REF2016 - November - Antwerp 2016, Belgium

TMDs in xFitter

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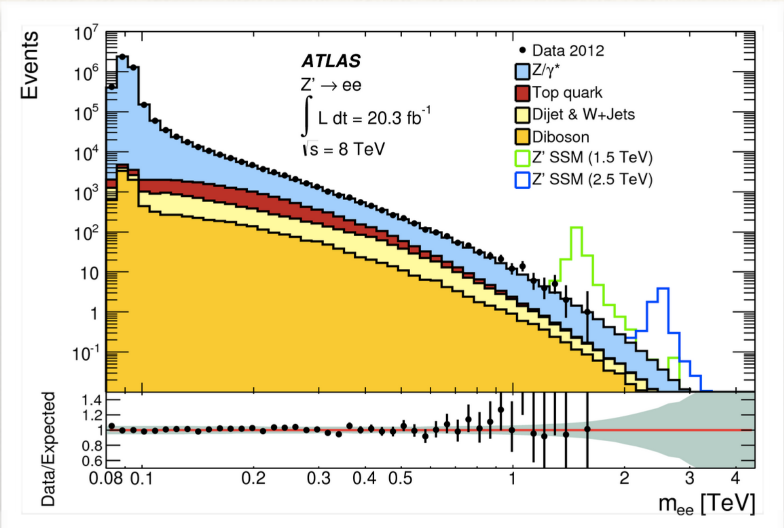
Search for new Physics

direct searches for new physics

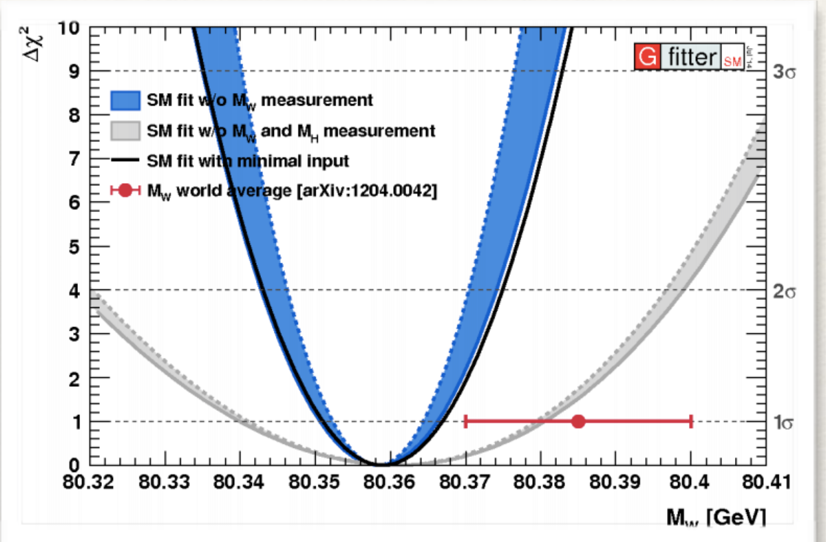
indirect searches via consistency test of SM

control of QCD background and SM parameters



[arXiv:1410.6810v2]

Interpretation of any cross section measurement which involves hadron in the initial state relies on factorisation concept:



Gfitter

$$\underbrace{\sigma(x,Q^2)}_{hadronic\ x-sec.} = \sum_{a,b} \int_0^1 dx_1 dx_2 \underbrace{f_a(x_1 Q^2) f_b(x_2 Q^2)}_{PDFs} \times \underbrace{\hat{\sigma}(x_1,x_2,Q^2)}_{partonic\ x-sec}$$

PDFs ↓ taken from data

partonic x-sec ↓ calculable

Improvement of PDFs precision demands high precision theory & experimental measurement:

Search for new Physics

direct searches for new physics

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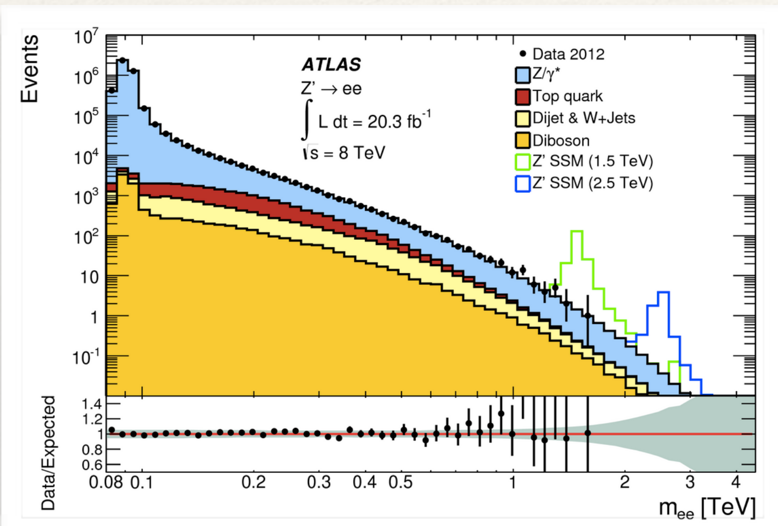

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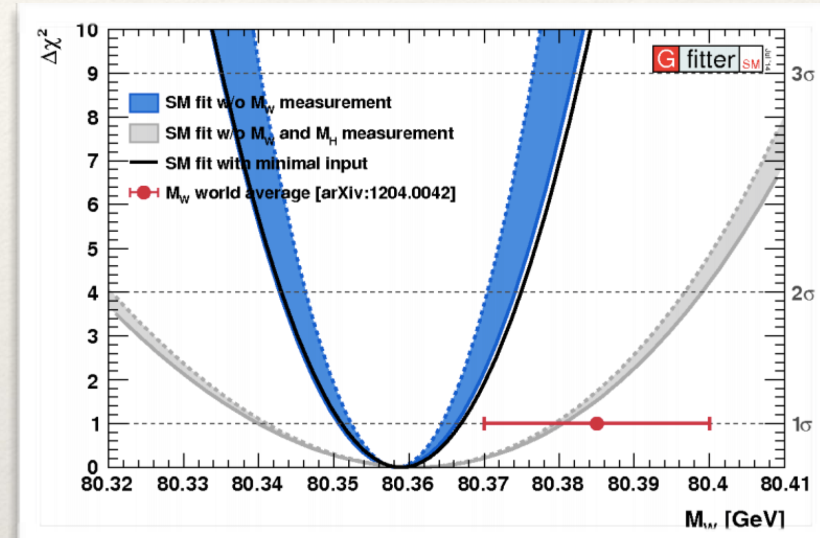

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PDFs ↓ taken from data

partonic x-sec ↓ calculable

Further dimension of hadrons: PDFs dependent on kT

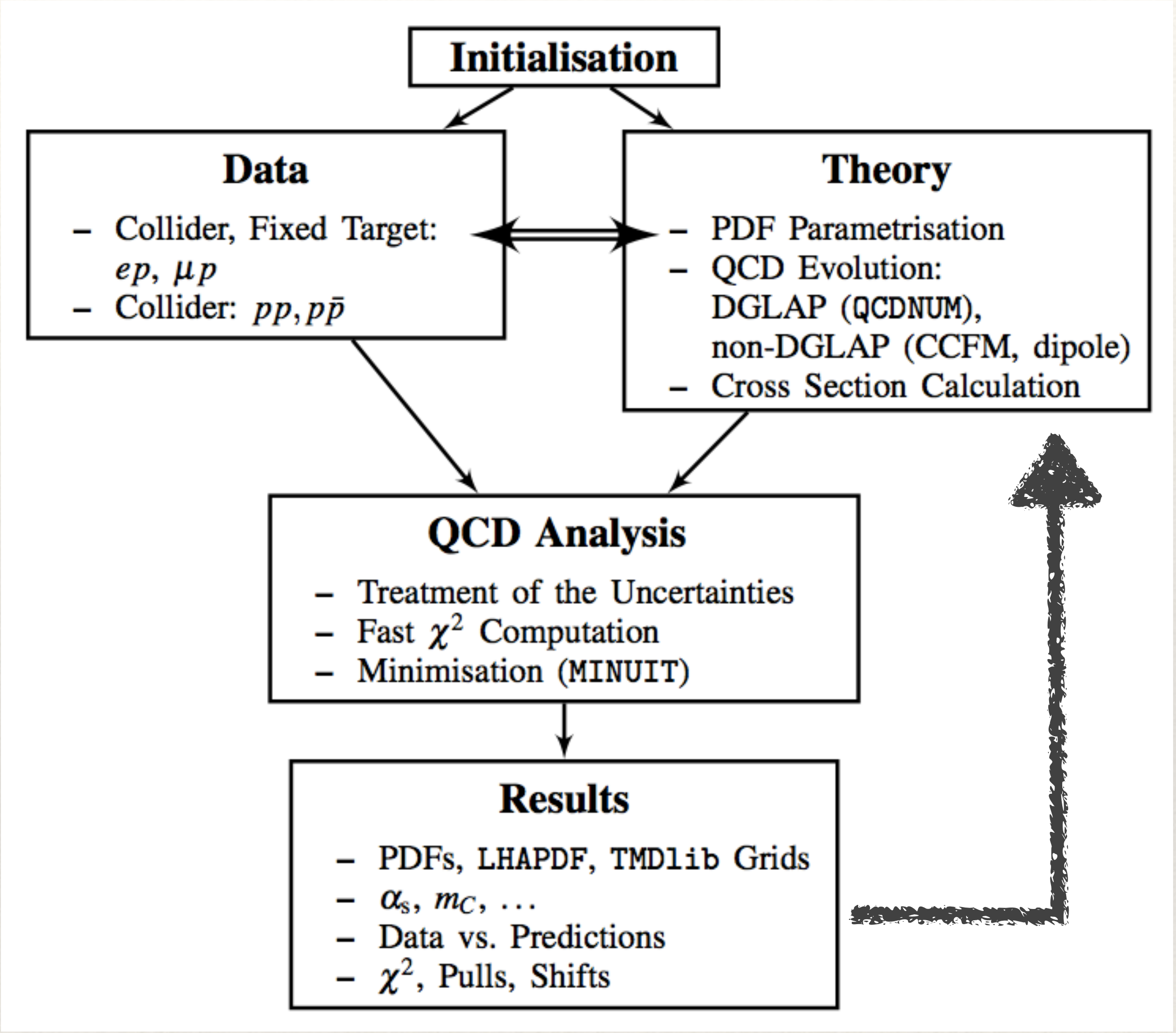
$$\sigma(pp \to q\bar{q} + X) = \int \frac{dx_{g1}}{x_{g1}} \frac{dx_{g2}}{x_{g2}} \int d^2k_{t1} d^2k_{t2} \hat{\sigma}(\hat{s}, k_t, \bar{q}) \times x_{g1} \mathcal{A}(x_{g1}, k_{t1}, \bar{q}) x_{g2} \mathcal{A}(x_{g2}, k_{t2}, \bar{q})$$

Mechanism of extracting PDFs:

Extraction of PDFs relies on precision measurements to challenge theory

interplay between data and theory

1. Parametrise PDFs at the starting scale
   - multiple options for functional forms
     - Standard Polynomial, Chebyshev, etc
2. Evolve to the scale corresponding to data point
   - QCD(DGLAP) evolution codes [QCDNUM, APFEL]
   - kt ordered evolution, Dipole models, QCD(DGLAP)+QED
3. Calculate the cross section
   - various heavy flavour schemes:
     - RT, ACOT, FONLL, FFNS(ABM)
   - fast grid techniques interfaced to DY:
     - APPLGRID, FASTNLO, APFELgrids
4. Compare with data via χ2:
   - multiple forms to account for correlations
5. Minimize χ2 with respect to PDF parameters
   - Profiling, reweighting
   - Fit: MINUIT, data driven regularisation



xFitter EPJC (2015), 75:304

~2000 iterations

[See Ringaile's slides for more details about xFitter]

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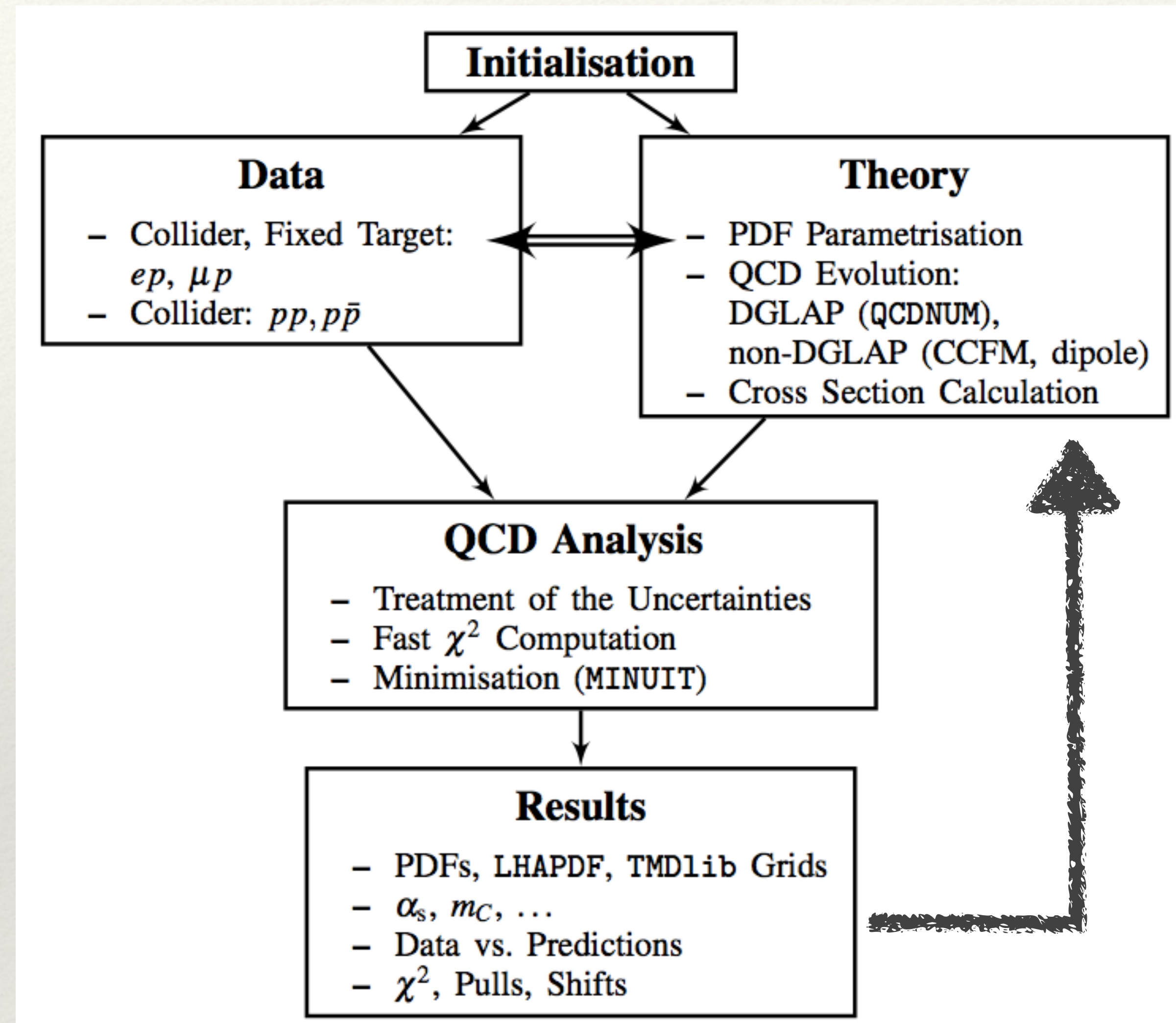


