Proton Structure for Precision

DIS2026

Royal Society University Research Fellow

University of Manchester

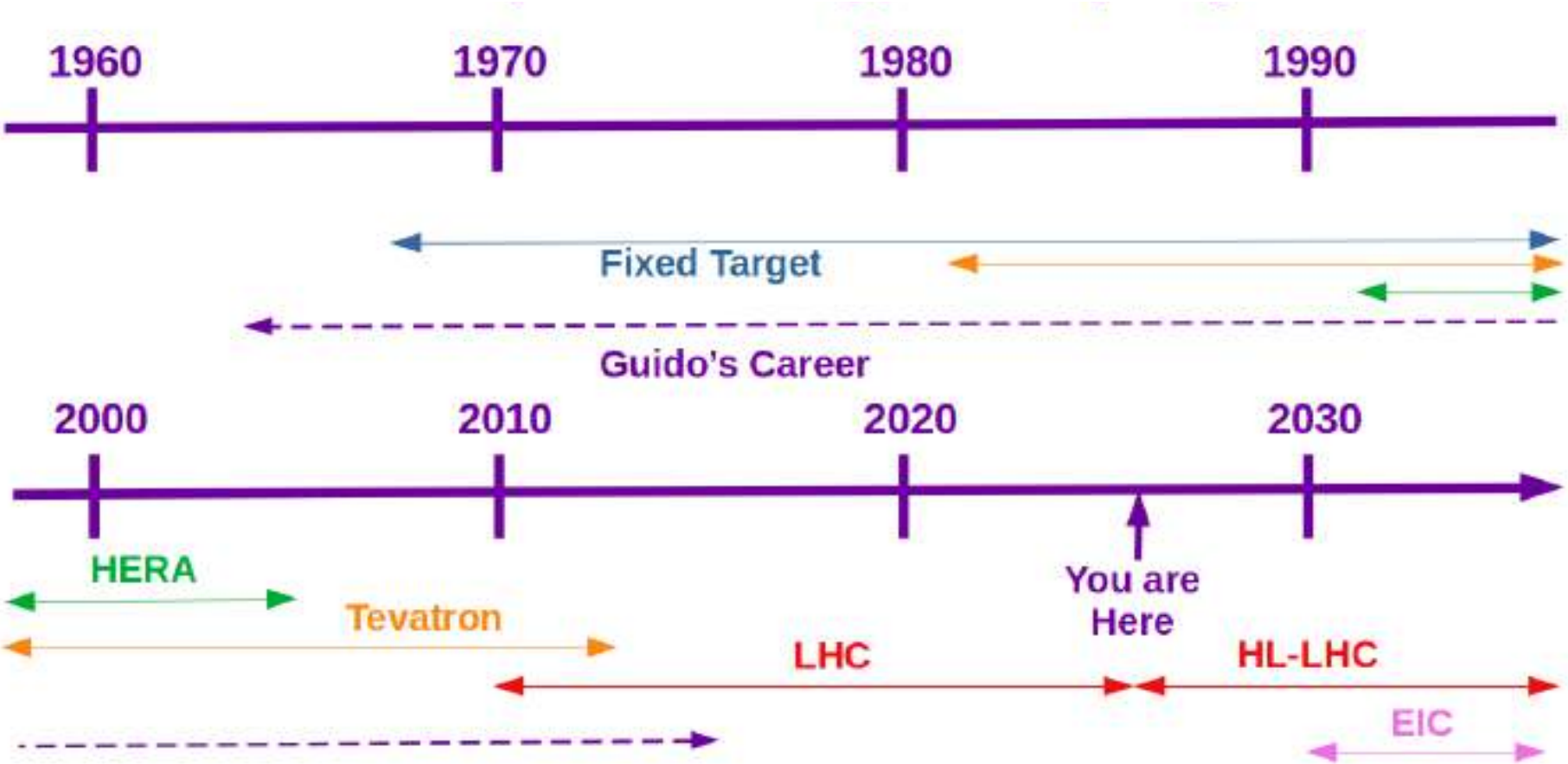
MANCHESTER 1824
The University of Manchester

