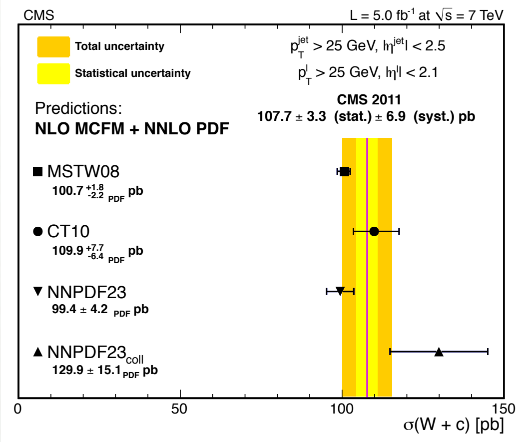
☑ *Direct photons*

additional, complementary probe of gluon PDF (same x as gg Higgs production)

☑ *W+charm production*

sensitivity to strange quark PDF (difficult to extract elsewhere)

CMS-SMP-12-002



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Fitting PDF

- *Theory predictions for relevant observables*
  - Theory predictions can be done at LO, NLO or NNLO (at the moment)

    - at each order PDF has modified meaning - need to use LO PDF with LO predictions etc.

    - leading-order

      - hard scattering results simple but with no scale dependance (no cancellation - large scale dependance)
      - LO PDF useful for some MC applications where only LO exists
      - data descriptions unsatisfactory

    - next-to-leading-order

      - scale cancellation between hard scattering and PDF - lesser scale dependance
      - hard scattering matrix elements complicated & need to be evaluated many times in a fit
      - NLO hard matrix elements together with NLO DGLAP - current state-of-the-art

    - next-to-next-to-leading-order

      - NNLO splitting functions known but not all relevant hard scattering matrix element known

        e.g. jets or other additional processes

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Fitting PDF

- *Theory predictions for relevant observables*
  - NLO & NNLO theory predictions complicated functions - need a way how to evaluate them quickly & efficiently
  - Full cross-section is a convolution of hard matrix elements with PDFs (or two convolutions)

$$\sigma(\mu_r, \mu_f) = \sum_{n,i} c_{n,i}(x_a, x_b, \mu_r, \mu_f) \otimes \left[\alpha_s^n(\mu_r) F_i(x_a, x_b, \mu_f)\right]$$

  - Old (but effective) method - use K-factors - lose some (N)NLO information about shape
  - Alternative - decouple PDFs and strong coupling dependance by putting everything on a (x,Q) grid & pre-compute complicated matrix element once and for all

$$\sigma(\mu) \simeq \sum_{n,i,k,l,m} \tilde{\sigma}_{n,i,k,l,m}(\mu)\, \alpha_s^n(\mu^{(m)})\, F_i(x_a^{(k)}, x_b^{(l)}, \mu^{(m)})$$

FastNLO

hep-ph/0609285

APPLGRID

arXiv:0911.2985

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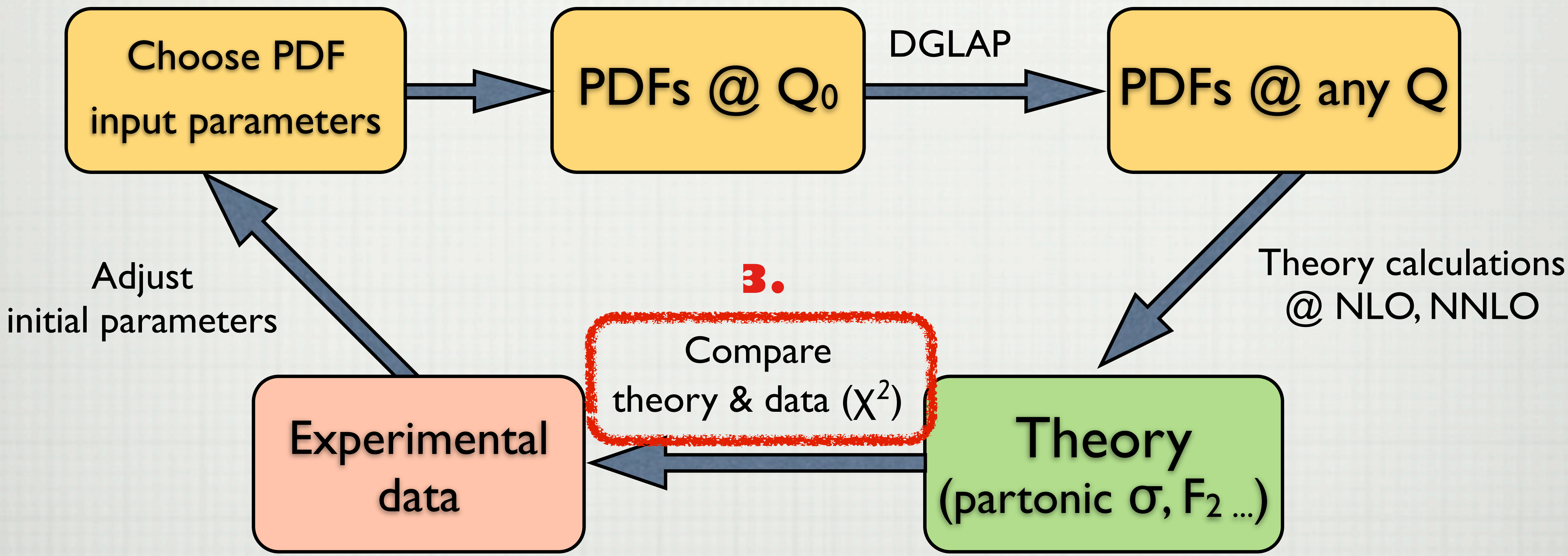
Fitting PDF

- *Parton Distribution Functions*
  - how do we determine them ? What are the moving parts in a typical PDF fitting-machine ?



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Fitting PDF

- *Parton Distribution Functions - χ^2-fit & errors*
  - Most PDF fitters use χ^2- function to measure the goodness of the fit

standard definition

$$\chi^2 = \sum_{i=1}^{N_{\rm dat}} \left(\frac{D_i - T_i}{\sigma_i} \right)^2$$

definition with correlated errors

$$\chi^2 = \sum_{i=1}^{N_{\rm dat}} \sum_{j=1}^{N_{\rm dat}} (D_i - T_i)(V^{-1})_{ij}(D_j - T_j) \qquad V_{ij} = \delta_{ij}(\sigma_i^{\rm uncorr})^2 + \sum_{k=1}^{N_{\rm corr}} \sigma_{k,i}^{\rm corr} \sigma_{k,j}^{\rm corr}$$

covariance matrix

  - Try to use all possible experimental information available
    - statistical errors
    - systematic errors - (un)correlated
    - normalisation uncertainty (might be multiplicative)

