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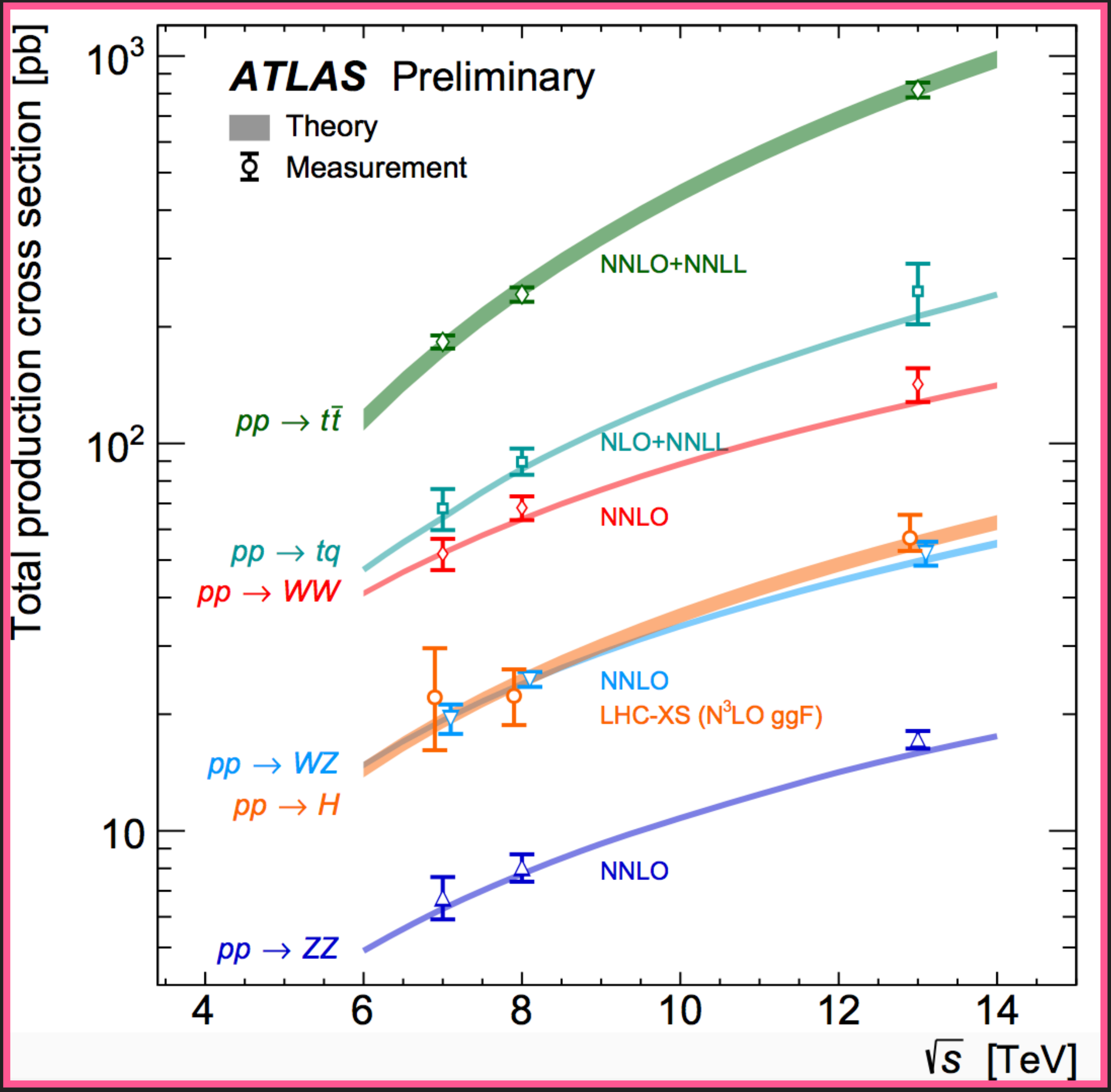
PARTON DISTRIBUTIONS FROM HIGH PRECISION DATA

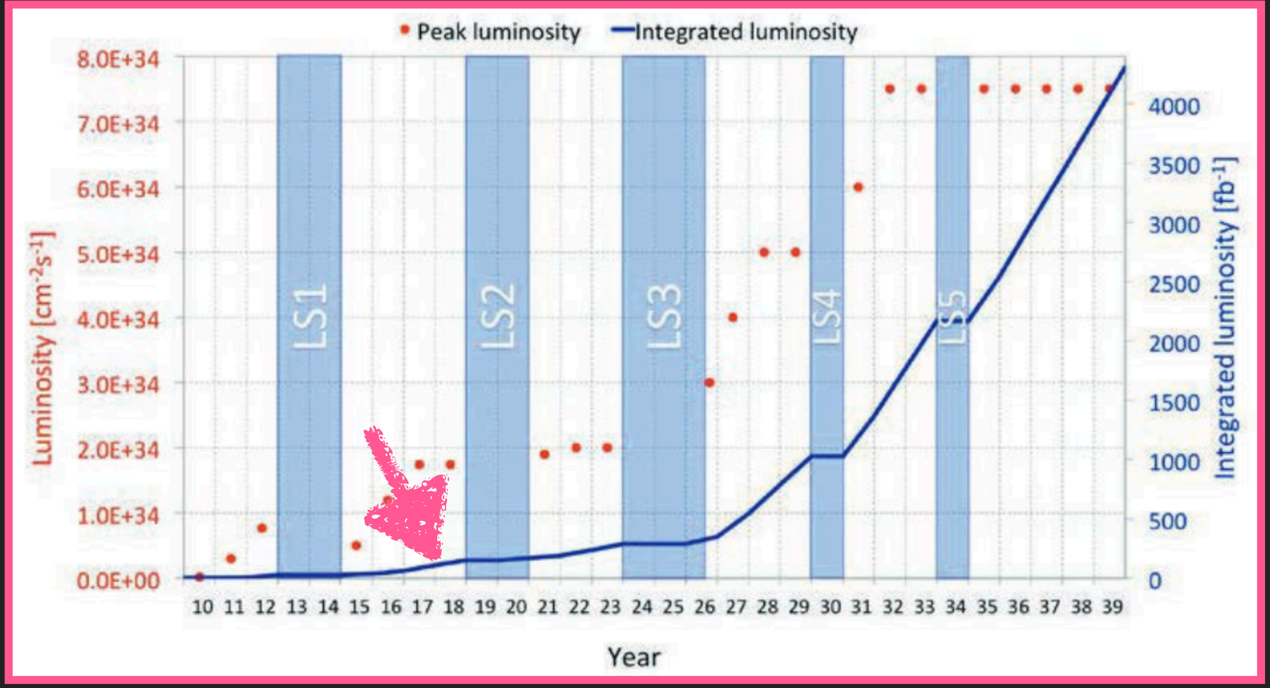
HIGH ENERGY THEORY AND GENDER

CERN, 26-28 SEPTEMBER 2018

A NEW PRECISION ERA IN PARTICLE PHYSICS

- ➡ LHC at the forefront of the exploration of the high energy regime
- ➡ Precise predictions are the key not to miss this unique opportunity!





Apollinari et al., CERN Yellow Report 4 (2017)

- ★ High-Luminosity LHC
- ★ Higher mass reach
- ★ Huge increase in integrated luminosity

ATLAS, SM summary plots

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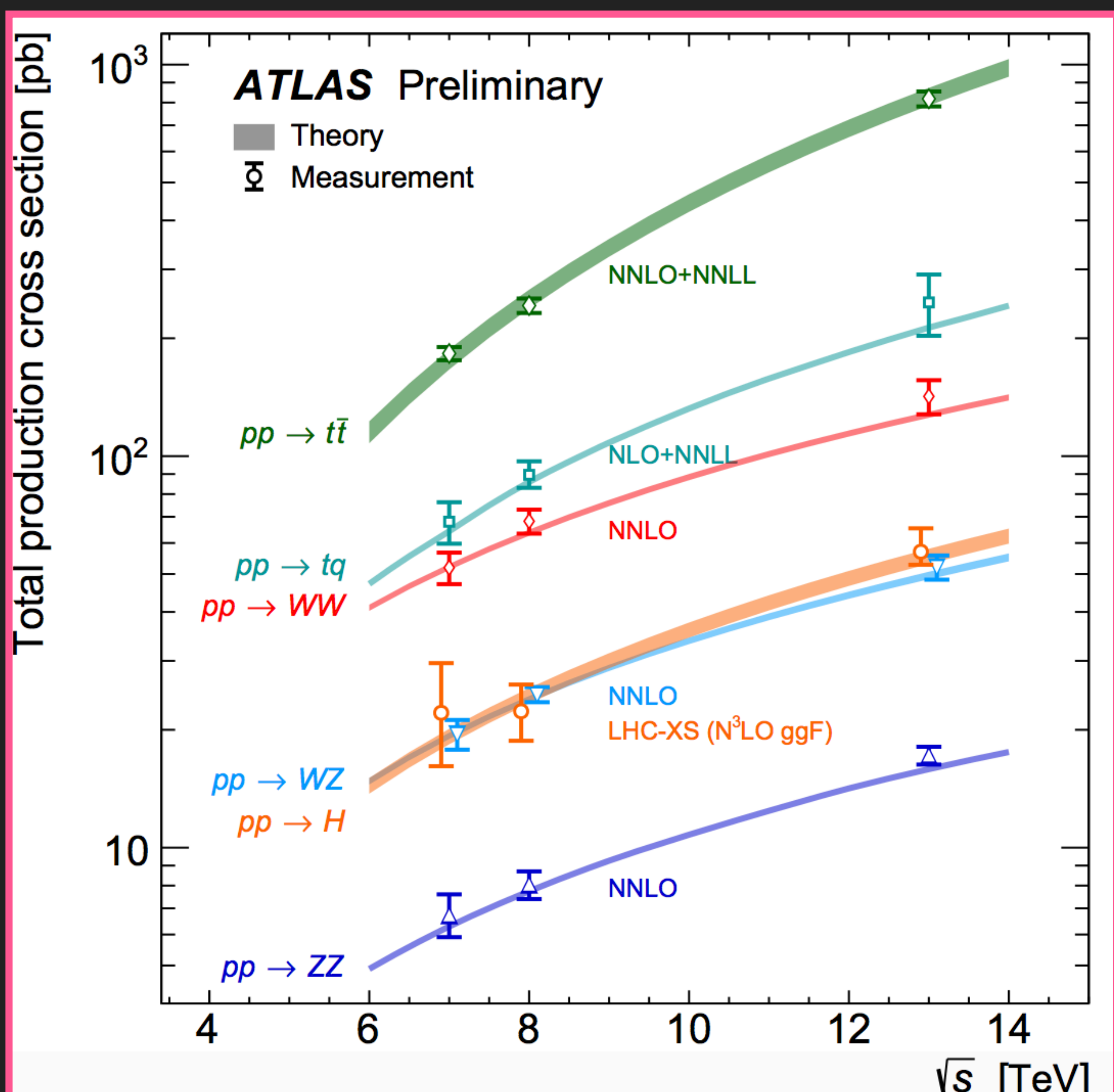

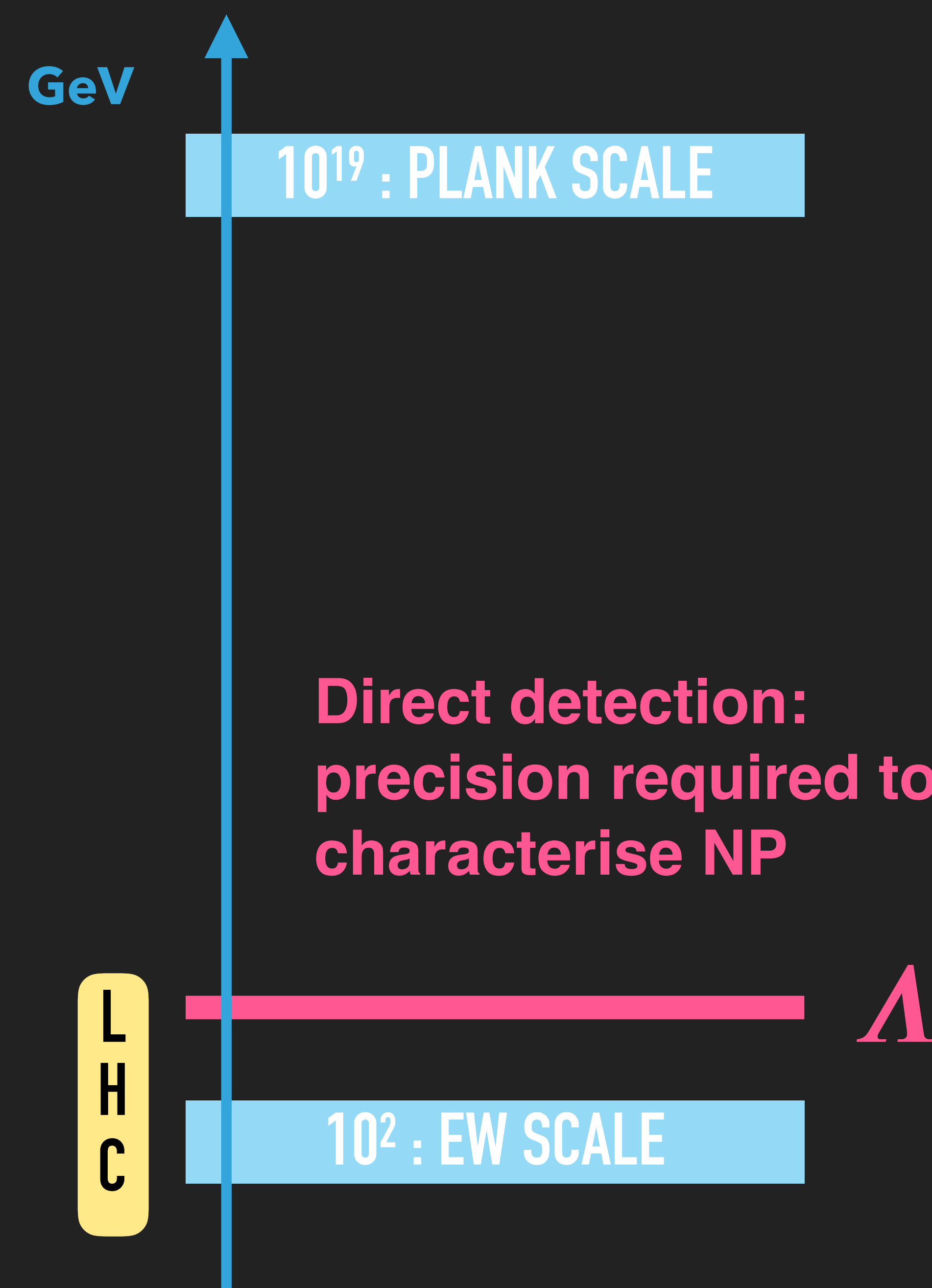

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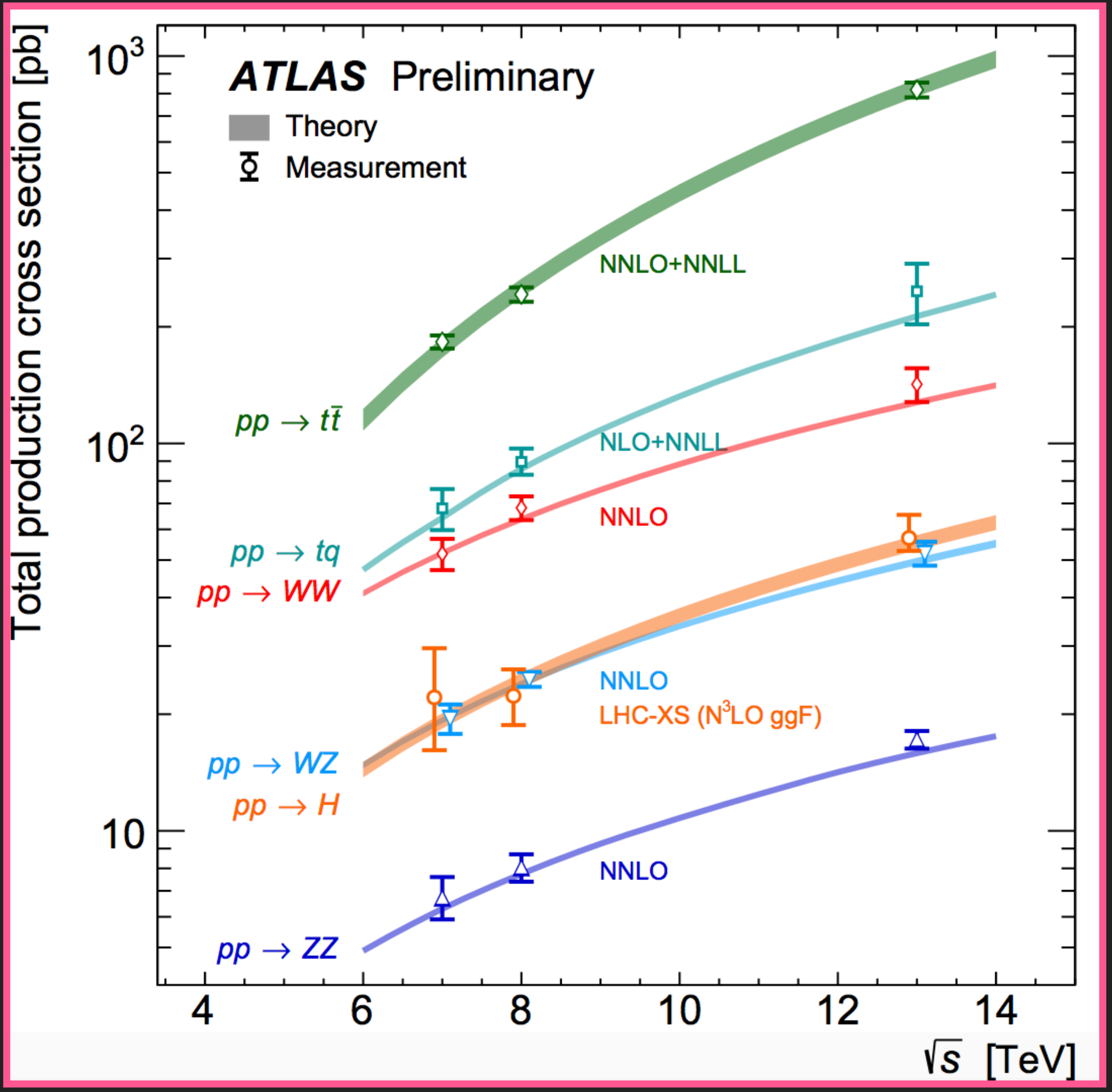
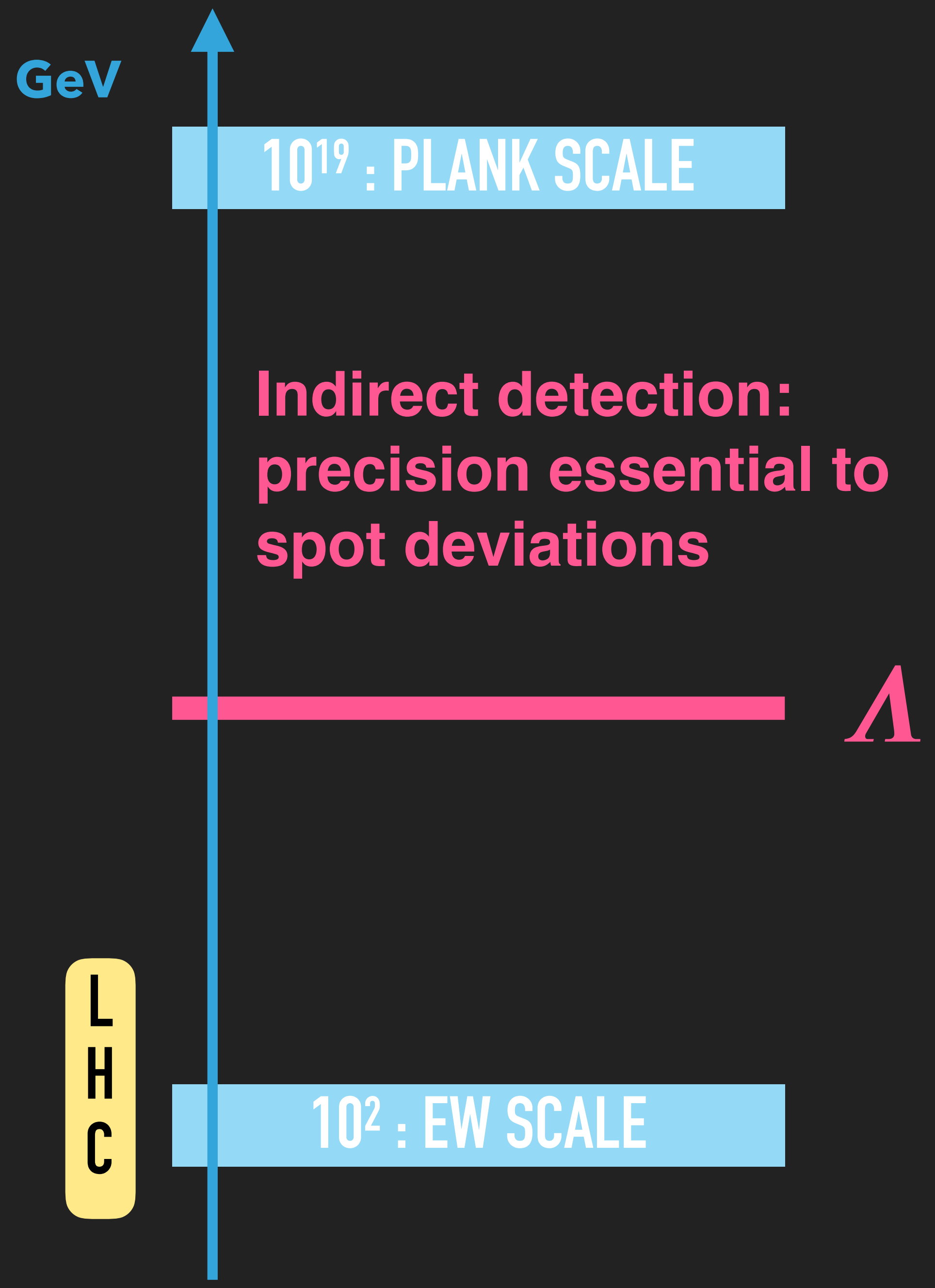
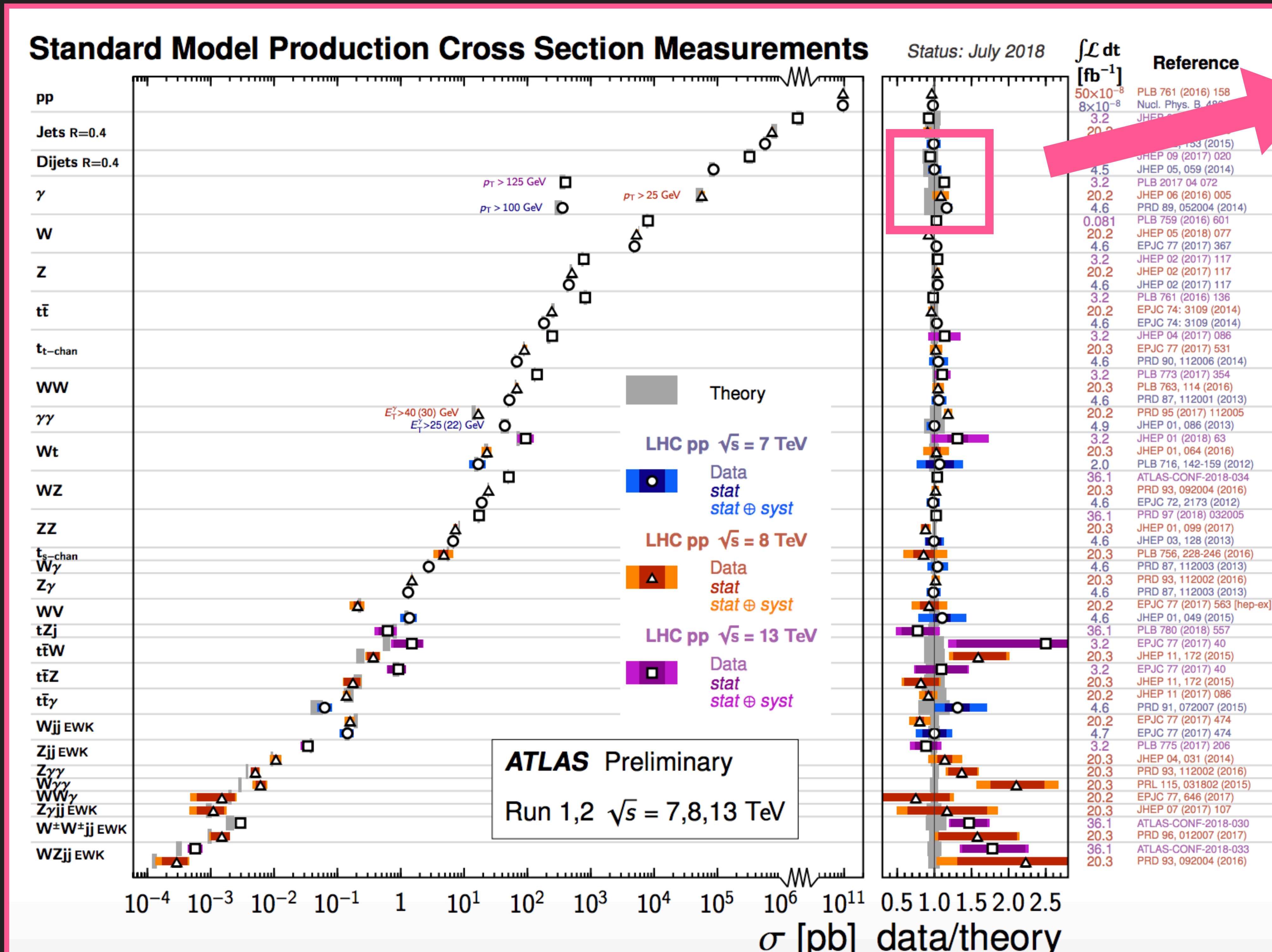
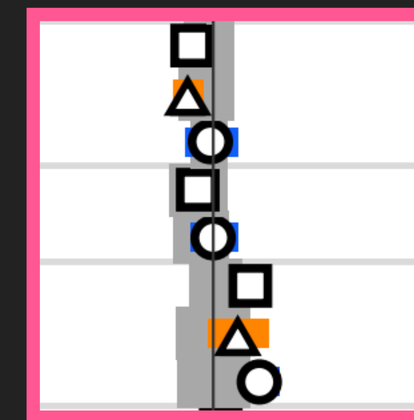