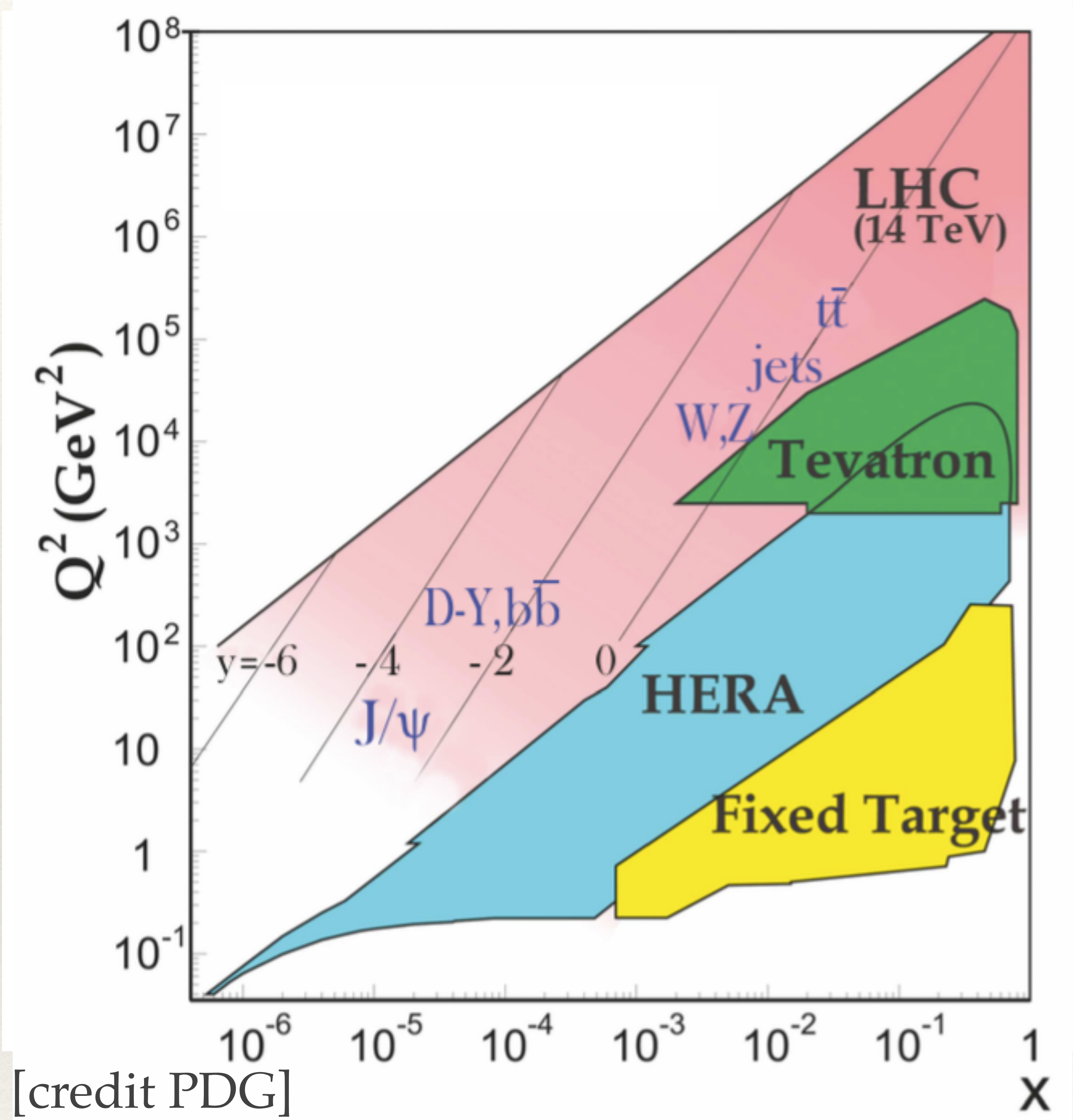
xFitter EPJC (2015), 75:304

~2000 iterations

[See Valerio's slides for details on APFEL, MELA…]

Tools for QCD Fits: xFitter, APFEL, Alpos, OPENQCDRAD, QCDNUM …

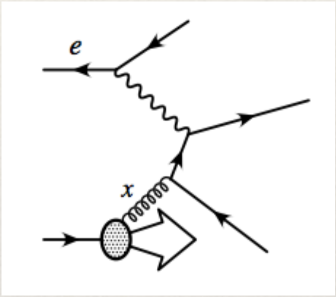
Data for studying Proton Structure



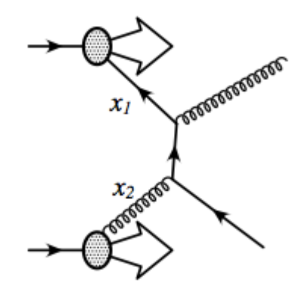
[credit PDG]

Persistent experimental effort over the last 40 years both by fixed-target and collider experiments around the world supported by the intense theoretical developments

- The cleanest way to probe Proton Structure is via Deep Inelastic Scattering [DIS]:



- Precision of proton structure can be complemented by the Drell Yan [DY] processes at the collider experiments



Q2: resolving power of experiment
x: fraction of proton's momentum

Multiple precision measurements from Fixed target, HERA, Tevatron, and LHC
Many groups to analyse these data and interpret them

Vector boson pT spectrum at the LHC

ATLAS and CMS both measured and studied the Z pT spectrum in rapidity bins:

high pT region: fixed order calculations up to O(α_s^2) and now even O(α_s^3) + EW corrections

comparison to fixed order:

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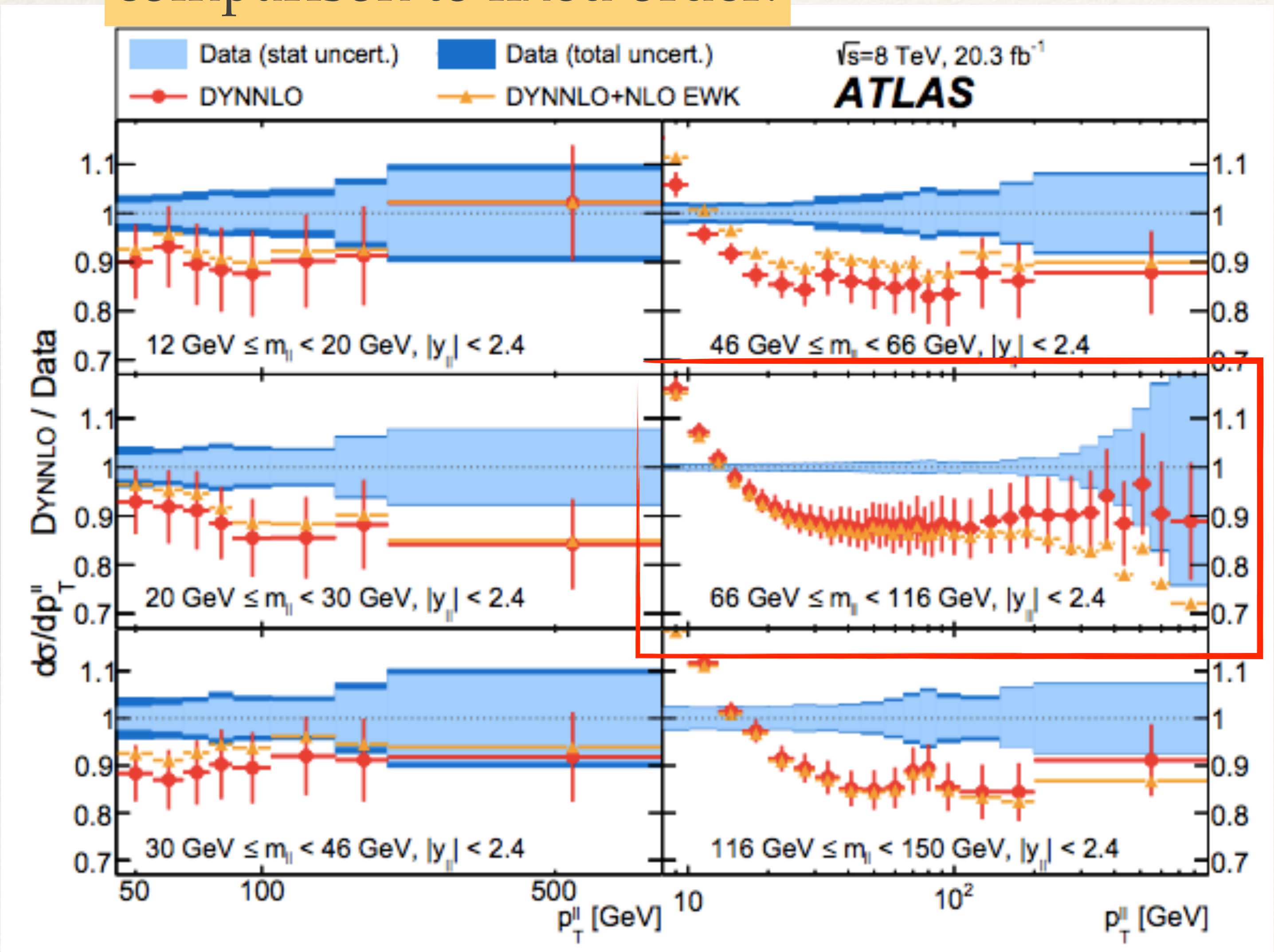
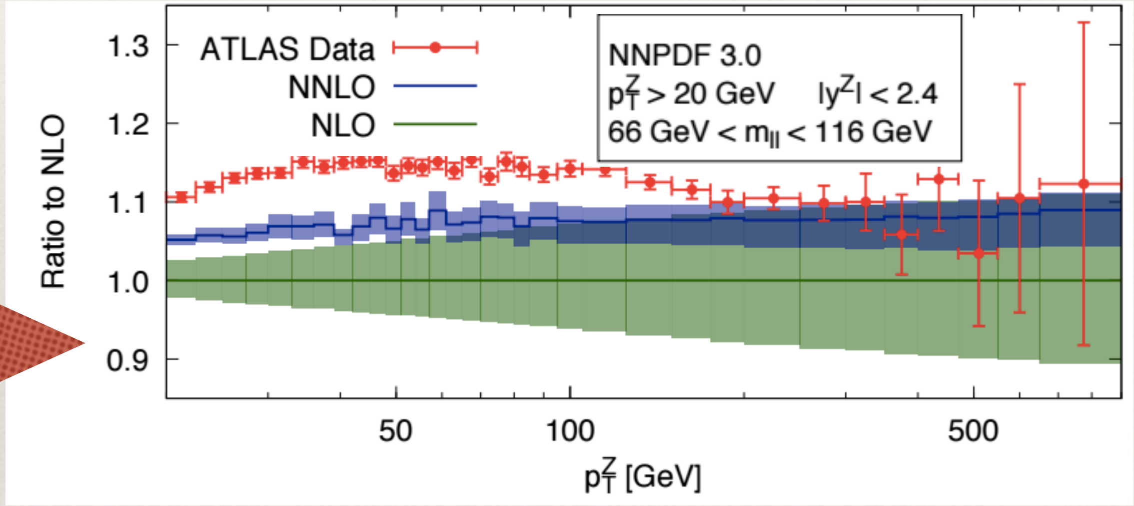


