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UNIVERSITÀ DEGLI STUDI DI MILANO
DIPARTIMENTO DI FISICA

Istituto Nazionale di Fisica Nucleare

UNIVERSITÄT FREIBURG

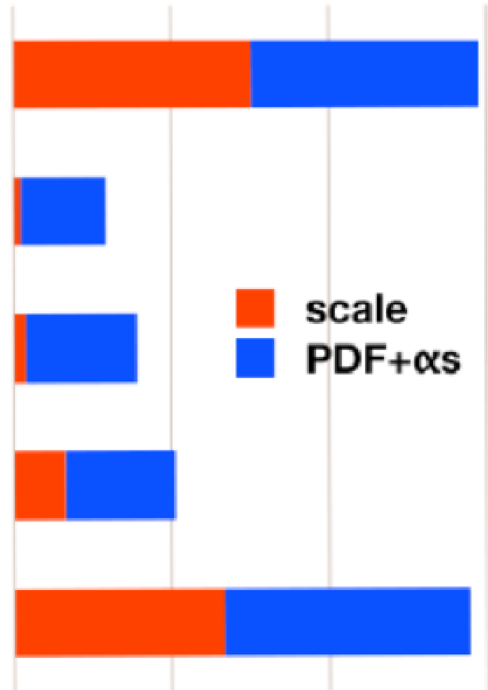
JANUARY 10, 2018

PROLOGUE

PAST (NOT SO LONG AGO)

HIGGS PRODUCTION

		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



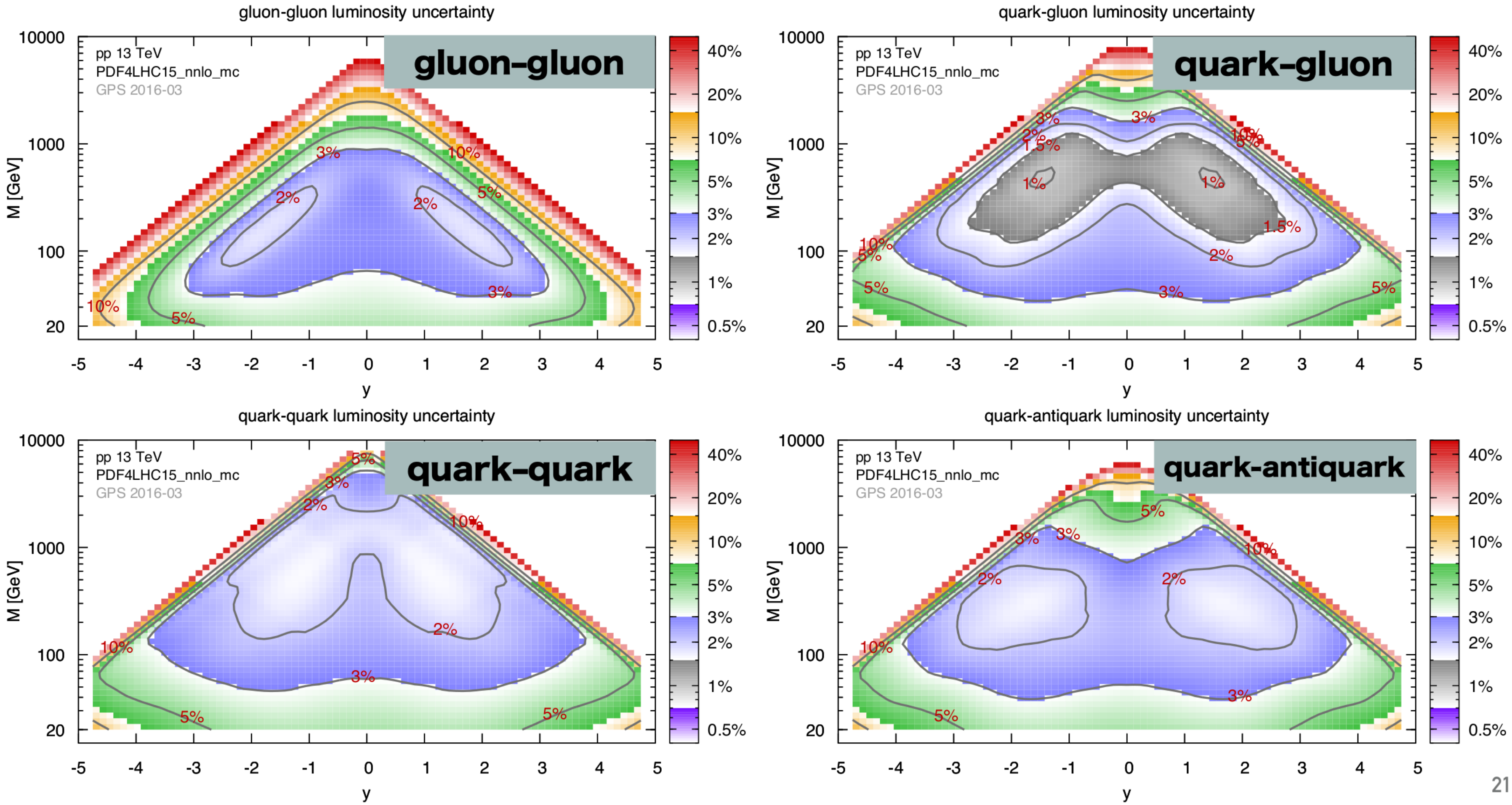
(J. Campbell, 2012)

PDF UNCERTAINTY EITHER DOMINANT, OR VERY LARGE, OR BOTH

TYPICAL PDF UNCERTAINTY $\sim 5 - 10\%$

PRESENT: THE PDF4LHC SET

LUMINOSITY UNCERTAINTIES VS RAPIDTY & MASS



G.P. Salam, 2016

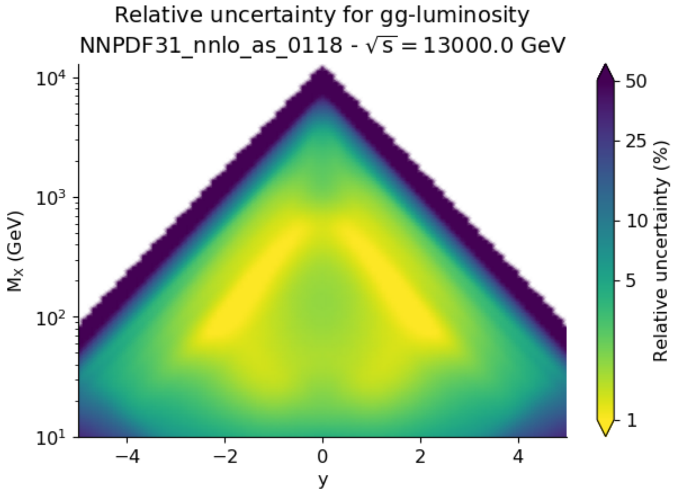
TYPICAL PDF UNCERTAINTY DOWN TO $\sim 2-5\%$

TOWARDS 1% PDF UNCERTAINTIES?

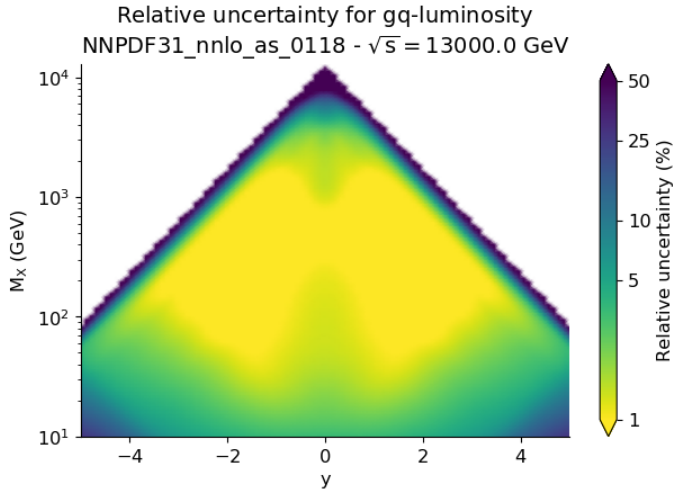
FUTURE: NNPDF3.1

LUMINOSITY UNCERTAINTIES VS RAPIDTY & MASS

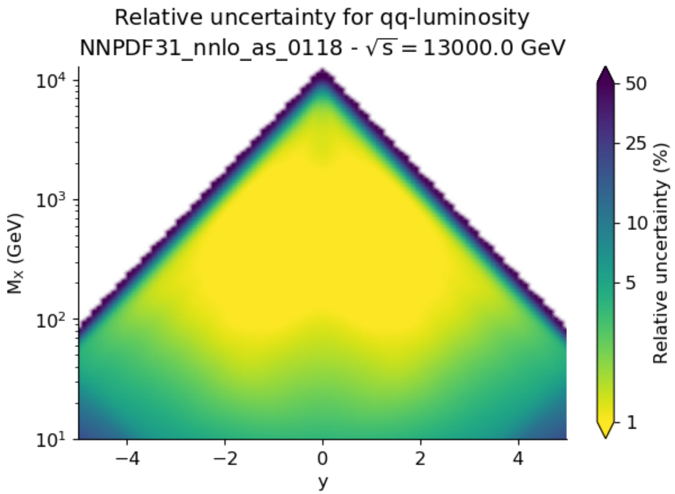
GLUON-GLUON



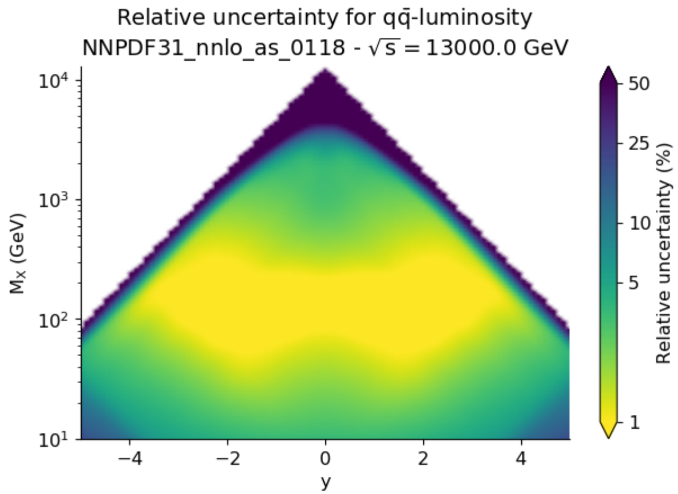
QUARK-GLUON



QUARK-QUARK



QUARK-ANTIQUARK



TYPICAL PDF UNCERTAINTY IN DATA REGION OF ORDER 1% !!
CAN WE BELIEVE IN 1% PDF UNCERTAINTIES? WHAT ARE THE CONSEQUENCES?

SUMMARY

THE IMPACT OF DATA

- WIDENING OF THE DATASET AND THE IMPACT OF LHC
- PDF UNCERTAINTIES
- FLAVOR SEPARATION & THE GLUON

METHODOLOGICAL ISSUES

- MONTE CARLO VS. HESSIAN
- PARAMETRIZATION ISSUES
- MINIMIZATION EFFICIENCY AND STATISTICAL TESTS
- CONTROLLING THE COVARIANCE MATRIX

THEORY ISSUES

- THE NNLO FRONTIER
- SMALL AND LARGE x RESUMMATION
- THE PHOTON PDF
- THE TREATMENT OF HEAVY QUARKS

THE IMPACT OF LHC DATA

CONTEMPORARY PDF TIMELINE (ONLY PUBLISHED GLOBAL)

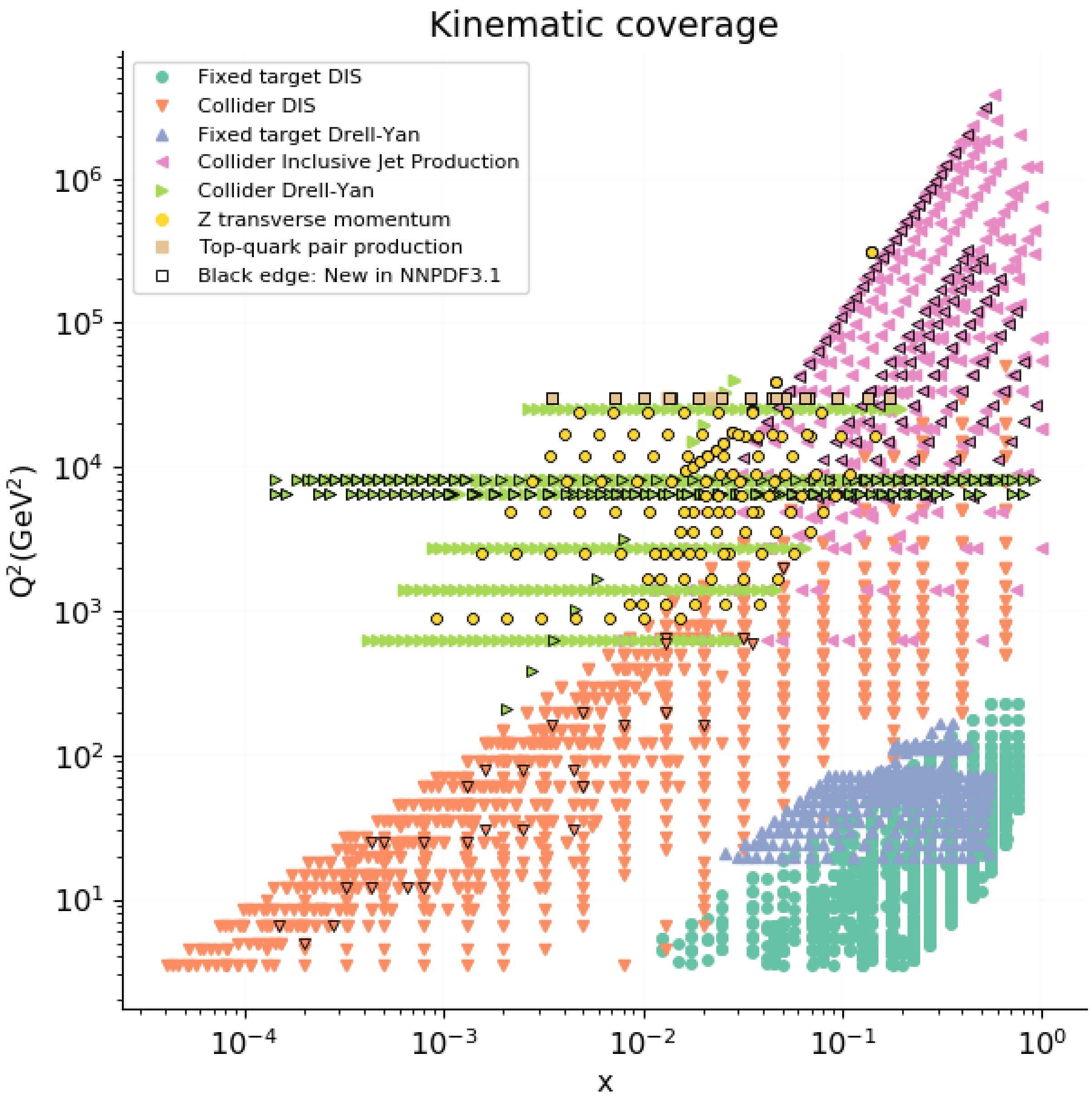
	2008		2009		2010		2011	2012		2013		2014		2015	2017	
SET / MONTH	CTEQ6.6 (02)	NNPDF1.0 (08)	MSTW (01)	ABKM09 (08)	NNPDF2.0 (02)	CT10 (NLO) (07)	NNPDF2.1 (NNLO) (07)	ABM11 (02)	NNPDF2.3 (07)	CT10 (NNLO) (02)	ABM12 (10)	NNPDF3.0 (10)	MMHT (12)	CT14 (06)	ABMP16 (01)	NNPDF3.1 (06)
F. T. DIS	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
ZEUS+H1-HI	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
COMB. HI	✗	✗	✗	✗	✔	✗	✔	✗	✔	✗	✔	✔	✗	✗	✔	✔
ZEUS+H1-HII	✗	✗	✗	✗	✗	✗	some	✗	✗	some	✗	✔	✗	✗	✔	✔
HERA JETS	✗	✗	✔	✗	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗	✗	✗
F. T. DY	✔	✗	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
TEV W+Z	✔	✗	✔	✗	✔	✔	✔	✗	✔	✔	✗	✔	✔	✔	✗	✔
LHC W+Z	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗	some	✔	✔	✔	some	✔
TEV JETS	✔	✗	✔	✗	✔	✔	✗	✔	✔	✔	✗	✔	✔	✔	✗	✔
LHC JETS	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗	✗	✔	✔	✔	✗	✔
TOP TOTAL	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✔	✔	✗	✗	✔	✔
SINGLE TOP TOTAL	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗
TOP DIFFERENTIAL	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✔
W p_T	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗	✗	✗	✗
W+C	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗	✗	✗	✗
Z p_T	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✔

THEORY PROGRESS:

- MSTW, ABKM: all NNLO; NNPDF NNLO since 07/11 (2.1), CT since 02/13 (CT10);
  NNPDF THRESHOLD RESUMMATION (3.0RESUM, 07/15), SMALL x RESUMMATION (3.1SX, 10/17)
- MSTW, CT, NNPDF all GM-VFN; NNPDF since 01/11 (2.1);
  ABM FFN+ZM-VFN since 01/17 (ABMP16)
- NNPDF FITTED CHARM since 05/16 (NNPDF3IC)
- PHOTON PDF: (mrst2004qed), NNPDF2.3QED (08/13), NNPDF3.0QED (06/16), NNPDF3.1LUXQED (12/17)