ATLAS, SM summary plots

THE PRECISION CHALLENGE

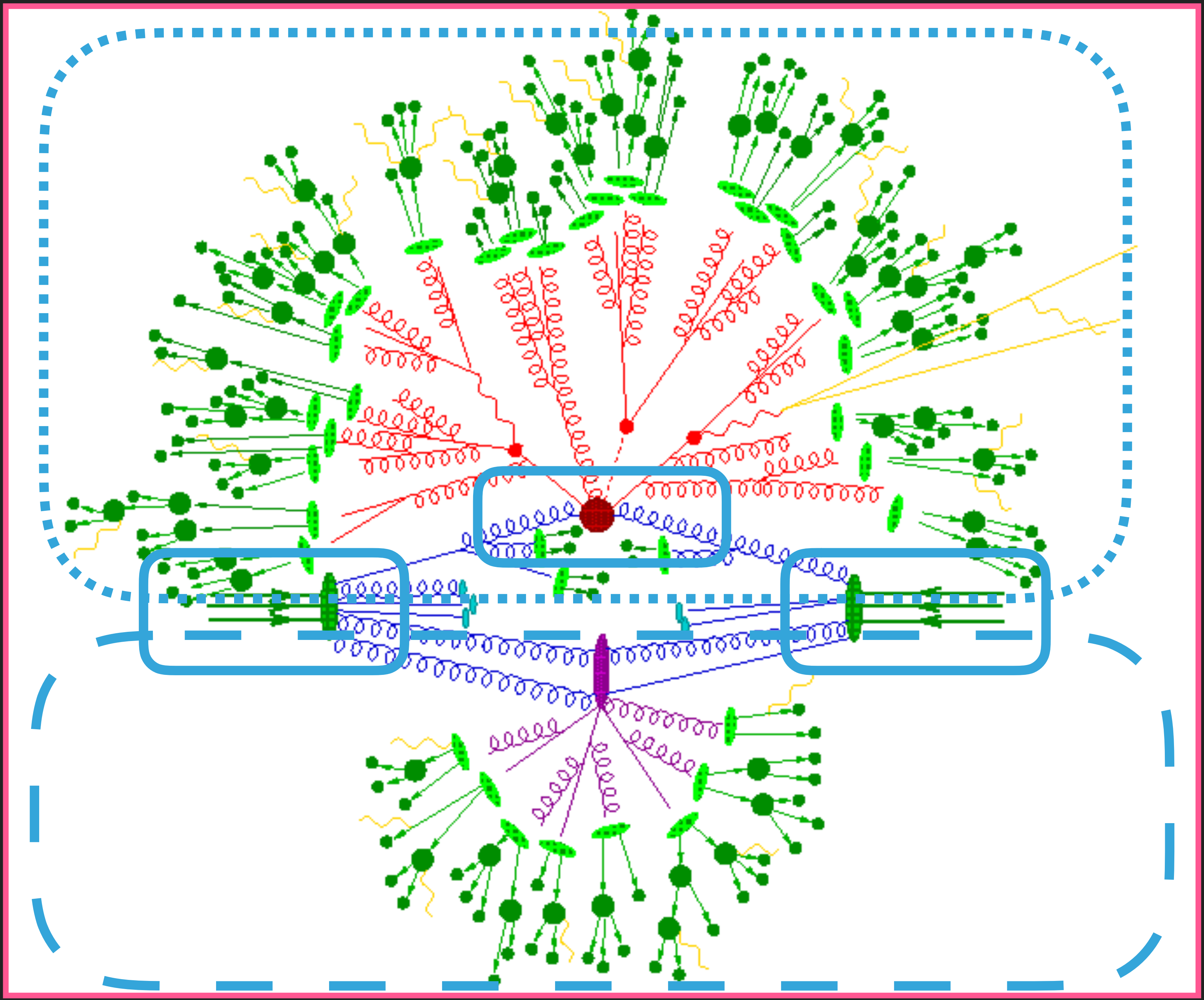




Theoretical predictions must catch up with experimental precision!

ATLAS, SM summary plots

THE PRECISION INGREDIENTS



SHERPA artist

- Hard scattering of partons (Perturbative QCD+EW)
- Parton Distribution Functions
- Parton Showering and Hadronization
- Multiple Parton Interaction, Underlying Events

OUTLINE OF MY TALK

- INTRODUCTION
  - ➡ WHAT PDFS ARE
  - ➡ WHY THEY CRUCIAL AT HADRON COLLIDERS
- HOW PDFS BECAME PRECISION PHYSICS
  - ➡ EXPERIMENTA DATA
  - ➡ THEORY PROGRESS
  - ➡ ROBUST STATISTICS
- NEW FRONTIERS
  - ➡ THEORETICAL UNCERTAINTIES IN PDFS
  - ➡ PDFS AND NEW PHYSICS

- Hard scattering of partons (Perturbative QCD+EW)
- Parton Distribution Functions
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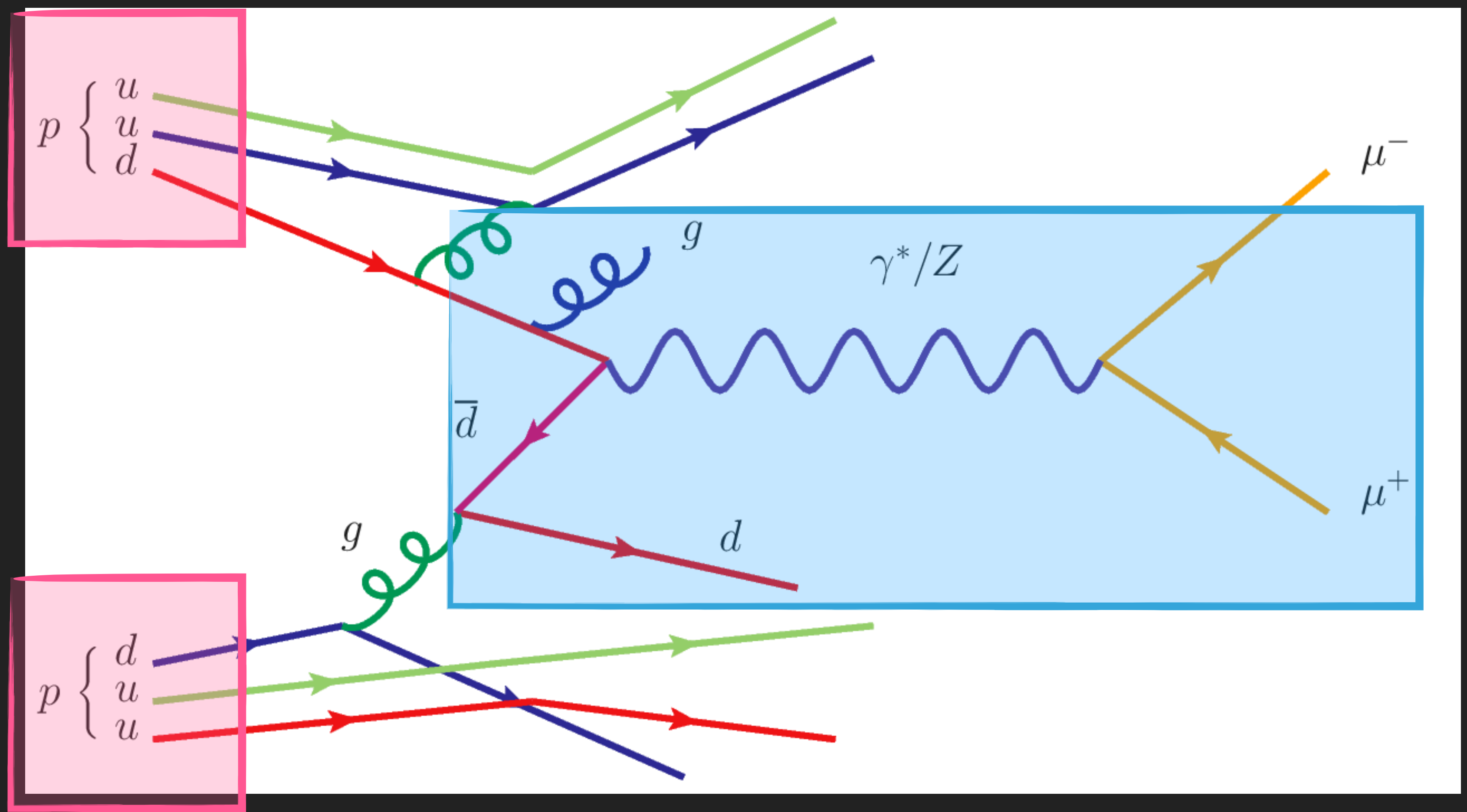
PART I

INTRODUCTION

WHAT PDFS ARE

Parton Distribution Functions (non-perturbative)



Hard Scattering (Perturbative QCD)

$$\frac{d\sigma^{pp\to ab}}{dX} = \sum_{i,j}\int \frac{dz_1}{z_1}\frac{dz_2}{z_2} f_i(z_1,\mu_F) f_j(z_2,\mu_F) \frac{d\hat{\sigma}^{ij\to ab}}{dX}(z_1 z_2 S, \alpha_s(\mu_R), \mu_F) + \mathcal{O}\left(\frac{\Lambda}{S}\right)$$

★ Universal: PDFs do not depend on hard scattering process

★ Dependence on scale μ predicted by pQCD (DGLAP evolution equations)

PDG 2016

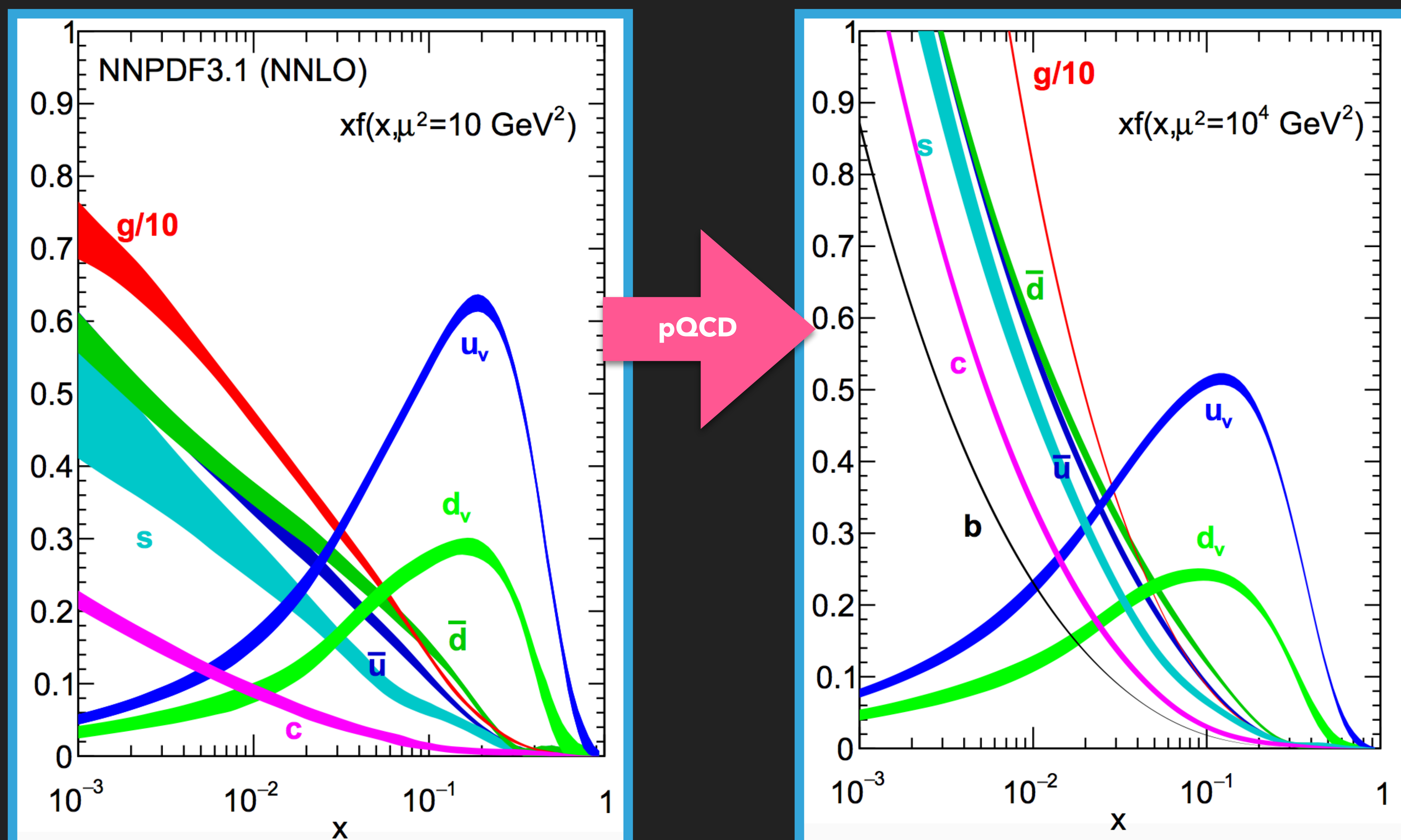
WHAT PDFS ARE

$$f_i(x, \mu)$$

Data — Perturbative QCD

Hadronic scale: global fit of PDFs

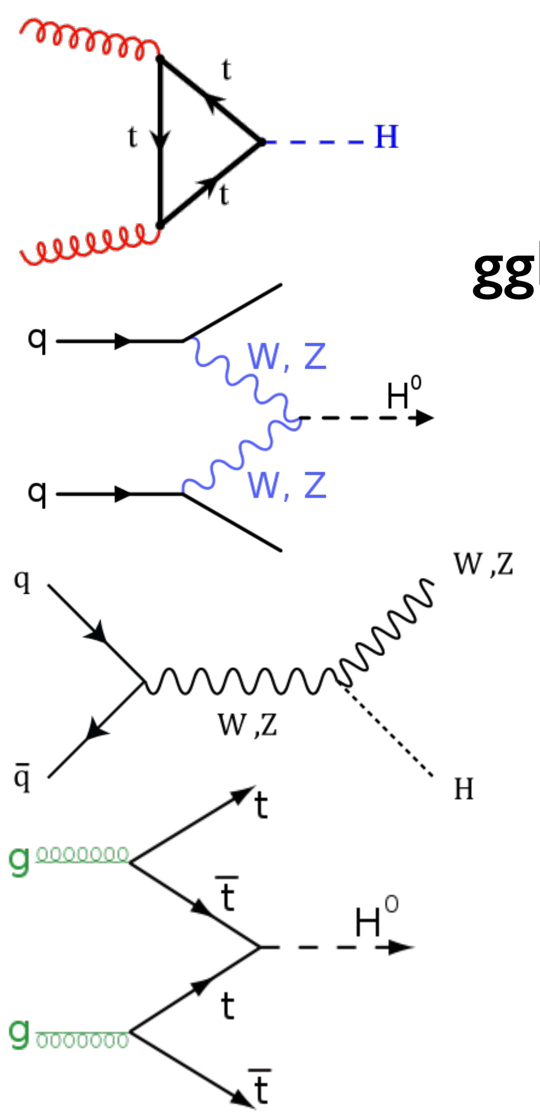
High scale: input to the LHC

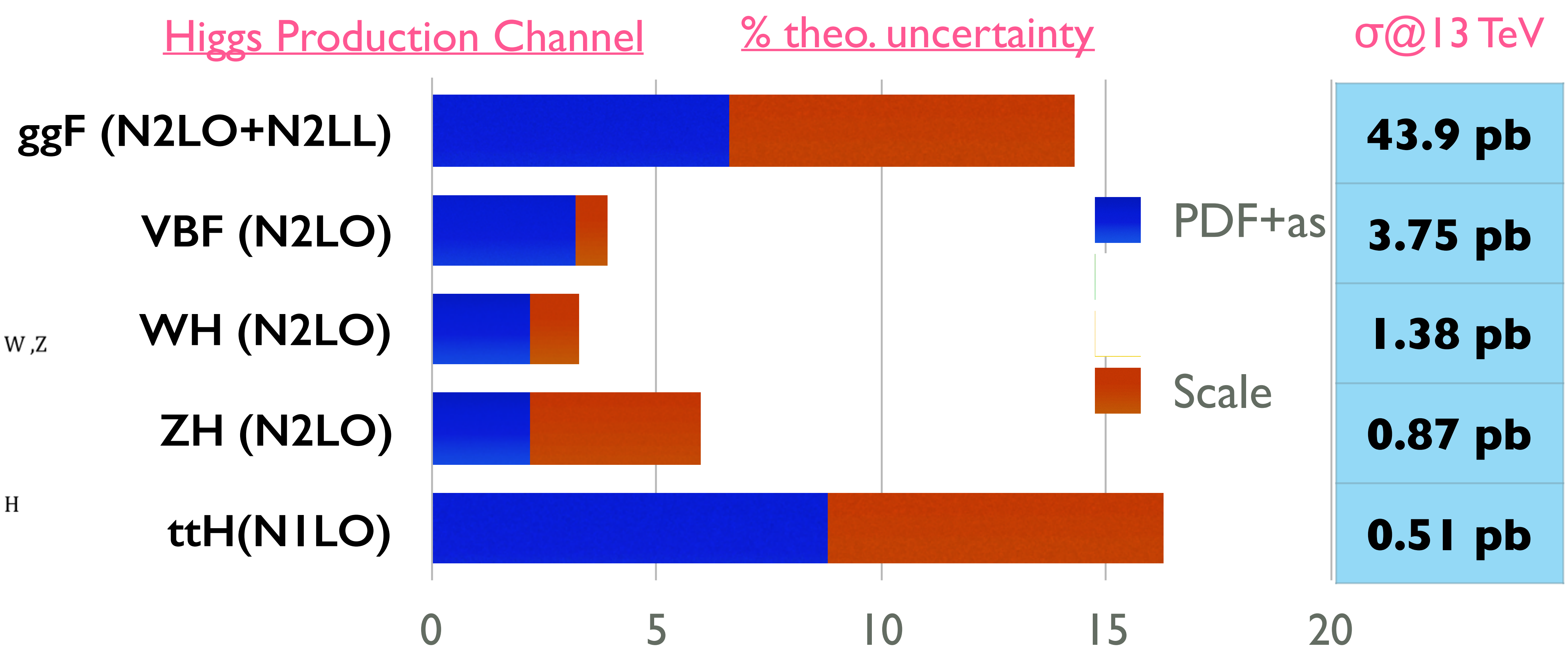


PDG 2016

WHY THEY ARE CRUCIAL

Yellow Report 3 (2013)