Higher Order corrections would improve data - theory agreement

arxiv:1605.04295



Measurement with constraining powers for PDFs and alphas

Vector boson pT spectrum at the LHC

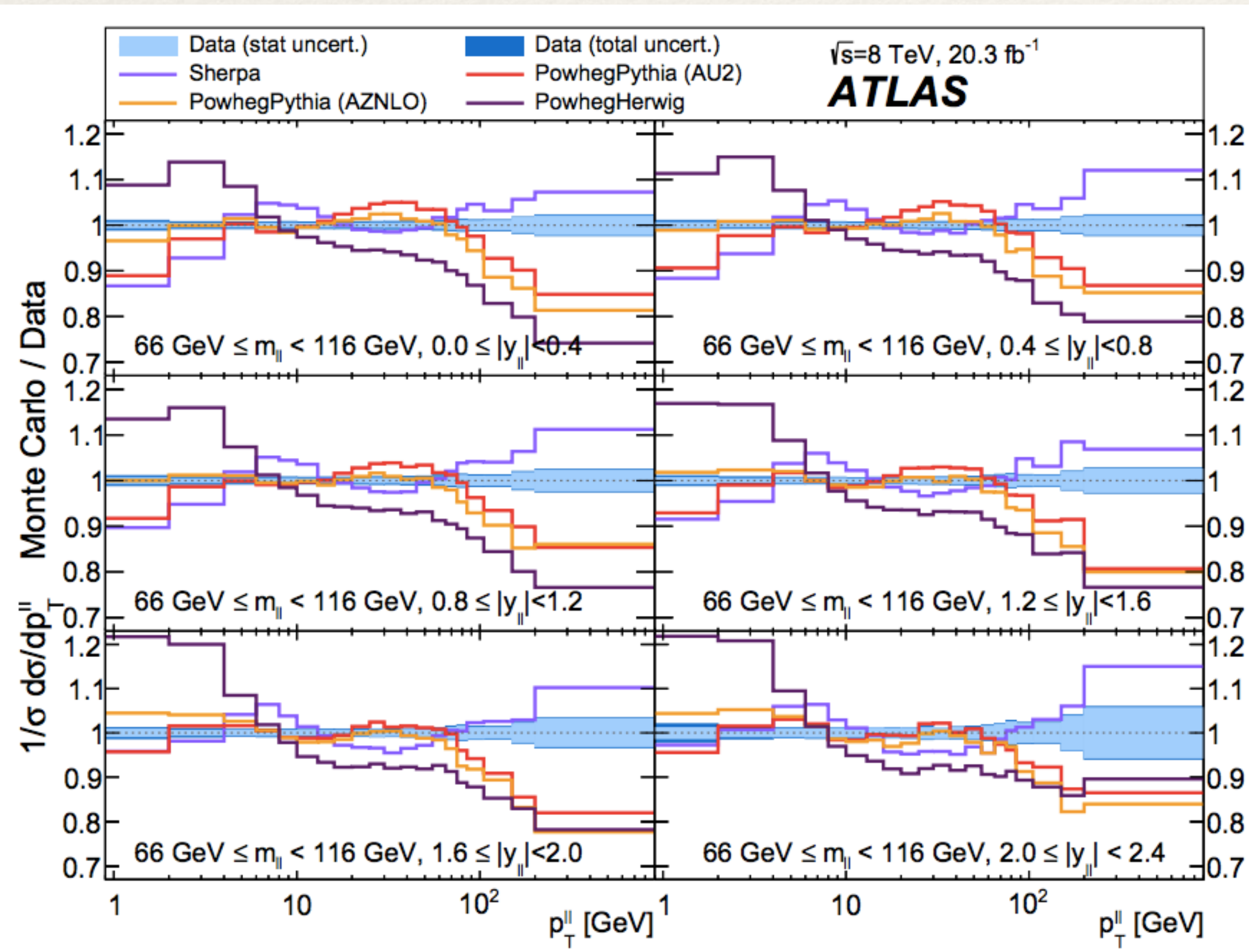
ATLAS and CMS both measured and studied the Z pT spectrum in rapidity bins

low pT region: dominated by the emission of soft gluons

—> fixed order calculations don't work —> need resummation and shower models

comparison to MC:

Precise data for MC tuning!



66 GeV ≤ m_{ll} < 116 GeV

MC with different PS models are compared

- Powheg+Pythia AZNLO [tuned to 7 TeV Z p_T]

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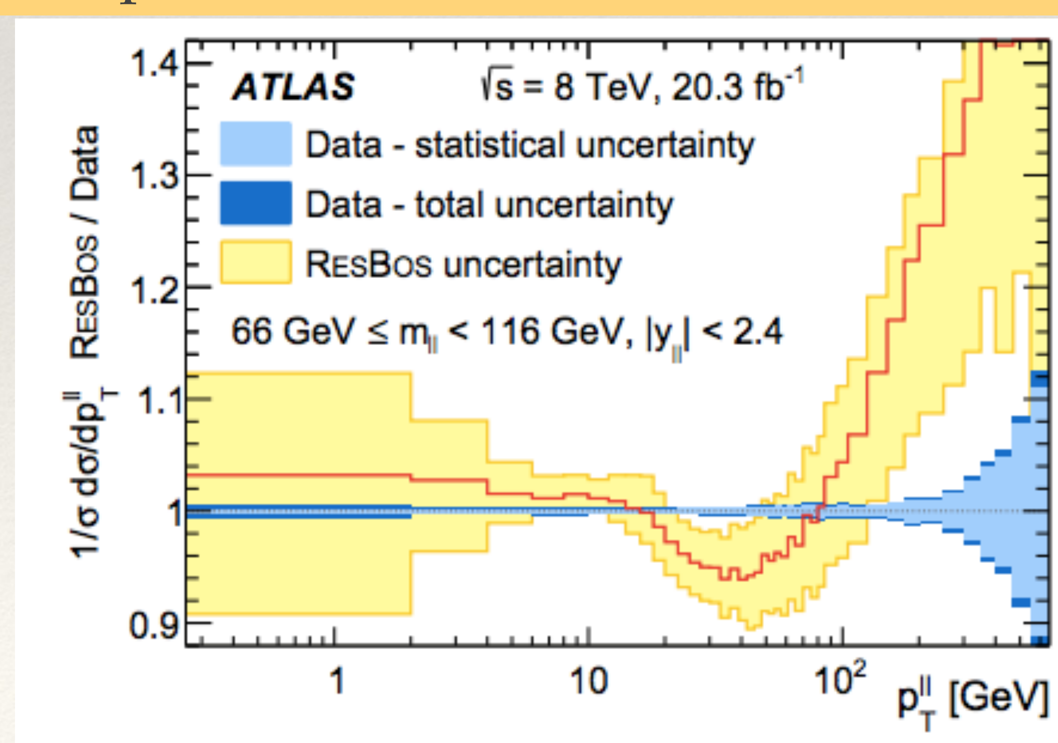
comparison to resummed calculations:



[Ref: ACTA PHYSICA POLONICA B: Vol. 46 (2015)]

Transverse Momentum Distributions

- Fixed order calculations dont always work and in order to improve the quality of PDF fits in small/high x regions
  —>a challenge to merge DGLAP, BFKL, cascade evolutions

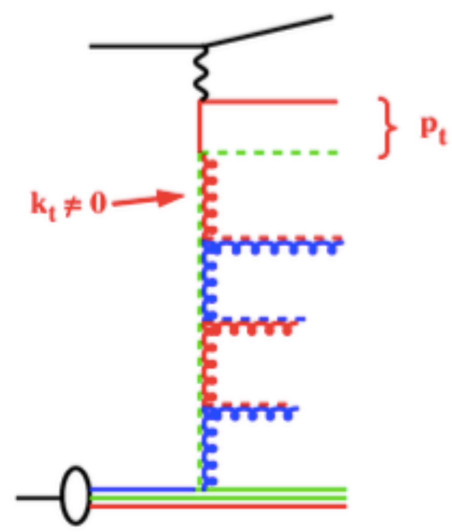
- TMDs were first introduced at small x as unintegrated gluon PDFs
  - intrinsic at small kT
  - perturbative evolution at large kT

- **However, the concept is now extended to the full kinematic space and to all quark species**

[see Hannes slides]

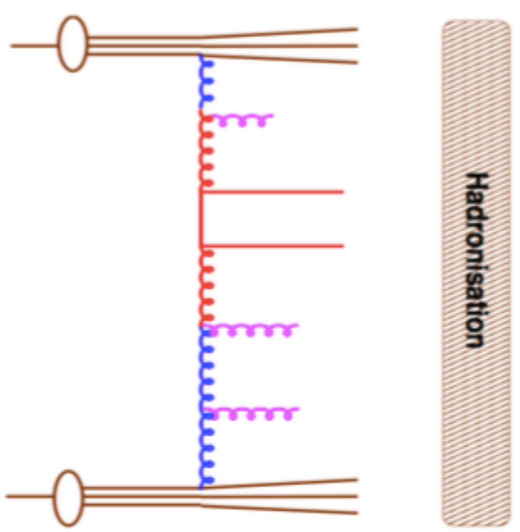
- in ep scattering:

$$\sigma(ep \to e'X) = \int dx_g/x_g \left[d^2k_t x_g \mathcal{A}_i(x_g, k_t, \bar{q})\right] \times \hat{\sigma}(x_g, k_t, x, \bar{q}, Q^2)$$



- in pp scattering

$$\sigma(pp \to q\bar{q} + X) = \int \frac{dx_{g1}}{x_{g1}} \frac{dx_{g2}}{x_{g2}} \int d^2k_{t1} d^2k_{t2} \hat{\sigma}(\hat{s}, k_t, \bar{q}) \times x_{g1}\mathcal{A}(x_{g1}, k_{t1}, \bar{q}) x_{g2}\mathcal{A}(x_{g2}, k_{t2}, \bar{q})$$



Transverse Momentum Distributions

MC simulation combines fixed order partonic calculations with PS and hadronisation
—> needs reshuffling of kinematic variables after PS generations
—> TMDs are introduced for a proper simulation of parton showers:

- generalisation of QCD factorisation with an explicit dependence on transverse momentum and polarisations

$$\sigma(pp \to q\bar{q} + X) = \int \frac{dx_{g1}}{x_{g1}} \frac{dx_{g2}}{x_{g2}} \int d^2k_{t1} d^2k_{t2} \hat{\sigma}(\hat{s}, k_t, \bar{q}) \times x_{g1} \mathcal{A}(x_{g1}, k_{t1}, \bar{q}) x_{g2} \mathcal{A}(x_{g2}, k_{t2}, \bar{q})$$

- they obey the evolution equations which generalise the ordinary RGE of collinear PDFs
  - solved using MC
  - reformulated using separate kernels gluons from sea quarks
    - —> perform the evolution separately

Transverse Momentum Distributions evolved using MC method

MC code

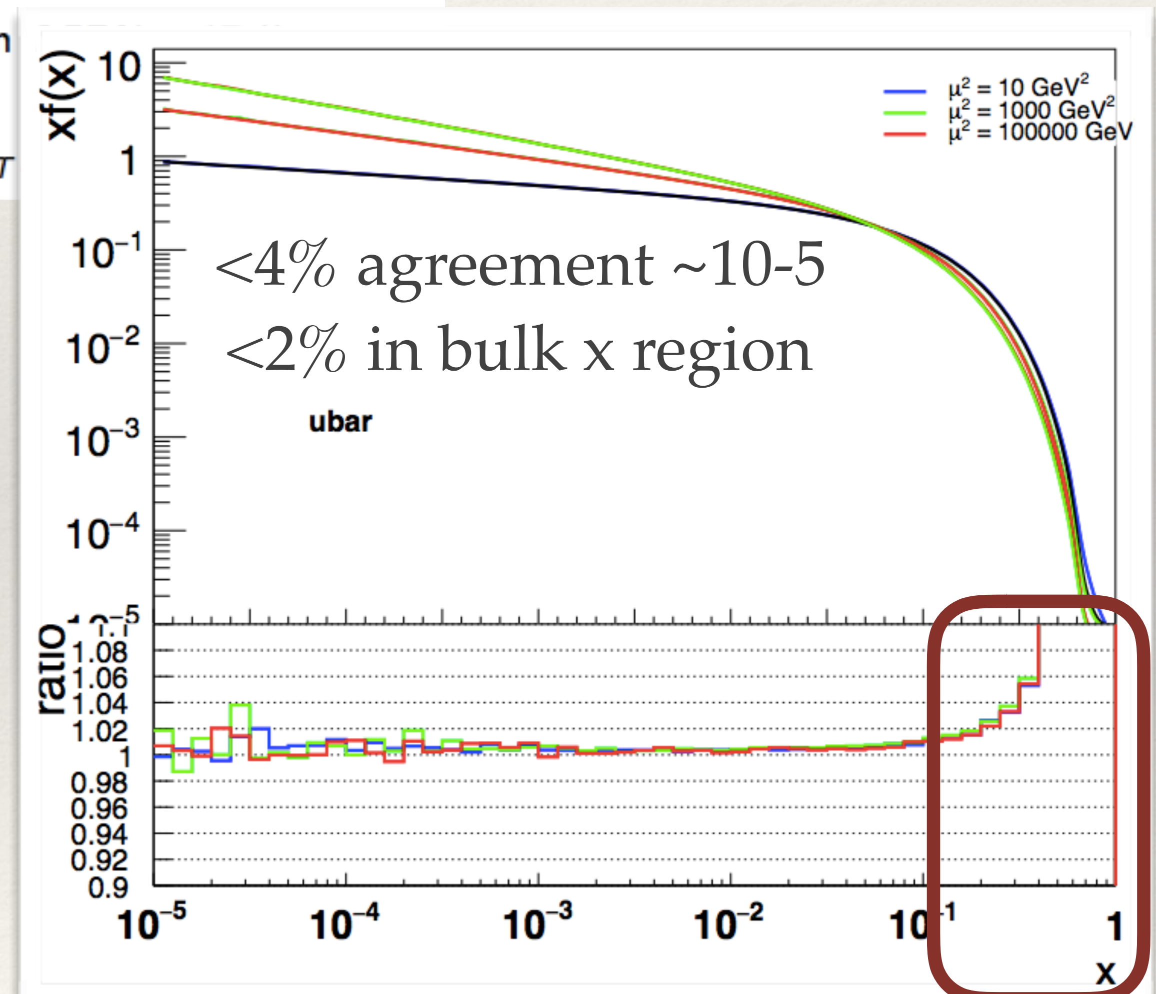
In this presentation: MC results obtained with updated and improved ‣ uPDFevolv code:

- full coupled quark and gluon DGLAP evolution (gluon, sea and valence evolution),
- fixed flavour number scheme,
- LO in $P(z)$,
- 1-loop-α_s (but also 2-loop-α_s implemented),
- $xf(x,t)$,
- the initial distributions for $u, d, s, \ldots, \overline{u}, \overline{d}, \overline{s}, \ldots$ and gluon come from other parametrization can be used).