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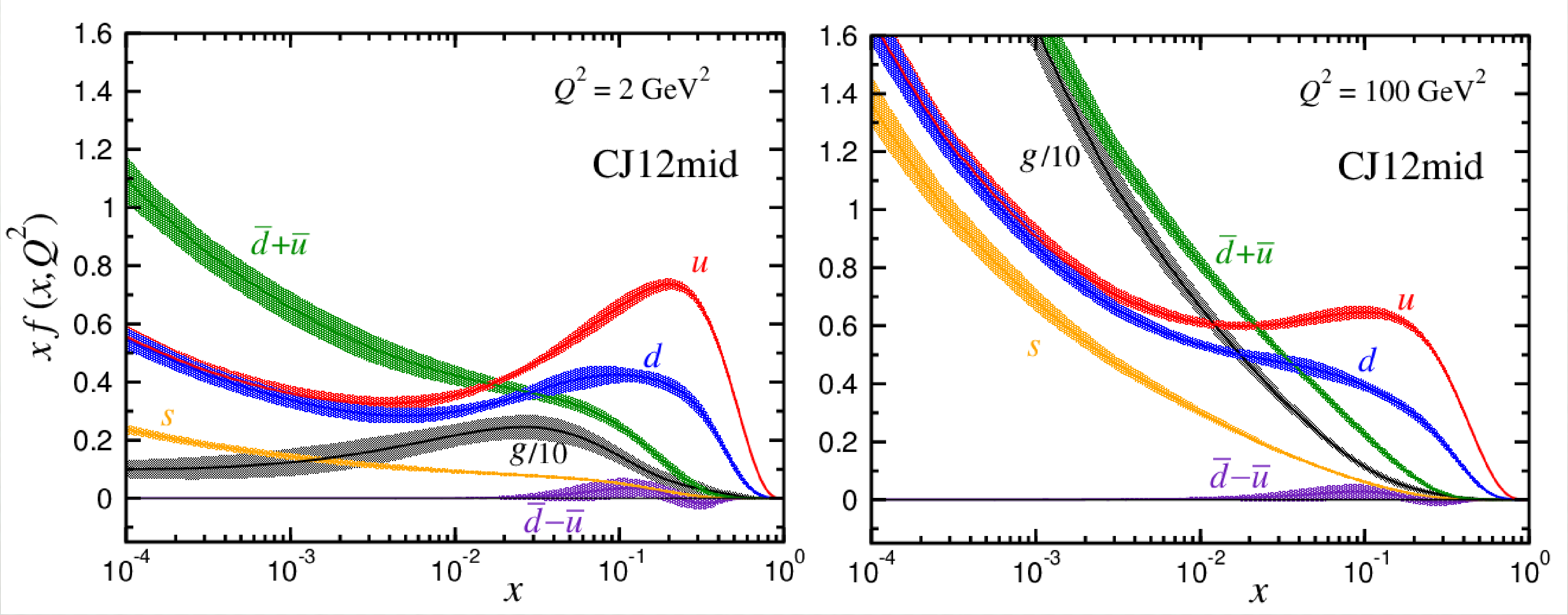
Fitting PDF

- *Parton Distribution Functions - what do we get ?*
  - What are the features we see in a typical PDF result ?
  - ☑ *u&d quarks - valence & sea*
    - valence part causes u&d dominate all other PDF at large-x where u>d
    - symmetric sea-quark: q & anti-q comparable at low-x
    - at high Q - contribution of the sea component increases through gluon radiation (DGLAP)
  - ☑ *strange quarks*
    - strange quark PDF suppressed at initial scale but enhanced at high-Q

arXiv:1212.1702



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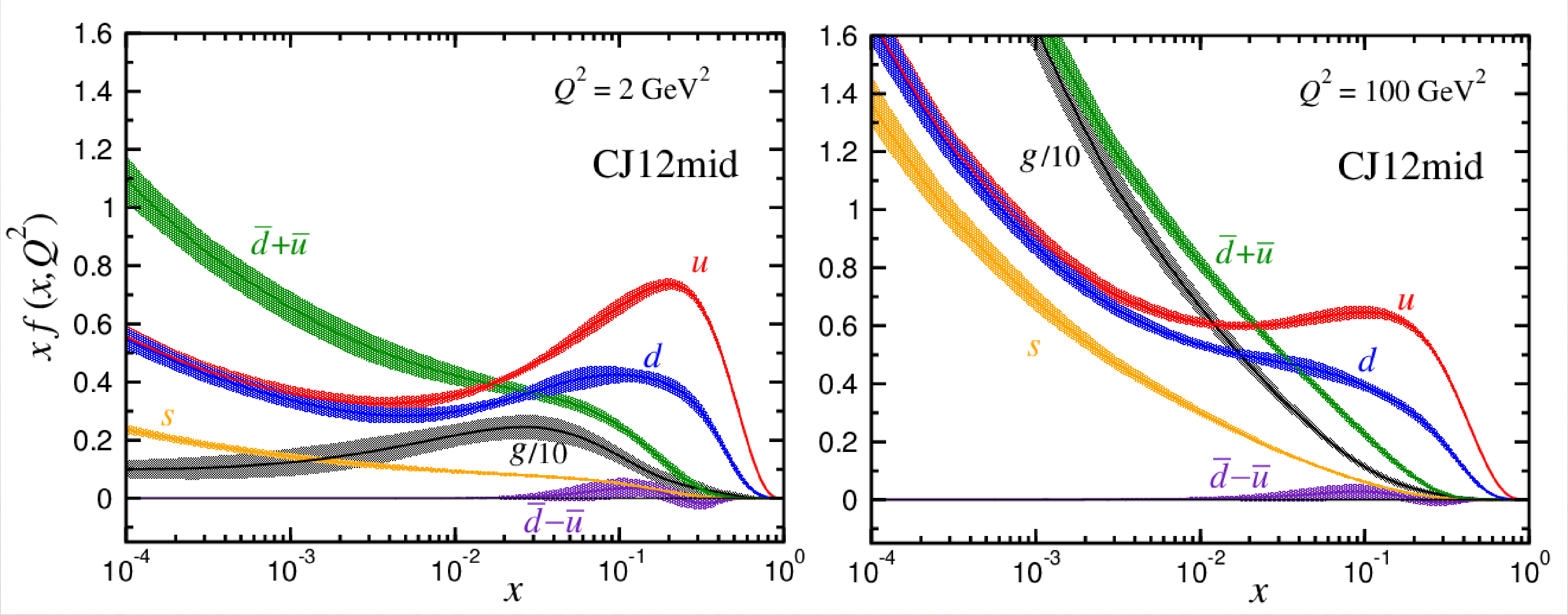
Fitting PDF

- *Parton Distribution Functions - what do we get ?*
  - What are the features we see in a typical PDF result ?

☑ *gluon*

- dominate at small-x but fall off steeply as x increases
- going to high-Q - gluon radiation reduces momenta of partons - everything shifts to smaller x
- gluon radiates q-qbar pairs or additional gluons - at small-x gluon PDF and sea quark PDF get steeper
- gluon can radiate even heavy quarks at high-Q so charm and bottom PDF are non-zero

arXiv:1212.1702



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PDF uncertainties

- *Parton Distribution Functions - what are PDF uncertainties*

  - ☑ *error PDF*
    - uncertainty of experimental data can be interpreted as uncertainty of the underlying PDF parameters
    - different approaches how to translate experimental uncertainties to PDFs

  - ☑ *other uncertainties (not in error PDFs)*
    - choice of data sets or observables (include neutrino DIS or not, LHC or not ...)
    - choice of kinematic cuts (looser cuts might constrain PDF better but ...)
    - parameterisation bias
    - pQCD choices (NLO vs NNLO, strong coupling)
    - heavy-quark schemes (FFS, ZM-VFNS, VF-VFNS)
    - higher-twist terms, nuclear corrections etc...

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PDF uncertainties

- *Parton Distribution Functions - χ²-fit & errors*
    - error PDFs are experimental errors translated to errors of free PDF parameters
    - all approaches to determine error PDFs give approx. the same results in regions with data

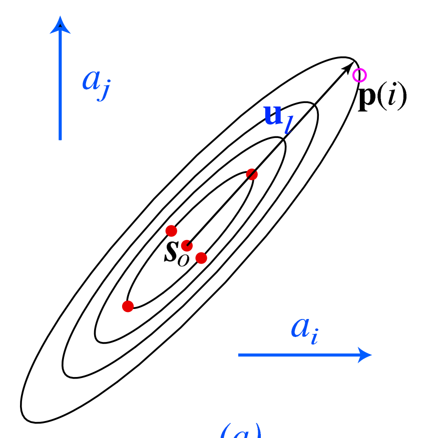
☑ *Hessian method*

the most widely used technique to determine error PDFs

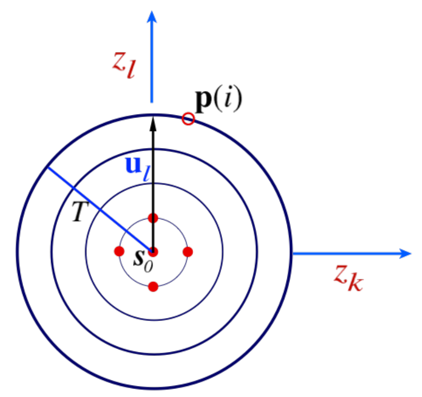
Expansion of χ^2:

Hessian — diagonal Hessian

$$\chi^2(a) = \chi_0^2 + \frac{1}{2}\frac{\partial\chi^2}{\partial a_i \partial a_j}(a-a_0)_i(a-a_0)_j + \ldots \rightarrow \chi_0^2 + \sum_i z_i^2$$



(a)
Original parameter basis



(b)
Orthonormal eigenvector basis

hep-ph/0201195

PDF uncertainties

- *Parton Distribution Functions - χ²-fit & errors*
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☑ ***Hessian method***

the most widely used technique to determine error PDFs

Expansion of χ^2:

Hessian ↘ diagonal Hessian ↓

$$\chi^2(a) = \chi_0^2 + \frac{1}{2}\frac{\partial\chi^2}{\partial a_i \partial a_j}(a-a_0)_i(a-a_0)_j + \ldots \rightarrow \chi_0^2 + \sum_i z_i^2$$

Choice of $\Delta\chi^2 = \chi^2 - \chi_0^2$:

ideal choice $\Delta\chi^2 = 1$ pragmatic choice $\Delta\chi^2 \gg 1$ $\Delta\chi^2 \sim 50 - 100$

error PDFs ↓

Construct error PDFs for each parameter in 2 directions:

$$z_i = \pm\sqrt{\Delta\chi^2} \qquad X_i^{\pm}(z) = X_i^{\pm}(0,0,\ldots,\pm\sqrt{\Delta\chi^2},\ldots,0,0)$$

Calculate PDF uncertainty of cross-section

$$(\Delta\sigma)^2 \approx \frac{1}{4}\sum_i^{N_p}\Big(\sigma(X_i^+) - \sigma(X_i^-)\Big)^2$$

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PDF uncertainties

- *Parton Distribution Functions - χ²-fit & errors*

  - *Hessian method - dynamical tolerance criterion*

    - Ideal case would require using $\Delta\chi^2 = 1$ for one sigma (68% CL) or $\Delta\chi^2 = 2.71$ for 90% CL
      BUT we are fitting data from multiple not necessarily compatible experiments

dynamical tolerance by MSTW

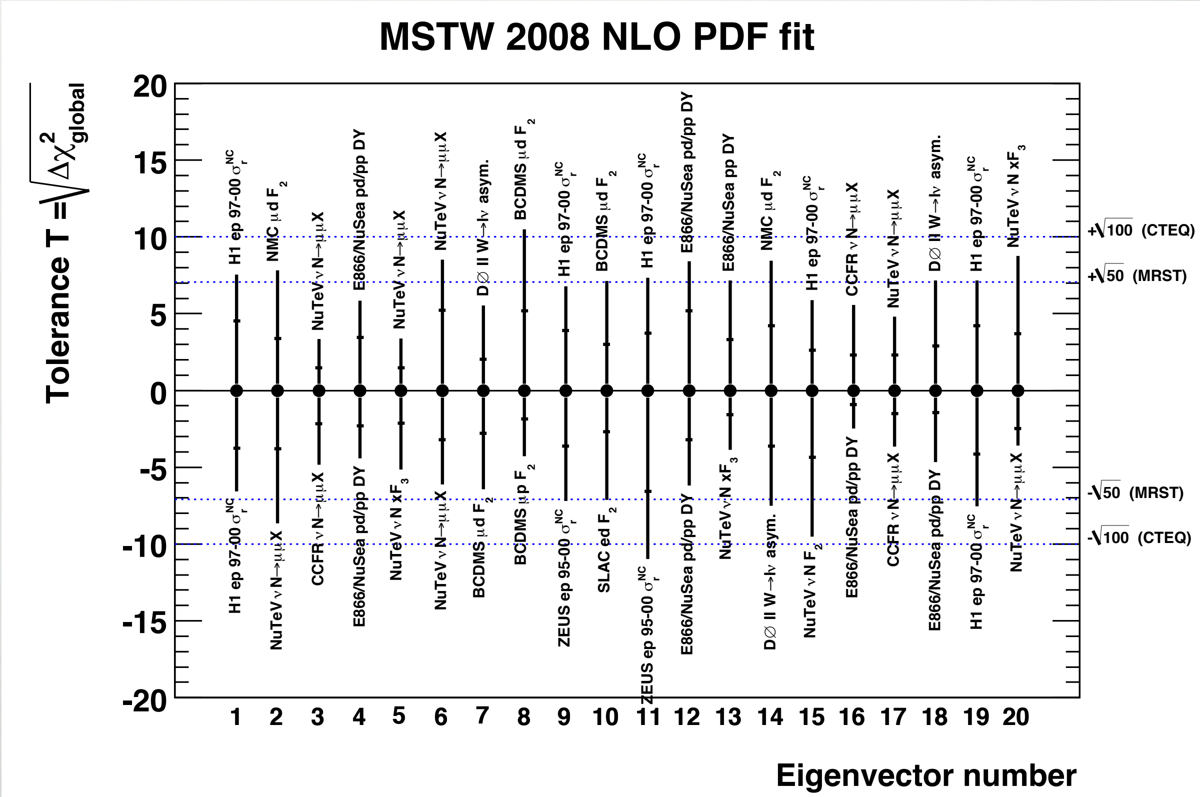
- Each experiment (N data points) have to be described up to 90%CL for variations along one eigenvector

$$P_N(\chi^2) = \frac{(\chi^2)^{N/2-1} e^{-\chi^2/2}}{2^{N/2}\Gamma(N/2)}$$

$$\int_0^{\xi_{90}} \mathrm{d}\chi^2 P_N(\chi^2) = 0.90$$

- For each eigenvector, take $\Delta\chi_n^2$ where all experiments are described within 90% CL

- Translate $\Delta\chi_n^2$ to (different) shifts in each parameter



PDF uncertainties

- *Parton Distribution Functions - χ^2-fit & errors*
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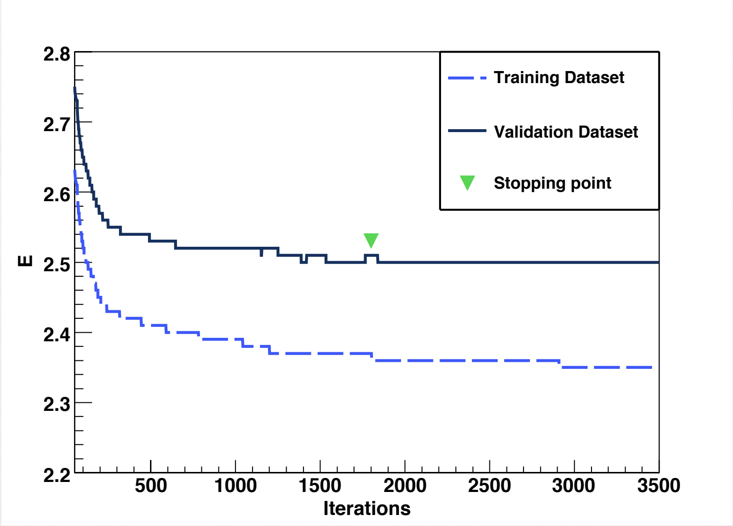
☑ *Monte Carlo method (as used by NNPDF)*
new technique which allows for more flexible PDF x-shapes