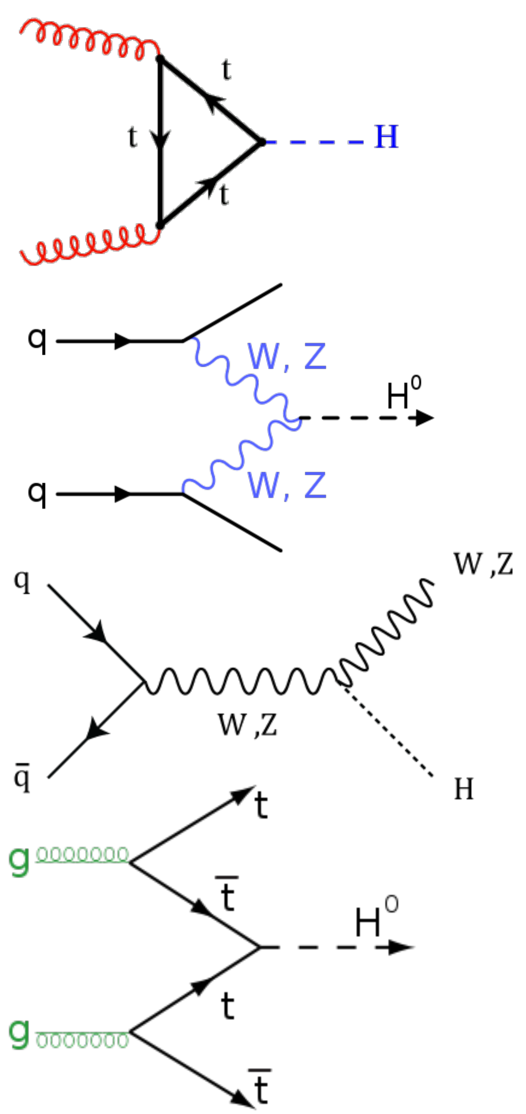


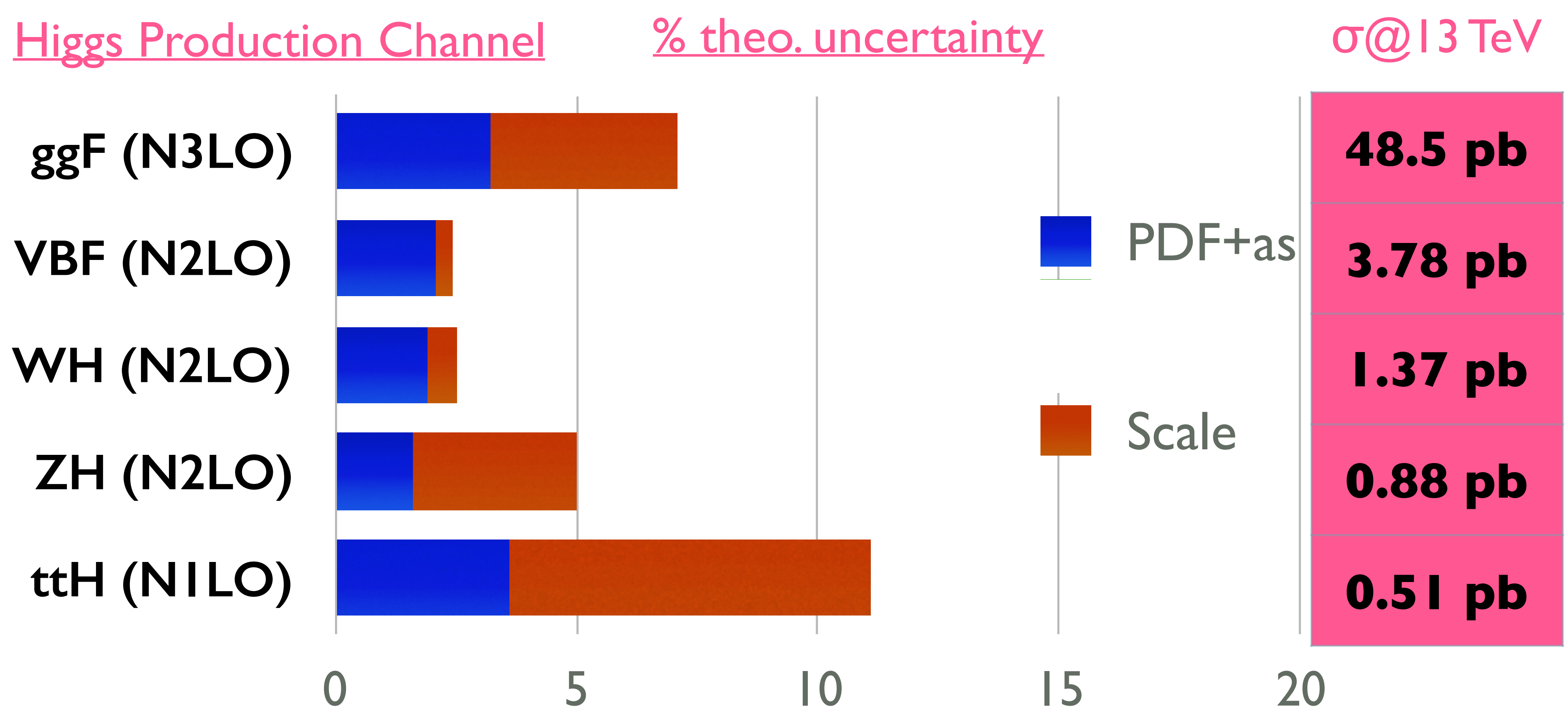


PDF uncertainties limiting factor in the accuracy of theoretical predictions

WHY THEY ARE CRUCIAL

Yellow Report 4 (2016)

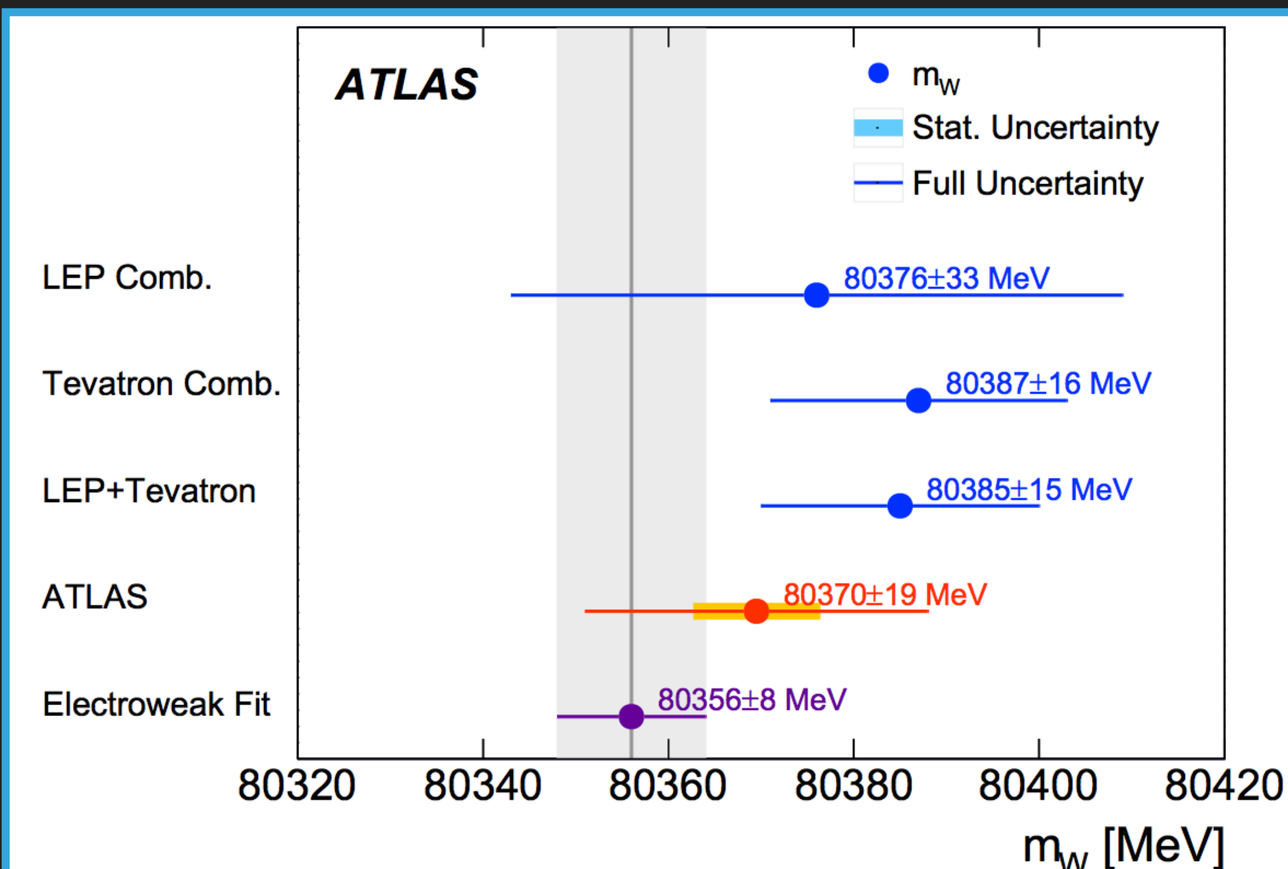




PDF uncertainties down to 1-5%
but crucial for Higgs physics

WHY THEY ARE CRUCIAL

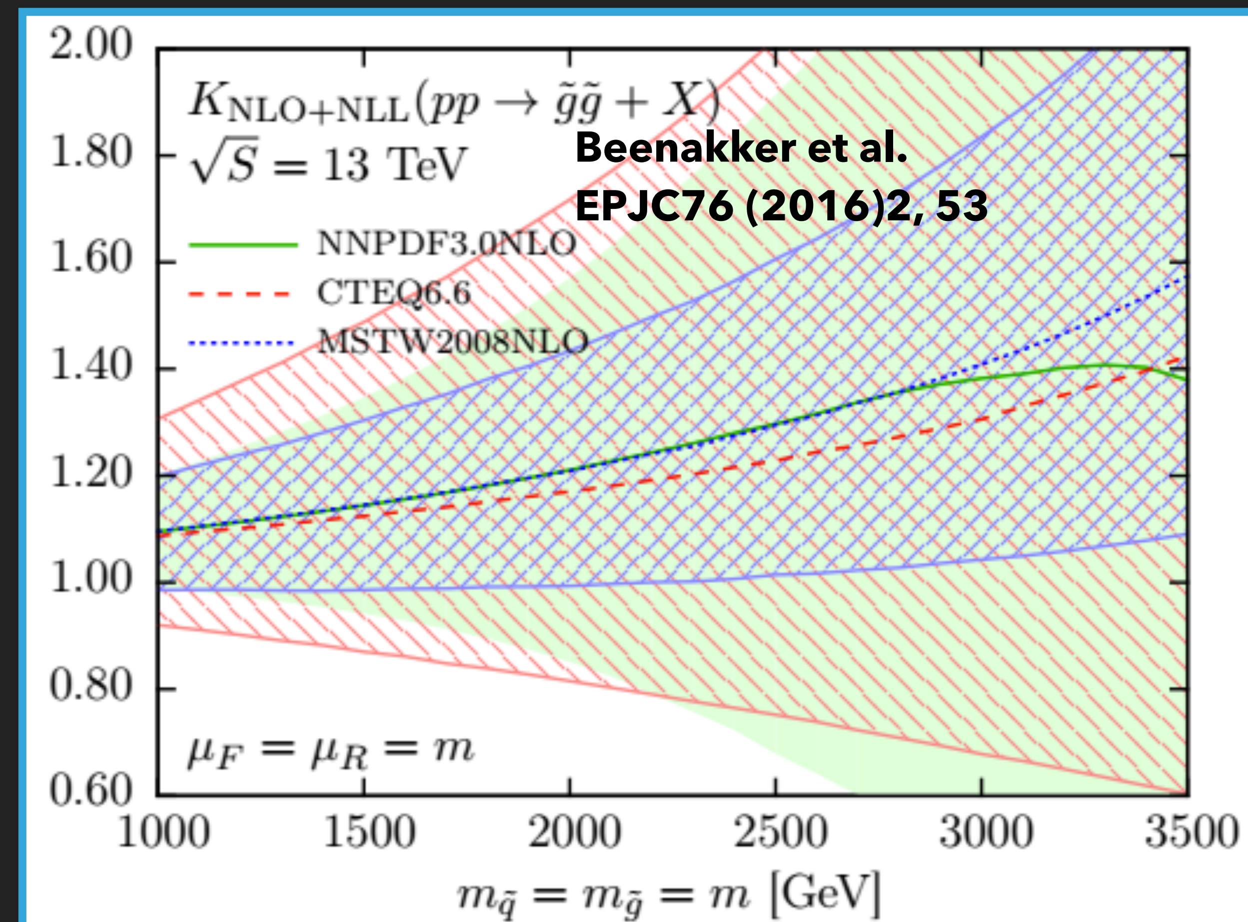
M_W determination



ATLAS collaboration, EPJC 78 (2018) 110

Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

Gluino production



Beenakker et al, EPJC 76 (2016) 2

Fundamental parameters of SM

New physics searches/characterisation

PART II

HOW PDFS BECAME PRECISION PHYSICS

A TREMENDOUS PROGRESS

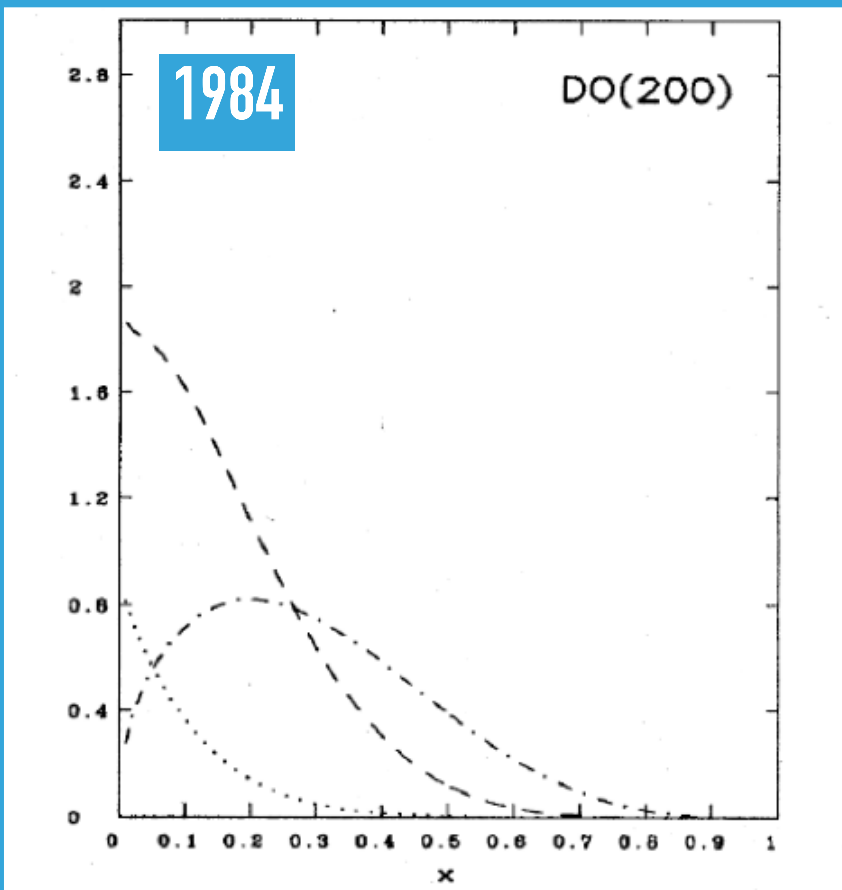
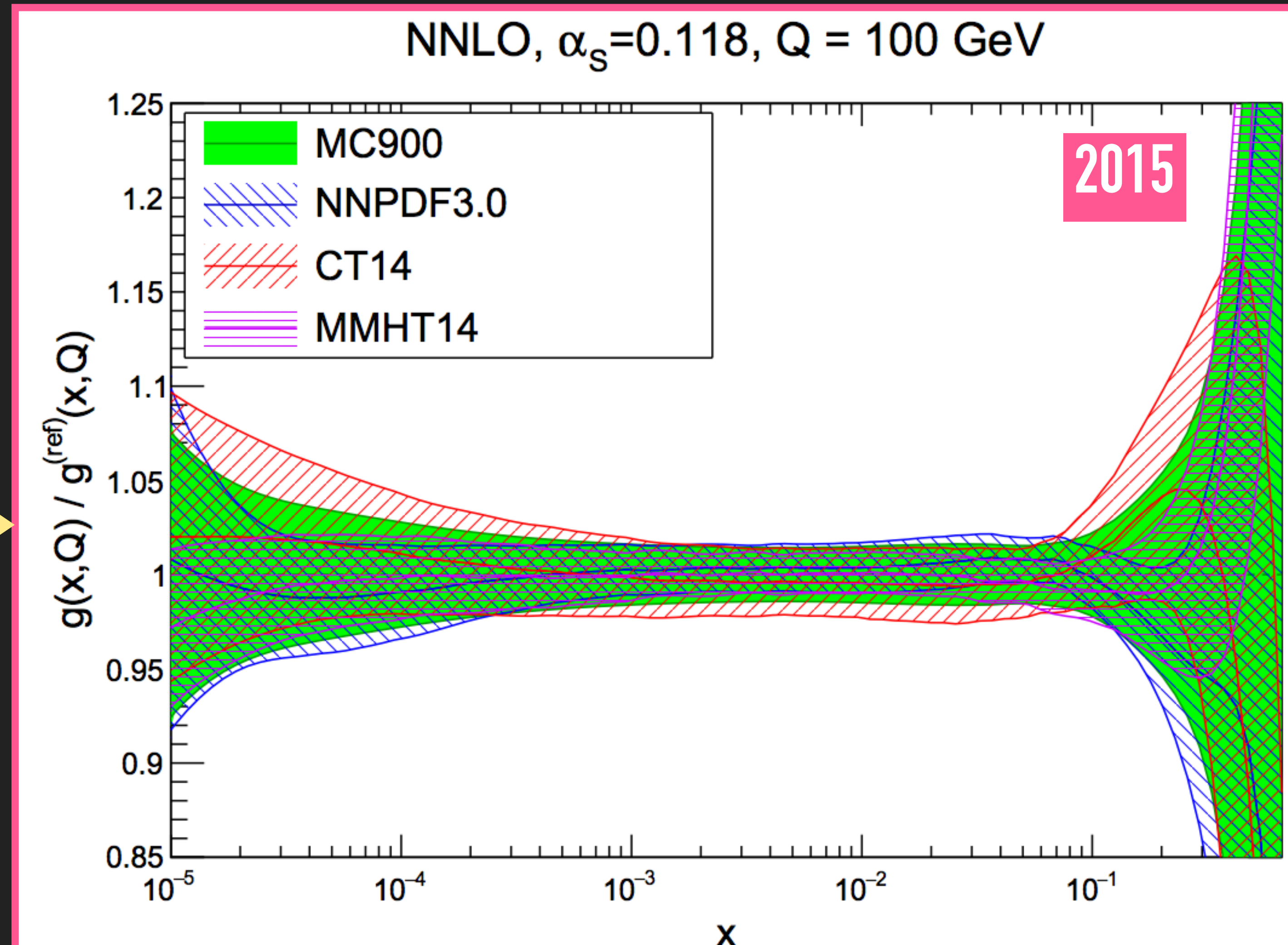


FIG. 27. "Soft-gluon" ($\Lambda = 200$ MeV) parton distributions of Duke and Owens (1984) at $Q^2 = 5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_v(x)$ (dotted line).