Evolution over the whole range in x, Q^2 and all kinematically allowed k_T

A sample of validation plots:
Analytical integration vs MC of
solving DGLAP

[see Ola's slides for more]



due to
grid

TMDs in xFitter: implementation

Steering block:
assign which evolution to be used
assign initial values for fitted parameters

Initialise theory

Evolve initial objects

Calculate Observables (SFs, Xsec)

minimize the chi2

QCDNUM
block for
storing output of PDFs for display

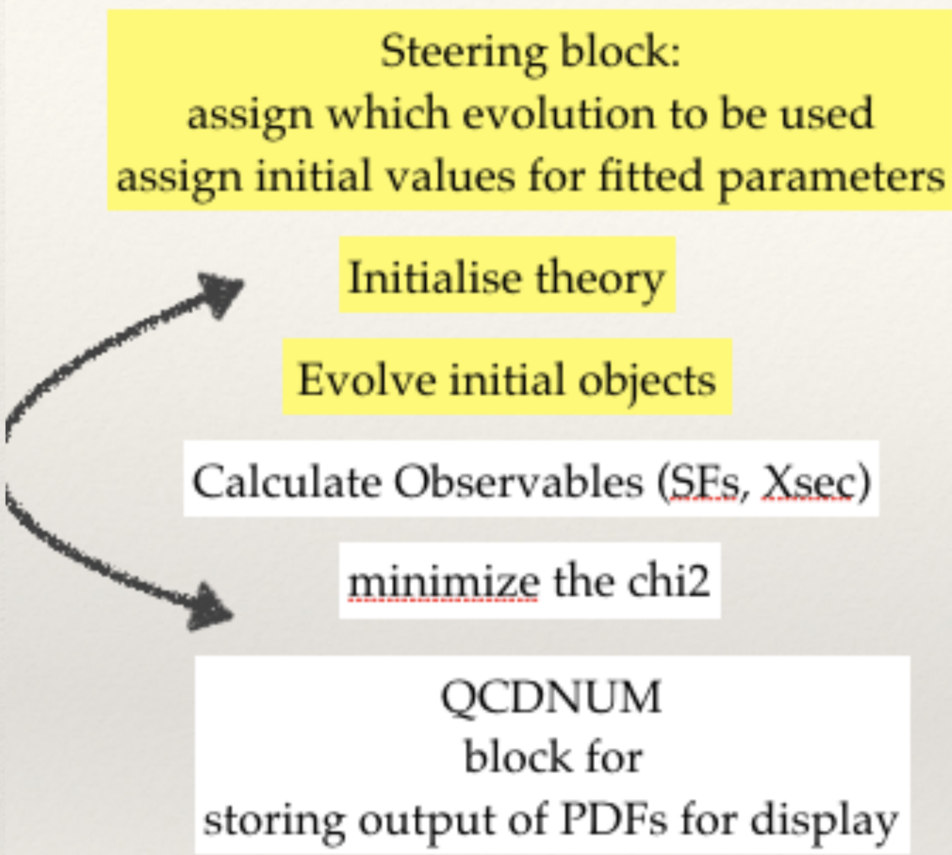
Currently in xFitter:

```
'DGLAP' ! 'DGLAP'  -- colinear evolution
        ! 'DGLAP_APFEL'      -- collinear evolution with APFEL
        ! 'DGLAP_QEDEVOL'    -- collinear evolution with QEDEVOL
        ! 'DGLAP_APFEL_QED'  -- collinear evolution with APFEL with QED corrections
        ! 'DGLAP_TMDEVOL'     -- colinear TMD evolution
        ! 'DIPOLE' -- dipole model
        ! 'uPDF'    -- un-integrated PDFs
                 !uPDF1 fit with kernel ccfm-grid.dat file
                 !uPDF2 fit evolved uPDF, fit just normalisation
                 !uPDF3 fit using precalculated grid of sigma hat
```

```
external LHAPDFsubr
external APFELsubr
external APFELsubrPhoton
external QEDEVOLsubr
external TMDEVOLsubr
```

Toolkit: TMDs in xFitter implementation

Steps in implementations:



A. create a new module which can be steerable via configure flag
   - ./configure - - enable-NEWMODULE

B. Add new option in the steering card
   - TheoryType = 'DGLAP_TMDEVOL' ! 'DGLAP' -- colinear TMD evolution

C. Interfacing the new module to xFitter:

1. reading the steering card
   - src/read_steer.f: it requires new internal index
2. initialise evolution:
   - src/init_theory.f: call NEWMODULE_ini assigned to the new index
3. create a routine that sets all input parameters of your new routine (passing of the inputs) and protect against the case when the module is not linked (can be done via configure commands)

4. during the evolution: skip the default evolution which is taken from QCDNUM
   - assign the IPDFSET >6 (external PDFs to QCDNUM)

6. PDF decomposition -> transform them into basis of your choice to be passed into your code
   - create a new subroutine stored in src/evolution.f
7. Storing/Filling the grids:
   - done on src/evolution.f via call from QCDNUM
   - call PDFEXT(NEWMODULE_subr,IPDFSET,dble(0.001),epsi)

QCD Settings for iTMD extraction

The QCD settings are optimised for HERA measurements of proton structure functions:

PDFs are parametrised at the starting scale Q_0^2=1.9 GeV^2 as follows: *arXiv:1506.06042*

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g},\\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right),\\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}},\\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1+D_{\bar{U}}x),\\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

fixed or constrained by sum-rules

parameters set equal but free

NC structure functions

$$F_2 = \frac{4}{9}\left(xU + x\bar{U}\right) + \frac{1}{9}\left(xD + x\bar{D}\right)$$

$$xF_3 \sim xu_v + xd_v$$

CC structure functions

$$W_2^- = x(U+\overline{D}), \qquad W_2^+ = x(\overline{U}+D)$$

$$xW_3^- = x(U-\overline{D}), \qquad xW_3^+ = x(D-\overline{U})$$

—> 14 free parameters after imposing Sum Rules, and assumption that xubar=xdbar x—>0

- TMDs are evolved via MC evolution equations to LO ($\alpha_S(M_Z)$=0.118)
- Thorne-Roberts GM-VFNS for heavy quark coefficient functions – as used in MMHT
- χ^2 definition used in the minimisation [MINUIT] accounts for correlated uncertainties:

$$\chi^2_{\mathrm{exp}}(\boldsymbol{m},\boldsymbol{s}) = \sum_i \frac{\left[m^i - \sum_j \gamma^i_j m^i s_j - \mu^i\right]^2}{\delta^2_{i,\mathrm{stat}}\,\mu^i m^i + \delta^2_{i,\mathrm{uncor}}\,(m^i)^2} + \sum_j s_j^2$$

m - th prediction
μ - data
s - sys shift

Propagation of experimental uncertainties to iTMDs

There are two standardised approaches to propagate the exp. uncertainties:

- Hessian Eigenvectors: based on expansion of the χ2 function

$$\Delta\chi^2 = \chi^2 - \chi_0^2 = \sum_{i=1}^{d}\sum_{j=1}^{d} H_{ij}\,(a_i - a_i^0)\,(a_j - a_j^0)$$

PDF parameters: $\{a_i\}$ $i=1 \ldots d$

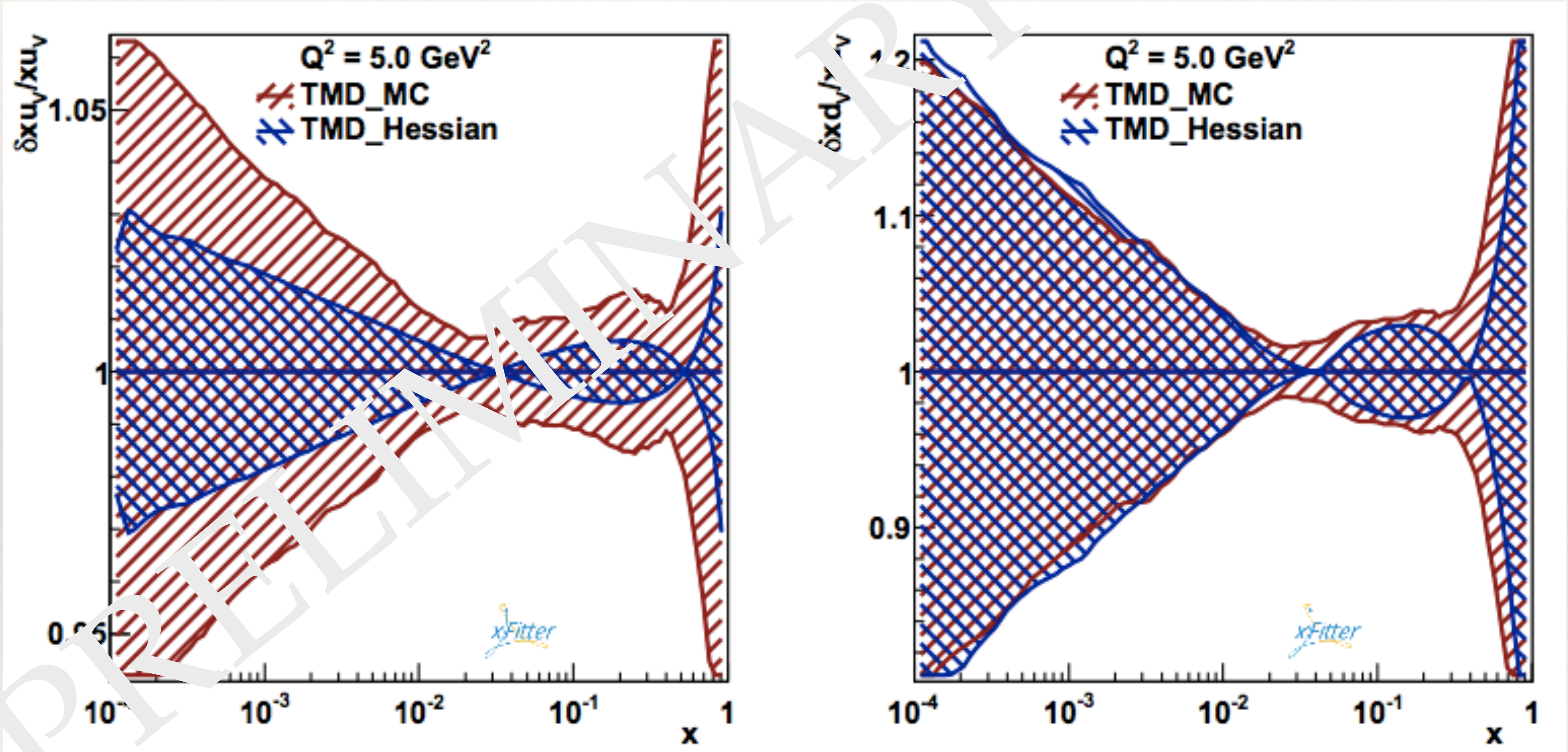
Hessian matrix of second derivatives: $H_{ij} = \frac{1}{2}\frac{\partial^2 \chi^2_{\mathrm{global}}}{\partial a_i \partial a_j}\Big|_0$

  - in xFitter: Δχ2= 1 for one sigma (68% CL)

- Monte Carlo Replica:
  - generation of replicas of experimental data by smearing the central values of data pointy by statistical and systematical uncertainty (accounting for the correlations)
  - perform a separate fit using each data replica

First LHAPDF TMD for full kinematic plane

it can be distributed using Hessian Error estimation or Monte Carlo Replica



MC error estimation is generally more robust

—> LHgrid that can be plugged in any other application

[Ref: ACTA PHYSICA POLONICA B: Vol. 46 (2015)]

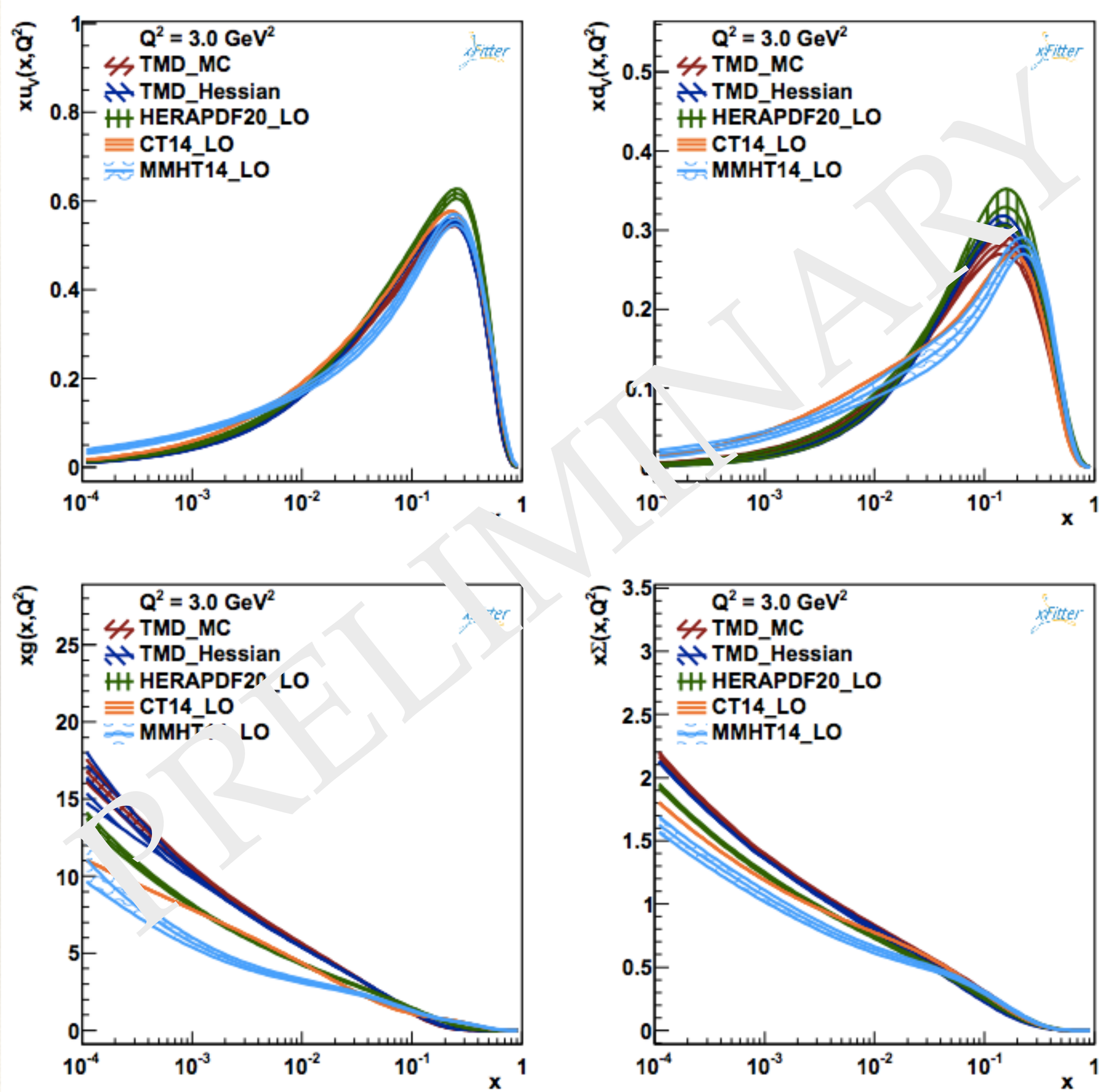
First LHAPDF TMD for full kinematic plane

Integrated PDFs from TMD evolution using MC method
(compared with standard LO PDFs)

$\chi 2$	iTMD	HERAPDF2.0	CT14	MMHT14
HERA	**1393**	1635	2090	2178

1145 points (-14 free param)

