UNDERSTANDING of the LHC PARTONIC BEAMS

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RWTH, Aachen

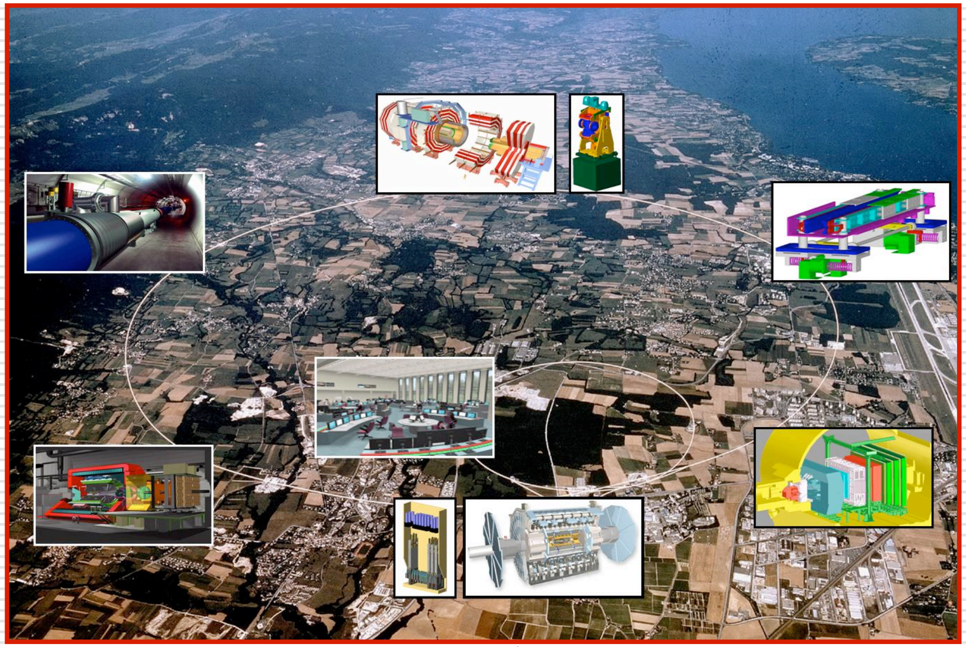
“Challenges for precision physics at the LHC”

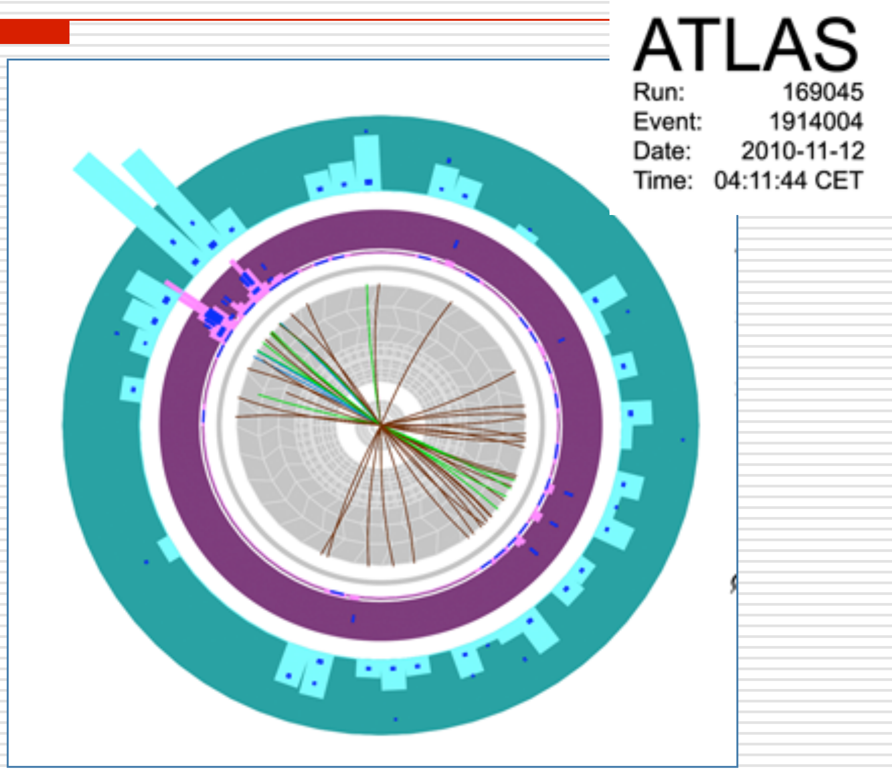
LPTHE, Paris

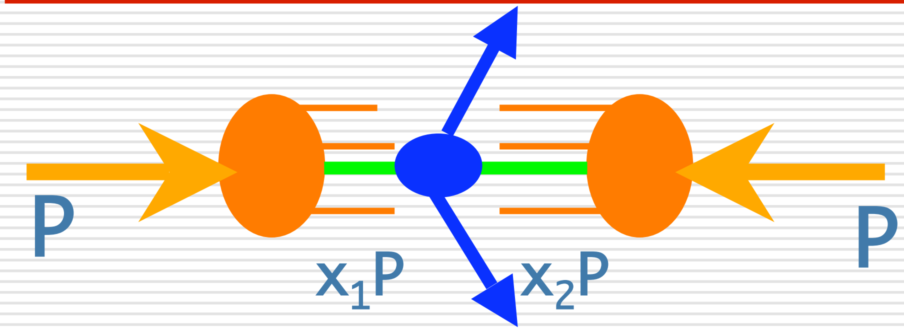
16th December 2010

LHC collisions

Partonic beams

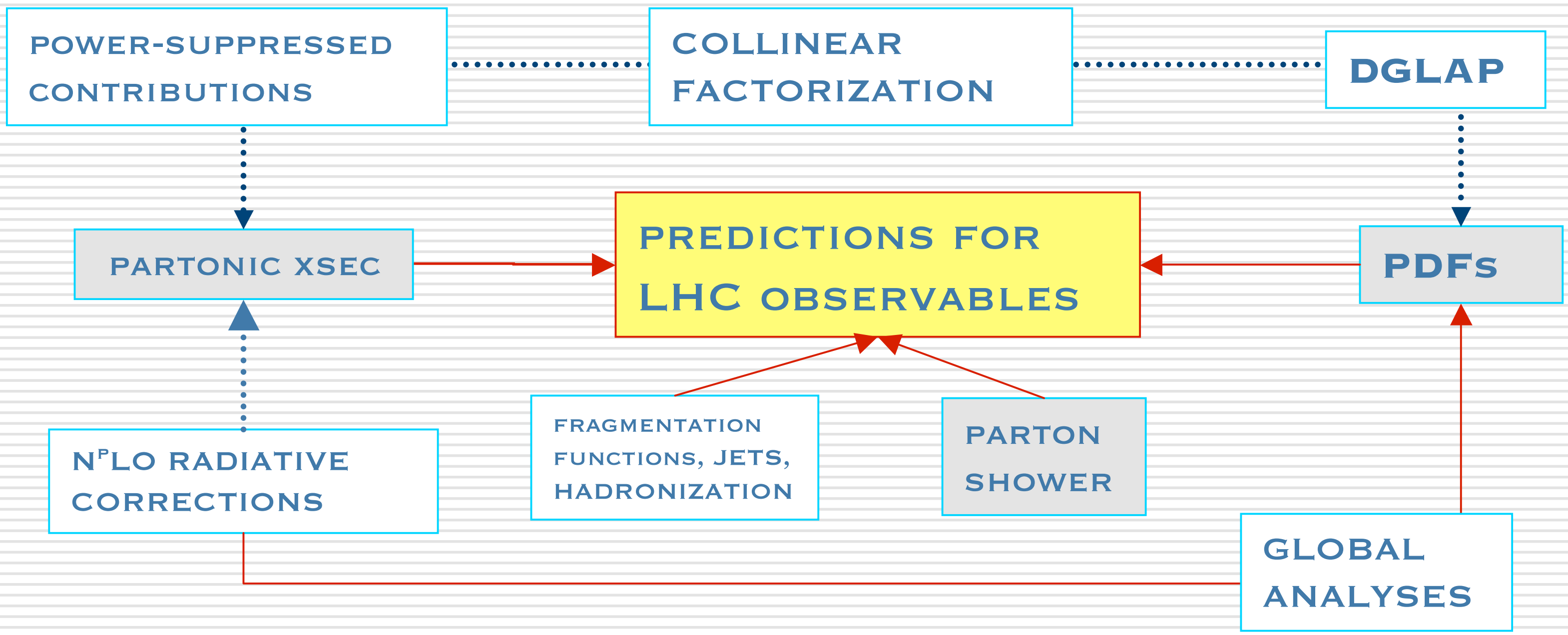




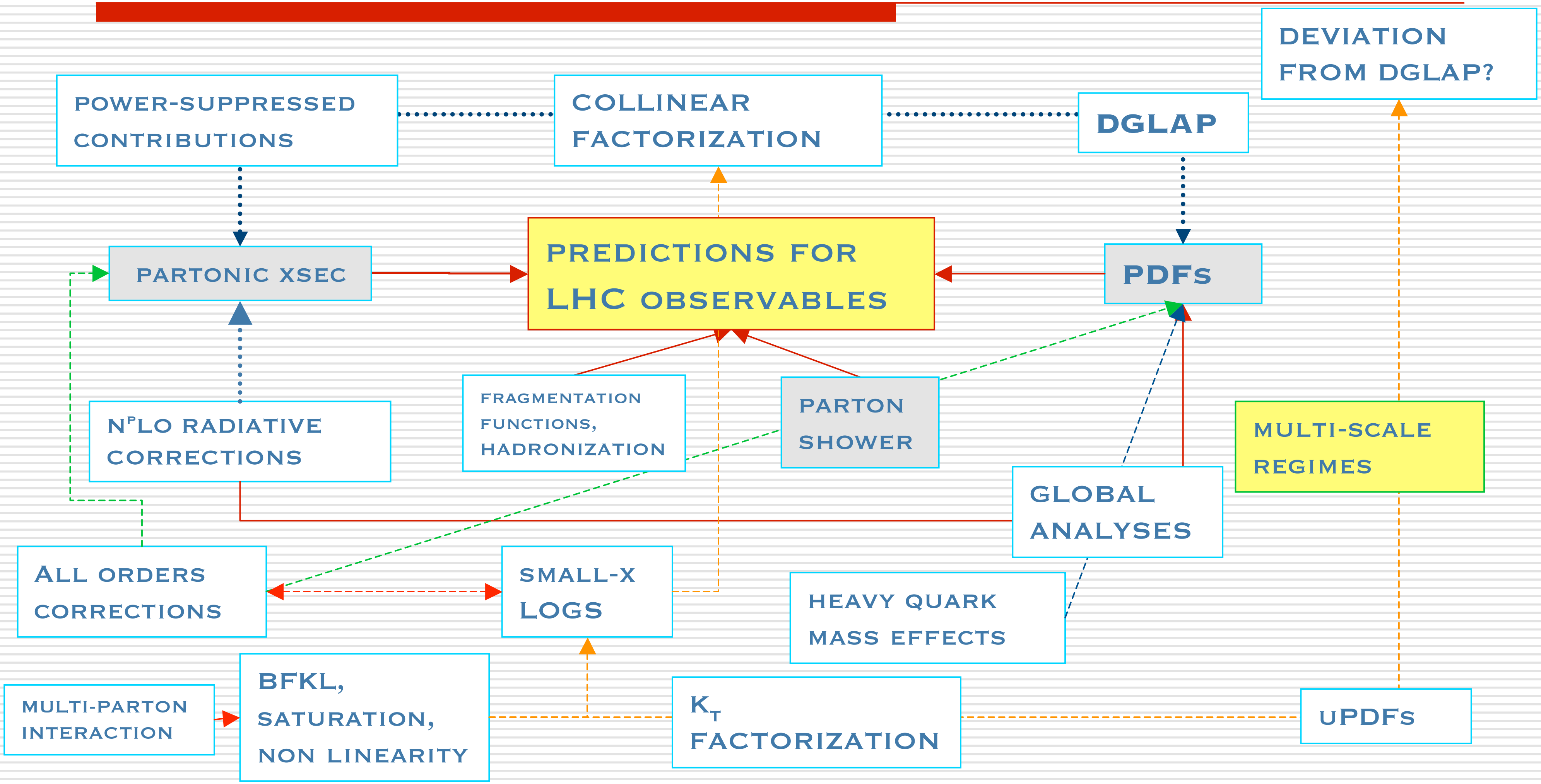


The deep knowledge of proton beams is essential to relate theory to experimental observation at the LHC.

LHC collisions
QCD predictions



LHC collisions
QCD predictions



OVERVIEW

- PDFs: where do we stand?
  - Statistical and theoretical challenges
  - State of the art
- PDFs and the LHC
  - Predictions for LHC standard candles
  - Improve over PDFs knowledge
- Outlook and open questions for the LHC
  - Interface with Monte Carlo event generators
  - Beyond DGLAP
  - Unintegrated PDFs
- Conclusions

PART I

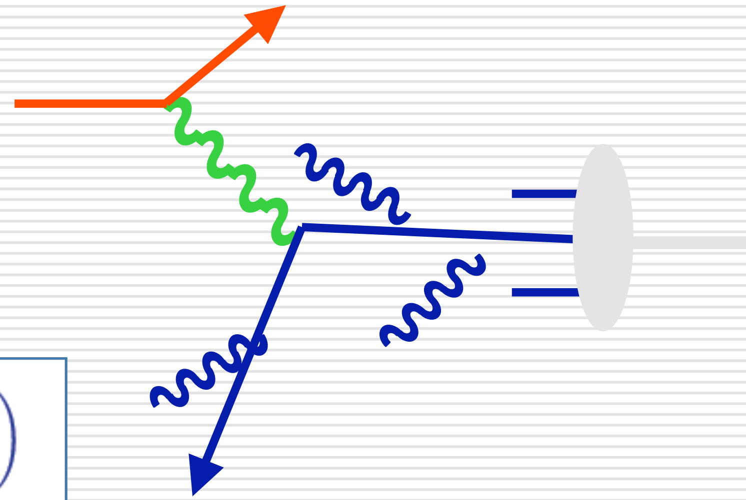
PDFs: where do we stand?

- Statistical issues
- Theoretical errors
- State of the art

Parton Distribution Functions

Scaling violation and QCD

$f_a^{(H)}(x,\mu^2)$



Collinear factorization theorem

$$d\sigma = \sum_a \int_0^1 \frac{d\xi}{\xi} f_a(\xi,\mu^2) d\hat{\sigma}_a\left(\frac{x}{\xi}, \frac{\hat{s}}{\mu^2}, \alpha_s(\mu^2)\right) + \mathcal{O}\left(\frac{1}{Q^p}\right)$$

PDFs are universal

DGLAP evolution equations

$$\frac{\partial}{\ln Q^2} q^{NS}(\xi, Q^2) = P^{NS}(\xi, \alpha_s) \otimes q^{NS}(\xi, Q^2)$$

$$\frac{\partial}{\ln Q^2} \begin{pmatrix} \Sigma \\ g \end{pmatrix} (\xi, Q^2) = \begin{pmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} (\xi, \alpha_s) \otimes \begin{pmatrix} \Sigma \\ g \end{pmatrix} (\xi, Q^2)$$

splitting functions are known up to NNLO [2004: Moch,Vogt, Vermaseren]

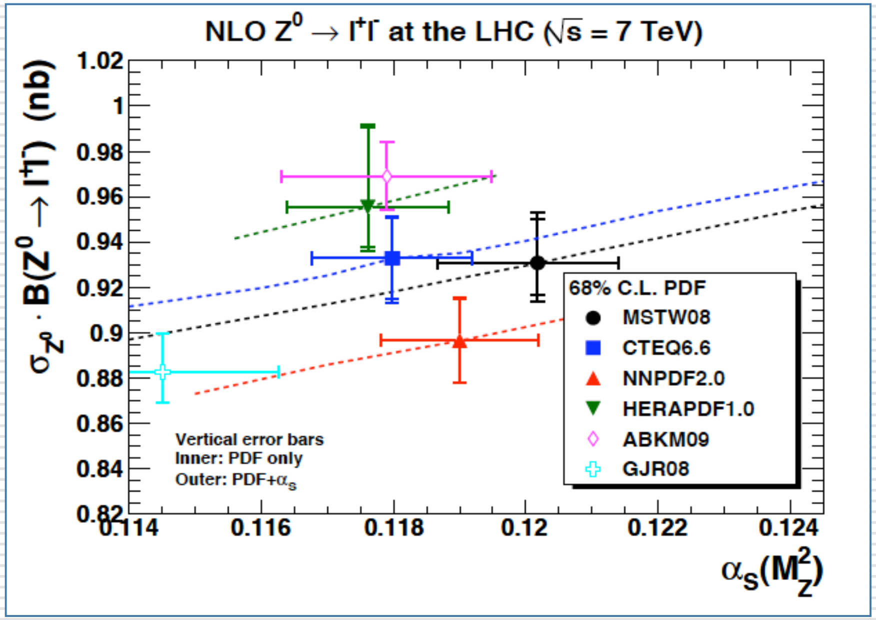
Parton Distribution Functions

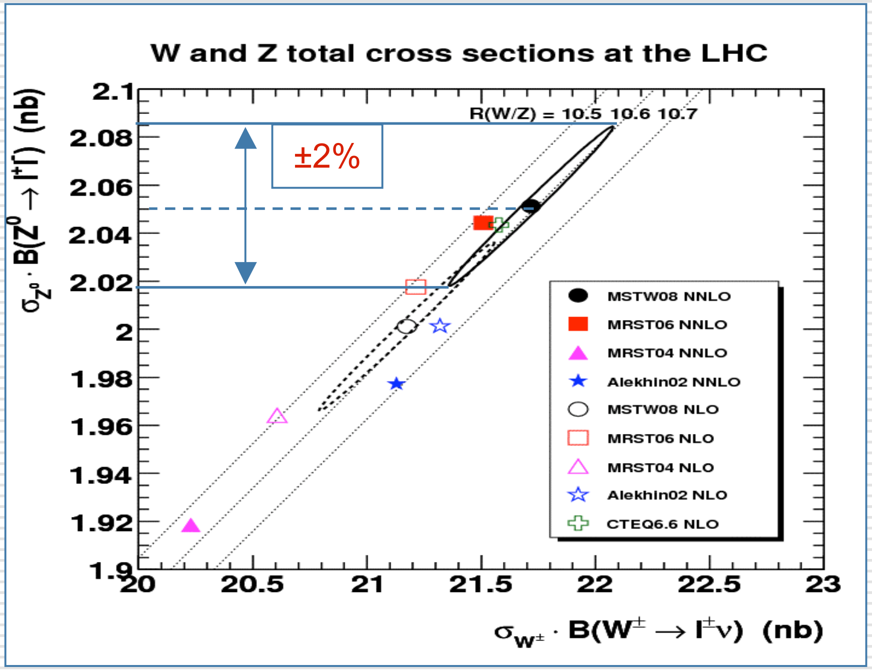
Why should we care about PDFs?

PDFs uncertainty is the dominating one in many standard candle processes at the LHC

σ(Z) @ LHC: $\Delta\sigma_{pdf} \sim 2\%$, $\Delta\sigma_{ho} \sim 2\%$

[MSTW 0901.0002]





[Watt, PDF4LHC 2010]

Need a careful assessment of PDFs uncertainty

Parton Distribution Functions
Then and now

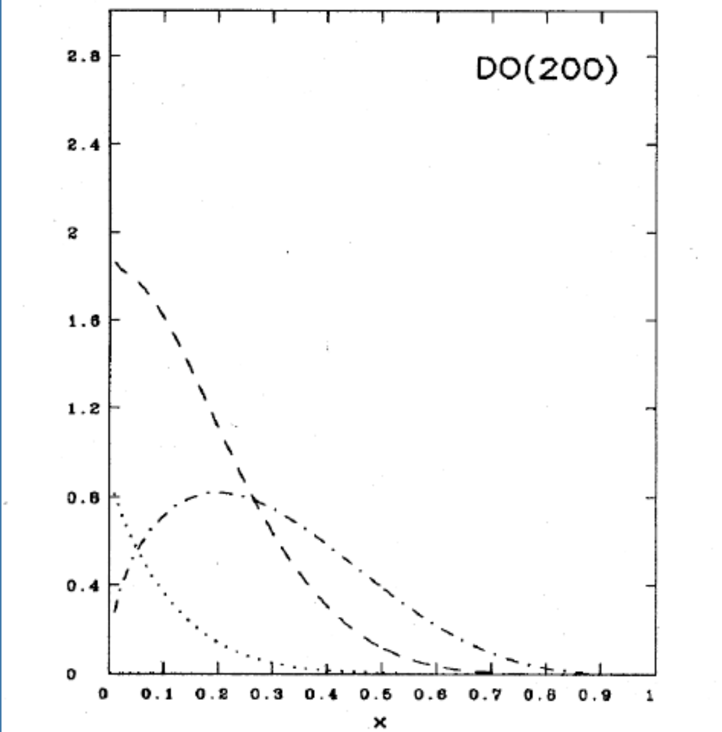
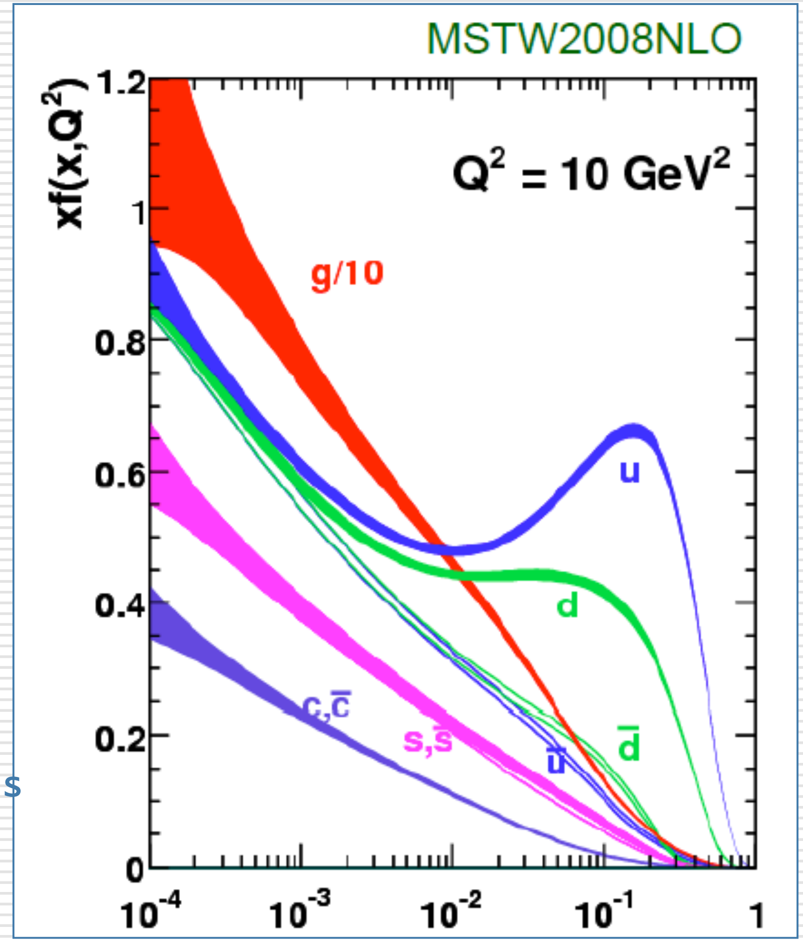


FIG. 27. "Soft-gluon" ($\Lambda = 200$ MeV) parton distributions of Duke and Owens (1984) at $Q^2 = 5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_v(x)$ (dotted line).

< 2002
Sets without uncertainty

2002-2003
MRST and CTEQ (global) + Alekhin (DIS) first parton sets with uncertainty

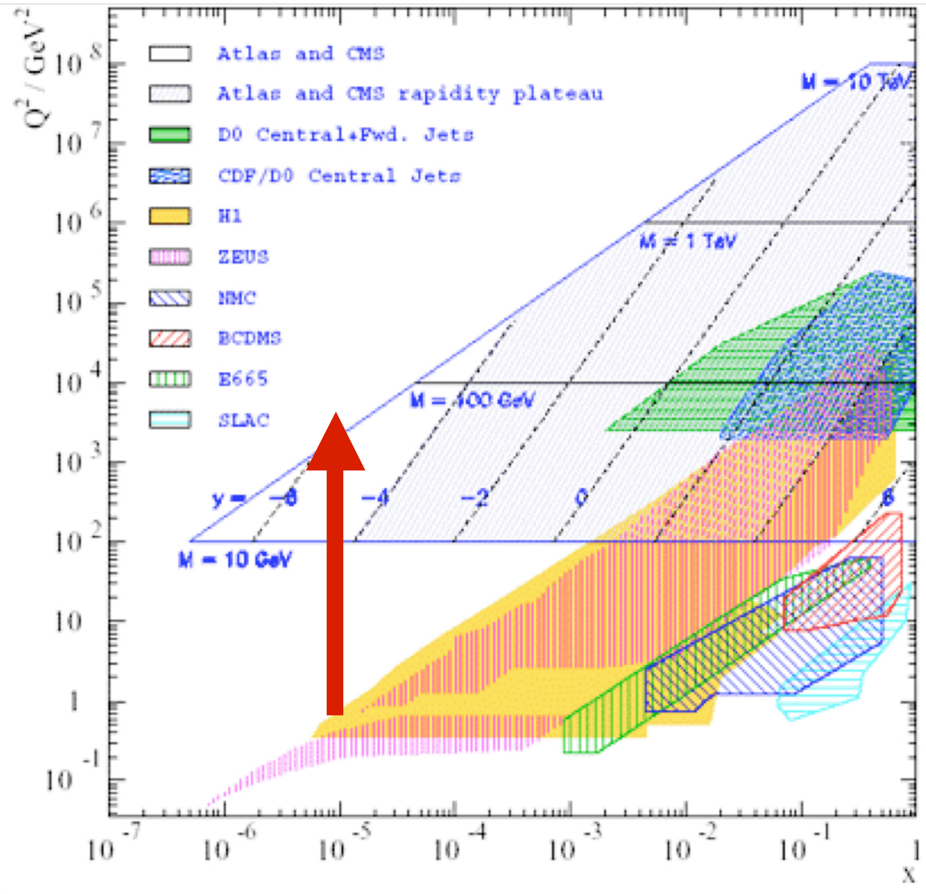
2003-2010
ABKM, CTEQ/CT, MSTW, NNPDF, HERAPDF, GJR more refined statistical analysis and theoretical treatment



1985 http://projects.hepforge.org/lhapdf/ 2010

Data

Where are PDFs extracted from?



PDFs are extracted mainly from

- **DIS data (Fixed Target and HERA)**
- Neutrino data
- Drell-Yan pair production
- Tevatron and HERA jets
- Tevatron vector boson productions

NC	$F_1^{\gamma,Z} = \sum_i e_i^2 (q_i + \bar{q}_i)$
CC	$F_1^{W^+} = \bar{u} + d + s + \bar{c}$
CC	$-F_3^{W^+}/2 = \bar{u} - d - s + \bar{c}$

$$F_2 = 2xF_1$$

- q, $\bar{q}$ at all $x>10^{-4}$
- g at moderate and small x, scaling and F_L
- Deuteron data: disentangle isospin triplet and singlet contr.