DATASET WIDENING

NNPDF3.0 VS NNPDF3.1

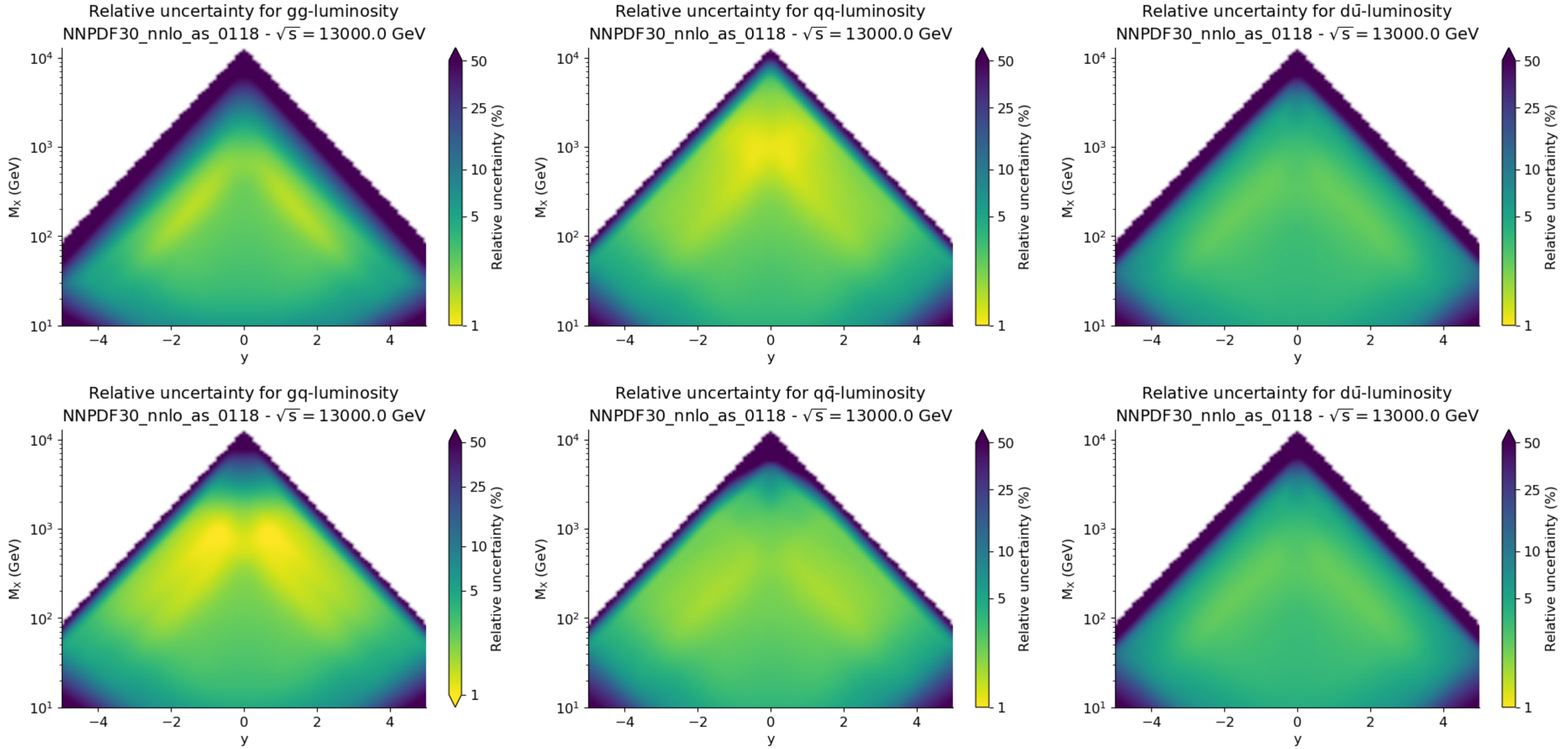


NEW DATA: (BLACK EDGE)

- HERA COMBINED F_2^b
- D0 W LEPTON ASYMMETRY
- ATLAS W, Z 2011, HIGH & LOW MASS DY 2011; CMS $W^{\pm}$ RAPIDITY 8TEV LHCB W, Z 7TEV & 8TEV
- ATLAS 7TEV JETS 2011, CMS 2.76TEV JETS
- ATLAS & CMS TOP DIFFERENTIAL RAPIDITY
- ATLAS Z p_T DIFFERENTIAL RAPIDITY & INVARIANT MASS 8TEV, CMS Z p_T DIFFERENTIAL RAPIDITY 8TEV

THE IMPACT OF LHC DATA
PDF UNCERTAINTIES IN DETAIL: NNPDF3.0 (NNLO)

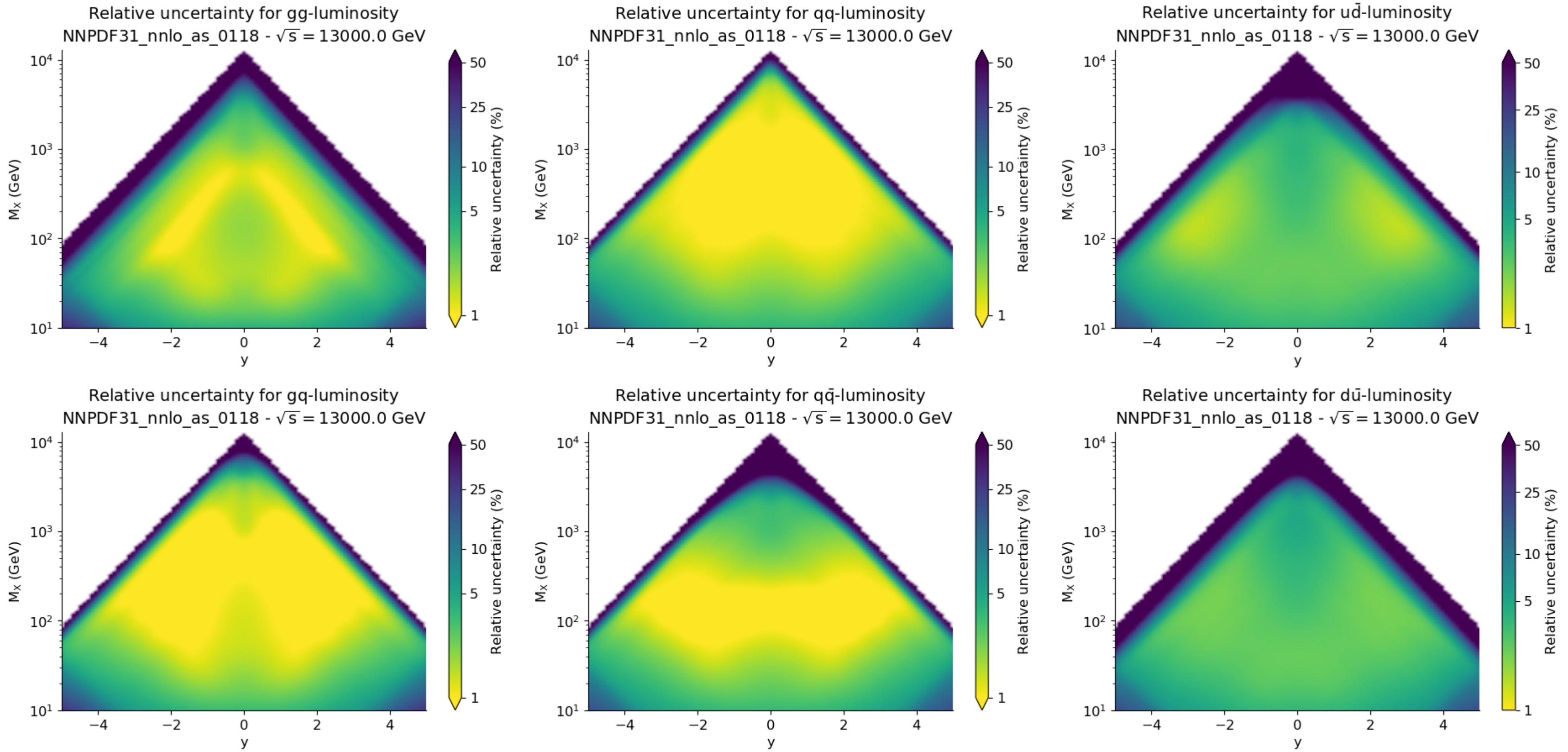
GLUON SINGLET FLAVORS



- GLUON BETTER KNOWN AT SMALL x, VALENCE QUARKS AT LARGE x, SEA QUARKS IN BETWEEN
- TYPICAL UNCERTAINTIES IN DATA REGION $\sim 3-5\%$
- SWEET SPOT: VALENCE Q - G; DOWN TO 1%
- UP BETTER KNOWN THAN DOWN; FLAVOR SINGLET BETTER THAN INDIVIDUAL FLAVORS

THE IMPACT OF LHC DATA
PDF UNCERTAINTIES IN DETAIL: NNPDF3.1 (NNLO)

GLUON SINGLET FLAVORS



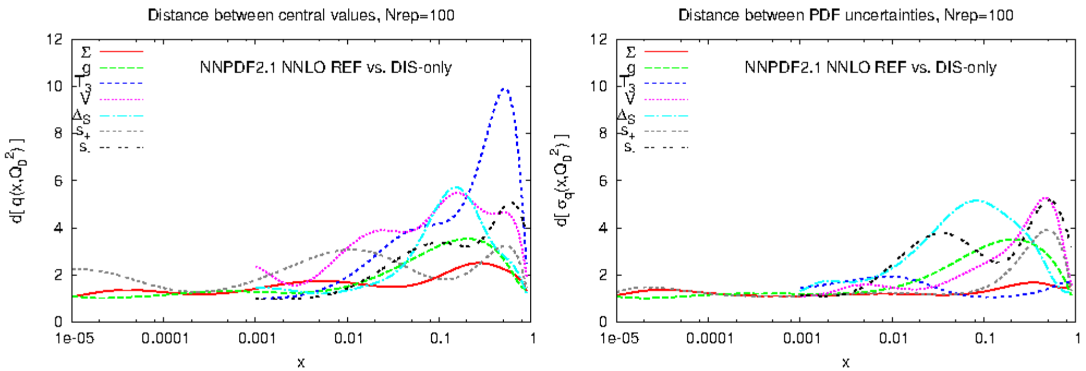
- GLUON BETTER KNOWN AT SMALL x, VALENCE QUARKS AT LARGE x, SEA QUARKS IN BETWEEN
- TYPICAL UNCERTAINTIES IN DATA REGION $\sim 1-3\%$
- SWEET SPOT: VALENCE Q - G; 1% OR BELOW
- UP BETTER KNOWN THAN DOWN; FLAVOR SINGLET BETTER THAN INDIVIDUAL FLAVORS
- NEW LHC DATA $\Rightarrow$ SIZABLE REDUCTION IN UNCERTAINTIES

THE IMPACT OF LHC DATA

BEFORE LHC: PDFS MOSTLY DETERMINED BY DIS DATA

NNPDF2.1 VS NNPDF2.1 DIS ONLY

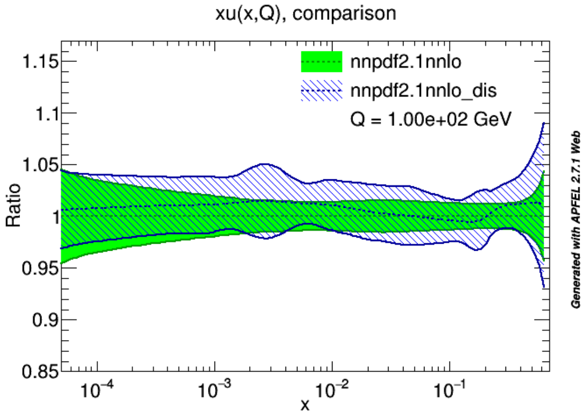
DISTANCES (difference in units of st. dev.)



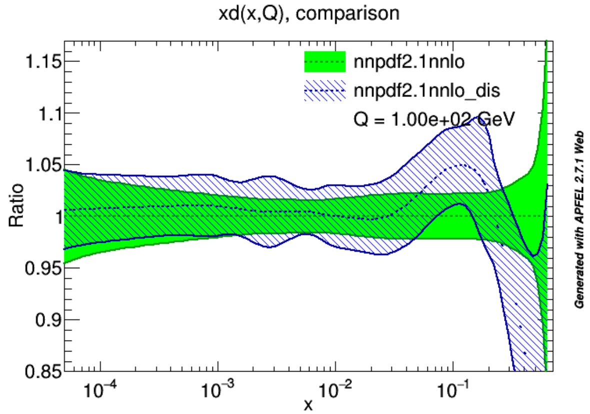
$d = 10 \Leftrightarrow$ one sigma difference

PDF COMPARISON

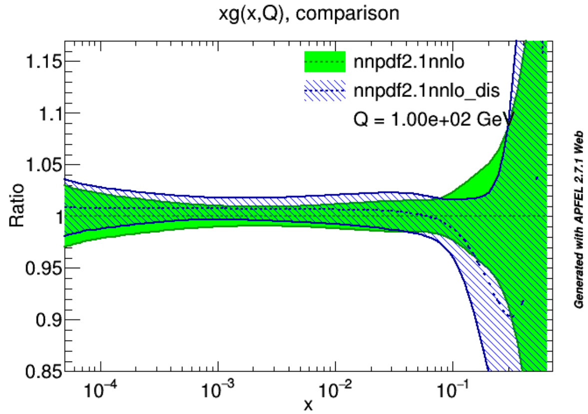
UP



DOWN



GLUON

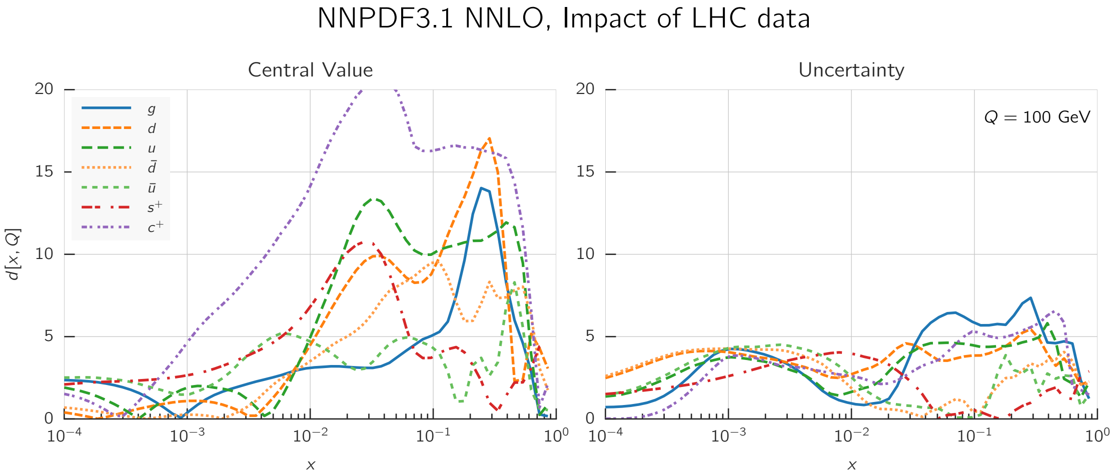


- ALL DIFFERENCES BELOW ONE SIGMA
- ONLY UP-DOWN SEPARATION SIGNIFICANTLY AFFECTED

THE IMPACT OF LHC DATA

NOW: PDFs LARGELY DETERMINED BY LHC DATA

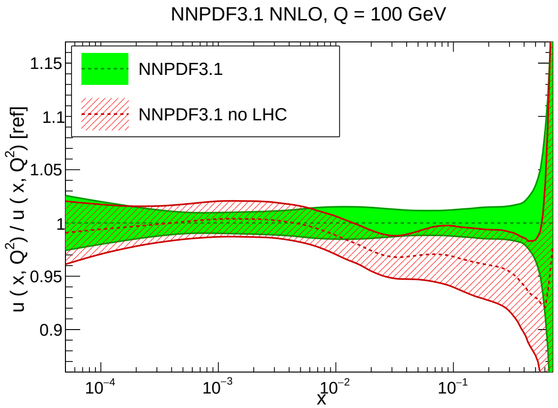
NNPDF3.1 VS NNPDF3.1 NO LHC
DISTANCES (difference in units of st. dev.)



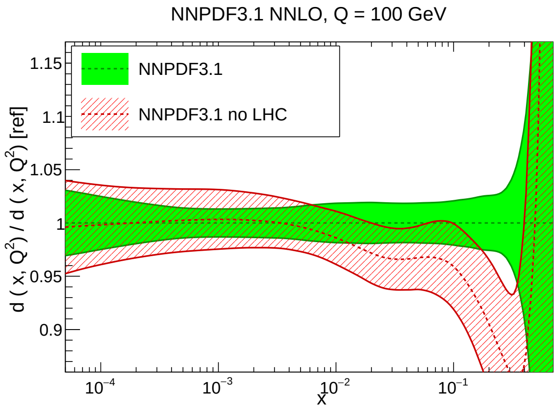
$d = 10 \Leftrightarrow$ one sigma difference

PDF COMPARISON

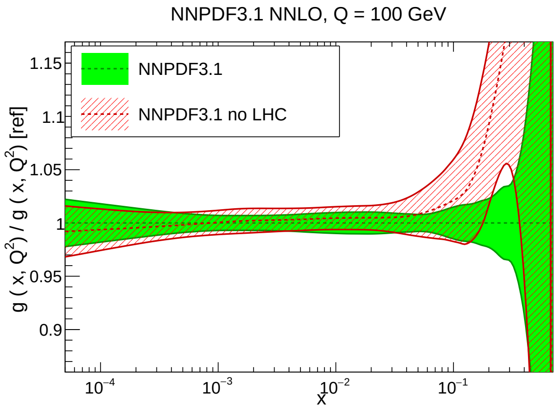
UP



DOWN



GLUON

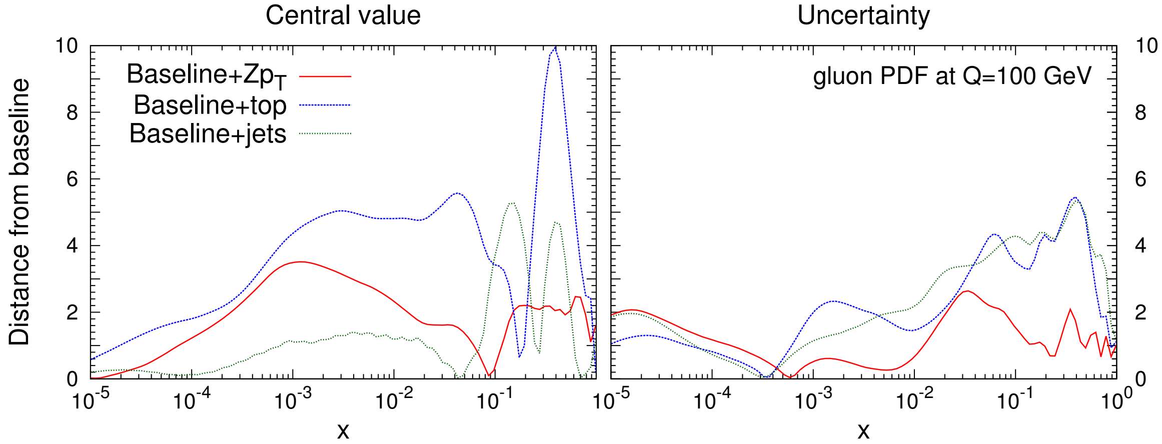


- MANY PDFs CHANGE BY MORE THAN ONE SIGMA
- BOTH FLAVOR SEPARATION & GLUON SIGNIFICANTLY AFFECTED

THE IMPACT OF LHC DATA
THE GLUON

- BEFORE LHC $\Rightarrow$ DIS SCALING VIOLATIONS, TEV JETS AT LARGE X
- AFTER LHC $\Rightarrow$ JETS; $Z\ p_t$, TOP

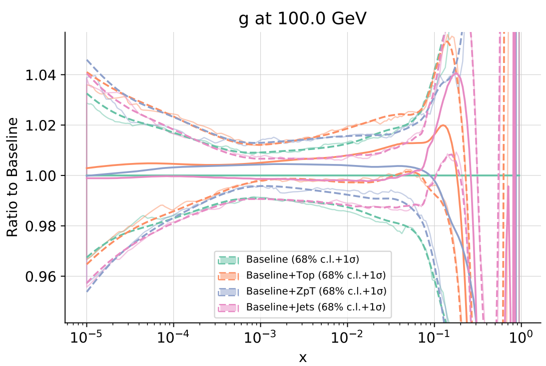
DISTANCES (difference in units of st. dev.)