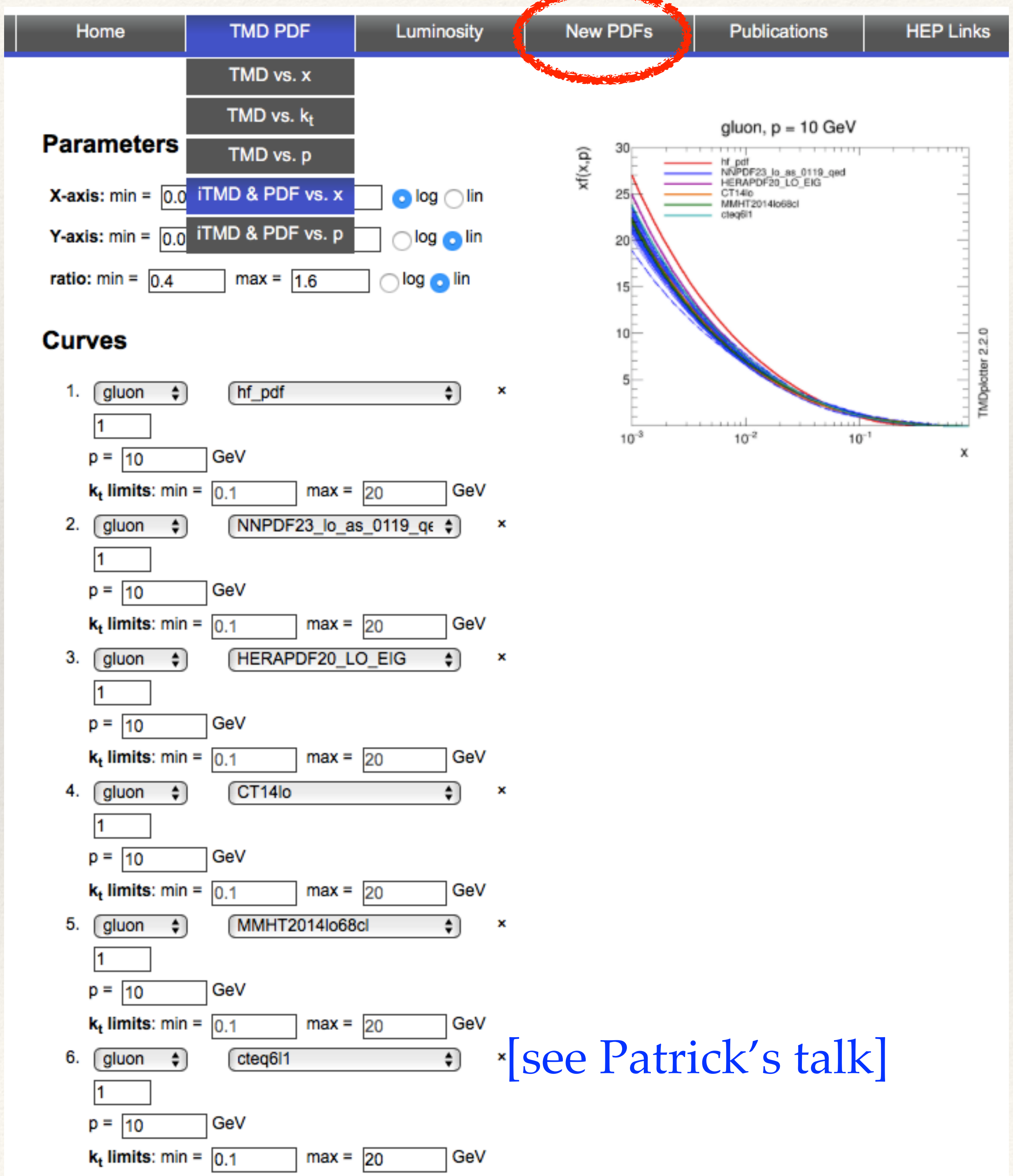
[not including PDF uncertainties]



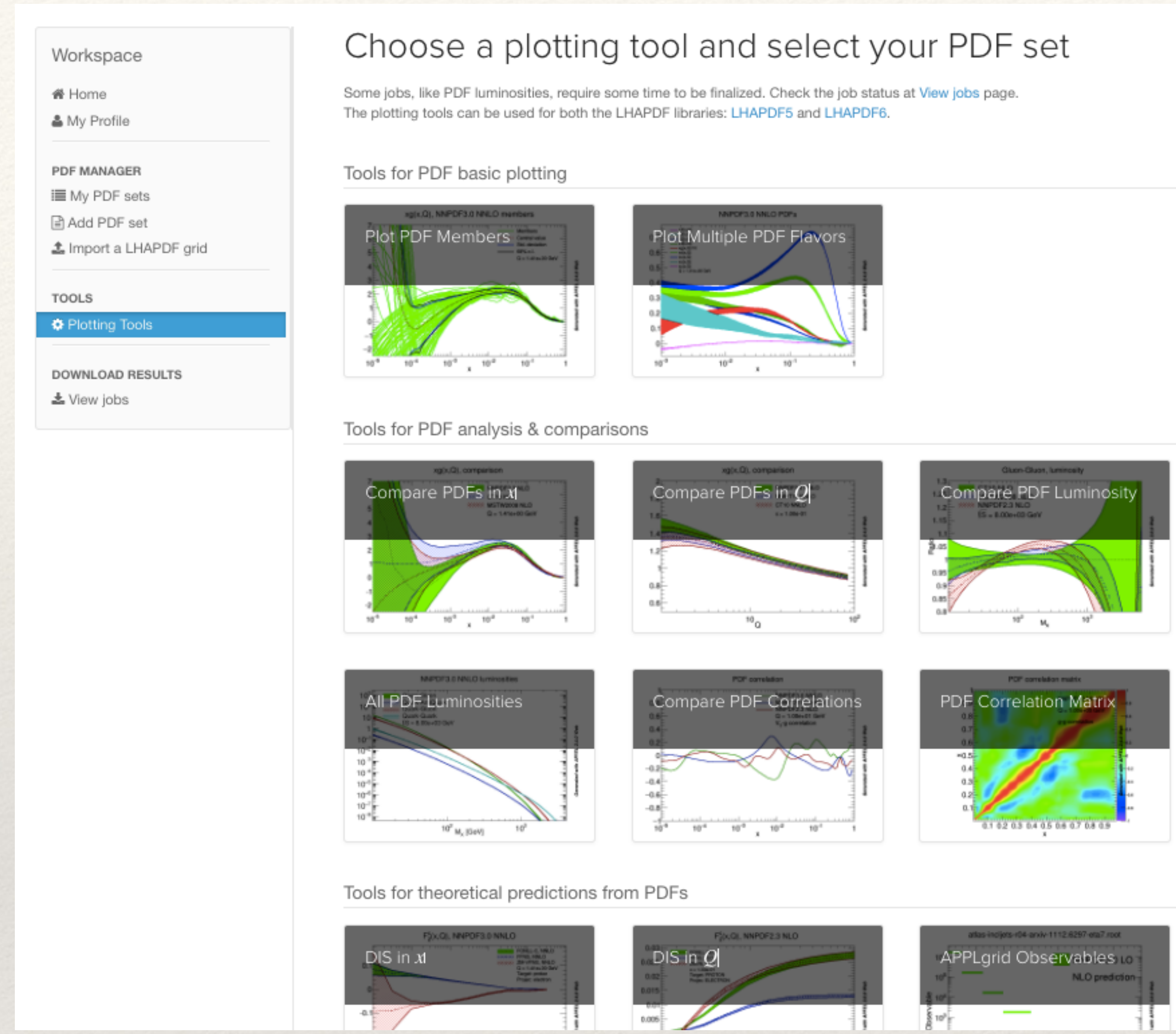
--> LHgrid that can be plugged in any other application

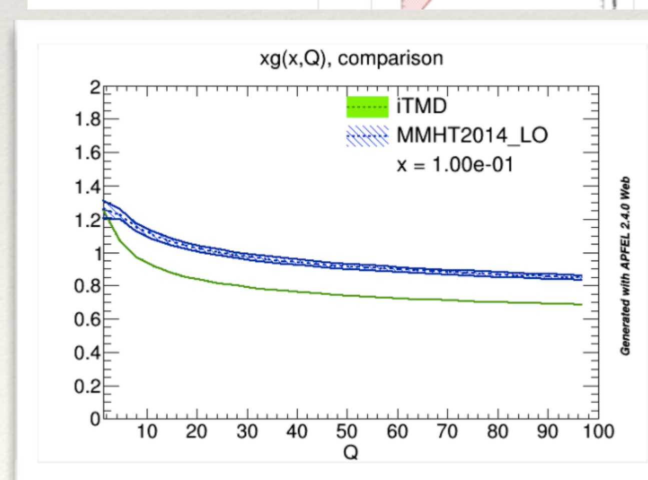
Example: using tmdplotter or apfel web interface

- TMDplotter http://tmdplotter.desy.de
- APFEL http://apfel.mi.infn.it/



[see Patrick's talk]





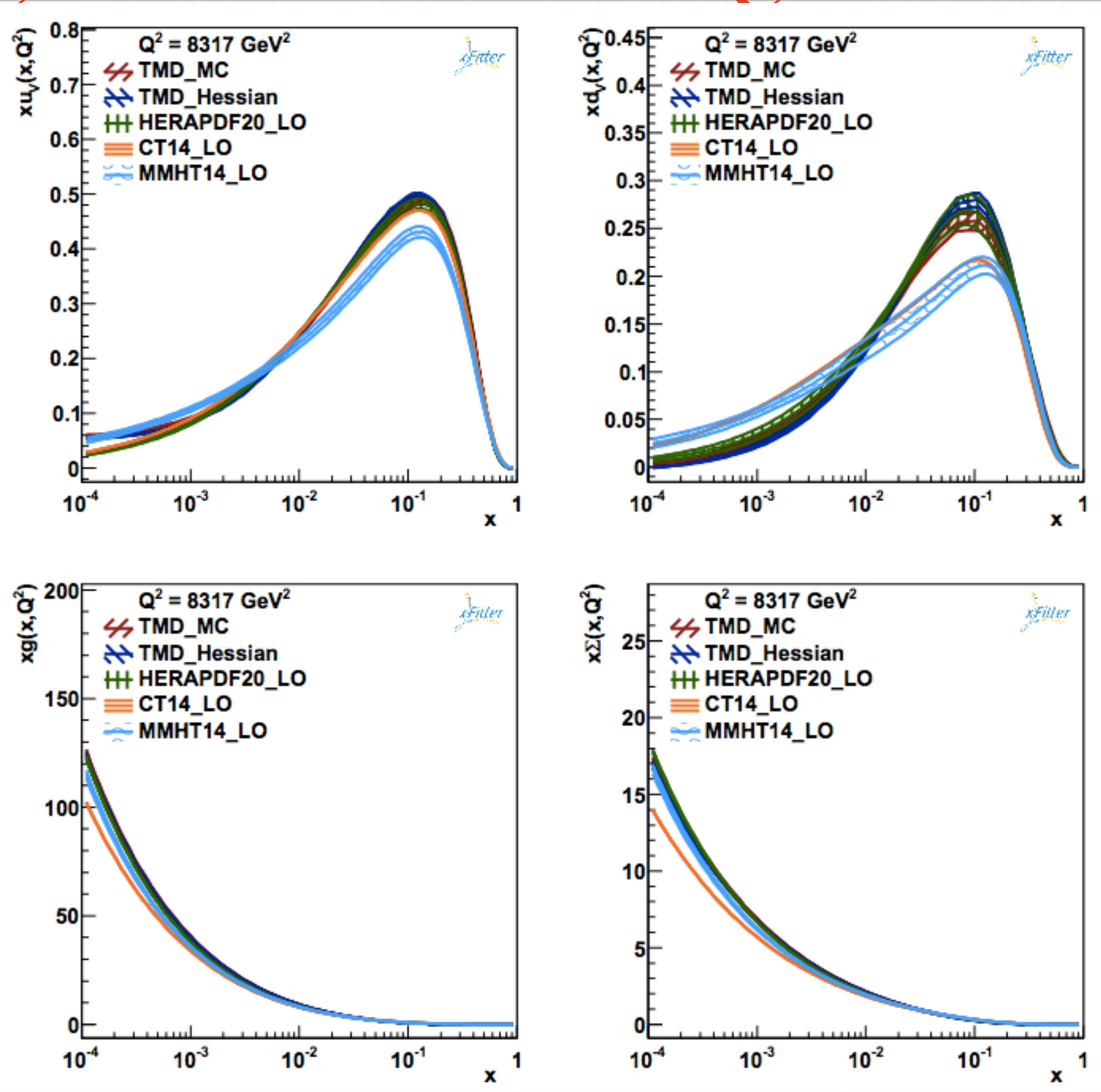
[see Valerio's slides]