Data

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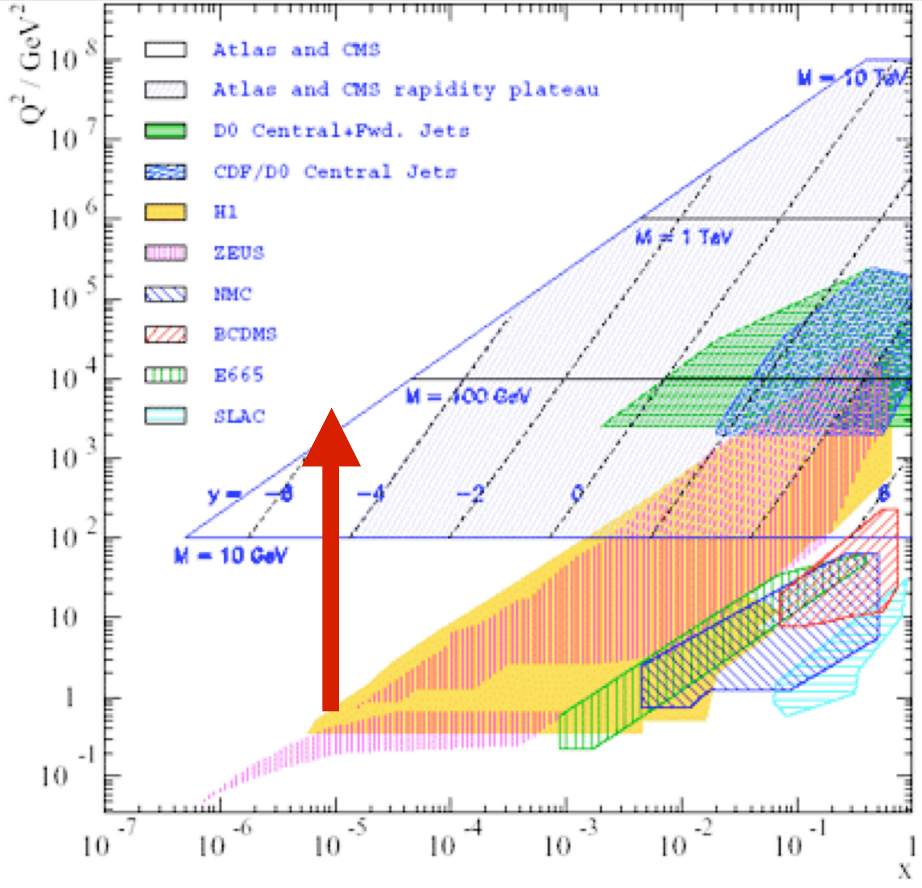

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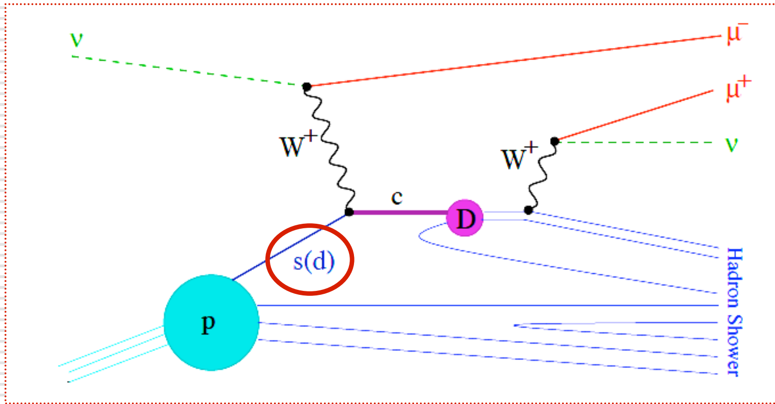

- s, $\bar{s}$ at moderate-x ($x > 10^{-2}$)

Data

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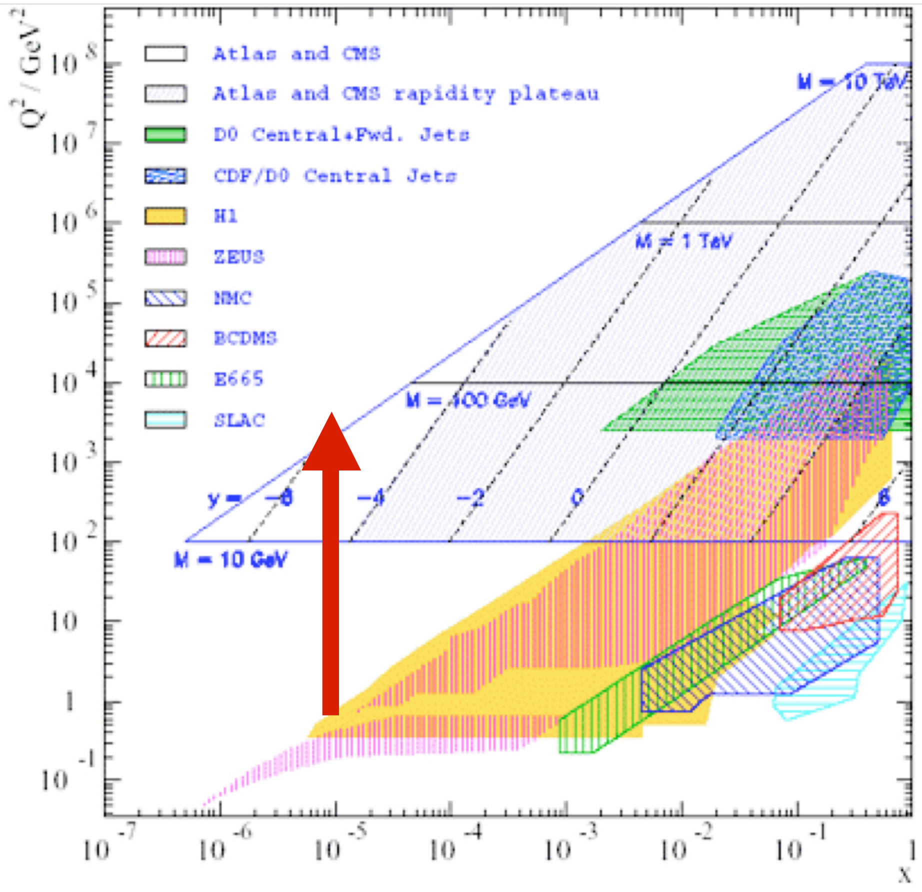

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$$\sigma^{DY,p} \propto u(x_1)\bar{u}(x_2) + d(x_1)\bar{d}(x_2)$$

$$\sigma^{DY,d} \propto u(x_1)(\bar{u}+\bar{d})(x_2) + d(x_1)(\bar{u}+\bar{d})(x_2)$$

$$A_W = \frac{d\sigma(W^+)/dy_{W^+} - d\sigma(W^-)/dy_{W^-}}{d\sigma(W^+)/dy_{W^+} + d\sigma(W^-)/dy_{W^-}}$$

$$\frac{u(x_1)d(x_2) - d(x_1)u(x_2)}{u(x_1)d(x_2) + d(x_1)u(x_2)}$$

Data

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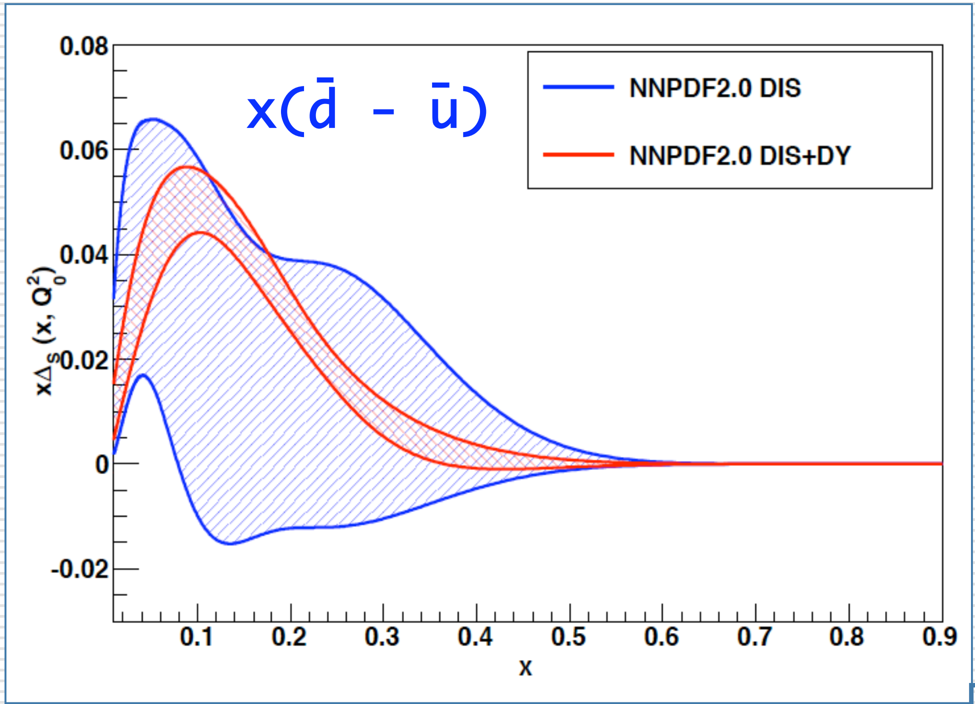

[NNPDF2.0, Ball et al, ArXiv: 1002.4407]

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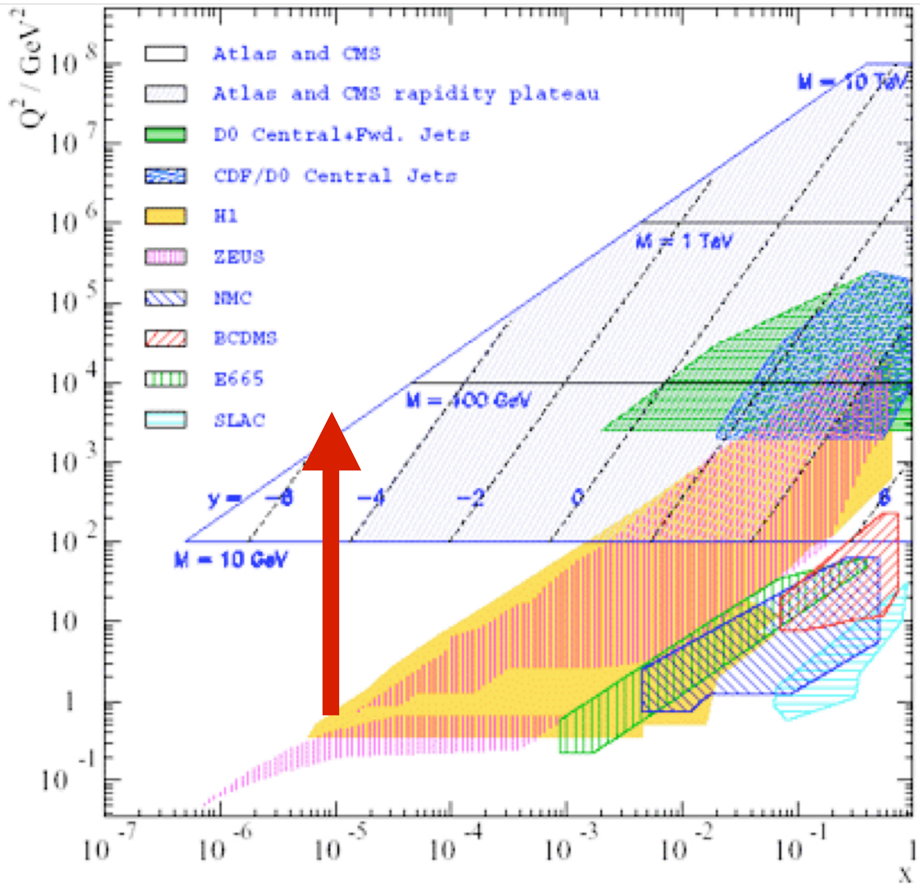

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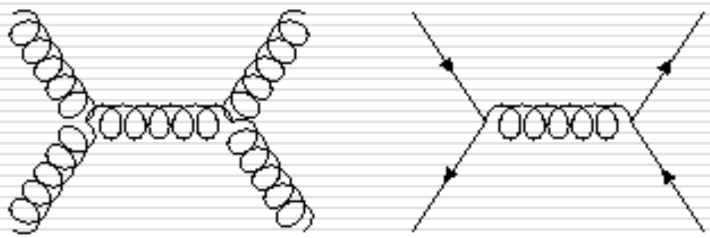
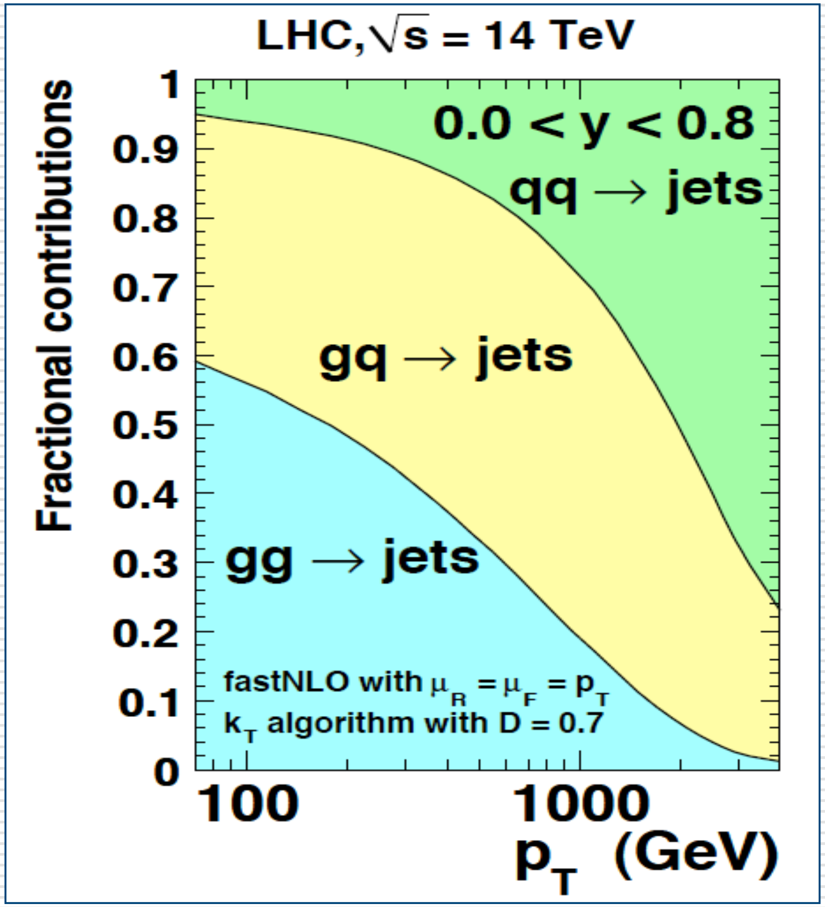


$$x_1^0 = \frac{p_T}{\sqrt{s}} e^{\eta} \,, \qquad x_2^0 = \frac{p_T}{\sqrt{s}} e^{-\eta}$$

Data

Where are PDFs extracted from?



[MSTW, ArXiv: 0901.0002]

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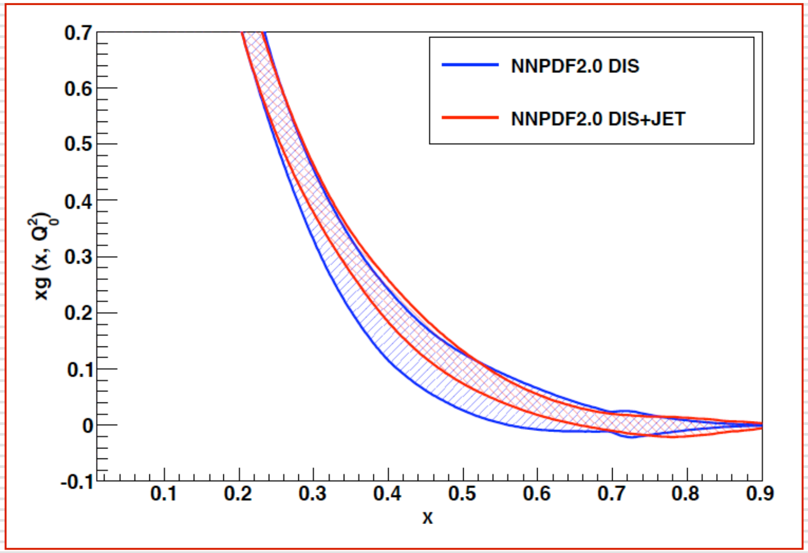


[NNPDF, 1002.4407]

Statistical issues

Error estimation and parametrization

- **Error estimation:**

$$\langle \mathcal{F}[f(x)] \rangle = \int [\mathcal{D}f]\, \mathcal{F}[f(x)] \mathcal{P}[f(x)]$$

  - Hessian method: project into parameter space and use linear approximation [CTEQ/CT, MSTW, HERAPDF, AB(K)M, (G)JR]
  - Monte Carlo sampling in the space of data [NNPDF, HERA studies]

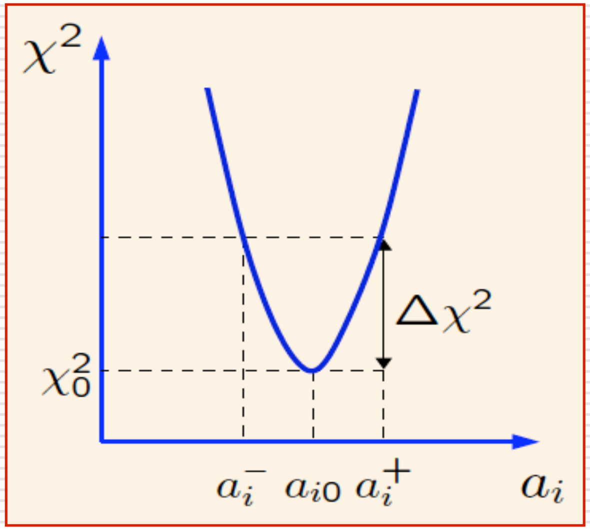
- **Parameterization:**

$$f_i(x, Q_0^2) = a_0\, x^{a_1}\, (1-x)^{a_2} P(x, a_3, a_4, \ldots),$$

  - Too rigid ➔ Global fit might not have flexibility to describe data or inadequate small uncertainties where there are no data
  - Too flexible ➔ Fit might develop artifacts driven by statistical fluctuations of the data

Statistical issues

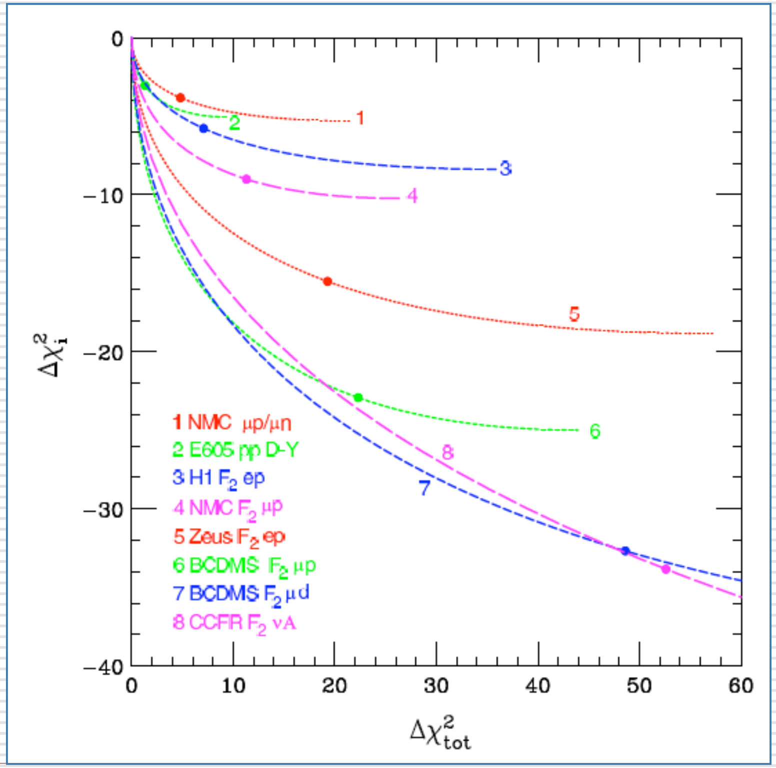
Error estimation: Hessian approach



$$\Delta\chi^2_{\text{global}} \equiv \chi^2_{\text{global}} - \chi^2_{\text{min}} = \sum_{i,j=1}^{n} H_{ij}(a_i - a_i^0)(a_j - a_j^0)$$

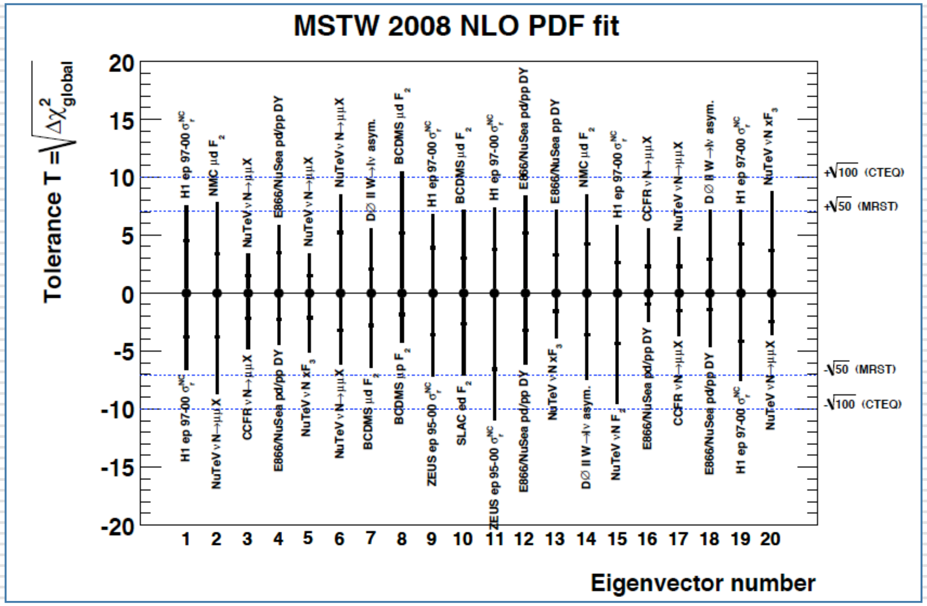
- Standard statistics: $\Delta\chi^2 = 1$
- Not adequate when dealing with large enough dataset. Incompatibilities?
- Determine T = $\Delta\chi^2 > 1$ considering χ^2_{exp} about global minimum. Take envelope.

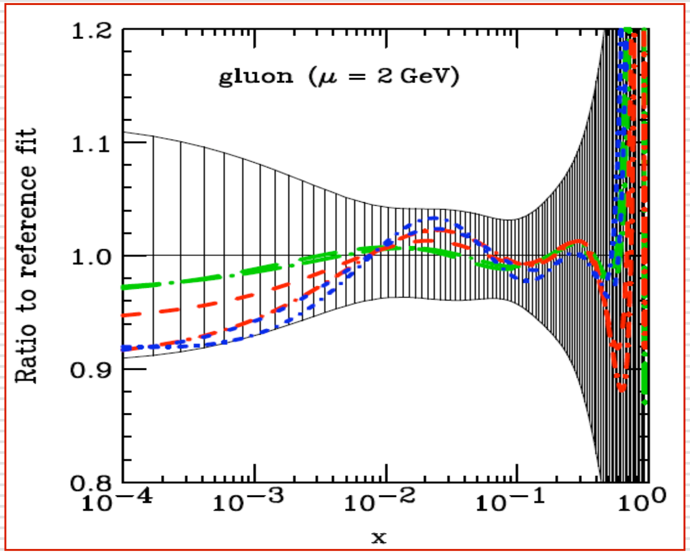
[Collins, Pumplin, hep-ph/0105207]



Statistical issues
Tolerance and parametrization

- $\Delta\chi^2 = 1$, AB(K)M fits and HERA (non global)
- $T^2 = 100$ [CTEQ6.6], $T^2 = 50$ [MRST2001]
- Uncertainty inflated by a factor 6 - 4?
- Concept refined by using dynamical tolerance [MSTW08], $T^2 \leq 40$, $8 < T^2 < 25$

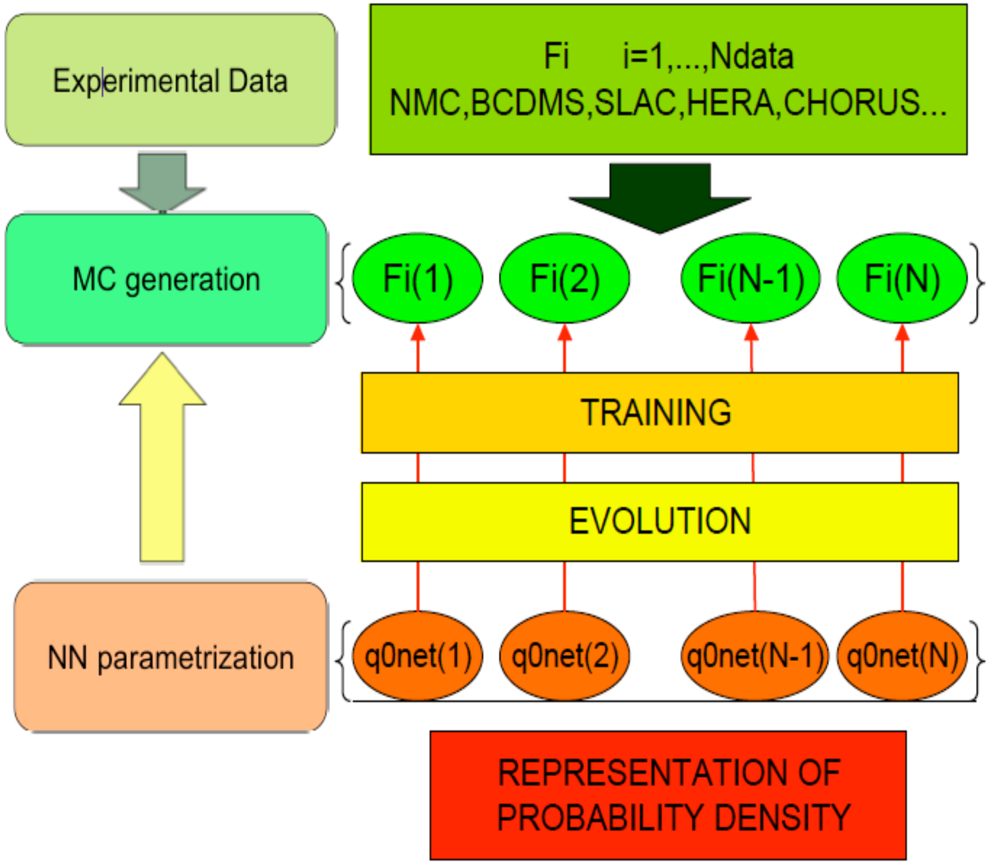


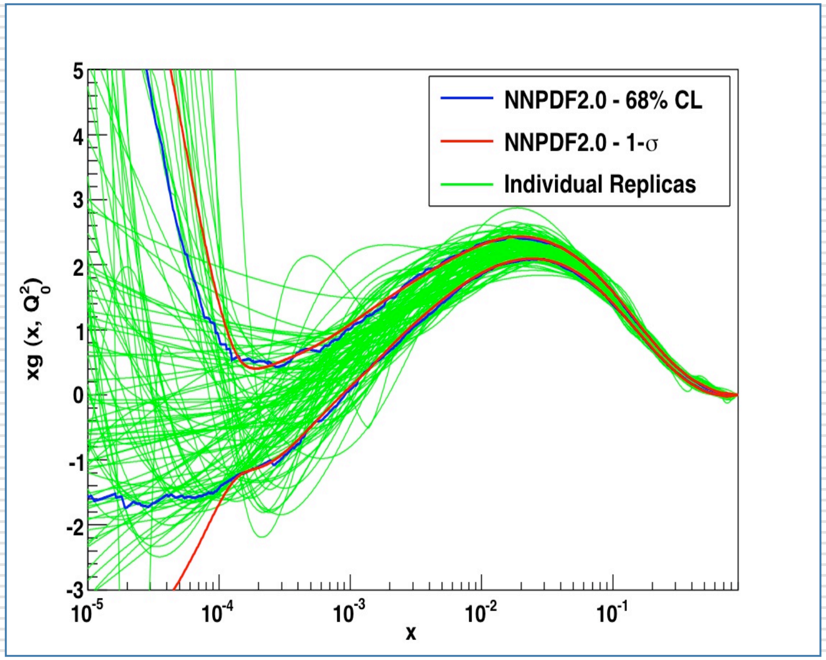


- J. Pumplin: data incompatibility or lack of flexibility in parametrization?
- Study of the distribution of distances between global and subset minima:
  $T^2 \sim 10$ [ArXiv: 0909.0268]
- Using more general parametrization obtain variations about χ^2_{min} which span additional [ArXiv:0909.5176]
  $T^2 = 10$ (CTEQ6.6 param)

Statistical issues
Error estimation: MC approach

- In the Monte Carlo approach the probability distribution in parameter space is given by assigning a Monte Carlo sample of replicas of the total parameter space





$$\left\langle F_i^{(\mathrm{net})} \right\rangle_{\mathrm{rep}} = \frac{1}{N_{\mathrm{rep}}} \sum_{k=1}^{N_{\mathrm{rep}}} F_i^{(\mathrm{net})(k)}$$

[NNPDF, Ball, Del Debbio, Forte, Guffanti, Latorre, Rojo, MU, 0808.1231]]

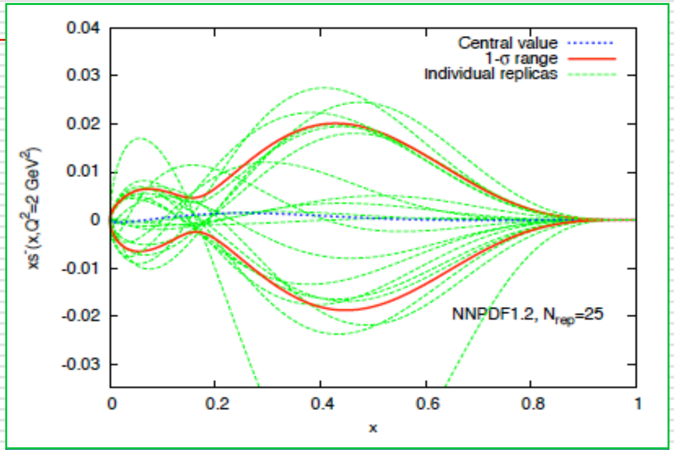
Statistical issues

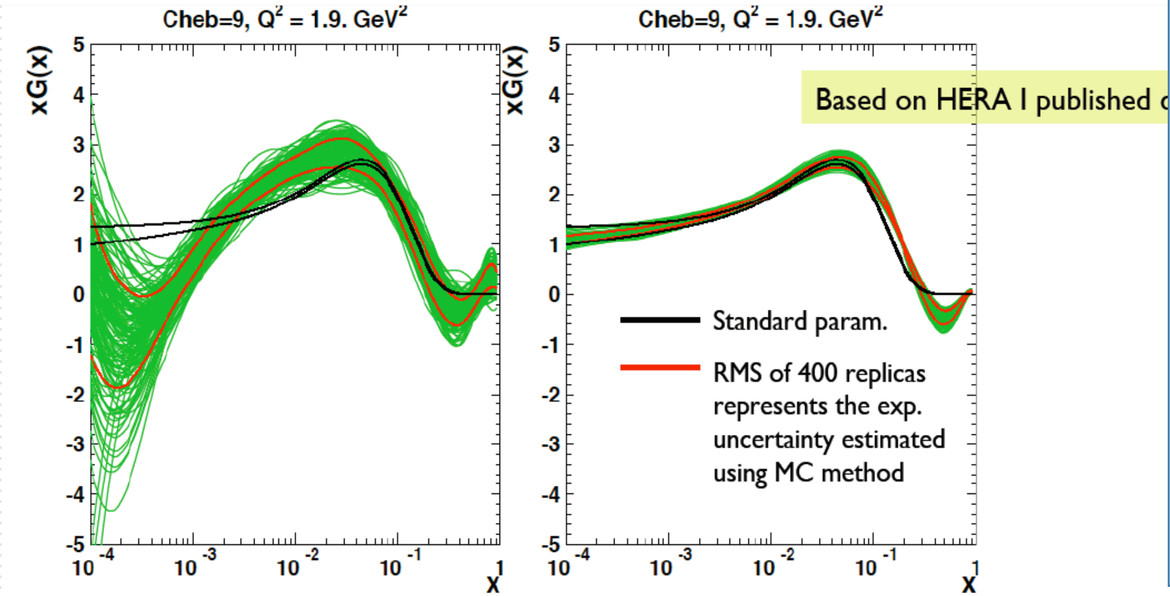
Parametrization

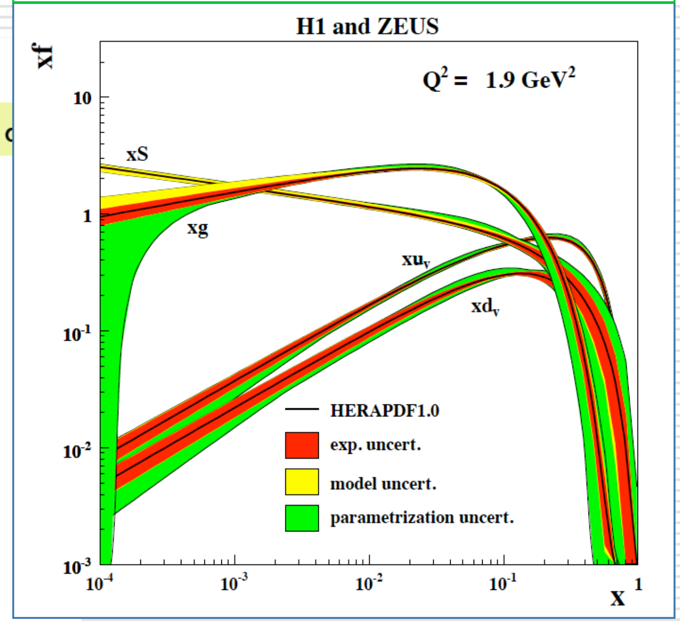
✓ NNPDF approach, large and redundant param coupled to dynamical stopping
[Ball et all, NNPDF, 0907.4614]