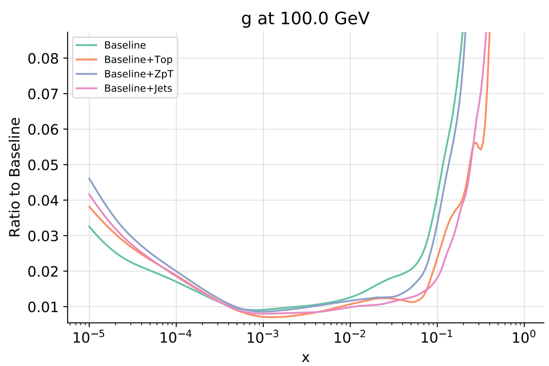
(Nocera, Ubiali, 2017)

PDF COMPARISON: GLUON

CENTRAL VALUE



UNCERTAINTY

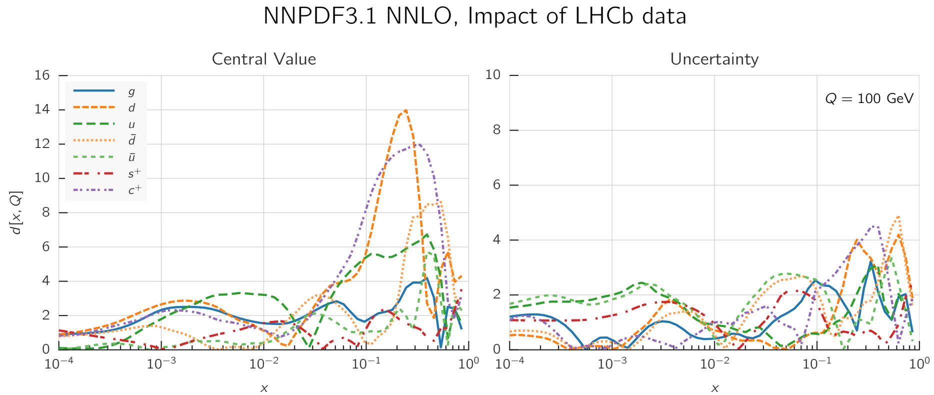


- TOP HAS LARGEST IMPACT, FOLLOWED BY JETS
- ALL LHC DATA PULL CENTRAL VALUE IN SAME DIRECTION!

THE IMPACT OF LHC DATA
FLAVOR SEPARATION

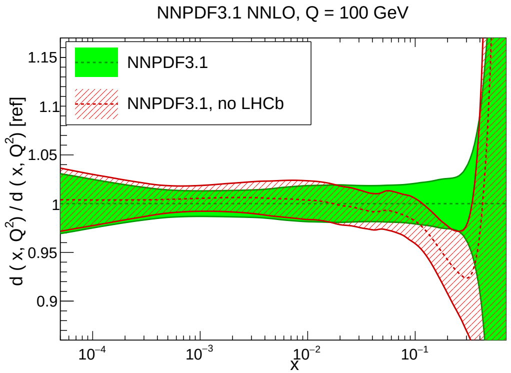
- BEFORE LHC ⇒ CC DIS, TEV FIXED-TARGET DY, W ASYM.
- AFTER LHC ⇒ WIDE RANGE OF W, Z PRODUCTION DATA

IMPACT OF LHCB
DISTANCES (difference in units of st. dev.)

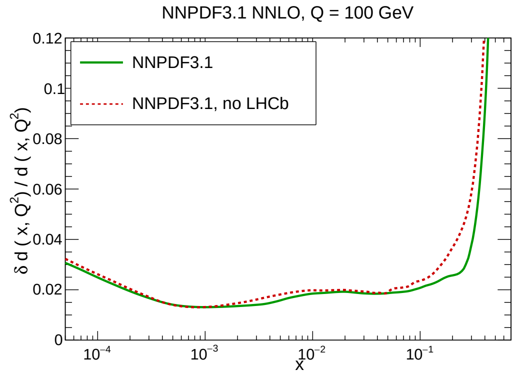


PDF COMPARISON: DOWN

CENTRAL VALUE



UNCERTAINTY



- SIZABLE SHIFT OF CENTRAL VALUE BY ALMOST ONE SIGMA
- LARGE x UNCERTAINTY DOWN BY LARGE FACTOR!

NEW DATA: SUMMARY

- LHC DATA NOW HAVE THE DOMINANT IMPACT ON PDFS
- METHODOLOGY AND THEORY MUST ACCORDINGLY ADAPT

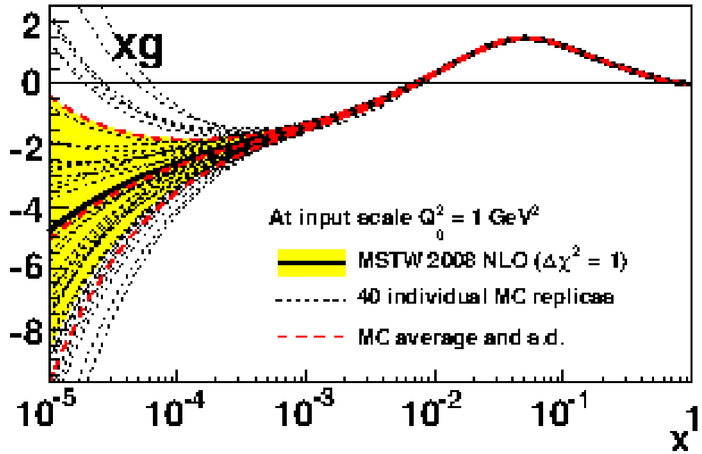
THE LIMITS OF METHODOLOGY

PDF PARAMETRIZATION & DELIVERY

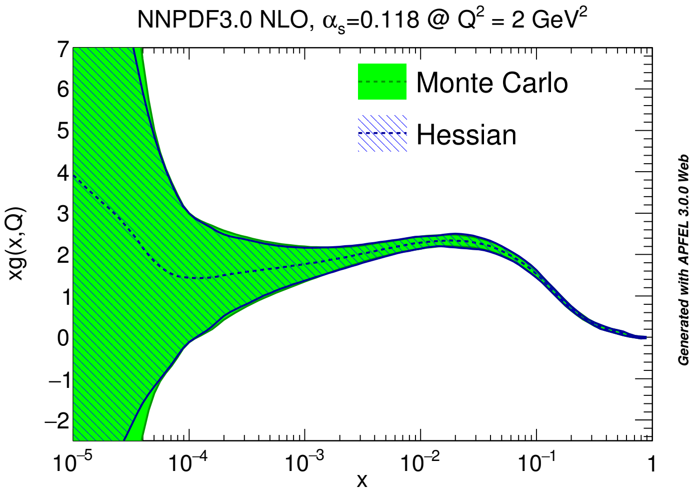
- TRADITIONALLY, TWO DELIVERY METHODS FOR PDFS
- HESSIAN A CENTRAL PDF SET, & ERROR SETS CORRESPONDING TO EIGENVECTORS OF THE COVARIANCE MATRIX IN PARAMETER SPACE
  ADVANTAGE: EFFICIENT REPRESENTATION OF UNCERTAITY
  DISADVANTAGES: ASSUMES GAUSSIANITY
- MONTECARLO A SET OF PDF REPLICAS WHICH REPRESENTS THE PROBABILITY IN PDF SPACE (SO THE MEAN UNBIASEDLY ESTIMATES THE CENTRAL VALUE &C)
  ADVANTAGE: FAITHFUL REPRESENTATION OF PROBABILITY
  DISADVANTAGES: MAY NEED LARGE NUMBER OF REPLICAS
- TRADITIONALLY, DELIVERY $\Leftrightarrow$ PARAMETRIZATION/MINIMIZATION
  HESSIAN USED WITH RELATIVELY SIMPLE FUNCTIONAL FORMS (SMALL NUMBERS OF PARAMETERS) $\Leftrightarrow$ HESSIAN MINIMIZATION

PROGRESS I
MC $\Leftrightarrow$ HESSIAN

- TO CONVERT HESSIAN INTO MONTECARLO GENERATE MULTIGAUSSIAN REPLICAS IN PARAMETER SPACE
- ACCURATE WHEN NUMBER OF REPLICAS SIMILAR TO THAT WHICH REPRODUCES DATA



(Thorne, Watt, 2012)

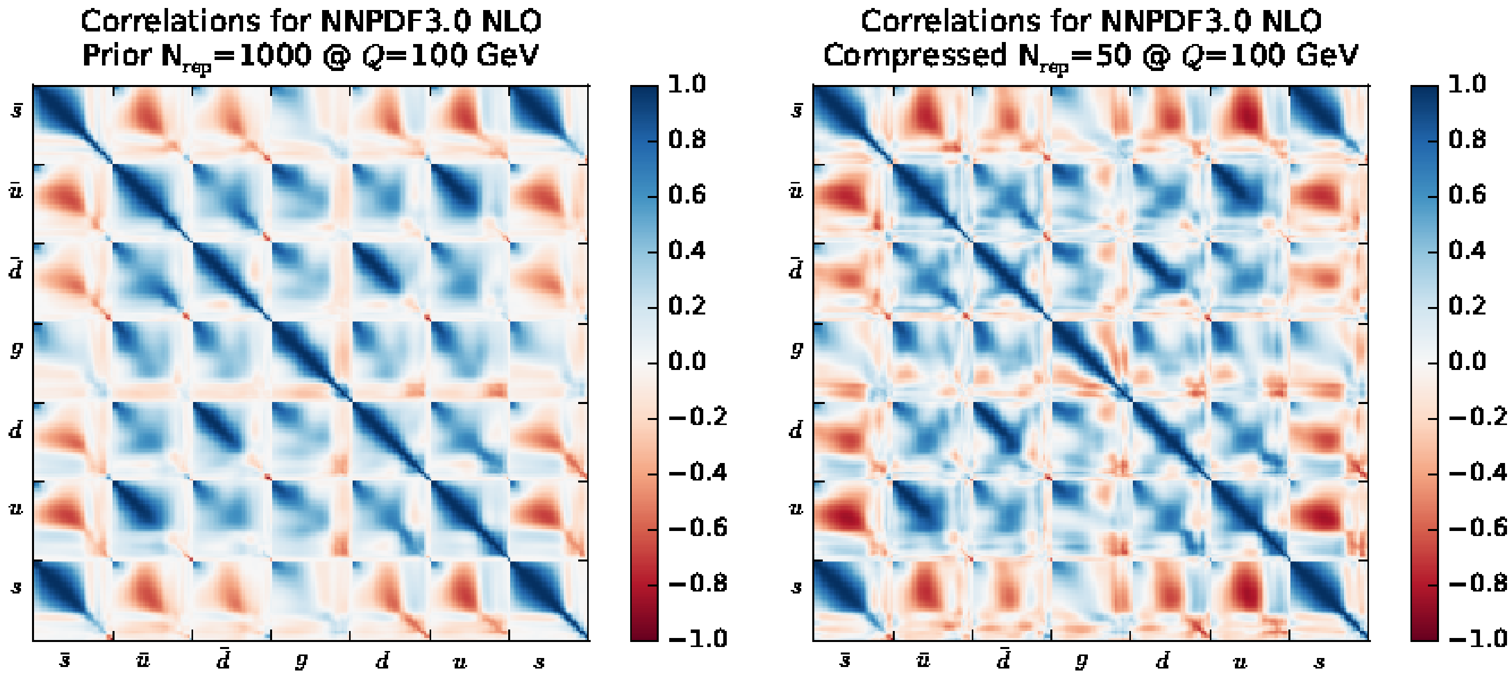


(Carrazza, SF, Kassabov, Rojo, 2015)

- TO CONVERT MONTE CARLO INTO HESSIAN, SAMPLE THE REPLICAS $f_i(x)$ AT A DISCRETE SET OF POINTS & CONSTRUCT THE ENSUING COVARIANCE MATRIX
- EIGENVECTORS OF THE COVARIANCE MATRIX AS A BASIS IN THE VECTOR SPACE SPANNED BY THE REPLICAS BY SINGULAR-VALUE DECOMPOSITION
- NUMBER OF DOMINANT EIGENVECTORS SIMILAR TO NUMBER OF REPLICAS $\Rightarrow$ ACCURATE REPRESENTATION

PROGRESS II

MONTECARLO COMPRESSION



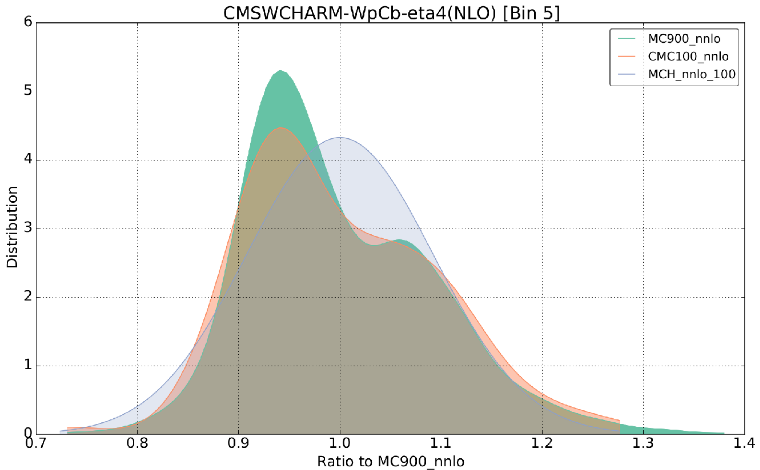
(Carrazza, Latorre, Kassabov, Rojo, 2015)

- CONSTRUCT A VERY LARGE REPLICA SAMPLE
- SELECT (BY GENETIC ALGORITHM) A SUBSET OF REPLICAS WHOSE STATISTICAL FEATURES ARE AS CLOSE AS POSSIBLE TO THOSE OF THE PRIOR
- $\Rightarrow$ FOR ALL PDFS ON A GRID OF POINTS// MINIMIZE DIFFERENCE OF: FIRST FOUR MOMENTS, CORRELATIONS; OUTPUT OF KOLMOGOROV-SMIRNOV TEST (NUMBER OF REPLICAS BETWEEN MEAN AND σ, 2σ, INFINITY)
- 50 COMPRESSED REPLICA REPRODUCE 1000 REPLICA SET TO PRECENT ACCURACY

NONGAUSSIAN BEHAVIOUR

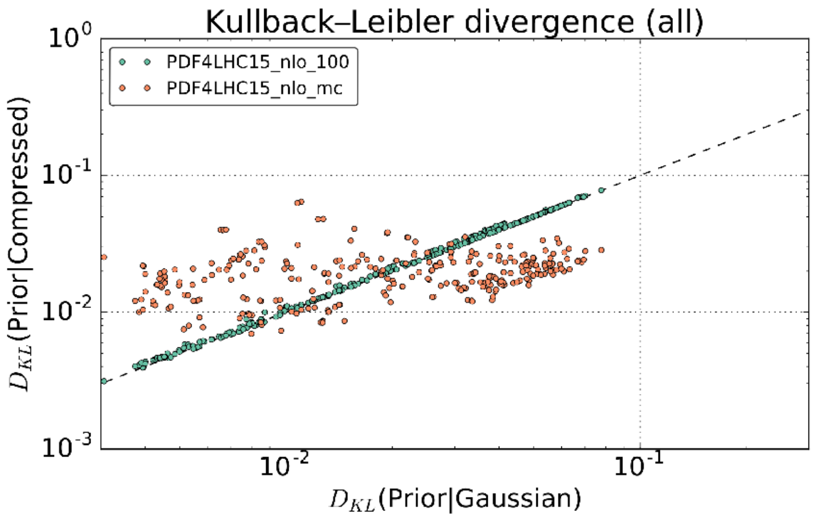
MONTE CARLO COMPARED TO HESSIAN

CMS $W + c$ production



- DEVIATION FROM GAUSSIANITY E.G. AT LARGE x DUE TO LARGE UNCERTAINTY + POSITIVITY BOUNDS
  $\Rightarrow$ RELEVANT FOR SEARCHES
- CANNOT BE REPRODUCED IN HESSIAN FRAMEWORK
- WELL REPRODUCED BY COMPRESSED MC

- DEFINE KULLBACK-LEIBLER DIVERGENCE
  $D_{\mathrm{KL}} = \int_{-\infty}^{\infty} P(x) \frac{\ln P(x)}{\ln Q(x)}\, dx$
  BETWEEN A PRIOR P AND ITS REPRESENTATION Q
- D_{KL} BETWEEN PRIOR AND HESSIAN DEPENDS ON DEGREE OF GAUSSIANITY
- D_{KL} BETWEEN PRIOR AND COMPRESSED MC DOES NOT



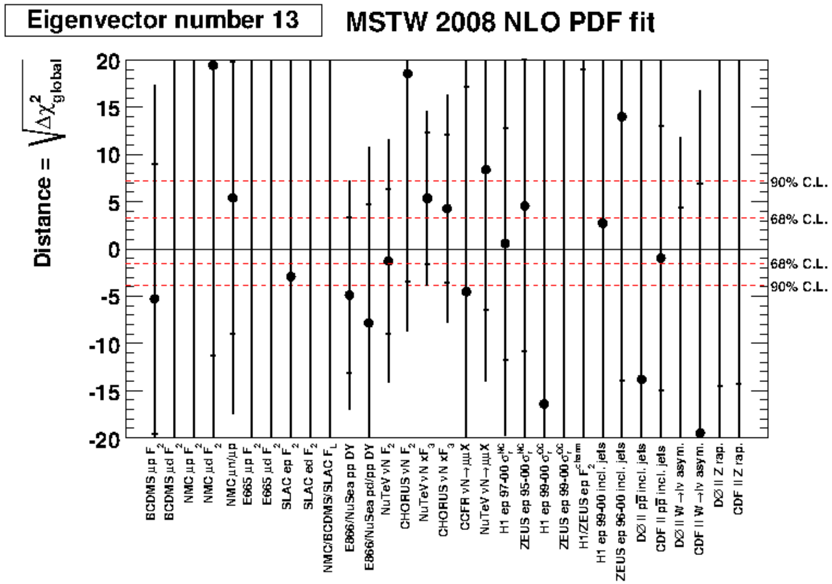
CAN (A) GAUGE WHEN MC IS MORE ADVANTAGEOUS THAN HESSIAN;
(B) ASSESS THE ACCURACY OF COMPRESSION