Rev.. Mod. Phys. 1984



PDF4LHC recommendation 2015
J.Phys. G43 (2016) 023001

★ 30 years of steady progress in PDF community have produced a huge impact on understanding of proton structure and precision physics

A COMPLEX MACHINERY

EXPERIMENTAL DATA

- FIXET TARGET EXPERIMENTS, TEVATRON, HERA, LHC…
- DIS, DRELL-YAN, JETS, TOP, DIRECT PHOTON…

$$\sigma = f_1(\otimes f_2) \otimes \hat{\sigma}$$

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THEORY

- FIXED ORDER CALCULATION
- FAST INTERFACES
- HEAVY QUARK SCHEMES
- EW CORRECTIONS …

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THEORY
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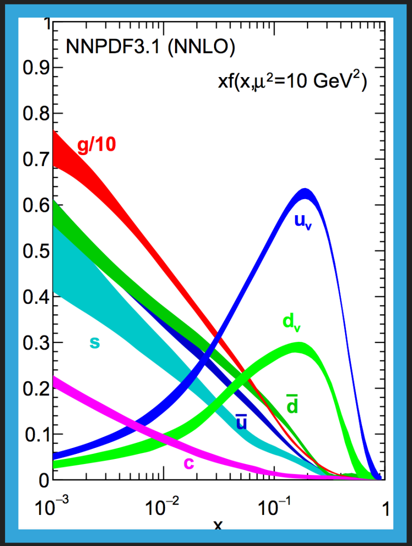
STATISTICAL FRAMEWORK
- PDF PARAMETRISATION
- PDF UNCERTAINTIES AND PROPAGATION
- MINIMISATION ROBUSTNESS

A COMPLEX MACHINERY



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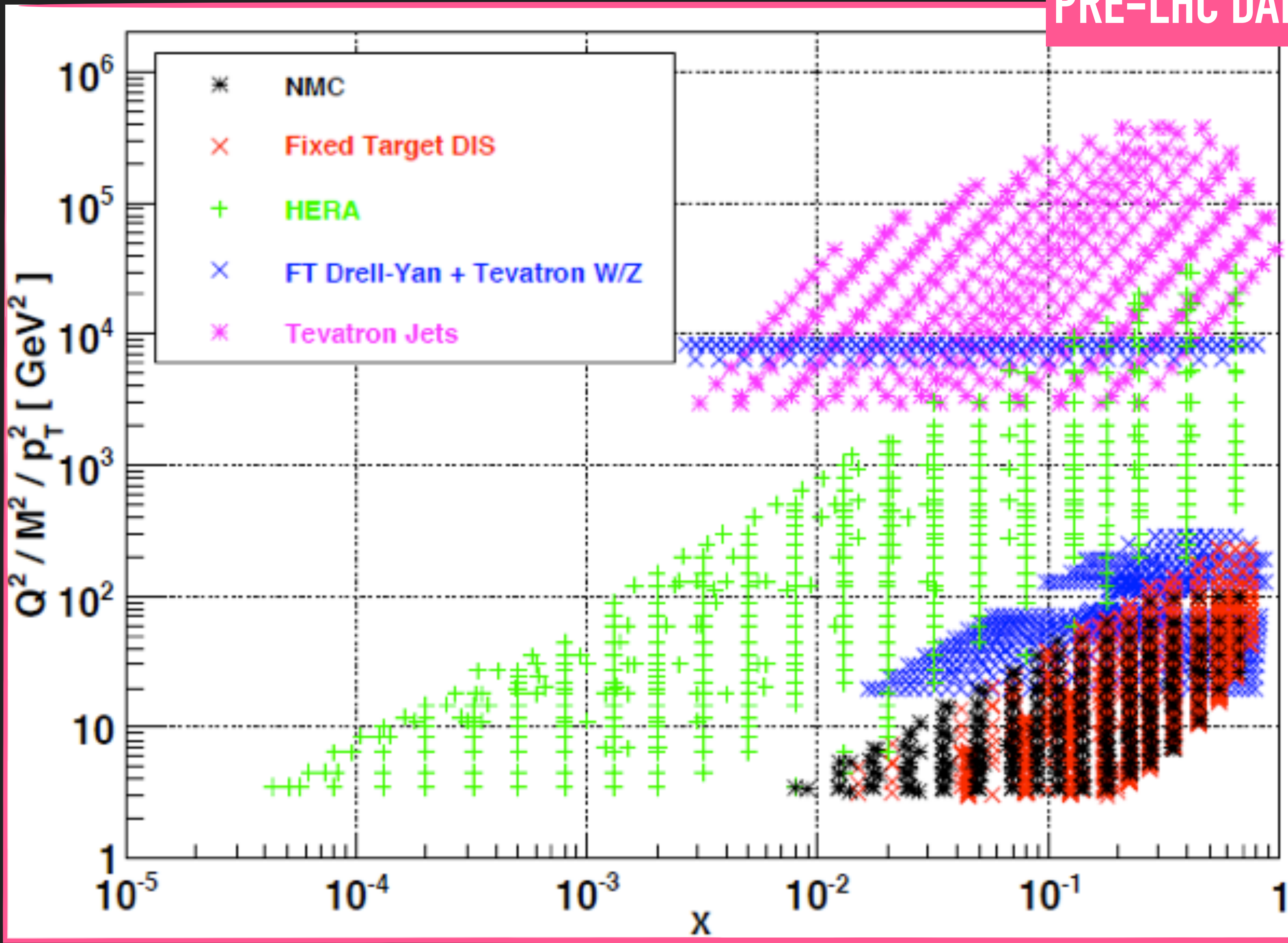
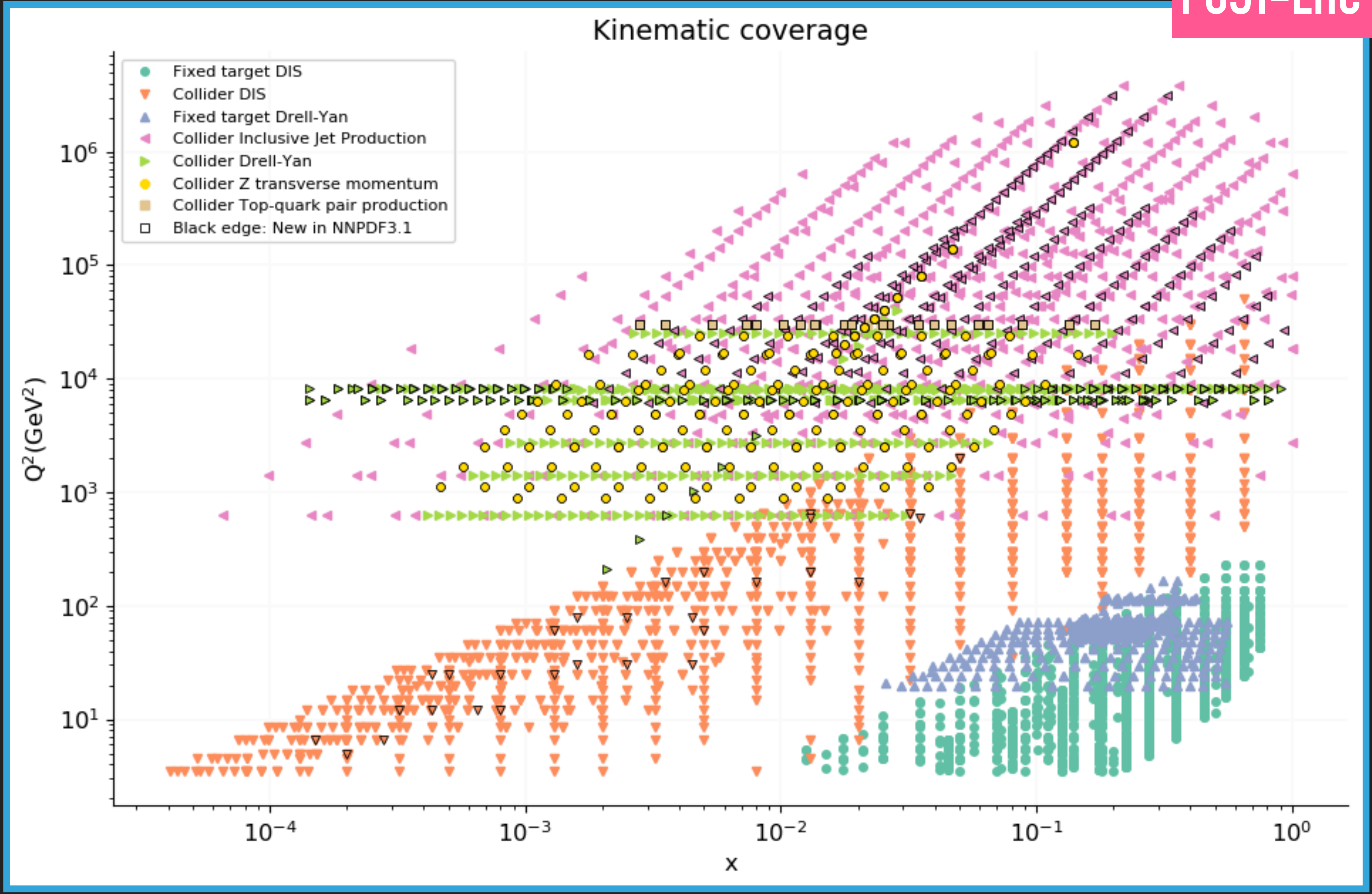
EXPERIMENTAL DATA

PRE-LHC DATA



EXPERIMENTAL DATA

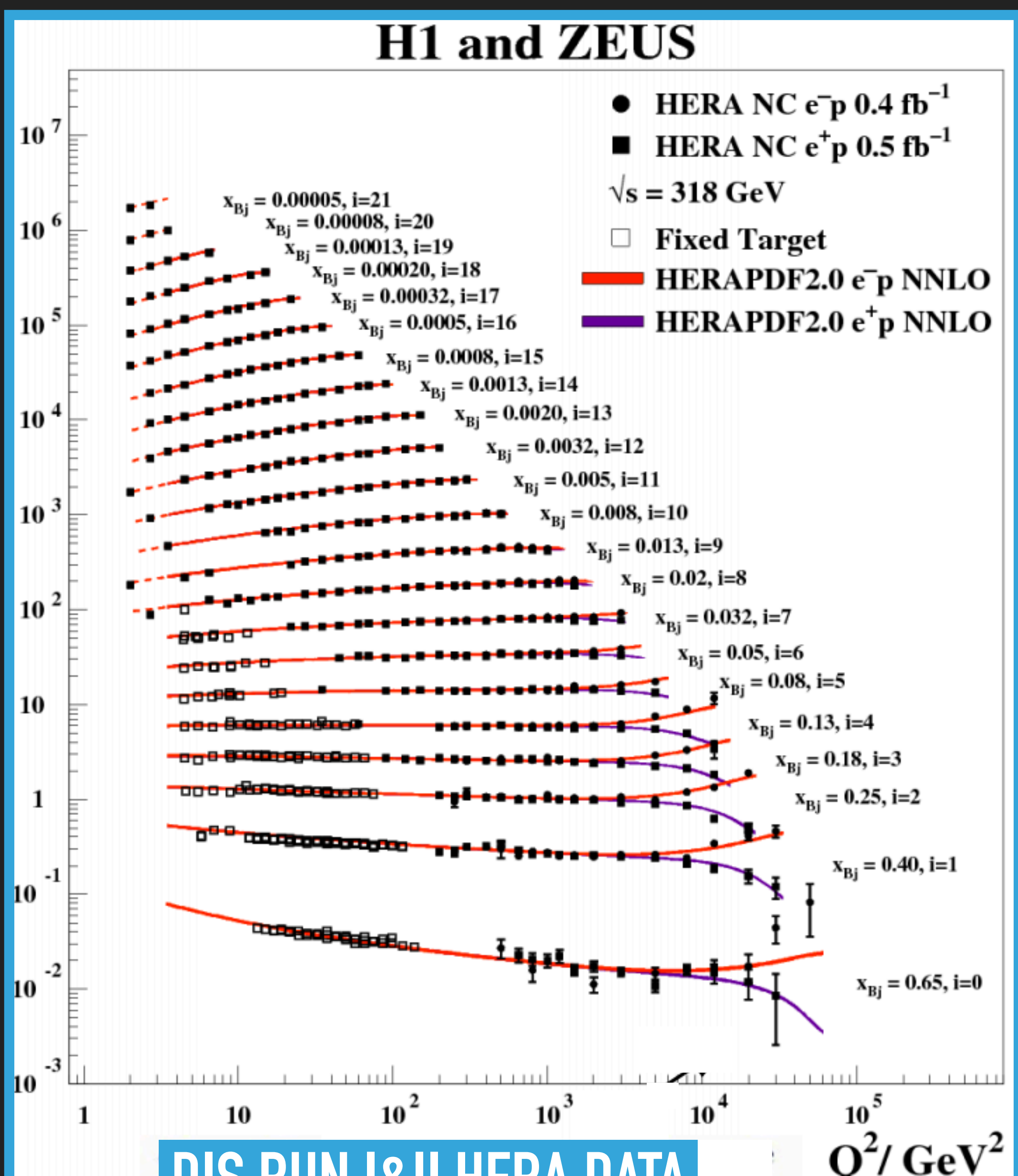
POST-LHC DATA



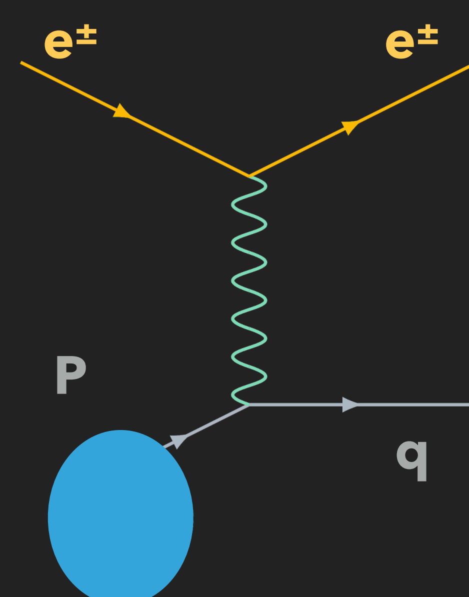
Ball et at, EPJC 77 (2017)

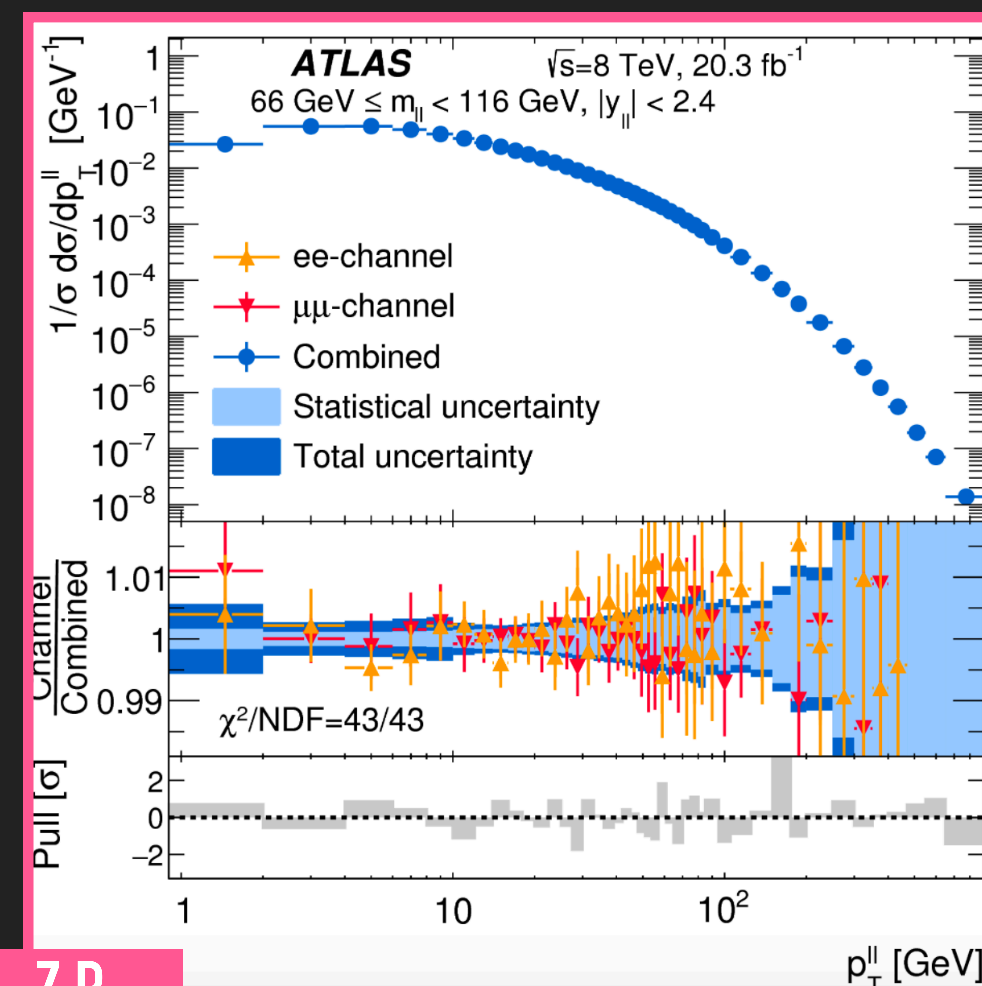
EXPERIMENTAL DATA

- ➡ Increased reach at large and low-x and new constraints
- ➡ Amazing precision of experimental data



DIS RUN I&II HERA DATA





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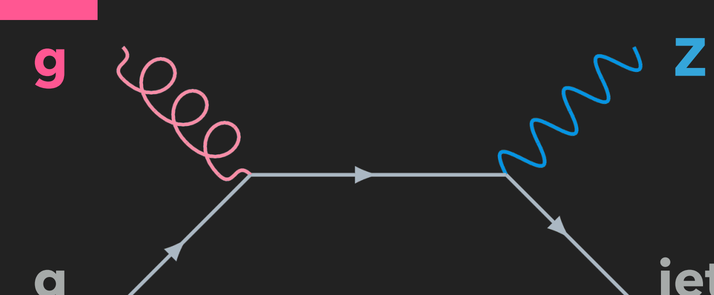

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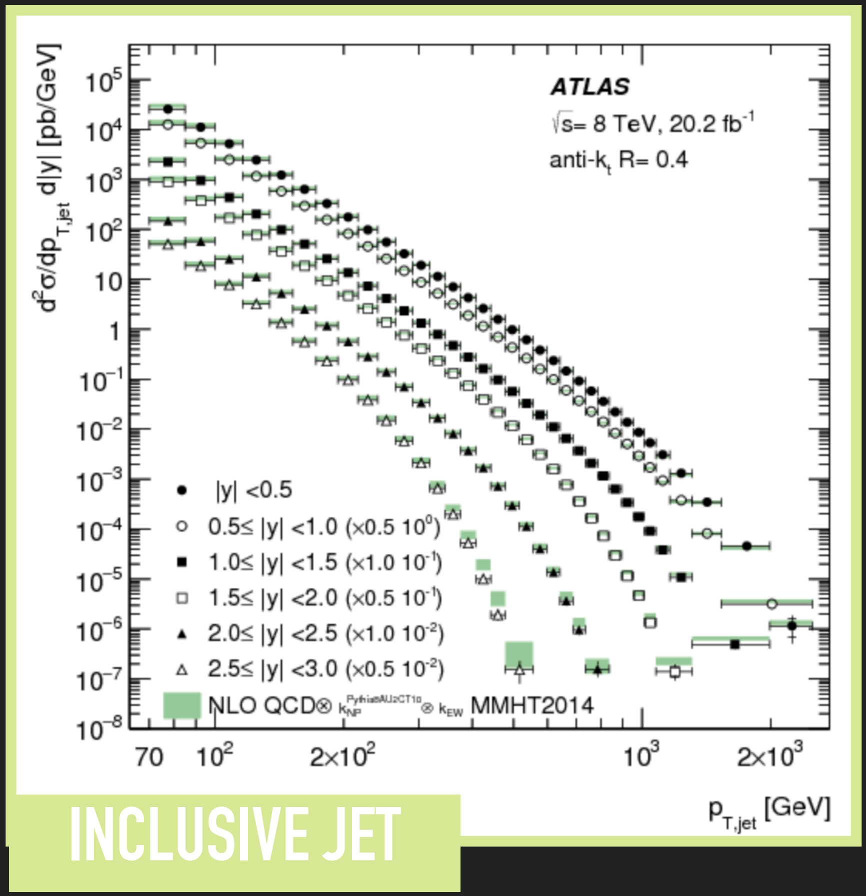
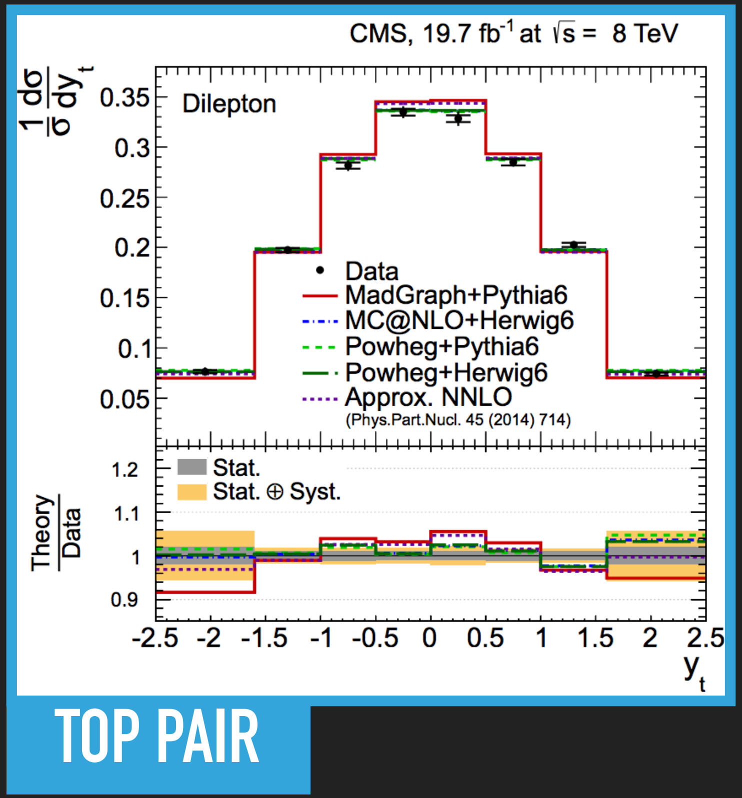
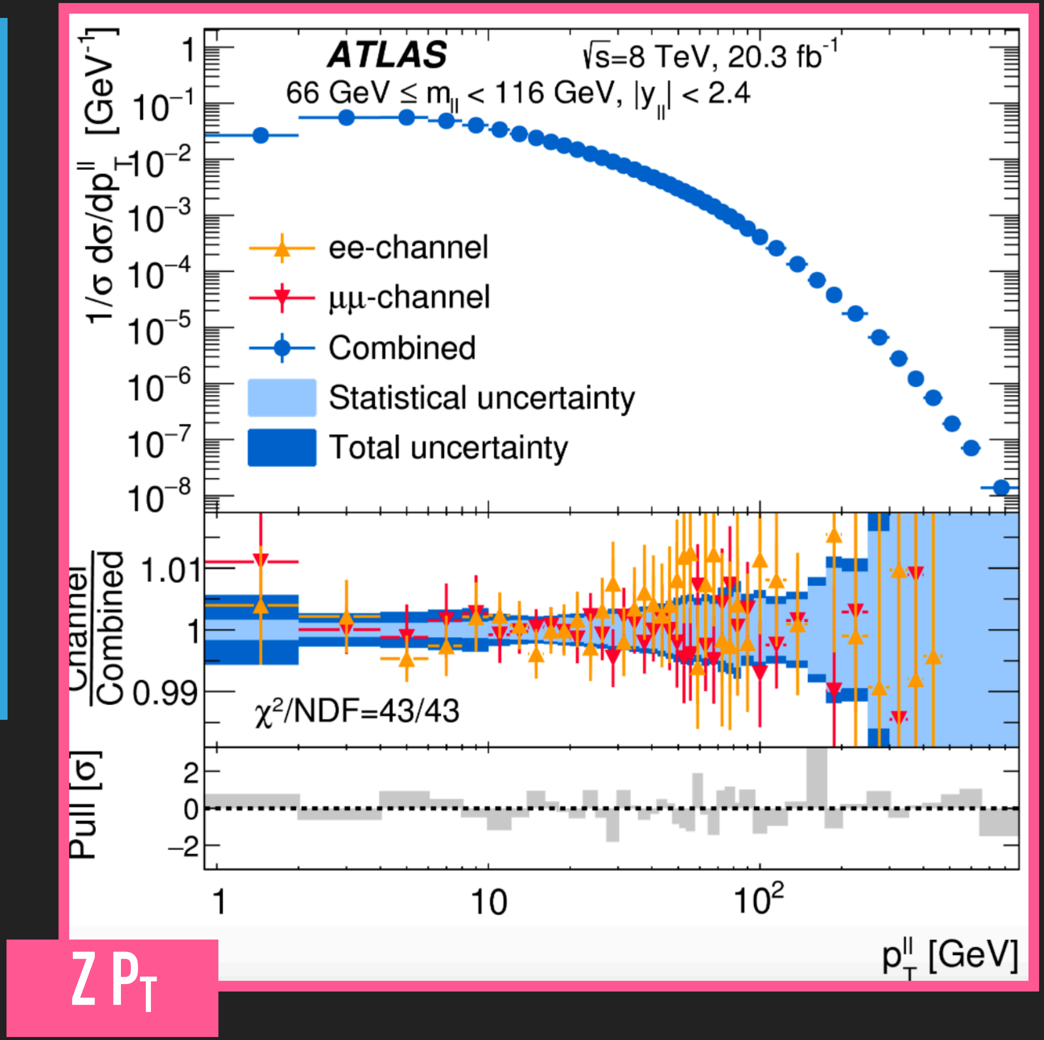
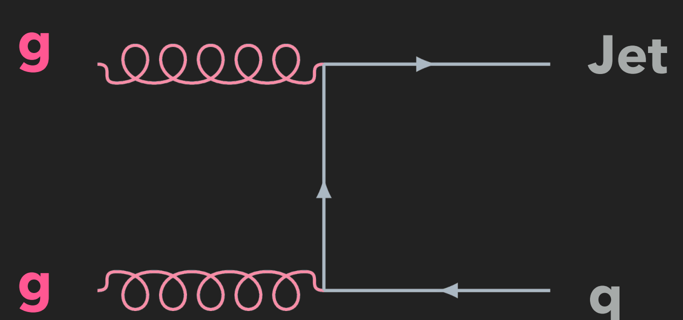
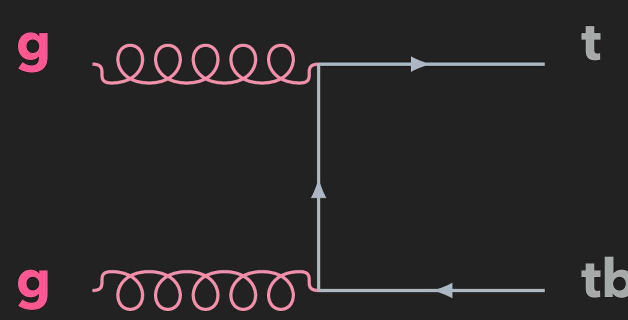
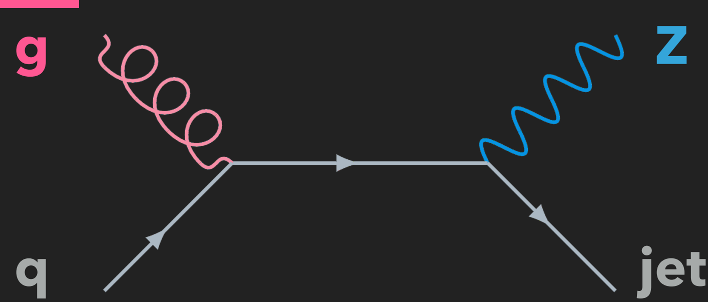