✓ Study of param bias using orthonormal Chebyshev polynomial with smoothness prior
[Glazov, Moch, Radescu, 1009.6170]

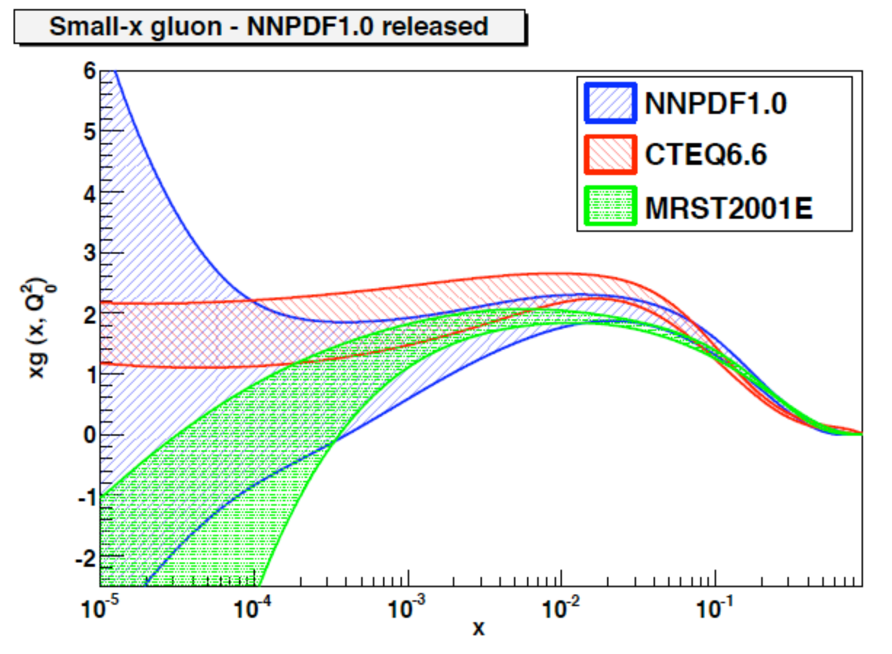
✓ Parametrization uncertainty is dominant in region where data do not constrain PDFs

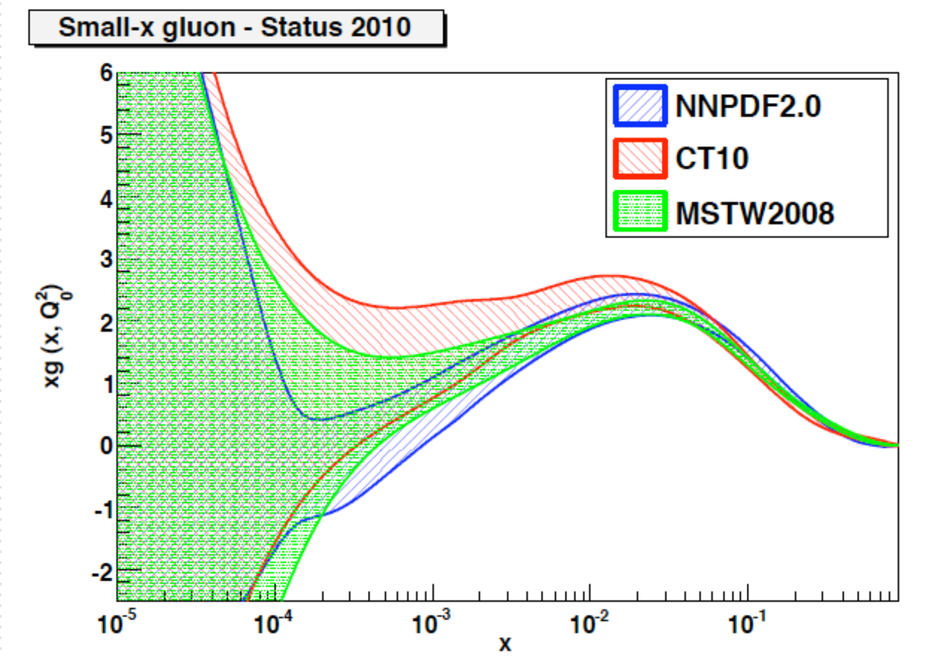






Statistical issues
Parametrization

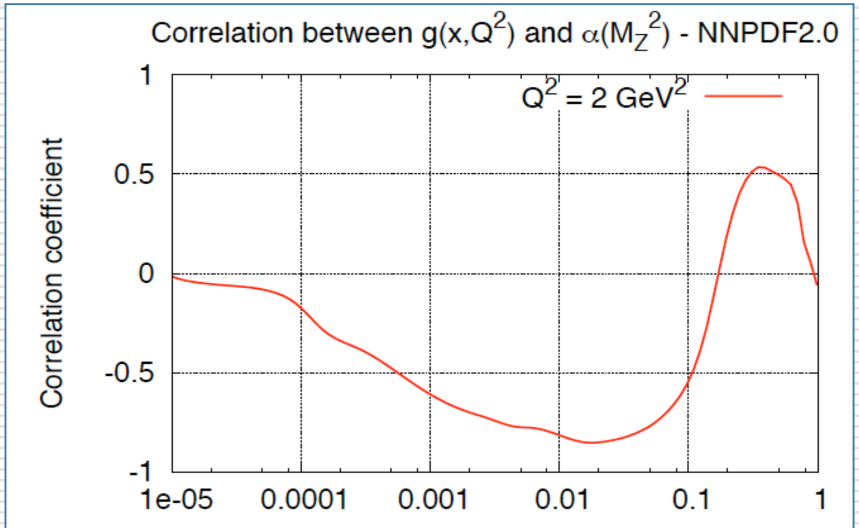




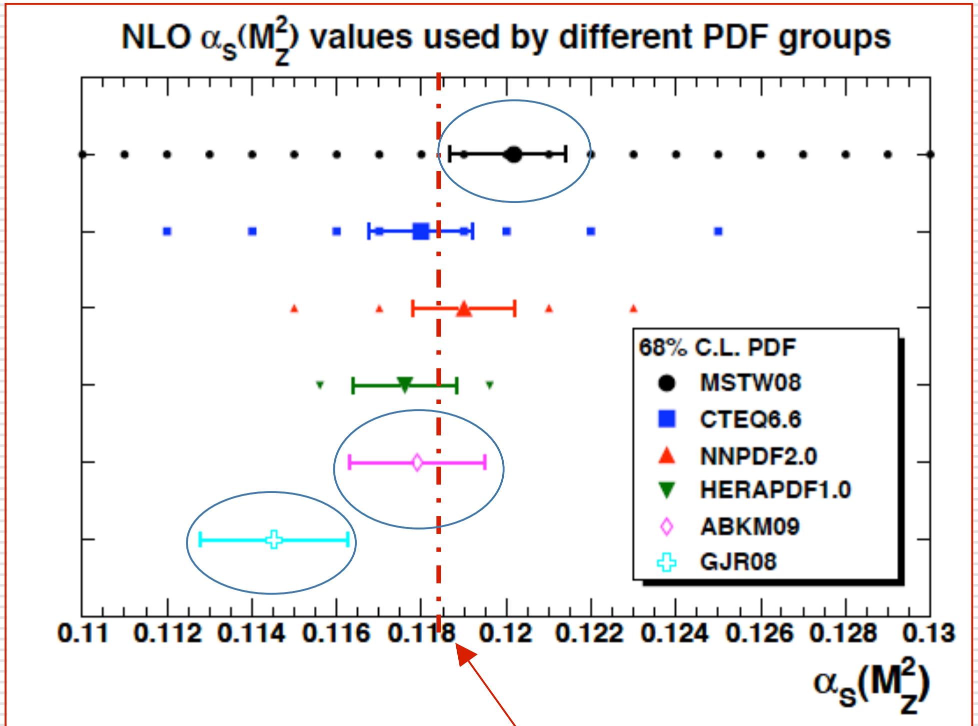
NNPDF1.0 ➔ NNPDF2.0 uses same parametrization for all fits
MRST2006 ➔ MSTW08 Added one param for small x gluon
CTEQ6.6 ➔ CT10 Added one param for small x gluon

Theoretical error
What α_s value should be used?

- PDFs and α_s strongly correlated
- How shall we compare predictions?
- Several groups (CTEQ/CT, MSTW, NNPDF, HERAPDF) provide varying PDF α_s sets: α_s can then be varied both in hard coefficients and PDFs
- What is a realistic α_s variation for phenomenology (±0.002)?



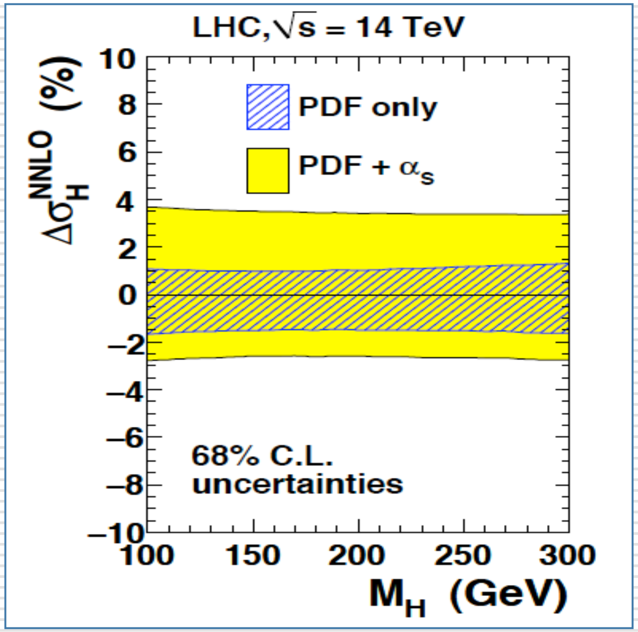
[1005.0397 M.U. et all]

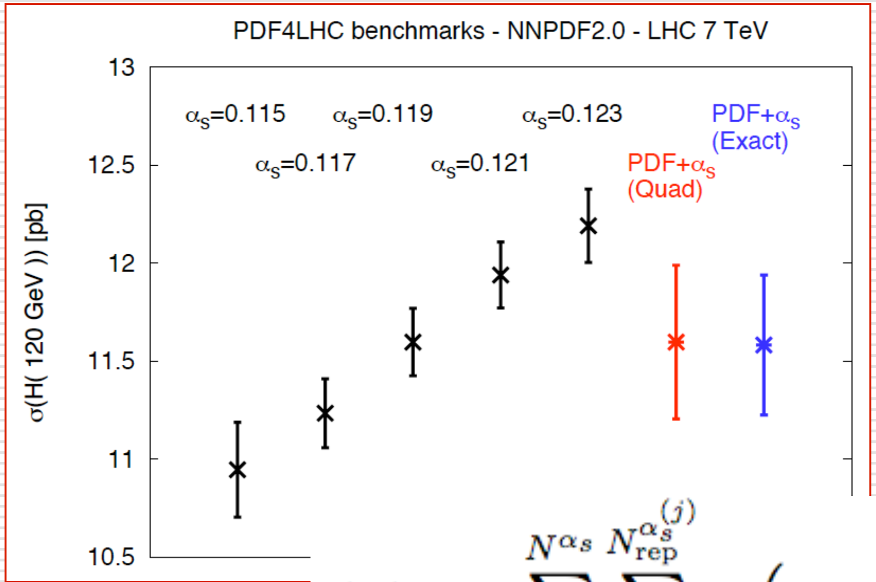


$\alpha_s = 0.1184 \pm 0.0007$
[Bethke 2009]

Theoretical error

Combined PDFs+α_s uncertainty



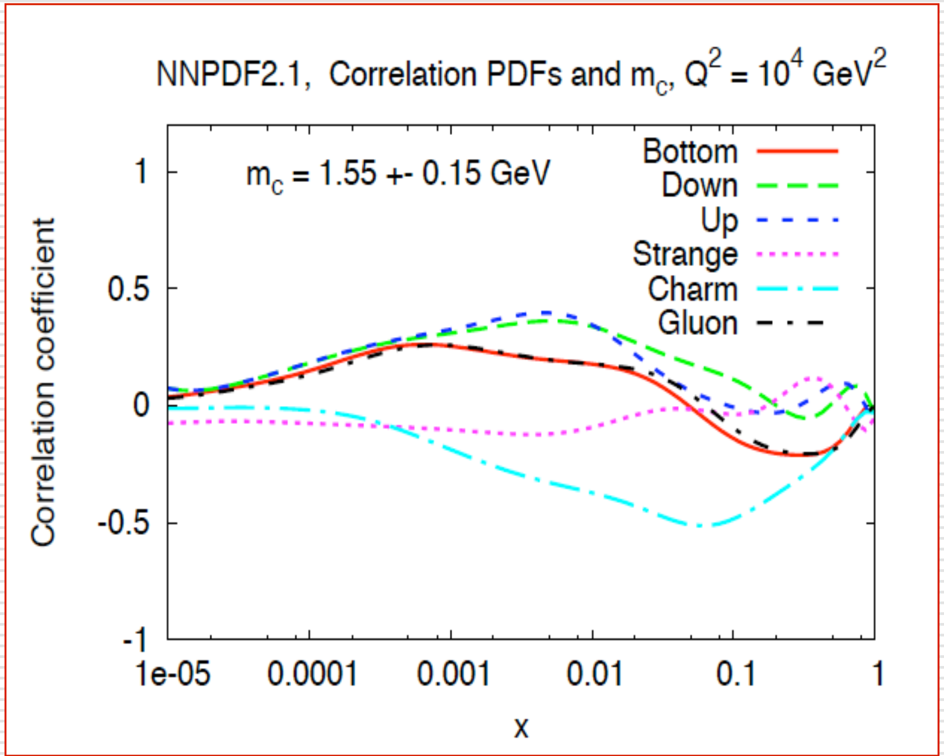


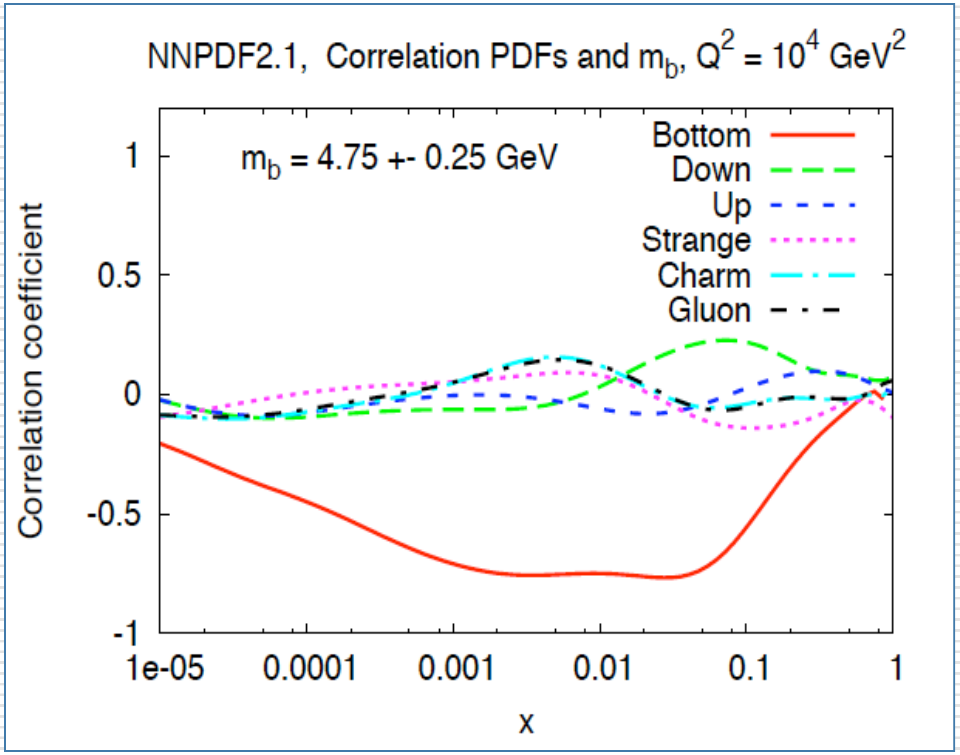
$$\langle \mathcal{F} \rangle_{\rm rep} = \sum_{j=1}^{N^{\alpha_s}} \sum_{k_j=1}^{N_{\rm rep}^{\alpha_s^{(j)}}} \mathcal{F}\left(PDF^{(k_j,j)}, \alpha_s^{(j)}\right)$$

- CTEQ/CT: Add them in quadrature, in Hessian approximation quadrature=exact [ArXiv:1004.4624]
- MSTW: Use variation of α_s (68% CL ,90%CL) associated to different PDF error sets [ArXiv:0905.3531]
- NNPDF: Exact α_s+PDFs uncertainty obtained as average over the joined PDF-α_s Monte Carlo ensemble [ArXiv:1005.0397]

Theoretical error

PDFs+m_Q uncertainty

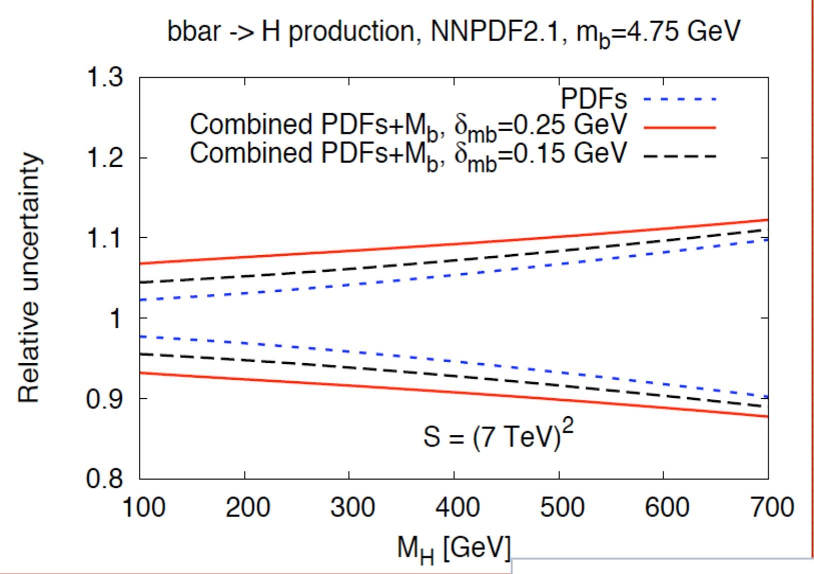




Theoretical error

PDFs+m_Q uncertainty

[J. Rojo talk, PDF4LHC Nov 2010]



$$\langle \mathcal{F} \rangle_{\rm rep} = \frac{1}{N_{\rm rep}} \sum_{i=1}^{N_{m_c}} \sum_{j=1}^{N_{m_b}} \sum_{k_{ij}=1}^{N_{\rm rep}^{(i,j)}} \mathcal{F}\left(\mathrm{PDF}^{(k_{ij},i,j)}, m_c^{(i)}, m_b^{(j)}\right)$$

$$N_{\rm rep}^{(i,j)} \propto \exp\left(-\frac{\left(m_c^{(i)} - m_c^{(0)}\right)^2}{2\delta^2_{m_c}} - \frac{\left(m_b^{(j)} - m_b^{(0)}\right)^2}{2\delta^2_{m_b}} \right)$$

- For some processes Δ(PDFs+δm_Q) can be up to twice Δ(PDFs)
- 40% variation in size of uncertainty for W production @14TeV

[MSTW, ArXiv: 1007.2624]

LHC, $\sqrt{s} = 14$ TeV	$B_{\ell\nu} \cdot \sigma^W$	$B_{\ell^+\ell^-} \cdot \sigma^Z$	σ^H
Central value	21.72 nb	2.051 nb	50.51 pb
PDF only uncertainty	+1.7% −1.7%	+1.7% −1.6%	+1.0% −1.6%
PDF+α_S uncertainty	+2.6% −2.2%	+2.6% −2.1%	+3.6% −2.7%
PDF+α_S+$m_{c,b}$ uncertainty	+3.0% −2.7%	+3.1% −2.8%	+3.7% −2.8%

Theoretical error

Treatment of heavy quarks in DIS

Two distinct regimes:

❶ When $Q^2 \sim m_H^2$, heavy quarks not partons. Created in the final states.
FFN description with $n_f = n_l$

$$F(x,Q^2) = C_k^{(nl)}(Q^2/m^2_H) \otimes f^{(nl)}_k(Q^2)$$

FFN does not resum collinear logs of the mass of the heavy quark

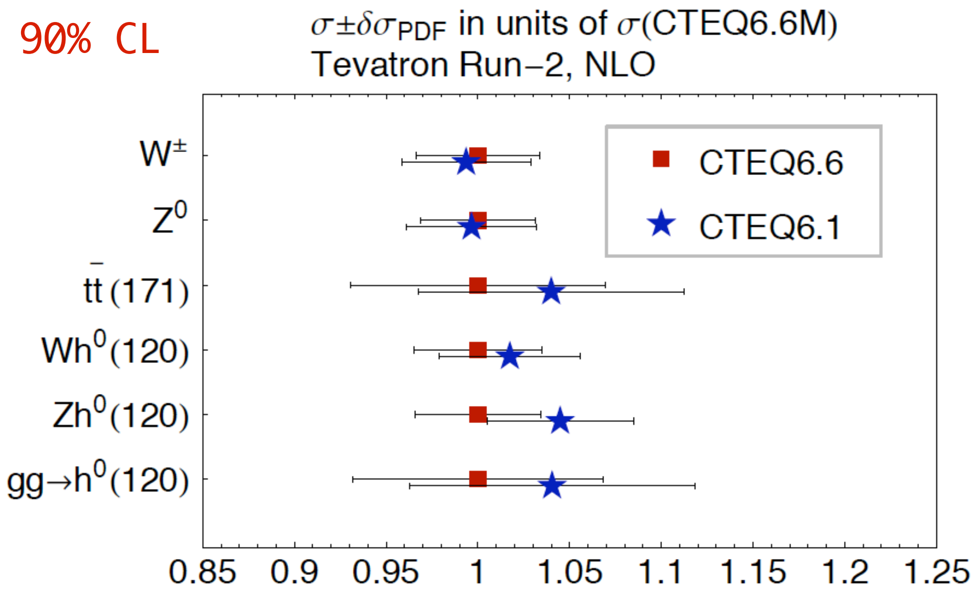
❷ When $Q^2 \gg m_H^2$ heavy quark massless partons.
ZM-VFN description with $n_f = n_a$

$$F(x,Q^2) = C_k^{(na)}(m^2_H=0) \otimes f^{(na)}_k(Q^2)$$

$\mathrm{Log}(m_H^2/Q^2)$ are resummed in PDFs evolution but $O(m_H^2/Q^2)$ terms are ignored

➔ Two regimes matched in
GM-VFNS description
Several schemes [ACOT, RT, RT', FONLL]

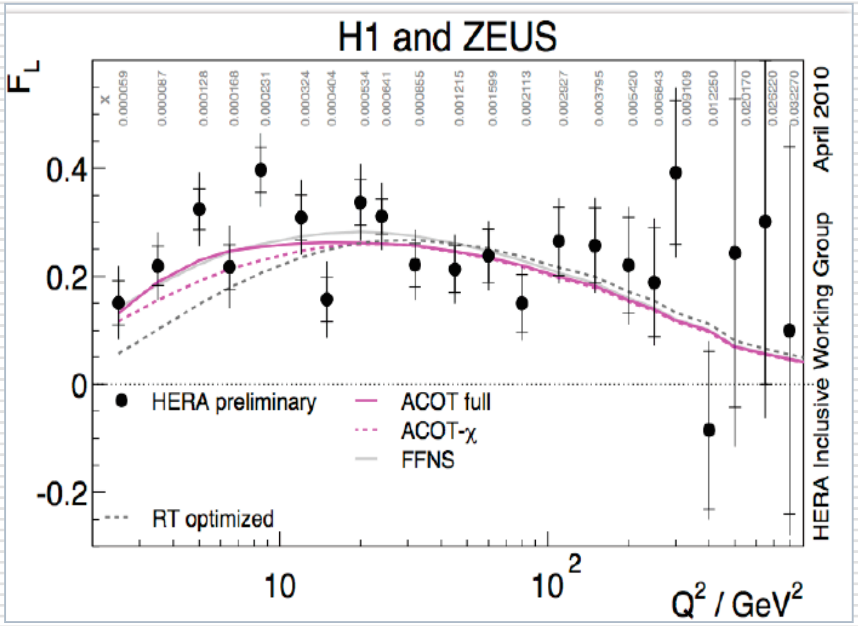
90% CL

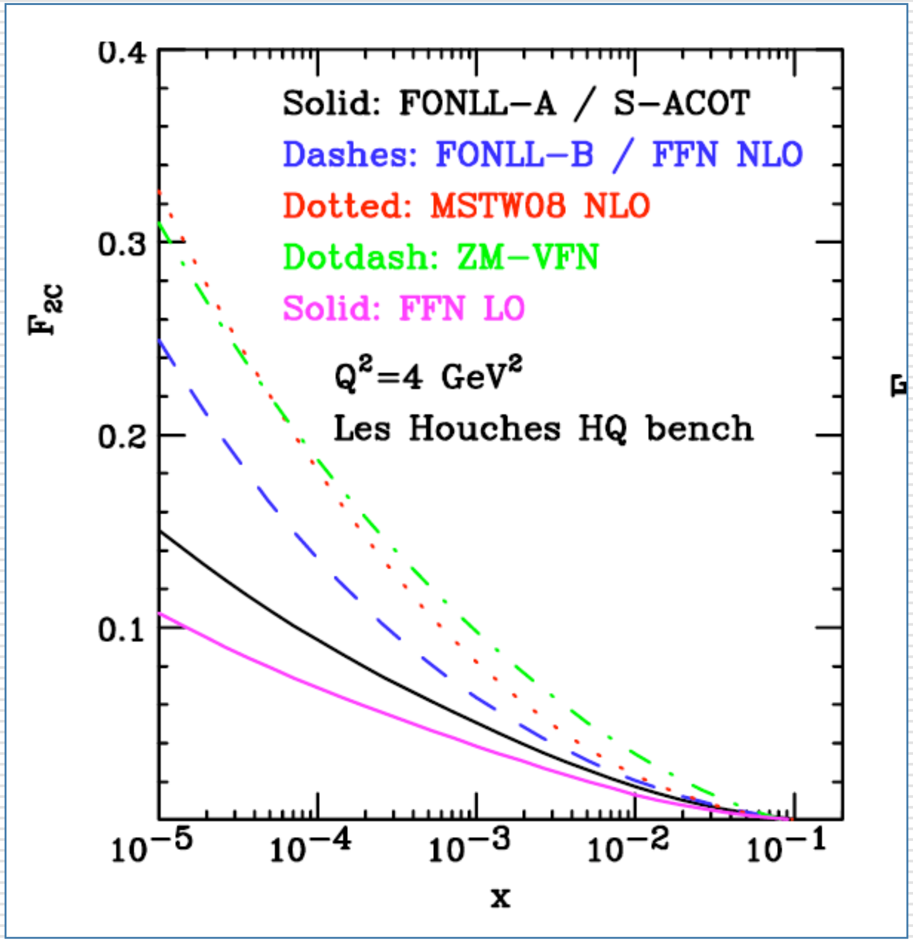


CTEQ61 does not include $O(m_H^2/Q^2)$ terms
ZM-VFNS scheme

CTEQ66 does include $O(m_H^2/Q^2)$ terms
ACOT scheme

Theoretical error
Heavy quarks in DIS





- All GM-VFNS include terms included in ZM-VFN scheme and FFNS at a given order in PT, but sub-leading terms are different
- The latter may have a not negligible impact
- See LH benchmark [Andersen et al, 1003.1241] and HERA studies [Placakyte's talk, QCD@LHC]

Theoretical error
Tools for including higher orders

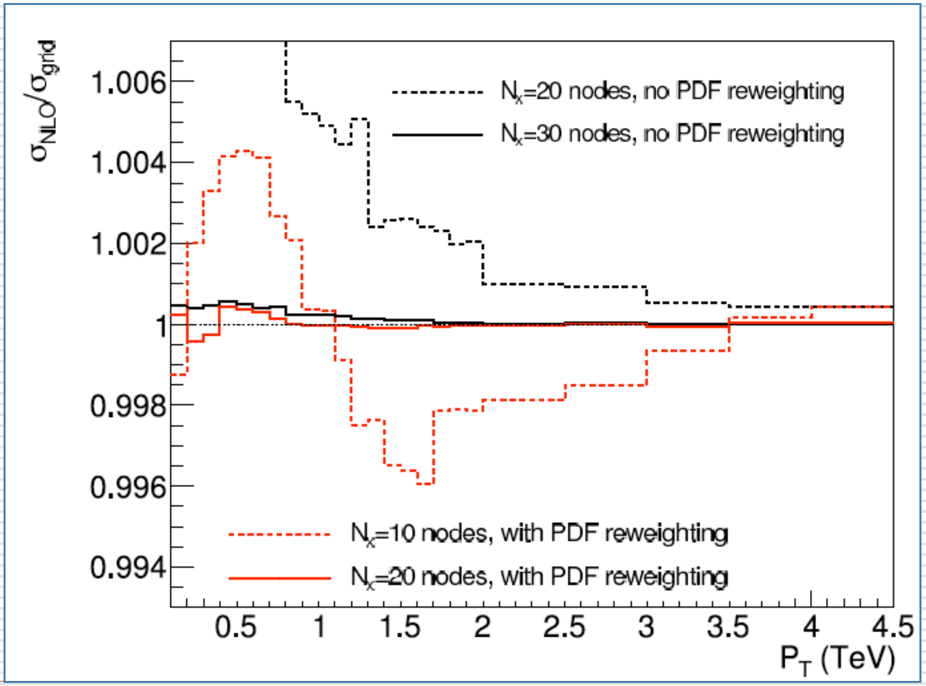
$$d\sigma = \sum_p \sum_{m=1}^{N} w_m^{(p)} \left(\frac{\alpha_s(Q_m^2)}{2\pi}\right)^p f_1(x_{1m}, Q_m^2)\, f_2(x_{2m}, Q_m^2)$$