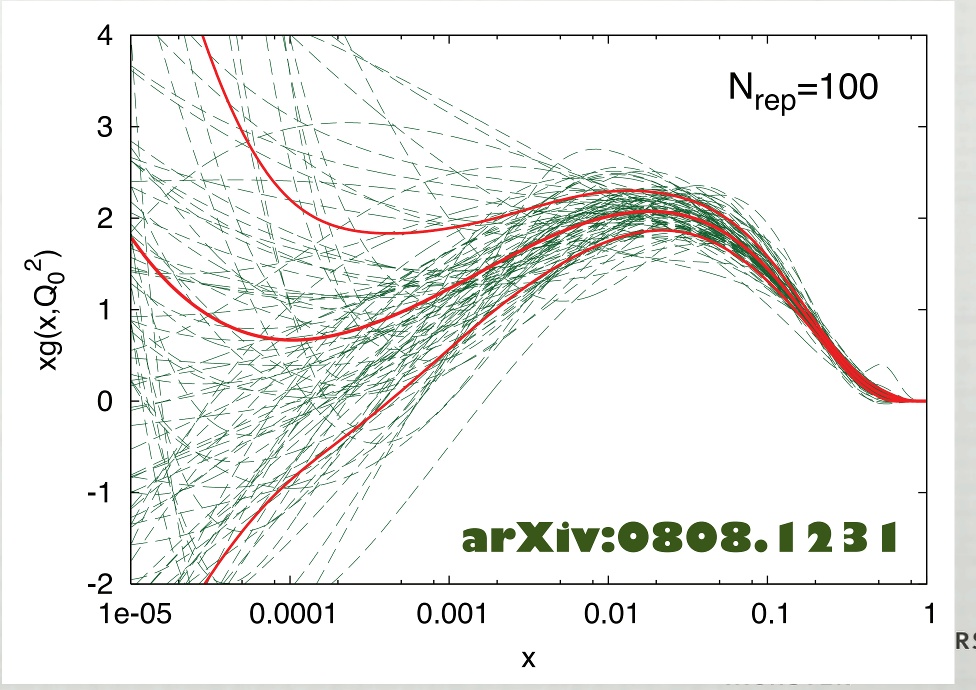
- neural network is used to (over-)parametrize PDFs @ Q_0
- $N_{\rm set}$ artificial replicas of data points generated assuming multi-Gaussian probability distribution
- random separation into training & validation data subsets
- minimize error function (not χ^2) for training set
- stop before overlearning



error/replica PDFs

$$\langle\sigma(X)\rangle = \frac{1}{N_{\rm set}}\sum_{i=1}^{N_{\rm set}}\sigma(X^i)$$

$$\Delta\sigma(X) = \left(\sum_{i=1}^{N_{\rm set}}\left[\sigma(X^i) - \langle\sigma(X)\rangle\right]^2\right)^{1/2}$$



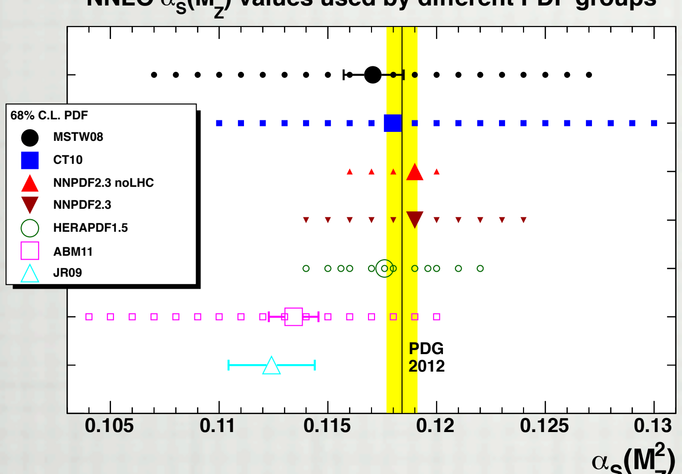
RSITÄT

Misc topics in PDF

- *Parton Distribution Functions - theory & related issues*
  - theory calculations @ LO, NLO or NNLO include several important constants which can have large impact on PDFs

☑ *strong coupling α_s*

treated as an external parameter or fitted together with PDFs

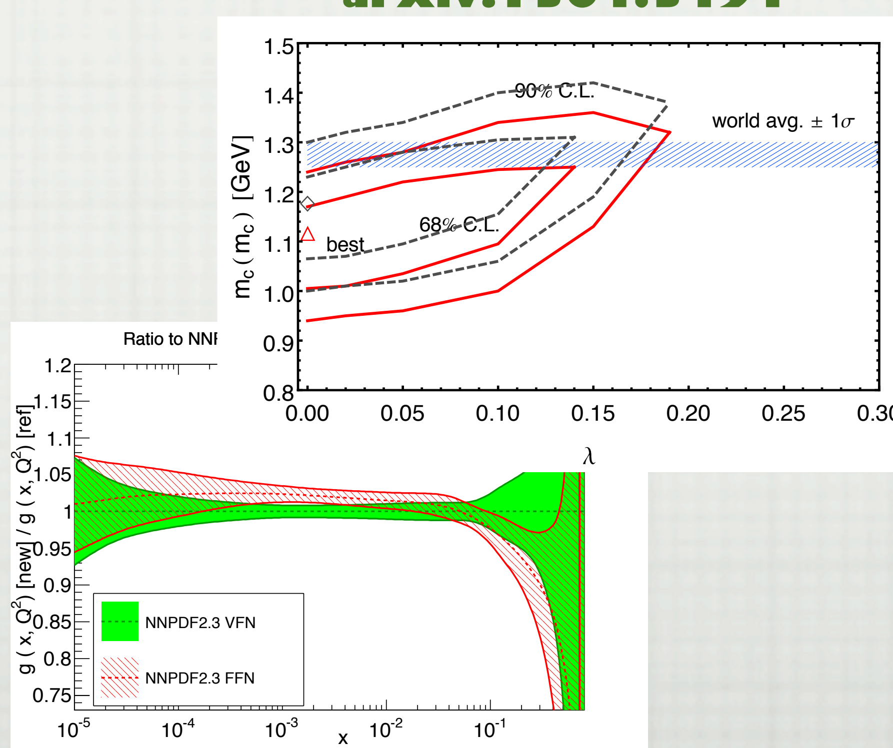


arXiv:1301.6754

☑ *quark masses m_c, m_b & heavy quark treatment*

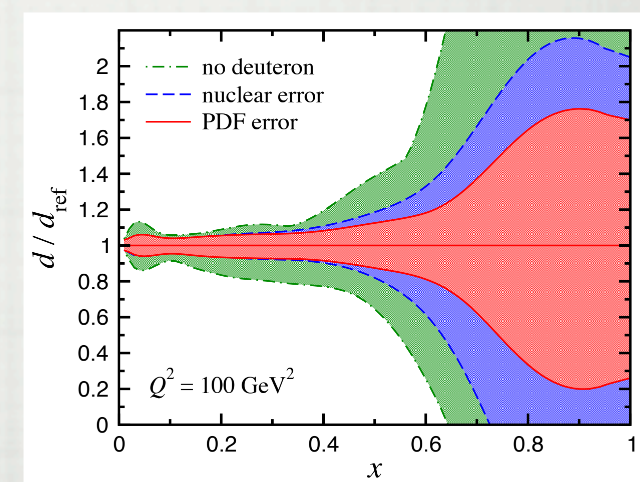
quark masses enter the evolution & their treatment influences gluon PDFs

arXiv:1304.3494



☑ *treatment of deuterium*

fixed target DIS experiments provide important high-x constraints but done not on proton but deuterium



arXiv:1212.1702

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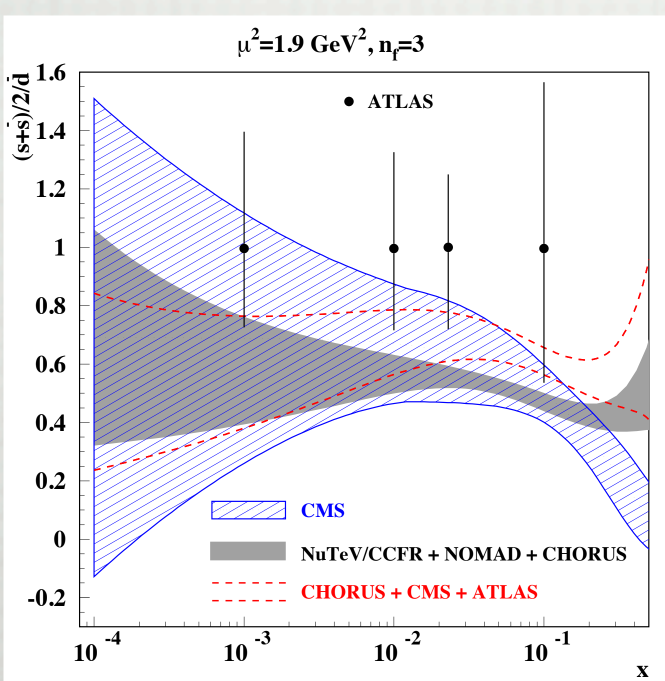
Misc topics in PDF