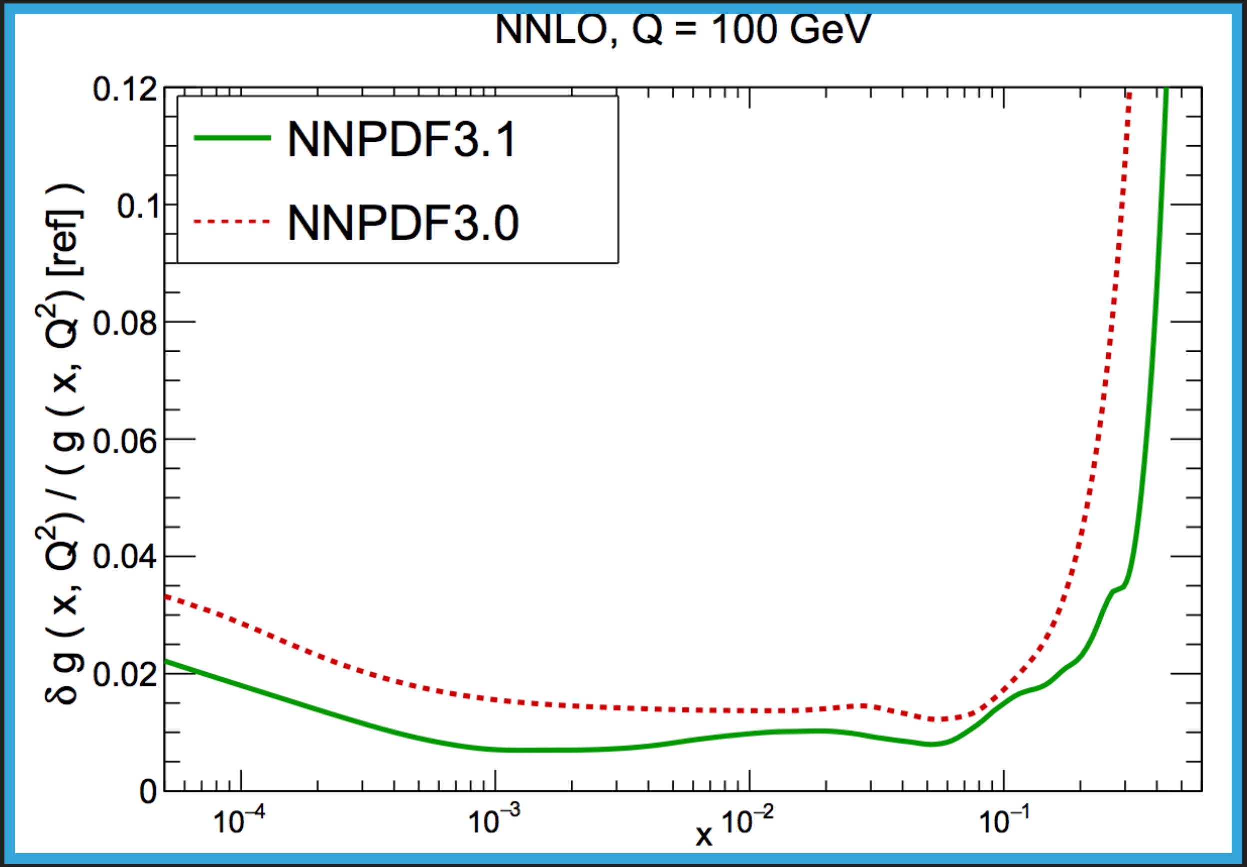


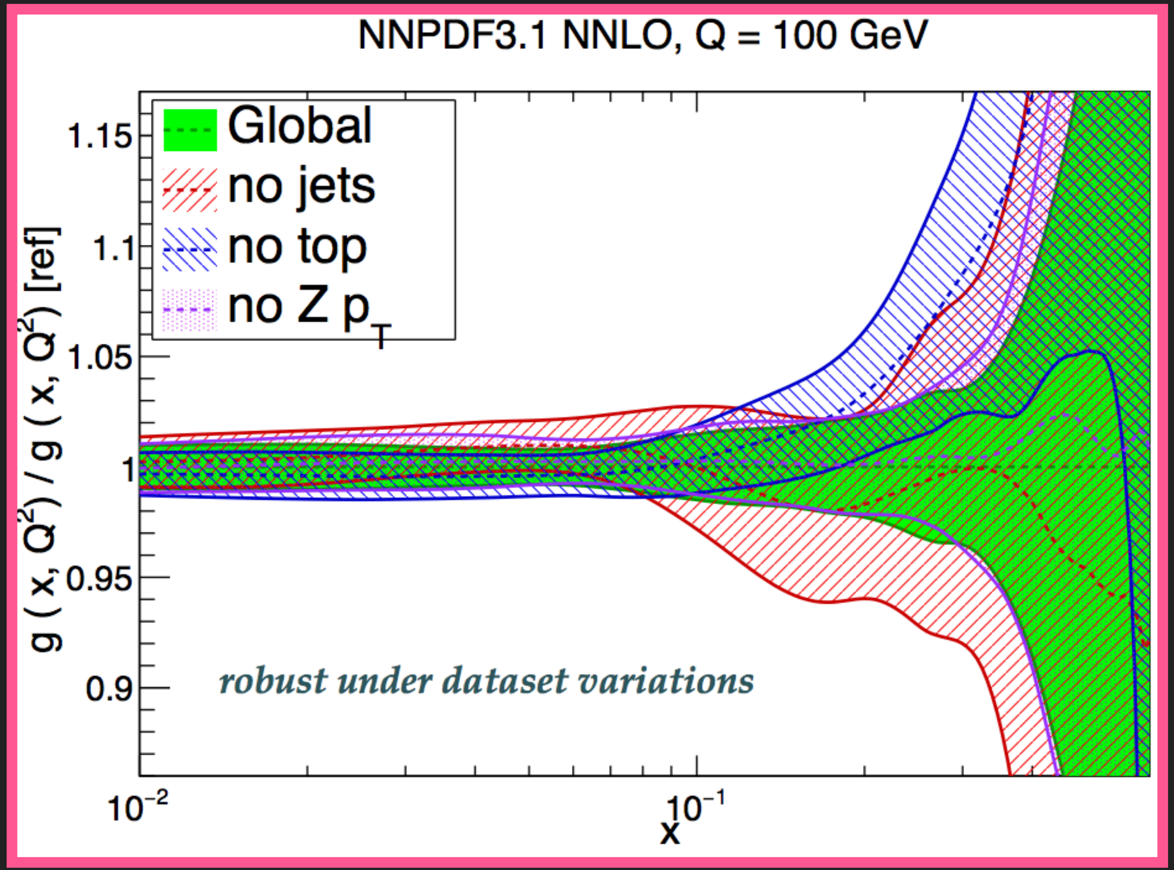


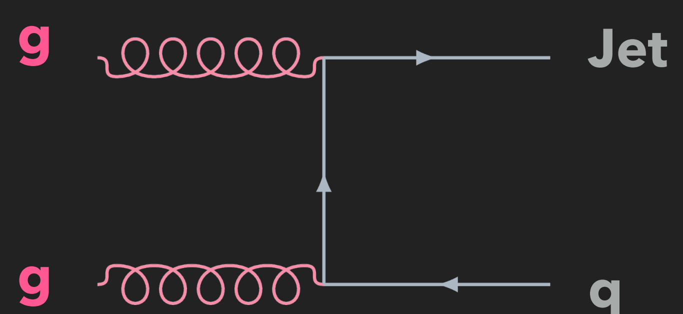


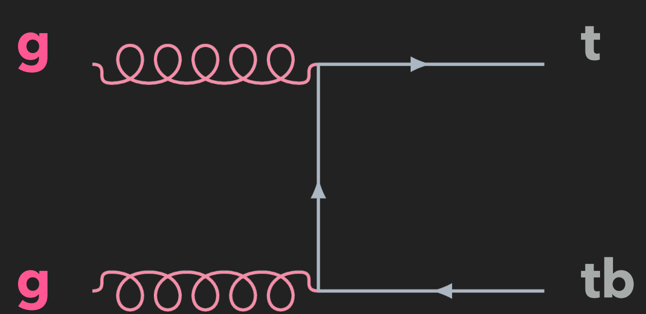
EXPERIMENTAL DATA & INSIGHT ON THE GLUON

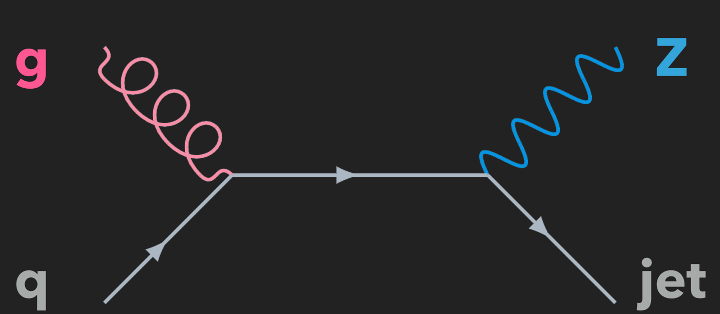
- Large-x gluon constrained by three independent processes
- Consistent picture and analysis robustness











THEORY: THE NNLO FRONTIER

- NNLO calculations are essential to reduce theoretical uncertainties in PDF analyses
- Stunning progress made on calculation of some key process for PDF determination

✓ NNLO top pair production
  Czakon et al [PRL 110(2013)]
  Czakon et al [JPCP (2014)]
  Czakon et al [JHEP 1301(2015)]

✓ W/Z+j and W/Z transverse momentum distributions
  Gehrmann-De Ridder et al [JHEP 07 (2016)]
  Gehrmann-De Ridder et al [JHEP 11 (2016)]
  Boughezal et al [PRL 16 (2016)]
  Boughezal et al [PRD 14 (2016)]

✓ Inclusive jet and di-jets
  Currie et al [PRL 118 (2017)]
  Currie et al [PRL 119 (2017)]
  Gehrmann-De Ridder et al [PRL 110 (2016)

✓ Inclusive DIS jets
  Currie et al [JHEP 17 (2017)]

✓ Direct photon
  Campbell et al [PRL 118 (2017)]

✓ Single top
  Bruchersfeier et al [PRB 736 (2014)]

THEORY: THE NNLO FRONTIER

- NNLO calculations are essential to reduce theoretical uncertainties in PDF analyses
- Stunning progress made on calculation of some key process for PDF determination
- Great progress also in tools to interface NLO (NNLO?) codes to PDF fitting code
  APPLgrid, Carli et al (2010) & FASTNLO, Kluge et al (2010)
- Breakthrough in determining photon PDF **(Manohar et al 2016)**

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STATS: ERROR PROPAGATION

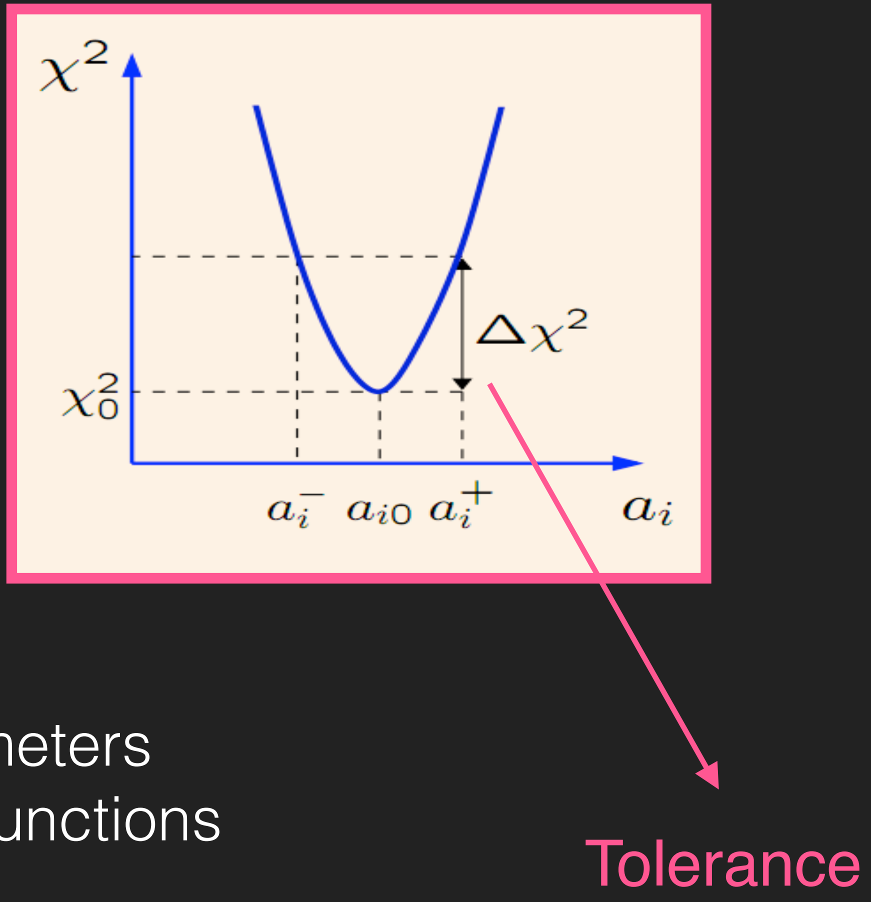
$$\langle \mathcal{O}[\{f\}] \rangle = \int [\mathcal{D}f] \mathcal{O}[\{f\}] \mathcal{P}[\{f\}]$$

- Given a finite number of experimental data points want a set of functions with errors
- Want to find a infinite-dimensional object from a finite number of information

Propagation of experimental uncertainty

$$\langle \mathcal{O}[\{f\}] \rangle = \int da_1 da_2 \cdots da_n \mathcal{O}[\vec{a}] \mathcal{P}[\vec{a}]$$

- Hessian approach: Project into a n-dimensional space of parameters and use linear approximation around minimum χ^2

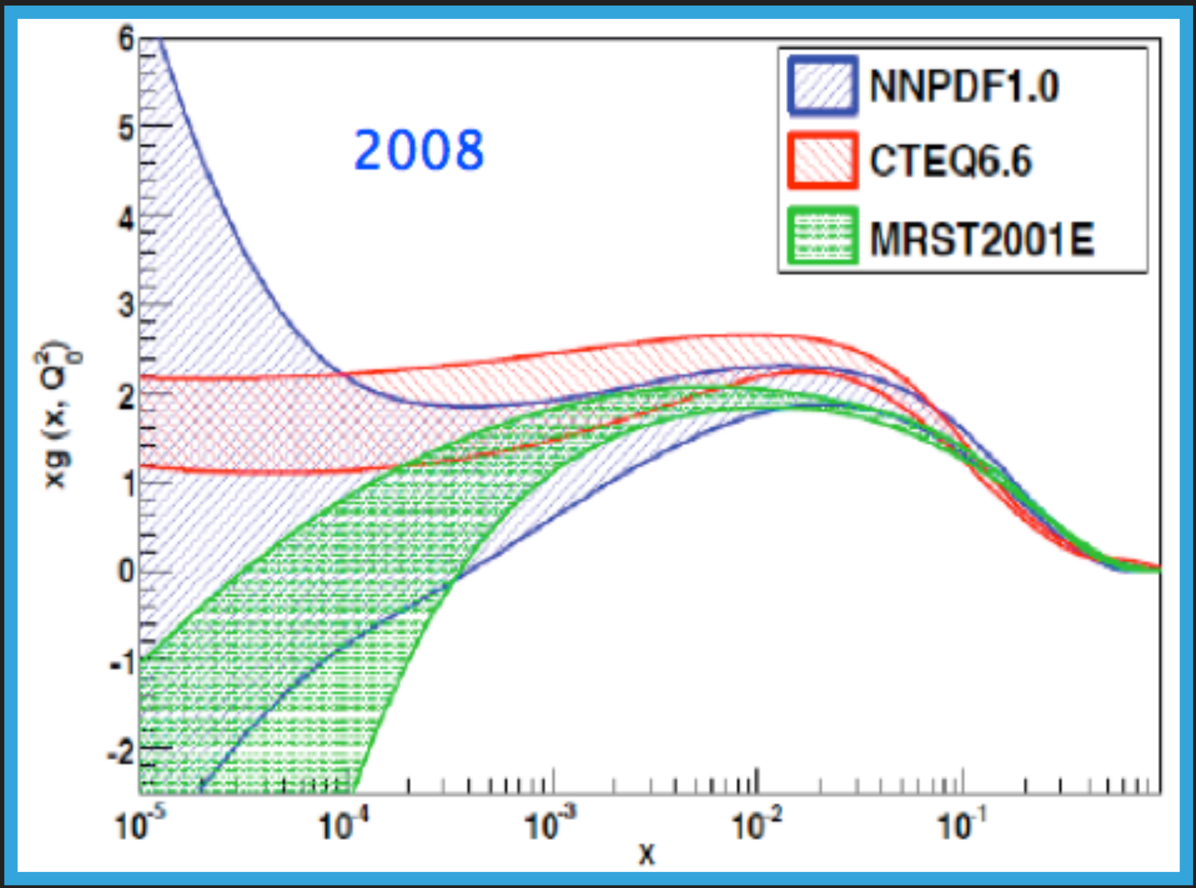


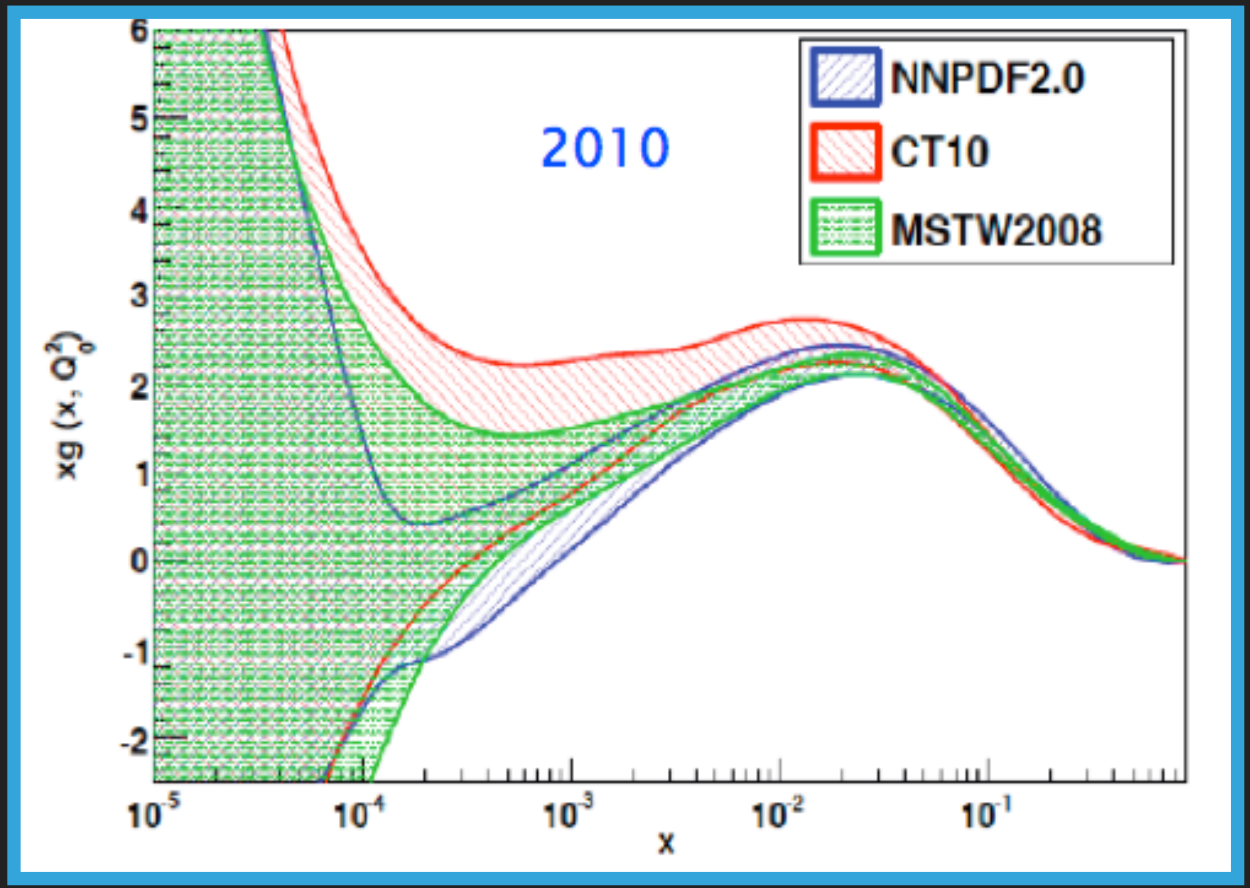
Parametrisation

- Introduce a simple functional form with enough free parameters
- Typically about 20-40 free parameters for 7 independent functions