- NLO/NNLO computations of hadronic processes too slow for parton fits
  ➔ K-factor approximation

- Interpolation grid-based methods provide fast and accurate computation of NLO/NNLO cross-sections

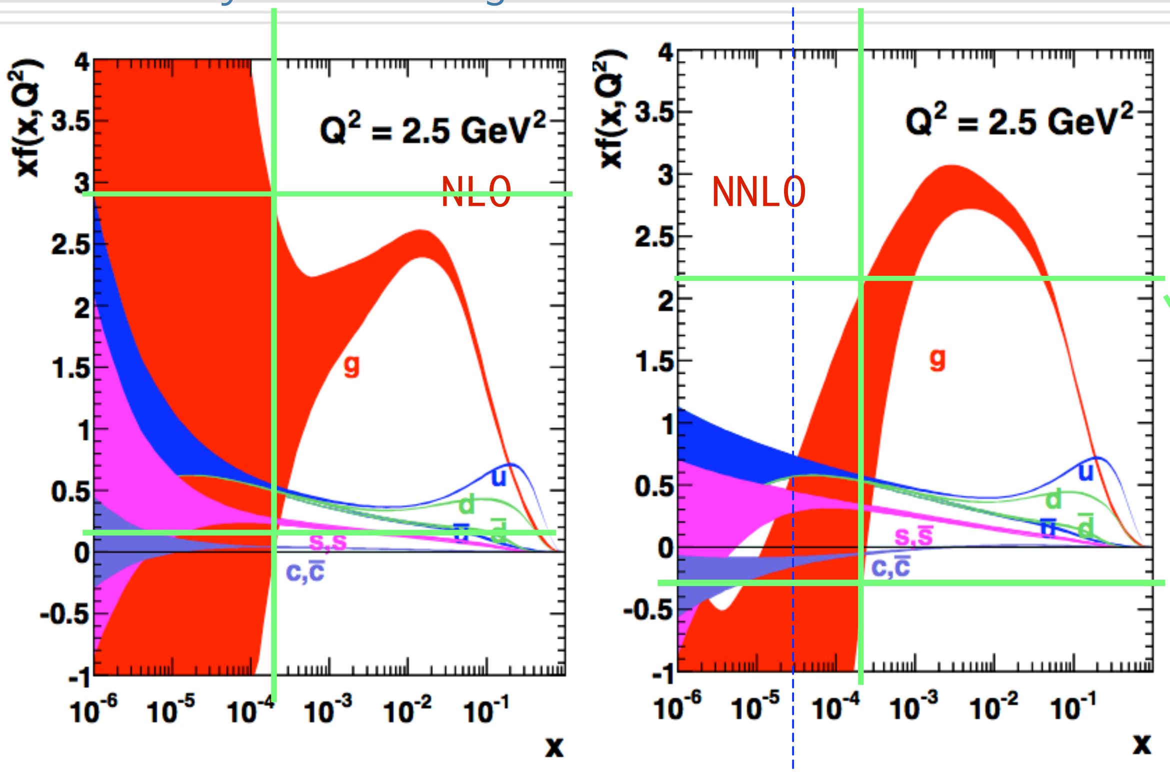
- FastNLO for jet cross-sections
  [Kluge, Rabbetz, Wobbech, 2006]
- APPLGRID potentially universal interface implemented for jets, W and Z production
  [Carli et all, 2009]
- FastKernel interfaced to N-space computation of DGLAP Green functions, fast-DY
  [Ball et all, 2009]

[Carli et al, ArXiv:0911.2985]



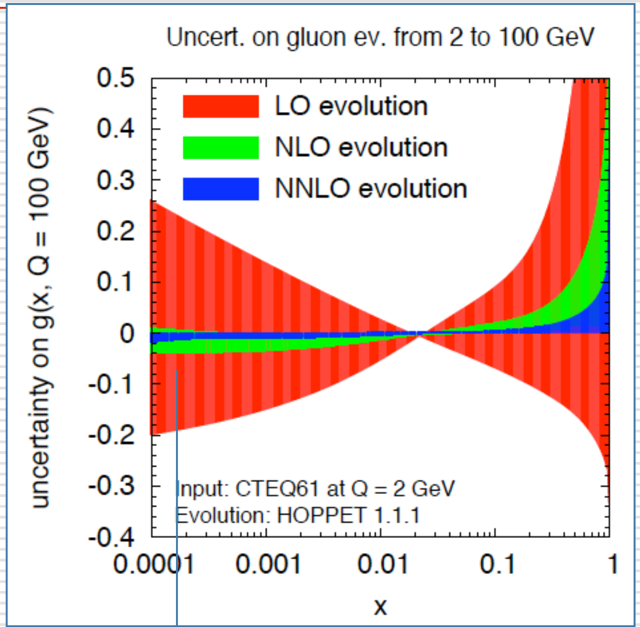
Theoretical error
Higher orders: NNLO

- ✓ NNLO parton sets to match NNLO theoretical predictions
- ✓ NNLO evolution reduces theoretical uncertainty
- ✓ Caveat: jets cross-sections and coefficient functions for massive heavy quark production still at NLO
- ✓ NNLO partons: only slight improvement of global χ^2, and uncertainty in data region.



extrapolation

MSTW08, 0901.0002



Salam, 1011.5131

scale variation

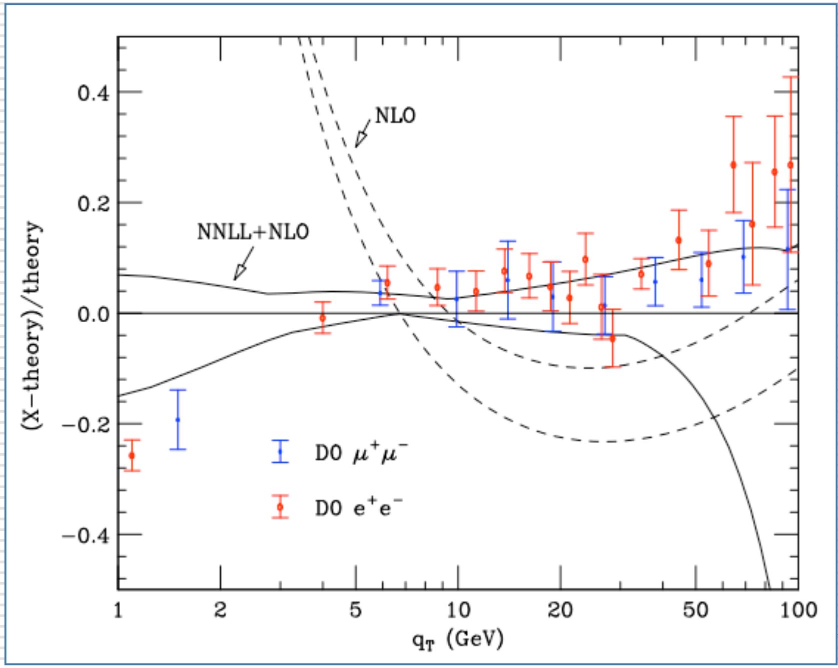
PDFs uncertainty

Theoretical error

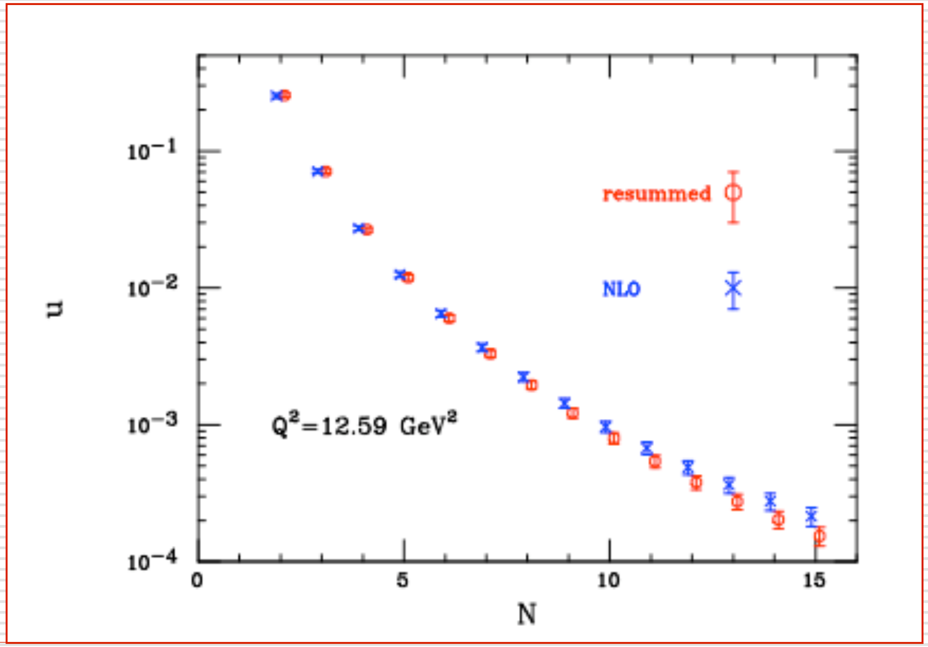
Higher orders: beyond NNLO

- Beyond NNLO?
- Neither small-x (high-energy) nor large-x (threshold) resummations have been systematically incorporated in current parton fits
- Some attempts at large-x limited to DIS [Corcella, Magnea, 2005]
- And small-x [Thorne, White 2007], [Rojo et al 2009]

THRESHOLD RESUMMATION IN DY PAIR PRODUCTION



SMALL IMPACT FOR DIS, TOY PDFs



[Bozzi, Catani, Ferrera, de Florian, Grazzini 2010]

Parton Distribution Functions

Most recent partonic fits

	Data	Pert. Order	HQ scheme	a_s	Parametrisation	Stat. treatment
CT10(w)	global eP & PP data (combined HERA)	NLO	SACOT-chi	external parameter - several as values	6 independent PDFs Polynomial param 26 pars	Hessian with dynamical tolerance
MSTW08	global eP & PP data (HERA jets)	LO NLO NNLO (*)	ACOT + TR'	external parameter - several as + fitted	7 independent PDFs Polynomial param 20(28) pars	Hessian with dynamic tolerance
NNPDF2.1	global eP & PP data (combined HERA)	NLO	FONLL-A	external parameter - several as values	7 independent PDFs Neural Networks 259 pars	Monte Carlo sampling + cross validation
HERAPDF1.0 HERAPDF1.5	DIS HERA data [1.5] Added prel HERA II	NLO NNLO	ACOT + TR'	external parameter	5 independent PDFs Polynomial param + Chebyshev polynomial	Conventional Hessian, Monte Carlo
ABKM09 ABM10	global DIS + Fixed-Target DY (combined HERA)	NLO NNLO	FFNS n_f=4 matched with BMSN	fitted,not external parameter	6 independent PDFs Polynomial param	Hessian with no tolerance
JR08	DIS + Jets + Fixed-Target DY	NLO NNLO	FFN, nf=3 VFN	fitted,not external parameter	5 independent PDFs Valence-like assumpt 20 pars	Hessian with fixed tolerance

PART II

PDFs and the LHC

- Comparisons between PDF sets
- Learning about PDFs from LHC measurements

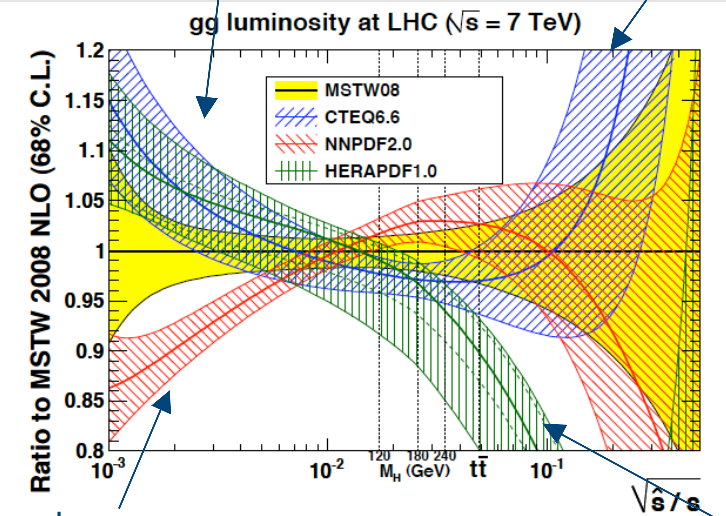
PDFs @ the LHC

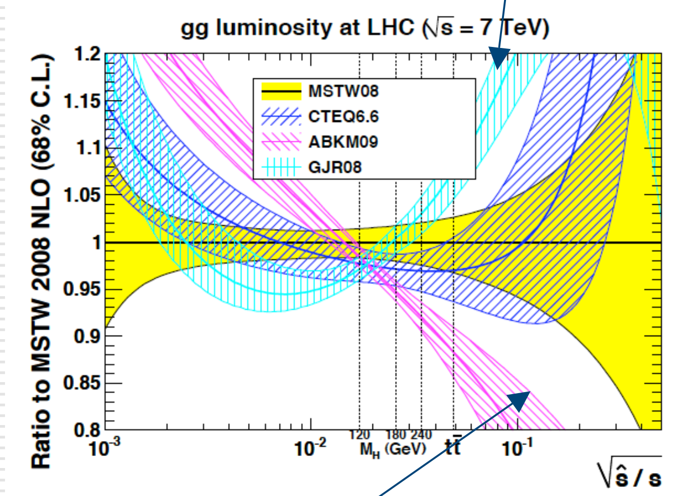
Where do we stand?

run I versus run II jet data

positivity constraint on input gluon

more restricted parametrization





ZM-VFNS scheme

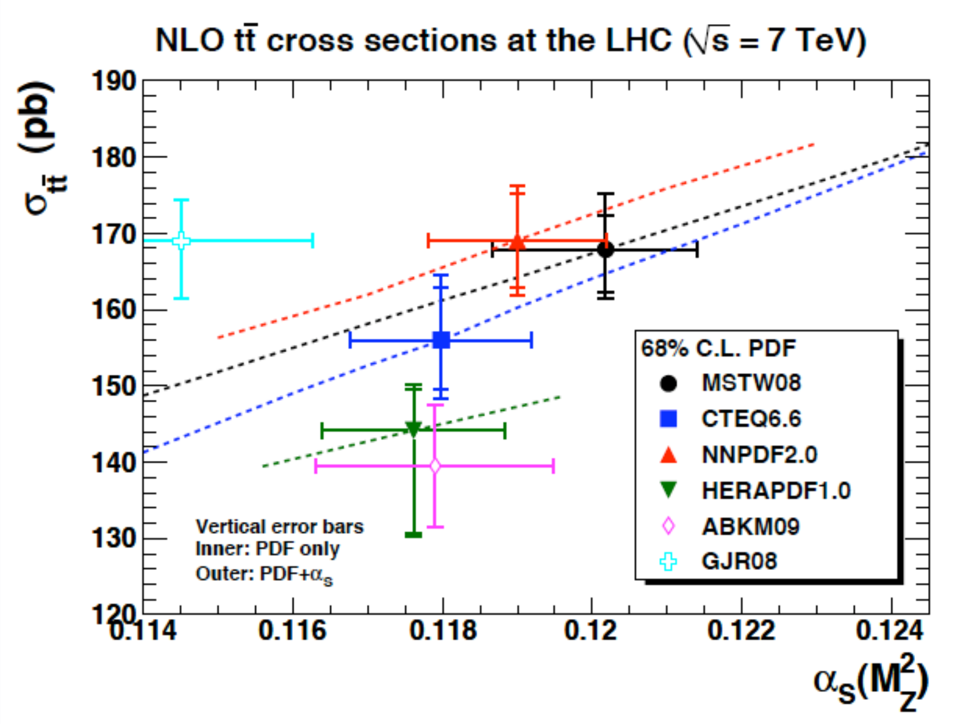
no Tevatron data nor FT DIS

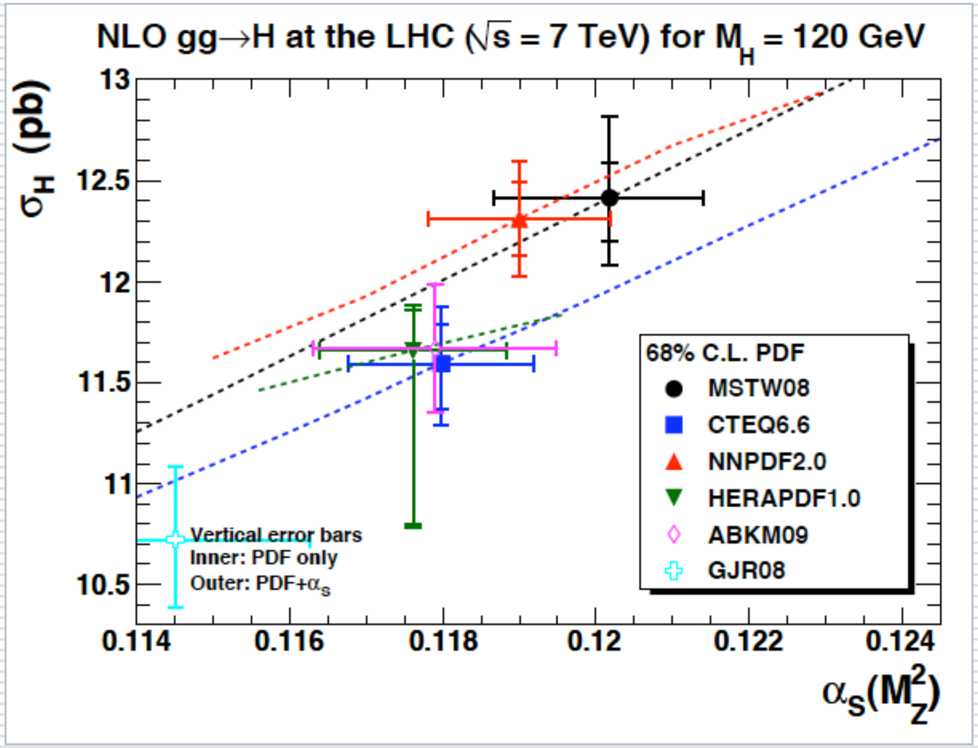
$$\frac{dL_{ij}}{d\hat{s}\,dy} = \frac{1}{s}\,\frac{1}{1+\delta_{ij}}\left[f_i(x_1,\mu)f_j(x_2,\mu) + (1 \leftrightarrow 2)\right]$$

Parton luminosities

PDFs @ the LHC

Where do we stand?

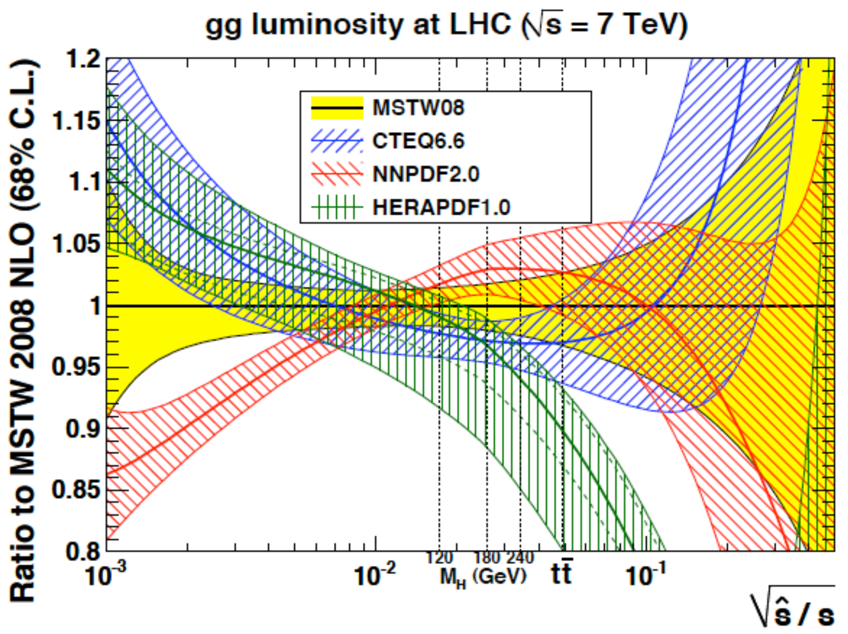


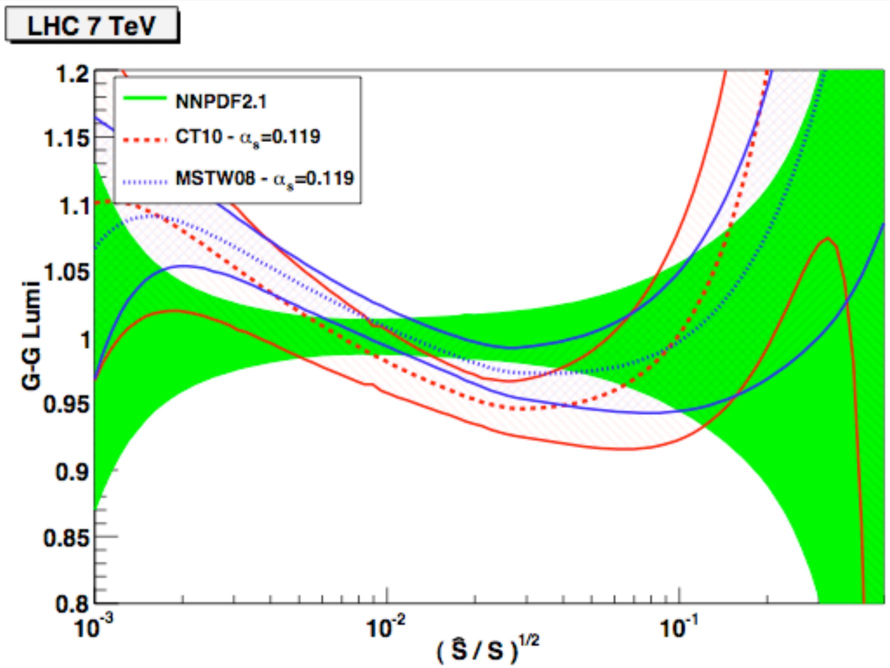


$$\sigma = \sum_{i,j} \int \left(\frac{d\hat{s}}{\hat{s}}\right) \left(\frac{dL_{ij}}{d\hat{s}}\right) (\hat{s}\,\hat{\sigma}_{ij})$$

cross-sections

PDFs @ the LHC
Towards an increasing agreement





$$\frac{dL_{ij}}{d\hat{s}\,dy} = \frac{1}{s}\frac{1}{1+\delta_{ij}}\left[f_i(x_1,\mu)f_j(x_2,\mu) + (1 \leftrightarrow 2)\right]$$

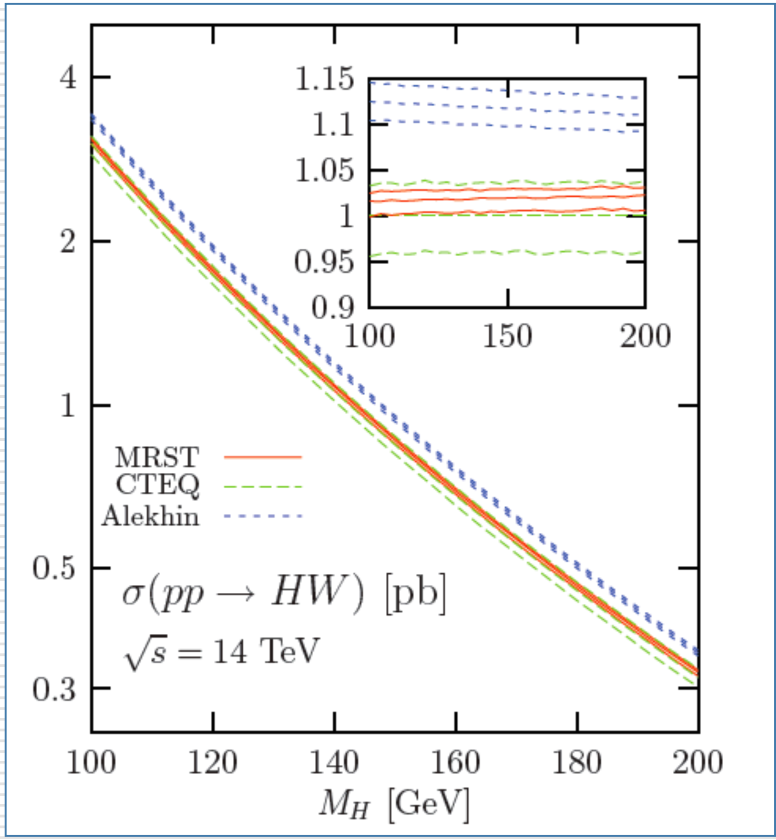
Parton luminosities

PDFs @ the LHC

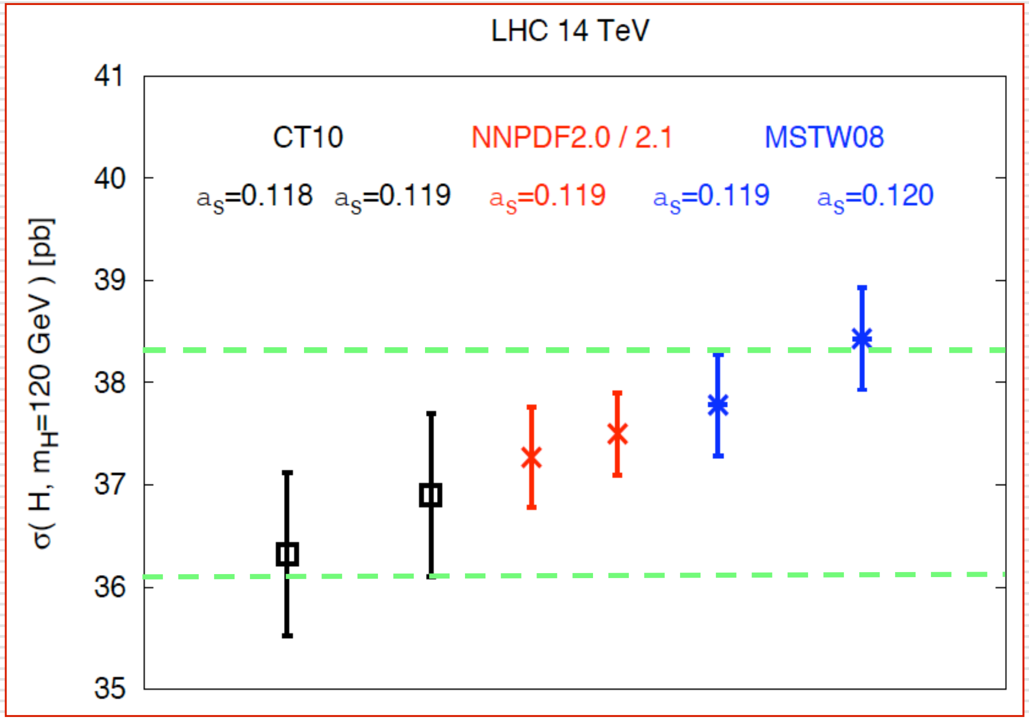
Towards an increasing agreement

Example: Higgs cross-section

2003



2010

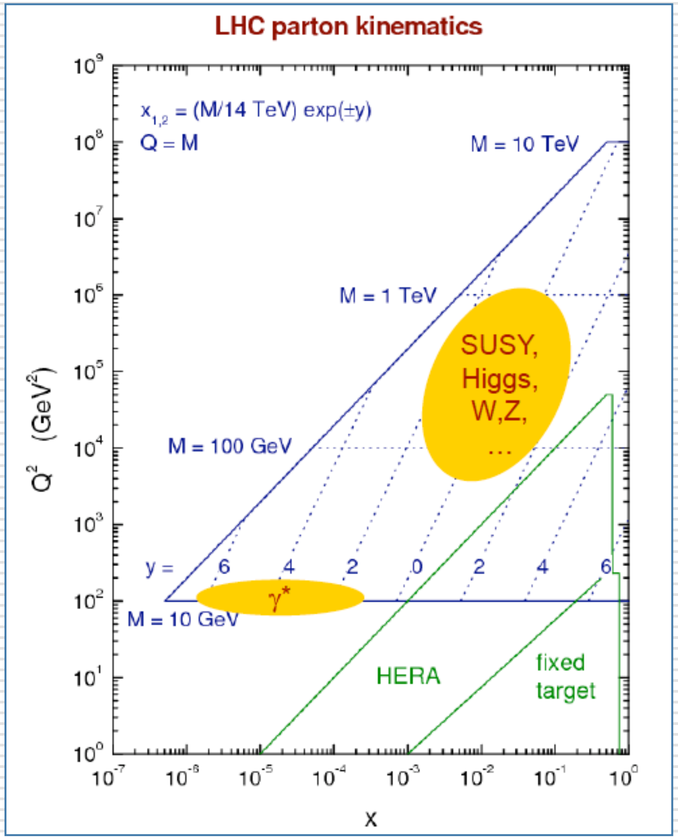


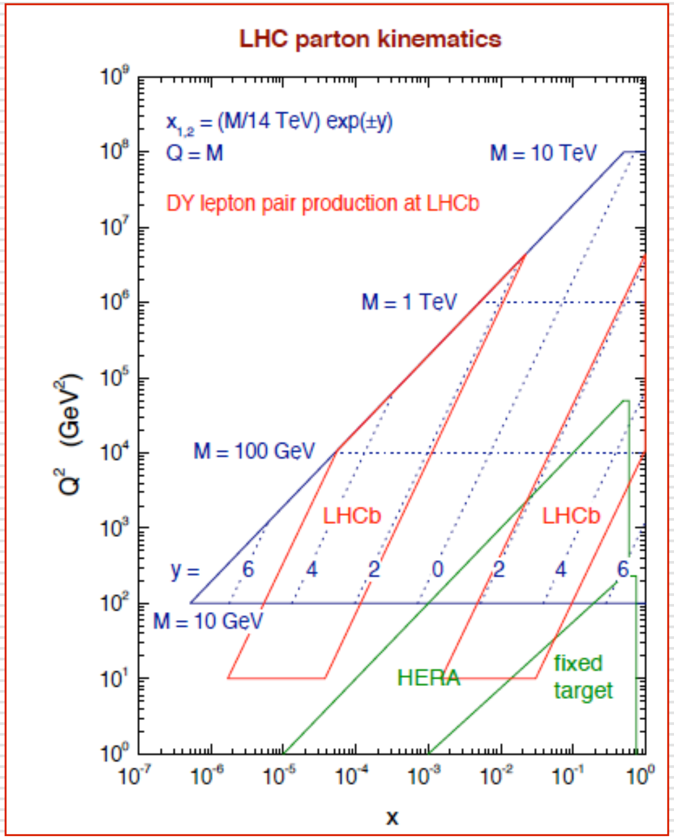
Djouadi, Ferrag hep-ph/0310209

PDFs and the LHC

Learning more about PDFs from LHC

- W and Z production at higher center of mass energy and higher statistics
- Prompt photon, heavy quark production...
- Ratios between standard candles by exploiting correlations
- LHCb: unique η range $1.9 < y < 4.9$ and trigger on low momentum muon $p > 8$ GeV, $p_T > 1$ GeV