PDF PARAMETRIZATION ISSUES

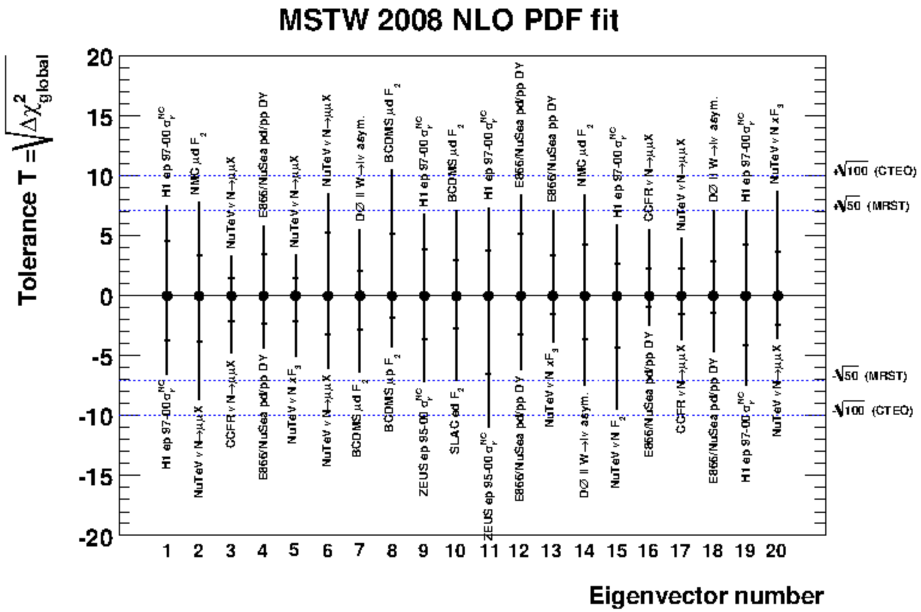
- Q: WHY ARE PDF UNCERTAINTIES ON GLOBAL FITS OF SIMLAR SIZE?
  - SIMILAR DATASETS
  - BUT DIFFERENT PROCEDURES
- A: UNCERTAINTY TUNING

TOLERANCE (MMHT-CT)

MSTW TOLERANCE PLOT FOR 13TH EIGENVEC.



GLOBAL MSTW TOLERANCE

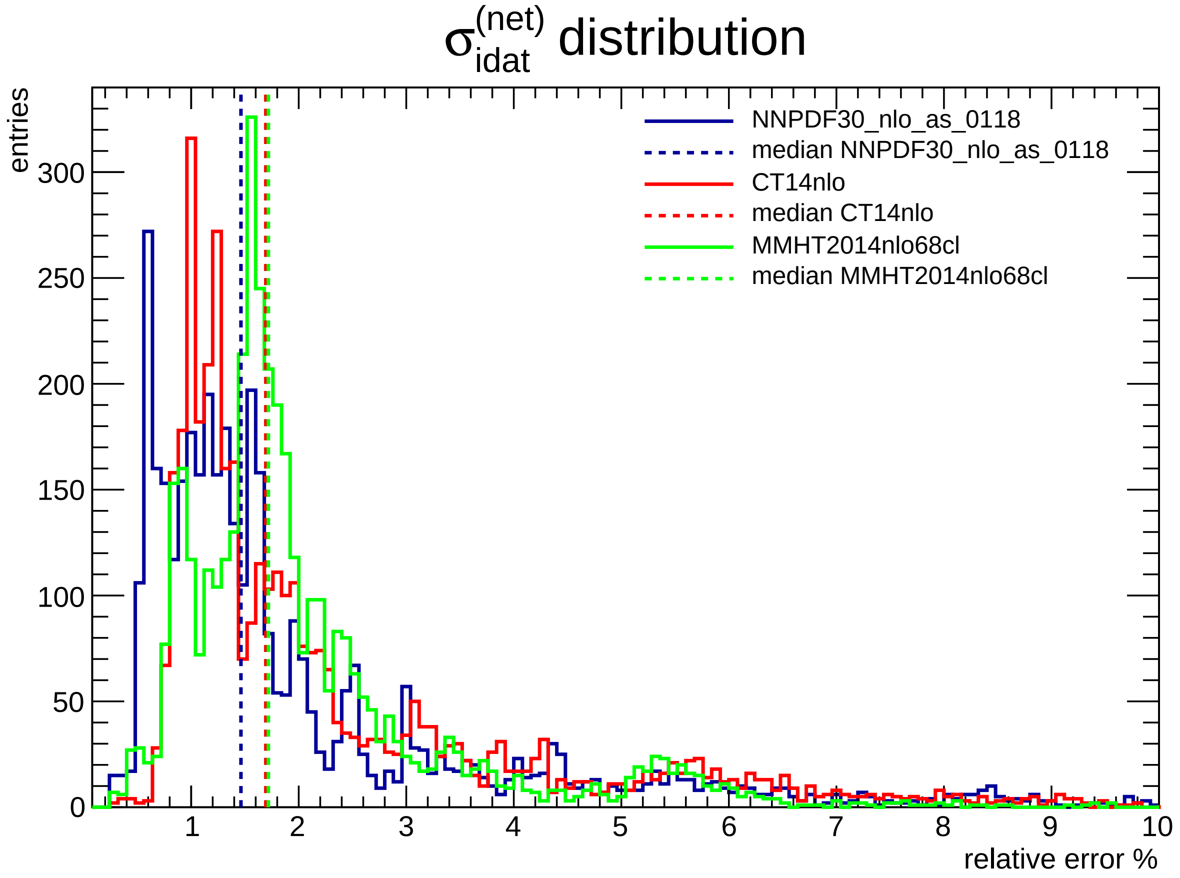


- (MSTW/MMHT) FOR EACH EIGENVECTOR IN PARAMETER SPACE DETERMINE CONFIDENCE LIMIT FOR THE DISTRIBUTION OF BEST-FITS OF EACH EXPERIMENT
- RESCALE $\Delta\chi^2 = T$ INTERVAL SUCH THAT CORRECT CONFIDENCE INTERVALS ARE REPRODUCED
- WHY DO WE NEED TOLERANCE?
- DO WE UNDERSTAND PDF UNCERTAINTIES?

PDF UNCERTAINTIES: HOW MUCH DO THEY VARY?

- COMPUTE PERCENTAGE PDF UNCERTAINTY ON ALL DATA INCLUDED IN GLOBAL FIT
- COMPARE GLOBAL FITS

PERCENTAGE PDF UNCERTAINTY ON PREDICTIONS



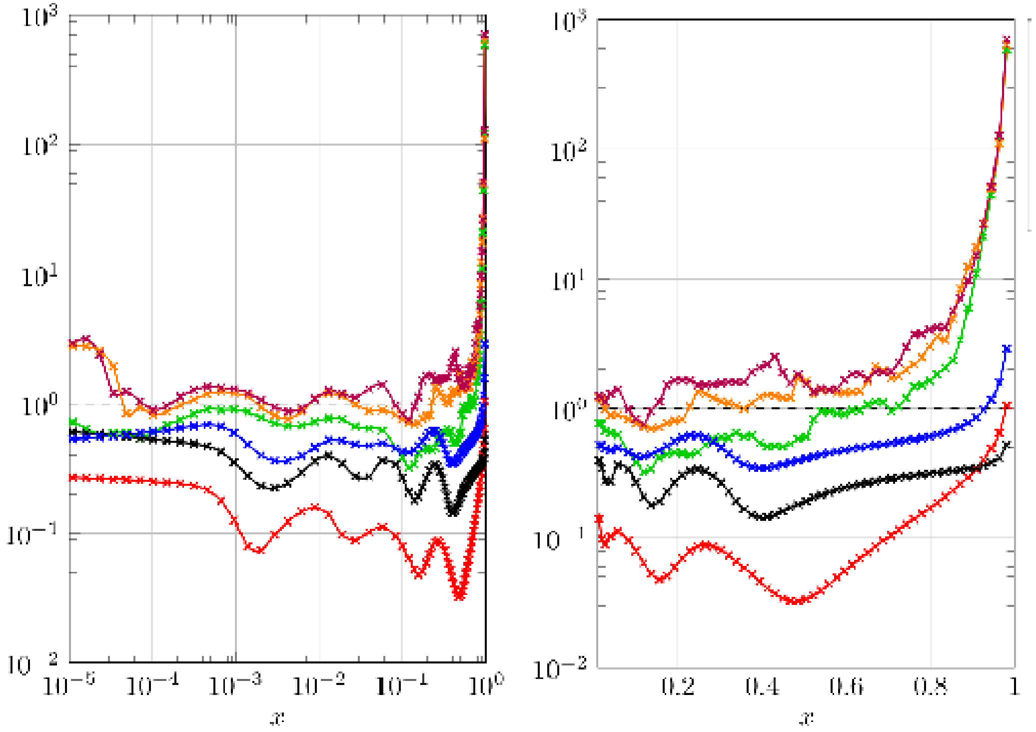
- MEDIAN SIMILAR
- DISTRIBUTION VERY DIFFERENT!
- NNPDF: SMALLER MODE, BUT FAT TAIL $\Leftrightarrow$ GREATER FLEXIBILITY

CLOSURE TESTING
BASIC IDEA

- ASSUME PDFs KNOWN: GENERATE FAKE EXPERIMENTAL DATA
- CAN DECIDE DATA UNCERTAINTY (ZERO, OR AS IN REAL DATA, OR . . .)
- FIT PDFs TO FAKE DATA:
  - LEVEL 0: ZERO UNCERTAINTY
    - CHECK WHETHER MINIMZATION EFFICIENT
    - CHECK FOR INTERPOLATION UNCERTAINTY
  - LEVEL 1: DATA UNCERTAINTY, BUT NO REPLICAS
    - CHECK FOR UNIQUENESS OF BEST FIT ⇒ "FUNCTIONAL" UNCERTAINTY (Pumplin, 2010)
  - LEVEL 2: AS IN STANDARD PROCEDURE
    - CHECK WHETHER TRUE VALUE GAUSSIANLY DISTRIBUTED ABOUT FIT
    - CHECK WHETHER UNCERTAINTIES FAITHFUL

CLOSURE-TESTING: THE PARAMETRIZATION DEPENDENCE

GLUON PDF UNCERTAINTY NORMALIZED TO MSTW08



(C. Mascaretti, 2016)

- CLOSURE TEST PERFORMED WITH DATA GENERATED BASED ON MST08 FUNCTIONAL FORM
- REFITTED EITHER WITH NNPDF OR MSTW FUNCTIONAL FORM
- LEVEL 0: VANISHING DATA UNCERTAINTY
  - MSTW-CT: FIT HAS ZERO UNCERTAINTY
  - NNPDF: ABOUT HALF OF TOTAL UNCERTAINTY
- LEVEL 1: NOMINAL DATA UNCERTAINTY, BUT REPLICAS FITTED W/O PSEUDODATA
  - MSTW-CT: FIT HAS SMALL UNCERTAINTY
  - NNPDF: ABOUT 2/3 OF FINAL UNCERTAINTY
- LEVEL 2
  - NNPDF UNCERTAINTY LARGER THAN MSTW-CT
  - NNPDF UNCERTAINTY SIMILAR TO TRUE MSTW

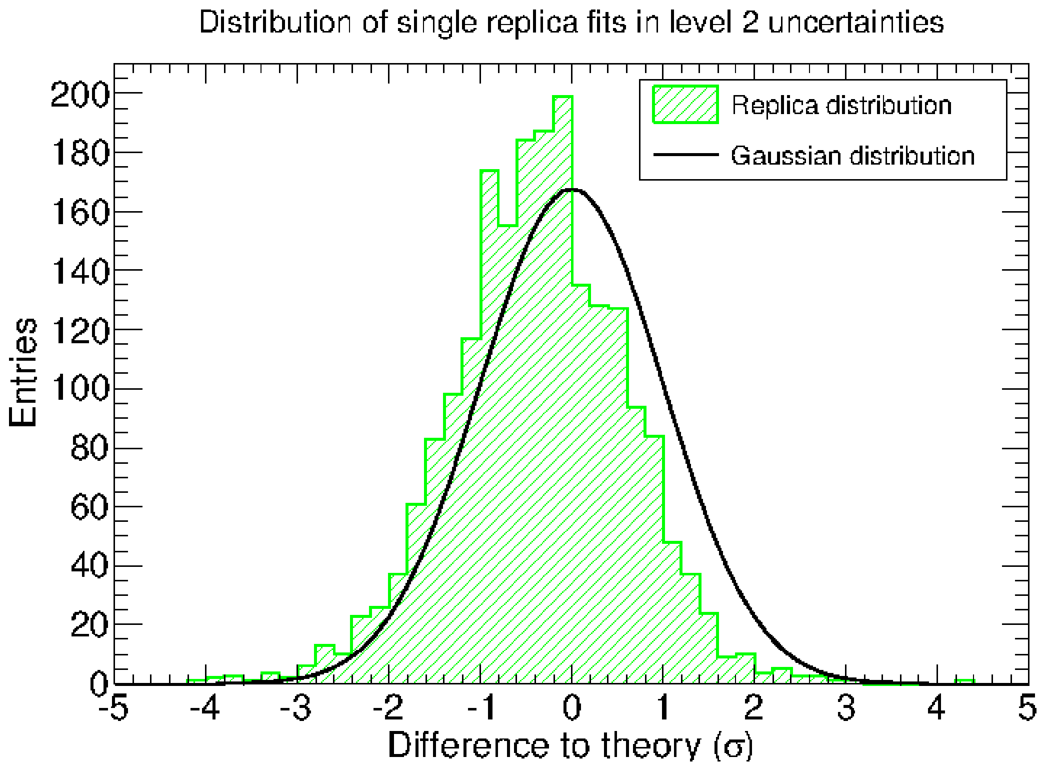
"STANDARD" PARAMETRIZATION MISSES INTERPOLATION & FUNCTIONAL UNCERTAINTY?

THE $\Delta\chi^2$ PROBLEM

- TOLERANCE MIGHT COMPENSATE FOR MISSING FUNCTIONAL UNCERTAINTY
- BUT WHAT IS $\Delta\chi^2$ FOR AN NNPDF FIT?
- CAN ANSWER USING HESSIAN CONVERSION! $\Delta\chi^2 = 16 \pm 15$
  - NON-PARABOLIC BEHAVIOUR NEAR MINIMUM ON SCALE OF UNCERTAINTIES?
  - INEFFICIENCY OF THE MINIMIZATION PROCEDURE?

CLOSURE-TESTING THE PDF UNCERTAINTIES
RESULTS

UNCERTAINTIES: DISTRIBUTION OF DEVIATIONS BETWEEN FITTED AND "TRUE" PDFS, SAMPLED AT 20 POINTS BETWEEN 10^{-5} AND 1

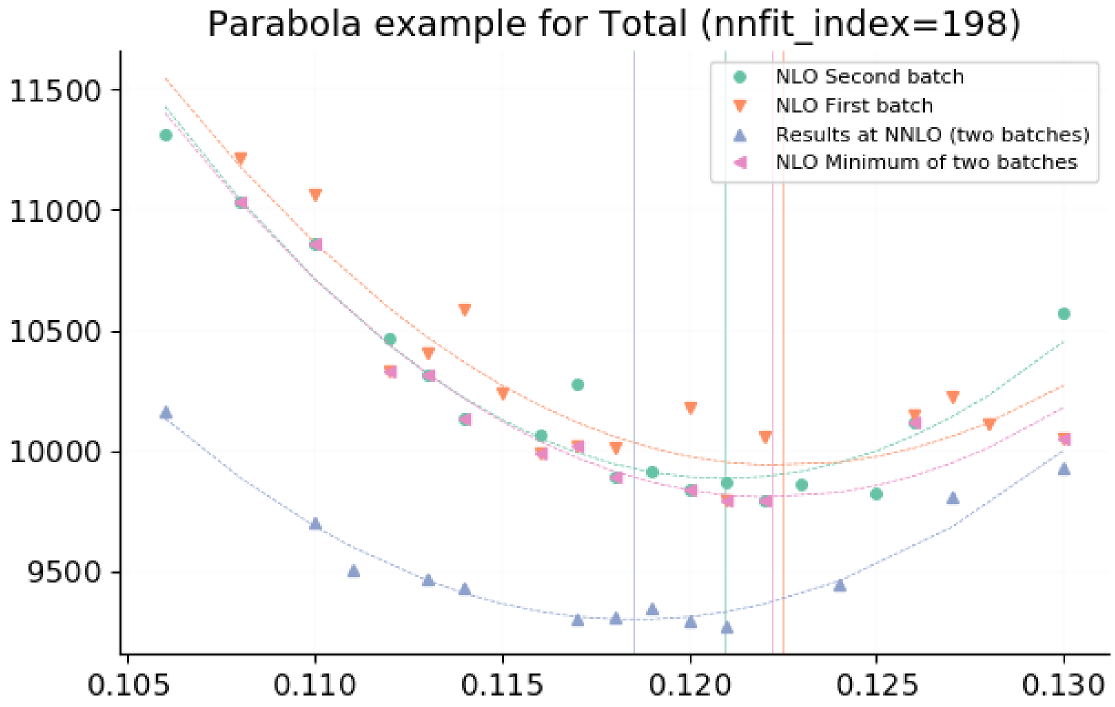


FIND 0.699% FOR ONE-SIGMA, 0.948% FOR TWO-SIGMA C.L.

- PDF UNCERTAINTIES ARE FAITHFUL
- BUT ARE THEY THE SMALLEST FROM GIVEN DATA?

MORE EFFICIENT MINIMIZATION?