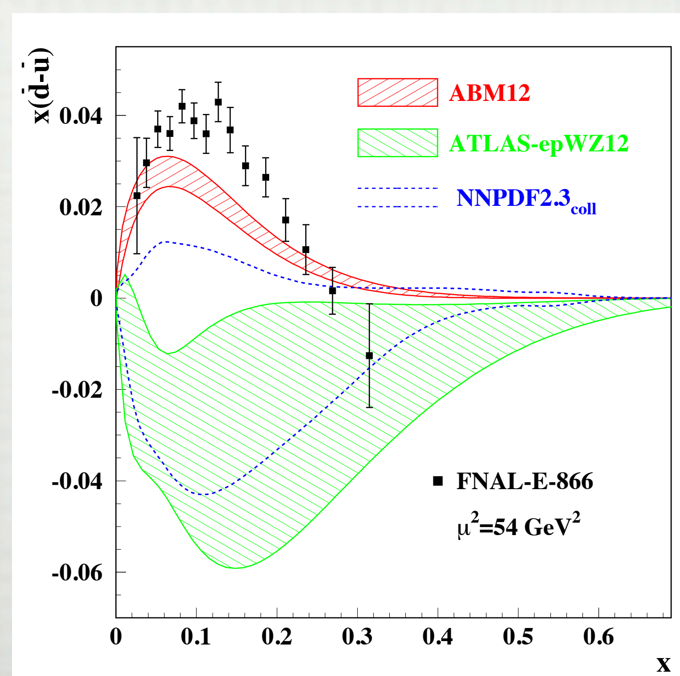
strange quark PDF

- not many data constrain strange quark PDF - the best pre-LHC contraint comes from neutrino DIS and di-muon subset of DIS (CHORUS, NuTeV, NOMAD)
- new measurements of W+c production from ATLAS & CMS provide new constraints
- with no handle on the strange quark - assumptions were introduced which tied strange PDF to other sea quarks - now these assumptions can be tested

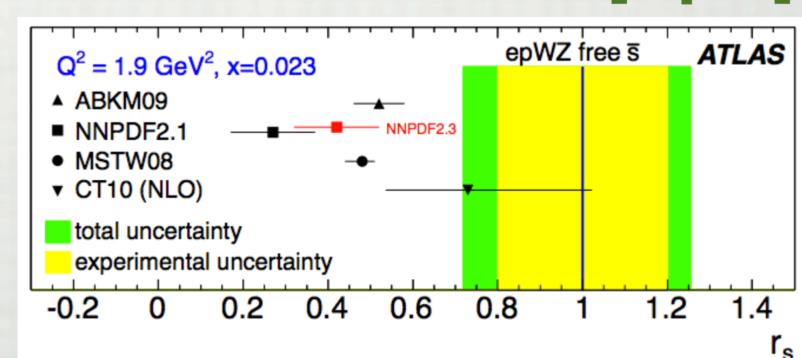
$$s = \bar{s} = \frac{\kappa}{2}\left(\bar{u} + \bar{d}\right) \qquad\qquad r_s = \frac{1}{2}\left(s + \bar{s}\right)/\bar{d}$$

arXiv:1404.6469





arXiv:1203.4051 [hep-ex]



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Current PDFs

- *Parton Distribution Functions - summary of existing PDFs*

	DATA	Order	HQ	α_s	Params.	Uncert.
CT14	global	LO,NLO, NNLO	GM-VFNS (s-ACOT)	external	6 indep. PDFs (26 params)	Hessian ($\Delta\chi^2\sim100$)
MSTW08	global	LO,NLO, NNLO	GM-VFNS (TR)	fit	7 indep. PDFs (20 params)	Hessian ($\Delta\chi^2\sim25$)
NNPDF	global	LO,NLO, NNLO	GM-VFNS (FONLL)	external	7 indep. PDFs (259 params)	Monte Carlo
CJ12	global	LO,NLO	ZM-VFNS	external	5 indep. PDFs (22 params)	Hessian ($\Delta\chi^2=100$)
HERApdf	DIS (HERA)	NLO NNLO	GM-VFNS (TR)	external	5 indep. PDFs (14 params)	Hessian ($\Delta\chi^2=1$)
ABM11	DIS+DY	NLO NNLO	FFN	fit	6 indep. PDFs (25 params)	Hessian ($\Delta\chi^2=1$)

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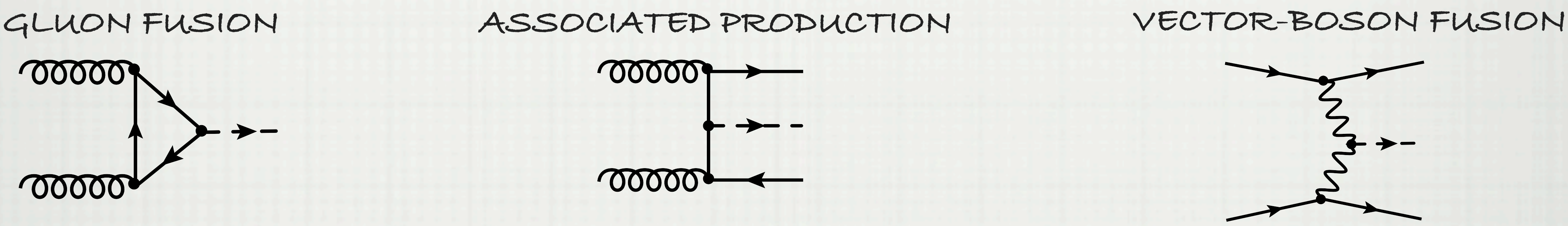
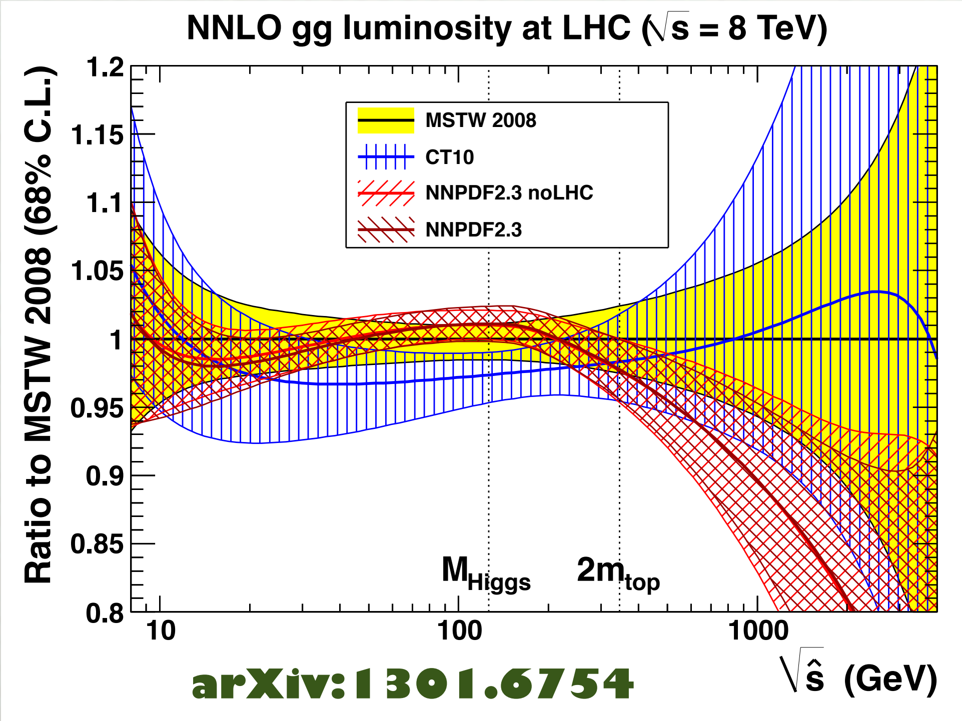
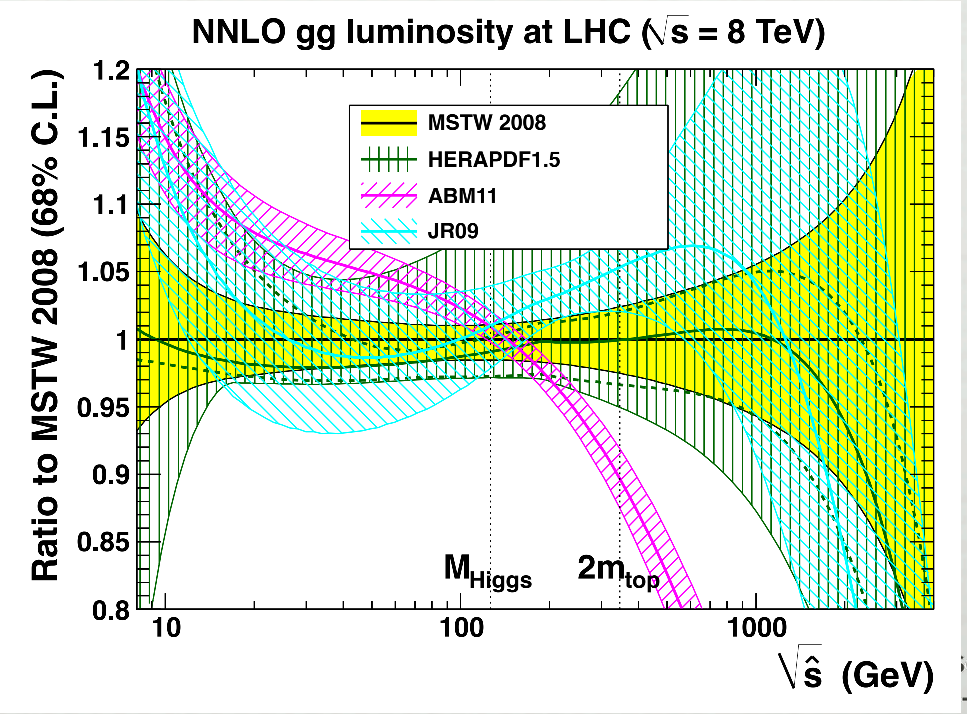
Current PDFs