J. Stirling plots

PDFs and the LHC

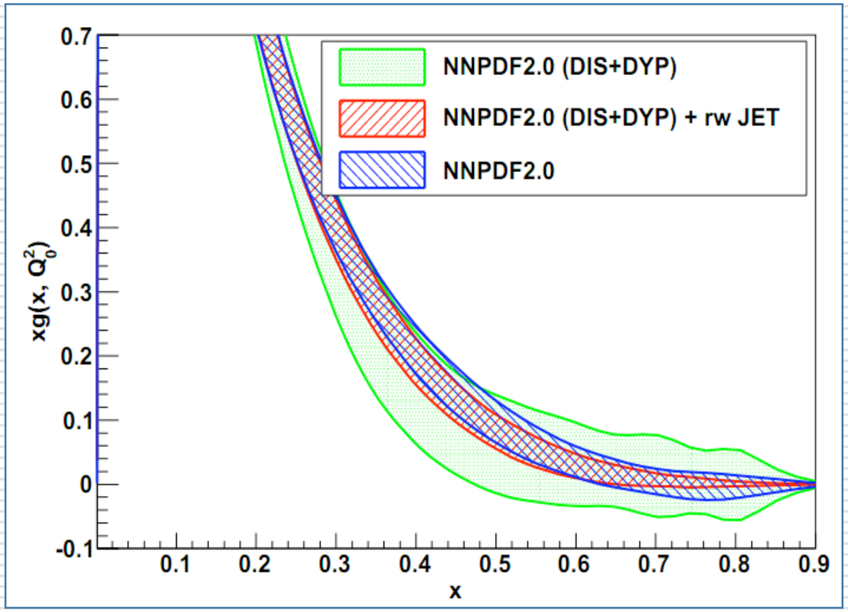
Bayesian reweighting

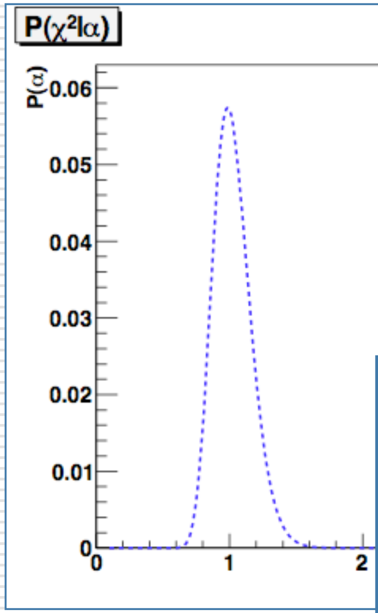
✓ In a MC approach one can update the probability distribution after including the information from new data (Bayes' theorem)

[Ball et al, 1012.0836]

$$\langle \mathcal{O} \rangle_{\rm new} = \int \mathcal{O}[f]\mathcal{P}_{\rm new}(f)\mathcal{D}f = \frac{1}{N}\sum_{k=1}^{N} w_k \mathcal{O}[f^{(k)}]$$

$$\mathcal{N}_\chi \, (\chi^2_k)^{n/2-1} \, e^{-\frac{1}{2}\chi^2_k}$$





$$\chi^2_\alpha = \chi^2/\alpha$$

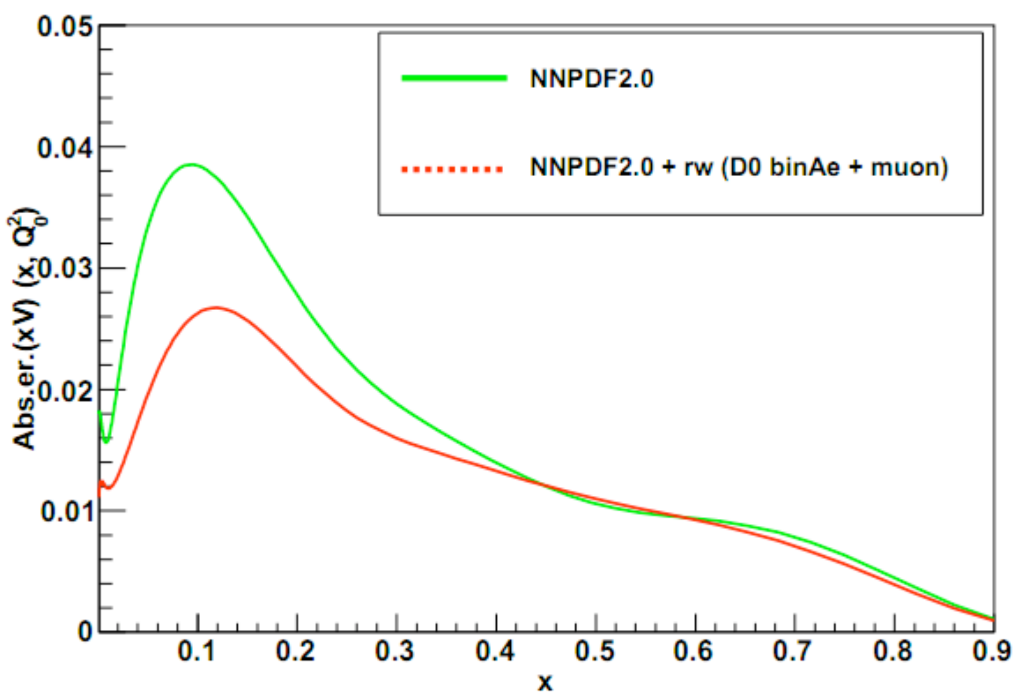
$$w_k(\alpha) = \left(\chi^2_\alpha\right)^{n/2-1} \mathrm{e}^{-\chi^2_\alpha/2}$$

$$P(\alpha) = \frac{\mathcal{N}}{\alpha}\sum_{k=1}^{N} w_k(1)\cdot w_k(\alpha)$$

PDFs and the LHC

Bayesian reweighting

✓ Study of impact of W lepton asymmetry data from D0 not included in the global analysis [Ball et al, 1012.0836].



Can be applied by ANY external user to assess impact/compatibility of LHC data or new experiment pseudo-data

- Take NNPDF parton set
- Compute new observable for each error set $PDF^{(k)}$ using any external code ➔ w_k
- Data compatibility
- New PDFs

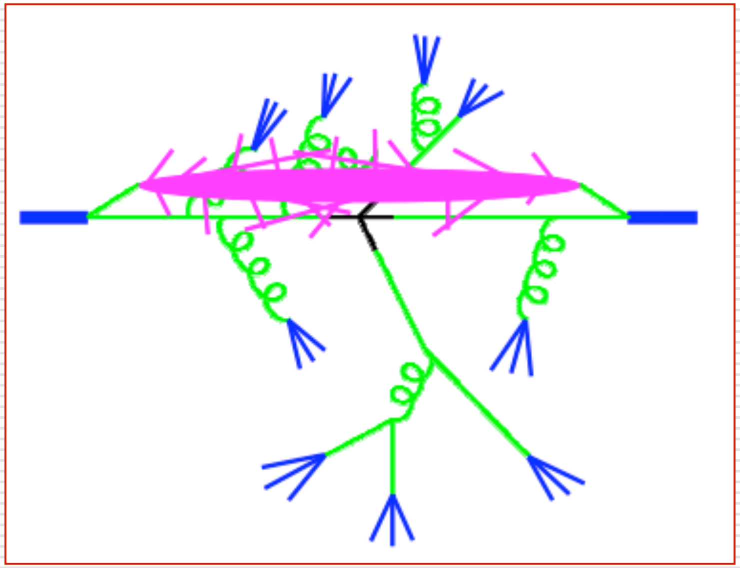
PART III

Outlook and open questions for the LHC

- Interface of PDFs with MC event generators
- Deviation from DGLAP and small-x
- Unintegrated PDFs

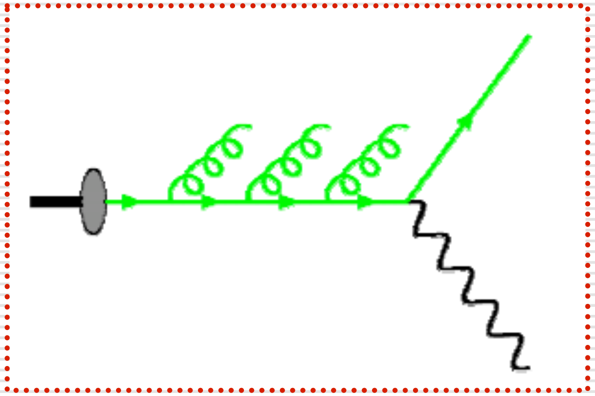
PDFs @ Monte Carlo

Monte Carlo event generators



For realistic simulations of experimental events:
- Hard Process
- Initial and final state parton showers
- Hadronization
- Underlying event (multiple interaction)

The parton shower (PS) algorithms evaluate to all orders enhanced collinear splitting contributions in both initial and final states



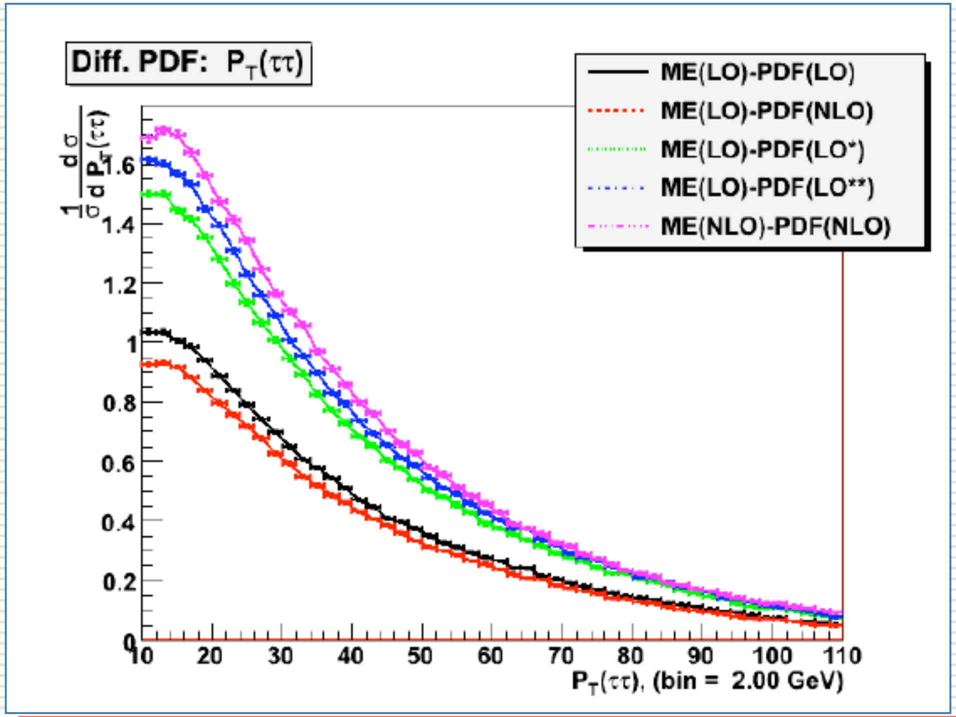
- In Monte Carlo event generators such as HERWIG/PYTHIA/SHERPA PS algorithms are based on implementation of DGLAP equation & collinear factorization
- Only $P_{a\leftarrow b}^{LO}$ in parton shower + some high order effects (coherent gluon branching)
- Towards NLO parton showers [Jadach et al]

PDFs @ Monte Carlo

Partons for LO Monte Carlo event generators

Which PDFs to use in Monte Carlo event generators?

- If NLO matrix element is available (POWHEG, MC@NLO), use NLO PDFs
- What if only LO matrix element is available: use LO? NLO?
- ME(LO) + PDF(LO) does not work well



- LO*
  LO PDFs with violation of momentum sum rules and NLO α_s [arXiv:0711.2473]

- LO**
  LO* PDFs with modifies α_s scale in PDFs evolution [arXiv:0807.2132]

[Shernstev, Thorne, ArXiv:0807.2132]

PDFs @ Monte Carlo

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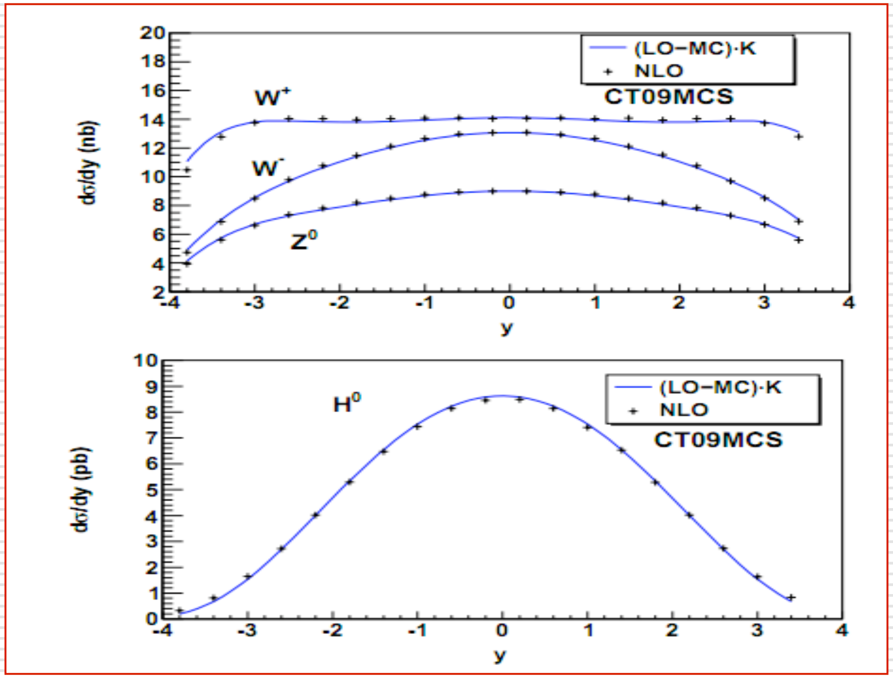


[Lai et al, ArXiv:0910.4183]

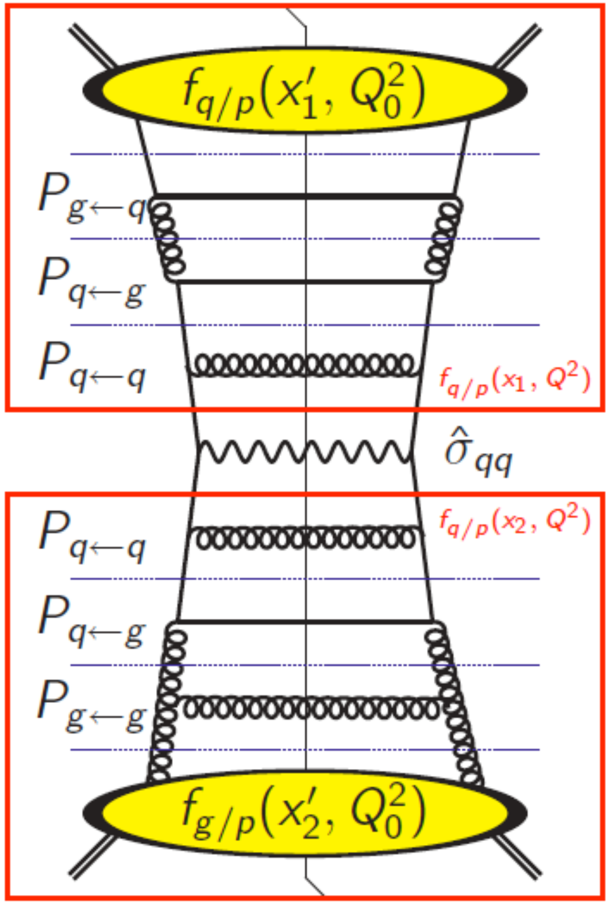
- CT09MCs, CT09MC1, CT09CT2:

Based on the idea of producing reliable predictions for future experiments (include pseudo-data based on NLO theory among data in global fits)

- Intrinsic limitations of LO
- ISR is present in MC event generators but not in global analyses of PDFs
- Strong ordered emission versus ordered emission (zero k_T versus finite k_T)

Can we do better than that?

Collinear factorization
DGLAP evolution



- Collinear factorization
  ➔ Renormalization Group Evolution
  ➔ Resummation of collinear logs

- Approximation implicit in DGLAP formalism: transverse momentum of emitted partons in initial states much smaller than hard scale

➔ Standard pQCD framework (up to formally suppressed higher twist terms)

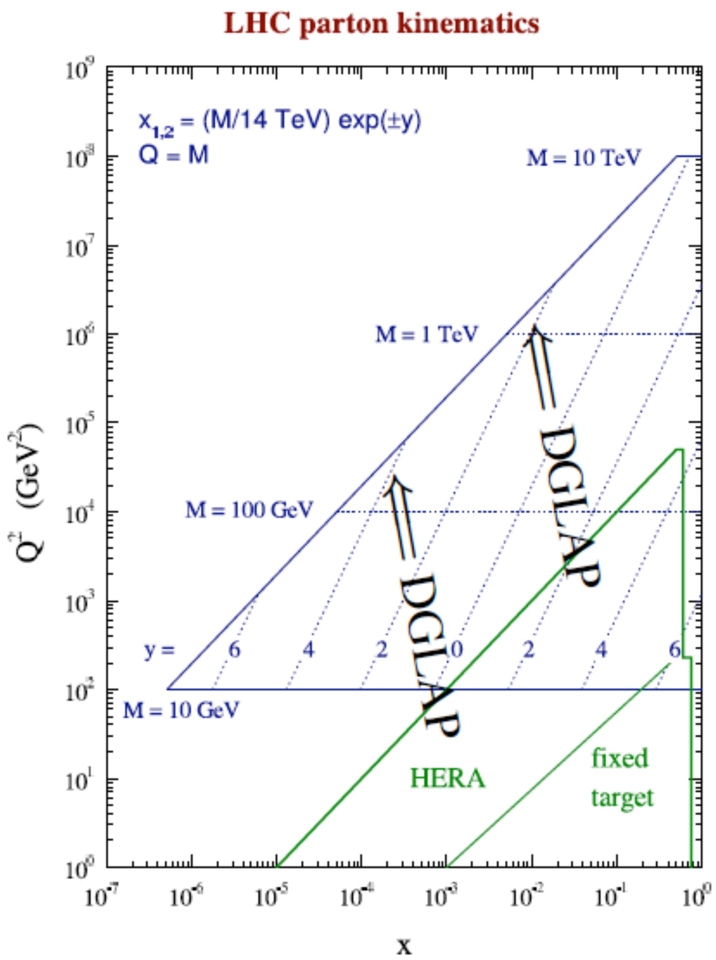
- Works well for inclusive processes with one hard scale

- When there are two disparate hard scales fixed order perturbative approach might fail

- $s \gg M^2$ high-energy regime, small x logarithms enhanced

Collinear factorization

DGLAP evolution



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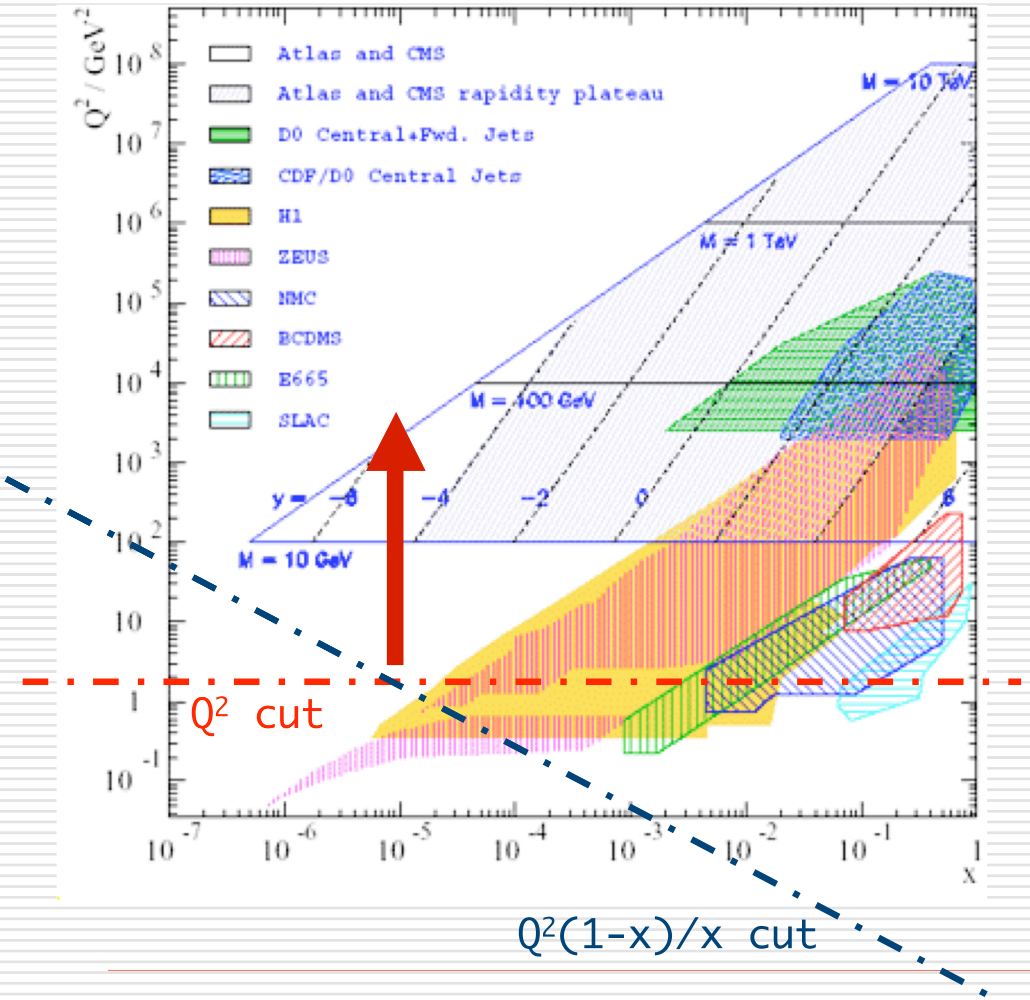
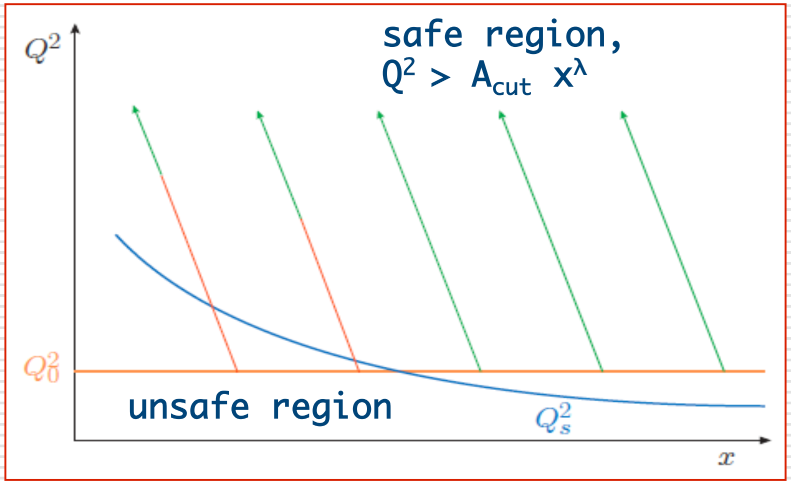
- Deviations from DGLAP?

Deviations from DGLAP

Kinematical cuts





DGLAP describes successfully scaling up to $Q^2>10$. What about small-x/Q^2?

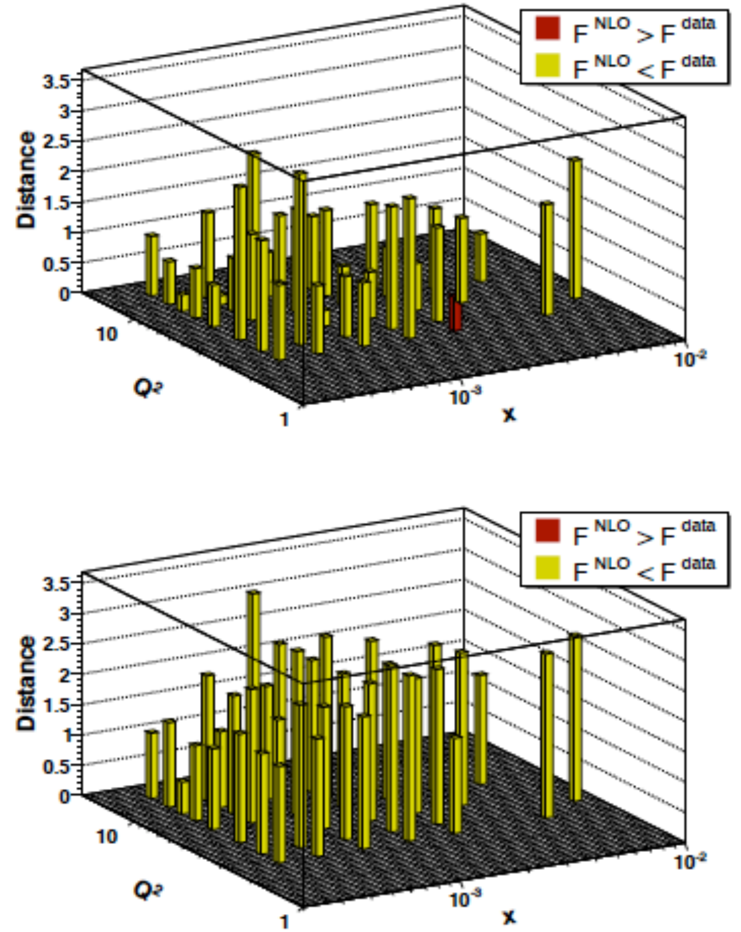
Possible non-DGLAP effects:

- leading twist small-x perturbative resummation
- non linear evolution
- parton saturation
- other higher twist effects

Deviations from DGLAP

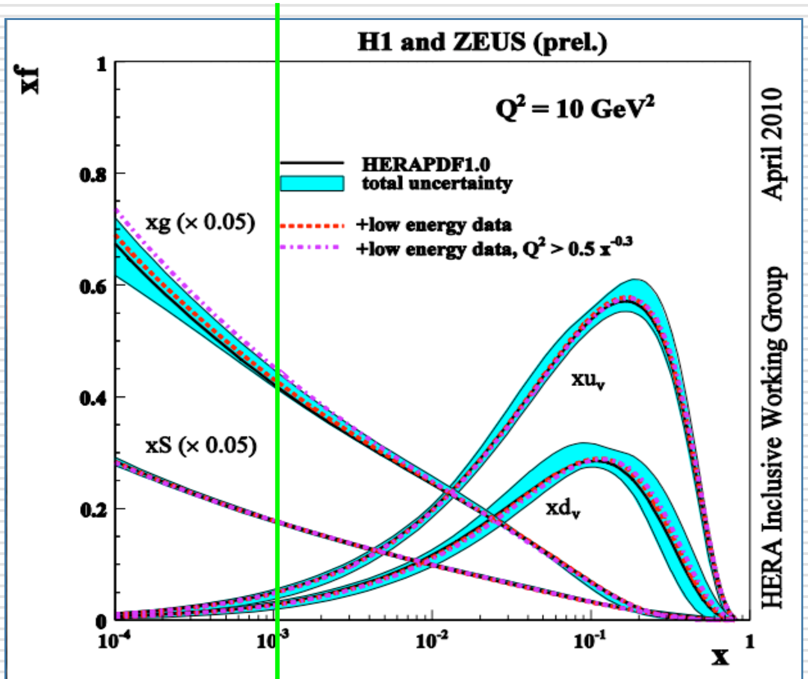
Small-x/Q^2 region

NNPDF2.0



[Caola et al, ArXiv: 1007.5405]

- Backward evolution of PDFs determined in the safe region
- Compute distance between data and backward evolved prediction in unsafe region
- Hints of deviations confirmed by HERA analysis (thanks to precision of combined data)



[Cooper-Sarkar, PDF4LHC 07/2010]

Deviations from DGLAP

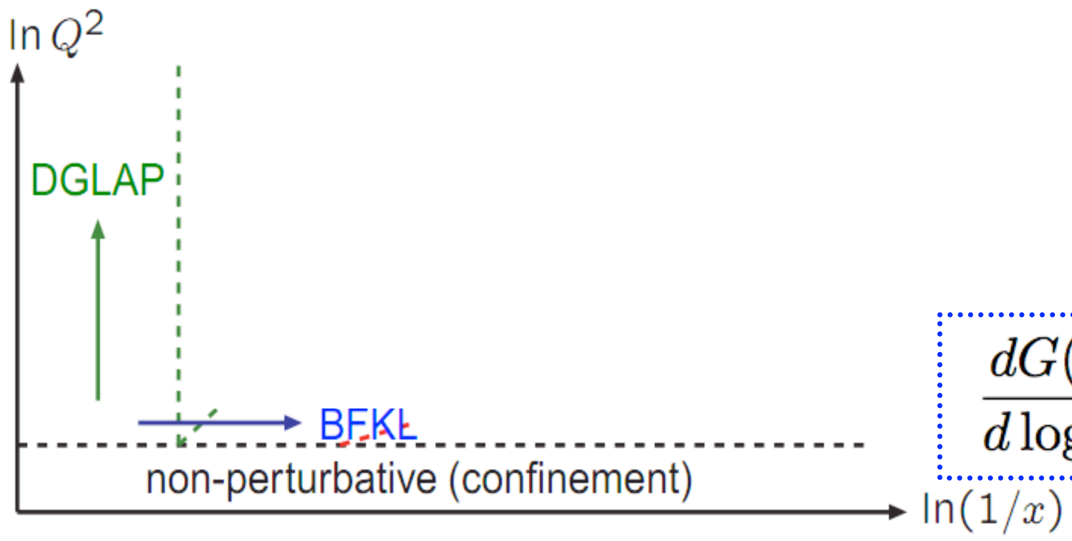
Small-x resummation

- A possible explanation for deviation from DGLAP evolution at small-x/Q^2 is the need of resumming log(1/x) to all orders
- Small-x terms resummed to all orders at leading and sub-leading level

[BFKL 75-76, Lipatov-Fadin 98]

$$\frac{dg(x,Q^2)}{d\log Q^2} = \int \frac{dz}{z} P_{gg}\left(\frac{x}{z}\right) g(z,Q^2)$$

→ collinear factorization



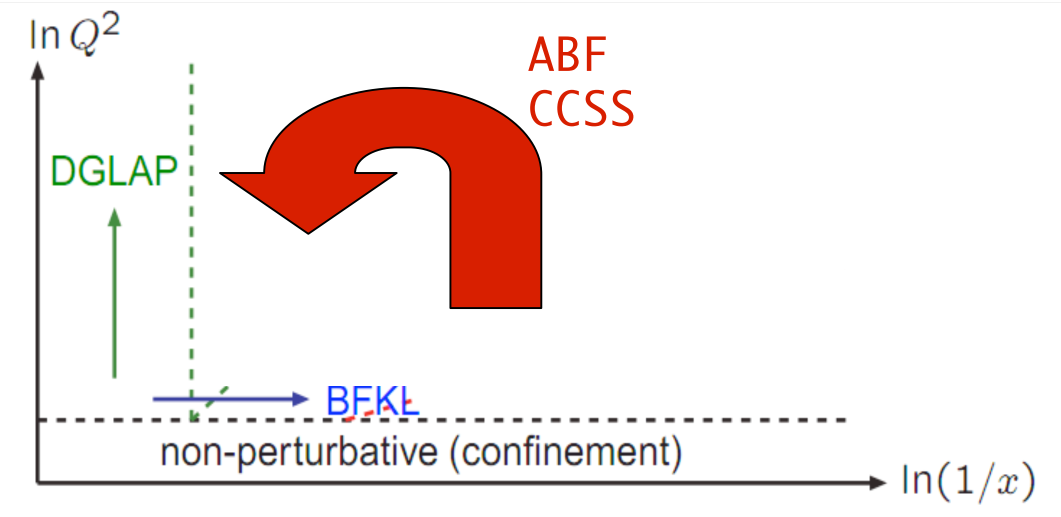
k_T factorization

$$\frac{dG(x,k^2)}{d\log(1/x)} = \int \frac{dk'^2}{k'^2} \mathcal{K}\left(\frac{k}{k'}\right) G(x,k^2)$$

Deviations from DGLAP

Small-x resummation

- Two approaches to match DGLAP and BFKL
  - Resum small-x into DGLAP [Altarelli, Ball, Forte, 2003]
  - Inclusion in BFKL of fixed-order DGLAP [Ciafaloni, Colferai, Salam, Stasto, 2003]
- Lead to stable perturbative expansion of DGLAP up to NLO at small-x by providing a resummed anomalous dimension
- Small-x corrections to hard cross-sections known at leading non-trivial order for several processes [Catani, Ciafaloni, Hautmann, Marzani, Ball, Ellis, Diana, Vicini, Del Duca ...]