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

STATS: DATA-DRIVEN PROGRESS

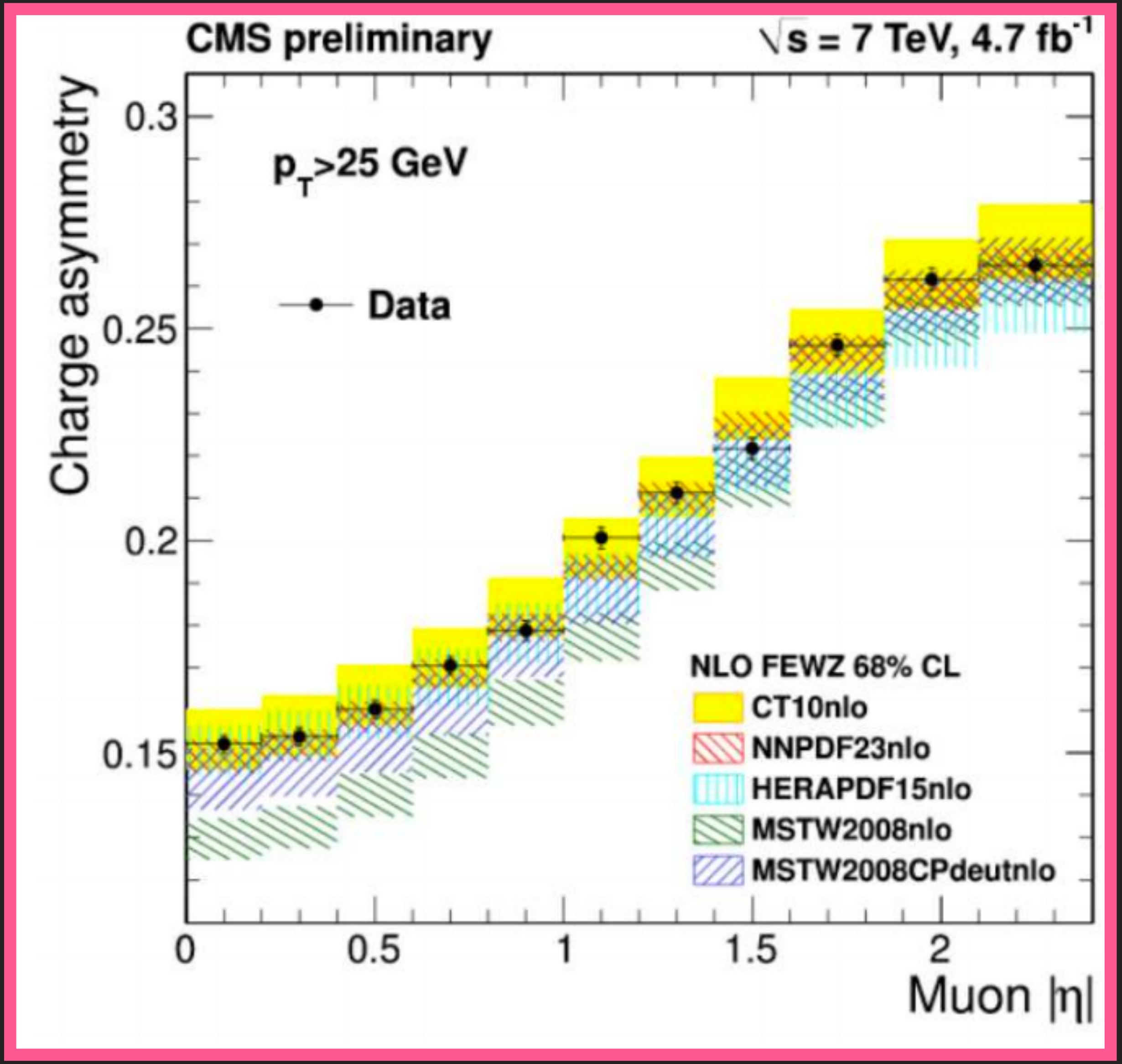


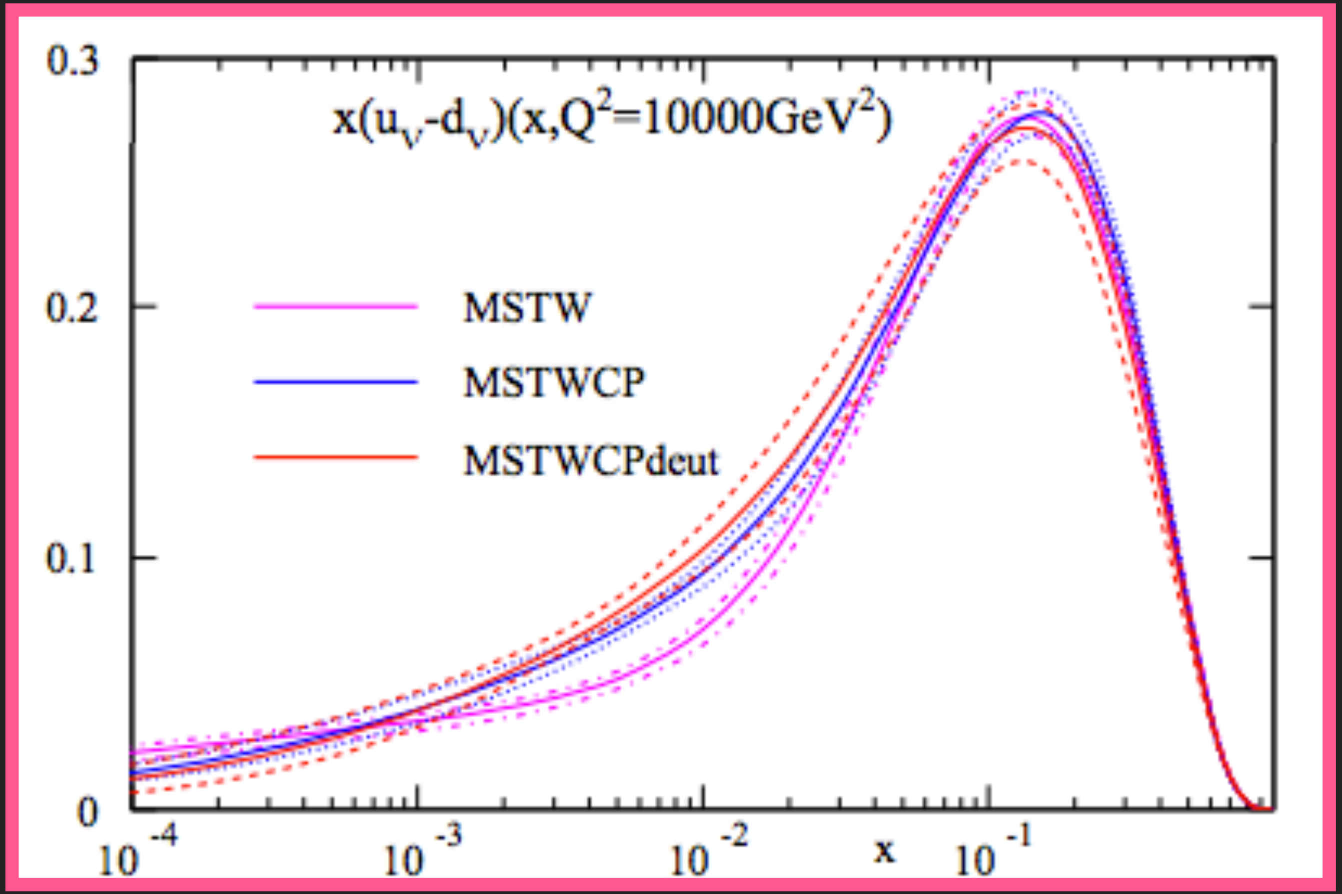


$$xg = A_g\, x^{\delta_g} (1-x)^{\eta_g} (1 + \epsilon_g \sqrt{x} + \gamma_g\, x) + A_{g'}\, x^{\delta_{g'}} (1-x)^{\eta_{g'}}$$

- PDF uncertainties tuned to data (tolerance $\Delta\chi^2 > 1$ - many studies/improvements)
- Fixed parametrisation was forced to be more flexible by new data => less biased parametrisation form (a posteriori data-driven progress)

STATS: DATA-DRIVEN PROGRESS





Martin et al
EPJC73 (2013) 2, 2318

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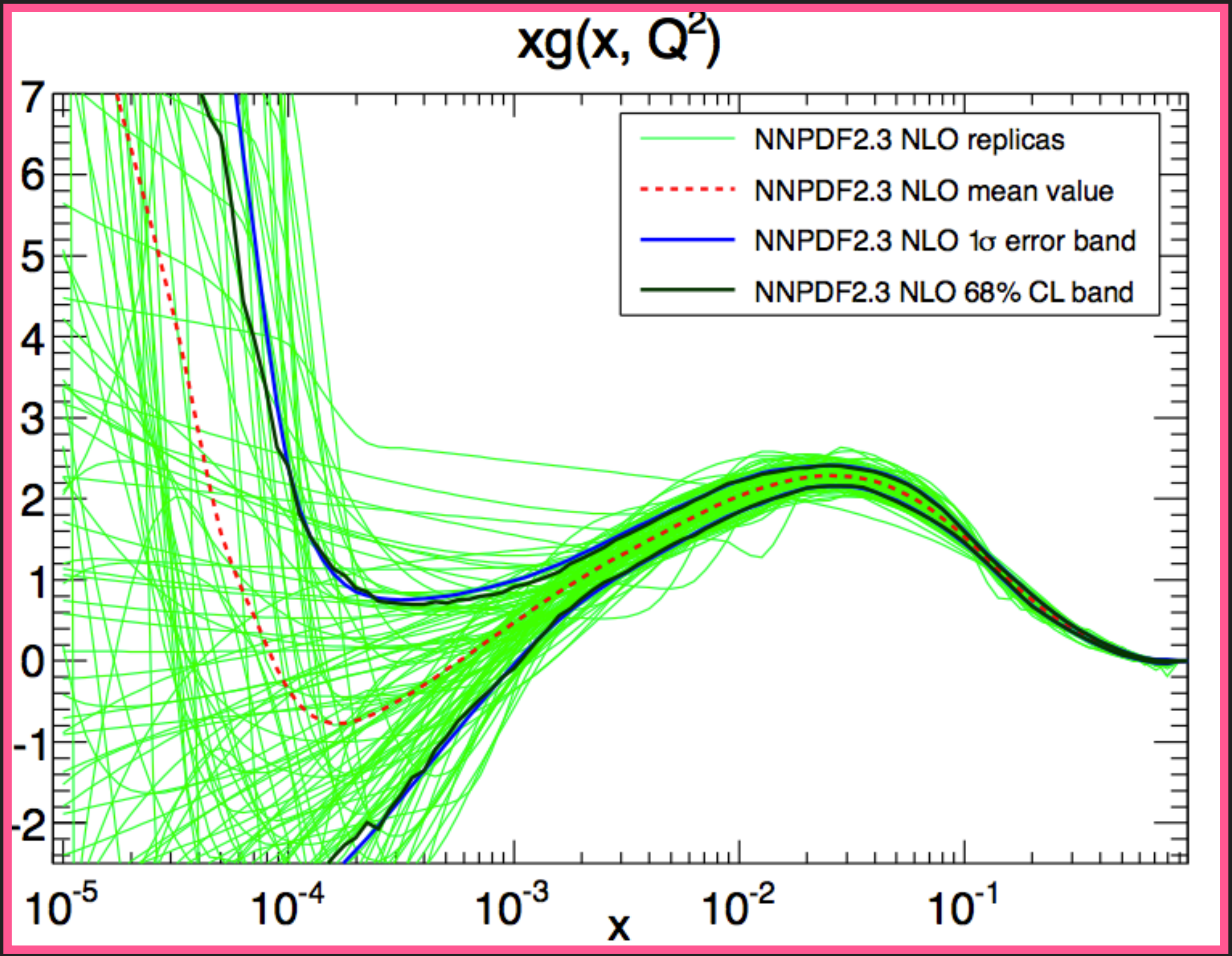
STATS: MONTE CARLO APPROACH



NNPDF collaboration

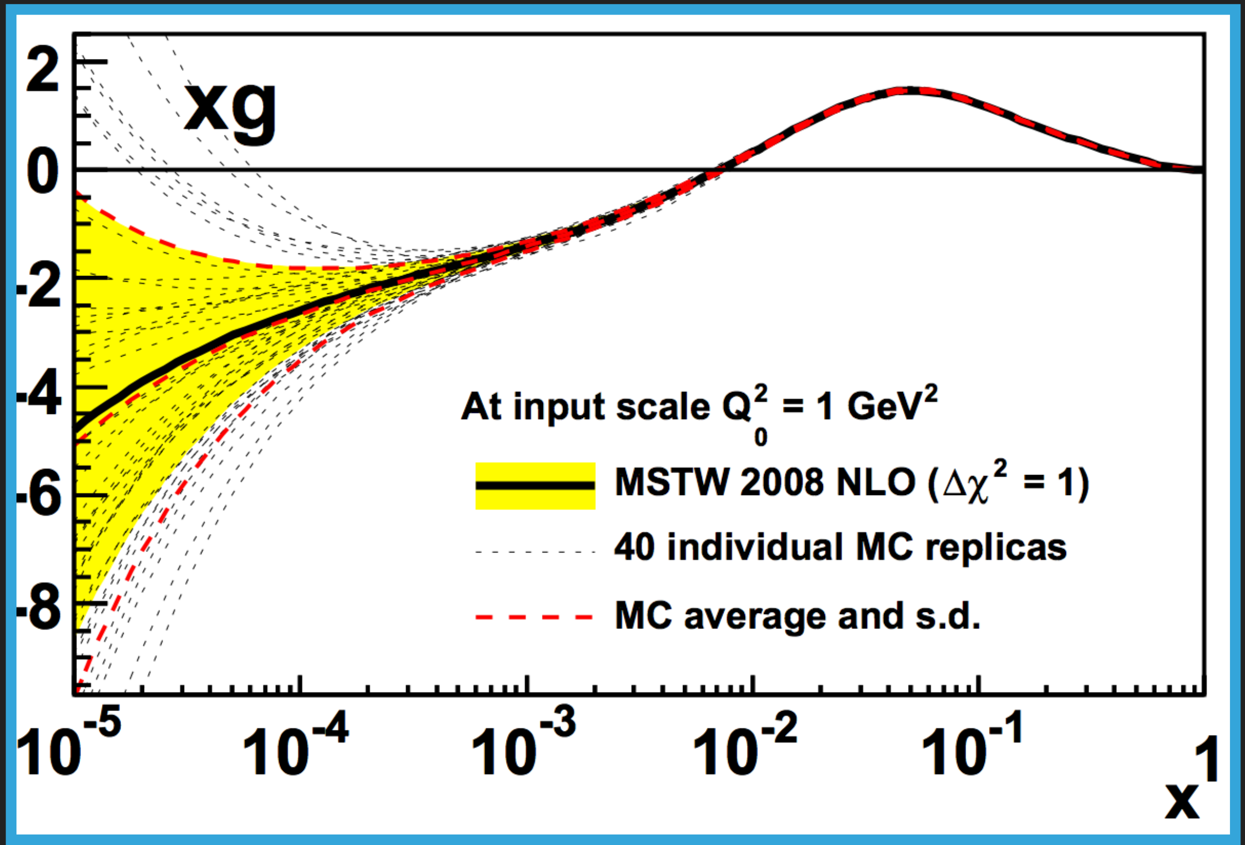
- Monte Carlo techniques: sampling the probability measure in PDF functional space from data

$$\langle \mathcal{O}[\{f\}] \rangle = \frac{1}{N} \sum_{k=1}^{N} \mathcal{O}[f_k]$$

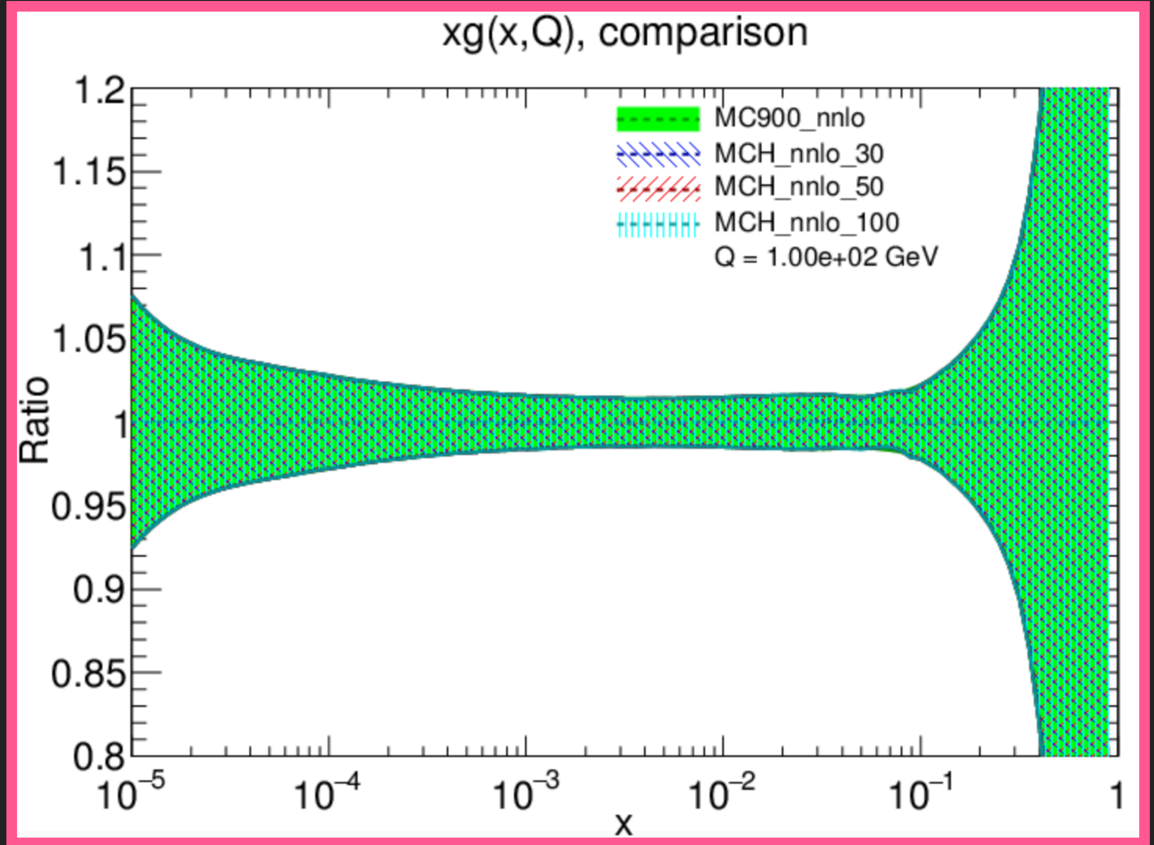
- Neural Networks: all independent PDFs are associated to an unbiased and flexible parametrization: O(300) parameters versus O(30) in polynomial parametrization

MONTE CARLO <=> HESSIAN

- Great progress in cross-talk between Hessian and MC approaches to propagate experimental data error into PDF error bands
- Hessian => Monte Carlo by generate multi-gaussian replicas in parameter space
- Monte Carlo => Hessian by sampling replicas f(x) at discrete sets of points and contract covariance matrix