- Guido Altarelli Award -

8th May 2026

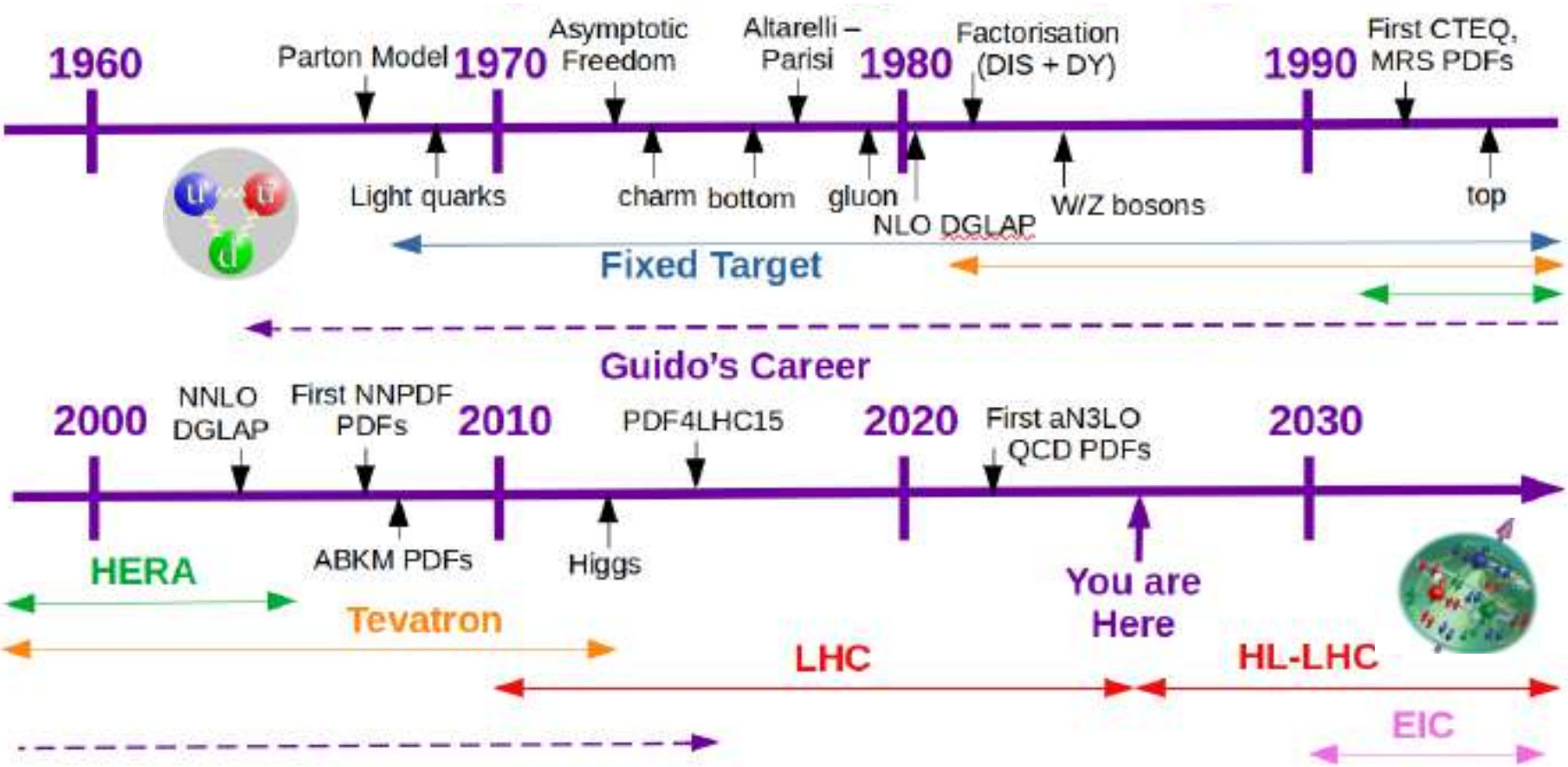
THE ROYAL SOCIETY

Collider Timeline (1960 – Today) – PDF perspective



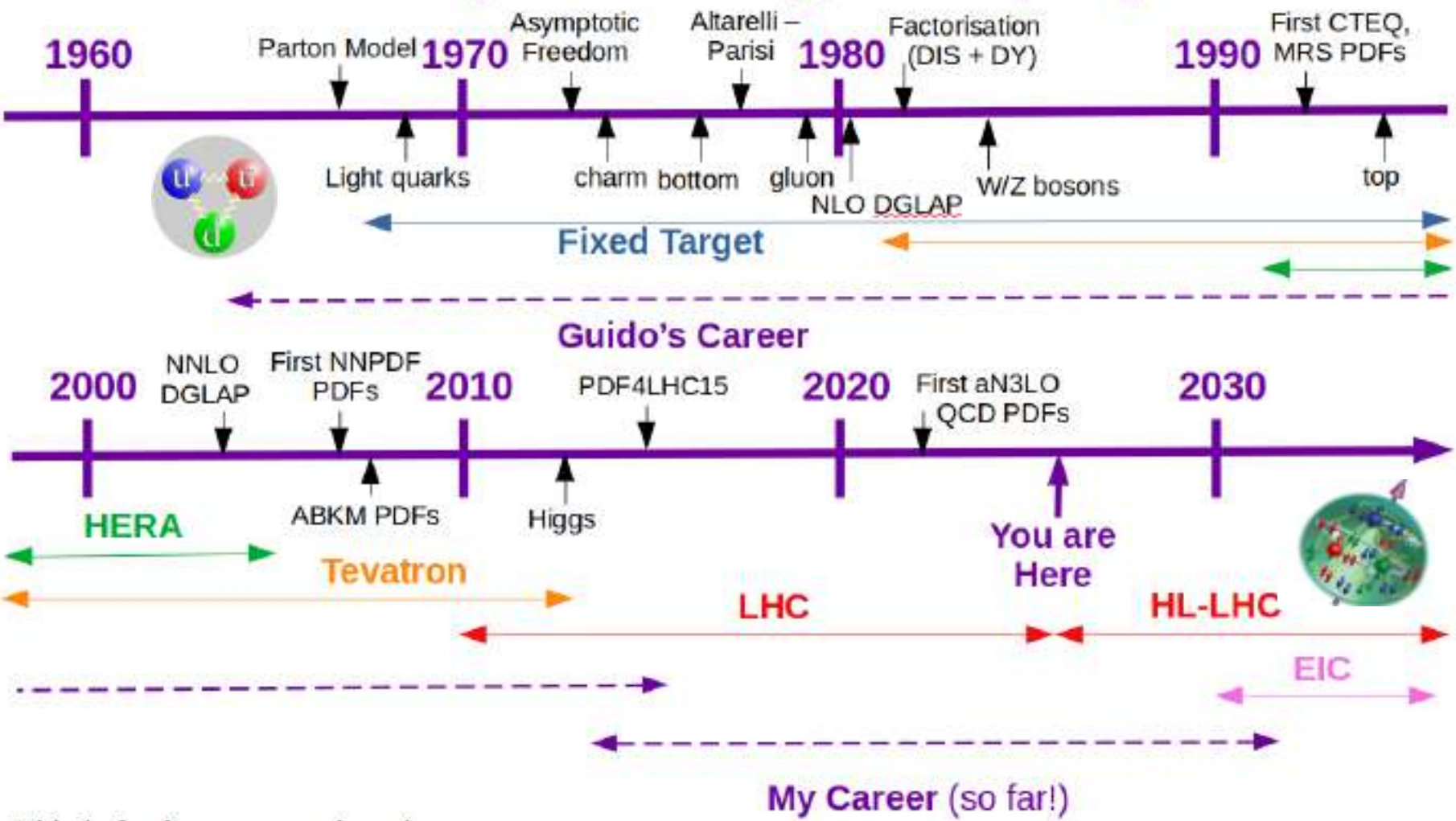
*this is far from comprehensive
+ apologies for any errors!

Collider Timeline (1960 – Today) – PDF perspective



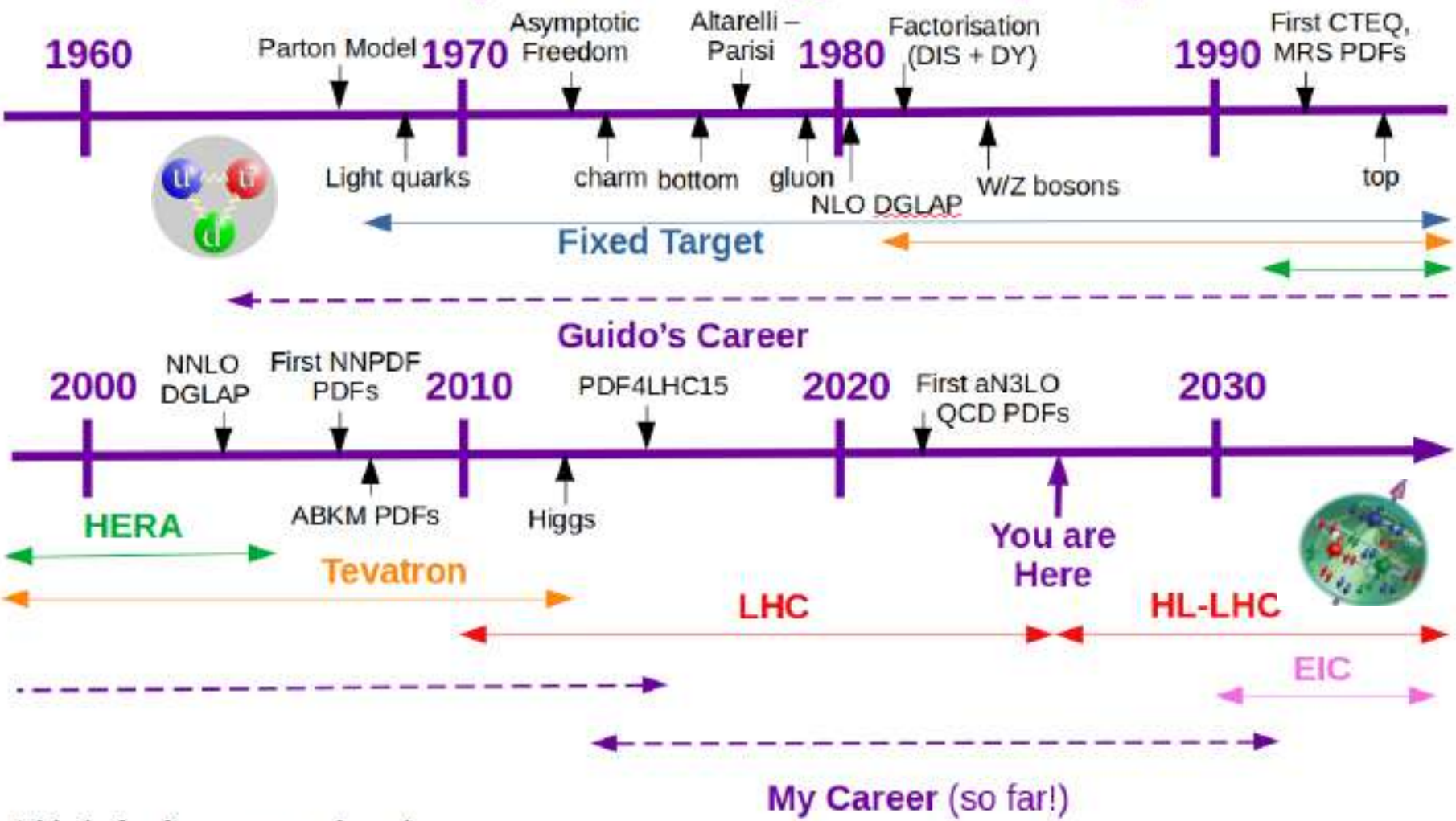
*this is far from comprehensive
+ apologies for any errors!

Collider Timeline (1960 – Today) – PDF perspective



*this is far from comprehensive
+ apologies for any errors!

Collider Timeline (1960 – Today) – PDF perspective



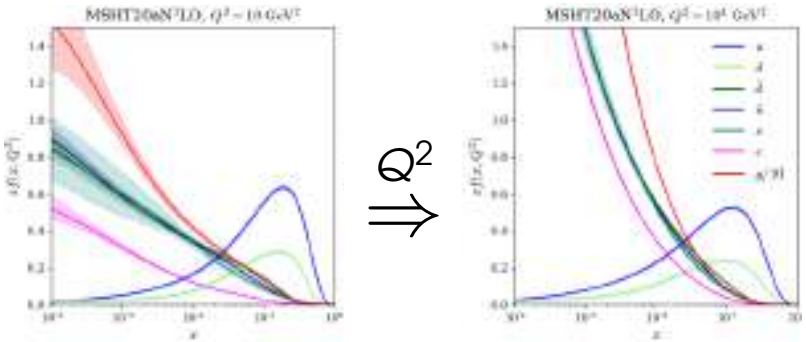
*this is far from comprehensive
+ apologies for any errors!