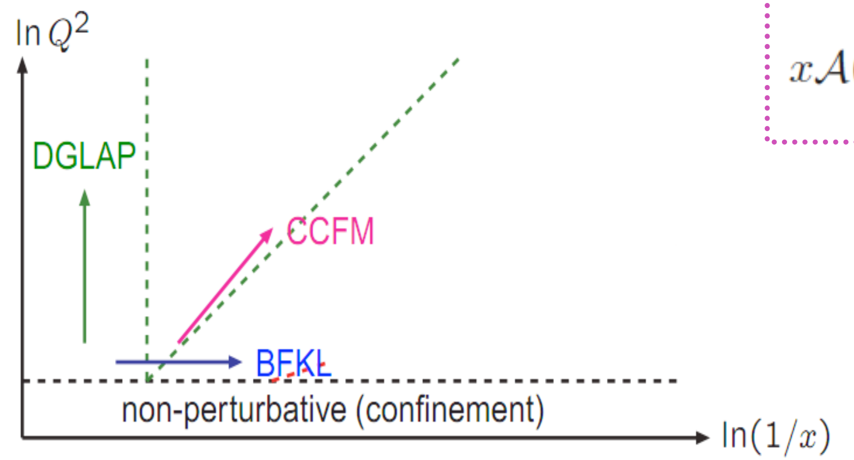


Allow for analysis of effect of small-x resummation in PDFs fit [Thorne, White 2007]

Unintegrated PDFs
In a nutshell

Motivation: neglecting transverse momenta of partons during evolution not good description in regions where k_T not << Q^2

- Fully unintegrated PDFs: Set up new factorization with subtraction formalism using exact over-all kinematics on initial and final states
  [Collins, Soper, Sterman, Stasto, Watt, Zu, ...]
- Unintegrated PDFs: work in the k_T factorization theorem framework and extract unintegrated PDFs in (x,k_T,μ) [Jung, Ciafaloni, Catani, Fiorani, Marchesini, Hansson, Hautman, Martin, Ryskin, Salam, Anderdson, Gustavson ...]



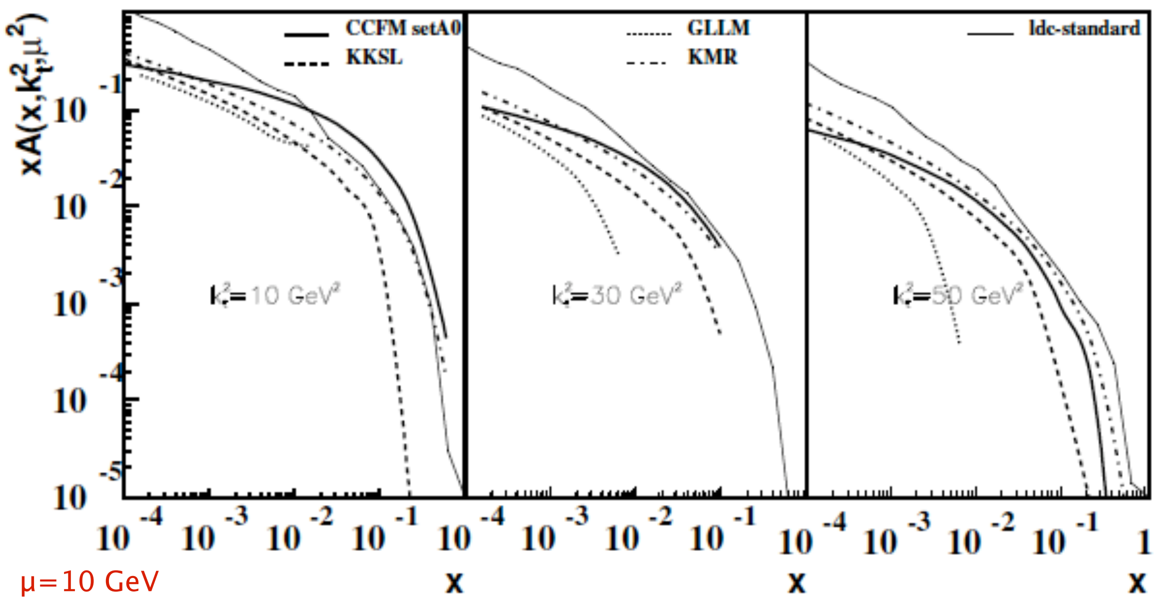
$$xA(x,k_\perp,\bar{q}) = \int dx' A_0(x',k_\perp) \cdot \frac{x}{x'} \tilde{A}\left(\frac{x}{x'},k_\perp,\bar{q}\right)$$

CCFM describes the evolution in an angular ordered region of phase space

* Reproduces BFKL and DGLAP asymptotically
* Difficult extension to quarks

Unintegrated PDFs
Global fits

Is it possible to perform fits of uPDFs as we do for PDFs?



Collins et al
HERALHC proceedings 2006

Extracted from $F_2(x,Q^2)$ HERA data at x<0.01 and Q^2<100 GeV^2

Now developments: use F^2_c and dijet measurements from HERA [Jung, Hansson]
Different shapes at low x and insensitivity.

- CCFM obtained from CCFM evolution
- LDC standard obtained from a generalization of CCFM evolution equations
- GLLM from BK equation
- KMR extracted from PDFs using Sudakov form factor
- KKSL from combined DGLAP and BFKL evolution (Stasto, Kutak)

Unintegrated PDFs
Global fits

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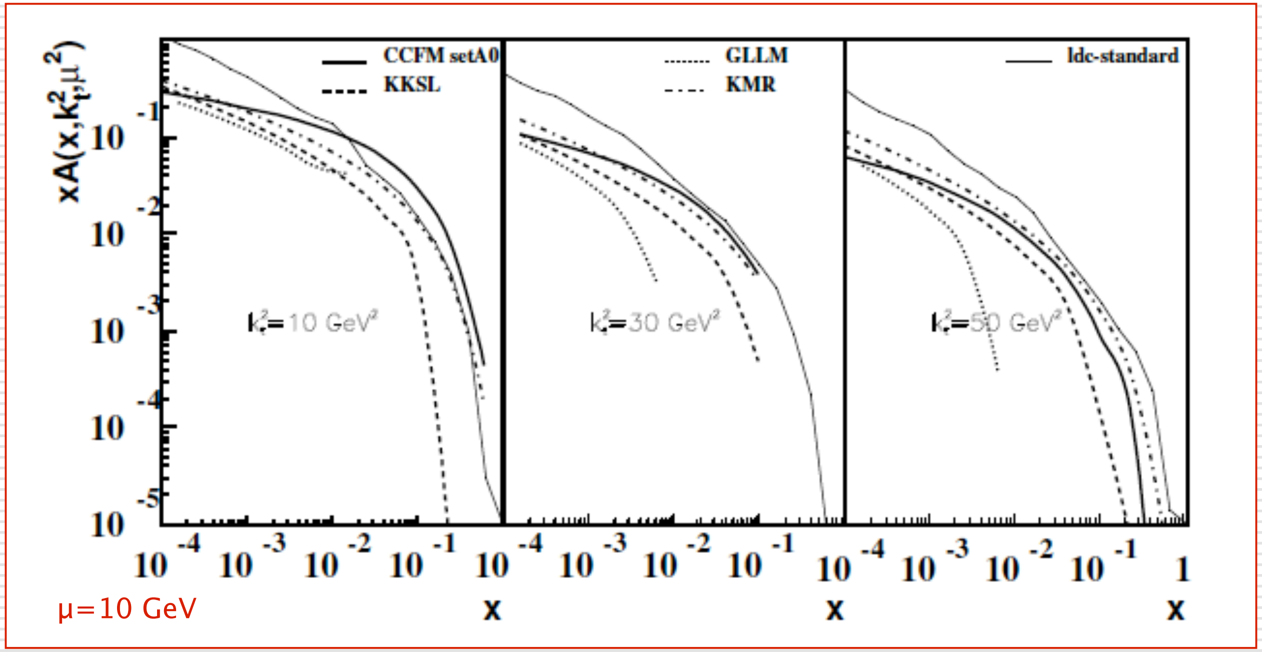

Collins et al
HERALHC proceedings 2006

- For higher x,Q^2 HERA data not much constraining
- Data: forward jets? heavy quark production?
- Extrapolation to LHC? When evolve to LHC predictions pick unconstrained regions
- In most of these approaches only gluon is fitted
- Universality?

➔ Up to now unintegrated PDFs fits are a check of consistency of the formalism, long way before becoming comparable to PDFs global fit
➔ Success in MC generator based on unintegrated PDFs for high-energy showers [CASCADE, SMALLX, LDCMC] but not yet at level of multi-purpose generators

Conclusions

- PDFs uncertainty still dominating one for LHC analyses
- During the last few years the understanding of PDFs has enormously increased both from statistical and theoretical point of views
- Towards an increasing agreement: smaller envelope
- Improvement expected from LHC data, important to include new data as soon as they come out

- Room for improvement in matching PDFs and parton shower approach
- Ideas?
- Hints for small-x/Q^2 deviation from DGLAP evolution
- How will this affect LHC measurements?
- Small-x resummation not yet included systematically in PDFs fit
- Unintegrated PDFs: lots of work to be done and upcoming developments

- Nuclear PDFs
- Double PDFs and multi-parton scattering

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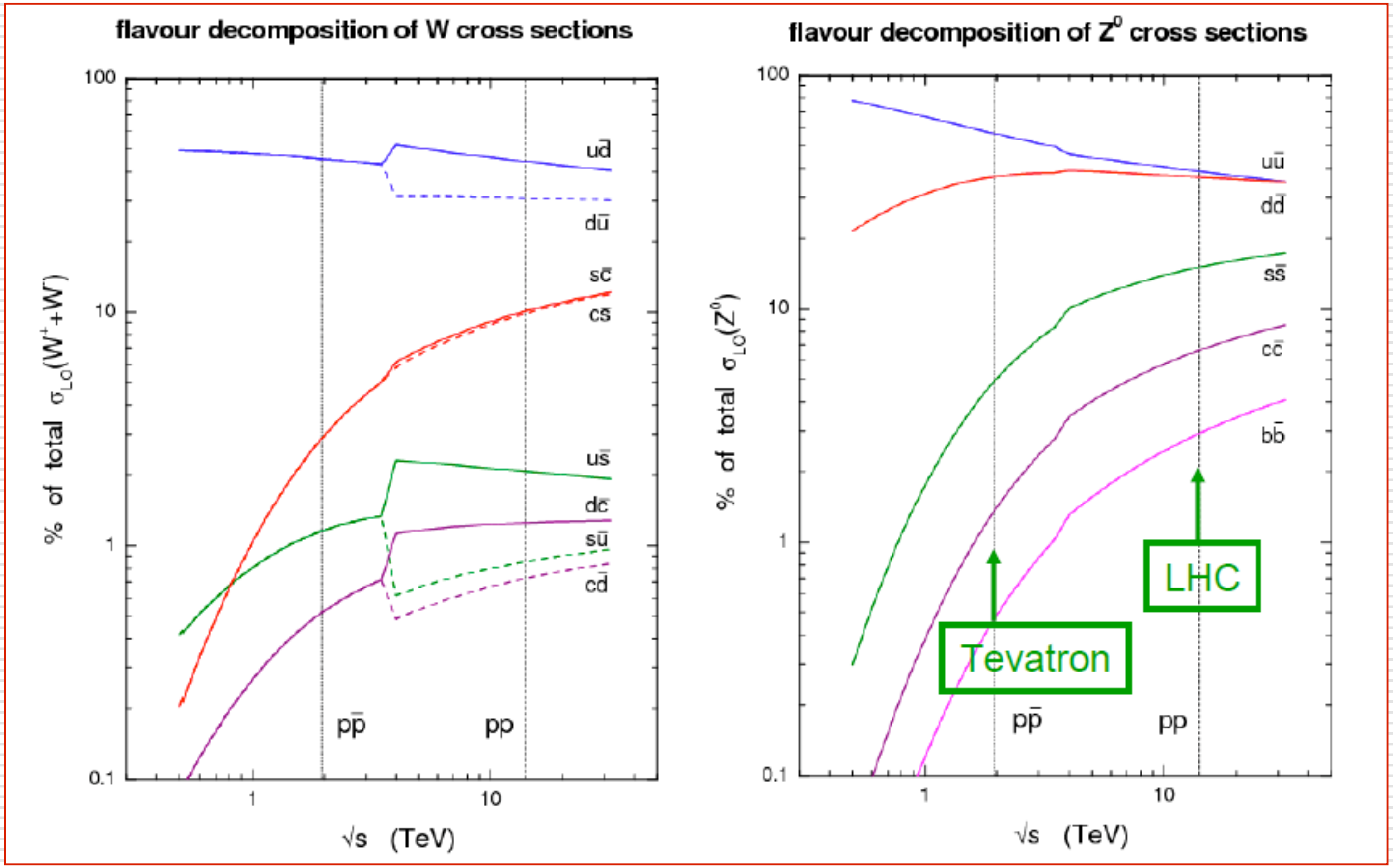
THANK YOU!

BACKUP

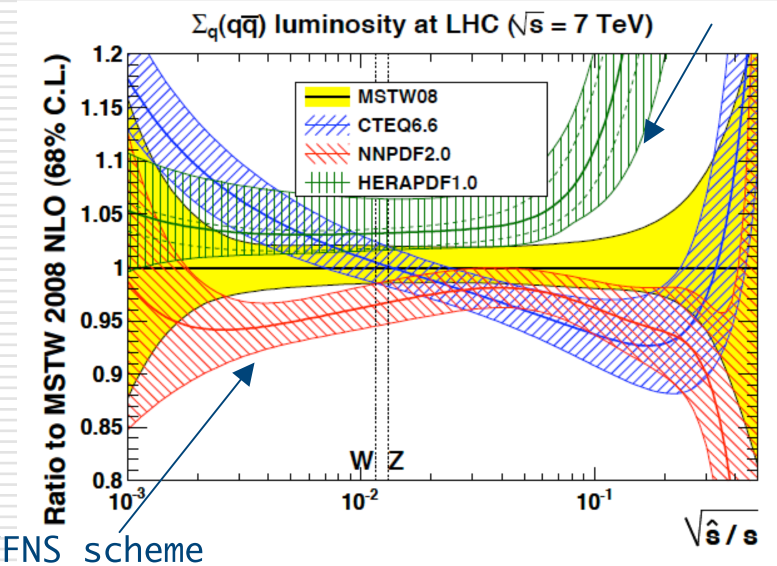
Standard candles at the LHC



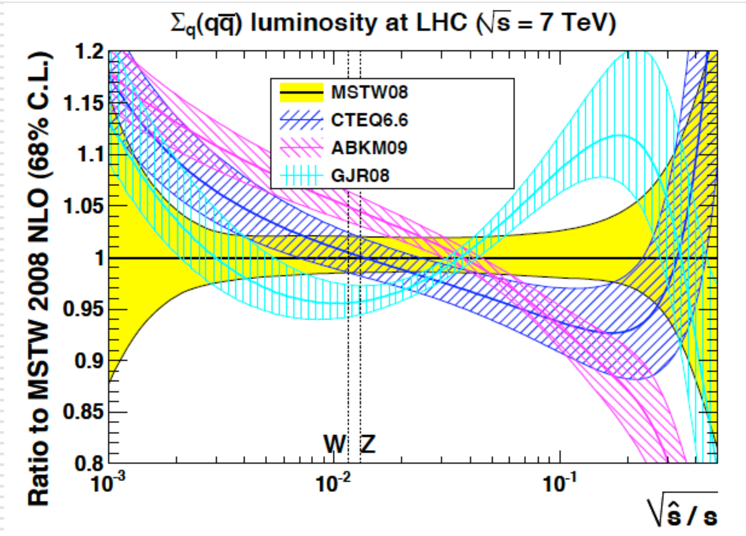
J. Stirling plots, QCD@LHC

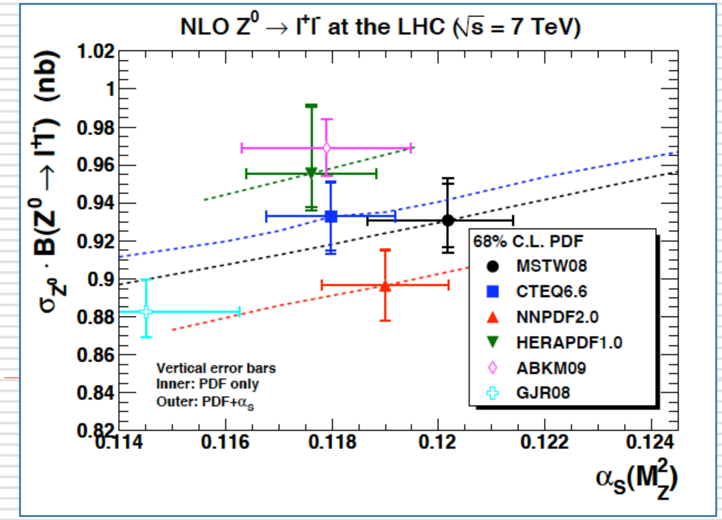
BACKUP
Standard candles

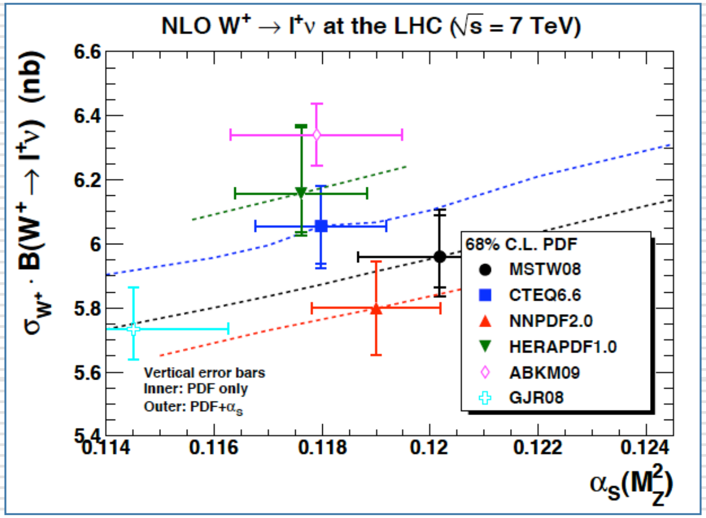
more precise HERA combined data



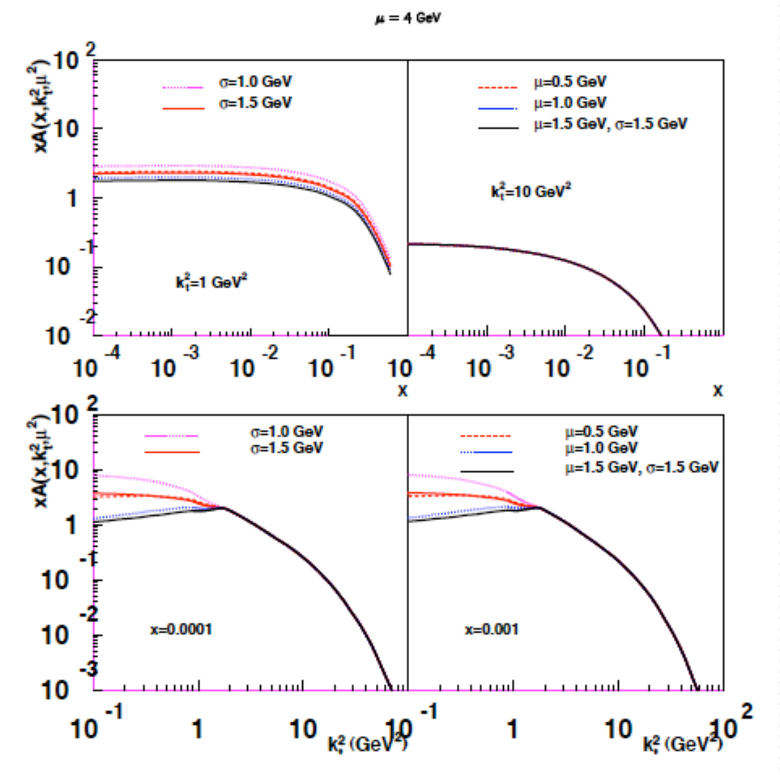
ZM-VFNS scheme



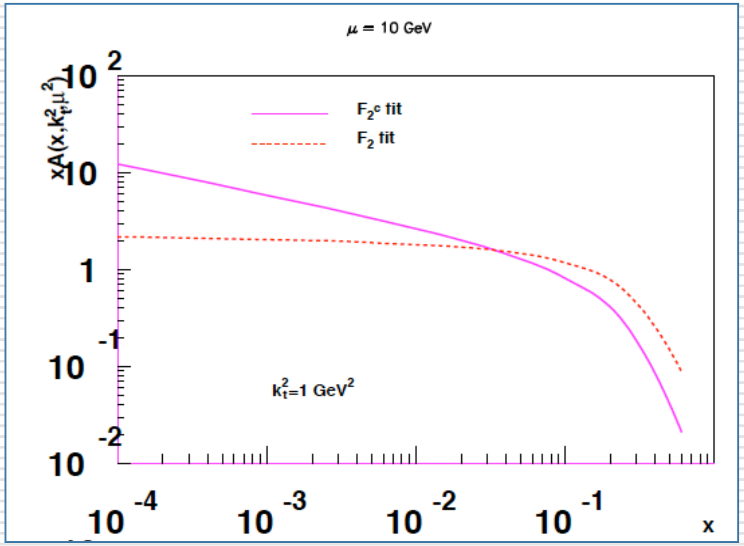




BACKUP
Unintegrated PDFs



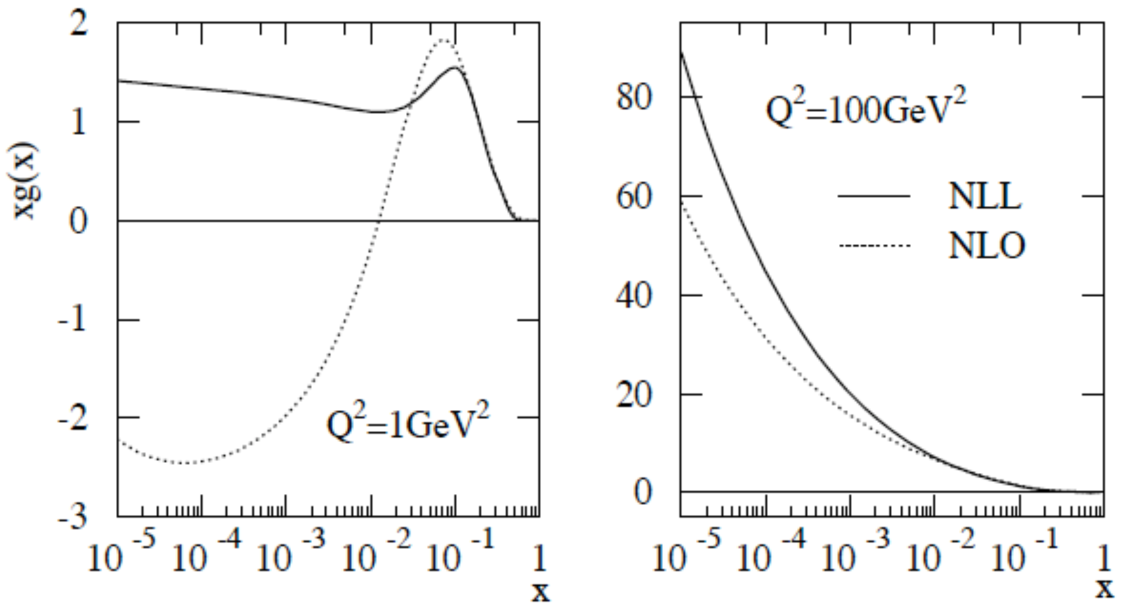
Jung et al, hep-ph/0611093



Hansson, hep-ph/0611093

BACKUP

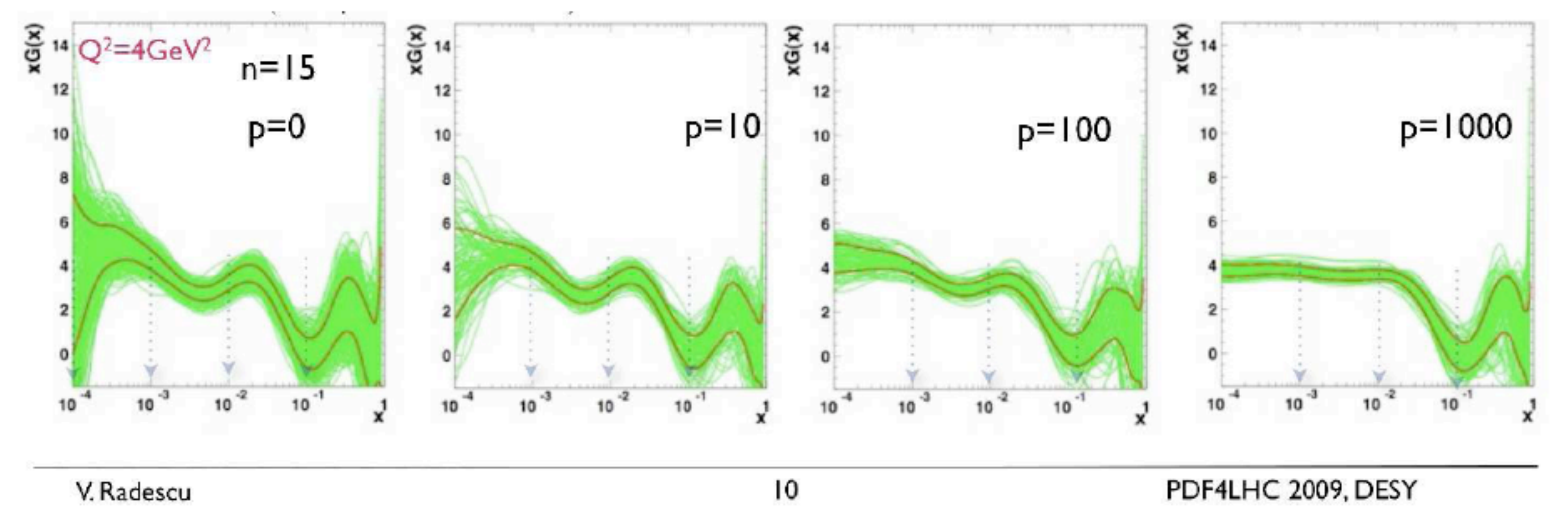
Resummed small-x fits

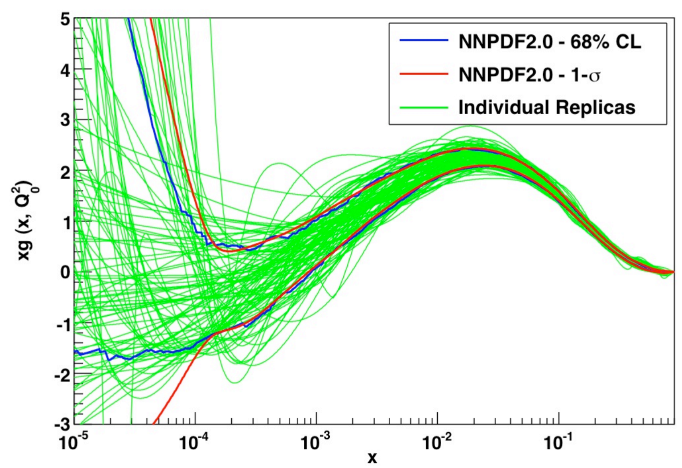


[Thorne, White 2007]