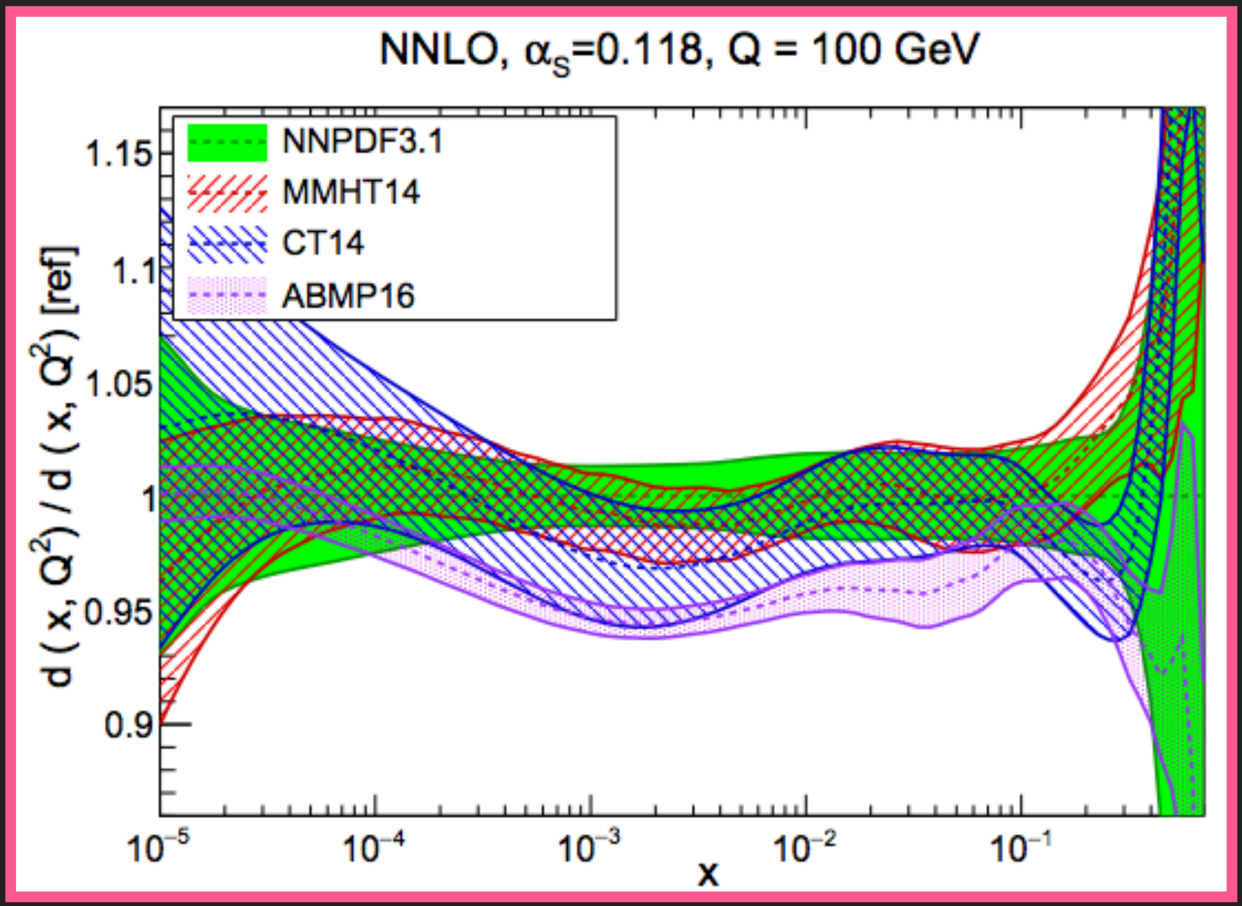


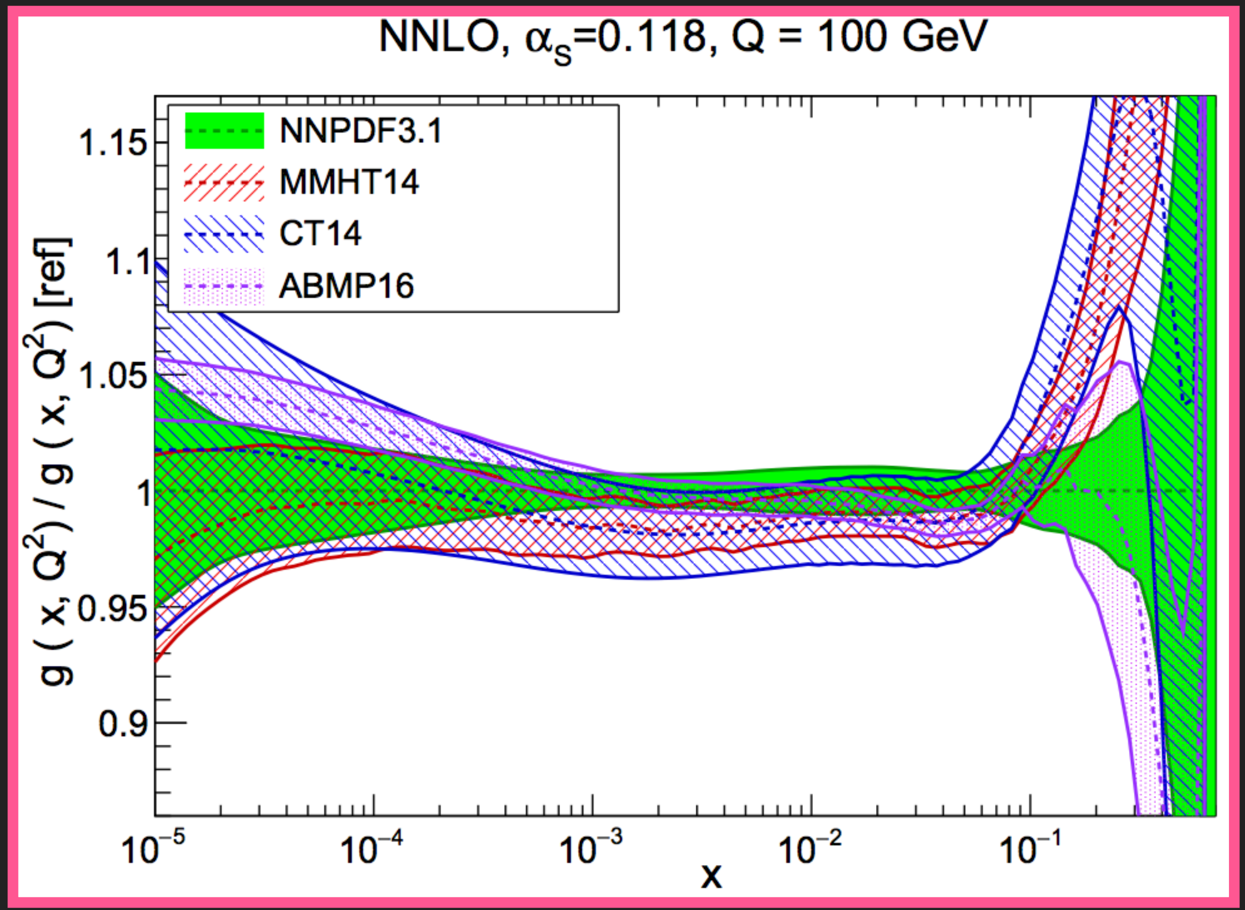
Watt, Thorne, JHEP 08 (2012)



Butterworth et al, J.Phys. G43 (2016)

STATE-OF-THE-ART PDFS





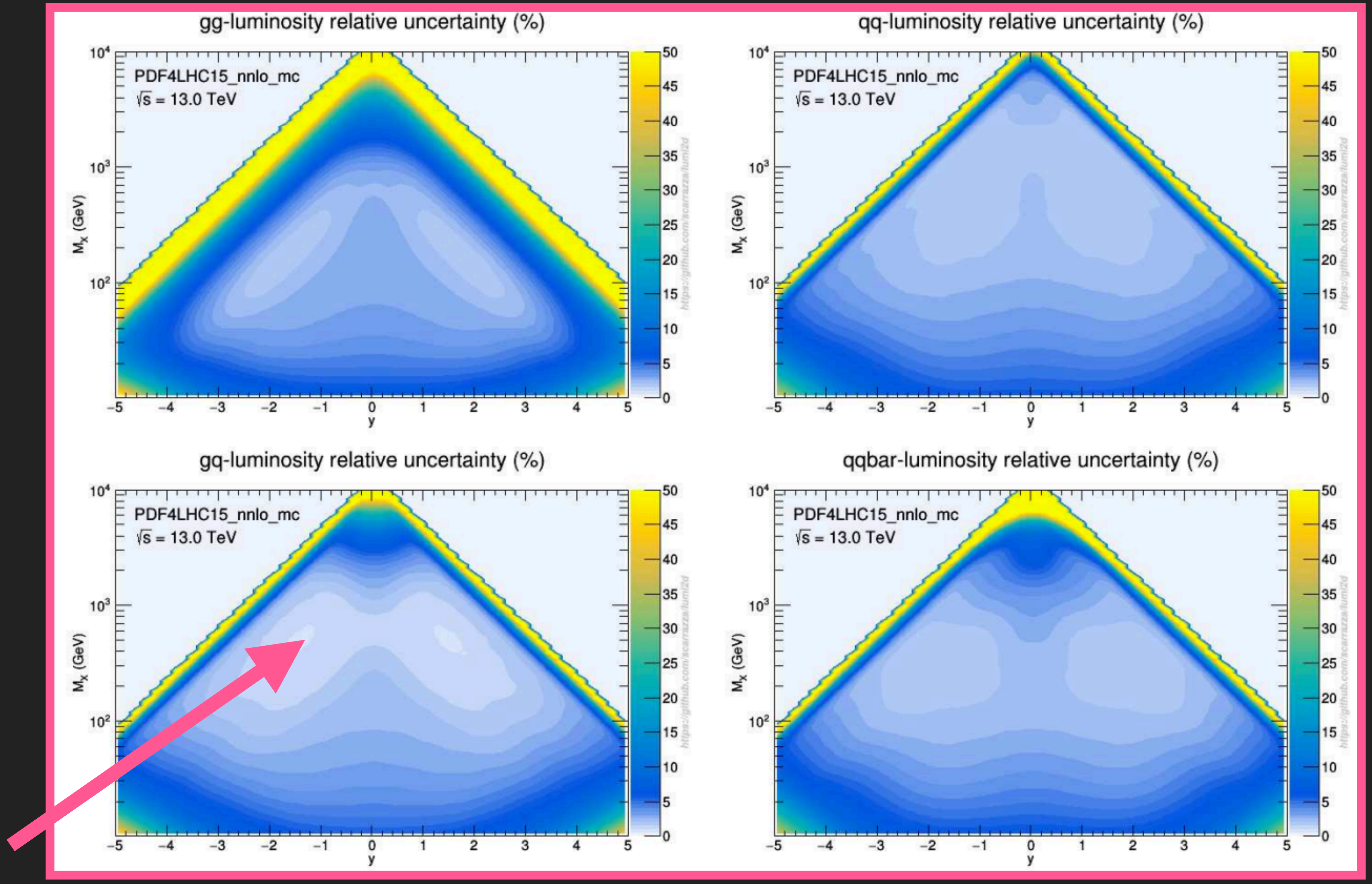
J.Gao et al, Phys.Rept. 742 (2018)

- Pretty good agreement for gluon PDF
- Some differences in quark PDFs, especially down and strangeness
- How to improve?
  - ➡ Closure test to test methodology (!)
  - ➡ Data
  - ➡ Theory (K-factors and MC integration error…)

PART III

NEW FRONTIERS

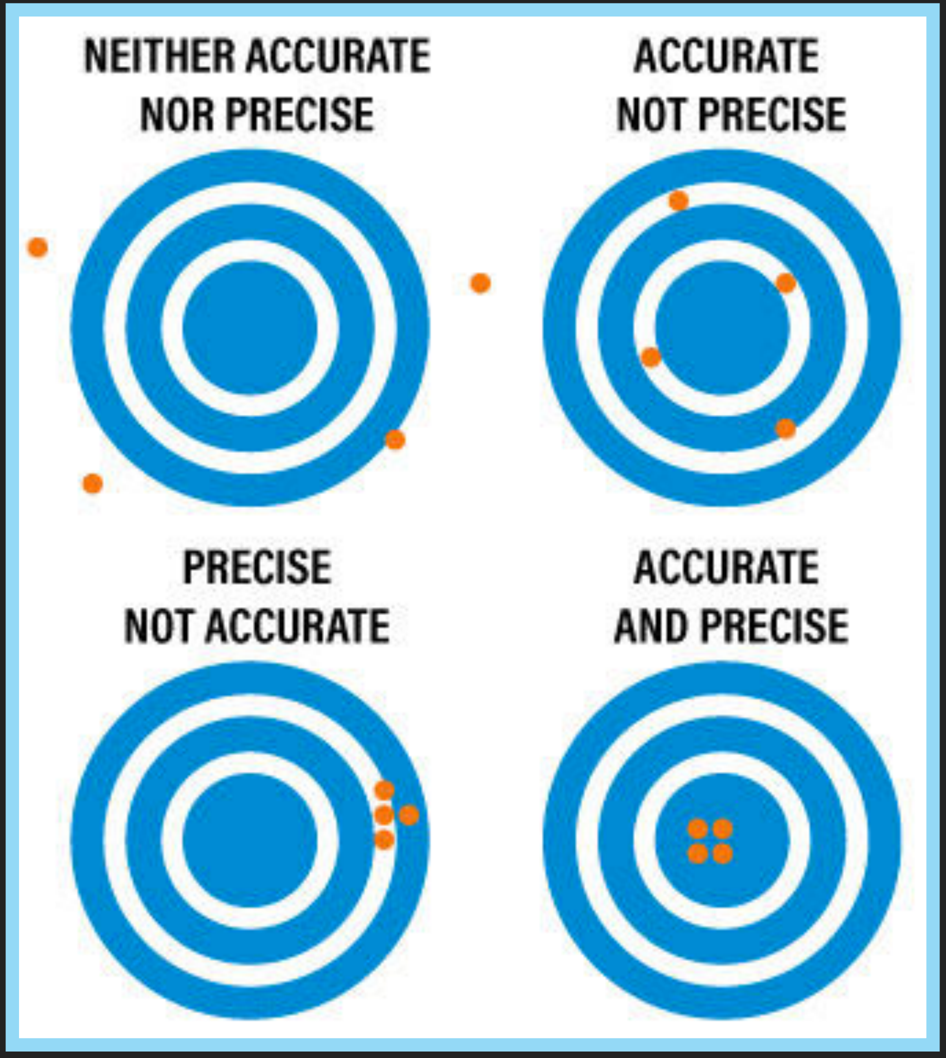
PDF UNCERTAINTIES

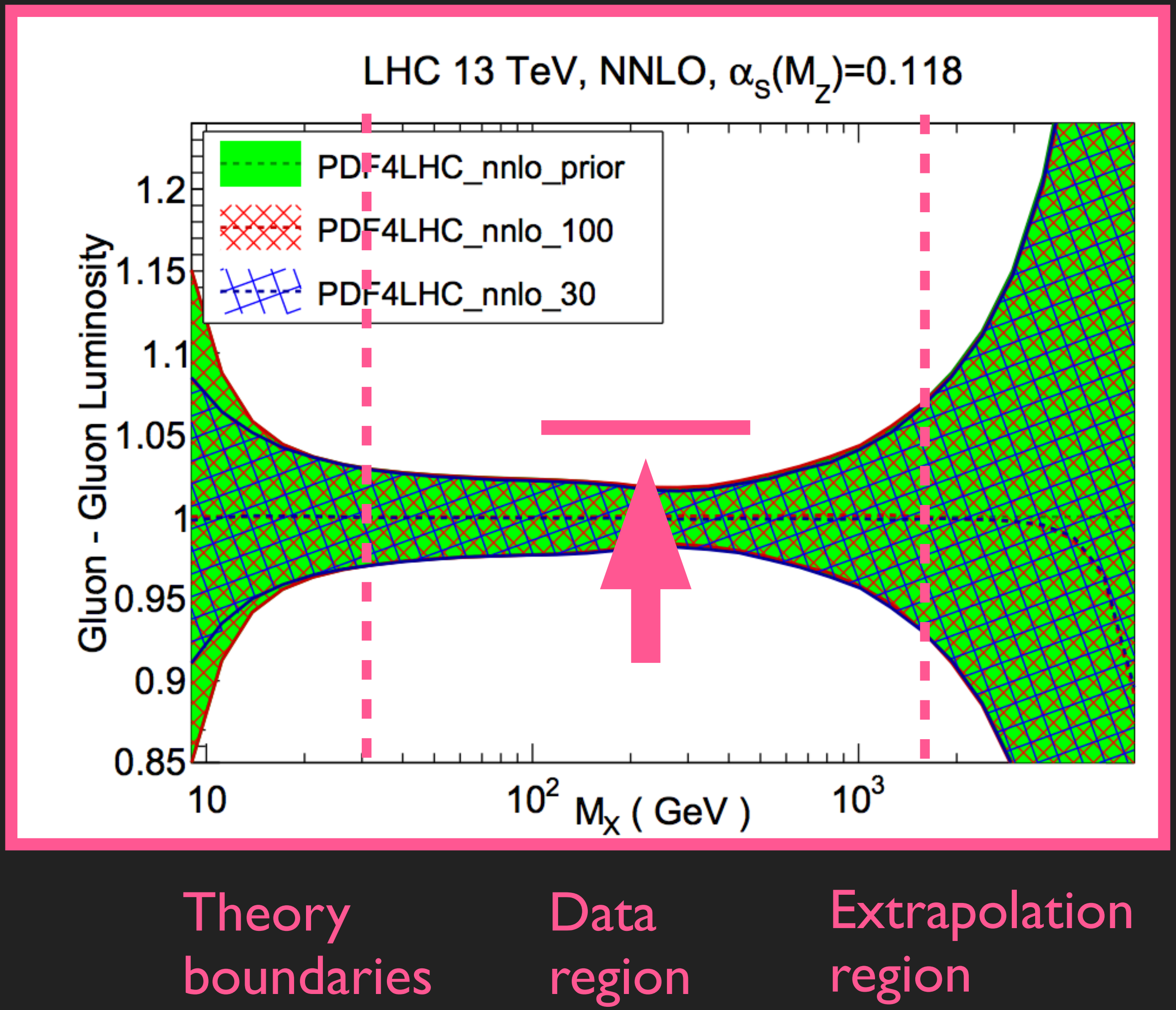


Can we trust 1% accuracy?

THEORY UNCERTAINTIES

In updated PDF analysis, shift between old and new set may be larger than PDF uncertainties

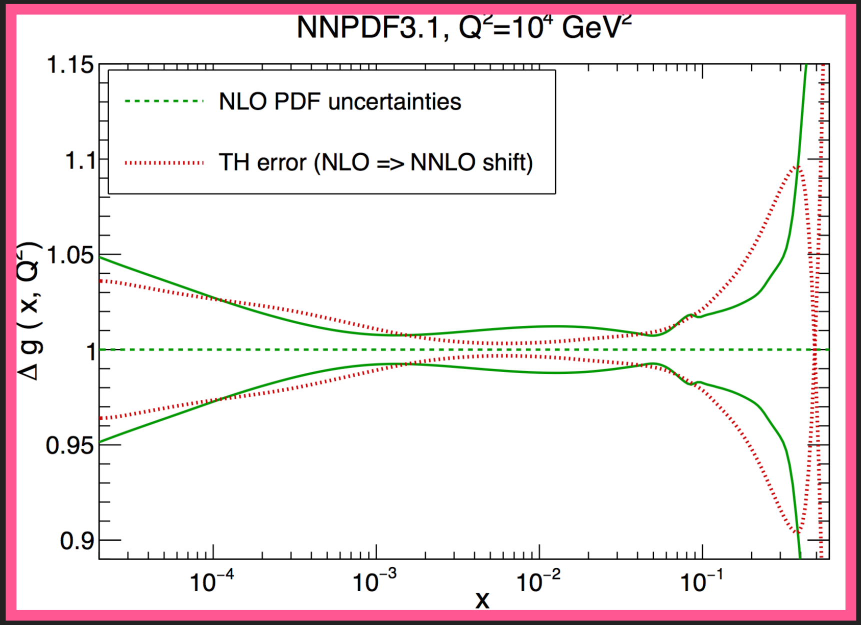




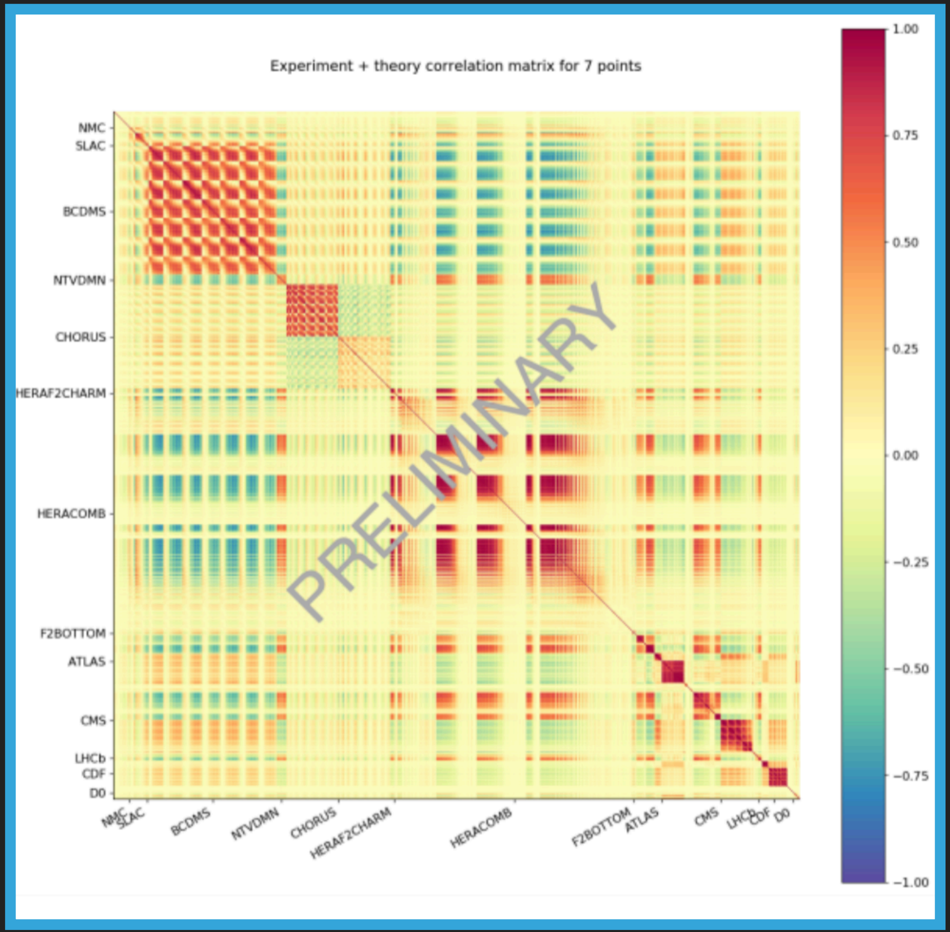
- Inconsistent data → Tolerance/ Statistical estimators
- **Changes in theory?**
- Updated parametrization
- Differences in fitting methodology/minimisation? → Closure Test