$\Rightarrow$ *My "Altarelli Number" is 2*

Altarelli's Research and Legacy

- DGLAP evolution - foundation of PDF determination and PDF universality.

$$\frac{\partial f_a(x,Q^2)}{\partial \ln Q^2} = \sum_b \left(P_{ab} \otimes f_b\right)(x,Q^2)$$



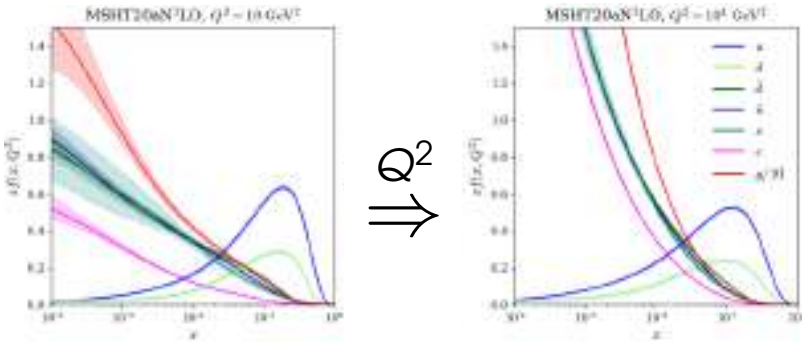
Altarelli's Research and Legacy

"A leading figure of modern particle physics who contributed to almost all the relevant aspects of the Standard Theory."

Maiani and Martinelli, (2018)

- DGLAP evolution - foundation of PDF determination and PDF universality.

$$\frac{\partial f_a(x,Q^2)}{\partial \ln Q^2} = \sum_b \left(P_{ab} \otimes f_b\right)(x,Q^2)$$



- Drell-Yan production - continues to be a key precision channel for understanding SM.
- Standard Model Parameters - α_S, EW.
- Small-x resummation.
- PDF positivity, polarised PDFs, etc

Altarelli's Research and Legacy

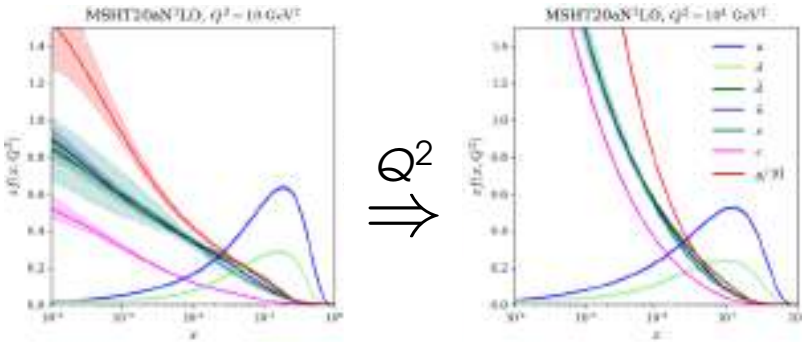
"A leading figure of modern particle physics who contributed to almost all the relevant aspects of the Standard Theory."

Maiani and Martinelli, (2018)

"Guido Altarelli was one of the central figures in establishing modern QCD as the correct theory of the strong force." AI...

- DGLAP evolution - foundation of PDF determination and PDF universality.

$$\frac{\partial f_a(x,Q^2)}{\partial \ln Q^2} = \sum_b \left(P_{ab} \otimes f_b\right)(x,Q^2)$$



- Drell-Yan production - continues to be a key precision channel for understanding SM.
- Standard Model Parameters - α_S, EW.
- Small-x resummation.
- PDF positivity, polarised PDFs, etc

Altarelli's Research and Legacy

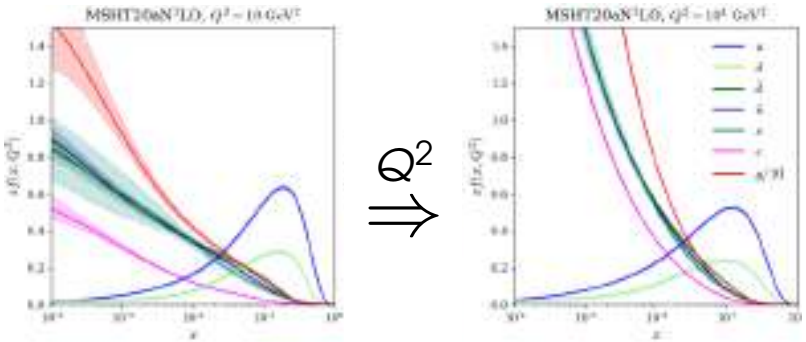
"A leading figure of modern particle physics who contributed to almost all the relevant aspects of the Standard Theory."

Maiani and Martinelli, (2018)

"Guido Altarelli was one of the central figures in establishing modern QCD as the correct theory of the strong force." AI...

- DGLAP evolution - foundation of PDF determination and PDF universality.

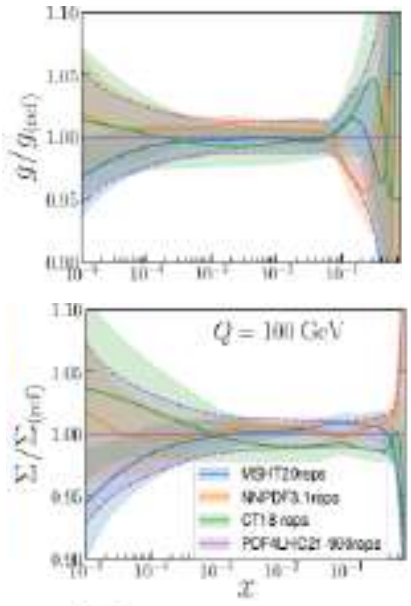
$$\frac{\partial f_a(x,Q^2)}{\partial \ln Q^2} = \sum_b \left(P_{ab} \otimes f_b\right)(x,Q^2)$$



- Drell-Yan production - continues to be a key precision channel for understanding SM.
- Standard Model Parameters - α_S, EW.
- Small-x resummation.
- PDF positivity, polarised PDFs, etc

▶ We are still trying to understand many of these aspects of QCD and the Standard Model and their consequences today.

Modern Global PDFs:

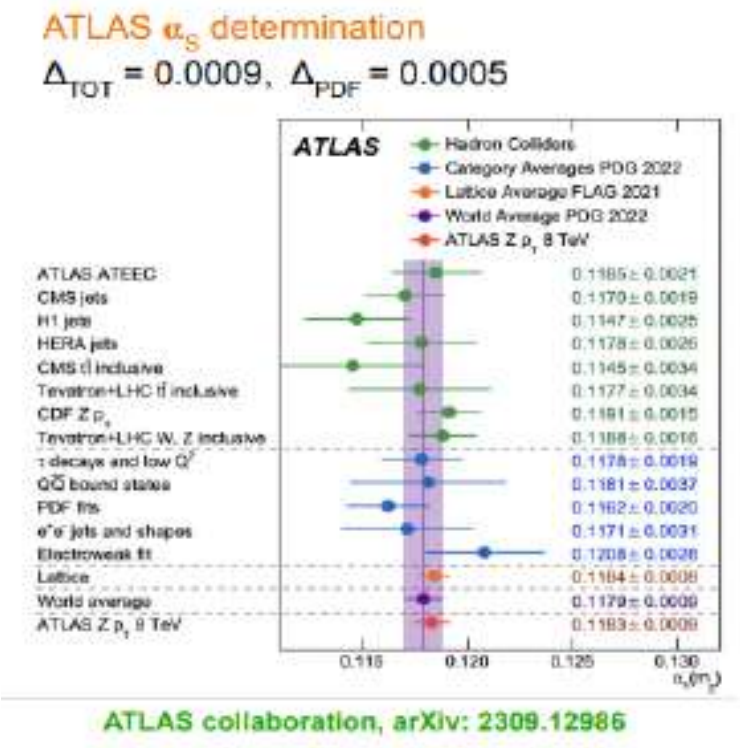


- We have come a long way, now we have PDFs at Approximate N3LO in QCD + NLO in QED/EW.
- Approaching $\mathcal{O}(\%)$ precision in key regions.
- Fundamental to LHC/collider physics programme.

PDFs for the LHC - Precision:

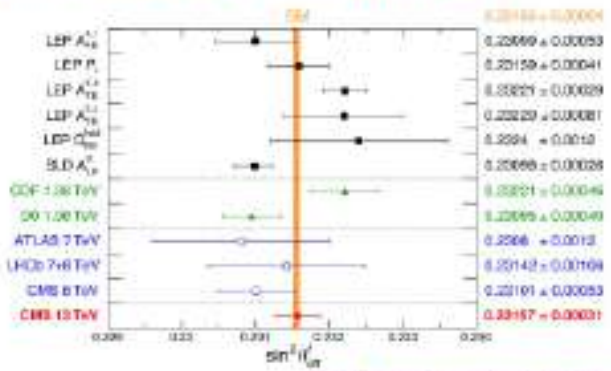
- PDFs are a key input and output of many calculations/measurements.
- Moreover, they are often a dominant contribution to the uncertainty.
- In era of *precision LHC physics*, we need precise and accurate PDFs.