Summary

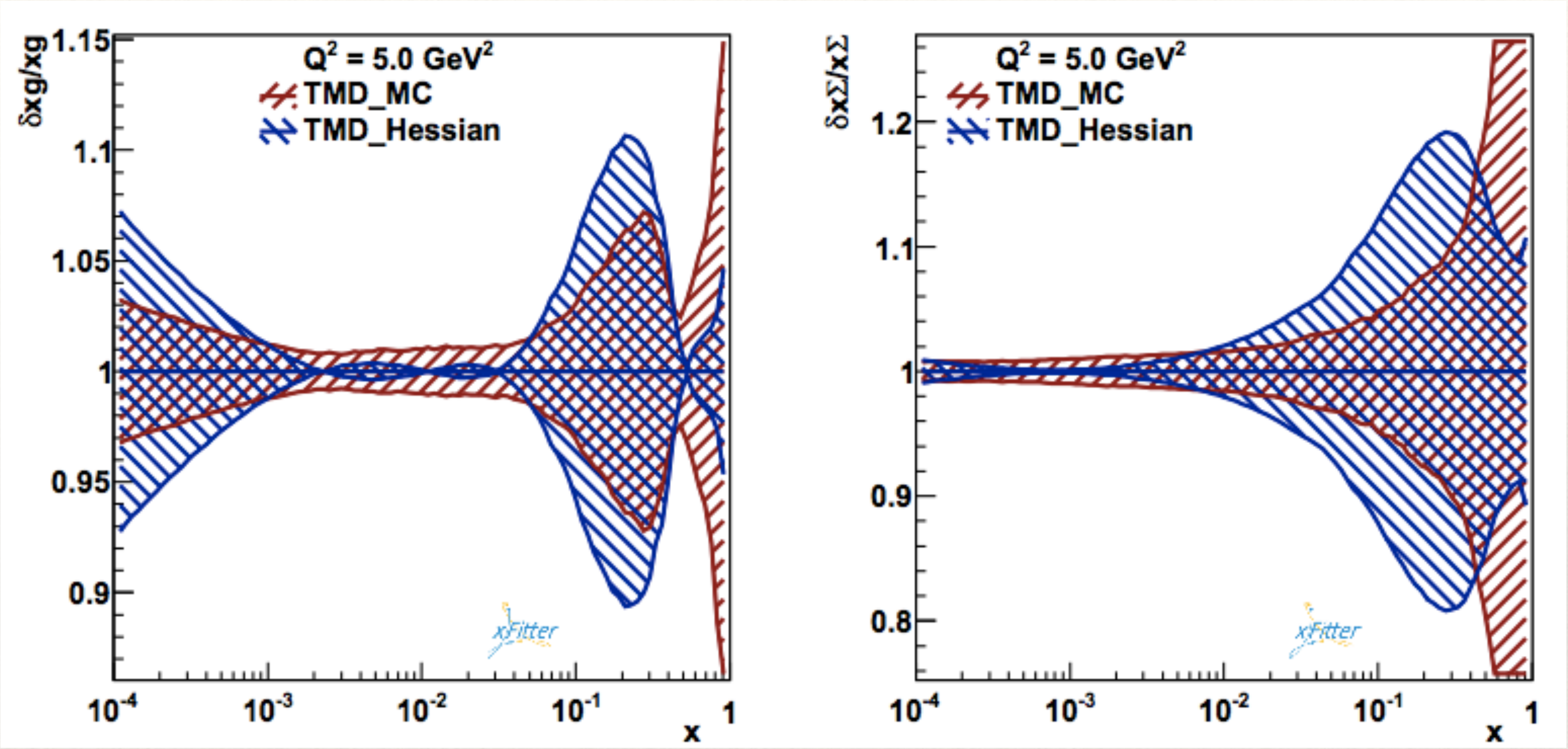
- The precision measurements at the LHC dictate for more scrutiny to allow for an interpretation in the context of QCD:
  - many observables suffer from a lack of a complete data modelling in a concise matter in a full kinematic phase space
- TMDs can be expanded from their role in the low x region to the full kinematic space for all quark species:
  - a first TMD using MC solution for DGLAP evolution at LO with experimental uncertainties estimated using replica or hessian methods has been extracted using xFitter QCD platform - a promising new avenue to provide a consistent modeling of the experimental data (from low to high pt)
    - fits based on DIS data from HERA
  - the iTMDs are automatically produced in LHAPDF grid formats
  - next goal is to extend the solution to NLO

Thank you!

integrated TMDs vs global PDFs



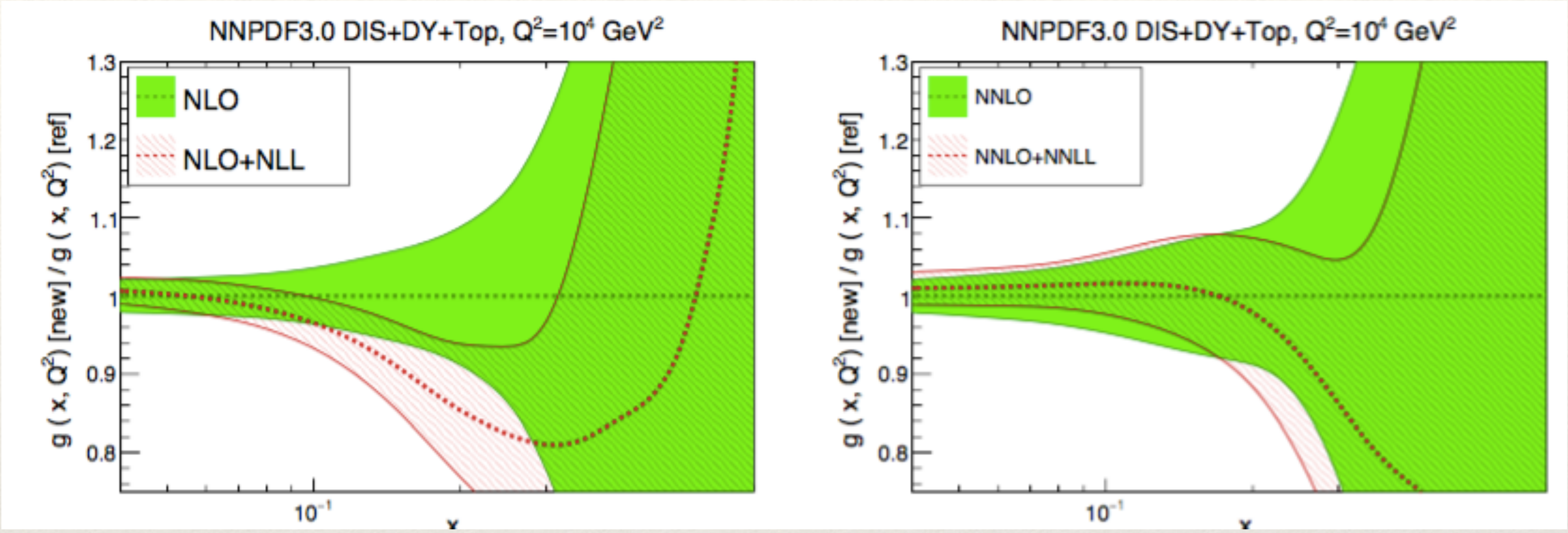
MC vs Hessian uncertainties



New developments: PDFs from resummed calculations

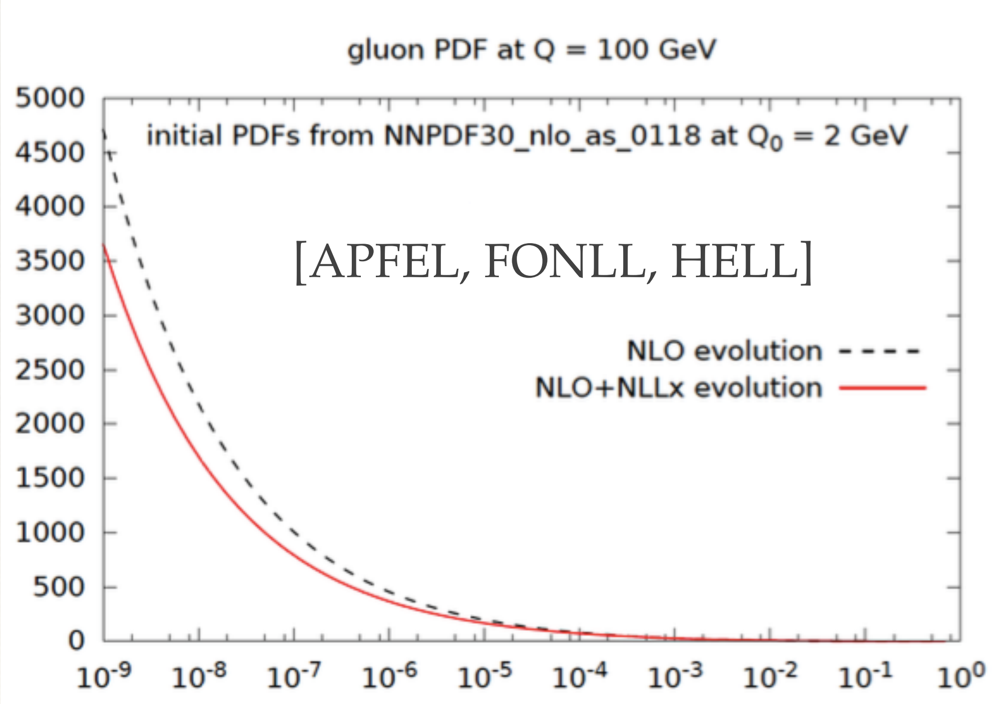
- Fixed order calculations dont always work and in order to improve the quality of PDF fits in small/ high x regions there have been efforts in providing PDFs consistent with Resummed Computations

[using NNPDF framework]



- PDF fits with threshold resummation tested [high x]
  - sizeable effect at NLO+NLL, smaller effect at NNLO+NNLL

- PDF fits with high-energy resummation show promising results [low x]
  - NLO+NLLx evolution



[ref: M. Bonvini QCD@LHC2016]

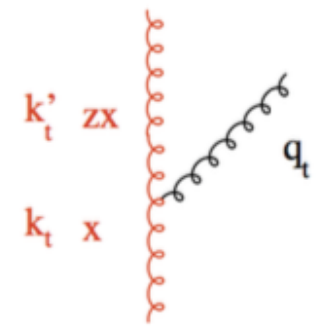
It would be interesting to see the effects combined: PDFs with resummed threshold and high-energy

MC evolution of parton densities

https://updfevolv.hepforge.org/

- Evolution consists of step-by-step simulation of individual branchings
  - at each branching, exact energy-momentum conservation is applied, including k_t

    $\vec{k'}_t = \vec{k}_t + \vec{q}_t$
  - with this, a TMD can be constrcuted, once q_t is known
  - evolution happens in q_t (for DGLAP) case with $q'_t \gtrsim q_t$
    - evolution in CCFM would be different ..
  - since only real splittings are simulated, z_{max} must be specified for splitting function.
    - virtual corrections are correctly treated with Sudakov form factor (see presentation by Ola at Dubna meeting)
- Apart from TMD densities, automatically (integrated) collinear densities are obtained:
  - evolution itself does not depend on k_t
- k_t enters the kinematics fro the x-section only



new version:

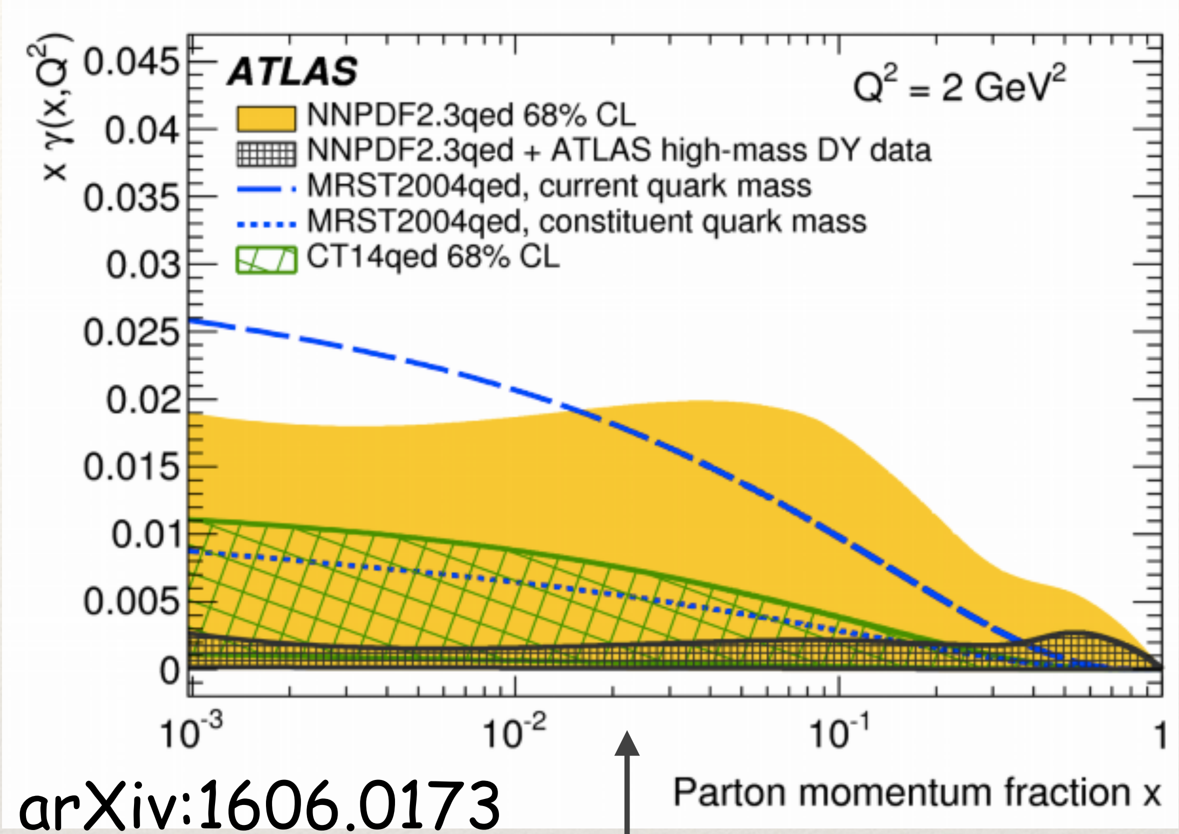
- full coupled quark and gluon DGLAP evolution (gluon, sea and valence evolution)
- fixed flavour number scheme (only u,d,s)
- LO in $P(z)$ (we plan to have NLO in $P(z)$),
- 1-loop-α_s (but also 2-loop-α_s implemented).
- $xf(x,t)$,

Evolution over the whole range in x, Q^2 and all kinematically allowed k_T.

[H. Jung, xFitter meeting]

New Developments for PDF extraction: photon PDF

- It starts to become relevant implementation of combined QCD+QED evolution in determining a complete set of PDFs including photon PDFs.