- LOOK AT α_s DEPENDENCE (CORRELATED REPLICAS)
- SIGNIFICANT FLUCTUATIONS ABOUT PARABOLIC SHAPE
  NOT DUE TO FINITE-SIZE MONTE CARLO SAMPLE



BATCH MINIMIZATION

- MINIMIZE EACH REPLICA MORE THEN ONCE & KEEP BEST RESULTS
- SIGNIFICANT STABILIZATION

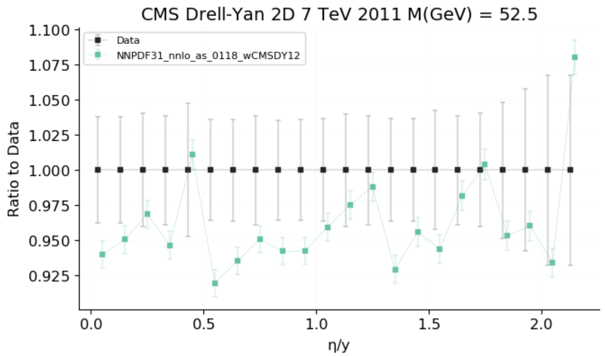
CORRELATIONS & THE COVARIANCE MATRIX

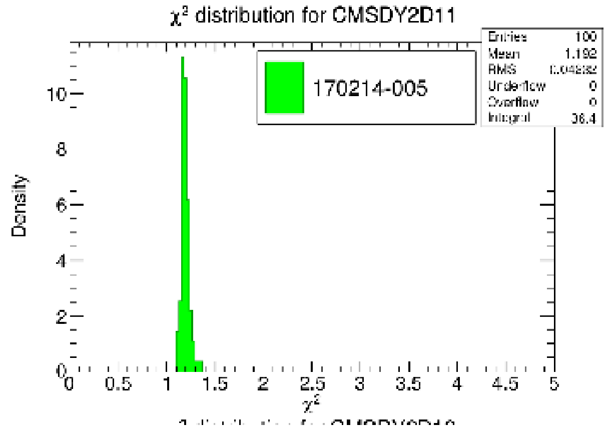
THE CMS DOUBLE-DIFFERENTIAL DRELL-YAN 2011

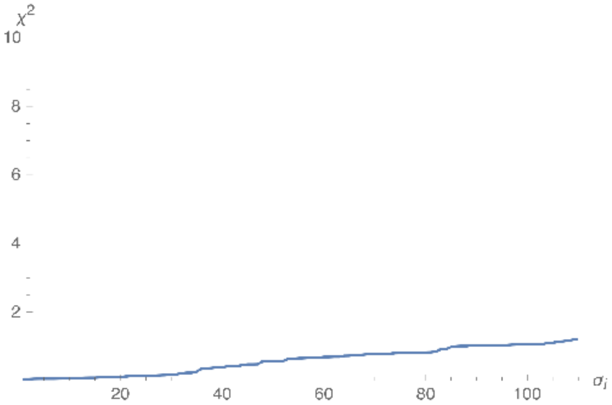
DATA/THEORY VS. DATA BIN

χ^2/dof HIST. OVER REPLICAS

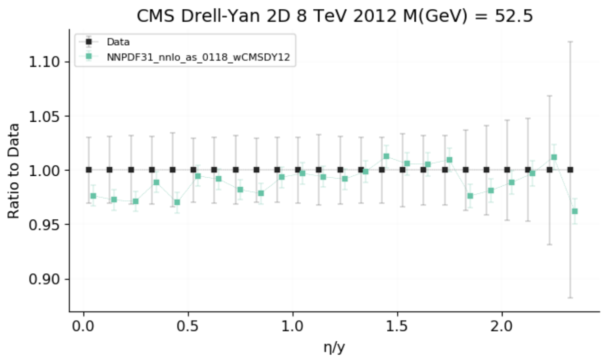
χ^2 AS COVMAT EIGVECS ADDED

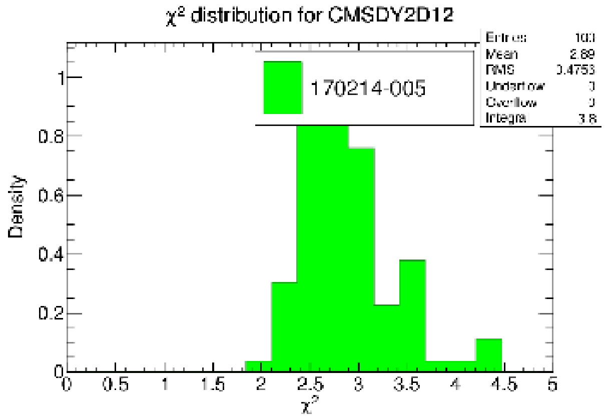


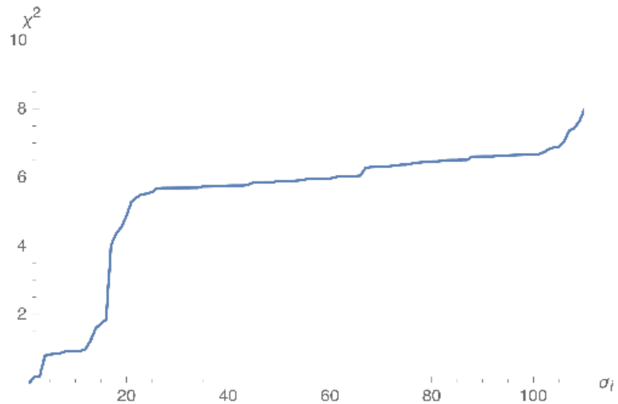




2012





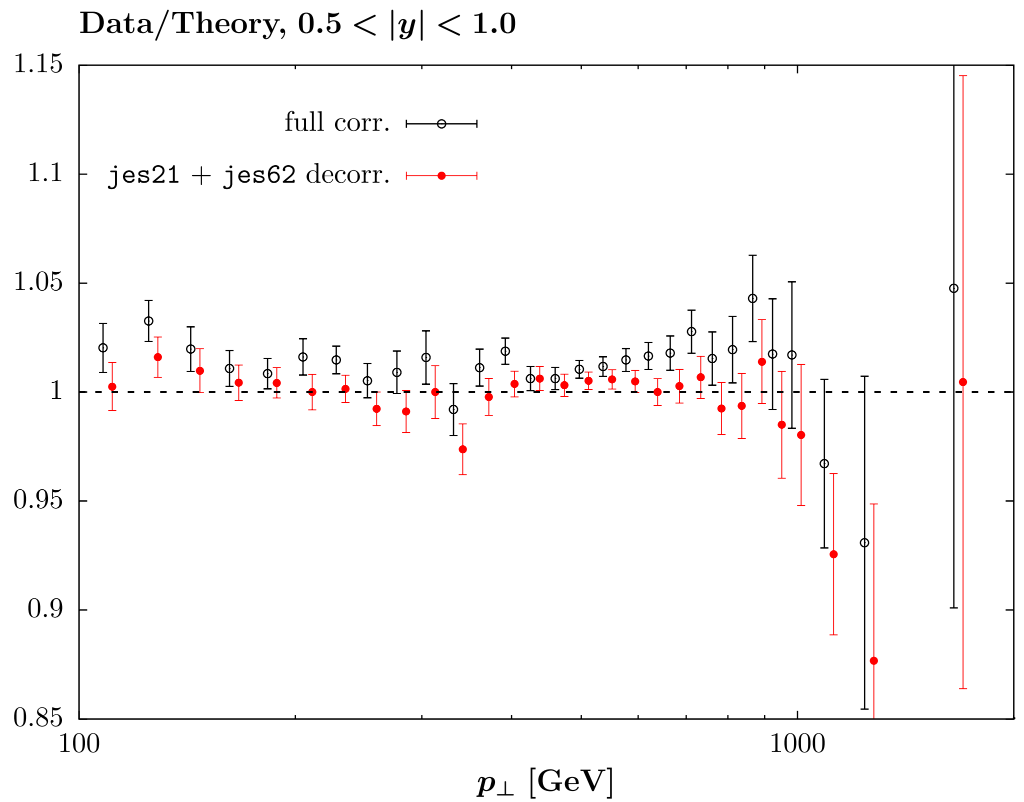


- FROM 2011 TO 2012, UNCORRELATED UNCERTAINTIES DOWN TO SUB-PERMILLE
- 2011: $\chi^2/dof \sim 1$; 2012: IMPOSSIBLE TO FIT BETTER THAN $\chi^2/dof \sim 3$
- PATHOLOGICAL BEHAVIOUR OF COVARIANCE MATRIX $\Rightarrow$ WHAT IS THE UNCERTAINTY ON IT?

CORRELATIONS & THE COVARIANCE MATRIX

THE ATLAS 7TEV JETS

- EACH RAPIDITY BIN CAN BE FITTED WITH $\chi^2/dof \sim 1$
- EACH LEADS TO INDISTIGUISHABLE BEST-FIT PDFS
- IF ALL BINS FITTED SIMULTANEOUSLY, $\chi^2/dof \sim 3$

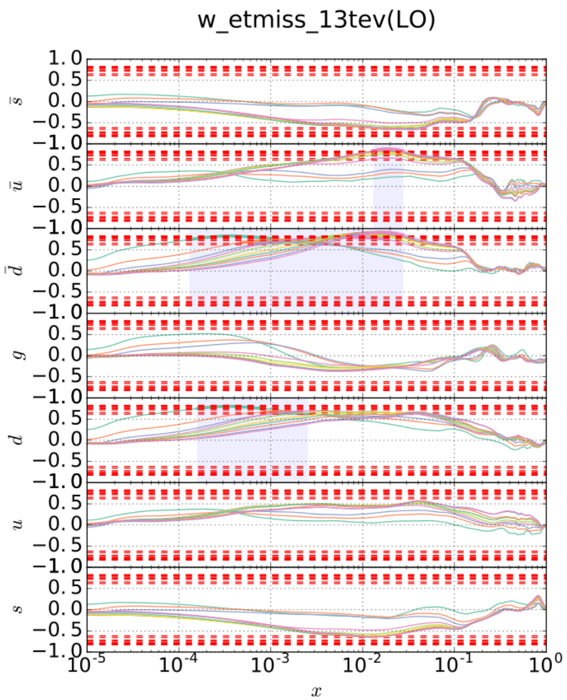


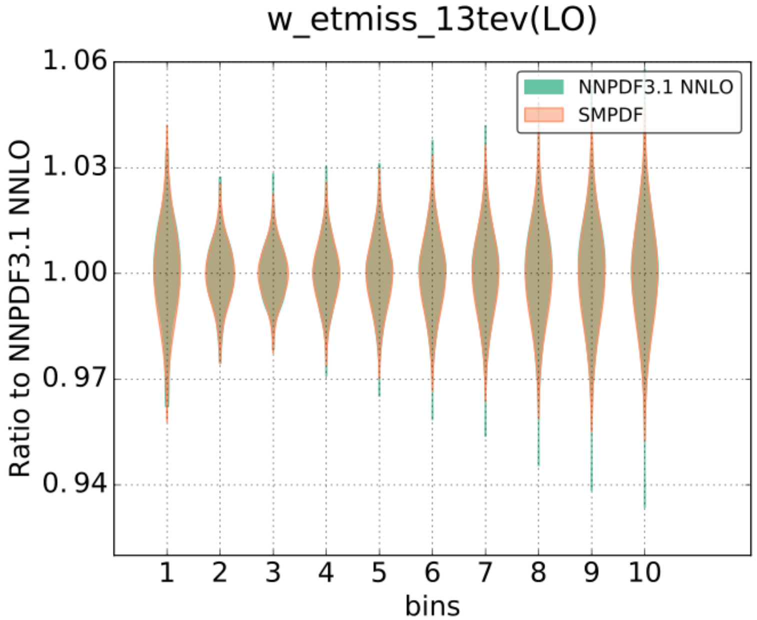
(Harland-Lang, Martin, Thorne, 1016)

- MISESTIMATED CORRELATIONS?
- CAN SINGLE OUT WHICH CORRELATION OUGHT TO BE REMOVED

SMPDF
A POWERFUL TOOL

- old aspiration: PDFs optimized to processes (Pumplin 2009)
- select subset of the covariance matrix correlated to a given set of processes
- perform SVD on the reduced covariance matrix, select dominant eigenvector, project out orthogonal subspace
- iterate until desired accuracy reached
- can add processes to given set; can combine different optimized sets
- Web interface available





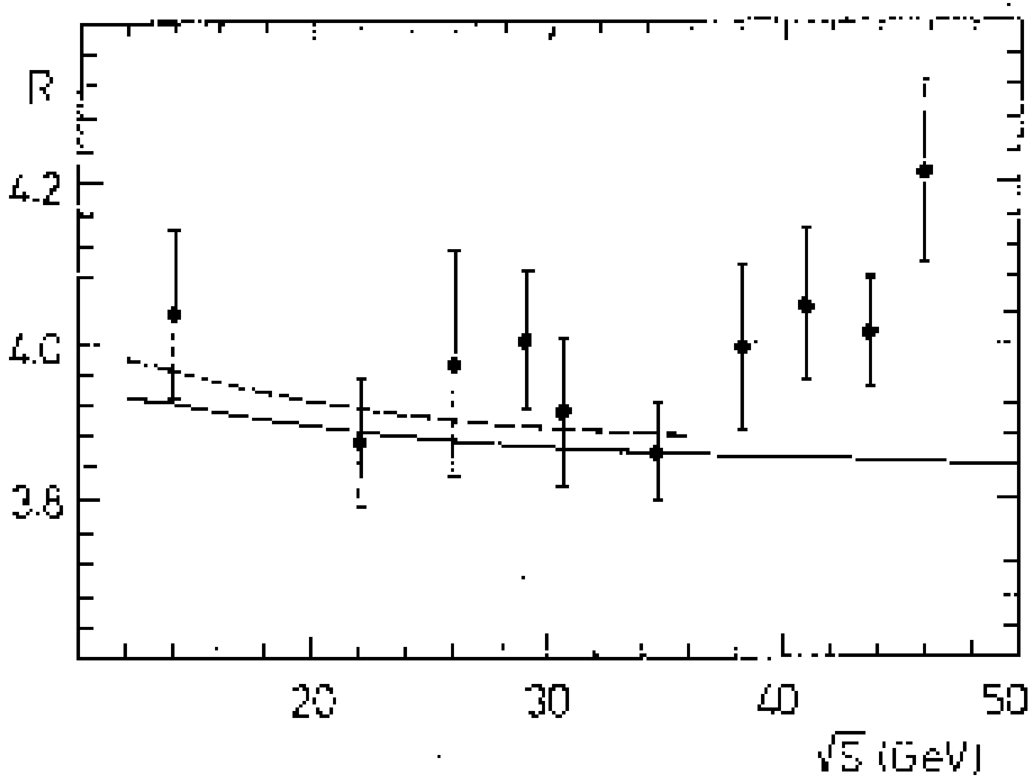
(Carrazza, SF, Kassabov, Rojo, 2016)

- eg ggH, $Hb\bar{b}$, $W\ E_T^{\rm miss}$ $\Rightarrow$ 11 eigenvectors
- study correlations of PDFs to data and among themselves!

AN OLD PROBLEM

THE D'AGOSTINI BIAS

$$R = \frac{e^+e^- \to \text{hadrons}}{e^+e^- \to \mu^+\mu^-}$$



(CELLO collab., 1987)

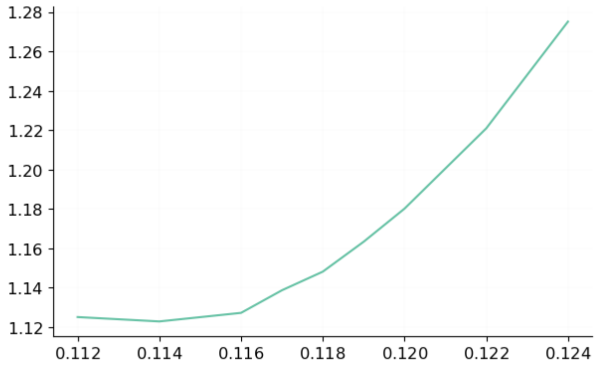
- MULTIPLICATIVE UNCERTAINTIES IN COVARIANCE MATRIX
  $\Rightarrow$ FIT BIASED DOWNWARDS IF DATA INCONSISTENT (d'Agostini, 1994)
  EQUIVALENT TO RESCALING DATA BUT NOT UNCERTAINTIES

- MUST USE ITERATIVE PROCEDURE
  COVARIANCE MATRIX COMPUTED FROM PREVIOUS FIT (NNPDF, 2010)

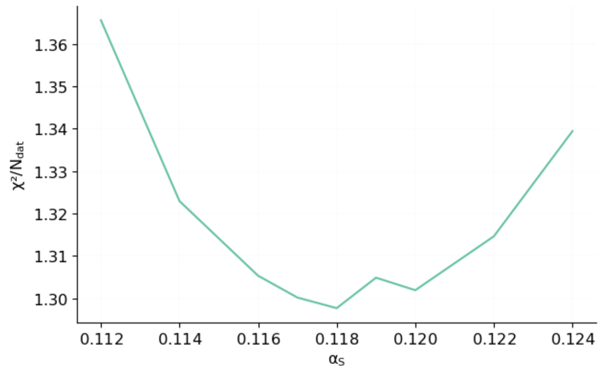
THE D'AGOSTINI BIAS

A SUBTLE EXAMPLE: α_s IN A PDF FIT

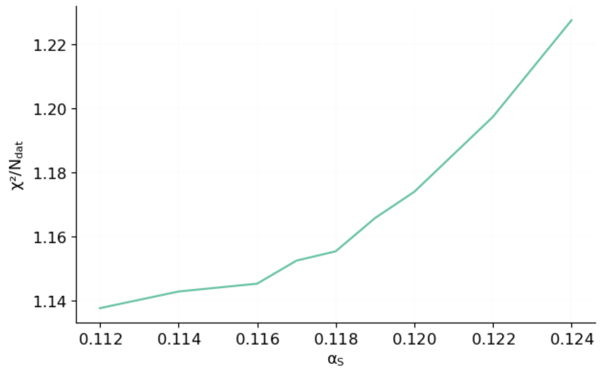
GLOBAL



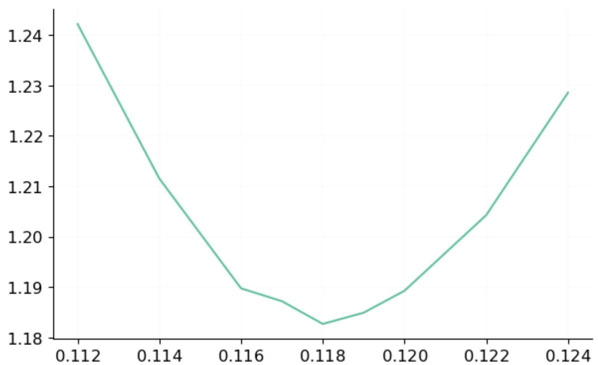
ADDITIVE (NMC, FT)