1. Precision EW:



ATLAS collaboration, arXiv: 2309.12986

CMS collaboration, arXiv: 2412.13872



CMS $\sin^2\theta_W$ determination

Δ_{TOT} = 31 x 10^{-4}

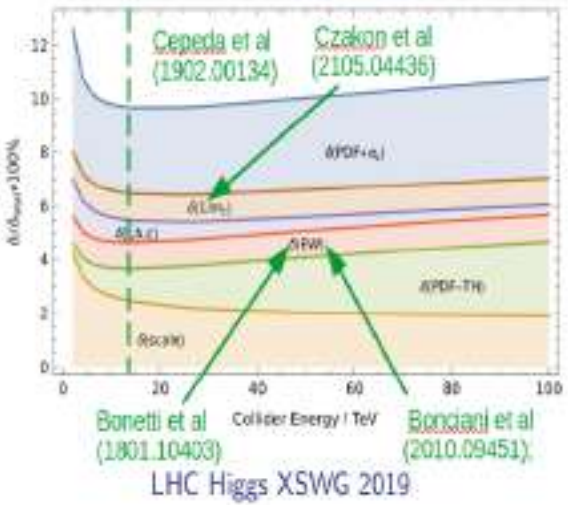
Δ_{PDF} = 27 x 10^{-4}

CMS collaboration, arXiv: 2408.07622

PDFs for the LHC - Precision:

- PDFs are a key input and output of many calculations/measurements.
- Moreover, they are often a dominant contribution to the uncertainty.
- In era of *precision LHC physics*, we need precise and accurate PDFs.

2. Higgs:



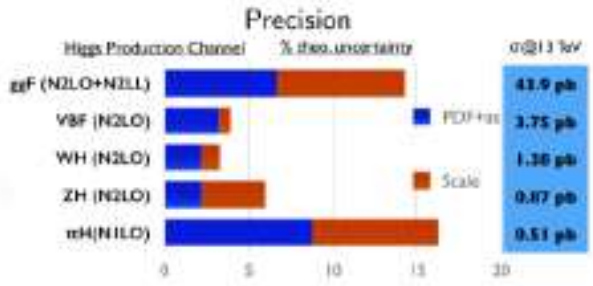
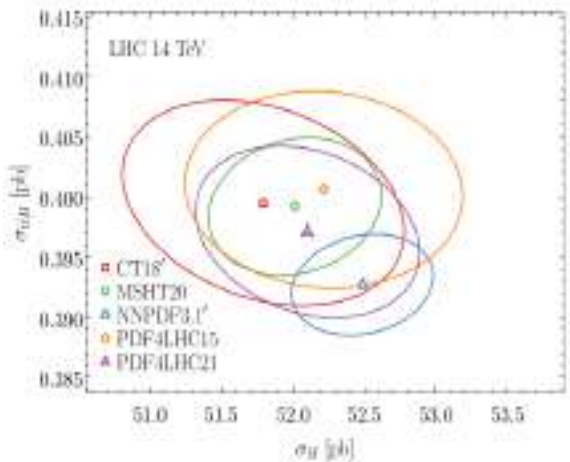


Image: E. Nocera

Often $\delta_{\rm PDF} \sim \frac{1}{2}\delta_{\rm tot}$

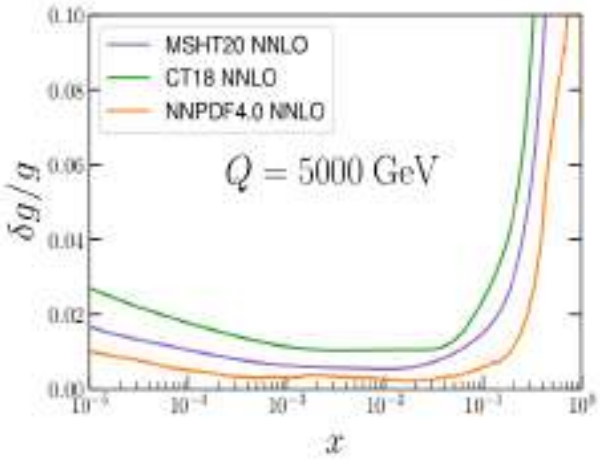


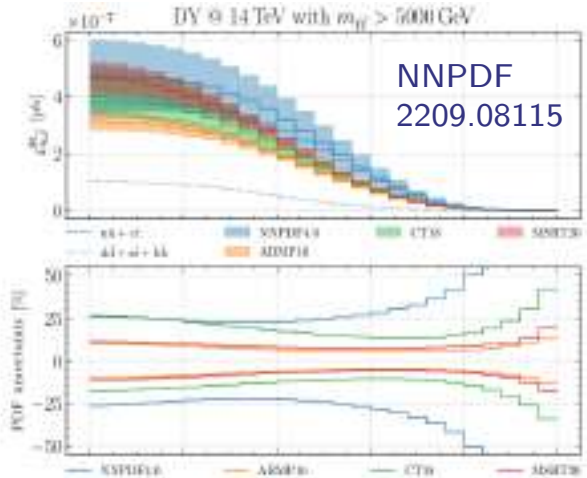
PDF4LHC21: 2203.05506

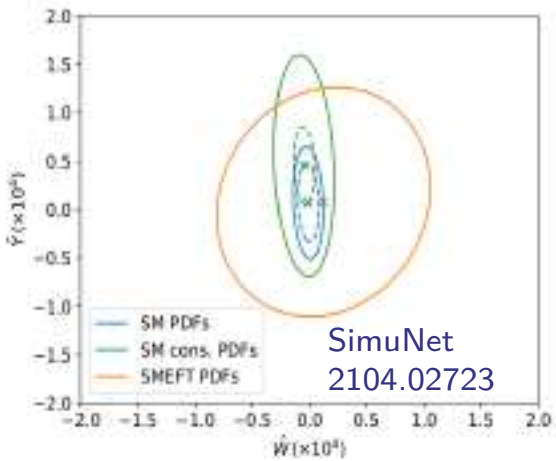
PDFs for the LHC - Discovery:

- PDFs are a key input and output of many calculations/measurements.
- Moreover, they are often a dominant contribution to the uncertainty.
- In era of *precision LHC physics*, we need precise and accurate PDFs.

3. BSM:







If looking in high energy tails for new BSM effects, PDFs limit sensitivity - (left) for dijet searches the gluon PDF uncertainty blows up, (right) for DY AFB the PDF uncertainty grows.

Or if looking for small deviations from SM, need precise PDFs to separate out new physics.

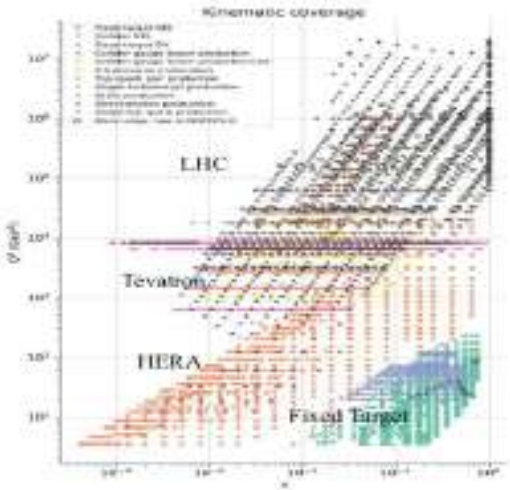
Global PDF Determination:

Talk by: Cruz-Martinez

$$\sigma = \sum_{ij} \int dx_1 dx_2 f_{i/p}(x_1, Q^2) f_{j/p}(x_2, Q^2) \hat{\sigma}(x_1 x_2 s)$$

1) Experiment

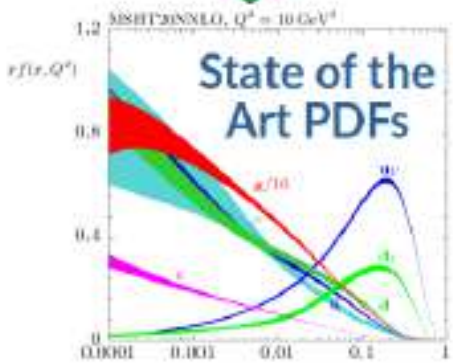
- Latest experimental data
- Fixed target, collider DIS, Tevatron, LHC, etc
- EW boson, jets, top, ...
- Large range in x, Q^2



2) Methodology

- Parameterise at low scale
- DGLAP, flavour schemes, ...
- Minimisation of χ^2
- Uncertainty prescription