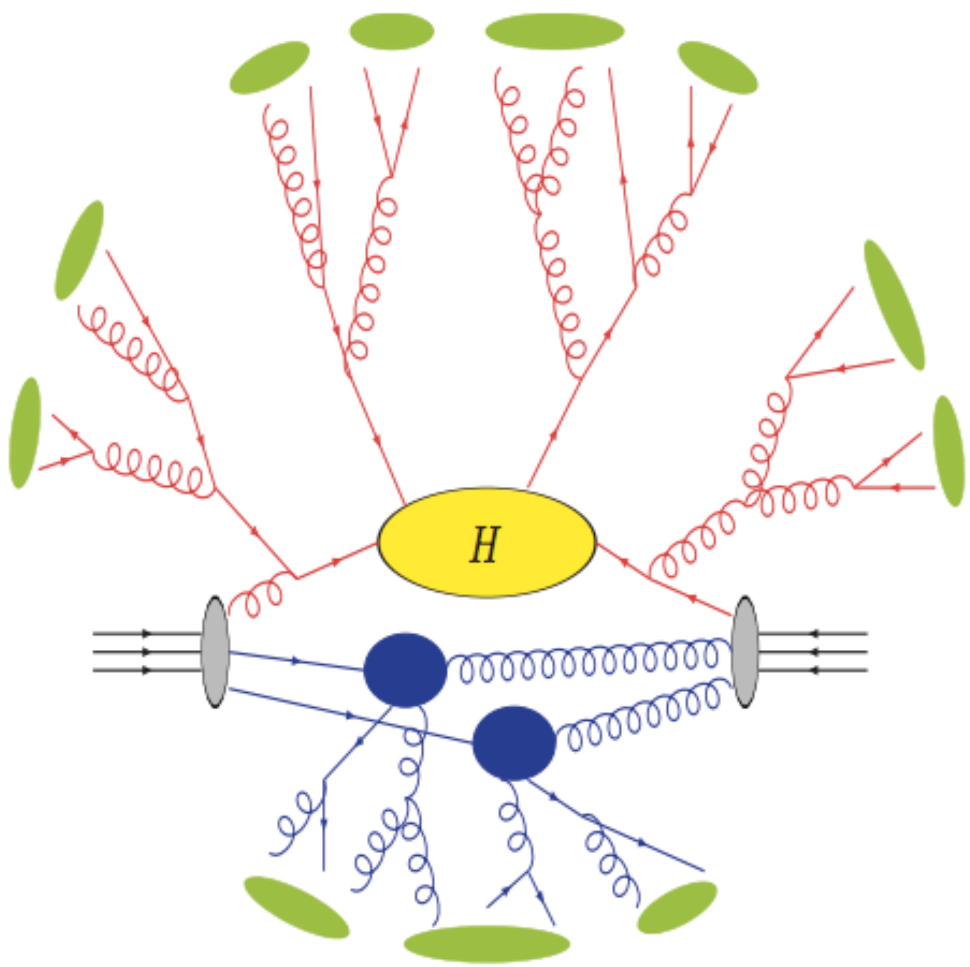


- **Studies that account for the photon PDF:**
  - Gluck, Pisano, Reya 2002
  - MRST2004 QED
  - NNPDF2.3 QED —> NNPDF3.0 QED
    - fit to data
  - CT14 QED, CT14 QED_inc
  - Harland-Lang, Khoze, Ryskin 2016
  - LUXqed 2016: Manohar, Nason, Salam, Zanderighi
    - use ep scattering and construct a hypothetical model for neutral lepton

Data has a lot of potential

Roles of PDFs in MC tuning

- Structure of an event at the LHC (courtesy of Z. Nagy)



1. Incoming hadron (gray bubbles)
   - Parton distribution function
   - Multi parton distribution functions
2. Hard part of the process (yellow bubble)
   - Matrix element calculation, cross sections at LO, NLO, NNLO level
3. Radiation (red graphs)
   - Parton shower calculation
   - Partonic decay
   - Matching to NLO, NNLO
4. Underlying event (blue graphs)
   - Models based on multiple interaction
   - Diffraction
5. Hardonization (green bubbles)
   - Universal models
   - Hadronic decay
   - ....

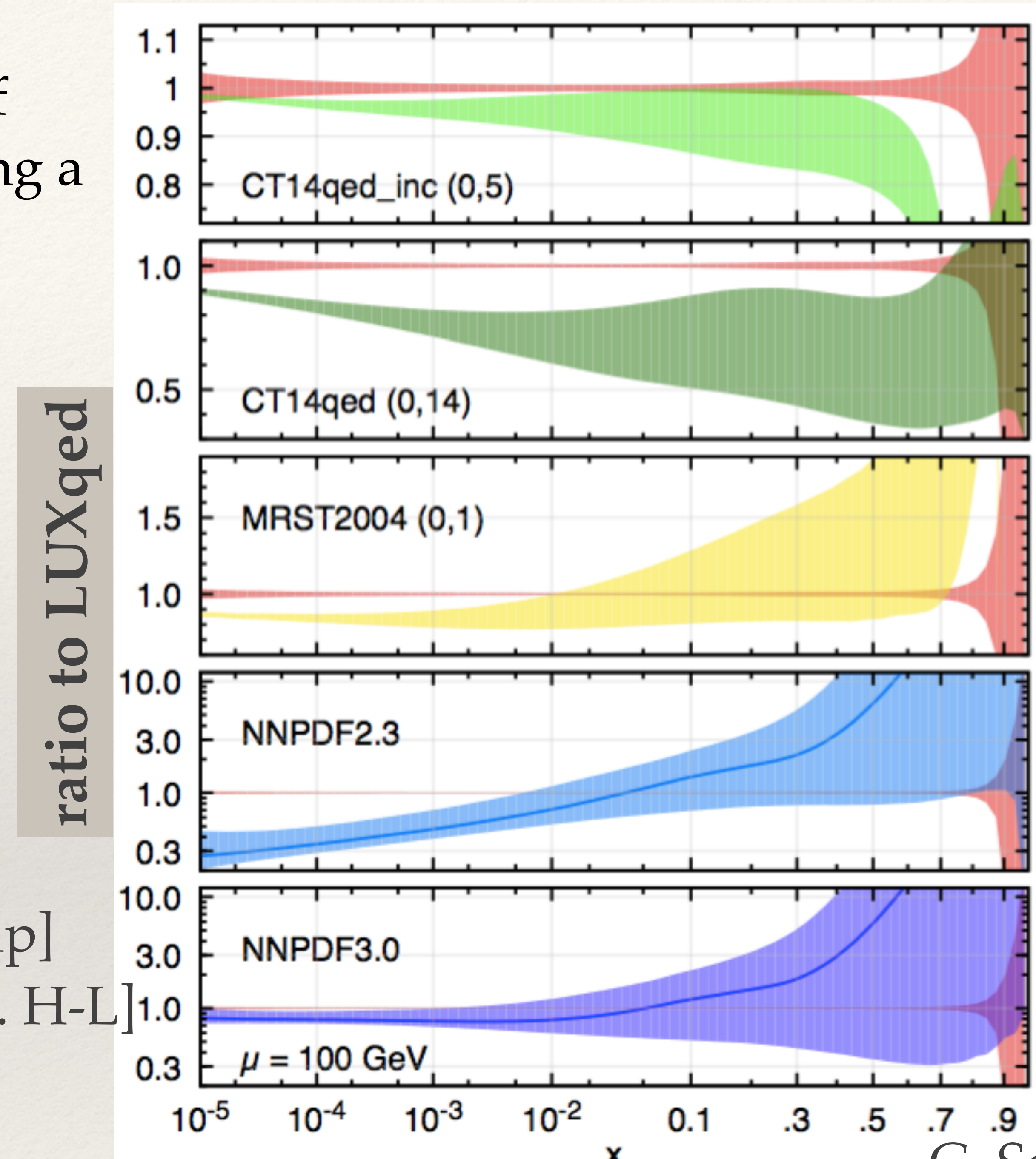
Perturbative framework:

- LO: easy to calculate: several matrix element generators are available:
  - ALPGEN, HELAC, MADGRAPH, SHERPA
  - Strong dependence on the unphysical scales
  - well defined with LO PDF
- NLO is the New Standard: HELAC, MADGRAPH, SHERPA+BLACKHAT, AUTODIPOLE, TEVJET, AMC@NLO
  - The scale dependence can be still big in some processes
- NNLO & NkLO: Resummation - Parton Showers: POWEHEG

New Developments for PDF extraction: photon PDF

- It starts to become relevant implementation of combined QCD+QED evolution in determining a complete set of PDFs including photon PDFs.

limited experimental constraints



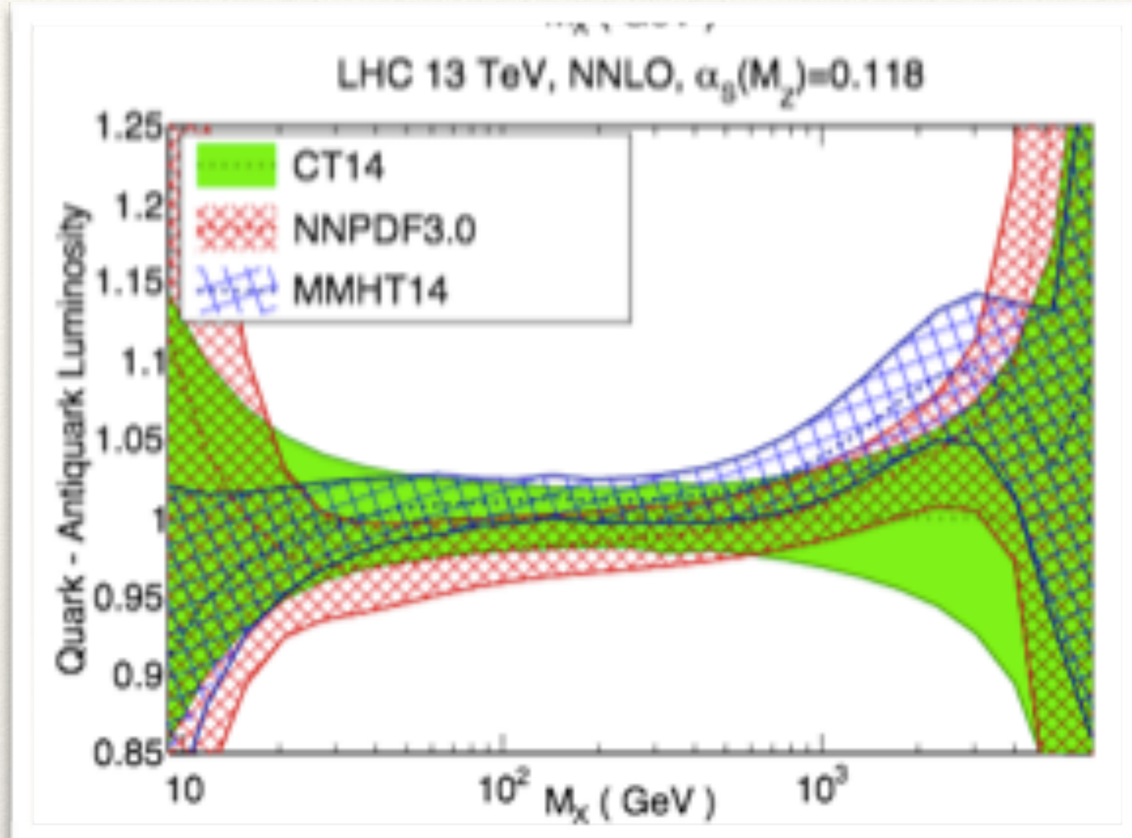
G. Salam

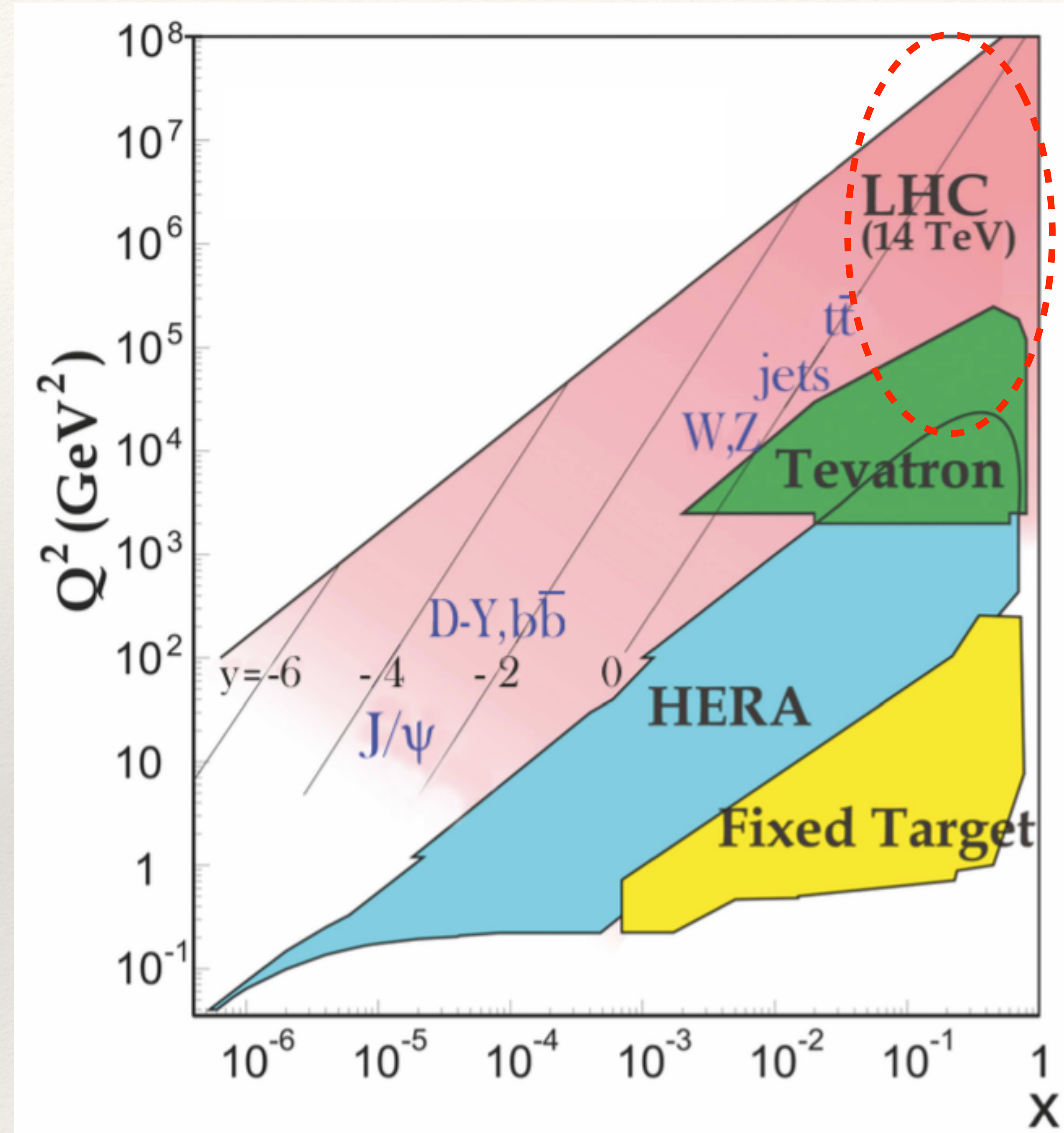
- **Studies that account for the photon PDF:**
  - Gluck, Pisano, Reya 2002
  - MRST2004 QED
  - NNPDF2.3 QED —> NNPDF3.0 QED
    - fit to data
  - CT14 QED, CT14 QED_inc [see D. Stump]
  - Harland-Lang, Khoze, Ryskin 2016 [see L. H-L]
  - LUXqed 2016: Manohar, Nason, Salam, Zanderighi
    - use ep scattering and construct a hypothetical model for neutral lepton

—> interesting to confront these models with data

Search for new physics at high scales:

[arXiv:1410.6810v2]





For masses >1 TeV, PDF uncertainties increase to > 15%

—> can we then distinguish a possible signal?