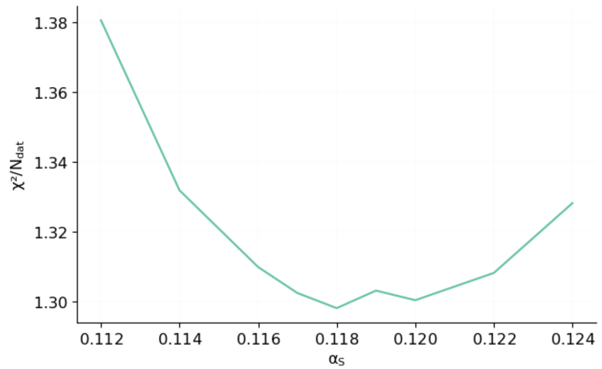


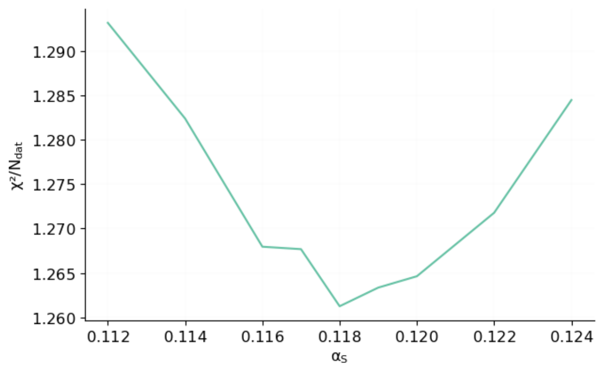
MULTIPLICATIVE (HERA, COLL)



CONSISTENT (ITERATIVE)







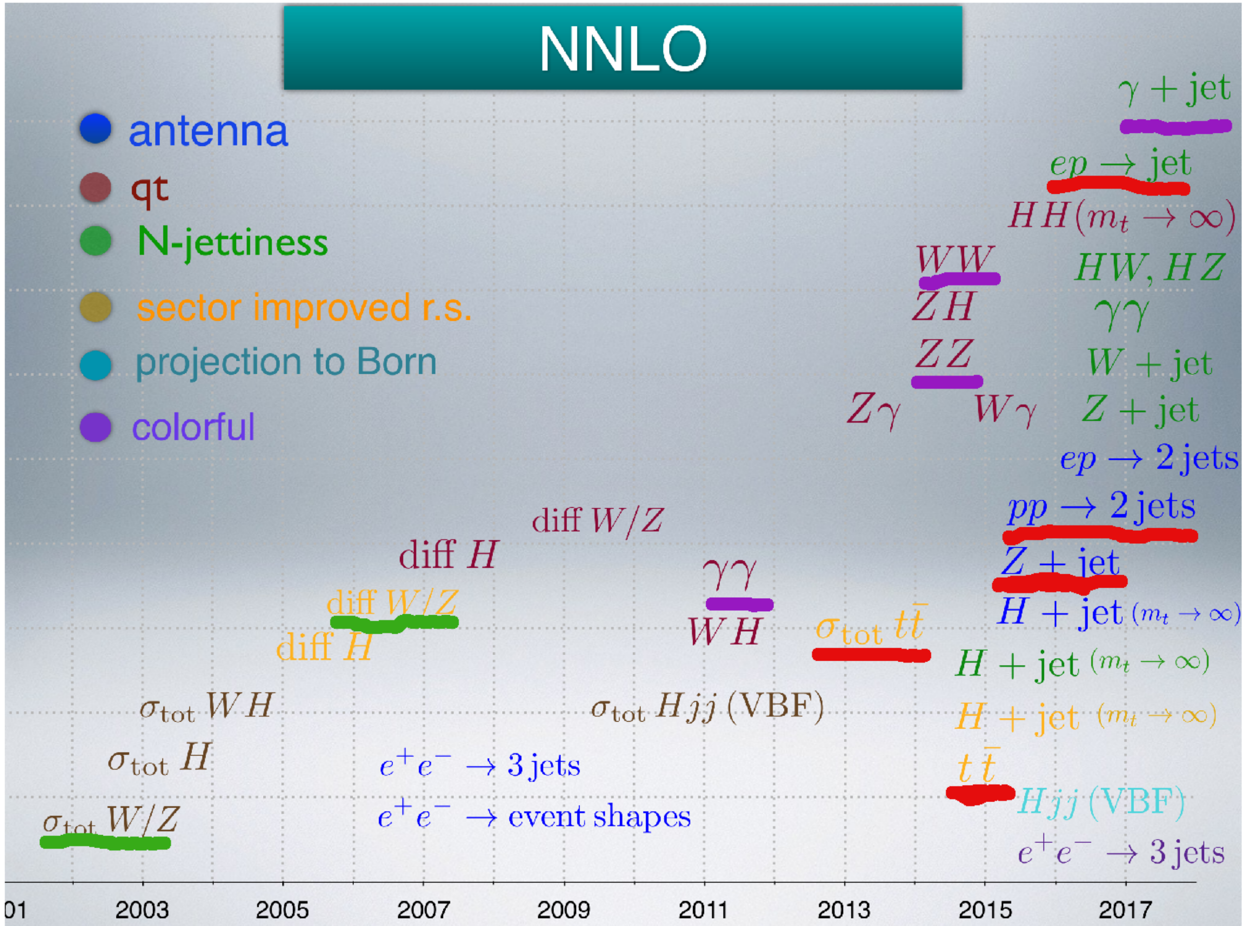
- χ^2 COMPUTED FROM COVARIANCE MATRIX $\Rightarrow$ BIASED LOW FIT FAVORED
- LESS EVOLUTION $\Leftrightarrow$ LOW α_s
- ONLY WHEN MULTIPLICATIVE UNCERTAINTIES DOMINATE
  COLLIDER ONLY, NOT FIXED TARGET

METHODOLOGY: SUMMARY

- STATISTICAL ANALYSIS TOOLS NECESSARY TO COPE WITH DATA ACCURACY
- PDF UNCERTAINTIES ARE FAITHFUL, BUT NOT OPTIMAL

THE FRONTIER OF THEORY

THE NNLO FRONTIER

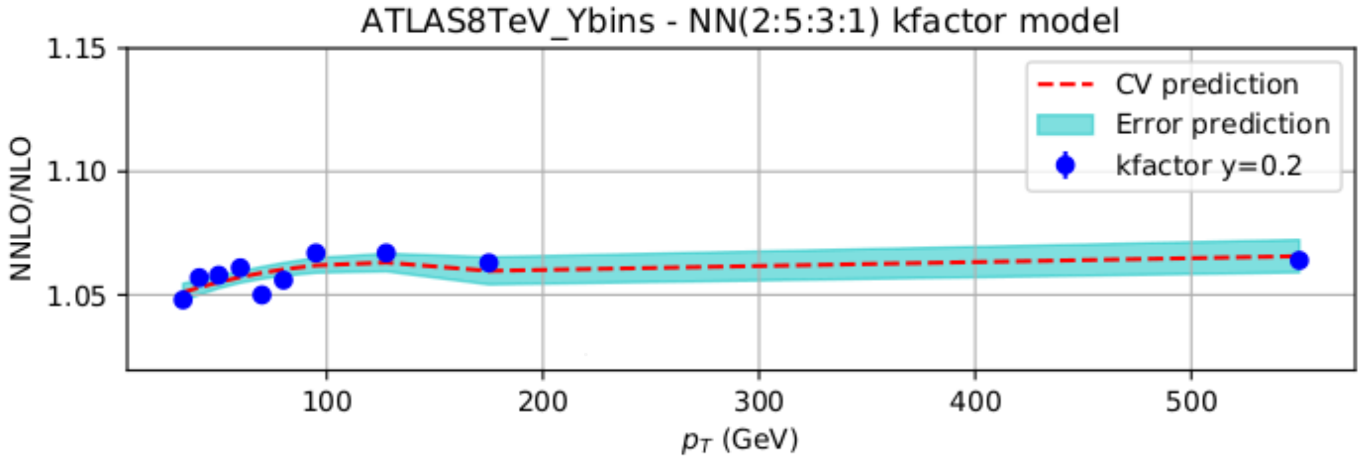


(G. Heinrich, LHCP, May 2017)

- NNLO CORRECTIONS NOW KNOWN AT INCREASINGLY EXCLUSIVE LEVEL (INCLUDING DECAYS)
- TYPICALLY LARGER THAN NAIVE SCALE VARIATION $\Rightarrow$ NEEDED FOR PRECISION PHENO
- NNLO PDF STANDARD SINCE $\sim$ 2010 INCLUDE DIS, DRELL-YAN
- NEW GENERATION PDFS ALSO TOP, JETS, Z p_t
- FUTURE GENERATIONS: PROMPT PHOTON, DIBOSON...

THEORY CHALLENGES
THE UNCERTAINTY IN THEORY CALCULATIONS

AN EXAMPLE: ATLAS 7 TEV p_T DISTRIBUTION
THE NNLO/NLO K-FACTOR



(Boughezal, Liu, Petriello, 2016-2017)

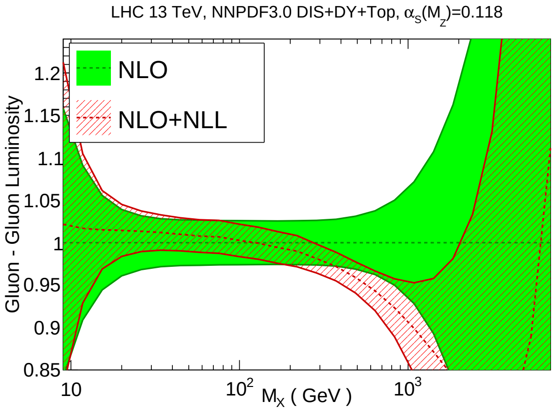
- UNCORRELATED STATISTICAL UNCERTAINTIES AT PERMILLE LEVEL
- LARGE NNLO CORRECTIONS $\sim 10\%$
- NOMINAL K-FACTOR UNCERTAINTIES VERY SMALL: UNDERESTIMATED?
- FIT ONLY POSSIBLE WITH RELIABLE ESTIMATE OF UNCERTAINTY ON THEORY PREDICTION
- NNPDF3.1: EXTRA 1% THEORY UNCERTAINTY ESTIMATED BASED ON FLUCTUATIONS W.R. TO INTERPOLATION (SHADED IN PLOT)

RESUMMED PDFs

- RESUMMATION NOT INCLUDED IN DEFAULT PDF SETS
- RESUMMED CALCULATIONS MUST USE RESUMMED PDFs! (M. Spira)
- KEPT UNDER CONTROL IN FITS BY CHOICE OF CUTS

PDFs WITH THRESHOLD (LARGE x) RESUMMATION

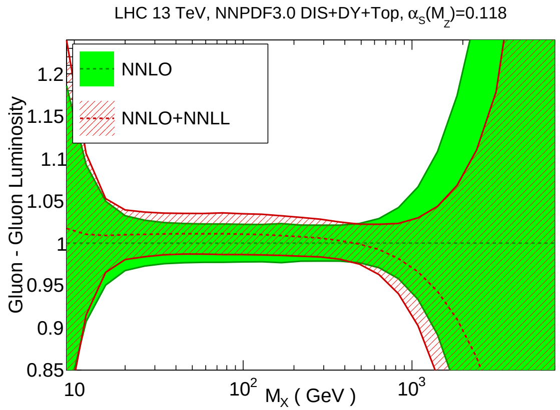
GLUON: NLO VS NLL



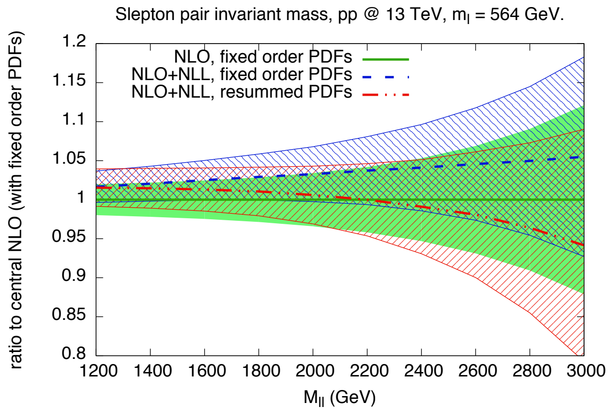
- FIRST SET: `NNPDF3.0resum`
- RESUMMATION INCLUDED IN FIT (DIS, DY, TOP DATA), EFFECTS NOT NEGLIGIGLE AT NLLO, LARGE x, MORE MODERATE AT NNLO
- EFFECT ON PDFs COMPARABLE TO EFFECT ON MATRIX ELEMENT, ANTICORRELATED TO IT
- RELEVANT FOR NEW PHYSICS SEARCHES

(Bonvini et al., 2015)

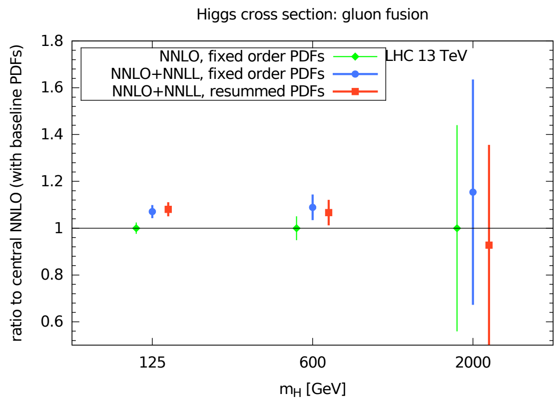
GLUON: NNLO VS NNLL



SLEPTON PAIR PRODUCTION

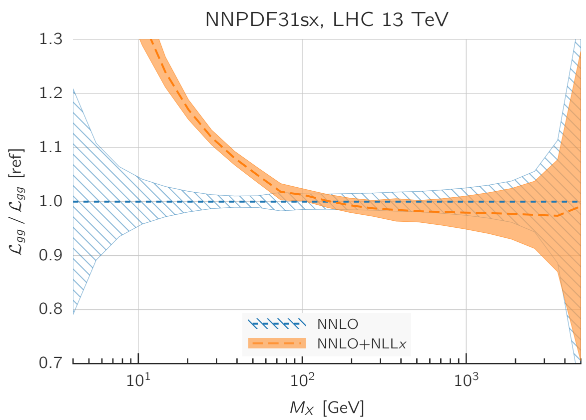


HIGGS IN GLUON FUSION VS m_H



PDFs WITH HIGH ENERGY (SMALL x) RESUMMATION

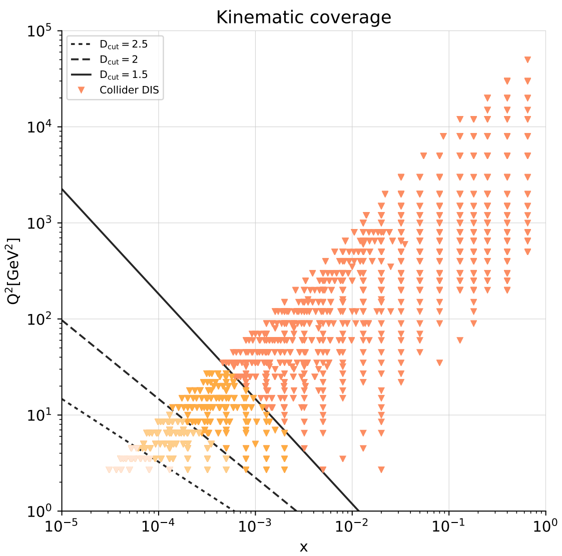
GLUON LUMINOSITY



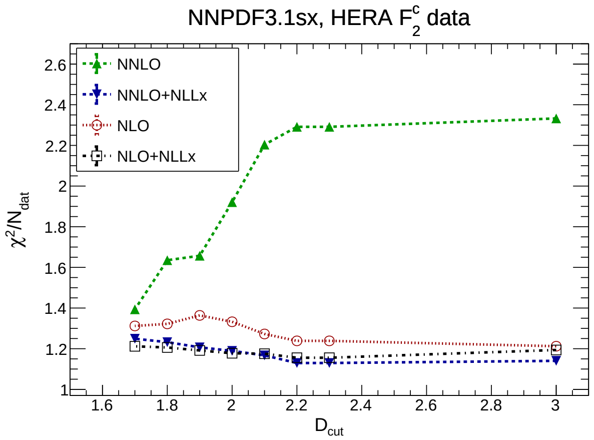
- FIRST SET: `NNPDF3.0sx`
- HIGH ENERGY RESUMMATION INCLUDED IN GLAP EVOLUTION& FOR DIS, EFFECTS
- STABILIZES PERTURBATIVE EXPANSION
- LARGE EFFECTS FOR FUTURE COLLIDERS, OR LIGHT FINAL STATES (b PRODUCTION AT LHC)

(Ball et al., 2017)