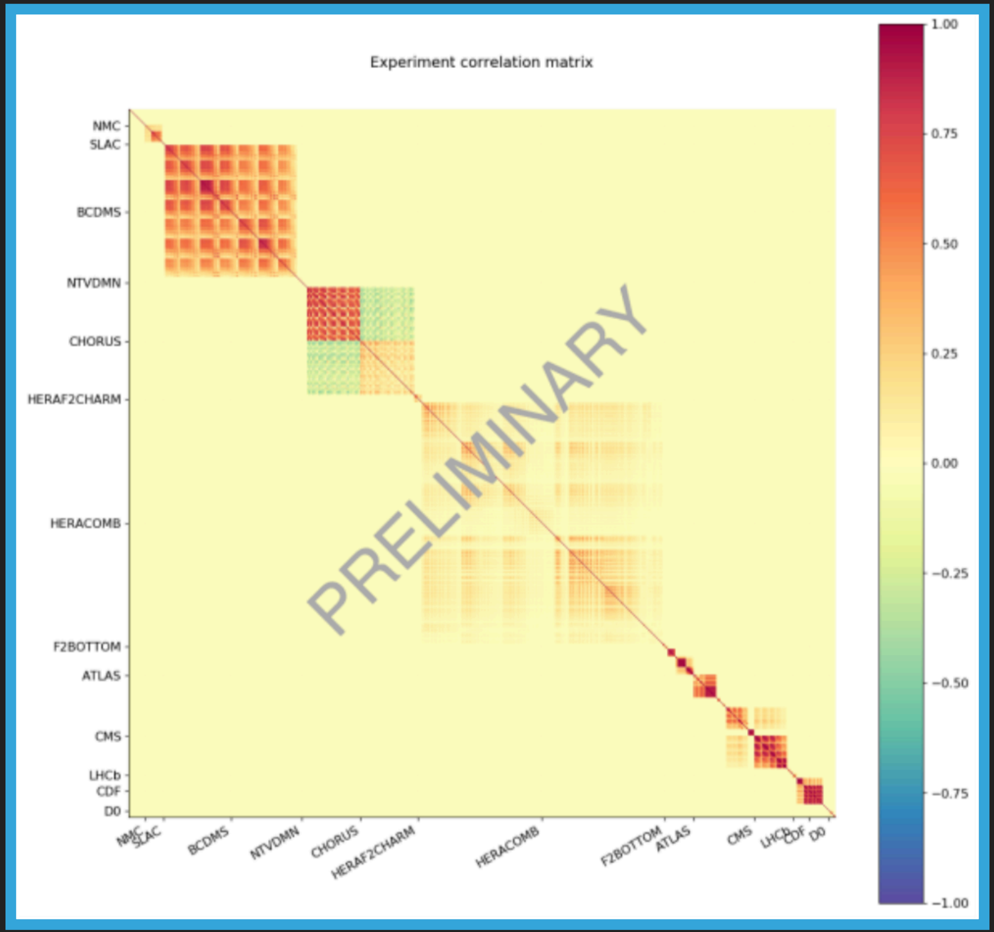
THEORY UNCERTAINTIES

- PDF fits performed at given perturbative order
- PDF uncertainties only reflect lack of information from data
- How to estimate MHOU in PDF fits?
- Idea: build theory covariance matrix
- Add it to experimental one **[NNPDF collaboration in progress]**



Ball et al, EPJC 77 (2017)

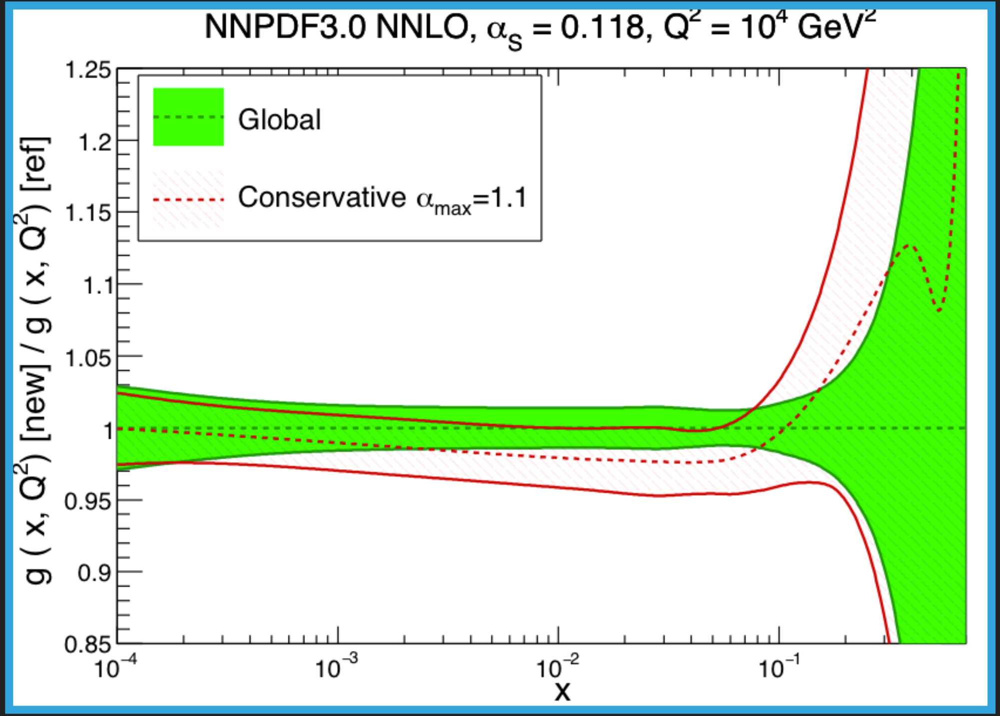


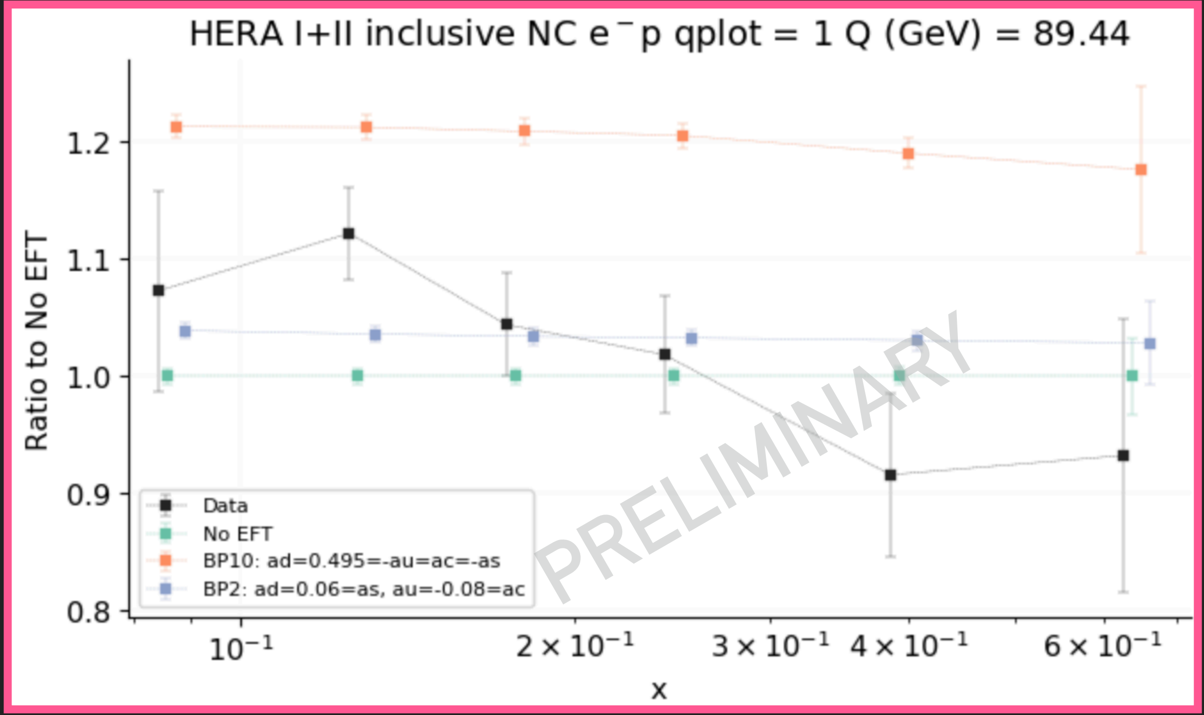


C. Voisey, QCD18

NEW PHYSICS AND PDFS

- Q: As more data at higher energy will be released, how can we make sure that we will not absorb new physics in the PDFs?
- Inconsistencies between data that enter a global PDF analysis can distort statistical interpretation of PDF uncertainties
- Inconsistency of any individual dataset with the bulk of global fit may suggest its understanding is incomplete
- Conservative partons & studies on impact of EFT operators on PDF fits way forward to systematically include new data





Carrazza, Degrande, Rojo, MU

CONCLUSIONS AND OUTLOOK

[…] Global QCD Analysis of available hard processes critically tests the validity of the PQCD framework, allows the determination of the non-perturbative parton distribution functions, thereby provides the necessary input to calculate and predict most Standard Model and New Physics processes for future, higher, energy interactions. **After two decades of steady progress in this venture, has global QCD analysis of parton distributions reached the End of the Road (as some have proclaimed); or, will the physics challenges of the next generation of colliders usher in the Dawn of a New Era, with fresh ideas and more powerful methodology (as some have promised)? That, is the question.**
Wu-Ki Tung - CERN-TH colloquium 2000

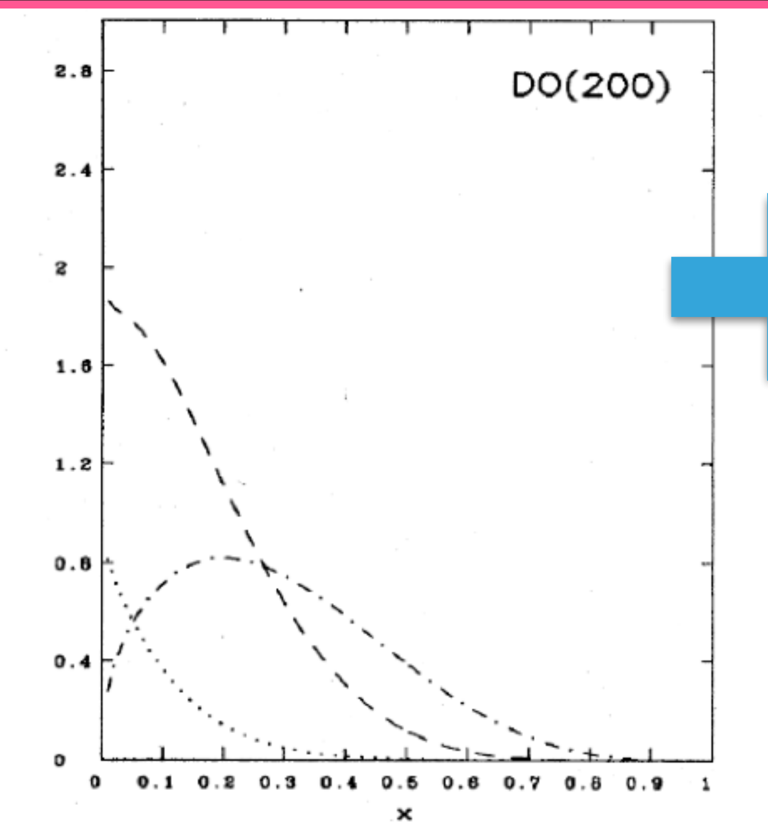
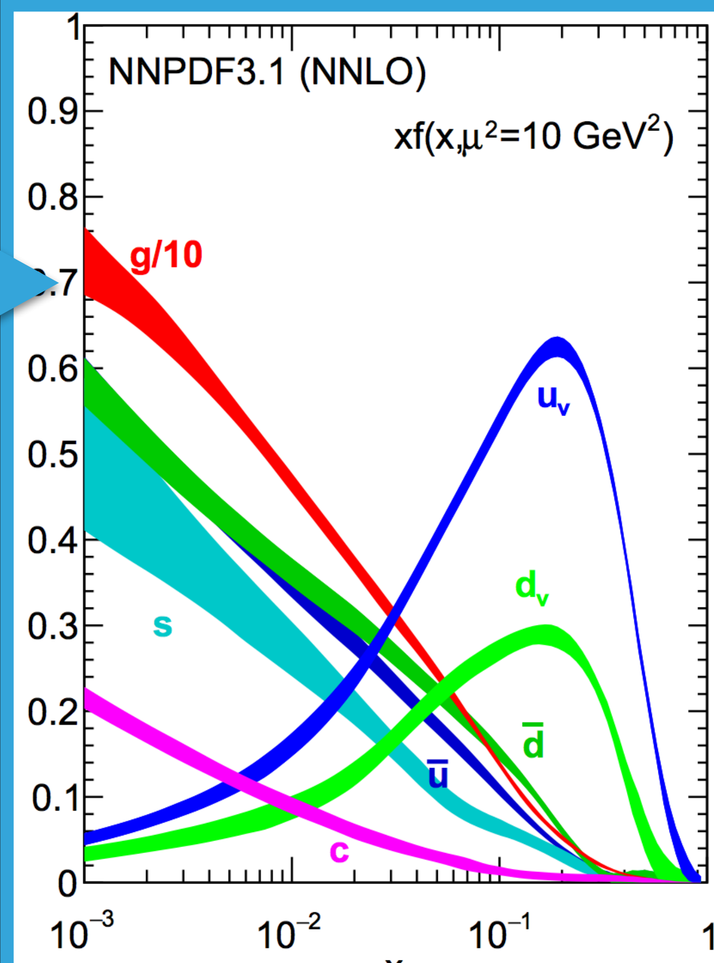


FIG. 27. "Soft-gluon" ($\Lambda = 200$ MeV) parton distributions of Duke and Owens (1984) at $Q^2 = 5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_s(x)$ (dotted line).



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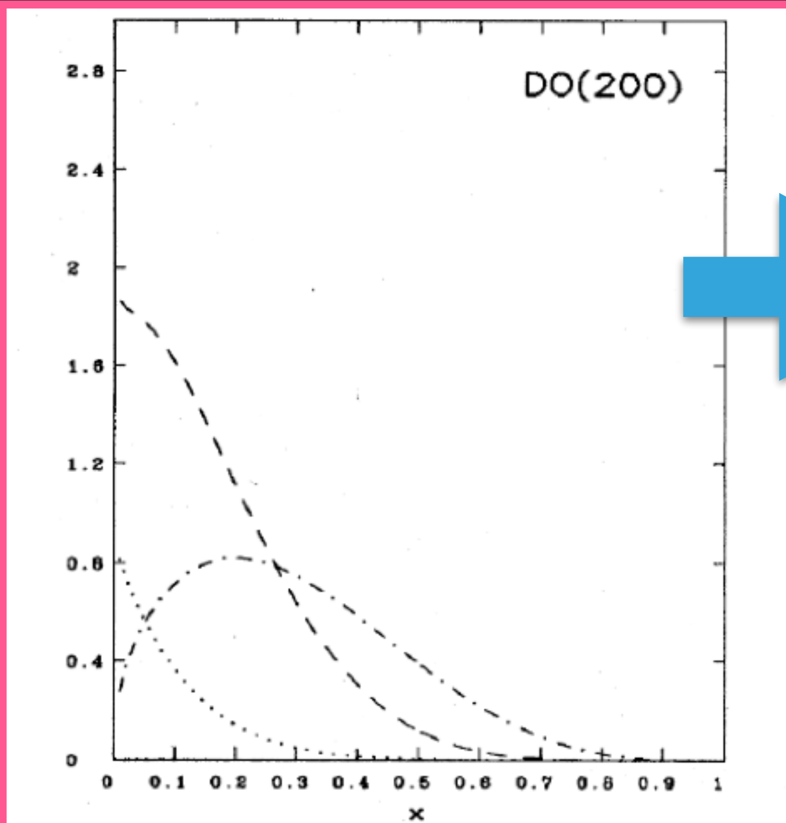

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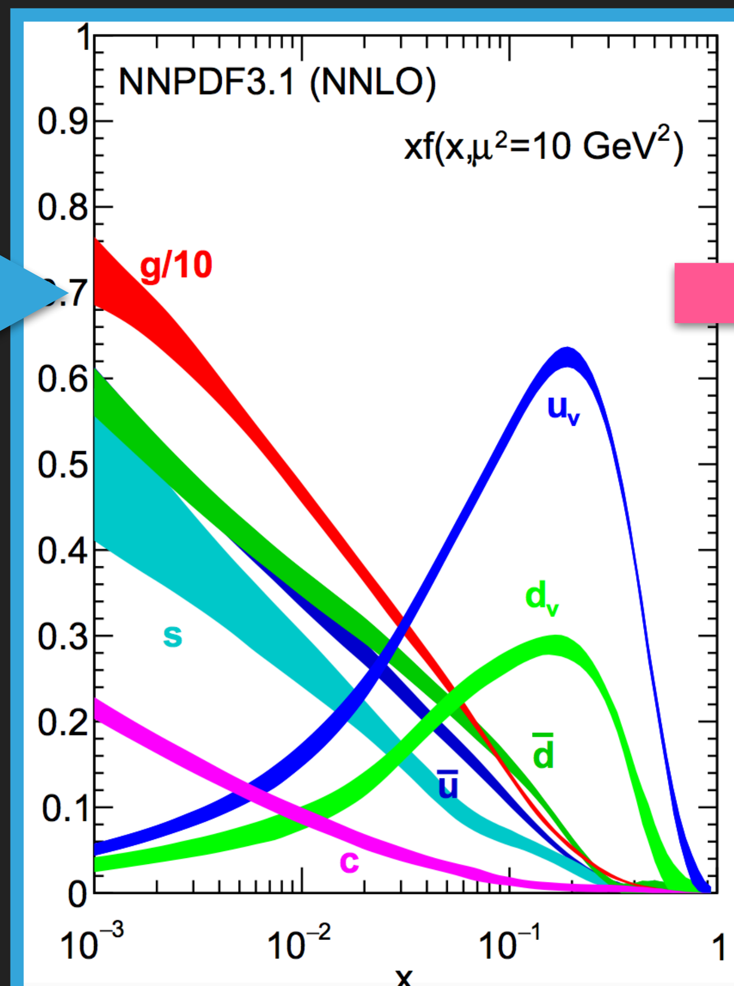
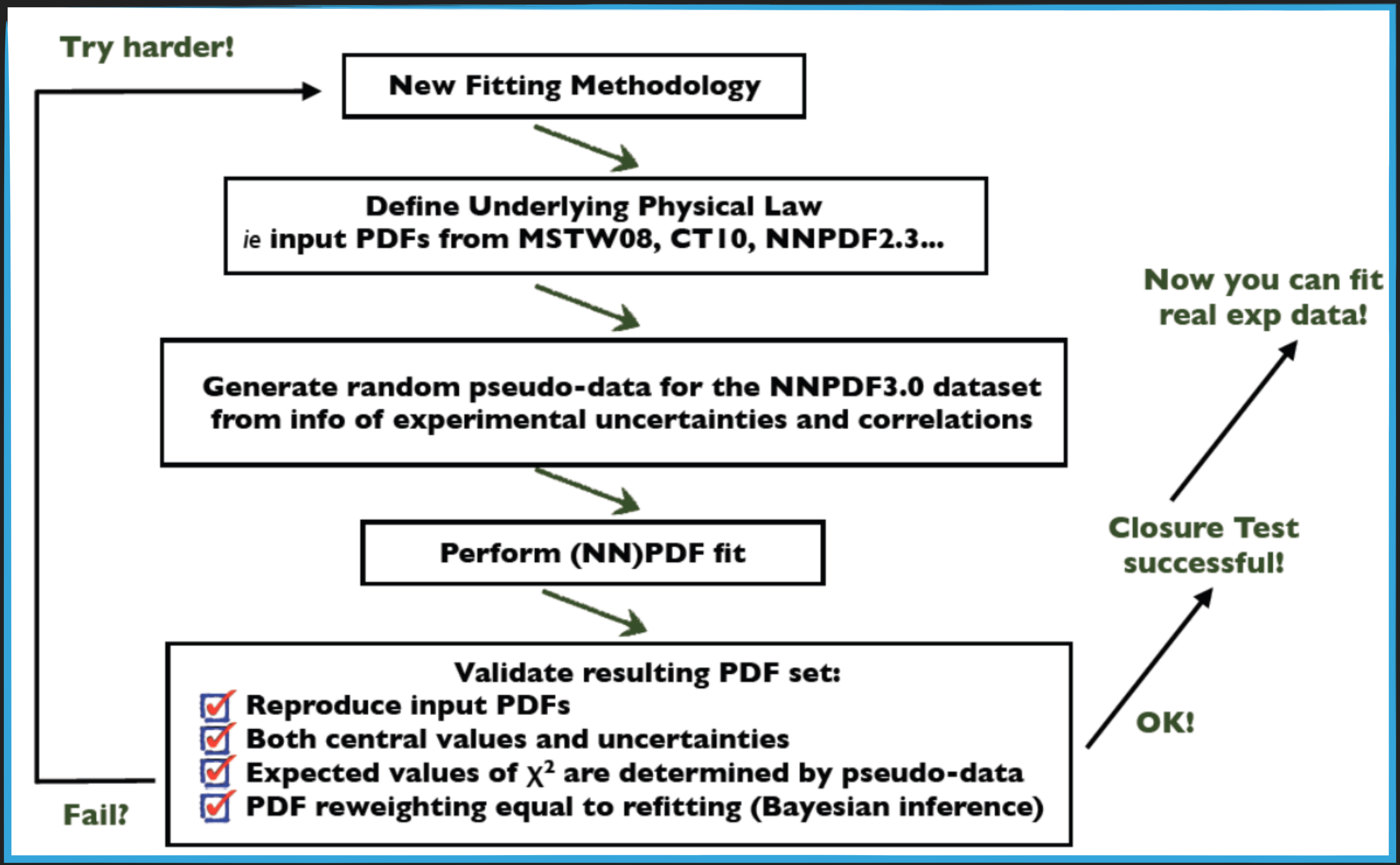


EXTRA MATERIAL

ROBUST STATISTICS: A POWERFUL TEST



THEORY UNCERTAINTIES

- Theory is perturbative expansion to some order : $t_p = \sum_{m=0}^{p} c_m$
- Standard case: $P(d|t_p) \propto \exp\Big(-\frac{1}{2} \underbrace{(d-t_p)^T \mathrm{cov}_{\mathrm{exp}}^{-1} (d-t_p)}_{\chi^2_{\mathrm{exp}}} \Big)$
- Bayes' theorem: $P(t_p|d) = \frac{P(d|t_p)P(t_p)}{P(d)} \propto P(d|t_p)P(t_p)$
- Assume Gaussian theory prior:

$$P(t_p) = \prod_{m=0}^{p} P(c_m) \quad \text{where} \quad P(c_m) \propto \exp\Big(-\frac{1}{2} \underbrace{c_m^T \mathrm{cov}_{\mathrm{th},m}^{-1} c_m}_{\chi^2_{\mathrm{th}}} \Big)$$

- Assume MHOUs due to $\mathcal{O}(\alpha^{p+1})$ terms only → marginalise these terms:

$$P(t_p|d) \propto \int dc_{p+1} P(d|c_{p+1}) P(t_{p+1})$$

$$\propto \exp\Big(-\frac{1}{2} \underbrace{(d-t_p)^T (\mathrm{cov}_{\mathrm{exp}} + \mathrm{cov}_{\mathrm{th}})^{-1} (d-t_p)}_{\chi^2_{\mathrm{tot}}} \Big)$$

- Include higher order terms by induction

C. Voisey, QCD18