BACKUP

Parametrization studies

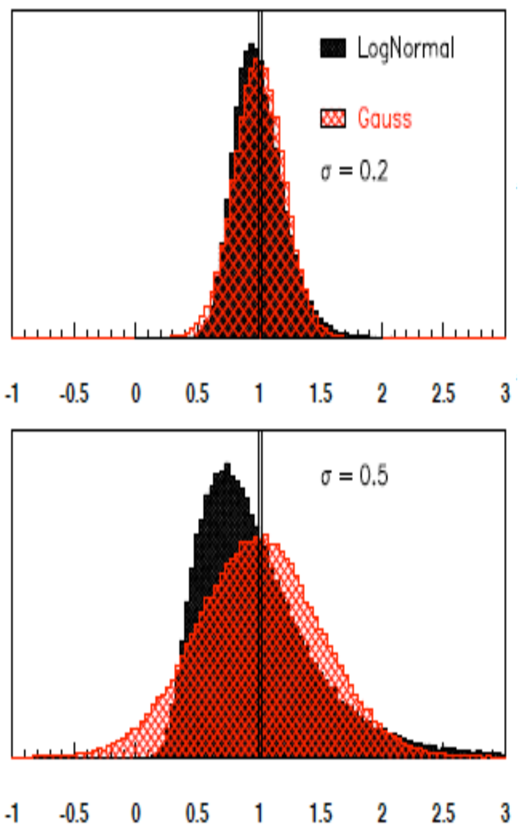


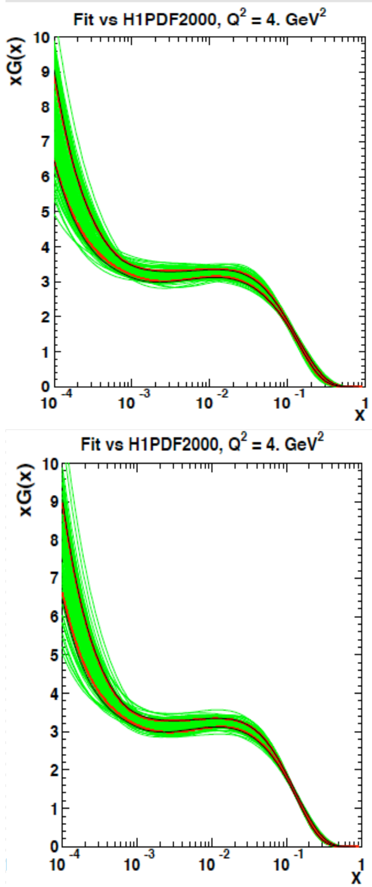


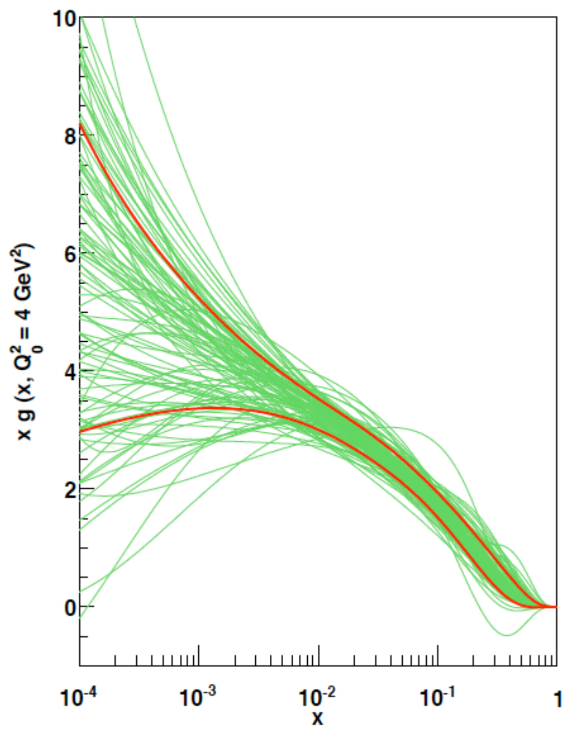
Compare neural net and redundant orthonormal polynomial parametrization: p is the penalty to fits with long arc lengths (therefore oscillations). Oscillations are only tamed by large penalty. NN, even of double number of pars does not display such an instability.

BACKUP

Monte Carlo studies







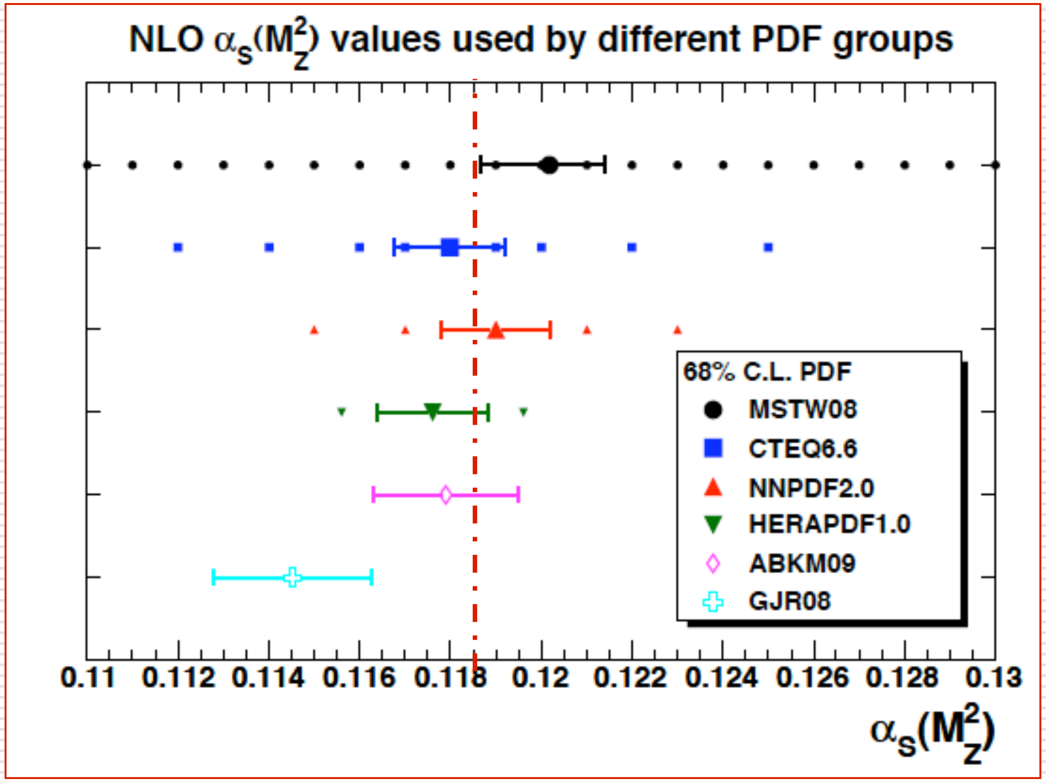
BACKUP

The problem of α_s

- PDG 2009: older measurements not included due to large uncertainty
- used a more realistic uncertainty estimate ±0.002

$\alpha_s = 0.1184 \pm 0.0007$
[Bethke 2009]

- N3LO determination [Blumlein et all, 2009] from non-singlet scaling violations is 3σ from average $\alpha_s = 0.124^{+0.005}_{-0.008}$
- If truncated moments are used, NLO result from non-singlet scaling violations is $\alpha_s = 0.124^{+0.005}_{-0.008}$
- MSTW see a change of 2σ from NLO $\alpha_s = 0.1202^{+0.0012}_{-0.0015}$ to NNLO $\alpha_s = 0.1171 \pm 0.0014$



We need a believable conservative α_s average for phenomenology.

BACKUP

The strange content of the proton

$$R^- = \frac{\sigma^{NC}(\nu) - \sigma^{NC}(\bar{\nu})}{\sigma^{CC}(\nu) - \sigma^{CC}(\bar{\nu})} \qquad [F^-] \equiv \int_0^1 dx\, f(x)$$

$$= \frac{1}{2} - \sin^2\theta_W + \left[\frac{([U^-] - [D^-]) + ([C^-] - [S^-])}{[U^-] + [D^-]}\right]$$

- Measurement of Paschos-Wolgestein ratio provides a direct measurement of θ.

NuTeV

$\sin^2\theta_W = 0.2276 \pm 0.0014$

- Constraints also from electro-weak fit.

EW fit

$\sin^2\theta_W = 0.2223 \pm 0.0002$

>3σ discrepancy !!

BACKUP

The strange content of the proton

$$R^- = \frac{\sigma^{NC}(\nu) - \sigma^{NC}(\bar{\nu})}{\sigma^{CC}(\nu) - \sigma^{CC}(\bar{\nu})} = \frac{1}{2} - \sin^2\theta_W + \left[\frac{([U^-]-[D^-]) + ([C^-]-[S^-])}{[U^-]+[D^-]}\right]$$

$$[F^-] \equiv \int_0^1 dx\, f(x)$$

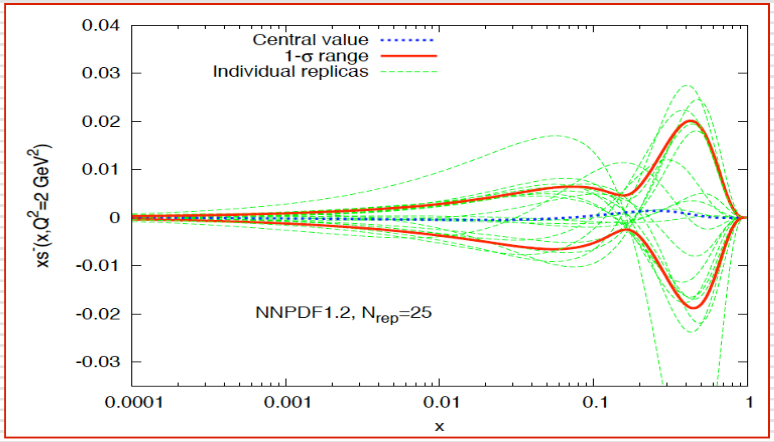
- In the NuTeV analysis:
  - [S-] =0 (s = sbar)
  - [U-] - [D-]=0 (no isospin violation)
  - [C-]=0 (c = cbar)

- How can we interpret the discrepancy?
- New physics?
- [U-] - [D-] ≠ 0?
- MRST2004QED found that this helped but was not enough to explain the discrepancy
- [S-]≠0 ?

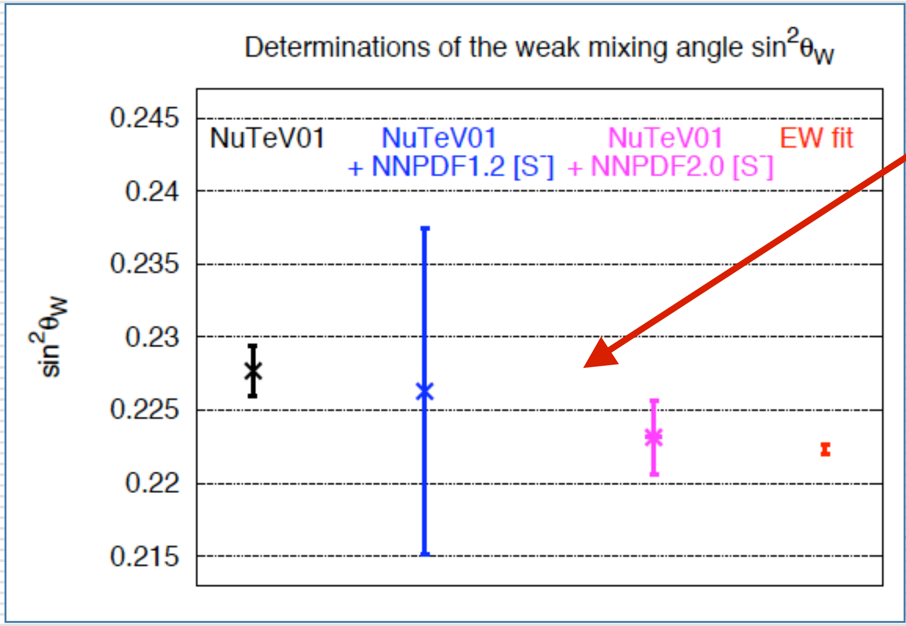
$$\delta_S \sin^2\theta_W \sim -0.240 \frac{[S^-]}{[U^-]+[D^-]}$$

BACKUP

The strange content of the proton



Analysis	$[S^-]\left(Q^2_{\rm ref} = 20\ {\rm GeV}^2\right)\cdot 10^3$
NNPDF1.2	0.5 ± 8.6
MSTW08	1.4 ± 1.2
Tung:2006tb	1.2 ± 1.2
AKP08	1.0 ± 1.3

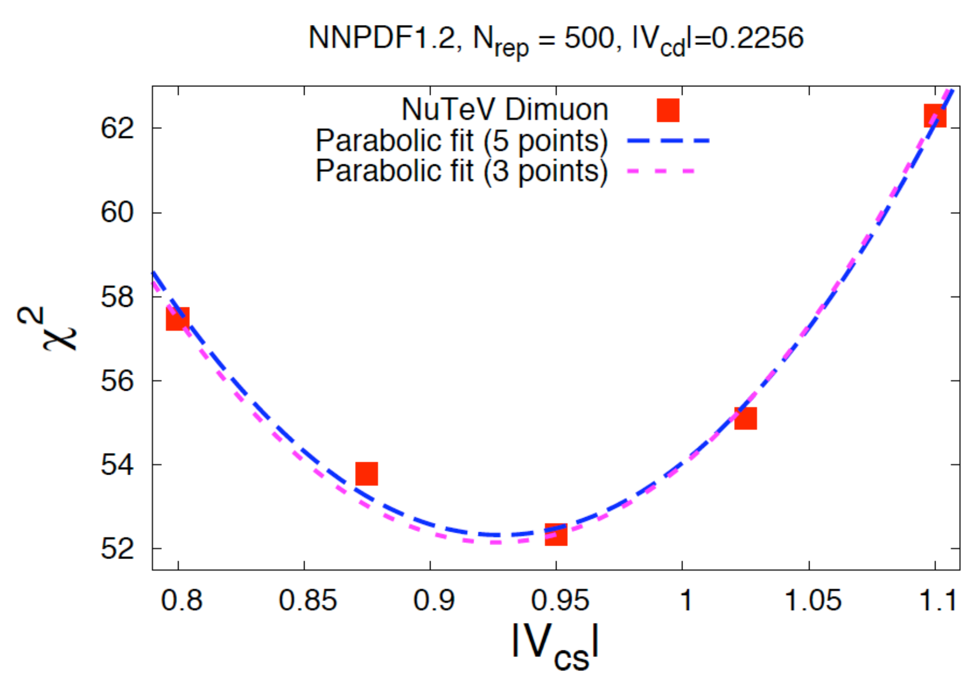


The anomaly is gone!

If we want to make sure to identify new physics signals we must make sure not to underestimate QCD background uncertainty.

BACKUP

The strange content of the proton



CKM fit

$$V_{cs} = 0.97334 \pm 0.00023,\ \Delta V_{cs} \sim 0.02\%$$

Direct Determination

V_{cs}	$=$	$1.04 \pm 0.06,\ \Delta V_{cs} \sim 6\%$	D/B decays
V_{cs}	$>$	0.59	DIS fit

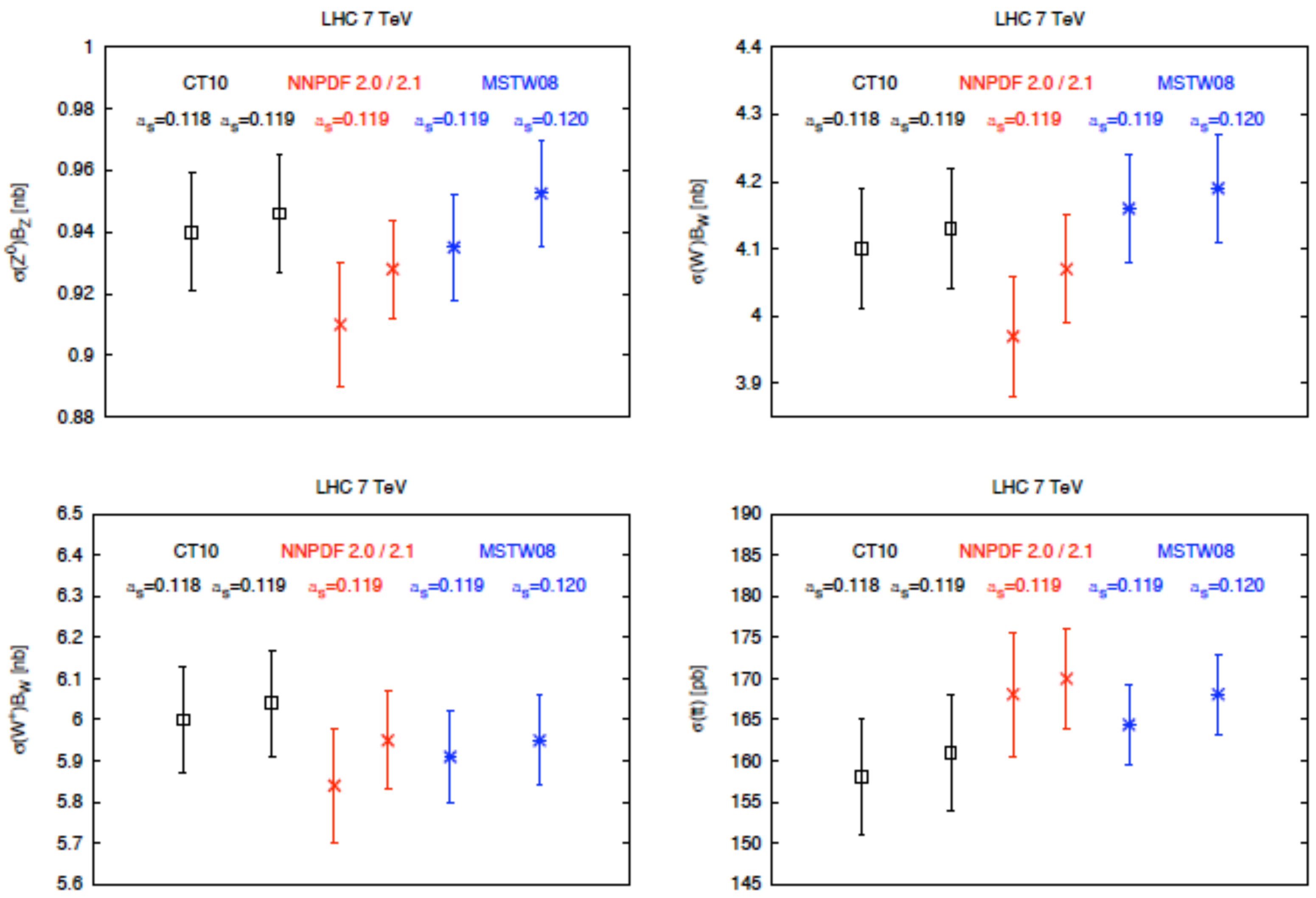
NNPDF1.2 analysis

$$V_{cs} = 0.97 \pm 0.07,\ \Delta V_{cs} \sim 6\%$$

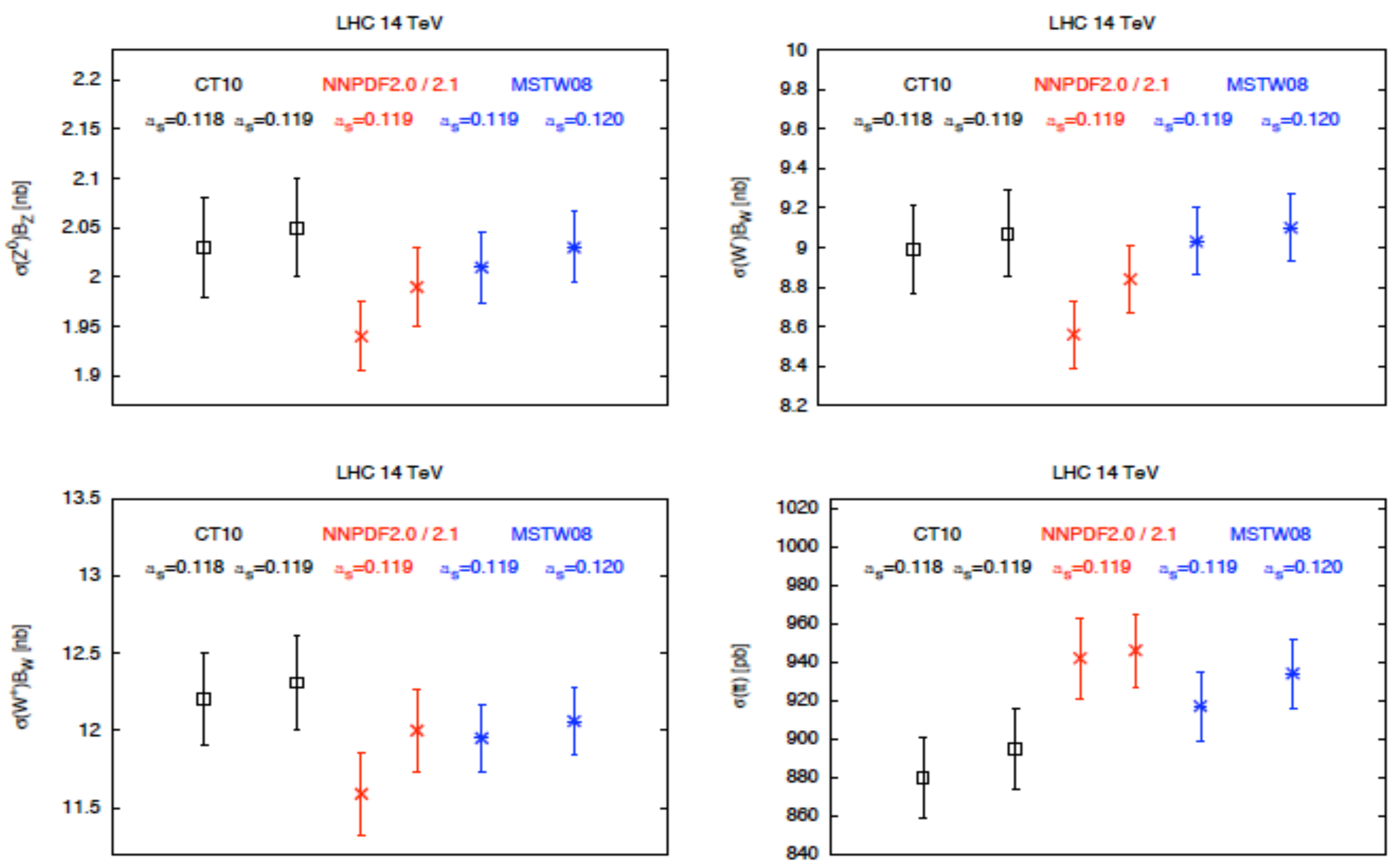
- Commonly assumed that no info on Vcs comes from DIS fits due to the uncertainty in the determination of strange.
- Best determination from DIS fits was Vcs>0.59 at 90%CL.
- Despite the large uncertainty in strange, we get good determination of Vcs.

BACKUP

Up-to-date benchmark

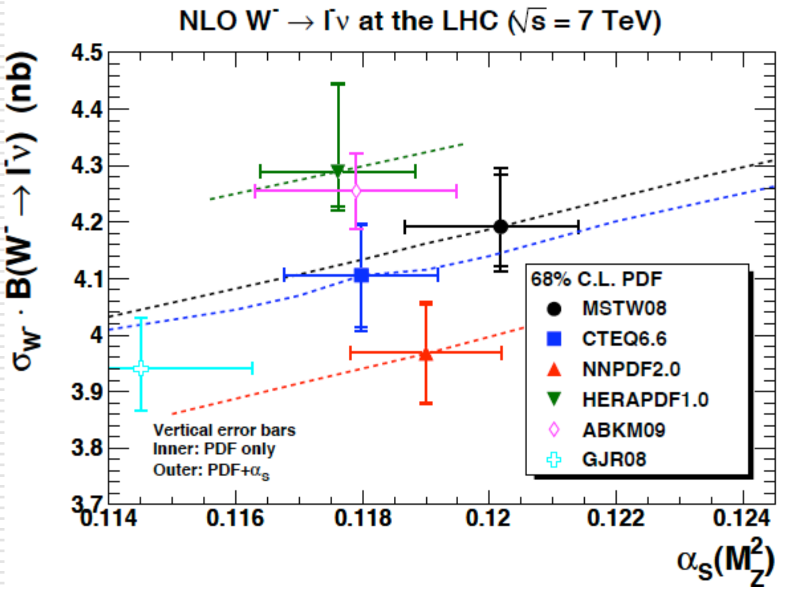


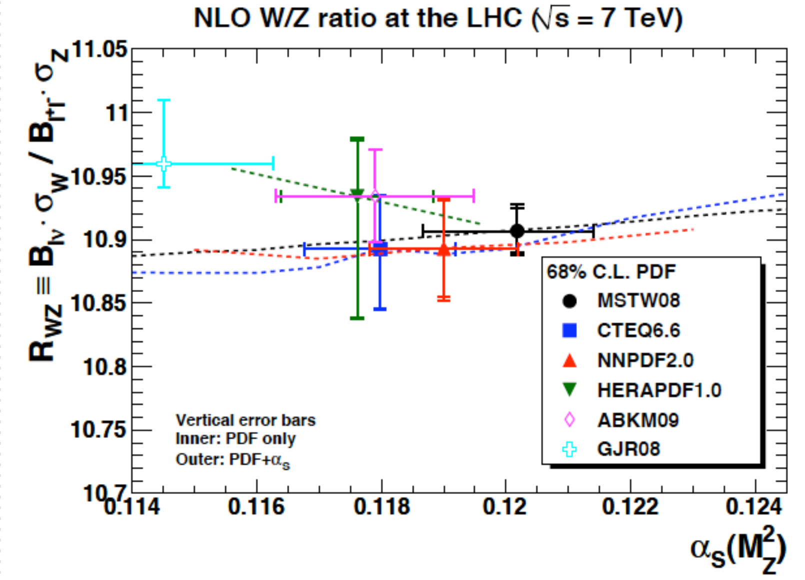
BACKUP
Up-to-date benchmark



BACKUP

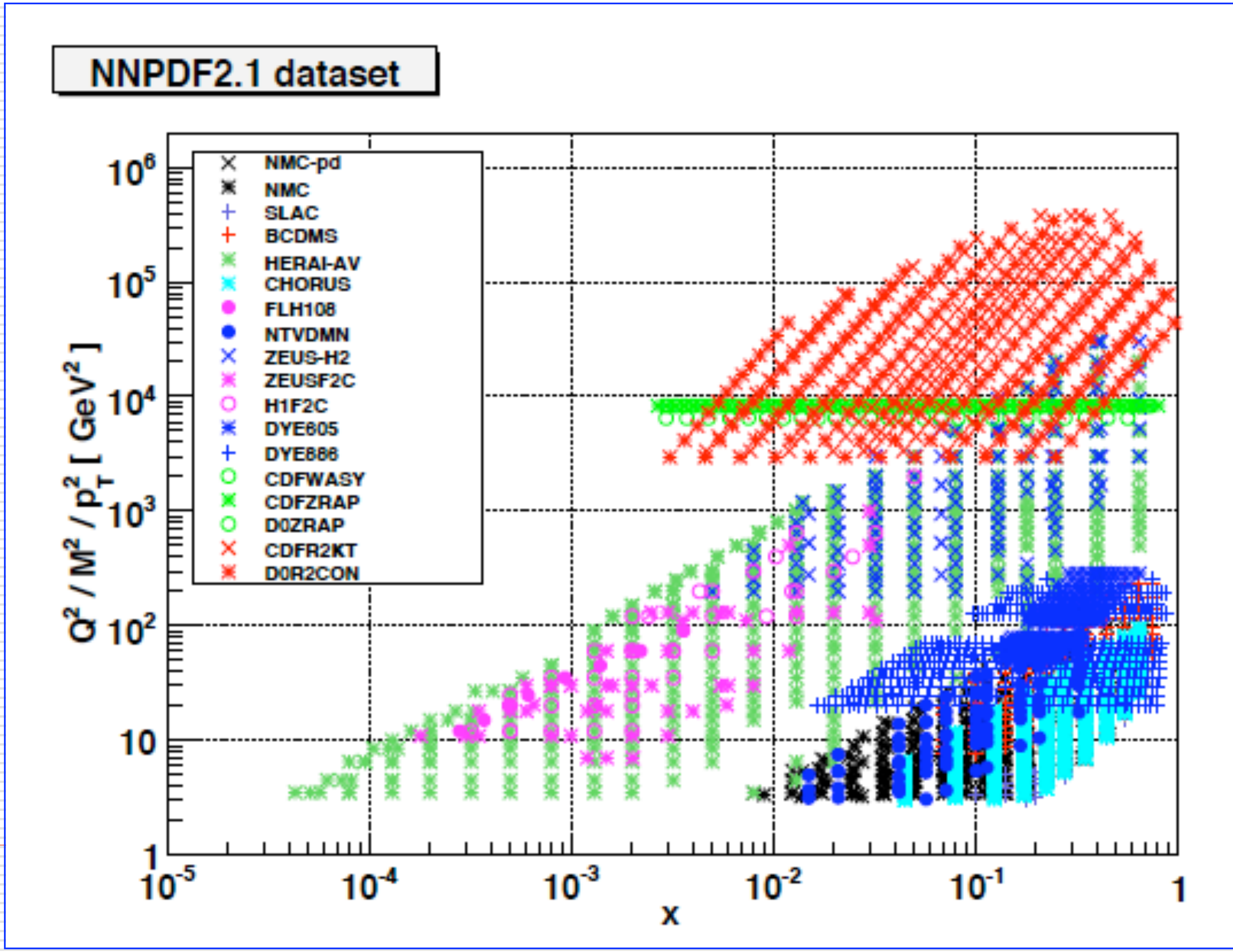
More Observables





BACKUP

Data


NNPDF2.1 dataset
NMC-pd
NMC
SLAC
BCDMS
HERAI-AV
CHORUS
FLH108
NTVDMN
ZEUS-H2
ZEUSF2C
H1F2C
DYE605
DYE886
CDFWASY
CDFZRAP
D0ZRAP
CDFR2KT
D0R2CON
$Q^2 / M^2 / p_T^2$ [GeV^2]
x
1
10
10^2
10^3
10^4
10^5
10^6
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1