- *Parton Distribution Functions in Higgs production*
  - Higgs is pre-dominantly produced through gluon fusion - **gluon PDFs at $x=M_H/\sqrt{s} \sim 0.02$ are crucial**
  - sub-leading Higgs production via VBF is sensitive to quark & anti-quark PDFs







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Current PDFs

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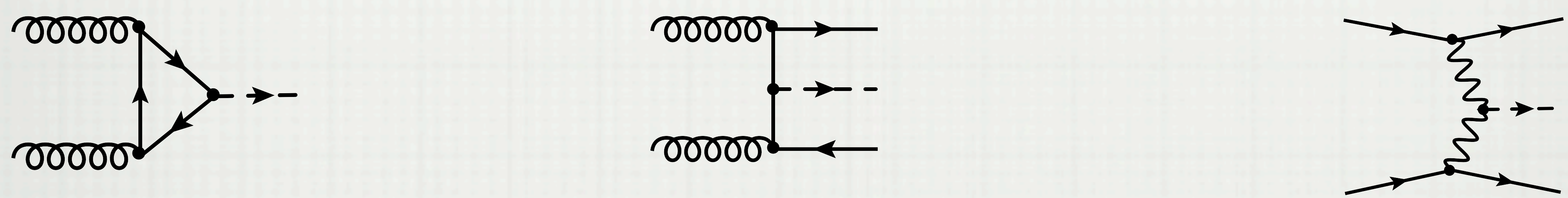
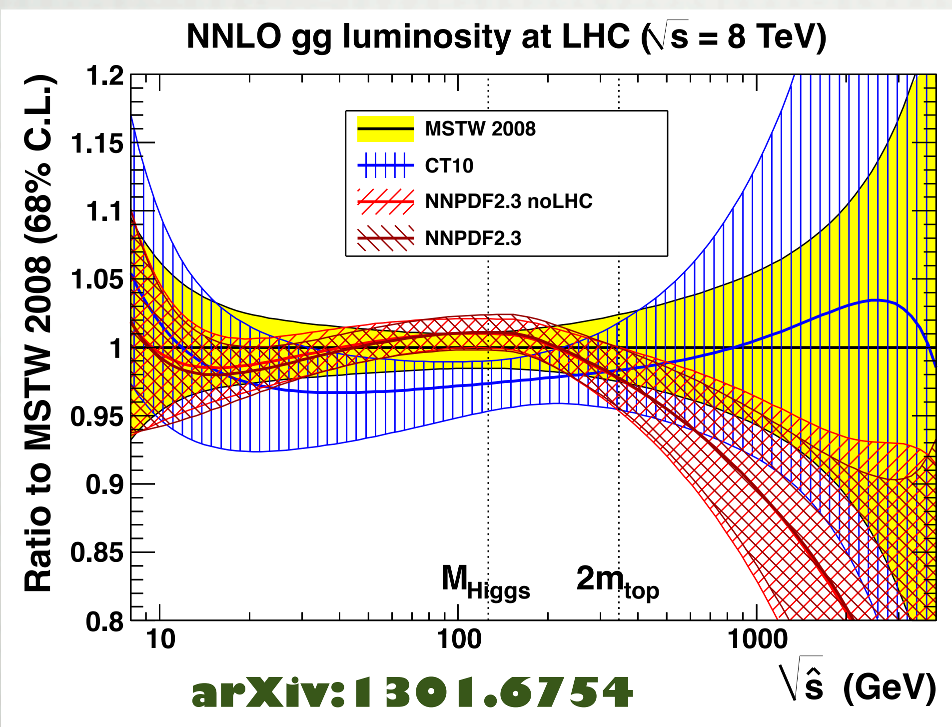
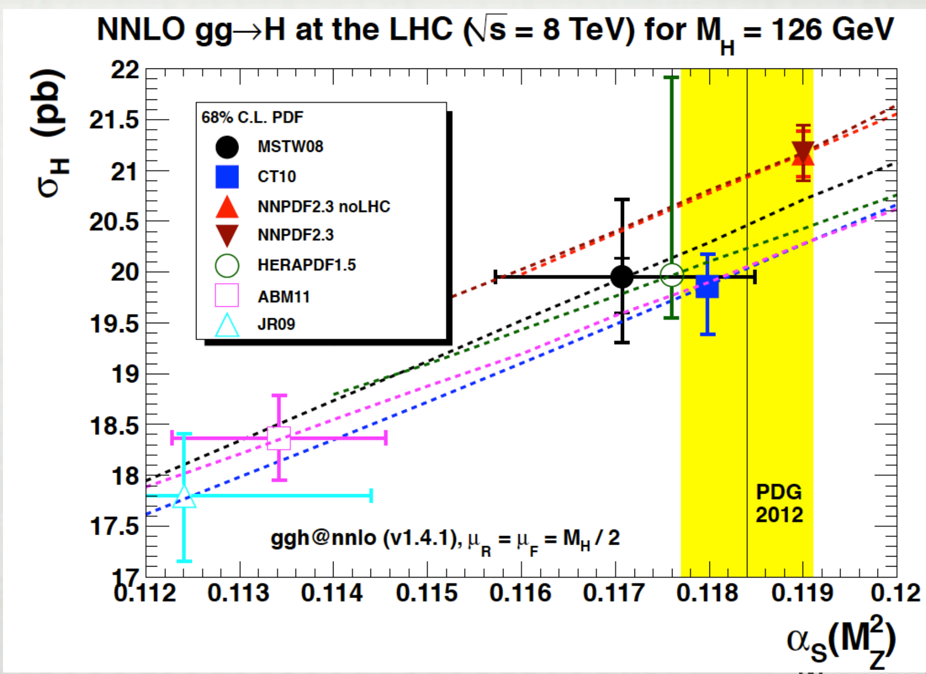
GLUON FUSION ASSOCIATED PRODUCTION VECTOR-BOSON FUSION