Global PDF fit



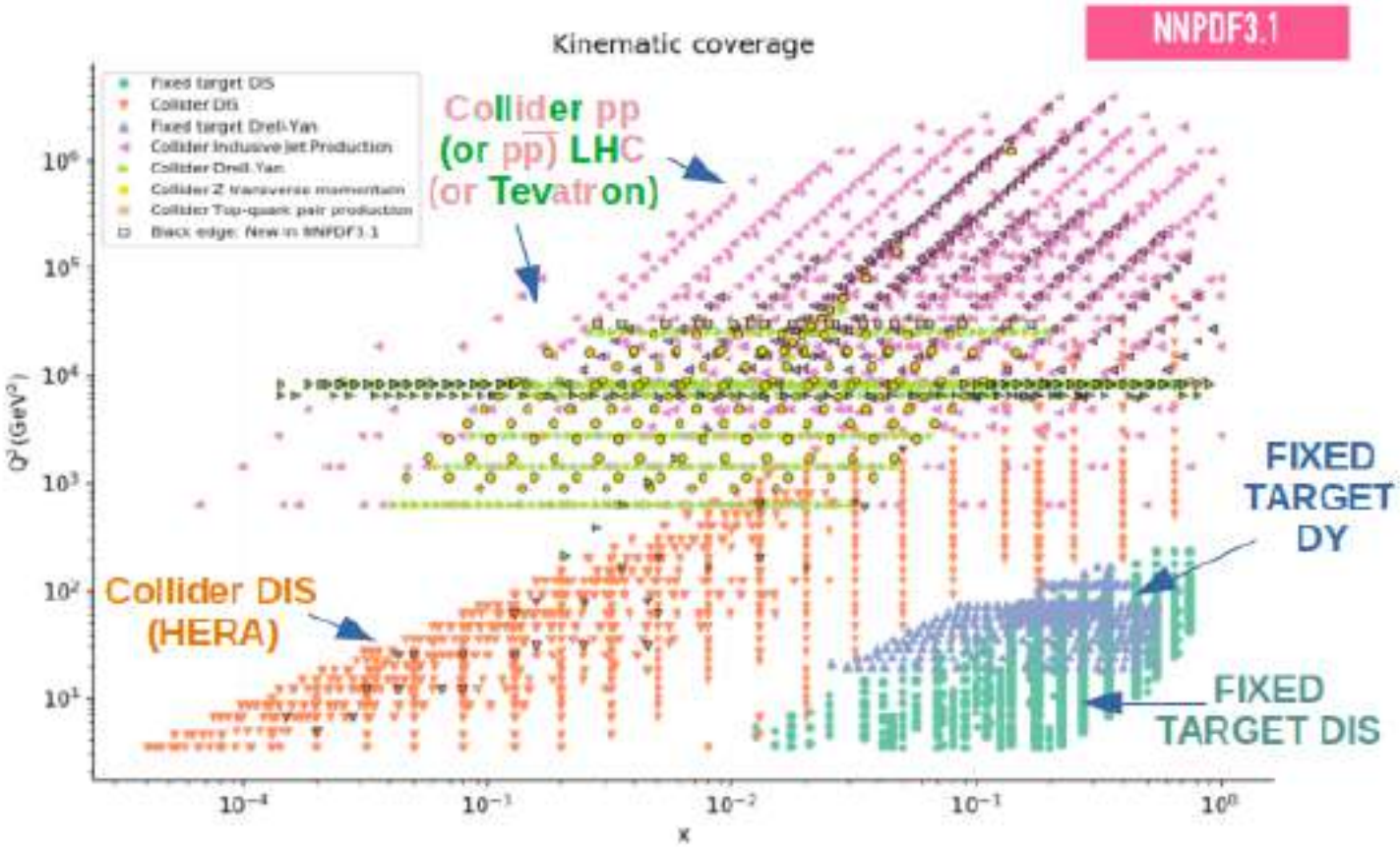
3) Theory

- Most precise theoretical calculations available – usually grids + k-factors
- NNLO QCD + NLO EW standard
- Approximate N3LO + theory uncertainties available

- Combine latest experimental data and cutting-edge theory calculations to produce state of the art PDFs.
- Rely on effort of experimental and theoretical communities.

Global PDF - Data:

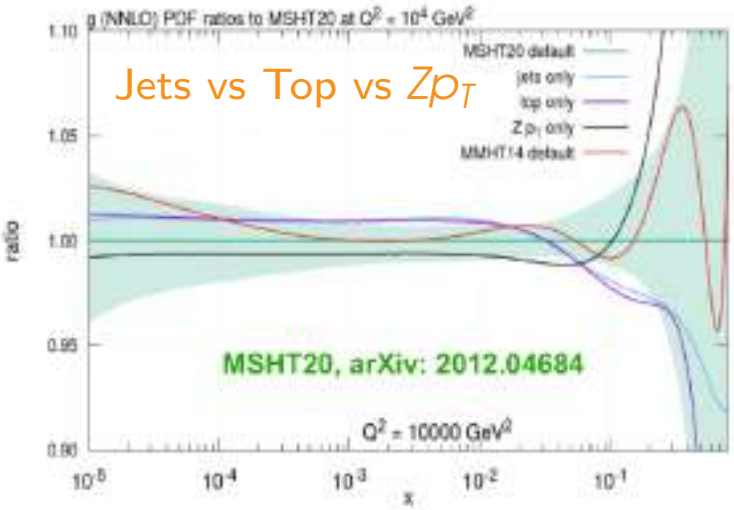
Talks by: Hekhorn, Melnitchouk, Nadolsky, Thorne, Accardi, Alanko, Jiménez-Lopez, Lin, Ma, Surrow, Whitehill and others



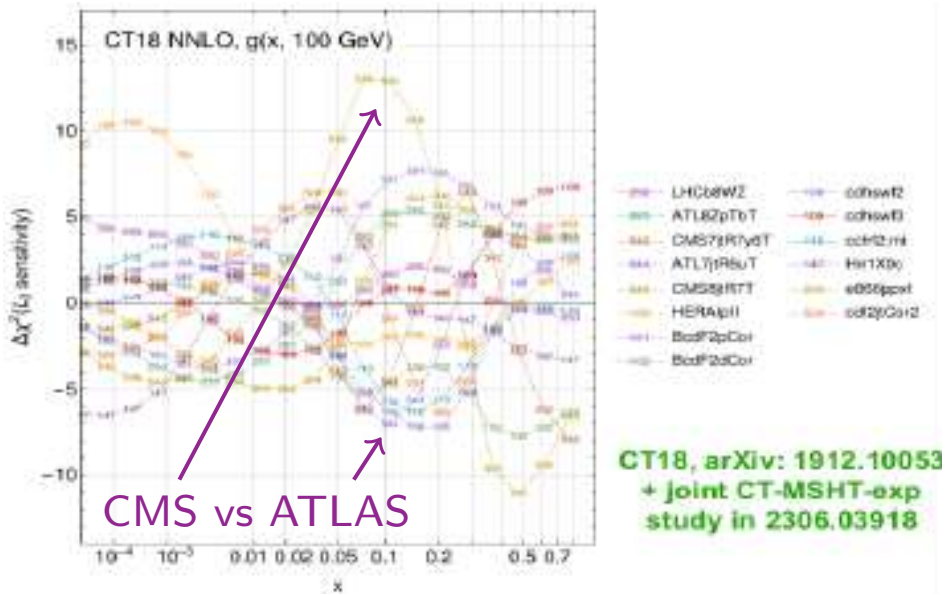
- Fixed Target and HERA data still form backbone of Global PDFs.
- LHC data increasingly large part of determination.
- Typically $\gtrsim$ 5000 points. Number and breadth of datasets $\Rightarrow$ robust.

Global PDF - Data Challenges:

- Wide range of data in global PDFs $\Rightarrow$ robust + reduces uncertainties.
- But global fits are adversial - datasets pull in different directions $\Rightarrow$ data tensions both between different data types (e.g. jet vs top vs Zp_T) and different datasets of same type (e.g. ATLAS vs CMS).