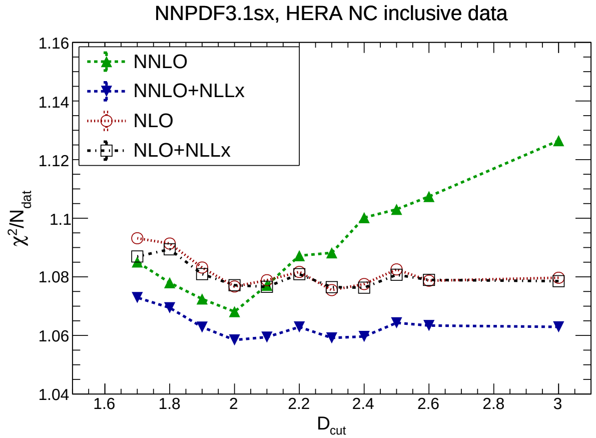
KINEMATIC CUTS



INCLUSIVE F_2 FIT QUALITY

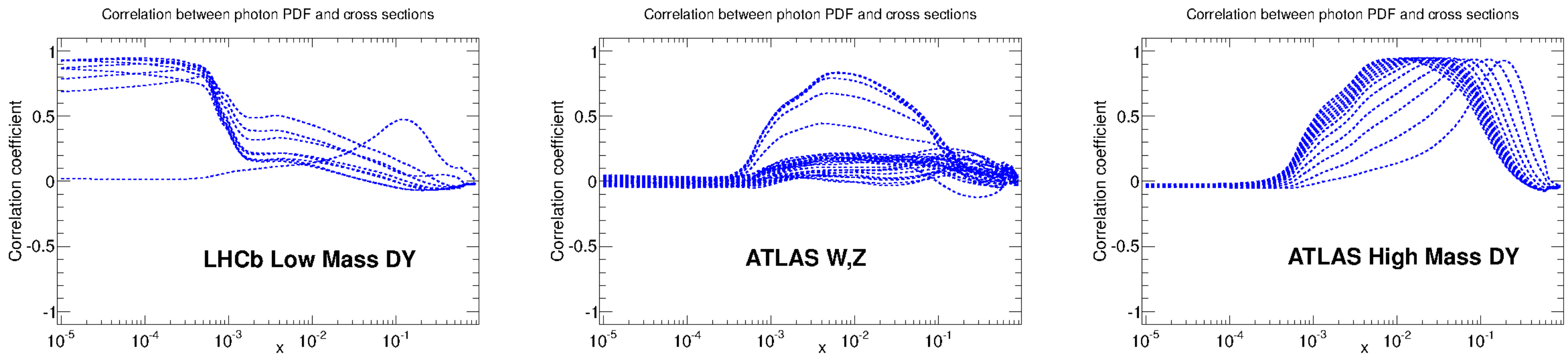


CHARM F_2^c FIT QUALITY



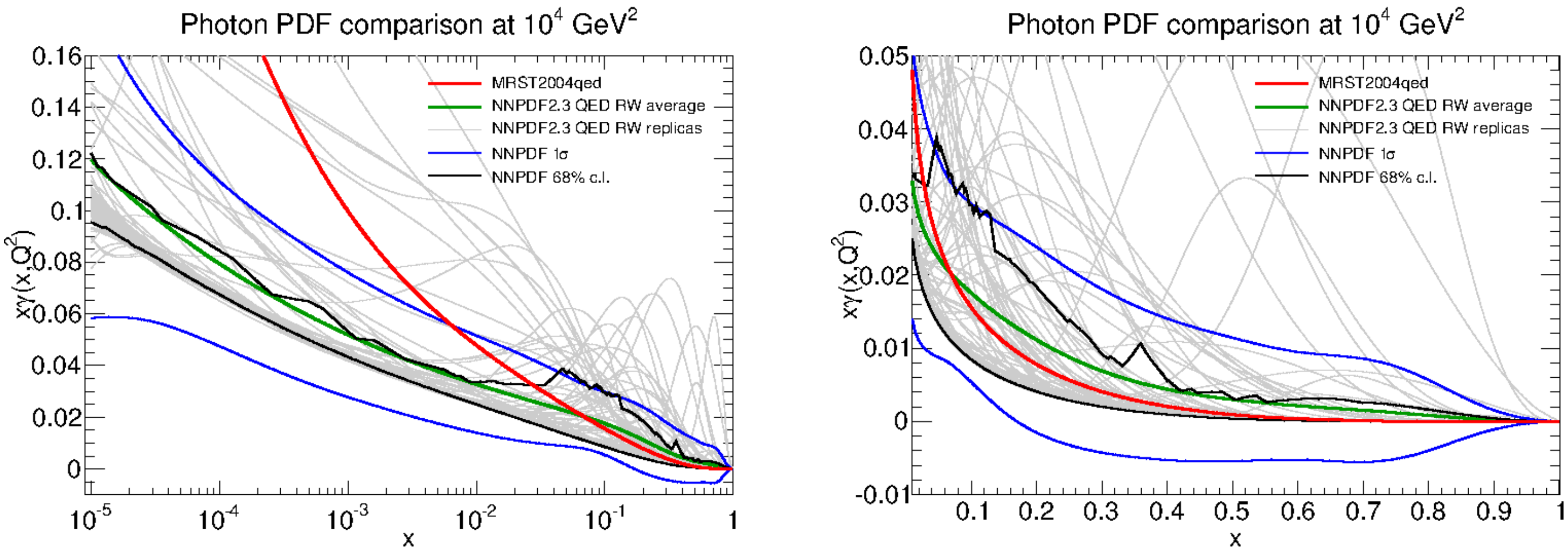
THE PHOTON PDF

CORRELATION BETWEEN DATA AND γ PDF



- PHOTON-INDUCED CONTRIBUTIONS CAN BE SIZABLE
- PHOTON PDF MODELED (MRST2004) OR DETERMINED FROM DRELL-YAN WITH SIZABLE UNCERTAINTY (NNPDF2.3-NNPDF3.0QED)
- SIGNIFICANT UNCERTAINTY EG ON SEARCHES

NNPDF2.3QED PHOTON



THE PHOTON PDF BREAKTHROUGH

(Manohar, Nason, Salam, Zanderighi, 2016)

- QED IS PERTURBATIVE DOWN TO LOW SCALES $\Rightarrow$ THE PHOTON PDF MUST BE COMPUTABLE IF THE INPUT QUARK SUBSTRUCTURE IS KNOWN
- WRITE THE CROSS-SECTION FOR A CHOSEN PROCESS: SUSY PRODUCTION IN EP COLLISION (Drees, Zeppenfeld, 1989)
- COMPUTE IT DIRECTLY, OR USING THE PHOTON PDF
- $\Rightarrow$ PDF EXPRESSED IN TERMS OF THE STRUCTURE FUNCTION INTEGRATED OVER ALL SCALES
- F_s AT HIGH Q^2 FROM PDFS, IN RESONANCE REGION FROM DATA, IN ELASTIC LIMIT FROM FORM FACTORS

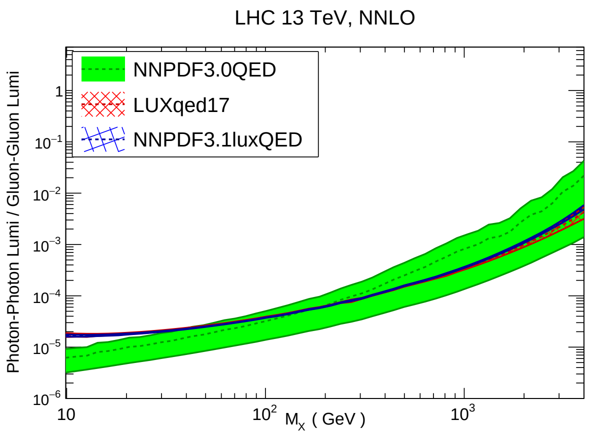
$$x f_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{dz}{z} \left\{ \int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} \alpha^2(Q^2) \left[\left(z p_{\gamma q}(z) + \frac{2x^2 m_p^2}{Q^2} \right) F_2(x/z, Q^2) - z^2 F_L\left(\frac{x}{z}, Q^2\right) \right] - \alpha^2(\mu^2) z^2 F_2\left(\frac{x}{z}, \mu^2\right) \right\},$$

THE LUXQED PHOTON PDF

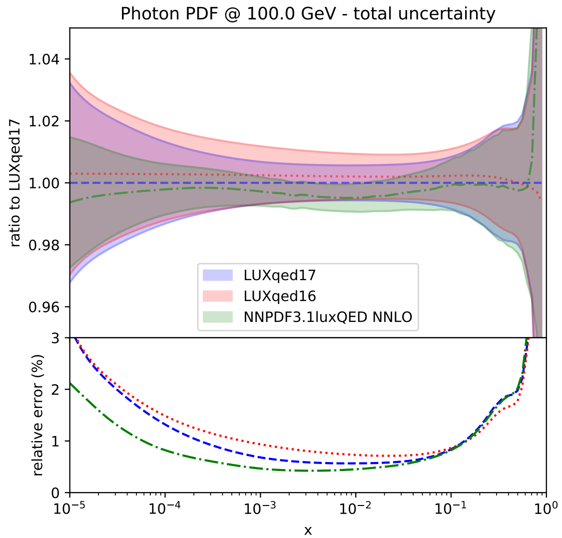
(Carrazza et al., 2017)

- LUX16/LUX17 SETS CONSTRUCTED FROM PDF4LHC15 $\Rightarrow$ AGREE WELL WITH NNPDF3.0 QED, MUCH SMALLER UNCERTAINTY
- FIRST PDF SET BASED ON CONSISTENT FIT WITH LUX CONSTRAINT: NNPDF3.0LUXQED
- NNPDF3.1LUXQED VS LUX17: GOOD AGREEMENT BUT SMALLER UNCERTAINTIES
- SIZABLE IMPACT ON PRECISION PHYSICS: EG ASSOCIATE HIGGS PROD. WITH W

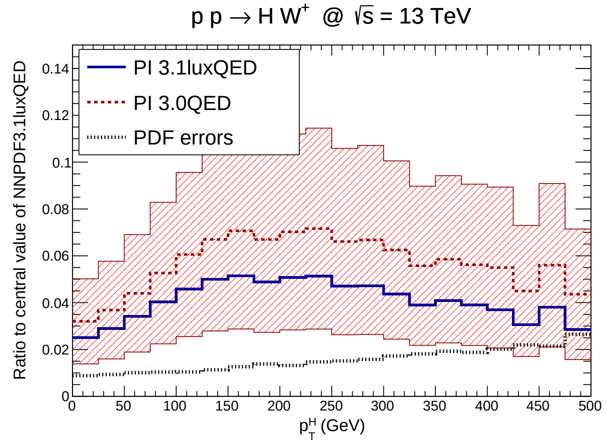
$\gamma\gamma$ LUMI: NNPDF3.0QED, LUX17, NNPDF3.1LUXQED



γ PDF: LUX17 VS. NNPDF3.1LUXQED



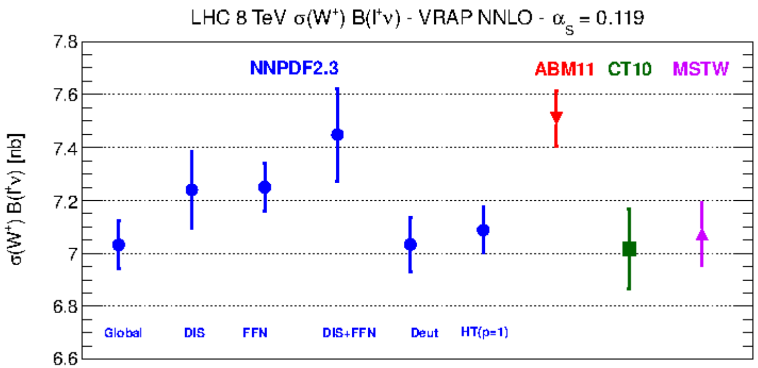
γ-INDUCED VS QCD: HW



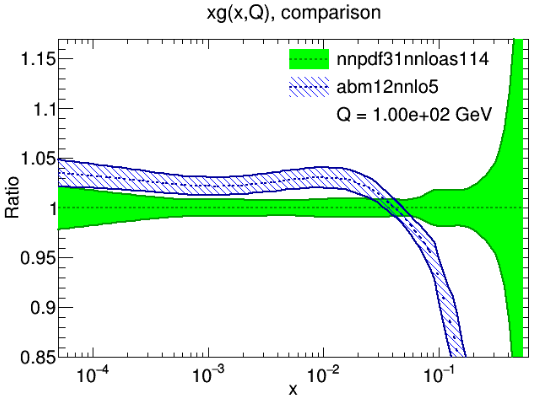
HEAVY QUARKS
DECOUPLING SCHEMES

- ALL GLOBAL PDF SETS USE MATCHED VARIABLE-FLAVOR HQ SCHEMES
  ACOT, FONLL, THORNE-ROBERTS EXTENSIVELY BENCHMARKED 2010-2014
- ABM USE MASSIVE FFN SCHEME
  $\Rightarrow$ SERIOUS DISCREPANCY, BEST FIT $\alpha_s = 0.113$
- ABMP16 $n_3 f = 3$ FOR DIS, $n_f = 5$ FOR LHC $\Rightarrow$ EFFECTIVELY, ZM-VFN
  $\Rightarrow$ DISCREPANCY REDUCED, BEST FIT $\alpha_s = 0.115$

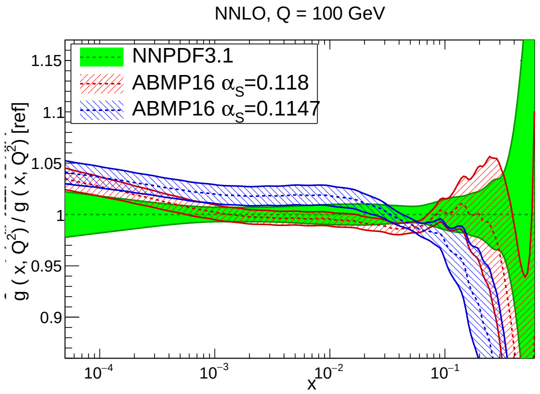
W^+ TOTAL XSECT



GLUON: ABM12 VS NNPDF3.0 ($\alpha_s = 0.114$)



GLUON: ABMP16 VS. NNPDF3.1

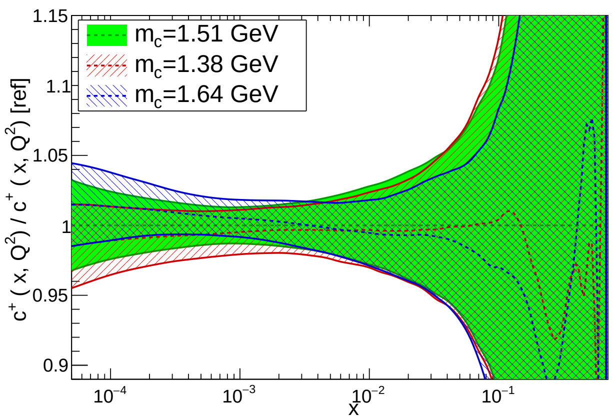


HEAVY QUARKS
DETERMINING CHARM FROM THE DATA

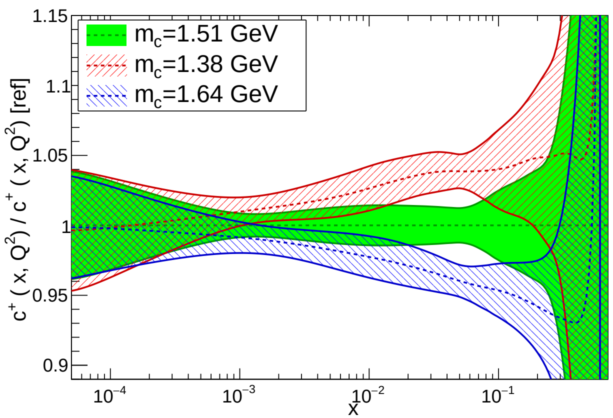
WHY SHOULD THE CHARM PDF BE DETERMINED FROM THE DATA?

- BECAUSE ITS SIZE SHOULD NOT DEPEND STRONGLY ON THE CHARM MASS
- BECAUSE IT MIGHT HAVE A NONPERTURBATIVE COMPONENT

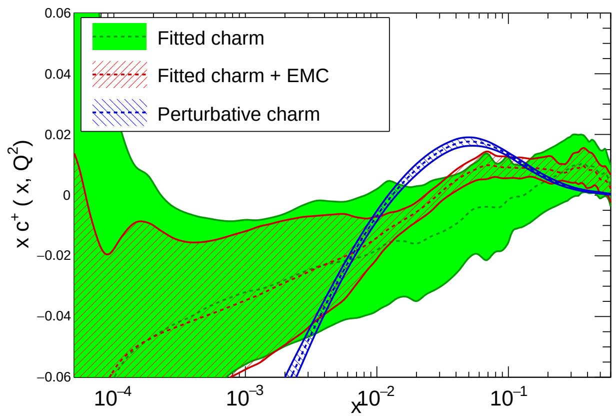
FITTED CHARM VS m_c



PERTURBATIVE CHARM VS m_c



FITTED VS. PERTURBATIVE CHARM

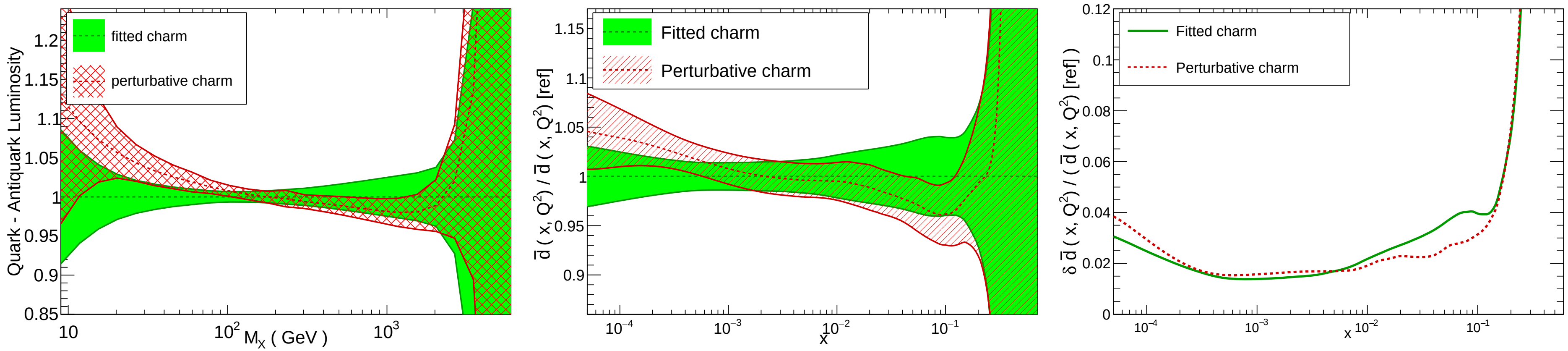


- BECAUSE ITS SHAPE SHOULD NOT BE DETERMINED BY FIRST-ORDER MATCHING (NO HIGHER NONTRIVIAL ORDERS KNOWN)
- $\Rightarrow$ SUPPRESSED AT MEDIUM-SMALL x, ENGANCED AT VERY SMALL, VERY LARGE x

HEAVY QUARKS
IMPACT ON LIGHT QUARK PDFS

FITTED VS. PERTURBATIVE CHARM

QQBAR LUMI — ANTIDOWN PDF — ANTIDOWN PDF UNCERTAINTY

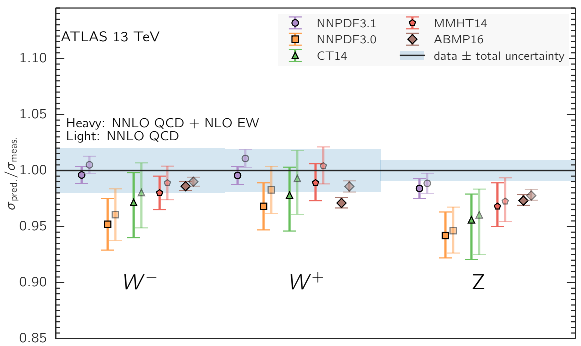


THE CHARM PDF FROM DATA...