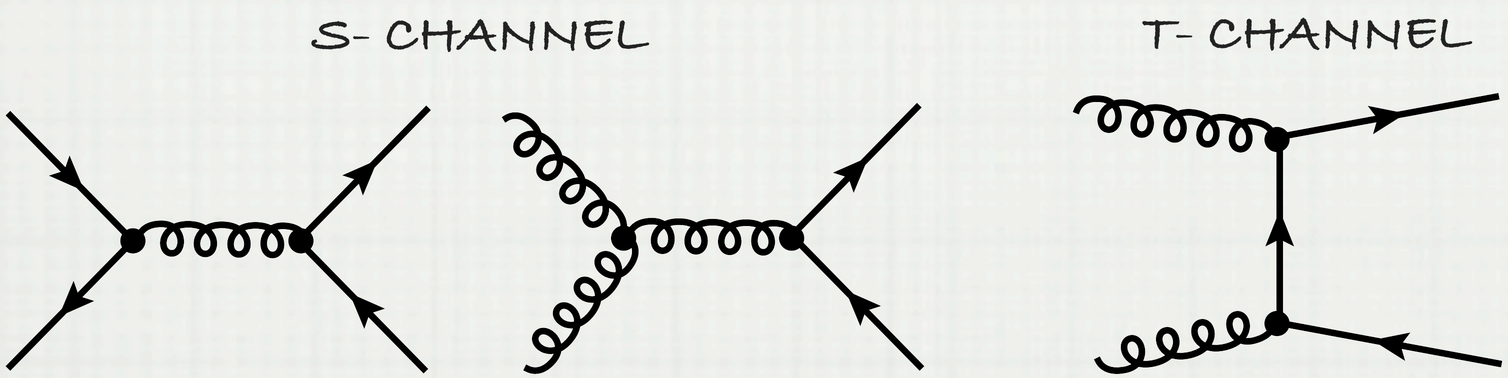


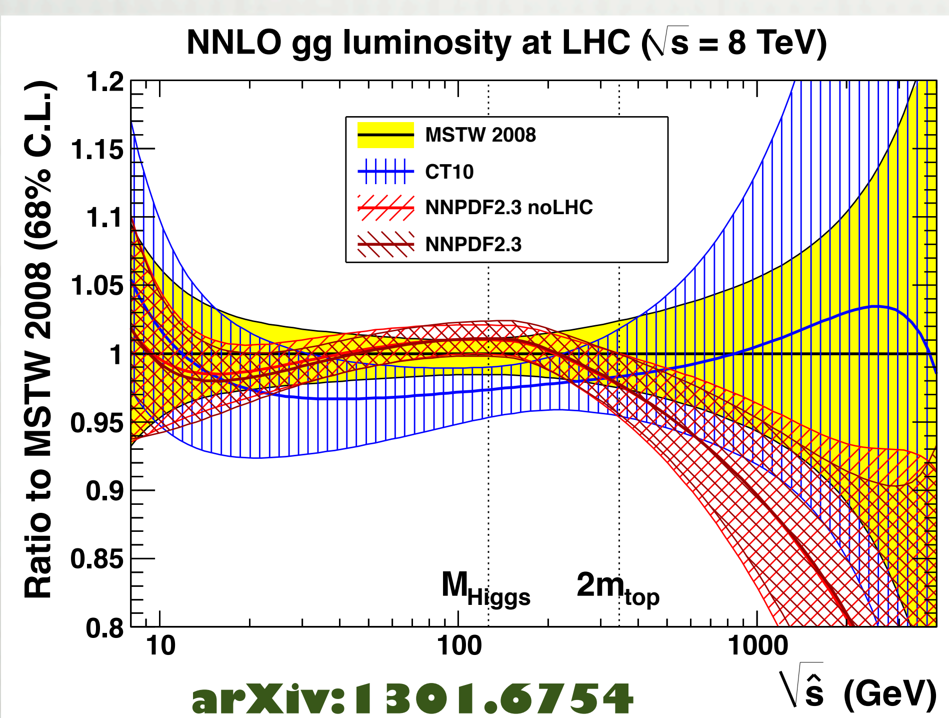


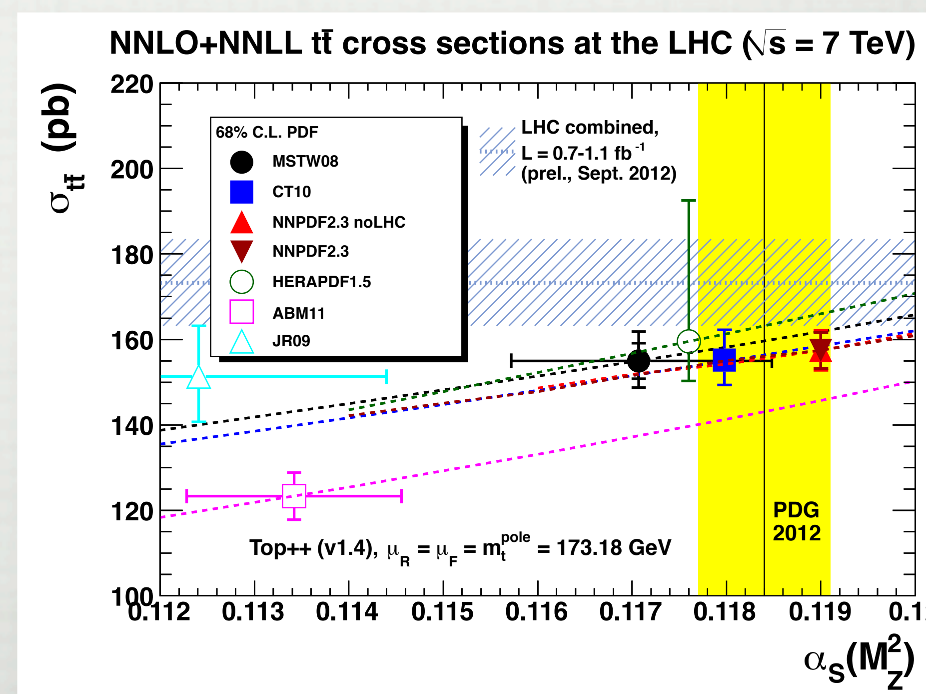


Current PDFs

- *Parton Distribution Functions in top quark pair production*
    - Top quark pair production is dominated by s-channel diagrams where valence quarks & gluons are important at **$x=2m_t/\sqrt{s}$ ~ 0.05**







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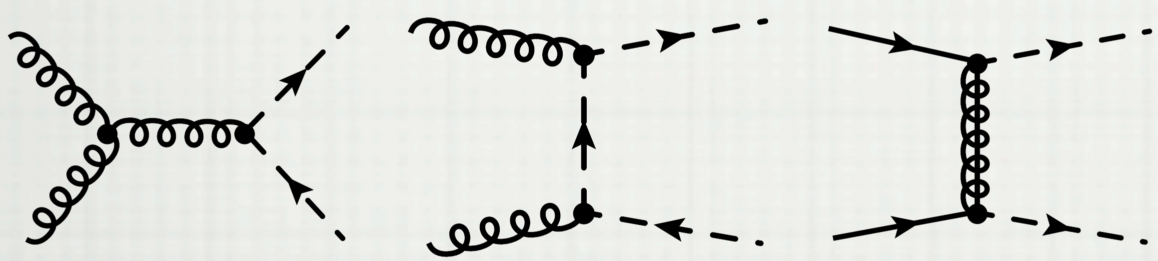
Current PDFs

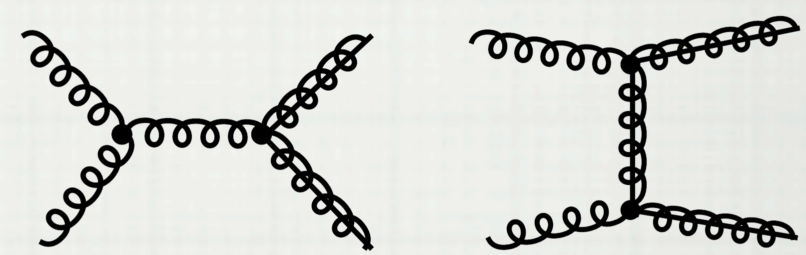
- *Parton Distribution Functions in SUSY production*
  - production of SUSY coloured particles (squarks & gluinos) very sensitive to gluon PDF at very high $\mathbf{x=2m_X/\sqrt{s} \sim 0.2\text{-}0.7}$