MSHT global	LO	NLO	NNLO	aN3LO
χ^2/N_{pts} (4363)	2.57	1.33	1.17	1.14

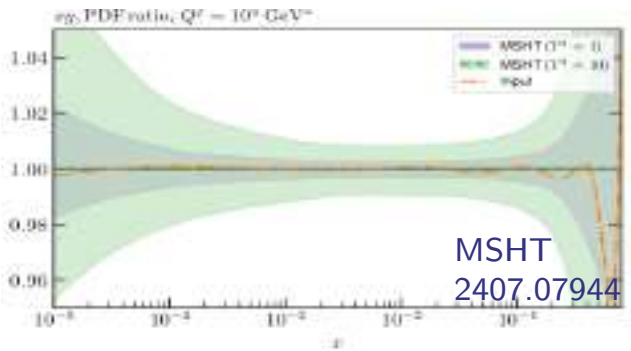


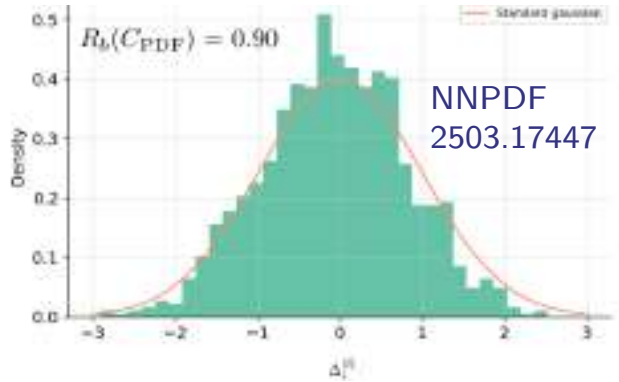
- Limits improvements in precision + causes $\chi^2/N_{\rm pts} > 1$.
- Many reasons, sometimes connected with treatment of systematics.

Global PDF - Methodology:

Talks by: Courtoy, Kusina, Nadolsky, Schoefbeck, Schutze, Thorne and others

- PDF methodology being studied every more closely - comparisons of Hessian vs Replica, parameterisation vs neural net.
- Global PDFs increasingly validated via "Closure Testing".

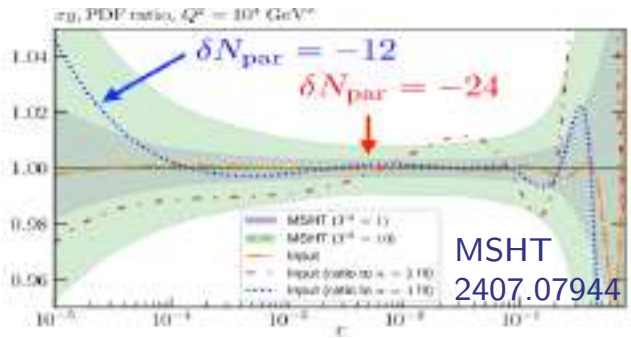




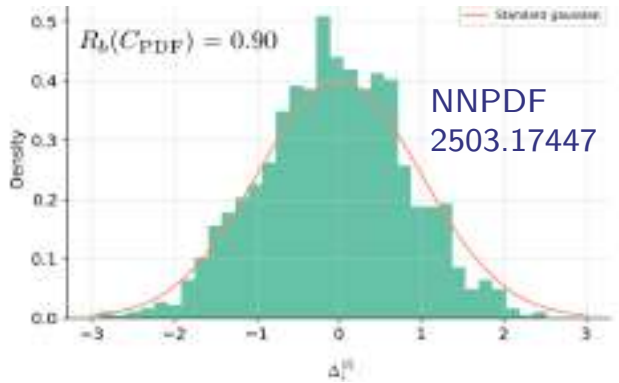
Global PDF - Methodology:

Talks by: Courtoy, Kusina, Nadolsky, Schoefbeck, Schutze, Thorne and others

- PDF methodology being studied every more closely - comparisons of Hessian vs Replica, parameterisation vs neural net.
- Global PDFs increasingly validated via "Closure Testing".
  - But careful of using too few parameters
  ⇒ Unknown biases and too small errors.



MSHT
2407.07944

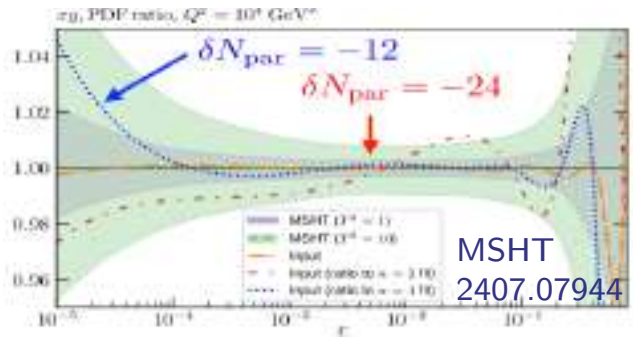


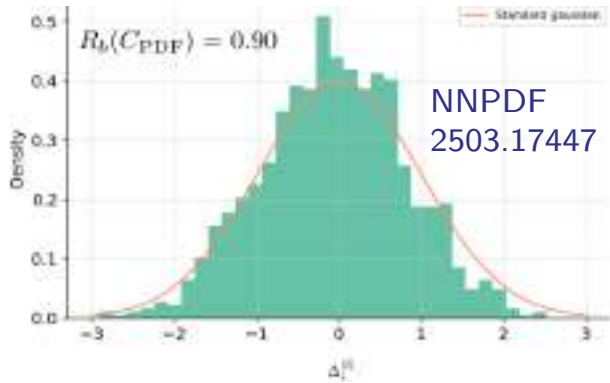
NNPDF
2503.17447

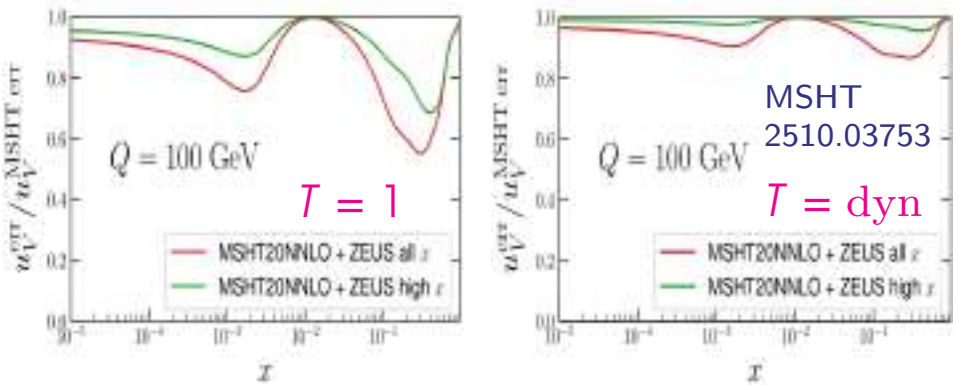
Global PDF - Methodology:

Talks by: Courtoy, Kusina, Nadolsky, Schoefbeck, Schutze, Thorne and others

- PDF methodology being studied every more closely - comparisons of Hessian vs Replica, parameterisation vs neural net.
- Global PDFs increasingly validated via "Closure Testing".
  - But careful of using too few parameters ⇒ Unknown biases and too small errors.
- Ongoing studies of uncertainty quantification in presence of tensions ⇒ tolerance.
- Analysis of PDF profiling impacts - must be consistent with PDF fit (e.g. tolerance).







Global PDF - Theory:

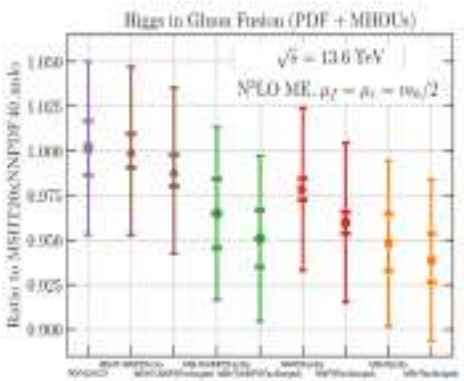
Talks by: TC, Guzzi, Sharma, ter Hoeve, Bonvini, Giuli, Gehrmann, Sotnikov, Yrjänheikki and others

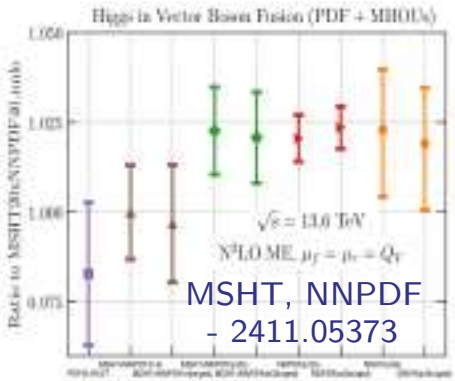
- Ever-increasing exp. precision demands improvements in theory.

Global PDF - Theory:

Talks by: TC, Guzzi, Sharma, ter Hoeve, Bonvini, Giuli, Gehrmann, Sotnikov, Yrjänheikki and others

- Ever-increasing exp. precision demands improvements in theory.
  1. Approximate N3LO PDFs with inclusion of theory uncertainties.
     - MSHT and NNPDF have produced + updated aN3LO PDFs (+QED).
     - aN3LO combination, impacts on precision pheno. - Ongoing CT studies.