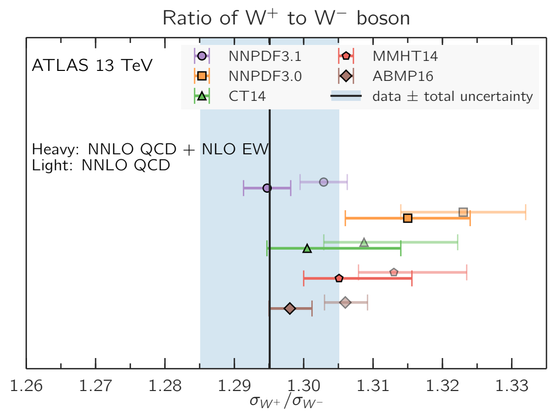
- QUARK (ESPECIALLY QUARK-ANTIQUARK) LUMI AFFECTED BECAUSE OF CHARM SUPPRESSION AT MEDIUM-x
- FLAVOR DECOMPOSITION ALTERED
- UNCERTAINTIES ON LIGHT QUARKS NOT SIGNIFICANTLY INCREASED

HEAVY QUARKS
THE CHARM PDF & PRECISION LHC PHYSICS

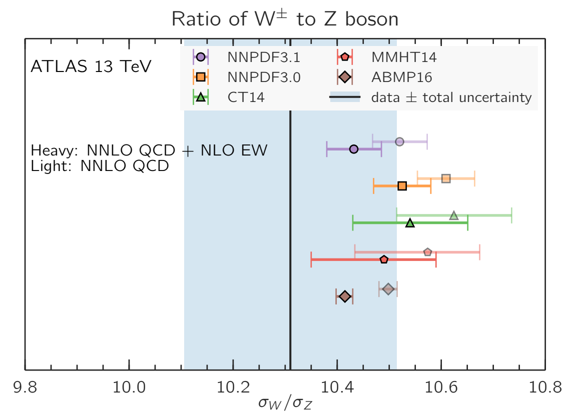
DRELL-YAN XESCTS



W^+/W^- XSECT RATIO



W/Z XSECT RATIO



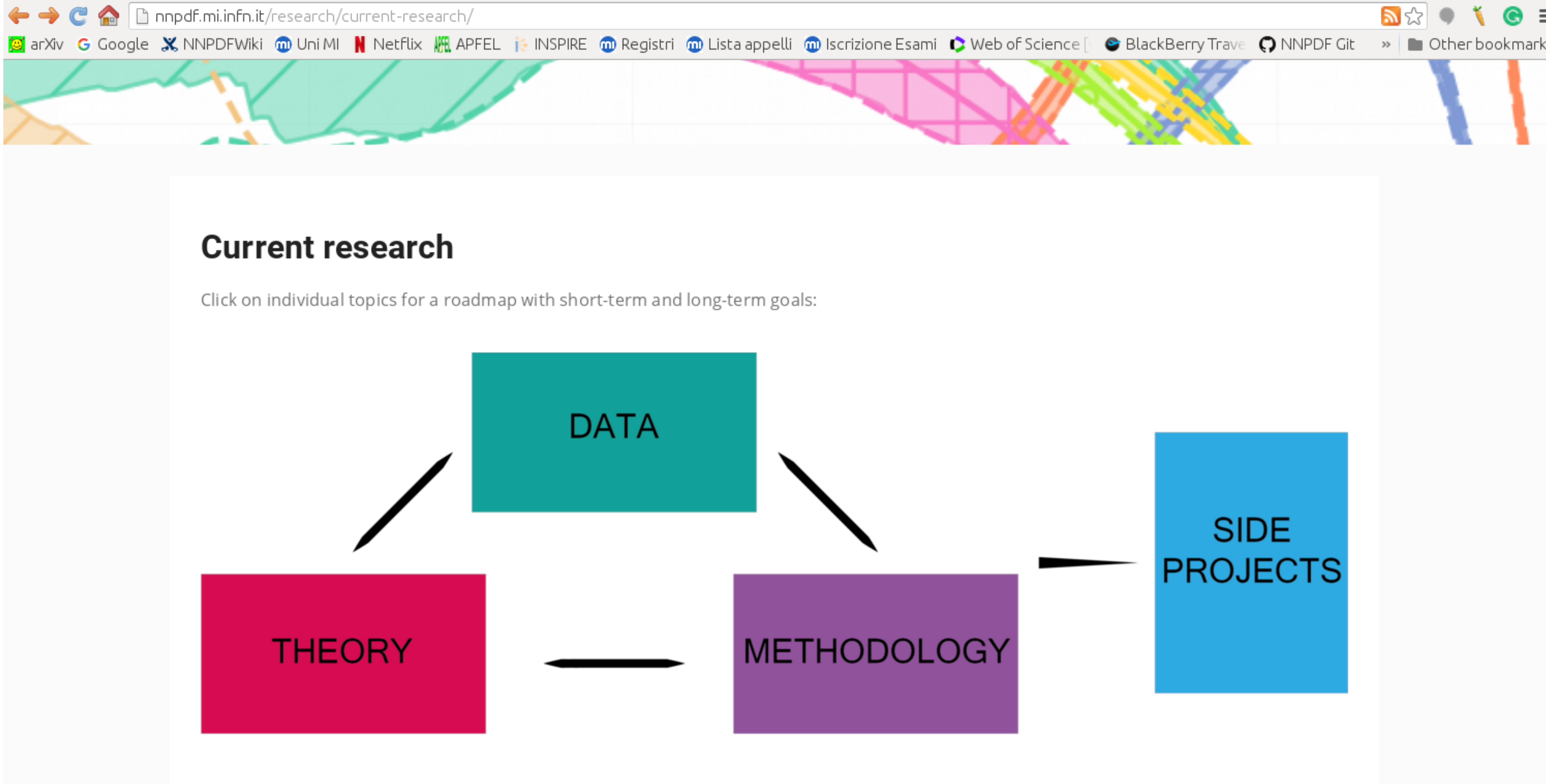
- W, Z CROSS-SECTIONS AT 13 TEV IN PERFECT AGREEMENT WITH DATA
  DIFFICULT TO FIT WITH PERTURBATIVE CHARM
- ELECTROWEAK CORRECTIONS IMPORTANT
- NOTE ALSO SMALL-x RESUMMATION OF F_2^c REQUIRES FITTED CHARM

THEORY: SUMMARY

- WITH SUB-PERCENT DATA UNCERTAINTIES, THEORY UNCERTAINTIES DOMINANT
- RESUMMATION ADVANTAGEOUS
- ELECTROWEAK CORRECTIONS MANDATORY

BEYOND THE FRONTIER

OPEN ISSUES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Current research
Click on individual topics for a roadmap with short-term and long-term goals:
DATA
THEORY
METHODOLOGY
SIDE PROJECTS

DATA

Data

All to be implemented including NNLO QCD, photon-induced, and NLO electroweak

Short-term goals

OLD DATASETS

- NNPDF3.1 wrap-up: full implementation, restoring data cut because of large PI or EW
  - ATLAS W, Z 7TeV
  - ATLAS high-mass Drell-Yan 8 TeV
  - Low-mass DY
- New datasets for processes already in NNPDF3.1:
  - LHCb 8, 13 TeV W, Z production
  - ttbar 5, 8, 13 TeV
  - jets 8Tev, 13 Tev

NEW DATASETS

- Prompt photons
- Single top
- Dijets

Medium-term goals

In rough order of priority:

NEW DATASETS

- Diboson production
- Z phi* distribution
- Z+c
- Hera jets
- V+jets
- LHC D* production
- W+c

METHODOLOGY

nnpdf.mi.infn.it/research/current-research/methodology/

Methodology

Short-term goals

- PDF parametrization
  - Fit preprocessing
  - Neural network architecture:
    - Single-layer for each PDF
    - One single (multilayer or perhaps deep) NN for all PDFs
- Minimization algorithms
  - CMA algorithm: validation
    - Closure test
    - Check against reweighting
    - Check of positivity
  - CMA algorithm: optimization
    - Grid search

Mid- to long-term goals

- Minimization algorithms
  - CMA algorithm: optimization
    - Gradient-based methods
  - Weight minimization + other new methods

THEORY

Theory

Short to Medium-term goals

- Missing Higher Order Corrections Uncertainties (MHOU)
  - Implementation of scale variation at NLO
  - Determination of the contribution to the covariance matrix due to MHOU estimated with scale variation
  - Fit with the MHOU uncertainty included in the covariance matrix
  - Fit with scale variation in the theory
  - Comparison of:
    - NNLO-NLO shift
    - shift due to scale variation in the fit
    - increase of PDF uncertainties due to MHOU included in covariance matrix
- Nuclear & deuterium corrections:
  - Fit with one ore more models
  - Implementation in the covariance matrix as for MHOU
  - Fit with extra nuclear uncertainty
- Full computation for all processes in fit of NLO EW and PI
- Inclusion in the covariance matrix of further uncertainties in the NNLO QCD computation:
  - N3LO terms due to the use of K-factors
  - Uncertainties on NNLO corrections due to numerical instabilities, estimated by refitting

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Medium to Long-term goals

- Implementation of scale variation at NNLO
- Alternative ways of estimating MHOU, including constrained partial dataset fitting
- Approximate N3LO PDFs

SIDE PROJECTS

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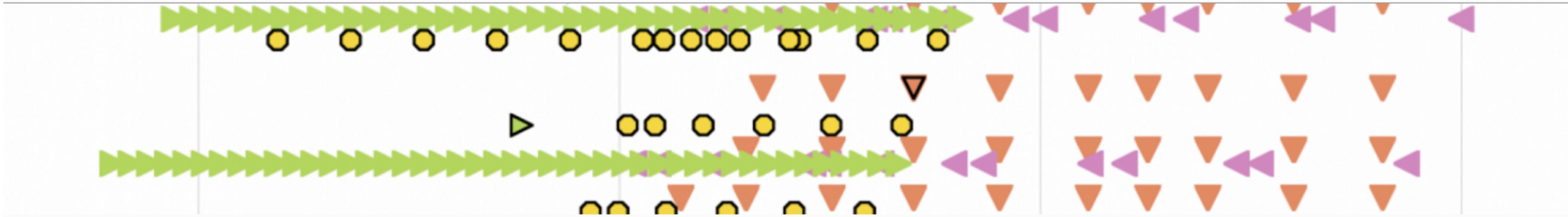


Side projects

Short-term goals

- Jets: choice of scale and comparison of theory predictions to data before inclusion in the fit
- Polarized PDFs
- Fragmentation functions

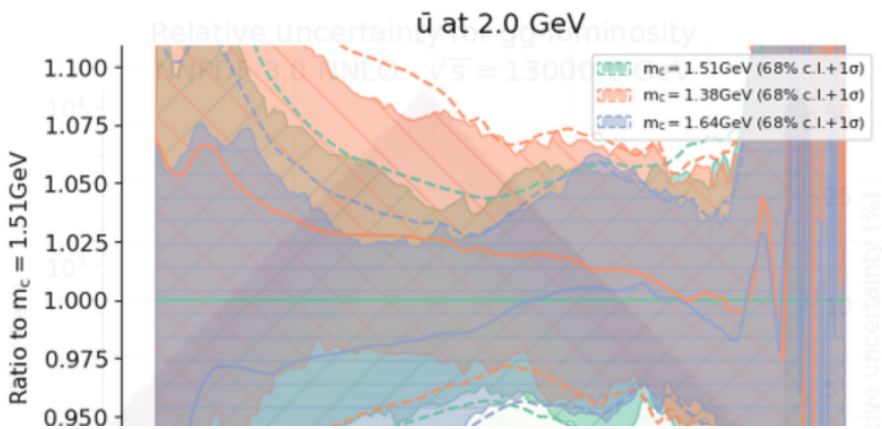
Medium-term goals

- Polarized PDFs
- Fragmentation functions
- Resummed PDF sets for LHC phenomenology
- PDFs at the LH-HE collider

N^{3}PDF

N3PDF
Machine Learning • PDFs • QCD

The **N3PDF** project, led by PI **Stefano Forte**, aims at revolutionizing the theory of strong interactions and its application to the determination of the structure of the proton, by introducing extensively techniques of artificial intelligence (AI). The core of the project is the development of an AI agent for the determinations of the parton distributions which encode the quark and gluon structure of the proton, using machine learning techniques. The project also includes an integrated set of studies on higher-order computations and resummation in perturbative QCD, and the development of parton distributions interfaced to resummation and Monte Carlo generators. The project will work in synergy with the NNPDF collaboration, to which it will provide methods and tools, and from which it will gain physics input and insight.



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After 40 years of studying the strong nuclear force, a revelation theguardian.com/science/life-a...
Me at Life & #Physics on BFKL and all that.

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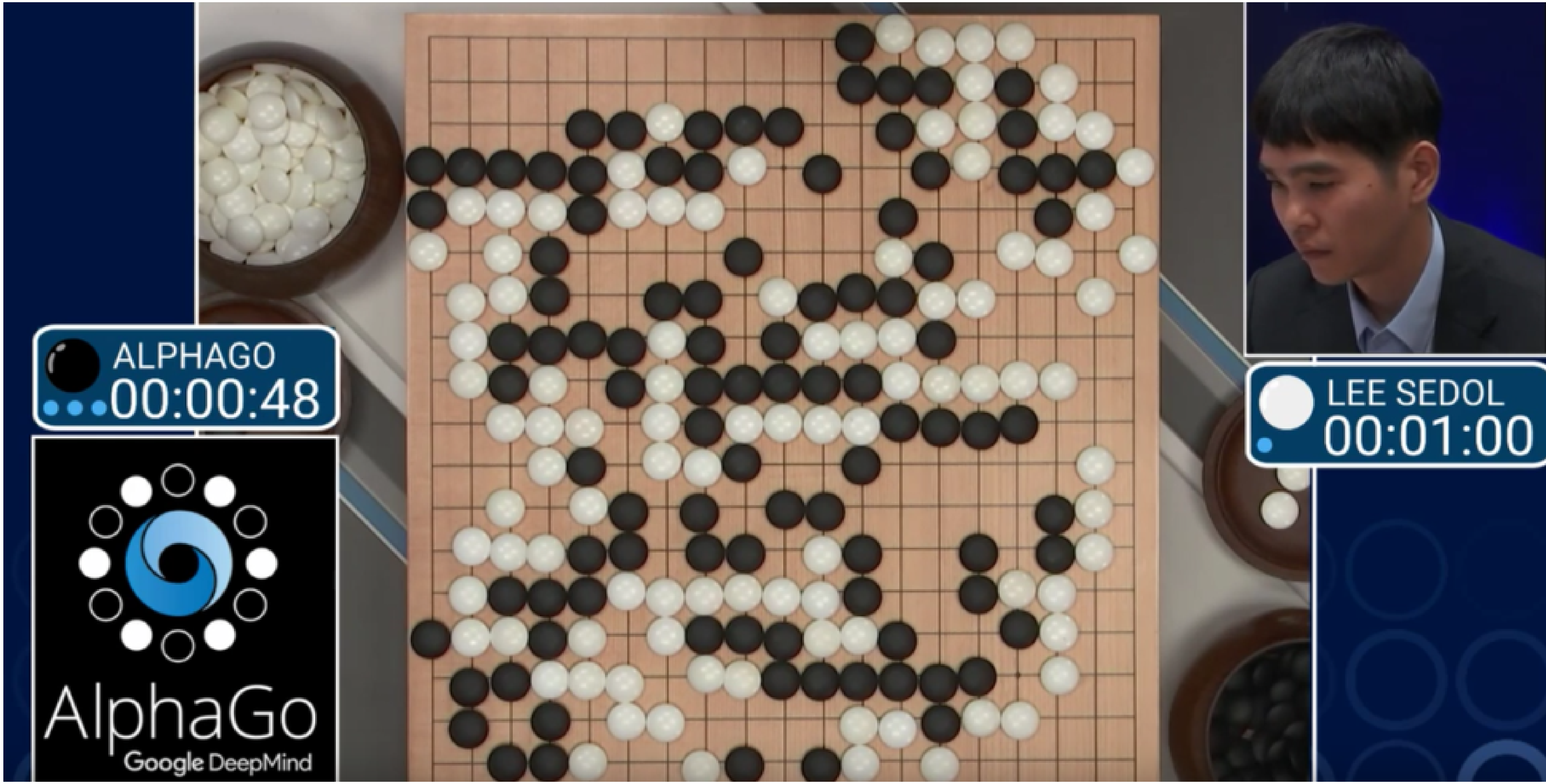
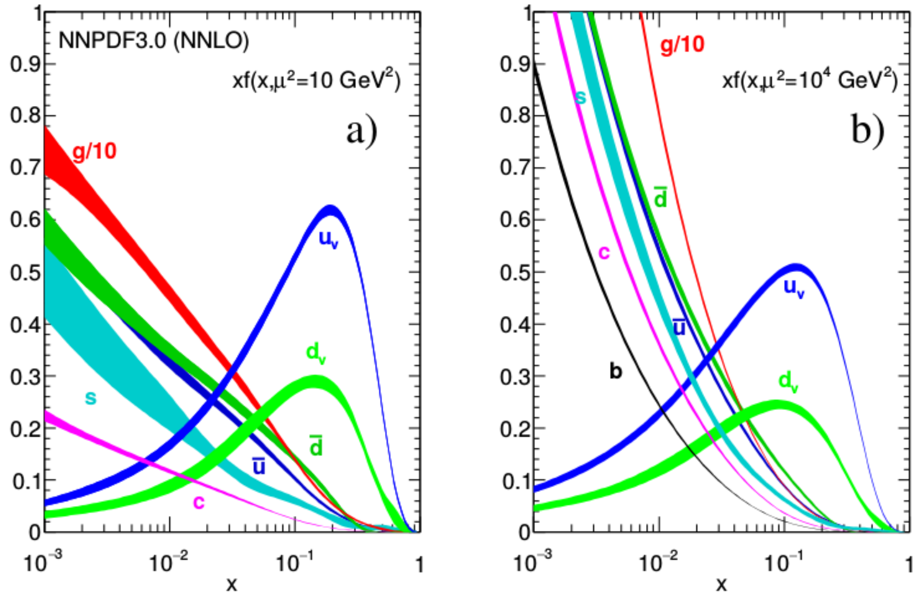
JOBS

There are currently no positions available but we will be looking for two PhD students very soon!

AI & GO



AI & PDFs



N3PDF

Machine Learning • PDFs • QCD