BACKUP

Heavy quark schemes

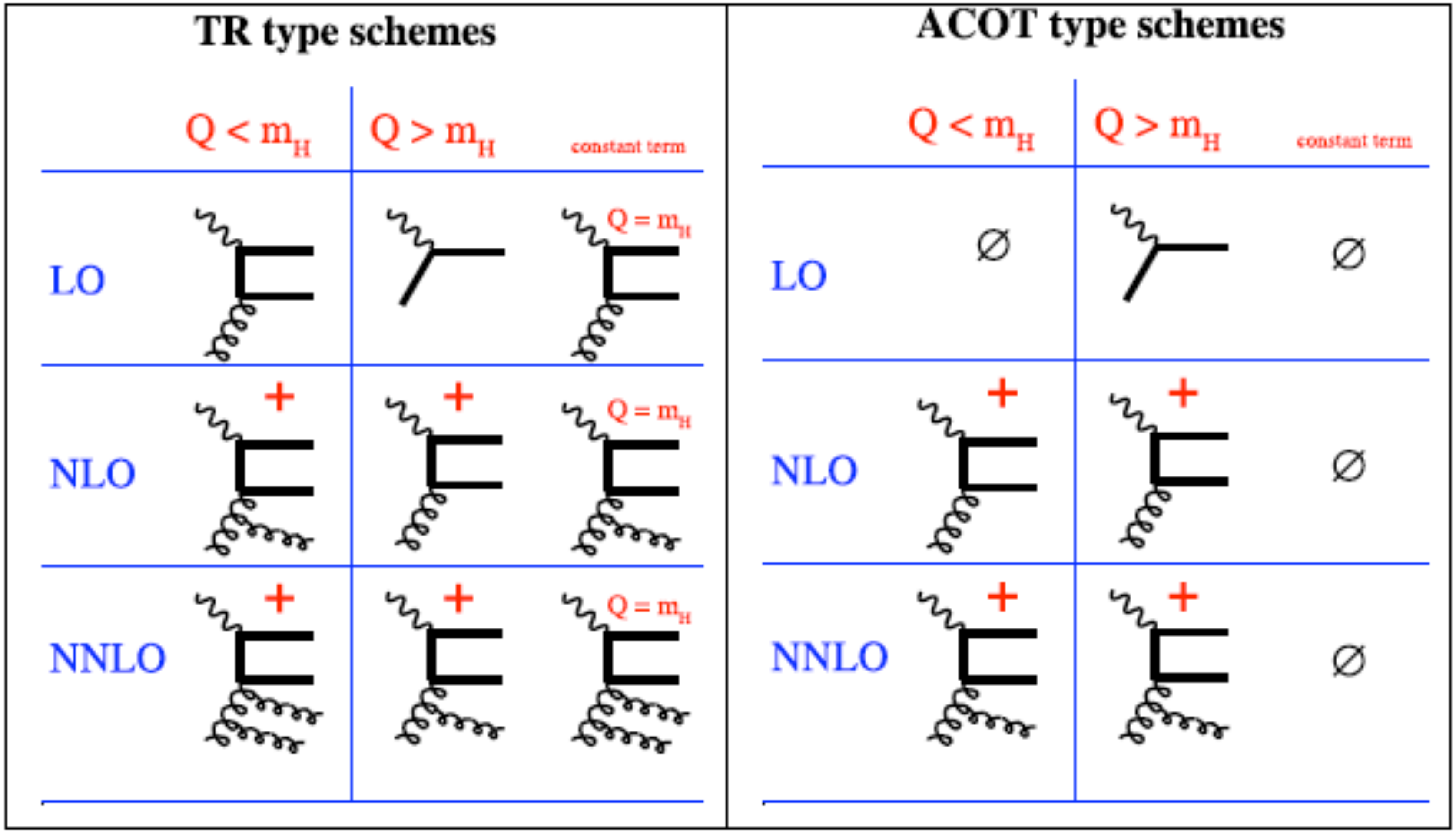
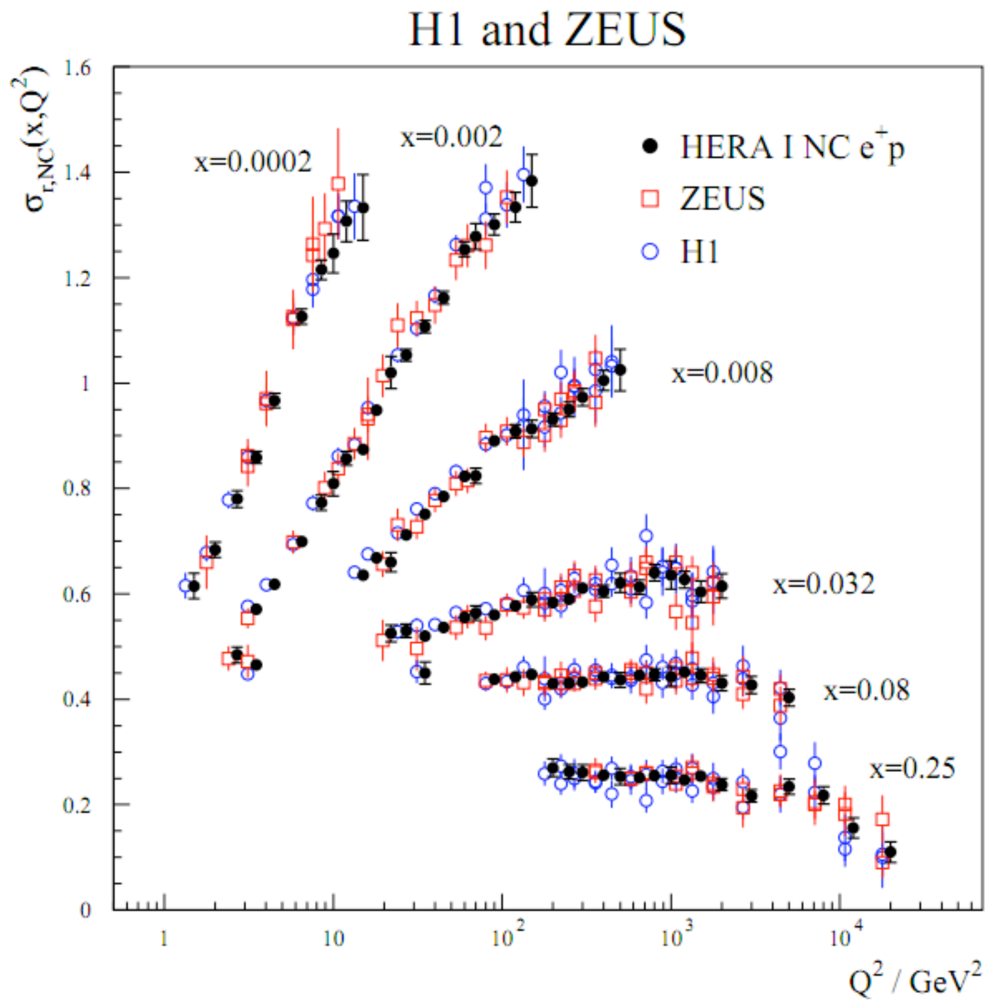


Figure from F. Olness and I. Schienbein [arXiv:0812.3371]

BACKUP
Combined HERA data

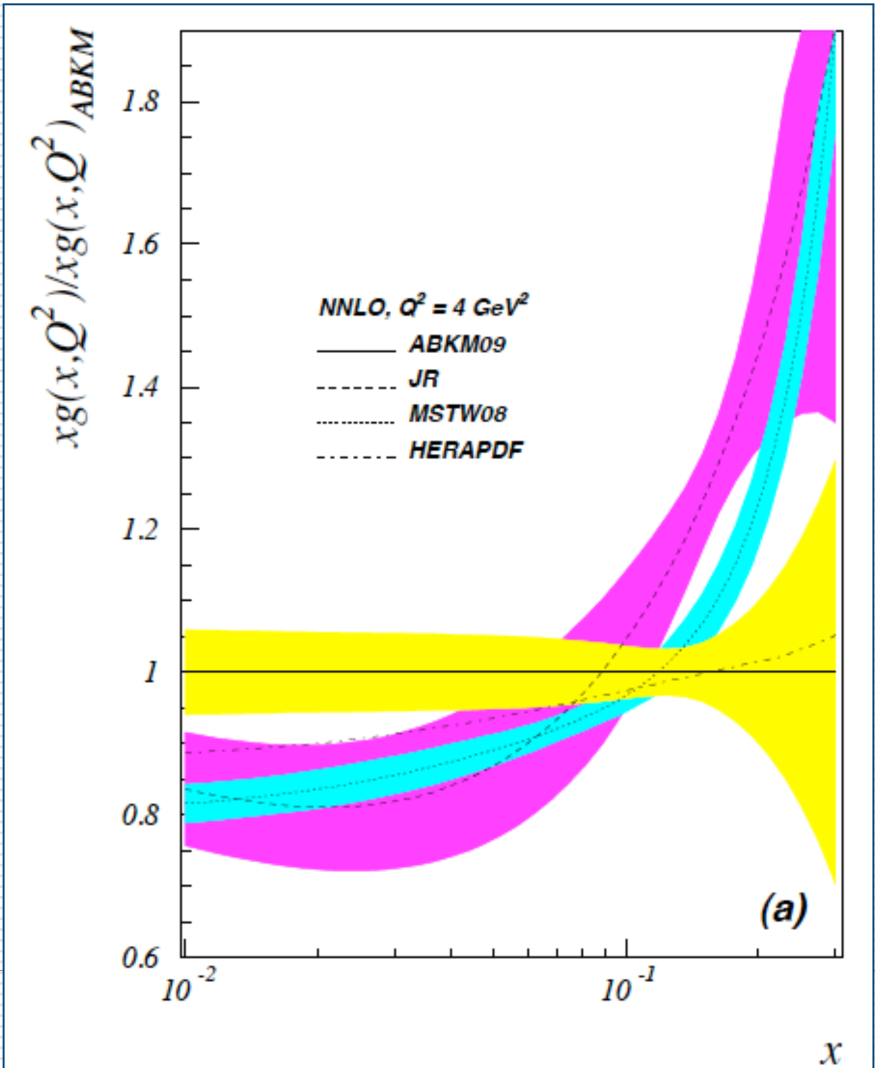


Combined data set

- systematic uncertainties < statistical uncertainties.

- small total uncertainties (1 – 2%) over a large part of the kinematic plane.

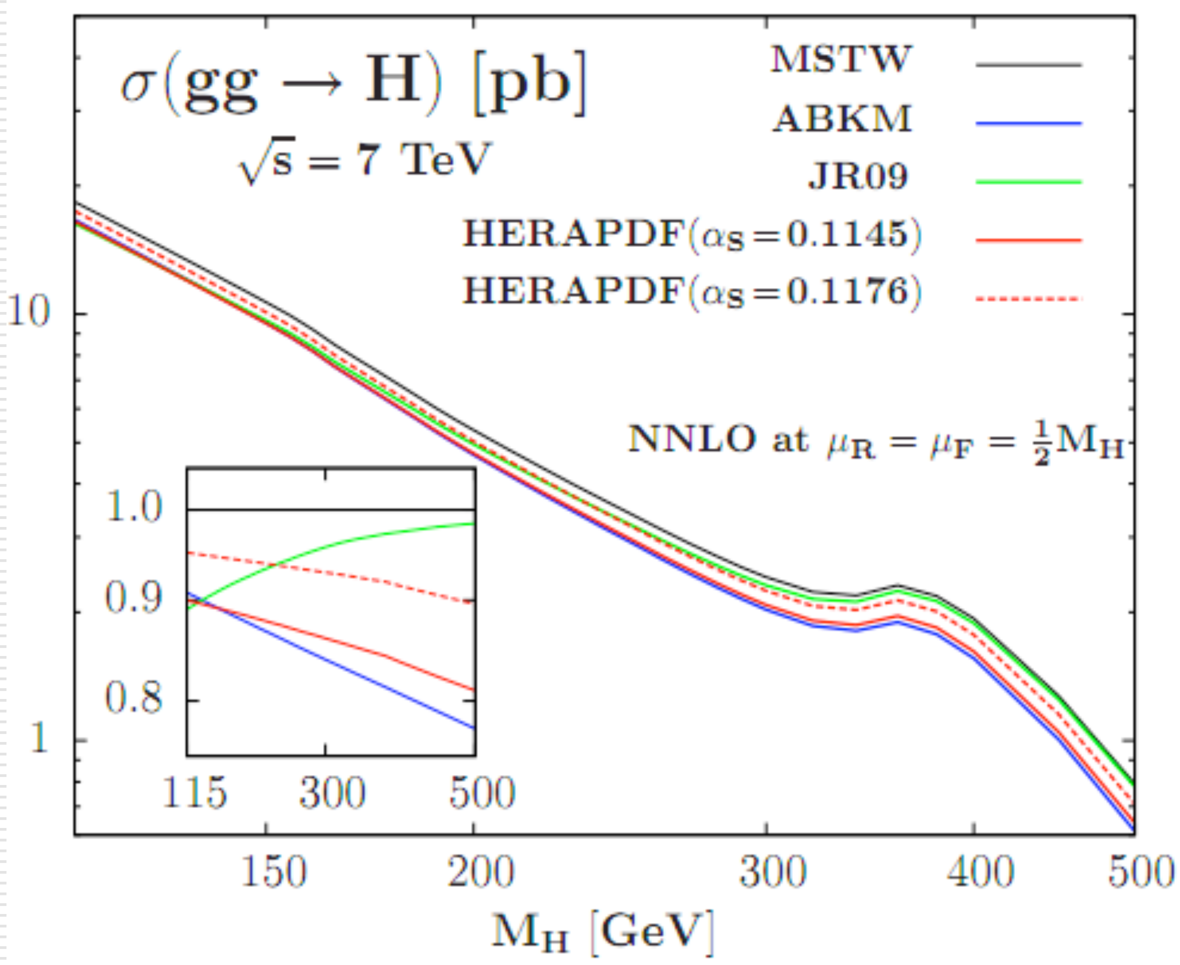
BACKUP
NNLO benchmark



- Recent benchmark of NNLO parton distributions.
- Significant differences between parton fits at NNLO.
- Data? Value of a_s? Statistical approach?

Alekhin et al
arXiv:1011.6259

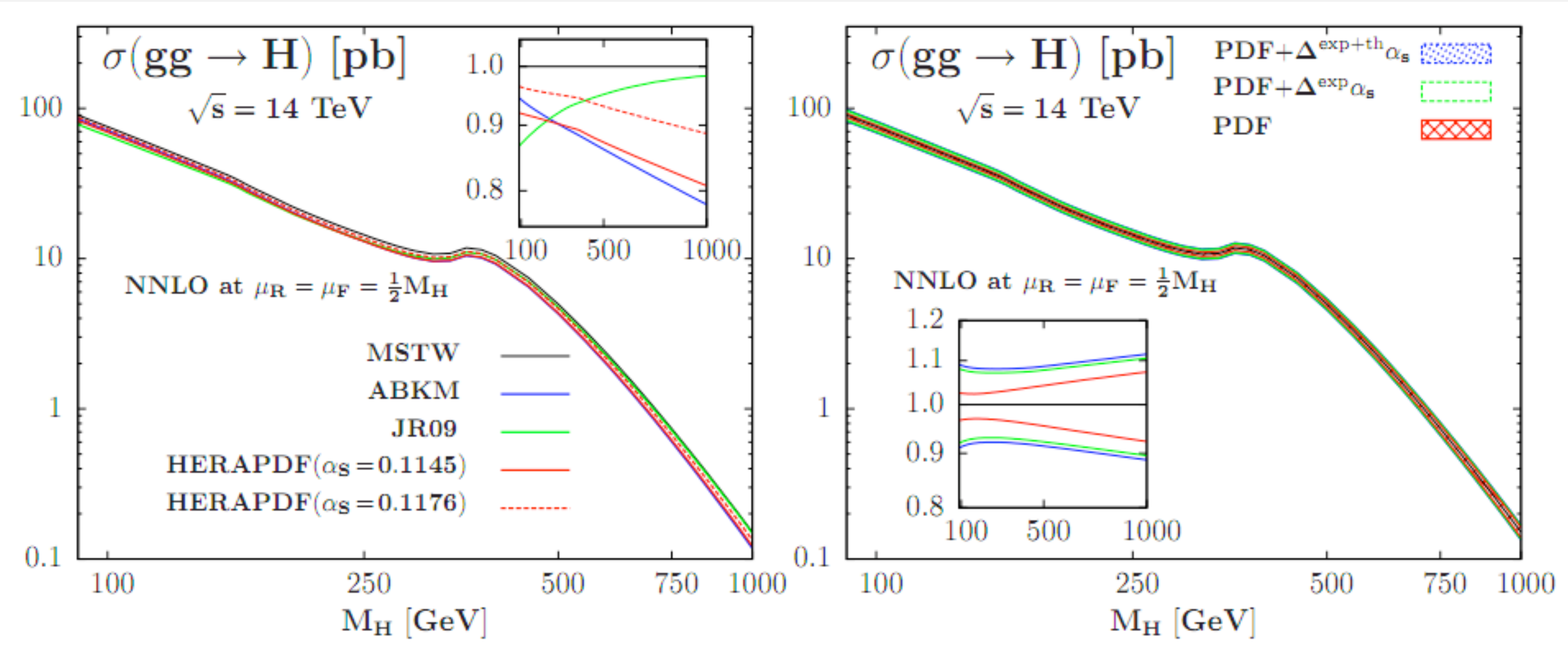
BACKUP
Higgs cross sections at NNLO



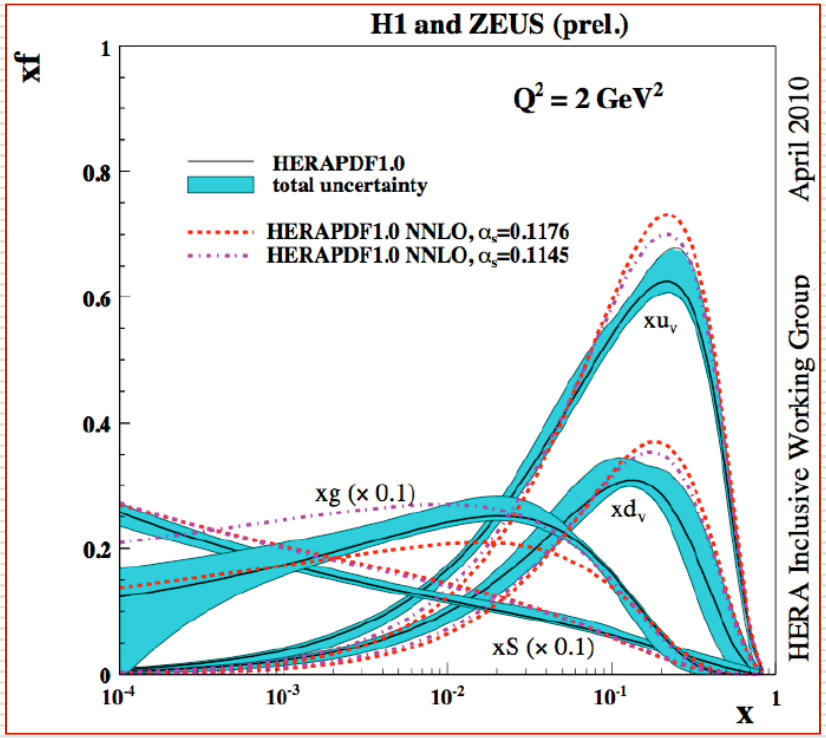
Baglio, Djouadi
1012.0530

BACKUP
Higgs cross sections at NNLO

Baglio, Djouadi
1012.0530



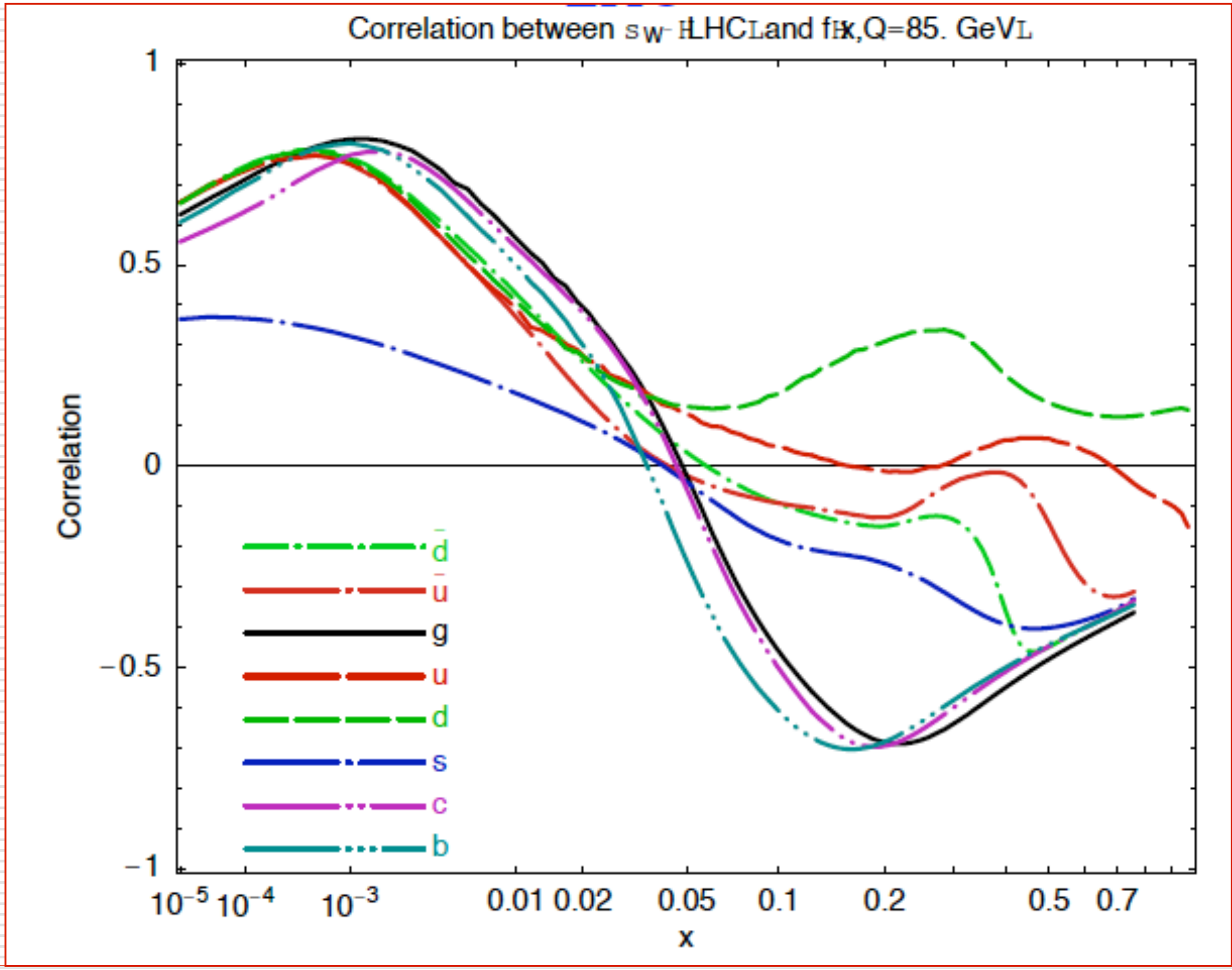
BACKUP
NNLO parton densities



V. Radescu Talk, QCD@LHC

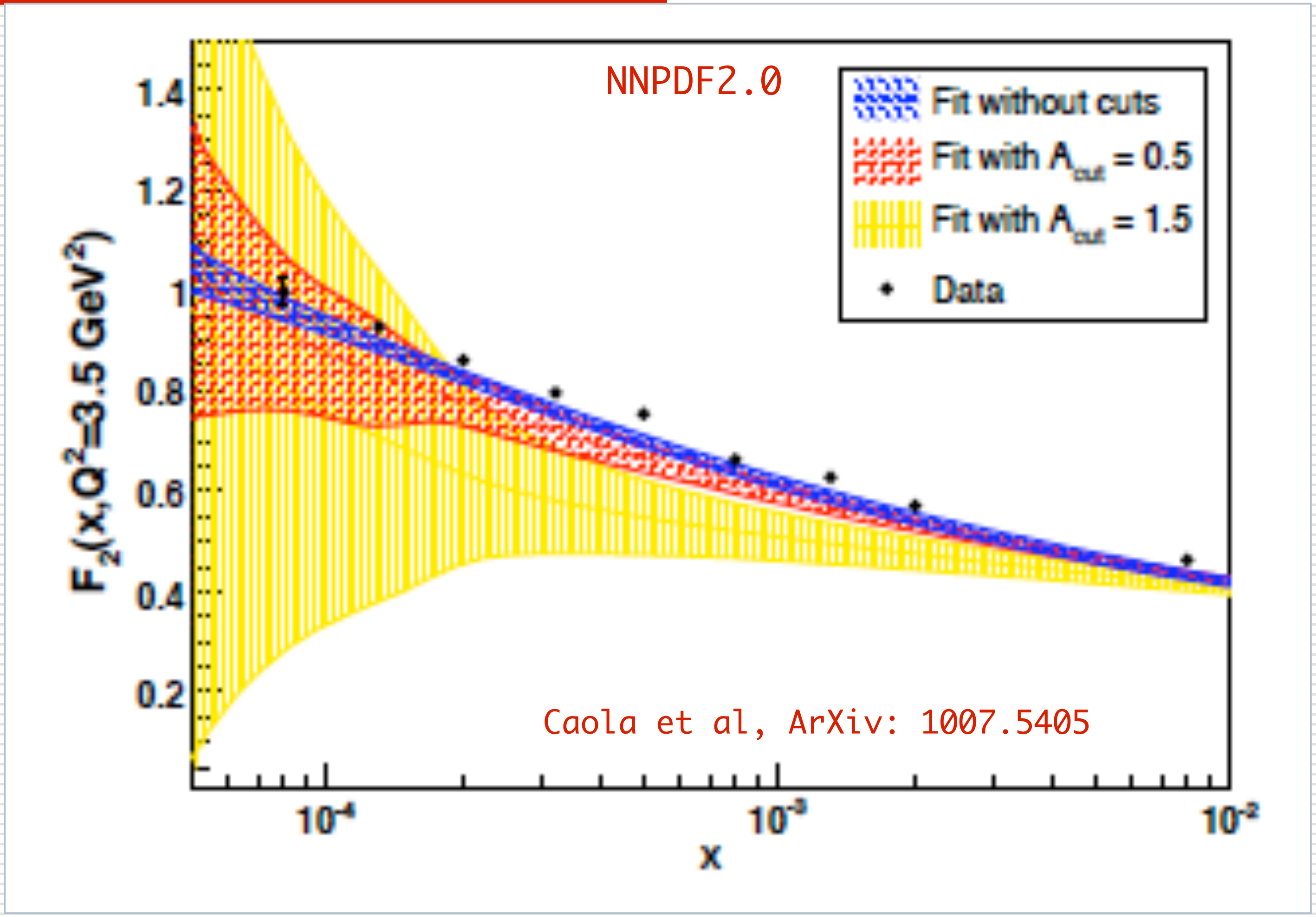
BACKUP

Small x region



BACKUP

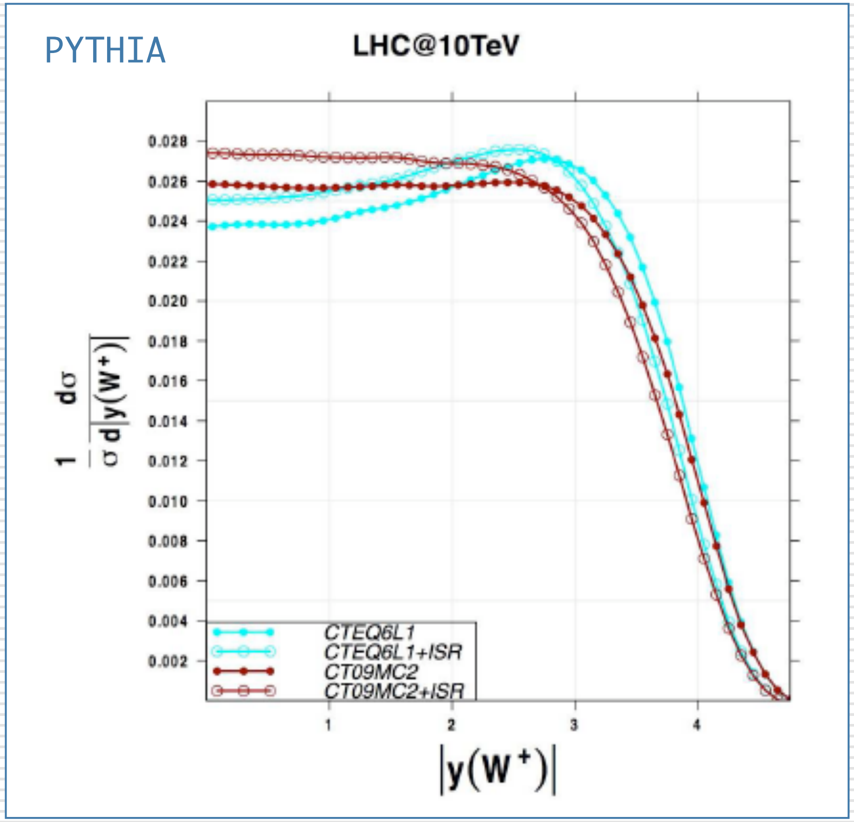
Small-x/Q^2 region



BACKUP
Initial state radiation

- PDFs are used
  - in the hard sub-processes matrix elements
  - in the backward showering algorithm for initial-state radiation (ISR)
  - in the calculation of the multi-parton interaction (underlying event)

- Few facts about initial state radiation
  - Different event generators treat ISR differently
  - In DGLAP partons emitted collinearly, in ISR radiated at finite angles ⇒ k_T finite
  - Should we keep into account the kinematic suppression due to parton showering when deriving PDFs for MC?



[Lai et al, ArXiv:0910.4183]