—> scale uncertainties (missing HO) vs PDFs

PDFs then drive the main theory uncertainty

how to improve?

LHC data vs state-of-the-art theory (@NNLO)

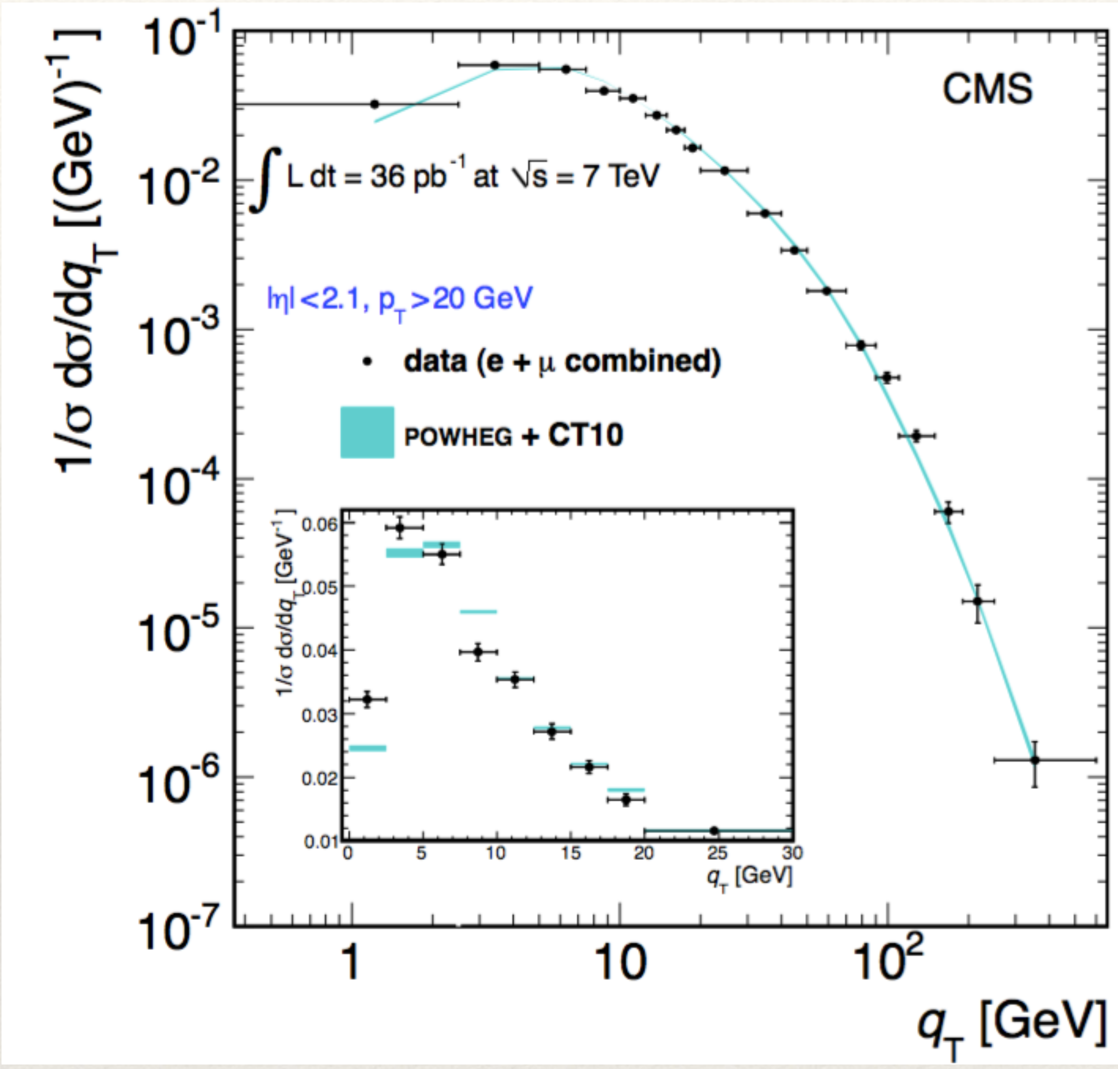
- ttbar can be interesting channel
- high mass DY can extend to high lever arm reach
- jet data

high mass <—> high x

Fixed order calculations vs Resummed or + PS

- Fixed order calculations dont always work and in order to improve the quality of PDF fits in small/high x regions there have been efforts in providing PDFs consistent with Resummed Computations

- high-qT region
  - it is expected to be described by f.o
- at low and peak qT
  - QCD radiation not described by truncated pQCD
  - it requires methods to resum arbitrary many parton emissions



low peak high

There are different approaches to address the failure of f.o. calculations

TMDs

- Fixed order calculations dont always work and in order to improve the quality of PDF fits in small/high x regions there have been efforts in providing PDFs consistent with Resummed Computations

MC simulation combine f.o. partonic calculations with PS and hadronisation
—> need reshuffling of kinematic variables after PS generations required by energy-momentum conservation

generalisation of QCD factorisation where now the explicit dependence on transverse momentum and polarisations —> TMDs
they obey the evolution equations which generalise the ordinary RGE of collinear PDFs
—> allows resummations of large logs (M/qT) to all orders in alphas

New approach to solve coupled gluon and quark DGLAP evolution equation for Monte Carlos:

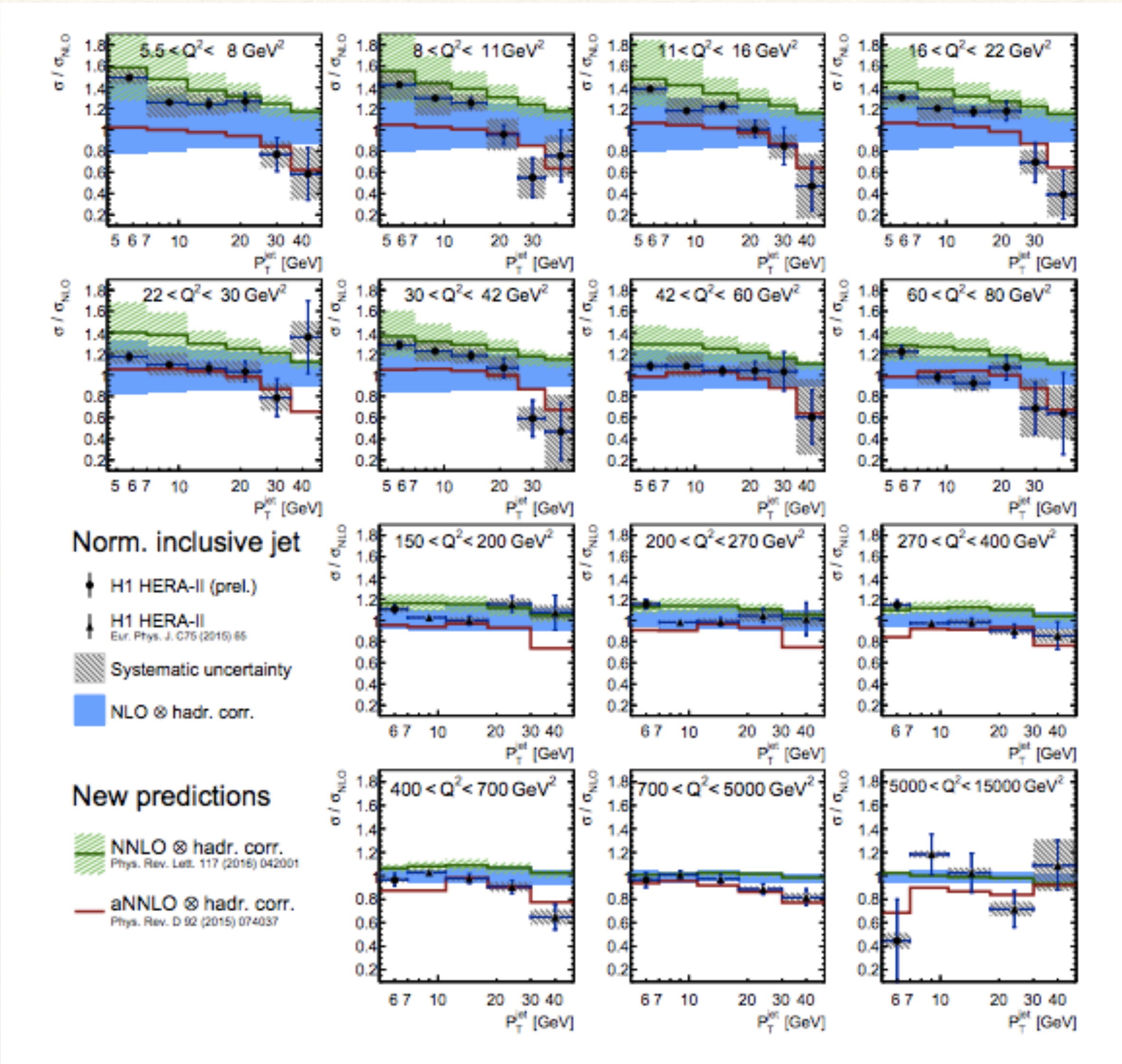
Advantages:

- a full TMD pdf evolution including gluon, sea and valence quarks over the full range in x and Q^2 with the k_T dependence in the whole kinematically available range (not limited to the small k_T),
- reproduce semi-analytical solution (results consistent with QCDNum),
- direct usage in PS matched calculation.

[using TMDs in xFitter]
credit: H. Jung, F. Hautmann, A. Lelek

First NNLO for jets @ H1, HERA

H1prelim-16-062



Predictions	NLO	aNNLO	NNLO
Jet cross sections			
Program	nlojet++	JetViP	NNLOJET
pQCD order	NLO [8]	approximate NNLO [12]	NNLO [15]
Calculation detail	Dipole subtraction	NLO plus NNLO contributions from unified threshold resummation formalism	Antenna subtraction
NC DIS cross sections			
Program	QCDNUM	APFEL	APFEL
Heavy quark scheme	ZM-VFNS	FONLL-C	FONLL-C
Order	NLO	NNLO	NNLO
PDF	NNPDF3.0_NLO	NNPDF3.0_NNLO	NNPDF3.0_NNLO
$\alpha_s(M_Z)$	0.118	0.118	0.118
Hadronisation corrections	Djangoh and Rapgap		
Available for			
Normalised inclusive jet	✓	✓	✓
Normalised dijet	✓		✓
Normalised trijet	✓		

- This opens up a new avenue for PDF fits

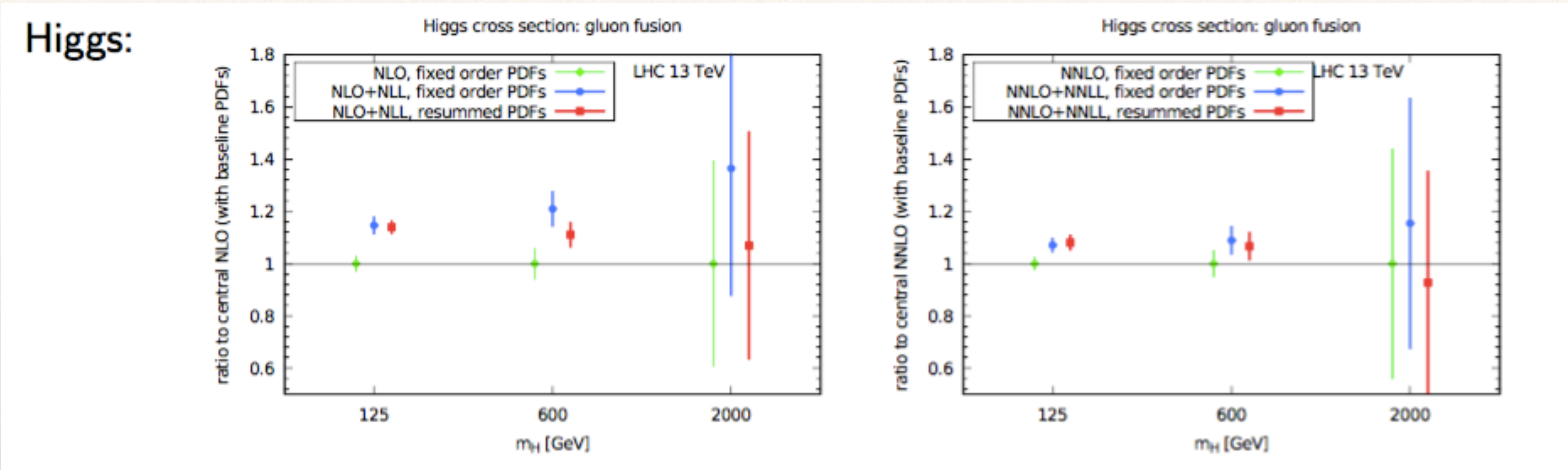
  —> a boost to re-analyse Tevatron and LHC jets !

Expectations from LHC data

- **Gluon:**
  - Inclusive jets, dijets, trijets —> medium/large x
  - Isolated photon and photon+jets —> medium/large x
  - ttbar production —> large x
  - Zpt spectrum —> small/medium x
- **Quarks:**
  - W and Z rapidity spectra —> medium x
  - High pT W+jets —> medium /large x
  - Low mass and high mass DY —> small/large x
  - W+c rapidity spectrum —> strange at medium x
  - single top differential —> medium/high x
- **Photon:**
  - WW production
  - High Mass DY

PDFs with resummed calculations

- Impact of the resummed PDFs vs fixed order PDFs:



- Tools for fitting development:
  - HELL: High-Energy Large Logarithms interfaced to APFEL
    - based on the ABF approach for resummation
    - which delivers resummed splitting functions and coefficient functions
    - Therefore could be used for fitting using resummed evolution together with the resummed coefficient functions