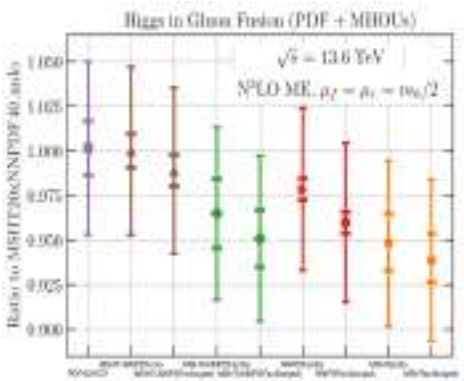


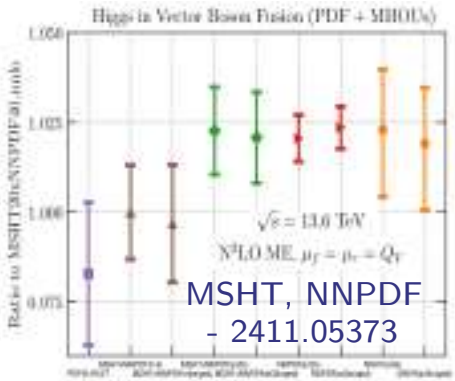


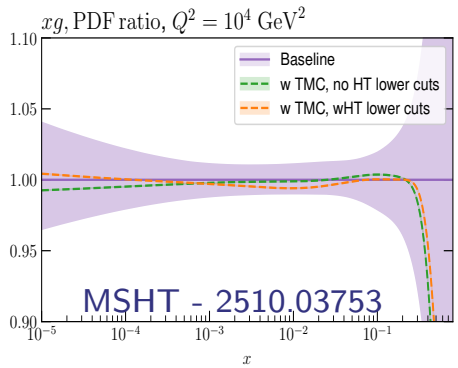
Global PDF - Theory:

Talks by: TC, Guzzi, Sharma, ter Hoeve, Bonvini, Giuli, Gehrmann, Sotnikov, Yrjänheikki and others

- Ever-increasing exp. precision demands improvements in theory.
  1. Approximate N3LO PDFs with inclusion of theory uncertainties.
     - MSHT and NNPDF have produced + updated aN3LO PDFs (+QED).
     - aN3LO combination, impacts on precision pheno. - Ongoing CT studies.
  2. Higher Twists and Target Mass Corrections.



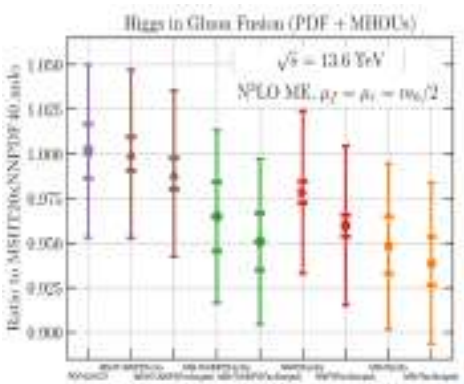


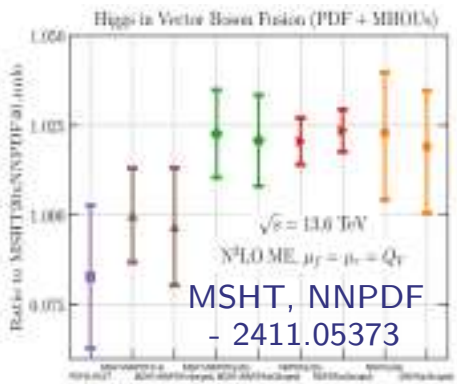


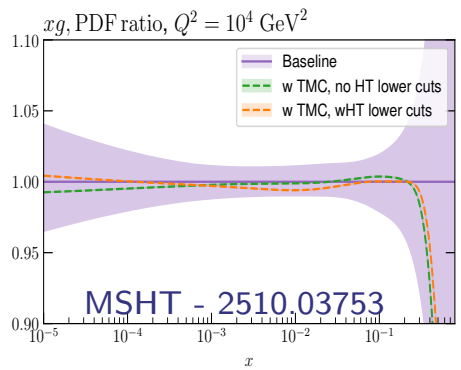
Global PDF - Theory:

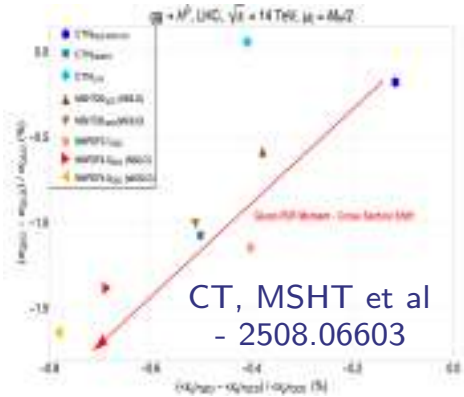
Talks by: TC, Guzzi, Sharma, ter Hoeve, Bonvini, Giuli, Gehrmann, Sotnikov, Yrjänheikki and others

- Ever-increasing exp. precision demands improvements in theory.
  1. Approximate N3LO PDFs with inclusion of theory uncertainties.
     - MSHT and NNPDF have produced + updated aN3LO PDFs (+QED).
     - aN3LO combination, impacts on precision pheno. - Ongoing CT studies.
  2. Higher Twists and Target Mass Corrections.
  3. QED Effects - understanding of differences observed between groups, "PDF4LHC" recommendation on their inclusion (mandatory for precision).





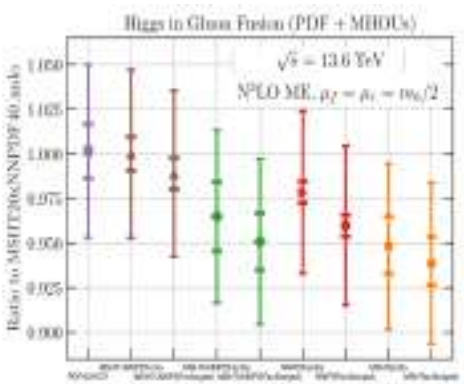


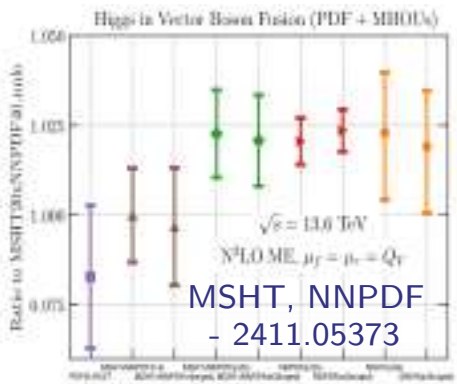


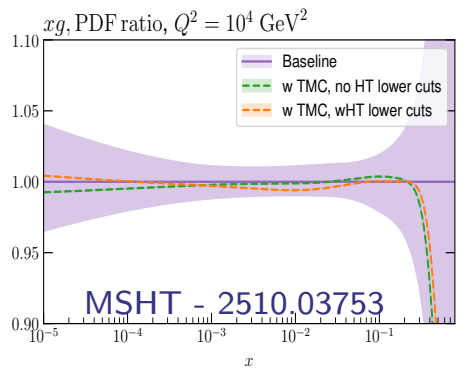
Global PDF - Theory:

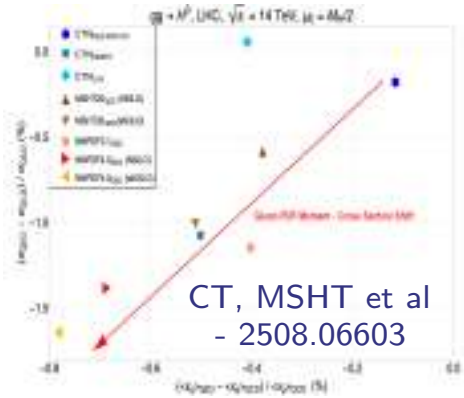
Talks by: TC, Guzzi, Sharma, ter Hoeve, Bonvini, Giuli, Gehrmann, Sotnikov, Yrjänheikki and others

- Ever-increasing exp. precision demands improvements in theory.
  1. Approximate N3LO PDFs with inclusion of theory uncertainties.
     - MSHT and NNPDF have produced + updated aN3LO PDFs (+QED).
     - aN3LO combination, impacts on precision pheno. - Ongoing CT studies.
  2. Higher Twists and Target Mass Corrections.
  3. QED Effects - understanding of differences observed between groups, "PDF4LHC" recommendation on their inclusion (mandatory for precision).









- All give $\mathcal{O}(\%)$ shifts to PDFs and cross-sections (more for aN3LO on gluon).
- Many of these effects seem to act to reduce the gluon in Higgs region.