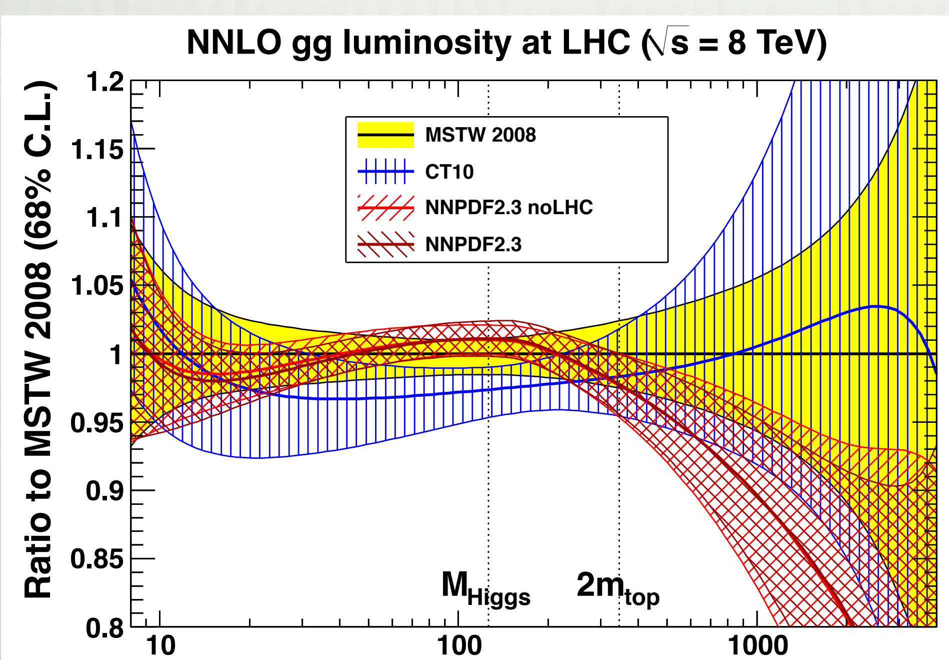
very problematic

SQUARK PRODUCTION

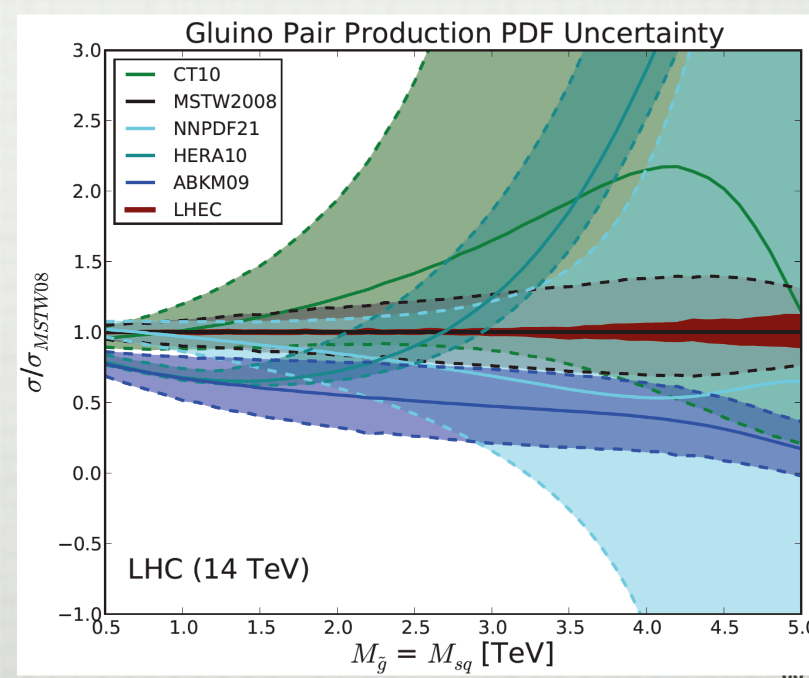


GLUINO PRODUCTION





arXiv:1301.6754

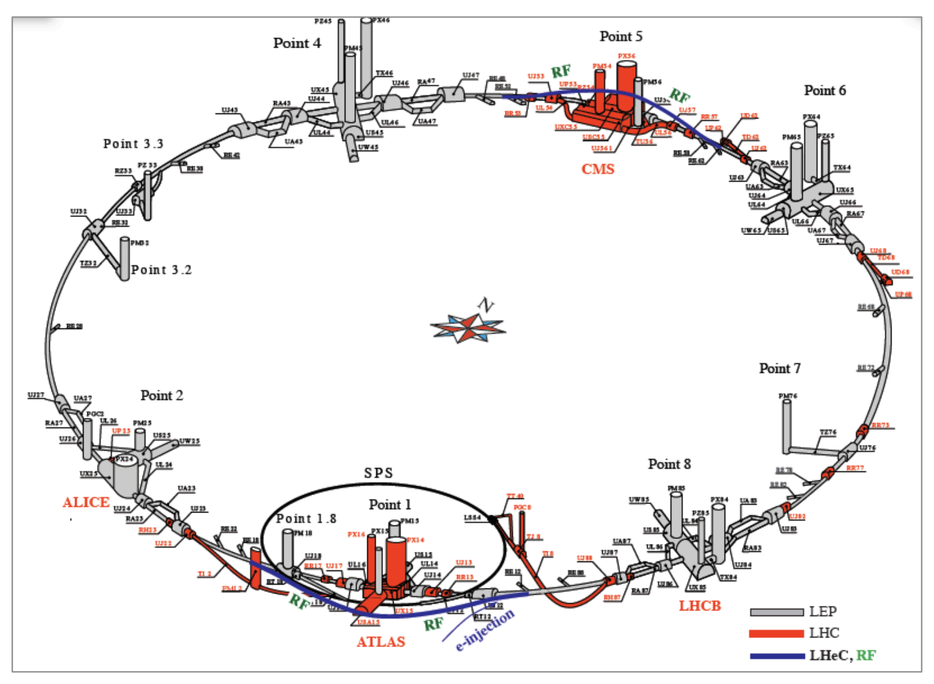


arXiv:1206.2913

PDF after LHC

- *Parton Distribution Functions - new dedicated data*
  - new projects with large possible impact on PDFs

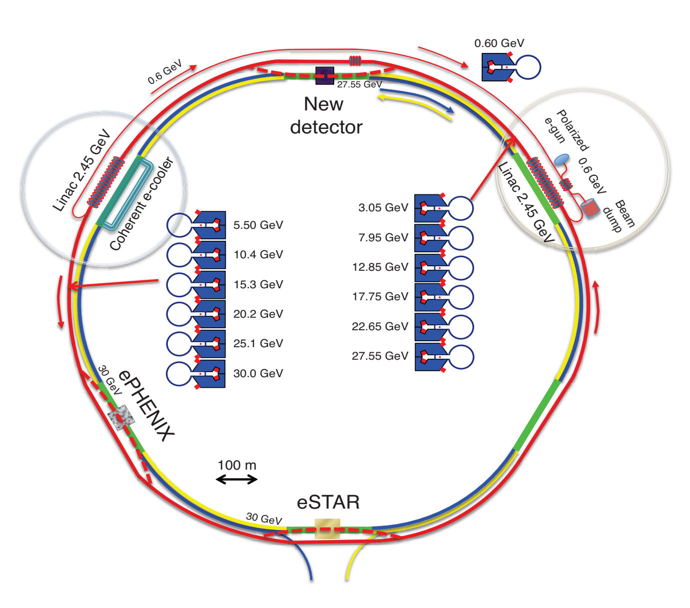
arXiv:1206.2913



LHeC

colliding electrons / positrons with LHC protons / nuclei

- unprecedented coverage in x-Q^2 plane
- precise determination of the gluon PDF
- interesting also for Higgs & BSM physics programs
- breakthrough machine for nuclear PDFs



arXiv:1212.1701

EIC

electron ion collider

- high-intensity precision machine with polarized beams
- good coverage in x-Q^2 plane (down to x~10^{-4})
- precise determination of the gluon PDF
- breakthrough machine for nuclear PDFs, saturation, polarized PDFs...

THANK YOU