Precision SM Parameters:

Talks by: TC, Sharma, ter Hoeve, Whitehill and others

- PDF/theory uncertainties limit precision.

  $\underline{\alpha_S(M_Z)}$
- Vital for LHC programme. $\Delta\alpha_S(M_Z) \Rightarrow \Delta\sigma_H \approx 2\%$.

Precision SM Parameters:

Talks by: TC, Sharma, ter Hoeve, Whitehill and others

- PDF/theory uncertainties limit precision.

  $\underline{\alpha_S(M_Z)}$

- Vital for LHC programme. $\Delta\alpha_S(M_Z) \Rightarrow \Delta\sigma_H \approx 2\%$.

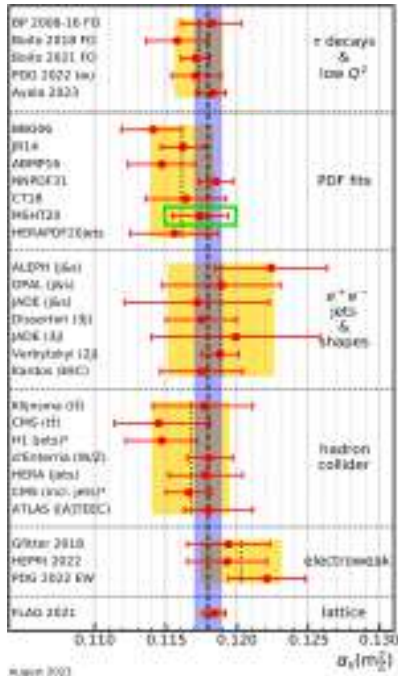
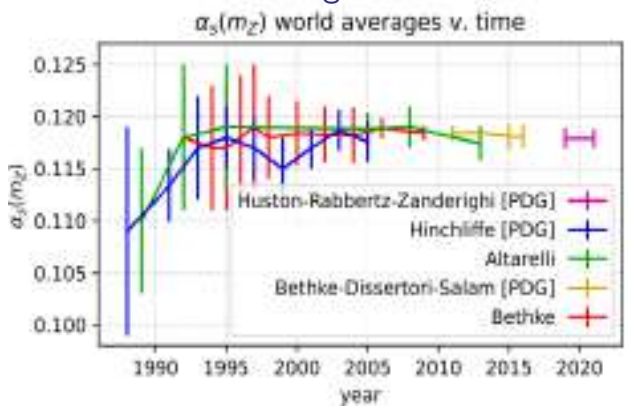


Image Credit: G. Salam



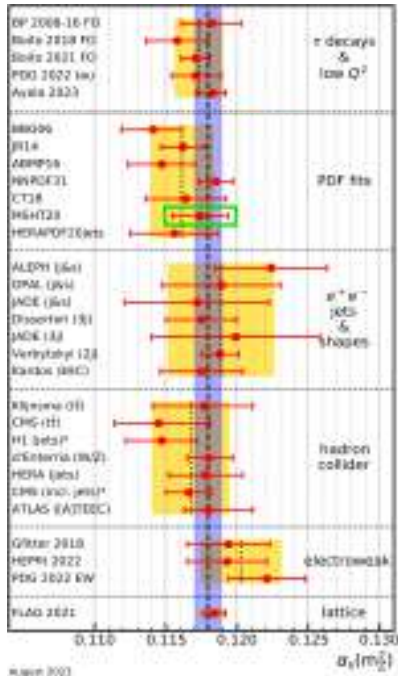
Precision SM Parameters:

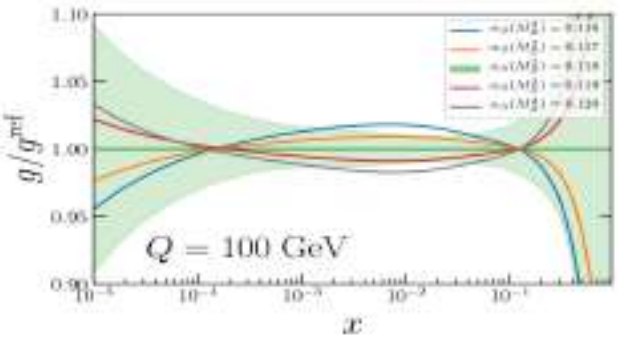
Talks by: TC, Sharma, ter Hoeve, Whitehill and others

- PDF/theory uncertainties limit precision.

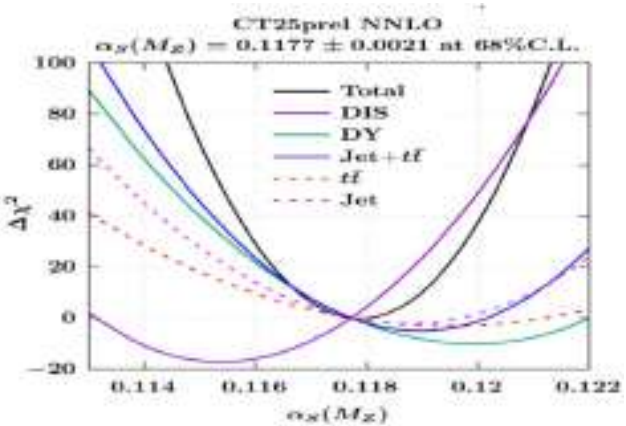
  $\alpha_S(M_Z)$

- Vital for LHC programme. $\Delta\alpha_S(M_Z) \Rightarrow \Delta\sigma_H \approx 2\%$.
- Strongly correlated with PDFs .
- Global PDF fits combine datasets $\Rightarrow$ robust.
- Extension to m_t - ABMP, CT, MSHT, NNPDF.
- Beware theory uncertainties + correlations. Precision required demands greater care in treatment.



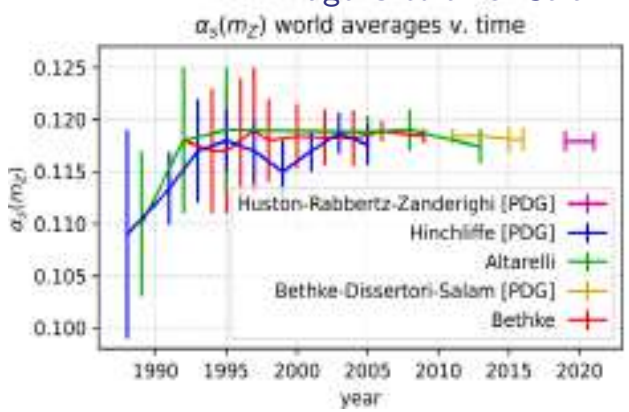


MSHT - 2404.02964



CT - 2512.23792

Image Credit: G. Salam



Conclusions

- In the 50 years since the early days of QCD we continue to learn new things.
- PDFs and precision SM parameters are fundamental to the collider programme at LHC and beyond.
- With increasingly experimental precision the demands we place on PDFs/Theory will only grow.

Conclusions

- In the 50 years since the early days of QCD we continue to learn new things.
- PDFs and precision SM parameters are fundamental to the collider programme at LHC and beyond.
- With increasingly experimental precision the demands we place on PDFs/Theory will only grow. $\Rightarrow$ Exciting field of research!

Conclusions

- In the 50 years since the early days of QCD we continue to learn new things.
- PDFs and precision SM parameters are fundamental to the collider programme at LHC and beyond.
- With increasingly experimental precision the demands we place on PDFs/Theory will only grow. $\Rightarrow$ Exciting field of research!

Special thanks:

- **It is an honour to receive this award.**
- Selection Committee, DIS International Advisory Committee, Local Organising Committee, Altarelli and family.
- Sponsors - EPJ, INFN, World Scientific.
- Scientific Mentors - Robert Thorne, Frank Tackmann, Benjamin Allanach. Collaborators - Lucian Harland-Lang, PDF and DESY Colleagues.
- Family, partner and friends outside physics.
- To all of you! At the least for listening to me the 4th time this conference!

Conclusions

- In the 50 years since the early days of QCD we continue to learn new things.
- PDFs and precision SM parameters are fundamental to the collider programme at LHC and beyond.
- With increasingly experimental precision the demands we place on PDFs/Theory will only grow. $\Rightarrow$ Exciting field of research!

Special thanks:

- **It is an honour to receive this award.**
- Selection Committee, DIS International Advisory Committee, Local Organising Committee, Altarelli and family.
- Sponsors - EPJ, INFN, World Scientific.
- Scientific Mentors - Robert Thorne, Frank Tackmann, Benjamin Allanach. Collaborators - Lucian Harland-Lang, PDF and DESY Colleagues.
- Family, partner and friends outside physics.
- To all of you! At the least for listening to me the 4th time this conference!

Thankyou!